Hints for new physics from SM precision measurements: experimental investigation of vector boson scattering

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Physics beyond the Standard Model: Modern Approaches

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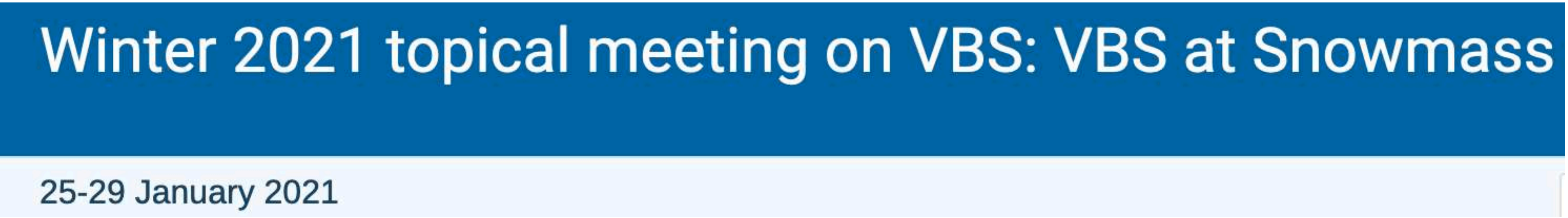
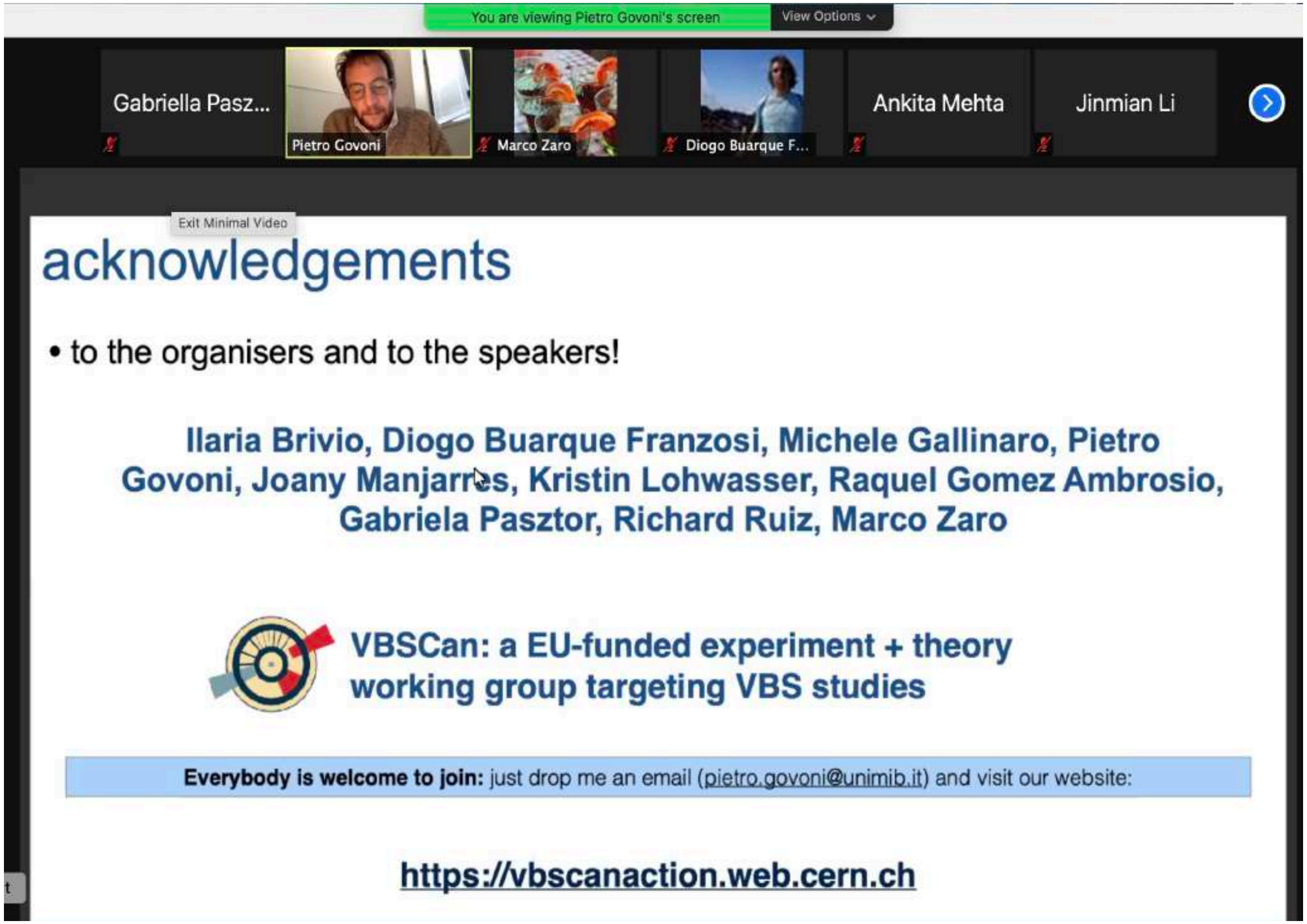
Most material was taken from https://indico.cern.ch/event/980773/overview



Winter 2021 topical meeting on VBS: VBS at Snowmass

25-29 January 2021



acknowledgements

- to the organisers and to the speakers!

Ilaria Brivio, Diogo Buarque Franzosi, Michele Gallinaro, Pietro Govoni, Joany Manjarres, Kristin Lohwasser, Raquel Gomez Ambrosio, Gabriela Pasztor, Richard Ruiz, Marco Zaro

VBSCan: a EU-funded experiment + theory working group targeting VBS studies

Everybody is welcome to join: just drop me an email (pietro.govoni@unimib.it) and visit our website:

https://vbscanaction.web.cern.ch

In particular, thanks for the slides of the following colleagues

- Ansgar Denner (theory)
- Joany Manjarres (ATLAS)
- Kenneth Long (CMS)
- Kristin Lohwasser (ATLAS)
- Flavia Cetorelli (CMS)

Slides marked by

BONUS

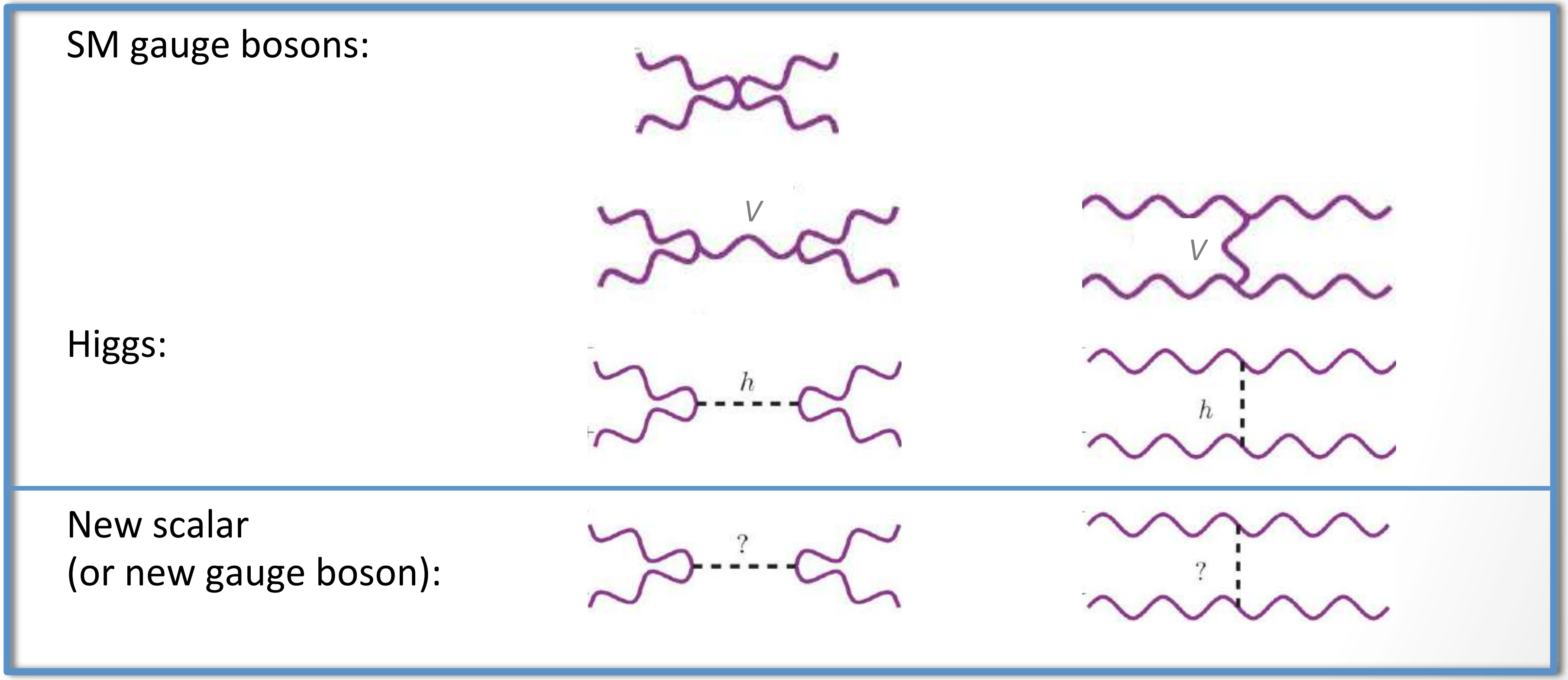
only for people interested
In more technical details

VV scattering: a probe of EWSB

Vector boson scattering is „intimately” connected to EWSB and new physics

- In SM, unitarity in VV scattering is restored by Higgs exchange: $\sigma \sim O(E^2) - O(E^2) \rightarrow O(E^0)$
- If HVV coupling is not exactly the SM value, unitarity is not realized [$\sigma \sim O(E^2)$] or „delayed” until a new high-mass state enters

Even if no new physics is observed directly (finite energy reach, large backgrounds), VV scattering can reveal its existence



SM gauge bosons:

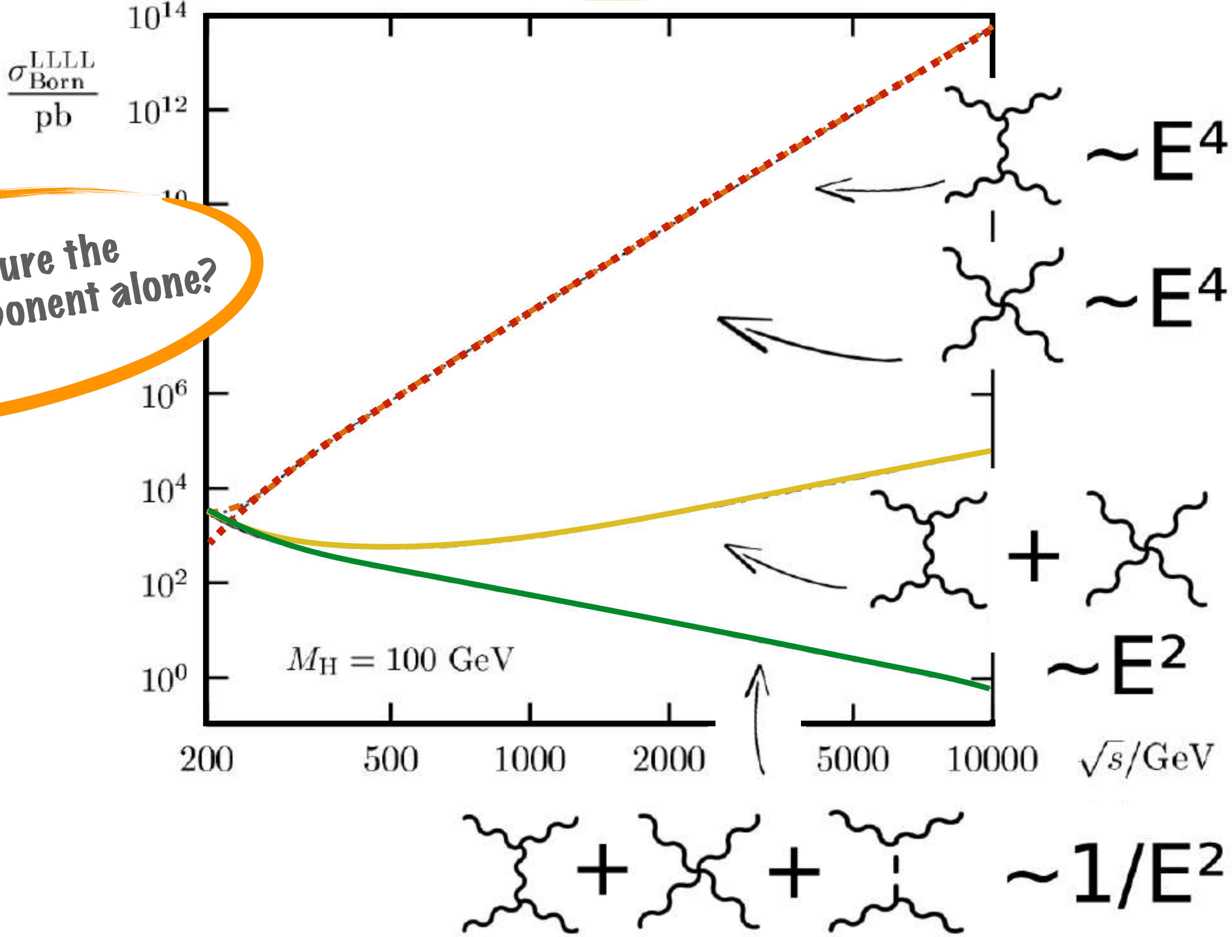
Higgs:

New scalar
(or new gauge boson):

Why Vector Boson scattering is interesting?

- Example: Cross-section for longitudinal $W_L^+W_L^- \rightarrow W_L^+W_L^-$ scattering

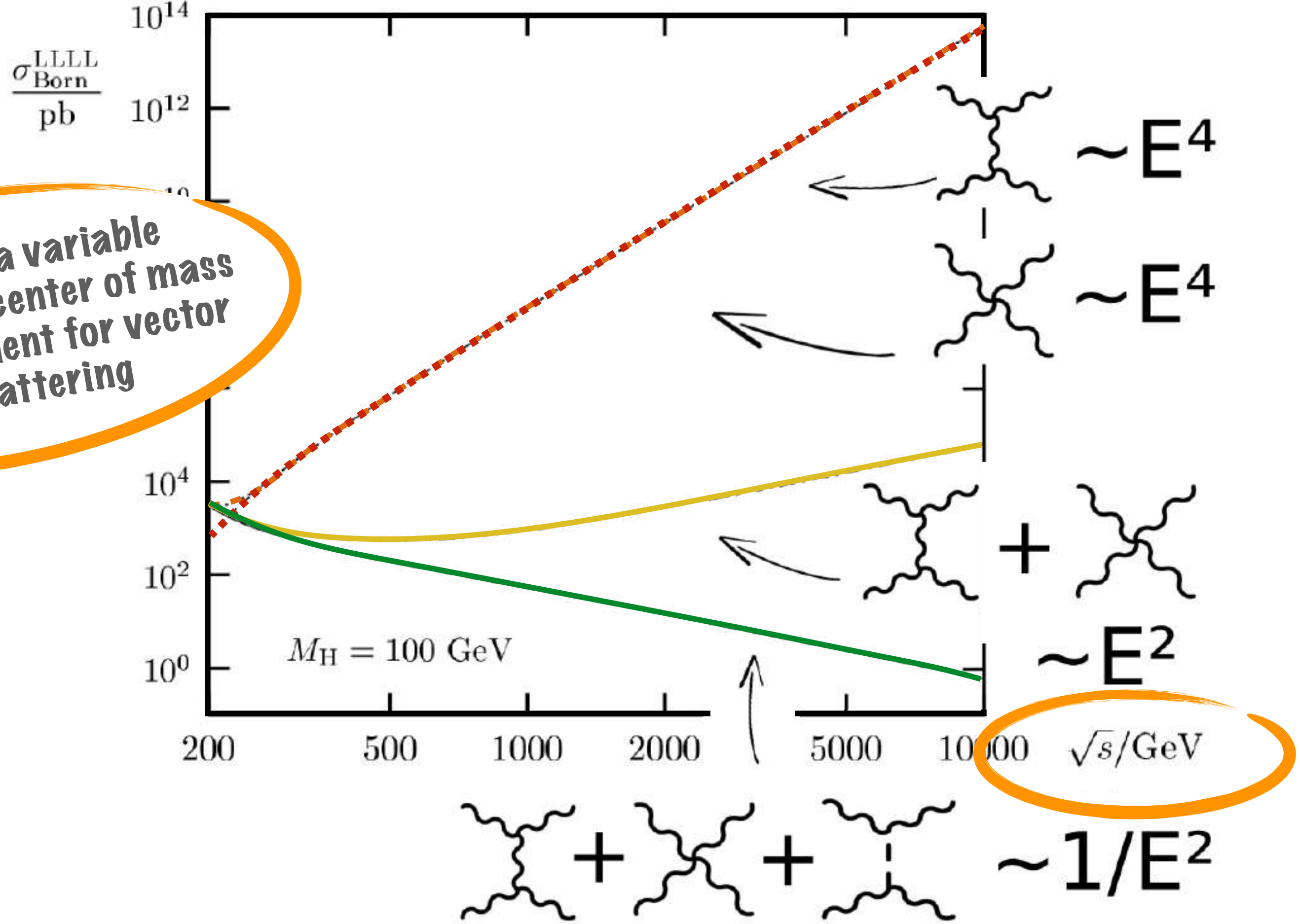
[Denner, Hahn, 1997]



Can we measure the longitudinal component alone?

- Test of electroweak sector and EW Symmetry Breaking
- Complementary to “direct” Higgs boson property studies
- Differences in this sector will be indications of new physics

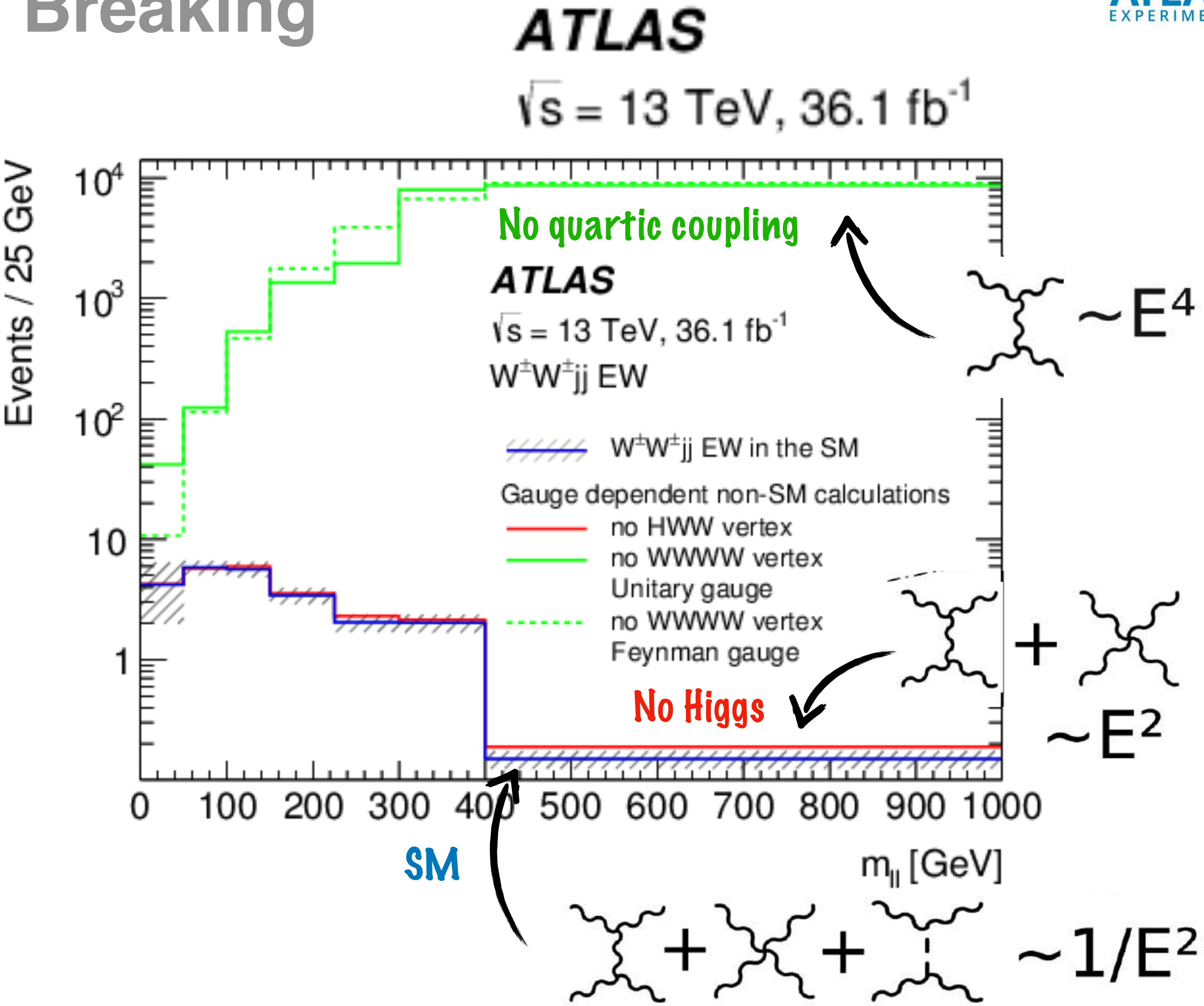
Why Vector Boson scattering is interesting?



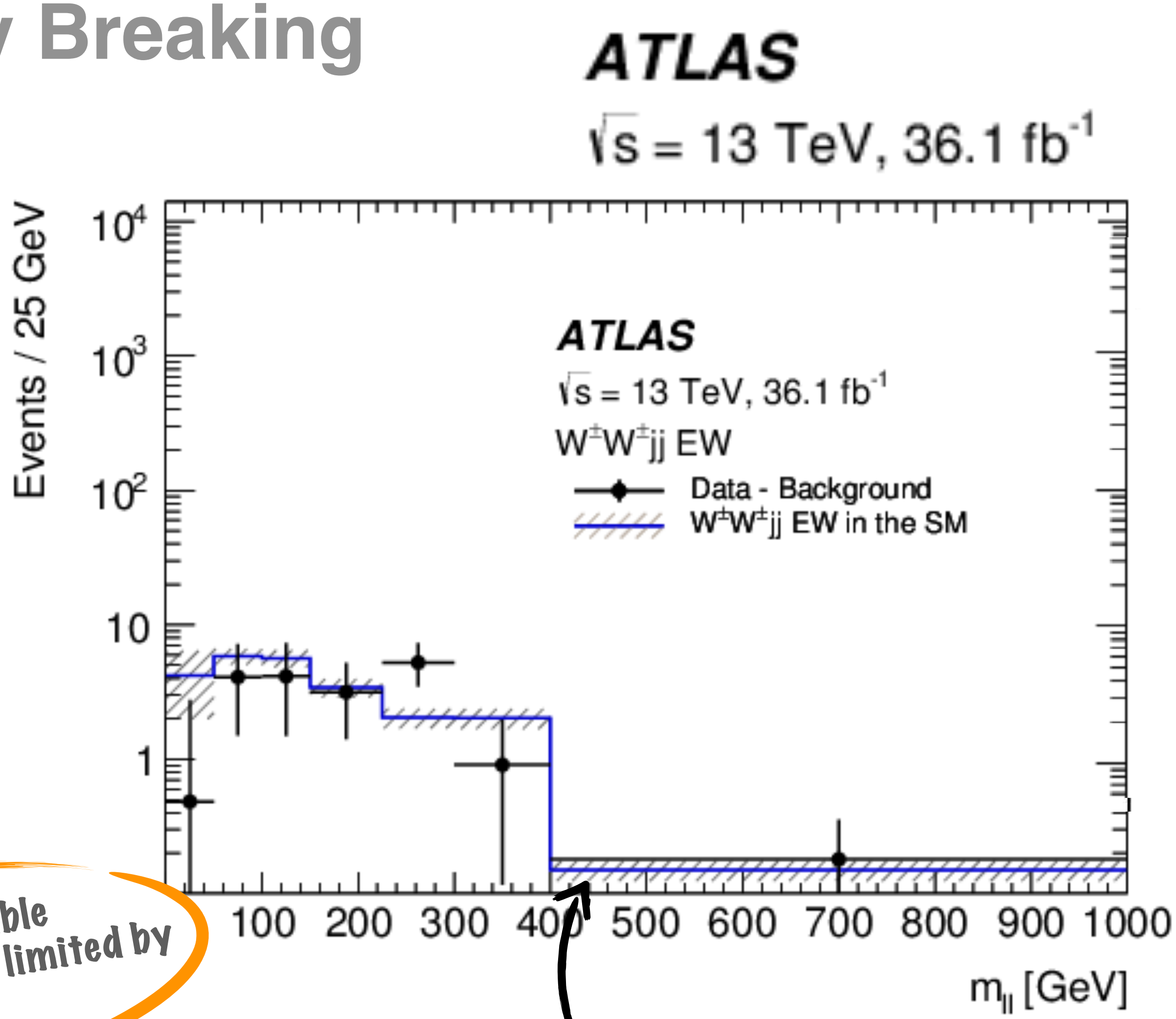
[Denner, Hahn, 1997]

Need to find a variable sensitive to the center of mass energy, not evident for vector boson scattering

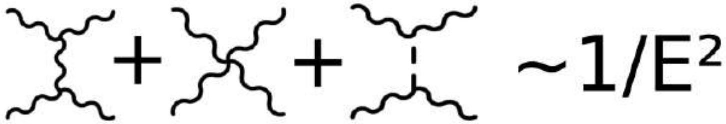
Testing the electroweak sector and EW Symmetry Breaking



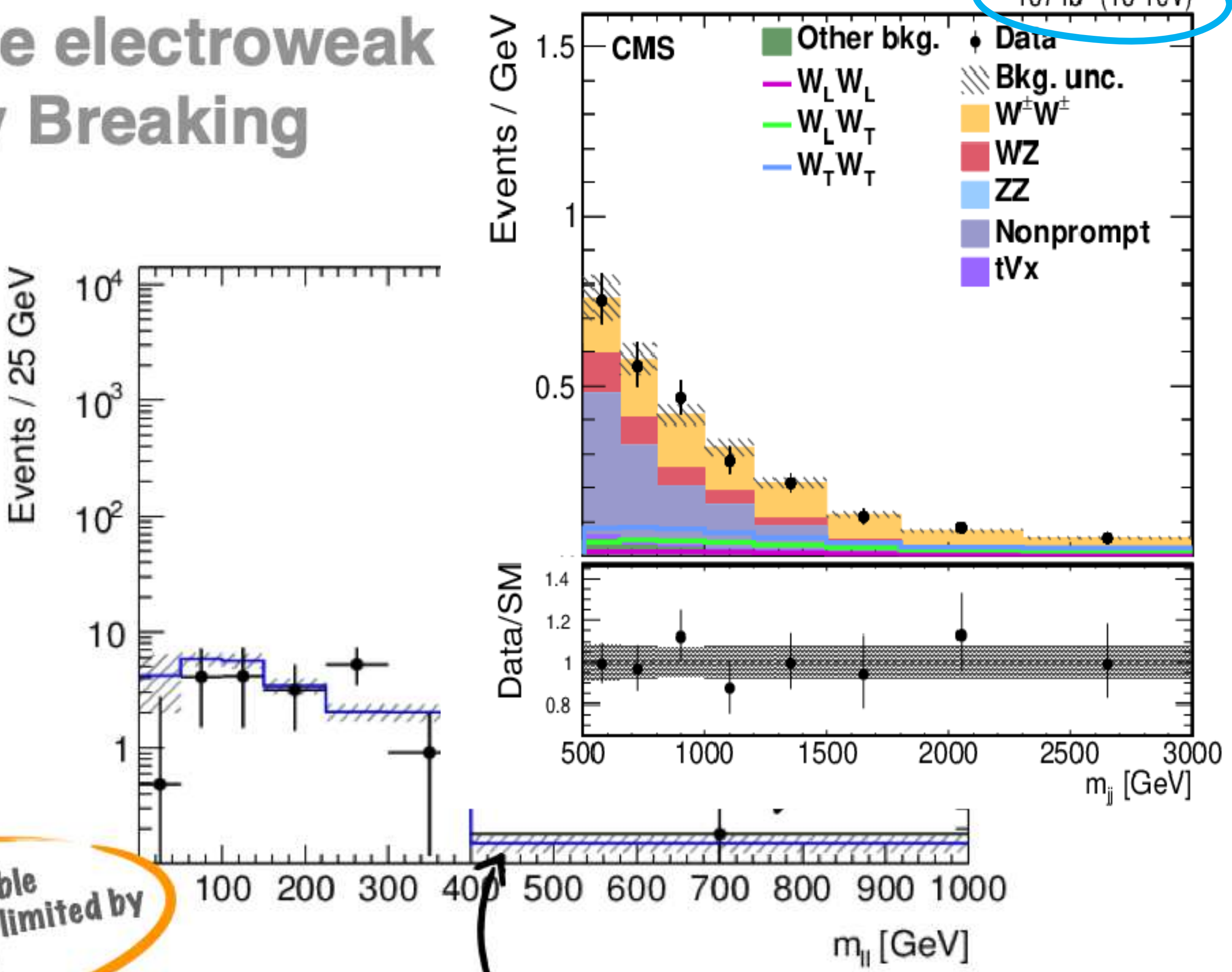
Testing the electroweak sector and EW Symmetry Breaking



So far compatible with the SM, but still limited by statistics!

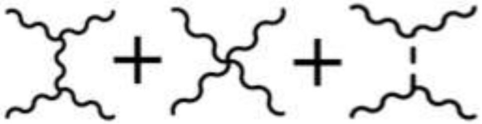


Testing the electroweak Symmetry Breaking



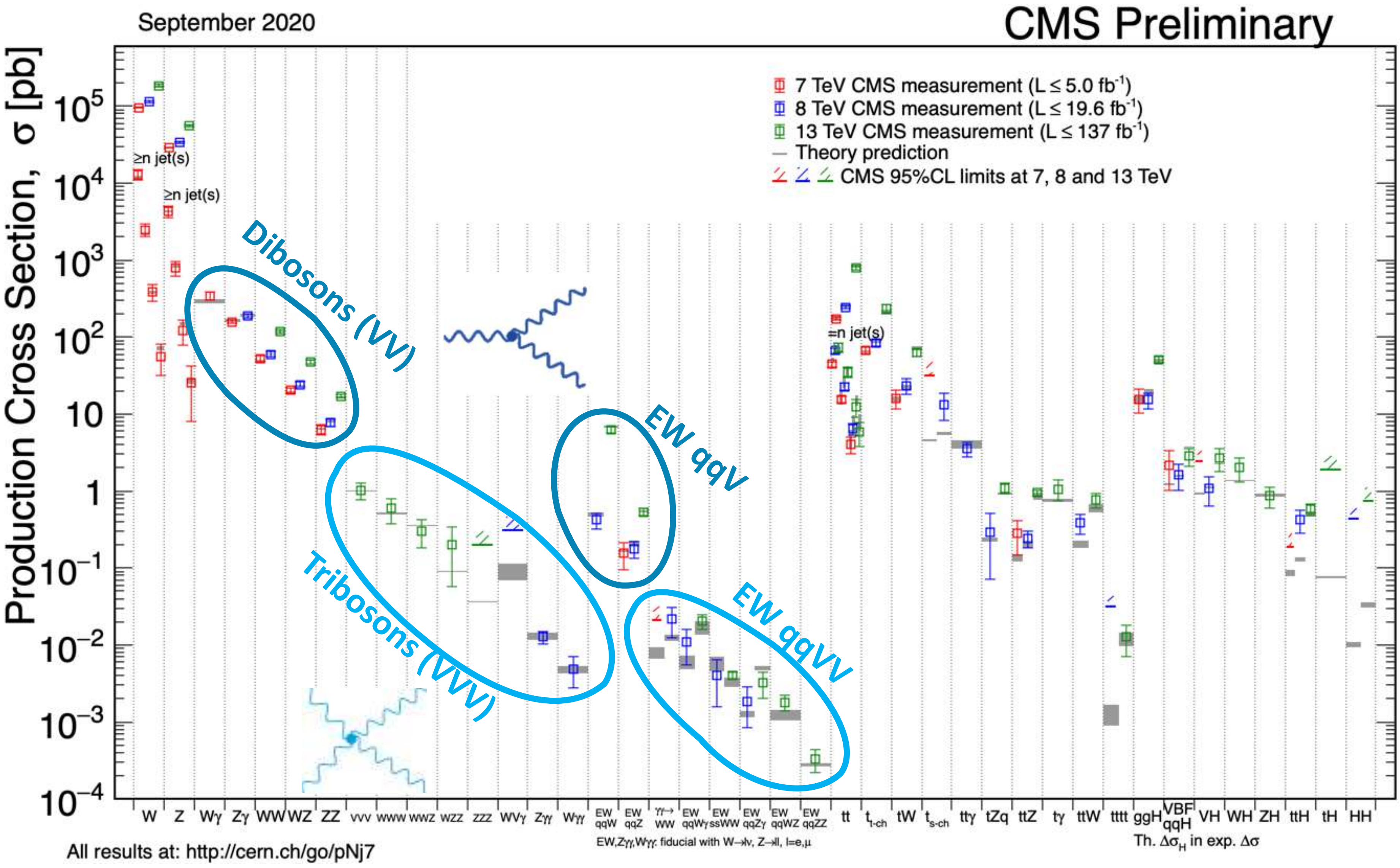
x4 statistics

So far compatible with the SM, but still limited by statistics!

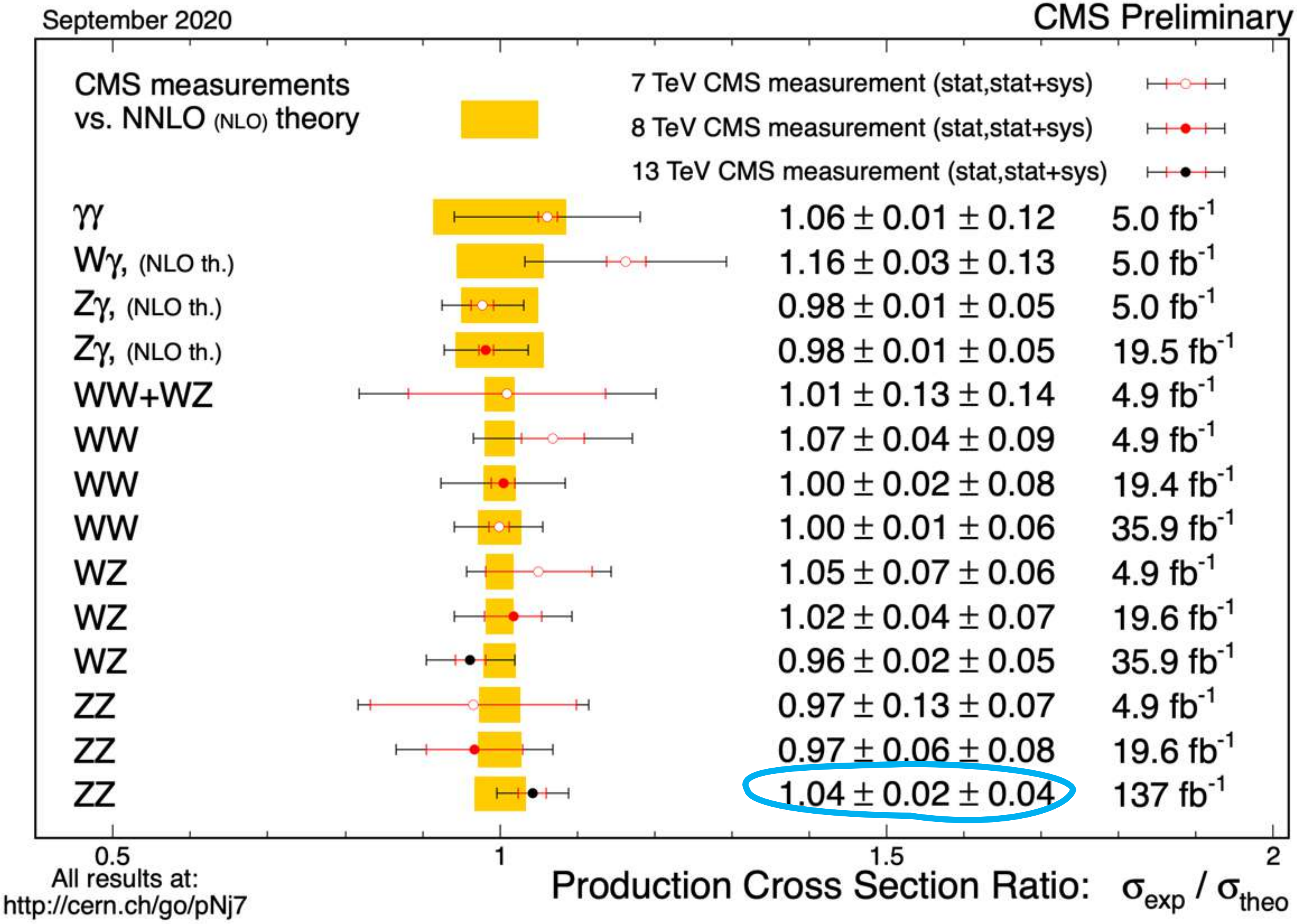


$\sim 1/E^2$

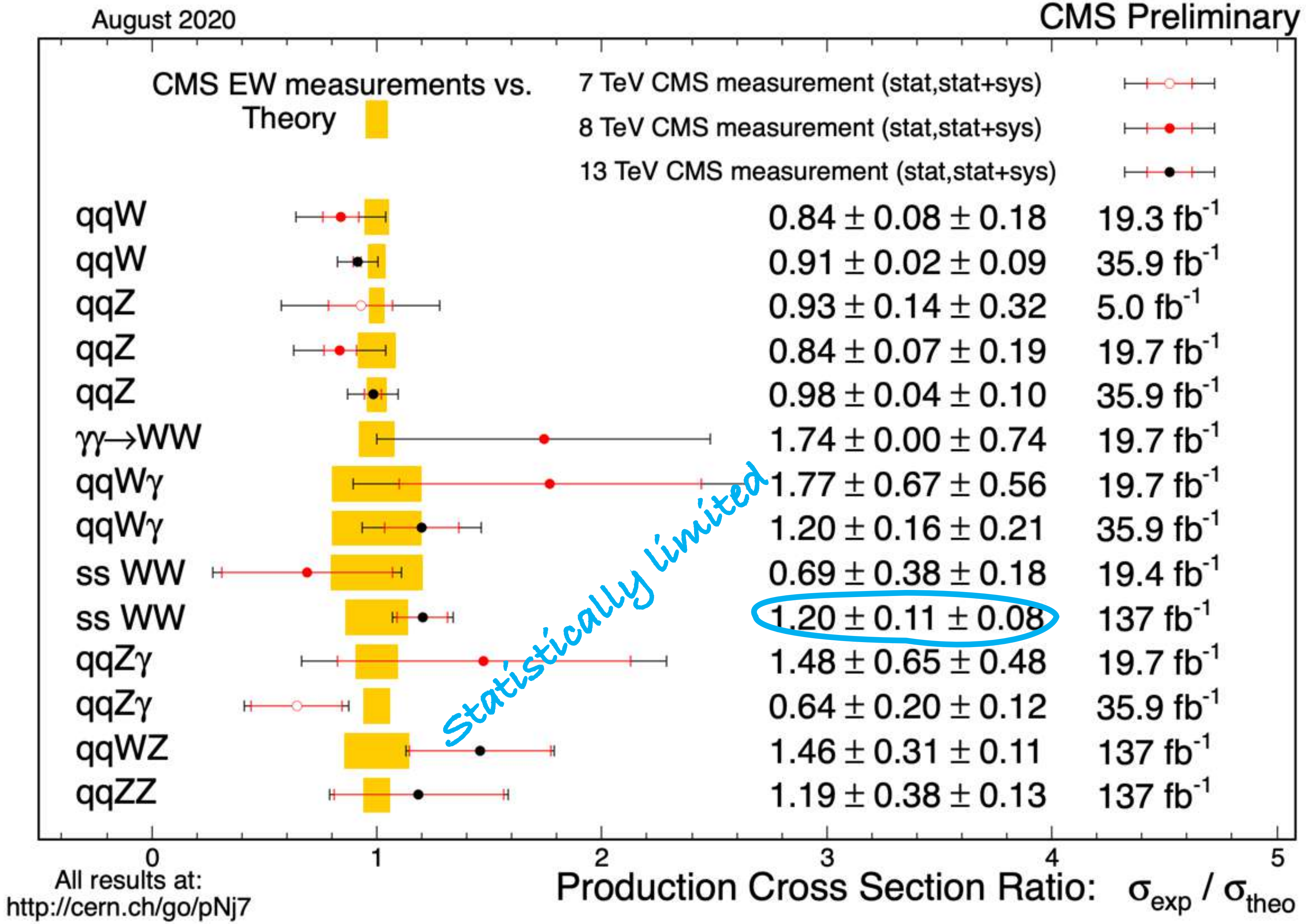
Challenge: very low cross-sections



Diboson cross-sections: Δσ ≳ 4%



EW qqVV cross-sections: Δσ ≳ 14%



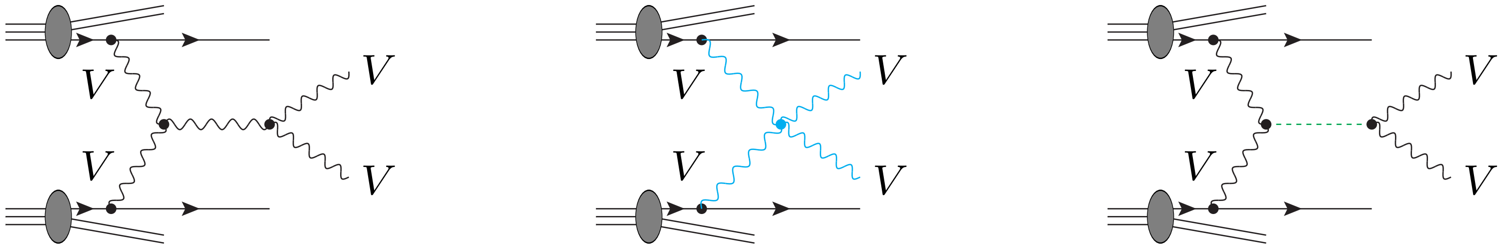
Statistically limited

LHC programme

- Run 1:
  - Discovery of the Higgs boson
  - exclusion limits for new physics models
- Run 2:
  - Study of properties of the Higgs boson
  - precise measurements of standard-candle processes ($\mathrm{Drell\text{-}Yan}, \mathrm{t\bar{t}}, VV, \ldots$)
  - measurement of new SM processes ($\mathrm{t\bar{t}H}$, VBS, VVV, . . .)
  - further exclusion limits for new physics models
- Run 3 and beyond:
  - improved precision tests of SM processes and parameters
  - measurement of further new SM processes
  - discovery of New Physics?

Precise theoretical predictions needed to match improved experimental accuracy!

Electroweak vector-boson scattering at the LHC



Physics issues of vector-boson scattering (VBS): $(V = \mathrm{W}, \mathrm{Z})$

- key process to test electroweak symmetry breaking
  Higgs boson crucial for unitarity of process
- search for anomalous quartic-gauge-boson couplings
  sensitivity grows with energy of gauge bosons

Improvement of experimental precision

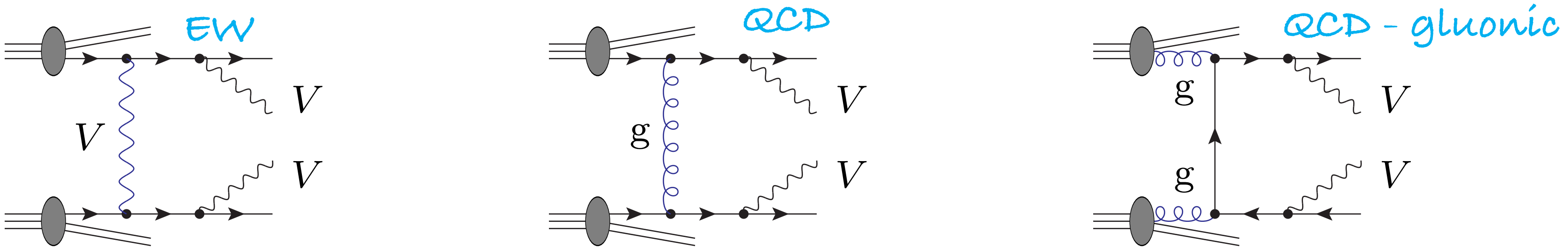
Integrated Luminosity	36 fb	150 fb	300 fb	3000 fb-
Year	2016	2019	2022	2038
EW(VBS) W±W±	20%	10%	7%	2%
EW (VBS) ZZ	35%	18%	13%	6%
EW (VBS) WZ	35% personally anticipated	18%	13%	6%

Jakob Salfeld-Nebgen in https://indico.cern.ce/event/711256

must be matched by theoretical calculations

Irreducible background to VBS

Final state: $VV + 2\mathrm{j} \quad (4l + 2\mathrm{j})$



- Full electroweak (EW) process $[\mathcal{O}(\alpha^4)$ for stable Vs]
  not separable from VBS
- QCD process $[\mathcal{O}(\alpha_\mathrm{s}^2\alpha^2)$ for stable Vs]
  gauge-invariant contribution
- interferences between EW and QCD contributions
  $[\mathcal{O}(\alpha_\mathrm{s}\alpha^3)$ for stable Vs]
  appear only for channels with identical or weak-isospin partner quarks
- gluonic channels for neutral final states
- irreducible background can be suppressed by cuts on M_jj and $|\Delta y_\mathrm{jj}|$

$$\sigma_\mathrm{EW}^{\mathrm{W}^+\mathrm{W}^+} \sim 10\,\sigma_\mathrm{QCD}^{\mathrm{W}^+\mathrm{W}^+}, \qquad \sigma_\mathrm{EW}^{\mathrm{W}^+\mathrm{Z}} \sim 0.25\,\sigma_\mathrm{QCD}^{\mathrm{W}^+\mathrm{Z}}, \qquad \sigma_\mathrm{EW}^{\mathrm{ZZ}} \sim 0.1\,\sigma_\mathrm{QCD}^{\mathrm{ZZ}}$$

Best EW/QCD ratio

Clean experimental signature

Expansion in multiple couplings

LO: pure EW diagrams $\mathcal{O}(e^6)$ and diagrams with gluons $\mathcal{O}(e^4 g_s^2)$

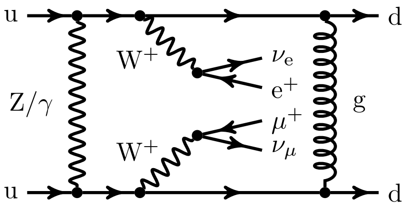
NLO: EW and QCD corrections to both types of diagrams

at level of cross section:

$$\begin{tikzcd}
\textbf{LO} & & \mathcal{O}(\alpha^6) \arrow[dl, "\text{EW}"'] \arrow[dr, "\text{QCD}"] & & \mathcal{O}(\alpha_s\alpha^5) \arrow[dl, "\text{EW}"'] \arrow[dr, "\text{QCD}"] & & \mathcal{O}({\alpha_s}^2\alpha^4) \arrow[dl, "\text{EW}"'] \arrow[dr, "\text{QCD}"] & \\
\textbf{NLO} & \mathcal{O}(\alpha^7) & & \mathcal{O}(\alpha_s\alpha^6) & & \mathcal{O}({\alpha_s}^2\alpha^5) & & \mathcal{O}({\alpha_s}^3\alpha^4)
\end{tikzcd}$$

Virtual diagrams mix QCD and EW corrections:

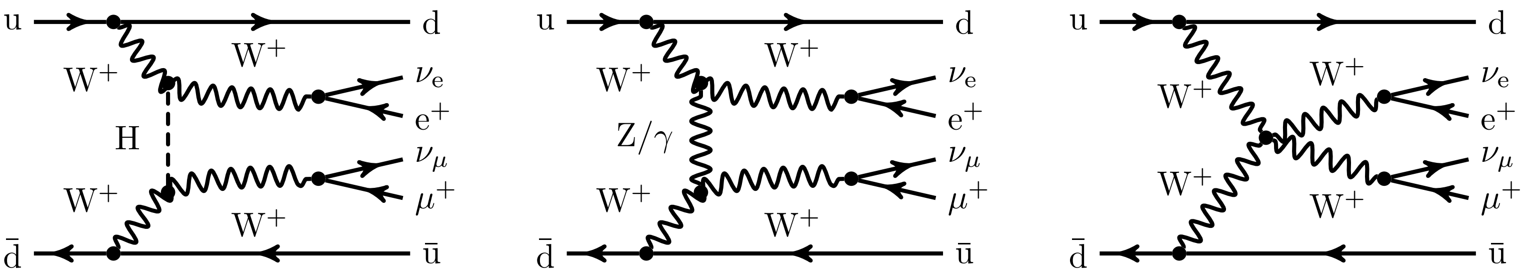
- EW correction to LO QCD amplitude
- QCD correction to LO EW amplitude



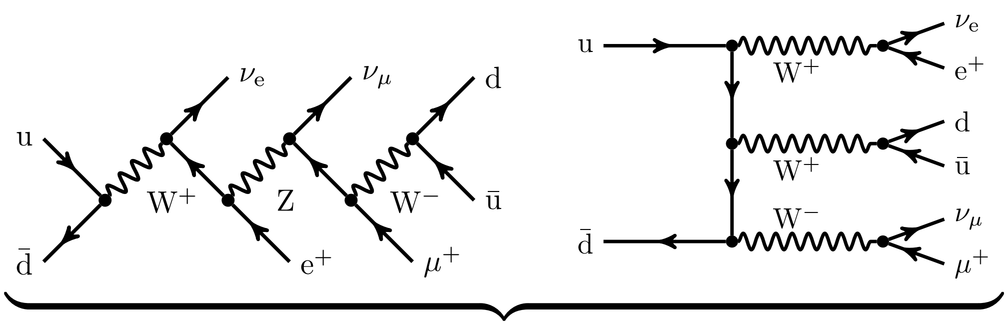
⇒ QCD and EW corrections mix at $\mathcal{O}\left(\alpha_s\alpha^6\right)$ and $\mathcal{O}\left(\alpha_s^2\alpha^5\right)$
QCD and EW corrections cannot be separated in general
possible in VBS approximation (neglects interferences)

Contributions to $\mathrm{pp} \to \mu^+\nu_\mu \mathrm{e}^+\nu_\mathrm{e}\mathrm{jj}$ at LO

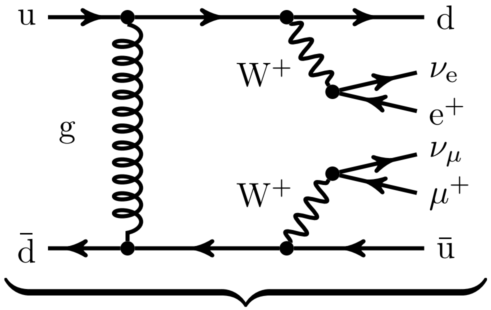
Vector-boson scattering (VBS) topologies: $\mathcal{O}\left(g^6\right)$ all t channel



irreducible background to VBS:



EW background $\mathcal{O}(g^6)$, s channel



QCD background $\mathcal{O}(g_\mathrm{s}^2 g^4)$
only t channel

t channel: incoming quarks/antiquarks connected to outgoing quarks/antiquarks
u channel: exchange identical quarks/antiquarks in final state
s channel: incoming quark and anti-quark connected, all boson propagators time like
VBS approximation: only t and u channel, no interferences (see slides 22-23)

Existing NLO calculations – state of the art

Calculations for VBS within the SM

- all processes known at NLO QCD accuracy matched to PS (see next slide)
  - in VBS approximation (no s channel, no interferences)
  - for both QCD-/EW-induced process
  - all available in VBFNLO (apart from QCD-induced $\mathrm{W^+W^-}$)
  - all available in POWHEG-BOX (⇒ PS matching)
  - possible to generate in MG5_AMC@NLO or SHERPA
- NLO EW corrections known for $\mathrm{W^+W^+}$, WZ, and ZZ ($\mathrm{W^+W^-}$ in progress)
- full NLO computation only available for $\mathrm{W^+W^+}$ (ZZ in progress)
- no NNLO results known

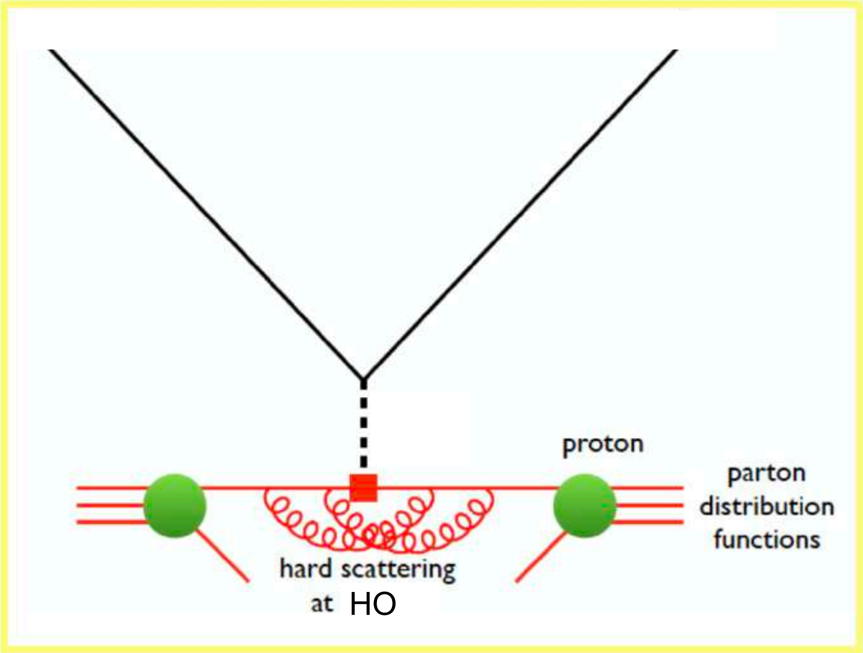
Matching higher order calculations and parton shower

Higher Order

good perturbative accuracy, accurate inclusive cross-sections, but limited to low multiplicity and parton level only

Parton shower:

less accurate, but realistic description, including multi-parton interactions, resummation, hadronization effects



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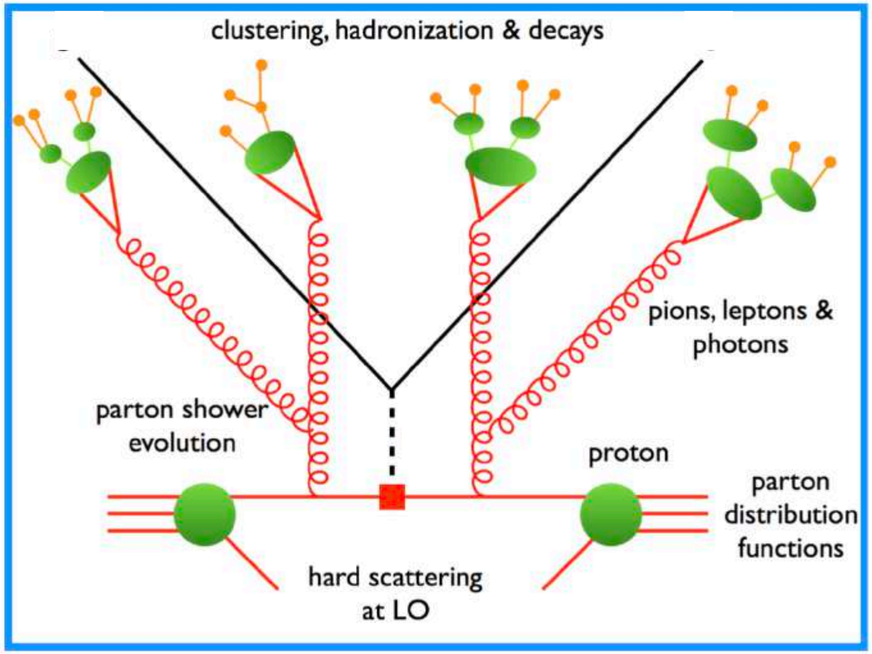

Matching higher order calculations to parton shower (deserves a lecture of its own ☺)

Higher Order

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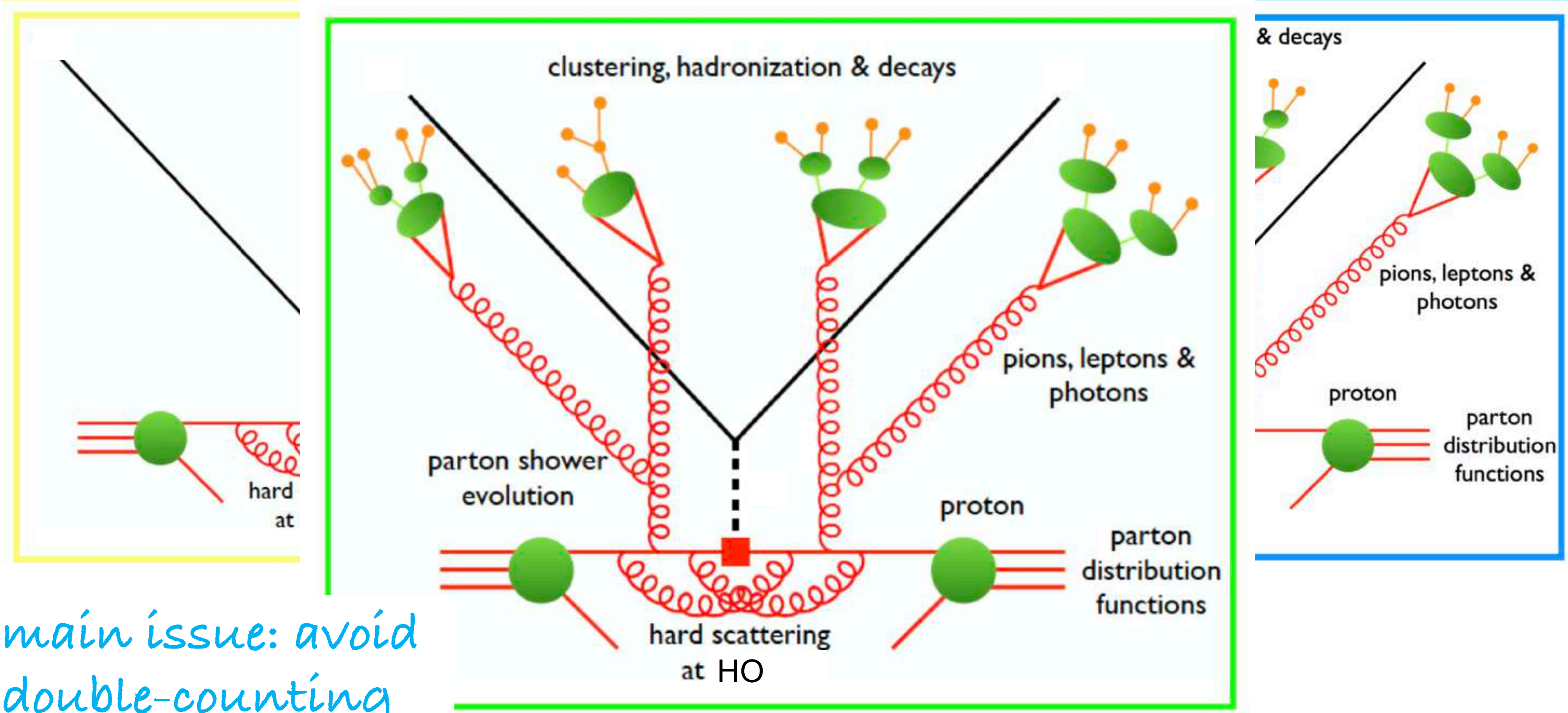

main issue: avoid double-counting

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Existing calculations for $VV+2$ jet production

- full LO predictions: Ballestrero, Franzosi, Maina ’10 (PHANTOM)

NLO QCD separately for EW ($\mathcal{O}(\alpha^6)$) and QCD-induced production ($\mathcal{O}(\alpha_\mathrm{s}^2\alpha^4)$)

- NLO QCD corrections to EW production in VBS approximation:
  Jäger, Oleari, Zeppenfeld (+ Bozzi) ’06, ’07, ’09 (VBFNLO);
  Denner, Hošeková, Kallweit ’12
  PS matching: Jäger, Zanderighi ’11, ’13 + Karlberg ’14 $(\mathrm{W^+W^+, W^+W^-, ZZ})$
  Rauch, Plätzer ’16 $(\mathrm{W^+W^-})$, Jäger, Karlberg, Scheller ’18 (WZ)
- NLO QCD corrections to QCD production:
  Melia, Melnikov, Röntsch, Zanderighi ’10, ’11 $(\mathrm{W^+W^+})$; Greiner et al. ’12 $(\mathrm{W^+W^-})$;
  Campanario, Kerner, Ninh, Zeppenfeld ’13, ’14 (VBFNLO) $(\mathrm{W^+W^+, WZ, ZZ})$
  PS matching: Melia, Nason, Röntsch, Zanderighi ’11 $(\mathrm{W^+W^+})$
- EW corrections for complete processes $\mathrm{pp} \to 4f + 2\mathrm{j}$
  - NLO EW and QCD corrections for $\mathrm{W^\pm W^\pm}$, WZ and ZZ final states
    Biedermann, Denner, Pellen ’16; Denner, Dittmaier, Pellen, Schwan ’19,
    Denner, Franken, Pellen, Schmidt ’20
  - full NLO corrections to $\mathrm{W^\pm W^\pm}$ Biedermann, Denner, Pellen ’17
  - NLO EW matched to EW PS and interfaced to QCD PS for $\mathrm{W^\pm W^\pm}$
    Chiesa, Denner, Lang, Pellen ’19

Fiducial cross section for $\mu^+\nu_\mu e^+\nu_e jj$ (W^+W^+jj)

Scale uncertainty reduced by factor 5: Biedermann et al. ’17

$$\sigma_{LO} = 1.6383(2)^{+11.66(2)\%}_{-9.44(2)\%}\ \mathrm{fb}, \qquad \sigma_{NLO} = 1.3577(7)^{+1.2(1)\%}_{-2.7(1)\%}\ \mathrm{fb}$$

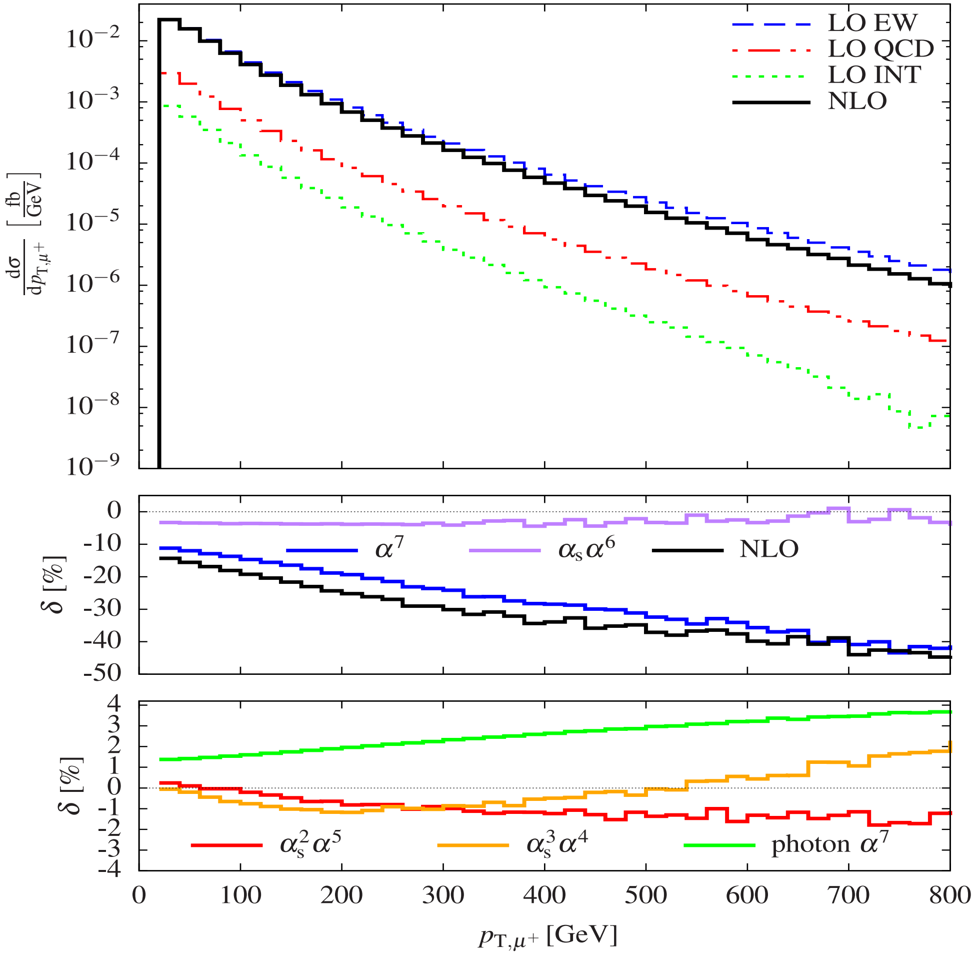
results for separate orders:

order	$\mathcal{O}(\alpha^6)$	$\mathcal{O}(\alpha_s\alpha^5)$	$\mathcal{O}(\alpha_s^2\alpha^4)$	sum
σ_{LO} [fb]	$1.4178(2)$	$0.04815(2)$	$0.17229(5)$	$1.6383(2)$
$\delta\sigma_{LO}/\sigma_{LO}$ [%]	86.5	2.9	10.5	100

order	$\mathcal{O}(\alpha^7)$	$\mathcal{O}(\alpha_s\alpha^6)$	$\mathcal{O}(\alpha_s^2\alpha^5)$	$\mathcal{O}(\alpha_s^3\alpha^4)$	sum
$\delta\sigma_{NLO}$ [fb]	$-0.2169(3)$	$-0.0568(5)$	$-0.00032(13)$	$-0.0063(4)$	$-0.2804(7)$
$\delta\sigma_{NLO}/\sigma_{LO}$ [%]	-13.2	-3.5	0.0	-0.4	-17.1

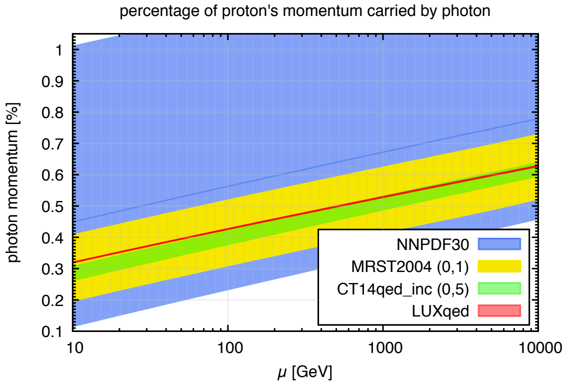
- LO EW contribution dominates for W^+W^+jj
- LO interference small but non-negligible
- surprisingly large EW corrections at $\mathcal{O}(\alpha^7)$
- photon-induced contribution at NLO $+1.5\%$ (LUXqed Manohar et al. ’16, ’17)

Distribution in transverse momentum of the anti-muon



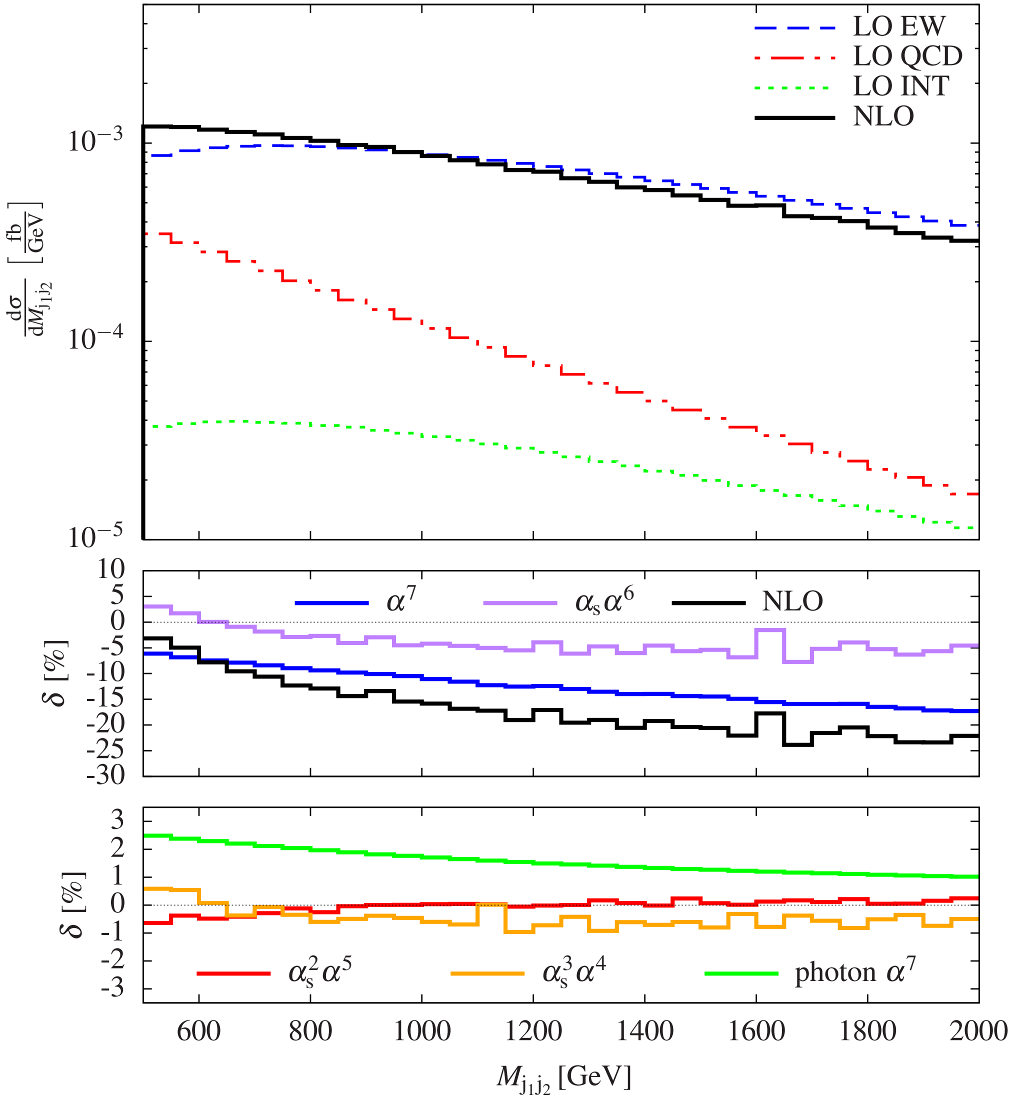
$$\mathrm{pp} \to \mu^+\nu_\mu \mathrm{e}^+\nu_\mathrm{e}\mathrm{jj}$$

- EW contribution dominates everywhere
- $\mathcal{O}(\alpha^7)$ -40% at $800\,\mathrm{GeV}$ (Sudakov logarithms) dominant correction
- $\mathcal{O}(\alpha_s\alpha^6)$ $-4\% - 0\%$
- $\mathcal{O}(\alpha_s^2\alpha^5)$, $\mathcal{O}(\alpha_s^3\alpha^4)$ between -2% and $+2\%$ cancelling for large $p_{T\mu^+}$
- photon-induced corrections increase to 4% at $p_{T\mu^+} = 800\,\mathrm{GeV}$ (photon PDF grows with energy)



- Corrections are large at high energies where new physics is expected to show up!
- To find signs of new physics, higher order calculations are important

Di-jet invariant-mass distribution

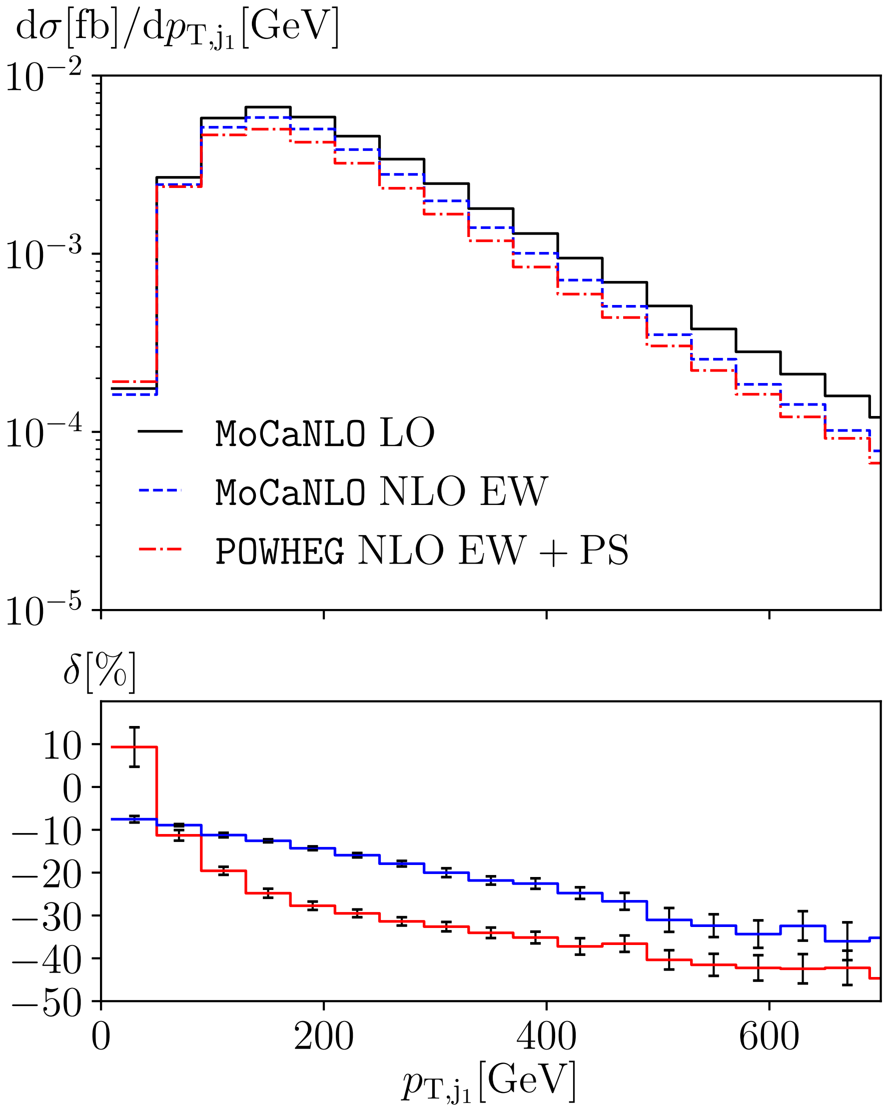


M_{jj} important to tag VBS signature

$$pp \to \mu^+\nu_\mu e^+\nu_e jj$$

- Large cross section also for high M_{jj}
- QCD-induced contrib. drops much faster
- $\mathcal{O}(\alpha^7)$ $-6\% - -17\%$
- $\mathcal{O}(\alpha_s\alpha^6)$ $+5\% - -5\%$
- $\mathcal{O}(\alpha_s^2\alpha^5)$, $\mathcal{O}(\alpha_s^3\alpha^4)$ tiny
- photon-induced corrections decrease with M_{jj}

Event generator for $\mathrm{W}^{\pm}\mathrm{W}^{\pm}$ with QED PS matching



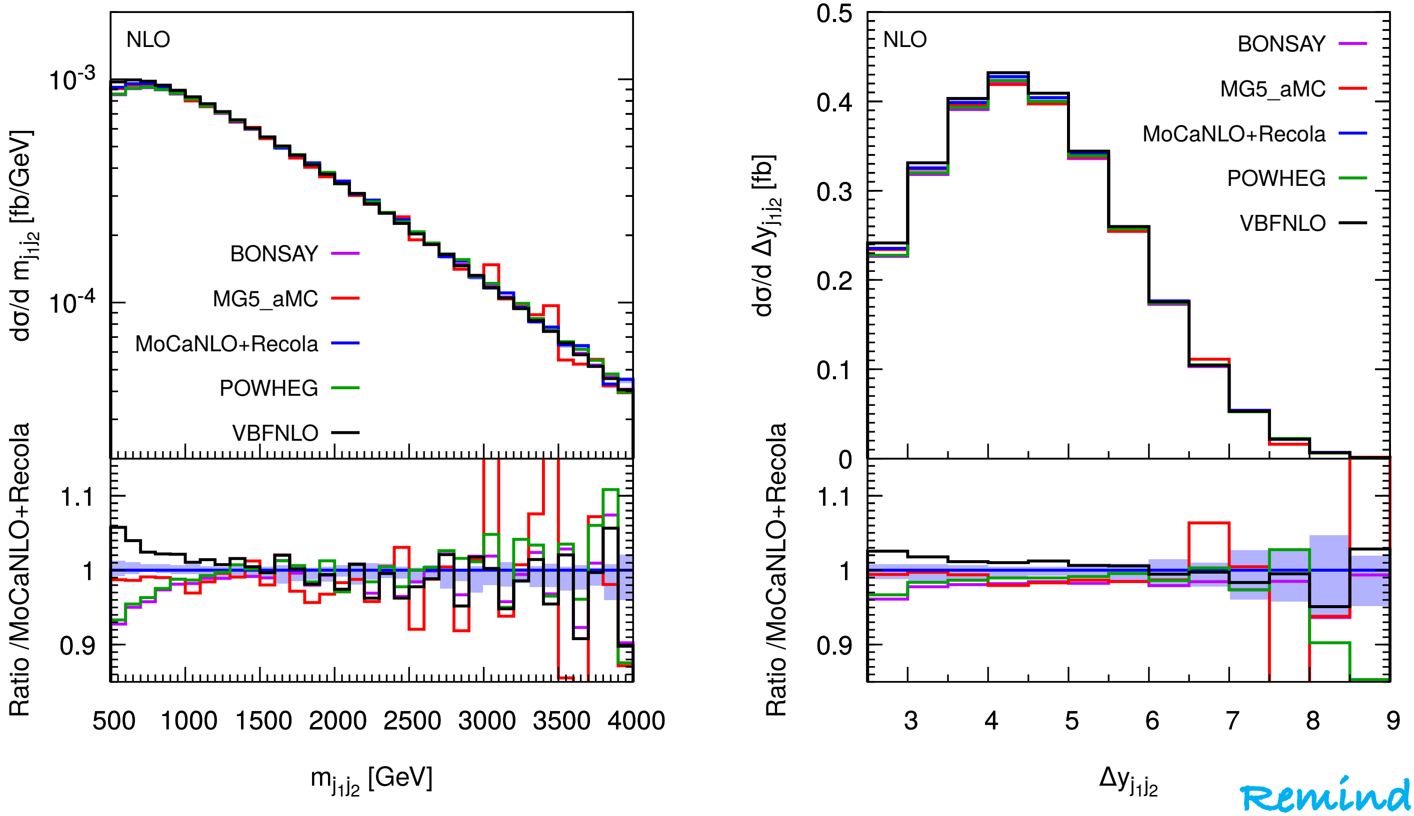
Chiesa et al. ’19

- Event generator based on POWHEG and RECOLA for $\mathrm{pp} \to \mu^{\pm}\nu_{\mu}\mathrm{e}^{\pm}\nu_{\mathrm{e}}\mathrm{jj}$ and $\mathrm{pp} \to \mathrm{e}^{\pm}\nu_{\mathrm{e}}\mathrm{e}^{\pm}\nu_{\mathrm{e}}\mathrm{jj}$ including EW corrections matched to QED parton shower and interfaced to QCD parton shower
- PS shifts events to smaller $p_{\mathrm{T,j_1}}$, partially out of acceptance

Vector-boson scattering approximation at NLO QCD

Comparison of codes with VBS approximation (Bonsay, Powheg VBFNLO) and without VBS approximation (MoCaNLO+Recola, MG5_aMC)

$\mathrm{pp} \to \mu^+\nu_\mu \mathrm{e}^+\nu_\mathrm{e}\mathrm{jj}$ Ballestrero et al. ’18 (VBSCAN)



differences up to 10% outside the QCD scale uncertainty band

POWHEG, Bonsay: no s channel ⇒ reduction at small M_{jj}

VBFNLO: no interference ⇒ enhancement at small M_{jj}

Reminder:
VBS approximation
= no s-channel,
no interference

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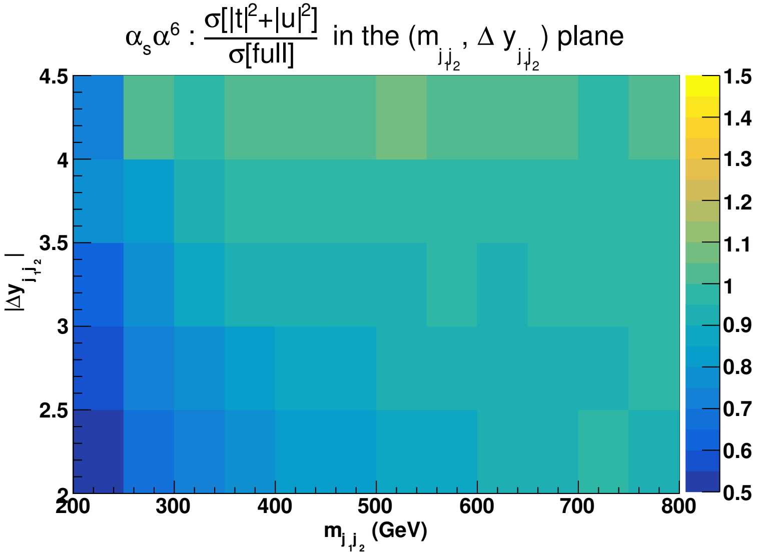
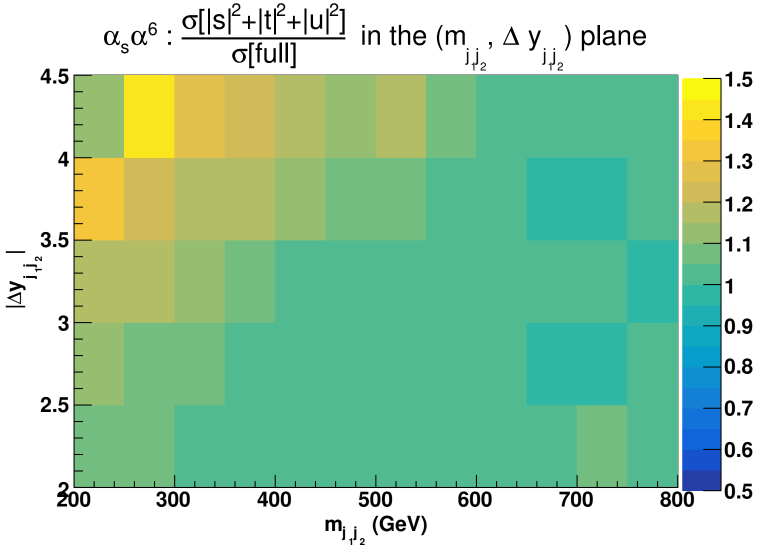
Vector-boson scattering approximation at NLO QCD

Comparison of codes with VBS approximation (VBFNLO) and without VBS approximation (MoCaNLO+Recola)

$\mathrm{pp} \to \mu^+\nu_\mu \mathrm{e}^+\nu_\mathrm{e}\mathrm{jj}$



Ballestrero et al. ’18 (VBSCAN)



- approximations worse at NLO than at LO:
  difference of up to 20% in fiducial region $M_{\mathrm{jj}} > 500\,\mathrm{GeV}$, $\Delta y_{\mathrm{jj}} > 2.5$
  (gluon bremsstrahlung fakes tagging jet in s channel)
- difference for fiducial cross section: ($M_{\mathrm{jj}} > 500\,\mathrm{GeV}$, $\Delta y_{\mathrm{jj}} > 2.5$)
  $|t| + |u|$ approximation: $\sim -2\%$ $|s| + |t| + |u|$ approximation: $\sim +1\%$
- difference for inclusive cross section: ($M_{\mathrm{jj}} > 200\,\mathrm{GeV}$, $\Delta y_{\mathrm{jj}} > 2$)
  $|t| + |u|$ approximation: -6% $|s| + |t| + |u|$ approximation: $+2.6\%$

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Corrections to fiducial cross sections

Large universal NLO EW corrections to VBS processes

process	$\sigma_{\mathrm{LO}}^{\mathcal{O}(\alpha^6)}$ [fb]	$\sigma_{\mathrm{NLO,EW}}^{\mathcal{O}(\alpha^7)}$ [fb]	δ_{EW} [%]
Biedermann et al. ’16			
$\mathrm{pp} \to \mu^+\nu_\mu \mathrm{e}^+\nu_\mathrm{e}\mathrm{jj}$ ($\mathrm{W^+W^+}$)	$1.5348(2)$	$1.2895(6)$	-16.0
Denner et al. ’19			
$\mathrm{pp} \to \mu^+\mu^- \mathrm{e}^+\nu_\mathrm{e}\mathrm{jj}$ ($\mathrm{ZW^+}$)	$0.25511(1)$	$2.142(2)$	-16.0
Denner et al. ’20			
$\mathrm{pp} \to \mu^+\mu^- \mathrm{e}^+\mathrm{e}^-\mathrm{jj}$ (ZZ)	$0.097681(2)$	$0.08214(5)$	-15.9

largely independent of cuts ⇒ intrinsic feature of VBS processes

Relative NLO EW corrections in logarithmic approximation

process	δ_{EW} [%]	$\delta_{\mathrm{EW}}^{\mathrm{log,int}}$ [%]	$\delta_{\mathrm{EW}}^{\mathrm{log,diff}}$ [%]	$\langle M_{4\ell}\rangle$ [GeV]
$\mathrm{pp} \to \mu^+\nu_\mu \mathrm{e}^+\nu_\mathrm{e}\mathrm{jj}$	-16.0	-16.1	-15.0	390
$\mathrm{pp} \to \mu^+\mu^- \mathrm{e}^+\nu_\mathrm{e}\mathrm{jj}$	-16.0	-17.5	-16.4	413
$\mathrm{pp} \to \mu^+\mu^- \mathrm{e}^+\mathrm{e}^-\mathrm{jj}$	-15.9	-15.8	-14.8	385

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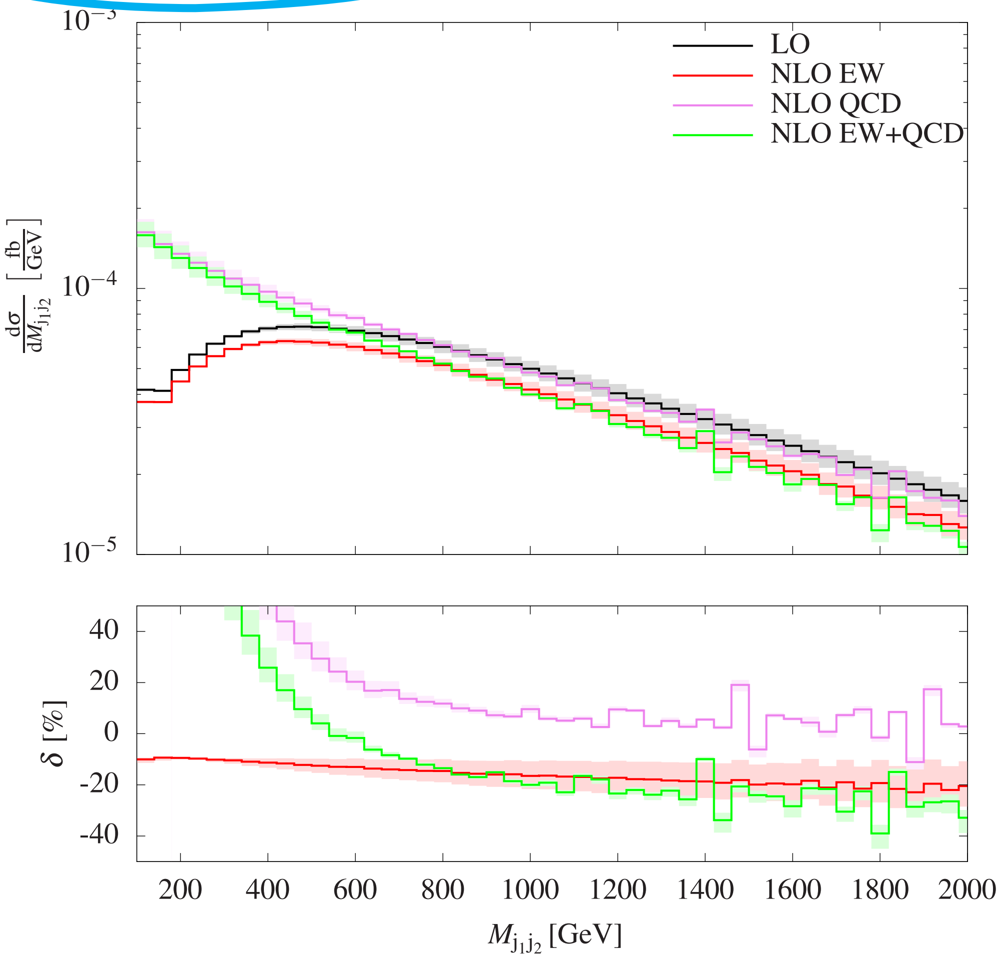
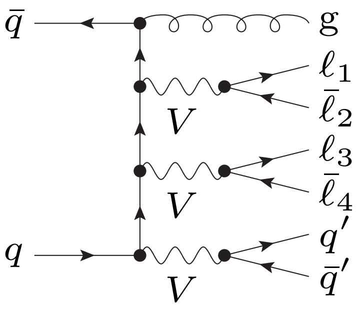
NLO QCD and EW corrections to ZZ production in VBS

$\mathrm{pp} \to \mu^+\mu^-\mathrm{e}^+\mathrm{e}^-\mathrm{jj}$

Denner et al. '20



- Loose VBS cut: $M_{\mathrm{jj}} > 100\,\mathrm{GeV}$ based on 1708.02812 (CMS)
- s-channel NLO contribution involving tri-boson prod.



Less suppression at NLO owing to extra gluon jet

- 24% NLO QCD corrections to fiducial cross section

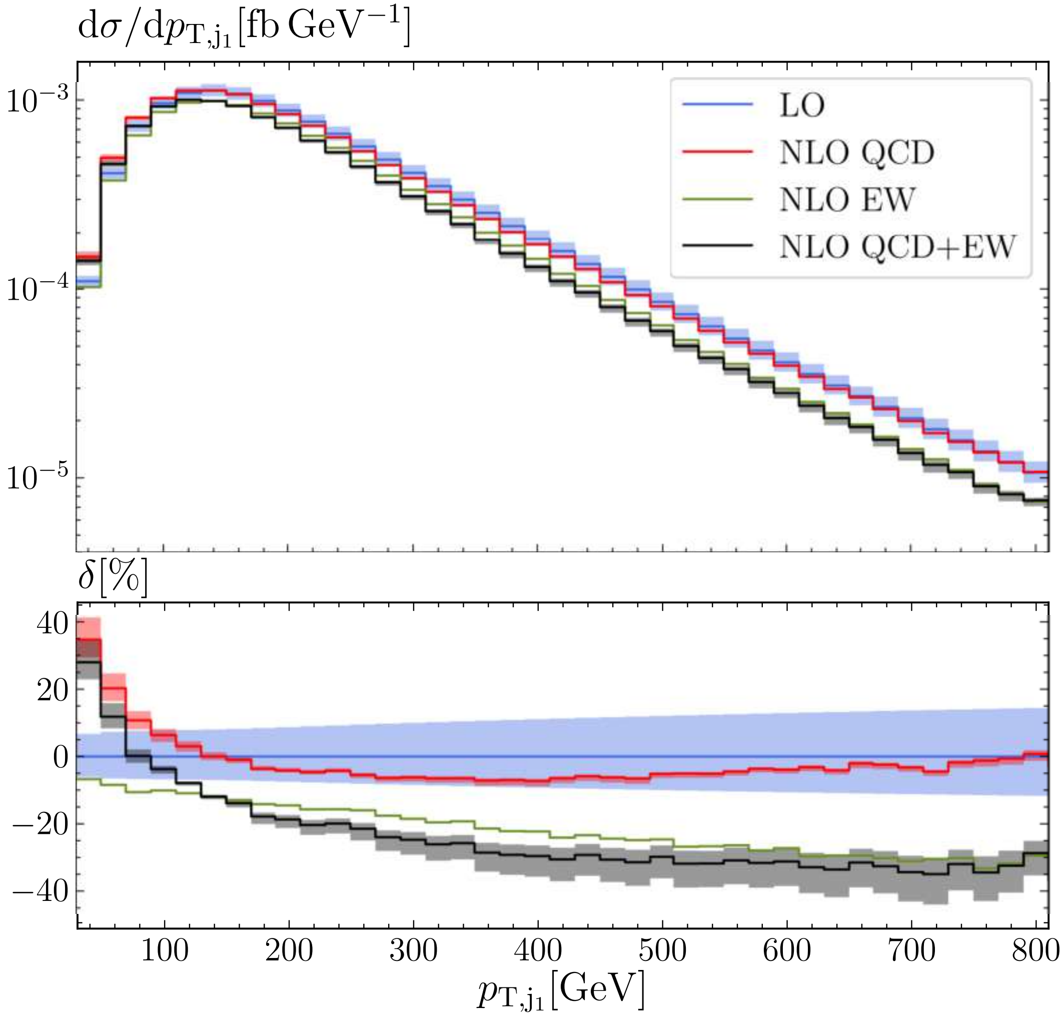
⇒ include tri-boson contrib. for loose VBS cuts

BONUS

Distributions for $\mathrm{pp} \to \mu^+\mu^-\mathrm{e}^+\nu_\mathrm{e}\mathrm{jj}$ $(\mathrm{ZW^+jj})$

Distribution in transverse momentum of the leading jet

Denner et al. ’19

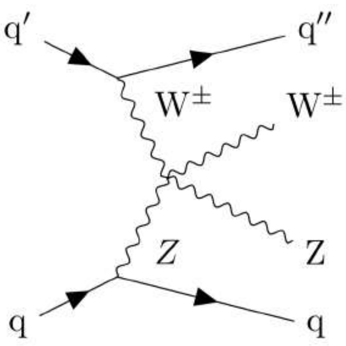


- $\mathcal{O}(\alpha^7) \sim -30\%$ at $p_{\mathrm{T,j_1}} = 800\,\mathrm{GeV}$ (Sudakov logarithms) dominant correction
- $\mathcal{O}(\alpha_\mathrm{s}\alpha^6) \lesssim 10\%$ for $p_{\mathrm{T,j_1}} > 100\,\mathrm{GeV}$ small QCD scale uncertainty owing to dynamical scale $\mu = \sqrt{p_{\mathrm{T,j_1}}p_{\mathrm{T,j_2}}}$
- large correction for small $p_{\mathrm{T,j_1}}$ due to phase-space suppression at LO (all jets have small p_T) redistribution of events at NLO

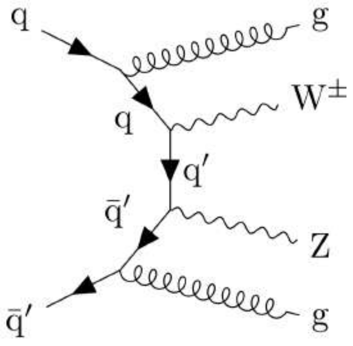
RECAP and move back to experiment

Introduction and experimental motivation

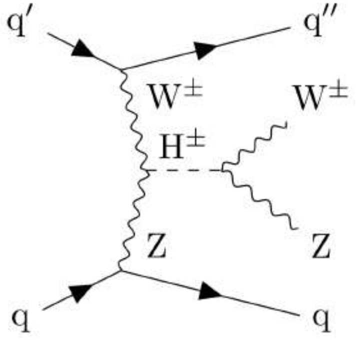
- VV production via vector boson scattering
  - Important component of VVjj production proceeding entirely via EW interactions at tree level
  - V self-interactions and interactions with H precisely predicted
    - Deviations from predictions signal new physics in EW sector



VBS WZjj



Non-VBS WZjj



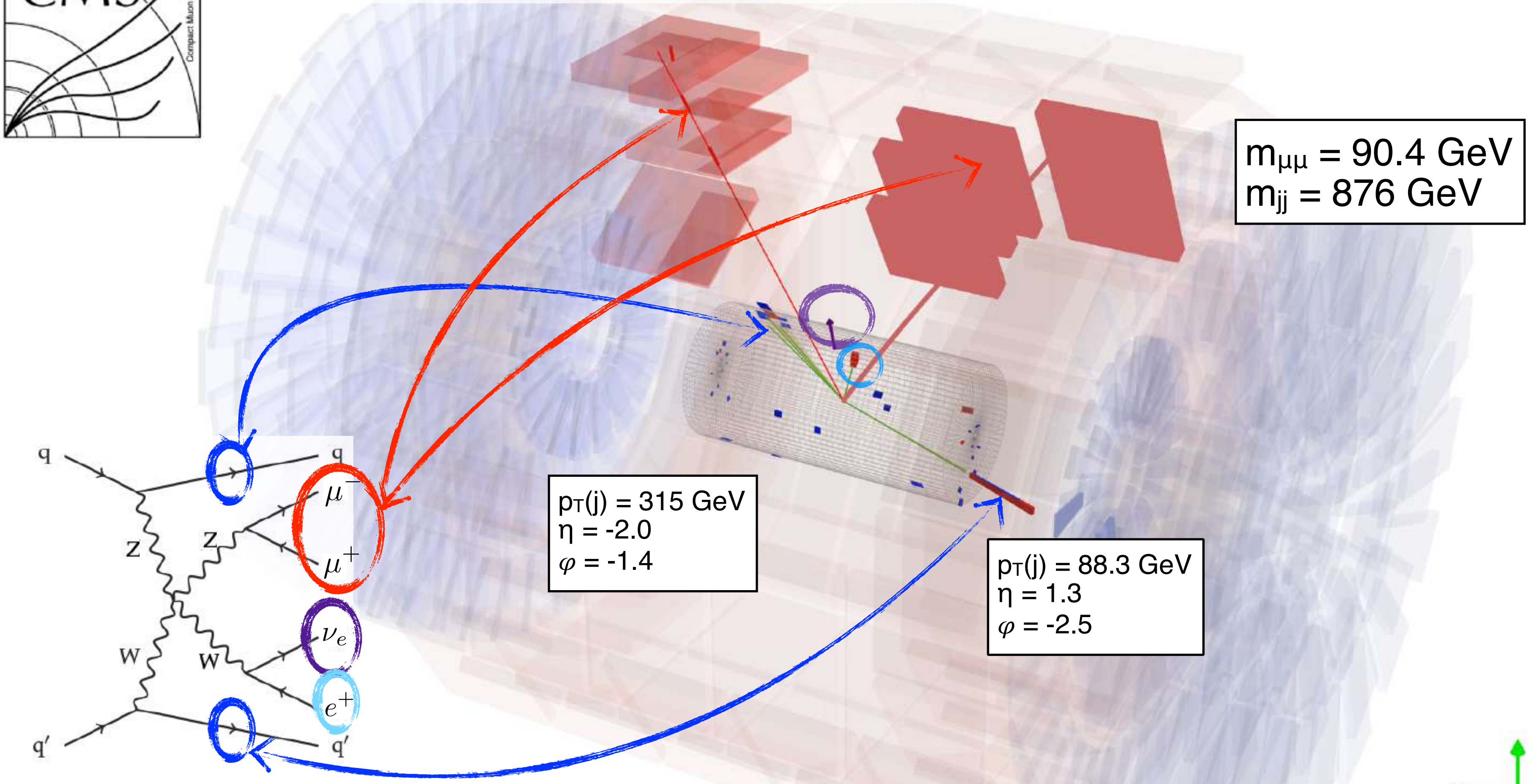
BSM H± Production

- New probe of the SM in the EW sector given high Run II (and Run III) lumi
  - Does VBS production occur with the rate predicted by the SM?
  - Do distributions show any signs of BSM physics?

- Excellent experimental challenge — can we achieve precision?
  - High multiplicity final state, complex and forward objects (jets)

Characteristics of VBS events

- Radiation of vector bosons, lack of color flow between jets
  - ➡ Distinct kinematic signature for VVjj EW component



$m_{\mu\mu}$ = 90.4 GeV
m_{jj} = 876 GeV

$p_T(j)$ = 315 GeV
η = -2.0
φ = -1.4

$p_T(j)$ = 88.3 GeV
η = 1.3
φ = -2.5

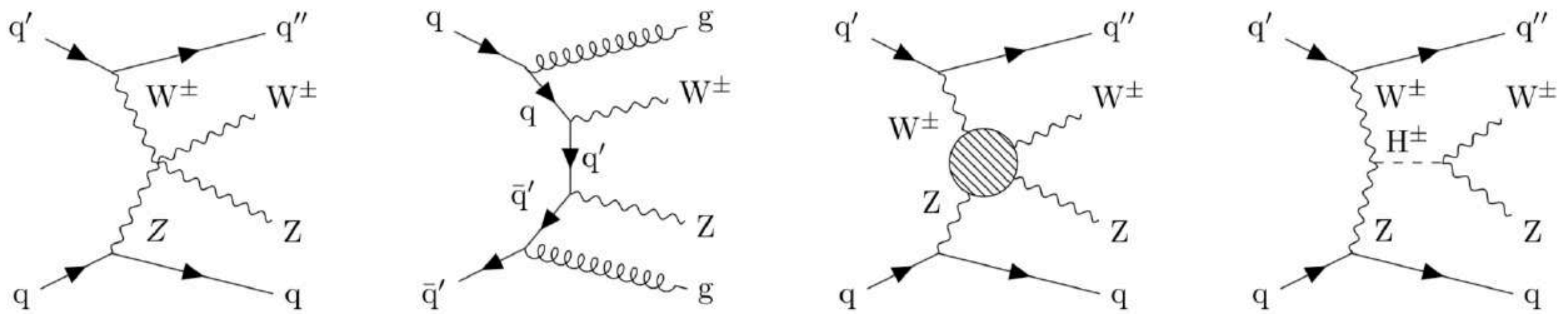
CMS Experiment at LHC, CERN
Data recorded: Wed Oct 12 18:07:34 2016 CDT
Run/Event: 283043 / 94262902

- Forward and high momentum jets
- Leptons central wrt jets

Anatomy of a VBS measurement

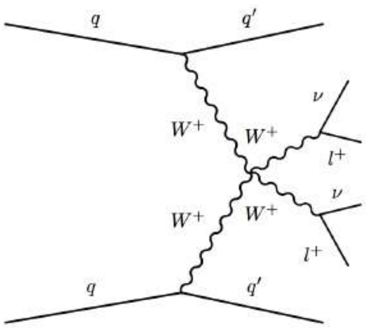
- Select VV events with VBS-like jets
  - Dominant experimental uncertainty: jet energy scale
- Estimate non-VV backgrounds — usually data driven

1. Measure VVjj cross section (treat (a) + (b) as signal)
   - Theoretical dependence minimal for cut-and-count analysis
2. Distinguish EW and QCD production mechanisms through kinematics variables (e.g., of two highest p_T jets)
   - Treat (a) as signal, (b) as background
   - Modeling uncertainties important for MC-driven backgrounds
   - Multi-variate — best sensitivity, less explicit theoretical assumptions
3. Look for new physics modifying VVV (VVVV) interaction
   - Interpret in terms of generic (EFT) (c) or explicit models (d)



(a) $O(\alpha^4)$ (b) $O(\alpha_s^2\alpha^2)$ (c) (d)

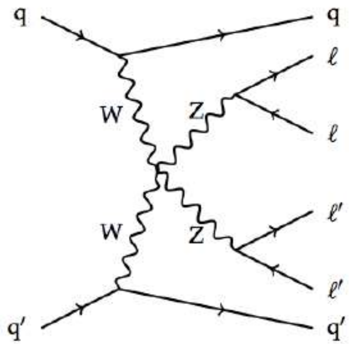
Landscape of VBS measurements today



PRL 120, 081801 (18)
- EW obs (exp) 6.5 (4.4)
- Via fit to m_{jj}+CR

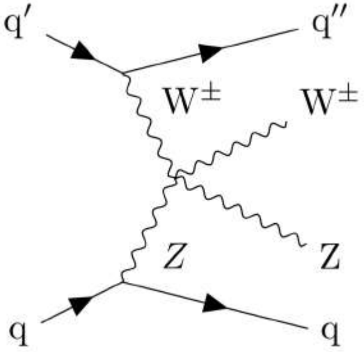
★PLB 809 (20) 135710
- EW obs ≫ 5.0σ
- via 2D fit to mjj/dEtajj
- unfolded xsecs

★PLB 812 (2020) 136018
- Polarisation search



★ arXiv:2004.10612
- EW obs (exp) 5.5 (4.3)
- via fit to BDT+CR

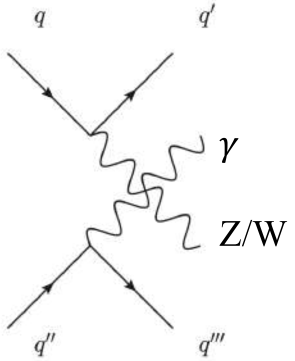
★PLB 812 (2020) 135992
- EW obs (exp) 4.0 (3.5)
- Via fit to ME discriminant



PLB 793 (2019) 469
- EW obs (exp) 5.3 (3.2)
- fit to BDT+CRs

★PLB 809 (20) 135710
- EW obs (exp) 6.8 (5.3)
- via 2D fit to mjj/ηjj +CRs

\+ Via fit to BDT



PLB 803 (20) 135341
- EW obs (exp) 4.1 (4.1)
- Via fit to BDT [Zγ]

JHEP 2006 (20) 076
- EW 3.9 (5.2) [Zγ]
- 2D fit to mjj/ηjj+CR
- combined w/ 8 TeV 4.7 (5.5)

PLB 811 (2020) 13598
- EW 4.9 (4.6) [Wγ]
- combined w/ 8 TeV 5.3 (4.8)

Typically higher observed than expected significance (except Zγ) for both experiments

Semi-leptonic decays

PRD 100, 032007 (2019)
EW obs (exp) 2.7 (2.5)
via fit to BDTs in 9 SR+CR

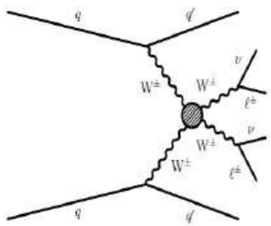
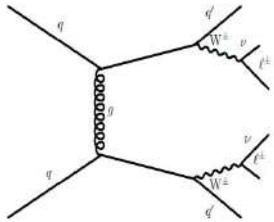
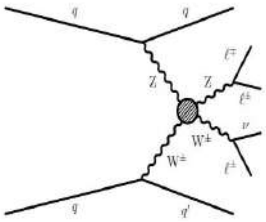
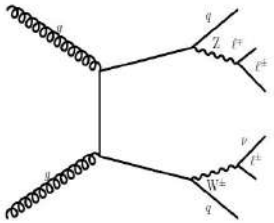
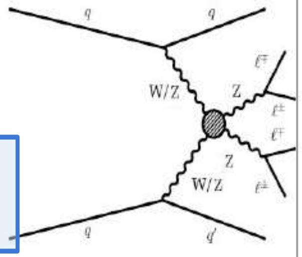
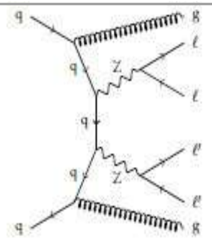
Phys. Lett. B 798 (2019)134985
Only BSM search

Zγ: fully reconstructable
Wγ: highest VBS xsection
(see backup)

Results from ATLAS and CMS at 13 TeV (36 fb^{-1} or ★140 fb^{-1})

Fully leptonic VV analyses

Statistically limited

	Signal	**Irreducible bkg**	**Other bkgs**	**Event topology**
W±W±jj Best EW/ QCD ratio			WZjj(ew/qcd) ZZ Non-prompt tVx Wγ Wrong-sign	2 same charge leptons 2 tag jets and MET
WZjj			ZZ Non-prompt tVx Wγ Wrong-sign	3 leptons with total charge -1/+1 2 tag jets and MET
ZZjj Cleanest channel, less statistics		 +ttZ, VVZ	Z+jets, tt+jets (negligible impact)	2 pair of opposite charge leptons 2 tags jets

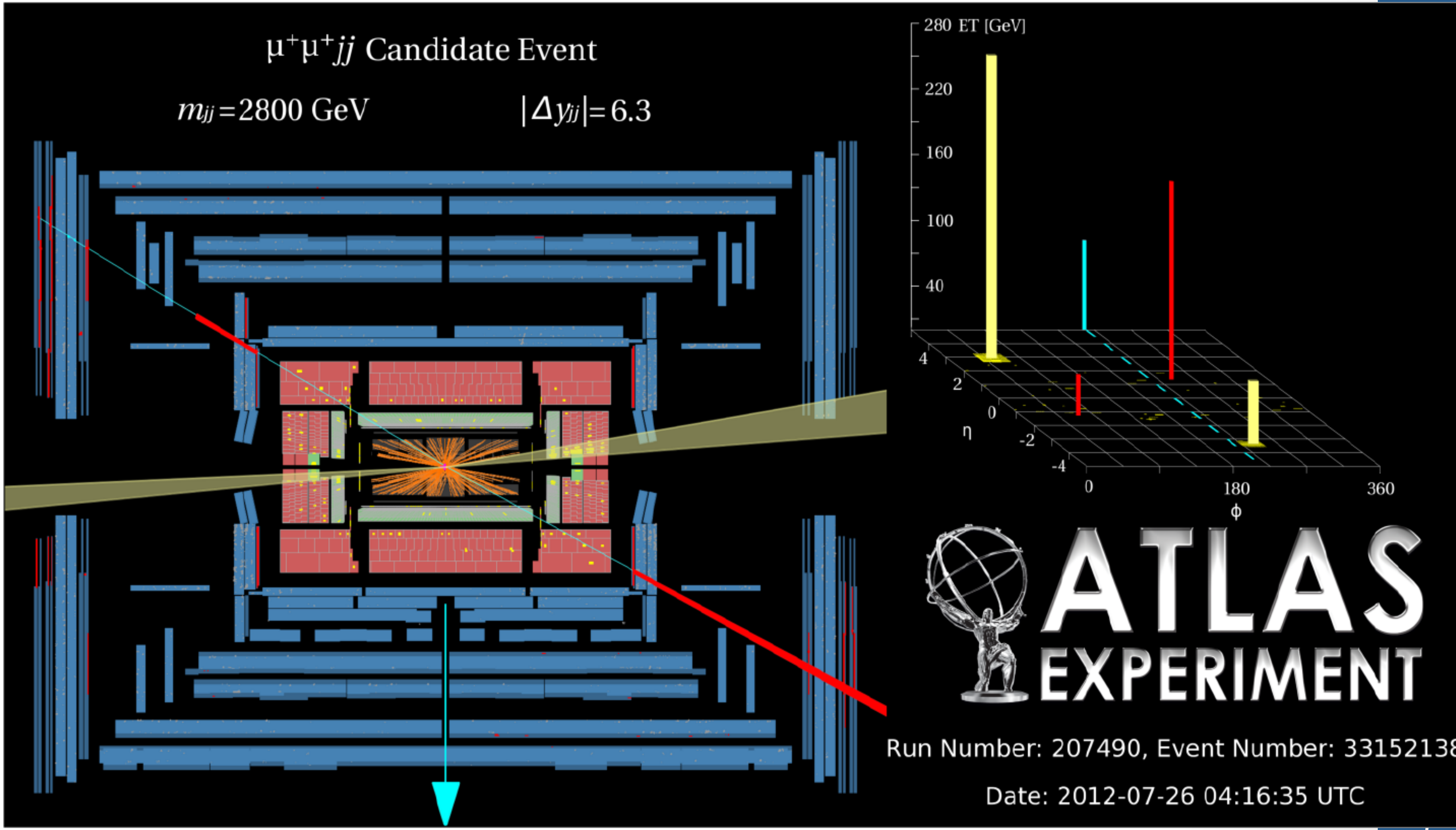
(see backup for Wγ and Zγ results)

$W^{\pm}W^{\pm}jj$ production

Vector-boson scattering

Other EW production

QCD production



Run Number: 207490, Event Number: 33152138

Date: 2012-07-26 04:16:35 UTC

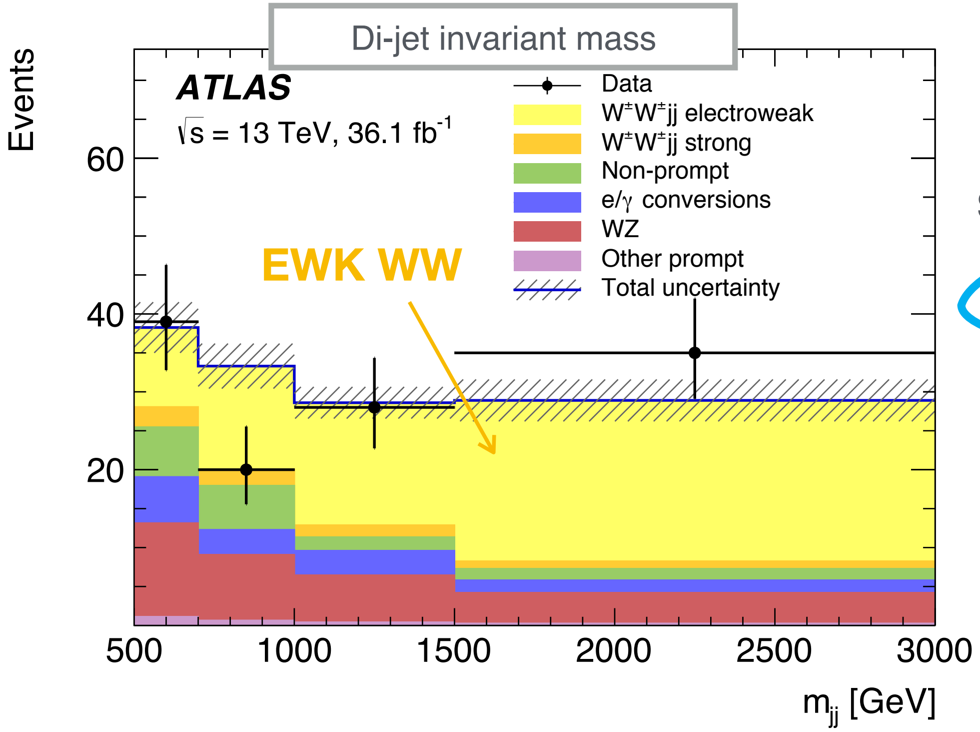
EWK same charge WW production

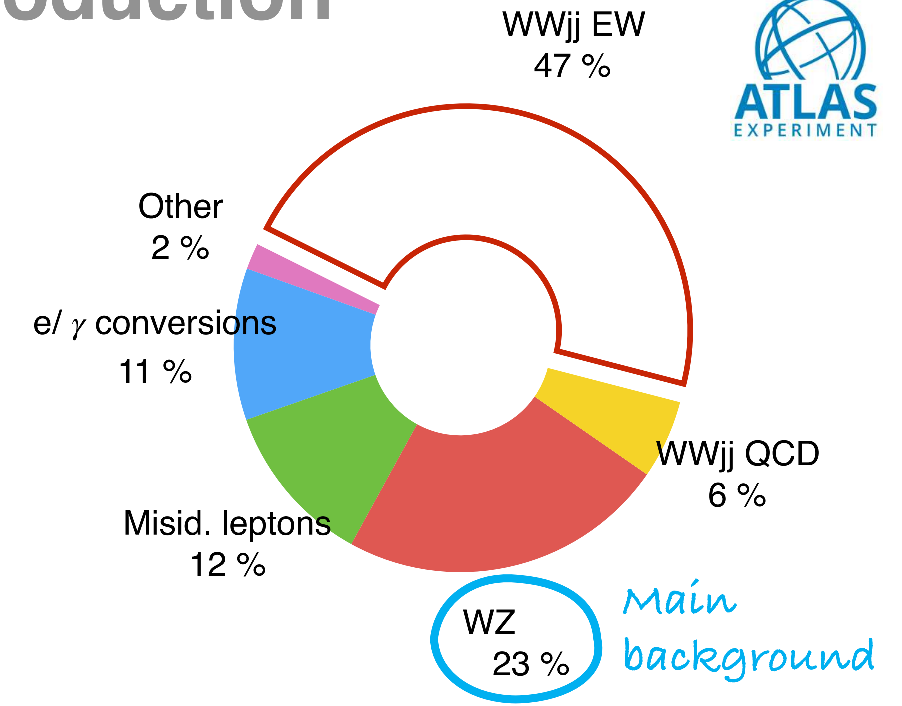
[Phys. Rev. Lett. 123 (2019) 161801]

$W^{\pm}W^{\pm} \rightarrow \ell\nu\ell\nu$

- Best EWK/QCD over background ratio!
- Main background WZ QCD mediated production:
  - Normalization taken from data
  - Shape taken from simulation
    - Theory uncertainties applied (PDF, scale, shower)

Di-jet invariant mass





Main background

Signal extraction strategy → Fitting framework development

- Simultaneous fit of dijet invariant mass (M_{jj}>200GeV) and WZ control region

Observation !!

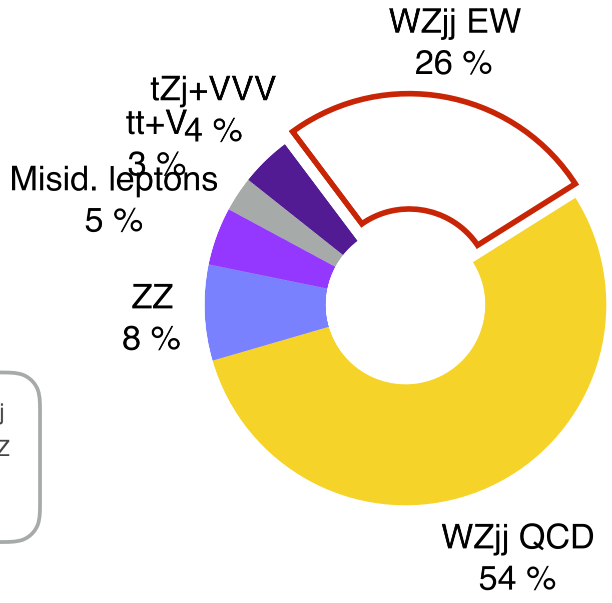
Observed (expected with Sherpa) significance is **6.5σ** (4.4σ)

Observation already with 2016 data

EWK WZjj production

$W^{\pm}Z \rightarrow \ell\nu\ell\ell$

[arXiv:1812.09740]



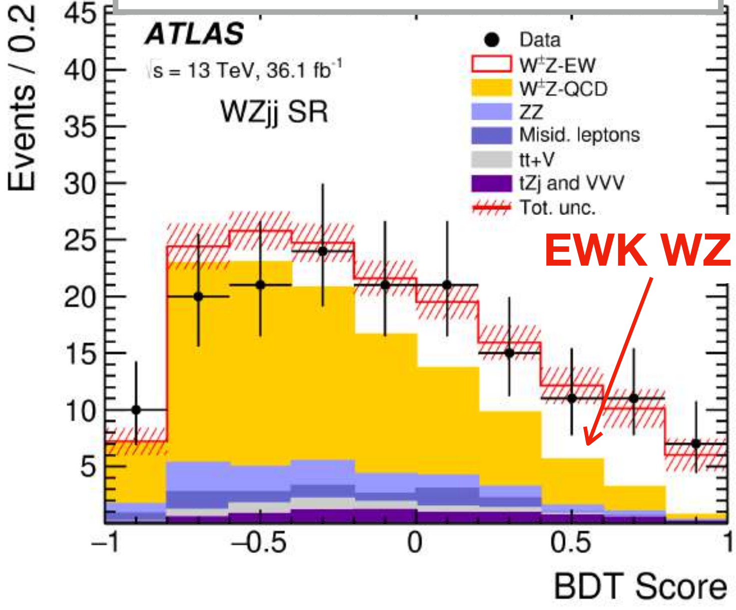
Signal extraction strategy

- Boosted Decision Tree trained on simulation events, to separate WZjj-EW from backgrounds
- 15 discriminant variables used

m_{jj}, N_{jets}, p_T^{j1}, p_T^{j2}, η^{j1}, $\Delta\eta_{jj}$, $\Delta\phi_{jj}$
$|y_{l,W} - y_Z|$, p_T^W , p_T^W, η^W, m_T^{WZ}
$\Delta R(j1, Z)$, $R_{p_T}^{hard}$, ζ_{lep}

- Simultaneous fit of BDT in signal region with 3 Control region regions (WZ QCD, ZZ and tZj)

BDT using 15 discriminant variable



EWK WZ

Results:

Observation !!

Observed (expected with Sherpa) significance is **5.3σ** (3.2σ)

- Fiducial cross section measurement

$$\sigma^{\text{fid.}}_{WZjj-\text{EW}} = 0.57 \,^{+0.14}_{-0.13}\,(\text{stat.}) \,^{+0.05}_{-0.04}\,(\text{exp. syst.}) \,^{+0.05}_{-0.04}\,(\text{mod. syst.}) \,^{+0.01}_{-0.01}\,(\text{lumi.})\ \text{fb}$$

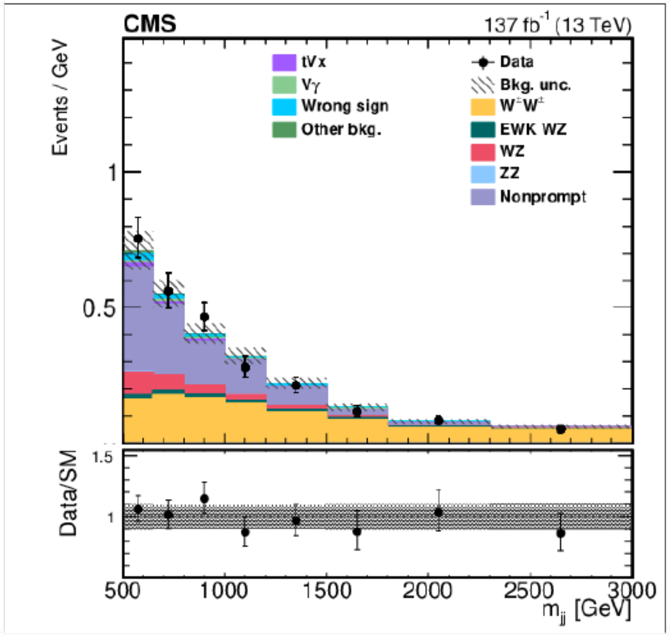
- LO Sherpa cross-section (No EW/QCD interference)

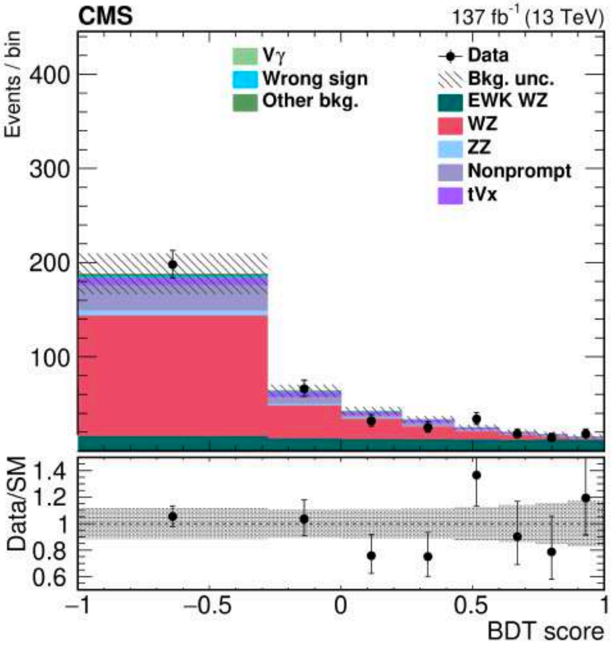
$$\sigma^{\text{fid., Sherpa}}_{WZjj-\text{EW}} = 0.321 \pm 0.002\,(\text{stat.}) \pm 0.005\,(\text{PDF})^{+0.027}_{-0.023}\,(\text{scale})\ \text{fb},$$

Electroweak W±W±+WZ: combined approach

PLB 809 (2020) 135710

- Simultaneous maximum likelihood fit with WZ and WW treated as signal
  - For WZ, train BDT with 13 variables to distinguish EW from QCD
    - Jet, V (lepton, MET), jet+V kinematics
    - ~20% improvement wrt 2D η_{jj}/m_{jj} approach used for WW
- Likelihood built from bins of WZ BDT in WZ SR, WW in 2D η_{jj}/m_{jj} in WW SR, and m_{jj} in b-tagged non prompt, tVq, and ZZ cRs
- Signals + tZq ,ZZ with unconstrained normalisations

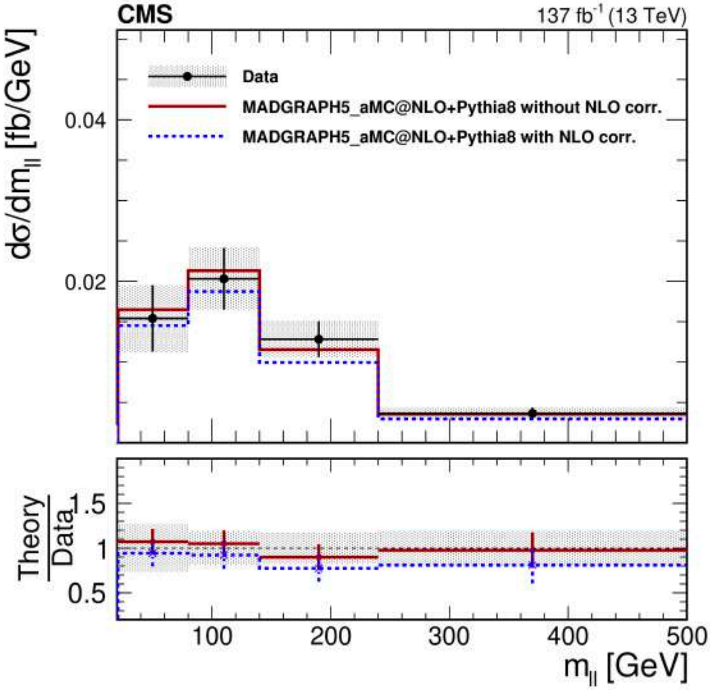


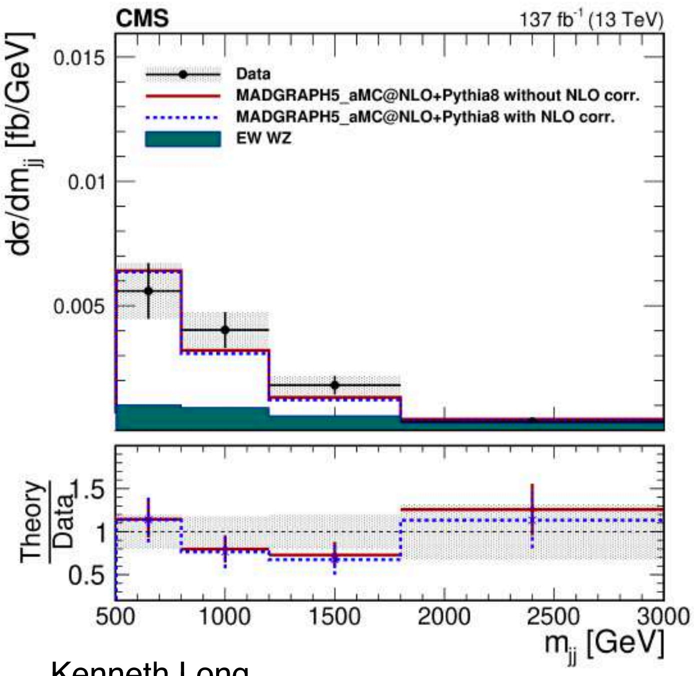


Electroweak $W^{\pm}W^{\pm}$ and WZ: results

- Sensitivity to WW far exceeds 5 sigma
- WZ significance obs. 6.8 (5.3 exp) s.d.
- Fiducial cross sections and unfolded distributions also reported
  - Unfolding via maximum likelihood fit without regularisation
  - WZ BDT replaced by mjj or observable

PLB 809 (2020) 135710





EW WZ also higher
(as for ATLAS)
but precision
statistically limited

Process	$\sigma\mathcal{B}$ (fb)	Theoretical prediction without NLO corrections (fb)	Theoretical prediction with NLO corrections (fb)
EW $W^{\pm}W^{\pm}$	3.98 ± 0.45 $0.37\,(\text{stat}) \pm 0.25\,(\text{syst})$	3.93 ± 0.57	3.31 ± 0.47
EW+QCD $W^{\pm}W^{\pm}$	4.42 ± 0.47 $0.39\,(\text{stat}) \pm 0.25\,(\text{syst})$	4.34 ± 0.69	3.72 ± 0.59
EW WZ	1.81 ± 0.41 $0.39\,(\text{stat}) \pm 0.14\,(\text{syst})$	1.41 ± 0.21	1.24 ± 0.18
EW+QCD WZ	4.97 ± 0.46 $0.40\,(\text{stat}) \pm 0.23\,(\text{syst})$	4.54 ± 0.90	4.36 ± 0.88
QCD WZ	3.15 ± 0.49 $0.45\,(\text{stat}) \pm 0.18\,(\text{syst})$	3.12 ± 0.70	3.12 ± 0.70

Physical interest in polarised cross sections

Preliminaries

- All information about polarised cross-sections is within angular distributions of final-state particles.
- Extracting polarised observables simplifies interpretation and theoretical analysis.

Polarized observables

- are important probes of Standard Model gauge and Higgs sectors,
- may provide discrimination power between SM and beyond-SM physics.

Longitudinal polarisation mode of vector bosons is

- a consequence of the Electroweak Symmetry Breaking,
- very sensitive to deviations from SM:
  unitarity of cross sections with longitudinally polarised vector bosons realized in SM via cancellation of different contributions

⇒ Extract experimental results for cross-sections with longitudinally polarised vector bosons.

Ambiguities of polarised cross sections with vector bosons

- Massive vector bosons appear only as virtual particles ⇒
  - no unique definition of vector-boson polarisations
  - diagrams without resonant vector bosons contribute to physical final state
- vector bosons are massive ⇒
  definition of polarisation depends on frame and on mass

Different definitions of polarised cross sections in the literature:

- Definition via projections on LO decay-angle distributions
  Baglio, Le Duc ’18, ’19
  - tailored to inclusive LO predictions
  - assumes small non-resonant background
  - only applicable for one polarised vector boson
  - results depend on cuts, background and NLO corrections
- Definition based on on-shell production and decay with spin correlations Franzosi et al. [Madgraph] ’19
  - neglects non-resonant contributions
  - only available for LO

Idea: use pole approximation to extract resonant contributions in gauge-invariant way Ballestrero, Maina, Pelliccioli ’17, ’19

Formulation developed by Denner, Pelliccioli ’20 (see next slide)

BONUS

Idea: use pole approximation to extract resonant contributions in gauge-invariant way Ballestrero, Maina, Pellicciolі '17, '19

Formulation developed by Denner, Pellicciolі '20

- Method is applicable to arbitrary processes and multiple resonances at LO, NLO and beyond.
- needs pole approximation (or double-pole approximation) for all NLO contributions including subtraction terms!
- results at NLO QCD exist for
  - $\mathrm{pp} \to \mu^+\nu_\mu \mathrm{e}^+\nu_\mathrm{e}$ ($\mathrm{W}^+\mathrm{W}^-$ production) Denner, Pellicciolі '20 and
  - $\mathrm{pp} \to \mu^+\mu^- \mathrm{e}^+\nu_\mathrm{e}$ ($\mathrm{W}^+\mathrm{Z}$ production) Denner, Pellicciolі '20
- results at LO exist for VBS for ss-WW, WZ, ZZ, os-WW
  Ballestrero, Maina, Pellicciolі '17, '19, '20 [PHANTOM]
- generalisation in progress towards VBS at NLO QCD and NLO EW

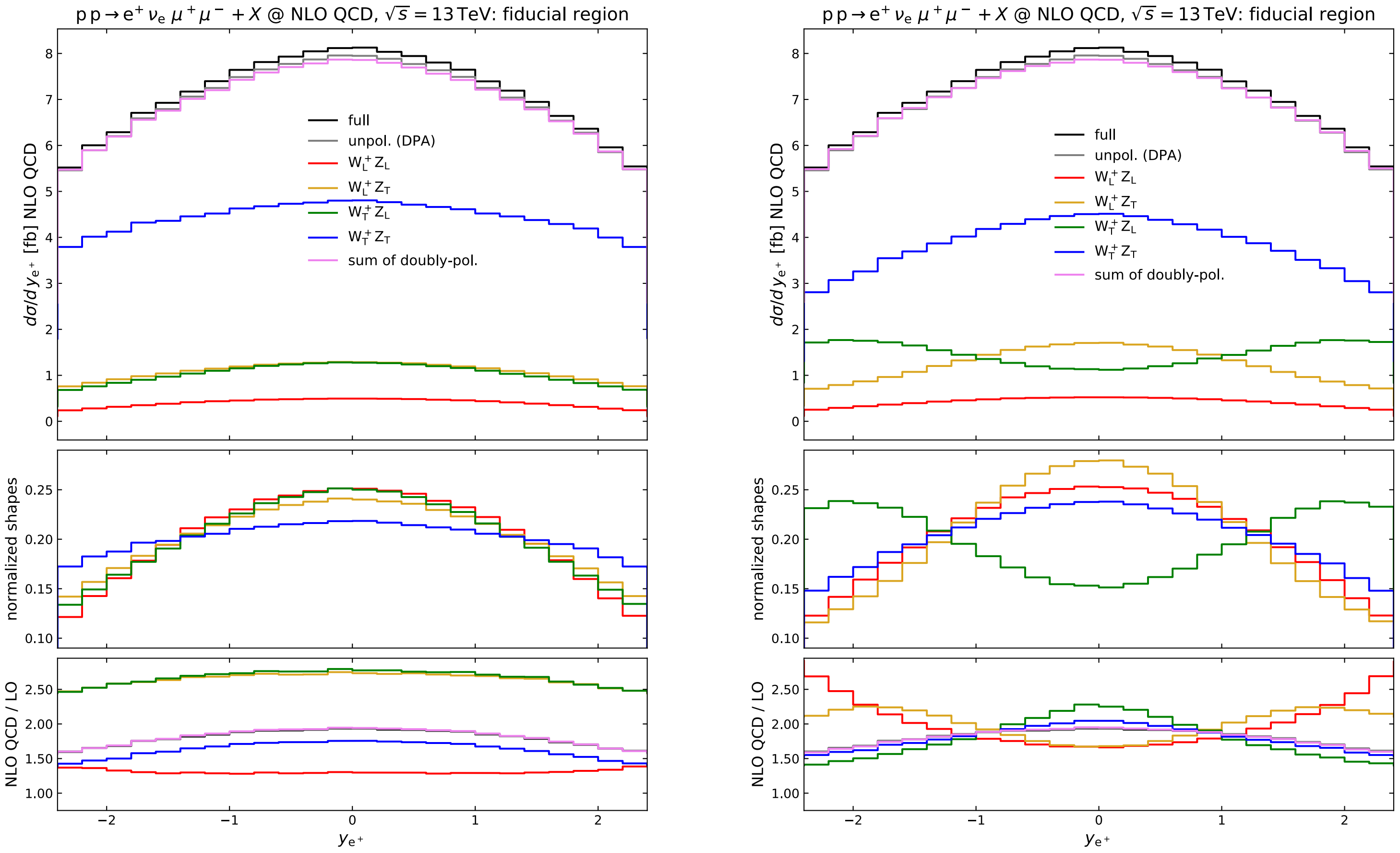
Method allows to separate

- polarised cross sections in arbitrary frames
- interference contributions between polarisations
- irreducible background.

Natural choices of frame
* Diboson center-of-mass
* Laboratory

Example results

$\mathrm{pp} \to \mathrm{e}^+ \nu_\mathrm{e} \mu^+ \mu^-$: Distributions in the positron rapidity in the fiducial region for polarisations defined in the CM (left) and in the LAB (right) frame.



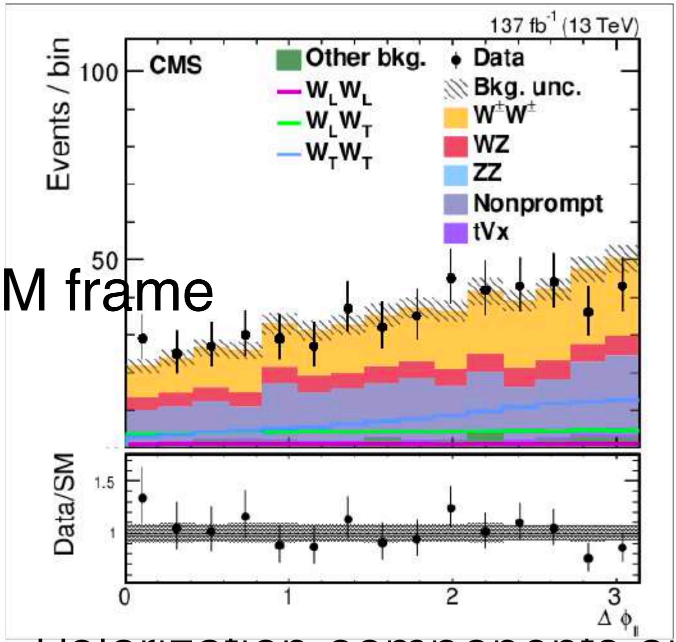
Distributions for pol. cross sections defined in different frames differ considerably!

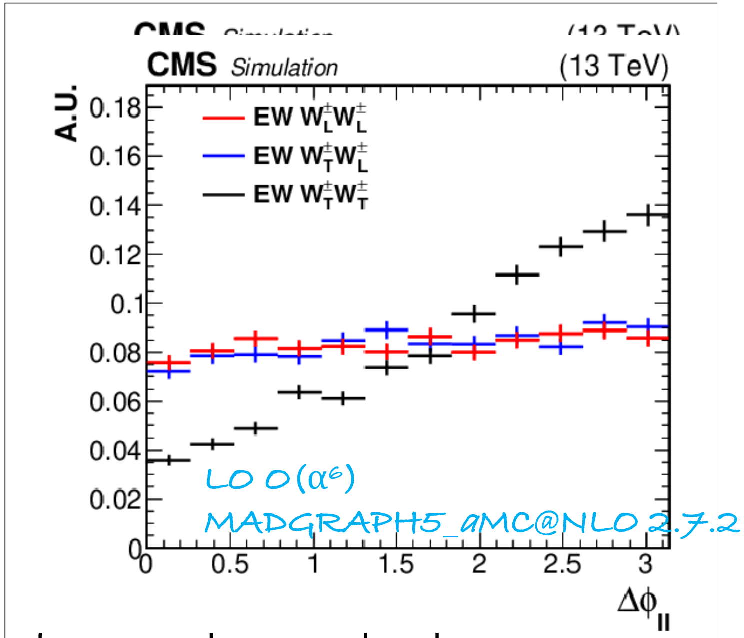
Electroweak W±W±: polarization study

PLB 812 (2020) 136018

- Longitudinal component of W±W± is of large interest (coupling to H, regulating perturbative SM)
  - ➡ Measurement of EW W±W± at ~10% precision allows first study
    - LL component ~10% of total
- Same selection and CRs (WZjj as background) as previous work
  - \+ use BDT to separate W±W± from all backgrounds (esp. nonprompt)
  - \+ BDTs to distinguish polarised components

WW COM frame





LO O(α^6)
MADGRAPH5_aMC@NLO 2.7.2

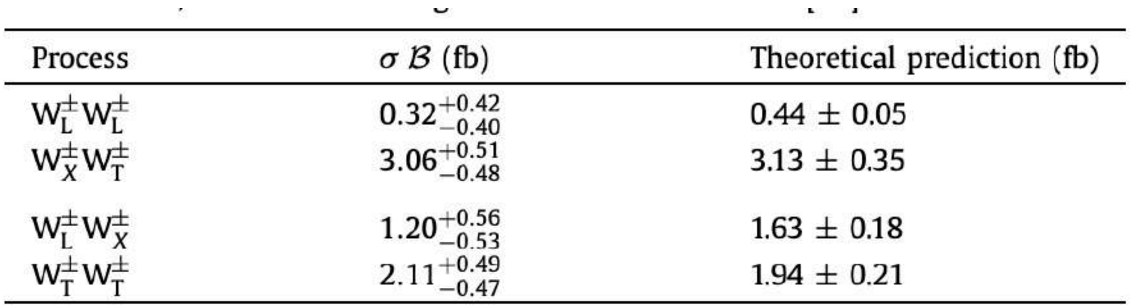
- Polarization components are frame dependent
  - Consider both WW and parton-parton COM frames

Electroweak W±W±: polarization results

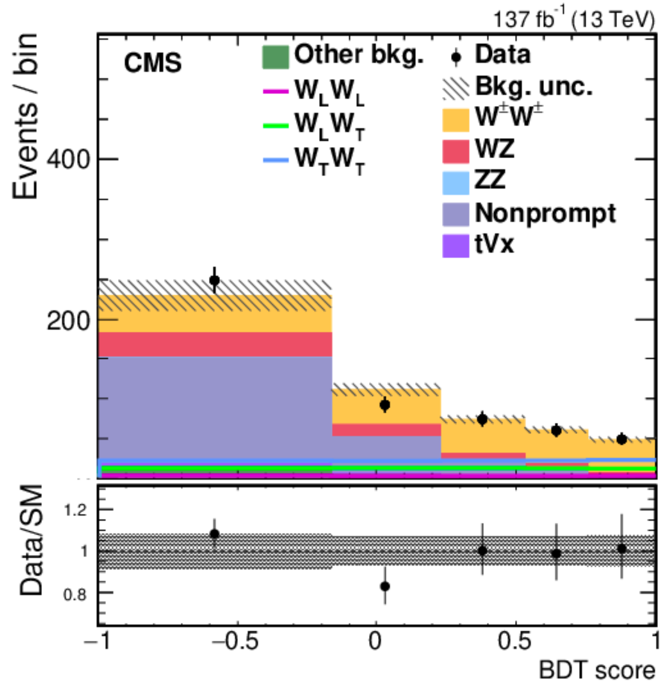
PLB 812 (2020) 136018

- Size of data set is not sufficient to measure LL, LT, and TT all simultaneously
  - Consider LL vs. XT and TT vs LX ⟹ BDTs trained for each
    - Jet, lepton/MET kinematics, and jet+V kinematics
  - Retrained for WW or parton-parton com frame

- Results in WW com frame
- 95% CL limits on LL ~2-3x SM
  - LL 95% CL limit: 1.17 (0.88) fb
  - LX observed at 2.3 (3.1) s.d.



Process	$\sigma\,\mathcal{B}$ (fb)	Theoretical prediction (fb)
$W^\pm_L W^\pm_L$	$0.32^{+0.42}_{-0.40}$	0.44 ± 0.05
$W^\pm_X W^\pm_T$	$3.06^{+0.51}_{-0.48}$	3.13 ± 0.35
$W^\pm_L W^\pm_X$	$1.20^{+0.56}_{-0.53}$	1.63 ± 0.18
$W^\pm_T W^\pm_T$	$2.11^{+0.49}_{-0.47}$	1.94 ± 0.21



WW COM frame

Electroweak ZZ: strong at high lumi

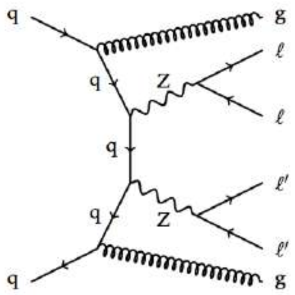
PLB 812 (2021) 135992

- Extremely clean four lepton signal (ℓ = e, μ)
  - Very low nonprompt (fake) background
  - Fully reconstructed final state
    - Access to boson polarizations

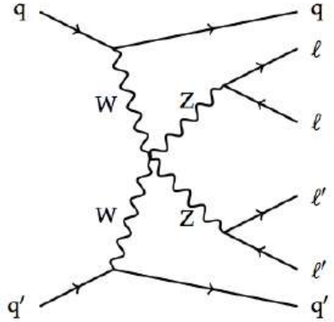
… But very low production cross section

- ZZ(4ℓ) Selection
  - 4 loose ID leptons, $p_T(\mu, e) > 5, 7$ GeV
  - $m_{jj} > 100$ GeV (ptr > 30 GeV)
    - Expected S/B ~1/20
- Estimating ZZjj QCD background is primary challenge
  - Predominately qq and qg induced, but gg-induced component significant in most signal-like region
  - Simulated with merged gg loop-induced +jets predictions with MG5_aMC

QCD production



VBS production



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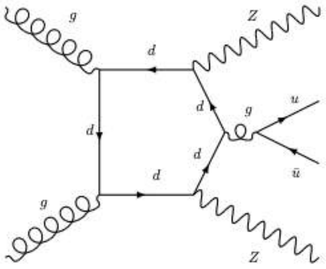
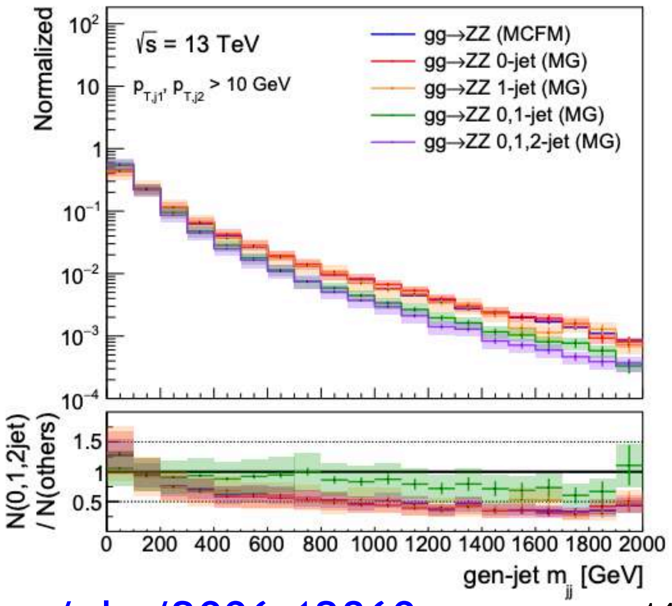


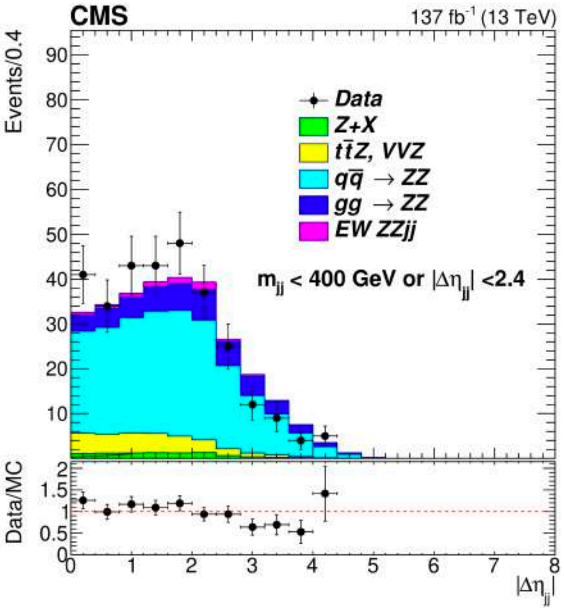


https://arxiv.org/abs/2006.12860

Electroweak ZZ results

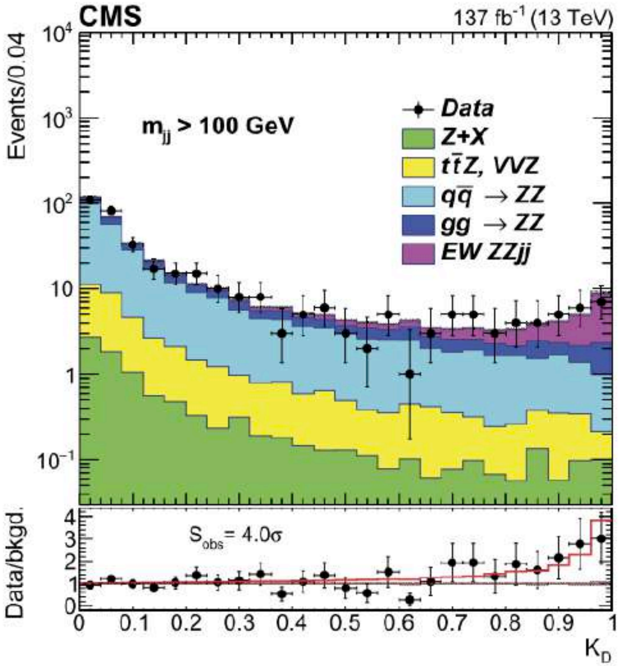
PLB 812 (2021) 135992

- Low S/B, but discrimination possible
  - Exploit matrix element discriminant (K_D)
  - Fit distribution in loose selection



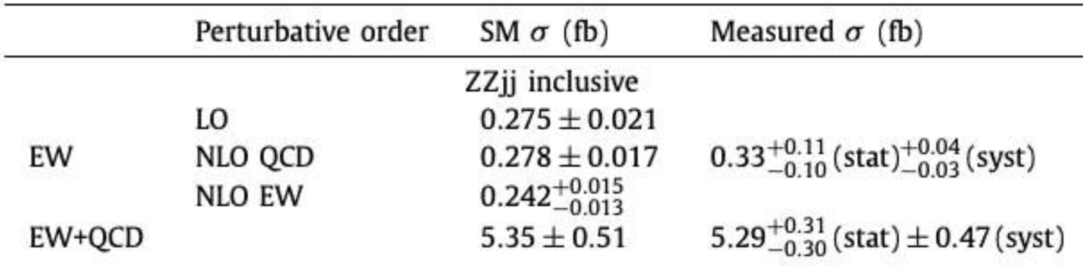
Left: subset of distribution used in fit (right)

$$\mu = \sigma_{obs}/\sigma_{th.} = 1.22^{+0.47}_{-0.40}$$



  - Observed (expected) of 4.0σ (3.5σ)
- Several fiducial cross sections of EW, EW+QCD production

MG5_aMC at LO
POWHEG NLO



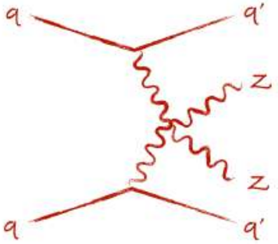
	Perturbative order	SM σ (fb)	Measured σ (fb)
		ZZjj inclusive	
EW	LO	0.275 ± 0.021	$0.33^{+0.11}_{-0.10}\,(\mathrm{stat})^{+0.04}_{-0.03}\,(\mathrm{syst})$
	NLO QCD	0.278 ± 0.017	
	NLO EW	$0.242^{+0.015}_{-0.013}$	
EW+QCD		5.35 ± 0.51	$5.29^{+0.31}_{-0.30}\,(\mathrm{stat}) \pm 0.47\,(\mathrm{syst})$

arXiv:2004.10612

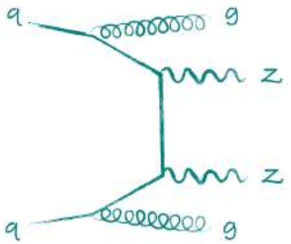
EWK ZZjj production

- ZZjj analysis performed in two channels $\ell\ell\ell\ell$jj and $\ell\ell\nu\nu$jj
- Interesting channel to probe neutral aQGCs
- Different background composition, data driven estimation for the main components
  - $\ell\ell\nu\nu$jj signal region:
    - WZ estimated in 3-lepton control region
    - Non-resonant (ttbar and WW) estimated in eμ$\nu\nu$ control region
  - $\ell\ell\ell\ell$jj signal region:
    - QCD ZZjj control region with low m_{jj} or $\Delta y(jj)$ included in the fit

EWK signal

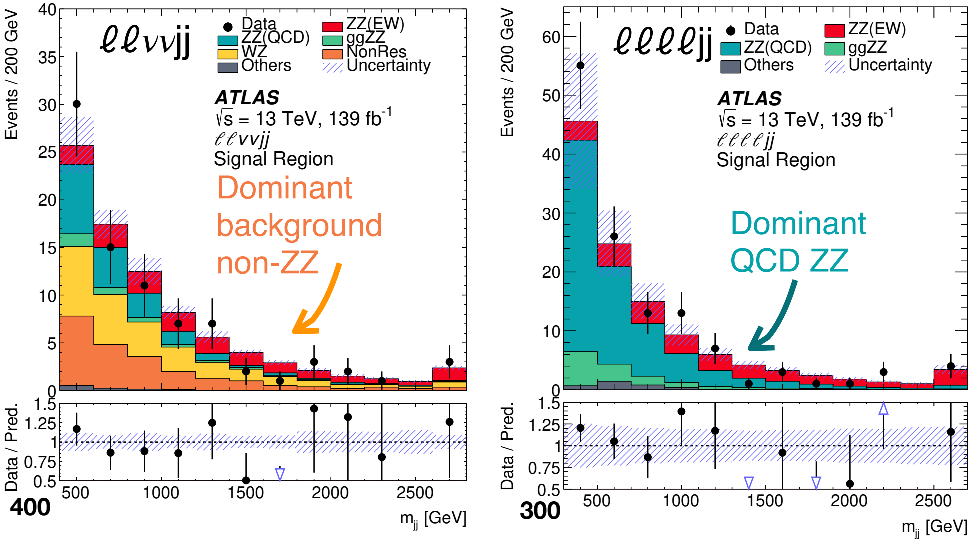


QCD background



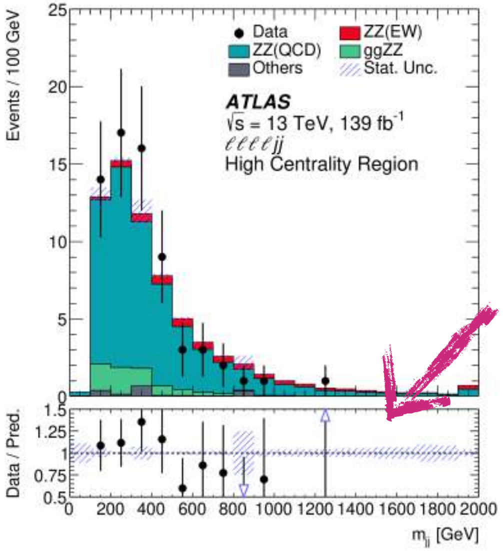
Di-jet invariant mass in the signal regions

● Data
🟥 ZZ(EW)
🟦 ZZ(QCD)
🟩 ggZZ
🟨 WZ
🟧 NonRes
⬛ Others
▨ Uncertainty



Dominant background non-ZZ

Dominant QCD ZZ



High centrality region to verify m_{jj} modeling

	Process	Generator	ME accuracy
🟥	ZZ EWK	MG5_NLO+Py8	LO
🟦	ZZ QCD	Sherpa 2.2.2	NLO (0j), LO (1-3j)
🟨	WZ	Sherpa 2.2.2	NLO (0j), LO (1-3j)

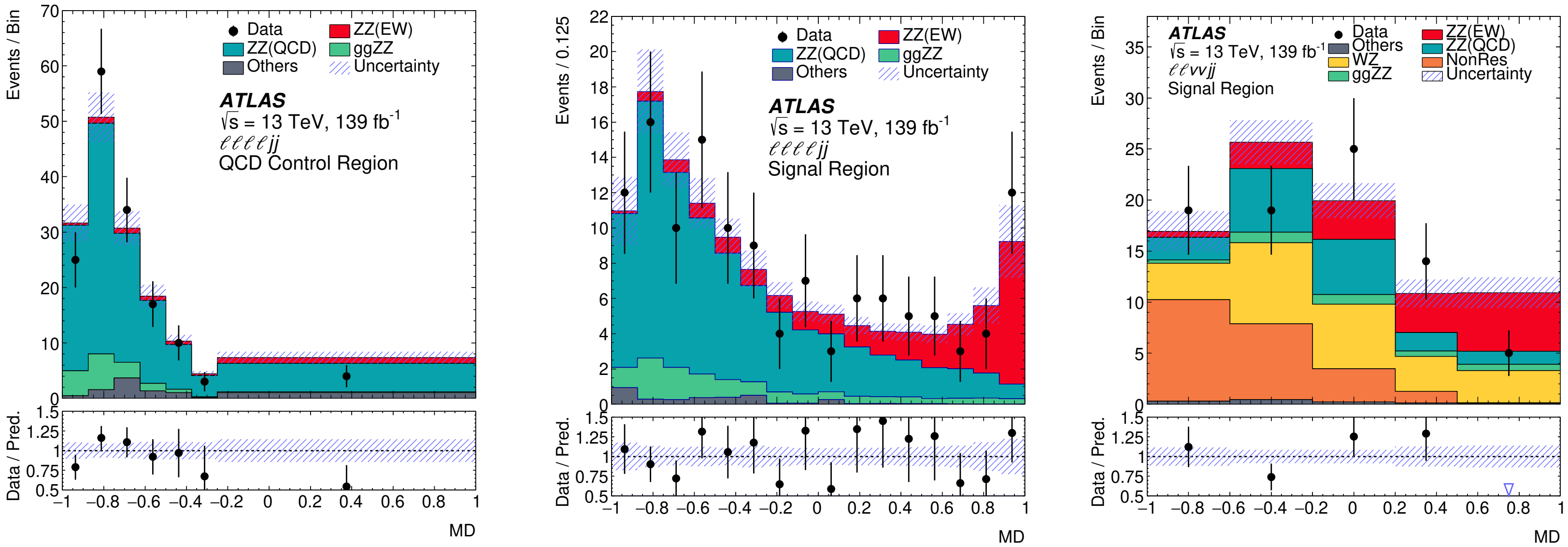
arXiv:2004.10612

EWK ZZjj results

- Extract inclusive cross-section EWK+QCD in the signal region

	Measured fiducial σ [fb]	Predicted fiducial σ [fb]
$\ell\ell\ell\ell jj$	$1.27 \pm 0.12(\text{stat}) \pm 0.02(\text{theo}) \pm 0.07(\text{exp}) \pm 0.01(\text{bkg}) \pm 0.03(\text{lumi})$	$1.14 \pm 0.04(\text{stat}) \pm 0.20(\text{theo})$
$\ell\ell\nu\nu jj$	$1.22 \pm 0.30(\text{stat}) \pm 0.04(\text{theo}) \pm 0.06(\text{exp}) \pm 0.16(\text{bkg}) \pm 0.03(\text{lumi})$	$1.07 \pm 0.01(\text{stat}) \pm 0.12(\text{theo})$

- Then use Multivariate Discriminants (MD) to separate the EWK component. Three MD fitted together



Observation!!

	μ_{EW}	$\mu_{\text{QCD}}^{\ell\ell\ell\ell jj}$	Significance Obs. (Exp.)
$\ell\ell\ell\ell jj$	1.5 ± 0.4	0.95 ± 0.22	5.5 (3.9) σ
$\ell\ell\nu\nu jj$	0.7 ± 0.7	–	1.2 (1.8) σ
Combined	1.35 ± 0.34	0.96 ± 0.22	5.5 (4.3) σ

Fiducial cross-section in agreement with the SM

Semileptonic final states

Experimentally

- Semileptonic final state offer more statistics
- much stronger QCD background
- hadronically decaying vector boson can be reconstructed using jet-substructure techniques $\Rightarrow 6.5\%$ at 3ab^{-1} and $27\,\text{TeV}$ Cavaliere et al. ’18
- first results from ATLAS 1905.07714 (2σ significance) and CMS 1905.07445

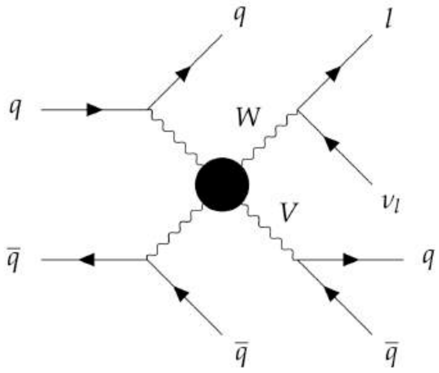
theoretically

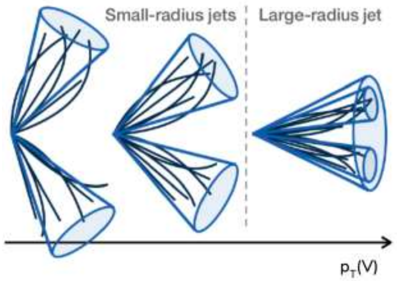
- Proliferation of partonic channels in full calculation
  60 quark-induced partonic channels for $\text{pp} \to \mu^+\mu^-\text{e}^+\text{e}^-\text{jj}$,
  + 40 gluon-induced channels (+ b-induced channels)
  even more channels for semi-leptonic final states (4-quark final states)
- LO diagrams of orders $\mathcal{O}(g^6)$, $\mathcal{O}(g^4 g_\text{s}^2)$, $+\,\mathcal{O}(g^2 g_\text{s}^4)$
  $\Rightarrow$ need strategy to simplify calculation
- consider only contributions involving a virtual VV' pair in theoretical calculation to reduce number of contributions
  use double-pole approximation to calculate NLO corrections
  (gauge invariant, accuracy of DPA 1% for $\text{pp} \to \mu^+\nu_\mu\text{e}^+\nu_\text{e}\text{jj}$)
  $\Rightarrow$ calculation of NLO corrections should be feasible

Semi-leptonic VBS: experimental challenge

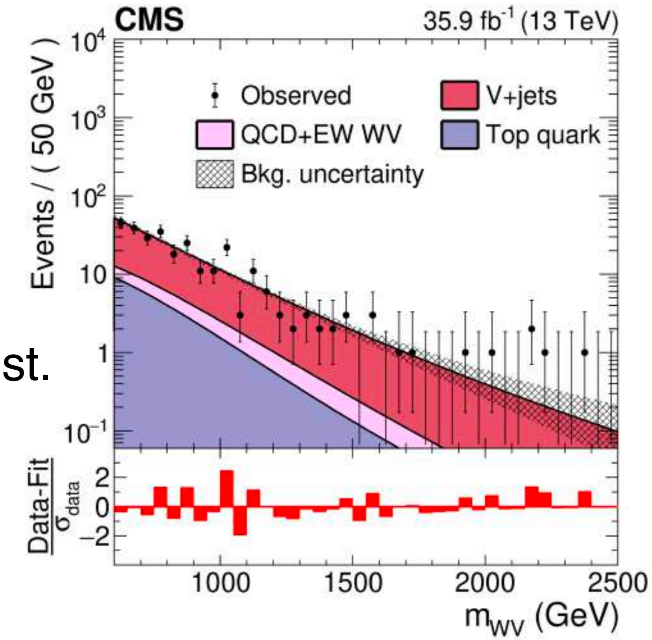
PLB 798 (2019)134985

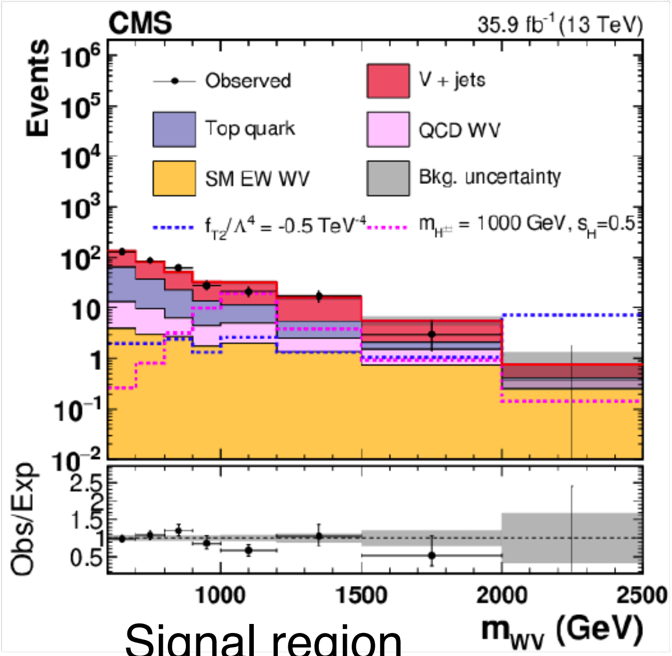
- High cross section ⟹ sensitive to BSM
  - But very experimentally complex!
  - Overwhelming backgrounds not just from VVjj, but also from V+jets and top production
    - Focus on BSM, boosted Vqq events ("fat" V jets)
- Require high-pt lepton + MET or two leptons
- V+jets background estimation primary challenge
  - Estimated from sideband region of fat jet mass (off m_V)





Background est.





Signal region

Anomalous couplings: overview

- Studied using basis of Eboli, Gonzlez-Garcia, Mizukoshi [2]
  - All parity and charge conserving operators with pure V,H couplings

$$\mathcal{L}_{SM} \longrightarrow \mathcal{L}_{eff} = \mathcal{L}_{SM} + \sum_{n=1}^{\infty} \sum_{i} \frac{c_i^{(n)}}{\Lambda^n} \mathcal{O}_i^{(n+4)}$$

  - Operators constructed from Higgs fields only, gauge field only, and Higgs and gauge fields

$$\boxed{\mathcal{L}_{S,0} = \left[(D_\mu \Phi)^\dagger D_\nu \Phi \right] \times \left[(D^\mu \Phi)^\dagger D^\nu \Phi \right]} \qquad \boxed{\mathcal{L}_{M,0} = \mathrm{Tr}\left[\hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \right] \times \left[(D_\beta \Phi)^\dagger D^\beta \Phi \right]}$$

$$\boxed{\mathcal{L}_{T,0} = \mathrm{Tr}\left[\hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \right] \times \mathrm{Tr}\left[\hat{W}_{\alpha\beta} \hat{W}^{\alpha\beta} \right]}$$

(Φ denotes H field)

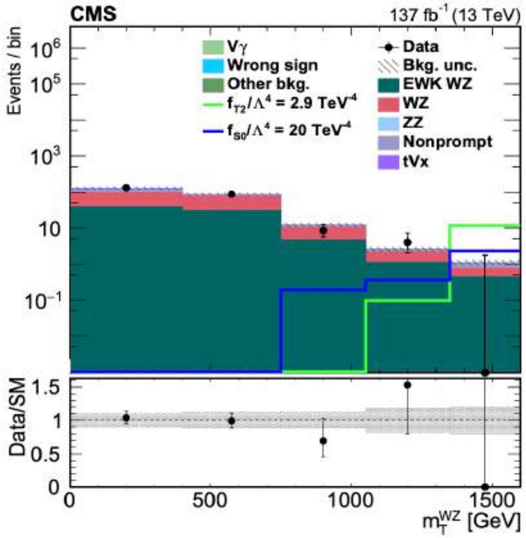
- All realized as excess at high m_{WZ}
- Generalizes V,H interactions
- With some caveats…
  - Assume dimension-6 operators (should dominate) are negligible
  - Applicability of EFT assumes $\hat{s} \ll \Lambda$
- We are aware of recent studies of dimension-6 affects in VBS channels
  - Expect to explore this at CMS in the future

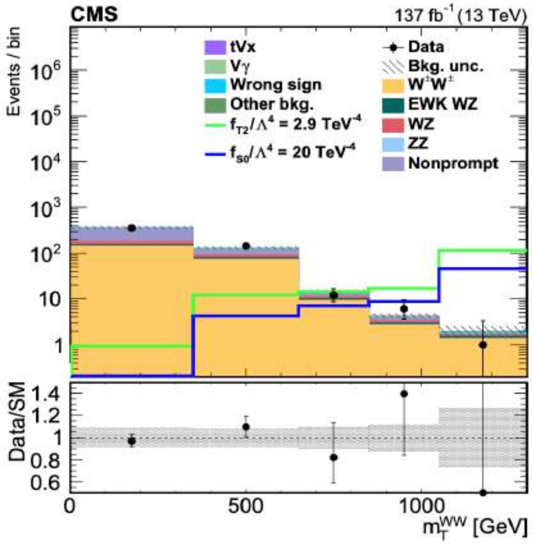
[2] https://arxiv.org/abs/hep-ph/0606118

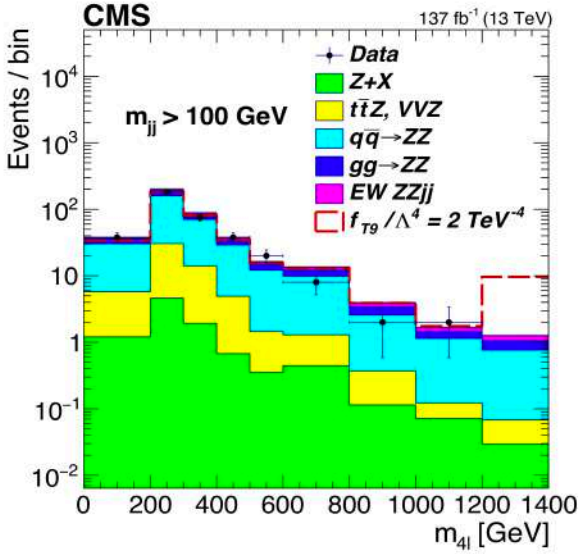
Diboson final states in scattering topologies
and triboson final states used to set limits on aQGCs

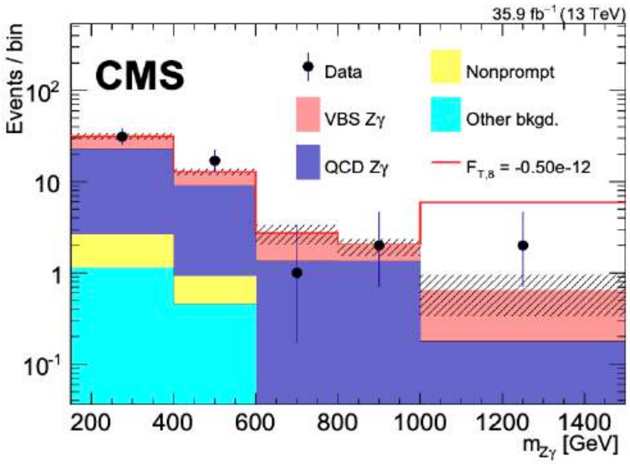
Anomalous couplings: approach

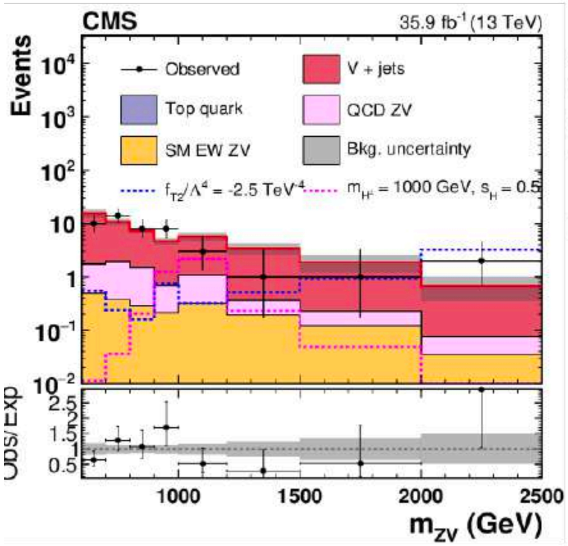
- Exploit variables sensitive to modification from high-mass interaction

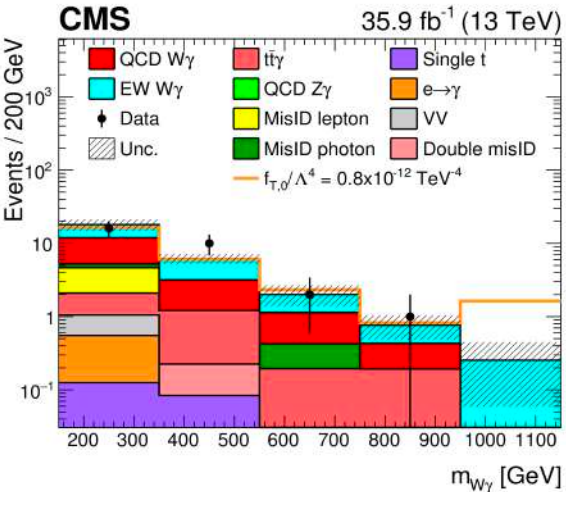






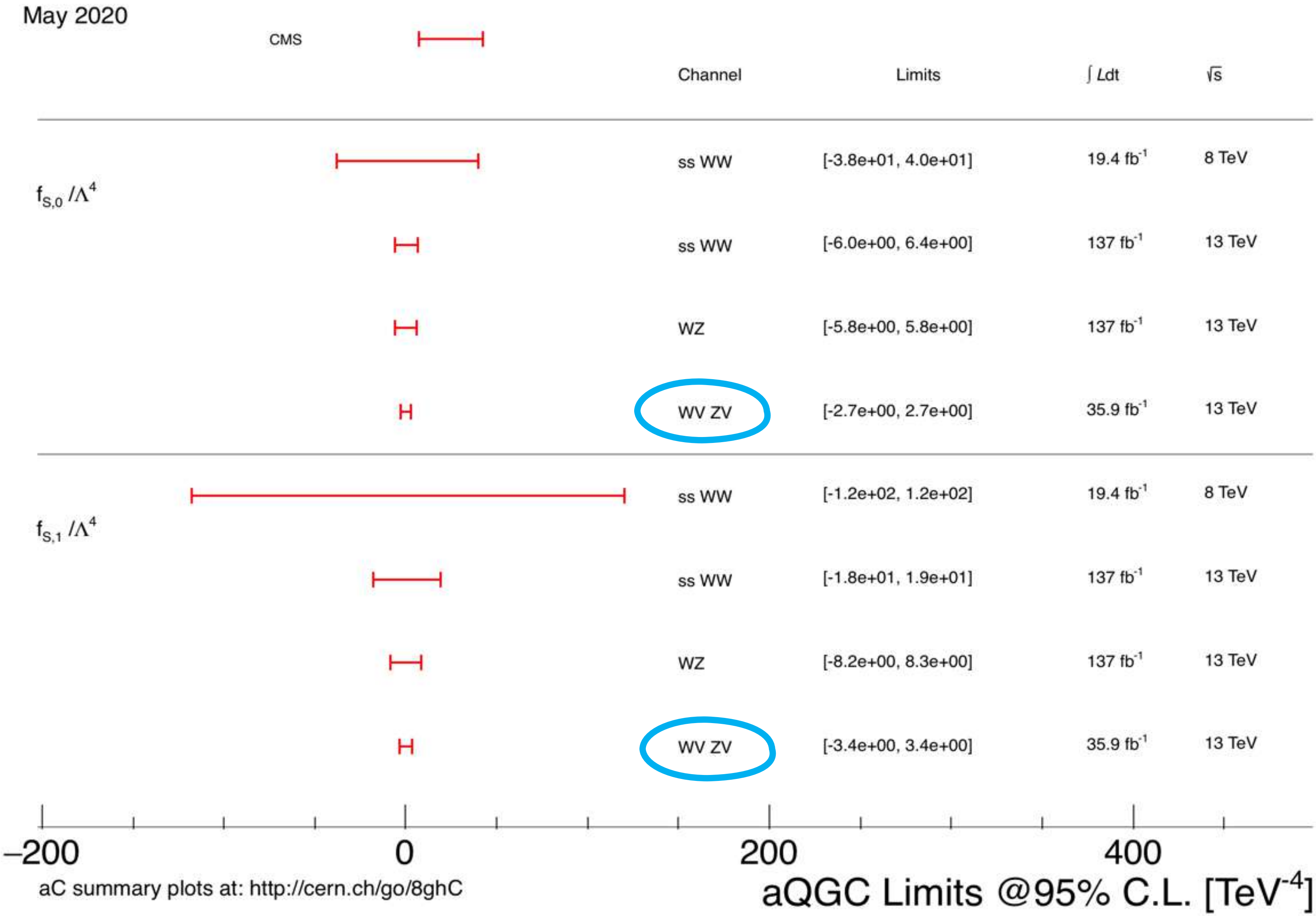






Limits on dim-8 EFT scalar/longitudinal parameters

using Madgraph conventions

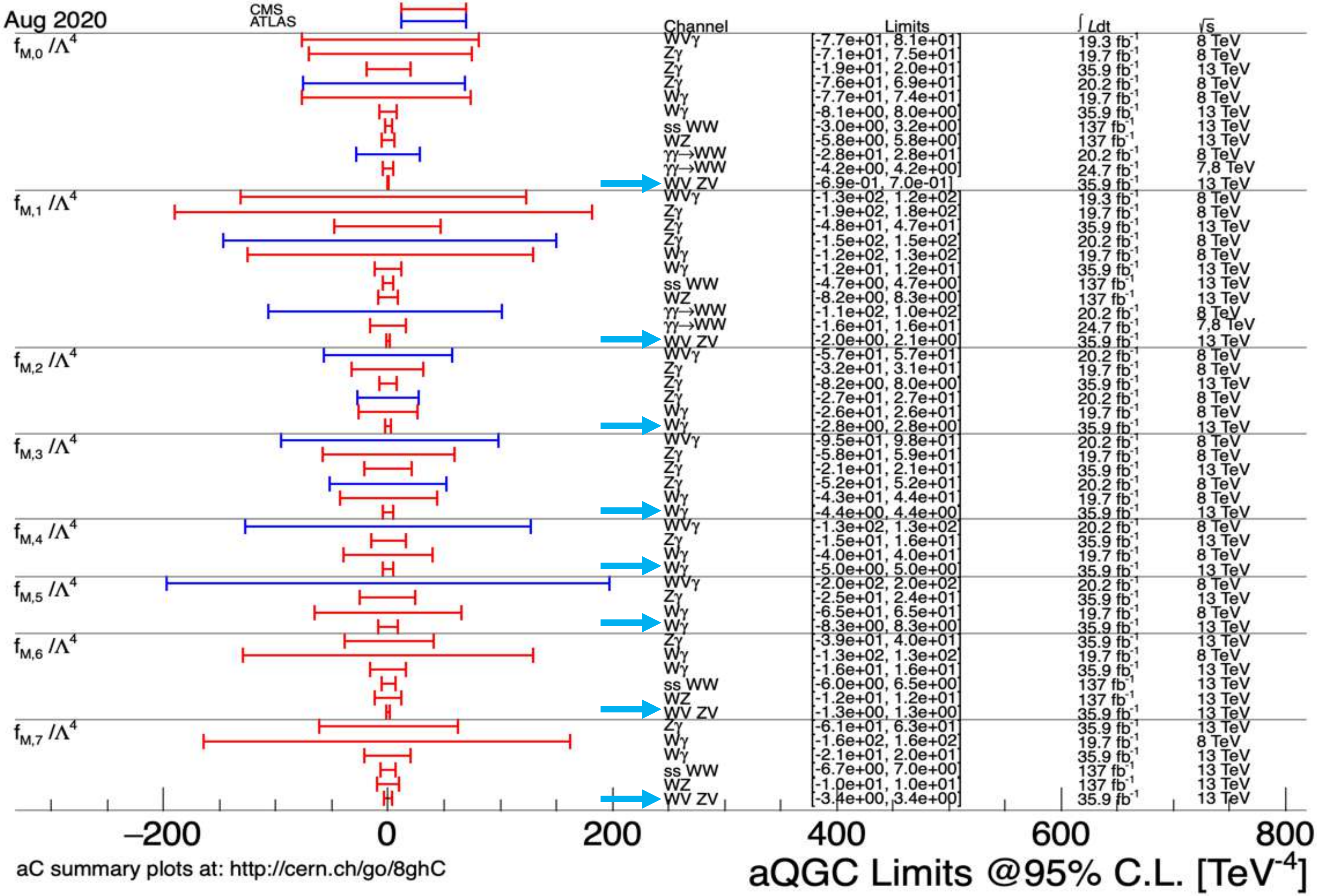


	Channel	Limits	$\int Ldt$	$\sqrt{s}$
$f_{S,0}/\Lambda^4$	ss WW	[-3.8e+01, 4.0e+01]	19.4 fb^{-1}	8 TeV
	ss WW	[-6.0e+00, 6.4e+00]	137 fb^{-1}	13 TeV
	WZ	[-5.8e+00, 5.8e+00]	137 fb^{-1}	13 TeV
	WV ZV	[-2.7e+00, 2.7e+00]	35.9 fb^{-1}	13 TeV
$f_{S,1}/\Lambda^4$	ss WW	[-1.2e+02, 1.2e+02]	19.4 fb^{-1}	8 TeV
	ss WW	[-1.8e+01, 1.9e+01]	137 fb^{-1}	13 TeV
	WZ	[-8.2e+00, 8.3e+00]	137 fb^{-1}	13 TeV
	WV ZV	[-3.4e+00, 3.4e+00]	35.9 fb^{-1}	13 TeV

aC summary plots at: http://cern.ch/go/8ghC

Limits on dim-8 EFT mixed transverse and longitudinal parameters

using Madgraph conventions

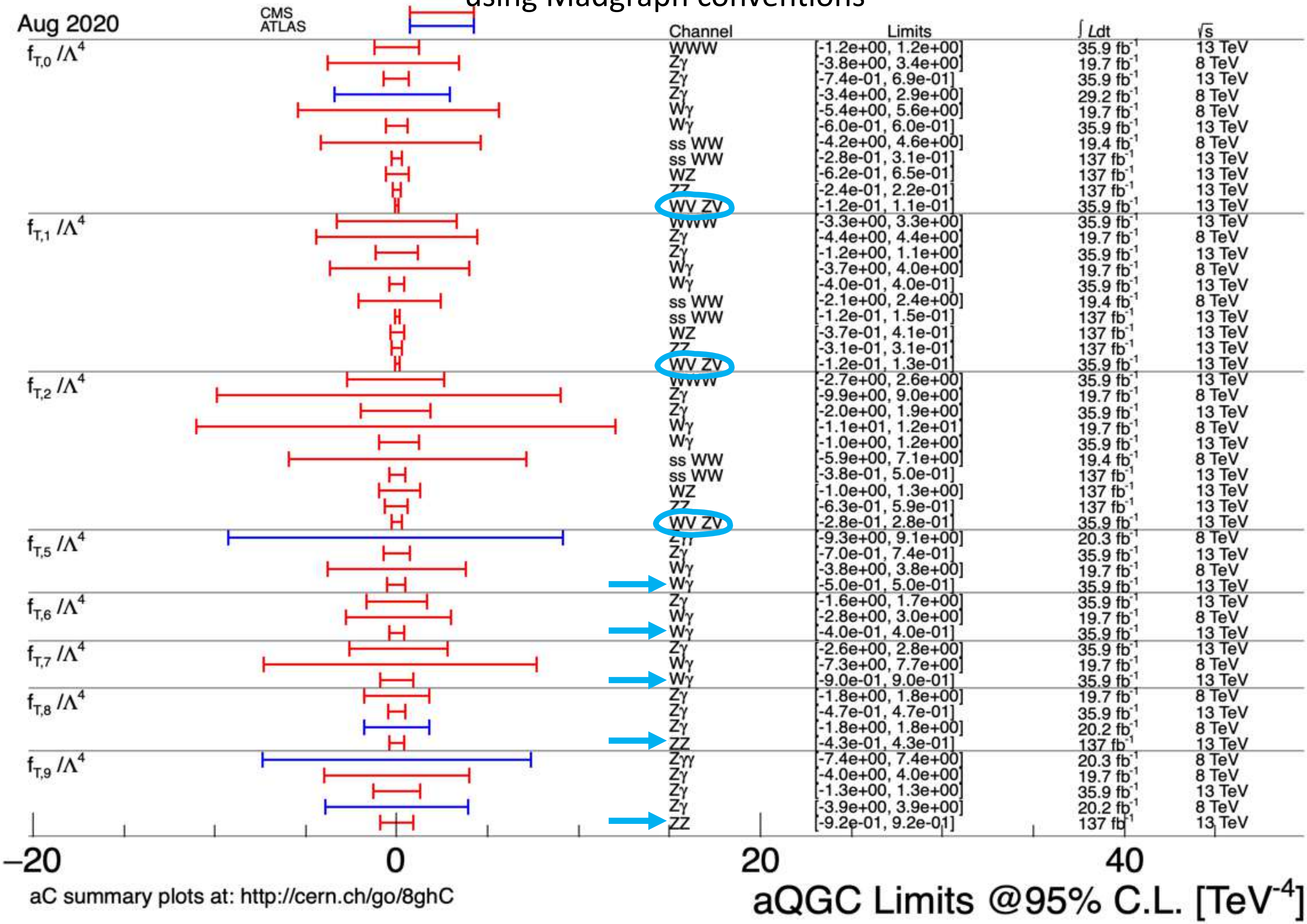


	Channel	Limits	$\int L dt$	$\sqrt{s}$
$f_{M,0}/\Lambda^4$	WVγ	[-7.7e+01, 8.1e+01]	19.3 fb^{-1}	8 TeV
	Zγ	[-7.1e+01, 7.5e+01]	19.7 fb^{-1}	8 TeV
	Zγ	[-1.9e+01, 2.0e+01]	35.9 fb^{-1}	13 TeV
	Zγ	[-7.6e+01, 6.9e+01]	20.2 fb^{-1}	8 TeV
	Wγ	[-7.7e+01, 7.4e+01]	19.7 fb^{-1}	8 TeV
	Wγ	[-8.1e+00, 8.0e+00]	35.9 fb^{-1}	13 TeV
	ss WW	[-3.0e+00, 3.2e+00]	137 fb^{-1}	13 TeV
	WZ	[-5.8e+00, 5.8e+00]	137 fb^{-1}	13 TeV
	γγ→WW	[-2.8e+01, 2.8e+01]	20.2 fb^{-1}	8 TeV
	γγ→WW	[-4.2e+00, 4.2e+00]	24.7 fb^{-1}	7,8 TeV
	WV ZV	[-6.9e-01, 7.0e-01]	35.9 fb^{-1}	13 TeV
$f_{M,1}/\Lambda^4$	WVγ	[-1.3e+02, 1.2e+02]	19.3 fb^{-1}	8 TeV
	Zγ	[-1.9e+02, 1.8e+02]	19.7 fb^{-1}	8 TeV
	Zγ	[-4.8e+01, 4.7e+01]	35.9 fb^{-1}	13 TeV
	Zγ	[-1.5e+02, 1.5e+02]	20.2 fb^{-1}	8 TeV
	Wγ	[-1.2e+02, 1.3e+02]	19.7 fb^{-1}	8 TeV
	Wγ	[-1.2e+01, 1.2e+01]	35.9 fb^{-1}	13 TeV
	ss WW	[-4.7e+00, 4.7e+00]	137 fb^{-1}	13 TeV
	WZ	[-8.2e+00, 8.3e+00]	137 fb^{-1}	13 TeV
	γγ→WW	[-1.1e+02, 1.0e+02]	20.2 fb^{-1}	8 TeV
	γγ→WW	[-1.6e+01, 1.6e+01]	24.7 fb^{-1}	7,8 TeV
	WV ZV	[-2.0e+00, 2.1e+00]	35.9 fb^{-1}	13 TeV
$f_{M,2}/\Lambda^4$	WVγ	[-5.7e+01, 5.7e+01]	20.2 fb^{-1}	8 TeV
	Zγ	[-3.2e+01, 3.1e+01]	19.7 fb^{-1}	8 TeV
	Zγ	[-8.2e+00, 8.0e+00]	35.9 fb^{-1}	13 TeV
	Zγ	[-2.7e+01, 2.7e+01]	20.2 fb^{-1}	8 TeV
	Wγ	[-2.6e+01, 2.6e+01]	19.7 fb^{-1}	8 TeV
	Wγ	[-2.8e+00, 2.8e+00]	35.9 fb^{-1}	13 TeV
$f_{M,3}/\Lambda^4$	WVγ	[-9.5e+01, 9.8e+01]	20.2 fb^{-1}	8 TeV
	Zγ	[-5.8e+01, 5.9e+01]	19.7 fb^{-1}	8 TeV
	Zγ	[-2.1e+01, 2.1e+01]	35.9 fb^{-1}	13 TeV
	Zγ	[-5.2e+01, 5.2e+01]	20.2 fb^{-1}	8 TeV
	Wγ	[-4.3e+01, 4.4e+01]	19.7 fb^{-1}	8 TeV
	Wγ	[-4.4e+00, 4.4e+00]	35.9 fb^{-1}	13 TeV
$f_{M,4}/\Lambda^4$	WVγ	[-1.3e+02, 1.3e+02]	20.2 fb^{-1}	8 TeV
	Zγ	[-1.5e+01, 1.6e+01]	35.9 fb^{-1}	13 TeV
	Wγ	[-4.0e+01, 4.0e+01]	19.7 fb^{-1}	8 TeV
	Wγ	[-5.0e+00, 5.0e+00]	35.9 fb^{-1}	13 TeV
$f_{M,5}/\Lambda^4$	WVγ	[-2.0e+02, 2.0e+02]	20.2 fb^{-1}	8 TeV
	Zγ	[-2.5e+01, 2.4e+01]	35.9 fb^{-1}	13 TeV
	Wγ	[-6.5e+01, 6.5e+01]	19.7 fb^{-1}	8 TeV
	Wγ	[-8.3e+00, 8.3e+00]	35.9 fb^{-1}	13 TeV
$f_{M,6}/\Lambda^4$	Zγ	[-3.9e+01, 4.0e+01]	35.9 fb^{-1}	13 TeV
	Wγ	[-1.3e+02, 1.3e+02]	19.7 fb^{-1}	8 TeV
	Wγ	[-1.6e+01, 1.6e+01]	35.9 fb^{-1}	13 TeV
	ss WW	[-6.0e+00, 6.5e+00]	137 fb^{-1}	13 TeV
	WZ	[-1.2e+01, 1.2e+01]	137 fb^{-1}	13 TeV
	WV ZV	[-1.3e+00, 1.3e+00]	35.9 fb^{-1}	13 TeV
$f_{M,7}/\Lambda^4$	Zγ	[-6.1e+01, 6.3e+01]	35.9 fb^{-1}	13 TeV
	Wγ	[-1.6e+02, 1.6e+02]	19.7 fb^{-1}	8 TeV
	Wγ	[-2.1e+01, 2.0e+01]	35.9 fb^{-1}	13 TeV
	ss WW	[-6.7e+00, 7.0e+00]	137 fb^{-1}	13 TeV
	WZ	[-1.0e+01, 1.0e+01]	137 fb^{-1}	13 TeV
	WV ZV	[-3.4e+00, 3.4e+00]	35.9 fb^{-1}	13 TeV

aC summary plots at: http://cern.ch/go/8ghC

Limits on dim-8 EFT transverse parameters

using Madgraph conventions



	Channel	Limits	$\int Ldt$	$\sqrt{s}$
$f_{T,0}/\Lambda^4$	WWW	[-1.2e+00, 1.2e+00]	35.9 fb^{-1}	13 TeV
	Zγ	[-3.8e+00, 3.4e+00]	19.7 fb^{-1}	8 TeV
	Zγ	[-7.4e-01, 6.9e-01]	35.9 fb^{-1}	13 TeV
	Zγ	[-3.4e+00, 2.9e+00]	29.2 fb^{-1}	8 TeV
	Wγ	[-5.4e+00, 5.6e+00]	19.7 fb^{-1}	8 TeV
	Wγ	[-6.0e-01, 6.0e-01]	35.9 fb^{-1}	13 TeV
	ss WW	[-4.2e+00, 4.6e+00]	19.4 fb^{-1}	8 TeV
	ss WW	[-2.8e-01, 3.1e-01]	137 fb^{-1}	13 TeV
	WZ	[-6.2e-01, 6.5e-01]	137 fb^{-1}	13 TeV
	ZZ	[-2.4e-01, 2.2e-01]	137 fb^{-1}	13 TeV
	WV ZV	[-1.2e-01, 1.1e-01]	35.9 fb^{-1}	13 TeV
$f_{T,1}/\Lambda^4$	WWW	[-3.3e+00, 3.3e+00]	35.9 fb^{-1}	13 TeV
	Zγ	[-4.4e+00, 4.4e+00]	19.7 fb^{-1}	8 TeV
	Zγ	[-1.2e+00, 1.1e+00]	35.9 fb^{-1}	13 TeV
	Wγ	[-3.7e+00, 4.0e+00]	19.7 fb^{-1}	8 TeV
	Wγ	[-4.0e-01, 4.0e-01]	35.9 fb^{-1}	13 TeV
	ss WW	[-2.1e+00, 2.4e+00]	19.4 fb^{-1}	8 TeV
	ss WW	[-1.2e-01, 1.5e-01]	137 fb^{-1}	13 TeV
	WZ	[-3.7e-01, 4.1e-01]	137 fb^{-1}	13 TeV
	ZZ	[-3.1e-01, 3.1e-01]	137 fb^{-1}	13 TeV
	WV ZV	[-1.2e-01, 1.3e-01]	35.9 fb^{-1}	13 TeV
$f_{T,2}/\Lambda^4$	WWW	[-2.7e+00, 2.6e+00]	35.9 fb^{-1}	13 TeV
	Zγ	[-9.9e+00, 9.0e+00]	19.7 fb^{-1}	8 TeV
	Zγ	[-2.0e+00, 1.9e+00]	35.9 fb^{-1}	13 TeV
	Wγ	[-1.1e+01, 1.2e+01]	19.7 fb^{-1}	8 TeV
	Wγ	[-1.0e+00, 1.2e+00]	35.9 fb^{-1}	13 TeV
	ss WW	[-5.9e+00, 7.1e+00]	19.4 fb^{-1}	8 TeV
	ss WW	[-3.8e-01, 5.0e-01]	137 fb^{-1}	13 TeV
	WZ	[-1.0e+00, 1.3e+00]	137 fb^{-1}	13 TeV
	ZZ	[-6.3e-01, 5.9e-01]	137 fb^{-1}	13 TeV
	WV ZV	[-2.8e-01, 2.8e-01]	35.9 fb^{-1}	13 TeV
$f_{T,5}/\Lambda^4$	Zγγ	[-9.3e+00, 9.1e+00]	20.3 fb^{-1}	8 TeV
	Zγ	[-7.0e-01, 7.4e-01]	35.9 fb^{-1}	13 TeV
	Wγ	[-3.8e+00, 3.8e+00]	19.7 fb^{-1}	8 TeV
	Wγ	[-5.0e-01, 5.0e-01]	35.9 fb^{-1}	13 TeV
$f_{T,6}/\Lambda^4$	Zγ	[-1.6e+00, 1.7e+00]	35.9 fb^{-1}	13 TeV
	Wγ	[-2.8e+00, 3.0e+00]	19.7 fb^{-1}	8 TeV
	Wγ	[-4.0e-01, 4.0e-01]	35.9 fb^{-1}	13 TeV
$f_{T,7}/\Lambda^4$	Zγ	[-2.6e+00, 2.8e+00]	35.9 fb^{-1}	13 TeV
	Wγ	[-7.3e+00, 7.7e+00]	19.7 fb^{-1}	8 TeV
	Wγ	[-9.0e-01, 9.0e-01]	35.9 fb^{-1}	13 TeV
$f_{T,8}/\Lambda^4$	Zγ	[-1.8e+00, 1.8e+00]	19.7 fb^{-1}	8 TeV
	Zγ	[-4.7e-01, 4.7e-01]	35.9 fb^{-1}	13 TeV
	Zγ	[-1.8e+00, 1.8e+00]	20.2 fb^{-1}	8 TeV
	ZZ	[-4.3e-01, 4.3e-01]	137 fb^{-1}	13 TeV
$f_{T,9}/\Lambda^4$	Zγγ	[-7.4e+00, 7.4e+00]	20.3 fb^{-1}	8 TeV
	Zγ	[-4.0e+00, 4.0e+00]	19.7 fb^{-1}	8 TeV
	Zγ	[-1.3e+00, 1.3e+00]	35.9 fb^{-1}	13 TeV
	Zγ	[-3.9e+00, 3.9e+00]	20.2 fb^{-1}	8 TeV
	ZZ	[-9.2e-01, 9.2e-01]	137 fb^{-1}	13 TeV

aC summary plots at: http://cern.ch/go/8ghC

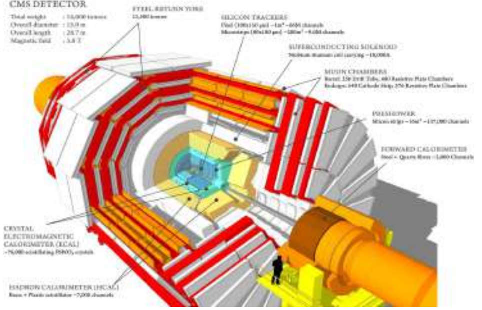
Projections for HL-LHC

Instantaneous luminosity: up to L = 7.5 x 10^{34}Hz/cm^2(~ 3 times RunII)

Integrated luminosity: up to 3000 fb^{-1} → Improved statistics

Pile up: 140-200 per bunch crossing

Similar upgrade plans for ATLAS!



Need upgrade to cope with hardest conditions.

- Inner Tracker up to $|\eta|<4$
- Muon system coverage improved
- MTD timing layer
- High Granularity endcap calorimeter
- DAQ and trigger systems (L1 and HLT -7.5 kHz)

Timing layer (30 ps) helps to suppress pile-up

~10 kHz trigger bandwidth allows to keep object pT thresholds low

The **extended tracker** should improve the lepton identification → suppress contamination of ttbar,WZ, ZZ

The **highly granular calorimeter** should significantly enhance the capability to observe this signal.

Uncertainties as Yellow Report 18:

- **theoretical** uncertainties → **½**
- **experimental** uncertainties → **$1/\sqrt{L}$** until the achievable accuracy with the upgraded detector.

VBS scattering in HL LHC

VBS status @13 TeV RunII:
$W^{\pm}W^{\pm}jj$ WZjj CMS-SMP-19-012
ZZjj CMS-SMP-20-001

Dominated by statistics

→

VBS projections HL-LHC:
$W^{\pm}W^{\pm}jj$ CMS-PAS-FTR-18-005
WZjj CMS-PAS-FTR-18-038
ZZjj CMS-PAS-FTR-18-014

Dominated by systematics

Increased c.m. energy → ✓ Increased cross section ~15-20%

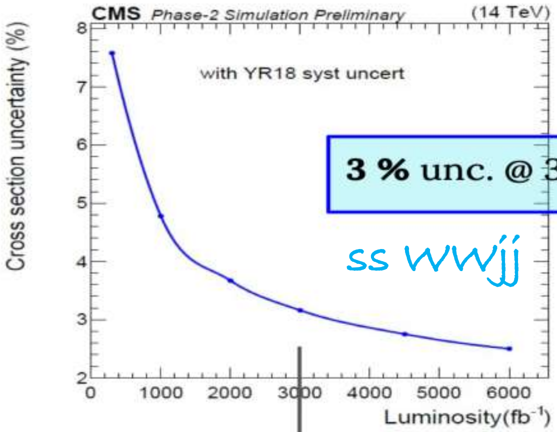
Extended tracker coverage → ✓ Better rejection of:
- pile up jets,
- additional leptons.

More statistics → better calibration → ✓ Reduction of experimental uncertainties.

- The **more signal** yield could allow:
  - division in more **categories** → enhance final sensitivity
  - more raffinate **Machine Learning** techniques → to disentangle from the intrinsic QCD background.
- Better **detector performance** could suppress reducible backgrounds e.g.:
  - in W+W- (not observed yet) could help reducing the limiting top background.
  - Helps further the study semi-leptonic final state, which guarantees an higher statistics than the leptonic ones.

HL-LHC projections

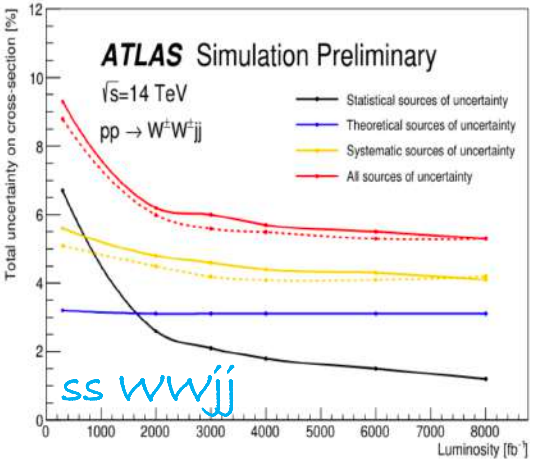
usually some reasonable simplifying assumptions used



3 % unc. @ 3000 fb^{-1}

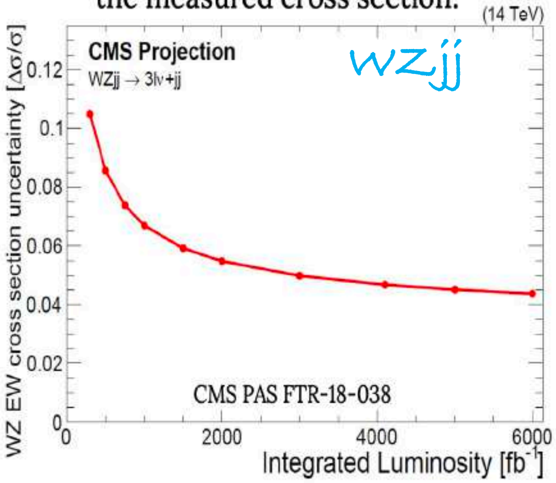
ss WWjj

From this point, combination of ATLAS+CMS

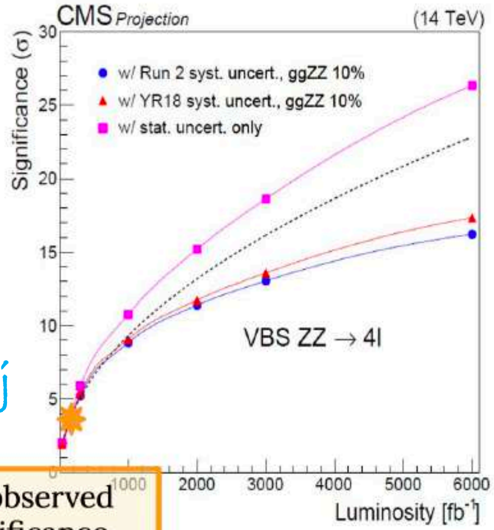


ss WWjj

~4-5% @ 3000-6000 /fb
systematic uncertainties
will dominate the accuracy of the measured cross section.



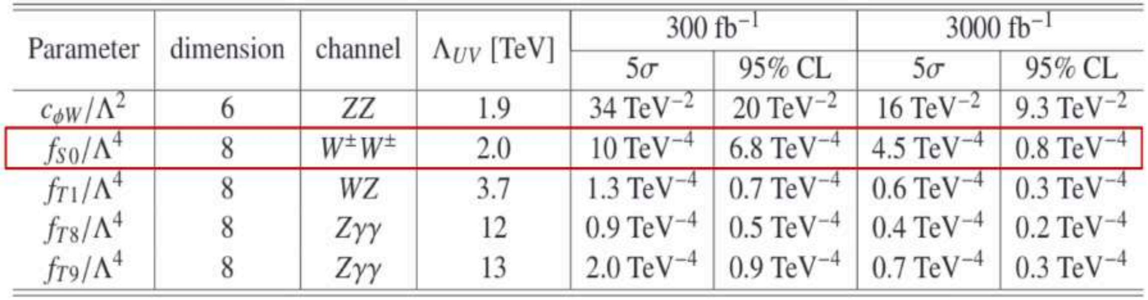
WZjj



ZZjj

4.0 observed significance
SMP-20-001
(2008.07013v2)

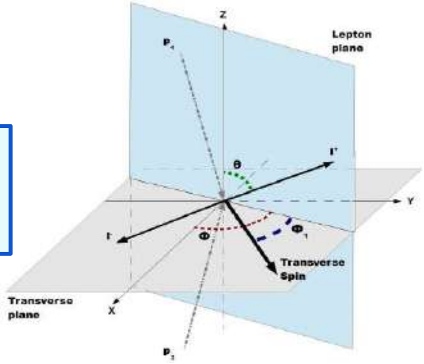
ATLAS



Parameter	dimension	channel	Λ_{UV} [TeV]	300 fb^{-1}		3000 fb^{-1}	
				5σ	95% CL	5σ	95% CL
$c_{\phi W}/\Lambda^2$	6	ZZ	1.9	34 TeV^{-2}	20 TeV^{-2}	16 TeV^{-2}	9.3 TeV^{-2}
f_{S0}/Λ^4	8	$W^\pm W^\pm$	2.0	10 TeV^{-4}	6.8 TeV^{-4}	4.5 TeV^{-4}	0.8 TeV^{-4}
f_{T1}/Λ^4	8	WZ	3.7	1.3 TeV^{-4}	0.7 TeV^{-4}	0.6 TeV^{-4}	0.3 TeV^{-4}
f_{T8}/Λ^4	8	$Z\gamma\gamma$	12	0.9 TeV^{-4}	0.5 TeV^{-4}	0.4 TeV^{-4}	0.2 TeV^{-4}
f_{T9}/Λ^4	8	$Z\gamma\gamma$	13	2.0 TeV^{-4}	0.9 TeV^{-4}	0.7 TeV^{-4}	0.3 TeV^{-4}

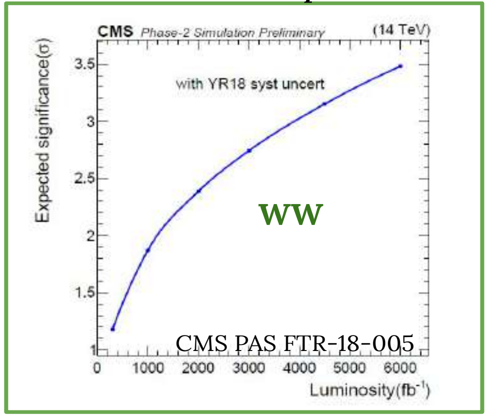
Typically projections age well and actual performance is similar or better than expected (hard work for many years on optimisation, new methods etc.)

Polarization studies

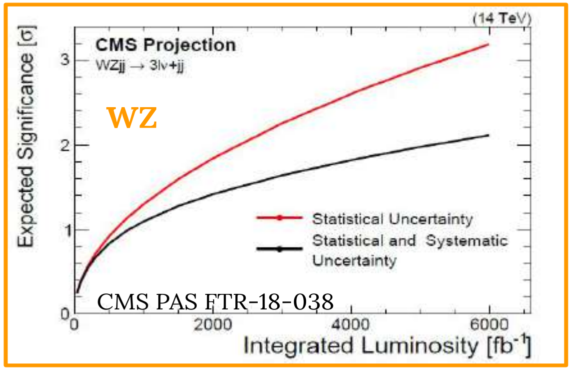


- ★ **Massive V bosons**: 1 longitudinal (L) + 2 transverse (T) polarization mode.
- ★ **Longitudinal component**: directly related to
  - ○ the Electroweak Spontaneous Symmetry Breaking
  - ○ and to Higgs boson → cancellation of divergences @ high energy.
- ★ **ZZ channel** particularly suitable: **complete reconstructions** of the final state particle.

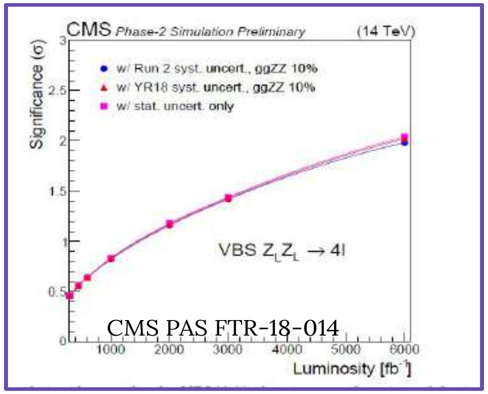
< 10 % of the inclusive cross section



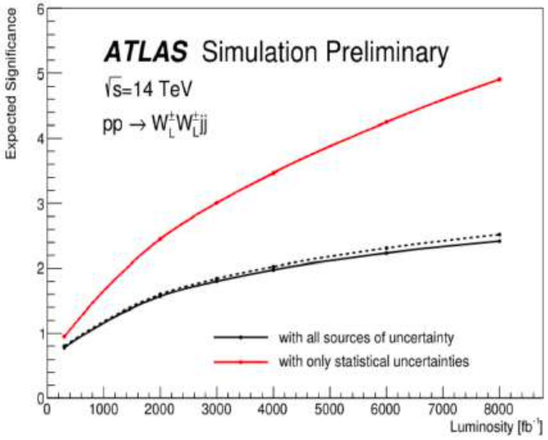
CMS PAS FTR-18-005



CMS PAS FTR-18-038



CMS PAS FTR-18-014



Polarization studies are and will remain challenging

More and more effort is invested to the field both from theoretical and experimental sides

Experimental summary

- Precision measurements are alternatives to direct searches for new physics phenomena, like heavy particles
- Vector boson scattering -- while a rare process -- is especially exciting as it is intimately related to EWSB: stringent probe of SM and probe of New Physics
- LHC collaborations analysed up to 140 fb^{-1} data at 13 TeV, and expect a total of 300 fb^{-1} in a few years and 3000 fb^{-1} by the end of HL-LHC at 14 TeV
- These data so far show SM-like behavior with the currently statistics limited precision
- We expect to probe precisely the already observed processes (ss WW, WZ), reach observation level for ZZ, os WW, access new final states (like semi-leptonic decays)
- More and more stringent results on anomalous couplings, EFTs
- Understanding subtle differences needs more data, further improved techniques (machine learning!) and close collaboration between theory and experiment
- At HL-LHC even VBS studies will become systematics limited!
- First measurement of longitudinal polarisation performed and will help to understand the HL-LHC projections better
- Improve modelling with better calculations tuned from data
- Very active area with opportunities and challenges for both experimentalist and theorists

Conclusion

Status of NLO calculations for VBS

- NLO QCD corrections matched to PS available for all VBS processes
  NLO QCD corrections at level of few percent if $p_{\mathrm{T,j}}$ or M_{jj} not small
- VBS approximation might not be sufficient at NLO   Ballestrero et al. '18
  NLO-QCD tri-boson contributions of $\mathcal{O}(20\%)$ for loose VBS cuts
- electroweak corrections for VBS
  - full NLO EW corrections known for
    $\mathrm{pp} \to \mu^+\nu_\mu \mathrm{e}^+\nu_\mathrm{e}\mathrm{jj}\ (\mathrm{W^+W^+})$ Biedermann et al. '16, '17
    $\mathrm{pp} \to \mu^+\mu^- \mathrm{e}^+\nu_\mathrm{e}\mathrm{jj}\ (\mathrm{WZ})$ Denner et al. '19
    $\mathrm{pp} \to \mu^+\mu^- \mathrm{e}^+\mathrm{e}^-\mathrm{jj}\ (\mathrm{ZZ})$ Denner et al. '20
  - -16% EW corrections for fiducial cross section
    intrinsic feature of VBS, reproducible by simple approximations
  - EW corrections in distributions even larger
    -40% for $p_{\mathrm{T,j_1}} = 800\,\mathrm{GeV}$
- NLO EW corr. for $\mathrm{W^+W^+}$scattering matched to QED PS   Denner et al. '19
- full NLO corrections for $\mathrm{W^+W^+}$scattering   Denner et al. '17
  only measurement of full process is well-defined!

Significant theoretical progress in VBS in recent years!

Outlook

Expected progress in theoretical predictions to VBS

- NLO EW corrections for $\mathrm{pp} \to \mu^+\nu_\mu\bar{\nu}_\mathrm{e}\mathrm{e}^-\mathrm{jj}$ ($\mathrm{W^+W^-}$) (in progress)
- predictions for VBS with semileptonic final states (needed)
- NLO corrections for polarised VBS within reach
- matching to EW parton showers (long term project)
- predictions for VBS within extended models feasible
  once LO and NLO matrix elements available
- predictions for VBS within SMEFT including (approximative) NLO corrections $\Rightarrow$ need to extend/combine tools

Extra

Winter 2021 topical meeting on VBS: VBS at Snowmass

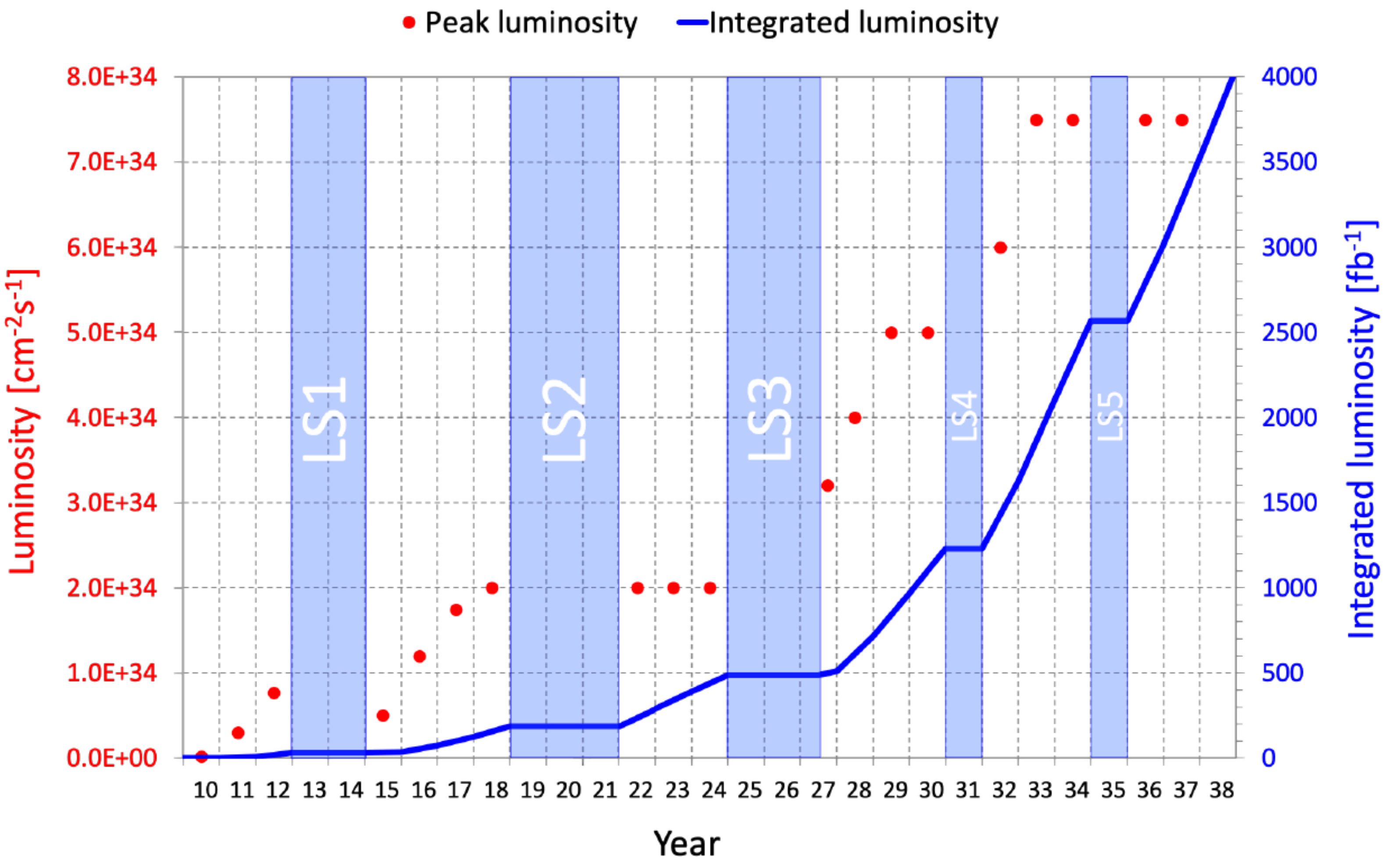
25-29 January 2021

Welcome	*Pietro Govoni*	14:00 - 14:15
Precise theoretical predictions for VBS	*Ansgar Denner*	14:15 - 14:45
ATLAS VBS Results	*Joany Manjarres*	14:45 - 15:15
CMS VBS results	*Kenneth Long*	15:15 - 15:45
Break/discussion		15:45 - 16:15
Review of ATLAS projections on VBS	*Kristin Lohwasser*	16:15 - 16:45
Review of CMS projections on VBS	*Flavia Cetorelli*	16:45 - 17:15

The VBS viewpoint on the EFT landscape	*Dr Raquel Gomez Ambrosio*	14:00 - 14:30
SM EFT effects in Vector-Boson Scattering at the LHC	*Michal Szleper*	14:30 - 15:00
Detecting anomaly in vector boson scattering	*Jinmian Li et al.*	15:00 - 15:30
Break/Discussion		15:30 - 16:00
An overview of future pp colliders	*Patrizia Azzi*	16:00 - 16:30
axion-like particle searches with VBS	*Jorge Fernandez De Troconiz*	16:30 - 17:00
electroweak pdfs	*Keping Xie*	17:00 - 17:30

lessons learned from LHC data up to now, and outlook	*Marc Riembau*	14:00 - 14:30
HL-LHC performance CMS	*Matteo Marchegiani*	14:30 - 14:50
HL-LHC performance ATLAS	*Karolos Potamianos*	14:50 - 15:10
MC challenges and implementation of EW shower in VINCIA	*Rob Verheyen*	15:10 - 15:40
Break/Discussion		15:40 - 16:00
New physics at LH-LHC with VBS signatures	*Richard Ruiz*	16:00 - 16:30
Machine Learning for VBS	*Thea Aarrestad*	16:30 - 17:00

future muon colliders and BSM with VBS	*Antonio Costantini*	14:00 - 14:30
future electron colliders and the VBS physics	*Jürgen Reuter*	14:30 - 15:00
future muon colliders and EFT with VBS	*Luca Mantani*	15:00 - 15:30
Break/Discussion		15:30 - 16:00
Double Higgs Boson Production from Resonances in Longitudinal VBS at a 100 TeV Collider	*Ashutosh Kotwal et al.*	16:00 - 16:30
Fermion Loops in VBS	*Carlos Quezada Calonge*	16:30 - 17:00



● Peak luminosity
Integrated luminosity
Luminosity [cm^{-2}s^{-1}]
Integrated luminosity [fb^{-1}]
8.0E+34
7.0E+34
6.0E+34
5.0E+34
4.0E+34
3.0E+34
2.0E+34
1.0E+34
0.0E+00
4000
3500
3000
2500
2000
1500
1000
500
0
LS1
LS2
LS3
LS4
LS5
10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38
Year

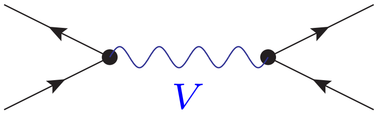
Definition of polarisation based on pole approximation I

Idea: use pole approximation to extract resonant contributions in gauge-invariant way Ballestrero, Maina, Pelliccioli ’17, ’19

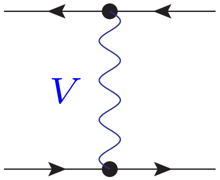
Formulation developed by Denner, Pelliccioli ’20

- Not all diagrams involve required resonances
  resonant diagrams   non-resonant diagrams

$$\frac{R(k^2)}{k^2-M^2+\mathrm{i}M\Gamma} =$$



$$N(k^2) =$$



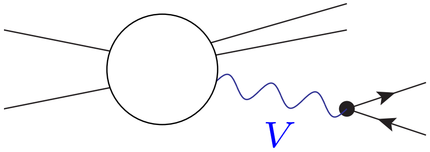
- split full matrix element into resonant part and non-resonant part using pole expansion (gauge-invariant)

$$\begin{aligned}\mathcal{A} &= \frac{R(k^2)}{k^2-M^2+\mathrm{i}M\Gamma} + N(k^2)\\ &= \frac{R(M^2)}{k^2-M^2+\mathrm{i}M\Gamma} + \frac{R(k^2)-R(M^2)}{k^2-M^2} + N(k^2) = \mathcal{A}_{\mathrm{res}} + \mathcal{A}_{\mathrm{nonres}}\end{aligned}$$

- consider non-resonant part as irreducible background: no resonance

Definition of polarisation based on pole approximation II

Separate polarisation modes of resonant amplitude



split propagator numerator of resonant particle

$$\mathcal{A}_{\mathrm{res}} = \mathcal{P}_\mu \frac{-g^{\mu\nu}}{k^2 - M_{\mathrm{W}}^2 + \mathrm{i}\Gamma_{\mathrm{W}} M_{\mathrm{W}}} \mathcal{D}_\nu = \mathcal{P}_\mu \frac{\sum_\lambda \varepsilon_\lambda^{\mu\,*}(k)\varepsilon_\lambda^\nu(k)}{k^2 - M_{\mathrm{W}}^2 + \mathrm{i}\Gamma_{\mathrm{W}} M_{\mathrm{W}}} \mathcal{D}_\nu$$

$$= \sum_{\lambda=\mathrm{L},\pm} \frac{\mathcal{M}_\lambda^{\mathrm{prod}}\,\mathcal{M}_\lambda^{\mathrm{dec}}}{k^2 - M_{\mathrm{W}}^2 + \mathrm{i}\Gamma_{\mathrm{W}} M_{\mathrm{W}}} =: \sum_{\lambda=\mathrm{L},\pm} \mathcal{A}_\lambda \,,$$

$$\left|\mathcal{A}_{\mathrm{res}}\right|^2 = \sum_\lambda \left|\mathcal{A}_\lambda\right|^2 + \sum_{\lambda\neq\lambda'} \mathcal{A}_\lambda^* \mathcal{A}_{\lambda'}$$

- incoherent sum $\sum_\lambda \left|\mathcal{A}_\lambda\right|^2$: $\left|\mathcal{A}_\lambda\right|^2 \propto$ “polarised cross sections”
- interferences $\sum_{\lambda\neq\lambda'} \mathcal{A}_\lambda^* \mathcal{A}_{\lambda'}$
  vanish for quantities fully inclusive in decay products but not in general

Polarisation vectors are defined in specific frames. Natural choices are the (di-boson-)centre-of-mass frame and the laboratory frame.

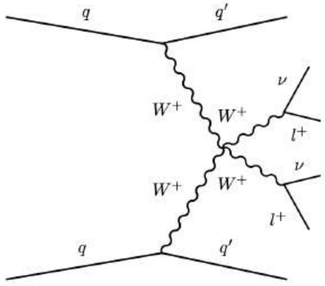
Best EW / QCD ratio!

Electroweak W±W±: the golden channel

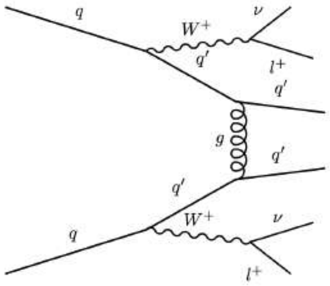
PLB 809 (2020) 135710

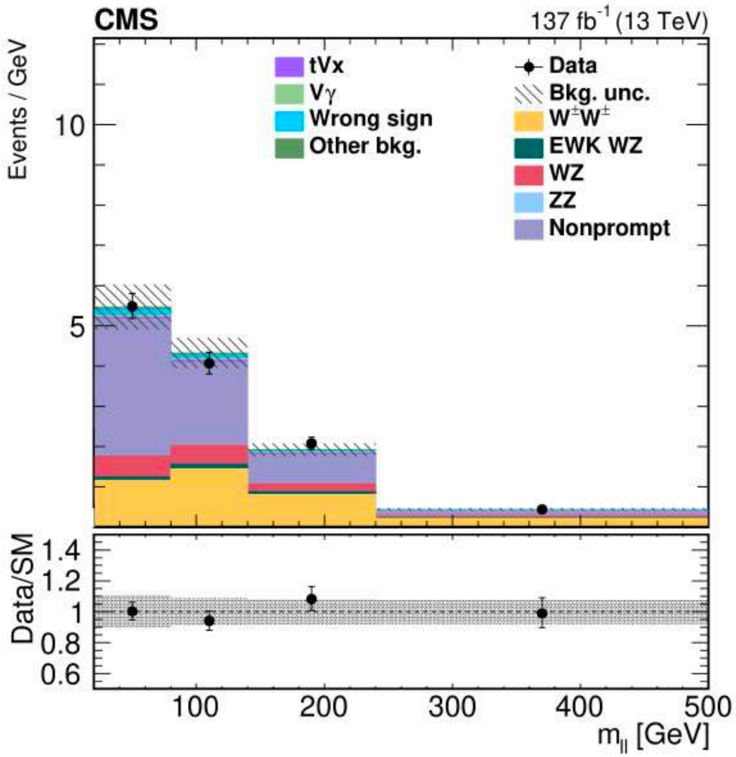
- ★ EW production dominant over QCD-induced
- ★ Distinct same-sign (SS) lepton state
- First studied at 8 TeV, observations with 2016 data
- Moving from search to precise measurement with full Run II data and beyond
- Backgrounds
  - Non-prompt backgrounds ⟹ data driven
  - Charge mis-ID
    - Simulation corrected with data
  - ≥ 2 prompt SS leptons from MC
    - WW QCD (small)
    - ★ WZ EW+QCD
      - Correct using 3ℓ data

VBS production



QCD production





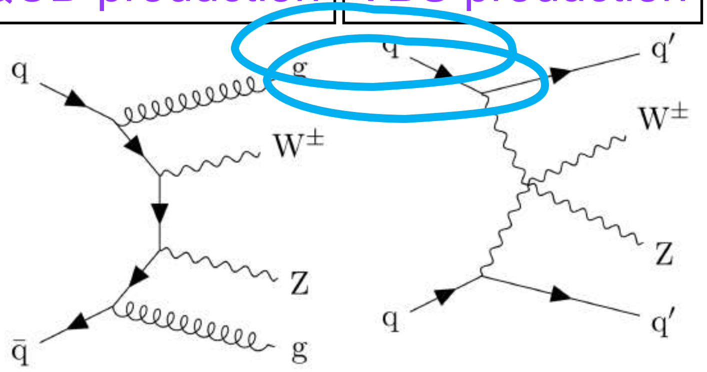
Electroweak WZ: massive charged probe

PLB 809 (2020) 135710

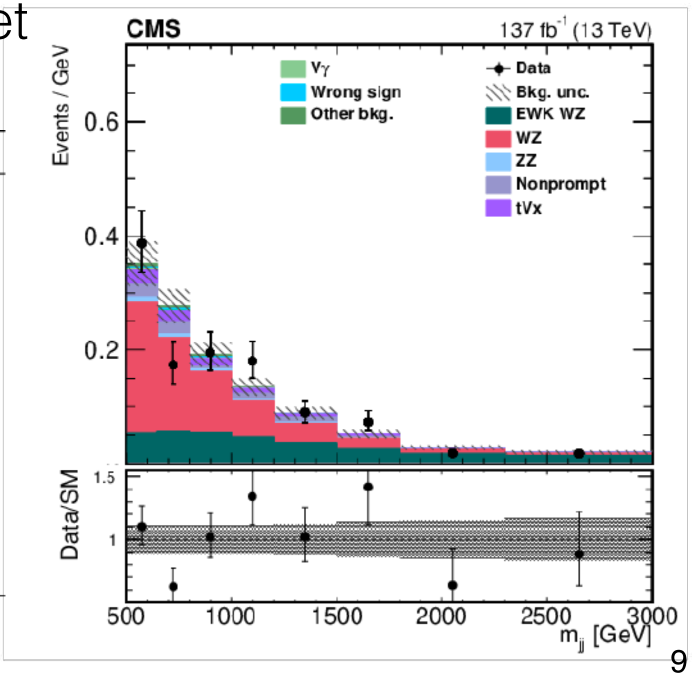
- Background estimation for W±W± is a measurement
  - ➡Measure simultaneously
- Use huge data set to constrain other MC estimates (ZZ), (top)
- Sensitive to charged resonances or couplings (including Higgs-like)
  - Less clean signature than ZZ, W±W±, but cross section accessible with large dataset

QCD production

VBS production

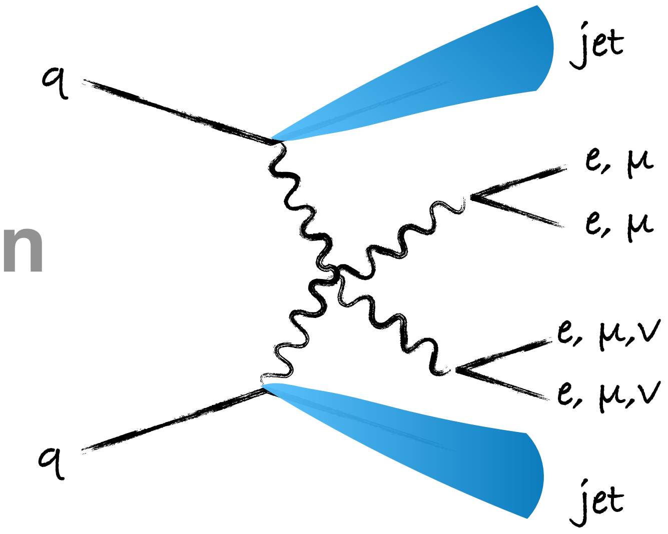


Variable	$W^{\pm}W^{\pm}$	WZ
Leptons	2 leptons, $p_T > 25/20\,\text{GeV}$	3 leptons, $p_T > 25/10/20\,\text{GeV}$
p_T^j	$>50\,\text{GeV}$	$>50\,\text{GeV}$
$\lvert m_{\ell\ell} - m_Z \rvert$	$>15\,\text{GeV}$ (ee)	$<15\,\text{GeV}$
$m_{\ell\ell}$	$>20\,\text{GeV}$	—
$m_{\ell\ell\ell}$	—	$>100\,\text{GeV}$
p_T^{miss}	$>30\,\text{GeV}$	$>30\,\text{GeV}$
b quark veto	Required	Required
$\max(z_\ell^*)$	<0.75	<1.0
m_{jj}	$>500\,\text{GeV}$	$>500\,\text{GeV}$
$\lvert\Delta\eta_{jj}\rvert$	>2.5	>2.5

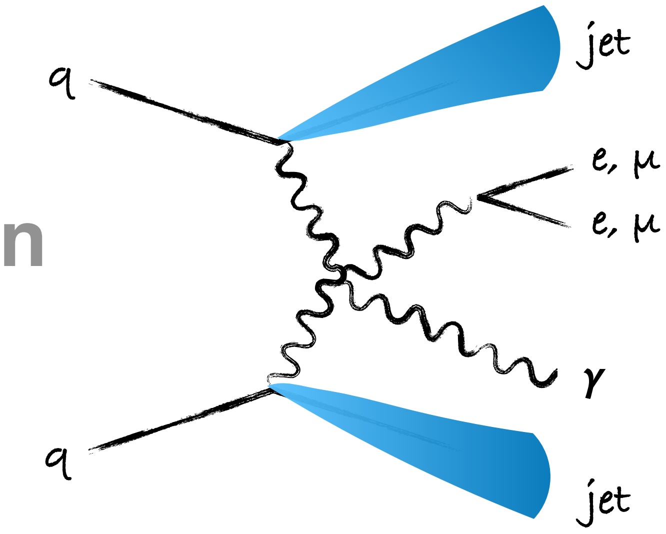


Kenneth Long

Electroweak ZZjj production

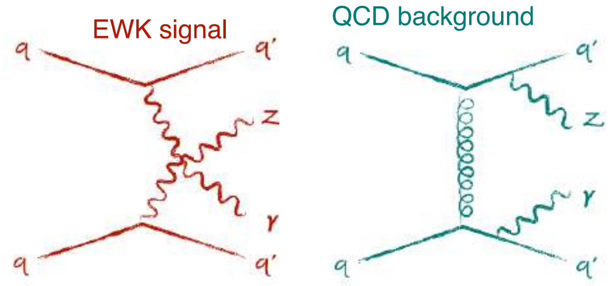


Electroweak Zγjj production

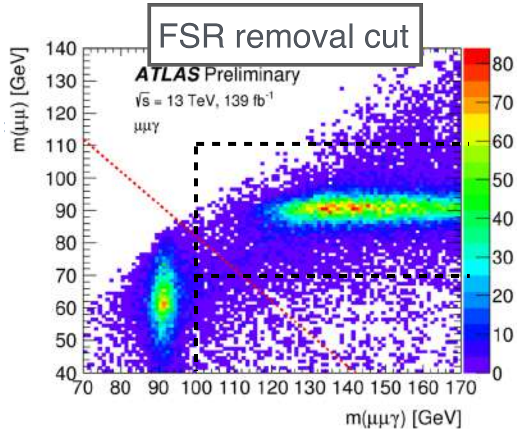


Phys. Lett. B 803 (2020) 135341

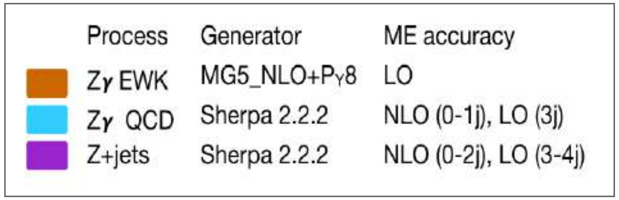
EWK Zγjj production



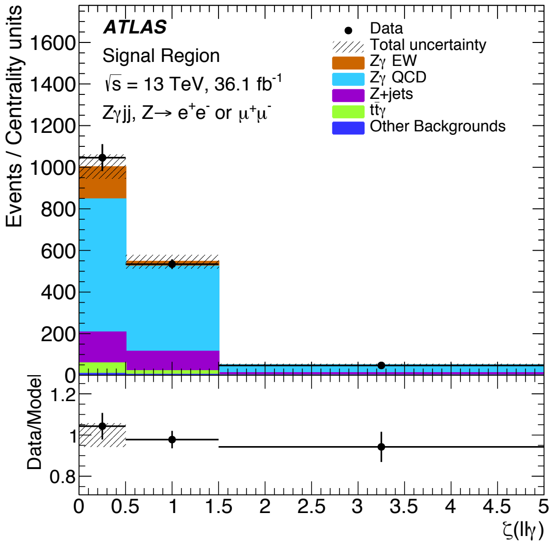
- Electroweak Zγ+2j production not yet observed.
  - Strong evidence reported by both ATLAS and CMS with 13 TeV data
  - Latest ATLAS result using 2015+2016 data (36fb^{-1})
- Interesting channel to probe neutral aQGCs (larger cross section than ZZ), sensitive to WWZγ vertex
- Analysis selection:
  - Uses an mll+mllγ cut to reduce FSR contributions
  - Veto b-jets
  - $\Delta\eta_{jj}>1$, centrality (Zγ)<5 and $m_{jj}>150$GeV → *Looser than the usual VBS selections used*

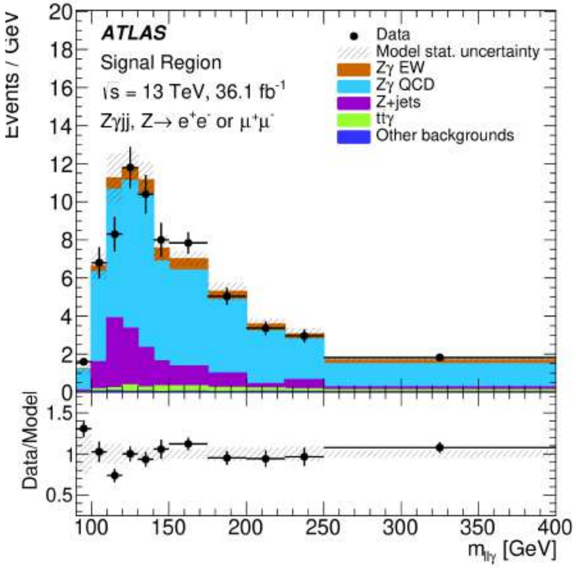


- Simulation



	Process	Generator	ME accuracy
🟧	Zγ EWK	MG5_NLO+Pγ8	LO
🟦	Zγ QCD	Sherpa 2.2.2	NLO (0-1j), LO (3j)
🟪	Z+jets	Sherpa 2.2.2	NLO (0-2j), LO (3-4j)





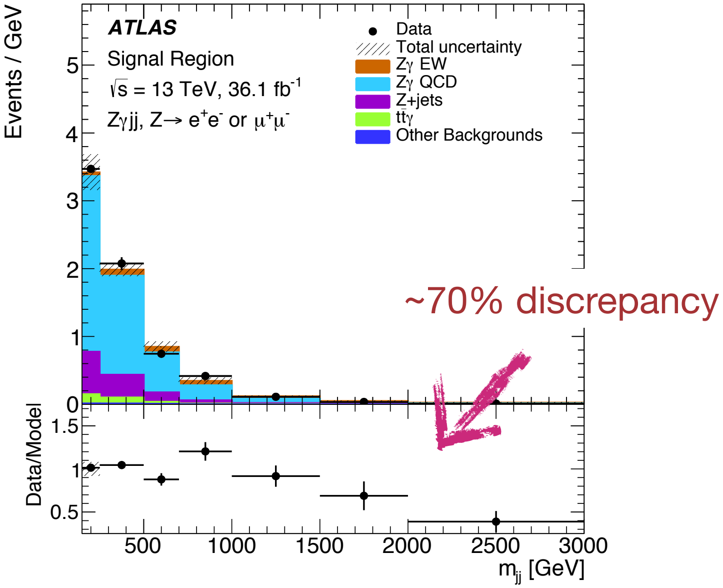
[Phys. Lett. B 803 (2020) 135341](https://doi.org/10.1016/j.physletb.2020.135341)

Background estimation

- **QCD Zγ+2j**
  - Normalization estimated from data (pre-correction 0.91), and then fitted in the signal region
- **Z+jet**: DD estimate of shape and normalization
  - 2D sideband method (photon ID, isolation), in region close to SR except: jet pT 30 GeV, mjj<150 GeV
  - Extrapolation to SR using ratio Z+jet/Zγ
- **ttbar γ**:
  - Pre-correction factor from data: 1.41 + fit in a CR
  - Dedicated CR (b-CR): >=1 b-jet -> ~70% purity, 25% Zγ QCD.
- **Smaller backgrounds: WZ, Wt**
  - From MC (less than 0.5% in SR)

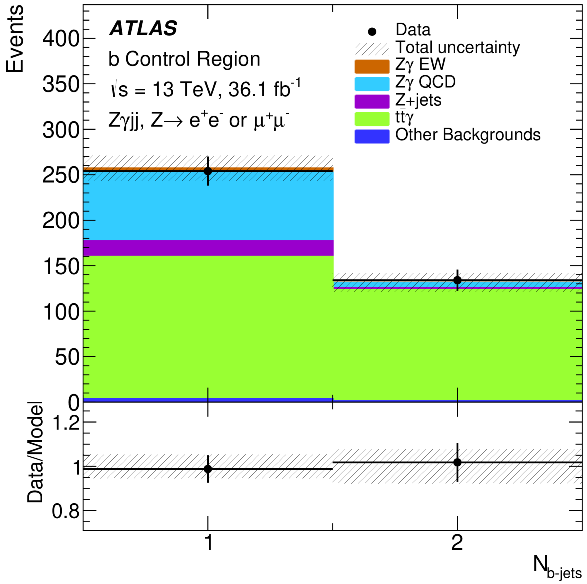
● Data
▨ Total uncertainty
🟧 Zγ EW
🟦 Zγ QCD
🟪 Z+jets
🟩 ttγ
🟦 Other Backgrounds

Signal Region - dijet invariant mass



~70% discrepancy

b-jet enriched Control Region



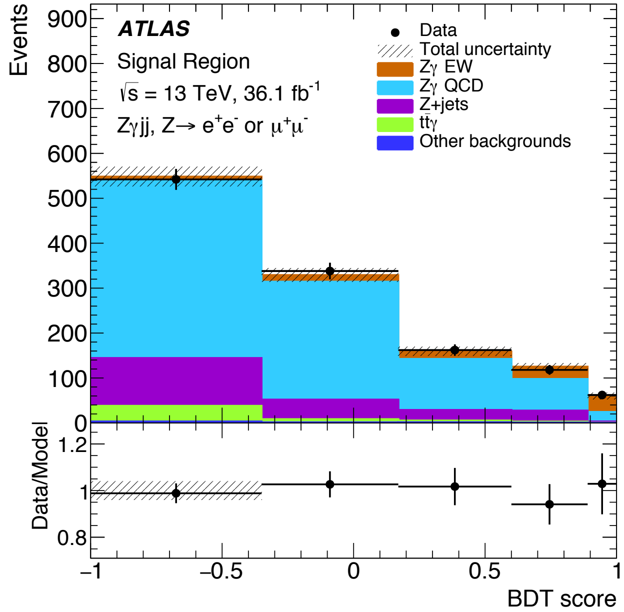
Phys. Lett. B 803 (2020) 135341

Zγjj results

- EWK Zγjj signal extraction:
  - Fitted BDT distribution trained to separate EW signal from background (13 variables)
  - Simultaneous fit of signal region and b-CR

Variable used in the BDT
m_{jj}
$\Delta\eta_{jj}$
$\zeta(\ell\ell\gamma)$
$m_{\ell\ell\gamma}$
$p_T^{\ell\ell\gamma}$
$m_{\ell\ell}$
$p_T^{\ell\ell}$
$p_T^{\text{lead lep}}$
$p_T^{\text{lead jet}}$
$\eta^{\text{lead jet}}$
$\min\Delta R(\gamma, j)$
$\Delta\phi(\ell\ell\gamma, jj)$
$\Delta R(\ell\ell\gamma, jj)$

BDT score in the signal region



Evidence !!

4.1σ expected and observed significance

- Measured cross sections:

$$\sigma^{\text{fid.}}_{Z\gamma jj\text{-EW}} = 7.8 \pm 1.5\,(\text{stat.}) \pm 1.0\,(\text{syst.})\,^{+1.0}_{-0.8}\,(\text{mod.})\ \text{fb}$$

$$\sigma^{\text{fid., MadGraph}}_{Z\gamma jj\text{-EW}} = 7.75 \pm 0.03\,(\text{stat.}) \pm 0.20\,(\text{PDF} + \alpha_S) \pm 0.40\,(\text{scale})\ \text{fb}$$

$$\sigma^{\text{fid., Sherpa}}_{Z\gamma jj\text{-EW}} = 8.94 \pm 0.08\,(\text{stat.}) \pm 0.20\,(\text{PDF} + \alpha_S) \pm 0.50\,(\text{scale})\ \text{fb}$$

- Combined EW+QCD Zγjj cross-section also measured: same method and phase spaces, except for CRs which are excluded

$$\sigma^{\text{fid.}}_{Z\gamma jj} = 71 \pm 2\,(\text{stat.})\,^{+9}_{-7}\,(\text{syst.})\,^{+21}_{-17}\,(\text{mod.})\ \text{fb}$$

$$\sigma^{\text{fid., MadGraph+Sherpa}}_{Z\gamma jj} = 88.4 \pm 2.4\,(\text{stat.}) \pm 2.3\,(\text{PDF} + \alpha_S)^{+29.4}_{-19.1}\,(\text{scale})\ \text{fb.}$$

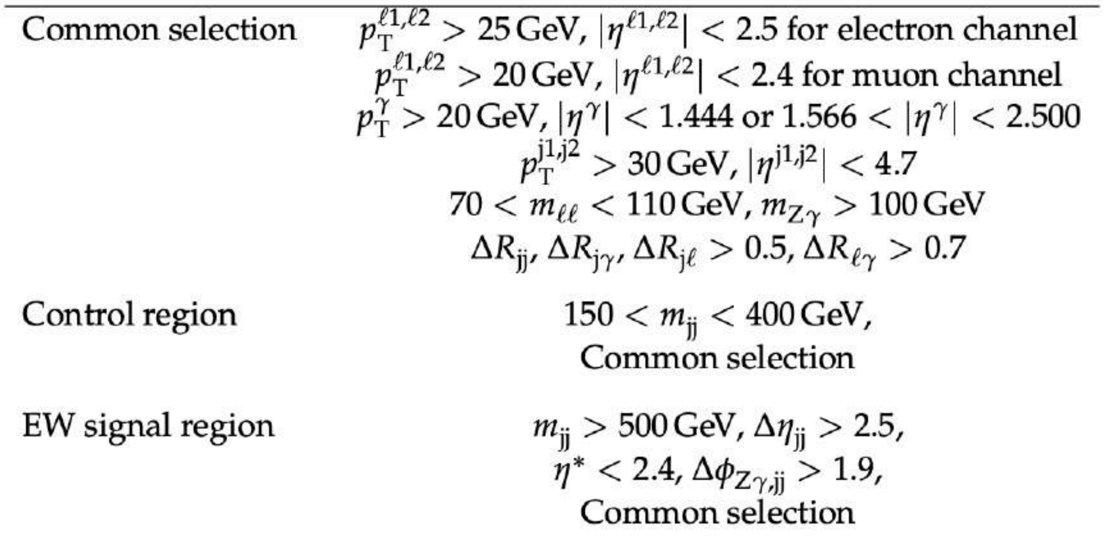
In agreement with the expectation. Large uncertainties from theory modeling!

$Z\gamma$: neutral interactions + photons

JHEP 2006 (2020) 076

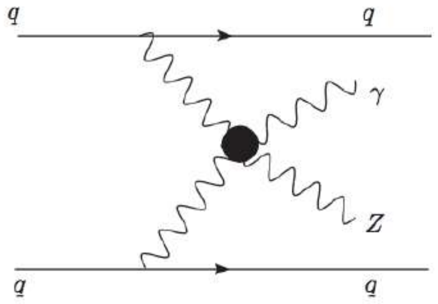
- Probe neutral quartic couplings
  - Clean signal from leptonic Z decay
  - Fully reconstructed final state
  - Neutral probe with higher cross section than ZZ

$$\eta^* = |\eta_{Z\gamma} - (\eta_{j1} + \eta_{j2})/2|$$

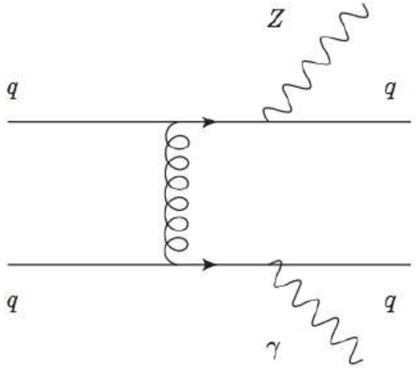


Common selection	$p_T^{\ell 1,\ell 2} > 25\,\text{GeV}$, $\lvert\eta^{\ell 1,\ell 2}\rvert < 2.5$ for electron channel $p_T^{\ell 1,\ell 2} > 20\,\text{GeV}$, $\lvert\eta^{\ell 1,\ell 2}\rvert < 2.4$ for muon channel $p_T^{\gamma} > 20\,\text{GeV}$, $\lvert\eta^{\gamma}\rvert < 1.444$ or $1.566 < \lvert\eta^{\gamma}\rvert < 2.500$ $p_T^{j1,j2} > 30\,\text{GeV}$, $\lvert\eta^{j1,j2}\rvert < 4.7$ $70 < m_{\ell\ell} < 110\,\text{GeV}$, $m_{Z\gamma} > 100\,\text{GeV}$ $\Delta R_{jj}, \Delta R_{j\gamma}, \Delta R_{j\ell} > 0.5$, $\Delta R_{\ell\gamma} > 0.7$
Control region	$150 < m_{jj} < 400\,\text{GeV}$, Common selection
EW signal region	$m_{jj} > 500\,\text{GeV}$, $\Delta\eta_{jj} > 2.5$, $\eta^* < 2.4$, $\Delta\phi_{Z\gamma,jj} > 1.9$, Common selection

VBS production



QCD production



- Backgrounds with nonprompt photons and leptons estimated with data-driven approach
  - Other background from MC
  - Control region to validate and constrain QCD $Z\gamma$

Electroweak Zγ: CMS results

JHEP 2006 (2020) 076

- Fit to 2D distribution of m_{jj} and $\Delta\eta_{jj}$
  - EW cross section obtained from best-fit signal strength
    - Include yield in 100 < mjj < 400 GeV CR (constrain QCD VVjj)
  - Separate bins per photon barrel/endcap and lepton flavour

$$\boxed{\mu_{EW} = \sigma_{obs}/\sigma_{th.} = 0.65 \pm 0.24}$$

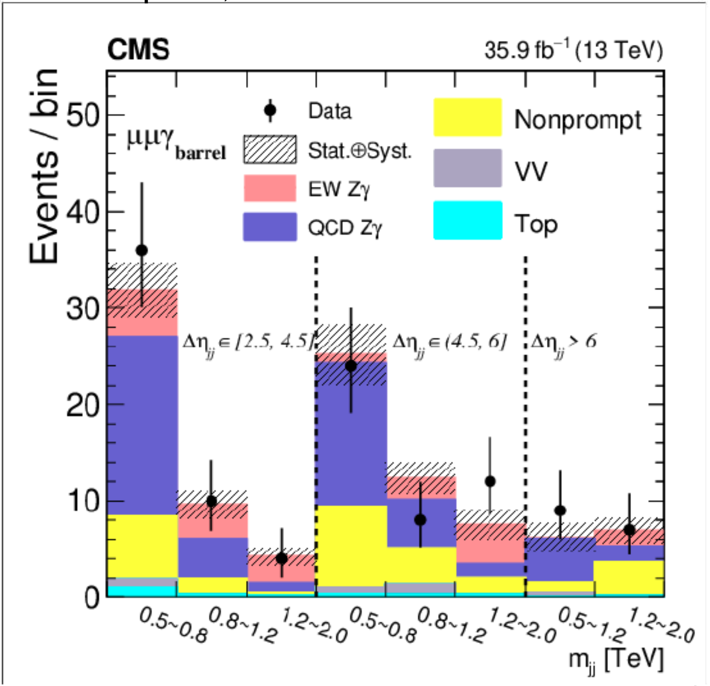
$\sigma_{th.}$ from MG_aMC LO

- Observed (expected) significance 3.9σ (5.2σ)
  - ➡4.7 (5.5) combined with 8 TeV assuming $\mu_{EW} = \mu_{EW,SM} = 1$

- Also perform fit with EW and QCD signal

$$\boxed{\sigma_{fid} = 14.3 \pm 1.1\ (\text{stat}) \pm 2.7\ (\text{syst})\ \text{fb}}$$

- Agrees with MG5_aMC prediction, $\sigma_{LO} = 15.7 \pm 1.7$ fb



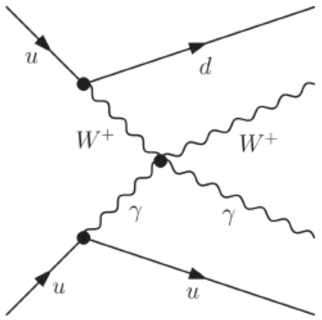
Kenneth Long

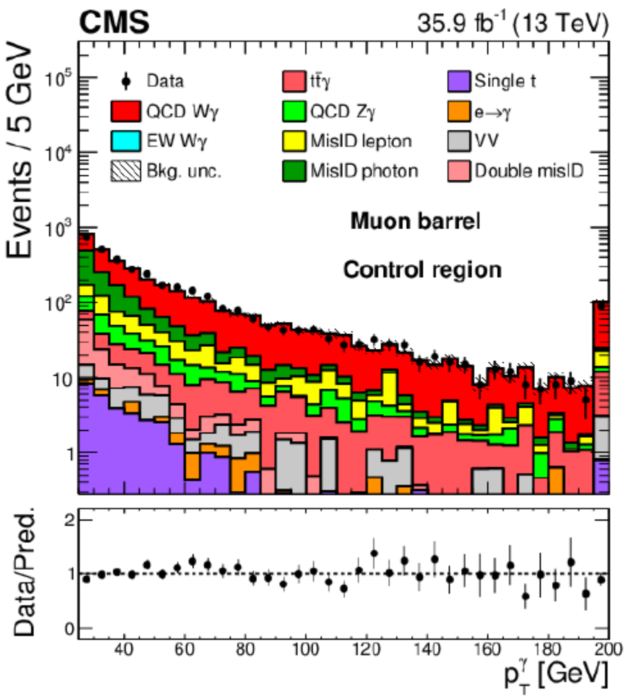
Wγ: charged interactions + photons

PLB 811 (2020) 135988

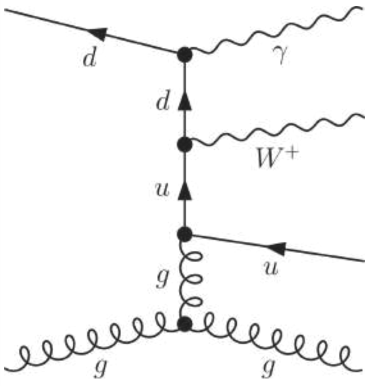
- Probe charged couplings with photons
    - Highest VBS cross section
    - Challenging experimental state
        - Significant contribution from mis-ID photons and leptons
- Select moderate pt lepton, MET, photon
    - Electron channel: $m_{\ell\gamma}$ not consistent with m_Z
    - $m_{jj} > 500$ GeV and $\Delta\eta > 2.5$
    - $|y_{W\gamma} - (y_{j1} + y_{j2})/2| < 1.2$
- Very similar approach to $Z\gamma$ for background estimation
    - Backgrounds data driven or MC (prompt/nonprompt)

VBS production





QCD production



Electroweak Wγ: results

PLB 811 (2020) 135988

- Very similar approach to Gamma analysis
  - EW, EW+QCD via fit to 2D distribution of m_{jj} and $\Delta\eta_{jj}$
  - Control region of m_{jj} 200 - 400 to constrain QCD norm.

$$\boxed{\mu = \sigma_{obs}/\sigma_{th.} = 1.20 \, {}^{+0.26}_{-0.24}}$$

$\sigma_{th.}$ from MG_aMC LO

- Observed (expected) significance 4.9σ (4.6σ)

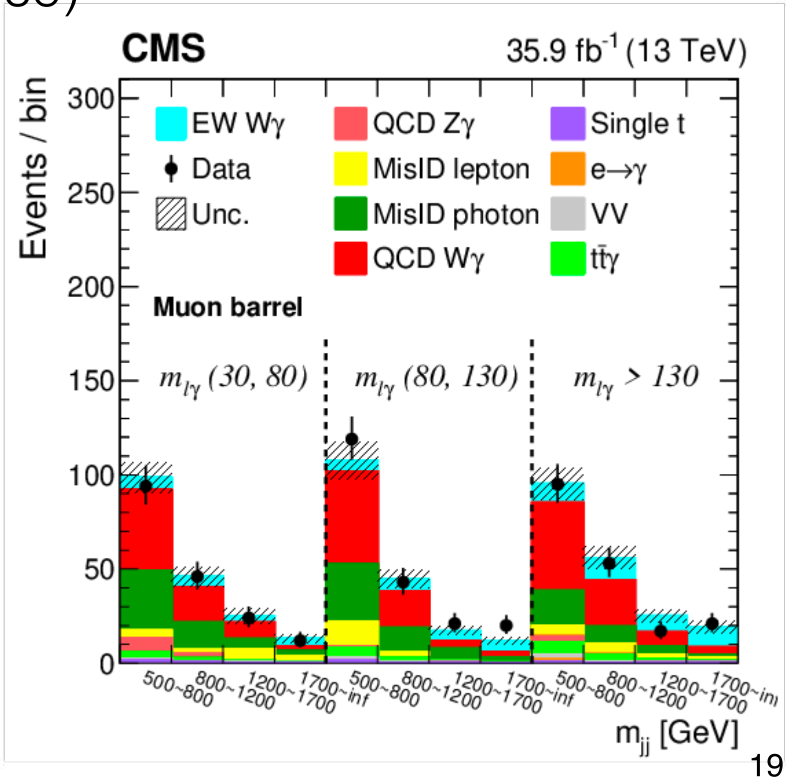
  ➡5.3 (4.8) combined with 8 TeV assuming $\mu_{EW} = \mu_{EW,SM} = 1$

- Also perform fit with EW and QCD signal

$$\boxed{\sigma_{fid} = 108 \pm 5\,(\text{stat}) \pm 15\,(\text{syst})\ \text{fb}}$$

- Agrees with MG5_aMC prediction @LO

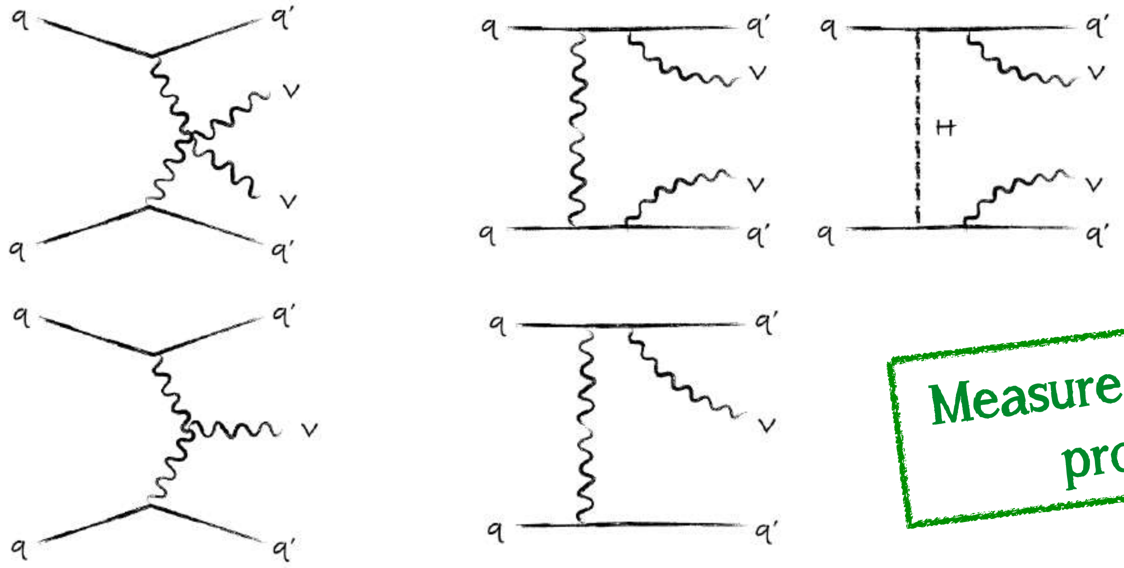
$$\boxed{\mu = \sigma_{obs}/\sigma_{th.} = 1.21 \, {}^{+0.17}_{-0.16}}$$



VBS and VBF: measurable, but not measurable

- Protons in LHC serve as source of vector boson beams
- Not possible to separate VBS (or VBF) in a gauge invariant way → Measure EWK V(V)jj production

Vector Boson Scattering/Fusion **Vector Boson bremsstrahlung**

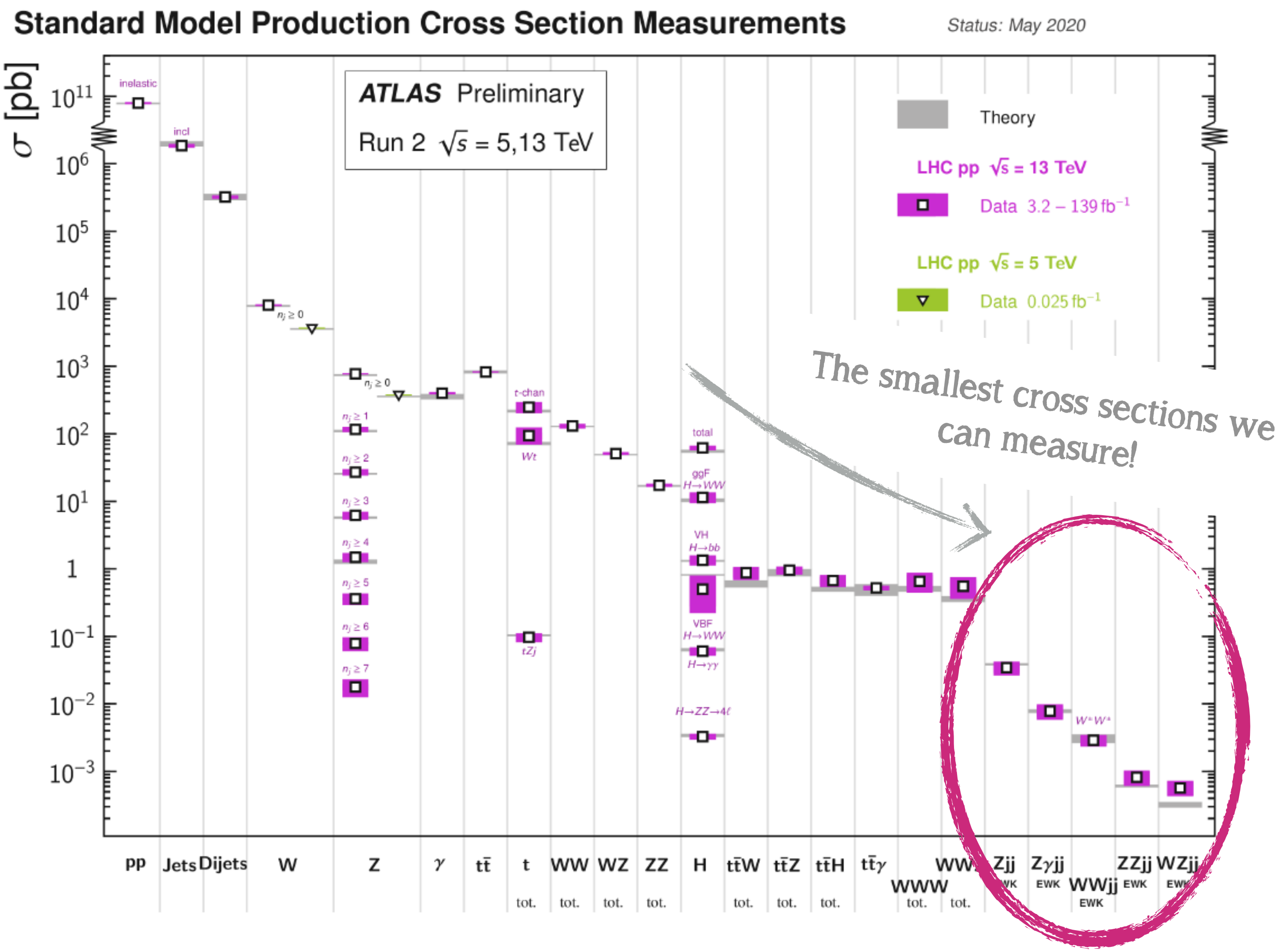


Measure EWK V(V)jj production

- Usually QCD mediated production of V(V)jj at the LHC has larger cross sections than the EWK production → ***crucial for a precise measurement to understand and reduce the QCD background!***

Published measurements

- What has been done so far, and what will be covered in this talk ?



The smallest cross sections we can measure!

Published measurements

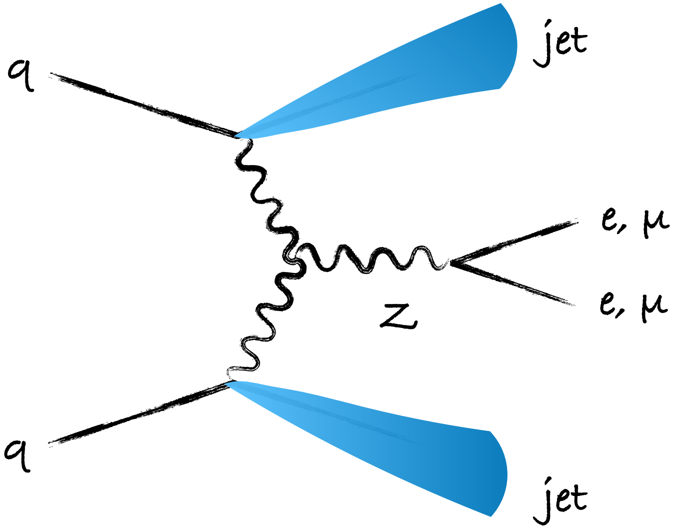
- What has been done so far, and what will be covered in this talk ?

	Channel		**Energy (Luminosity)**	**Observed (Expected) σ**
VBF	$W^\pm$ jj	Eur. Phys. J. C 77 (2017) 474	7, 8 TeV (5, 20 fb^{-1})	$> 5\sigma$
	Z jj	2006.15458	13 TeV (139 fb^{-1})	$> 5\sigma$
VBS	$W^\pm W^\pm$ jj	Phys. Rev. Lett. 123 (2019) 161801	13 TeV (36 fb^{-1})	6.5σ (4.4)
	$W^\pm Z$ jj	Phys. Lett. B 793 (2019) 469	13 TeV (36 fb^{-1})	5.3σ (3.2)
	$W^\pm\gamma$ jj	-	-	-
	$Z\gamma$ jj	Phys. Lett. B 803 (2020) 135341	13 TeV (36 fb^{-1})	4.1σ (4.1)
	ZZ jj	2004.10612	13 TeV (139 fb^{-1})	5.5σ (4.3)
	$W^\pm V$ semi-lept jj	Phys. Rev. D 100 (2019) 032007	13 TeV (36 fb^{-1})	$< 3\sigma$

Covered in this talk!

Covered in this talk!

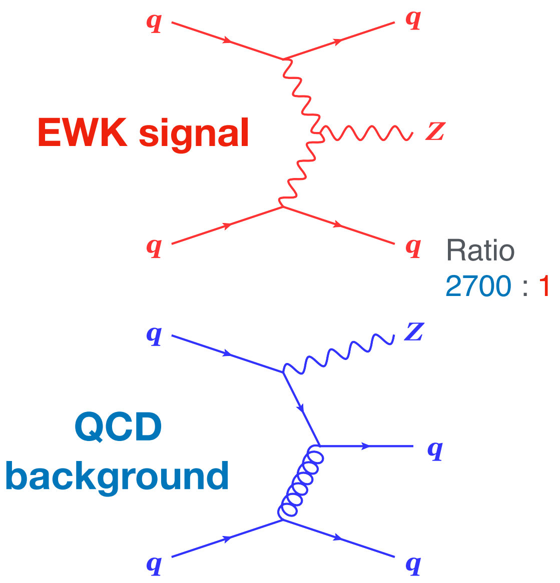
Electroweak Zjj production



[arXiv:2006.15458](https://arxiv.org/abs/2006.15458)

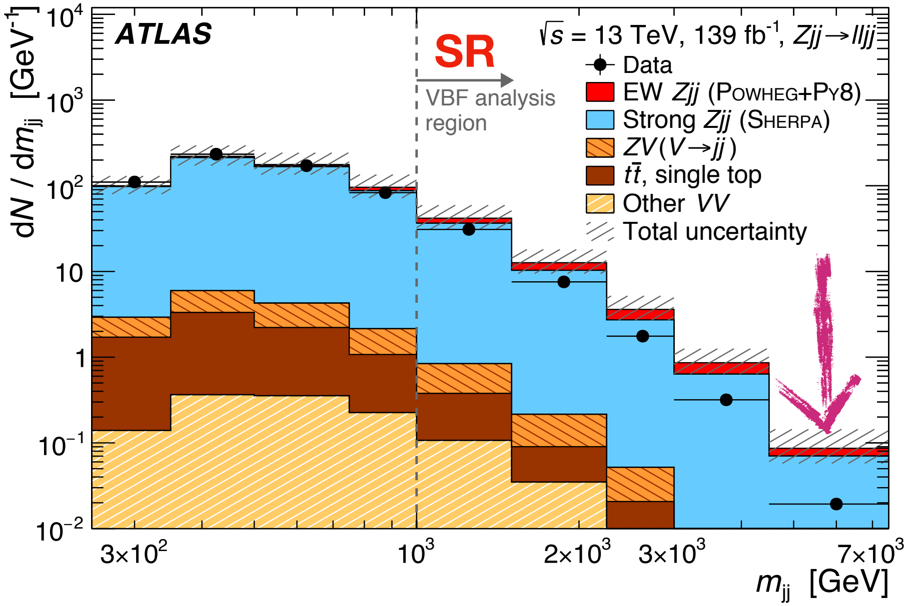
EWK Zjj differential cross sections

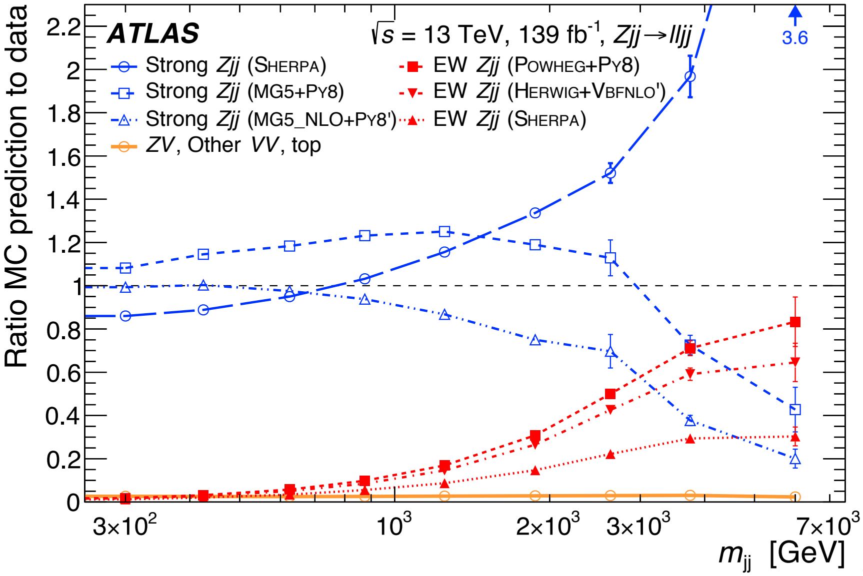
- Signal region built requiring high di-jet invariant mass, no hadronic activity in between the tagging jets and Z boson centrality
- QCD background (strong) has the largest contribution over the spectra
- Large QCD background miss-modeling, huge efforts to extract it in a data driven way!



	QCD production			EWK production	
	Generator	ME accuracy		Generator	ME accuracy
-○-	Sherpa 2.2.1	NLO (0–2j), LO (3–4j)	-■-	Powheg+Py8	NLO
-□-	MG5+Py8	LO (0–4j)	-▼-	Herwig7+VBFNLO	NLO
-△-	MG5_NLO+Py8	NLO (0–2j), LO (3–4j)	▲	Sherpa 2.2.1	LO (2–4j)

Di-jet invariant mass (pre-fit)





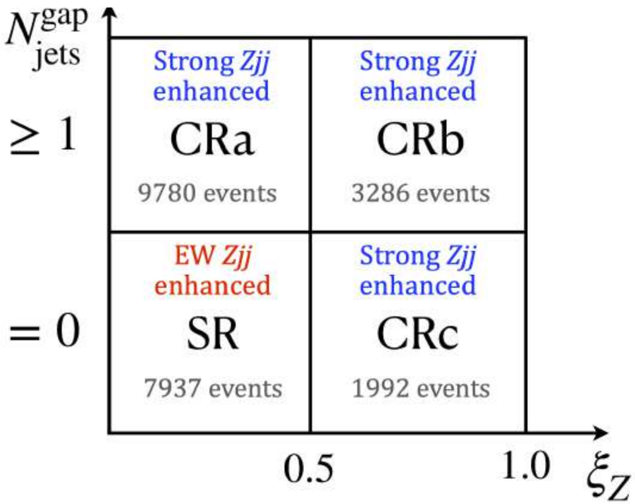
arXiv:2006.15458

Signal extraction steps

Binned maximum likelihood fit performed to reduce dependence on MC mis-modeling. In the fit:

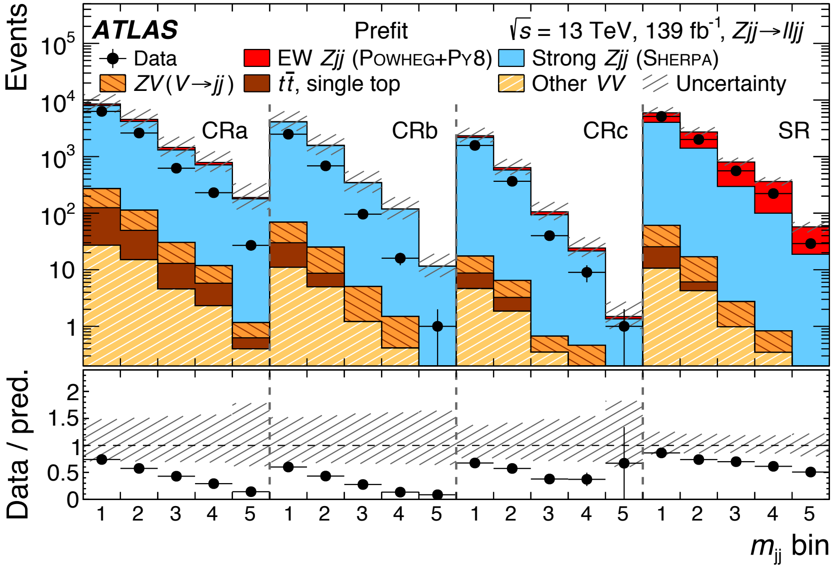
1. QCD background is estimated → 4 different regions using two uncorrelated variables:
    - Bin-by-bin weights for strong Zjj, separate for low and high centrality and linked within the gap jets bins
    - Linear correction applied to strong Zjj to correct for residual dependence on the N gap jets
2. Bin-by-bin electroweak Zjj signal strengths (same in all regions)
3. Procedure repeated for different MC generators
4. The final EWK signal is taken to be the midpoint of the envelope of yields obtained using the three different QCD Zjj event generators

Regions for data-driven background

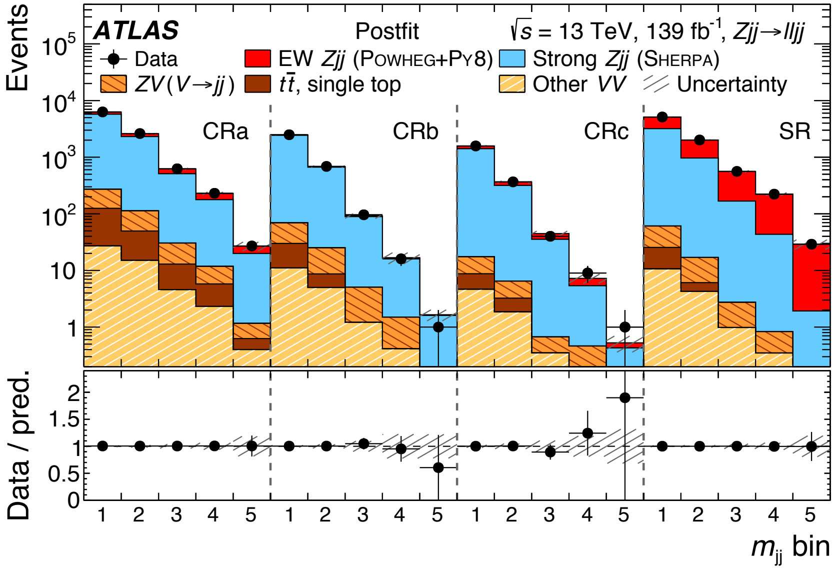


$N^{\text{gap}}_{\text{jets}}$	$\xi_Z < 0.5$	$0.5 < \xi_Z < 1.0$
≥ 1	Strong *Zjj* enhanced CRa 9780 events	Strong *Zjj* enhanced CRb 3286 events
$= 0$	EW *Zjj* enhanced SR 7937 events	Strong *Zjj* enhanced CRc 1992 events

Pre-fit



Post-fit

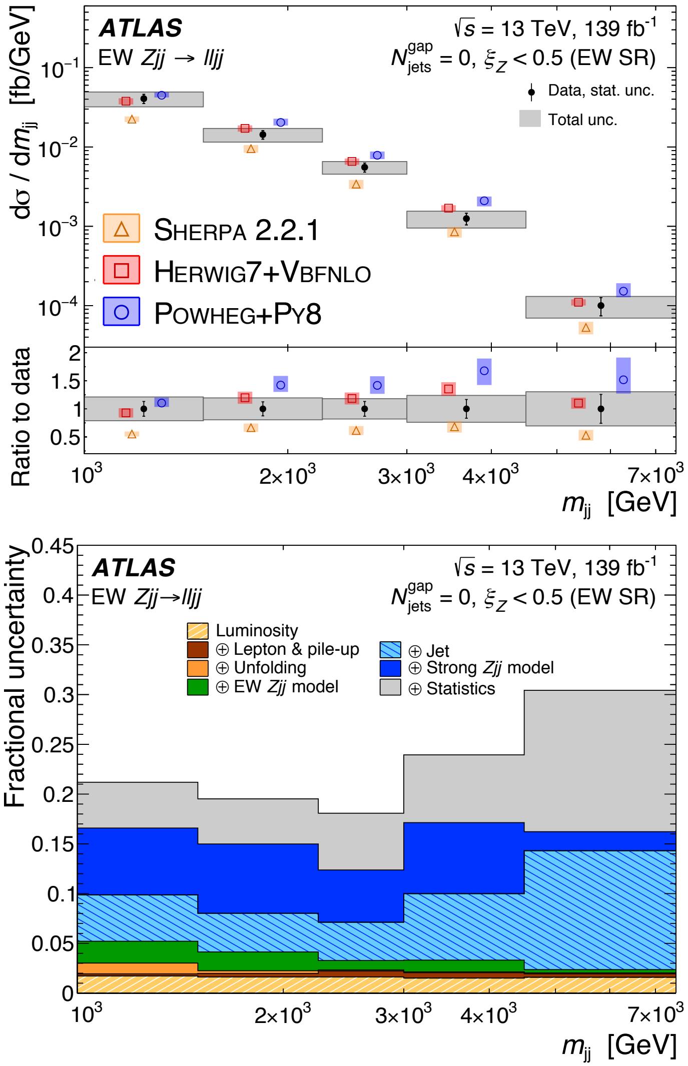


arXiv:2006.15458

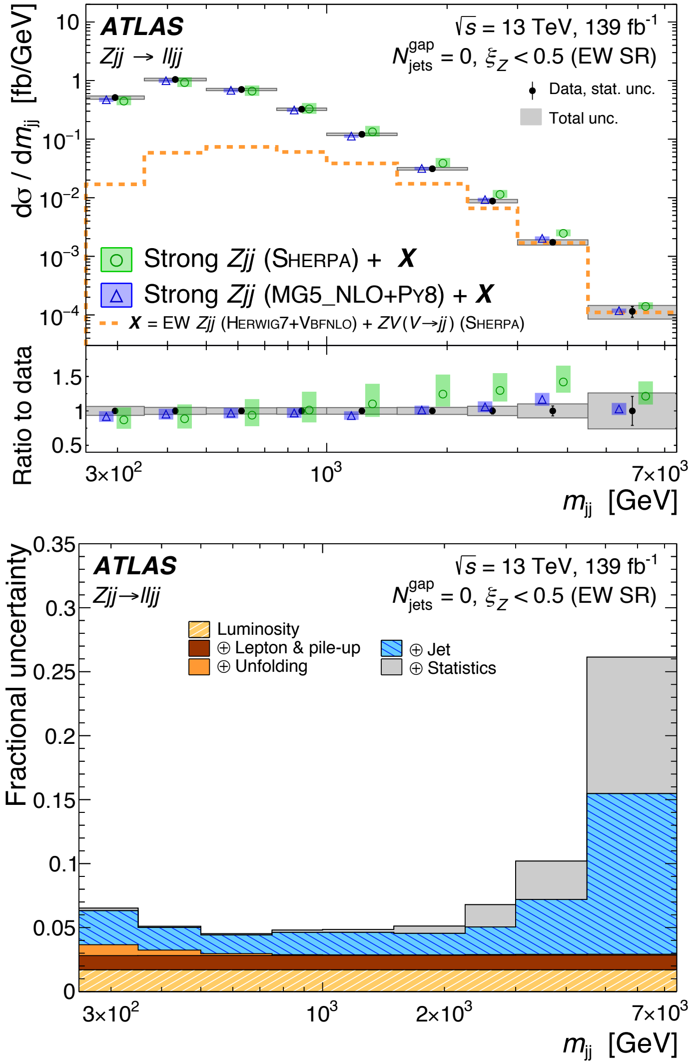
Zjj differential cross sections results

- Differential cross sections extracted for EWK only and EWK+QCD production as a function of four observables: m_{jj} , $|\Delta y_{jj}|$, $p_{T,ll}$ and $\Delta\phi_{jj}$

EWK Zjj production



EWK+QCD Zjj production



arXiv:2006.15458

Effective Field Theory interpretation

- To capture the EFT effects cross sections can be written as :

$$\sigma = \underbrace{\sigma_{SM}}_{\text{SM}} + \underbrace{\sum_i \frac{c_i}{\Lambda^2}\sigma_{SM,i}^{interf}}_{\substack{\text{EFT-SM interference} \\ \text{(linear in } c_i \propto 1/\Lambda^2)}} + \underbrace{\sum_i \frac{c_i^2}{\Lambda^4}\sigma_i^{NP} + \sum_{ij,\, i\neq j} \frac{c_i c_j}{\Lambda^4}\sigma_{ij}^{NP\text{-}interf}}_{\substack{\text{Pure EFT terms} \\ \text{(quadratic in } c_i \propto 1/\Lambda^4)}}$$

Quadratic: ┈┈ $|\mathcal{M}_{d6}|^2$

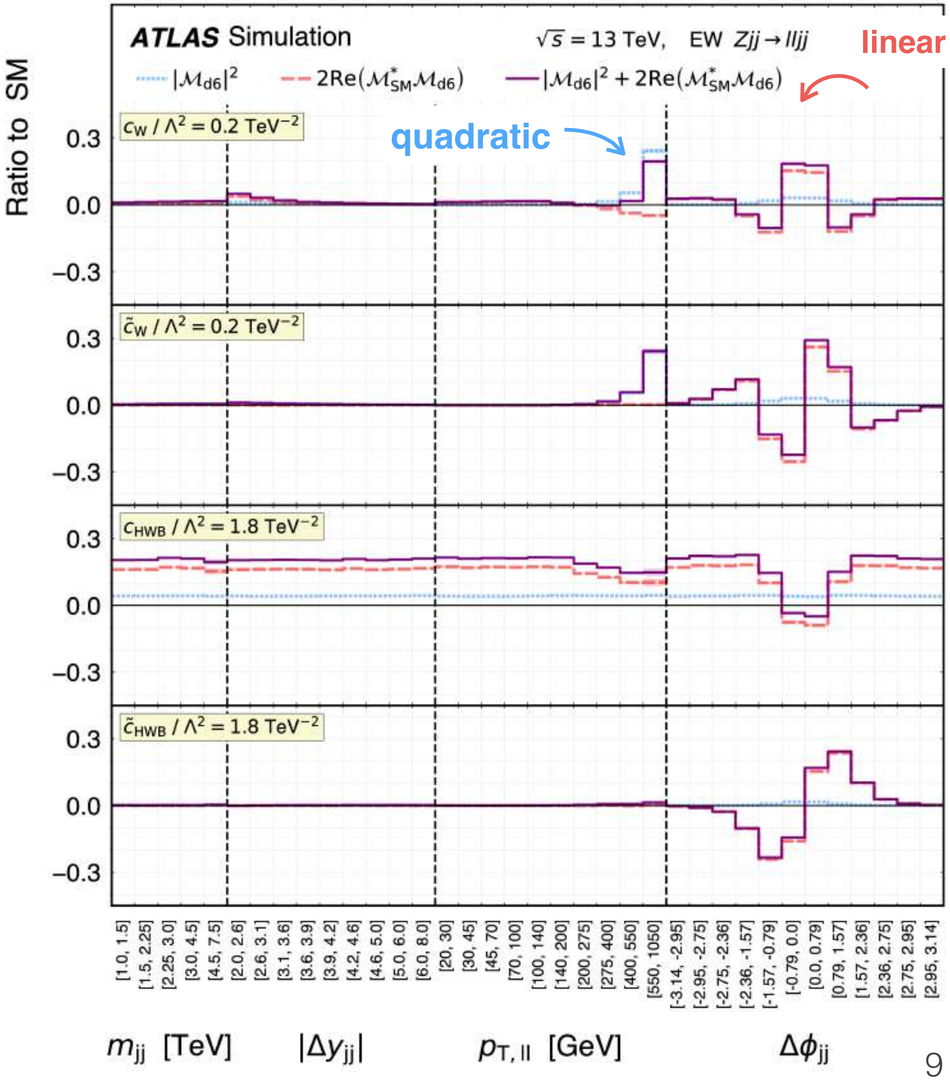
EFT-SM linear: - - $2\mathrm{Re}(\mathcal{M}_{SM}^*\mathcal{M}_{d6})$

full EFT: — $|\mathcal{M}_{d6}|^2 + 2\mathrm{Re}(\mathcal{M}_{SM}^*\mathcal{M}_{d6})$

- Expectation: EFT-SM interference (linear) leading contribution
- Different distributions show different sensitivities to the linear and quadratic terms (Madgraph SMEFT at LO)
- Limits extracted using the measured EW Zjj differential cross-section as a function of the parity-odd $\Delta\phi_{jj}$

Wilson coefficient	Includes $\lvert\mathcal{M}_{d6}\rvert^2$	95% confidence interval [TeV^{-2}] Expected	Observed	p-value (SM)
c_W/Λ^2	no	[−0.30, 0.30]	[−0.19, 0.41]	45.9%
	yes	[−0.31, 0.29]	[−0.19, 0.41]	43.2%
$\tilde{c}_W/\Lambda^2$	no	[−0.12, 0.12]	[−0.11, 0.14]	82.0%
	yes	[−0.12, 0.12]	[−0.11, 0.14]	81.8%
c_{HWB}/Λ^2	no	[−2.45, 2.45]	[−3.78, 1.13]	29.0%
	yes	[−3.11, 2.10]	[−6.31, 1.01]	25.0%
$\tilde{c}_{HWB}/\Lambda^2$	no	[−1.06, 1.06]	[0.23, 2.34]	1.7%
	yes	[−1.06, 1.06]	[0.23, 2.35]	1.6%

- Strongest limits when pure dim-6 are excluded from the theoretical prediction!



Charged WWγ and WWZ aTGC results

LEP parametrization: arXiv:hep-ph/9601233

respects SU(2)xU(1) gauge invariance

conserves charge conjugation (C) and parity (P) symmetries

5 parameters each defined to be zero in SM

$$\Delta g_1^Z = g_1^Z - 1 \qquad \Delta\kappa_\gamma = \kappa_\gamma - 1 \qquad \Delta\kappa_Z = \kappa_Z - 1 \qquad \lambda_\gamma \qquad \lambda_Z$$

only 3 parameters independent (gauge invariance)

$$\Delta\kappa_Z = \Delta g_1^Z - \Delta\kappa_\gamma tan^2\theta_W \qquad \lambda_\gamma = \lambda_Z$$

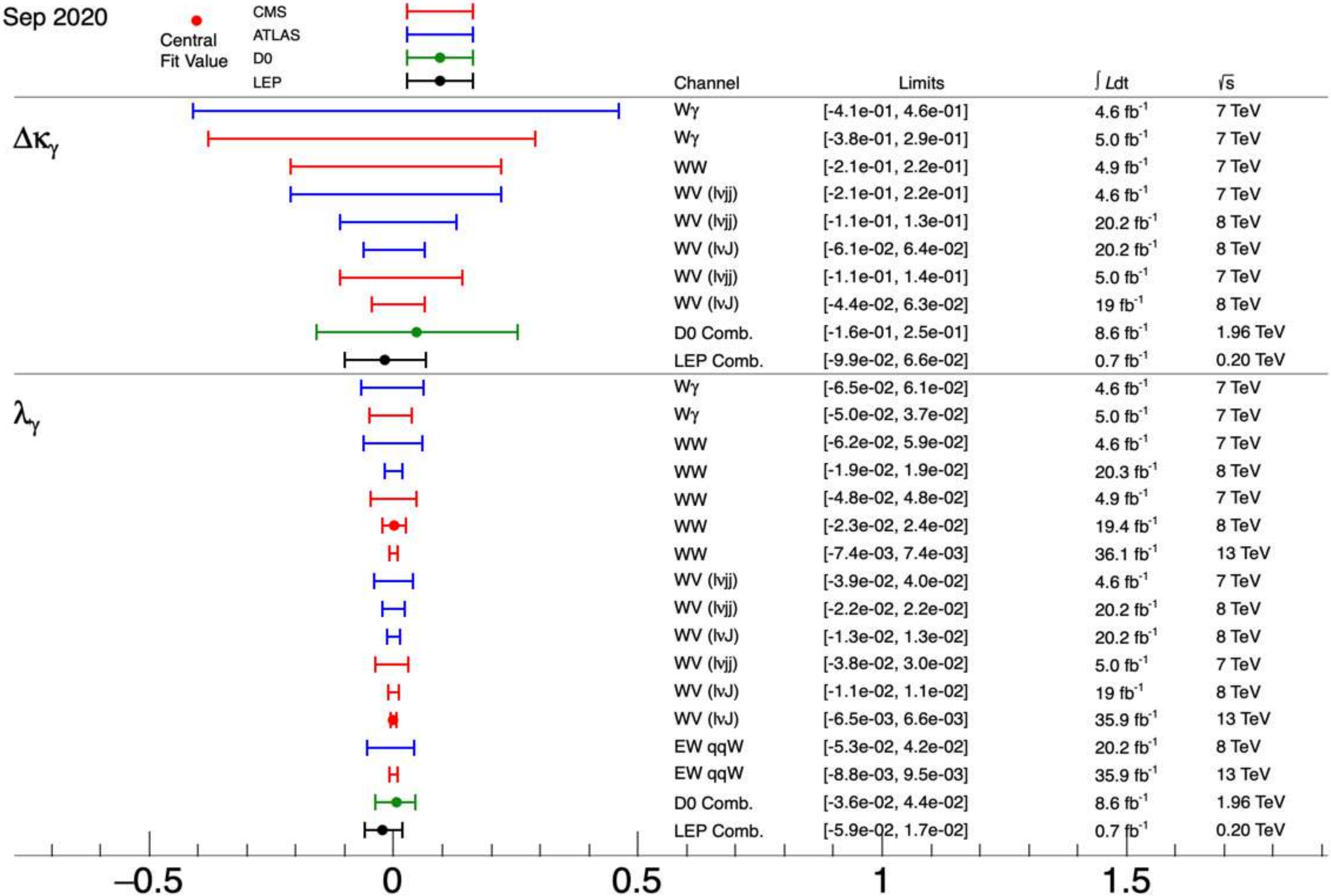
Typically no form-factors (FF) or FF = ∞

When FF used cut-off energy of same order as kinematic limit of collision energy (results without FF weaker)

EFT to LEP parameterization conversions using $\alpha(M_Z)$ and $\sin^2\theta_W(M_Z)$

More details at

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMPaTGC



$\Delta\kappa_\gamma$

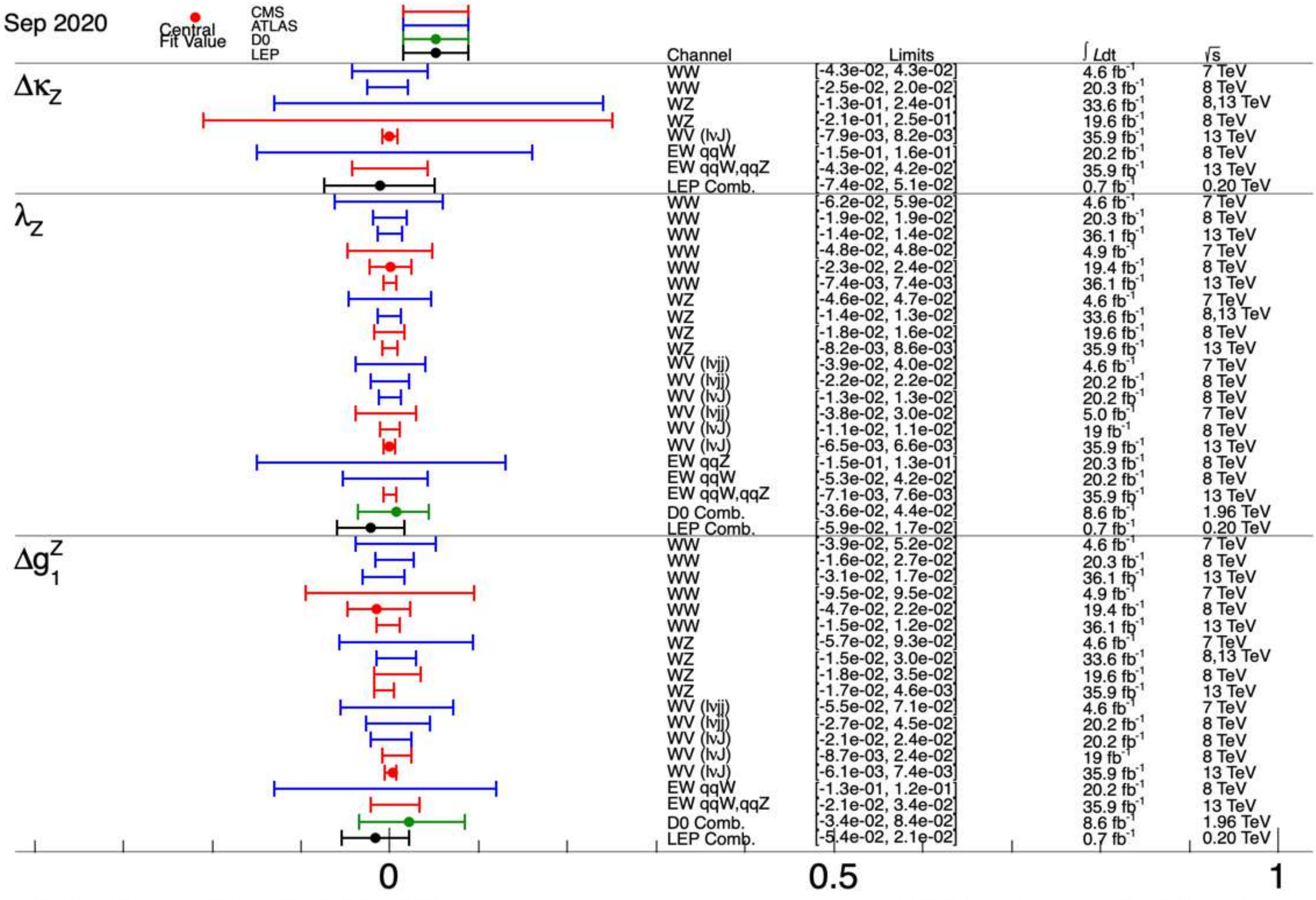
Channel	Limits	$\int Ldt$	$\sqrt{s}$
Wγ	[-4.1e-01, 4.6e-01]	4.6 fb^{-1}	7 TeV
Wγ	[-3.8e-01, 2.9e-01]	5.0 fb^{-1}	7 TeV
WW	[-2.1e-01, 2.2e-01]	4.9 fb^{-1}	7 TeV
WV (lνjj)	[-2.1e-01, 2.2e-01]	4.6 fb^{-1}	7 TeV
WV (lνjj)	[-1.1e-01, 1.3e-01]	20.2 fb^{-1}	8 TeV
WV (lνJ)	[-6.1e-02, 6.4e-02]	20.2 fb^{-1}	8 TeV
WV (lνjj)	[-1.1e-01, 1.4e-01]	5.0 fb^{-1}	7 TeV
WV (lνJ)	[-4.4e-02, 6.3e-02]	19 fb^{-1}	8 TeV
D0 Comb.	[-1.6e-01, 2.5e-01]	8.6 fb^{-1}	1.96 TeV
LEP Comb.	[-9.9e-02, 6.6e-02]	0.7 fb^{-1}	0.20 TeV

λ_γ

Channel	Limits	$\int Ldt$	$\sqrt{s}$
Wγ	[-6.5e-02, 6.1e-02]	4.6 fb^{-1}	7 TeV
Wγ	[-5.0e-02, 3.7e-02]	5.0 fb^{-1}	7 TeV
WW	[-6.2e-02, 5.9e-02]	4.6 fb^{-1}	7 TeV
WW	[-1.9e-02, 1.9e-02]	20.3 fb^{-1}	8 TeV
WW	[-4.8e-02, 4.8e-02]	4.9 fb^{-1}	7 TeV
WW	[-2.3e-02, 2.4e-02]	19.4 fb^{-1}	8 TeV
WW	[-7.4e-03, 7.4e-03]	36.1 fb^{-1}	13 TeV
WV (lνjj)	[-3.9e-02, 4.0e-02]	4.6 fb^{-1}	7 TeV
WV (lνjj)	[-2.2e-02, 2.2e-02]	20.2 fb^{-1}	8 TeV
WV (lνJ)	[-1.3e-02, 1.3e-02]	20.2 fb^{-1}	8 TeV
WV (lνjj)	[-3.8e-02, 3.0e-02]	5.0 fb^{-1}	7 TeV
WV (lνJ)	[-1.1e-02, 1.1e-02]	19 fb^{-1}	8 TeV
WV (lνJ)	[-6.5e-03, 6.6e-03]	35.9 fb^{-1}	13 TeV
EW qqW	[-5.3e-02, 4.2e-02]	20.2 fb^{-1}	8 TeV
EW qqW	[-8.8e-03, 9.5e-03]	35.9 fb^{-1}	13 TeV
D0 Comb.	[-3.6e-02, 4.4e-02]	8.6 fb^{-1}	1.96 TeV
LEP Comb.	[-5.9e-02, 1.7e-02]	0.7 fb^{-1}	0.20 TeV

aC summary plots at: http://cern.ch/go/8ghC

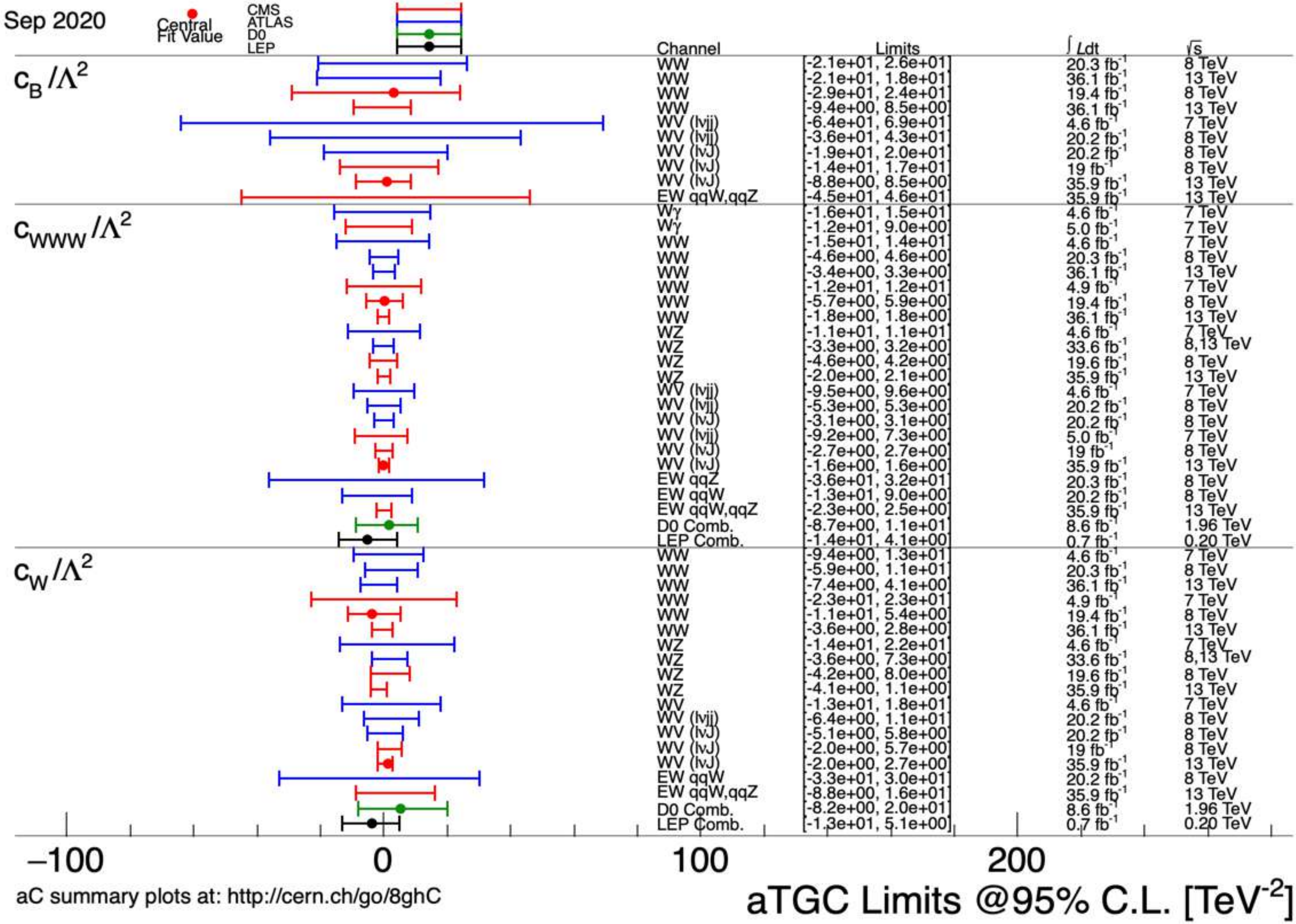
aTGC Limits @95% C.L.



	Channel	Limits	$\int L dt$	$\sqrt{s}$
$\Delta\kappa_Z$	WW	[-4.3e-02, 4.3e-02]	4.6 fb^{-1}	7 TeV
	WW	[-2.5e-02, 2.0e-02]	20.3 fb^{-1}	8 TeV
	WZ	[-1.3e-01, 2.4e-01]	33.6 fb^{-1}	8,13 TeV
	WZ	[-2.1e-01, 2.5e-01]	19.6 fb^{-1}	8 TeV
	WV (lνJ)	[-7.9e-03, 8.2e-03]	35.9 fb^{-1}	13 TeV
	EW qqW	[-1.5e-01, 1.6e-01]	20.2 fb^{-1}	8 TeV
	EW qqW,qqZ	[-4.3e-02, 4.2e-02]	35.9 fb^{-1}	13 TeV
	LEP Comb.	[-7.4e-02, 5.1e-02]	0.7 fb^{-1}	0.20 TeV
λ_Z	WW	[-6.2e-02, 5.9e-02]	4.6 fb^{-1}	7 TeV
	WW	[-1.9e-02, 1.9e-02]	20.3 fb^{-1}	8 TeV
	WW	[-1.4e-02, 1.4e-02]	36.1 fb^{-1}	13 TeV
	WW	[-4.8e-02, 4.8e-02]	4.9 fb^{-1}	7 TeV
	WW	[-2.3e-02, 2.4e-02]	19.4 fb^{-1}	8 TeV
	WW	[-7.4e-03, 7.4e-03]	36.1 fb^{-1}	13 TeV
	WZ	[-4.6e-02, 4.7e-02]	4.6 fb^{-1}	7 TeV
	WZ	[-1.4e-02, 1.3e-02]	33.6 fb^{-1}	8,13 TeV
	WZ	[-1.8e-02, 1.6e-02]	19.6 fb^{-1}	8 TeV
	WZ	[-8.2e-03, 8.6e-03]	35.9 fb^{-1}	13 TeV
	WV (lνjj)	[-3.9e-02, 4.0e-02]	4.6 fb^{-1}	7 TeV
	WV (lνjj)	[-2.2e-02, 2.2e-02]	20.2 fb^{-1}	8 TeV
	WV (lνJ)	[-1.3e-02, 1.3e-02]	20.2 fb^{-1}	8 TeV
	WV (lνjj)	[-3.8e-02, 3.0e-02]	5.0 fb^{-1}	7 TeV
	WV (lνJ)	[-1.1e-02, 1.1e-02]	19 fb^{-1}	8 TeV
	WV (lνJ)	[-6.5e-03, 6.6e-03]	35.9 fb^{-1}	13 TeV
	EW qqZ	[-1.5e-01, 1.3e-01]	20.3 fb^{-1}	8 TeV
	EW qqW	[-5.3e-02, 4.2e-02]	20.2 fb^{-1}	8 TeV
	EW qqW,qqZ	[-7.1e-03, 7.6e-03]	35.9 fb^{-1}	13 TeV
	D0 Comb.	[-3.6e-02, 4.4e-02]	8.6 fb^{-1}	1.96 TeV
	LEP Comb.	[-5.9e-02, 1.7e-02]	0.7 fb^{-1}	0.20 TeV
Δg_1^Z	WW	[-3.9e-02, 5.2e-02]	4.6 fb^{-1}	7 TeV
	WW	[-1.6e-02, 2.7e-02]	20.3 fb^{-1}	8 TeV
	WW	[-3.1e-02, 1.7e-02]	36.1 fb^{-1}	13 TeV
	WW	[-9.5e-02, 9.5e-02]	4.9 fb^{-1}	7 TeV
	WW	[-4.7e-02, 2.2e-02]	19.4 fb^{-1}	8 TeV
	WW	[-1.5e-02, 1.2e-02]	36.1 fb^{-1}	13 TeV
	WZ	[-5.7e-02, 9.3e-02]	4.6 fb^{-1}	7 TeV
	WZ	[-1.5e-02, 3.0e-02]	33.6 fb^{-1}	8,13 TeV
	WZ	[-1.8e-02, 3.5e-02]	19.6 fb^{-1}	8 TeV
	WZ	[-1.7e-02, 4.6e-03]	35.9 fb^{-1}	13 TeV
	WV (lνjj)	[-5.5e-02, 7.1e-02]	4.6 fb^{-1}	7 TeV
	WV (lνjj)	[-2.7e-02, 4.5e-02]	20.2 fb^{-1}	8 TeV
	WV (lνJ)	[-2.1e-02, 2.4e-02]	20.2 fb^{-1}	8 TeV
	WV (lνJ)	[-8.7e-03, 2.4e-02]	19 fb^{-1}	8 TeV
	WV (lνJ)	[-6.1e-03, 7.4e-03]	35.9 fb^{-1}	13 TeV
	EW qqW	[-1.3e-01, 1.2e-01]	20.2 fb^{-1}	8 TeV
	EW qqW,qqZ	[-2.1e-02, 3.4e-02]	35.9 fb^{-1}	13 TeV
	D0 Comb.	[-3.4e-02, 8.4e-02]	8.6 fb^{-1}	1.96 TeV
	LEP Comb.	[-5.4e-02, 2.1e-02]	0.7 fb^{-1}	0.20 TeV

aC summary plots at: http://cern.ch/go/8ghC

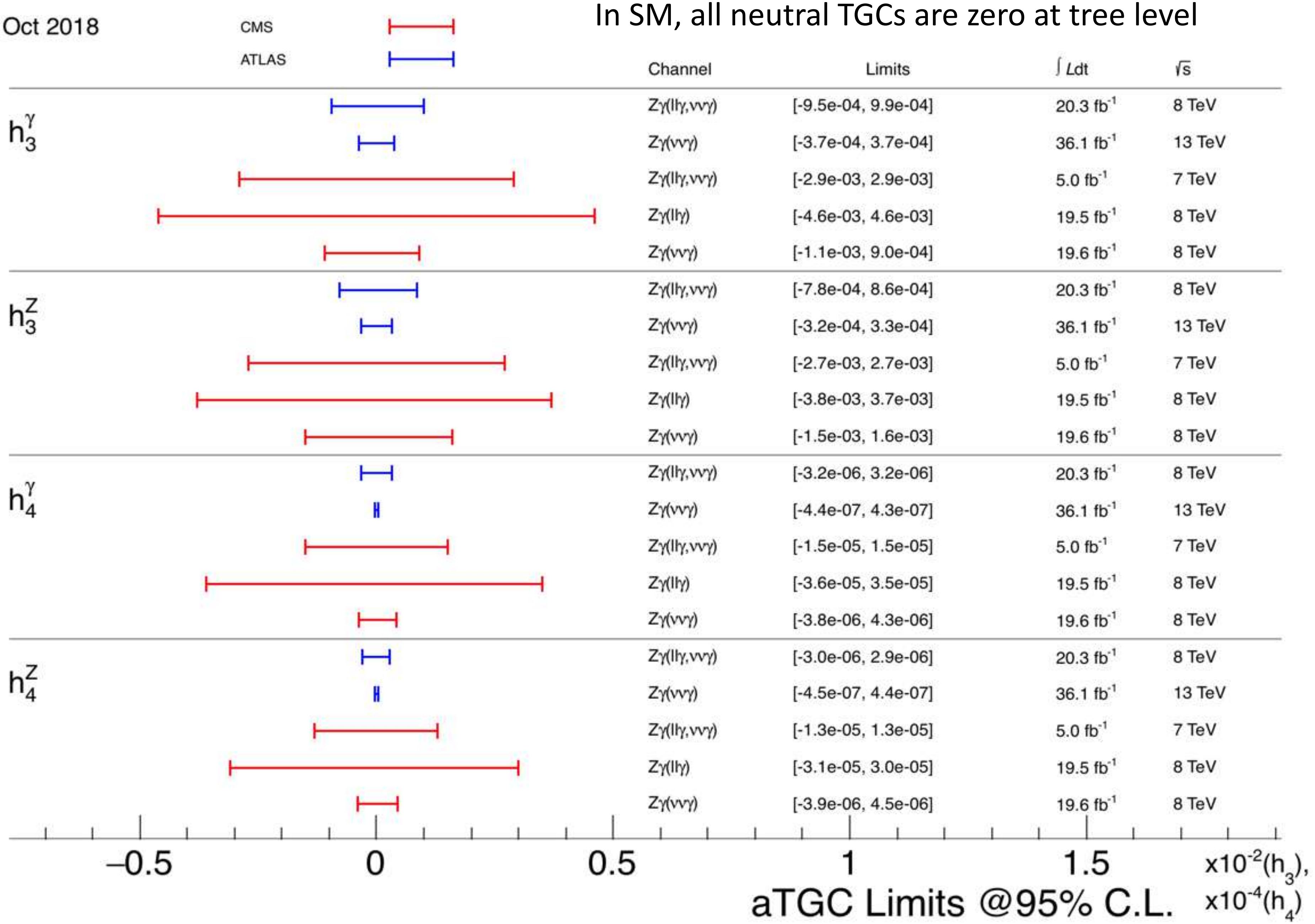
Effective field theory interpretation



	Channel	Limits	$\int L dt$	$\sqrt{s}$
c_B/Λ^2	WW	[-2.1e+01, 2.6e+01]	20.3 fb^{-1}	8 TeV
	WW	[-2.1e+01, 1.8e+01]	36.1 fb^{-1}	13 TeV
	WW	[-2.9e+01, 2.4e+01]	19.4 fb^{-1}	8 TeV
	WW	[-9.4e+00, 8.5e+00]	36.1 fb^{-1}	13 TeV
	WV (lvjj)	[-6.4e+01, 6.9e+01]	4.6 fb^{-1}	7 TeV
	WV (lvjj)	[-3.6e+01, 4.3e+01]	20.2 fb^{-1}	8 TeV
	WV (lvJ)	[-1.9e+01, 2.0e+01]	20.2 fb^{-1}	8 TeV
	WV (lvJ)	[-1.4e+01, 1.7e+01]	19 fb^{-1}	8 TeV
	WV (lvJ)	[-8.8e+00, 8.5e+00]	35.9 fb^{-1}	13 TeV
	EW qqW,qqZ	[-4.5e+01, 4.6e+01]	35.9 fb^{-1}	13 TeV
c_{WWW}/Λ^2	Wγ	[-1.6e+01, 1.5e+01]	4.6 fb^{-1}	7 TeV
	Wγ	[-1.2e+01, 9.0e+00]	5.0 fb^{-1}	7 TeV
	WW	[-1.5e+01, 1.4e+01]	4.6 fb^{-1}	7 TeV
	WW	[-4.6e+00, 4.6e+00]	20.3 fb^{-1}	8 TeV
	WW	[-3.4e+00, 3.3e+00]	36.1 fb^{-1}	13 TeV
	WW	[-1.2e+01, 1.2e+01]	4.9 fb^{-1}	7 TeV
	WW	[-5.7e+00, 5.9e+00]	19.4 fb^{-1}	8 TeV
	WW	[-1.8e+00, 1.8e+00]	36.1 fb^{-1}	13 TeV
	WZ	[-1.1e+01, 1.1e+01]	4.6 fb^{-1}	7 TeV
	WZ	[-3.3e+00, 3.2e+00]	33.6 fb^{-1}	8,13 TeV
	WZ	[-4.6e+00, 4.2e+00]	19.6 fb^{-1}	8 TeV
	WZ	[-2.0e+00, 2.1e+00]	35.9 fb^{-1}	13 TeV
	WV (lvjj)	[-9.5e+00, 9.6e+00]	4.6 fb^{-1}	7 TeV
	WV (lvjj)	[-5.3e+00, 5.3e+00]	20.2 fb^{-1}	8 TeV
	WV (lvJ)	[-3.1e+00, 3.1e+00]	20.2 fb^{-1}	8 TeV
	WV (lvjj)	[-9.2e+00, 7.3e+00]	5.0 fb^{-1}	7 TeV
	WV (lvJ)	[-2.7e+00, 2.7e+00]	19 fb^{-1}	8 TeV
	WV (lvJ)	[-1.6e+00, 1.6e+00]	35.9 fb^{-1}	13 TeV
	EW qqZ	[-3.6e+01, 3.2e+01]	20.3 fb^{-1}	8 TeV
	EW qqW	[-1.3e+01, 9.0e+00]	20.2 fb^{-1}	8 TeV
	EW qqW,qqZ	[-2.3e+00, 2.5e+00]	35.9 fb^{-1}	13 TeV
	D0 Comb.	[-8.7e+00, 1.1e+01]	8.6 fb^{-1}	1.96 TeV
	LEP Comb.	[-1.4e+01, 4.1e+00]	0.7 fb^{-1}	0.20 TeV
c_W/Λ^2	WW	[-9.4e+00, 1.3e+01]	4.6 fb^{-1}	7 TeV
	WW	[-5.9e+00, 1.1e+01]	20.3 fb^{-1}	8 TeV
	WW	[-7.4e+00, 4.1e+00]	36.1 fb^{-1}	13 TeV
	WW	[-2.3e+01, 2.3e+01]	4.9 fb^{-1}	7 TeV
	WW	[-1.1e+01, 5.4e+00]	19.4 fb^{-1}	8 TeV
	WW	[-3.6e+00, 2.8e+00]	36.1 fb^{-1}	13 TeV
	WZ	[-1.4e+01, 2.2e+01]	4.6 fb^{-1}	7 TeV
	WZ	[-3.6e+00, 7.3e+00]	33.6 fb^{-1}	8,13 TeV
	WZ	[-4.2e+00, 8.0e+00]	19.6 fb^{-1}	8 TeV
	WZ	[-4.1e+00, 1.1e+00]	35.9 fb^{-1}	13 TeV
	WV	[-1.3e+01, 1.8e+01]	4.6 fb^{-1}	7 TeV
	WV (lvjj)	[-6.4e+00, 1.1e+01]	20.2 fb^{-1}	8 TeV
	WV (lvJ)	[-5.1e+00, 5.8e+00]	20.2 fb^{-1}	8 TeV
	WV (lvJ)	[-2.0e+00, 5.7e+00]	19 fb^{-1}	8 TeV
	WV (lvJ)	[-2.0e+00, 2.7e+00]	35.9 fb^{-1}	13 TeV
	EW qqW	[-3.3e+01, 3.0e+01]	20.2 fb^{-1}	8 TeV
	EW qqW,qqZ	[-8.8e+00, 1.6e+01]	35.9 fb^{-1}	13 TeV
	D0 Comb.	[-8.2e+00, 2.0e+01]	8.6 fb^{-1}	1.96 TeV
	LEP Comb.	[-1.3e+01, 5.1e+00]	0.7 fb^{-1}	0.20 TeV

Neutral $Z\gamma\gamma$ and $ZZ\gamma$ aTGC results

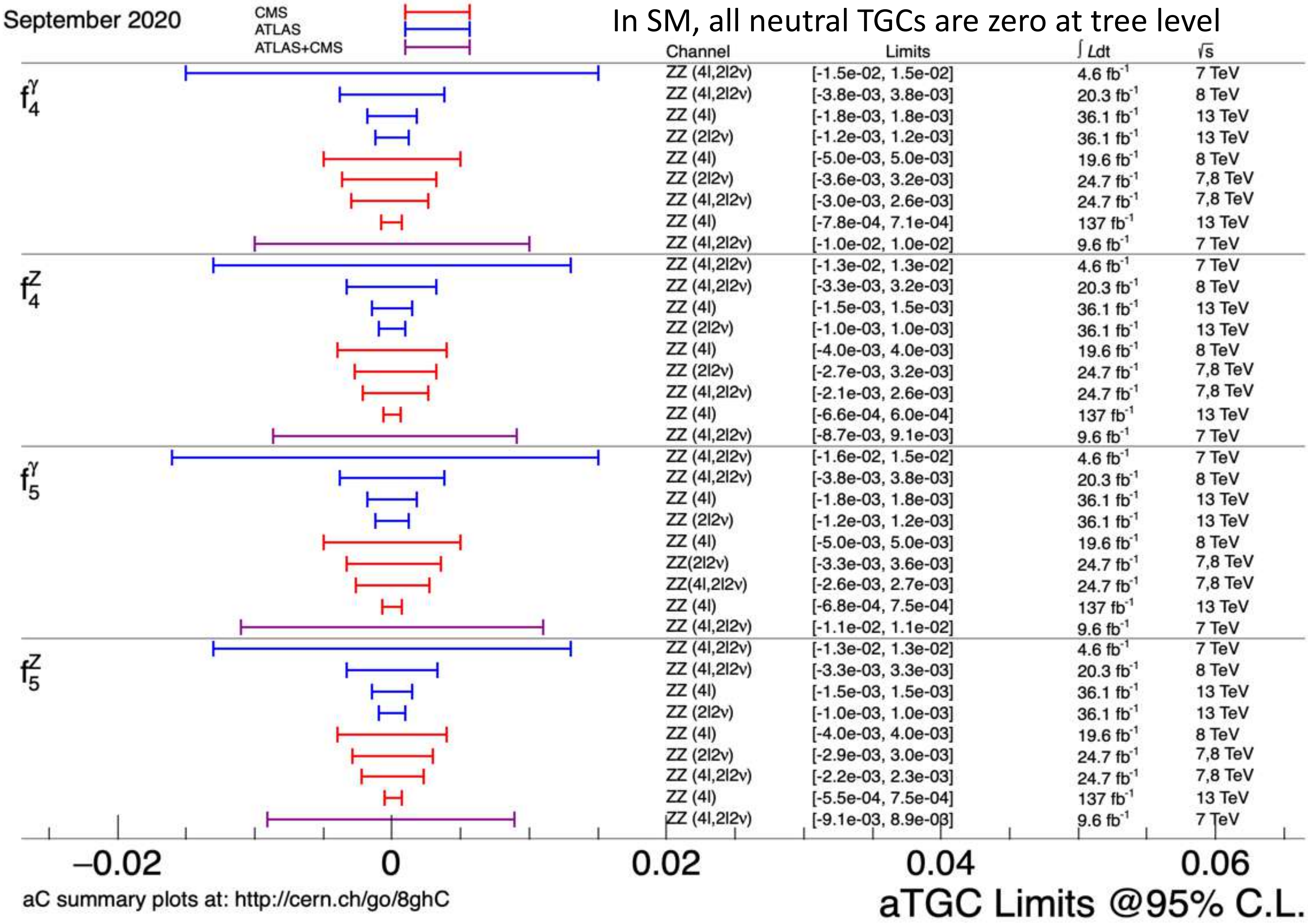
In SM, all neutral TGCs are zero at tree level



	Channel	Limits	$\int Ldt$	$\sqrt{s}$
h_3^γ	Zγ(llγ,ννγ)	[-9.5e-04, 9.9e-04]	20.3 fb^{-1}	8 TeV
	Zγ(ννγ)	[-3.7e-04, 3.7e-04]	36.1 fb^{-1}	13 TeV
	Zγ(llγ,ννγ)	[-2.9e-03, 2.9e-03]	5.0 fb^{-1}	7 TeV
	Zγ(llγ)	[-4.6e-03, 4.6e-03]	19.5 fb^{-1}	8 TeV
	Zγ(ννγ)	[-1.1e-03, 9.0e-04]	19.6 fb^{-1}	8 TeV
h_3^Z	Zγ(llγ,ννγ)	[-7.8e-04, 8.6e-04]	20.3 fb^{-1}	8 TeV
	Zγ(ννγ)	[-3.2e-04, 3.3e-04]	36.1 fb^{-1}	13 TeV
	Zγ(llγ,ννγ)	[-2.7e-03, 2.7e-03]	5.0 fb^{-1}	7 TeV
	Zγ(llγ)	[-3.8e-03, 3.7e-03]	19.5 fb^{-1}	8 TeV
	Zγ(ννγ)	[-1.5e-03, 1.6e-03]	19.6 fb^{-1}	8 TeV
h_4^γ	Zγ(llγ,ννγ)	[-3.2e-06, 3.2e-06]	20.3 fb^{-1}	8 TeV
	Zγ(ννγ)	[-4.4e-07, 4.3e-07]	36.1 fb^{-1}	13 TeV
	Zγ(llγ,ννγ)	[-1.5e-05, 1.5e-05]	5.0 fb^{-1}	7 TeV
	Zγ(llγ)	[-3.6e-05, 3.5e-05]	19.5 fb^{-1}	8 TeV
	Zγ(ννγ)	[-3.8e-06, 4.3e-06]	19.6 fb^{-1}	8 TeV
h_4^Z	Zγ(llγ,ννγ)	[-3.0e-06, 2.9e-06]	20.3 fb^{-1}	8 TeV
	Zγ(ννγ)	[-4.5e-07, 4.4e-07]	36.1 fb^{-1}	13 TeV
	Zγ(llγ,ννγ)	[-1.3e-05, 1.3e-05]	5.0 fb^{-1}	7 TeV
	Zγ(llγ)	[-3.1e-05, 3.0e-05]	19.5 fb^{-1}	8 TeV
	Zγ(ννγ)	[-3.9e-06, 4.5e-06]	19.6 fb^{-1}	8 TeV

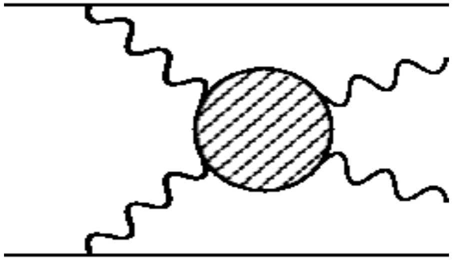
Neutral $ZZ\gamma$ and ZZZ aTGC results

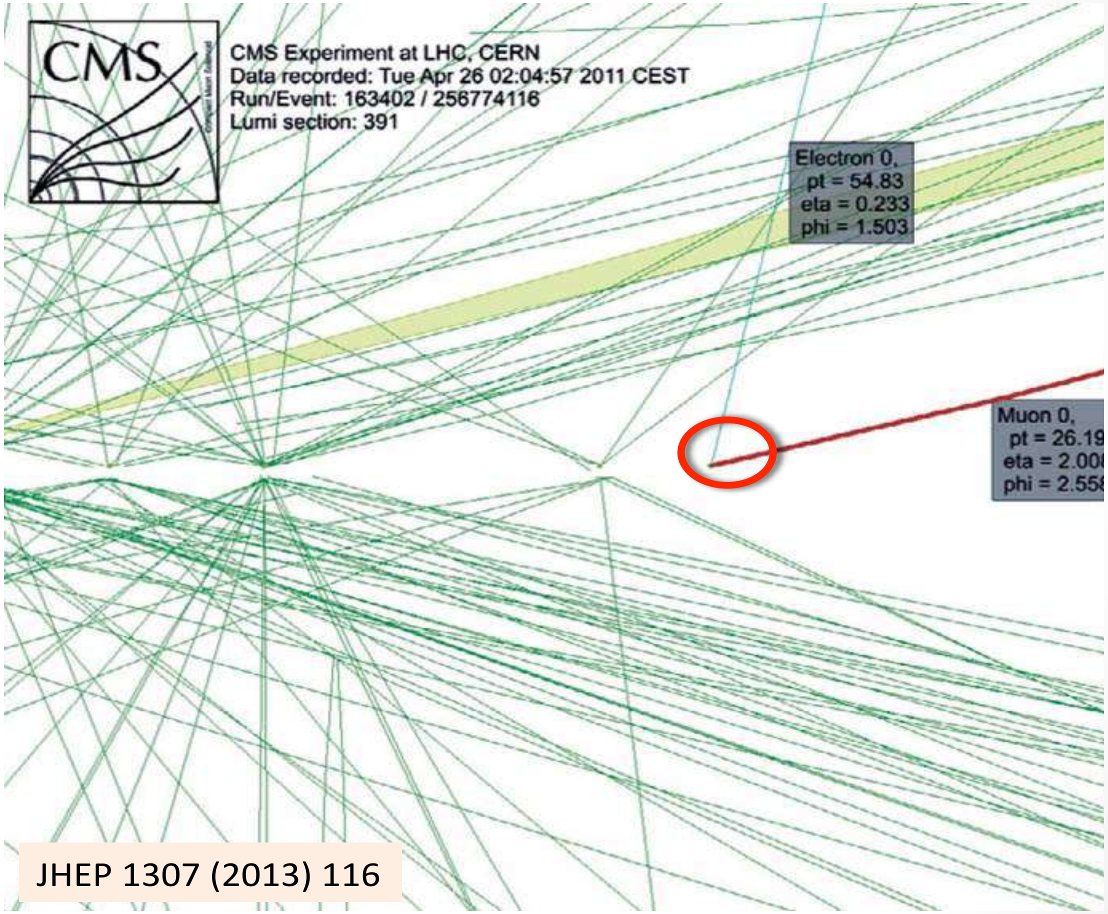
In SM, all neutral TGCs are zero at tree level



	Channel	Limits	∫ Ldt	√s
f_4^γ	ZZ (4l,2l2ν)	[-1.5e-02, 1.5e-02]	4.6 fb^{-1}	7 TeV
	ZZ (4l,2l2ν)	[-3.8e-03, 3.8e-03]	20.3 fb^{-1}	8 TeV
	ZZ (4l)	[-1.8e-03, 1.8e-03]	36.1 fb^{-1}	13 TeV
	ZZ (2l2ν)	[-1.2e-03, 1.2e-03]	36.1 fb^{-1}	13 TeV
	ZZ (4l)	[-5.0e-03, 5.0e-03]	19.6 fb^{-1}	8 TeV
	ZZ (2l2ν)	[-3.6e-03, 3.2e-03]	24.7 fb^{-1}	7,8 TeV
	ZZ (4l,2l2ν)	[-3.0e-03, 2.6e-03]	24.7 fb^{-1}	7,8 TeV
	ZZ (4l)	[-7.8e-04, 7.1e-04]	137 fb^{-1}	13 TeV
	ZZ (4l,2l2ν)	[-1.0e-02, 1.0e-02]	9.6 fb^{-1}	7 TeV
f_4^Z	ZZ (4l,2l2ν)	[-1.3e-02, 1.3e-02]	4.6 fb^{-1}	7 TeV
	ZZ (4l,2l2ν)	[-3.3e-03, 3.2e-03]	20.3 fb^{-1}	8 TeV
	ZZ (4l)	[-1.5e-03, 1.5e-03]	36.1 fb^{-1}	13 TeV
	ZZ (2l2ν)	[-1.0e-03, 1.0e-03]	36.1 fb^{-1}	13 TeV
	ZZ (4l)	[-4.0e-03, 4.0e-03]	19.6 fb^{-1}	8 TeV
	ZZ (2l2ν)	[-2.7e-03, 3.2e-03]	24.7 fb^{-1}	7,8 TeV
	ZZ (4l,2l2ν)	[-2.1e-03, 2.6e-03]	24.7 fb^{-1}	7,8 TeV
	ZZ (4l)	[-6.6e-04, 6.0e-04]	137 fb^{-1}	13 TeV
	ZZ (4l,2l2ν)	[-8.7e-03, 9.1e-03]	9.6 fb^{-1}	7 TeV
f_5^γ	ZZ (4l,2l2ν)	[-1.6e-02, 1.5e-02]	4.6 fb^{-1}	7 TeV
	ZZ (4l,2l2ν)	[-3.8e-03, 3.8e-03]	20.3 fb^{-1}	8 TeV
	ZZ (4l)	[-1.8e-03, 1.8e-03]	36.1 fb^{-1}	13 TeV
	ZZ (2l2ν)	[-1.2e-03, 1.2e-03]	36.1 fb^{-1}	13 TeV
	ZZ (4l)	[-5.0e-03, 5.0e-03]	19.6 fb^{-1}	8 TeV
	ZZ(2l2ν)	[-3.3e-03, 3.6e-03]	24.7 fb^{-1}	7,8 TeV
	ZZ(4l,2l2ν)	[-2.6e-03, 2.7e-03]	24.7 fb^{-1}	7,8 TeV
	ZZ (4l)	[-6.8e-04, 7.5e-04]	137 fb^{-1}	13 TeV
	ZZ (4l,2l2ν)	[-1.1e-02, 1.1e-02]	9.6 fb^{-1}	7 TeV
f_5^Z	ZZ (4l,2l2ν)	[-1.3e-02, 1.3e-02]	4.6 fb^{-1}	7 TeV
	ZZ (4l,2l2ν)	[-3.3e-03, 3.3e-03]	20.3 fb^{-1}	8 TeV
	ZZ (4l)	[-1.5e-03, 1.5e-03]	36.1 fb^{-1}	13 TeV
	ZZ (2l2ν)	[-1.0e-03, 1.0e-03]	36.1 fb^{-1}	13 TeV
	ZZ (4l)	[-4.0e-03, 4.0e-03]	19.6 fb^{-1}	8 TeV
	ZZ (2l2ν)	[-2.9e-03, 3.0e-03]	24.7 fb^{-1}	7,8 TeV
	ZZ (4l,2l2ν)	[-2.2e-03, 2.3e-03]	24.7 fb^{-1}	7,8 TeV
	ZZ (4l)	[-5.5e-04, 7.5e-04]	137 fb^{-1}	13 TeV
	ZZ (4l,2l2ν)	[-9.1e-03, 8.9e-03]	9.6 fb^{-1}	7 TeV

Vector-boson scattering as probe of EWSB and new physics





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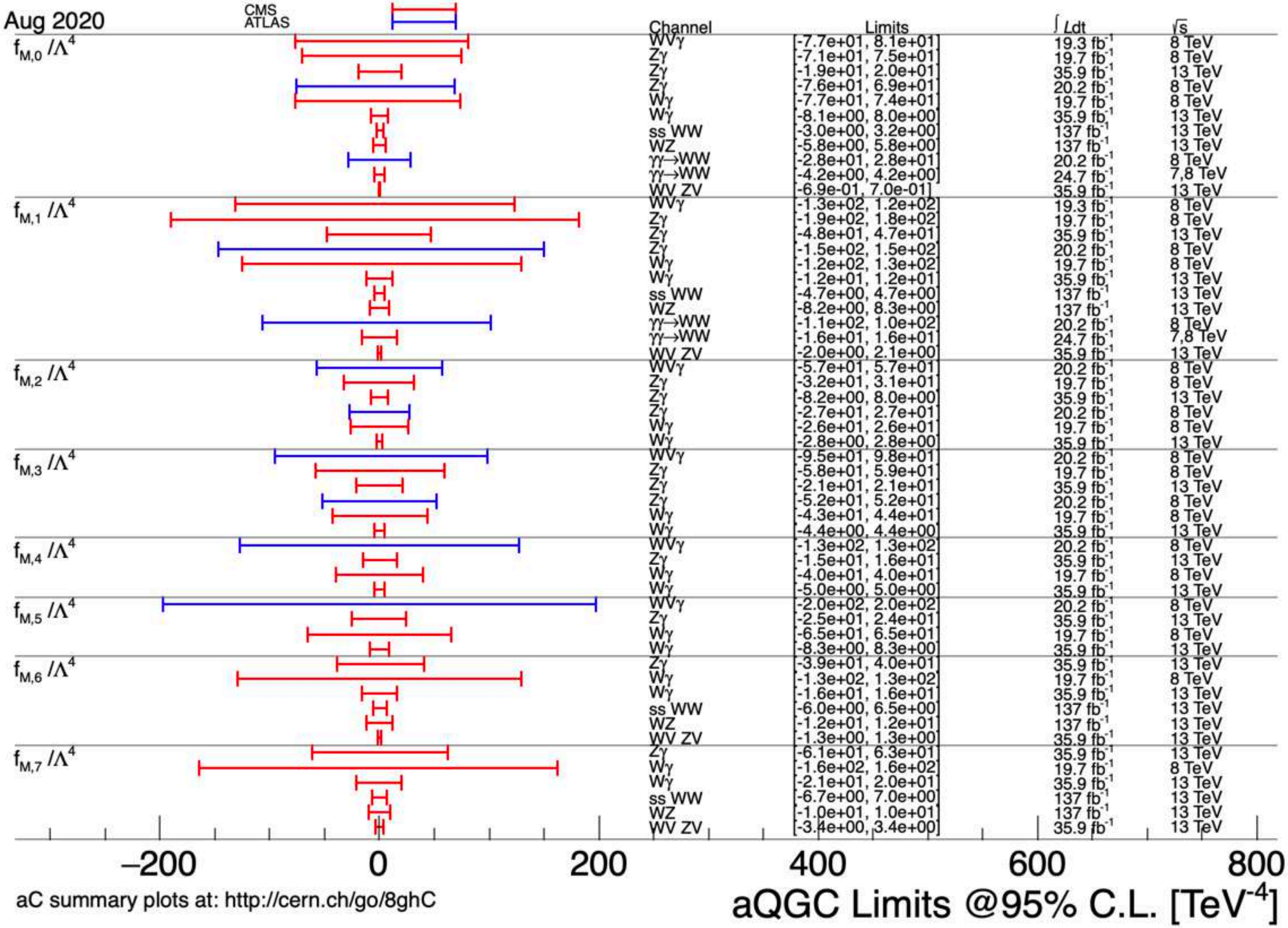
Exclusive $\gamma\gamma$ → WW production candidate

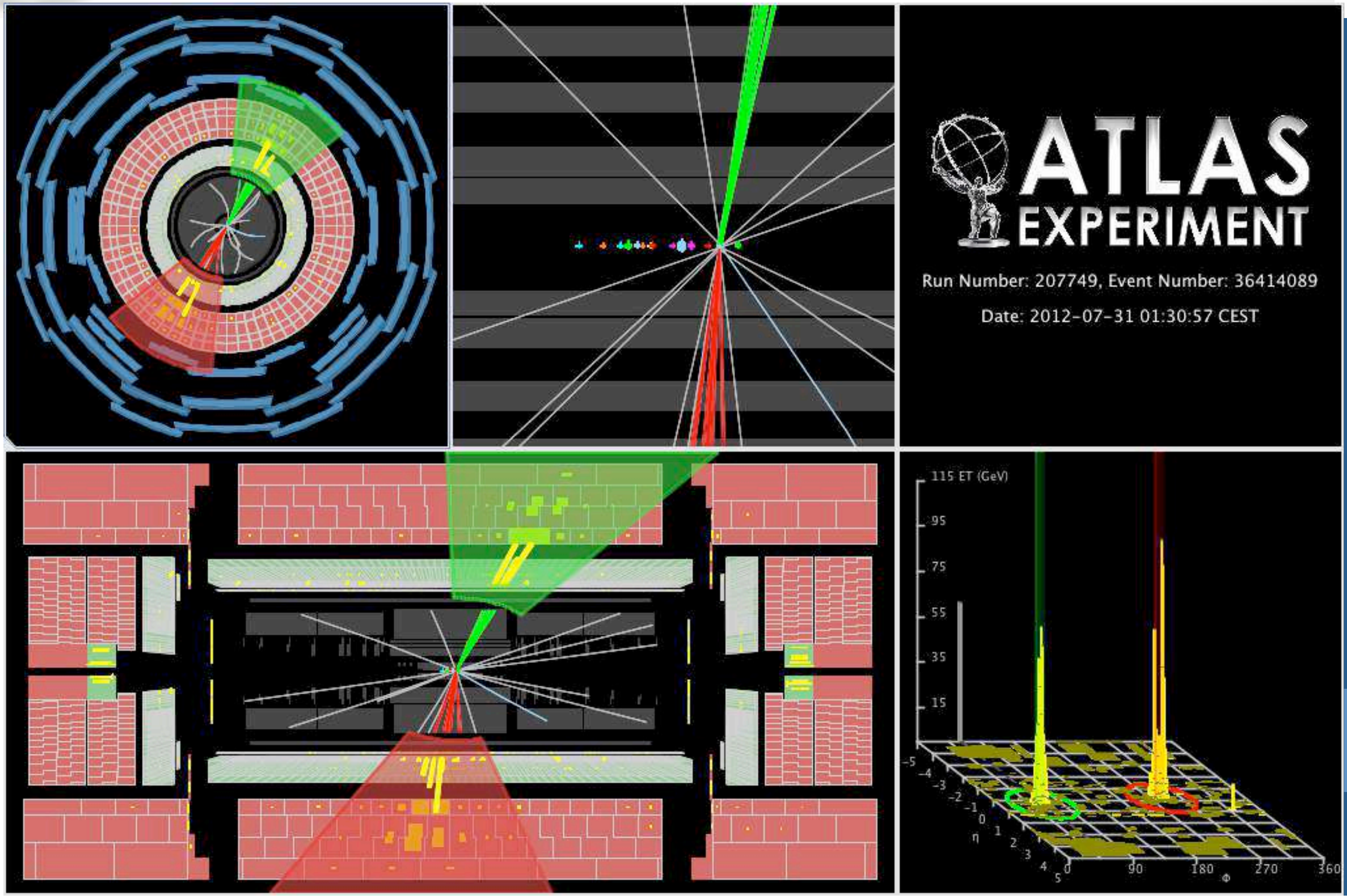
Anomalous couplings: illustrative results



	Channel	Limits	$\int L dt$	$\sqrt{s}$
$f_{M,0}/\Lambda^4$	WVγ	[-7.7e+01, 8.1e+01]	19.3 fb^{-1}	8 TeV
	Zγ	[-7.1e+01, 7.5e+01]	19.7 fb^{-1}	8 TeV
	Zγ	[-1.9e+01, 2.0e+01]	35.9 fb^{-1}	13 TeV
	Zγ	[-7.6e+01, 6.9e+01]	20.2 fb^{-1}	8 TeV
	Wγ	[-7.7e+01, 7.4e+01]	19.7 fb^{-1}	8 TeV
	Wγ	[-8.1e+00, 8.0e+00]	35.9 fb^{-1}	13 TeV
	ss WW	[-3.0e+00, 3.2e+00]	137 fb^{-1}	13 TeV
	WZ	[-5.8e+00, 5.8e+00]	137 fb^{-1}	13 TeV
	γγ→WW	[-2.8e+01, 2.8e+01]	20.2 fb^{-1}	8 TeV
	γγ→WW	[-4.2e+00, 4.2e+00]	24.7 fb^{-1}	7,8 TeV
	WV ZV	[-6.9e-01, 7.0e-01]	35.9 fb^{-1}	13 TeV
$f_{M,1}/\Lambda^4$	WVγ	[-1.3e+02, 1.2e+02]	19.3 fb^{-1}	8 TeV
	Zγ	[-1.9e+02, 1.8e+02]	19.7 fb^{-1}	8 TeV
	Zγ	[-4.8e+01, 4.7e+01]	35.9 fb^{-1}	13 TeV
	Zγ	[-1.5e+02, 1.5e+02]	20.2 fb^{-1}	8 TeV
	Wγ	[-1.2e+02, 1.3e+02]	19.7 fb^{-1}	8 TeV
	Wγ	[-1.2e+01, 1.2e+01]	35.9 fb^{-1}	13 TeV
	ss WW	[-4.7e+00, 4.7e+00]	137 fb^{-1}	13 TeV
	WZ	[-8.2e+00, 8.3e+00]	137 fb^{-1}	13 TeV
	γγ→WW	[-1.1e+02, 1.0e+02]	20.2 fb^{-1}	8 TeV
	γγ→WW	[-1.6e+01, 1.6e+01]	24.7 fb^{-1}	7,8 TeV
	WV ZV	[-2.0e+00, 2.1e+00]	35.9 fb^{-1}	13 TeV
$f_{M,2}/\Lambda^4$	WVγ	[-5.7e+01, 5.7e+01]	20.2 fb^{-1}	8 TeV
	Zγ	[-3.2e+01, 3.1e+01]	19.7 fb^{-1}	8 TeV
	Zγ	[-8.2e+00, 8.0e+00]	35.9 fb^{-1}	13 TeV
	Zγ	[-2.7e+01, 2.7e+01]	20.2 fb^{-1}	8 TeV
	Wγ	[-2.6e+01, 2.6e+01]	19.7 fb^{-1}	8 TeV
	Wγ	[-2.8e+00, 2.8e+00]	35.9 fb^{-1}	13 TeV
$f_{M,3}/\Lambda^4$	WVγ	[-9.5e+01, 9.8e+01]	20.2 fb^{-1}	8 TeV
	Zγ	[-5.8e+01, 5.9e+01]	19.7 fb^{-1}	8 TeV
	Zγ	[-2.1e+01, 2.1e+01]	35.9 fb^{-1}	13 TeV
	Zγ	[-5.2e+01, 5.2e+01]	20.2 fb^{-1}	8 TeV
	Wγ	[-4.3e+01, 4.4e+01]	19.7 fb^{-1}	8 TeV
	Wγ	[-4.4e+00, 4.4e+00]	35.9 fb^{-1}	13 TeV
$f_{M,4}/\Lambda^4$	WVγ	[-1.3e+02, 1.3e+02]	20.2 fb^{-1}	8 TeV
	Zγ	[-1.5e+01, 1.6e+01]	35.9 fb^{-1}	13 TeV
	Wγ	[-4.0e+01, 4.0e+01]	19.7 fb^{-1}	8 TeV
	Wγ	[-5.0e+00, 5.0e+00]	35.9 fb^{-1}	13 TeV
$f_{M,5}/\Lambda^4$	WVγ	[-2.0e+02, 2.0e+02]	20.2 fb^{-1}	8 TeV
	Zγ	[-2.5e+01, 2.4e+01]	35.9 fb^{-1}	13 TeV
	Wγ	[-6.5e+01, 6.5e+01]	19.7 fb^{-1}	8 TeV
	Wγ	[-8.3e+00, 8.3e+00]	35.9 fb^{-1}	13 TeV
$f_{M,6}/\Lambda^4$	Zγ	[-3.9e+01, 4.0e+01]	35.9 fb^{-1}	13 TeV
	Wγ	[-1.3e+02, 1.3e+02]	19.7 fb^{-1}	8 TeV
	Wγ	[-1.6e+01, 1.6e+01]	35.9 fb^{-1}	13 TeV
	ss WW	[-6.0e+00, 6.5e+00]	137 fb^{-1}	13 TeV
	WZ	[-1.2e+01, 1.2e+01]	137 fb^{-1}	13 TeV
	WV ZV	[-1.3e+00, 1.3e+00]	35.9 fb^{-1}	13 TeV
$f_{M,7}/\Lambda^4$	Zγ	[-6.1e+01, 6.3e+01]	35.9 fb^{-1}	13 TeV
	Wγ	[-1.6e+02, 1.6e+02]	19.7 fb^{-1}	8 TeV
	Wγ	[-2.1e+01, 2.0e+01]	35.9 fb^{-1}	13 TeV
	ss WW	[-6.7e+00, 7.0e+00]	137 fb^{-1}	13 TeV
	WZ	[-1.0e+01, 1.0e+01]	137 fb^{-1}	13 TeV
	WV ZV	[-3.4e+00, 3.4e+00]	35.9 fb^{-1}	13 TeV

aC summary plots at: http://cern.ch/go/8ghC

Search for heavy bosons in VV final states



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Photon pdf

- http://luxqed.web.cern.ch/luxqed/