Search for SUSY at the LHC

Dezső Horváth

horvath.dezso@wigner.mta.hu

Wigner RCP, Budapest and Atomki, Debrecen

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Outline

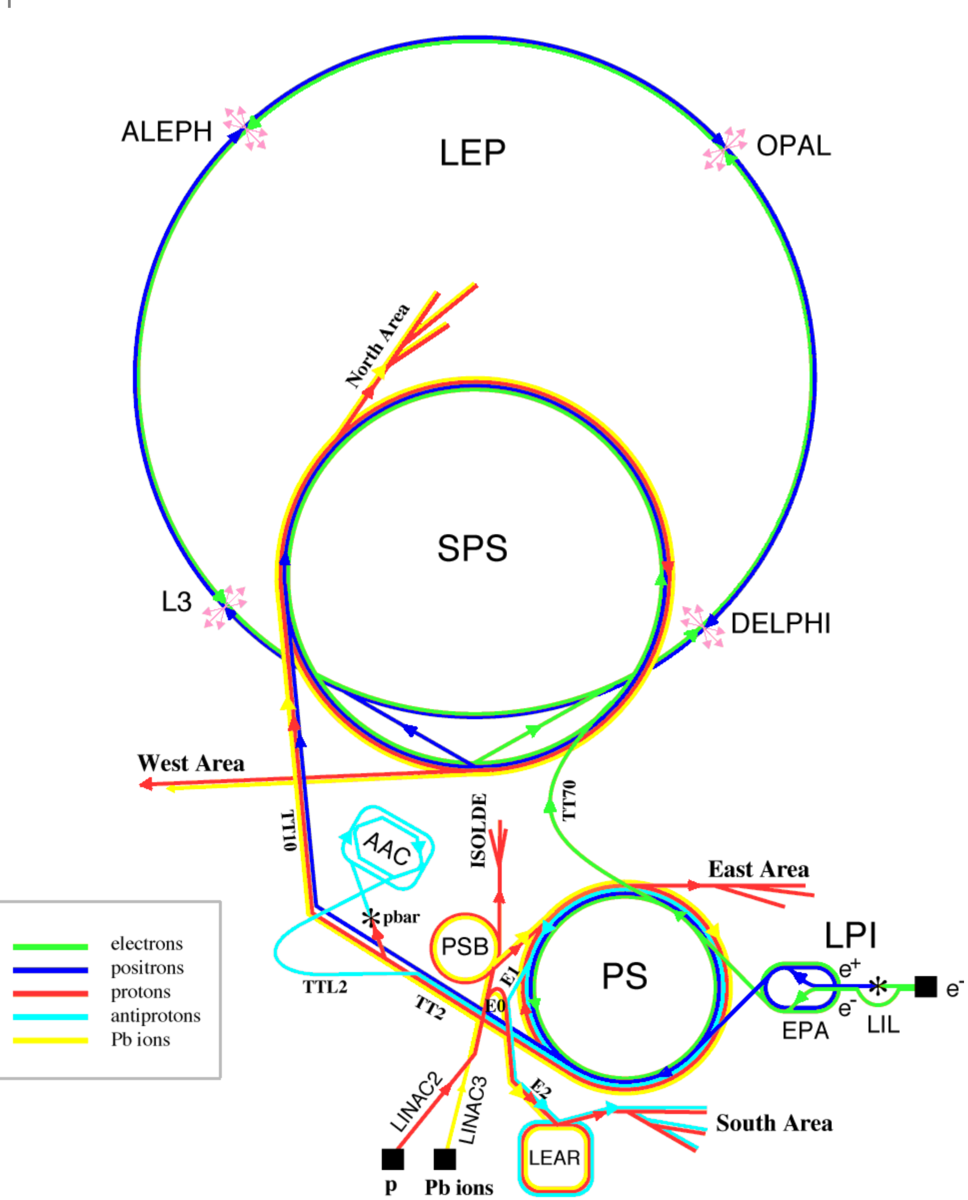
- Problems of the Standard Model
- Supersymmetry (SUSY): a solution for all?
- Searching for SUSY phenomena
- Natural SUSY: finished?
- Status and prospects

Best introduction to SUSY:

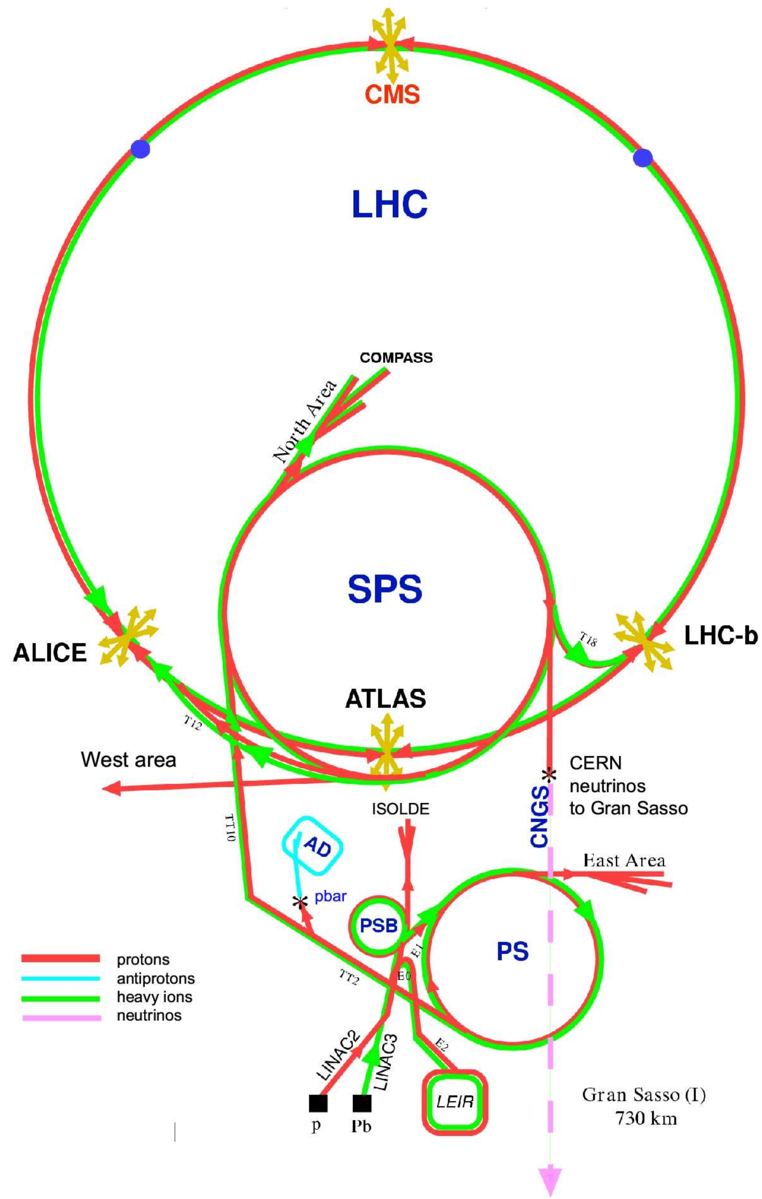
A Supersymmetry Primer
by Stephen P. Martin
https://arxiv.org/abs/hep-ph/9709356v7
(last revised in 2016)

Accelerators at CERN

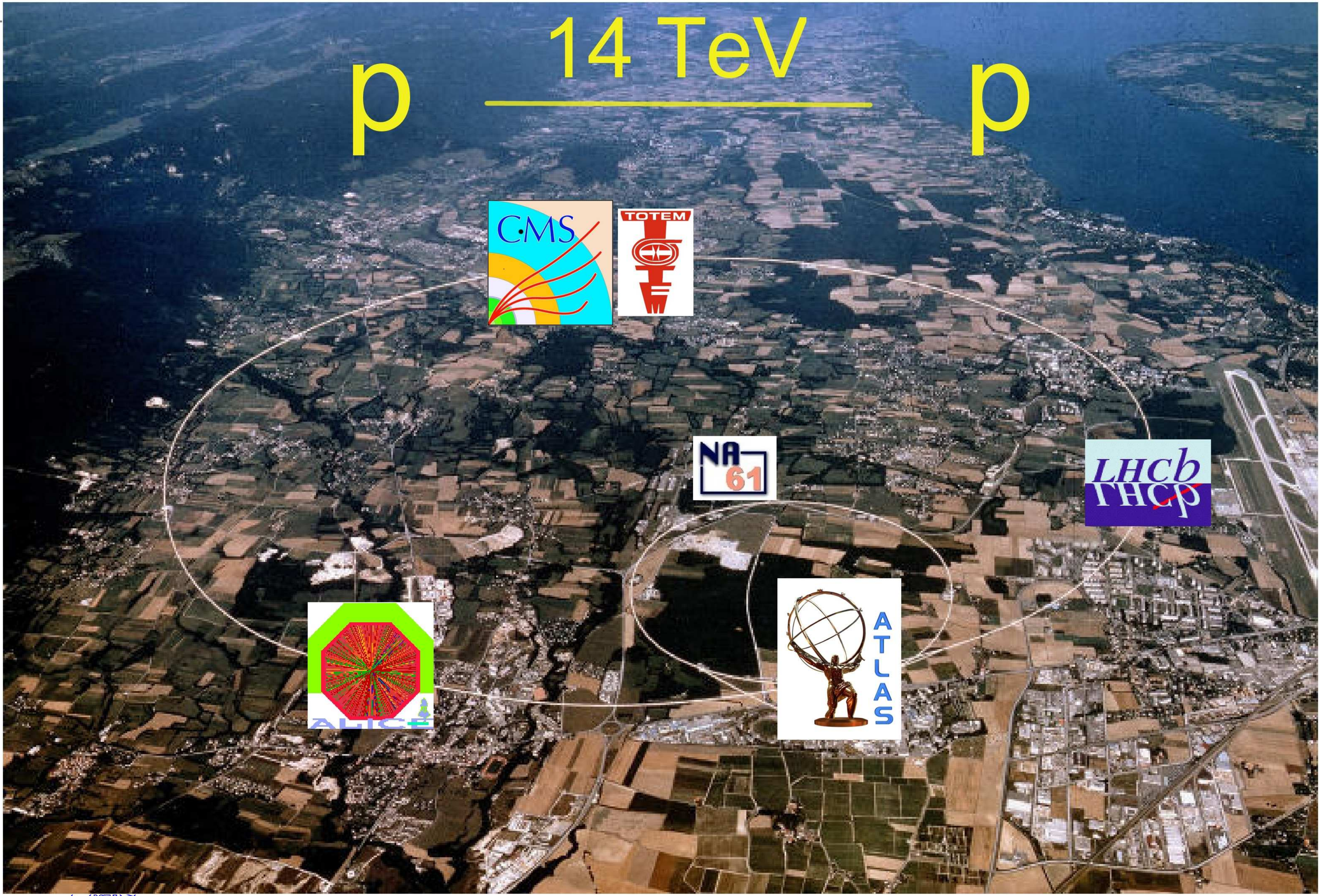
1989–2000



2009–2025??



CERN



SM: parameter fitting, 2018

$\frac{\text{Expt} - \text{theory}}{\text{uncertainty}}$

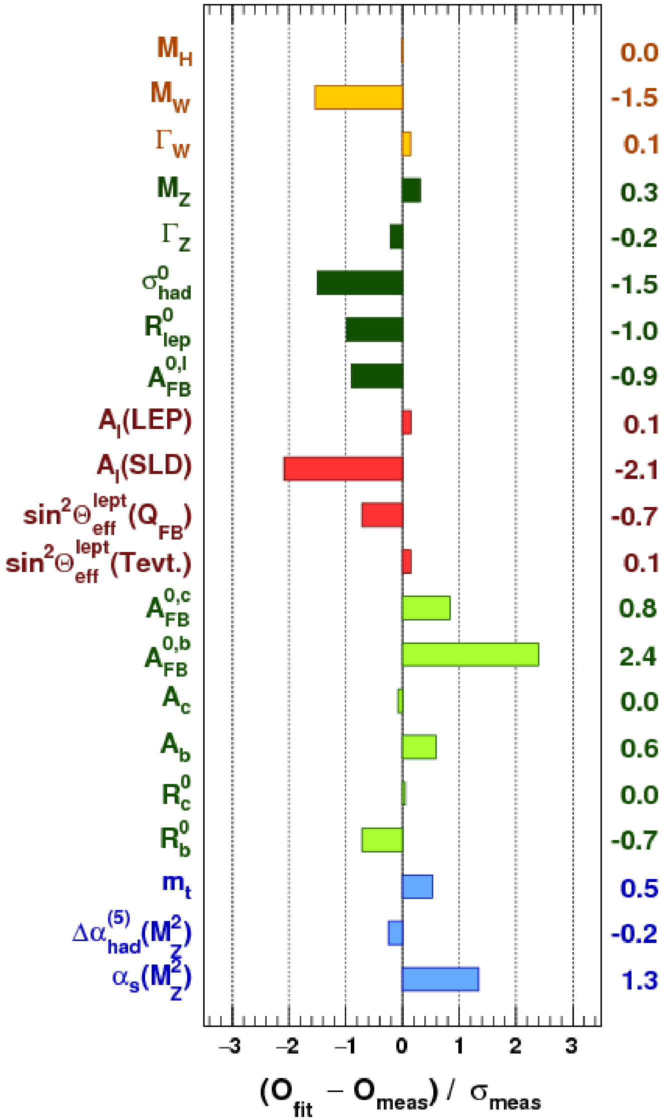
Measurements by all experiments

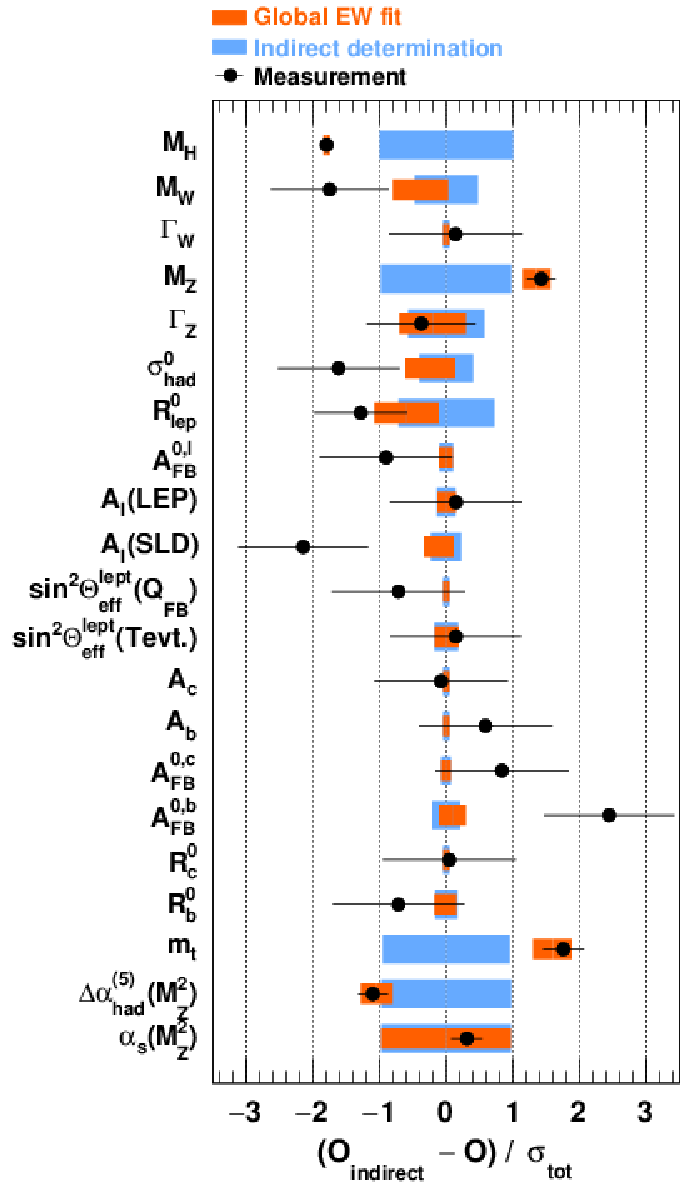
Left: global EW fit

Right: fit w/o measured value of given parameter

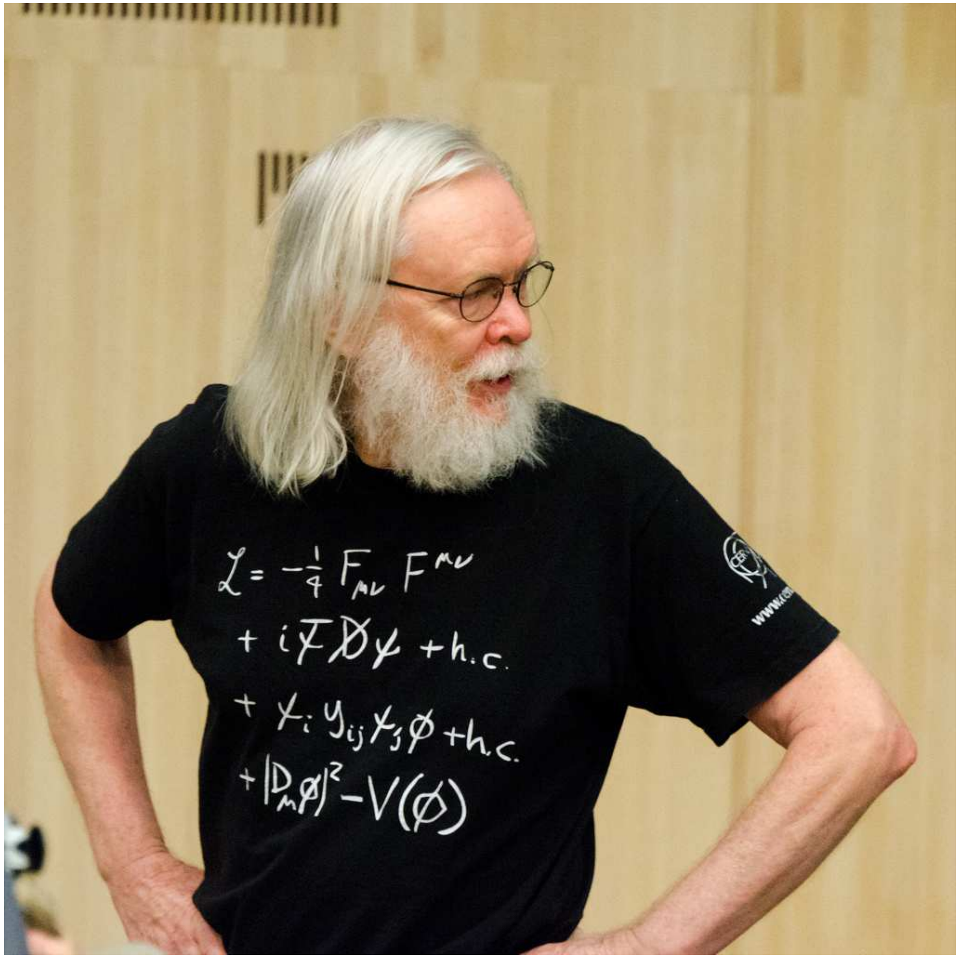
All within statistics

J. Haller et al, arXiv:1803.01853



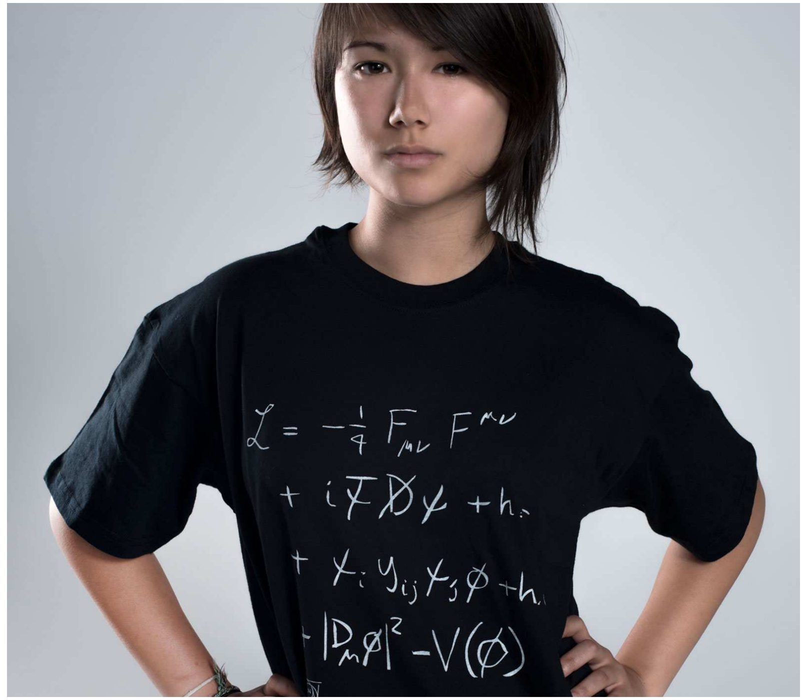


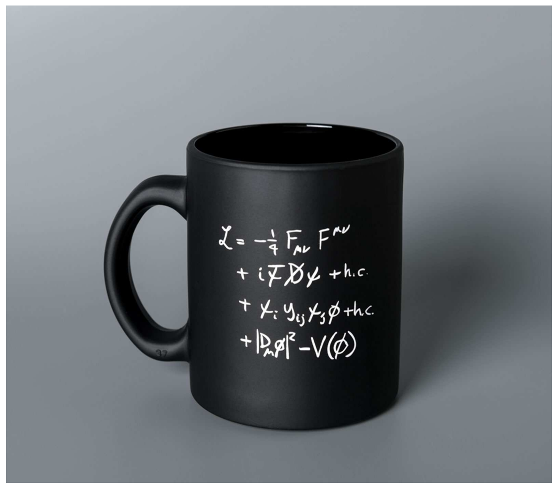
SM at CERN's souvenir shop

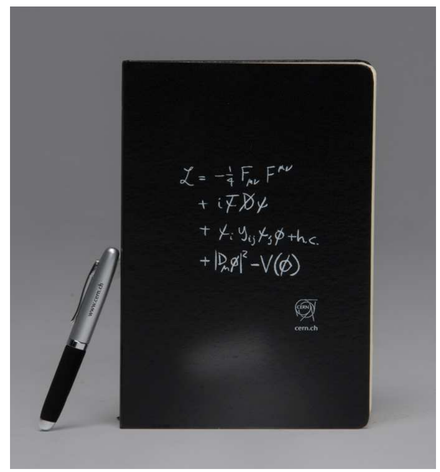


John Ellis, the creator

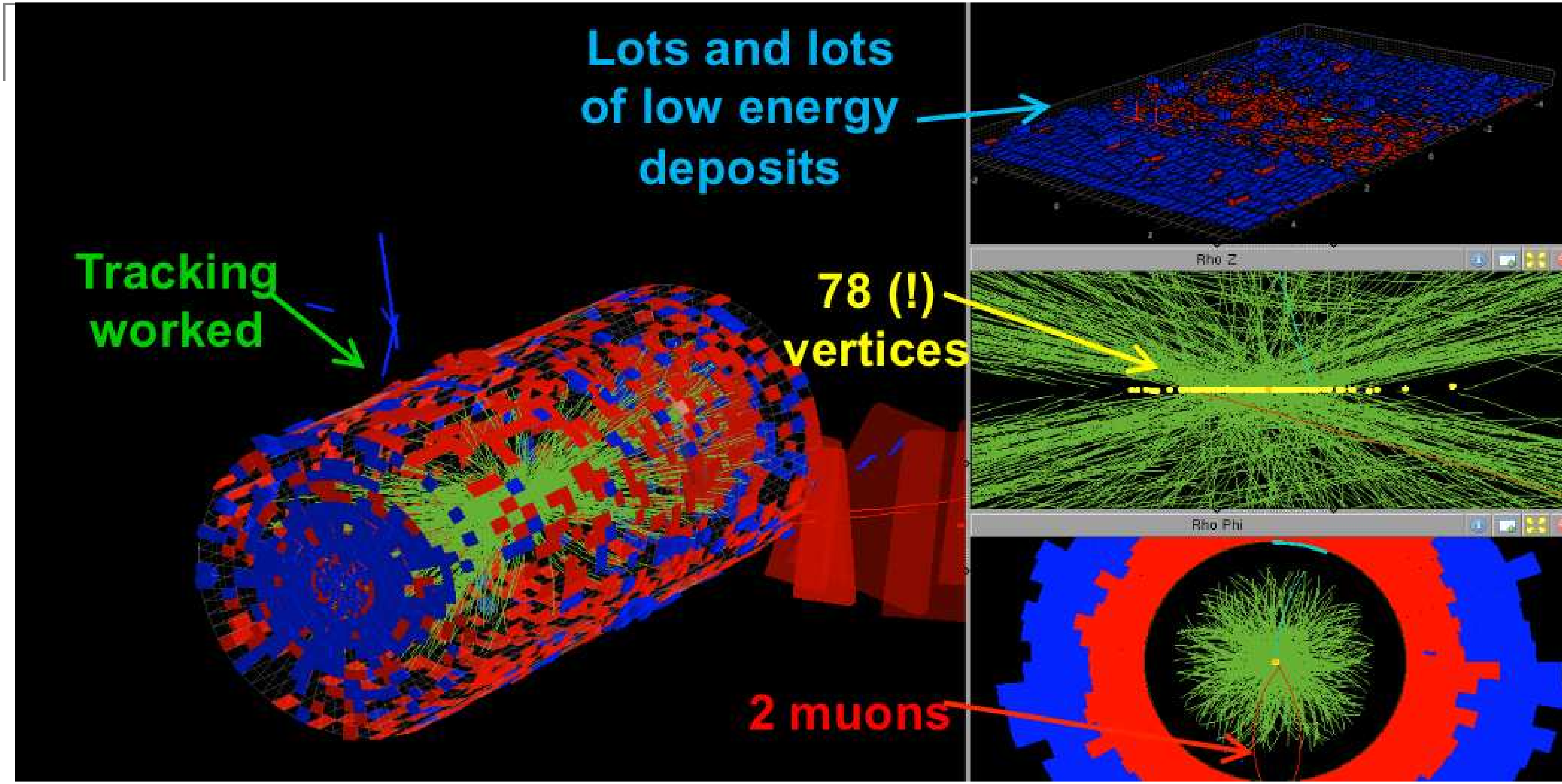
h.c. = Herm. conj. or hot coffee?







CMS: 78 p-p collisions in one event!



An event (i.e. bunch crossing) can have many p-p collisions.
This increases the statistics and complicates the analysis.

ATLAS vs. CMS

Both optimized to detect (and study!) the production and decay of Higgs-bosons. Very different detectors giving very similar results.

	ATLAS	CMS
Magnet	toroid + *small(?)* 2 T solenoid	large 3.8 T solenoid
Tracker	semiconductor + TRD	semiconductor
E-m calorimeter	LAr with steel and Pb	$PbWO_4$ scint.
Hadron cal.-m.	steel + scint. tiles	brass + scint. tiles
Far forward h-cal	LAr with Cu and W	steel with quartz Cher.
Muon detector	chambers (4 types)	chambers (3 types)
Size	$\oslash 25$ m $\times$ 46 m (23000 m^3)	$\oslash 15$ m $\times$ 21.6 m (3800 m^3)
Trigger	3-level	2-level
Weight	7000 t	14000 t
Participants (sci)	3000	2300

CMS & ATLAS, signal strengths

So how Higgs study can help to find new physics?

Compare precise measurements with SM predictions

Production rate (cross section) ratios:

$\mu_i = \sigma_i/(\sigma_i)_{\rm SM}$ (i = ggF, VBF, WH, ZH, ttH)

Relative decay rates (ratios of branching fractions):

$\mu^f = B^f/(B^f)_{\rm SM}$ (f = ZZ, WW, $\gamma\gamma$, $\tau\tau$, bb, $\mu\mu$)

Production and decay cannot be separated, what is really measured:

$$\mu_i^f = \frac{\sigma_i B^f}{(\sigma_i)_{\rm SM}(B^f)_{\rm SM}} = \mu_i \mu^f$$

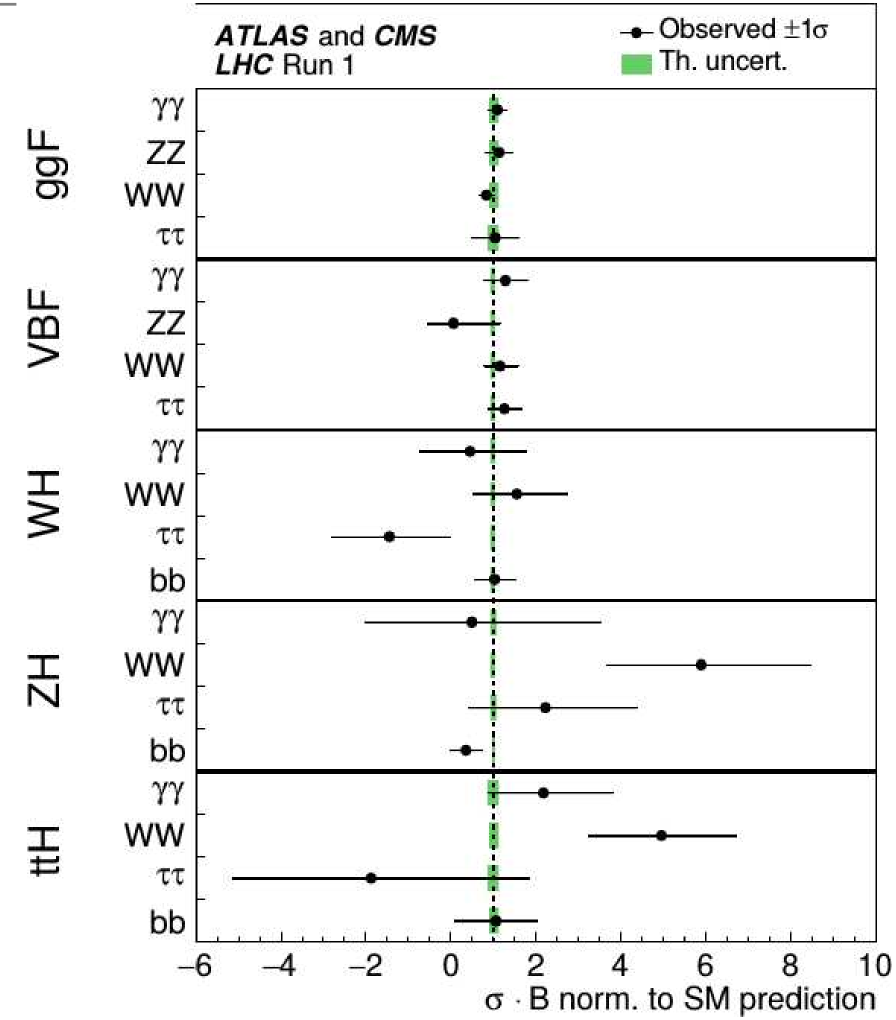
Allowing for BSM interpretation: $\sigma_i B^f = \sigma_i(\underline{\kappa}) \cdot \Gamma^f(\underline{\kappa})/\Gamma_H$

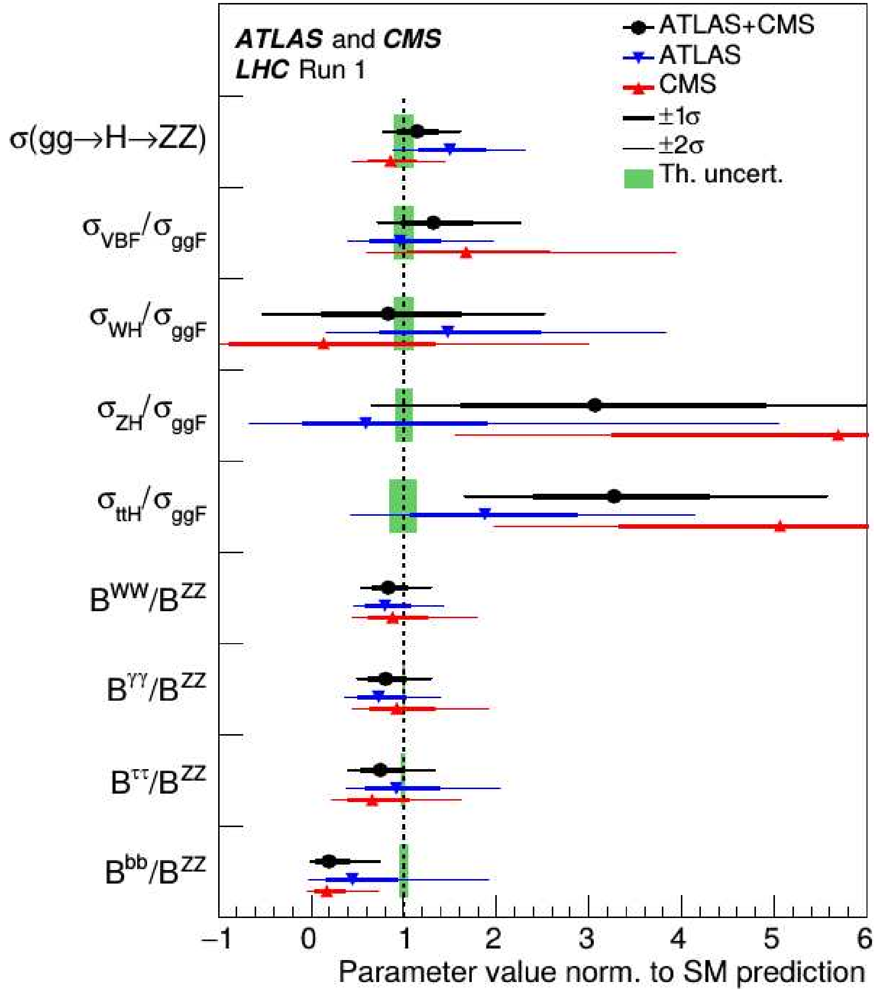
Γ_H, Γ^f: total and frac. decay widths,

Coupling modifiers: $\kappa_j^2 = \sigma_j/\sigma_j^{\rm SM}$ (prod.); $\kappa_j^2 = \Gamma^j/\Gamma^j_{\rm SM}$ (decay)

[ATLAS and CMS Collaborations], JHEP **1608** (2016) 045.

CMS & ATLAS, signal strengths, Run 1

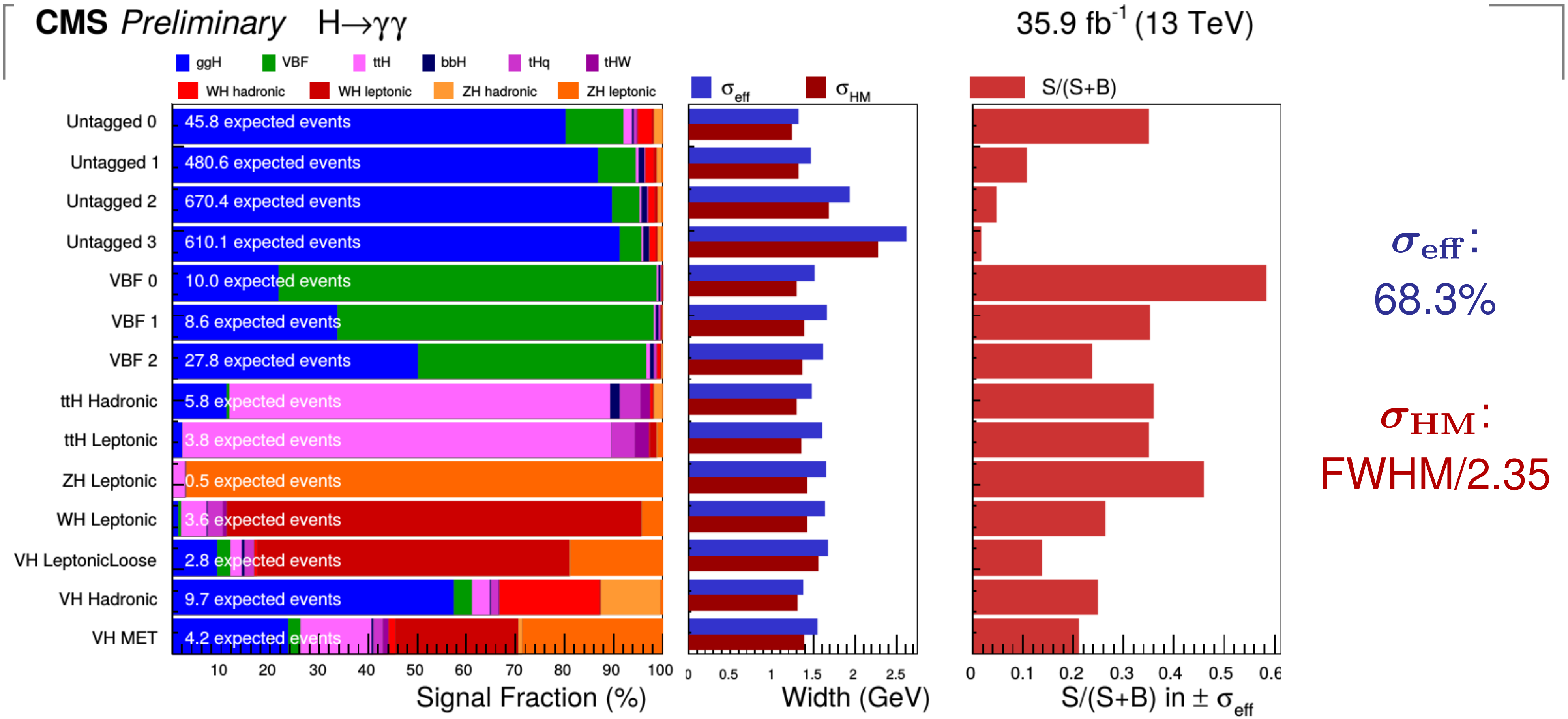




$$\mu = 1.09 \pm 0.07(\text{stat}) \pm 0.04(\text{expt}) \pm 0.03(\text{thbgd}) \{^{+0.07}_{-0.06}\}(\text{thsig})$$

[ATLAS and CMS Collaborations], JHEP **1608** (2016) 045. $\Uparrow \sigma(\text{ggF})!$

Production channels: CMS, $H \to \gamma\gamma$



σ_{eff}: 68.3%

σ_{HM}: FWHM/2.35

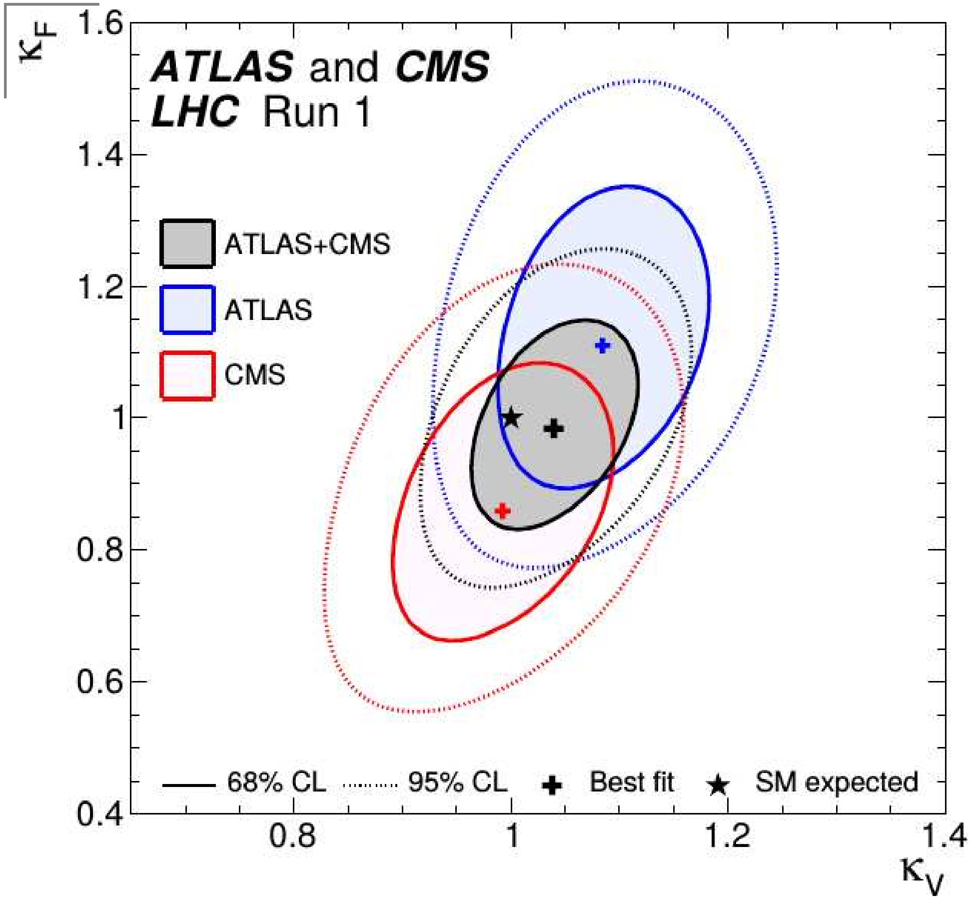
Best-fit average signal strength (at a floating H mass):

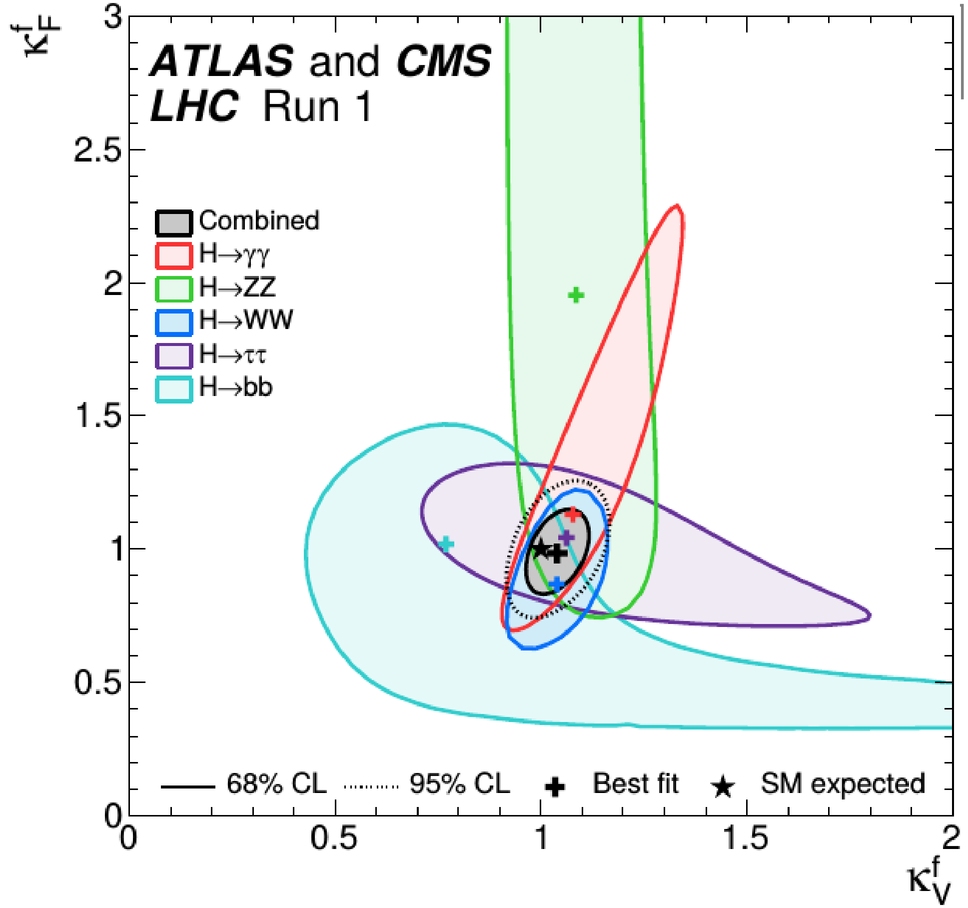
$$\mu = (\sigma \times \text{BR})_{\text{meas}} / (\sigma \times \text{BR})_{\text{SM}} =$$

$$1.18 \left\{ {+0.12 \atop -0.11} \right\} \text{(stat.)} \left\{ {+0.09 \atop -0.07} \right\} \text{(syst.)} \left\{ {+0.07 \atop -0.06} \right\} \text{(theo.)}$$

CMS, arXiv:1804.02716, 2018

ATLAS & CMS: coupling mod's, Run 1





Coupling to fermions & bosons: per expt. and average per decay mode

[ATLAS and CMS Collaborations], JHEP **1608** (2016) 045.

Problems of the Standard Model – 1

- Gravity? $S = 2$ graviton?
- Asymmetries: right ⇔ left World ⇔ Antiworld
- Artificial mass creation: Higgs-field *ad hoc*
- Charge quantization: $Q_{\mathrm{e}} = Q_{\mathrm{p}},\ Q_{\mathrm{d}} = Q_{\mathrm{e}}/3$
- Why the 3 fermion families?
- Nucleon spin: how $1/2$ produced?
- 19 free parameters (too many ??):
  - 3 couplings: $\alpha,\ \Theta_W,\ \Lambda_{\mathrm{QCD}}$; 2 Higgs: $M_H,\ \lambda$
  - 9 fermion masses: $3 \times M_\ell,\ 6 \times M_q$
  - 4 parameters of the CKM matrix: $\Theta_1,\ \Theta_2,\ \Theta_3,\ \delta$
  - QCD-vacuum: Θ

Problems of the Standard Model – 2

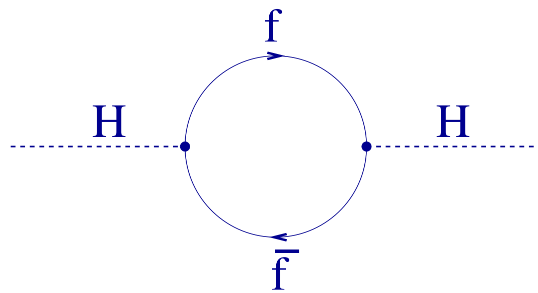
- Neutrino mysteries
  - $M_\nu > 0 \Rightarrow +3$ masses, $+4$ mixing matrix
    The SM does not like them...
  - Are $\nu_{\mathrm{R}},\ \overline{\nu}_{\mathrm{L}}$ sterile with no interaction?
  - What makes them oscillate (extra interaction)?
  - Are they Majorana particles $\overline{\nu} \equiv \nu$?
- Gravitational mass of the Universe:
  - 4% ordinary matter (H, He, stars, gas, dust, ν)
  - 23% invisible *dark matter* (out of SM!)
  - 73% mysterious *dark energy*
- Naturalness (hierarchy):
  The mass of the Higgs boson quadratically diverges due to radiative corrections. Cancelled if fermions and bosons exist in pairs!

Hierarchy problem

BEH potential: $V = -m_H^2\Phi^2 + \lambda\Phi^4$ $\quad m_{\rm H} = 125{\rm GeV}$

Corrections to the mass of the Higgs boson:

Fermion loop:



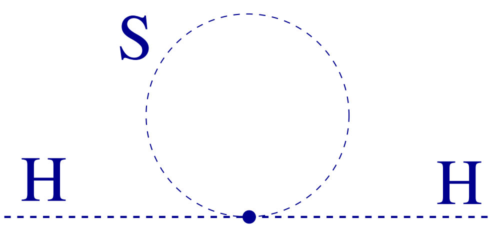
$$\Delta m_H^2 = \frac{|\lambda_f|^2}{8\pi^2}[-\Lambda_{\rm UV}^2 + 6m_f^2 \ln\frac{\Lambda_{\rm UV}}{m_f} + \ldots]$$

For the top quark $\lambda_t \approx 1$

UV cutoff: $\Lambda_{\rm UV} > 10^{14}$ GeV!

Tuning of the BEH parameters with the precision of 10^{-12}!

If there were two heavy scalar particles:



$\mathrm{f} \leftrightarrow \mathrm{S}_1, \mathrm{S}_2$: $\lambda_S = \lambda_f^2; \quad m_S = m_f$

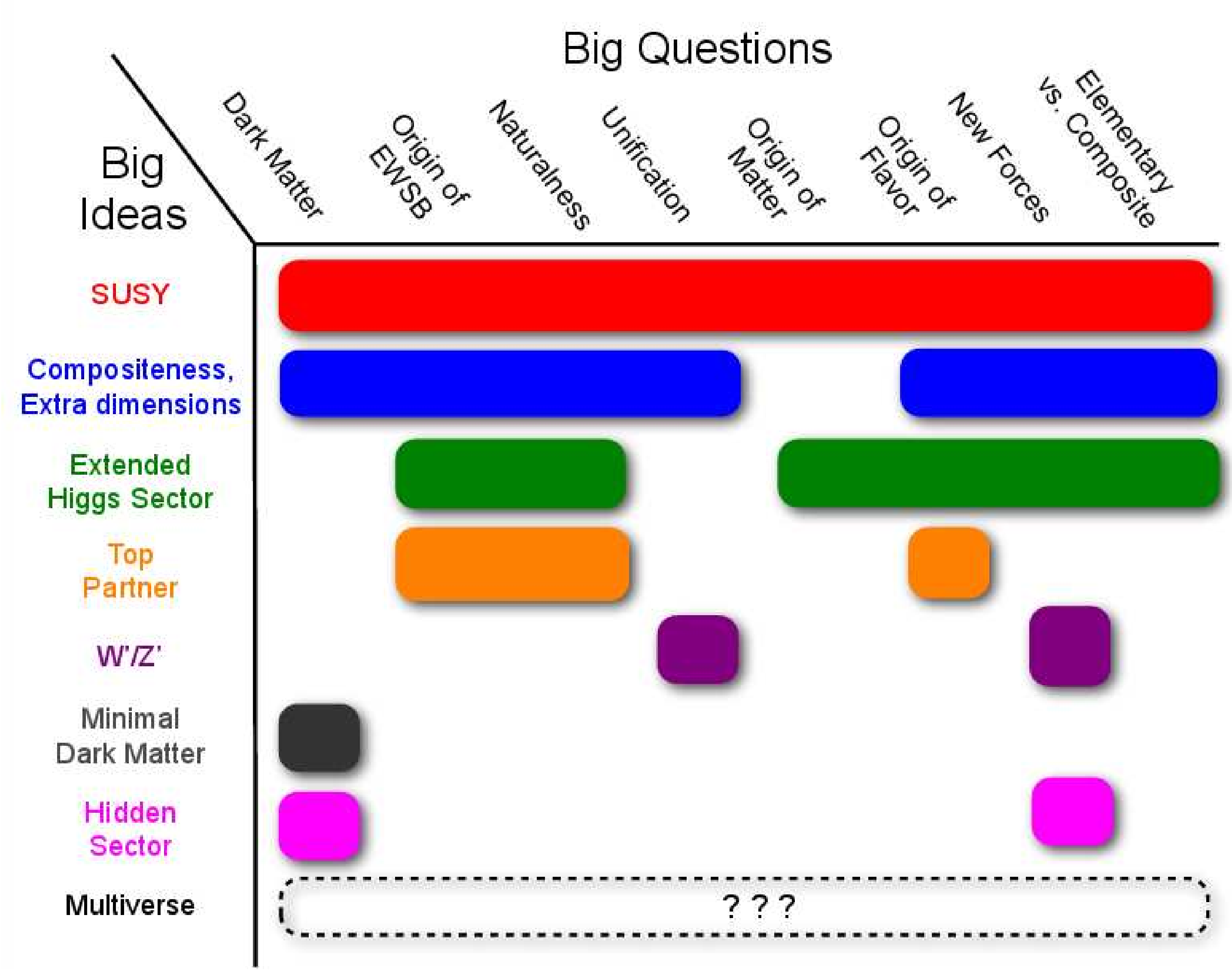
$$\Delta m_H^2 = \frac{\lambda_S}{16\pi^2}[+\Lambda_{\rm UV}^2 - 2m_S^2 \ln\frac{\Lambda_{\rm UV}}{m_S} + \ldots]$$

Λ^2 corrections would cancel out

Question: Why do we need two scalars for one fermion?

Many-many different models

Beyond the Standard Model



Y. Gershtein *et al.*, „Working Group Report: New Particles, Forces, and Dimensions,”

arXiv:1311.0299.

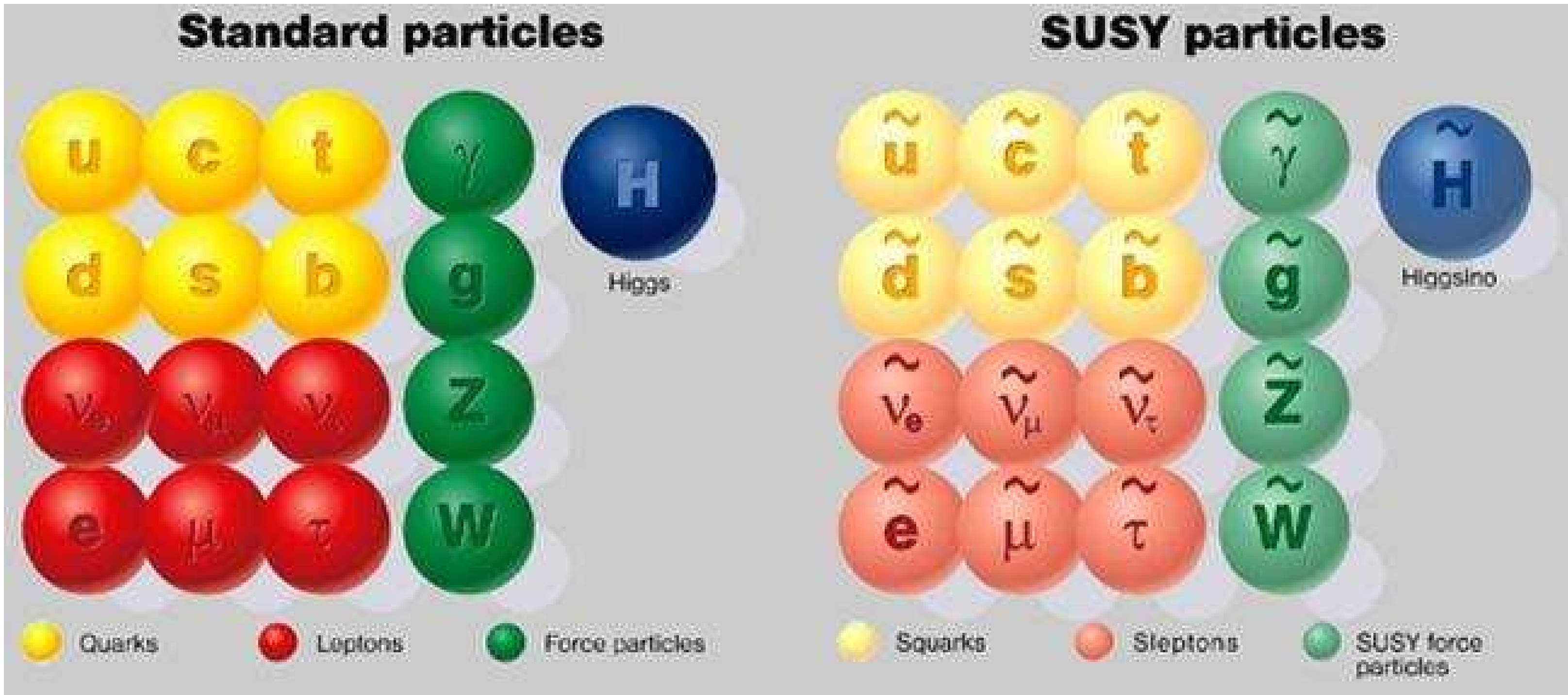
Supersymmetry (SUSY)

Hypothesis: Fermions and bosons exist in pairs:

$$Q|\mathrm{F}\rangle = |\mathrm{B}\rangle; \quad Q|\mathrm{B}\rangle = |\mathrm{F}\rangle \qquad m_B = m_F$$

Identical particles, just spins different

Broken at low energy, partners: much larger mass?



SUSY should solve many problems

SUSY: Higgs sector

2 Higgs doublets ⇒ masses to upper and lower fermions

Extended left–right asymmetry:

$m_L = m_R$, but $\tilde{m}_L \neq \tilde{m}_R$

Question: Why should the scalar SUSY partners of the left- and right-polarized SM fermions be distinctly different particles with different masses?

8 Higgs fields ⇒ 5 Higgs bosons: $\mathbf{h^0, H^0, A^0, H^\pm}$

Higgs parameters: tan$\beta = v_1/v_2$, masses

Question: How can the two Higgs (BEH) doublet fields result in five Higgs-bosons? Why do the 5 Higgs bosons have four higgsino partners (and not five) in the SUSY space?

LSP = dark matter?

SUSY's quantum number: R parity $R = (-1)^{3B-L+2S}$

(B: baryon charge, L: lepton charge, S: spin)

$R = +1$ particle, $R = -1$ SUSY partner

Parity-like: $R^2 = +1$

If R conserved, lightest SUSY particle (LSP) is stable

R parity may not be much violated: we would detect LSP decays

Neutral LSP: excellent dark matter candidate

Minimal Supersymmetric SM

Electroweak symmetry breaking $\Rightarrow$
MSSM-fermions mix into mass eigenstates

{Electroweak gauginos + higgsinos} $\Rightarrow$ {charginos and neutralinos }

$$\left\{\tilde{\mathbf{B}}(=\tilde{\gamma}), \tilde{\mathbf{W}}^{\pm}, \tilde{\mathbf{W}}^{0}(=\tilde{\mathbf{Z}}); \tilde{\mathbf{h}}^{0}, \tilde{\mathbf{H}}^{0}, \tilde{\mathbf{H}}^{\pm}\}\right\} \Rightarrow \left\{\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^{\pm}; \tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0\right\}$$

(mass grows with index) Question: gluinos do not mix?

Lightest SUSY particle (LSP) depends on model, e.g. $\tilde{\chi}_1^0$

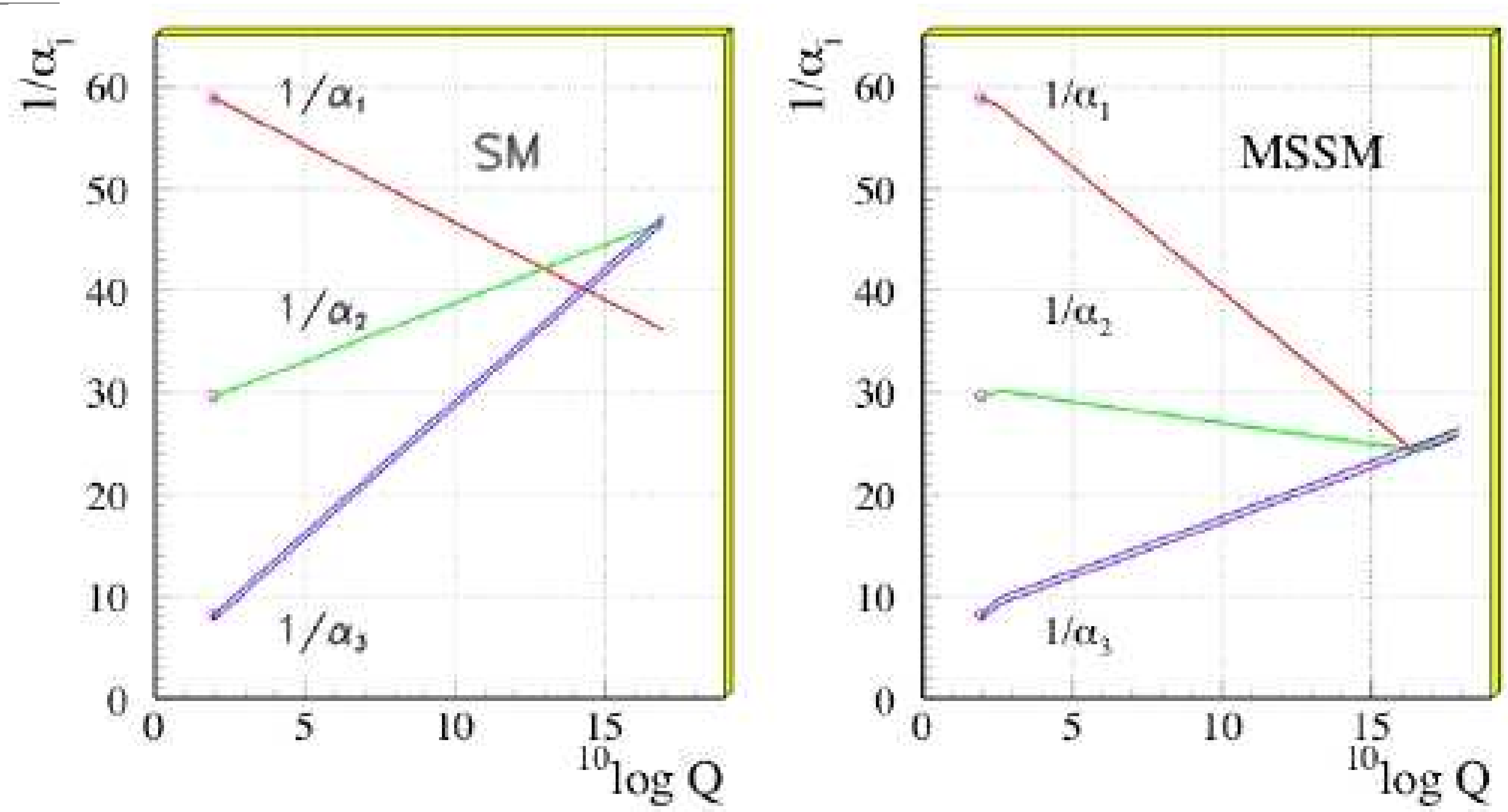
SUSY breaking (how?) $\Rightarrow$ many (> 100) new parameters
masses, couplings, mixing angles
Lots of model variants, huge parameter space, different constraints.
hMSSM: $m(\mathrm{h}) = 125$ GeV (with corrections!)

Questions: Why should neutralinos be Majorana particles (their own antiparticles)? What should prevent the LSP as dark matter to make dark galaxies and black holes?

The missing MSSM menagerie

Kind	spin	R parity	gauge eigenstate	mass eigenstate
Higgs bosons	0	+1	$\mathbf{H_1^0, H_2^0, H_1^+, H_2^-}$	$\mathbf{h^0, H^0, A^0, H^\pm}$
squark	0	-1	$\tilde{u}_L, \tilde{u}_R, \tilde{d}_L, \tilde{d}_R$ $\tilde{s}_L, \tilde{s}_R, \tilde{c}_L, \tilde{c}_R$ $\tilde{t}_L, \tilde{t}_R, \tilde{b}_L, \tilde{b}_R$	same same $\tilde{t}_1, \tilde{t}_2, \tilde{b}_1, \tilde{b}_2$
slepton	0	-1	$\tilde{e}_L, \tilde{e}_R, \tilde{\nu}_e$ $\tilde{\mu}_L, \tilde{\mu}_R, \tilde{\nu}_\mu$ $\tilde{\tau}_L, \tilde{\tau}_R, \tilde{\nu}_\tau$	same same $\tilde{\tau}_1, \tilde{\tau}_2, \tilde{\nu}_\tau$
neutralino	1/2	-1	$\tilde{B}^0, \tilde{W}^0, \tilde{H}_1^0, \tilde{H}_2^0$	$\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0$
chargino	1/2	-1	$\tilde{W}^\pm, \tilde{H}_1^+, \tilde{H}_2^-$	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^\pm$
gluino	1/2	-1	$\tilde{g}$	same
goldstino gravitino	1/2 3/2	-1	$\tilde{G}$	same

SUSY: coupling constants



Minimal Supersymmetric Standard Model: Unification!

Bend at low energies: SUSY enters with many new particles $\Rightarrow$ more loop corrections

MSSM mass spectrum: preconceptions

Even if we remain sceptic it is worthwhile to know what do most of the model constructors think (after S.P. Martin)

- R parity is barely violated
- LSP: $\tilde{\chi}_1^0$ or gravitino
- Gluino mass $M_3 \equiv m(\tilde{g}) \gg m(\tilde{\chi}_1^0), m(\tilde{\chi}_2^0), m(\tilde{\chi}_1^\pm)$
- $m(\tilde{u}_i) \sim m(\tilde{d}_i) \sim m(\tilde{c}_i) \sim m(\tilde{s}_i) \gg m(\tilde{\ell}_i)$
- $m(\tilde{u}_i) \sim m(\tilde{d}_i) \sim m(\tilde{c}_i) \sim m(\tilde{s}_i) > (0,6_{\mathrm{MSUGRA}} \ldots 0,8_{\mathrm{GMSB}}) m(\tilde{g})$
- $m(\tilde{u}_L) \geq m(\tilde{u}_R) \ldots m(\tilde{s}_L) \geq m(\tilde{s}_R)$ and $m(\tilde{e}_L) \geq m(\tilde{e}_R), m(\tilde{\mu}_L) \geq m(\tilde{\mu}_R)$ as $M_L^2 \sim M_R^2 + 0,5 m_{1/2}^2$.
- $\tilde{\mathrm{t}}_1, \tilde{\mathrm{b}}_1$ lightest squarks and $\tilde{\tau}_1$ lightest charged slepton (mixing, Higgs coupling)
- $m(\mathrm{h}^0) \lesssim 150$ GeV $\ll m(\mathrm{A}), m(\mathrm{H}^\pm), m(\mathrm{H}^0)$

SUSY search

Production in pairs, decay to other SUSY particle
(if R conserved)

Lightest (LSP) stable, neutral, not observable

Signal: missing energy

Hypothetical SUSY decays (LSP = $\tilde{\chi}_1^0$):

- squark: $\tilde{q} \rightarrow q + \tilde{g}; \quad q + \tilde{\chi}_1^0$
- slepton: $\tilde{\ell} \rightarrow \ell + \tilde{\chi}_1^0$
- gluino: $\tilde{g} \rightarrow q + \overline{q} + \tilde{\chi}_1^0; \quad g + \tilde{\chi}_1^0$
- wino: $\tilde{W} \rightarrow e + \nu_e + \tilde{\chi}_1^0$

Simplified Models

Few on-shell particles, simple topology and decays

Not model-independent, but possibly associated with several models.

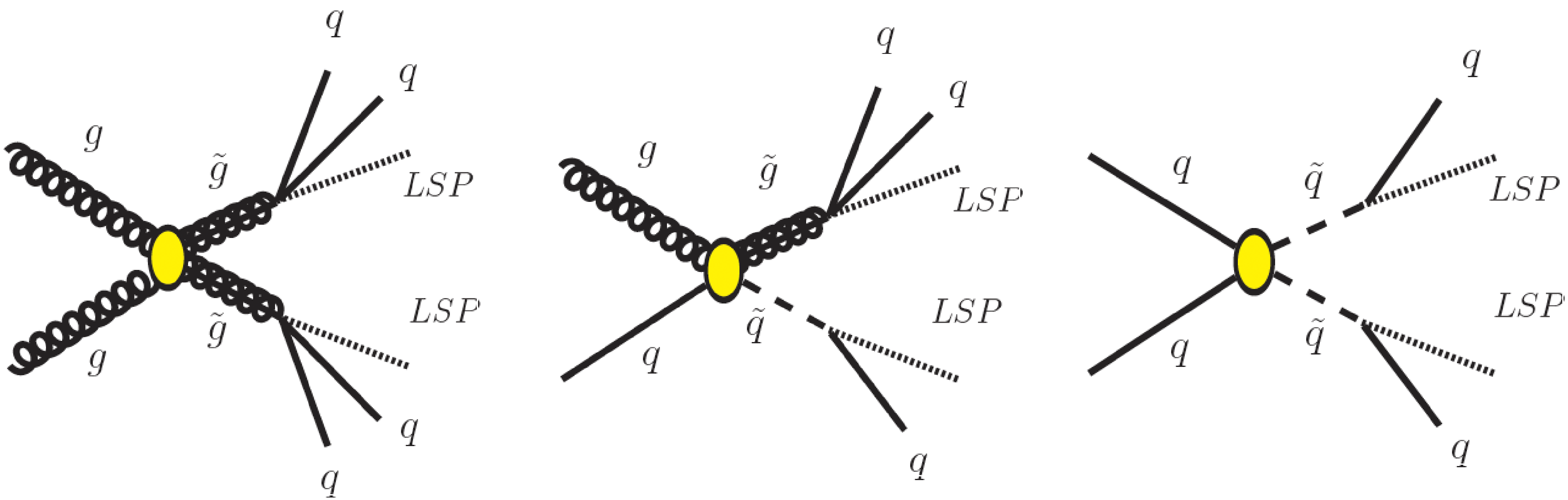
Possible new physics on well understood SM-base

What can we learn of such analysis?

- Boundaries of search sensitivity, both for data analysis and for new theories.
- Characterizing new physics signals: what models can be associated?
- Limits on more general models: from possible cross-sections.

Simplified models for SUSY searches

Basic topologies with no lepton and missing energy
(signal of Lightest SUSY Particle, LSP):



gg → g̃g̃
→ 2(qq + LSP)

qg → q̃g̃
→ qqq + 2 LSP)

qq → q̃q̃
→ qq +2 LSP)

and we can add one or more leptons.

Negative search results confirm the SM

Search methods: examples

- α_T search for early discovery in (forced) 2-jet events ($E_T(J_1) > E_T(J_2)$):
  Cut $\alpha_T = \frac{E_T(J_2)}{M_T(J_1,J_2)}$
  $= \frac{E_T(J_2)}{\sqrt{(E_T(J_1)+E_T(J_2))^2-(p_x(J_1)+p_x(J_2))^2-(p_y(J_1)+p_y(J_2))^2}}$
  Exclusive 2-jet, inclusive 3-jet search
- Jets + $\not{H}_T$ for > 2 jets, inclusive
  Scalar mom. sum: $H_T = \sum_i |\underline{p}_T(J_i)|$;
  Missing transverse mom.:
  $MHT = \not{H}_T = |-\sum_i \underline{p}_T(J_i)|$
- Razor search: test kinematic consistency for pair production of heavy particles
  Two jets (inv. mass M_R) + 0 or 1 lepton

Experimental limits, constraints

No SUSY phenomenon observed, the data limit the parameter space

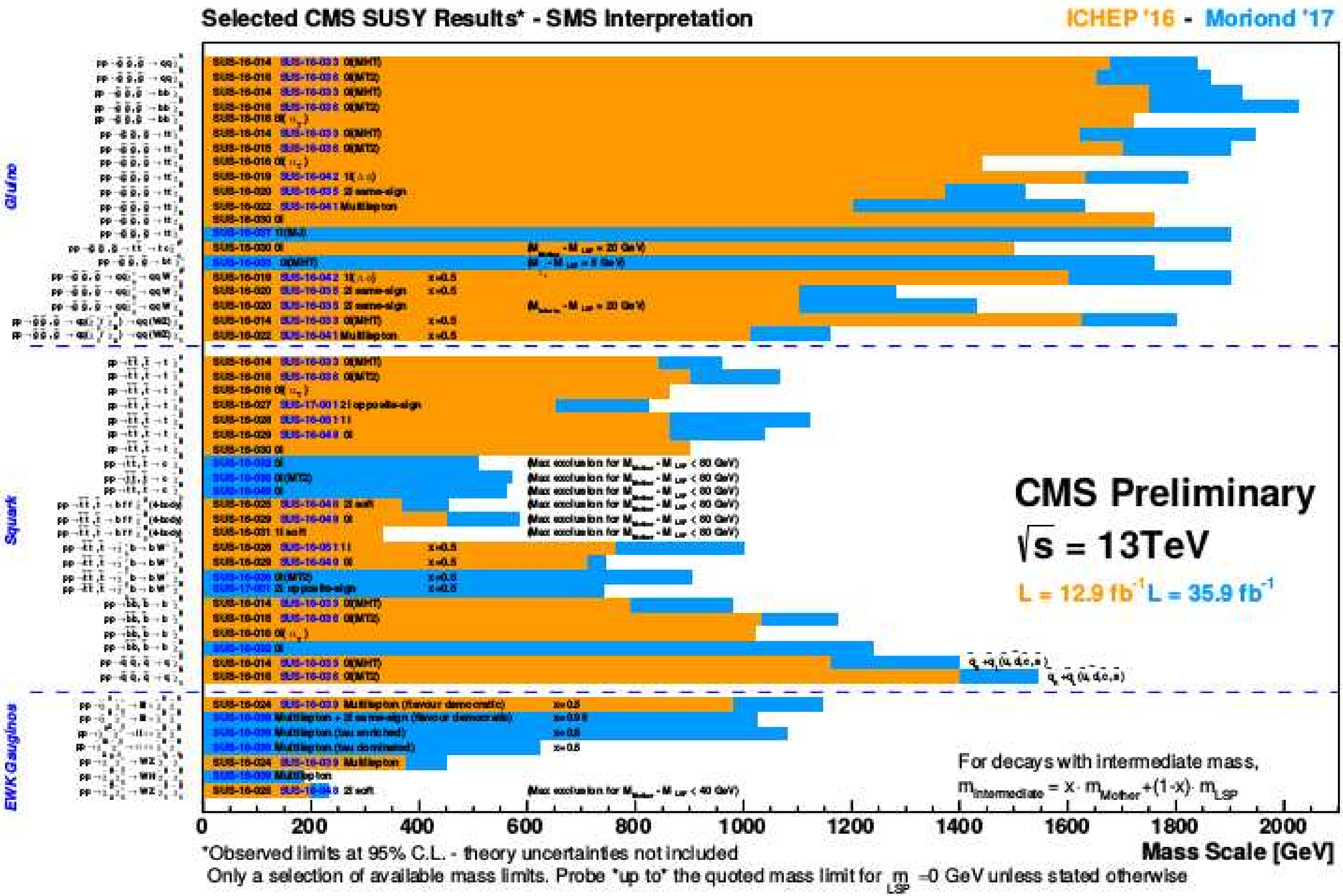
- LEP, Tevatron, LHC: Higgs sector
  - Mass of SM Higgs from direct searches
    $M_{\mathrm{H}} = 125$ GeV; $\mathbf{H} \sim \mathbf{h}^0$
  - Fitting electroweak data
  - Search for neutral Higgs bosons (h and A)
- $BR(\mathrm{b}\rightarrow\mathrm{s}\gamma)$ measurements at B-factories
- Anomalous magnetic moment of the muon (BNL)
- Satellite expts WMAP and Planck:
  density of dark matter (DM), indirect
- Direct searches for DM with ν-detectors and AMS2

Natural SUSY?

- Light ($\sim 1\,$TeV) SUSY particles help to eliminate the hierarchy problem and keep the lightest Higgs-boson light ($\mathbf{\tilde{h}^0_{MSSM} = H_{SM}}$).
- Heavy SUSY particles add huge 2nd-order (log) corrections, ruining the hierarchy elimination.
- Unfortunately, naturalness is less and less probable as the lower limits on SUSY masses grow.

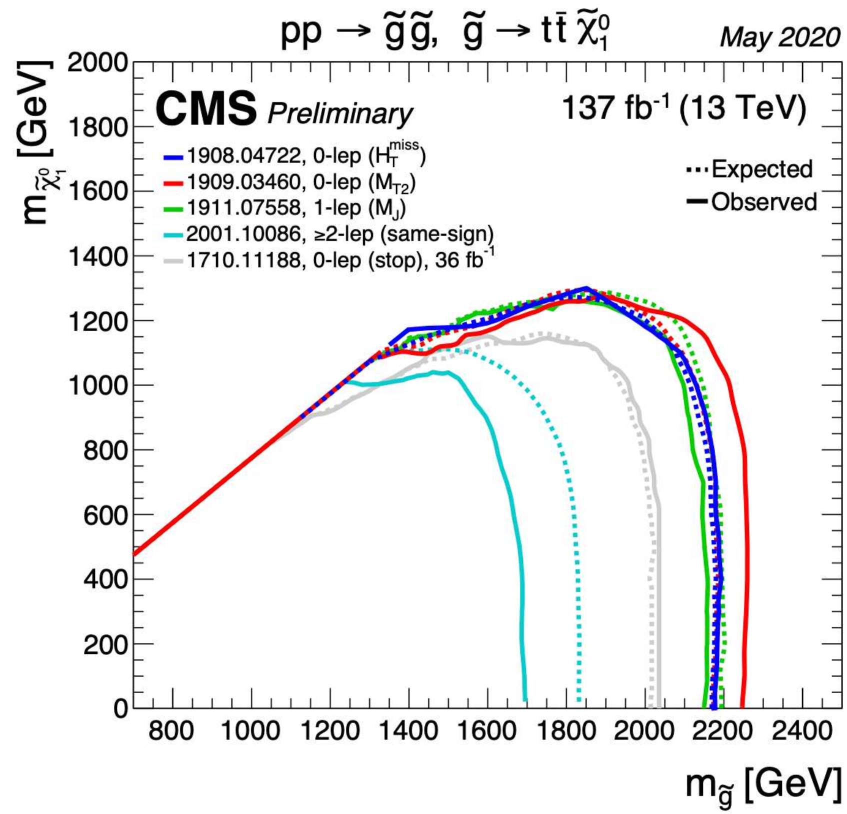
E.g., $\mathrm{\tilde{t}}$ is assumed to be the lightest squark, now having $m(\mathrm{\tilde{t}}) \gtrsim 1\,$TeV, and a possible decay of the gluino is to $\mathrm{t\tilde{t}}$...

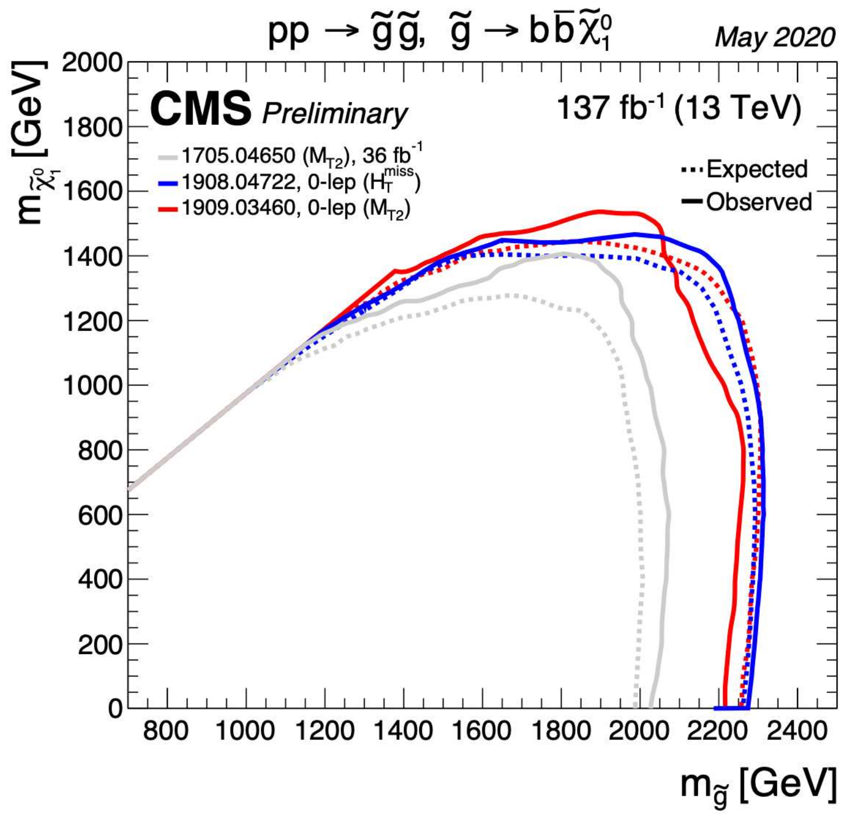
CMS SUSY summary plot, 2017



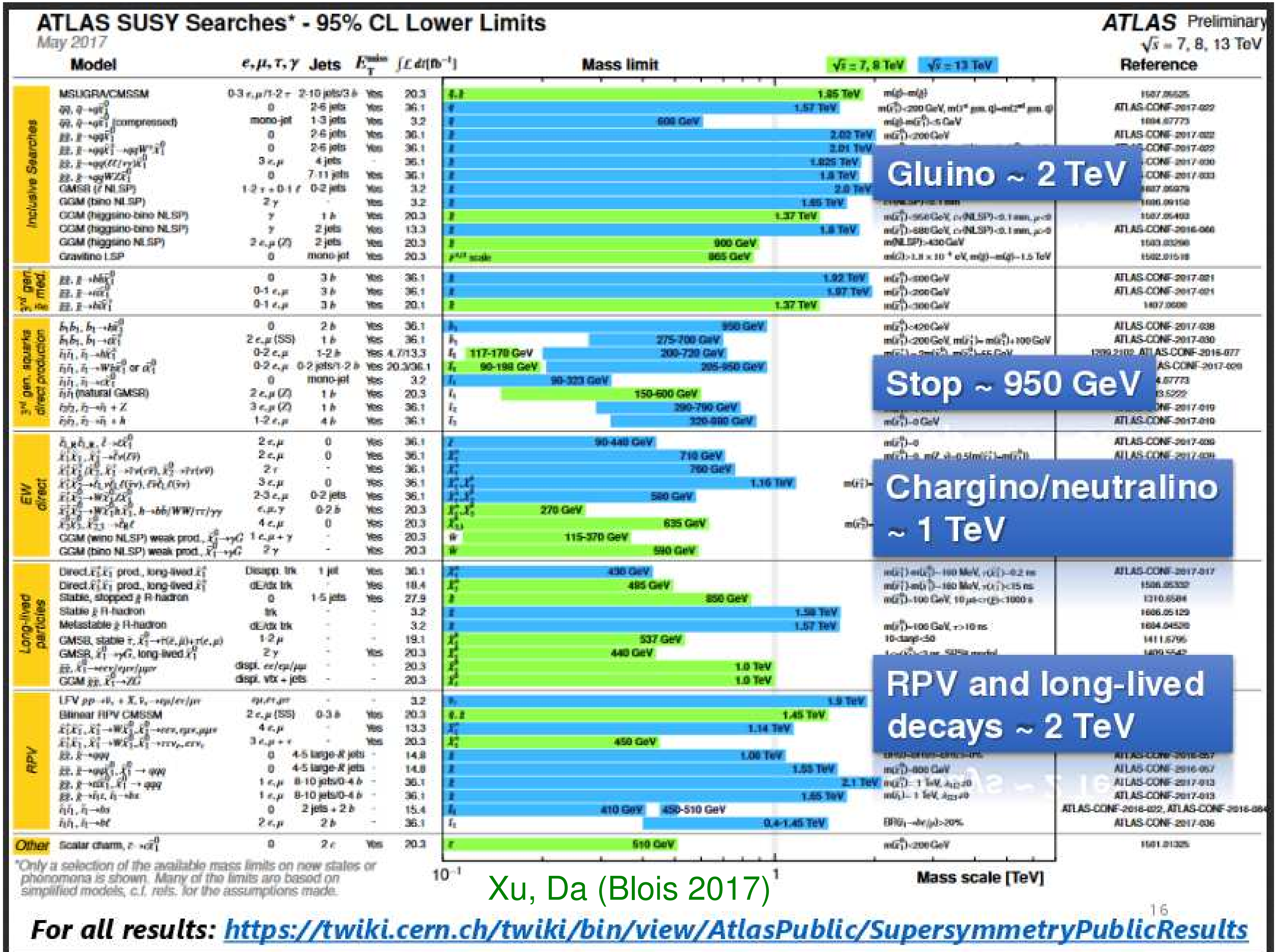
Simplified Model Spectrum (SMS) topologies

CMS limits, 2020: gluino pairs

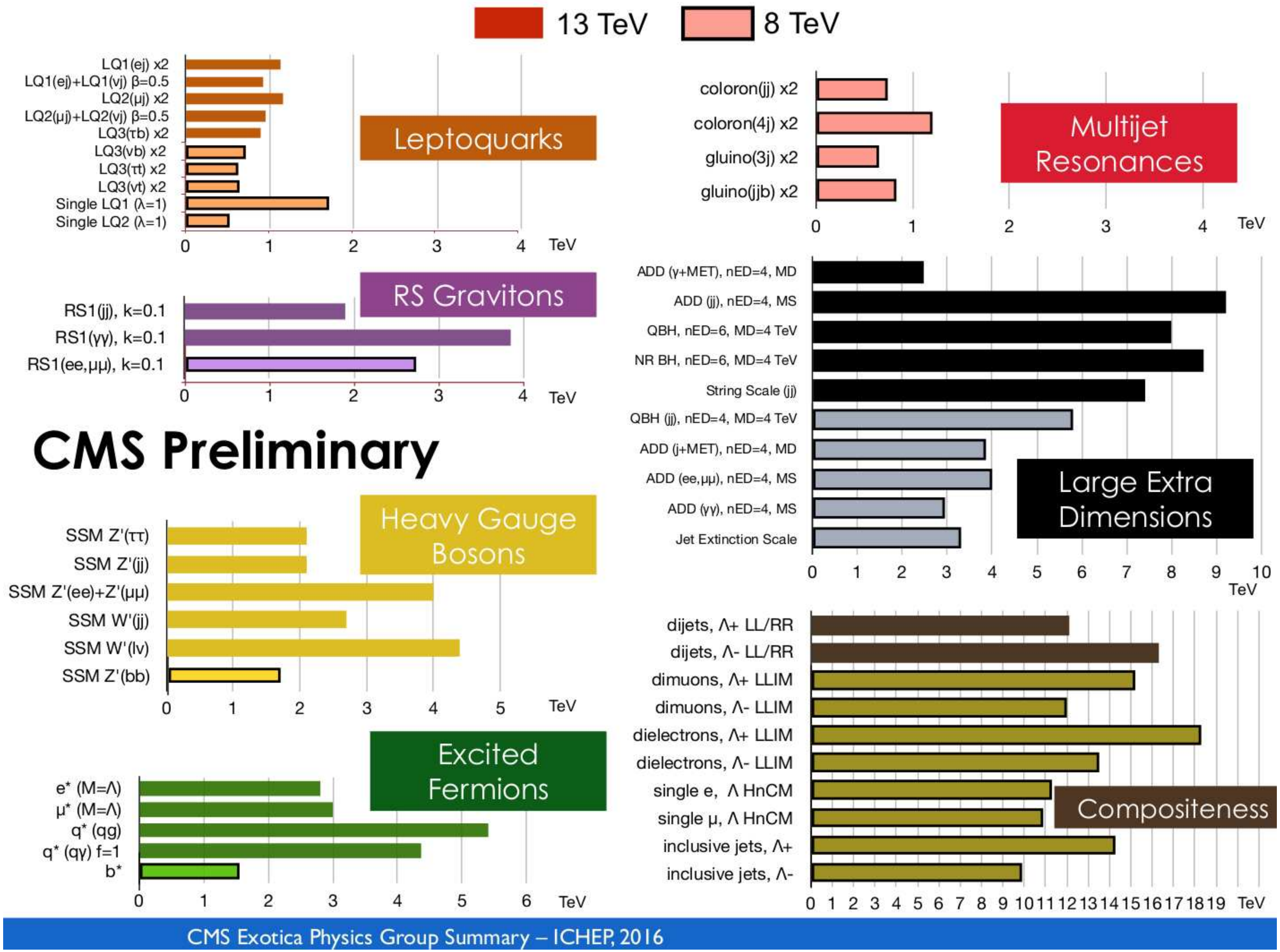




ATLAS SUSY summary plot, 2017

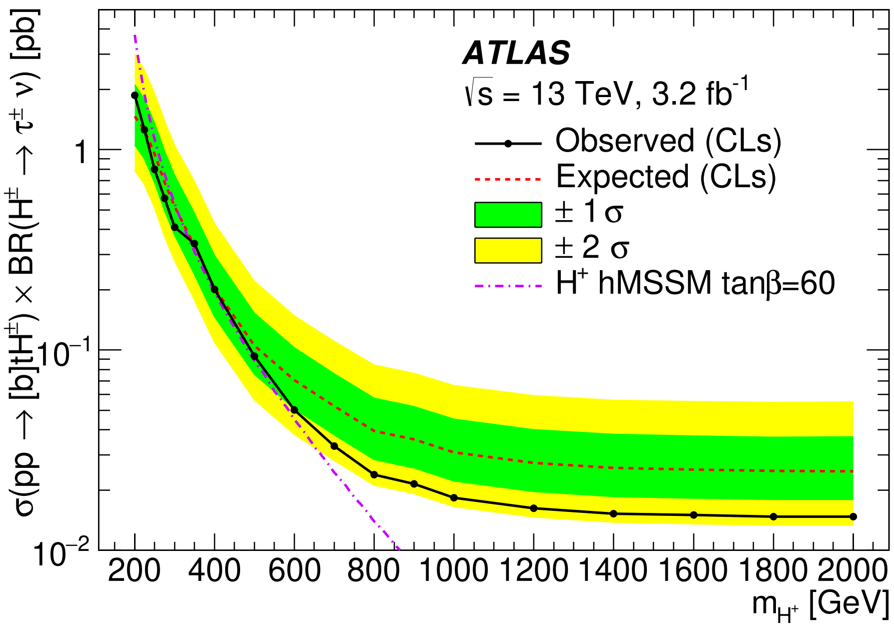


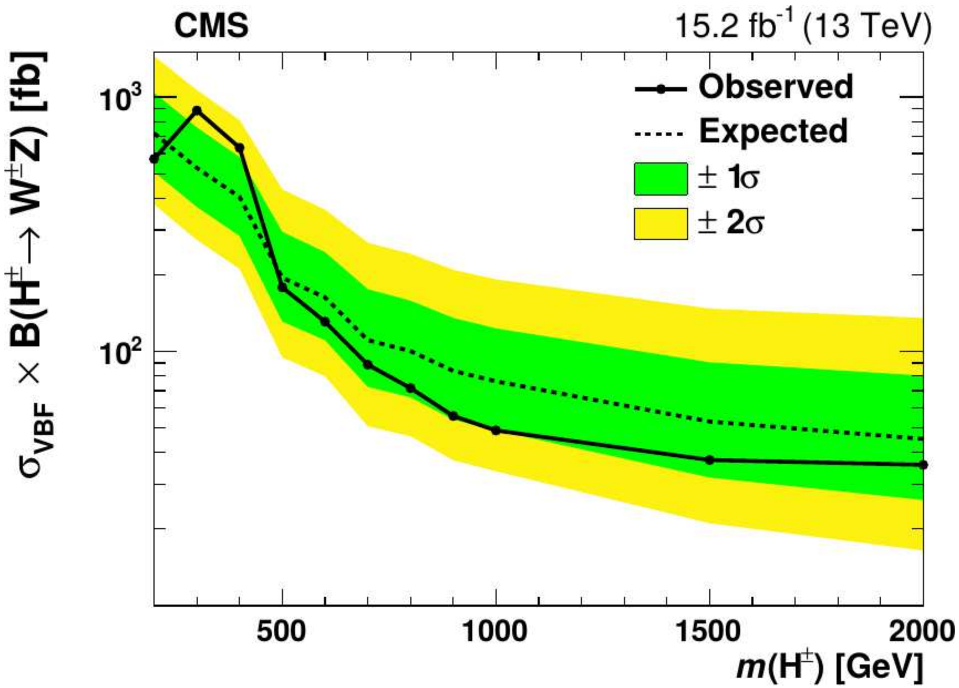
CMS: search for exotica



Search for charged Higgs bosons

Just two examples from the 13 TeV exclusion plots





M. Aaboud *et al.* [ATLAS Collaboration], *Search for charged Higgs bosons produced in association with a top quark and decaying via $H^{\pm} \to \tau\nu$ using pp collision data recorded at $\sqrt{s} = 13$ TeV by the ATLAS detector*, Phys. Lett. B **759** (2016) 555

A. M. Sirunyan *et al.* [CMS Collaboration], *Search for charged Higgs bosons produced in vector boson fusion processes and decaying into a pair of W and Z bosons using proton-proton collisions at sqrt(s) = 13 TeV*, arXiv:1705.02942 [hep-ex].

$\mathbf{b \to s\gamma}$: FCNC decay

Flavour-changing neutral current, forbidden in SM

Pure loop effect

New physics could affect

CLEO, BELLE, BABAR:

$$\frac{\Gamma(b\to s\gamma)}{\Gamma(b\to Xe\nu)} = \left(3,35\,{}^{+0,50}_{-0,44}\right) \times 10^{-3}$$

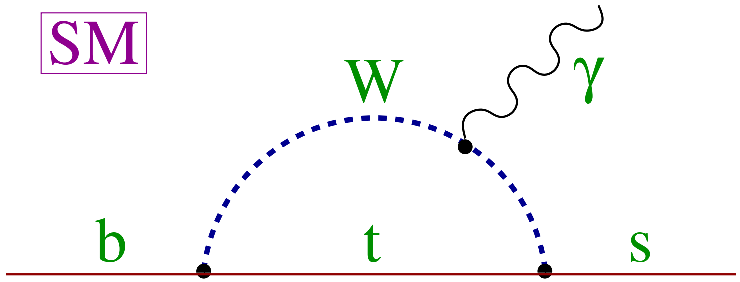
SM: $(3,22 \pm 0,09) \times 10^{-3}$

Agrees with SM

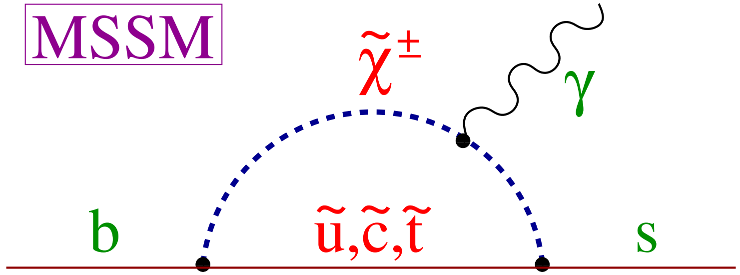
$\Downarrow$

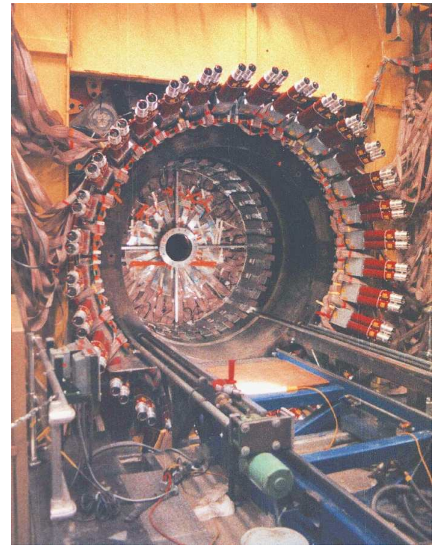
limits MSSM

SM



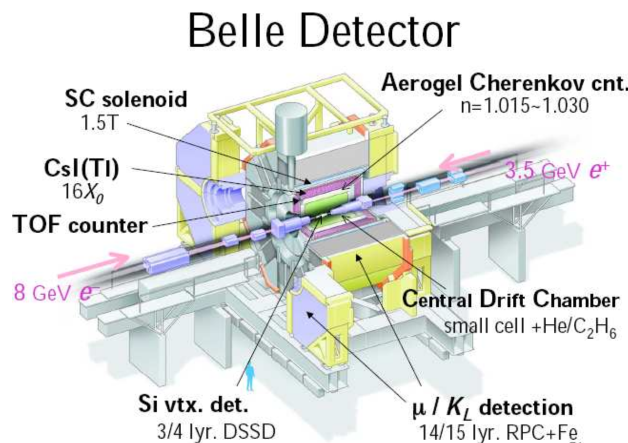
MSSM





CLEO, Cornell

BABAR, Stanford



BELLE, Tsukuba

CMS $H \to \gamma\gamma$ in *The Big Bang Theory*

It would be nice if in the (not too distant) future we could see an observed SUSY event in a popular TV show!

Conclusion

- We have observed **the** Standard Model Higgs boson or (unfortunately, much less probably) a Higgs boson of a more general model.
- All measured properties are consistent with the predictions for the SM Higgs-boson with a mass of 125 GeV.
- Let us hope for some deviation from the Standard Model (although none seen yet).
- The simplest SUSY models do not seem to be supported by experimental data (g-2, LEP, WMAP, LHC, ...)
- We are looking for and hoping to find new physics (SUSY, Dark Matter, extra Higgs bosons, ...) at the LHC.

Thanks for your attention!