Broken symmetries in particle physics

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Outline

- Symmetries and conservation laws
- CPT invariance and antimatter
- Broken mirror symmetries: P, CP, T
- Global and local gauge invariance
- Spontaneous symmetry breaking and masses
- Open problems of the Standard Model
- New physics? Supersymmetry?
- Plans and hopes at LHC

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Symmetries in Particle Physics

Wigner's name is associated with symmetries in physics

The particle theory, the Standard Model, is based on symmetries

- Continuous symmetries ⇒ conservation laws (Noether's theorem):
  - space-time shift and rotation ⇒ momentum, energy and angular momentum conservation
  - Spin SU(2), Dirac U(1) and colour SU(3) gauge symmetries ⇒ conservation of spin, fermion current and colour charges (source of strong interaction)
- Discrete symmetry: CPT (simultaneous Charge conjugation, Parity switch and Time reflection)

Standard Model: Three interactions are derived of local gauge symmetries, strong from local SU(3) and electroweak from local U(1)⊗SU(2) gauge invariance with spontaneous symmetry breaking.

E. P. Wigner on gauge invariance

In quantum theory, invariance principles permit even further reaching conclusions than in classical mechanics.

HOWEVER:

This qauge invariance is, of course, an artificial one, similar to that which we could obtain by introducing into our equations the location of a ghost. The equations must then be invariant with respect to changes of coordinates of that ghost. One does not see, in fact, what good the introduction of the coordinates of the ghost does.

E. P. Wigner: *Symmetries and Reflections*,
as quoted by David J. Gross, *Symmetry in Physics: Wigner's Legacy*, Physics Today **48N12** (1995) 46.

CPT invariance

Basic assumption of field theory:

$CPT|\mathrm{p}(\boldsymbol{r},\boldsymbol{t})\rangle \sim |\overline{\mathrm{p}}(-\boldsymbol{r},-\boldsymbol{t})\rangle \sim |\mathrm{p}(\boldsymbol{r},\boldsymbol{t})\rangle$

meaning free antiparticle

$\sim$

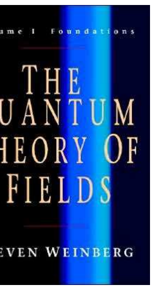
particle going backwards in space and time.

Giving up CPT one has to give up:

- locality of interactions ⇒ causality, or
- unitarity ⇒ conservation of matter, information,
- ... or Lorentz invariance

Motivation to doubt:

- Asymmetric Universe: no antimatter galaxies



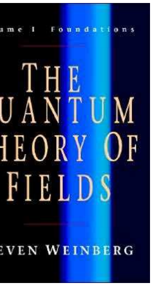
Broken (violated) symmetries

„.. the fundamental equations of physics have more symmetry than the actual physical world does”

Frank Wilczek: *In search of symmetry lost,*
Nature **433** (2005) 239

„Accidental symmetries” Steven Weinberg

- Parity (P, CP), flavour-SU(2) in weak interaction
- Electroweak BEH-mechanism
- Supersymmetry??



The Standard Model

Derive 3 interactions of local $U(1)$, $SU(2)$ and $SU(3)$ symmetries

Unify and separate e-m $U(1)$ and weak $SU(2)$ interactions

using spontaneous symmetry breaking:

(Anderson-Englert-Brout-Higgs-

Guralnik-Hagen-Kibble (BEH) mechanism, 1963-64)

Add a 4-component, symmetry breaking field to vacuum.

Separate a good $U(1)$ local symmetry from the ruined

$$U(1) \otimes SU(2)$$

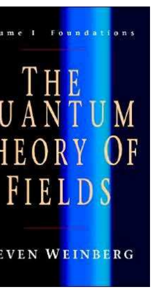
$$\Downarrow$$

electromagnetism + zero-mass photon, OK!

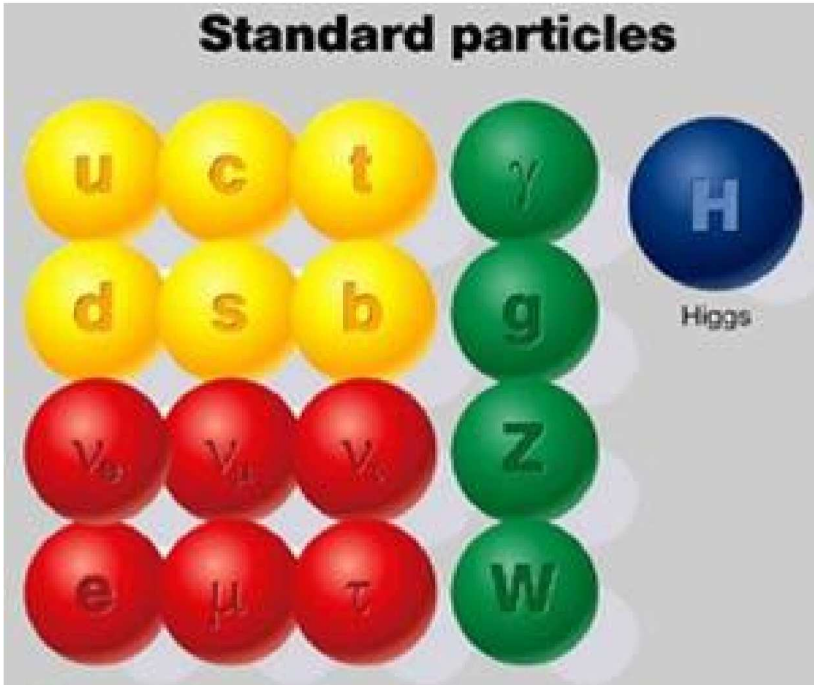
Turn 3 d.f. of BEH field to create masses for Z, W^+, W^-,

get a correct weak interaction with 3 heavy gauge bosons.

4th degree of freedom: heavy scalar Higgs boson.



The zoo of the Standard Model



3 fermion families:
1 pair of quarks and
1 pair of leptons in each

3 kinds of gauge bosons:
the force carriers

All identified and studied!

Higgs boson (M_{H} = 125 GeV)

Colour: the charge of the strong interaction
colored quarks ⇒ *colourless* **composite hadrons** of 2 kinds

hadrons = mesons ($q\bar{q}$) + baryons (qqq)

The Standard Model describes all known particles and phenomena of the microworld

Glory road of the Standard Model

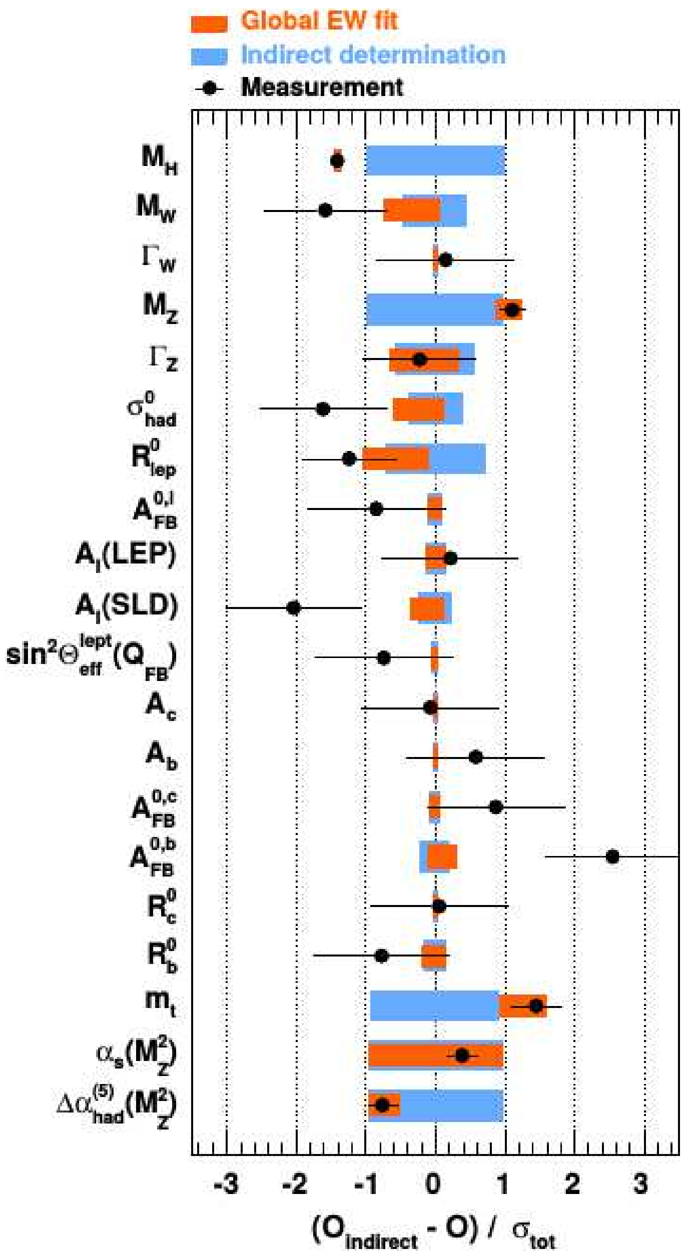
Includes hundreds of measurements of all experiments

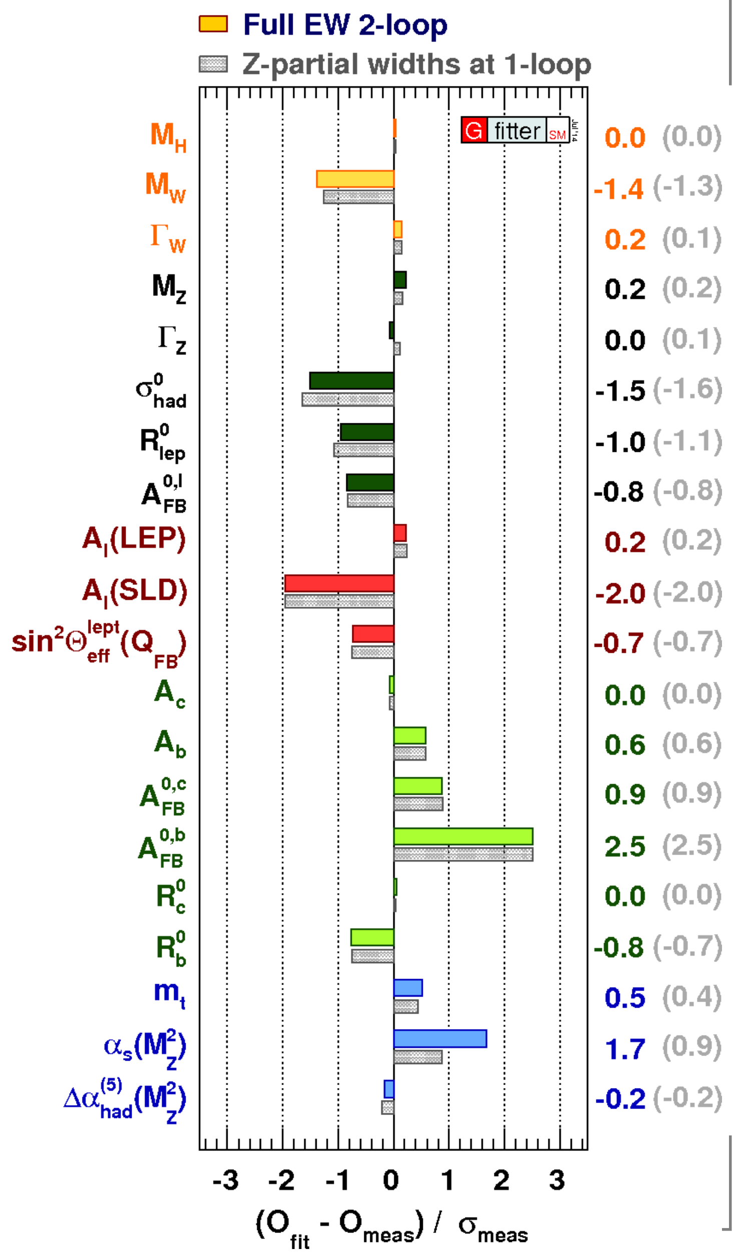
$$\frac{\text{Expt} - \text{theory}}{\text{expt. uncertainty}}$$

All within statistics

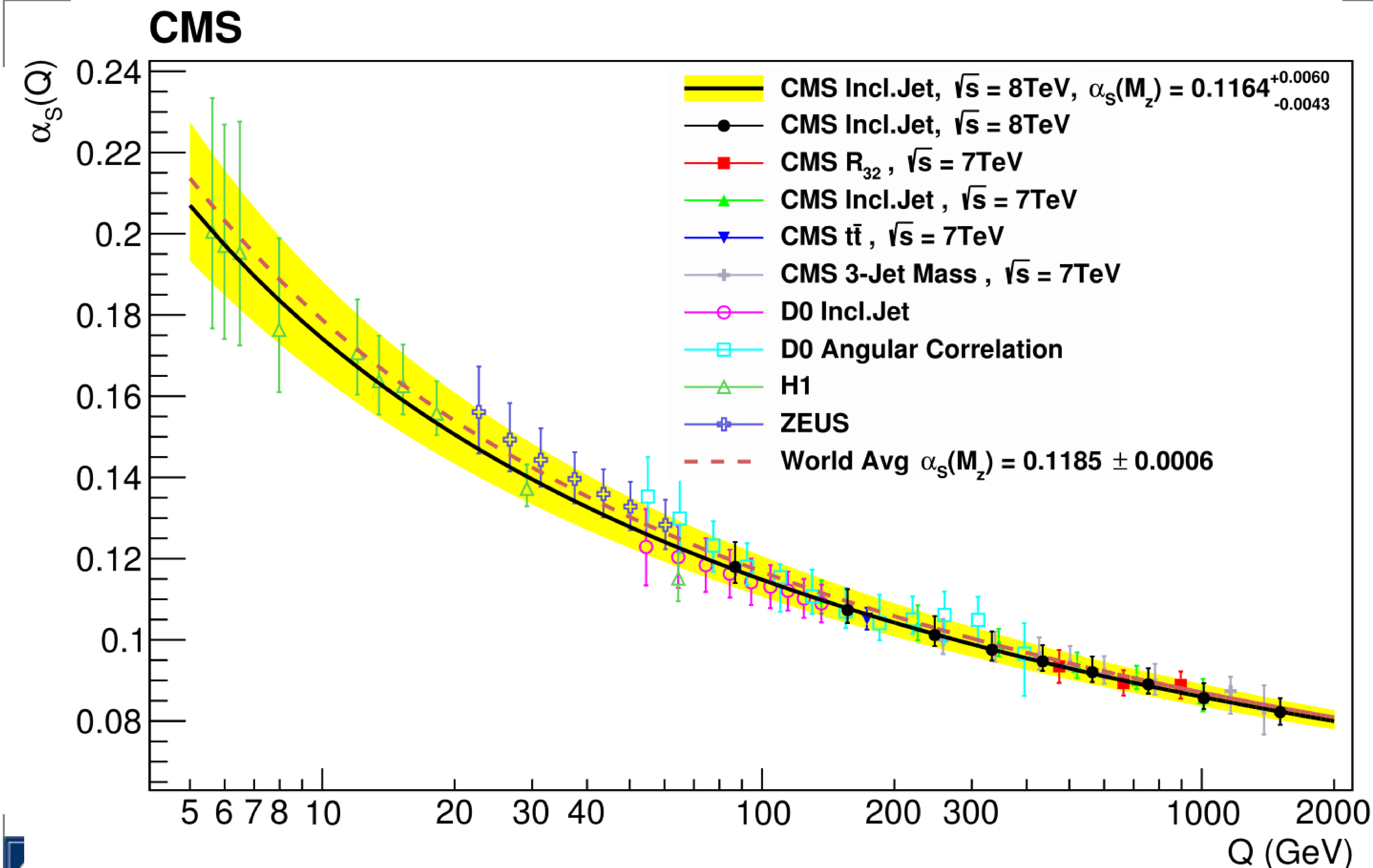
Slightly deviating quantity: forward-backward asymmetry of $e^+e^- \to Z \to b\bar{b}$

The Gfitter Group: arxiv.org:1407.3792



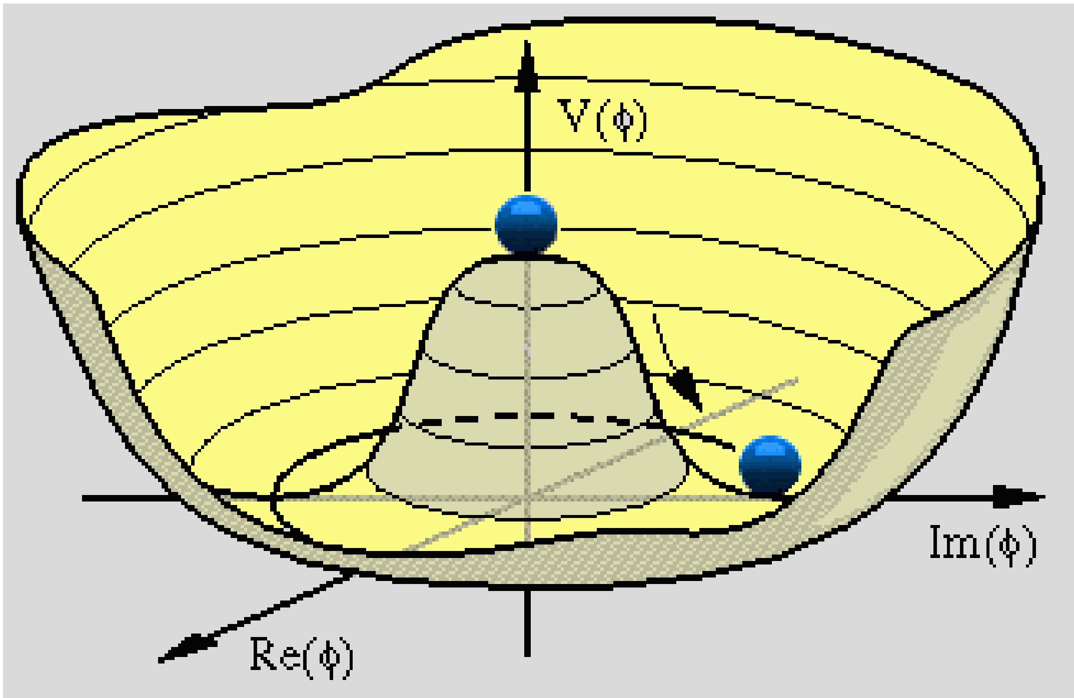


CMS, 2016: α_s running with energy



The Higgs boson of the Standard Model

Spontaneous symmetry breaking



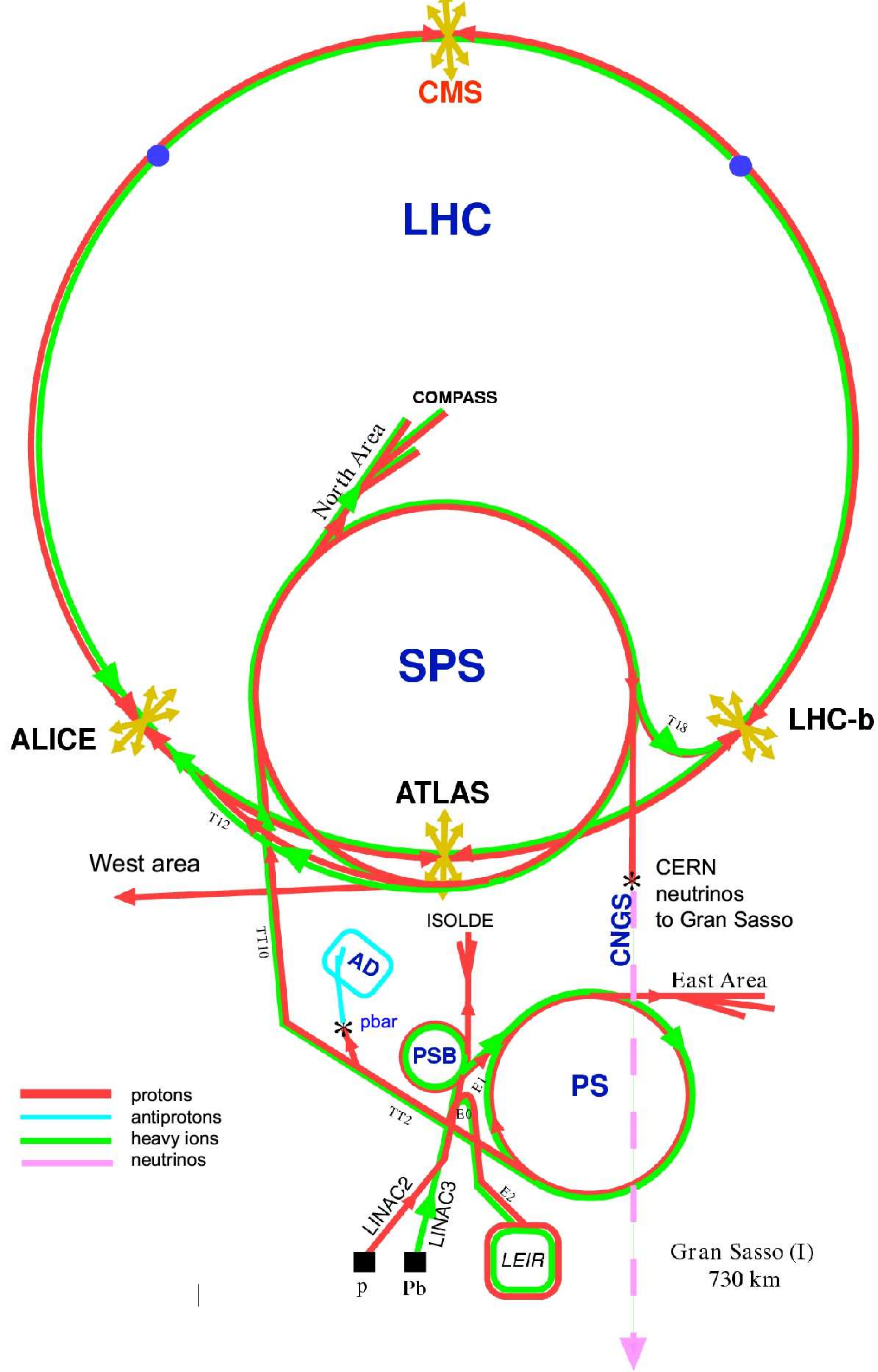
Spinless, neutral, heavy particle

The scalar particle needed for renormalisation

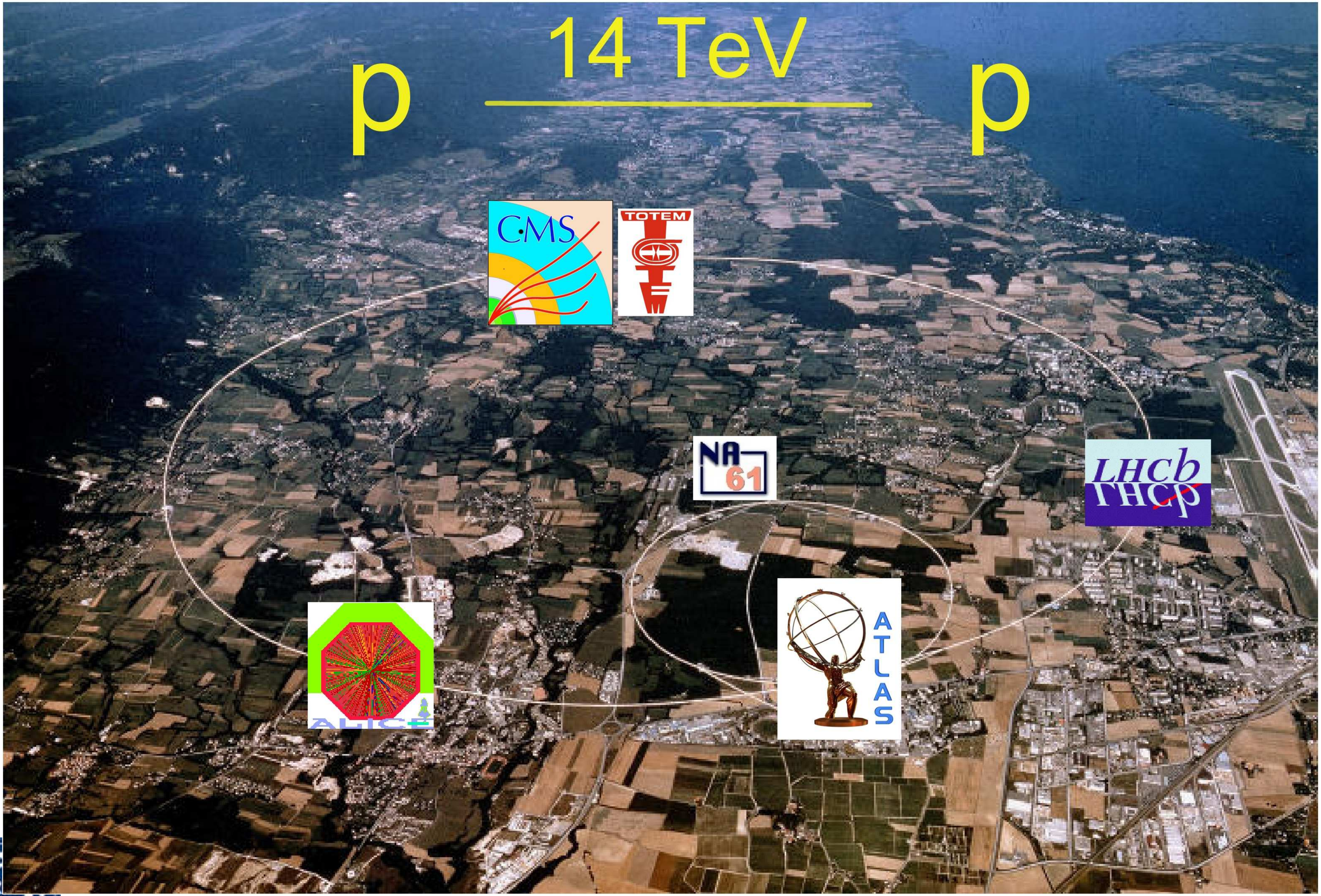
Does it really exist? SM: it must!

Accelerators of CERN

LHC:	Large Hadron Collider
SPS:	Super Proton Synchrotron
AD:	Antiproton Decelerator
ISOLDE:	Isotope Separator On Line DEvice
PSB:	Proton Synchrotron Booster
PS:	Proton Synchrotron
LINAC:	LINear ACcelerator
LEIR:	Low Energy Ion Ring
CNGS:	Cern Neutrinos to Gran Sasso



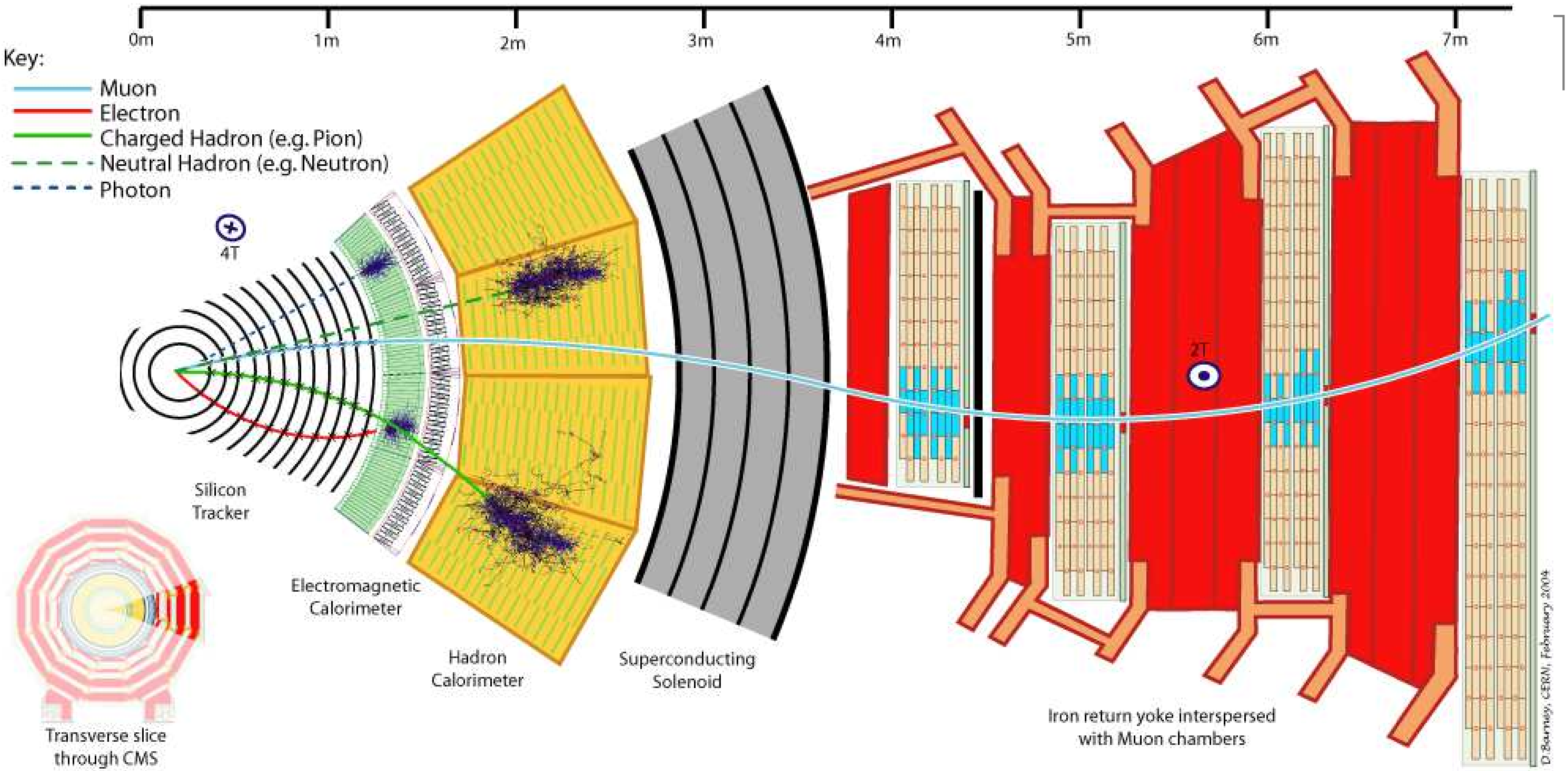
LHC and its main experiments



Dipole magnets of LHC in the tunnel

LHC is like Formula 1: boring without collisions

CMS: Compact Muon Solenoid



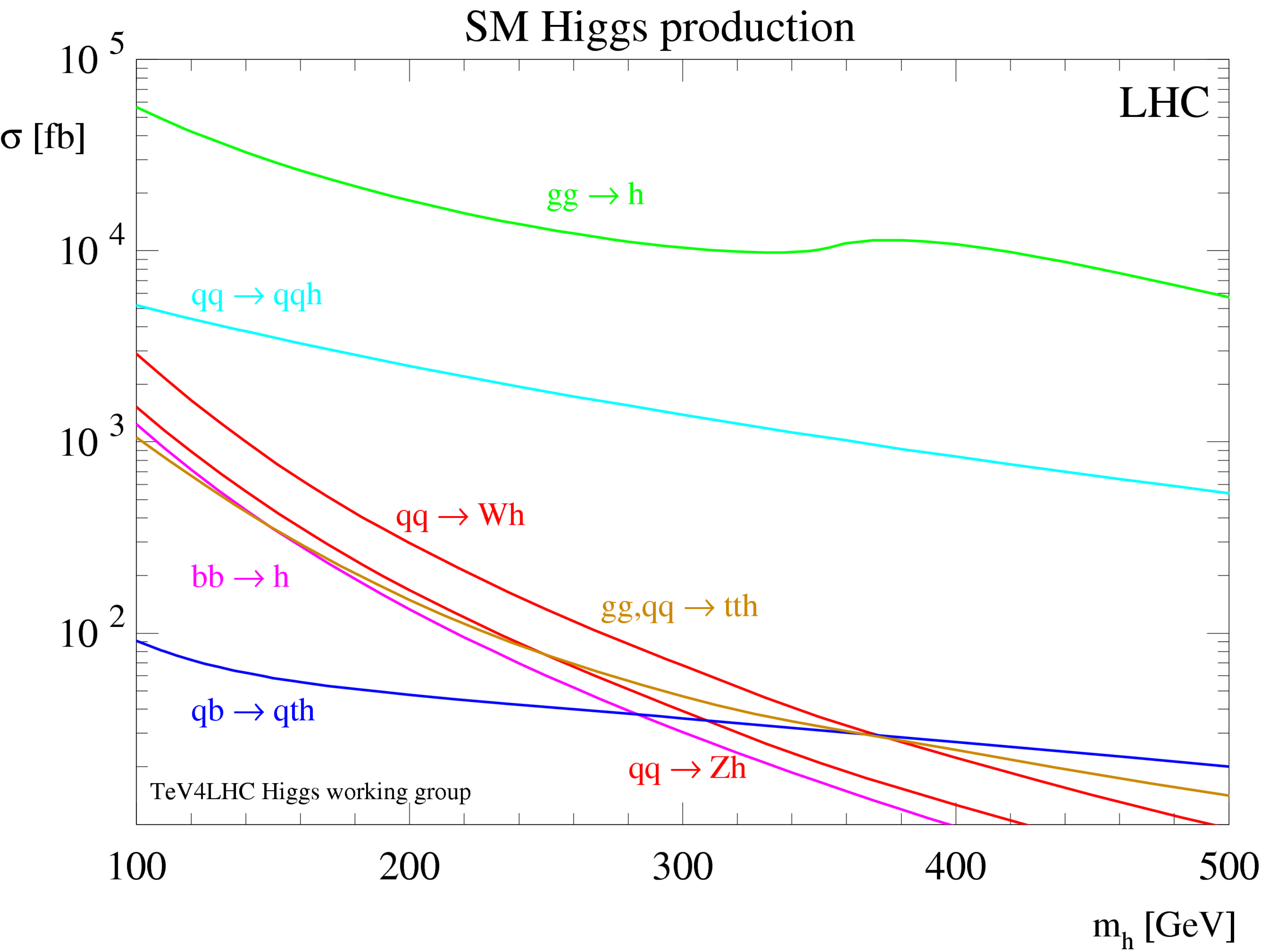
14000 ton digital camera:

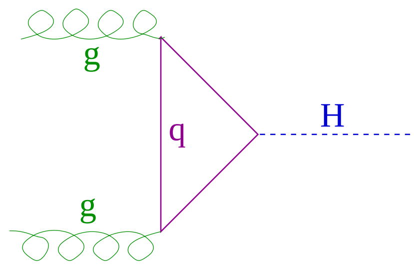
200 M pixel, 40 M pictures/sec, 1000 GB/sec data

Processes cc. 1000 pictures/sec ⇒ intelligent filter!!

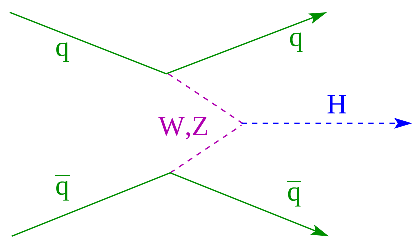
Production of the SM Higgs boson

in p-p collisions at LHC



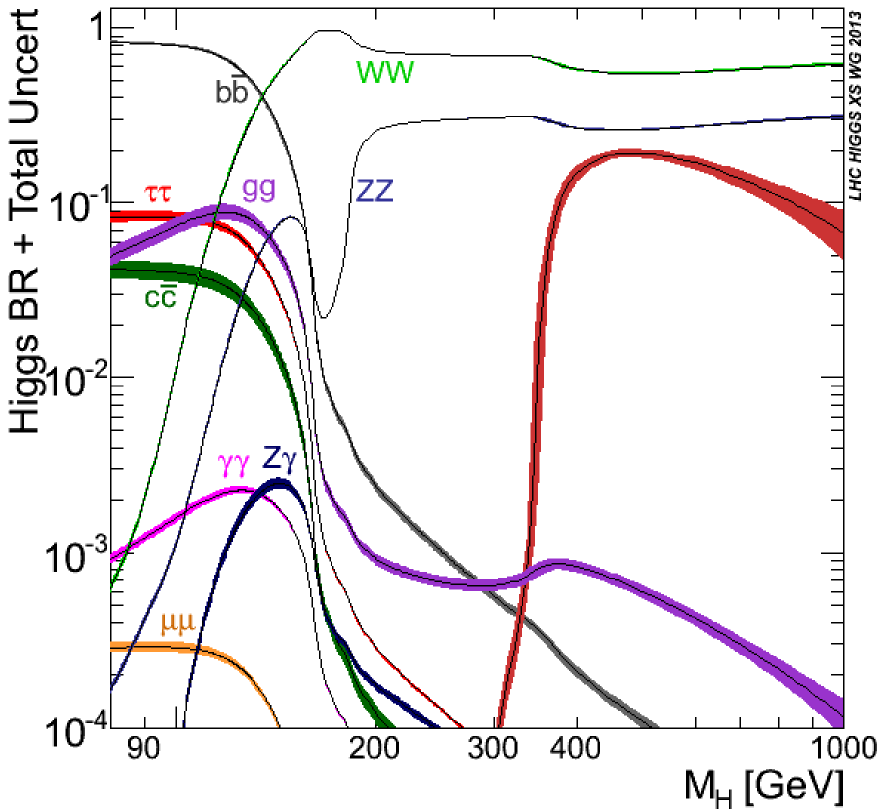


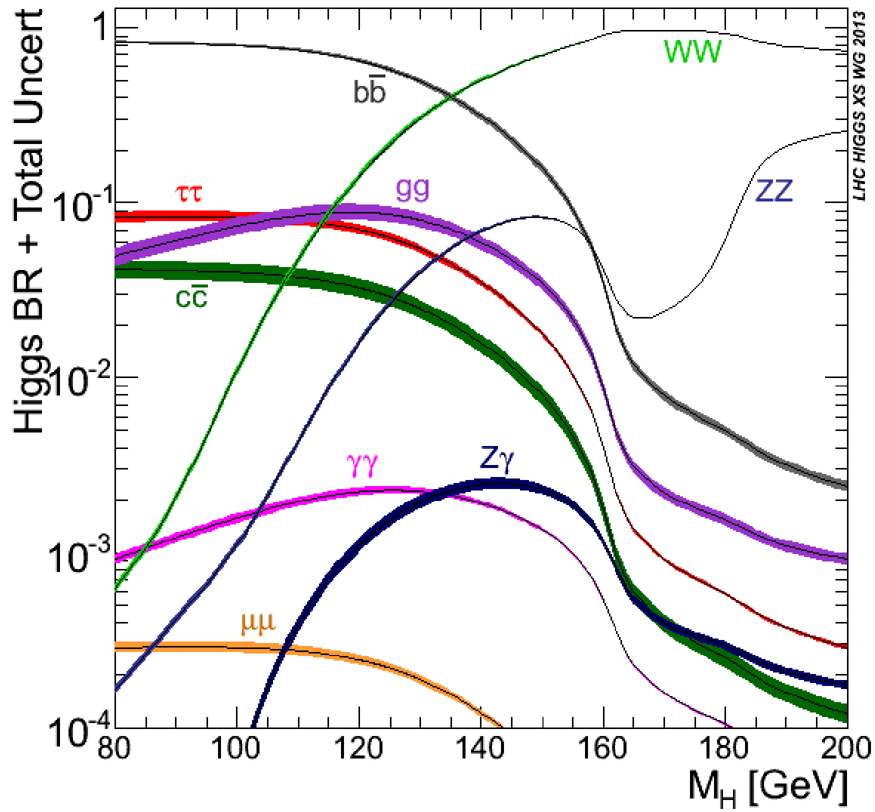
gluon fusion



vector boson fusion

Decay of the SM Higgs boson





At 125 GeV many decay processes compete.

Best identified ($\Delta M/M = 1 \cdots 2\%$):

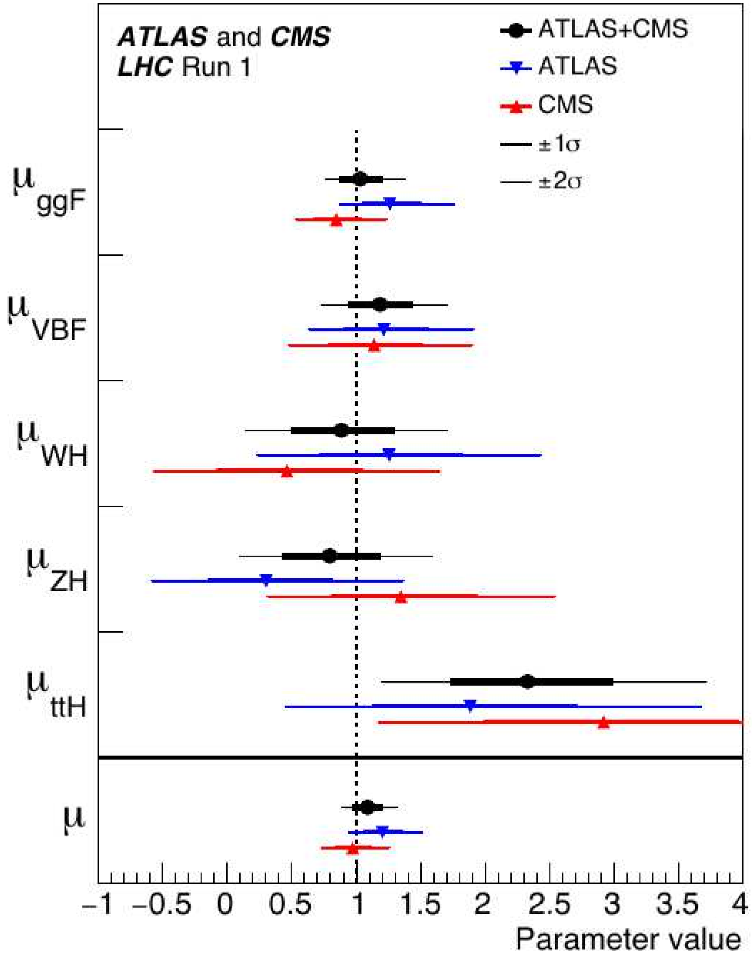
H $\rightarrow$ ZZ* $\rightarrow \ell^+\ell^-\ell^+\ell^-$ ($\ell = e, \mu$): BR = 1.24×10^{-4}, S/B > 1)

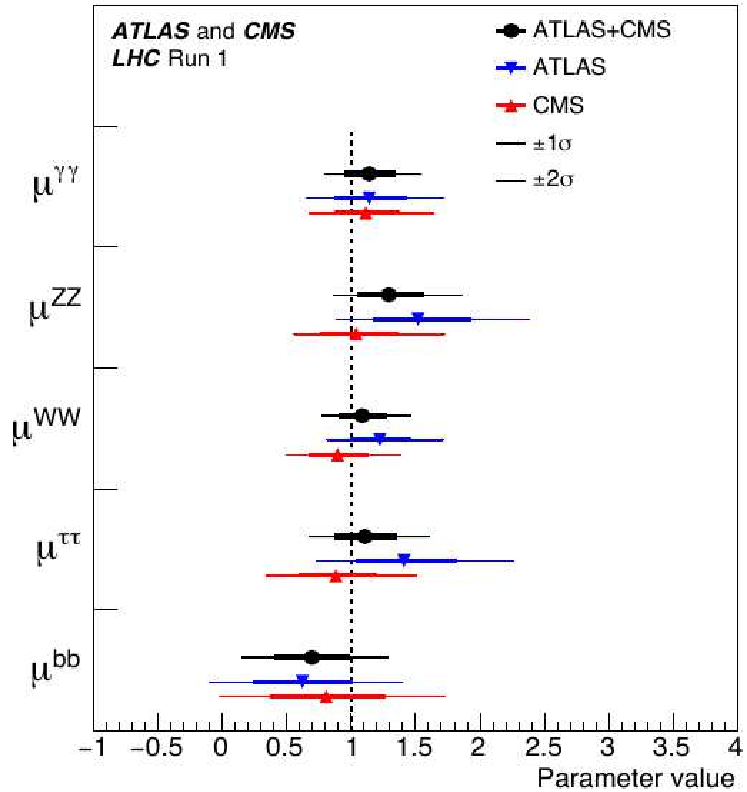
H $\rightarrow \gamma\gamma$: BR = 2.27×10^{-3}, S/B $\ll 1$

LHC Higgs Cross Section Working Group, arXiv:1610.07922

Production & decay of SM Higgs boson

relative signal strengths μ = expt/theory in Run 1

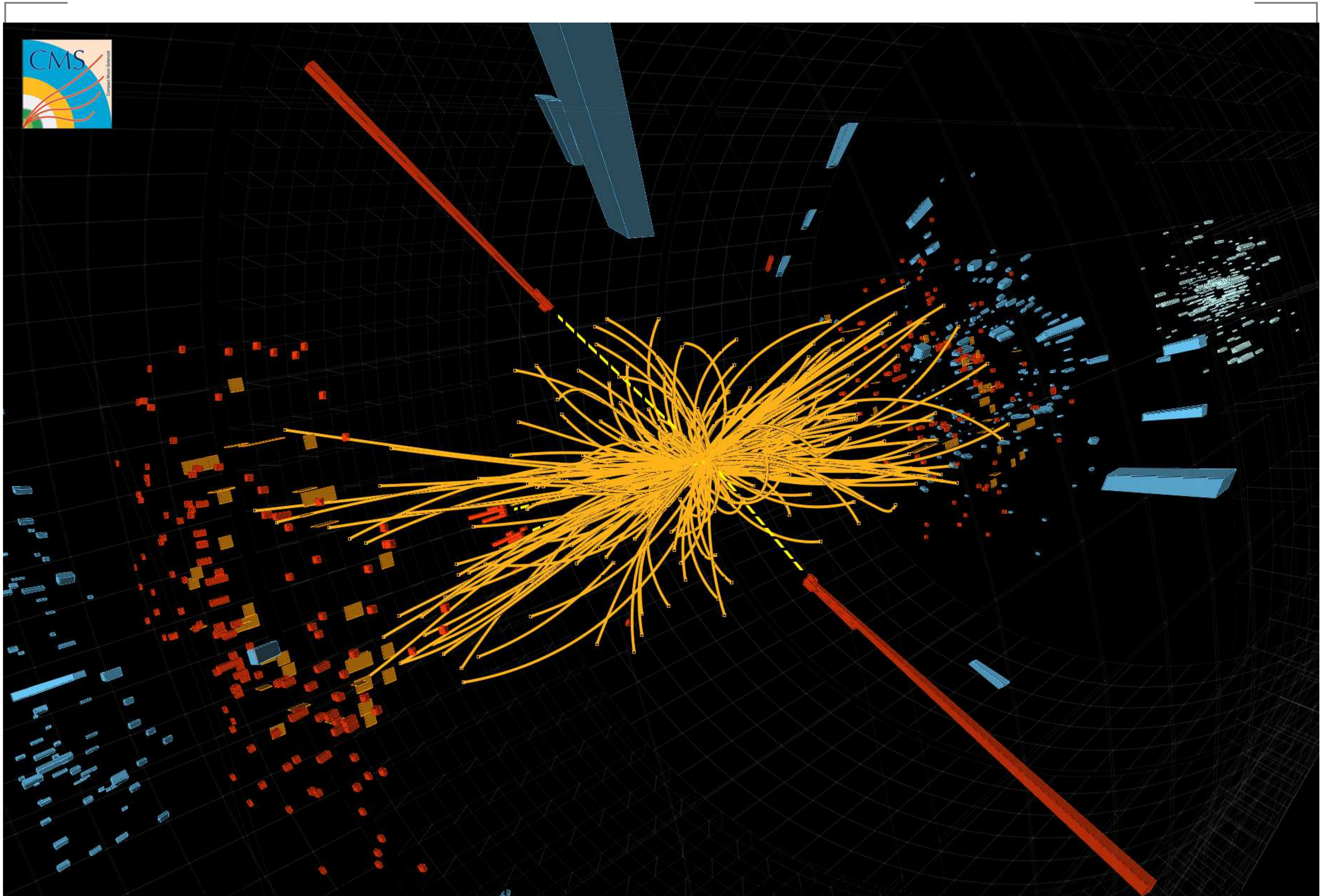




Excellent agreement in all channels for both experiments

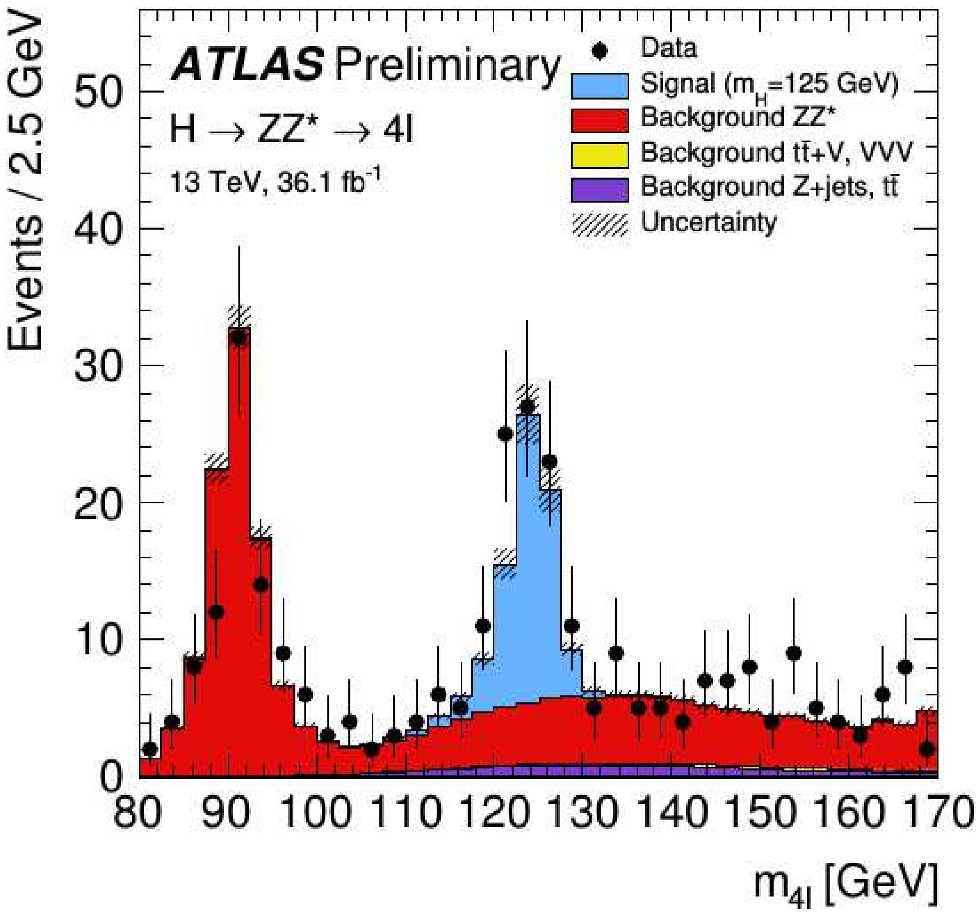
[ATLAS and CMS Collaborations, 5113 authors], JHEP **1608** (2016) 045.

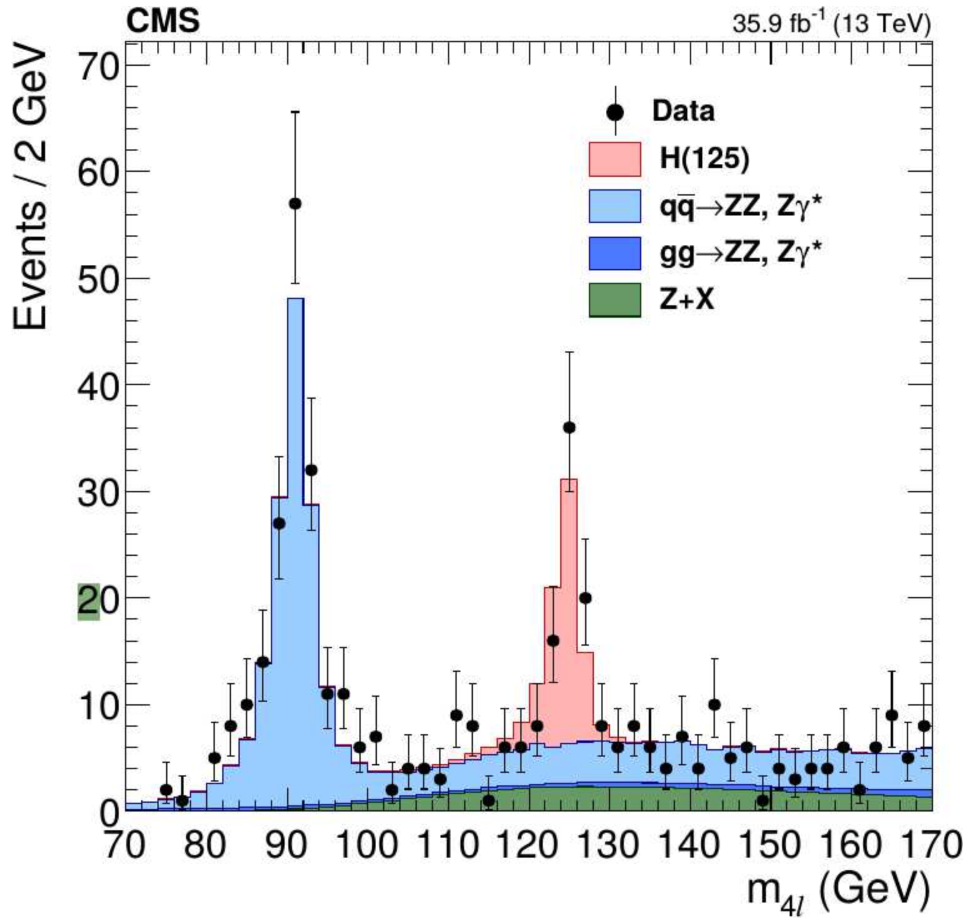
A CMS event: $H \to \gamma\gamma$ candidate



$\mathbf{H \to 4\ell}$

Invariant mass spectra at $\sqrt{s} = 13$ TeV





124.88 ± 0.37(stat) $\pm\, 0.05$ (syst)

ATLAS-CONF-2017-046

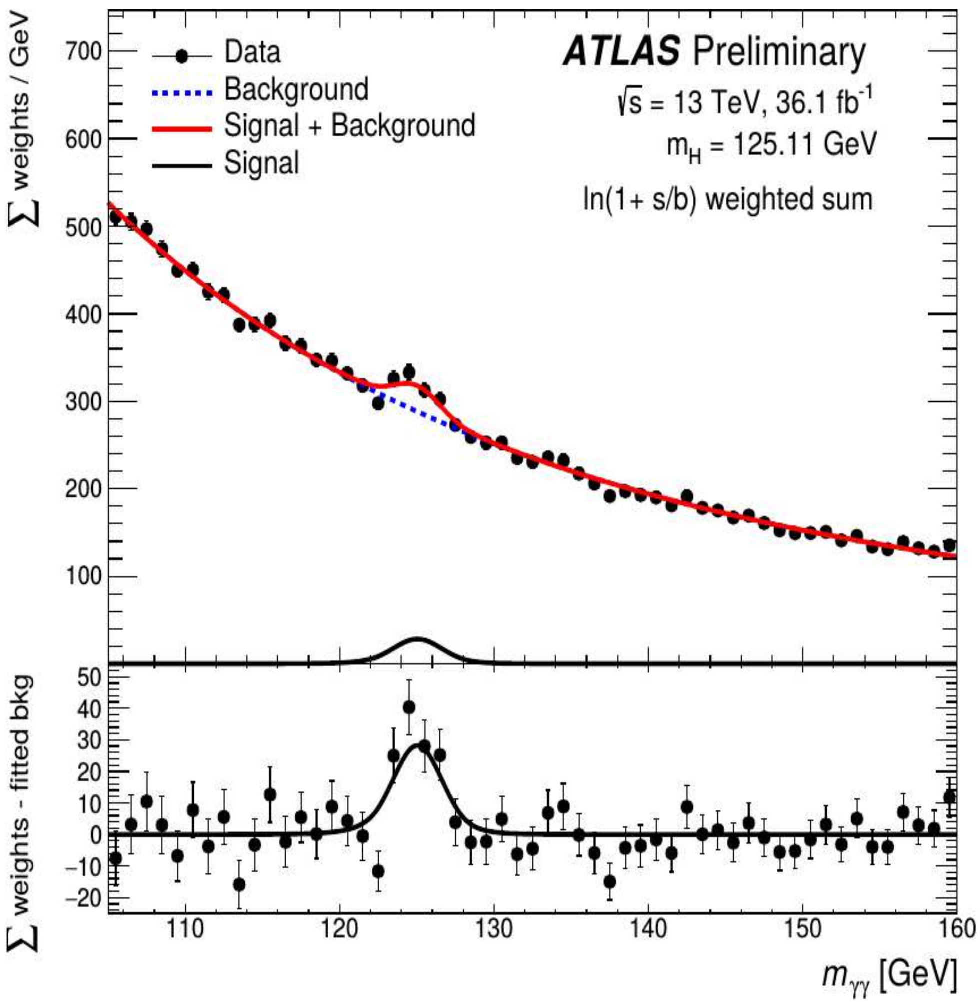
125.26 ± 0.20(stat) $\pm\, 0.08$ (syst)

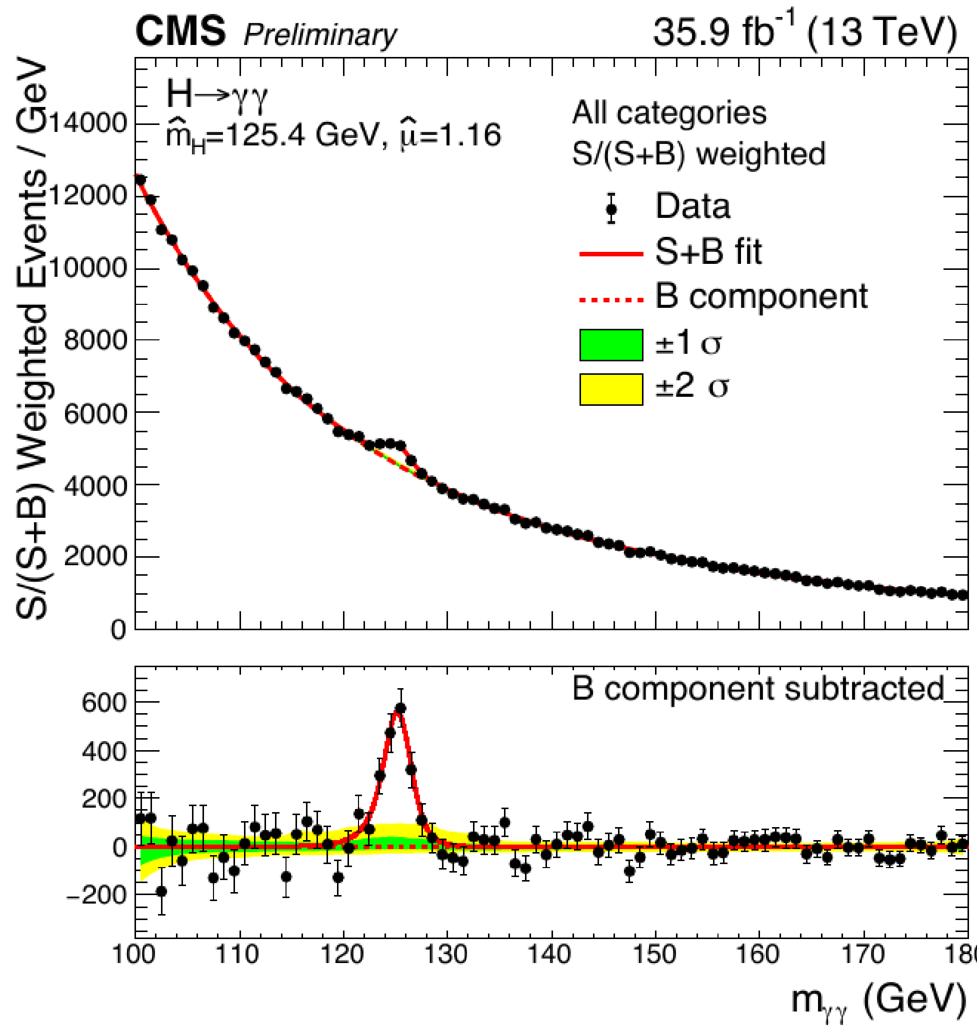
CMS-HIG-16-041

Both statistically limited.

$\mathbf{H} \to \gamma\gamma$

Invariant mass spectra at $\sqrt{s} = 13$ TeV





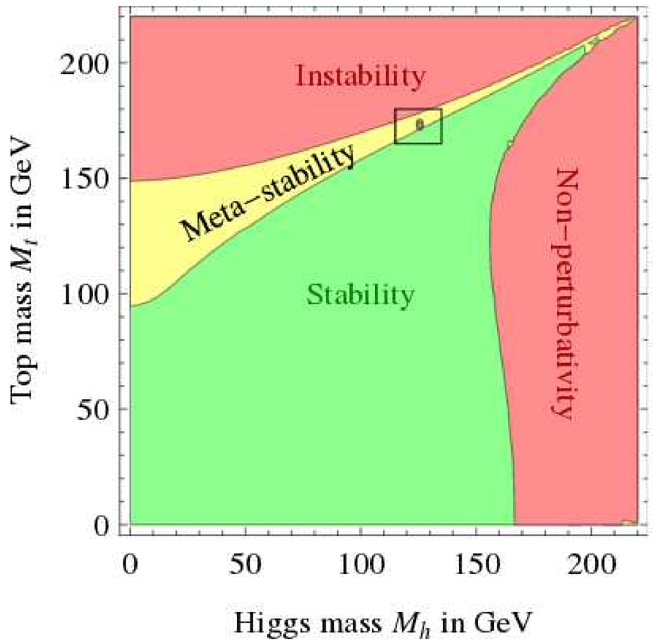
$\mathbf{125.11 \pm 0.21}$(stat) $\pm\ \mathbf{0.36}$ (syst)

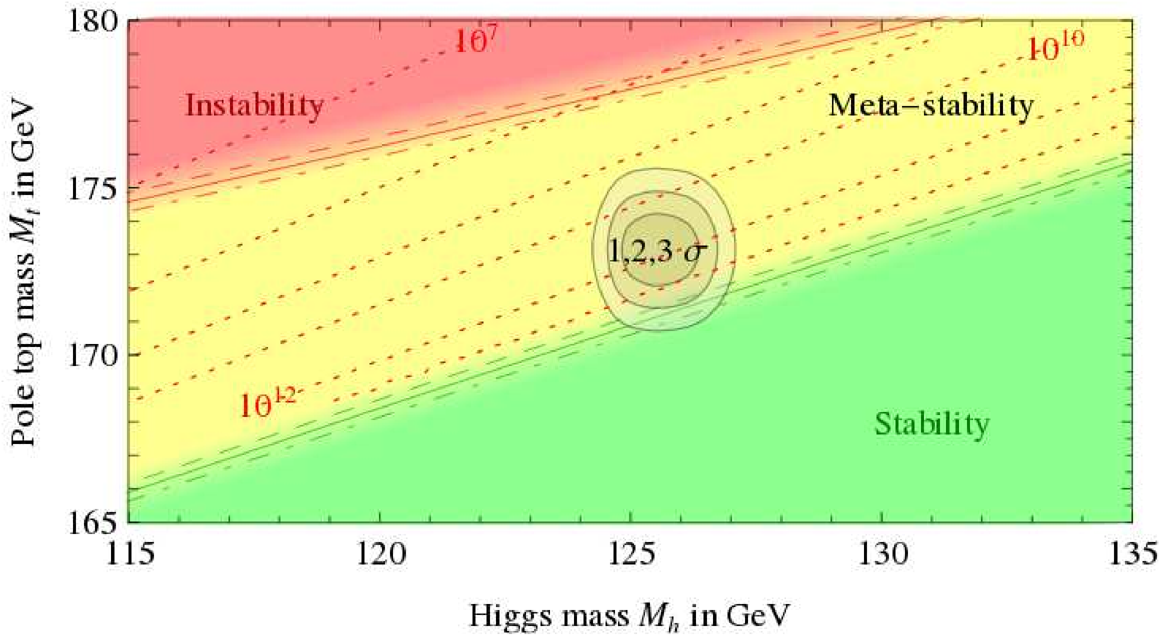
ATLAS-CONF-2017-046

$\mathbf{125.4 \pm 0.15}$(stat) $\pm\ \mathbf{(0.2 \ldots 0.3)}$ (syst)

CMS-PAS-HIG-16-040

Top vs. Higgs: vacuum stability





G. Degrassi, S. Di Vita, J. Elias-Miro, J. R. Espinosa, G. F. Giudice, G. Isidori and A. Strumia, „Higgs mass and vacuum stability in the Standard Model at NNLO," JHEP **1208** (2012) 098

How stable is our EW vacuum? Depends on the masses of the Higgs boson and of the top quark

What next?

Supersymmetry (SUSY)?

Why? Who needs that?

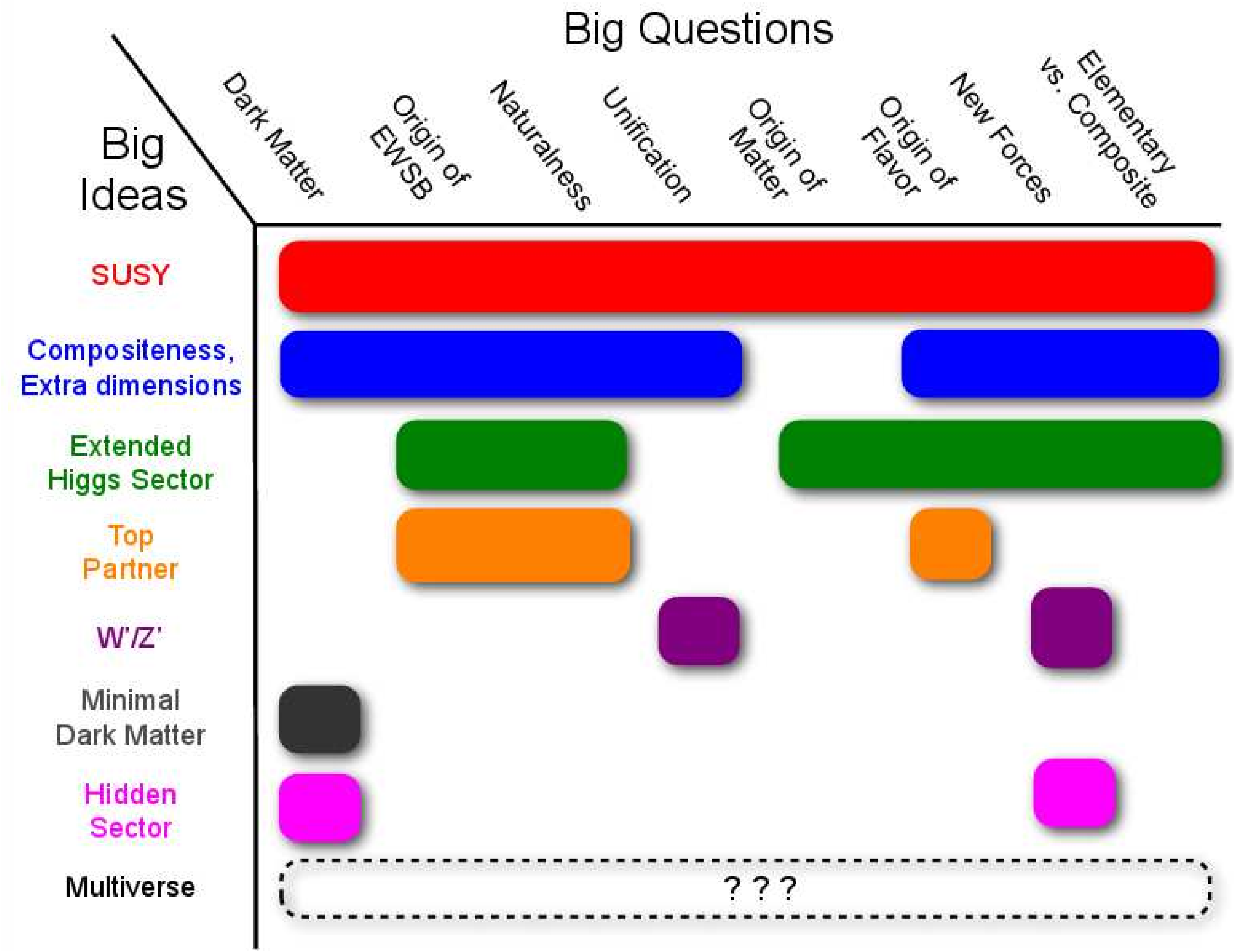
Problems of the Standard Model – 1

- 3 *independent (?)* components: $U(1)_Y \otimes SU(2)_L \otimes SU(3)_C$
- Gravitation? $S = 2$ graviton?
- Asymmetries: right ⇔ left World ⇔ Antiworld
- Artificial mass creation: Higgs-field *ad hoc*
- Many fundamental particles:
  $8 + 3 + 1 + 1 = 13$ bosons
  $3 \times 2 \times (2 + 3 \times 2) = 48$ fermions
- Charge quantization: $Q_\mathrm{e} = Q_\mathrm{p}, \; Q_\mathrm{d} = Q_\mathrm{e}/3$
- Why the 3 fermion families?
  Originally: Who needs the muon??
- Nucleon spin: how $1/2$ produced?

Problems of the Standard Model – 2

- 19 free parameters (too many ??):
  - 3 couplings: α, Θ_W, $\Lambda_{\rm QCD}$; 2 Higgs: M_H, λ
  - 9 fermion masses: $3 \times M_\ell$, $6 \times M_q$
  - 4 parameters of the CKM matrix: Θ_1, Θ_2, Θ_3, δ
  - QCD-vacuum: Θ
- $M_\nu > 0 \Rightarrow +3$ masses, $+4$ mixing matrix
- Gravitational mass of the Universe:
  - 4% ordinary matter (stars, gas, dust, ν)
  - 23% invisible *dark matter*
  - 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.

Beyond the Standard Model



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

arXiv:1311.0299.

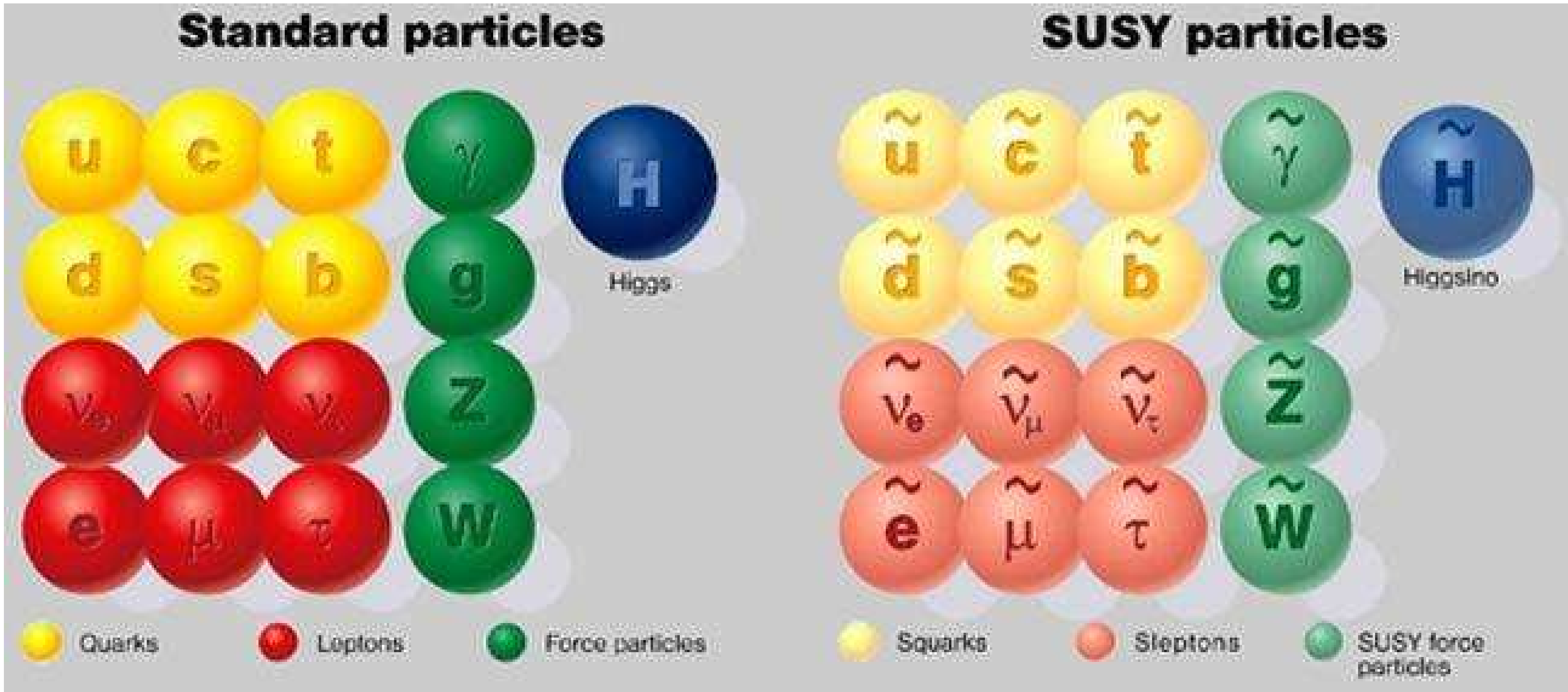
Supersymmetry (SUSY)

Hypothesis: Fermions and bosons exist in pairs:

$Q|\mathrm{F}\!>\,=|\mathrm{B}\!>; \quad Q|\mathrm{B}\!>\,=|\mathrm{F}\!> \qquad m_B = m_F$

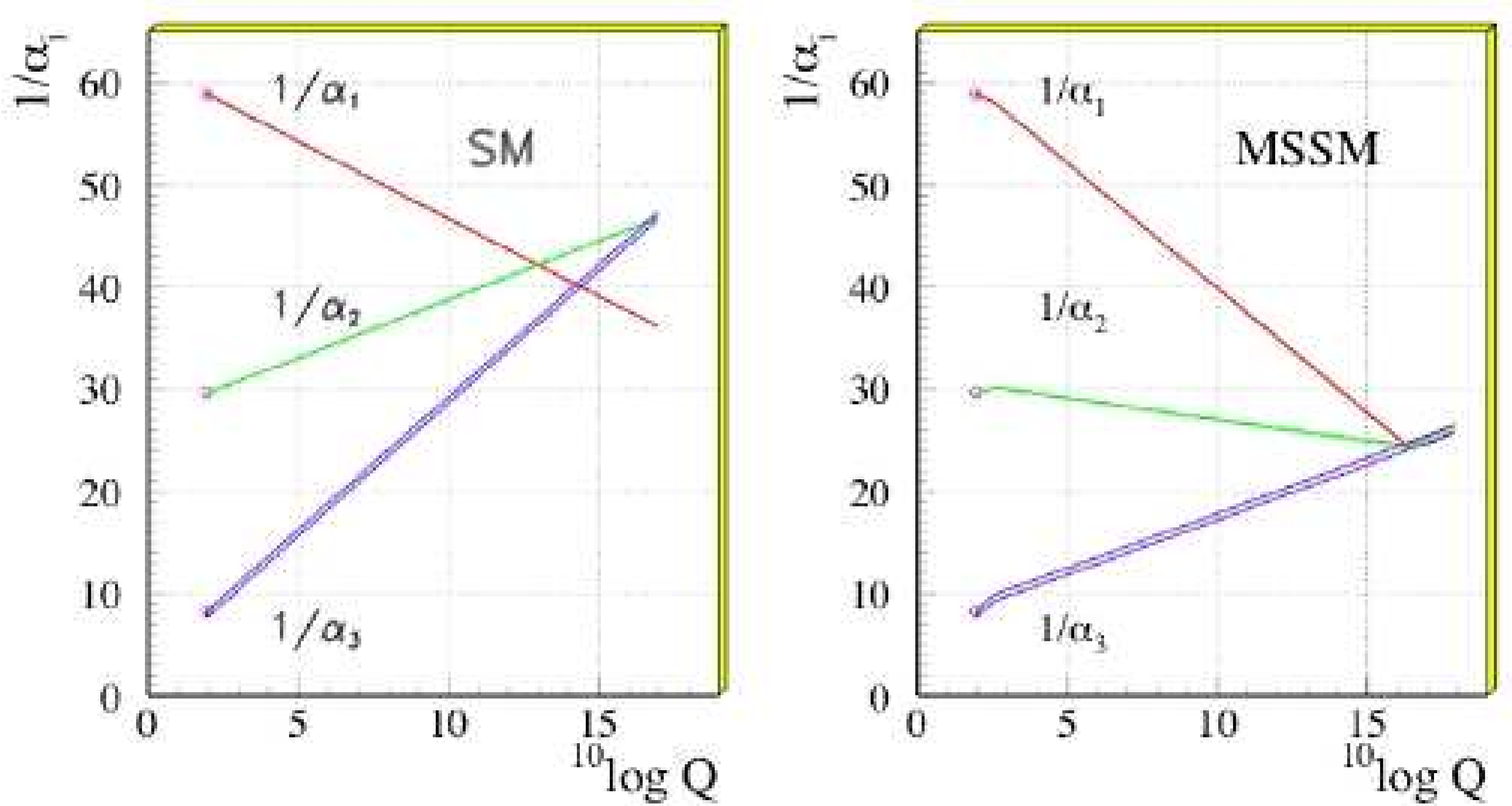
Identical particles, just spins different $\quad (\tilde{S} = S - \frac{1}{2})$

Broken at low energy, no partners: much larger mass?



Almost 50 % (SM) discovered already!!

SUSY: coupling constants



Unification OK!

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

Many-many alternative models

SUSY search

Production in pairs, decay to other SUSY particle

Lightest (LSP) stable, neutral, not observable

Neutral LSP: excellent dark matter candidate

Signal for observation: missing energy

2 Higgs doublets ⇒ masses to upper and lower fermions

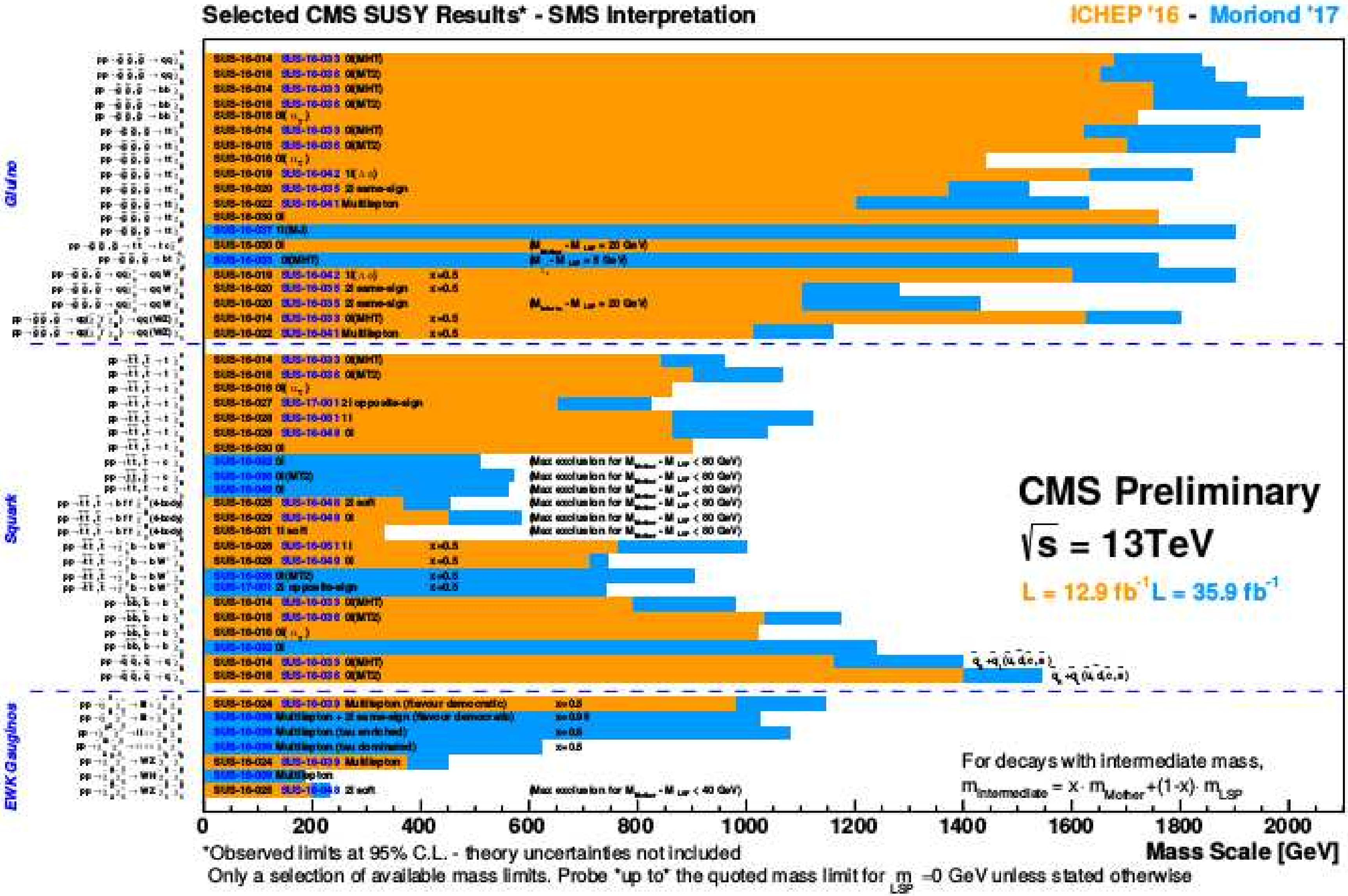
5 Higgs bosons: $\mathbf{h^0, H^0, A^0, H^\pm}$

Simplest SUSY models (105 ⇒ 4 parameters)
are excluded by LHC data

Even if SUSY is valid, minimal models may not be.

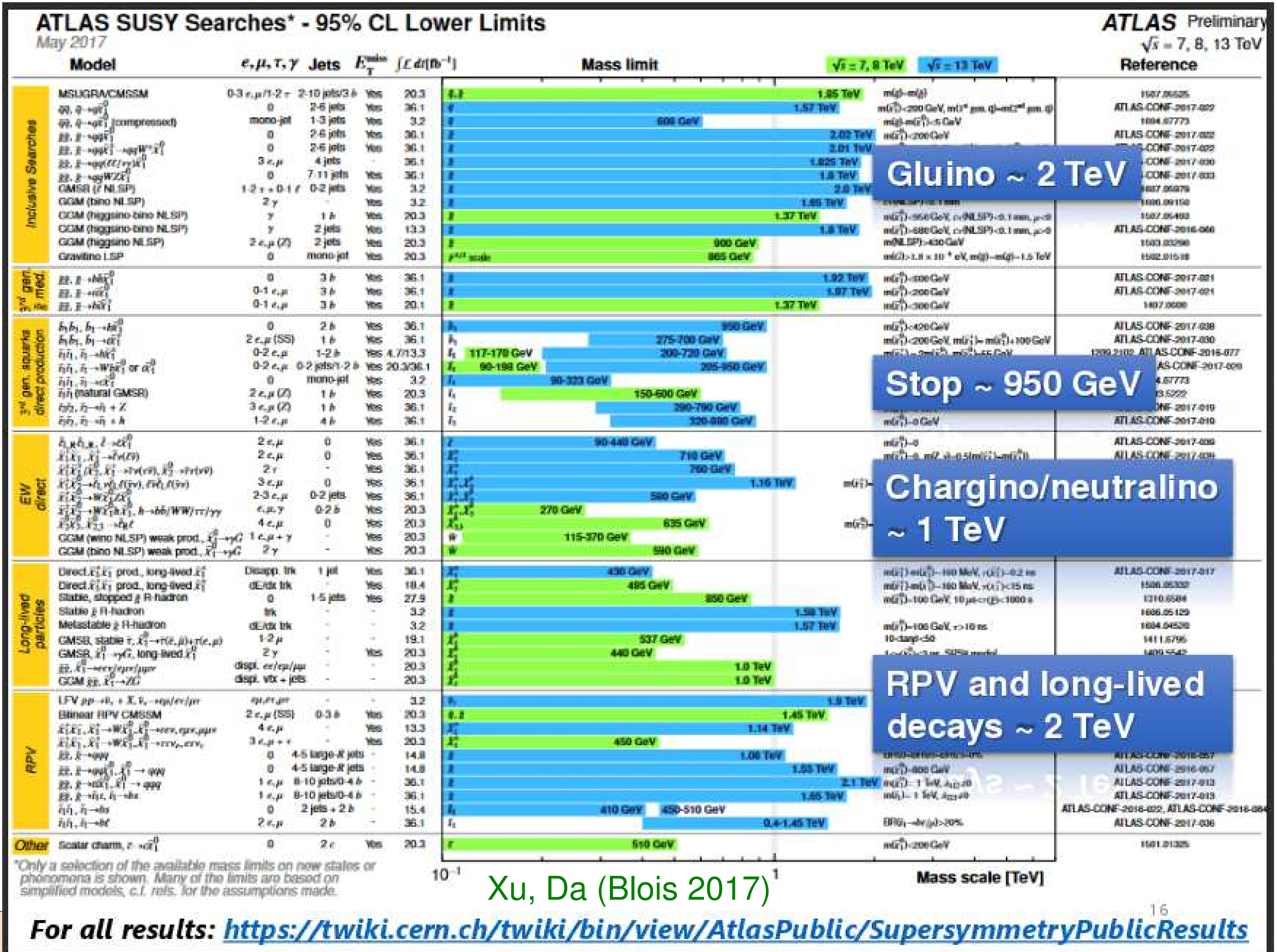
- Search for more Higgs bosons or
- Check simplified phenomenology

CMS SUSY summary plot, 2017

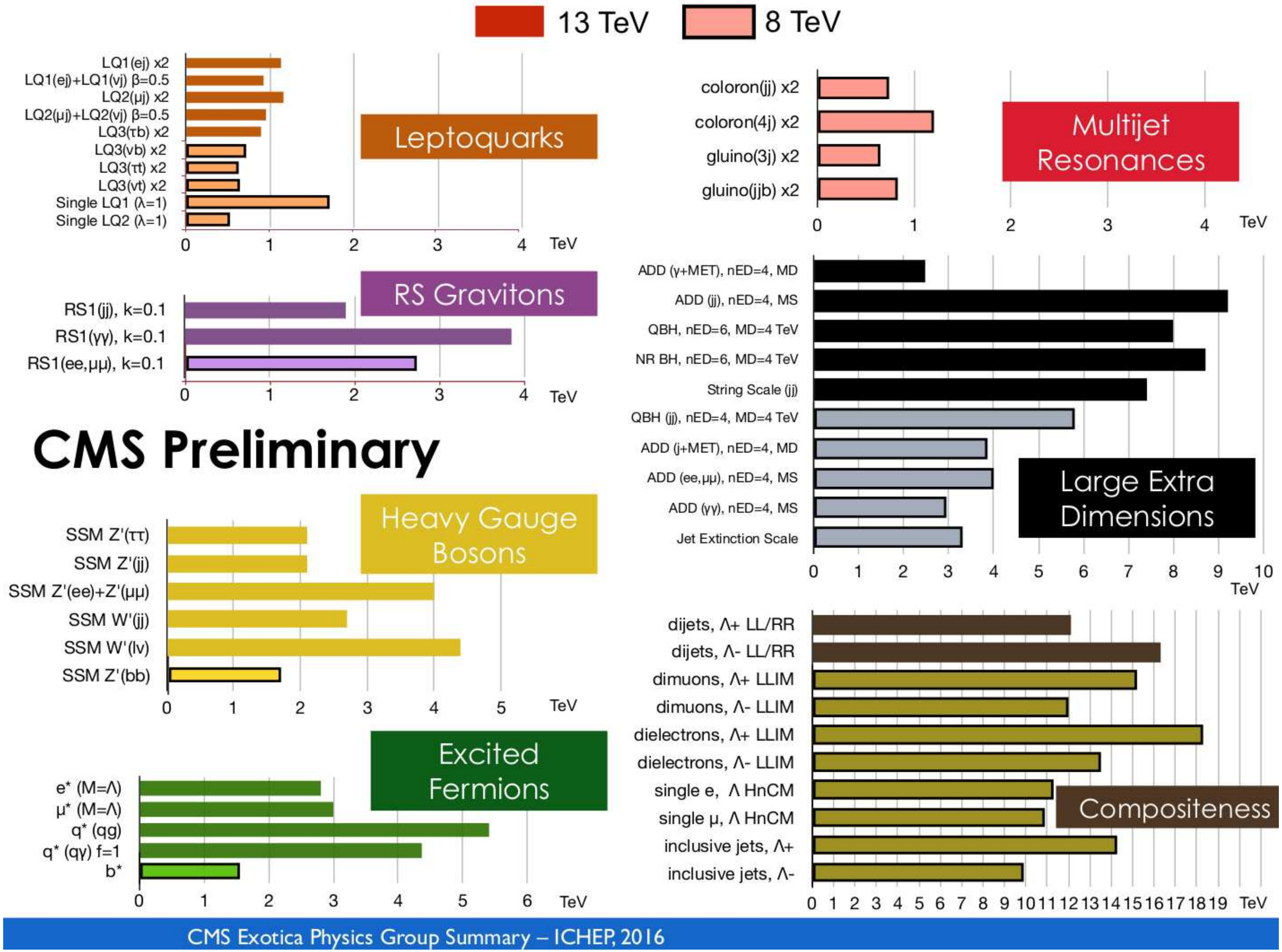


Simplified Model Spectrum (SMS) topologies

ATLAS SUSY summary plot, 2017



CMS: search for exotica



Conclusion

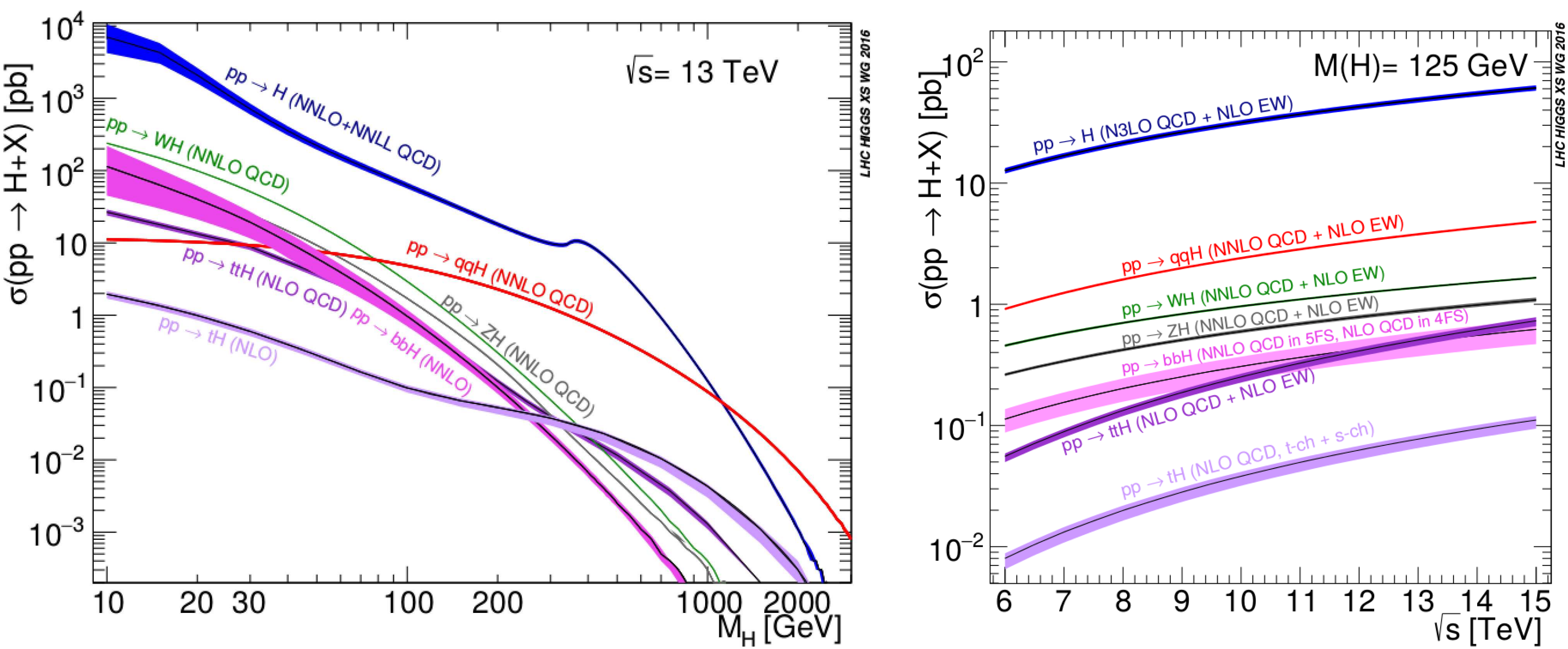
- Broken symmetries play a fundamental role in particle physics.
- At LHC we have observed the SM Higgs boson in 8 TeV p-p collisions and it does not look like a Higgs boson of a more general model.
- Since 2015 the LHC collides protons at 13 TeV and its luminosity is steadily increasing. Let us hope 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, ...)
- Simplified approaches: search for non-SM phenomena in simple reactions with on-shell particles. If found, try to relate the new observation with possible models
- Adjust theory to data, not the other way around.

Thank you for your attention

Spare slides for questions

Production of the SM Higgs boson

in p-p collisions at LHC (Run 2)



D. de Florian *et al.* [LHC Higgs Cross Section Working Group], *Handbook of LHC Higgs Cross Sections: 4. Deciphering the Nature of the Higgs Sector*, arXiv:1610.07922

The CMS Collaboration (2017)

- 5250 participants from 198 institutions of 45 countries
- 995 engineers, 279 technicians
- 1963 physicists with PhD (326 women, 1637 men)
- 922 doctoral students (202 women, 720 men)
- 994 MSc students (241 women, 753 men)
- Participants by countries of institutes (in 2012):
  USA: 1149, Italy: 439, Germany: 298, Russia: 234
- 70 petabytes of data, 700 publications

CMS detector: huge joint effort
3000 people worked on it for 20 years!

$\mathbf{H \to W^+W^-}$

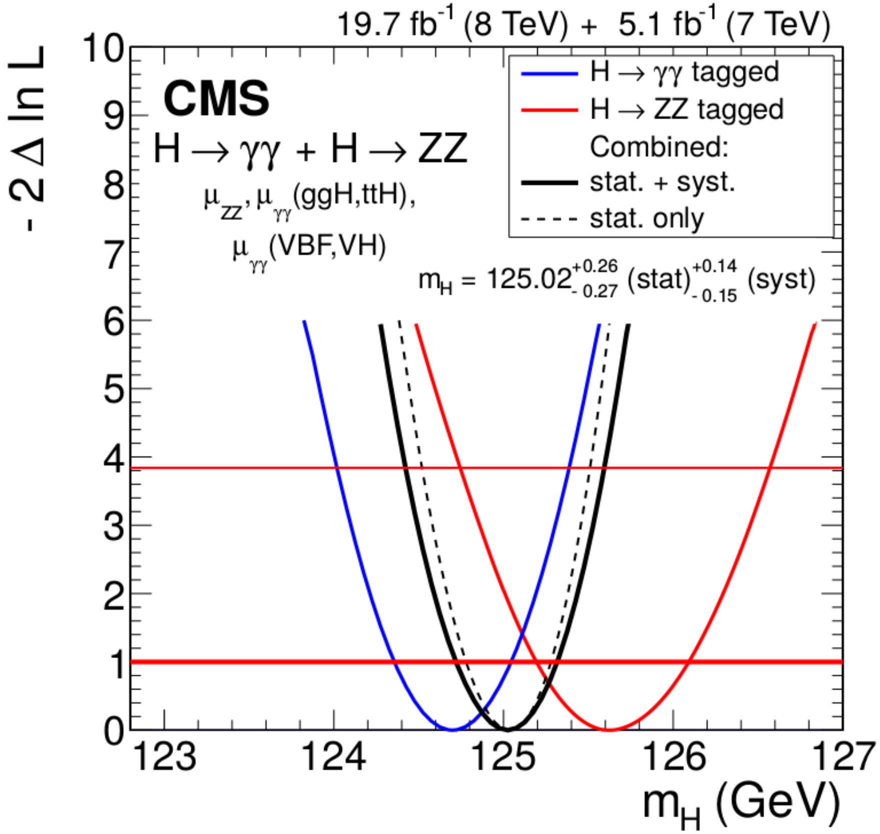
3rd most significant decay channel for the 125 GeV Higgs boson: observed and studied.

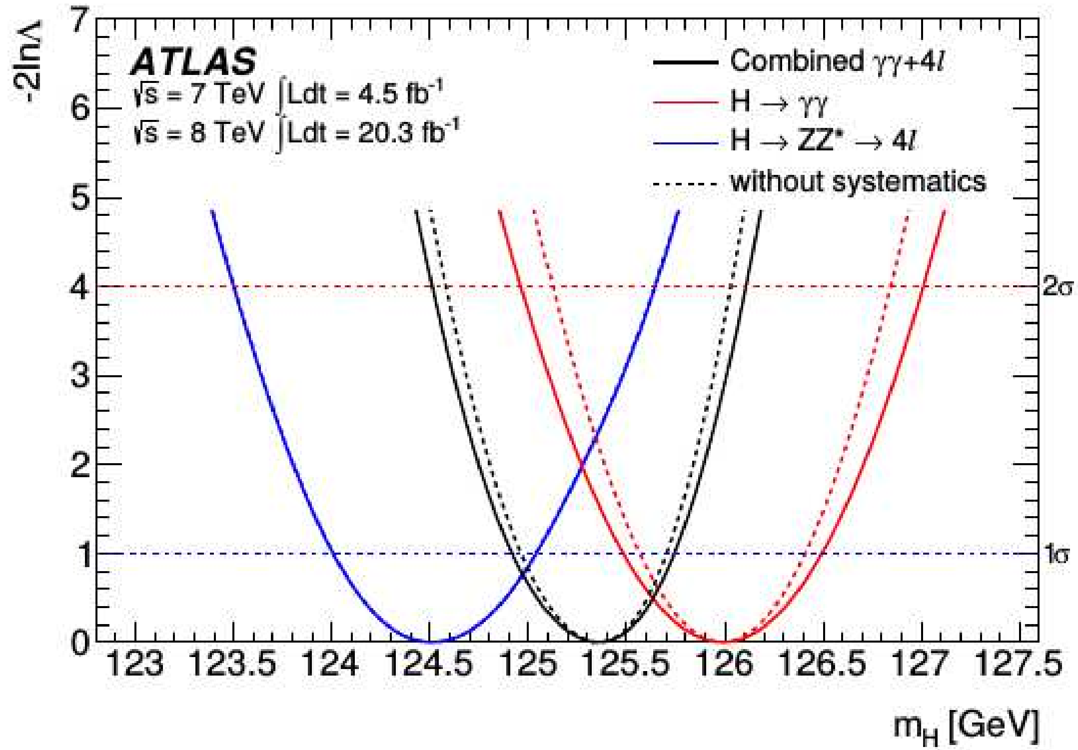
When in 2012 added to $\gamma\gamma$ and 4ℓ, increased the observed significance for ATLAS from 5σ to 6.1σ and decreased it for CMS to 4.9σ.

- ATLAS, Run 1: 6.8σ and $\mu = 1.22^{+0.23}_{-0.21}$
- CMS, Run 1: 4.8σ and $\mu = 0.90^{+0.23}_{-0.21}$
- ATLAS + CMS in Run 1: $\mu = 1.09^{+0.18}_{-0.16}$

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

CMS vs. ATLAS: Run 1 masses





Combined ATLAS + CMS Higgs-boson mass:

$$\mathbf{125.09 \pm 0.21(stat) \pm 0.11(syst)}\ \text{GeV}$$

[ATLAS and CMS Collaborations, 5113 authors],

Phys. Rev. Lett. **114** (2015) 191803; arXiv:1503.07589.

CMS strategies for discovery

- 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

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	$\mathbf{\tilde{u}_L, \tilde{u}_R, \tilde{d}_L, \tilde{d}_R}$	same
			$\mathbf{\tilde{s}_L, \tilde{s}_R, \tilde{c}_L, \tilde{c}_R}$	same
			$\mathbf{\tilde{t}_L, \tilde{t}_R, \tilde{b}_L, \tilde{b}_R}$	$\mathbf{\tilde{t}_1, \tilde{t}_2, \tilde{b}_1, \tilde{b}_2}$
slepton	0	-1	$\mathbf{\tilde{e}_L, \tilde{e}_R, \tilde{\nu}_e}$	same
			$\tilde{\mu}_L, \tilde{\mu}_R, \tilde{\nu}_\mu$	same
			$\tilde{\tau}_L, \tilde{\tau}_R, \tilde{\nu}_\tau$	$\tilde{\tau}_1, \tilde{\tau}_2, \tilde{\nu}_\tau$
neutralino	1/2	-1	$\mathbf{\tilde{B}^0, \tilde{W}^0, \tilde{H}_1^0, \tilde{H}_2^0}$	$\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0$
chargino	1/2	-1	$\mathbf{\tilde{W}^\pm, \tilde{H}_1^+, \tilde{H}_2^-}$	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^\pm$
gluino	1/2	-1	$\mathbf{\tilde{g}}$	same
goldstino	1/2	-1	$\mathbf{\tilde{G}}$	same
gravitino	3/2			