Broken Symmetries and the Higgs Boson

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Outline

- Broken Symmetries of the Standard Model.
- The Higgs Boson.
- Its Search and Observation at LHC.
- What Next, Supersymmetry (SUSY)?
- Plans and hopes.

With the support of the Hungarian OTKA Grants NK-81447 and K-103917

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

Three interactions are derived of local gauge symmetries, strong from local SU(3) and electroweak from local U(1)$\otimes$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.

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

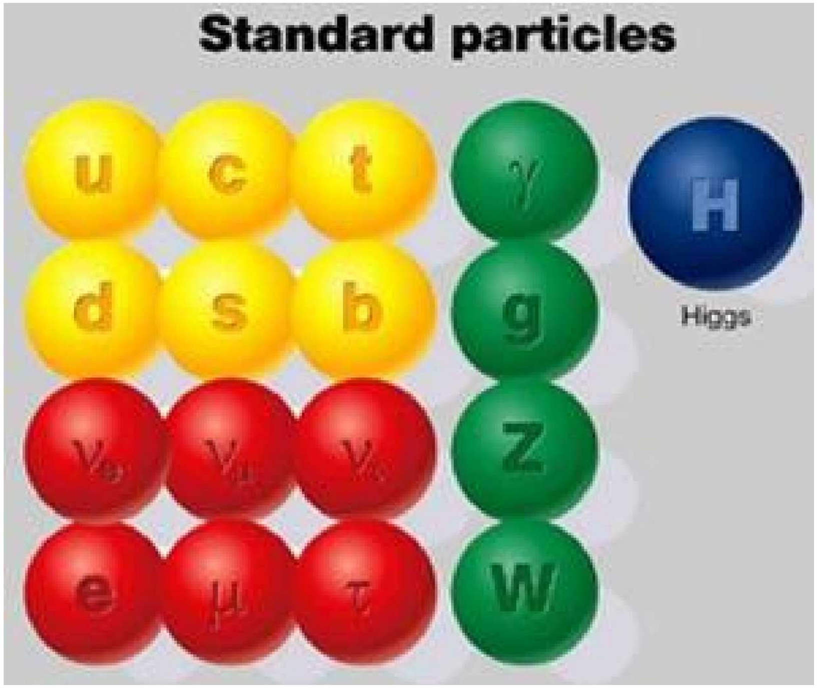
$$\Downarrow$$

electromagnetism + zero-mass photon, OK!

Turn 3 d.f. of Higgs-field to create masses for Z, W^+, W^-, get a correct weak interaction with 3 heavy gauge bosons.

4th degree of freedom: heavy scalar 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!

+ the Higgs boson

Color: the charge of the strong interaction
colored quarks ⇒ *colorless* **composite hadrons** of 2 kinds

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

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

Glory Road of the Standard Model

Status in 2013

Includes hundreds of measurements of all experiments

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

Slightly deviating quantity used to change

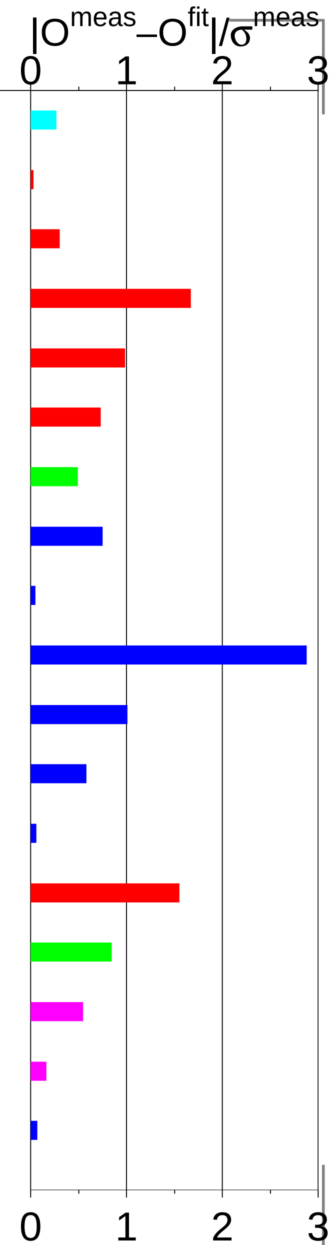
Now it is forward-backward asymmetry of

$$e^+e^- \to Z \to b\bar{b}$$

LEP Electroweak Working Group:

http://lepewwg.web.cern.ch/

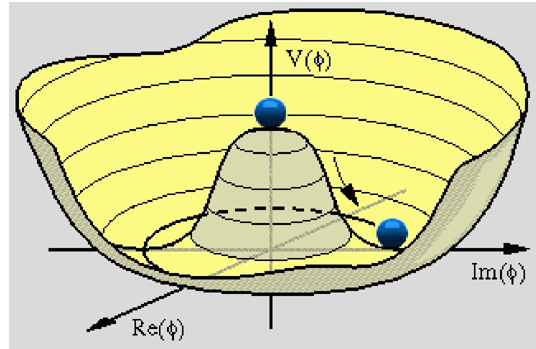
	Measurement	Fit
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02750 ± 0.00033	0.02759
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959
σ^0_{had} [nb]	41.540 ± 0.037	41.478
R_l	20.767 ± 0.025	20.742
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.01645
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481
R_b	0.21629 ± 0.00066	0.21579
R_c	0.1721 ± 0.0030	0.1723
$A^{0,b}_{fb}$	0.0992 ± 0.0016	0.1038
$A^{0,c}_{fb}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1481
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.385 ± 0.015	80.377
Γ_W [GeV]	2.085 ± 0.042	2.092
m_t [GeV]	173.20 ± 0.90	173.26



March 2012

The Higgs boson of the Standard Model

Spontaneous symmetry breaking



Spinless, neutral, heavy particle

The scalar particle needed for renormalisation

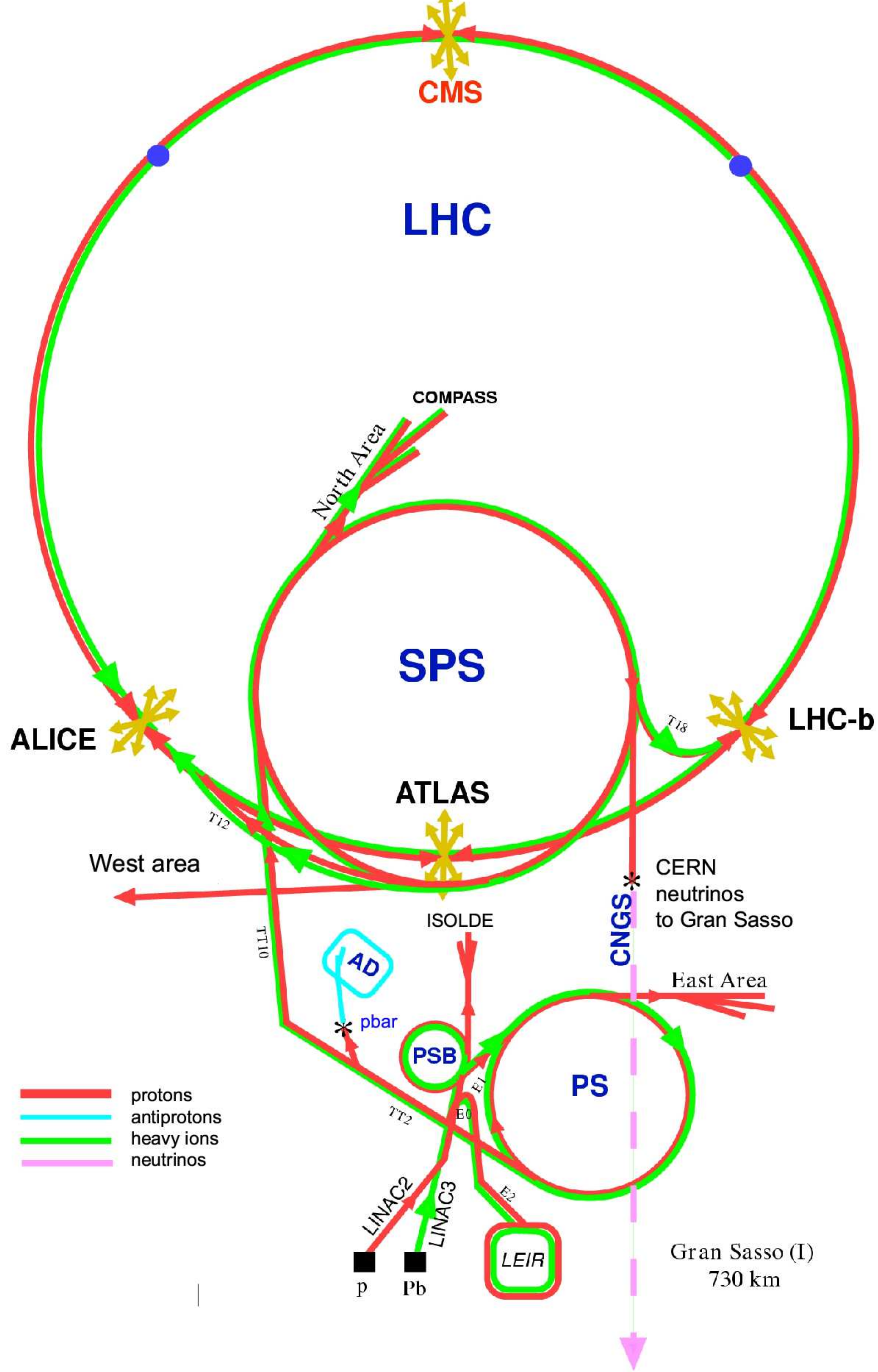
Does it really exist? SM: it must!

Many jokes were of the Higgs boson before the discovery

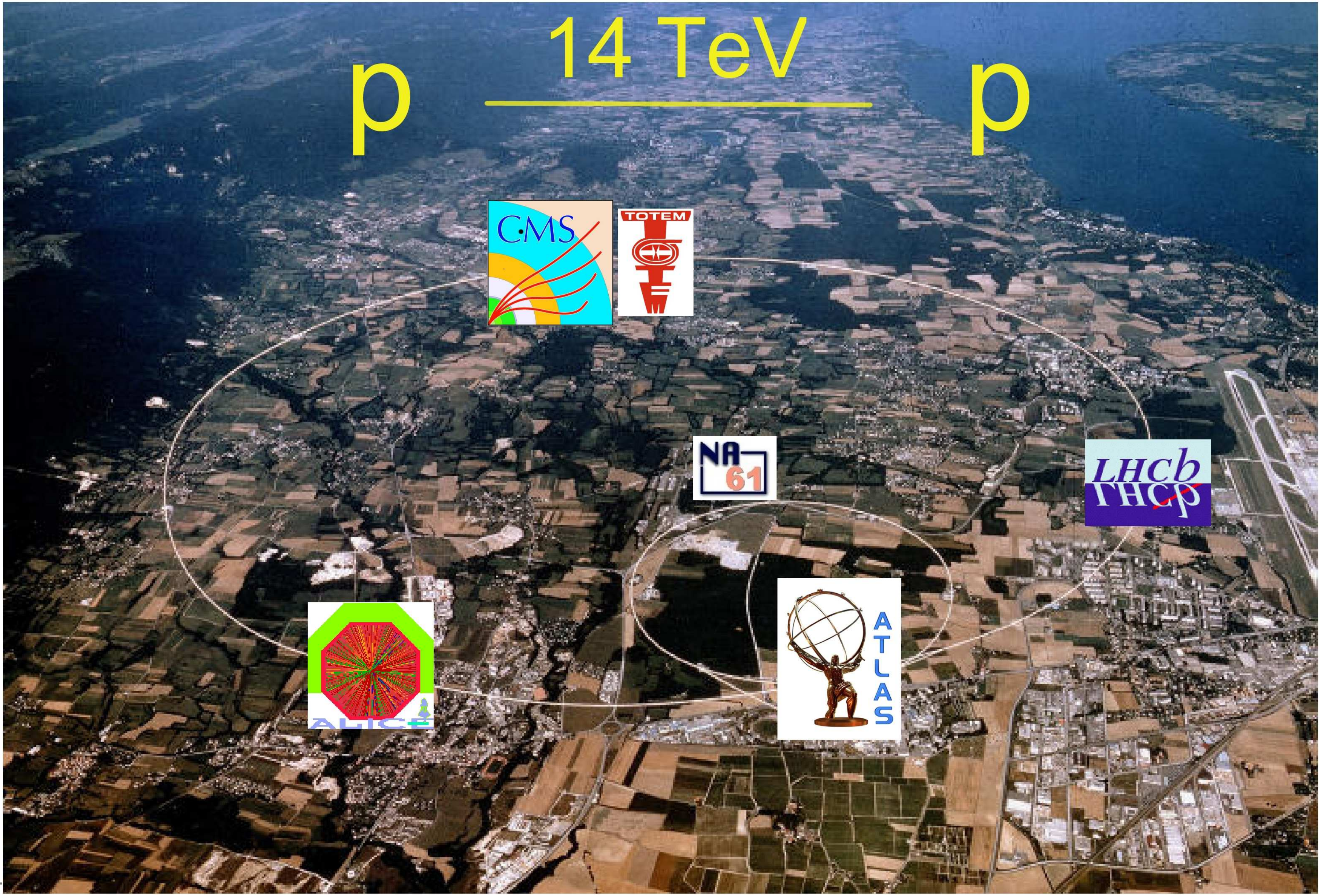
- The Higgs boson walks into a bar. The bartender says "Watch out, there were some guys looking for you."
- I'm trying to find a good Higgs joke. It may take years, but I'm sure it exists.
- The Higgs boson walks into a church. The priest says „Your kind is not welcome here". The boson replies: „But without me how can you have mass?"
- The Higgs boson walks into a bar. The bartender does not understand...

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

Luminosity L: collision yield

The measure of the performance of a collider machine

Corresponds to the **flux** at fixed-target accelerators (same units as well)

Rate of reaction with cross section σ at ϵ efficiency

$$R = \epsilon\sigma L$$

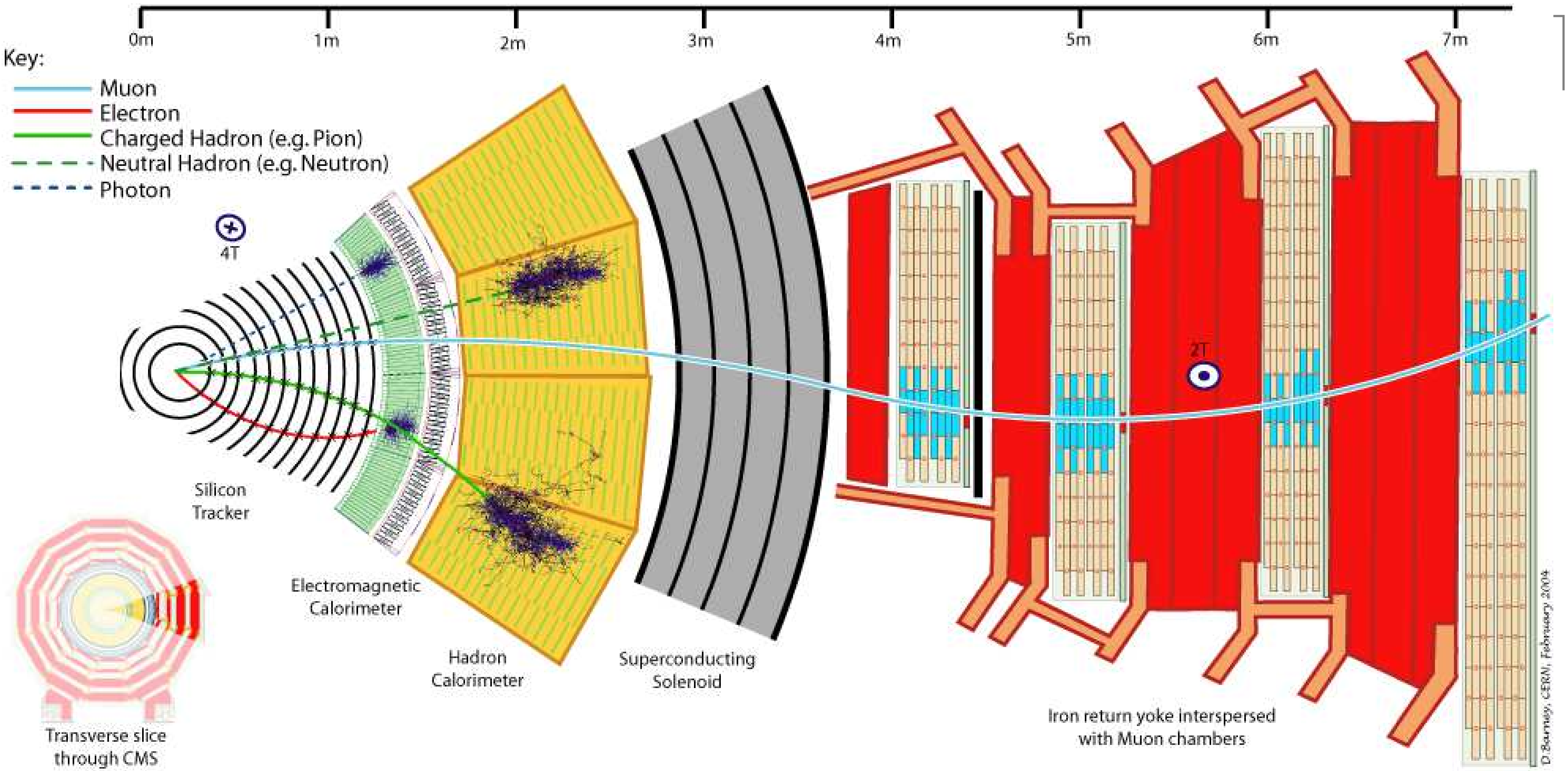
Integrated luminosity: $\int_{t_1}^{t_2} L dt$; $[\mathrm{pb}^{-1},\ \mathrm{fb}^{-1}]$

Amazing performance of LHC since start in 2009

In proton-proton regime: 2010: 0.04 fb^{-1} at 7 TeV; 2011: 5.6 fb^{-1} at 7 TeV; 2012: 23.3 fb^{-1} at 8 TeV

LHC is like Formula 1: boring without collisions

CMS: Compact Muon Solenoid



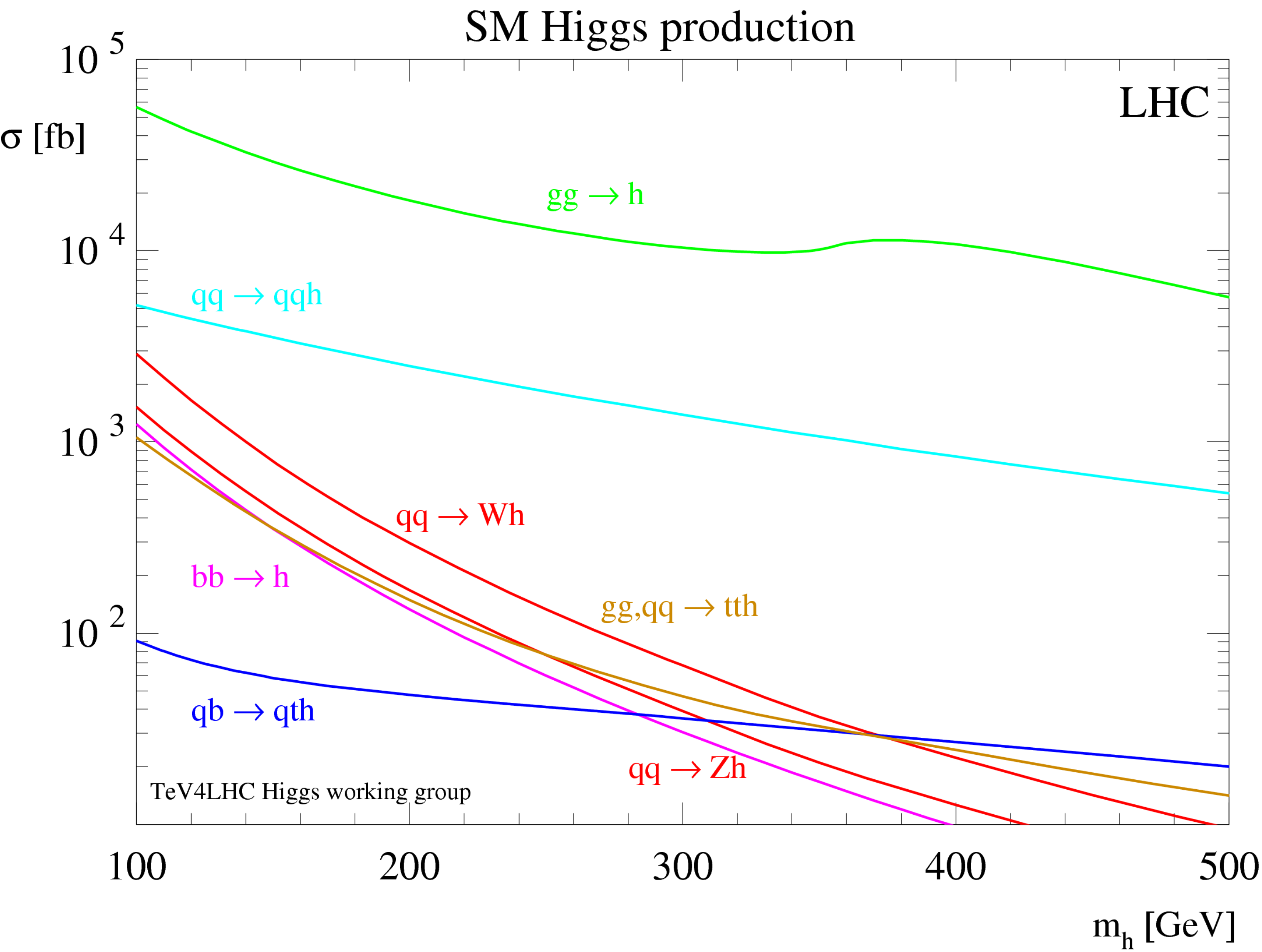
14000 ton digital camera:

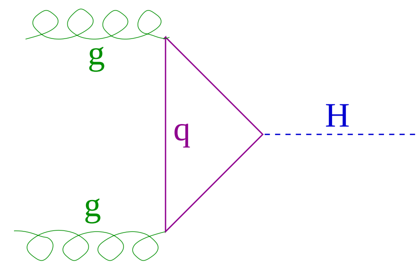
100 M pixel, 20 M pictures/sec, 1000 GB/sec data

Processes cc. 400 pictures/sec ⇒ intelligent filter!!

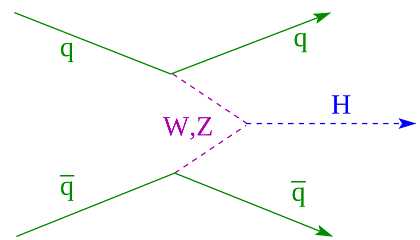
Formation of the SM Higgs boson

in p-p collisions at LHC





gluon fusion



vector boson fusion

Decay of the SM Higgs boson

March 2012

Not excluded by 2011 CMS data:

$114 < M_{\mathrm{H}} < 127$ GeV

(at 95% CL)

(many decay processes)

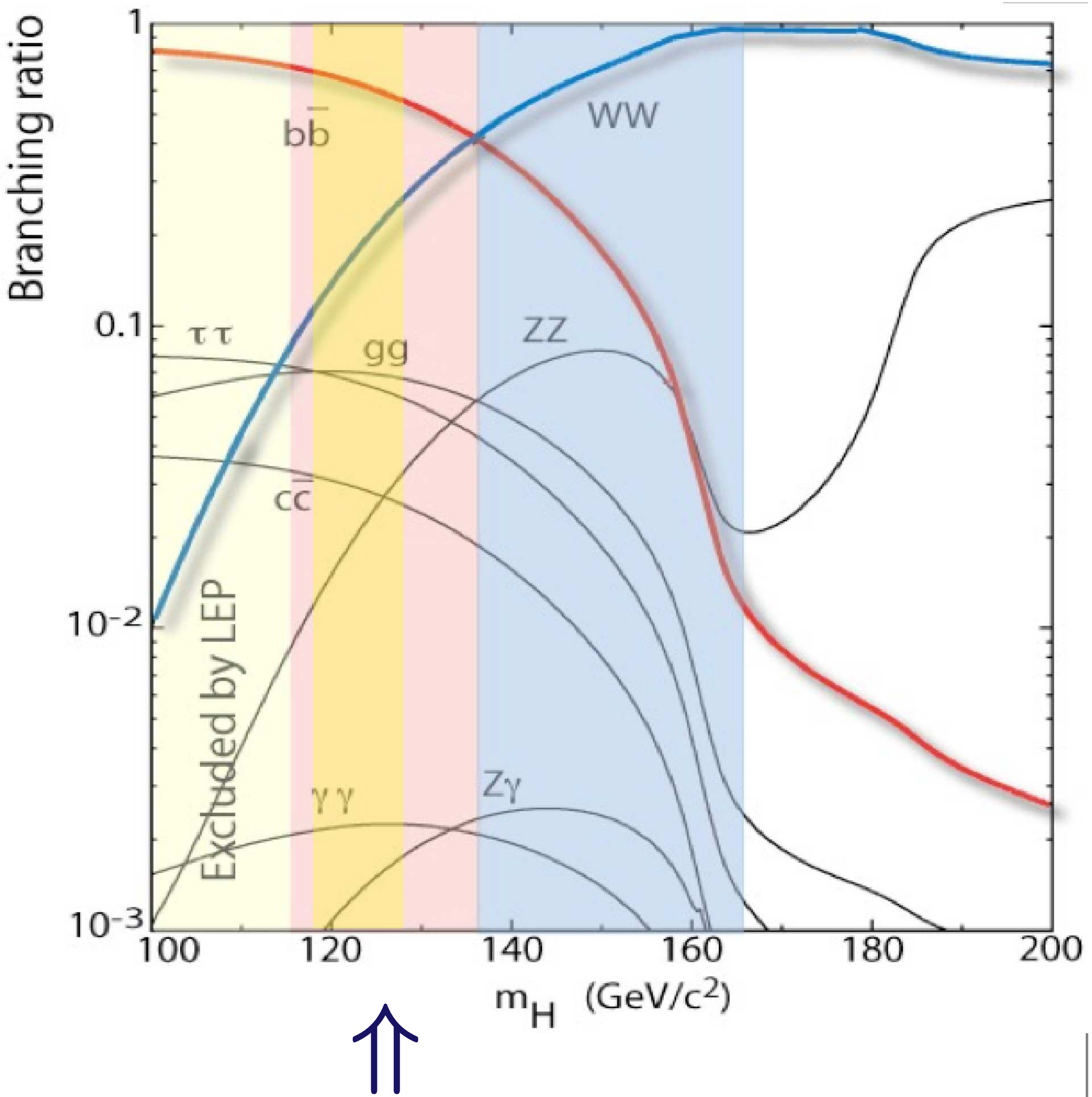
Best identified: $\mathrm{H} \to \gamma\gamma$

and

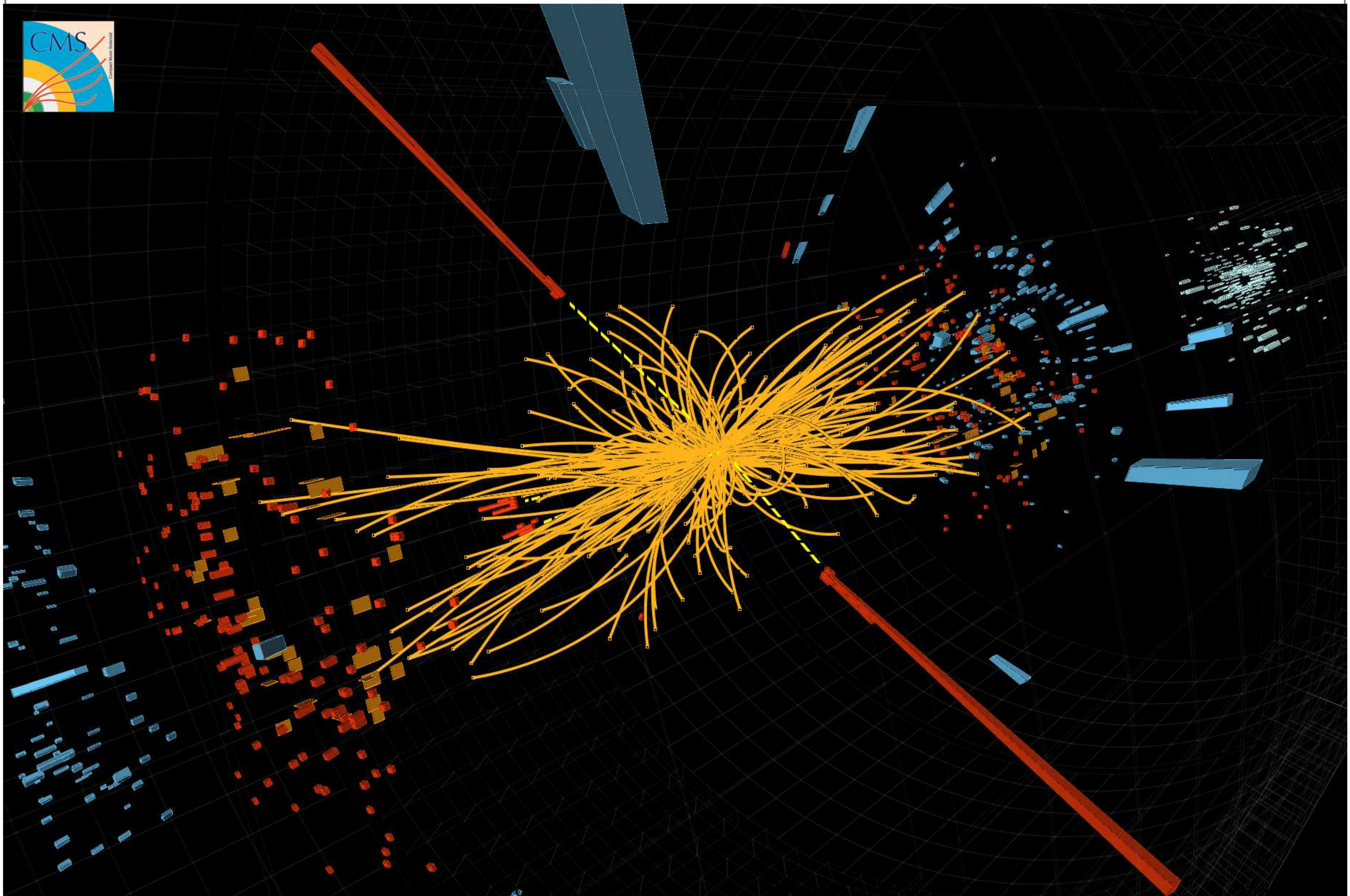
$\mathrm{H} \to \mathrm{ZZ} \to \ell^+\ell^-\ell^+\ell^- \quad (\ell = \mathrm{e}, \ \mu)$

Excess observed

$2 - 3\sigma$ at $\sim$125 GeV!



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



4 July 2012: we have something!

ATLAS and CMS, at LHC collision energies 7 and 8 TeV, in two decay channels $\mathrm{H} \to \gamma\gamma$ and $\mathrm{H} \to \mathrm{ZZ} \to \ell^+\ell^-\ell^+\ell^-$, at invariant mass of $m \approx 126$ GeV see a new boson at a convincing statistical significance of 5σ conf. level each with properties corresponding to those of the SM Higgs boson.

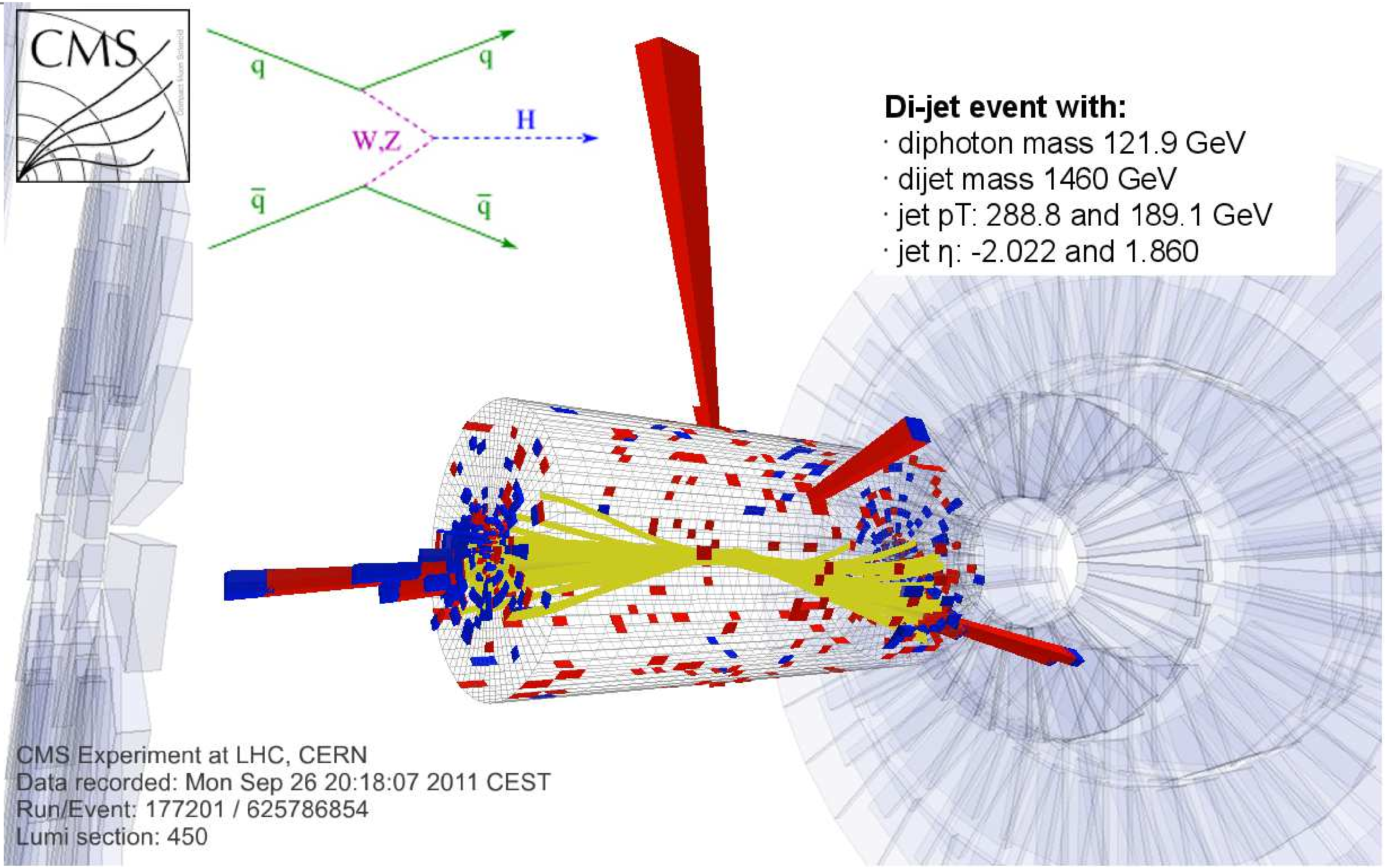
$\mathrm{H} \to \gamma\gamma \Rightarrow J_H = 0$ or 2

Data analysis was optimized for SM Higgs search...

Nevertheless, it had to be shown to be the SM Higgs, e.g.

- $J_H^P = 0^+$: H $\to$ ZZ and H $\to$WW angular distribution of decay products
- H $\to$ XY... cross sections follow the SM predictions
- There is one Higgs boson only (no charged or more neutral ones)

CMS: H $\rightarrow \gamma\gamma$ (VBF)



Vertex for measuring the $\gamma\gamma$ invariant mass:

two hadron jets from vector boson fusion.

CMS: $H \to \gamma\gamma$ mass distribution

CMS Collaboration:

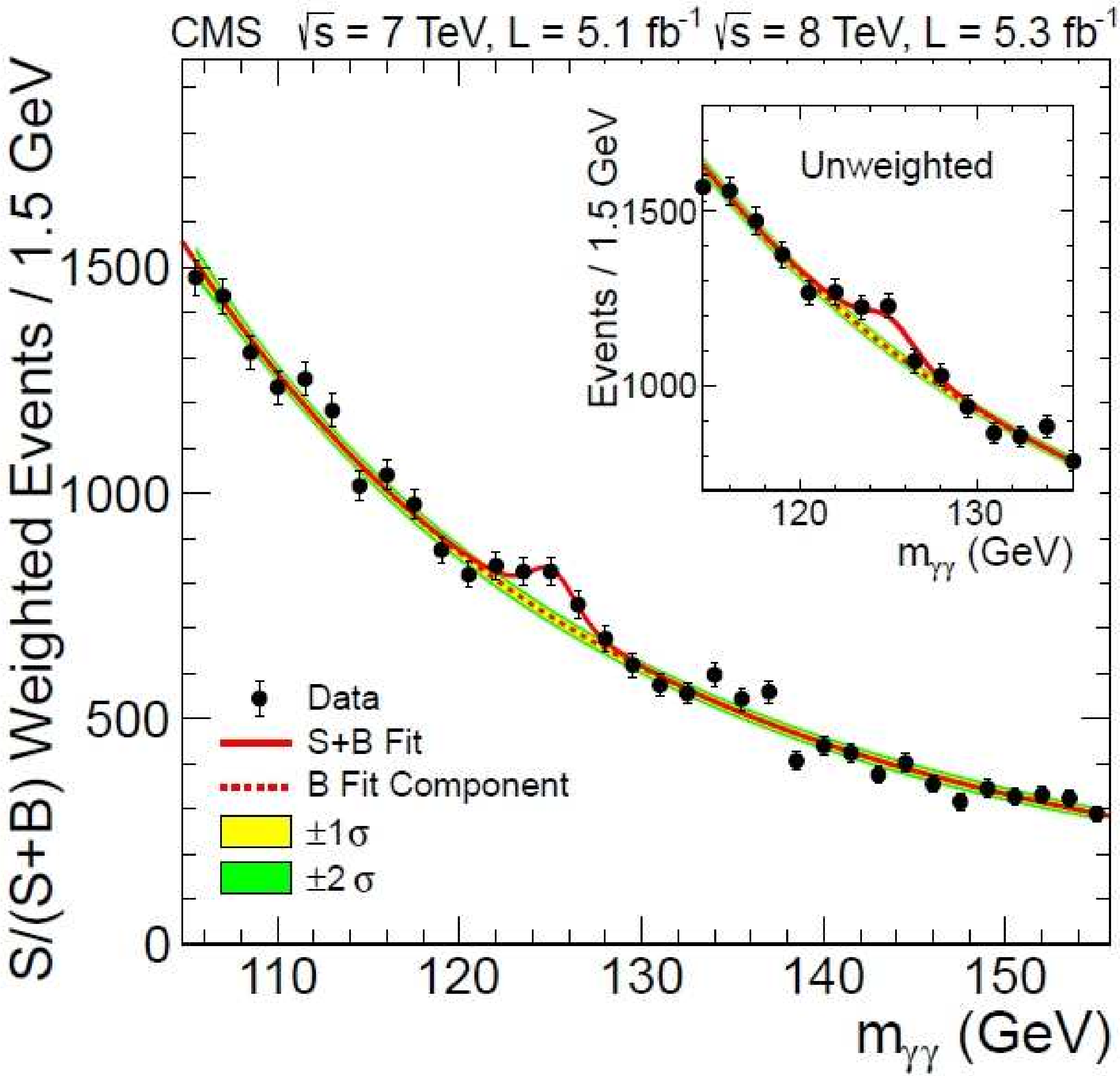
Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC

Phys. Lett. B 716 (2012) 30-61

text: 50%,

2899 authors

in 16 pp.

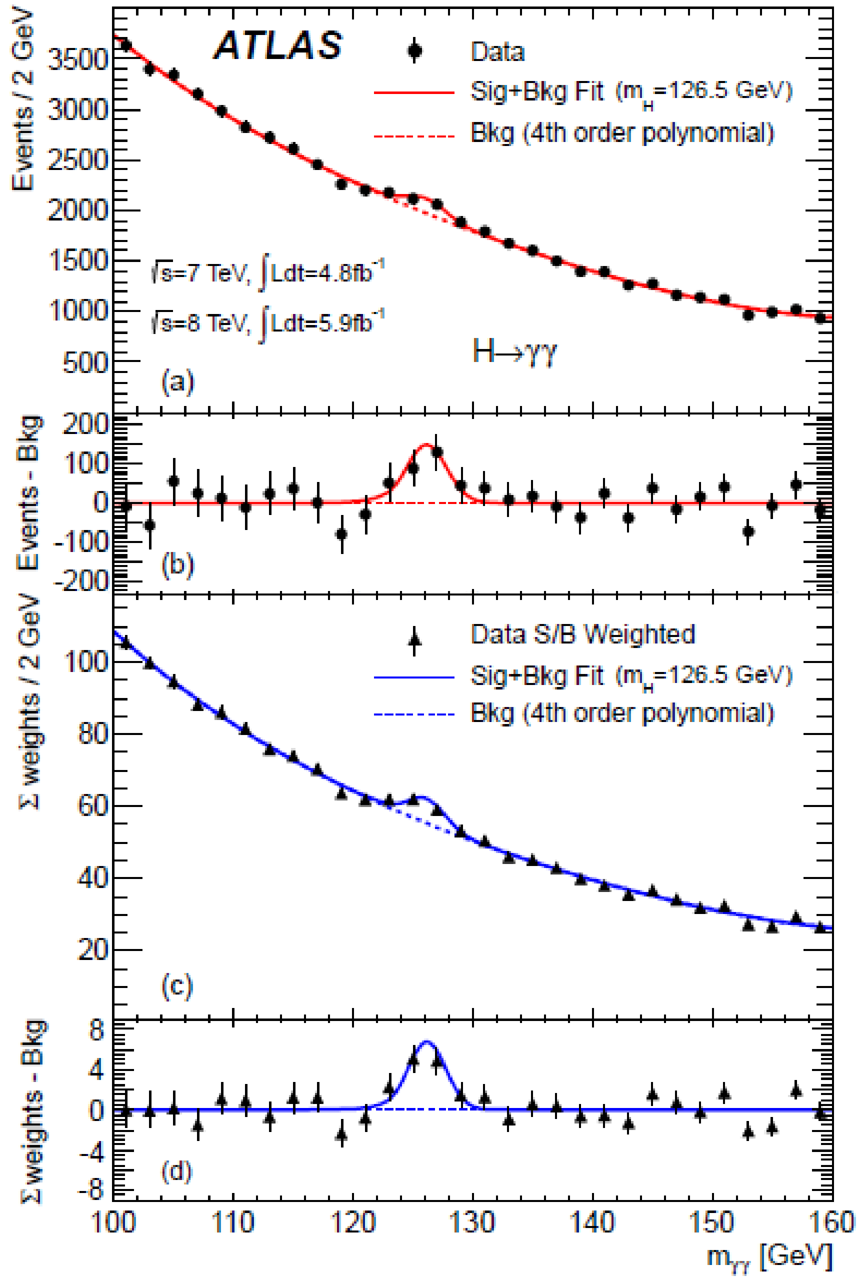


ATLAS: H $\rightarrow \gamma\gamma$ mass distribution

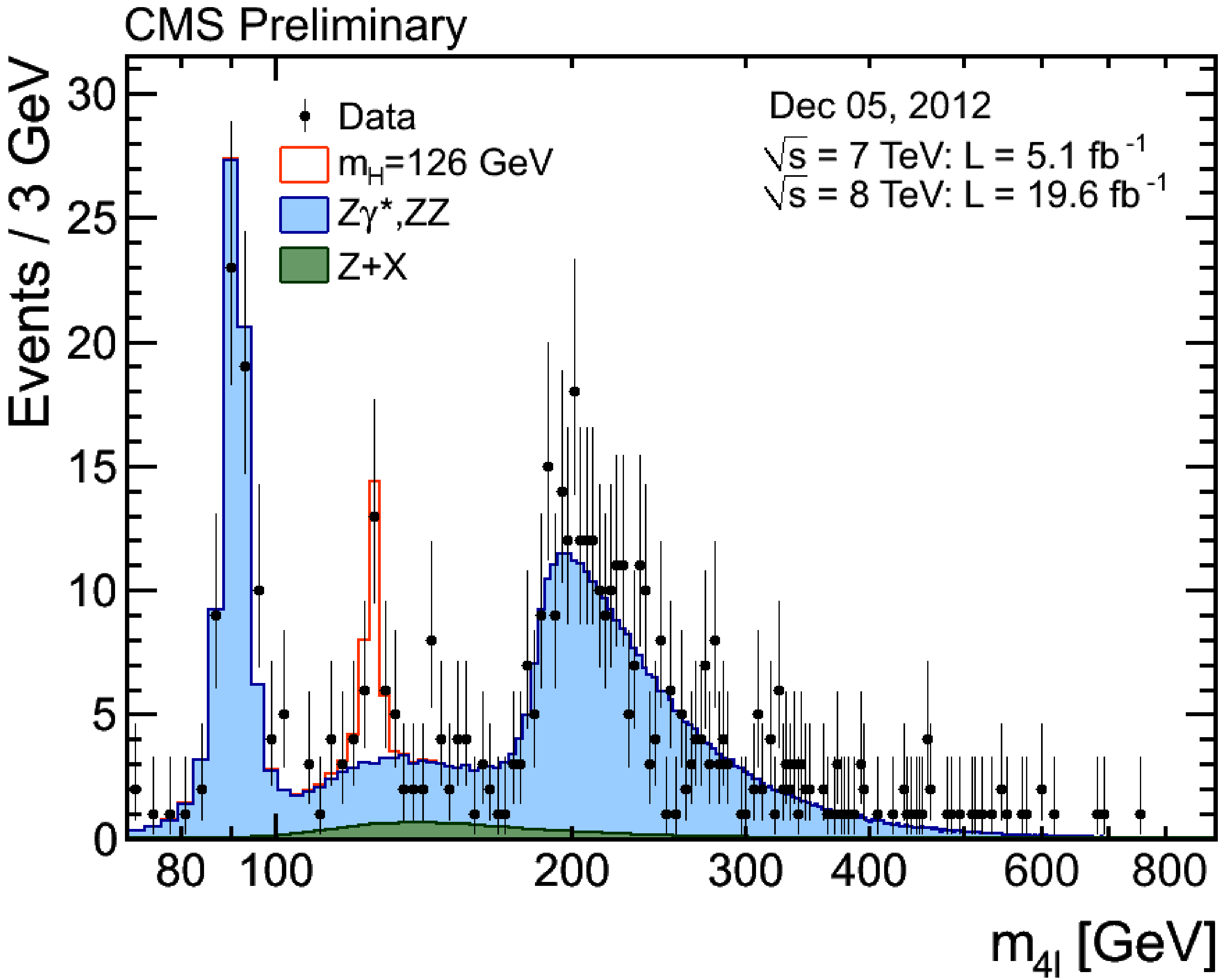
ATLAS Collaboration
(2931 authors):

Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC

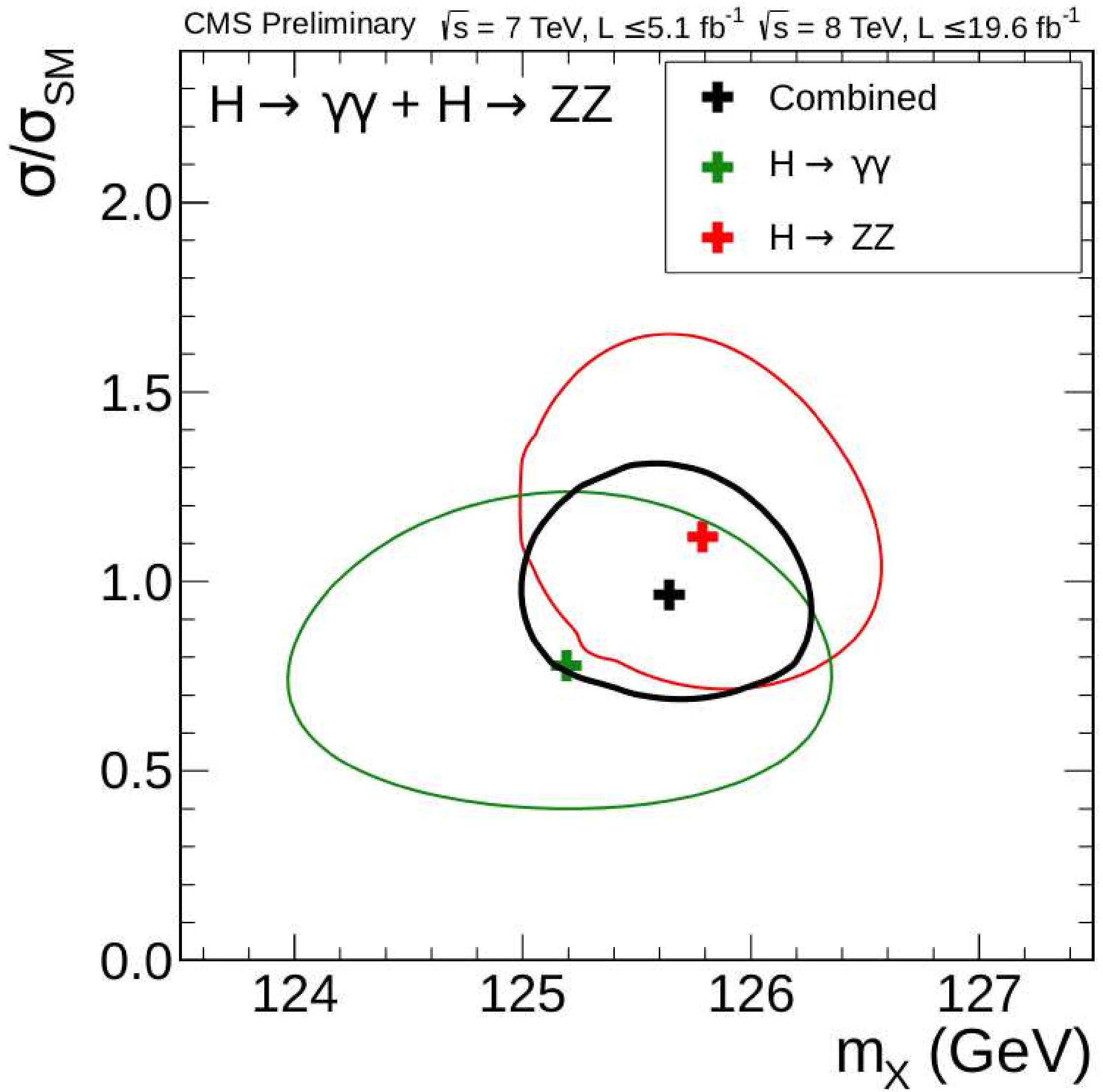
Phys. Lett. B 716 (2012) 1–29



CMS: $\mathrm{H} \rightarrow \mathrm{ZZ}^* \rightarrow \ell^+\ell^-\ell^+\ell^-$

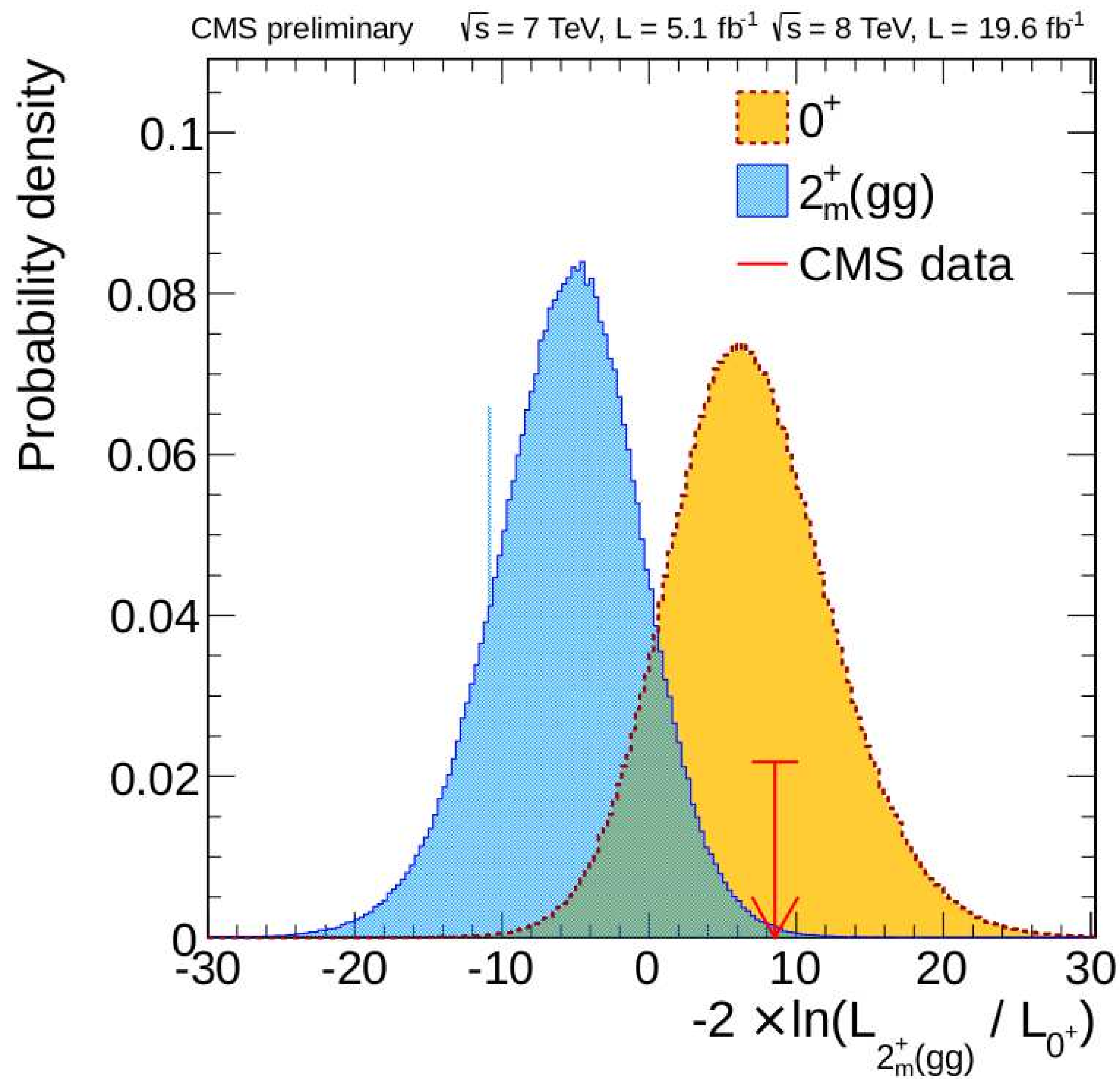


CMS, March 2013: mass vs. x-sec



$$< M_{\mathrm{X}} >= 125.7 \pm 0.3(\mathrm{stat}) \pm 0.3(\mathrm{syst})\ \mathrm{GeV}/c^2$$

CMS, March 2013: spin, parity

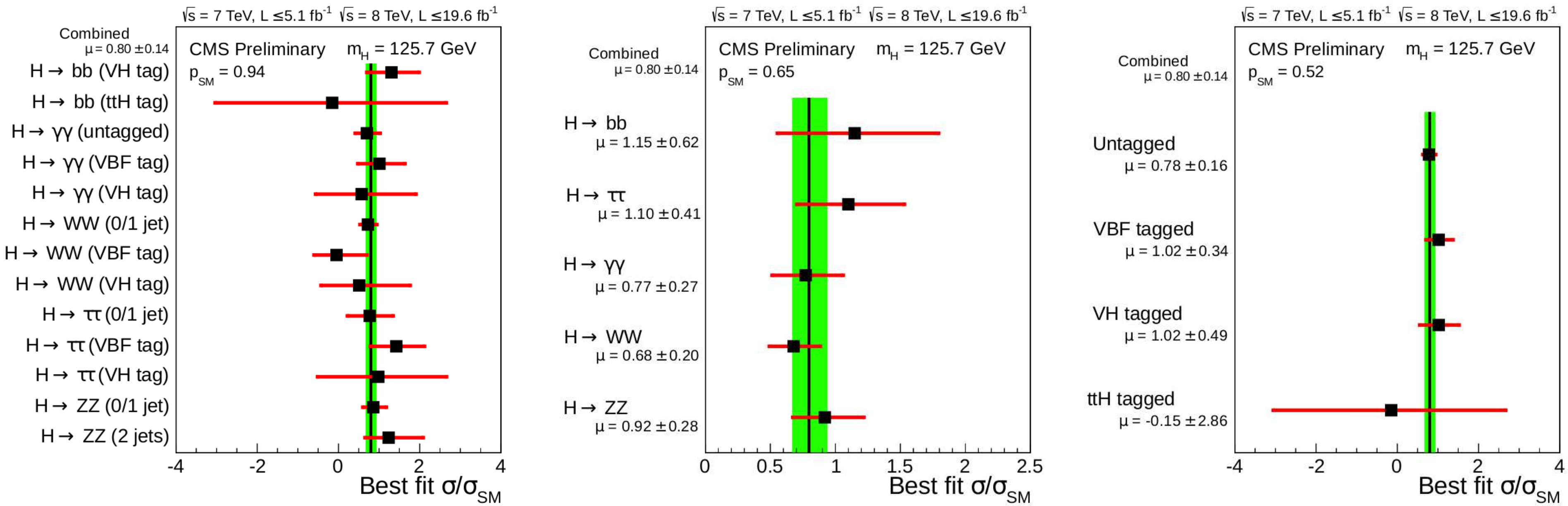


CMS data favor **+** parity and $J_X = 0$

CMS Physics Analysis Summary HIG-13-005

Is it the SM Higgs boson?

It is a Higgs boson! Is it that of the Standard Model?



Branching ratios of different decay channels

as compared to SM predictions for a 126 GeV Higgs boson

$$< \sigma/\sigma_{SM} >= 0.80 \pm 0.14$$

CMS Physics Analysis Summary HIG-13-005

ATLAS result is similar (ATLAS-CONF-2013-034):

$$< \sigma/\sigma_{SM} >= 1.3 \pm 0.13 \text{ (stat) } \pm 0.14 \text{ (syst)}$$

Mass and signal strength

(determined consistently, in various ways)

Mass averaged for decay modes

ATLAS: $\mathbf{125.5 \pm 0.2(stat)} \left\{ \begin{array}{c} \mathbf{+0.5} \\ \mathbf{-0.6} \end{array} \right\} \mathbf{(syst)}$ GeV/c^2

CMS: $\mathbf{125.7 \pm 0.3(stat) \pm 0.3(syst)}$ GeV/c^2

Total production probability summarized for all decay channels as compared to the SM prediction for $M_H = 126$ GeV:

CMS: $\mathbf{0.80 \pm 0.14}$

ATLAS: $\mathbf{1.43 \pm 0.16(stat) \pm 0.14(syst)}$

All agree with the Standard Model (unfortunately)

Nobel Prize in Physics, 2013

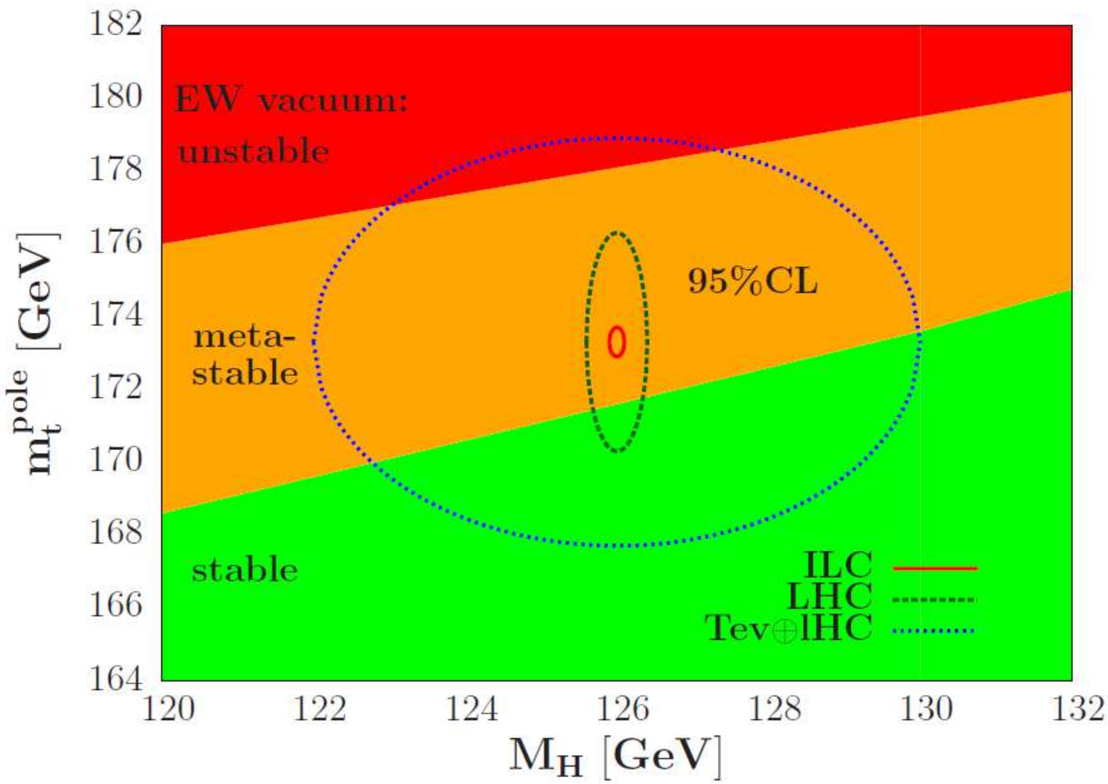
The Nobel prize was awarded to François Englert and Peter W. Higgs "for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider."

Rolf-Dieter Heuer, the Director General of CERN, announces the Nobel Prize in the ATLAS-CMS building of CERN

What does $M_{\rm H} = 126$ GeV mean?

Conference *Why $M_H = 126$ GeV?*, Madrid, 25-27 Sep. 2013

- $M_{\rm H}$ vs. $M_{\rm top}$ is critical, at vacuum stability border
- Need very precise $M_{\rm H}$, $M_{\rm top}$ and α_s.
- SM may be valid until Planck energy (10^{18} GeV)!
- New physics anywhere??



S. Alekhin et al., arXiv:1207.0980, 2012

OR:

- *Somebody is pulling our leg???*
- *Anthropic principle???*

Higgs Jokes after the Discovery

- The Higgs discovery unleashed a Big Bang of bad jokes.
- The Higgs discovery makes me feel heavier already. What we need instead is the anti-Higgs. A particle that takes mass away.
- Physicists *massively* celebrated the Higgs discovery.
- Are you there God Particle? It’s me, Average Person that doesn’t understand you.
- Better double check. I thought I discovered a Higgs boson under my couch last year but turned out to be an old marble.
- If we can control the Higgs field then we can really build Weapons of Mass Destruction.
- A top quark and a Higgs had a public break up on the weekend. The quark stormed off, complaining that the Higgs kept telling it how heavy it was and had nothing else to say.

What Next?

Supersymmetry (SUSY)?

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: $\alpha, \ \Theta_W, \ \Lambda_{QCD}$; 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
- $M_\nu > 0 \Rightarrow +3$ 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.

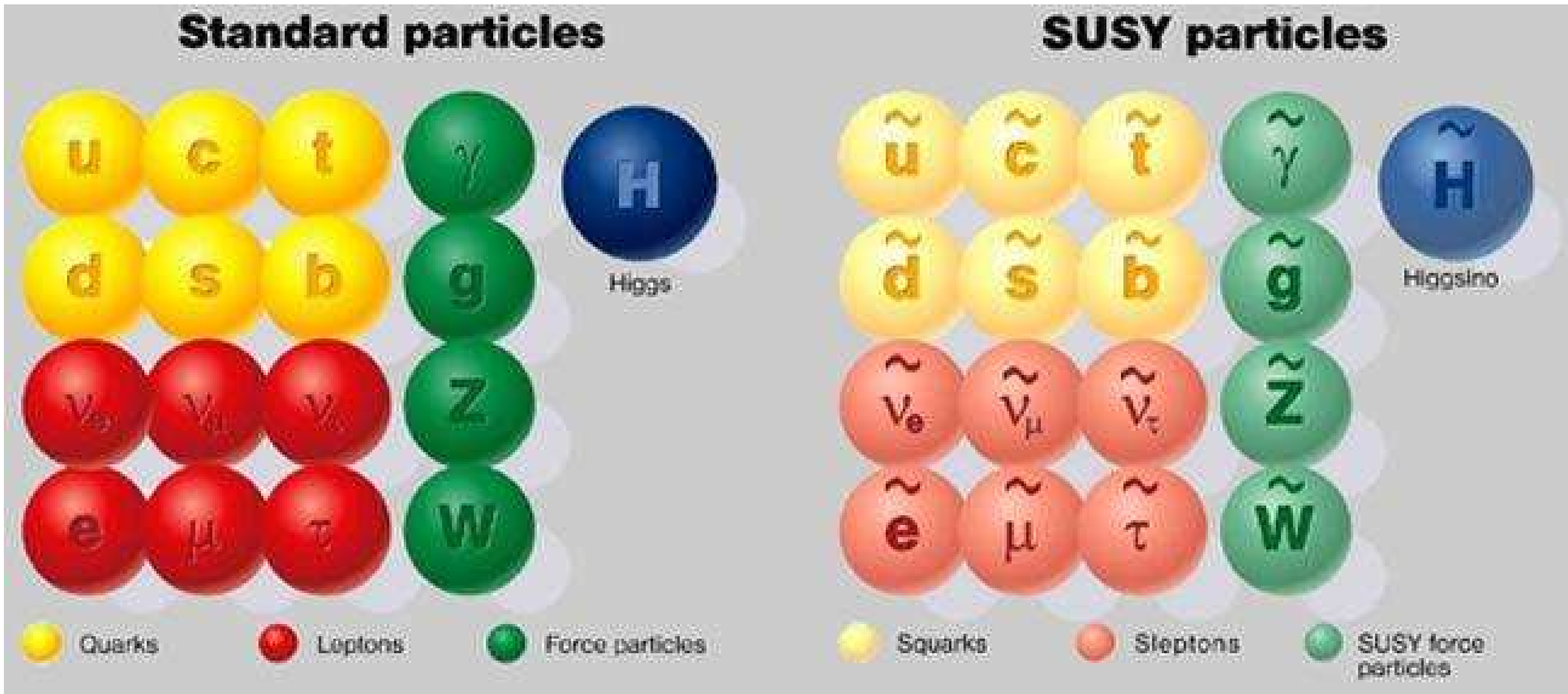
Supersymmetry (SUSY)

Hypothesis: Fermions and bosons exist in pairs:

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

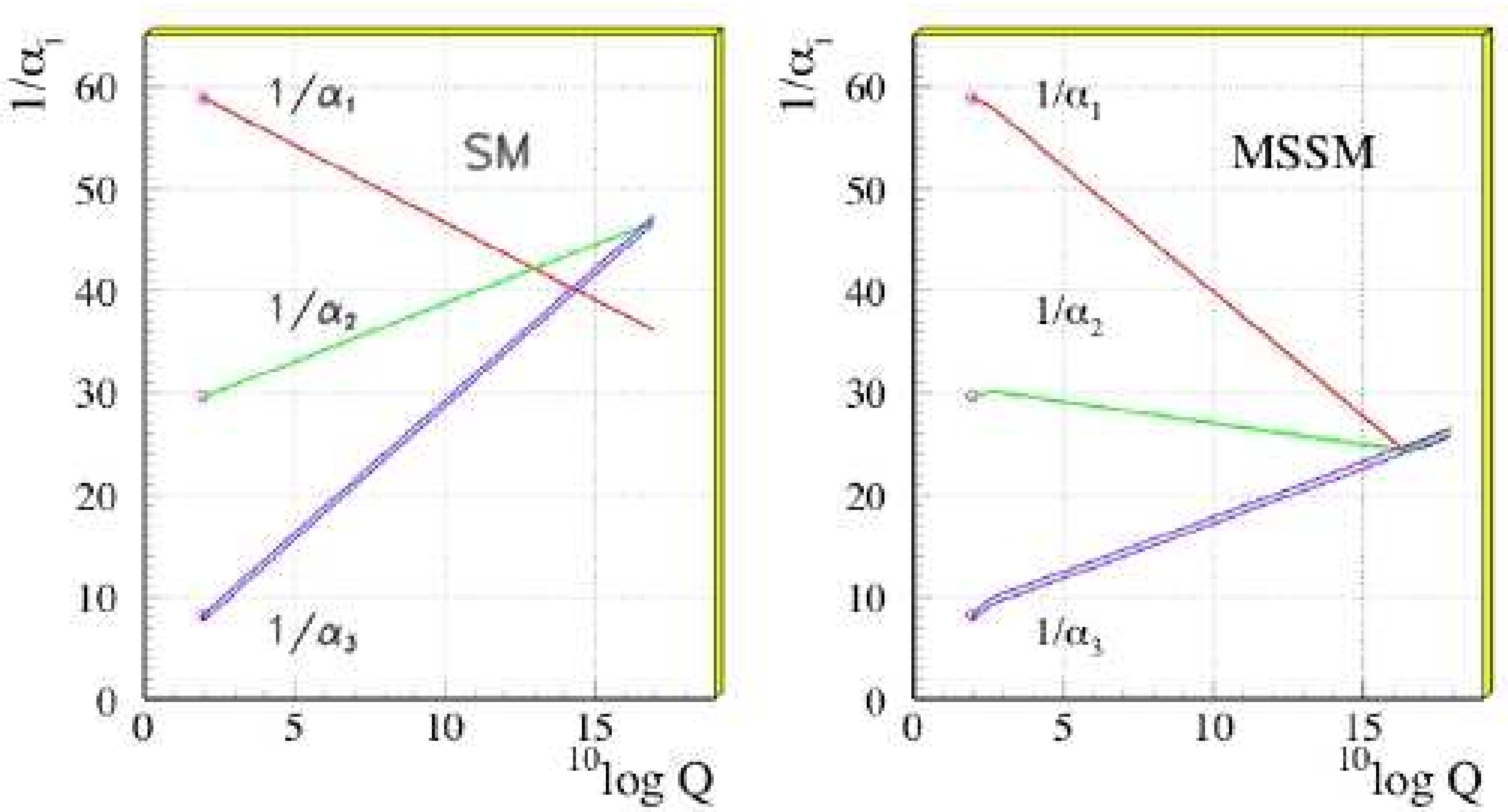
Identical particles, just spins different $\quad (\tilde{S} = S - \frac{1}{2})$

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 ⇒ 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 $\Rightarrow$ masses to upper and lower fermions

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

Simplest SUSY models (105 $\Rightarrow$ 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

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?

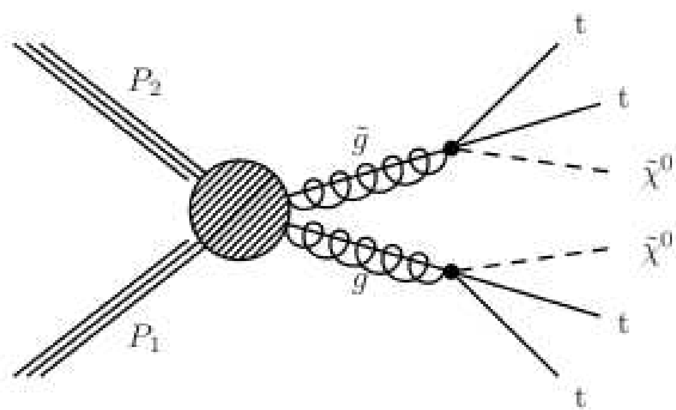
- Boundaries of search sensitivity, both for data analysis and for new theories.
- Characterizing new physics signals: what models can be associated?
- Limits on more general models: from possible cross-sections.

Exclusion with simplified models

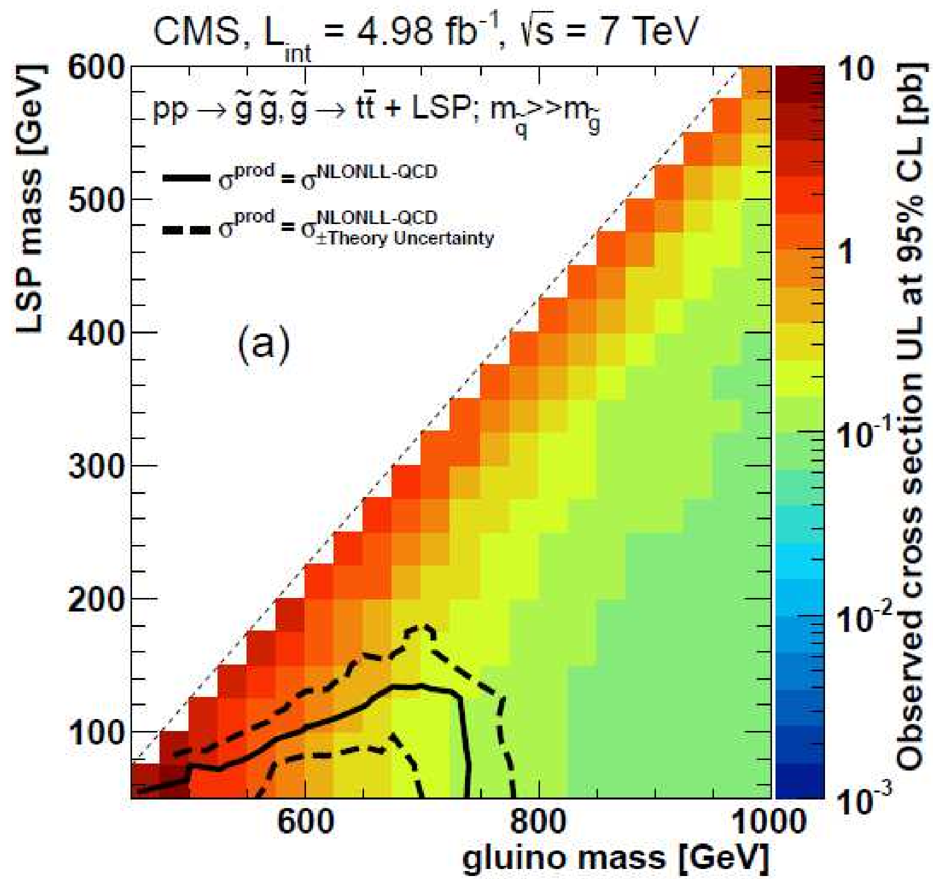
Search for supersymmetry in events with b-quark jets and missing transverse energy in pp collisions at 7 TeV,

Phys.Rev. D86 (2012) 072010

Pure hadronic events: no neutrino, missing momentum from LSP only



$\tilde{g}\tilde{g} \to$ 4 t-jets + LSPs



CL 95% exclusion for production of gluino pairs to test models

Conclusion

- Broken symmetries play a fundamental role in particle physics.
- At LHC we very probably observed the SM Higgs boson or maybe a Higgs boson of a more general model.
- The LHC will restart in 2015 with much higher energy and luminosity. 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

CMS strategies for discovery

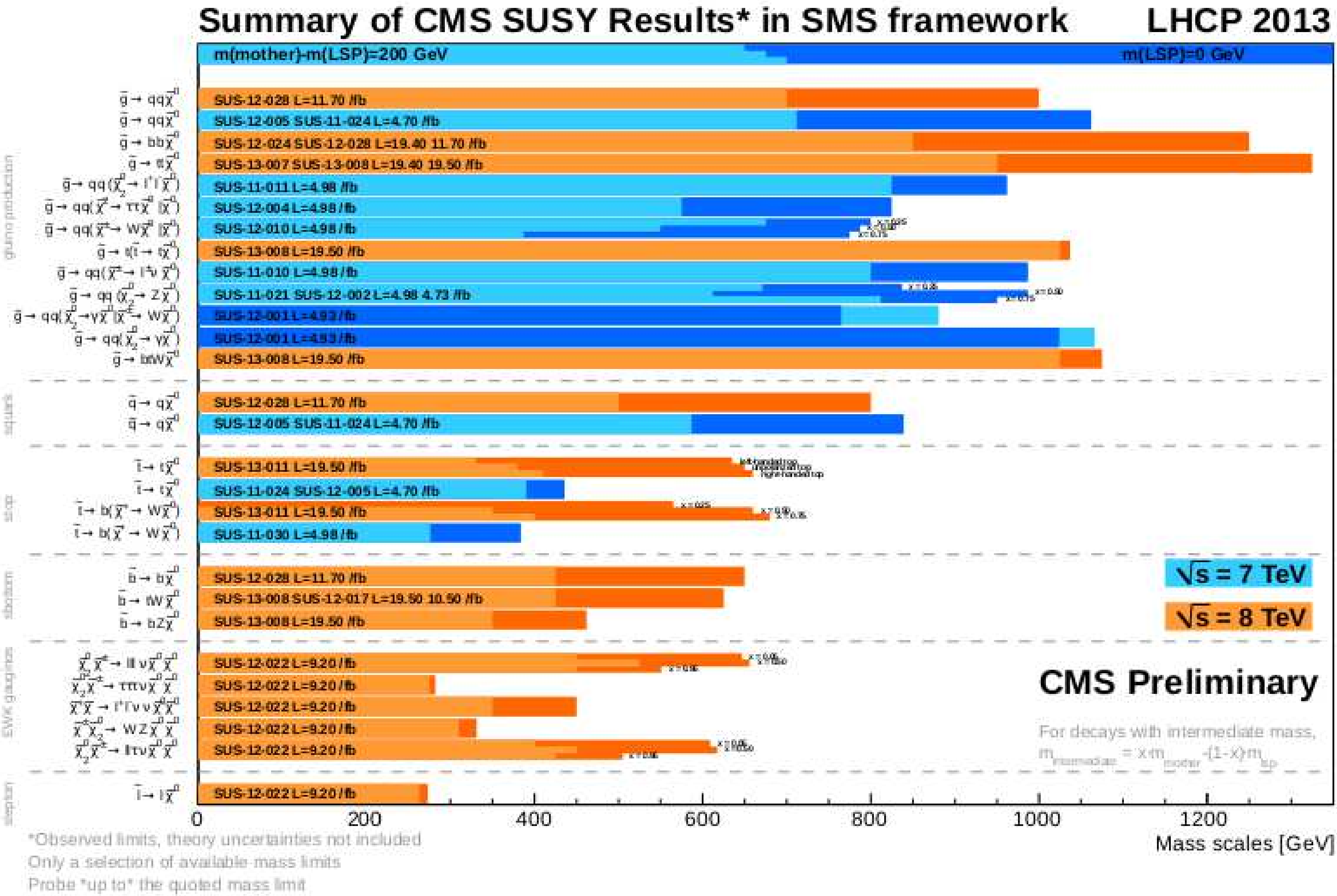
- α_T search for early discovery in (forced) 2-jet events $(E_T(J_1) > E_T(J_2))$:
  Cut $\alpha_T = \frac{E_T(J_2)}{M_T(J_1,J_2)}$
  $= \frac{E_T(J_2)}{\sqrt{(E_T(J_1)+E_T(J_2))^2-(p_x(J_1)+p_x(J_2))^2-(p_y(J_1)+p_y(J_2))^2}}$
  Exclusive 2-jet, inclusive 3-jet search

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


Summary of CMS SUSY Results* in SMS framework
LHCP 2013
m(mother)-m(LSP)=200 GeV
m(LSP)=0 GeV
SUS-12-028 L=11.70 /fb
SUS-12-005 SUS-11-024 L=4.70 /fb
SUS-12-024 SUS-12-028 L=19.40 11.70 /fb
SUS-13-007 SUS-13-008 L=19.40 19.50 /fb
SUS-11-011 L=4.98 /fb
SUS-12-004 L=4.98 /fb
SUS-12-010 L=4.98 /fb
SUS-13-008 L=19.50 /fb
SUS-11-010 L=4.98 /fb
SUS-11-021 SUS-12-002 L=4.98 4.73 /fb
SUS-12-001 L=4.93 /fb
SUS-12-001 L=4.93 /fb
SUS-13-008 L=19.50 /fb
SUS-12-028 L=11.70 /fb
SUS-12-005 SUS-11-024 L=4.70 /fb
SUS-13-011 L=19.50 /fb
SUS-11-024 SUS-12-005 L=4.70 /fb
SUS-13-011 L=19.50 /fb
SUS-11-030 L=4.98 /fb
SUS-12-028 L=11.70 /fb
SUS-13-008 SUS-12-017 L=19.50 10.50 /fb
SUS-13-008 L=19.50 /fb
SUS-12-022 L=9.20 /fb
SUS-12-022 L=9.20 /fb
SUS-12-022 L=9.20 /fb
SUS-12-022 L=9.20 /fb
SUS-12-022 L=9.20 /fb
SUS-12-022 L=9.20 /fb
√s = 7 TeV
√s = 8 TeV
CMS Preliminary
For decays with intermediate mass,
0
200
400
600
800
1000
1200
Mass scales [GeV]
*Observed limits, theory uncertainties not included
Only a selection of available mass limits
Probe *up to* the quoted mass limit