Search for Higgs and SUSY in the CMS experiment at LHC

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Dezső Horváth

on behalf of the CMS Collaboration

horvath.dezso@wigner.mta.hu

Wigner Research Centre for Physics,
Institute for Particle and Nuclear Physics, Budapest, Hungary
& ATOMKI, Debrecen, Hungary

Outline

- The Higgs boson of the Standard Model.
- Its (*possible*) observation at LHC.
- Supersymmetry (SUSY).
- Exclusion of the simplest versions.
- New search strategy: simplified models.
- Results of 2011-12.
- Plans and hopes.

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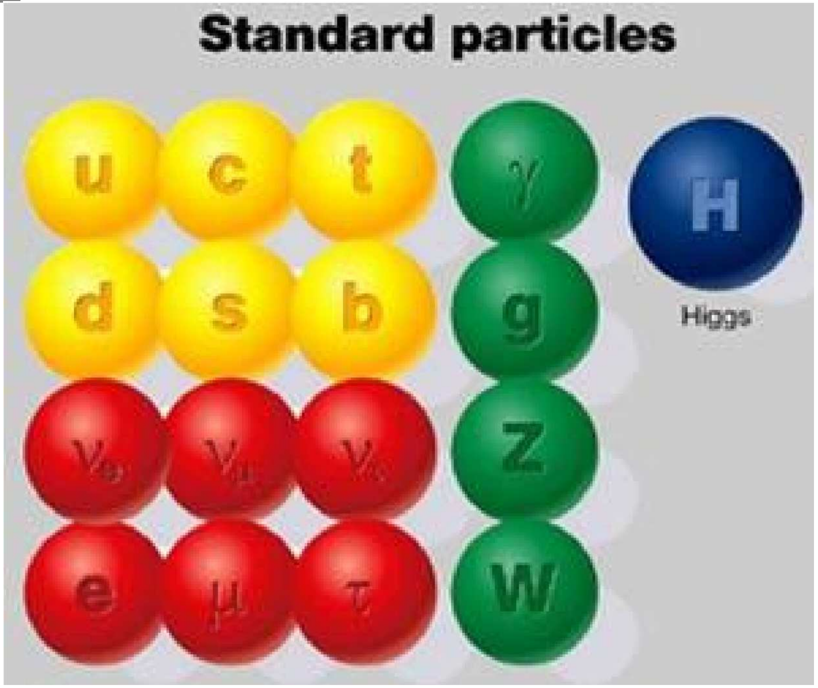
References

- The 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.
- Public Physics Analysis Summaries of CMS on Higgs search
- S.P. Martin: *A Supersymmetry Primer*, hep-ph/9709356, Version 6, September 2011
- D.S.M. Alves et al., The LHC New Physics Working Group: *Simplified Models for LHC New Physics Searches*, arXiv:1105.2838v1 [hep-ph] 13 May 2011
- The CMS Collaboration: Many papers on search for supersymmetry in arXiv, 2012 and Public Physics Analysis Summaries.

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 ($q\bar{q}$) + baryons (qqq)

Nucleons ($I = \frac{1}{2}$): p = (uud) n = (udd) $\bar{p} = (\bar{u}\bar{u}\bar{d})$

Pions, the lightest mesons:

$$\pi^+ = (u\bar{d}) \quad \pi^0 = \frac{1}{\sqrt{2}}(u\bar{u} - d\bar{d}) \quad \pi^- = (\bar{u}d)$$

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 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.

Glory Road of the Standard Model

Status in 2012

Includes hundreds of measurements of all experiments

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

Slightly deviating quantity used to change

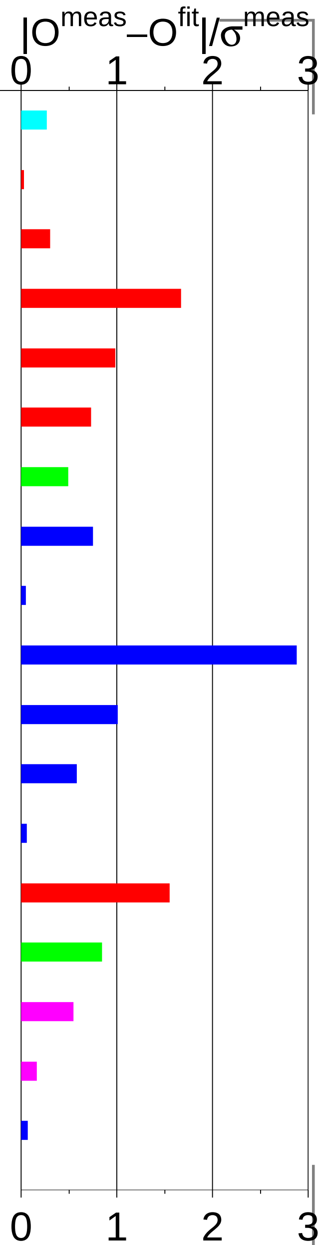
Now it is forward-backward asymmetry of

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

LEP Electroweak Working Group:

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

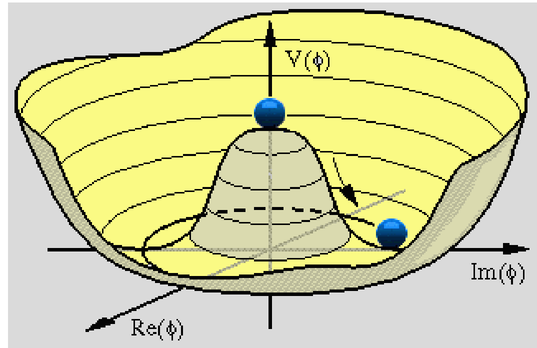
	Measurement	Fit
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02750 ± 0.00033	0.02759
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959
σ^0_{had} [nb]	41.540 ± 0.037	41.478
R_l	20.767 ± 0.025	20.742
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.01645
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481
R_b	0.21629 ± 0.00066	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 of the Higgs boson in press...

The Higgs boson walks into a bar. The bartender says "Watch out, there were some guys looking for you."

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?”

Where is the Higgs boson?

By-product of spontaneous symmetry breaking of the SM

Most wanted particle of physics as

the only missing piece of the Standard Model.

Experimentally not observed before 2012,

LEP (2002): M(H) > 114.4 GeV

„It was in 1972 ...

that my life as a boson really began"

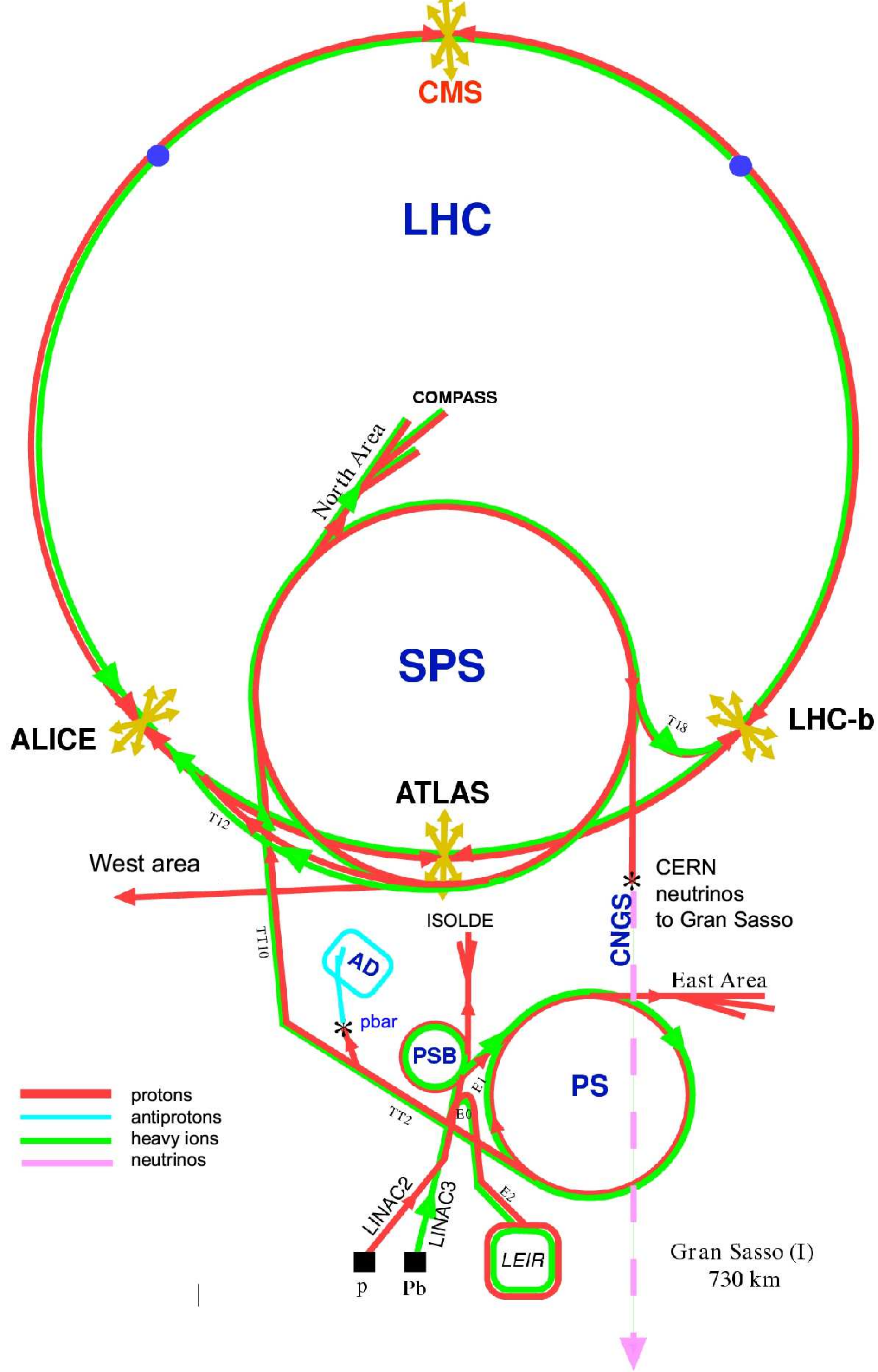
Peter Higgs:

My Life as a Boson: The Story of „The Higgs",

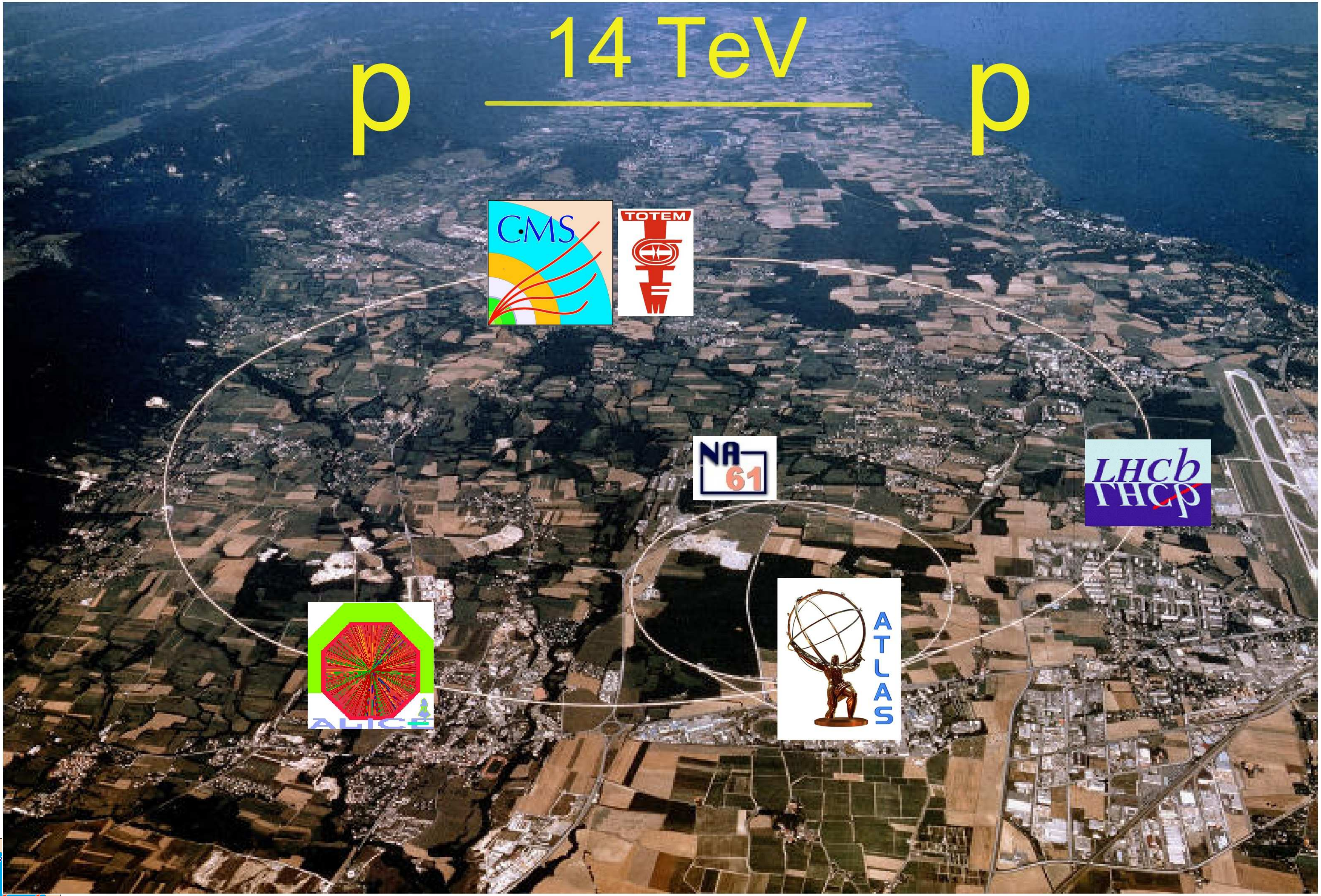
Int. J. Mod. Phys. A **17** Suppl. (2002) 86-88.

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



Steering magnets of LHC

1232 superconducting magnets (before installation)
($L = 15$ m, $M = 35$ t, $T = 1.9$ K, $B = 8.3$ T)

Dipole magnets of LHC in the tunnel

Luminosity

Luminosity: $\boxed{L = fn\frac{N_1 N_2}{A}}$ $[L] = \mathrm{s}^{-1}\mathrm{cm}^{-2}$ ($\sim$ flux)

f: circulation frequency; n: nr. of bunches in ring;
N_1, N_2 particles/bunch; A: spatial overlap

Rate of reaction with cross section σ at ϵ efficiency

$$R = \epsilon\sigma L$$

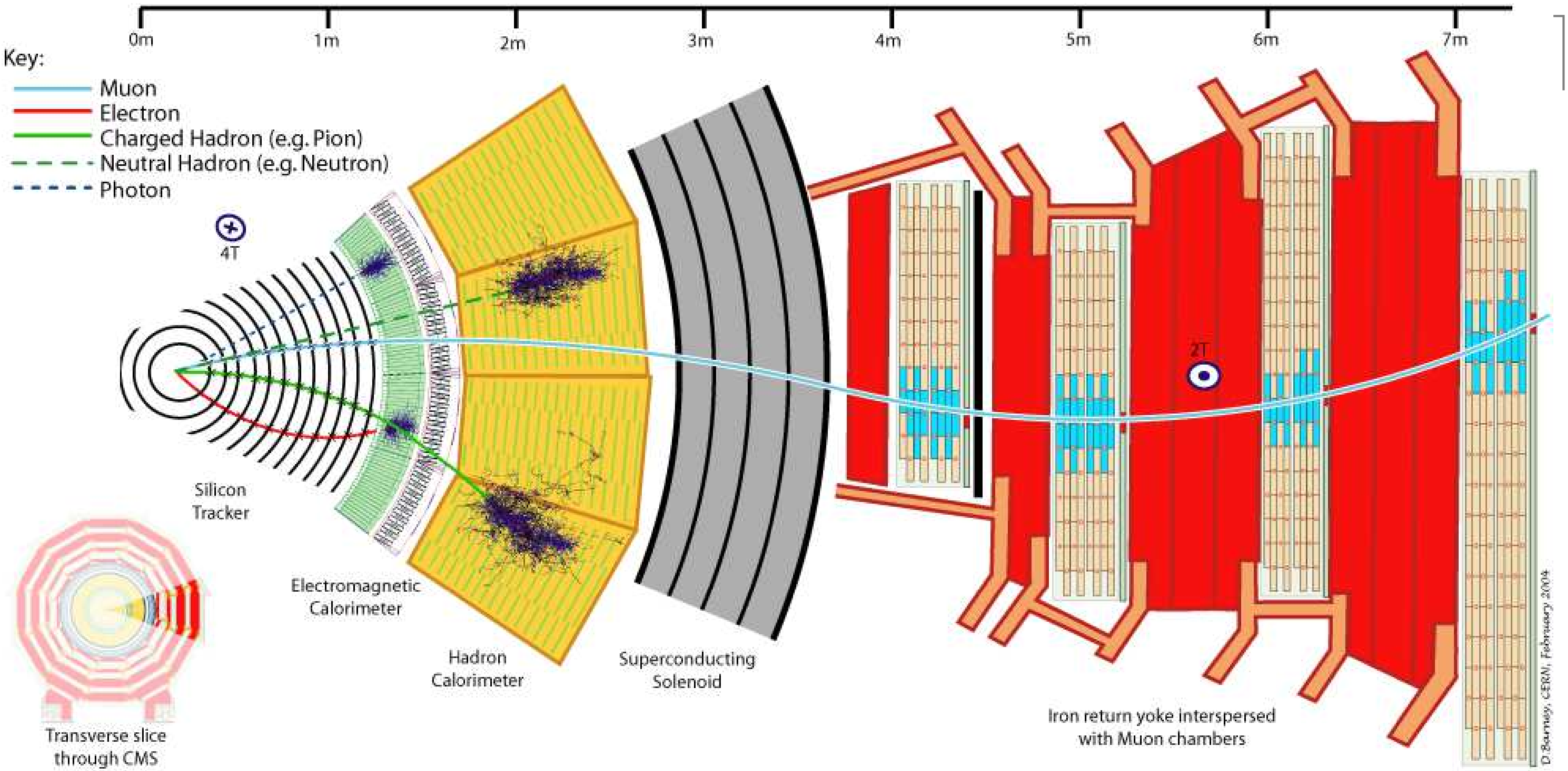
Integrated luminosity: $\int_{t_1}^{t_2} L dt$; $[\mathrm{pb}^{-1},\ \mathrm{fb}^{-1}]$

Amazing performance of LHC!

2010: 0.04 fb^{-1} at 7 TeV; 2011: 5.6 fb^{-1} at 7 TeV;
2012: so far 22 fb^{-1} at 8 TeV (expect ~ 25 fb^{-1})

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 max 400 pictures/sec ⇒ intelligent filter!!

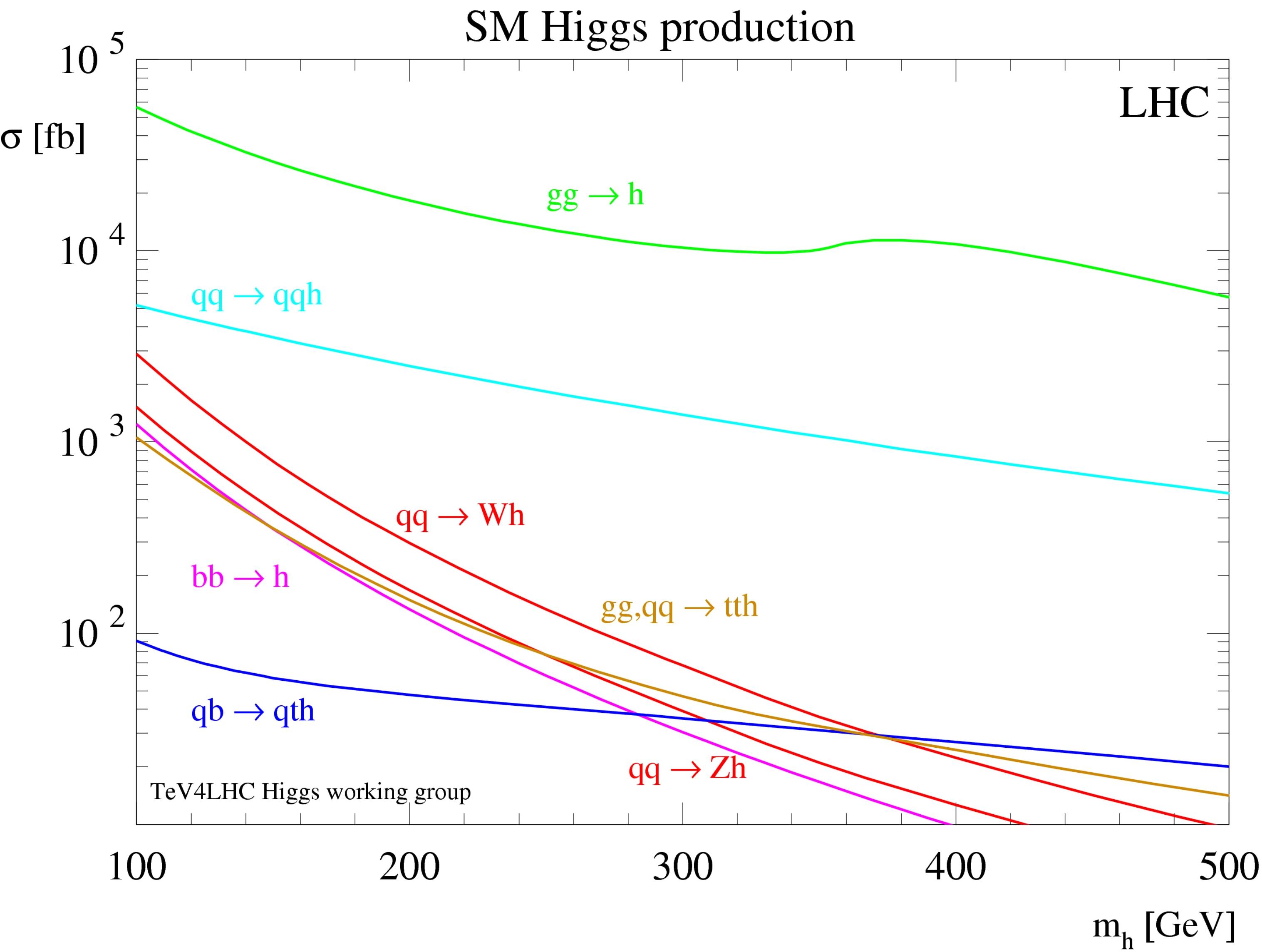
The CMS Collaboration (2012)

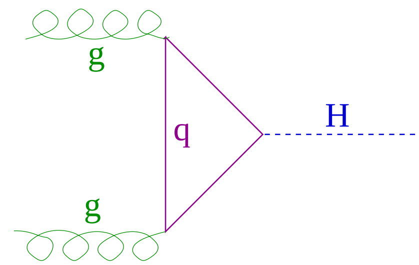
- 179 institutions of 41 countries
- 3275 physicists (incl. 1535 students)
- 790 engineers and technicians
- Participants by countries of institutes:
  USA: 1149, Italy: 439, Germany: 298, Russia: 234

Huge joint effort:
3000 people worked on it for 20 years!

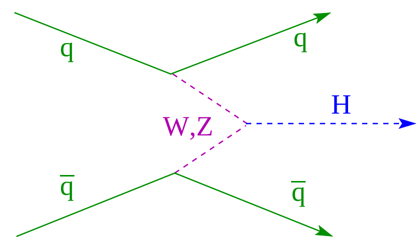
Formation of the SM Higgs boson

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)

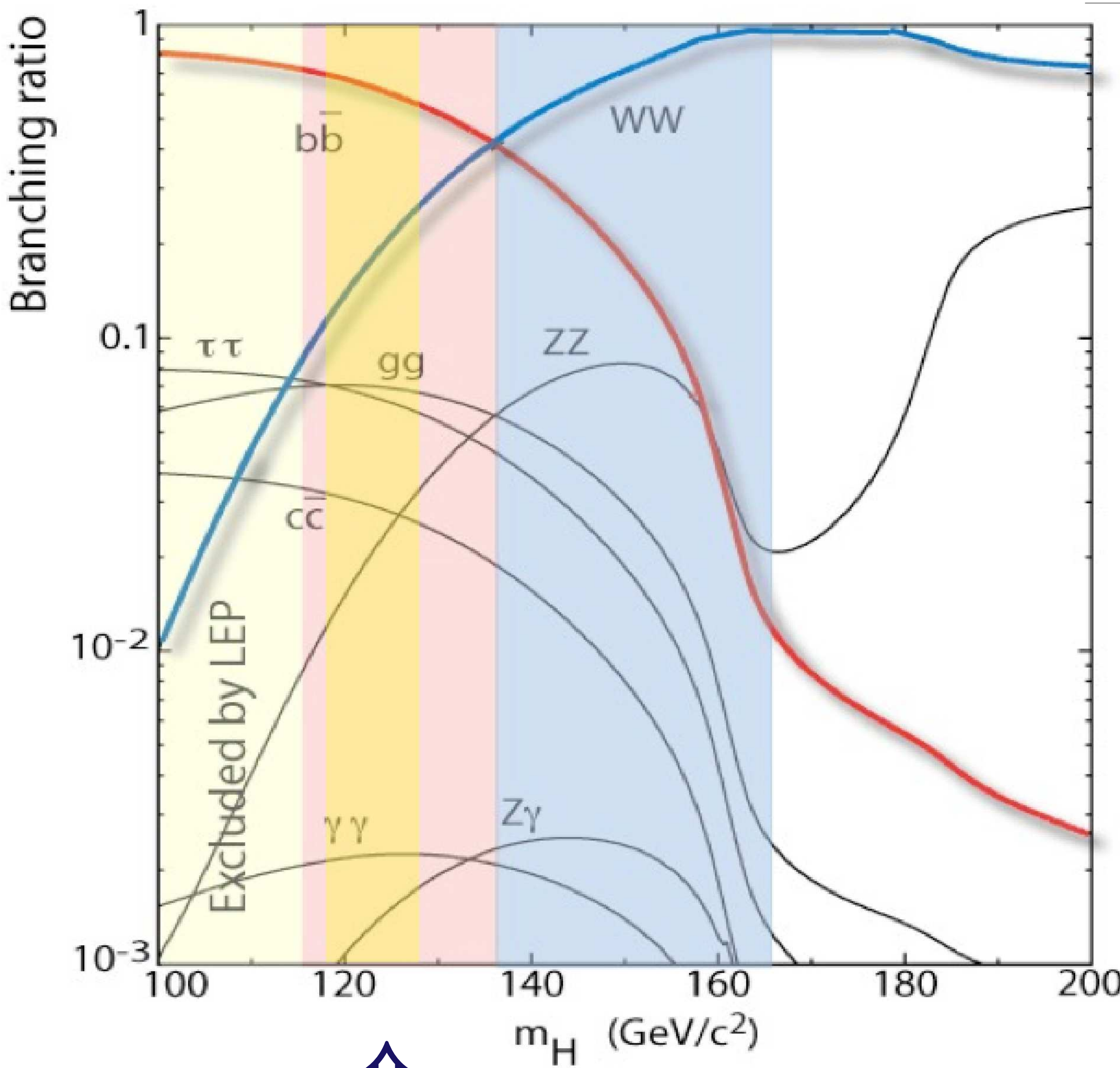
(where many decay processes contest)

Best identified:

$\mathrm{H} \to \gamma\gamma$

Excess observed

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



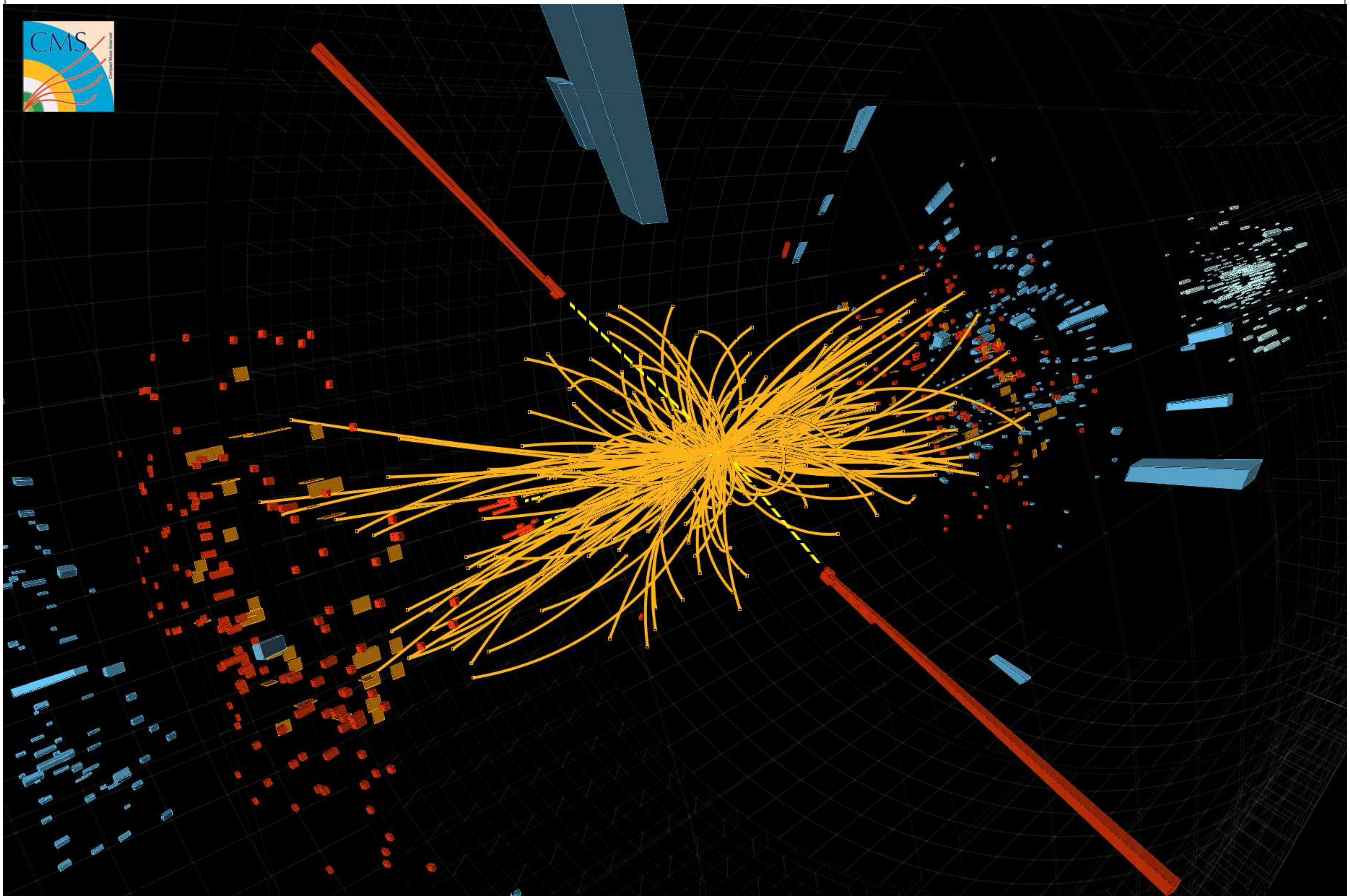
$\Uparrow$

CMS: elektromagnetic calorimeter

optimized for studying H $\rightarrow \gamma\gamma$

75,848 $PbWO_4$ single crystal scintillators

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 H $\rightarrow \gamma\gamma$ and H $\rightarrow$ ZZ $\rightarrow \ell^+\ell^-\ell^+\ell^-$, 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.

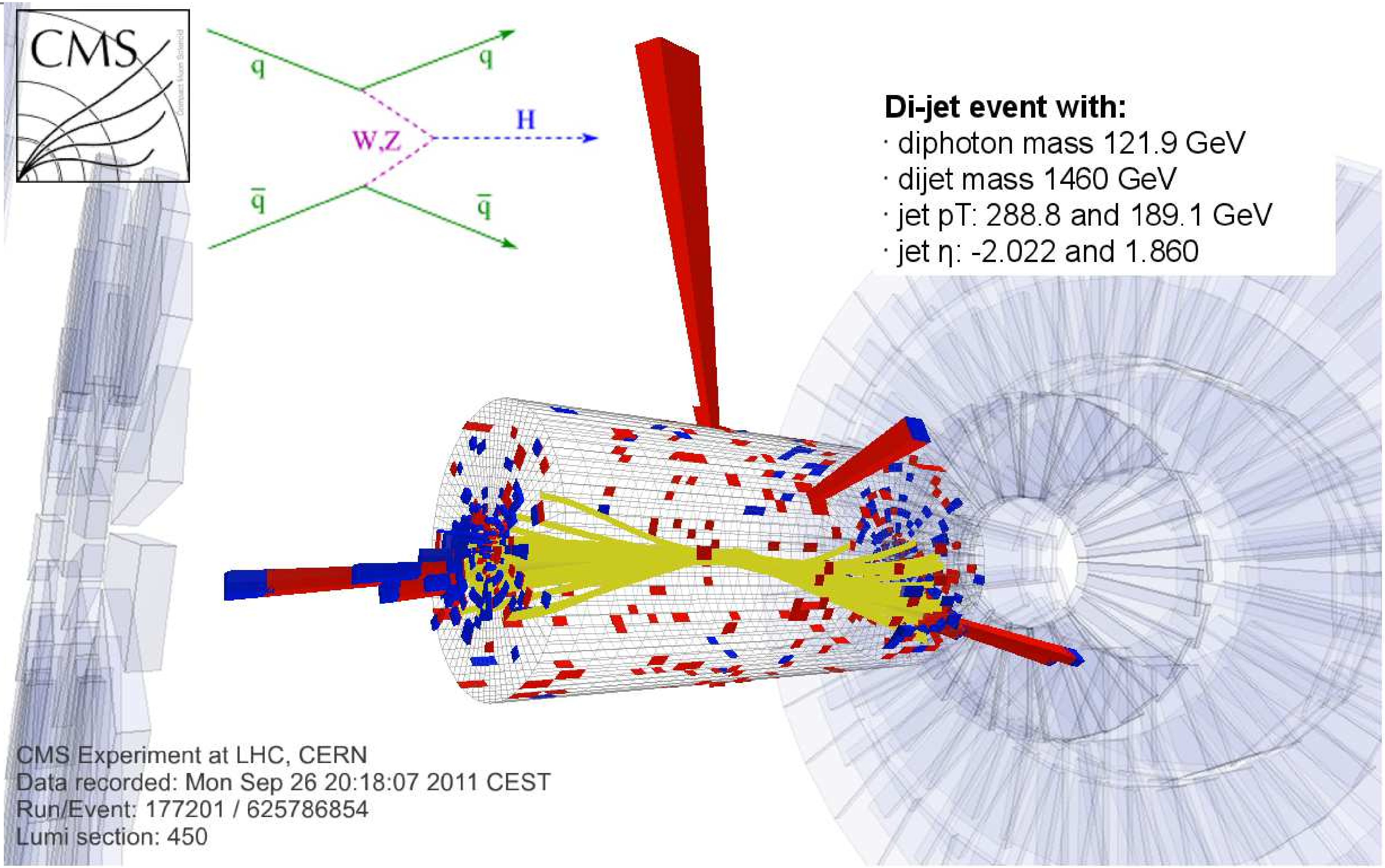
H $\rightarrow \gamma\gamma \Rightarrow S_H =$ 0 or 2

Data analysis was optimized for SM Higgs search...

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

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

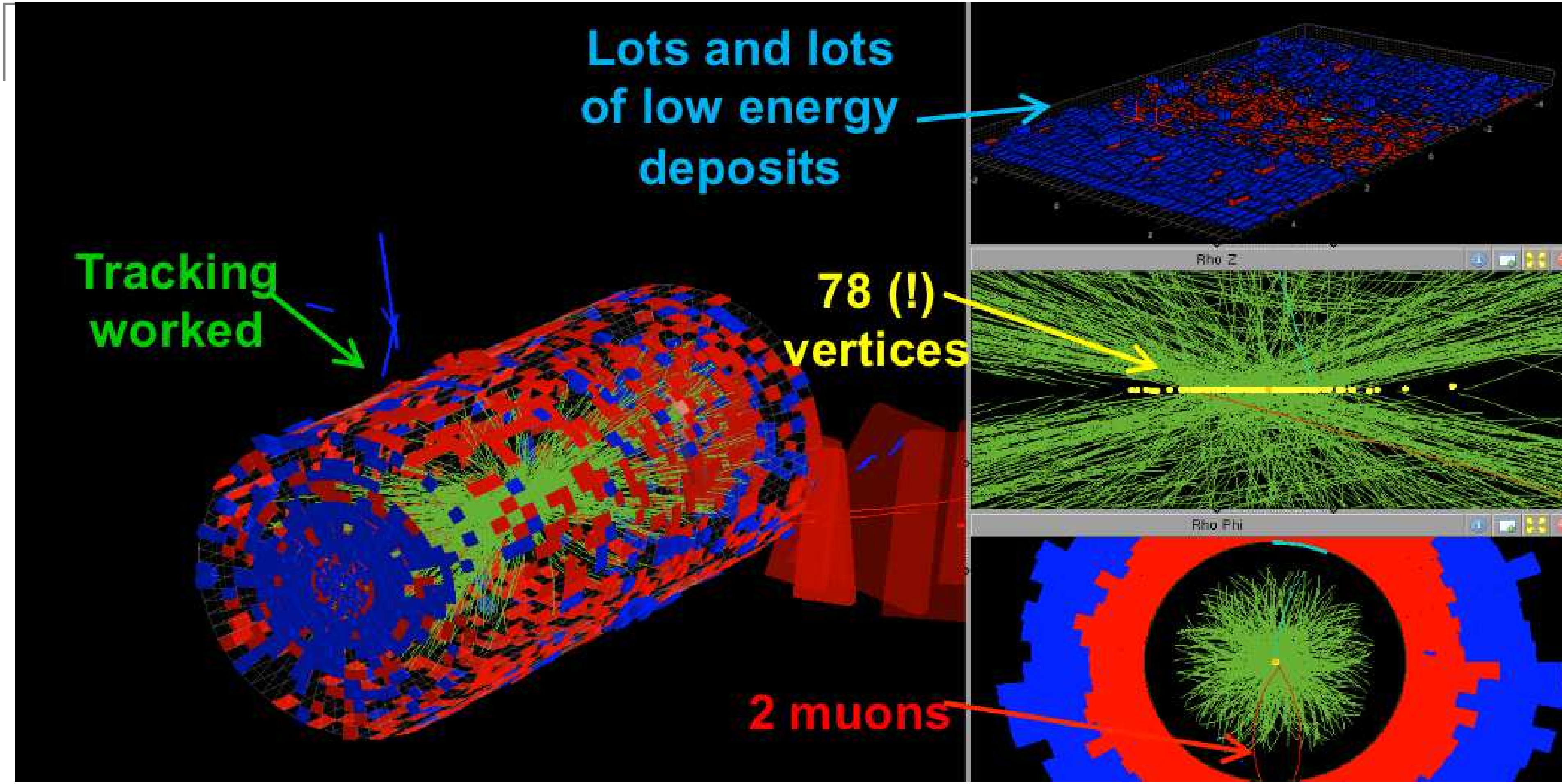
CMS: $H \to \gamma\gamma$ (VBF)



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

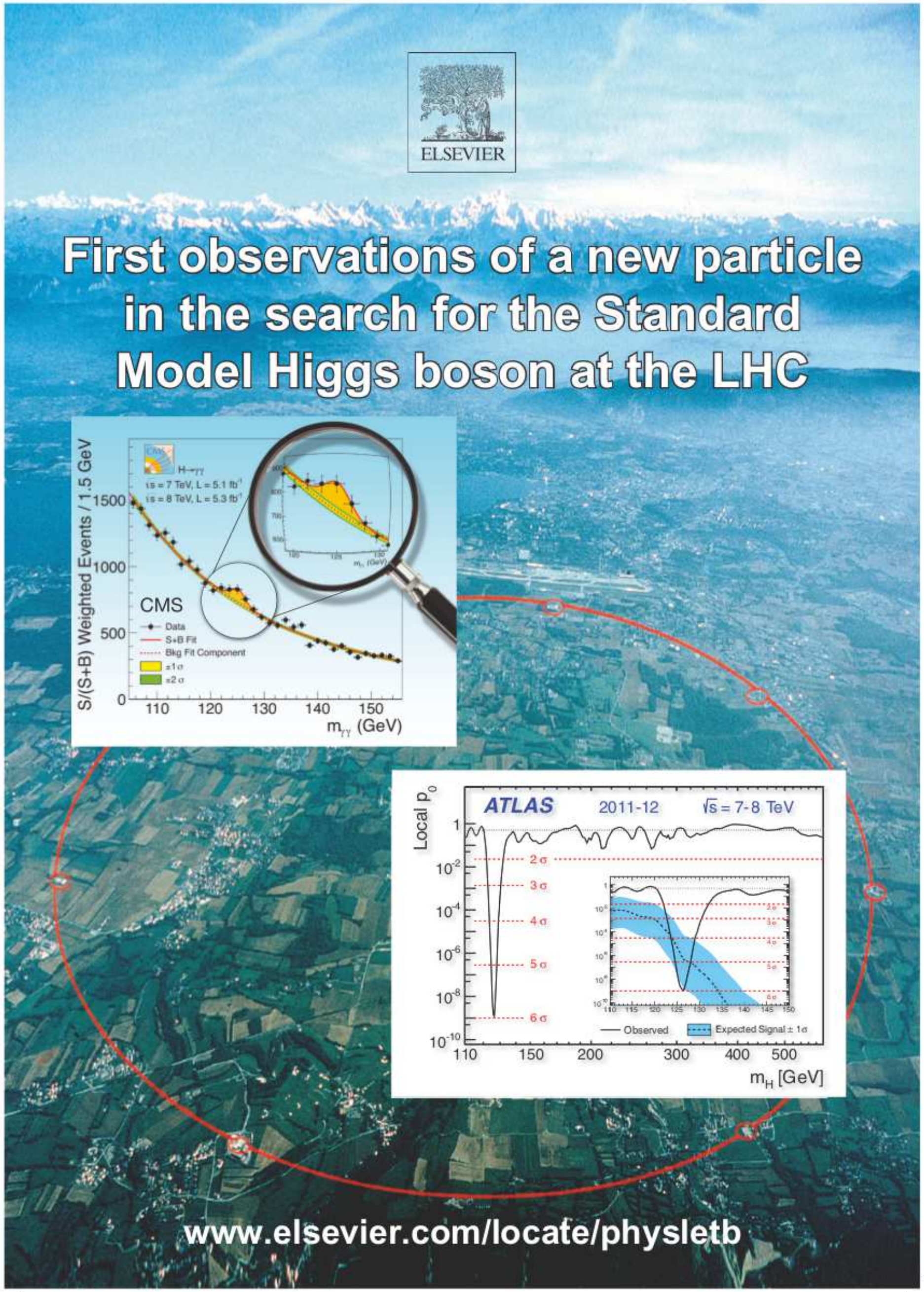
two hadron jets from vector boson fusion.

CMS: 78 identified vertices!



Many p-p collisions can be in the same event (same bunch collision). Record: 78 identified vertices. This increases data taking speed and makes life hard.

CMS and ATLAS: A new boson



Physics Letters B 716 (2012) 1–29

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Physics Letters B

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

ATLAS Collaboration *

This paper is dedicated to the memory of our ATLAS colleagues who did not live to see the full impact and significance of their contributions to the experiment.

ARTICLE INFO

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ABSTRACT

A search for the Standard Model Higgs boson in proton–proton collisions with the ATLAS detector at the LHC is presented. The datasets used correspond to integrated luminosities of approximately 4.8 fb^{-1} collected at $\sqrt{s}=7$ TeV in 2011 and 5.8 fb^{-1} at $\sqrt{s}=8$ TeV in 2012. Individual searches in the channels $H \to ZZ^{(*)} \to 4\ell$, $H \to \gamma\gamma$ and $H \to WW^{(*)} \to e\nu\mu\nu$ in the 8 TeV data are combined with previously published results of searches for $H \to ZZ^{(*)}$, $WW^{(*)}$, $b\bar{b}$ and $\tau^+\tau^-$ in the 7 TeV data and results from improved analyses of the $H \to ZZ^{(*)} \to 4\ell$ and $H \to \gamma\gamma$ channels in the 7 TeV data. Clear evidence for the production of a neutral boson with a measured mass of 126.0 ± 0.4 (stat) ± 0.4 (sys) GeV is presented. This observation, which has a significance of 5.9 standard deviations, corresponding to a background fluctuation probability of 1.7×10^{-9}, is compatible with the production and decay of the Standard Model Higgs boson.

ATLAS: 2931 authors, 4 Hungarian

Physics Letters B 716 (2012) 30–61

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Physics Letters B

www.elsevier.com/locate/physletb

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

CMS Collaboration *

CERN, Switzerland

This paper is dedicated to the memory of our colleagues who worked on CMS but have since passed away. In recognition of their many contributions to the achievement of this observation.

ARTICLE INFO

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ABSTRACT

Results are presented from searches for the standard model Higgs boson in proton–proton collisions at $\sqrt{s}=7$ and 8 TeV in the Compact Muon Solenoid experiment at the LHC, using data samples corresponding to integrated luminosities of up to 5.1 fb^{-1} at 7 TeV and 5.3 fb^{-1} at 8 TeV. The search is performed in five decay modes: $\gamma\gamma$, ZZ, W^+W^-, $\tau^+\tau^-$, and $b\bar{b}$. An excess of events is observed above the expected background, with a local significance of 5.0 standard deviations, at a mass near 125 GeV, signalling the production of a new particle. The expected significance for a standard model Higgs boson of that mass is 5.8 standard deviations. The excess is most significant in the two decay modes with the best mass resolution, $\gamma\gamma$ and ZZ; a fit to these signals gives a mass of $125.3 \pm 0.4(\text{stat.}) \pm 0.5(\text{syst.})$ GeV. The decay to two photons indicates that the new particle is a boson with spin different from one.

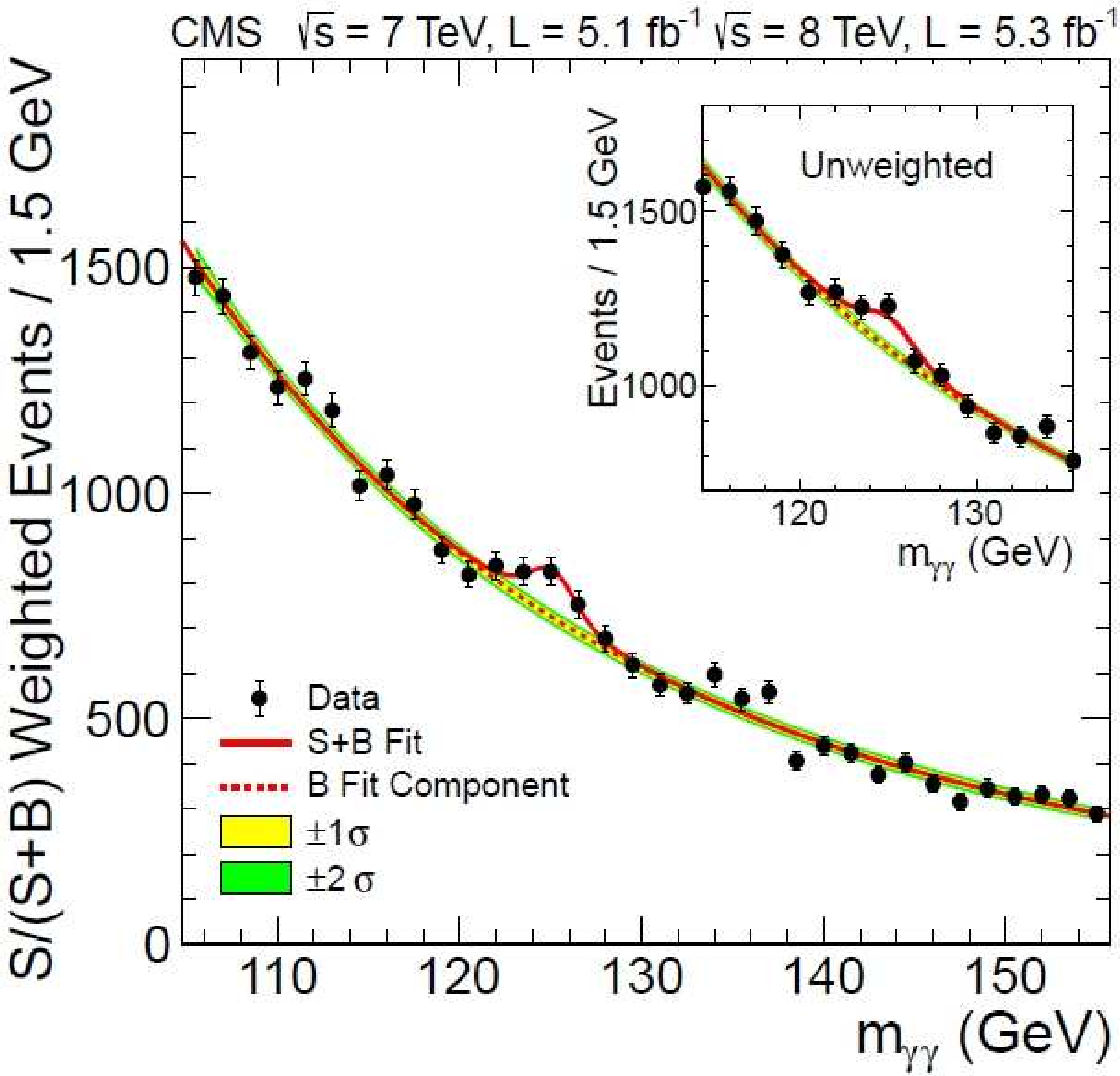
CMS: 2899 authors, 21 Hungarian

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.

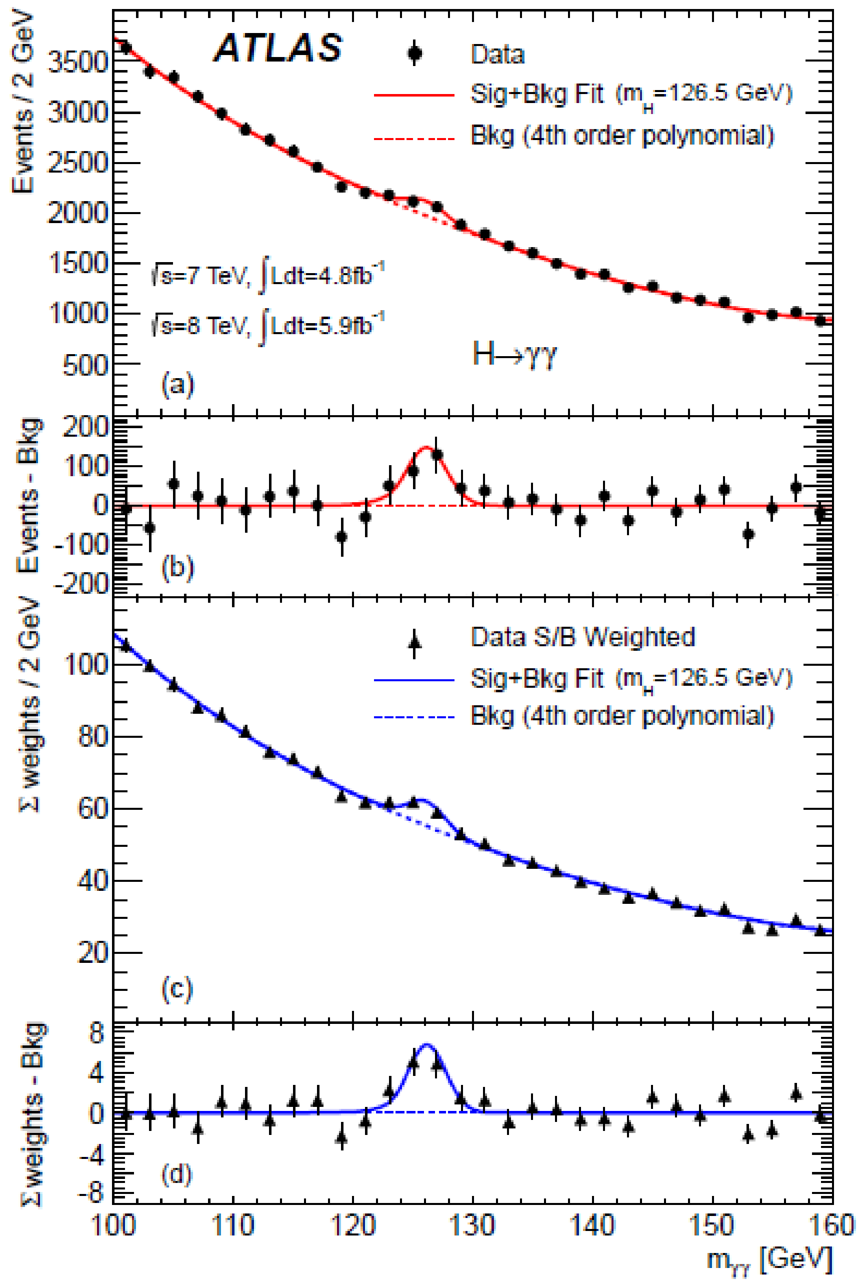


ATLAS: H → γγ mass distribution

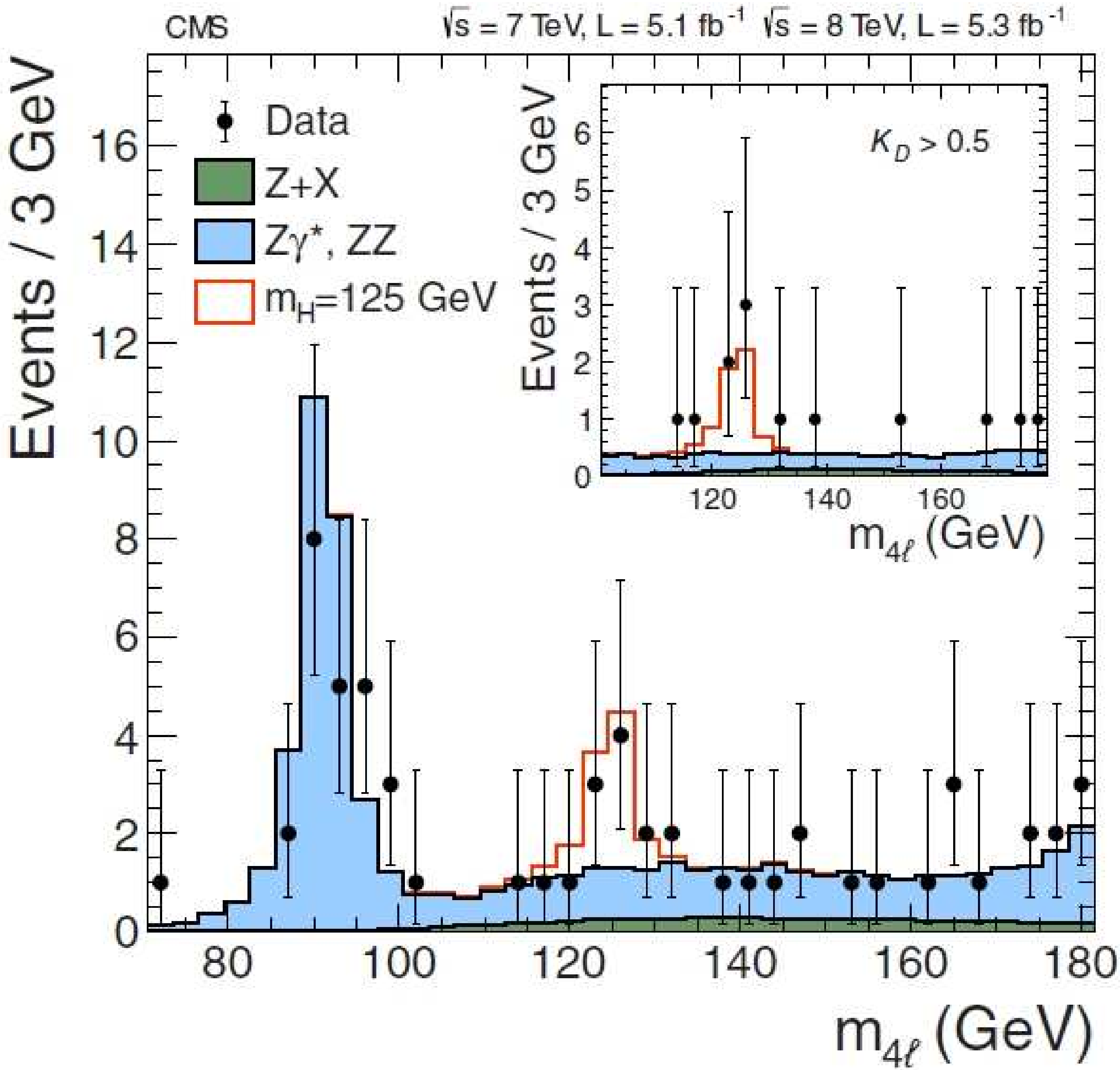
ATLAS Collaboration
(2931 authors):

arXiv:1207.7214

Phys. Lett. B 716 (2012) 1–29

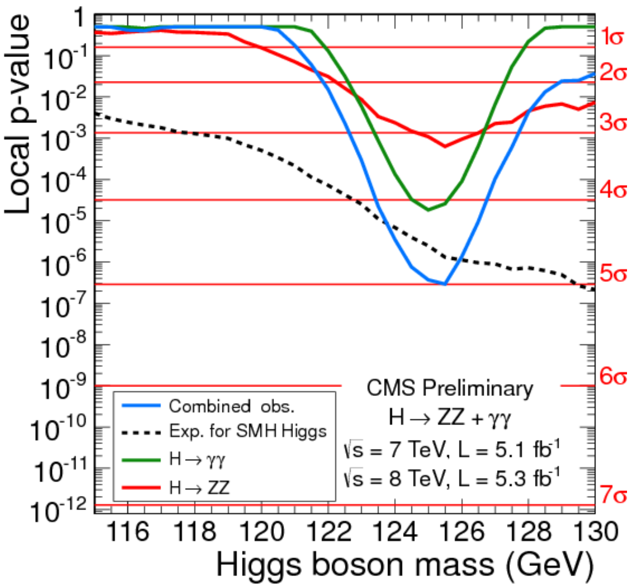


CMS: $H \to ZZ^* \to \ell^+\ell^-\ell^+\ell^-$

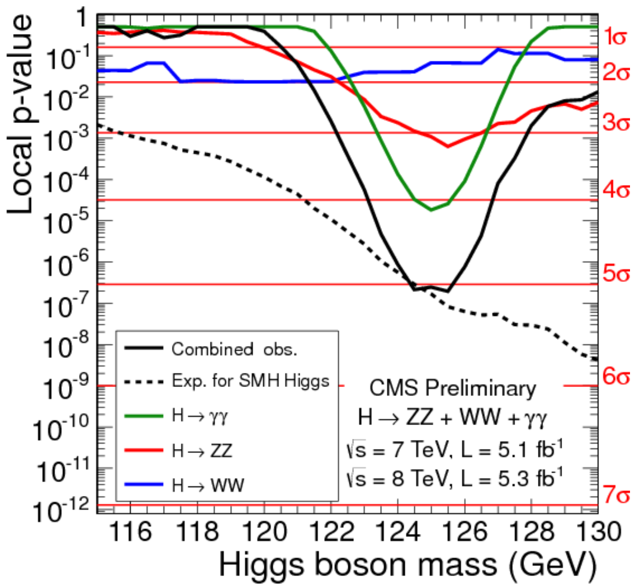


CMS: $p-$distributions (4 July 2012)

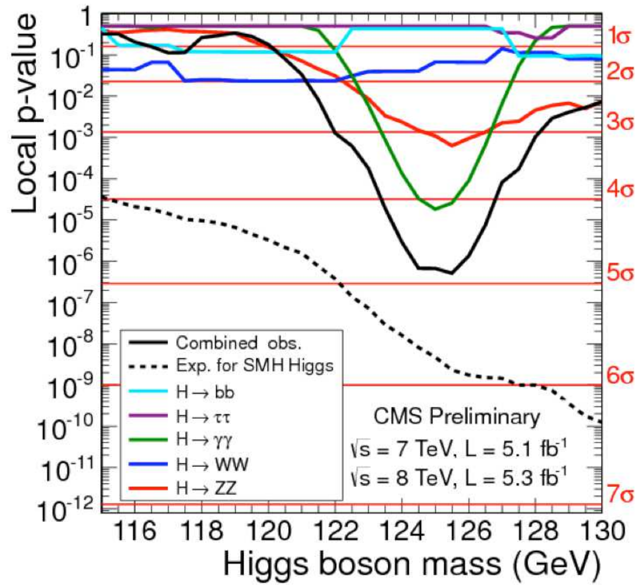
The probablility that random fluctuation of the measured background could give the observed excess.



$\gamma\gamma$ and ZZ: $\mathbf{5.0\sigma}$



$\gamma\gamma$, ZZ and WW: $\mathbf{5.1\sigma}$

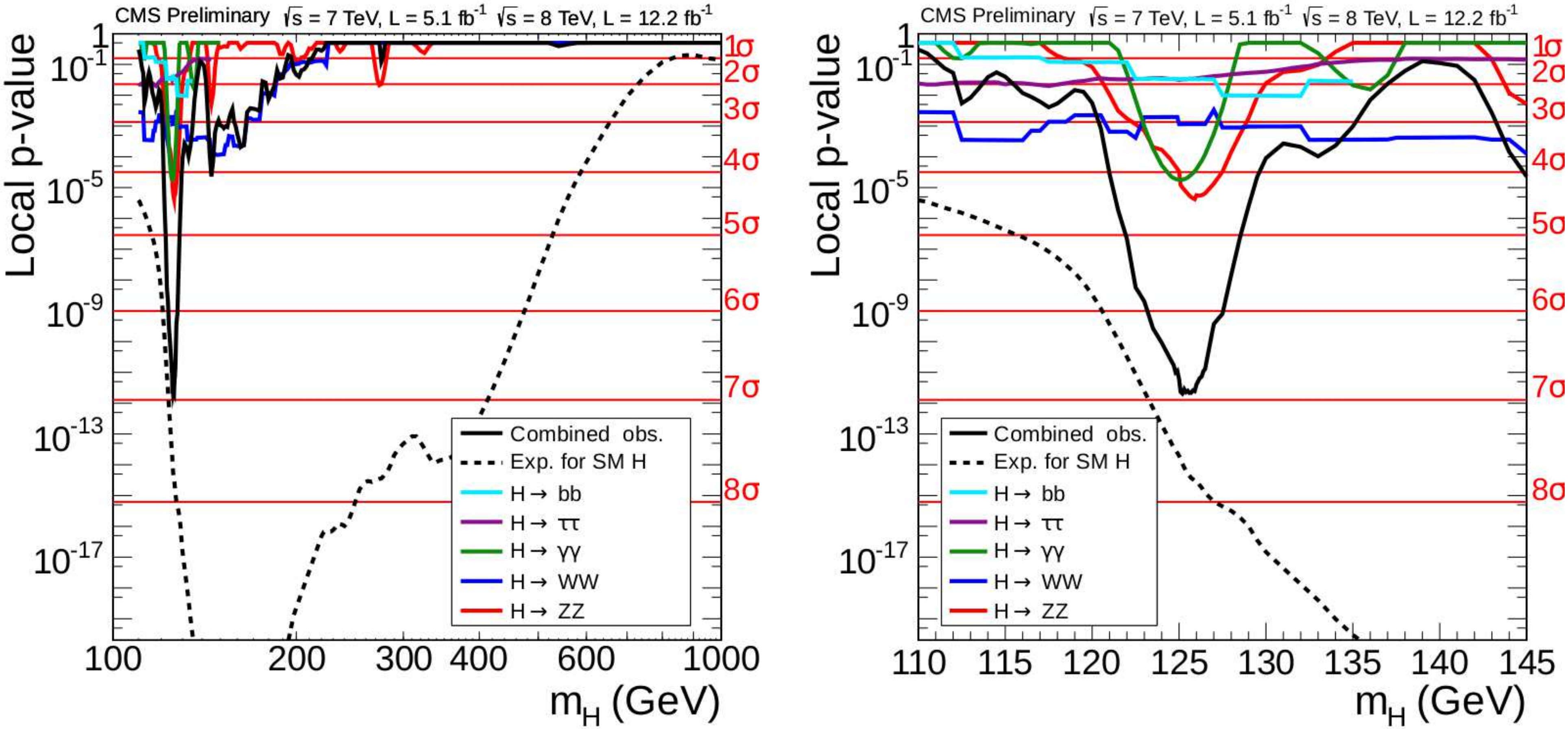


Mind együtt: $\mathbf{4.9\sigma}$

ATLAS got the same: $\gamma\gamma$ and ZZ: $\mathbf{5.0\sigma}$

Adding WW increased the ATLAS excess to $\mathbf{6.0\sigma}$

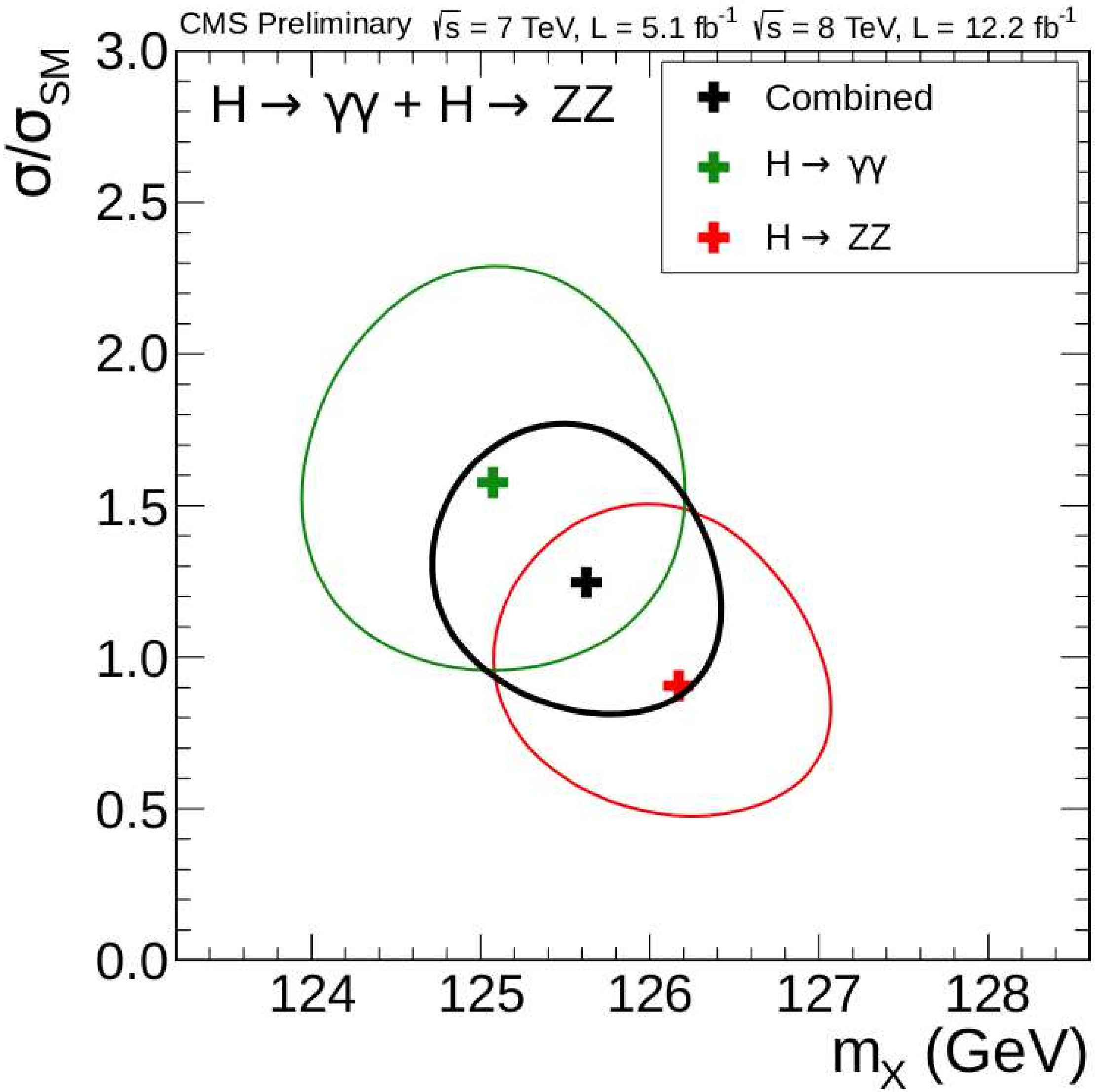
CMS, November 2012: significance



Doubling 2012 statistics increased CMS excess to 6.9 σ

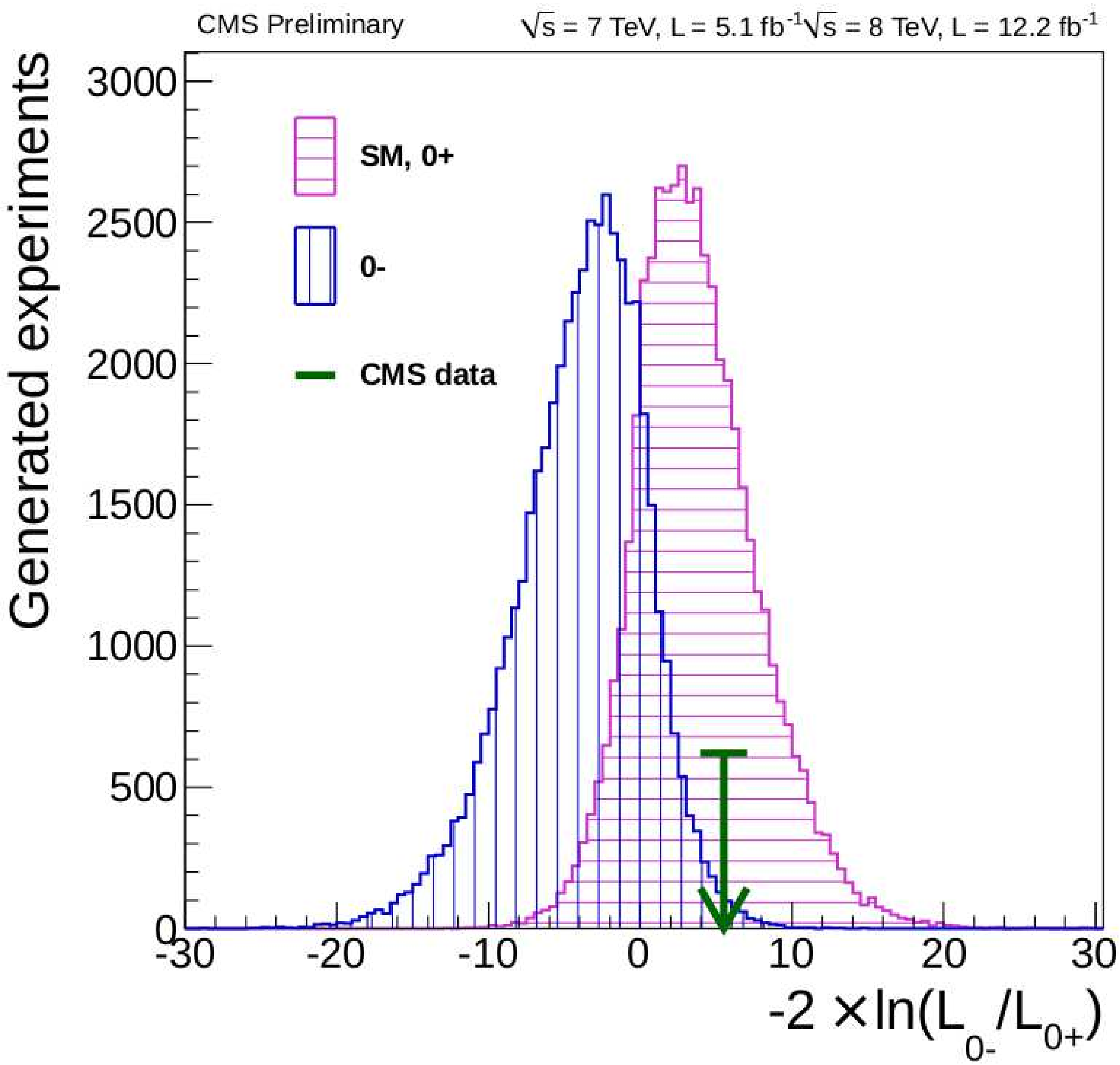
Sharp peak, close to SM exp. at 126 GeV, far less elsewhere

CMS, November 2012: mass vs. x-sec



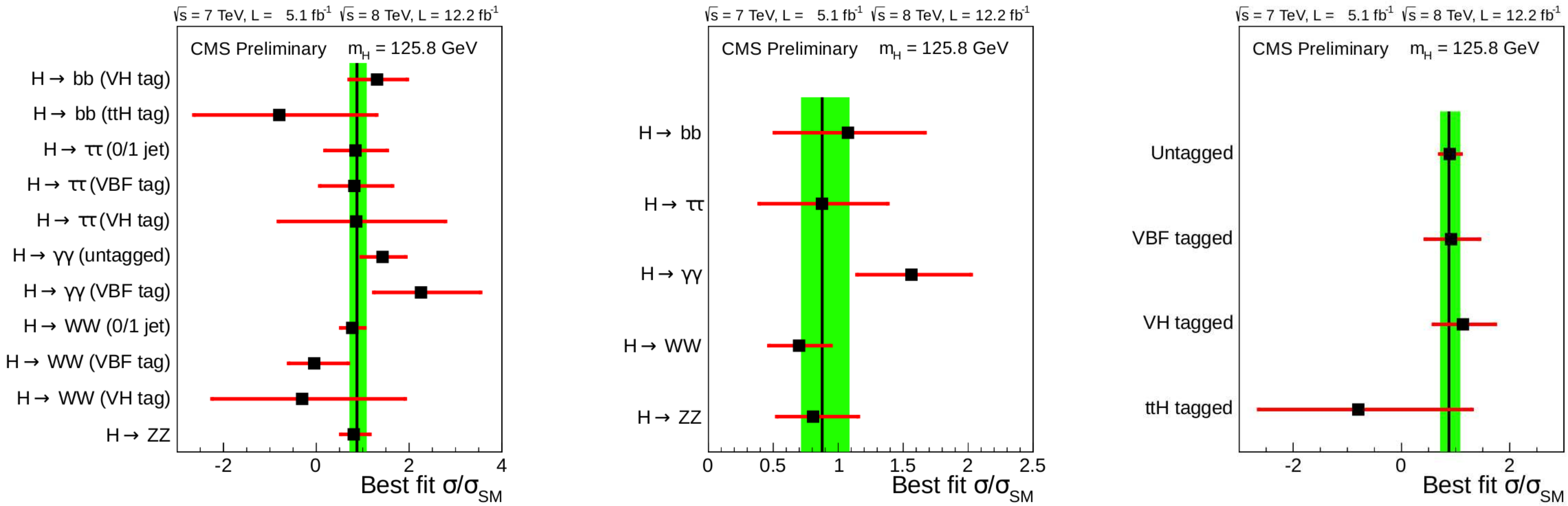
$$< M_X >= 125.8 \pm 0.4(\text{stat}) \pm 0.4(\text{syst})$$

CMS, November 2012: parity



CMS data favor **+** parity for $S_{\mathrm{X}} = 0$

CMS: is it the SM Higgs boson?



Branching ratios of different decay channels
as compared to SM predictions for a 126 GeV Higgs boson

$$< \sigma/\sigma_{SM} >= 0.88 \pm 0.21$$

Getting closer to SM, August: 0.80 ± 0.22
ATLAS, November: 1.3 ± 0.3

CMS vs. ATLAS: mass and signal strength

(determined consistently, in various ways)

CMS, November 2012 (updated for HCP-2012)

$M_H = 125.8 \pm 0.4$ (stat) ± 0.4 (syst) GeV

Local significance of the observation ($M_H = 126$ GeV): 6.9σ

H $\to \gamma\gamma$: $\sigma/\sigma(\mathrm{SM}) = 1.56 \pm 0.43$

H $\to$ all: $\sigma/\sigma(\mathrm{SM}) = 0.88 \pm 0.21$

ATLAS: Phys. Lett. B 716 (2012) 1-29.

$M_H = 126.0 \pm 0.4$ (stat) ± 0.4 (syst) GeV

Local significance of the observation ($M_H = 122 - 131$ GeV): 5.9σ,

H $\to \gamma\gamma$: $\sigma/\sigma(\mathrm{SM}) = 1.9 \pm 0.5$

H $\to$ ZZ $\to 4\ell$: $\sigma/\sigma(\mathrm{SM}) = 1.26 \pm 0.14$

H $\to$ all: $\sigma/\sigma(\mathrm{SM}) = 1.4 \pm 0.3$

Supersymmetry (SUSY)

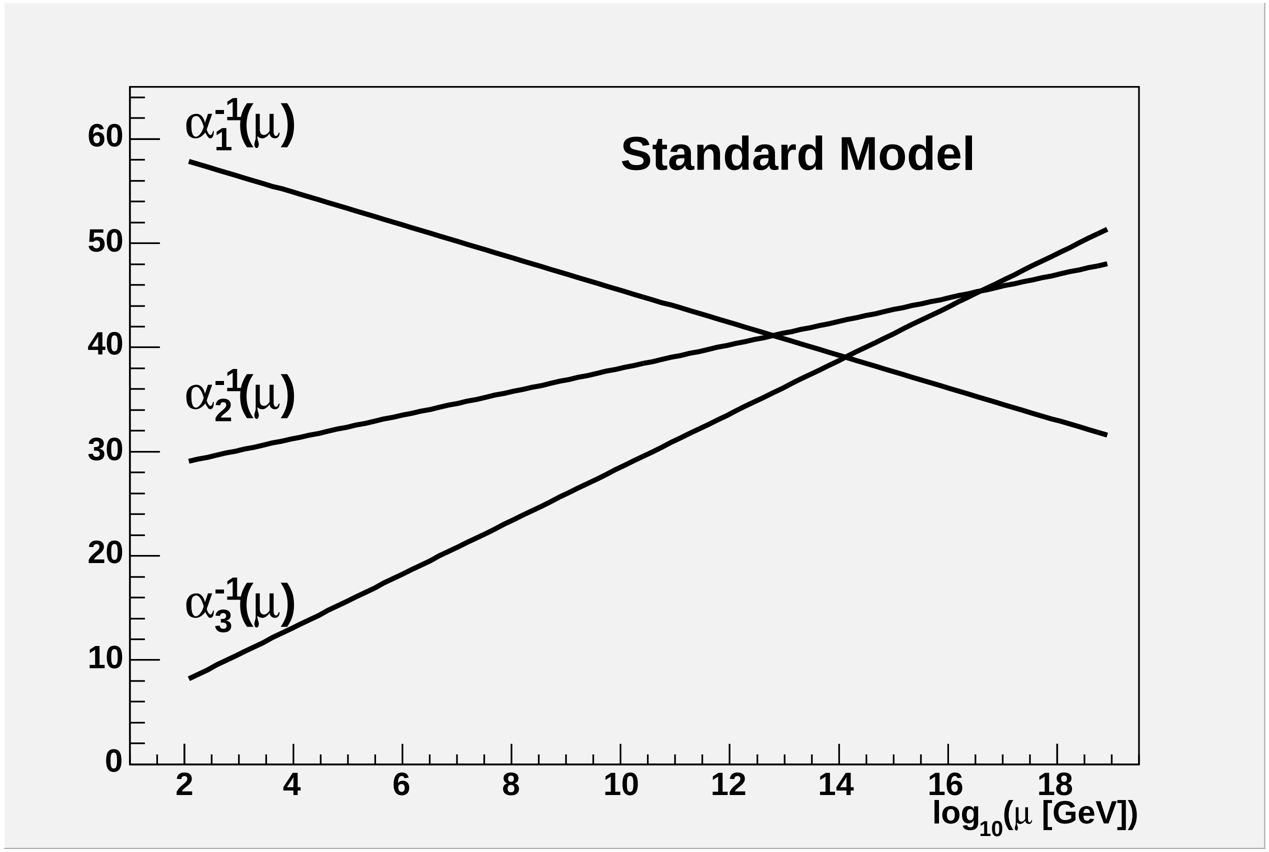
Problems of the Standard Model – 1

- 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: $Q_e = Q_p,\ Q_d = Q_e/3$
- 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: $\alpha, \ \Theta_W, \ \Lambda_{\rm QCD}$; 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.

Coupling constants



α_i: Local $SU(i)$ couplings

They almost meet at $\mu \sim 10^{13} - 10^{16}$ GeV

Do they unite at high energy?

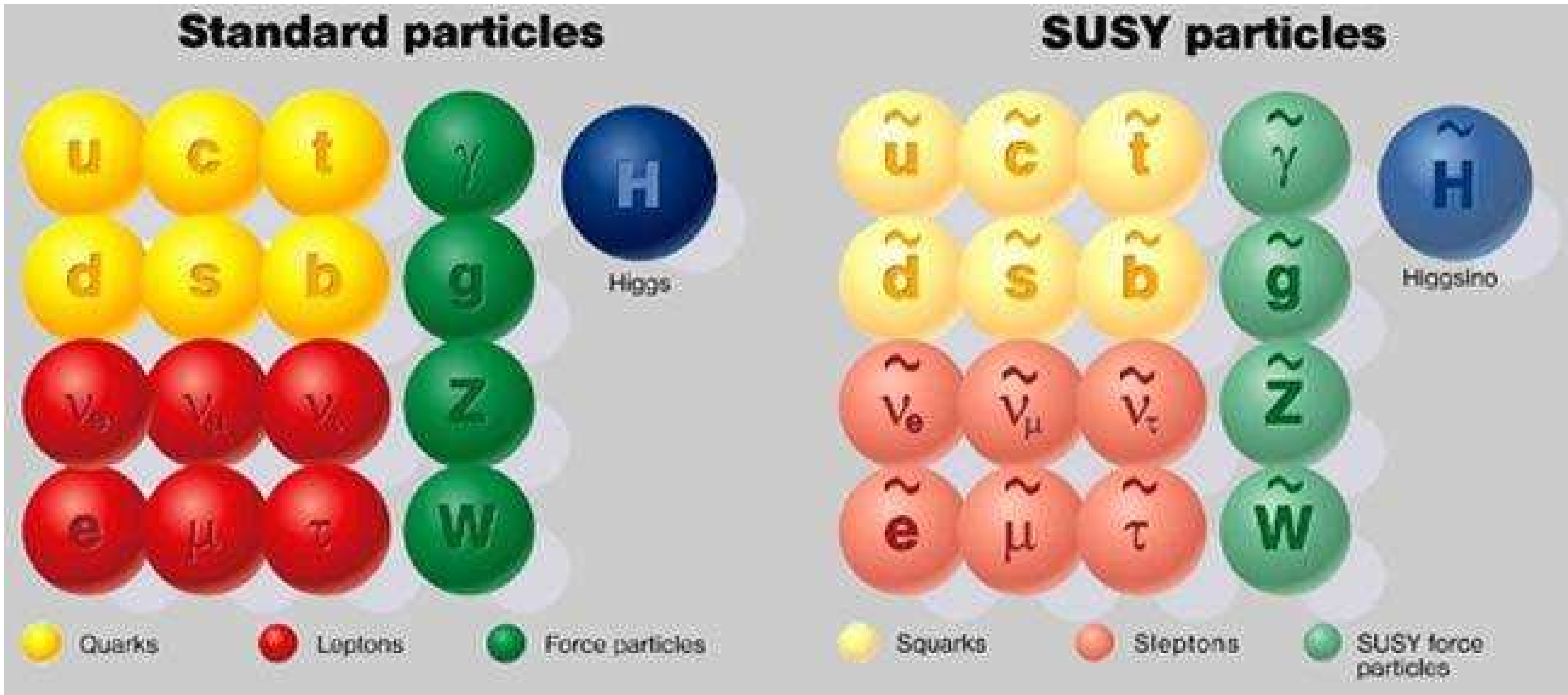
Supersymmetry (SUSY)

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

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



Almost 50 % discovered already!!

We see half (–1) of all SUSY particles

SUSY, cont'd.

2 Higgs doublets ⇒ masses to upper and lower fermions
$m_L = m_R$, but $\tilde{m}_L \neq \tilde{m}_R$

8 Higgs fields ⇒ 5 Higgs bosons: $\mathrm{h}^0, \mathrm{H}^0, \mathrm{A}^0, \mathrm{H}^\pm$
Higgs-parameters: tan$\beta = v_1/v_2$, masses

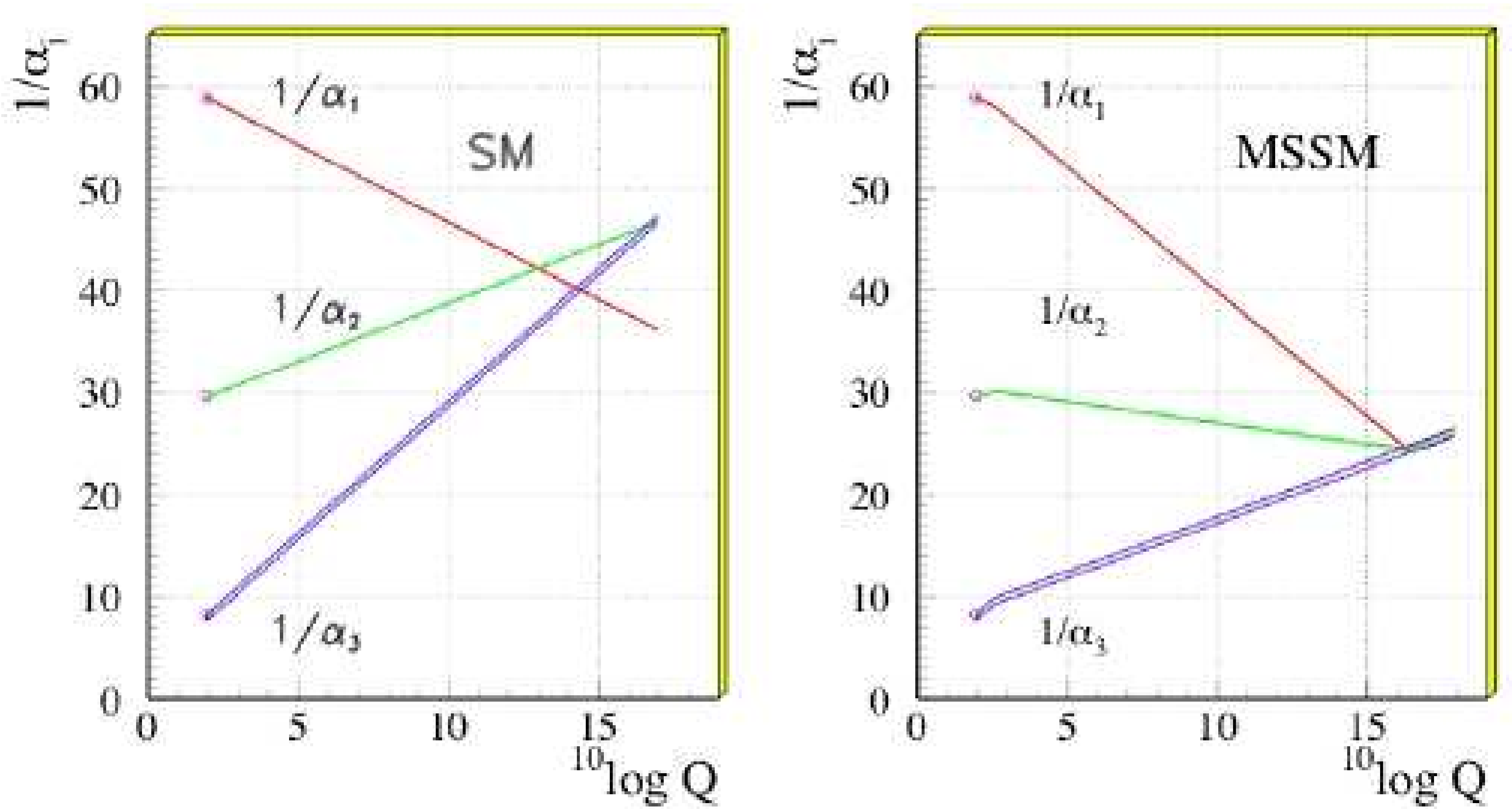
SUSY's quantum number: R parity $\quad R = (-1)^{3B-L+2S}$
$R = +1$ particle, $R = -1$ SUSY partner (sparticle)

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

If R conserved, lightest sparticle (LSP) stable
R parity may not be much violated: we would see

Neutral LSP: excellent dark matter candidate

SUSY: coupling constants



Unification OK!

Bend at low energies: SUSY enters with many new particles ⇒ more loop corrections

CMSSM, mSUGRA

Constrained Minimal Supersymmetric Standard Model

Many simplification constraints (boundary conditions),
105 $\Rightarrow$ 5 or 6 parameters, e.g. in mSUGRA:

- $m_{1/2}$: fermion masses at the Grand Unification energy (GUE $\sim 10^{14} - 10^{15}$ GeV)
- m_0: boson masses at GUE
- A_0: SUSY-breaking triple (X–Y–Higgs) couplings at GUE
- $\tan\beta = v_1/v_2$: vacuum exp. values upper/lower Higgs fields
- m_A: mass of a Higgs boson (optional)
- μ: mixing parameter of the higgsinos (sign $\pm$)

Really sensitive parameters: m_0 and $m_{1/2}$

CMSSM is practically excluded by 2011 LHC data †

Many-many alternative models

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 (?); $\mathbf{H \sim h^0}$
  - Fitting electroweak data
  - Search for neutral Higgs bosons (h and A)
- $BR(\mathrm{b}\to\mathrm{s}\gamma)$ measurements at B-factories
- Anomalous magnetic moment of the muon (BNL)
- WMAP (Wilkinson Microwave Anisotropy Probe): density of dark matter (DM), indirect
- Direct searches for DM with ν-detectors

SUSY search

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

Lightest (LSP) stable, neutral, not observable

Signal: missing energy

Tipical 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: $\tilde{W} \rightarrow e + \nu_e + \tilde{\chi}_1^0$

What and where to look for?

Even if SUSY is valid, MSSM or cMSSM may not be.
If we find new physics, how can we tell it is SUSY?
Simplified models $\Rightarrow$ easier interpretation

LHC inverse problem:
Given model and parameters $\Rightarrow$ prediction of reactions
But experiment works the other way around:
We have to tell which model from the data.

SUSY: Cascade decays are model-dependent
Simplified models give reactions with few particles $\Rightarrow$ dependence on few masses and cross sections with relatively wide allowed intervals $\Rightarrow$ characteristic for several models

Simplified Models

Few on-shell particles, simple topology and decays

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

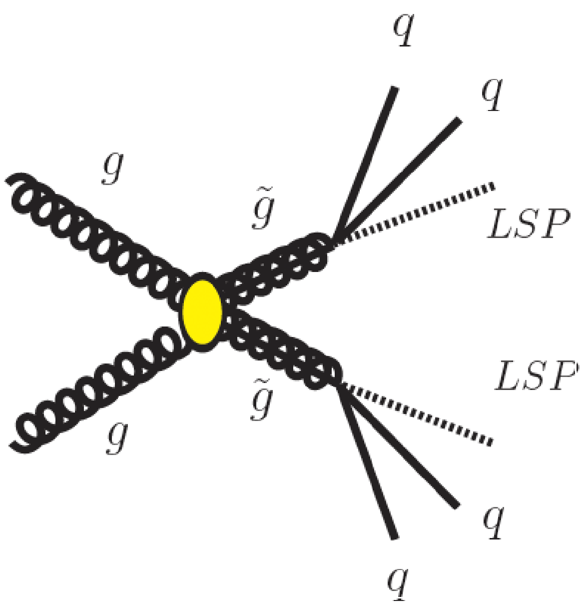
Possible new physics on well understood SM-base

What can we learn of such analysis?

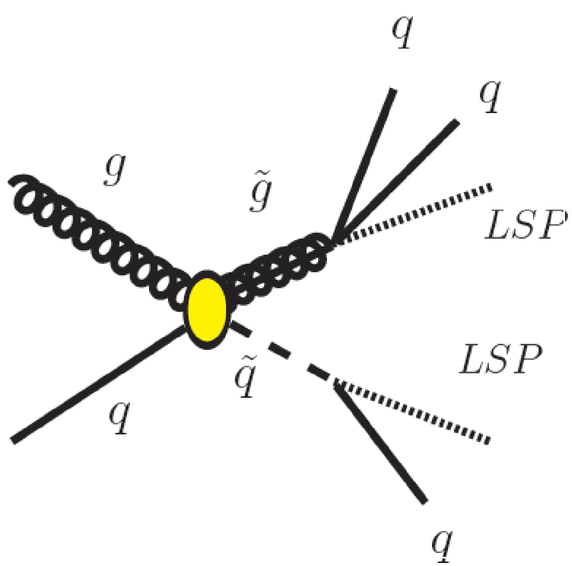
- Boundaries of search sensitivity, both for data analysis and for new theories.
- Characterizing new physics signals: what models can be associated?
- Limits on more general models: from possible cross-sections.

Topologies of simplified models

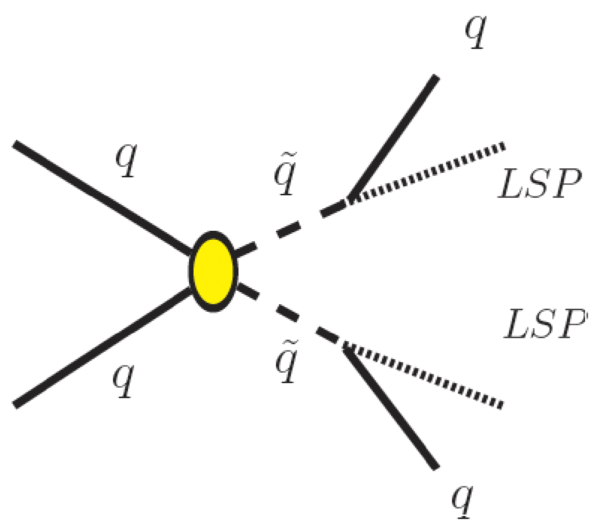
Basic topologies with no lepton:



$gg \to \tilde{g}\tilde{g}$
$\to 2(qq + \text{LSP})$



$qg \to \tilde{q}\tilde{g}$
$\to qqq + 2\ \text{LSP})$



$qq \to \tilde{q}\tilde{q}$
$\to qq + 2\ \text{LSP})$

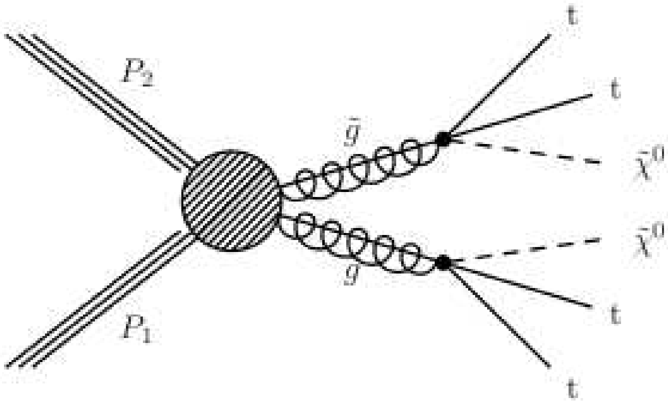
and we can add one or more leptons.

Exclusion with simplified models

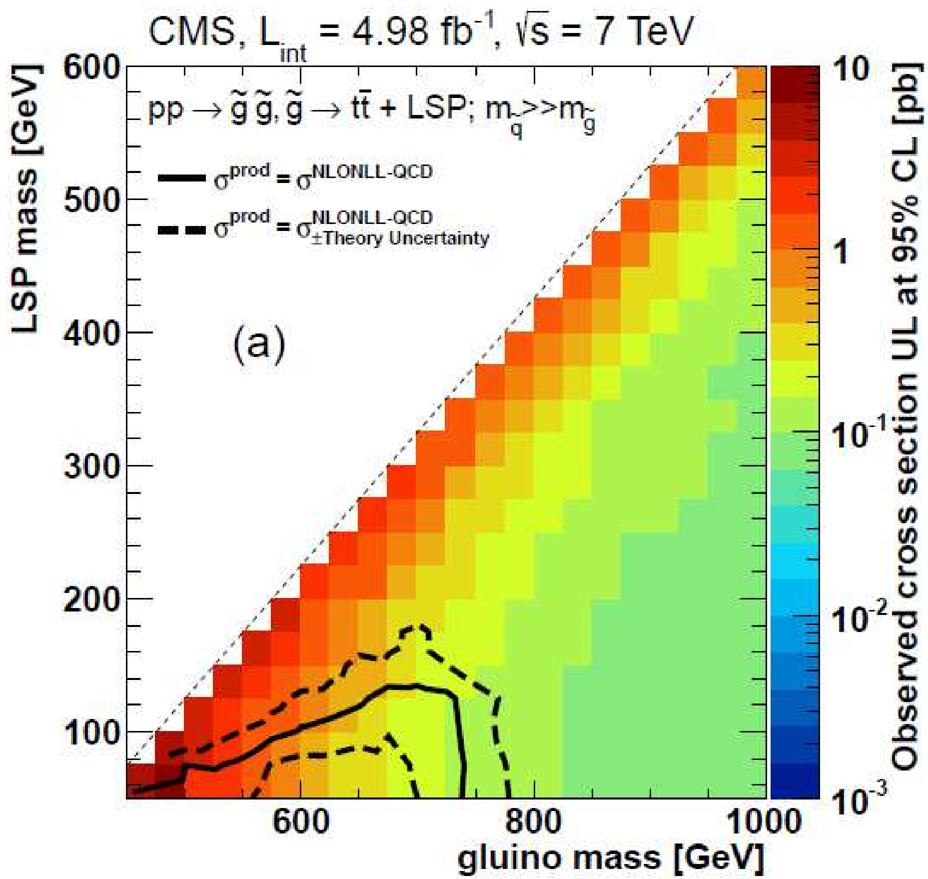
Search for supersymmetry in events with b-quark jets and missing transverse energy in pp collisions at 7 TeV,

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

- We very probably observed the SM Higgs boson or some new boson of spin 0 (or 2), e.g. a Higgs boson of a more general model.
- Let us hope for some deviation from the Standard Model (although none seen yet).
- The simplest SUSY model, mSUGRA does 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.
- It may help to find new, characteristic reactions.
  If found, identify the new observation with possible models
- Adjust theory to data, not the other way around.

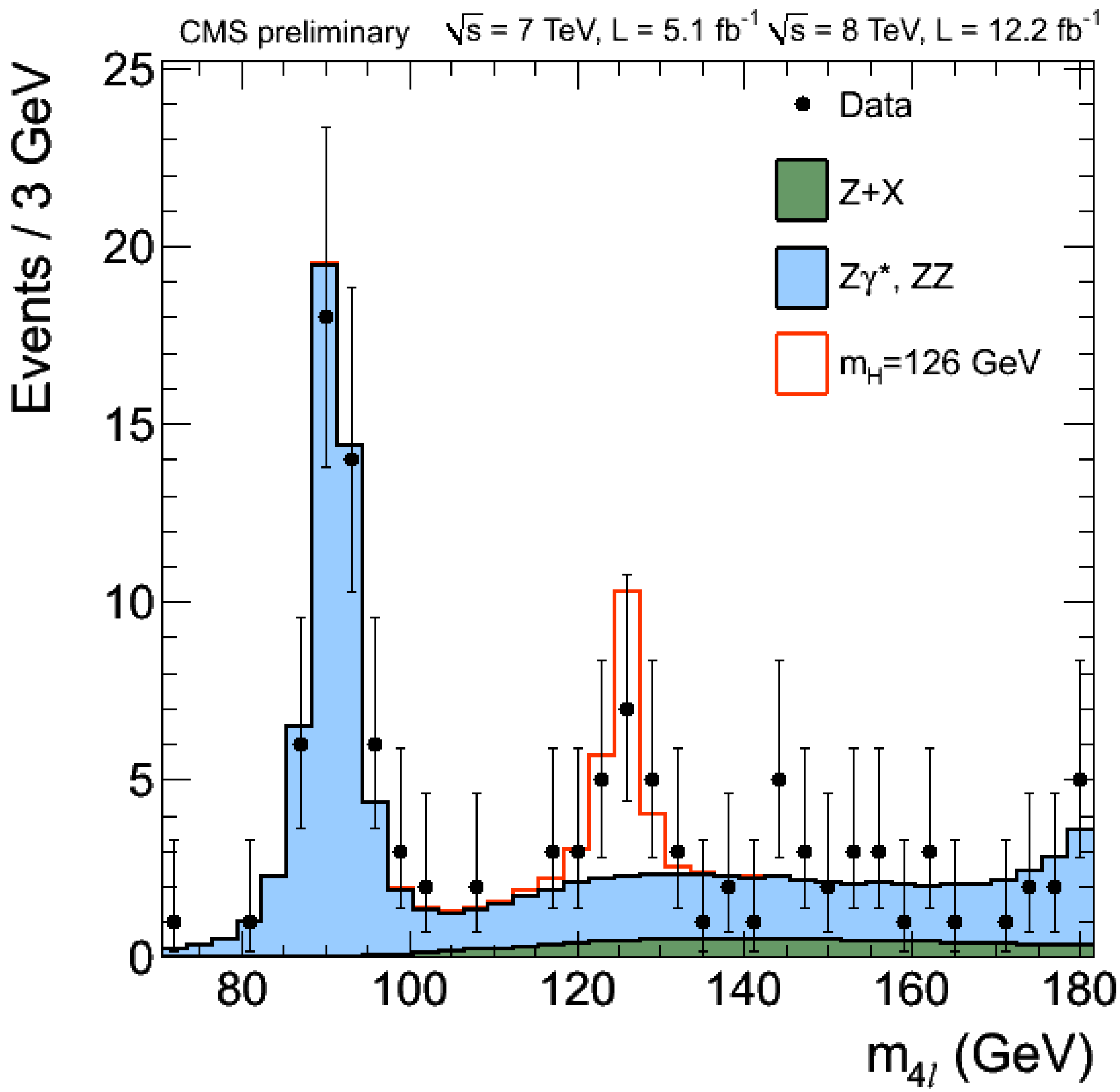
Conclusion–2

- Experimentalist: *What happens to* **you** *if we exclude the whole SUSY in 2012?*
- Theorist: *We are far from that, MSSM is not the whole SUSY. And anyways, we are not doing* **that** *only ...*

Thank you for your attention

Spare slides for questions

CMS, November 2012: 4ℓ mass



Minimal Supersymmetric SM (MSSM)

Electroweak symmetry breaking

$\Downarrow$

MSSM-fermions mix into $\Rightarrow$ mass eigenstates

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

$$\{\tilde{\gamma}, \tilde{W}^{\pm}, \tilde{Z}; \tilde{h}^0, \tilde{H}^0, \tilde{H}^{\pm}\} \Rightarrow \{\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^{\pm}; \tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0\}$$

mass grows with index

Lightest SUSY particle (LSP) depends on model, e.g.
mSUGRA: $\tilde{\chi}_1^0$ or GMSB: gravitino ($\tilde{G}$)

SUSY breaking $\Rightarrow$ many (> 100) new parameters
masses, couplings, mixing angles

Lots of model variants, huge parameter space, different constraints.

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)

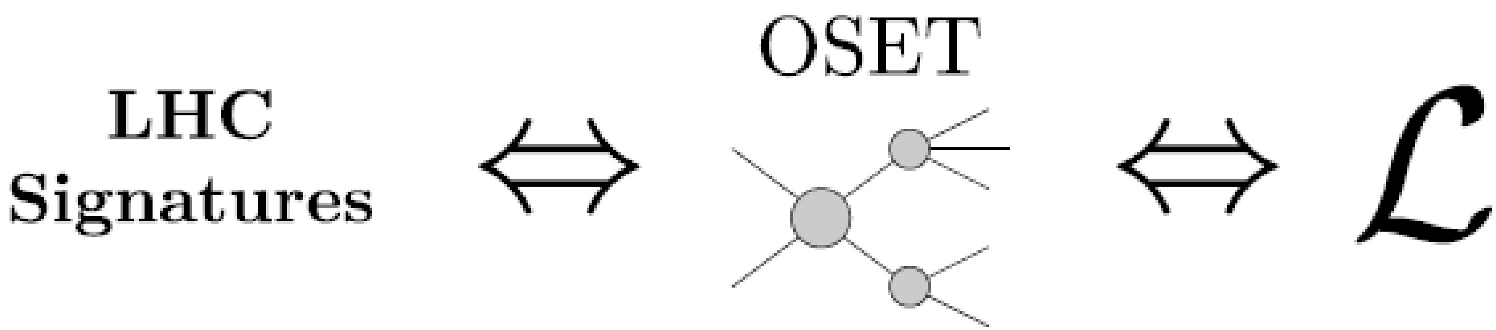
- R parity is barely violated
- LSP: $\tilde{\chi}_1^0$ or gravitino
- Gluino mass $M_3 \equiv m(\tilde{g}) \gg m(\tilde{\chi}_1^0), m(\tilde{\chi}_2^0), m(\tilde{\chi}_1^\pm)$
- $m(\tilde{u}_i) \sim m(\tilde{d}_i) \sim m(\tilde{c}_i) \sim m(\tilde{s}_i) \gg m(\tilde{\ell}_i)$
- $m(\tilde{u}_i) \sim m(\tilde{d}_i) \sim m(\tilde{c}_i) \sim m(\tilde{s}_i) > (0,6_{\mathrm{MSUGRA}} \ldots 0,8_{\mathrm{GMSB}}) m(\tilde{g})$
- $m(\tilde{u}_L) \geq m(\tilde{u}_R) \ldots m(\tilde{s}_L) \geq m(\tilde{s}_R)$ 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 $\ll m(\mathrm{A}), m(\mathrm{H}^\pm), m(\mathrm{H}^0)$

OSET: On-Shell Effective Theory

CMS + theory, 2007–2008

Off-shell particles: hard to identify, missing energy harder to determine

Assume simple production and simple decay of new particle, analyze decay spectra, find corresponding deviations from SM.

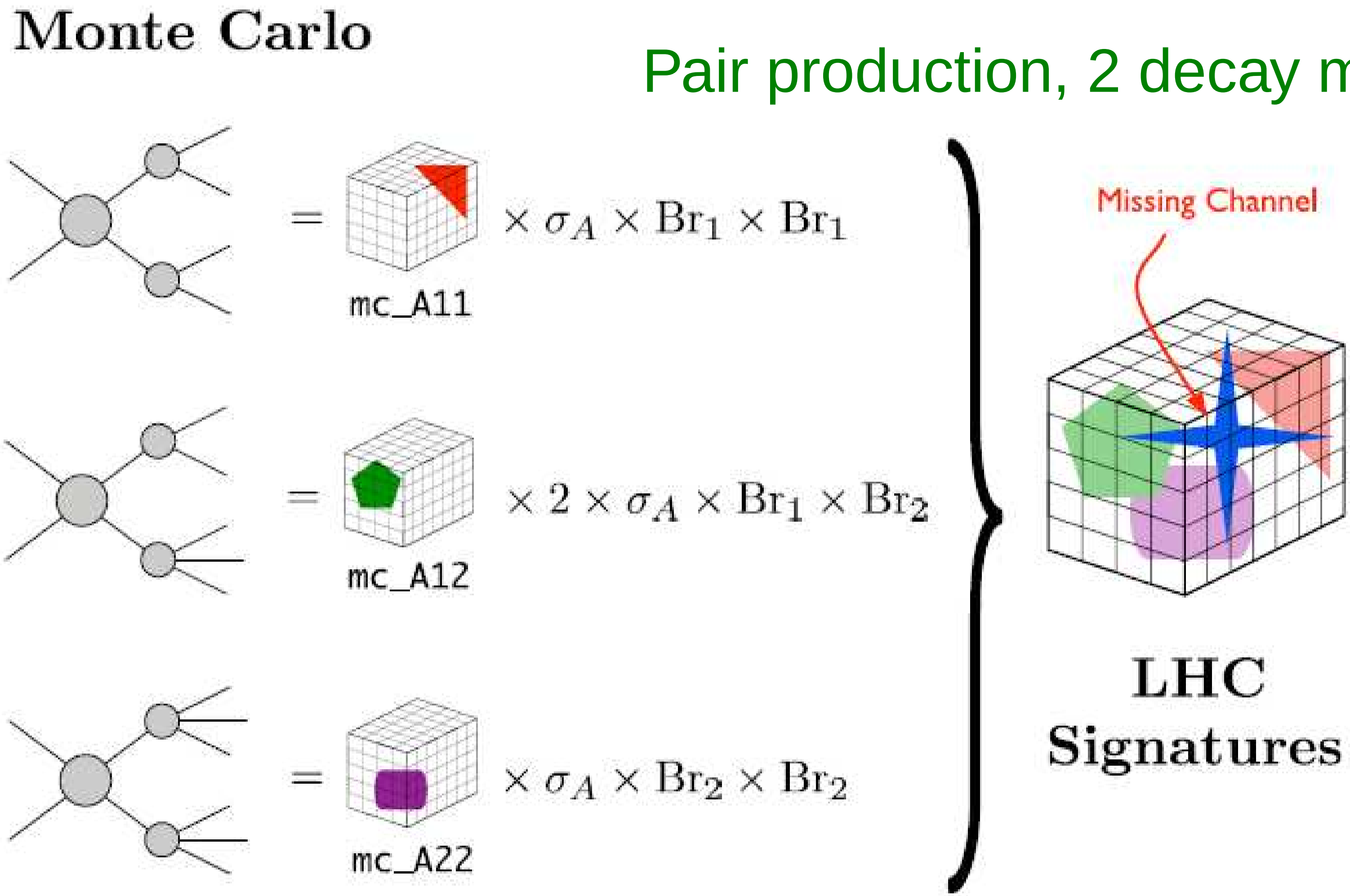


LHC phenomena ⇔ Lagrangian of new physics
http://tools.marmoset-mc.net/osetology_wordpress/

Main study: gluino and sqark production and decay

OSET: On-Shell Effective Theory

Pair production, 2 decay modes



Amplitudes (cross-sections and branching ratios) free parameters

N.Arkani-Hamed et al: MARMOSET, hep-ph/0703088

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

Phenomenological MSSM

Random space points in (105 $\rightarrow$) 19-parameter pMSSM
(1st and 2nd generation sfermions assumed degenerate)

- 10 (real) sfermion masses
- 3 gaugino masses
- 3 trilinear couplings)
- μ, $\tan\beta$, M_A.

Masses: 50-100 GeV ... 1-3 TeV, $1 < \tan\beta < 60$

Experimental and theoretical constraints applied

So far (mSUGRA, GMSB, ...) overlooked phenomena could emerge

C.F.Berger, J.S.Gainer, J.L.Hewett, T.G.Rizzo:
Supersymmetry Without Prejudice, JHEP 0902:023,2009.

The missing MSSM menagerie

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

CMS SUSY summary plot