HELSINGIN YLIOPISTO
HELSINGFORS UNIVERSITET
UNIVERSITY OF HELSINKI

HELSINKI INSTITUTE OF PHYSICS

Elementary particles as seen by the LHC

Symposium ”Randomness and order in the exact sciences – Quantum physics in the large and small”

Paula Eerola

Dept of Physics and Helsinki Institute of Physics

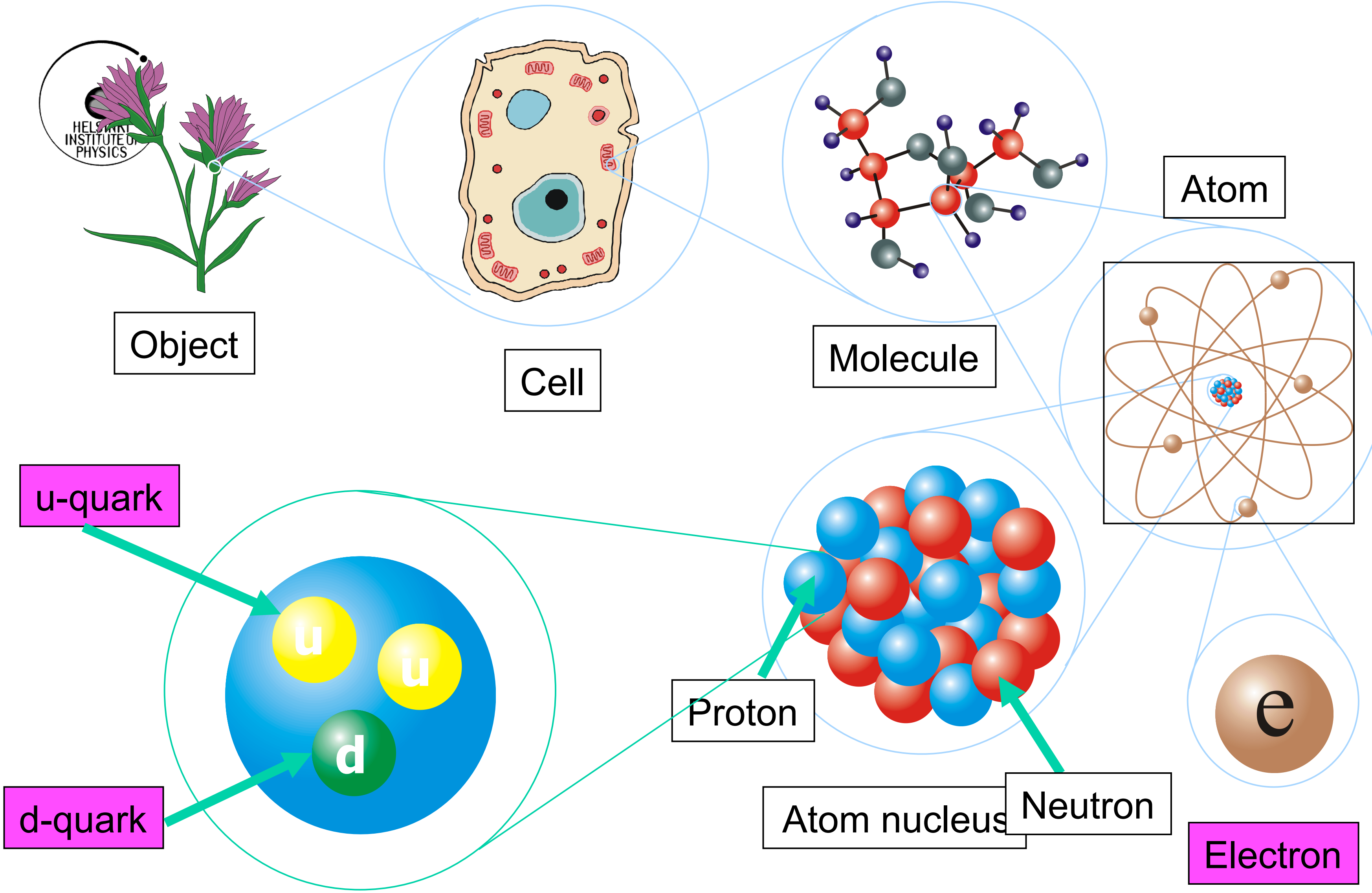
September 2013

Outline

- ***Introduction:***
  - ***Elementary particles***
  - ***Large Hadron Collider, LHC***
- ***A closer look at some of the elementary particles:***
  - ***Heavy quarks – top, b (c)***
  - ***Higgs***
  - ***Beyond the Standard Model***
- ***Future***
- ***Summary***

Elementary particles

- **Smallest constituents of matter** and their **interactions**



Known elementary particles

- Matter particles (fermions)
- Force carrier particles (bosons)

FERMIONS

matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin =1/2

Flavor	Mass GeV/c^2	Electric charge
ν_L lightest neutrino*	$(0-0.13)\times10^{-9}$	0
e electron	0.000511	–1
ν_M middle neutrino*	$(0.009-0.13)\times10^{-9}$	0
μ muon	0.106	–1
ν_H heaviest neutrino*	$(0.04-0.14)\times10^{-9}$	0
τ tau	1.777	–1

Quarks spin =1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.002	2/3
d down	0.005	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	173	2/3
b bottom	4.2	–1/3

BOSONS

force carriers
spin = 0, 1, 2, ...

Unified Electroweak spin = 1

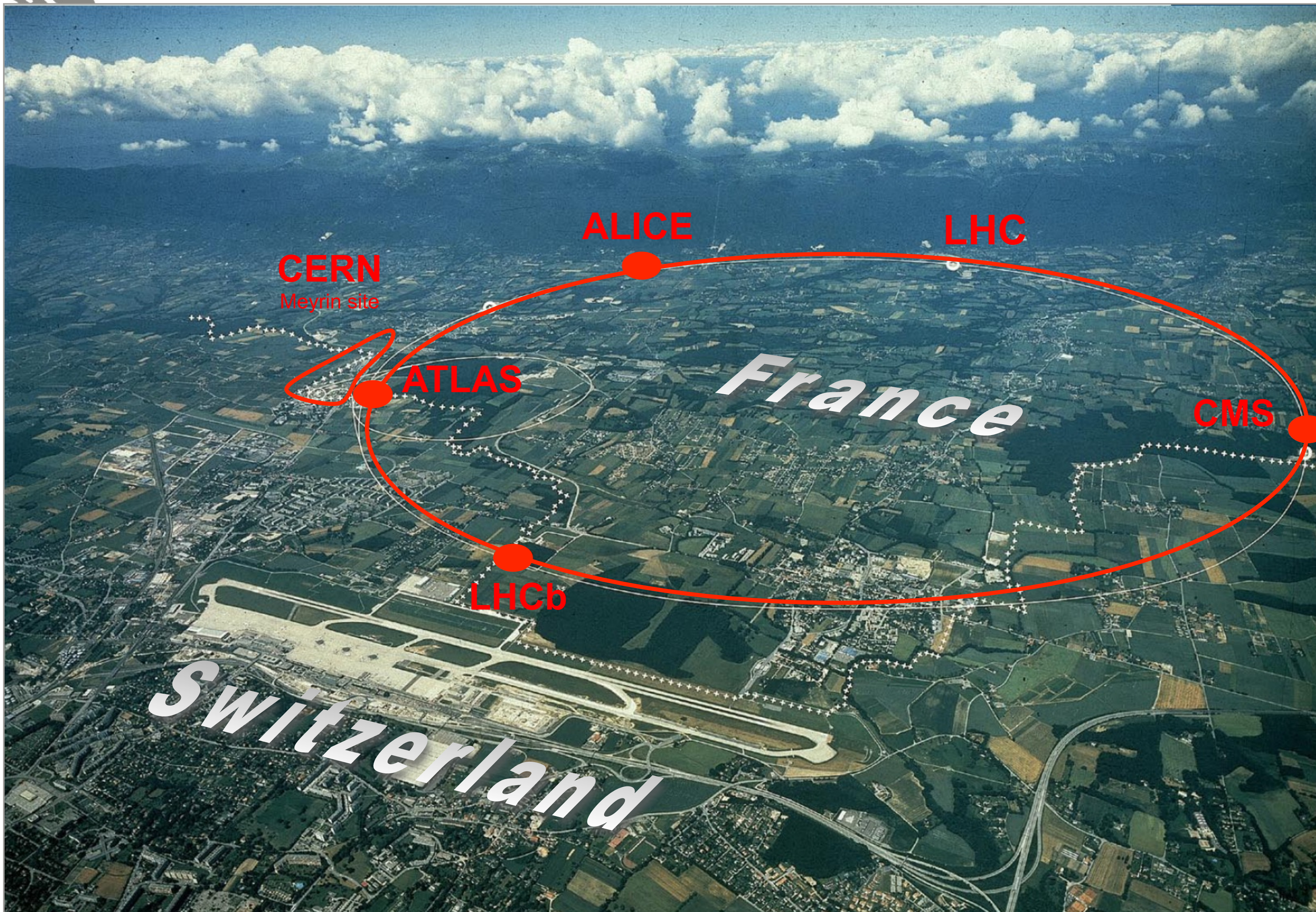
Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.39	–1
W^+ W bosons	80.39	+1
Z^0 Z boson	91.188	0

Strong (color) spin =1

Name	Mass GeV/c^2	Electric charge
g gluon	0	0

Large Hadron Collider, LHC

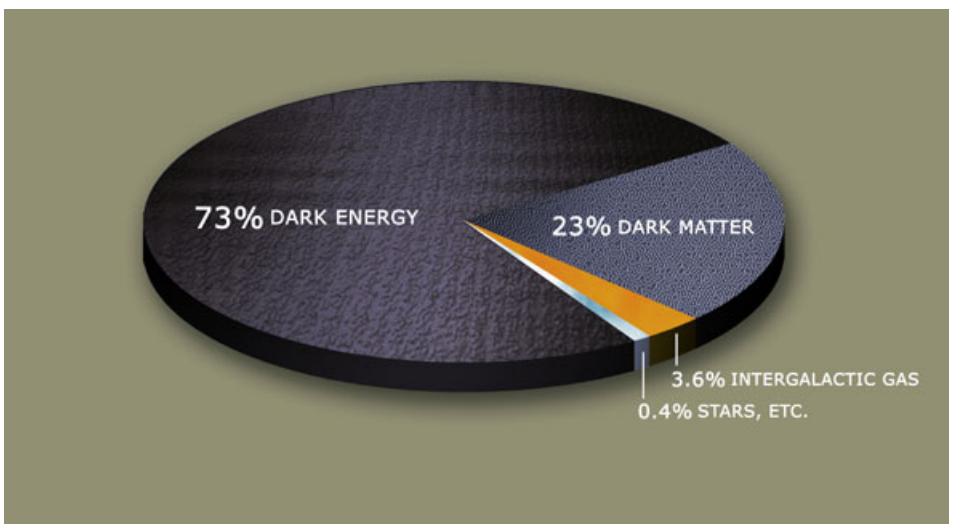
LHC

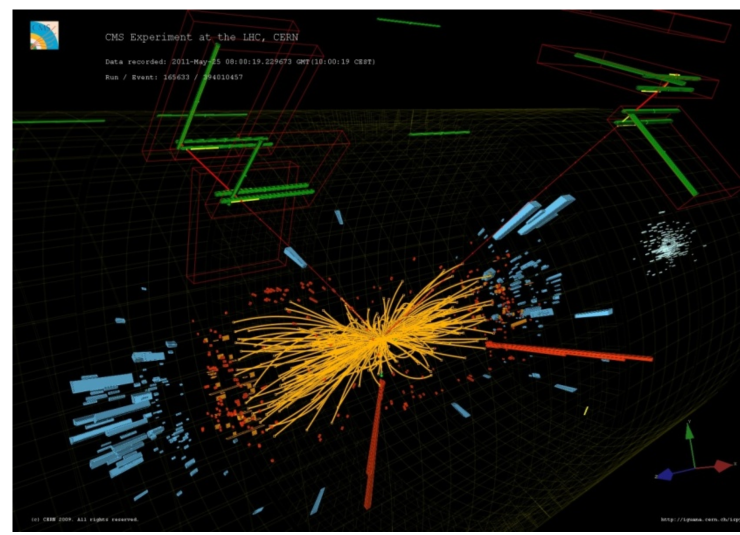


Collider at CERN, pp, 7-8 TeV (14 TeV), started 2009

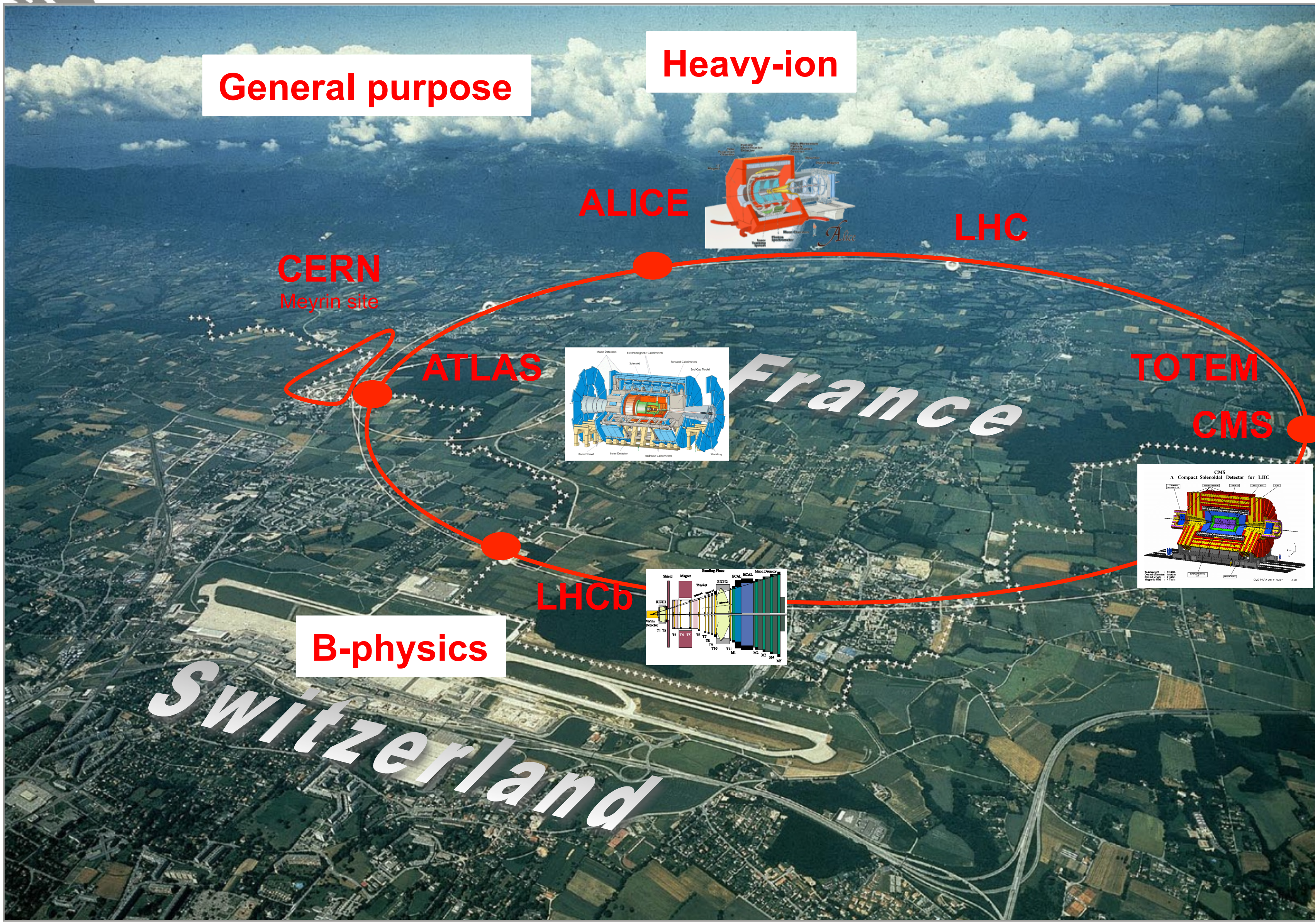
LHC physics goals

- Look for new particles (signatures of new physics beyond the Standard Model)
  - Higgs bosons – mass problem ✔
  - Dark matter – supersymmetry?
  - Where did the antimatter go ?
  - New dimensions? Unification of forces? Something exotic?
- More precise measurements of known particles and forces ✔
- Nanonano physics: TeV-energy-scale corresponds to ~10^{-19} m





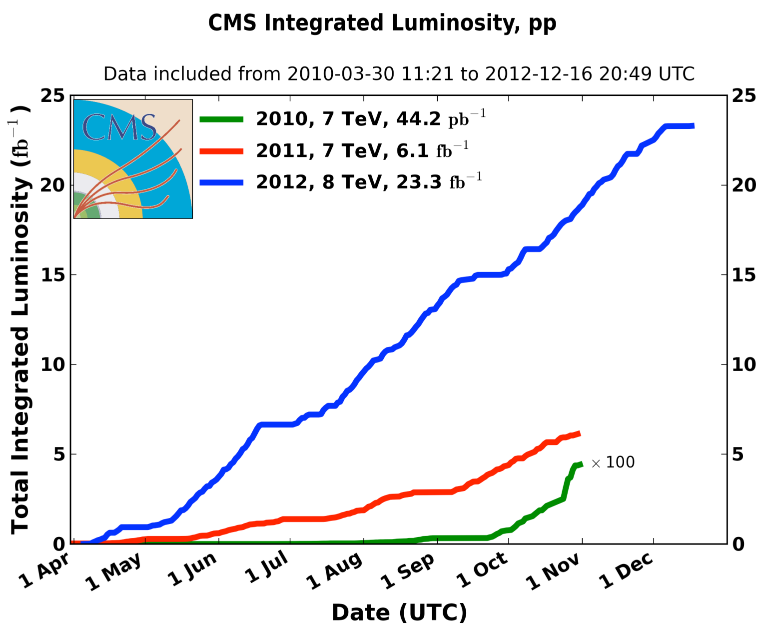
LHC

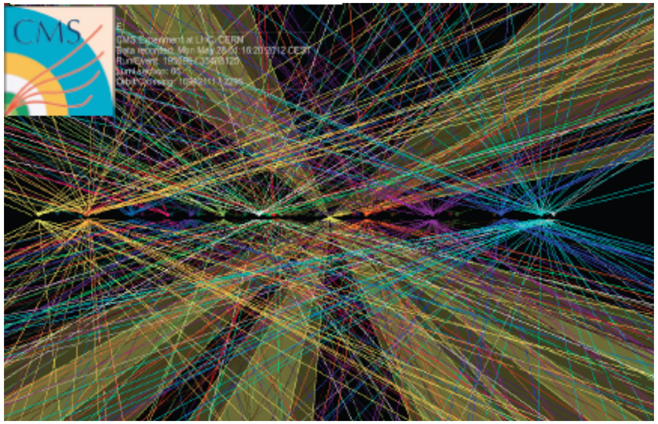

General purpose
Heavy-ion
ALICE
LHC
CERN
Meyrin site
ATLAS
France
TOTEM
CMS
LHCb
B-physics
Switzerland

LHC performance

- 2010 – energy 7 TeV, $\mathcal{L}$ = 44 pb^{-1} *), peak L = 2 × 10^{32} cm^{-2} s^{-1}
- 2011 – energy 7 TeV, $\mathcal{L}$ = 6 fb^{-1}, peak L = 4 × 10^{33} cm^{-2} s^{-1}
- 2012 – energy 8 TeV, $\mathcal{L}$ = 23 fb^{-1}, peak L = 7.7 × 10^{33} cm^{-2} s^{-1} (77% of the final design target 10^{34} cm^{-2} s^{-1})
- Challenges: pileup 2011-2012
- 2013-2014 – long shutdown 1

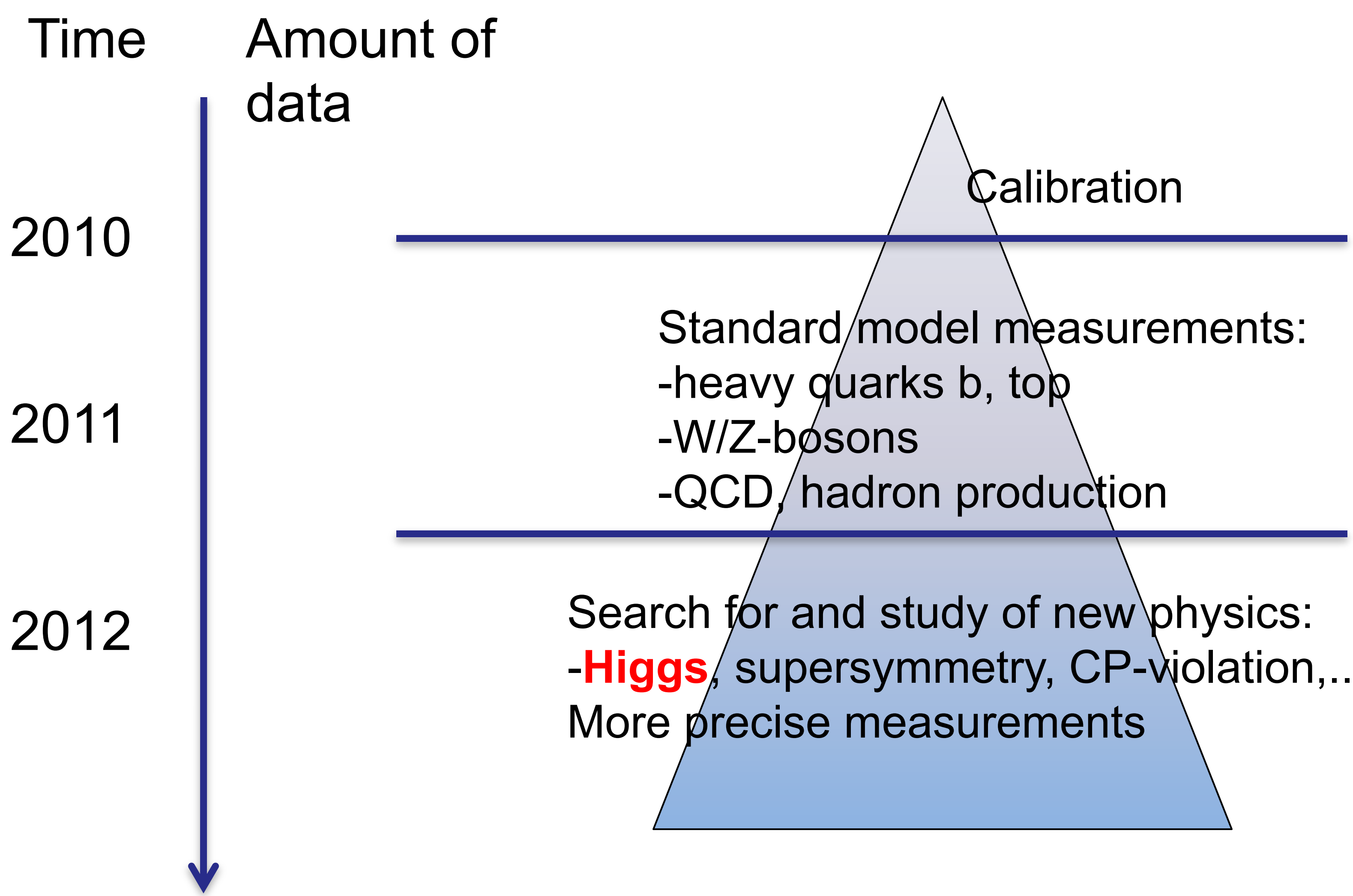
*) 1 b = 1 barn = 10^{-24} cm^2





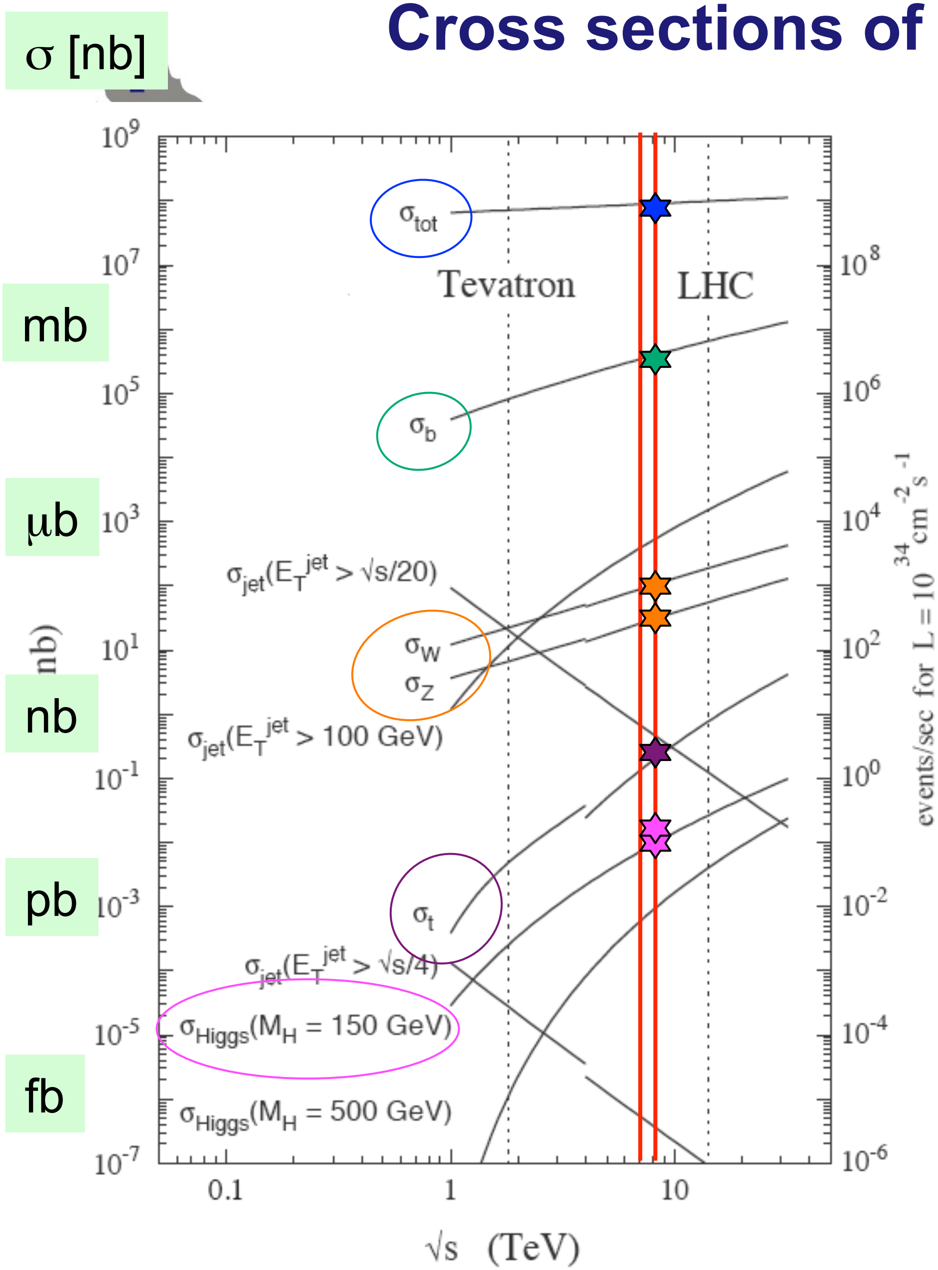
2012: Pileup average 22 overlapping events

LHC-physics 2010 →



A closer look at elementary particles as seen by the LHC

Cross sections of physics processes



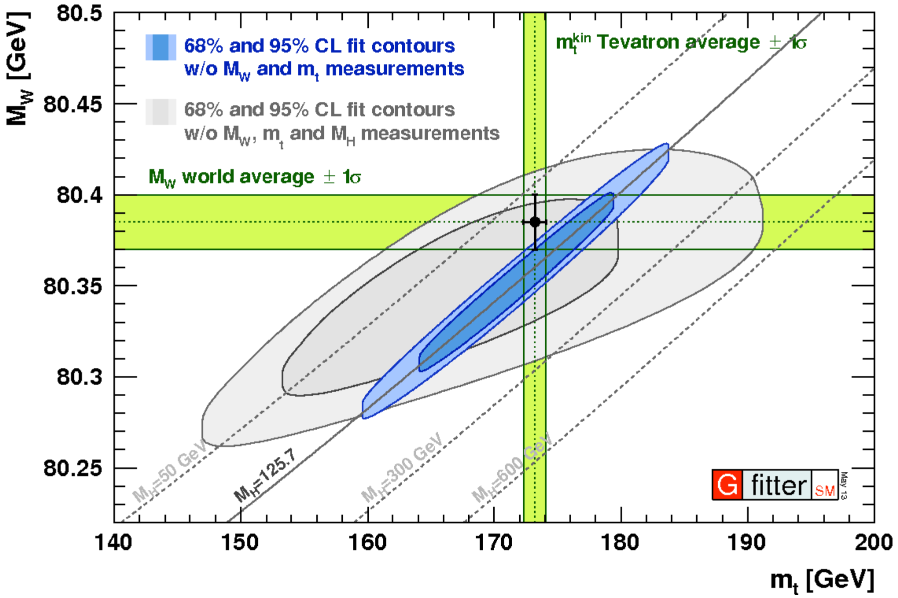
- **N(number of events) = σ(cross section) x $\mathcal{L}$(int. Luminosity)**
  - **Anything: σ ~ 100 mb**
  - **b-quarks: σ ~ 300 μb**
  - **W/Z: σ ~ 100 nb /50 nb**
  - **top-quarks: σ ~ 200 pb**
  - **Higgs(150 GeV): σ ~ 10 pb**
  - **Higgs(125 GeV): σ ~ 20 pb**

eg. N(H125 in 2012) = 20×10^3 fb x 20 fb^{-1}

= 4 x 10^5 events

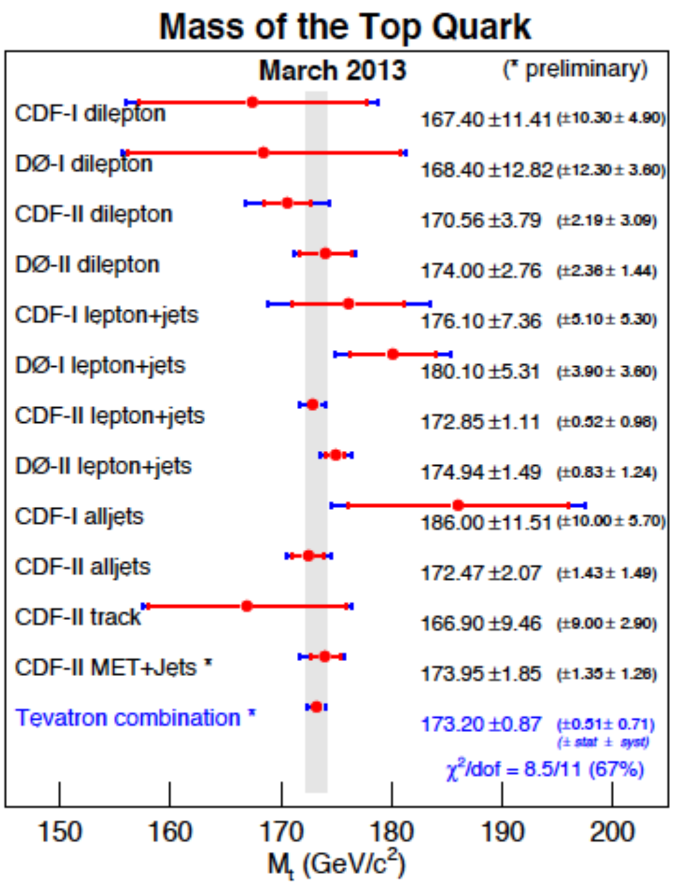
Top quark

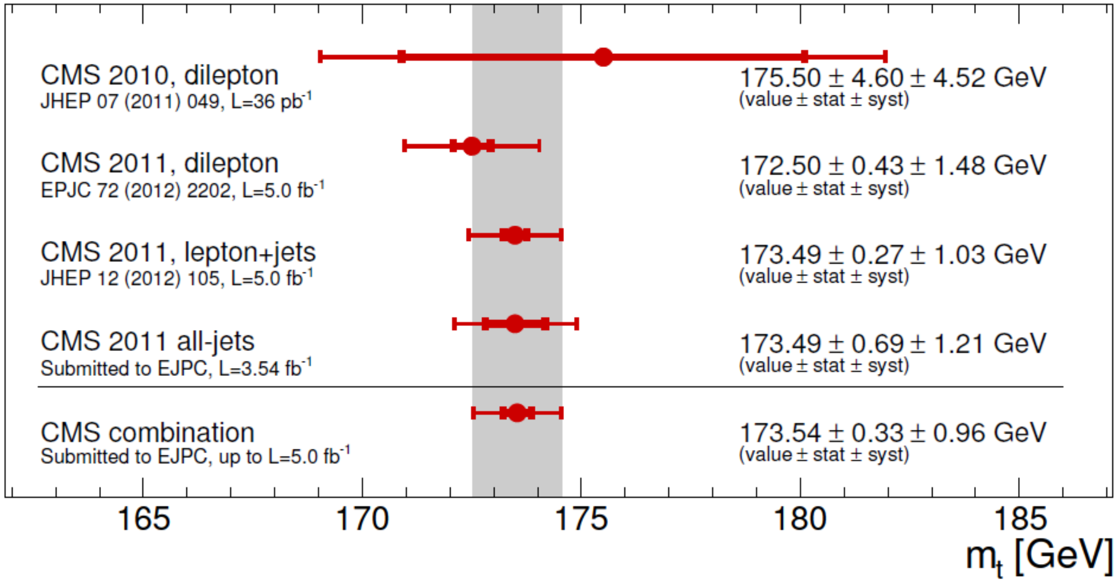
- "Newest" quark, found 1995 at Tevatron
- Heaviest known elementary particle
- **Precision measurements**: mass, intrinsic properties, cross section, decays, couplings
  - **Sensitive test of SM: consistency of Higgs, top and W masses, related through electroweak loop corrections**
  - Searches for new heavy particles: couplings, decays, cross section



Top mass:

- **Tevatron final results:**
  m_t = (173.20 ± 0.51 ± 0.71) GeV, accuracy 0.5%, arXiv:1305.3929 [hep-ex]
- **Best LHC measurement at the moment from CMS:**
  m_t = (173.54 ± 0.33 ± 0.96) GeV, accuracy 0.6%, arXiv:1307.4617 [hep-ex]
  Statistical precision already better than Tevatron
- **CMS+ATLAS combination in progress**





Test CPT with mass difference between top and antitop:

Δm = [-272 ± 196(stat.) ± 122 (syst.)] MeV

CMS PAS TOP-12-031

Example of searches for non-standard top decays

- Normal top-quark decay: $t \rightarrow b W^+$, $W^+ \rightarrow$ qqbar'(jj) or $l^+\nu$
- Search for baryon-number violating decays

  $t \rightarrow$ bbar cbar μ^+, $t \rightarrow$ bbar ubar e^+
- No significant excess over background observed

  BR($t \rightarrow$ bbar cbar μ^+) < 0.0016 at 95% CL

  BR($t \rightarrow$ bbar ubar e^+) < 0.0017 at 95% CL
- CMS PAS B2G-12-023

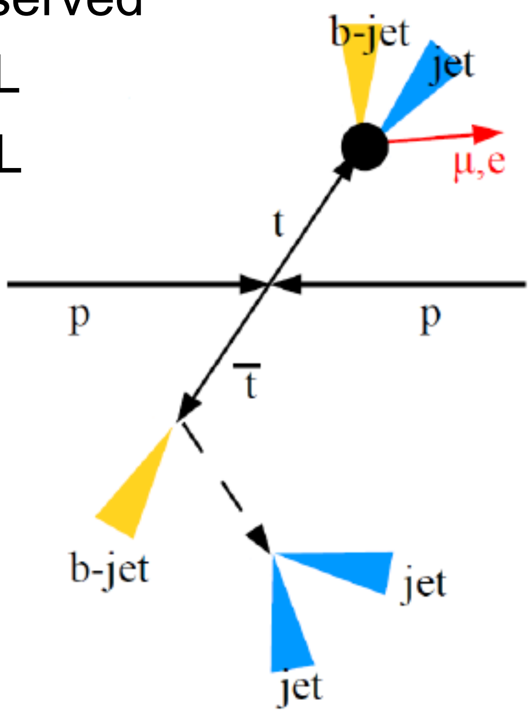
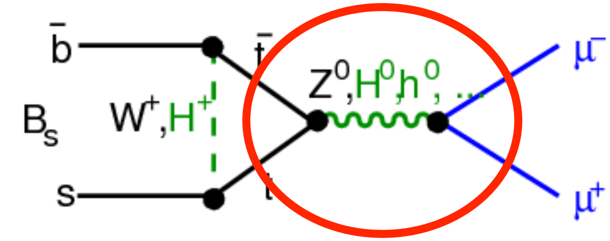


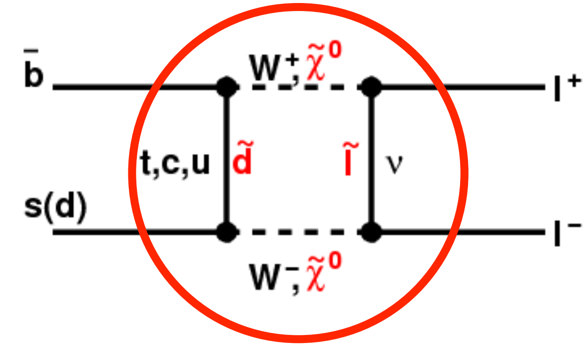
Figure from S. Strandberg, EPS HEP 2013 Stockholm

Heavy flavour quarks: b- and c-quarks

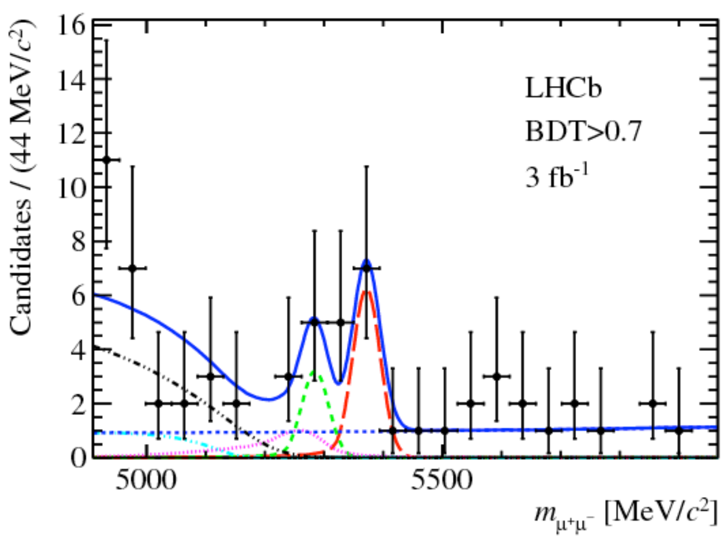
- **Examples:**
- **Very rare b-decays**
- **Exotic quarkonia (ccbar, bbbar)**

Looking for new physics using the $B^0_{d,s} \rightarrow \mu^+\mu^-$ decays

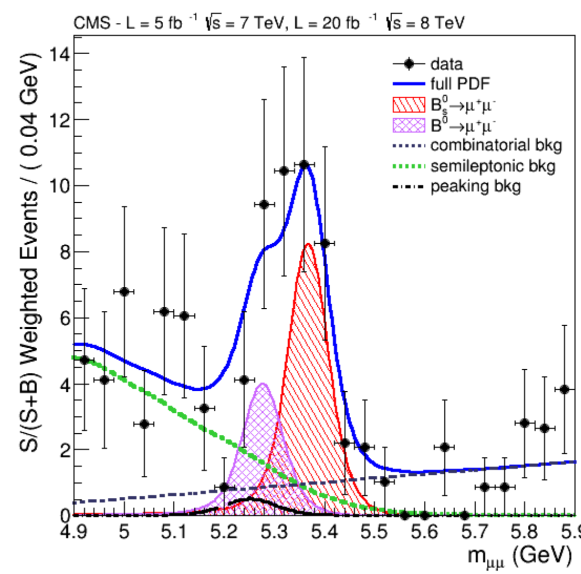




- **Very rare in the SM due to GIM and helicity suppression: $BR(B^0_s \rightarrow \mu^+\mu^-) = (3.2 \pm 0.2) \times 10^{-9}$**
- **Sensitive to physics beyond the SM: new particles entering in the loops**
- **First results in 2013:**
- **LHCb: $BR(B^0_s \rightarrow \mu^+\mu^-) = 2.9^{+1.1}_{-1.0} \times 10^{-9}$, 4.0σ**
- **CMS: $BR(B^0_s \rightarrow \mu^+\mu^-) = 3.0^{+1.0}_{-0.9} \times 10^{-9}$, 4.3σ**
- **Combined: $BR(B^0_s \rightarrow \mu^+\mu^-) = (2.9 \pm 0.7) \times 10^{-9}$**



LHCb results

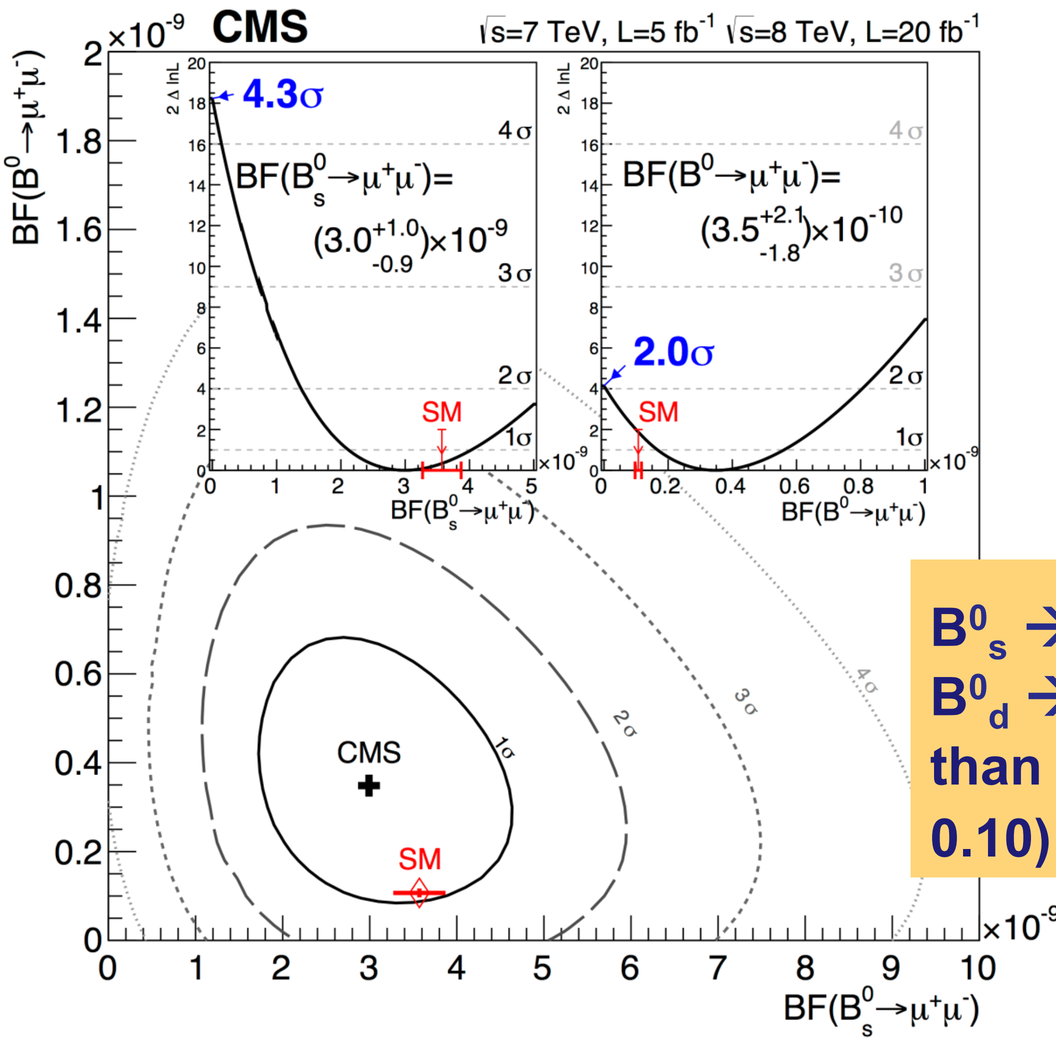


CMS results

Results also for $B^0_d \rightarrow \mu^+\mu^-$

CMS: $BR(B^0_d \rightarrow \mu^+\mu^-) < 1.1 \times 10^{-9}$ at 95% CL $\rightarrow BR(B^0_d \rightarrow \mu^+\mu^-) = 3.5^{+2.1}_{-1.8} \times 10^{-10}$, 2.0σ

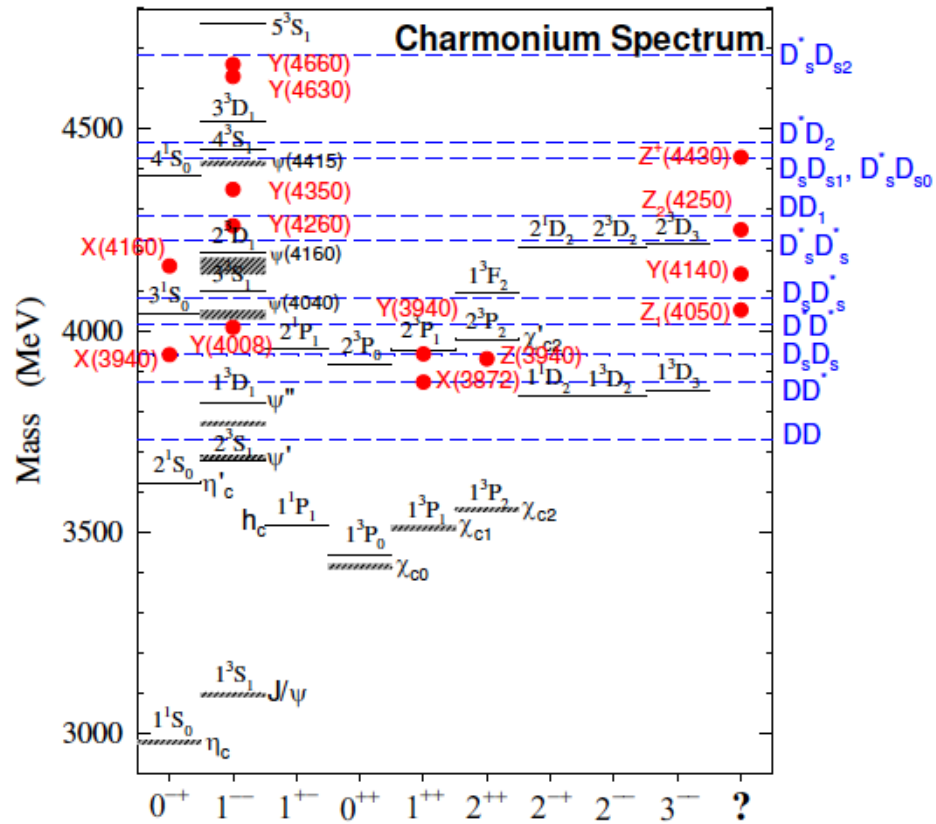
LHCb: $BR(B^0_d \rightarrow \mu^+\mu^-) < 7.4 \times 10^{-10}$ at 95% CL $\rightarrow BR(B^0_d \rightarrow \mu^+\mu^-) = 3.7^{+2.5}_{-2.1} \times 10^{-10}$, 2.0σ



$B^0_s \rightarrow \mu^+\mu^-$ consistent with the SM
$B^0_d \rightarrow \mu^+\mu^-$ (2.0σ signals) higher than SM: $BR(B^0_d \rightarrow \mu^+\mu^-) = (1.07 \pm 0.10) \times 10^{-10}$

Exotic charmonium and bottomonium states

- Bound ccbar charmonia: starting from 2003 Belle experiment discovering X(3872) (→J/ψ $\pi^+\pi^-$), many new bound charmonia states not fitting the conventional/predicted states have been found
  - X(3872), Y(4140), …
- Suggested possibilities
  - Hybrids (“glueballs” ccbar g)
  - Molecular states – loosely bound pair of meson
  - Tetraquark states – tightly bound diquark-diantiquark state
  - Threshold effects
- First evidence in bottomonia:
  - Y_b(10888) Belle 2010
- LHC: good place to study
  - Large rates
  - Also access to bbbar-states



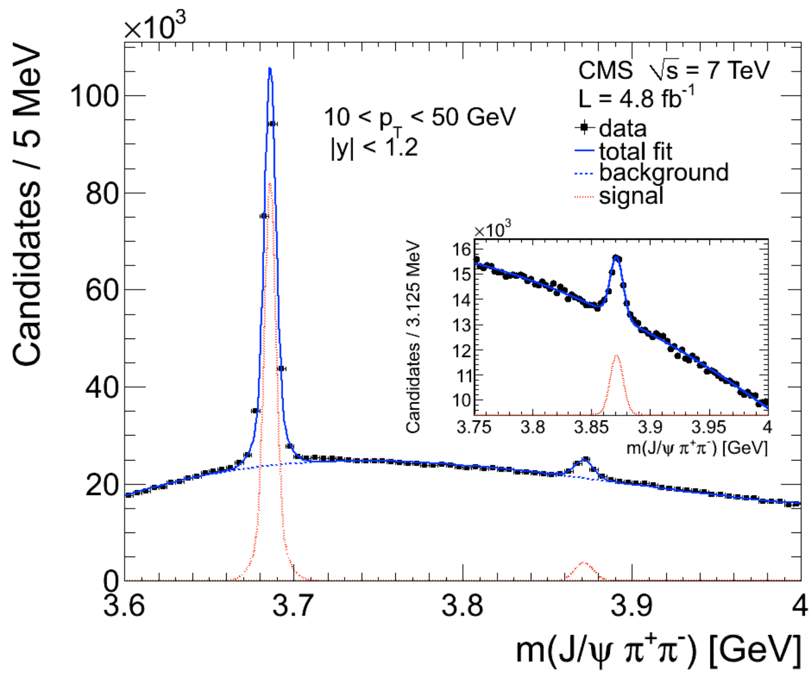
S. Godfrey arXiv: 0910.3409 [hep-ex]

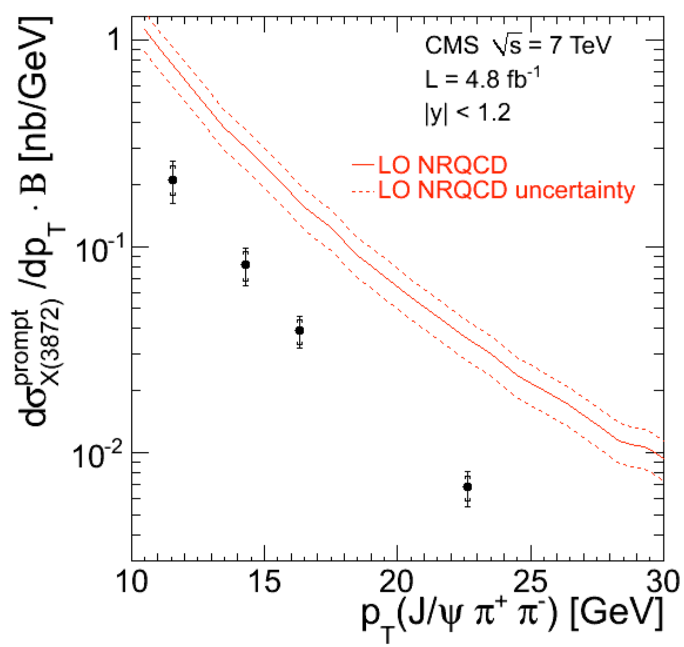
Quarkonium Working Group
arXiv: 1010.5827 [hep-ex]

State	m (MeV)	Γ (MeV)	J^{PC}	Process (mode)	Experiment (#σ)	Year	Status
$X(3872)$	3871.52 ± 0.20	1.3 ± 0.6	$1^{++}/2^{-+}$	$B\to K(\pi^+\pi^- J/\psi)$	Belle [85, 86] (12.8), BABAR [87] (8.6)	2003	OK
		(<2.2)		$p\bar{p}\to(\pi^+\pi^- J/\psi)+...$	CDF [88–90] (np), DØ [91] (5.2)		
				$B\to K(\omega J/\psi)$	Belle [92] (4.3), BABAR [93] (4.0)		
				$B\to K(D^{*0}\bar{D}^0)$	Belle [94, 95] (6.4), BABAR [96] (4.9)		
				$B\to K(\gamma J/\psi)$	Belle [92] (4.0), BABAR [97, 98] (3.6)		
				$B\to K(\gamma\psi(2S))$	BABAR [98] (3.5), Belle [99] (0.4)		
$X(3915)$	3915.6 ± 3.1	28 ± 10	$0/2^{?+}$	$B\to K(\omega J/\psi)$	Belle [100] (8.1), BABAR [101] (19)	2004	OK
				$e^+e^-\to e^+e^-(\omega J/\psi)$	Belle [102] (7.7)		
$X(3940)$	3942^{+9}_{-8}	37^{+27}_{-17}	$?^{?+}$	$e^+e^-\to J/\psi(D\bar{D}^*)$	Belle [103] (6.0)	2007	NC!
				$e^+e^-\to J/\psi\ (...)$	Belle [54] (5.0)		
$G(3900)$	3943 ± 21	52 ± 11	1^{--}	$e^+e^-\to\gamma(D\bar{D})$	BABAR [27] (np), Belle [21] (np)	2007	OK
$Y(4008)$	4008^{+121}_{-49}	226 ± 97	1^{--}	$e^+e^-\to\gamma(\pi^+\pi^- J/\psi)$	Belle [104] (7.4)	2007	NC!
$Z_1(4050)^+$	4051^{+24}_{-43}	82^{+51}_{-55}	?	$B\to K(\pi^+\chi_{c1}(1P))$	Belle [105] (5.0)	2008	NC!
$Y(4140)$	4143.4 ± 3.0	15^{+11}_{-7}	$?^{?+}$	$B\to K(\phi J/\psi)$	CDF [106, 107] (5.0)	2009	NC!
$X(4160)$	4156^{+29}_{-25}	139^{+113}_{-65}	$?^{?+}$	$e^+e^-\to J/\psi(D\bar{D}^*)$	Belle [103] (5.5)	2007	NC!
$Z_2(4250)^+$	4248^{+185}_{-45}	177^{+321}_{-72}	?	$B\to K(\pi^+\chi_{c1}(1P))$	Belle [105] (5.0)	2008	NC!
$Y(4260)$	4263 ± 5	108 ± 14	1^{--}	$e^+e^-\to\gamma(\pi^+\pi^- J/\psi)$	BABAR [108, 109] (8.0)	2005	OK
					CLEO [110] (5.4)		
					Belle [104] (15)		
				$e^+e^-\to(\pi^+\pi^- J/\psi)$	CLEO [111] (11)		
				$e^+e^-\to(\pi^0\pi^0 J/\psi)$	CLEO [111] (5.1)		
$Y(4274)$	$4274.4^{+8.4}_{-6.7}$	32^{+22}_{-15}	$?^{?+}$	$B\to K(\phi J/\psi)$	CDF [107] (3.1)	2010	NC!
$X(4350)$	$4350.6^{+4.6}_{-5.1}$	$13.3^{+18.4}_{-10.0}$	$0,2^{++}$	$e^+e^-\to e^+e^-(\phi J/\psi)$	Belle [112] (3.2)	2009	NC!
$Y(4360)$	4353 ± 11	96 ± 42	1^{--}	$e^+e^-\to\gamma(\pi^+\pi^-\psi(2S))$	BABAR [113] (np), Belle [114] (8.0)	2007	OK
$Z(4430)^+$	4443^{+24}_{-18}	107^{+113}_{-71}	?	$B\to K(\pi^+\psi(2S))$	Belle [115, 116] (6.4)	2007	NC!
$X(4630)$	4634^{+9}_{-11}	92^{+41}_{-32}	1^{--}	$e^+e^-\to\gamma(\Lambda_c^+\Lambda_c^-)$	Belle [25] (8.2)	2007	NC!
$Y(4660)$	4664 ± 12	48 ± 15	1^{--}	$e^+e^-\to\gamma(\pi^+\pi^-\psi(2S))$	Belle [114] (5.8)	2007	NC!
$Y_b(10888)$	10888.4 ± 3.0	$30.7^{+8.9}_{-7.7}$	1^{--}	$e^+e^-\to(\pi^+\pi^-\Upsilon(nS))$	Belle [37, 117] (3.2)	2010	NC!

X(3872) results at LHC

- CMS collected >12 000 X(3872) candidates from 2011 data (4.8 fb^{-1})
- Dipion mass spectrum: decay via intermediate state X(3872) → $J/\psi\rho^0$ → $J/\psi\pi^+\pi^-$ favoured
- Separate X(3872) coming from B decays and from primary production
- NRQCD model prediction for primary production badly off: measure σ x BR = (1.06 ± 0.11 ± 0.15) nb, prediction (4.01 ± 0.88) nb

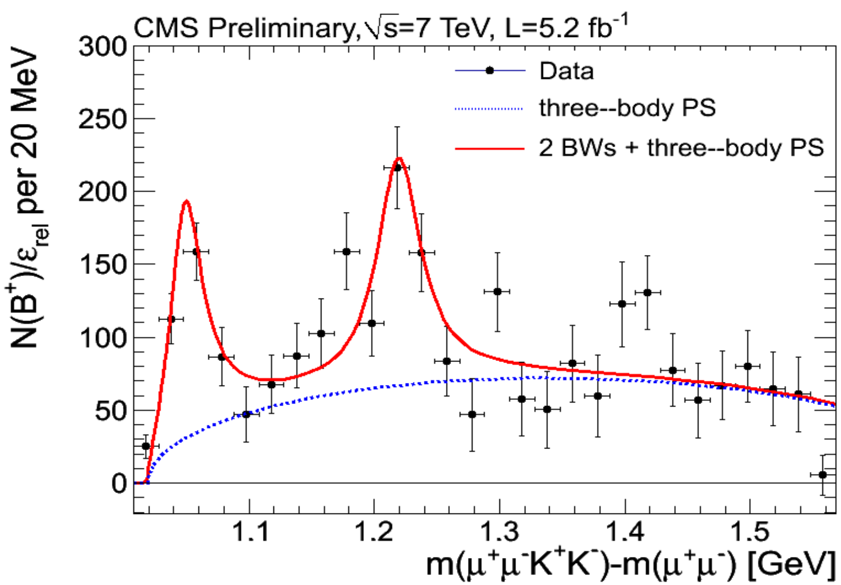




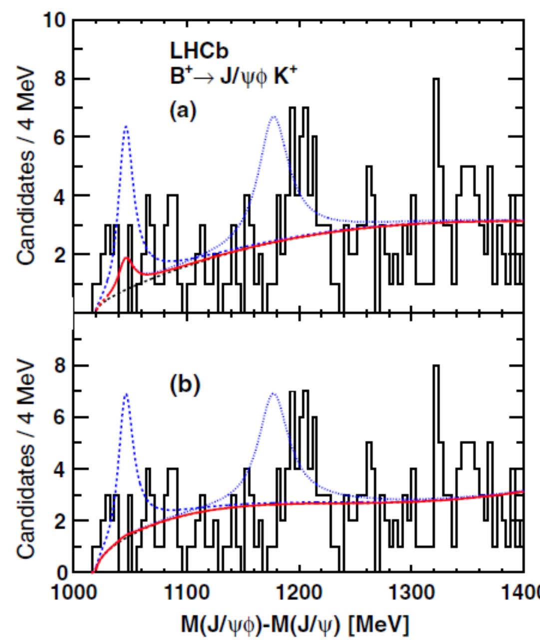
JHEP 04 (2013) 154

Y(4140)

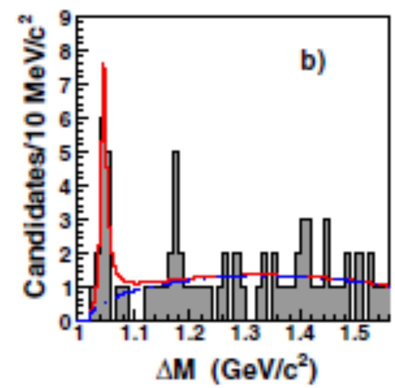
- LHC: search for structures in the $J/\psi\phi$ spectrum in $B^+ \rightarrow J/\psi\phi K^+$ decays
- CMS: over 5σ evidence for structure at m = (4148.2 ± 2.0 ± 4.6) MeV – also seen by CDF (3.8σ signal with 2.7 fb^{-1})
- Second structure at m = (4316.7 ± 3.0 ± 7.3) MeV
- LHCb: no Y(4140) signal with 0.37 fb^{-1}, 2.4σ disagreement with CDF



CMS PAS BPH-11-026



LHCb, PRD 85, 091103(R) (2012)



CDF, PRL 102, 242002 (2009)

Search for X_b

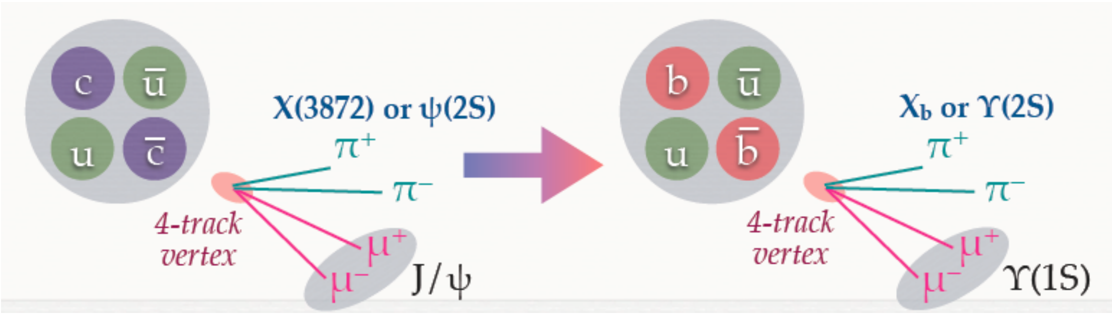
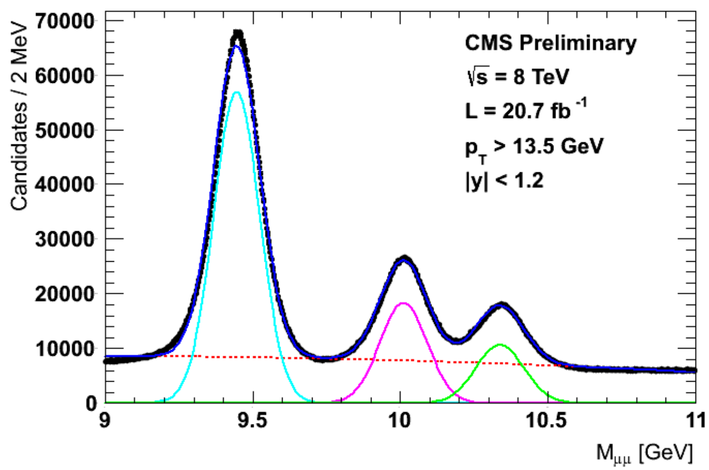
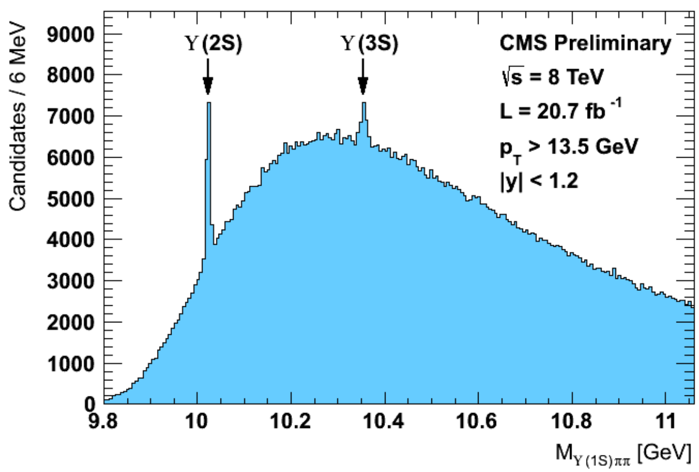


Figure from K.-F. Chen, EPS HEP 2013 Stockholm

- CMS: Search for the bottomonium counterpart of X(3872) from 2012 data (20.7 fb^{-1})
- Look for peaks other than Υ(2S), Υ(3S), in the $\Upsilon(1S)\pi^+\pi^-$ mass spectrum
- No obvious signal found: σ x BR /σ x BR(Υ(2S)) < (0.9-5.4)% [6.6% in the similar charmonium case X(3872)]

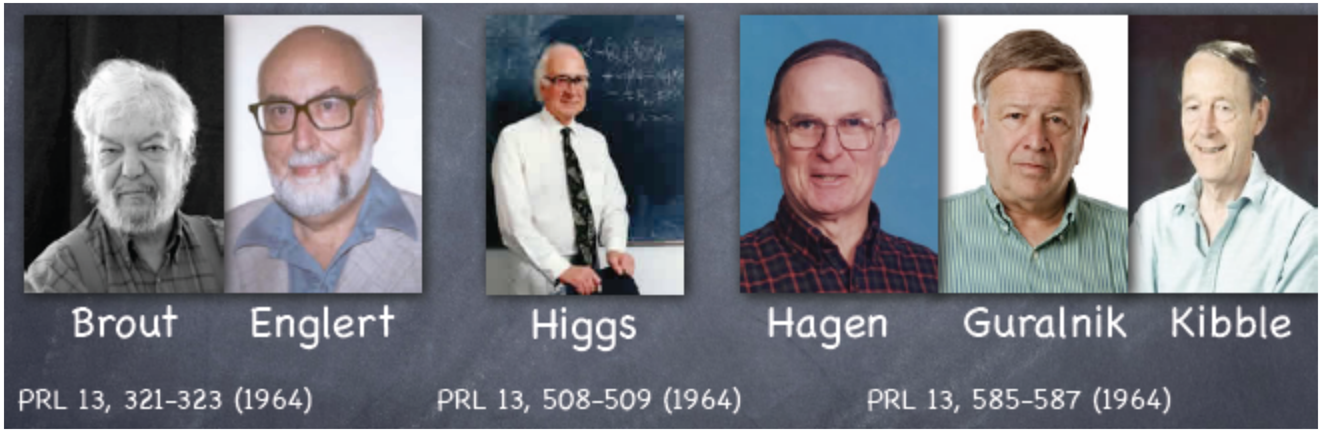
CMS PAS BPH-11-016
arXiv:1309.0250 [hep-ex]





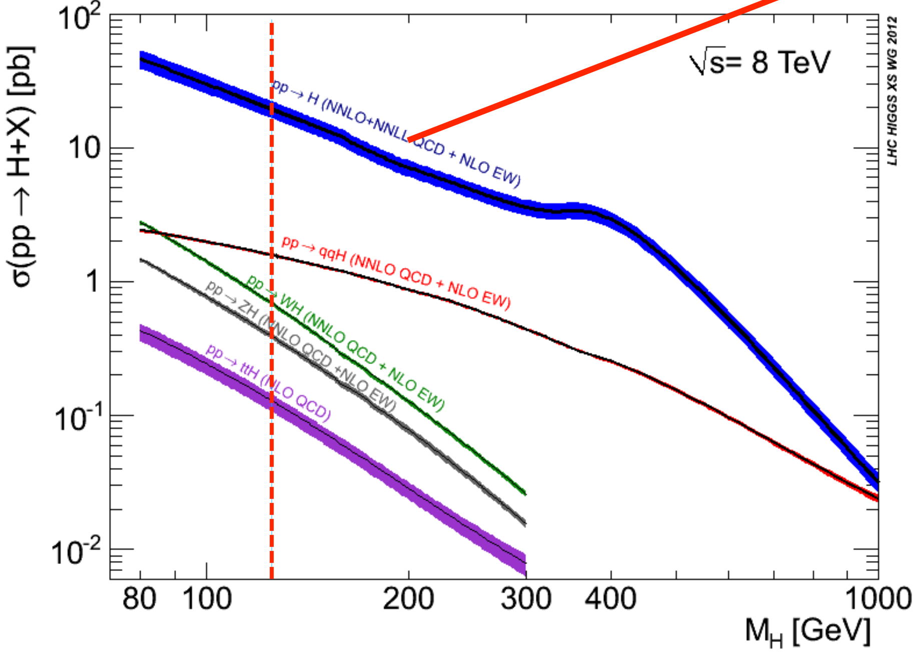
The Higgs boson

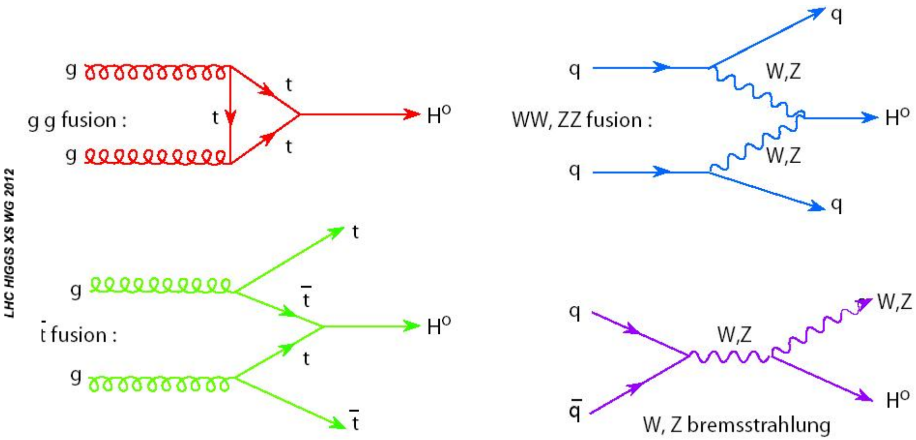
- The Standard Model, which combines weak and electromagnetic interactions, was not fully verified
- Requires an additional mechanism to generate masses to elementary particles
- The Higgs mechanism, or the Brout-Englert-Higgs mechanism (1964): electroweak symmetry is spontaneously broken
  - $W^{\pm}$ and Z become massive, γ remains massless
  - the same mechanism can generate masses to fermions
  - Requires at least one elementary scalar particle, a Higgs boson

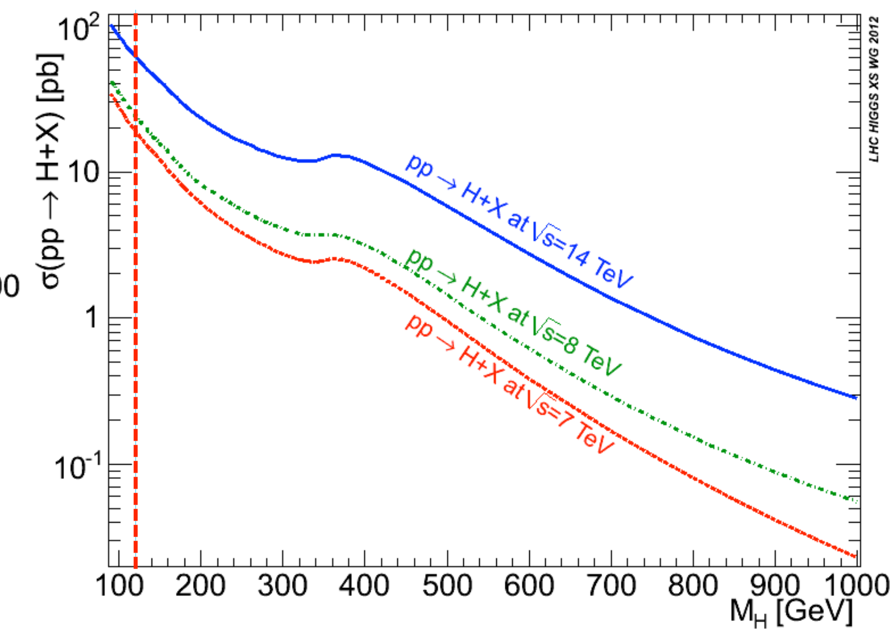


Brout-Englert-Higgs-Hagen-Guralnik-Kibble

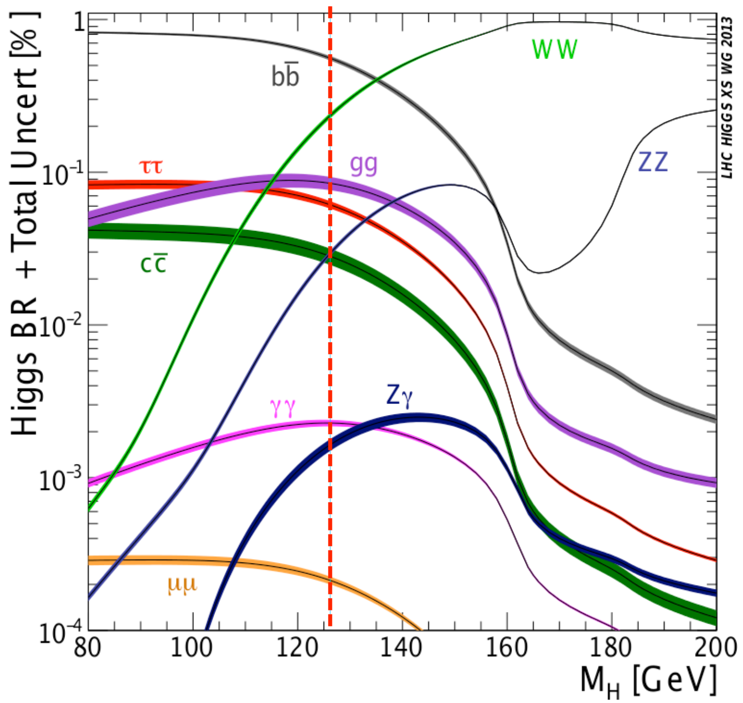
Higgs production

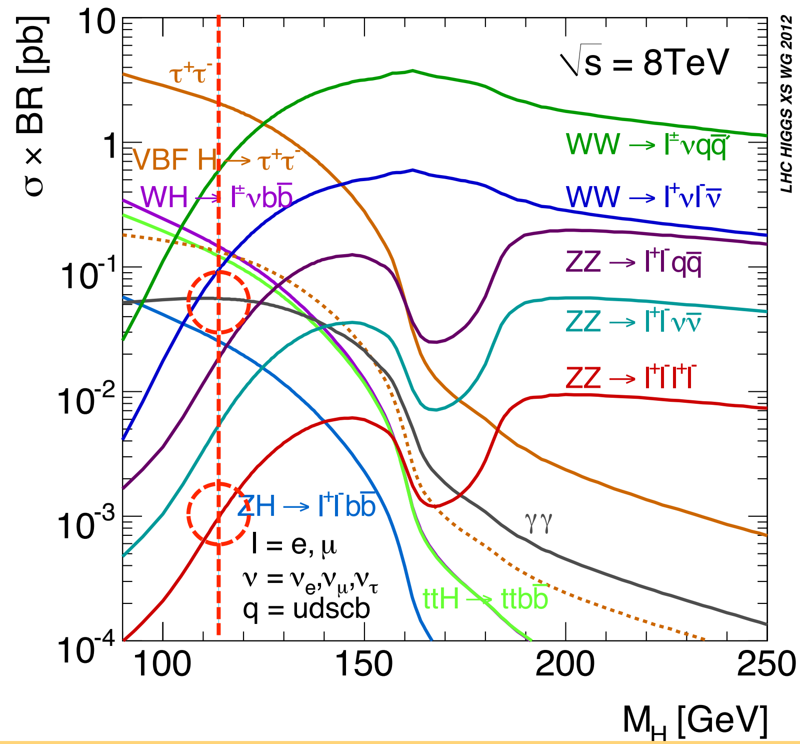






Higgs decays



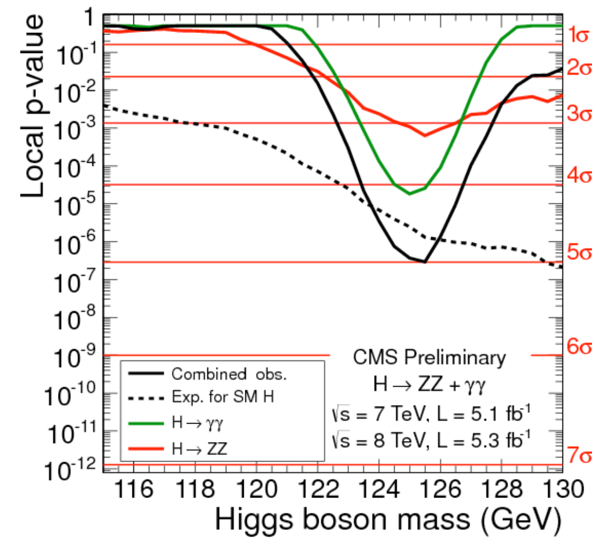


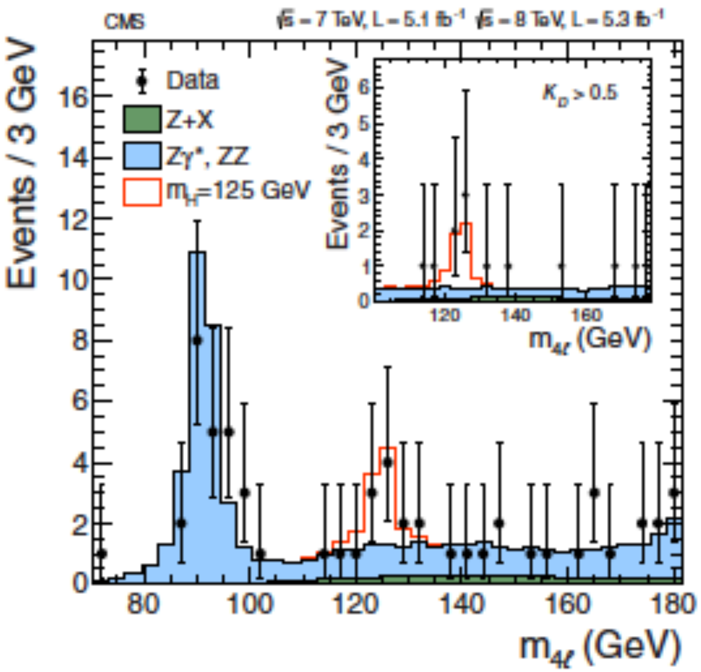
Decay modes searched for in the mass range 90-200 GeV:

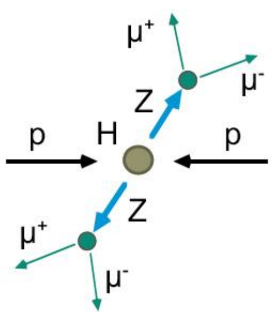
- **ZZ → 4l, 2l2ν, 2l2j good mass resolution, small background, small rate**
- **γγ, good mass resolution, large background, medium rate**
- **WW → lνlν , lν2j mass badly measured, background, large rate**
- **bbbar large rate, poor mass resolution, trigger issues → only possible as ZH, WH, ttbarH**
- **$\tau^+ \tau^-$ poor mass resolution, large rate, trigger issues**
- **Zγ, good mass resolution, small background, small rate**

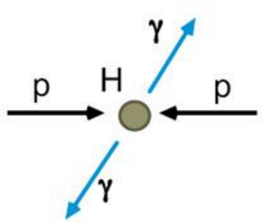
Results made public 4.7.2012 by ATLAS and CMS

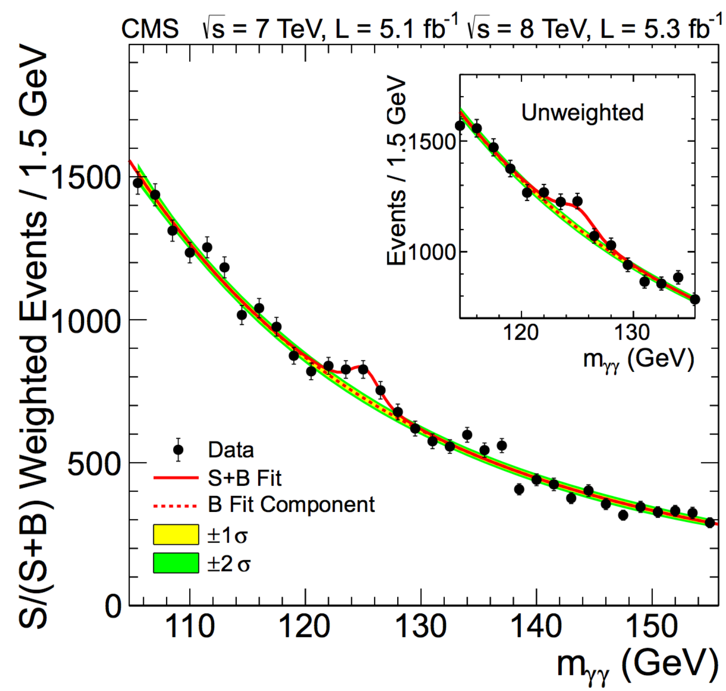
Observation of a signal with 5σ significance, mass ~125 GeV
- ZZ → 4l and γγ most significant
- Both experiments obtain ~identical results



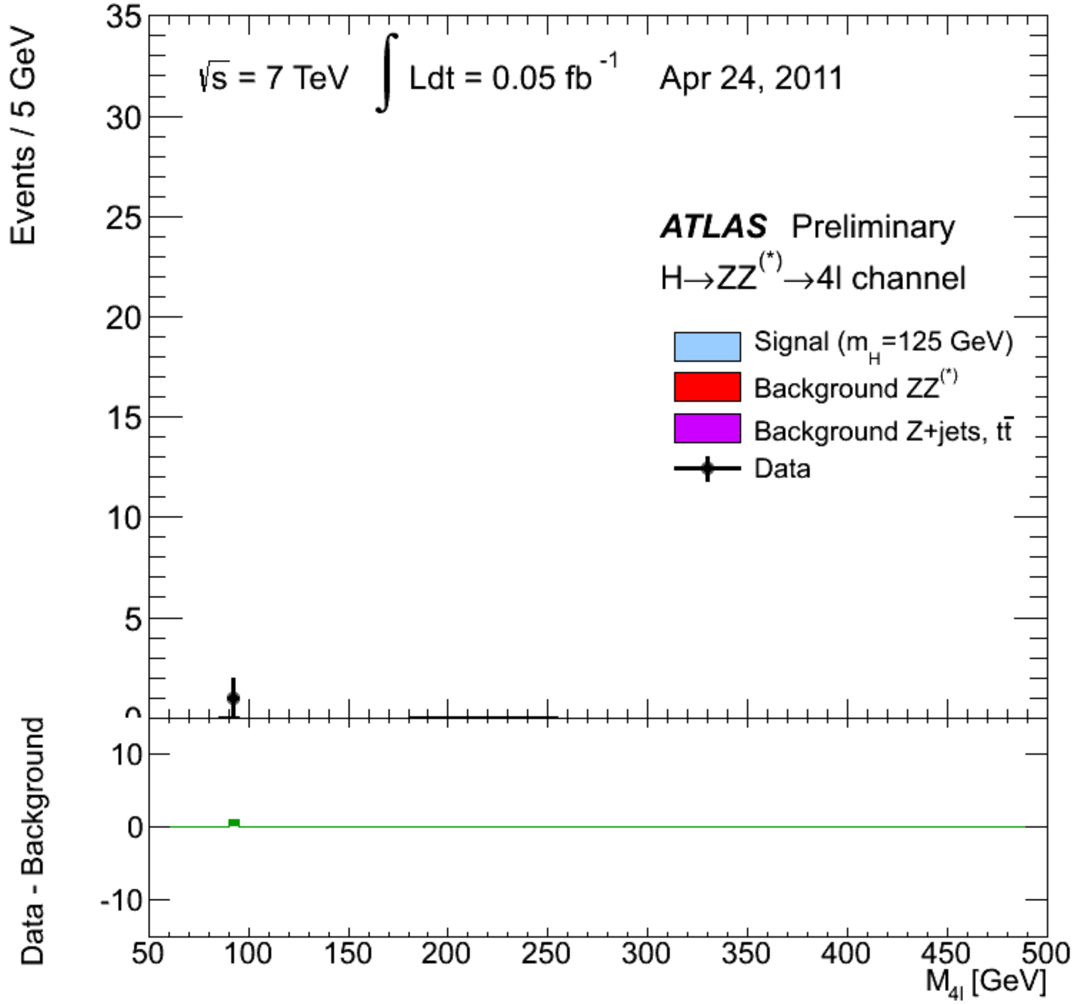




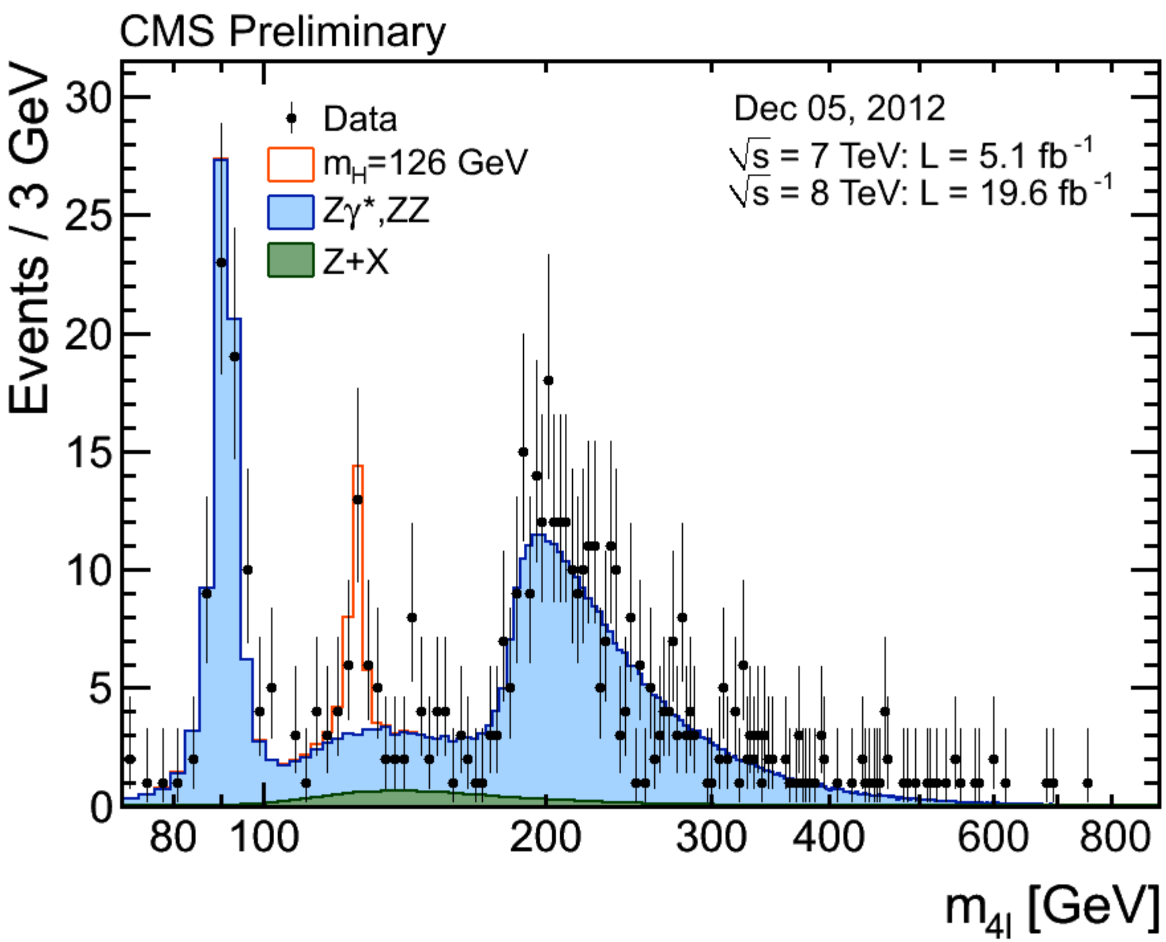




Higgs decay to four leptons: H → ZZ$^{(*)}$ → 4e, 4μ, 2e+2μ



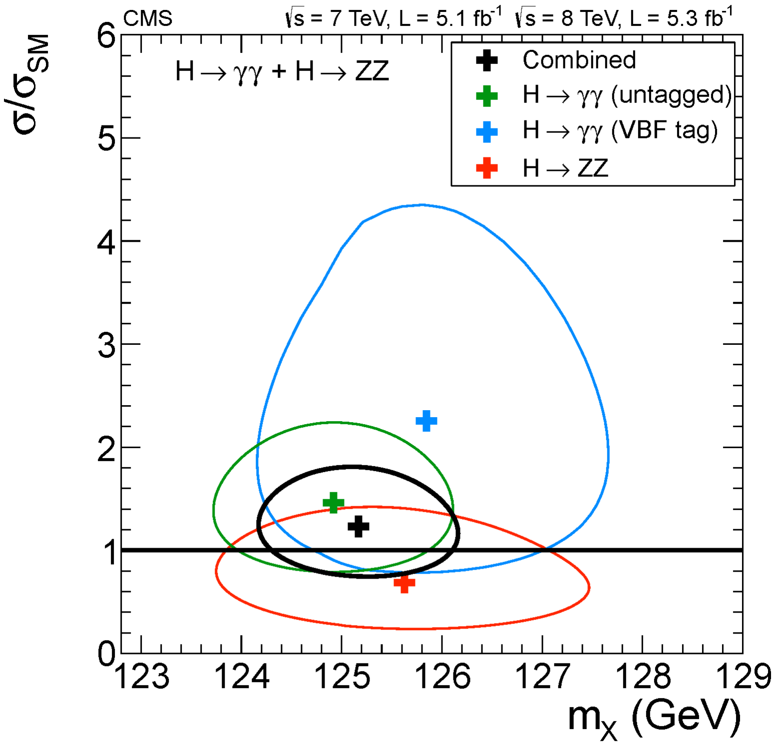
Higgs decay to four leptons: H → ZZ$^{(*)}$ → 4e, 4μ, 2e+2μ

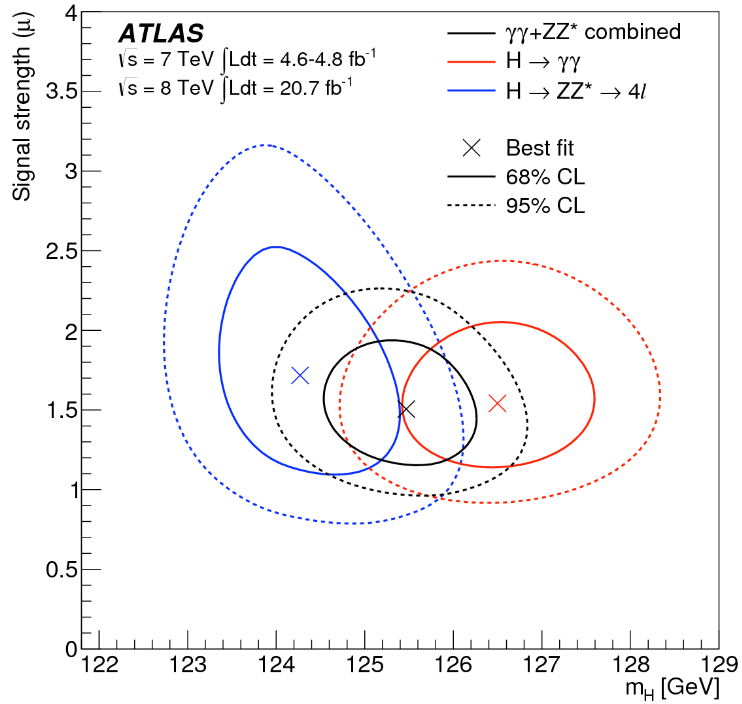


Is it a Higgs – the Higgs?

- Measure particle properties:
  - Mass, width
  - Internal properties – charge, spin, parity
  - Production cross section, decay branching fractions
    $H \rightarrow \gamma\gamma$, ZZ, WW, $\tau\tau$, bb
- One or several?
  - Minimum (Standard Model): one H^0
  - Supersymmetry: at least 5 Higgses
    - 3 neutral h^0, H^0, A^0
    - 2 charged H^+, H^-
  - Also more exotic, like H^{++}
  - Non-standard Higgs ←→ also other new particles

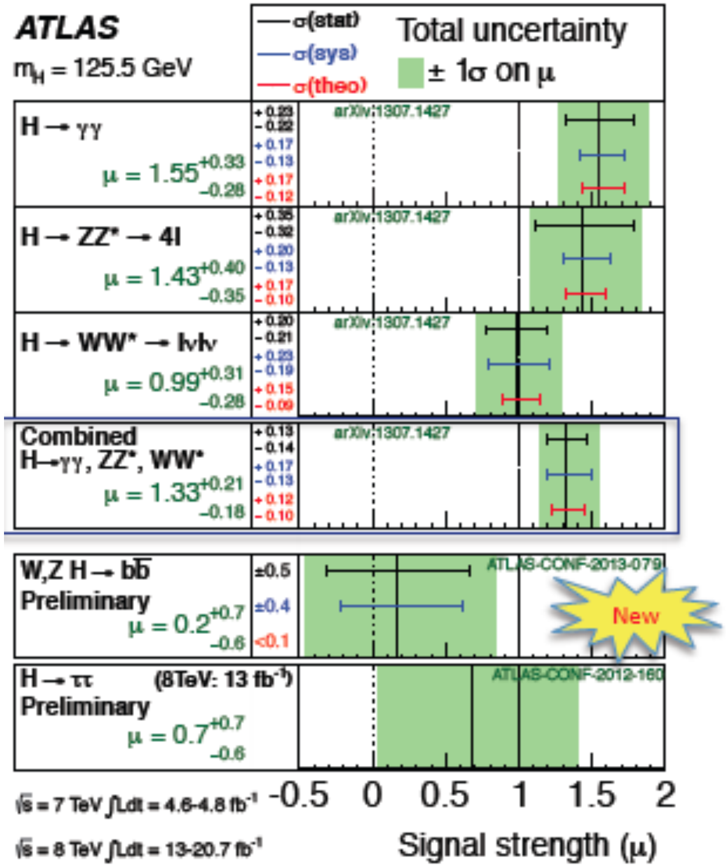
Mass

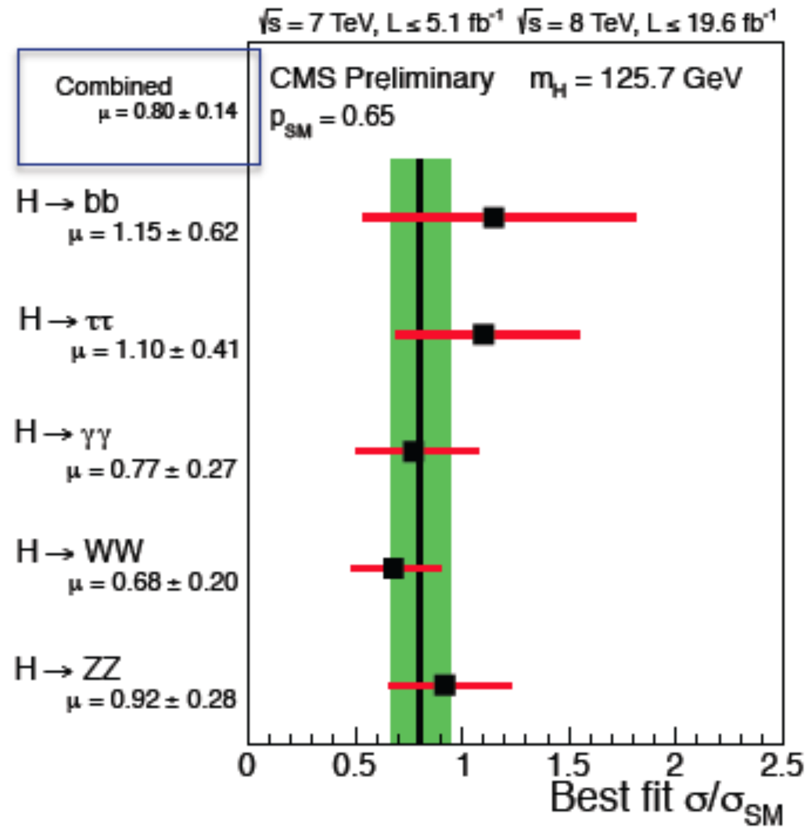




- **ATLAS: 125.5 ± 0.2 $^{+0.5}_{-0.6}$ GeV**
- **CMS: 125.7 ± 0.3 ± 0.3 GeV**
- **Mass already measured with 0.3-0.5% precision (compare top mass precision 0.5%)**

Production cross section × branching fraction





- **ATLAS: σ/σ_{SM} = (1.33 ± 0.20) γγ, ZZ*, WW*** (1.23 ± 0.18 including bbbar and ττ)
- **CMS: σ/σ_{SM} = (0.80 ± 0.14) γγ, ZZ*, WW*, bbbar, ττ**

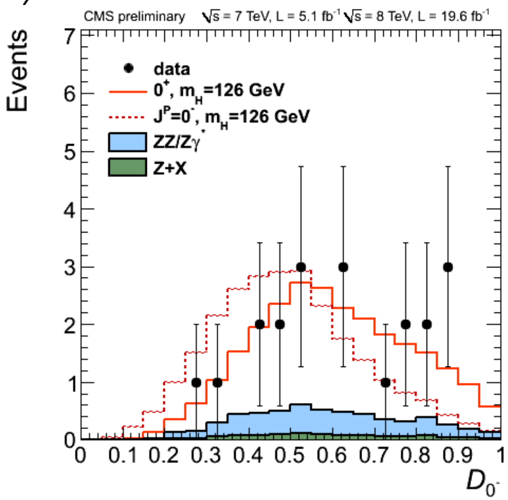
Spin and parity

SM: $J^P = 0^+$

H → ZZ* → 4l sensitive to J^P: 2 masses and 5 angles

H → γγ sensitive to J: decay angle

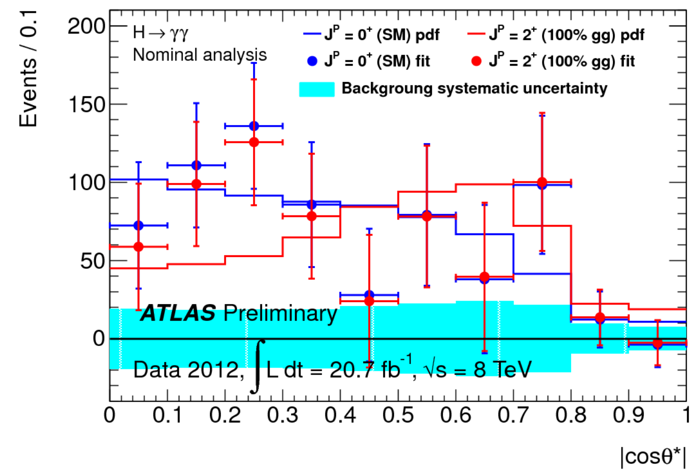
$J^P = 0^+$ vs. 0^-

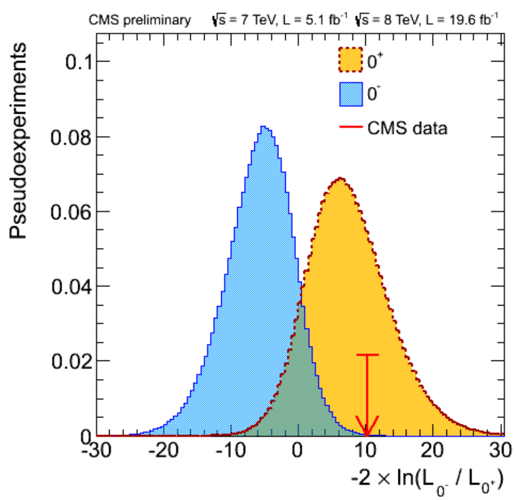


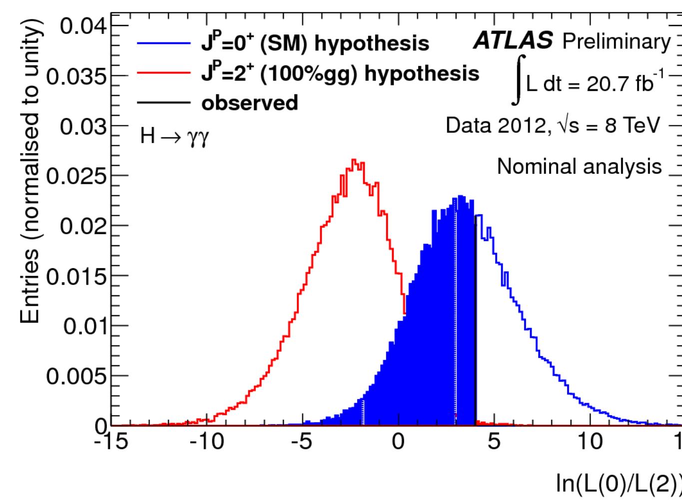
0^- -excluded at 99.8% CL

2^+ excluded at >99.9 CL

$J^P = 0^+$ vs. 2^+

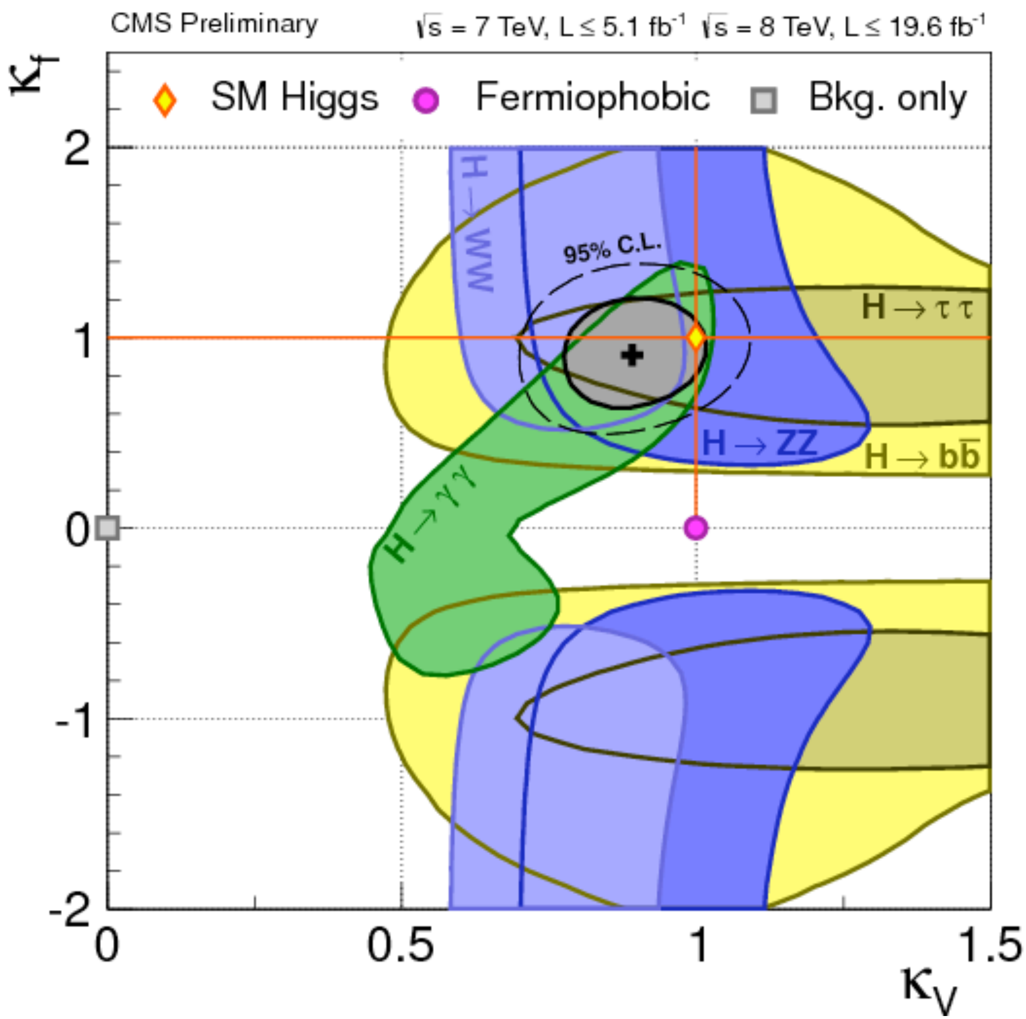






Couplings to fermions and bosons

SM: $\kappa_V = \kappa_f = 1$
$\kappa_f = 0$ excluded at $>5\sigma$

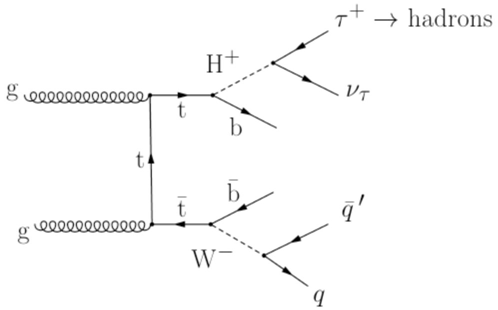


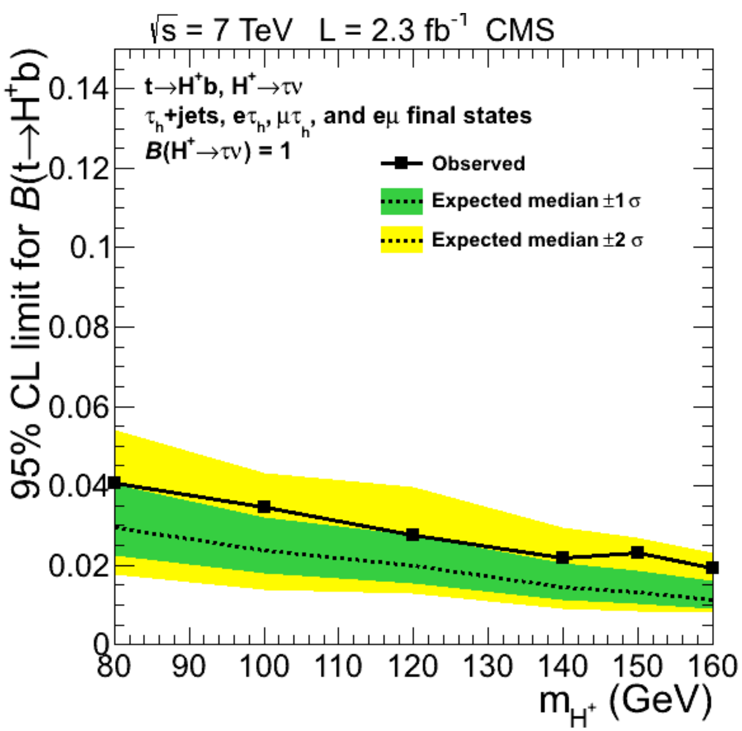
Higgs summary

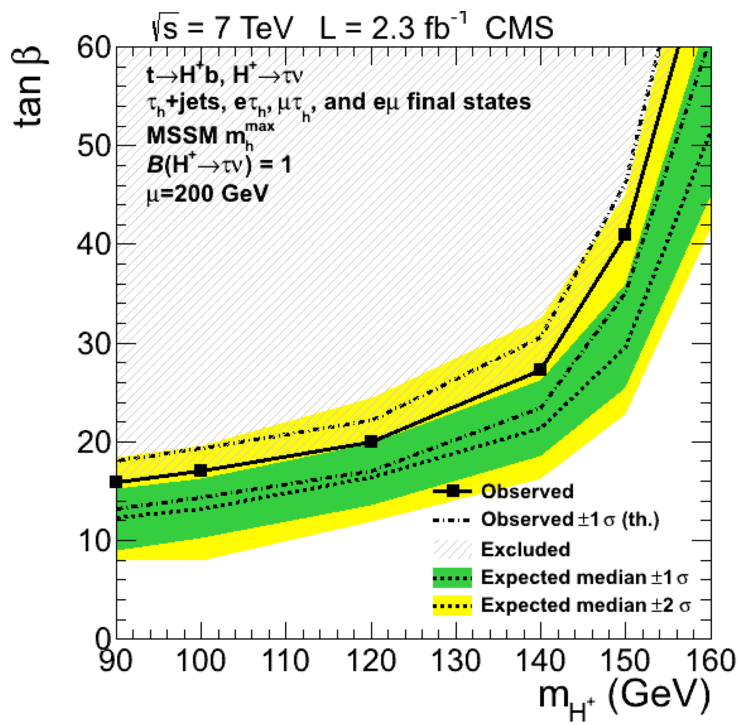
Question	Status?	How?
Statistically significant?	Yes, 7-10σ	Mass peaks
Is it a boson?	Yes	Decays to 2 photons
Mass?	0.3% accuracy	$\gamma\gamma$- and ZZ*-final states
Spin?	J=0 J=2 excl. at >99% CL	Final state kinematics
Parity?	$J^P = 0^+$ $J^P = 0^-$ excl. at >99% CL	Final state kinematics
Is it a Higgs boson?	Yes	Spin-parity, cross sections, decays and couplings
Is it a SM Higgs boson?	Improving, more data helps	Measure cross sections, decays and couplings. Probe further (and rarer) decay channels.
Are there other Higgs bosons?	In progress, need more data	Direct searches

Charged Higgs

- Would be smoking gun for an extended Higgs sector, and possibly extended theories
- Search below top-mass: stringent limits





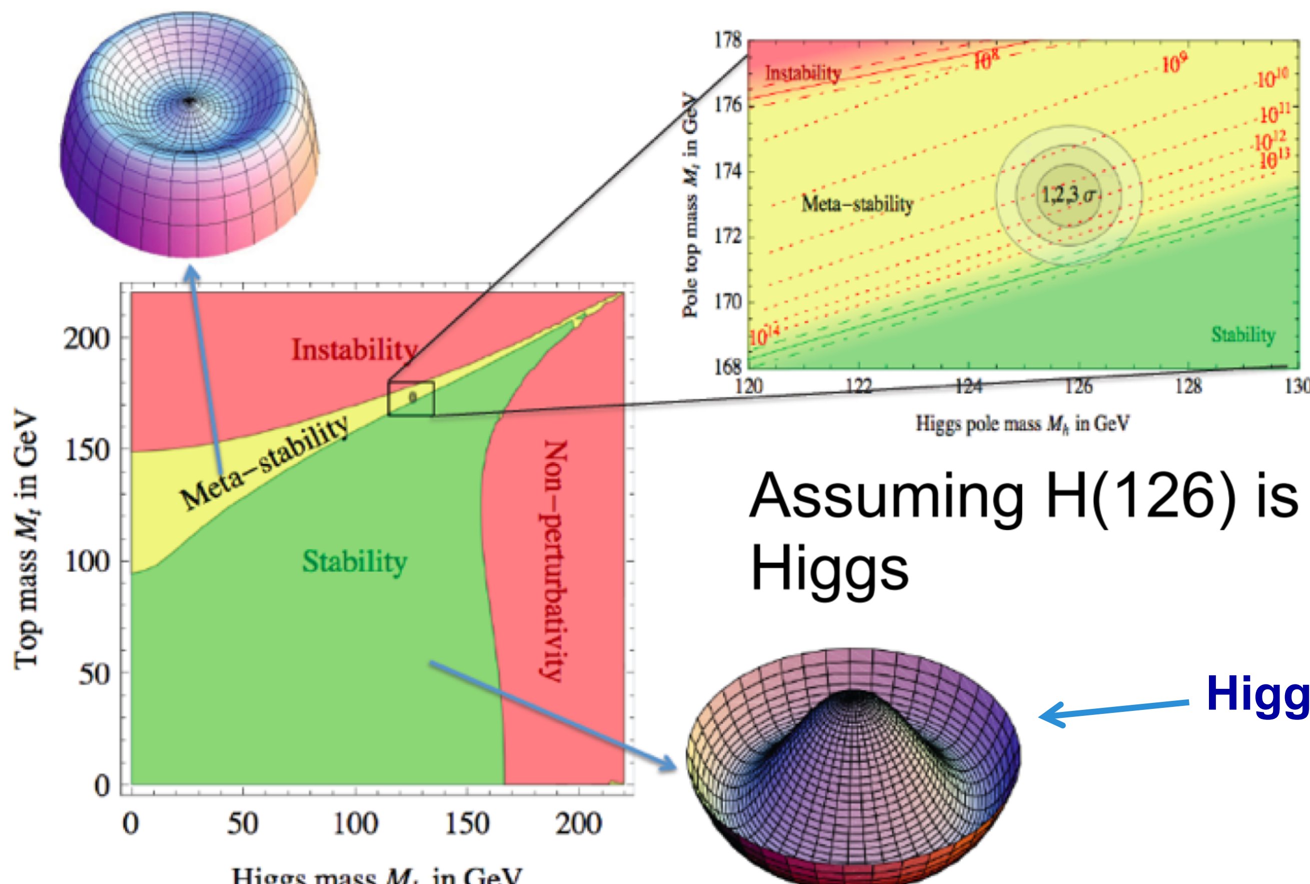


If we have the SM Higgs, are we in a metastable universe?

Are we in a metastable universe ?

Top mass: vacuum stability

A. Strumia, Moriond EWK 2013

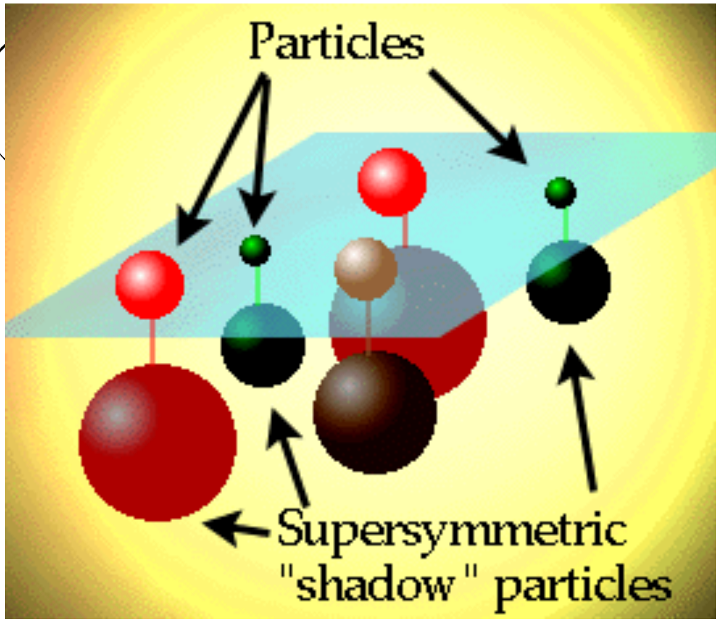


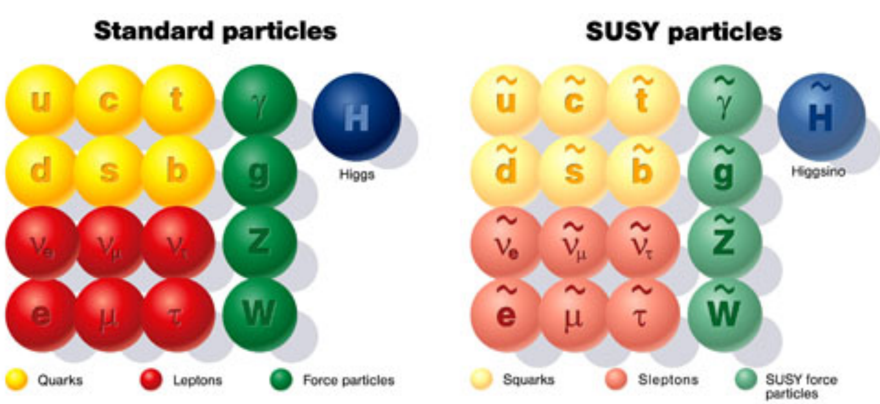
Assuming H(126) is THE SM Higgs

Higgs potential

Searching for Supersymmetry and other New Physics

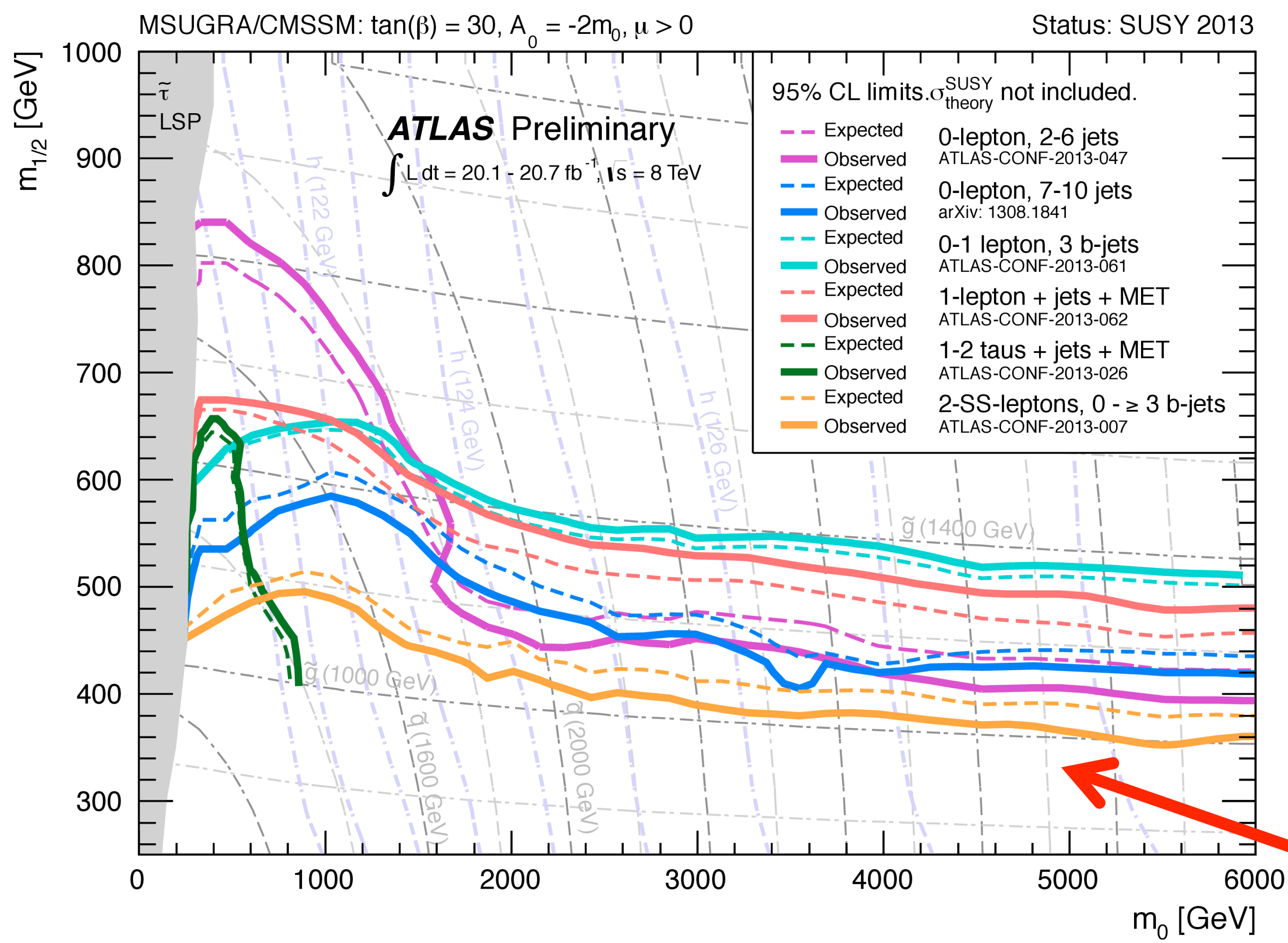
Supersymmetry - SUSY





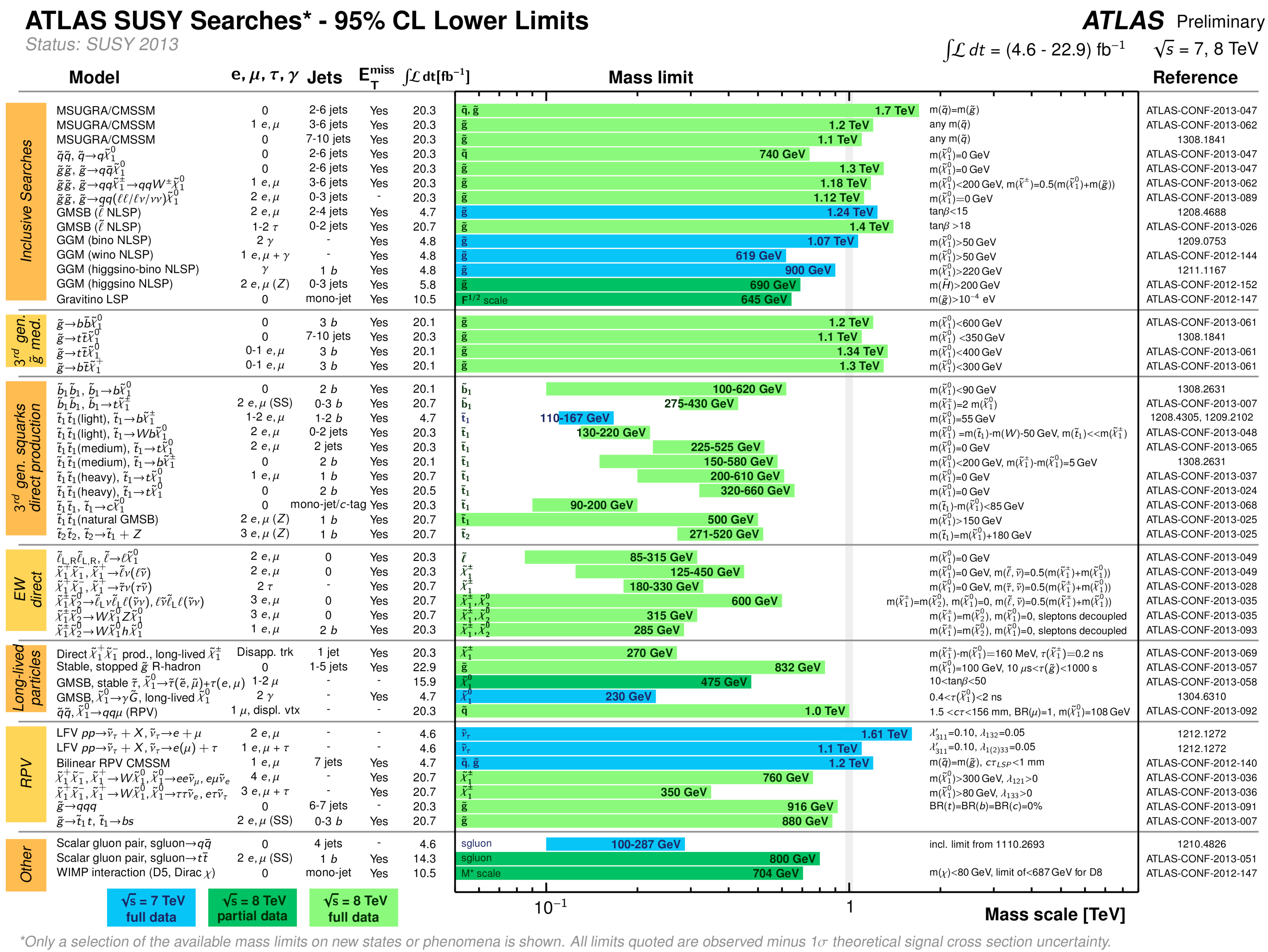
- Unified theory
- Elegant way of solving the hierarchy problem of the Standard Model (radiative corrections to Higgs mass grow to very large values)
- Lightest SUSY particle the ”best” candidate for dark matter

Supersymmetric particles: nothing so far



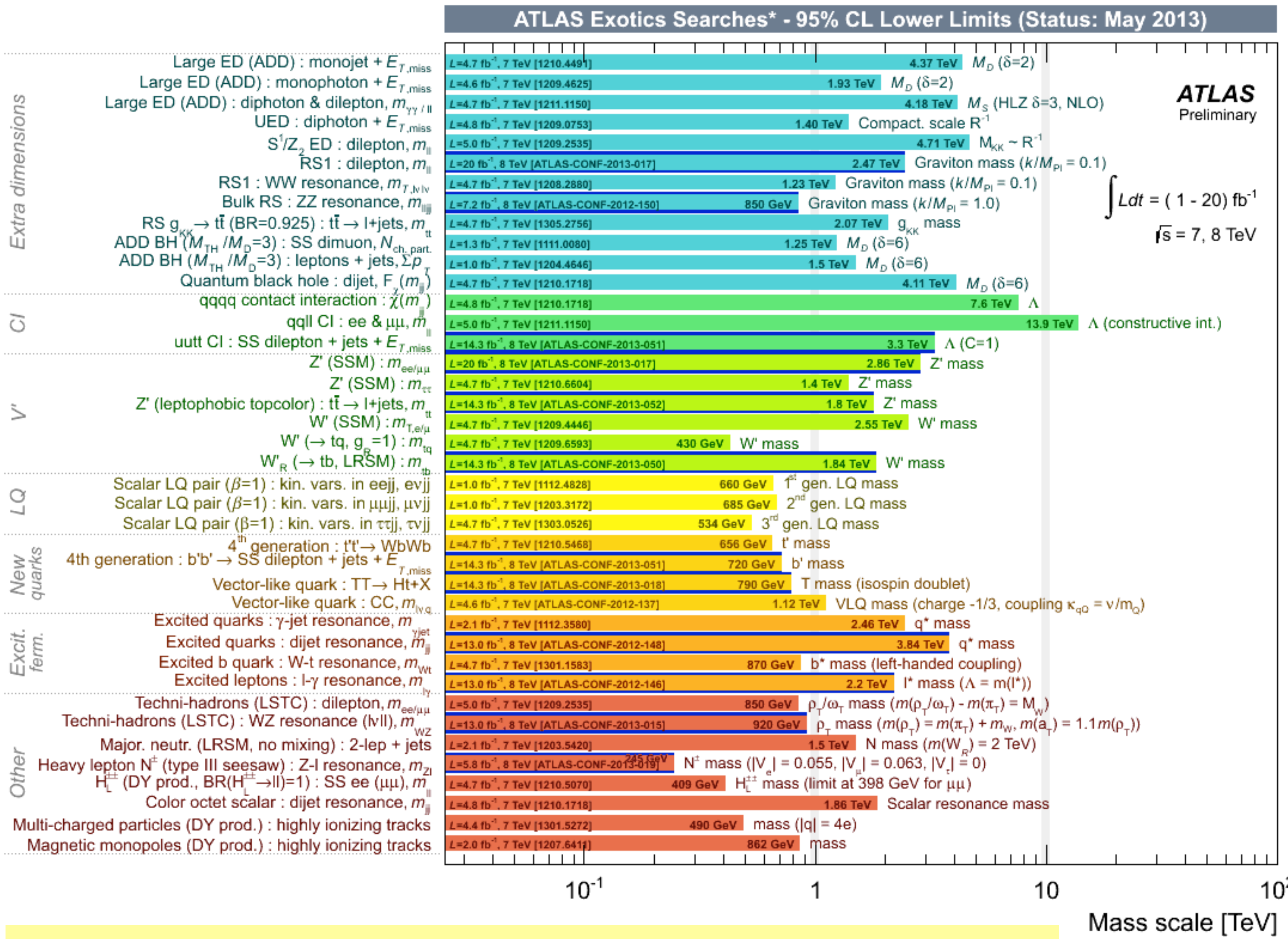
Excluded range

Status of SUSY searches



Much focus lately on the third generation (Higgs mass, CMSSM in problems)

Searches for other new particles (not SUSY)



Mass scale up to 1 TeV largely excluded

LHC future

- Run 1 2010-2012 finished
- 2013-2014 – long shutdown 1, dipole magnet repairs, maintenance and improvements
- 2015-2017 → energy 13-14 TeV, luminosity 100-120% of the design target $10^{34}cm^{-2}s^{-1}$
- 2018 – long shutdown 2, detector upgrades
- 2019-2021 – energy 14 TeV, intensiteetti 240% of the design target
- 2022 – long shutdown 3, major detector upgrades
- …continue till 2030's…?

Summary

- LHC: enormous amounts of new results in a new energy domain
- Higgs bosons:
  - Discovery 2012 – breakthrough after decades of searches
  - What kind?
- Everything according to the Standard Model
- No signs of new physics (yet?), Supersymmetry being constrained more and more…

- The accelerator and the experiments have been working in a fantastic way
- Very rapid take-over of global leadership in high-energy physics


3D
ent at LHC, CERN
d: Mon Mar 14 06:44:11 2011 CEST
60432 / 212419
4
g: 787815 / 1886
Rho Z
Rho Phi
3D

Thank You!