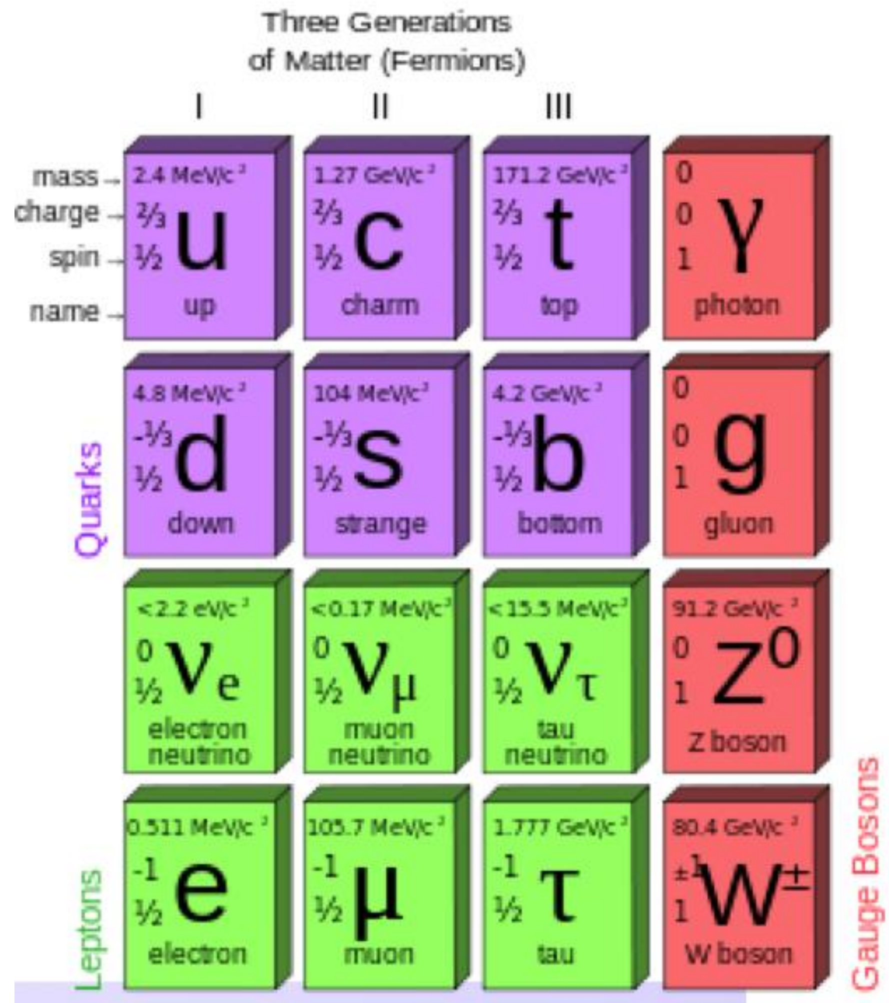
Physics at the LHC run 1

C. Charlot / LLR- École Polytechnique

Thematic CERN School of Computing, 16-25 juin 2014, Split, Crotia

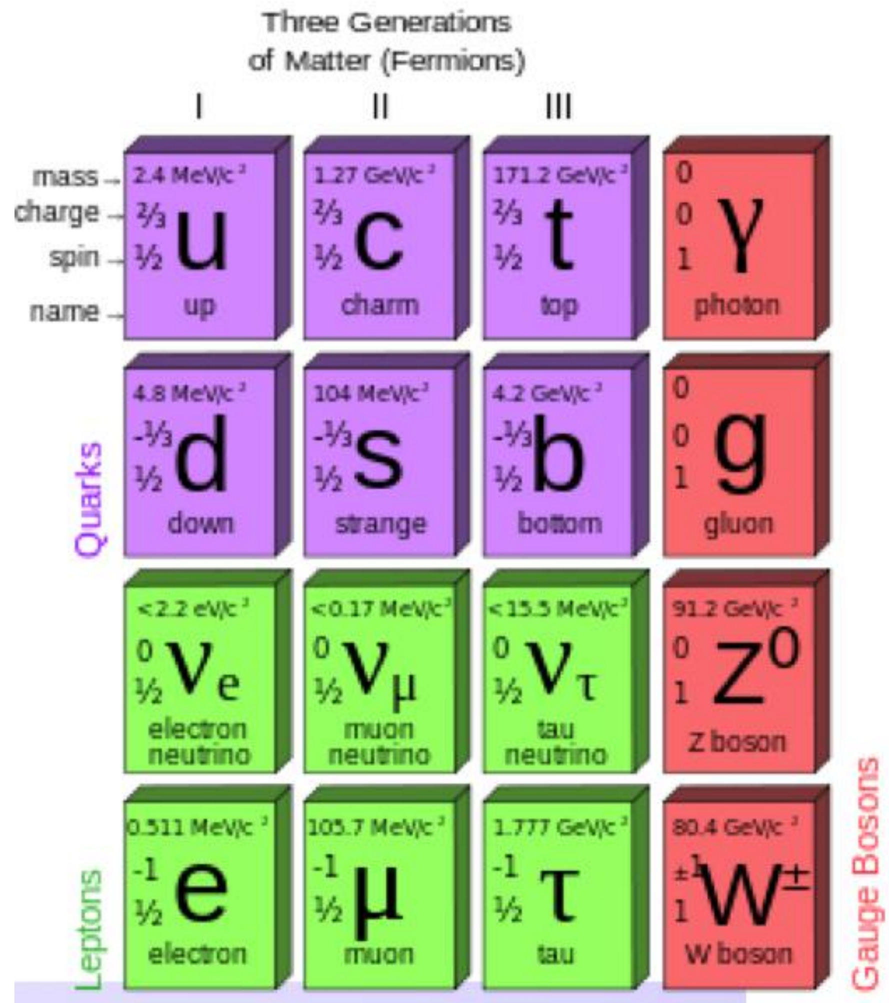
Standard Model of Particle Physics

- Elementary matter consist of quark and leptons
- The standard model of elementary particles is built upon gauge symmetries
- Internal symmetries (extending over geometrical symmetries)
- Conserved quantities (quantum numbers): electric charge, colour, spin, …



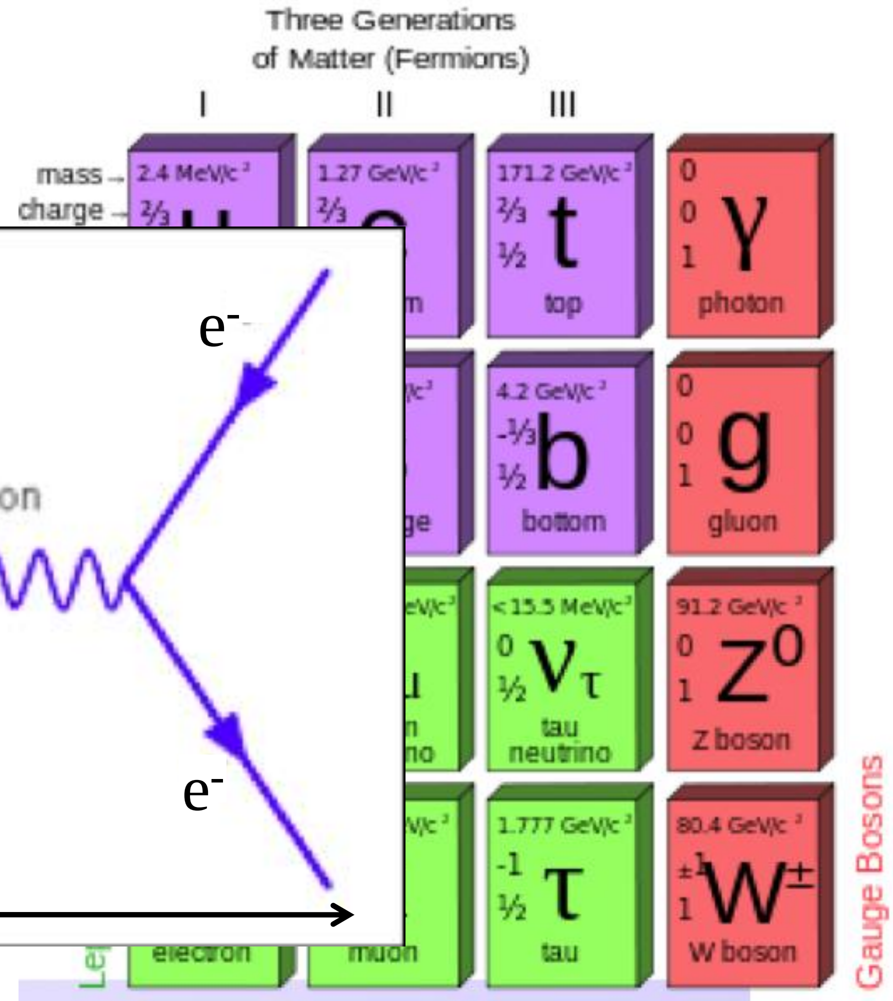
Standard Model of Particle Physics

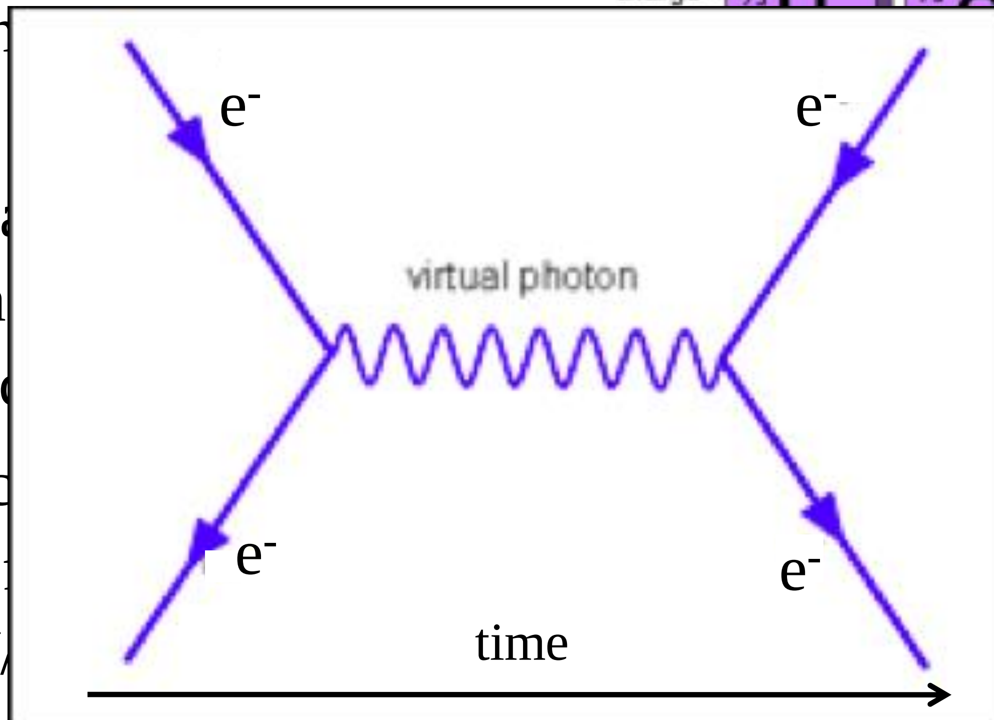
- Gauge symmetries have modified our understanding of forces / interactions
- Gauge invariance naturally leads to interactions terms, no need to introduce forces between particles
- Interactions consist of exchanges of a certain of particles = vector bosons (γ, g, Z^0, $W^{+/-}$)



Standard Model of Particle Physics

- Gauge symmetries have modified our understan interactions
- Gauge invari to interaction introduce for
- Interactions c of a certain o bosons (γ, W/



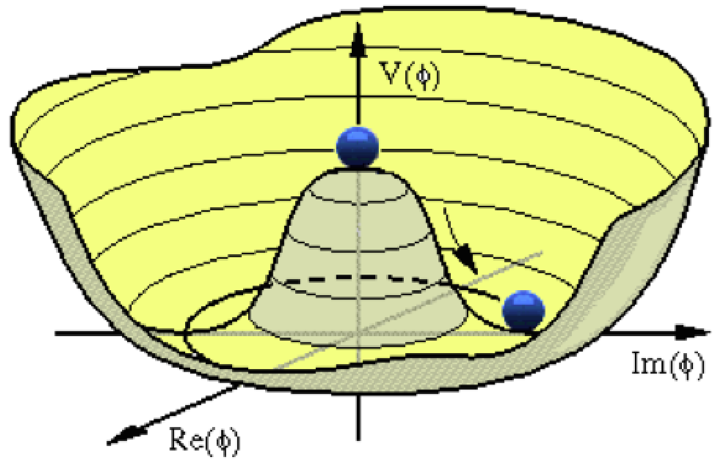


A problem

- This picture has been extremely successful but gauge invariance implies massless gauge bosons, or, equivalently, interactions of infinite range
- It is known experimentally fact that the gauge bosons associated with the weak interaction (W^+,W^-,Z^0), i.e. that weak interactions have a short range
  - m_Z=91.2 GeV and m_W=80.4 GeV
- Therefore, either the picture of interaction as the exchange of vector bosons is wrong, or there is a way to preserve this description in the case of short range interactions (or massive vector bosons)

Spontaneous Electroweak Symmetry Breaking

- The solution is spontaneous symmetry breaking
- A physics system has a symmetry but the state of lowest energy (e.g. the vacuum) does not have the symmetry
- As a consequence of EWSB the weak W and Z bosons become massive and a new (scalar) particle appears: the Higgs boson
- It turns out that this mechanism also allows to introduce masses for the quarks and the leptons

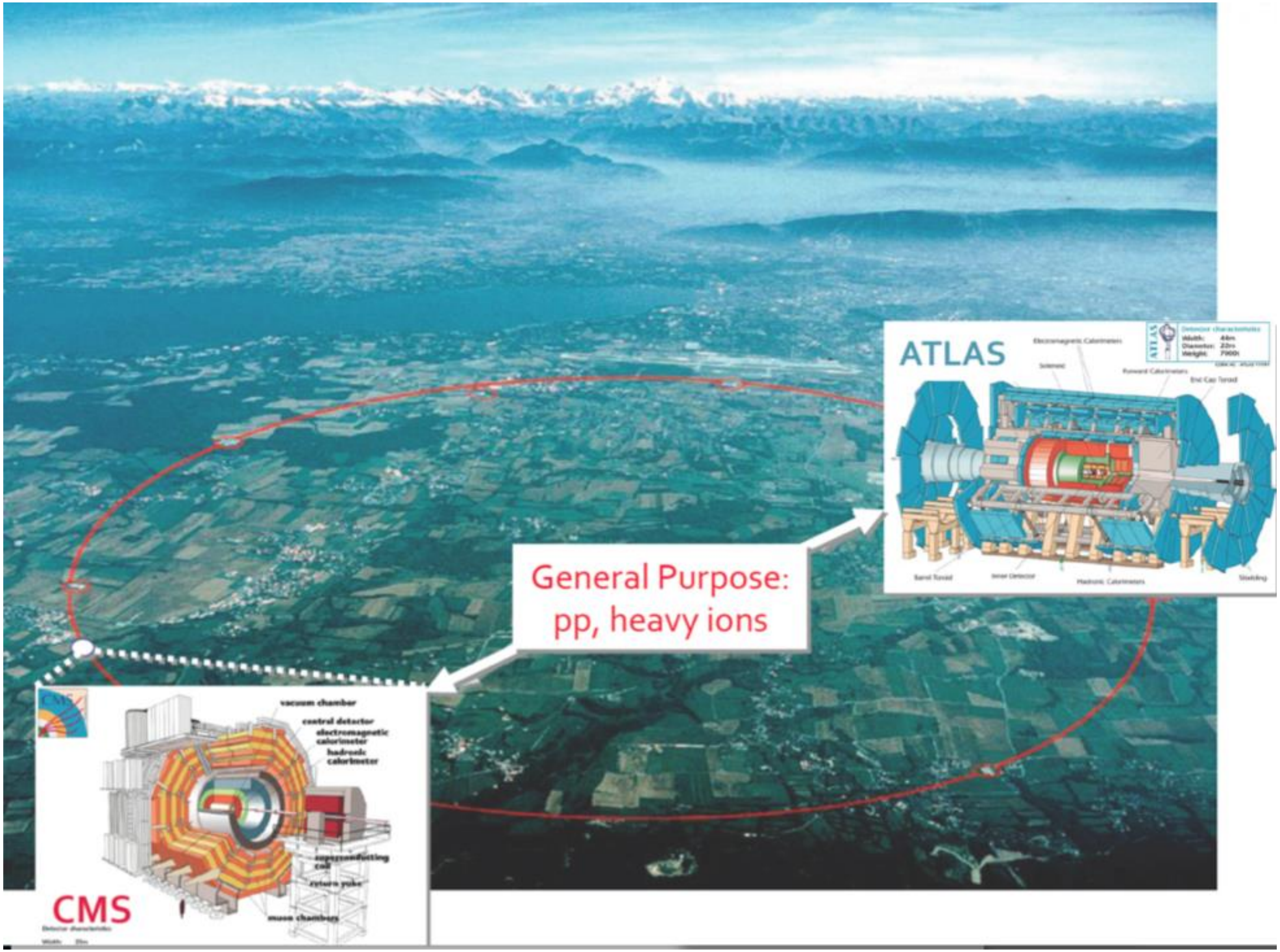


New scalar field ϕ

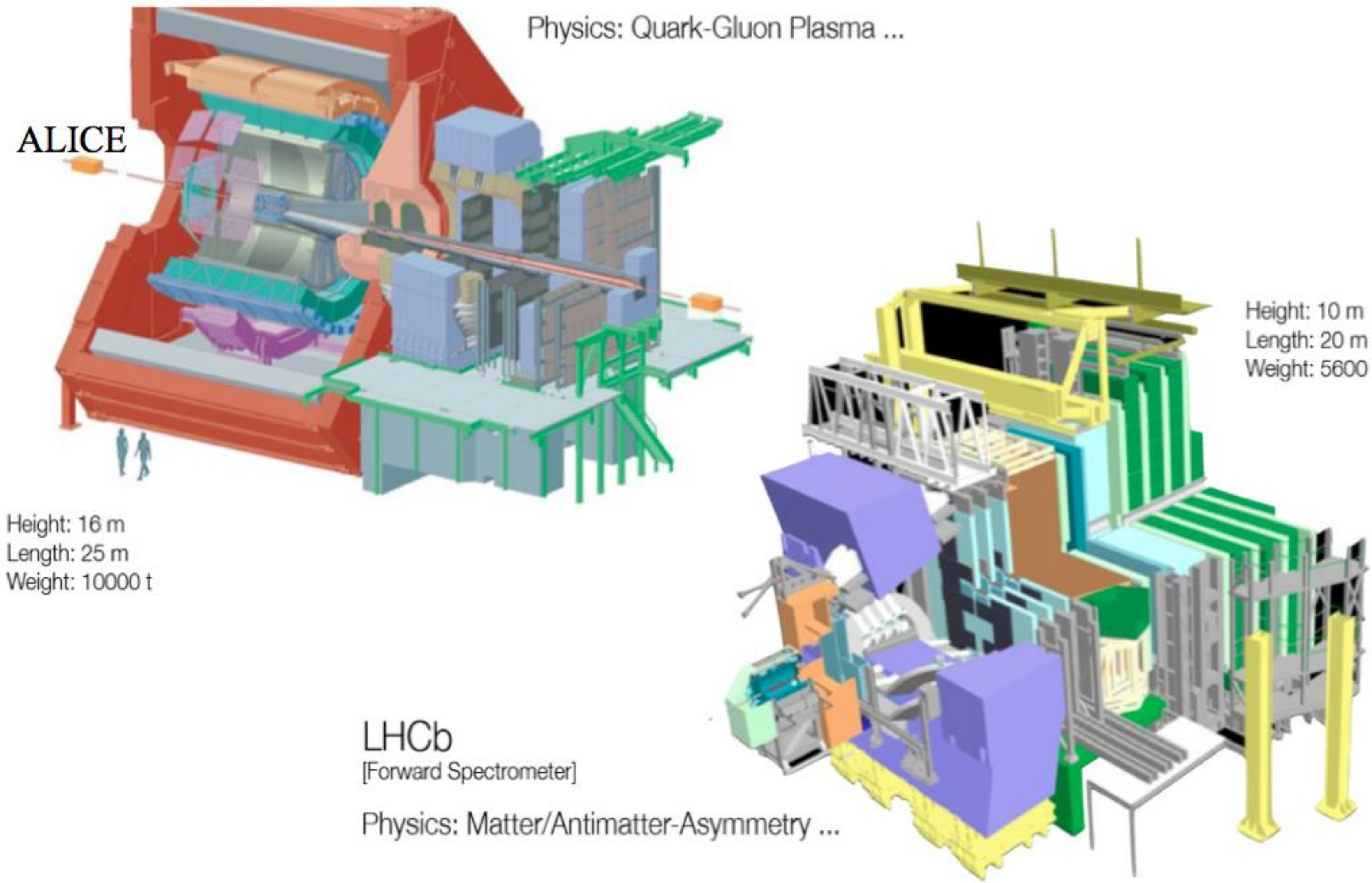
Brout, Englert, Guralnik, Hagen, Higgs, Kibble (1964)

Large Hadron Collider

LHC experiments

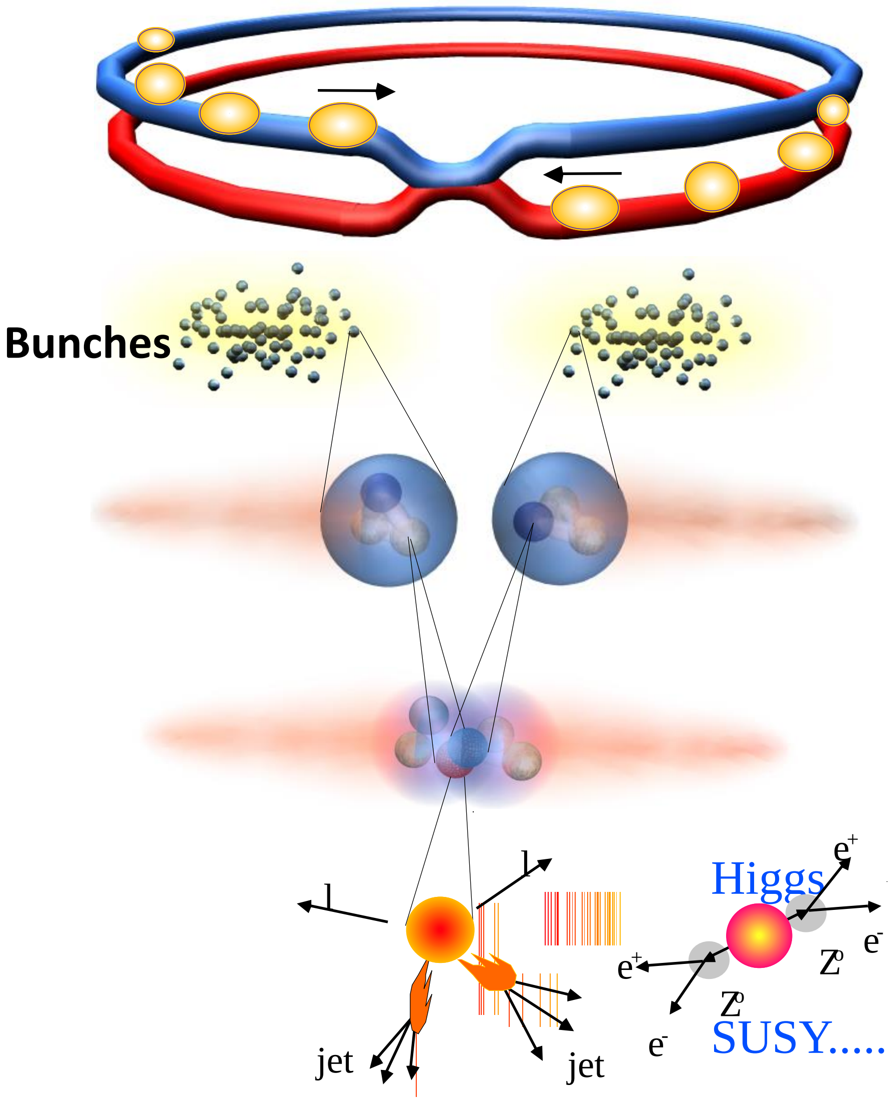


LHC experiments



LHC experiments

Collisions at LHC



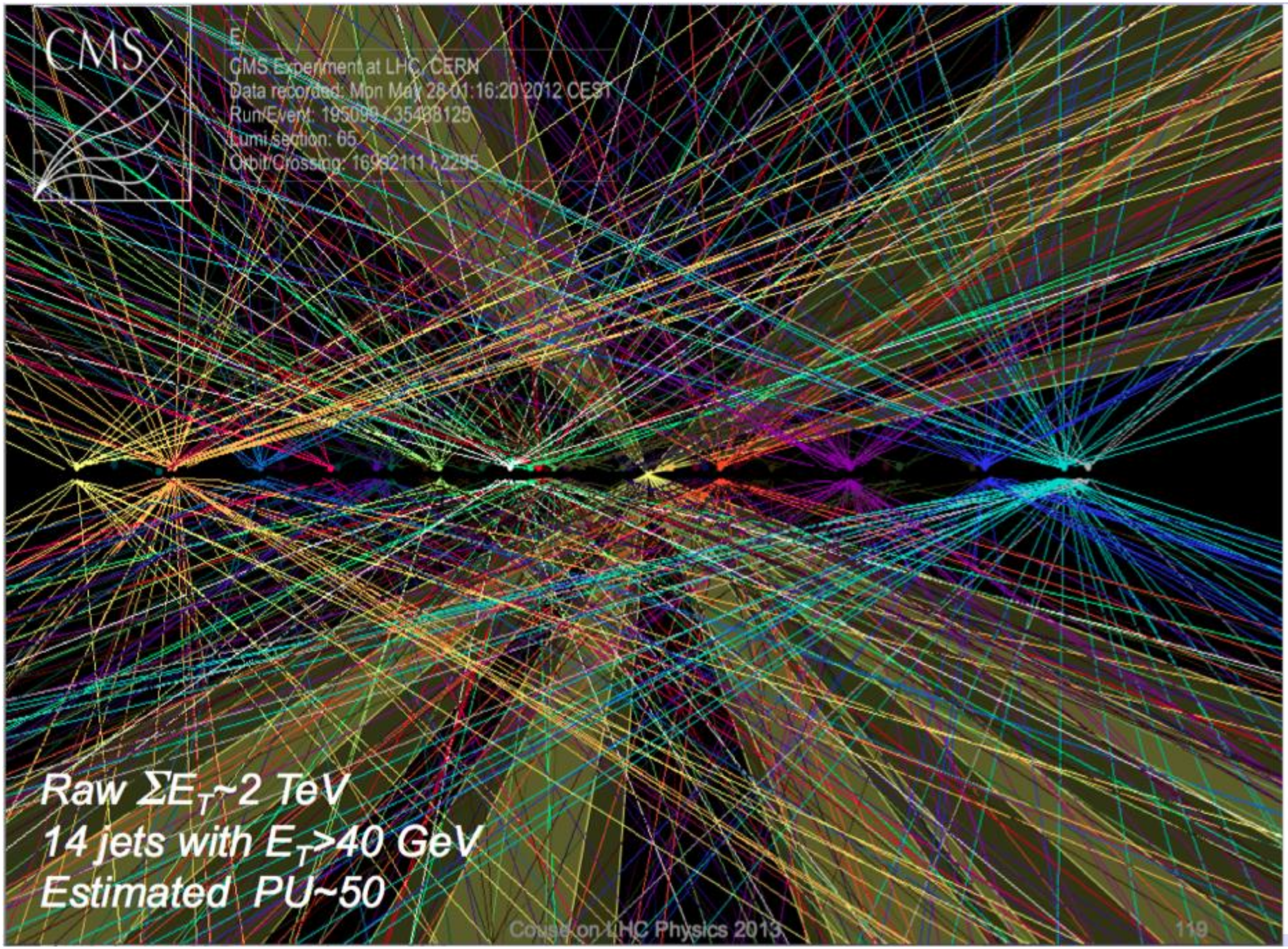
Proton - Proton	1300 bunches/beam
Protons/bunch	10^{11}
Beam energy	4 TeV (4×10^{12} eV)
Luminosity *	10^{34} cm^{-2} s^{-1}
Bunch collision frequency	20 MHz
Proton collision frequency	~5.10^{8} Hz (μ~25)

* A measure of the intensity and focalisation of the beams = rate of events for a given process N = L x σ

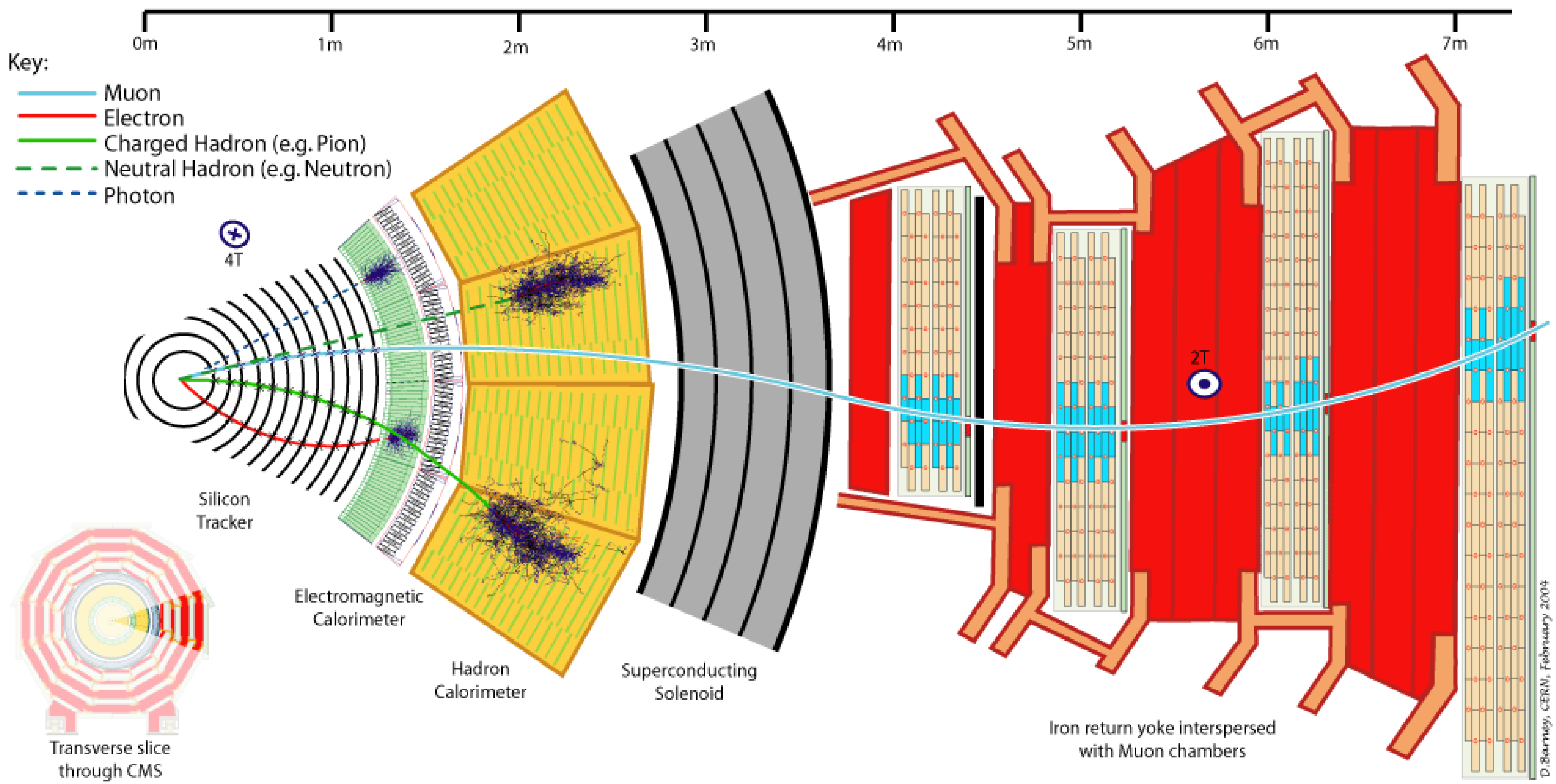
"New physics" frequency .00001 Hz (o(10^{2}) / an)

Event selection:
1 u 10 000 000 000 000

Pileup conditions



Particle detection



Si TRACKER

Silicon Microstrips

CALORIMETERS

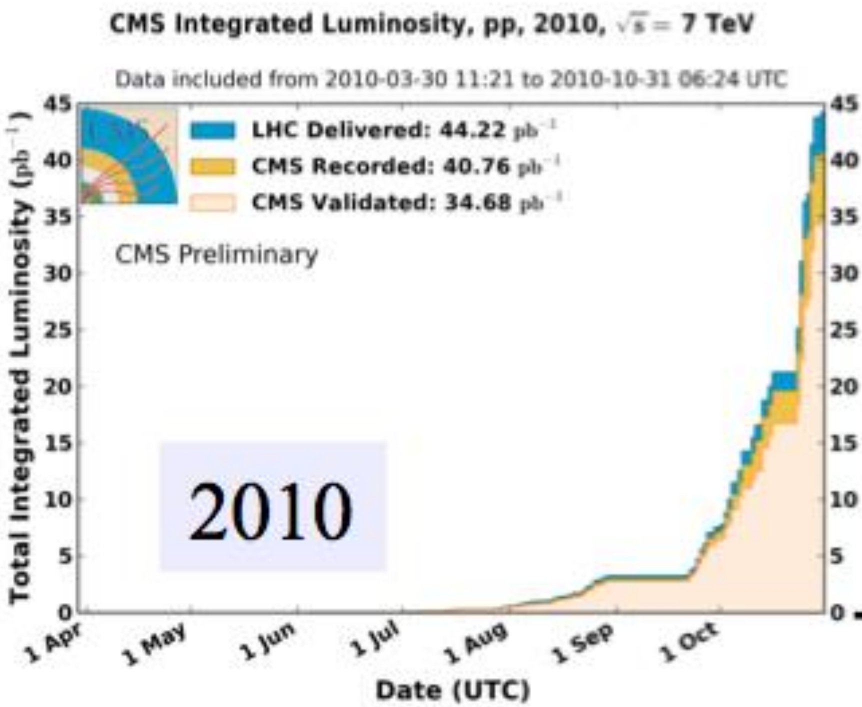
Scintillating $PbWO_4$ crystals

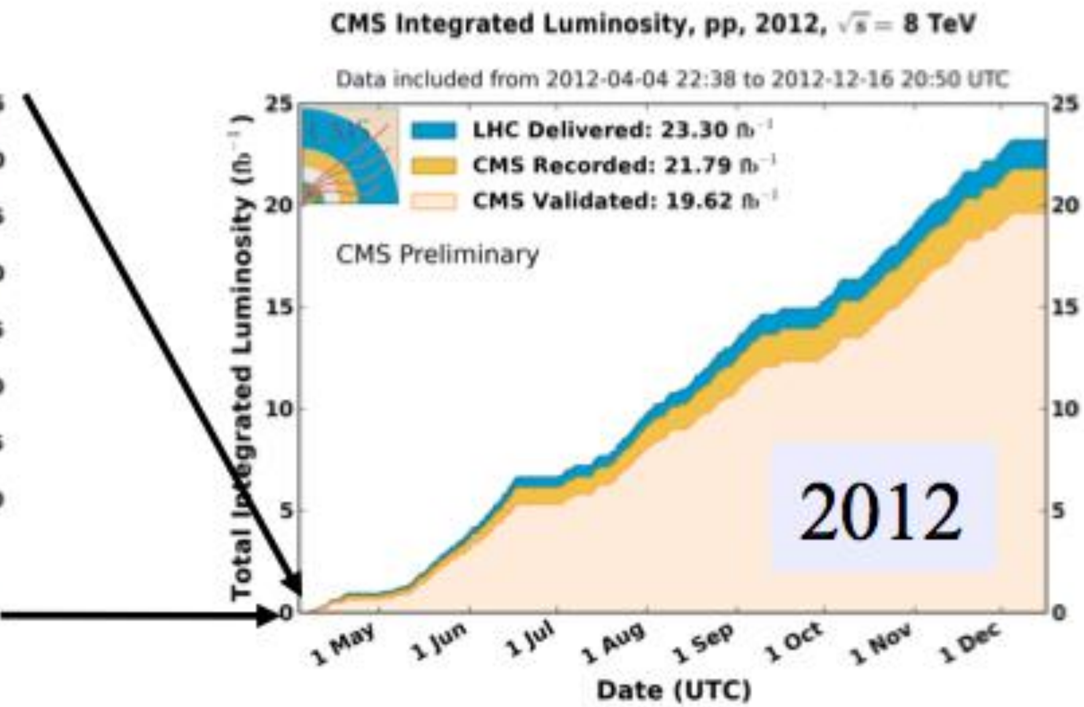
Plastic scintillator/brass sandwich

MUON DETECTOR

Chambers (**DT**) Chambers (**RPC**)

Data taking



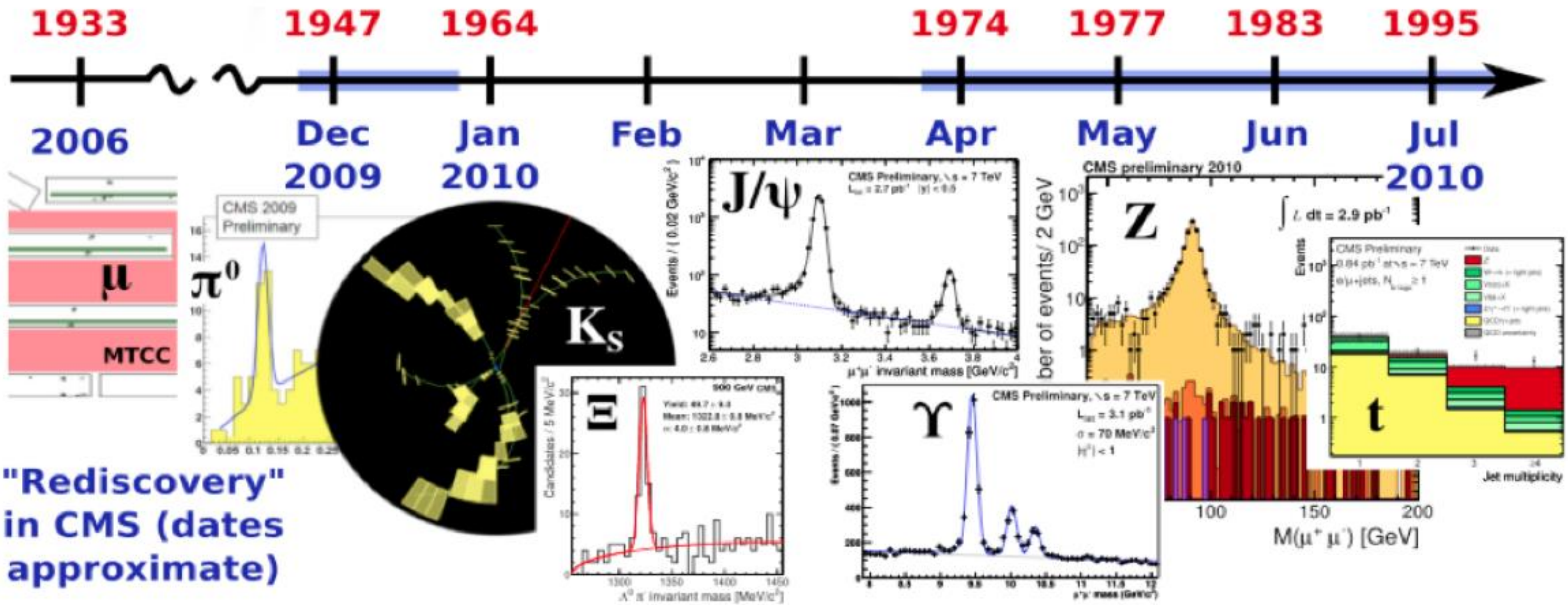


- ❑ Huge increase in luminosity at the beginning (notice the change of scale!)
- ❑ Then ~ steady operation (~linear increase with time)

ATLAS and CMS

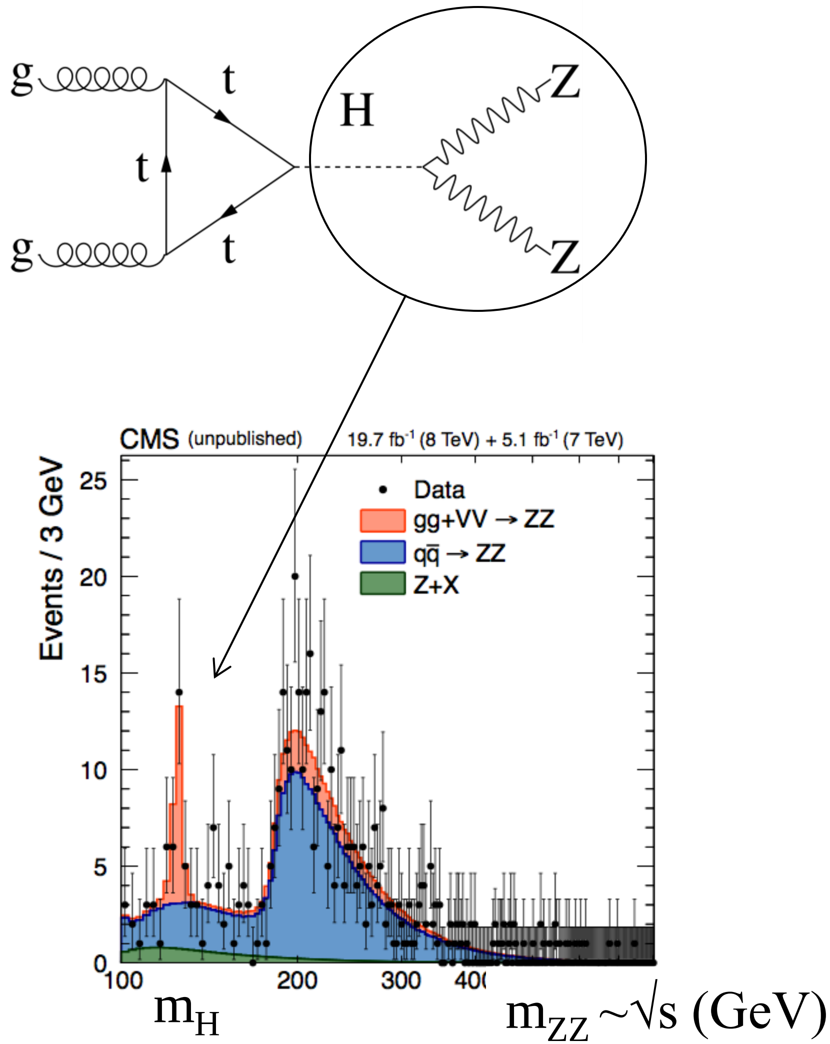
- Study of the Standard Model
  - QCD
  - EWK physics, top physics
- Higgs boson search and Higgs physics
  - Search for other Higgs bosons
  - Properties
- Search for physics beyond the Standard Model
  - Supersymmetry
  - New resonances
- Anything new we have not anticipated …

Rediscovery of the Standard Model



What is a particle?

- Most elementary particles are unstable
- Unstable particles characterized by decay width which relates to the couplings to other particles
  - Higher couplings => shorter lifetime
  - From quantum mechanics => higher fluctuation of the energy of the system
- Particles therefore seen as peaks at the resonant energy with a width that characterizes its couplings to the other particles

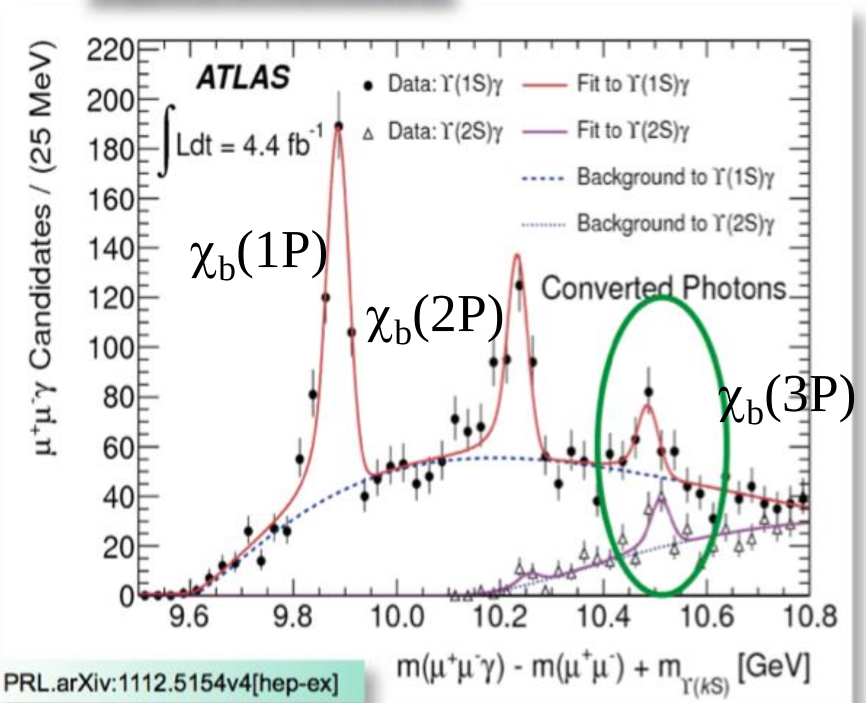


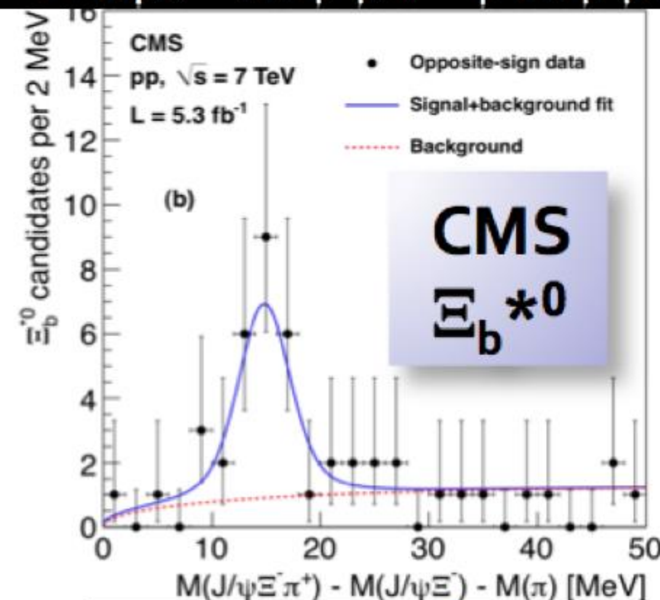
- Intrinsic width can be smaller than experimental resolution

New particles

$\Xi_b^{*0} \to \Xi_b^- \pi^+ \to \Xi^- J/\psi\, \pi^+ \to \Lambda \pi^- \mu^+ \mu^- \pi^+ \to p^+ \pi^- \pi^- \mu^+ \mu^- \pi^+$

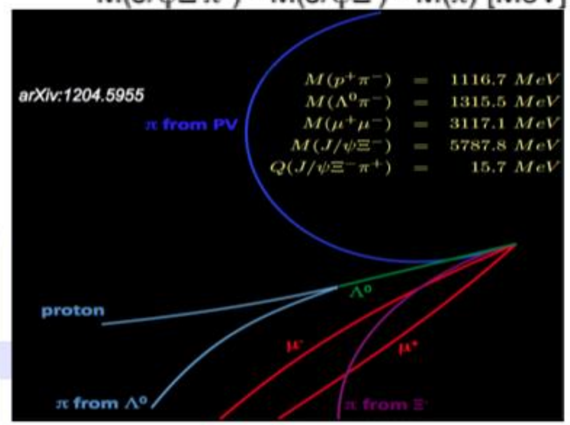
$X_b(3P) \to \Upsilon(1s,2s)\, \gamma \to \mu\mu\gamma$





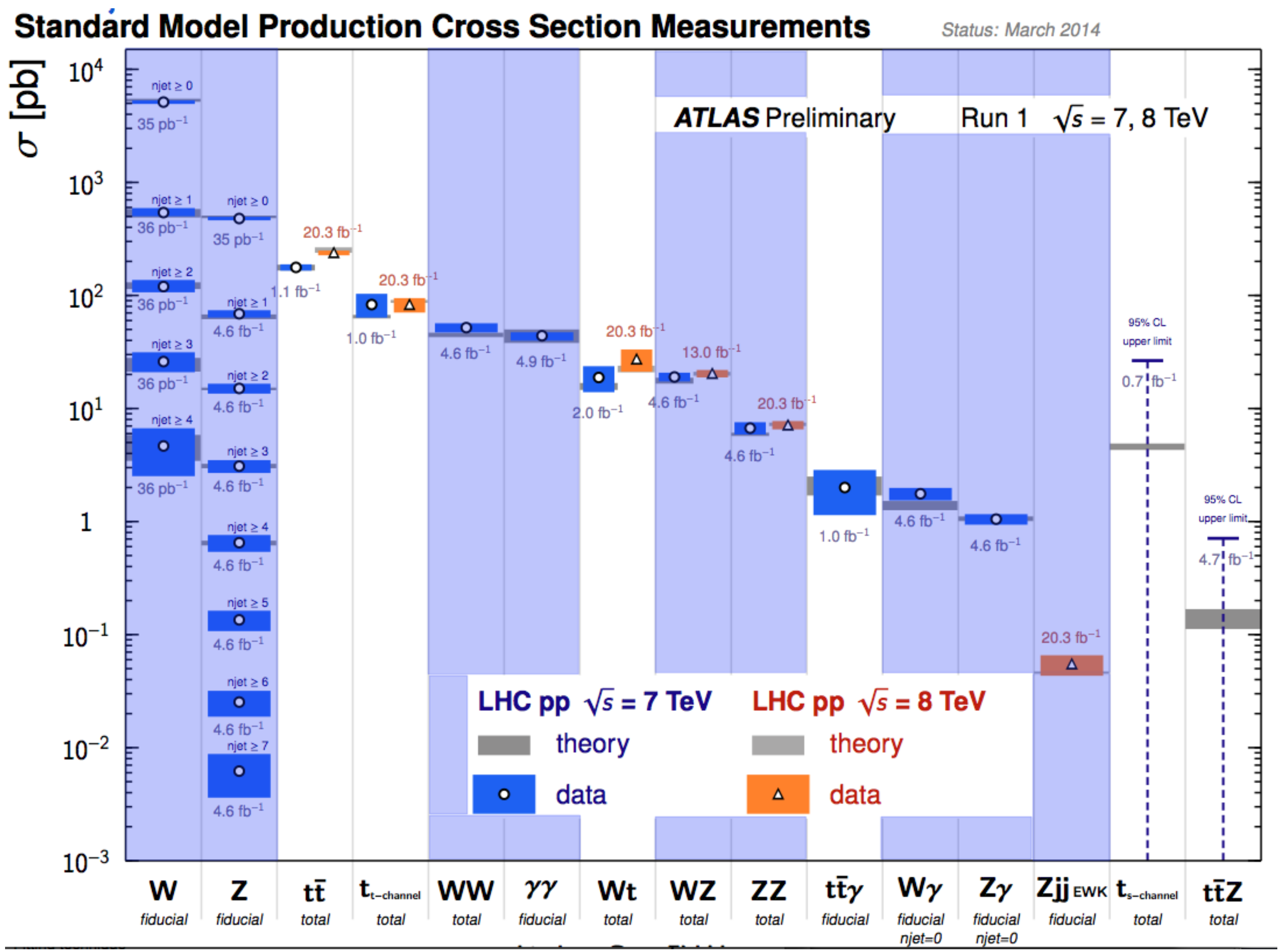
$m\ [\chi_b(3P)] = 10.530 \pm 0.005\ (stat) \pm 0.009$

$X_b(nP) \to \Upsilon(1s,2s)\, \gamma \to \mu\mu\, \gamma$
$X_b(1P)$ m= 9.9 GeV and $X_b(2P)$
m= 10.2 GeV states clearly visible
New structure at 10.5 GeV $\to X_b(3P)$
Confirmed with ϒ(2s) data and with
un-converted photons
Significance > 6 σ
As theoretically predicted



Overview of LHC physics, LCG-France meeting, may 2013

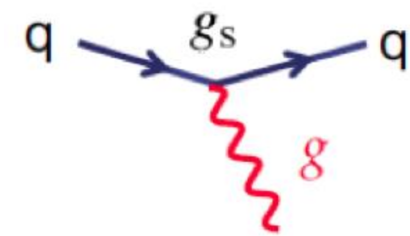
Standard model after the run 1

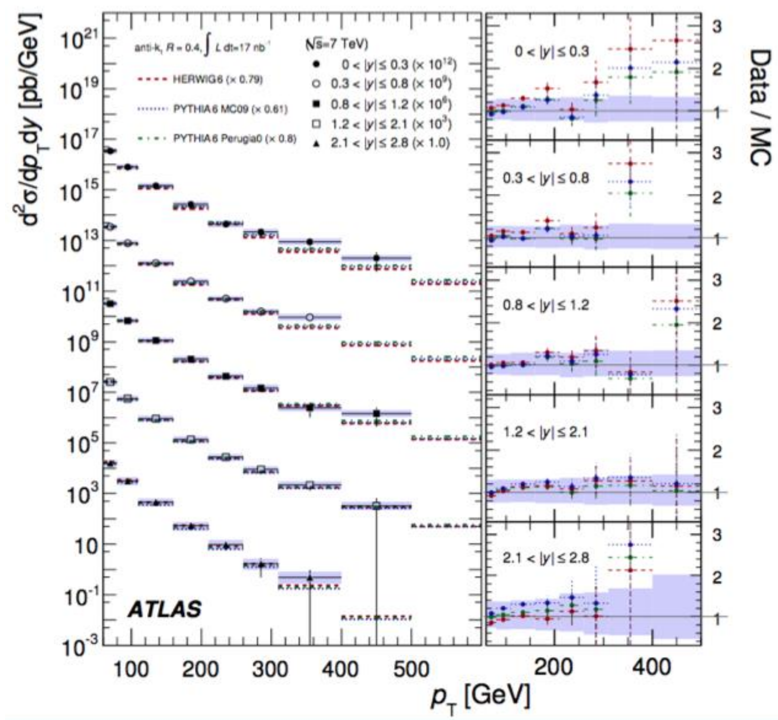


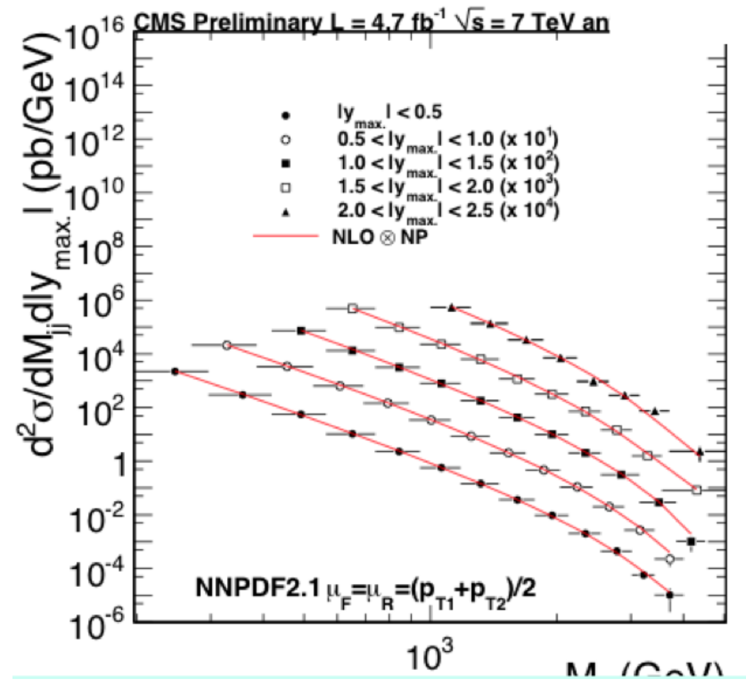
- Lots of data, impressive agreement with predictions

QCD and jets

- Test of perturbative QCD in a new regime (x, Q^2)
  - Tuning of MC generators, PDFs and α_s measurement



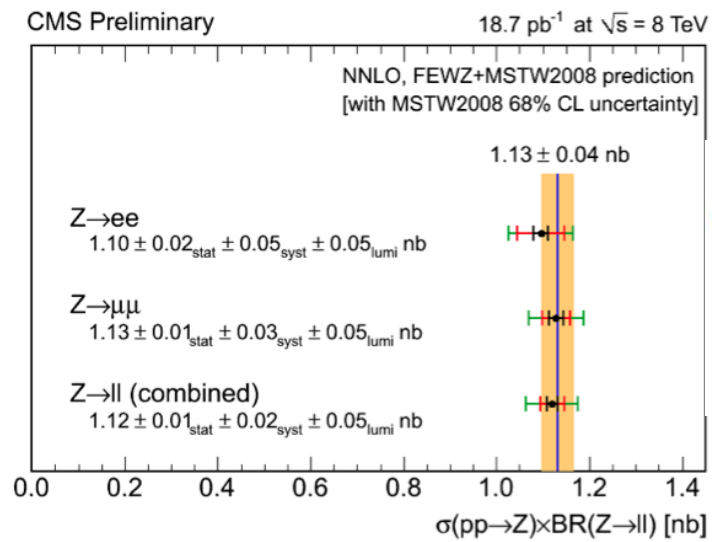


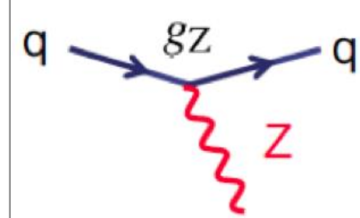


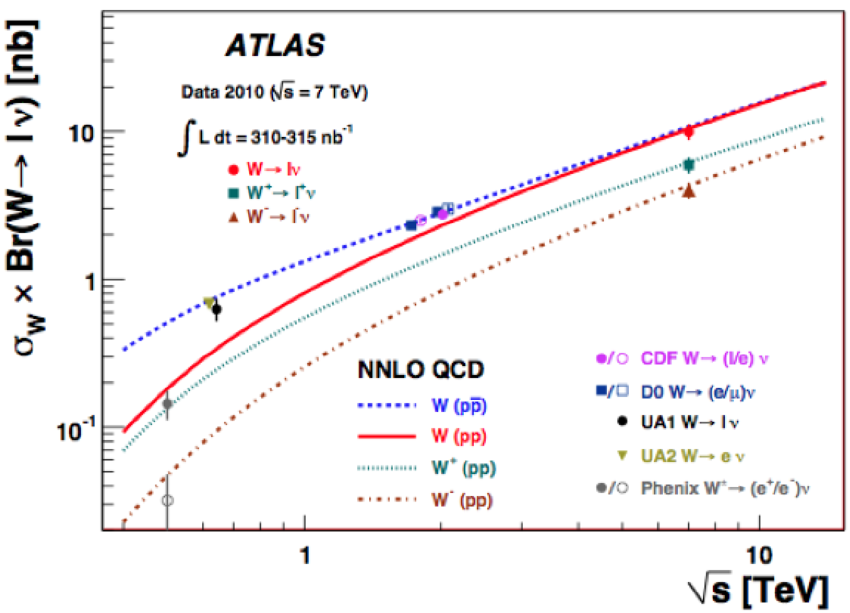
- Excellent agreement over many decades

EWK boson production

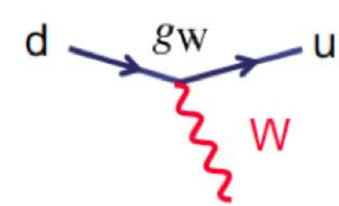
- Universal decay to leptons Z → ll (l=e,μ,τ) => combine the channels
- Rates in agreement with expectation





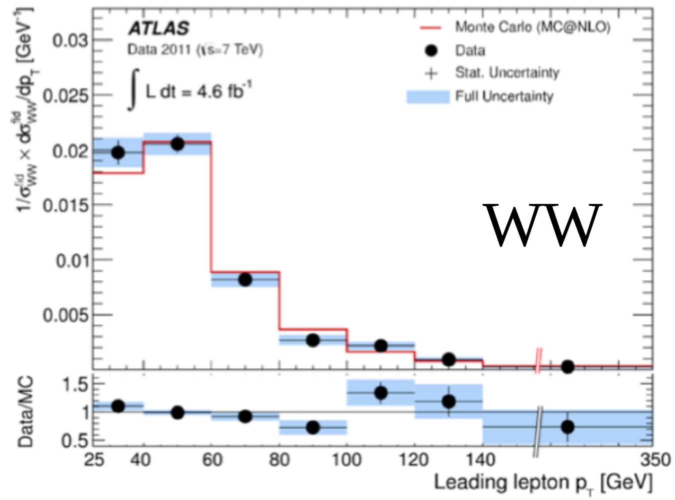


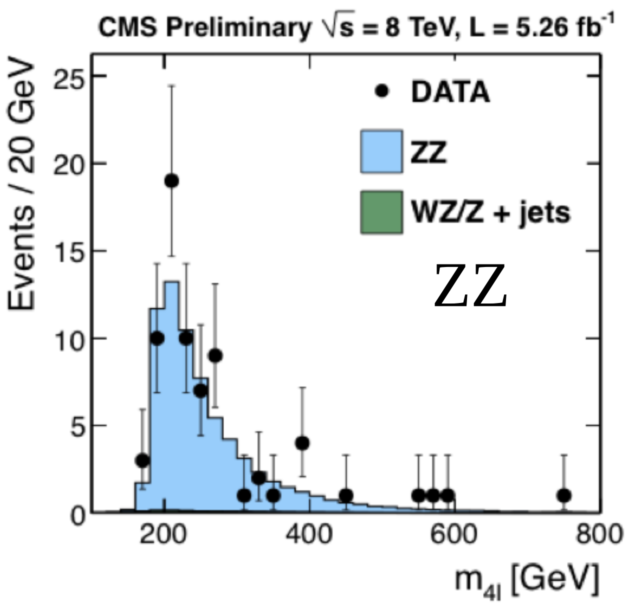
- W cross section vs √s
- Difference between pp and ppbar as expected from (anti-)quark content

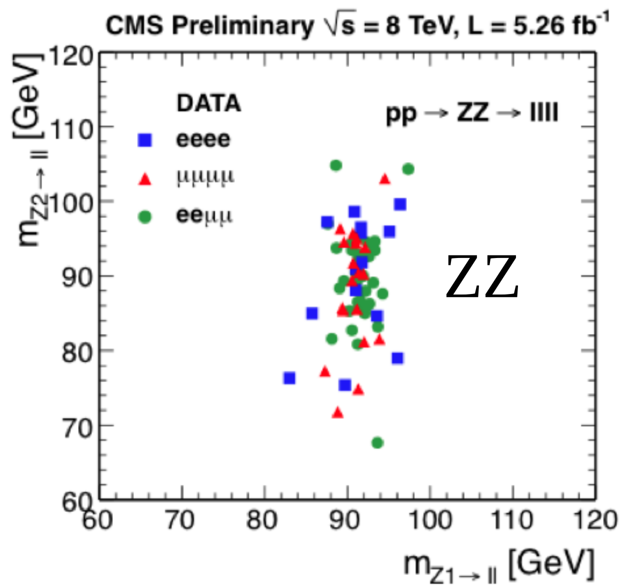


Dibosons: WW, WZ and ZZ

- Rare processes: only a few events at the Tevatron
- Path to discovery of new particles, background to Higgs boson search





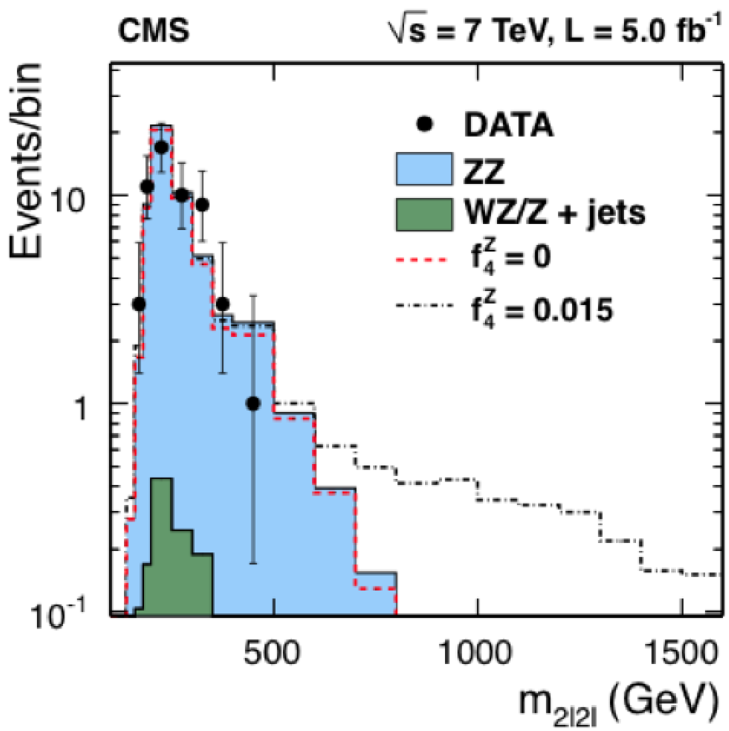


(updated to 20/fb)

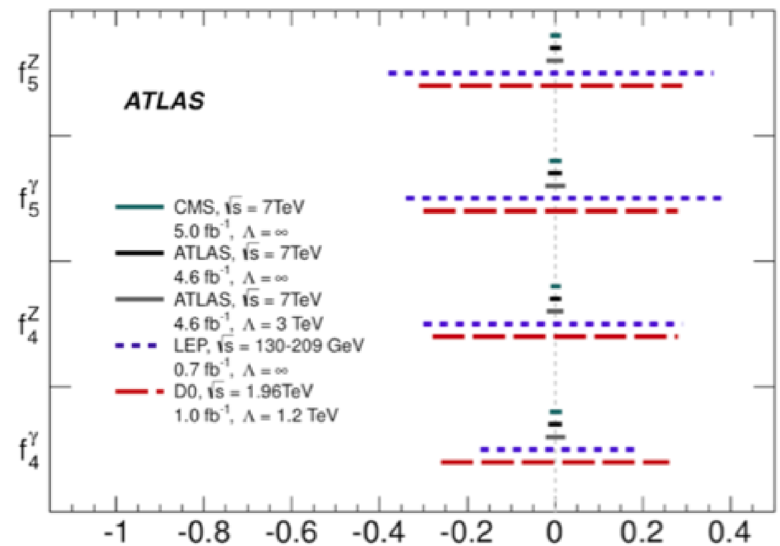
- Results compatible with expectations

Dibosons: WW, WZ, ZZ

- Search for anomalous triple gauge couplings / deviations from Standard Model

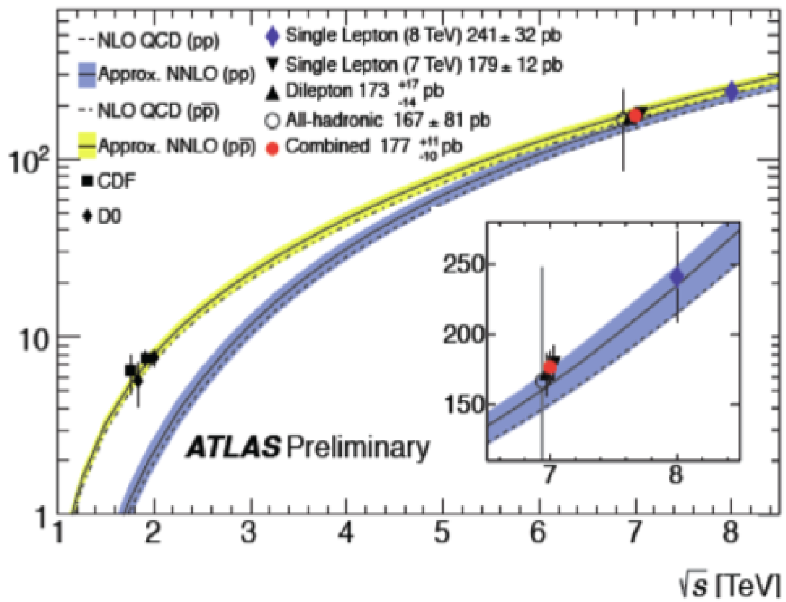


- Example of an expected deviation for a particular model



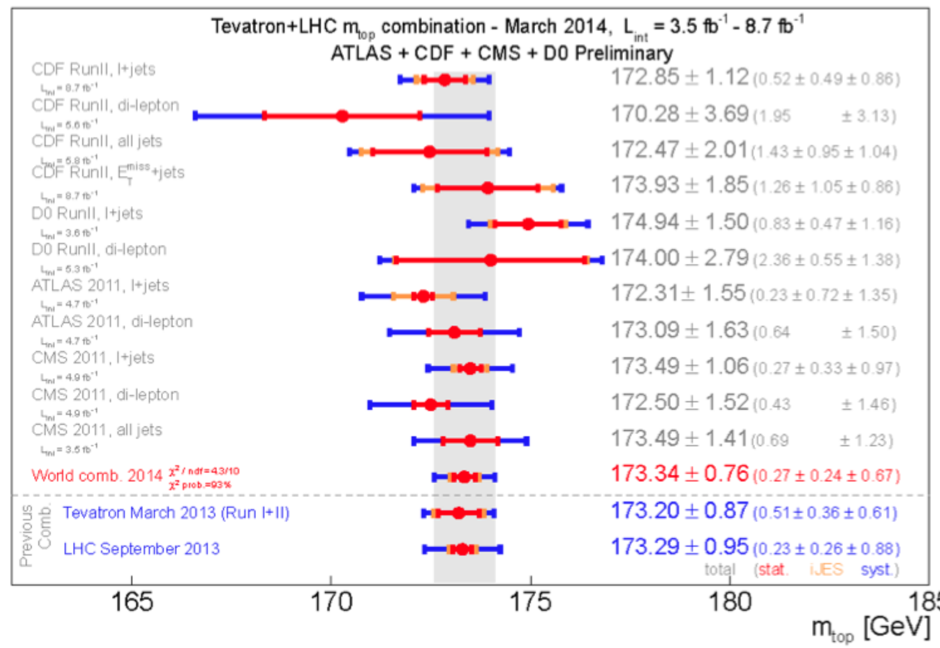
- Resulting measurements much more precise than at LEP

Top physics



- Good description of production vs center of mass energy, pp vs ppbar

- Precision on top mass close to Tevatron

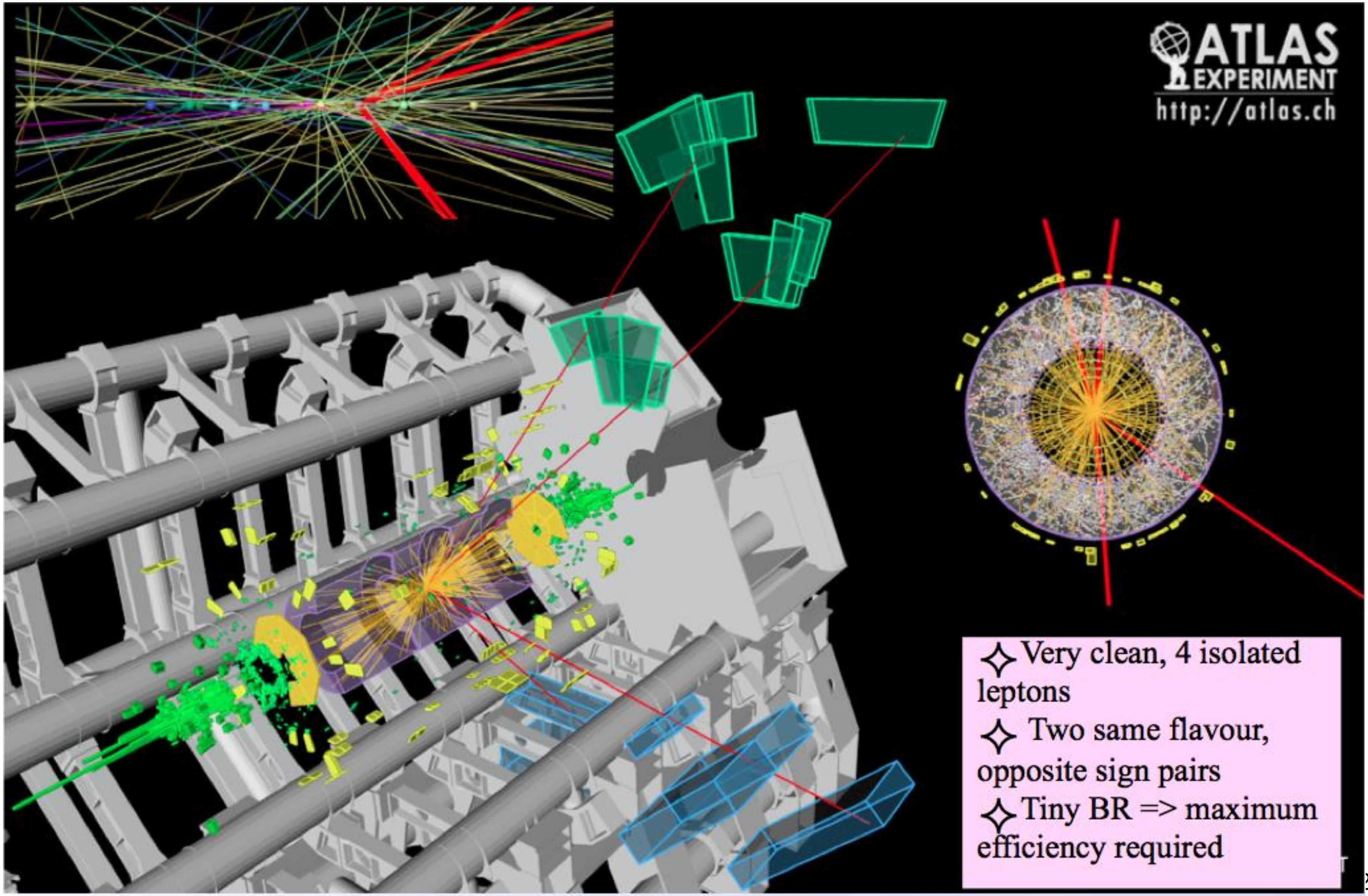


- LHC/Tevatron combination: 173.34±0.76 GeV (Tevatron: ±0.87, LHC: ±0.95)

The Higgs

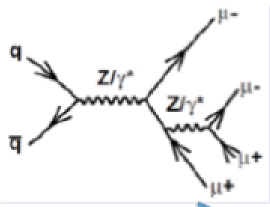

PHYSICS LETTERS B
SciVerse ScienceDirect
ATLAS
2011-12
4 July 2012

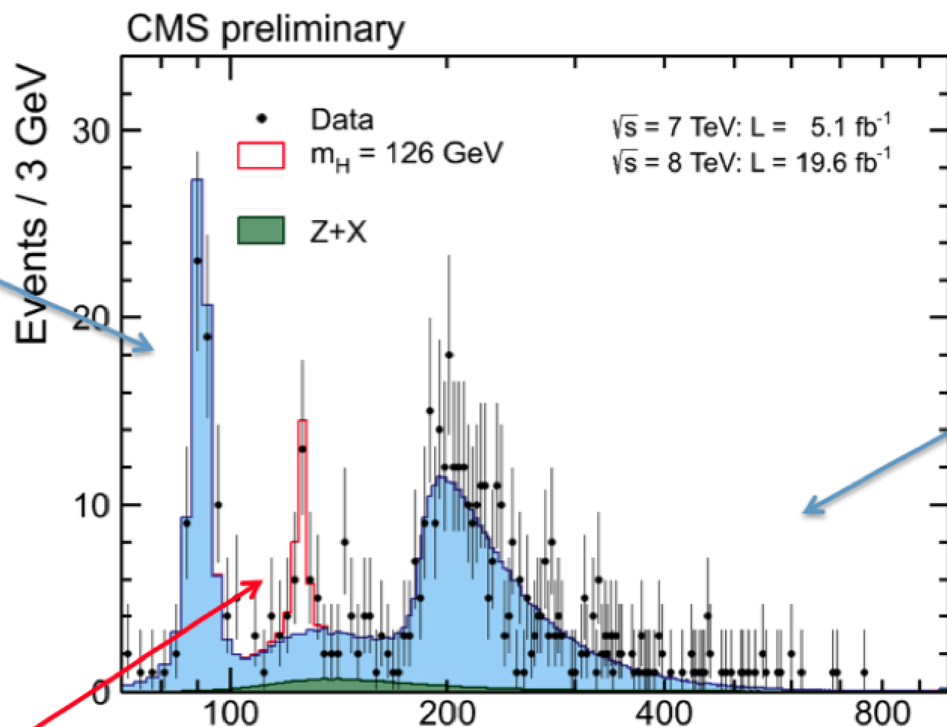
H→ZZ→4leptons



- Very clean, 4 isolated leptons
- Two same flavour, opposite sign pairs
- Tiny BR => maximum efficiency required

H→ZZ*→4leptons





Very good control of the dominant ZZ background

M(4l)>160 GeV
Data 380
MC 364.5

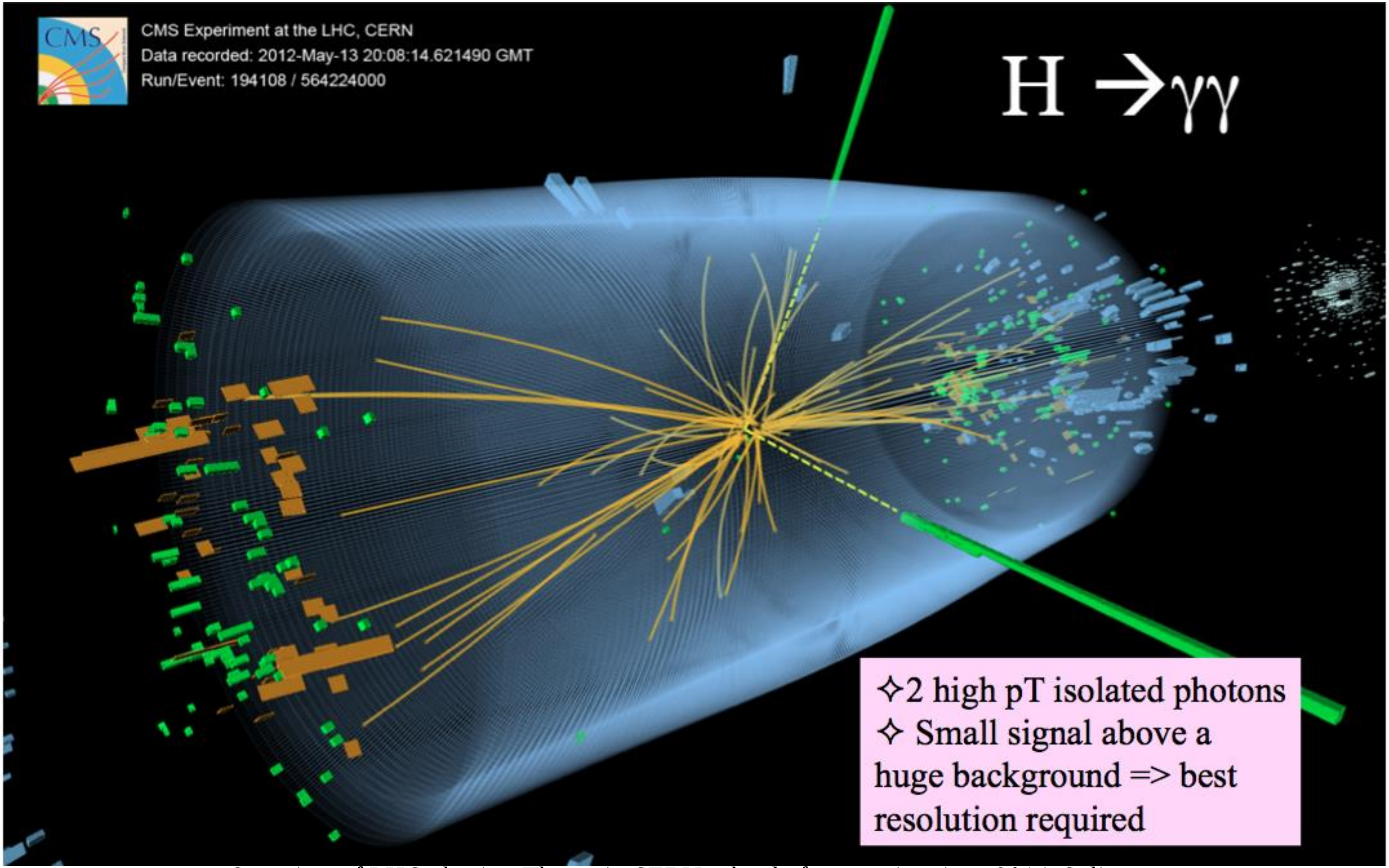
Clean signal peak at ~126 GeV

- ❑ Low background

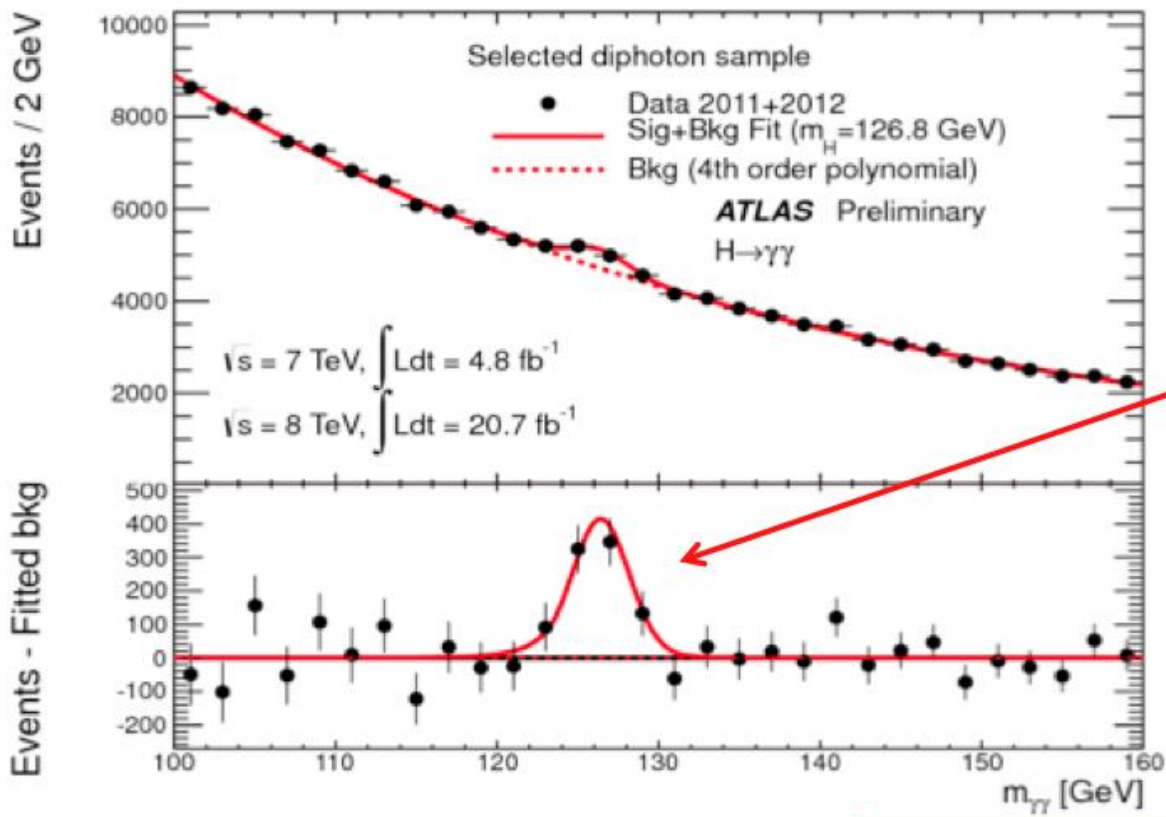
Experiment	Expected	Observed
ATLAS	4.4σ	6.6σ
CMS	7.1σ	6.7σ

(as of winter 2013)

H→γγ


CMS Experiment at the LHC, CERN
Data recorded: 2012-May-13 20:08:14.621490 GMT
Run/Event: 194108 / 564224000
H →γγ
✧2 high pT isolated photons
✧ Small signal above a
huge background => best
resolution required

H→γγ



Clean signal peak at ~126 GeV

- High background from
  - γγ (irreducible)
  - γ+jet (reducible)

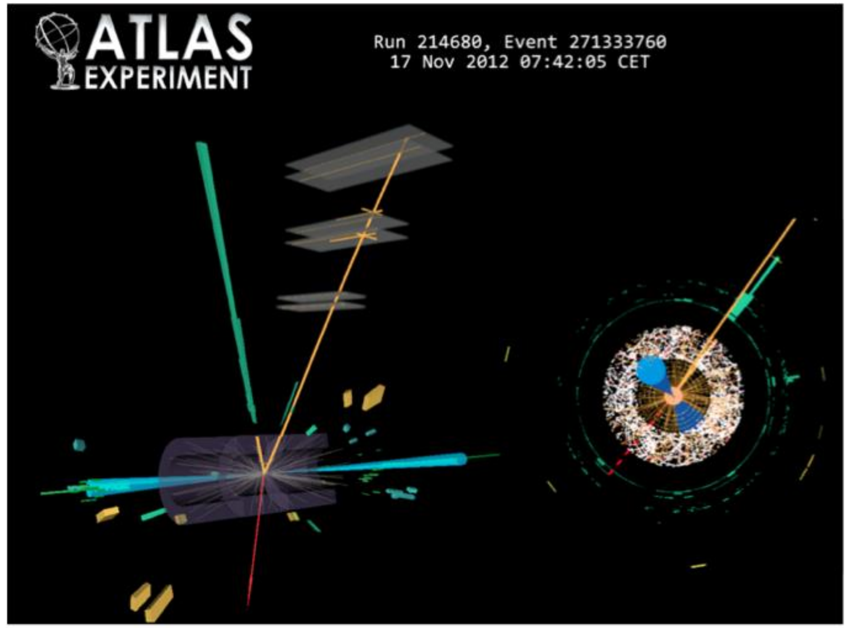
Experiment	Expected	Observed
ATLAS	4.1σ	7.4σ
CMS	4.2σ	3.2σ

(as of winter 2013)

H→WW

- Low resolution channel
  - neutrinos
- High event yield
- High background

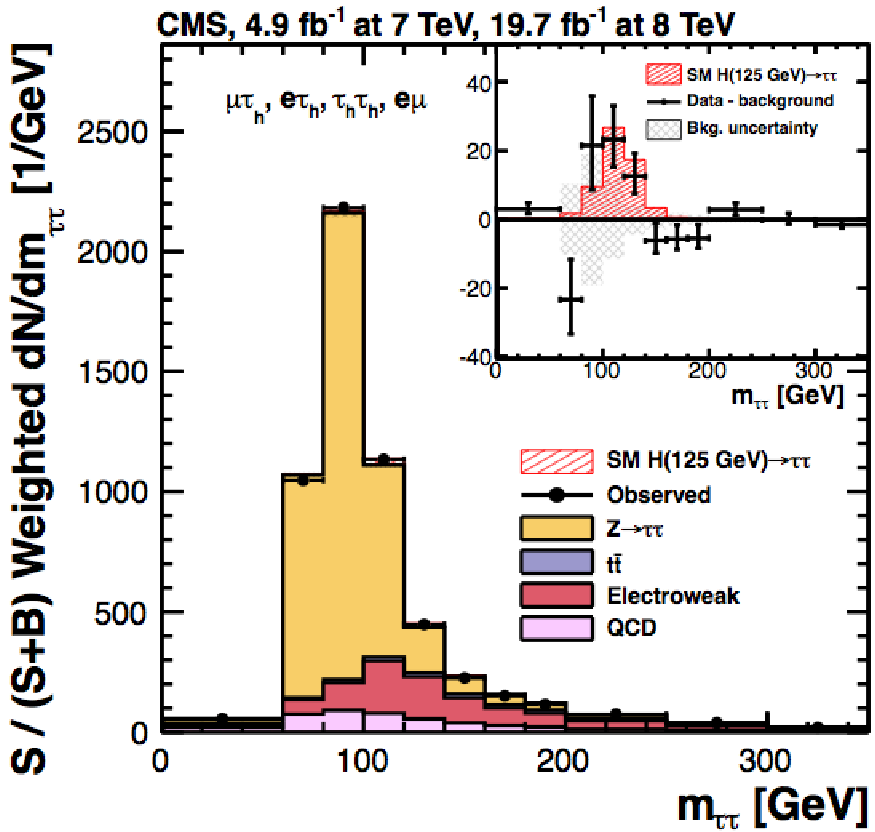
(reducible + irreducible)

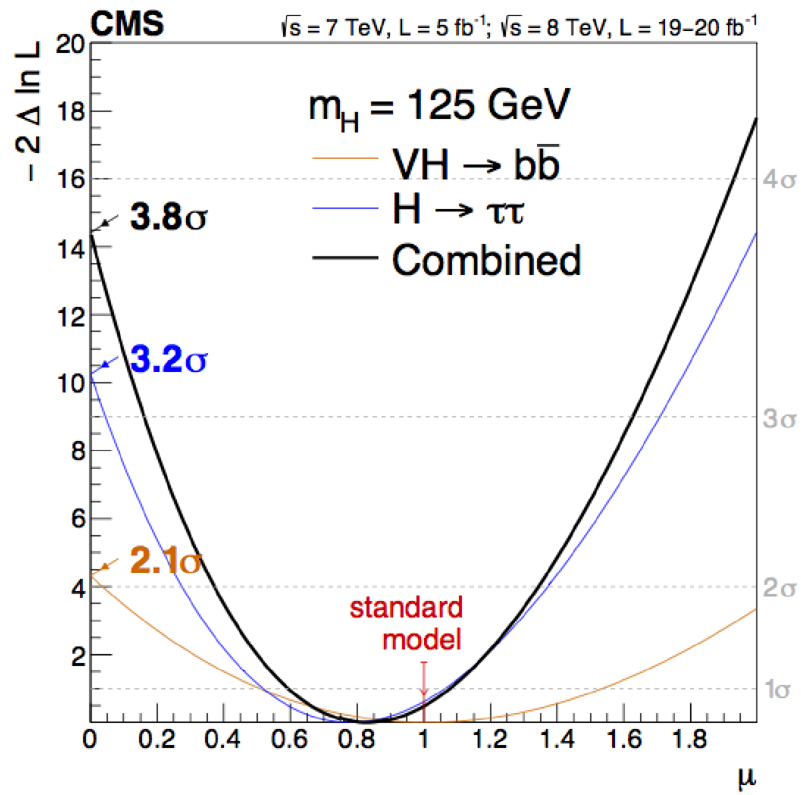


Experiment	Expected	Observed
ATLAS	4.1σ	7.4σ
CMS	4.2σ	3.2σ

(as of winter 2013)

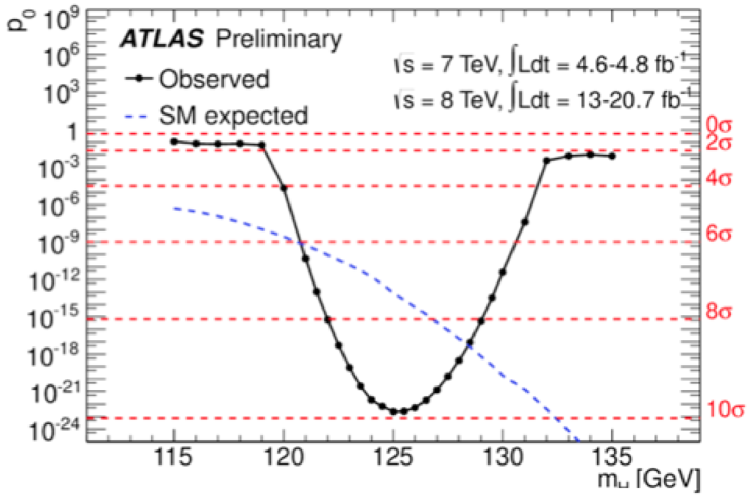
Higgs coupling to fermions





- 3.2σ evidence from H→ττ
- Combined H→ττ and VH, H→bb: 3.8σ

Higgs: properties

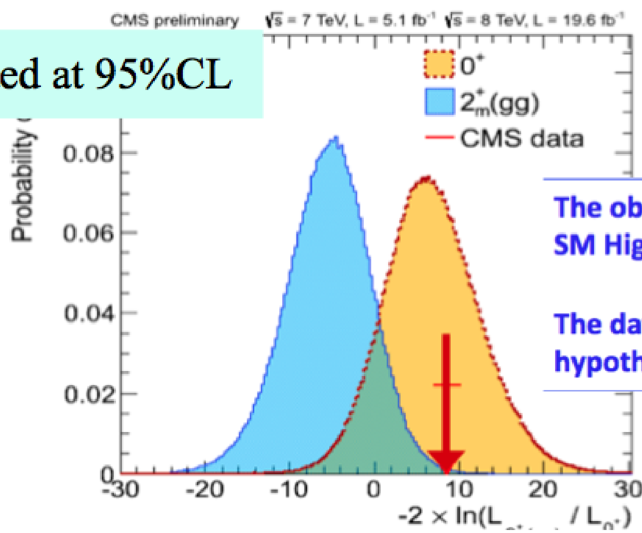


Experiment	Signal strength
ATLAS	1.30+-0.13 (stat.) +- 0.14 (syst.)
CMS	0.80 +- 0.14 (stat.+syst.)

Experiment	mass (γγ+4l)
ATLAS	125.5+-0.2 (stat.) +-0.6 (syst.)
CMS	125.7+-0.3 (stat.) +-0.3 (syst.)

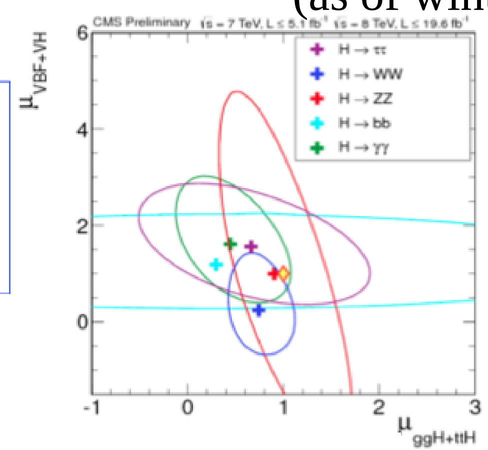
(as of winter 2013)

2^+ excluded at 95%CL



The observation is well compatible with SM Higgs expectations (0^+).

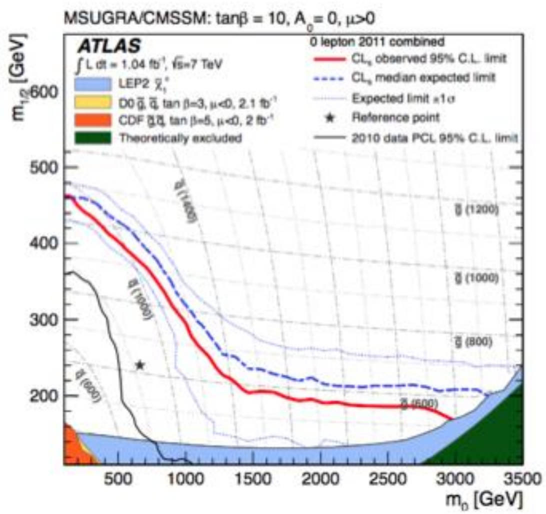
The data disfavours the the $2^+_m(gg)$ hypothesis with a CLs value of 0.6%

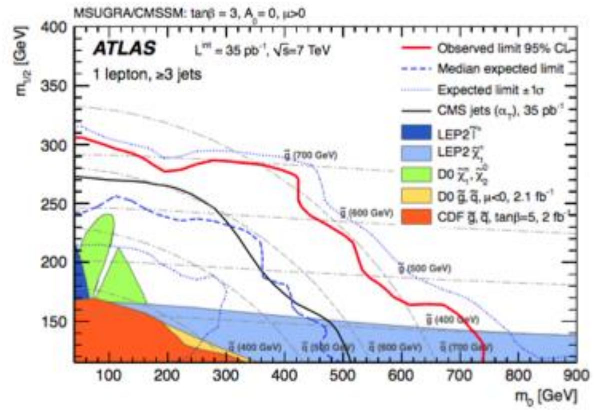


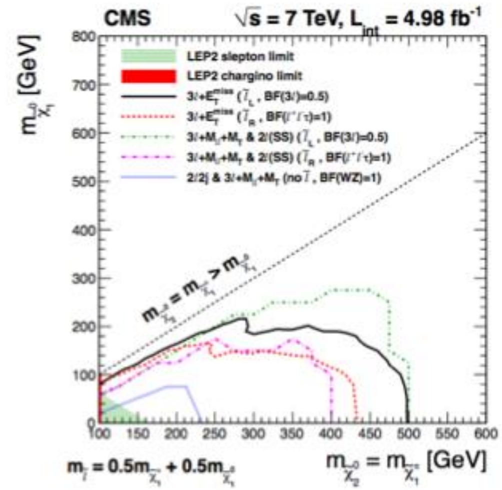
- ❑ And many more results, so far all consistent with SM …

Beyond Standard Model

Unification of interactions: SUSY?

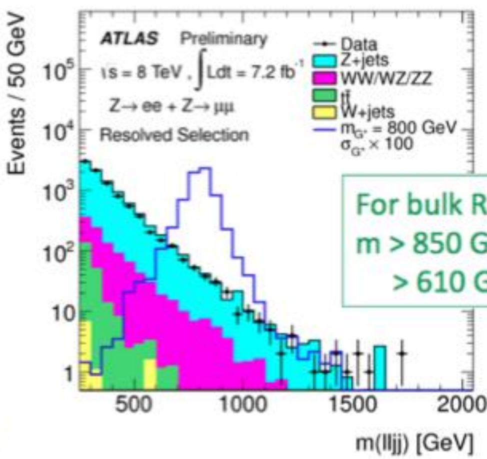




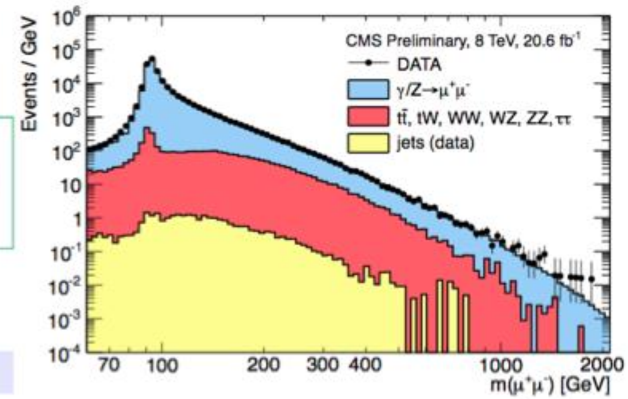


New resonances, new symmetries?

No sign yet..

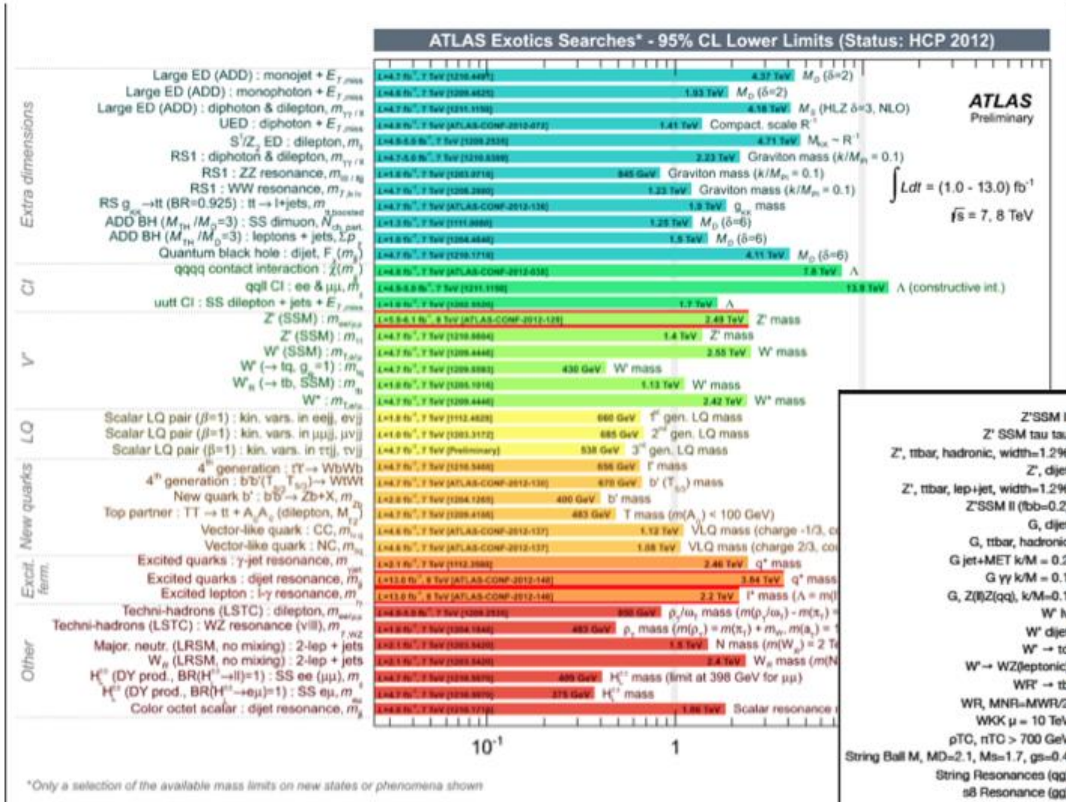


For bulk RS gravitons
m > 850 GeV (k/M_{Pl} = 1.00) [ATLAS]
> 610 GeV (k/M_{Pl} = 0.50) [CMS]

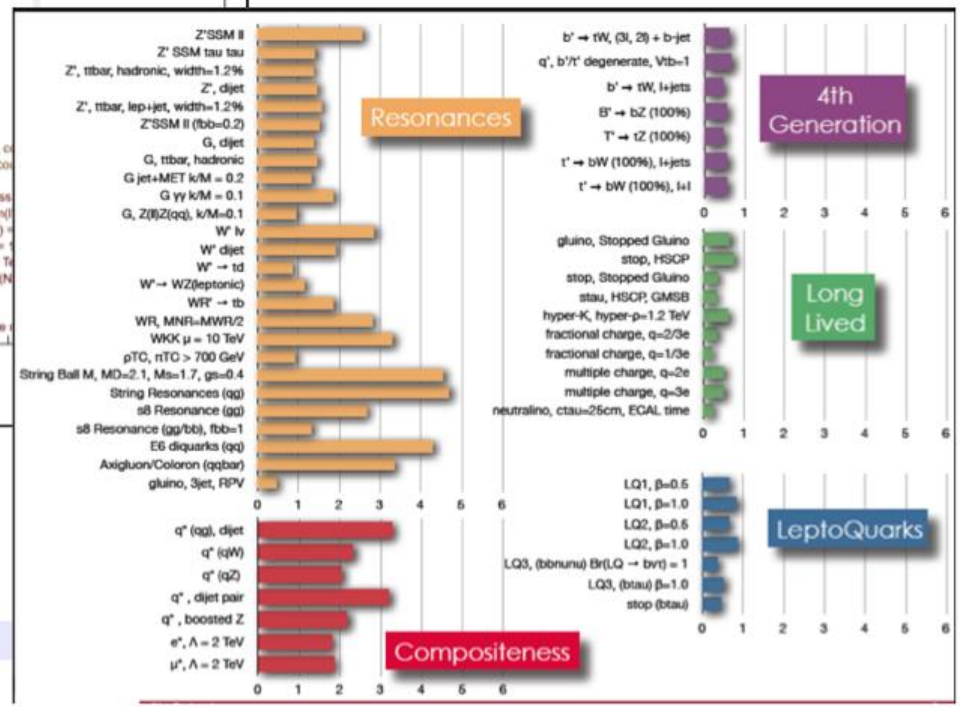


Overview of LHC phys

Beyond Standard Model



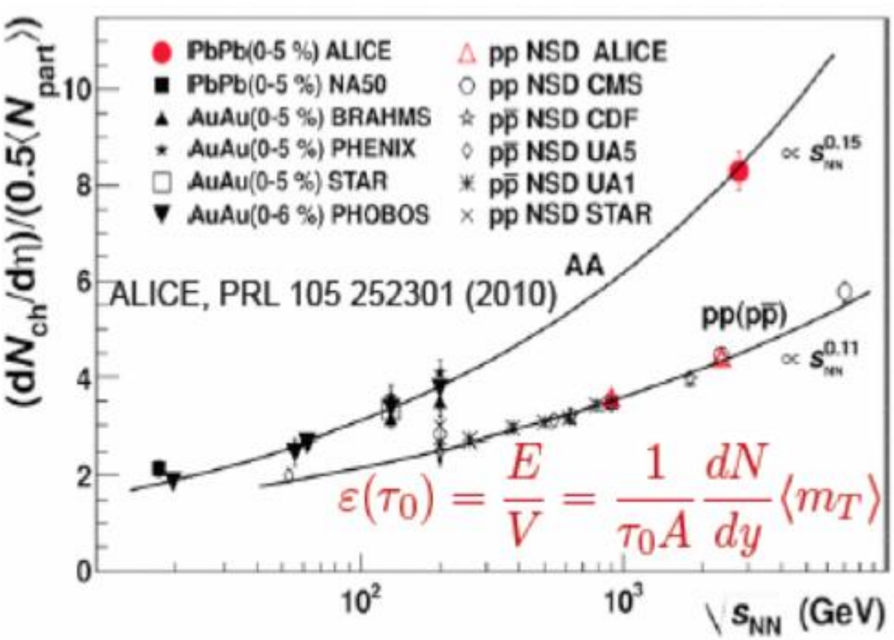
- Searches by ATLAS and CMS for new phenomena are probing the TeV scale
- The SM has proved incredibly resilient
  - Searches at the LHC have not found evidence for BSM physics…yet!



Heavy ions

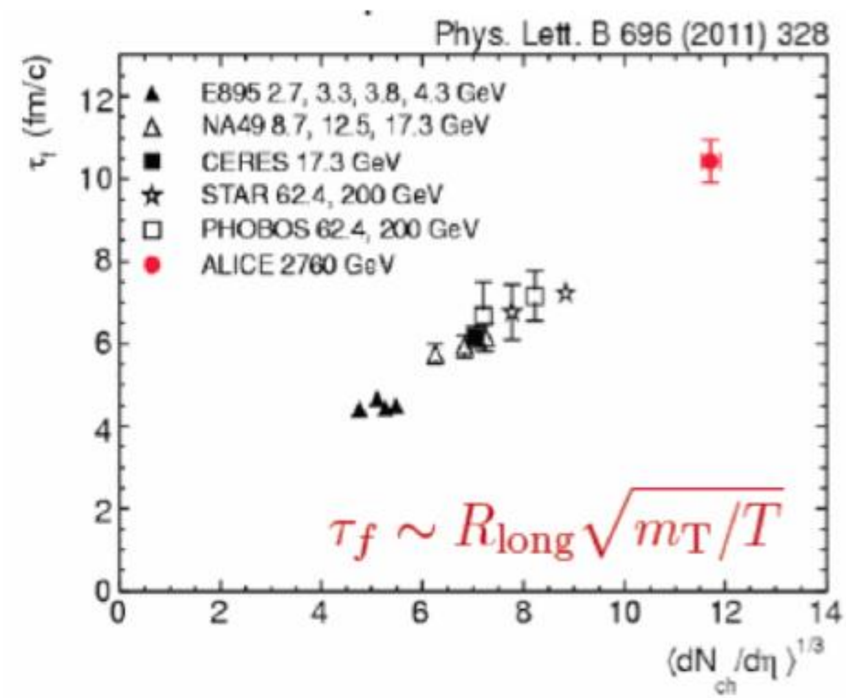
- Charged particle production, soft QCD
- Search for / study of the quark-gluon plasma
  - Jet quenching
  - Elliptic flow
  - Quarkonia

Energy density, volume, lifetime



- Energy density: ~8 GeV/fm3 (3x RHIC)
- Lifetime: ~10 fm/c (1.2x RHIC)

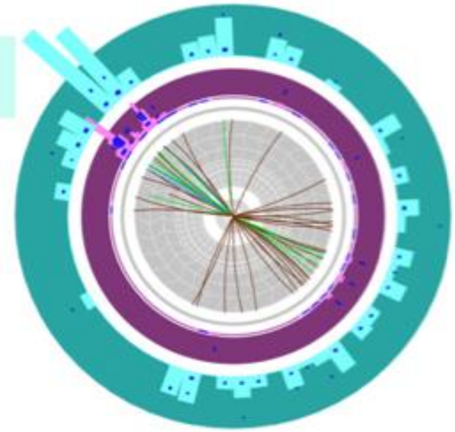
- Volume: ~4800 fm3 (2x RHIC)
- Temperature: ~300 MeV(1.3x RHIC)

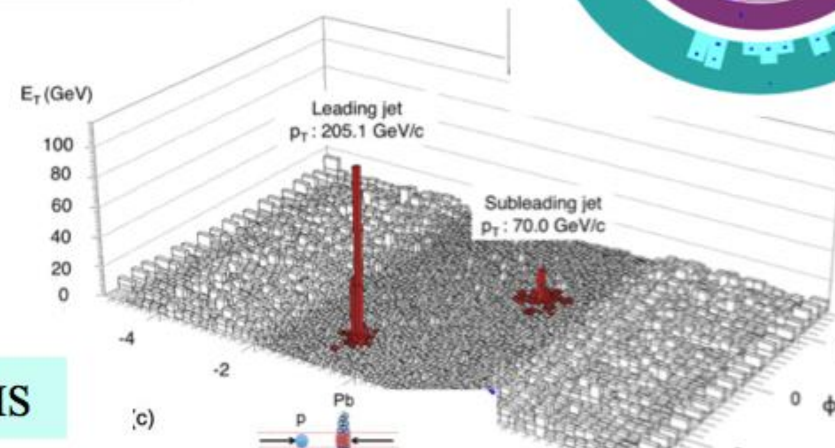


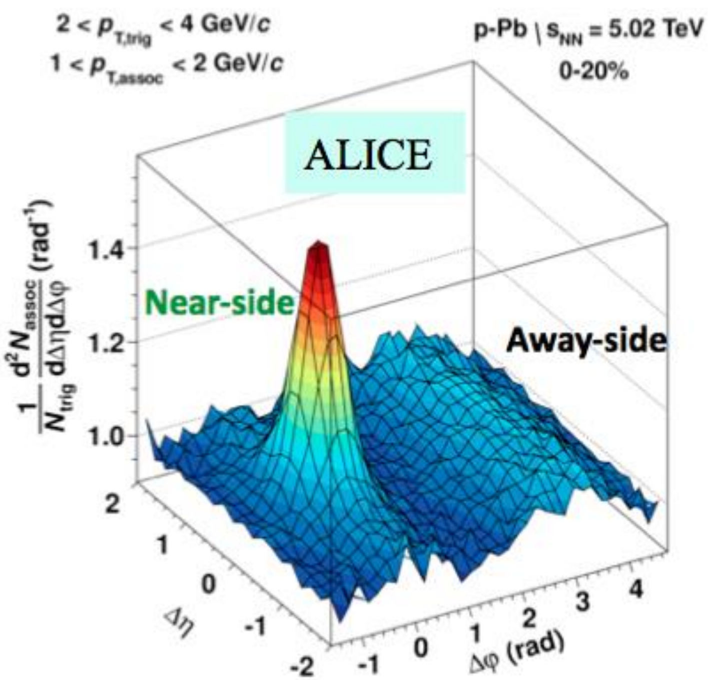
Particle correlation, jet quenching

- Strong di-jet imbalance observed in Pb-Pb
- increase with centrality consistent with jet quenching
- Long range correlations

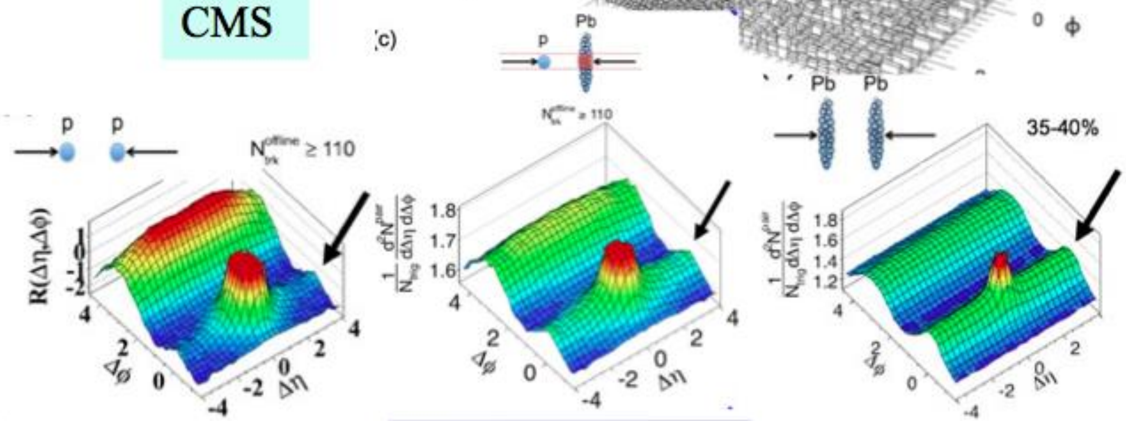
ATLAS





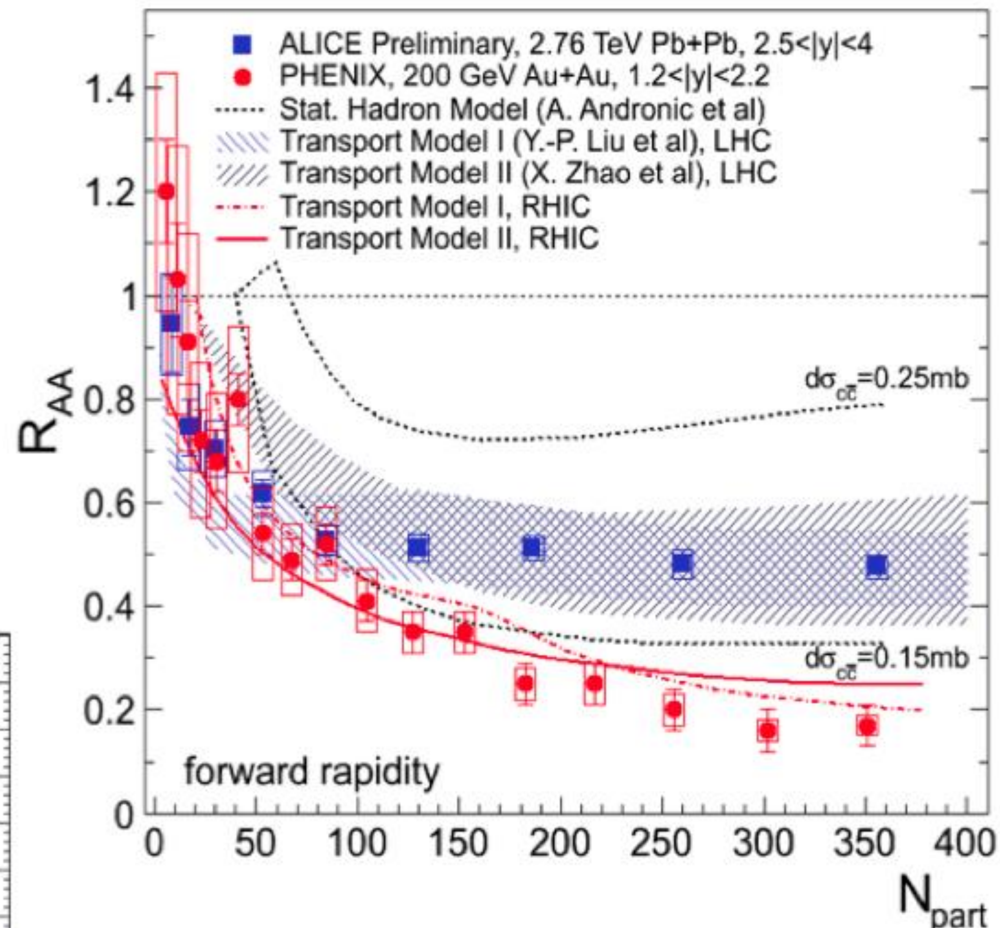


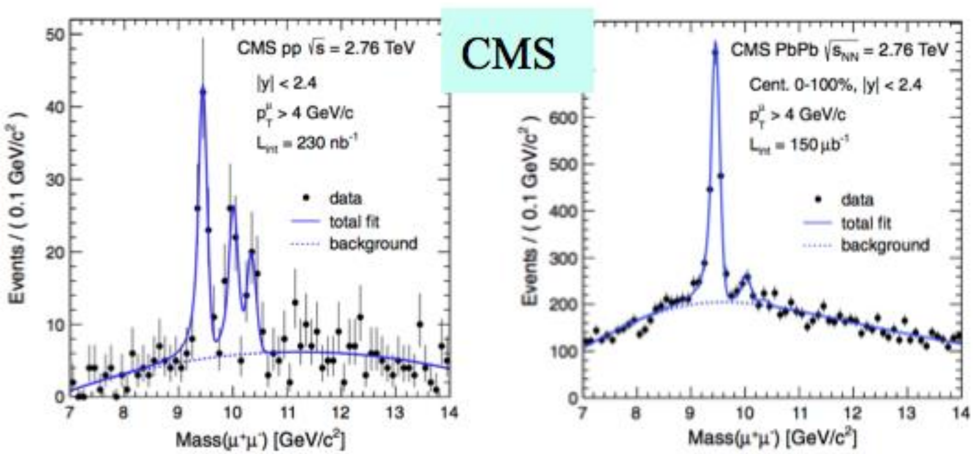
CMS



Color screening in QGP

- J/Psi and Υ suppression for central collisions due to color screening is one of the original predictions for QGP
- At LHC less suppression than at RHIC: re-generation?



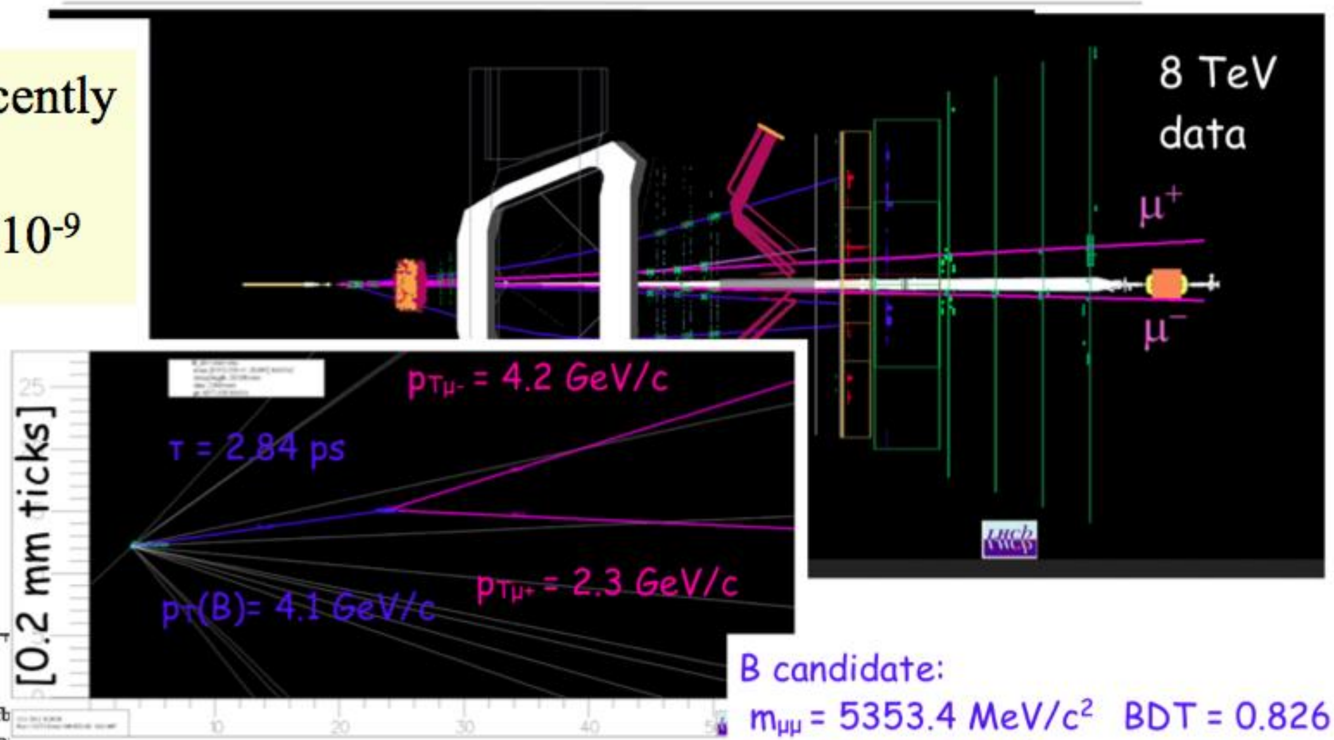


LHCb

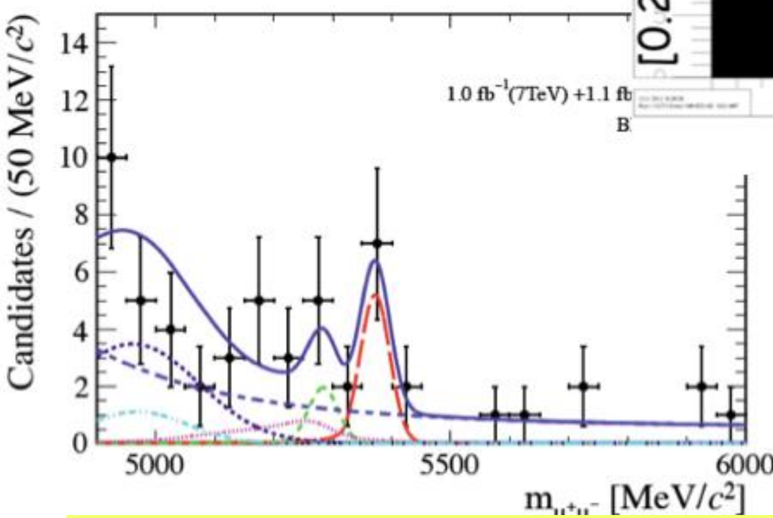
- Flavor physics
  - Observe rarest decays
  - Understand CP violation, matter / anti-matter asymmetry
  - Search for new physics (indirect effects)
  - Discovery of new particles

$B_s \to \mu\mu$

- Extremely rare decay recently observed by LHCb
- Branching fraction: few 10^{-9}



B candidate:
$m_{\mu\mu}$ = 5353.4 MeV/c² BDT = 0.826
p_T = 4077.4 MeV/c t = 2.84 ps



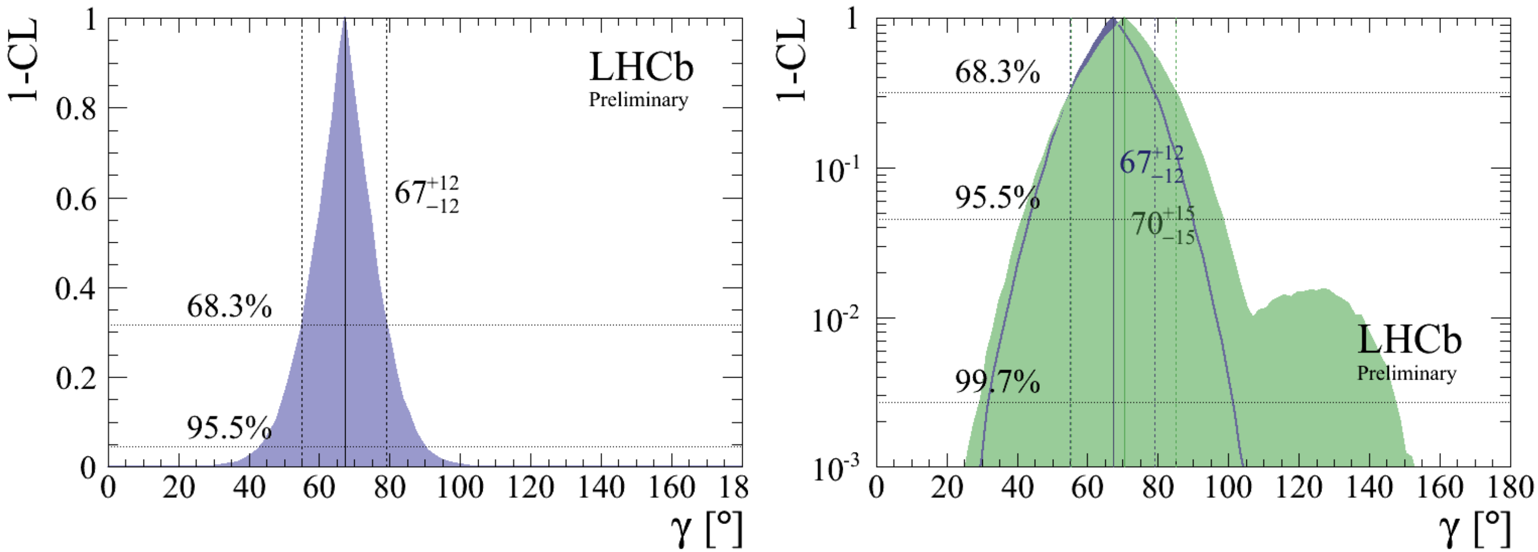
$$BR = (3.2^{+1.4}_{-1.2}\,(stat)\,{}^{+0.5}_{-0.3}\,(syst))\times 10^{-9}$$

SM expectation
$(3.54 \pm 0.30) \times 10^{-9}$

Important result in 2013: LHCb+CMS combined: >5σ for B_s -> μμ

LHCb: CKM matrix

- Recent combination from LHCb
  - Uses analyses of B→DK and D→K_sKK or $K_s\pi\pi$
  - Preliminary result γ=67+-12°



Comparison of 1/fb-only and updated confidence intervals for DK

•These results lead to updated CKM fits:

γ = 68.0 ° *(CKMFitter, FPCP 2013),*

γ = 70.1±7.1° *(UTFit, EPS 2013).*

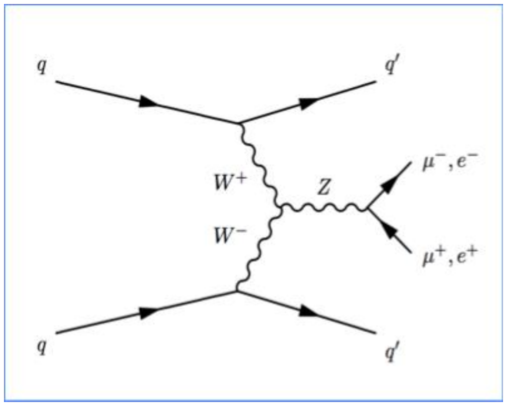
Summary and conclusions

- 2010-2013 has been a very exciting period for particle physics
  - The accelerator and the detectors have been working very well
  - Plenty of physics result and the major discovery of the awaited Higgs boson
- A new period will start in 2015 after LS1
  - Precise measurement of the Higgs properties
    - Already started but will benefit from increased statistics
  - From where comes the EWSB? Other Higgs bosons?
  - Search for beyond standard model physics
  - How to stabilize the Higgs mass? Unification at high energy? Supersymmetry? Reasons for the 3 families? … ?
  - More on QGP, flavour physics and CP violation
- Much more luminosity but also more pileup
  - A new challenge for computing and software

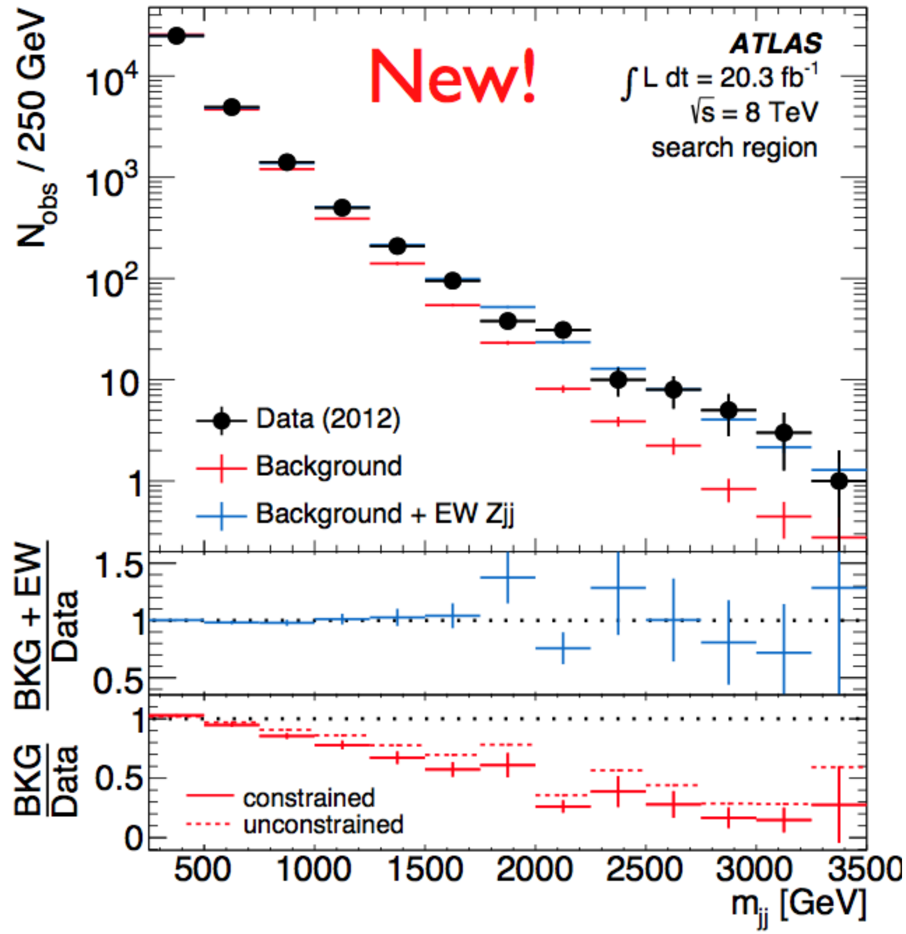
Additional material

EWK Z production

- Important test of WWZ coupling

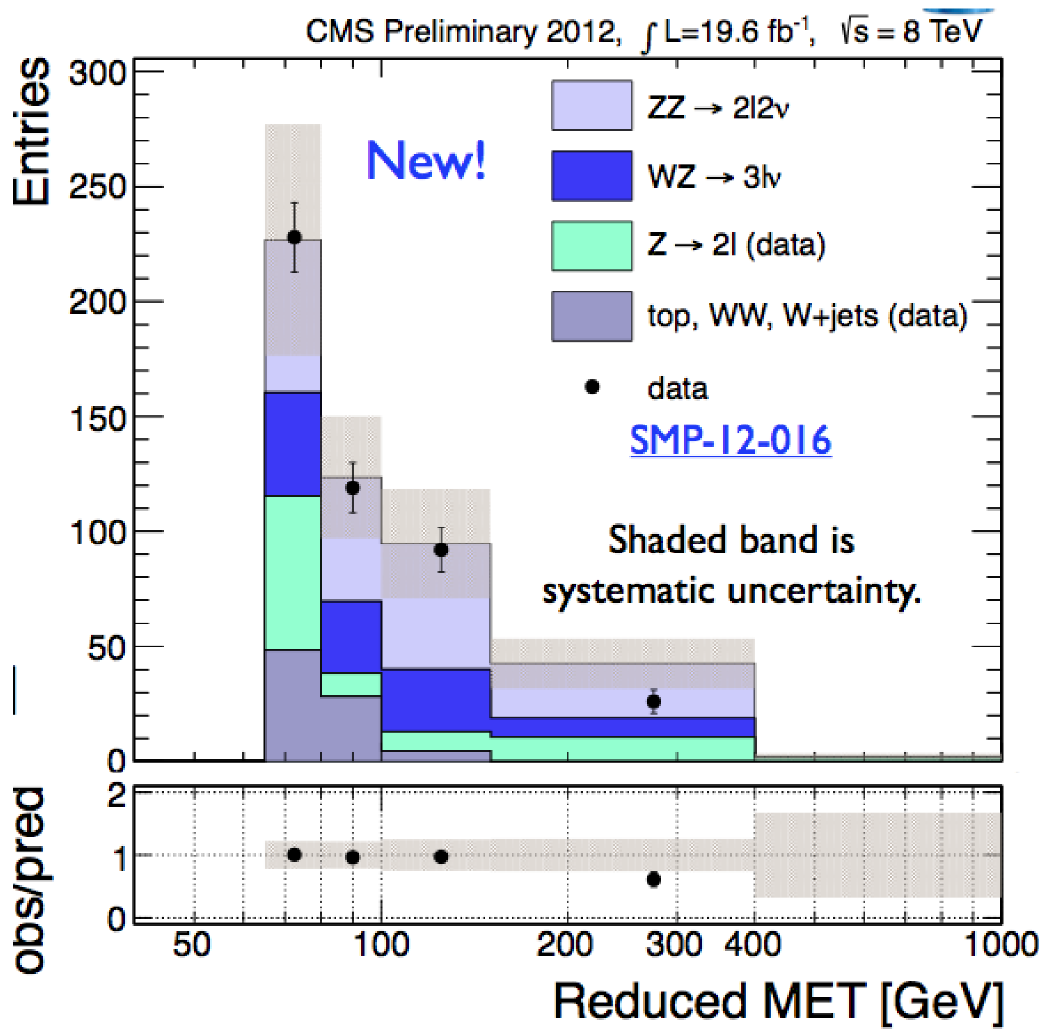


- >5sigma observation with 8 TeV data



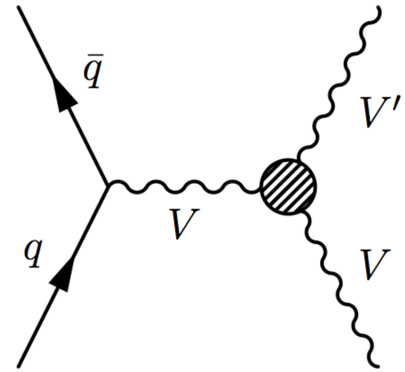
ZZ

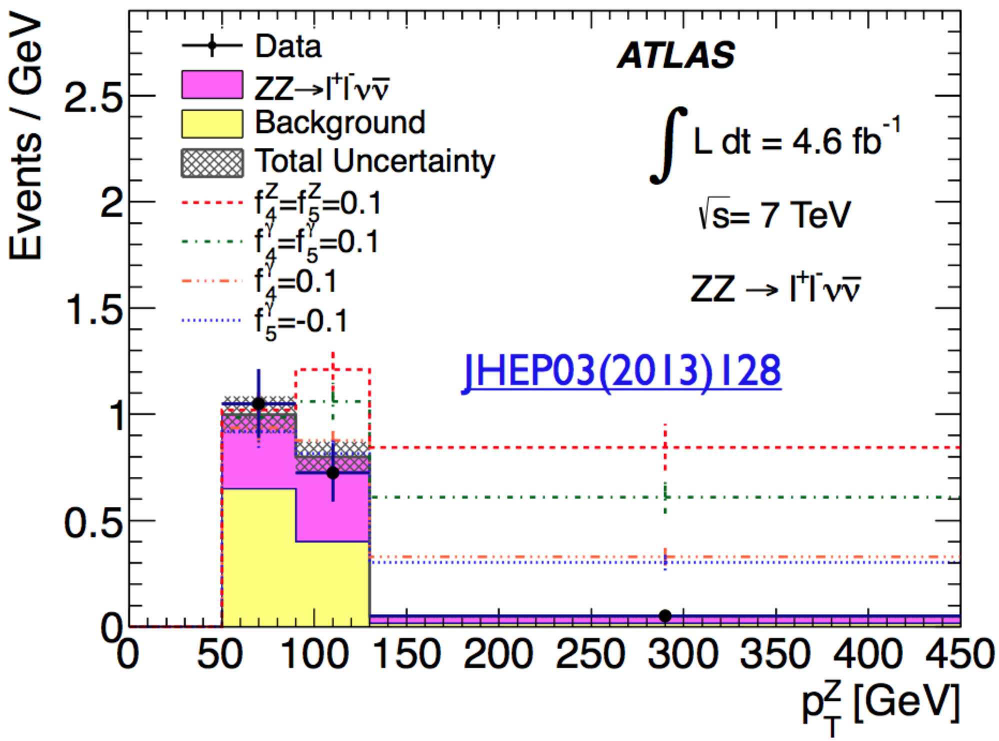
- ZZ->llnunu cross section measurement
- Reduced MET gives better rejection of the DY background
- Updated aTGC limit
- New ATLAS result



aTGC

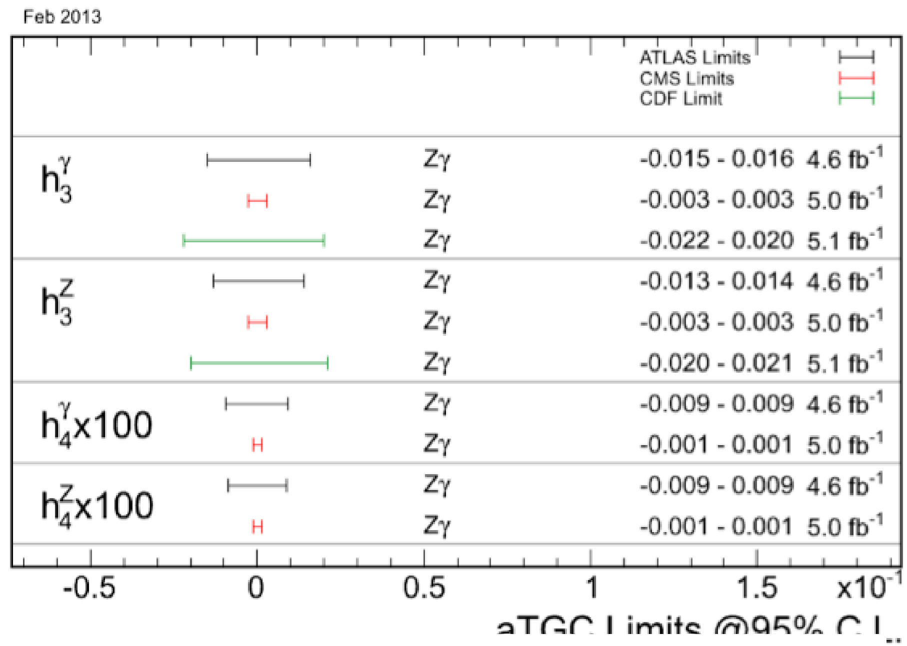
- Search for effect of higher order operators in the SM lagrangien
  - Effect of new particles in loops
  - Massive propagator in 4 boson vertex
- Operators generate new couplings that become important at high transverse momentum

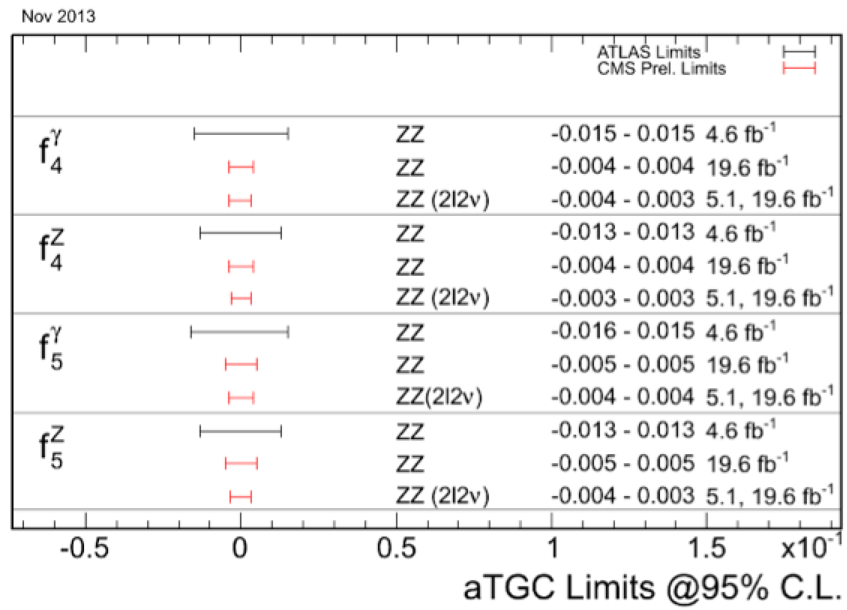




aTGC

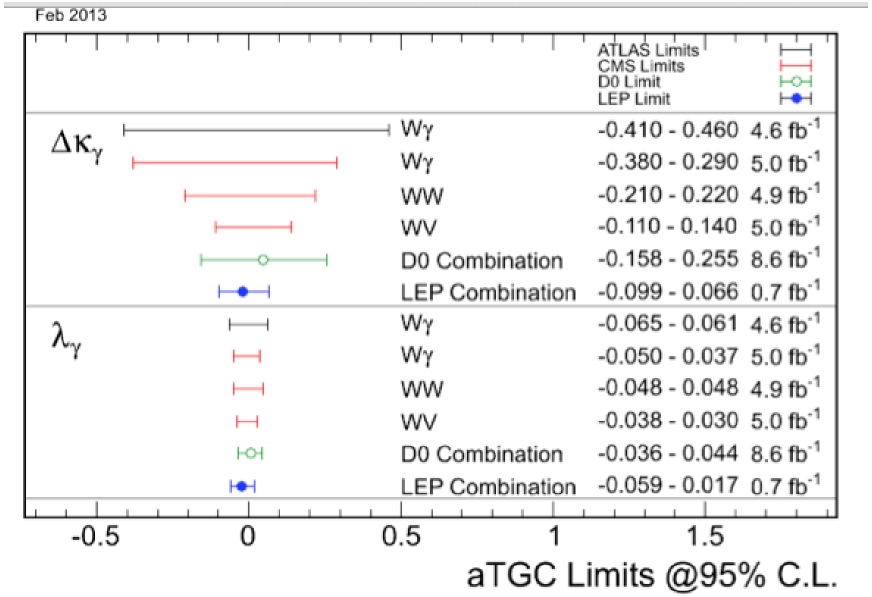
- Update in neutral anomalous couplings
- CMS 2l2nu analysis
- High branching fraction
- Further constraint by combining the channel underway

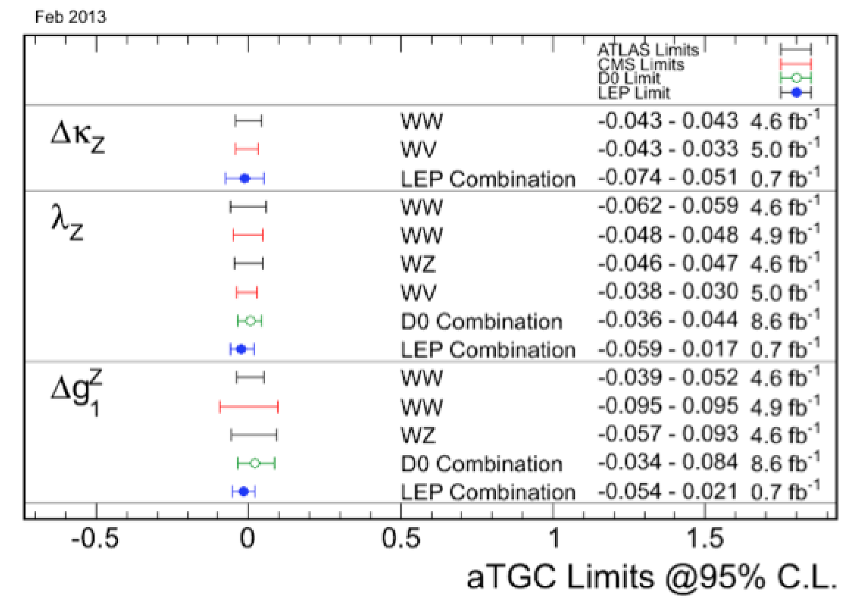




aTGC

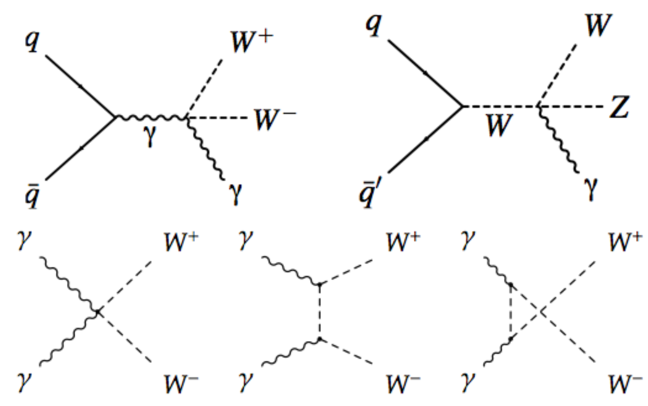
- Charged anomalous triple gauge coupling
- LHC approaching LEP results
- Surpassing LEP in some cases!
- New final states exploited
- WV, V->jj
- Analysis still ongoing in several channels
- Further improvements expected

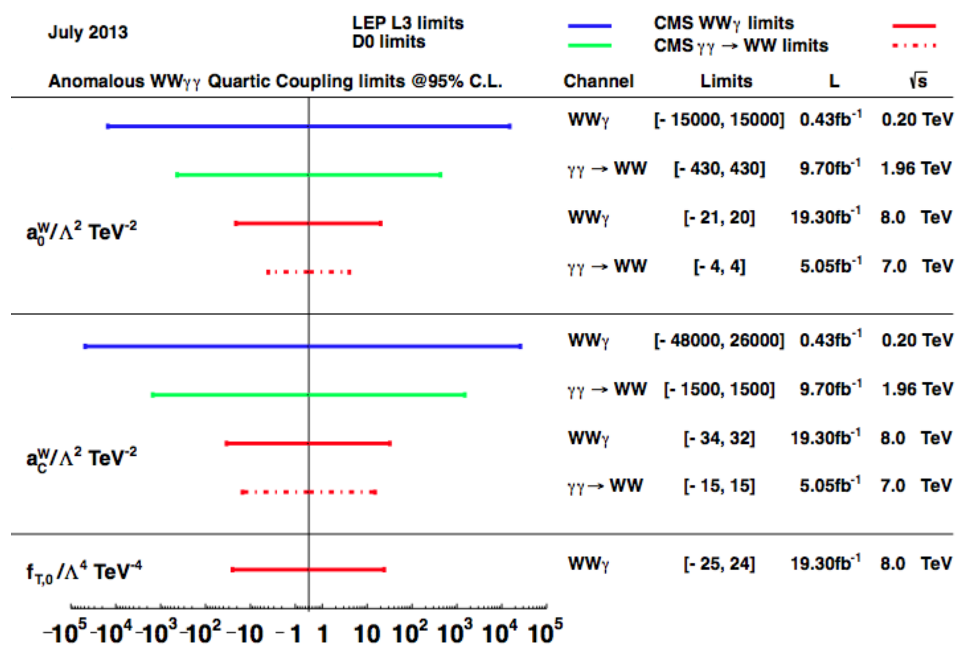




Anomalous Quartic Couplings

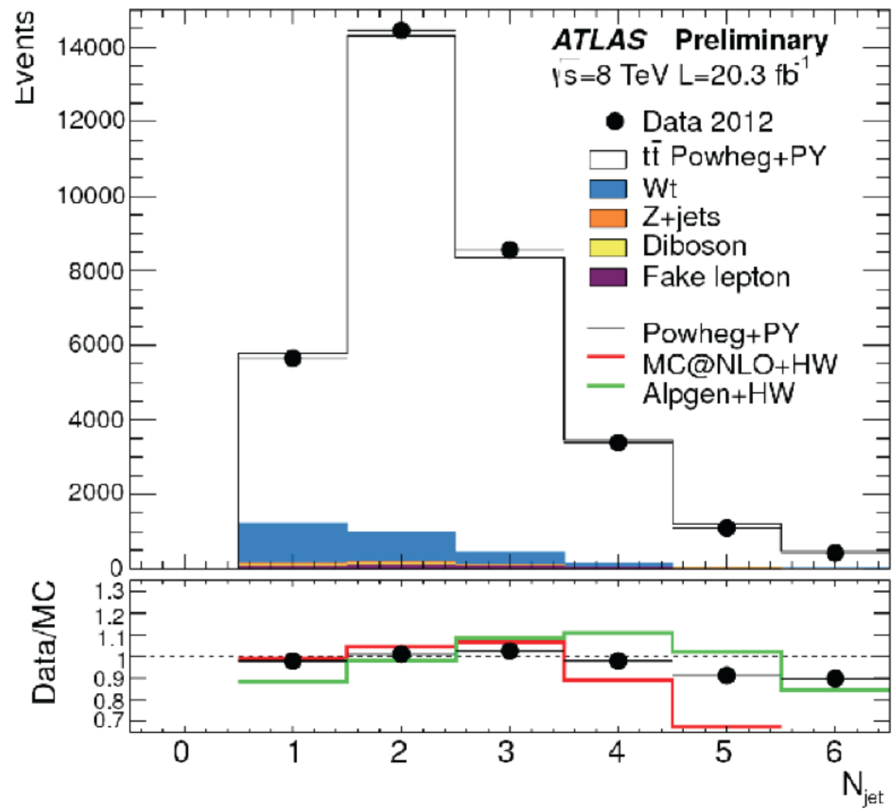
- Pure quartic contributions accessed through WW exclusive production, WWgamma and WZgamma
  - In the latter case use decay in 2j for one massive gauge boson
- New measurements
  - WWgg and WWZg
- Significantly improves over D0 and LEP





Top production

- ttbar production: precision cross sections, differential distributions, ttbar +HF, ttbar +gamma/W/Z
- World's most precise cross section: total uncertainty of 4.8%

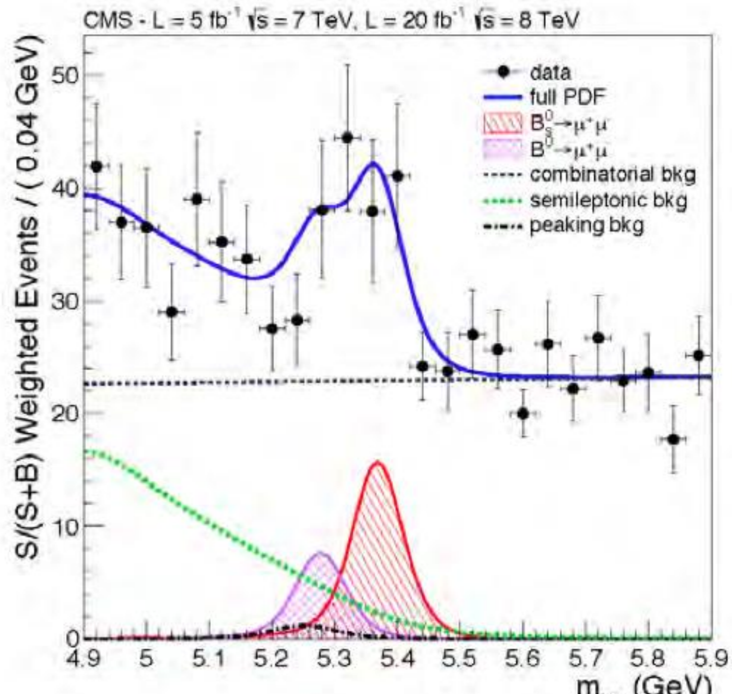


Heavy flavour

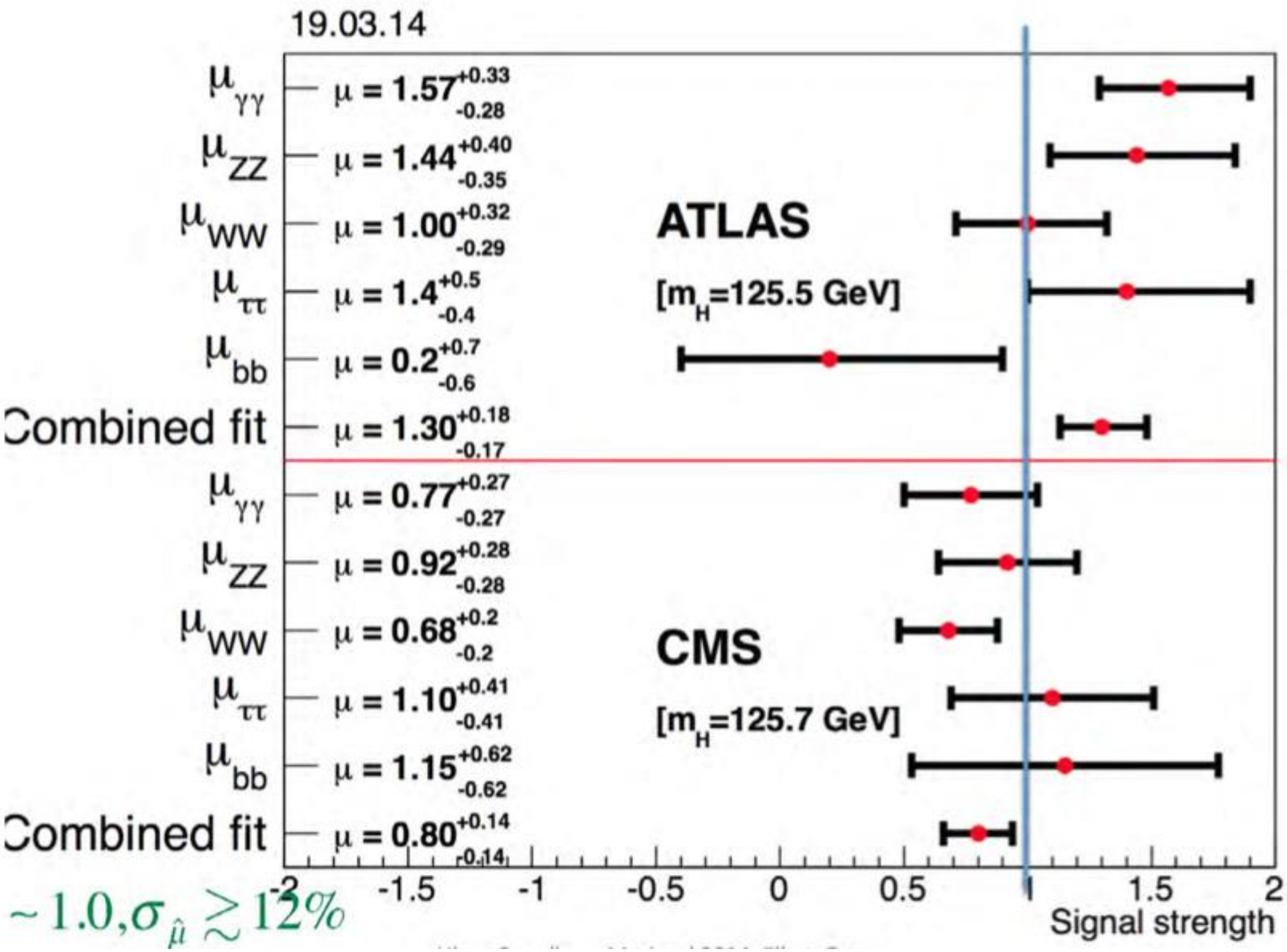
- CMS and ATLAS contributes
- Important result in 2013:
- 5sigma Bs->mumu from combined CMS and LHCb result

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (2.9 \pm 0.7) \times 10^{-9}, \quad > 5\sigma$$

$$\mathcal{B}(B^0 \to \mu^+\mu^-) = \left(3.6\,^{+1.6}_{-1.4}\right) \times 10^{-10}, \quad < 3\sigma$$

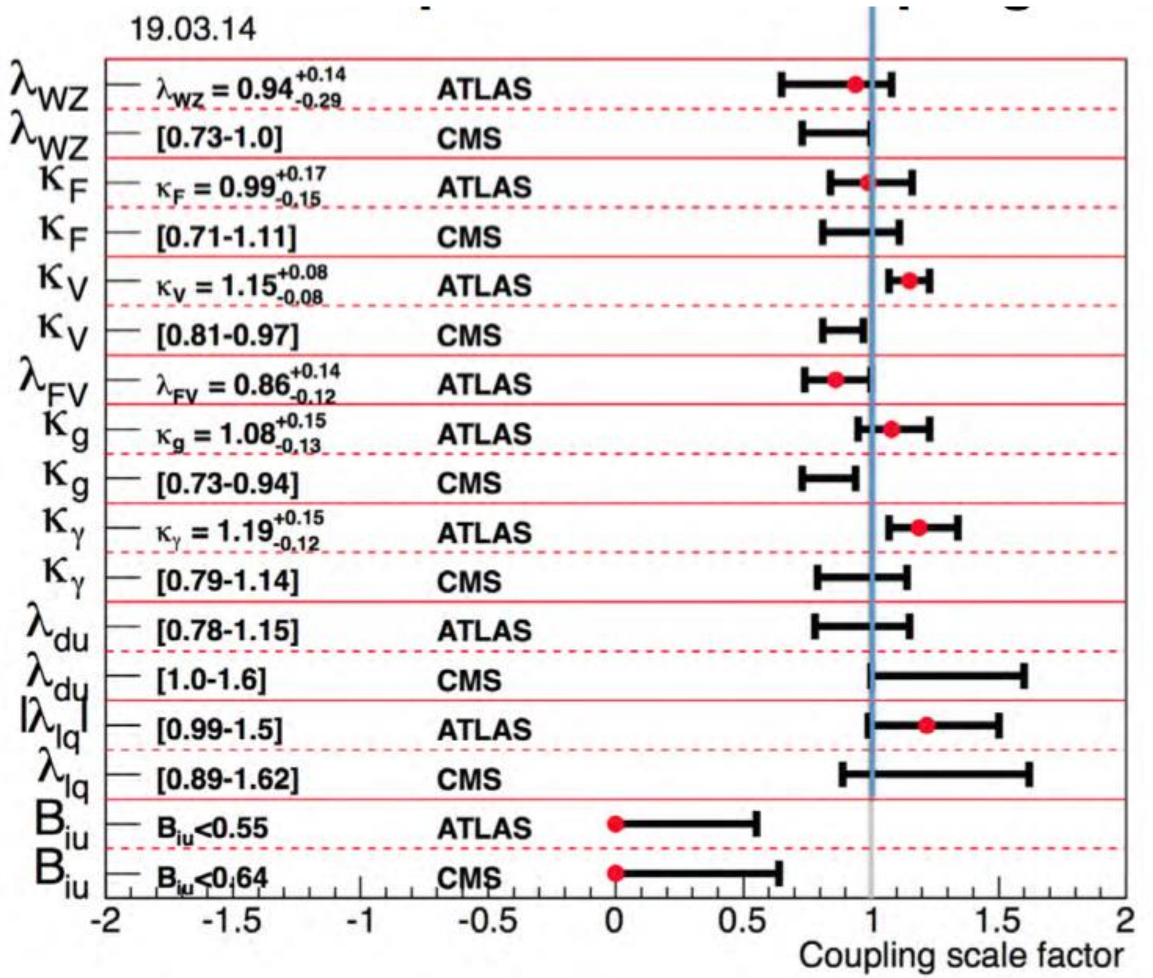


Higgs couplings

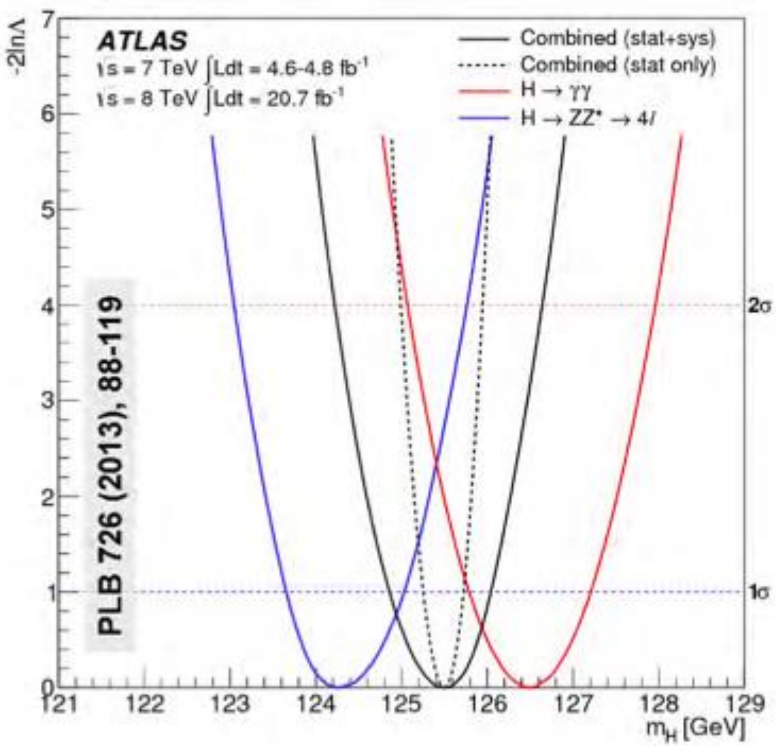


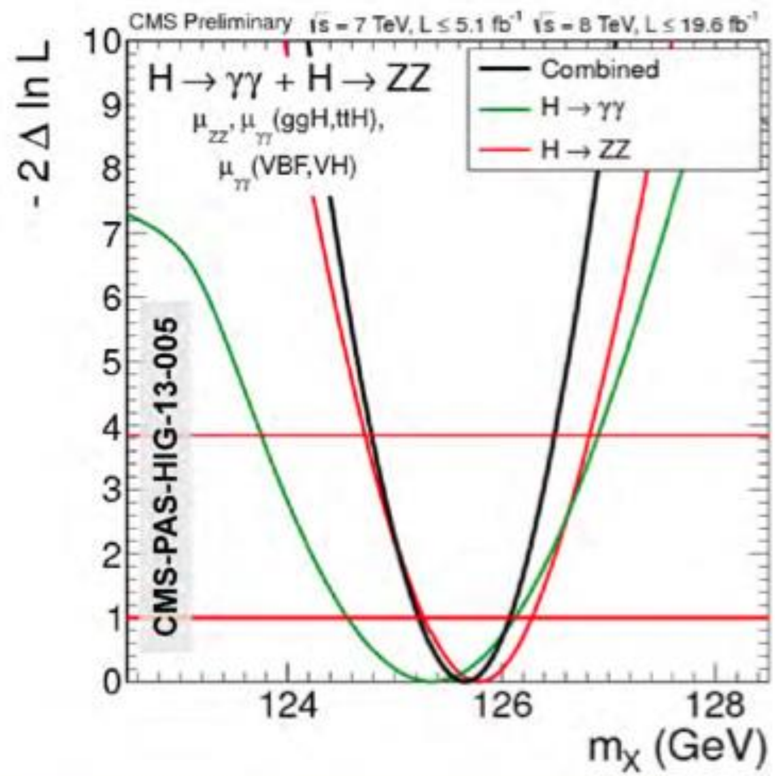
$\sim 1.0, \sigma_{\hat{\mu}} \gtrsim 12\%$

Higgs couplings



Properties





ATLAS	CMS (new ZZ(4l) not used)
125.5 +-0.2 (stat) $^{+0.5}_{-0.6}$(syst) GeV	125.7 +- 0.3(stat) +- 0.3(syst) GeV

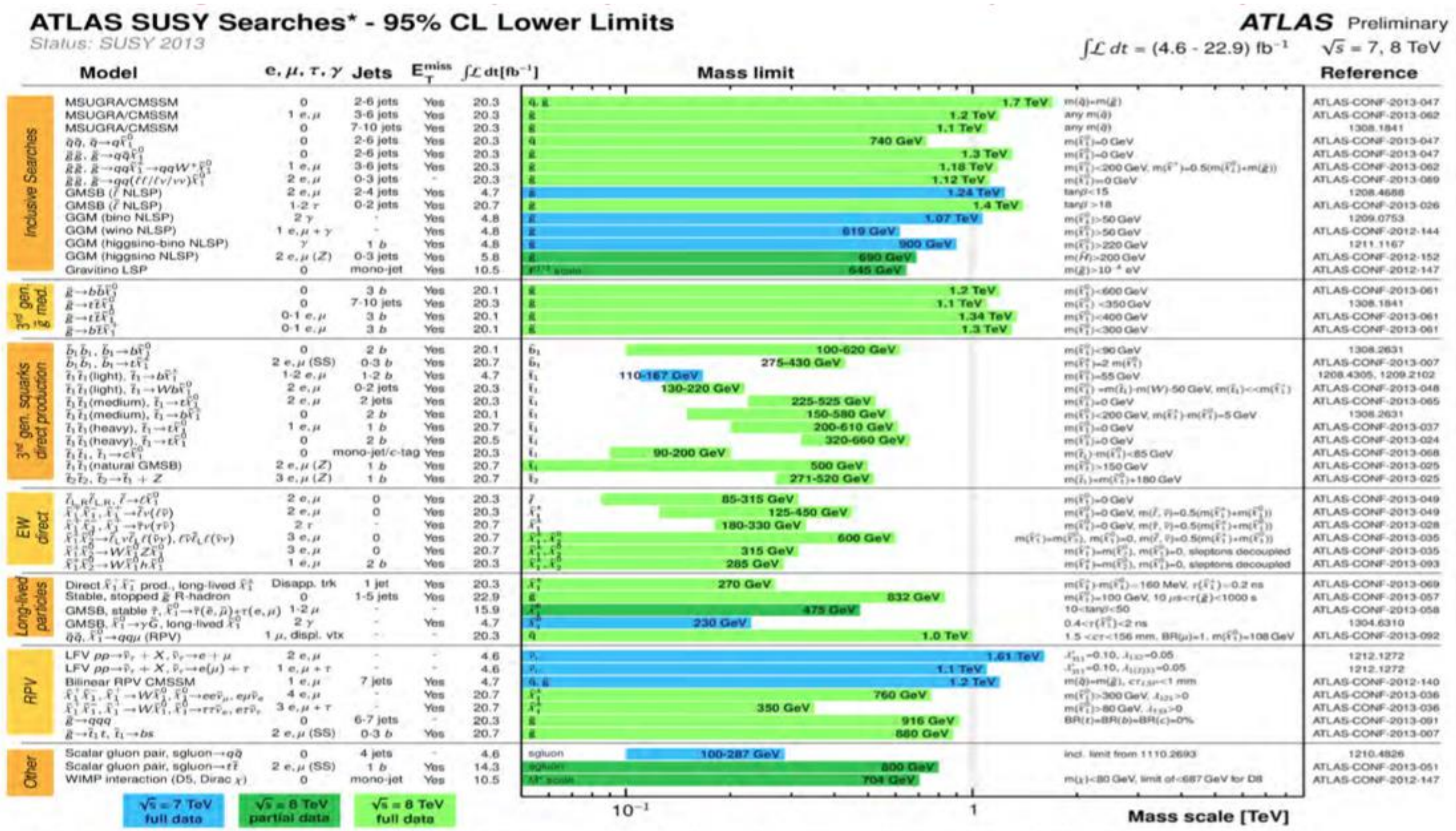
Search for BSM Higgses

- Two different approaches: "indirect" using coupling results, "direct" using targeted searches (*Thompson*).
- Limits from recent ATLAS couplings analysis:
  - Minimal Composite Higgs (MCHM)
  - Additional EW singlet
  - 2HDM
  - Simplified MSSM
  - Higgs Portal

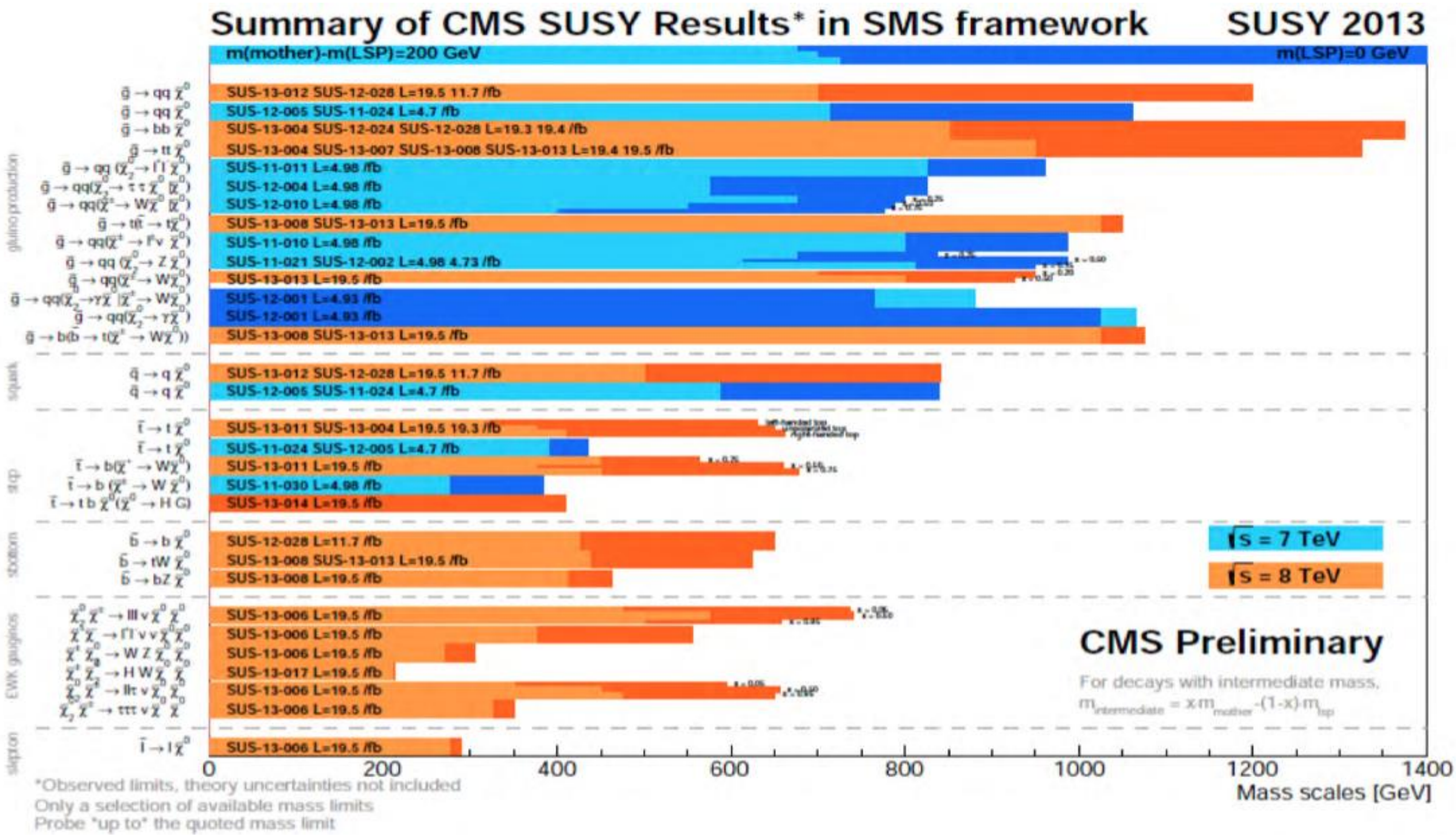
No sign of BSM Higgs (yet) !

- Limits from direct Searches:
  - H -> hh, A -> Zh (CMS)
  - 2HDM limits (CMS)
  - t -> cH (CMS) and t -> qH (ATLAS)
  - MSSM H -> $\tau\tau$ (CMS)
  - Charged Higgs (ATLAS)

SUSY limits ATLAS

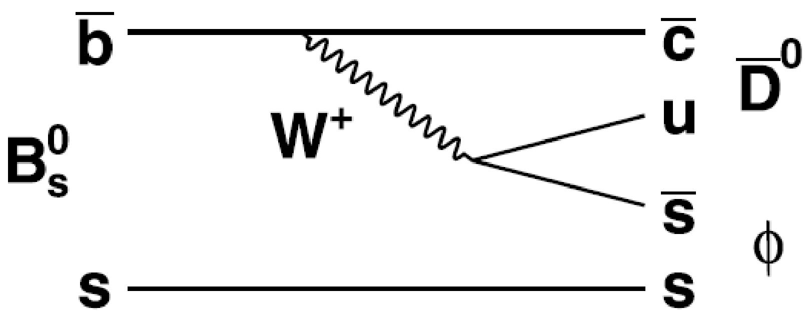


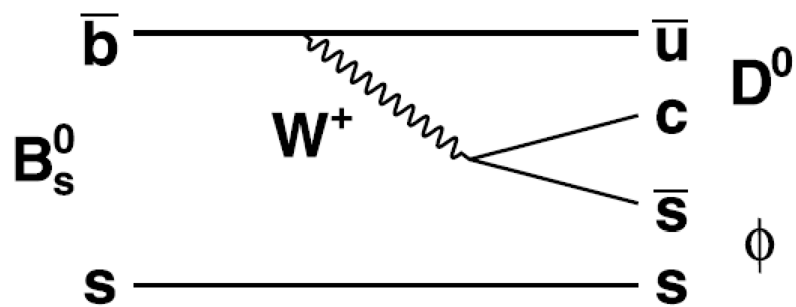
SUSY limits CMS



LHCb: observation of B_s->$D^o\phi$

- Time-dependent analysis of the $B_s \to D^0 \varphi$ decay can measure γ and φ_s (Phys. Lett. **B 253** (1991) 483).
- Using the now-known sign of $\Delta\Gamma_s$, this determination can be made unambiguous (Phys. Rev. **D 85** (2012) 114015).
- A time-***in***dependent analysis can also measure γ, provided enough D^0 final states are included (Phys. Rev. **D 69** (2004) 113003, Phys. Lett. **B 649** (2007) 61). This has advantages for LHCb, as it means flavour-tagging is not required.





- First step is to make the first observation of the decay, using the Cabibbo-favoured $D^0 \to K^+\pi^-$ decay mode.