LHC Physics: results from run I

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LCG-France meeting, Ecole Polytechnique, may 2013

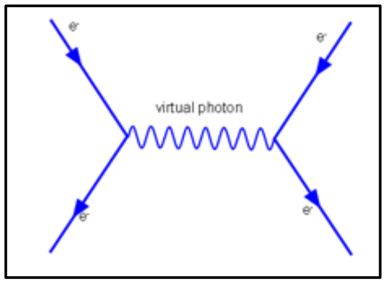
Foreword

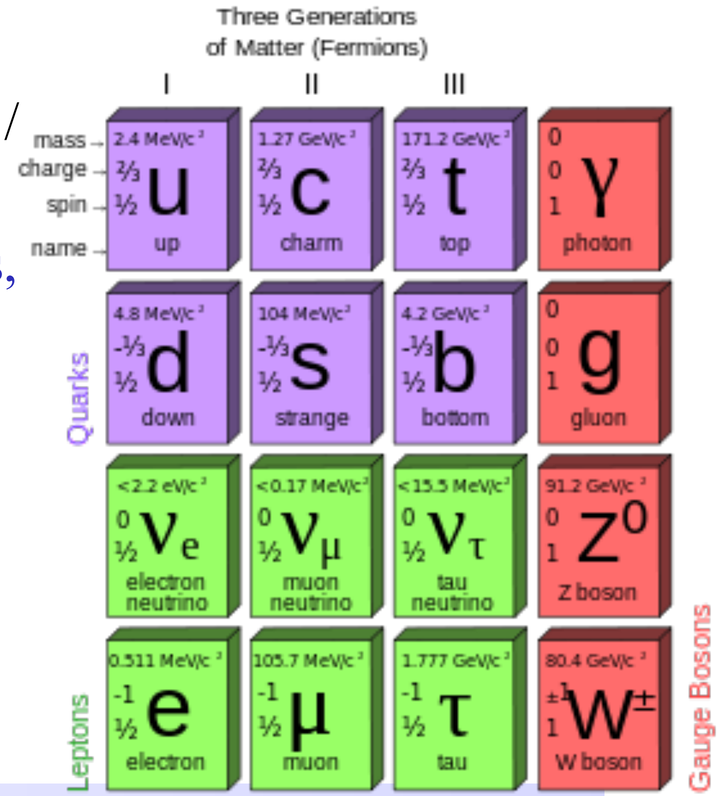
- Overview of physics results from run I
  - Ended beginning of this year, so good time for it
- Many many results obtained
  - QCD, QGP, EWK, spectroscopy/new particles, heavy flavours, top, Higgs, Beyond Standard Model
- Will not cover everything
  - Rather illustrate some of the results obtained to give you a flavour of what has been done and of the most important results
  - Apologize in advance for results not shown

Standard Model of Particle Physics

- The Standard Model is built upon gauge symmetries
  - Internal symmetries (extending upon geometrical symmetries)
  - Conserved quantities (quantum numbers): electric charge, colour, spin,..
  - Invariance principles always played a major role in physics (principle of relativity, electromagnetism, special and general relativity)

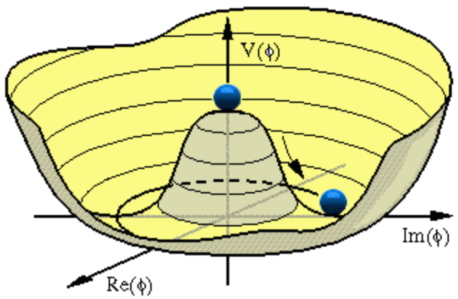
- Gauge symmetries modified are understanding of forces / interactions
  - Gauge invariance naturally leads to interaction terms, no need to introduce forces between particles
  - Interactions consist in the exchange of particles (vector boson)





A problem

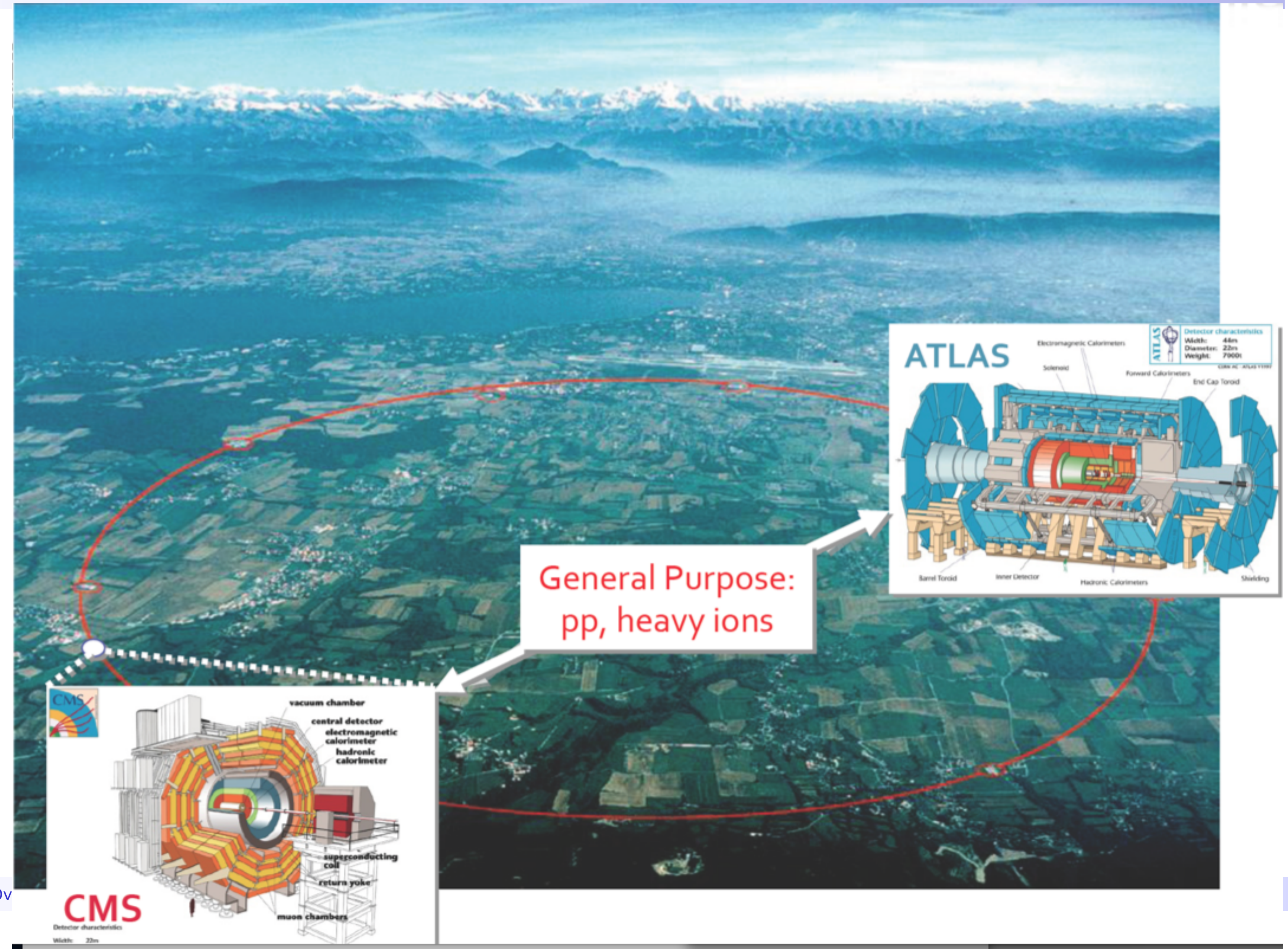
- This picture has been very successful but gauge invariance implies massless vector bosons, or, equivalently, interactions of infinite range
- And it is known experimentally that weak interactions are of very short range, the masses of the carrier of the weak interactions are:
  - m_Z=91.2 GeV and m_W=80.4 GeV
- Thus **either it is our picture of the interactions as the exchange of vector bosons which is wrong or there is a way to preserve this description for short range interactions (e.g. massive vector bosons)**
- A possible way is the spontaneous symmetry breaking
- As a consequence the weak W and Z bosons become massive and a new scalar neutral particle appears: this is the Higgs boson



- It turns out that this mechanism also allows to introduce the fermion (quarks and leptons) masses

LHC and LHC experiments

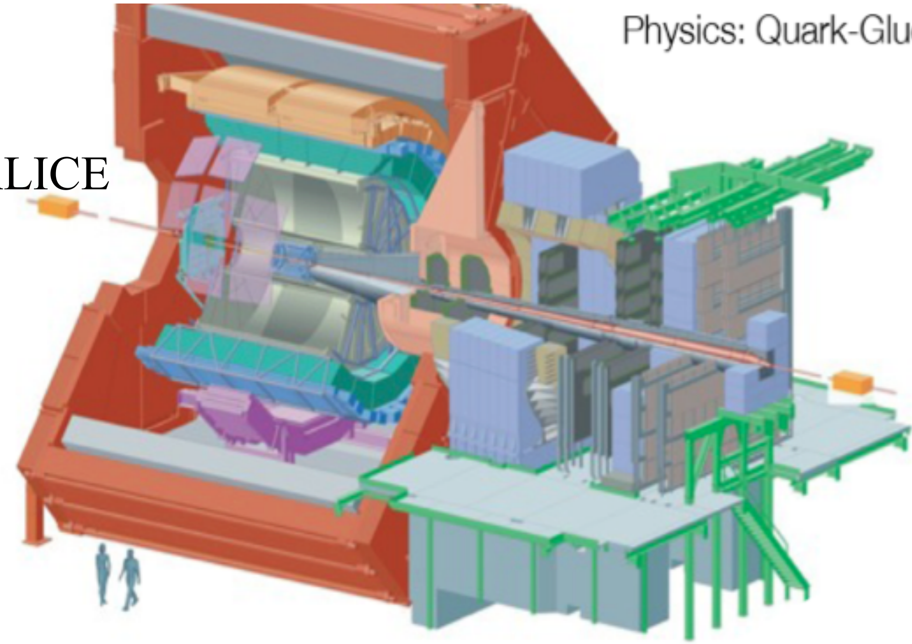
LHC and LHC experiments



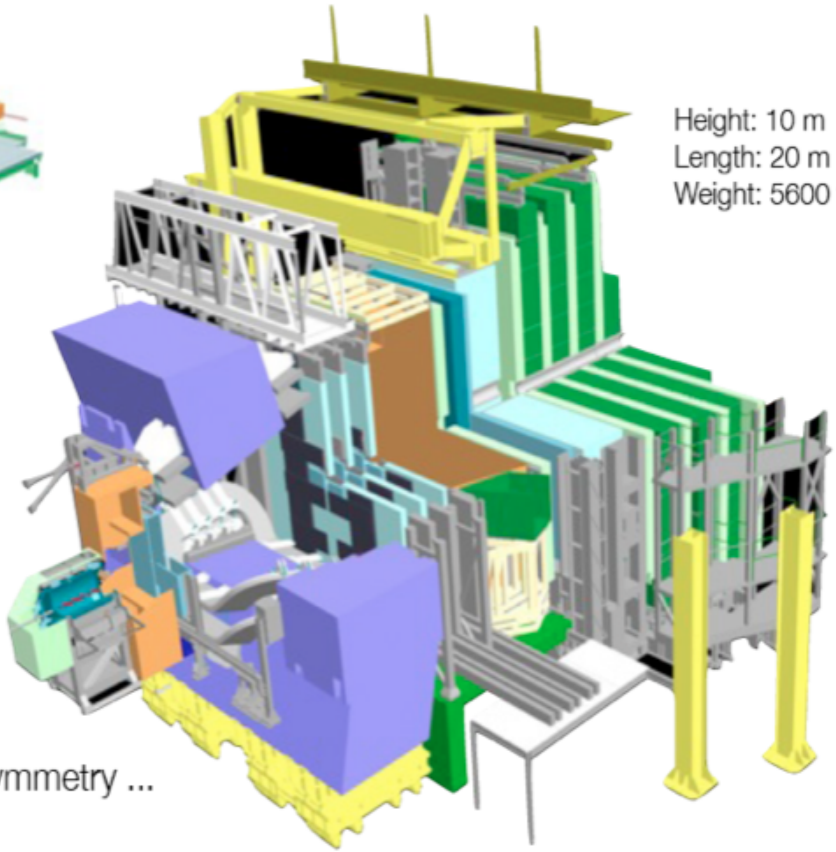
LHC and LHC experiments

Physics: Quark-Gluon Plasma ...

ALICE



Height: 16 m
Length: 25 m
Weight: 10000 t



Height: 10 m
Length: 20 m
Weight: 5600 t

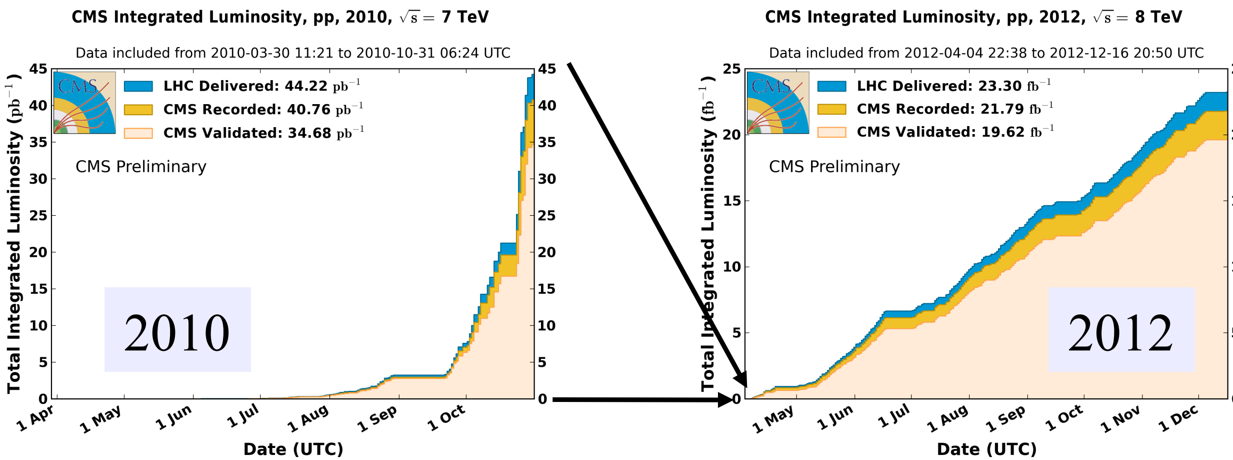
LHCb
[Forward Spectrometer]

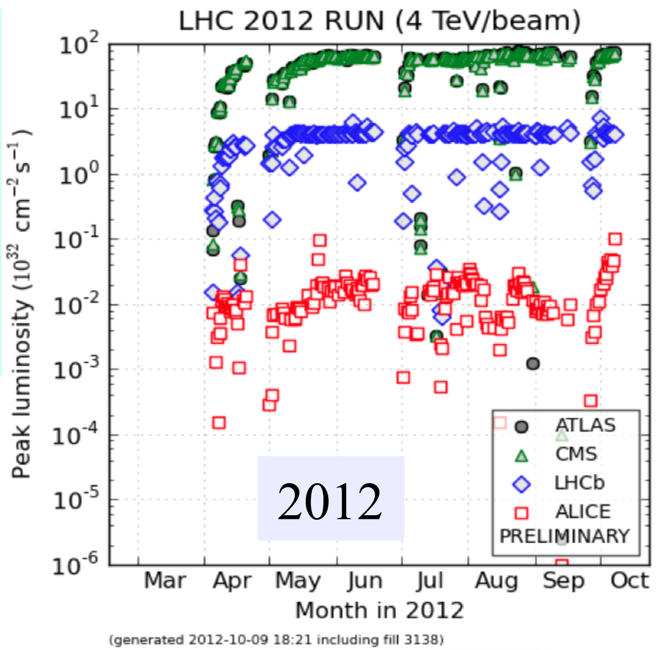
Physics: Matter/Antimatter-Asymmetry ...

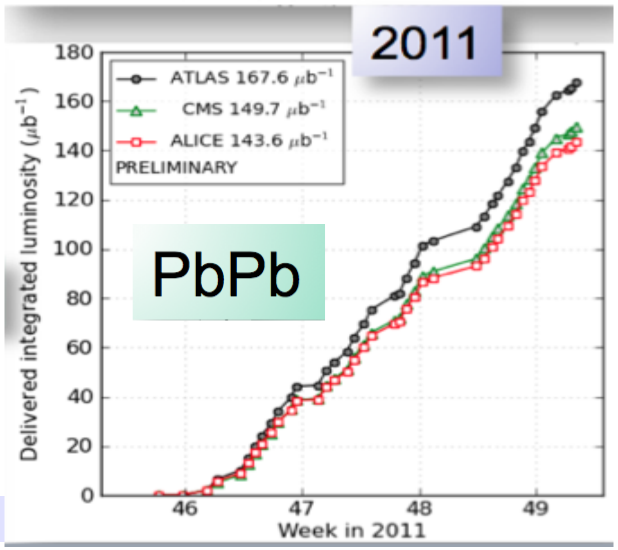
LHC and LHC experiments

Data taking Run 1

- The LHC has been working extremely well
- 8 TeV center of mass energy since 30/03/2008
- Max reached instantaneous luminosity of 7.3 10^{33} cm^2s^{-1} (nominal is 1 10^{34} cm^2s^{-1})

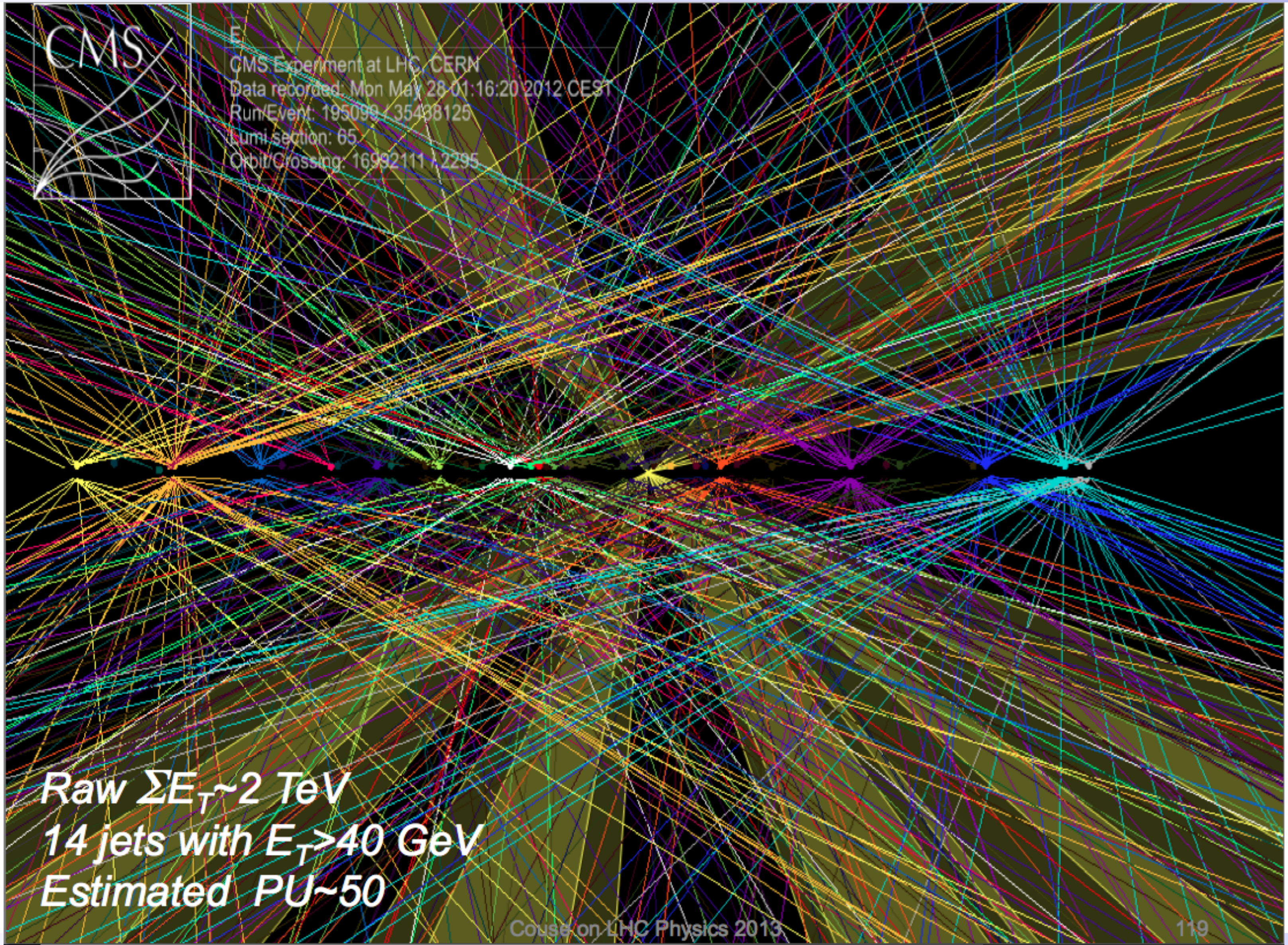






Efficiency: 90% of delivered data used for physics (ATLAS and CMS)

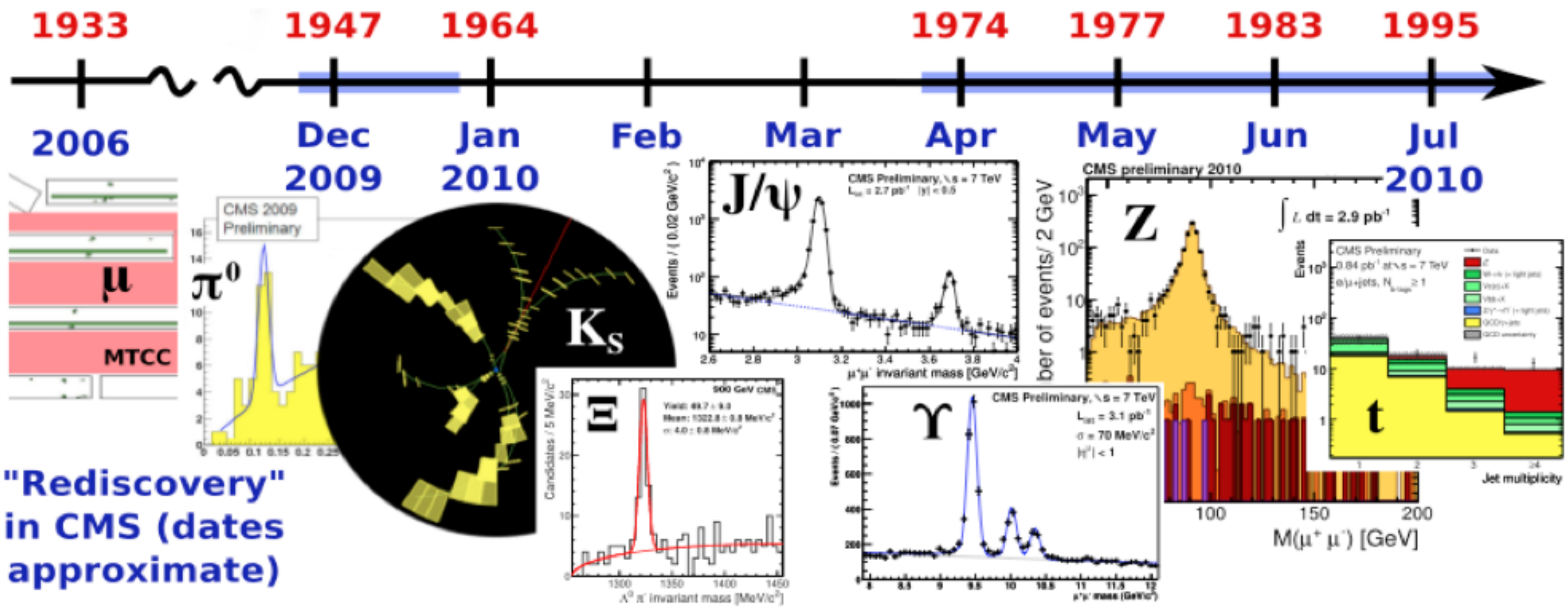
Pileup conditions



ATLAS and CMS

- Study of the Standard Model
  - QCD
  - EWK physics, top physics
  - Higgs boson
- Search for physics Beyond Standard Model
  - Supersymetry
  - New resonances
  - Anything new..

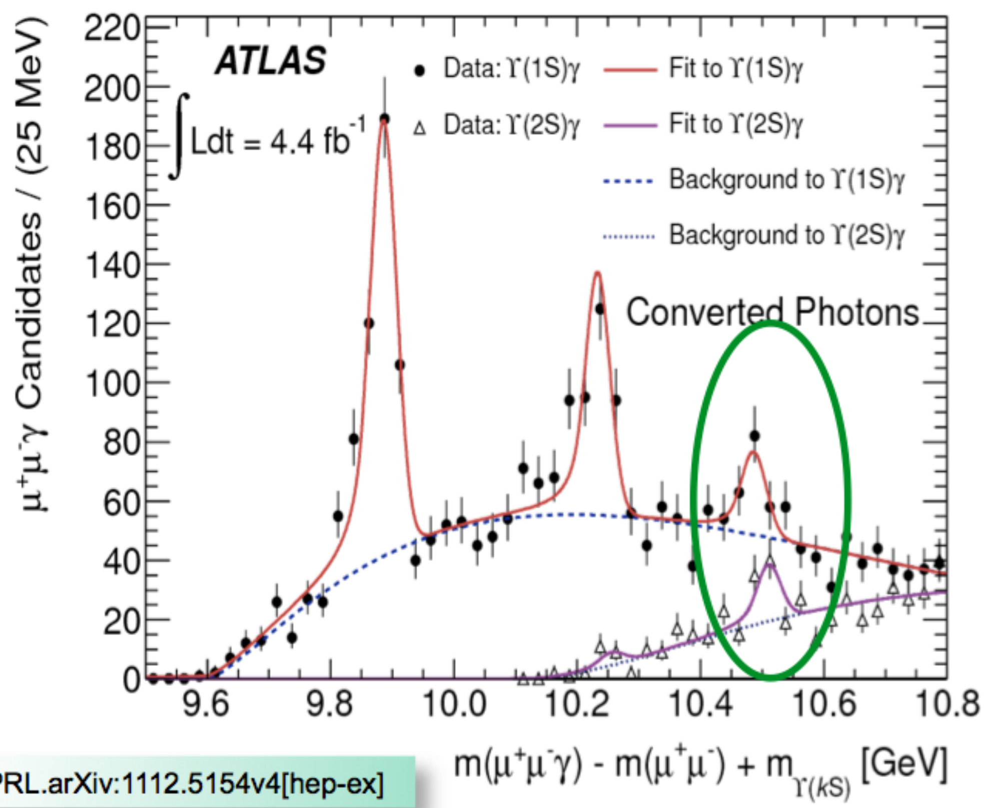
Rediscovery of the SM



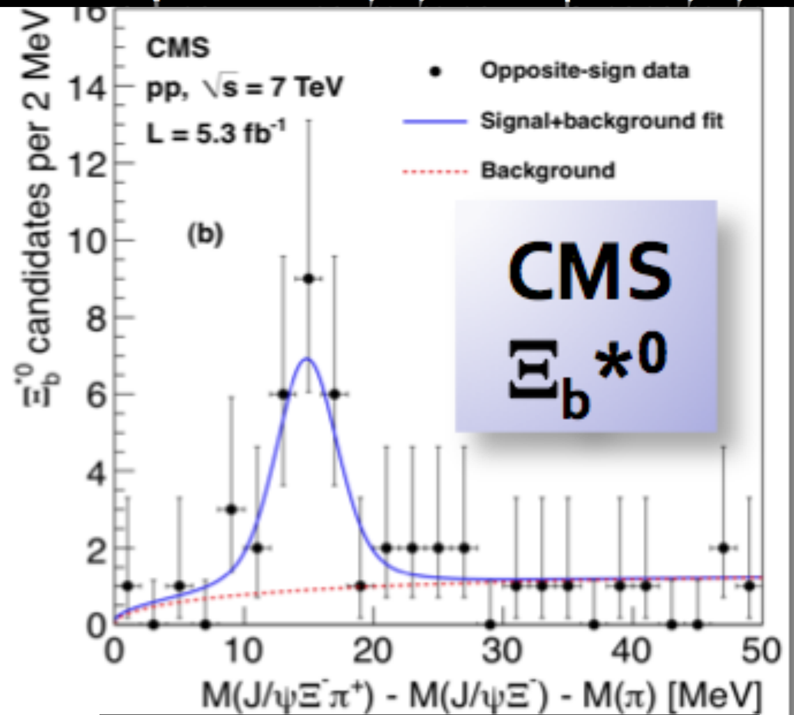
New particles

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

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

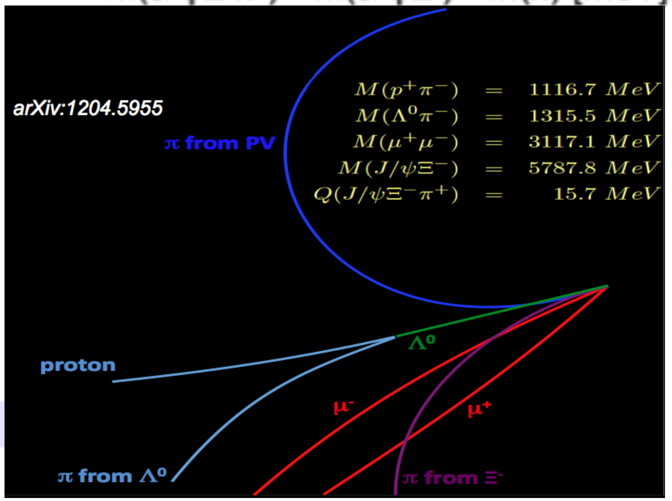


PRL.arXiv:1112.5154v4[hep-ex]

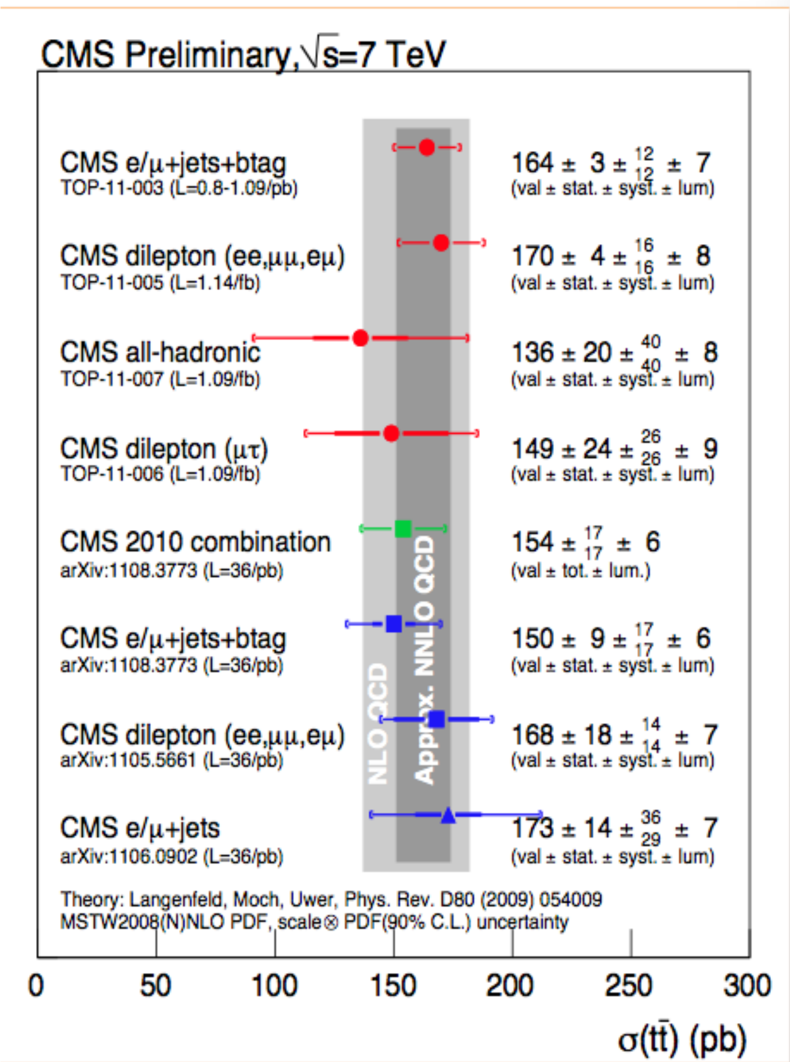


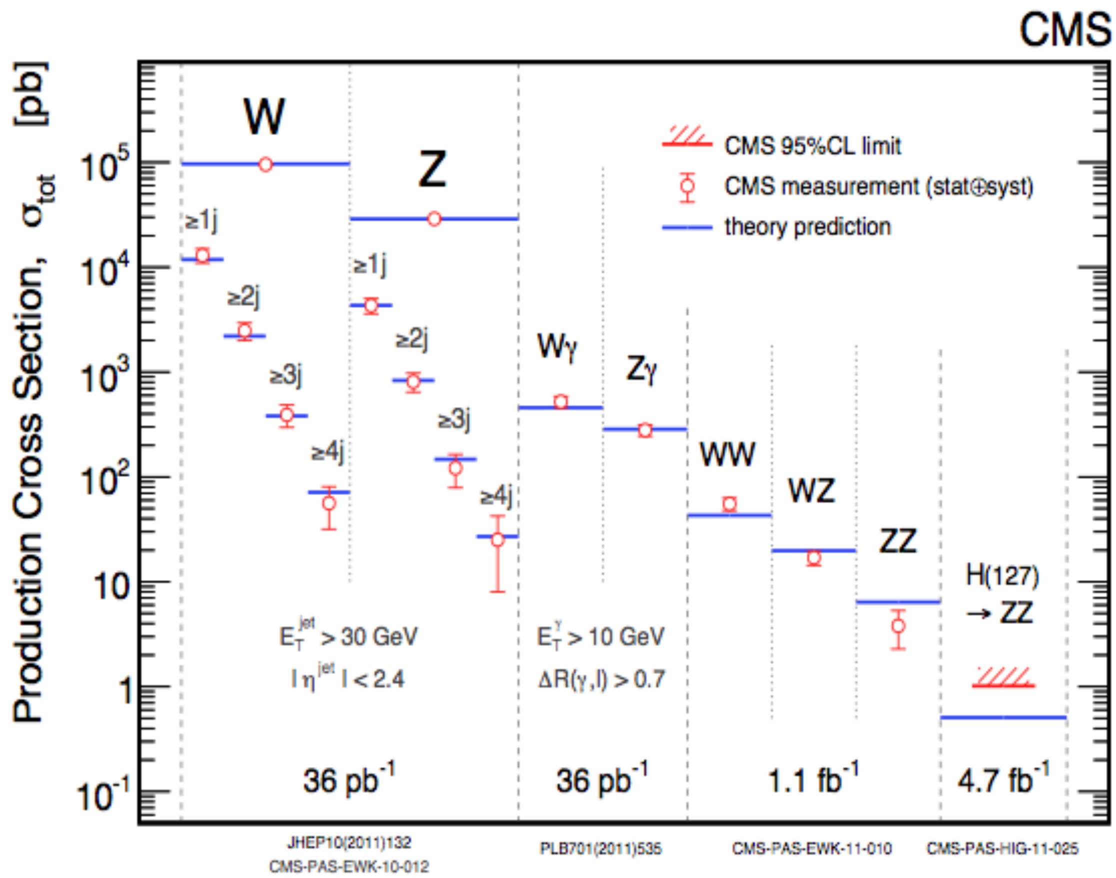
$m\,[X_b(3P)] = 10.530 \pm 0.005\ (\text{stat}) \pm 0.009$

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



Standard Model after 7 TeV run



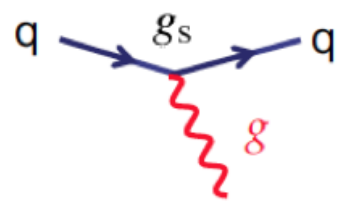


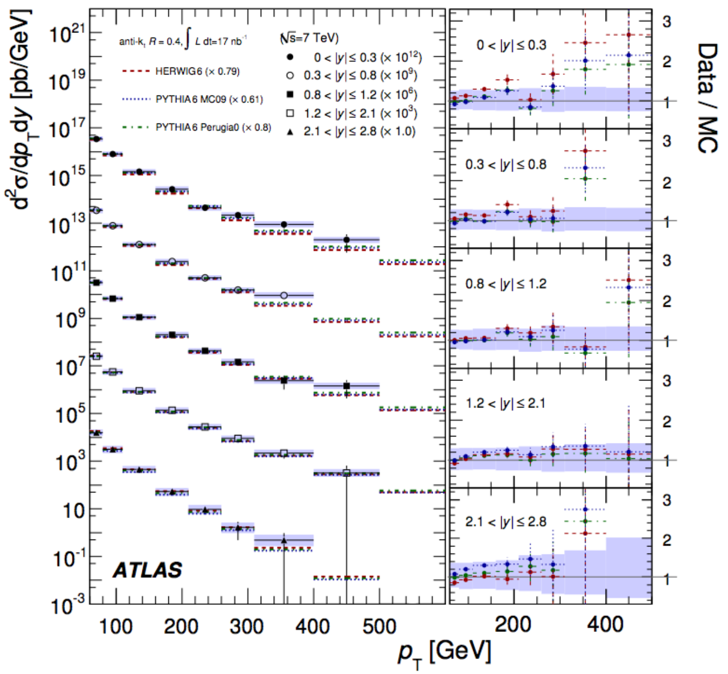
⇒ Lot's of data

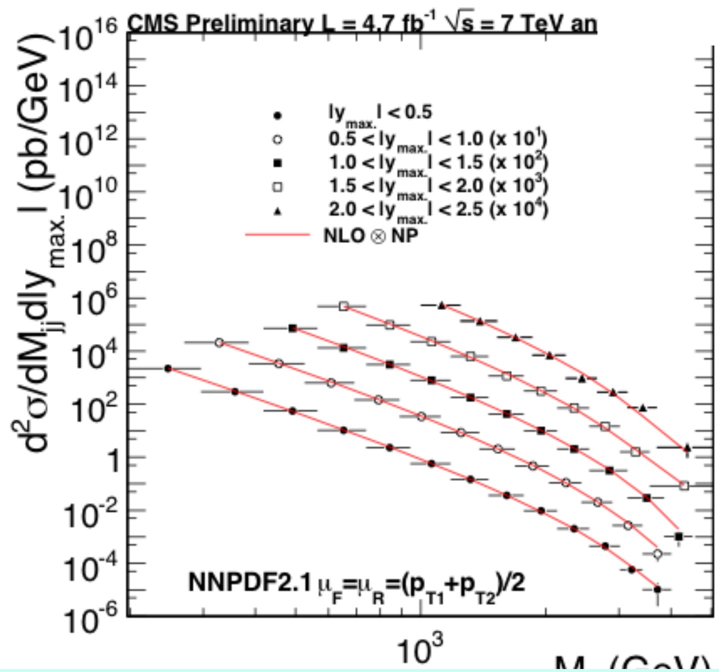
⇒ Impressive agreement

QCD/Jets

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



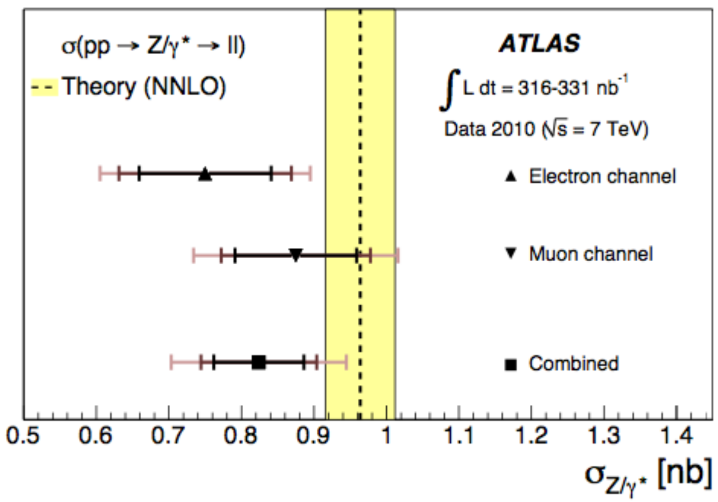


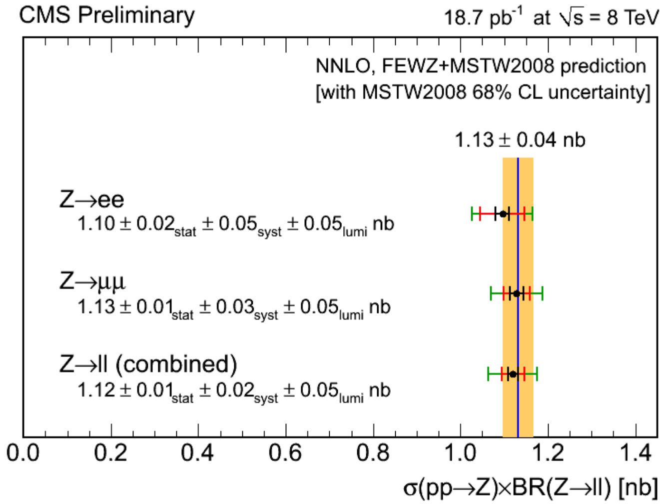


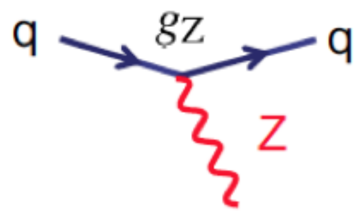
⇒ Excellent agreement, over many decades

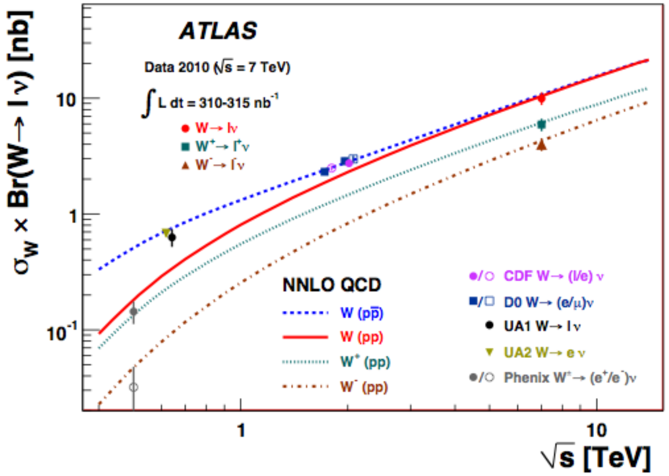
⇒ Some generator/PDFs describe the data better than others: useful for tuning and constraining generators and PDFs

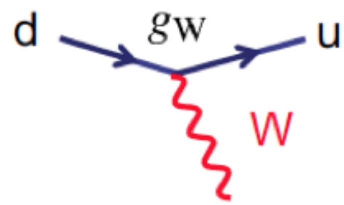
EWK Bosons Production





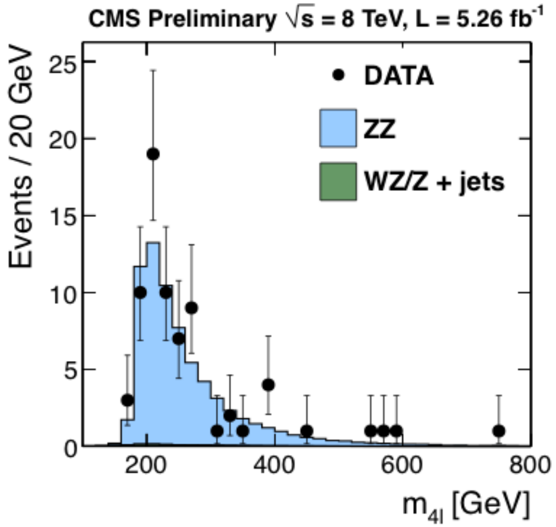


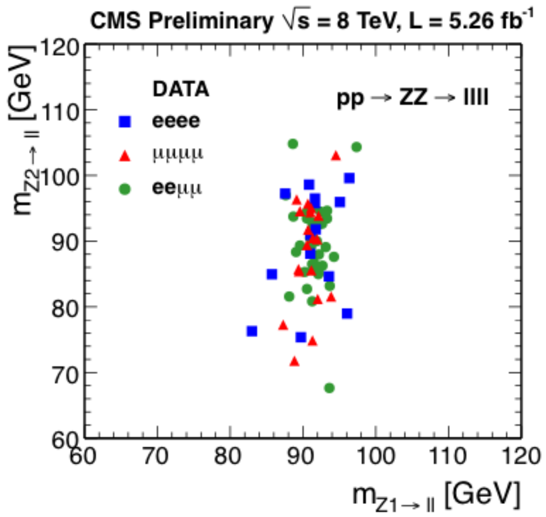


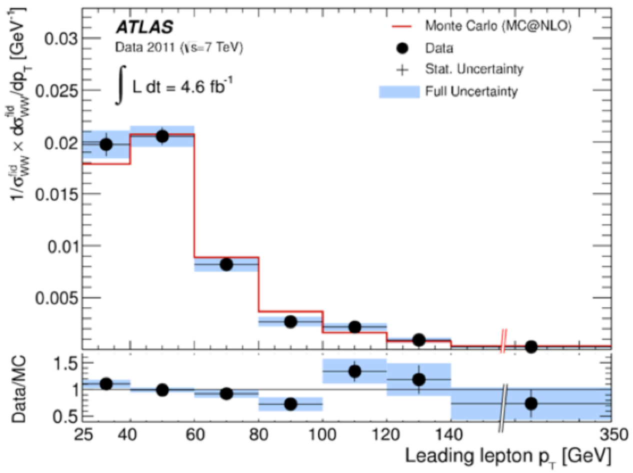


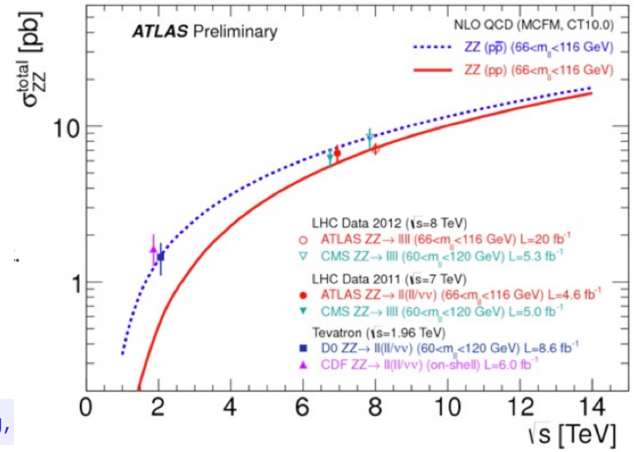
Dibosons: WW, WZ, ZZ

- Rare SM processes, only few events at Tevatron
- Path to discovery of new heavy particles, background to Higgs searches (WW, ZZ)





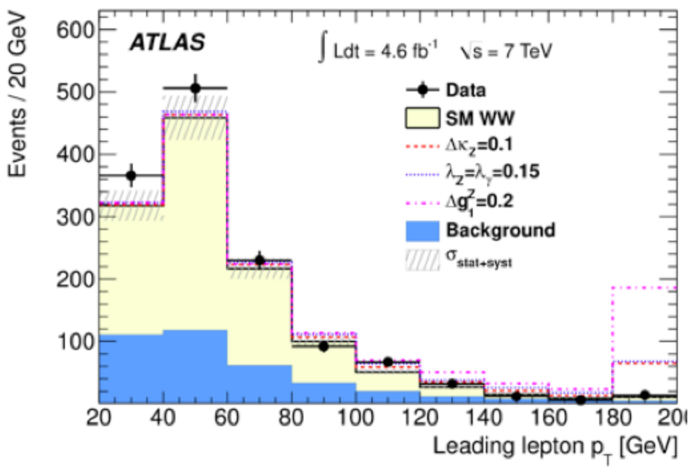


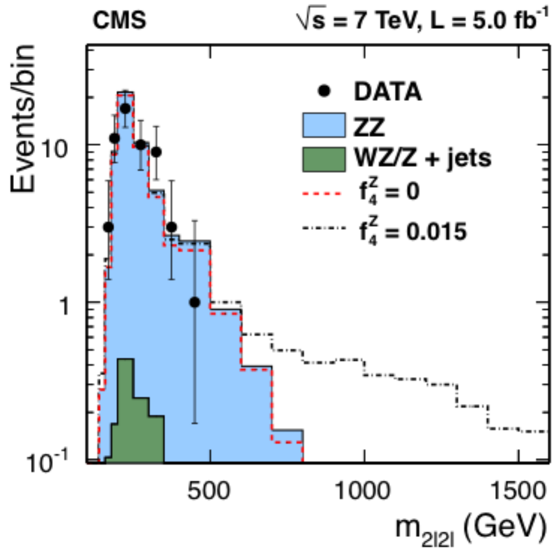


- Results compatible with SM expectations

Dibosons: WW, WZ, ZZ

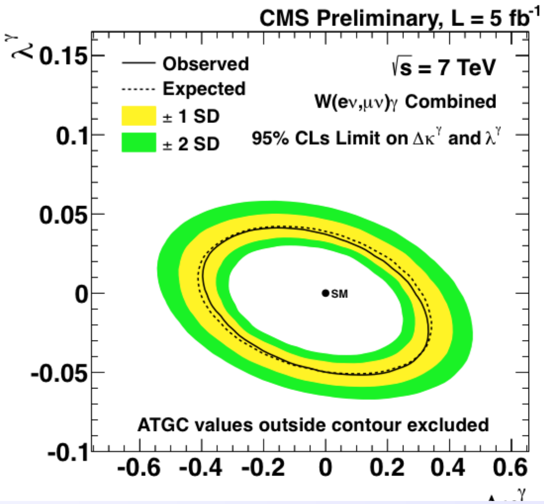
- Search for anomalous triple gauge couplings / deviations wrt Standard Model

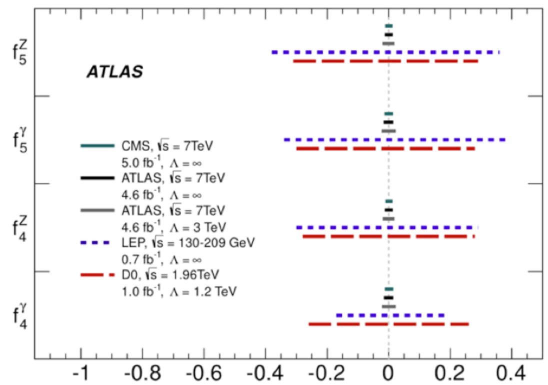




ZZ

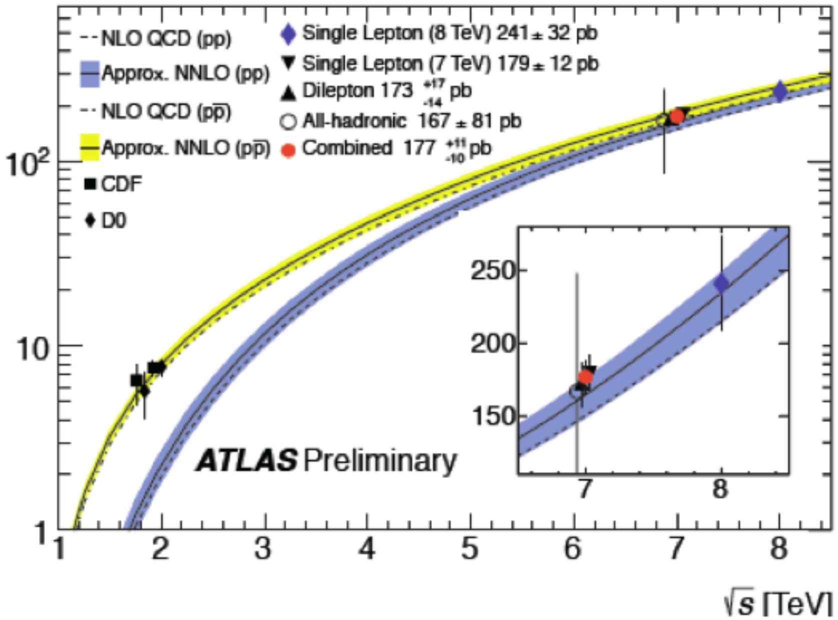
WW





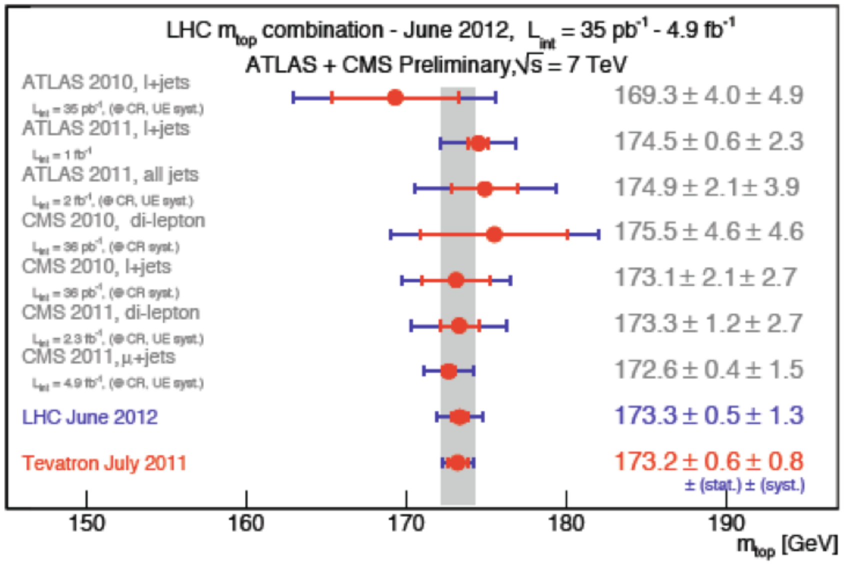
=> Results compatible with SM expectations

Top Physics

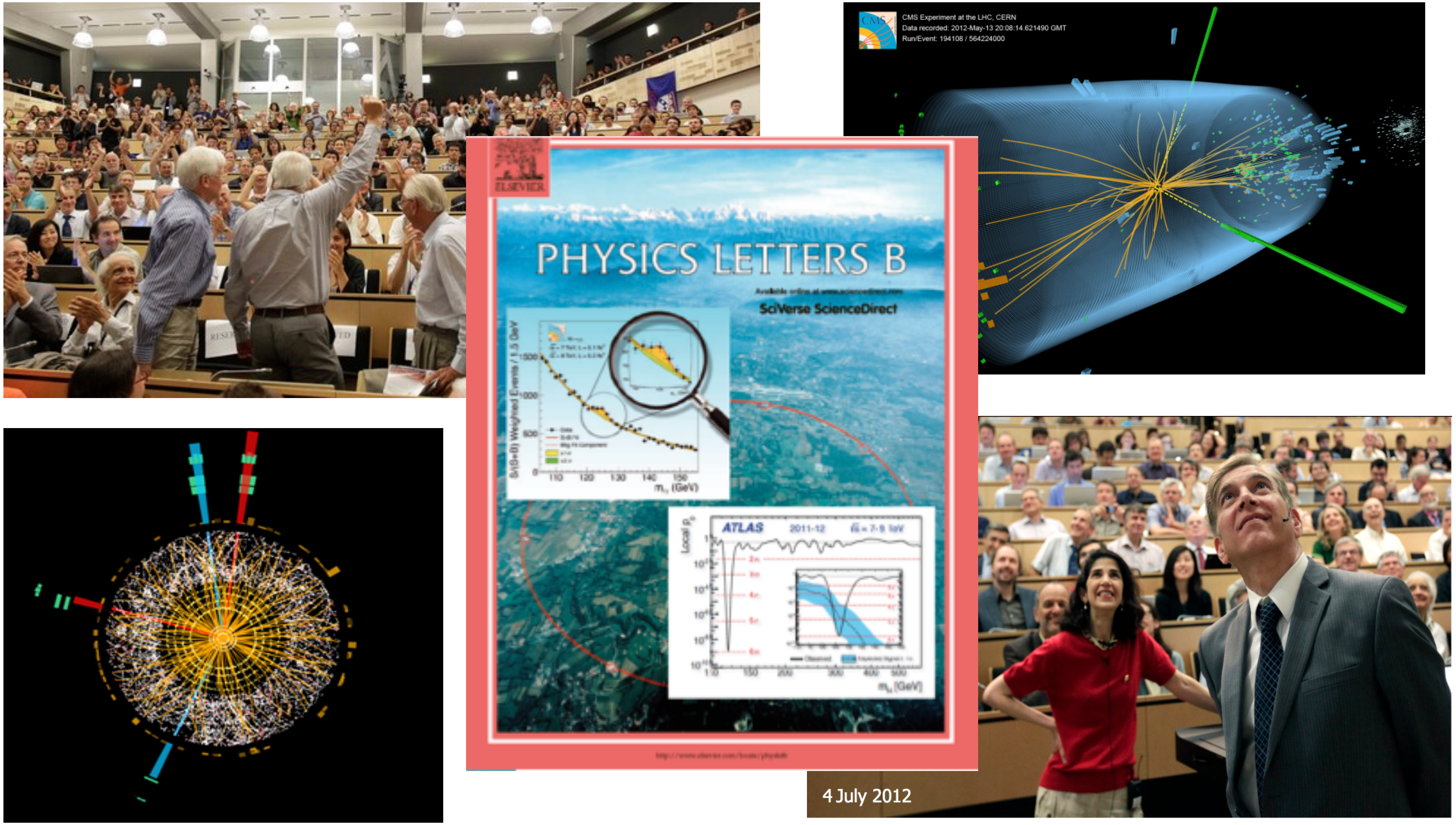


- Good description of production vs center of mass energy, pp vs ppbar

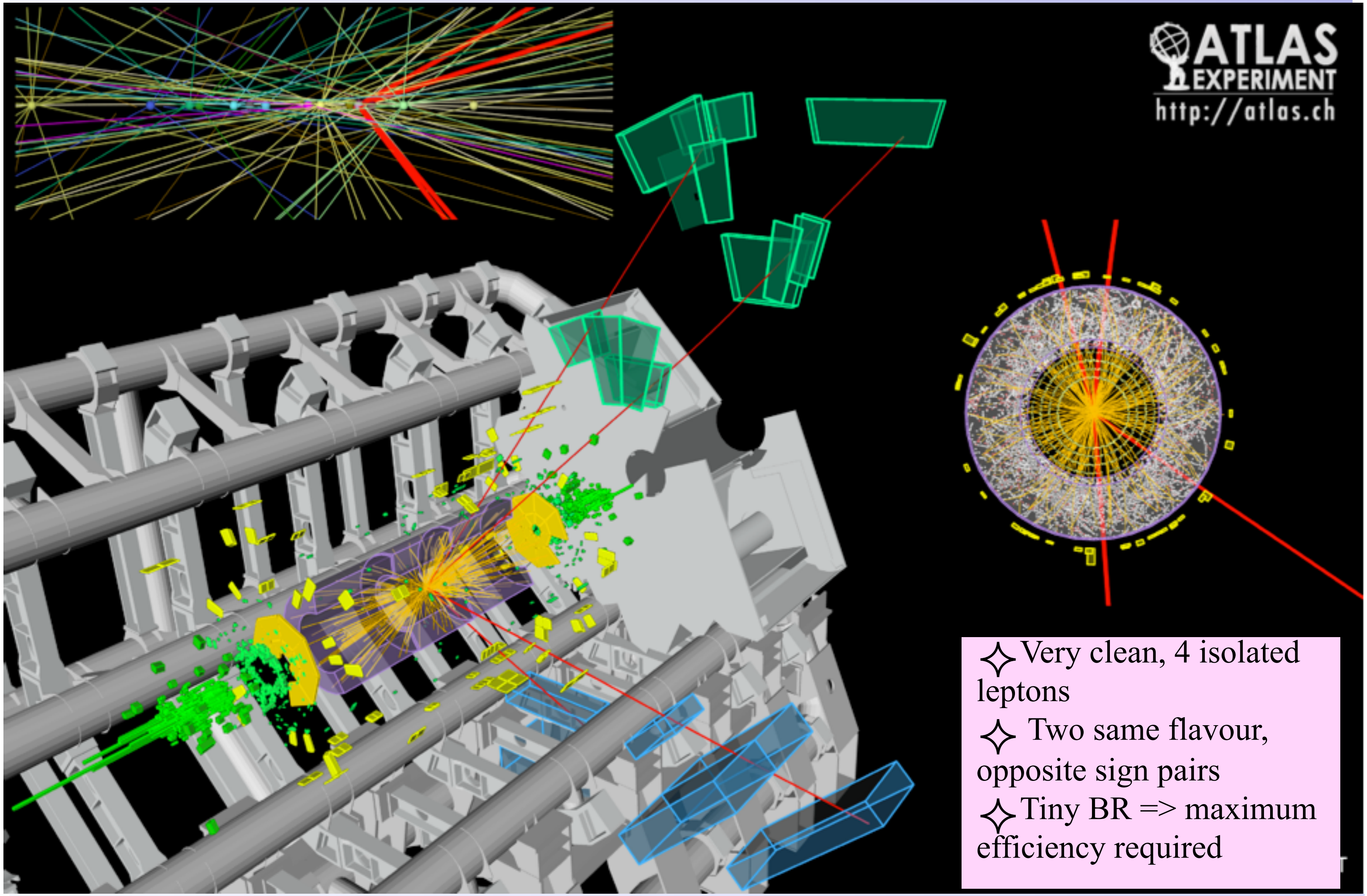
- Precision on top mass close to Tevatron



The Higgs

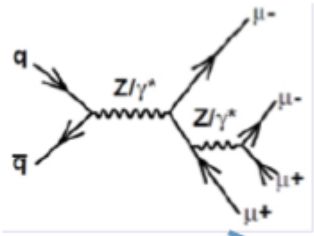

CMS Experiment at the LHC, CERN
Data recorded: 2012-May-13 20:08:14.621490 GMT
Run/Event: 194108 / 564224000
ELSEVIER
PHYSICS LETTERS B
SciVerse ScienceDirect
ATLAS
2011-12
4 July 2012

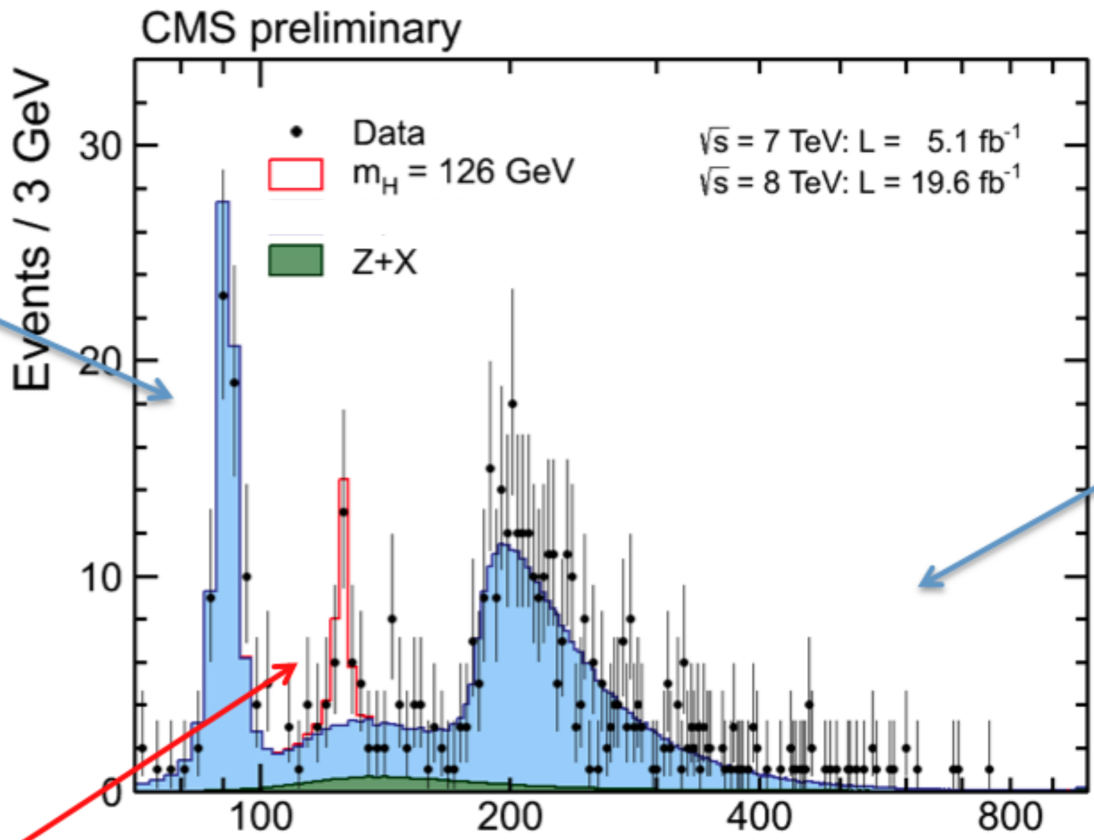
Higgs: H->ZZ->4leptons



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

Higgs:H->ZZ->4leptons





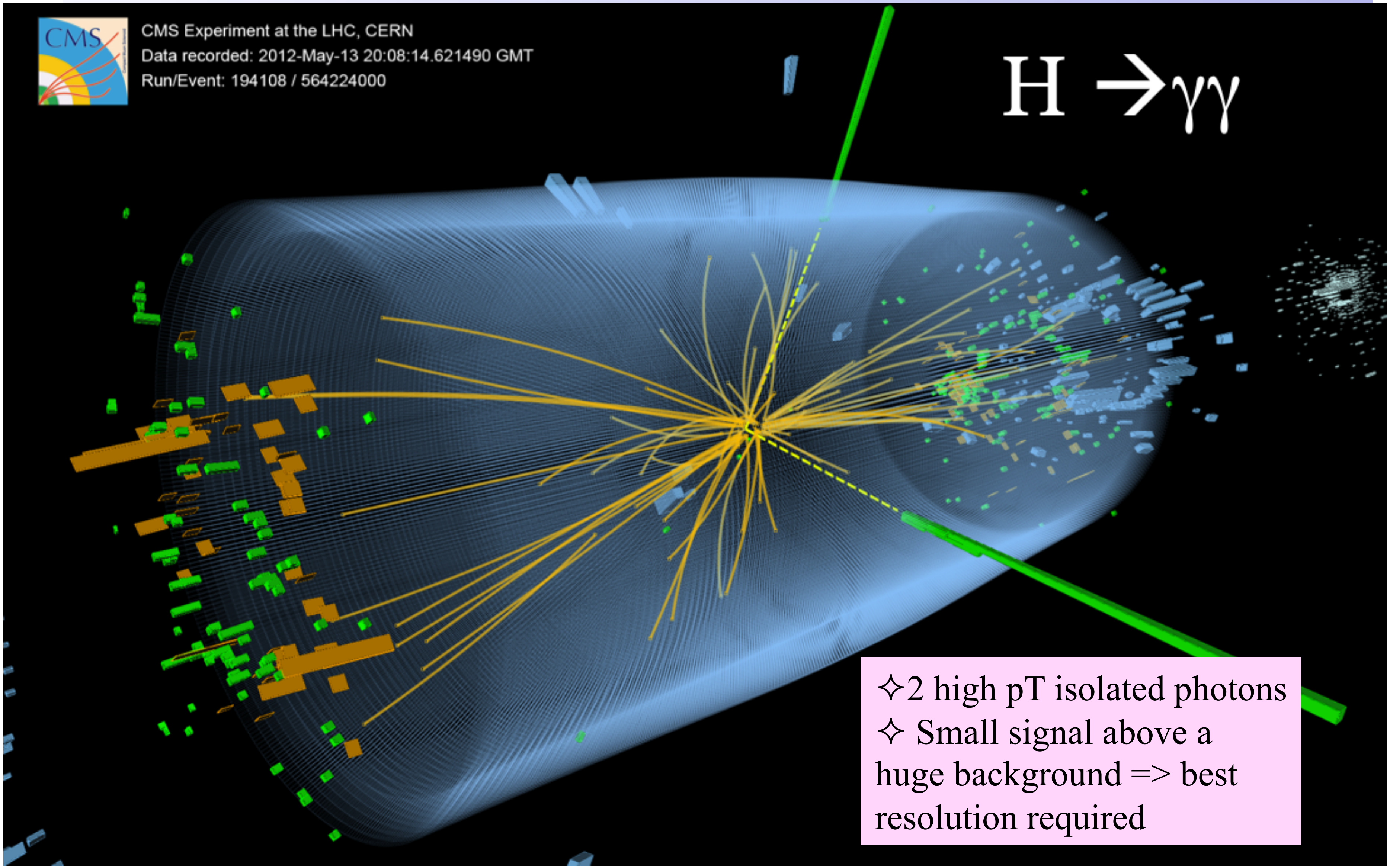
Very good control of the dominant ZZ background

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

Clean signal peak at ~126 GeV

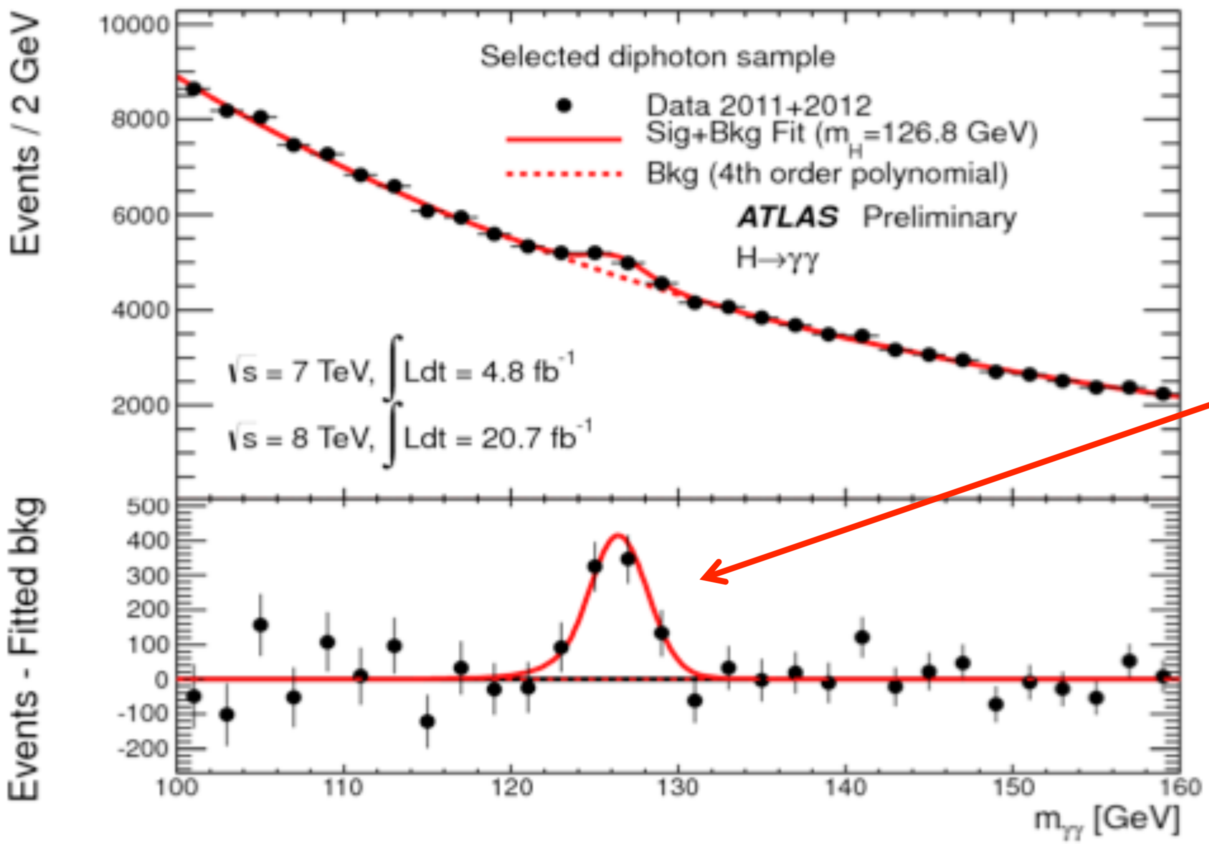
Experiment	Expected	Observed
ATLAS	4.4σ	6.6σ
CMS	7.1σ	6.7σ

Higgs: H->gammagamma



✧2 high pT isolated photons
✧ Small signal above a huge background => best resolution required

Higgs: H->gammagamma

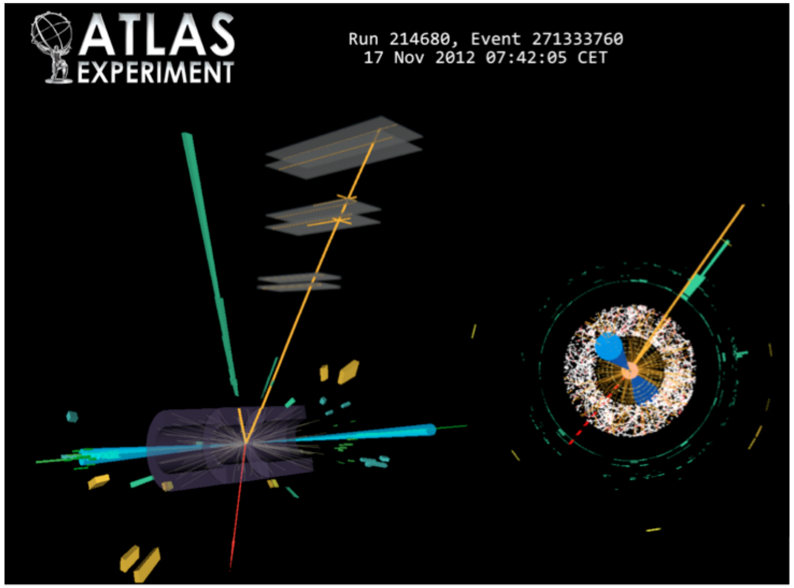


Clean signal peak at ~126 GeV

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

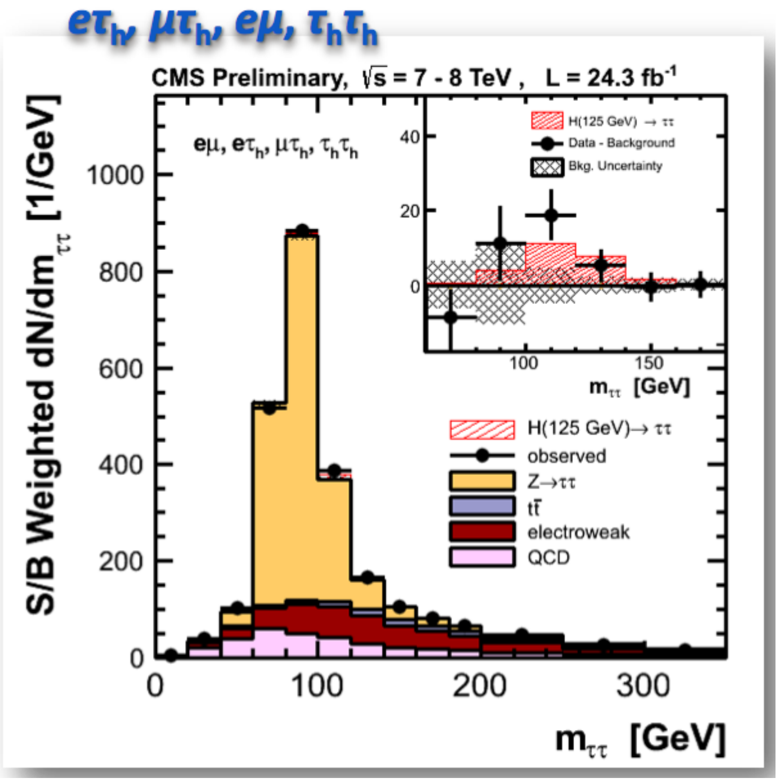
Higgs : Low resolution channels

H->WW->lνlν



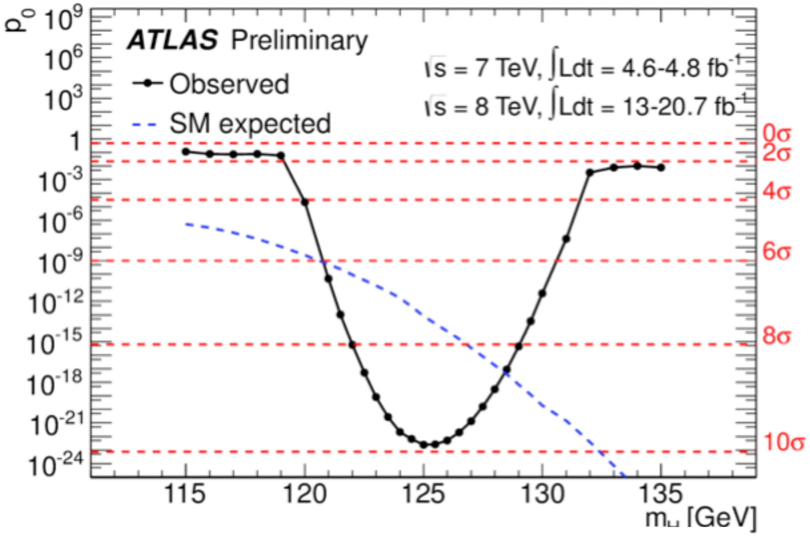
Experiment	Expected	Observed
ATLAS	3.7σ	3.8σ
CMS	5.1σ	4.0σ

H->ττ



2.9σ evidence for H->ττ

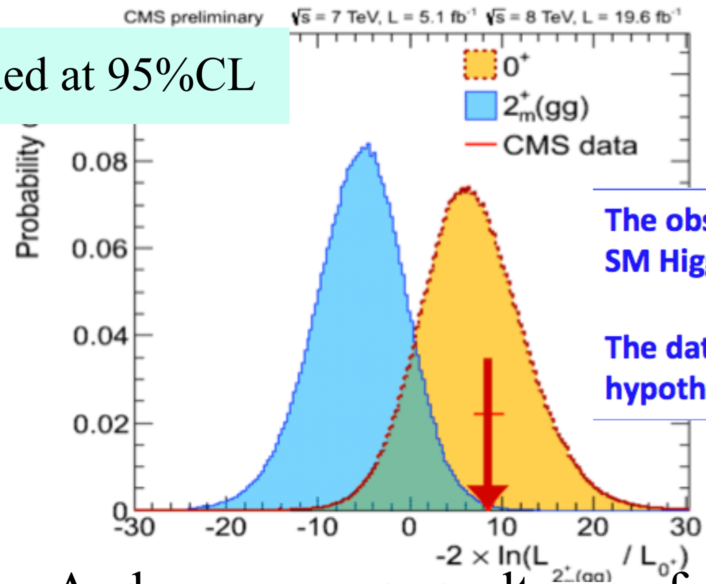
Higgs: properties



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

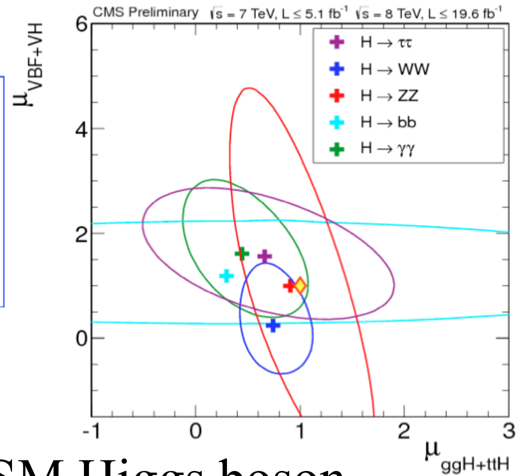
Experiment	mass (γγ+4l)
ATLAS	125.5+-0.2 (stat.) +-0.6 (syst.)
CMS	125.7+-0.3 (stat.) +-0.3 (syst.)

0^- excluded at 95%CL



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

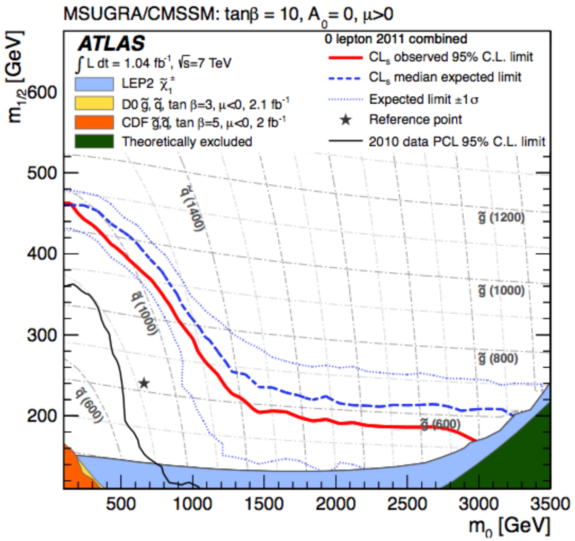
The data disfavours the the 2^+_m(gg) hypothesis with a CLs value of 0.6%

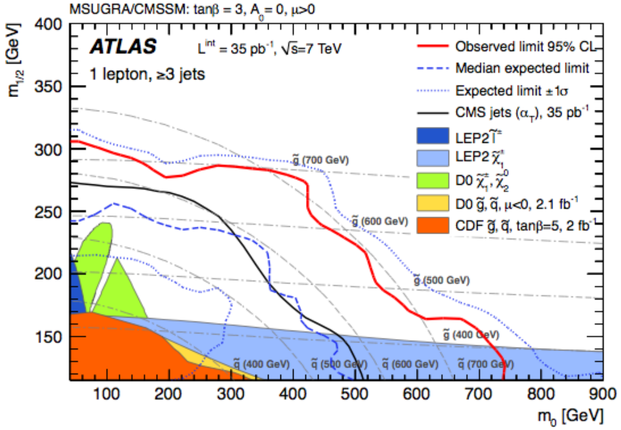


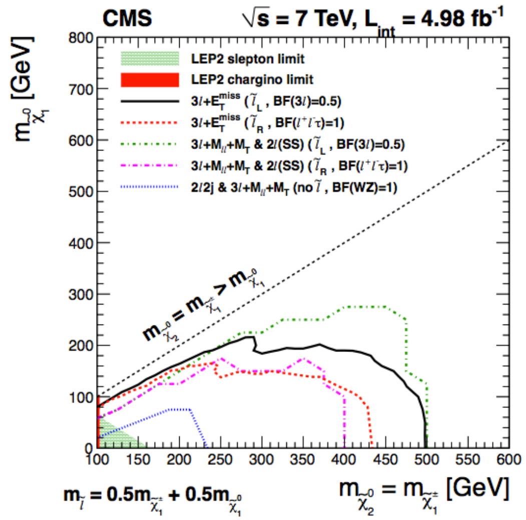
And many more results .. so far all consistent with a SM Higgs boson

Beyond Standard Model

Unification of interactions: SUSY?

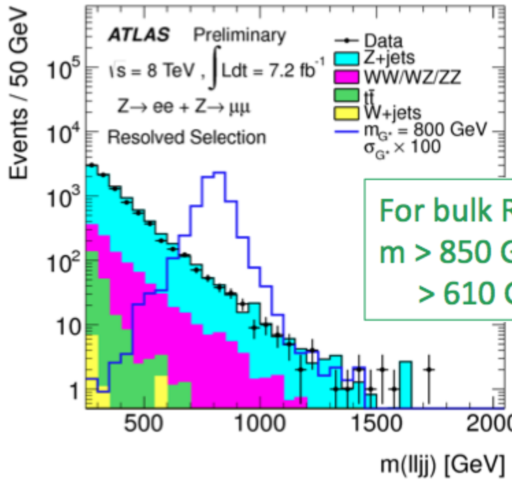






New resonances, new symmetries?

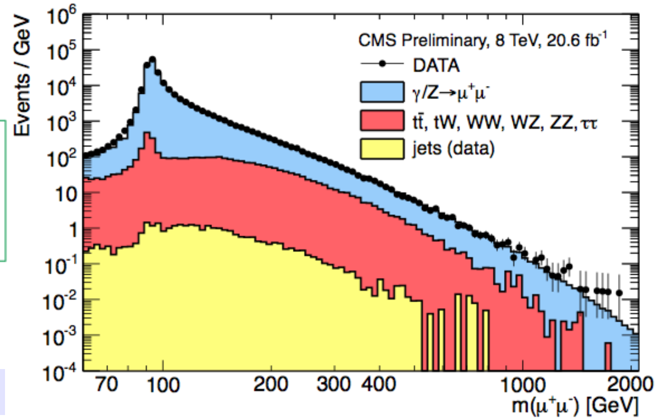
No sign yet..



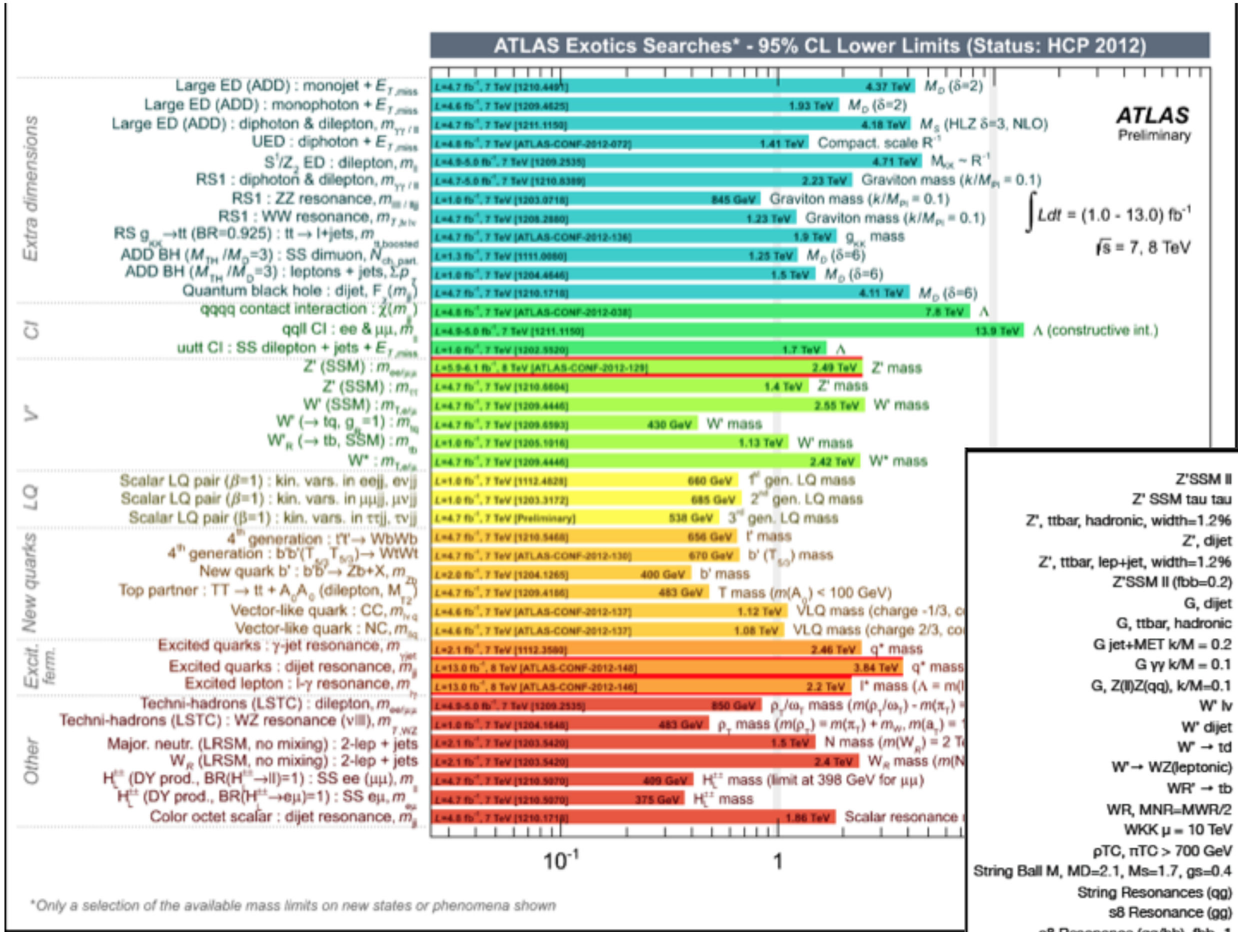
For bulk RS gravitons

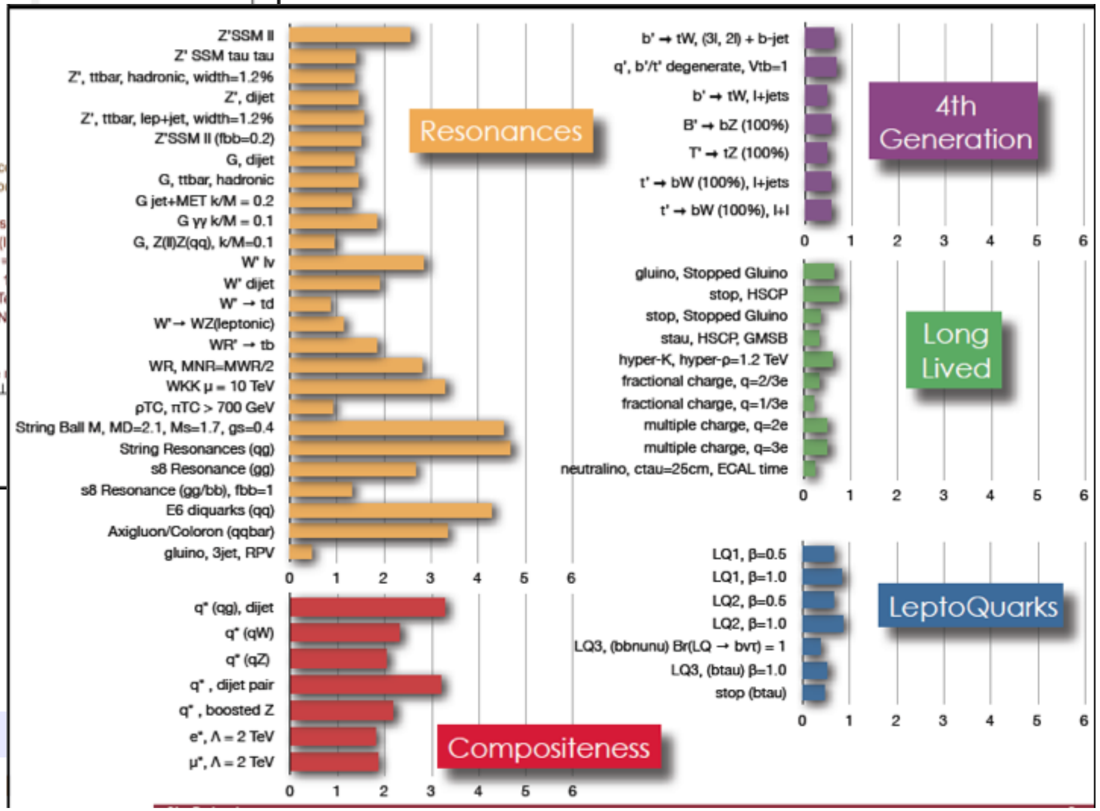
$m > 850$ GeV ($k/M_{Pl} = 1.00$) [ATLAS]

> 610 GeV ($k/M_{Pl} = 0.50$) [CMS]



Beyond Standard Model



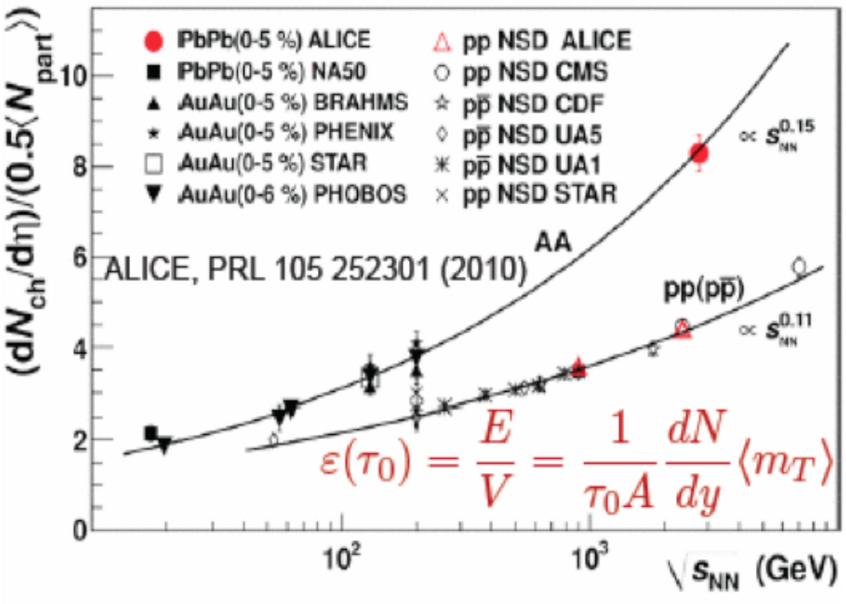


- Searches by ATLAS and CMS for new phenomena are probing the TeV scale
- The SM has proved incredibly resilient
  - Searches at the LHC have not found evidence for BSM physics…yet!

ALICE
(+CMS+ATLAS)

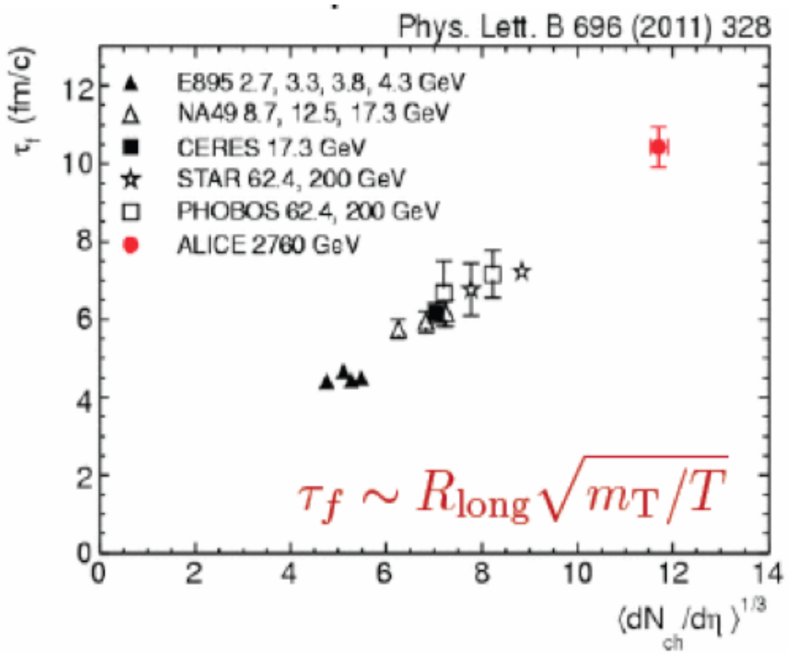
- Study the Quark Gluon Plasma
  - Charged particle production, soft QCD
  - Jet quenching
  - Elliptic flow
  - Quarkonia

Energy density, volume, lifetime



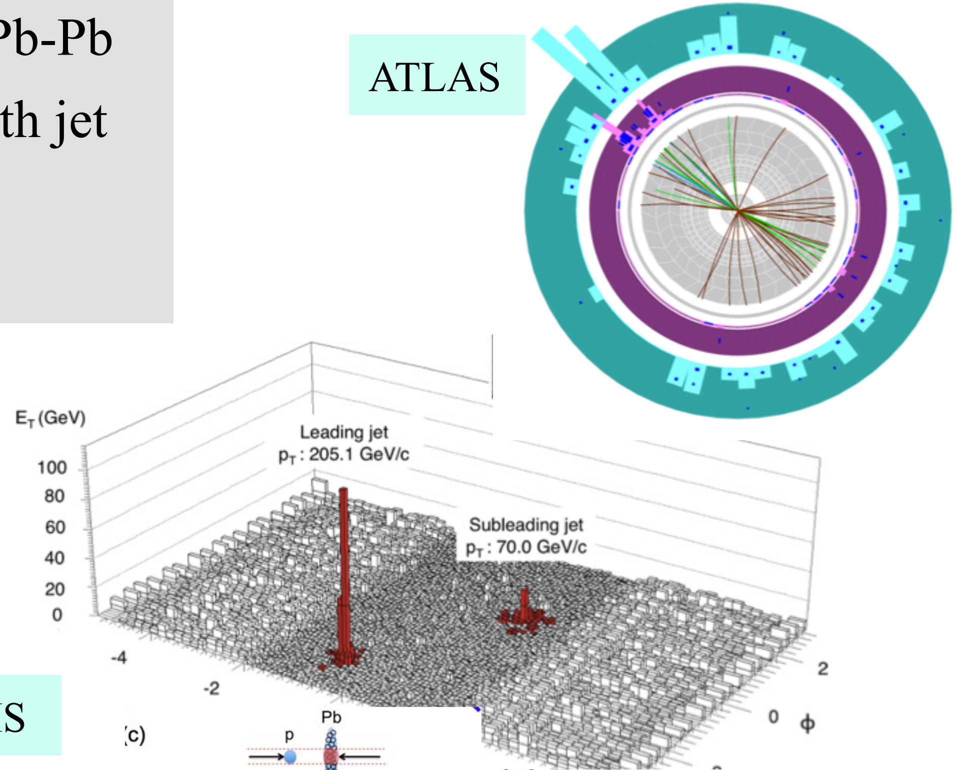
- Energy density: ~8 GeV/fm3 (3x RHIC)
- Lifetime: ~10 fm/c (1.2x RHIC)

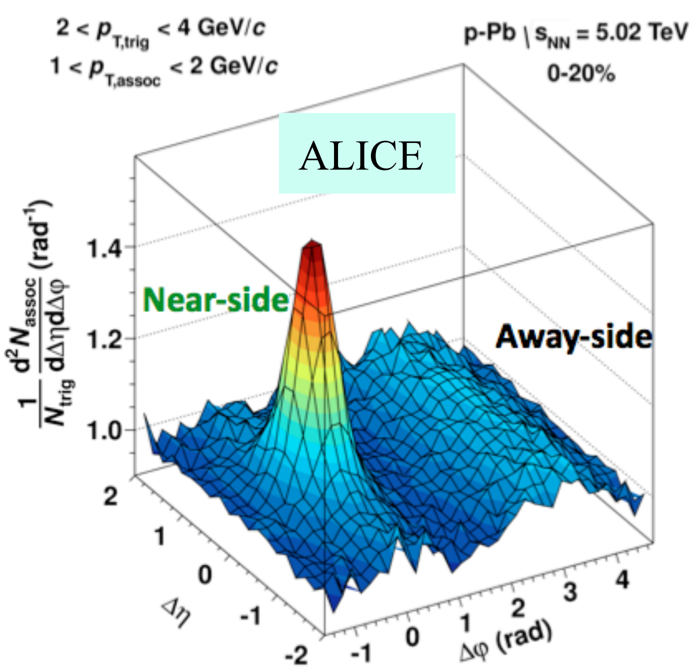
- Volume: ~4800 fm3 (2x RHIC)
- Temperature: ~300 MeV(1.3x RHIC)

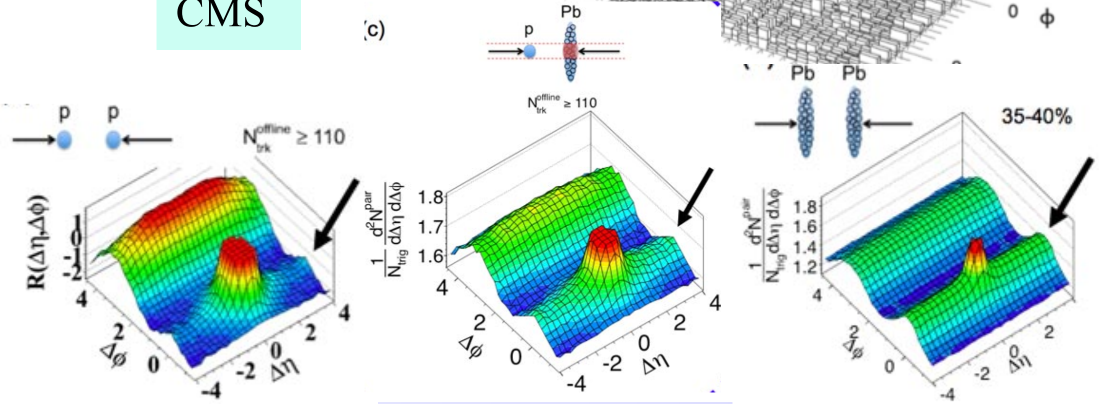


Particle correlations, jet quenching

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

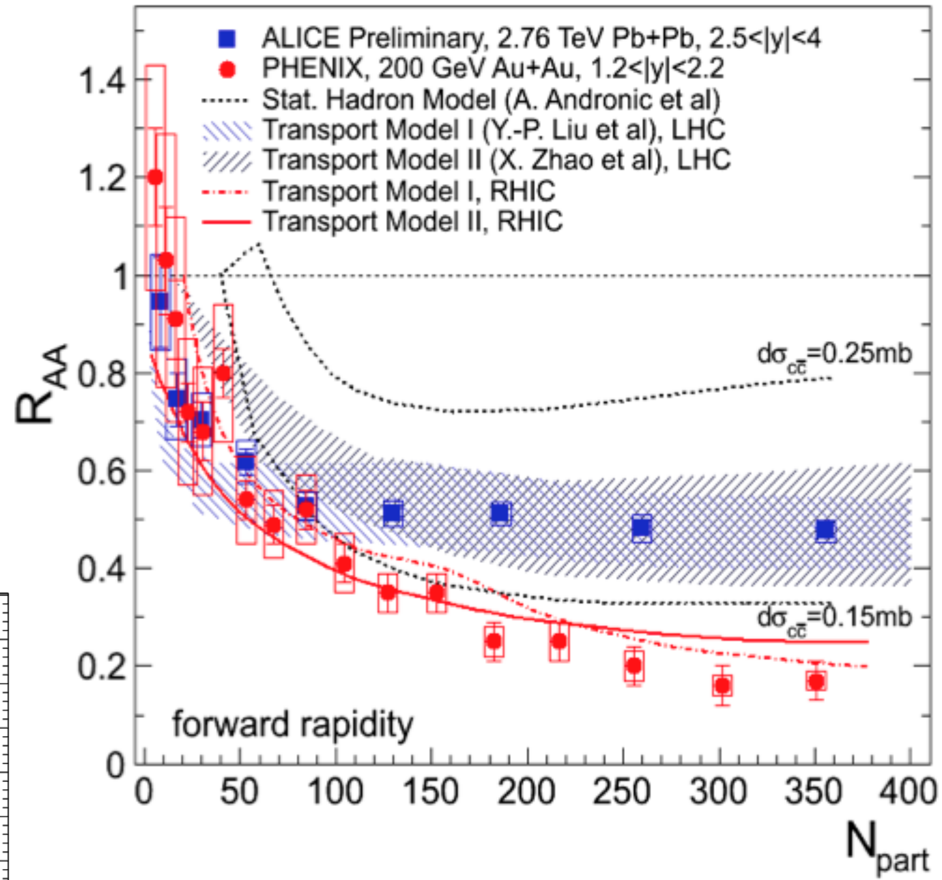


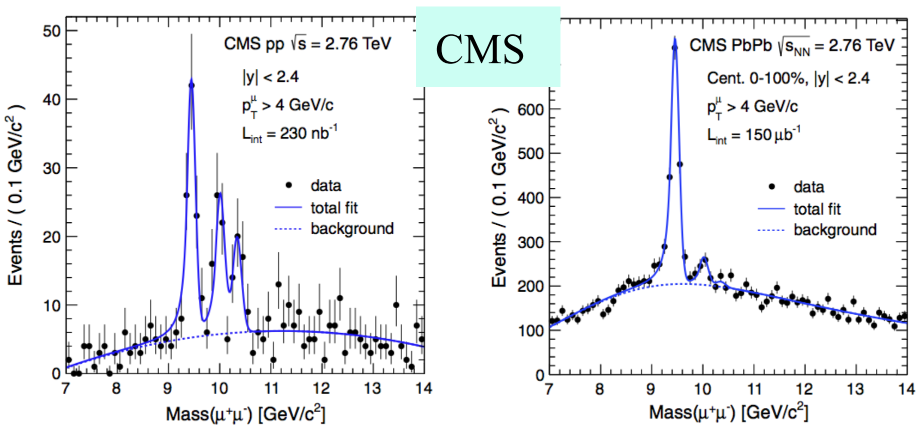




Color screening in QGP

- J/Psi and Y 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?



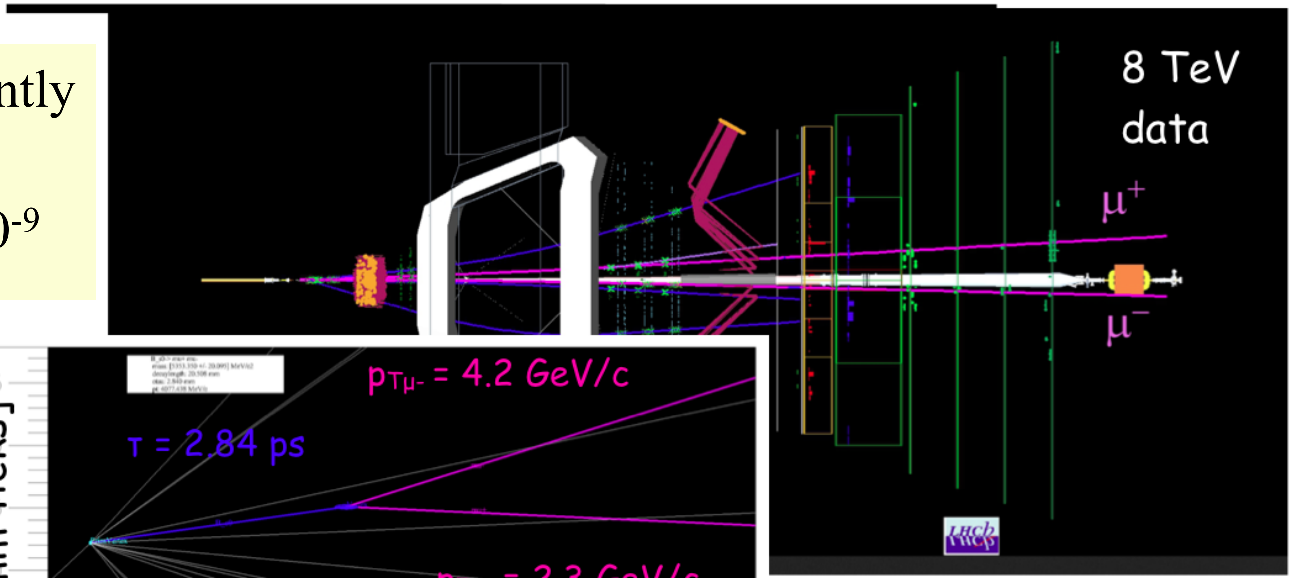


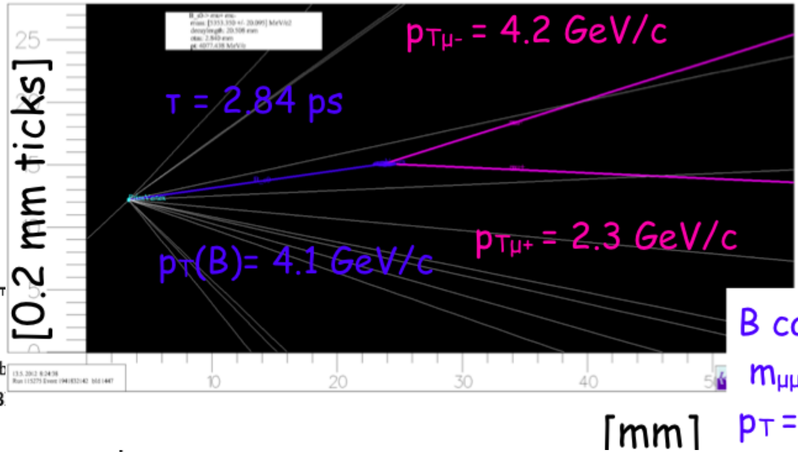
LHCb

- Studying the heavy flavour sector
    - Observe the rarest decays
    - Understand CP violation, matter/anti-matter asymmetry
    - Find indirect evidence for new physics at very high scale (if any)
    - Discover new particles

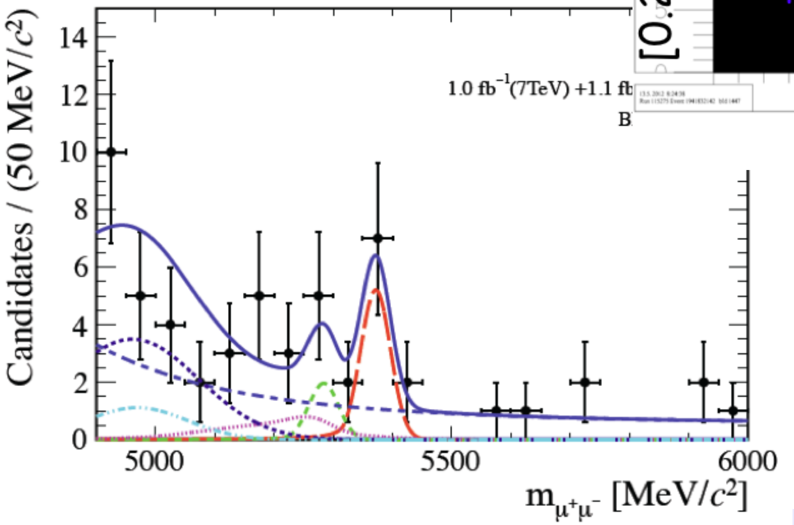
LHCb: Bs->mumu

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





B candidate:
$m_{\mu\mu}$ = 5353.4 MeV/c^2 BDT = 0.826
p_T = 4077.4 MeV/c t = 2.84 ps

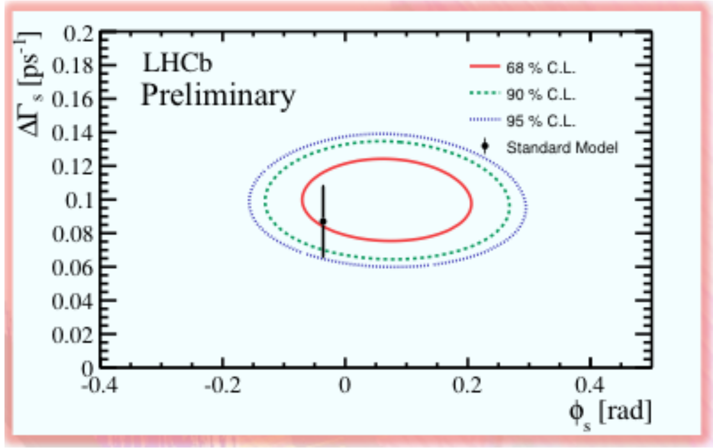


$$BR = (3.2^{+1.4}_{-1.2}\,(stat)\,^{+0.5}_{-0.3}\,(syst))\times 10^{-9}$$

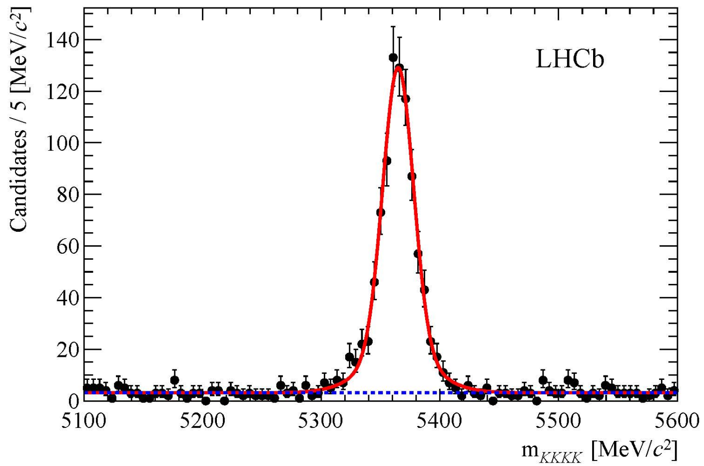
SM expectation
$(3.54\pm 0.30)\times 10^{-9}$

LHCb: CP violation

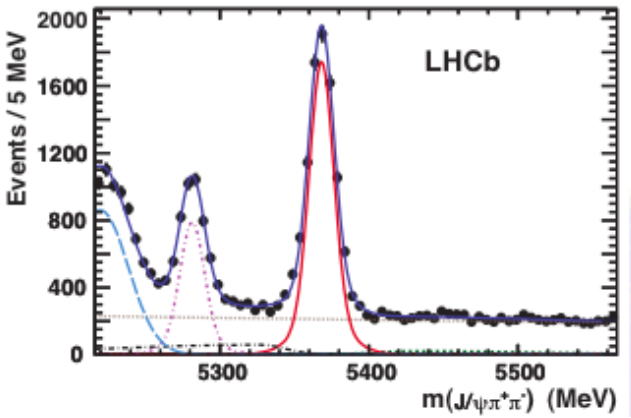
$B_s \rightarrow J/\psi\phi$: Results



- First measurement of the CP-violating phase in hadronic B_s->$\phi\phi$ decays



$B_s \rightarrow J/\psi\pi^+\pi^-$



- Most accurate measurements of CP violation in the B_s system

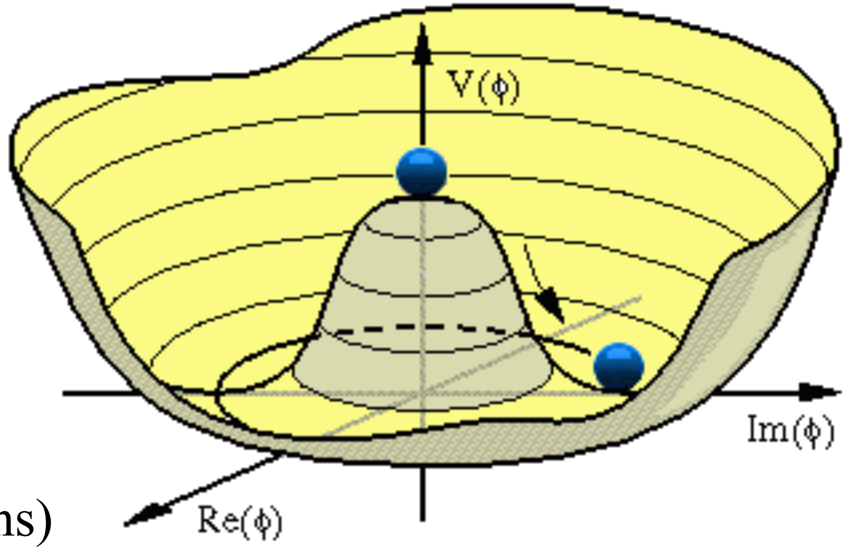
Conclusions and Outlook

- The 2010-2012 run has been a very exciting period
  - The machine and detectors have been working very well
  - Plenty of physics results and major discovery of the awaited Higgs boson
- A new period will start in 2015 after LS1
  - Precise measurement of the Higgs boson properties
    - Already started but will benefit from much more statistics
    - Is it the Standard Model Higgs boson?
  - Search for Beyond Standard Model physics
    - How to stabilize the Higgs mass? Unification at high energy? Supersymmetry? Reasons for 3 families? ..?)
  - More on QGP, heavy flavour and CP violation
- Much more luminosity, much more pileup
  - New Challenge for the computing and the Grid

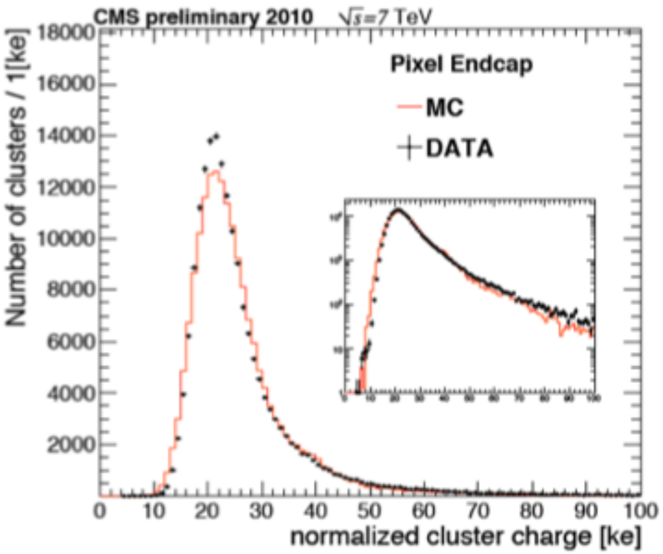
Backup

The Higgs mechanism

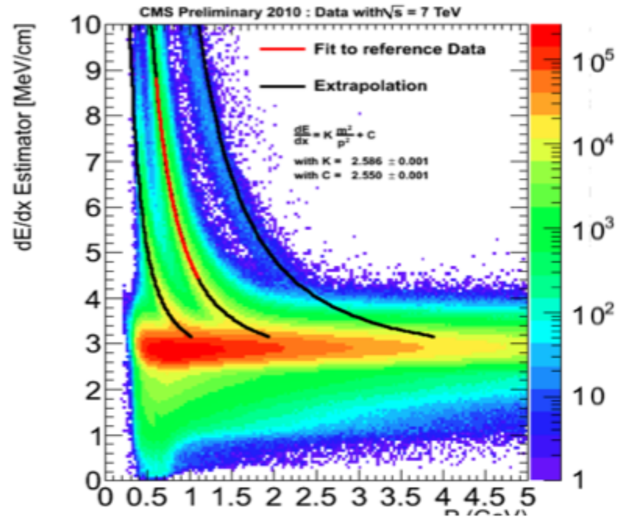
- The way to reconcile gauge symmetry and the existence of massive vector bosons is called the **spontaneous symmetry breaking**
- In the Higgs mechanism, the potential has a rotational symmetry but the ground state do not have that symmetry
  - Mexican hat shape of the potential
- As the a consequence the weak W and Z bosons become massive and a new scalar neutral particle appears: this is the Higgs boson
- It turns out that this mechanism also allows to introduce mass for fermions (quarks and leptons)
  - Implying that the mass of the fermions is proportional to their coupling to the Higgs field
- This is why we often say that the Higgs field "generates" or "gives" masses



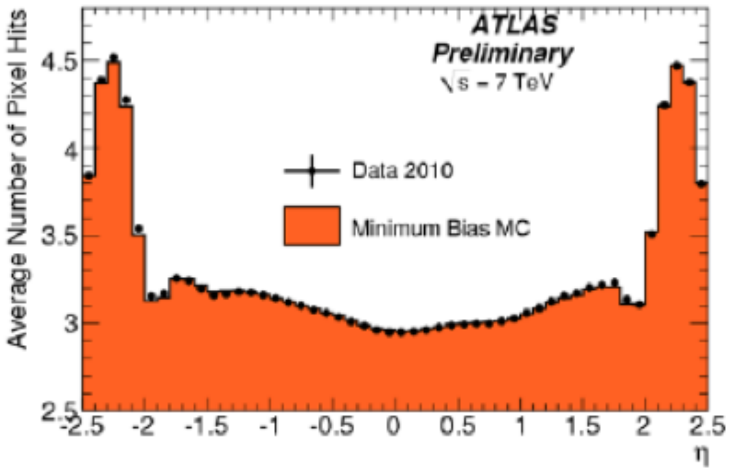
Tracking performances



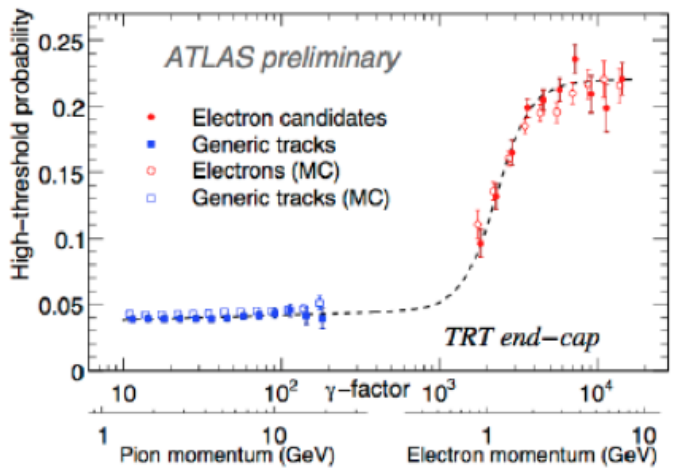
de/dx in the strips



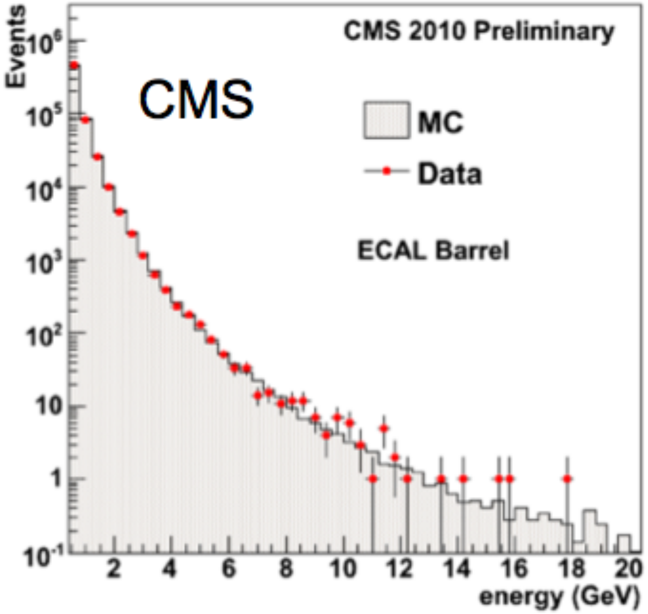
Pixel Det.

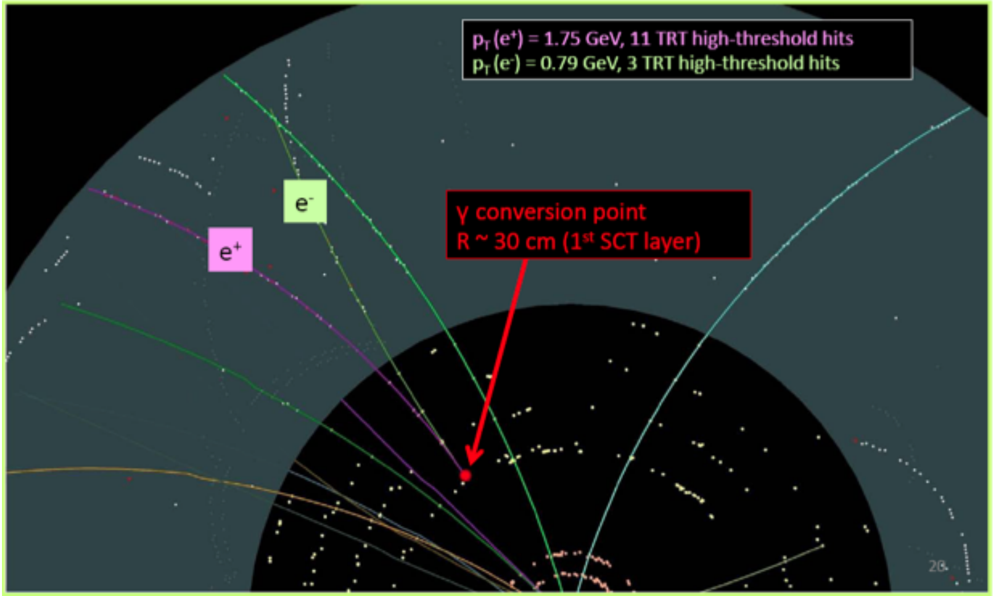


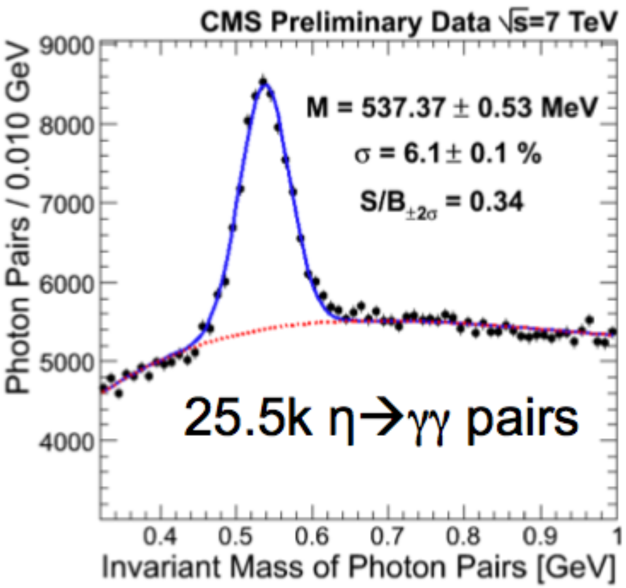
TRT Det.

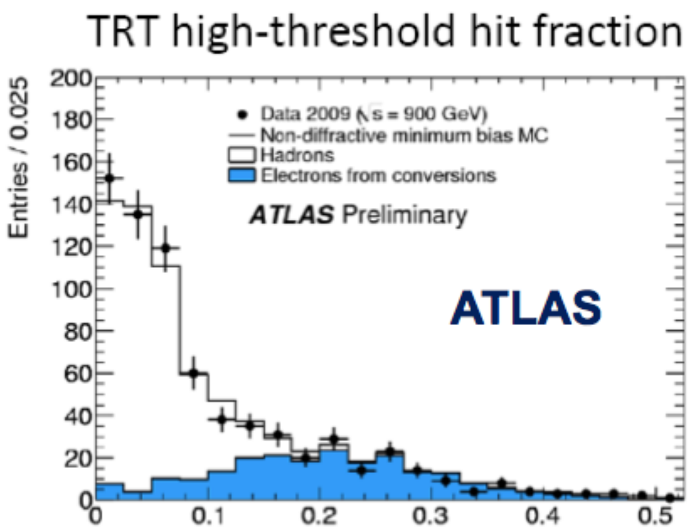


Photons and electrons

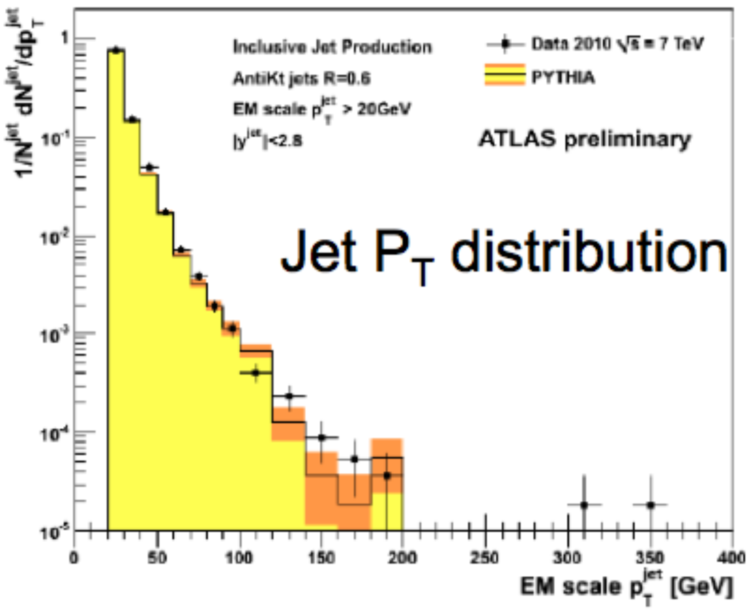




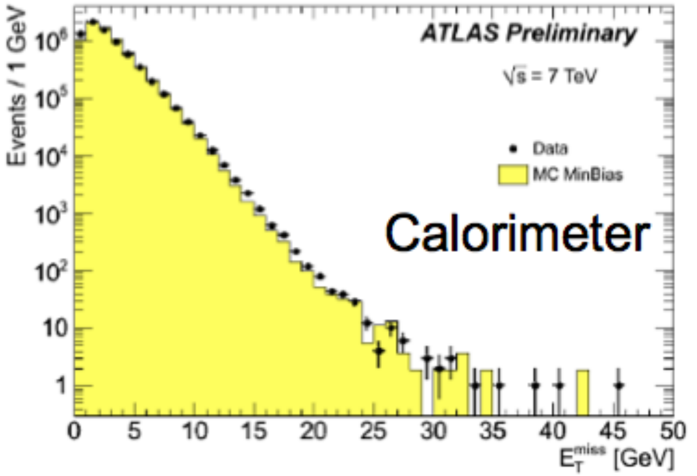


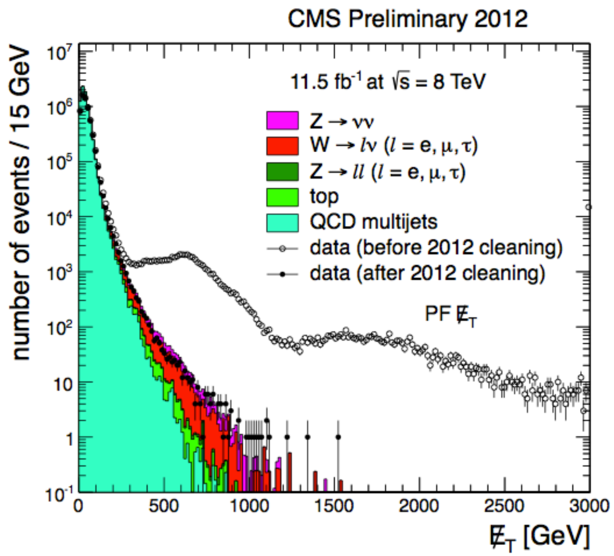


Jets and MET



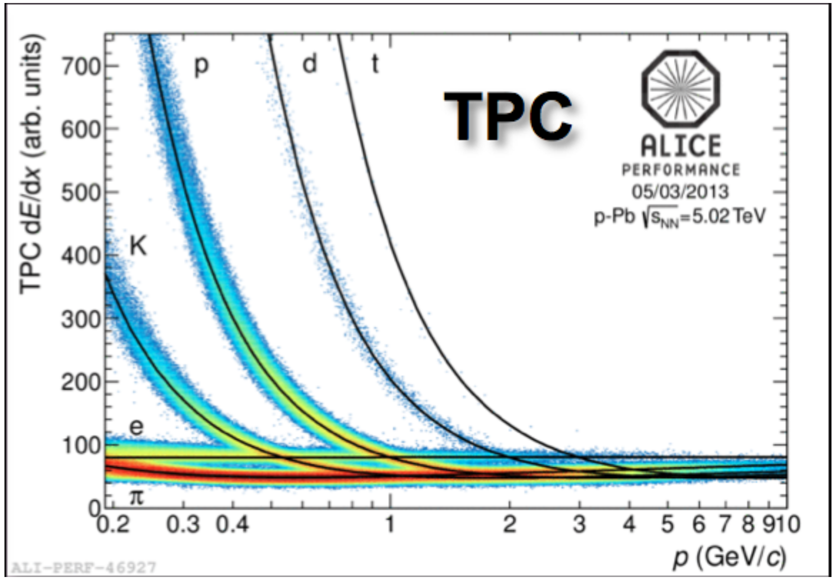
Missing Transverse Energy





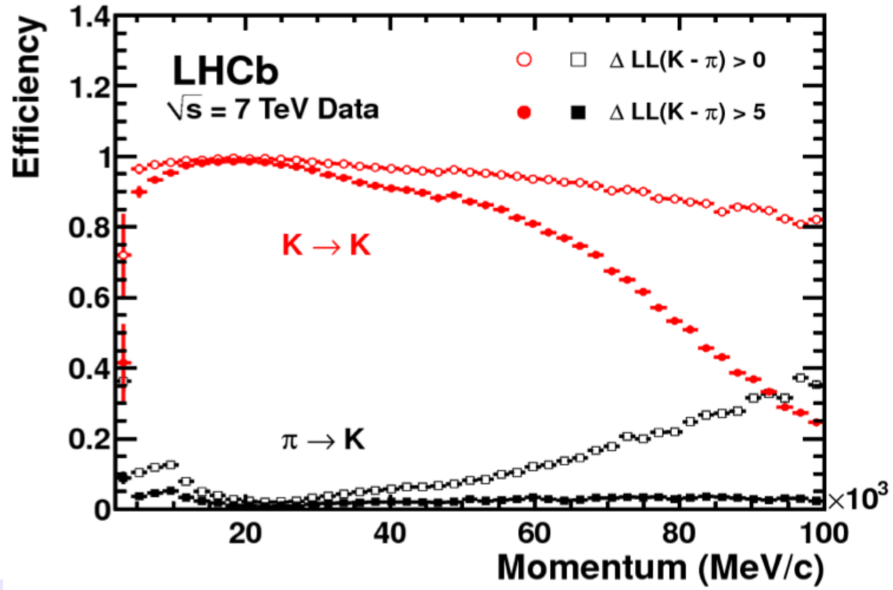
- ❑ Excellent understanding of the detectors thanks to detailed simulations

Particle ID in LHCb and ALICE

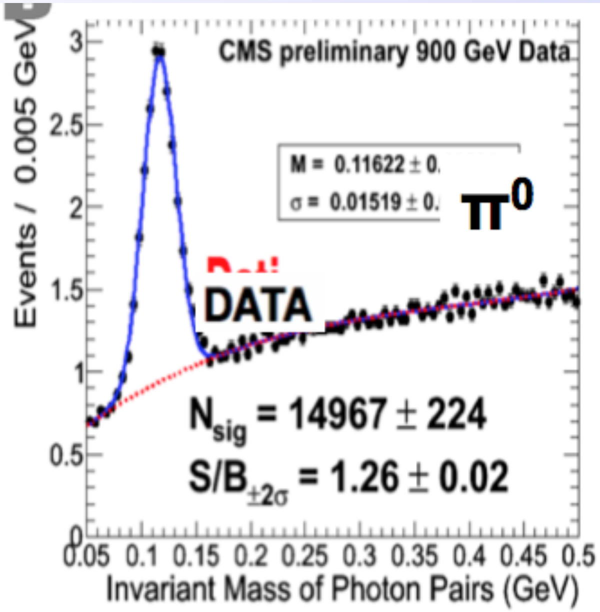


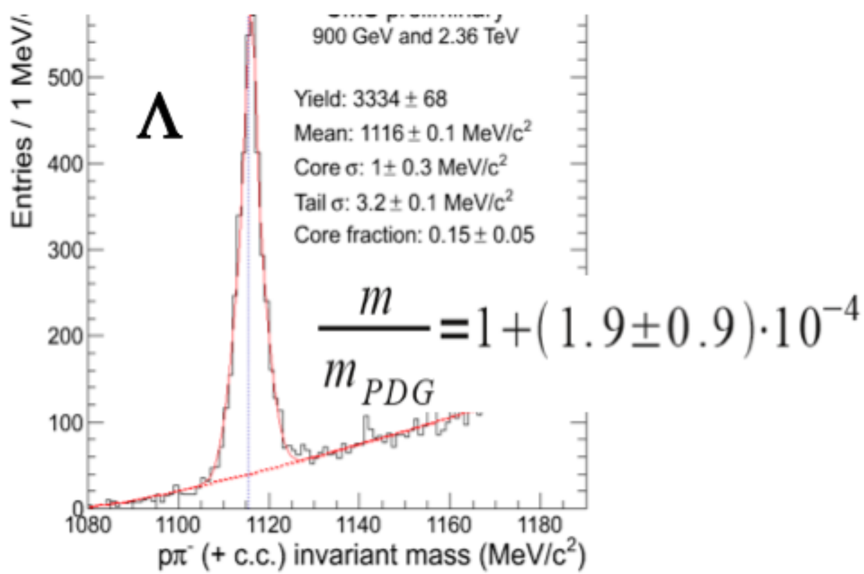
- ALICE particle ID: Si tracker, TPS, TOF
- Tracking down to very low momentum (~100 MeV)

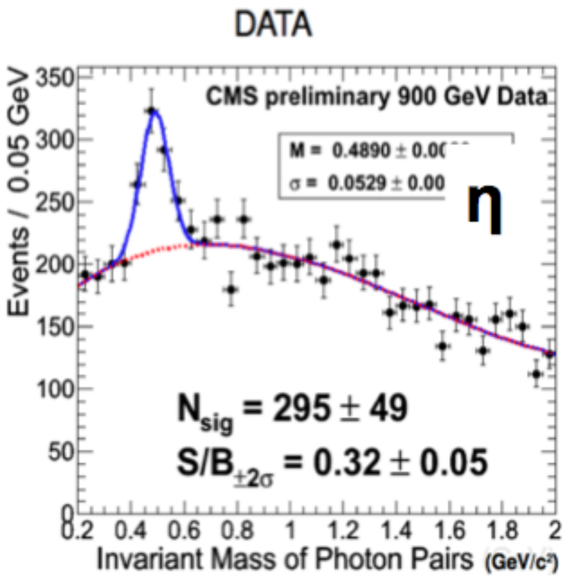
- RICH particle ID in LHCb: ~95% efficiency for 5% π-K contamination

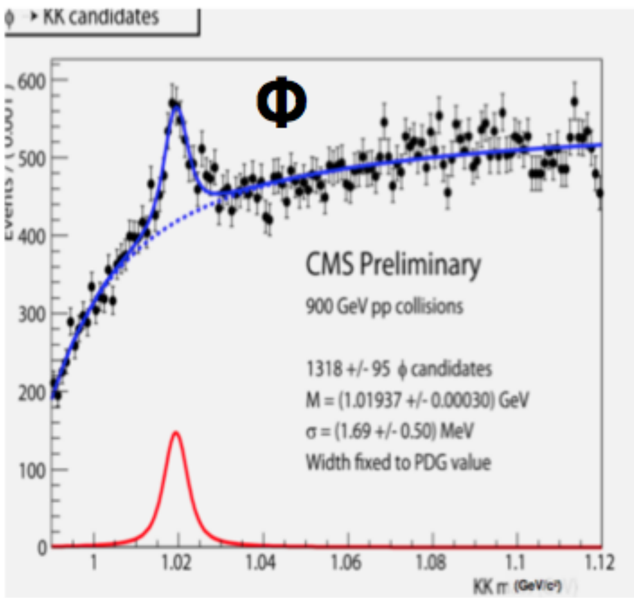


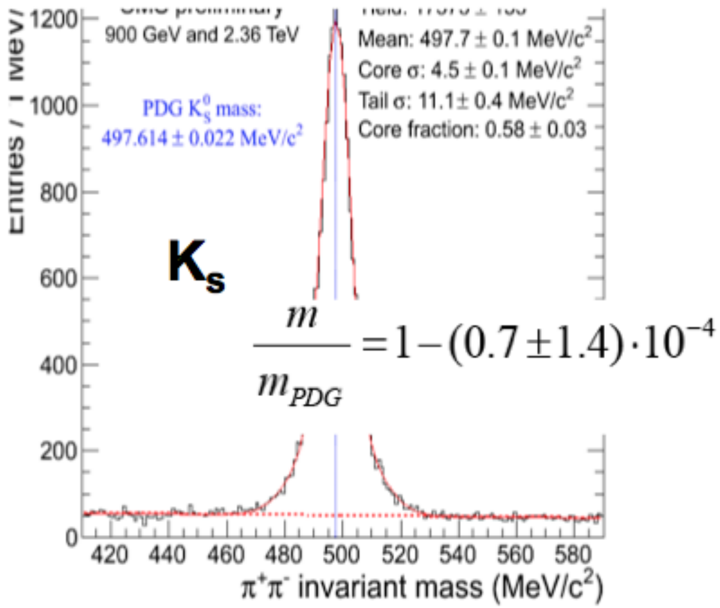
Rediscovery of resonances





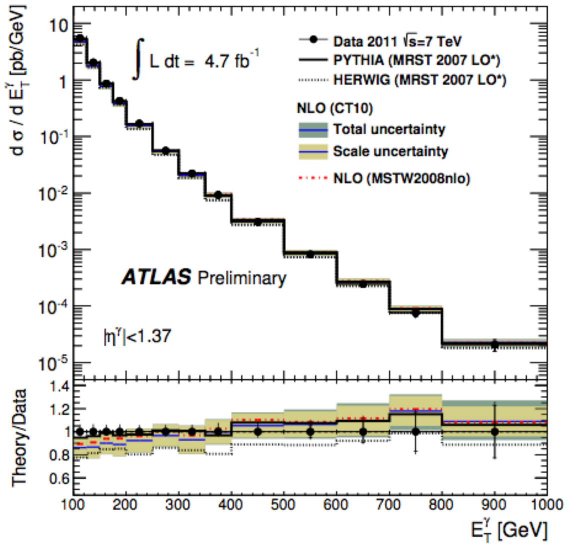


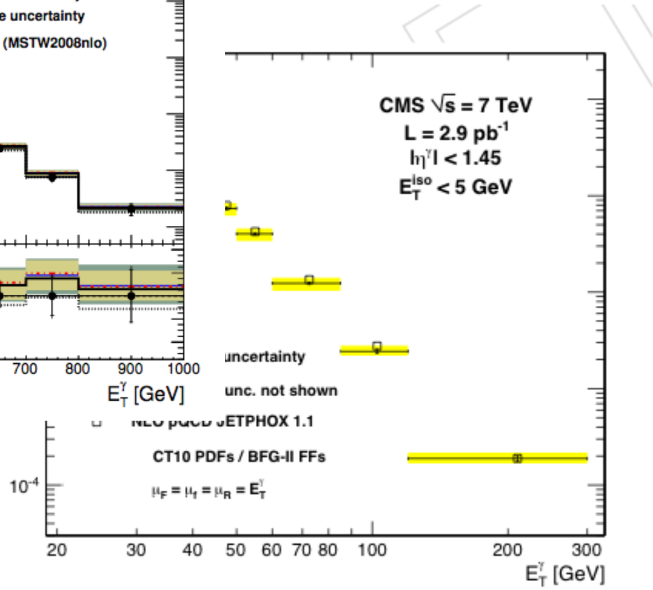


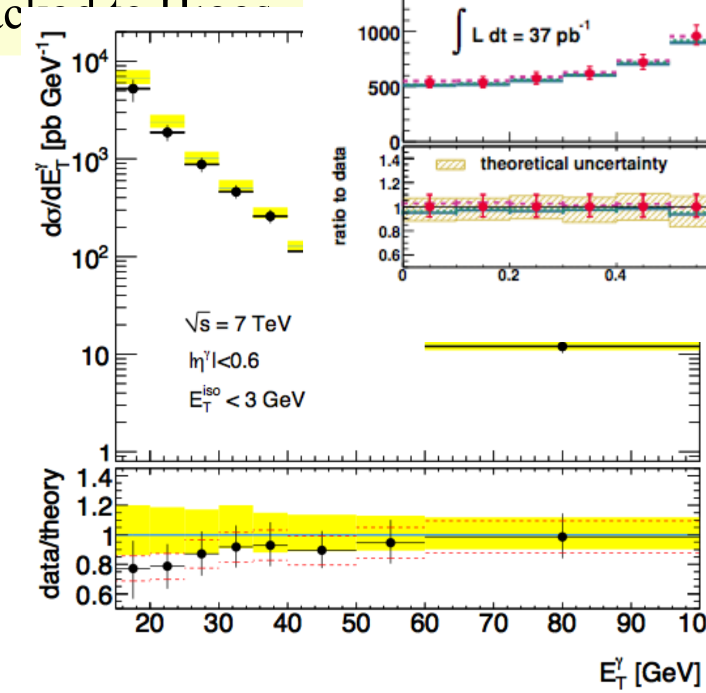


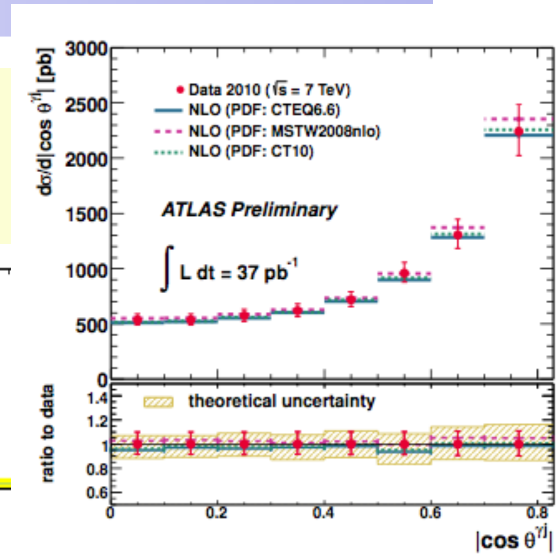
QCD/direct photons

- Direct photon produced in association with a hard jet
- Test of perturbative QCD, predictions available at NLO
- Also interesting for photon energy calibration, bac







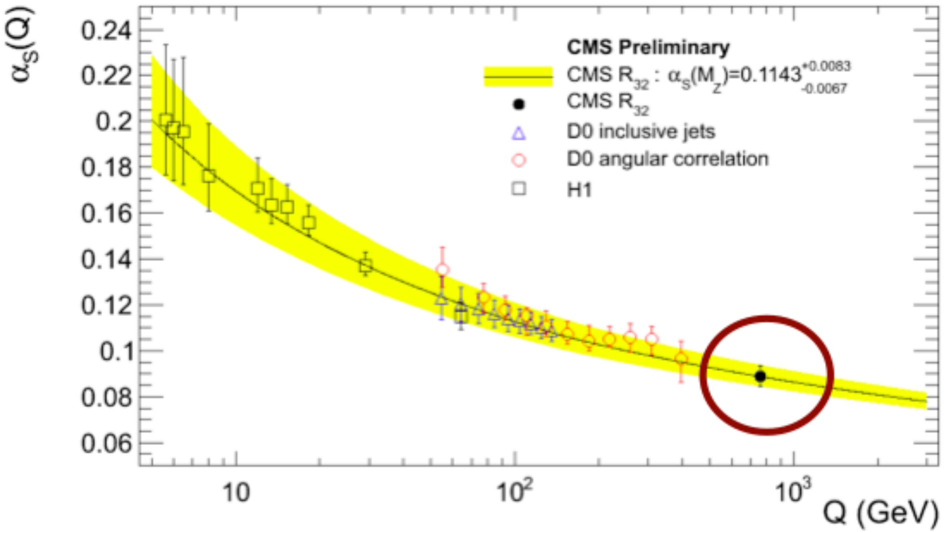


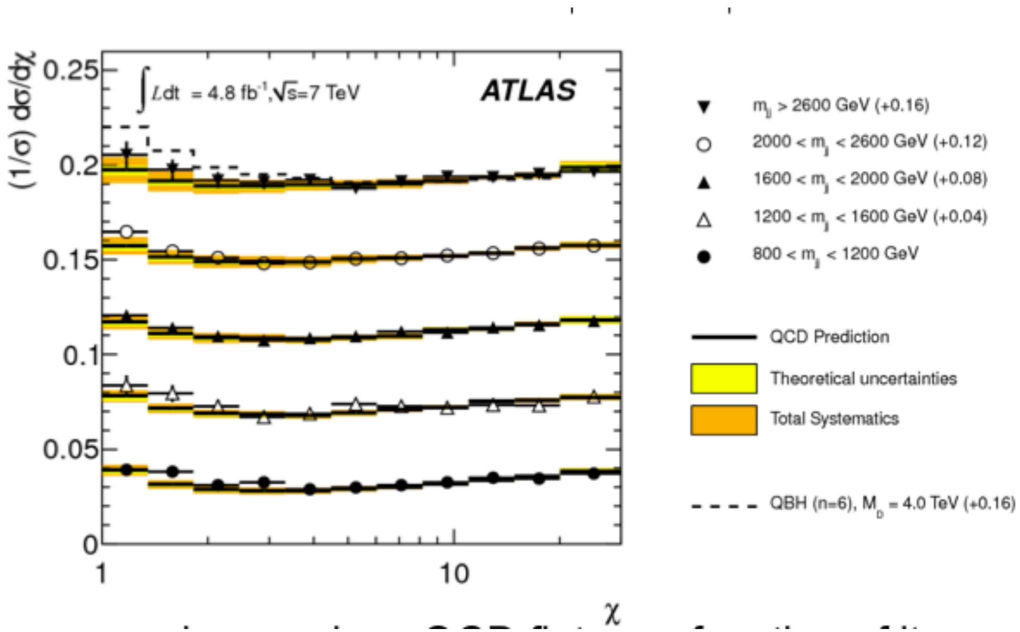
=> Good agreement

⇒ Less good for Et<25, more difficult region for pQCD (small x, NLOprediction less accurate)

QCD/Jets

⇒**First and very precise measurement at the TeV scale.**

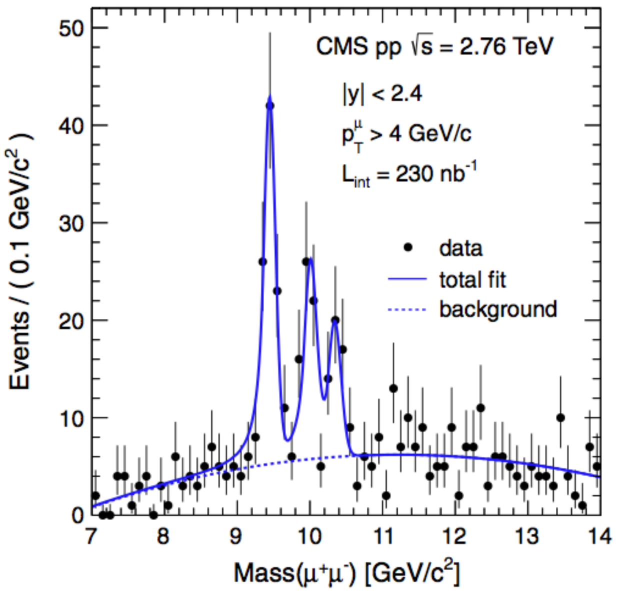


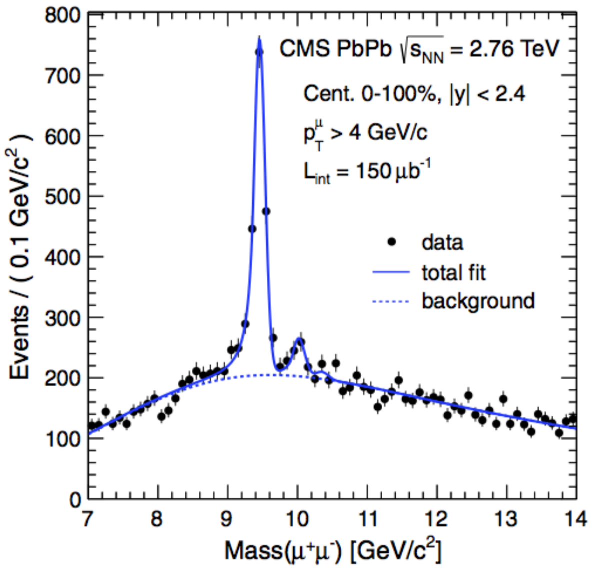


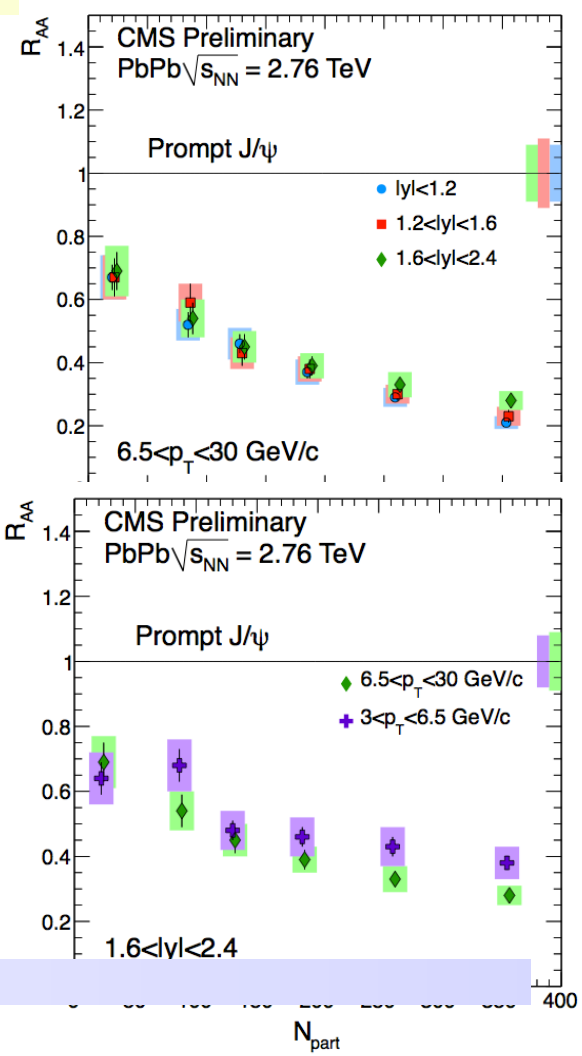
⇒ **Dijet angular correlations: good agreement between data and theory**

QGP

- ❑ Lead-lead collisions also performed at LHC
- ❑ Aim at studying new state of matter: QGP, properties of hot/dense matter



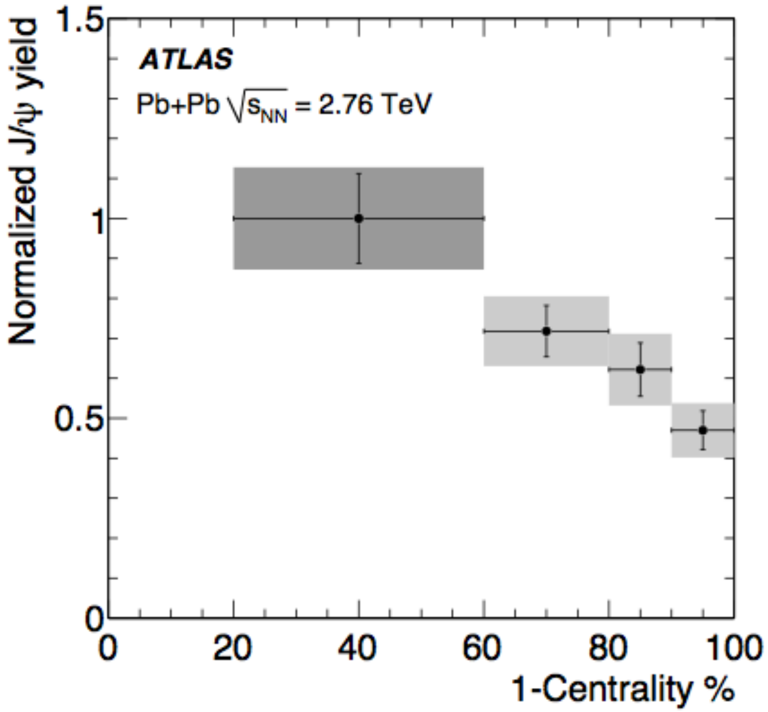


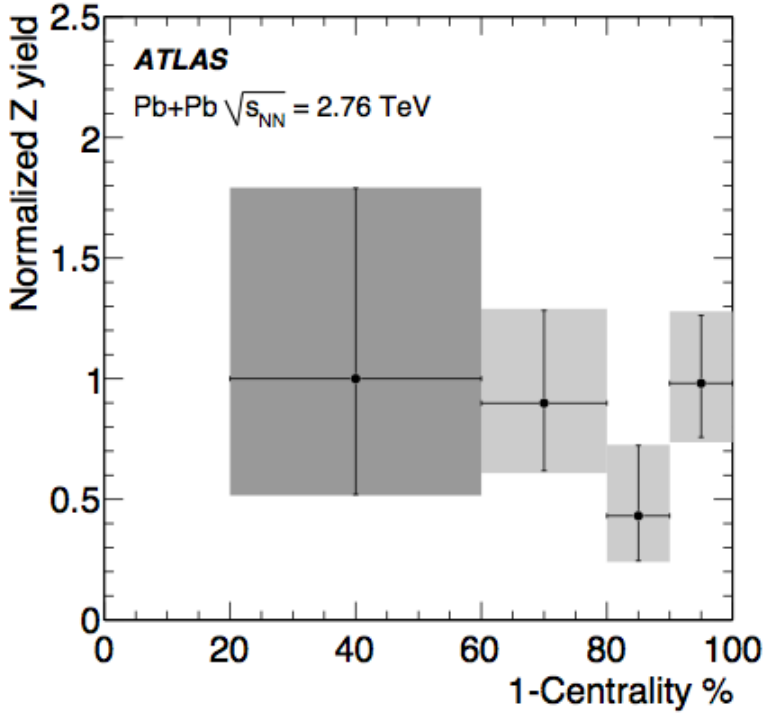


- ❑ Quarkonium suppression

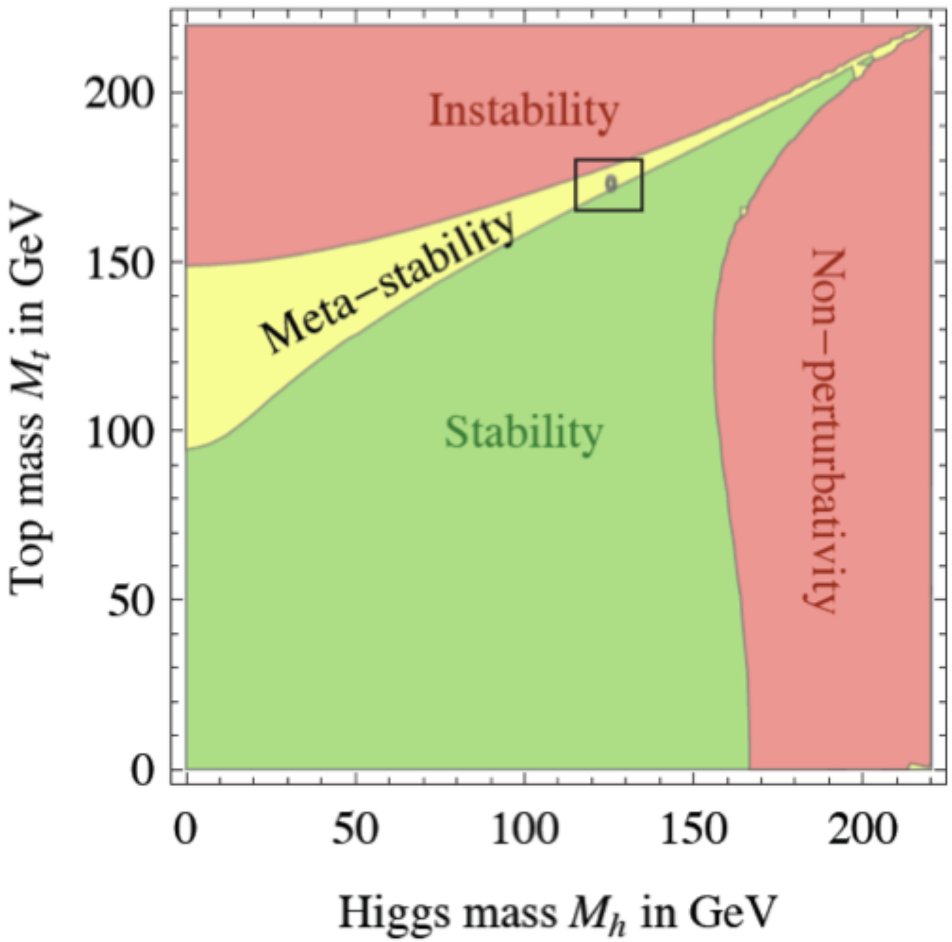
QGP

- Lead-lead collisions also performed at LHC
- Aim at studying new state of matter: QGP, properties of hot/dense matter





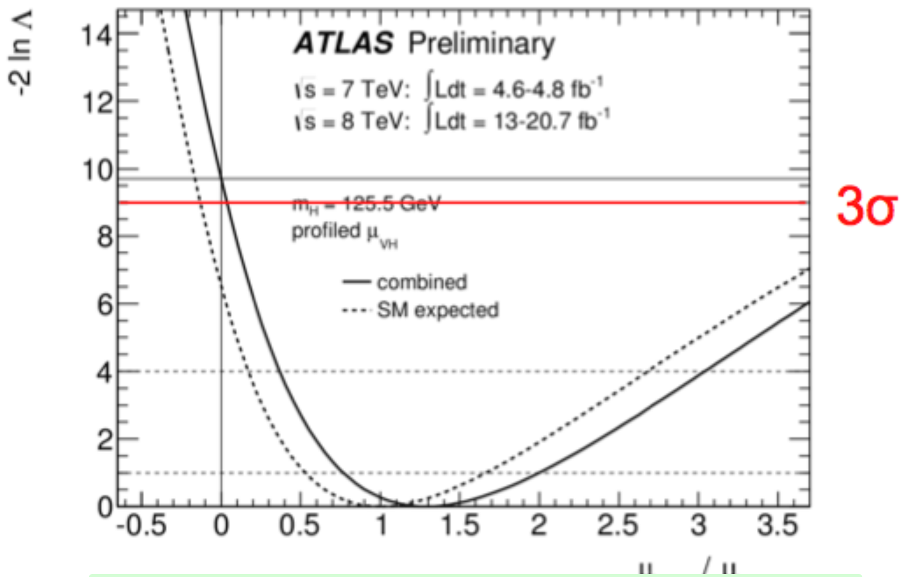
Top mass



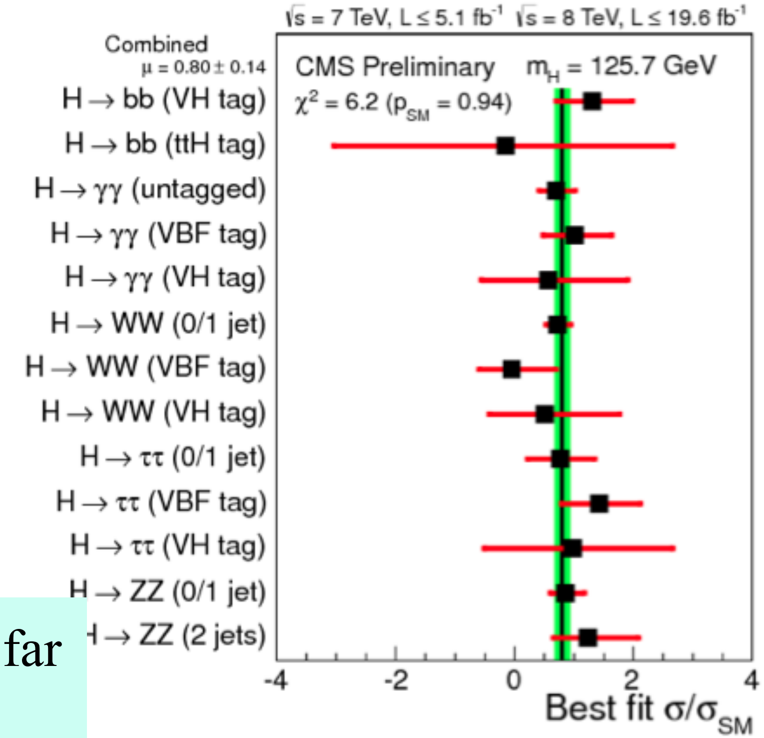
⇒ Maybe (much) more important than previously thought!

Higgs: properties

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



3.1σ evidence for VBF production



All observations compatible with a SM Higgs boson so far
Coupling to fermions and VBF production showing up