# Towards the LHC Run2

Giovanni Marchiori
LPNHE-Paris

FCPPL workshop @ USTC
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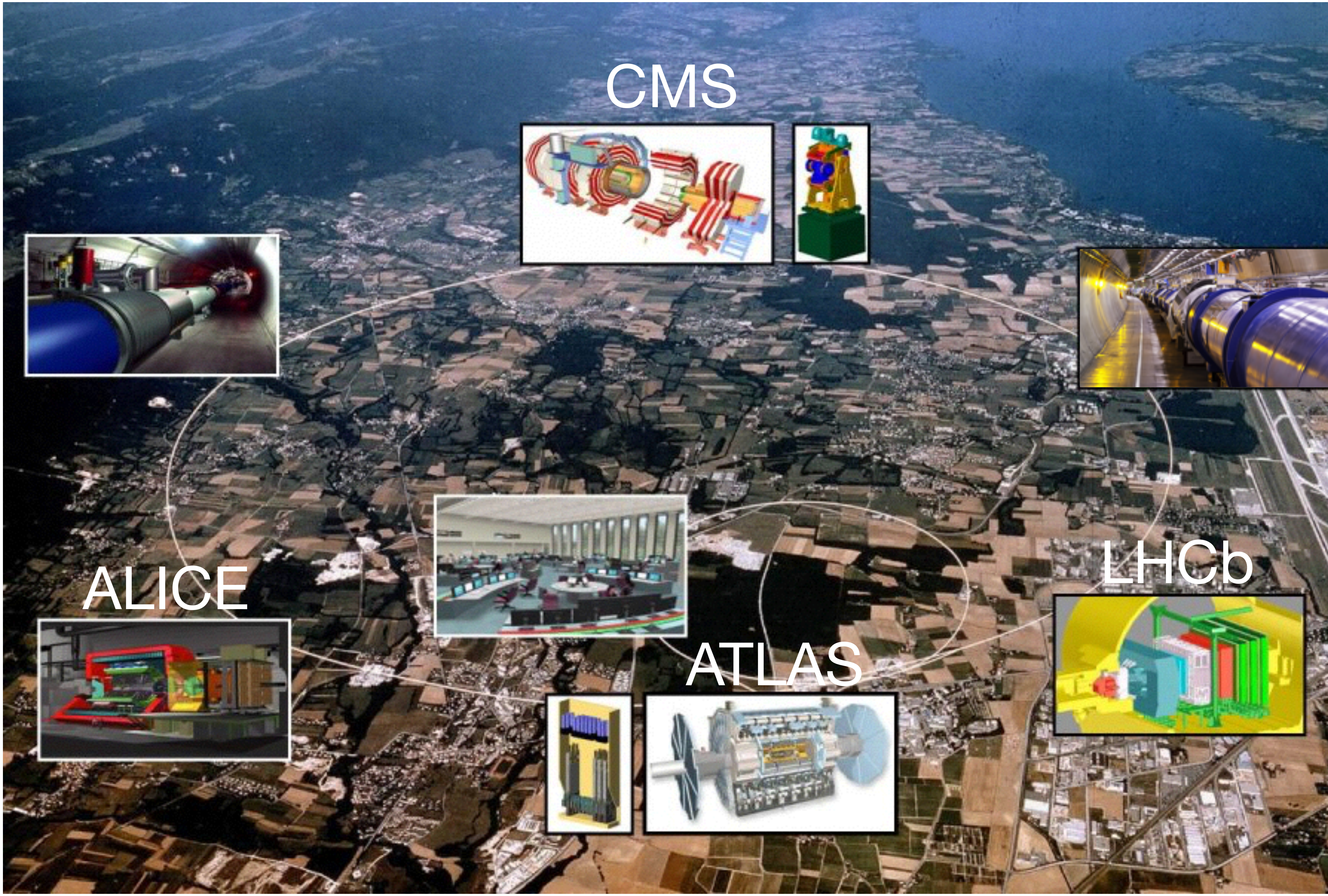
LPNHE PARIS   CNRS IN2P3 Les deux infinis   ATLAS

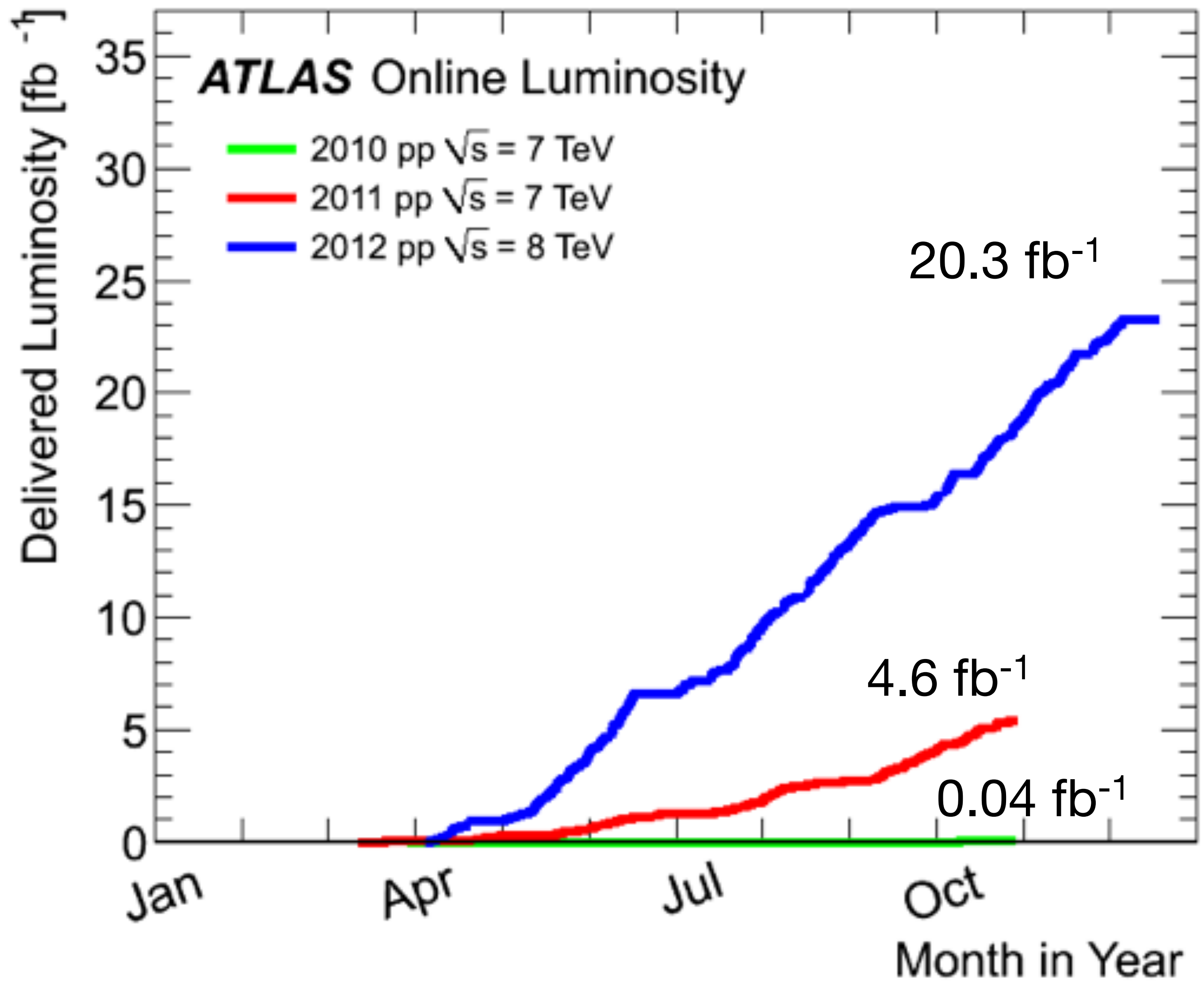
# The main experiments of the LHC physics program



# The current status

# LHC Run1: a brief recap

- 1984-2009: 25 years of conception, design, & construction
- 2009: start of Run1, first beams
- 2010: first pp collisions at $\sqrt{s}$=7 TeV
- 2011: stable pp collisions at 7 TeV, increased luminosity (peak & total)
- 2012: stable pp collisions at 8 TeV, higher luminosity (peak, integrated)
- early 2013: end of Run1 after heavy ion (HI) run

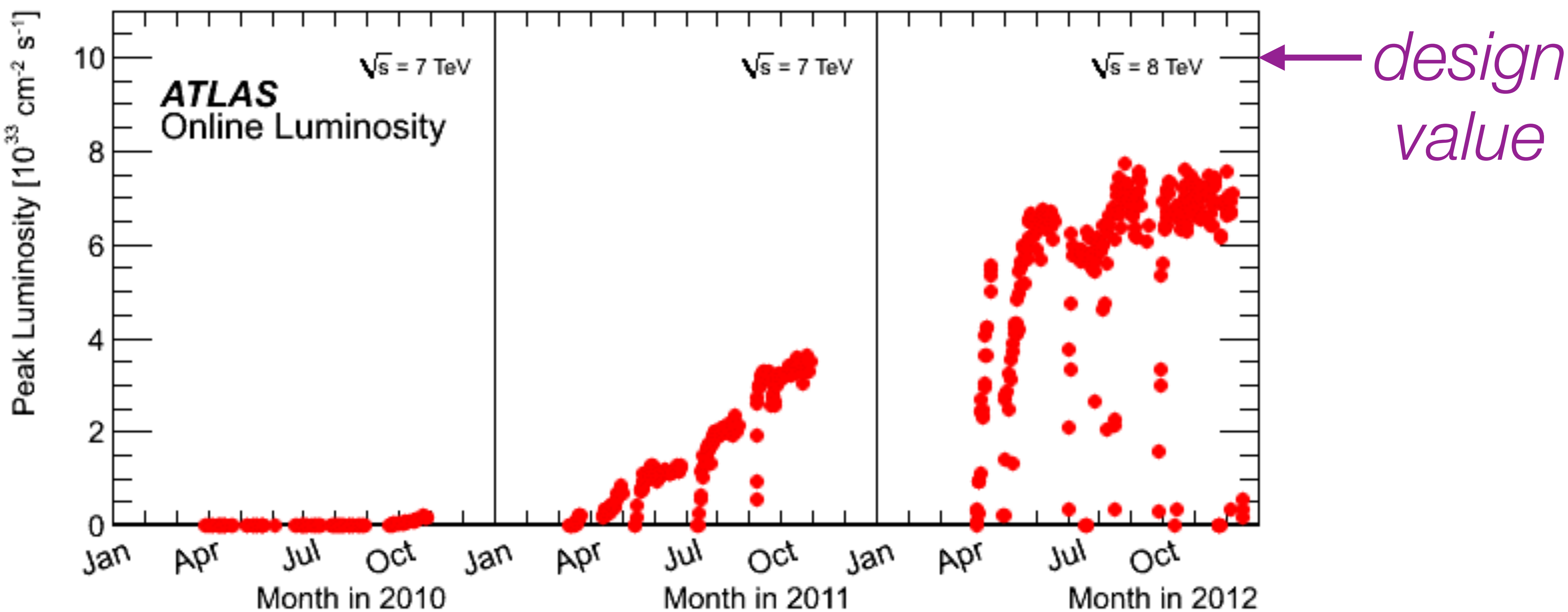



- Total delivered luminosity in Run1:
  - pp: ~25 $fb^{-1}$ to ATLAS and CMS; 3 $fb^{-1}$ to LHCb (lumi levelling)
  - HI: ~10 (2010)+160 (2011) $\mu b^{-1}$ Pb-Pb, 30 $nb^{-1}$ p-Pb to ALICE/ATLAS/CMS

# The path to high luminosity

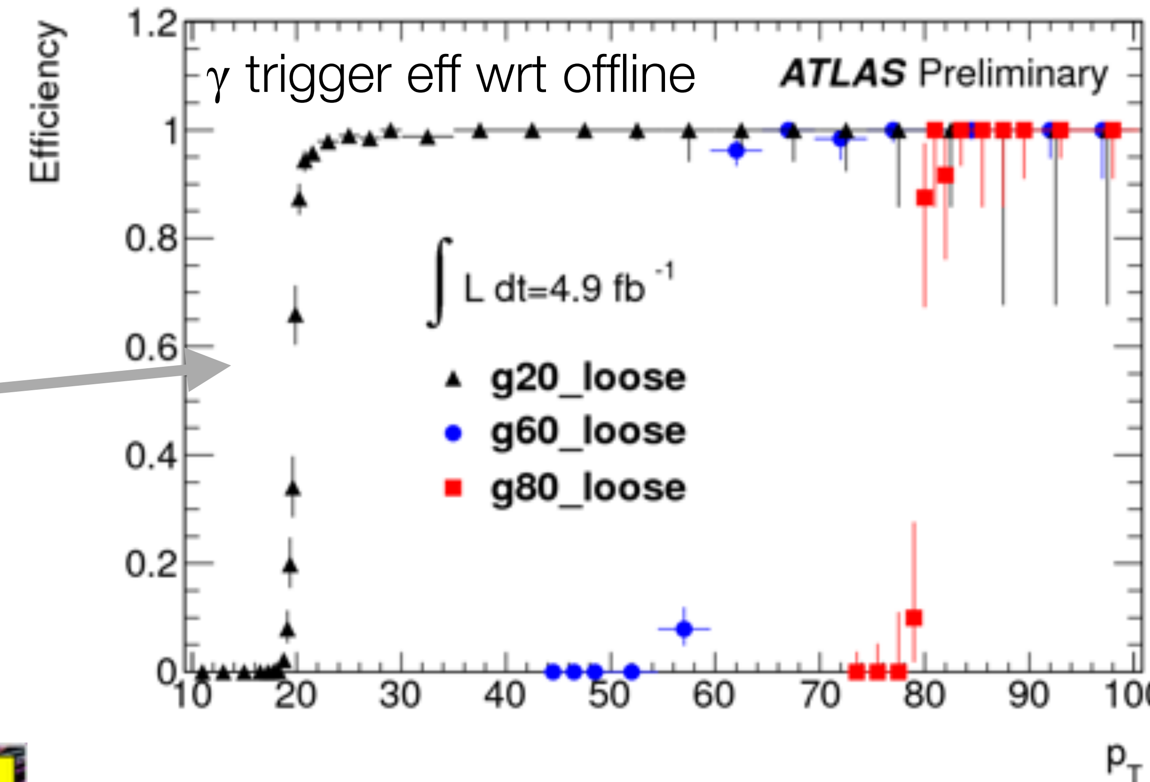
- optimally focused beams at IP (β*)
- many, high-intensity bunches (number of bunches, bunch intensity)
- small emittance (spread of beam in transverse phase space)

| Parameter | 2010 | 2011 | 2012 | design value |
|---|---|---|---|---|
| Beam energy | 3.5 | 3.5 | 4 | 7 |
| β* in IP 1 and 5 (m) | 2.0/3.5 | 1.5/1.0 | 0.6 | 0.55 |
| Bunch spacing (ns) | 150 | 75/50 | 50 | 25 |
| Max. number of bunches | 368 | 1380 | 1380 | 2808 |
| Max. bunch intensity (protons per bunch) | $1.2 \times 10^{11}$ | $1.45 \times 10^{11}$ | $1.7 \times 10^{11}$ | $1.15 \times 10^{11}$ |
| Normalized emittance at start of fill (mm mrad) | ≈2.0 | ≈2.4 | ≈2.5 | 3.75 |
| Peak luminosity ($cm^{-2}s^{-1}$) | $2.1 \times 10^{32}$ | $3.7 \times 10^{33}$ | $7.7 \times 10^{33}$ | $1 \times 10^{34}$ |
| Max. mean number of events per bunch crossing | 4 | 17 | 37 | 19 |
| Stored beam energy (MJ) | ≈28 | ≈110 | ≈140 | 362 |



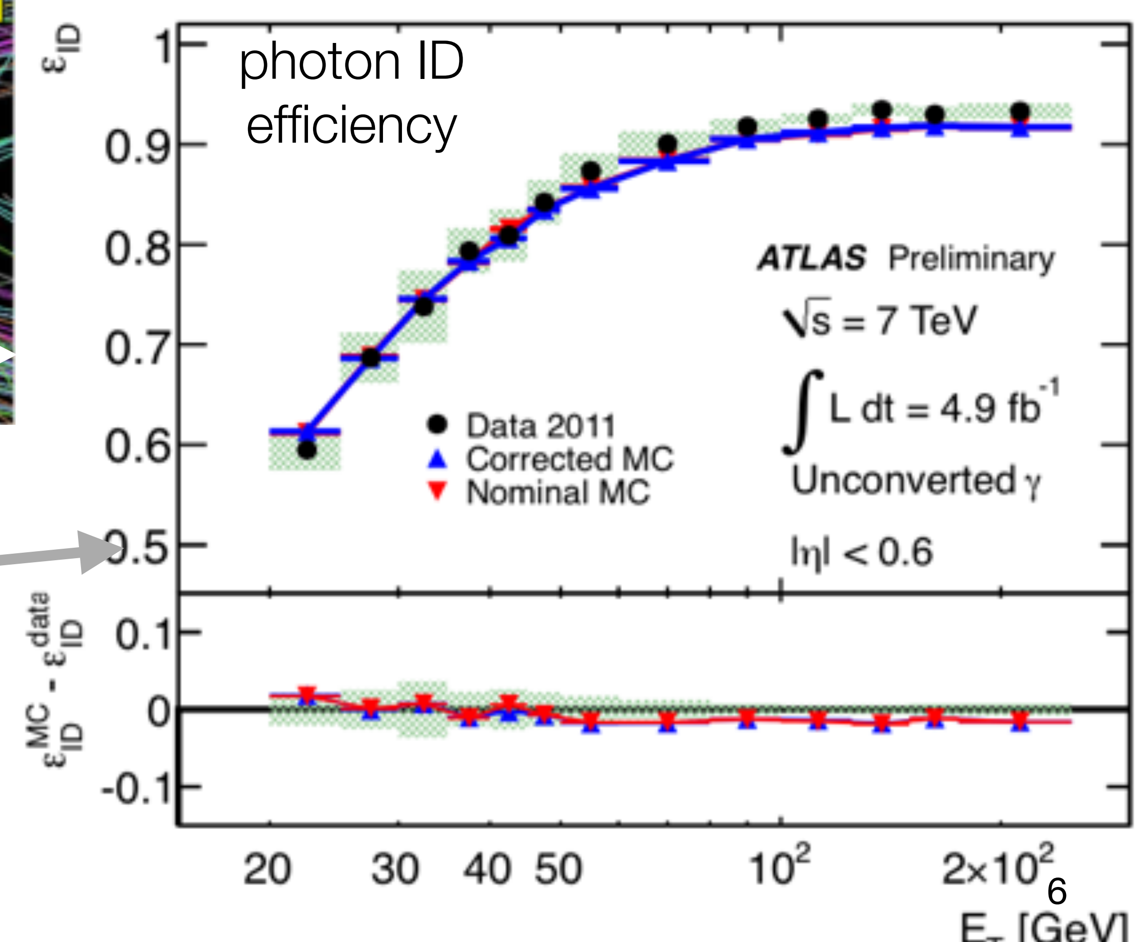
# Excellent detectors for an excellent machine

- High data-taking efficiency (dead-time, dead channels, bad data quality <10%)
- High trigger efficiency for physics channels of interest (close to 100% with respect to phase space selected offline for best $S/\sqrt{B}$)

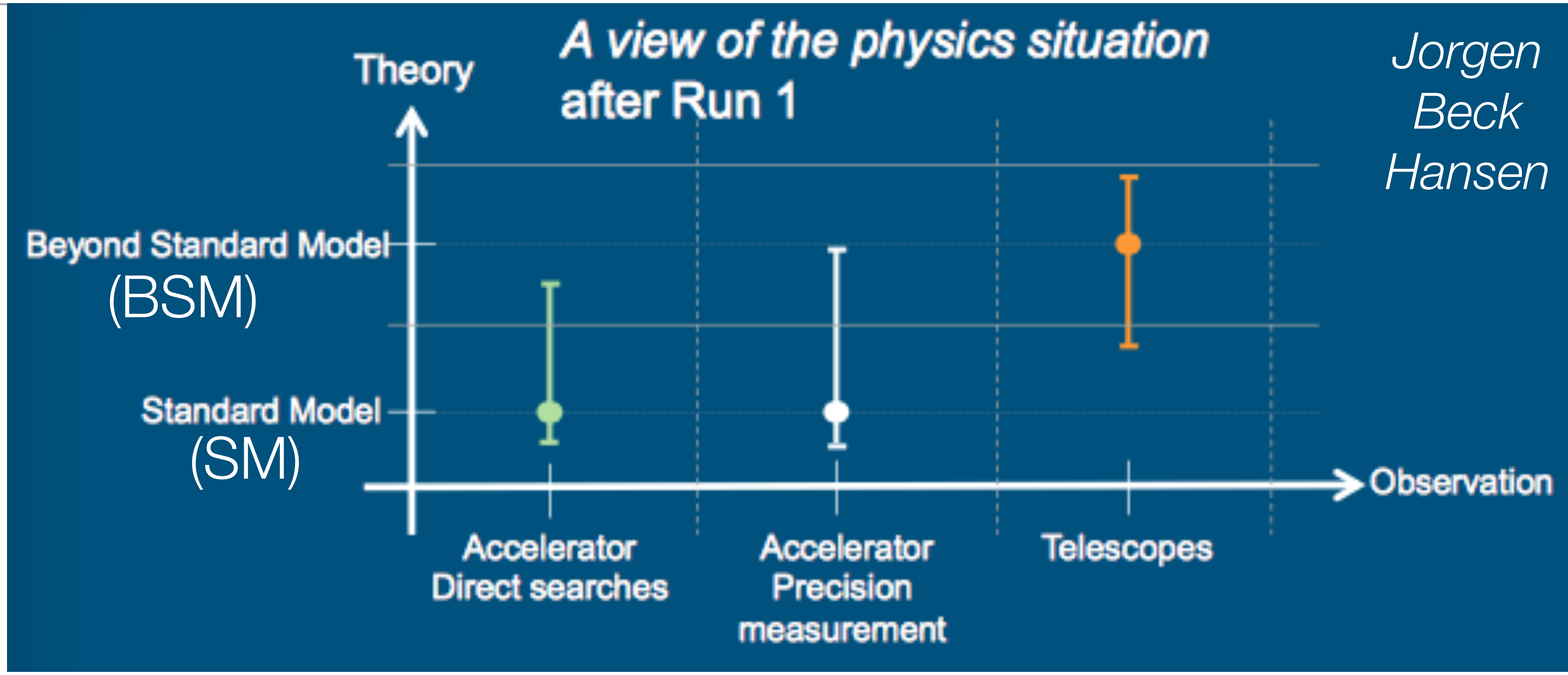



- Pile-up robust algorithms to cope with #interactions/crossing > design value (~25)


- Data-driven measurements of detector performance to squeeze systematic uncertainties to % level or better



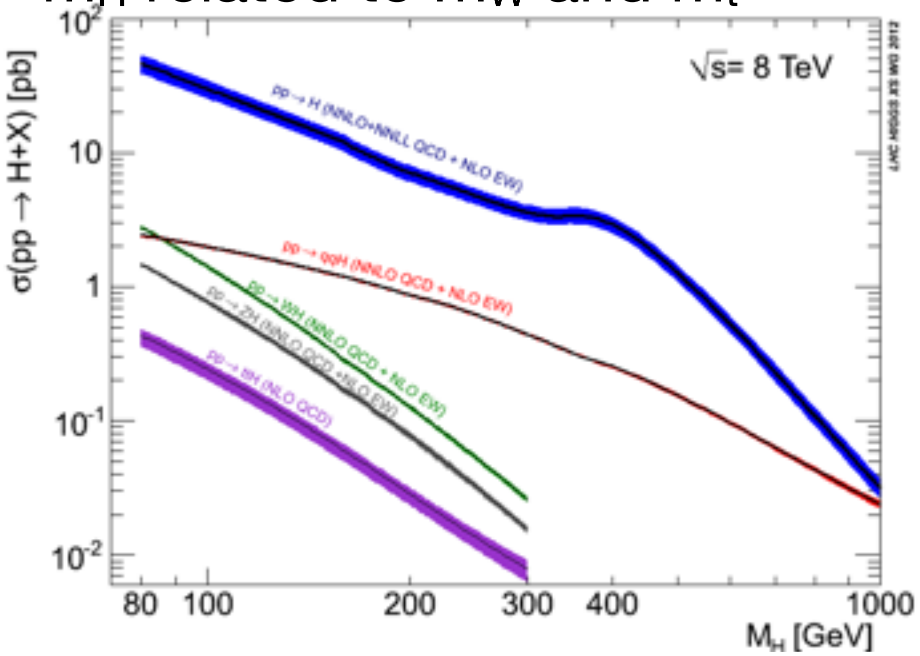
# What do we know after Run1?

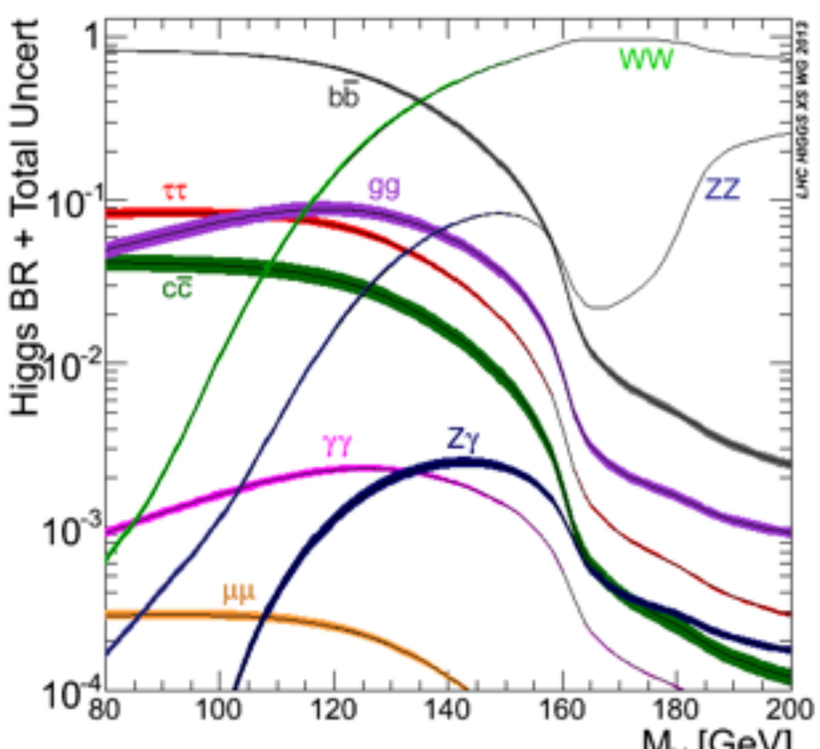



- **Consolidated** the SM: comprehensive set of measurements at $\sqrt{s}$=7 and 8 TeV
  - Precision EW and QCD
  - Rare processes particularly sensitive to New Physics like $B_s \to \mu\mu$
- **Completed** the Standard Model: Higgs boson discovery (ATLAS & CMS)!!
  - clear evidence in various final states for same mass~125 GeV:
    - 5-8$\sigma$ for each of $H\to\gamma\gamma$, $H\to WW^*\to l\nu l\nu$ and $H\to ZZ^*\to 4l$ per experiment
    - ~4$\sigma$ $H\to\tau\tau$ and ~2$\sigma$ W/Z+$H\to bb$ per experiment (+3$\sigma$ $VH\to bb$ @Tevatron)
  - $J^P$: >3$\sigma$ exclusion of $0^-$, $1^\pm$, $2^\pm$ vs $0^+$ per experiment ($\gamma\gamma$/lvlv/4l combined)
  - couplings: some measured to 20-30%, in agreement with SM values
  - BR(invisible) <~ 30%; no enhancement of rare decays ($\mu\mu$<7xSM, $Z\gamma$<10SM) [both exps]
- **NO evidence of new physics** (<~1 TeV) despite huge # of (direct&indirect) searches

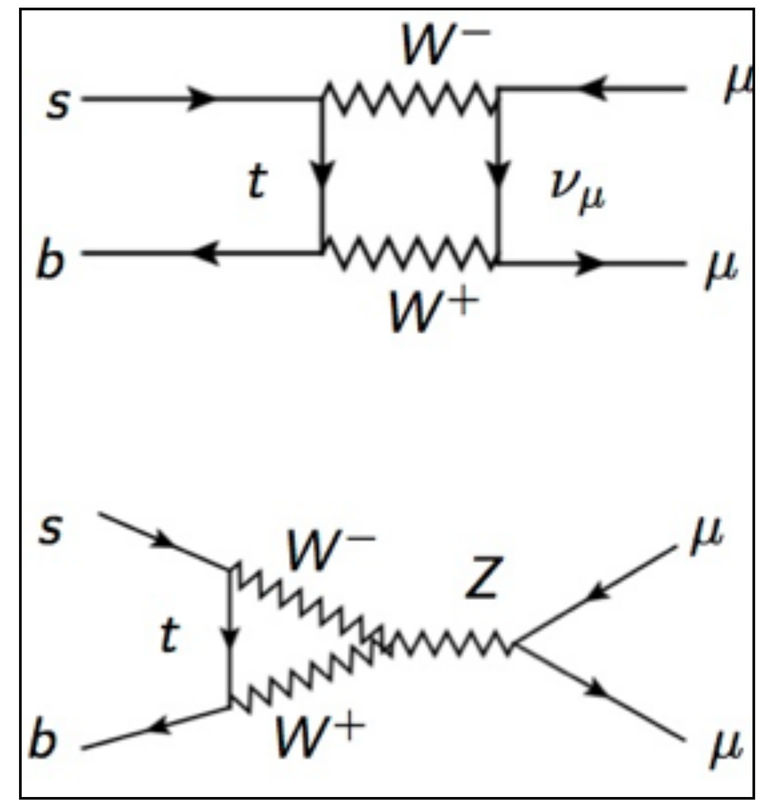
# Examples of indirect, precision searches

- In the Higgs boson sector:
  - SM Higgs sector very constrained
  - one neutral scalar
  - for given mass everything else fixed
  - $m_H$ related to $m_W$ and $m_t$

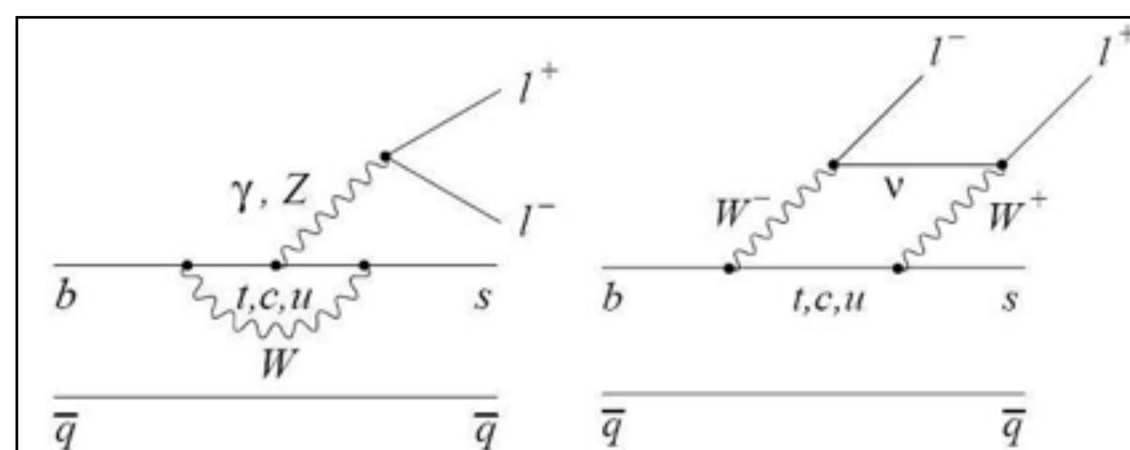



- In the flavour sector:
  - contributions to loop-induced processes by new particles



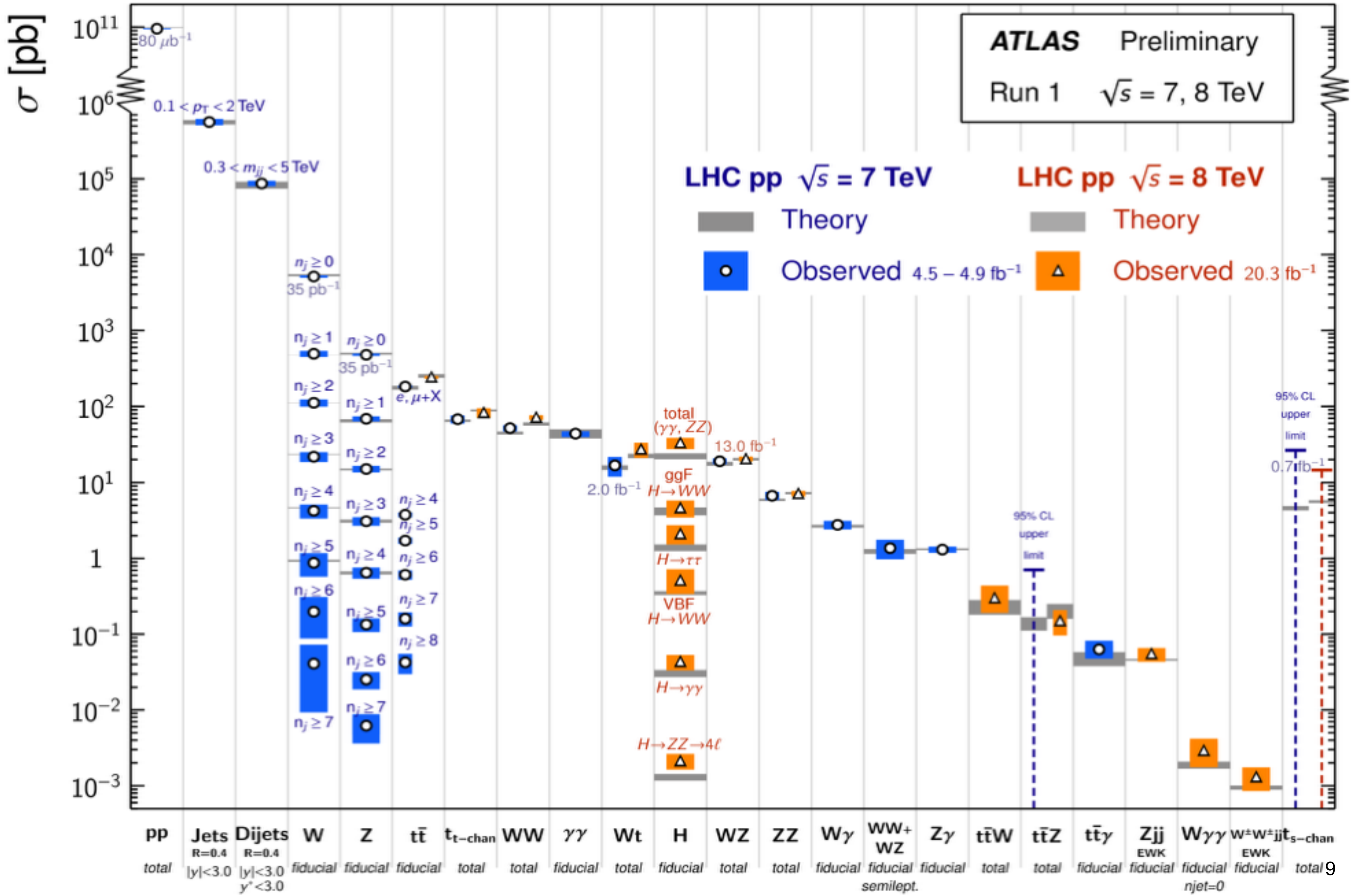

$B_s \to \mu\mu$



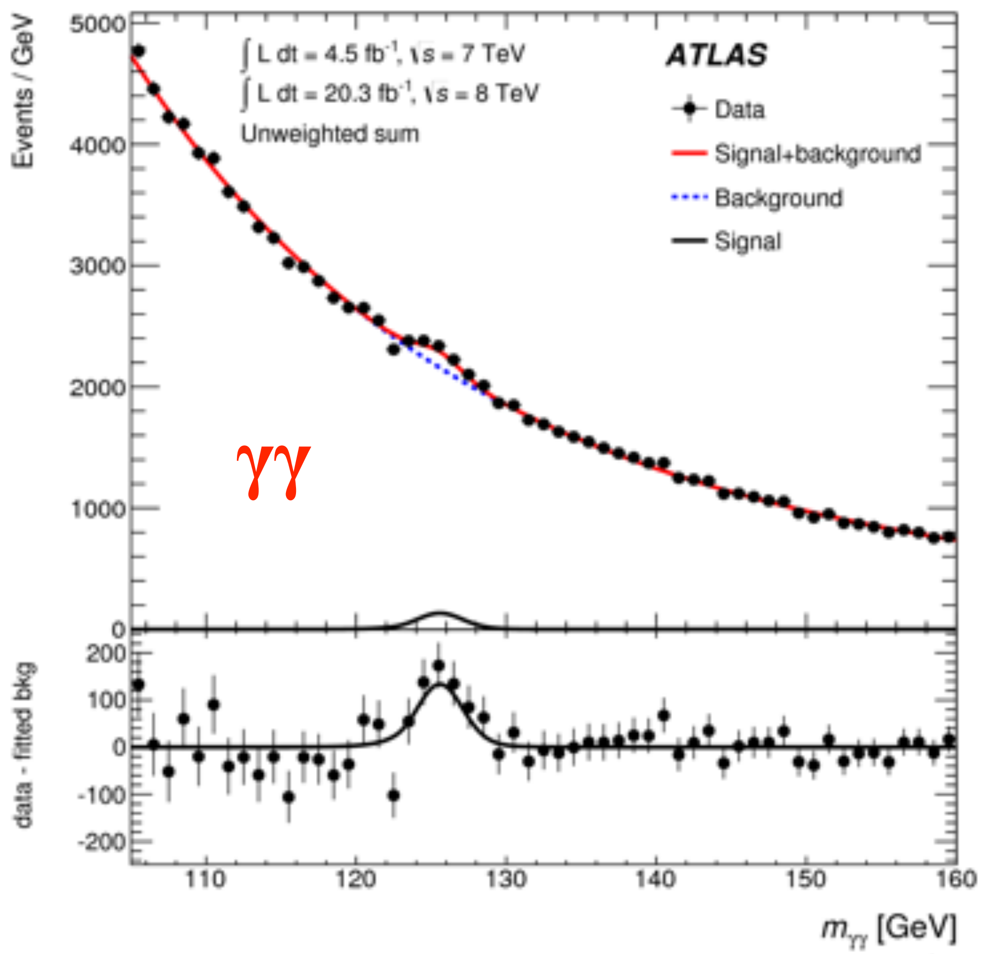

$B \to K^*\mu\mu$

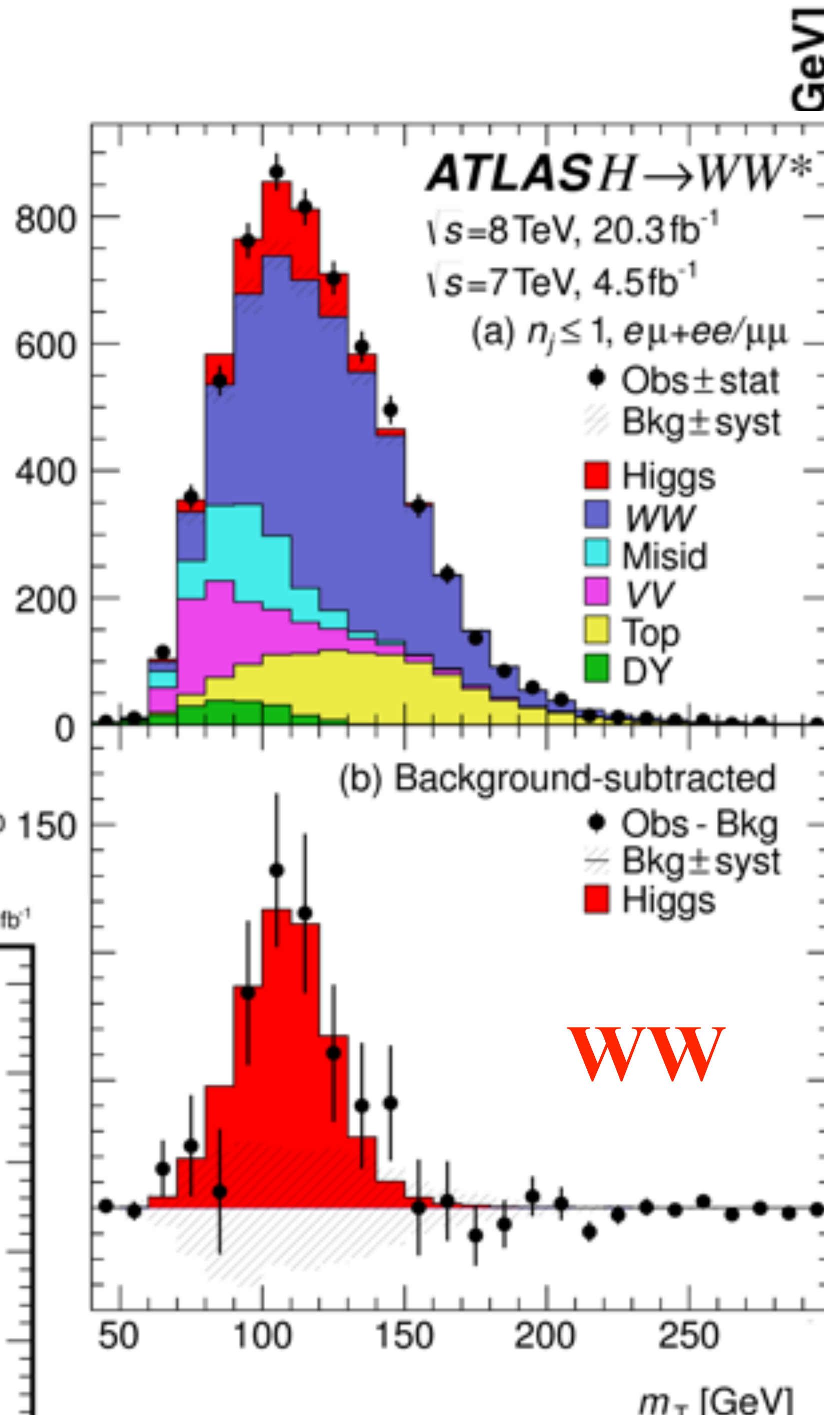
# ATLAS SM measurements

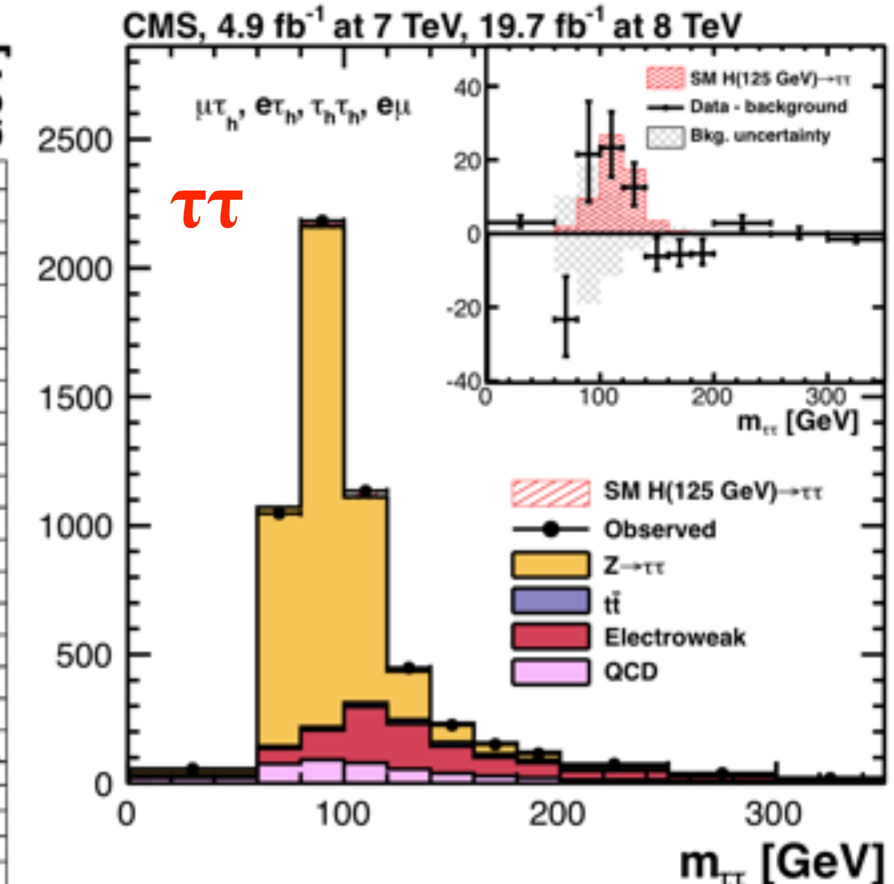
- similar results from CMS

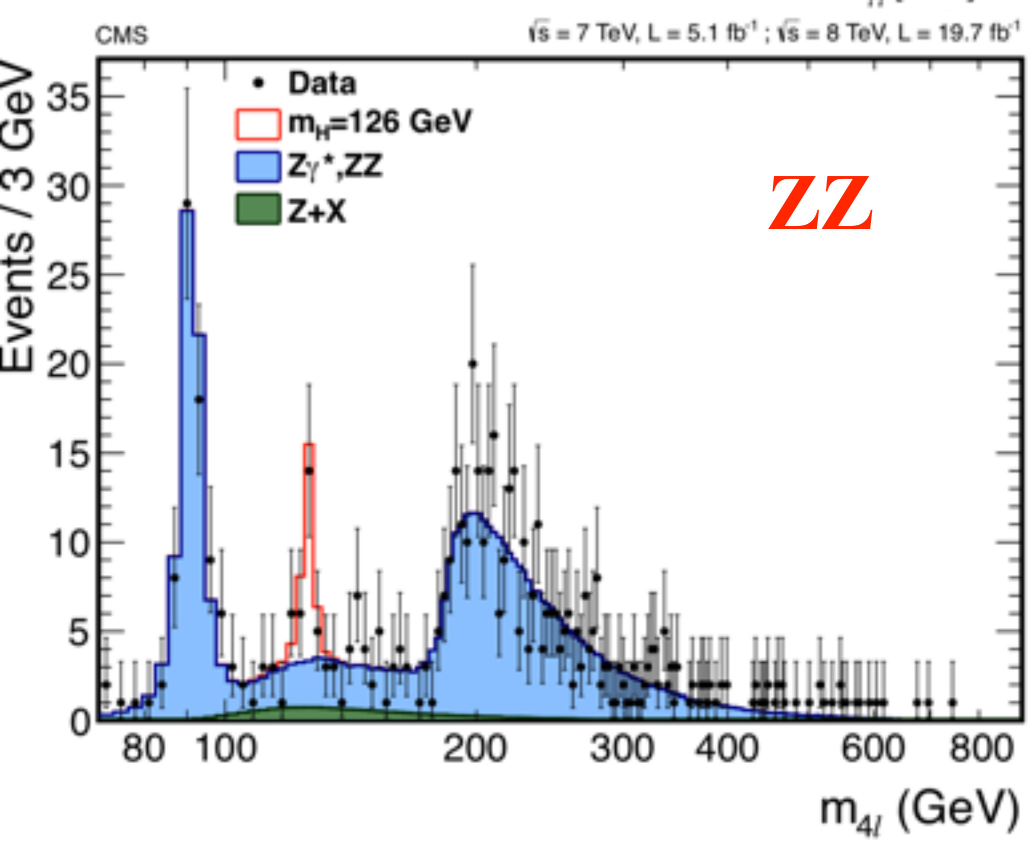


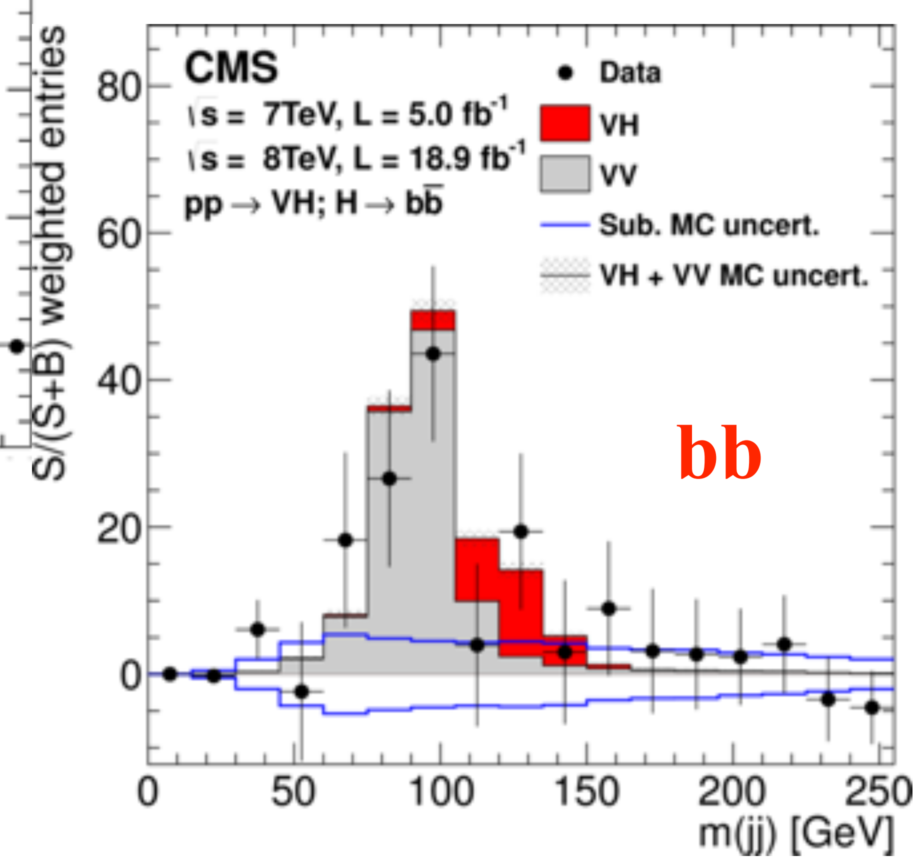
# ATLAS & CMS Higgs results: the evidence



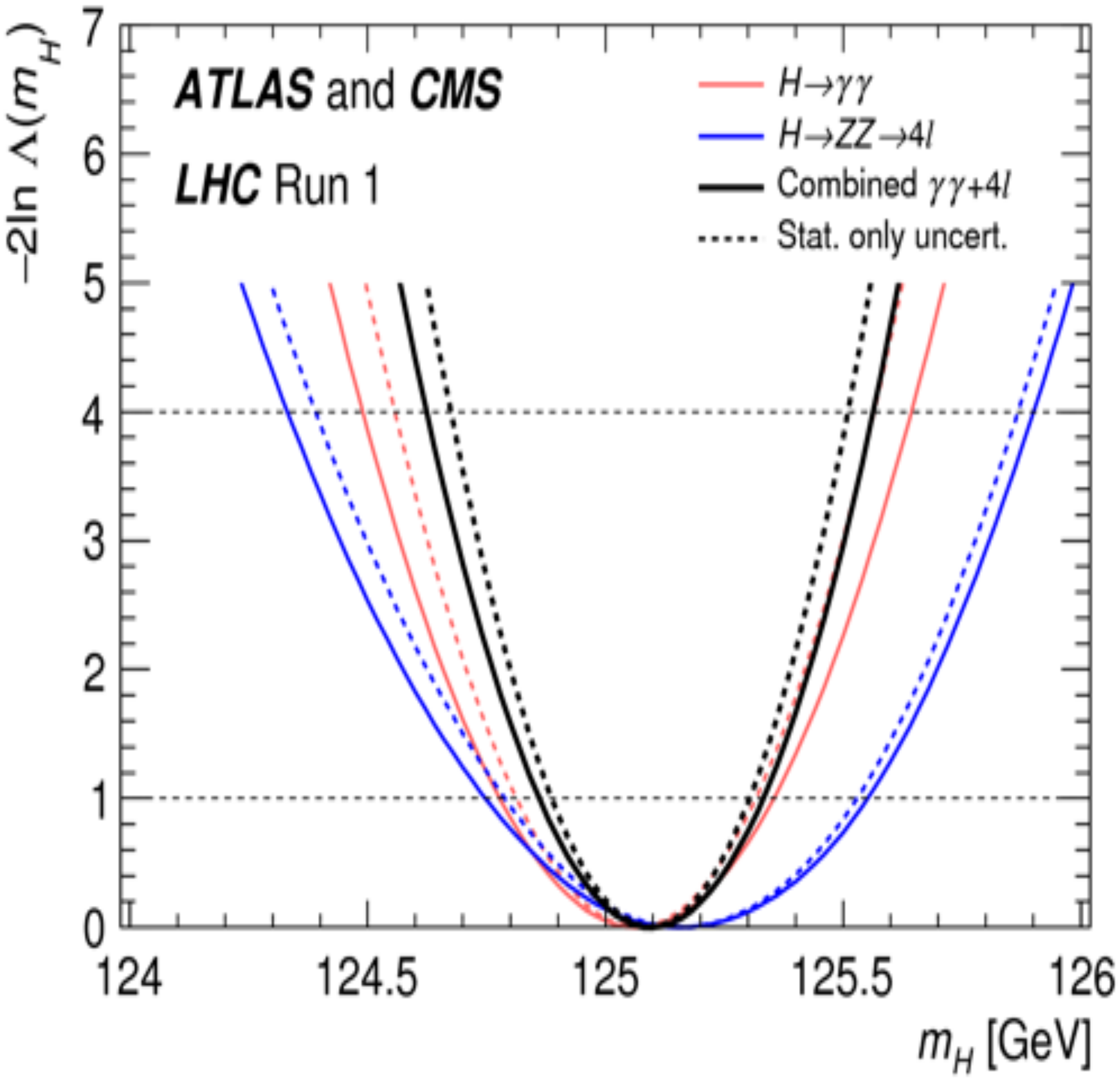



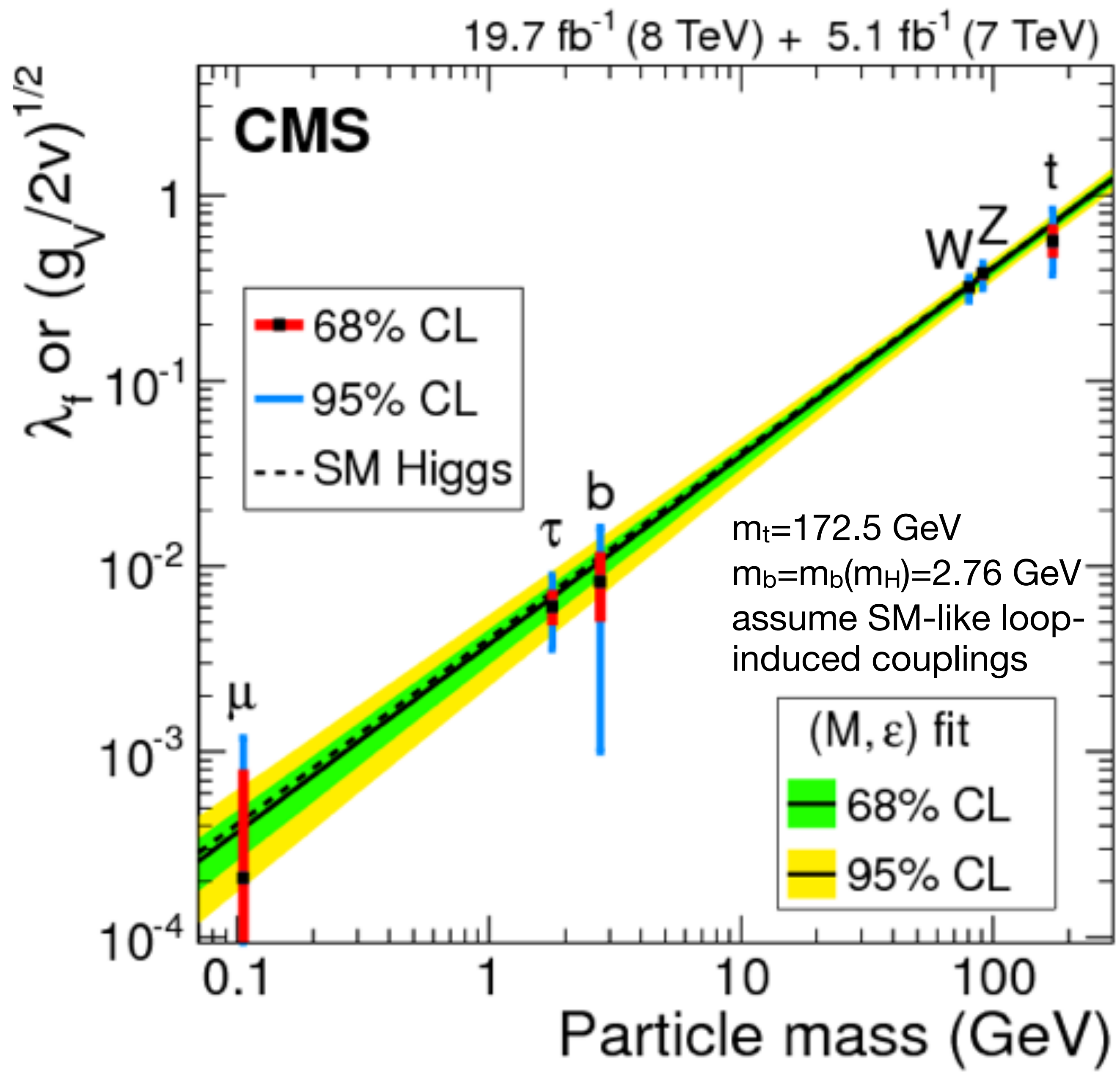



# ATLAS & CMS Higgs results: mass & couplings

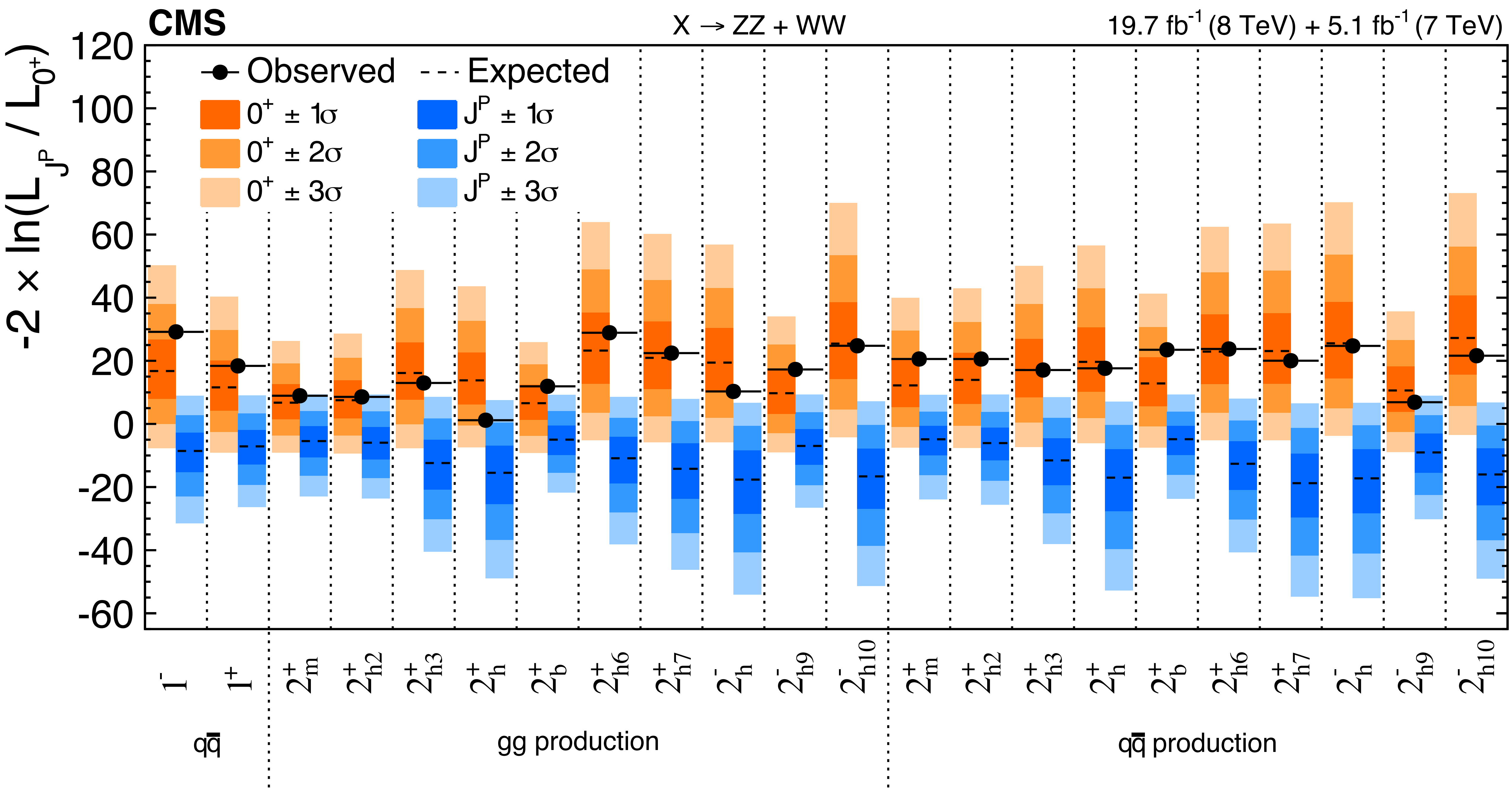



- $m_H$ =125.09±0.21(stat.)±0.11(syst.) GeV
- similar couplings from ATLAS

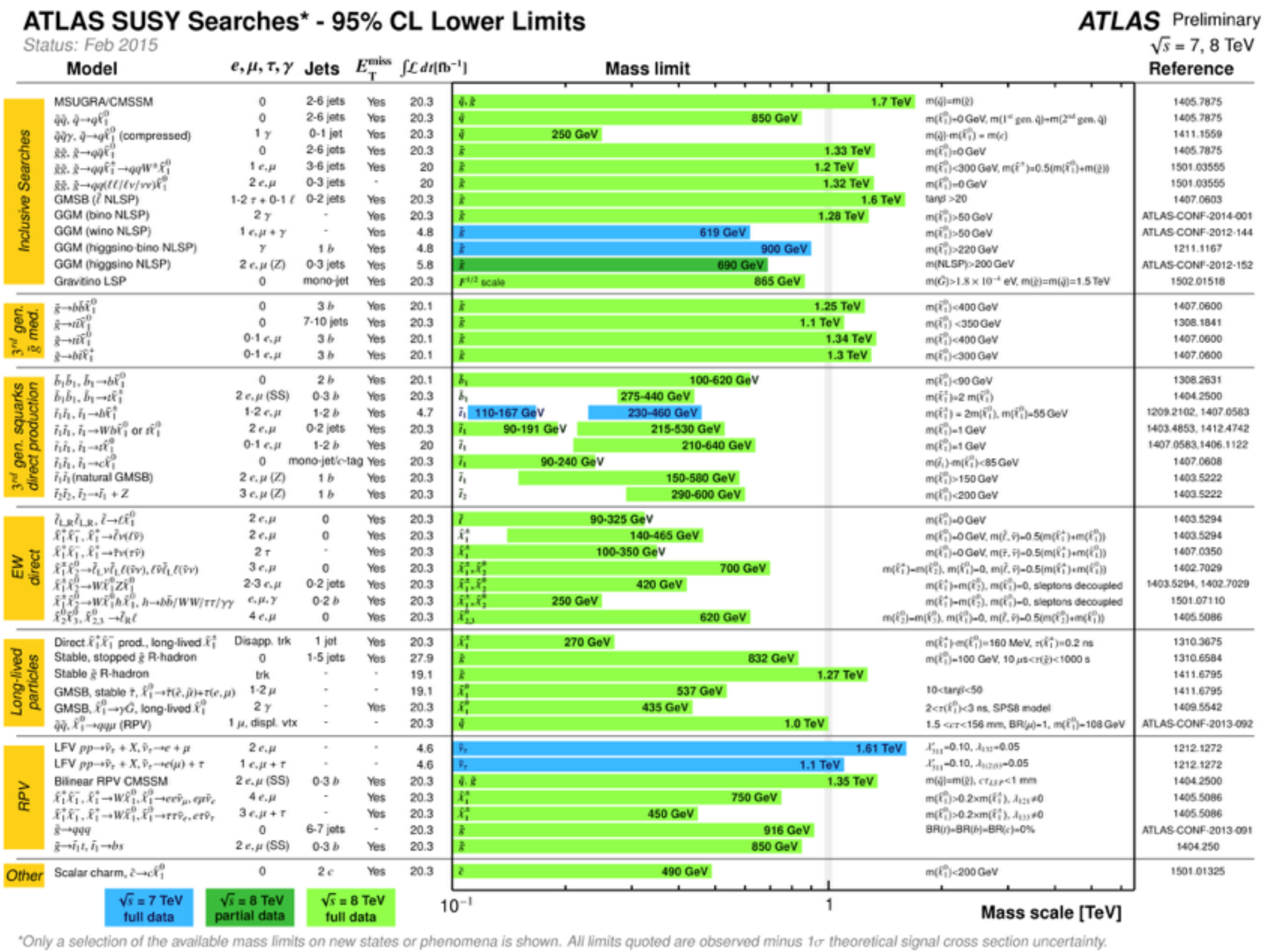
see talk by Yichen Li

# ATLAS & CMS Higgs results: spin & parity



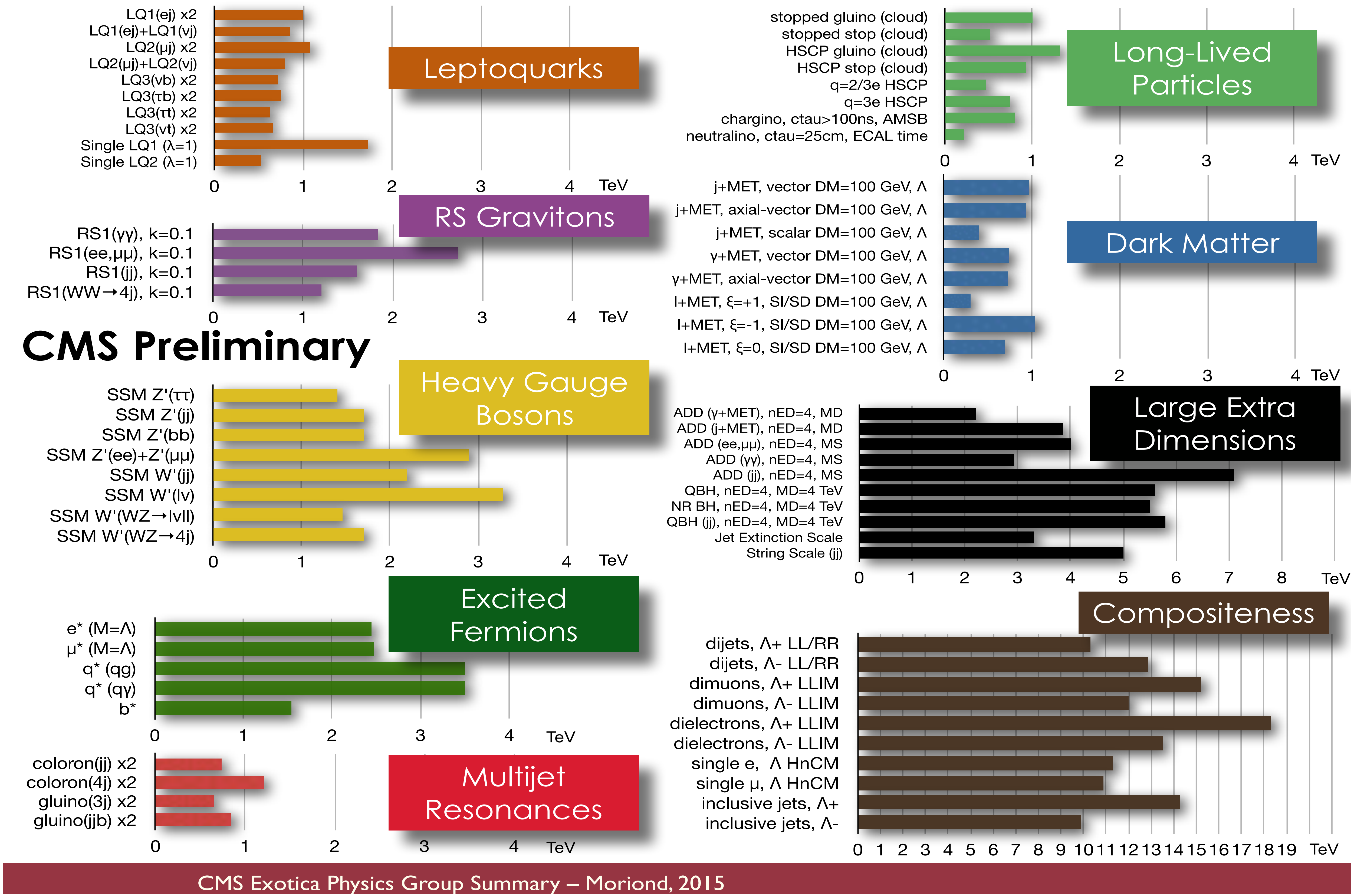
# ATLAS SUSY searches

- similar results from CMS

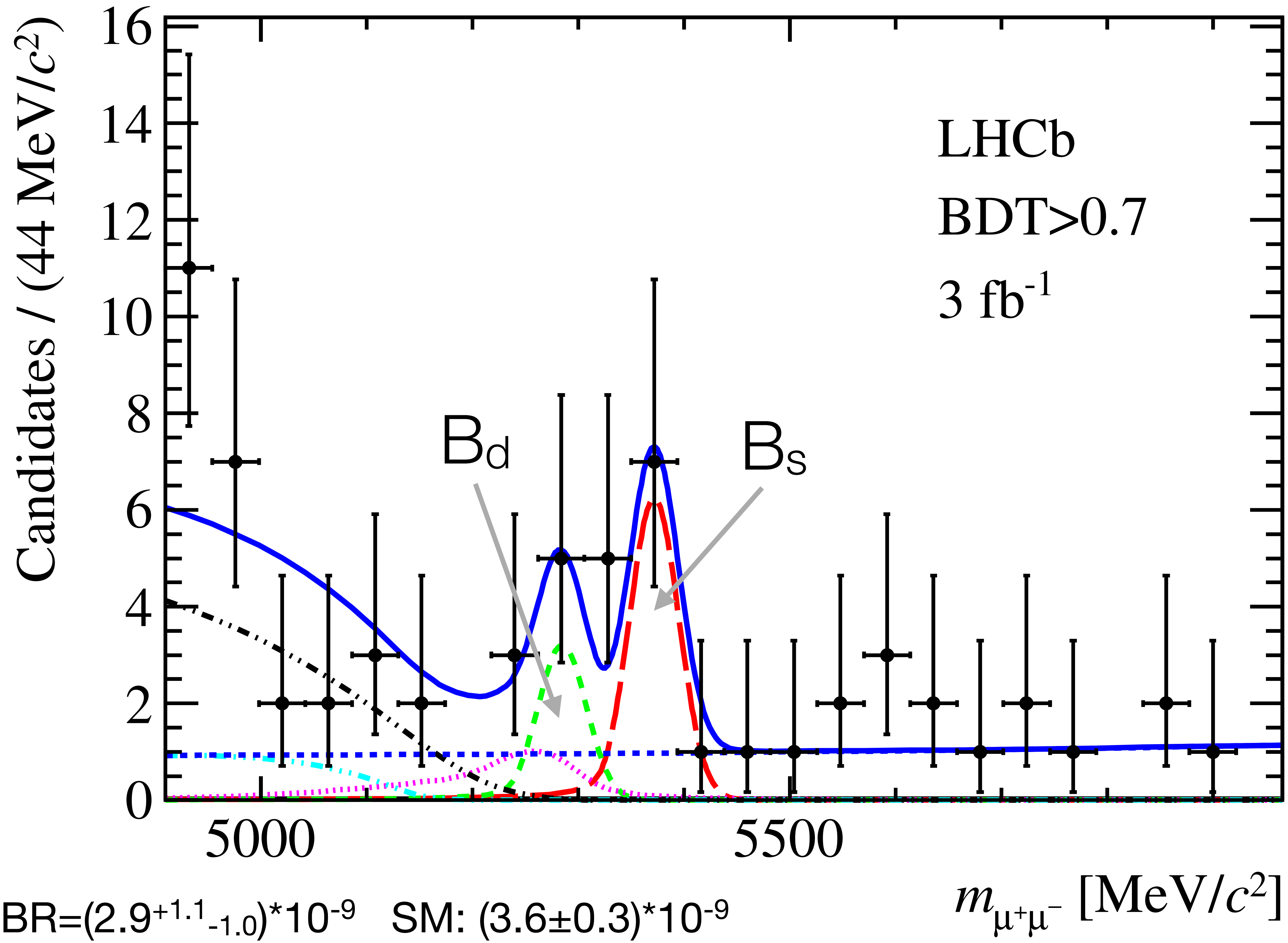


# CMS exotic searches

- similar results from ATLAS

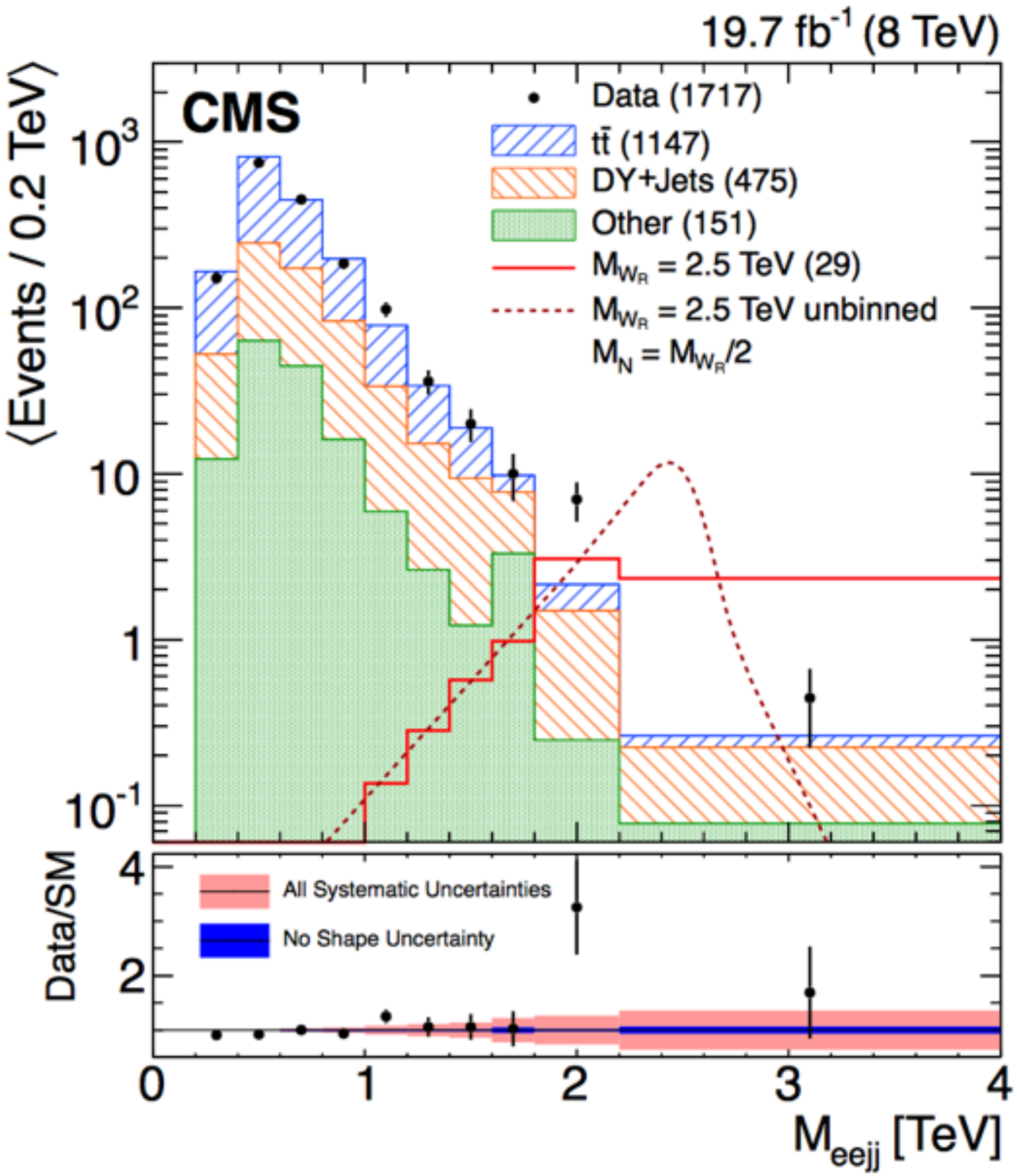


# LHCb $B_{s,d}\to\mu\mu$ with full Run1 data




- $B_s$: BR=$(2.9^{+1.1}_{-1.0})*10^{-9}$   SM: $(3.6\pm0.3)*10^{-9}$
- $B_d$: BR<$7.4*10^{-10}$ @95% CL   SM: $(1.1\pm0.1)*10^{-10}$

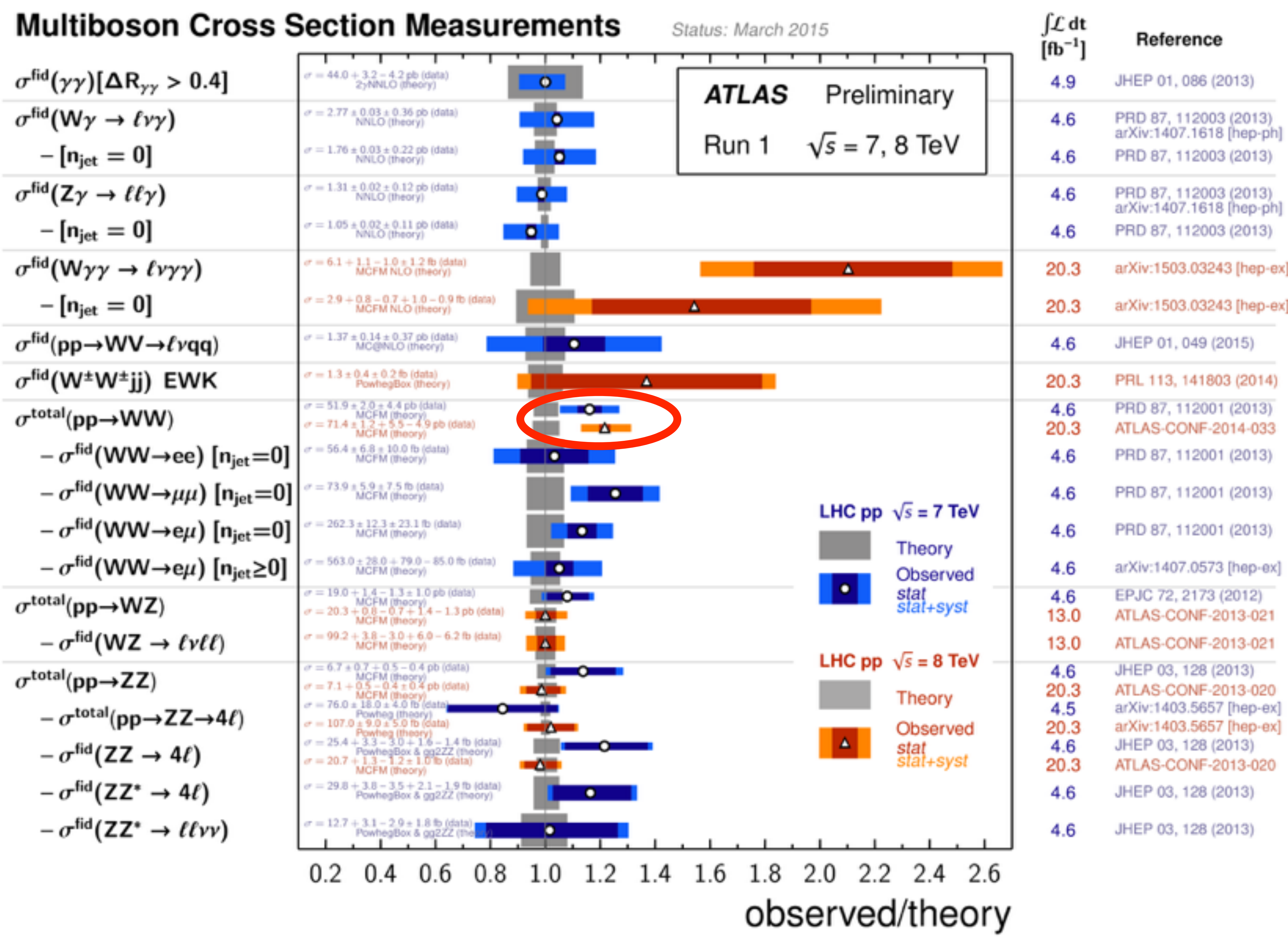
# Fluctuations..




**Search for heavy neutrinos and W bosons with right-handed couplings in proton-proton collisions at sqrt(s) = 8 TeV,**
*Eur. Phys. J. C 74 (2014) 3149*

*(see also CMS ~2 sigma excess in evbb shown yesterday in WH for m>1.8 TeV)*

..



Multiboson Cross Section Measurements
Status: March 2015
ATLAS Preliminary
Run 1 √s = 7, 8 TeV
∫ℒ dt [fb⁻¹]
Reference
LHC pp √s = 7 TeV
Theory
Observed
stat
stat+syst
LHC pp √s = 8 TeV
Theory
Observed
stat
stat+syst
observed/theory
0.2 0.4 0.6 0.8 1.0 1.2 1.4 1.6 1.8 2.0 2.2 2.4 2.6

# .. or anomalies?

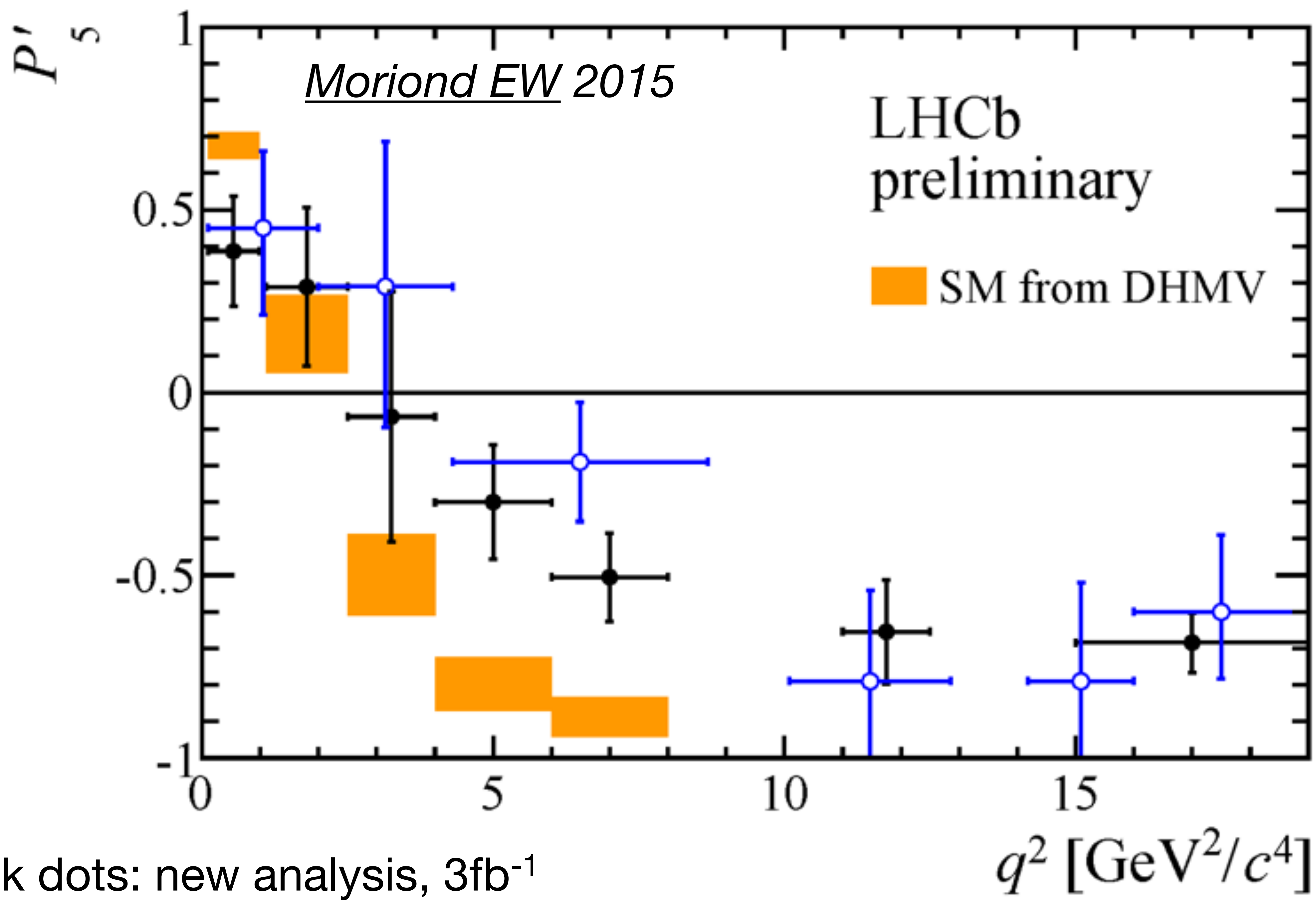
**Explaining the CMS eejj and evjj excess and leptogenesis in superstring inspired E6 models**
*Phys. Rev. D 91, 055010 (2015)*

**Stop that ambulance! New physics at the LHC?**
*JHEP12(2014)010*


*…*

*+ >=1 theory paper for ~any >~2 sigma effect seen so far*

# Not only the energy frontier: $B^0 \to K^{*0}\mu\mu$@LHCb

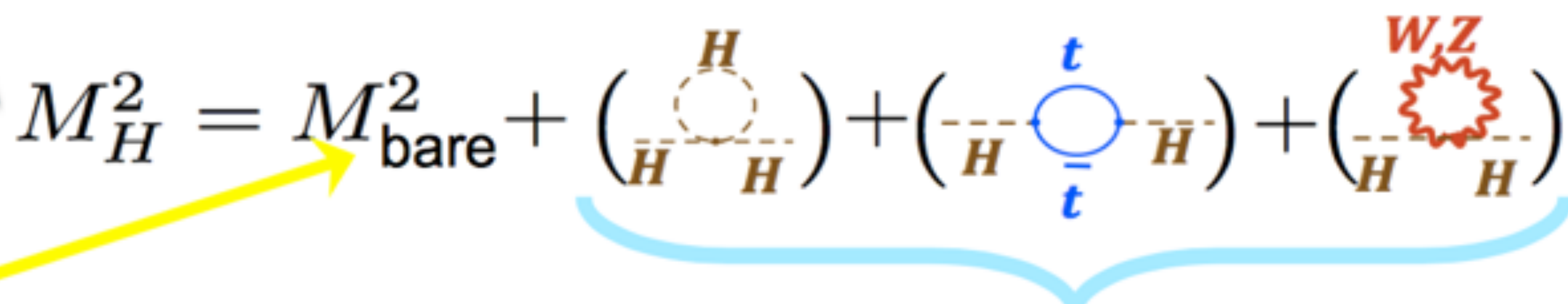



- Black dots: new analysis, 3fb$^{-1}$
- Blue dots: old analysis, 1fb$^{-1}$
- 2.9σ local deviation in 2 neighbouring bins (3.7σ naive combination) wrt SM (recent calculation, arXiv:1407.8526)

# The current landscape and the needs for next run

- The Puzzle: the SM can not be the ultimate theory of particle physics:
  - what is the nature of the dark part (96% !) of the universe ?
  - what is the origin of the matter-antimatter asymmetry ?
  - why is gravity so weak ?
  - why is the Higgs boson so light ("naturalness" problem) ?

Observed mass (~125GeV)




Bare mass to cancel radiative corrections

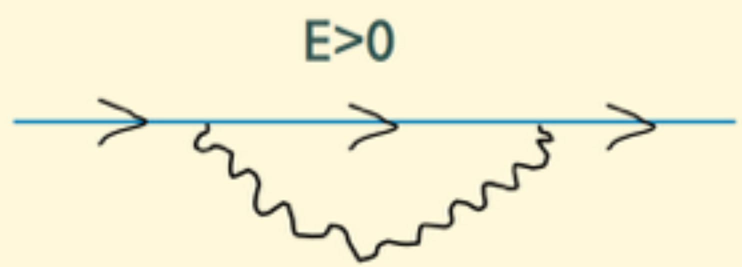
Radiative corrections, top loop dominates: $\sim m_t^2\Lambda^2$
$\Lambda^2$: the energy scale at which the SM breaks down

  - O(.1%) fine-tuning for Λ=10 TeV
- If NP exists at the ~TeV scale, it may be discovered through direct searches
  - higher energy to increase the production cross sections of NP signals
- If NP is at the TeV++ scale, its effects may be visible only in indirect measurements
  - much higher luminosity to do precision studies and search for small signals
- HARD TO MAKE DEFINITE PREDICTIONS…

# SUSY: one way to avoid fine tuning

- a similar “naturalness” problem: the electron mass

*M.L.Mangano,*
*after Murayama*



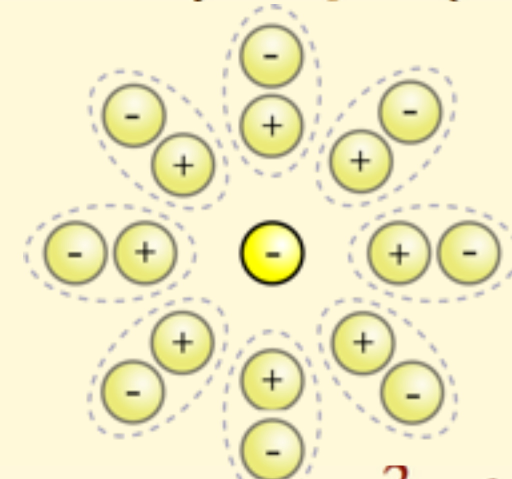

$$\Delta(mc^2)_{Coulomb} \sim \frac{e^2}{r}$$

Requiring:

$$\Delta m < m = 0.5 \text{ MeV}$$

$$\Lambda \equiv 1/r < 5 \text{ MeV}$$

Introduce the positron (Dirac, 1931)



$$\Delta(m)_{E>0 \oplus E<0} \sim e^2 m \log(\Lambda/m)$$

which is a correction of only 10% even at scales of the order of the Plank mass:

$$\Delta(m)_{E>0 \oplus E<0} \sim 0.1\, m$$

at

$$\Lambda = 10^{19} \text{ GeV}$$

- space-time symmetry (Lorentz invariance) ⇒ doubling of spectrum ⇒ reduced dependence on high-momentum physics: may history repeat itself with SUSY?
- more nice features: LSP as a dark matter candidate, gauge coupling unification

# Perspectives for Run2

# LHC activities during the shutdown

- Many consolidation activities to improve reliability at higher energy and rate
  - New dipoles: 18 out 1232 replaced
  - Stronger connections between dipoles: >10k electrical interconnections fitted with shunts to provide an alternative path for I=11kA in case of fault
  - Improved quench protection system to dissipate stored energy in controlled manner when abnormal voltage starts to develop in a magnet
  - Improved cryogenics: consolidation, maintenance of compressors, upgrade of control systems, renovation of cooling plant
  - More radiation-resistant electronics
  - ”Better” vacuum: inside of beam pipe coated with non-evaporable getter (NEG) to capture electrons. In places, solenoids wrapped around the beam pipe to keep electrons from deviating from the sides.
- Huge test program (electrical QA, electrical resistance measurements, leak tightness tests..)

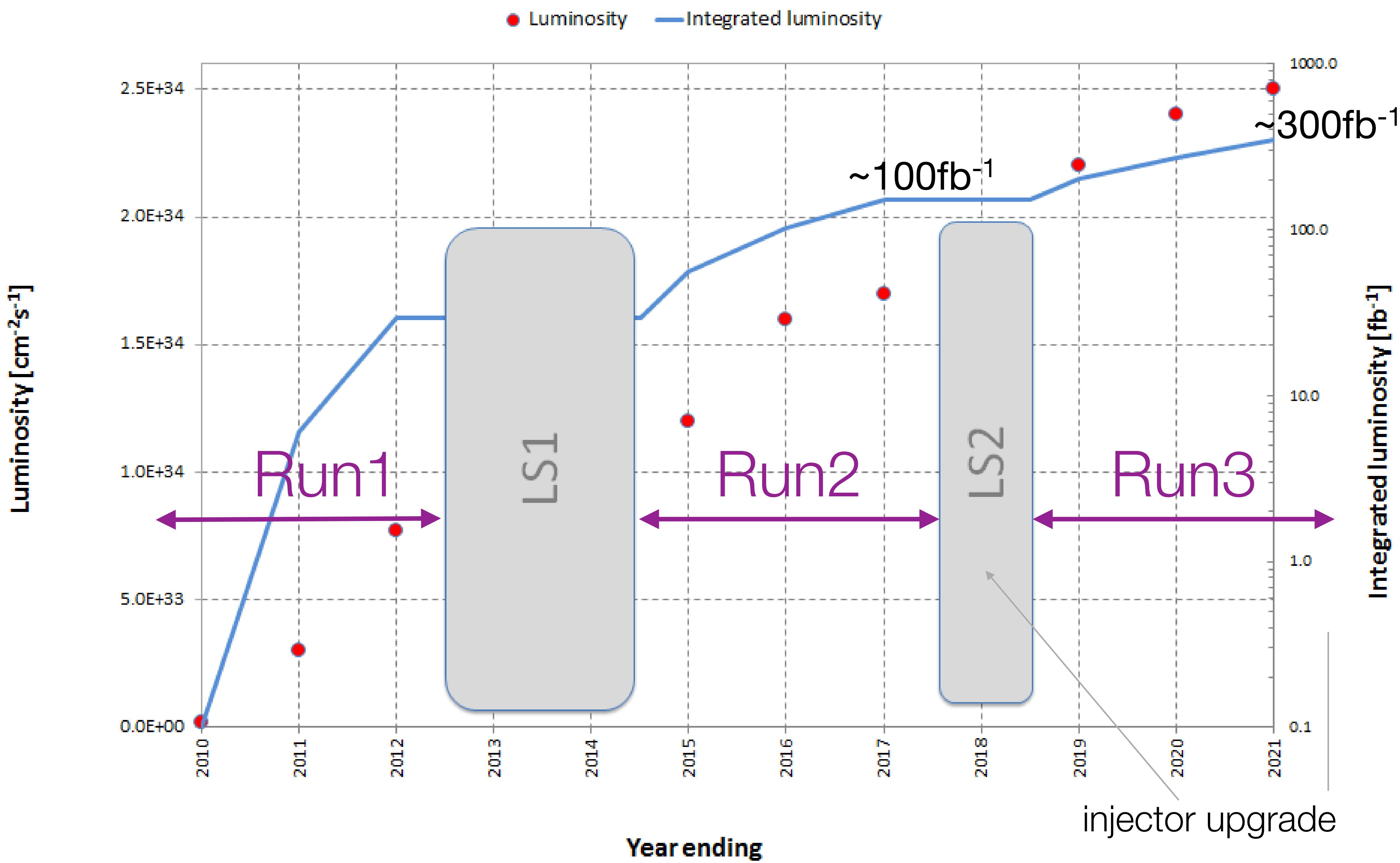
# LHC plans for Run2

- Higher energy: 6.5 TeV/beam vs 4 TeV/beam [possibly 7 TeV/beam after 2015]
  - operate radio frequency cavities at higher voltages
- Higher peak luminosity: $1.5 \times 10^{34}$ vs $7 \times 10^{33}$ $cm^{-2}s^{-1}$
  - Narrower beams: β* = .4m vs .6m
    - transverse beam size decreases with increasing energy
  - Closer (2x) proton packets (so 2x more bunches): 25 ns instead of 50 ns
    - slightly less populated ($1.2 \times 10^{11}$ vs $1.7 \times 10^{11}$ p/beam) to mitigate pile-up
- Performance to be achieved gradually through 1st year of operation (2015)
  - start first with 50ns separation, β* = 0.8m and improve gradually
  - commission beam with reduced emittance (1.65) for 2016 (~45 $fb^{-1}$/year)
- Beams back to LHC last weekend (at SPS energy) !

| Beam | $N_p$ ($10^{11}$) | ε* (μm) | $N_b$ | β* (m) | $L_{peak}$ ($cm^{-2}s^{-1}$) | μ | Days | $L_{int}$ ($fb^{-1}$) |
|---|---|---|---|---|---|---|---|---|
| 50 ns | 1.2 | 2.5 | 1368 | 0.8 | 4.8E+33 | 25 | 21 (Jun) | 0.5 |
| 25 ns | 1.1 | 2.5 | 2448 | 0.8 | 7.2E+33 | 21 | 30 (Aug) | 3 |
| 25 ns | 1.1 | 2.5 | 2448 | 0.4 | 1.2E+34 | 34 | 48 (Oct-Nov) | 8 |

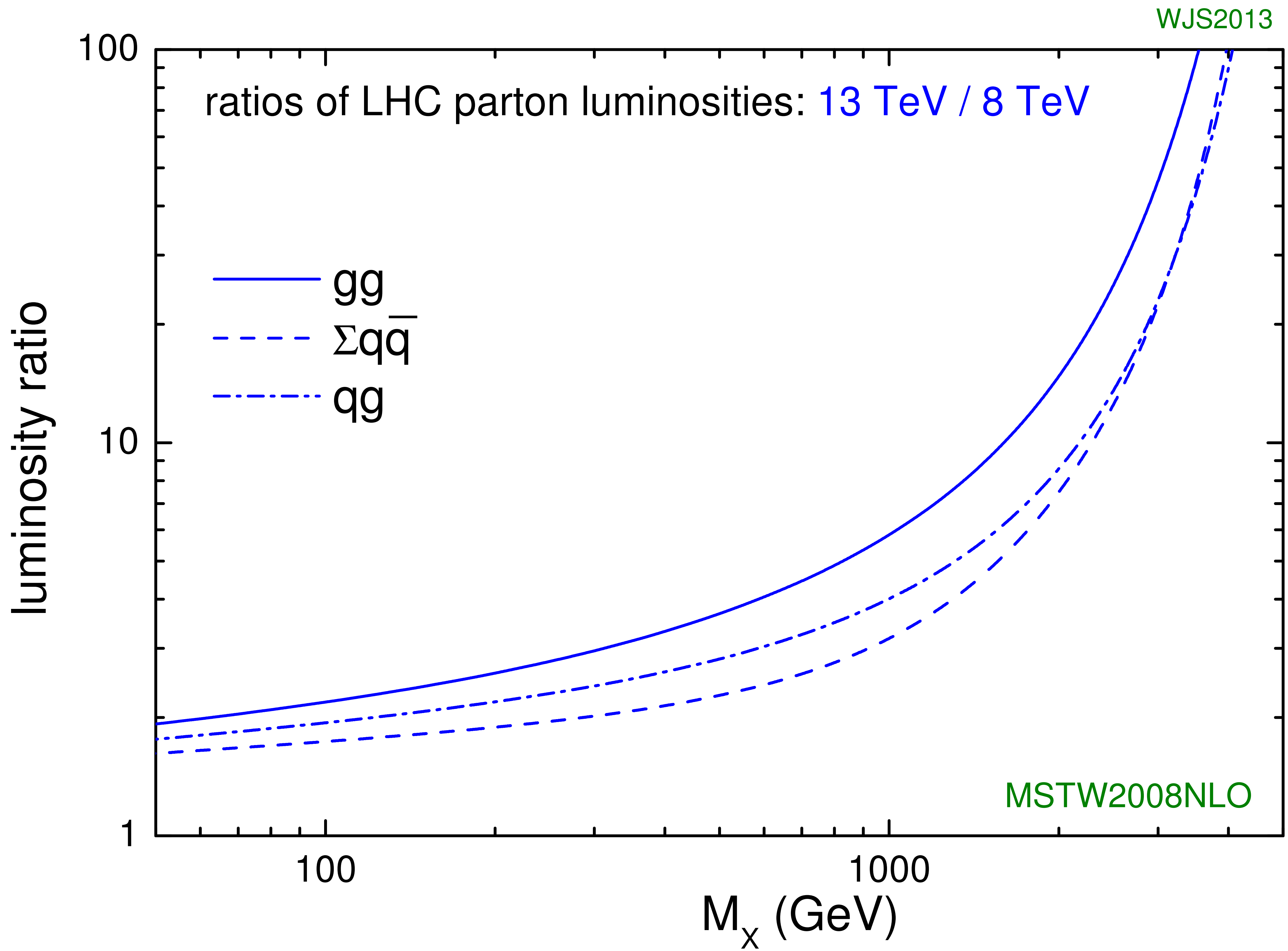
http://lhc-commissioning.web.cern.ch/lhc-commissioning/performance/2015-performance.htm

# LHC Run2 (and beyond) schedule

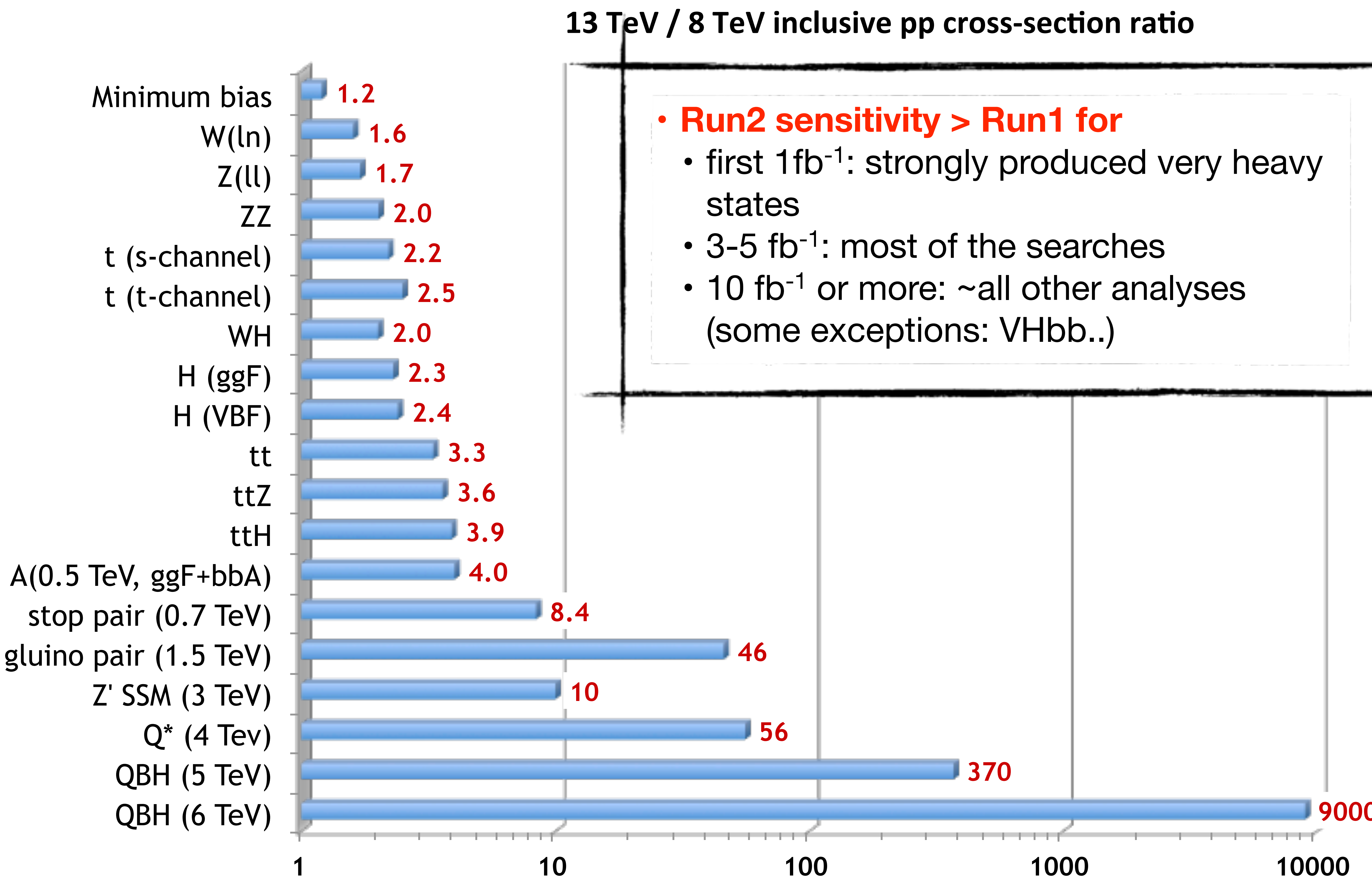



- some uncertainty on length of end-of-year breaks. Usual caveats apply..

# Why higher energy?

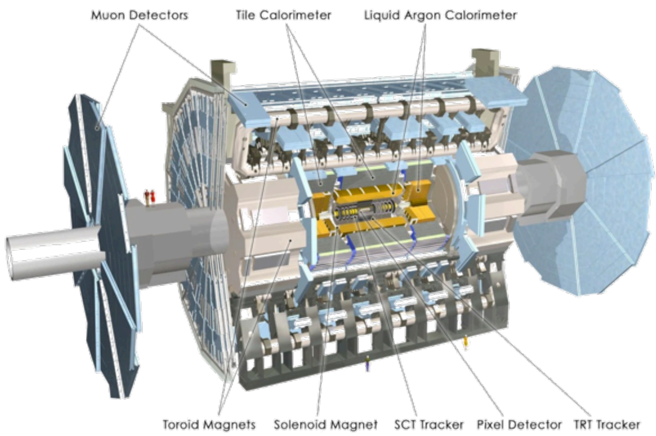


# Why higher energy?

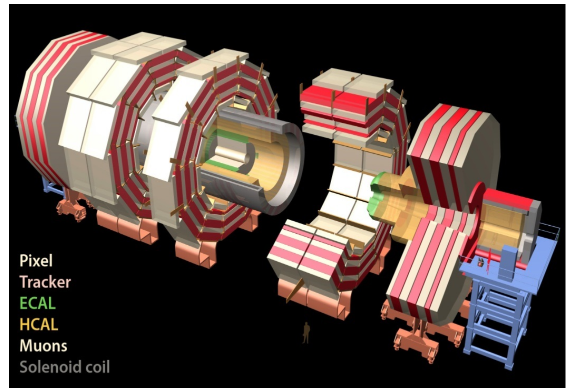



- **Run2 sensitivity > Run1 for**
  - first 1fb$^{-1}$: strongly produced very heavy states
  - 3-5 fb$^{-1}$: most of the searches
  - 10 fb$^{-1}$ or more: ~all other analyses (some exceptions: VHbb..)

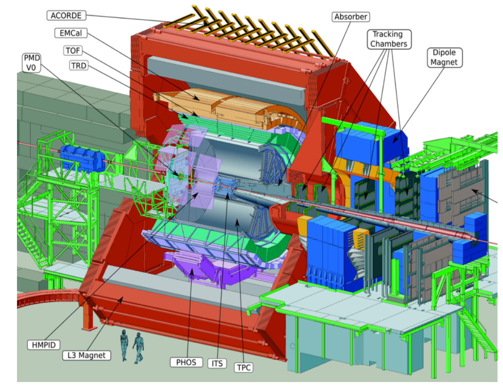
# Detector activities during the shutdown



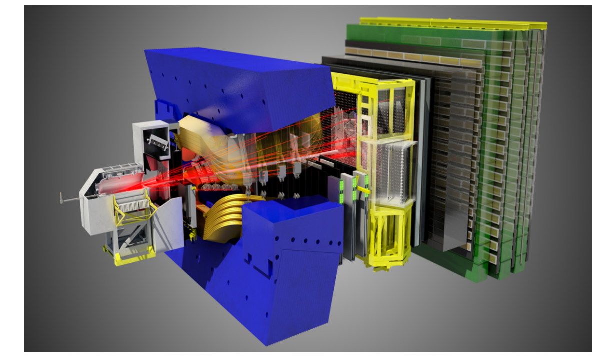

- new, smaller, thinner beam pipe
- 4th pixel layer at smaller radius
- installation of a final layer of muon chambers in one of 2 endcaps




- improved tracker cooling system to go from +4C to -15/-20C
- new beam pipe
- upgraded HCAL photodiodes with better S/B
- completed muon system (4th RPC disk in endcap)



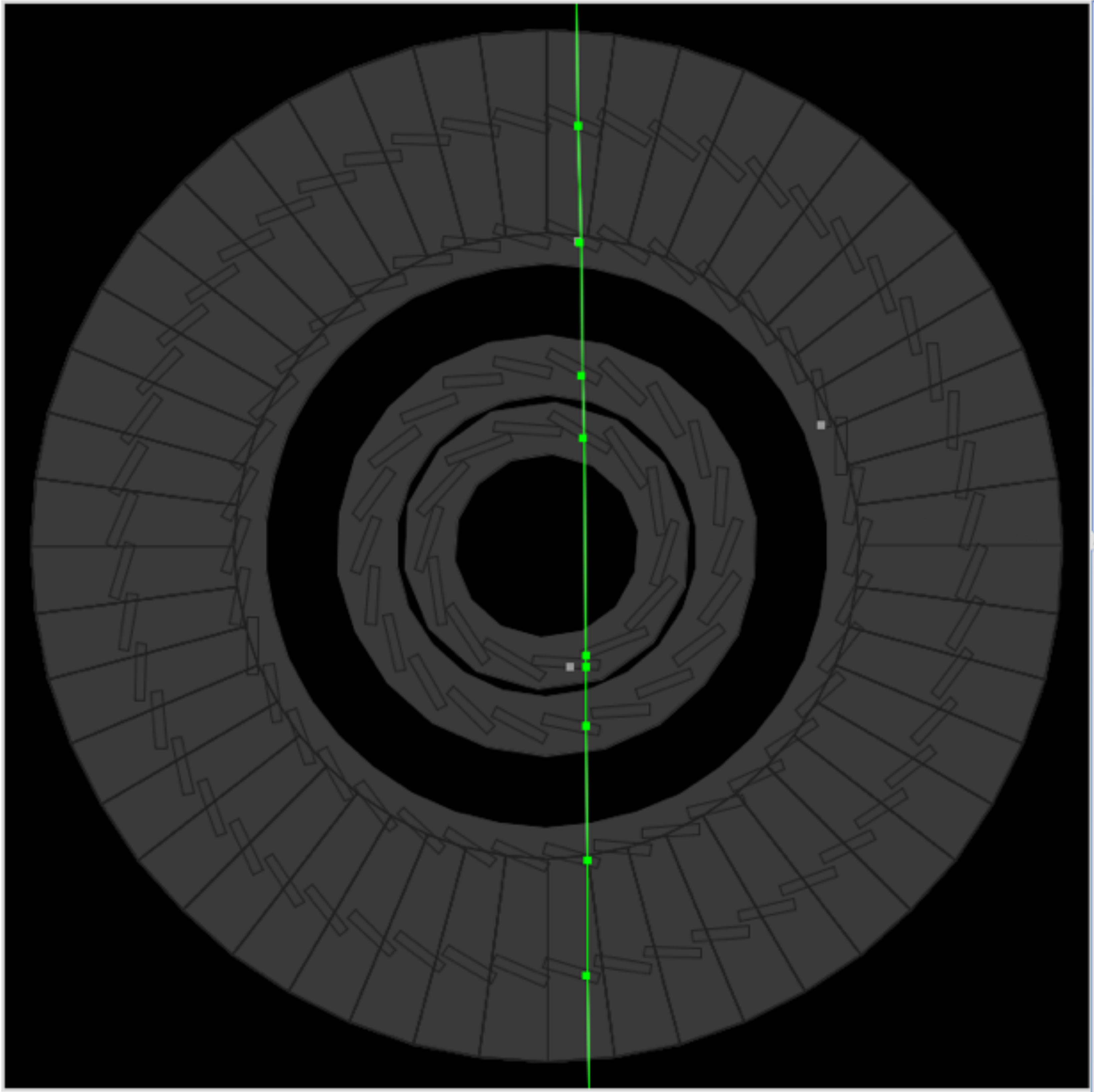
- upgrade to DAQ to double the rate
- better vacuum (NEG coating)

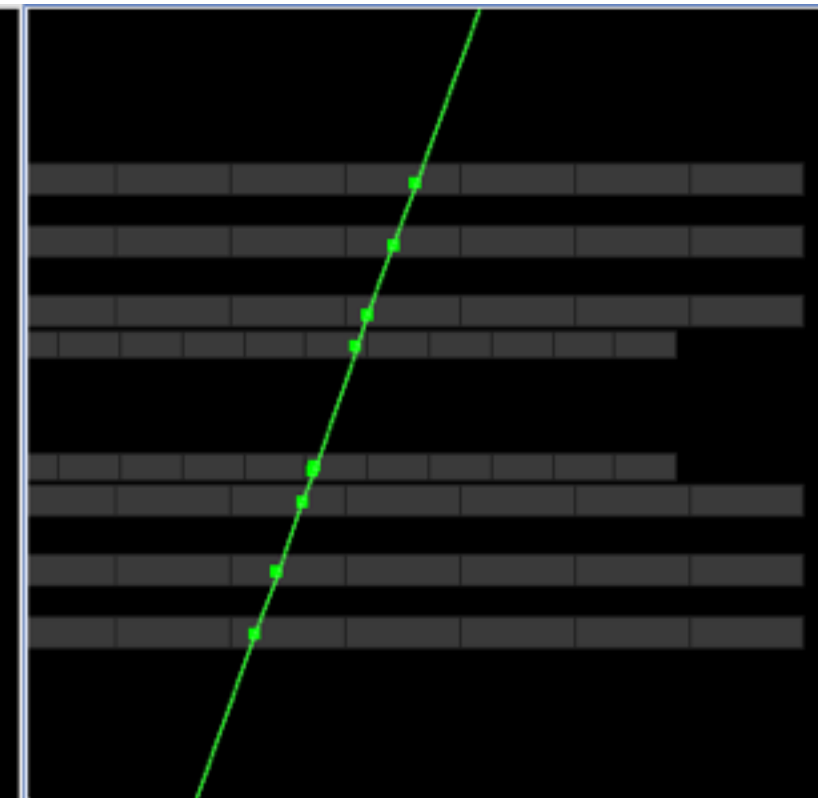


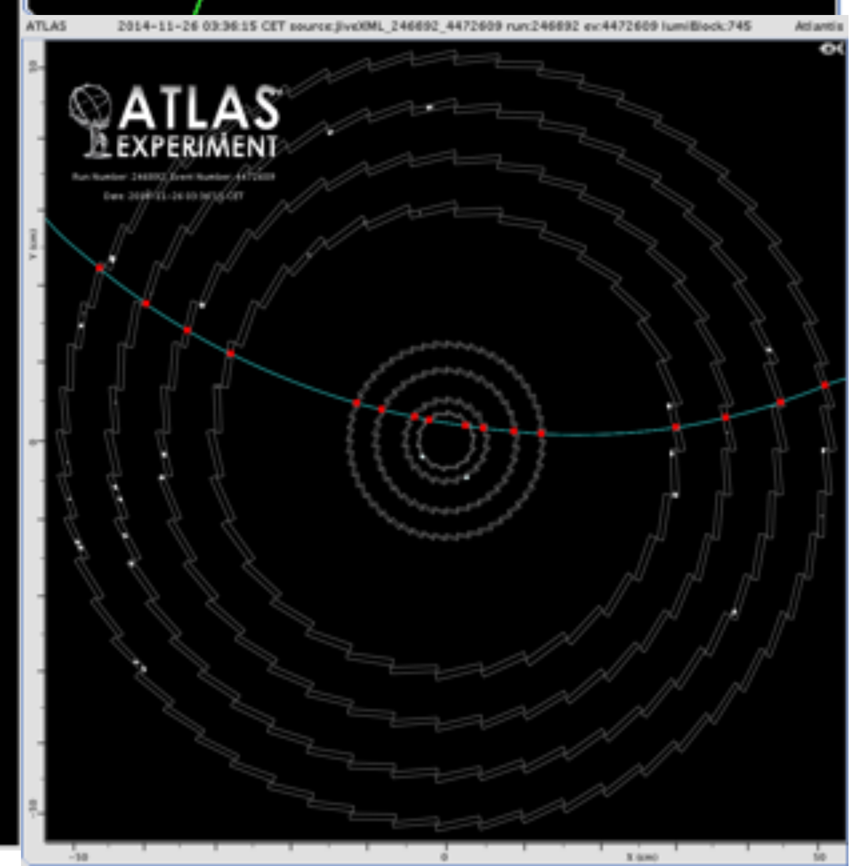
- new beam pipe
- magnetic field map measurement for improved track reconstruction

Retuning of the reconstruction and trigger algos for higher pile-up and bkg

# Commissioning the ATLAS IBL with cosmics







# The ATLAS and CMS physics programme in Run2

- Two main goals:
  - Extend the studies of the recently discovered 125 GeV Higgs boson
  - Search for NP as deviations from SM in the Higgs sector or elsewhere
- A rich physics program, including:
  - SM (non-Higgs)
    - high-energy EW, QCD, top production
    - rare processes: vector-boson scattering, triboson production ⇒ anomalous triple/quartic couplings, FCNC top decays, ..
  - H(125) Higgs boson
    - precise measurement (>5$\sigma$) of fermionic channels (bb,$\tau\tau$)
    - ttH ⇒ $y_t$
    - rare decays ($\mu\mu$, Z$\gamma$)
    - couplings and differential xsections
  - BSM extended Higgs sector
    - High mass 2HDM/MSSM neutral bosons: $\gamma\gamma$, WW, ZZ, $\tau\tau$, bb, $\mu\mu$ ..
    - Cascade Higgs decays: A→Zh→ll$\tau\tau$, llbb.. / H→hh→$\gamma\gamma$bb, 4b, bb$\tau\tau$, $\gamma\gamma$VV, ..
    - Charged Higgs: Wh, WZ, AW ..
    - Invisible decays: ZH→ll+ETmiss, VH→jj+ETmiss, VBFH→jj+ETmiss ..
    - LFV decays: $\tau\mu$, $\tau$e, e$\mu$
  - Direct searches
    - excited quarks, gravitons: dijet, photon+jet, diphoton resonances
    - heavy bosons (Z'): ll resonances
    - supersymmetric particles

# Selected perspectives

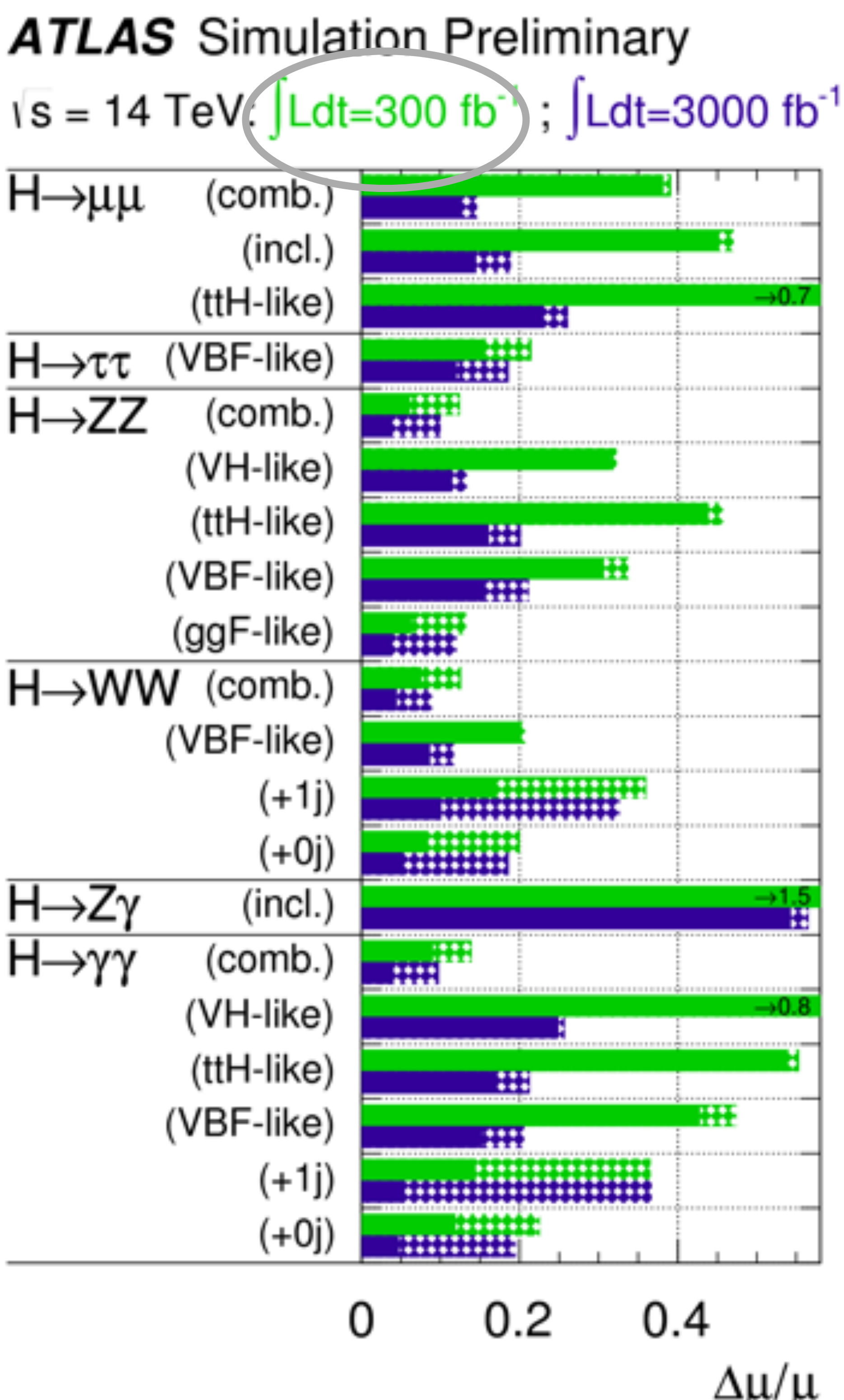
- Next slides based on prospect studies:
  - ATLAS (arXiv:1307.7292)
    - parametric simulations
    - similar analysis as Run1 (do not include improvements due to new techniques, improved understanding of bkg, reduced theory uncertainties)
  - CMS (arXiv:1307.7135)
    - extrapolation from Run1 current results with assumptions on errors
      - scenario A = same as Run1
      - scenario B = $\Delta$theory/2, rest $\propto 1/\sqrt{L}$

- ATLAS and CMS scenario A bay be somewhat pessimistic (no retuning..)

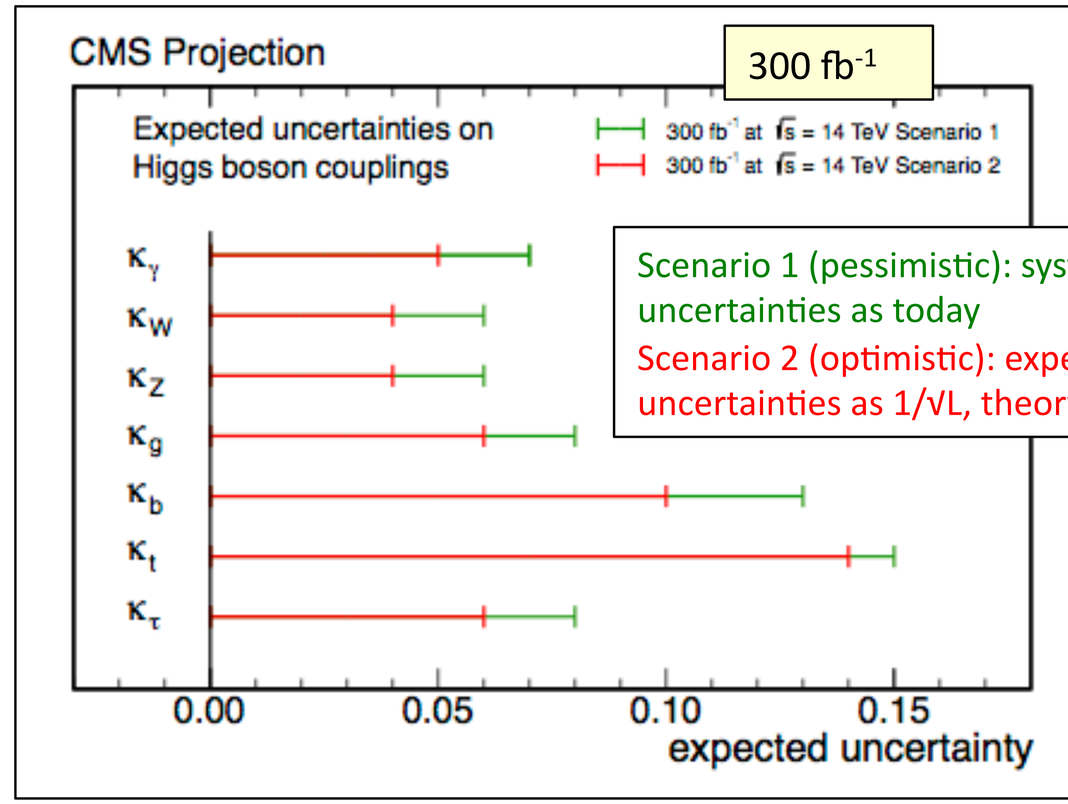
- Studies were done for both 300 $fb^{-1}$ and for the long-term high-luminosity (and high pile-up!) phase (3000 $fb^{-1}$, 2025-203x)
  - many plots are for 3000 $fb^{-1}$, but numbers are given also for 300 $fb^{-1}$ and are then (roughly!) extrapolated to 100$fb^{-1}$

# Higgs boson precision measurements

## signal strength



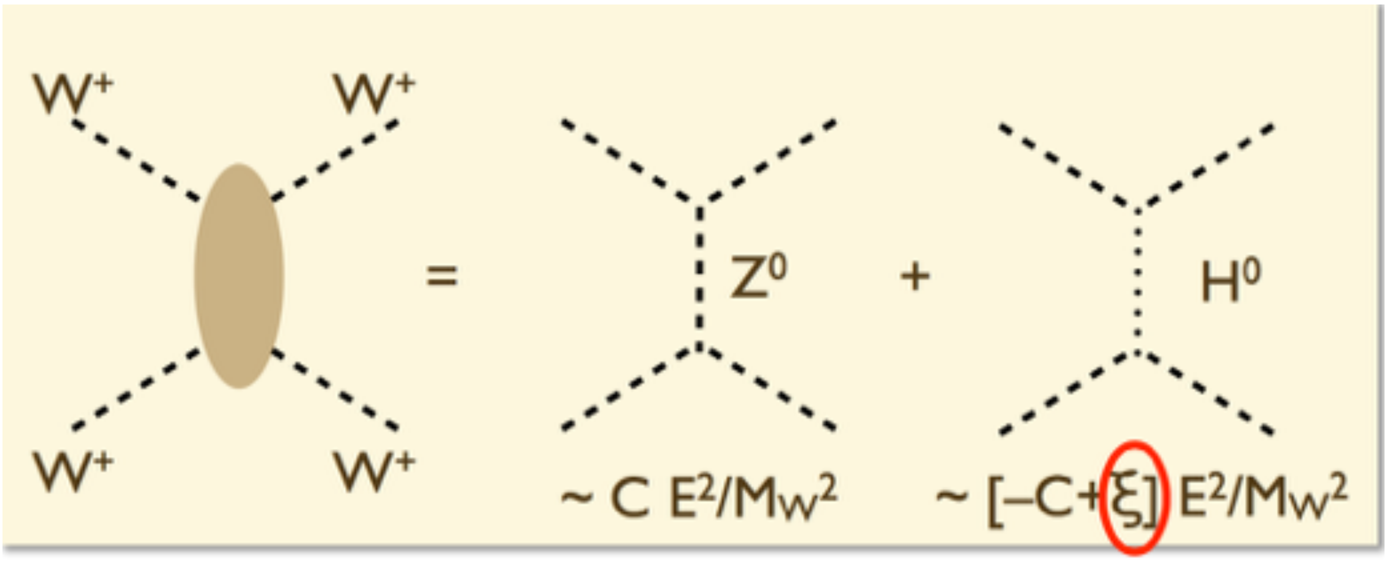

## couplings



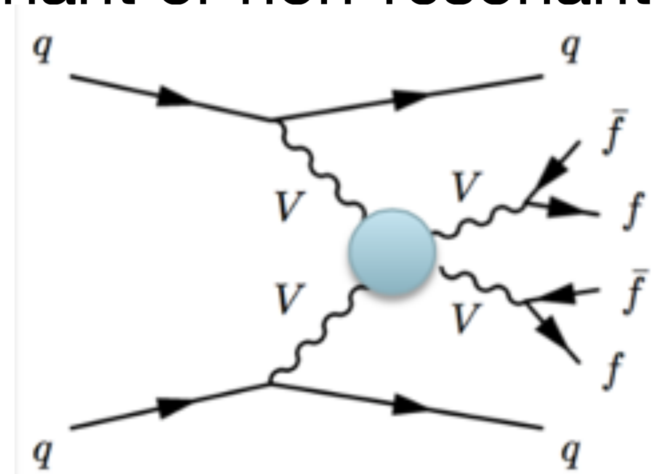

Scenario 1 (pessimistic): systematic uncertainties as today
Scenario 2 (optimistic): experimental uncertainties as 1/√L, theory halved

- $k_i$ = coupling normalised to SM value
- 100 $fb^{-1}$ is a factor 1.5 larger
- expected sensitivity with 100 $fb^{-1}$: 7-25%
- $k_\mu$: ~35-40%

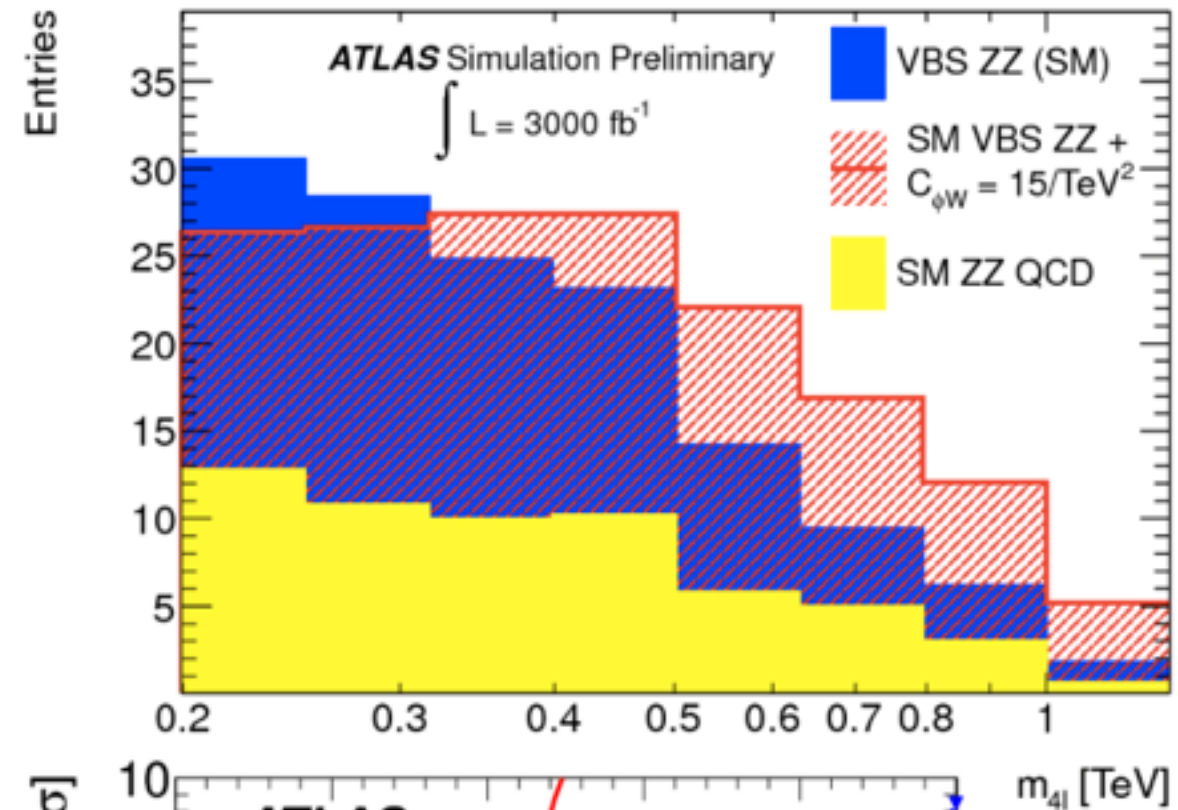
# Precision EW measurements: VBS

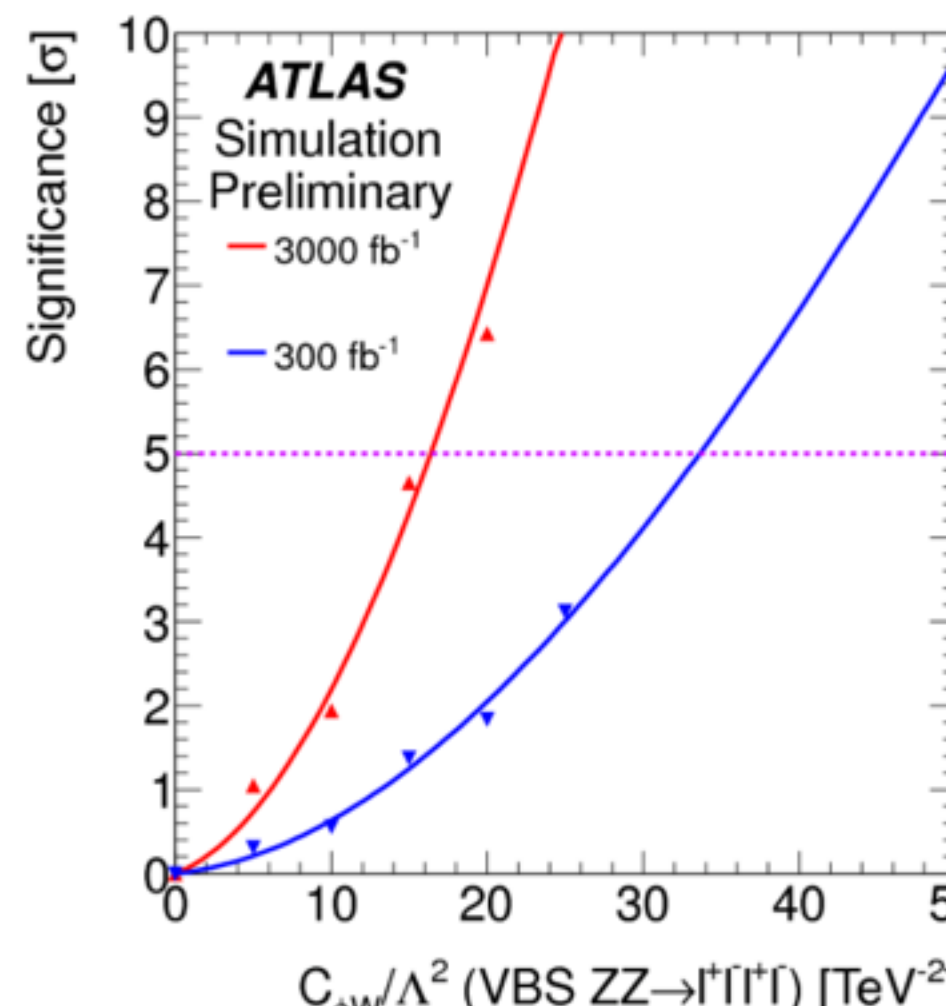



- In SM with Higgs, ξ=0; ξ≠0, would be sign for new (resonant or non-resonant) physics
- Analysis:



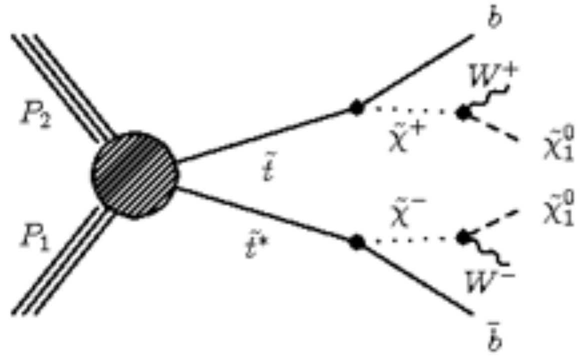

  - At least 2 high-$p_T$ jets (>50 GeV), forward, large invariant mass (> 1 TeV)
  - leptonic final states for better S/B: ZZ (4l), WZ (3l), WW (2l, same-sign)
  - bkg from non-VBS diboson + jet

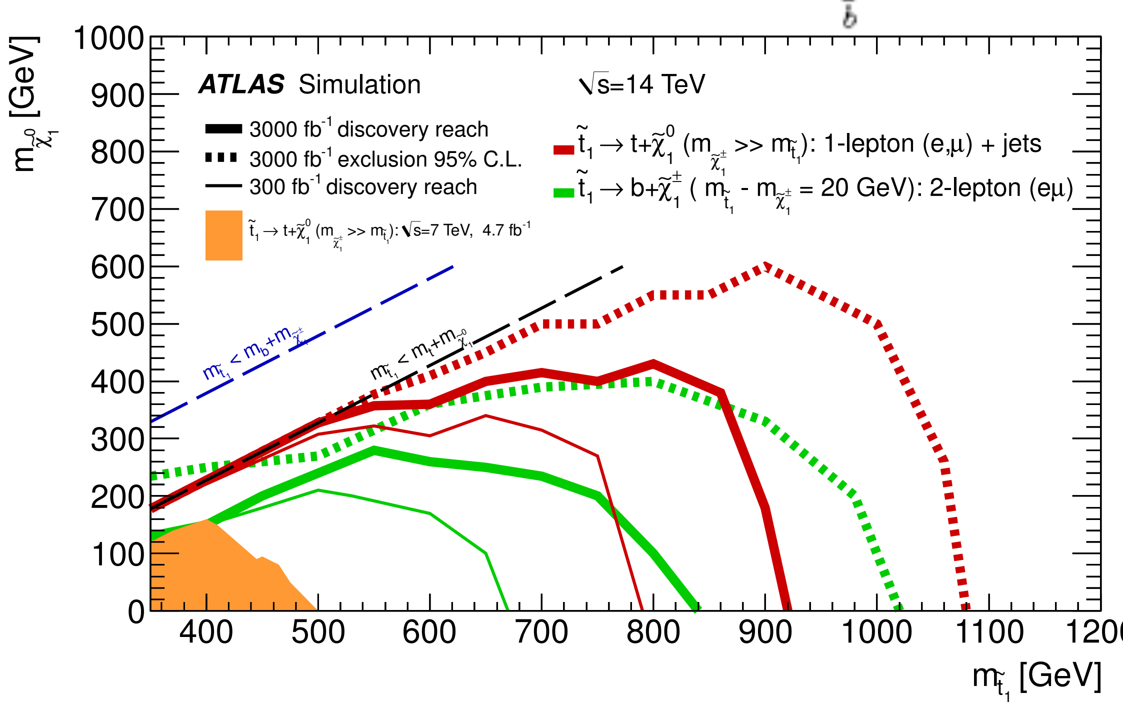


# SUSY searches

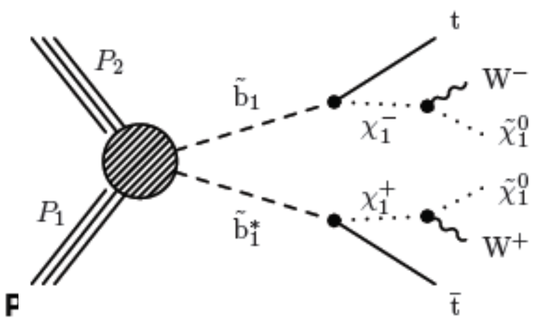
- direct stop production

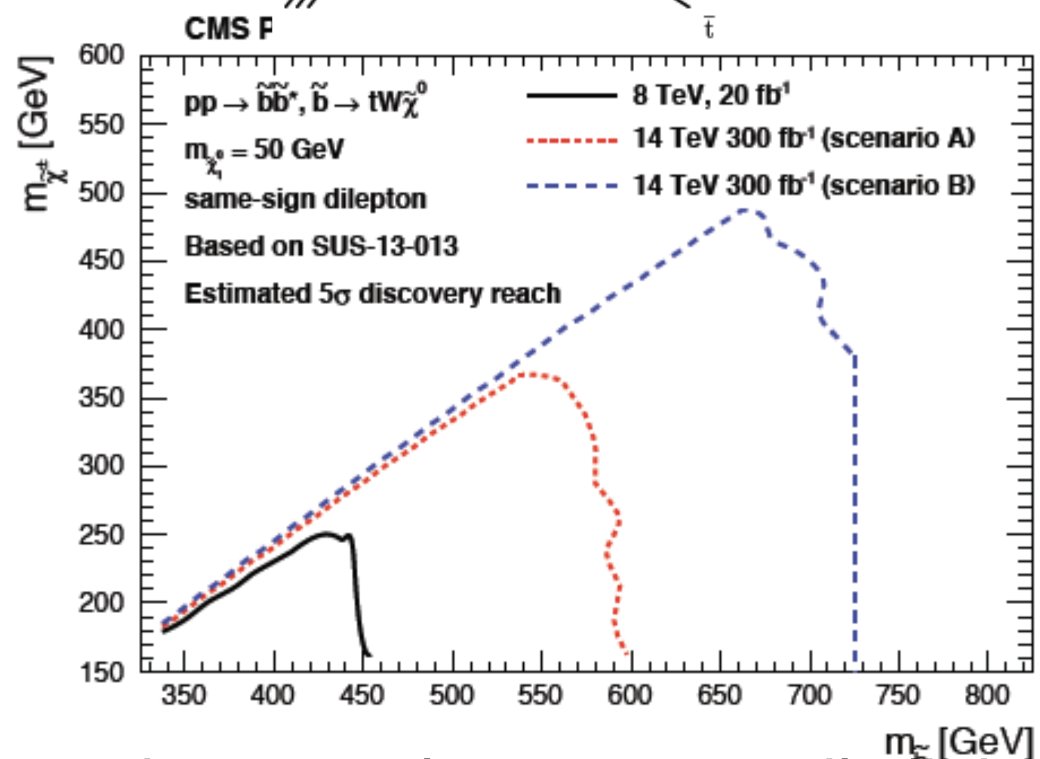





- naturalness ⇒ light (<1 TeV)
- challenging due to top bkgs
- 5σ discovery up to ~800 GeV in direct production with 300 fb$^{-1}$, ~700 GeV with 100 fb$^{-1}$

- direct sbottom production

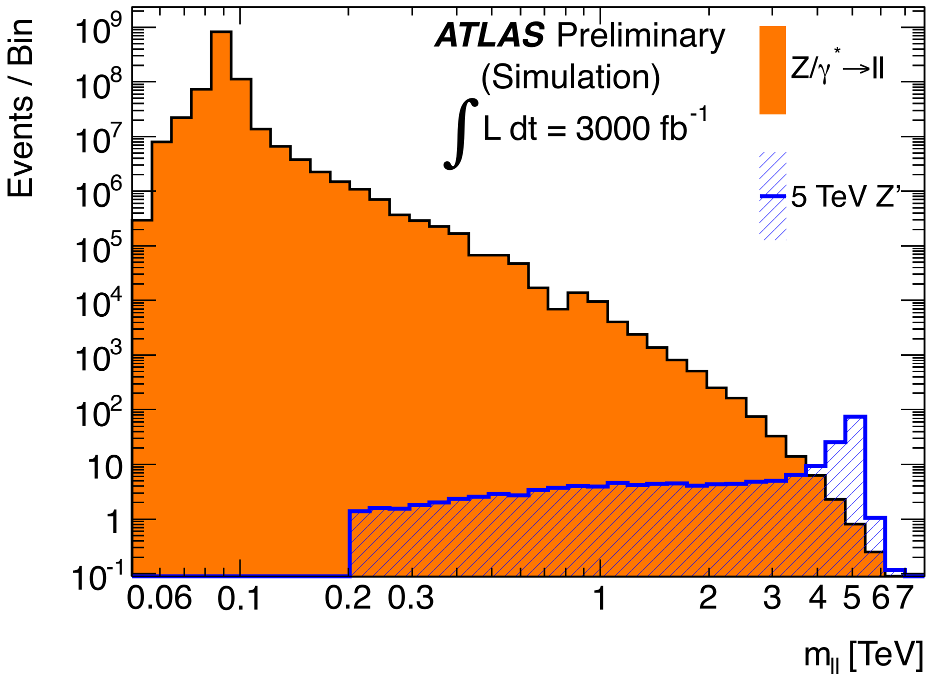


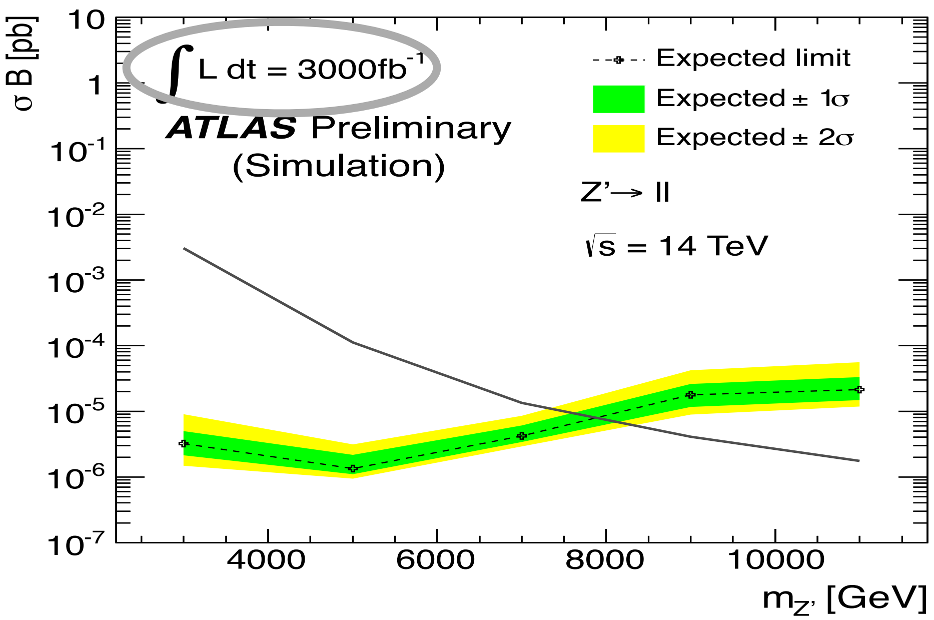



- sbottom also supposedly light due to mixing with stop
- final state: same-sign lepton pair, jets, b-tags, MET
- discovery for m(sbottom) up to 500+ GeV

# Heavy boson searches

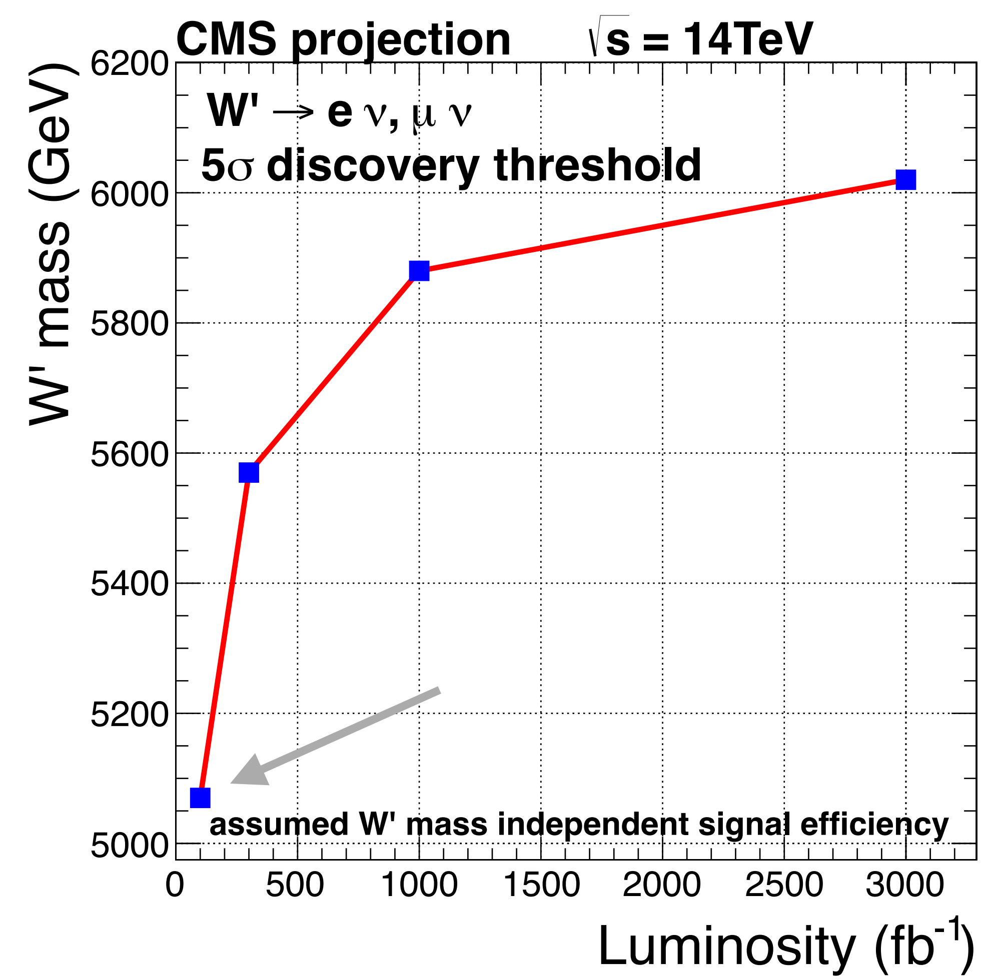
- Z’→ee, μμ




- <~5 TeV excluded with 100 $fb^{-1}$ for both ee and μμ

- W’→eν, μν
  - search for Jacobian peak in transverse mass, bkg from tails due to SM W




- <~5 TeV excluded with 100 $fb^{-1}$

# Conclusion

- A tremendous effort was produced during LHC Run1, leading to
  - the discovery of a (the?) Higgs boson
    - in excellent agreement with SM predictions
    - completing the SM
    - providing an explanation for EW symmetry breaking & mass generation
  - no evidence for BSM physics despite the wide-range searches
- There are reasons for believing that the SM is not the ultimate theory and that whatever is behind it may be in the TeV range
- Increasing the LHC energy to 13-14 TeV and the luminosity by an order of magnitude will significantly extend the reach of the direct searches and the accuracy of the indirect ones