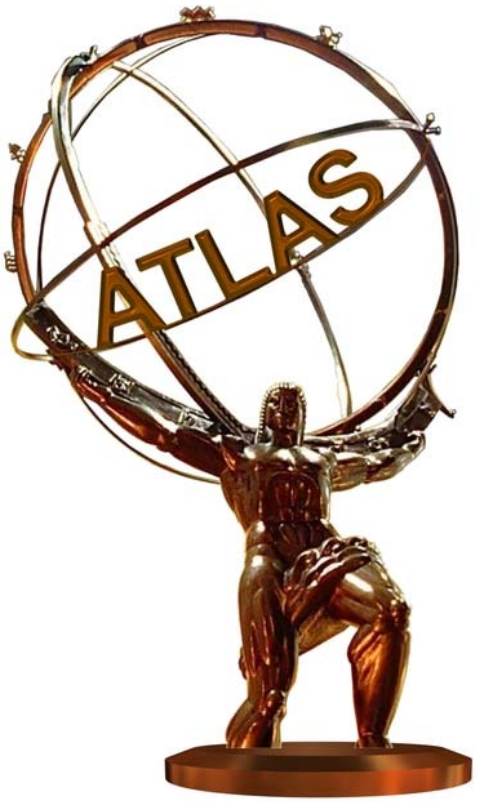
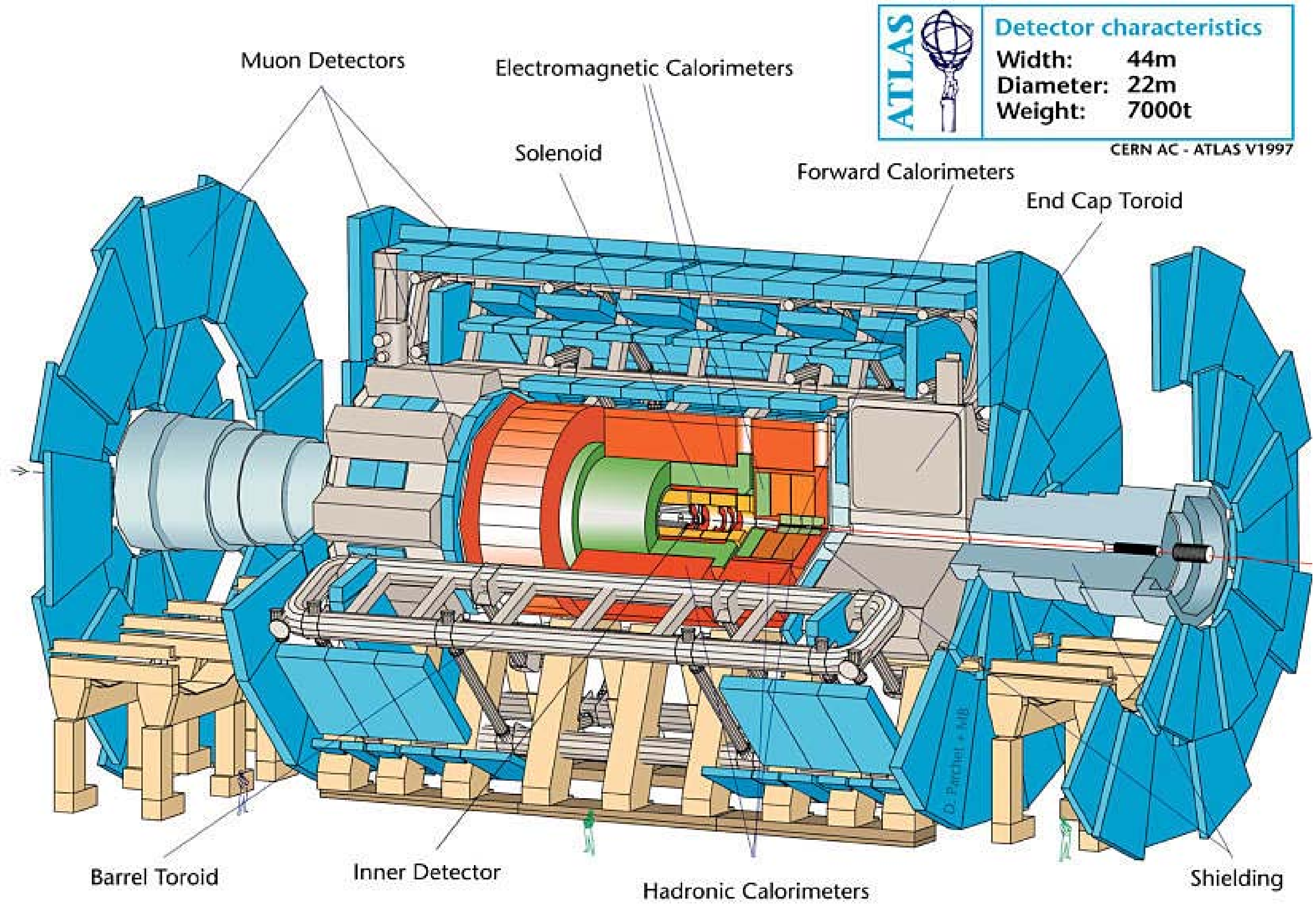
ATLAS Status and Results in the Dawn of Run 2



Thomas J. LeCompte
High Energy Physics Division
Argonne National Laboratory

(On behalf of the ATLAS Collaboration)

ATLAS Detector



Detector characteristics

Width: 44m

Diameter: 22m

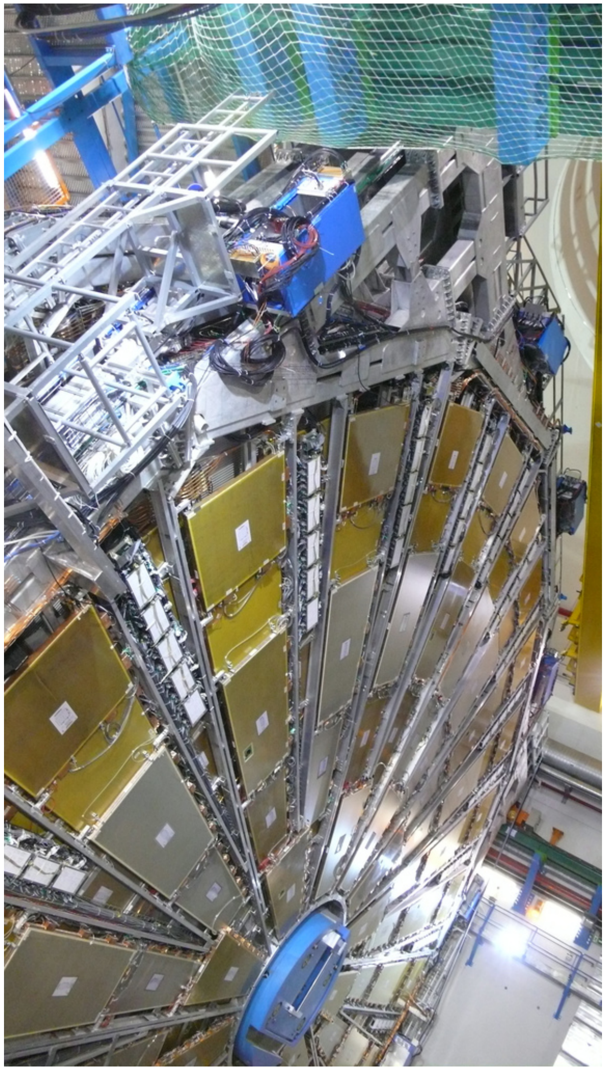
Weight: 7000t

CERN AC - ATLAS V1997

Muon Detectors

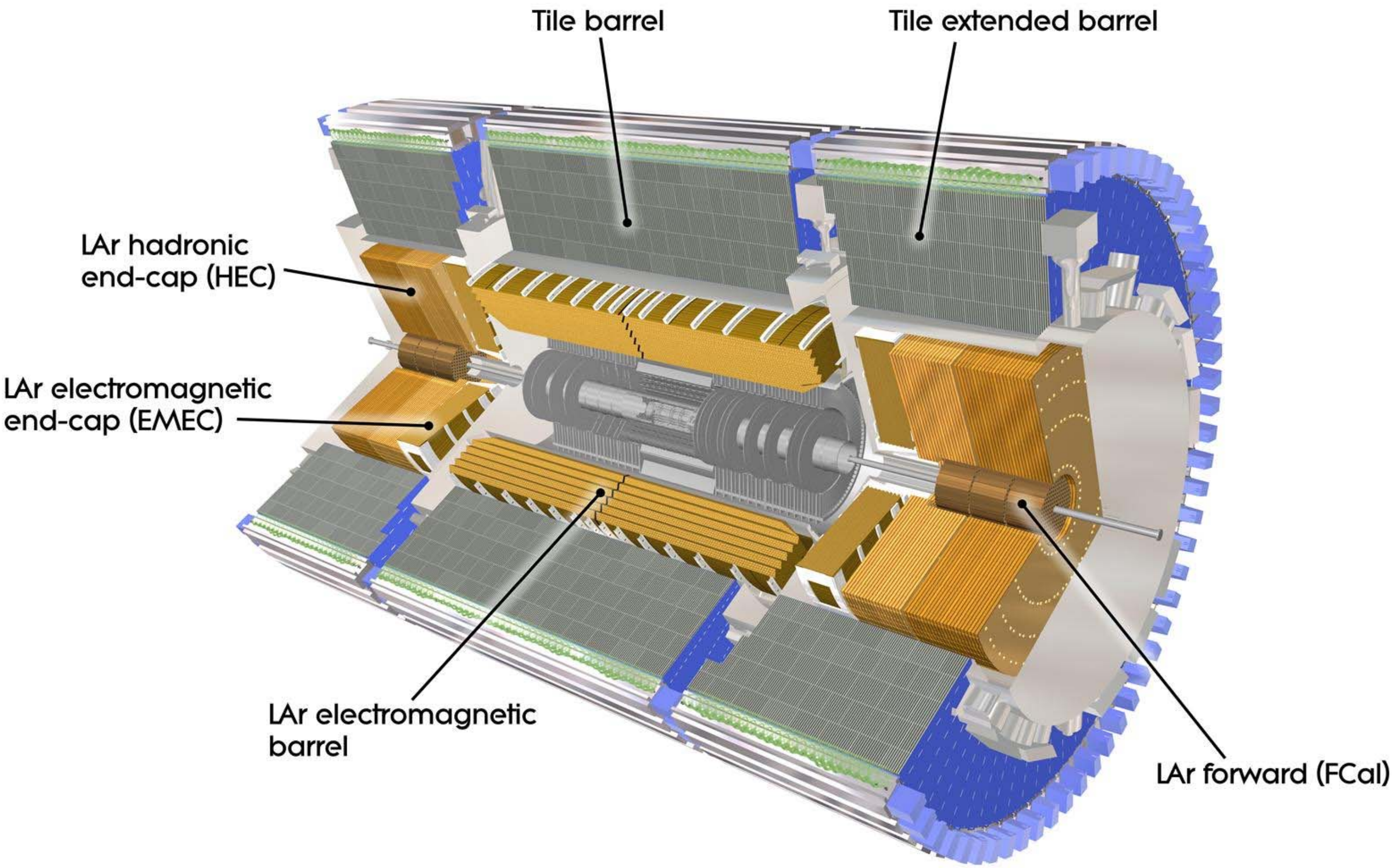
The “Small” Wheels

One of the Big Wheels

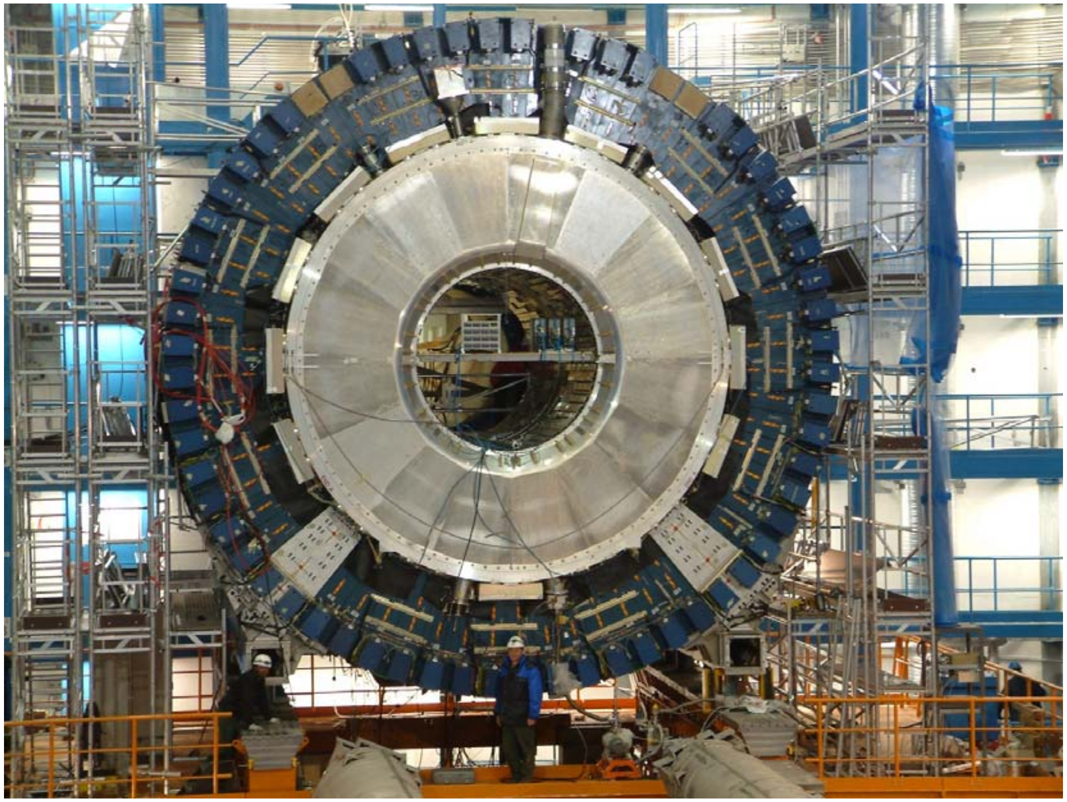


Key idea: good momentum resolution at high momentum → air-core toroids

ATLAS Calorimeters (Size of a house)



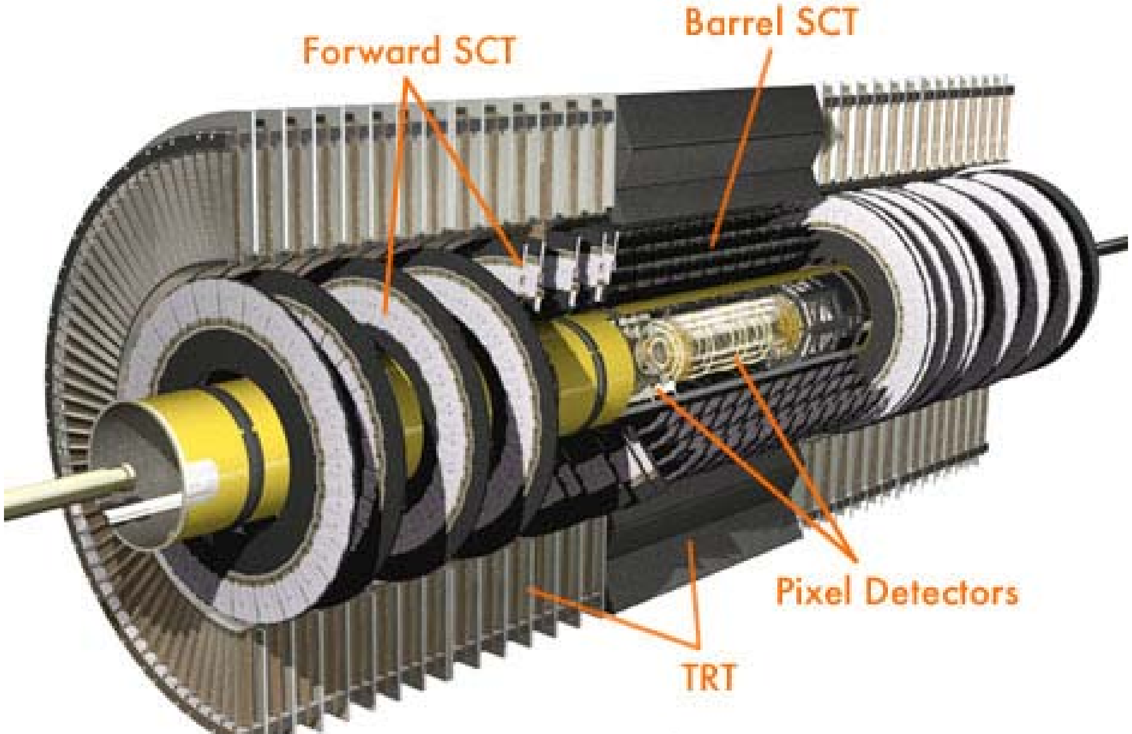
ATLAS Calorimeters

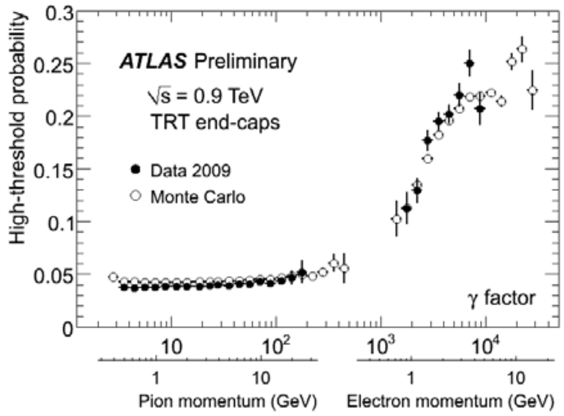


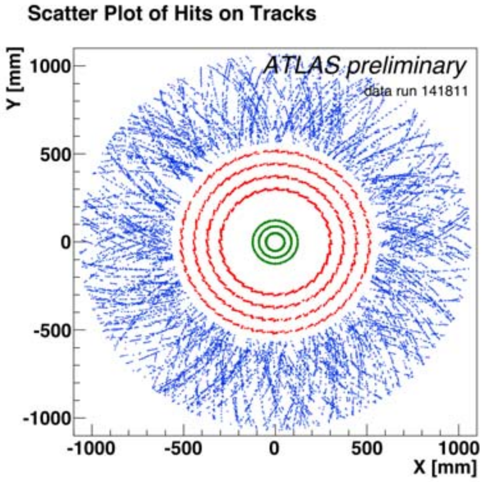
Key idea: good energy resolution and excellent background rejection

→ large radius and depth segmentation

Run 1 ATLAS Inner Detector (size of a small car)

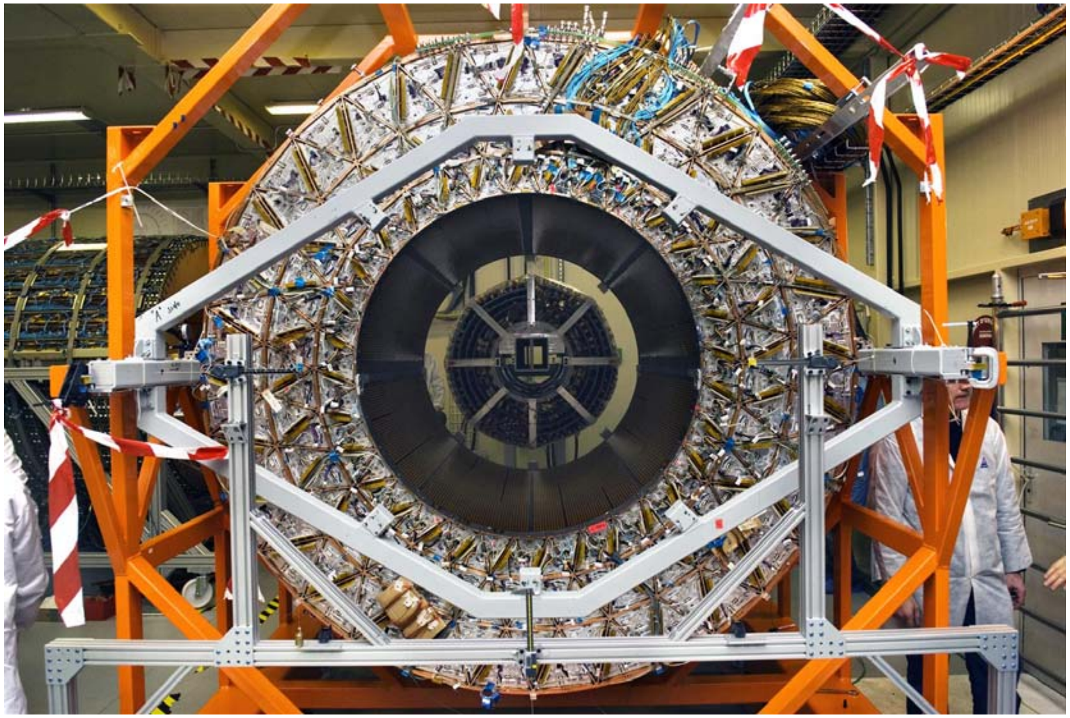


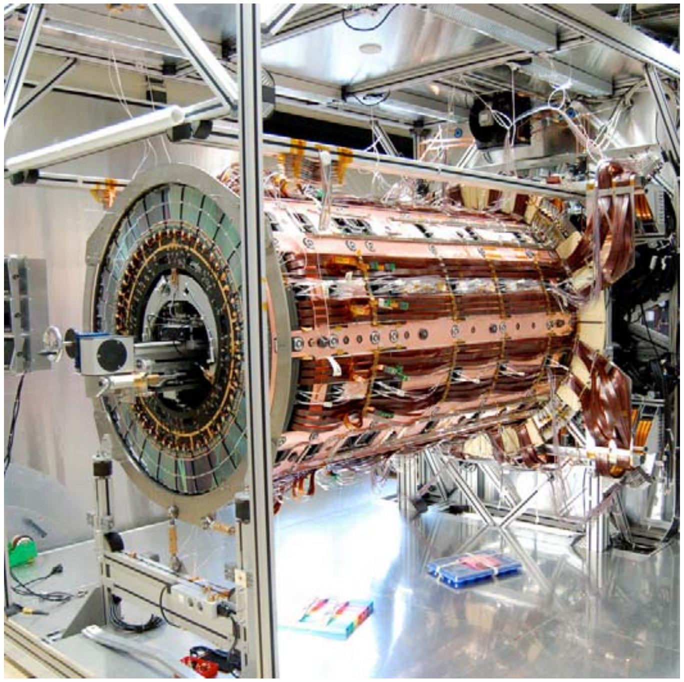


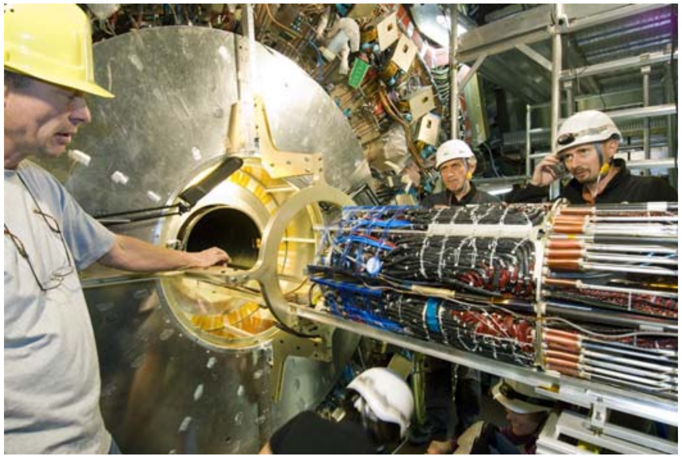

Scatter Plot of Hits on Tracks

- Pixels
  - 3 barrel layers
  - 2x3 end-cap disks
  - $\sigma_{r\text{-}\phi}$ ~ 10 μm; σ_z ~115 μm
- Semiconductor Tracker (SCT)
  - -Silicon strips
  - 4 barrel layers; 2x9 end-cap disks
  - z-measurement vis stereo
  - $\sigma_{r\text{-}\phi}$ ~ 17 μm; σ_z ~580 μm
- Transition Radiation Tracker (TRT)
  - 73 barrel straw layers
  - 2x160 end-cap radial straw disks
  - σ ~ 130 μm

Inner Detector

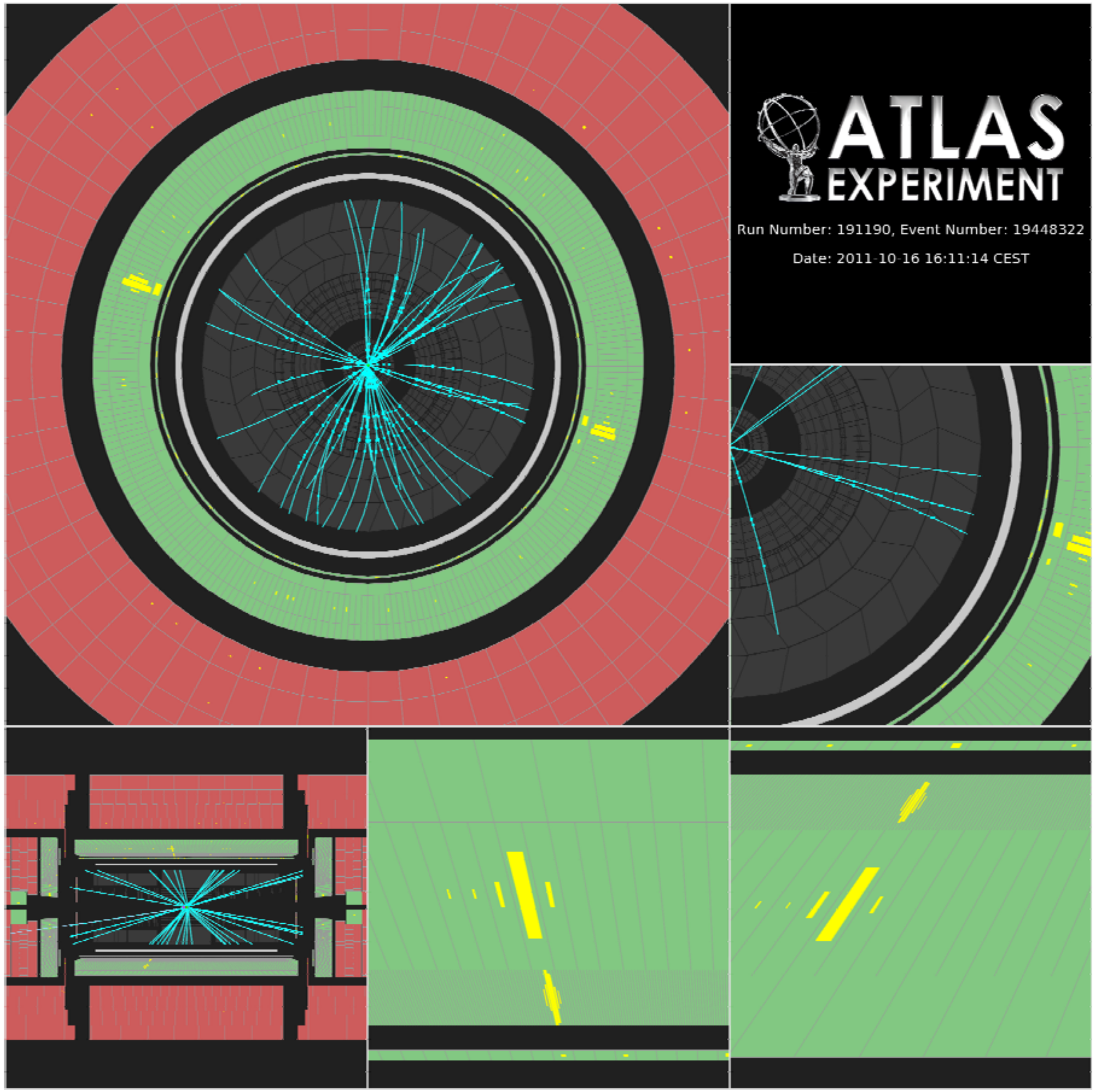






Key idea: silicon in the inner radius. Take advantage of the large bore to have straws sensitive to transition radiation for better e/π separation.

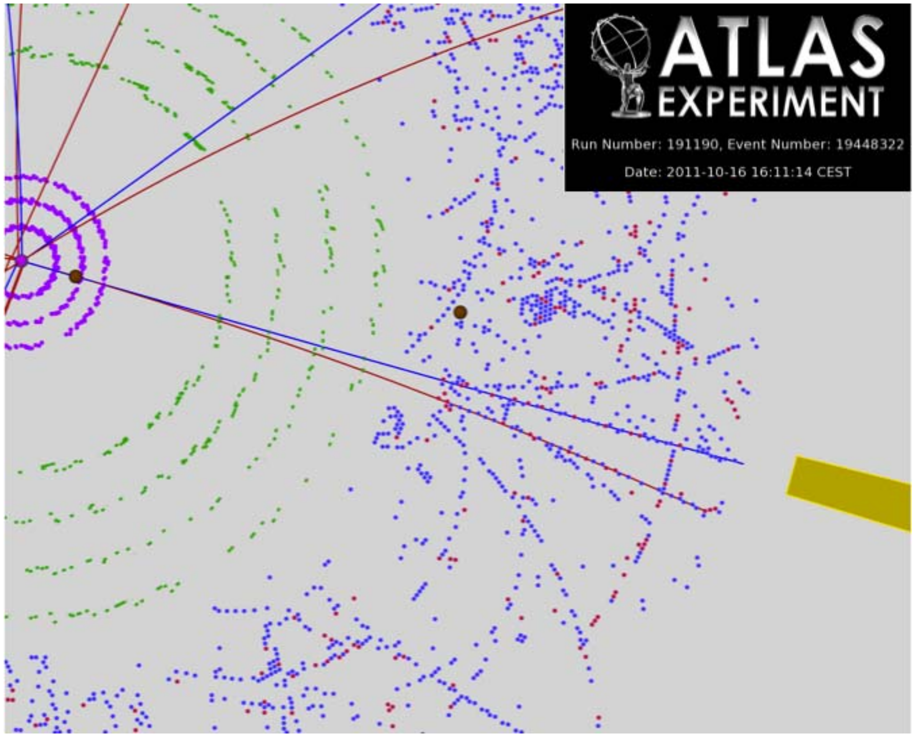
One Particular Higgs → γγ Candidate

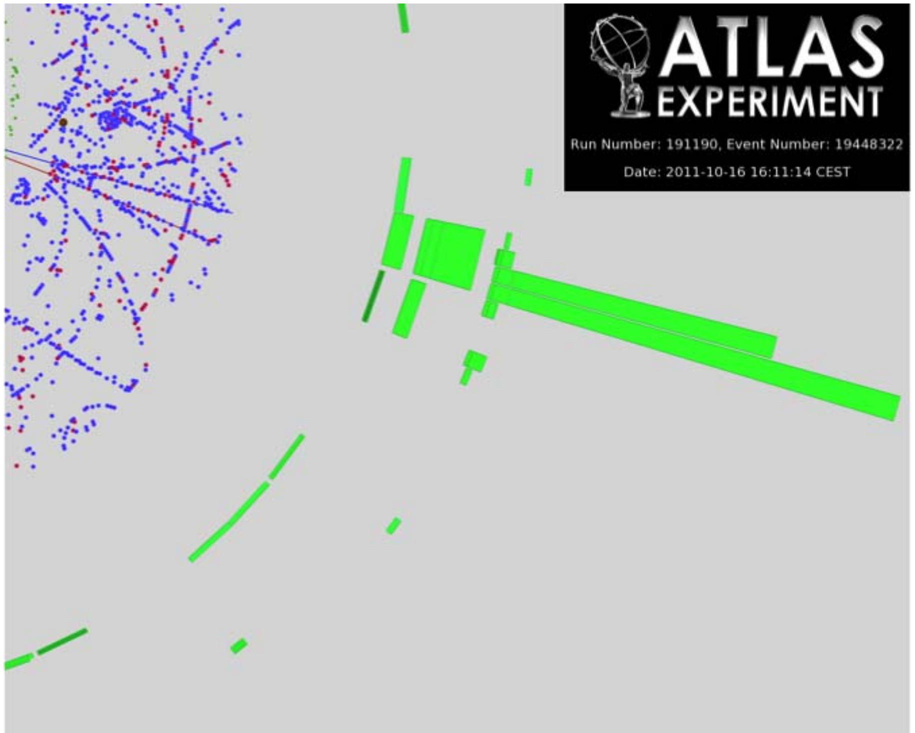


- This event has
  - One central unconverted photon
  - One central converted photon
  - A low pT(γγ) (6.5 GeV)

- Beautiful showers in the EM calorimeter

The Photon Conversion in More Detail



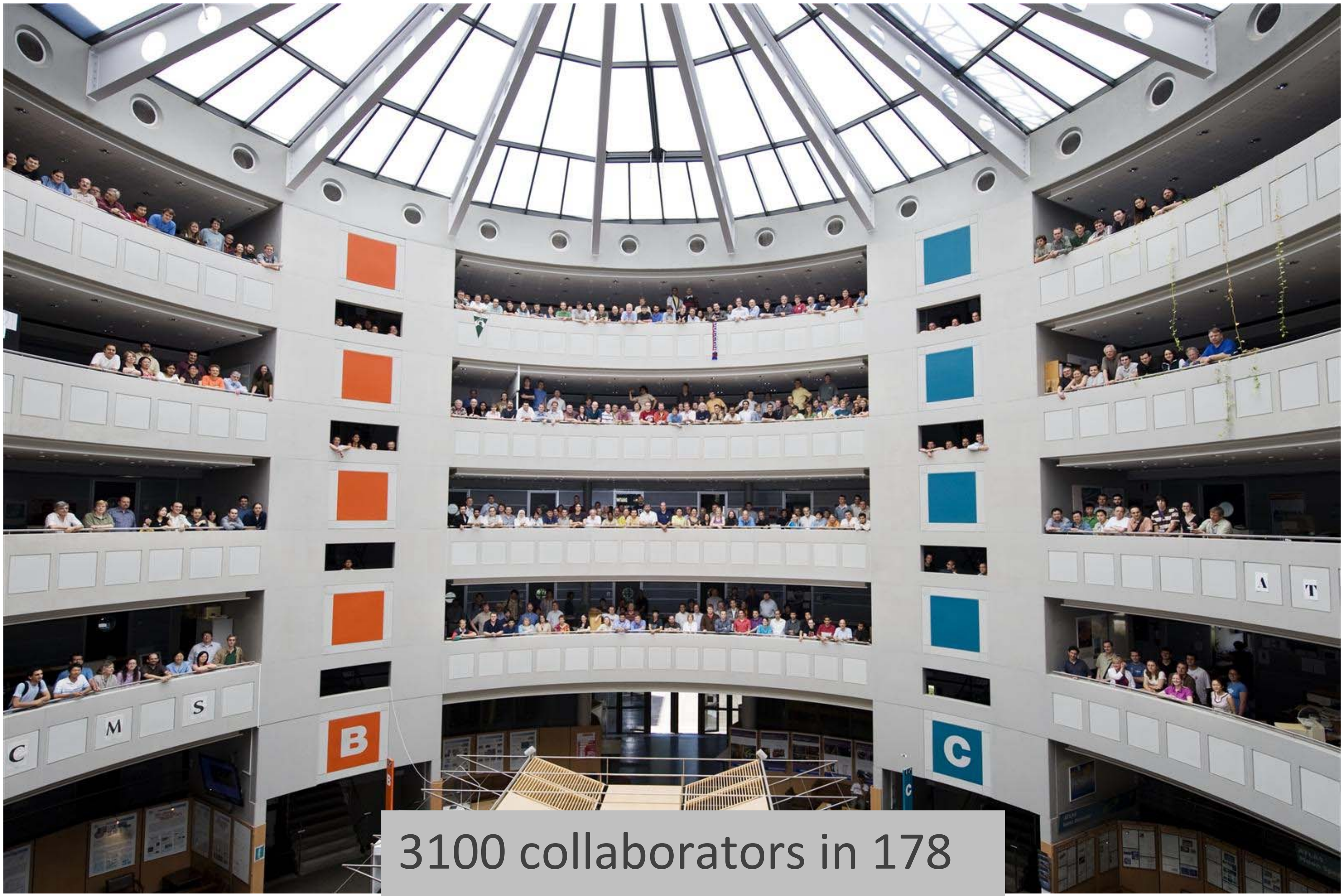


The tracks from γ → e+e- are clear and distinct. Red hits are high threshold TRT hits and confirm that these are in fact electrons.

The shape of the EM cluster in the calorimeter is consistent with two electrons very near each other.

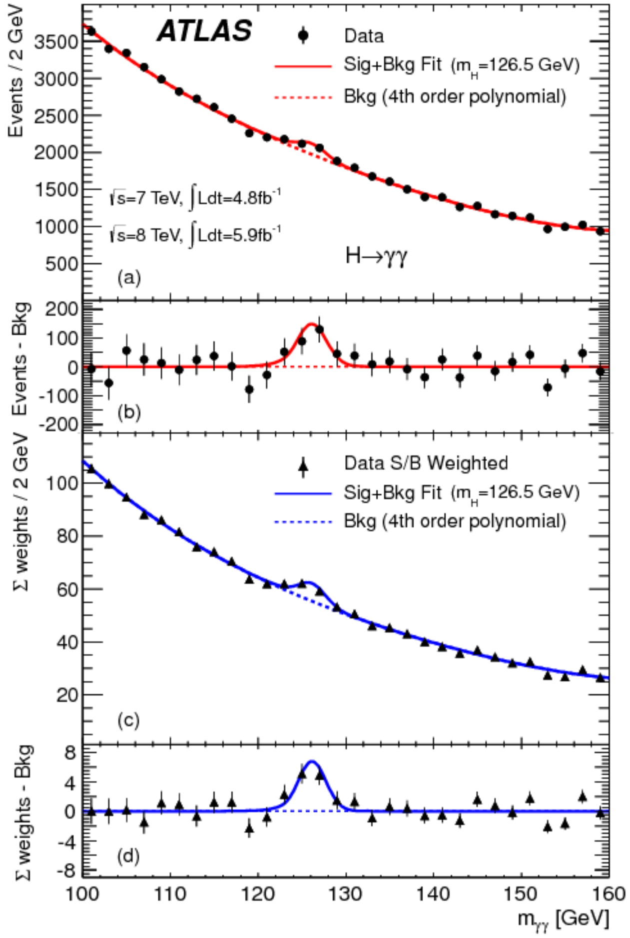
The ATLAS detector is more than a collection of components; the components work together to enable us to do the science.

The Most Important Component

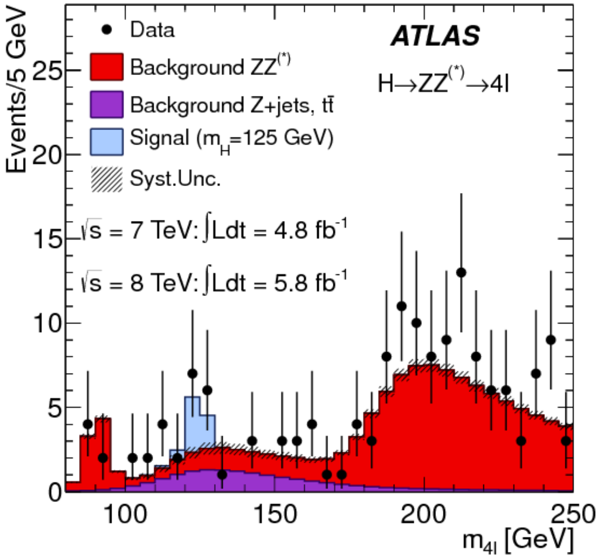


3100 collaborators in 178 institutions in 38 countries.

Higgs Discovery – July 4 2012

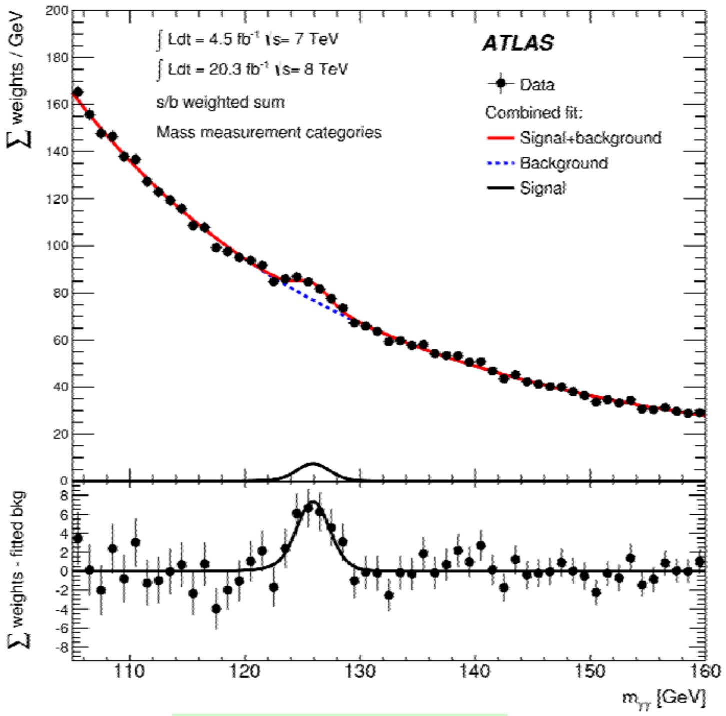


Diphoton Channel

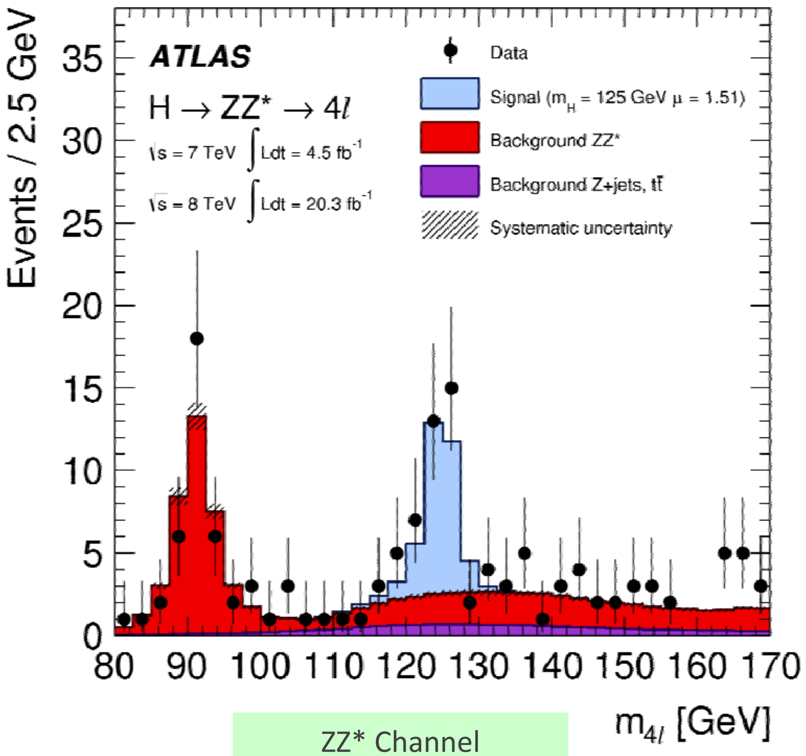


ZZ* Channel

Higgs Today



Diphoton Channel

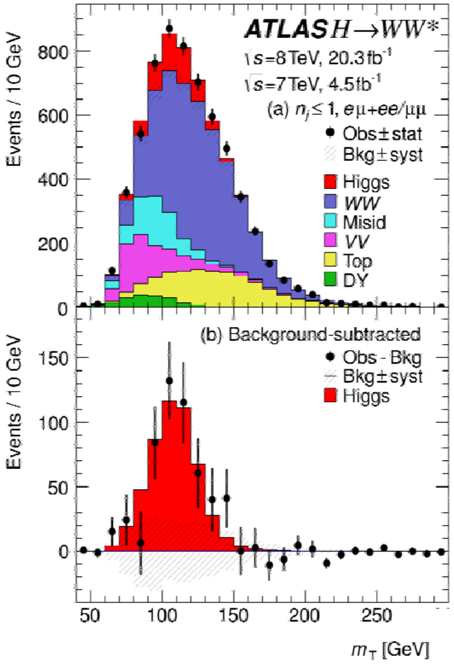


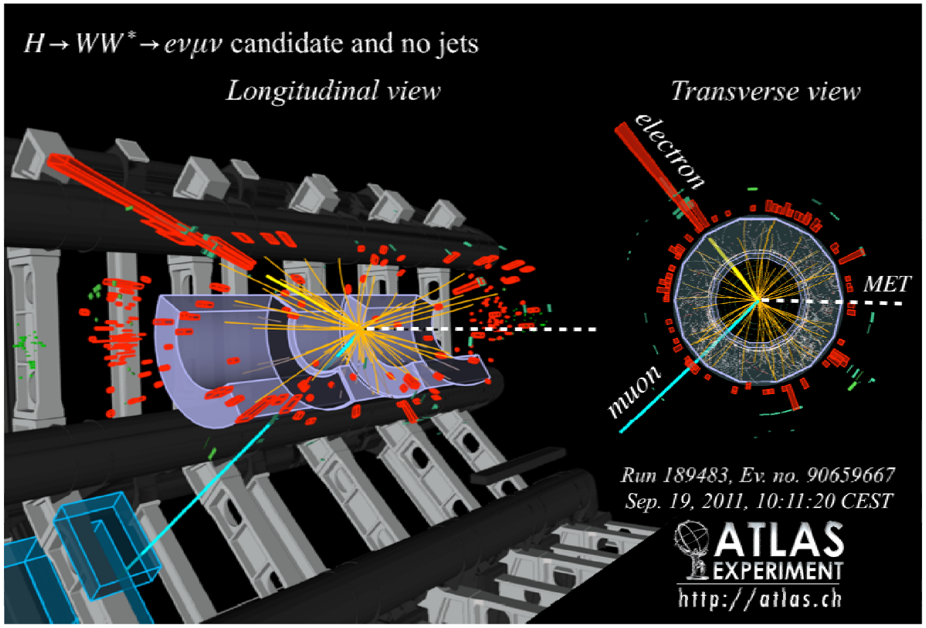
ZZ* Channel

The peaks in the discovery channels have grown proportional to the luminosity. They are not statistical fluctuations.

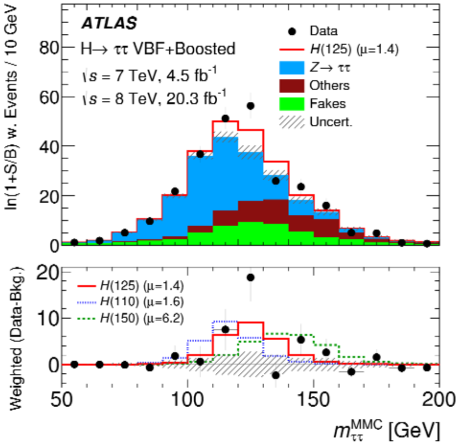
See F. Monticelli and G. Navarro’s talks

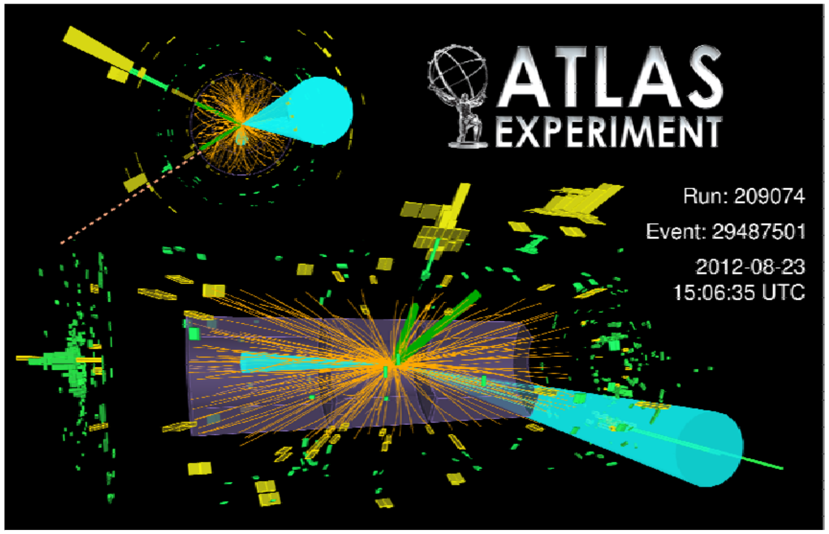
Post-Discovery Higgs Channels





H → WW is observed with a 6.1σ significance

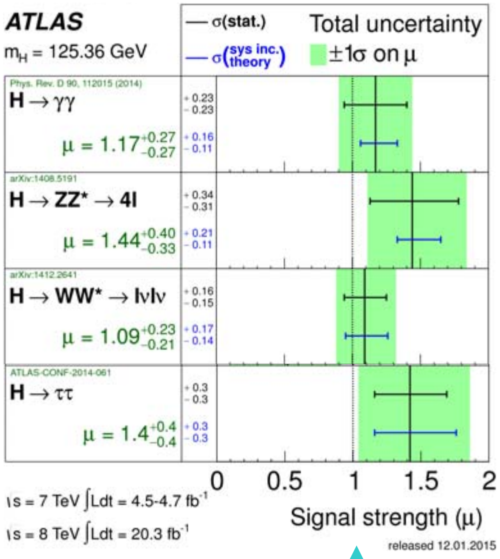




H → ττ is observed with a 4.5σ significance

What Does This Tell Us?

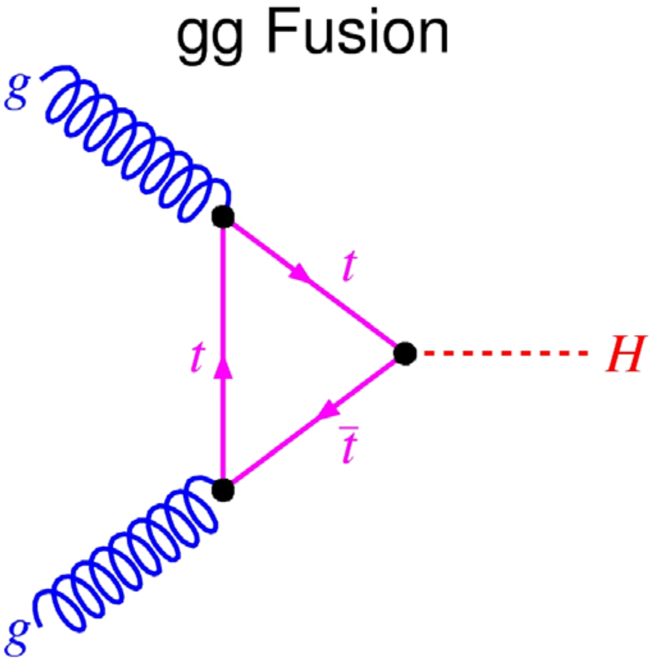
It tells us that there are **three and only three** sequential standard model families of fermions. If there is a fourth, it either is vector-like, or the child of another Higgs.



Higgs production rate for 3 Families

Higgs production rate for 4 Families

How Does This Work?



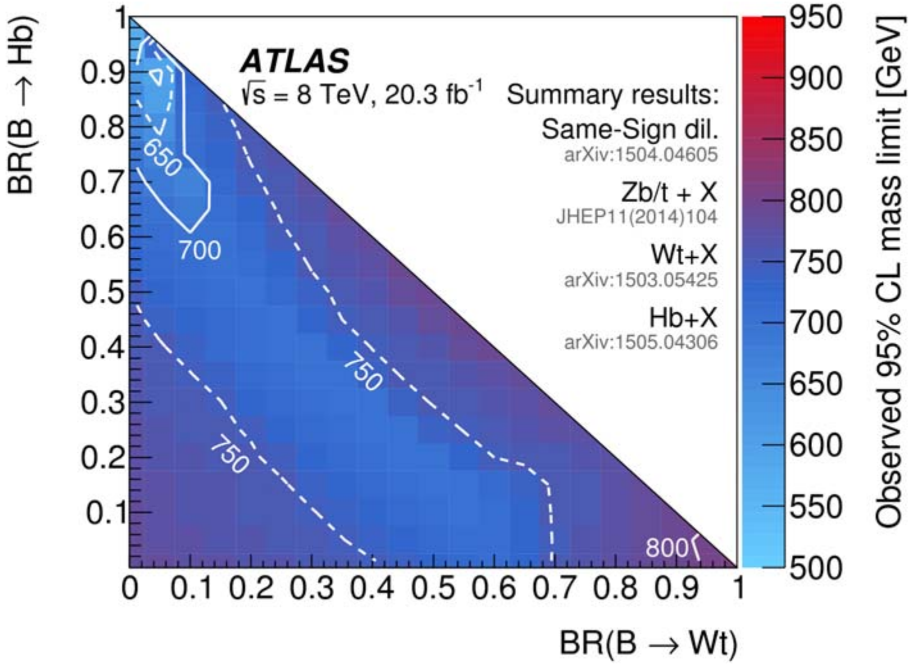
- Glue-glue fusion goes through a virtual quark loop

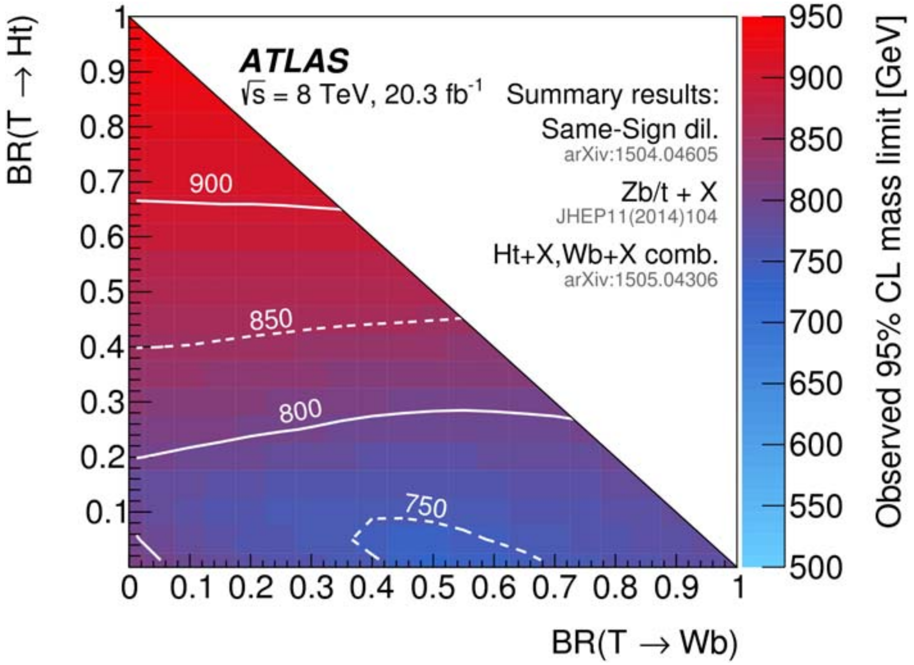
- As the quark mass gets heavy, the loop factor gets smaller
- As the quark mass gets heavy, the Higgs coupling gets bigger
- These effects exactly compensate – for heavy quarks, this contribution is independent of the quark mass.

- If there were a fourth generation, the *t*' and *b*' would have the same contribution as the *t*: irrespective of their mass.
  - A factor 3 in amplitude works out to a factor of ~9 in cross-section

Could There Be Vector-Like Quarks?

- VLQs do not get their mass from a Higgs Yukawa, so they evade this constraint.





- However, if these exist in nature, they are heavy:
  - B-like has m > 600-800 GeV (depending on branching fractions)
  - T-like has m > 750-900 GeV (again depending on branching fractions)

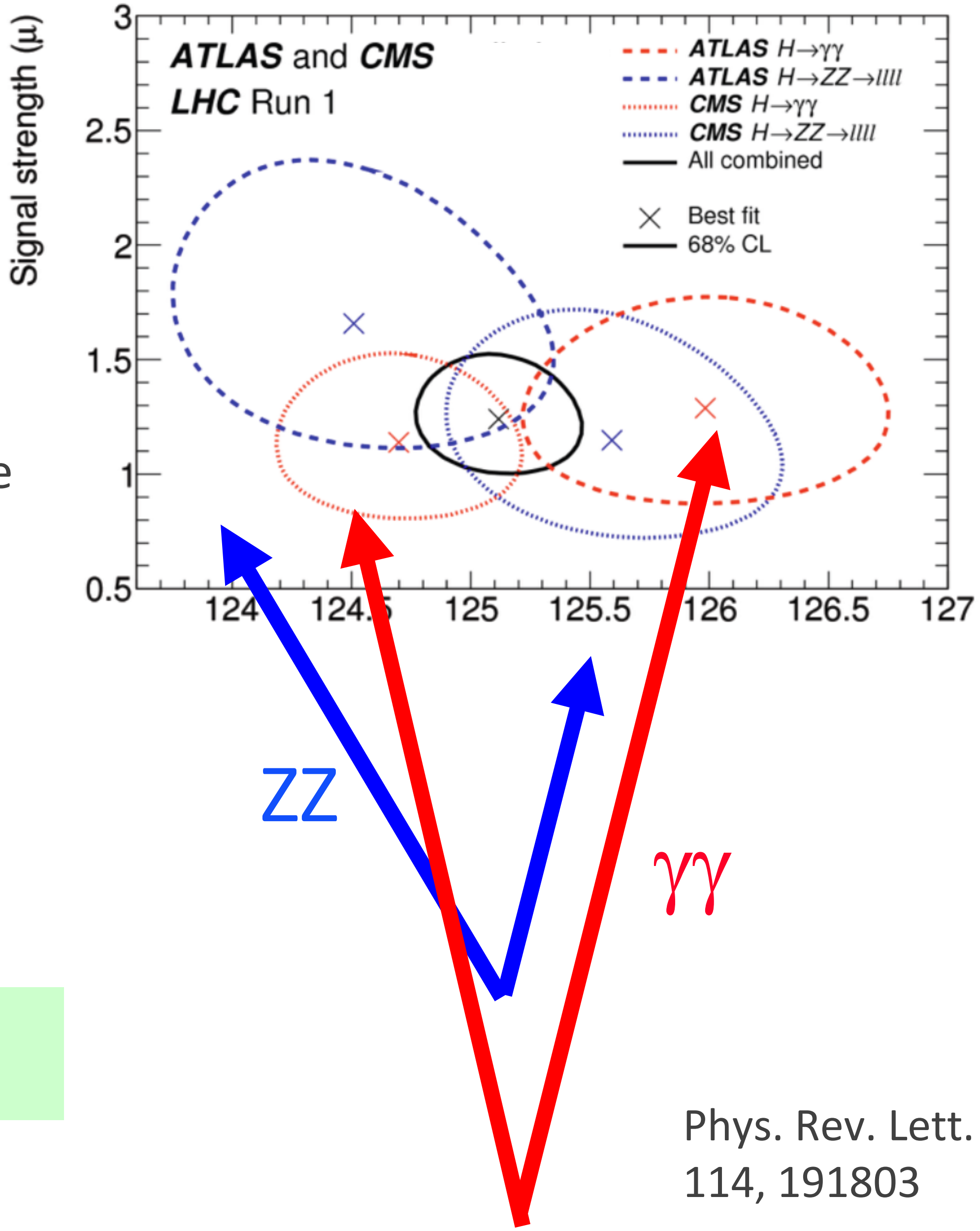
See N. Krumnack's talk

arXiv 1505.04306

Combined Higgs Mass

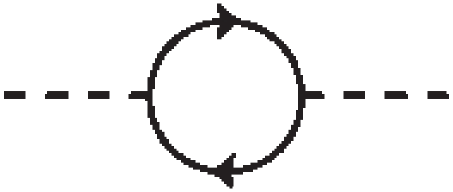
- 125.09 ± 0.21 ± 0.11 GeV
- Completely consistent with one particle, as opposed to two, one that decays to ZZ* and another that decays to $\gamma\gamma$.
- We've come a long way since July 4, 2012 – but still statistically limited.

The Higgs boson is too light to be heavy, and too heavy to be light.



Phys. Rev. Lett. 114, 191803

The Higgs Mass Doesn't Make Any Sense



- The Higgs mass makes perfect sense – at tree level
- Radiative corrections are of order $\delta m^2(H) \sim \alpha_{weak} \Lambda^2/4\pi$
  - Where Λ^2 is the scale of new physics
  - There is potentially a lot of new physics up there – including gravity at the Planck scale
  - This will drive the Higgs mass up and up and up
- To keep the Higgs mass light, these new contributions must cancel
- e.g. $\delta m^2(H)$ = 36,127,890,984,789,307,394,520,932,878,928,933,023 - 36,127,890,984,789,307,394,520,932,878,928,917,398

Thanks to Michael Dine!

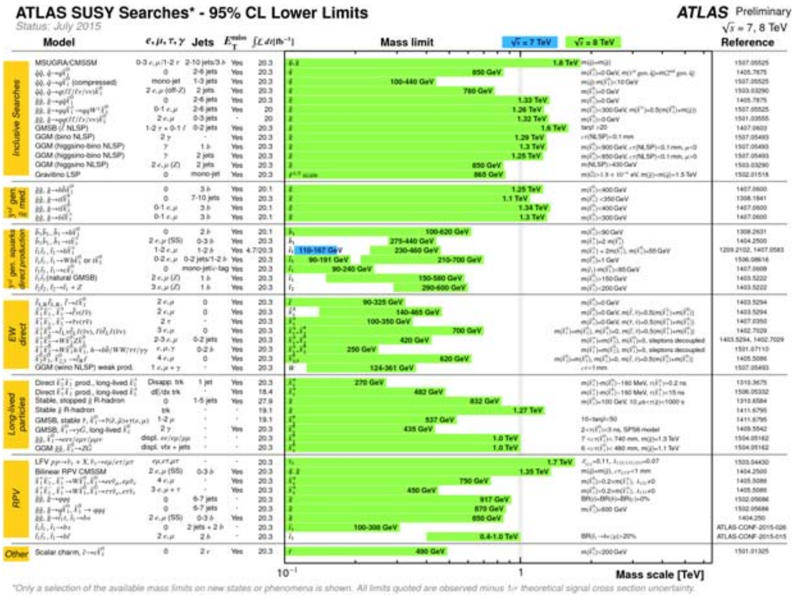
- This looks absurd, unless this is the result of some symmmetry
  - But that symmetry cannot be too exact, or the Higgs mass gets driven too low: perhaps even below the Z mass.

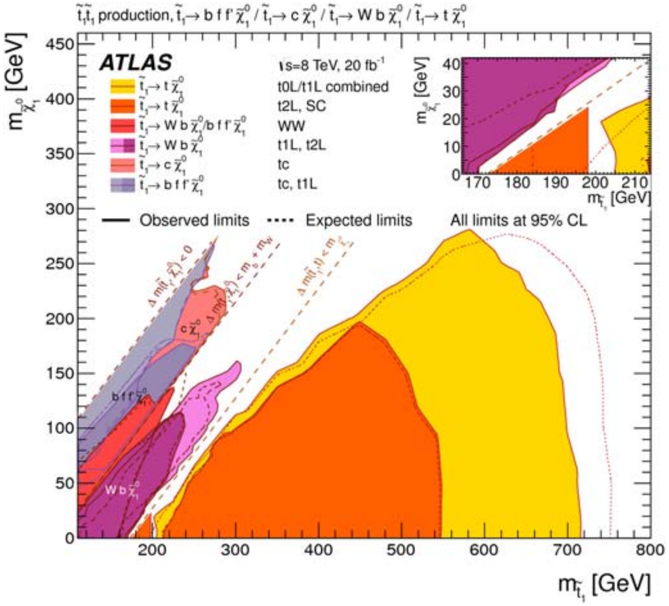
This is what I meant by "too light to be heavy, and too heavy to be light."

Is Supersymmetry The Answer?

See F. Alonso’s talk

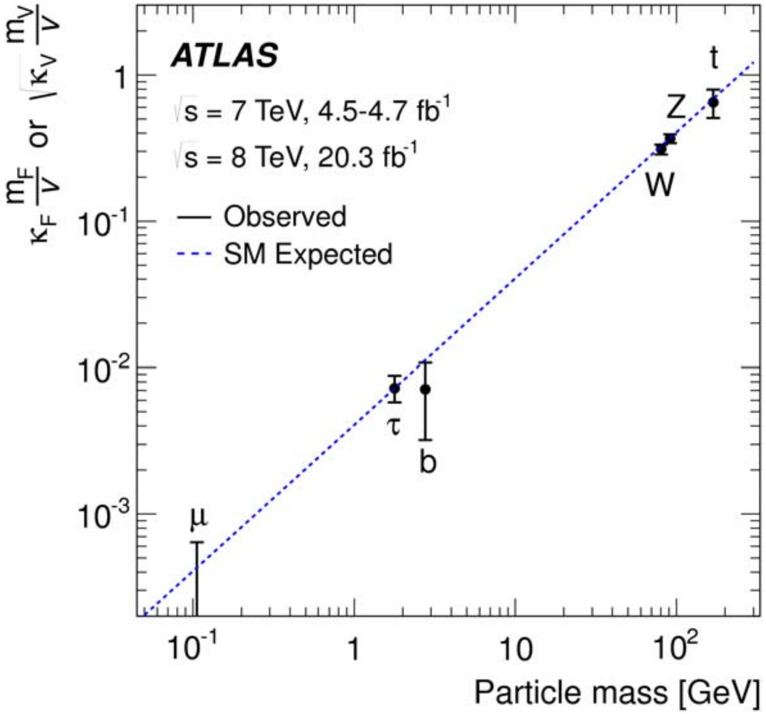
- It does provide this cancellation, and if it is broken in the right way, can naturally give a Higgs of the right mass:
  - Favors a light top squark (how light depends on your definition of “naturally”)
  - Gives a Dark Matter candidate for free





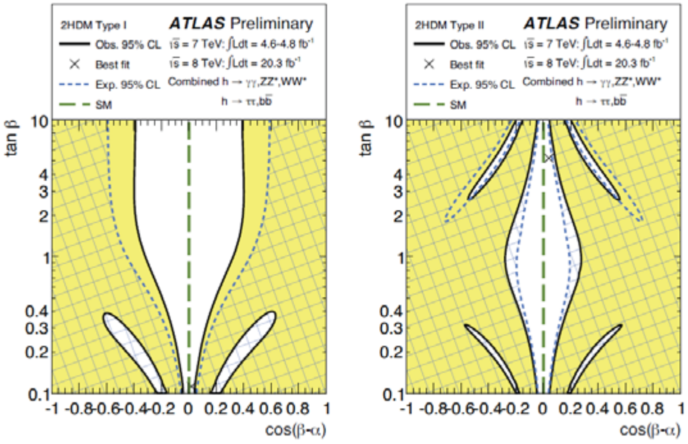
- Thus far, there is no sign of it anywhere
  - Limits are starting to be in tension with this idea (how “natural” is “natural”?)

Higgs Couplings

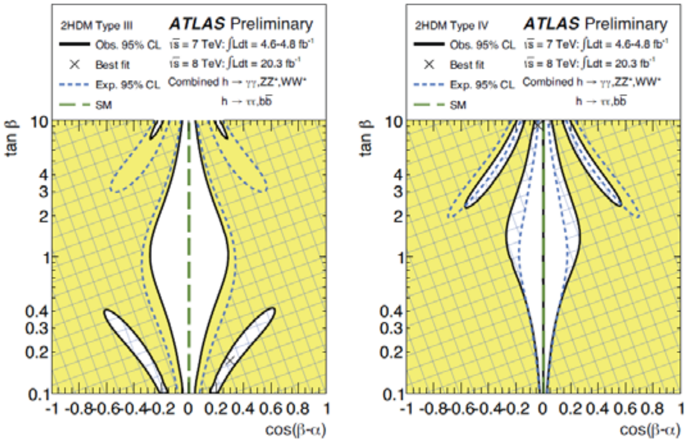


The coupling vs. mass is right for the Higgs.

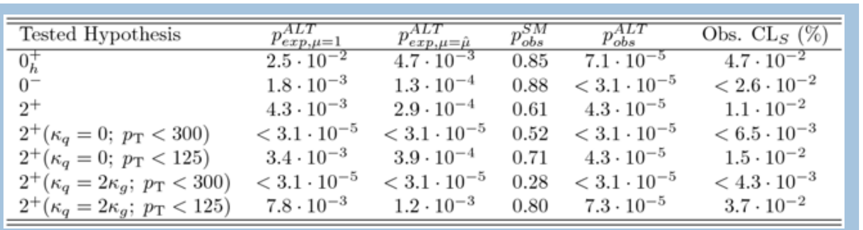
In a 2HDM, we observe that one Higgs (the one at 125 GeV) looks a lot like a SM Higgs.



(a) Type I (b) Type II



The 0^+ hypothesis for the Higgs spin and parity is strongly favored. While ATLAS uses a complex fit to extract as much information as possible, much of the separation is often from a single variable (1208.4311, wF. Petriello & R. Boughezal et al.). For example, the 0^+ and 0^- separation is primarily not from angular variables: it's energetics from the P-wave decay.

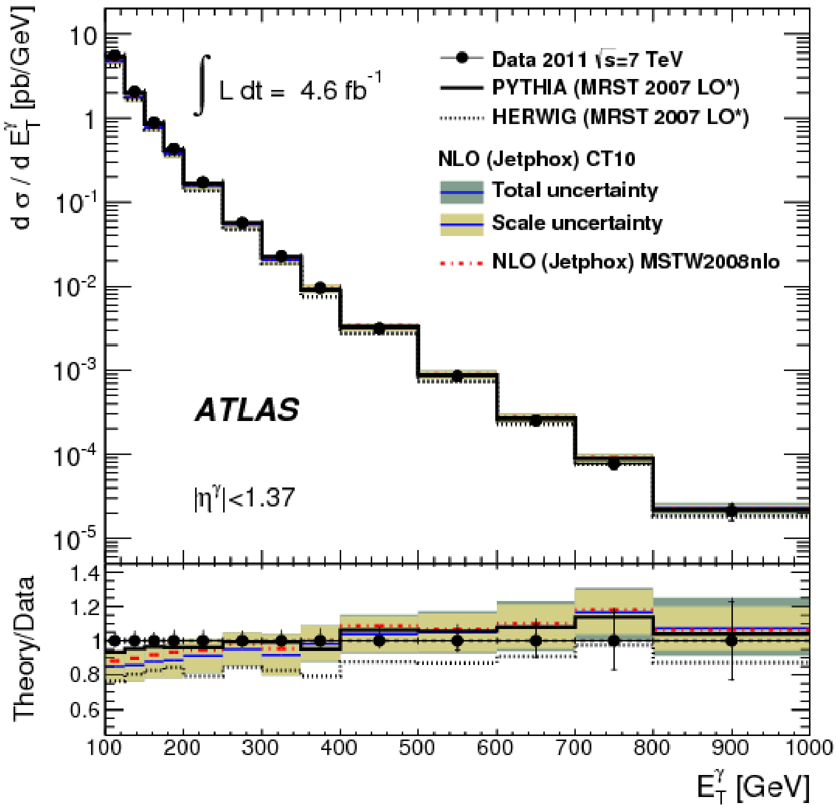


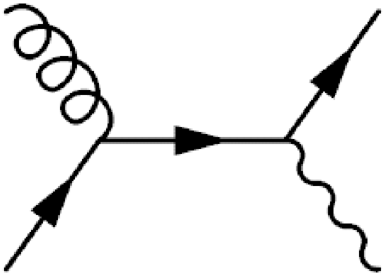
Tested Hypothesis	$p^{ALT}_{exp,\mu=1}$	$p^{ALT}_{exp,\mu=\hat{\mu}}$	p^{SM}_{obs}	p^{ALT}_{obs}	Obs. CL$_S$ (%)
0^+_h	$2.5 \cdot 10^{-2}$	$4.7 \cdot 10^{-3}$	0.85	$7.1 \cdot 10^{-5}$	$4.7 \cdot 10^{-2}$
0^-	$1.8 \cdot 10^{-3}$	$1.3 \cdot 10^{-4}$	0.88	$< 3.1 \cdot 10^{-5}$	$< 2.6 \cdot 10^{-2}$
2^+	$4.3 \cdot 10^{-3}$	$2.9 \cdot 10^{-4}$	0.61	$4.3 \cdot 10^{-5}$	$1.1 \cdot 10^{-2}$
$2^+(\kappa_q = 0;\ p_T < 300)$	$< 3.1 \cdot 10^{-5}$	$< 3.1 \cdot 10^{-5}$	0.52	$< 3.1 \cdot 10^{-5}$	$< 6.5 \cdot 10^{-3}$
$2^+(\kappa_q = 0;\ p_T < 125)$	$3.4 \cdot 10^{-3}$	$3.9 \cdot 10^{-4}$	0.71	$4.3 \cdot 10^{-5}$	$1.5 \cdot 10^{-2}$
$2^+(\kappa_q = 2\kappa_g;\ p_T < 300)$	$< 3.1 \cdot 10^{-5}$	$< 3.1 \cdot 10^{-5}$	0.28	$< 3.1 \cdot 10^{-5}$	$< 4.3 \cdot 10^{-3}$
$2^+(\kappa_q = 2\kappa_g;\ p_T < 125)$	$7.8 \cdot 10^{-3}$	$1.2 \cdot 10^{-3}$	0.80	$7.3 \cdot 10^{-5}$	$3.7 \cdot 10^{-2}$

$$m(H) = m(Z) + m(Z^*) + \frac{L^2}{2I}$$

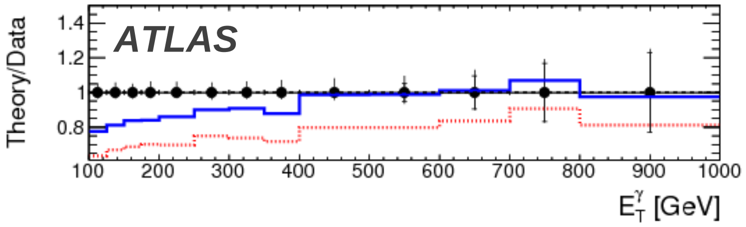
Direct Photons at ATLAS

See D. Moreno’s talk



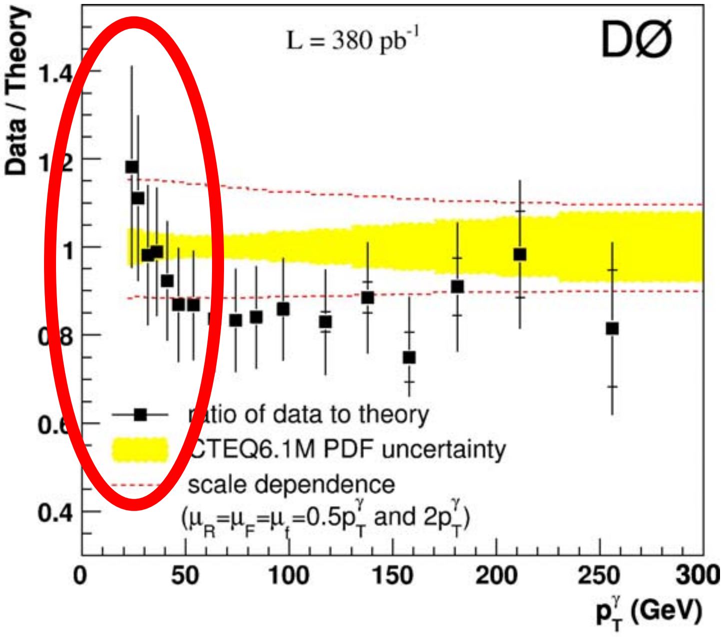


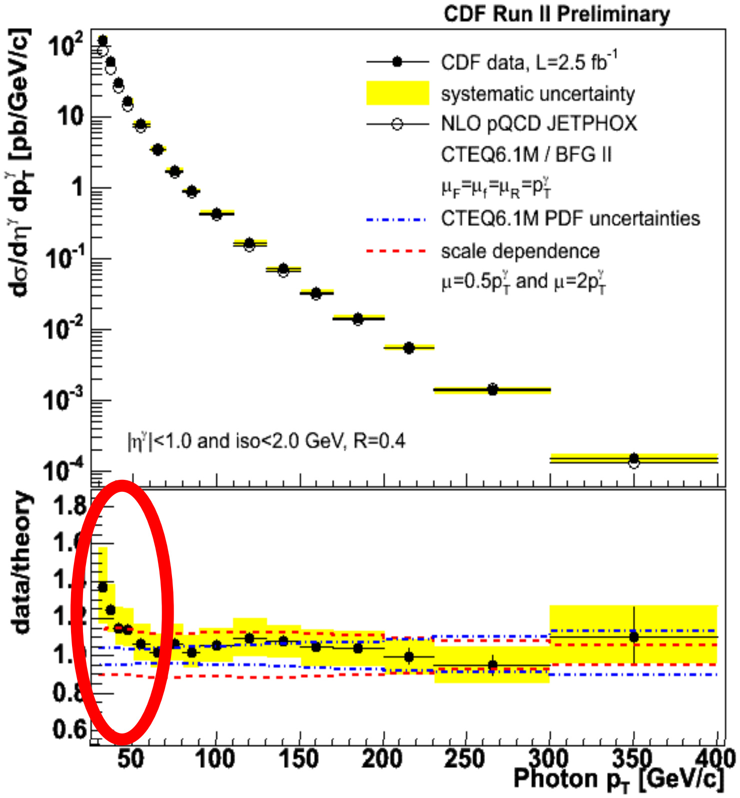
- Probe of the gluon PDF
- Relevant in Higgs coupling measurements : ingredient in ggF vs. VBF separation
- Dominated by q-g scattering (gluon Compton) but fragmentation photons are necessary for a good agreement with the data



However, for the last decade or so, they have not been used in the global PDF fits.

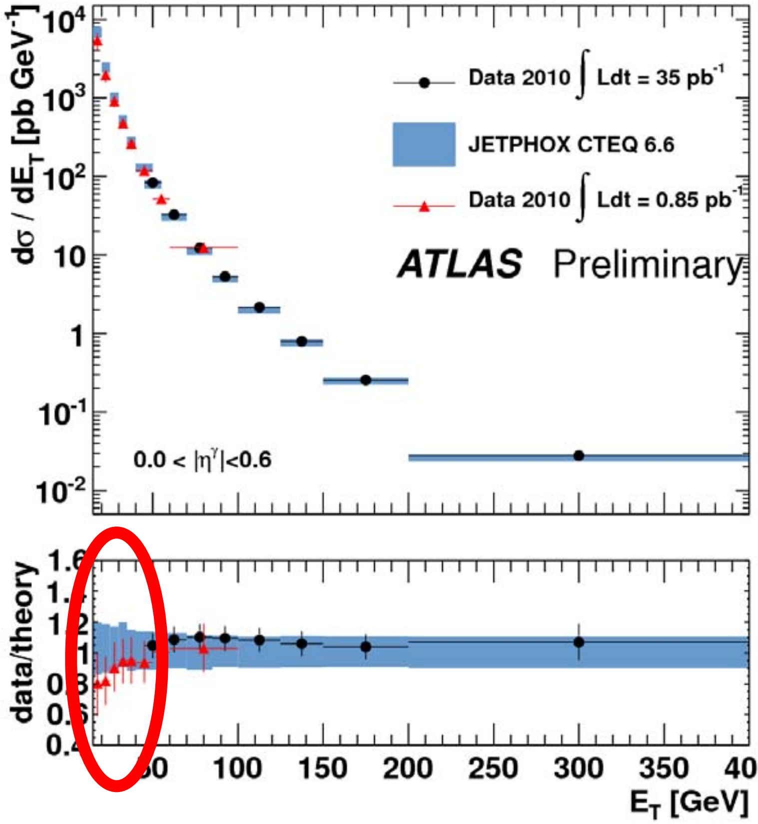
Why Direct Photons Are Out of the PDF Fits





- There is a discrepancy at low p_T, seen by both CDF and D0
- There are theoretical ideas on how to resolve this, but the cross-section calculation and the PDF measurements have become intertwined.
  - Can't constrain two things with a single measurement

ATLAS Resolves This Issue



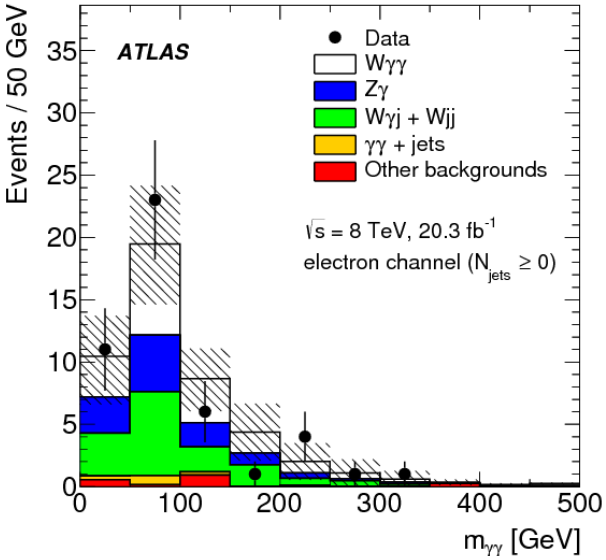
Same problem (only here it is an overcorrection)

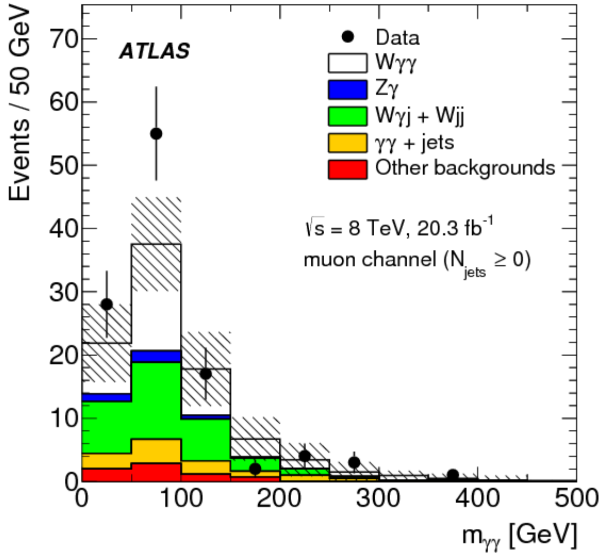
- The better constrained the gluon PDF is, the better we understand ggF vs. VBF separation for the Higgs
- Knowledge of the initial conditions affects any search that relies on Monte Carlo

- There is still something not understood going on below 50 GeV
  - But we know now that this is a function of E_T, not of x_T. This separates PDF effects from the calculational issues.
  - The PDFs are OK, as long as you stay above 50 GeV.
  - ATLAS published over the range 100-1000 GeV

- Photons can go back into the PDF fits
  - CJ12 includes LHC photons and Tevatron photons
  - Now that we understand this is an E_T issue, there is no reason not to include the Tevatron data (and it is included in CJ12)

Tribosons: Wγγ

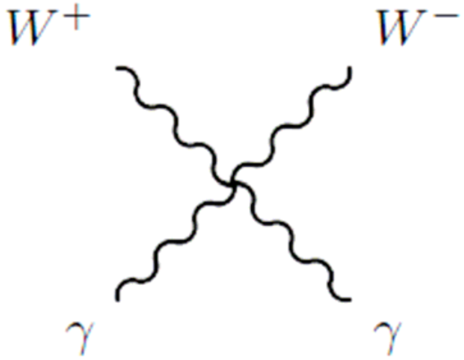




- 3.7σ evidence for Wγγ triboson production

- Why this is important:
  - Is SU(2)xU(1) an exact or approximate symmetry?
  - Wγγ production is the physical remnant of the w_1-w_2-w_3-w_3 coupling in unbroken SU(2)
  - Composite W's, Z's and H's could show deviations

- PRL 115, 031802 (2015)
  - An Editors' Suggestion

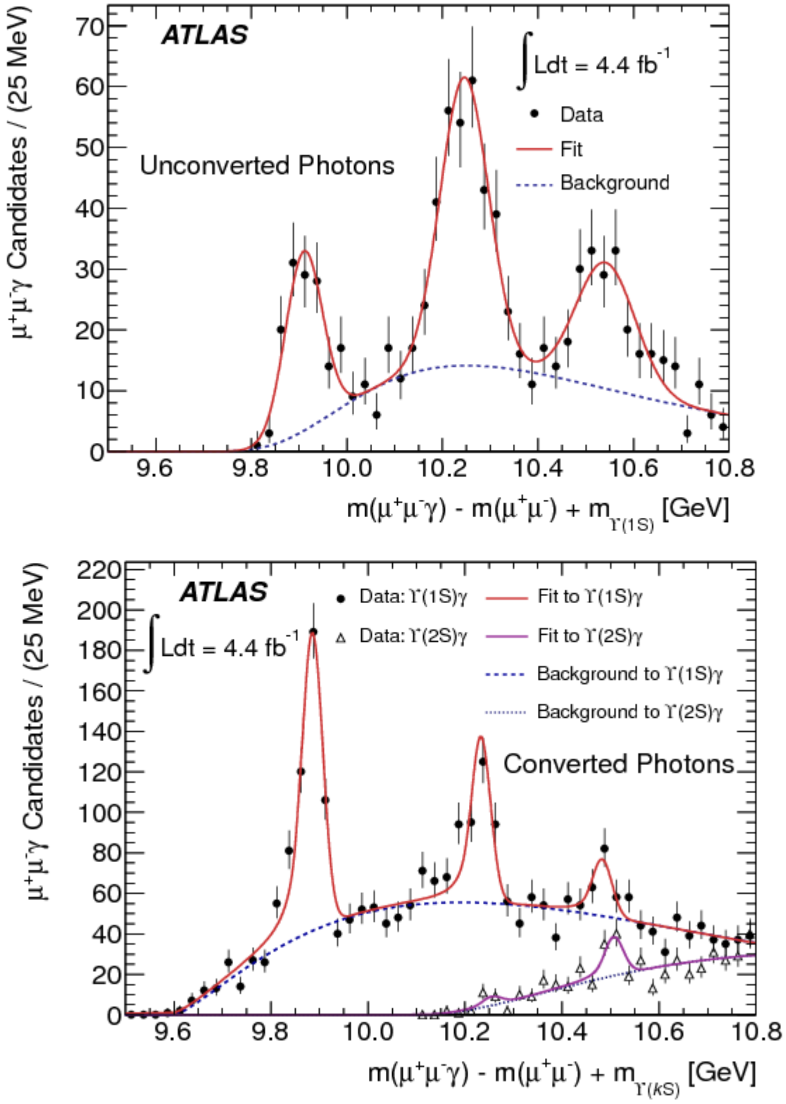


And Some Fun: ATLAS' First Boson Discovery

- Before there was the Higgs boson, there was the $\chi_b(3P)$ boson (actually, two, one 1^{++} and one 2^{++}), seen in the decays $\chi_b(3P) \rightarrow \Upsilon(1P,2P)+\gamma$

- ATLAS didn't set out to look for this particle – you won't find it in any TDR or any prospects talk

- Main Lesson for Run 2: ATLAS can discover the unexpected
  - A general-purpose detector
  - A trigger that is as inclusive as possible given the bandwidth



Phys.Rev.Lett. 108 (2012) 152001

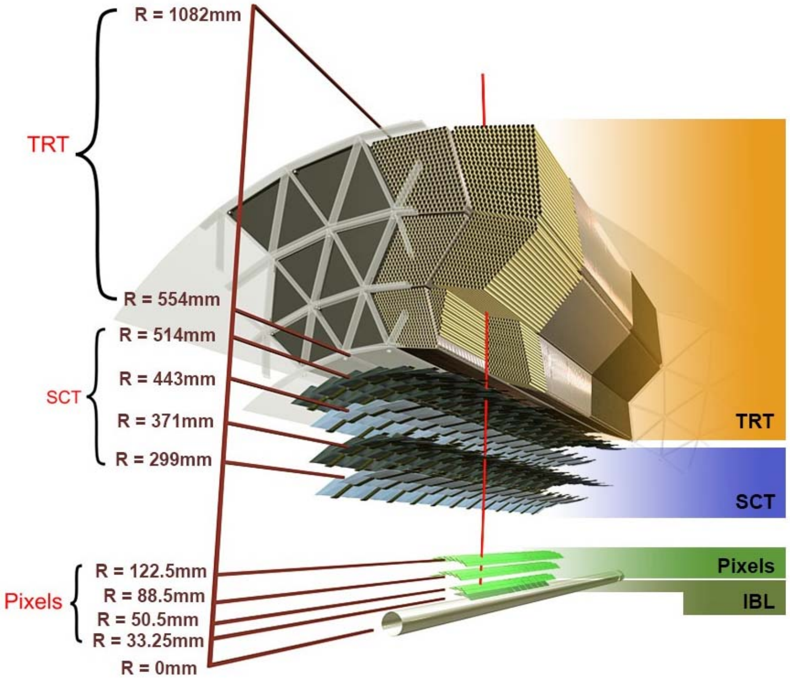
See E. Kneringer's talk

Run 1 Lessons → Run 2 Goals

- ATLAS and CMS discovered a Higgs Boson
  - The yield tells us there are exactly three fermion families
    - Any new family must be vector-like
    - Run 1 searches haven't uncovered anything
    - Run 2 will continue these searches
  - The mass suggests some new broken symmetry
    - Supersymmetry is the obvious example
    - Where is it? In particular, where is the stop squark?
  - If there is one, there could be more
    - Two pronged approach for Run 2 – direct searches, and precision measurements of H(125)

- We need Standard Model measurements to improve and inform our searches
  - Two examples were direct photons (measures the gluon)

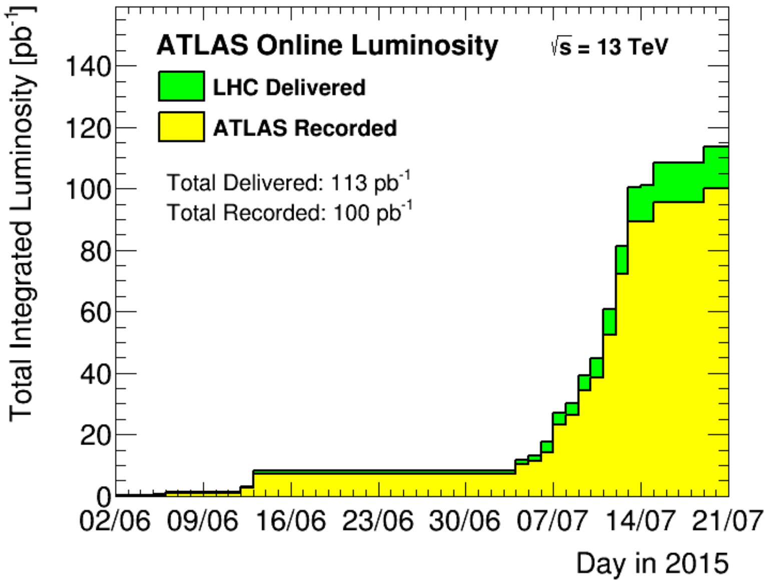
ATLAS Detector Upgrade

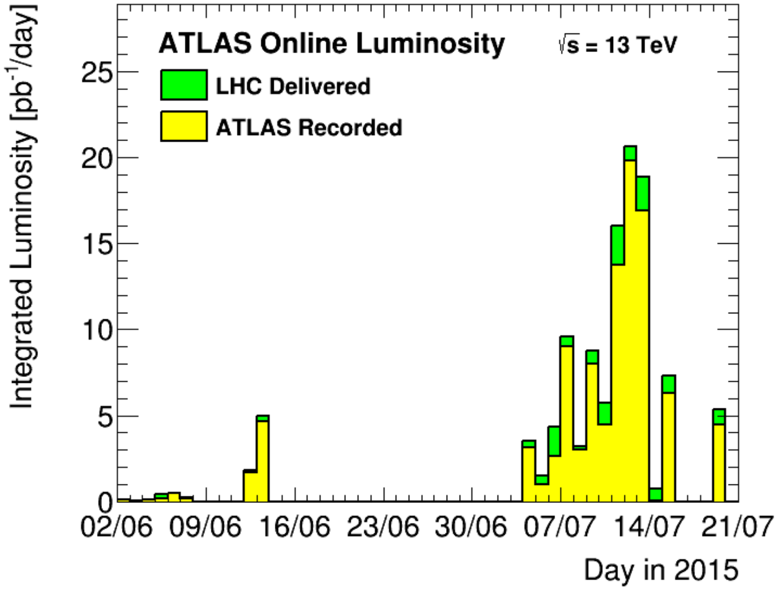


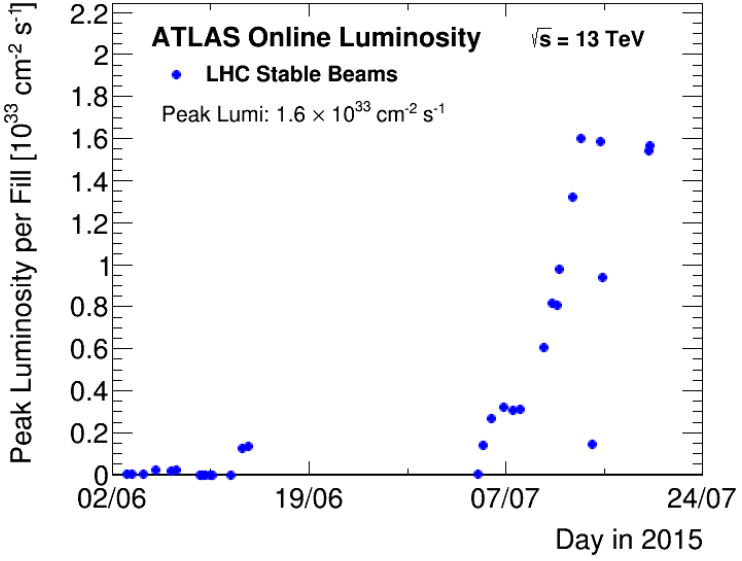
This is the ATLAS “Insertable B-Layer” silicon pixel detector.

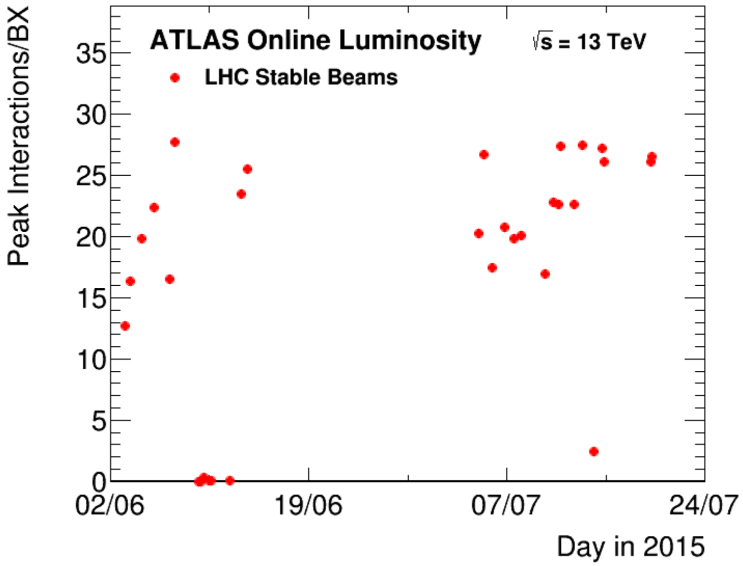
- ATLAS has other substantial improvements underway for the Run 2
  - Elements of the detectors that were descoped or deferred
  - Improvements to the trigger and data acquisition to read out more events

Run 2 is Now!

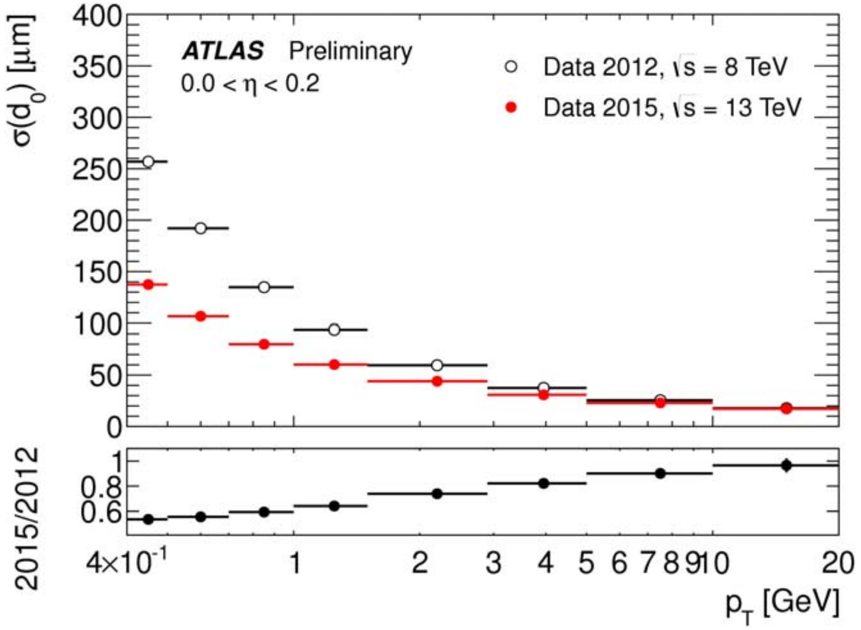

ATLAS Online Luminosity
√s = 13 TeV
🟩 LHC Delivered
🟨 ATLAS Recorded
Total Delivered: 113 pb^{-1}
Total Recorded: 100 pb^{-1}
Total Integrated Luminosity [pb^{-1}]
0
20
40
60
80
100
120
140
02/06
09/06
16/06
23/06
30/06
07/07
14/07
21/07
Day in 2015

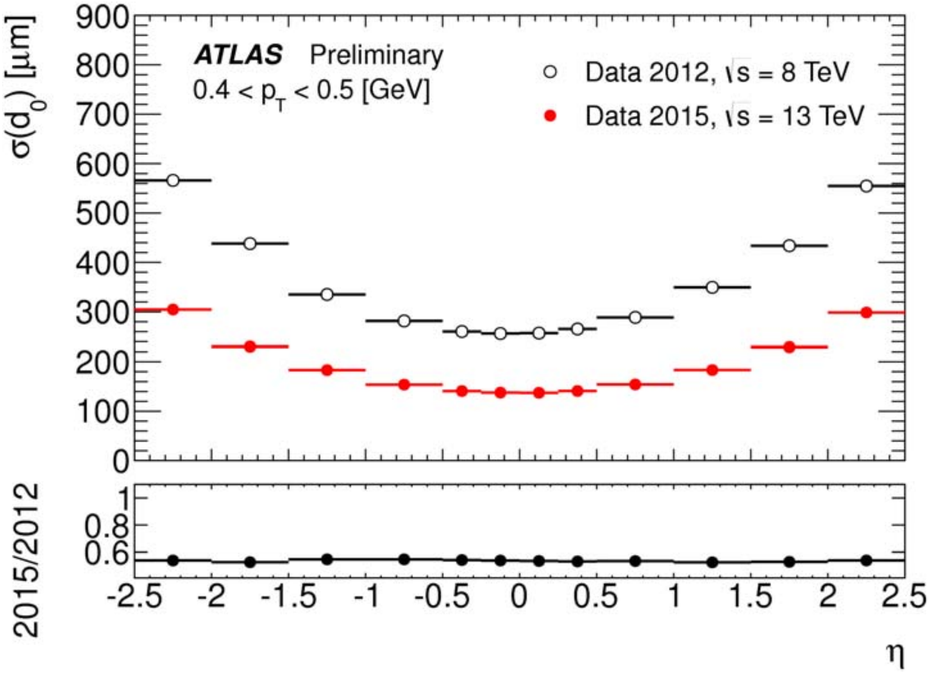

ATLAS Online Luminosity
√s = 13 TeV
🟩 LHC Delivered
🟨 ATLAS Recorded
Integrated Luminosity [pb^{-1}/day]
0
5
10
15
20
25
02/06
09/06
16/06
23/06
30/06
07/07
14/07
21/07
Day in 2015


ATLAS Online Luminosity
√s = 13 TeV
● LHC Stable Beams
Peak Lumi: 1.6 × 10^{33} cm^{-2} s^{-1}
Peak Luminosity per Fill [10^{33} cm^{-2} s^{-1}]
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
2.2
02/06
19/06
07/07
24/07
Day in 2015


ATLAS Online Luminosity
√s = 13 TeV
● LHC Stable Beams
Peak Interactions/BX
0
5
10
15
20
25
30
35
02/06
19/06
07/07
24/07
Day in 2015

IBL Performance



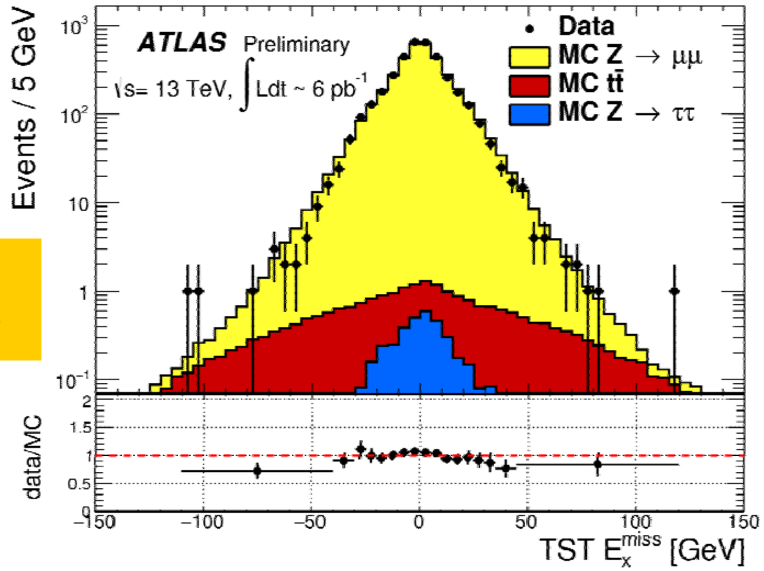


- These figures show that the impact parameter resolution is improving – by up to a factor of 2 with respect to Run 1

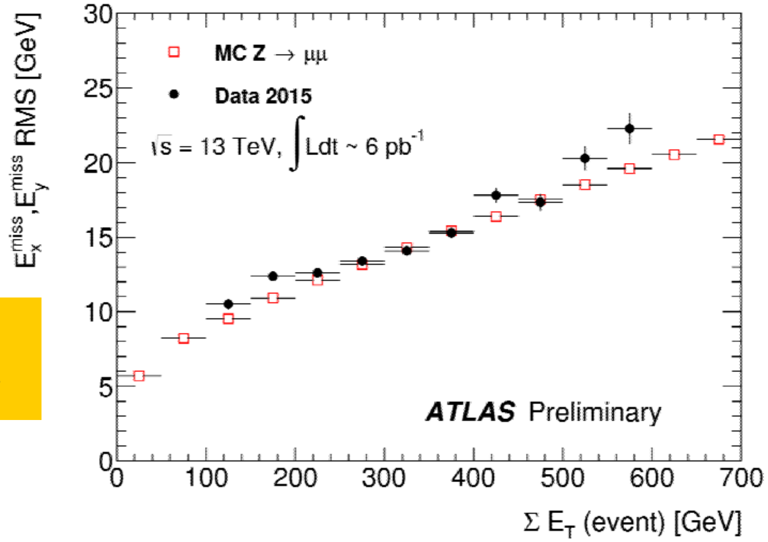
- What these plots don’t show is the improvement in pattern recognition that an additional (close-in) hit provides – a 2nd important benefit of the new device

Photons, Jets and Missing Energy

Low E_T^{miss}



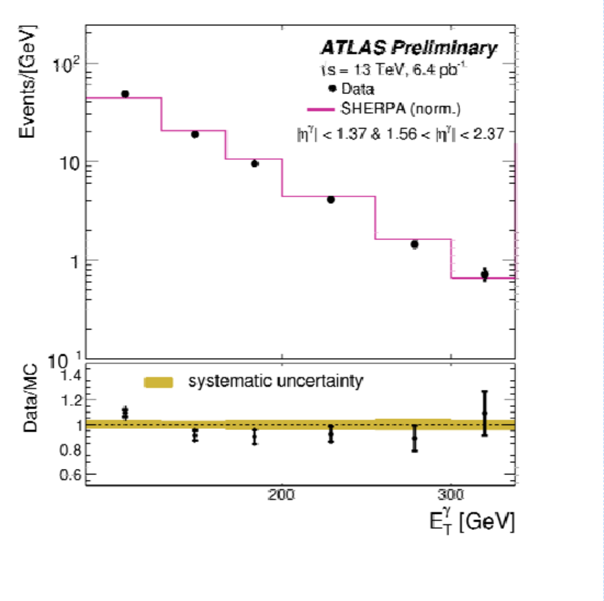
High E_T^{miss}



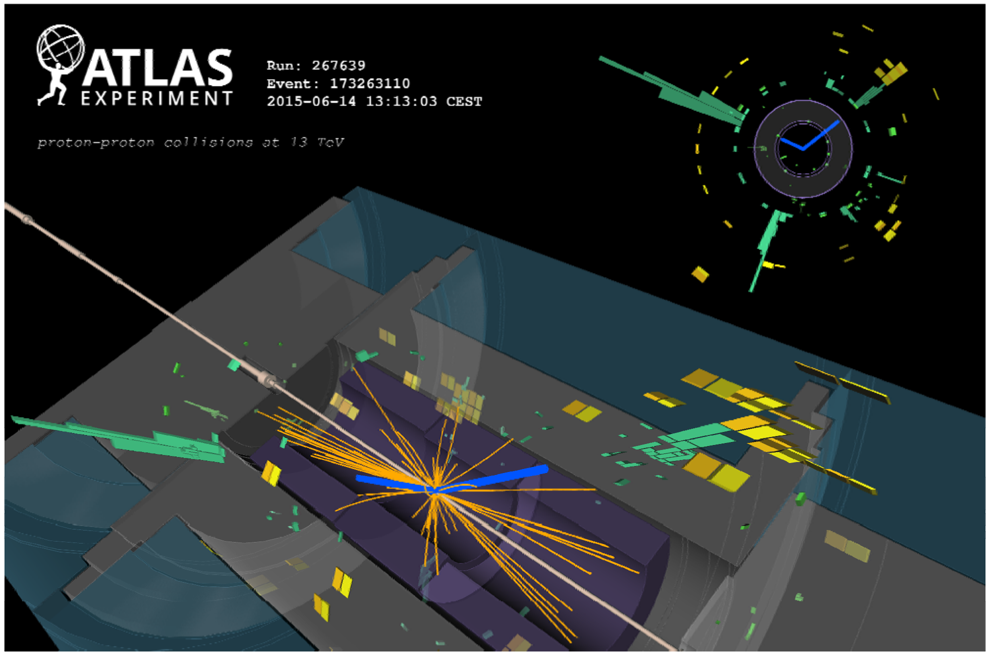
Missing energy distribution matches expectations in Z → μμ events.

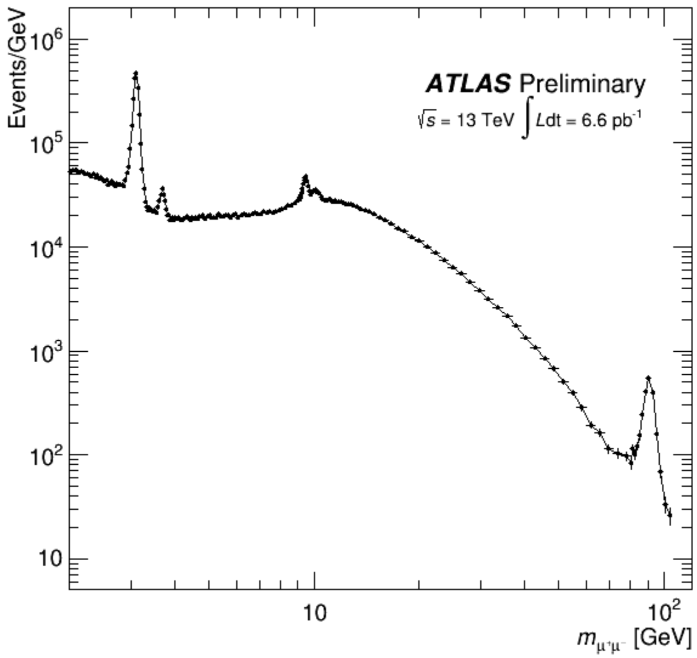
Here ATLAS is using tracking to measure the “soft” term: combines calorimetric and inner detector measurements.

Photon spectrum (pure calorimetry) matches Sherpa

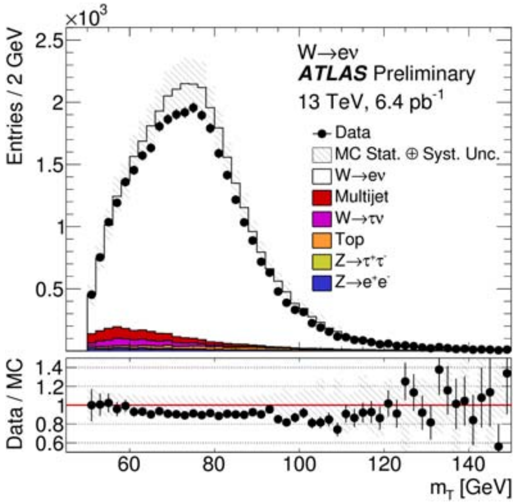


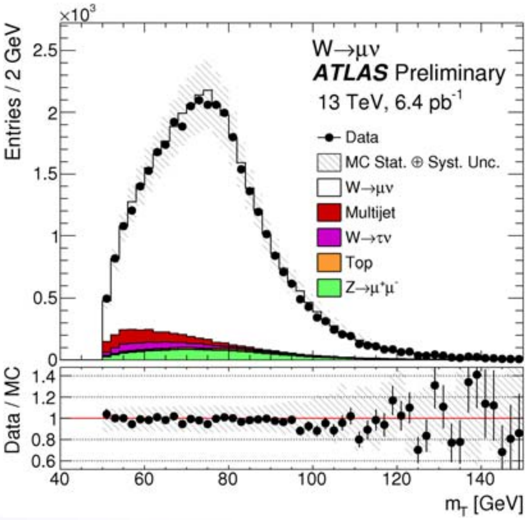
Electrons, Muons, W and Z Bosons



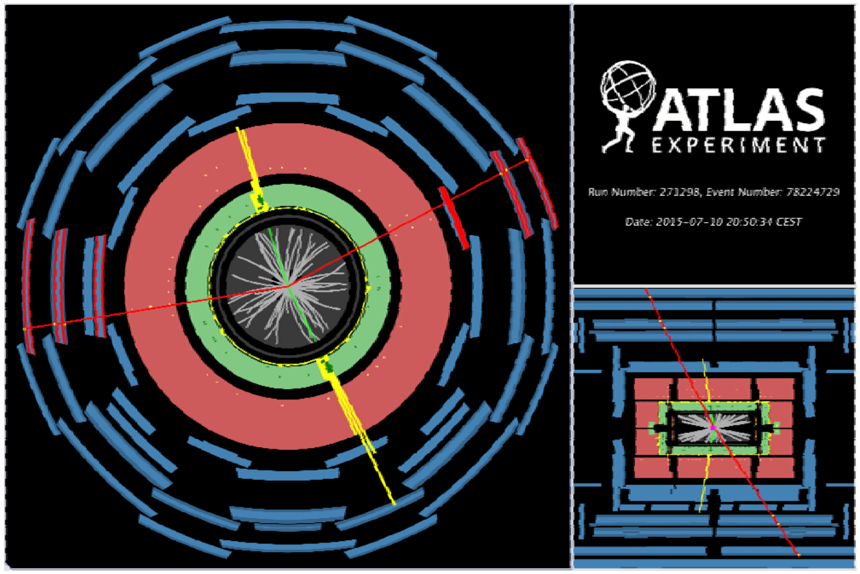


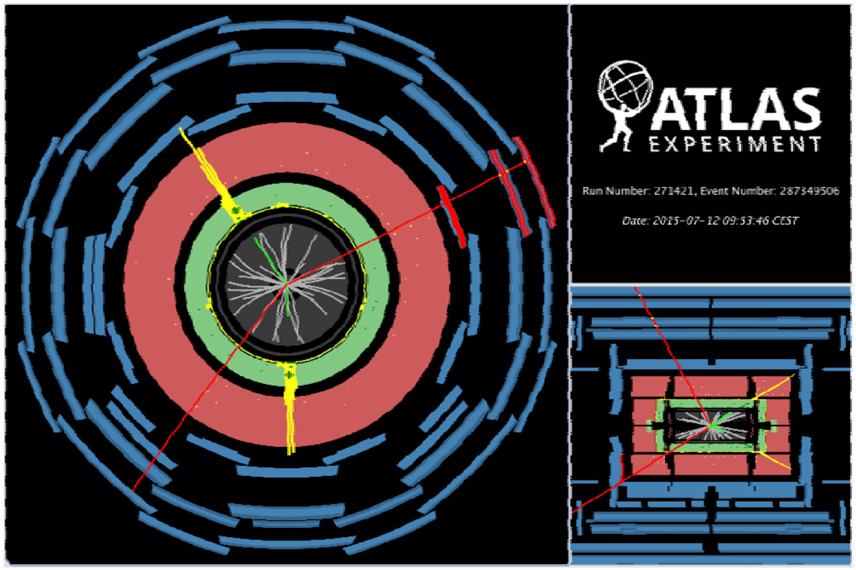
- Lepton reconstruction commissioning is on track and rediscovering the Standard Model





If You Like One EWK Boson – Why Not Two?

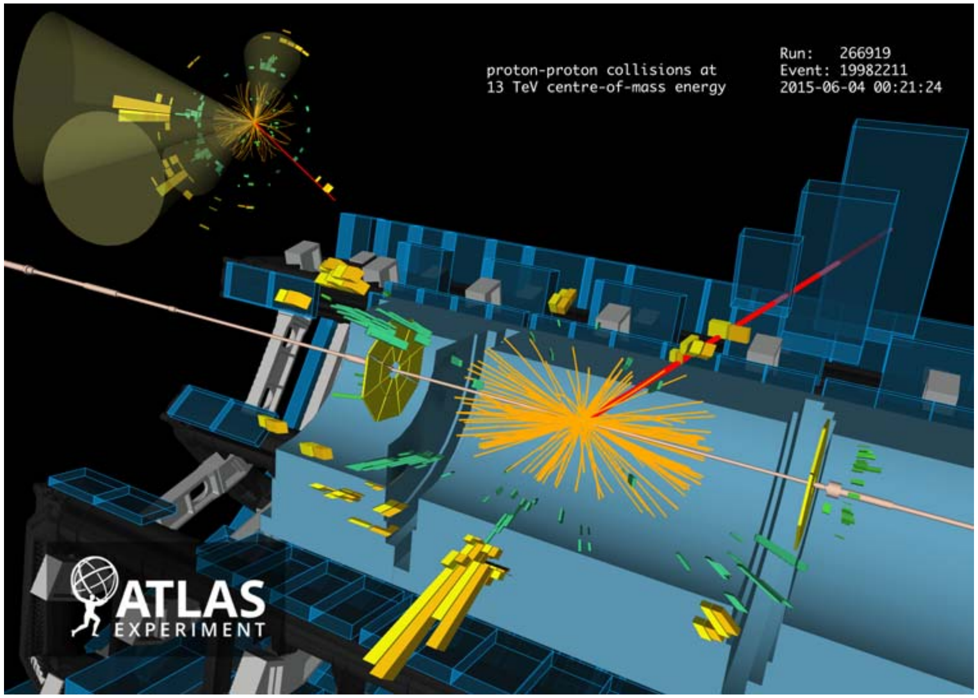




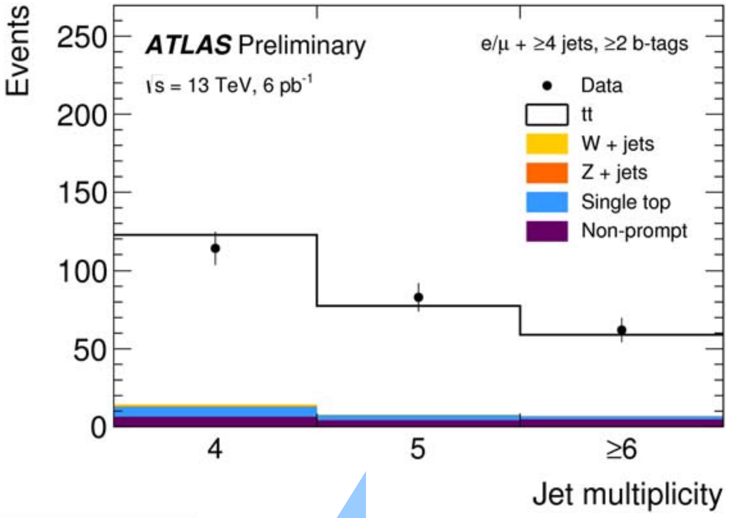
- Two different ZZ events, both eeμμ. (Very democratic!)
- Unfortunately, neither of these events is a Higgs Boson candidate

Putting All The Pieces Together: Top!

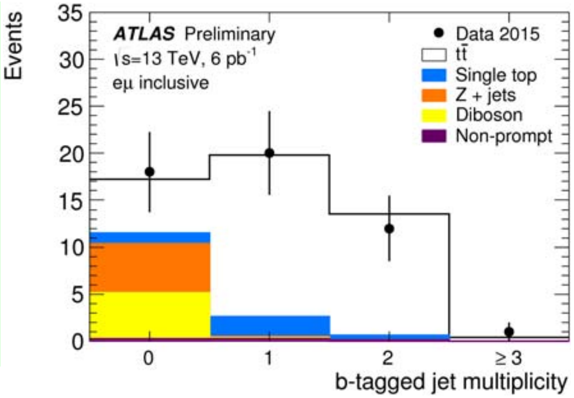
See A. Paramonov's talk



A lepton+4 jets event.
There are now thousands of such events per experiment.



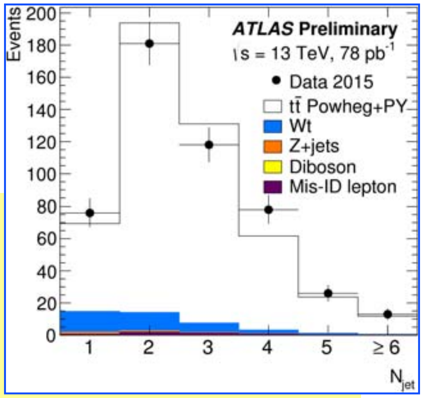
The signal to background improves with center-of-mass energy. The gg cross-section for top is increasing faster than the qqbar cross-section for W+jets.

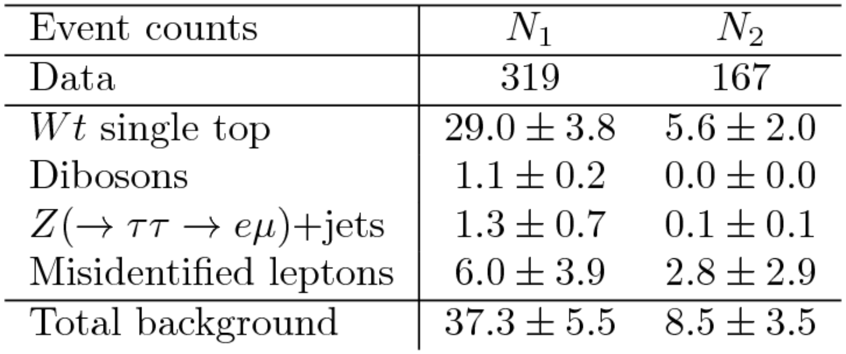


Of course ATLAS has dilepton events too. Look how well the b-tagging is working!

Top Cross-Section at 13 TeV

- Main Ideas:
  - Use the dilepton (e-μ only) channel – very low background
  - Count events with 1 and 2 b-tags
    - From two numbers, extract two numbers: the cross-section and the b-tagging efficiency

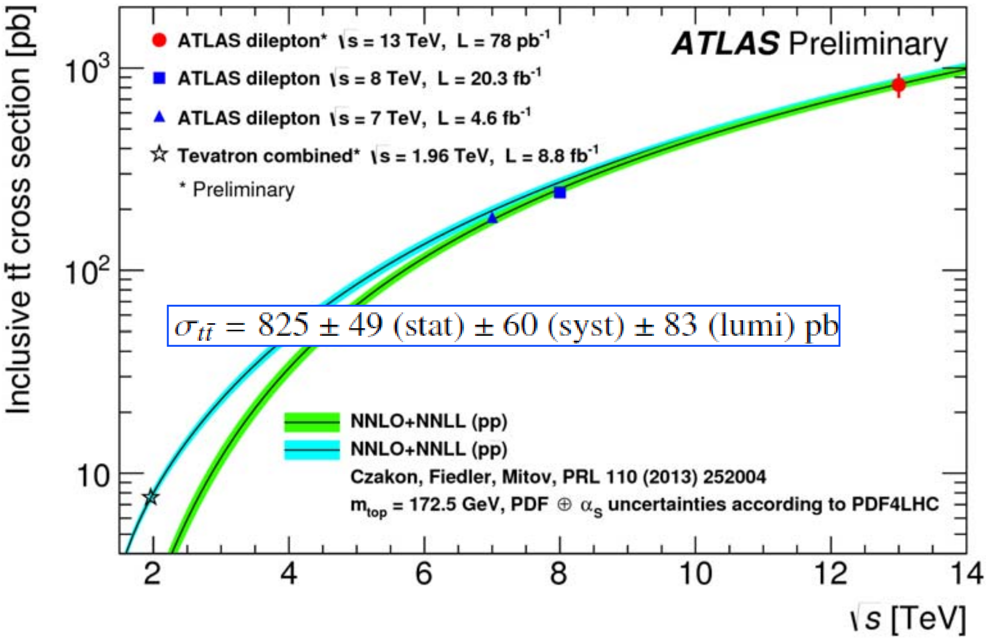




Event counts	N_1	N_2
Data	319	167
Wt single top	29.0 ± 3.8	5.6 ± 2.0
Dibosons	1.1 ± 0.2	0.0 ± 0.0
$Z(\to \tau\tau \to e\mu)$+jets	1.3 ± 0.7	0.1 ± 0.1
Misidentified leptons	6.0 ± 3.9	2.8 ± 2.9
Total background	37.3 ± 5.5	8.5 ± 3.5

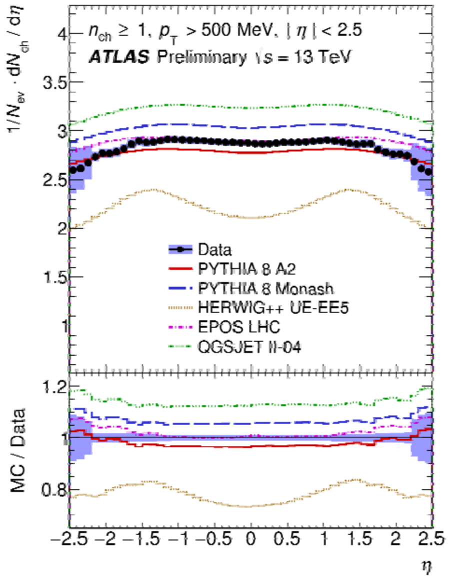
Systematic uncertainties

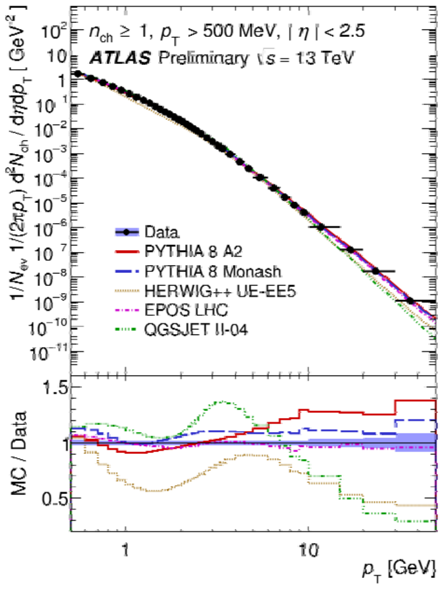
Luminosity	10%	Will greatly improve
Electron ID	4%	Will greatly improve
Top hadronization	4.5%	Will improve

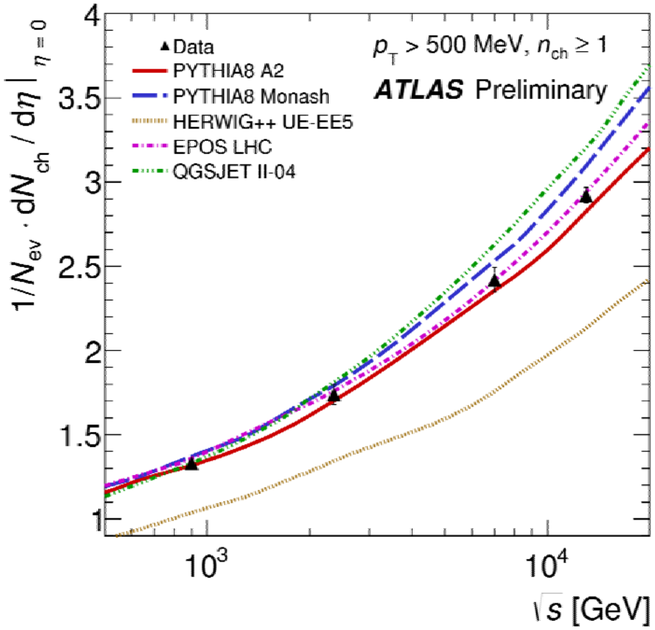


$$\sigma_{t\bar{t}} = 825 \pm 49\ (\text{stat}) \pm 60\ (\text{syst}) \pm 83\ (\text{lumi})\ \text{pb}$$

Charged Particle Spectrum at 13 TeV

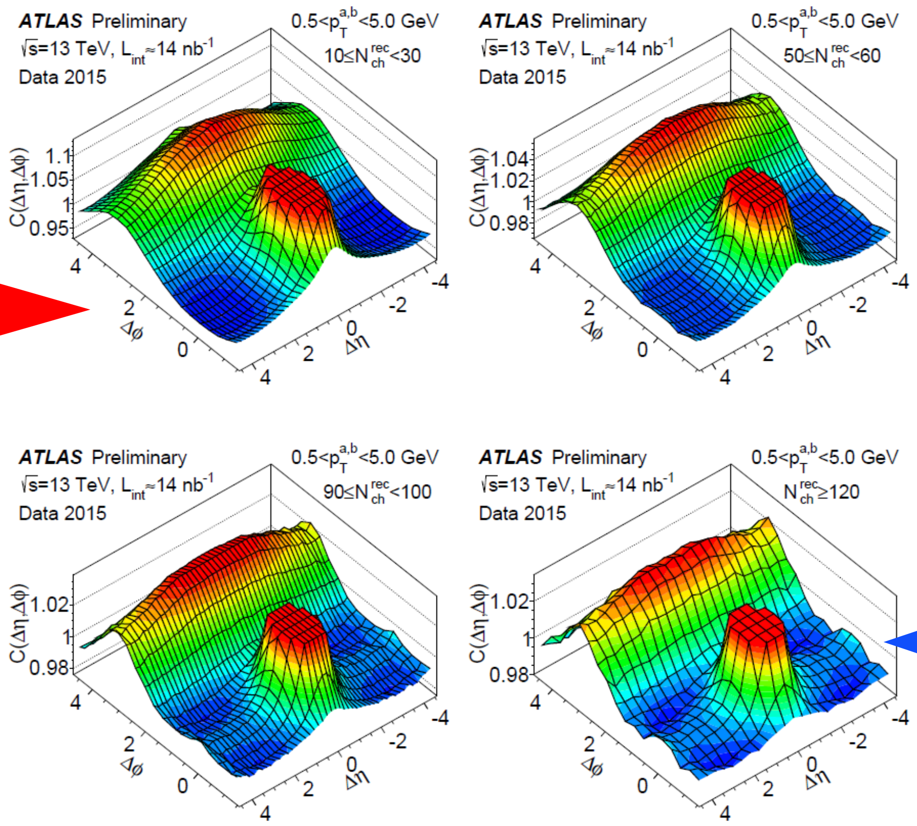






- The trend is as predicted by theory
- The data is already of sufficient quality to distinguish between models
- This is crucial data for modeling the detector response
  - There are dozens of additional collisions in every triggered event. These must be modeled correctly.

The pp “Ridge”



These are two-particle correlations, in $\Delta\eta - \Delta\phi$ space. The “away-side” ridge is due to jets (and momentum conservation). The near-side “bump” is due to correlations from jets and hadronic resonances.

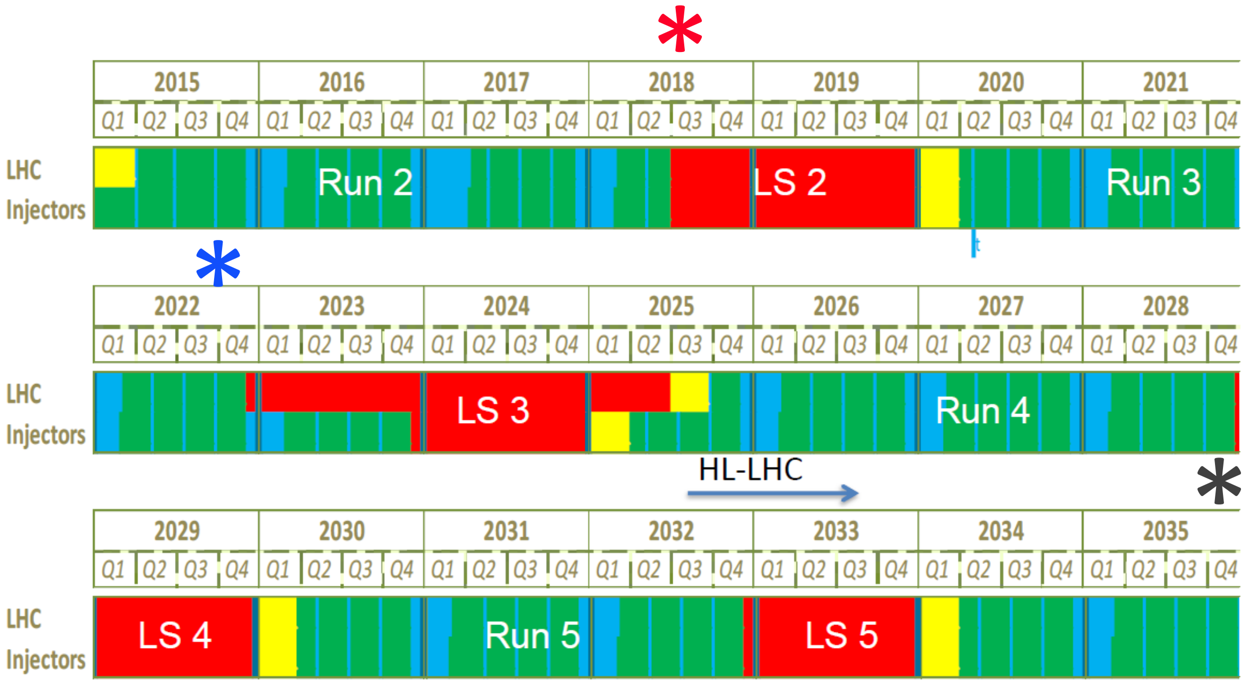
Low multiplicity – no near-side ridge

High multiplicity – has a near-side ridge

- In AA, the ridge is explained as collective behavior – but why then do we see it in a small system like pp? (First seen by CMS at 7 TeV: at 13 TeV, ATLAS sees the same effect for the same multiplicity)
- I hope this is just one of many mysteries to be provided by the LHC as we begin Run 2!

See E. Carquin’s talk

Future Plans



- * Have 3x today’s data (but at 13 TeV)
- * Have 10x today’s data
- * Have 100x today’s data

Rule of thumb: every three years of running roughly triples the dataset.

Summary and Conclusions

- Run 1 was a great success
  - ATLAS and CMS discovered a Higgs Boson
    - The yield tells us there are exactly three fermion families
      - Any new family must be vector-like
      - Run 1 searches haven’t uncovered anything
      - Run 2 will continue these searches
    - The mass suggests some new broken symmetry
      - Supersymmetry is the obvious example
      - Where is it? In particular, where is the stop squark?
    - If there is one, there could be more
      - Two pronged approach for Run 2 – direct searches, and precision measurements of H(125)
- Run 2 is underway
  - We are finishing up the necessary preliminary groundwork and the searches are about to resume!