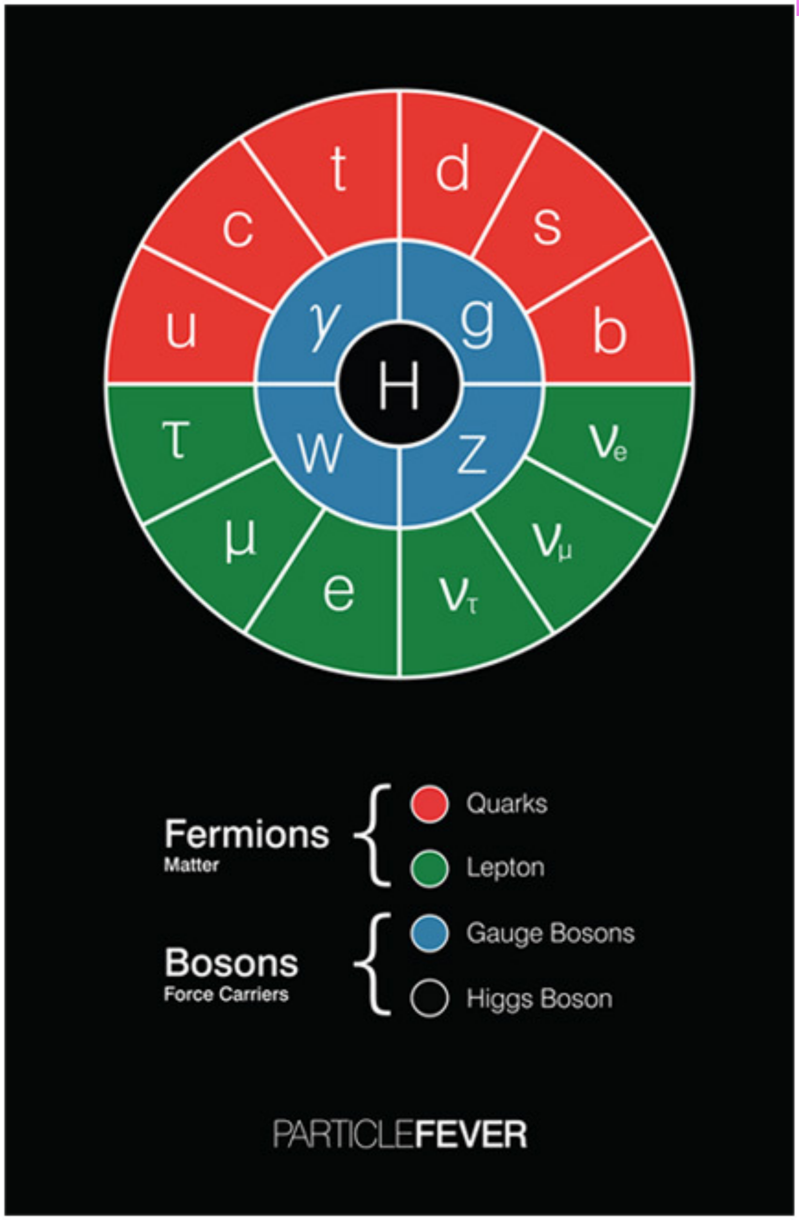

Higgs Physics at the LHC: an experimental perspective (but with some phenomenology)

J. Huston
Michigan State University
CTEQ SS 2015

I will be ATLAS-centric. Also, not much about statistics. For more CMS, and statistical wisdom, see Andrey Korytov's lectures from last year's CTEQ SS.

These lectures brought to you by

The Black Book of Quantum Chromodynamics

A QCD primer for the LHC era

J. M. Campbell

Theoretical Physics Department, Fermilab, P.O.Box 500, Batavia, IL 60510, USA

J. W. Huston

Department of Physics and Astronomy, Michigan State University, East Lansing, MI 48824, USA

F. Krauss

Institute for Particle Physics Phenomenology, Durham University, Durham DH1 3LE, UK

12

available for next CTEQ SS

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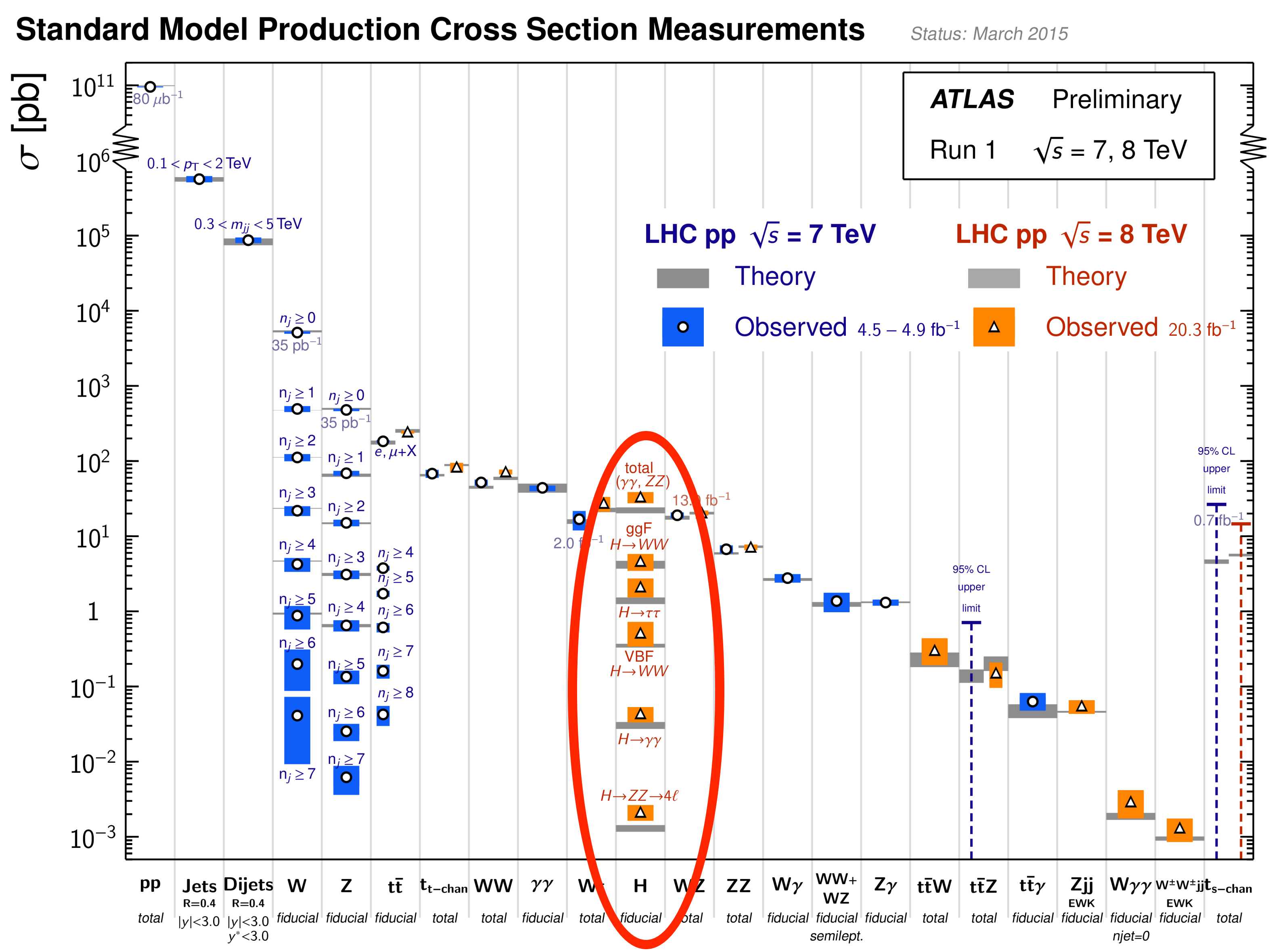
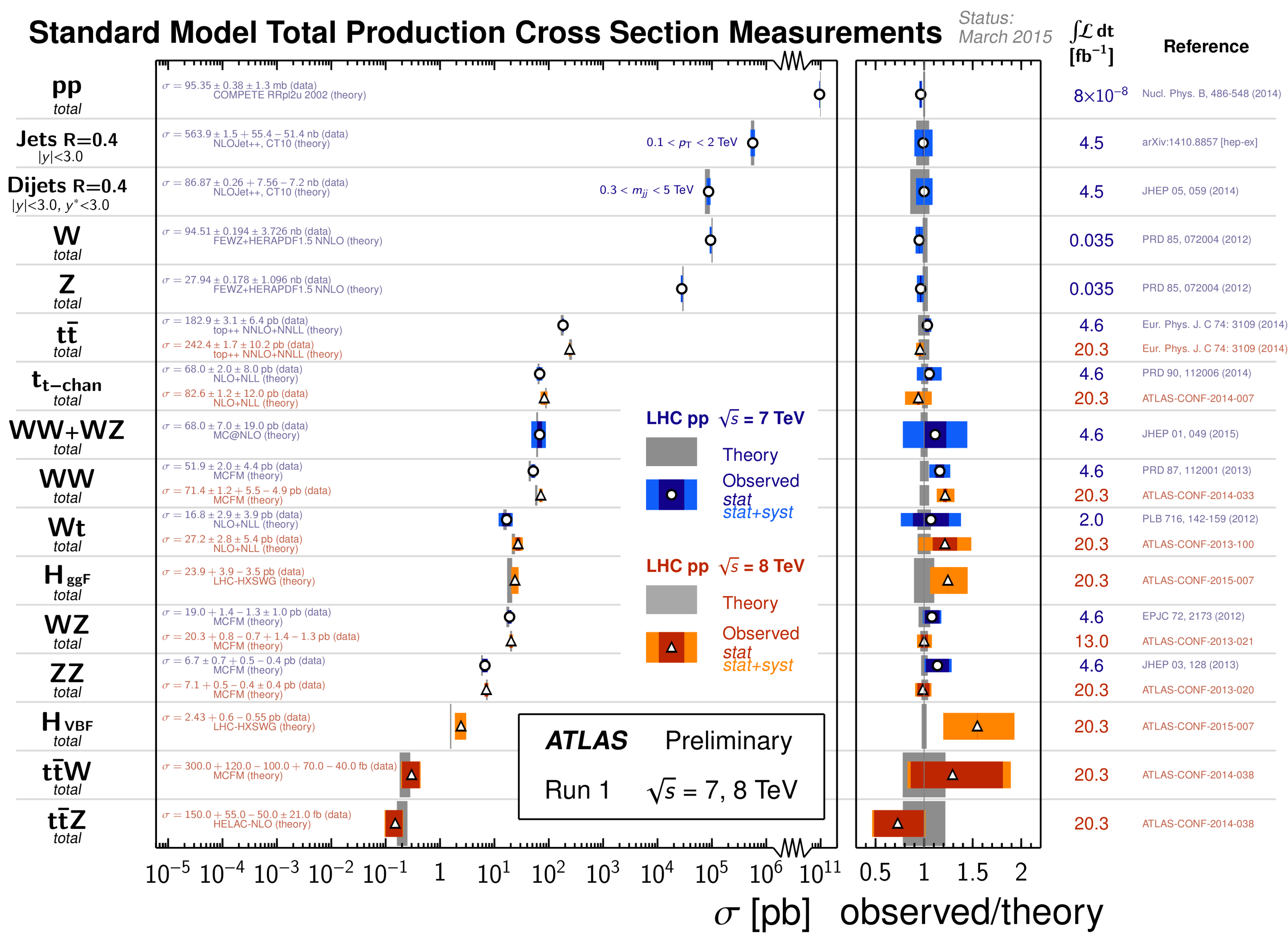
(SM) Physics from Run 1

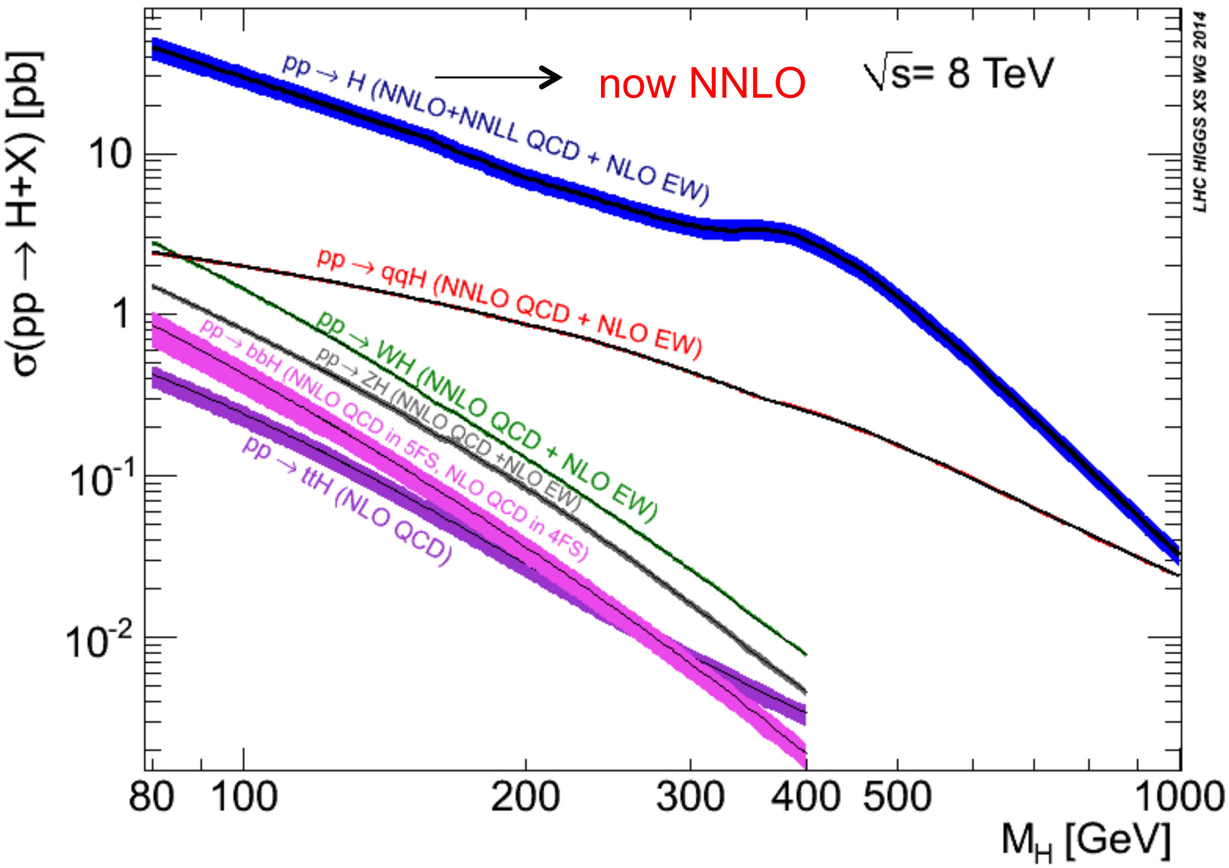


Physics from Run 1

…in most cases, good agreement with SM predictions (at NLO and higher). The techniques developed to 're-discover the standard model' were crucial for the discovery of the Higgs boson.

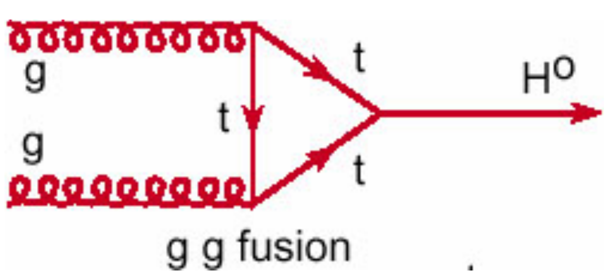


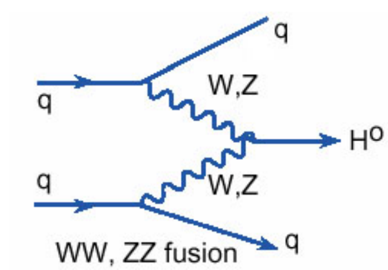
Higgs boson production modes

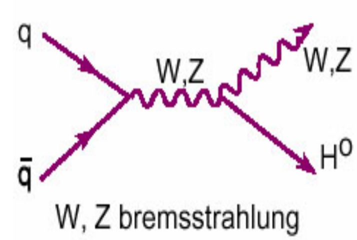


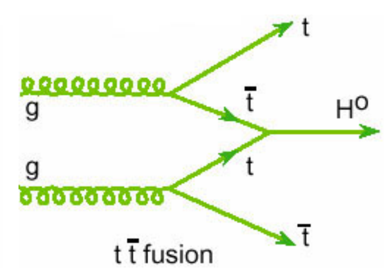
Both QCD and EW effects are important. Most cross sections are known to NNLO QCD +NLO EW. gg fusion is now known to NNNLO. The theory isn't required per se to find the Higgs boson*, but is required to determine its properties.

*but we do re-weight events according to S/B with S being the SM, so there is a SM bias. We would like to go away from this in Run 2.









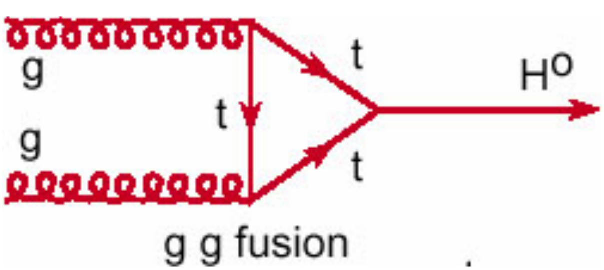
Higgs sector

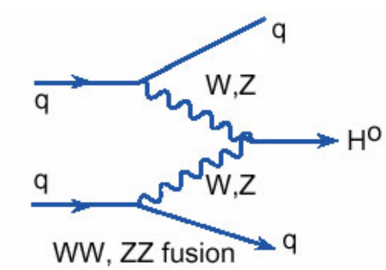
- Given its importance, it's not surprise the level of theoretical interest that has gone into higher order calculations (in both QCD and EW) for various final states involving Higgs production (and of its backgrounds)
- NB: NLO calculations now are *easy*/semi-automatic
- It's NNLO that's hard (and NLO EW)

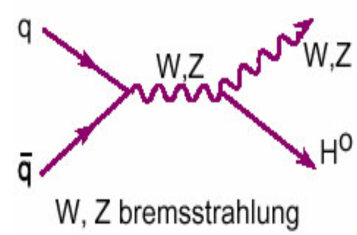
Process	known	desired	details
H	$d\sigma$ @ ~~NNLO~~ NNNLO QCD $d\sigma$ @ NLO EW finite quark mass effects @ NLO	$d\sigma$ @ NNNLO QCD + NLO EW MC@NNLO finite quark mass effects @ NNLO	H branching ratios and couplings
H + j	$d\sigma$ @ NNLO QCD $d\sigma$ @ NLO EW finite quark mass effects @ LO	$d\sigma$ @ NNLO QCD + NLO EW finite quark mass effects @ NLO	H p_T
H + 2j	$\sigma_{\rm tot}$(VBF) @ NNLO(DIS) QCD $d\sigma$(gg) @ NLO QCD $d\sigma$(VBF) @ NLO EW	$d\sigma$ @ NNLO QCD + NLO EW	H couplings
H + V	$d\sigma$ @ NNLO QCD $d\sigma$ @ NLO EW	with $H \to b\bar{b}$ @ same accuracy	H couplings
$t\bar{t}$H	$d\sigma$(stable tops) @ NLO QCD	$d\sigma$(top decays) @ NLO QCD + NLO EW	top Yukawa coupling
HH	$d\sigma$ @ LO QCD (full m_t dependence) $d\sigma$ @ NLO QCD (infinite m_t limit)	$d\sigma$ @ NLO QCD (full m_t dependence) $d\sigma$ @ NNLO QCD (infinite m_t limit)	Higgs self coupling

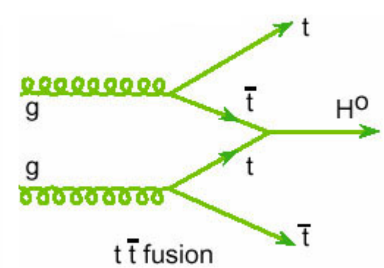
Table 1: Wishlist part 1 – Higgs (V = W, Z)

Les Houches high precision wishlist
arXiv.org:1405.1067









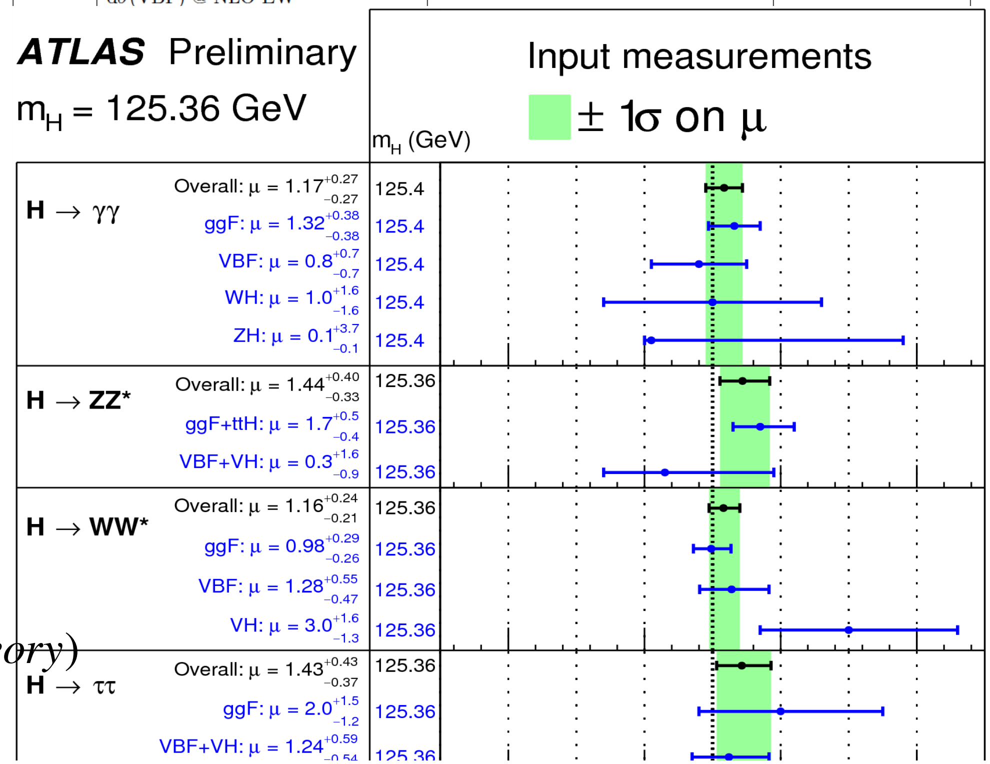
Higgs sector (overview)

- We currently know the production cross section for gg fusion to NNNLO QCD in the infinite m_t limit, including finite quark mass effects at NLO QCD and NLO EW.
- Current ATLAS/CMS experimental uncertainties are of the order of 20-40%->consistency with SM at that level
- NB: signal strength parameters make use of state-of-art calculations of **SM** Higgs cross sections and kinematics
- Global μ:

$$\mu = 1.18^{+0.15}_{-0.14} = 1.18 \pm 0.10(stat) \pm 0.07(expt)^{+0.08}_{-0.07}(theory)$$

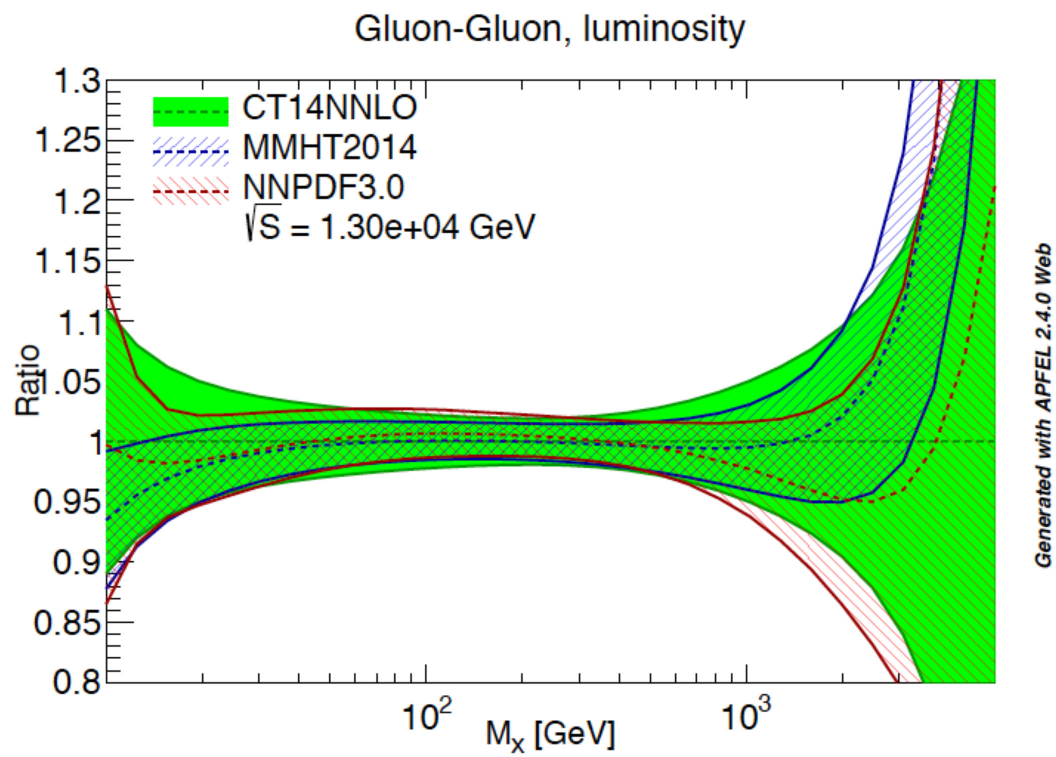
- Theory error is competitive with other errors**->theory improvements needed**

Process	known	desired	details
H	$d\sigma$ @ NNLO QCD $d\sigma$ @ NLO EW finite quark mass effects @ NLO	$d\sigma$ @ NNNLO QCD + NLO EW MC@NNLO finite quark mass effects @ NNLO	H branching ratios and couplings
H + j	$d\sigma$ @ NNLO QCD (g only) $d\sigma$ @ NLO EW finite quark mass effects @ LO	$d\sigma$ @ NNLO QCD + NLO EW finite quark mass effects @ NLO	H p_T
H + 2j	σ_{tot}(VBF) @ NNLO(DIS) QCD $d\sigma$(gg) @ NLO QCD $d\sigma$(VBF) @ NLO EW	$d\sigma$ @ NNLO QCD + NLO EW	H couplings



(Aside)PDFs: the next generation

- NNPDF3.0 (arXiv:1410.8849)
- MMHT14 (arXiv:1412.3989)
- CT14 (arXiv:1506.07443)
- HERAPDF2.0 (arXiv:1506.06042)
- The gg PDF luminosities for the first three PDFs are in good agreement with each other in the Higgs mass range
- PDF uncertainty using the CT14, MMHT14, CT14 PDFs would be 2-2.5%, comparable to new scale dependence at NNNLO, and comparable to the α_s uncertainty

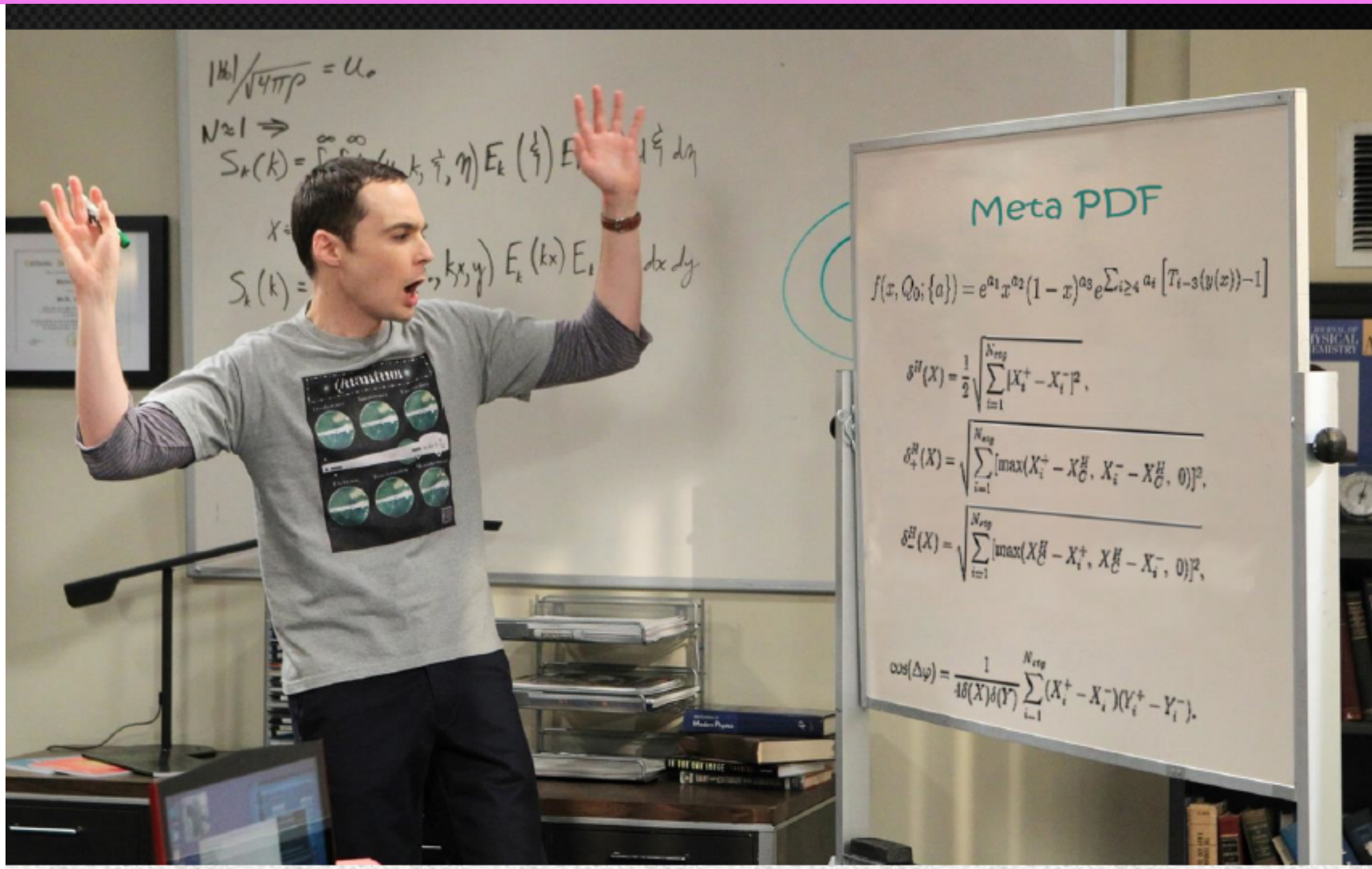


NNPDF down by 2-2.5%, CT14 up by ~1%, MMHT14 down by ~0.5%

partially data, partially corrections in fitting code, partially changes in fitting procedures

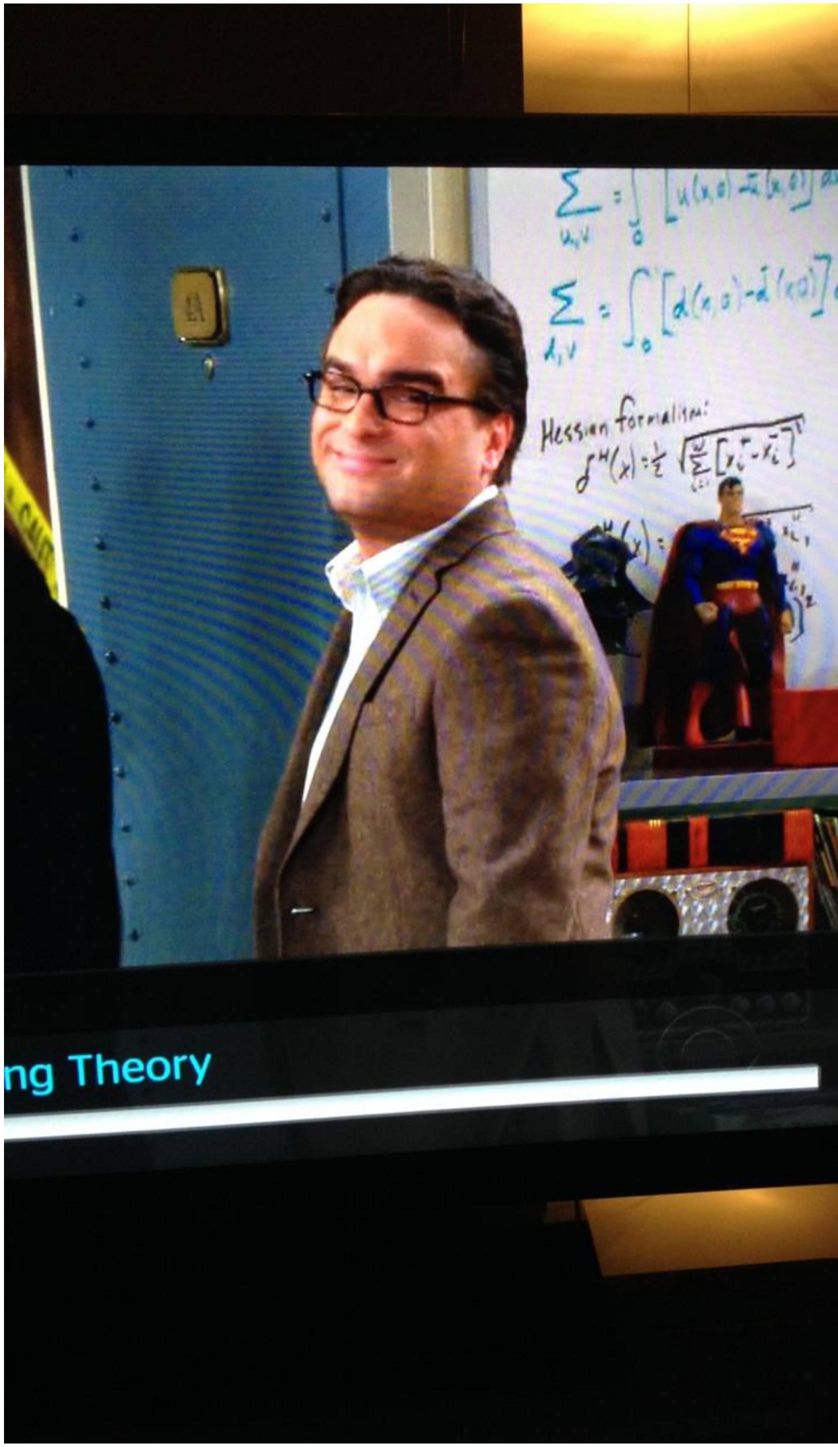
new PDF4LHC recommendation in progress using several techniques

One of the techniques is META-PDFs (Pavel Nadolsky, Jun Gao and myself)



Jun, Pavel,

Sheldon approves! META PDFs will be on the Big Bang Theory episode on Jan. 29, 2015. Regards, Joey


Hessian formalism:
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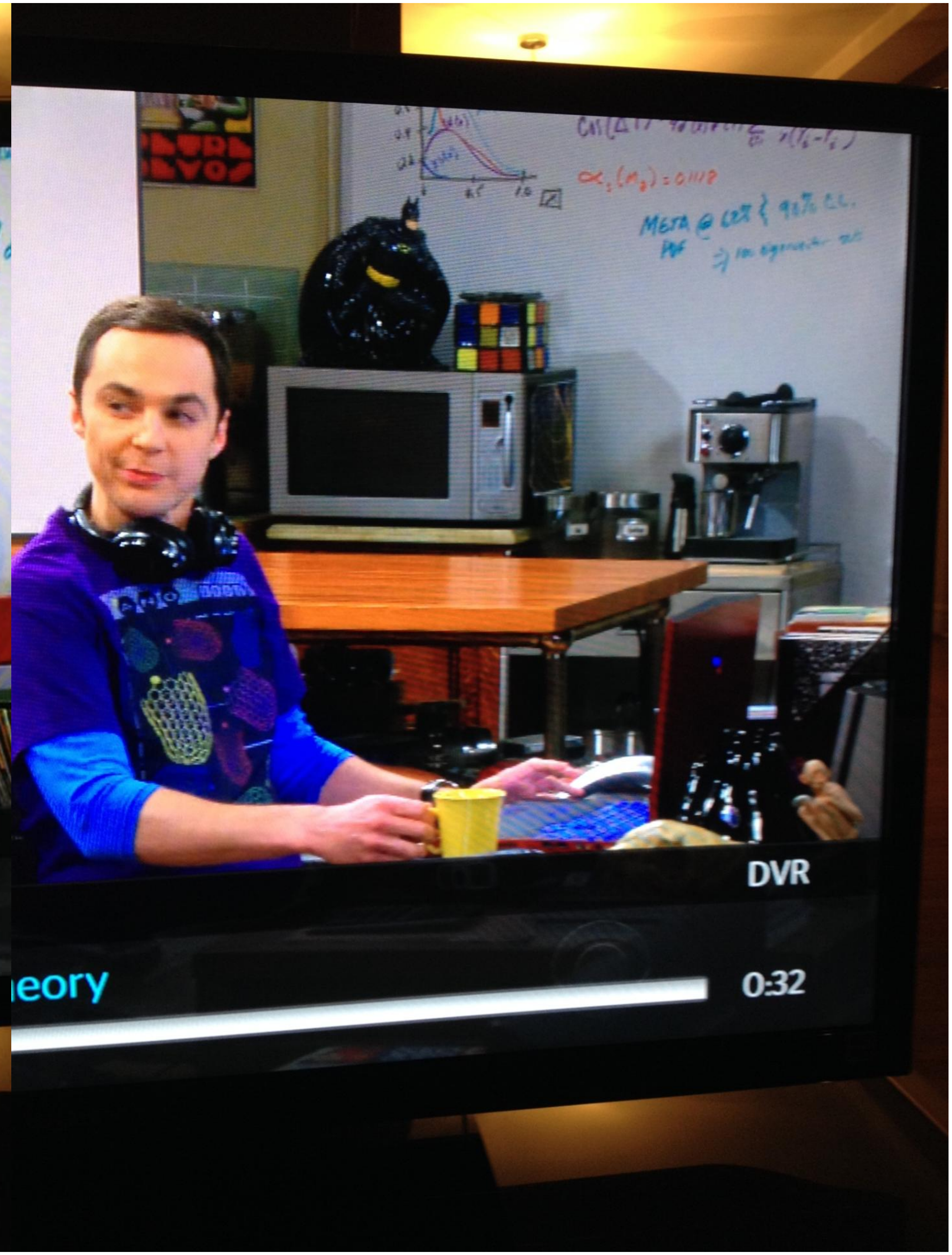
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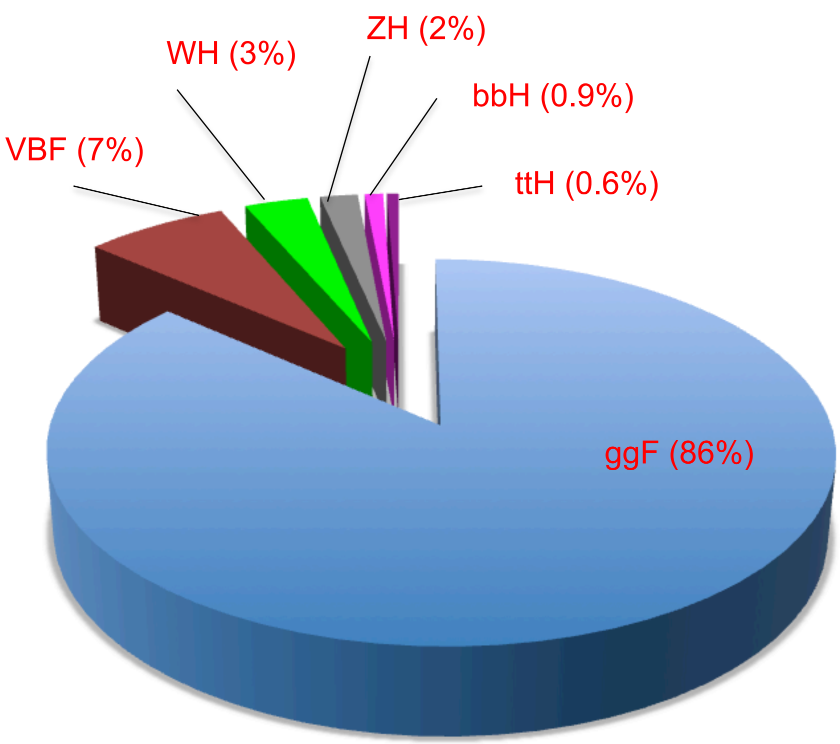
A comparison of ggF at NNLO

scale = m_H	CT14	MMHT2014	NNPDF3.0
8 TeV	18.66 pb -2.2% +2.0%	18.65 pb -1.9% +1.4%	18.77 pb -1.8% +1.8%
13 TeV	42.68 pb -2.4% +2.0%	42.70 pb -1.8% +1.3%	42.97 pb -1.9% +1.9%

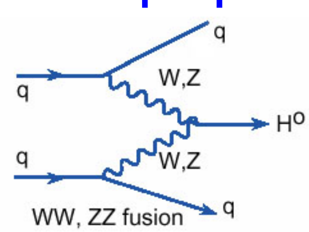
The PDF uncertainty using this new generation of PDFs will be similar in size to the NNNLO scale uncertainty and to the $\alpha_s(m_Z)$ uncertainty. Note that we have standardized on a value of $\alpha_s(m_Z)$ of 0.118 for the three PDFs above, with an $\alpha_s(m_Z)$ uncertainty of +/-0.001.

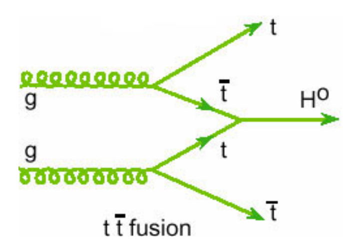
Higgs production modes



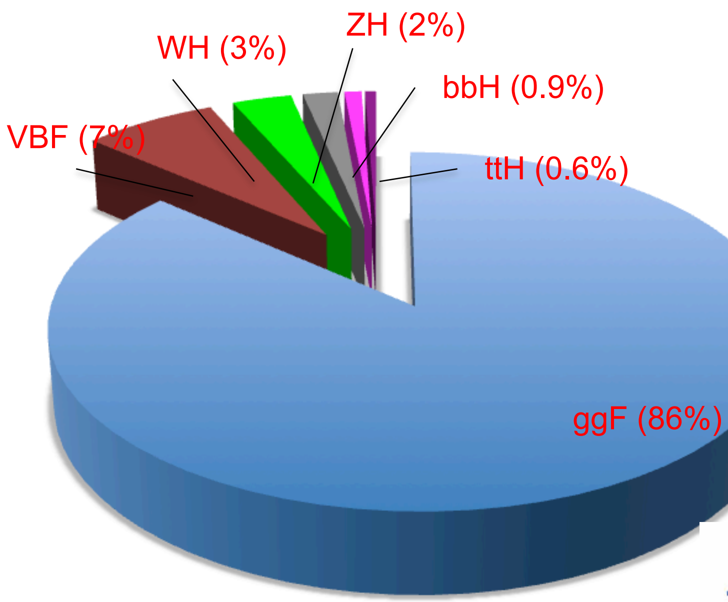
There is also tH production, which is suppressed by negative interference between coupling to weak bosons and the Yukawa coupling.

- Dominant production mode is gg fusion
- The other modes added to the discovery potential but are also important for a complete understanding of the Higgs boson properties
- For example, VBF probes coupling to W/Z bosons, ttH probes coupling to the top quark

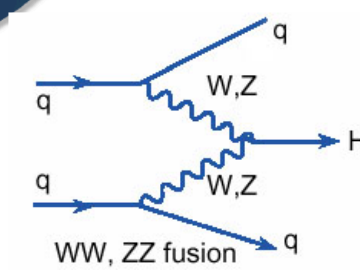


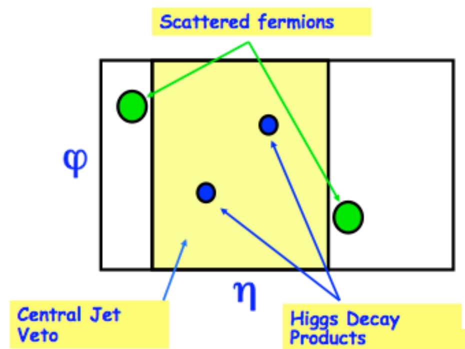


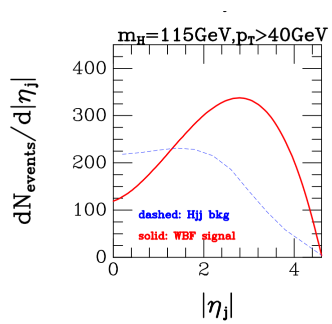
Production modes



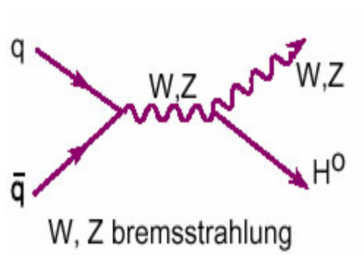
- To boost sensitivities, SM Higgs boson analyses sort events into exclusive categories targetting VBF and VH
  - VBF: two jets (p_T>30 GeV) with large dijet mass and large rapidity separation
    - can also require large rapidity gap





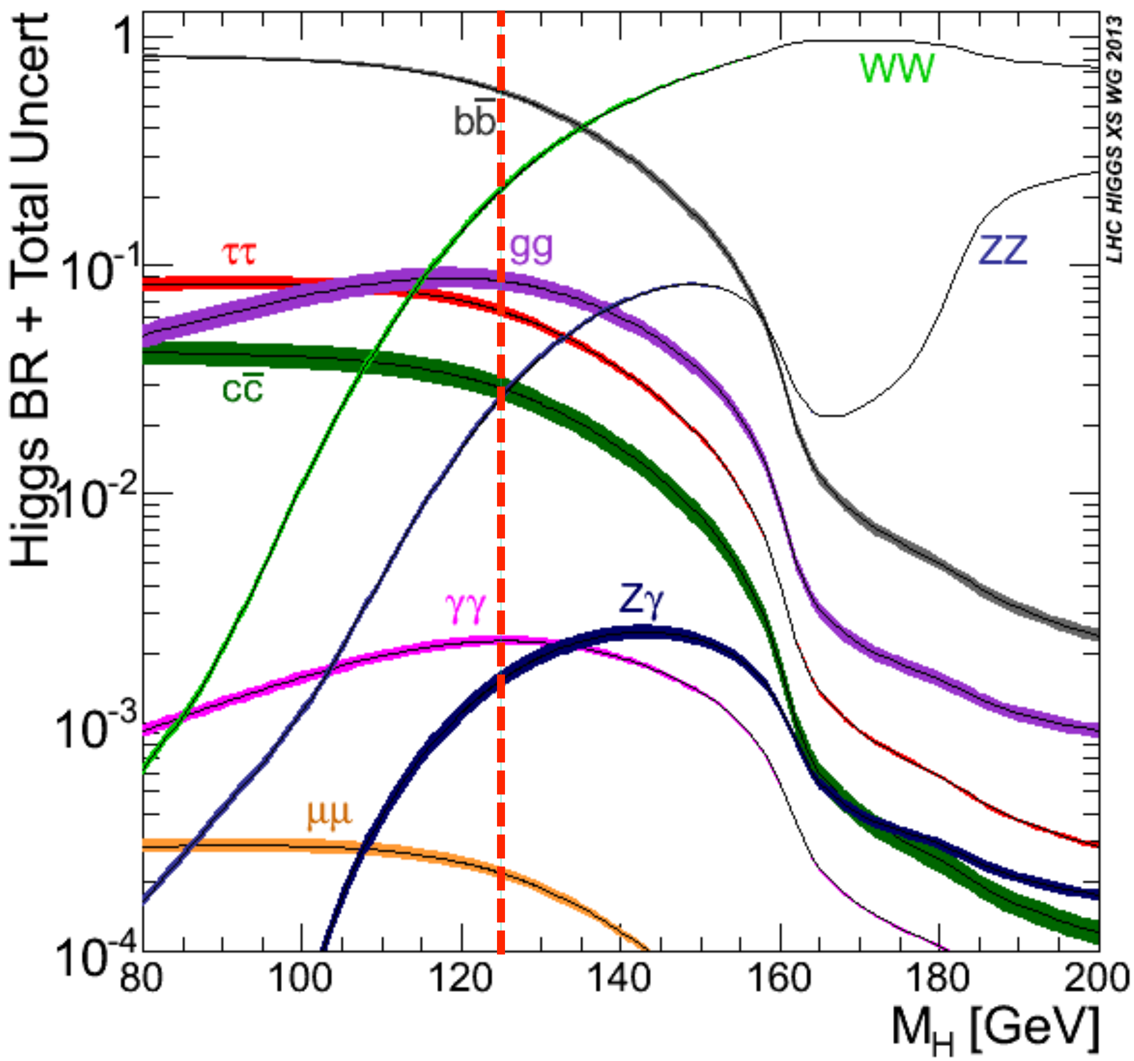


The two quark jets in VBF are naturally widely separated. They are much more central for gg fusion. Requiring a large Δy separation (>~3) between the two jets leads to VBF>ggF. Note also that VBF proceeds by color singlet exchange. Much less gluon radiation than for ggF, so the absence of extra jets also distinguishes VBF from ggF.



  - VH: Z->ll,Z->νν(MET), W->lν, V->jj (m_{jj}~m_V)
    - most often look for H->bb; better S/B when H is boosted (p_T>100 GeV)

Decay BR's



- The Higgs boson likes to decay to the heaviest particles kinematically allowed, like bB
- So it can't decay into WW/ZZ, but it can decay into WW*/ZZ*, where one W/Z is off-shell
- H->γγ, H->Zγ suppressed since couplings only exist through loops

QCD at Fixed Order: processes

Table 4.2 Branching ratios of a Standard Model Higgs boson of mass $m_H = 125$ GeV. The corresponding width is $\Gamma_H = 4.07$ MeV.

Decay mode	Branching ratio	Order of calculation
$b\bar{b}$	$0.577^{+3.2\%}_{-3.3\%}$	N^4LO QCD + NLO EW
WW	$0.215^{+4.3\%}_{-4.2\%}$	NLO QCD + NLO EW
gg	$0.0857^{+10.2\%}_{-10.0\%}$	N^3LO QCD + NLO EW
$\tau\tau$	$0.0632^{+5.7\%}_{-5.7\%}$	NLO EW
$c\bar{c}$	$0.0291^{+12.2\%}_{-12.2\%}$	N^4LO QCD + NLO EW
ZZ	$0.0264^{+4.3\%}_{-4.2\%}$	NLO QCD + NLO EW
$\gamma\gamma$	$0.00228^{+5.0\%}_{-4.9\%}$	NLO QCD + NLO EW
$Z\gamma$	$0.00154^{+9.0\%}_{-8.8\%}$	LO
$\mu\mu$	$0.00022^{+6.0\%}_{-5.9\%}$	NLO EW

Decay BR's

- H->γγ, H->Zγ suppressed since couplings only exist through loops

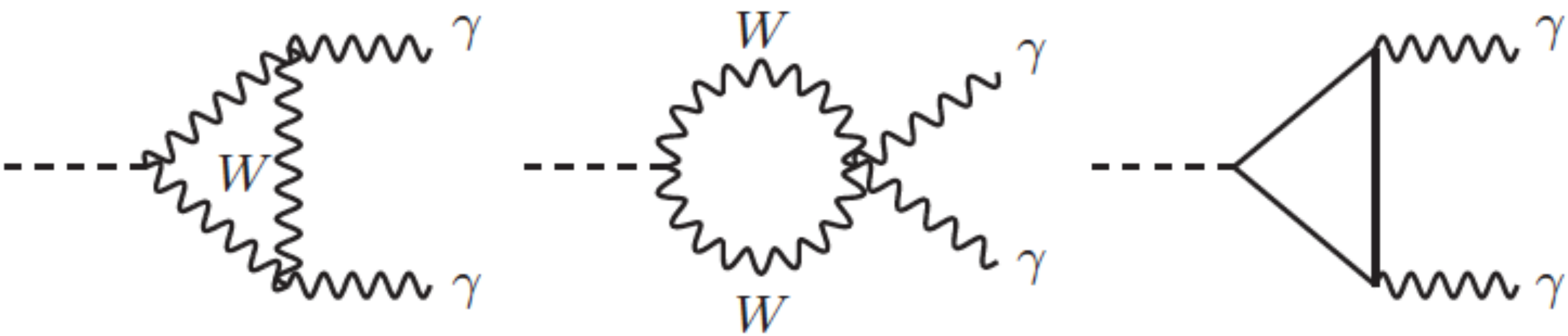
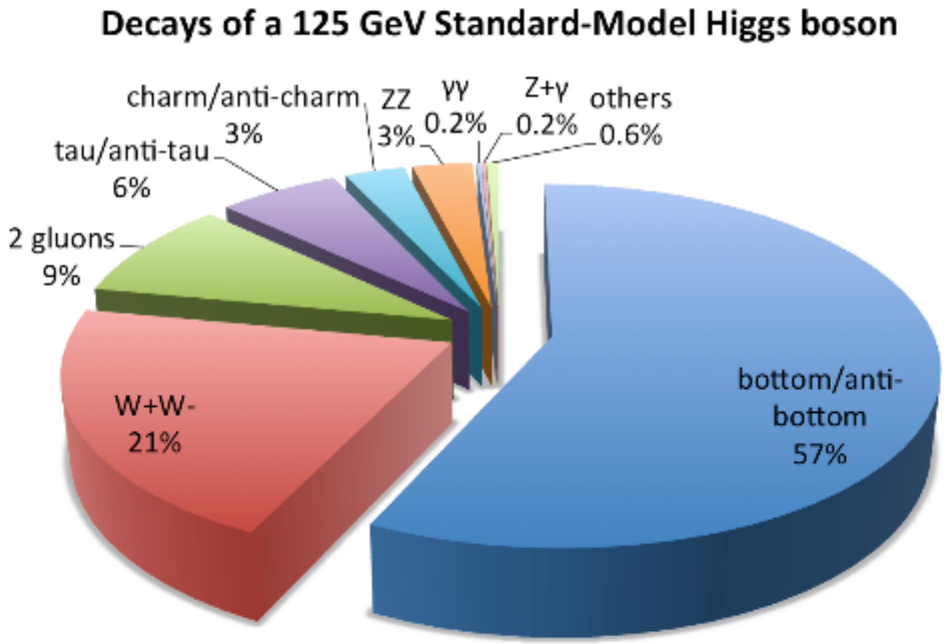
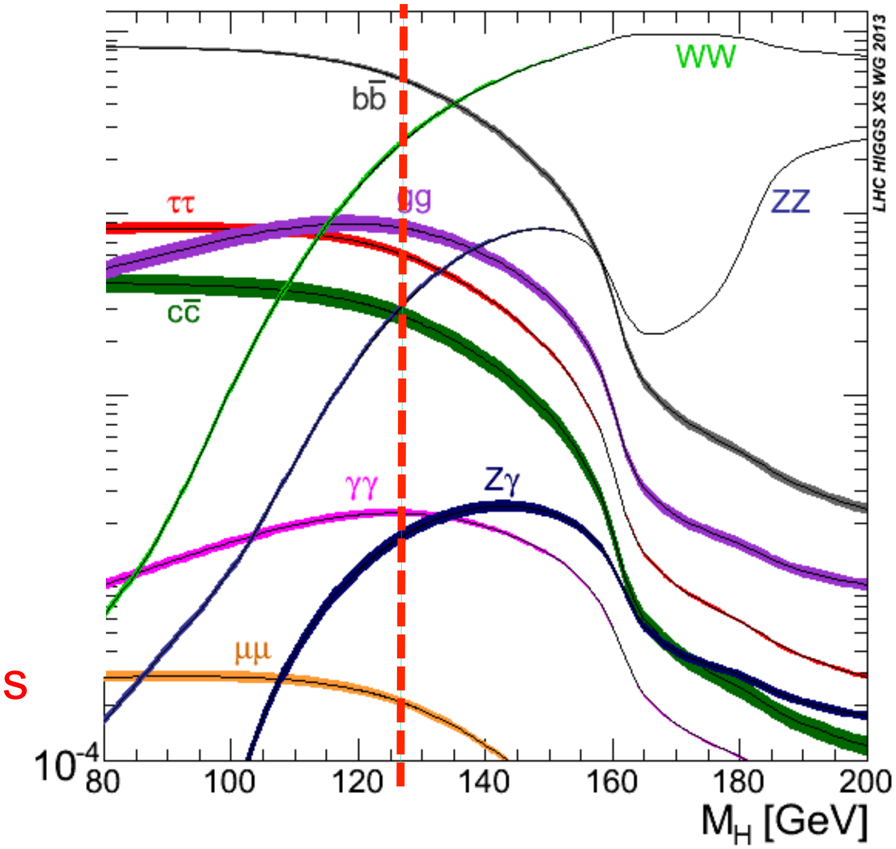


Fig. 4.53 Representative Feynman diagrams for the loop-induced coupling of a Higgs boson to two photons.

W loops more important than top loops for decays. Why are they not more Important for the production of a Higgs?

Decay BR's



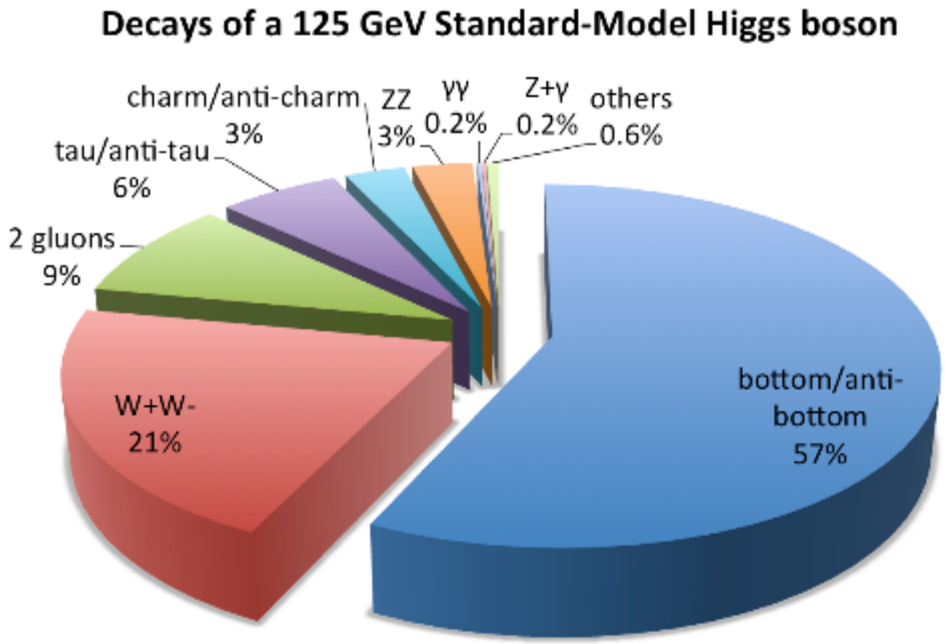


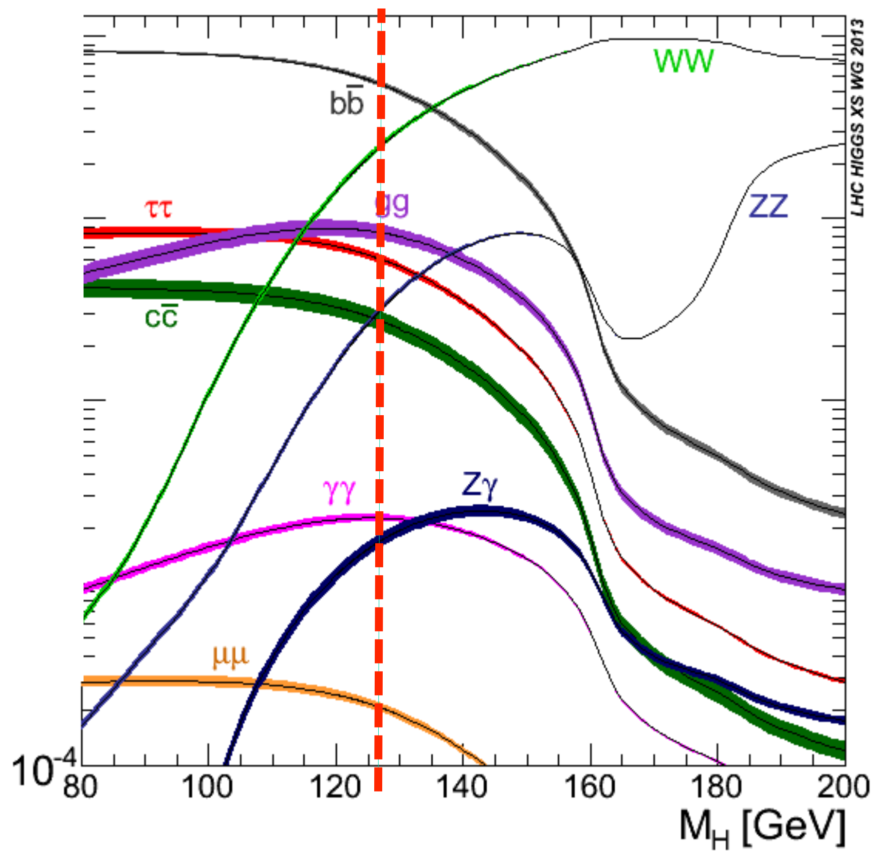
…so we'll be looking for W's, Z's, photons bottom quarks, charm quarks and taus

…which means we'll be measuring leptons, photons, jets and missing transverse energy

All of these final states have backgrounds from the standard model. All of these states have been measured in standard model analyses at ATLAS and CMS.

Decay BR's





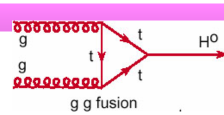
…so we'll be looking for W's, Z's, photons bottom quarks, charm quarks and taus

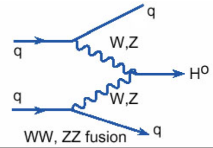
…which means we'll be measuring leptons, photons, jets and missing transverse energy

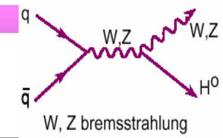
All of these final states have backgrounds from the standard model. Some backgrounds we can determine from the data. For others, we depend on theory.

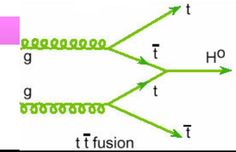
SM Higgs events in Run I (per experiment)

m_H=125 GeV









observed?

observed?	Decays		ggF (19.3 pb)	VBF (1.6 pb)	VH (1.1 pb)	ttH (0.13 pb)
			86%	7%	5%	0.6%
✓	ZZ → 4l	0.00014	77			
✓	γγ	0.0023	1,300			
✓	WW → lνlν	0.0028	1,500			
✓	ττ	0.062	34,000			
✓	bb	0.56	270,000	42,000		
	μμ	0.00021	120			
	Zγ → 2l γ	0.00011	61			
	γ*γ→ 2μ γ	2×10^{-5}	11			
	invisible	0.0012	663 (too small S/B at LHC, unless there is BSM)			

TOTAL PRODUCED: 500K events

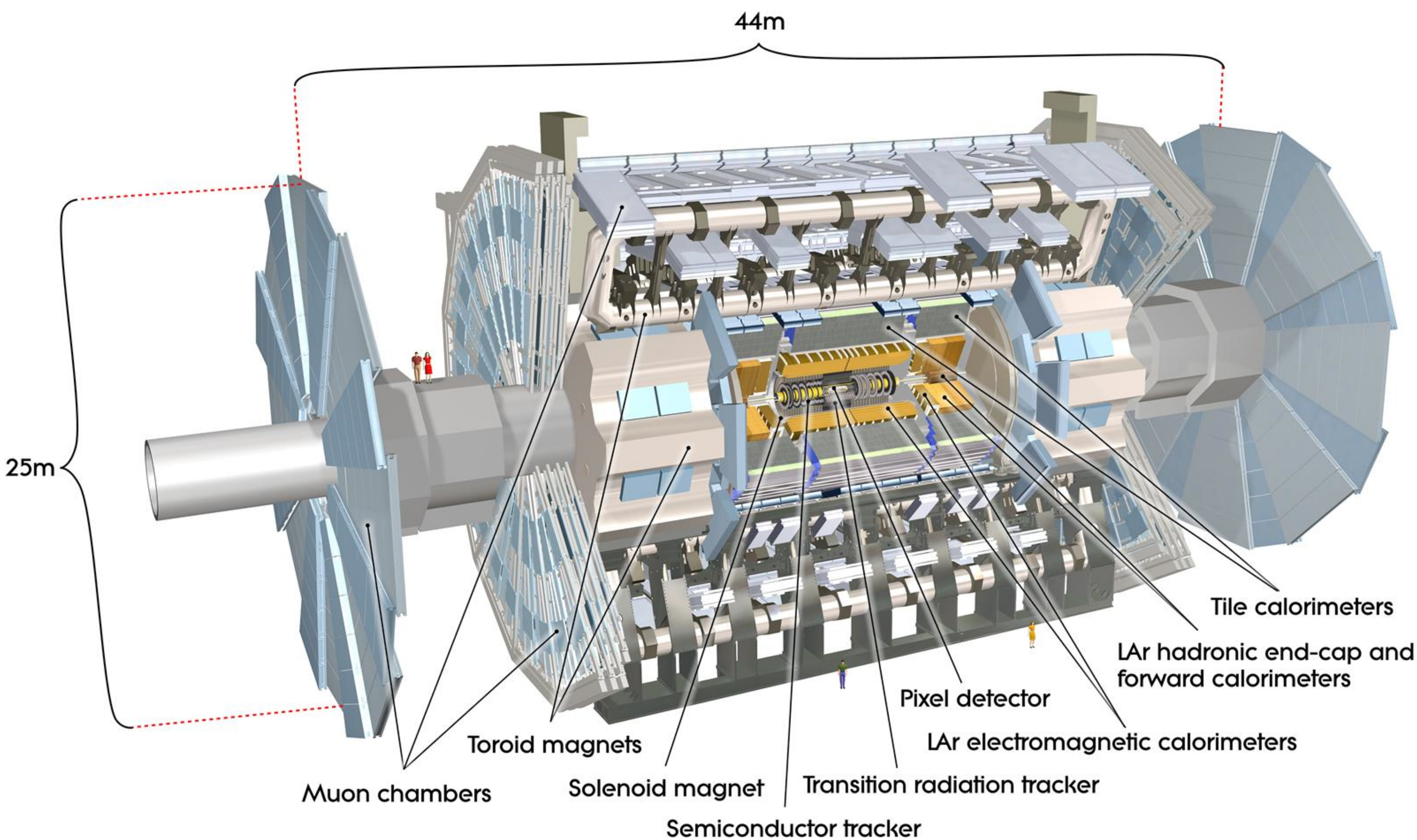
- before acceptance
- before reconstruction efficiency
- before event selection efficiency

Total number of inelastic pp-collisions produced in Run I – 1.5×10^{15}

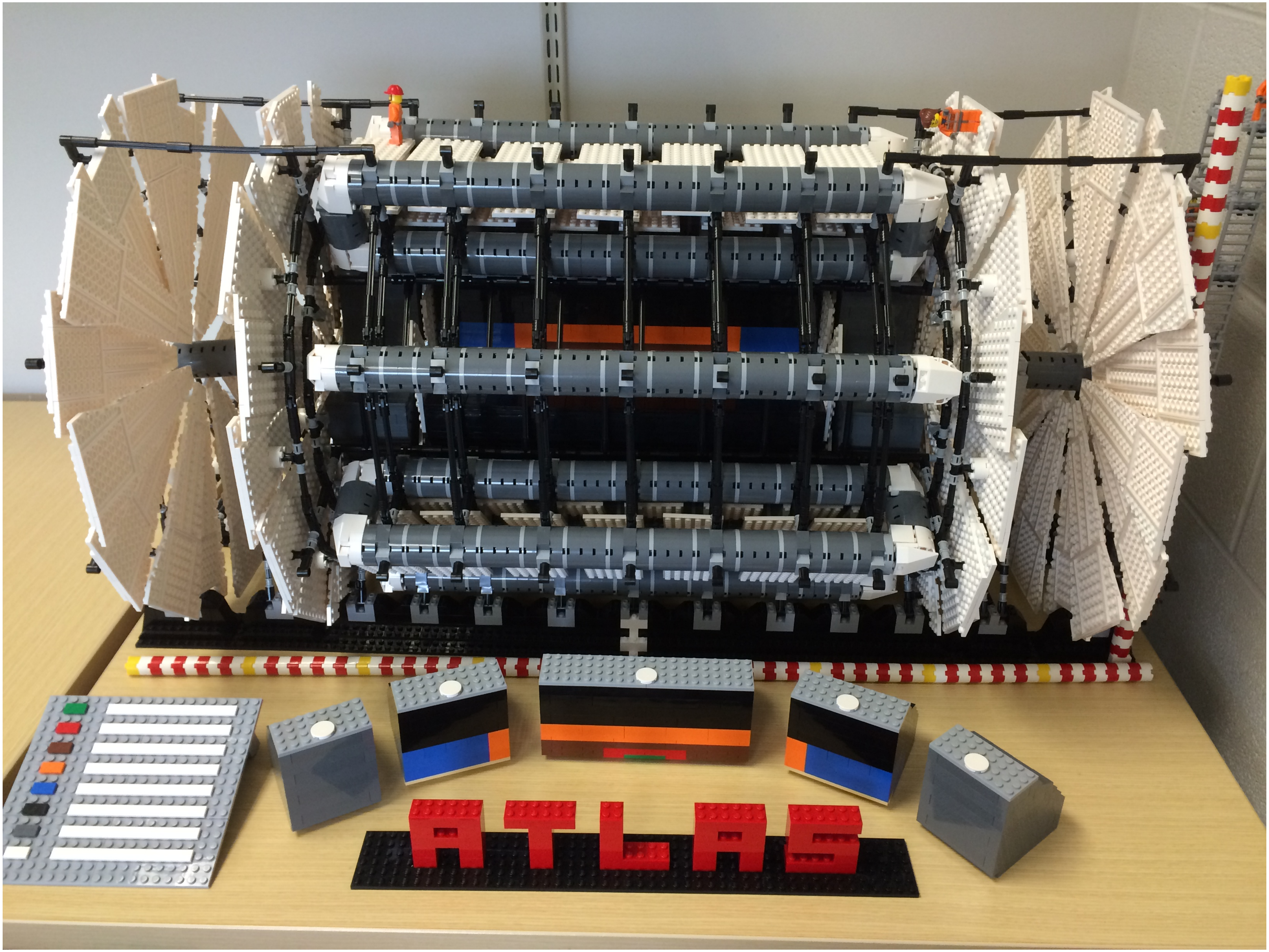
Andrey Korytov (UF)

What do we do with the Higgs boson?

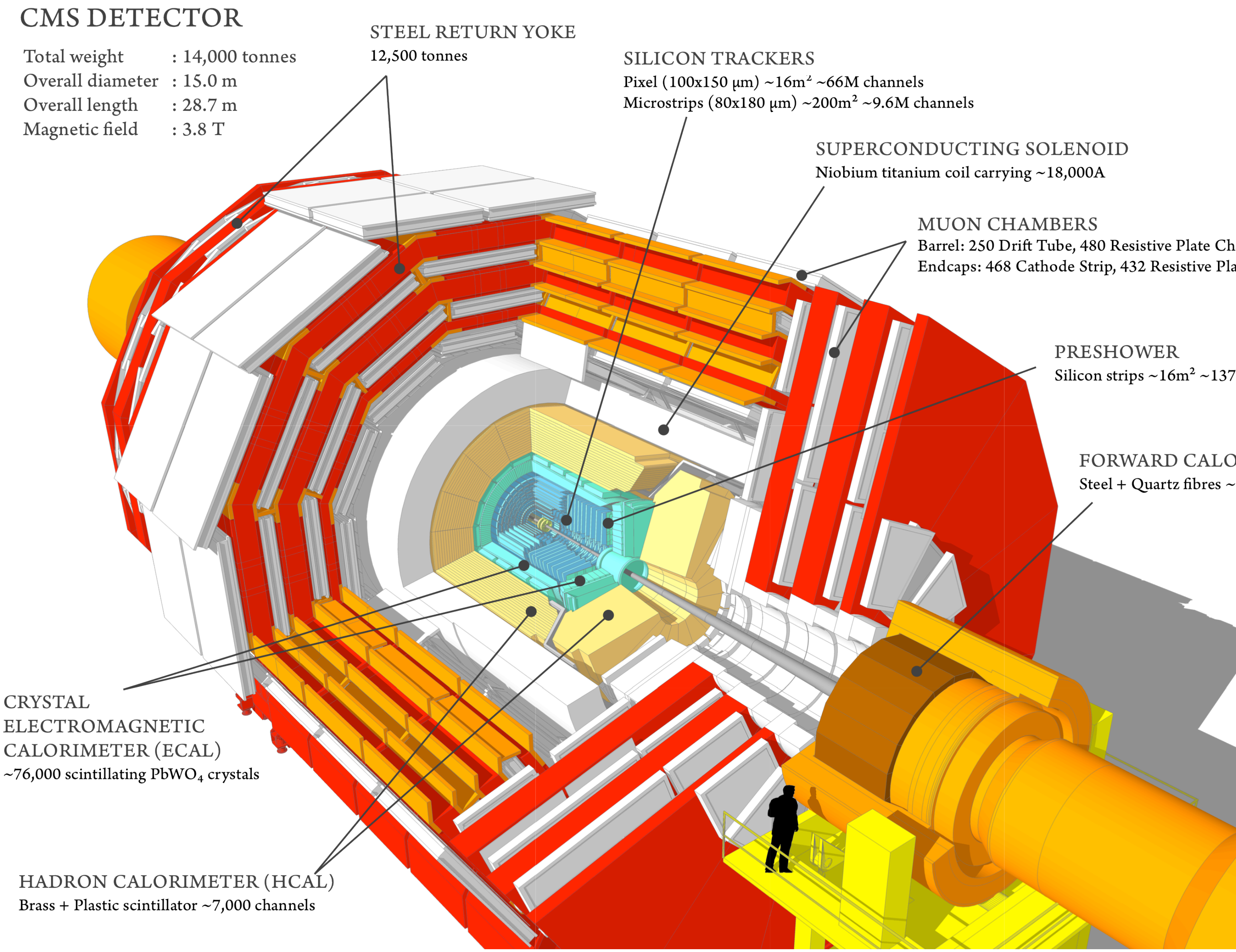
- We have conclusive evidence of its existence and a precise knowledge of its mass
  - in four decay channels (WW,ZZ,$\gamma\gamma$,$\tau\tau$)
- We want to know/measure its width
- We want to know its spin-parity quantum numbers
- We want to know the production+decay rates and recast them as measurements of couplings
- We want to measure differential distributions
- We want to search for experimentally difficult/rare decays
- We want to collect a Nobel prize 
- We want to search for more of them
- We want to look for exotic decays, for example into SUSY particles



4π coverage for measurement of photons, jets, heavy flavor jets, electrons, muons, missing ET


ATLAS

CMS


CMS DETECTOR
Total weight : 14,000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T
STEEL RETURN YOKE
12,500 tonnes
SILICON TRACKERS
Pixel (100x150 μm) ~16m² ~66M channels
Microstrips (80x180 μm) ~200m² ~9.6M channels
SUPERCONDUCTING SOLENOID
Niobium titanium coil carrying ~18,000A
MUON CHAMBERS
Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
Endcaps: 468 Cathode Strip, 432 Resistive Plate Chambers
PRESHOWER
Silicon strips ~16m² ~137,000 channels
FORWARD CALORIMETER
Steel + Quartz fibres ~2,000 Channels
CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
~76,000 scintillating $PbWO_4$ crystals
HADRON CALORIMETER (HCAL)
Brass + Plastic scintillator ~7,000 channels

Design philosophies

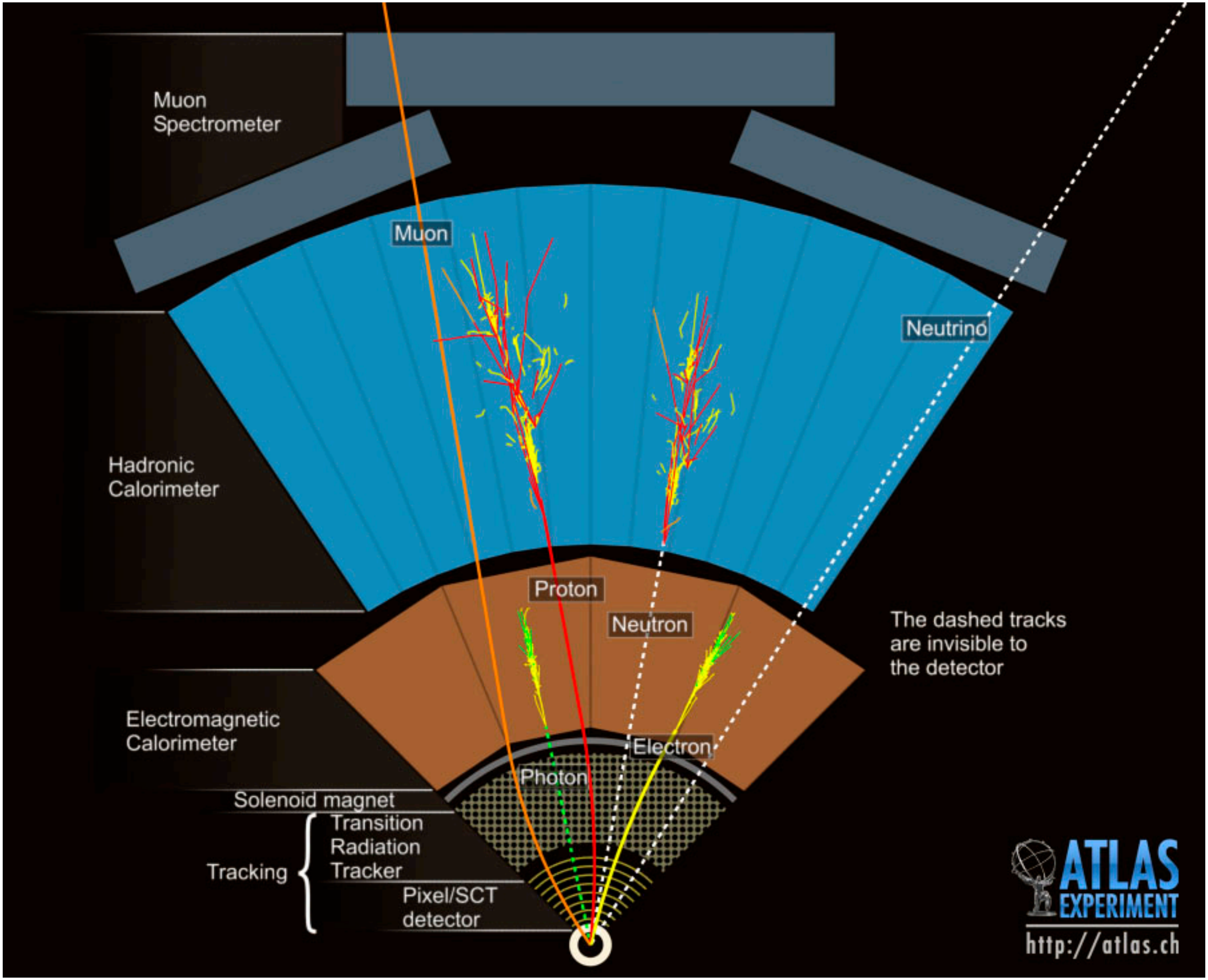
CMS

- a high performance system to detect and measure muons,
- a high resolution method to detect and measure electrons and photons (an electromagnetic calorimeter),
- a high quality central tracking system to give accurate momentum measurements, and
- a “hermetic” hadron calorimeter, designed to entirely surround the collision and prevent particles from escaping.

ATLAS

- a high performance system to detect and measure muons,
- a high resolution method to detect and measure electrons and photons (an electromagnetic calorimeter),
- a high quality central tracking system to give accurate momentum measurements, and
- a “hermetic” hadron calorimeter, designed to entirely surround the collision and prevent particles from escaping.

Both ATLAS and CMS have finer granularity than CDF and D0. It’s partially because of advances in technology and partially because there’s more money (CHF) to be spent.



Muon Spectrometer
Hadronic Calorimeter
Electromagnetic Calorimeter
Solenoid magnet
Tracking
Transition Radiation Tracker
Pixel/SCT detector
Muon
Neutrino
Proton
Neutron
Electron
Photon
The dashed tracks are invisible to the detector
ATLAS EXPERIMENT
http://atlas.ch

Different implementations

CMS

- is compact (hence the name)
  - only 15 m in diameter
- …so high B field (3.8 T)
- magnet coil outside of calorimeters
  - don't' have magnet coil affecting energy measurement of photons/ electrons
- …silicon tracking throughout (~75M channels)
- emphasize EM calorimeter resolution (76,000 $PbWO_4$ crystals); expensive, have to make detector small

ATLAS

- is not so compact (25 m in diameter)
- magnet coil inside calorimeters
- emphasizes air-core toroids and good muon momentum resolution (hence the name)
- has lower B field and larger tracking volume
- …so TRT layers in addition to silicon
- emphasize EM calorimeter resolution (PbLAr); larger radius, better shower separation; highly segmented, better photon discrimination

Design resolution:

$$\frac{\delta E}{E} = \frac{2.7\%}{\sqrt{E}} \oplus 0.55\% \oplus \frac{0.16\,\mathrm{GeV}}{E}$$

$$\frac{\sigma_E}{E} \approx \frac{10\%}{\sqrt{E}} \oplus 0.7\%\ ,\ |\eta| < 3.2$$

sampling term

constant term

Note that energy resolution gets better with energy, but then hits the wall of the constant term.

Inner detector :

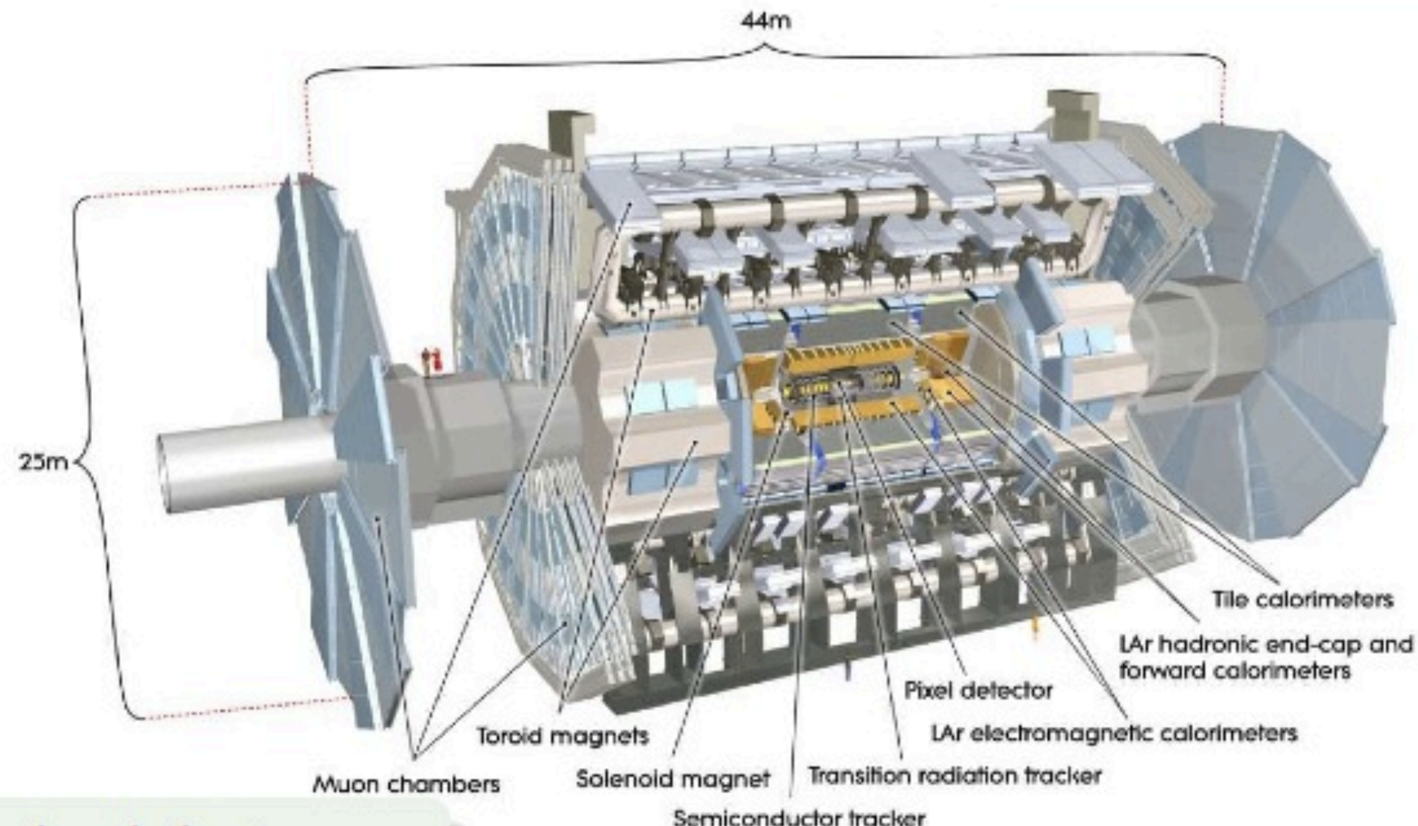
Pixel detector + SCT + TRT

$$\frac{\sigma_{p_T}}{p_T} \approx 0.05\% p_T \oplus 1\% \ , \ |\eta| < 2.5$$

EM calorimeter :

Lead-LAr sampling calo. with accordion geometry

$$\frac{\sigma_E}{E} \approx \frac{10\%}{\sqrt{E}} \oplus 0.7\% \ , \ |\eta| < 3.2$$



Hadronic calorimeter :

Steel and scintillating tiles in the barrel, copper and liquid argon in end-caps

$$\frac{\sigma_E}{E} = \frac{50\%}{\sqrt{E}} \oplus 3\%, \ |\eta| < 3.2$$

$$\frac{\sigma_E}{E} = \frac{100\%}{\sqrt{E}} \oplus 10\%, \ 3.1 < |\eta| < 4.9$$

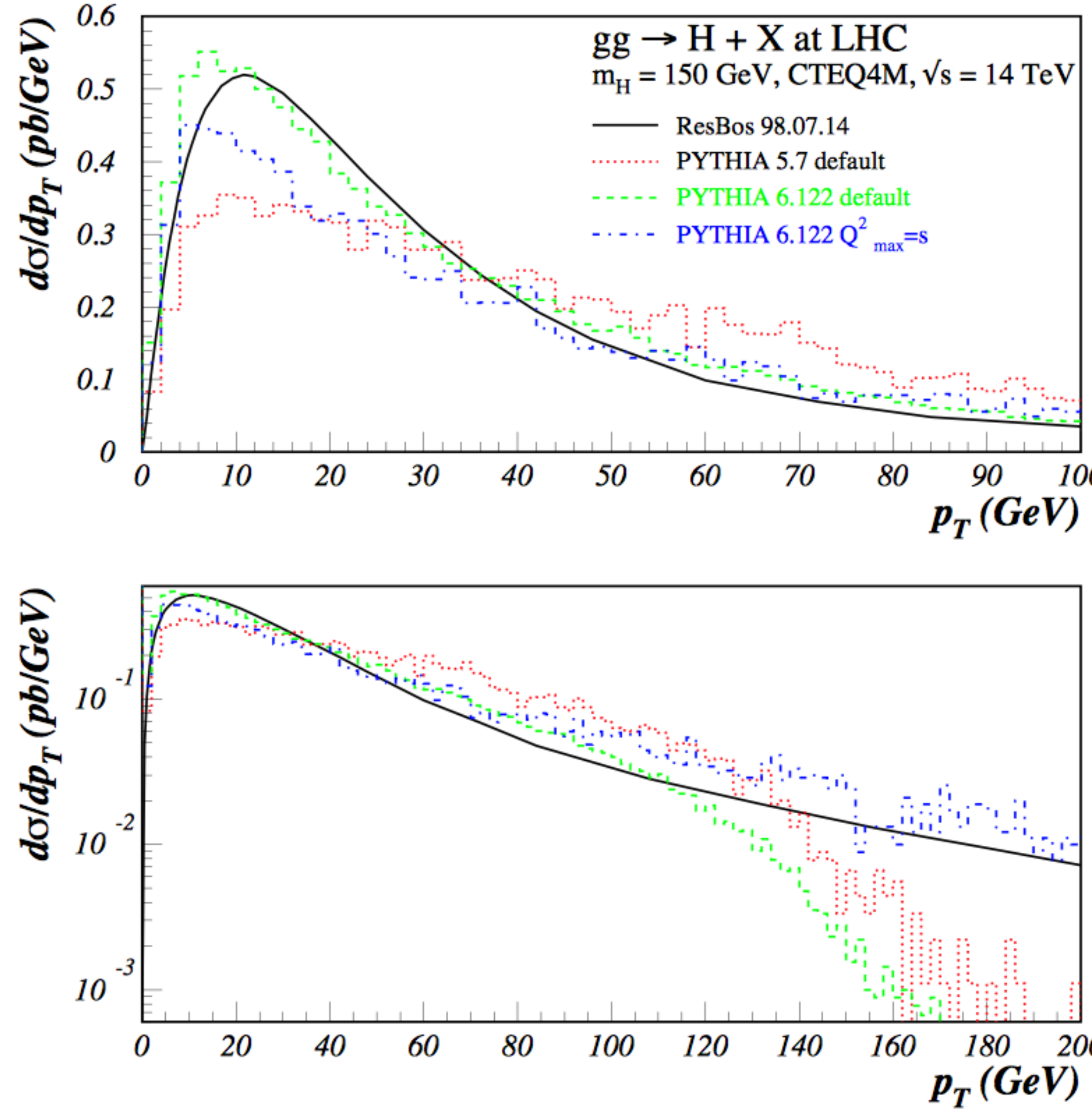
Muon spectrometer :

superconducting air-core toroid magnets, gaz based muon chambers

$$\frac{\sigma_{p_T}}{p_T} \approx 2\% \text{ at 50GeV to } 10\% \text{ at 1TeV}, \ |\eta| < 2.7$$

Pythia 5.7

- ATLAS and CMS were basically designed according to Pythia 5.7
- Note that Pythia 5.7 predicts a much harder Higgs p_T distribution than Pythia 6.1
- This difference was found in 1999 and caused much consternation
- How do you decide which vertex (out of say 20) was the one that the two photons from the Higgs decay came from?
- It's the one with the 50 GeV/c jet (in Pythia 5.7)
- In Pythia 6.1, not so much
- I was told by the CMS physics coordinator at the time that if Pythia 6.1 were available at the time, CMS would have added a central pre-shower detector (which ATLAS has)



The details

The older version of PYTHIA produces too many Higgs events at moderate p_T (in comparison to ResBos) at both the Tevatron and the LHC. Two changes have been implemented in the newer version. The first change is that a cut is placed on the combination of z and Q^2 values in a branching: $\hat{u} = Q^2 - \hat{s}(1-z) < 0$, where $\hat{s}$ refers to the subsystem of the hard scattering plus the shower partons considered to that point. The association with $\hat{u}$ is relevant if the branching is interpreted in terms of a $2 \to 2$ hard scattering. The corner of emissions that do not respect this requirement occurs when the Q^2 value of the spacelike emitting parton is little changed and the z value of the branching is close to unity. This effect is mainly for the hardest emission (largest Q^2). The net result of this requirement is a substantial reduction in the total amount of gluon radiation [19]. [10] In the second change, the parameter for the minimum gluon energy emitted in spacelike showers is modified by an extra factor roughly corresponding to the $1/\gamma$ factor for the boost to the hard subprocess frame [19]. The effect of this change is to increase the amount of gluon radiation. Thus, the two effects are in opposite directions but with the first effect being dominant.

[10] Such branchings are kinematically allowed, but since matrix element corrections would assume initial state partons to have $Q^2 = 0$, a non-physical $\hat{u}$ results (and thus no possibility to impose matrix element corrections). The correct behavior is beyond the predictive power of leading log Monte Carlos.

Higgs production: A Comparison of parton showers and resummation
C. Balazs (Hawaii U. & Fermilab), J. Huston (Michigan State U. & Fermilab), I. Puljak (Ecole Polytechnique & Split U. & Fermilab). Feb 2000. 29 pp.
Published in **Phys.Rev. D63 (2001) 014021**
FERMILAB-PUB-00-032-T, CTEQ-015, MSUHEP-00126, UH-511-954-00
DOI: 10.1103/PhysRevD.63.014021
e-Print: **hep-ph/0002032** | **PDF**

- Let’s look at the different final states

Identifying photons

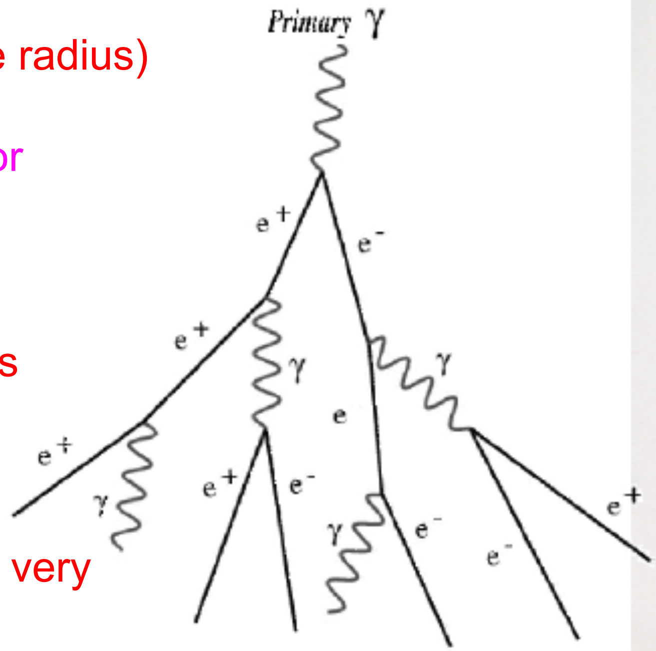
photon(electron) showers are compact
R_M~7 A/Z (gm/cm^2) (Moliere radius)

for lead, R_M~17.7 gm/cm^2, or about 1.5 cm

2 R_M contain abut 95% of an electromagnetic shower's energy

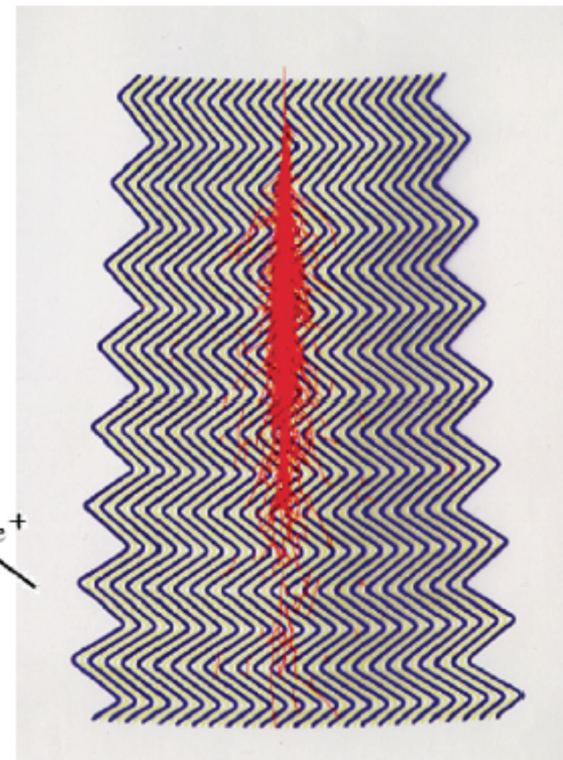
note that EM processes are very collinear

angles are like 1/γ; shower width comes from multiple scattering of softer electrons



A schematic of an electromagnetic shower

~1000 electrons at shower max (t_{max}) for a 50 GeV photon



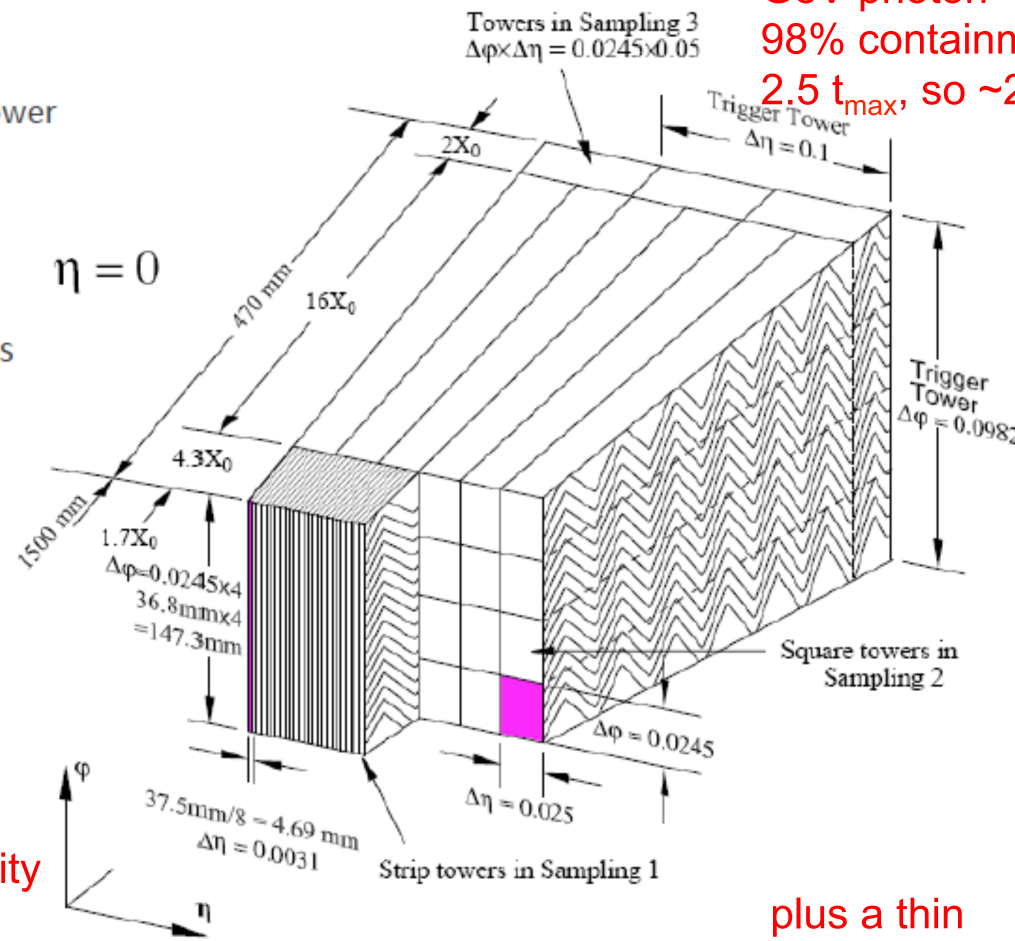
A GEANT simulationof an electromagnetic shower

Identifying photons

t_{max}~8 X_o for a 50 GeV photon
98% containment in 2.5 t_{max}, so ~20 $_{Xo}$

ATLAS Liquid Argon Calorimeter Module

- Highly segmented
  - Allows measurement of shower development
    - Rejects background
  - Has some pointing ability
- Very good (but not as good as CMS) energy resolution
- "Accordion" faster than other LAr calorimeters
  - Still slower than crystals



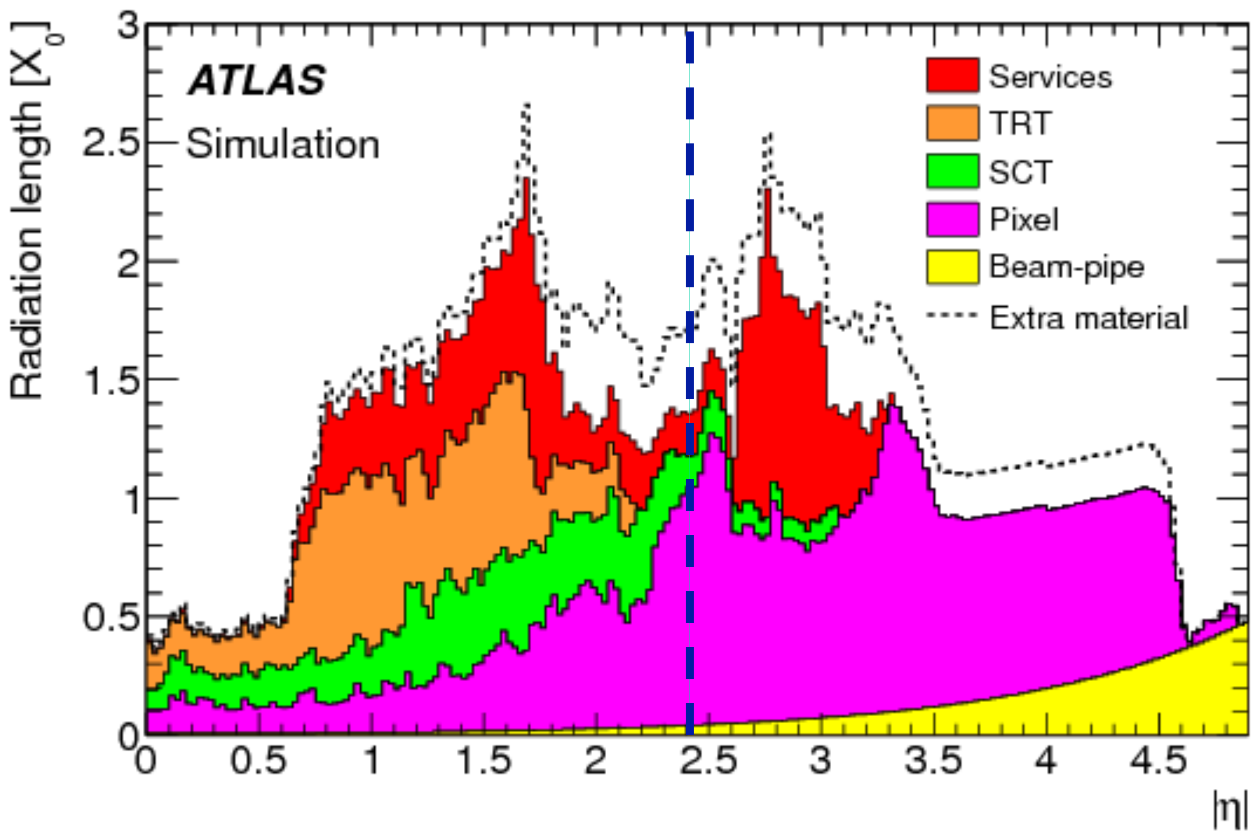
3 longitudinal depth segments

- 4 X_o: segmented into high granularity strips in the η direction (0.003X0.001 in ηXϕ): provides γ/π^o discrimination
- 17 X_o: granularity of 0.025X0.025
- 2-12 X_o: account for longitudinal fluctuations of high energy showers

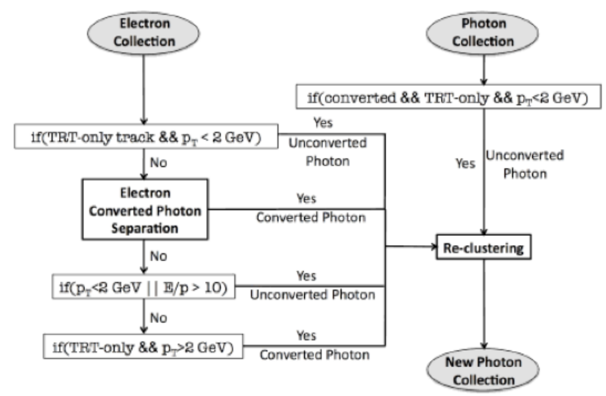
plus a thin pre-sampler in front to correct for energy losses before calorimeter

Photon conversions

- There's a lot of material in front of the ATLAS detector (and the CMS detector as well)
- That means a lot of the photons are going to convert…and the resulting electron/ positron tracks will be bent by the B field
  - average distance a photon will travel before converting is $9/7X_o$
- That means we have to deal with H->$\gamma\gamma$ events in which one or more photon converts

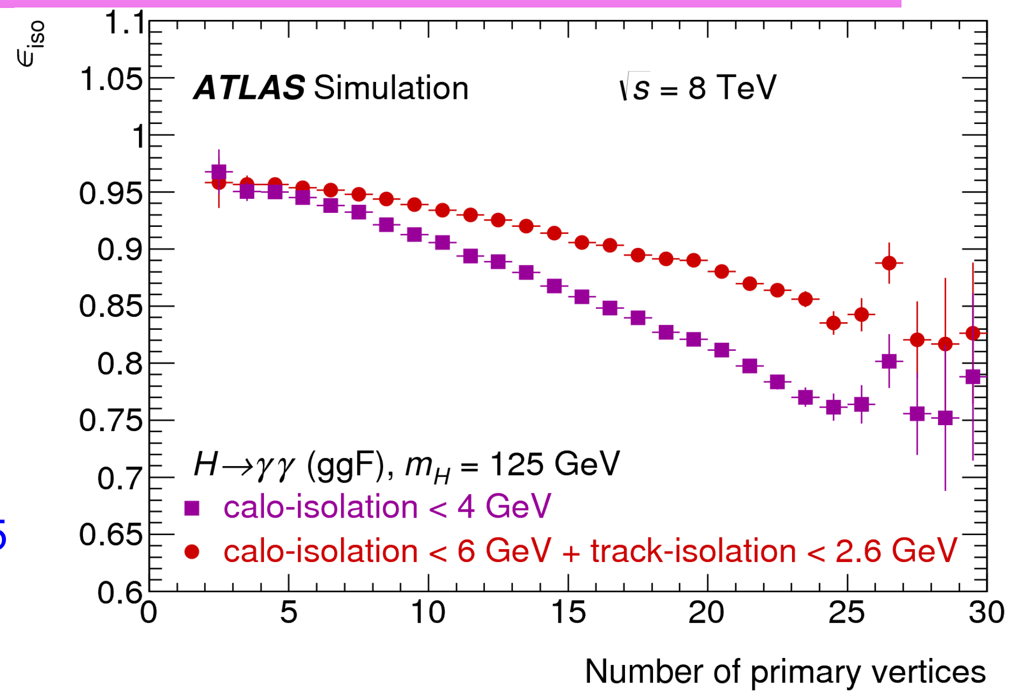


have to separate converted photons from electrons

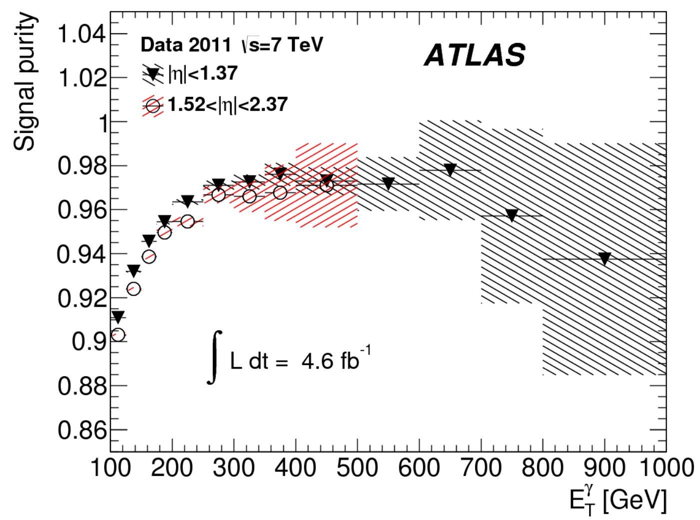


Photon ID

- Photon reconstruction seeded by clusters in projective towers of size 0.075 X 0.125 in η X ϕ plane
- Look for matches between clusters and tracks
- Clusters matched to pairs of tracks consistent with γ->e+e- are classified as converted photon candidates
- 0.075 X 0.125 cluster used for unconverted photons and 0.075 X 0.175 for converted photons (to account for opening angle in ϕ of e+e-)
- Expect a photon to be isolated, so impose an isolation cut in a cone of ΔR=0.4 around photon direction: < 6 GeV
  - exclude photon cluster energy (and lateral extrapolation)
  - subtract on event-by-event basis energy from underlying event and pileup
- Additional track isolation cut: sum of all tracks within cone of 0.2 < 2.6 GeV
  - less sensitive to pileup

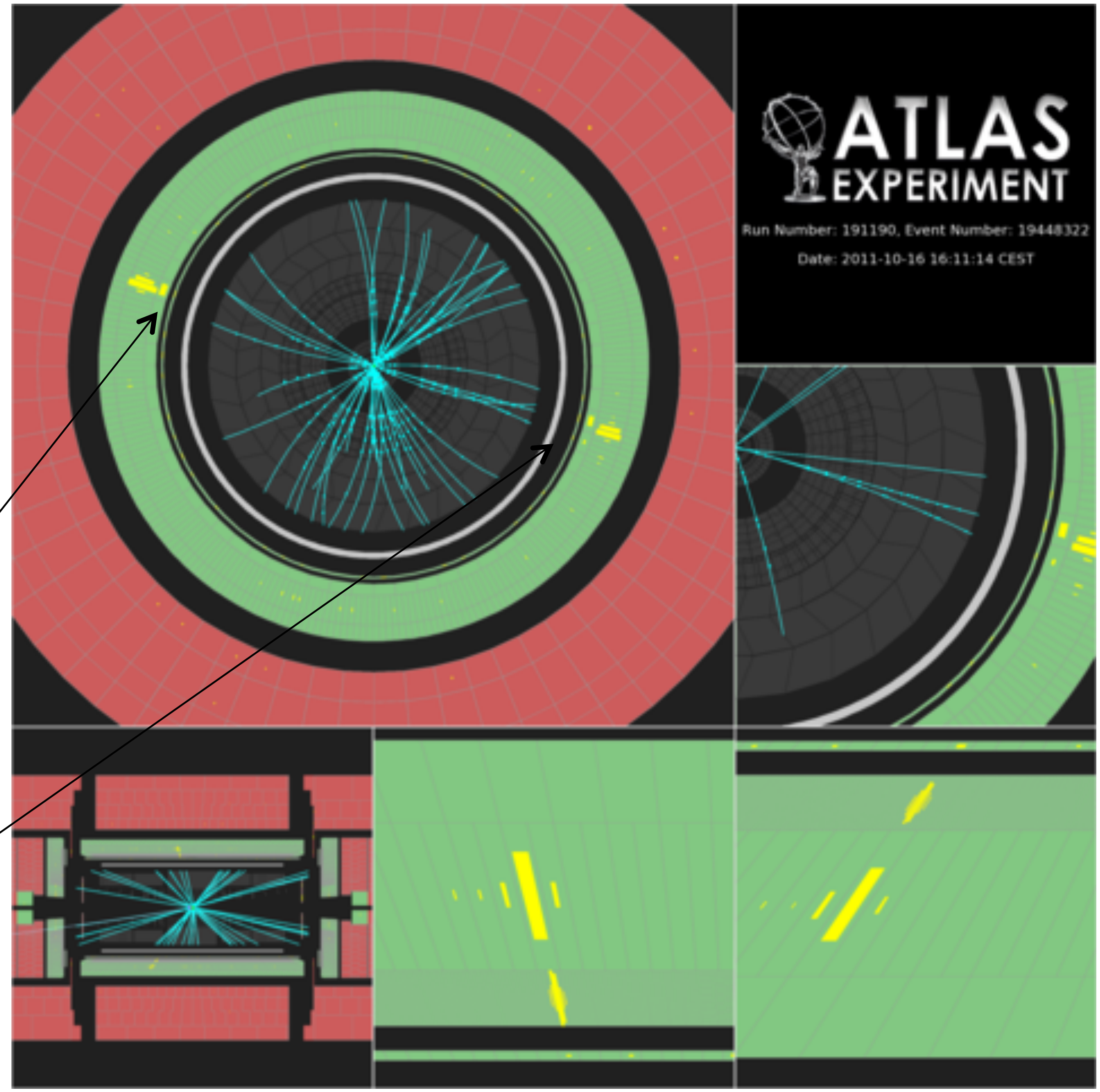


side note: any isolated high p_T EM object is a photon



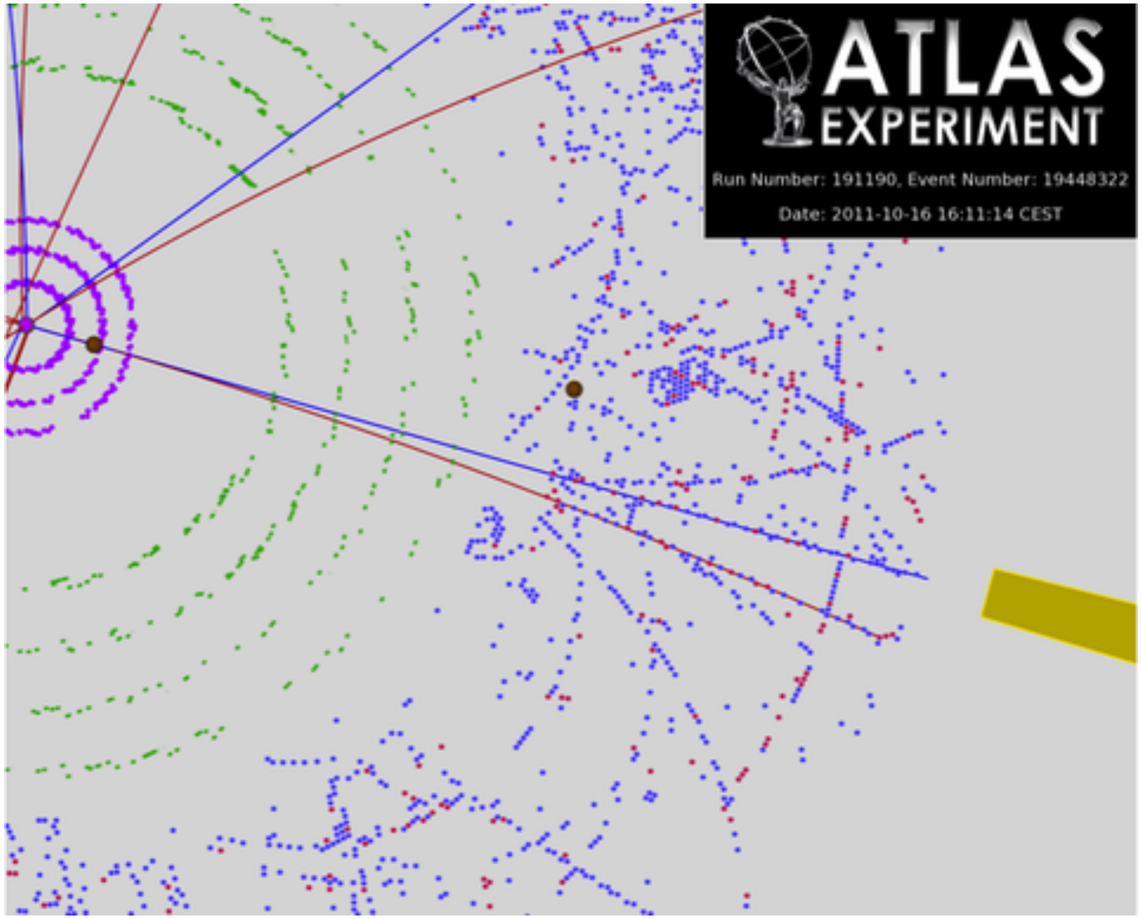
Photons

- This is event 19448322 from Run 191190
- The measured diphoton mass is 125.8 GeV
- Both photons are in the central rapidity region
- Note that neither of the photons deposts any energy in the hadronic calorimeter
  - EM calorimeter is thick
  - that's another discrimination variable for photons
- One photon is unconverted, the other has converted



Converted photons

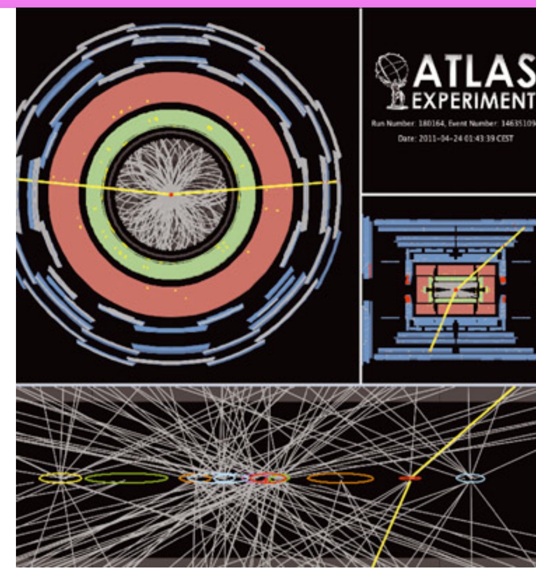
- Here are the hits in the tracking system for the converted photon
- It converted at a radius of 8.1 cm (in the pixel detector; tracks in magenta)
- The SCT (silicon) tracks are shown in green and the TRT (transition radiation detector) hits are shown in blue and red, with the red dots corresponding to the high energy deposition expected from electrons

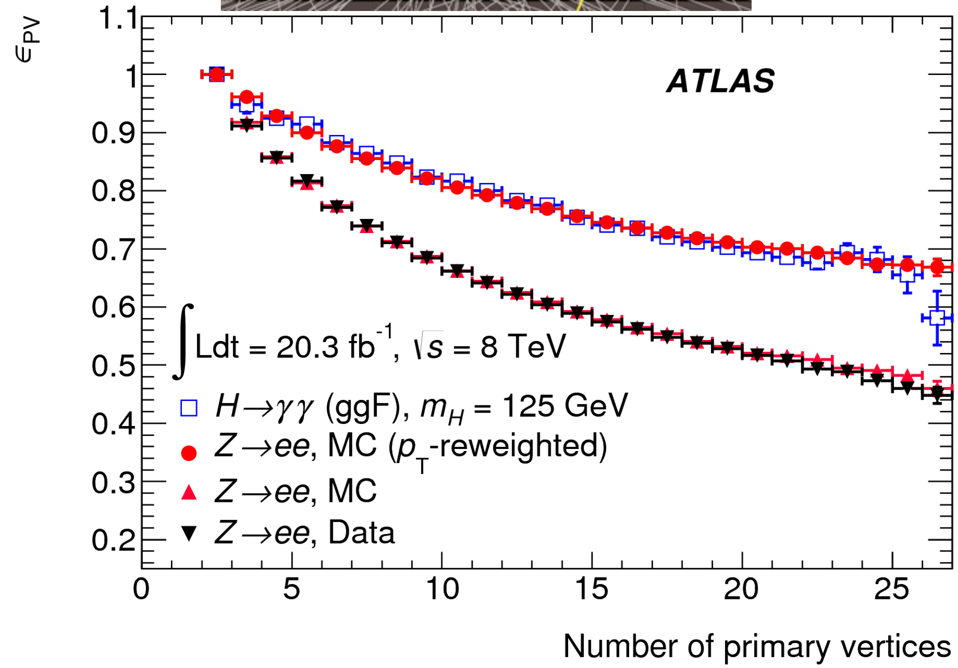


The blue track has a momentum of 56.1 GeV/c and matches to the EM cluster shown. The red track has a momentum of 4 GeV/c and the energy deposition is outside of the EM cluster.

H->γγ selection

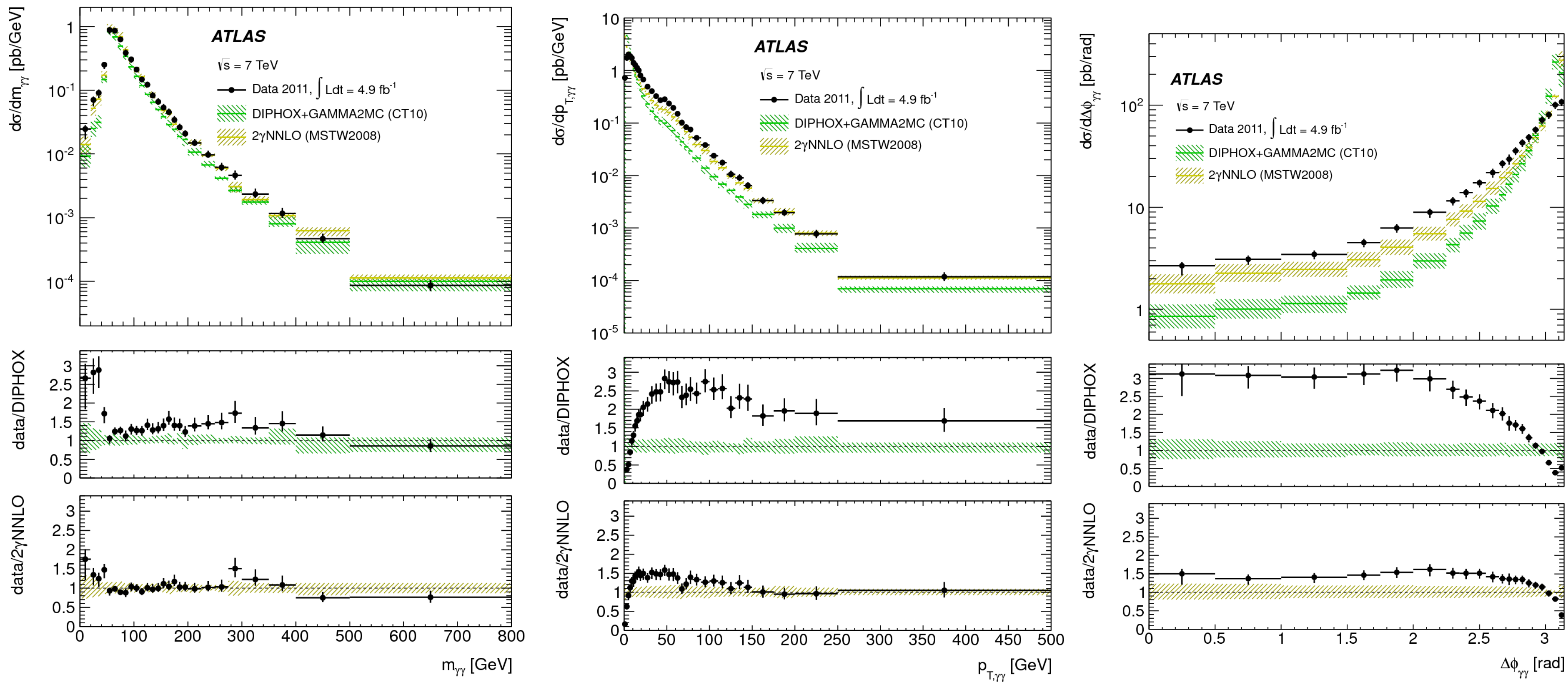
- At least two photon candidates in |η|<2.37 (excluding region from 1.37=1.56)
  - $E_T/m_{\gamma\gamma}$>0.35 (0.25) for leading, second photon
- Resolution for diphoton vertex (using EM pointing as well as track information) is ~15 mm in z
  - enough to keep opening angle resolution < energy resolution
- Note the degradation of the efficiency for choosing the right vertex with increasing pileup





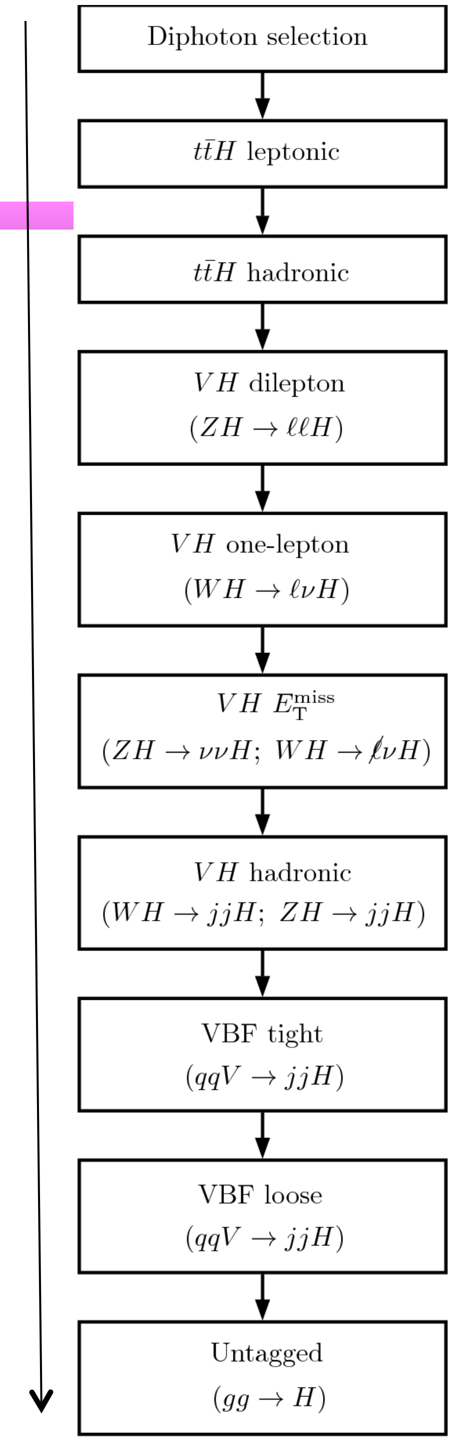
SM diphoton measurements

- Final state very rich in QCD effects; importance of higher multiplicity contributions in corners of phase space
- Diphoton cross section known to NNLO QCD and NLO EW
- Resummation effects very important for $\gamma\gamma$ p_T



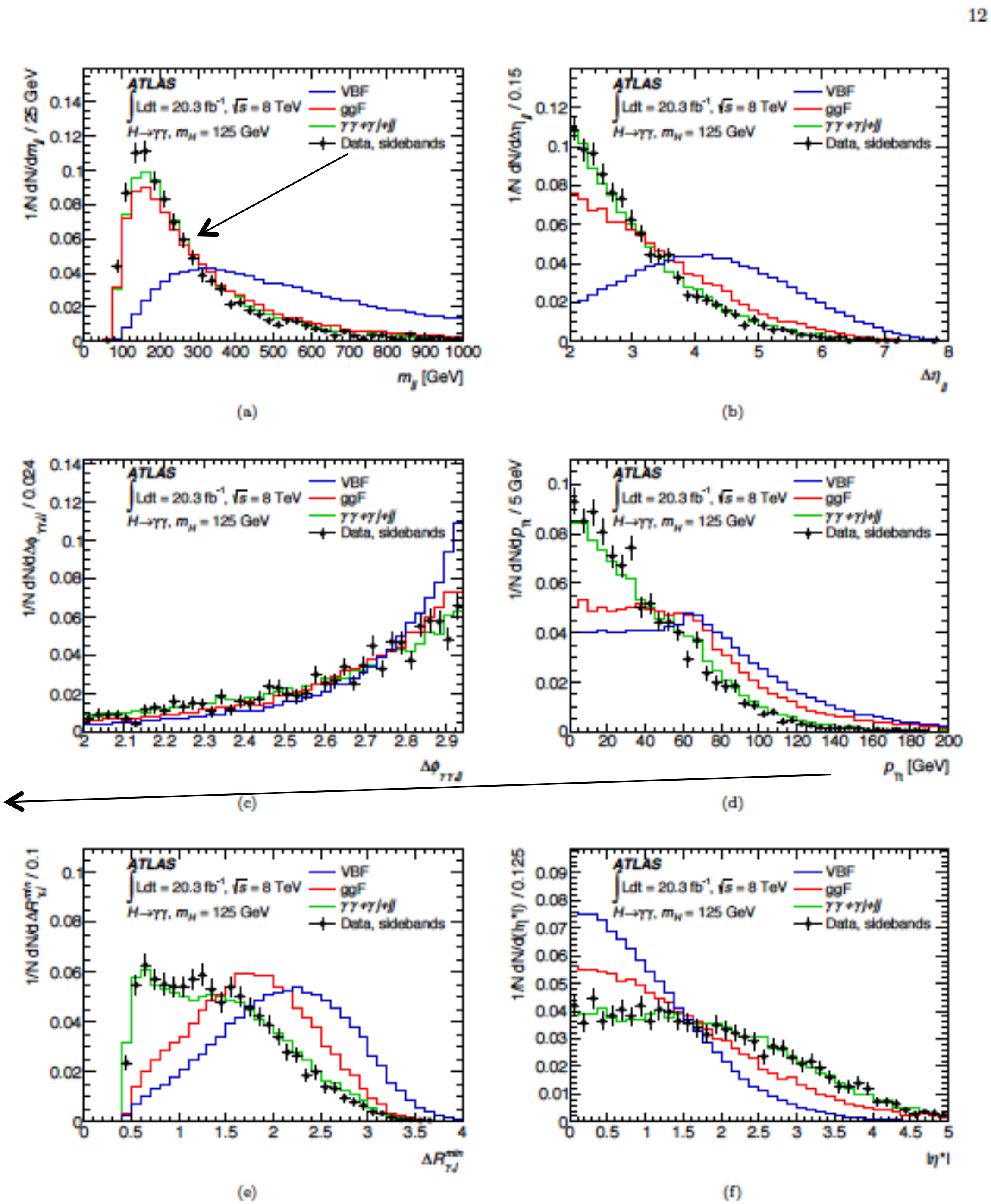
Higgs categories for diphoton analysis

- Dominant contribution from gg fusion (87%)
- VBF (7%), VH(5%),ttH(1%)
- Based on properties, selected diphoton events (94566 in 8 TeV sample) assigned to 12 exclusive categories
- Each category optimized to maximize expected **SM** signal strength of process
  - for example, leptons for VH, two widely separated jets for VBF, etc
  - need to do this because S/B is bad for diphoton channel, and need to use every tool at your disposal
  - S/B varies widely by category; width of Higgs peak also varies with category
- More globally, four main categories
  - ttH
  - VH
  - VBF
  - untagged

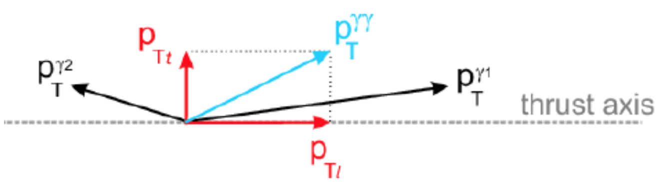


Take for example trying to separate VBF from ggF (and from the diphoton backgrounds; see also next slide).

There are a number of variables with discrimination power used to build the boosted decision tree.

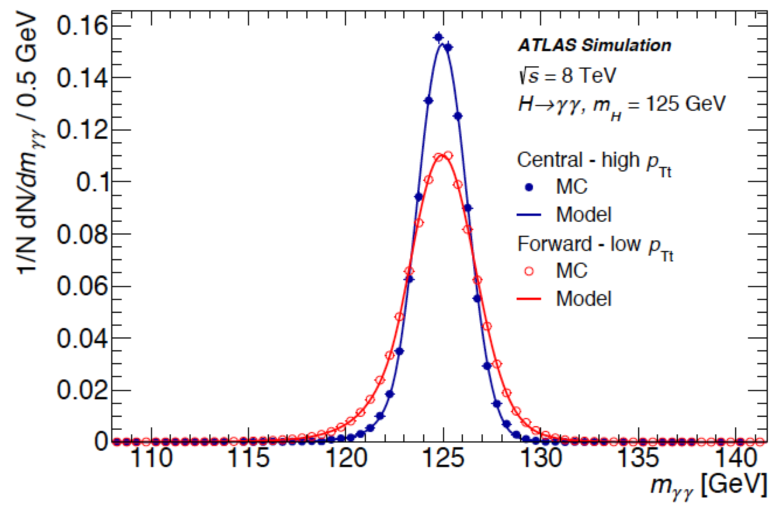


- What is pTt? Why use it?

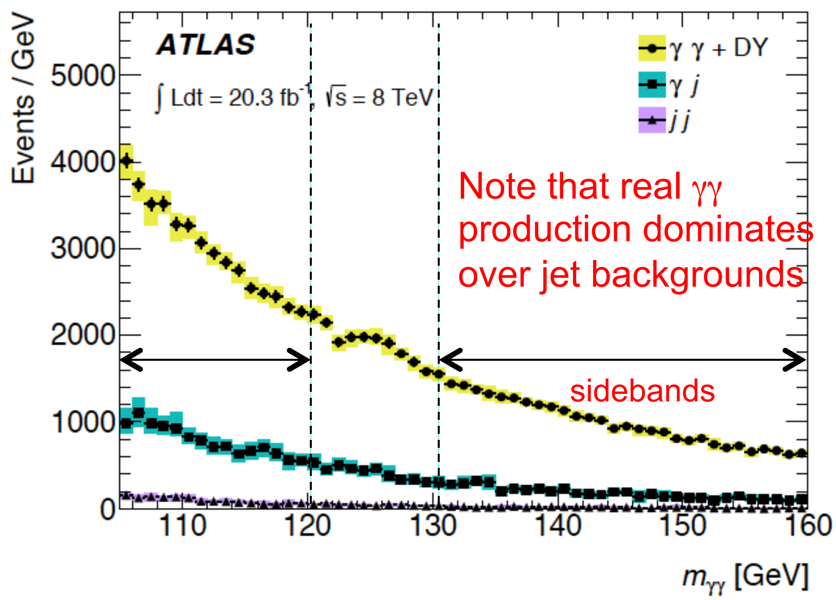


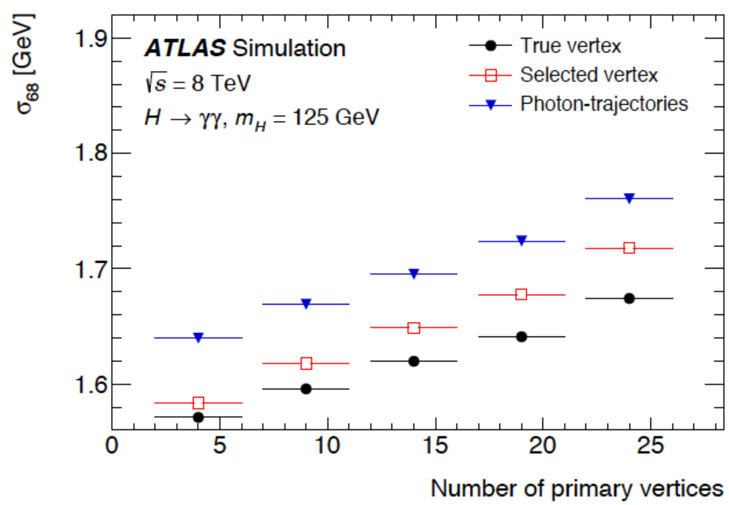
better discrimination power than $p_T^{\gamma\gamma}$

- The expected diphoton mass resolution is shown to the top right for the category with the best resolution and the worst
- The resolution as a function of # vertices is shown on the bottom right
- The raw distribution of events is shown below



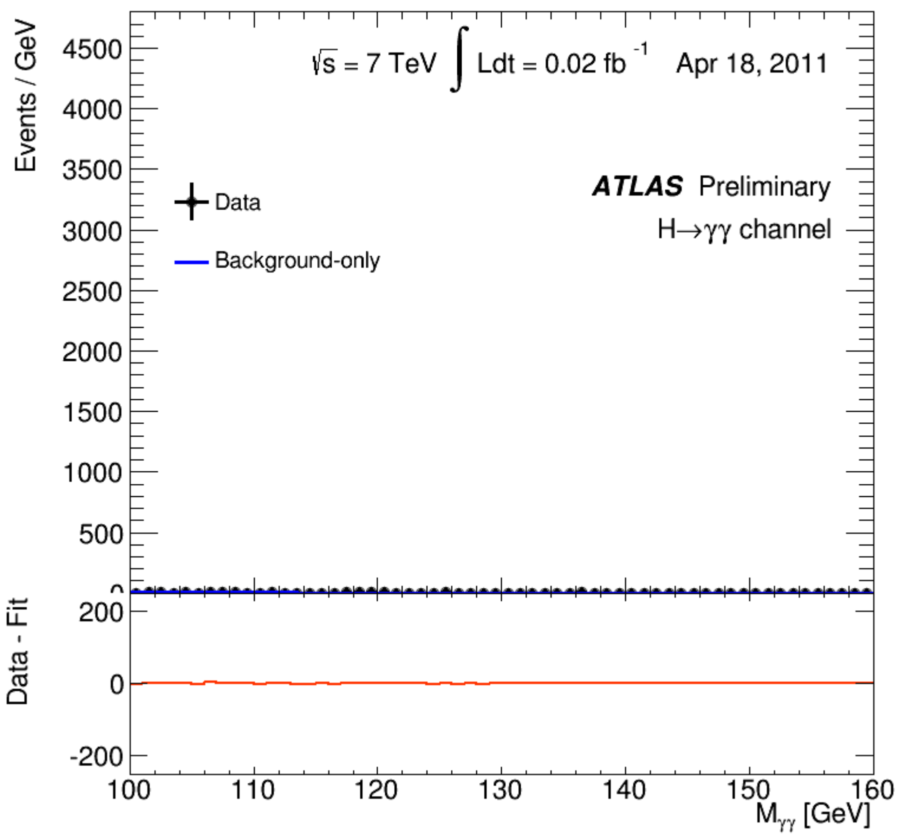
Remember the intrinsic width is about 4 MeV. so can't be directly measured…or can it?

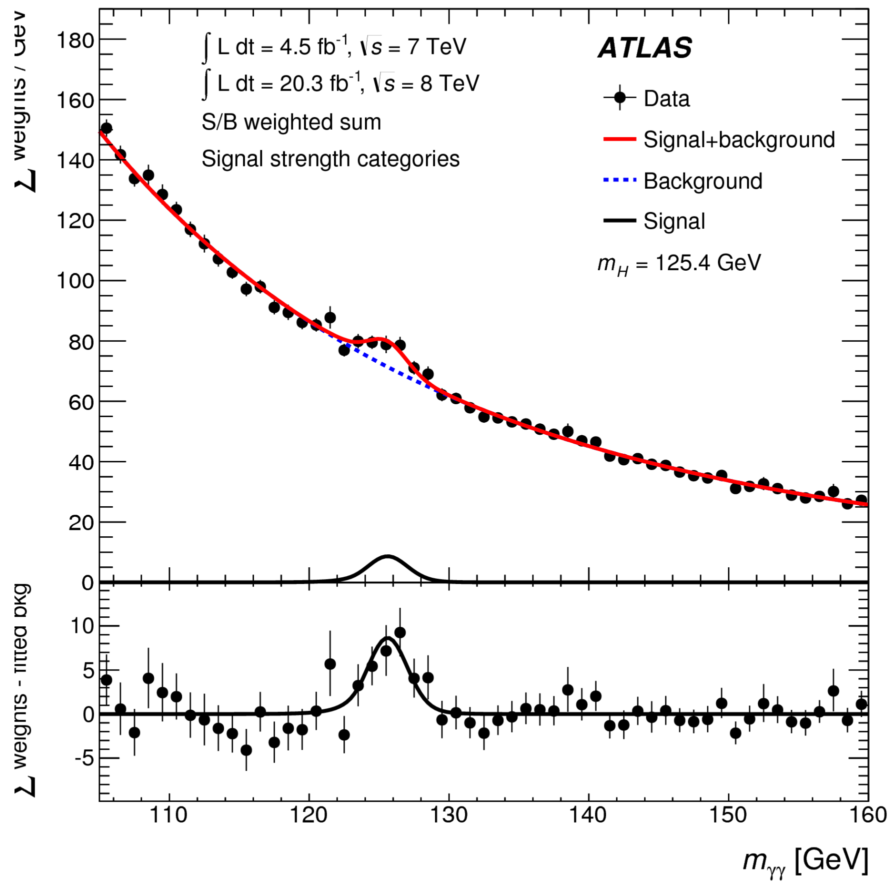




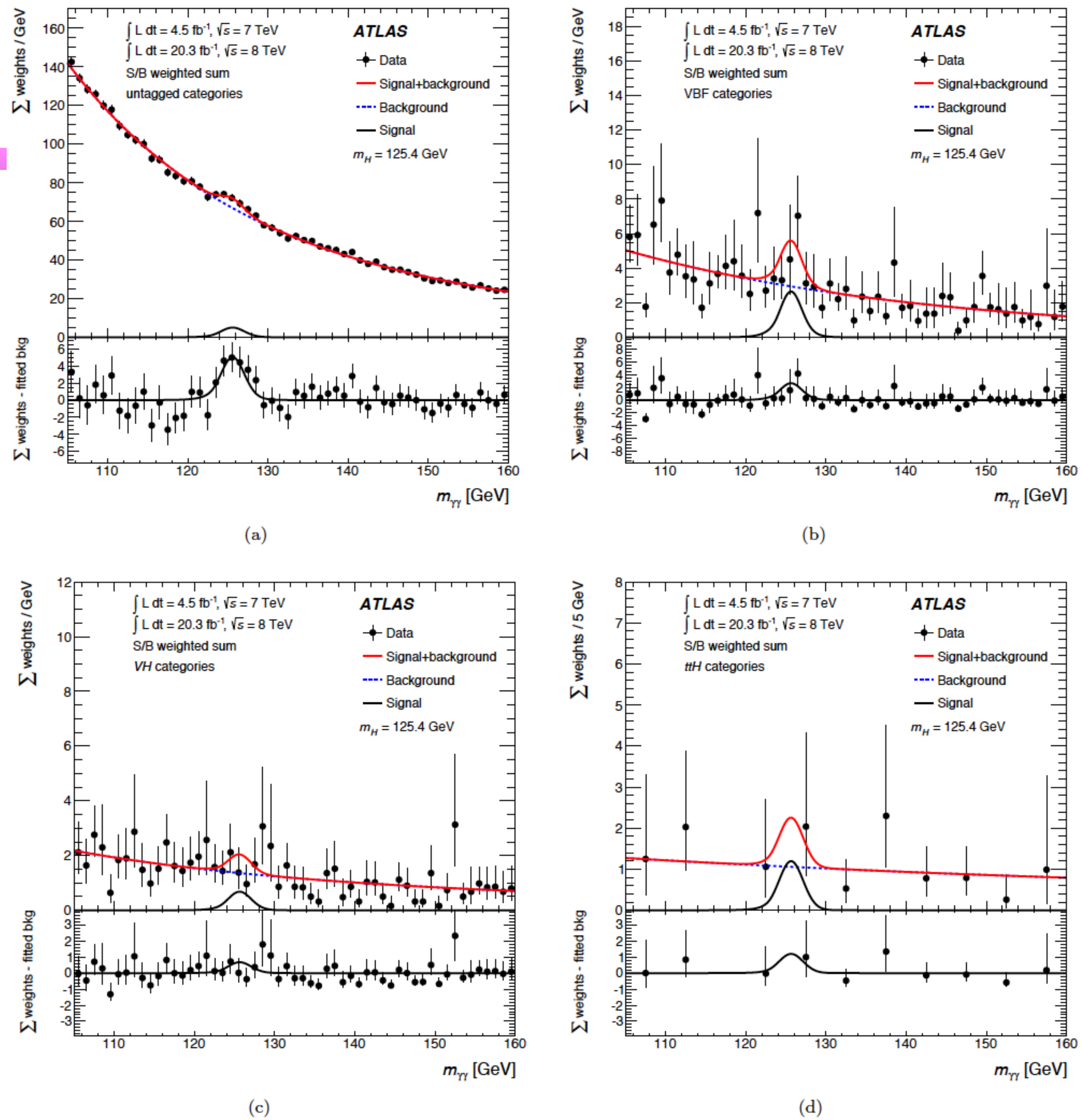
Results

- For each category of event, a weight is determined based on the expected **SM** S/B ratio for that category
- The weighted (**SM** S/B for each category) event distribution for 7+8 TeV combined is shown on the right

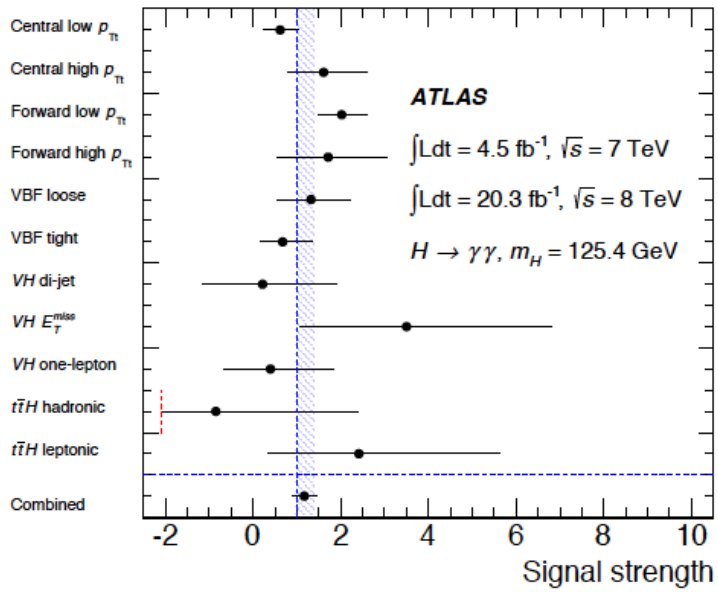


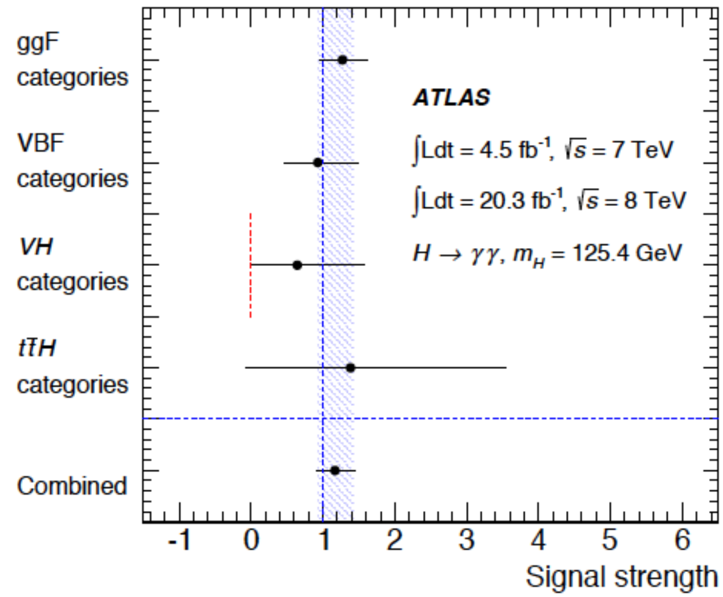


- Results for 4 general categories



Signal strengths

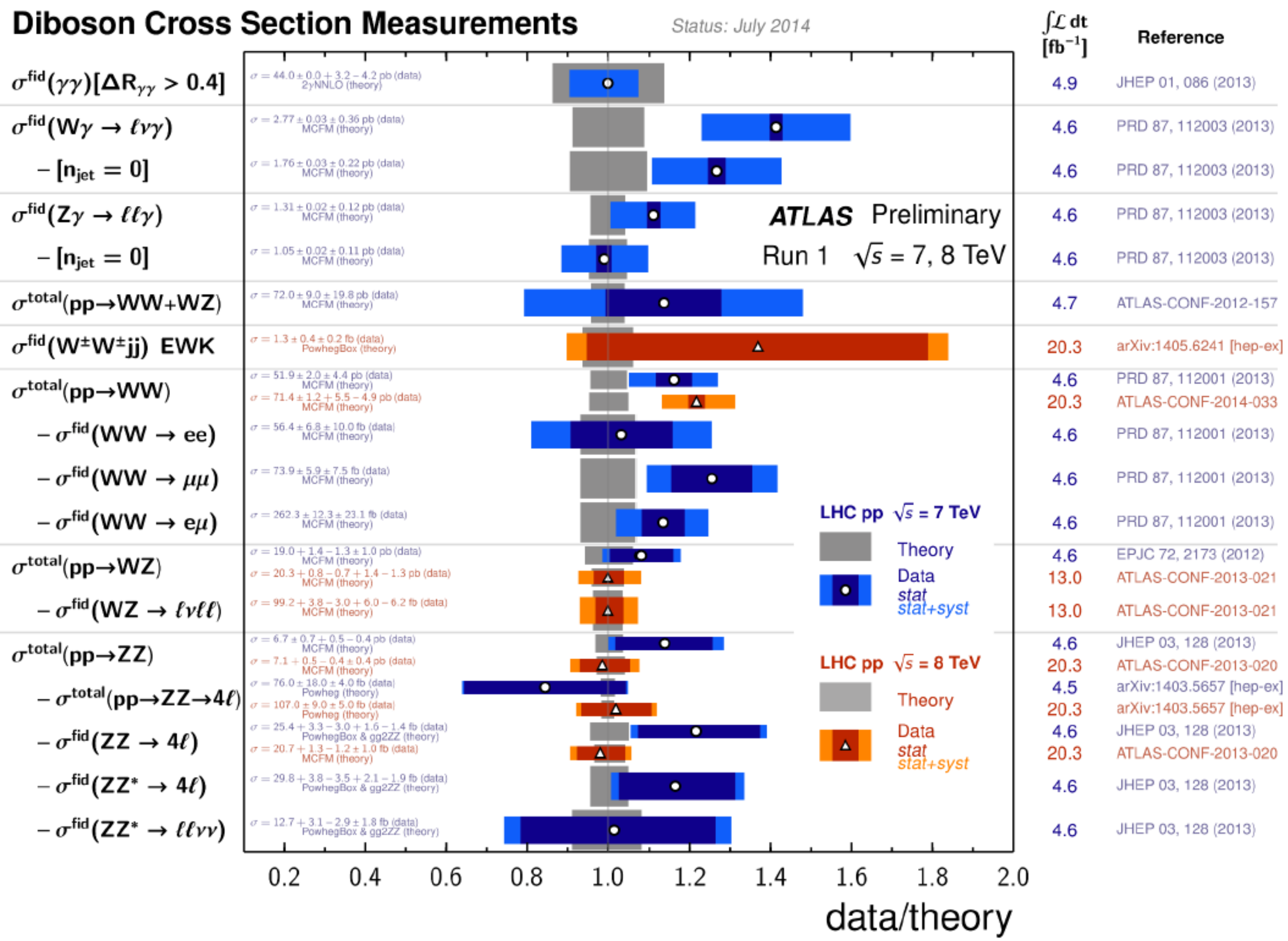




$$\begin{aligned}
\mu_{\rm ggF} &= 1.32\ \pm 0.32\ (\text{stat.})\ ^{+0.13}_{-0.09}\ (\text{syst.})\ ^{+0.19}_{-0.11}\ (\text{theory}) \\
&= 1.32 \pm 0.38, \\
\mu_{\rm VBF} &= 0.8\ \pm 0.7\ (\text{stat.})\ ^{+0.2}_{-0.1}\ (\text{syst.})\ ^{+0.2}_{-0.3}\ (\text{theory}) \\
&= 0.8 \pm 0.7, \\
\mu_{WH} &= 1.0 \pm 1.5\ (\text{stat.})\ ^{+0.3}_{-0.1}\ (\text{syst.})\ ^{+0.2}_{-0.1}\ (\text{theory}) \\
&= 1.0 \pm 1.6, \\
\mu_{ZH} &= 0.1\ ^{+3.6}_{-0.1}\ (\text{stat.})\ ^{+0.7}_{-0.0}\ (\text{syst.})\ ^{+0.1}_{-0.0}\ (\text{theory}) \\
&= 0.1\ ^{+3.7}_{-0.1}, \\
\mu_{t\bar{t}H} &= 1.6\ ^{+2.6}_{-1.8}\ (\text{stat.})\ ^{+0.6}_{-0.4}\ (\text{syst.})\ ^{+0.5}_{-0.2}\ (\text{theory}) \\
&= 1.6\ ^{+2.7}_{-1.8}.
\end{aligned}$$

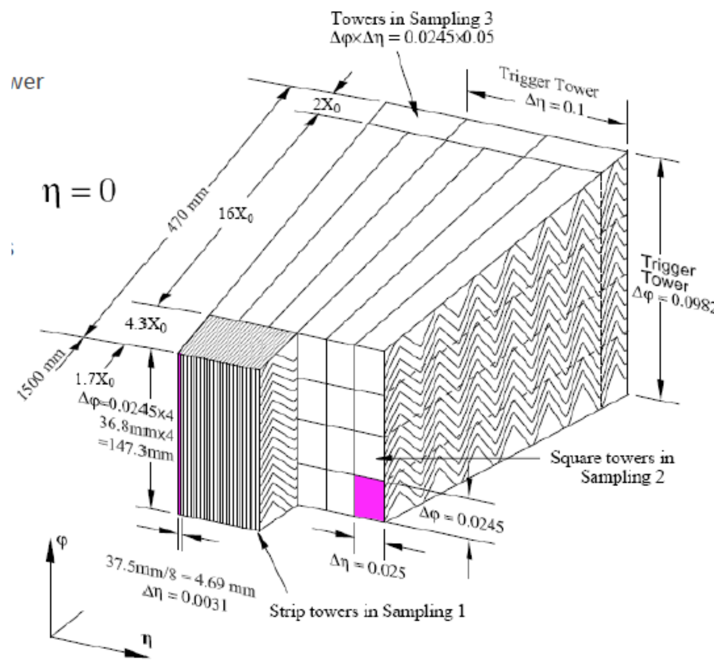
Higgs->4 leptons

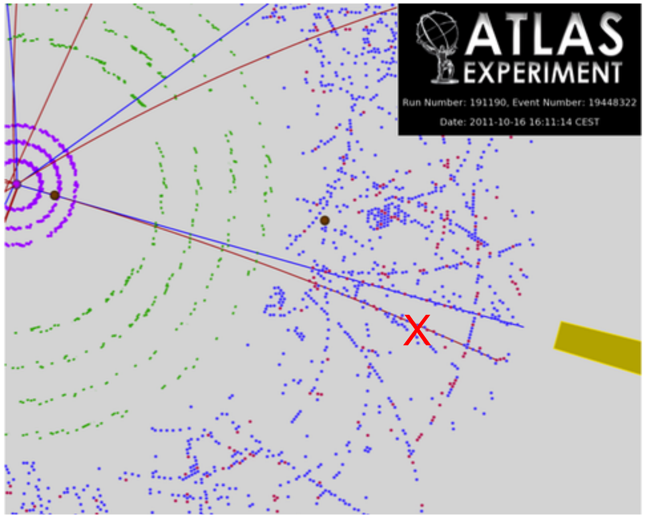
- Many SM diboson measurements in ATLAS and CMS including 4 lepton final states; good agreement with theory; WW cross section known to NNLO



Electron identification

- Again, the EM calorimeter is important, but not as crucial as for the diphoton case
- S/B is >> than the diphoton case, so narrow(est) width is not needed
- Electron defined as an EM cluster associated with an inner detector track
    - and not to be associated with a photon conversion into an e^+e^- pair
- Require longitudinal and transverse shower profiles to be consistent with EM showers, track and cluster positions to match, and the presence of 'high-threshold TRT hits'
- Similar isolation cuts as for photons





Muon definition

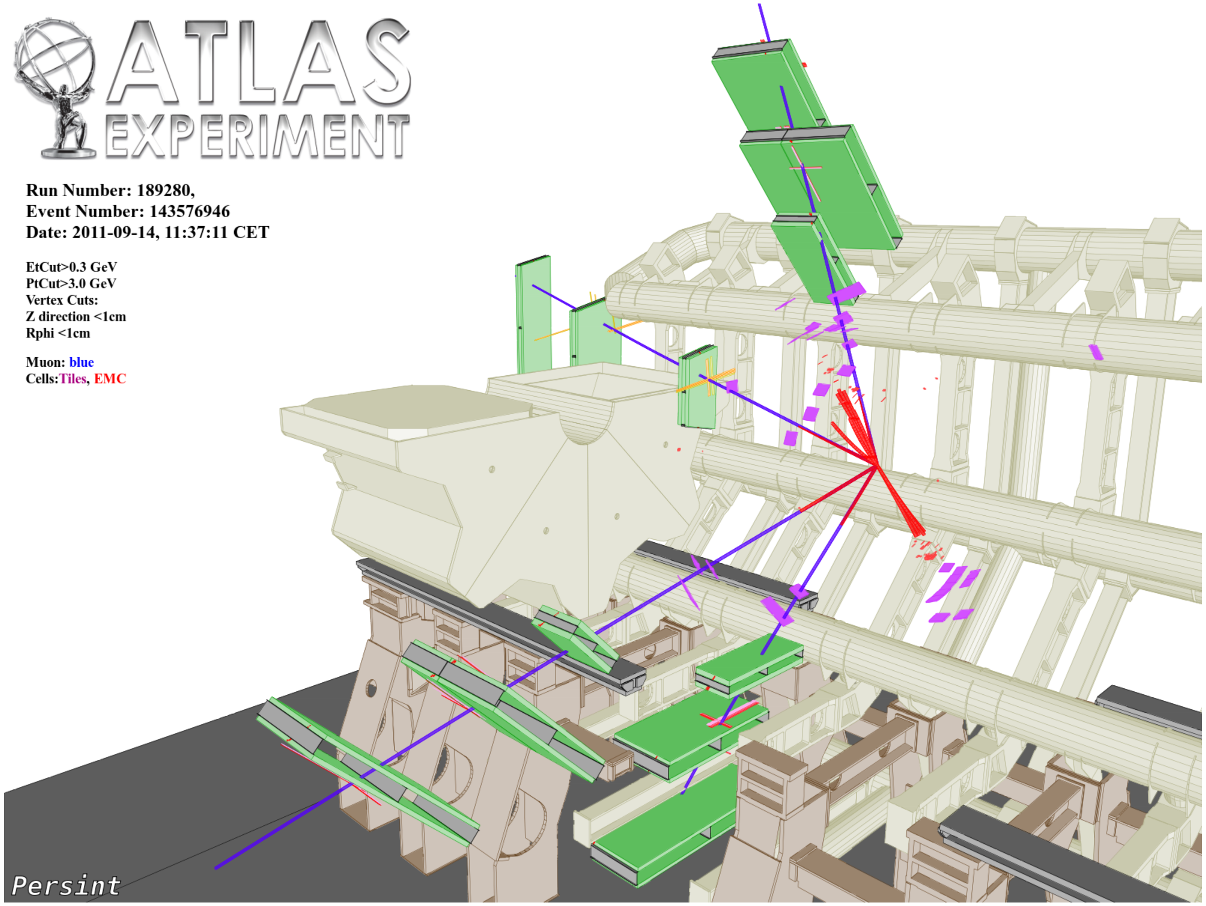
- Muon momentum measured in both the ID and in the muon spectrometer
- In best case, match a reconstructed ID track with a MS track
- But in some cases, there may be no MS track or no ID track, and muons can still be identified, for example by looking at calorimeter energy depositions

Muon spectrometer :

superconducting air-core toroid magnets, gaz based muon chambers

$$\frac{\sigma_{p_T}}{p_T} \approx 2\% \text{ at 50GeV to 10\% at 1TeV, } |\eta| < 2.7$$

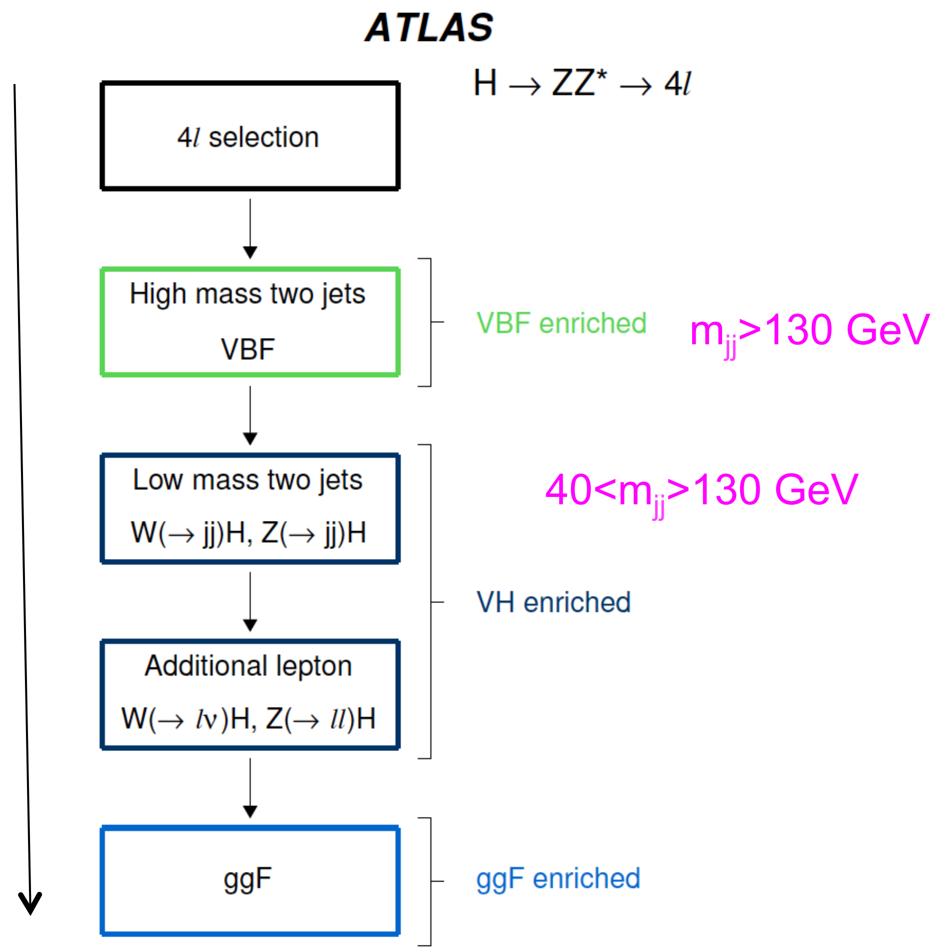
NB: resolution degrades with p_T



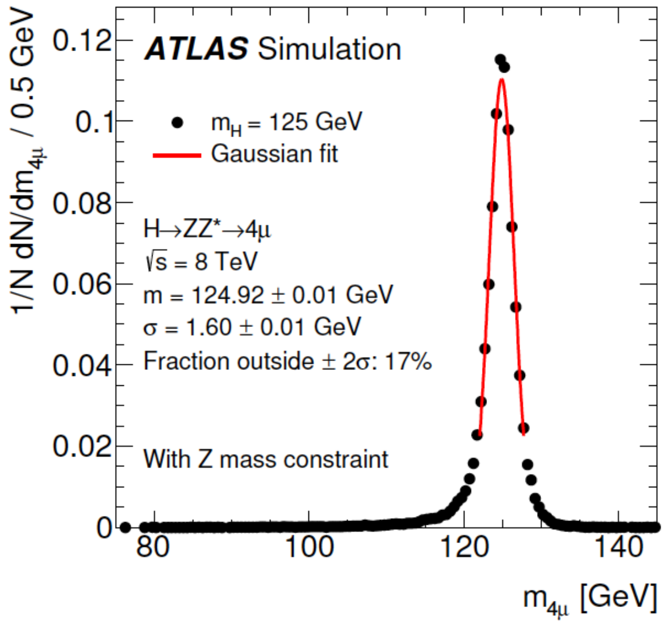
Higgs->4 lepton cuts

- Both electrons and muons radiate EM energy
- Some of this energy can be identified in the calorimeter and be incorporated into the 4-lepton measurement
  - collinear photons only associated with muons
  - non-collinear photons can be associated with either muons or electrons
- Higgs boson events are formed by selecting two same-flavor, opposite-sign lepton pairs
  - for each channel, lepton pair with mass closest to the Z is termed the leading dilepton and its mass must be between 50 and 106 GeV; second dilepton pair is formed from remaining two leptons
- Both track and calorimeter isolation requirements applied
  - after subtracting event-by-event underlying event and pileup energy

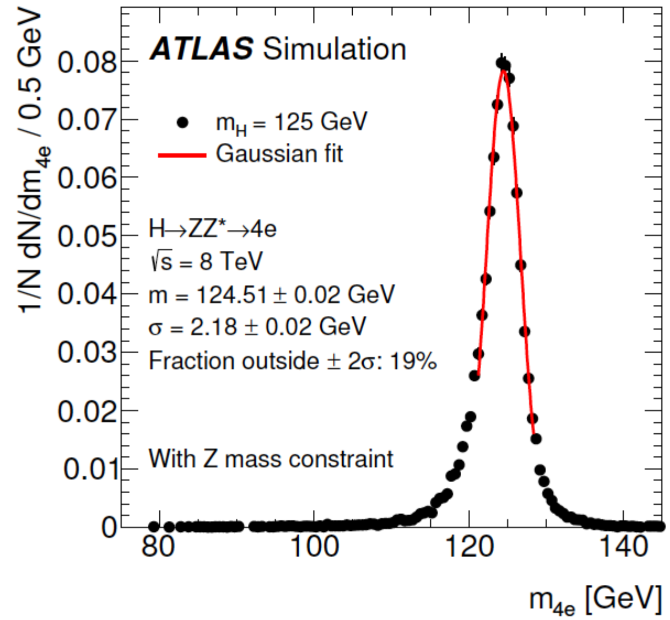
- Each four lepton Higgs candidate is assigned to one of four categories



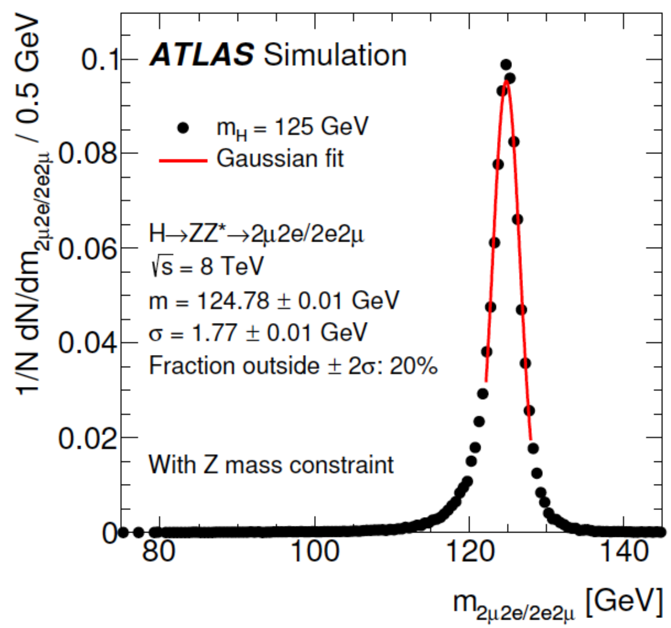
expected resolutions



(a)



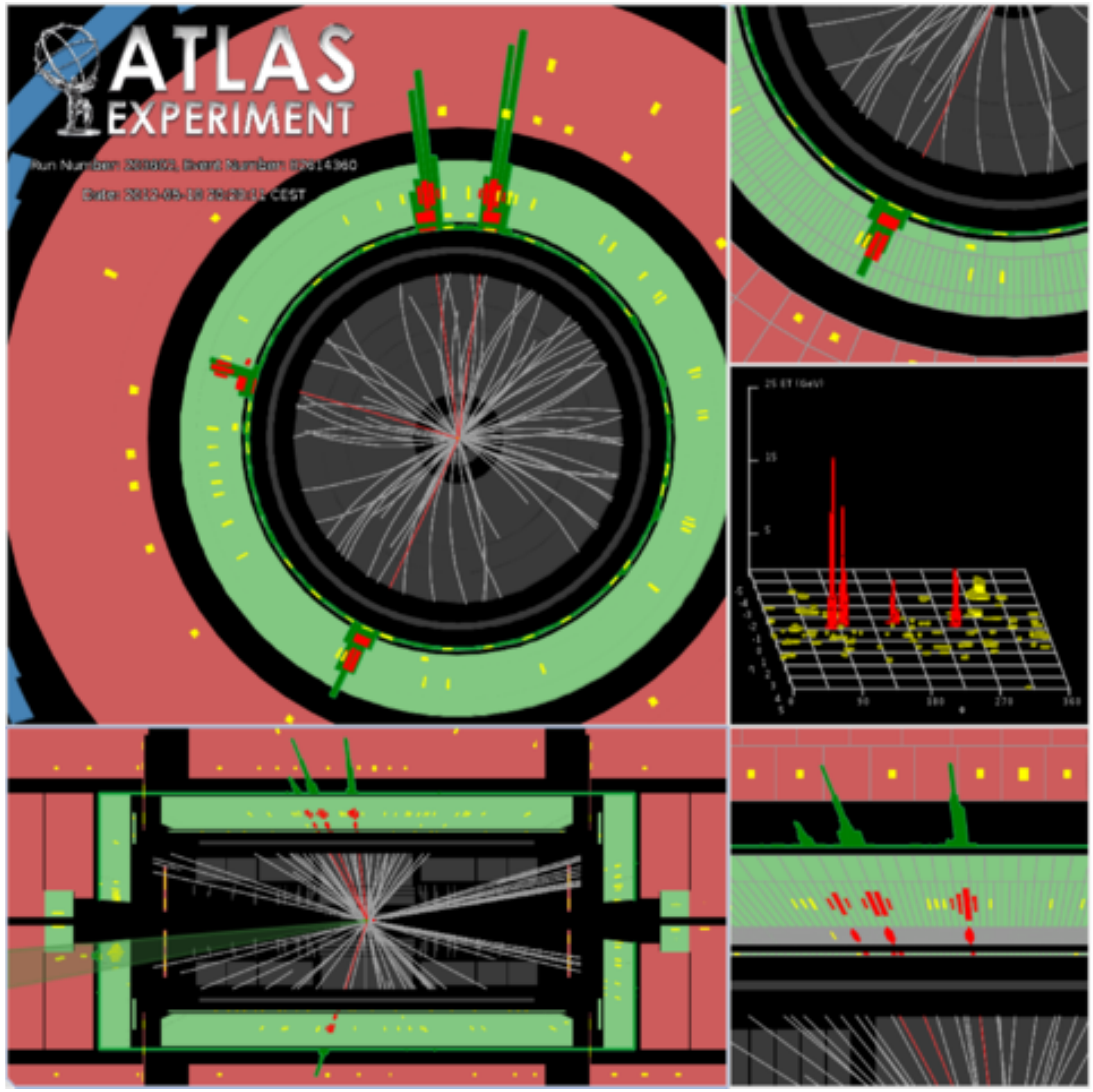
(b)



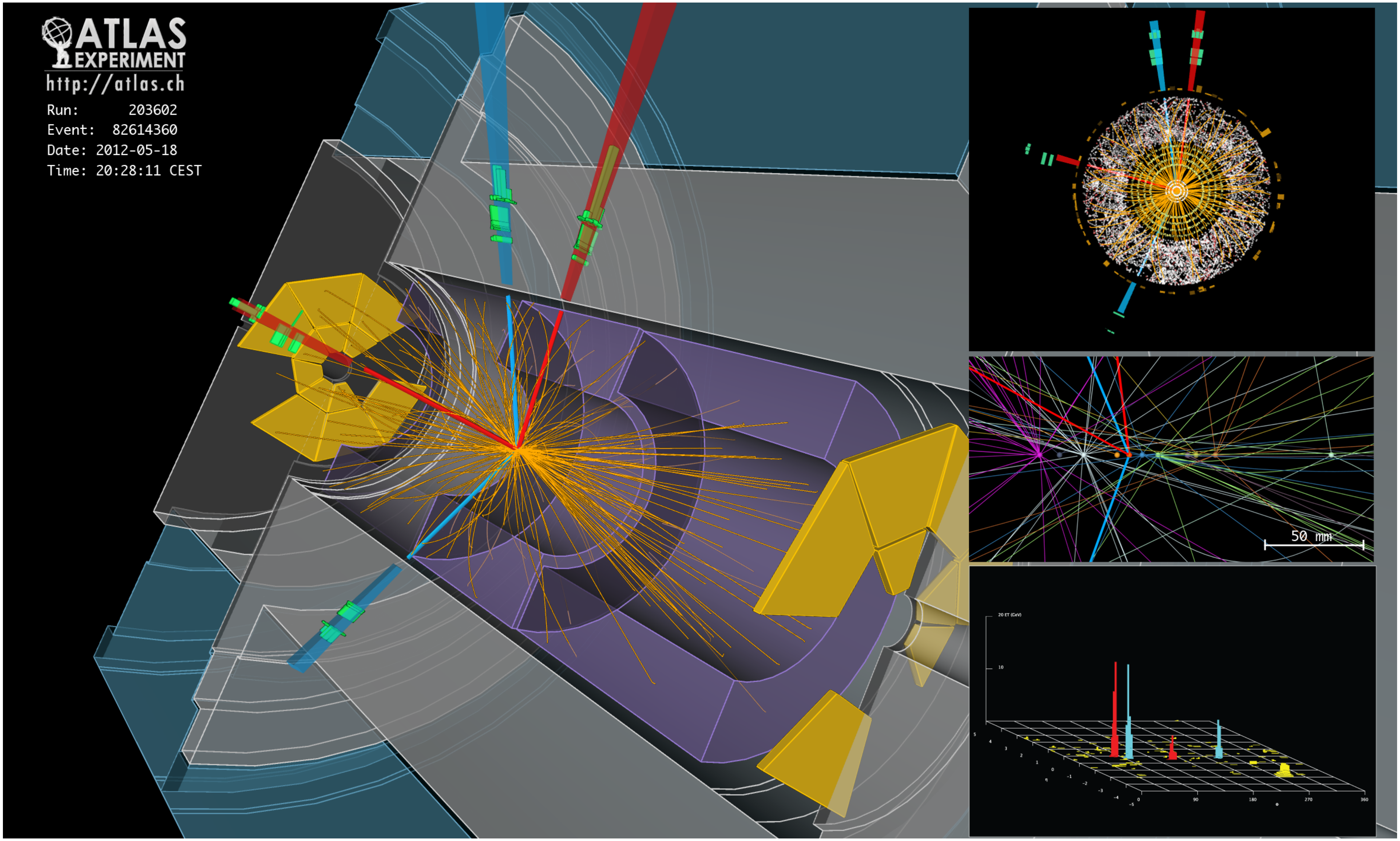
(c)

H->4 electrons

- M_{4l}=124.6 GeV
- M_{12}=70.6 GeV
- M_{34}=44.7 GeV

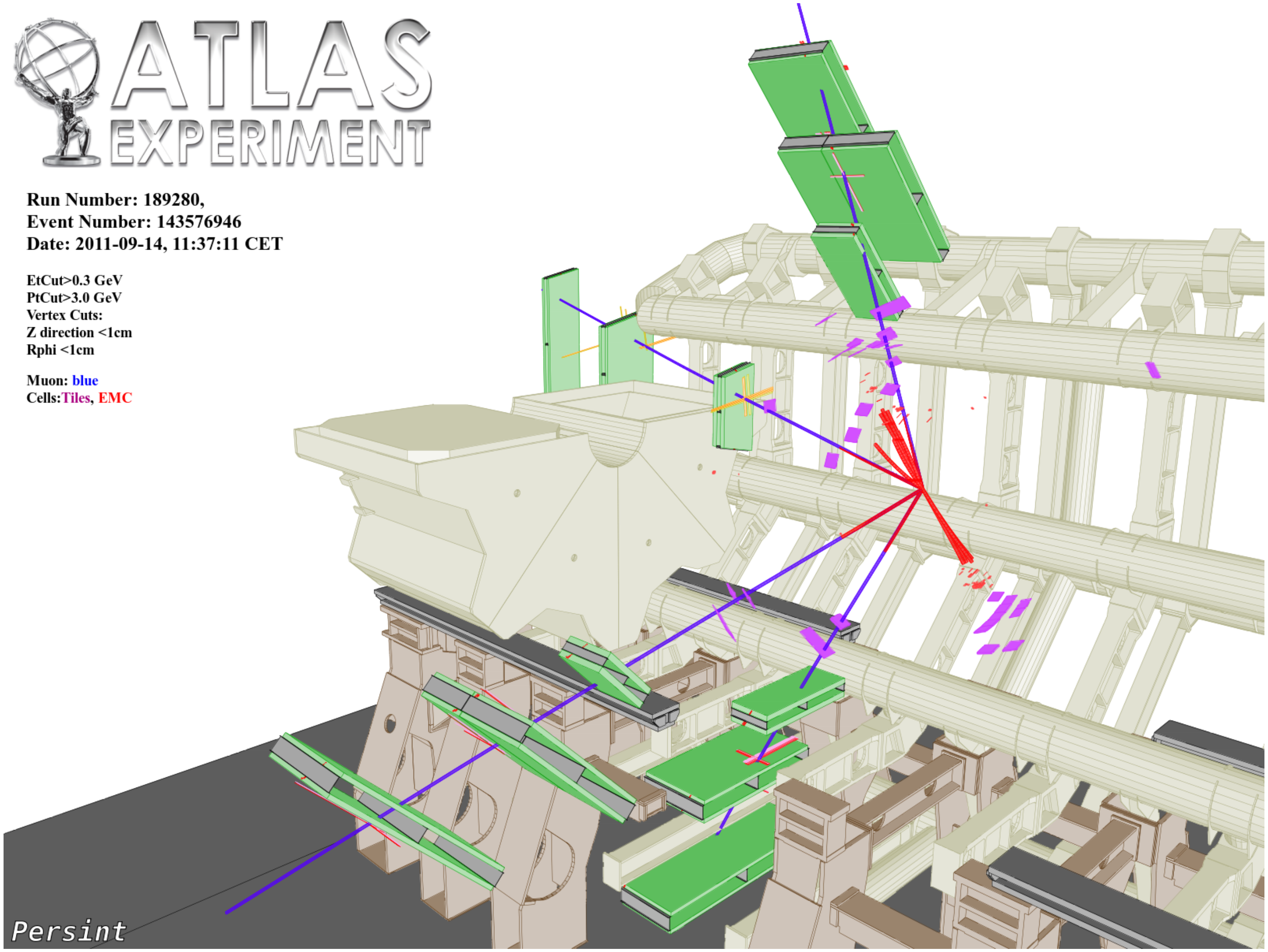


H->4 electrons

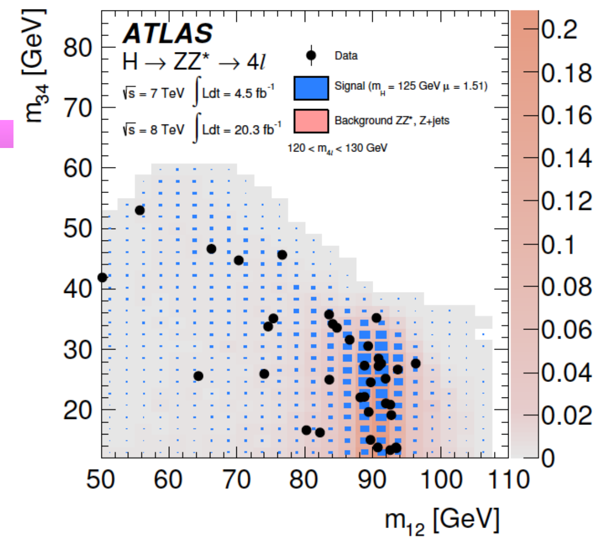


H->4μ

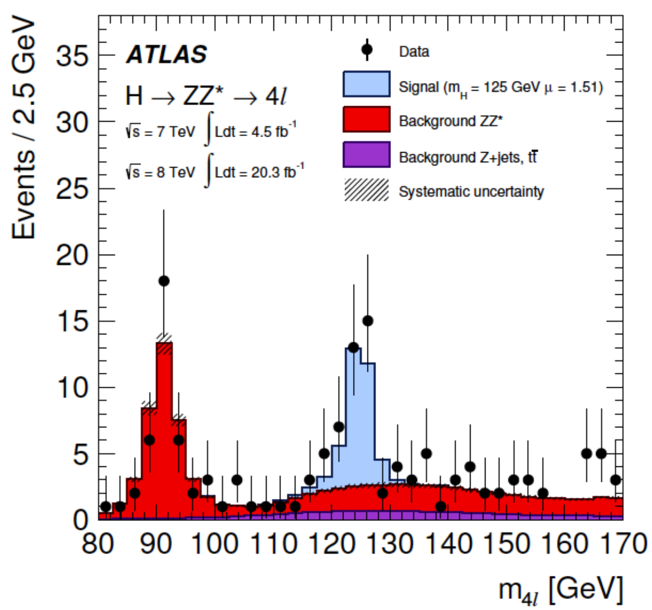
- M_{4l}=124.6 GeV
- M_{l1l2}=89.7 GeV
- M_{l3l4}=24.6 GeV

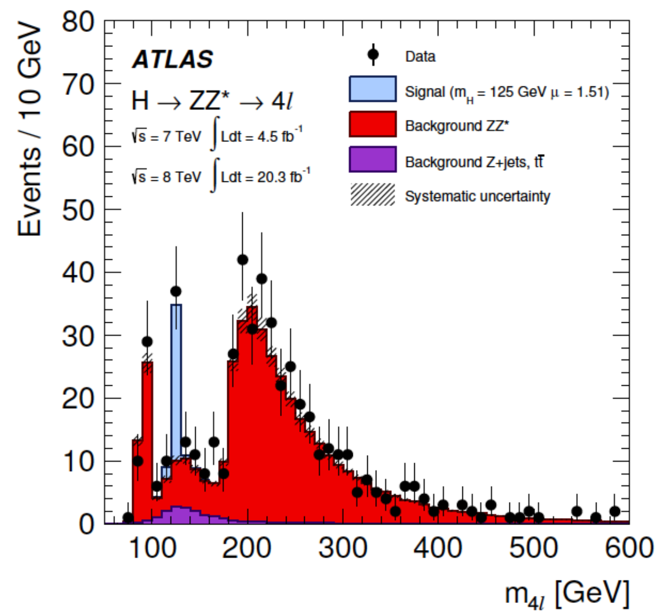


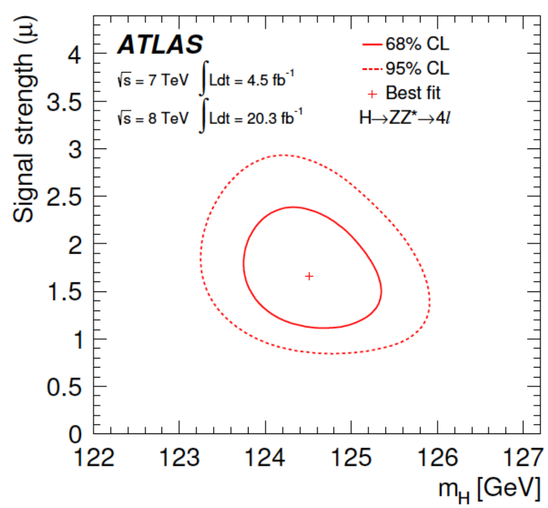
Final state	Signal full mass range	Signal	ZZ^*	$Z+\text{jets}, t\bar{t}$	S/B	Expected	Observed
			$\sqrt{s}=7$ TeV				
4μ	1.00 ± 0.10	0.91 ± 0.09	0.46 ± 0.02	0.10 ± 0.04	1.7	1.47 ± 0.10	2
$2e2\mu$	0.66 ± 0.06	0.58 ± 0.06	0.32 ± 0.02	0.09 ± 0.03	1.5	0.99 ± 0.07	2
$2\mu2e$	0.50 ± 0.05	0.44 ± 0.04	0.21 ± 0.01	0.36 ± 0.08	0.8	1.01 ± 0.09	1
$4e$	0.46 ± 0.05	0.39 ± 0.04	0.19 ± 0.01	0.40 ± 0.09	0.7	0.98 ± 0.10	1
Total	2.62 ± 0.26	2.32 ± 0.23	1.17 ± 0.06	0.96 ± 0.18	1.1	4.45 ± 0.30	6
			$\sqrt{s}=8$ TeV				
4μ	5.80 ± 0.57	5.28 ± 0.52	2.36 ± 0.12	0.69 ± 0.13	1.7	8.33 ± 0.6	12
$2e2\mu$	3.92 ± 0.39	3.45 ± 0.34	1.67 ± 0.08	0.60 ± 0.10	1.5	5.72 ± 0.37	7
$2\mu2e$	3.06 ± 0.31	2.71 ± 0.28	1.17 ± 0.07	0.36 ± 0.08	1.8	4.23 ± 0.30	5
$4e$	2.79 ± 0.29	2.38 ± 0.25	1.03 ± 0.07	0.35 ± 0.07	1.7	3.77 ± 0.27	7
Total	15.6 ± 1.6	13.8 ± 1.4	6.24 ± 0.34	2.00 ± 0.28	1.7	22.1 ± 1.5	31
			$\sqrt{s}=7$ TeV and $\sqrt{s}=8$ TeV				
4μ	6.80 ± 0.67	6.20 ± 0.61	2.82 ± 0.14	0.79 ± 0.13	1.7	9.81 ± 0.64	14
$2e2\mu$	4.58 ± 0.45	4.04 ± 0.40	1.99 ± 0.10	0.69 ± 0.11	1.5	6.72 ± 0.42	9
$2\mu2e$	3.56 ± 0.36	3.15 ± 0.32	1.38 ± 0.08	0.72 ± 0.12	1.5	5.24 ± 0.35	6
$4e$	3.25 ± 0.34	2.77 ± 0.29	1.22 ± 0.08	0.76 ± 0.11	1.4	4.75 ± 0.32	8
Total	18.2 ± 1.8	16.2 ± 1.6	7.41 ± 0.40	2.95 ± 0.33	1.6	26.5 ± 1.7	37



Note that one pair likes to be on the Z-pole







Add diphoton and 4 lepton decay modes