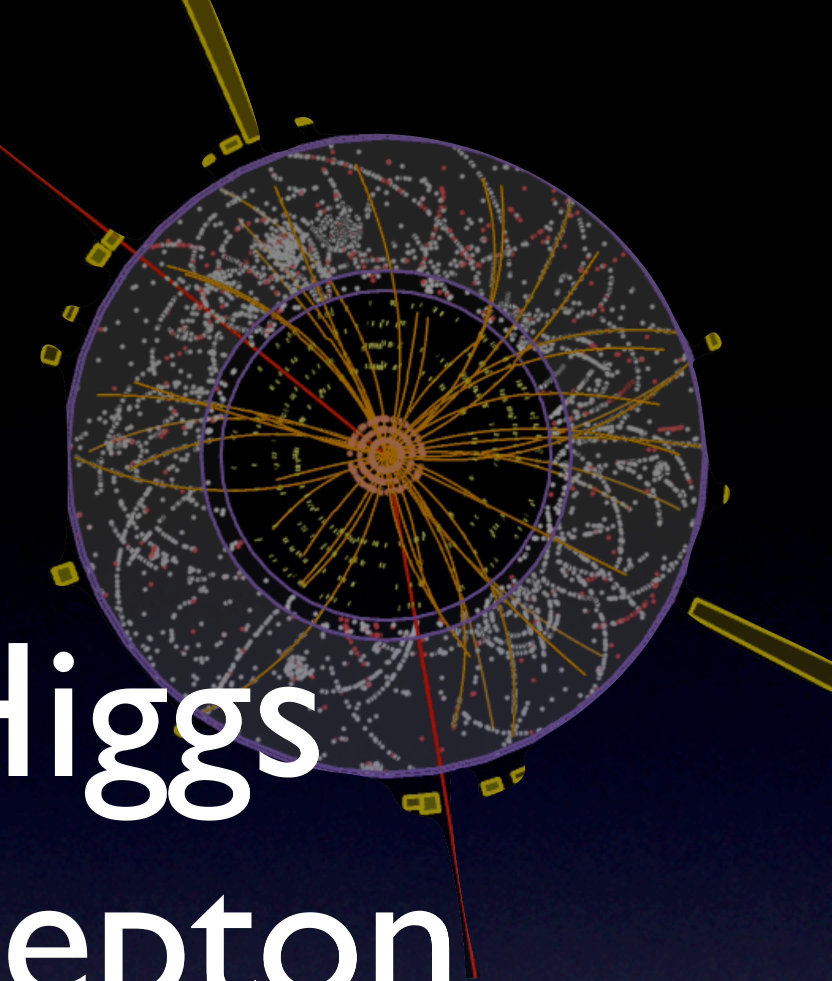
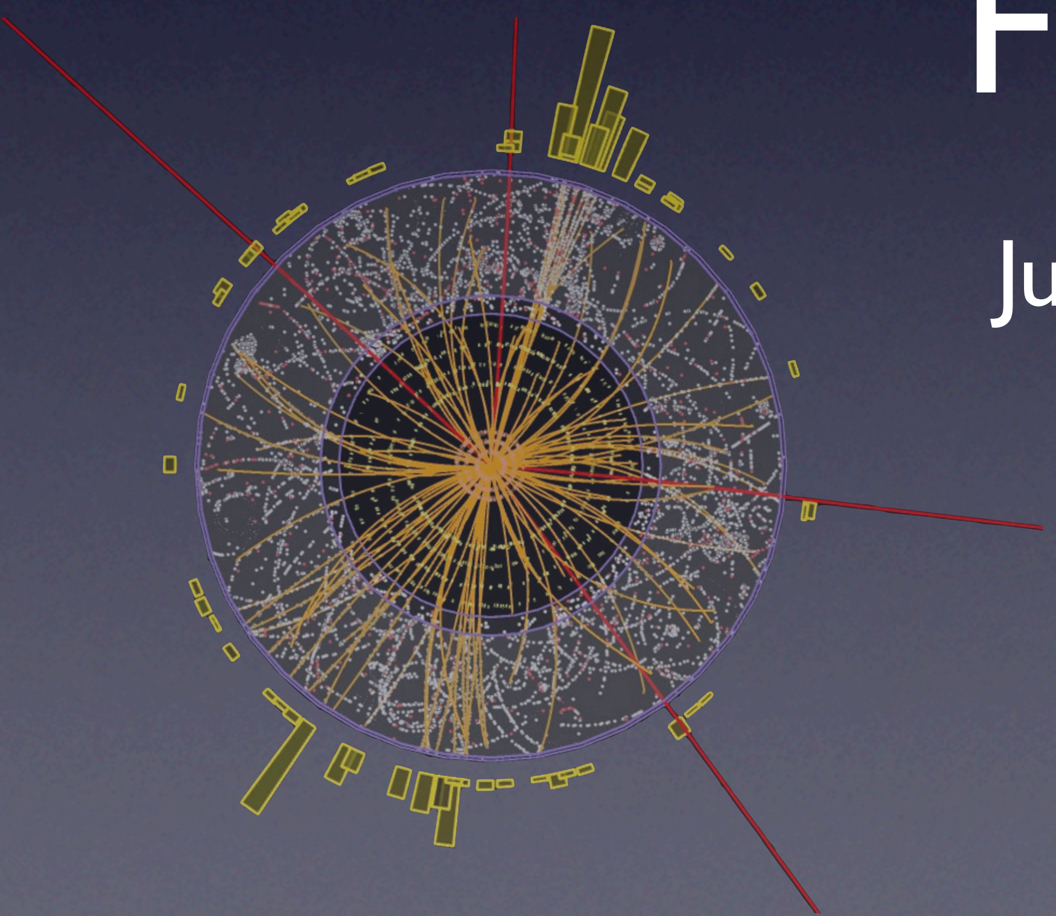


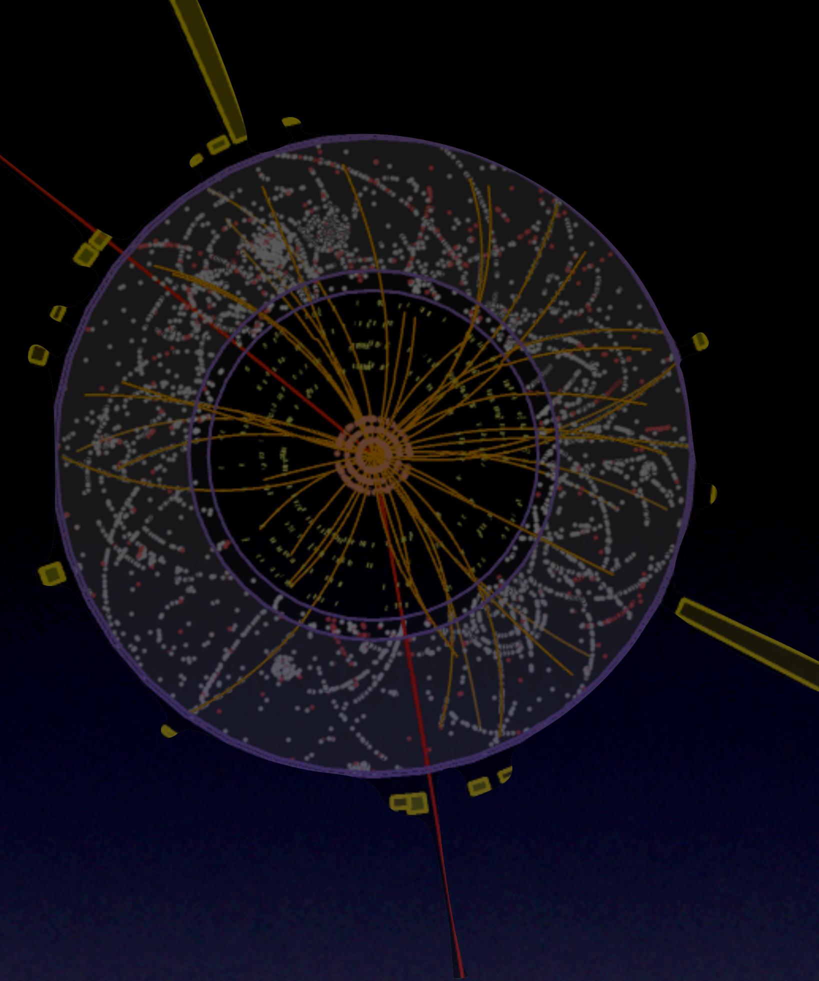
Standard Model Higgs Searches In The 4 Lepton Final State



Julia Hoffman, SMU

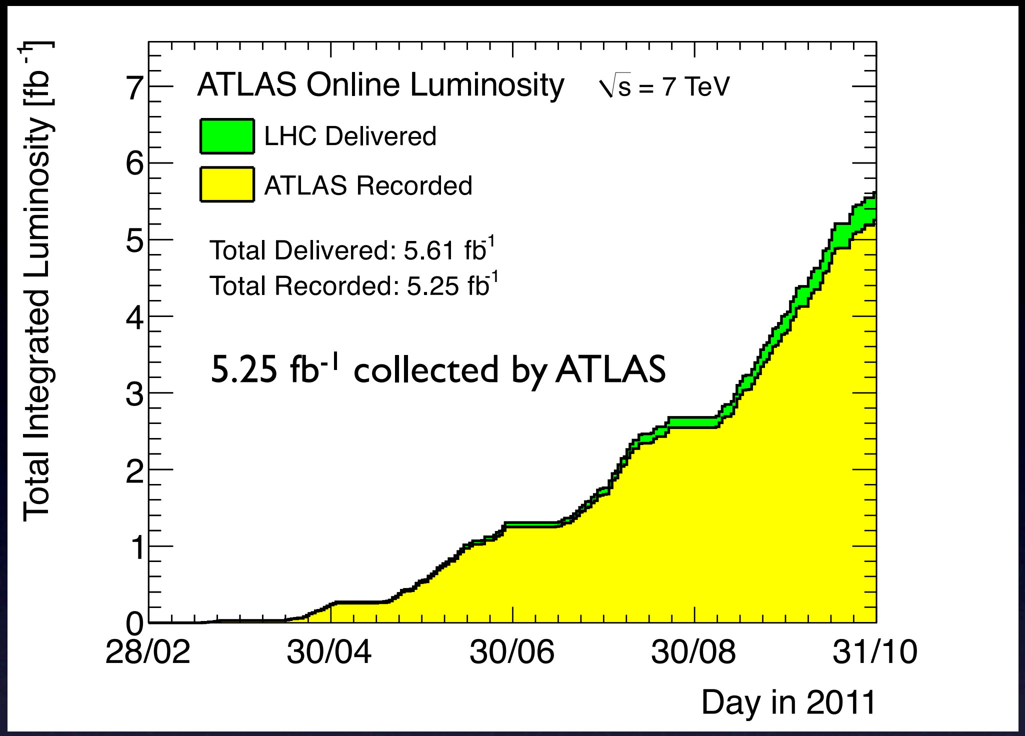
January 6, 2012

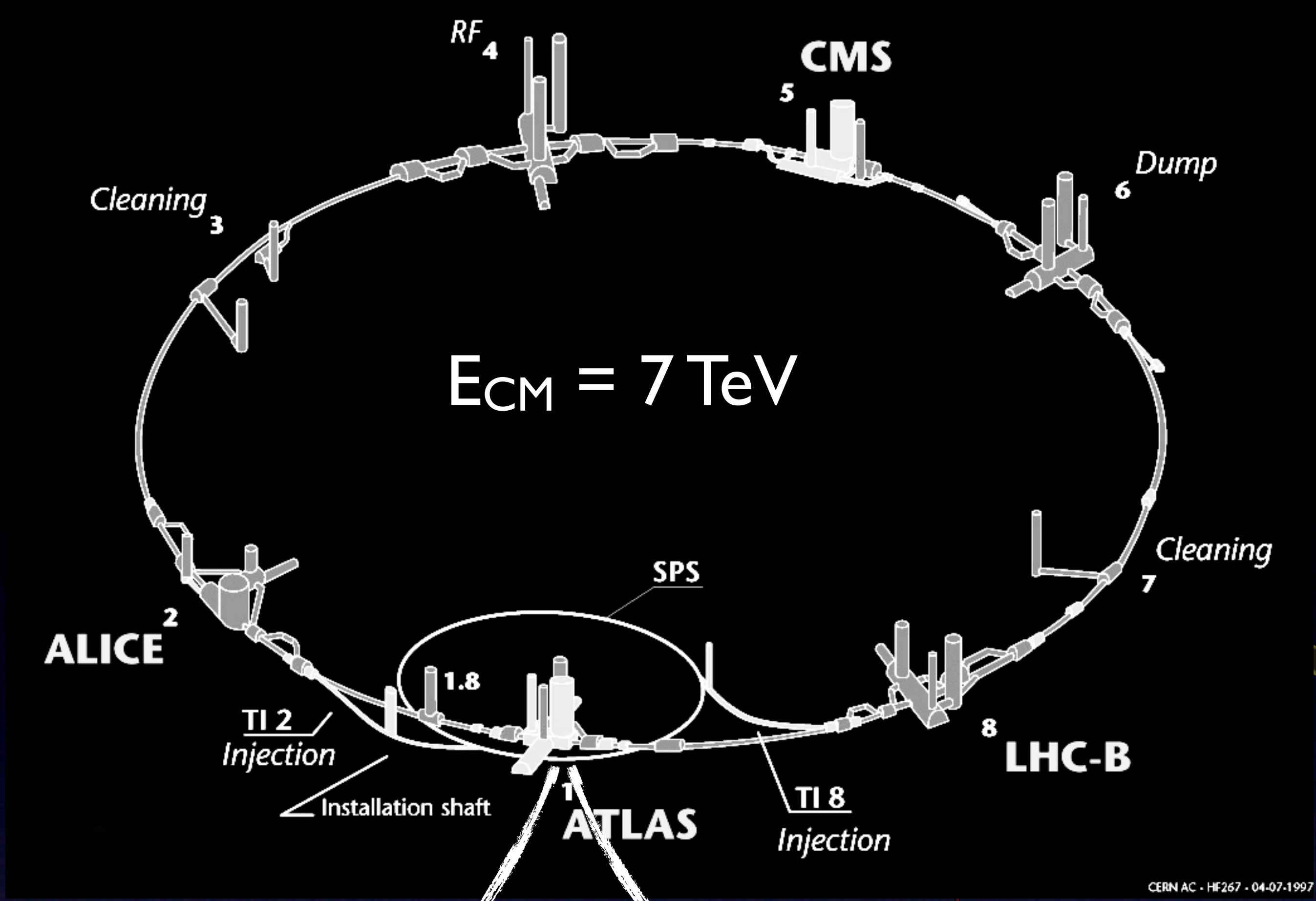
Outline



- LHC & ATLAS at CERN
- Higgs Boson
- Electrons in ATLAS
- Muons in ATLAS
- $H \rightarrow ZZ^{(*)} \rightarrow 4l$ analysis and results
- Summary

LHC & ATLAS at CERN





Tracking

- Pixel, Silicon detector, Transition Radiation Tracker; in a solenoidal magnetic field

Calorimetry

- Liquid Argon + Scintillators

Muon Spectrometer

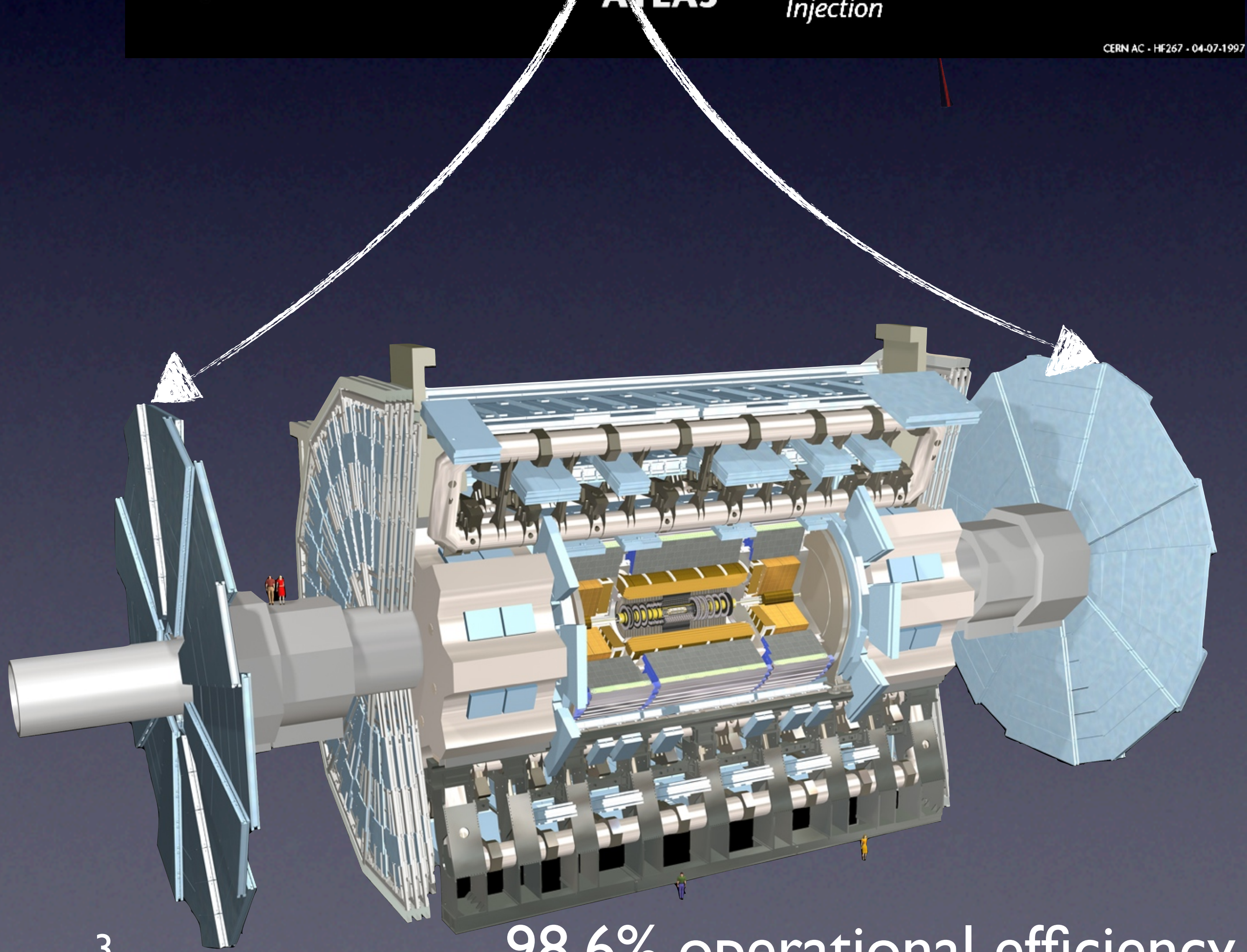
- Cathode Strip Chambers, Monitored Drift Tubes, Resistive Plate Chambers, and Thin Gap Chambers; in a toroidal magnetic field

Trigger

- A complex trigger system determines the events that are recorded, 3 levels.
  → Level 1 has a < 2.5 μs decision time

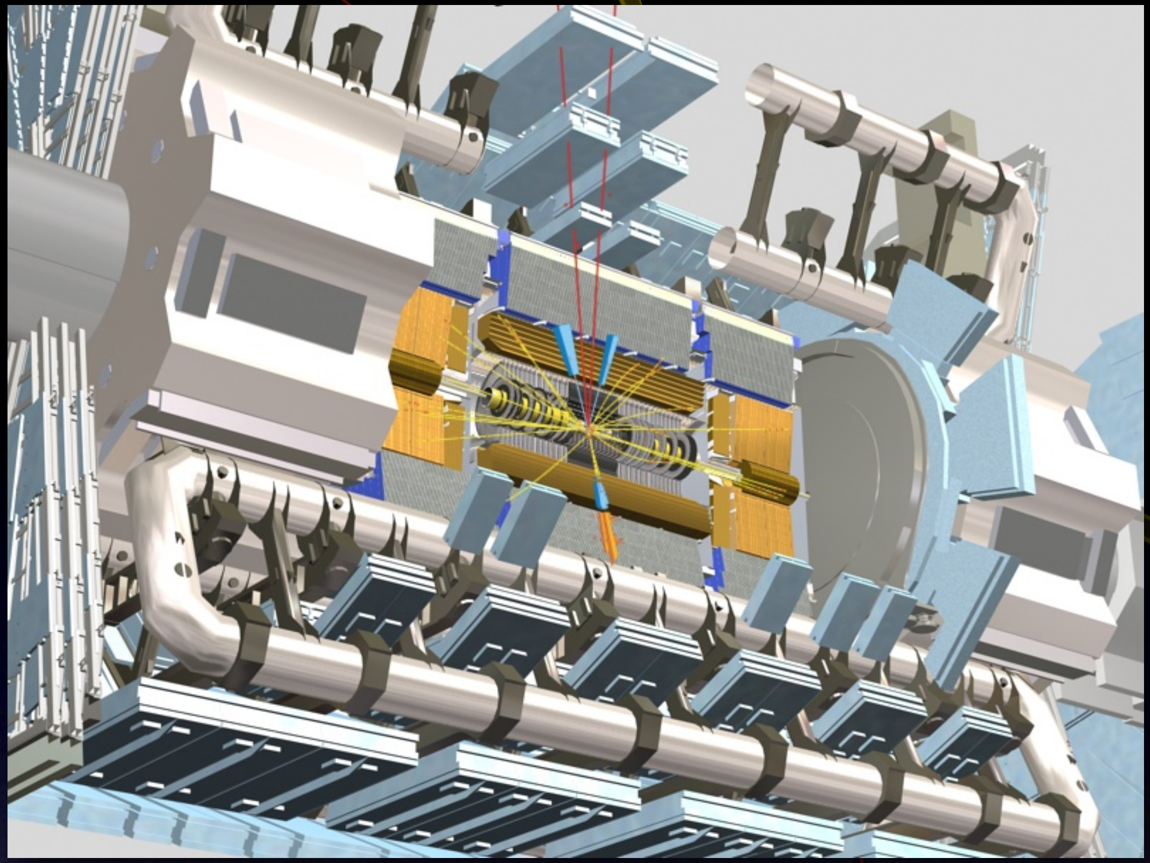
Magnets

- 2T solenoid and 3 air-core toroids



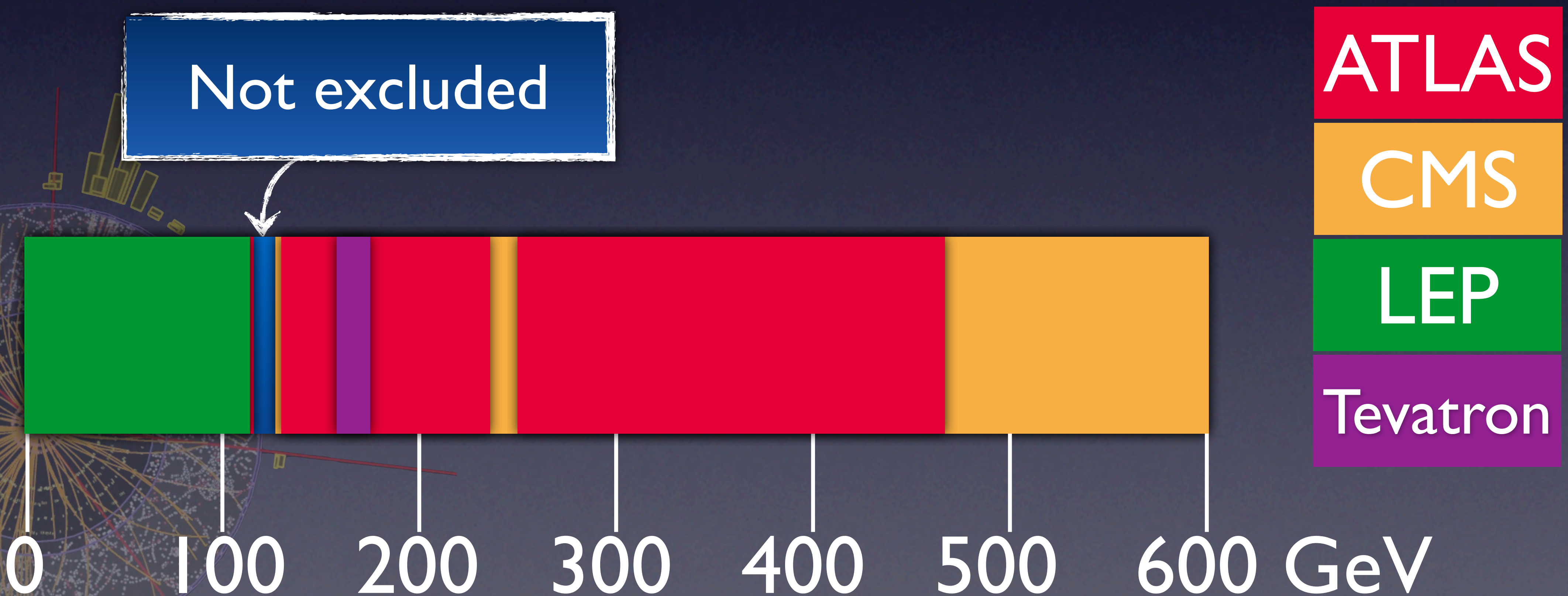
98.6% operational efficiency

Higgs Boson



- Hypothetical (still!) massive particle, whose existence is postulated to resolve inconsistencies in the Standard Model.
- It explains electroweak symmetry breaking.
- Resolves the problem of gauge boson scattering amplitudes exceeding unitarity limit.
- It is a consequence of the Standard Model Higgs mechanism that explains how most of the known elementary particles become massive.
- If it exists, it is a scalar boson.
- Theory does not predict Higgs boson mass.
- Other theories (like Minimal Supersymmetric extension of the Standard Model) predict existence of more than one Higgs boson.
- Theories that do not anticipate the Higgs boson: Higgsless models.
  - Technicolor, extra dimensions, Abbott-Fahri models (composite Z, W), top quark condensate.

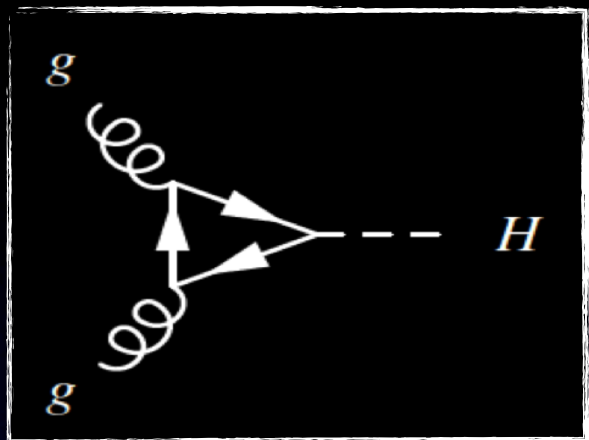
- Masses below 114.4 GeV (LEP) and 158-175 GeV (Tevatron) already excluded at 95%CL.
- ATLAS excluded mass ranges:
    - 112.7 - 115.5 GeV,
    - 131.0 - 237.0 GeV,
    - 251.0 - 468.0 GeV at 95%CL.
- CMS excluded masses 127 - 600 GeV at 95%CL.

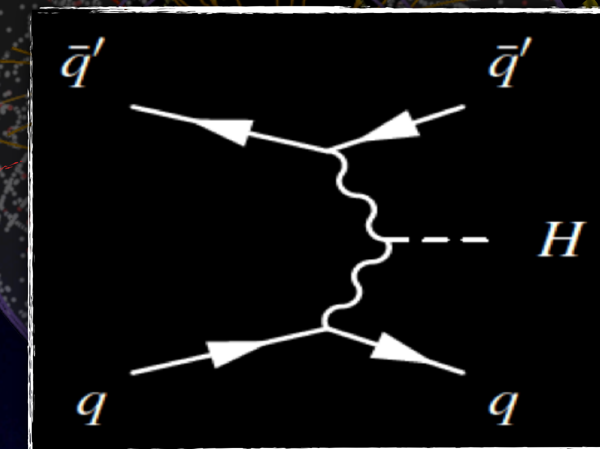


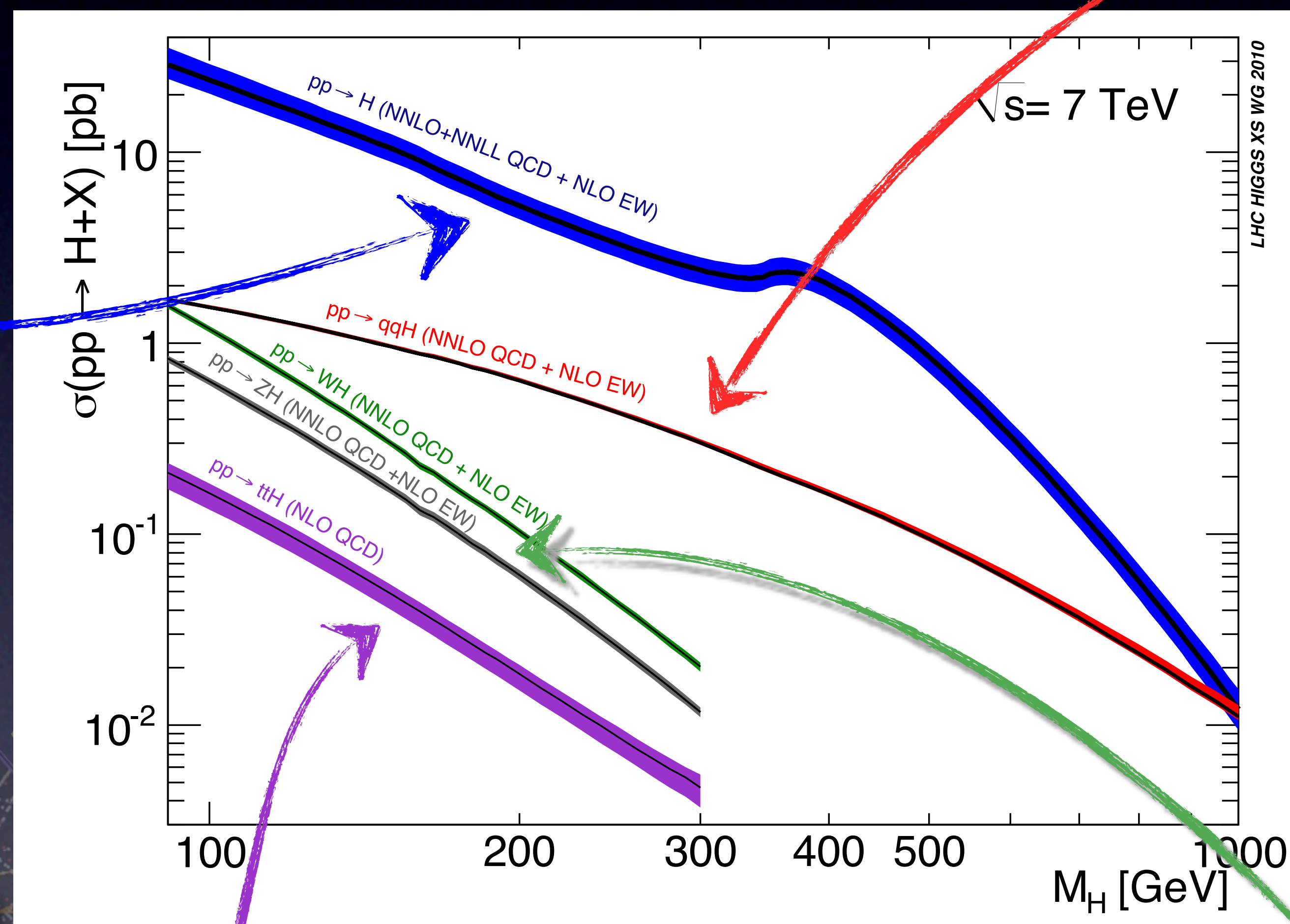
Higgs Boson Production

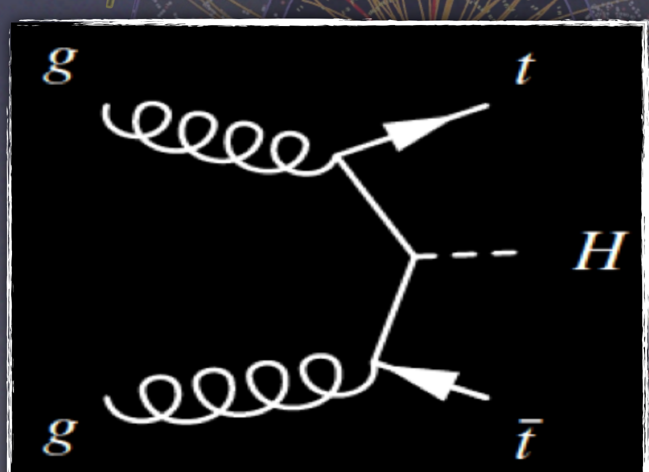
Dominant process:

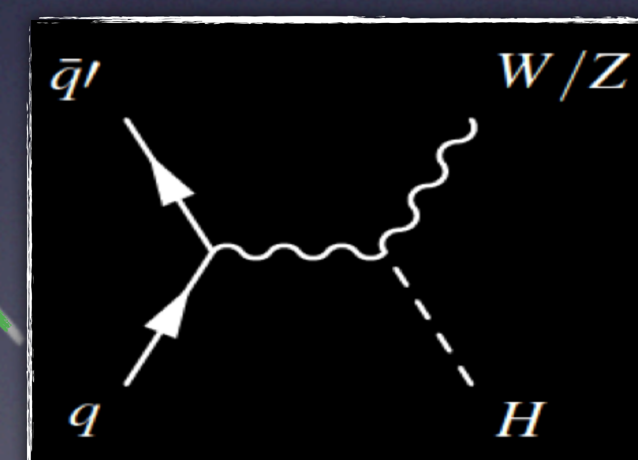
gluon-gluon fusion (~87%)



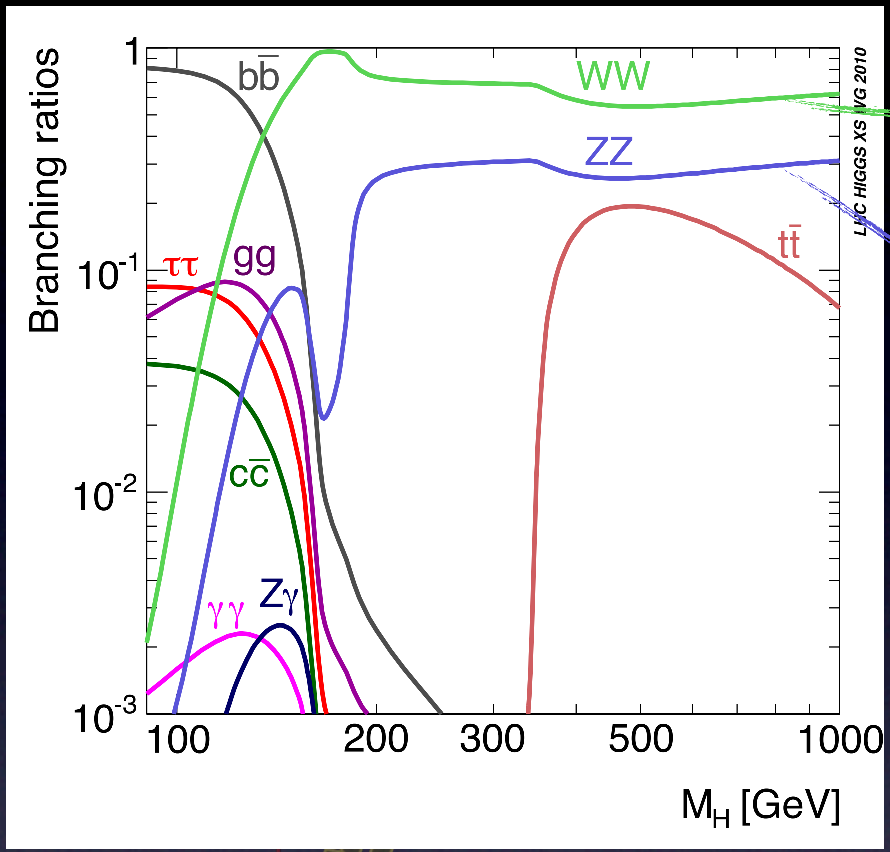


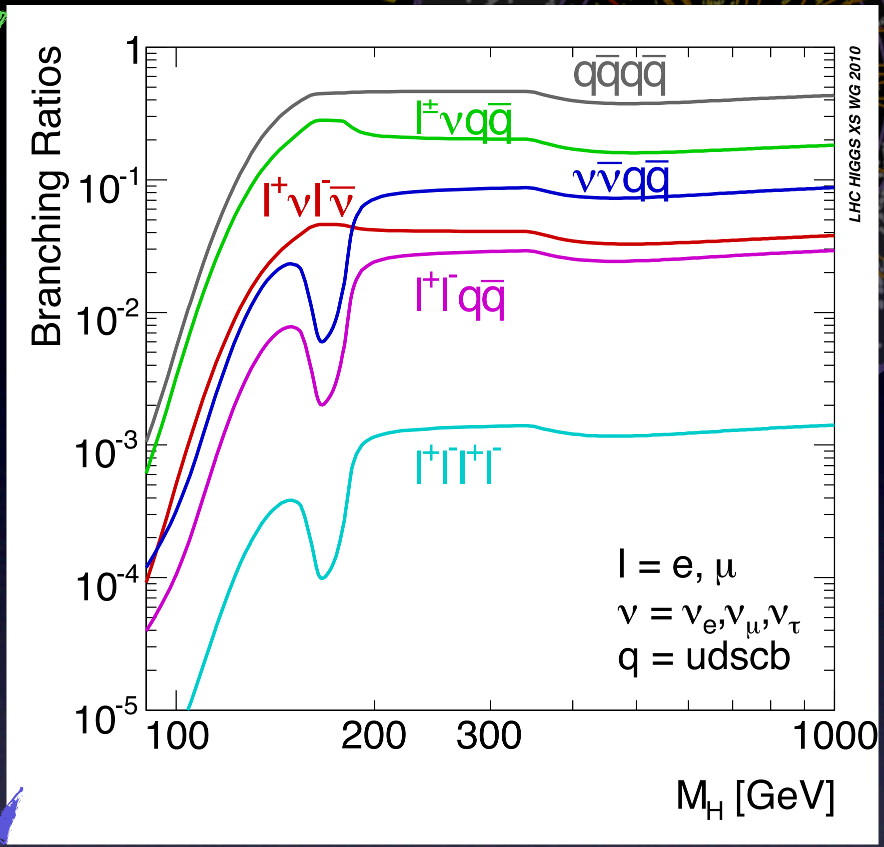






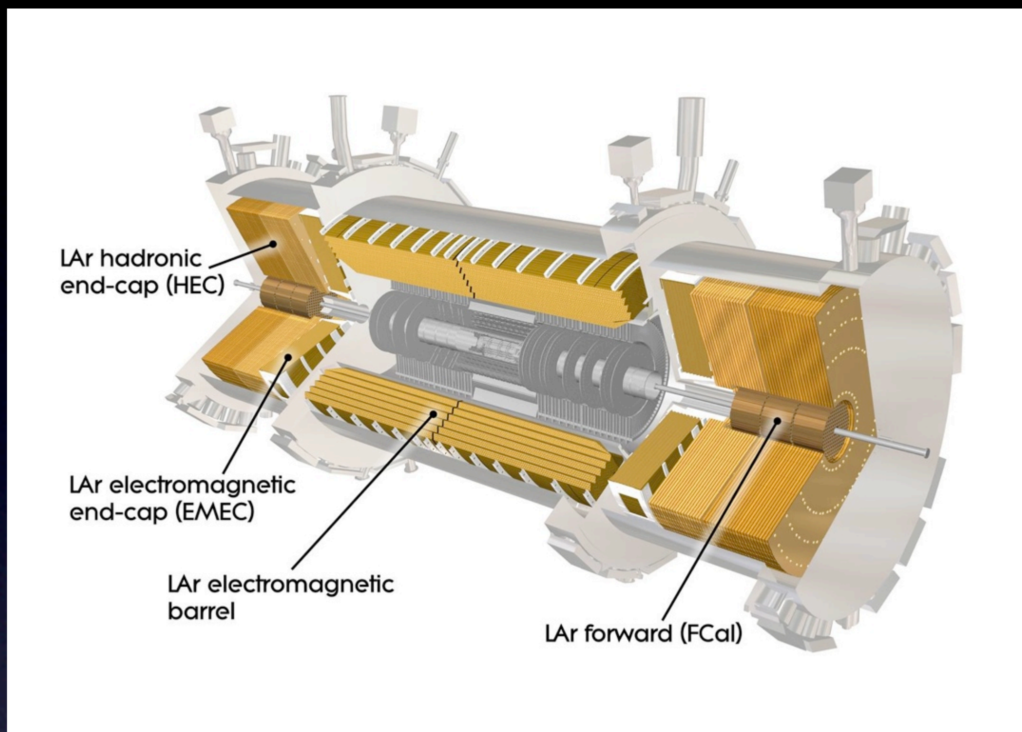
Higgs Boson Decay



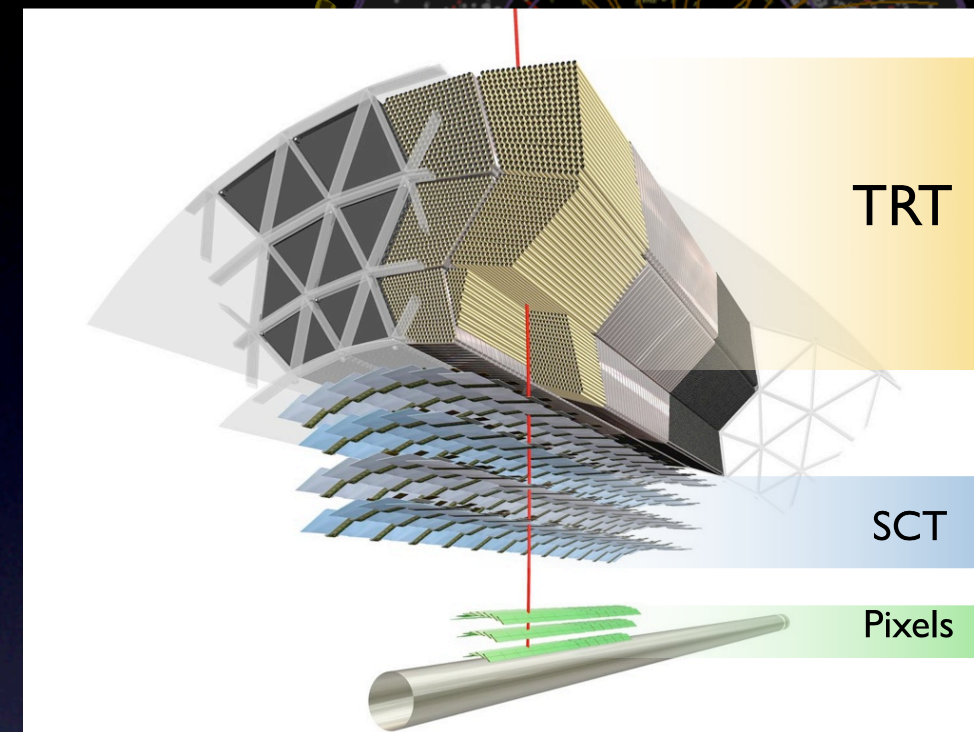


- Four lepton final state is known as the "Golden Channel".
    - Clean signature, but small branching ratio.
- Backgrounds:
    - Irreducible - ZZ→4l.
    - Reducible - $Zb\bar{b}$ & $t\bar{t}$.
    - Negligible backgrounds include QCD.
    - Final backgrounds are small, especially the reducible ones.

Electrons in ATLAS



$\eta = -\ln(\tan(\theta/2))$



- EM Calorimeter ($|\eta|<3.2$)
- Pb-LAr sampling calorimeter
  - 3 longitudinal compartments + pre-sampler in front of EM
- Accordion for full Φ coverage

- Tracker ($|\eta|<2.5$):
- Pixel (3 layers)
- SCT: Semiconductor Tracker (8 layers)
- TRT: Transition Radiation Tracker ($|\eta|<3.2$) (straw tube, ~30 hits for track)

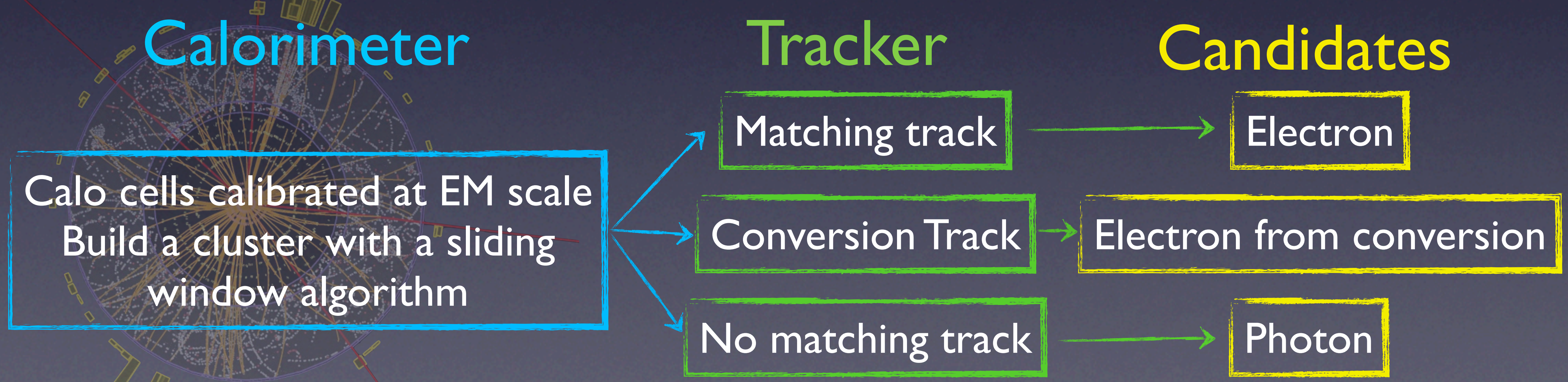
Electron Reconstruction

Track-seeded algorithm:

- High-quality tracks ➟ energy deposition in the calorimeter.
- Mainly for low-p_T electrons (J/Ψ) and electrons in jets (semi-leptonic decays of b and c quarks).

Calorimeter-seeded algorithm: ←

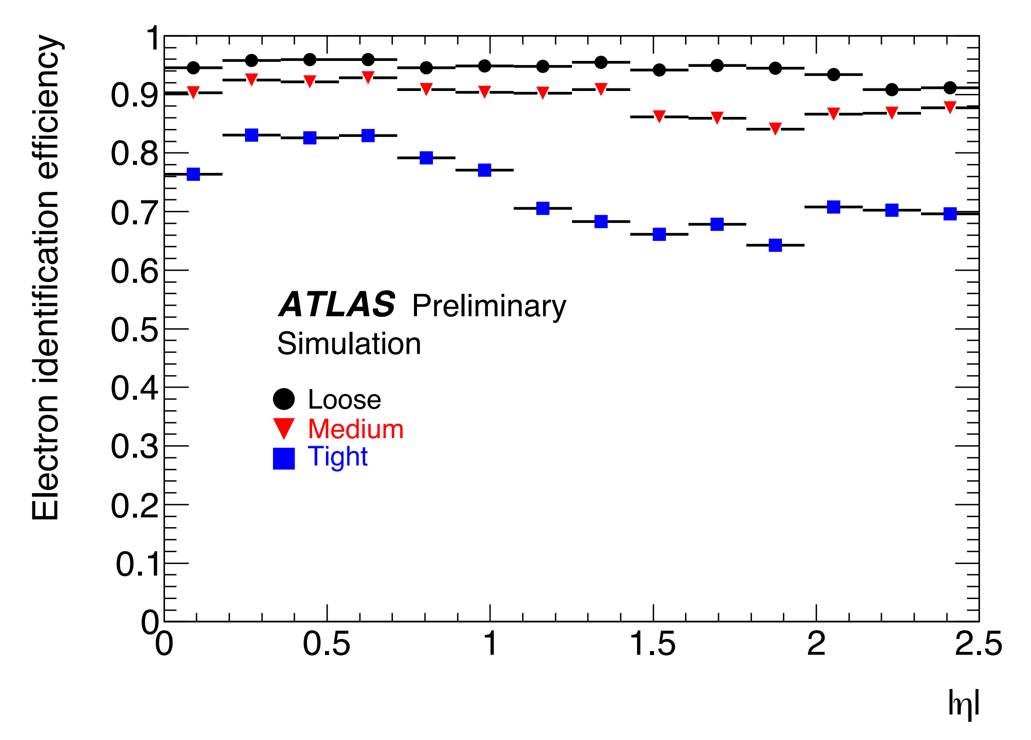
- Formed cluster in the calorimeter ➟ matching track is searched.
- High-p_T isolated electrons (W/Z, Higgs, SUSY,...).



Electron Identification

Cut based, with discriminating variables from:

- Leakage of the shower into the Hadron Calorimeter.
- Shower shape in the 1st and 2nd compartment of EM Calorimeter.
- Track quality cuts.
- Inner Detector/Calorimeter spatial matching.
- Inner Detector/Calorimeter energy matching.
- Transition radiation information in the TRT.



<u>Electron qualities:</u>

Loose:

- Shower shape variables of the 2nd calorimeter layer and hadronic leakage variables are used in the loose selection.

Medium:

- Loose + 1st calorimeter layer cuts, track quality requirements and track-cluster matching.

Tight:

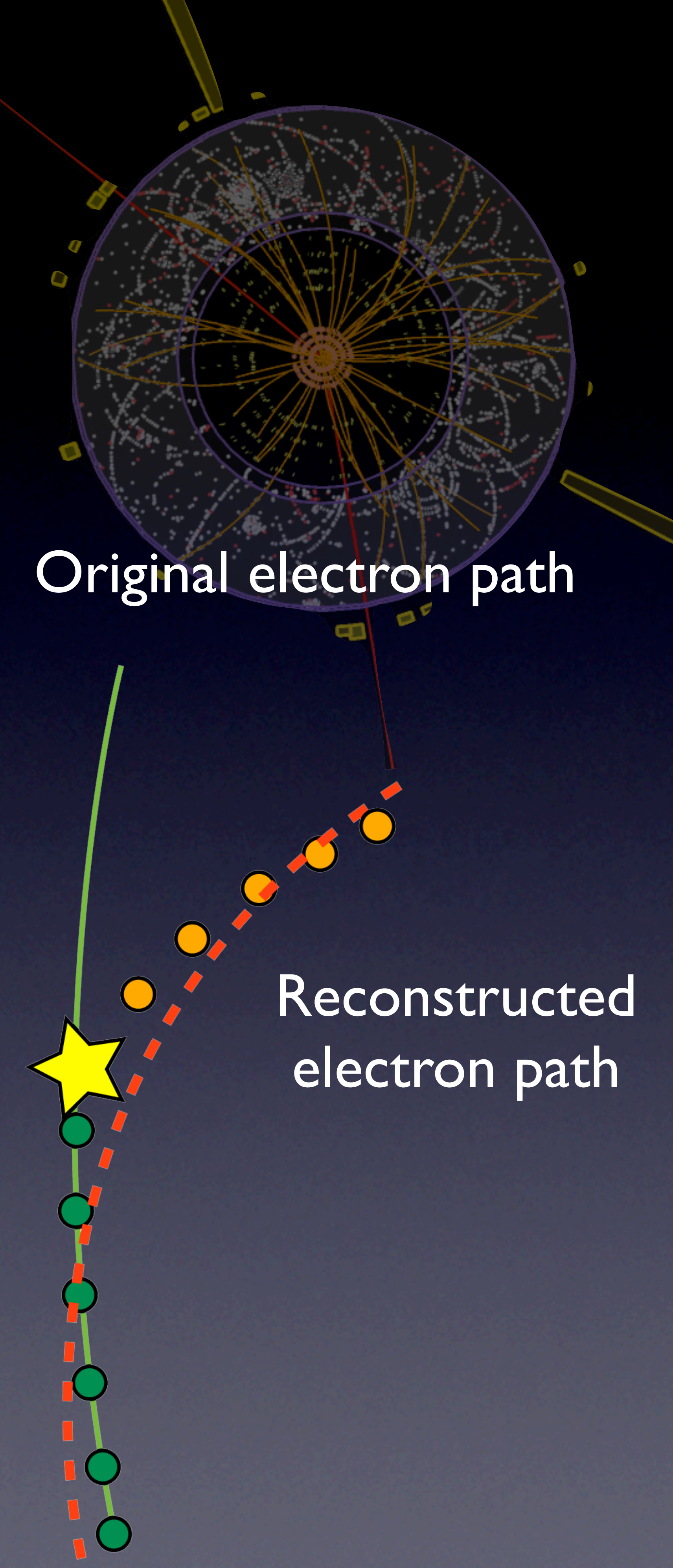
- Medium + E/p, b-layer hit requirements and the particle identification potential of the TRT.

Loose++, Medium++, Tight++ have some cuts re-optimized for better efficiency.

GSF Electrons

Problem with electrons:

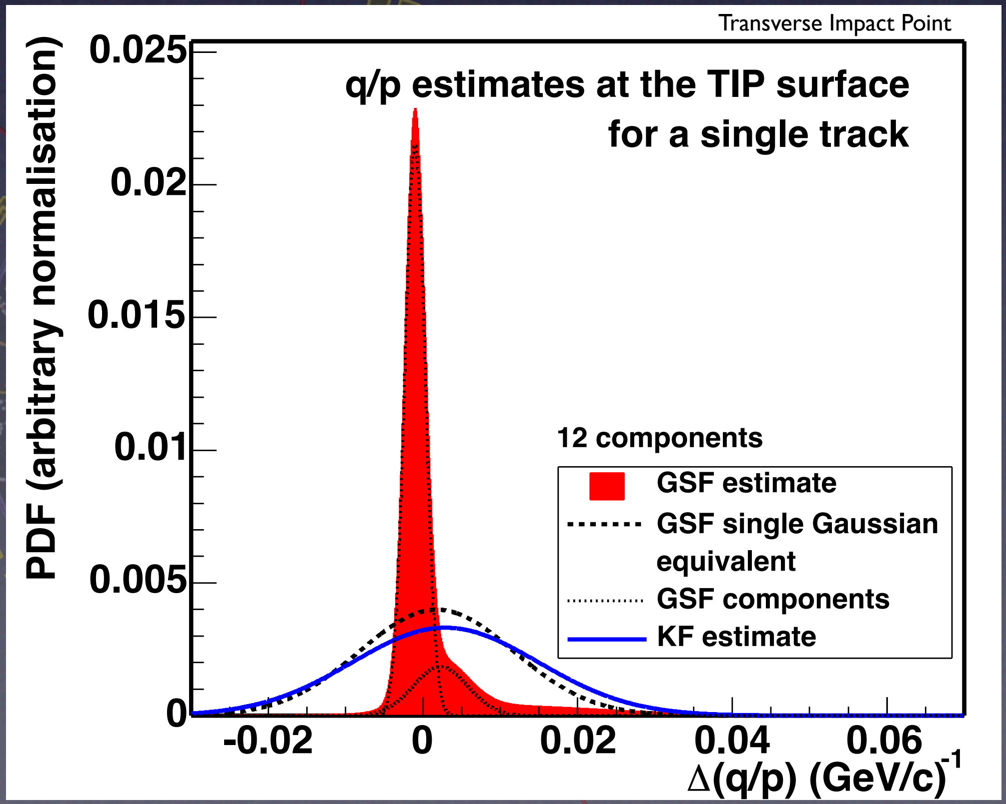
- Large fraction of energy radiated inside the inner detector (20 - 50%, η-dependent).
- All tracks created in the Inner Detector are fitted under the hypothesis they are pions.
- For electrons this leads to the track parameters being poorly reconstructed (esp. in the bending plane).
    - No energy loss allowed along the track.
    - Momentum is underestimated at the primary vertex.
- Two track fitters in the ATLAS reconstruction software have been specifically designed to reconstruct electrons in a more accurate manner:
    - GSF (Gaussian Sum Filter) ←
    - DNA (Dynamic Noise Adjustment)

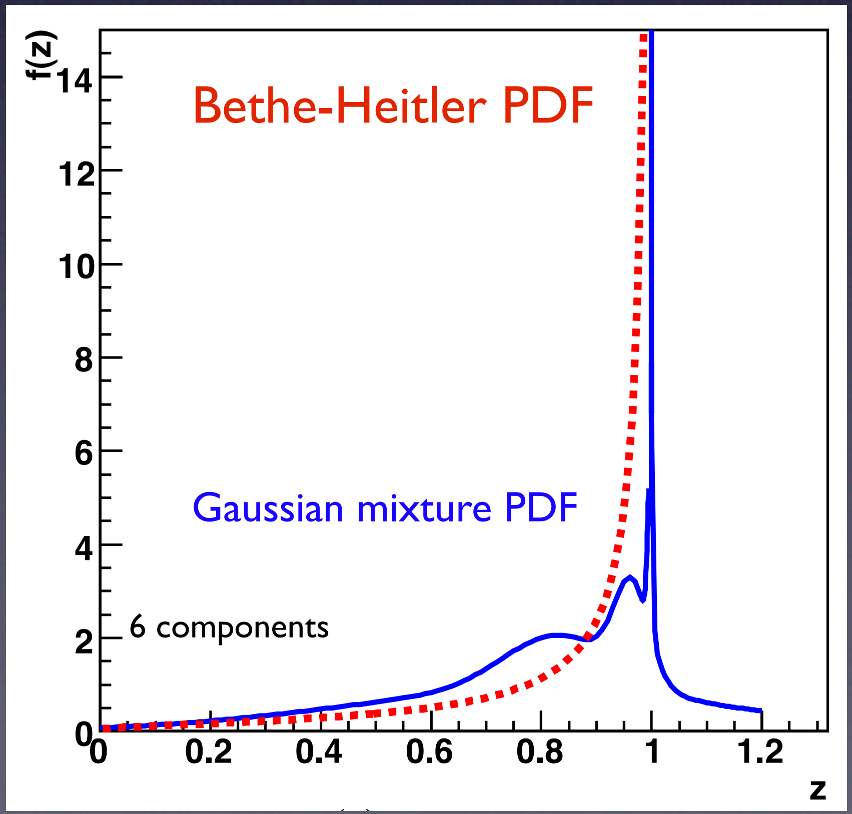


GSF Electrons, cont.

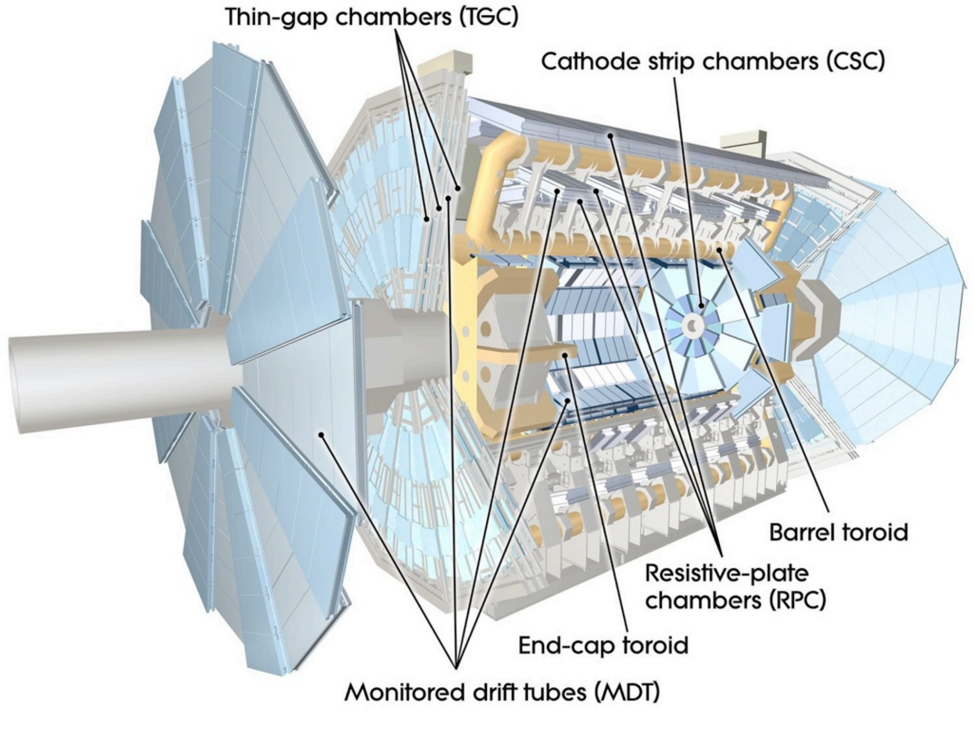
GSF solution:

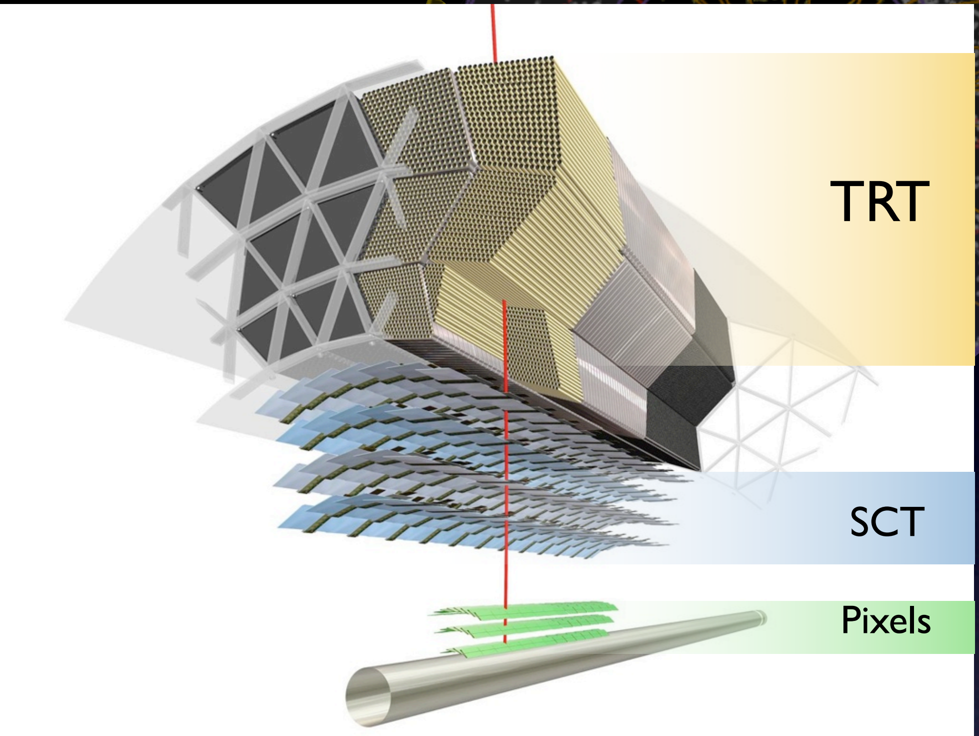
- Non linear extension of the Kalman Filter.
- Ideal for non-Gaussian material effect (bremsstrahlung).
- Works as a series of Kalman Filters working in parallel.
- Energy loss is modeled by a weighted sum of Gaussians.
- GSF produces a PDF (a weighted sum of Gaussians) describing the track parameters.
- The most probable value of the PDF is then passed to the user for analysis.

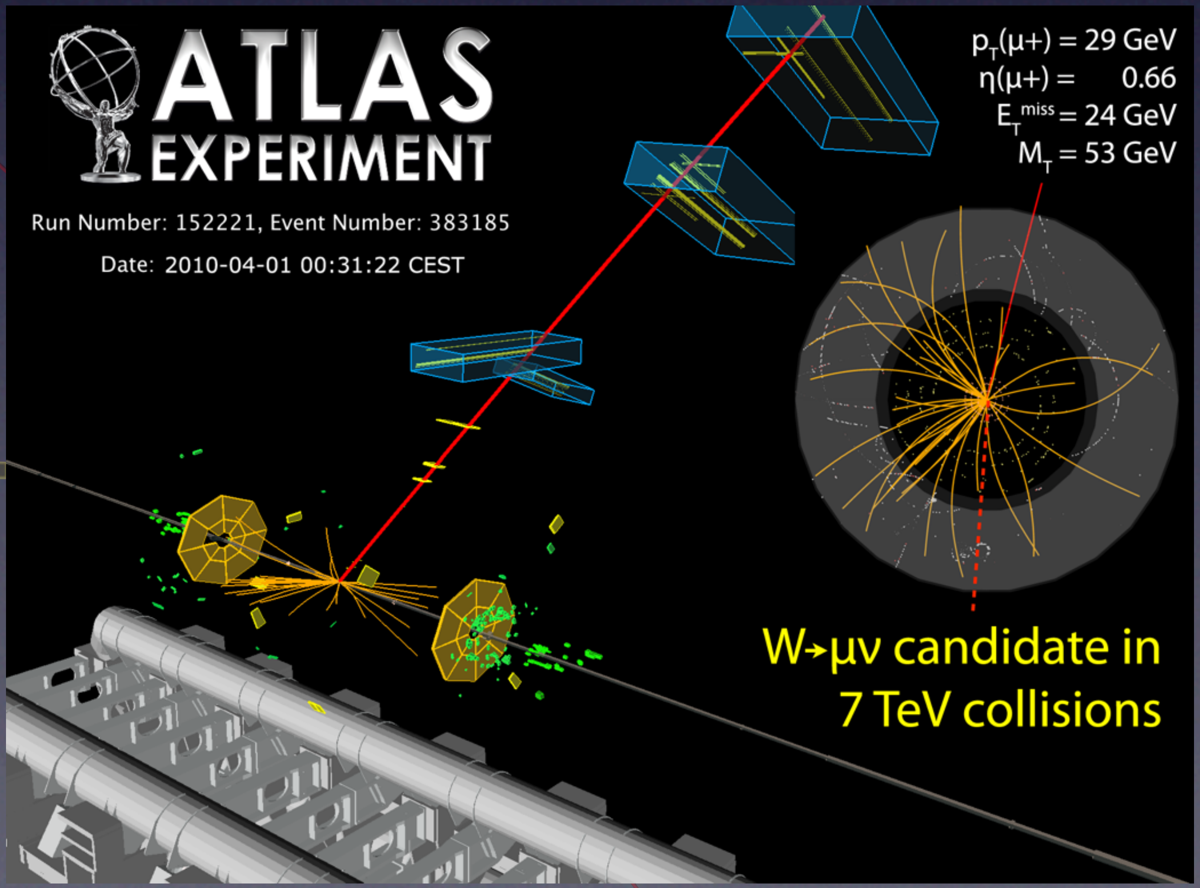




Muons in ATLAS







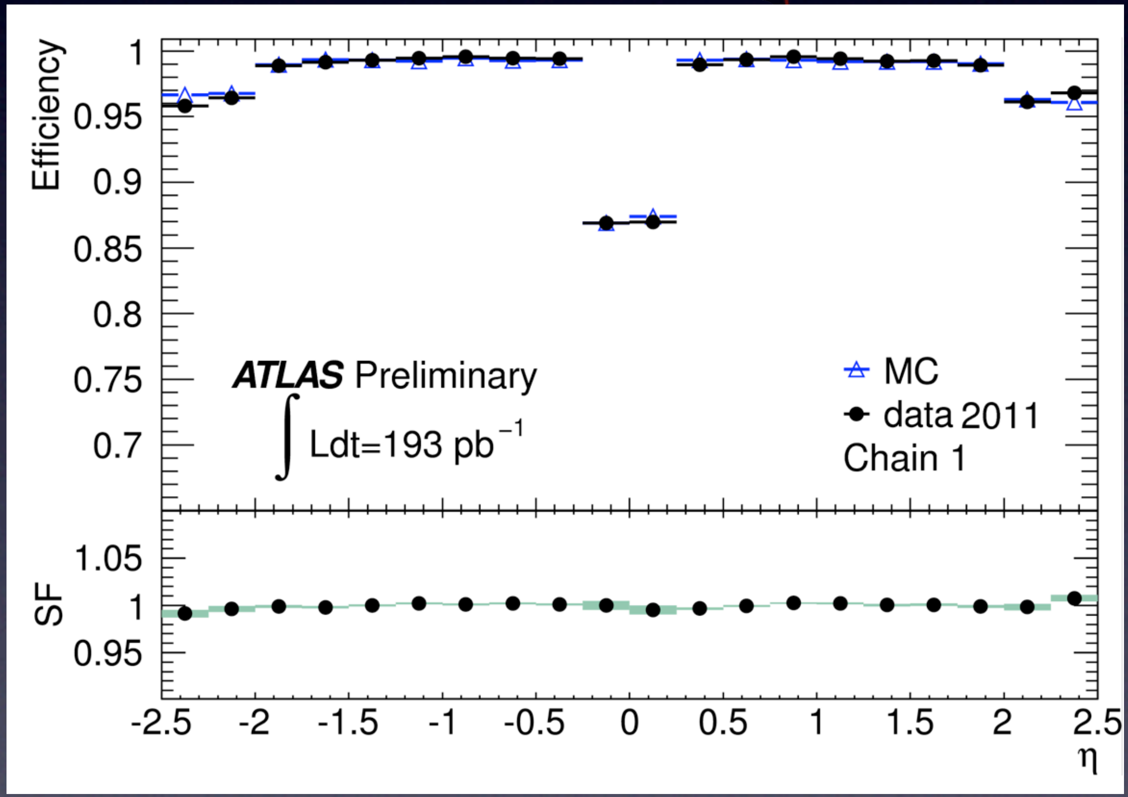
There are more than 20 muon reconstruction algorithms which provide the following types of muons:

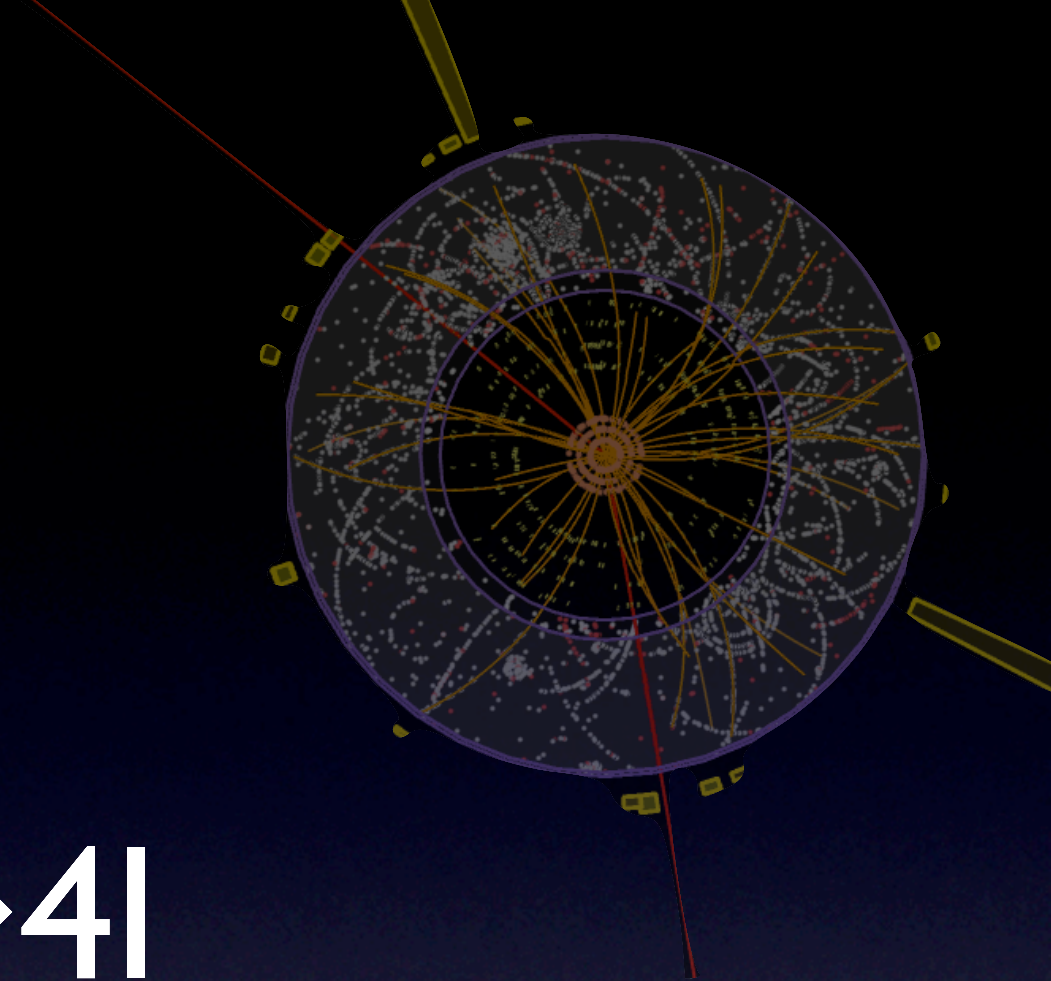
- ***Calo-tagged***: muons are reconstructed using inner detector tracks that are extrapolated to all layers of calorimetry.
- ***Combined***: muons are reconstructed using the combined track output from the muon spectrometer and inner detector algorithms.
- ***Segment-tagged***: muons are reconstructed via hit-pattern recognition in the MDT and CSC.
- ***Standalone***: muons are reconstructed using muon spectrometer "standalone" track code.

Muon Reconstruction

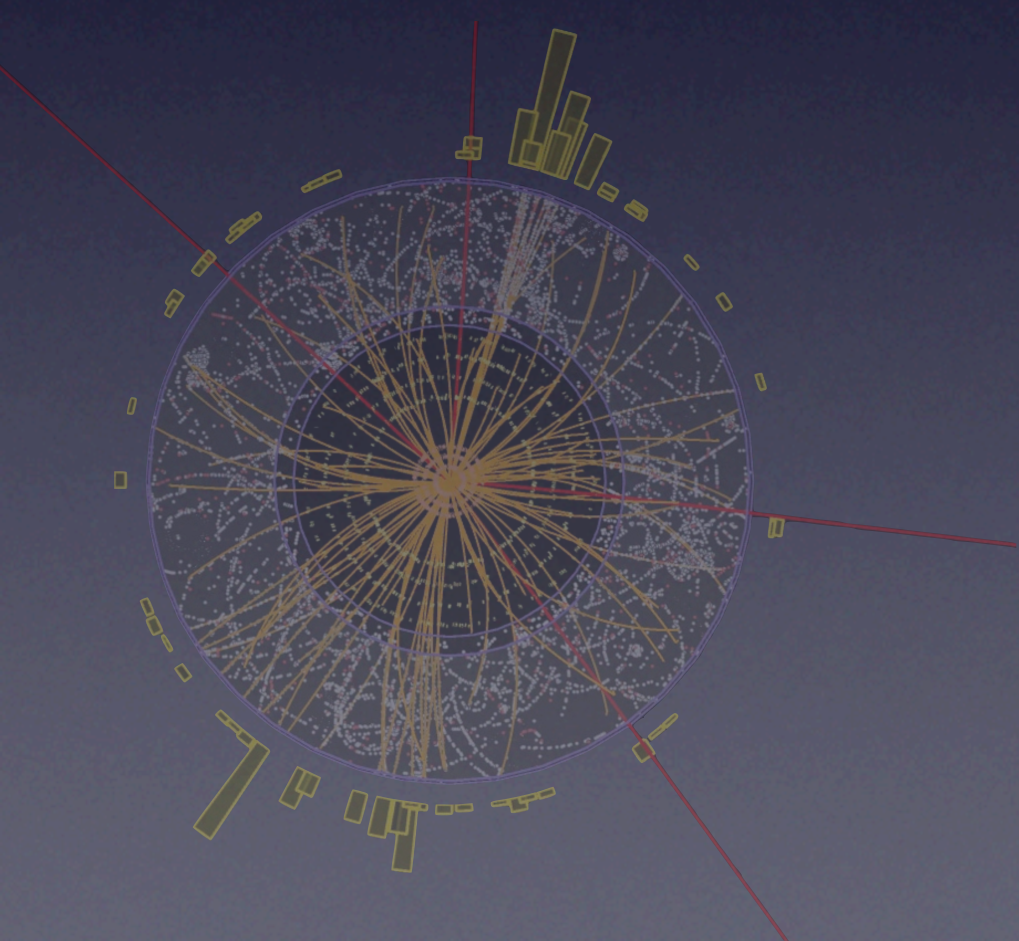
STACO muon reconstruction chain contains muons found by 3 different algorithms:

- Muonboy:
  - Starts from hit information in the muon spectrometer (*standalone* segments and tracks).
  - These tracks are extrapolated to the vertex.
- STAtistical COmbination (STACO):
  - Combines ID track with a muon spectrometer track using a statistical method.
  - Produces *combined* muons.
- MuTag:
  - Identifies muons by associating ID track with Muonboy segments.
  - ID tracks not combined in STACO algorithm and segments not belonging to a MS track already in STACO algorithm are used here (➠*Segment-tagged* Muon).





$H \rightarrow ZZ^{(*)} \rightarrow 4l$ analysis



Data and Monte Carlo Samples

Data:

- Collected during 2011
- After the requirements for data quality, beam/detector: the integrated luminosity:
  - 4.81 fb^{-1}: 4μ
  - 4.81 fb^{-1}: $2e2\mu$
  - 4.91 fb^{-1}: $4e$
  - uncertainty: 3.9%

MC Signal:

- PowHeg gluon-gluon fusion: $gg \to H$
  p_T reweighting to HqT2.0
- PowHeg Vector Boson Fusion: $qq \to qqH$
- PYTHIA: $qq \to WH$, ZH
- Cross-sections:
  provided by LHC Higgs σ working group https://twiki.cern.ch/twiki/bin/view/AtlasProtected/HiggsCrossSection

Signal cross section and BR

$H \to 4\ell,\ \ell = e, \mu$

m_H [GeV]	$\sigma(gg \to H)$ [pb]	$\sigma(qq \to Hqq)$ [pb]	$\sigma(qq \to WH)$ [pb]	$\sigma(qq \to ZH)$ [pb]	$BR(H \to 4\ell) \cdot 10^{-3}$
130	$14.1^{+2.7}_{-2.1}$	$1.154^{+0.032}_{-0.027}$	0.501 ± 0.020	0.278 ± 0.014	0.19
150	$10.5^{+2.0}_{-1.6}$	$0.962^{+0.028}_{-0.021}$	0.300 ± 0.012	0.171 ± 0.009	0.38
200	$5.2^{+0.9}_{-0.8}$	$0.637^{+0.022}_{-0.015}$	0.103 ± 0.005	0.061 ± 0.004	1.15
300	2.4 ± 0.3	$0.301^{+0.014}_{-0.008}$	0.020 ± 0.001	0.012 ± 0.001	1.38
400	2.0 ± 0.3	$0.162^{+0.010}_{-0.005}$	–	–	1.21
600	0.33 ± 0.06	$0.058^{+0.005}_{-0.002}$	–	–	1.23

MC Backgrounds:

- $ZZ^{(*)}$: generator PYTHIA; x-section & shape MCFM; data-driven: no (but constrained also from the m_{4l} fit)
- Zbb: generator ALPGEN; x-section MCFM; data driven: yes
- Z inclusive: generator ALPGEN/PYTHIA; x-section MCFM, data driven: yes
- ttbar: generator MC@NLO; x-section HATHOR; checked against data

Event Selection

Trigger:

lowest single lepton un-prescaled trigger

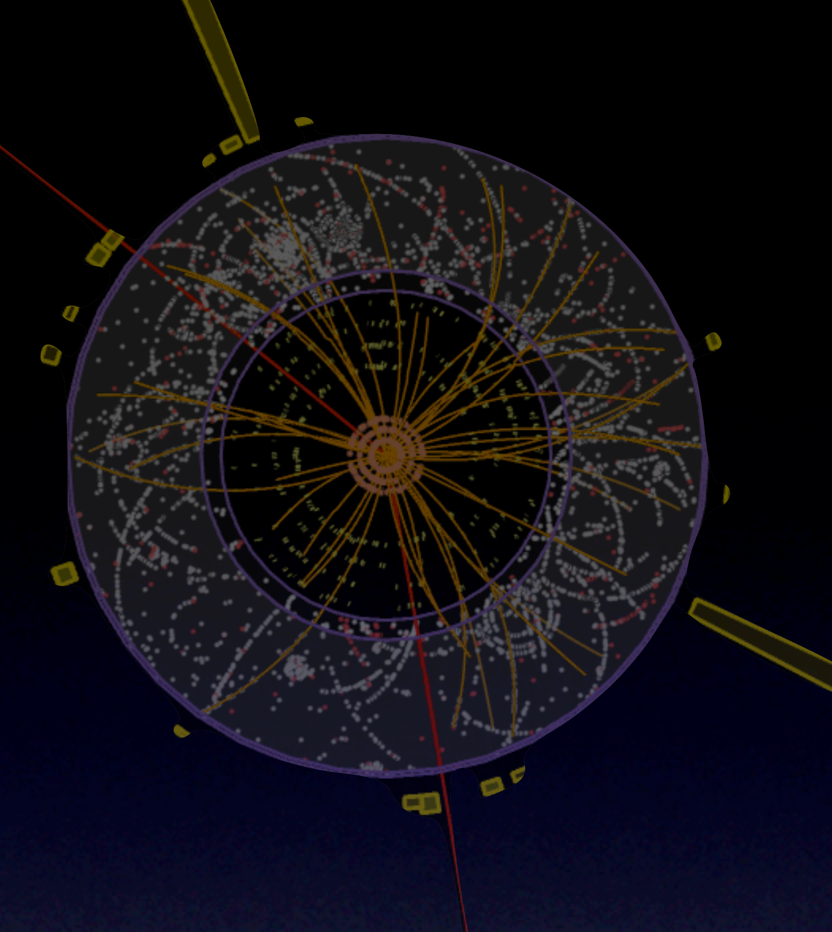
- 4e: Single OR Di-electron trigger
- 4μ: Single OR Di-muon trigger
- 2e2μ: 4e OR 4μ trigger

Event Preselection	
Electrons: Loose++ quality GSF electrons with E_T>7 GeV and $\|\eta\|$<2.47 Muons: Combined or segment-tagged muons with p_T>7 GeV and $\|\eta\|$<2.7	
Event Selection	
Kinematic Selection	At least one quadruplet of leptons consisting of two pairs of same flavor opposite charge leptons fulfilling the following requirements. At least two leptons in the quadruplet with p_T>20 GeV Leading di-lepton pair mass requirement $\|m_{12}-m_Z\|$<15 GeV Sub-leading di-lepton pair mass requirement $m_{threshold}<m_{34}<115$ GeV $\Delta R_{(l,l')}$> 0.1 for all leptons in the quadruplet.
Isolation	Lepton track isolation (ΔR=0.2): $\Sigma p_T/p_T<0.15$ Lepton calorimeter isolation (ΔR=0.2): $\Sigma E_T/E_T<0.3$
Impact parameter significance	Apply impact parameter significance cut to the 2 less energetic leptons of the quadruplet For electrons: $\|d_0/\sigma_{d0}\|$ < 6.0 For muons: $\|d_0/\sigma_{d0}\|$ < 3.5 for m_{4l}>190 GeV no requirement applied

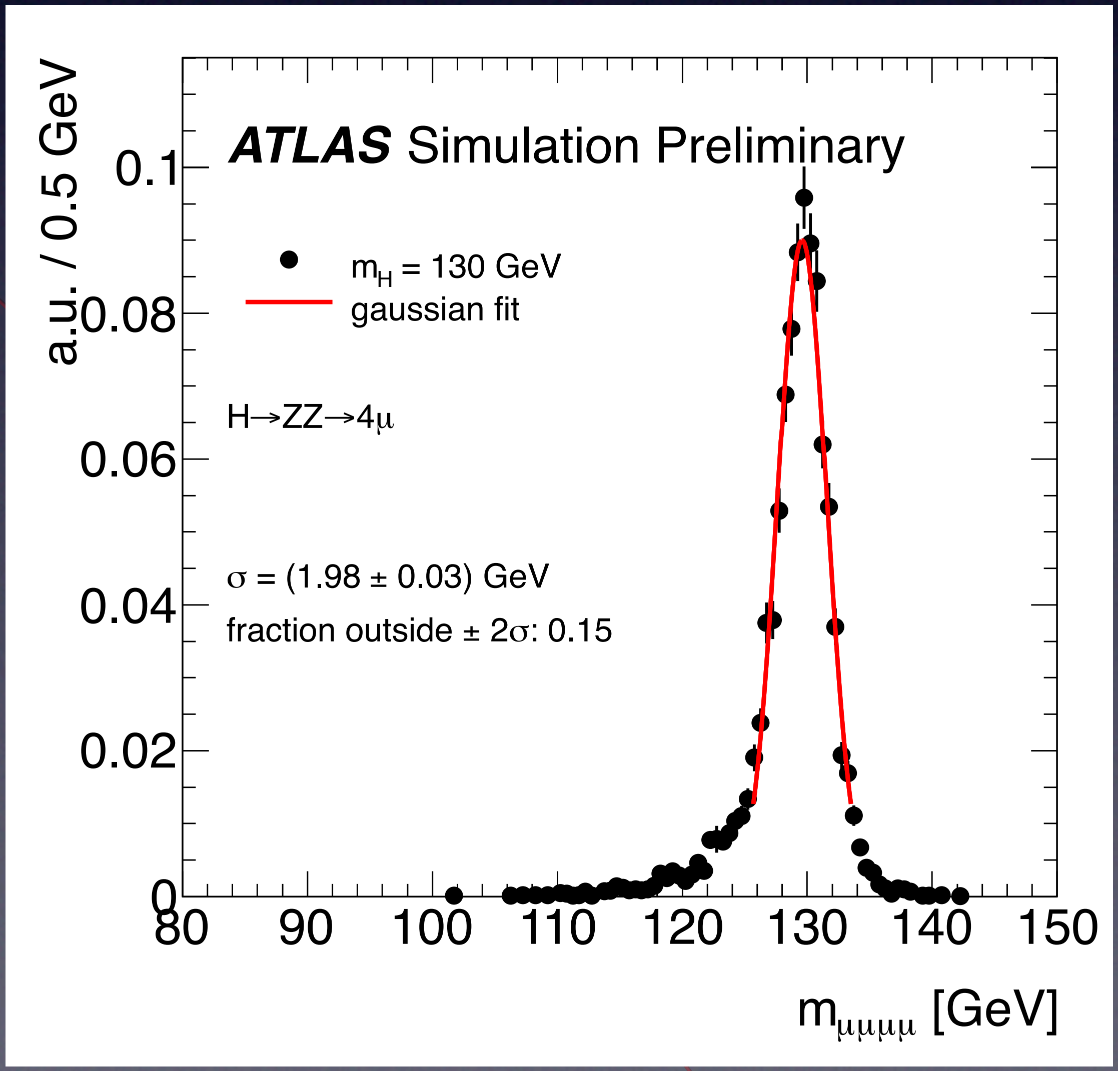
Sub-leading di-lepton pair mass requirements

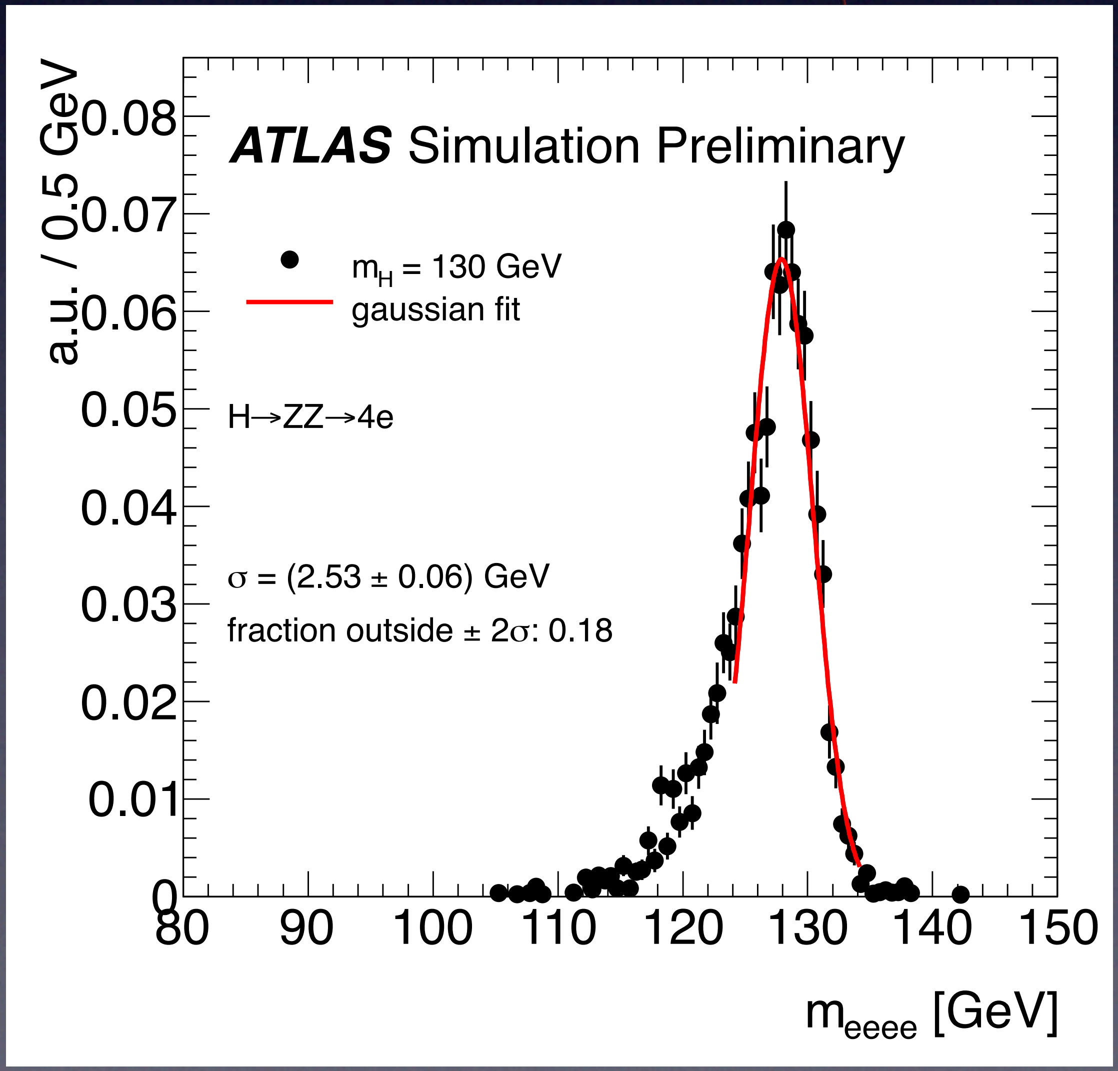
m_{4l} (GeV)	≤120	130	140	150	160	165	180	190	≥200
threshold (GeV)	15	20	25	30	30	35	40	50	60

M_{4l} Resolution



Resolution m_{4l} :
4e : 2.53 GeV @ m_H = 130 GeV
4μ : 1.98 GeV @ m_H = 130 GeV
for high mass :
dominated by natural width
35 GeV @ m_H = 400 GeV (FWHM)





Studies of selected cuts with Z→ee/μμ

Tag&Probe studies on Z→ee/μμ

- Apply individually or simultaneously:
  - track isolation,
  - calorimeter isolation,
  - impact parameters significance.
- Extract efficiency.
- Results:
  - Ratio between Data and MC for p_T compatible with 1.0 within uncertainties.
  - No need to apply scale factors for muon/electron to improve the Z shape.
  - For low E_T (7-10 GeV) electrons: extrapolation from 10-15 GeV down to 7 GeV.
  - 5% (conservative) systematic per electron added for low E_T (7-15 GeV) electrons.

Studies with non-isolated additional leptons

This study can be used later in extrapolating the controlled region to the background region.

- Look at events containing a reconstructed $Z \rightarrow ee/\mu\mu$ decay with additional leptons (e,μ).
- The performance of additional leptons are studied after imposing:
  - track isolation,
  - calorimeter isolation,
  - impact parameter significance.

muons:

Z+μ: good agreement between data and MC

electrons:

Z+e: good agreement between data and MC

- Separate jets→e and conversion photons (based on pixel, B-layer requirements, ...)
- The efficiency of isolation and impact parameter criteria when applied to the additional electron of Z+e classified as jets and photons

Background Estimation

- The main backgrounds of $H \rightarrow ZZ^{(*)} \rightarrow 4l$ are:
  - $ZZ^{(*)} \rightarrow 4l$,
  - Z+QQ (Q=b,c),
  - Z+light jets (“fake” lepton(s)),
  - ttbar.
- The irreducible background:
  - MC simulation is used to estimate $ZZ^{(*)} \rightarrow 4l$.
    - Normalized to MCFM shape & cross-section.
- Data-driven estimation technique for the other backgrounds:
  - Control regions which are similar to the signal region with the exception of inverted cuts are used.
    - QCD multi-jet production
    - ttbar ($e^{\pm}\mu^{\pm}$ pairs+leptons)
    - Z+QQ

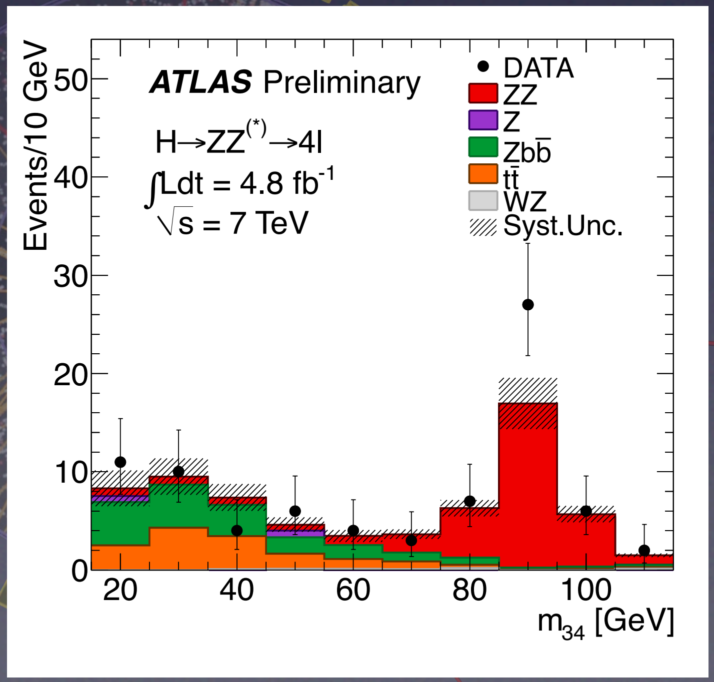
ttbar Background Estimation

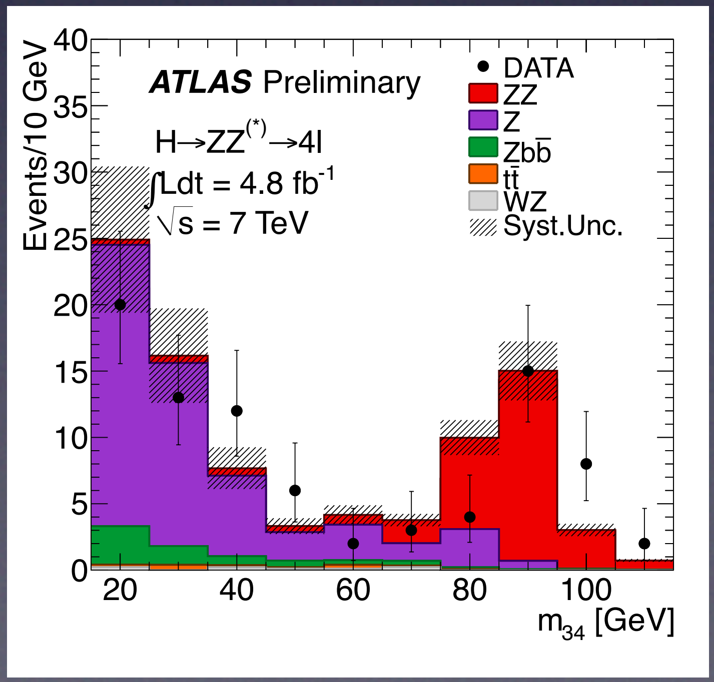
- If no $Z \rightarrow e^+e^-$ or $Z \rightarrow \mu^+\mu^-$ candidate is found → search for $e^{\pm}\mu^{\mp}$, $p_T > 20$ GeV.
- $|M_{e\mu}-M_Z| < 15$ GeV.
- Search for additional leptons with $p_T > 7$ GeV.
- MC expectation is used.

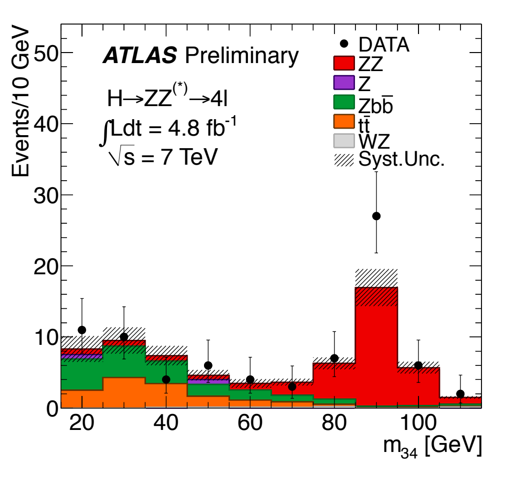
Z ($QQ \rightarrow ee/\mu\mu$) Background Estimation

Agreement is shown in the control region within the kinematic phase space.
No isolation or impact parameter significance on the second pair.

μμ Invariant mass distribution of the second lepton pair. ee



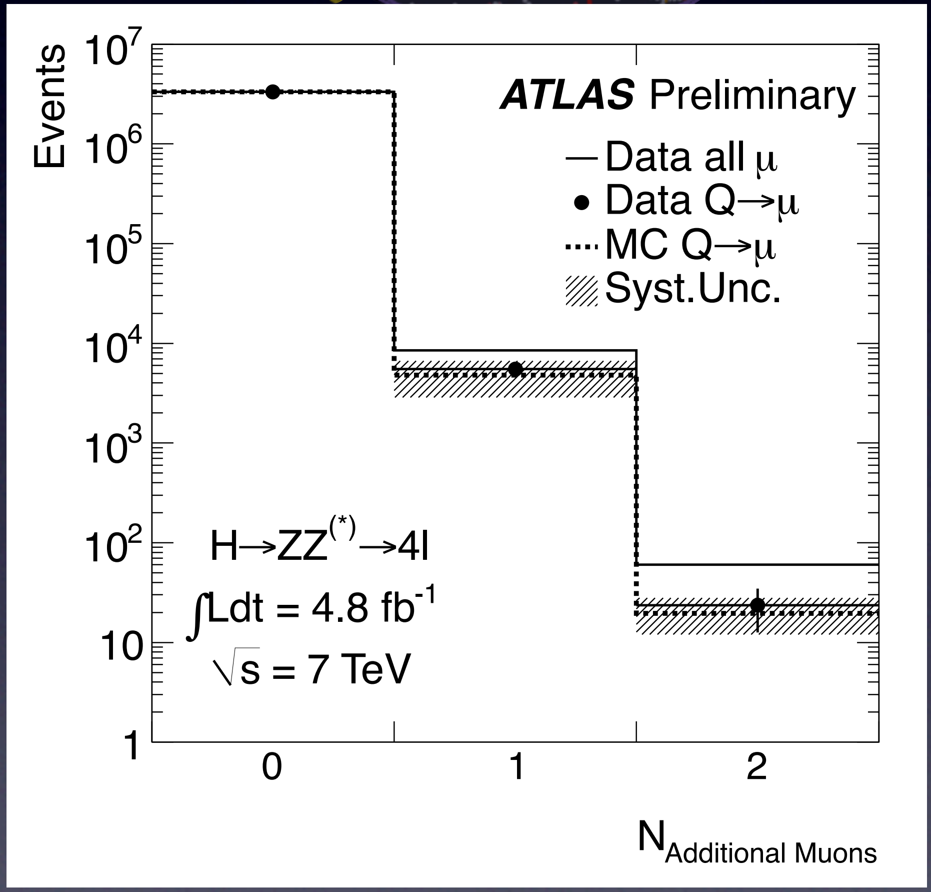


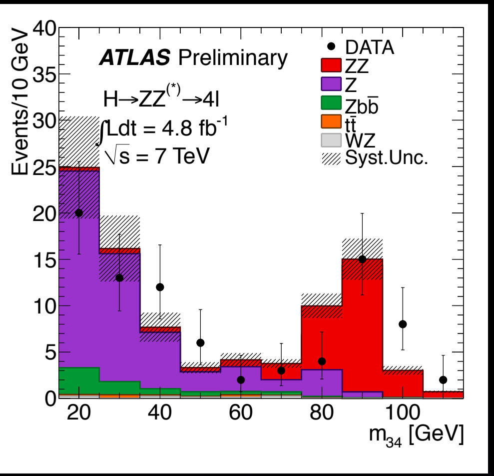


Z (QQ→ee/μμ) Background Estimation, cont.

Muon channel:

- Study of Z+μμ, with M_{34} >15 GeV.
- Apply M_{34}< 72 GeV to further suppress the ZZ background.
- Additional Muons: Q(b,c)→l, q→l
    - No isolation or impact parameter significance is applied.
- Main source of q : muons from π/K decays
- Using a weighting procedure assigned to each charged track.
    - selected by the same selection as the additional muons,
    - a probability to be reconstructed as a muon
    - Estimation of fake muons (20% systematic uncertainty)
- Estimated QQ (Data)=Total - Fakes - WZ - ZZ - ttbar
- The Z+QQ are in agreement between data and Monte Carlo (Z+Q are also in agreement)





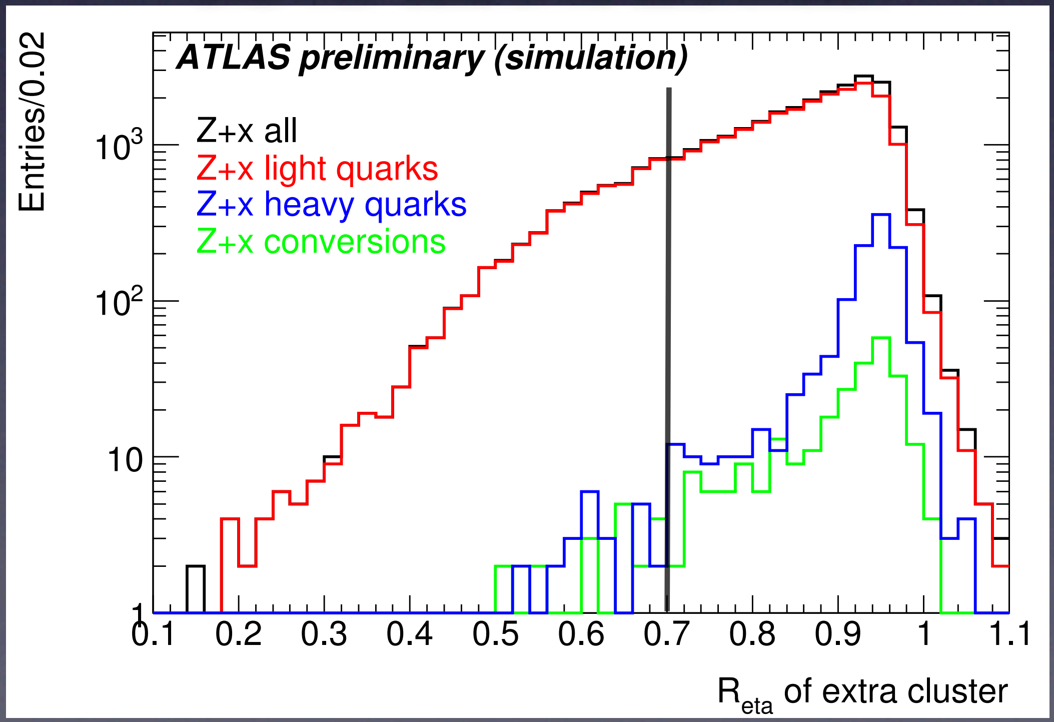
Z (QQ→ee/μμ) Background Estimation, cont.

Electron channel:

- Normalize the Zjj and ZjX MC to the data using the Z+2(egamma container level candidates for $R_\eta < 0.7$).
- Estimate expected number of Z+2 Loose++ electrons using the MC.
- Background composition estimated from MC after checks done in data.

Estimated Z+jX composition:
jj and jγ are the biggest contributions
The statistical uncertainty on this composition is the main contribution to the systematic uncertainty of 45%.

R_η: Ratio of the energy sum in 3x7 (ηxφ) over 7x7 cells in he calorimeter.



Systematic Uncertainties

Uncertainty on the normalization to account for the uncertainty on the data-driven estimation (statistical uncertainty in the control sample and the MC-based extrapolation to the signal region).

- Zbb : 40%
- Z+jets : 45%
- Shape systematic uncertainty estimated by relaxing/tightening the isolation criteria.

Signal efficiency :

- 2% systematic uncertainty (Pythia/PowHeg)
- Cut efficiency for electrons low-E_T electrons overall systematic uncertainty (1.5%-6%).

Electron efficiency for ZZ background:

- Overall and shape systematic uncertainty: 1.0% - 3.4%.

Muon efficiency for ZZ background:

- Overall systematic uncertainty: 0.08% - 0.22%.

Results

Expected and observed signal and background:

71 (62±9) four lepton events observed (expected) after full selection.

	$\mu\mu\mu\mu$		$ee\mu\mu$		$eeee$	
	Low $m_{4\ell}$	High $m_{4\ell}$	Low $m_{4\ell}$	High $m_{4\ell}$	Low $m_{4\ell}$	High $m_{4\ell}$
Int. Luminosity	4.81 fb^{-1}		4.81 fb^{-1}		4.91 fb^{-1}	
$ZZ^{(*)}$	2.0±0.3	16.3±2.4	2.8±0.6	25.2±3.8	1.3±0.3	10.3±1.5
Z, $Zb\bar{b}$, and $t\bar{t}$	0.16±0.06	0.02±0.01	1.4±0.5	0.17±0.08	1.6±0.7	0.18±0.08
Total Background	2.2±0.3	16.3±2.4	4.2±0.8	25.4±3.8	2.9±0.8	10.5±1.5
Data	3	21	3	27	2	15
$m_H = 125$ GeV	0.58 ± 0.10		0.73 ± 0.13		0.25 ± 0.05	
$m_H = 130$ GeV	1.00 ± 0.17		1.22 ± 0.21		0.43 ± 0.08	
$m_H = 150$ GeV	2.1 ± 0.4		2.9 ± 0.4		1.12 ± 0.18	
$m_H = 200$ GeV	4.9 ± 0.7		7.7 ± 1.0		3.1 ± 0.4	
$m_H = 300$ GeV	2.9 ± 0.4		4.9 ± 0.6		2.1 ± 0.3	
$m_H = 400$ GeV	2.0 ± 0.3		3.3 ± 0.5		1.49 ± 0.21	
$m_H = 600$ GeV	0.34 ± 0.04		0.62 ± 0.10		0.30 ± 0.06	

- For mass M_{4l}<160 GeV (to compare with CMS results: 13 events observed, 9.5±1.3 expected):

  6 four lepton events observed after full selection.

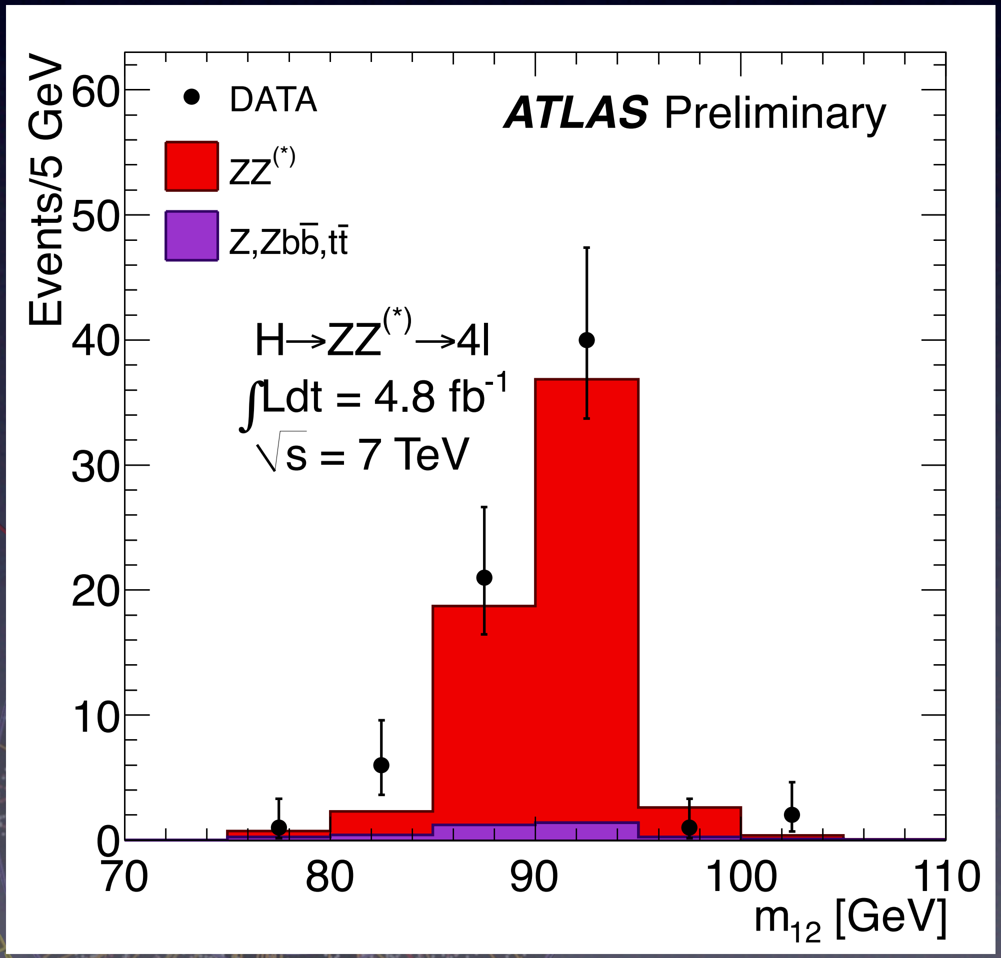
  Expected: 6.1±1.0

  - ZZ: 3.3 ± 0.5, other 2.8 ±1.0 (includes Z+j 2.3 ±1.0)
- At low mass M_{4l}<180 GeV : 8 (9.4±1.8) four lepton events observed (expected) after full selection.
- At high mass M_{4l}>180 GeV : 63 (52.2±7.2) four lepton events observed (expected) after full selection.

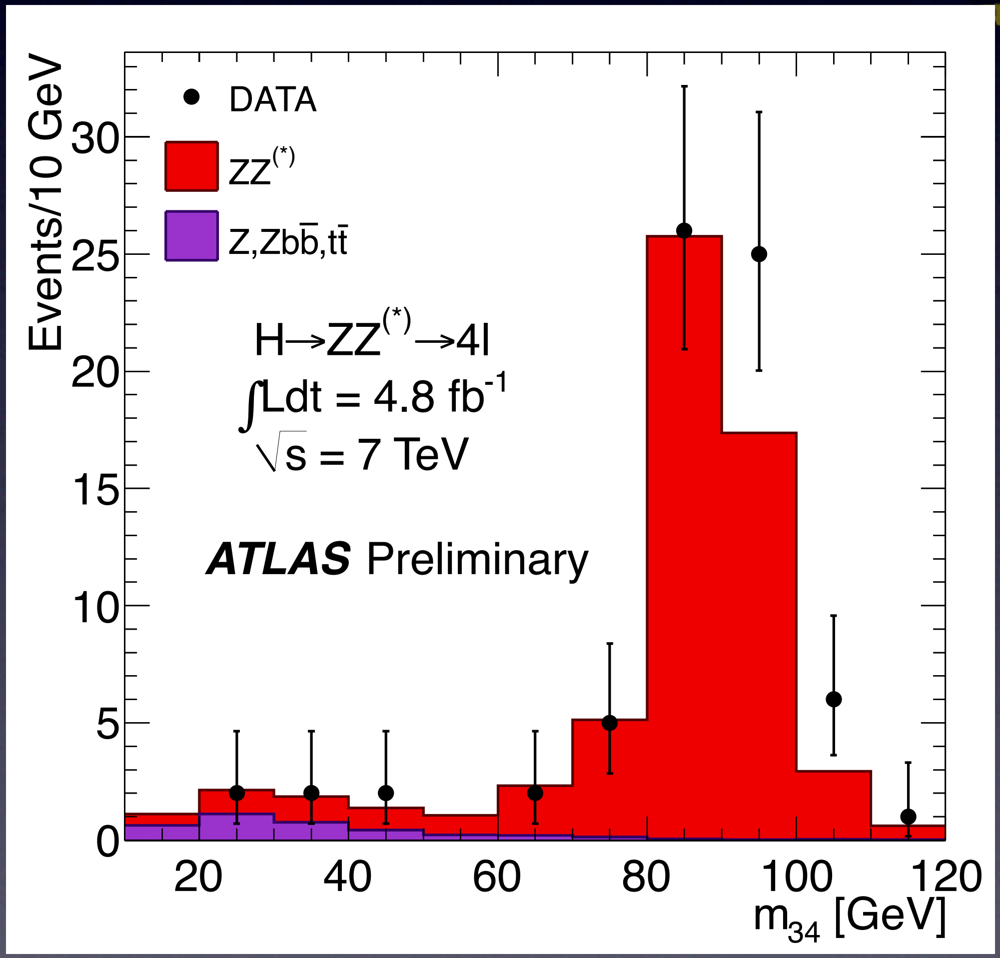
Results, cont.

Expected and observed signal and background.
Mass distribution after the full selection.

Mass distribution of M_{12}



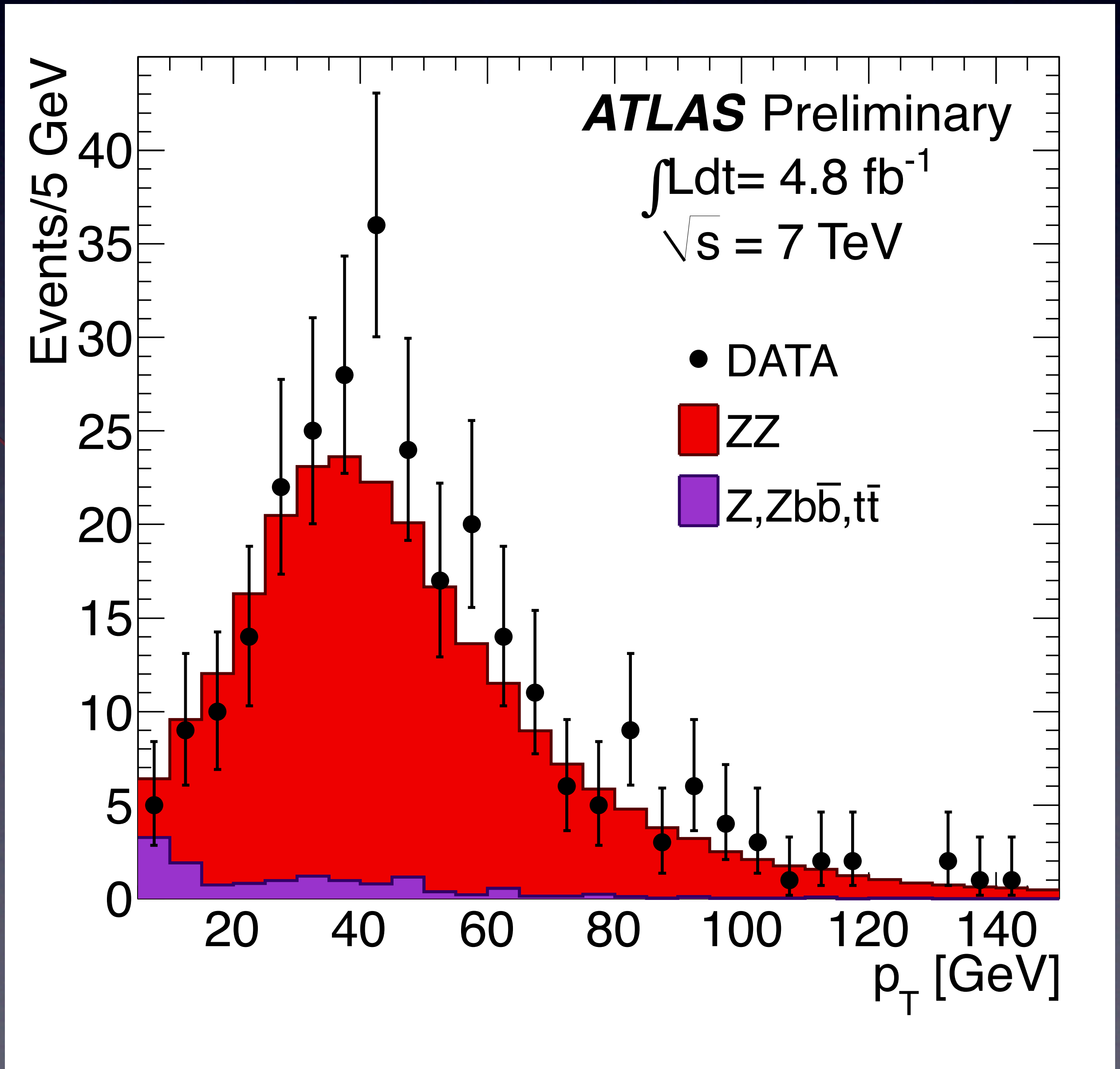
Mass distribution of M_{34}

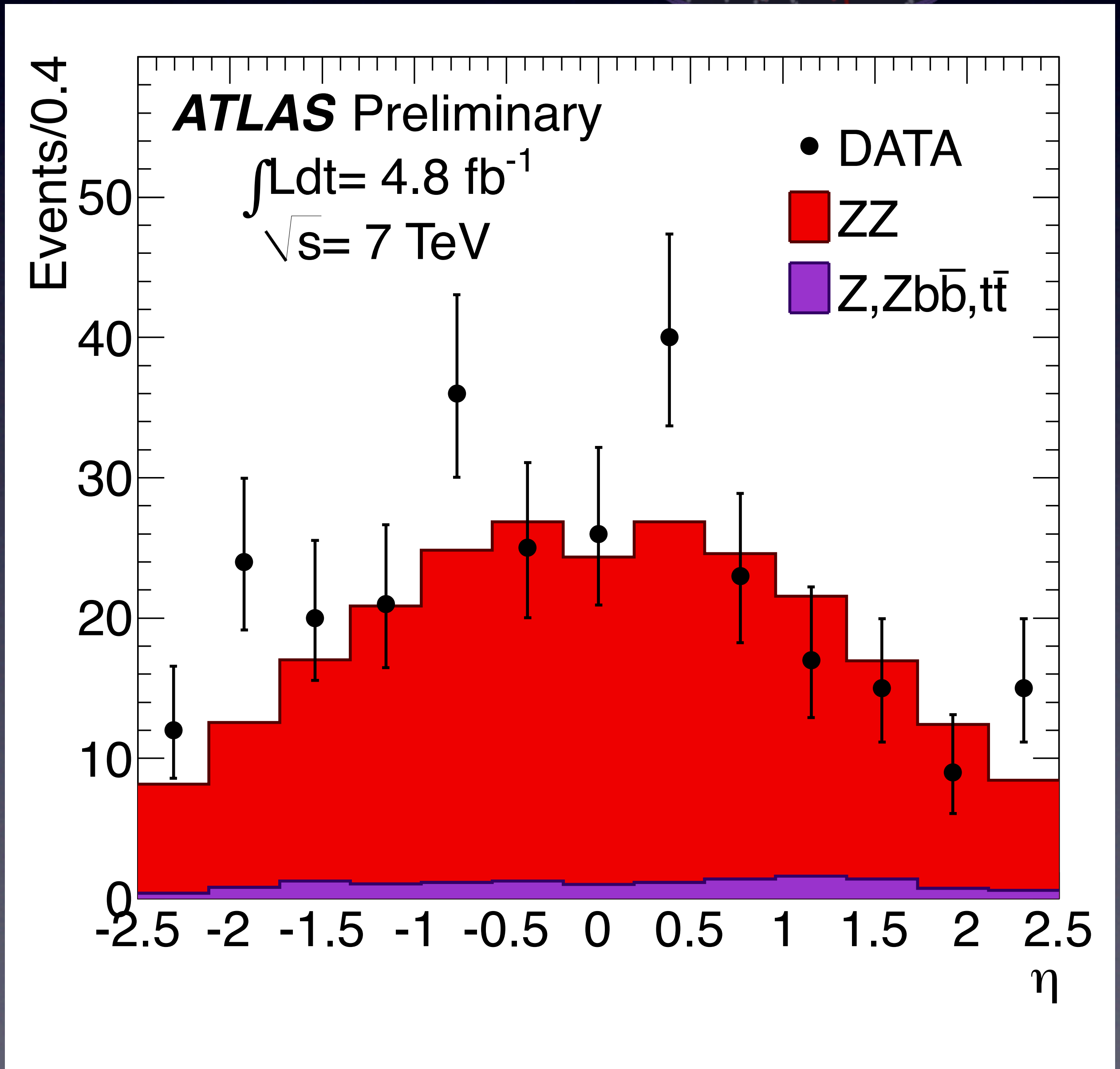


All plots show comparisons with background expectation from the dominant ZZ and the sum of ttbar, Zbb and Z+jets processes.

Results, cont.

p_T and η distribution for the leptons of the 71 candidates surviving the selection criteria. The expected background distributions are also shown. Error bars represent the 68.3% central confidence levels.



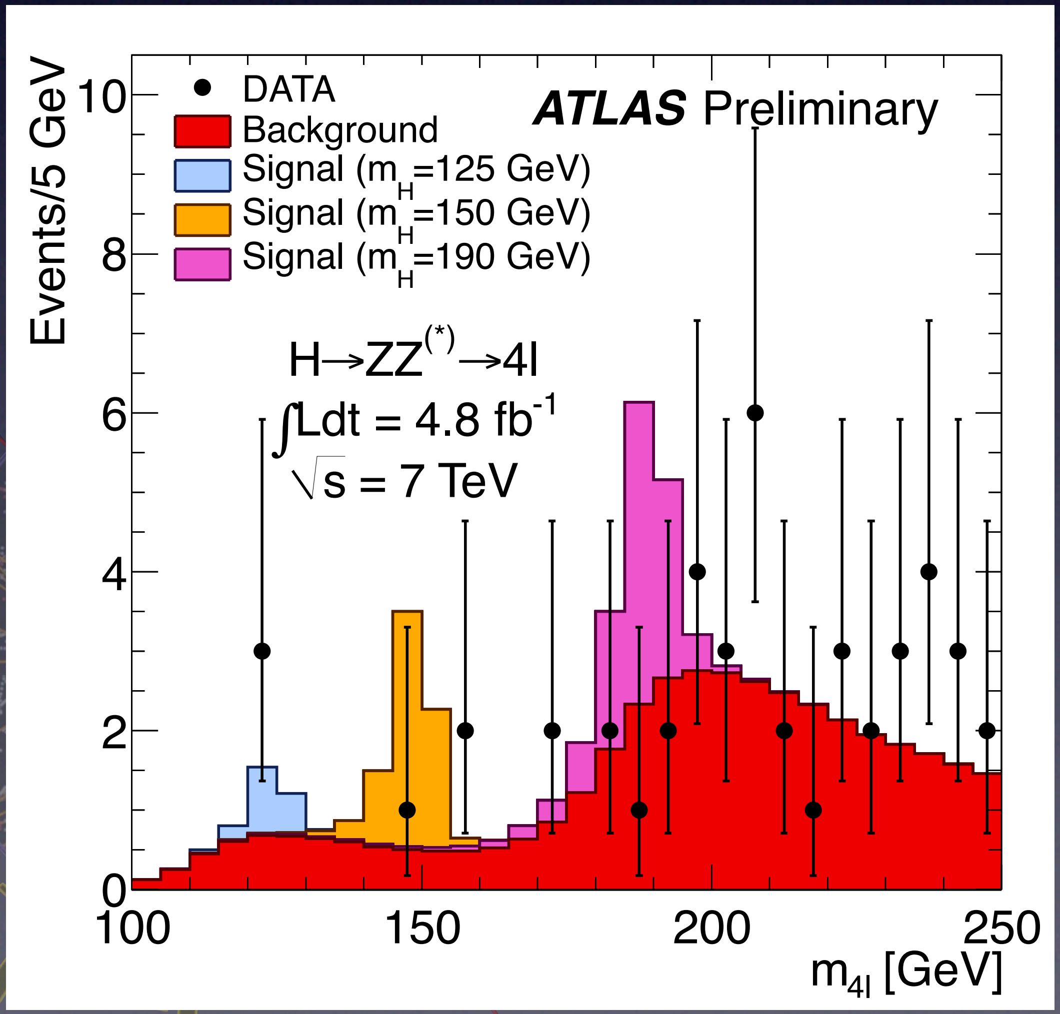


Results, cont.

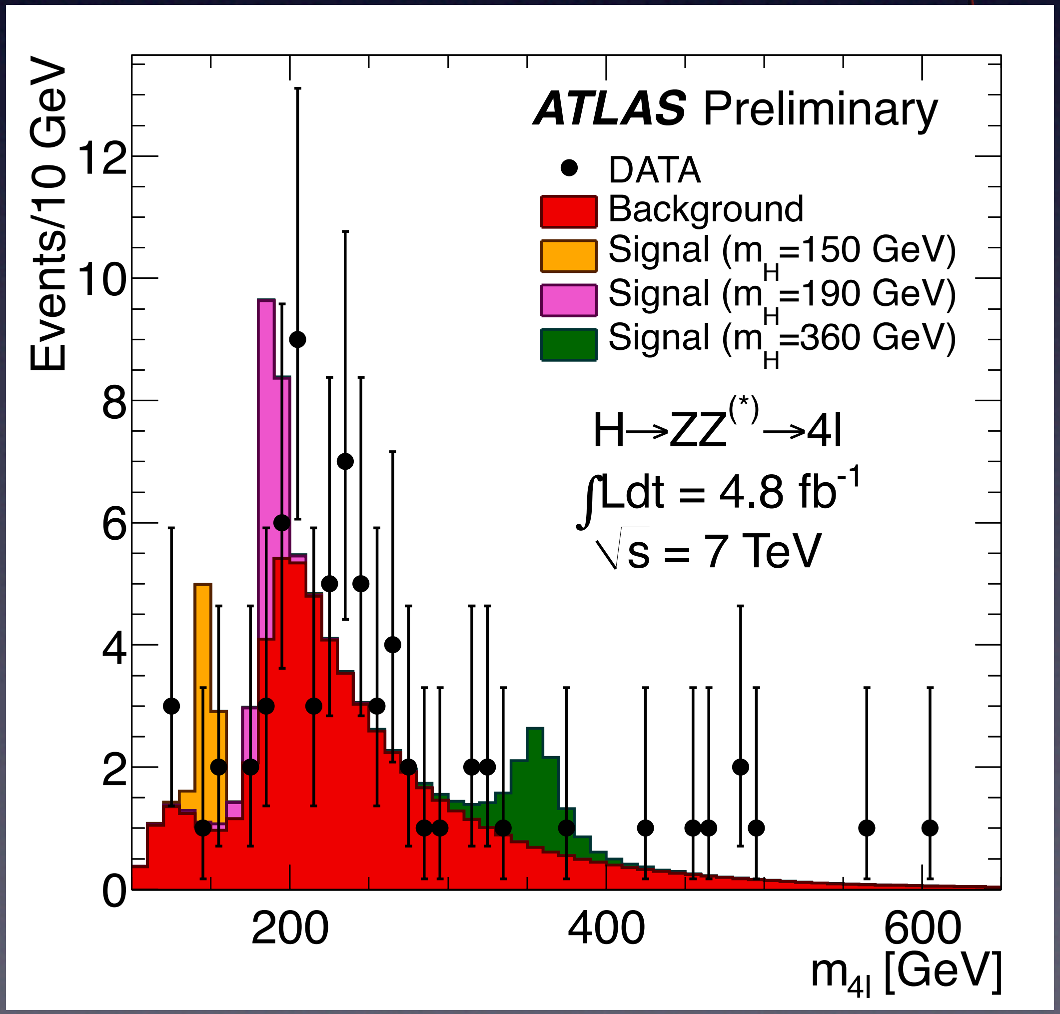
Expected and observed signal and background:

Mass distribution after the full selection.

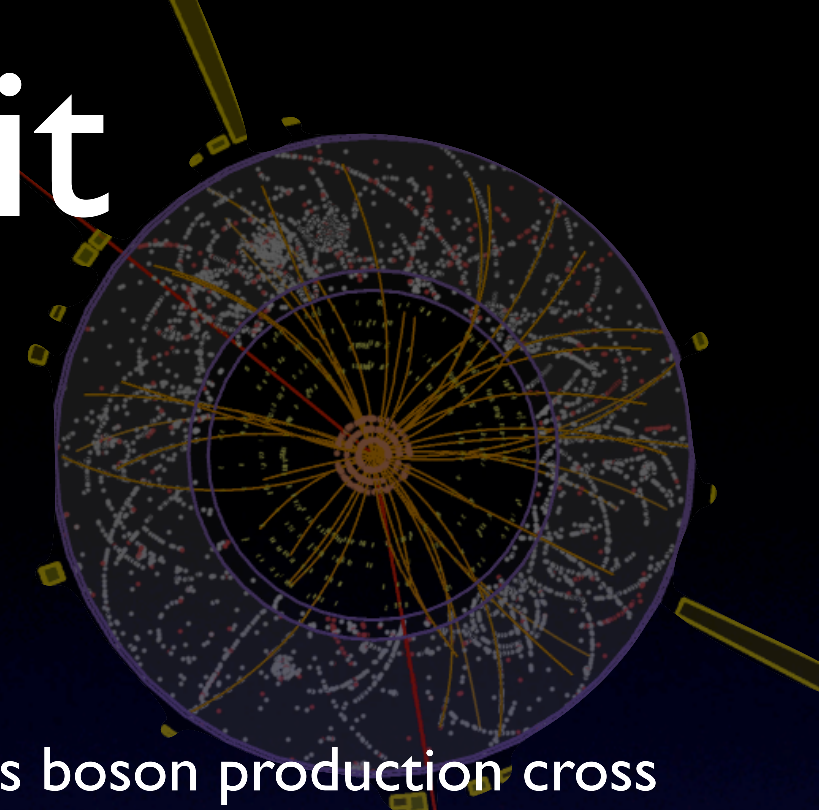
Mass distribution of M_{4l}



Mass distribution of M_{4l}

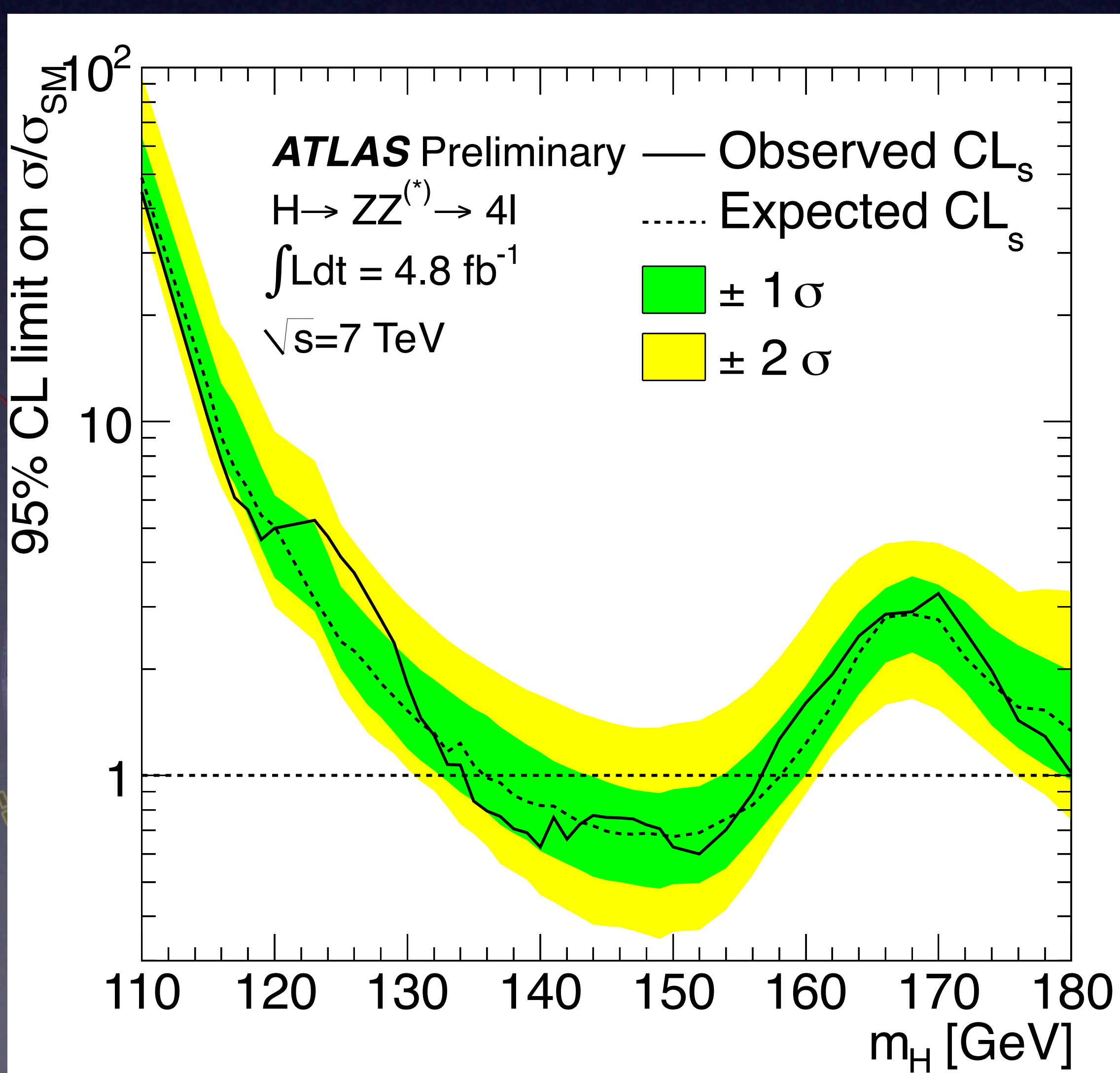


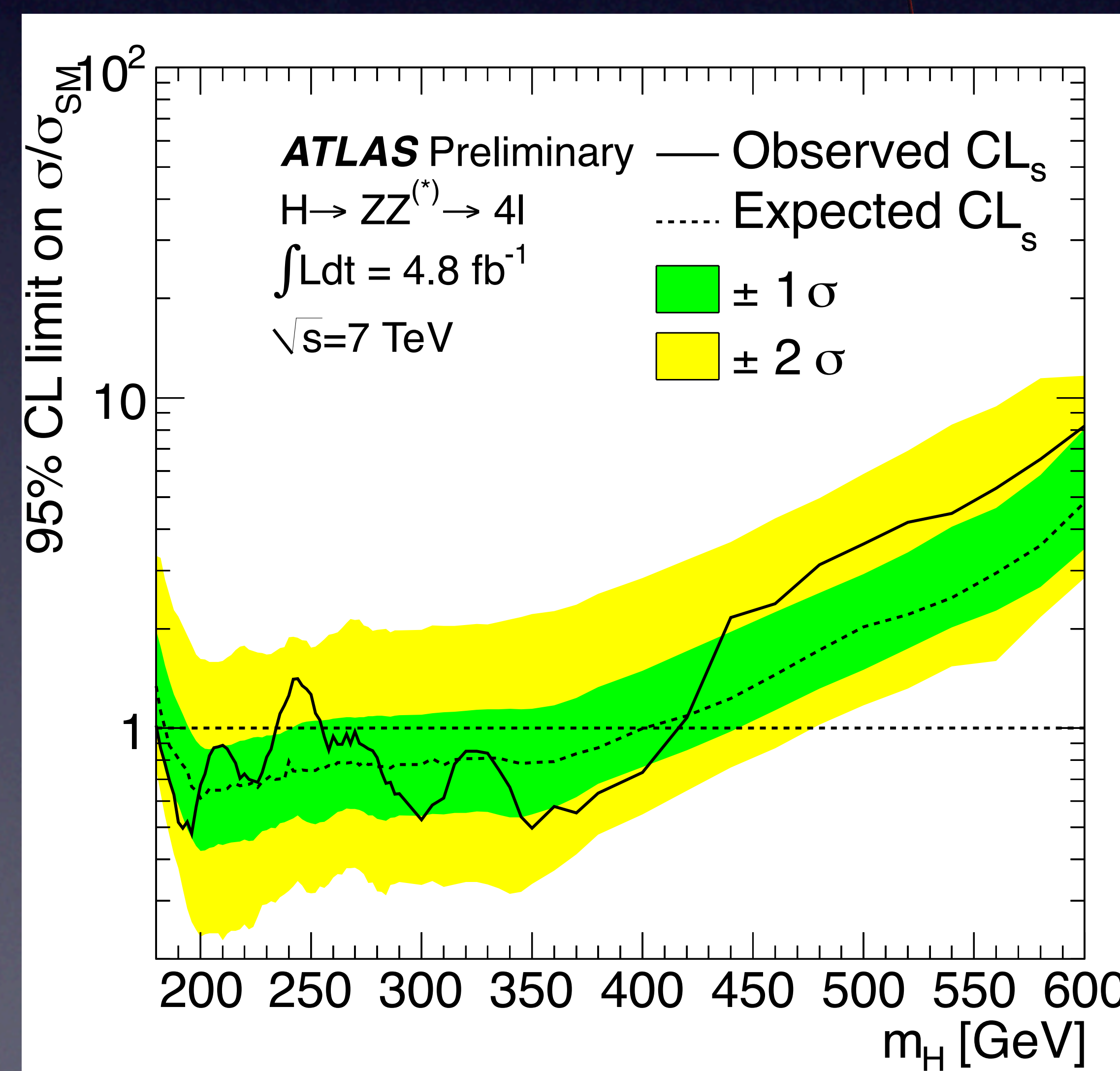
Exclusion limit



Exclusion (observed) :
133.5−156.0 GeV
180.5−234.0 GeV
255.0−416.0 GeV

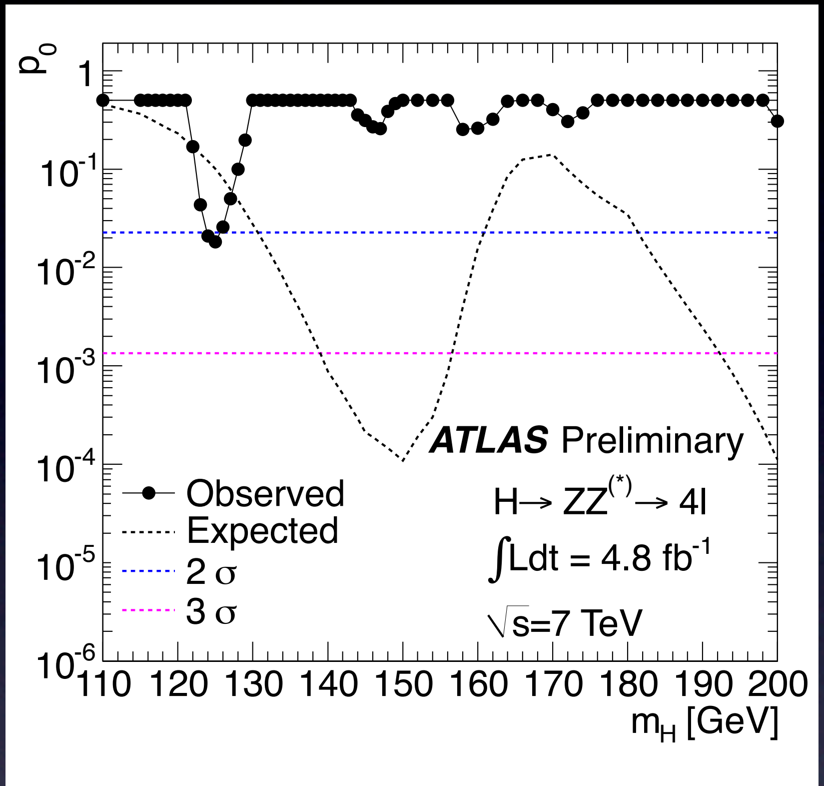
Median expected and observed 95% CL upper limit on the SM Higgs boson production cross section, in multiples of the SM rate, as a function of the Higgs boson mass in GeV, obtained with CLs.

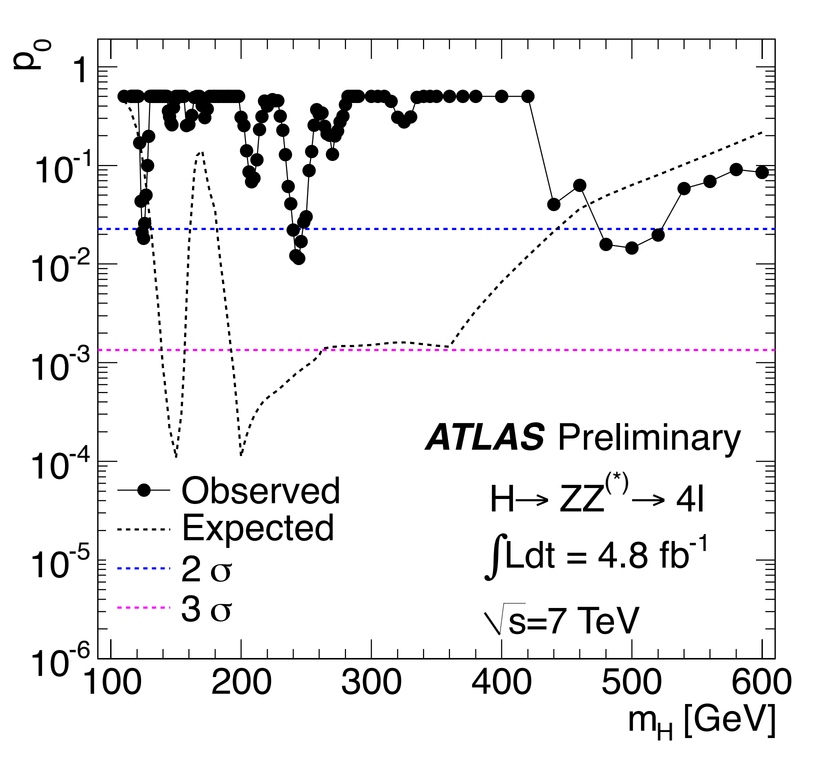




Local P-values

The observed local p-value characterize probabilities for the predicted background to fluctuate at least as high as the observed excesses.





p-values do not include the trials factor arising from the look-elsewhere effect (LEE)

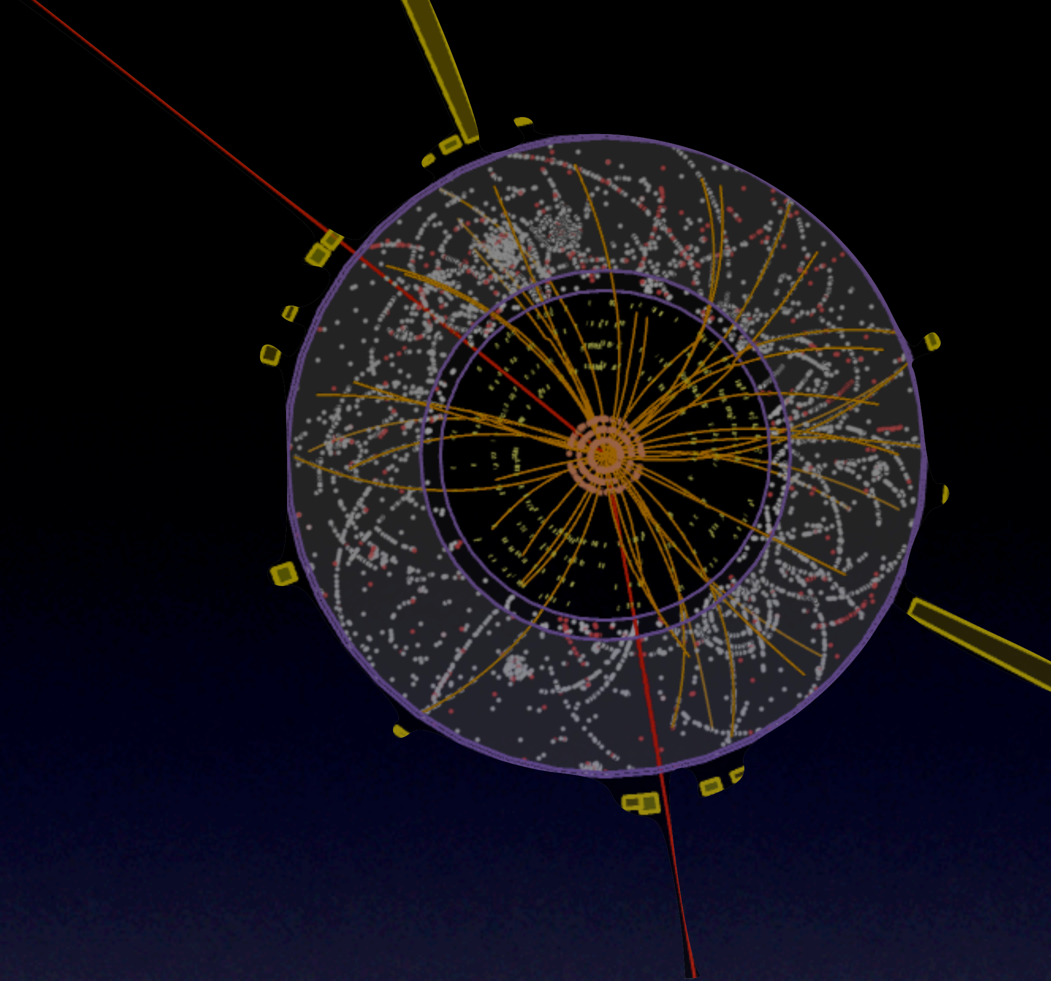
hypothesis of a Standard Model Higgs boson production signal

The most significant deviations from the background-only hypothesis are observed for:

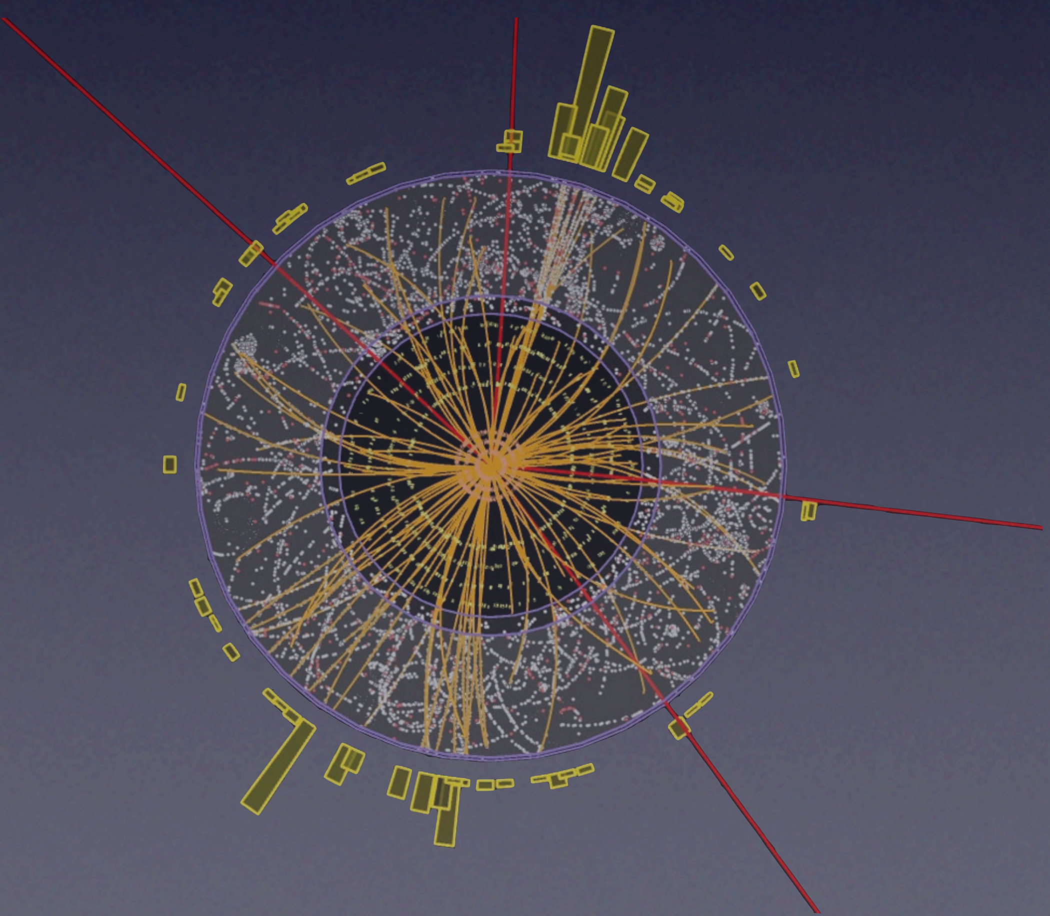
- **m_{Higgs} = 125 GeV** with a p_0-value of 1.8%
- **m_{Higgs} = 244 GeV** with a p_0-value of 1.1%
- **m_{Higgs} = 500 GeV** with a p_0-value of 1.4%

Summary

- A search for the Standard Model Higgs boson in the decay channel $H \to ZZ^{(*)} \to 4l$ has been performed using the ~4.8 fb^{-1} of p-p collisions at $\sqrt{s}$ = 7 TeV.
- The background yields have been studied, demonstrating good agreement of the background modeling with the observation.
- 71 candidates fulfilling all the selection criteria have been identified.
- We can exclude the following mass range using only $H \to ZZ^{(*)} \to 4l$:
    - 133.5−156.0 GeV
    - 180.5−234.0 GeV
    - 255.0−416.0 GeV
- The largest deviations from the background expectation are observed for
    - m_H = 125 GeV with a p_0-value of 1.8%,
    - m_H = 244 GeV with a p_0-value of 1.1%,
    - m_H = 500 GeV with a p_0-value of 1.4%.
    - These p_0-values increase substantially once the "look-elsewhere" effect is considered.



Backup

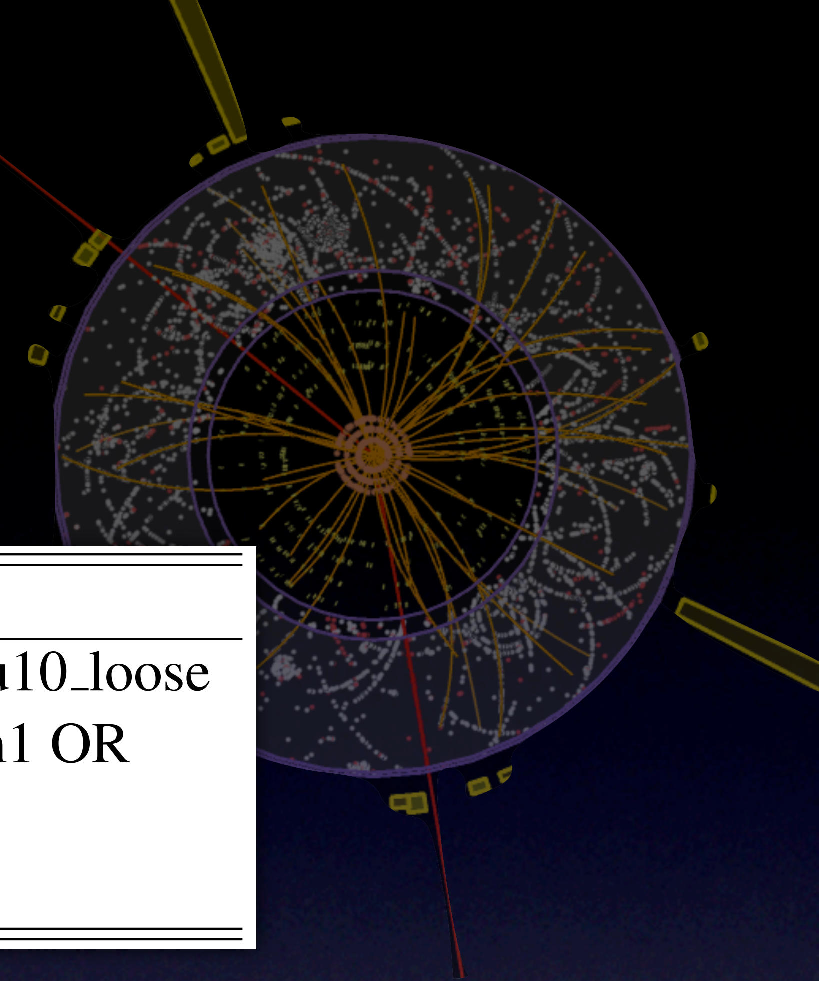


GSF principle

- The Kalman Filter (KF) is a mathematical method whose purpose is to use a series of measurements observed over time, containing noise (random variations) and other inaccuracies, and produce estimates that tend to be closer to the true unknown values than those that would be based on a single measurement alone.
- A filter treats the trajectory as a dynamic system, evolving as a function of the path-length.
- The KF is the optimal filter only if the process noise and measurement errors are gaussian distributed.
- In general, this condition is not fulfilled: measurement errors are not always gaussian - often there is a tail of outlying observations; tails in multiple scattering, distributions are not gaussian, particularly if the material is inhomogeneous; for electrons, energy loss is dominated by bremsstrahlung which is described by a stochastic, highly non-gaussian distribution.

- A non-linear generalisation of the KF, called the Gaussian-Sum Filter (GSF), can be used to take such effects into account, if the error distributions can be approximated as gaussian sums.
- The GSF dismantles the experimental noise into individual gaussian components and uses a separate Kalman filter to process each one. Therefore, the GSF consists of a number of Kalman filters running in parallel.

Trigger

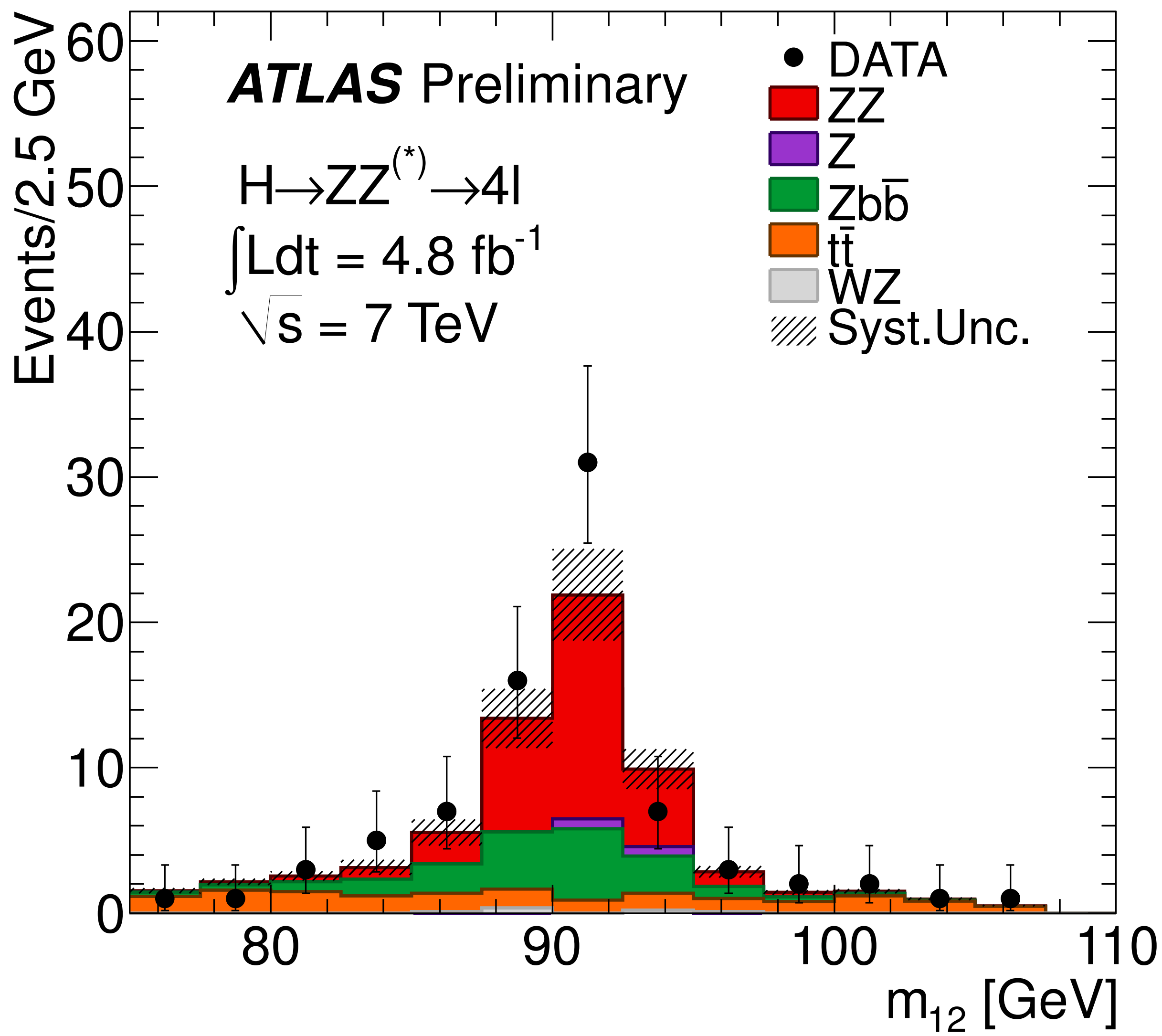


Triggers used in the MC

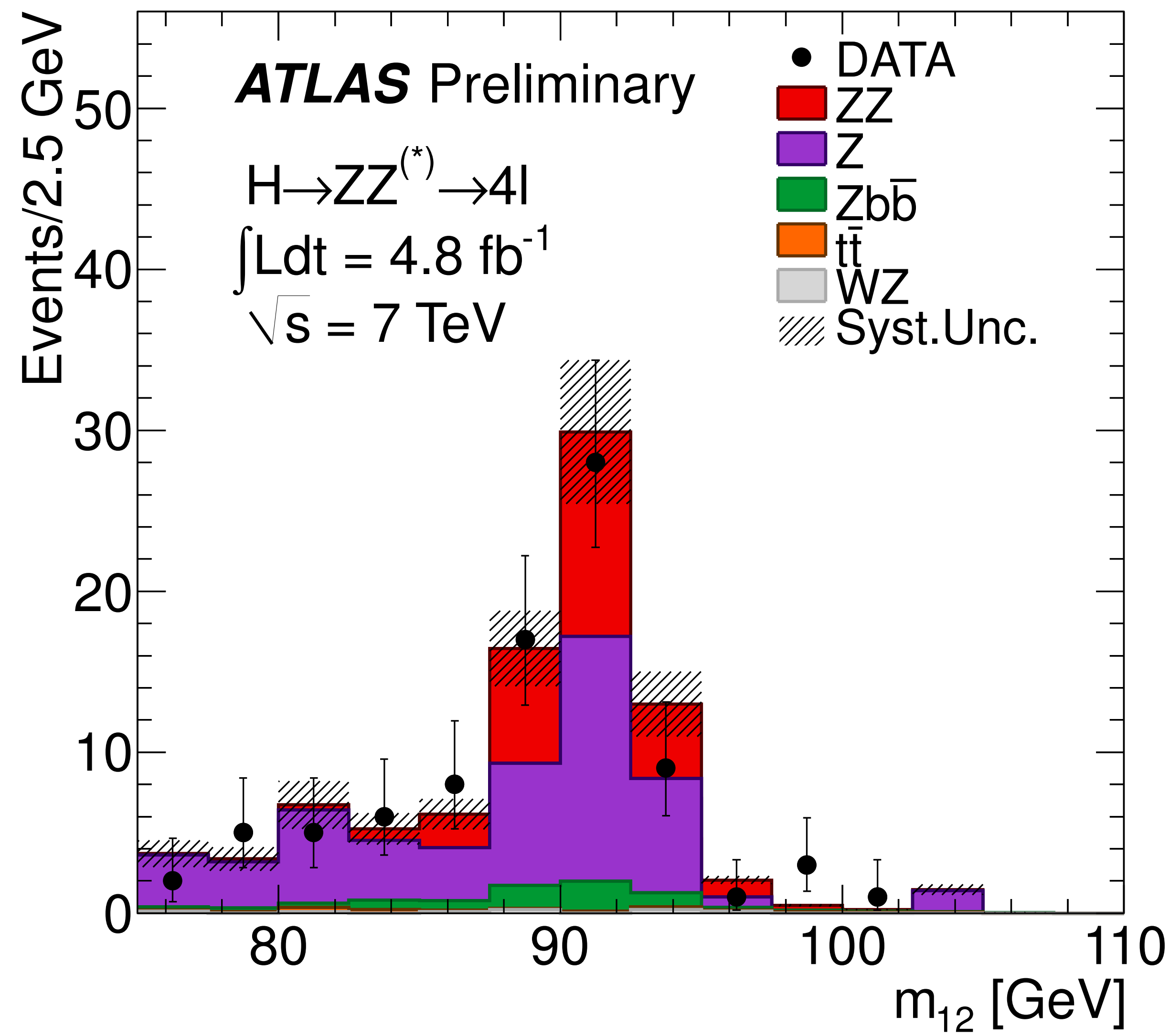
MC	to match unprescaled trigger during data taking
4μ	EF_mu18_MG, EF_mu18_MG_medium OR EF_2mu10_loose
$4e$	EF_e20_medium, EF_e22_medium, EF_e22_medium1 OR EF_2e12_medium, EF_2e12T_medium
$2e2\mu$	4μ OR $4e$

Triggers used in the Data

Single-lepton triggers				
Period	B-I	J	K	L-M
4μ	EF_mu18_MG	EF_mu18_MG_medium	EF_mu18_MG_medium	EF_mu18_MG_medium
$4e$	EF_e20_medium	EF_e20_medium	EF_e22_medium	EF_e22vh_medium1
$2e2\mu$	4μ OR $4e$			
Di-lepton triggers				
Period	B-I	J	K	L-M
4μ	EF_2mu10_loose	EF_2mu10_loose	EF_2mu10_loose	EF_2mu10_loose
$4e$	EF_2e12_medium	EF_2e12_medium	EF_2e12T_medium	EF_2e12Tvh_medium
$2e2\mu$	4μ OR $4e$			



(a)



(b)

Figure 9: Invariant mass distribution of the first lepton pair:(a) $\mu\mu$ and (b) ee. The kinematic selections of the analysis have been applied. Isolation requirements have been applied on the first lepton pair. No charge requirements were applied to the second lepton pair.