Physics with Electrons in the ATLAS detector

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PhD Thesis Defense
June 21, 2016

Outline/Timeline

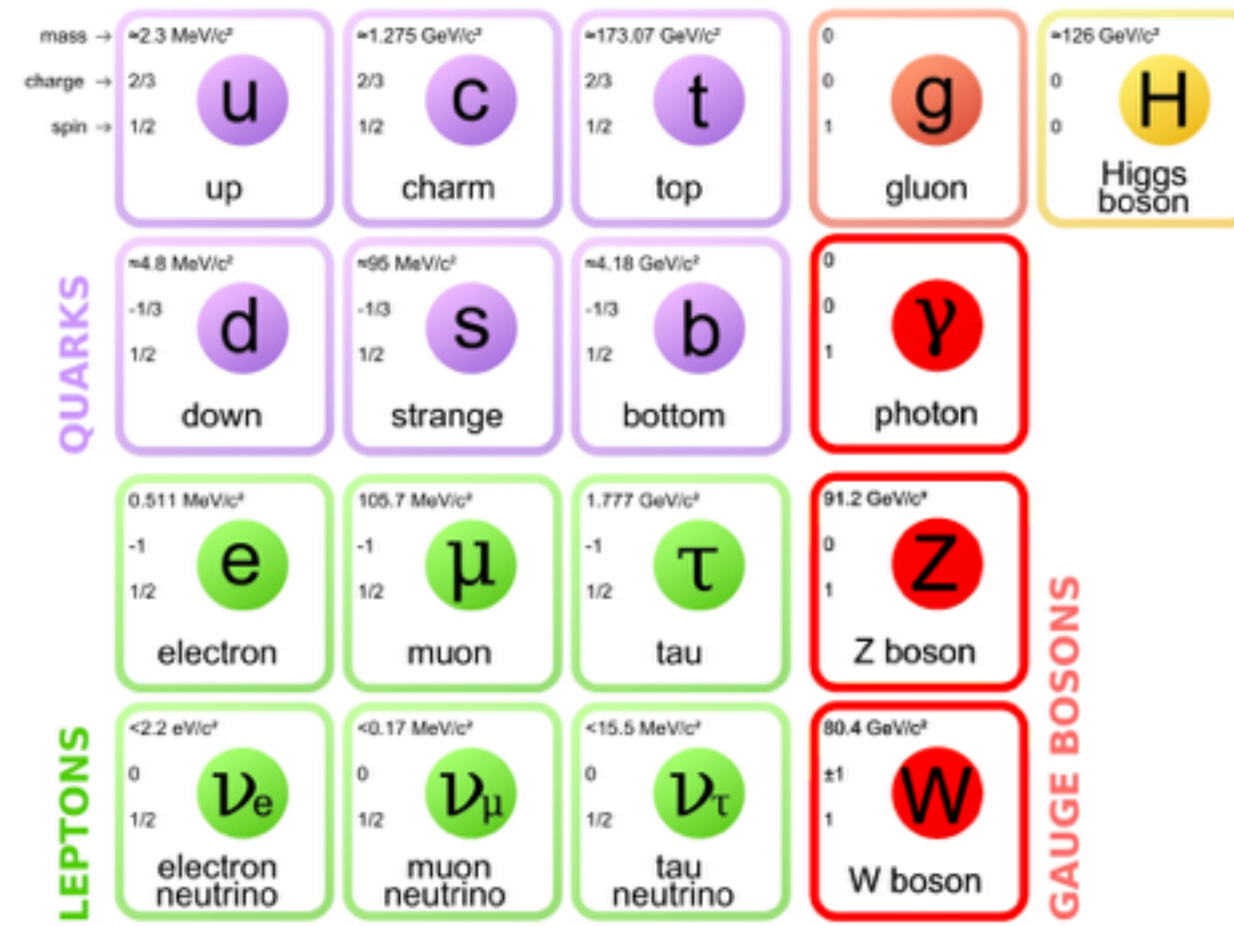
- 2010-2012
  - Classes
  - Detector: TRT Alignment
- 2011-2016: Performance work and analysis

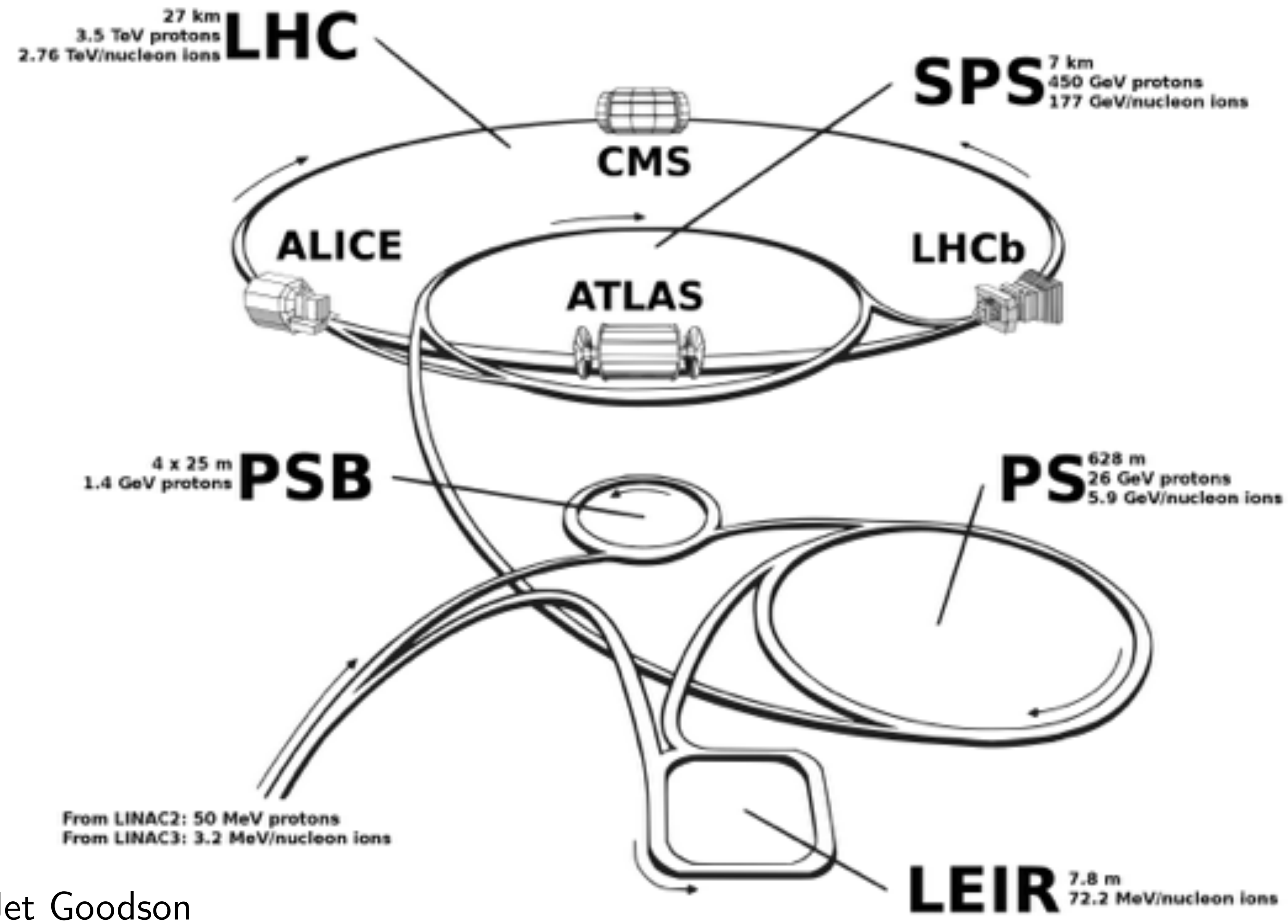
- Performance: Electrons
  - Electron identification (likelihood method)
  - Electron efficiency measurements

- Analysis:
  - $H \rightarrow ZZ^* \rightarrow 4\ell$
  - $WZ \rightarrow 3\ell$

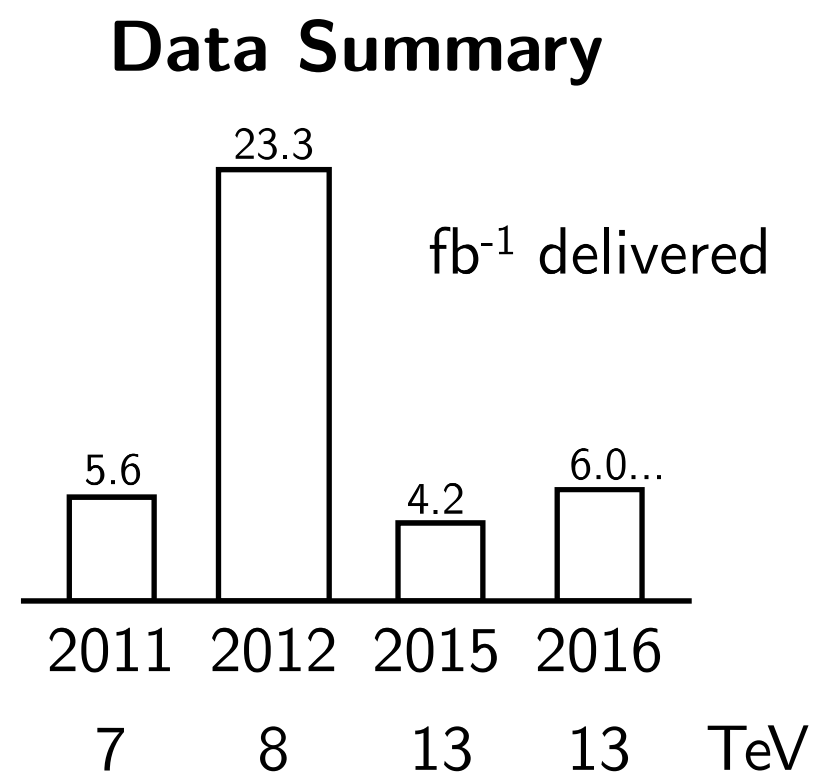
Highlighted Components

- **Higgs Boson**
  - Particle hypothesized as part of electroweak symmetry breaking
- **Electroweak Gauge Bosons**
  - Higgs decays to WW, ZZ
  - Potential mediators of new physics
  - Decays to lepton pairs: $Z \to \ell^+\ell^-$, $W \to \ell\nu$
- **Leptons** (in particular, electron)
  - One of the signatures in the detector
  - Window into electroweak gauge sector



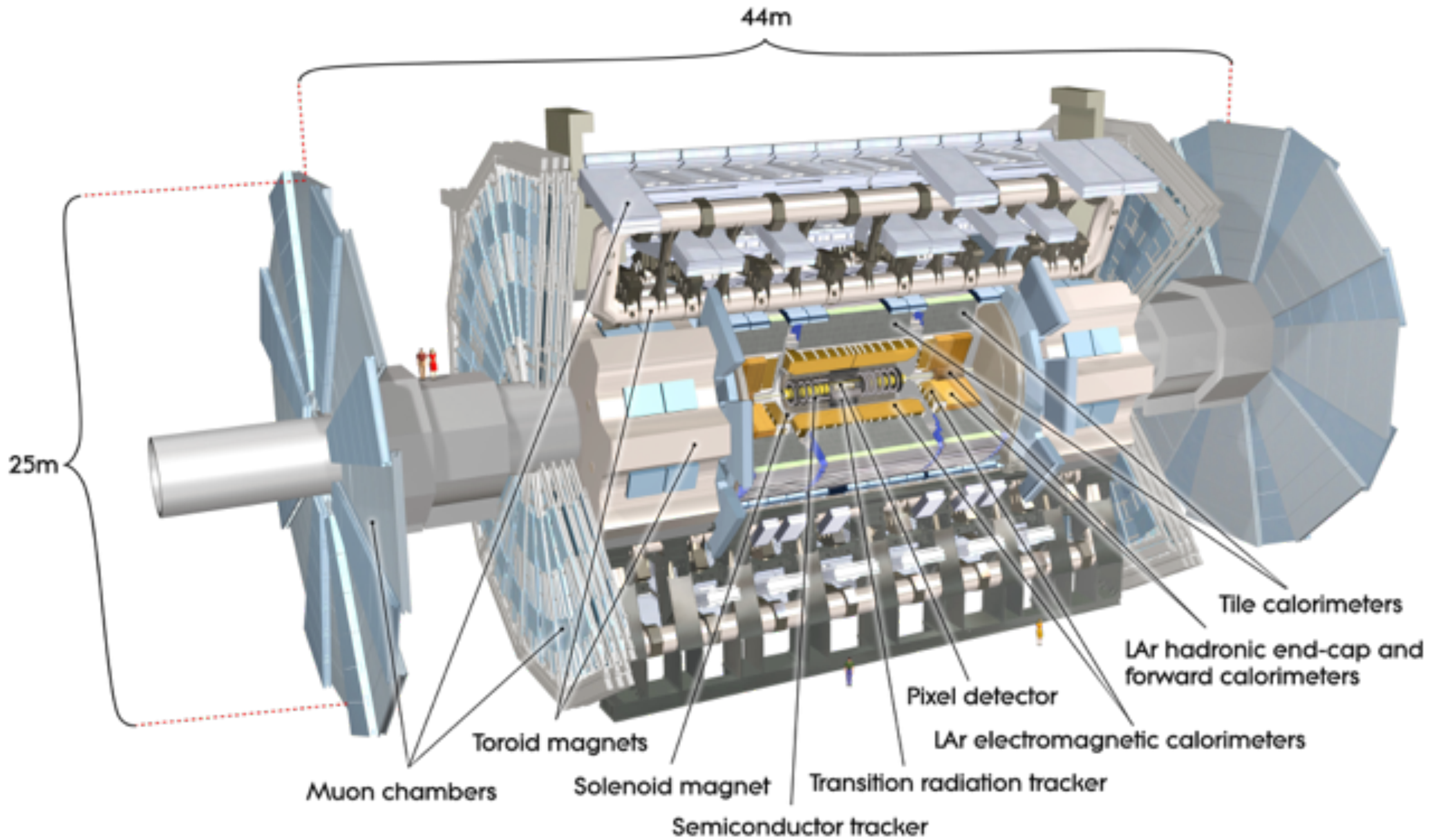


Courtesy Jet Goodson



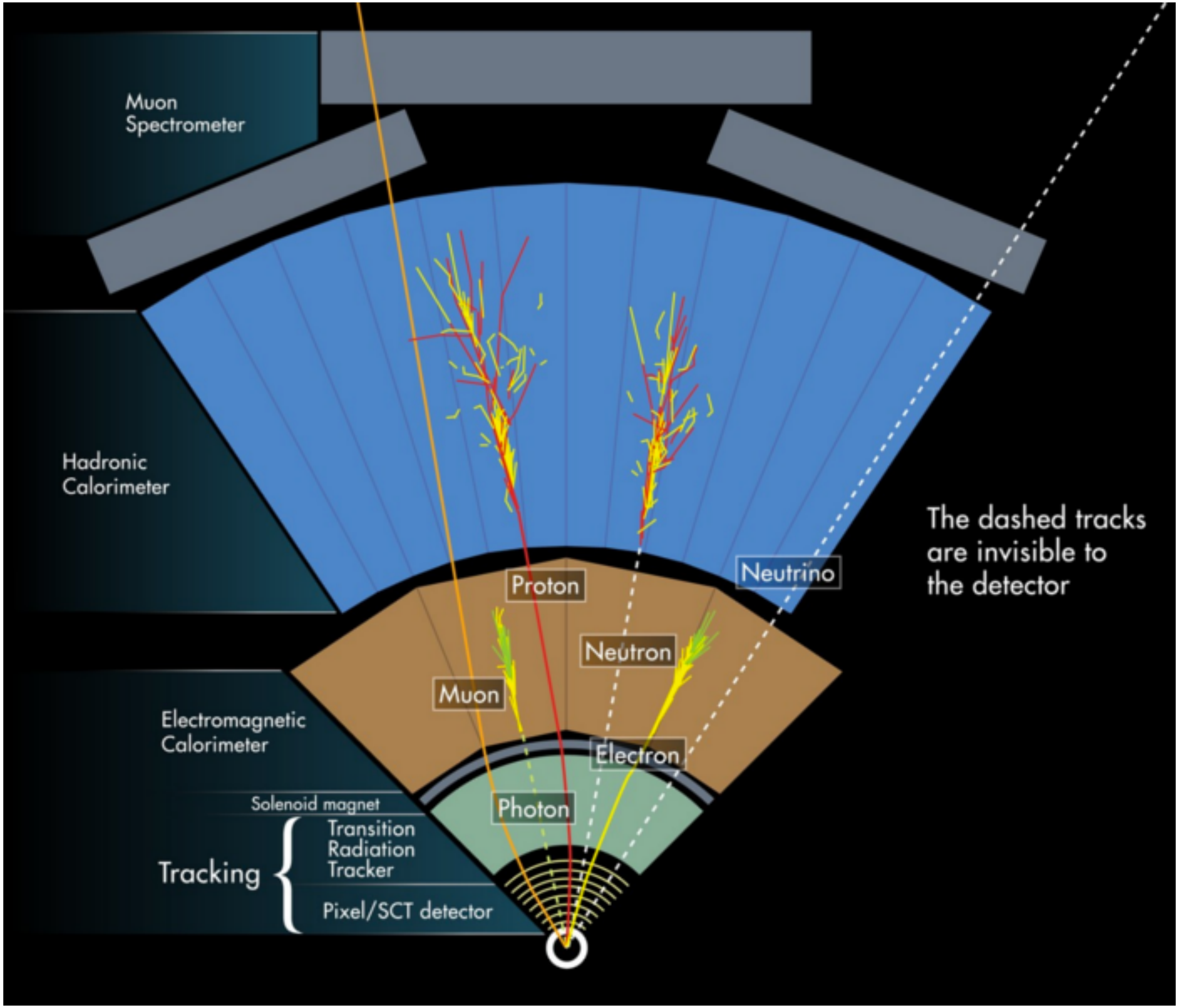
- Bunches of 100,000,000,000 protons collided at energies of 7, 8 and 13 TeV
- LHC delivers proton-proton bunch crossings at a rate of 40,000,000/s
- On average 10-40 interactions per bunch crossing
- Two all-purpose detectors built to discover the Higgs boson and search for new physics: ATLAS and CMS
- Excellent delivery of data so far

The ATLAS Detector



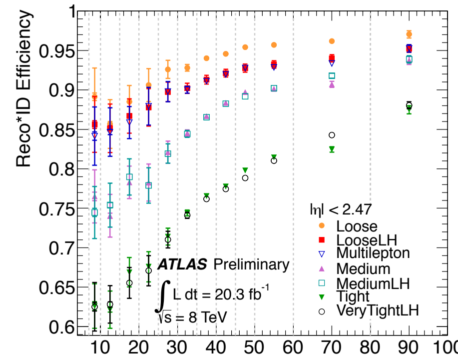
- Tracking detectors (and solenoid) to measure charged particle tracks
- Calorimeter detectors:
  - Electromagnetic calorimeters to collect the energy of electrons and photons
  - Hadronic calorimeter to collect the energy of hadronic jets
- Muon spectrometer (and toroid): measure momentum of muons
- Trigger system
  - Must reduce 40,000,000/s rate down to ~1000/s stored events

Particle Signatures



How ATLAS work gets done

Detector



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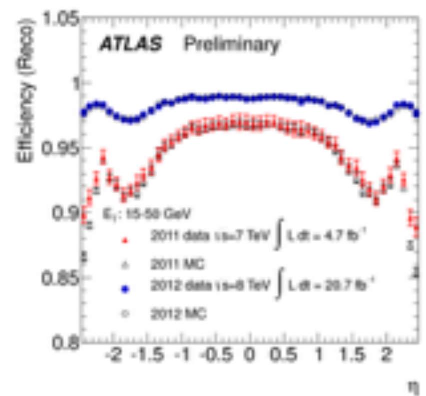
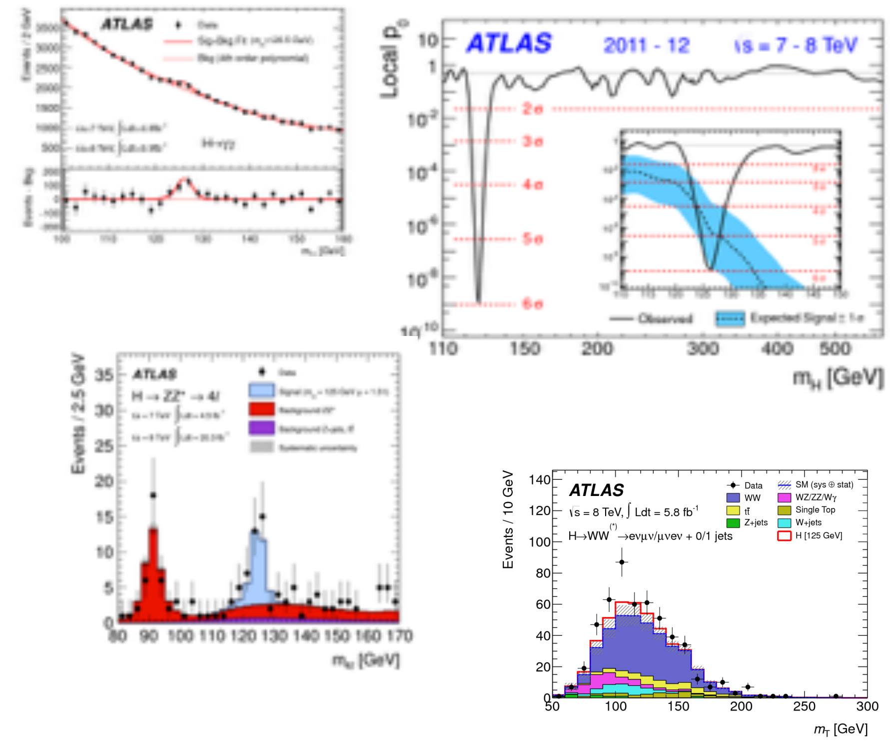


Analysis



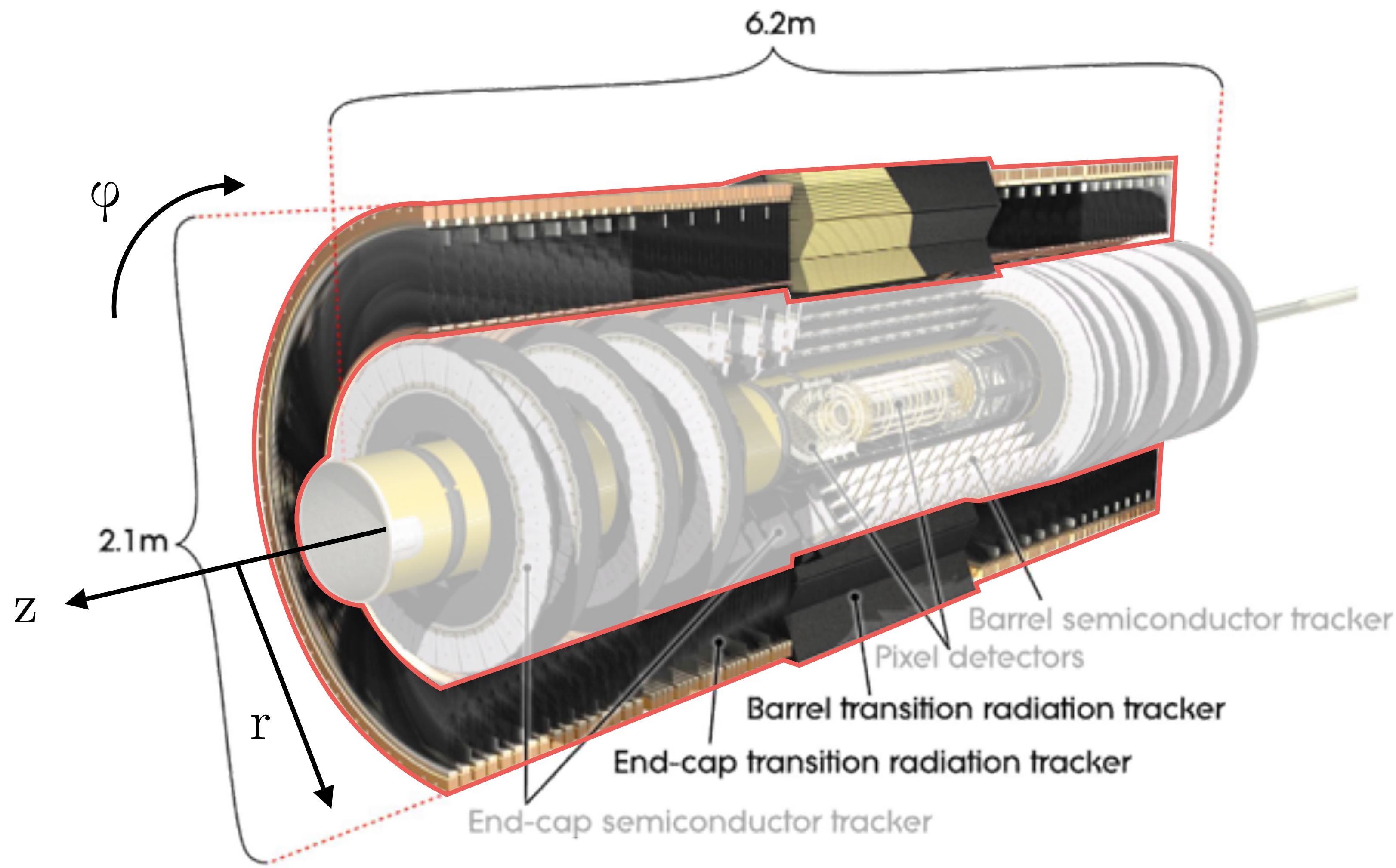
Today, there are four main types of activity:

- **Hardware/Detector Experts**: physicists that ensure working detectors
- **Data preparation:** Ensure good-quality, promptly-delivered data
- **Combined Performance Groups**: groups of analyzers with common problems (e.g. characterizing electrons, photons, jets) work collectively on a problem. Solving them can benefit many analyses
- **Physics analysis Group**: Use the data to make a measurement or search for new physics

I spent a lot of my time on combined performance (electrons)

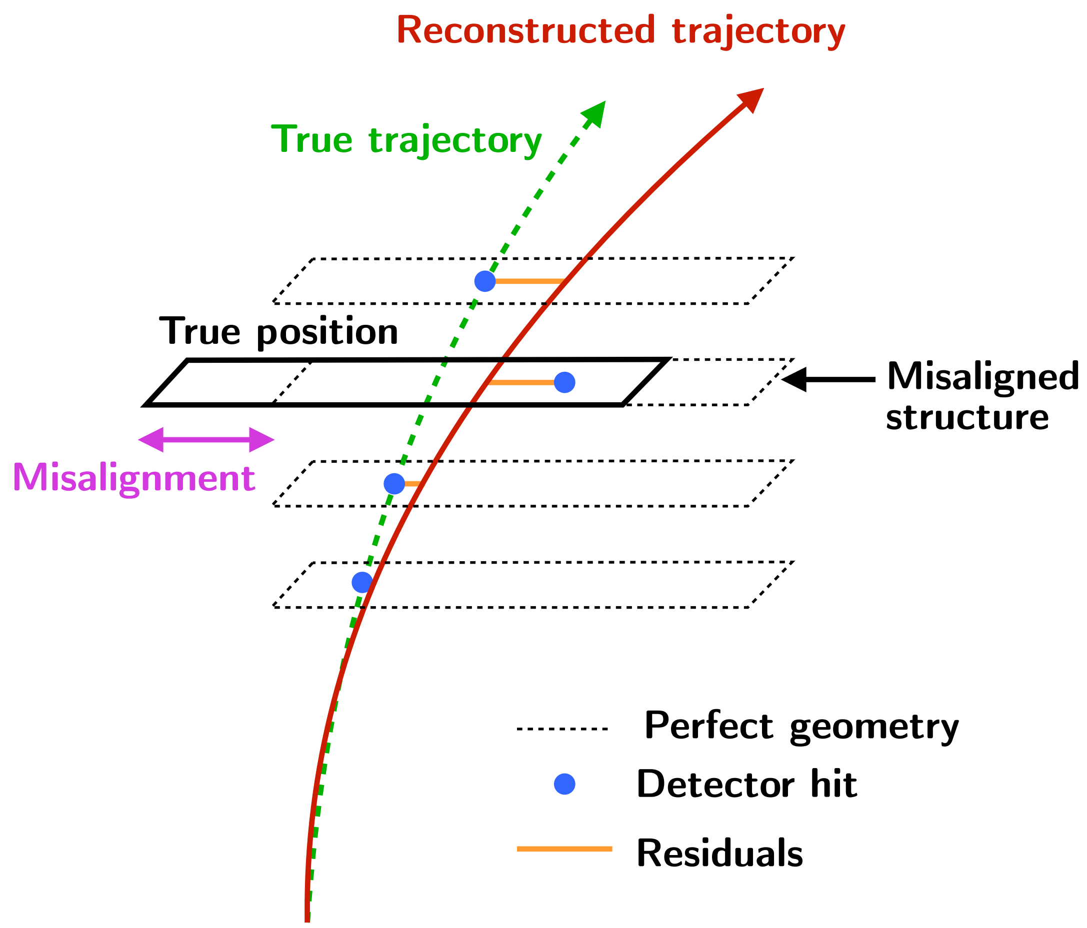
TRT ALIGNMENT

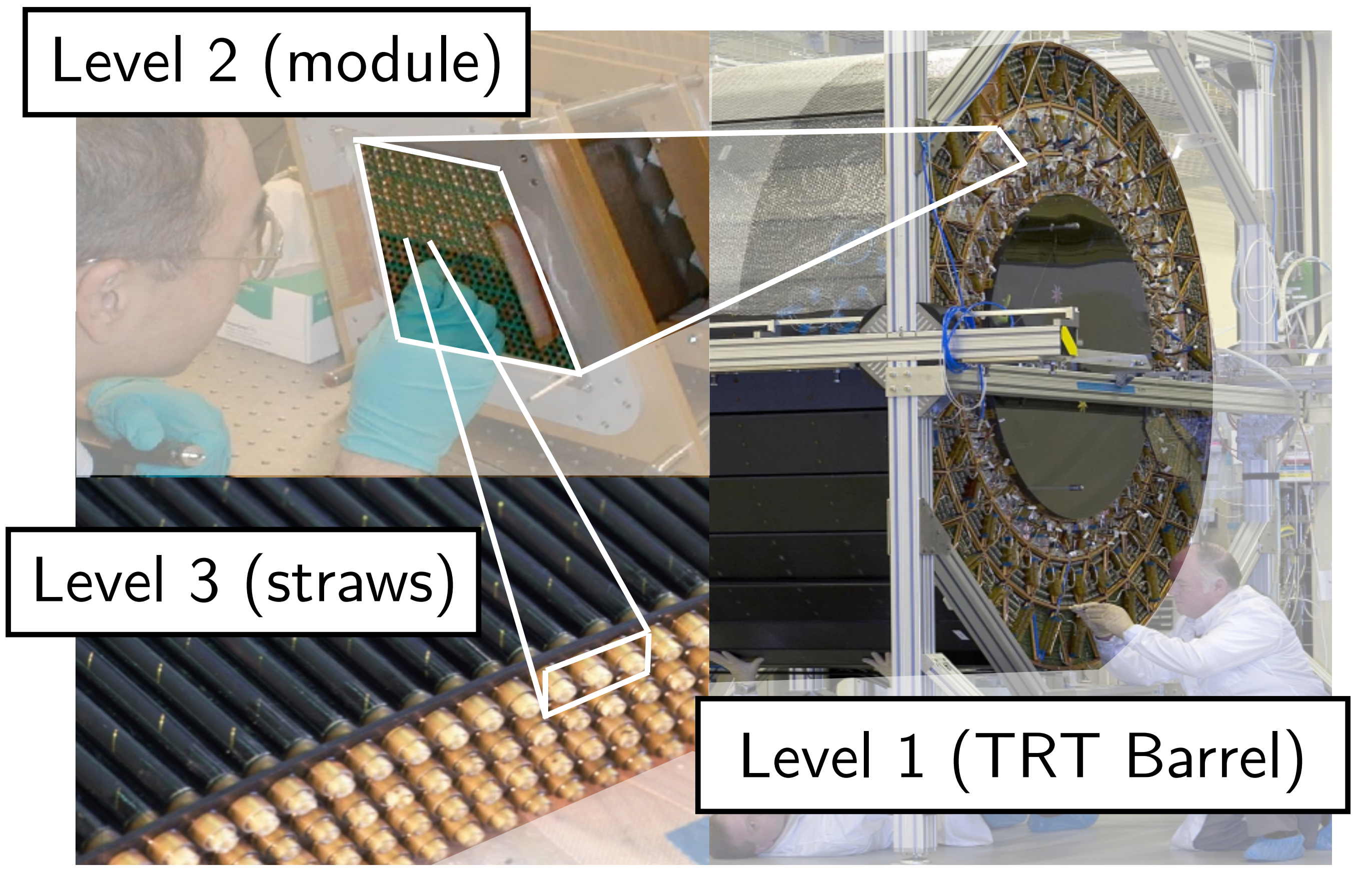
Transition Radiation Tracker: Overview



- Straw tubes filled with Xenon (Argon) gas, with radiator in between
- Collect hits from particles traversing the straws, reconstruct tracks from these hits
- Electrons emit transition radiation
    - Induces a high-threshold hit, important for electron identification on ATLAS
- 350,000 straws, intrinsic resolution of ~130 µm → need a good description of the geometry

Correcting Detector Misalignments

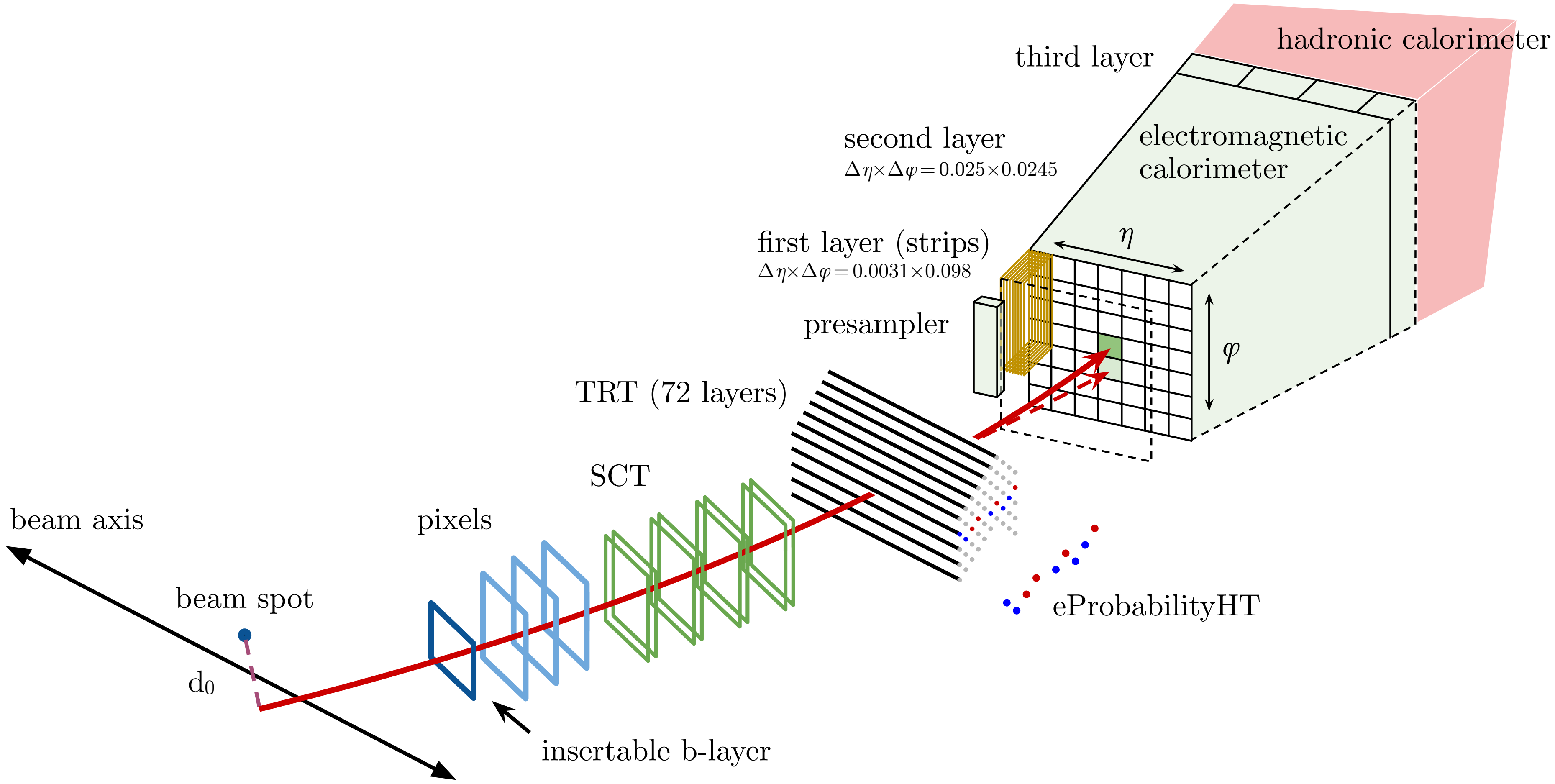




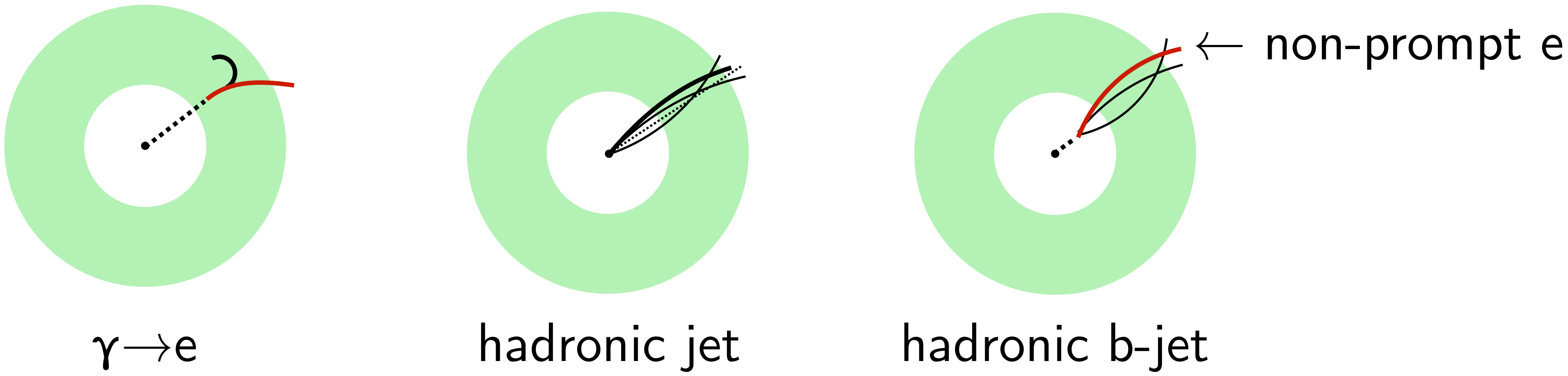
- Detector elements can be misaligned compared to "perfect" geometry description
- Tracks reconstructed with misalignments will have large residuals
- Alignment: collect millions of tracks; minimize the residuals using a χ^2 minimization procedure
- The construction of the TRT is highly modular (corresponding to assembly procedure)
- TRT: align at three levels: Barrel and Endcaps (L1), Modules (L2), and Straw Level (L3)
- I worked to align the TRT at the straw level

ELECTRON ID

- Developed a multivariate electron identification technique
- Measured electron efficiencies using Z→ee events



- Electrons that we are looking for are **prompt: participant in the p–p hard scatter**
- Electron bends in uniform magnetic field from 2T solenoid, interacts with material in the detector
  - Inner Detector measures particle trajectory and estimates the electron momentum
  - Deposits transition radiation in the TRT
- Electron deposits most of its remaining energy in EM calorimeter
  - Energy deposit is localized in $\eta \times \varphi$
- *Electron is an electromagnetic cluster matched to a track*

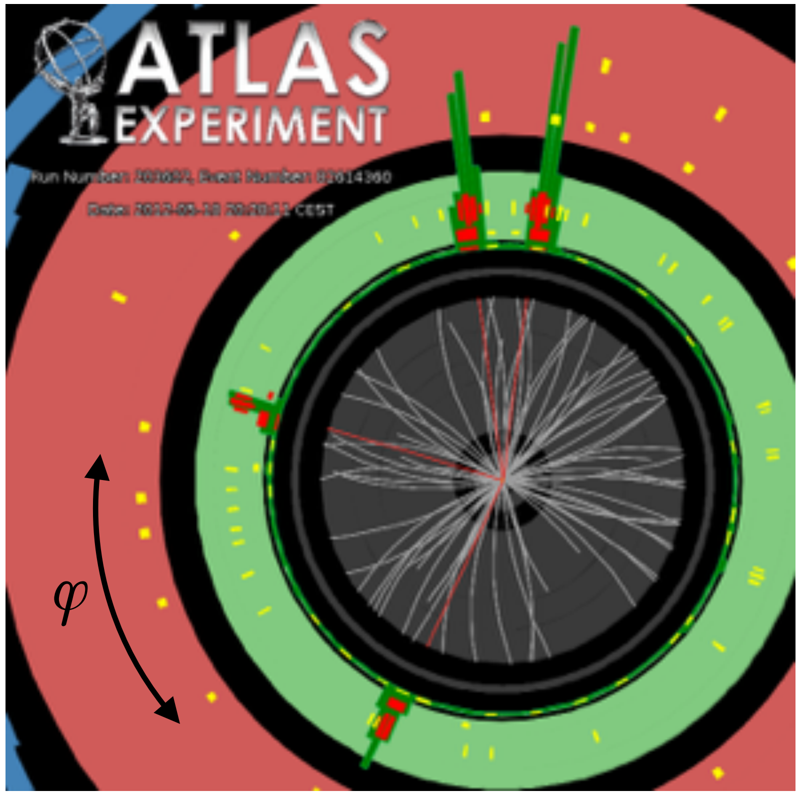


What are the electron backgrounds?

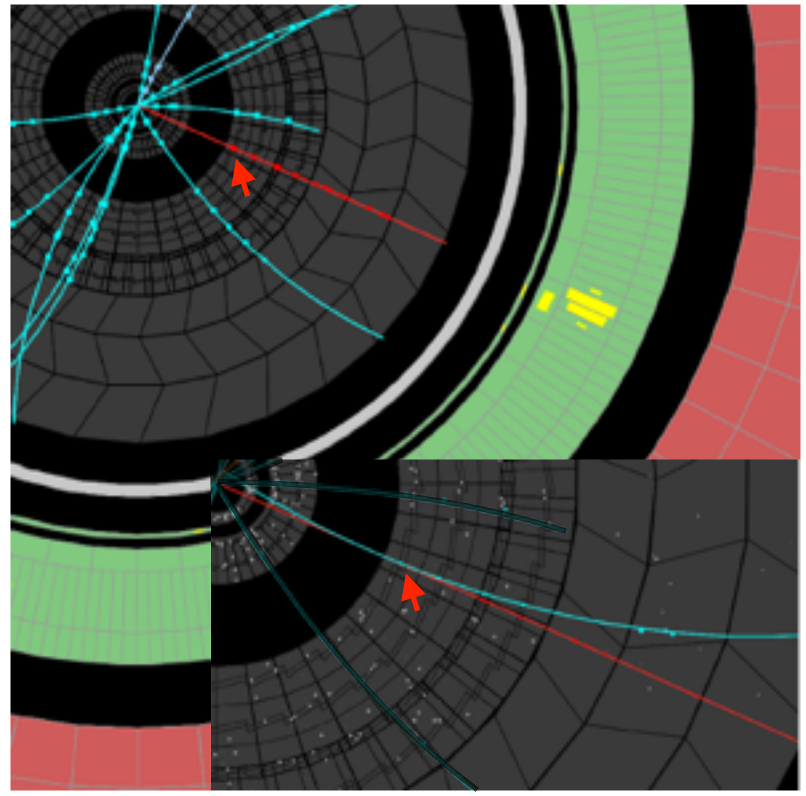
- Photon conversion: prompt γ from hard scatter or inside jet converts to e^+e^-
- Charged particle from a hadronic jet misidentified as an electron
- Displaced b-jet decay with electron in the decay chain

How can we distinguish them?

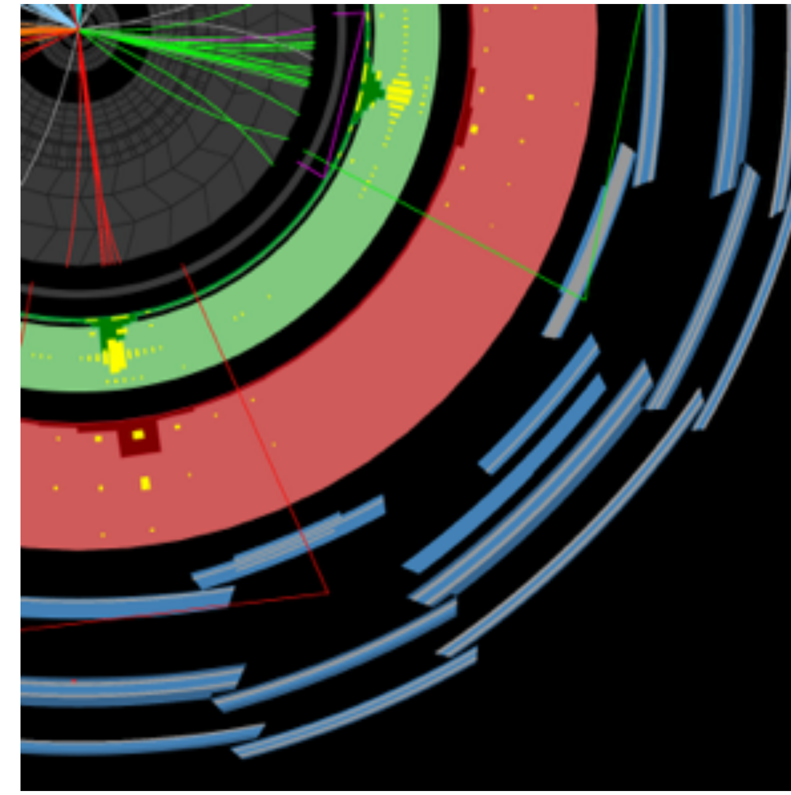
- Hadronic jets have more activity (from the parton showering and hadronization)
- Converted photon will have a displaced vertex from interaction with material
- b-jets have displaced vertex and local activity



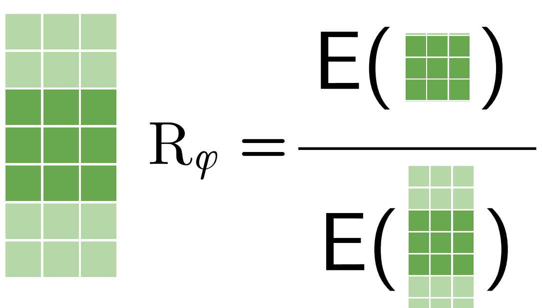
4 electron candidates

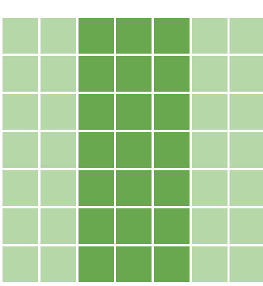


converted photon



two jets





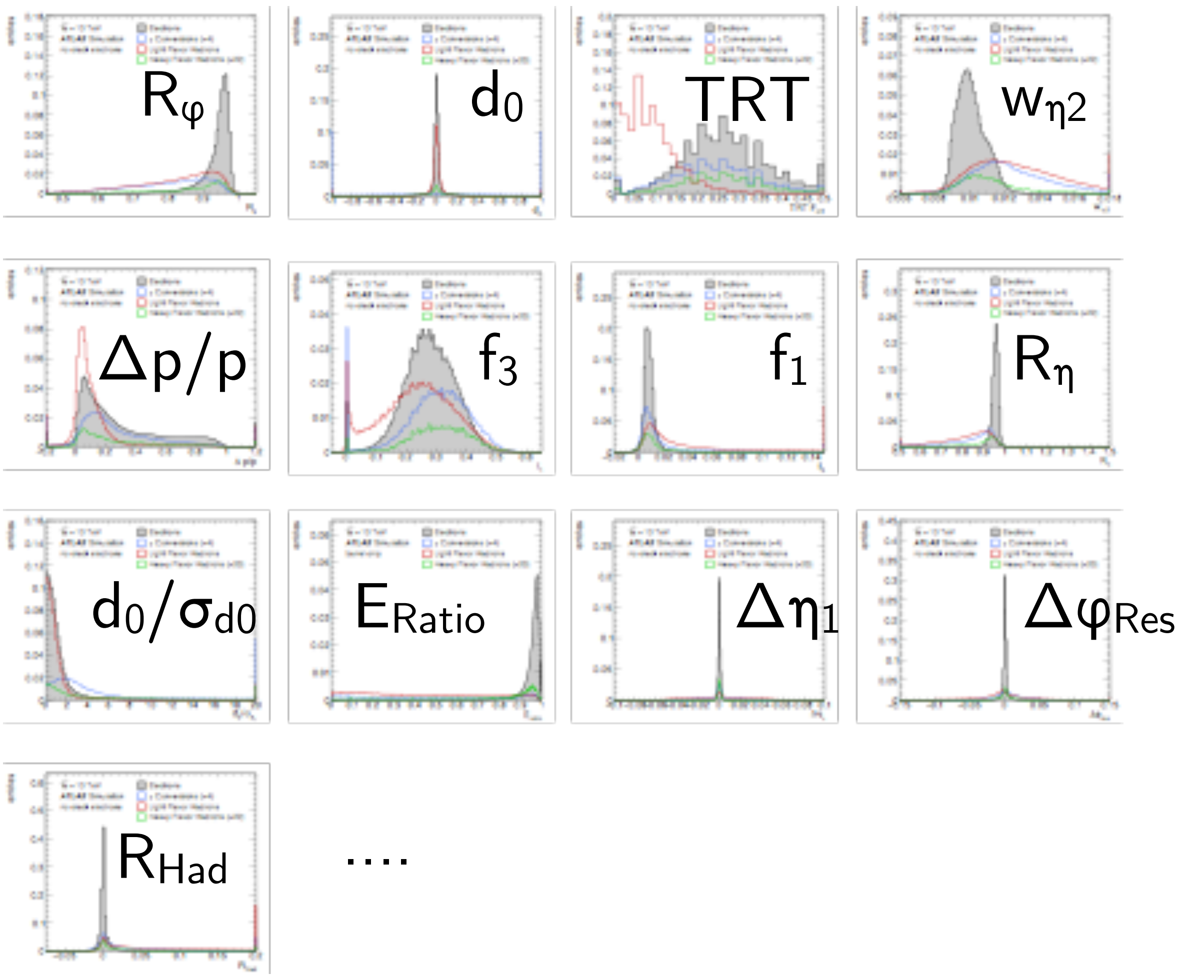
R_η

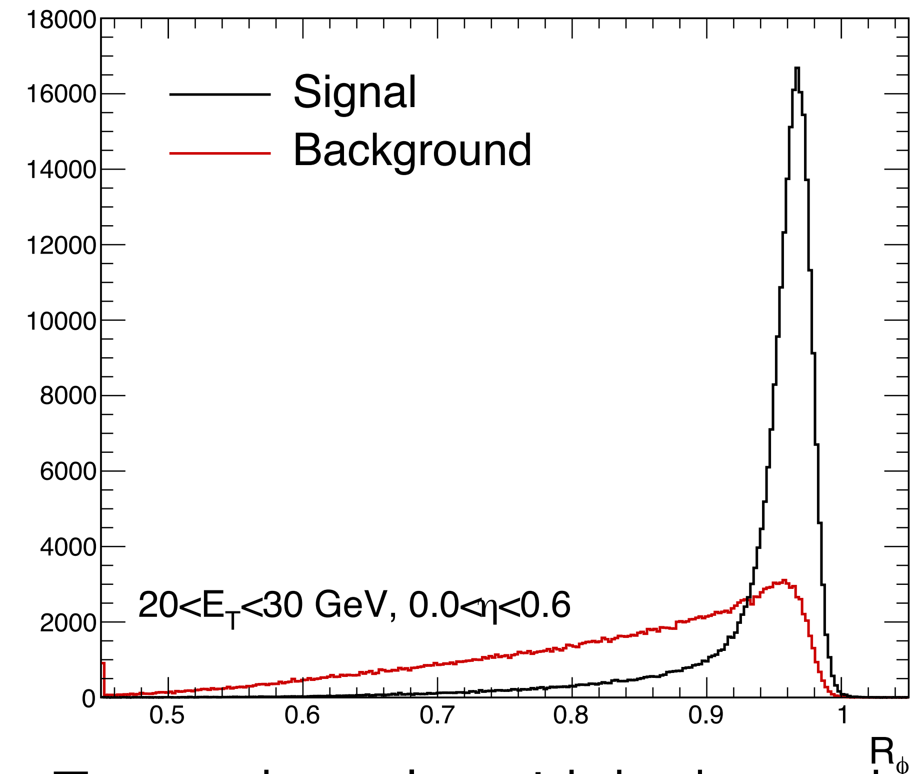
At our disposal:

- Energy ratios and widths of the calorimeter deposit
- Distances from track to primary vertex
- TRT High Threshold Hits
- Variables to describe how isolated electron candidates are from other tracks / calorimeter activity

Electron Identification on ATLAS

Variables at our disposal





Too much overlap with background to make an efficient cut

- 2011-2012: ATLAS used sets of simple cut requirements, called "cut-based menus"
  - Main drawback: inefficiencies due to losses in tails of distributions
  - Some powerful cuts cannot be used because they overlap with background too much
- 2012: Developed a multivariate technique for electron identification, to improve on cut-based ID - The Likelihood Method

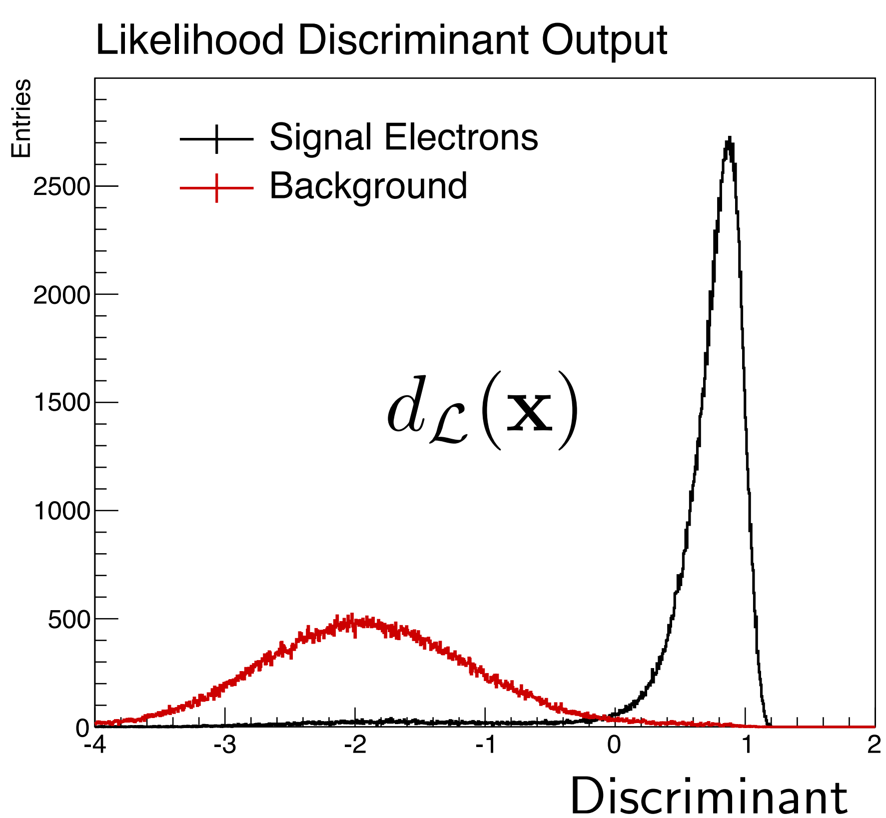
- Given a collection of variables $\mathbf{x}$ describing electrons, construct a discriminating test

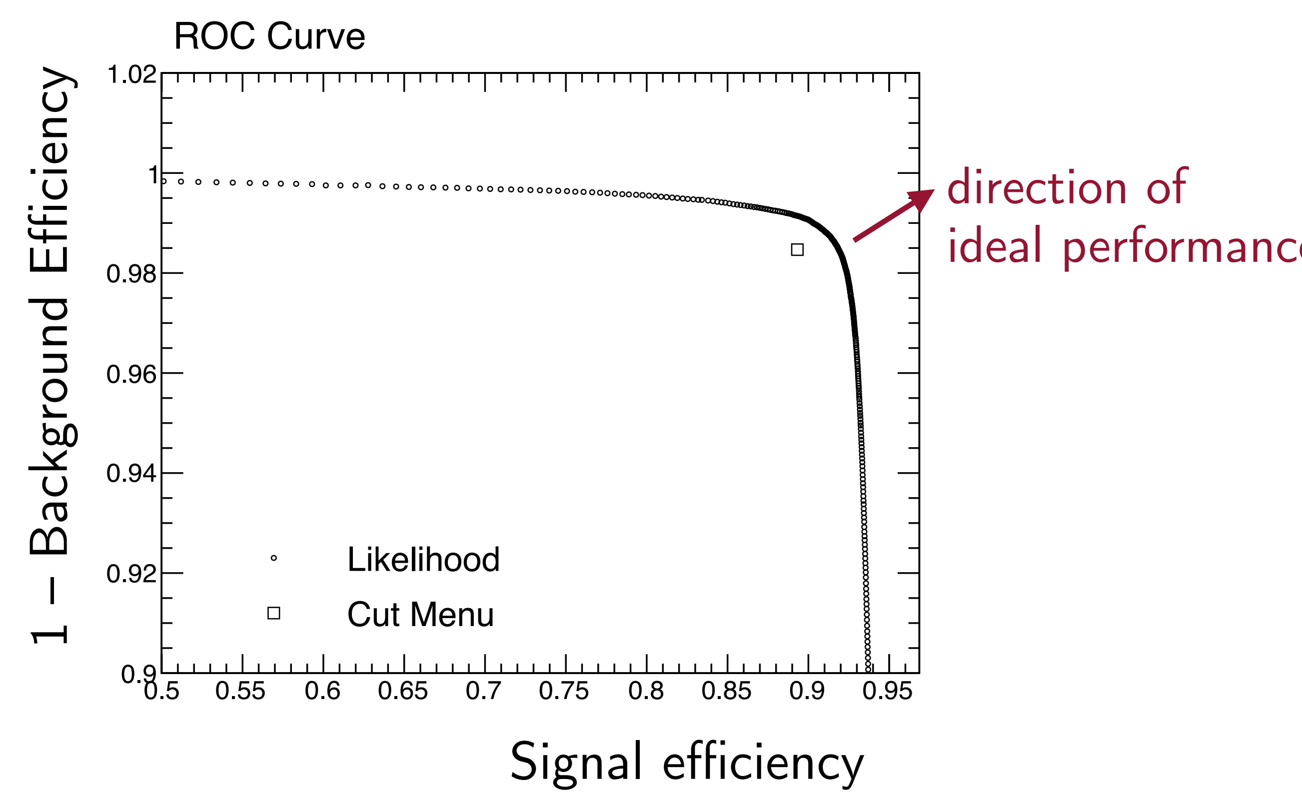
$$d_{\mathcal{L}}(\mathbf{x}) = \frac{p(H_s|\mathbf{x})}{p(H_s|\mathbf{x}) + p(H_b|\mathbf{x})}$$

  - where p is exact probability density function (PDF) in the space of variables $\mathbf{x}$ of a an electron
- Neyman-Pearson Lemma guarantees that this is the best discriminating test
- We make the assumption that all variables are uncorrelated, so the PDF is the product of n one-dimensional variable PDFs (histograms):

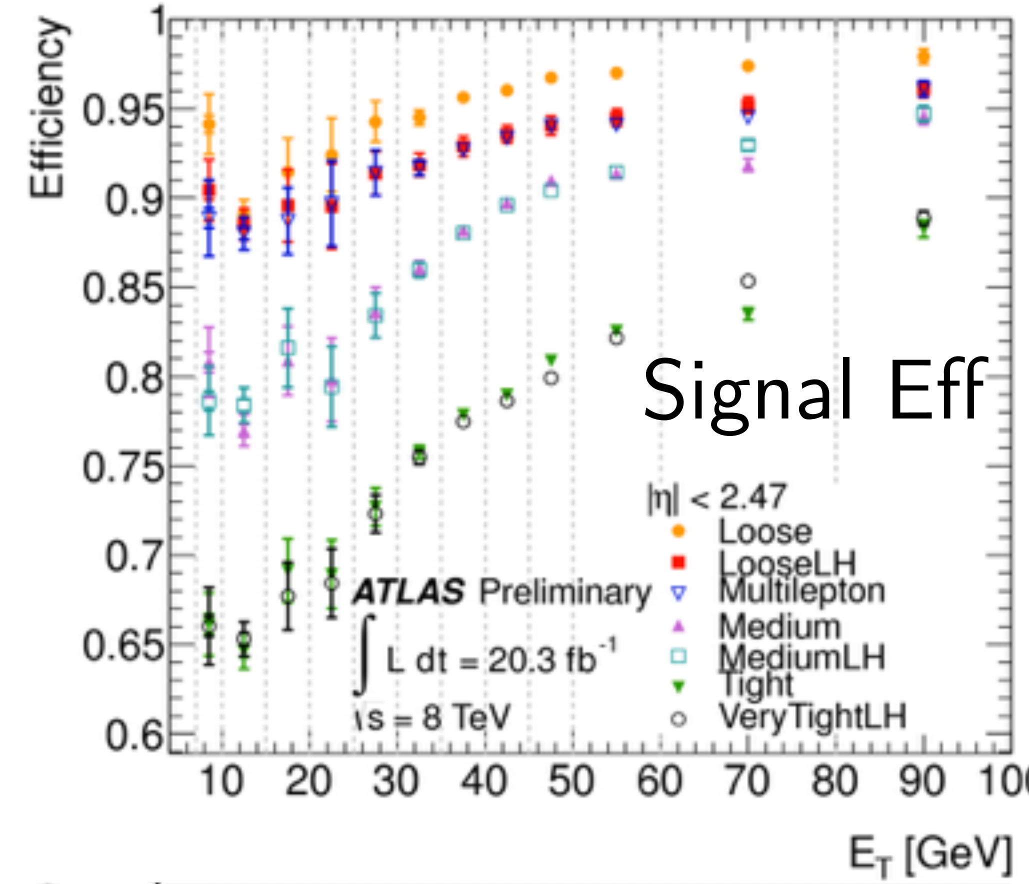
$$p(H|\mathbf{x}) = \prod_{i=1}^{n} p(H|x_i)$$

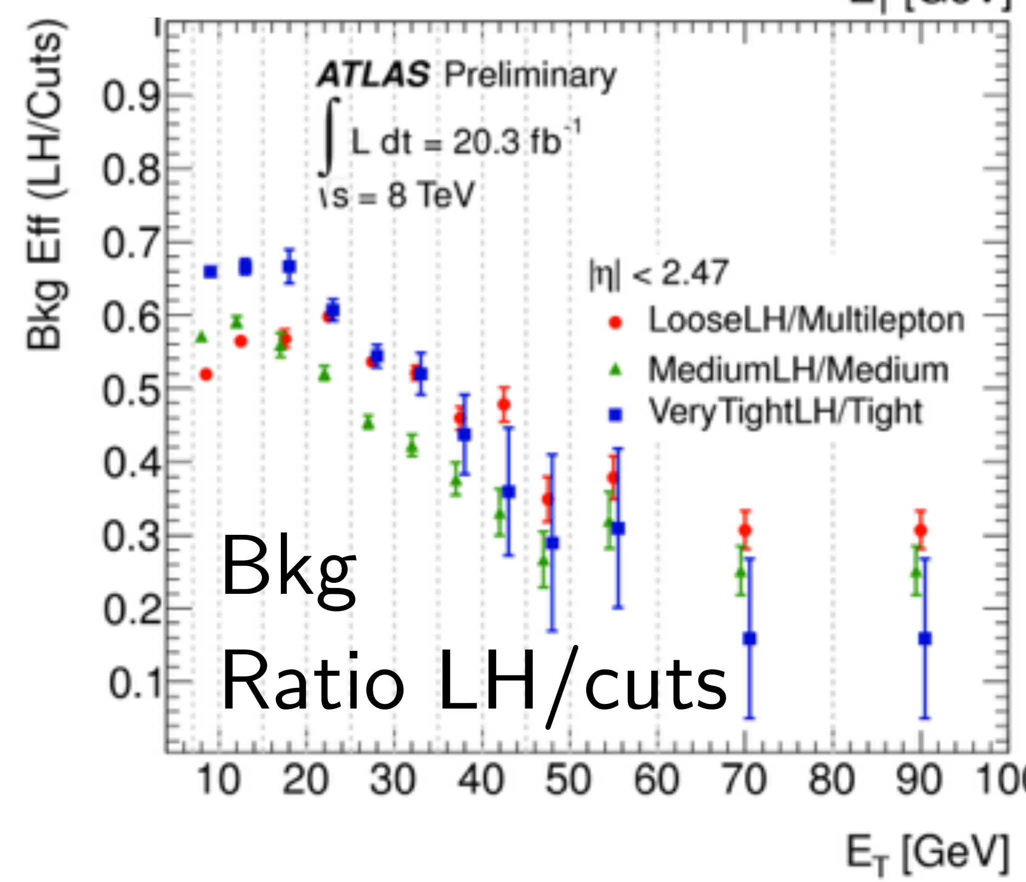
- Benefit over cut-based methods: "drawing circles instead of squares" in 11-dimensional variable space





- Our likelihood
  - Data-driven (don't rely on simulation)
  - Electrons describing PDFs collected from the Z→ee process
- Right: Performance of the Likelihood menus
- Bottom: better background rejection (about a factor of 2) for the same signal efficiency
- 2012 Electron likelihood customers:
  - H→ZZ*→4ℓ
  - H→WW*→ℓνℓν
  - ttH multilepton
- **With the hard work of Penn collaborators:**
  - Electron likelihood now used ATLAS-wide
  - Used in trigger to collect events in 2015 and 2016!
- R.R.M.G. Fletcher, J. Reichert, L. Flores





HIGGS BOSON

- Worked in the H→ZZ*→4ℓ channel
- Helped improve the electron identification
- Worked on the differential cross section measurements

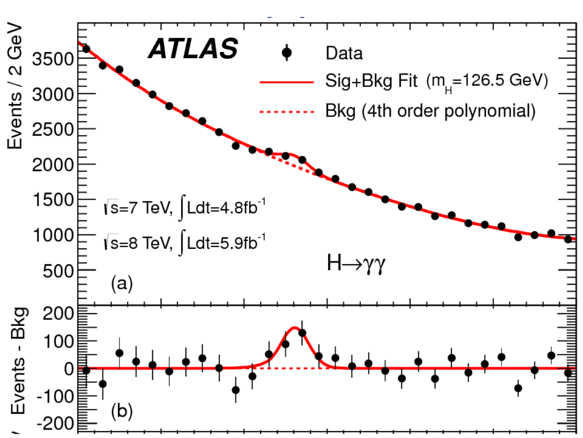
The New York Times

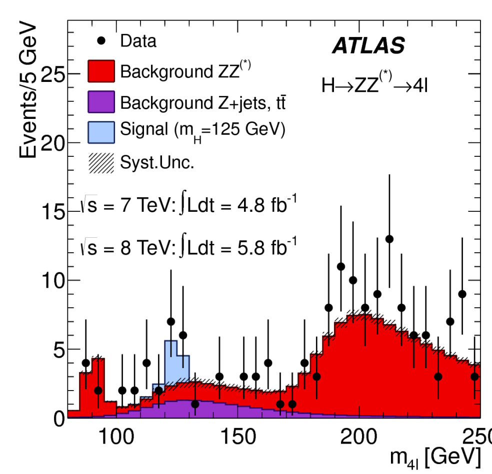
WEDNESDAY, JULY 4, 2012

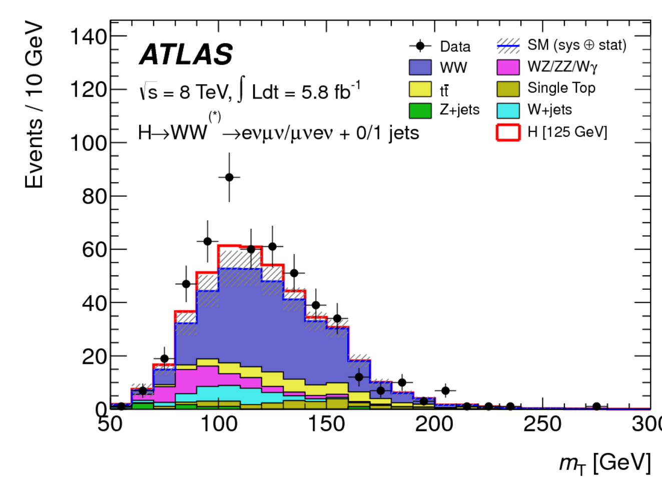
Physicists Find Elusive Particle Seen as Key to Universe

Scientists in Geneva on Wednesday applauded the discovery of a subatomic particle that looks like the Higgs boson.

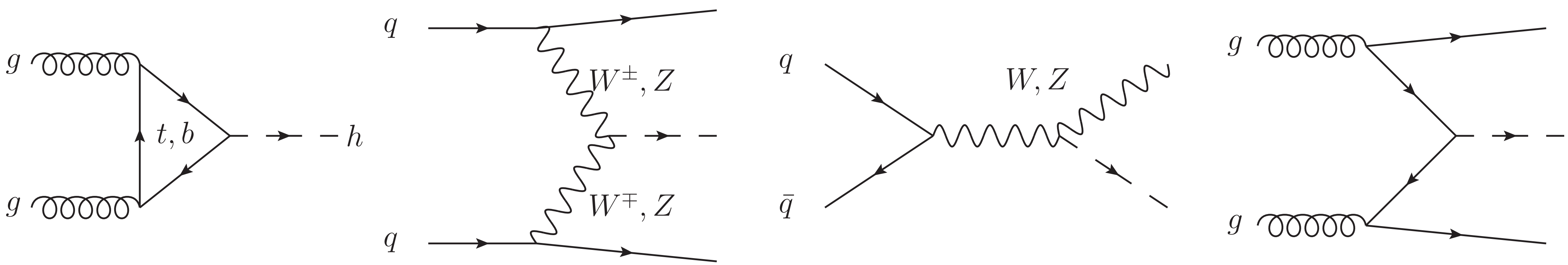
- July 4, 2012







Measurements of the Higgs Boson



gluon fusion | vector boson fusion | "higgstrahlung" | ttH

Higgs production modes

Decay Mode	Branching ratio (%)
$H \to b\bar{b}$	57.1
$H \to WW$	22.1
$H \to gg, cc, ss, tt$	11.4
$H \to \tau\tau$	6.25
$H \to ZZ$	2.74
$H \to \gamma\gamma$	0.228
$H \to Z\gamma$	0.157
$H \to \mu\mu$	0.021

Higgs Decay Modes

- After discovery, it is time to characterize the Higgs
- Search for deviations from SM predictions
- I worked on first **differential cross section measurements** in the H→ZZ*→4**ℓ** decay channel

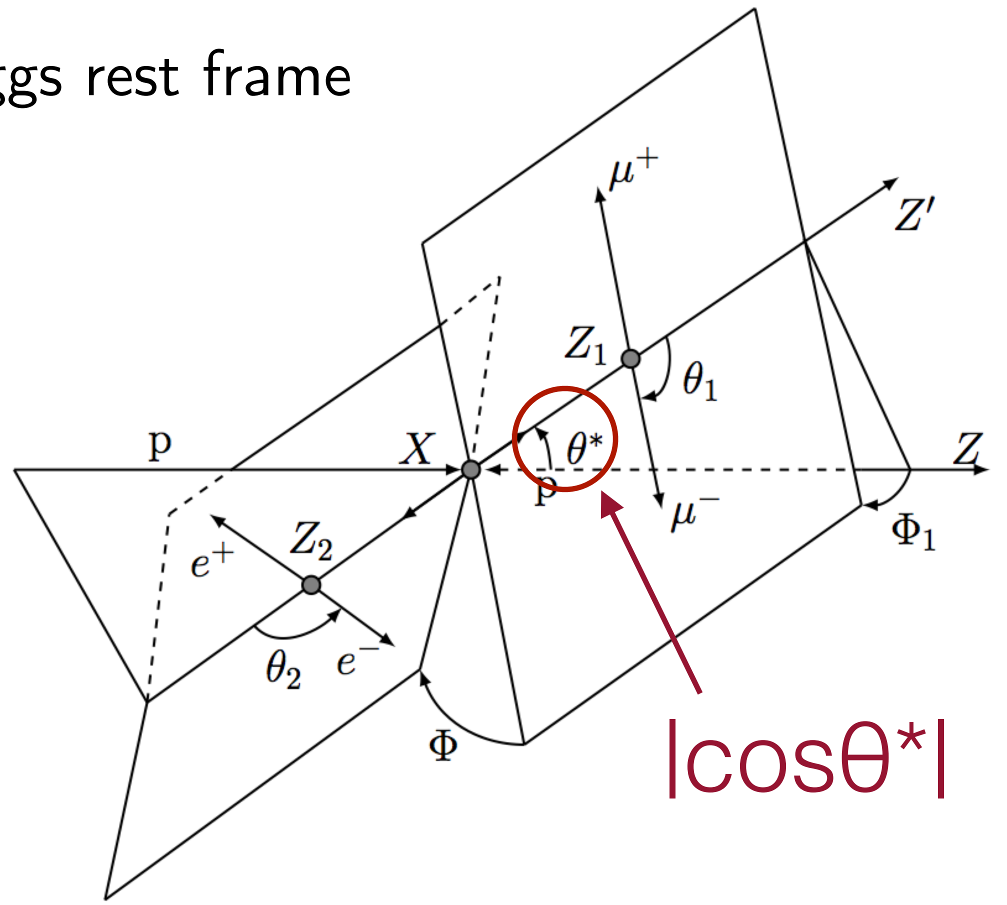
Higgs Fiducial Differential Cross Sections

Cross section: probability of an interaction, e.g. pp→H→ZZ*→4ℓ

Fiducial cross section: probability of an interaction and subsequent decay in ~instrumented region

Differential fiducial cross section: fiducial cross section as a function of some kinematic variable
- Choose variables that are sensitive to interesting physics:

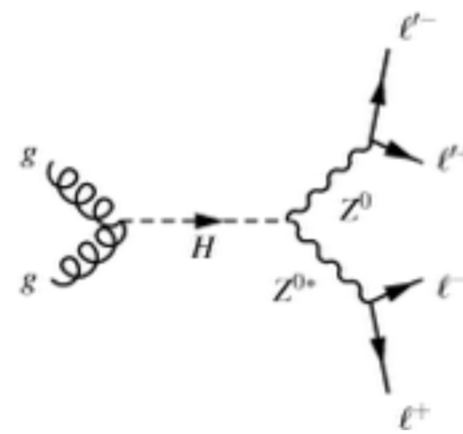
- **p_T**: sensitive to new physics; a well-studied distribution
- **|cosθ*|** - angle between beam axis and Z_1 decay in the Higgs rest frame
  - Sensitive to spin properties of the particle
- **N_{jet}, p_{Tjet1}** - jet variables sensitive to associated jet radiation, and production modes
- **|y|** - ability to distinguish parton distribution functions
- **m_{34}**

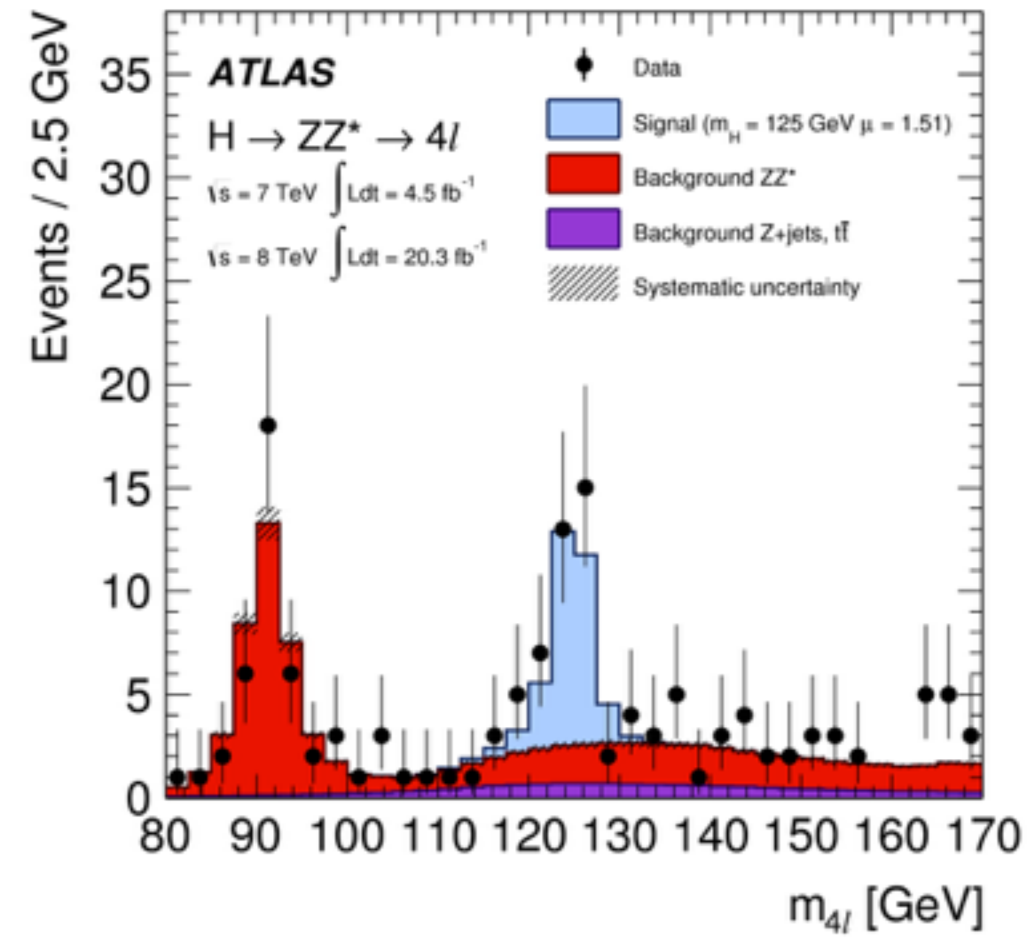


Brief Overview of Analysis

- One on-shell Z; one off-shell Z^*
- Four 4ℓ channels: 4μ, 2μ2e, 2e2μ, 4e
- Two main backgrounds:
  - **Irreducible** from SM $Z^{(*)}Z^{(*)} \to 4\ell$, modeled using simulation
  - **Reducible** from Z+jets and tt, modeled using data-driven methods
  - Improvement in electron identification (likelihood) reduces Z+jet background by ~factor of 2
- Event Selection:

Lepton selection		
Muons:	$p_T > 6$ GeV, $\lvert\eta\rvert < 2.7$	
Electrons:	$p_T > 7$ GeV, $\lvert\eta\rvert < 2.47$	
Lepton pairing		
Leading pair:	SFOS lepton pair with smallest $\lvert m_Z - m_{\ell\ell}\rvert$	
Subleading pair:	Remaining SFOS lepton pair with smallest $\lvert m_Z - m_{\ell\ell}\rvert$	
Event selection		
Lepton kinematics:	$p_T > 20, 15, 10$ GeV	
Mass requirements:	$50 < m_{12} < 106$ GeV	Z_1
	$12 < m_{34} < 115$ GeV	Z_2





- 4ℓ Mass window: 118-129 GeV for cross section measurements

Fiducial Cross Section Calculation

- Relate the number of events observed to the fiducial cross section using a correction factor in each bin:

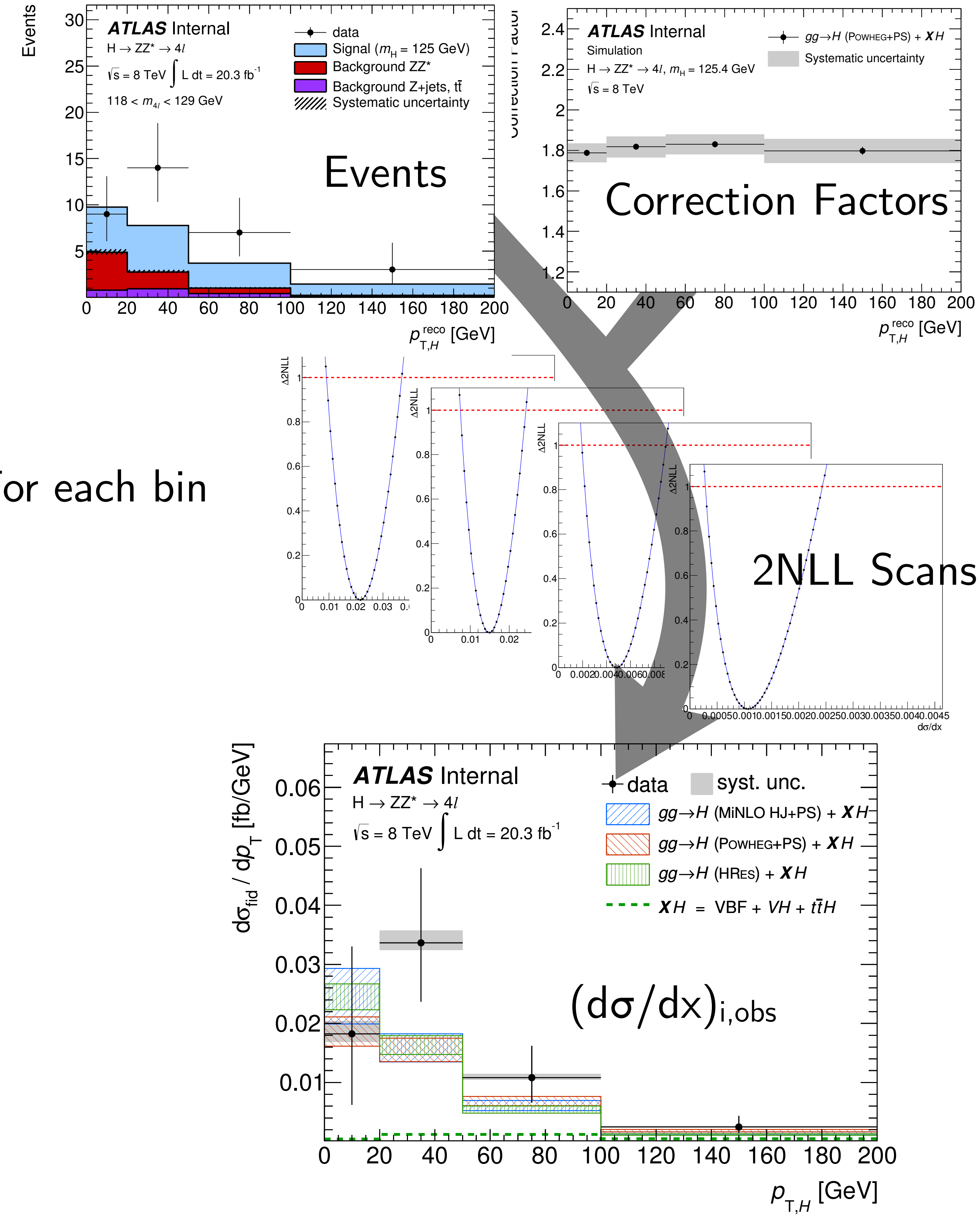
$$C = \frac{N^{\mathrm{MC}}_{\mathrm{reconstructed}}}{N^{\mathrm{MC}}_{\mathrm{true}}}$$

- Relate to fiducial cross section:

$$\sigma^{\mathrm{fid.}}_{H\to ZZ^*\to 4\ell} = \frac{N_{\mathrm{signal}}}{\mathcal{L}_{\mathrm{int}} \cdot C}$$

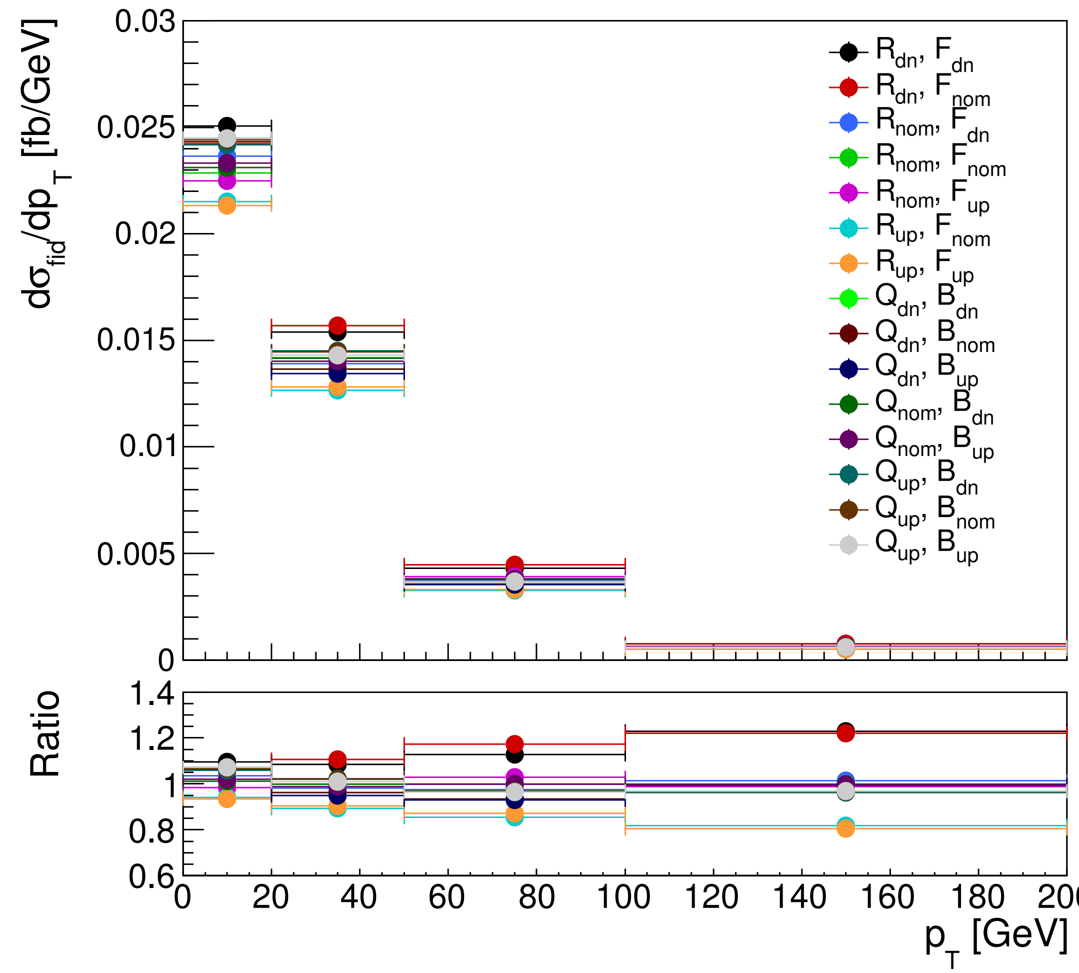
For each bin

- Simultaneous signal extraction in all bins, by minimizing (-2x) a profile likelihood ratio
  - Allows correlation of systematics across differential bins



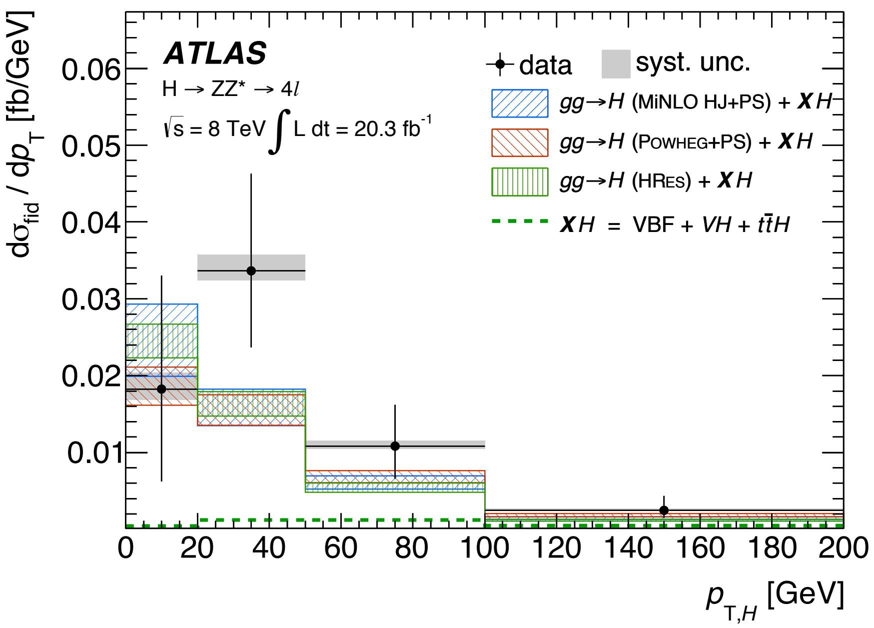
Theoretical Predictions

- Compare results to predictions from leading generators
  - **Powheg+Pythia** (NLO at QCD)
  - **HRes** (NNLO+NNLL - p_T distribution)
  - **Minlo H+1j** (Multi-scale improved NLO) - jet variable distributions
  - Sub-dominant contributions from ttH, VBF, and VH taken from Powheg generator
  - Predictions are normalized to the most precise cross section prediction → **shape comparison**
- Lots of work in theory community to understand distributions
- Theory uncertainties dominated by ggF production mode (scale)
- I ran predictions, and evaluated:
  - PDF uncertainties
  - Scale uncertainties

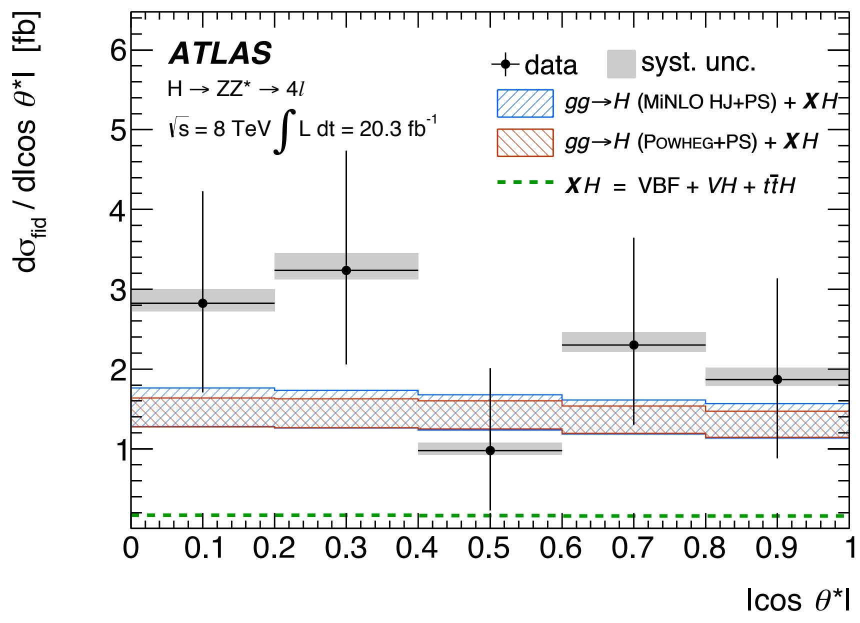


Scale variations for HRes 2.2 prediction of p_T

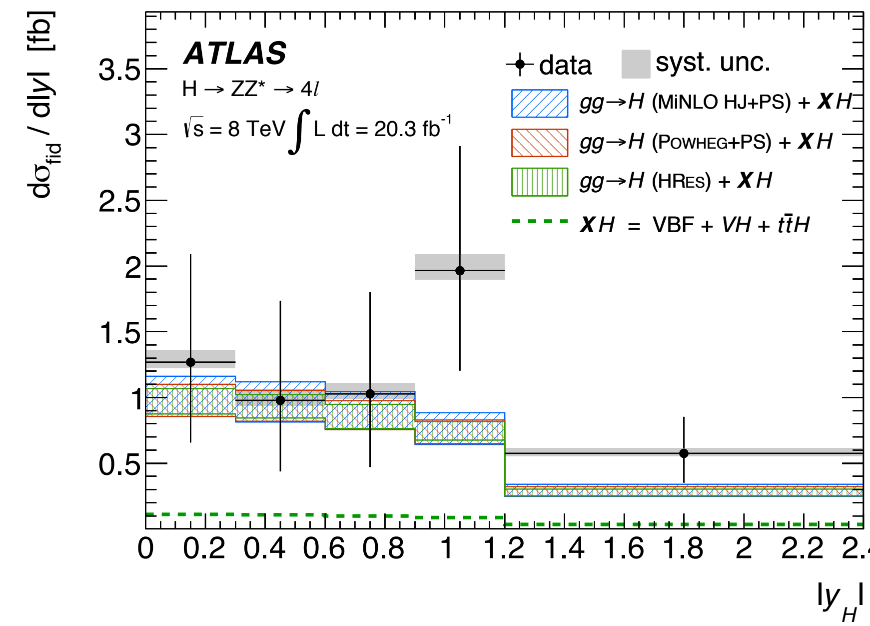
Differential Cross Section Results



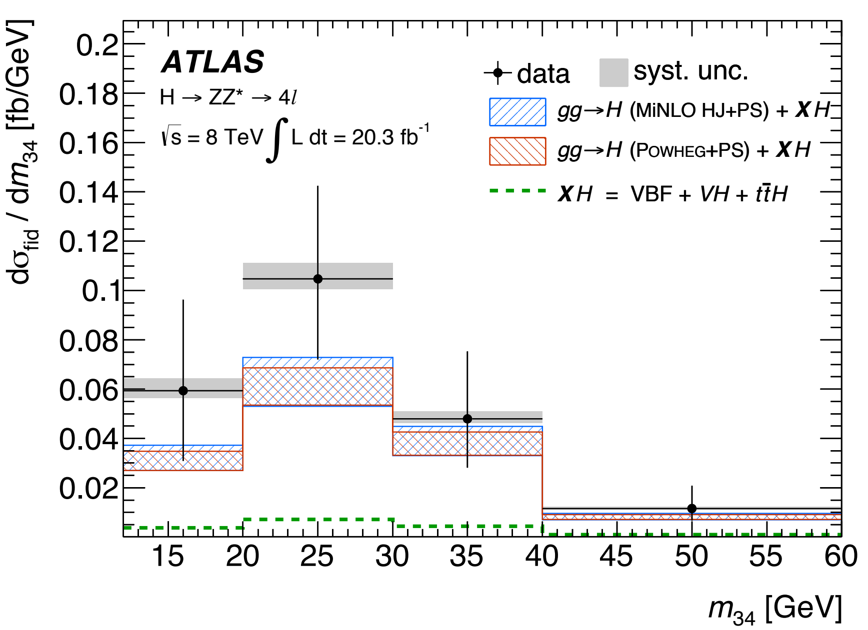
p_T



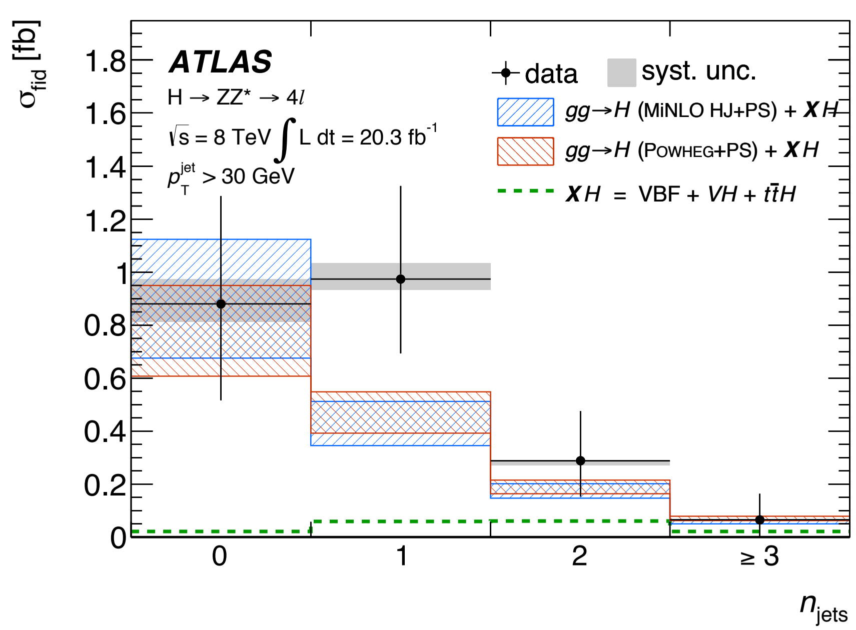
$|\cos\theta^*|$



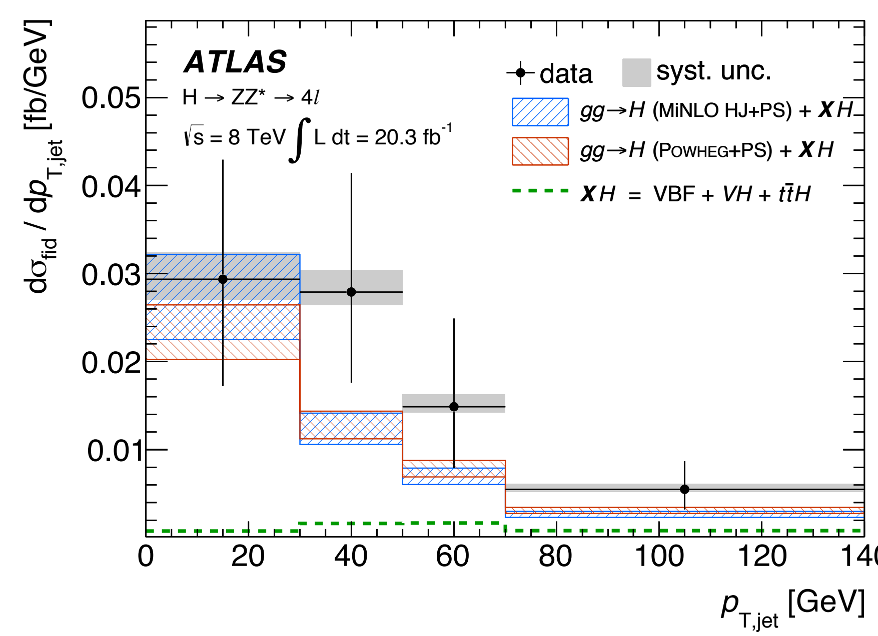
$|y|$



m_{34}



N_{jet}



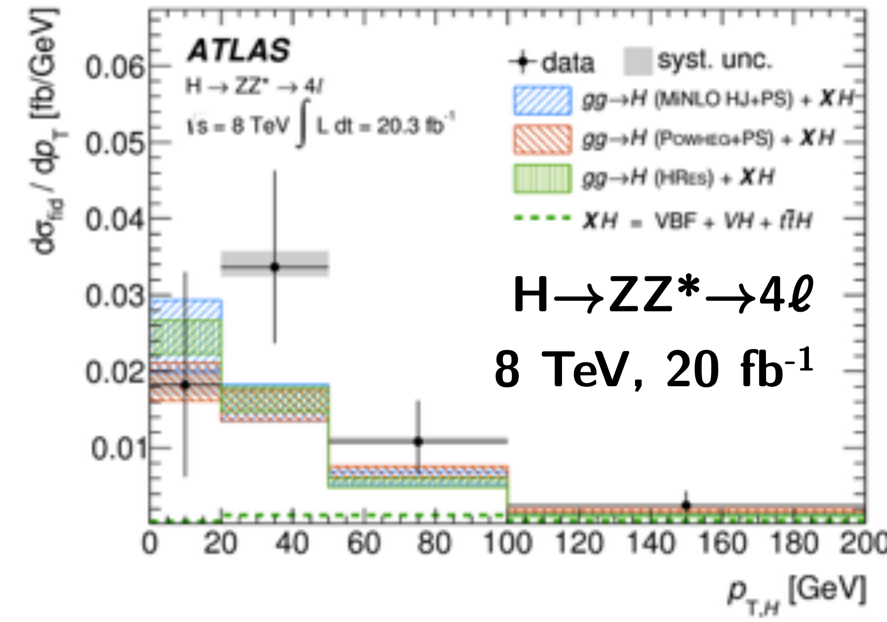
p_{Tjet1}

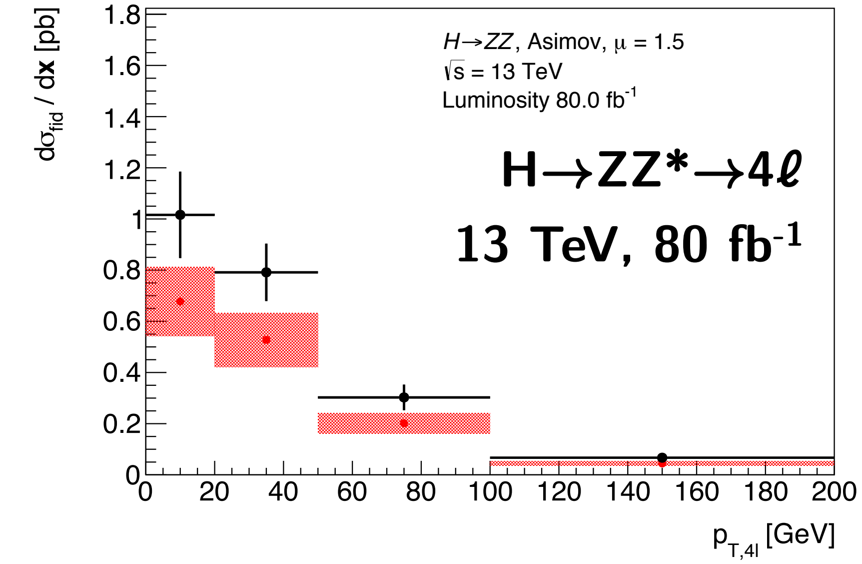
Conclusions and Prospects

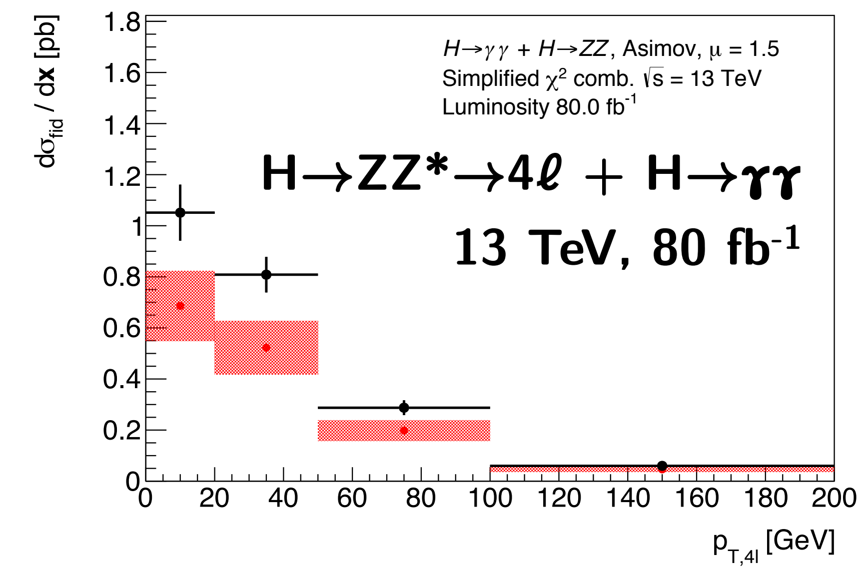
Variable	p-values POWHEG	MINLO	HRES2
$p_{\mathrm{T},H}$	0.30	0.23	0.16
$\lvert y_H \rvert$	0.37	0.45	0.36
m_{34}	0.48	0.60	-
$\lvert\cos\theta^*\rvert$	0.35	0.45	-
n_{jets}	0.37	0.28	-
$p_{\mathrm{T,jet}}$	0.33	0.26	-

χ^2 Compatibility with SM prediction

- Performed a χ^2 compatibility test with leading generators, normalized to NNLO cross section
- Consistent with the predictions - large statistical uncertainties
- Studied prospects for Run II data taken at 13 TeV
  - ~10% statistical errors with 80 fb^{-1}.

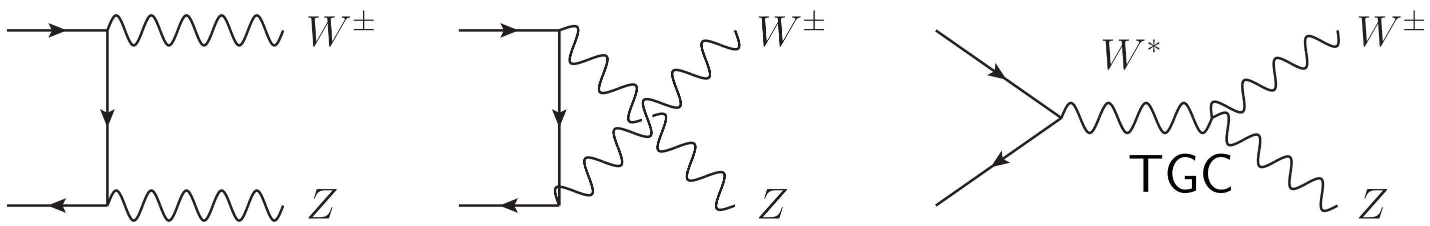




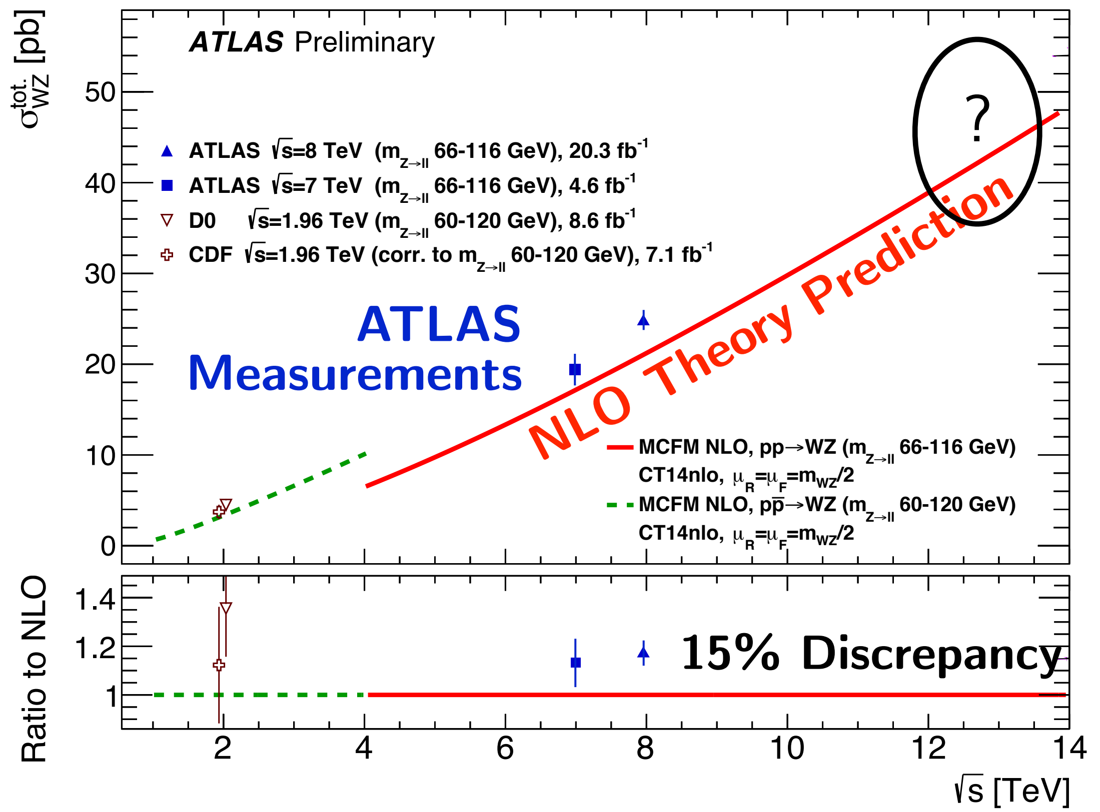


From Higgs to Supersymmetry to Standard Model WZ

- After Higgs Boson discovery, many outstanding questions, including why the Higgs mass is 125 GeV
  - Loop corrections to the Higgs mass should increase its value to the Planck scale
- Hoped to search for the answer in supersymmetry, which predicts a new symmetry protecting the Higgs mass from these large loop corrections
- Aimed to search for SUSY particles decaying via intermediate **W and Z bosons** to three leptons
  - Use expertise in lepton identification to access areas of phase space not well studied
- However, a search using 3.2 fb^{-1} of data collected in 2015 would not surpass our Run I sensitivity
- Focus on the largest background, Standard Model WZ production

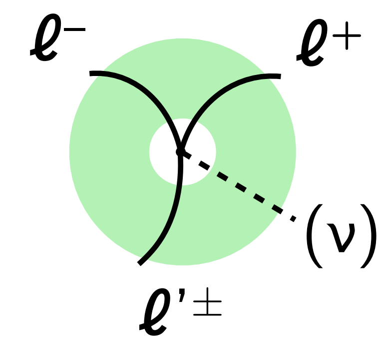


- Test of the gauge boson self-interaction terms of the SM Lagrangian
  - Production includes a **Triple Gauge coupling vertex**
  - Deviations between theoretical predictions and experimental results could indicate new physics
- Tension between ATLAS measurements and NLO theoretical predictions
- We measure the fiducial cross section of WZ decaying to 3 leptons

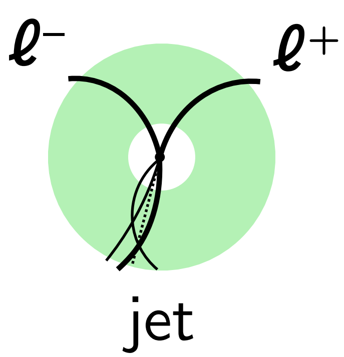


WZ Analysis Description

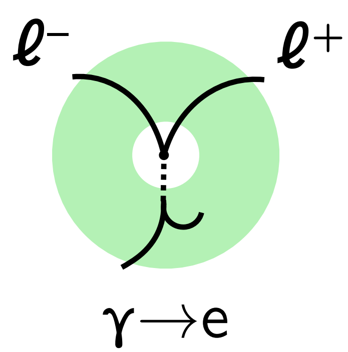
- **Measure the WZ process in the 3ℓ channel**
  - Z → ee or Z → μμ
  - W → eν or W → μν
  - 4 channels: μμμ, eμμ, μee, eee (in order of decreasing S/B)



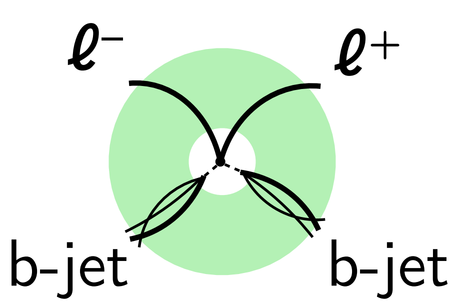
WZ



Z+jet



Zγ



tt

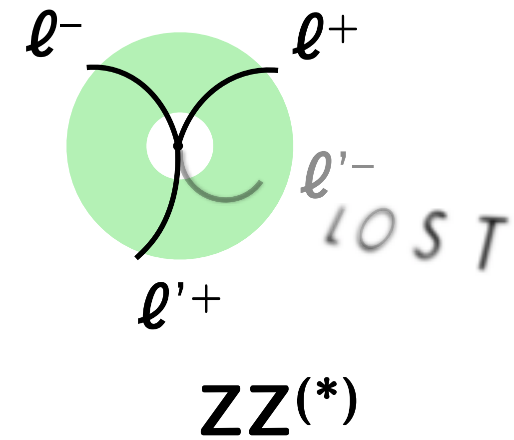
Main Background Processes:

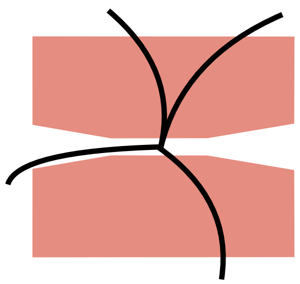
- **Reducible: Z+Jet / Zγ**
  - 2 real same-flavor, opposite sign leptons, consistent with Z boson
  - jet or converted (ISR) photon fakes a lepton; non-prompt lepton inside a jet
- **Reducible: $t\bar{t}$**
  - 2 real (same-flavor or different-flavor) opposite sign leptons
  - typically a non-prompt lepton from decaying b-jet from top decay fakes a prompt lepton

....

Main Background Processes (cont'd):

- **ZZ→4ℓ**
  - **Irreducible**: one lepton falls outside detector/kinematic acceptance (low-p_T or high-$|\eta|$)
  - **Reducible**: 4 leptons inside acceptance but one fails reconstruction/ID
- **Irreducible: rare processes (ttv, tZ, VVV)**





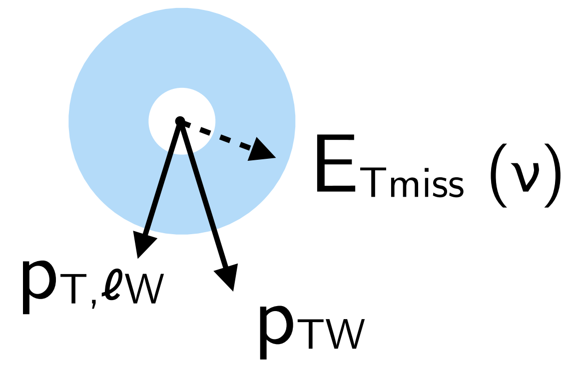
Strategy

- **Reducible backgrounds:**
  - Measure $t\bar{t}$ in a control region
  - Use Fake Factor Method for Z+Jet/Zγ
- **Irreducible backgrounds and ZZ:**
  - Use Monte Carlo simulation, with theoretical uncertainties

Event Selection

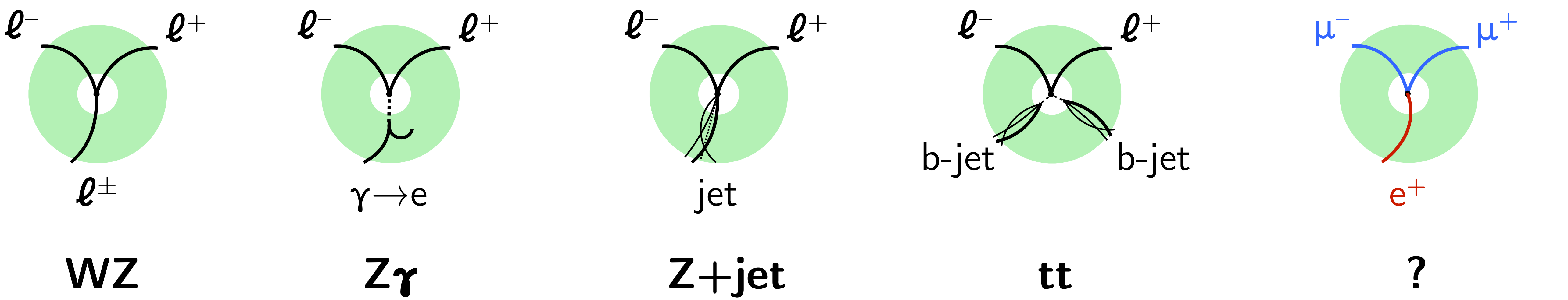
Designed to reduce...

- Veto events with four loosely identified "loose" leptons **ZZ**
- Require exactly 3 leptons
- Require 2 same-flavor, opposite sign leptons consistent with a Z boson (within 10 GeV of Z boson mass, 90 GeV) **tt**
- Require $m_{TW} > 30$ GeV (transverse mass of other lepton and the missing transverse momentum) **Z+jet/Zγ/ZZ**
- Tight identification requirements on the non-Z lepton **Z+jet/Zγ**

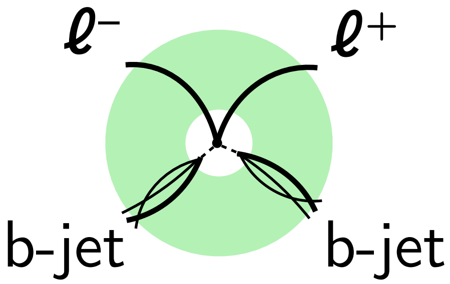


Introduction to fake leptons

What happens at particle level ("truth") | **What we see at Reconstruction**



- When we select signal leptons, we cannot tell whether a lepton is real or fake ( )
- The rates at which γ, jet and b-jet fake a lepton are different, and sometimes not modeled well by our simulation
- *Seek to characterize reducible backgrounds using data-driven methods*

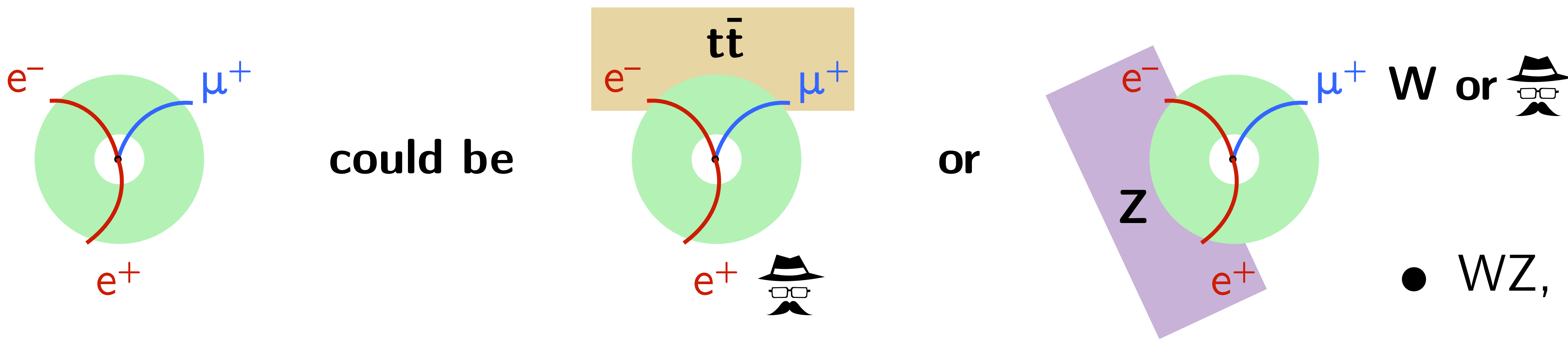


- **Use a dedicated control region**
  - Exploit specific combinations of lepton flavor and charge

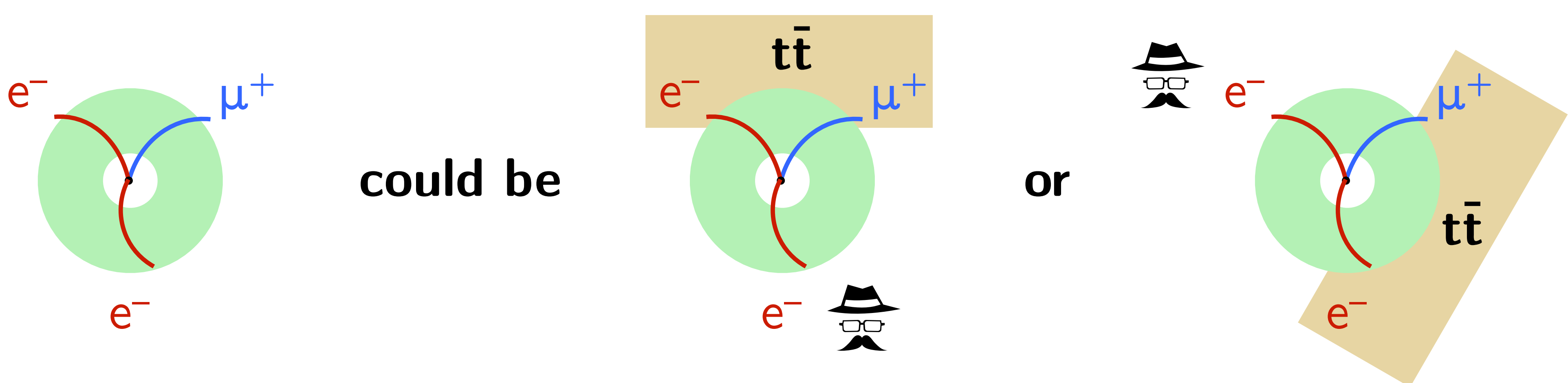
- *Note: We actually estimate "top-like" backgrounds (backgrounds with a same signature as above):
  - $t\bar{t}$, Wt, WW+jet

Disentangling tt from Z+jet/Zγ

- $t\bar{t}$ has an **opposite-charge pair of real leptons**
- Z+fake has an **opposite-charge, same-flavor pair of real leptons**
- WZ has an **opposite-charge, same-flavor pair of real leptons**



- WZ, $t\bar{t}$ or Z+jet/Zγ



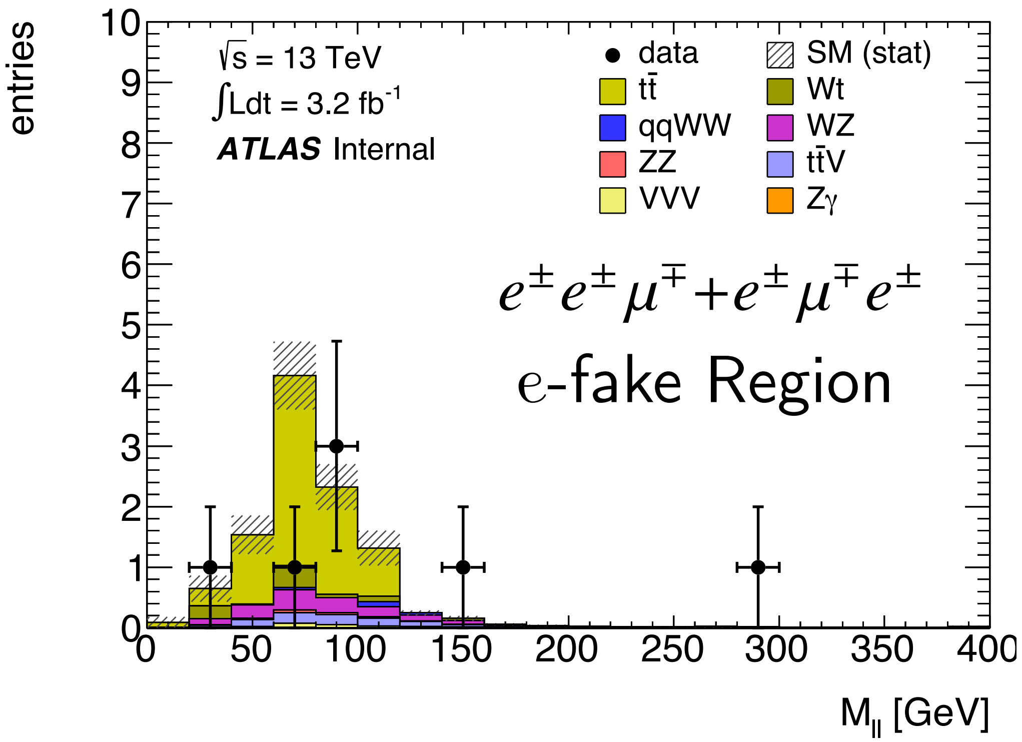
- only $t\bar{t}$
- fake must be an electron

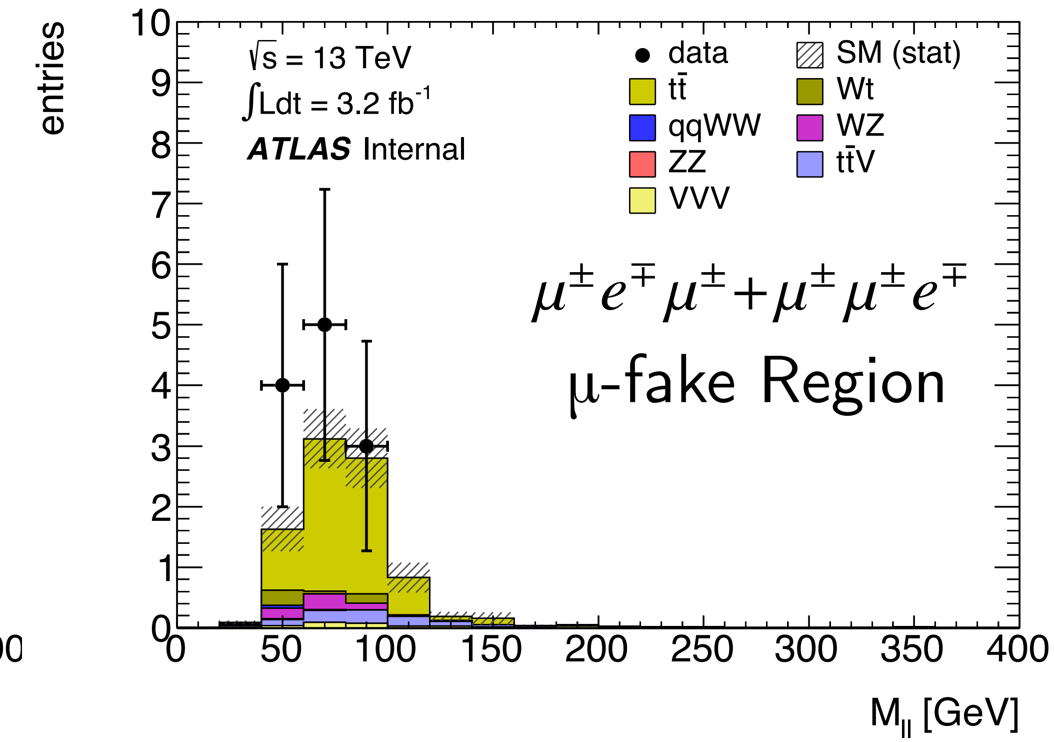
$e^-e^-\mu^+$ (and similar constructions) are purely $t\bar{t}$, and fix the fake lepton flavor

Control Region for predicting tt in signal region

Make a list of the possible lepton flavor / charge combinations, identify tt-enriched combinations

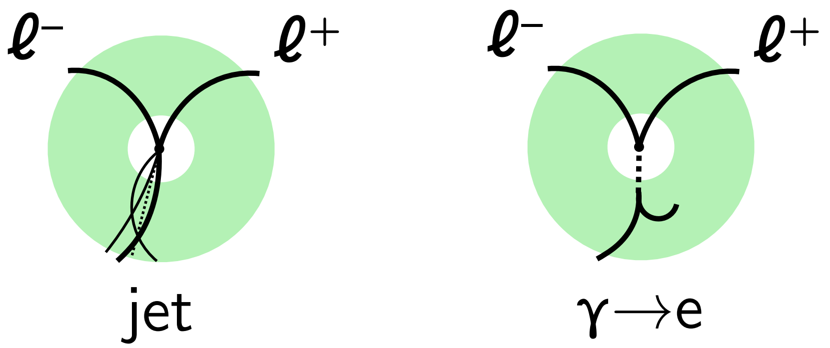
	$e^\pm$	$e^\mp$	$\mu^\pm$	$\mu^\mp$
$e^\pm e^\mp$	SR	SR	SR	SR
$e^\pm \mu^\mp$	$t\bar{t}$ CR (e)	-	-	$t\bar{t}$ CR (μ)
$\mu^\pm e^\mp$	-	$t\bar{t}$ CR (e)	$t\bar{t}$ CR (μ)	-
$\mu^\pm \mu^\mp$	SR	SR	SR	SR





Measure $t\bar{t}$ in control regions above, with 3 signal leptons

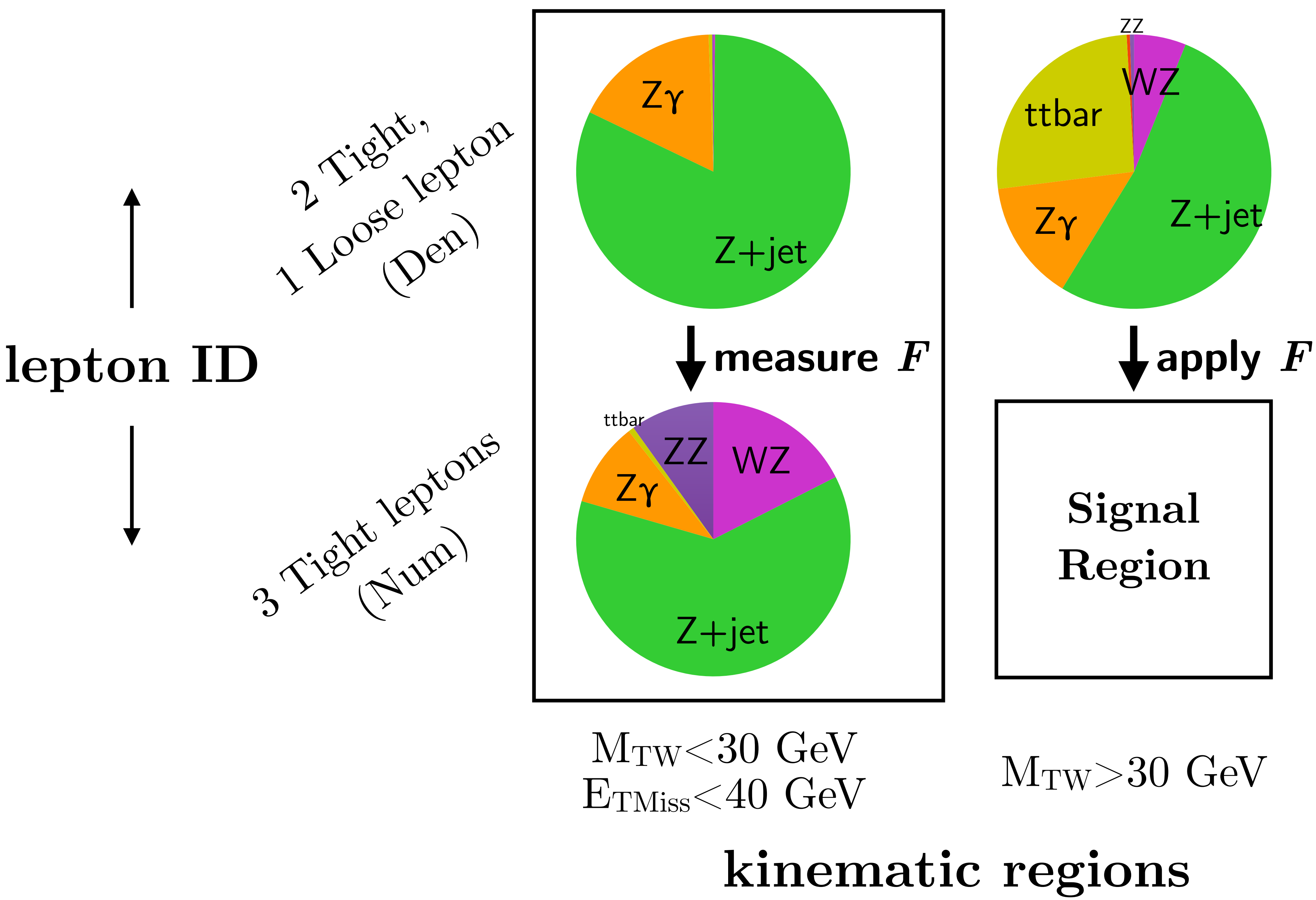
- 75% pure in $t\bar{t}$
- Use this region to derive a data/MC scale factor:
  - Separate scale factors for events with an electron fake and a muon fake
- Use the MC $t\bar{t}$ prediction in the signal region, multiplied by this scale factor



- Use the "Fake Factor Method"
  - Extrapolate from fake-enriched (Loose) region to signal region
    - Define a fake-enriched region by inverting lepton identification cuts
    - Define the region as having 2 signal (Tight) leptons, 1 Loose lepton
    - Extrapolate from [2 Tight, 1 Loose] Region to Signal Region (3 Tight)
  - Measure extrapolation factor N_{Tight}/N_{Loose} (fake factor) in region enriched in Z+jet/Zγ
    - Same construction: Denominator is 2 Tight, 1 Loose and Numerator is 3 Tight
    - Fake factor is measured as a function of Loose lepton p_T

Estimating Z+jet / Zγ

- **Z+jet** and **Zγ** are sufficiently similar that we treat them simultaneously
- Fake factor is measured in a kinematic control region enriched in Z+jet/Zγ
- Applied in region identical to Signal Region, but with 1 Loose Lepton



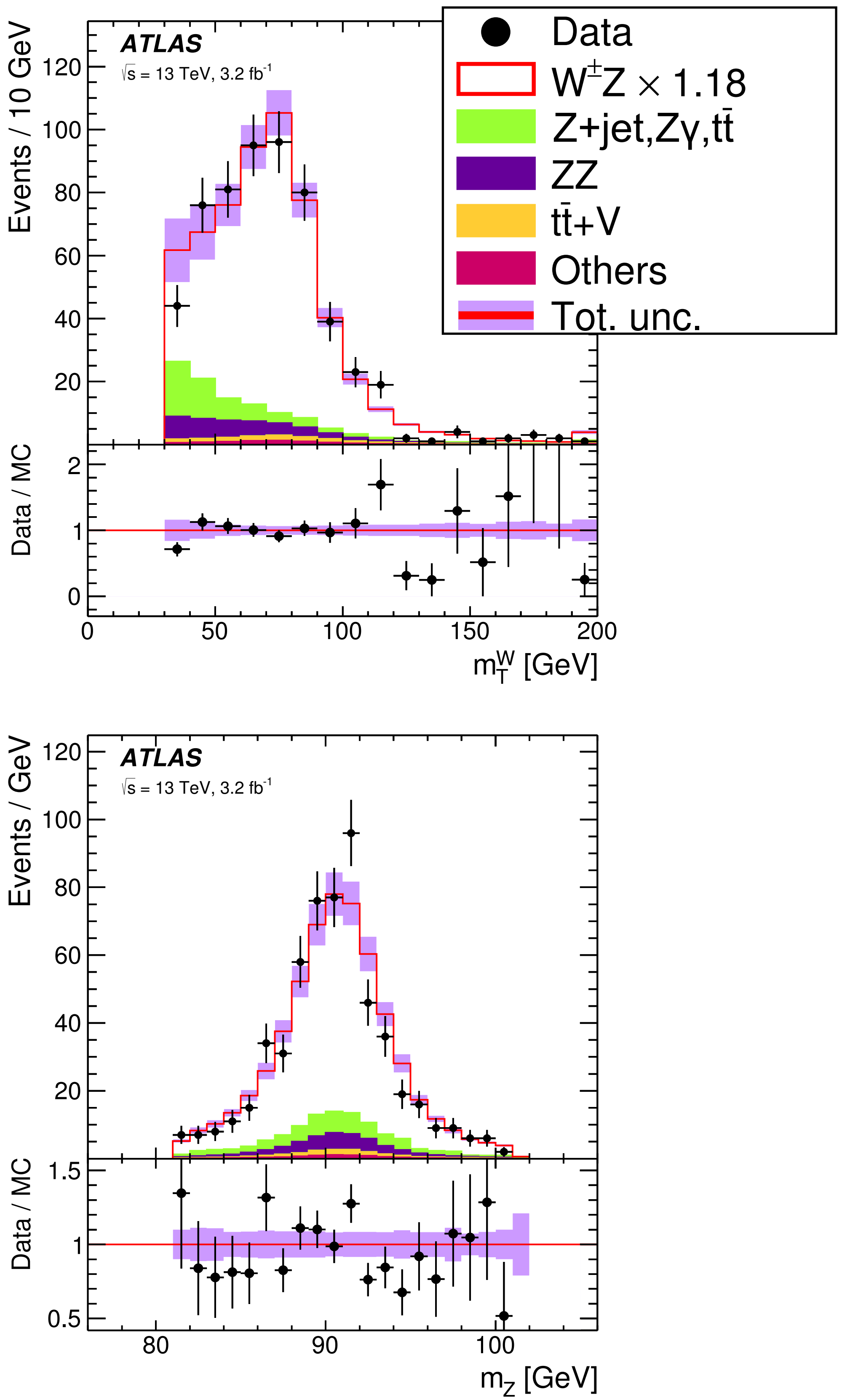
$$F = \frac{N_{\mathrm{Tight}}}{N_{\mathrm{Loose}}}$$

WZ Results (I)

Channel	All	
Data	569	
Total Expected	510	± 40
WZ (Powheg+Pythia8)	403	± 32
$Z+j$, $Z\gamma$	45	± 17
ZZ	36	$\pm$ 4
$t\bar{t}+V$	12.3	$\pm$ 1.6
$t\bar{t}$, Wt, $WW+j$	9.2	$\pm$ 3.1
tZ	6.8	$\pm$ 1.1
VVV	1.16	$\pm$ 0.18

fake lepton backgrounds

Kinematic Distributions

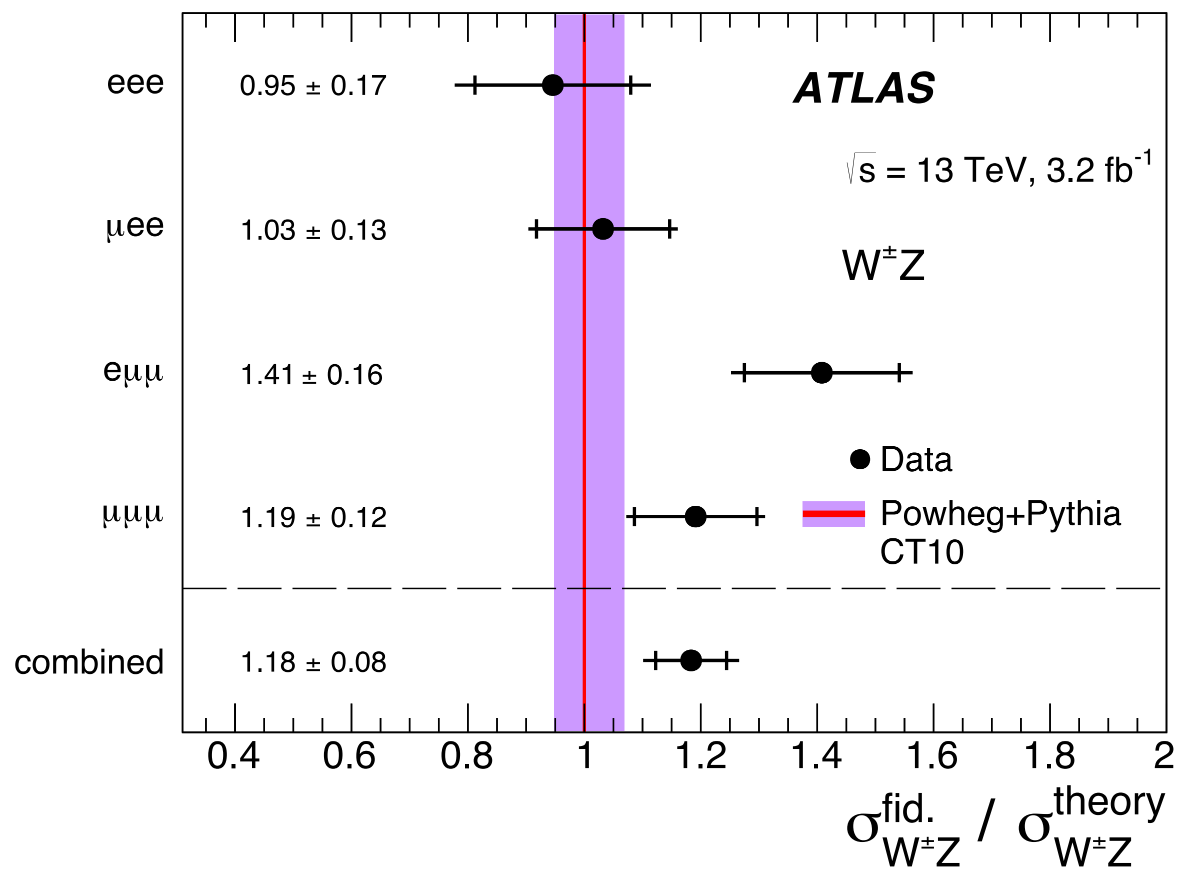


- Largest backgrounds:
  - Z+jet/Zγ, ZZ, ttV
- Largest uncertainties:
  - Statistics, Fake Factor, Pile-up, ZZ background, e/μ efficiency

Total sys. uncertainty	4.1 %
Luminosity	2.4 %
Statistics	5.1 %
Total	7.0 %

WZ Results (II)

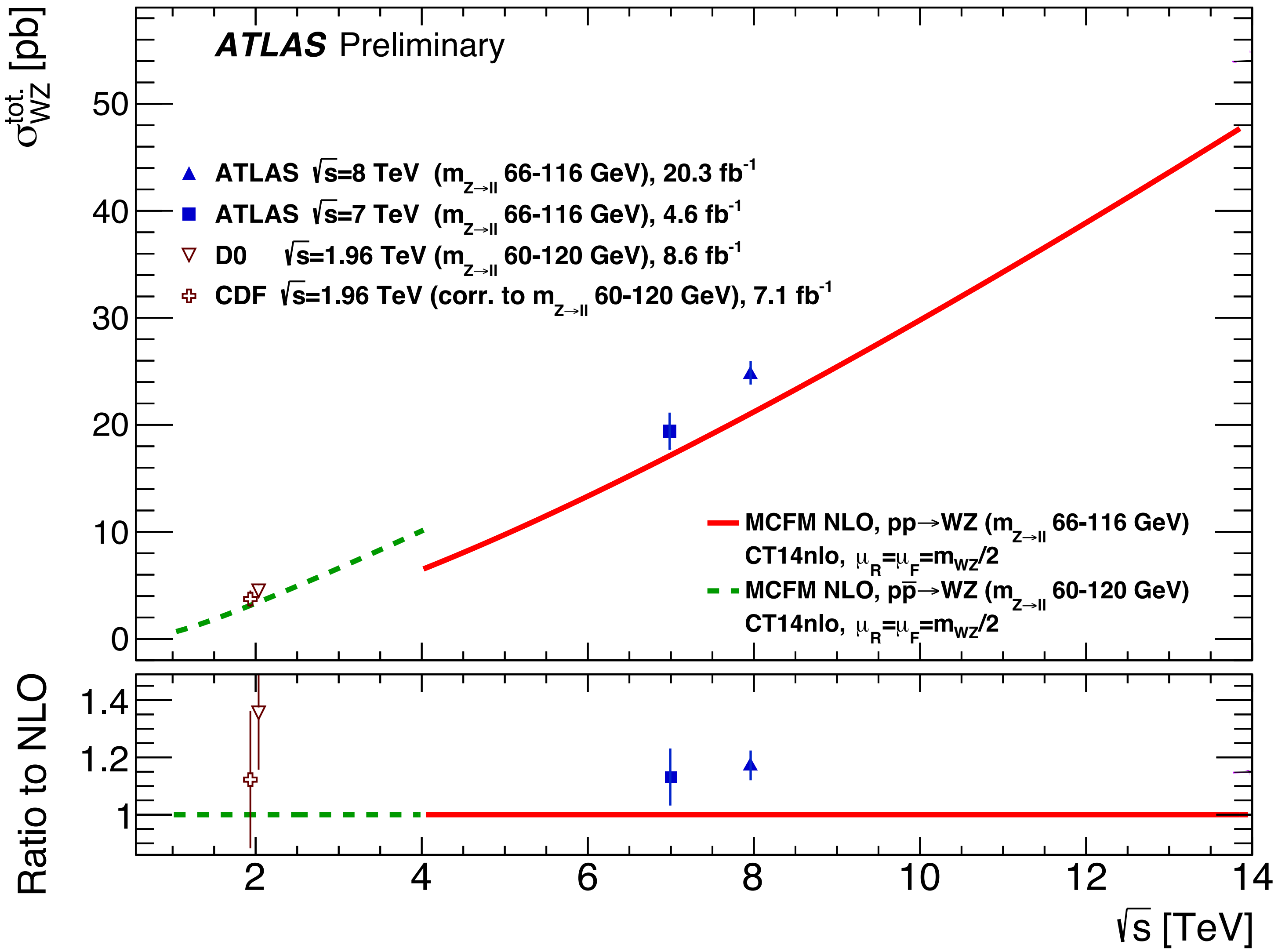
- Fiducial cross section is calculated: $\sigma^{\text{fid.}}_{W^\pm Z\to\ell'\nu\ell\ell} = \frac{N_{\text{data}} - N_{\text{bkg}}}{\mathcal{L}_{\text{int}} \cdot C_{WZ}} \times \left(1 - \frac{N_\tau}{N_{\text{all}}}\right)$,
- Four channels are statistically combined using a χ^2 minimization process (treating correlated systematic uncertainties as nuisance parameters)
- Fiducial cross sections in each channel:



- Result of combination of fiducial cross sections:

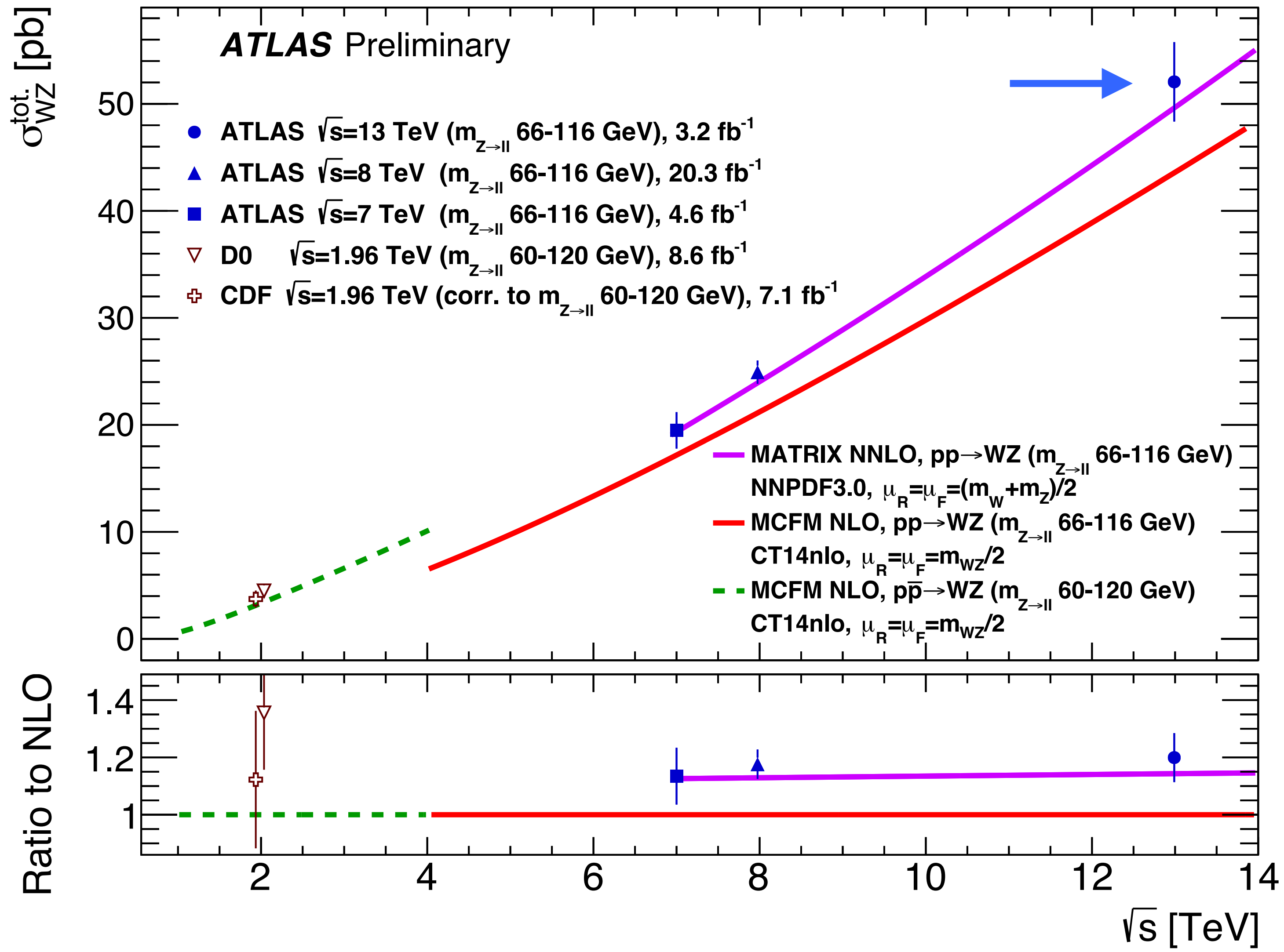
$$\begin{aligned}\sigma^{\text{fid.}}_{W^\pm Z\to\ell'\nu\ell\ell} &= 62.2 \pm 3.2\,(\text{stat.}) \pm 2.5\,(\text{sys.}) \pm 3.5\,(\text{lumi.})\ \text{fb} \\ &= 62.2 \pm 5.4\ \text{fb}.\end{aligned}$$

WZ Results (III)



- Recall tensions between NLO theory prediction and ATLAS measurements
- 13 TeV Measurement is extrapolated to total cross section
- Extrapolate from fiducial cross section to total cross section using:

$$\sigma^{\text{tot.}}_{W^\pm Z} = \frac{\sigma^{\text{fid.}}_{W^\pm Z \to \ell'\nu\ell\ell}}{\mathcal{B}_W\, \mathcal{B}_Z\, A_{WZ}}$$ with branching ratios $\mathcal{B}_W, \mathcal{B}_Z$ and acceptance factor $A_{WZ} = \frac{N^{\text{MC}}_{\text{total}}}{N^{\text{MC}}_{\text{fiducial}}}$



- Total cross section:

$$\sigma^{\text{tot.}}_{W^\pm Z} = 49.8 \pm 2.6\,(\text{stat.}) \pm 2.0\,(\text{sys.}) \pm 0.9\,(\text{th.}) \pm 2.8\,(\text{lumi.})\ \text{pb}$$
$$= 49.8 \ \pm\ 5.2\ \text{pb}.$$

- NNLO theory prediction agrees with all three ATLAS measurements!

Conclusions

- Aligned the Transition Radiation Tracker straw elements
- Delivered high-quality electron identification methods to ATLAS Analyses
- Measurement of the Higgs differential fiducial cross sections in the $H \rightarrow ZZ^* \rightarrow 4\ell$ decay channel at 8 TeV
- Measurement of the $WZ \rightarrow \ell'\nu\ell\ell$ fiducial and total cross section at 13 TeV

- Many thanks to Penn Faculty, Staff, and students, friends, and my family!

Team Egamma
John Alison
Chris Lester
Sarah Heim
Rob Fletcher
Joey Reichert
Lucas Flores

Team TRT Alignment
John Alison
John Stahlman
Will DiClemente

Team H→ZZ
John Stahlman
Sarah Heim
Bijan Haney

Team WZ
Joana Miguéns
Will DiClemente
Elodie Resseguie

Distinguished Alumni
Tuna
Jamie Saxon
Liz Hines
Dominick Olivito
Ryan Reece
Josh Kunkle
Rami Vanguri
Jackknife

Alignment

[4] ATLAS Collaboration, *Study of alignment-related systematic effects on the ATLAS Inner Detector track reconstruction*, ATLAS-CONF-2012-141, 2012. http://cdsweb.cern.ch/record/1483518. (document)

Electron identification and efficiency

[5] ATLAS Collaboration, *Electron efficiency measurements with the ATLAS detector using the 2012 LHC proton–proton collision data*, ATLAS-CONF-2014-032, 2014. http://cdsweb.cern.ch/record/1706245. (document), 5.1.1, 6.1

[6] ATLAS Collaboration, T. A. collaboration, *Electron efficiency measurements with the ATLAS detector using the 2015 LHC proton-proton collision data*, . (document)

H→ZZ*→4ℓ

[7] ATLAS Collaboration, *Fiducial and differential cross sections of Higgs boson production measured in the four-lepton decay channel in pp collisions at* $\sqrt{s} = 8$ *TeV with the ATLAS detector*, Phys. Lett. B **738** (2014) 234, arXiv:1408.3226 [hep-ex]. (document)

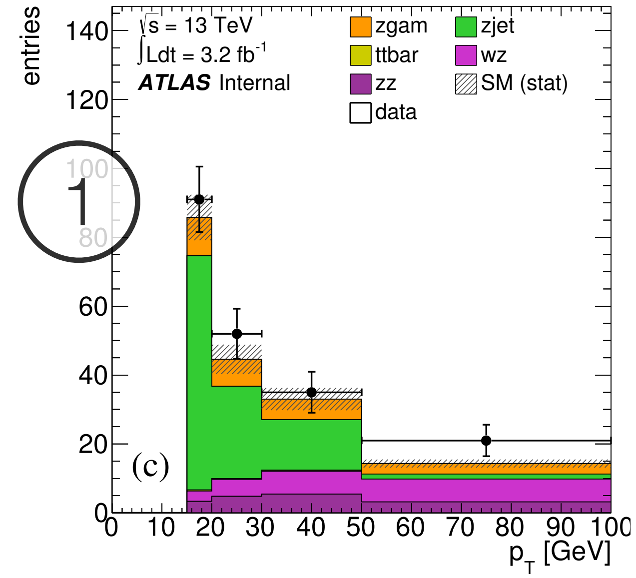
[1] ATLAS Collaboration, *Measurements of Higgs boson production and couplings in the four-lepton channel in pp collisions at center-of-mass energies of 7 and 8 TeV with the ATLAS detector*, Phys. Rev. D **91** (2015) 012006, arXiv:1408.5191 [hep-ex]. (document)

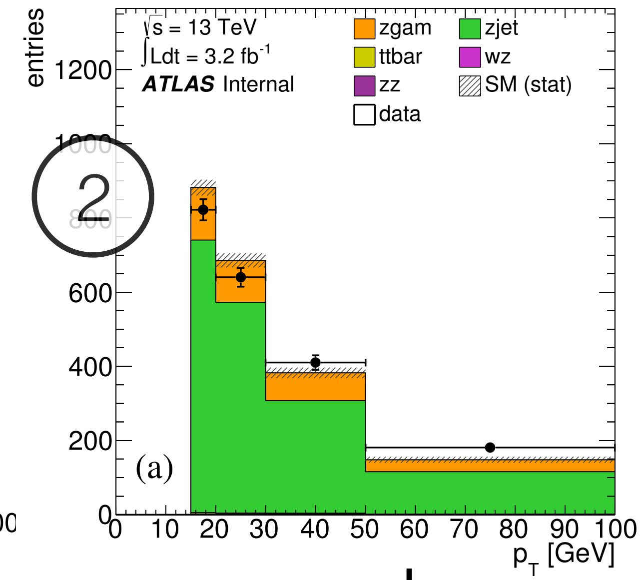
W→ℓ'νℓℓ

[8] ATLAS Collaboration, M. Aaboud et al., *Measurement of the* $W^{\pm}Z$ *boson pair-production cross section in pp collisions at* $\sqrt{s} = 13$ *TeV with the ATLAS Detector*, Submitted to Phys. Lett. **B** (2016) , arXiv:1606.04017 [hep-ex]. (document)

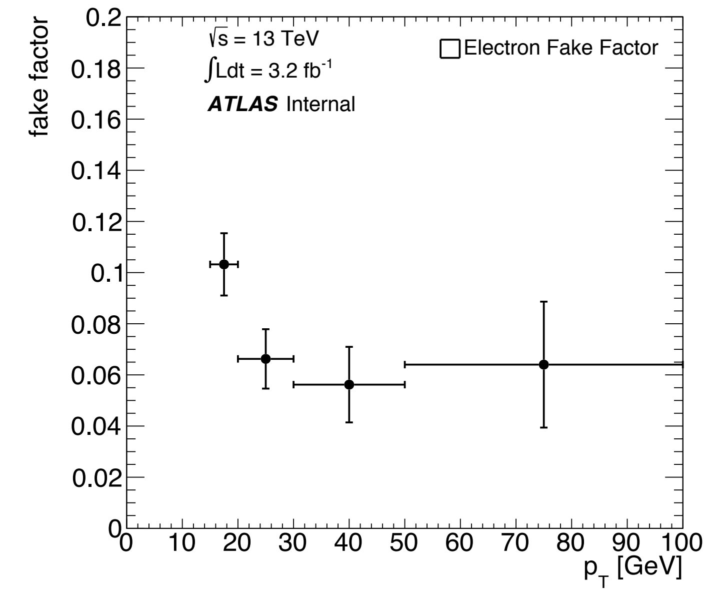
BACKUP

Fake Factor Method



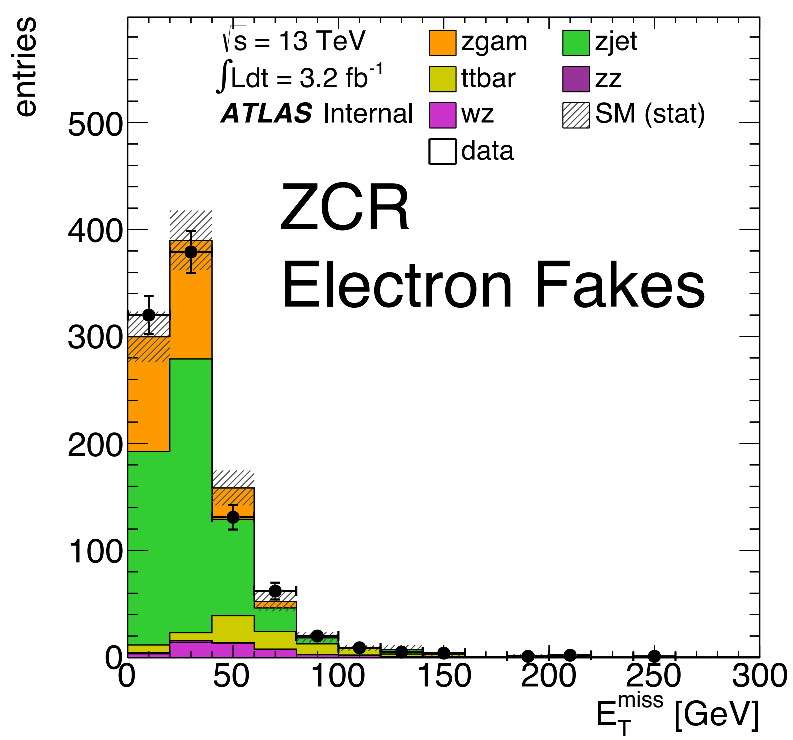


$$FF = \frac{N_{ID}}{N_{anti\text{-}ID}}$$

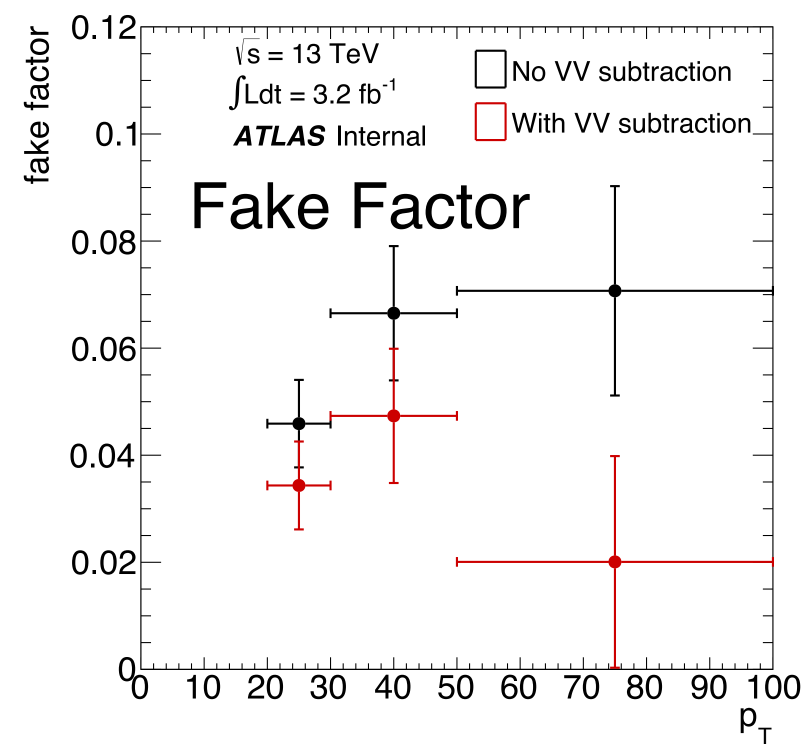


- Z+jet (3L) region:
  ($E_{TMiss} < 40$ GeV, $M_{TW} < 30$ GeV)
  - Assume that lepton assigned to the W is fake
  - Assume that Z+jet fakes in low-MET, low-M_T region are similar to Z+jet fakes in our SR (MT > 30 GeV)
- Define ID Numerator
  - analysis-level signal lepton ID
- Define "Anti-id" Denominator
  - Explicitly fail the numerator requirement
  - Very little signal contamination
  - Enhanced in the fake composition of interest
- Calculate FF: $N_{ID}/N_{anti\text{-}id}$ (in bins of p_T)

- Apply the fake factors to a CR with every SR cut applied, except one of the leptons is an "anti-ID"
- In fact there are 3 CRs where we apply the FF:
  - "LTT" ($L_W T_{Z1} T_{Z2}$) - typical Z+Jet Topology
  - "TLT" - mispaired Z+Jet
  - "TTL" - mispaired Z+Jet
- We'll ignore the mispairing regions in the eμμ and μee channels
- Looking at these control regions we will spot challenges:
  - ttbar contamination
  - WZ contamination



x



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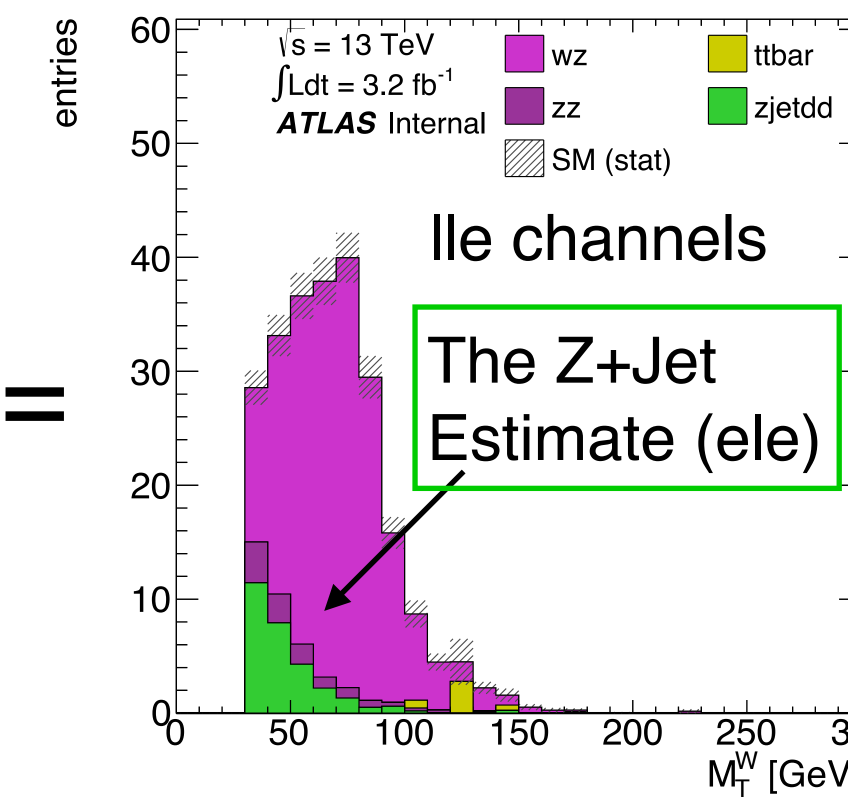
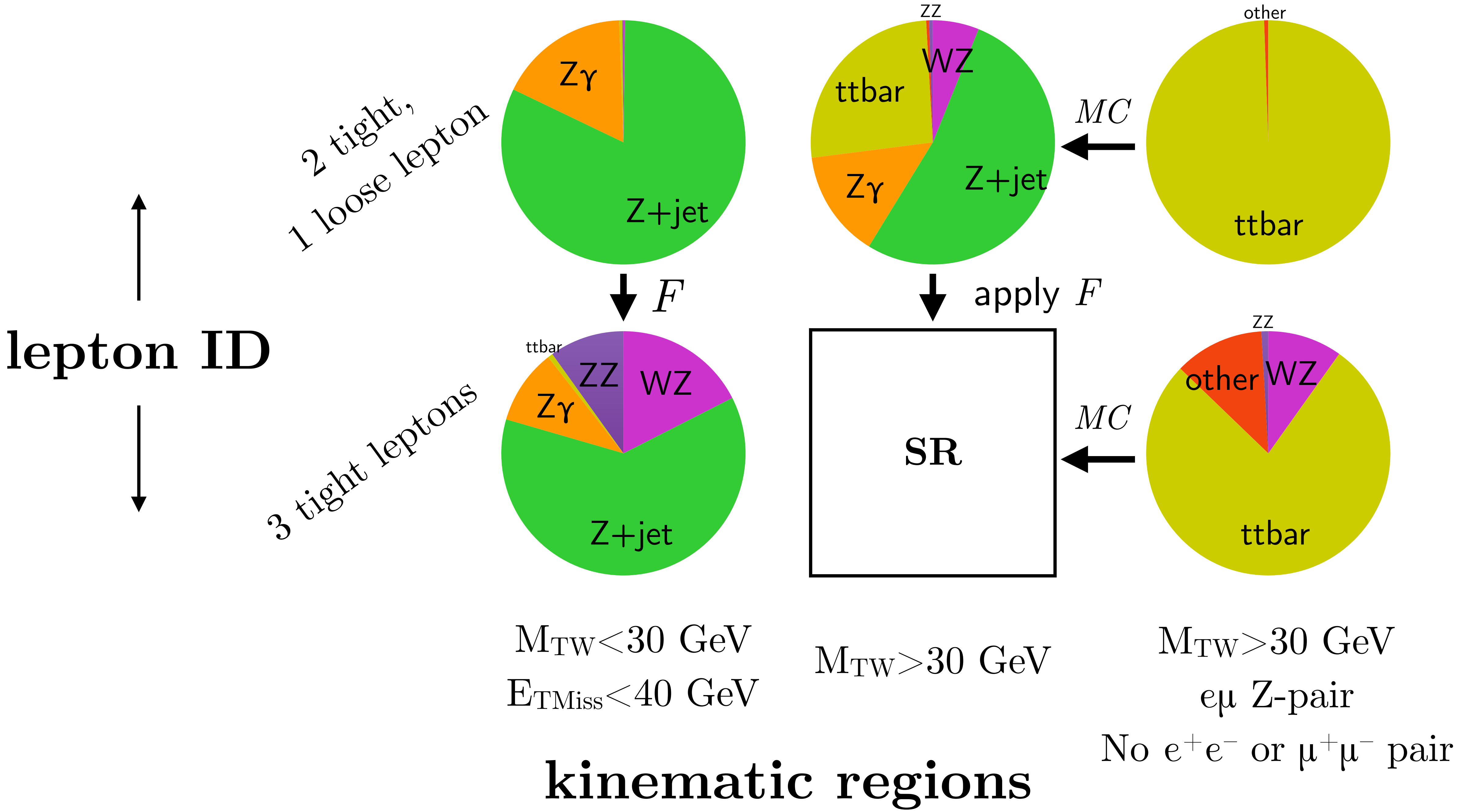


Estimating Z+jet / Zγ



WZ - Full Expected and Observed events

Channel	eee	μee	$e\mu\mu$	$\mu\mu\mu$	All
Data	98	122	166	183	569
Total Expected	104 $\pm$ 10	120 $\pm$ 10	128 $\pm$ 11	161 $\pm$ 12	510 $\pm$ 40
WZ (Powheg+Pythia8)	75 $\pm$ 6	98 $\pm$ 8	98 $\pm$ 8	131 $\pm$ 11	403 $\pm$ 32
$Z+j$, $Z\gamma$	16 $\pm$ 7	7 $\pm$ 5	14 $\pm$ 7	9 $\pm$ 5	45 $\pm$ 17
ZZ	6.8 $\pm$ 0.7	8.8 $\pm$ 1.0	8.7 $\pm$ 0.9	11.9 $\pm$ 1.2	36 $\pm$ 4
$t\bar{t}+V$	2.7 $\pm$ 0.4	3.3 $\pm$ 0.4	2.9 $\pm$ 0.4	3.5 $\pm$ 0.5	12.3 $\pm$ 1.6
$t\bar{t}$, Wt, $WW+j$	1.2 $\pm$ 0.8	2.0 $\pm$ 0.9	2.4 $\pm$ 0.9	3.6 $\pm$ 1.5	9.2 $\pm$ 3.1
tZ	1.30 $\pm$ 0.21	1.67 $\pm$ 0.27	1.65 $\pm$ 0.26	2.16 $\pm$ 0.34	6.8 $\pm$ 1.1
VVV	0.24 $\pm$ 0.04	0.29 $\pm$ 0.05	0.27 $\pm$ 0.04	0.35 $\pm$ 0.06	1.16 $\pm$ 0.18

Systematic uncertainties

	eee	μee	$e\mu\mu$	$\mu\mu\mu$	combined
Relative uncertainties [%]					
e energy scale	0.5	0.2	0.3	<0.1	0.2
e id. efficiency	1.4	1.1	0.6	—	0.7
μ momentum scale	<0.1	<0.1	<0.1	0.1	<0.1
μ id. efficiency	—	0.6	1.0	1.4	0.7
$E_{\mathrm{T}}^{\mathrm{miss}}$ and jets	0.3	0.4	0.8	0.7	0.6
Trigger	<0.1	0.1	0.1	0.2	0.1
Pile-up	0.7	1.1	1.0	0.7	0.9
Misid. lepton background	10	4.6	4.8	3.2	3.6
ZZ background	1.0	0.7	0.6	0.7	0.7
Other backgrounds	0.5	0.5	0.3	0.3	0.4
Uncorrelated	2.2	1.3	1.4	1.7	0.8
Total sys. uncertainty	11	5.1	5.3	4.1	4.1
Luminosity	2.4	2.4	2.3	2.3	2.4
Statistics	14	11	10	8.8	5.1
Total	18	12	11	10	7.0

WZ Reconstruction-level distributions

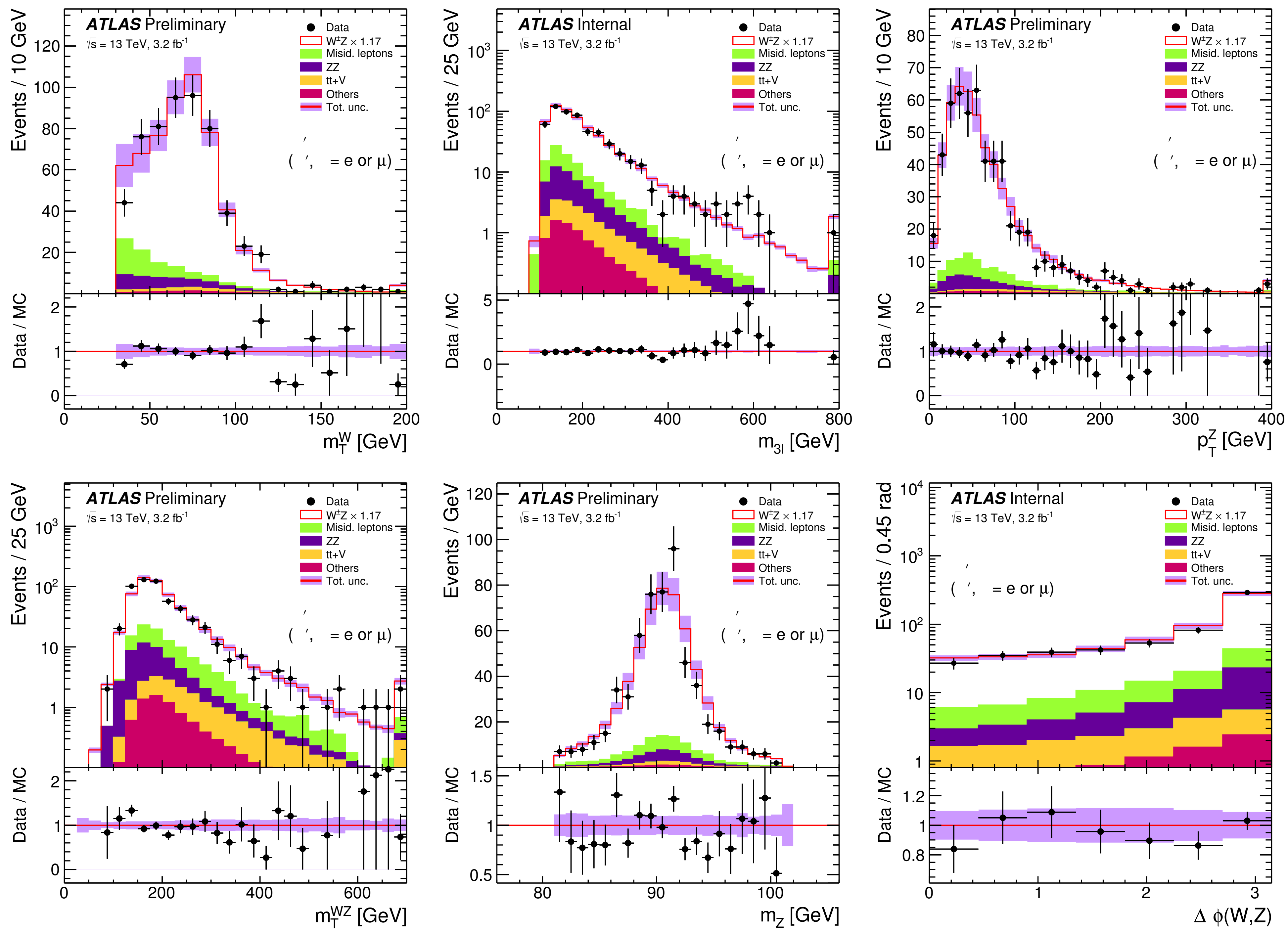


Figure 8.20: Reconstructed signal-level distributions in the WZ signal region. The Powheg+Pythia8 MC prediction is used for the WZ signal contribution, scaled by a global factor of 1.17 to match the measured inclusive WZ cross section.

Electron Efficiency Measurements

- Made efficiency measurements via Z→ee events
- "Tag and probe" method
- "Tag" a well-identified electron
- Second "probe" leg is unbiased
- Use m_{ee} to discriminate signal
- Background subtraction via templates from data
  - Apply same tag and probe method, but
  - Reverse an ID menu or suite of cuts on the probe
  - Take the m_{ee} shape from this selection
  - Normalize template to high-mll tail (mostly bkg)
- 2012-2013: re-optimized templates and refined method
  - Roughly a 50% reduction in uncertainties vs previous methods
  - Result: ~5% uncertainty on low-pT electrons
  - Results used by entire ATLAS collaboration