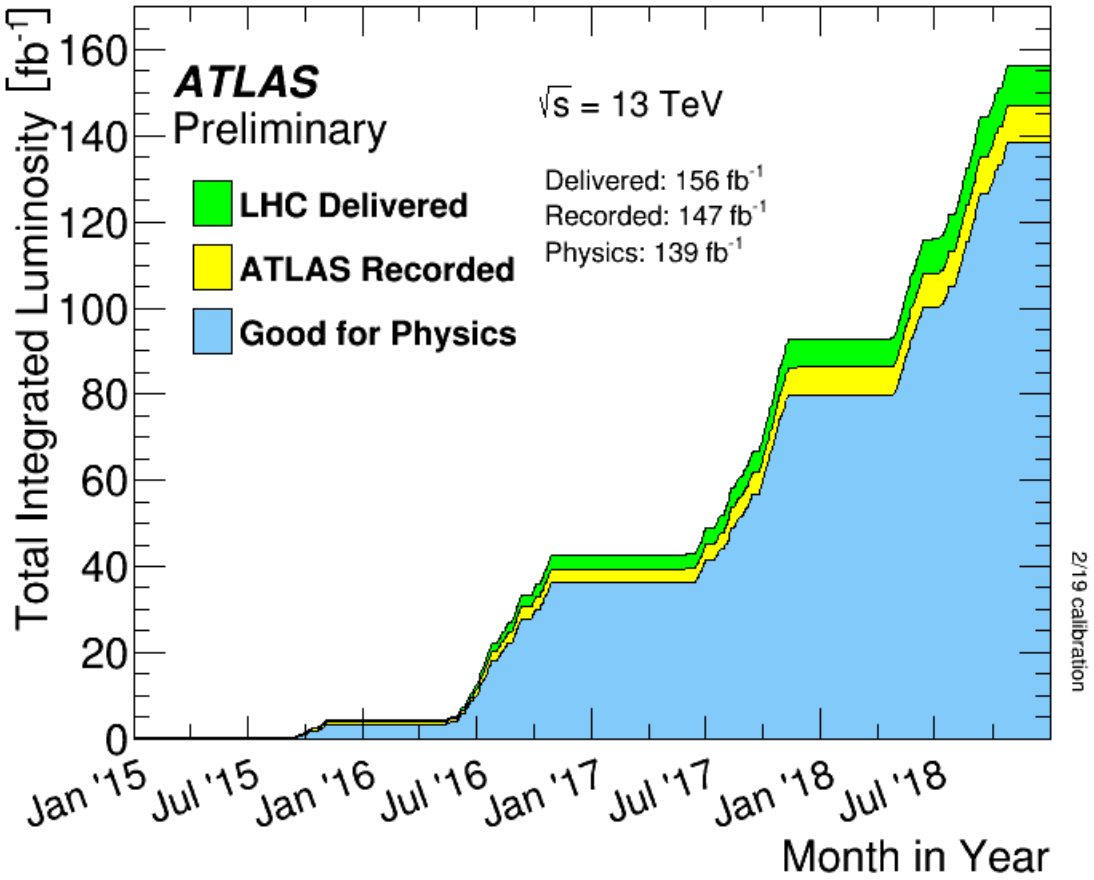
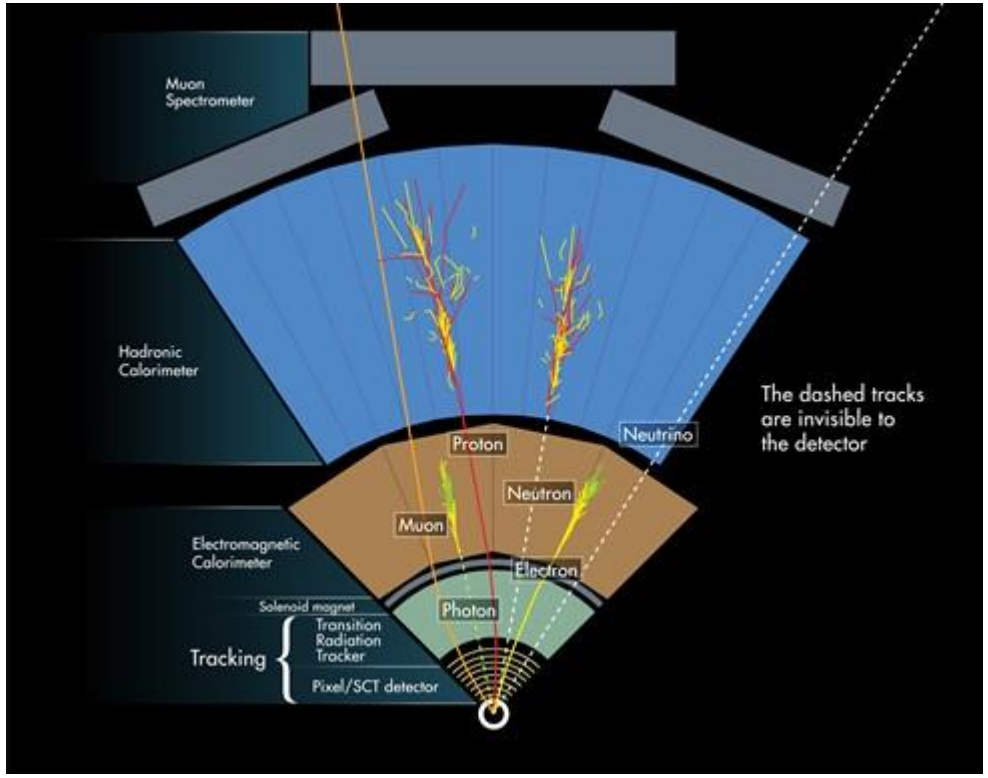
Measurements of Inclusive Multi-Boson Production at ATLAS

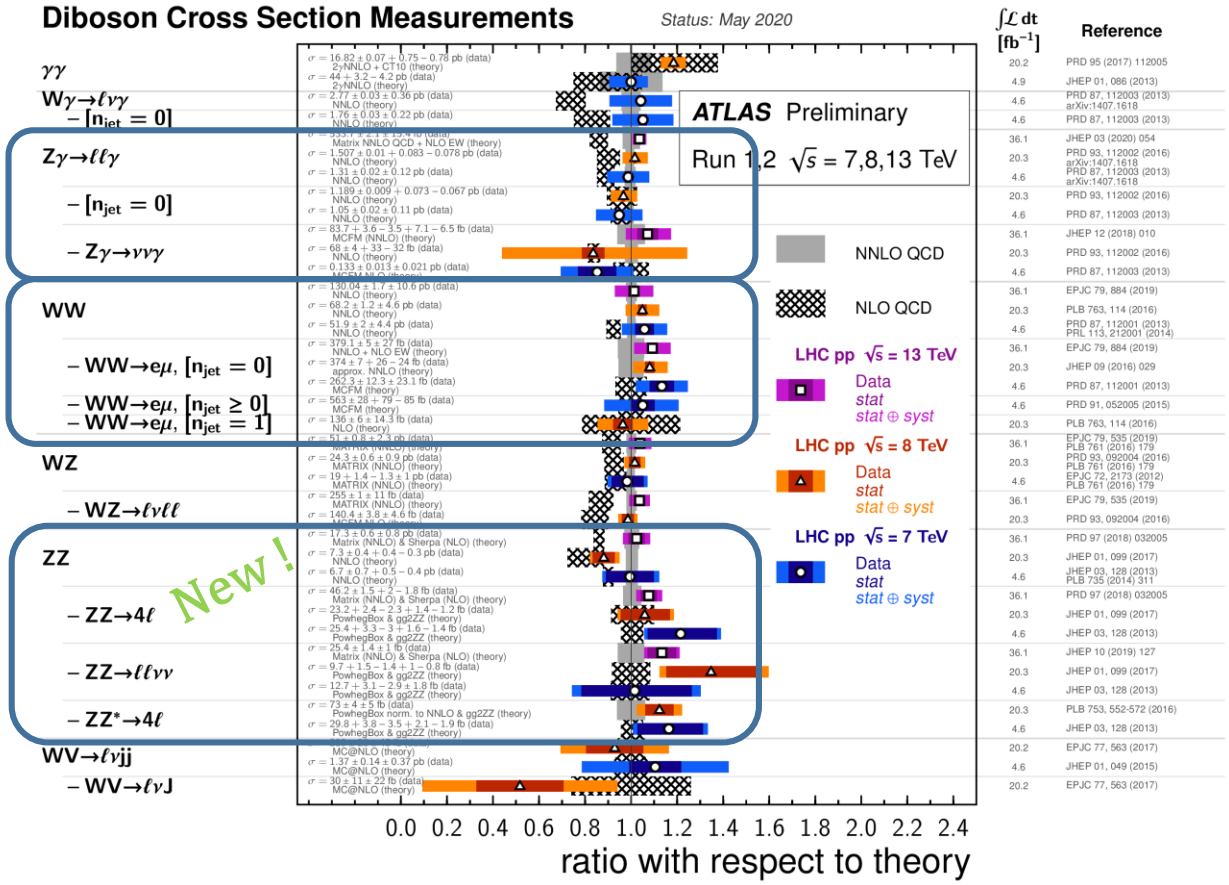
Siyuan Sun, Ph.D. on Behalf of the ATLAS Collaboration

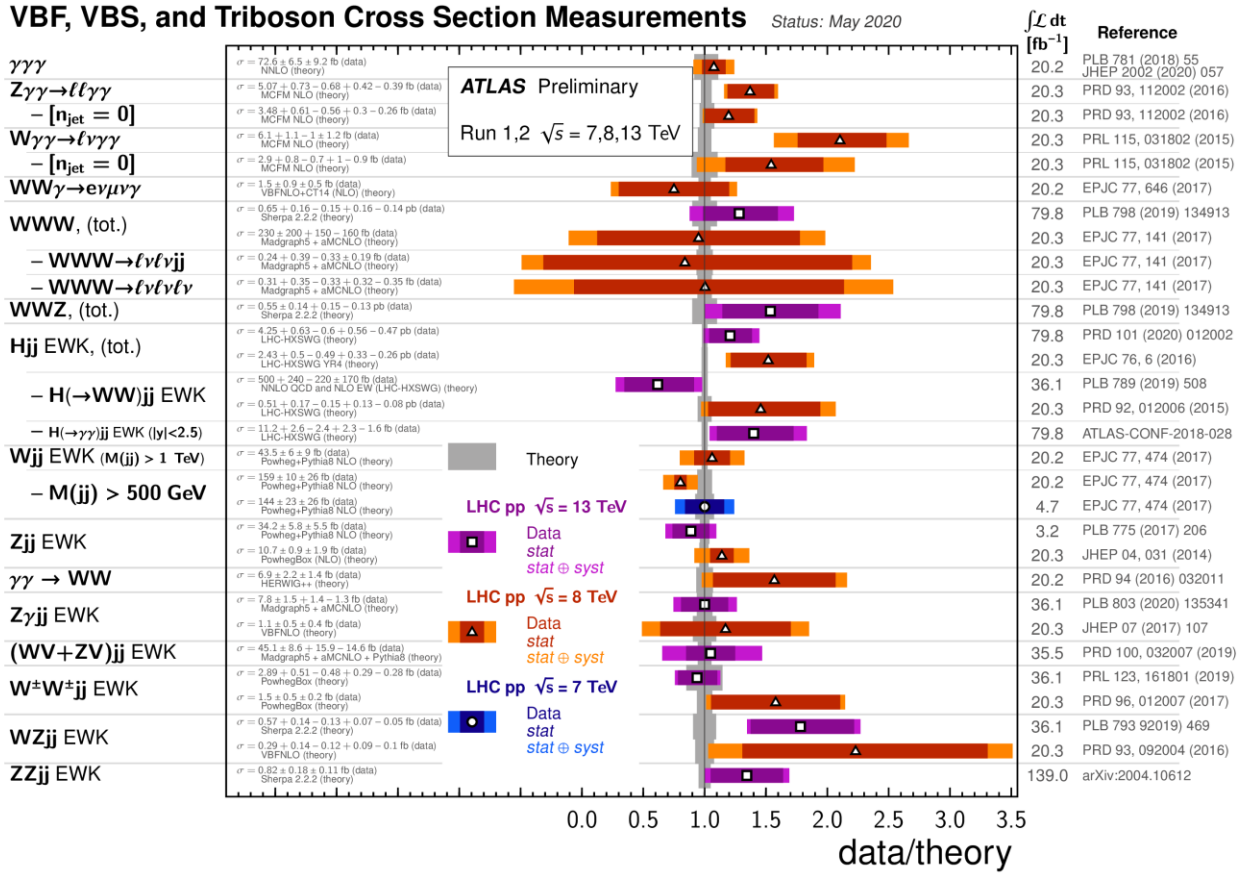
ATLAS Detector and Data





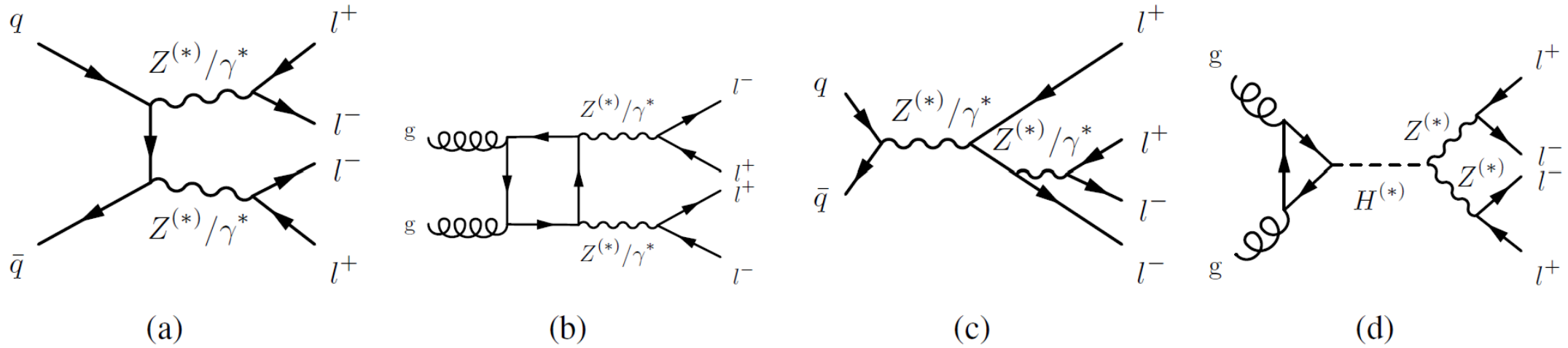
Summary of EWK Measurements at ATLAS





https://twiki.cern.ch/twiki/bin/view/AtlasPublic/StandardModelPublicResults

Inclusive m4l Measurement



- New result with full 139 fb^{-1} dataset
- Inclusive measurement of 4l production from 20 GeV < m4l < 2 TeV
- Optimized for inclusivity and model independence

- More details can be seen in the post session
  https://indico.cern.ch/event/868940/contributions/3816387/
  https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2020-042/

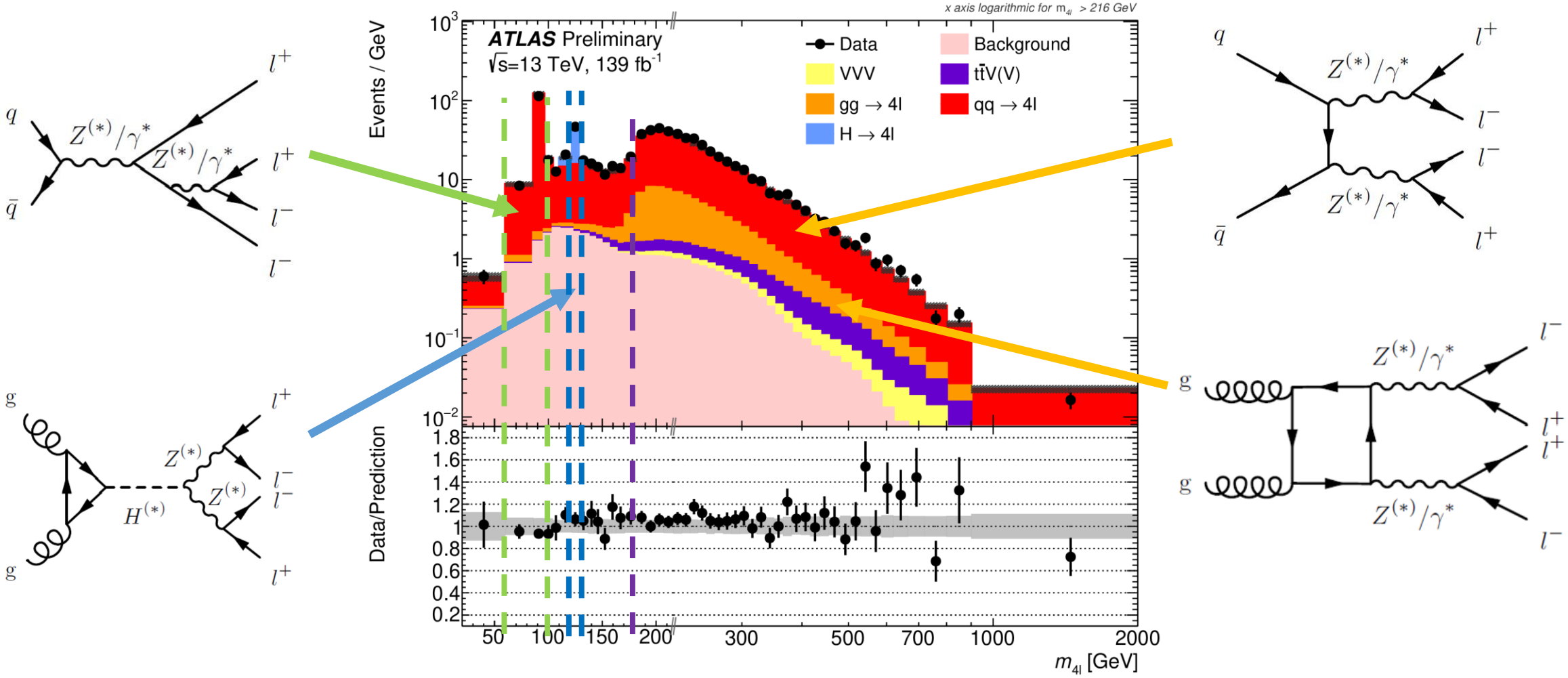
Inclusive m4l Measurement

- Select isolated, high quality, muons pT > 5 GeV and electrons pT > 7 GeV
- Select events with at least 2 e^+e^- and/or $\mu^+\mu^-$ pairs.
  - If more than 2, select the two with mass closest to the Z mass

Category	Requirement
Event Preselection	Fire at least one lepton trigger $\geq$1 vertex with 2 or more tracks
Four-lepton signature	At least 4 leptons (e, μ)
Lepton kinematics	$p_T > 20/10$ GeV for leading two leptons
Lepton separation	$\Delta R_{ij} > 0.05$ for any two leptons
J/ψ-Veto	$m_{ij} > 5$ GeVfor all SFOS pairs
Trigger matching	Baseline leptons matched to at least one lepton trigger
Quadruplet formation	At least one quadruplet with 2 Same-Flavour, Opposite-Sign (SFOS) pairs
Quadruplet categorisation	4 signal, 0 non-signal: signal region $\leq$ 3 signal, $\geq$ 1 non-signal: background control region

Suppresses J/ψ and photon conversions

Inclusive m4l Signal Region



Non-Prompt Lepton Bkg Estimation

- Estimate using Z+jet events where the hadronic jet is mis-identified as a lepton
- $Fake\ Factor = \frac{Events\ with\ Isolated\ Lepton}{Events\ of\ Non{-}Isolated\ Lepton}$
- Apply the factor to signal-like region but with non-isolated leptons to estimate background rate in the signal region

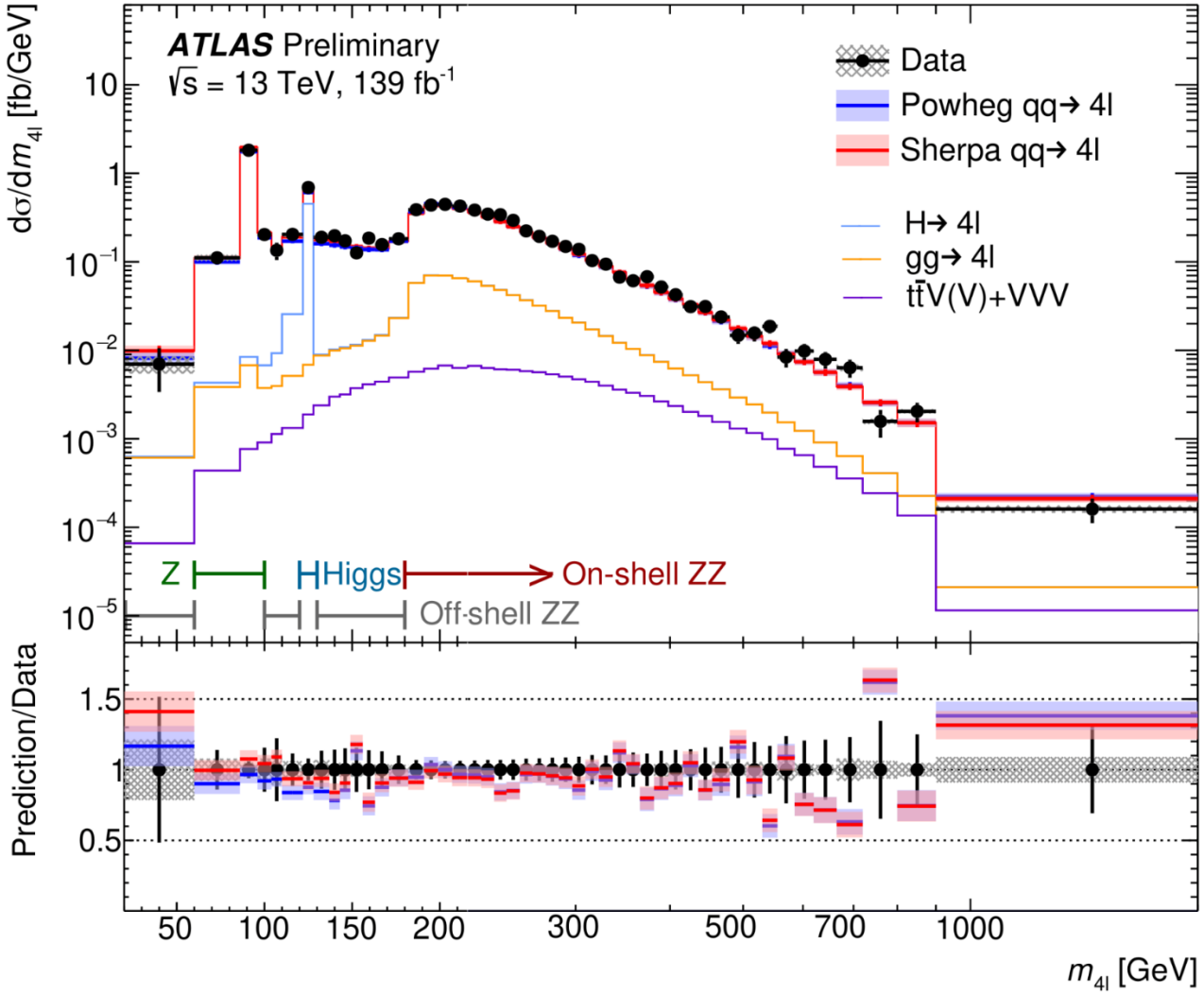
- Validated in signal-like regions but with lepton-pairs that have the same charge

Differential Cross-Section in m4l

- Fiducial cross-section is defined as the cross-section within the fiducial phase space under the area with detector coverage.

$$\sigma_{\text{fid}} = \frac{N_{\text{obs}} - N_{\text{bkg}}}{C \times \mathcal{L}}$$

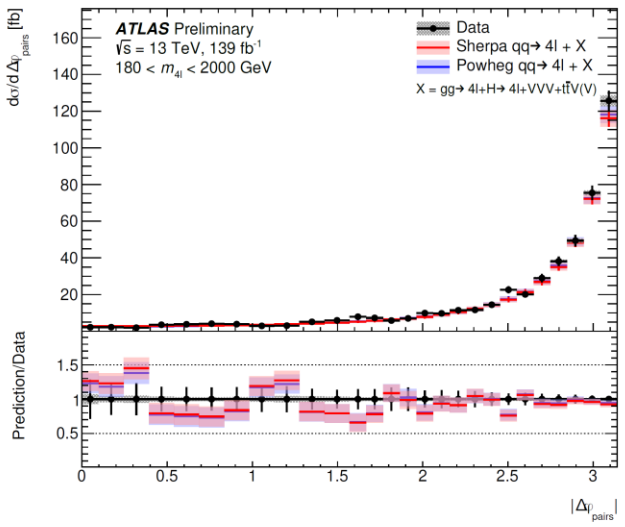
- Where $\mathcal{L}$ is the integrated luminosity and C is the correction factor that accounts for resolution and reconstruction efficiency



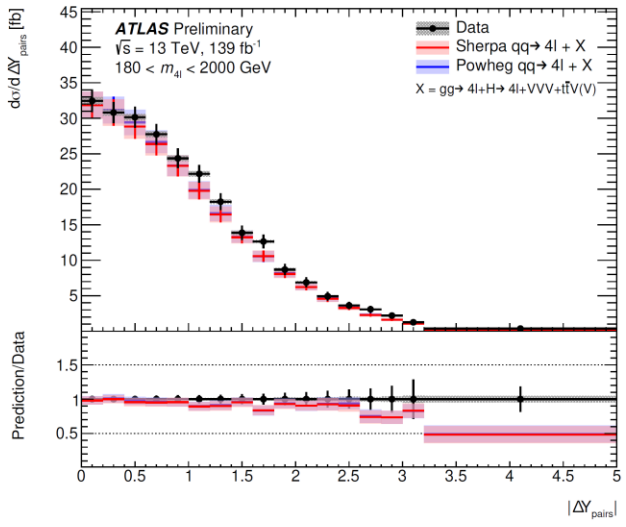
Differential Cross Sections

- Differential cross sections are also measured with respect to
  1. m_{12}, m_{34} lepton pair mass
  2. $|\Delta\varphi_{pairs}|, |\Delta y_{\text{pairs}}|$
  3. $P_{T\ 12}, P_{T\ 34}$ lepton pair pT
  4. $|\Delta\varphi_{leading\ leptons}|$
  5. $|\cos\theta^*_{12}|, |\cos\theta^*_{34}|$ decay angles for each lepton pairs

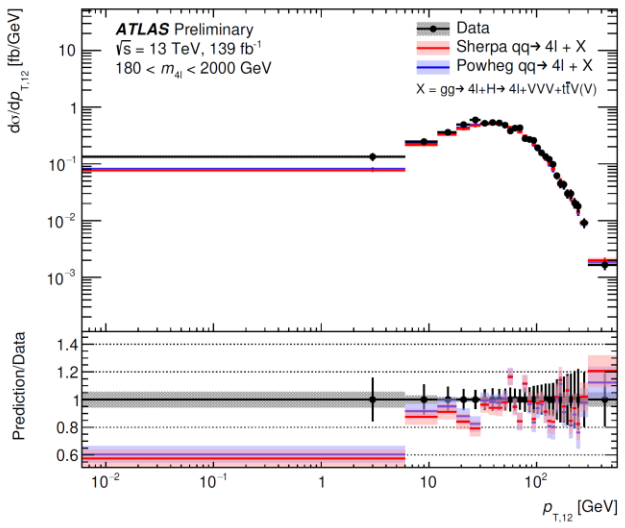
- Different differential cross section distributions is sensitive to different BSM physics



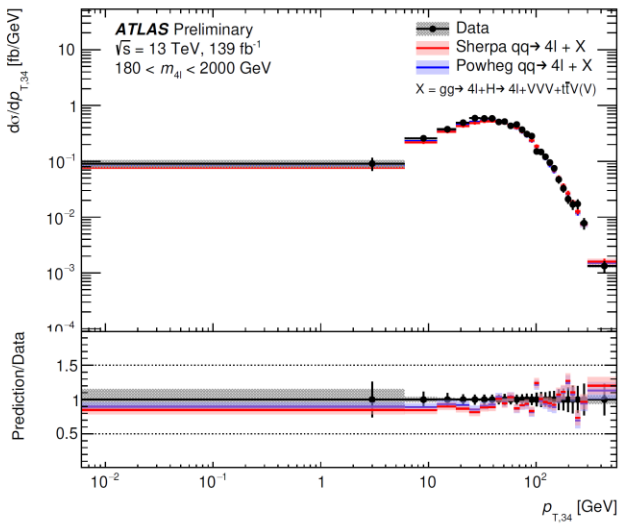
(a) $|\Delta\phi_{\text{pairs}}|$



(b) $|\Delta y_{\text{pairs}}|$



(c) $p_{\text{T},12}$



(d) $p_{\text{T},34}$

B – L Symmetry Interpretation

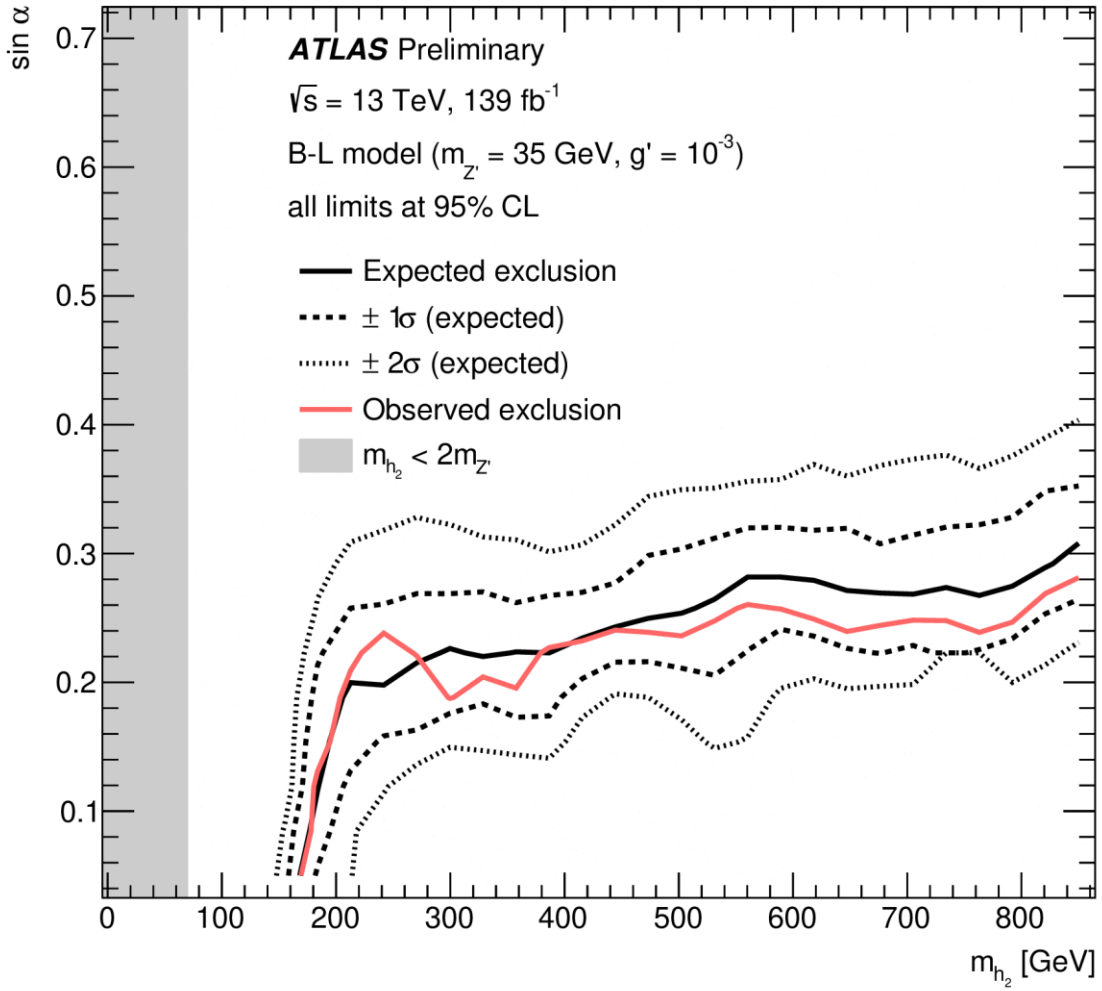
- Baryon Number – Lepton Number is a conserved quantity in SM
- Introduce additional $U_{B\text{-}L}(1)$ gauge symmetry that is broken with another Higgs

$$SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)_{B-L}$$

- Z'Z' production contribute to the 4l cross-section.

m_{h_2} ~ mass of the second Higgs particle

$\sin\alpha$ ~ mixing angle between the SM and B-L Higgs fields



Zγ Production Cross-Section Measurement

- Differential cross section measurement with 139 fb^{-1} of data
- Published March 2020 at ***JHEP 03 (2020) 054***

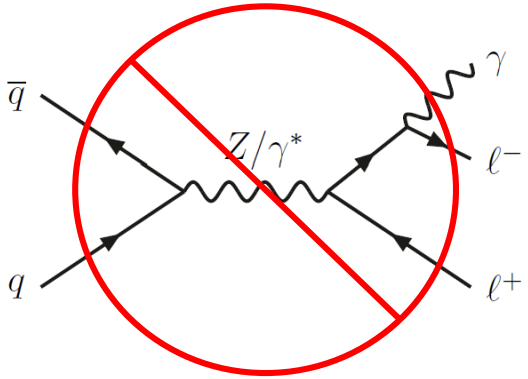
	Photons	Electrons	Muons
Kinematics:	$E_T > 30$ GeV	$p_T > 30, 25$ GeV	$p_T > 30, 25$ GeV
	$\lvert\eta\rvert < 2.37$	$\lvert\eta\rvert < 2.47$	$\lvert\eta\rvert < 2.5$
	excl. $1.37 < \lvert\eta\rvert < 1.52$	excl. $1.37 < \lvert\eta\rvert < 1.52$	
Identification:	Tight [59]	Medium [59]	Medium [60]
Isolation:	FixedCutLoose [59]	FCLoose [59]	FCLoose_FixedRad [60]
	$\Delta R(\ell, \gamma) > 0.4$	$\Delta R(\mu, e) > 0.2$	
Event selection:	$m(\ell\ell) > 40$ GeV,	$m(\ell\ell) + m(\ell\ell\gamma) > 182$ GeV	

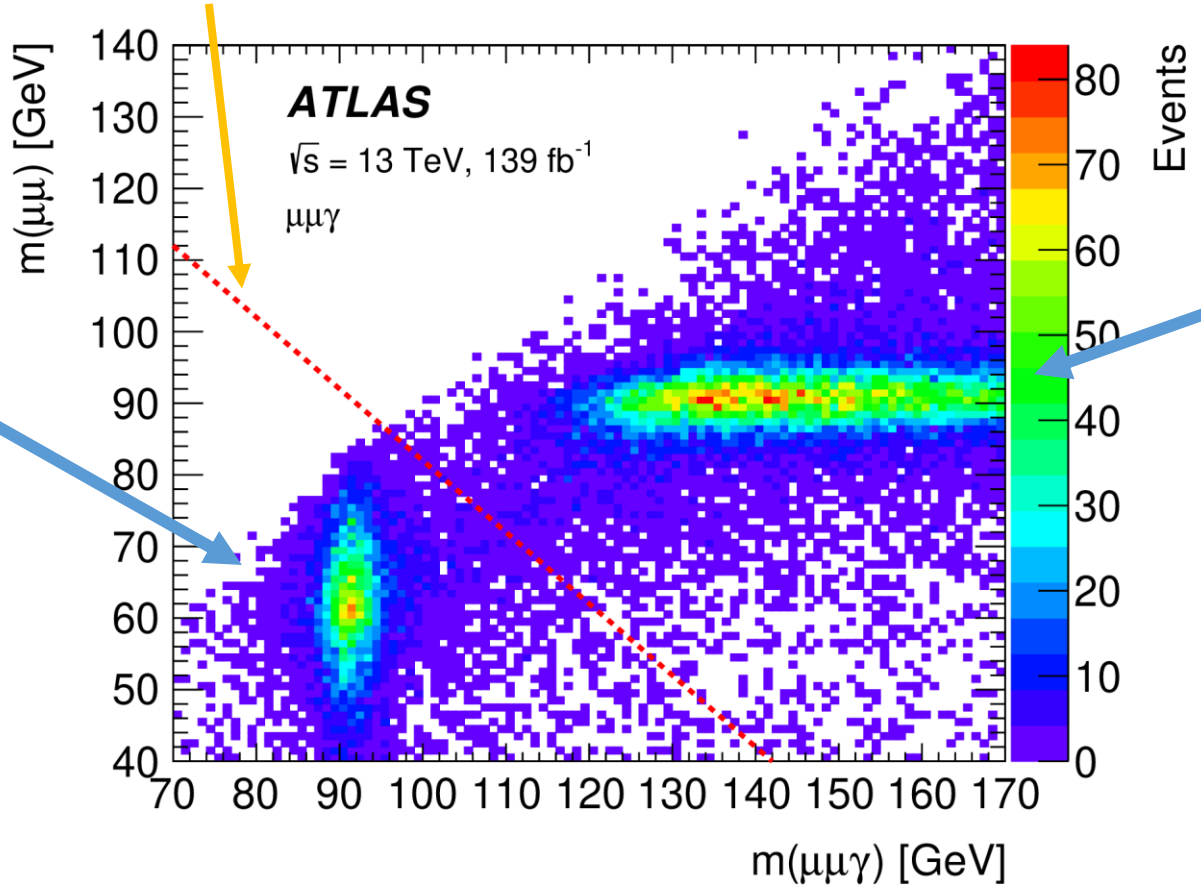
Reject events where photon is a part of the Z decay

Zγ Signal Region Rejects FSR photons

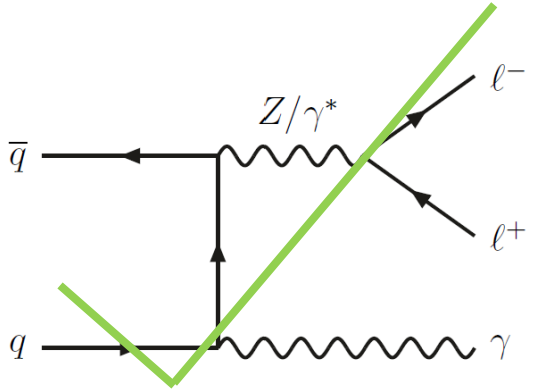
$m(ll) + m(ll\gamma) > 182$ GeV Cut

Reject Z bosons that also emits a final state radiation photon

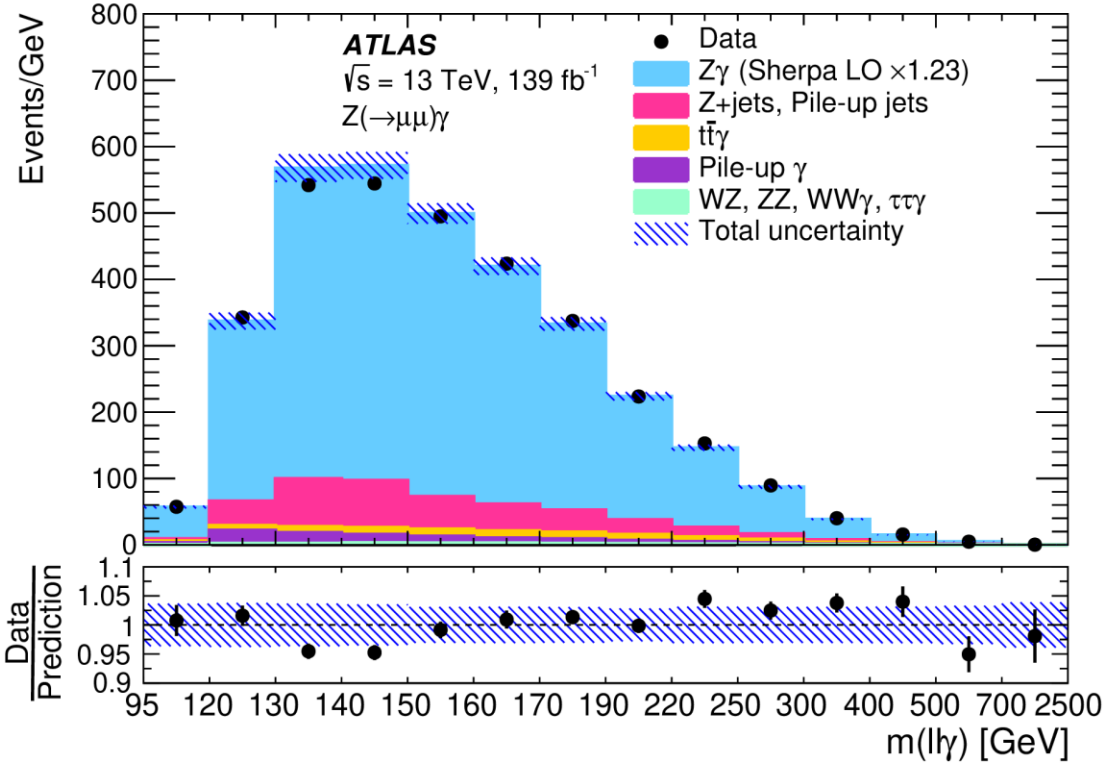


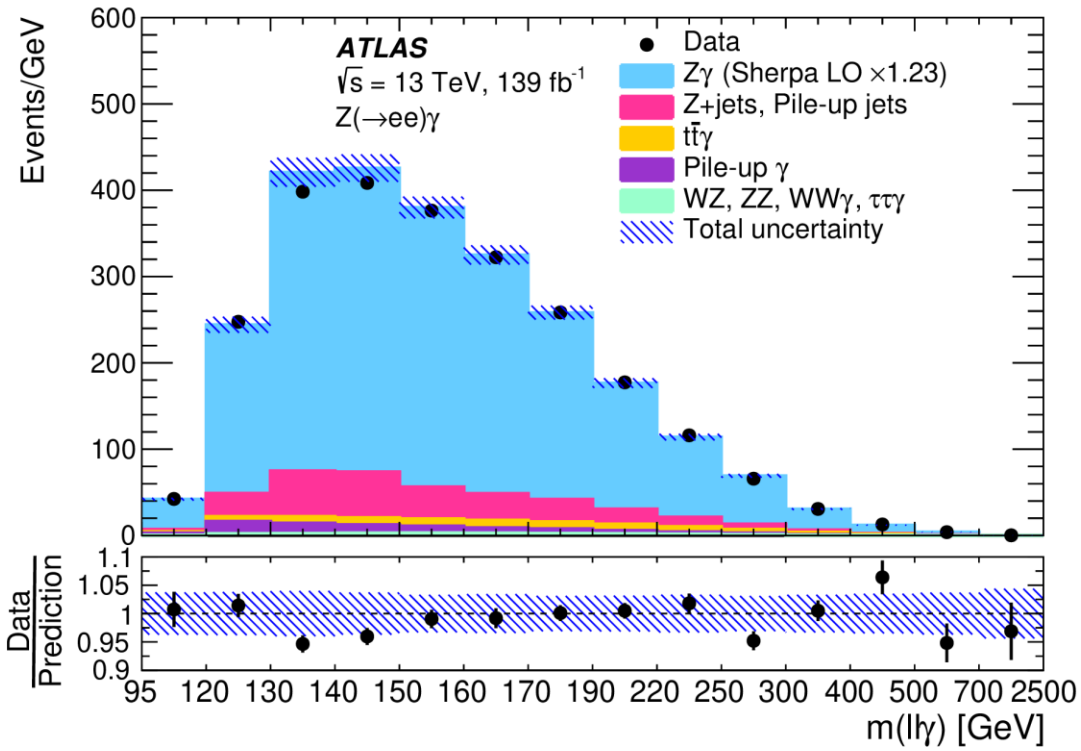


Accept Zγ events where the photon is part of the initial state radiation



Zγ Signal Region Distribution





- Major background also include Z+jets where jets are mis-reconstructed as photons

Measurement of Fiducial Cross-Section

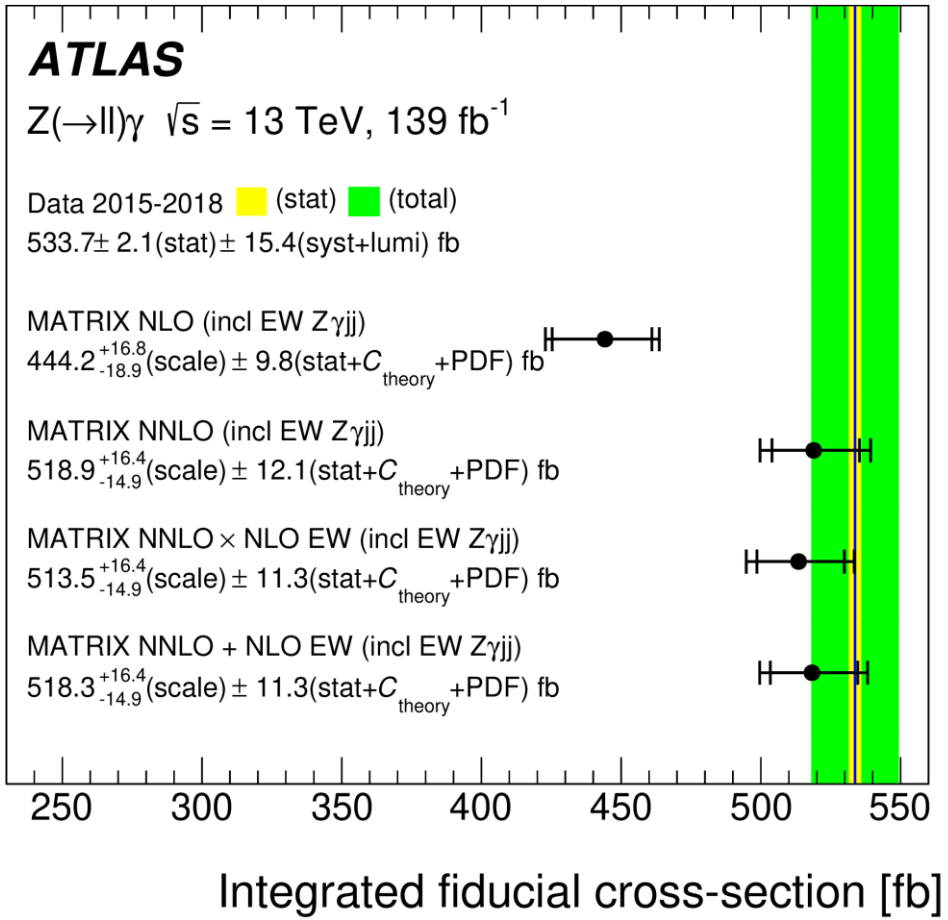
- Fiducial cross-section is defined as the cross-section within the fiducial phase space under the area with detector coverage.

$$\sigma_{\text{fid}} = \frac{N_{\text{obs}} - N_{\text{bkg}}}{C \times \mathcal{L}}$$

- Where $\mathcal{L}$ is the integrated luminosity and C is the correction factor that accounts for detector resolution and reconstruction efficiency
- C is estimated using Zγ MC

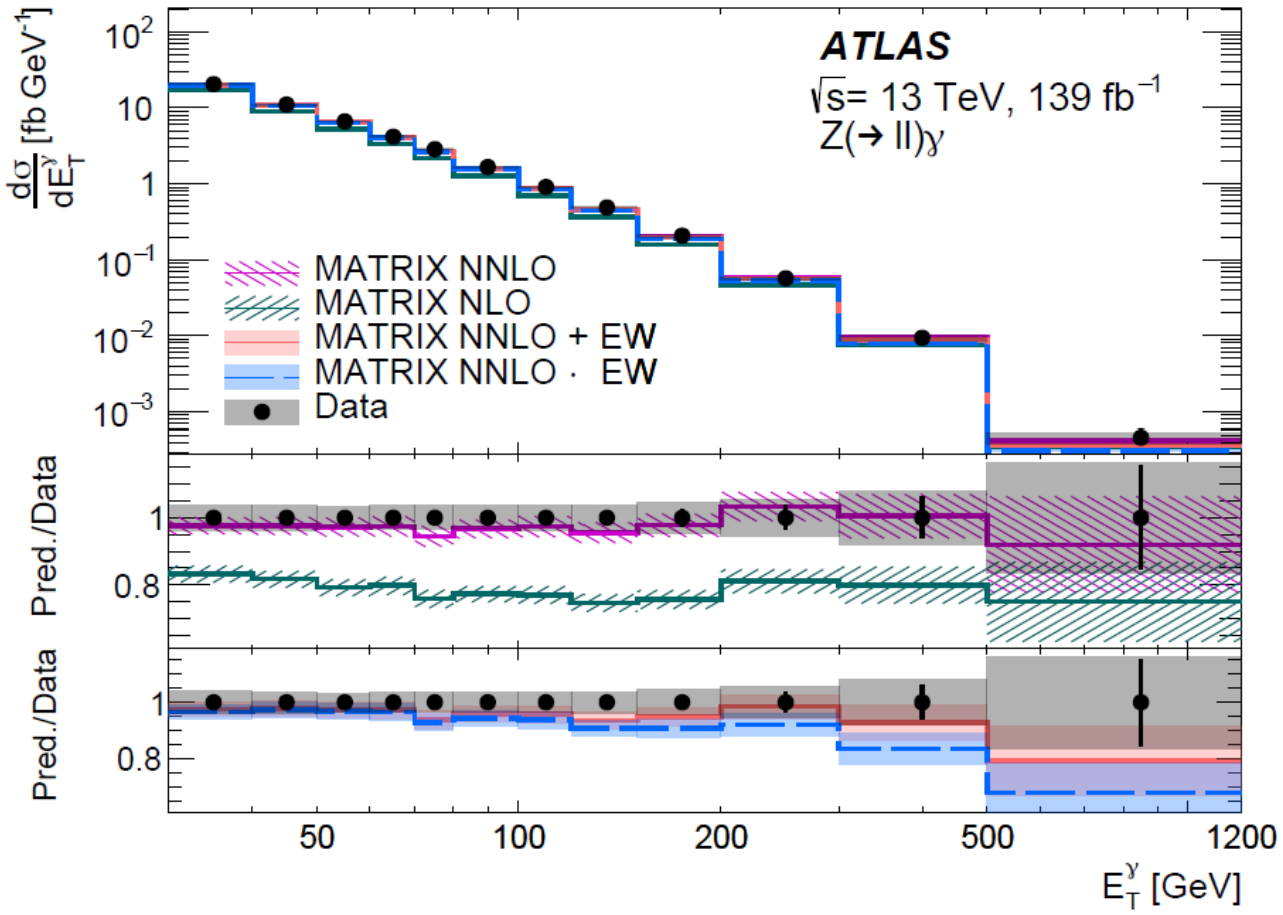
$$\sigma_{\text{fid}} = 533.7 \pm 2.1(\text{stat}) \pm 12.4(\text{syst}) \pm 9.1(\text{lumi})\ \text{fb}\,.$$

- Measurements agrees Matrix NNLO and Sherpa NLO predicted cross-sections to within errors



Zγ Differential Cross Section

- Differential cross sections with respect to $E_T^\gamma, |\eta^\gamma|, m(ll\gamma), p_T^{ll\gamma}, p_T^{ll\gamma}/m(ll\gamma)$ and $\Delta\varphi(\mathrm{ll},\gamma)$ are all measured
- Both NLO EW and NNLO QCD correction for Zγ cross-section has been computed.
- However no complete computation of how to combine the two corrections
- The E_T^γ distribution agrees better with the combining the two additively instead of multiplicatively

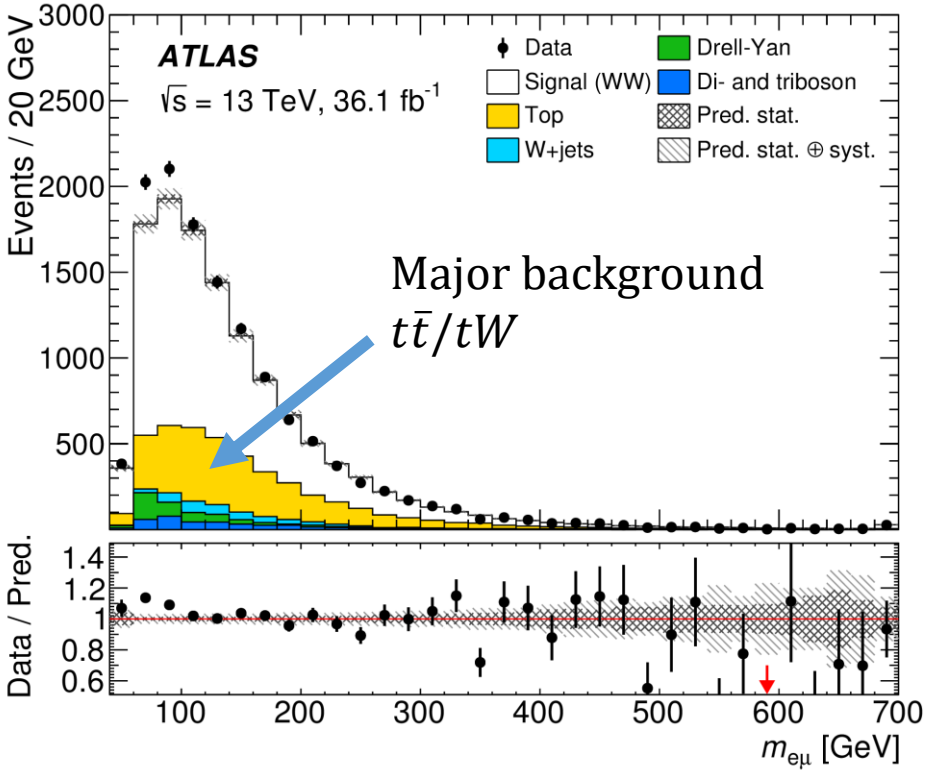


WW Differential Cross Section Measurement

- Measured using 36 fb^{-1} of data
- Published October 2019 at ***Eur. Phys. J. C 79 (2019) 884***

Selection requirement	Selection value
p_T^{ℓ}	> 27 GeV
η^{ℓ}	$\lvert\eta^e\rvert < 2.47$ (excluding $1.37 < \lvert\eta^e\rvert < 1.52$), $\lvert\eta^\mu\rvert < 2.5$
Lepton identification	*TightLH* (electron), *Medium* (muon)
Lepton isolation	*Gradient* working point
Number of additional leptons (p_T > 10 GeV)	0
Number of jets (p_T >35 GeV, $\lvert\eta\rvert$ <4.5)	0
Number of *b*-tagged jets (p_T > 20 GeV, $\lvert\eta\rvert$ <2.5)	0
$E_T^{miss,track}$	> 20 GeV
$p_T^{e\mu}$	> 30 GeV
$m_{e\mu}$	> 55 GeV

Suppress top background



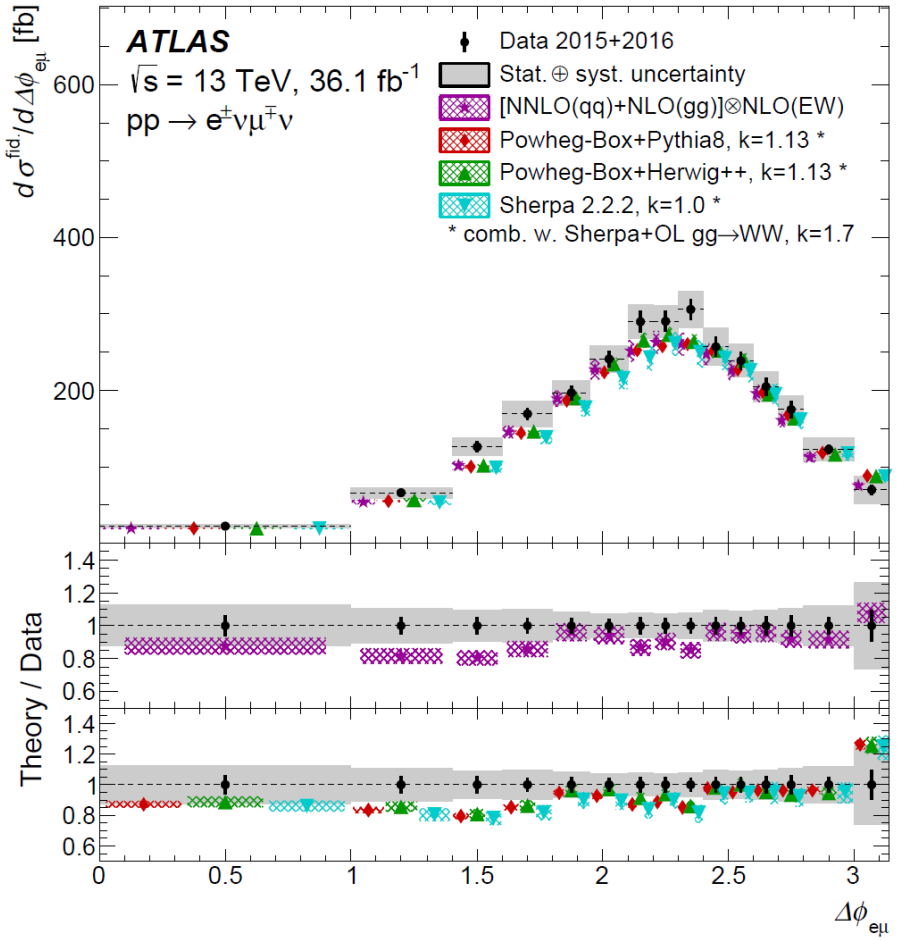
WW Results

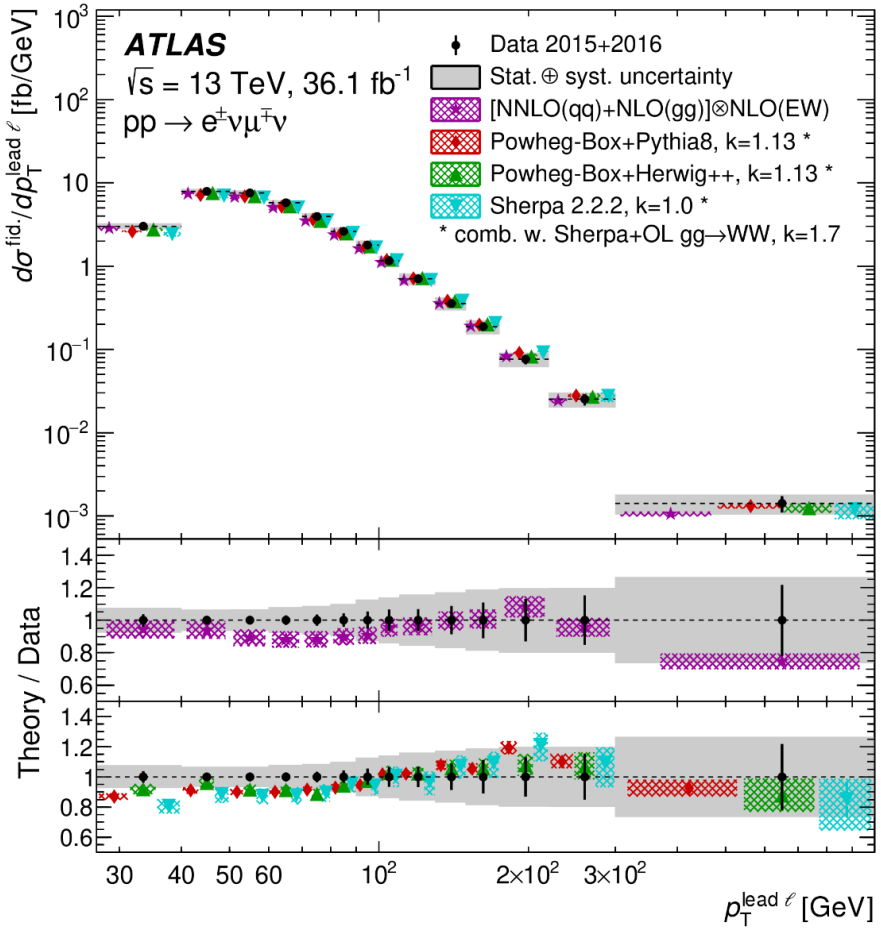
- Measured integrated fiducial cross section agrees well with NNLO predictions

$$\sigma_{\text{fid}} = (379.1 \pm 5.0\,(\text{stat}) \pm 25.4\,(\text{syst}) \pm 8.0\,(\text{lumi}))\,\text{fb}$$

Prediction	Reference	Normalization	σ_{fiducial} [fb]
MATRIX NNLO $q\bar{q} \to WW$ and $gg \to WW$ @ LO	[101–103]	–	357 ± 20
MATRIX NNLO $q\bar{q} \to WW$ and $gg \to WW$ @ NLO	[104]	–	368 ± 21
(MATRIX NNLO $q\bar{q}$ and gg @ NLO) × NLO EW	[105]	–	347 ± 20
Sherpa 2.1.1 + OpenLoops $gg \to WW$	[36]	NLO [104]	19.0 ± 1.9
Powheg-Box + Pythia 8 $q\bar{q} \to WW$ (+ Sh.+OL $gg \to WW$)	[30–34, 38]	NNLO [101–103]	350 ± 7
Powheg-Box + Herwig++ $q\bar{q} \to WW$ (+ Sh.+OL $gg \to WW$)	[30–34, 41]	NNLO [101–103]	357 ± 11
Sherpa 2.2.2 $q\bar{q} \to WW$ (+ Sh.+OL $gg \to WW$)	[54]	NNLO [101–103]	341 ± 20

WW Differential Cross-Sections





- MC under predicts cross-section at low lead lepton pT and $\Delta\varphi_{e\mu}$
- Global χ^2/DoF difference is still small. Max 18.5/14 for Sherpa+OpenLoop in $p_T^{lead\ \ell}$

WW Measurement: Limit on aTGC

- 5 dimension six operators can be added to the SM lagrangian to parameterize the effects of BSM physics in an model independent way

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i + \cdots$$

- Limits can be placed on the dimensionless coefficients c_i

$$\begin{aligned}
\mathcal{O}_{WWW} &= \mathrm{Tr}[W_{\mu\nu}W^{\nu\rho}W^{\mu}_{\rho}] \\
\mathcal{O}_{W} &= (D_\mu\Phi)^\dagger W^{\mu\nu}(D_\nu\Phi) \\
\mathcal{O}_{B} &= (D_\mu\Phi)^\dagger B^{\mu\nu}(D_\nu\Phi) \\
\mathcal{O}_{\tilde{W}WW} &= \mathrm{Tr}[\tilde{W}_{\mu\nu}W^{\nu\rho}W^{\mu}_{\rho}] \\
\mathcal{O}_{\tilde{W}} &= (D_\mu\Phi)^\dagger \tilde{W}^{\mu\nu}(D_\nu\Phi)
\end{aligned}$$

Parameter	Observed 95% CL [TeV^{-2}]	Expected 95% CL [TeV^{-2}]
c_{WWW}/Λ^2	$[-3.4, 3.3]$	$[-3.0, 3.0]$
c_W/Λ^2	$[-7.4, 4.1]$	$[-6.4, 5.1]$
c_B/Λ^2	$[-21, 18]$	$[-18, 17]$
$c_{\tilde{W}WW}/\Lambda^2$	$[-1.6, 1.6]$	$[-1.5, 1.5]$
$c_{\tilde{W}}/\Lambda^2$	$[-76, 76]$	$[-91, 91]$

Where

$$D_\mu = \partial_\mu + \frac{i}{2}g\tau^I W^I_\mu + \frac{i}{2}g' B_\mu$$

$$W_{\mu\nu} = \frac{i}{2}g\tau^I(\partial_\mu W^I_\nu - \partial_\nu W^I_\mu + g\epsilon_{IJK}W^J_\mu W^K_\nu)$$

$$B_{\mu\nu} = \frac{i}{2}g'(\partial_\mu B_\nu - \partial_\nu B_\mu)$$

Conclusion

- Lots of results and measurements coming from ATLAS
- Many I could not cover here today:
  ZZ production in the llνν final state
  https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2017-03/
  WZ production cross section and gauge boson polarization
  https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2018-03/
- Stay tuned for more updates in the coming months
  Please check the ATLAS SM public results twiki
  https://twiki.cern.ch/twiki/bin/view/AtlasPublic/StandardModelPublicResults

Backup Slides

M4l Analysis: Electrons and Muons

- Looser quality "Baseline" leptons are used in background estimation

Category	Requirement	
Kinematics	Muons :	$p_T > 5$ GeV If CaloTag: >15 GeV $\|\eta\| < 2.7$
	Electrons:	$p_T > 7$ GeV $\|\eta\| < 2.47$
Vertex association	Both :	$\|z_0 \sin\theta\|$ <0.5 mm
Identification:	Muons: Electrons:	Loose ID LooseLH ID
Overlap removal: Lepton-favoured		

- Tighter quality "signal" leptons with additional requirements on top of baseline requirements are used in for signal region measurement

Input objects	Baseline electrons and muons that are part of the quadruplet
Isolation	FixedCutPflowLoose working point *Contribution from all other baseline leptons is subtracted*
Cosmic muon veto	Muons: $\|d_0\|$ <1 mm
Impact Parameter	Muons: d_0/σ_{d_0} <3 Electrons: d_0/σ_{d_0} <5
Stricter Electron ID	Electrons: LooseBLayerLH ID

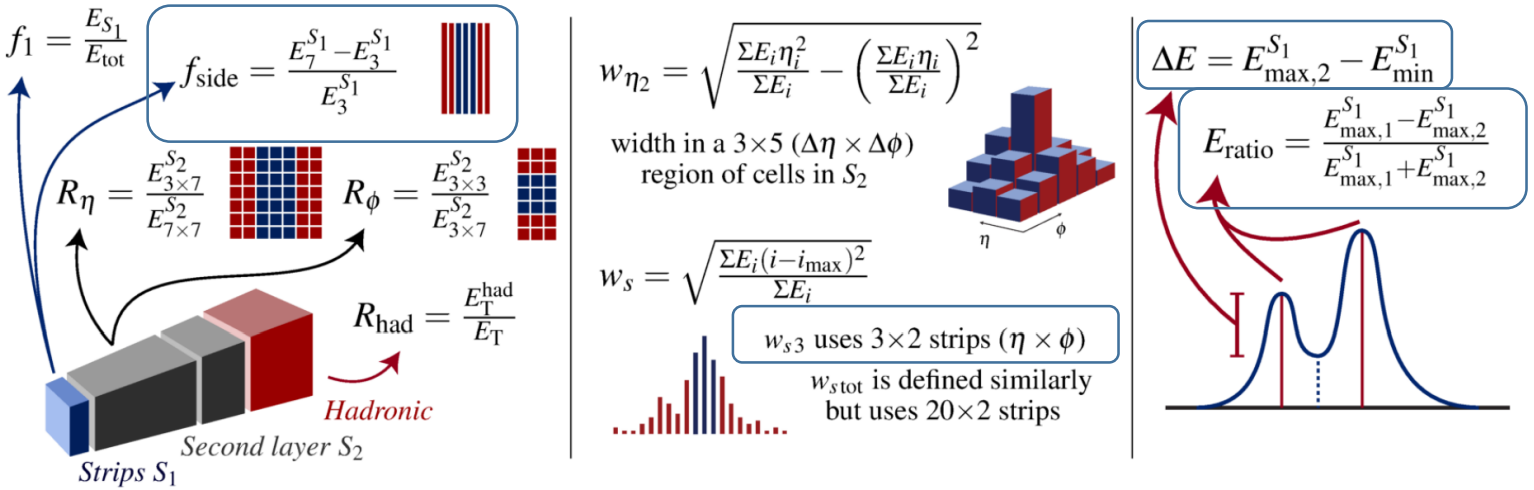
Zγ Analysis: Z+jet Estimation

https://arxiv.org/pdf/1810.05087.pdf

- Analogous to the non-prompt electron/muon estimation in the m4l analysis except now it's photons
- Measure the number of photons which fail quality/isolation
- The number of estimated Z+jets background events in the A is predicted by

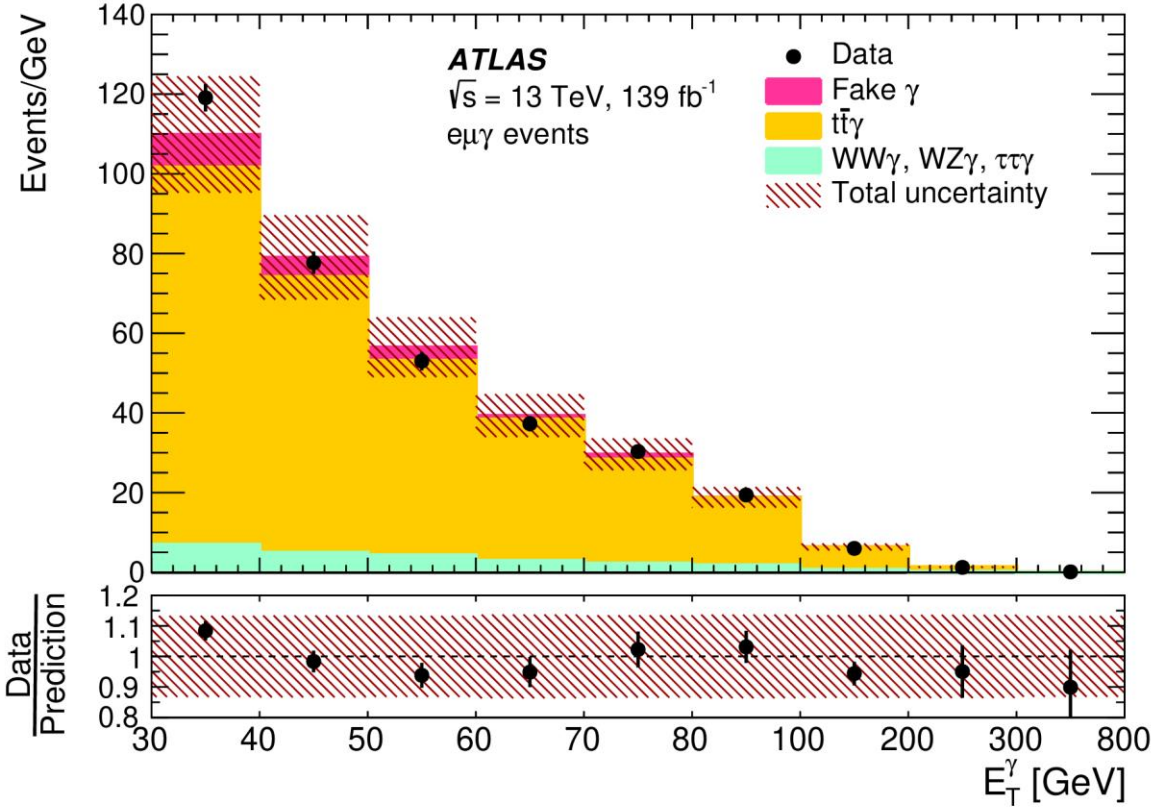
$$\#bkg\ in\ A = \#bkg\ in\ B * \frac{\#bkg\ in\ C}{\#bkg\ in\ D} * R$$

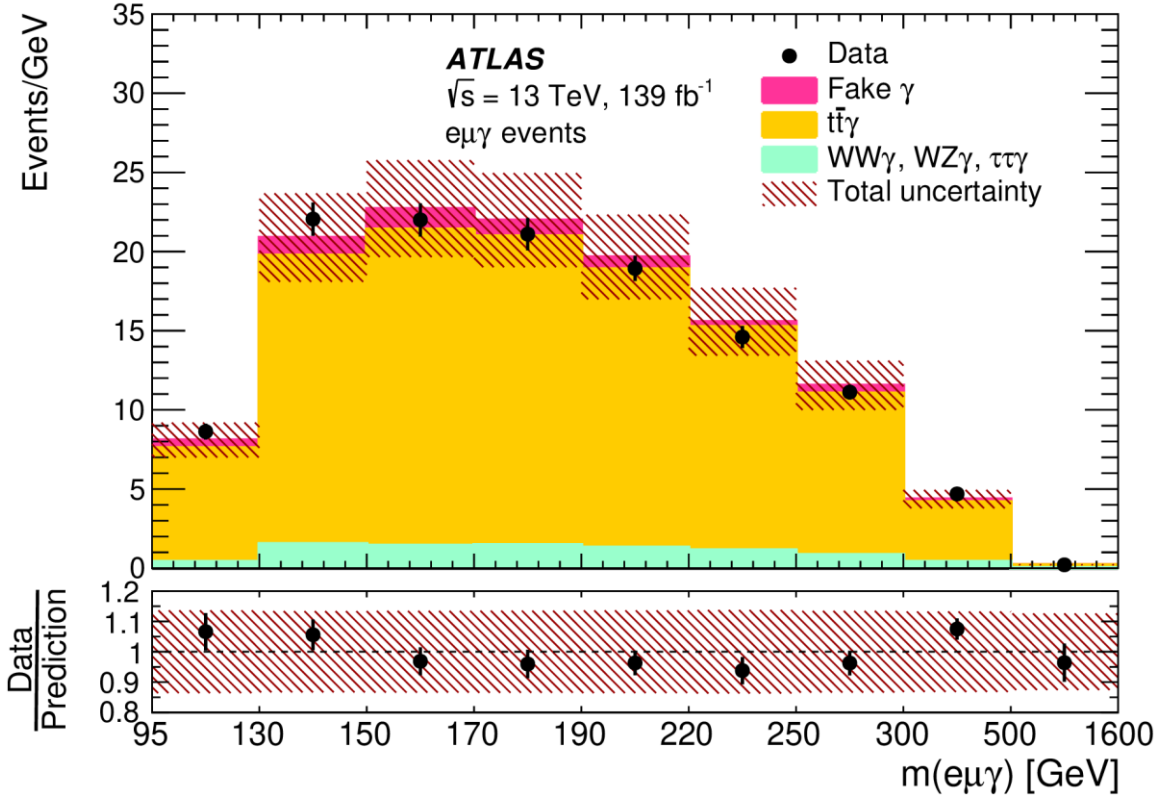
$$R_{\mathrm{bkg}} = \frac{N_{\mathrm{bkg}}^{A,\mathrm{MC}} \cdot N_{\mathrm{bkg}}^{D,\mathrm{MC}}}{N_{\mathrm{bkg}}^{B,\mathrm{MC}} \cdot N_{\mathrm{bkg}}^{C,\mathrm{MC}}},$$



C) Same as SR but photons fail quality	A) Signal Region requirements
D) Fail both quality + isolation	B) Same as SR but photons fail isolation

Zγ Analysis: TTγ estimation





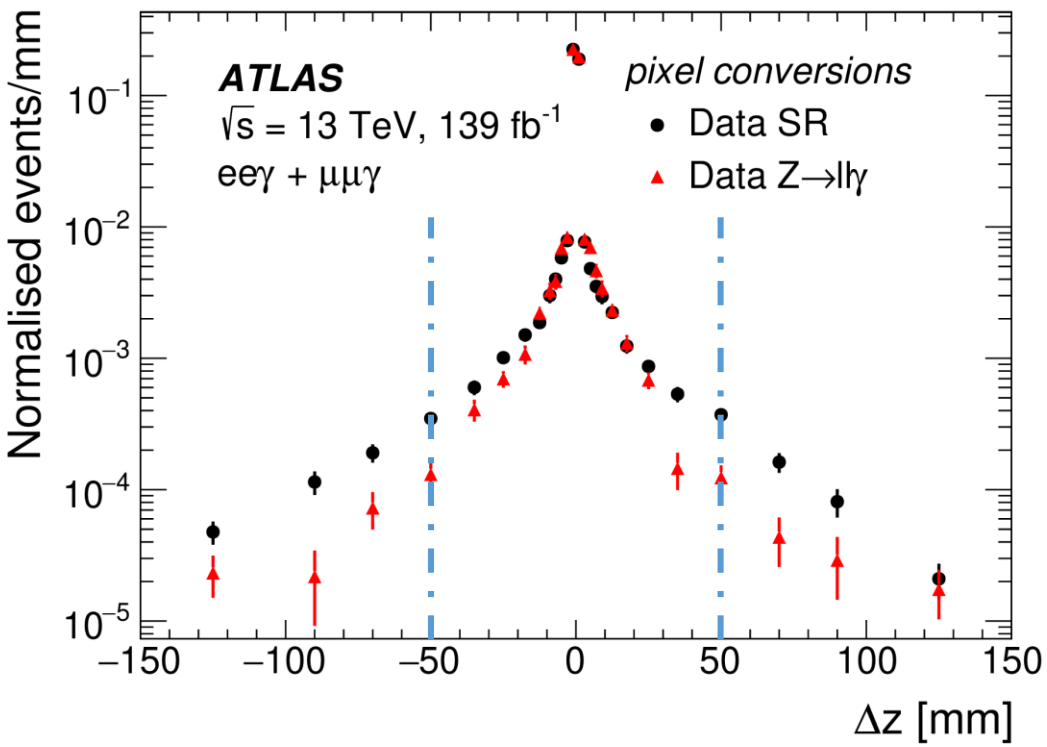
- Simulated using MC.
- Cross-checked in a region kinematically similar to the signal region but with e+mu flavors instead of same flavor ee or mumu leptons.

Pile-Up Photon Estimation

- On average 33 pp collisions occur in the same bunch crossing
- Photons that originate far from the pp interaction that produced the Z mainly come from other "pile up" pp collisions

- Select photons which convert to a pair of electrons on the inner most layer of the silicon tracker.
- Reconstruct the original direction of the photon based on the converted electrons
- Find the difference in the longitudinal coordinate (z) of the photon and the Z boson production vertex

$$\Delta z = z_\gamma - z_{\mathrm{vtx}}$$



|Δz| > 50 mm Dominated by pileup photons

Zγ Analysis: Z+jet Estimation

- Analogous to the non-prompt electron/muon estimation in the m4l analysis except now it's photons

- Find

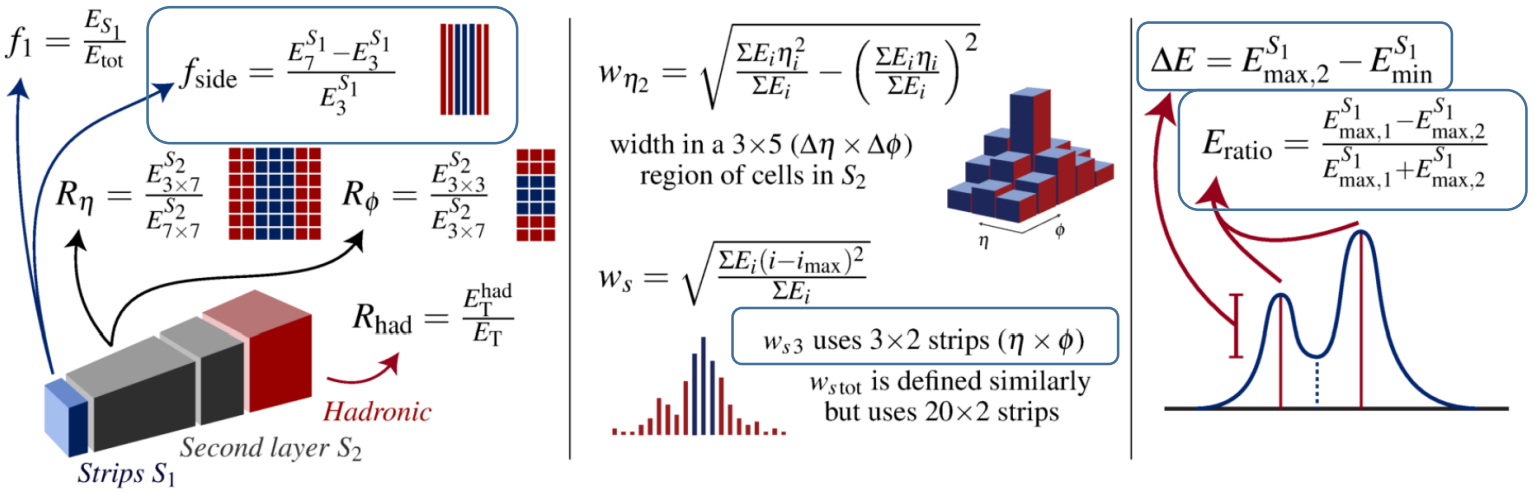


Figure 2: Schematic representation of the photon identification discriminating variables, from Ref. [23]. $E_C^{S_N}$ identify the electromagnetic energy collected in the N-th longitudinal layer of the electromagnetic calorimeter in a cluster of properties C, identifying the number and/or properties of selected cells. E_i is the energy in the i-th cell, η_i the pseudorapidity centre of that cell.

$$E_T^{iso} > 0.065 * \left(E_T^{\gamma} + 2\ GeV\right) \text{ Instead of } \frac{E_T^{iso}}{E_T^{\gamma}} < 0.065$$

https://arxiv.org/pdf/1810.05087.pdf

Zγ Analysis: Z+jet Estimation

- The number of estimated Z+jet background events in the A is predicted by

$$\#bkg\ in\ A = \#bkg\ in\ B\ * \frac{\#bkg\ in\ C}{\#bkg\ in\ D} * R$$

- Where R is the correlation between isolation and photon quality estimated using MC
- Also have to subtract expected Zγ signal events from each region B,C and D when estimating background.

C) Same as SR but photons fail quality	A) Signal Region requirements
D) Fail both quality + isolation	B) Same as SR but photons fail isolation

$$R_{\text{bkg}} \cdot \left((N^{B,\text{data}} - f^{B,\text{MC}} N^{A,\text{data}}_{\text{signal}}) \cdot \frac{(N^{C,\text{data}} - f^{C,\text{MC}} N^{A,\text{data}}_{\text{signal}})}{(N^{D,\text{data}} - f^{D,\text{MC}} N^{A,\text{data}}_{\text{signal}})} \right)$$

$$R_{\text{bkg}} = \frac{N^{A,\text{MC}}_{\text{bkg}} \cdot N^{D,\text{MC}}_{\text{bkg}}}{N^{B,\text{MC}}_{\text{bkg}} \cdot N^{C,\text{MC}}_{\text{bkg}}},$$

Zγ NLO EWK + QCD Combination

$$\begin{aligned}\sigma^{\mathrm{NLO}} &= \sigma^{\mathrm{LO}}\left[\left(1+\delta_{\mathrm{QCD}}\right)\left(1+\delta_{\mathrm{EW},q\bar{q}}\right)+\delta_{\mathrm{EW},q\gamma}+\left(\delta_{\gamma\gamma}\right)\right] \\ &= \sigma^{\mathrm{NLO\,QCD}}\left(1+\delta_{\mathrm{EW},q\bar{q}}\right)+\Delta\sigma_{q\gamma}^{\mathrm{NLO\,EW}}+\left(\Delta\sigma_{\gamma\gamma}\right), \qquad (2.4)\end{aligned}$$

where the relative QCD, EW, and photon-induced corrections are defined by

$$\delta_{\mathrm{QCD}} = \frac{\sigma^{\mathrm{NLO\,QCD}}-\sigma^{\mathrm{LO}}}{\sigma^{\mathrm{LO}}}, \qquad \delta_{\mathrm{EW},q\bar{q}} = \frac{\Delta\sigma_{q\bar{q}}^{\mathrm{NLO\,EW}}}{\sigma^{0}},$$

$$\delta_{\mathrm{EW},q\gamma} = \frac{\Delta\sigma_{q\gamma}^{\mathrm{NLO\,EW}}}{\sigma^{\mathrm{LO}}}, \qquad \delta_{\gamma\gamma} = \frac{\Delta\sigma_{\gamma\gamma}}{\sigma^{\mathrm{LO}}}, \qquad (2.5)$$

https://link.springer.com/content/pdf/10.1007/JHEP02(2016)057.pdf

WW top Background Estimation

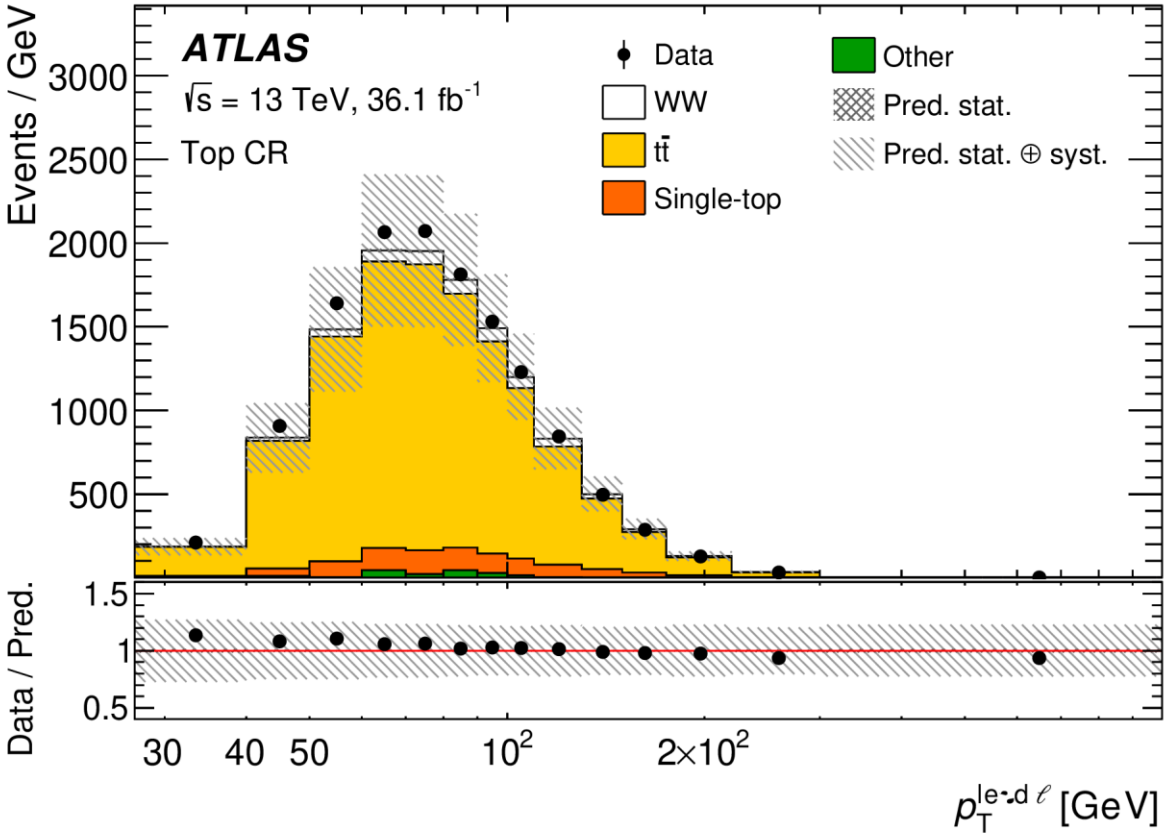
- Largest background is ttbar and tW

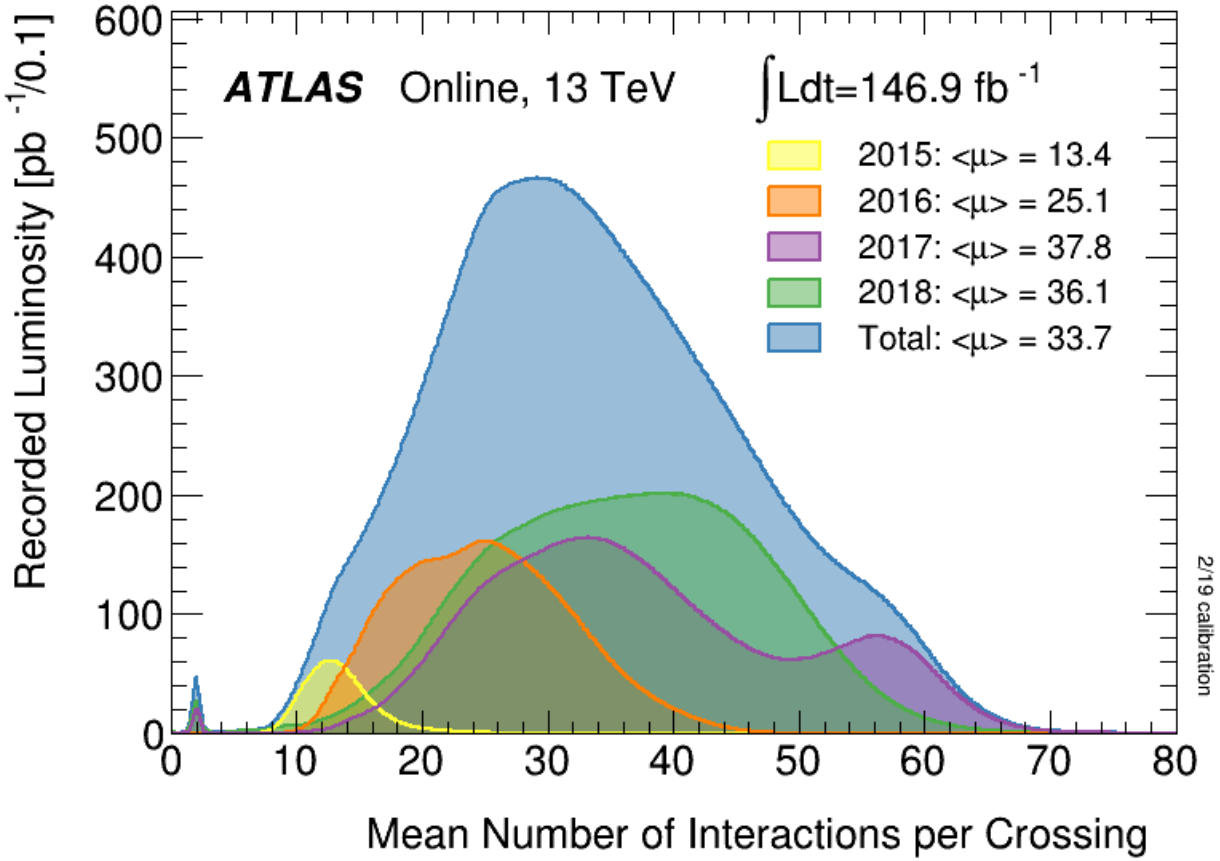
- Top background is selected for by removing b jet and jet veto requirements
- An $H_T > 200$ GeV requirement is added to limit the amount of WW

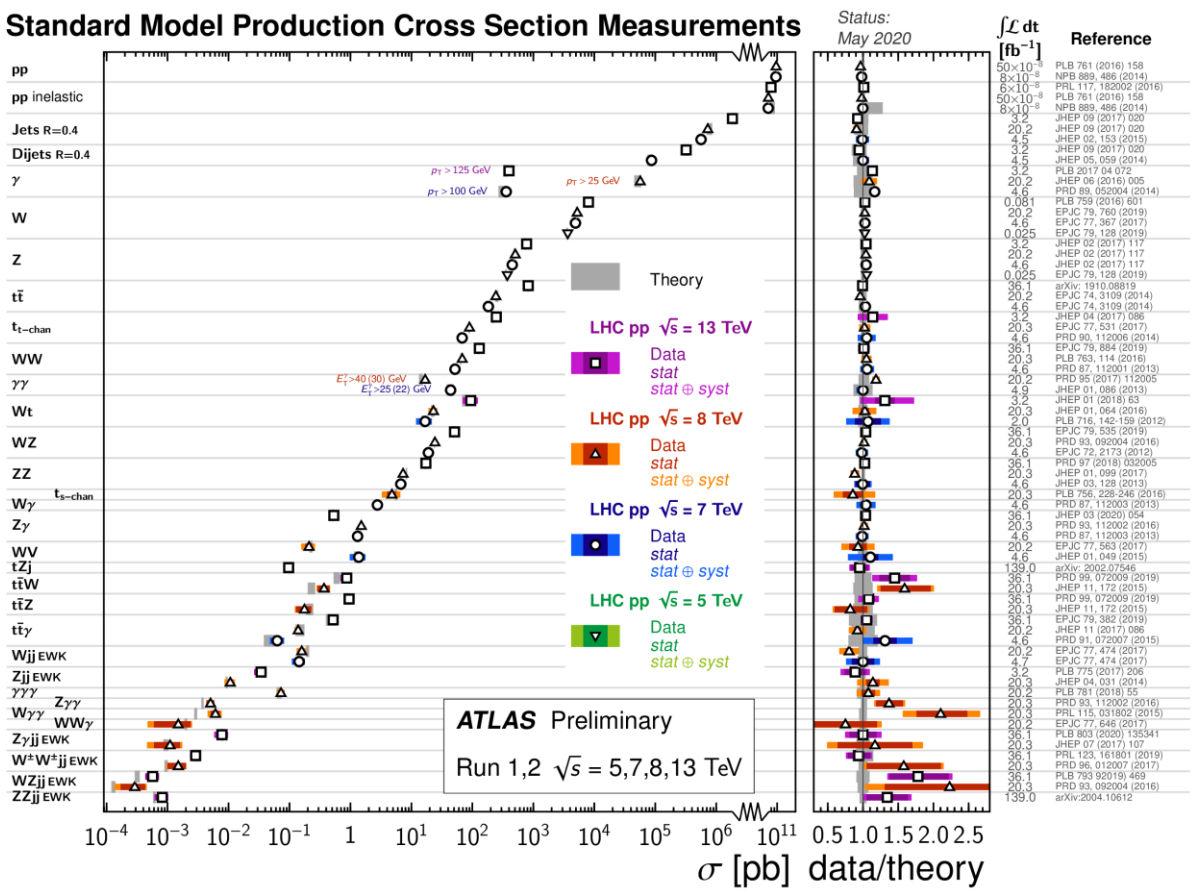
$$N_{\mathrm{SR}}^{\mathrm{top}} = \frac{N_{\mathrm{CR}}^{\mathrm{top}}}{\epsilon_{H_{\mathrm{T}}}} \times \epsilon_{\text{jet-veto}}$$

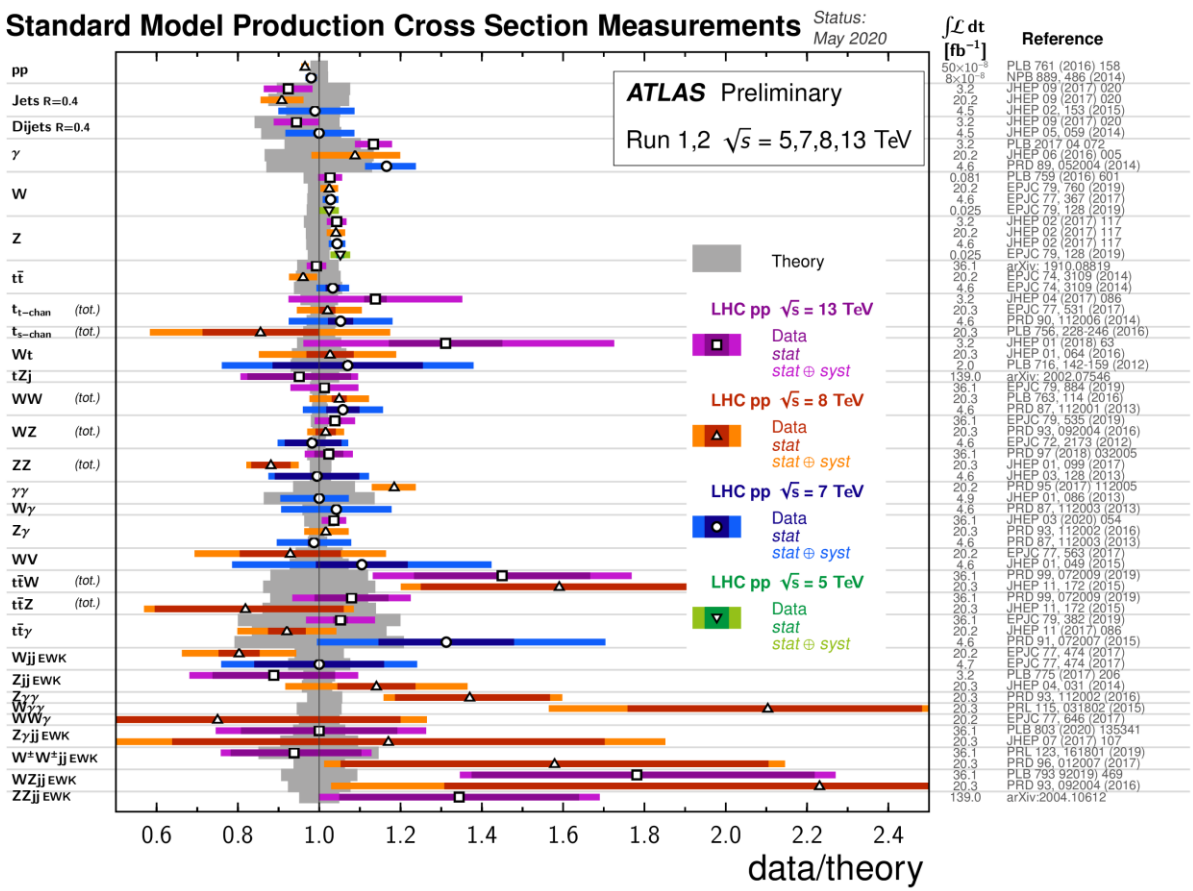
- The estimated amount of top in the signal region is the number of tops observed in the control region scaled by the efficiency of the jet veto and H_T cuts

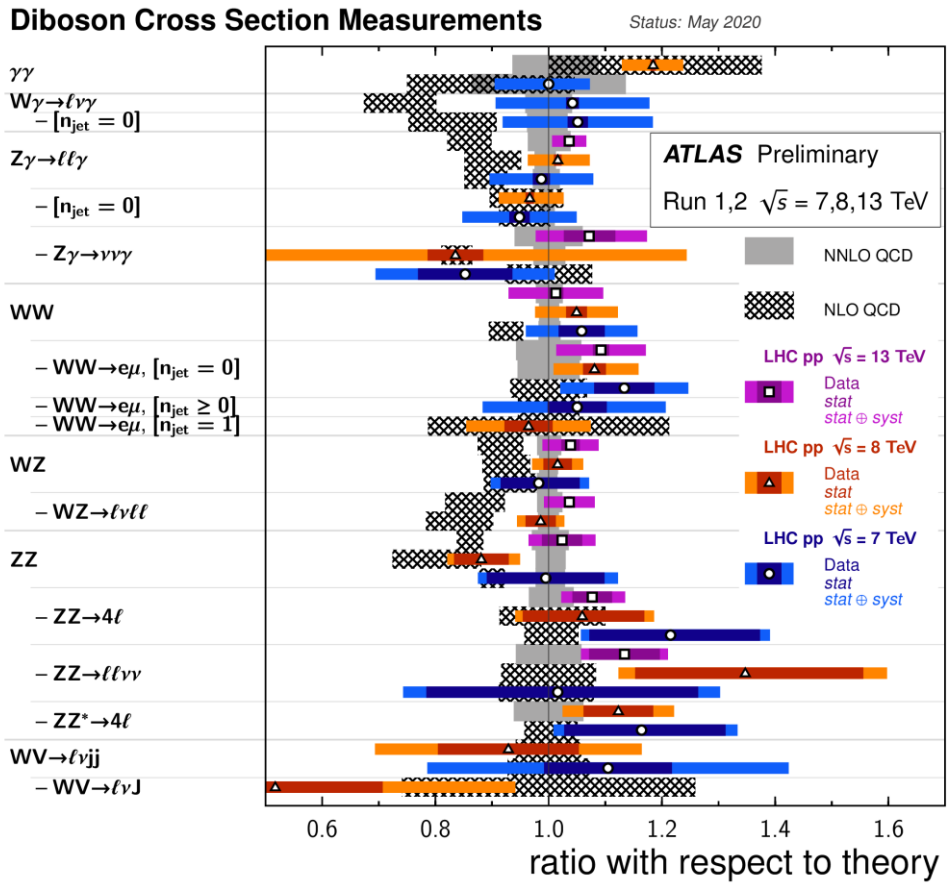
- Efficiencies are mainly derived from MC but with a correction factor using data



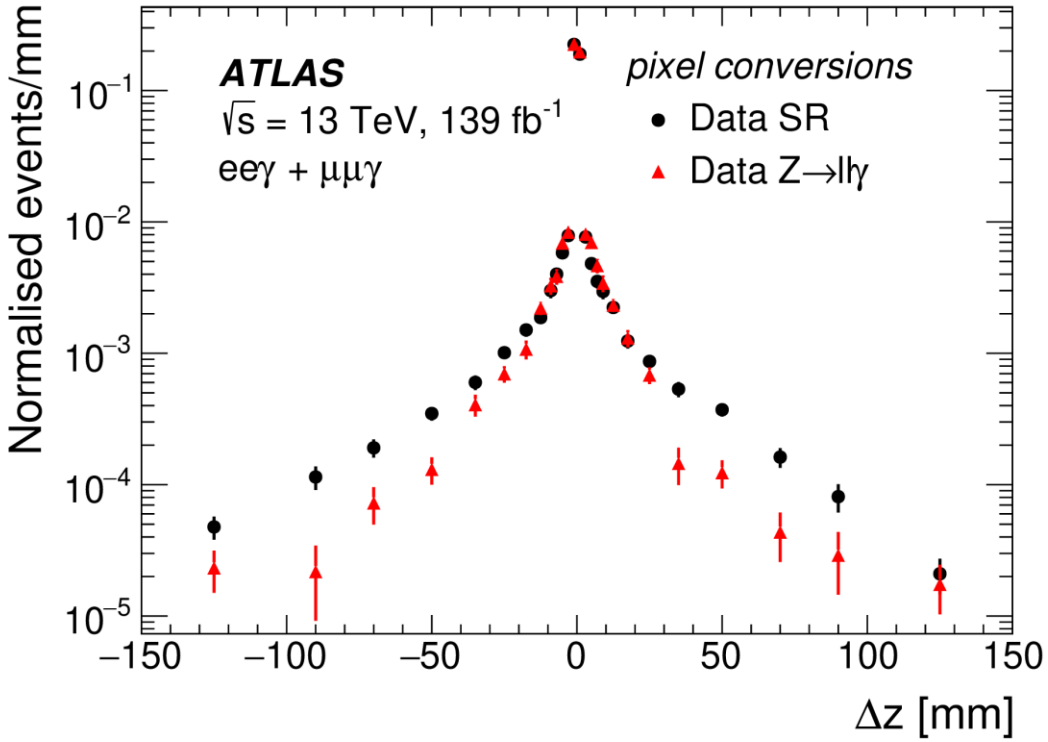

ATLAS Online, 13 TeV
∫Ldt=146.9 fb -1
2015: <μ> = 13.4
2016: <μ> = 25.1
2017: <μ> = 37.8
2018: <μ> = 36.1
Total: <μ> = 33.7
Recorded Luminosity [pb -1/0.1]
Mean Number of Interactions per Crossing
2/19 calibration
0
100
200
300
400
500
600
0
10
20
30
40
50
60
70
80

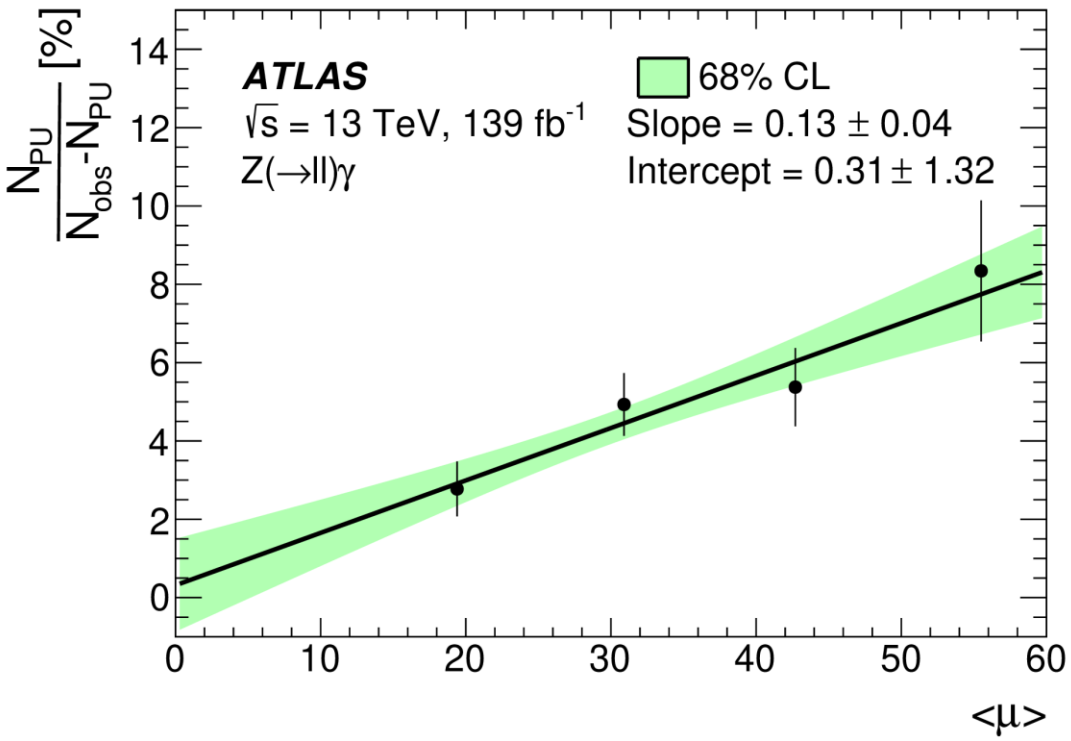

Standard Model Production Cross Section Measurements
Status: May 2020
$\int \mathcal{L}\,dt$ [fb^{-1}]
Reference
pp
pp inelastic
Jets R=0.4
Dijets R=0.4
γ
W
Z
tt̄
t t-chan
WW
γγ
Wt
WZ
ZZ
Wγ t s-chan
Zγ
WV
tZj
tt̄W
tt̄Z
tt̄γ
Wjj EWK
Zjj EWK
γγγ
Zγγ
Wγγ
WWγ
Zγjj EWK
W±W±jj EWK
WZjj EWK
ZZjj EWK
p_T > 125 GeV
p_T > 100 GeV
p_T > 25 GeV
E_T^γ>40 (30) GeV
E_T^γ>25 (22) GeV
Theory
LHC pp √s = 13 TeV
Data
stat
stat ⊕ syst
LHC pp √s = 8 TeV
Data
stat
stat ⊕ syst
LHC pp √s = 7 TeV
Data
stat
stat ⊕ syst
LHC pp √s = 5 TeV
Data
stat
stat ⊕ syst
ATLAS Preliminary
Run 1,2 √s = 5,7,8,13 TeV
10^{-4} 10^{-3} 10^{-2} 10^{-1} 1 10^{1} 10^{2} 10^{3} 10^{4} 10^{5} 10^{6} 10^{11}
σ [pb]
0.5 1.0 1.5 2.0 2.5
data/theory


Standard Model Production Cross Section Measurements
Status: May 2020
ATLAS Preliminary
Run 1,2 √s = 5,7,8,13 TeV
Theory
LHC pp √s = 13 TeV
Data
stat
stat ⊕ syst
LHC pp √s = 8 TeV
Data
stat
stat ⊕ syst
LHC pp √s = 7 TeV
Data
stat
stat ⊕ syst
LHC pp √s = 5 TeV
Data
stat
stat ⊕ syst
pp
Jets R=0.4
Dijets R=0.4
γ
W
Z
tt̄
t t−chan (tot.)
t s−chan (tot.)
Wt
tZj
WW (tot.)
WZ (tot.)
ZZ (tot.)
γγ
Wγ
Zγ
WV
tt̄W (tot.)
tt̄Z (tot.)
tt̄γ
Wjj EWK
Zjj EWK
Zγγ
Wγγ
WWγ
Zγjj EWK
W±W±jj EWK
WZjj EWK
ZZjj EWK
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
data/theory
∫ℒ dt [fb⁻¹]
Reference
50×10⁻⁹ PLB 761 (2016) 158
8×10⁻⁸ NPB 889, 486 (2014)
3.2 JHEP 09 (2017) 020
20.2 JHEP 09 (2017) 020
4.5 JHEP 02, 153 (2015)
3.2 JHEP 09 (2017) 020
4.5 JHEP 05, 059 (2014)
3.2 PLB 2017 04 072
20.2 JHEP 06 (2016) 005
4.6 PRD 89, 052004 (2014)
0.081 PLB 759 (2016) 601
20.2 EPJC 79, 760 (2019)
4.6 EPJC 77, 367 (2017)
0.025 EPJC 79, 128 (2019)
3.2 JHEP 02 (2017) 117
20.2 JHEP 02 (2017) 117
4.6 JHEP 02 (2017) 117
0.025 EPJC 79, 128 (2019)
36.1 arXiv: 1910.08819
20.2 EPJC 74, 3109 (2014)
4.6 EPJC 74, 3109 (2014)
3.2 JHEP 04 (2017) 086
20.3 EPJC 77, 531 (2017)
4.6 PRD 90, 112006 (2014)
20.3 PLB 756, 228-246 (2016)
3.2 JHEP 01 (2018) 63
20.3 JHEP 01, 064 (2016)
2.0 PLB 716, 142-159 (2012)
139.0 arXiv: 2002.07546
36.1 EPJC 79, 884 (2019)
20.3 PLB 763, 114 (2016)
4.6 PRD 87, 112001 (2013)
36.1 EPJC 79, 535 (2019)
20.3 PRD 93, 092004 (2016)
4.6 EPJC 72, 2173 (2012)
36.1 PRD 97 (2018) 032005
20.3 JHEP 01, 099 (2017)
4.6 JHEP 03, 128 (2013)
20.2 PRD 95 (2017) 112005
4.9 JHEP 01, 086 (2013)
4.6 PRD 87, 112003 (2013)
36.1 JHEP 03 (2020) 054
20.3 PRD 93, 112002 (2016)
4.6 PRD 87, 112003 (2013)
20.2 EPJC 77, 563 (2017)
4.6 JHEP 01, 049 (2015)
36.1 PRD 99, 072009 (2019)
20.3 JHEP 11, 172 (2015)
36.1 PRD 99, 072009 (2019)
20.3 JHEP 11, 172 (2015)
36.1 EPJC 79, 382 (2019)
20.2 JHEP 11 (2017) 086
4.6 PRD 91, 072007 (2015)
20.2 EPJC 77, 474 (2017)
4.7 EPJC 77, 474 (2017)
3.2 PLB 775 (2017) 206
20.3 JHEP 04, 031 (2014)
20.3 PRD 93, 112002 (2016)
20.3 PRL 115, 031802 (2015)
20.2 EPJC 77, 646 (2017)
36.1 PLB 803 (2020) 135341
20.3 JHEP 07 (2017) 107
36.1 PRL 123, 161801 (2019)
20.3 PRD 96, 012007 (2017)
36.1 PLB 793 92019) 469
20.3 PRD 93, 092004 (2016)
139.0 arXiv:2004.10612


Diboson Cross Section Measurements
Status: May 2020
γγ
Wγ→ℓνγ
– [n_jet = 0]
Zγ→ℓℓγ
– [n_jet = 0]
– Zγ→ννγ
WW
– WW→eμ, [n_jet = 0]
– WW→eμ, [n_jet ≥ 0]
– WW→eμ, [n_jet = 1]
WZ
– WZ→ℓνℓℓ
ZZ
– ZZ→4ℓ
– ZZ→ℓℓνν
– ZZ*→4ℓ
WV→ℓνjj
– WV→ℓνJ
ATLAS Preliminary
Run 1,2 √s = 7,8,13 TeV
NNLO QCD
NLO QCD
LHC pp √s = 13 TeV
Data
stat
stat ⊕ syst
LHC pp √s = 8 TeV
Data
stat
stat ⊕ syst
LHC pp √s = 7 TeV
Data
stat
stat ⊕ syst
0.6
0.8
1.0
1.2
1.4
1.6
ratio with respect to theory

Zγ Pile-Up Photon Estimation





Zγ Measurement of Fiducial Cross-Section

	Cross-section [fb]		
$e^+e^-\gamma$	530.4	$\pm$ 9.0 (uncorr)	$\pm$ 11.7 (corr) $\pm$ 9.0 (lumi)
$\mu^+\mu^-\gamma$	535.0	$\pm$ 6.1 (uncorr)	$\pm$ 11.5 (corr) $\pm$ 9.1 (lumi)
$\ell^+\ell^-\gamma$	533.7	$\pm$ 5.1 (uncorr)	$\pm$ 11.6 (corr) $\pm$ 9.1 (lumi)
SHERPA LO	438.9	$\pm$ 0.6 (stat)	
SHERPA NLO	514.2	$\pm$ 5.7 (stat)	
MADGRAPH NLO	503.4	$\pm$ 1.8 (stat)	
MATRIX NLO	444.2	$\pm$ 0.1 (stat)	$\pm$ 4.3 (C_{theory}) $\pm$ 8.8 (PDF) $^{+16.8}_{-18.9}$ (scale)
MATRIX NNLO	518.9	$\pm$ 2.0 (stat)	$\pm$ 5.1 (C_{theory}) $\pm$ 10.8 (PDF) $^{+16.4}_{-14.9}$ (scale)
MATRIX NNLO $\times$ NLO EW	513.5	$\pm$ 2.0 (stat)	$\pm$ 2.7 (C_{theory}) $\pm$ 10.8 (PDF) $^{+16.4}_{-14.9}$ (scale)
MATRIX NNLO + NLO EW	518.3	$\pm$ 2.0 (stat)	$\pm$ 2.7 (C_{theory}) $\pm$ 10.8 (PDF) $^{+16.4}_{-14.9}$ (scale)

- Fiducial cross-section is defined as the cross-section within the fiducial phase space under the area with detector coverage.

$$\sigma_{\text{fid}} = \frac{N_{\text{obs}} - N_{\text{bkg}}}{C \times \mathcal{L}}$$

- Where $\mathcal{L}$ is the integrated luminosity and C is the correction factor that accounts for detector acceptance and reconstruction efficiency
- C is estimated using Zγ MC

WW analysis ttbar Control Region