Measurements of multi-boson production including vector-boson scattering at ATLAS

February 25, 2022

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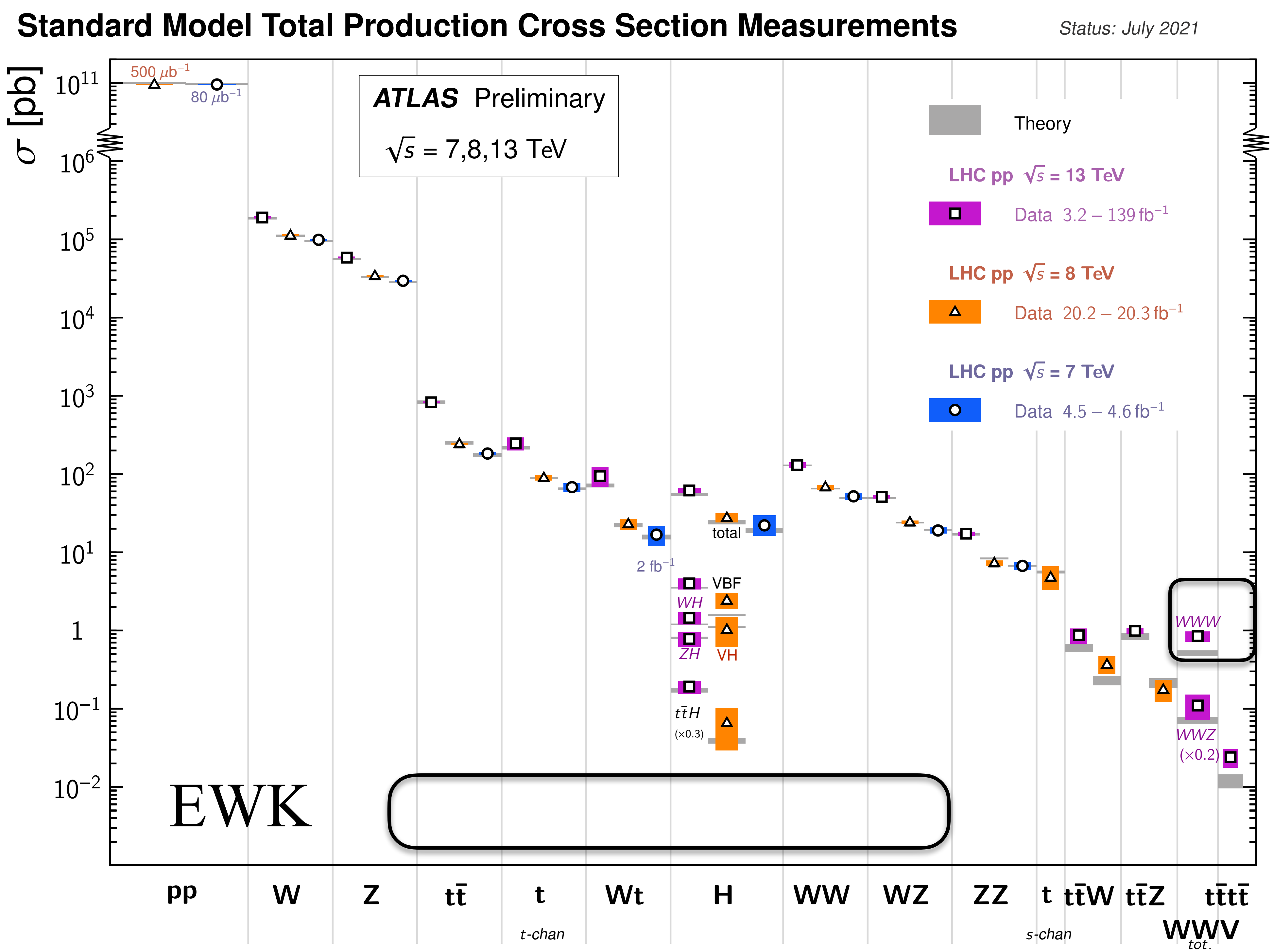
On behalf of the ATLAS collaboration

Outline

1. **Motivation & ATLAS**
   - Why rare EW processes
   - ATLAS detector
2. EW $\gamma Z \to \ell\ell$
   - Analysis strategy
   - Separating strong & EW
   - Results
3. EW $\gamma Z \to \nu\nu$
   - Invisible final state
   - Selections & background
   - Interplay with searches
4. WWW
5. Effective theory interpretation

Motivation

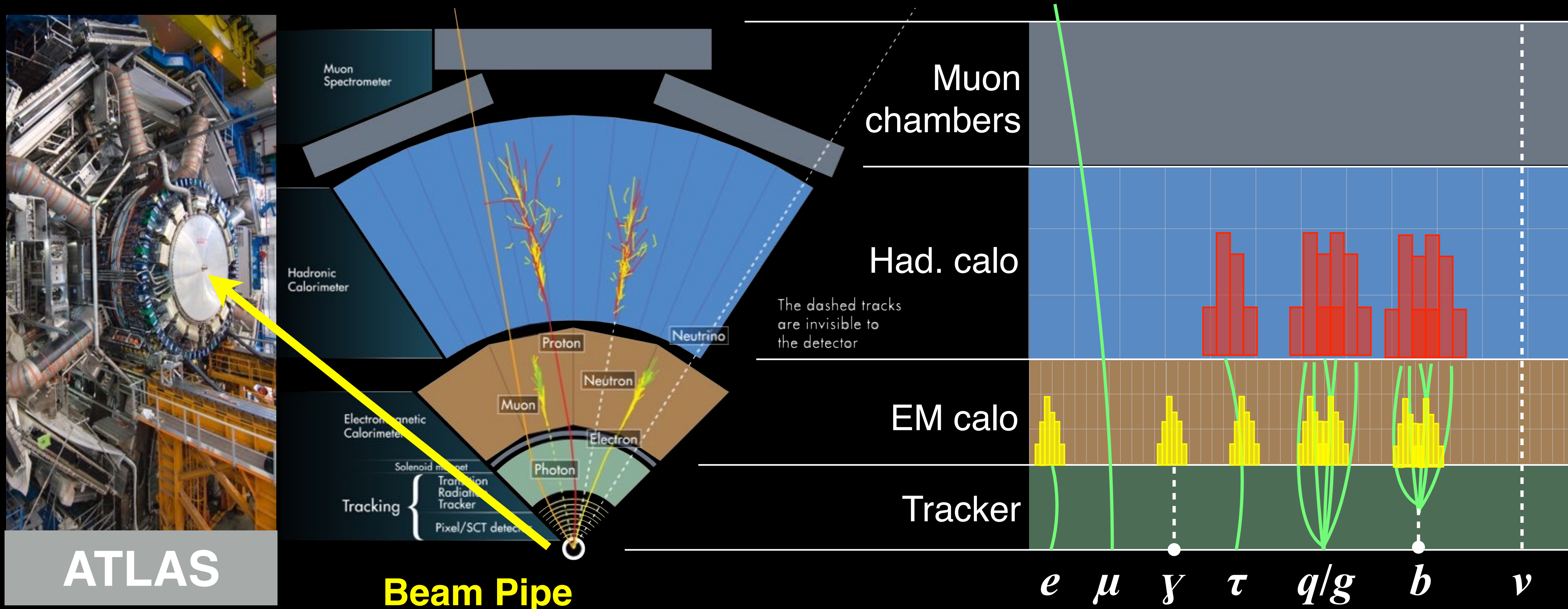
SM Public (link)



Measuring deviations in *rare* SM processes

Measuring rare SM backgrounds for **searches**

ATLAS detector



Hardware trigger (L1): select in 2.2 μs

40 MHz

coarse calorimeter and muon to L1

100 kHz

full calorimeter and muon data to HLT

Software trigger (HLT) select in ~0.1 s

~1 kHz

Save to permanent storage

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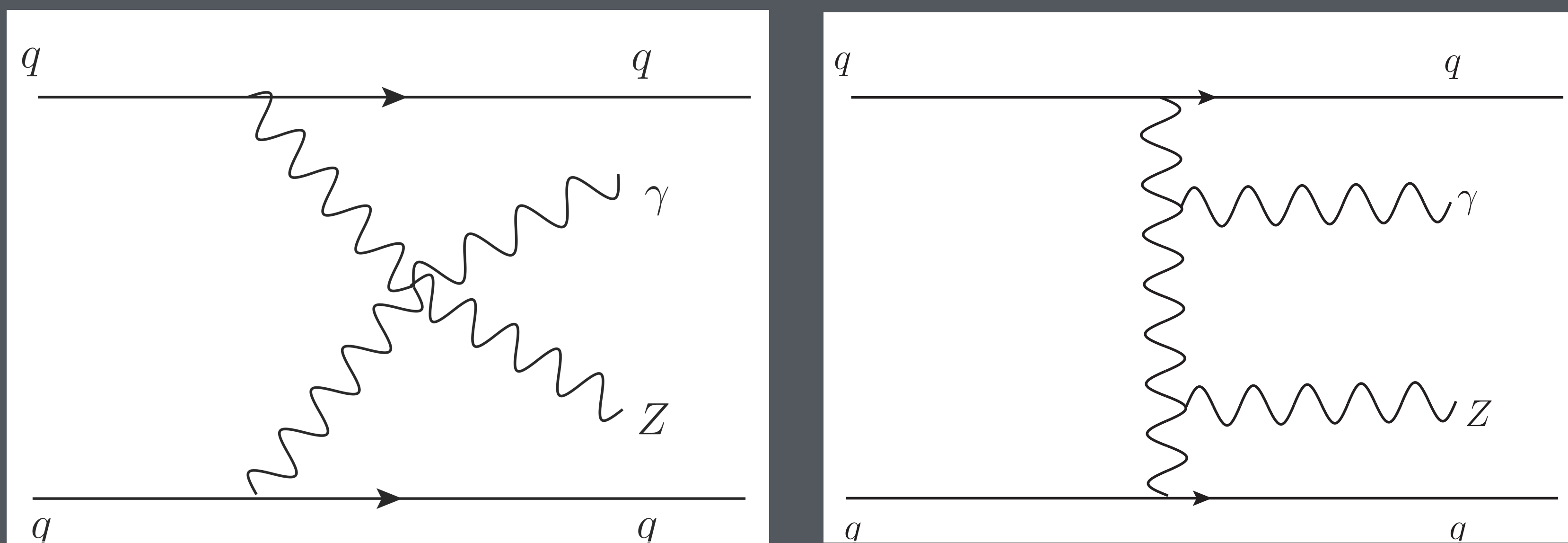
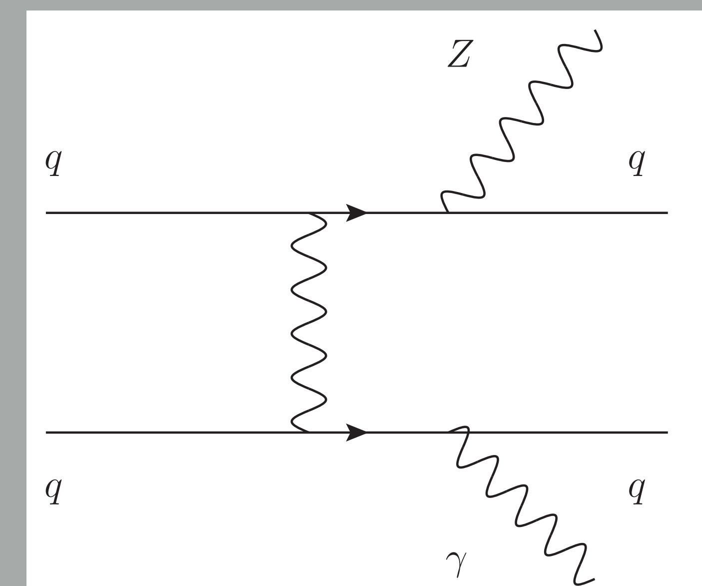
Electroweak processes

Electroweak diagrams are $O(\alpha_{EW}{}^4)$





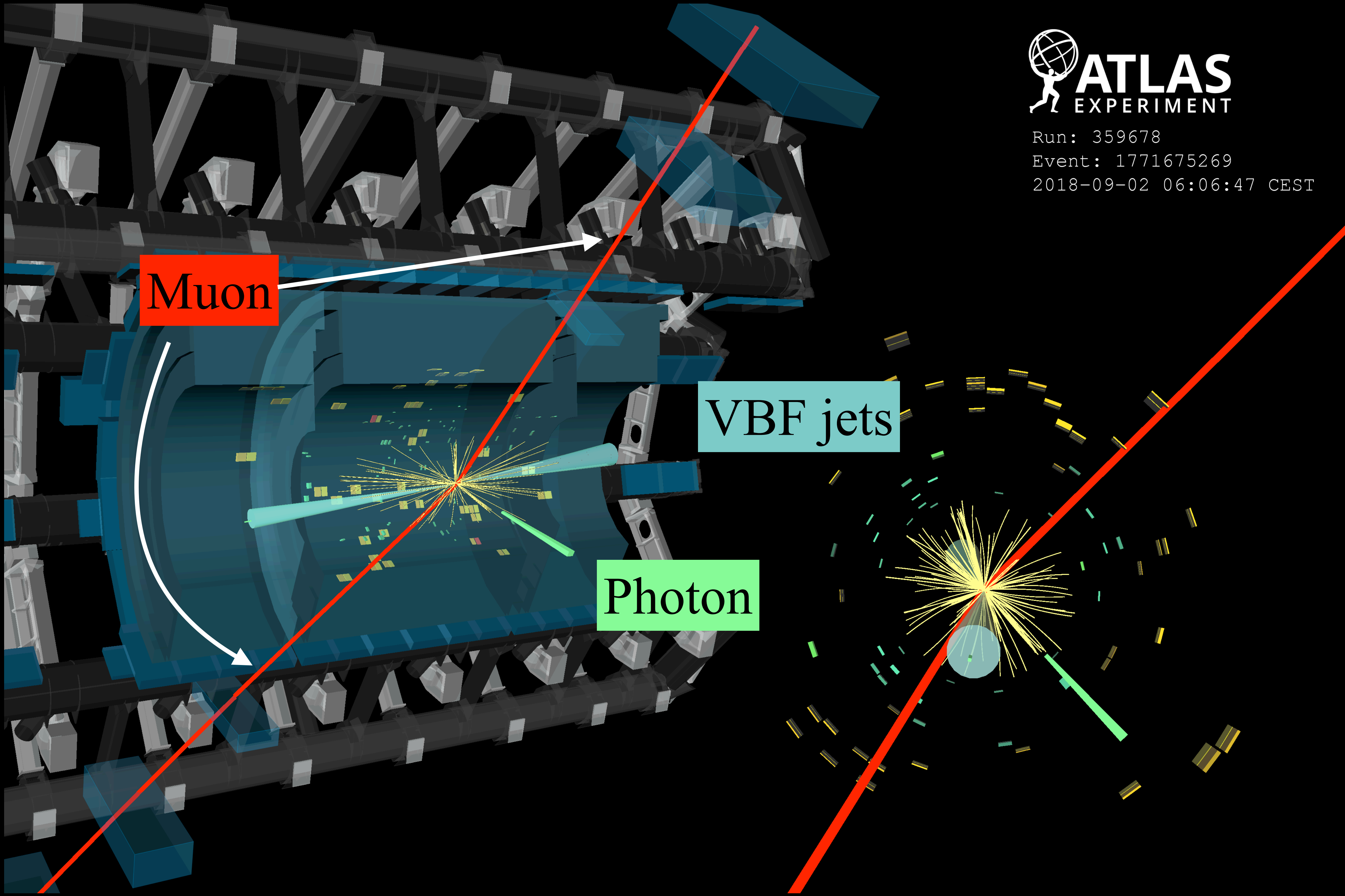
Vector boson scattering

non-VBS

$Z\gamma$ probes the neutral gauge coupling with a larger cross section than ZZ

$\gamma Z \rightarrow \ell\ell$

Phys. Lett. B 809 (2020) 135754



Spectacular signature in dilepton (ee,μμ) + γ final state

Selecting Z bosons

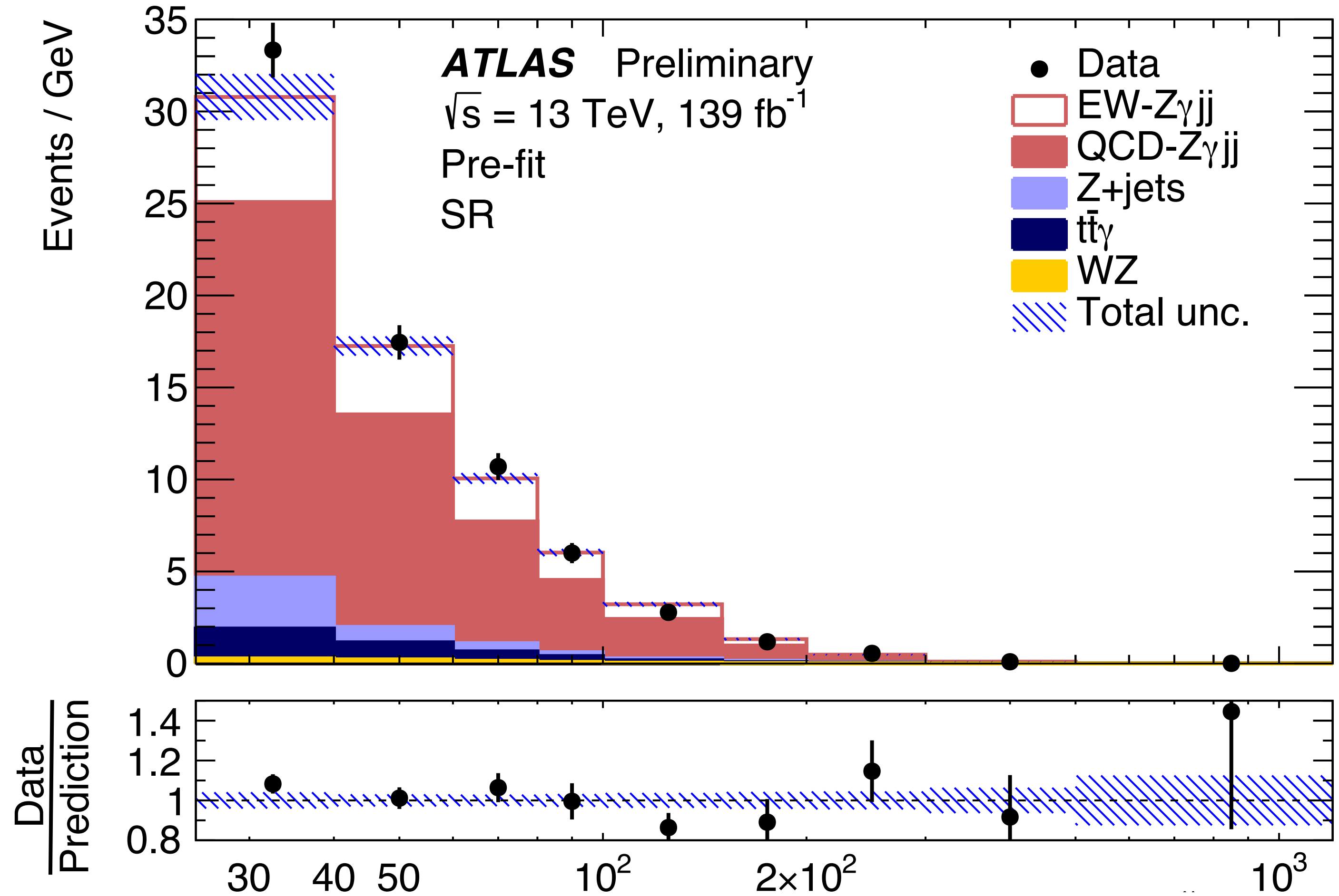
ATLAS-CONF-2021-038

Trigger on electrons or muons (~1/3 of recorded events)

- Single lepton trigger $p_T > 26$ GeV
- Two electron triggers: $p_T > 24$GeV
- Asymmetric two muon triggers: 22 (sub-leading 8) GeV

Offline requirements: opposite sign leptons & a photon

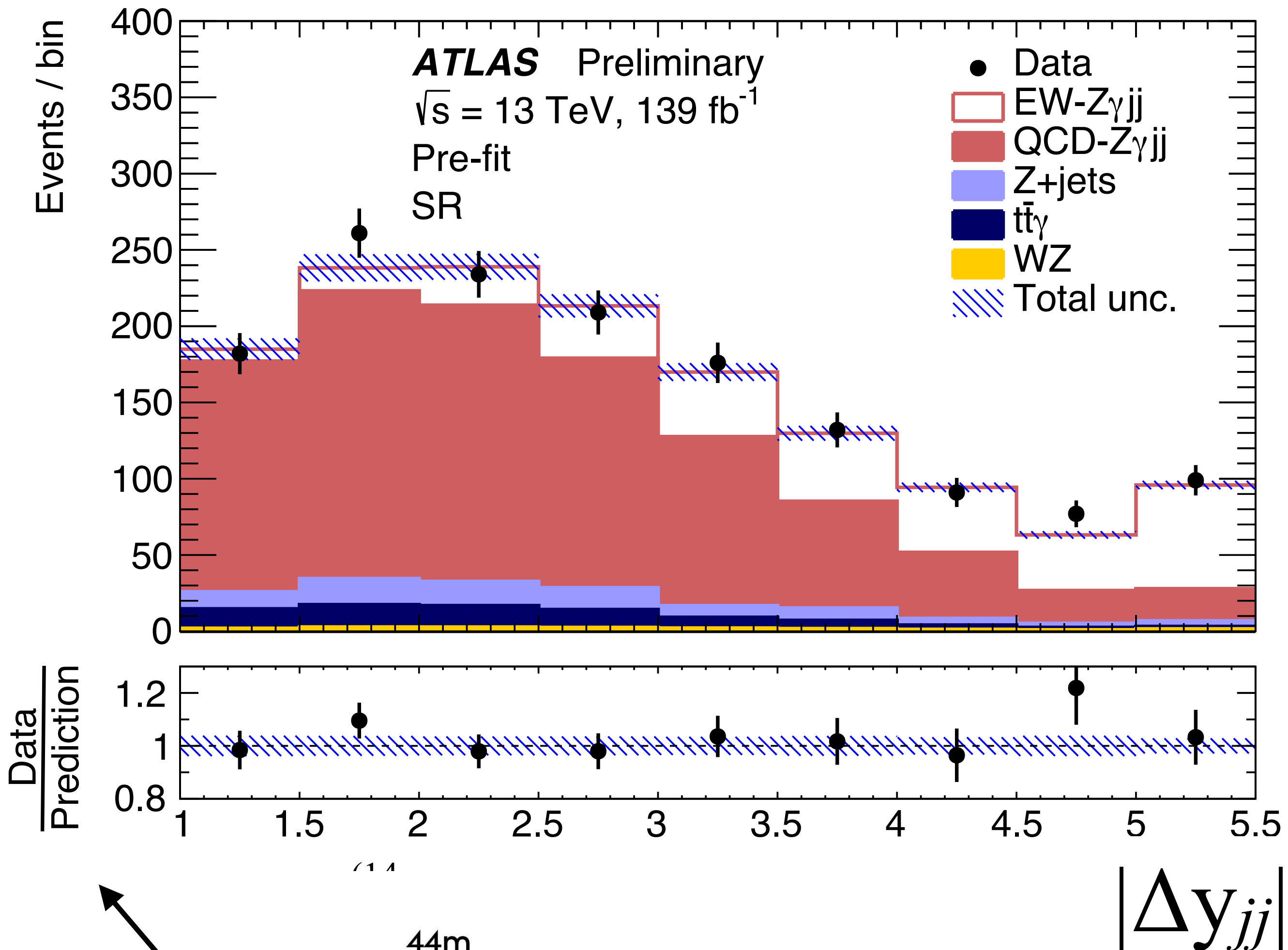
- Offline isolated electron muon with $p_T > 30$ (20) GeV
- Isolated photon with $p_T > 25$ GeV

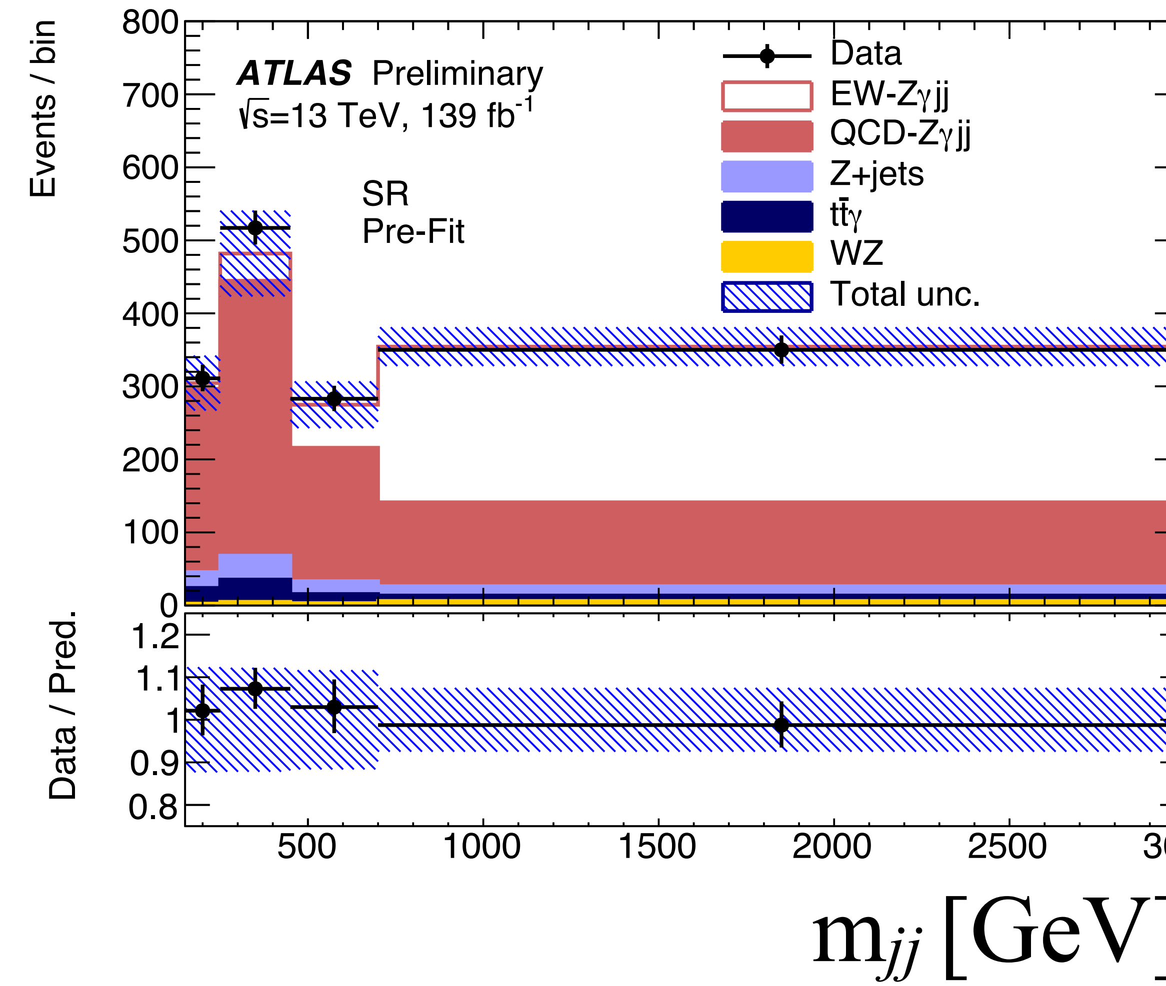


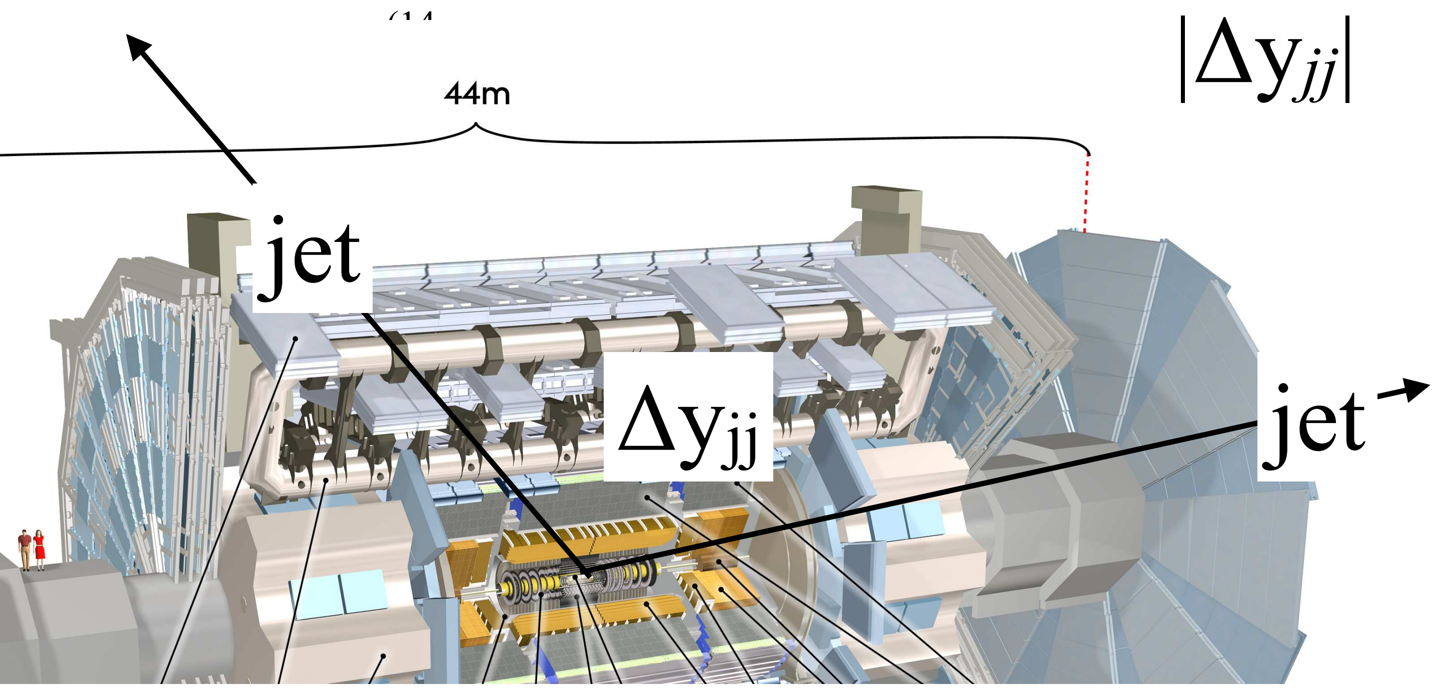
Photon E_T [GeV]

Electroweak selections

Large difference in dijet rapidity & dijet invariant mass m_{jj}







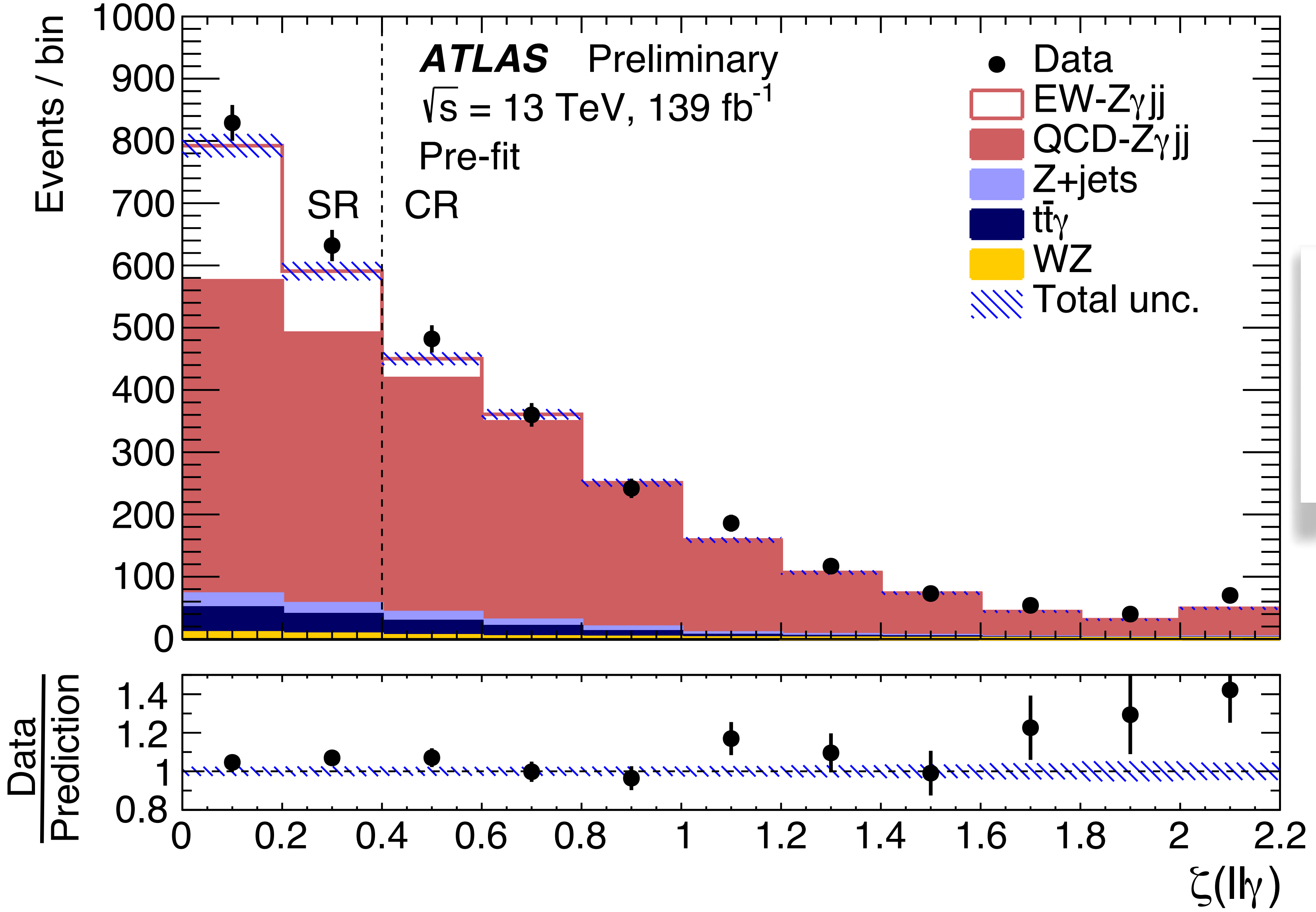
$$m_{jj} \approx \sqrt{P_{T1} \cdot P_{T2} \cdot e^{\Delta y}}$$

$$\sim \langle P_{T,\,jet} \rangle \, e^{\Delta y / 2}$$

- Example: $100 \cdot e^{5/2} = 1.2$ TeV

Centrality

Electroweak process tends to be more central



$\ell\ell\gamma$ systems with respect to VBF jets

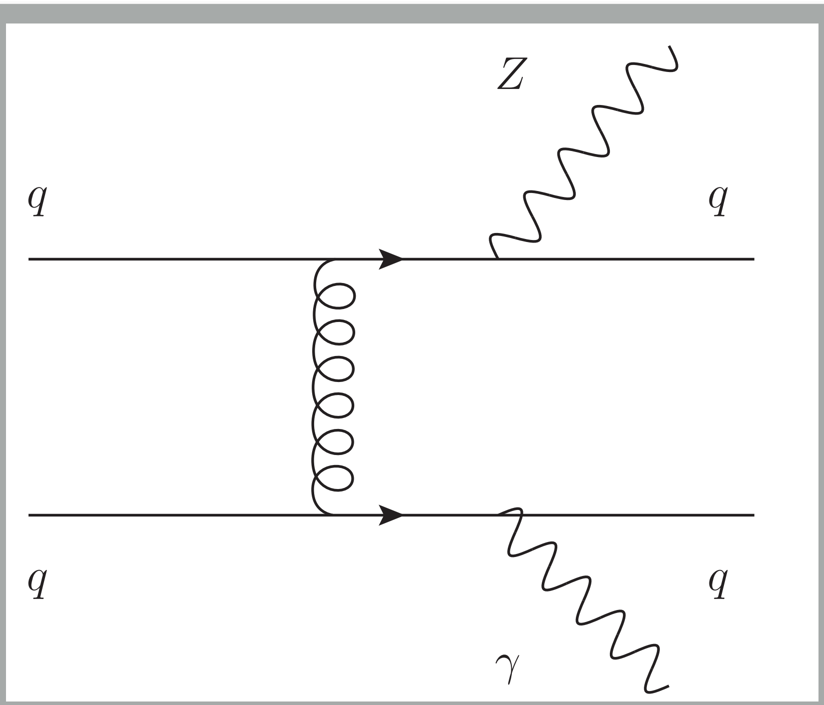
$$\zeta(\ell\ell\gamma) = \left| \frac{y_{\ell\ell\gamma} - (y_{j_1} + y_{j_2})/2}{y_{j_1} - y_{j_2}} \right|$$

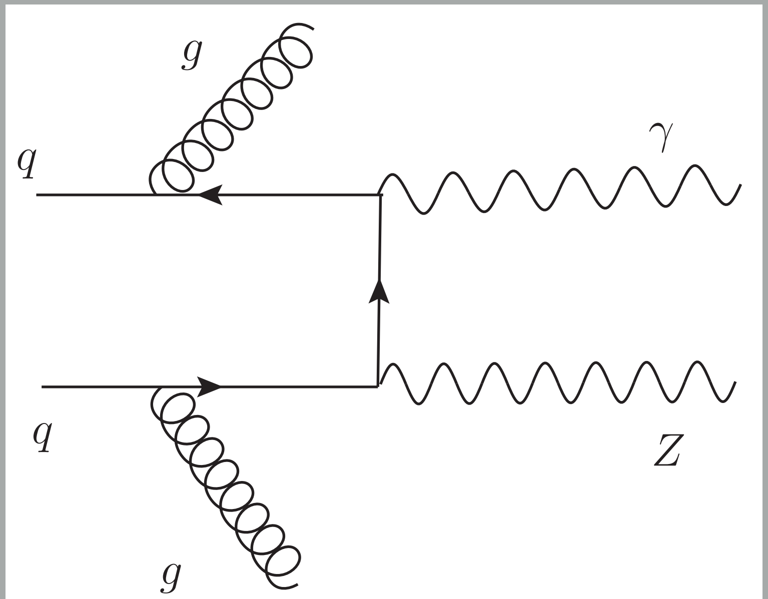
Signal enhanced

Control sample

Background & results

Dominant background from QCD γZ





QCD γZ estimated from simultaneous fit of control samples with $\zeta > 0.4$

$$\sigma_{EW} = 4.49 \pm 0.40\text{ (stat.)} \pm 0.42\text{ (syst.) fb}$$

$$\sigma_{EW}^{pred} = 4.73 \pm 0.01\text{ (stat.)} \pm 0.15\text{ (PDF)}^{+0.23}_{-0.22}\text{ (scale) fb.}$$

Measurement in agreement with prediction
Uncertainty of 13%

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EW $\gamma Z \rightarrow \nu\nu$

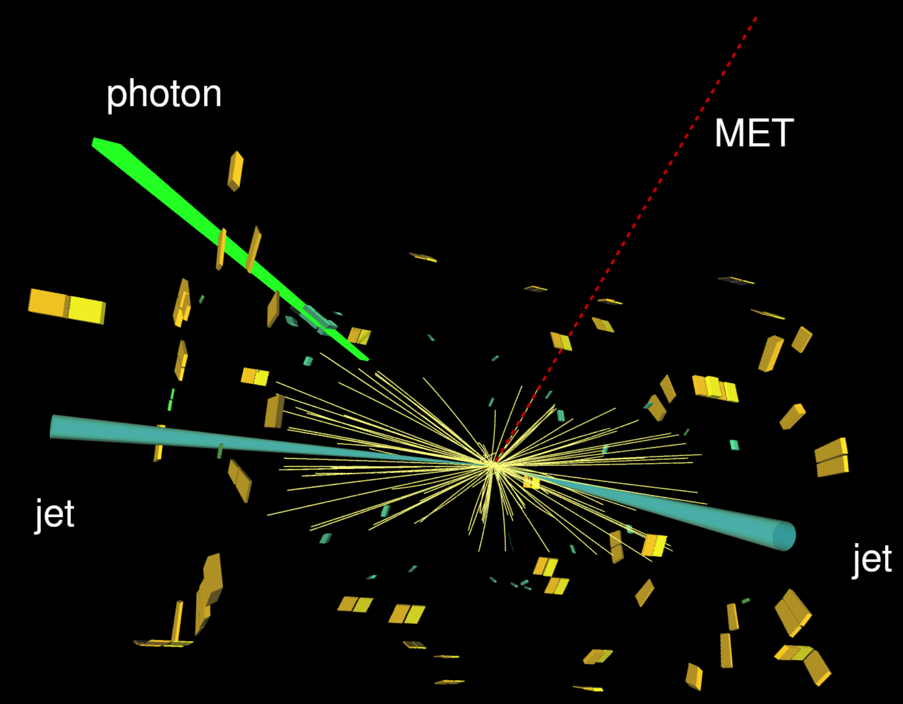
Eur. Phys. J. C 82 (2022) 105

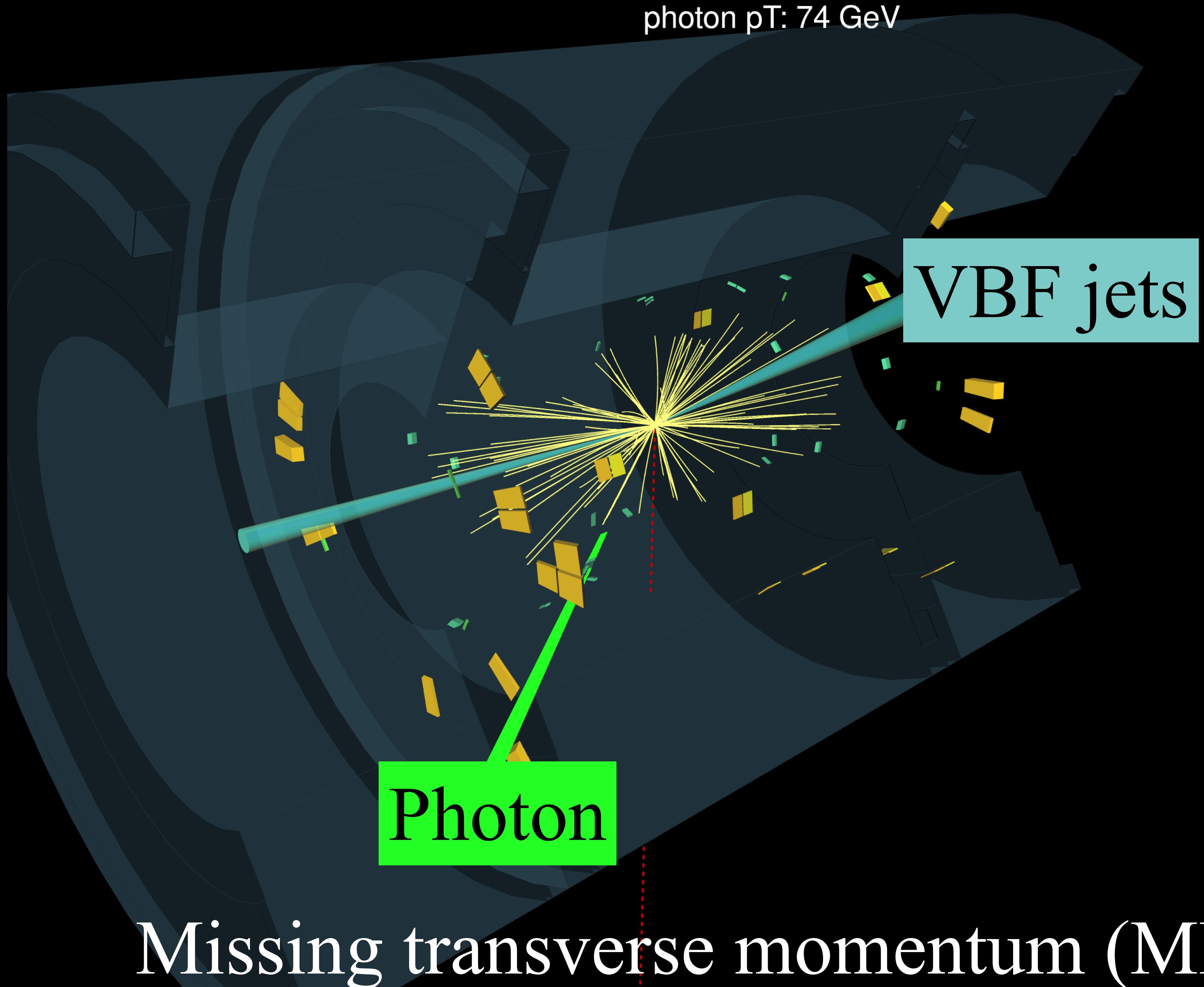
$$Br(Z \rightarrow \nu\nu) = 20\%$$

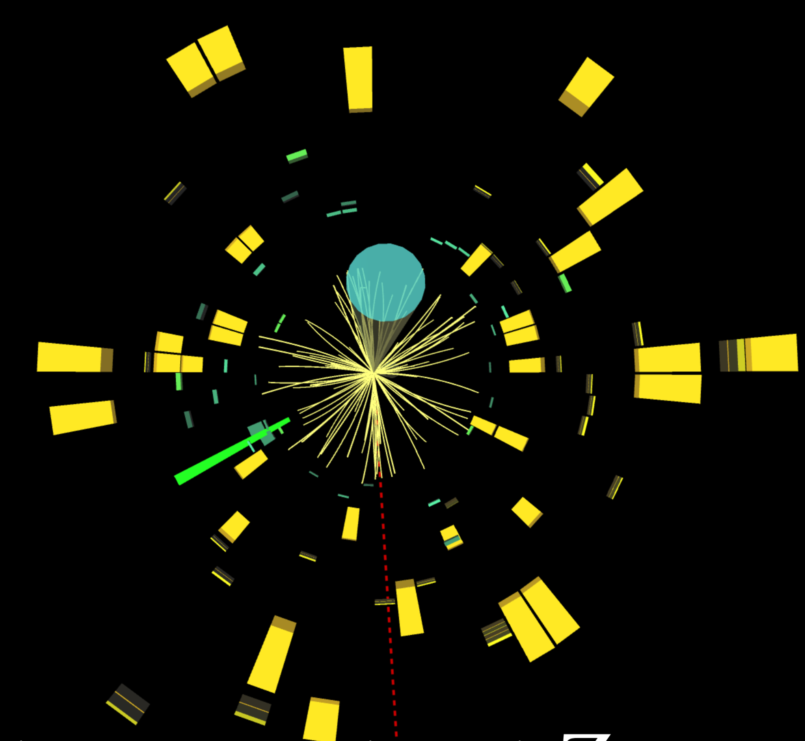
$$Br(\ell\ell) = 6\%$$

Run: 358300
Event: 1104384151
2018-08-14 14:20:39 CEST

jj mass: 3047 GeV
MET: 201 GeV
mT: 115 GeV
photon pT: 74 GeV







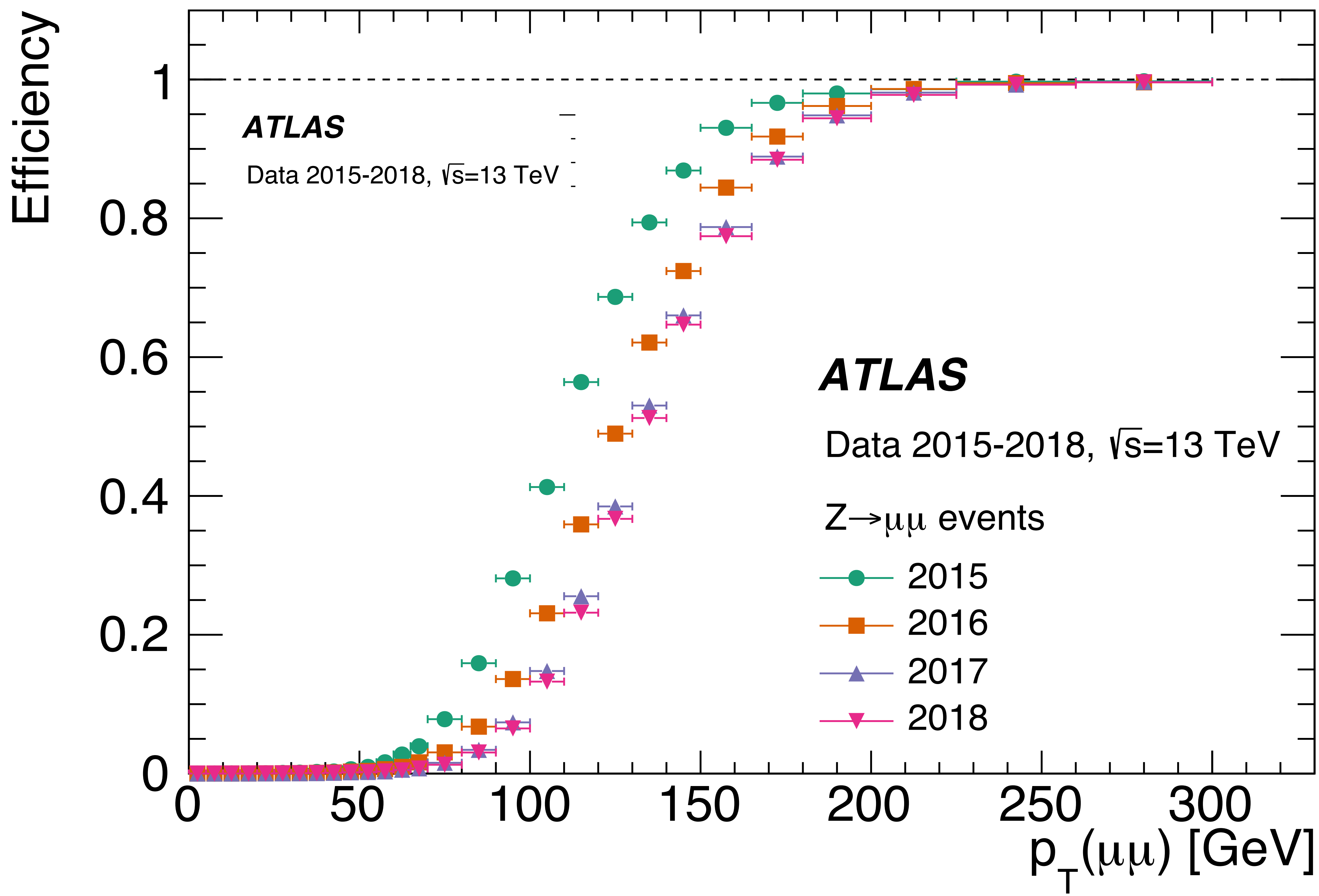
Missing transverse momentum (MET) to reconstruct $Z \rightarrow \nu\nu$

$\gamma Z \rightarrow \nu\nu$ Trigger

JHEP 2020 80 (2020)

Trigger on MET, with offline threshold of 150 GeV

- Useable with data/MC corrections at 150 GeV
- Compare to $Z \rightarrow \ell\ell$ with lower p_T lepton triggers



Backgrounds

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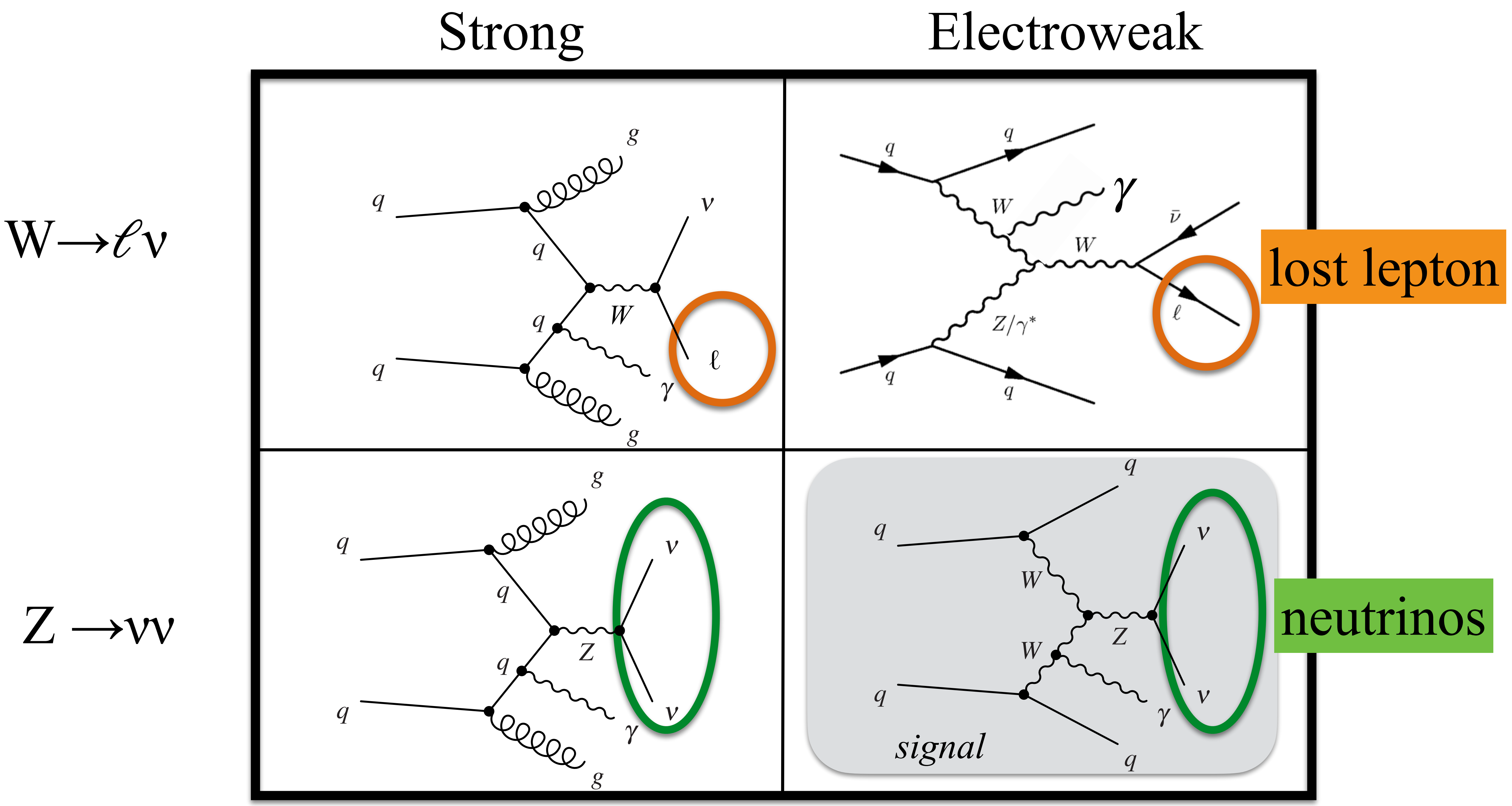

+ many more diagrams and interference

Separating strong EWK

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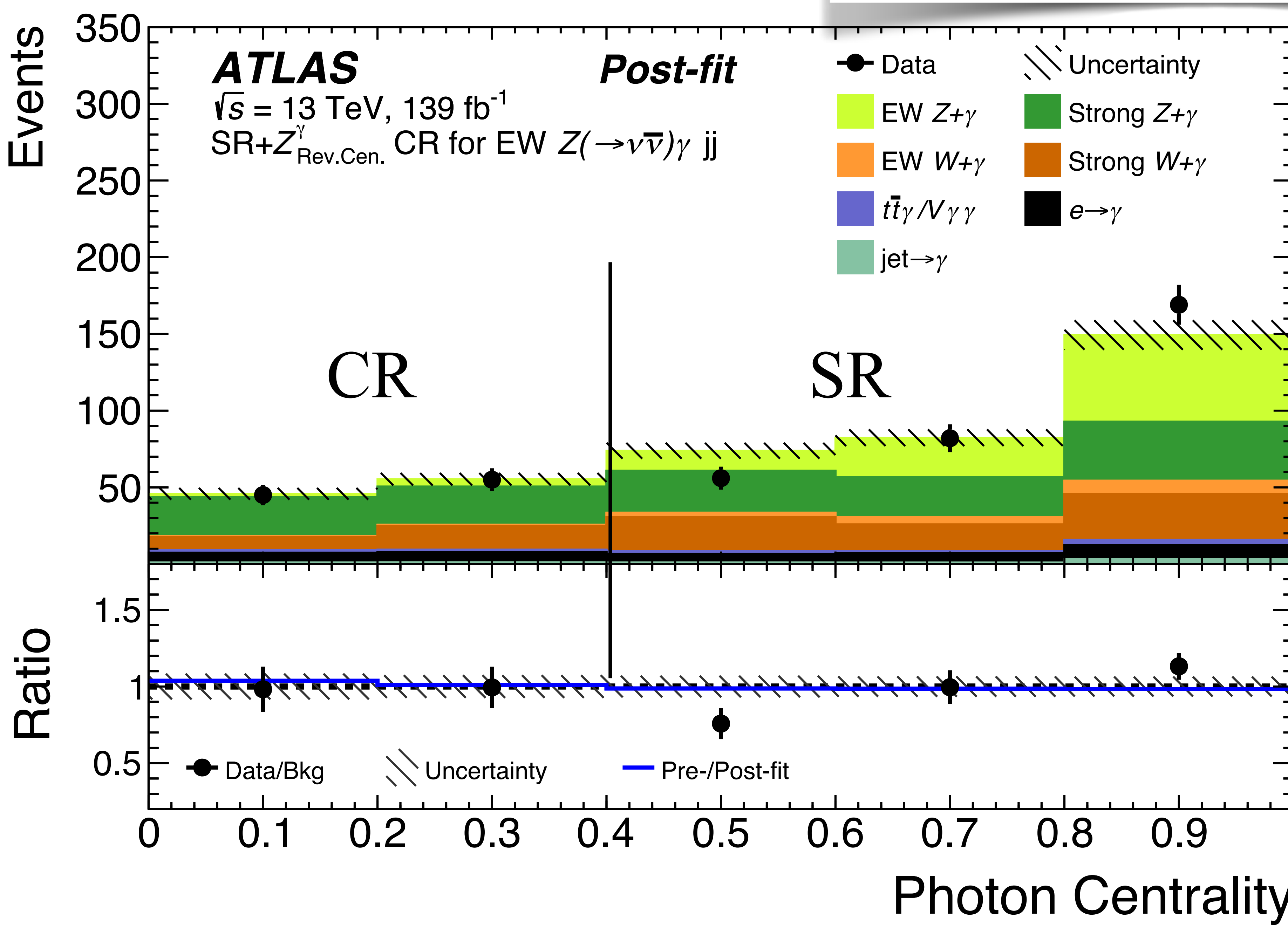
Photon centrality for inv. final state

$$C_\gamma = \exp\left[-\frac{4}{(\eta_1-\eta_2)^2}\left(\eta_\gamma - \frac{\eta_1+\eta_2}{2}\right)^2\right]$$

*note different variable than previous analysis



Enriched in strong Z

Enriched in EW Z

Selections

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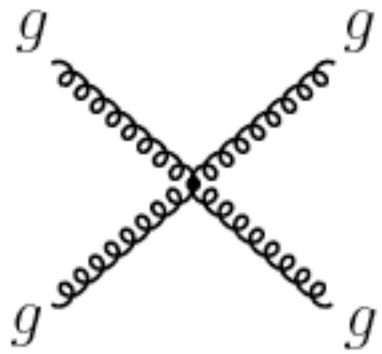
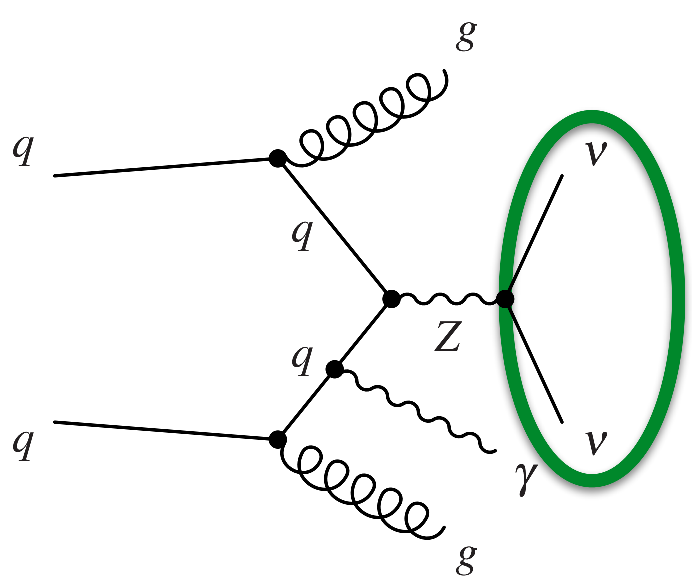
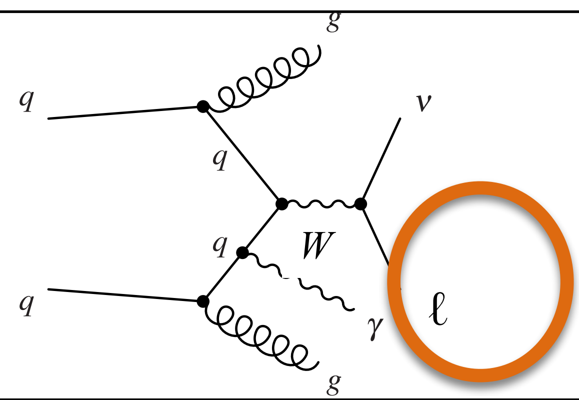
MET & Photon	 QCD	MET > 150 GeV H_T^{miss} > 130 GeV Photon p_T: 15-115 GeV
Dijet event	 Z to invisible	Jet p_T > 60, 50 GeV (VBF jets) N_{jet} = 2,3 p_T > 25 GeV Centrality > 0.4
m_{jj}, $\Delta\phi_{jj}$,$\Delta\eta_{jj}$		$\Delta\eta_{jj} > 3$ & $\eta_{j1} \cdot \eta_{j2} < 0$ m_{jj} > 500 GeV (binned)
Lepton veto	 W→ℓν	No electron (muon) with p_T > 4 GeV

Observation of EW $Z\gamma$

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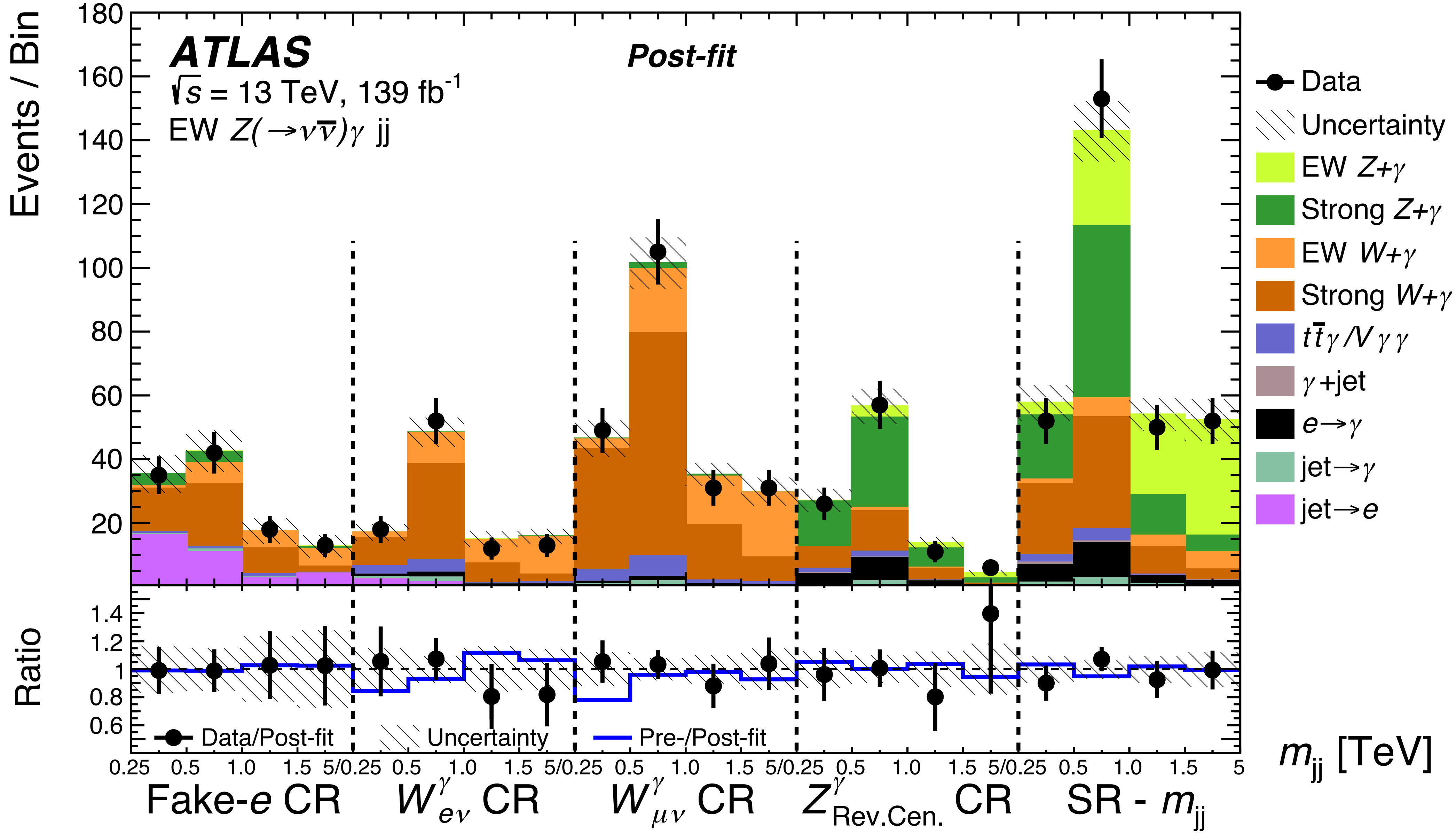
First time observed in $Z \rightarrow \nu\nu$ channel



$\mu_{Z\gamma_{\text{EW}}}$	$\beta_{Z\gamma_{\text{strong}}}$	$\beta_{W\gamma}$
1.03 ± 0.25	1.02 ± 0.41	1.01 ± 0.20

5.2σ observed (5.1σ expected)

Synergy with searches

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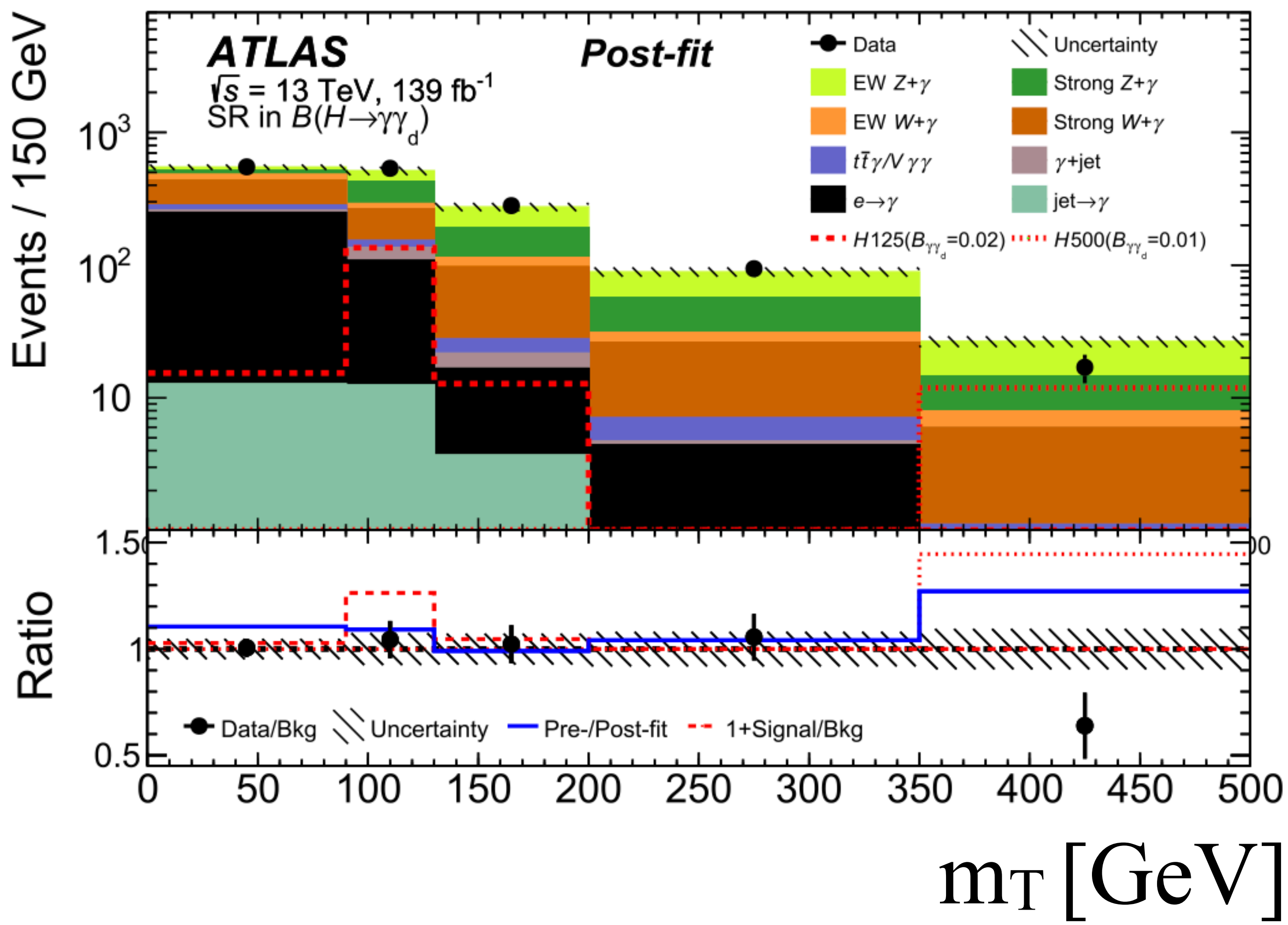
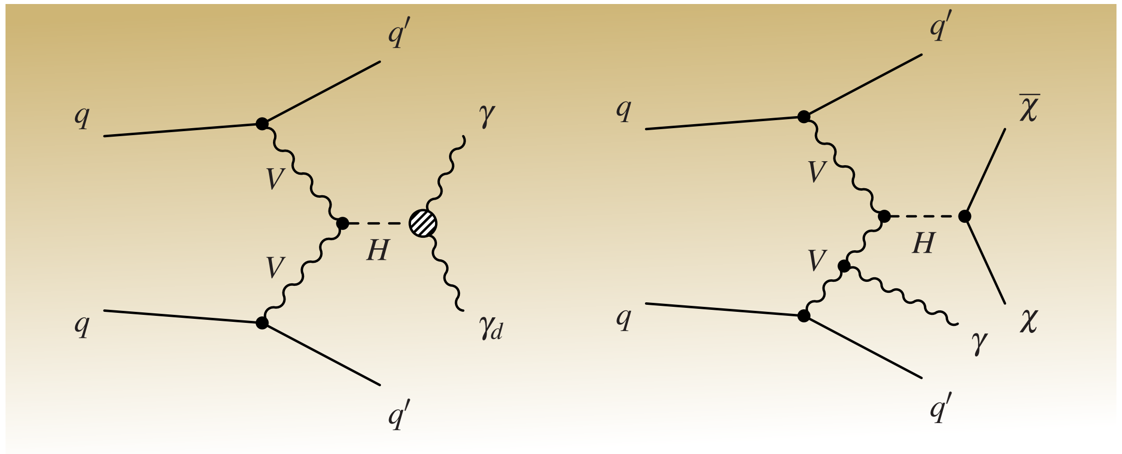
γZ is a background for Higgs to invisible and dark photon searches

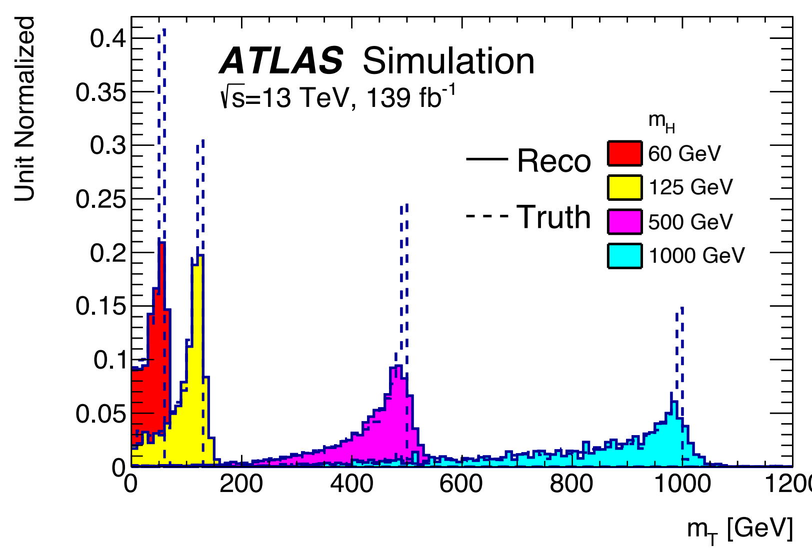




Br < 1.8% observed (1.7% expected)

Br < 37% (34% expected)

Rich final state with a measurement and two **search** interpretations



Recent result on **VBF** Higgs to invisible arXiv 2202.07953: 14.5% observed, 10.3% expected

Transverse mass to reconstruct mediator mass

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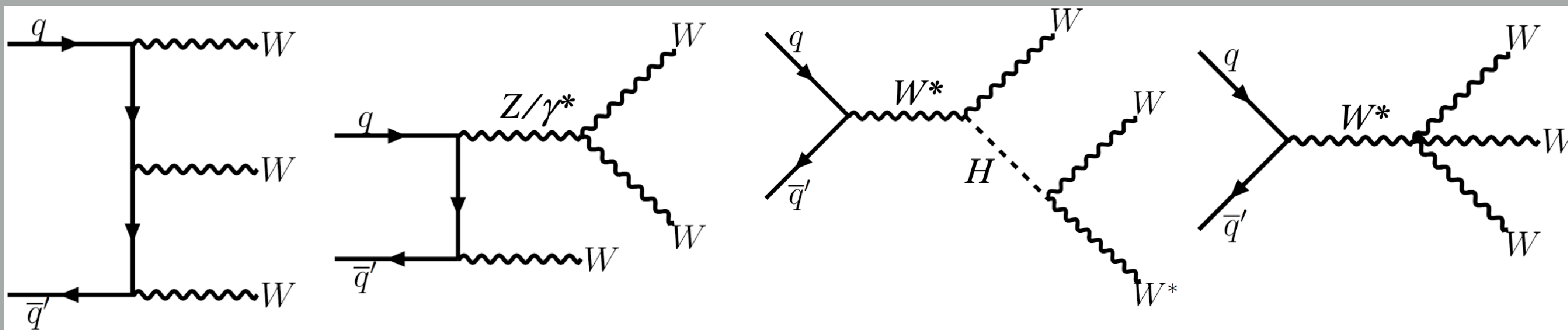
WWW

arXiv: 2201.13045

WWW process is sensitive to triple and quartic gauge boson self-interactions



Triple VH Quartic

Two final state categories with 2-3 leptonic W decays:

- 2ℓ same sign (SS), suppresses W, Z, top
- 3ℓ suppresses W, Z, top

Separate from VBS WW using m_{jj} < 160 GeV & $|\Delta\eta_{jj}|$ < 1.5

Train BDT using 11 input variables for each category

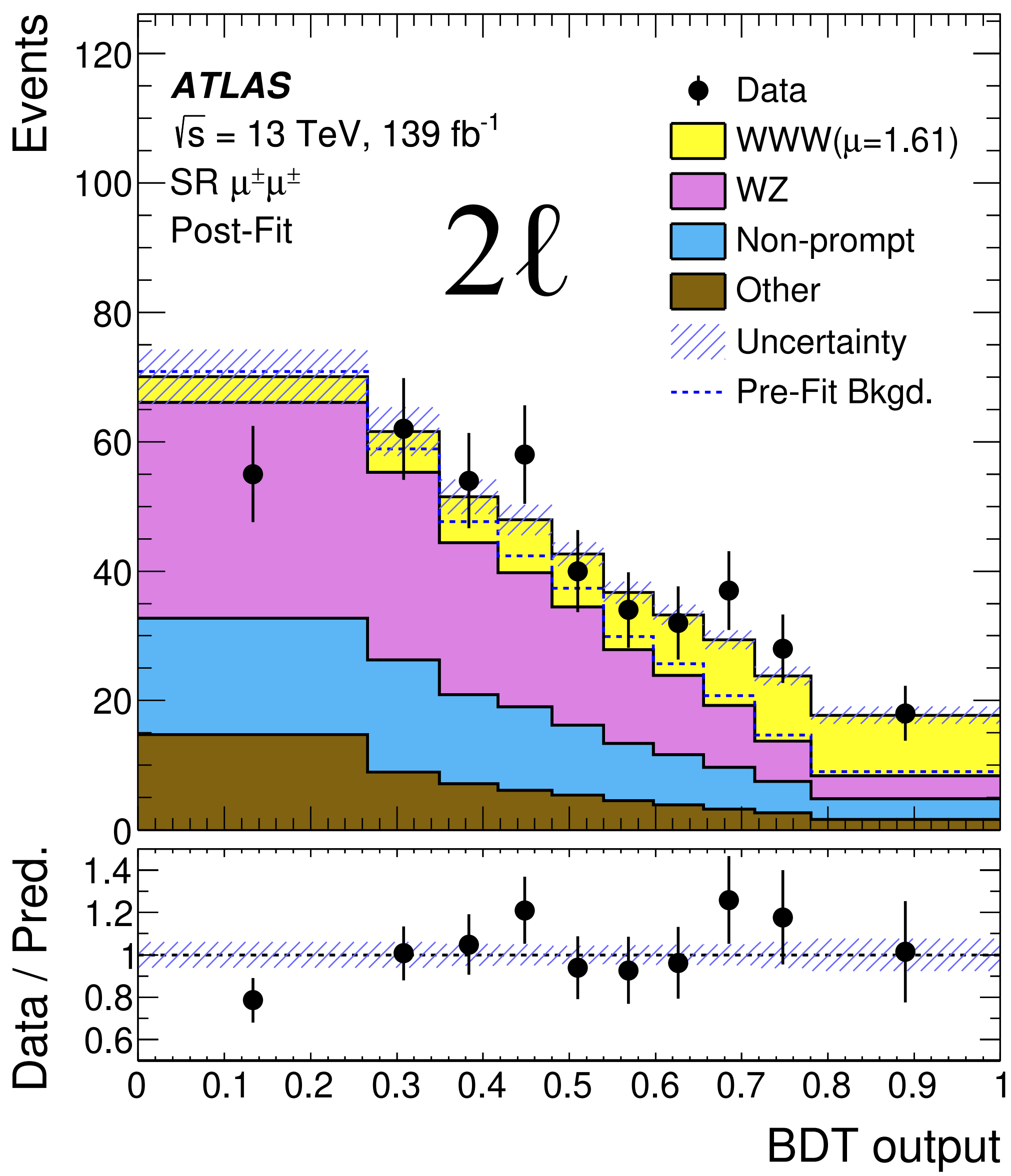
- Example: $|m_{jj}-m_{\ell\ell}|$ to identify hadronic W

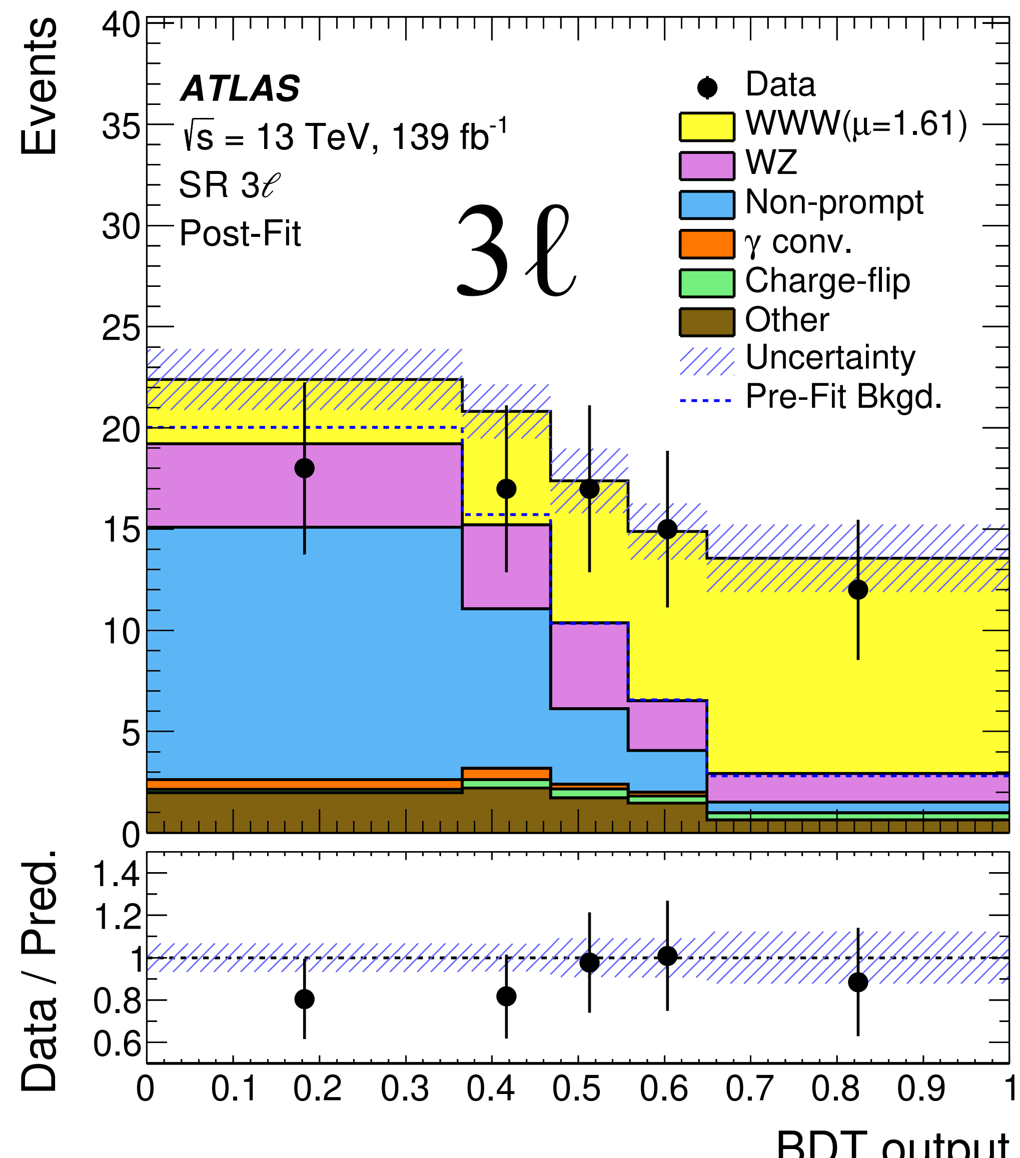
Observation of WWW

arXiv: 2201.13045

First ATLAS observation of WWW with 8.0σ observed (5.4σ exp.)

Fit	$\mu(WWW)$	Significance observed (expected)
$e^{\pm}e^{\pm}$	1.54 ± 0.76	2.2 (1.4) σ
$e^{\pm}\mu^{\pm}$	1.44 ± 0.39	4.1 (3.0) σ
$\mu^{\pm}\mu^{\pm}$	2.23 ± 0.46	5.6 (2.7) σ
2ℓ	1.75 ± 0.30	6.6 (4.0) σ
3ℓ	1.32 ± 0.37	4.8 (3.8) σ
Combined	**1.61 ± 0.25**	**8.0 (5.4) σ**





Sensitive to Non-SM physics in MET distribution arXiv: 2011.09551

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Effective theory

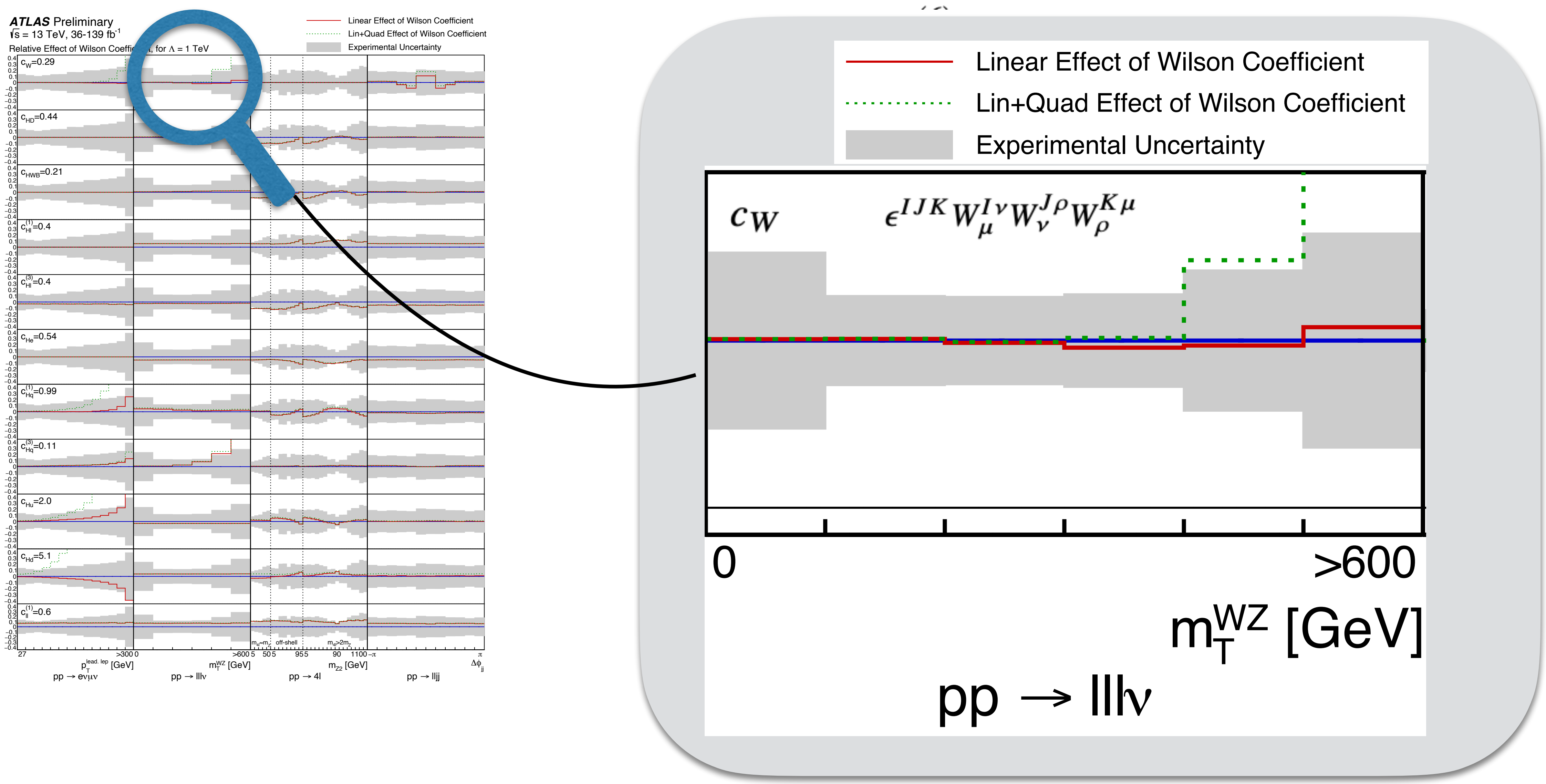
Interpret measurements from WW, WZ, 4ℓ and VBF Z

$\sigma \propto |\mathcal{M}_{\mathrm{SMEFT}}|^2$ Linear   Quadratic

$$= |\mathcal{M}_{\mathrm{SM}}|^2 + \boxed{\sum_i \frac{c_i^{(6)}}{\Lambda^2} 2\mathrm{Re}\left(\mathcal{M}_i^{(6)} \mathcal{M}_{\mathrm{SM}}^*\right)} + \boxed{\sum_i \frac{\left(c_i^{(6)}\right)^2}{\Lambda^4} \left|\mathcal{M}_i^{(6)}\right|^2} + \sum_{i<j} \frac{c_i^{(6)} c_j^{(6)}}{\Lambda^4} 2\mathrm{Re}\left(\mathcal{M}_i^{(6)} \mathcal{M}_j^{(6)*}\right)$$

$$+ \mathcal{O}\left(\Lambda^{-4}\right),$$

Impact of Wilson coefficients C on observables

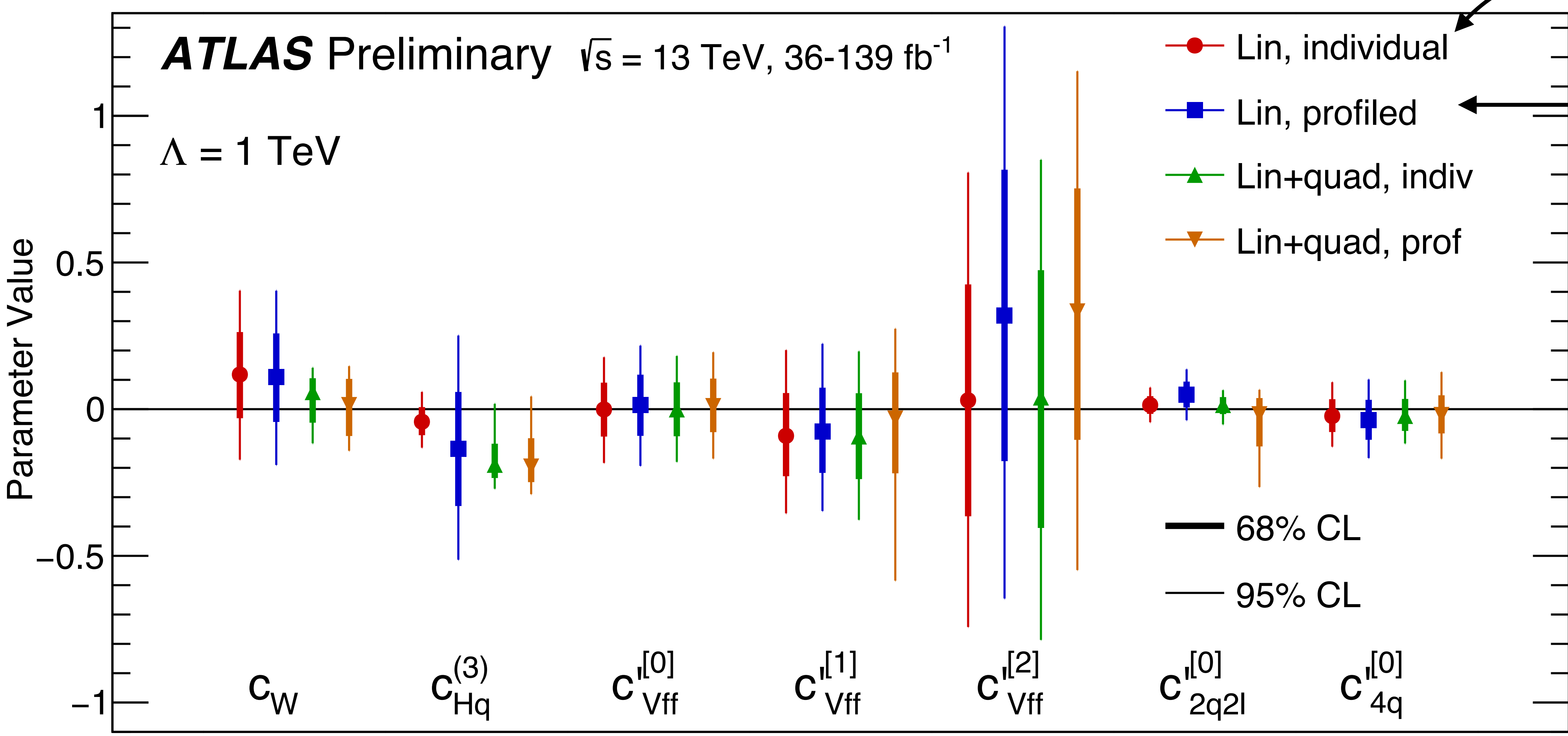


Effective theory Results

ATL-PHYS-PUB-2021-022

Example of 1D profiles of Wilson coefficients

- Parameter value of 0 corresponds to SM



One parameter scan, others fixed to 0

Combined fit

$c'^{[0]}_{Vff} \approx 0.81c_{HWB} + 0.38c_{HD} + 0.13c^{(1)}_{Hl} + 0.37c^{(3)}_{Hl} - 0.14c^{(1)}_{ll} + 0.12c^{(1)}_{Hq}$

$c'^{[1]}_{Vff} \approx 0.73c^{(1)}_{Hl} - 0.28c^{(3)}_{Hl} - 0.48c_{He} + 0.38c^{(1)}_{ll} + 0.13c^{(1)}_{Hq}$

$c'^{[2]}_{Vff} \approx 0.37c_{HWB} + 0.17c_{HD} - 0.31c^{(1)}_{Hl} - 0.53c^{(3)}_{Hl} + 0.25c_{He} + 0.59c^{(1)}_{ll} - 0.21c^{(1)}_{Hq}$

$c'^{[0]}_{2q2l} \approx -0.37c^{(1)}_{lq} + 0.89c^{(3)}_{lq} - 0.11c_{lu} - 0.21c_{eu} - 0.13c_{qe}$

$c'^{[0]}_{4q} \approx 0.11c^{(11)}_{qq} + 0.22c^{(18)}_{qq} + 0.95c^{(31)}_{qq} - 0.2c^{(38)}_{qq}$

Modified basis, described in ATL-PHYS-PUB-2019-042

Conclusions

1. EW $\gamma Z \to \ell\ell$

2. EW $\gamma Z \to \nu\nu$: observation!

3. WWW: observation!

Why measure EW processes

- Window into rare SM couplings
- Important for backgrounds in searches
- Synergy with searches for non-SM physics

Effective theory: general method to interpret ATLAS data to identify hints of non-SM operators

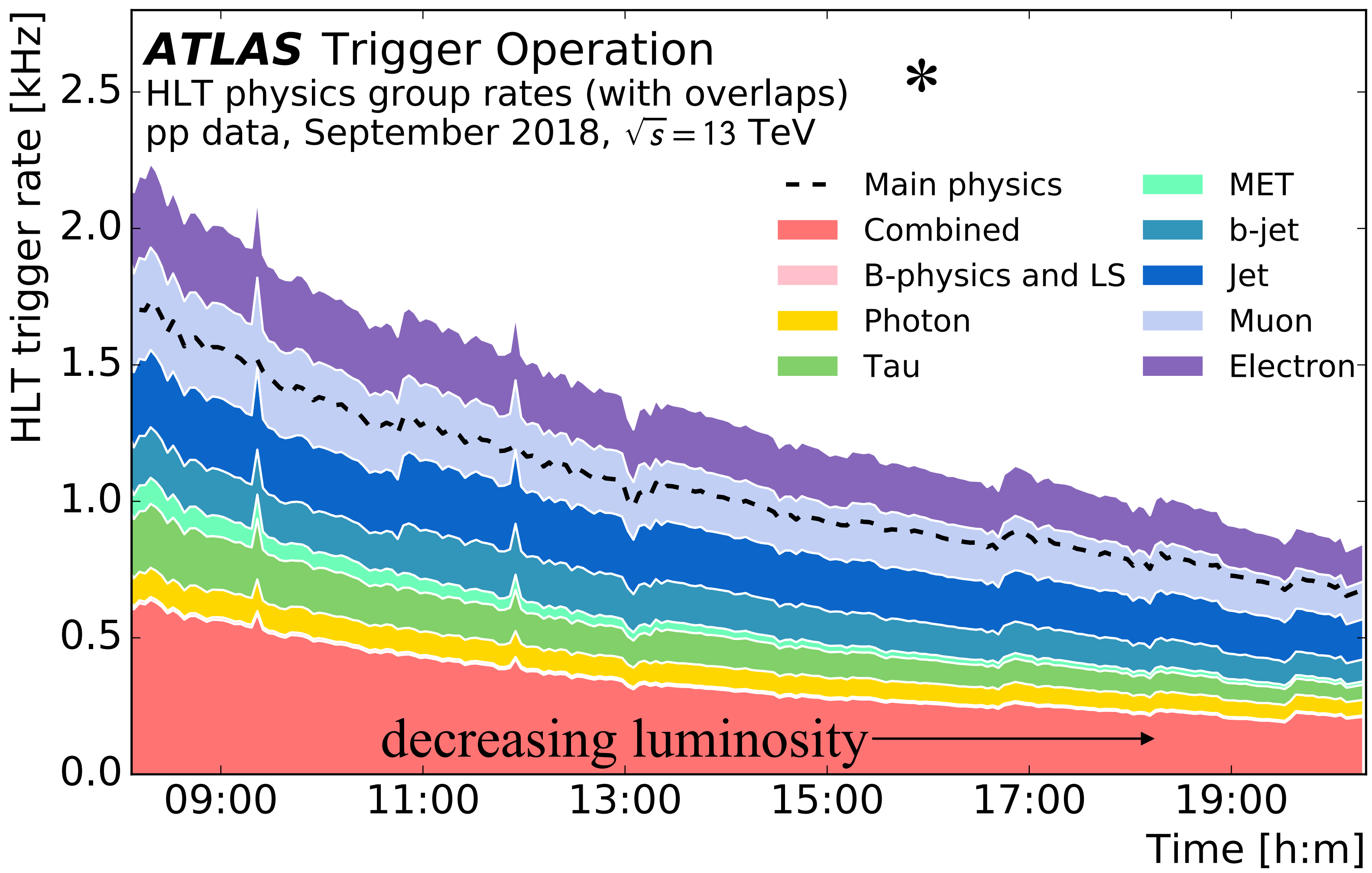
Backup

Trigger: HLT

Trigger Operations public (link)
Run 2 menu: ATL-COM-DAQ-2019-071

Single lepton triggers use approximately 1/4th the HLT rate

- Thresholds at ~27 GeV offline (though not 100% efficient, see backup)
- General purpose trigger for all kinds of physics (W, Z, H, exotics…)
- Offline thresholds for other objects differ on rate and use case



Algorithm	Offline thr.
μ	27
e	27
Jet	420
4 Jet	125
4 Jets, 2 b-tags	65
MET	~150
τ	170
$\tau\tau + \Delta R < 2.5$	40 (30)
γ	140
$\gamma\gamma$	25

*Total rate does not add equal to sum of contributions, because of overlaps

Selections

Lepton	$p_{\mathrm{T}}^{\ell} > 20, 30(\text{leading})$ GeV, $\lvert\eta_\ell\rvert < 2.47$ $N_\ell \geq 2$
Photon	$E_{\mathrm{T}}^{\gamma} > 25$ GeV, $\lvert\eta_\gamma\rvert < 2.37$ $E_{\mathrm{T}}^{cone20} < 0.07 E_{\mathrm{T}}^{\gamma}$ $\Delta R(\ell, \gamma) > 0.4$
Jet	$p_{\mathrm{T}}^{jet} > 50$ GeV, $\lvert y_{jet}\rvert < 4.4$ $\lvert\Delta y\rvert > 1.0$ $m_{jj} > 150$ GeV remove jets if $\Delta R(\gamma, j) < 0.4$ or if $\Delta R(\ell, j) < 0.3$
Event	$m_{\ell\ell} > 40$ GeV $m_{\ell\ell} + m_{\ell\ell\gamma} > 182$ GeV $\zeta(\ell\ell\gamma) < 0.4$ $N_{jets}^{gap} = 0$

Results

Sample	SR	CR
$N_{EW-Z\gamma jj}$	300 ± 36	55 ± 7
$N_{QCD-Z\gamma jj}$	987 ± 55	1352 ± 60
$N_{t\bar{t}\gamma}$	72 ± 11	59 ± 9
N_{WZ}	17 ± 3	14 ± 3
N_{Z+jets}	85 ± 30	143 ± 43
Total	1461 ± 38	1624 ± 40
N_{obs}	1461	1624

Selections

Variable	SR	$W^{\gamma}_{\mu\nu}$ CR	$W^{\gamma}_{e\nu}$ CR	$Z^{\gamma}_{\text{Rev.Cen.}}$ CR	Fake-e CR	Low-$E_{\text{T}}^{\text{miss}}$ VR
$p_{\text{T}}(j_1)$ [GeV]	> 60					
$p_{\text{T}}(j_2)$ [GeV]	> 50					
$p_{\text{T}}(j_{>2})$ [GeV]	> 25					
N_{jet}	2,3					
$N_{b\text{-jet}}$	< 2					
$\Delta\phi_{\text{jj}}$	< 2.5 [2.0]					
$\lvert\Delta\eta_{\text{jj}}\rvert$	> 3.0					
$\eta(j_1) \times \eta(j_2)$	< 0					
C_3	< 0.7					
m_{jj} [TeV]	> 0.25					0.25–1.0
$E_{\text{T}}^{\text{miss}}$ [GeV]	> 150	–	> 80	> 150	< 80	110–150
$E_{\text{T}}^{\text{miss,lep-rm}}$ [GeV]	–	> 150	> 150	–	> 150	110–150
$E_{\text{T}}^{\text{jets,no-jvt}}$ [GeV]	> 130					> 100
$\Delta\phi(j_i, \vec{E}_{\text{T}}^{\text{miss,lep-rm}})$	> 1.0					
N_{γ}	1					
$p_{\text{T}}(\gamma)$ [GeV]	$> 15, < 110$ [$> 15, < \max(110, 0.733 \times m_{\text{T}})$]					
C_{γ}	> 0.4	> 0.4	> 0.4	< 0.4	> 0.4	> 0.4
$\Delta\phi(\gamma, \vec{E}_{\text{T}}^{\text{miss,lep-rm}})$	> 1.8 [–]					
N_{ℓ}	0	1 μ	1 e	0	1 e	0
$p_{\text{T}}(\ell)$ [GeV]	–	> 30	> 30	–	> 30	–

Estimating W&Z

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Control sample	Signal sample
$W \rightarrow \ell\nu$ *found* lepton	$W \rightarrow \ell\nu$ *lost* lepton
$Z \rightarrow \nu\nu$ Centrality < 0.4	$Z \rightarrow \nu\nu$ Centrality > 0.4

Determine background normalization from simultaneous fit of CR

Features of VBF

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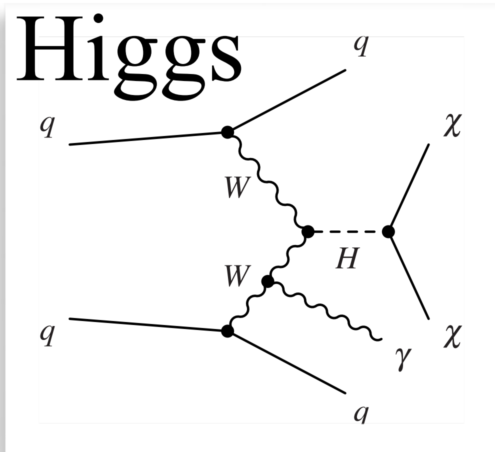
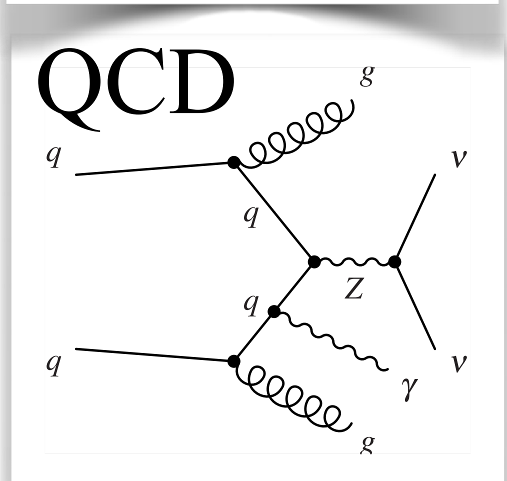
Elboli, Zeppenfeld Phys. Lett. B 495 147-154 (2000)

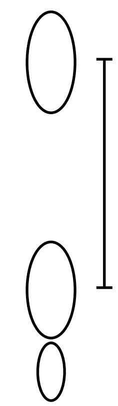




Energy deposits

Jets

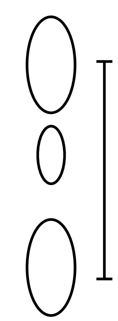
Invisible decay



Jets widely separated (η) & large m_{jj}

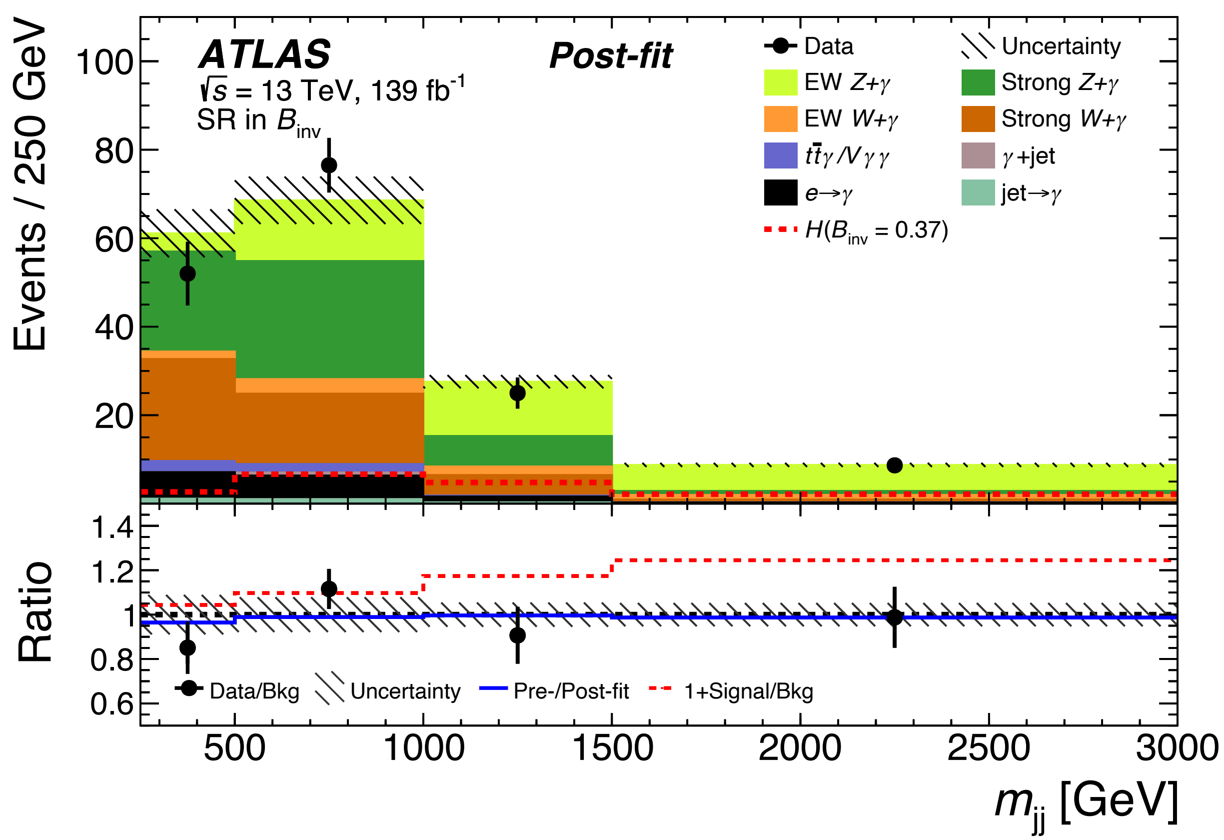
Jets recoil against Higgs (small Δϕ)

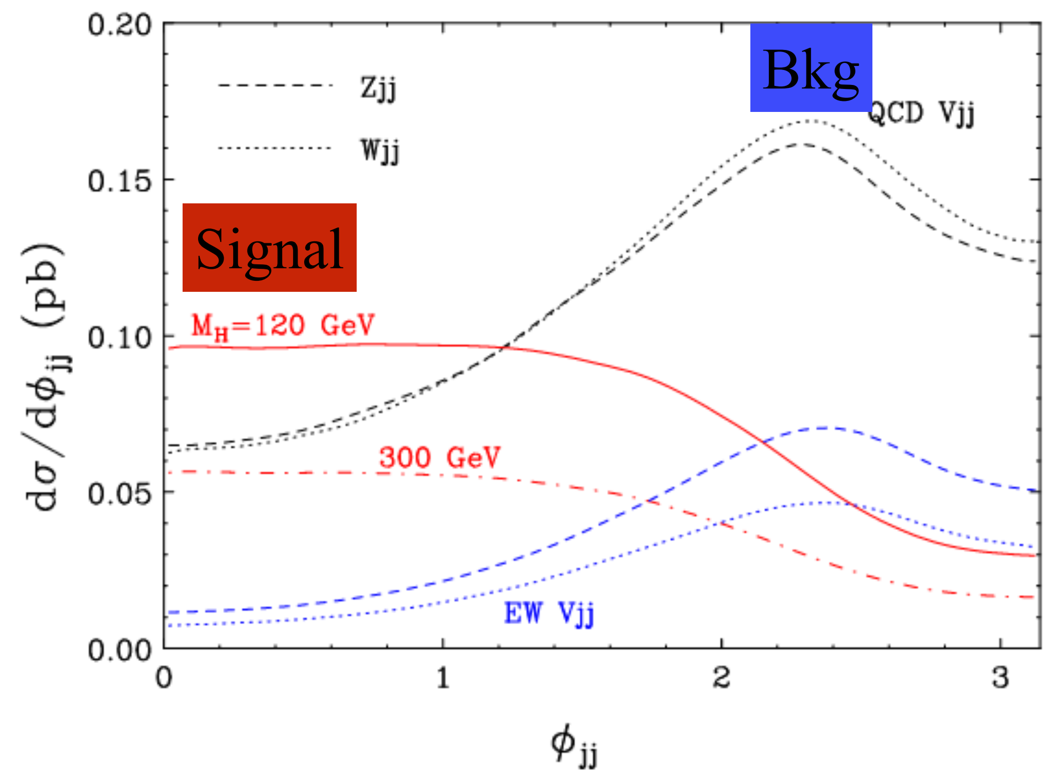
Hadronic activity (addition jets)



Jets not as separated

Jets back to back (ϕ)

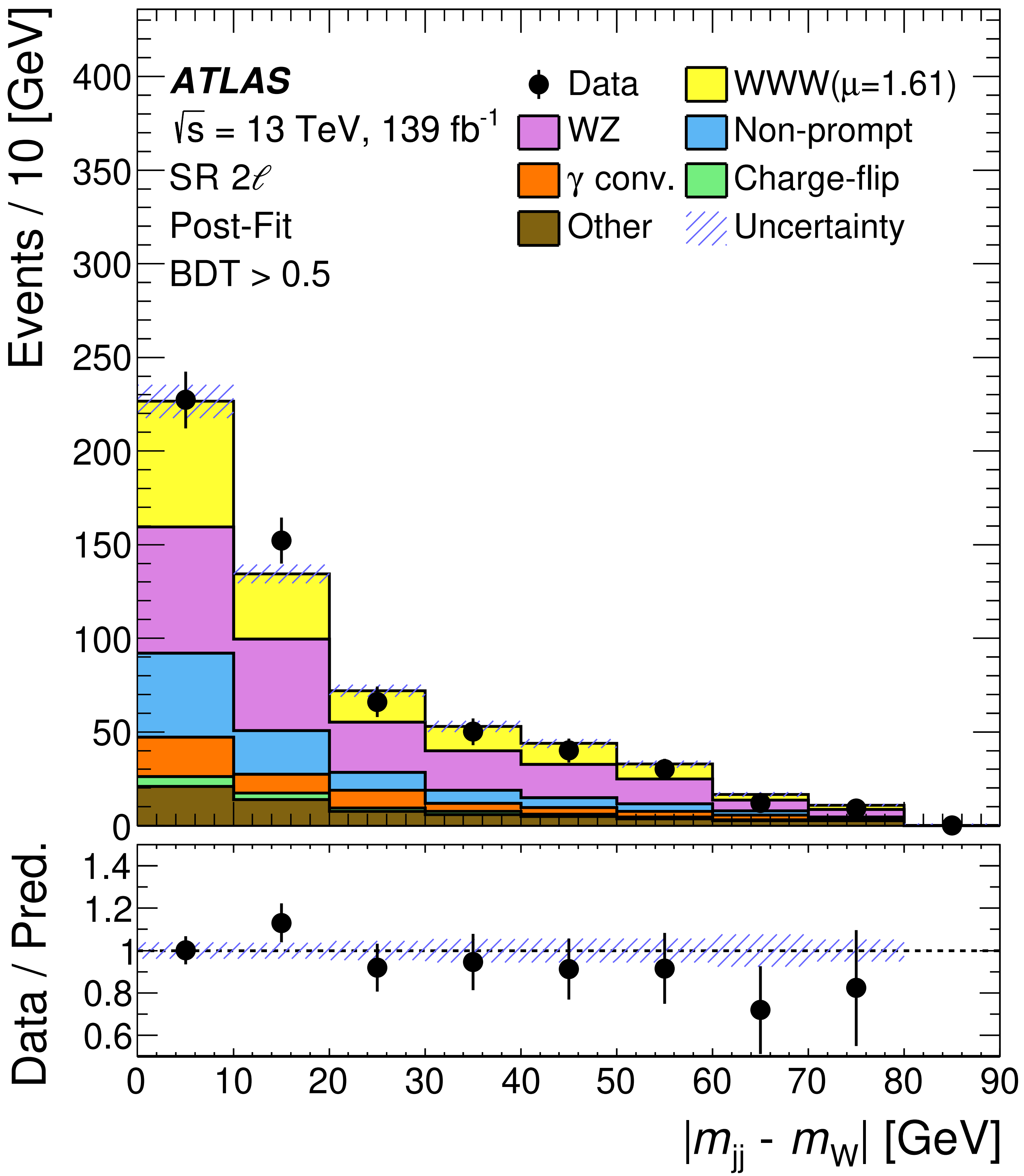




$\Delta\phi_{jj}$

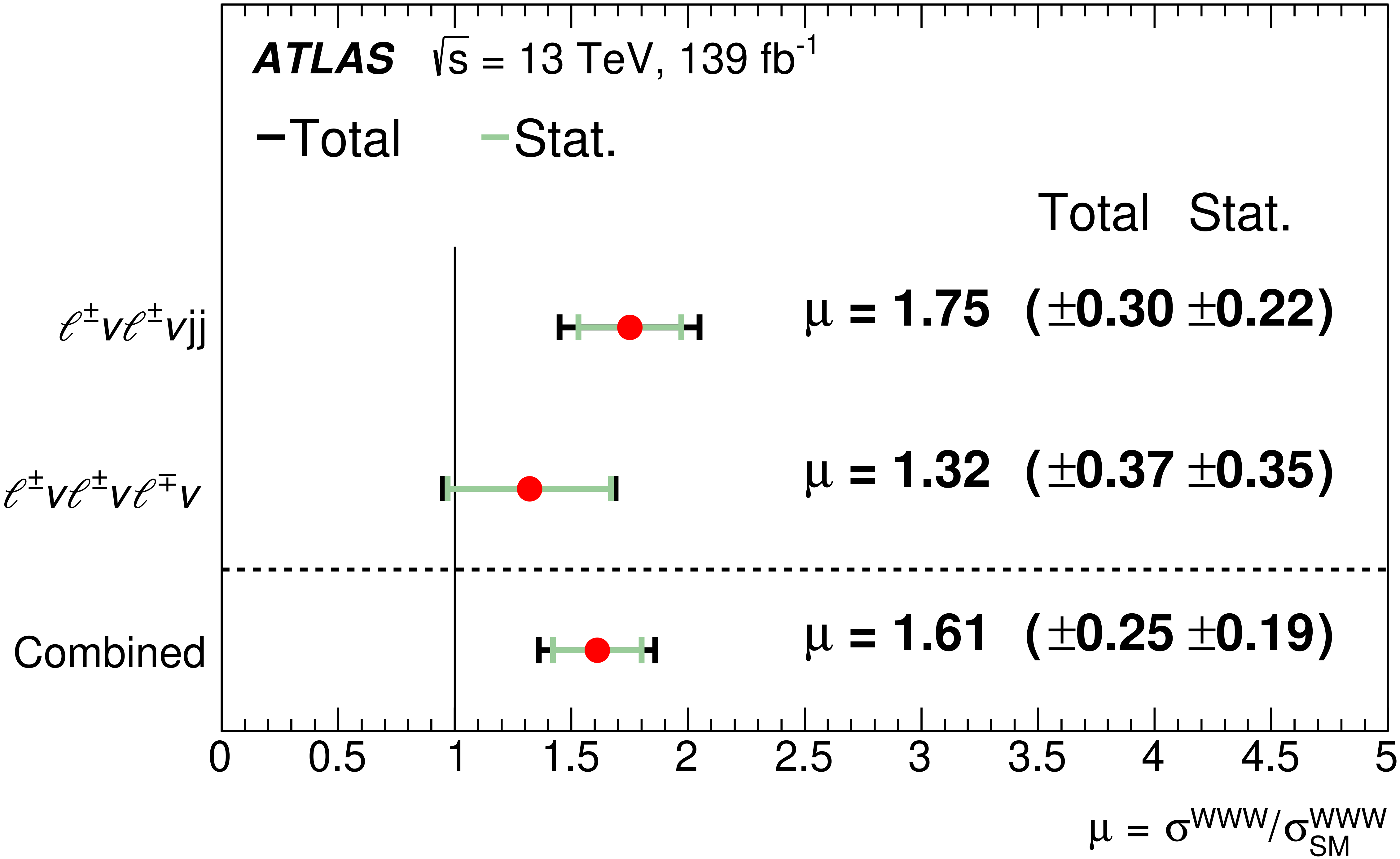
Input distribution

2ℓ	3ℓ
$\lvert m_{jj} - m_W \rvert$	$E_{\mathrm{T}}^{\mathrm{miss}}$ significance $\times 10 / E_{\mathrm{T}}^{\mathrm{miss}}$
p_{T}(forward jet)	$p_{\mathrm{T}}(\ell_2)$
$E_{\mathrm{T}}^{\mathrm{miss}}$ significance	N(jets)
$p_{\mathrm{T}}(j_2)$	same flavor $m_{\ell\ell}$
minimum $m(\ell, j)$	$m_{\mathrm{T}}(\ell\ell\ell, E_{\mathrm{T}}^{\mathrm{miss}})$
$m(\ell_2, j_1)$	$m(\ell_2, \ell_3)$
N(jets)	$\Delta\phi(\ell\ell\ell, E_{\mathrm{T}}^{\mathrm{miss}})$
p_{T} (ℓ_2)	minimum $\Delta R(\ell, \ell)$
$\lvert\eta(\ell_1)\rvert$	$p_{\mathrm{T}}(\ell_3)$
N(leptons in jets)	$m_{\mathrm{T}}(\ell_2, E_{\mathrm{T}}^{\mathrm{miss}})$
$m(\ell_1, j_1)$	$E_{\mathrm{T}}^{\mathrm{miss}}$ significance



WWW observation

arXiv: 2201.13045



New physics in WWW

arXiv: 2011.09551