Diboson Measurements

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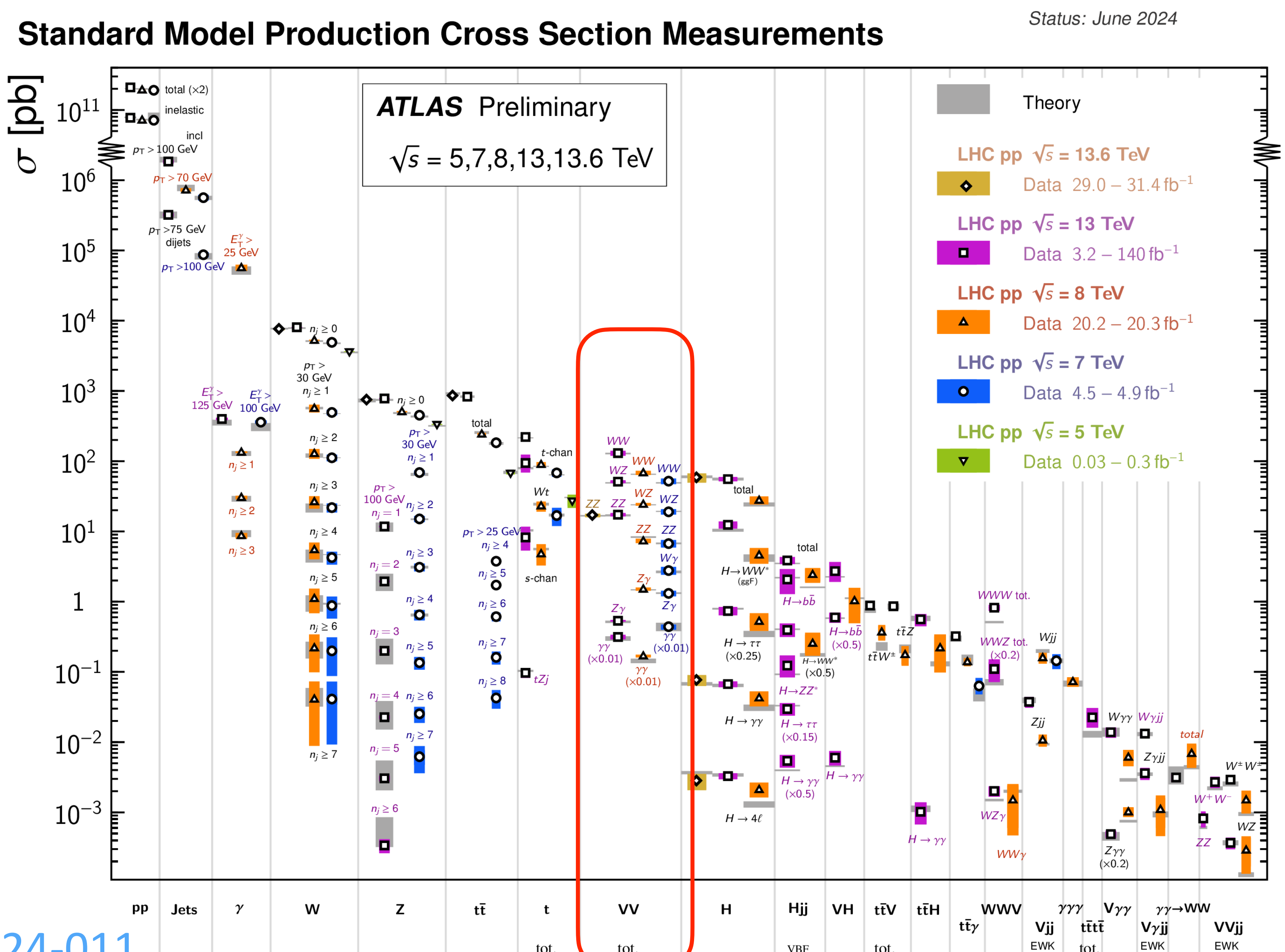
Introduction - why VV?

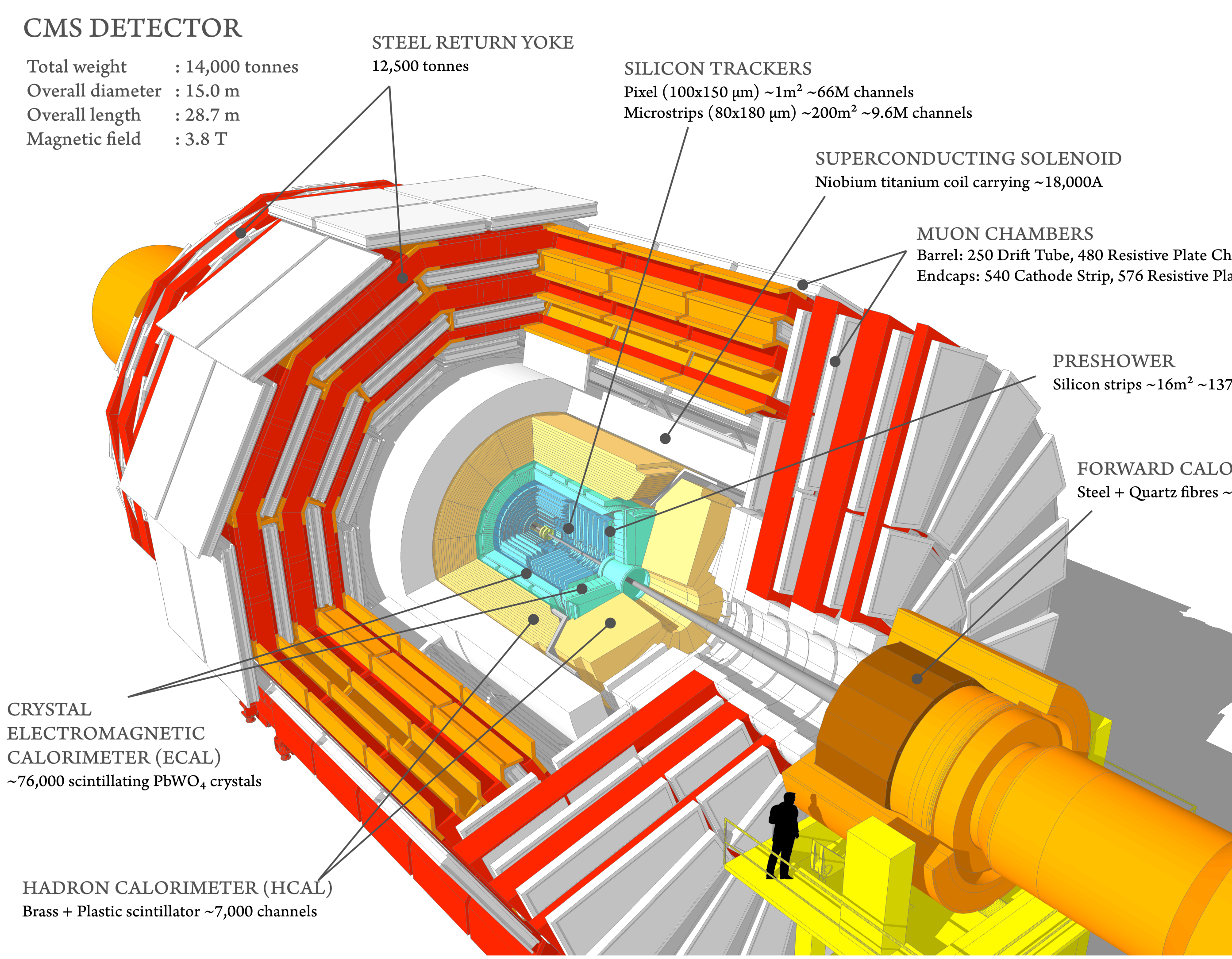
- Stringent test of the Standard Model of electroweak gauge interactions
  - VV: abundant production, relatively clean final state signatures
- Sensitive to Effective Field Theory(EFT)

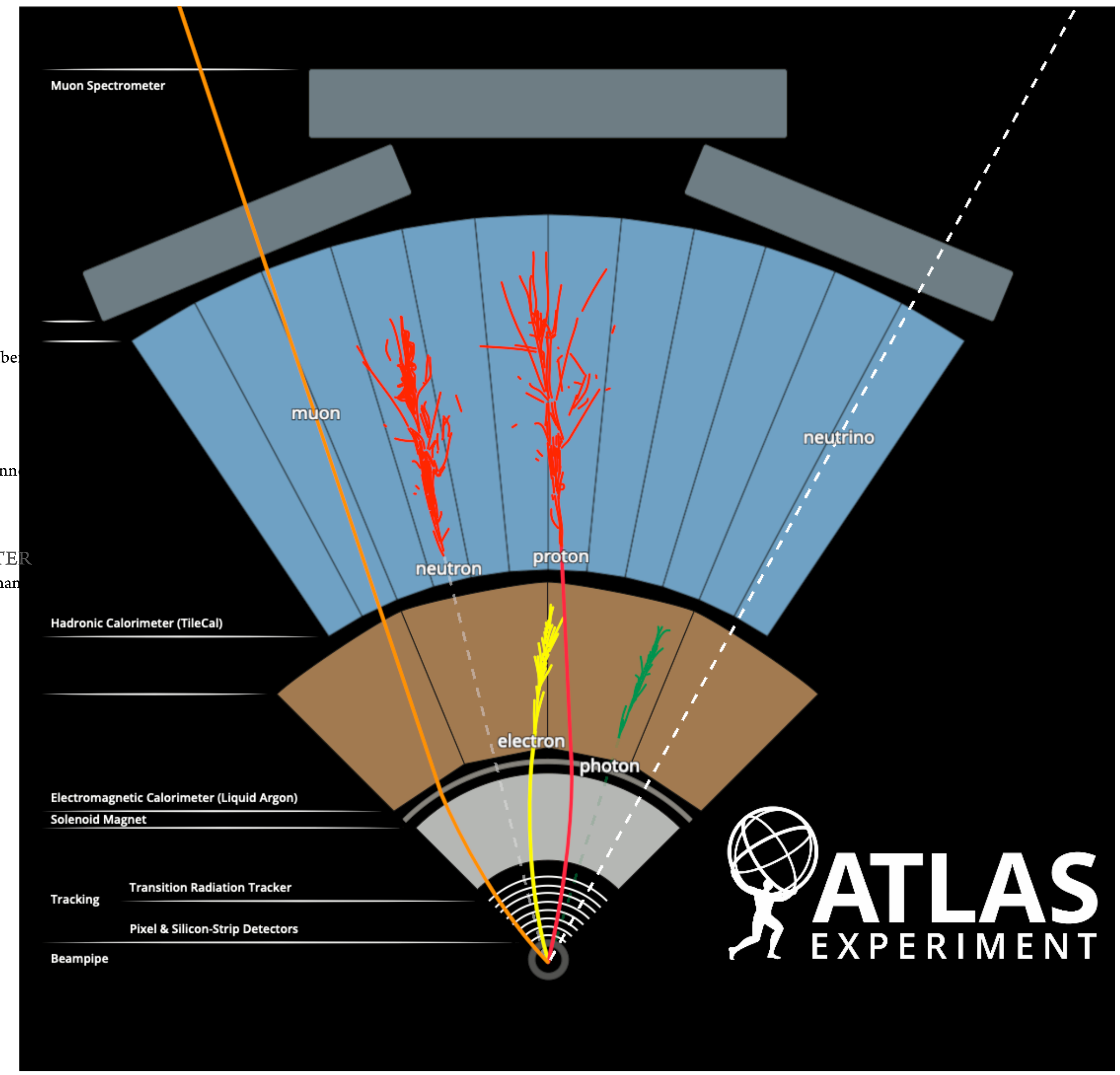


ATL-PHYS-PUB-2024-011

General Purpose Detectors

- ATLAS and CMS detectors are the two general purpose detectors on the Large Hadron Collider.





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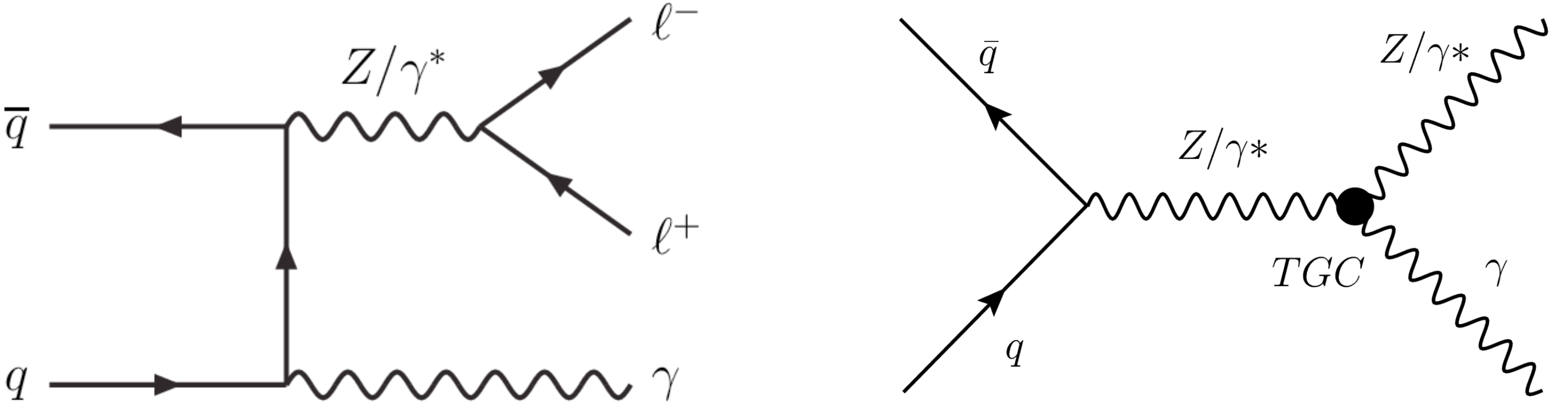
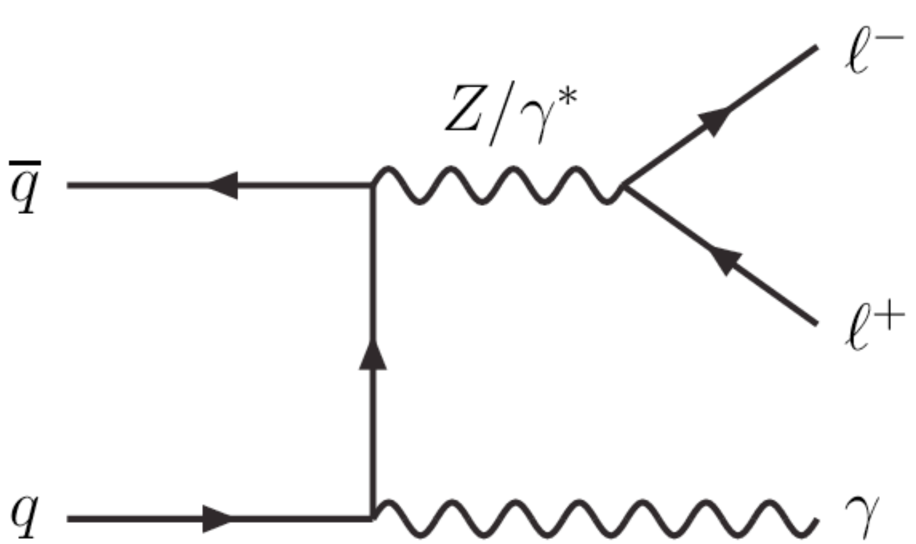
Z(ll)γ - neutral Triple Gauge Coupling

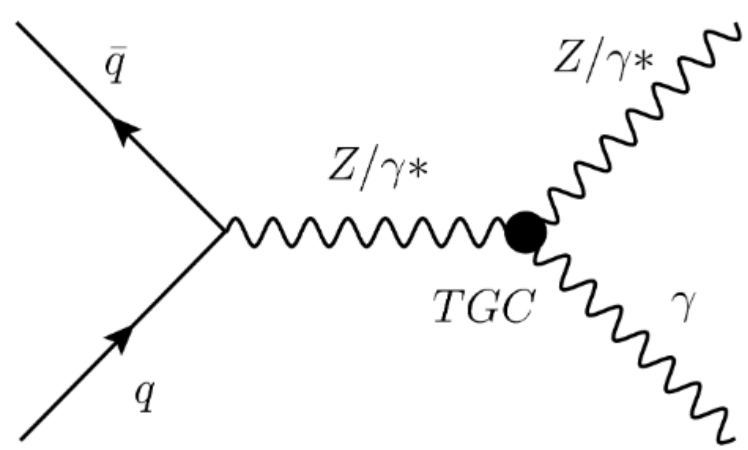
ATLAS-CONF-2025-001

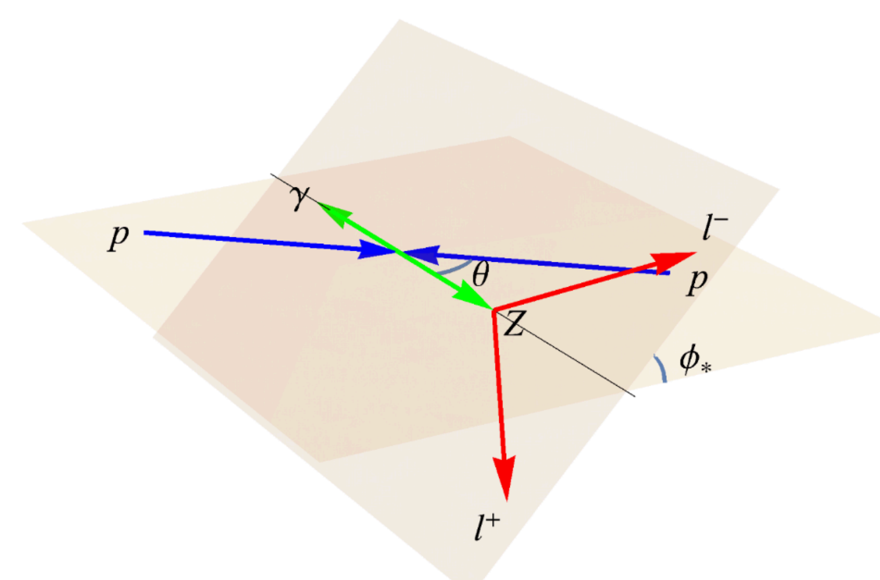


Z(ll)γ Highlights

- Study on-shell Z—>ll, with ATLAS 140 fb^{-1} full Run-2 data @ 13 TeV
- Neutral Triple Gauge Coupling(nTGC) forbidden at the SM tree level
  - BSM physics could introduce a non-0 nTGC vertex.
  - Dimension-8 Standard Model Effective Field Theory
- Extension of previous analyses ([production XS](), [differential XS]()), with a focus on the EFT model
- Measure p_T^{γ}
- Measure ϕ^*: between the scattering plane and the decay plane of Z boson, in the Z center-of-mass frame

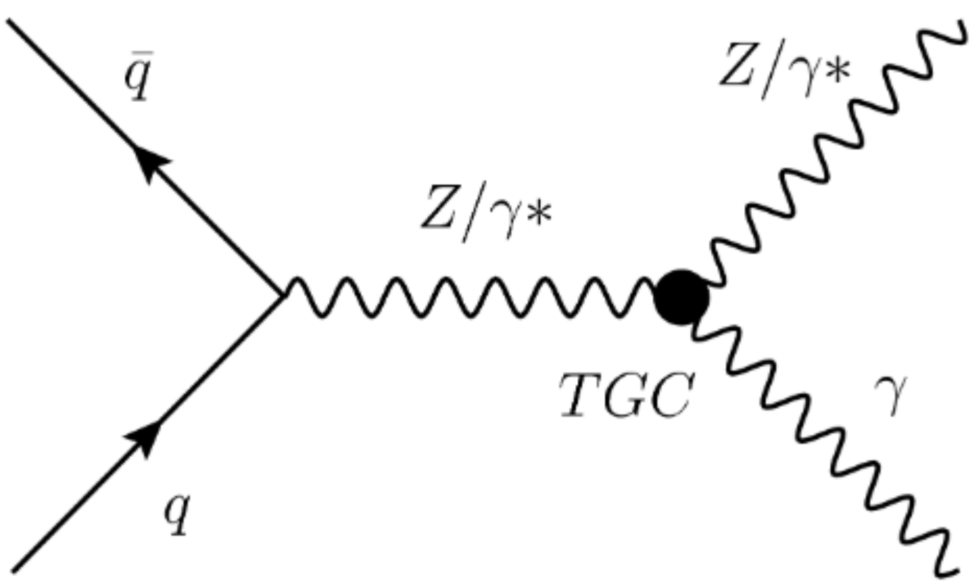


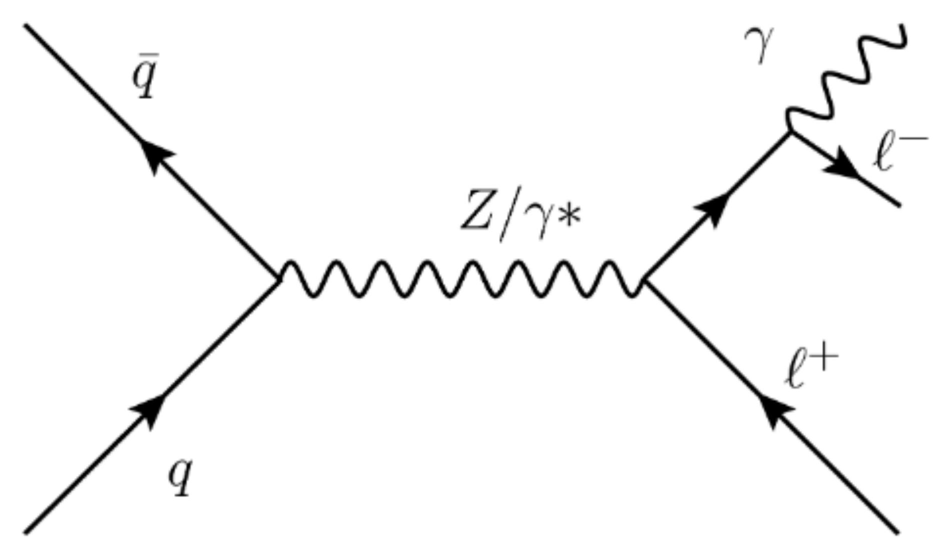




Selections

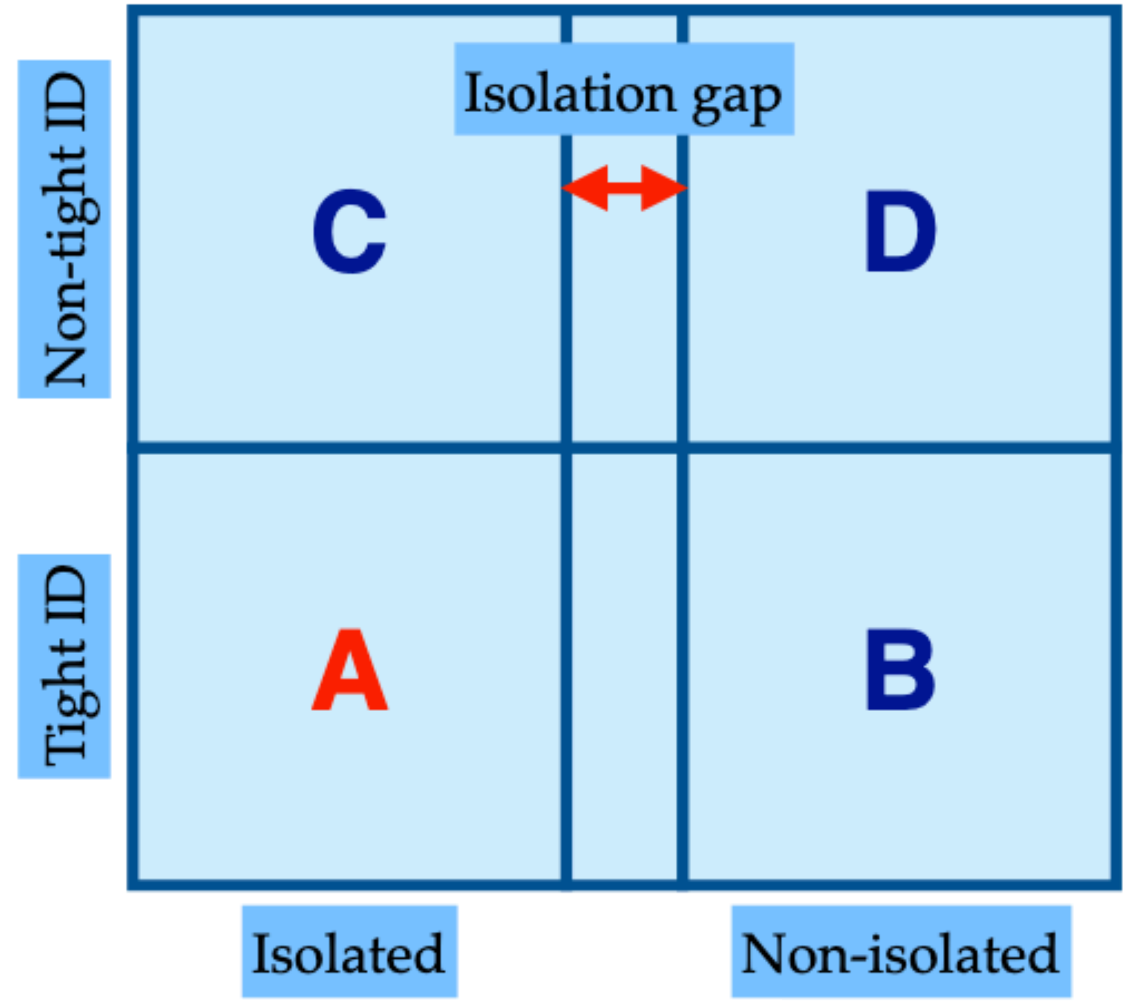
- Single and di-lepton trigger
- 2 opposite-sign same-flavor leptons + 1 photon
- min(|m_{ll} - m_Z|) < 10 GeV: selecting on-shell Z
- p_T^{γ} > 200 GeV: suppress SM Zγ process.
- 0 jets: suppress non-prompt background
- m_{ll} + $m_{ll\gamma}$ > 182 GeV ~ 2 m_Z
  - Suppress final state radiation ($m_{ll\gamma}$ ~ m_Z, m_{ll} < m_Z)





Background Estimation

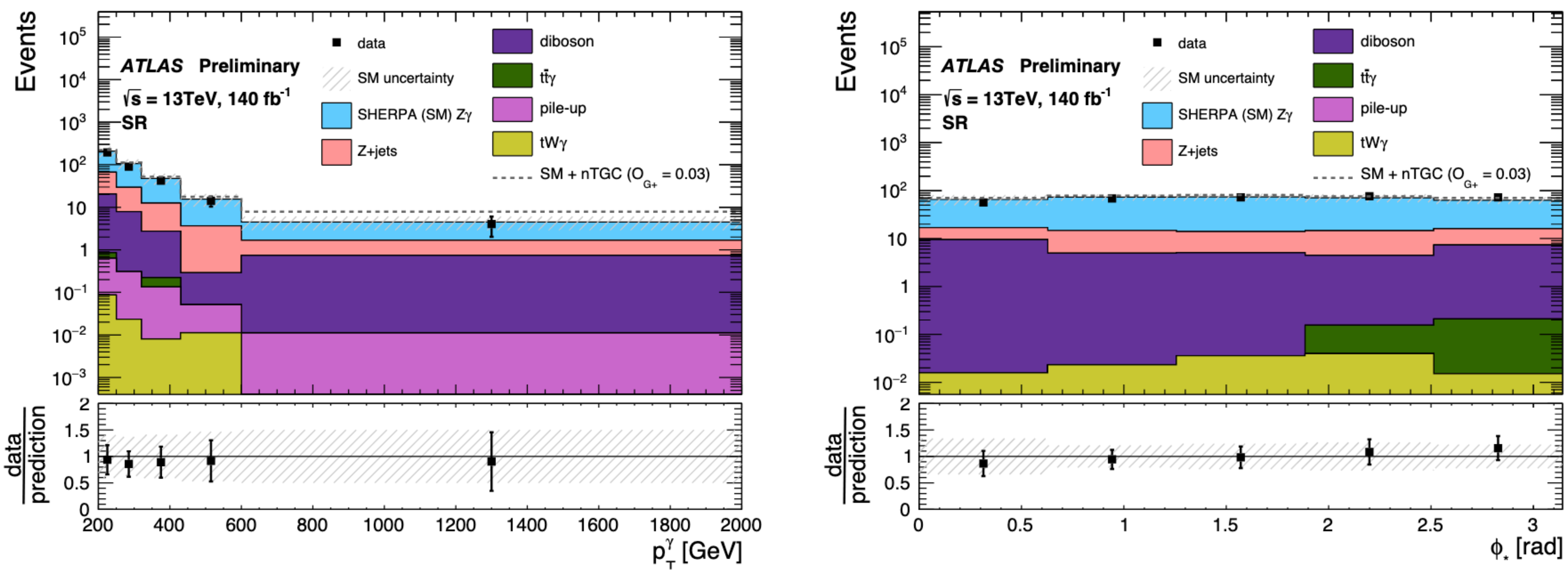
- Z+jets: data-driven ABCD method
  - Invert photon isolation and quality in control regions
  - Consider signal leakage in control regions
  - Use MC for ratio between region and signal leakage
- Multiboson: diboson and triboson MC samples
- Pile-up photons: high impact parameter(IP) region to select converted photon, scale to SR IP region



Source	$ee + \mu\mu$
$Z\gamma$ signal	271.0 ± 2.4 (stat.) ± 44.3 (syst.)
Z+jets	82 ± 71 (stat.) ± 98 (syst.)
multiboson	33.5 ± 4.6 (stat.) ± 10.0 (syst.)
pile-up	1.01 ± 0.11 (stat.) ± 0.20 (syst.)
$t\bar{t}\gamma$	0.31 ± 0.18 (stat.) ± 0.05 (syst.)
$tW\gamma$	0.13 ± 0.02 (stat.) ± 0.04 (syst.)
Total prediction	388 ± 71 (stat.) ± 108 (syst.)
Data	344

Reco-level result

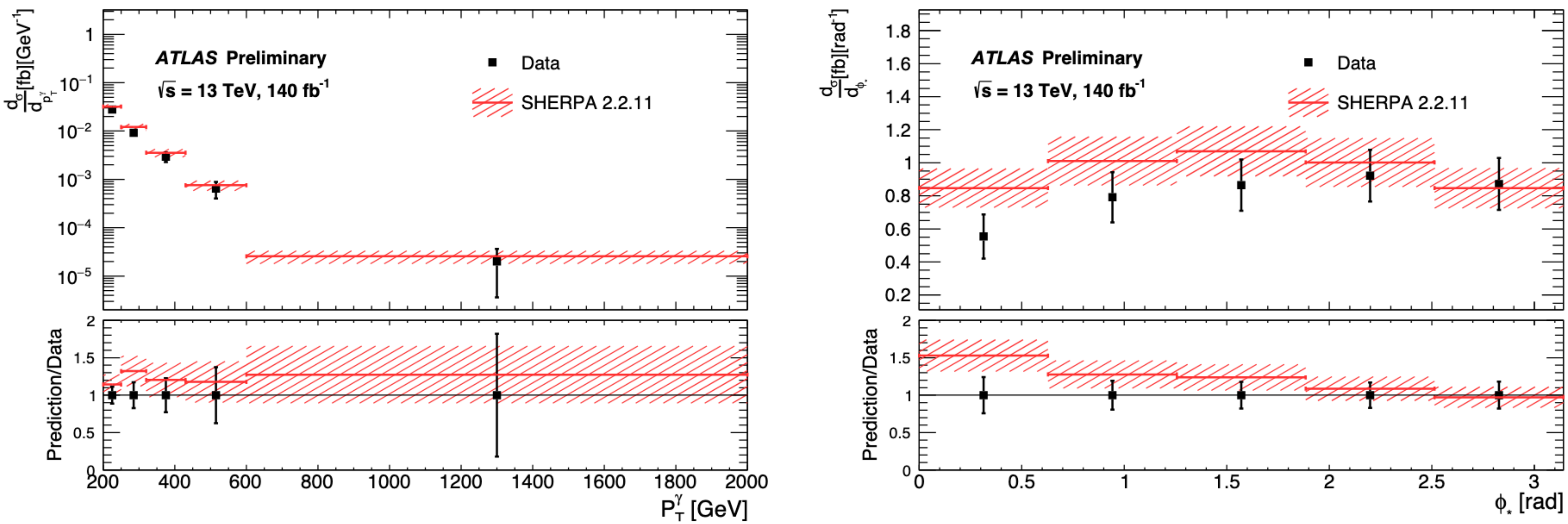
- p_T^γ sensitive to the EFT signal



Unfolded Results

- Unfolding: account for reconstruction efficiency, migration between bins, fiducial region correction
- Variables measured in fiducial level.

$$\begin{pmatrix} D_1 \\ \cdots \\ D_n \end{pmatrix} = \begin{bmatrix} \varepsilon_1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & \varepsilon_n \end{bmatrix} \times \begin{bmatrix} R_{11} & \cdots & R_{1n} \\ \vdots & \ddots & \vdots \\ R_{n1} & \cdots & R_{nn} \end{bmatrix} \times \begin{bmatrix} C_1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & C_n \end{bmatrix} \times \begin{pmatrix} T_1 \\ \cdots \\ T_n \end{pmatrix}$$



Systematics uncertainty

- Regular object systematic uncertainties, luminosity, theory uncertainties considered
  - Dominated by background uncertainty
- Uncertainty propagated through the unfolding process, **systematics** limited.

p_T^γ [GeV]	[200, 250]	[250, 320]	[320, 430]	[430, 600]	[600, 2000]
Statistical uncertainty	11.3	17.3	22.7	37.4	82.0
Luminosity uncertainty	0.83	0.83	0.83	0.83	0.83
Electrons	1.97	2.43	3.28	3.94	4.72
Muons	0.96	1.14	1.30	1.36	2.19
Jets	3.41	3.16	3.19	3.76	4.13
Photons	1.20	1.76	1.88	1.96	2.60
Pile-up	1.36	1.25	1.47	1.90	2.52
Generator	1.05	3.49	5.59	2.23	8.75
Scale	0.97	1.15	1.31	1.41	2.42
PDF	0.97	1.15	1.30	1.37	2.25
Unfolding	0.19	0.40	0.12	0.12	0.13
Background	22.0	21.3	21.8	24.9	25.6
Total	25.1	28.1	45.5	45.6	86.7

EFT interpretation

- Dimension-8 SMEFT
- Probing new physics at a higher energy scale

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_j \frac{c_j}{\Lambda_j^4} O_j$$

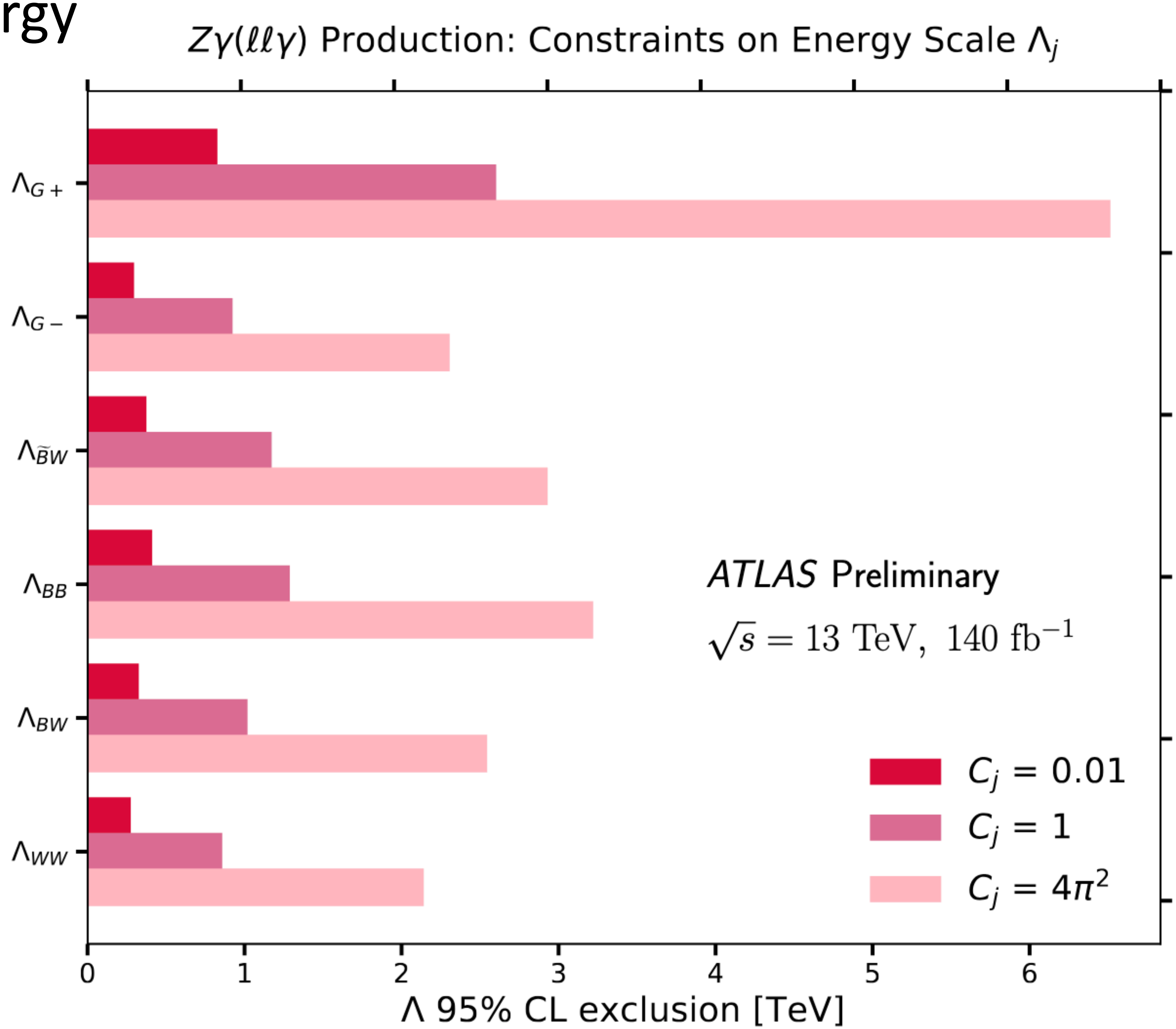
- For 6 Wilson coefficients with χ^2 test statistic of d.o.f. = 1, derive 95% Confidence Level Interval

$$\mathcal{L}(c,\vec{\theta}) = \frac{1}{\sqrt{(2\pi)^k \cdot |\mathbf{V}|}} e^{-\frac{1}{2}\chi^2(c,\vec{\theta})} \prod_{\vec{\theta}} \mathcal{G}(\vec{\theta})$$

Parameters	Limits at 95% C.L.	
	Observed 95% C.L. [TeV^{-4}]	Expected 95 % C.L. [TeV^{-4}]
C_{G+}/Λ^4	[-0.022, 0.020]	[-0.025, 0.023]
C_{G-}/Λ^4	[-1.41, 1.08]	[-1.50, 1.23]
C_{BB}/Λ^4	[-0.37, 0.37]	[-0.44, 0.44]
$C_{\tilde{B}W}/\Lambda^4$	[-0.54, 0.53]	[-0.62, 0.61]
C_{BW}/Λ^4	[-0.87, 0.95]	[-1.05, 1.14]
C_{WW}/Λ^4	[-1.90, 1.78]	[-2.26, 2.13]

EFT results

- Conversely, fix Wilson coefficients and measure cut off energy



nTGC: form factor formulation

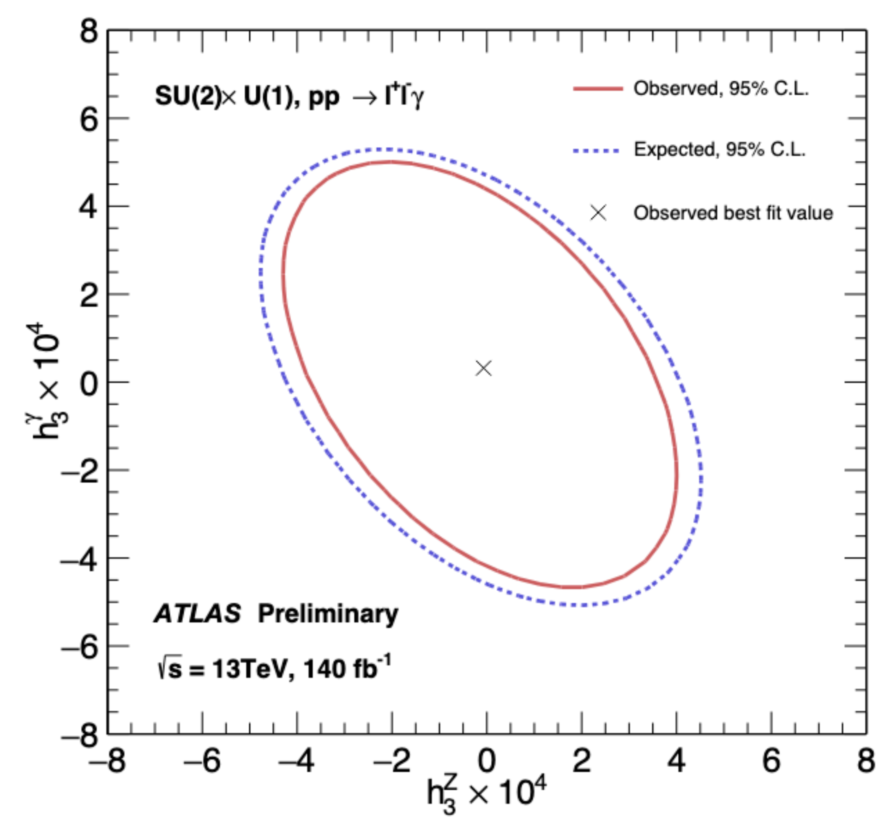
- Newly generalized form factor formulation for **neutral triple gauge** vertices
  - (h_3^Z, h_3^γ, h_4) map to the effective cutoff scale $[\Lambda_j^4] \equiv O_j/\Lambda_j^4$, where j = G^+, G^-, $\tilde{B}W$
  - First attempt to incorporate full electroweak gauge group symmetry of $SU(2)_L \otimes U(1)_Y$ of the SM
  - Superseding former $U(1)_{em}$ only formulation
- Form factor limits worsen by **2 orders of magnitude**, but is **more correct** than the old formulation used since LEP.
- 2D parametrization: interference between two Wilson coefficients taken into account.

$$h_4^Z = -\frac{1}{[\Lambda_{G+}^4]}\frac{v^2 M_Z^2}{s_W c_W} = \frac{c_W}{s_W} h_4^\gamma,$$

$$h_3^Z = \frac{1}{[\Lambda_{\tilde{B}W}^4]}\frac{v^2 M_Z^2}{2 s_W c_W} \quad \text{and}$$

$$h_3^\gamma = -\frac{1}{[\Lambda_{G-}^4]}\frac{v^2 M_Z^2}{2 c_W^2},$$

Parameters	Current limits at 95% C.L. (140 fb^{-1}) using new formalism	
	Observed 95% C.L.	Expected 95 % C.L.
h_4^γ	$[-1.3\times10^{-5}, 1.4\times10^{-5}]$	$[-1.5\times10^{-5}, 1.6\times10^{-5}]$
h_4^Z	$[-2.4\times10^{-5}, 2.6\times10^{-5}]$	$[-2.8\times10^{-5}, 3.0\times10^{-5}]$
h_3^γ	$[-3.5\times10^{-4}, 4.6\times10^{-4}]$	$[-4.0\times10^{-4}, 4.9\times10^{-4}]$
h_3^Z	$[-3.2\times10^{-4}, 3.2\times10^{-4}]$	$[-3.7\times10^{-4}, 3.6\times10^{-4}]$



Inclusive WZ production cross section

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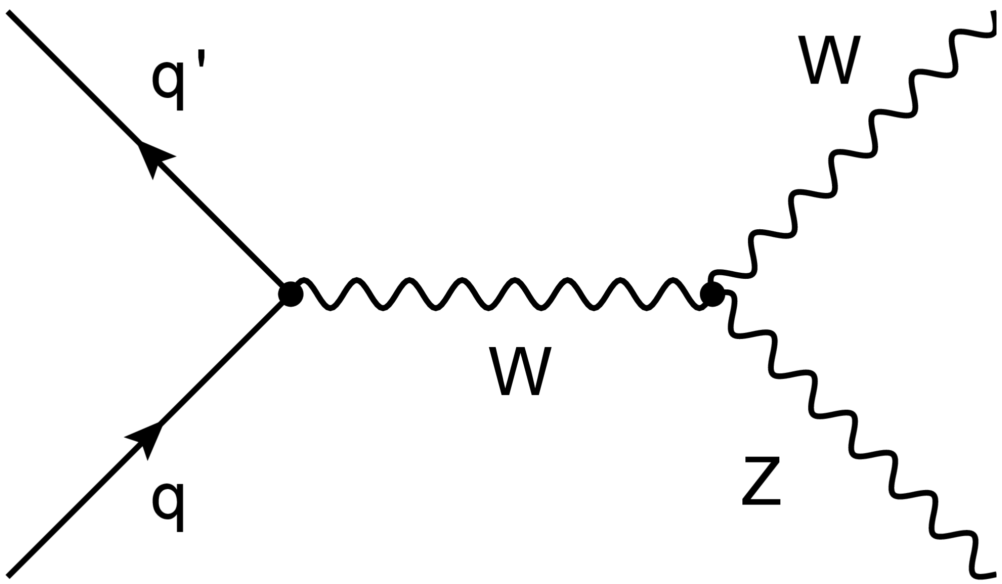
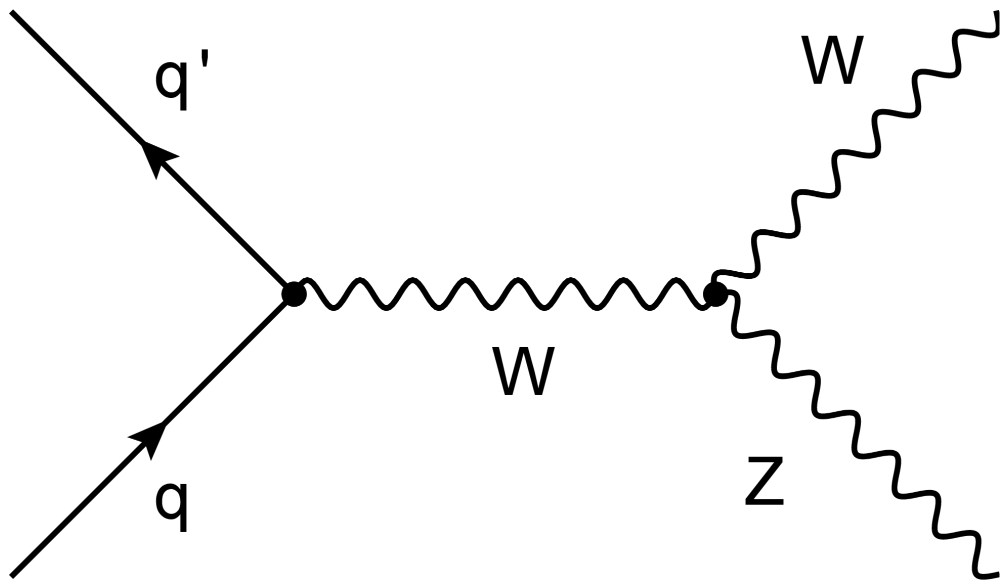
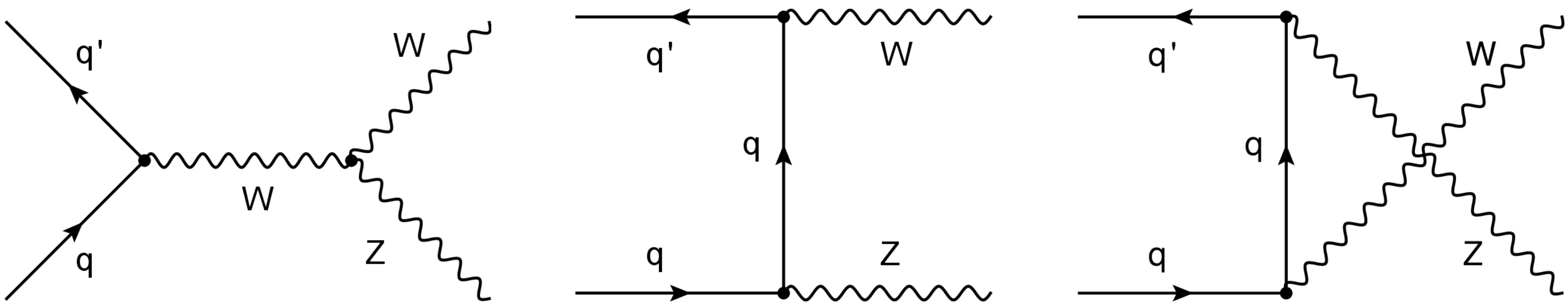




Introduction

- 34.7 fb^{-1} CMS partial run-3 data from 2022 @ 13.6 TeV
- Fully leptonic final states.
- Simultaneous likelihood fit in flavor composition channels: eee, eeμ, μμe, μμμ
- Solid test of SM production cross sections

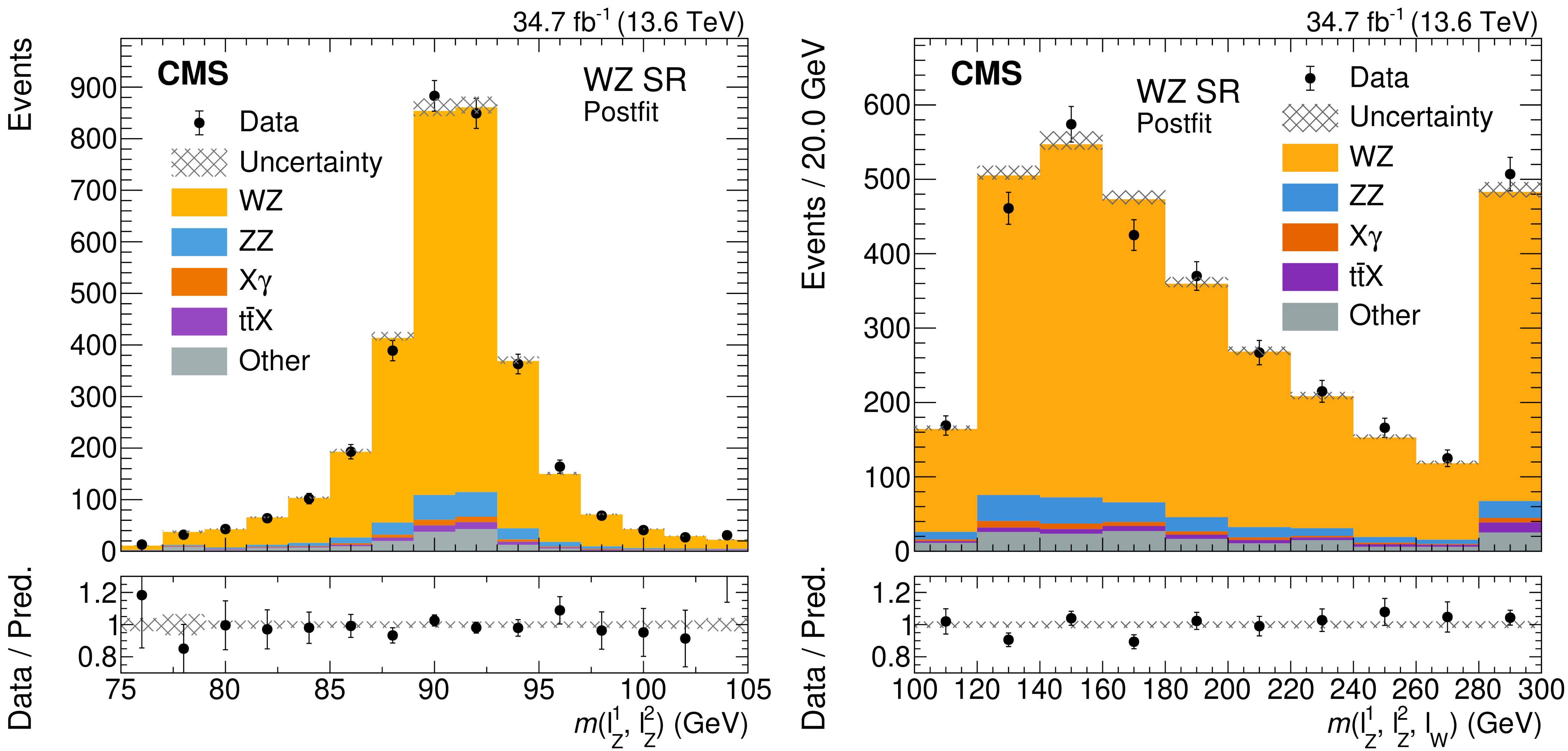


Selection

- Single and di-lepton triggers
- Signal region
  - Requires exactly 3 leptons
  - Similar strategy for Z selection: SFOS di-lepton mass close to $m_{Z.}$
  - $E_T^{Miss} > 35$ GeV: select neutrino from W
  - No b-tagged jets.
  - $m_{lll} > 100$ GeV: suppress Zγ
- Control region (CR) for background estimation
  - ZZ: 4 leptons
  - ttZ: >0 b-tagged jets
  - Conversions Xγ(—>e): invert E_T^{Miss} and m_{lll} cuts

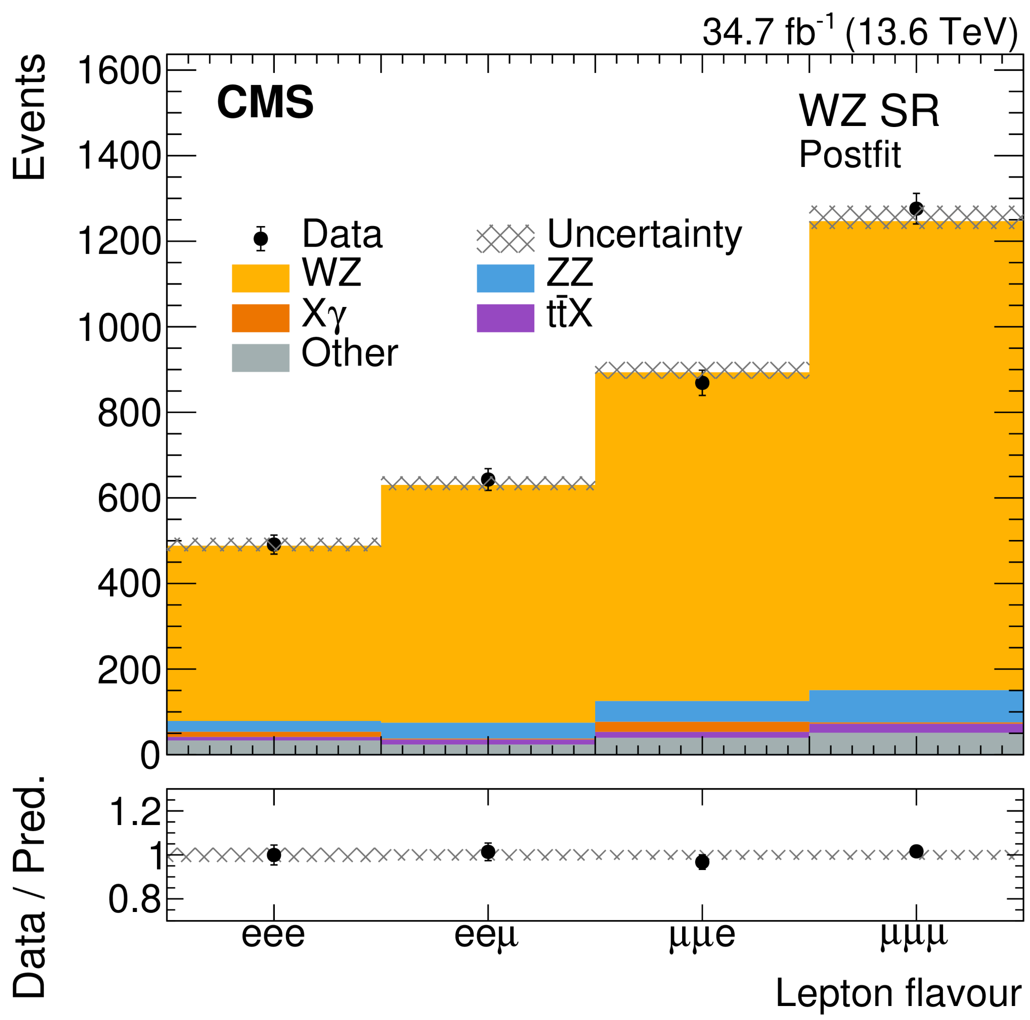
Background Estimation

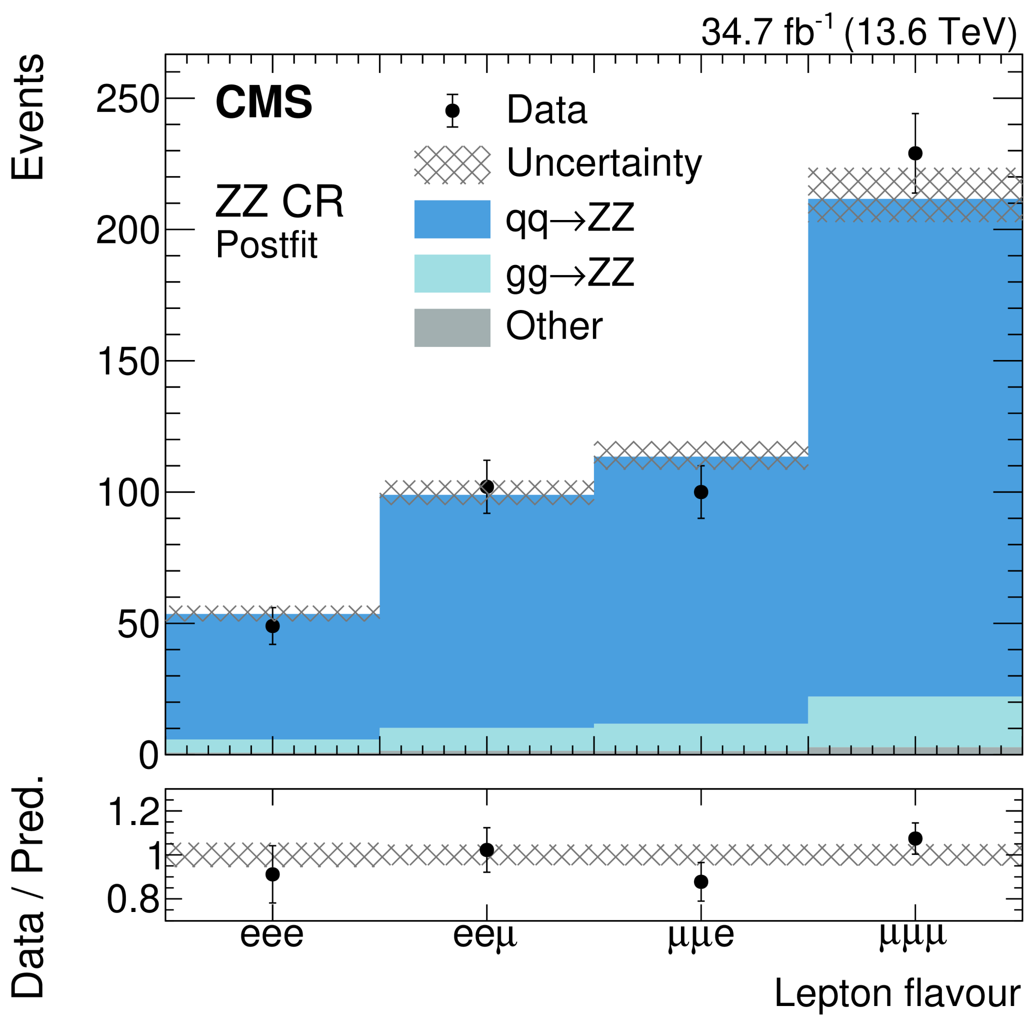
- Everything modeled by MC simulation
- Reducible Z+jets only O(3%)
- Irreducible background: ZZ, ttZ, Xγ, normalization as free floating parameters in the fit, constrained by the CR



Results

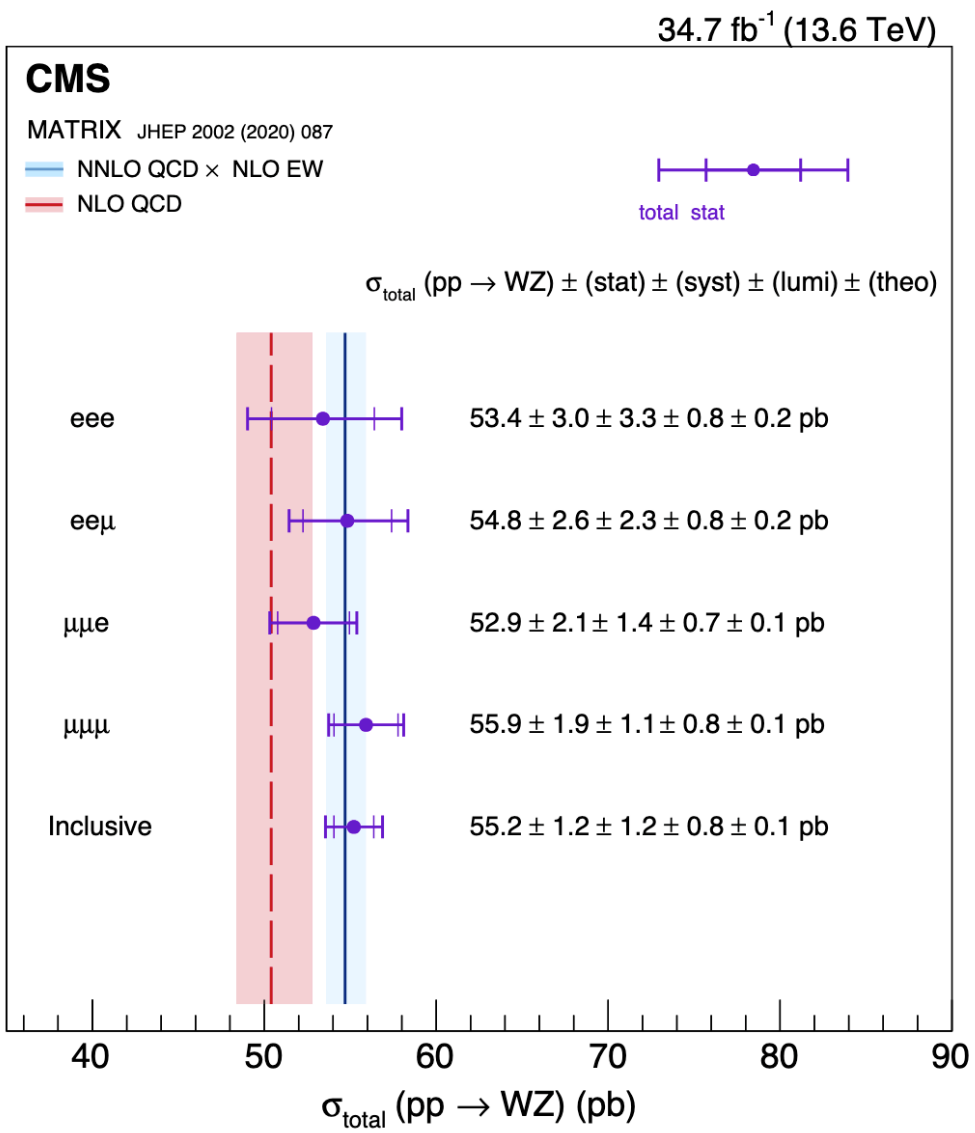
- High S/B ratio.
- Profile likelihood fit to lepton **flavor composition** distribution in SR and all CRs

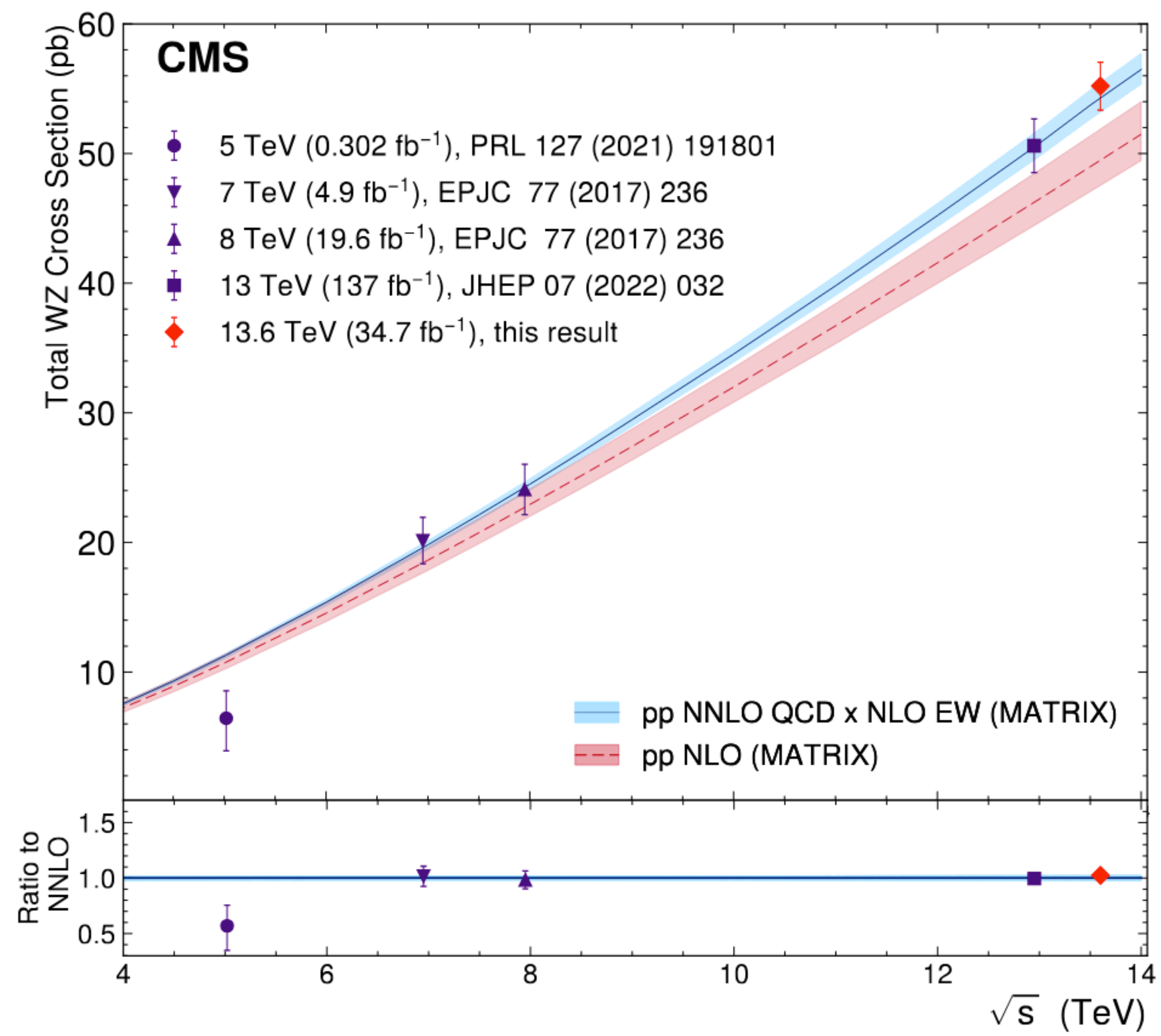




Cross section measurements

- Fitted cross section measured at detector-level
- Extrapolated to fiducial and total cross sections
- Uncertainty is **systematics** limited.
- Total cross section shown below, consistent with the NNLO QCD x NLO EW.





Review of recent results(including VBS)

- Most results are public with Run-2 dataset. Most utilizes fully leptonic final states.
- Observation —> inclusive, differential, fiducial XS —> VBS, EFT
- Heavy focus on WW. ATLAS has a lot of outputs in polarization, ZZ, Zγ, CMS has semi-leptonic final state.
- Additionally: also photon-induced di-boson production.
- No major deviation from Standard Model observed.

See Daniel's talk for the VBS results

ATLAS	W—>lν	Z—>ll	γ	Z—>νν
W—>lν	same-sign VBS WW polarization opposite-sign VBS WW same-sign VBS WW opposite-sign WW prodXS opposite-sign WW >= 1jet Double-parton interaction coming soon!	VBS WZ WZ polarization high pt WZ polarization	Wγ VBS, aQGC	
Z—>ll		ZZ Run3 - ATLAS CP properties VBS ZZ ZZ diffXS VBS ZZ observation	Zγ new aNTGC VBS Zγ Zγ diffXS Zγ prodXS	Coming soon!
Z—>νν			Zγ VBS	

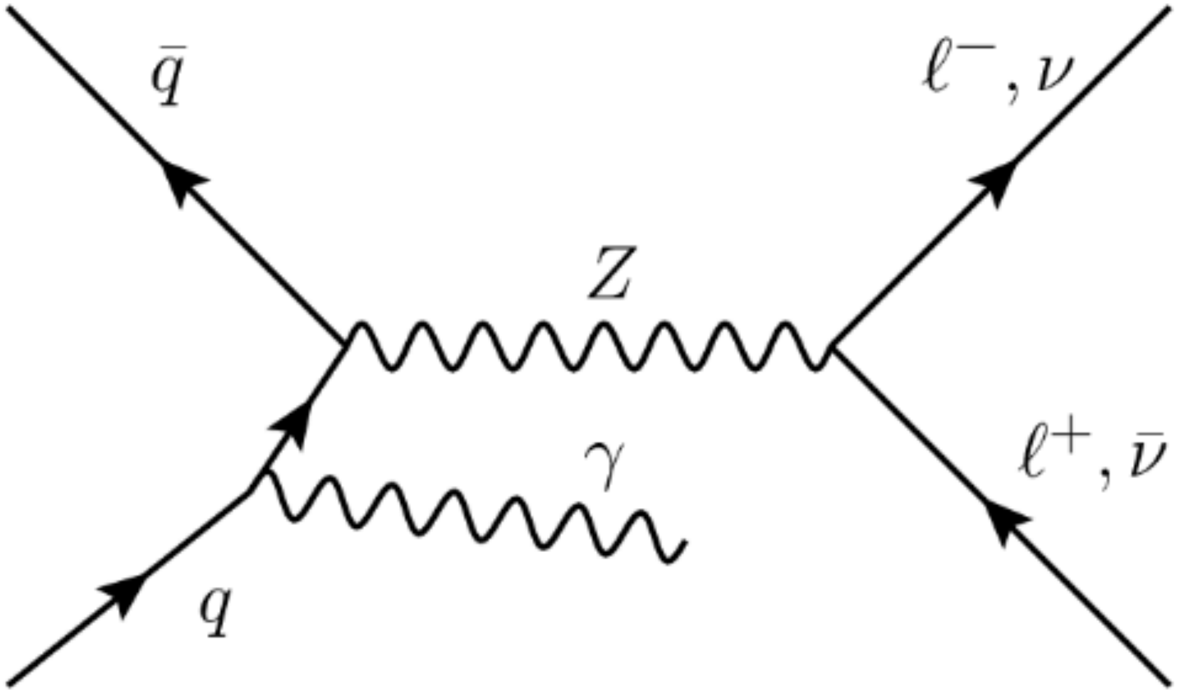
CMS	W—>lν	Z—>ll	γ	Z—>νν
W—>lν	same-sign WW with tau opposite-sign WW inclXS diffXS double-parton same-sign WW opposite-sign VBS WW polarized same-sign WW VBS WZ+ssWW aQGC	Run3 WZ InclXS WZ polarization angle, EFT VBS WZ+ssWW aQGC	VBS Wγ, aQGC Wγ diffXS EFT Wγ prodXS	
Z—>ll		ZZ+jets, ZZ aTGC, ZZjj evidence	VBS Zγ	
Z—>νν			Zγ aNTGC	
Others	VBS WV —> lνqq evidence, VBS ZV —> llqq and WV —> lνqq			

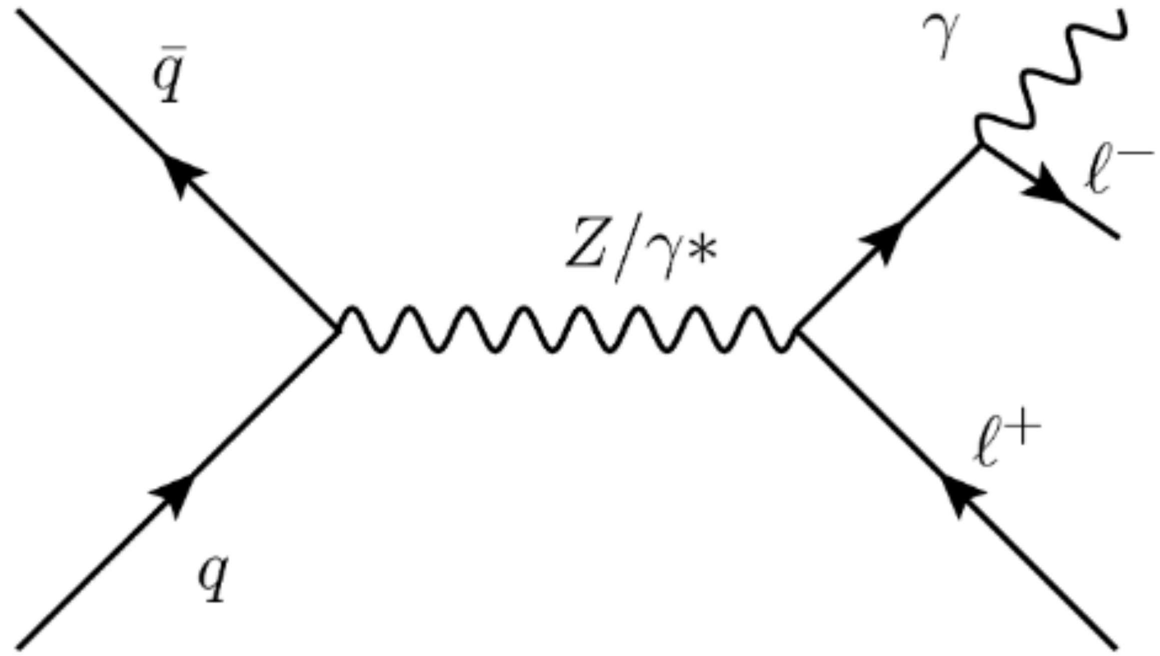
Summary

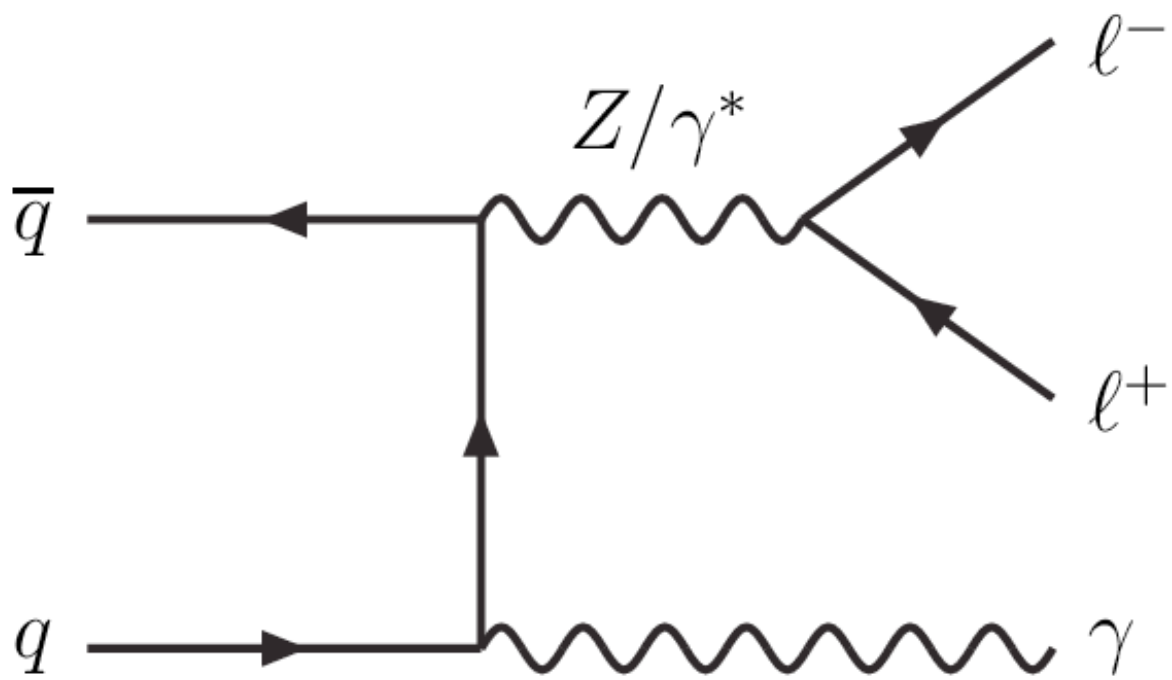
- Results:
  - ATLAS carried out Zγ cross section measurements and interpretation using the new nTGC formulation with full run-2 data.
  - CMS measured WZ inclusive cross sections with the 2022 data.
  - Both results agrees well with the Standard Model predictions.
- More di-boson results are in the publication pipeline and coming soon!
- Systematic uncertainty is dominant. Would need:
  - New techniques to reduce systematics.
  - Interesting theory models to measure.

Backup

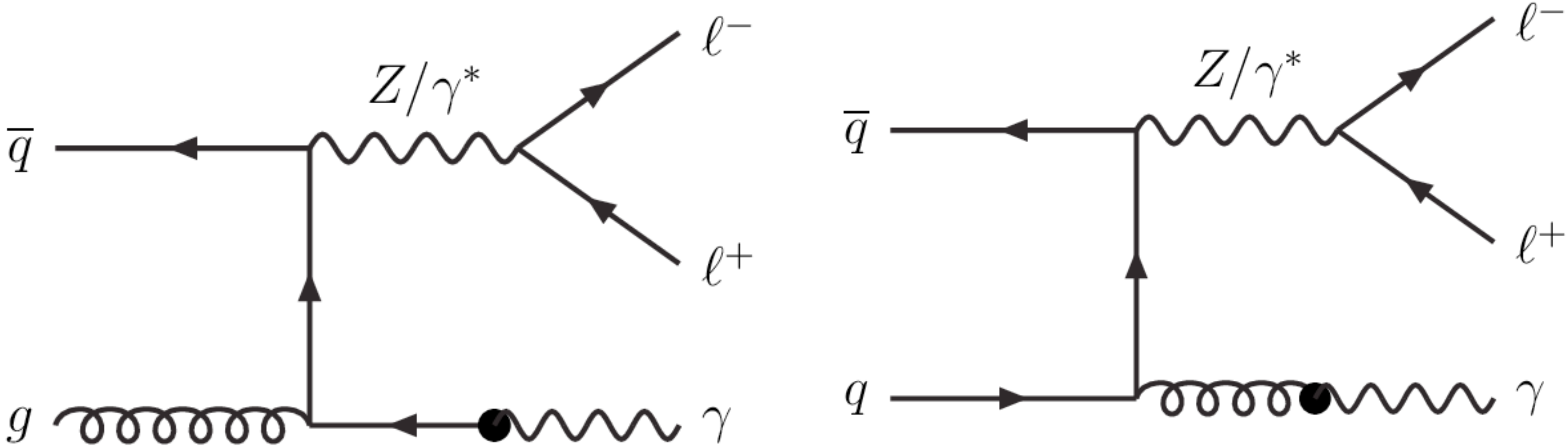
Zγ SM processes







Zγ SM QCD processes



Zγ reco and fiducial selection

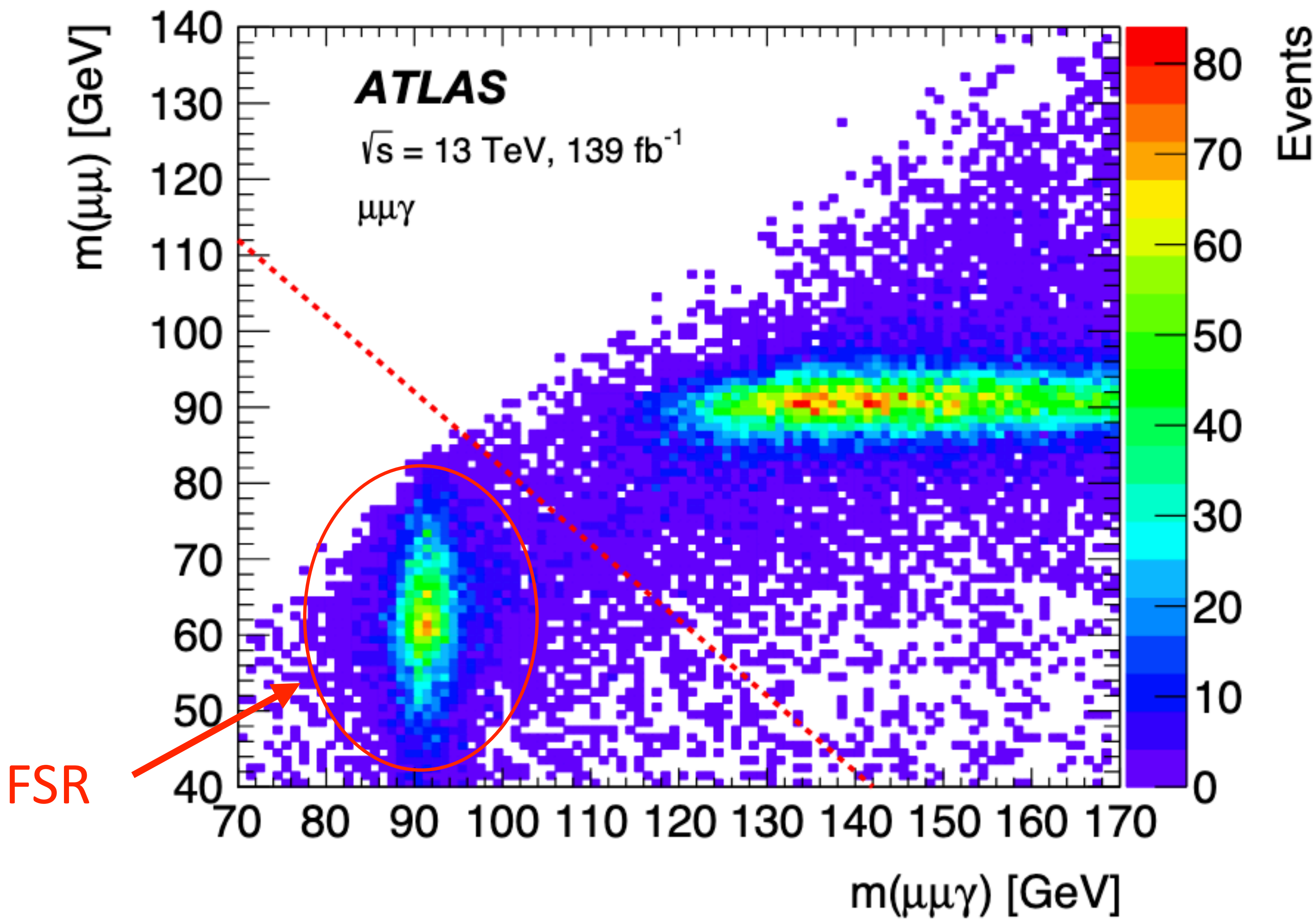
Requirements	Signal Region
Trigger	single or di-lepton triggers
N_{lepton}	≥ 2 OSSF leptons
Leading lepton p_T	> 30 GeV
N_{photon}	≥ 1 photon
Leading photon p_T	> 200 GeV
N_{jet}	exclusive, $= 0$
$m_{\ell\ell}$	$\lvert m_{\ell\ell} - m_Z \rvert < 10$ GeV
$m_{\ell\ell} + m_{\ell\ell\gamma}$	> 182 GeV

Quantity	Cuts
lepton kinematics	$p_T(\ell_1) > 30$ GeV, $p_T(\ell_2) > 25$ GeV, $\lvert\eta\rvert < 2.47$
photon kinematics	$p_T^{\gamma} > 200$ GeV, $\lvert\eta\rvert < 2.37$, $\Delta R(\gamma, \ell) > 0.4$
photon isolation	$E_T^{\text{cone20}}/E_T^{\gamma} < 0.07$
jet kinematics	$p_T(j) > 30$ GeV if $\lvert\eta\rvert < 2.5$ or $p_T(j) > 50$ GeV if $2.5 < \lvert\eta\rvert < 4.5$
invariant mass	$\lvert m_{\ell\ell} - m_Z \rvert < 10$ GeV, $(m_{\ell\ell} + m_{\ell\ell\gamma}) > 182$ GeV
jet multiplicity	$N_{\text{jet}} = 0$

Table 4: Definition of the fiducial region at particle level.

Sum of 2-body and 3-body

- $m_{ll} + m_{ll\gamma} > 182$ GeV ~ 2 m_Z



https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2018-04/fig_02.png

Zγ EFT results

Parameters	Limits at 95% C.L.	
	Observed 95% C.L. [TeV^{-4}]	Expected 95 % C.L. [TeV^{-4}]
C_{G+}/Λ^4	[-0.022, 0.020]	[-0.025, 0.023]
C_{G-}/Λ^4	[-1.41, 1.08]	[-1.50, 1.23]
C_{BB}/Λ^4	[-0.37, 0.37]	[-0.44, 0.44]
$C_{\tilde{B}W}/\Lambda^4$	[-0.54, 0.53]	[-0.62, 0.61]
C_{BW}/Λ^4	[-0.87, 0.95]	[-1.05, 1.14]
C_{WW}/Λ^4	[-1.90, 1.78]	[-2.26, 2.13]

Parameters	Observed 95% C.L. [TeV]			Expected 95% C.L. [TeV]		
Couplings	0.01	1	$4\pi^2$	0.01	1	$4\pi^2$
Λ_{G+}	0.82	2.60	6.51	0.80	2.51	6.30
Λ_{G-}	0.29	0.92	2.30	0.29	0.90	2.26
Λ_{BB}	0.41	1.28	3.21	0.39	1.23	3.08
$\Lambda_{\tilde{B}W}$	0.37	1.17	2.92	0.36	1.13	2.82
Λ_{BW}	0.32	1.01	2.54	0.31	0.97	2.43
Λ_{WW}	0.27	0.85	2.14	0.26	0.82	2.04

Zγ Form Factor results

Parameters	Current limits at 95% C.L. (140 fb^{-1}) using new formalism		Limits at 95% C.L. from Reference [59] (36.1 fb^{-1}) using old formalism	
	Observed 95% C.L.	Expected 95 % C.L.	Observed 95% C.L.	Expected 95 % C.L.
h_4^γ	$[-1.3\times10^{-5}, 1.4\times10^{-5}]$	$[-1.5\times10^{-5}, 1.6\times10^{-5}]$	$[-4.4\times10^{-7}, 4.3\times10^{-7}]$	$[-5.1\times10^{-7}, 5.0\times10^{-7}]$
h_4^Z	$[-2.4\times10^{-5}, 2.6\times10^{-5}]$	$[-2.8\times10^{-5}, 3.0\times10^{-5}]$	$[-4.5\times10^{-7}, 4.4\times10^{-7}]$	$[-5.3\times10^{-7}, 5.1\times10^{-7}]$
h_3^γ	$[-3.5\times10^{-4}, 4.6\times10^{-4}]$	$[-4.0\times10^{-4}, 4.9\times10^{-4}]$	$[-3.7\times10^{-4}, 3.7\times10^{-4}]$	$[-4.2\times10^{-4}, 4.3\times10^{-4}]$
h_3^Z	$[-3.2\times10^{-4}, 3.2\times10^{-4}]$	$[-3.7\times10^{-4}, 3.6\times10^{-4}]$	$[-3.2\times10^{-4}, 3.3\times10^{-4}]$	$[-3.8\times10^{-4}, 3.8\times10^{-4}]$

WZ regions

Region	N_ℓ	$p_T\{\ell_Z^1, \ell_Z^2, \ell_W(\ell_3), (\ell_4)\}$ (GeV)	N_{OSSF}	$\lvert m(\ell_Z^1, \ell_Z^2) - m_Z \rvert$ (GeV)	p_T^{miss} (GeV)	$N_{b\ tag}$	$\min(m(\ell, \ell'))$ (GeV)	$m(\ell_Z^1, \ell_Z^2, \ell_W(\ell_3))$ (GeV)
SR	=3	$>\{25, 15, 25\}$	≥1	<15	>35	=0	>4	>100
ZZ CR	=4	$>\{25, 15, 25, 15\}$	≥1	<15	—	=0	>4	>100
$t\bar{t}Z$ CR	=3	$>\{25, 15, 25\}$	≥1	<15	>35	>0	>4	>100
$X\gamma$ CR	=3	$>\{25, 15, 25\}$	≥1	—	≤35	=0	>4	<100

WZ systematics

Source	Inclusive (%)	eee (%)	eeμ (%)	$\mu\mu$e (%)	$\mu\mu\mu$ (%)
Integrated luminosity	1.5	1.5	1.4	1.4	1.5
Trigger efficiencies	0.5	1.0	1.0	1.0	0.7
b tagging	0.1	0.1	0.1	0.1	0.1
Pileup	0.4	0.6	0.8	0.2	0.4
Jet energy scales	0.9	1.3	0.7	1.1	0.7
Electron reconstruction	1.2	4.0	2.9	1.1	—
Electron ident. efficiencies	0.7	3.6	2.4	1.1	—
Electron energy scale	0.1	0.1	0.1	0.0	—
Muon efficiencies	0.7	—	0.3	0.8	1.2
Non-prompt bkg. normalization	0.7	1.6	0.5	0.7	0.7
VVV normalization	0.4	0.4	0.4	0.4	0.4
tZq normalization	0.1	0.1	0.1	0.1	0.1
ZZ normalization	0.3	0.8	0.7	0.5	0.5
$t\bar{t}Z$ normalization	0.3	0.7	0.6	0.4	0.5
Xγ normalization	0.2	0.7	0.3	0.4	0.2
VH normalization	0.2	0.2	0.2	0.1	0.2
ISR/FSR	0.3	0.5	0.2	0.4	0.3
WZ theory (μ_R, μ_F, PDF)	0.2	0.2	0.2	0.2	0.2
MC statistical	0.5	1.9	0.9	1.0	0.9
Statistical	2.0	5.3	4.6	3.8	3.3
Total	3.3	8.4	6.4	5.0	4.2