Measurement of Zy+jets differential cross section with ATLAS detector

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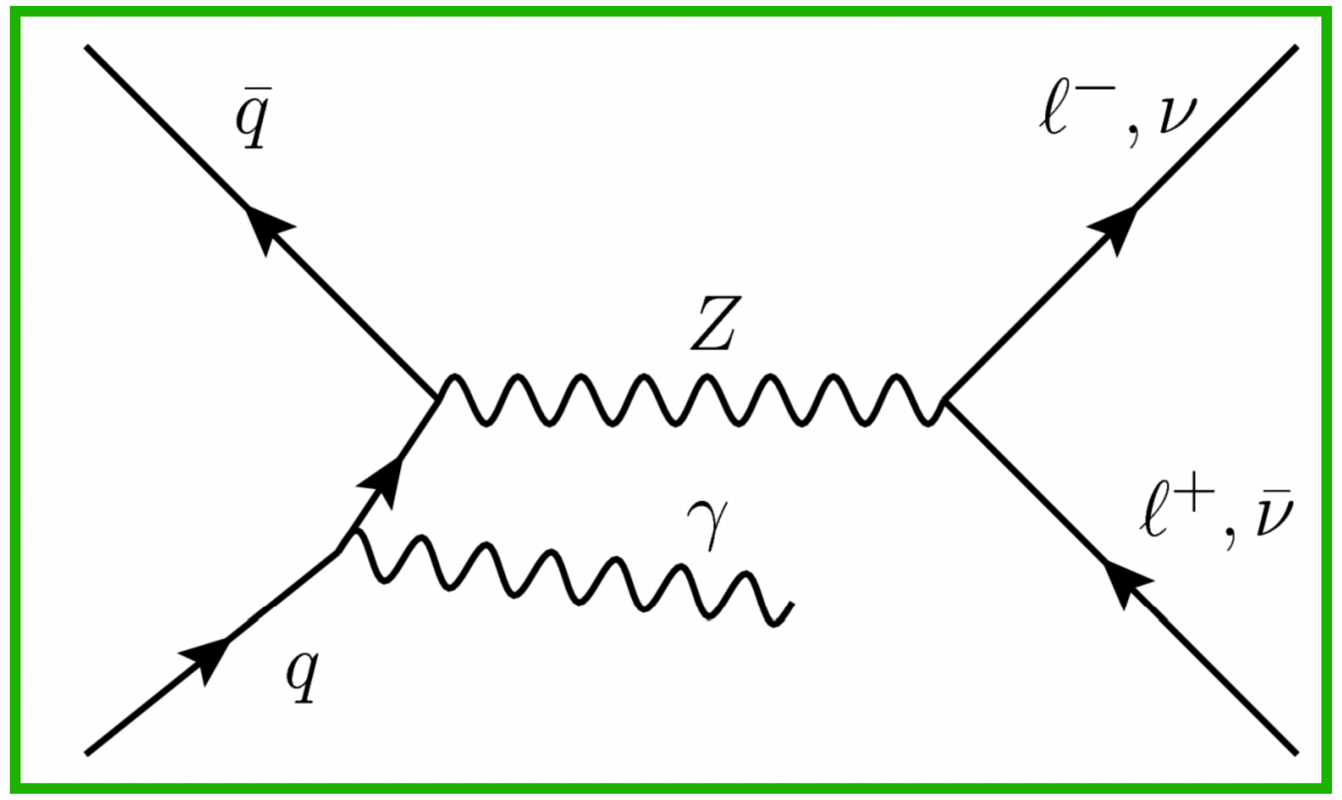
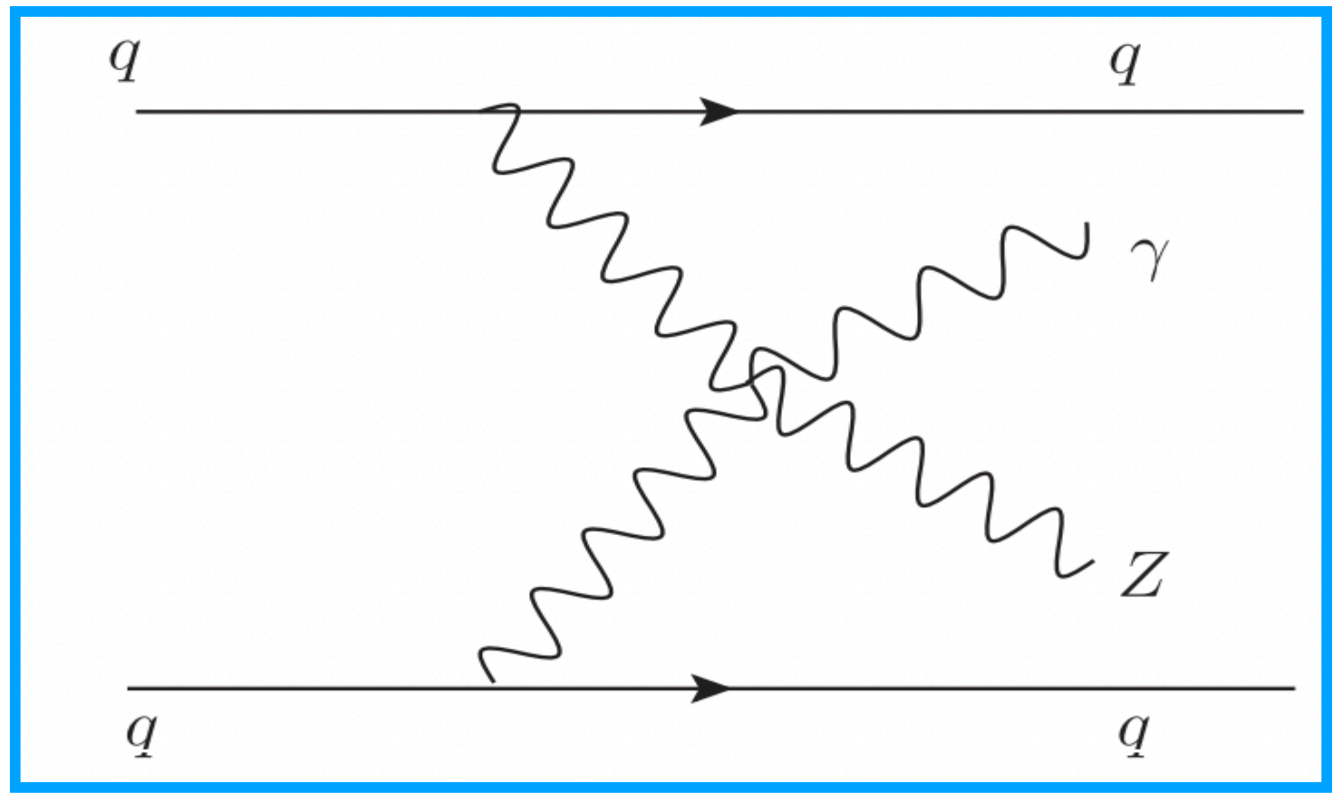
ATLAS EXPERIMENT

Motivation

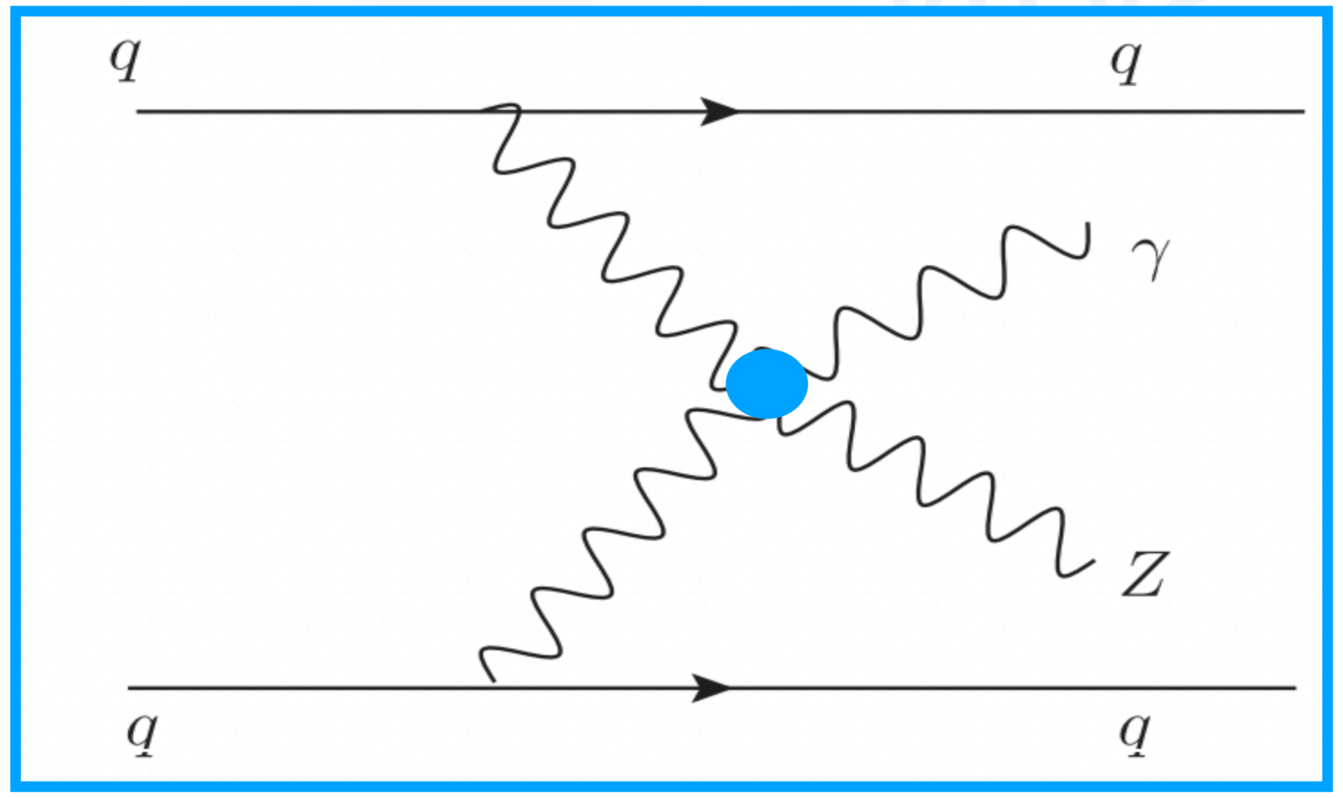
- First Measurement of Zγ+jets differential cross section in ATLAS
  - Jet inclusive measurement was done in previous round (JHEP03(2020)054)
- Advantages:
  - Large statistics (Drell-Yan process)
  - Clear signal (di-lepton in Z mass window), good S/B
- Could be used to study:
  - Test of resumption of Sudakov logarithms at fixed QCD order
  - Test Parton Shower effects
  - Background modeling of ZZ/Zγ in DM searches/H->Zγ
- Could be also used to do additional re-interpretations:
  - EFT studies
  - Polarization studies
  - Axion-like-particles (ALPs)

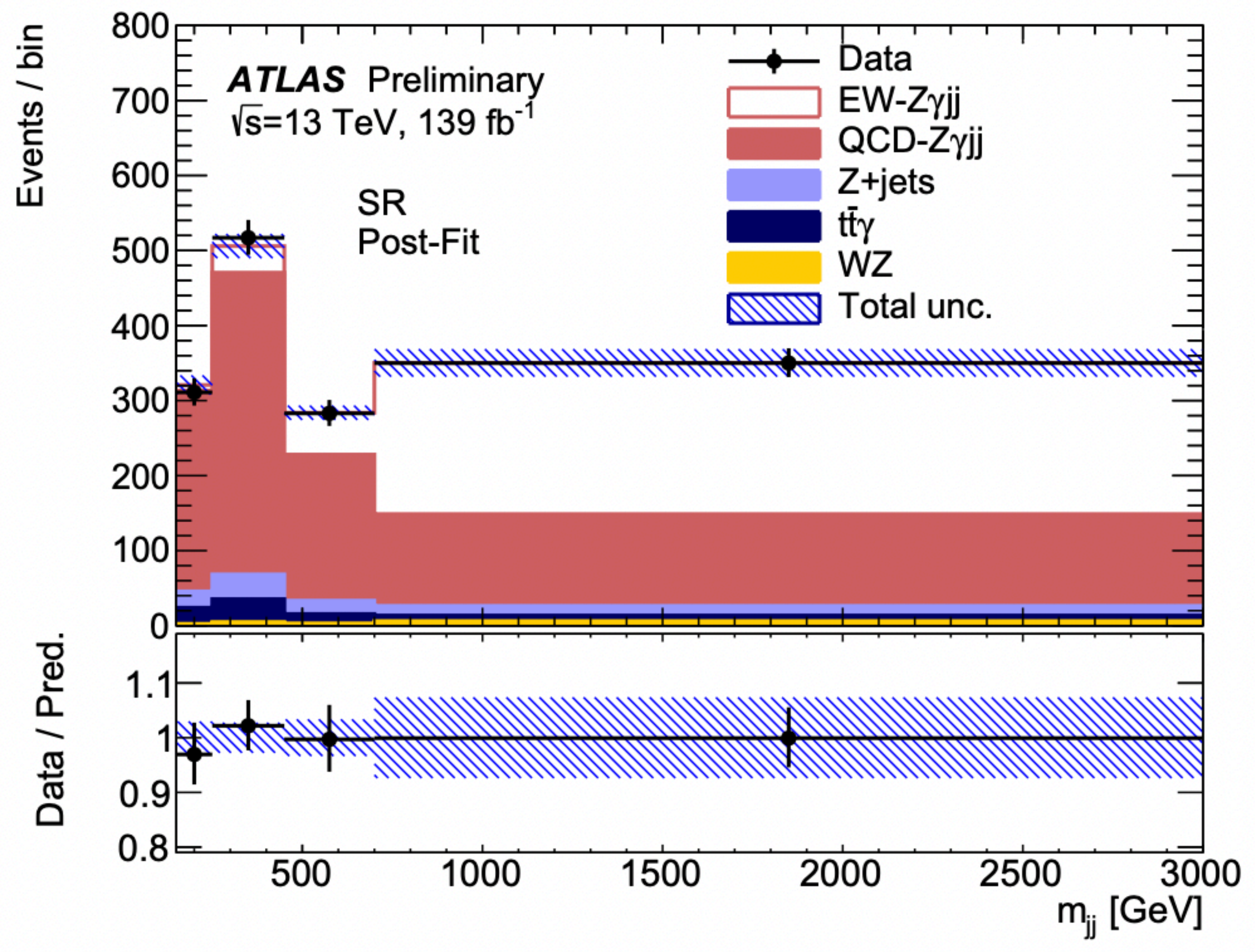


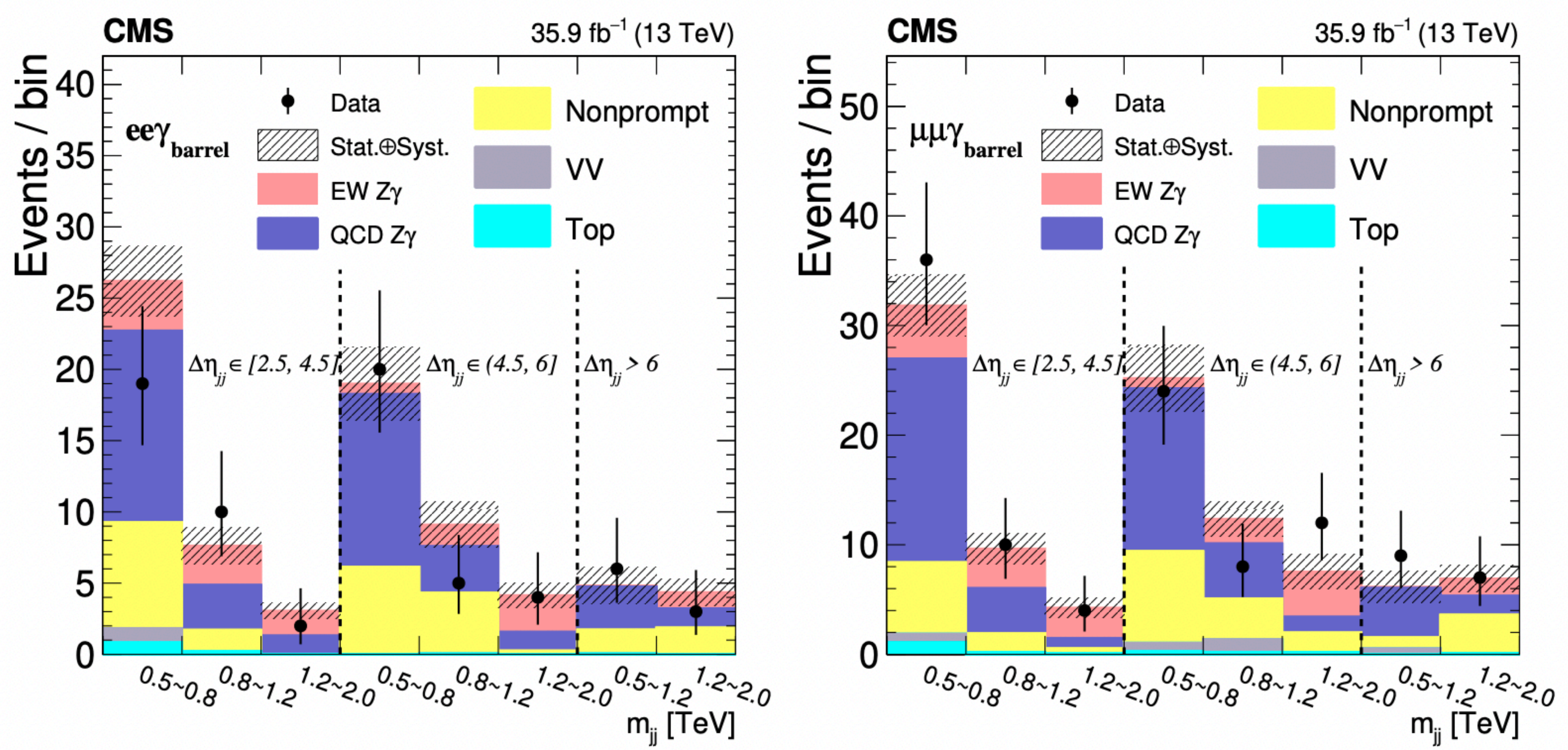


VBS ?

- VBS Zγ shares a similar final state
  - But a EWK vertex (quartic gauge coupling)
  - Featured two forward jets with large invariant mass
- A standalone analysis
  - First observation (5σ) in ALTAS! (ATLAS-CONF-2021-038)
  - Observed also by CMS (JHEP06(2020)076)
  - Differential cross section measurements on-going

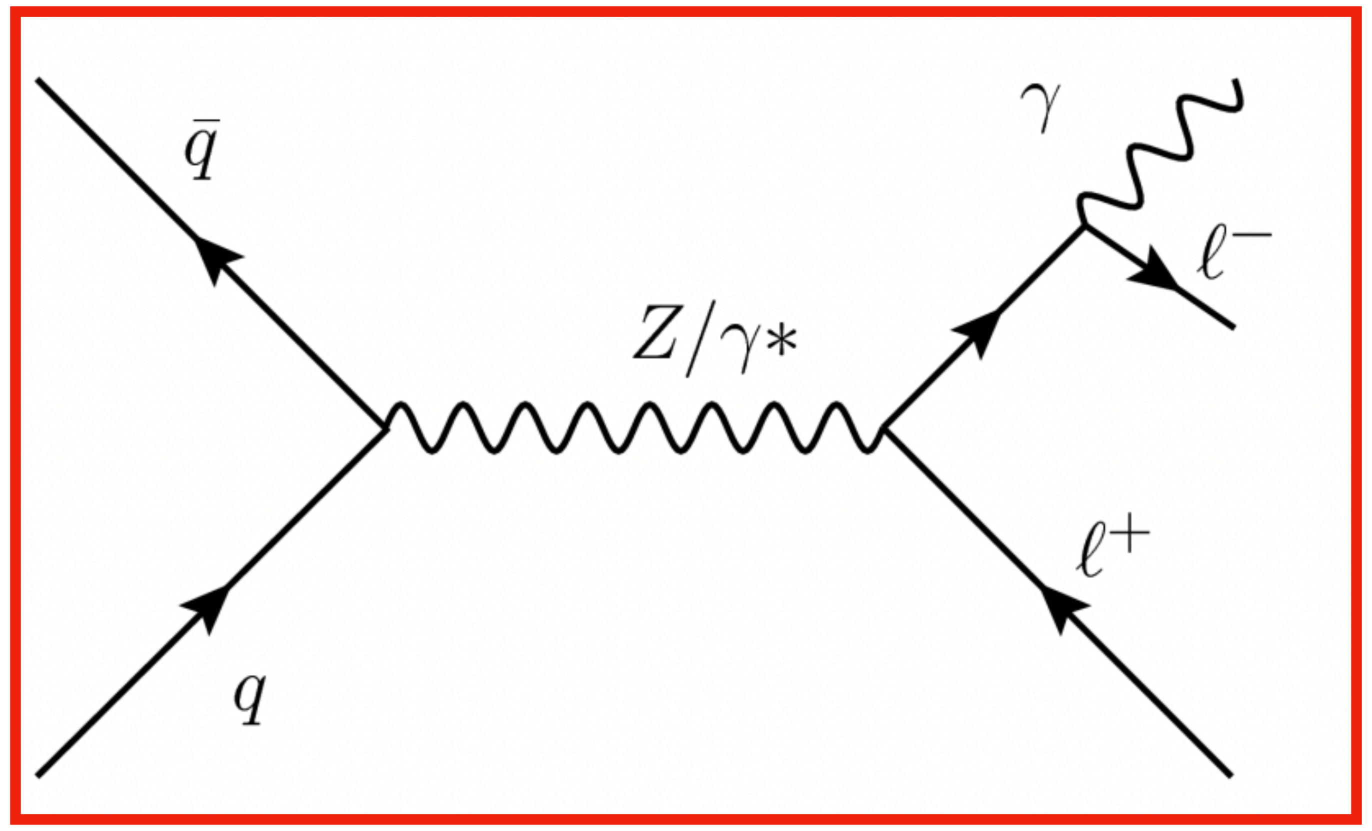




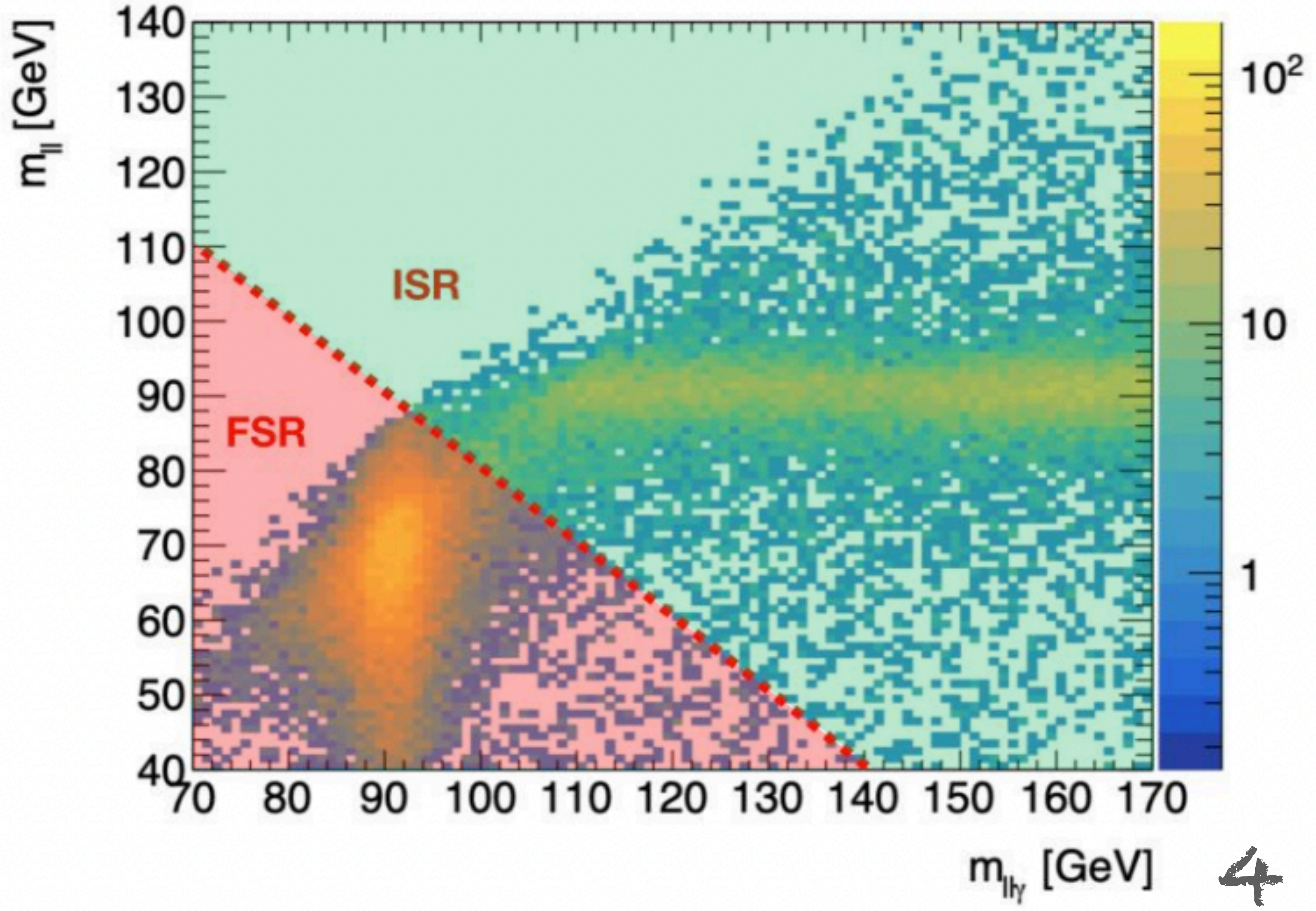


Event Selection

- Two same-flavor opposite-sign light leptons (e/μ)
- Mll > 40 GeV -> suppress low mass resonances (γ*)
- Mll + Mllγ > 182 GeV -> suppress FSR events
- No requirement on di-jet mass -> negligible VBS contribution
- SR enriched with ISR Zγ events
- Main backgrounds from jet-faking-photon, ttγ



Observable	Signal Region	$t\bar{t}\gamma$ Control Region
Number of signal leptons	2 Opposite Sign, Same Flavour	2 Opposite Sign, Different Flavour
Lepton	$p_T(\ell_1) > 30$ GeV, $p_T(\ell_2) > 25$ GeV	
Photon	≥ 1 photon with $p_T^\gamma > 30$ GeV	
$m_{\ell\ell}$	> 40 GeV	
$m_{\ell\ell} + m_{\ell\ell\gamma}$	> 182 GeV	



Observables

- 1D observables to probe QCD properties:
  - $N_{jet}, p_T^{Jet1(2)}, p_T^{Jet2}/p_T^{Jet1}, m_{ll\gamma j}, m_{jj}, H_T, p_T^{\gamma}/\sqrt{H_T}, \Delta\phi(Jet,\gamma), \Delta R(l,l), p_T^{ll}$
- Sudakov logarithms related:
  - $p_T^{ll\gamma}/m_{ll\gamma}$ in bins of $m_{ll\gamma}$
  - $p_T^{ll} - p_T^{\gamma}$ in bins of $p_T^{ll} + p_T^{\gamma}$
  - $p_T^{ll\gamma j}$ in bins of $p_T^{ll\gamma}$
  - $p_T^{ll} + p_T^{\gamma}, p_T^{ll} - p_T^{\gamma}, p_T^{ll\gamma j}$ inclusively

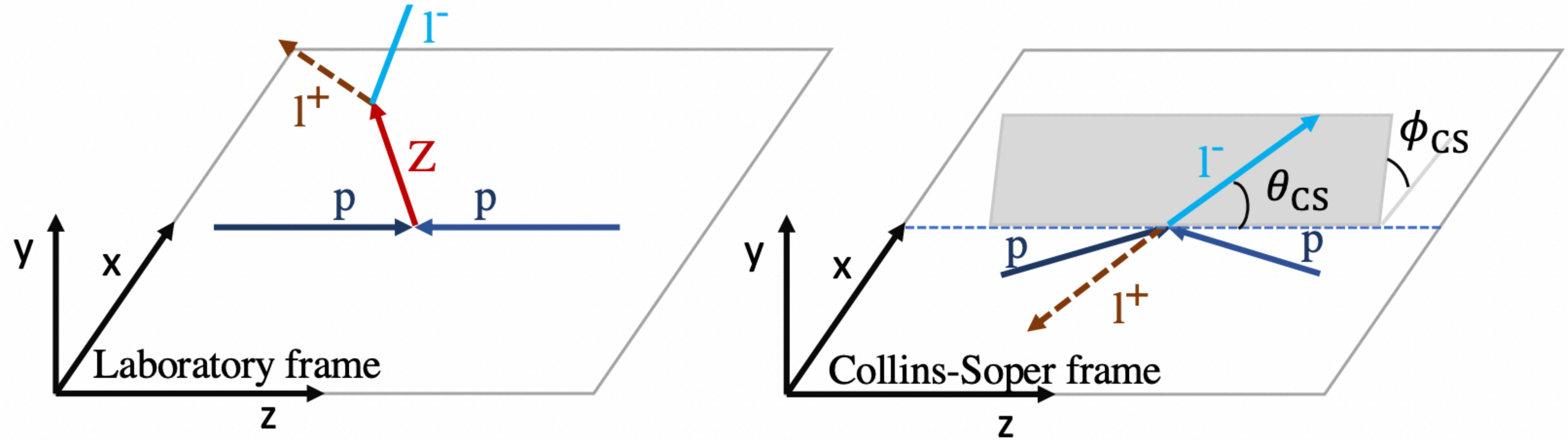
Hard variables: represents the hard scale of the process, which are not zero at Leading Order (LO),
Resolution variables: sensitive to additional, soft and collinear QCD radiation, which are zero at LO and become non-zero beyond LO

Sudakov logarithms: if q_T << Q, fixed order QCD calculations are dominated by Sudakov logarithm terms caused by soft and collinear emission of the order of $\alpha_s^n ln^m(q_T/M)$

Observables

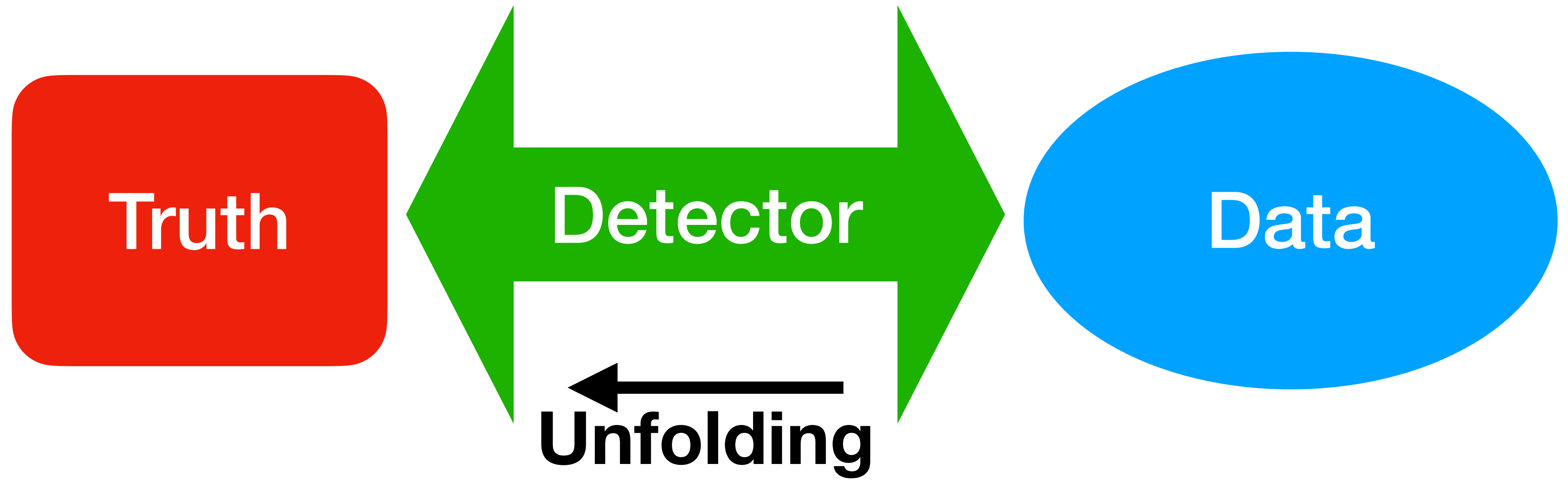
- Polarization related variables:
  - $cos\theta_{CS}$ v.s. p_T^Z 2D unfolding
  - ϕ_{CS} v.s. p_T^Z 2D unfolding
- Measured in Collins-Soper frame
  - Z-boson rest frame
  - θ and ϕ of negatively charged lepton
  - p_T^Z shifted higher due to ISR photon

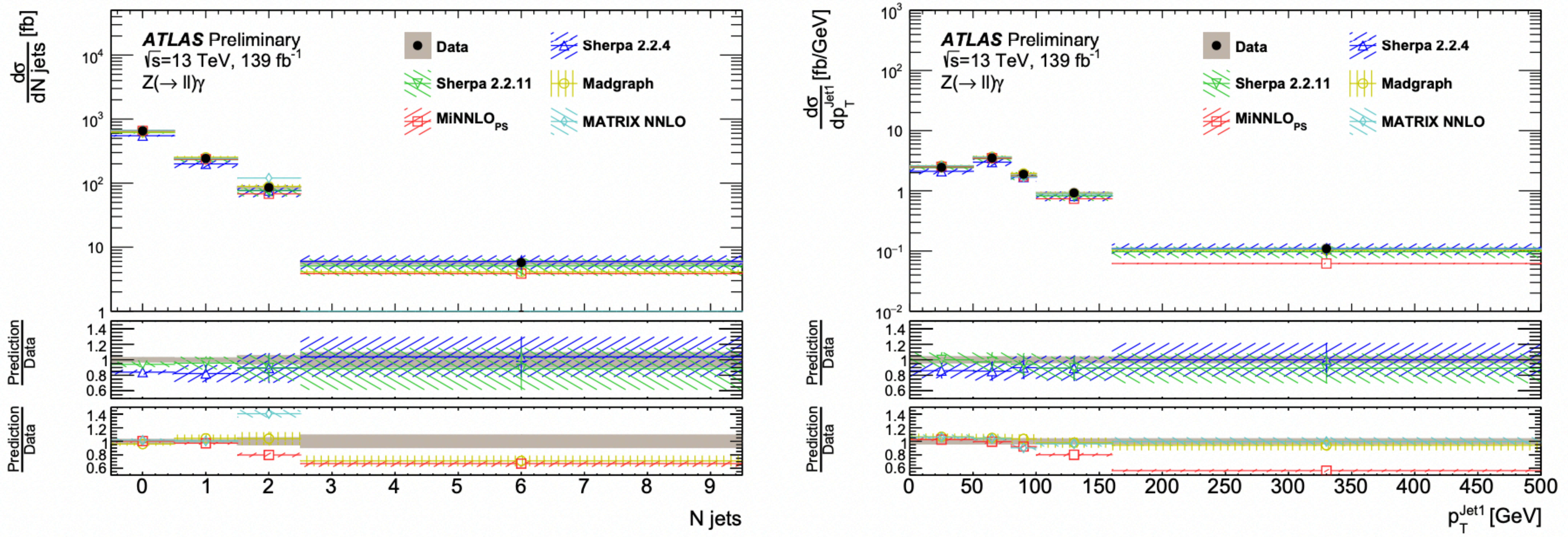
Polarization effect in fiducial phase space is not optimal, need re-interpreted to full space



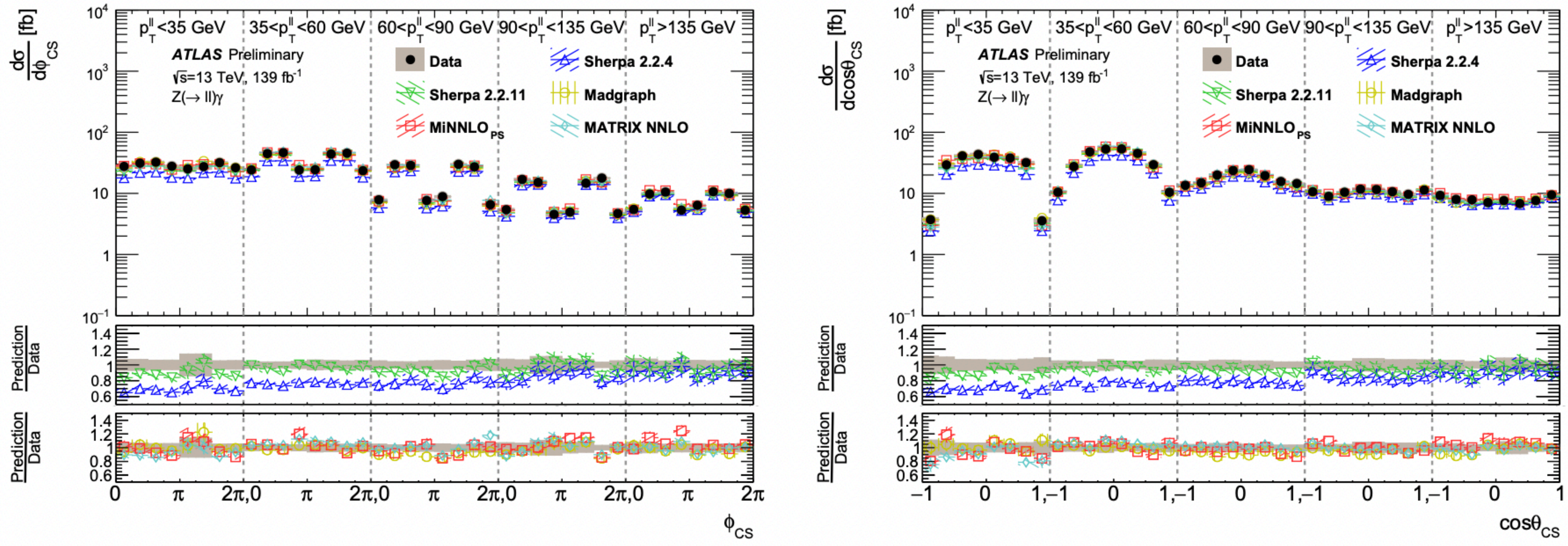
Unfolded observables

- Unfolding: Real data -> particle level (truth)
  - Acceptance and resolution of detector
- Comparing to various theoretical predictions:
  - Sherpa 2.2.4 (LO), Sherpa 2.2.11 (NLO), Madgraph
  - NNLO predictions of MiNNLO$_{PS}$
  - NNLO Fixed-order calculation MATRIX



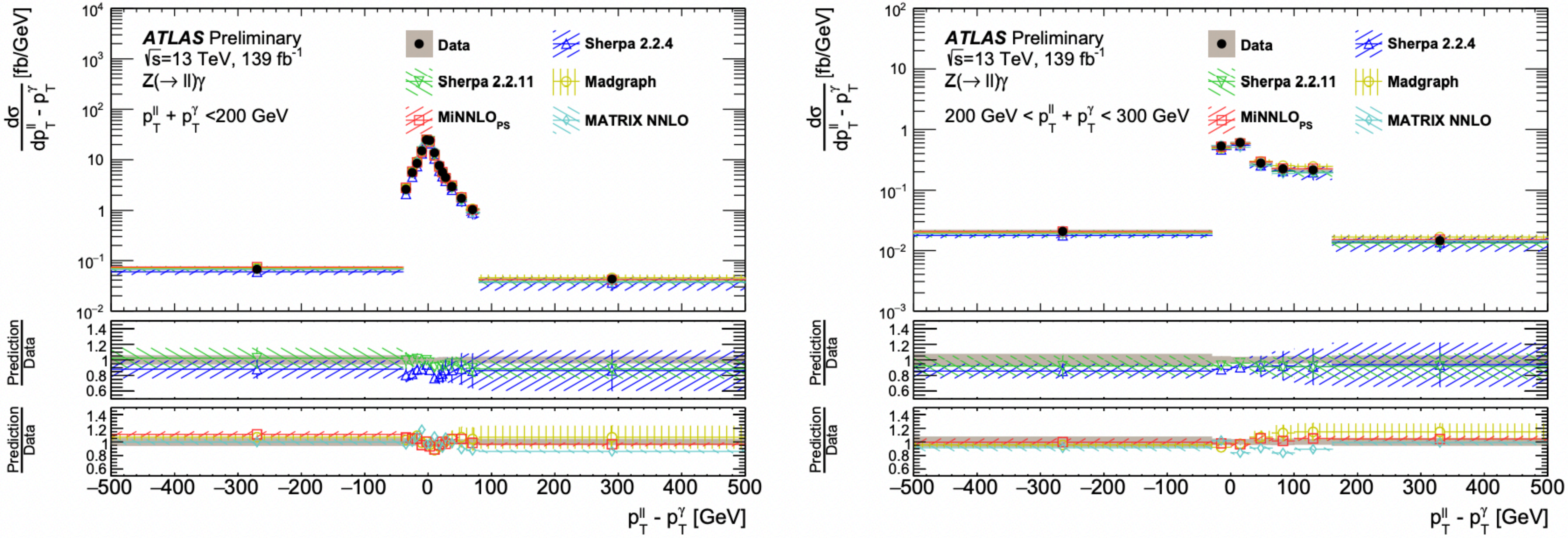


Unfolded Observables



2D unfolding of polarization variables, extended to one dimension

Unfolded Observables



Resolution variable $p_T^{ll} - p_T^{\gamma}$ in different $p_T^{ll} + p_T^{\gamma}$ bins

Uncertainties and Yields

Yields

Source	$ee + \mu\mu$	
$Z\gamma$+jets signal	73 500	± 50 (stat.) $\pm$ 2 600 (syst.)
Z + jets	9 800	± 460 (stat.) $\pm$ 2 100 (syst.)
$t\bar{t}\gamma$	3 600	± 10 (stat.) $\pm$ 540 (syst.)
pile-up	2 500	± 70 (stat.) $\pm$ 700 (syst.)
multiboson	950	± 5 (stat.) $\pm$ 160 (syst.)
$tW\gamma$	150	± 1 (stat.) $\pm$ 45 (syst.)
Total prediction	90 500	± 500 (stat.) $\pm$ 3 500 (syst.)
Data	96 410	

- Measured: $\sigma_{fid} = 533.7 \pm 2.1\ (stat) \pm 12.4\ (syst) \pm 9.1\ (lumi)$
- Sherpa2.2.11: $479.5 \pm 0.3\ (stat)$
- MiNNLO$_{PS}$: $493.0 \pm 3.0\ (stat)$

Uncertainties

N_{Jet}	0	1	2	> 2
Source	Uncertainty [%]			
Electrons	1.0	0.9	0.8	0.8
Muons	0.3	0.3	0.3	0.4
Jets	1.7	1.7	4.5	8.8
Photons	1.4	1.3	1.3	1.2
Pile-up	2.1	0.8	0.2	0.3
Background	1.8	1.8	3.0	4.4
Stat. MC	0.1	0.2	0.3	0.4
Stat. data	0.8	1.5	1.8	1.9
Luminosity	1.7	1.7	1.7	1.7
Theory	0.6	0.2	1.4	1.0
Total	4.2	3.8	6.3	10.3

Mainly from non prompt photon estimate and jets

EFT

$$L = L_{SM} + \sum_{d>4}\sum_{i}\frac{C_i}{\Lambda^{d-4}}O_i^d$$

- Neutral Triple Gauge Couplings (nTGCs)
  - Important to understand electroweak symmetry mechanism
  - A new window to search for BSM physics
- forbidden at tree level in the SM, but could arise from SMEFT dim-8 operators
- The anomalous coupling could:
  - Increase inclusive cross sections of Zγ
  - Increase differential cross sections at high Pt and high mass region
- As an example:
  - A new nTGC model proposed by Prof.John Ellis, Prof.Hongjian He and Dr.Ruiqing Xiao
  - arXiv: 2206.11676v2
- Could be very sensitive in Z->ll final states!

2σ, 5σ

$\sqrt{s}$	13 TeV ($\ell\bar{\ell}$)			13 TeV ($\ell\bar{\ell}, \nu\bar{\nu}$)		
$\mathcal{L}(\text{ab}^{-1})$	0.14	0.3	3	0.14	0.3	3
$\lvert h_4(\mathbb{O}_1)\rvert \times 10^5$	3.7 (11)	2.4 (7.1)	0.72 (1.9)	3.7 (11)	2.4 (7.1)	0.72 (1.9)
$\lvert h_4\rvert \times 10^6$	11 (21)	8.5 (16)	4.3 (7.3)	7.6 (14)	6.0 (11)	3.1 (5.3)
$\lvert h_3^Z\rvert \times 10^4$	2.2 (3.9)	1.7 (3.0)	0.89 (1.5)	1.5 (2.7)	1.2 (2.2)	0.67 (1.1)
$\lvert h_3^A\rvert \times 10^4$	2.5 (4.5)	2.0 (3.5)	1.0 (1.7)	1.8 (3.1)	1.4 (2.5)	0.77 (1.3)

Polarization

- Previously measured by ATLAS in run 1 (JHEP08(2016)159)
- Some disagreement seen, would like to further understand in run2
- Main difficulties:
  - Polarization effect only dominant in full space
  - As soon as selection applied on final state leptons, polarization information disappears
  - Need to properly taken into account the acceptance, if there is any new physics effect

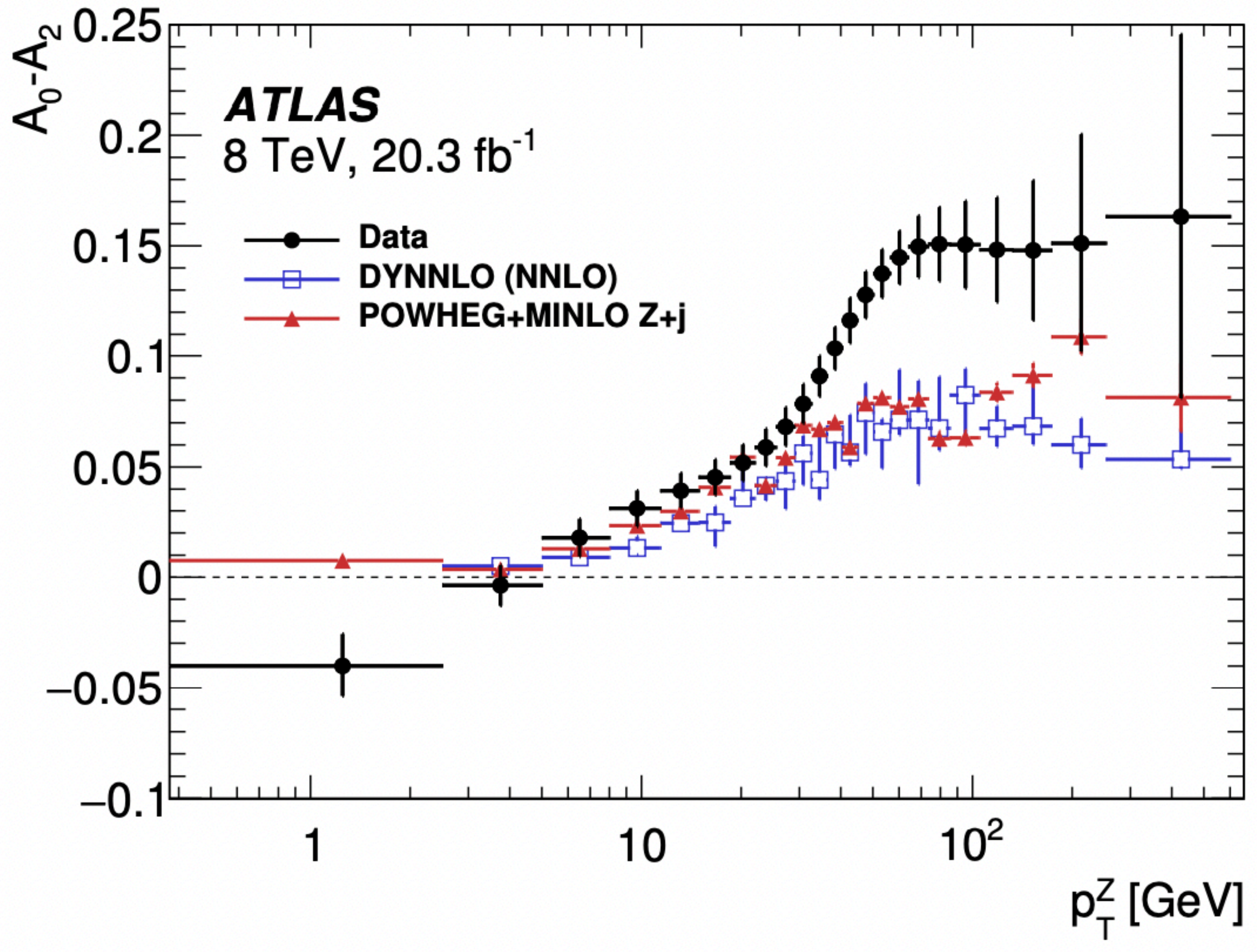
$$\frac{\mathrm{d}\sigma}{\mathrm{d}p_T^Z\,\mathrm{d}y^Z\,\mathrm{d}m^Z\,\mathrm{d}\cos\theta\,\mathrm{d}\phi} = \frac{3}{16\pi}\frac{\mathrm{d}\sigma^{U+L}}{\mathrm{d}p_T^Z\,\mathrm{d}y^Z\,\mathrm{d}m^Z} \times \Big\{(1+\cos^2\theta) + \frac{1}{2}A_0(1-3\cos^2\theta) + A_1\sin 2\theta\cos\phi + \frac{1}{2}A_2\sin^2\theta\cos 2\phi + A_3\sin\theta\cos\phi + A_4\cos\theta + A_5\sin^2\theta\sin 2\phi + A_6\sin 2\theta\sin\phi + A_7\sin\theta\sin\phi\Big\}. \tag{1.1}$$

Integrating eq. (1.1) over $\cos\theta$ yields:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}p_T^Z\,\mathrm{d}y^Z\,\mathrm{d}m^Z\,\mathrm{d}\phi} = \frac{1}{2\pi}\frac{\mathrm{d}\sigma^{U+L}}{\mathrm{d}p_T^Z\,\mathrm{d}y^Z\,\mathrm{d}m^Z} \times \Big\{1 + \frac{1}{4}A_2\cos 2\phi + \frac{3\pi}{16}A_3\cos\phi + \frac{1}{2}A_5\sin 2\phi + \frac{3\pi}{16}A_7\sin\phi\Big\}, \tag{1.2}$$

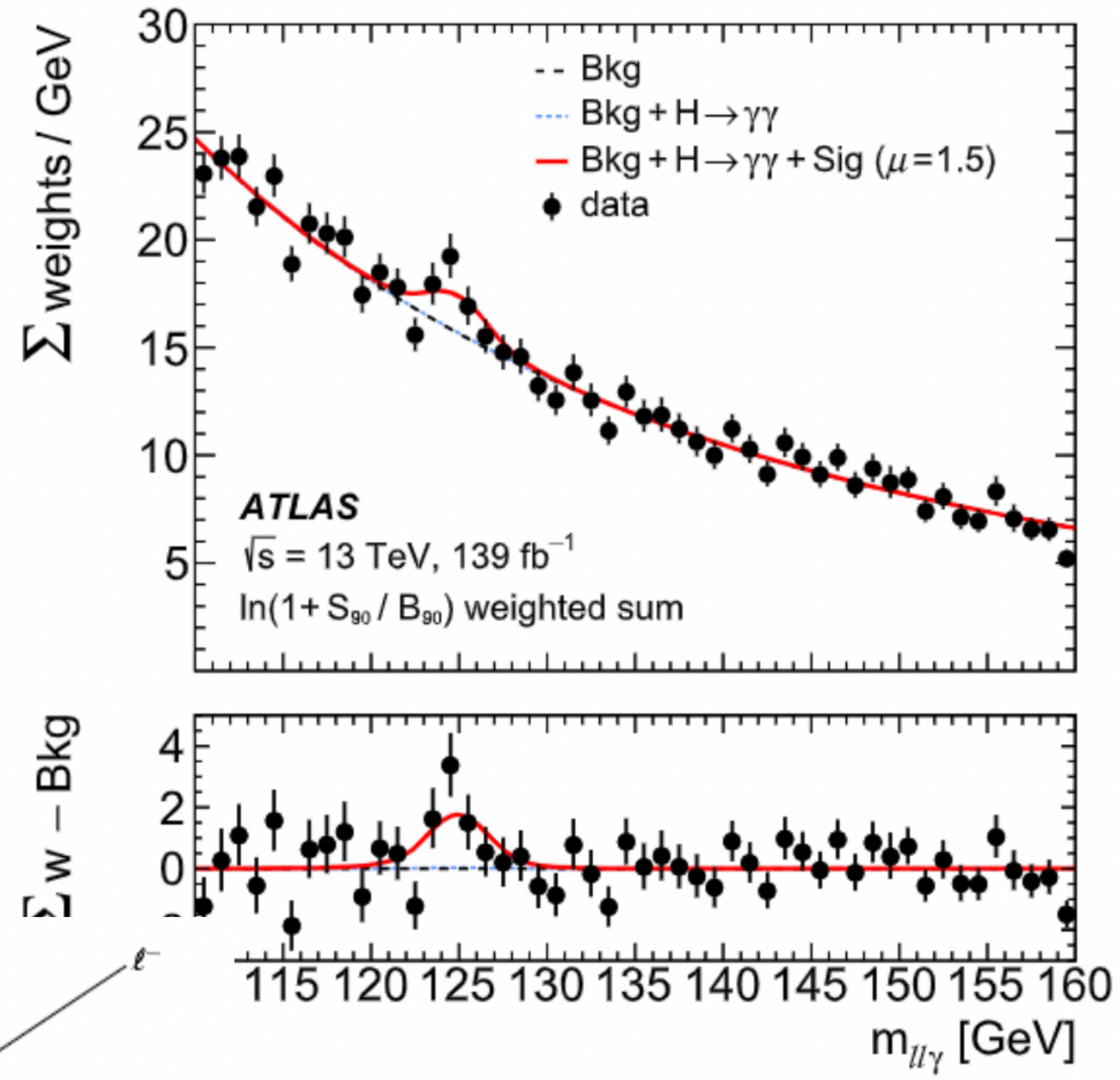
while integrating over ϕ yields:

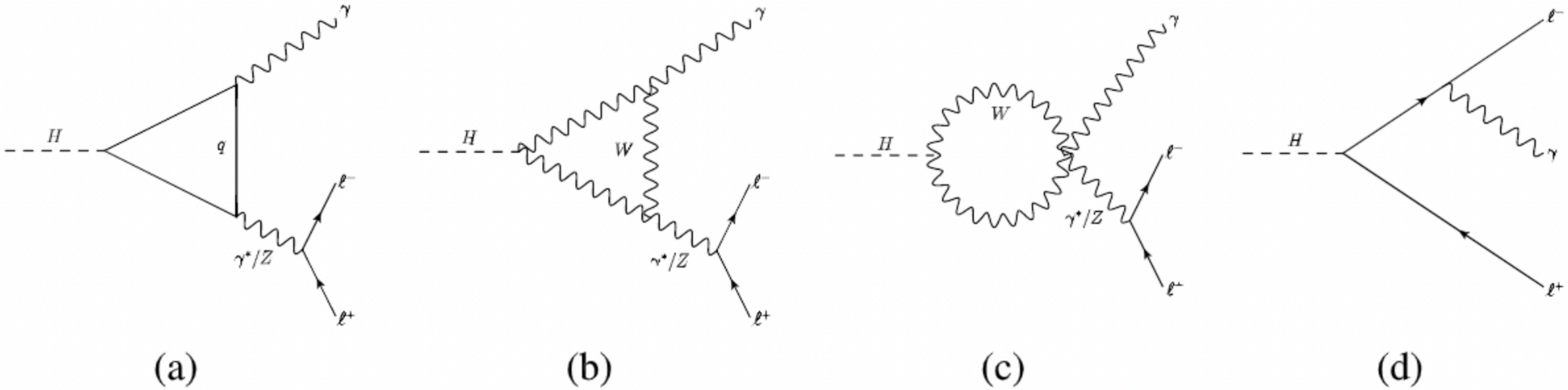
$$\frac{\mathrm{d}\sigma}{\mathrm{d}p_T^Z\,\mathrm{d}y^Z\,\mathrm{d}m^Z\,\mathrm{d}\cos\theta} = \frac{3}{8}\frac{d\sigma^{U+L}}{\mathrm{d}p_T^Z\,\mathrm{d}y^Z\,\mathrm{d}m^Z}\Big\{(1+\cos^2\theta) + \frac{1}{2}A_0(1-3\cos^2\theta) + A_4\cos\theta\Big\}. \tag{1.3}$$



H->Zγ

- A very interesting and promising decay mode of Higgs
  - Complementary to H->γγ
  - Could be the first "rare" decay mode observed
  - Also some similar but not the same decay mode, eg. $H \to \gamma^* \gamma$
  - SM Zγ as one of the main backgrounds
- Overview of run 2 results:
  - ATLAS $H \to Z\gamma \to ll\gamma$: 2.2σ (obs) 1.2σ (exp) (j.physletb.2020.135754)
  - ATLAS $H \to \gamma^*\gamma \to ll\gamma$: 3.2σ (obs) 2.2σ (exp) (j.physletb.2021.136412)
  - CMS $H \to Z\gamma \to ll\gamma$: 2.7σ (obs) 1.0σ (exp) (JHEP11(2018)152)





Summary

- Most up-to-date Zγ + jets differential cross section measurements
  - Currently only a conference note, paper will be published soon
- Measurement is simple, but it could be used as a probe to many interesting things:
  - Better understand and constrain SM parameters
  - Improve background modeling to search for rare processes
  - Re-interpretations (EFT, polarization…)

Thanks very much for your attention!