Precise measurement of $Z\gamma$ + jets and EFT interpretation with ATLAS Full Run-2

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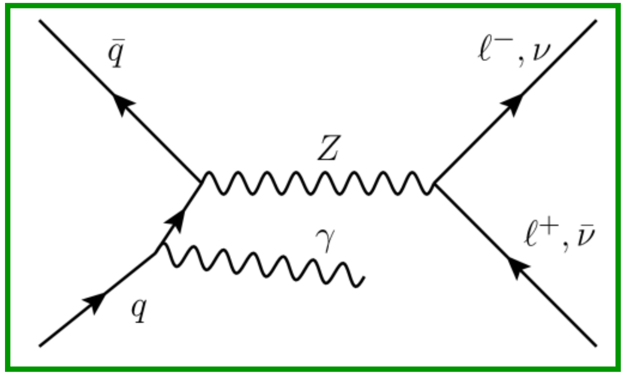
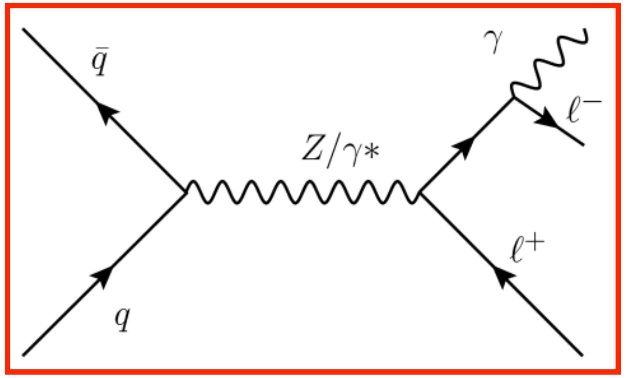
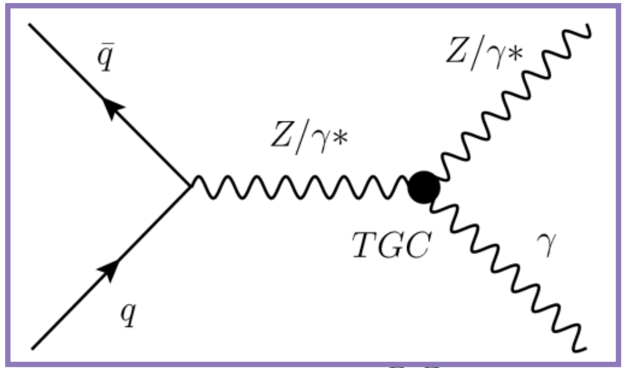
- Outline
  - Introduction
  - Event Selection
  - Background Sources
  - Systematics
  - Differential measurements
  - Summary

Introduction

- Motivation of $Z\gamma$ + jets measurement :
  - Large data statistics with small background
  - Differential distributions can be used to :
    - Constrain parameters of the SM Lagrangian
    - Test models like Parton Density Functions, Parton Shower predictions
    - Test of fixed-order QCD calculations with resummation of Sudakov logarithms
  - Possibility of Z boson polarization measurement
  - Search for physics beyond the SM, like ALPs and EFT
- FIRST measurement of differential cross-sections for $Z\gamma$ production in association with jets activities and can be used to constrain QCD predictions in ATLAS







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Feyman Diagrams for $Z\gamma$ production via the ISR process (top), $Z\gamma$ production via the FSR process (middle), $Z\gamma$ production with anomalous TGC process (bottom)

Measured Observables

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- In this $Z\gamma$ + jets differential measurement, different types of observables are measured
  - 1D observables
    - Interesting for QCD studies : $N_{jets}, p_T^{jet1}, p_T^{jet2}, p_T^{jet2}/p_T^{jet1}, m_{ll\gamma j}, m_{jj}$
    - Used in other analysis : $H_T, p_T^{\gamma}/\sqrt{H_T}, \Delta\Phi(j,\gamma), \Delta R(l,l), p_T^{ll}$
  - QCD-sensitive 2D observables
    - $p_T^{ll\gamma}/m_{ll\gamma}$ in 3 slices of $m_{ll\gamma}$
    - $p_T^{ll} - p_T^{\gamma}$ in 3 slices of $p_T^{ll} + p_T^{\gamma}$
    - $p_T^{ll\gamma j}$ in 3 slices of $p_T^{ll\gamma}$
    - Also inclusive $p_T^{ll} - p_T^{\gamma}, p_T^{ll} + p_T^{\gamma}, p_T^{ll\gamma j}$
  - **Polarization-sensitive 2D observables**
    - $cos\theta_{CS}$ in 5 bins of p_T^{ll}
    - ϕ_{CS} in 5 bins of p_T^{ll}

Variables are separated into 2 different types :

- Hard variables : represent the hard scale of the process (non-zero at LO)
  - e.g. : $p_T^{Z}, p_T^{\gamma}, m_{Z\gamma}$ and their linear combinations
- Resolution variables : sensitive to additional QCD variations
  - e.g. : $p_T^{Z\gamma}, N_{jets}$ and so on

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Polarization Variables

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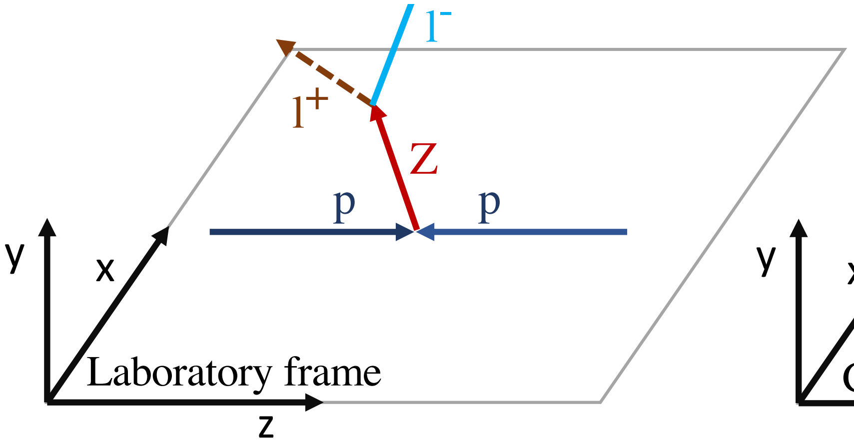
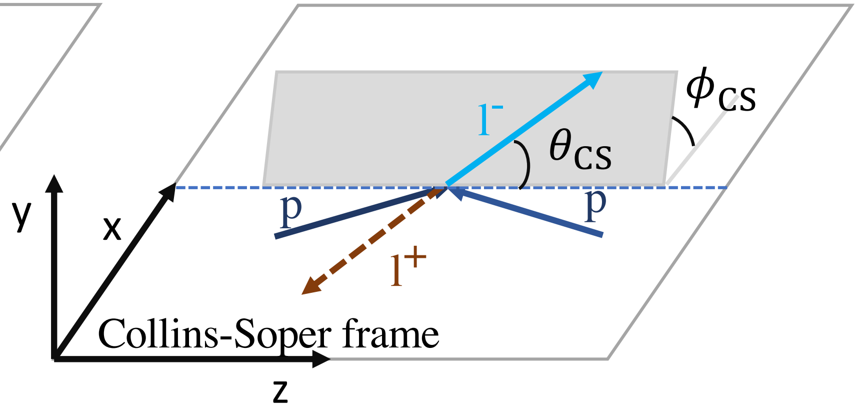
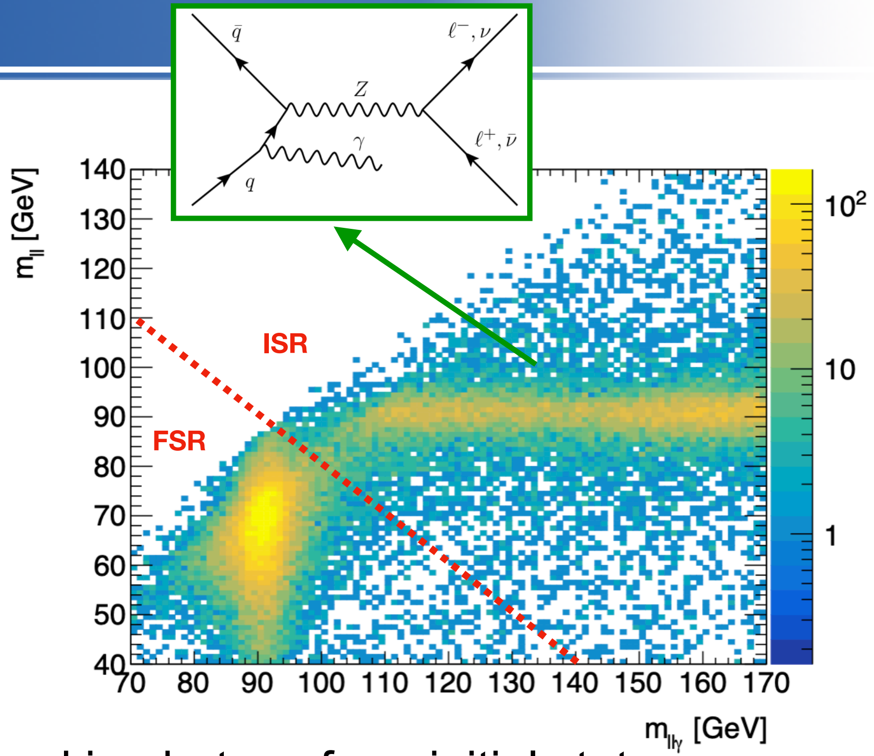
- Polarization variables in $Z\gamma$ + jets measurement :
  - Measurement of the polar and azimuthal distribution of l^+l^- pairs from Z decays in $Z\gamma$ final state
  - FIRST time to measure the lepton angular coefficients in events with photon associated production with DY
  - The transverse momentum of Z boson will be shifted a little higher due to the presence of ISR photons, which are different from the measurements of Z + jets event
  - $cos\theta_{CS}, \phi_{CS}$





Event Selection

- Due to the possibility to fully reconstruct the final states, only Z boson decays into pairs of electrons or muons are considered in charged lepton channel : $Z\gamma \rightarrow l^+l^-\gamma$
  - Candidate events must pass single lepton trigger
  - $m_{ll} > 40GeV$ is required to avoid low-mass resonances, e.g. γ^*
  - FSR events are reduced by requiring $m_{ll} + m_{ll\gamma} > 182GeV$
  - Control region in $e\mu$ channel is defined to check the modeling of the $t\bar{t}\gamma$ background, $t\bar{t}\gamma$ simulation is normalized to data



- Precise measurements are studied within a phase-space that is enriched in photons from initial state radiations (ISR)

Observable	Signal Region	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	

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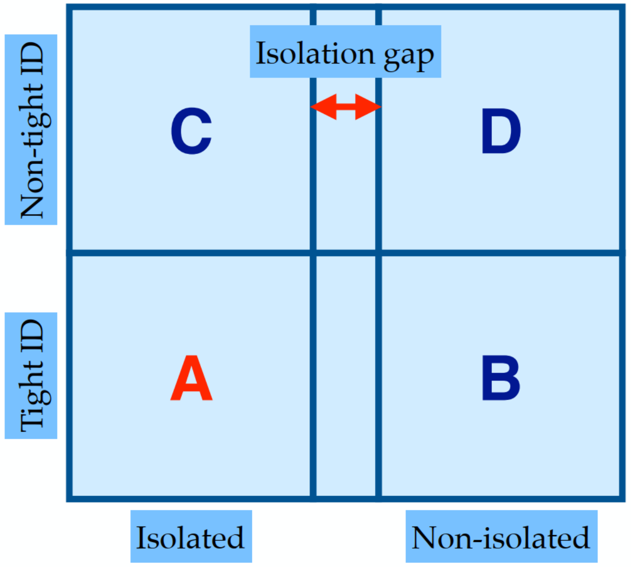
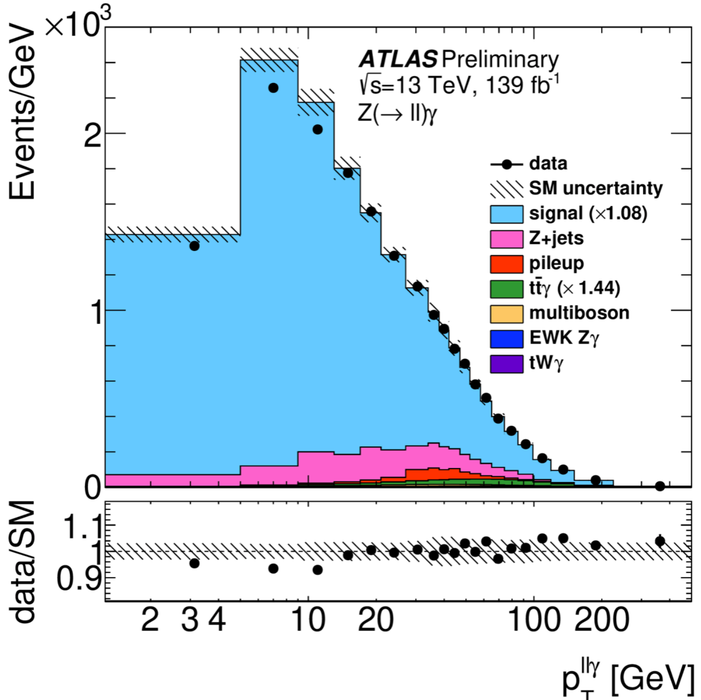
Background Sources

- Two main background processes :
  - Z + jets background — one of the jets is misidentified as a photon
    - Estimated with 2D sideband method (ABCD method)
    - Background systematics are come from : statistical, identification and isolation criteria
  - Pileup background — photon come from a vertex different from leptons
    - Estimated with data-driven method
- Other background processes :
  - $t\bar{t}\gamma$ background
    - Take $e\mu\gamma$ channel as a control region
    - Dominated by $t\bar{t}\gamma$ contribution, easy to check the modeling
  - Multi-boson, $tW\gamma$ backgrounds
    - Estimated directly from the MC





Background Estimation — Z + jets background

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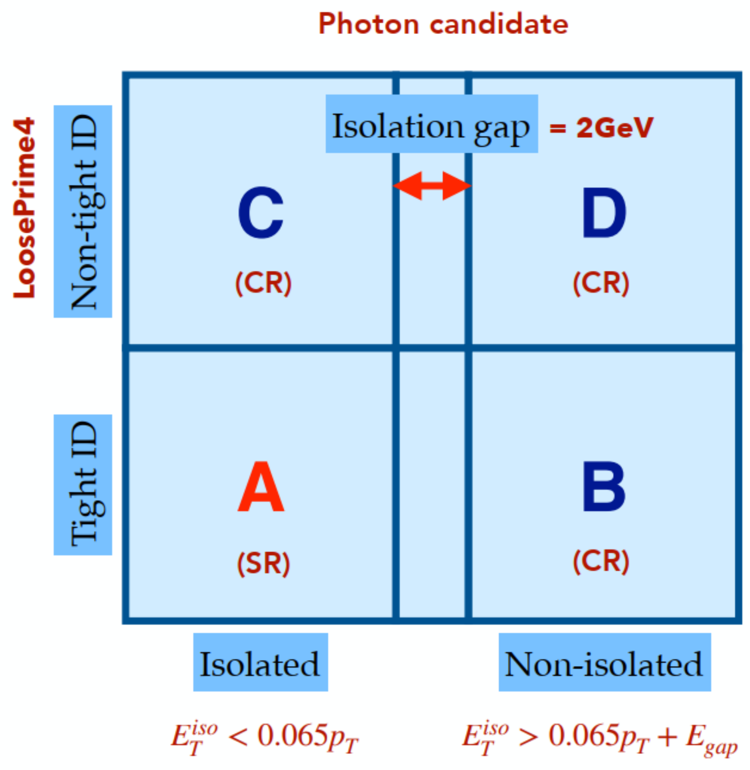
- Z + jets background
  - One of the jets is misidentified as a photon
  - 2D sideband method



- Correlation factor : $R = \frac{N_A^{Z+jets} \times N_D^{Z+jets}}{N_B^{Z+jets} \times N_C^{Z+jets}}$
  - $R = 1.30 \pm 0.04(stat) \pm 0.23(syst)$
- Signal leakage parameters : $c_B = \frac{N_B^{sig}}{N_A^{sig}}$, $c_C = \frac{N_C^{sig}}{N_A^{sig}}$, $c_D = \frac{N_D^{sig}}{N_A^{sig}}$
- Signal estimate :
  $N_A^{sig} = N_A^{data} - N_A^{bkg} - N_A^{Z+jets} = N^{sig}(N_X^{data}, N_X^{bkg}, R\,.\,c_X)$
- Fake Estimate : $N^{Z+jets} = (N_A^{data} - N_A^{bkg}) \times (1 - \frac{N_A^{sig}}{N_A^{data} - N_A^{bkg}})$ R
- Uncertainties estimate for Z + jets
  - Statistical
  - Signal leakage parameters : Comparing with Madgraph
  - Correlation factor R : varying the definition of the CRs
  - Anti-tight : use LoosePrime3 and LoosePrime5 to deduce the systematic uncertainty
  - Isolation gap : E_T^{gap} is varied to 1GeV and 3GeV

Background Estimation — pileup background

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- Pileup background
  - Data-driven method
  - Pileup photons, the photons and the leptons are produced from the different pp collisions in the same bunch crossing
  - Pileup estimation is done through the **pileup fraction** in data: $N_{PU} = f_{PU} \cdot N_{data}$

$$f_{PU} = \frac{1}{N_{data,pixel\ conv}} \cdot \frac{N_{data.pixel\ conv} - N_{Z\gamma MC,pixel\ conv}^{|\Delta z|>50mm}}{P(\Delta z > 50mm) = 0.32}$$

  - Only photons that converted in the inner detector are considered to get a better resolution $\sigma(z)$
- f_{PU} as a function of kinematic variables
  - Important to have a correct modeling of the shape of pileup background considering the differential cross-section measurement
- Shape information extraction
  - Truth sample : using MC sample by merging a Z+jets sample and a single photon sample
  - Pileup enhanced sample : select only photons whose z position is closer to the second hardest vertex than the primary one

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Background Estimation — $e\mu\gamma$ control region

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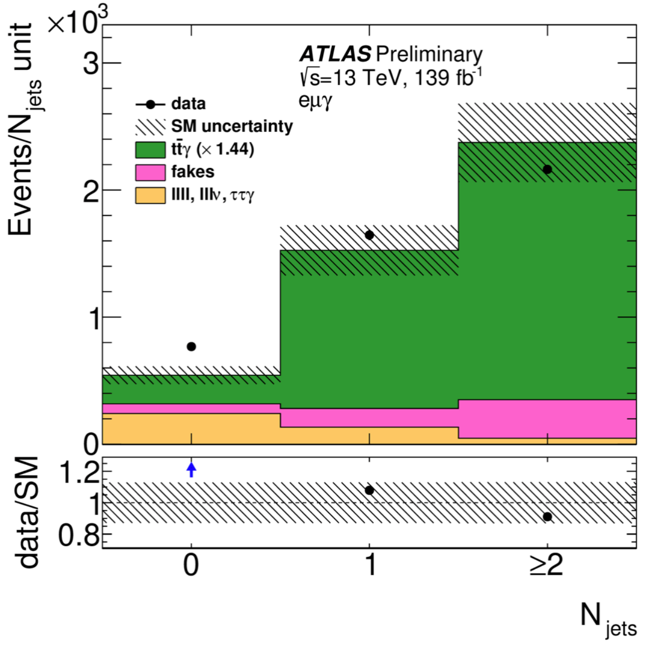
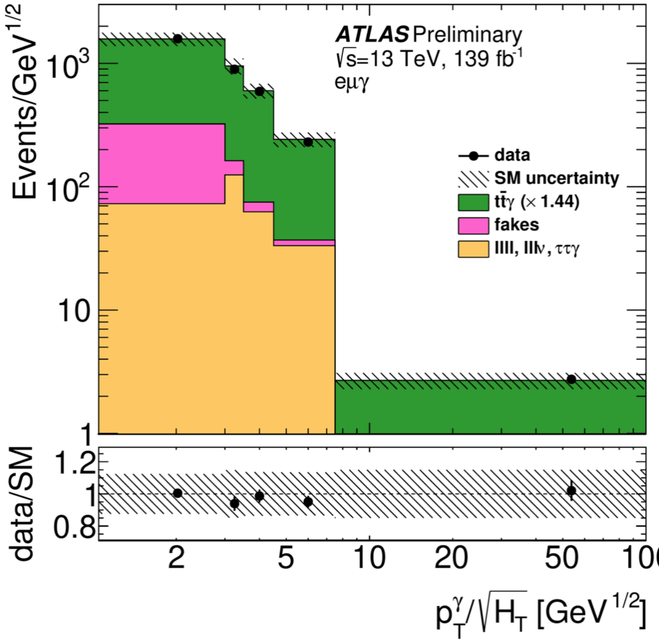
- Other minor backgrounds (tri-bosons and di-bosons) are estimated directly from MC
- Take $e\mu\gamma$ channel as a control region (receives no contribution from Z)
  - Scaled by a k-factor of 1.44 both in CR and SR
  - Dominated by $t\bar{t}\gamma$ contributions
  - Easy to check the modeling of $t\bar{t}\gamma$ background
  - Check the fake photon estimation, including jet-related variables
  - Good agreement is observed between the data and the SM estimated in the CR





Systematics

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- Experimental systematics
  - Detector reconstruction efficiency, calibration and the modeling of the reconstruction
  - Luminosity, jet, electron, muon and photon
- Theoretical systematics
  - Scale and PDF variations (variations of renormalization and factorization, PDF set)
- Unfolding systematics
  - Statistical uncertainty is propagated using pseudo-data (toys)
- Background Sysmematics
  - Both from simulated samples and data-driven method
- Experimental systematics have the largest impact on the signal region, especially jet systematics

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

Impact of the different systematic uncertainties in each bin of the N_{jet} distributions

Event Yields

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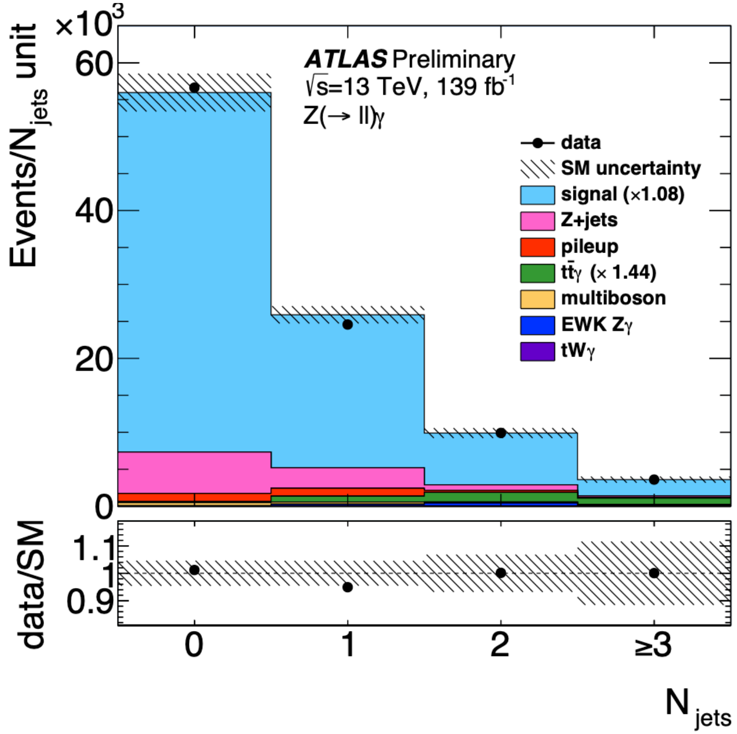
- Table listed below shows the data event yield and the signal and background estimates in the SR
  - Sherpa 2.2.11 MC used for $Z\gamma$ process
  - Scaled by a normalization factor of 1.08 to match the data
  - Statistical and systematic uncertainties are included in the table
- Good agreement is observed between the data and the SM estimates
  - Total experimental uncertainty is ~ 3% of the total prediction

Source	$ee + \mu\mu$	
$Z\gamma$ signal	**73 500**	±50 (stat.) ± 2 600 (syst.)
Z + jets	**9 800**	±460 (stat.) ± 2 100 (syst.)
$t\bar{t}\gamma$	**3 600**	±10 (stat.) ± 540 (syst.)
pile-up	**2 500**	±70 (stat.) ± 700 (syst.)
multiboson	**950**	±5 (stat.) ± 160 (syst.)
$tW\gamma$	**150**	±1 (stat.) ± 45 (syst.)
Total prediction	**90 500**	±500 (stat.) ± 3 500 (syst.)
Data	**96 410**	±310 (stat.)



Event Yields

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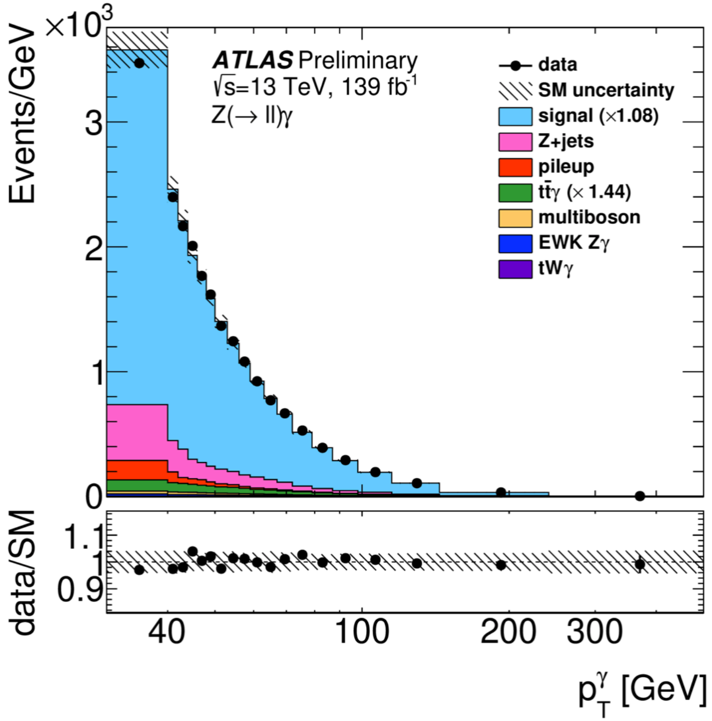
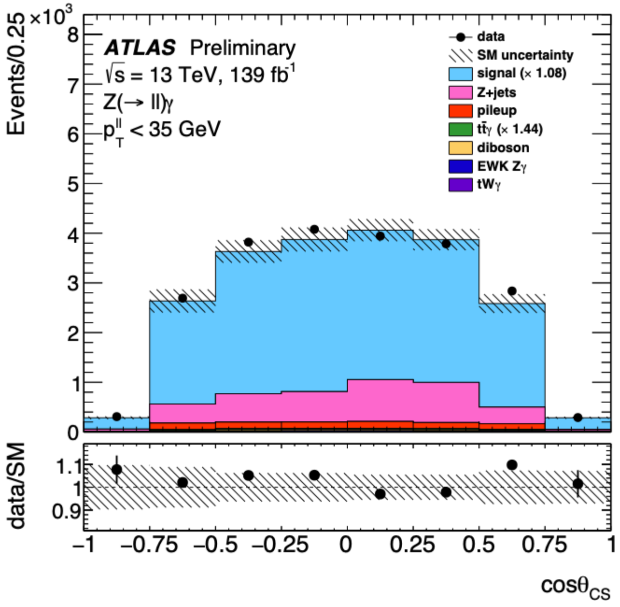
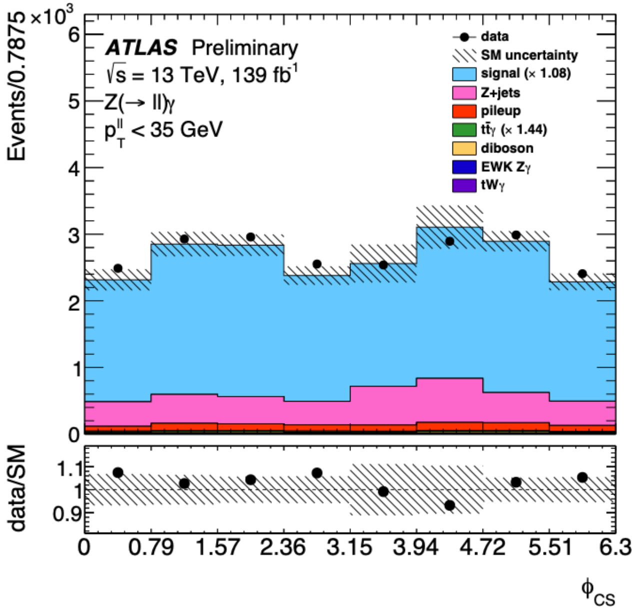
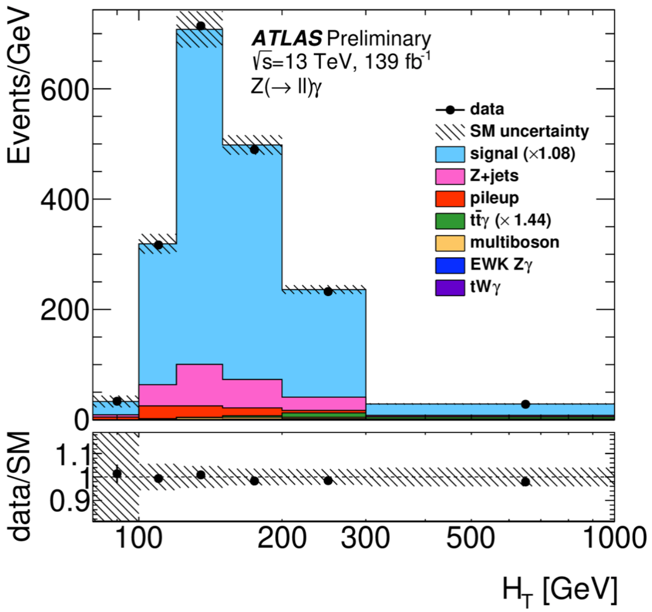
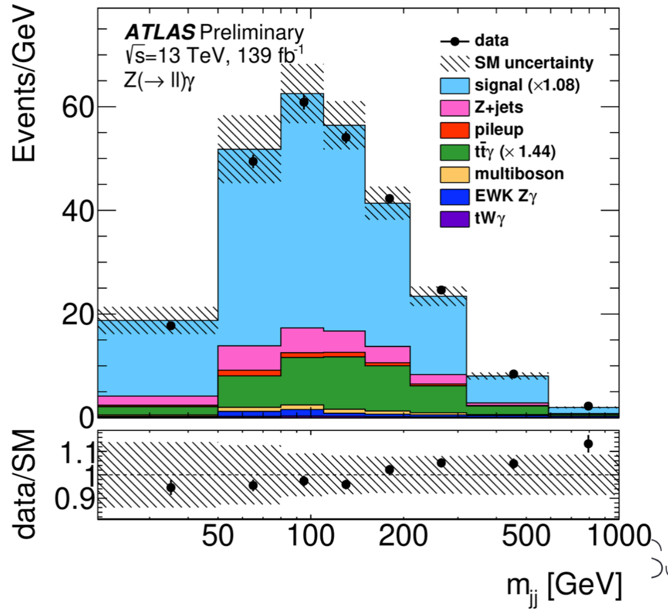
- Data/MC comparison results
  - Good Agreement observed !











Differential cross-sections measurements

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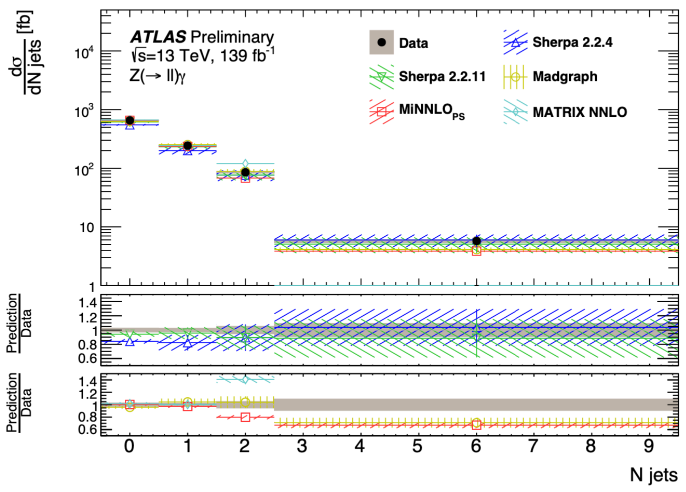
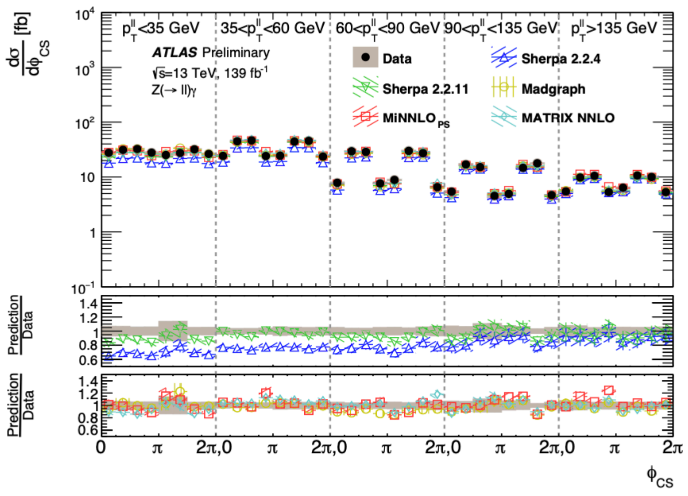
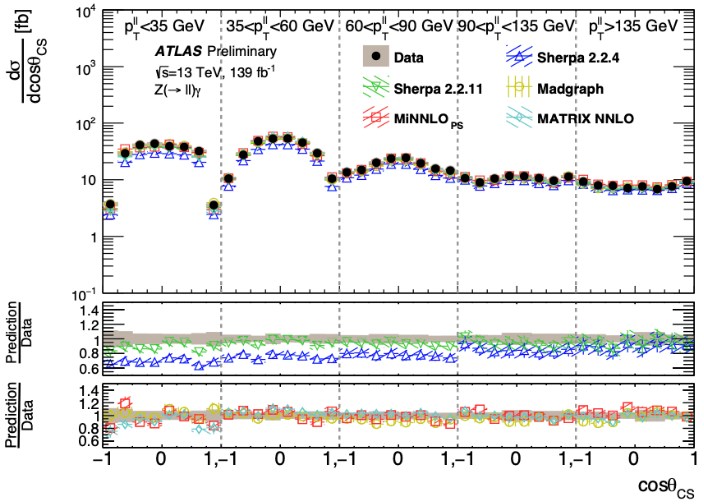
- Differential cross-sections are measured as function of the observables
  - Performed within a defined fiducial phase-space enhanced with ISR photons
  - With high statistics, high precision results for additional QCD radiations can be obtained
  - Good description of the data in wide range (in comparison with measured data and SM estimates, as well as NNLO theory predictions)
- Unfolding is performed by Bayesian iterative method (2 iterations)
  - Considering the compromise between bias and statistical uncertainty
  - Correction for migration between bins in the detector-level and particle-level distributions
  - Correction for fiducial and reconstruction efficiency







Differential cross-sections measurements

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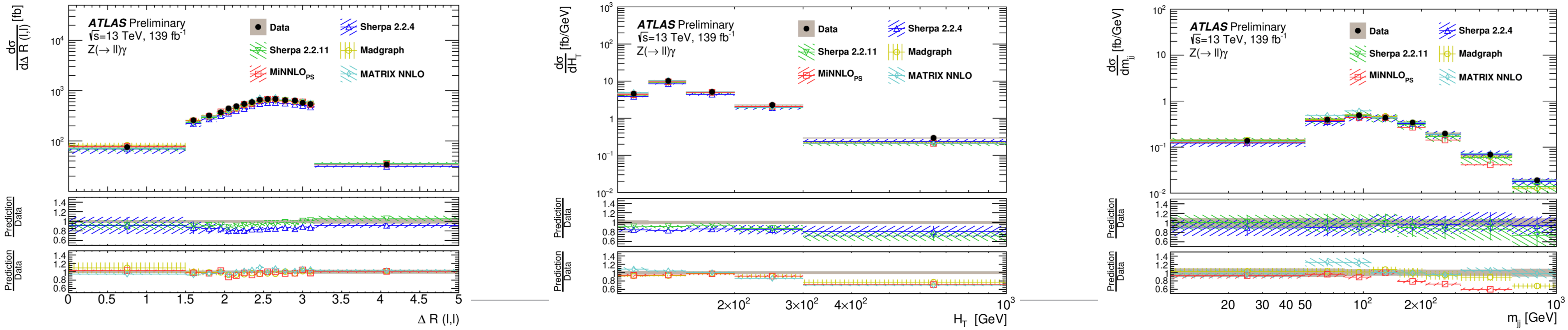
- Differential cross-section measurement results
  - Unfolded results are compared with different theoretical predictions
  - Including :
    - Calculation of Sherpa 2.2.4, Sherpa 2.2.11, and Madgraph
    - NNLO predictions of MiNNLO $_{PS}$
    - NNLO Fixed-order calculation MATRIX
      - No QED radiation, correction for born-to-particle for lepton/photon
      - Correction for non-perturbative effects by comparing the differential cross-section from samples w/o hadronization effects



Differential cross-sections measurements

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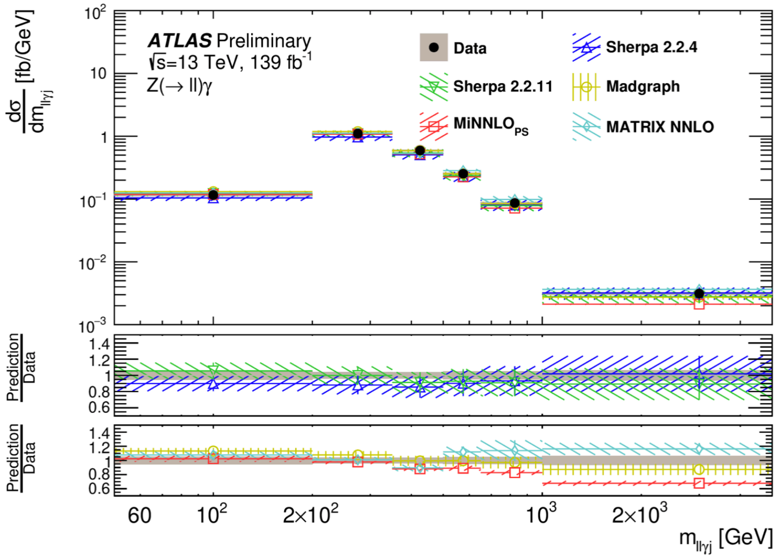
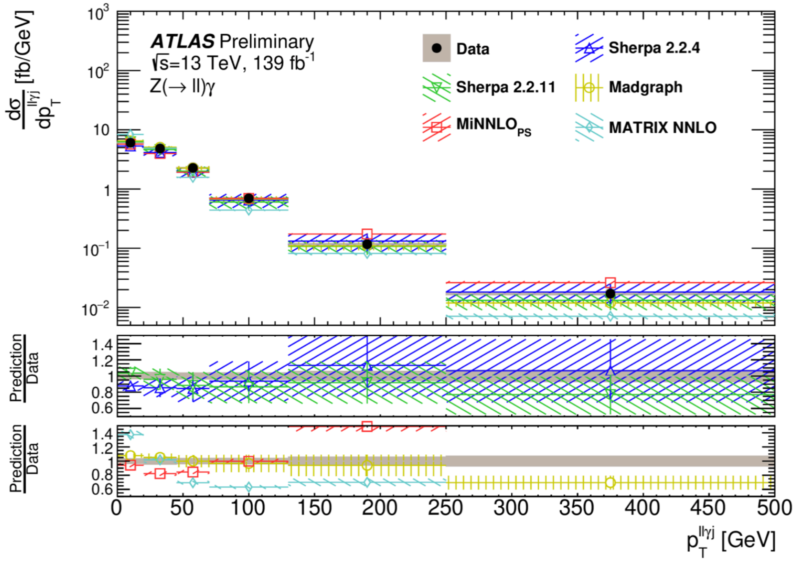
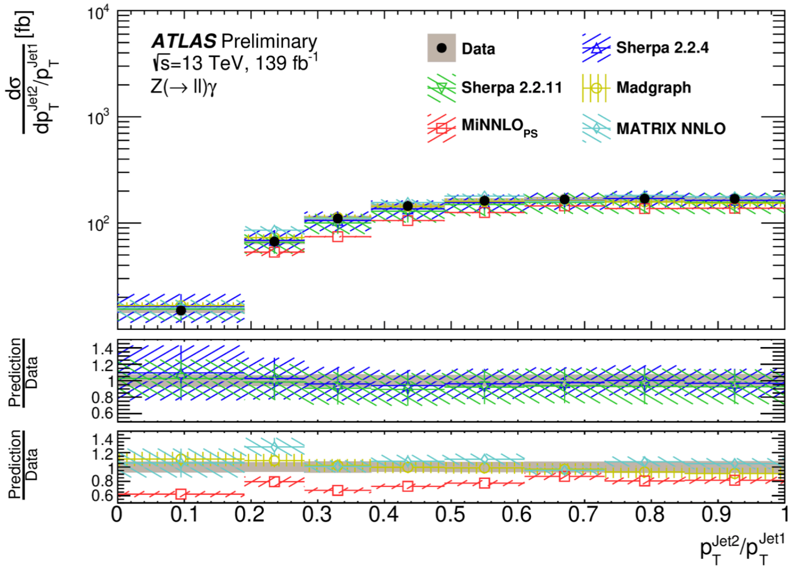
- Differential cross-section measurement results
  - Sherpa and Madgraph can both describe well the data
  - Sherpa 2.2.11 has a better agreement in shapes than Sherpa 2.2.4

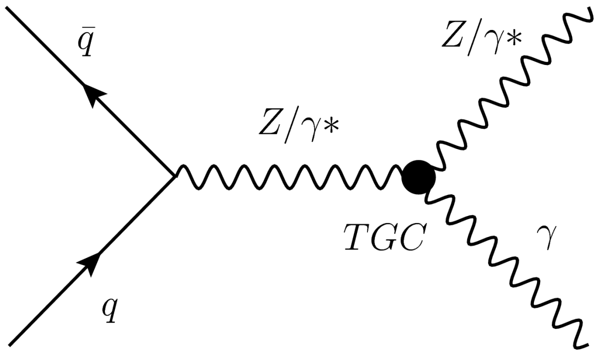




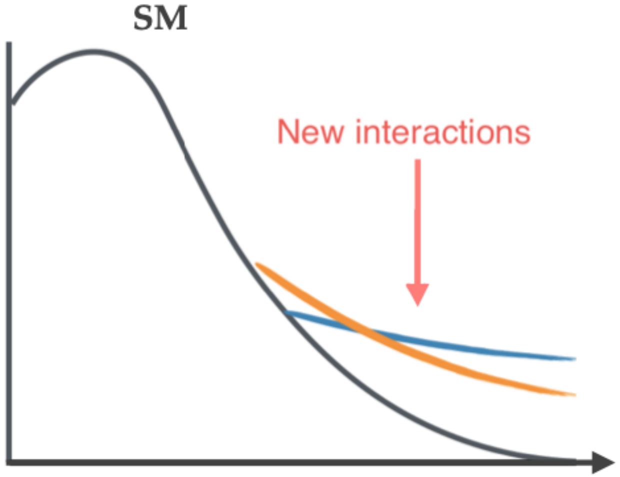


EFT interpretation — Neutral Triple Gauge Couplings

- Neutral Triple Gauge Couplings (nTGCs)
  - The study of nTGCs is important to understand electroweak symmetry mechanism
  - The probe of nTGCs is a new window to search for Beyond Standard Model Physics
  - nTGCs are forbidden at tree level in the SM, but could arise from SMEFT dim-8 operators
  - An EFT extension of the SM can be parameterized by the effective Lagrangian
  - $L = L_{SM} + \sum_{d>4} \sum_{i} \frac{C_i}{\Lambda^{d-4}} O_i^d$ (Λ is the new physics scale)
- If there are any anomalous couplings
  - Increase of total cross-sections
  - Increase of the differential cross-sections at high transverse momentum and high mass region



coupling	parameters	channel
$ZZ\gamma$	h_3^Z, h_4^Z	$Z\gamma$
$Z\gamma\gamma$	h_3^γ, h_4^γ	$Z\gamma$



EFT interpretation — Neutral Triple Gauge Couplings

- Recent nTGC update on theory side
  - A new nTGC model proposed by Prof. John Ellis, Prof. Hongjian He and Dr. Ruiqing Xiao
  - arXiv:2206.11676v2
  - Talk from Prof. John Ellis
  - Probing nTGC interactions via $pp \to Z\gamma$ production at the LHC, followed by $Z \to l^+l^-$ ($l = e, \mu$) decays
- nTGC theoretical exclusion limit results :
  - Given from the theoretical side, much promising to get new experimental limits ！

Parameter	Limit 95% C.L.					
$\sqrt{s}$	13 TeV(ll)			13 TeV(ll, $\nu\nu$)		
L(ab^{-1})	0.14	0.3	3	0.14	0.3	3
$\lvert h_4 \rvert$	1.1×10^{-5}	8.5×10^{-6}	4.3×10^{-6}	7.6×10^{-6}	6.0×10^{-6}	3.1×10^{-6}
$\lvert h_3^Z \rvert$	2.2×10^{-4}	1.7×10^{-4}	$\times 8.9 \times 10^{-5}$	1.5×10^{-4}	1.2×10^{-4}	6.7×10^{-5}
$\lvert h_3^\gamma \rvert$	2.5×10^{-4}	2.0×10^{-4}	1.0×10^{-4}	1.8×10^{-4}	1.4×10^{-4}	7.7×10^{-5}

Theoretical

Summary

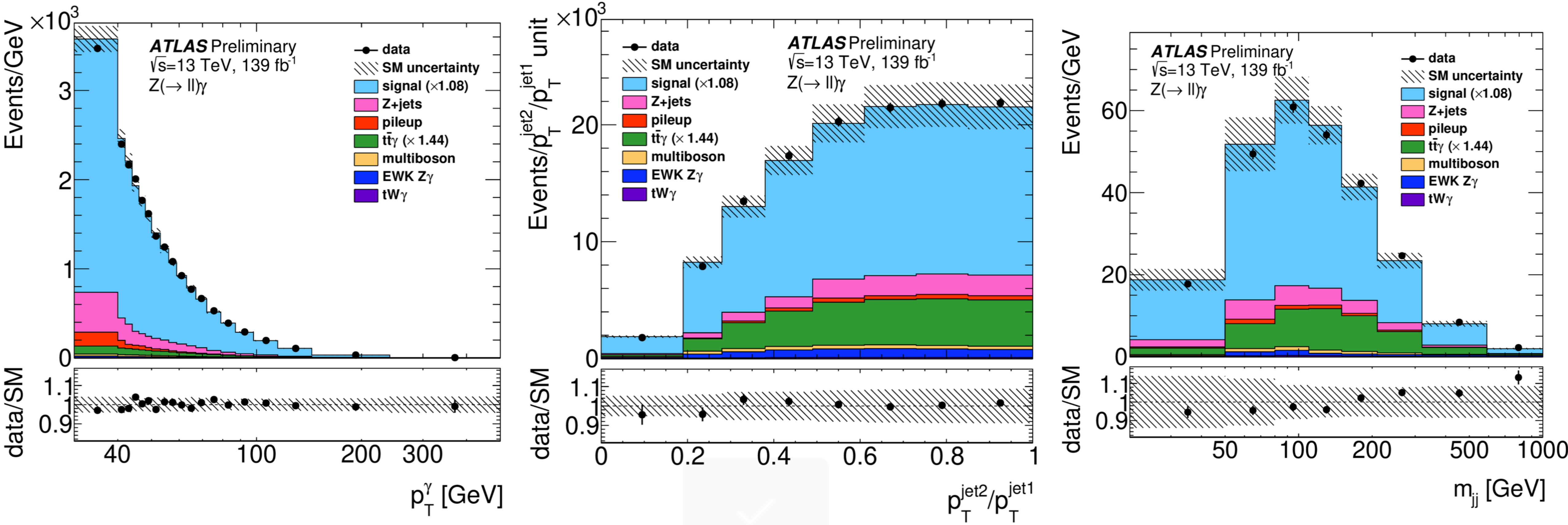
- The FIRST ATLAS measurement for $Z\gamma$ production in association with jet activities with Full Run-2 datasets
- Differential cross-sections for QCD-related variables in $Z\gamma$ productions are measured with good agreement
  - Good agreement observed between the measured data and the SM estimates
  - Good agreement observed between the measured data and the NNLO theory predictions
- nTGC EFT interpretations
  - With the increase of statistics, nTGC can be studied in $Z\gamma$ production with charged lepton decays
  - Very PROMISING to give new experimental constrains with this nTGC EFT model

Thank You !

Backup

Results

- Data/MC comparison results



Results

- Differential cross-section measurements