Precise measurement of Z+photon final states, Polarisation and Search for nTGCs with EFT at ATLAS

Danning Liu

Tsung-Dao Lee Institute, Shanghai Jiao Tong University

SYSU - PKU Collider Physics Forum For Young Scientists

Shanghai Jiao Tong University

TDLI 李政道研究所

2022.10.19

ATLAS EXPERIMENT

Introduction

- The Standard Model, explains how the basic building blocks of matter interact, governed by four fundamental forces
  - Best description of the elementary particles and interactions so far
  - Well tested by the experiments

Matter particles :

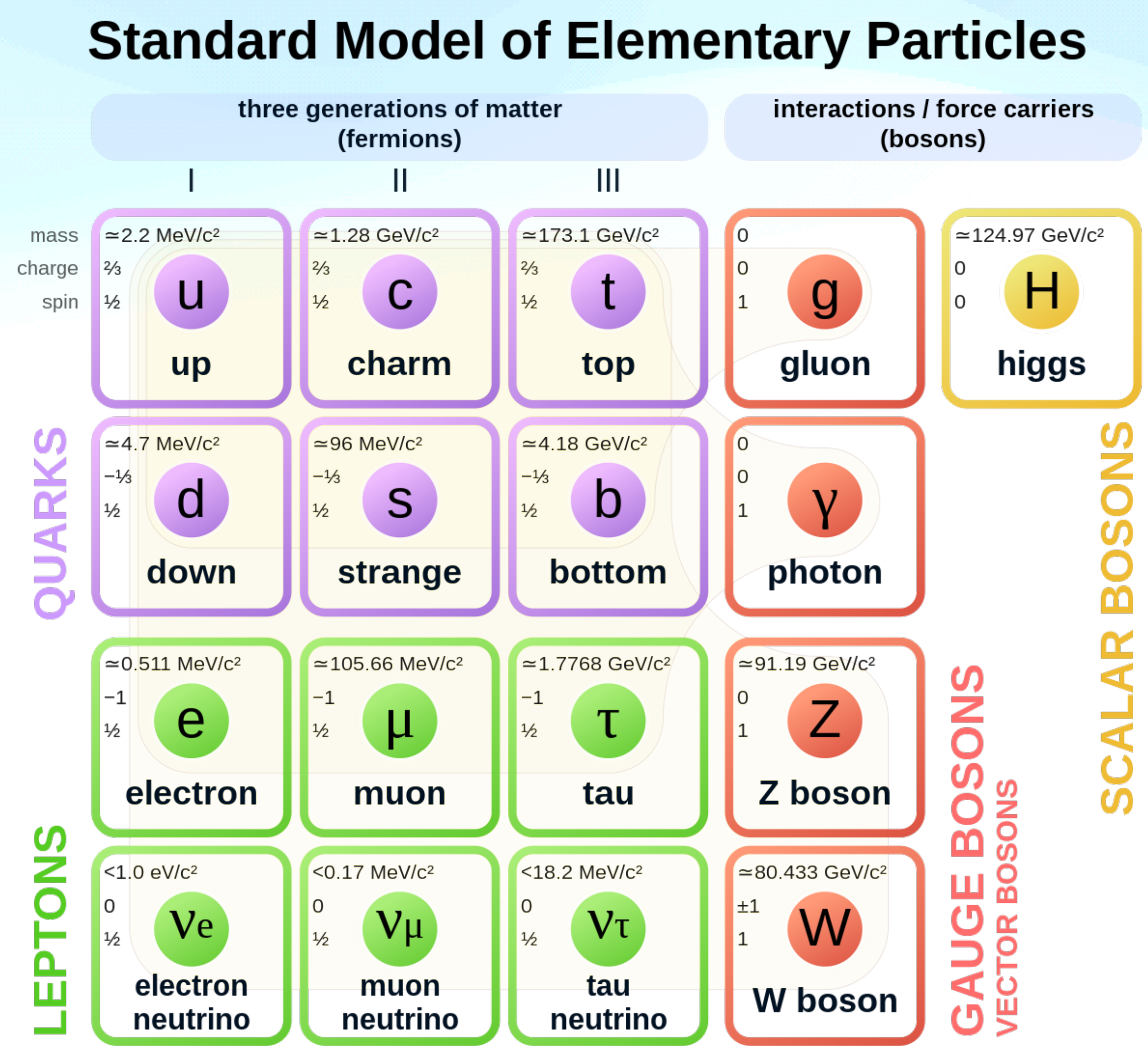
- Quarks and leptons
- 3 generations and in pairs
- Basic constituent of matter

Force carrier particles :

- Bosons (gluons, photons and $W^{\pm}, Z$)
- Carriers of fundamental forces (strong, weak and magnetic force)

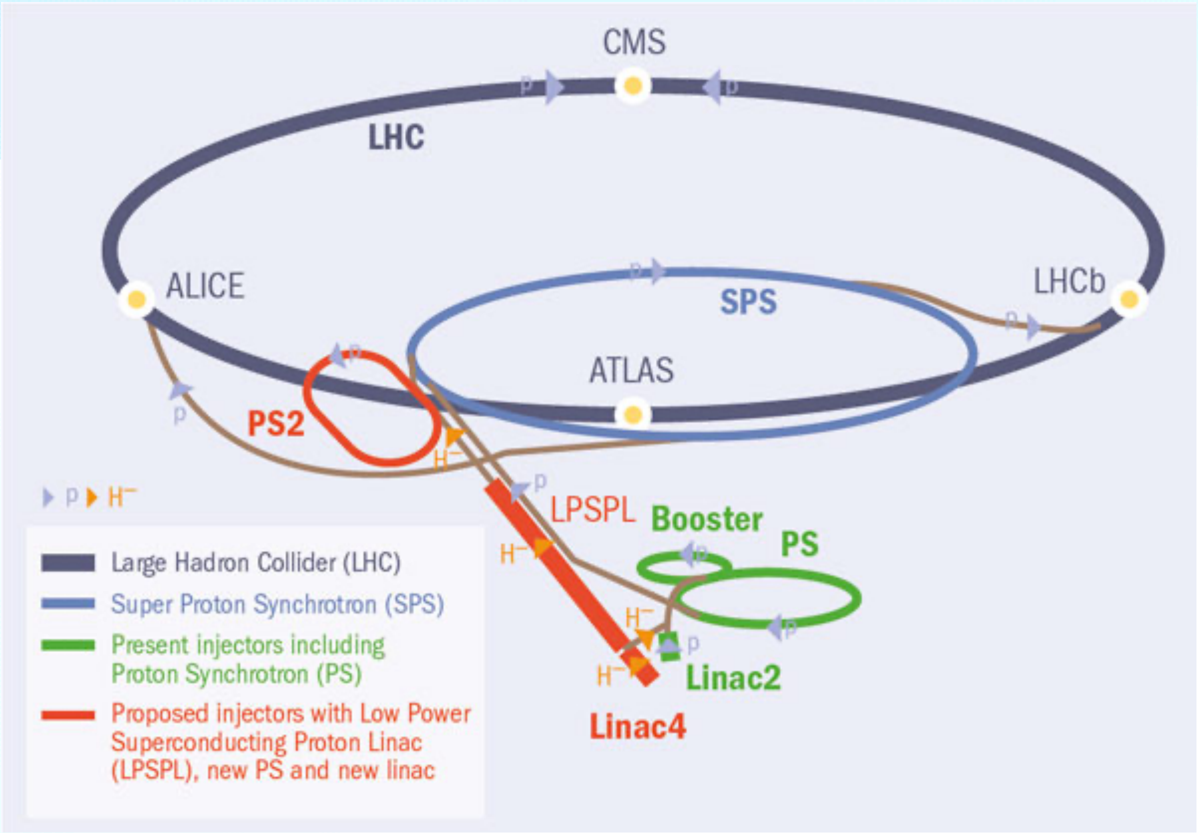
Higgs Boson :

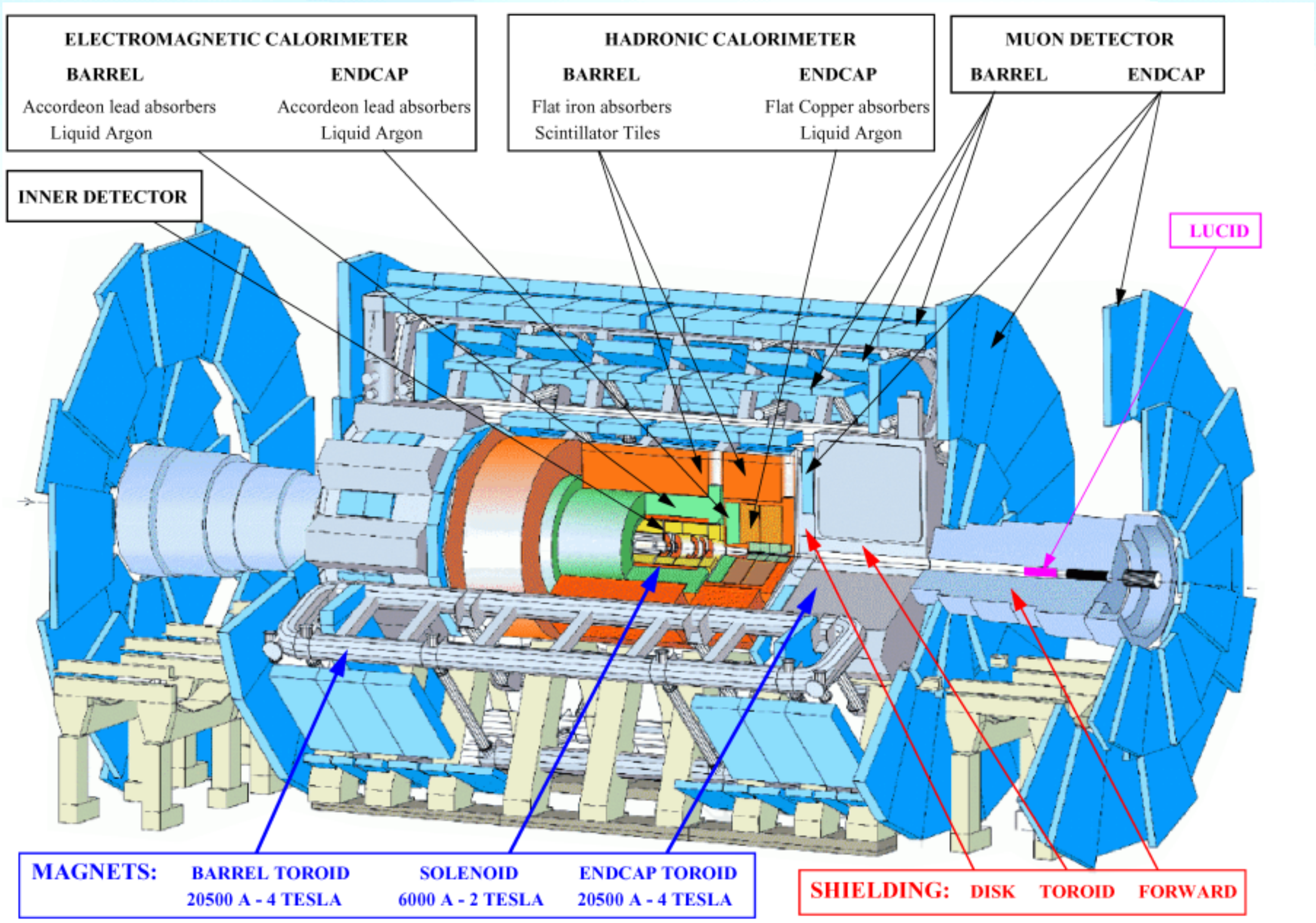
- An essential component of the SM
- Contributes to the understanding of the origin of mass particles



Introduction

- The Large Hadron Collider
  - The Largest and most powerful particle accelerator in the world
- ATLAS Detector
  - General-purpose particle physics experiment and the Large Hadron Collider at CERN





Motivation

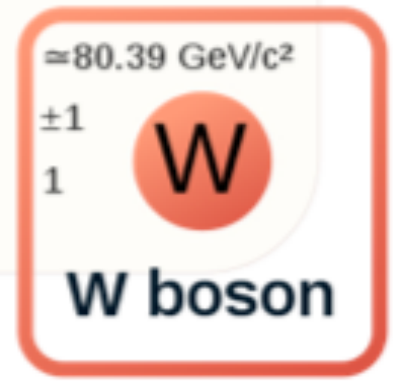
- $V\gamma$ measurement :

  - Large cross-section and high statistics : to test the electroweak sector of the Standard Model with high accuracy using multi-boson production cross section measurement

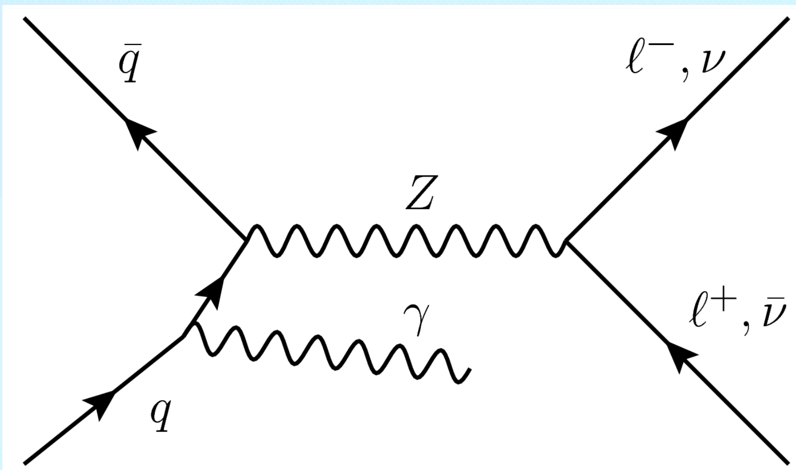
  - EFT interpretation : to search for signs of new physics using anomalous gauge-boson couplings (aTGC or aQGC) studies

  - MC tuning : SM multi-boson production is an important background fo Higgs and exotic searches, precision $V\gamma$ measurement can help to tune MC samples

  - To probe the gauge symmetry of the electroweak theory that determines the structure of self- couplings of the vector boson

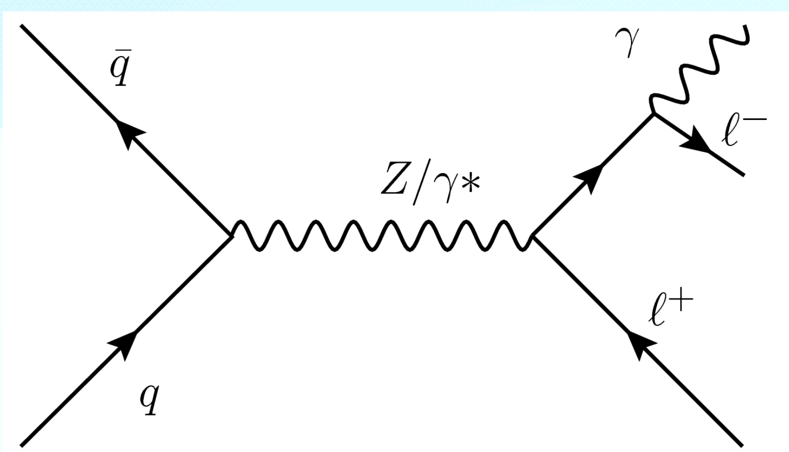


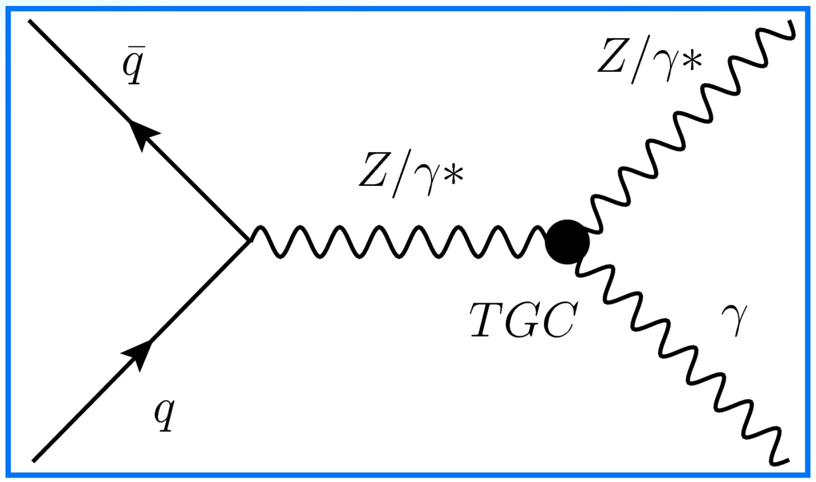
$Z + \gamma$ measurement



$Z\gamma$ Initial State Radiation

- Invariant mass of di-lepton pair : $m_{ll} \approx m_Z$
- Invariant mass of lepton-photon system :
- $m_{ll} + m_{ll\gamma} \geq 2m_Z$





$Z\gamma$ Final State Radiation

- Invariant mass of lepton-photon system :
- $m_{ll\gamma} \approx m_Z$

$Z\gamma$ Neutral Triple Gauge Couplings

- The probe of nTGCs is a new window to search for Beyond Standard Model Physics

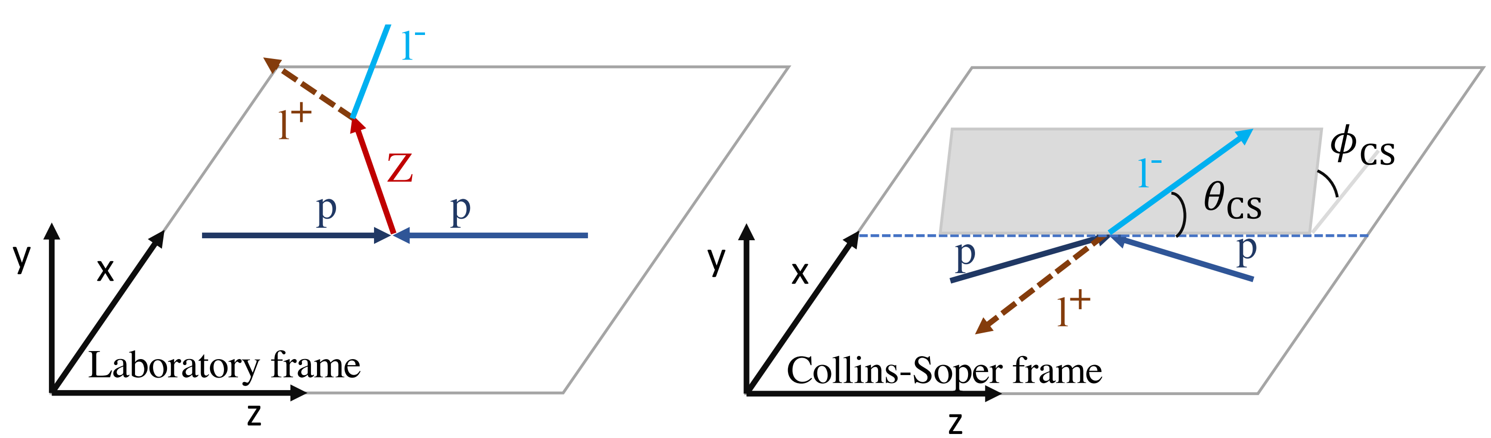
Measured Observables

ATLAS-CONF-2022-047

- In this $Z\gamma$+jets differential measurement, different types of observables are measured
  - 1D variables
    - Interesting for QCD studies : $N_{jets}, p_T^{jet1}, p_T^{jet2}, p_T^{jet1}/p_T^{jet2}, m_{ll\gamma j}, m_{jj}$
    - 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 variables
    - $p_T^{ll\gamma}/m_{ll\gamma}$ 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}
    - Also inclusive $p_T^{ll} - p_T^{\gamma},\ p_T^{ll} + p_T^{\gamma}, p_T^{ll\gamma j}$
  - Polarisation-sensitive 2D observables
    - $cos\theta_{CS}$ in 5 bins of p_T^{ll}
    - ϕ_{CS} in 5 bins of p_T^{ll}

First time measured !

The transverse momentum of Z boson will be shifted a little higher due to the presence of ISR photon, which are different from the measurements of $Z\gamma$ + jets event

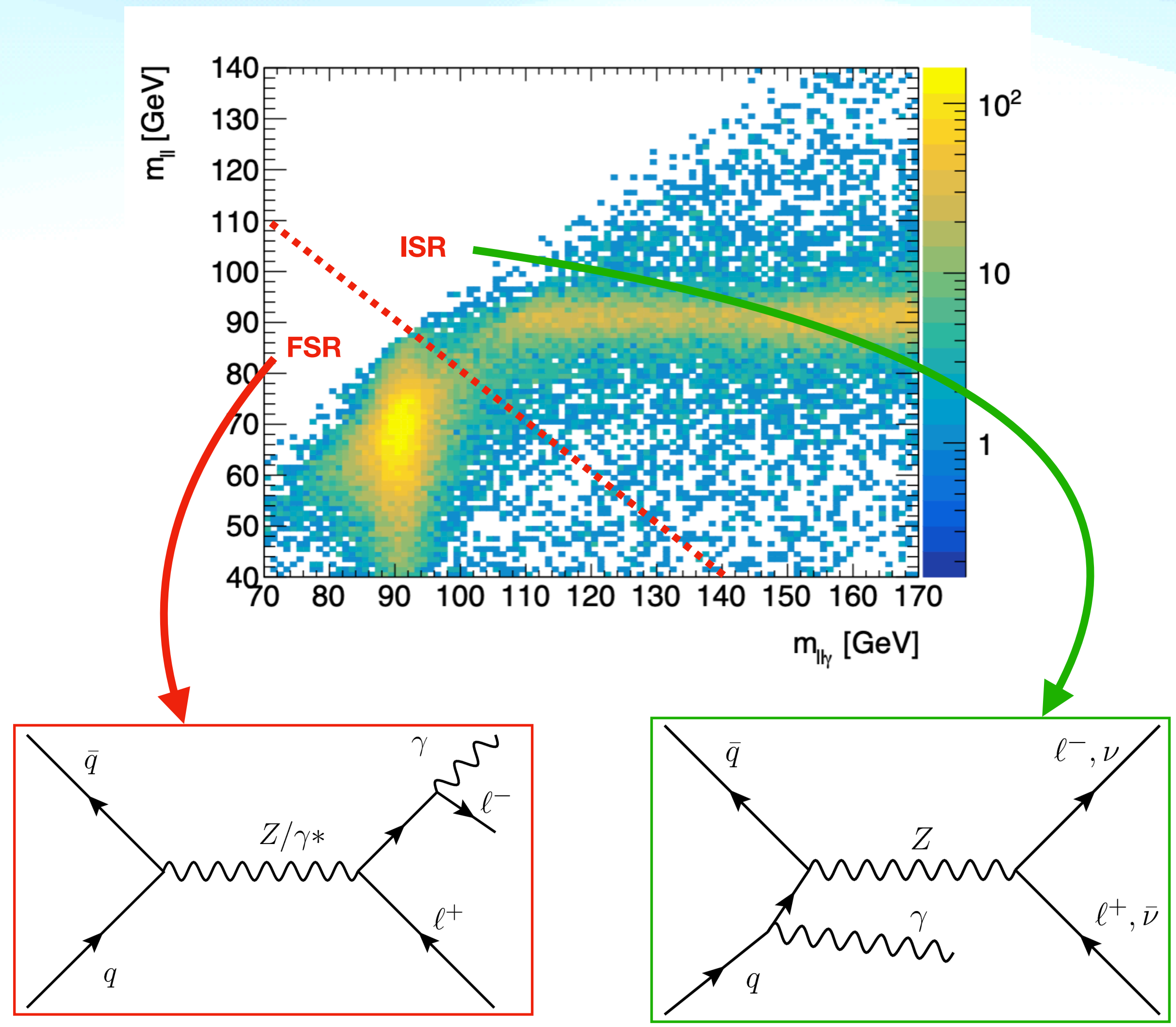


Signature of $Z + \gamma$ production

ATLAS-CONF-2022-047

- Signatures of $Z + \gamma$ candidate signal events
  - Single lepton triggers are applied in the analysis
  - Two opposite sign, same flavour leptons
  - At least 1 photons
  - Only Z bosons decay into pairs of electrons or muons are considered in charged lepton channel due to the possibility of fully reconstruction of the final state

Analysis Selection	
Variable	Cut
N_ℓ	2 signal leptons (OSSF for SR, OSDF for CR)
Trigger	single lepton trigger
Leading lepton	$p_\mathrm{T} > 30$ GeV
Photon	≥ 1 signal photon with $p_\mathrm{T} > 30$ GeV
$m_{\ell\ell}$	> 40 GeV
$m_{\ell\ell} + m_{\ell\ell\gamma}$	> 182 GeV

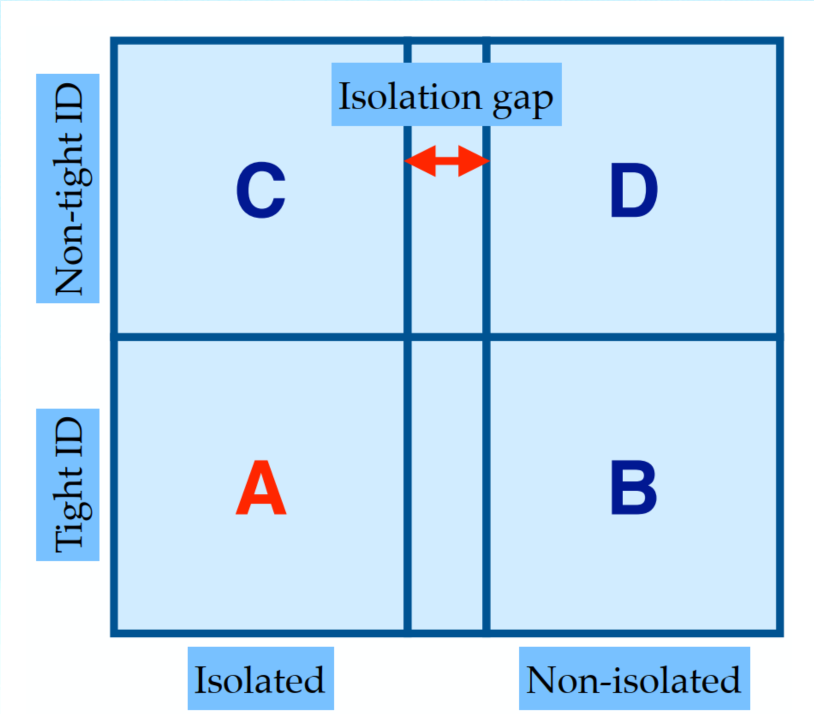


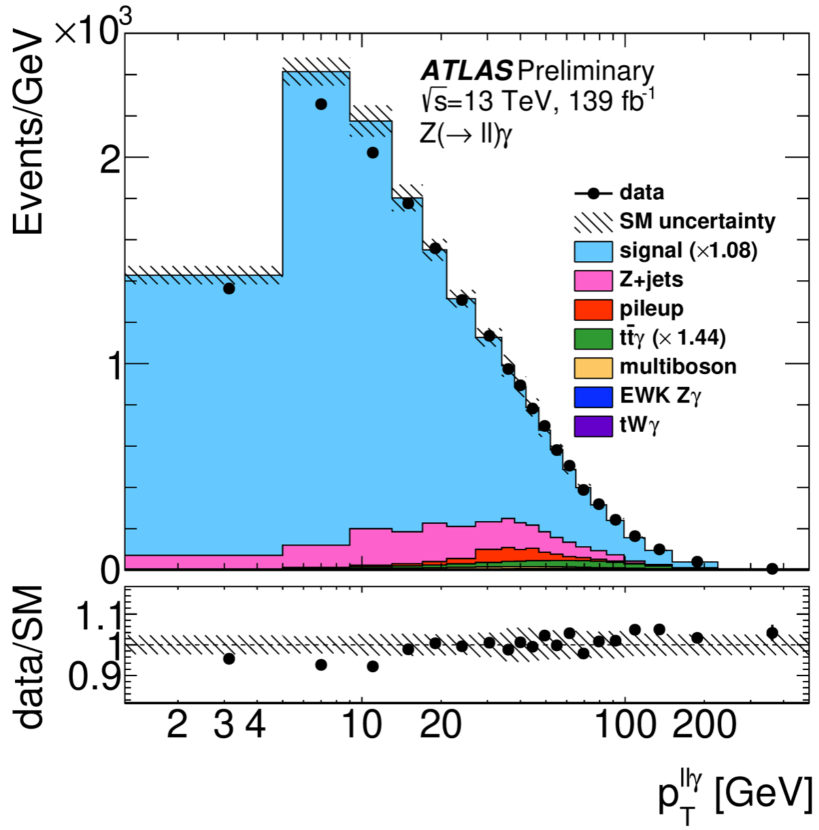
- Precise measurement are studied within a phase-space that is enriched in photons from initial state radiations
- QCD-related observables associated with the $Z\gamma$ process is measured

Background Sources

ATLAS-CONF-2022-047

- Two main backgrounds
  - 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 modelling
  - Multi-boson, $tW\gamma$ backgrounds
    - Estimated directly from the MC





Systematics

ATLAS-CONF-2022-047

- Experimental systematics
    - Detector reconstruction efficiency, calibration and the modelling of the reconstruction
    - Luminosity, jet, electron, muon and photon
- Theoretical systematics
    - Scale and PDF variables (variation of renormalisation and factorisation, PDF set)
- Unfolding systematics
    - Statistical uncertainty is propagated using pseudo-data
- Background systematics
    - Both from simulated sample 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

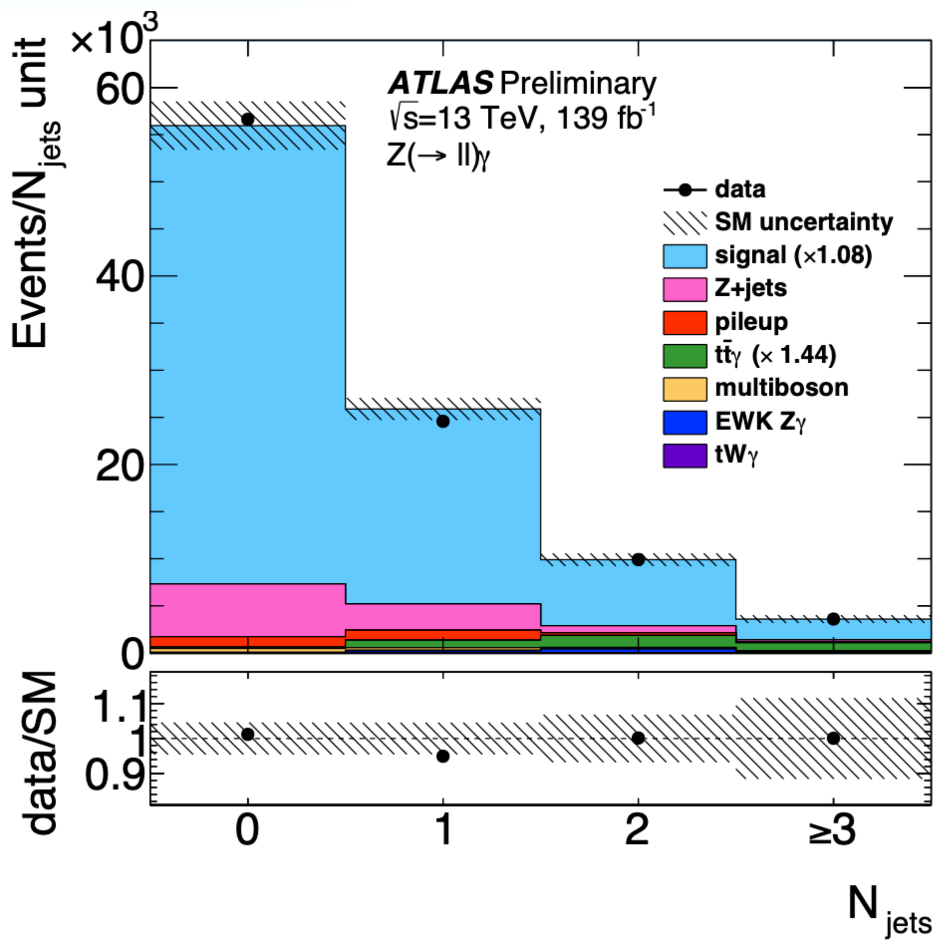
Impact of the different systematic uncertainties in each bin of the N_{jet} distributions

Data VS MC

ATLAS-CONF-2022-047

- Table and distribution listed below shows the data event yields and the signal, background estimation in the SR
  - Signal sample : $l^+l^- + \gamma$ + 0,1 jets @ NLO + 2, 3, 4 jets @ LO
  - Background sample : $t\bar{t}\gamma$, $tW\gamma$, multi-boson backgrounds
  - Both 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.)



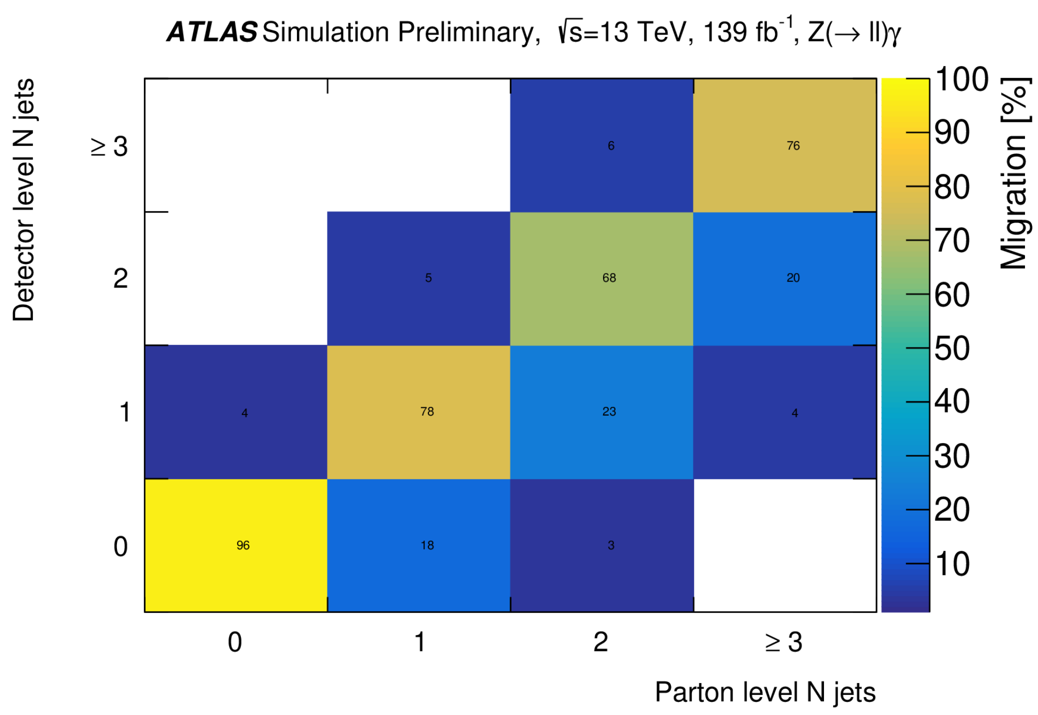
Differential measurement

ATLAS-CONF-2022-047

- In order to compare the experimental distribution with theoretical predictions, the detector effects should be corrected (unfolded) to the particle level
  - Detector effects such as smearing effect, limited acceptance and inefficiency

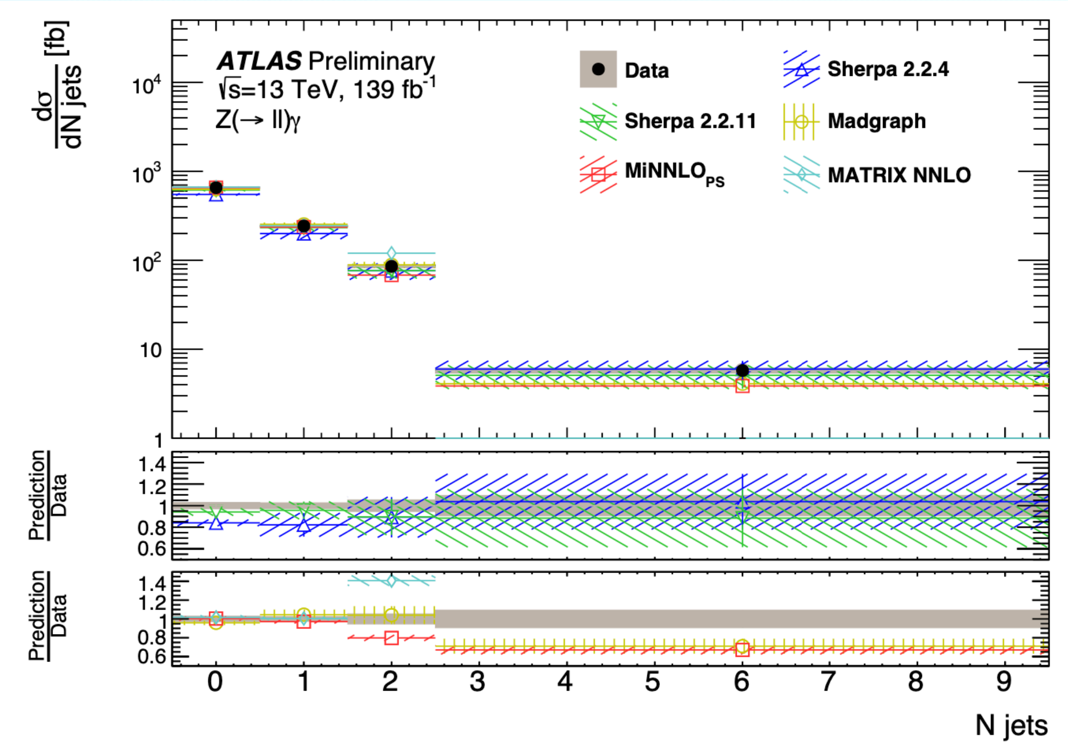
- Unfolding General Idea
  - Obtain fiducial cross-section of a given process from the measured events in data (minus backgrounds)

- Bayesian Unfolding — method
  - Unfolding matrix : Related the number of events in each bin of the truth distribution to those in the measured distribution



Differential cross-section measurements

- Differential cross-sections are measured as functions of the observables
  - Unfolding is performed by Bayesian iterative method
    - Statistical uncertainty, correction for migration between bins, fiducial and reconstruction efficiency



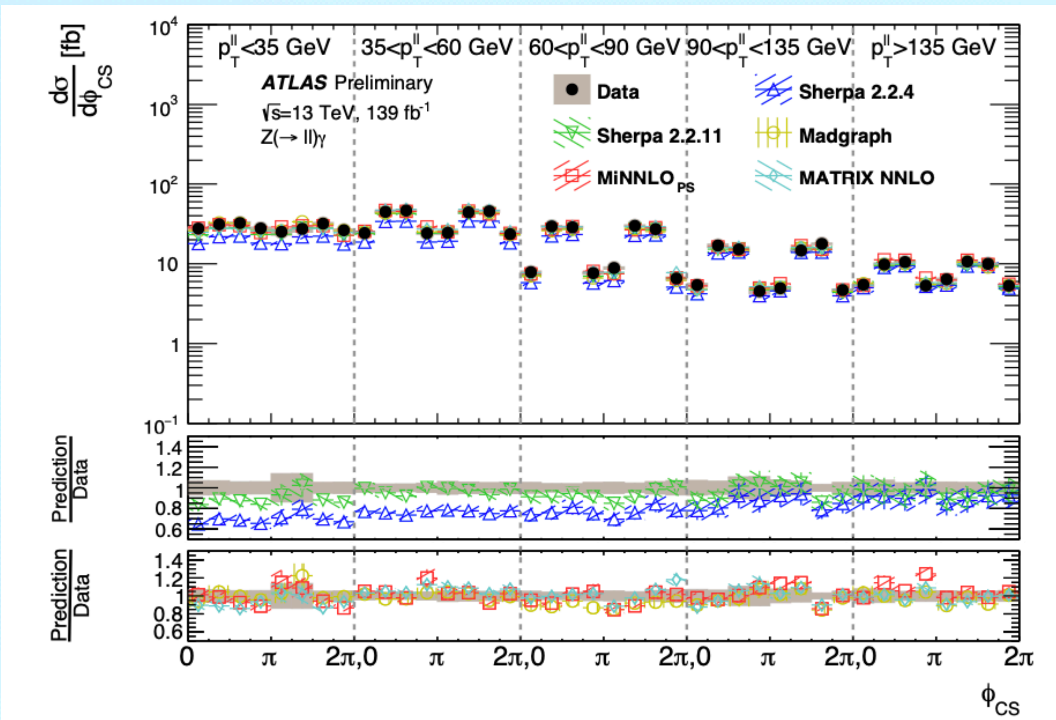
Unfolded results are compared with different theoretical predictions

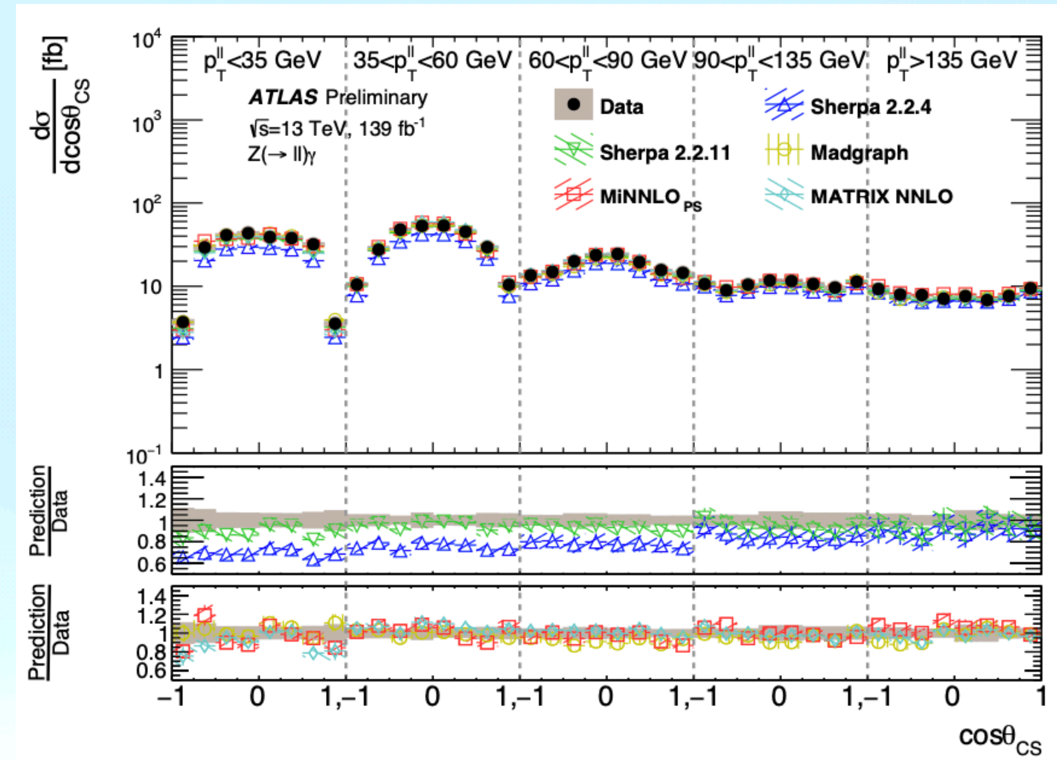
1. **Calculation of Sherpa 2.2.4, Sherpa 2.2.11 and Madgraph**
2. **NNLO prediction of MiNNLO$_{PS}$**
3. **NNLO Fixed-order calculation MATRIX**
4. **Consider the correction for born-to-particle and non-perturbative effects**

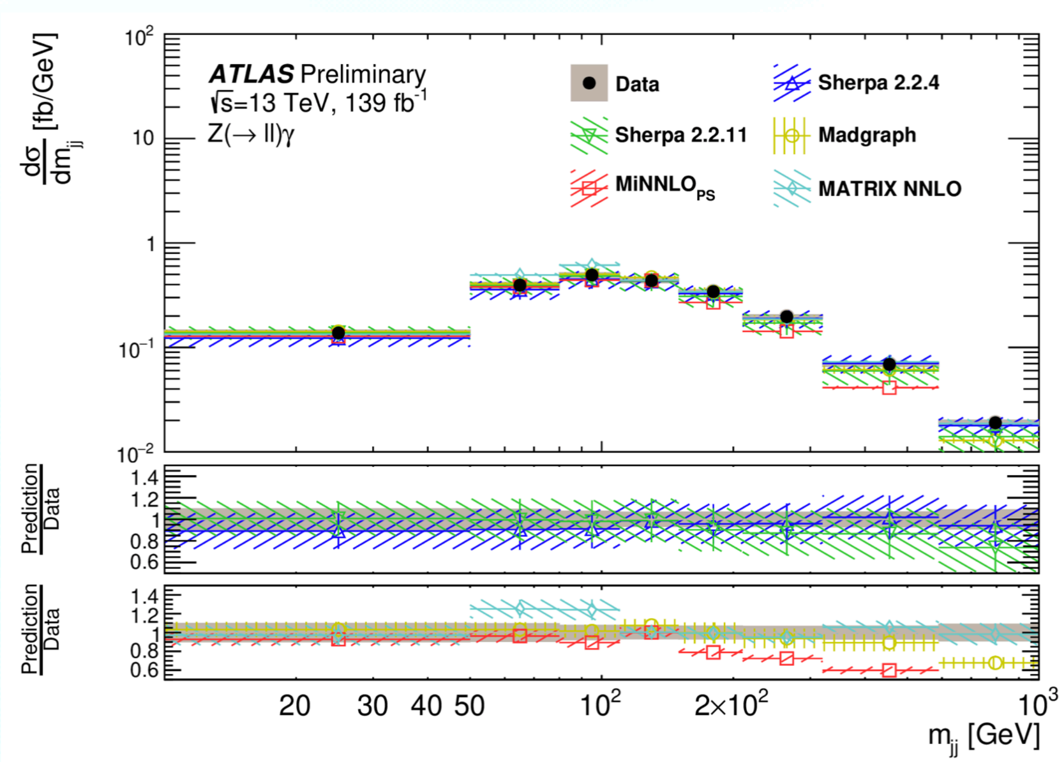
Good description of the data in wide range

ATLAS-CONF-2022-047

Differential cross-section measurements







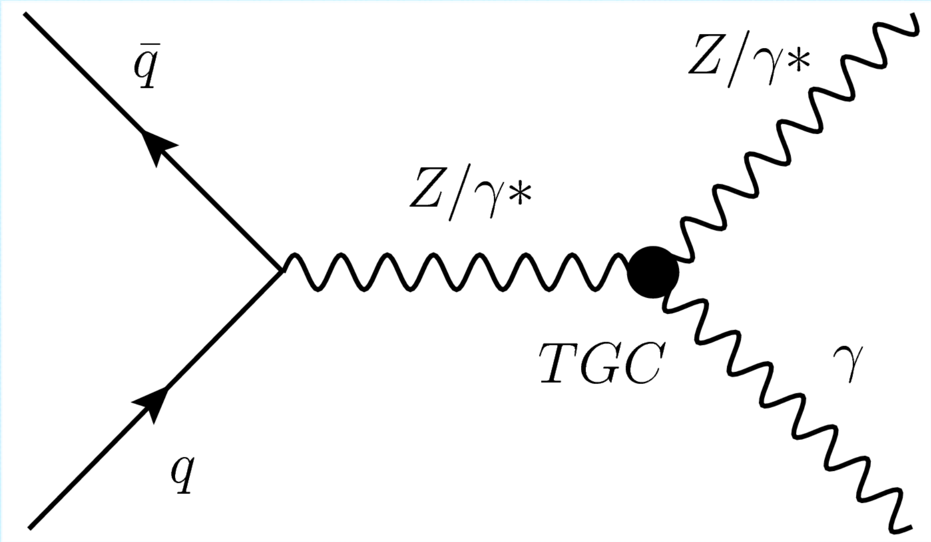
Differential cross-section results

- Both Sherpa and Madgraph can describe well the data
- Sherpa 2.2.11 has a better agreement in shapes than Sherpa 2.2.4

ATLAS-CONF-2022-047

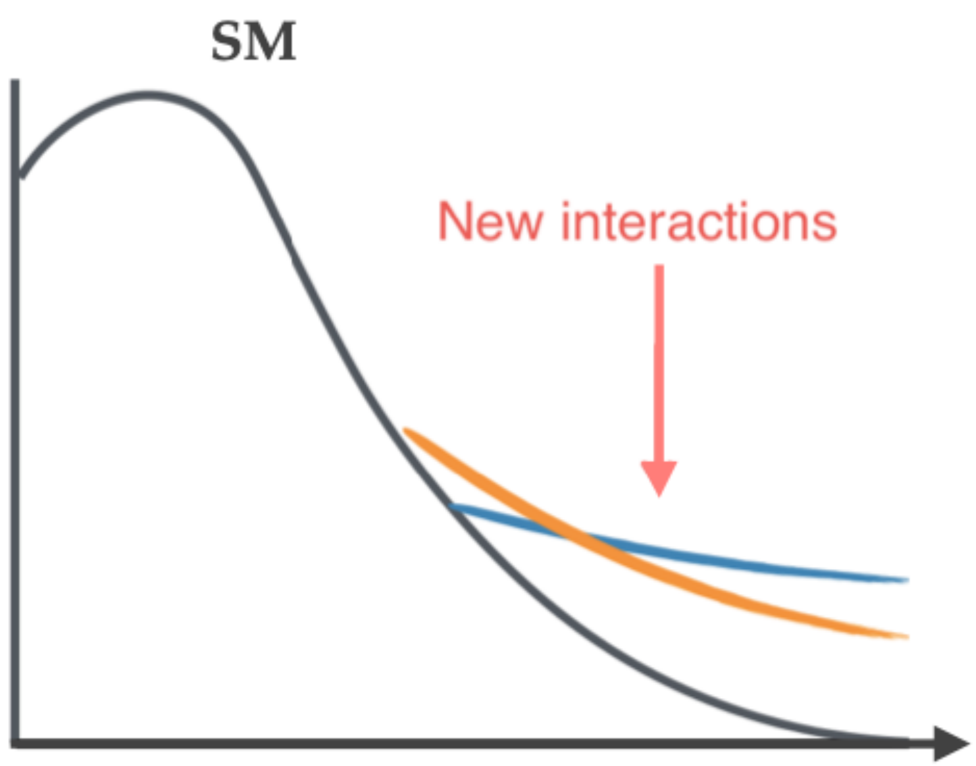
EFT interpretation — nTGCs

- Neutral Triple Gauge Couplings (nTGCs)
  - To understand electroweak symmetry mechanism
  - To provide a new window to search for BSM physics



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

- Anomalous couplings — increase of cross-section



Couplings	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 — nTGCs

arKiv:2206.1676

- Neutral Triple Gauge Couplings (nTGCs)
  - Forbidden in SM tree-level but could arise from high-order terms in the SMEFT
  - A new nTGC model proposed by Prof. John Ellis, Prof. Hongjian He, Dr. Ruiqing Xiao
  - Probing nTGC interactions via $pp \to Z\gamma$ production at the LHC, followed by $Z \to l^+l^-(l = e, \mu)$ decays

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
$\lvert h_4 \rvert$	1.4×10^{-5}	1.1×10^{-5}	5.2×10^{-6}	9.5×10^{-6}	7.5×10^{-6}	3.8×10^{-6}
$\lvert h_3^Z \rvert$	2.7×10^{-4}	2.1×10^{-4}	1.1×10^{-4}	1.9×10^{-4}	1.5×10^{-4}	8.0×10^{-5}
$\lvert h_3^\gamma \rvert$	3.2×10^{-4}	2.5×10^{-4}	1.3×10^{-4}	2.3×10^{-4}	1.8×10^{-4}	9.8×10^{-5}

Summary

- The FIRST ATLAS measurement of $Z\gamma$ production in association with jet activities with Full Run-2 datasets

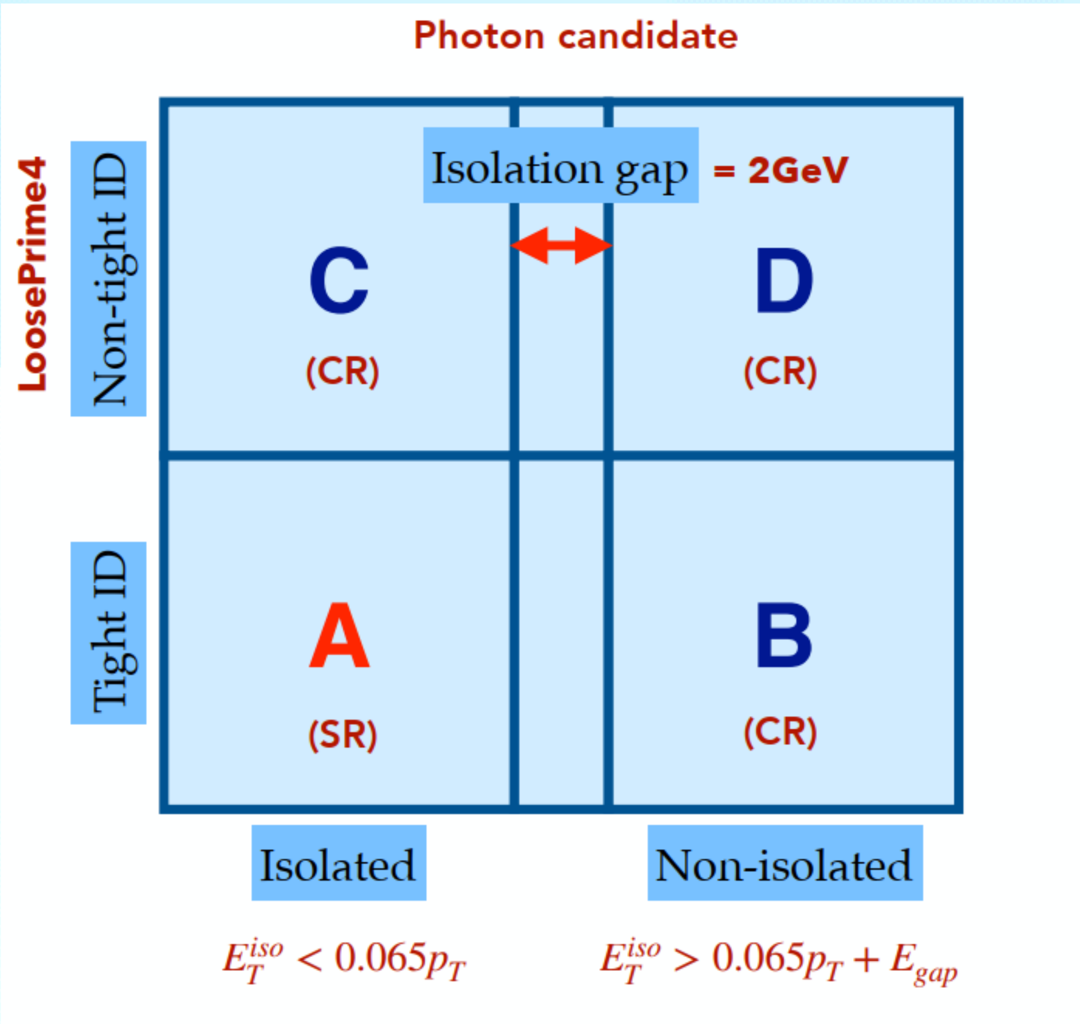
- Differential cross-sections for QCD-related variables in $Z\gamma$ productions are measured with good agreement
  - Good agreement observed between the measured data and the SM estimates
  - Good agreement observed between the measured data and the NNLO theory predictions

- nTGC EFT interpretations
  - With the increase of statistics, nTGC can be studied in $Z\gamma$ production with the charged lepton decays
  - PROMISING to give new experimental constrains with this nTGC EFT model

Backup

Background Estimation

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



- Correlation factor : $R = \dfrac{N_A^{Z+jets} \times N_D^{Z+jets}}{N_B^{Z+jets} \times N_C^{Z+jets}}$
  - $R = 1.30 \pm 0.04(stat) \pm 0.23(syst)$
- Signal leakage parameters :
  $c_B = \dfrac{N_B^{sig}}{N_A^{sig}},\ c_C = \dfrac{N_C^{sig}}{N_A^{sig}},\ c_D = \dfrac{N_D^{sig}}{N_A^{sig}}$
- 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 :
  $N^{Z+jets} = (N_A^{data} - N_A^{bkg}) \times \left(1 - \dfrac{N_A^{sig}}{N_A^{data} - N_A^{bkg}}\right)$ P
- 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

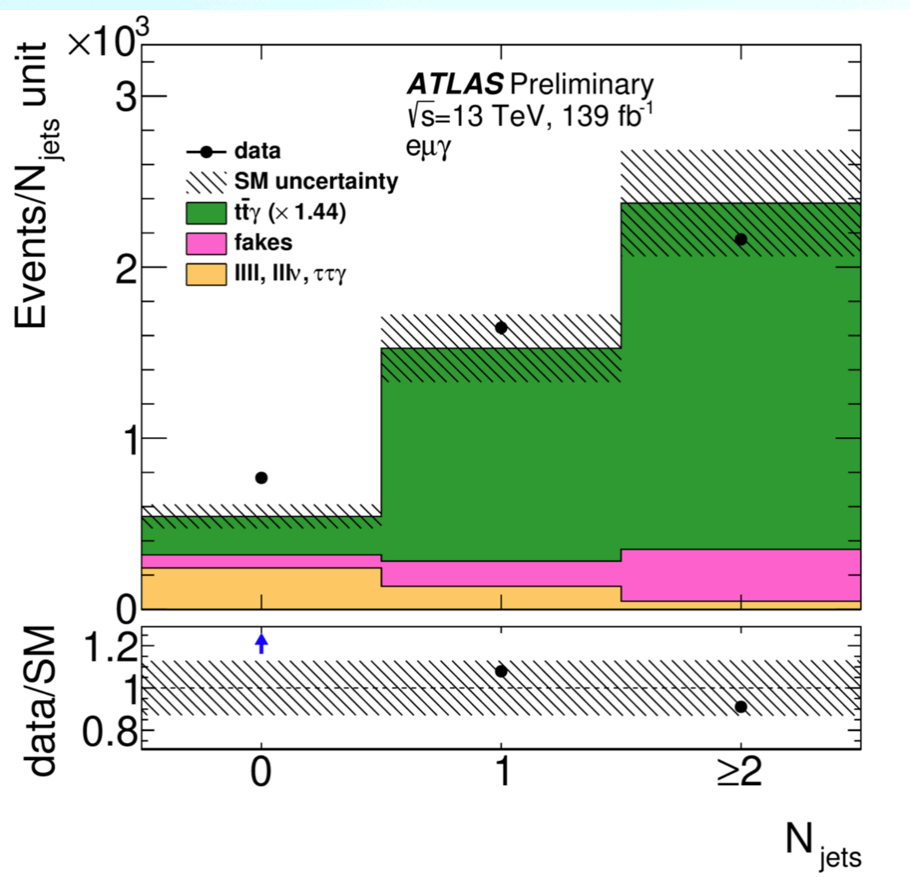
- Pileup background
  - Data-driven method
  - Pileup photons, the photons and the leptons are produced from the different pp collisions in the same bunch crossing
  - Pileup estimation is done through the **pileup fraction** in data : $N_{PU} = f_{PU} \, . \, N_{data}$

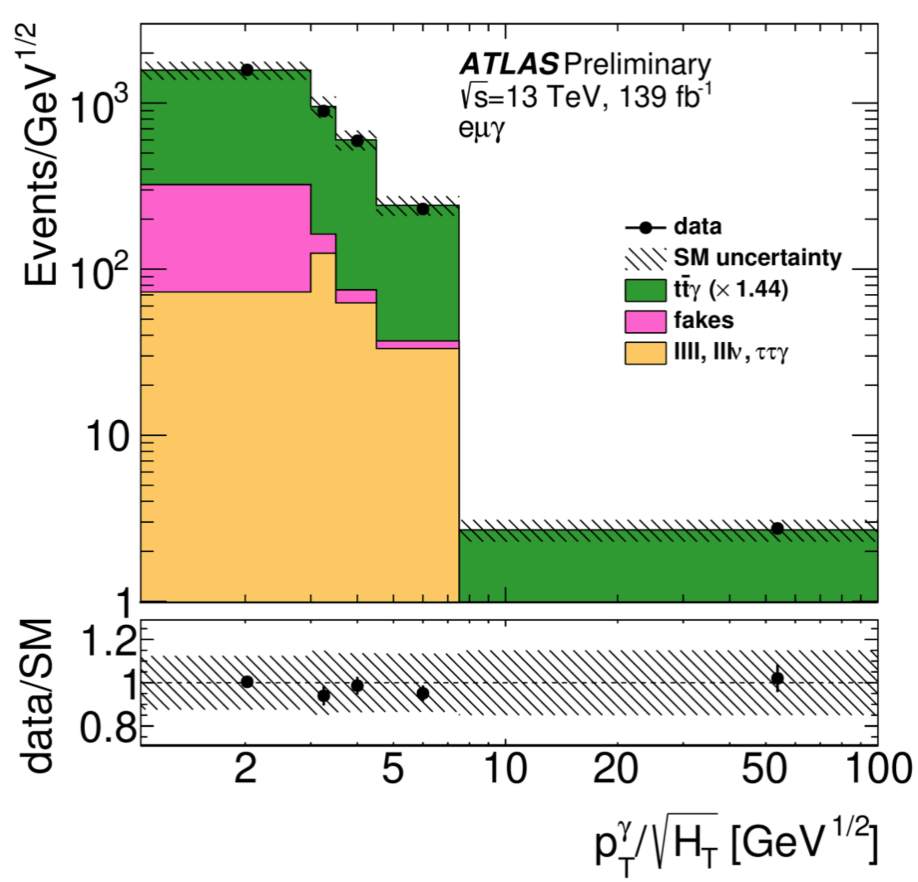
$$f_{PU} = \frac{1}{N_{data,pixel\ conv}} \cdot \frac{N_{data,pixel\ conv} - N^{|\Delta z|>50mm}_{Z\gamma MC,pixel\ conv}}{P(\Delta z > 50mm) = 0.32}$$

    - 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 modelling 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

Background Estimation

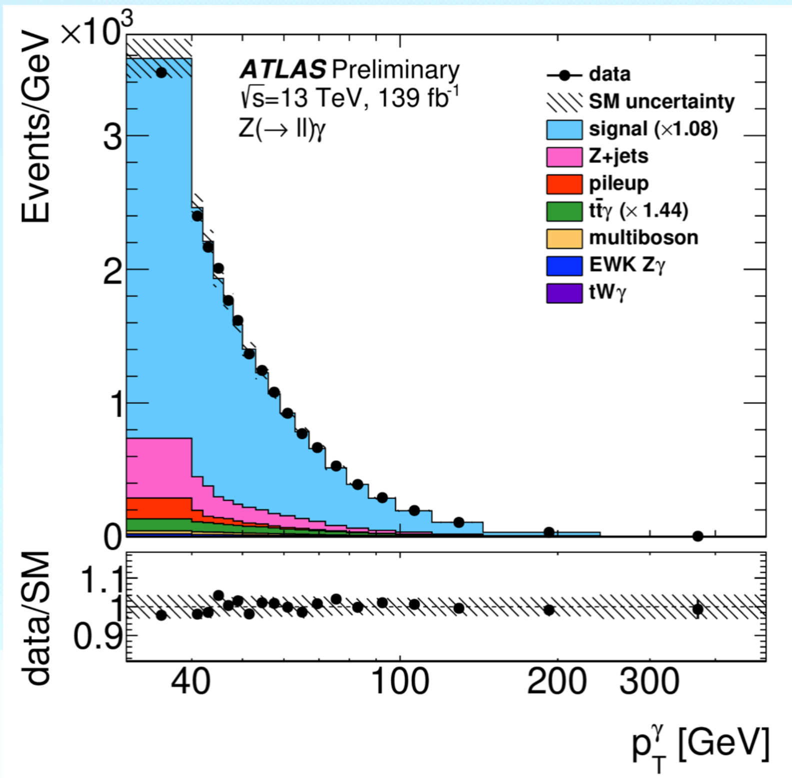
- Other minor backgrounds (tri-bosons and di-bosons) are estimated directly from MC
- Take $e\mu\gamma$ channel as a control region (receives no contribution from Z)
  - Scaled by a k-factor of 1.44 both in CR and SR
  - Dominated by $t\bar{t}\gamma$ contributions
  - Easy to check the modelling of $t\bar{t}\gamma$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

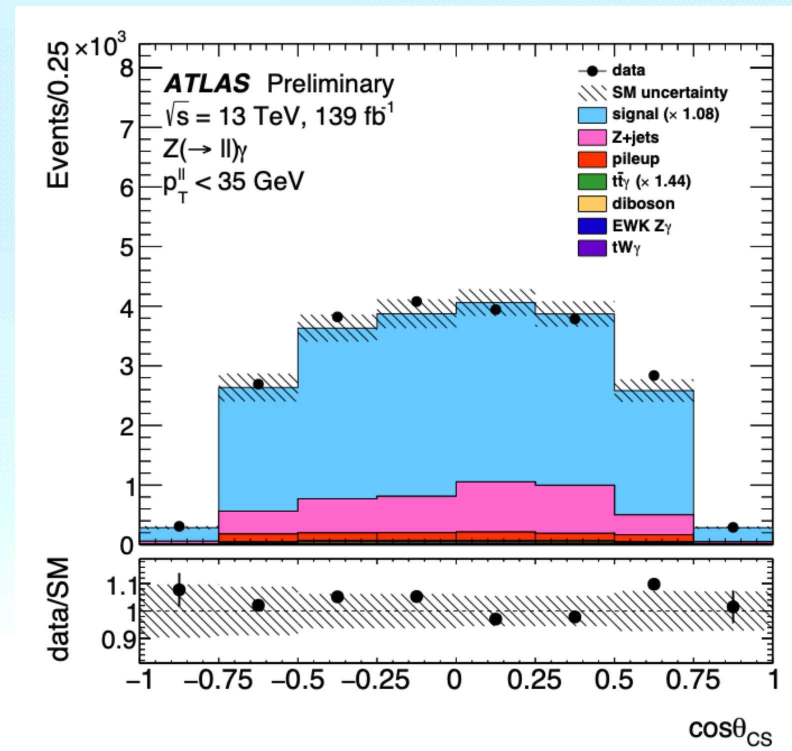


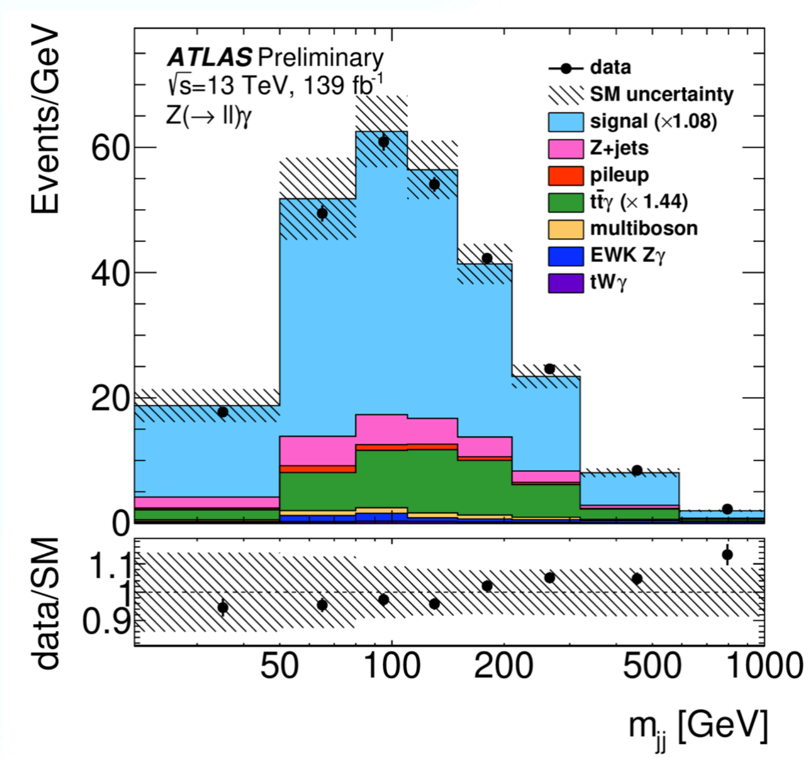


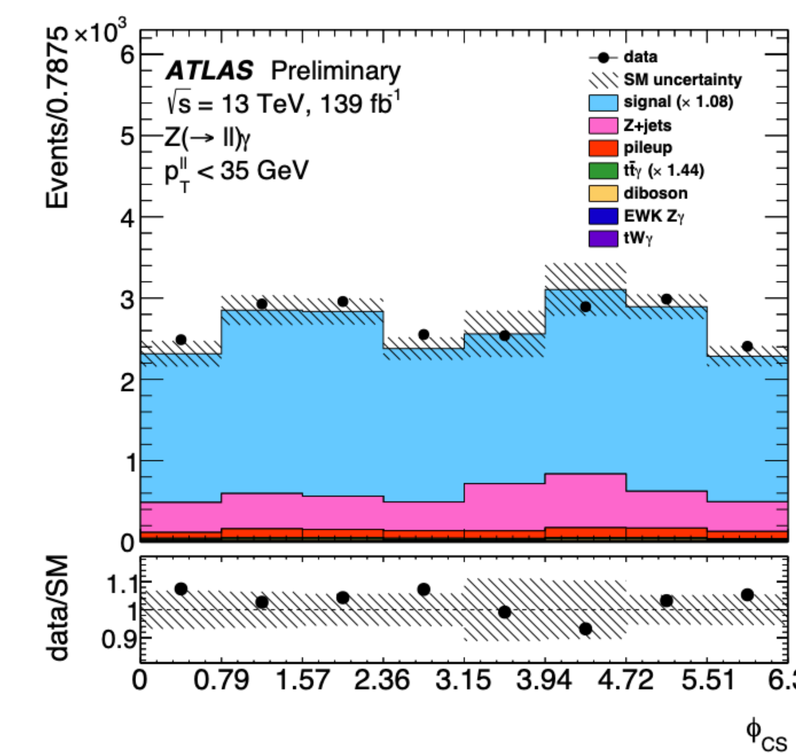
Data VS MC

- Data/MC comparison results — Good agreement observed !









EFT interpretation

JHEP 12 (2018) 010

- Previous results from $Z(\nu\nu)\gamma$
  - Partial Run-2 data : 36.1 fb^{-1}

Parameter	Limit 95% C.L.	
	Measured	Expected
h_3^γ	$(-3.7\times10^{-4}, 3.7\times10^{-4})$	$(-4.2\times10^{-4}, 4.3\times10^{-4})$
h_3^Z	$(-3.2\times10^{-4}, 3.3\times10^{-4})$	$(-3.8\times10^{-4}, 3.8\times10^{-4})$
h_4^γ	$(-4.4\times10^{-7}, 4.3\times10^{-7})$	$(-5.1\times10^{-7}, 5.0\times10^{-7})$
h_4^Z	$(-4.5\times10^{-7}, 4.4\times10^{-7})$	$(-5.3\times10^{-7}, 5.1\times10^{-7})$

- New nTGC search
  - Full Run-2 data : 139 fb^{-1}
  - A new momentum-dependent nTGC term with form factor has to be included, while not considered in previous nTGC analyses
  - Crucial and ensures the exact cancellation of the superficially large unphysical terms in the scattering amplitudes of $pp \to Z\gamma$ production

EFT interpretation

- Previous results from $Z(\nu\nu)\gamma$
  - Partial Run-2 data : 36.1 fb^{-1}

Parameter	Limit 95% C.L.	
	Measured	Expected
h_3^γ	$(-3.7\times10^{-4}, 3.7\times10^{-4})$	$(-4.2\times10^{-4}, 4.3\times10^{-4})$
h_3^Z	$(-3.2\times10^{-4}, 3.3\times10^{-4})$	$(-3.8\times10^{-4}, 3.8\times10^{-4})$
h_4^γ	$(-4.4\times10^{-7}, 4.3\times10^{-7})$	$(-5.1\times10^{-7}, 5.0\times10^{-7})$
h_4^Z	$(-4.5\times10^{-7}, 4.4\times10^{-7})$	$(-5.3\times10^{-7}, 5.1\times10^{-7})$

- New nTGC search
  - Full Run-2 data : 139 fb^{-1}

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
$\|h_4\|$	1.4×10^{-5}	1.1×10^{-6}	5.2×10^{-6}	9.5×10^{-6}	7.5×10^{-6}	3.8×10^{-6}
$\|h_3^Z\|$	2.7×10^{-4}	2.1×10^{-4}	1.1×10^{-4}	1.9×10^{-4}	1.5×10^{-4}	8.0×10^{-5}
$\|h_3^\gamma\|$	3.2×10^{-4}	2.5×10^{-4}	1.3×10^{-4}	2.3×10^{-4}	1.8×10^{-4}	9.8×10^{-5}