Precise measurement of Z+photon final states and search for nTGCs with EFT at ATLAS

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In collaboration with IHEP

- Outline
  - Physics motivation
  - Status of Zgamma measurements
  - EFT interpretation — nTGCs
  - Summary

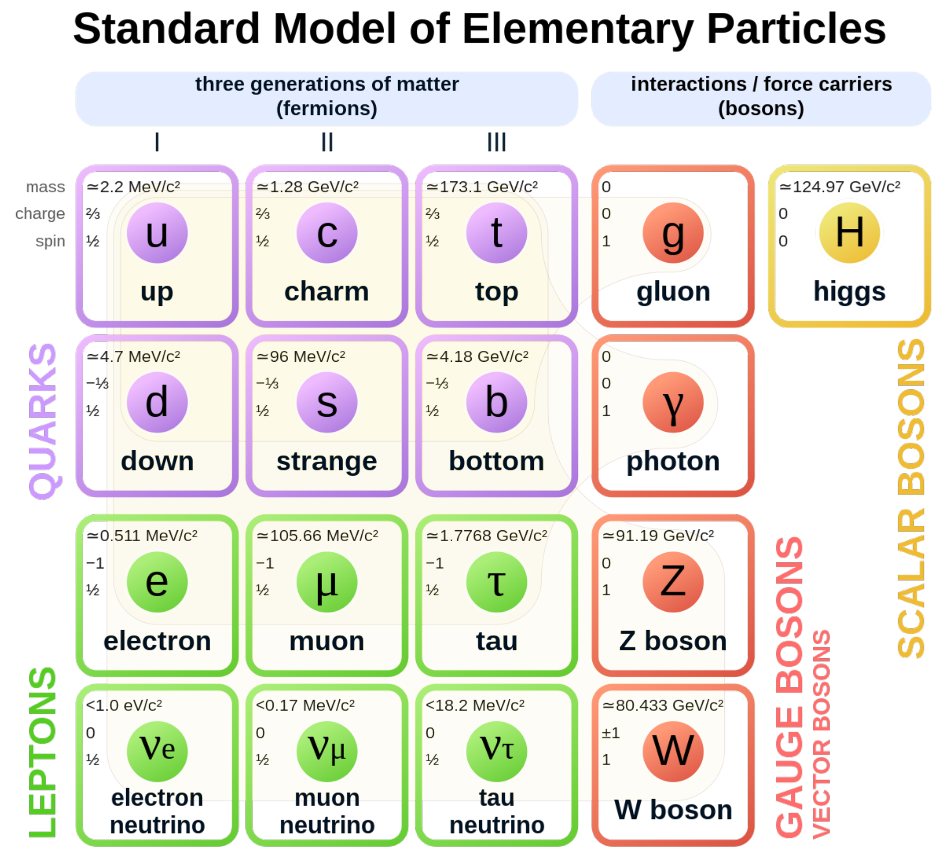
Introduction — the Standard Model

- The Standard Model (SM) 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 experiments

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

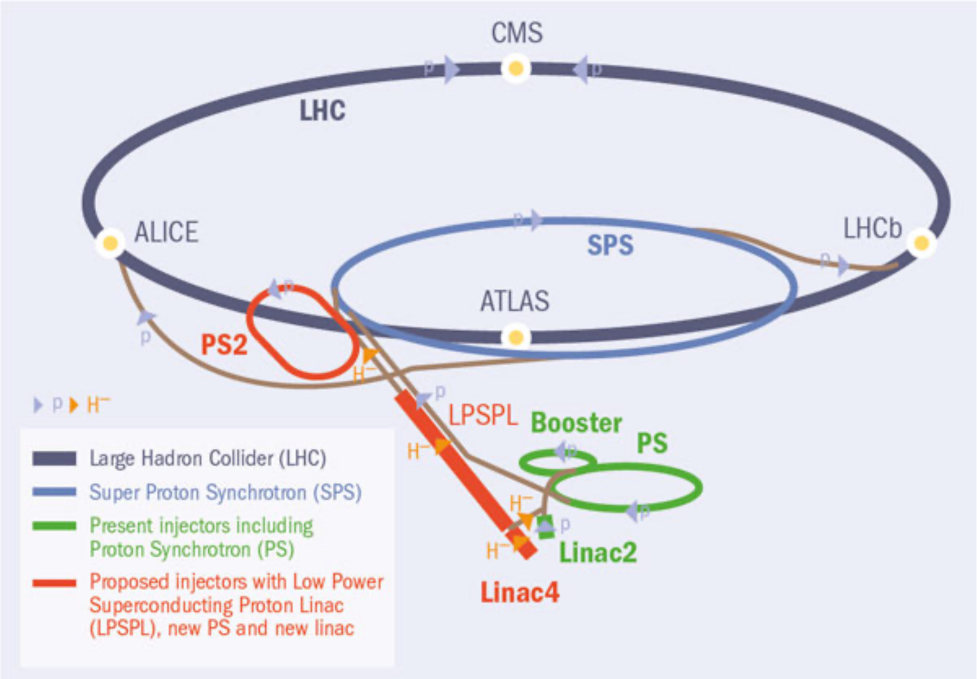
Force carrier particles :
- Bosons (gluons, photons and $W^{\pm}, Z$
- Carriers of fundamental forces (strong, weak and magnetic force)

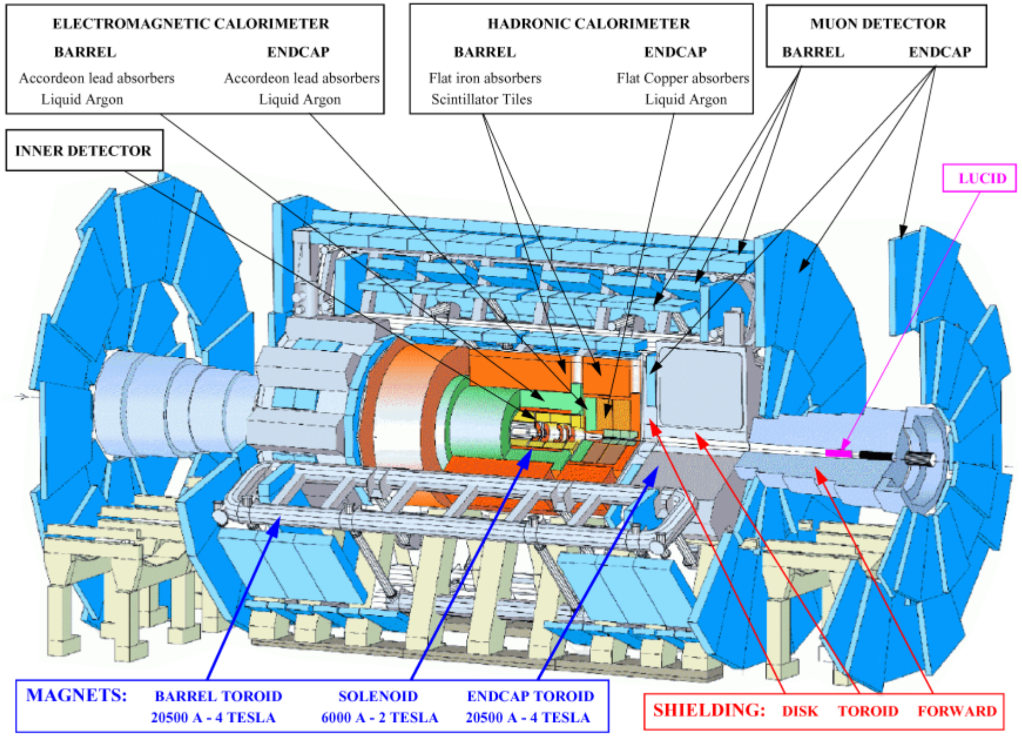
Higgs Boson :
- An essential component of the SM
- Contributes to the understanding of the origin of mass of particles



Introduction — ATLAS Experiment

- The Large Hadron Collider (LHC)
  - The largest and most powerful particle accelerator in the world
- ATLAS Detector
  - General-purpose particle physics experiment at the Large Hadron Collider at CERN
  - The largest detector ever constructed

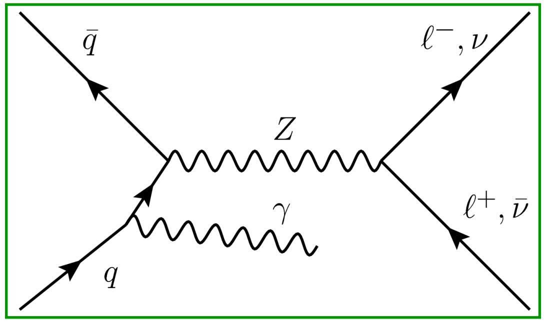




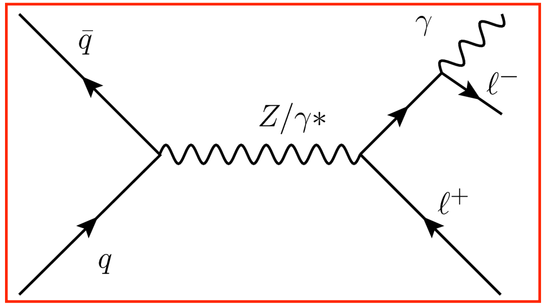
Physics motivation

- Importance of $Z + \gamma$ measurements
  - To test the electroweak sector of the Standard Model with high accuracy using multi-boson production cross-section measurements
  - To probe $SU(2)_L \times U(1)_Y$ gauge symmetry of the electroweak theory that determines the structure of self-couplings of the vector boson
  - To search for signs of new physics using anomalous triple gauge-boson couplings (aTGC) studies
  - SM multi-boson production is a background for Higgs and exotic searches, precise measurements can help to tune MC
- Motivations on $Z\gamma$ + jets analysis :
  - Large data statistics with small background — High accuracy
  - Differential distributions can be used to :
    - Constrain parameters of the SM Lagrangian
    - Test of Parton density function, Parton shower predictions and fixed-order QCD calculations
  - Possibility of Z boson polarization measurement

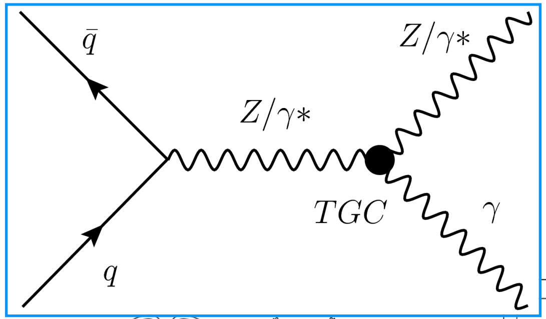
$Z\gamma$ production via ISR process



$Z\gamma$ production via FSR process



$Z\gamma$ production via TGC process



Measured Observables

- In this $Z\gamma$ + jets differential measurements, 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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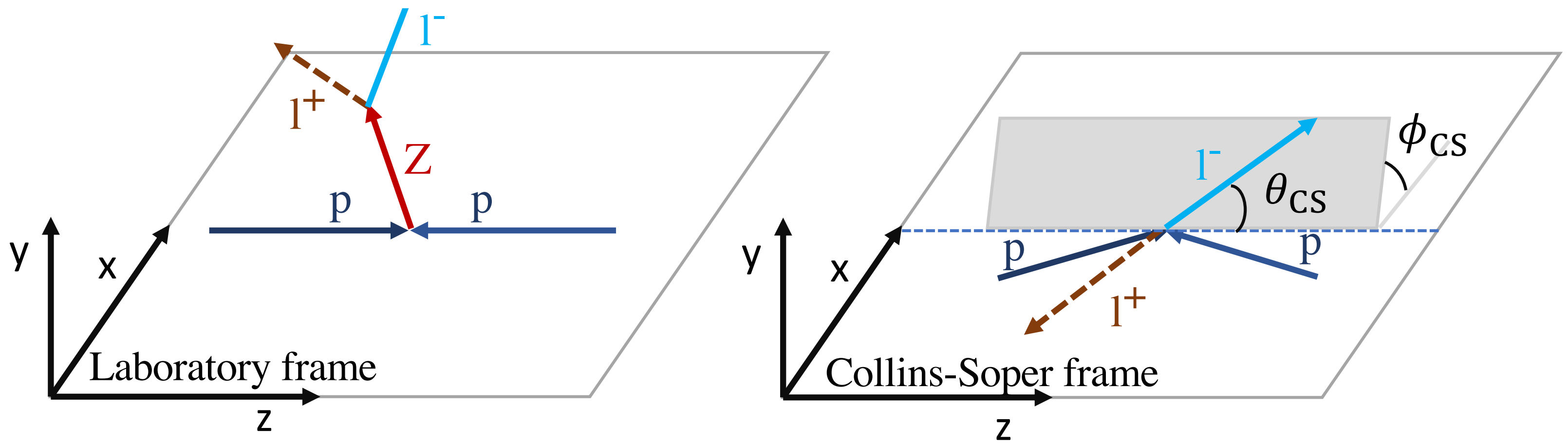
Polarization Variables

- 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 photon-induced Drell-Yan process
  - 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
  - $cos\theta_{CS}, \phi_{CS}$

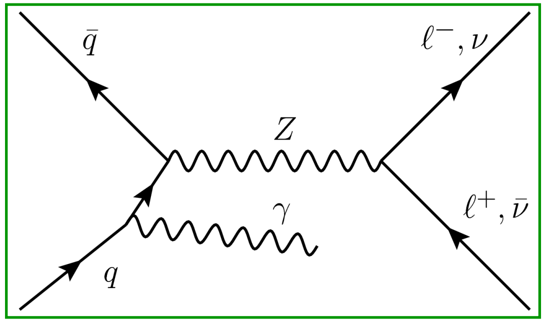


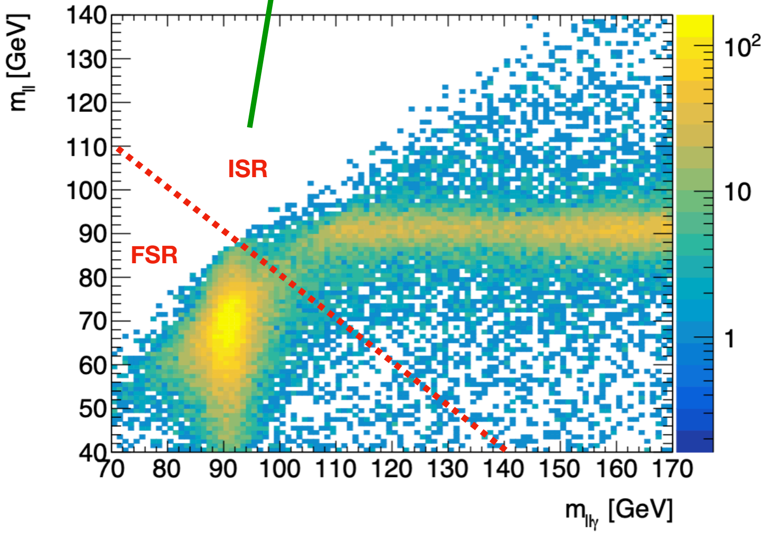
Signatures of $Z\gamma$ production

[ATLAS-CONF-2022-047]

Event Selections

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



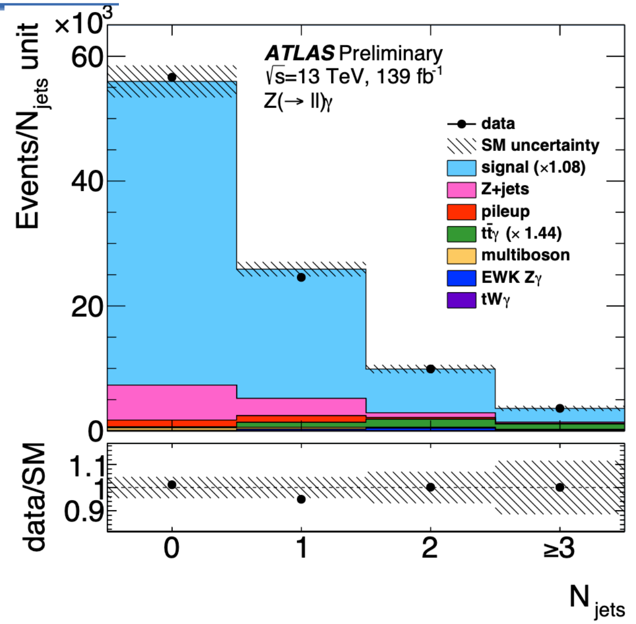


- Signatures of $Z\gamma$ production
  - Single lepton triggers are applied
  - 2 signal leptons + at least 1 signal photons
  - Only consider Z bosons decay into charged lepton channels (e, μ)
- Phase space defined with ISR photons enriched
  - $m_{ll} > 40GeV$ is required to avoid low-mass resonance
  - ISR events are chosen by requiring $m_{ll} + m_{ll\gamma} > 182GeV$
- Control regions in $e\mu$ channel is defined to check the modeling of $t\bar{t}\gamma$

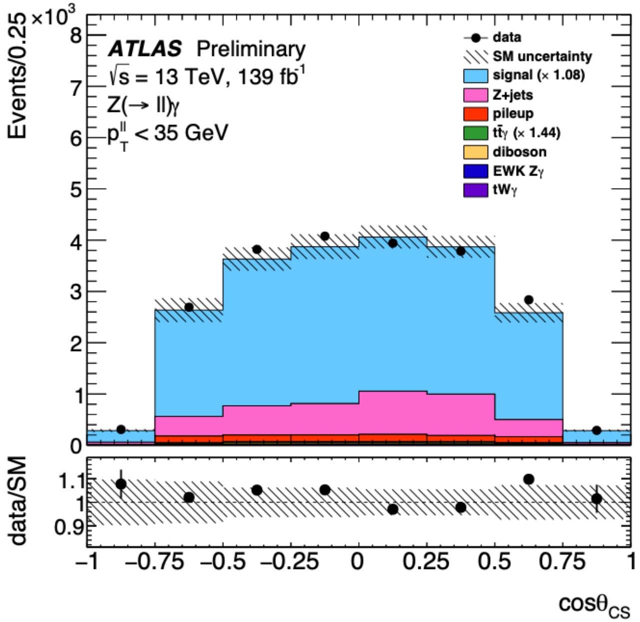
$Z(ll)\gamma$ + jets measurement @ 13 TeV

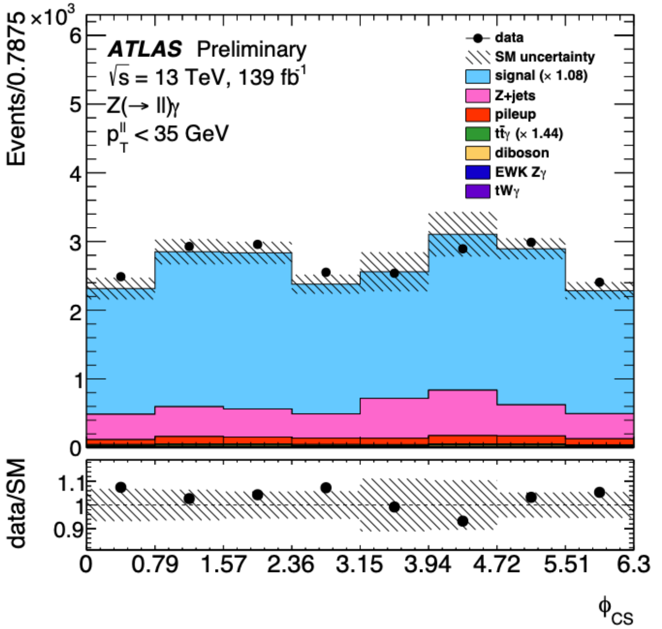
ATLAS-CONF-2022-047

- In this $Z\gamma$ + jets measurement :
  - Differential cross-sections of QCD-related observables associated with the $Z\gamma$ process is studied
- Data/MC comparison results in SR
  - A general good agreement is observed between the data and the SM estimates
  - Observables inclusive in the number of jets are well modeled
  - Total experimental are ~ 3% of the total predictions



Source	ee + $\mu\mu$	
$Z\gamma$+jets 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	





$Z(ll)\gamma$ + jets measurement @ 13 TeV

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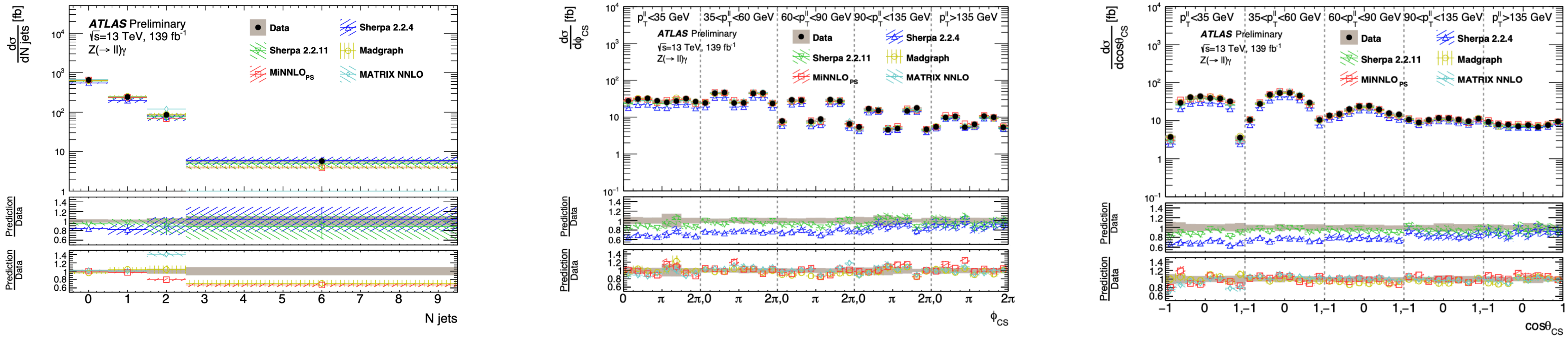
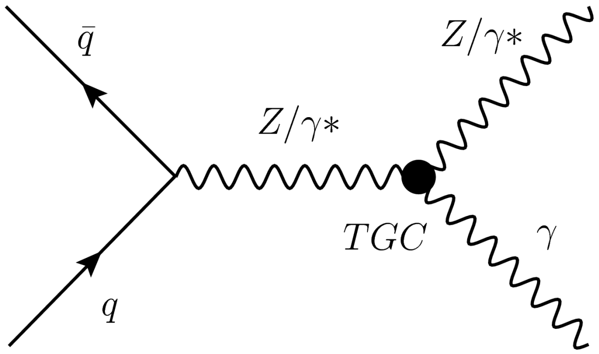
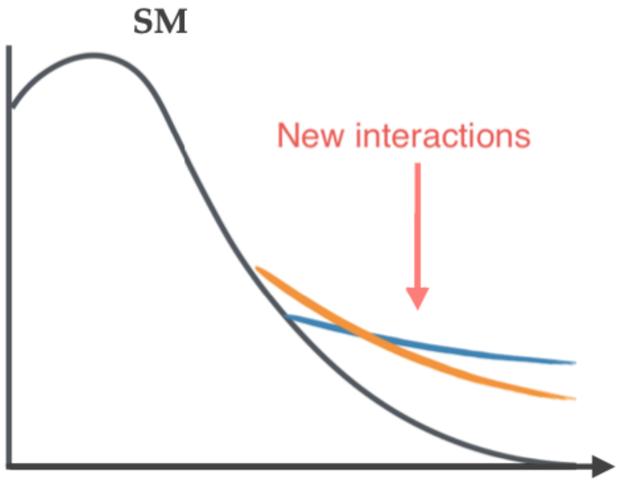
- Differential cross-sections are measured as functions of the observables
  - Performed in a fiducial phase-space enhanced with ISR photons
  - High statistics, high precision results for additional QCD radiations
  - Compared to state-of-the art (N)LO multi-jet-merged and NNLO predictions
    - Good description of data in wide range, sherpa2.2.11 has a general better agreement also in shape, especially for N_{jets}
- First measurement of the $Z\gamma$ production in association with jets and can be used to constrain QCD predictions and improve resumption calculations



- 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
  - 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 is any anomalous couplings
  - Increase of total cross-sections
  - Increase of differential cross-sections at high transverse momentum and high mass region

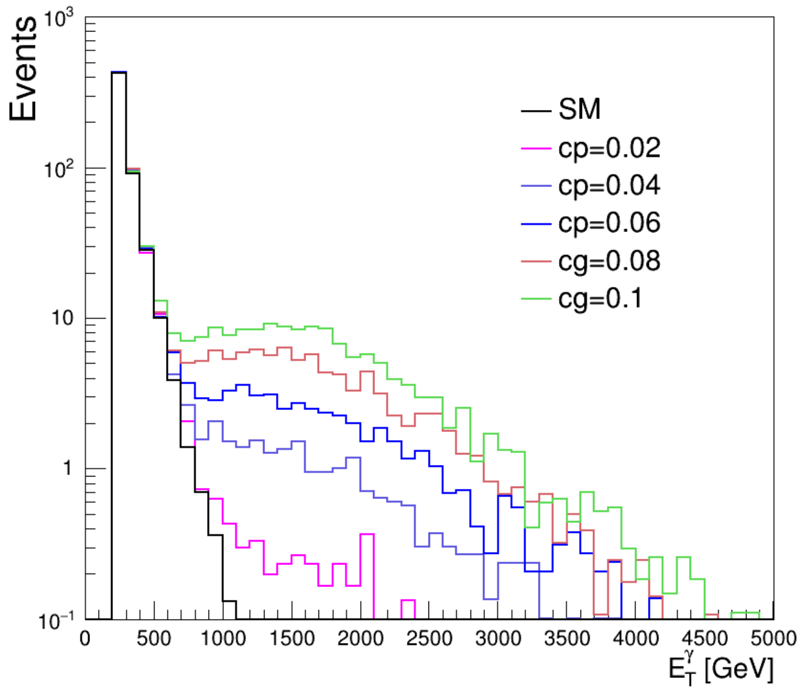


coupling	parameters	channel
$ZZ\gamma$	h_3^Z, h_4^Z	$Z\gamma$
$Z\gamma\gamma$	h_3^γ, h_4^γ	$Z\gamma$



EFT interpretation — Neutral Triple Gauge Couplings

- Recent nTGC theory updates :
  - 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 $Z \to l^+l^-$ (charge lepton) decays



- Improvement in this recent nTGC theory result :
  - A new momentum-dependent nTGC term with form-factor has to be included, while this is NOT included in previous nTGC studies
  - Crucial and ensures the exact cancellation of the superficially large unphysical terms in the scattering amplitudes of $q\bar{q} \to Z\gamma$ production
  - Might be helpful to give both new experimental and theoretical exclusion limits for parameters which are sensitive in $Z\gamma$ production

EFT interpretation — Neutral Triple Gauge Couplings

- nTGC searches has been studied in $Z(\nu\bar{\nu})\gamma$ channel with Run-2 datasets of 36.1 fb^{-1}
  - Experimental exclusion results are give as below :

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	$(-4.5\times10^{-7}, 4.4\times10^{-7})$	$(-5.3\times10^{-7}, 5.1\times10^{-7})$

$pp \rightarrow Z\gamma$ ($Z \rightarrow \nu\bar{\nu}$ decays)

36.1 fb^{-1} datasets @ 13TeV

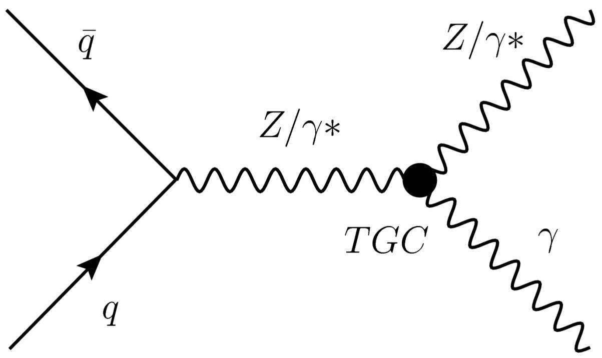
- nTGC theoretical exclusion results : from arXiv:2206.11676v2
  - Expected limits are much tighter than previous nTGC analyses, EXPECTING !

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}	$\times8.9\times10^{-5}$	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

EFT interpretation — Neutral Triple Gauge Couplings

- Work Plan — Neutral Triple Gauge Couplings
  - Proposed work strategy
    - Use Full Run-2 dataset in ATLAS Release 21
    - Inherit as much as possible from the recent $Z\gamma$ + jets analysis
      - Quick start on the new analysis optimizations
      - Avoid duplicated works
  - Development for EFT interpretation
    - Establish the cooperation between theoretical and experimental sides
    - Establish the cooperation between SJTU/TDLI and IHEP for EFT study in $Z\gamma$ production with charged lepton decays
    - Use new nTGC EFT model (proposed by Prof. John Ellis, Prof. Hongjian He and Dr. Ruiqing Xiao) to give experimental constrains for SMEFT dim-8 operators
    - Study polarization variables and angular distributions in BSM models (nTGC EFT model)



Summary

- Precise measurements for $Z\gamma$ productions have been performed with full Run-2 datasets

- Differential cross-sections for QCD-related variables in $Z\gamma$ production are FIRST measured in ATLAS and can be used to constrain QCD predictions
  - Good agreement observed between the measured data and the SM estimates, as well as the NNLO theory predictions

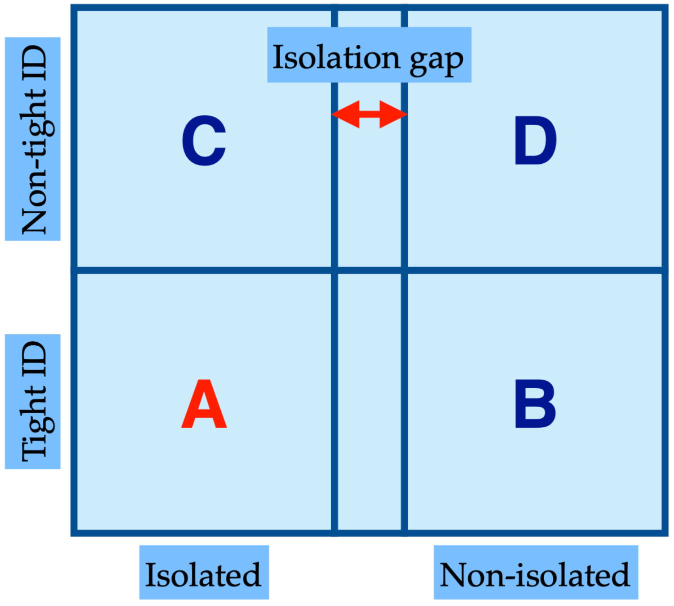
- nTGC EFT interpretations
  - With the increase of statistics, nTGC can be studied in $Z\gamma$ production with charged lepton decays and is very promising to give new experimental constraints with this nTGC EFT model

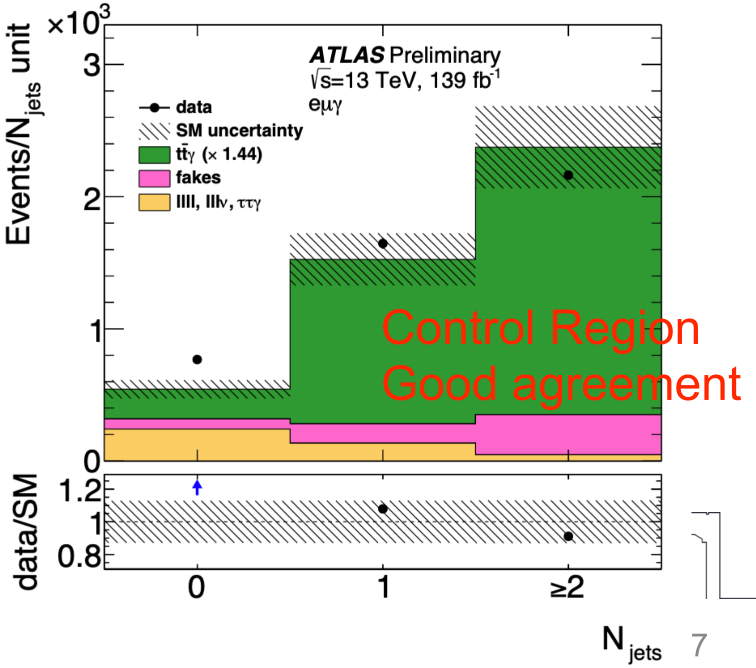
Thank You !

Backup

Background Estimation

- Two main backgrounds
  - Z+jets background — 2D sideband method
    - One of the jets is misidentified as a photon
    - Total uncertainties come from isolation, identification and statistical and so on
  - Pileup background — data-driven method
    - Photon come from a vertex different from leptons
- Other backgrounds
  - $t\bar{t}\gamma$ background — control region
    - Check the modeling of $t\bar{t}\gamma$ background sample
    - Check the fake photon estimation
    - Small distribution in SR, negligible
  - multiboson, $tW\gamma$
    - Minor backgrounds are estimated directly from MC samples





Systematics

- Sources of systematics
  - Experimental systematics
    - Detector reconstruction, calibration and the modeling of the reconstruction
    - Luminosity, jet, electron, muon and photon
  - Theoretical systematics
    - Scale and PDF (variations of renormalization and factorization , PDF set)
  - Unfolding systematics
    - Statistical uncertainty is propagated using pseudo-data (toys)
  - Background systematics
    - Both from simulated samples and data-driven methods
- 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