Precise Measurement of Z+γ final states and search for nTGCs with EFT at ATLAS

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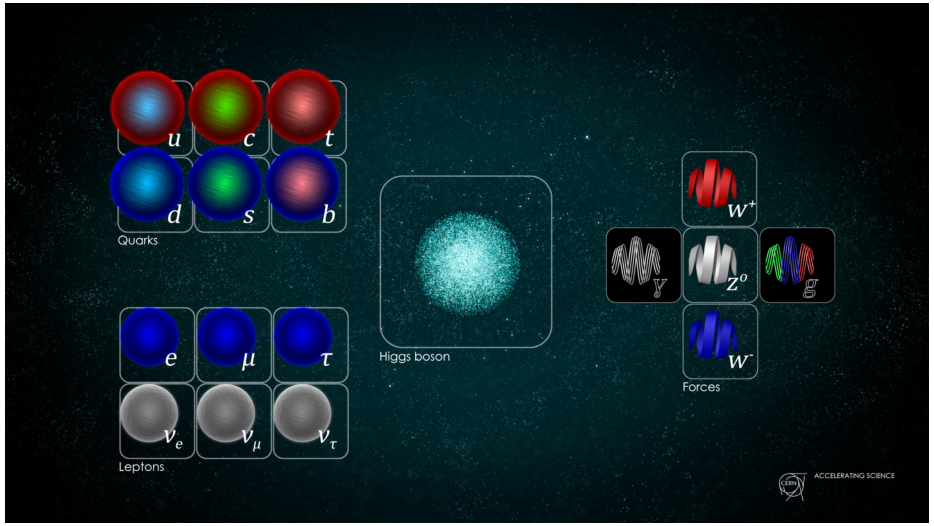
The Standard Model

- Particles of the Standard Model of particle physics



- 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 physics theory

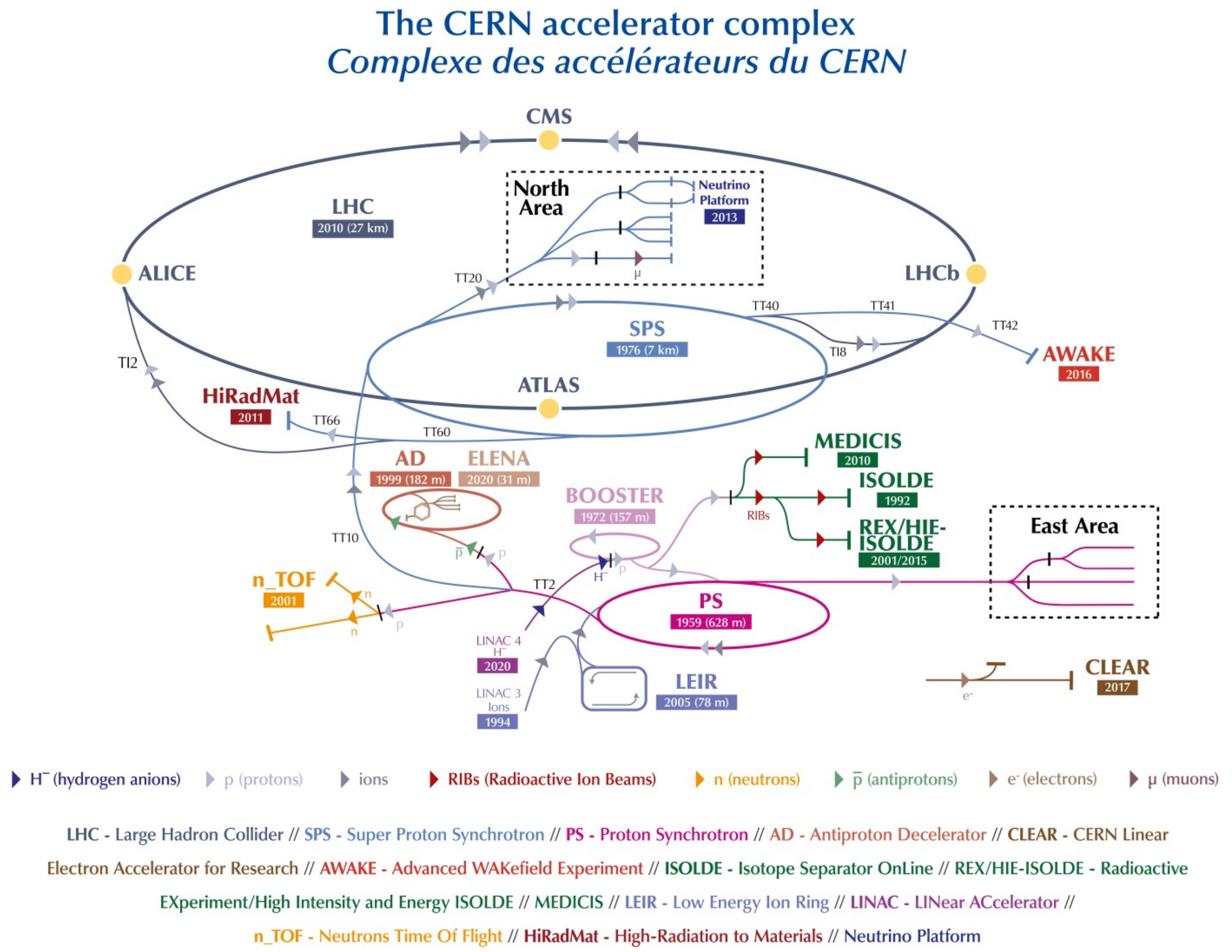
Matter particles :
- Quarks and leptons
- 3 generations and in pairs
- Basic constituent of matter

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

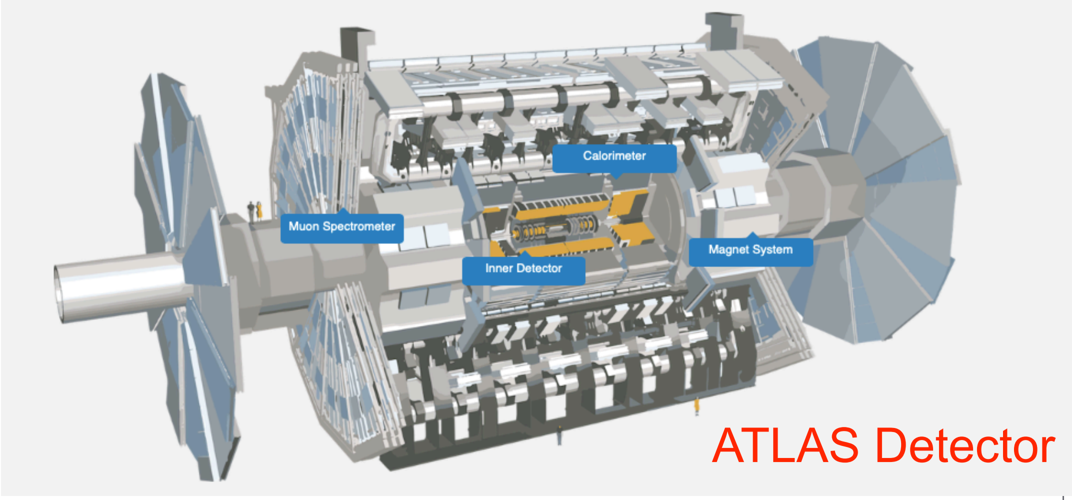
Higgs Boson :
- An essential component of the SM
- Contributes to the understanding of the origin of mass of particles

ATLAS Experiment

- The Large Hadron Collider
  - 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



Importance of $V\gamma$ measurements

- Measurement of Z boson production in association with a photon in proton-proton collisions is studied at $\sqrt{s}$ = 8 and 13 TeV
  - To test the electroweak sector of the Standard Model with high accuracy using multi-boson production cross section measurements
  - To probe the $SU(2)_L \times U(1)_Y$ 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 Precision $V\gamma$ measurement help to tune MC
- Covering the following signatures
  - Measurement of $Z\gamma$ and $Z\gamma\gamma$ @ 8TeV : Phys.Rev.D 93 (2016) 112002
  - Measurement of $Z\gamma$ @ 13 TeV : JHEP 04 (2020) 054
  - **Measurement of $Z\gamma$ + jets @ 13 TeV** : ATLAS-CONF-2022-047

$Z\gamma$ analysis retrospective

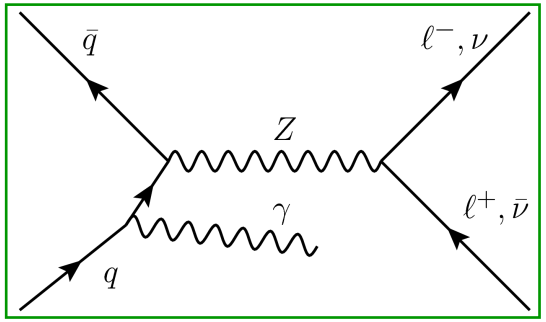
- The Standard Model cross sections for $Z\gamma$ production in ATLAS were measured with high accuracy with 8 TeV data (20.3 fb^{-1})

- Proton-proton collisions at 13 TeV with 139 fb^{-1} **allowed to improve measurements**

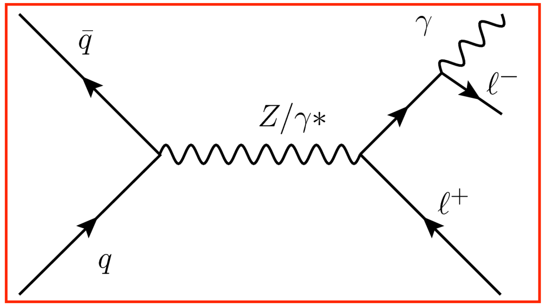
- All measurements have good agreement between the data and the SM estimates, as well as NNLO theory predictions
  - Agreements approved with increase of collision energy and integrated luminosity

- Limits for neutral couplings in ATLAS are also set
  - New nTGC analysis will start with full Run-2 datasets in $Z\gamma$ production

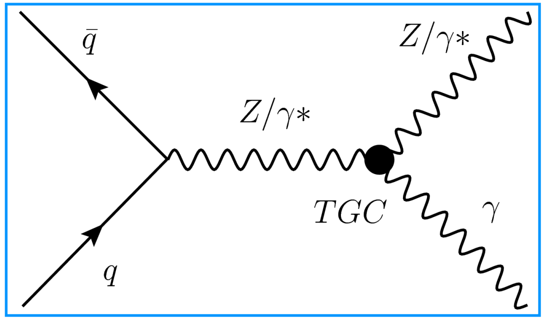
$Z\gamma$ production via ISR process



$Z\gamma$ production via FSR process



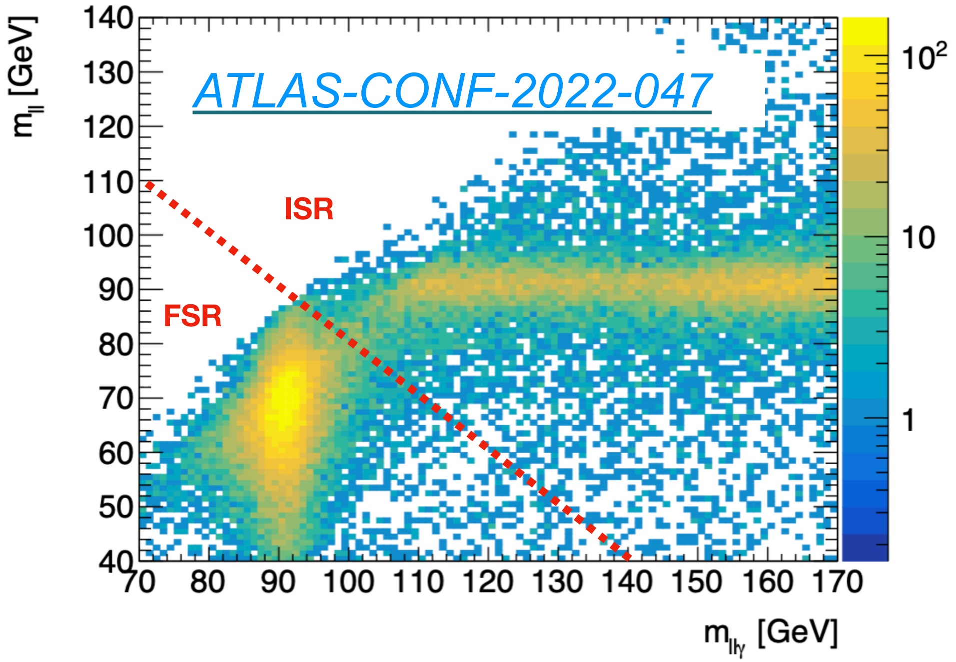
$Z\gamma$ production via TGC process



Selections for $Z\gamma$ analysis

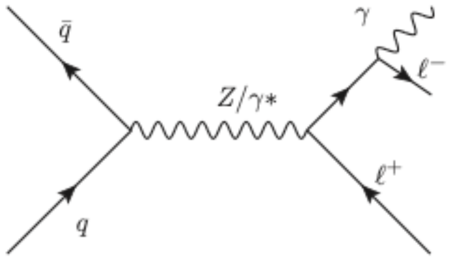
- Due to that the possibility to fully reconstruct the final state, only Z bosons decay into pairs of electrons or muons are considered : $Z\gamma \to l^+l^-\gamma$
  - Two opposite sign, same flavor leptons are chosen
  - At least 1 photons
  - Use invariant mass of di-lepton pair and 3-body system (di-lepton + photon) to identify ISR or FSR usually

- Measurements are performed within a defined phase-space
  - Different processes, different variables are measured in $Z\gamma$ analyses
  - Compare with theory predictions at NNLO



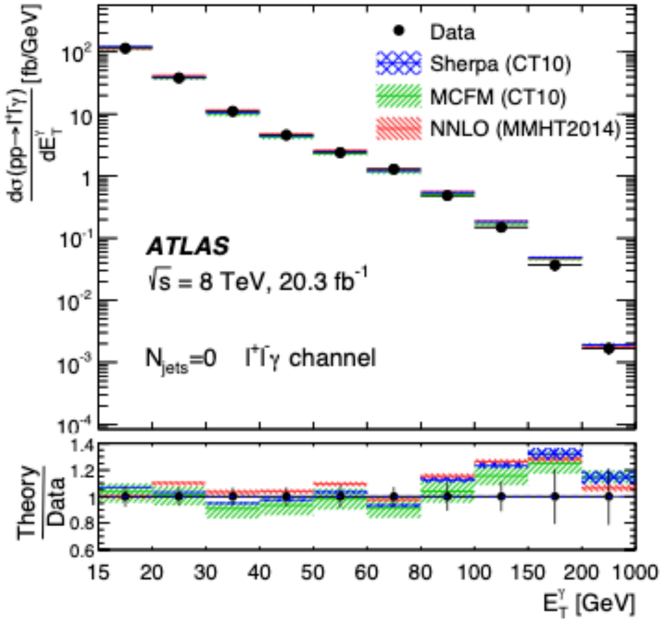
$Z(ll)\gamma$ measurement @ 8 TeV

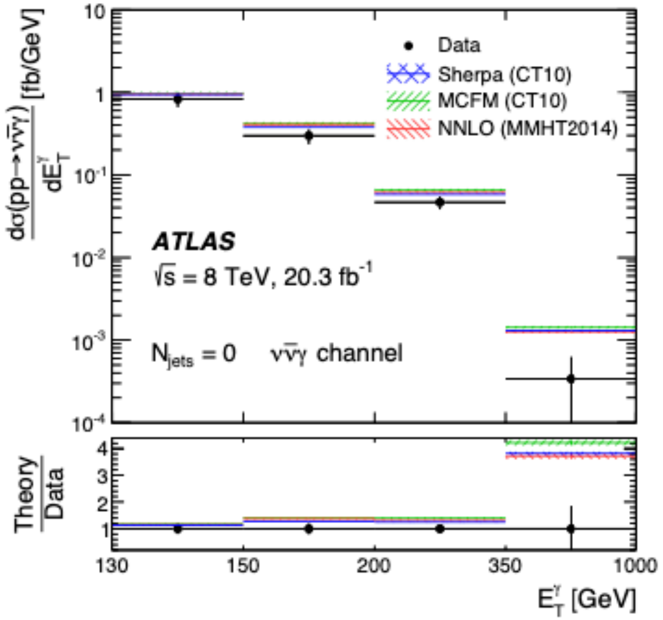
Phys.Rev.D 93 (2016) 112002



- This analysis use a data sample with an integrated luminosity of 20.3 fb^{-1}
  - $Z \to l^+l^-$ (where $l = e, \mu$) and $Z \to \nu\bar{\nu}$ decay channel are considered
  - Compare to SM predictions
    - Obtained with a Parton-shower MC simulation
    - Obtained with two higher-order perturbative Parton-level calculations at NLO and NNLO
- FIRST time to finish the comparison between experimental measurements and NNLO predictions

- Differential cross-sections measurements are performed and compared between theory and experiment
  - Good agreement between the measured and the SM estimates for E_T^γ distribution

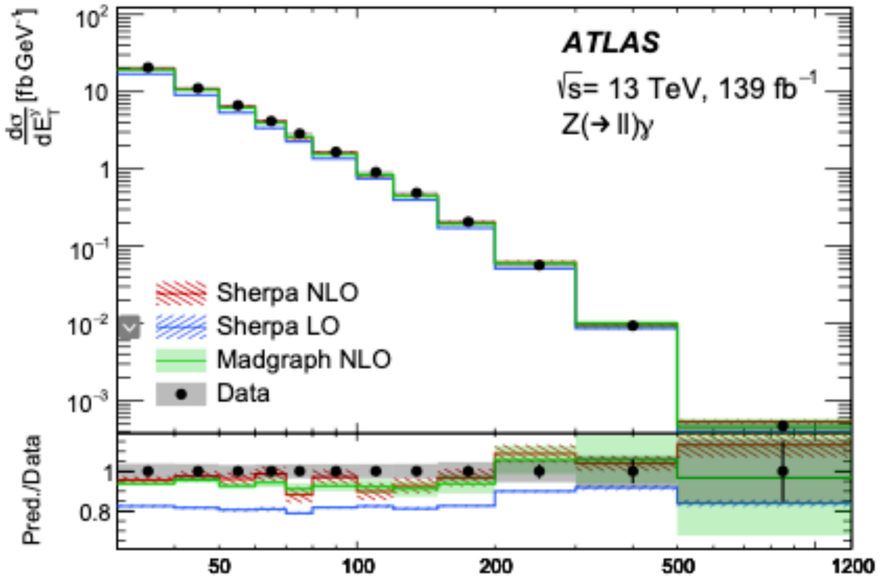


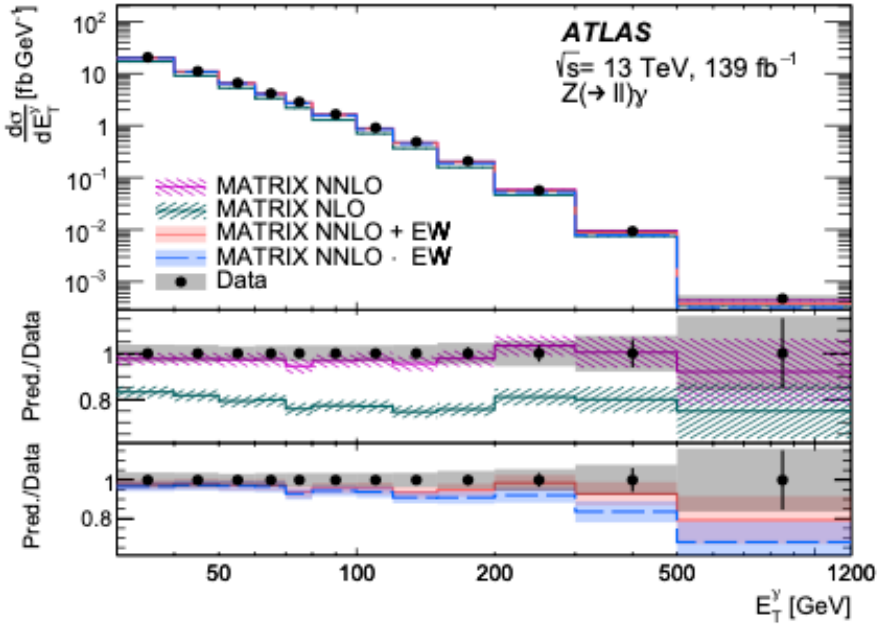


$Z(ll)\gamma$ measurement @ 13 TeV

JHEP 04 (2020) 054

- The production of a prompt photon in association with a Z boson is studied
  - Use full Run-2 dataset : 139 fb^{-1}
  - Integrated fiducial cross-section and differential fiducial cross-section are measured
- Integrated fiducial cross-section :
  - $\sigma_{fid} = 533.7 \pm 2.1(stat) \pm 12.4(syst) \pm 9.1(lumi)\ [fb]$
  - Overall relative precision is 2.9%
- Differential fiducial cross-section :
  - Relative precision of the differential cross-section measurements is in the range 3-7 %
  - Closer agreement between the observables and the data is observed from the MC sample at NLO
  - Fixed order prediction — MATRIX has generally underestimates the measured cross-section, but improved in recent $Z\gamma$ + jets analysis

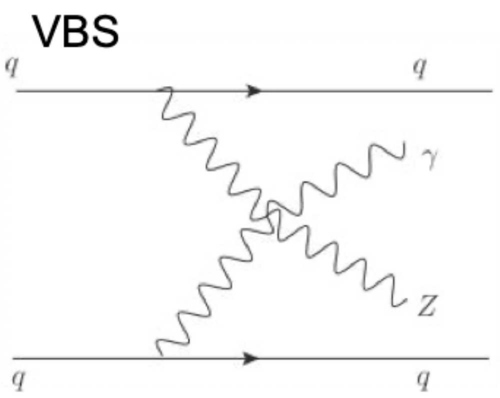


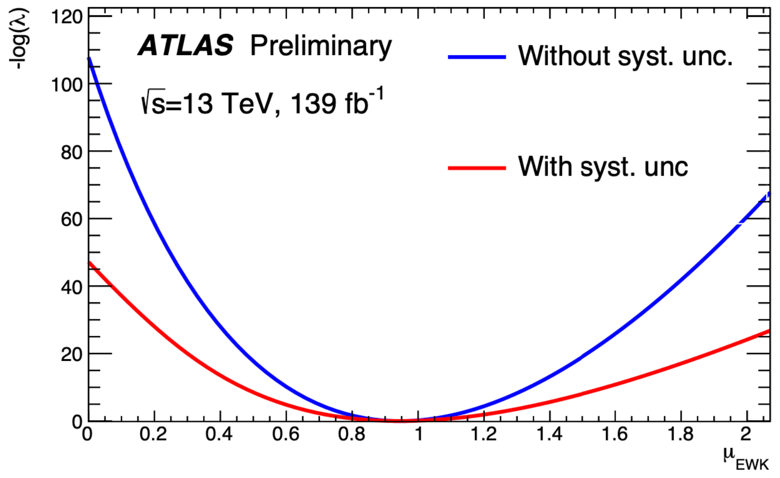


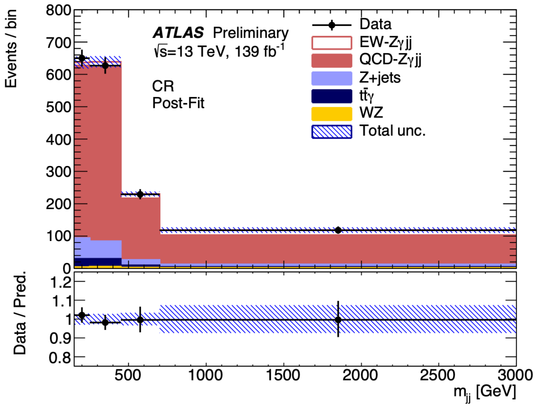
VBS $Z(ll)\gamma$ + 2jets observation @ 13 TeV

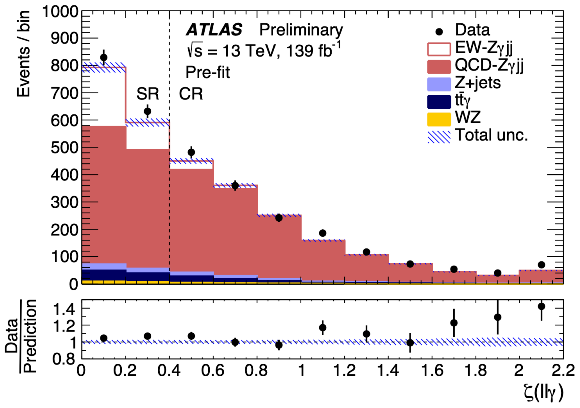
ATLAS-CONF-2021-038

- Observation of EW $Z(ll)\gamma jj$ and measurements of fiducial cross-section of EW and EW+QCD $Z(ll)\gamma jj$
  - $\mu_{EW} = 0.95^{+0.14}_{-0.13} = 0.95 \pm 0.08(stat) \pm 0.11(syst)$
  - 9.7 σ (10.6 σ expected)
  - Cross-sections measured from signal strength
    - $\sigma_{EW} = 4.49 \pm 0.40(stat) \pm 0.42(syst)\ fb$
    - $\sigma_{EW+QCD} = 20.6 \pm 0.6(stat)^{+1.2}_{-1.0}(syst)\ fb$









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

ATLAS-CONF-2022-047

- Considering the probability of lepton reconstruction, only electrons and muons are considered in this $Z\gamma$ + jets analysis
- Precise measurements are studied within a phase-space that is enriched in photons from initial state radiation (ISR)
- Differential cross sections of QCD-related observables associated with the $Z\gamma$ process is measured in this analysis
  - Sensitive to hadronic activity through kinematic recoil
  - ATLAS-CONF-2022-047

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

- Use 2015-2018 Run-2 dataset at $\sqrt{s}$ = 13 TeV
- Events are selected by requiring :
  - Invariant mass of ll to be greater than 40 GeV
  - Sum of invariant masses : $m_{ll} + m_{ll\gamma}$ > 182 GeV
- Define the phase space enriched by ISR photons

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

[ATLAS-CONF-2022-047]

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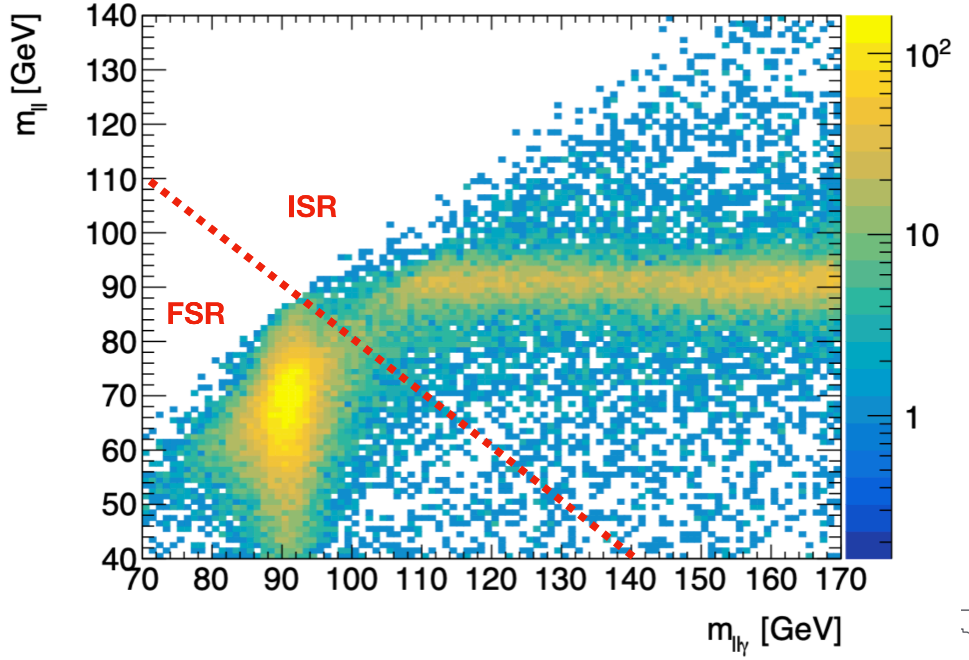
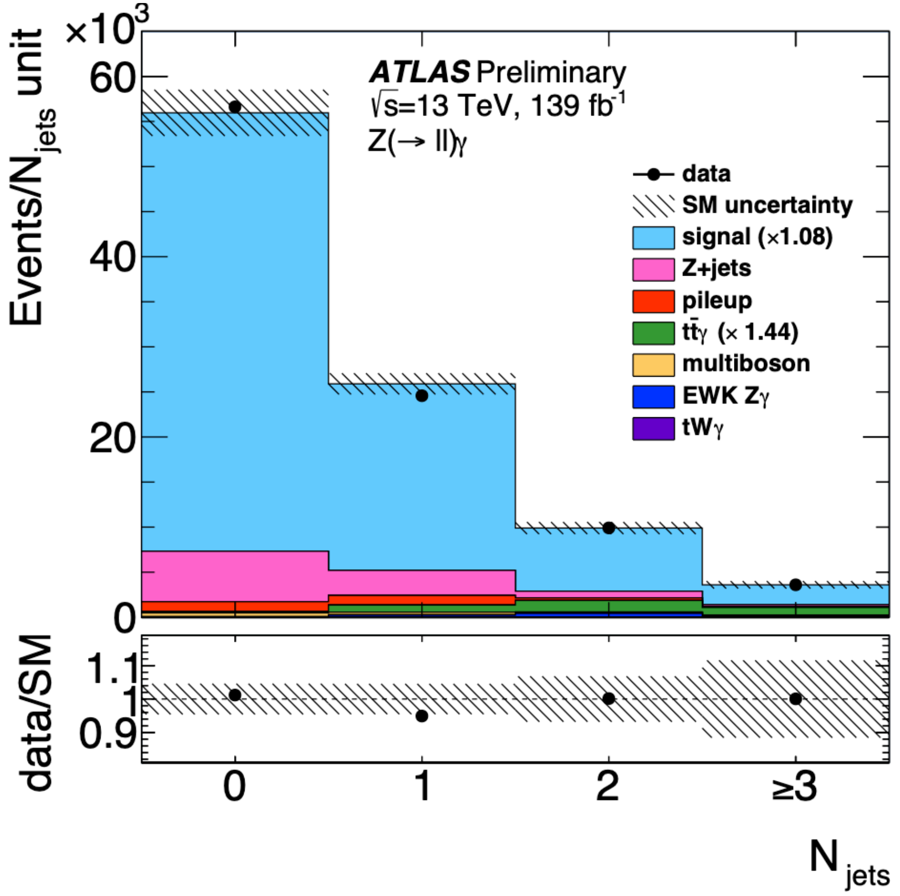


$Z(ll)\gamma$ + jets measurement @ 13 TeV

ATLAS-CONF-2022-047

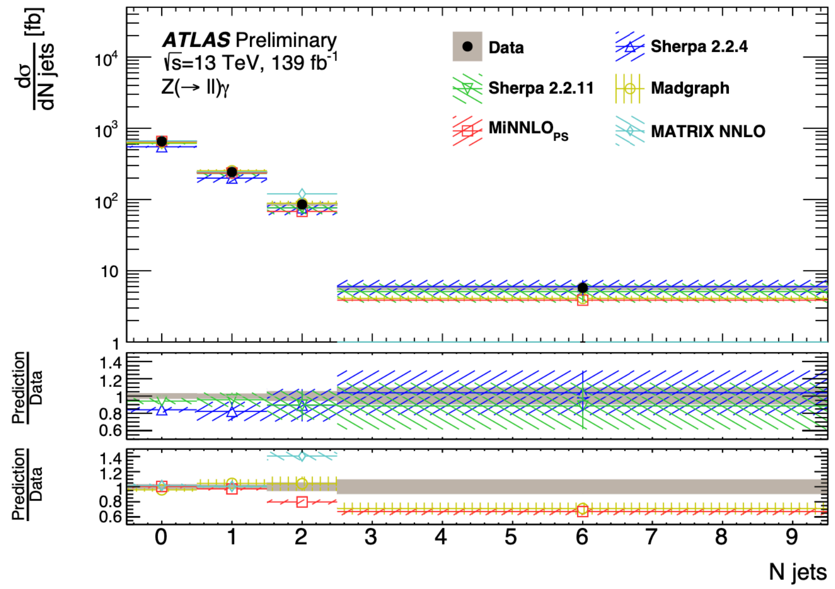
- In this $Z(ll)\gamma$ + jets measurement :
  - Differential cross sections of QCD-related observables associated with the $Z\gamma$ process is studied

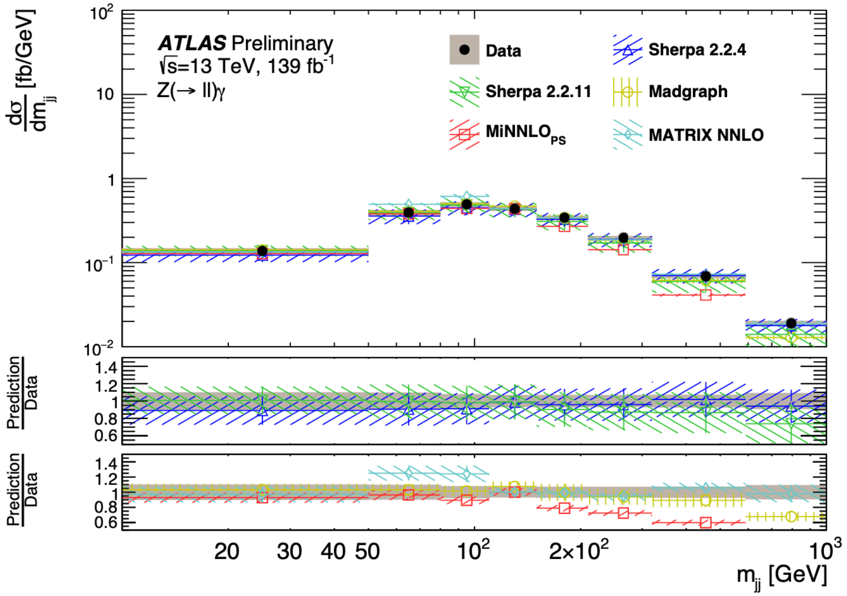
- Differential cross sections are measured for two types of variables
  - Hard variables : represent the hard scale of the process (non-zero at LO)
    - e.g. : $p_T^Z, p_T^\gamma, m_{Z\gamma}$ and their linear combinations
  - Resolution variables : sensitive to additional QCD radiation (zero at LO and non-zero at beyond LO)
    - e.g. : $p_T^{Z\gamma}$ or N_{jet} and so on
- A general good agreement is observed between the data and the SM estimates
  - Observables inclusive in the number of jets are well modeled



ATLAS-CONF-2022-047

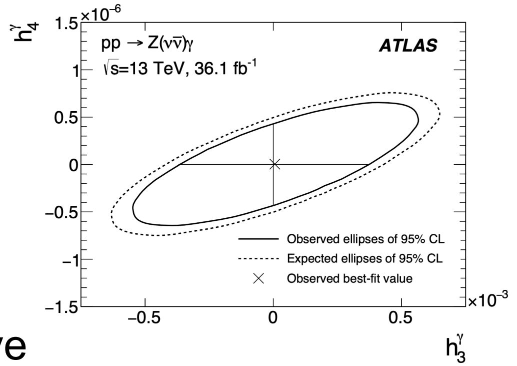
- Differential cross section as function of the observables
  - Performed in s fiducial phase-space enhanced in ISR photons
- High statistics, high-precision channel to study additional QCD radiation in multi boson environment
  - 4-10 % uncertainties depending on the number of jets
- Compared to state-of-the art (N)LO multijet-merged and NNLO predictions
  - From Sherpa, MadGraph+Pythia
  - NNLO predictions with Powheg MiNNLO$_{PS}$
  - NNLO predictions with MATRIX
  - Good description of data in wide range, sherpa 2.2.11 has a general better agreement also in shape, especially for N_{jet}
- First measurement of $Z\gamma$ production in association with jets and can be used to constraint QCD predictions and improve resumption calculations

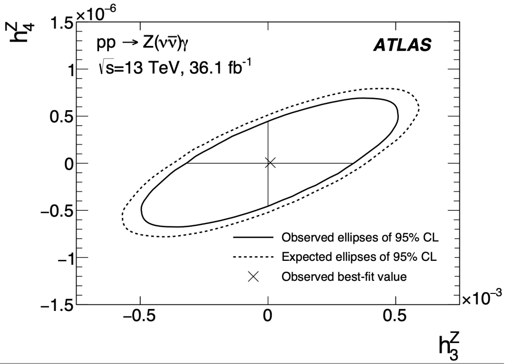


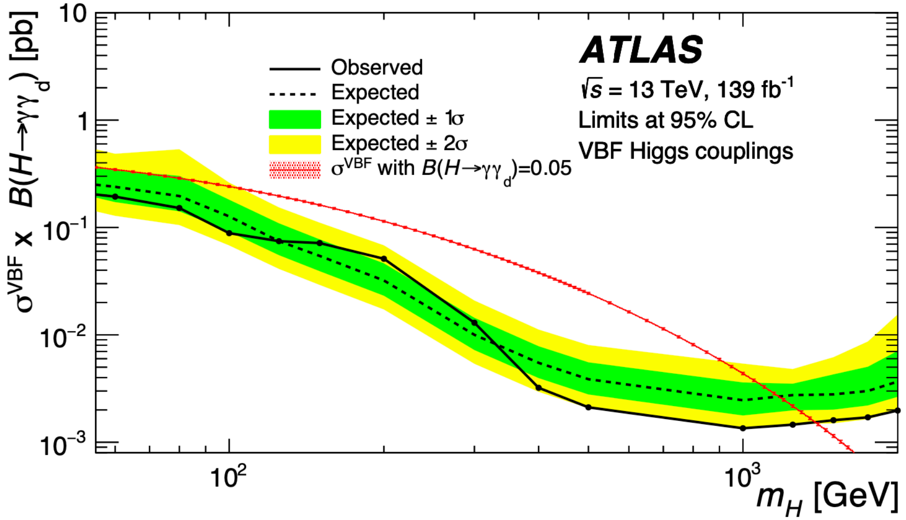


$Z(\nu\bar{\nu})\gamma$ production analyses

- Z decay to neutrino channel with a photon
  - Measurements of the production of Z bosons in association with a high-energy photon is studied in the neutrino decal channel ($pp \to Z(\nu\bar{\nu})\gamma$ channel) — [JHEP 12 (2018) 010]
    - Measures at $\sqrt{s}$ = 13 TeV with an integrated luminosity of 36.1 fb^{-1}
    - nTGC is sough in this analysis with NO excess observed relative to the Standard Model expectation
  - Measurements of the electroweak production of two jets in association with a $Z\gamma$ pair, with the Z boson decaying into two neutrinos — [Eur.Phys.J.C 82(2022) 105]
    - Measured at $\sqrt{s}$ = 13 TeV with an integrated luminosity of 139 fb^{-1}, observed with 5.2 σ, fiducial cross-section is 1.31±0.29 fb
    - Also search for invisible or partially invisible decays of a Higgs boson through VBF with a photon in the final state , upper limit of 0.37 at 95% is observed
- Z decay to neutrino channel is well measured at ATLAS, and also can be used to search nTGC , as well as to constraint invisible decay of Higgs and Higgs decay to dark photon



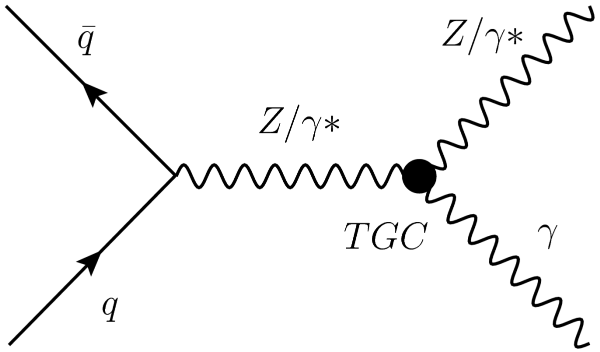


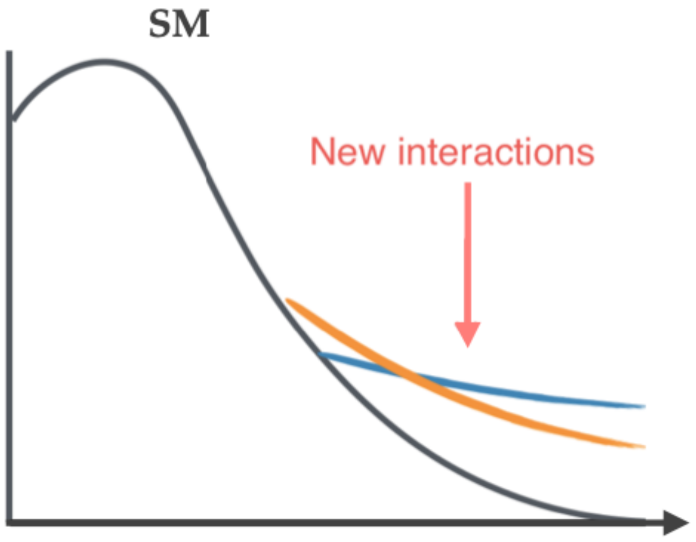


EFT interpretation — nTGCs

- If there is any anomalous couplings
  - Increase of total cross sections
  - And differential cross sections at high p_T and invariant mass
- Neutral Triple Gauge Couplings (nTGCs)
  - Important to understand electroweak symmetry mechanism
  - Forbidden at tree level in the SM, but could arise from SMEFT operators
  - EFT extension of the SM can be parameterized by the effective Lagrangian :
    - $\mathscr{L} = \mathscr{L}_{SM} + \sum_{d>4} \sum_{i} \frac{C_i}{\Lambda^{d-4}} O_i^d$ (Λ is the new physics scale)

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 — nTGCs

- Recent nTGC theory result : arXiv:2206.11676v1
  - Proposed by Prof. John Ellis, Prof. Hongjian He and Dr. Ruiqing Xiao
  - Probing dim-8 nTGC interactions by $pp \to Z\gamma$ production at the LHC
    - Followed by $Z \to f\bar{f}$ decays
  - Two new operators FIRST proposed in ATLAS experiment : O_{G+}, O_{G-}
- In recent nTGC theory result :
  - 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 $q\bar{q} \to Z\gamma$ production

Limits measured in $Z(\nu\bar{\nu})\gamma$ channel with 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	$(-4.5\times10^{-7}, 4.4\times10^{-7})$	$(-5.3\times10^{-7}, 5.1\times10^{-7})$

SJTU

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h_4^Z	$(-4.5\times10^{-7}, 4.4\times10^{-7})$	$(-5.3\times10^{-7}, 5.1\times10^{-7})$

Limits from recent nTGC theory paper

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}	$\times 8.9\times10^{-5}$	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}

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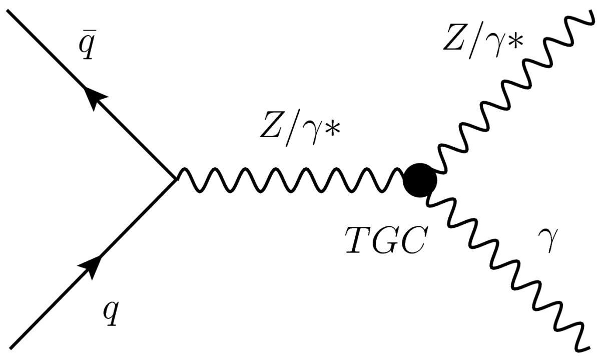
EFT interpretation — work plan

- Develop for EFT interpretation
  - A cooperation between theoretical and experimental side is established
  - A cooperation between SJTU/TDLI and IHEP is also established for EFT study in $Z\gamma$ channel
  - Use new nTGC EFT model to give constraints for SMEFT dim-8 operators
  - Study polarization variables and angular distribution in nTGC EFT model

- Proposed work strategy
  - Full Run-2 dataset analysis in R21
  - Inherit as much as possible from the previous $Z\gamma$ + jets analysis
    - Avoid duplication work
    - Quick start on the new analysis optimizations



Summary

- Cross-sections for $Z\gamma$ production (a prompt photon association with a Z boson) have been measured at8 TeV and 13 TeV (Z decays to leptons, and also VBS $Z\gamma$ observation)

- Differential cross-sections of $Z\gamma$ production in association with jets are FIRST measured in ATLAS and can be used to constraint QCD predictions

- Good agreements are observed between the data and the SM estimates in $Z\gamma$ + jets analysis, and better description of data is also observed

- EFT interpretation — nTGC will be studied in $Z\gamma$ channel with Z decays to lepton pairs

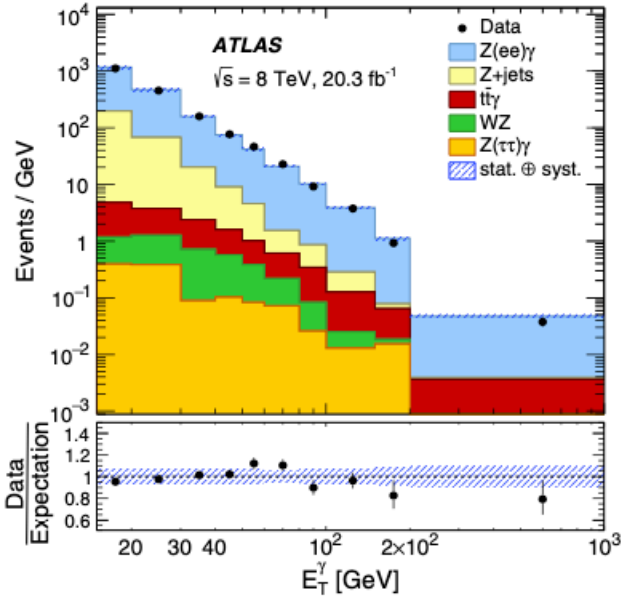
Thank You !

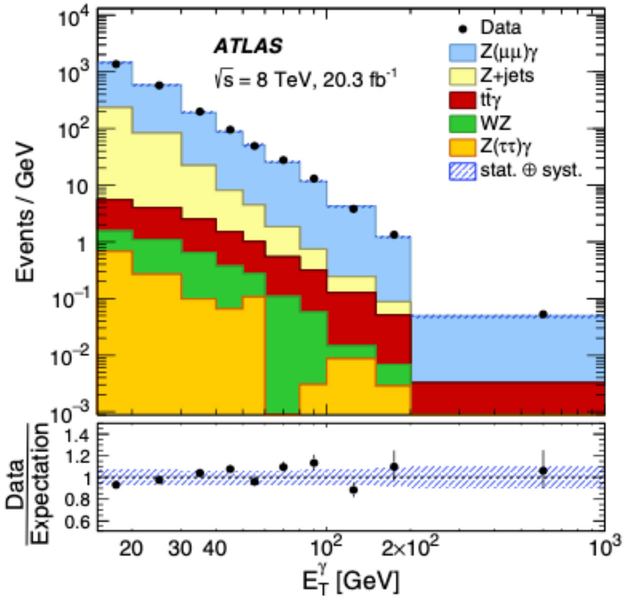
Backup

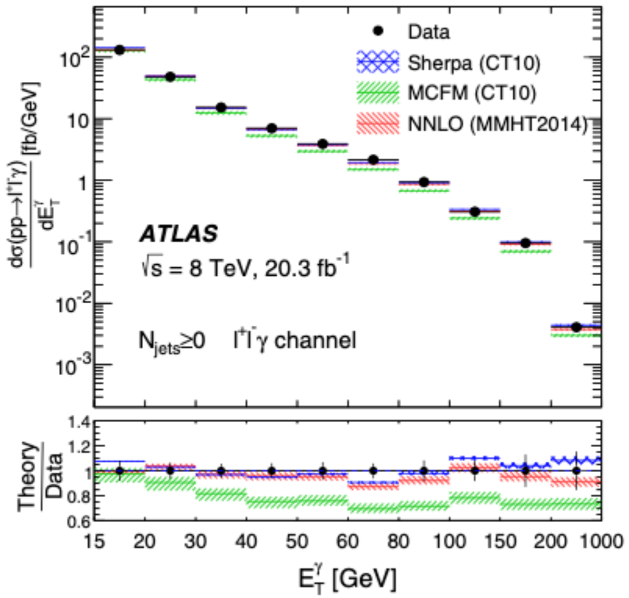
NNLO Predictions

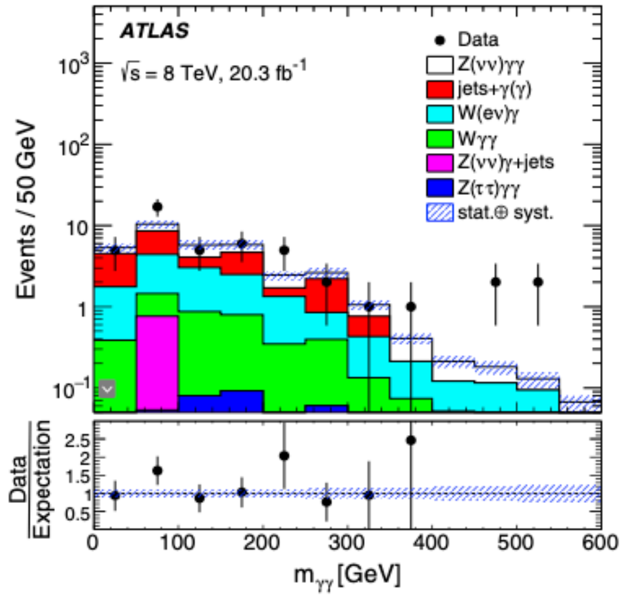
- Powheg MiNNLO$_{PS}$
  - A method to combine QCD calculations at NNLO with PS simulations
  - Based on transverse-momentum resumption
  - Features :
    - NNLO corrections are calculated directly during the generation of the events, with no need for further reweighting
    - No merging scale is required to separate different multiplicities in the generated event sample
    - When combined with transverse-momentum ordered parton showers, the matching preserves the leasing logarithmic structure of the shower simulation
- MATRIX
  - A computational framework that allows to evaluate fully differential cross sections for lots of processes in NNLO QCD
  - Based on using a process-independent implementation of the q_T-subtraction formalism in combination with a fully automated implementation of the Catani-Seymour dipole subtraction method within the MC program MUNICH
  - Features :
    - Control the systematics uncertainties inherent to the applied NNLO subtraction procedure down to the few permille level (or better) for the first time

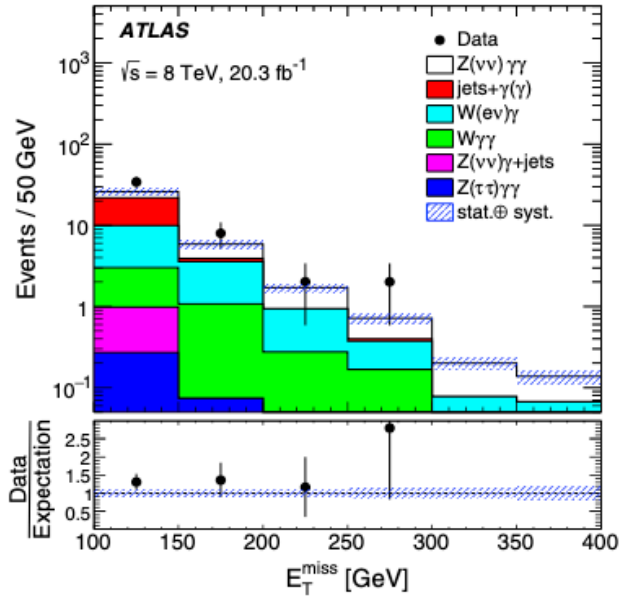
Results — $Z(ll)\gamma$ measurement @ 8 TeV

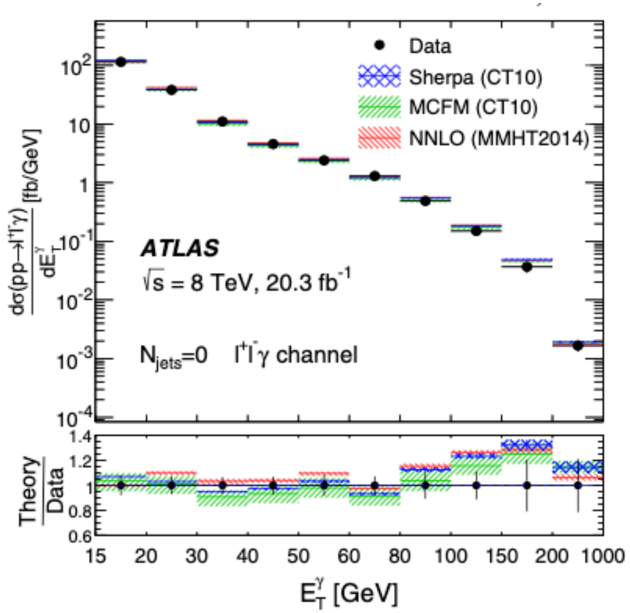




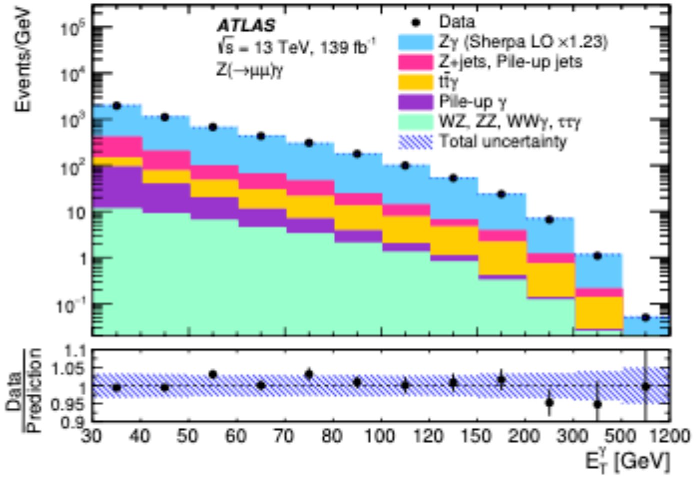


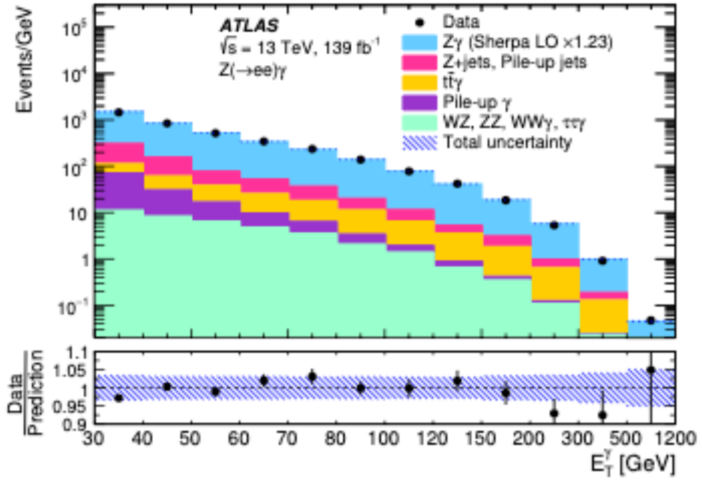


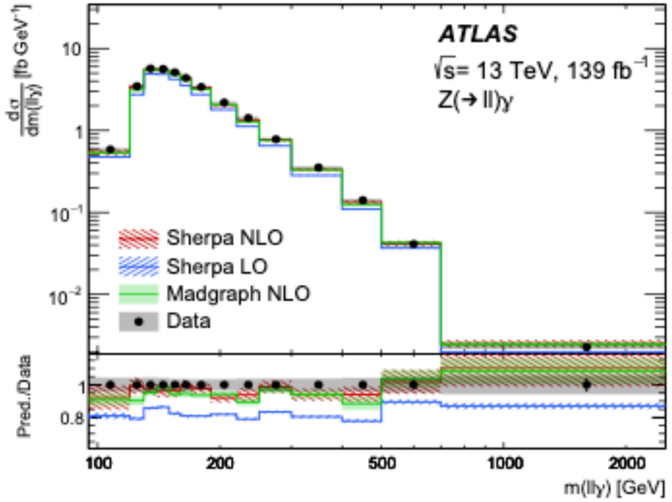


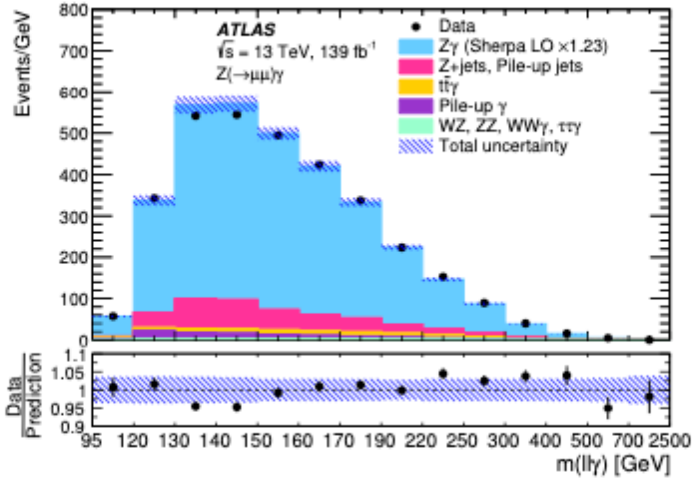


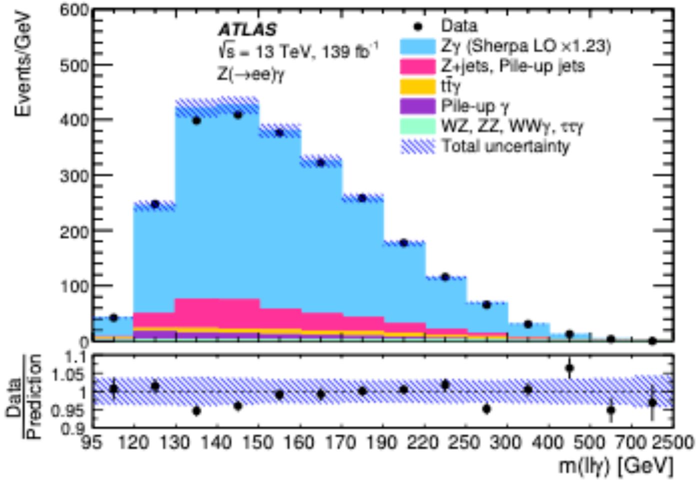
Results — $Z(ll)\gamma$ measurement @ 13 TeV

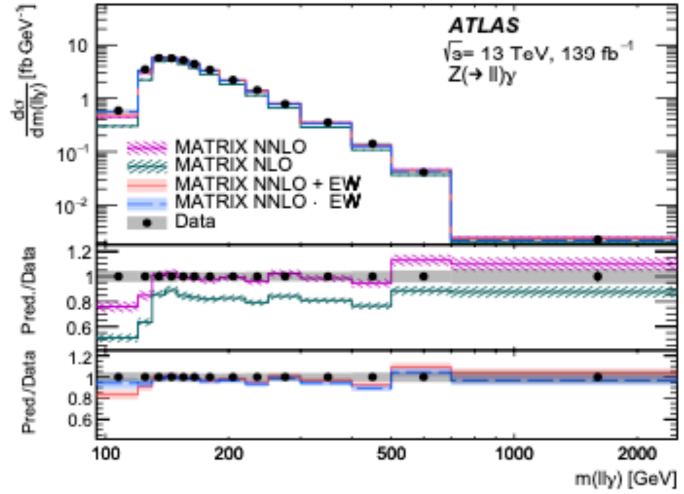












Results — $Z(ll)\gamma$ + jets measurement

- Data vs MC comparison plot
  - Good agreement can be observed