Imperial College London

CMS

THE ROYAL SOCIETY

Differential measurement of the Z/γ cross section and collinear Z emission

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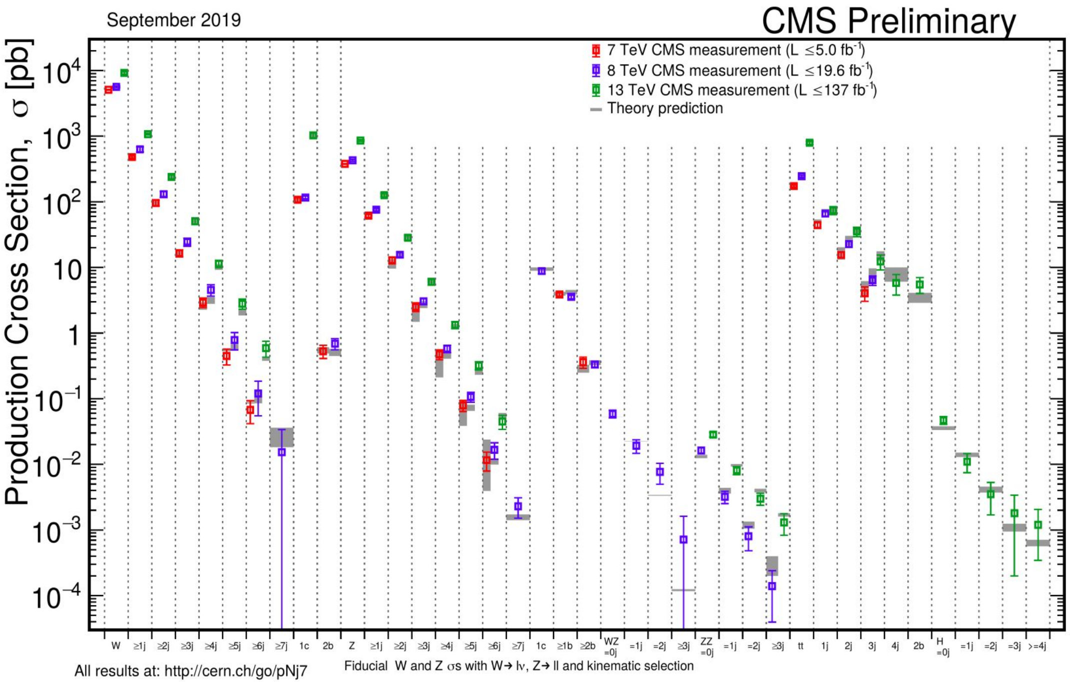
on behalf of the CMS collaboration

DIS2021: XXVIII International Workshop on Deep-Inelastic Scattering and Related Subjects
April 12-16, 2021

V+jets measurements

- Large statistics collected in Run2 gives the opportunity of studying regions of the phase space previously limited
- V+jets processes have a good versatility:
  - Probes of perturbative QCD
  - sensitive to higher order effects from QCD and EW
  - Important input for PDFs
  - Improve sensitivity of searches and measurements
- Active theoretical developments (N)NLO QCD and NLO EW



Need for experimental measurements to validate predictions

Outline

- Focusing on two V+jets results:
  - Z+jets/γ+jets differential in vector boson p_T
  - Study for collinear Z boson emission from a jet
- Paper submitted to JHEP, arXiv:2102.02238v1
- This is the :
  - First measurement of the differential cross section ratio of Z/γ at 13 TeV
  - First explicit study of the collinear emission of Z boson at the LHC

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

CERN-EP-2020-250
2021/02/05

CMS-SMP-19-010

Measurements of the differential cross sections of the production of Z + jets and γ + jets and of Z boson emission collinear with a jet in pp collisions at $\sqrt{s} = 13\,\text{TeV}$

The CMS Collaboration*

Abstract

Measurements of the differential cross sections of Z + jets and γ + jets production, and their ratio, are presented as a function of the boson transverse momentum. Measurements are also presented of the angular distribution between the Z boson and the closest jet. The analysis is based on pp collisions at a center-of-mass energy of 13 TeV corresponding to an integrated luminosity of 35.9 fb^{-1} recorded by the CMS experiment at the LHC. The results, corrected for detector effects, are compared with various theoretical predictions. In general, the predictions at higher orders in perturbation theory show better agreement with the measurements. This work provides the first measurement of the ratio of the differential cross sections of Z + jets and γ + jets production at 13 TeV, as well as the first direct measurement of Z bosons emitted collinearly with a jet.

Submitted to the Journal of High Energy Physics

*See Appendix A for the list of collaboration members

Z+jets / γ+jets

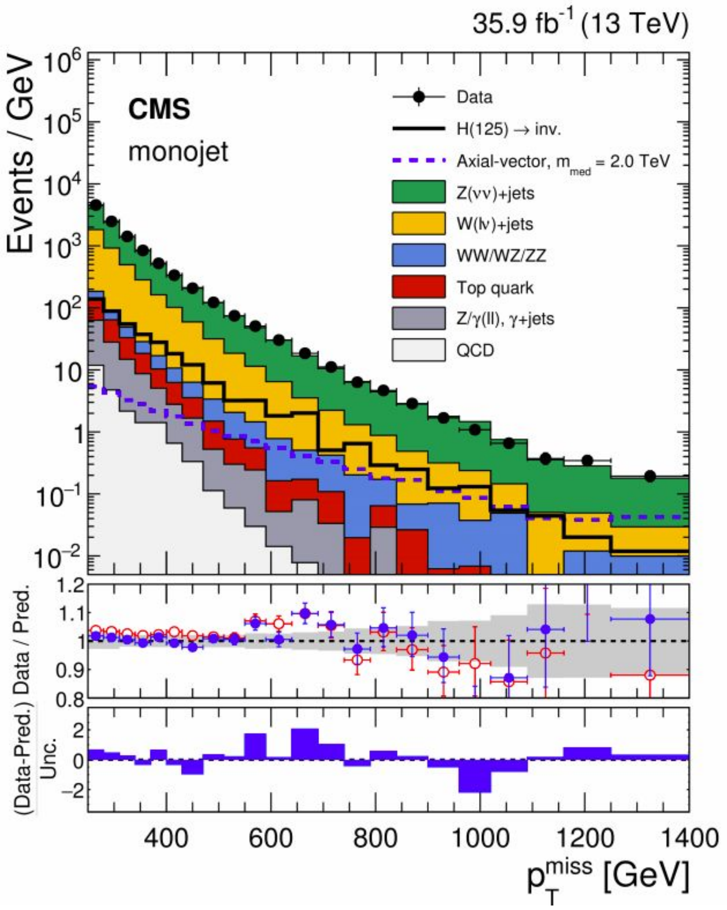
Motivation

Precision test of the SM at high p_T :

- Sensitive to higher order QCD and EW corrections
- Large EW Sudakov logarithms that grow with energy

Relevance for BSM searches:

- Z+jets and γ+jets used to model $Z \rightarrow \nu\bar{\nu}$ background.
- Probing small excess of events in tails of MET distribution relies on precise modeling of boson p_T distribution



Event selection

Data

- Using the 2016 dataset
- Single Muon and Single Photon samples for the $Z\rightarrow\mu\mu$ channel and the γ+jets channel respectively

MC :

- Signal from Drell-Yan to leptons and γ+jets samples
- Background: VBF Z+jets, Diboson,$t\bar{t}$, single top, $t\bar{t}V$, W+jets, $t\bar{t}\gamma$, $V\gamma$+jets, QCD multijet

For **Z+jets**:

- 2 tight ID muons with p_T>30 GeV, $|\eta| < 2.4$, opposite charged
- $71 < m_{ll} < 111$ GeV
- p_T of muon pair >200 GeV, $|y|<1.4$

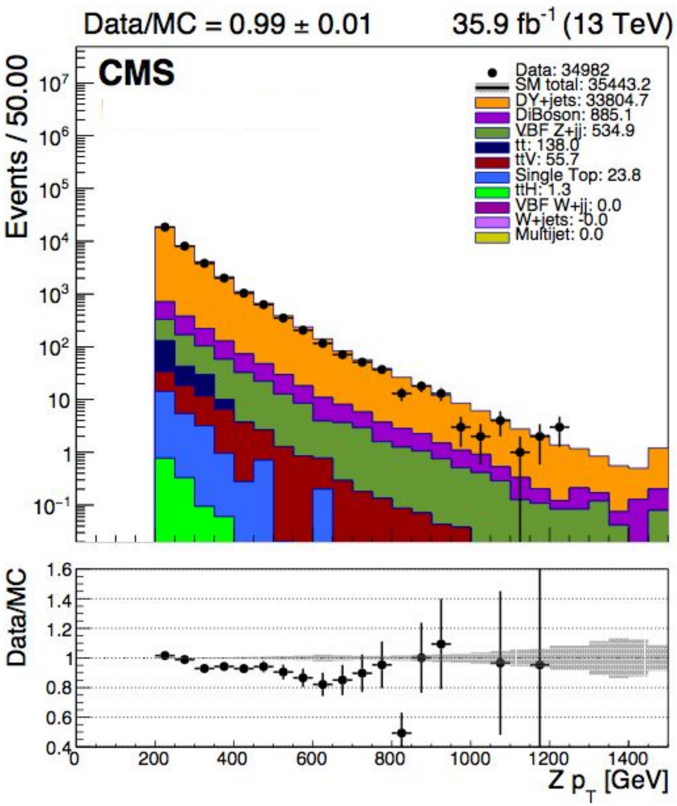
For γ**+jets**:

- 1 tight ID photon with p_T >200 GeV, $|y| < 1.4$

For **both**:

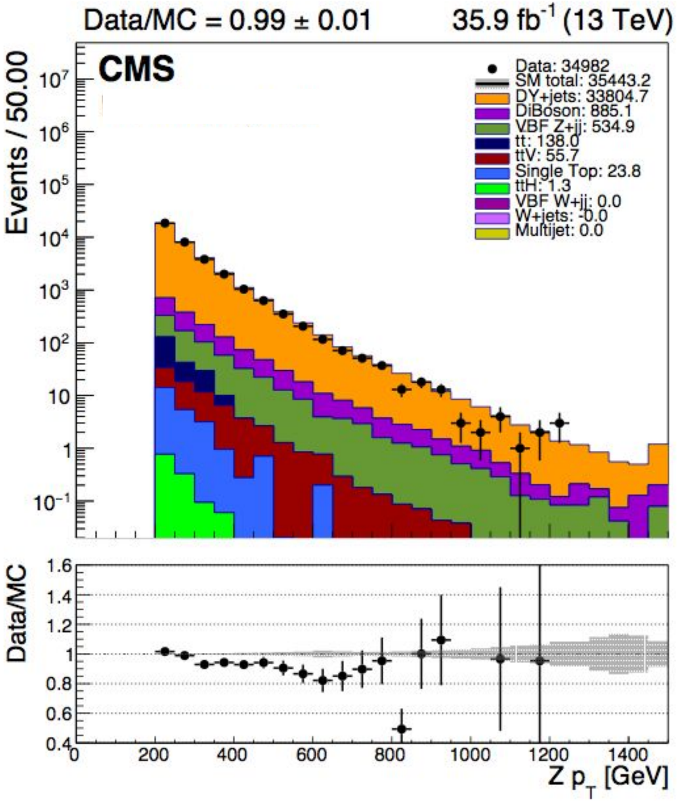
- Leading jet p_T> 100 GeV, $|\eta| < 2.4$
- N_{jets}> 1

Z+jets cross section

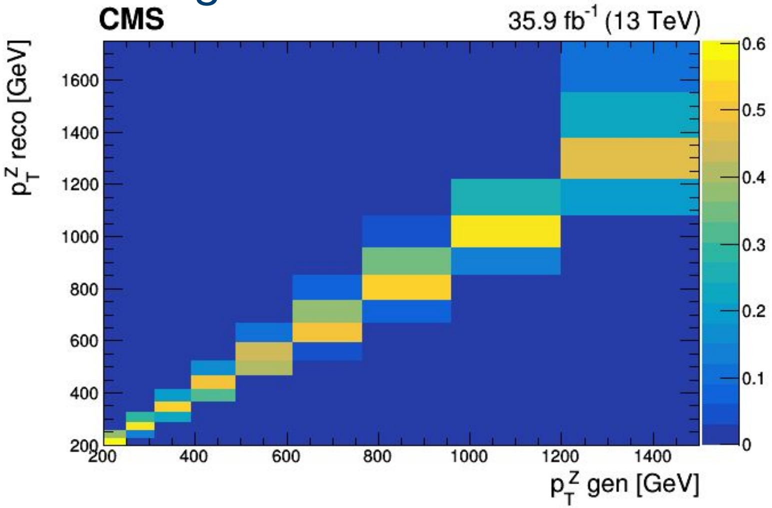


- Out-of the-box Data MC comparison
- Background at ~2.5% level
- Mainly from Diboson and VBF Z+jets
- MC background subtraction

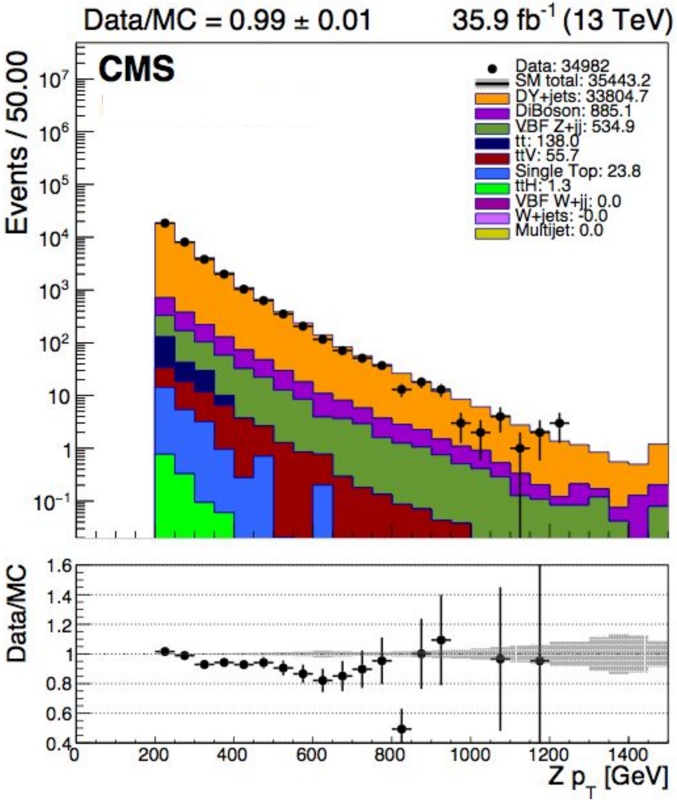
Z+jets cross section



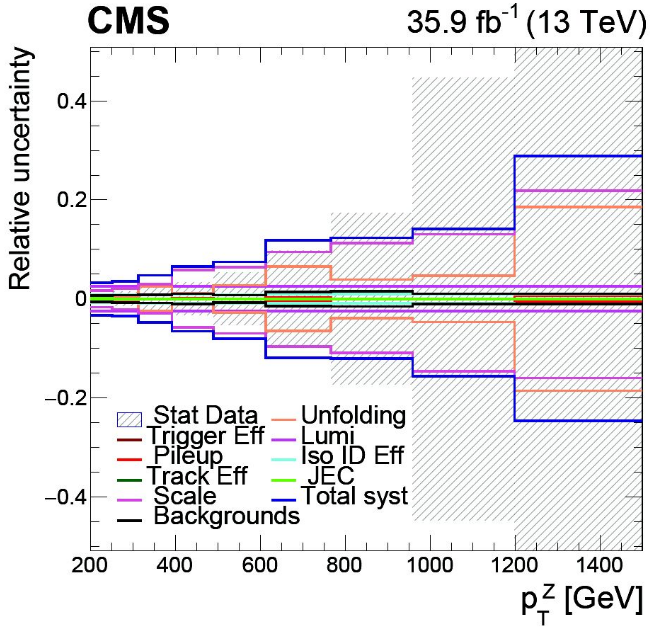
- Reconstructed events are unfolded to particle level
- Unfolding is performed using a least square minimization for matrix inversion, with Tikhonov regularization



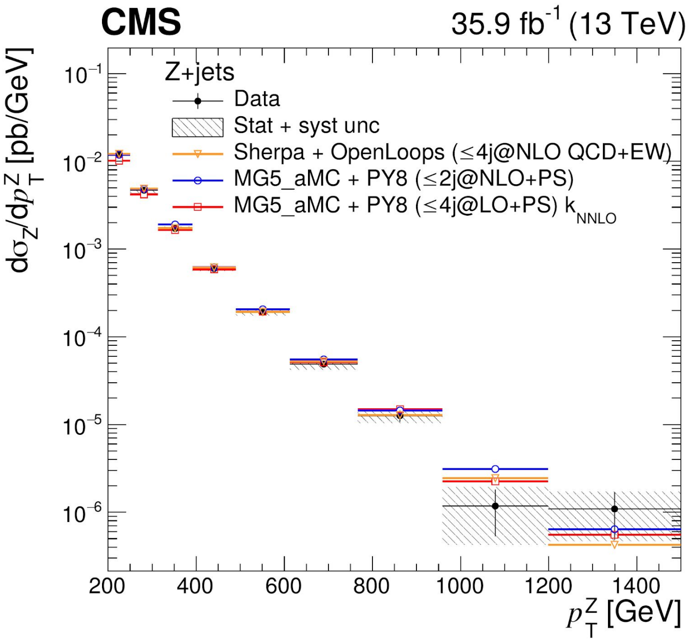
Z+jets cross section

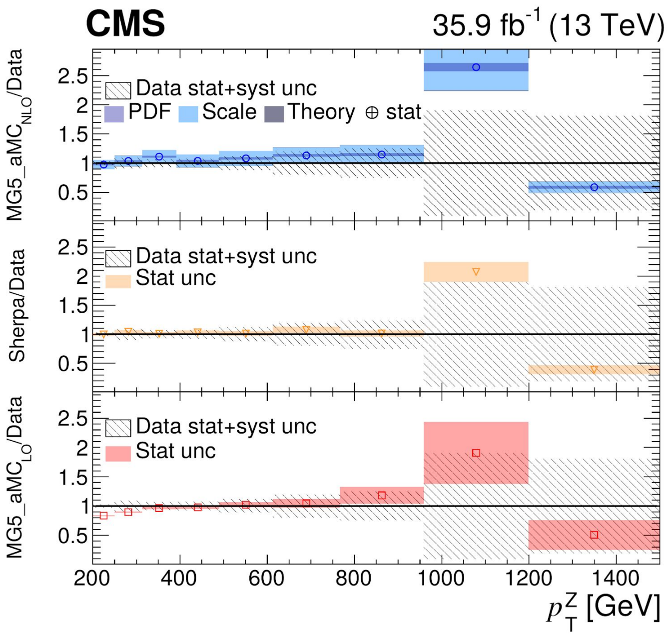


- Systematic impact is estimated repeating the unfolding procedure with alternative migration matrices - 1σ shifts variations



Z+jets cross section

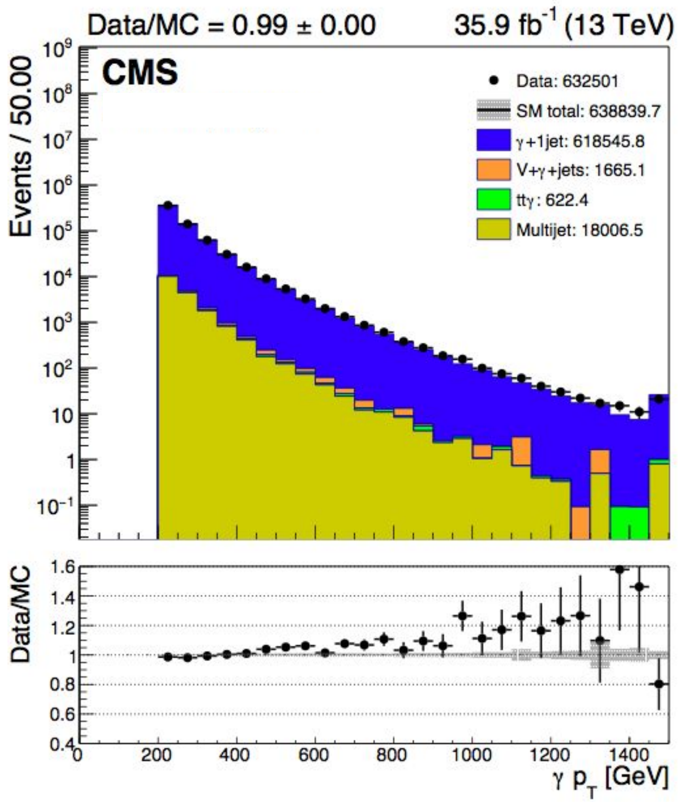




Compare unfolded Z p_T distribution to theoretical predictions from:

- Madgraph MC@NLO (2j NLO)
- SHERPA+OPENLOOPS (NLO QCD+EWK)
- Madgraph MC@NLO (4j LO)

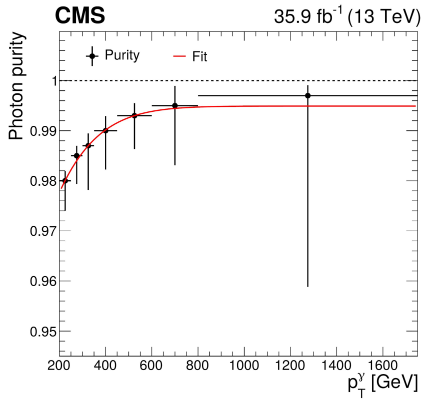
γ+jets cross section



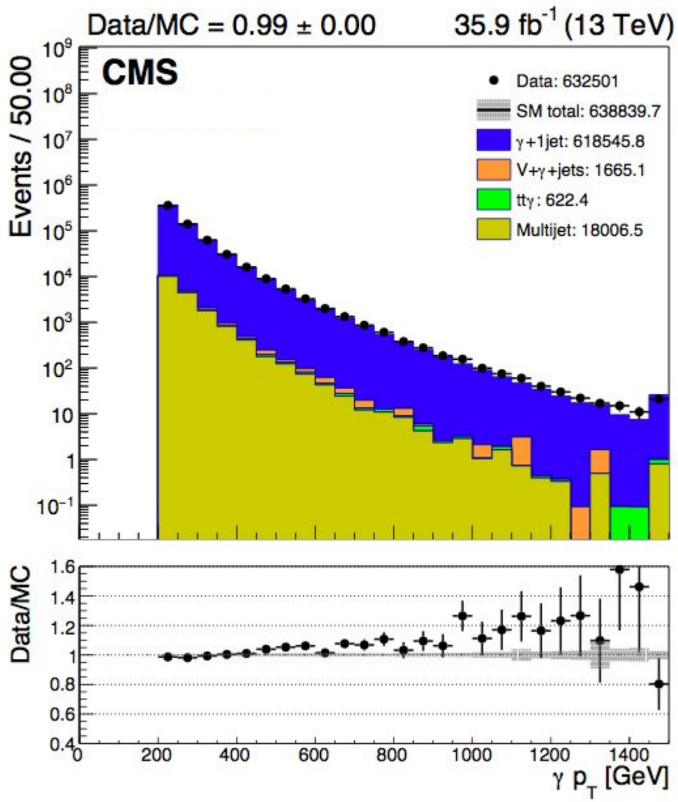
- Out-of the-box Data MC comparison
- Largest background contribution (~3%) from QCD multijet where electron or π^0 from a jet is misidentified as a photon candidate
- Dedicated data-driven background estimation to extract the purity of the photon sample

$$\text{Purity} = \frac{N^{\gamma}_{real}}{N^{\gamma}_{real}+N^{\gamma}_{fake}}$$

More details in the backup



γ+jets cross section



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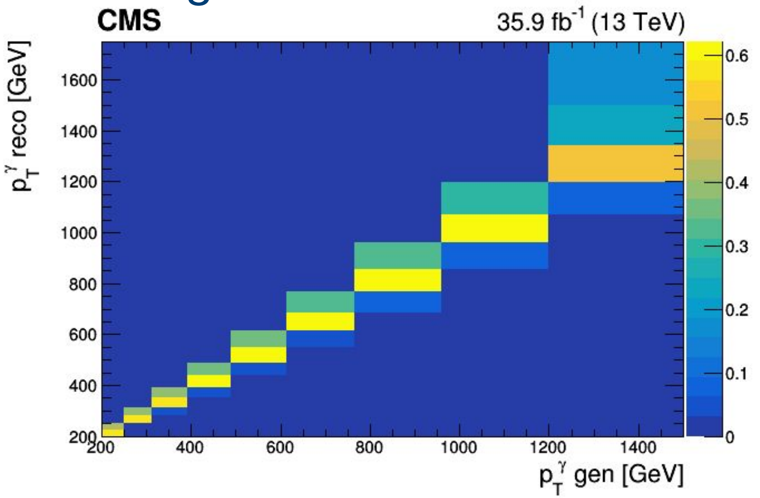
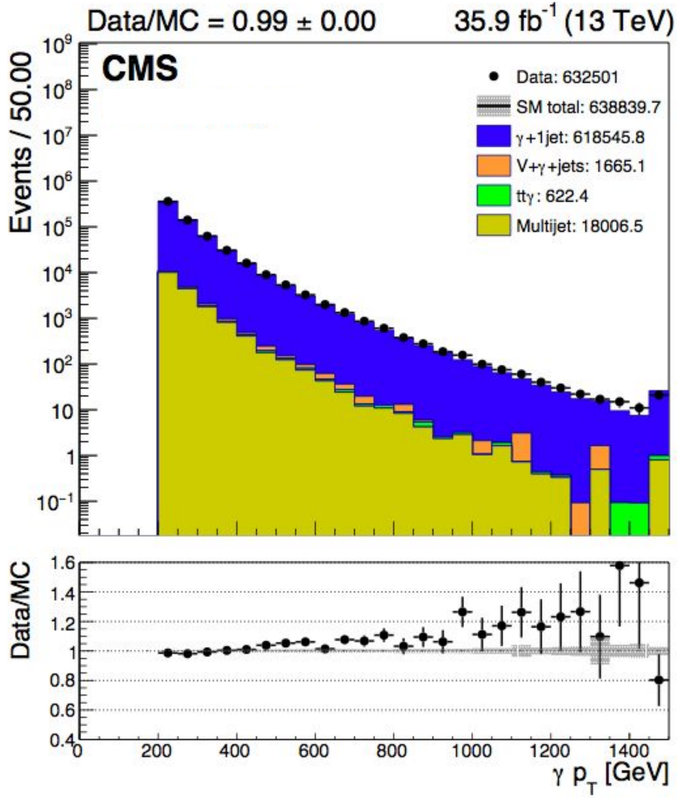


γ+jets cross section



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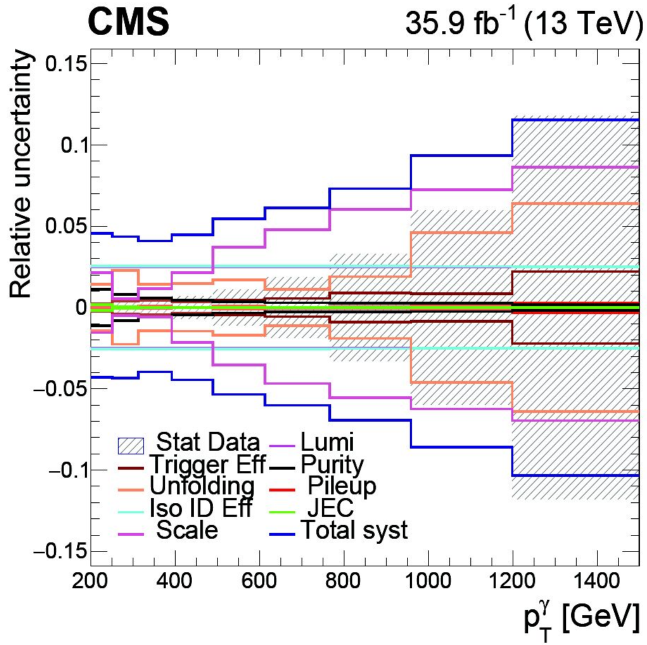
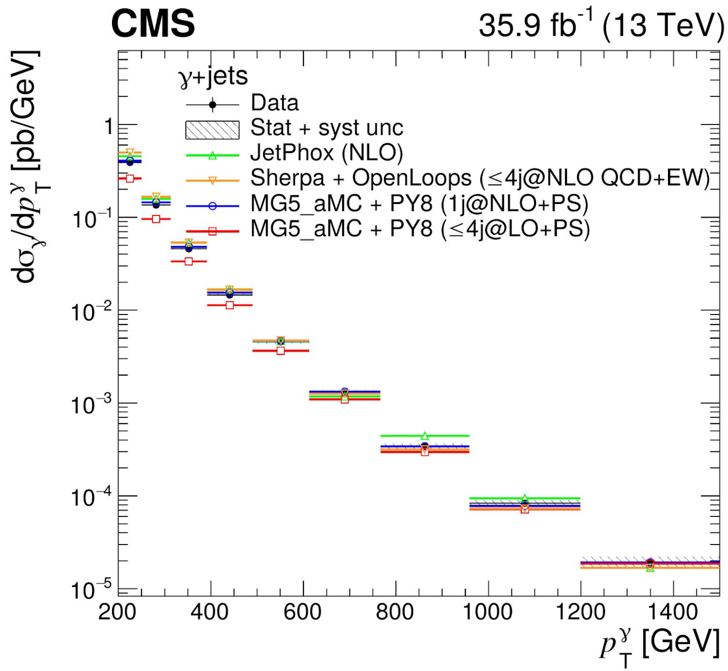
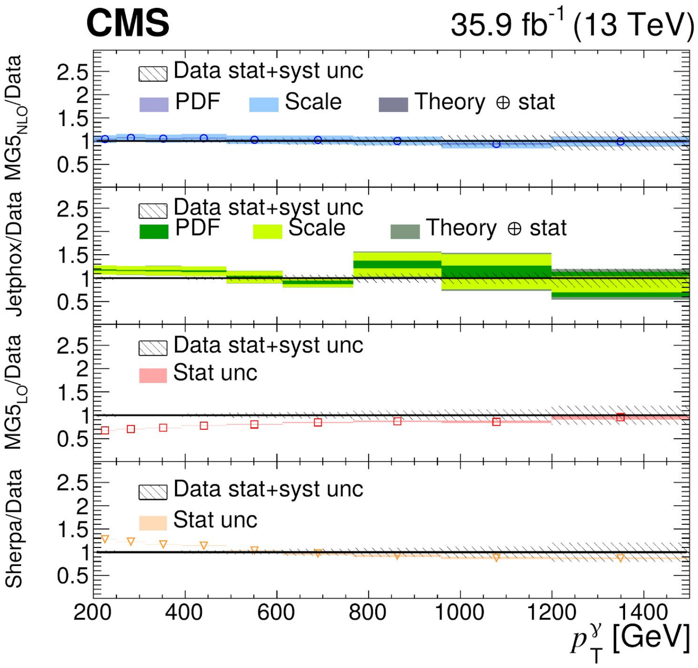


γ+jets cross section

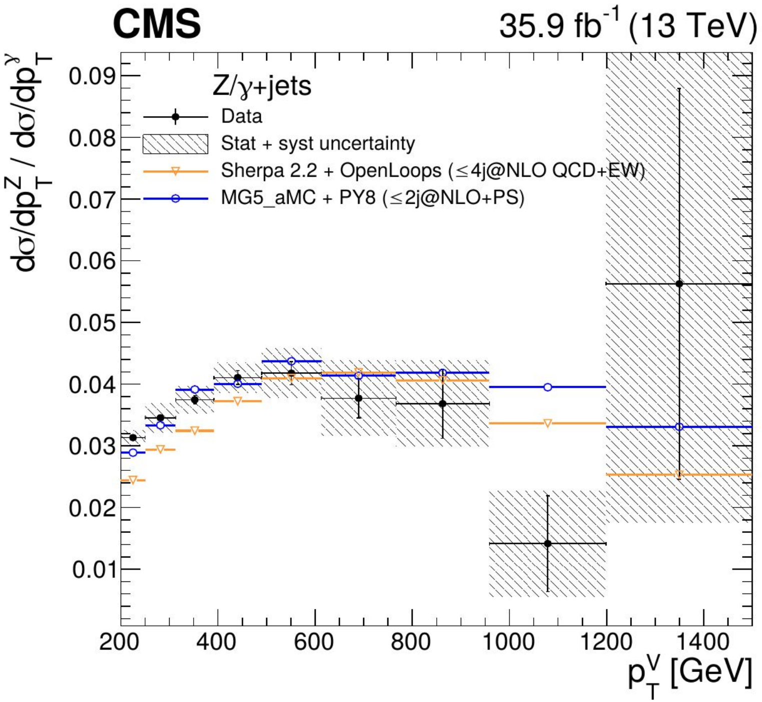


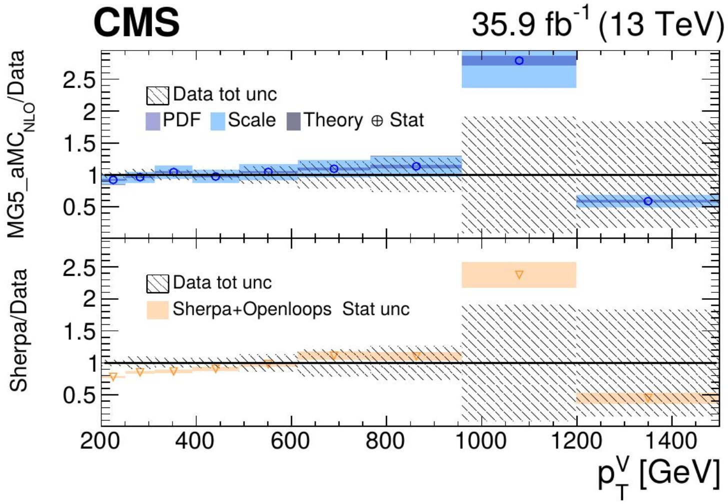


Compare unfolded γ p_T distribution to theoretical predictions from:

- Madgraph MC@NLO (2j NLO)
- JetPhox (1j NLO)
- SHERPA+OPENLOOPS (NLO QCD+EWK)
- Madgraph MC@NLO (4j LO)

Z/γ ratio



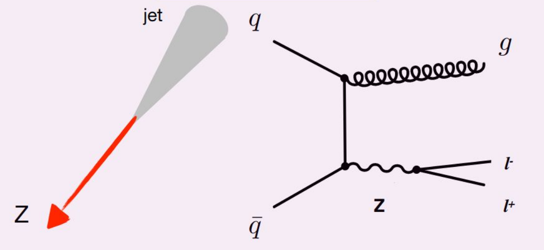


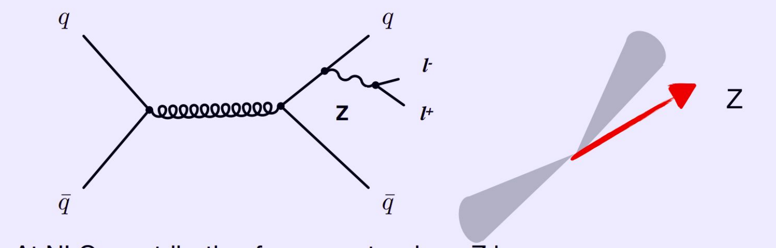
- Compared unfolded Z/γ p_T distribution to theoretical predictions from:
  - Madgraph MC@NLO
  - SHERPA+OPENLOOPS

Collinear Z boson emission

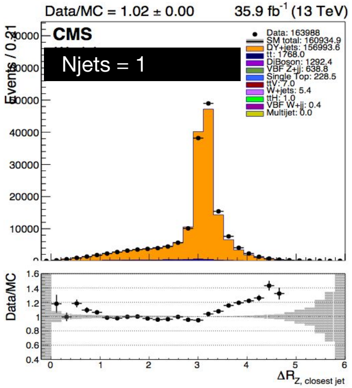
Collinear Z boson emission from jet

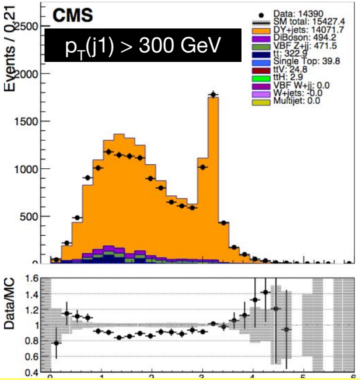
Dominated by back-to-back production of Z and jet

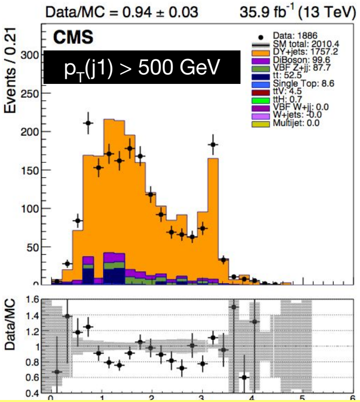




At NLO, contribution from events where Z is emitted collinear with jet



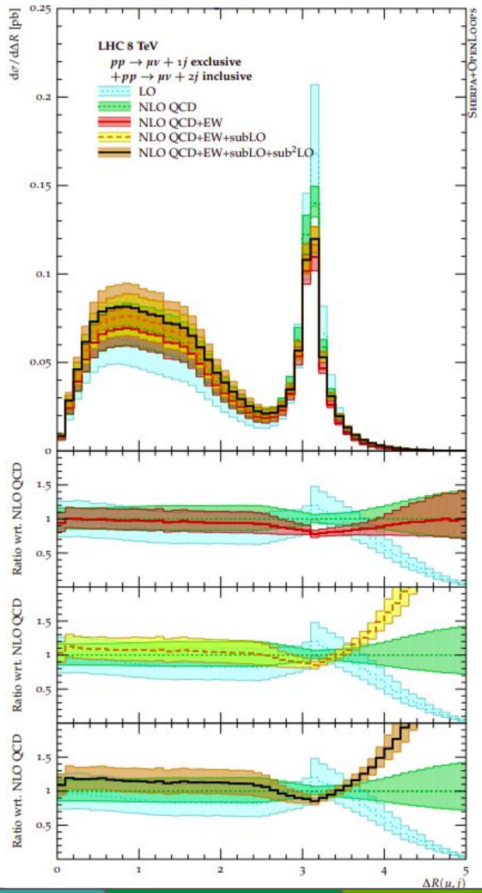




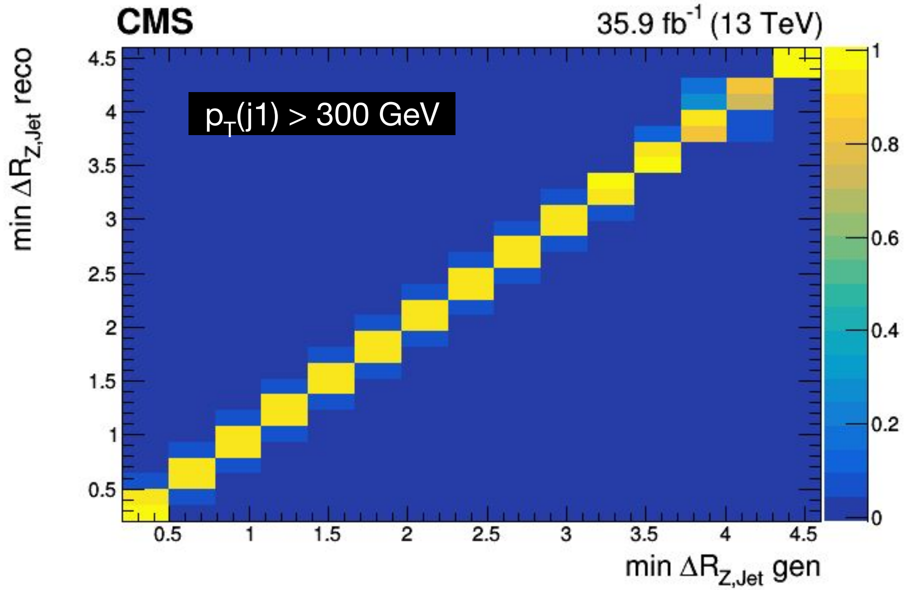
Enhancement of collinear emission of Z close to a jet is obtained by progressively higher thresholds on leading jet p_T

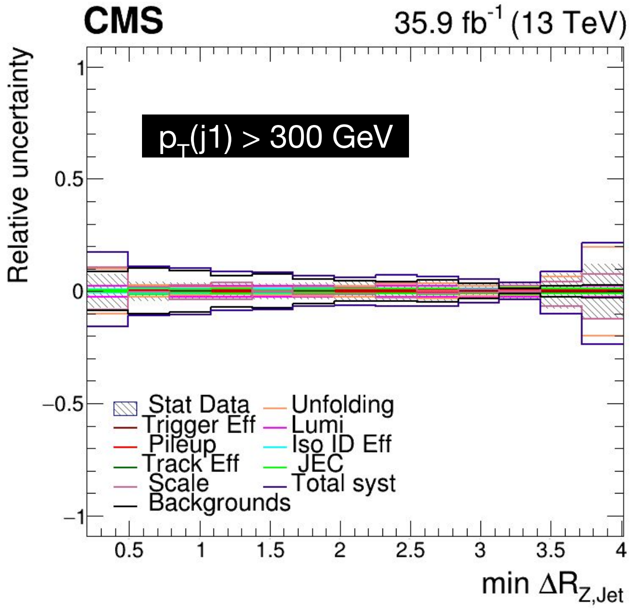
Collinear Z boson emission from jet

- Event selection:
  - lead jet p_T > 300 (500) GeV and $|\eta| < 2.4$
  - Muon cuts:
    - muon p_T > 30 GeV and $|\eta| < 2.4$
    - ΔR(muon,closest jet) > 0.5
- No cuts on Z p_T nor $|y|$
- Variable of interest:
  - ΔR(Z,closest jet)



Collinear Z boson emission from jet



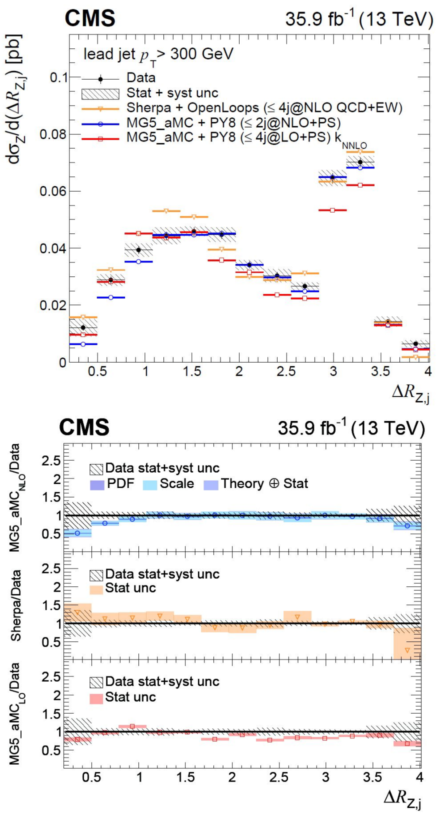


- Unfolding strategy similar to the ratio - caveat closest jet matching to generator level
- Uncertainty on muon scale and unfolding dominant
- High ΔR region (> 3.4) dominated by statistical uncertainty on unfolding matrix

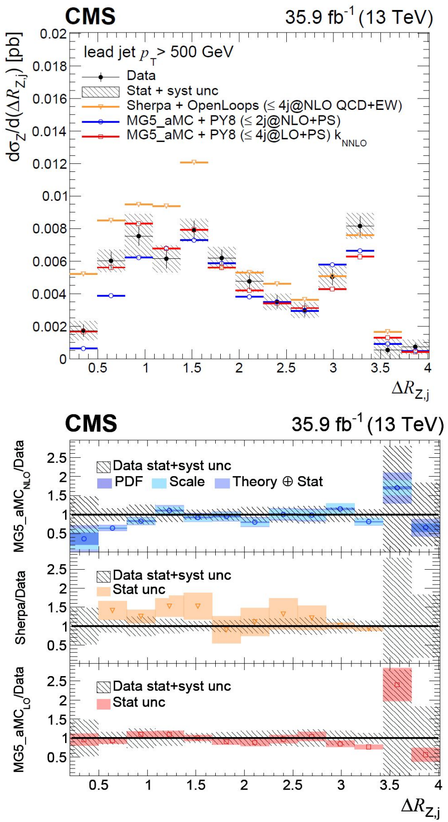
Collinear Z boson emission from jet

- Unfolded data compared to:
  - Madgraph aMC@NLO (2j NLO)
  - Madgraph aMC@NLO (4j LO)
  - SHERPA+OPENLOOPS (NLO QCD+EW)

$p_T(j1) > 300$ GeV

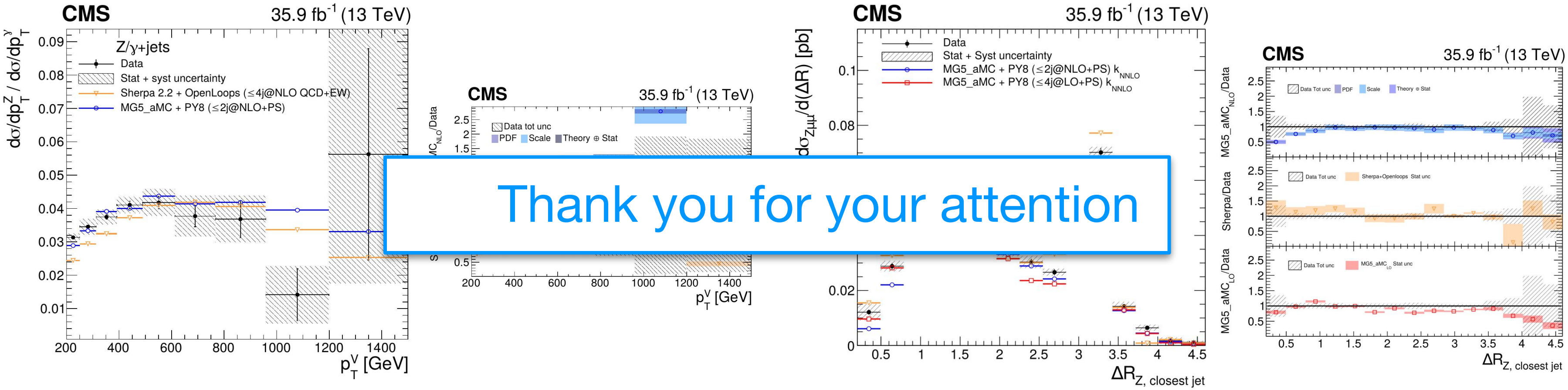


$p_T(j1) > 500$ GeV



Summary

- Presented differential cross section measurements of Z+jets, γ+jets, the Z/γ ratio and the collinear emission of a Z boson.
- Measurement of Z/γ ratio is the first study of this quantity in Run 2 of LHC, probes up to 1.3 TeV in boson p_T.
- First study of collinear emission of Z at the LHC.



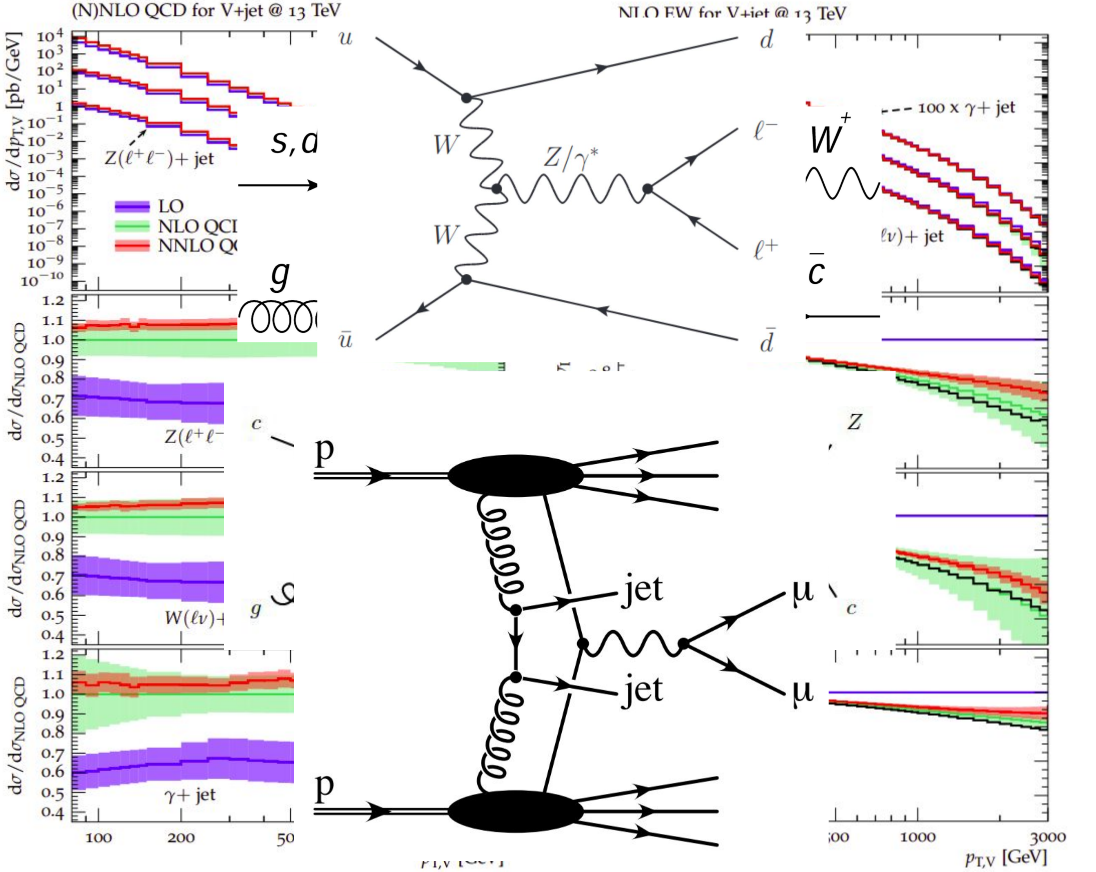
Thank you for your attention

Studying regions of ‘extreme phase space’ increasingly important in current era of LHC where we’re probing higher p_T thresholds and pushing to new territories

Backup

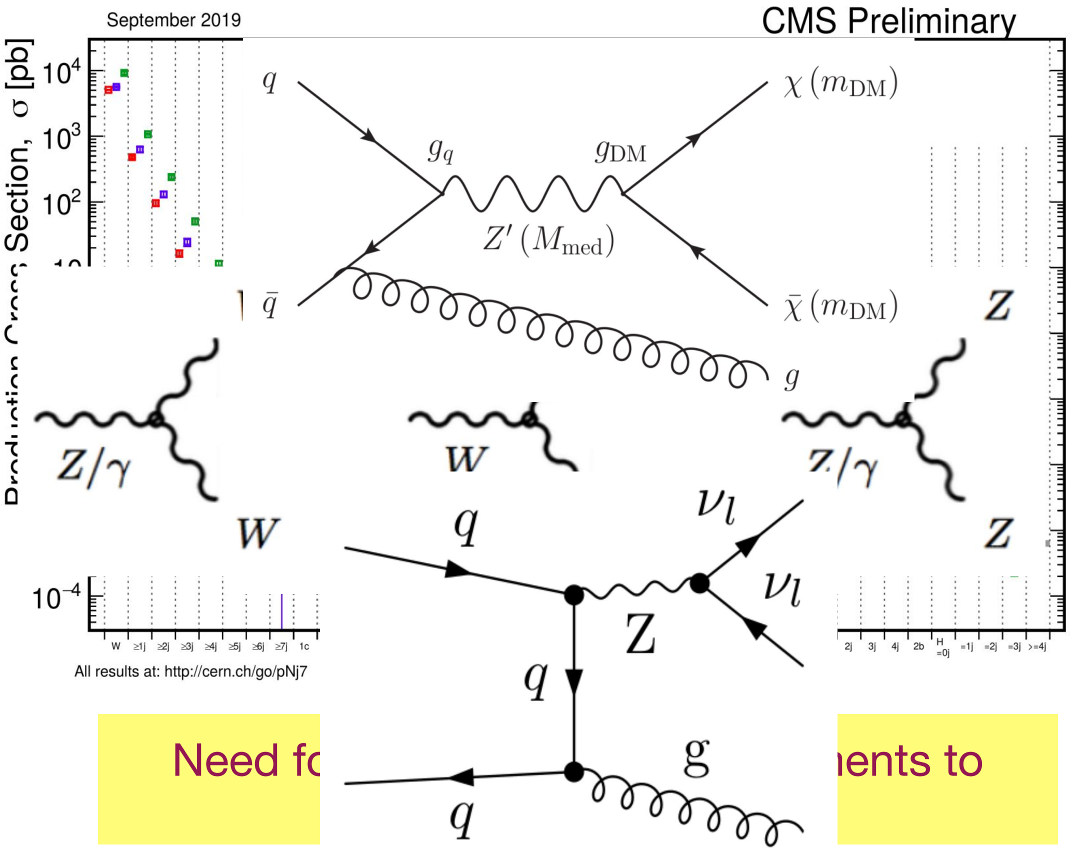
V+jets measurements

- With the large LHC Run2 dataset, precision measurements of V+jets processes are becoming valuable tools to probe SM
  - exploring extreme regions of the phase space sensitive to higher order QCD and EW effects
  - Important tool for PDF fits
  - hadronic activity, MPI, ...



V+jets measurements

- With the large LHC Run2 dataset, precision measurements of V+jets processes are becoming valuable tools to probe SM
- Improve sensitivity for many searches and measurements
  - large systematic in Higgs measurements
  - inputs for EFT
  - $Z \to \nu\bar{\nu}$ background
- Active theoretical developments
  - (N)NLO QCD and NLO EW calculations



Photon purity

- Largest background contribution to γ+jet events from QCD multijet where electron or π^0 from a jet is misidentified as a photon candidate
- ‘purity’ of γ+jet events defined as fraction of true isolated photons from hard scattering vs number of all photon candidates after full selection criteria.
- Purity extracted in each photon p_T bin with Template fit method in the shower shape variable $\sigma_{i\eta i\eta}$ with signal and background templates.
- Signal template from simulation
- Background template from sideband region in data.
  - Sideband defined using the Charged Hadron Isolation variable
  - Charged hadron isolation required to be 10 -15 GeV, following an optimization to reduce signal contamination and provide large data sample of fake photons
- Perform Binned maximum-likelihood fit implementing Beeston Barlow method to take into account finite statistics of the template.

Photon purity : Signal leakage subtraction

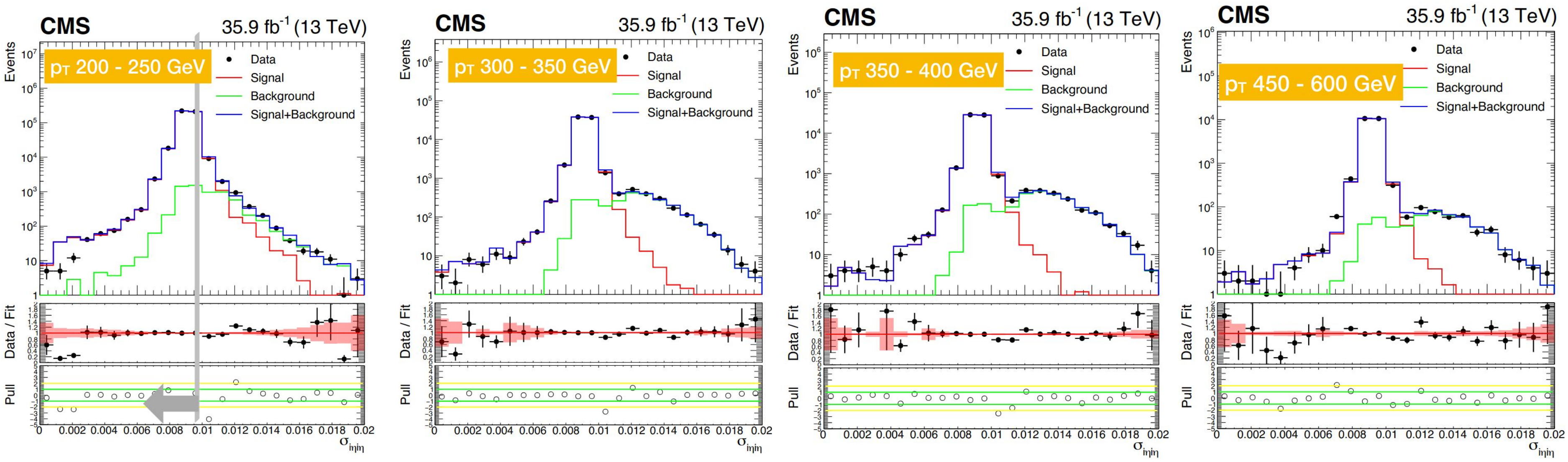
- Any remaining residual contribution from true photons is subtracted using simulation, verified by performing a validation test
- Vary choice of sideband and study effect of this on the $\sigma_{i\eta i\eta}$
- Difference in the shape of this distribution in the nominal sideband and one with a different charged hadron isolation range is estimated by constructing quantity $R_{\sigma i\eta i\eta}$
- Study behaviour of $R_{\sigma i\eta i\eta}$ for large number of possible sideband regions defined within charged hadron isolation of between 1 and 20 GeV

$$\boxed{R_{\sigma_{i\eta i\eta}} = \frac{N_{\sigma_{i\eta i\eta}<0.0094}}{N_{\sigma_{i\eta i\eta}>0.014}}}$$

Ratio of # events in true photon dominated region and fake photon dominated region

- Systematic uncertainty from choice of sideband obtained from maximum variation of background template across all possible regions that produce value of R independent of leakage.

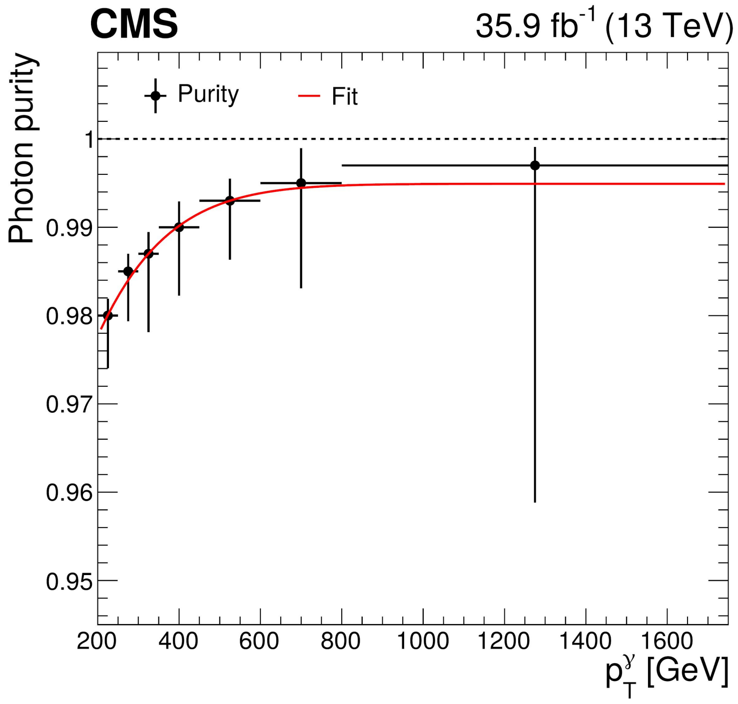
Photon purity: Fit



Purity extracted by integrating fitted template over fiducial region ($\sigma_{i\eta i\eta}$ < 0.00994)

Photon purity : Systematics

- 0.4% to 4.9% uncertainty on purity
- coarser binning chosen for purity fit to have sufficient statistics for fit
- Error function fitted to obtain a smooth parameterization of purity for analysis bins



- Systematics
  - SF variation: JEC, photon efficiencies, PU reweighting.
  - Shower shape reweighting
  - uncertainty on signal template from different MC
  - signal leakage subtraction
  - uncertainty on background template from maximum variation in suitable choice of sideband regions.

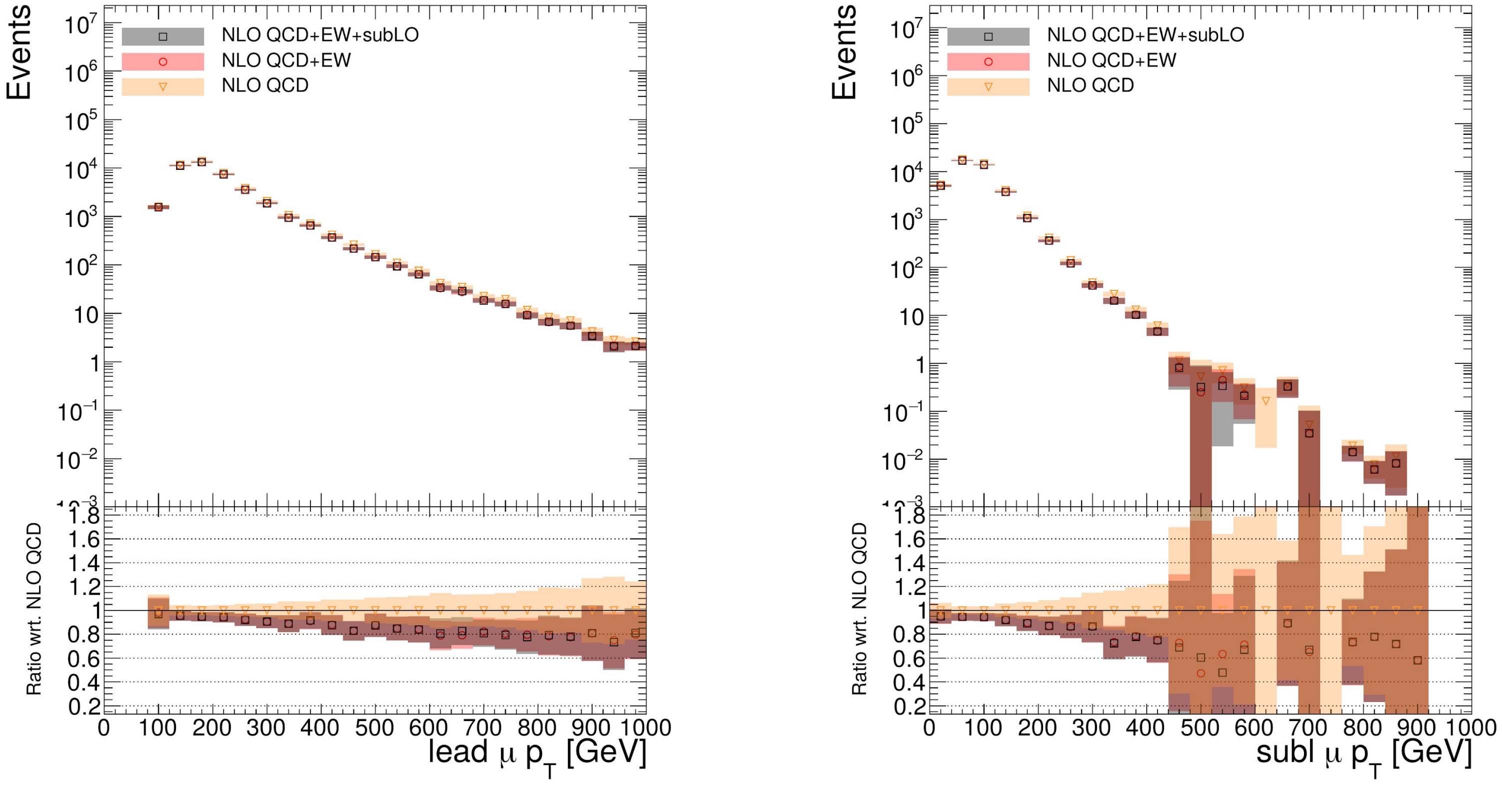
Sources of systematic uncertainty

- **Muon Uncertainties :** As provided by muon POG and obtained using tag and probe method
- **Trigger Efficiencies:** For muons, as provided by muon POG. For photons, as determined in this analysis.
- **Photon Uncertainties :** As provided by EGamma POG and obtained using tag and probe method.
- **Photon purity :** As discussed on previous slides
- **Jet Energy uncertainties :** up and down variations with respect to the central value provided by Jet Energy Resolution and Corrections
- **Unfolding:** Statistics of response matrix and choice of MC generator
- **Pileup:** The recommended 5% uncertainty is applied to the minimum bias cross-section
- **Luminosity:** 2.5% uncertainty on the total integrated luminosity is applied

Summary of systematics uncertainties

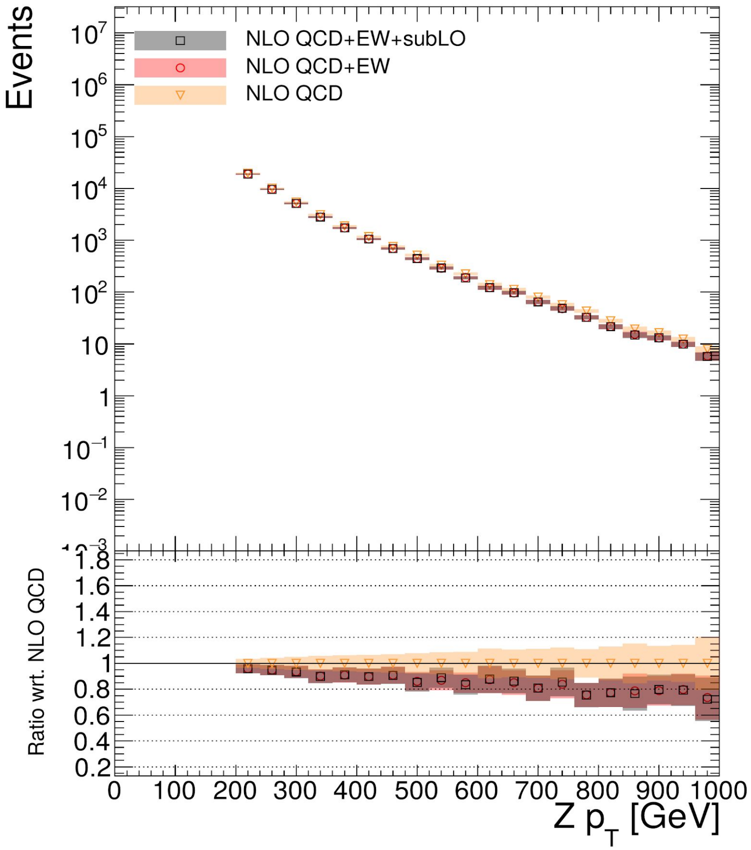
Systematic source	$Z+\text{jets}$ (%)	$\gamma+\text{jets}$ (%)	$Z+\text{jets}/\gamma+\text{jets}$ (%)	collinear region (%)
Trigger	0.0 – 0.1	0.2 – 2.2	0.2 – 2.2	0.5 – 0.8
Muon reconstruction and selection	0.8 – 1.0	–	0.8 – 1.0	0.7 – 1.8
Photon reconstruction and selection	–	2.6	2.6	–
Photon energy scale	–	0.3 – 9.8	0.3 – 9.8	–
Muon momentum scale	1.7 – 21.9	–	1.7 – 21.9	0.0 – 8.3
Photon purity	–	0.2 – 1.1	0.2 – 1.1	–
Background yields	0.5 – 1.6	–	0.5 – 1.6	1.1 – 10.2
Pileup	0.0 – 0.8	0.0 – 0.3	0.0 – 0.3	0.1 – 0.8
Luminosity	2.5	2.5	0.0 – 0.1	2.5
Unfolding	0.3 – 18.6	1.1 – 6.4	1.2 – 19.6	1.7 – 19.8
Jet energy scale/resolution	0.0 – 0.2	0.1 – 0.5	0.0	0.5 – 1.4
Total	3.3 – 28.9	4.0 – 11.6	3.5 – 39.3	3.7 – 21.0

Muons Pt - p_T distribution



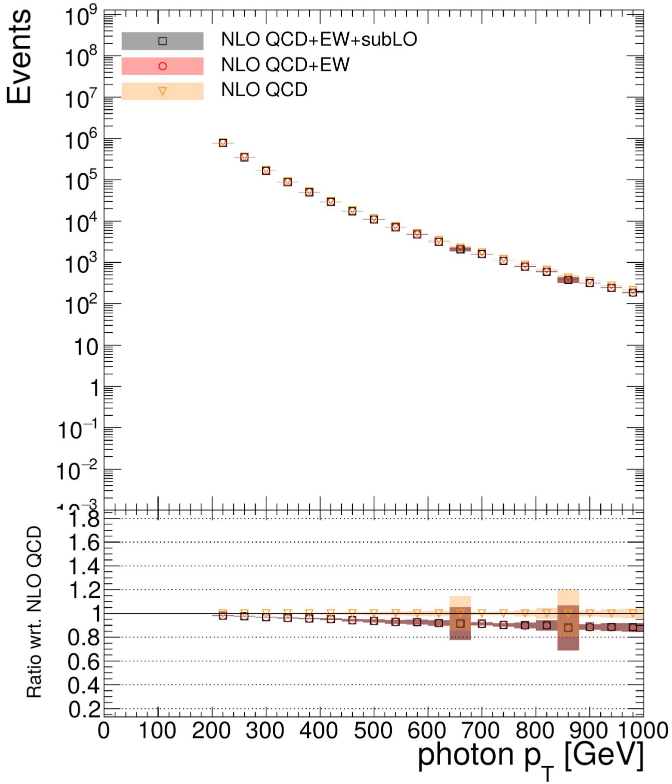
Z+jets - p_T distribution

- Errors are purely statistical
- Impact of NLO EW correction as expected with a decresing of cross section growing with p_T
- Subleading contributions do not change the behaviour, difference between NLO EW and subLO can be used as theory systematic



γ+jets - p_T distribution

- Errors are purely statistical
- Impact of NLO EW correction as expected with a decresing of cross section growing with p_T
- Subleading contributions do not change the behaviour, difference between NLO EW and subLO can be used as theory systematic



min ΔR (Z,j)

- Decrease of 15-20 % in the back-to-back peak as expected
- Smaller decrease at low delta R also expected