QCD and EW measurements with V+jets in CMS

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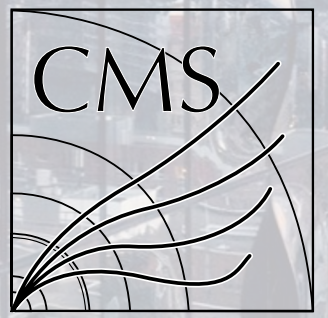
on behalf of the CMS Collaboration



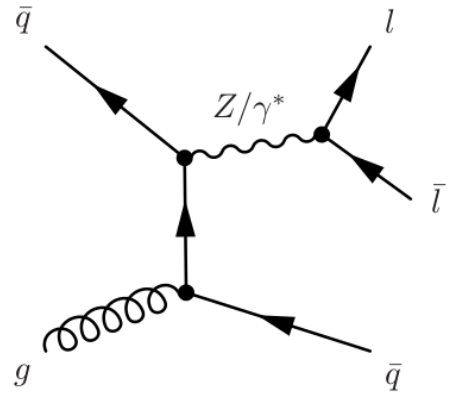
UCLouvain

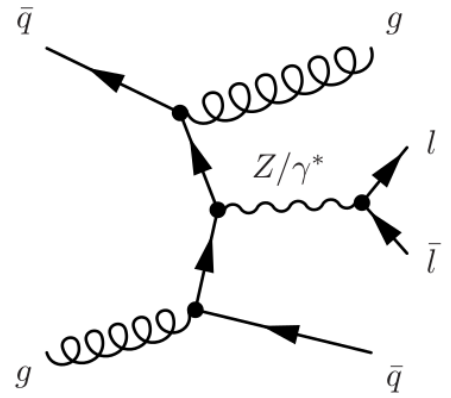
Introduction

- W and Z bosons are produced at high rate at the LHC
  → very large range of cross sections to study

- Important part of the LHC physics program:
  - Precision tests of the SM
  - To “tune” our simulation and improve perturbative calculations
  - QCD modelling
  - Tool for understanding our detectors
  - Irreducible background to BSM and Higgs analyses

- W and Z bosons are typically reconstructed via leptonic final states

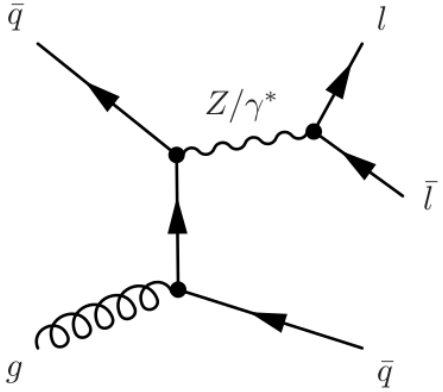


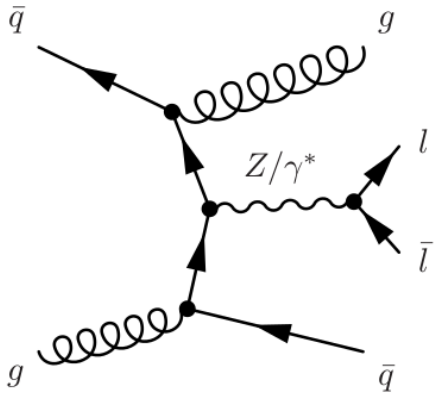


Outline

In today's talk: selected results from LHC Run 2

- Differential measurement of Z + jets (SMP-19-009, accepted by *PRD*)
- Azimuthal correlations in Z + jets events (*Eur.Phys.J.C* 83 (2023) 8, 722)
- Collinear Z emission (*JHEP* 05 (2021) 285)
- Measurement of Z($\rightarrow \boldsymbol{\nu\nu}$) + jets (*JHEP* 05 (2021) 205)
- Measurement of invisible Z width (*Phys. Lett. B* 842 (2023) 137563)



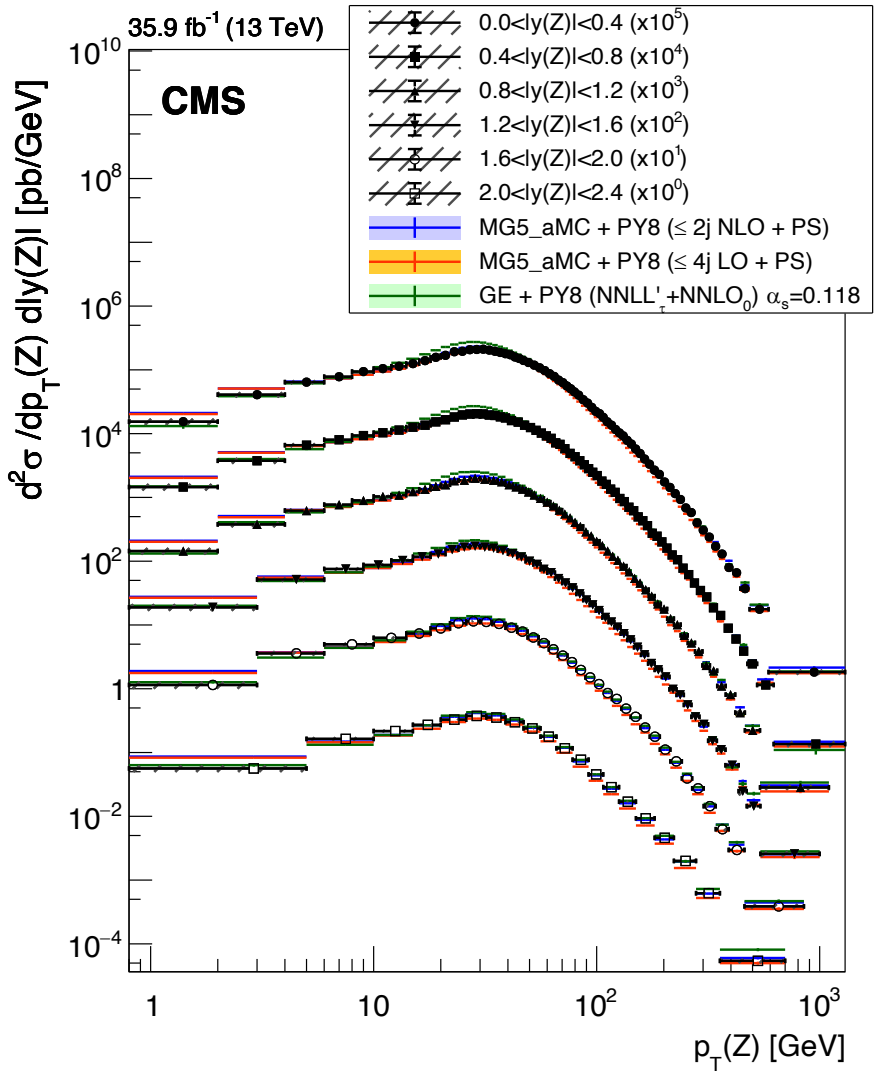


Full list of CMS Standard Model Physics publication is available here

Differential measurement of Z + jets

SMP-19-009, accepted by *PRD*

- Measurement of several observables of Z + jets
- Based on 2016 dataset
- $Z \to ee$ and $Z \to \mu\mu$ channel
- Differential cross section:
  - Double differential p_{T} and $|y|$of Z and jets
  - p_{T} and $|y|$of 5 leading jets
  - Inclusive & exclusive jet multiplicity: up to 8 jets
  - Angular variables
  - Dijet invariant mass
- Unfolded to particle level
- Precise measurements performed with very fine binning

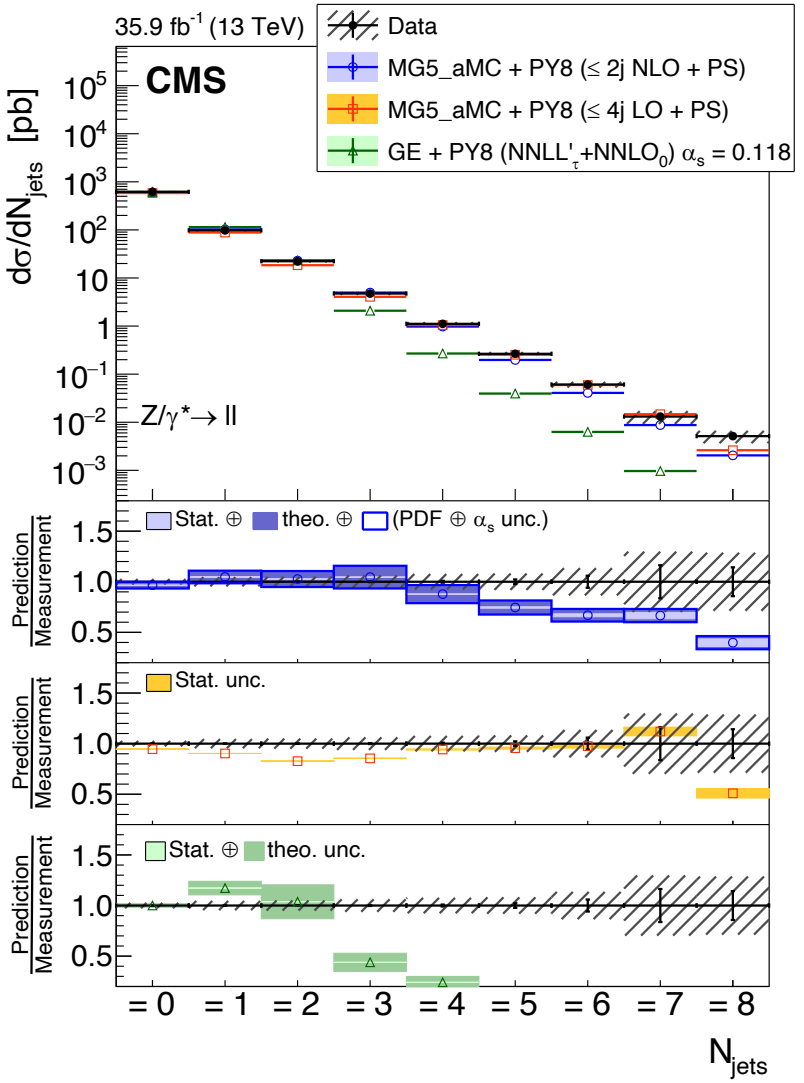


Differential measurement of Z + jets

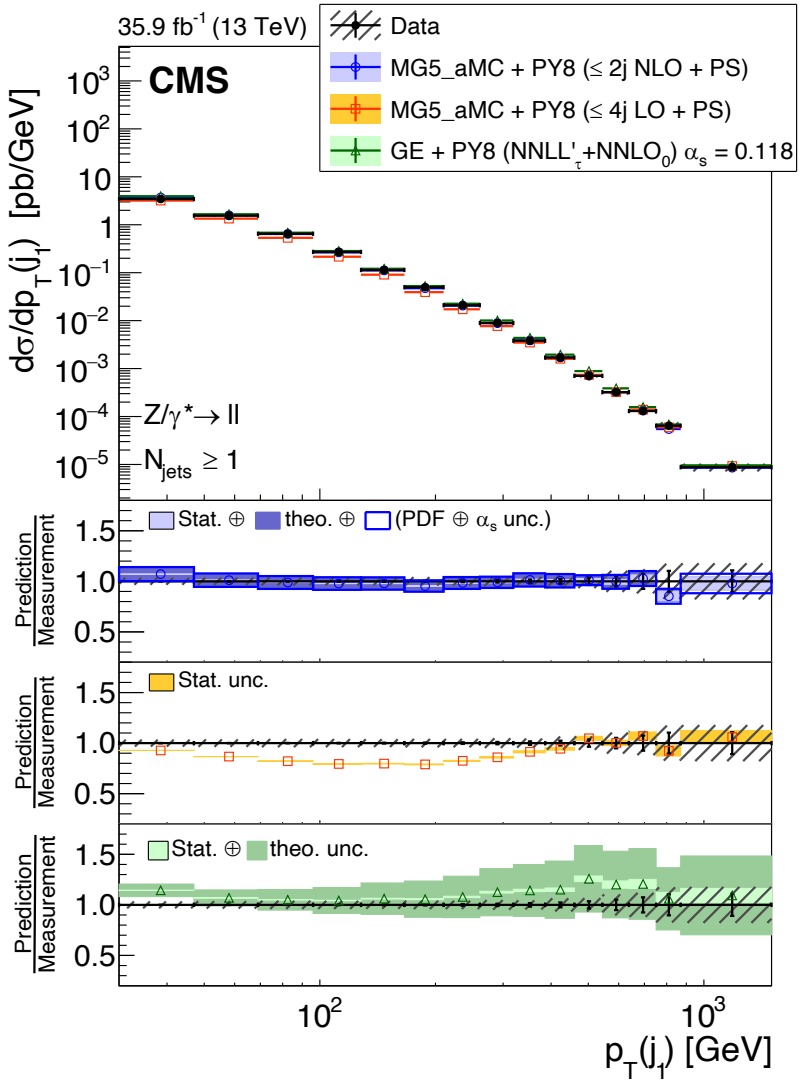
SMP-19-009, accepted by *PRD*

- Good agreement for NLO and LO MG5_aMC prediction with $N_{jets} \leq 4$ jets due to ME accuracy
- Geneva model corresponds to Z + up to 2 jets
  - Expected fall of for events with higher jet multiplicity
- In general, measured differential cross sections agree with the MC prediction within the experimental and theoretical uncertainties

N_{jets}



Leading jet p_T

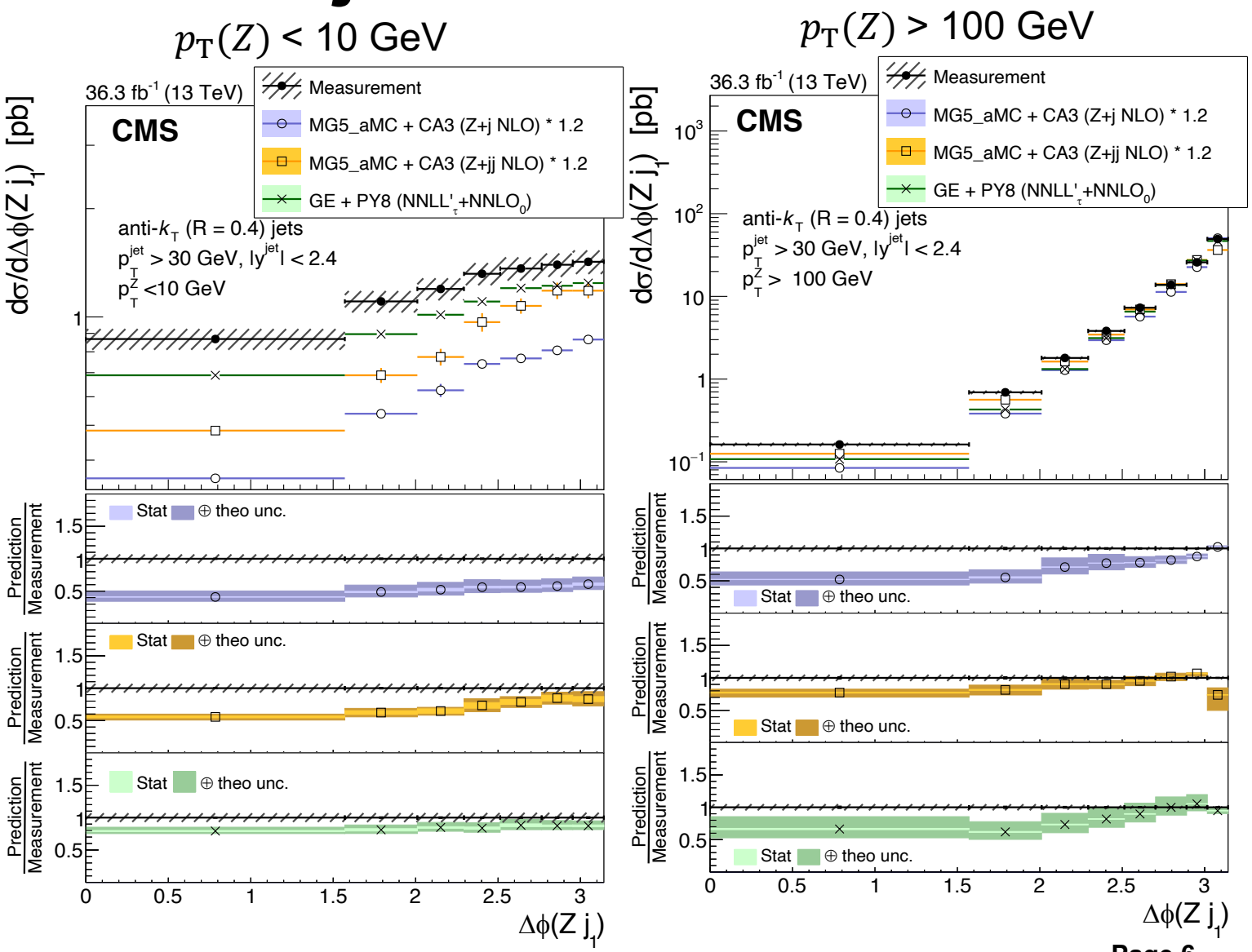


Eur.Phys.J.C 83 (2023) 8, 722

Azimuthal correlations in Z + jets

- Measurement of azimuthal correlation between Z boson and jets: $\Delta\phi$
- 3 different Z p_{T} regions:
  - $p_{\mathrm{T}}(Z)$ < 10 GeV
  - 30 < $p_{\mathrm{T}}(Z)$ < 50 GeV
  - $p_{\mathrm{T}}(Z)$ > 100 GeV
- $\Delta\phi$ mostly flat for $p_{\mathrm{T}}(Z)$ < 10 GeV

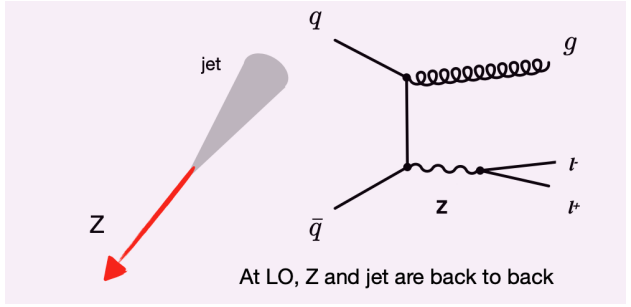
  → no correlation
- For $p_{\mathrm{T}}(Z)$ > 100 GeV: Z boson and jet are typically back-to-back
- Geneva model describes data well
- MG5_aMC + Cascade 3 (Z +2j NLO) in good agreement where MPI is negligible



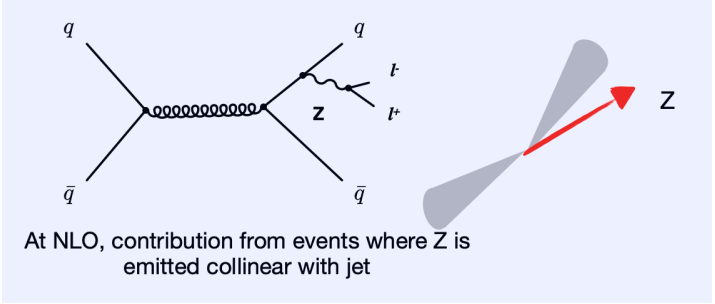
Collinear Z emission

JHEP 05 (2021) 285

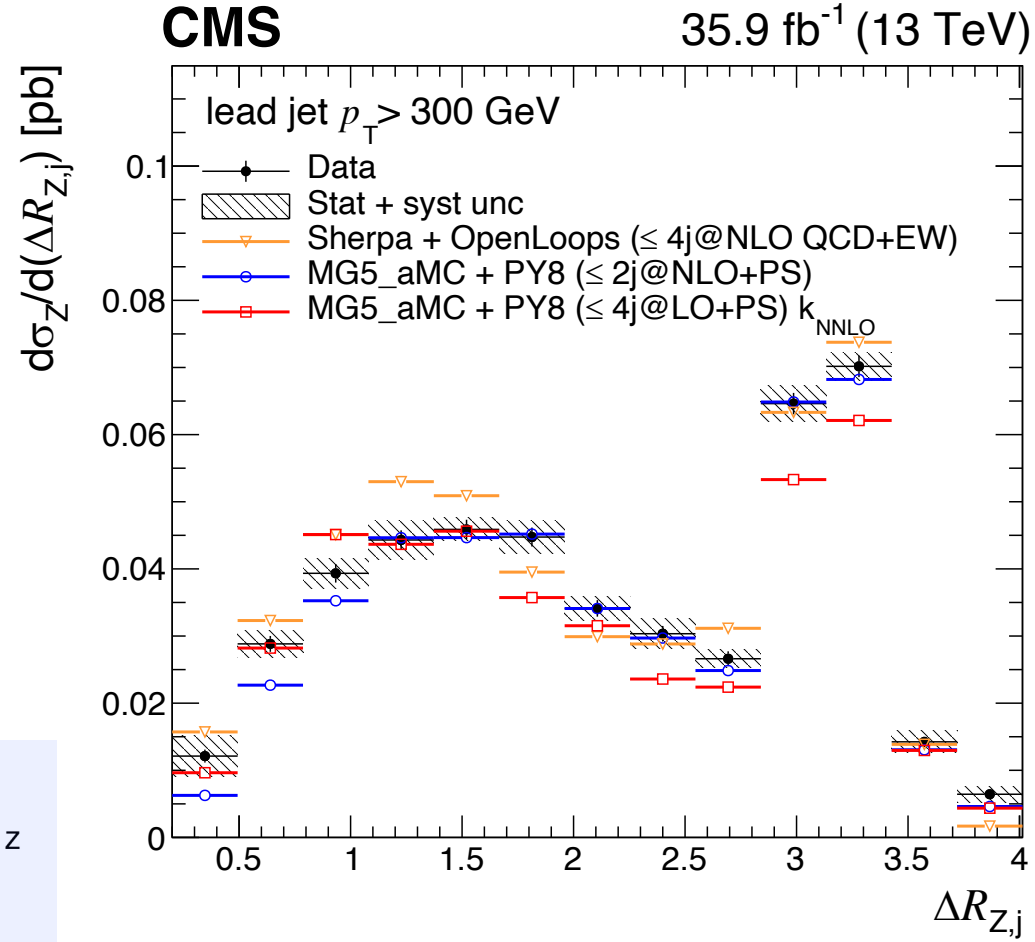
- First study of collinear region for Z+jet events at the LHC
- Measure differential cross section of Z+jet as function of $\Delta R(Z, \text{closest jet})$
- Complex admixture of Z+1 and 2 jets processes
- Particularly sensitive to higher order QCD and EWK corrections
- Leading jet p_T > 300GeV, 500GeV



At LO, Z and jet are back to back

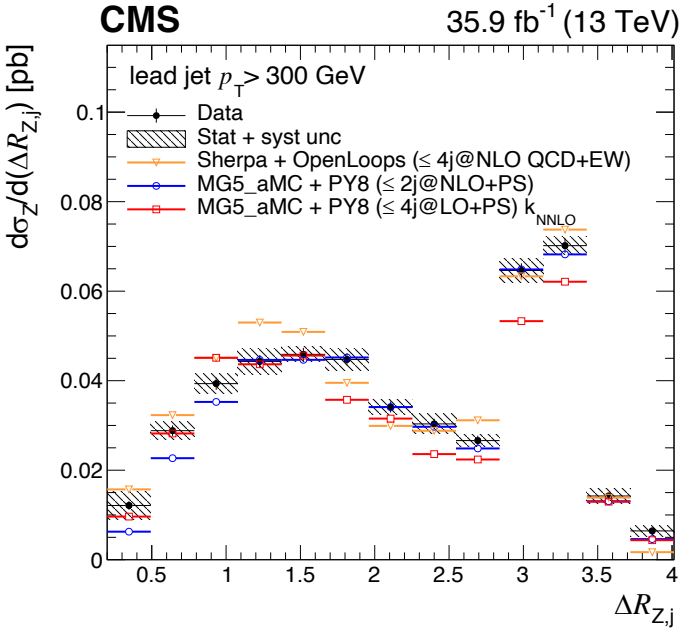


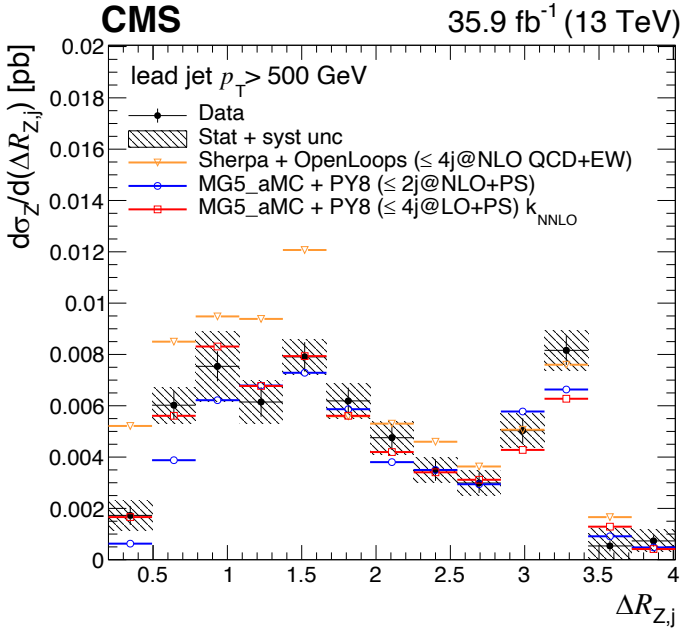
At NLO, contribution from events where Z is emitted collinear with jet

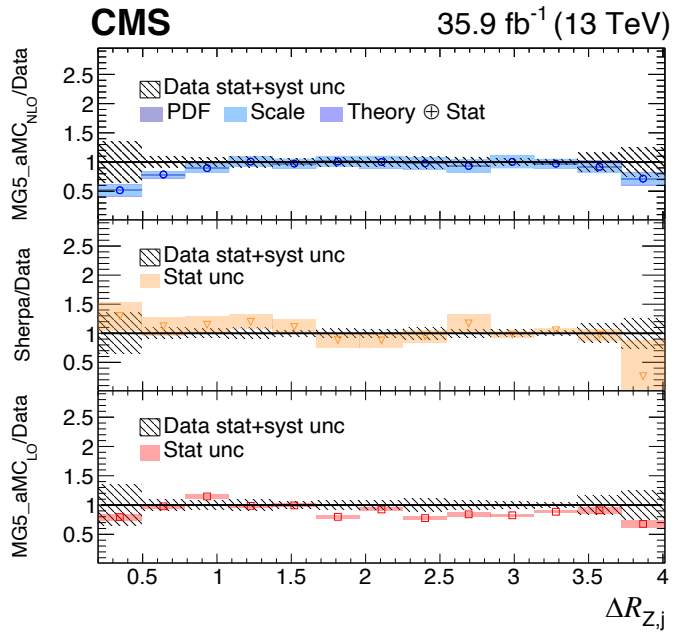


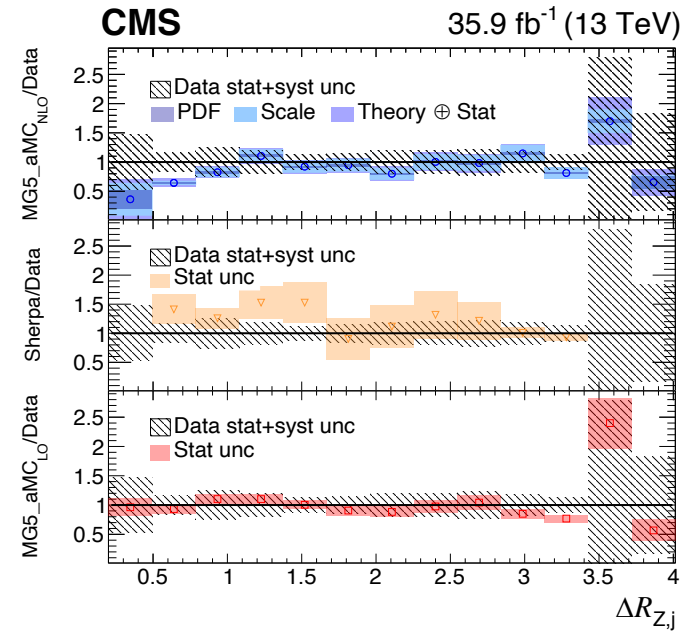
Collinear Z emission

- Low ΔR region is dominated by collinear Z emission
- $\Delta R \sim \pi$ region is dominated by back-to-back topology
- Unfolded data compared to LO and NLO predictions
- No single MC generator can accurately describe data across the entire range







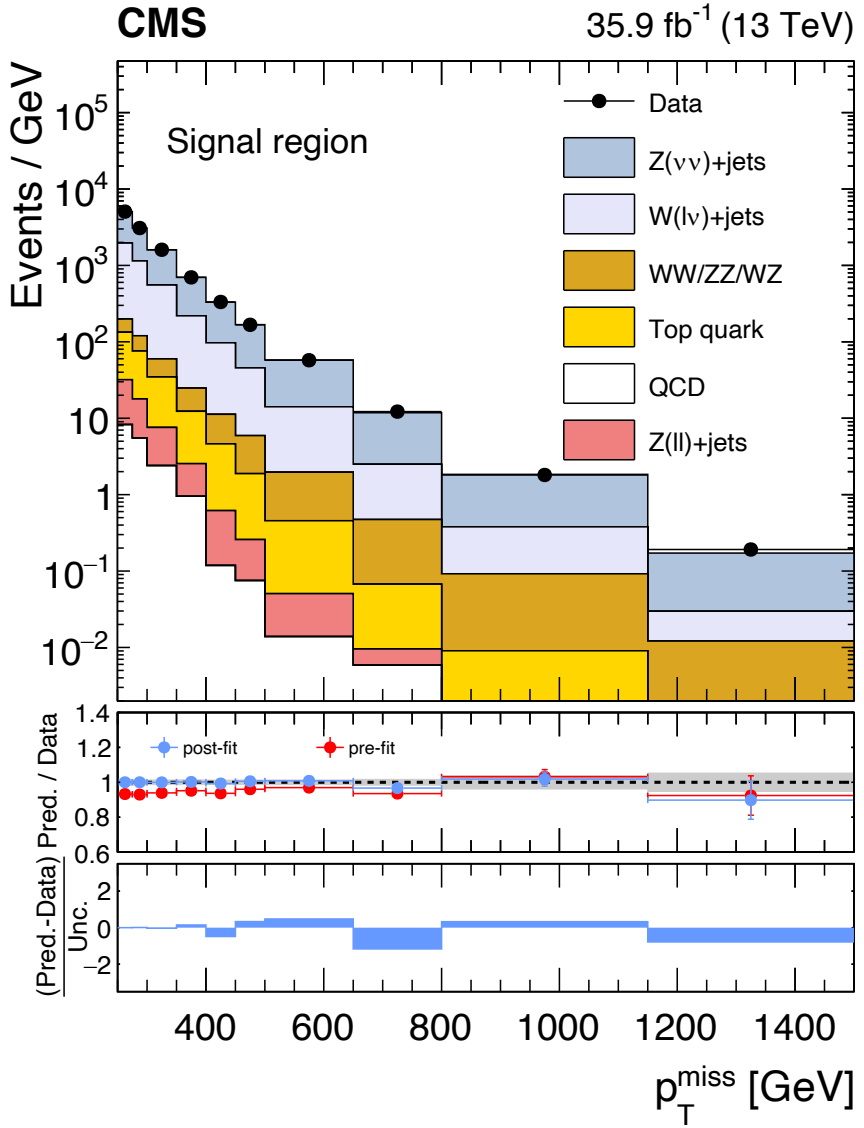


JHEP 05 (2021) 285

Measurement of Z($\rightarrow \nu\nu$) + jets

JHEP 05 (2021) 205

- Measurement of the total and differential cross section of Z$\rightarrow \nu\nu$
- Events are selected with $p_{\mathrm{T}}^{\mathrm{miss}}$ > 250 GeV and jets p_{T} > 100 GeV, and a lepton veto
- Control regions with single lepton to constrain the W background (the largest background, ~85%)
- Perform a simultaneous fit in a signal and W$\rightarrow l\nu$ control regions to obtain Z($\rightarrow \nu\nu$) signal cross section and W background rates

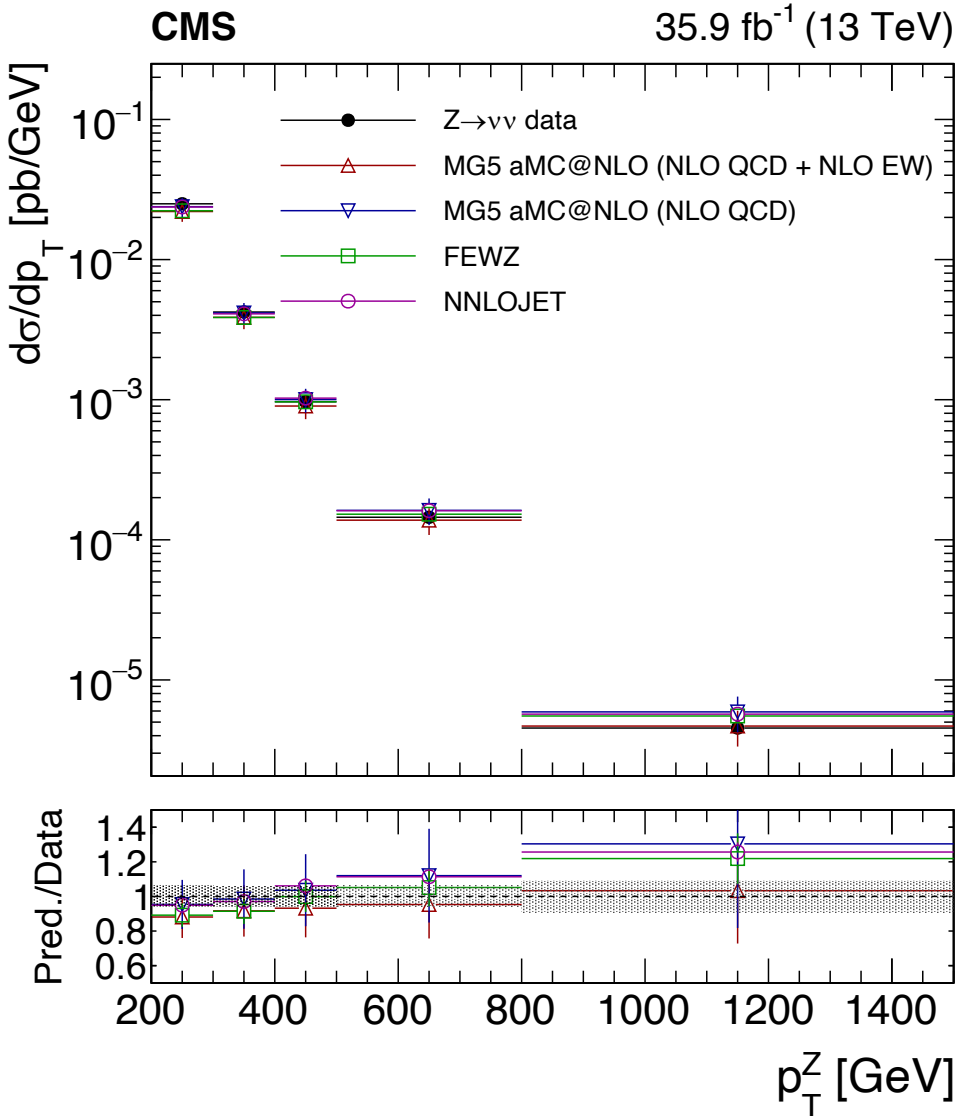


Measurement of Z($\rightarrow \nu\nu$) + jets

JHEP 05 (2021) 205

- Differential cross section up to Z boson $p_{\mathrm{T}} \sim 1400$ GeV
- Systematic uncertainties < 5%
  - Uncertainties are dominated by the by the jet energy scale and data statistical uncertainties at high Z p_{T}
- Data are compared to various MC predictions
- Predictions overestimate data at high Z p_{T} except MG5 aMC@NLO (NLO QCD + NLO EW)
- Improve statistical uncertainty at high Z p_{T} by combining results from Z($\rightarrow \nu\nu$) & Z($\rightarrow ll$) analyses

  $\rightarrow$ most precise measurement up to date
- Z$\rightarrow \nu\nu, ll$ at high p_{T} is important background for many searches



Phys. Lett. B 842 (2023) 137563

Measurement of invisible Z width

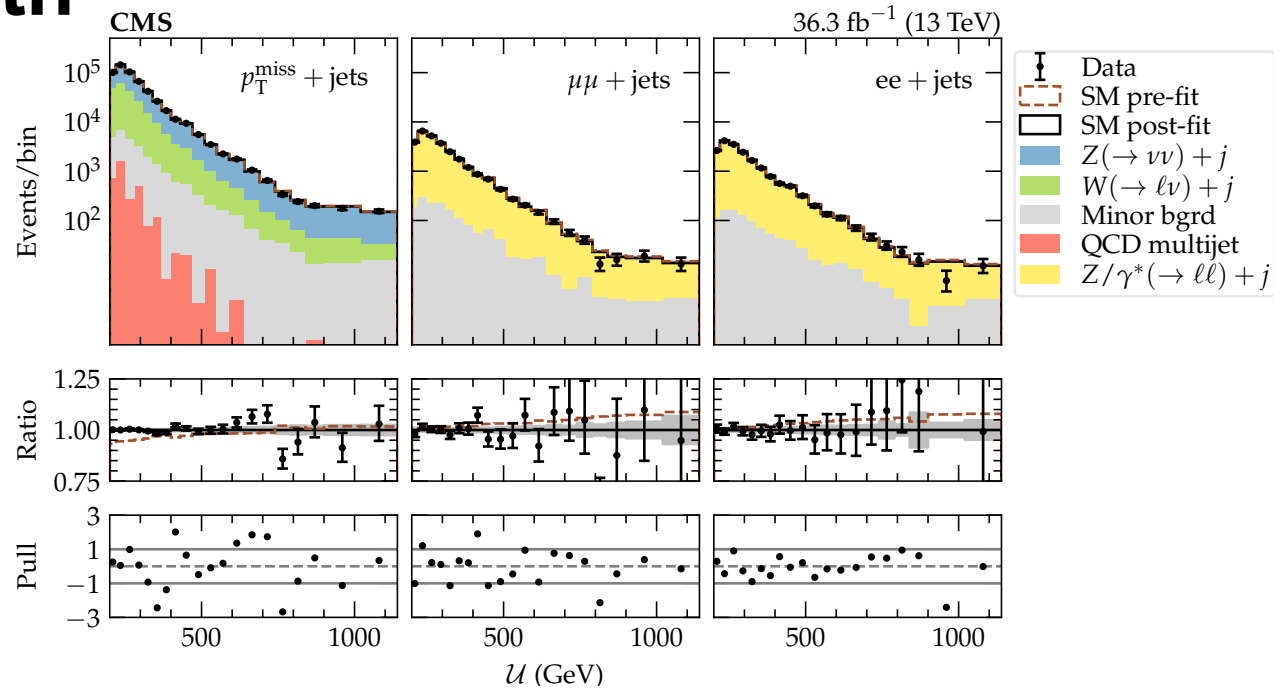
- Measurement of the Z invisible width at hadron collider
- Indirect measurement

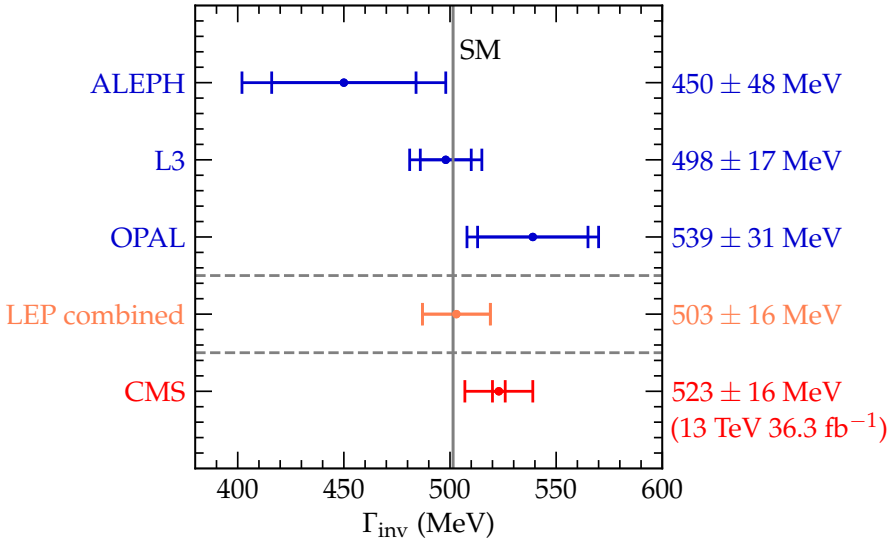
$$\Gamma(\mathrm{Z} \to \nu\bar{\nu}) = \frac{\sigma(\mathrm{Z+jets})\mathcal{B}(\mathrm{Z} \to \nu\bar{\nu})}{\sigma(\mathrm{Z+jets})\mathcal{B}(\mathrm{Z} \to \ell\ell)}\Gamma(\mathrm{Z} \to \ell\ell)$$

- Z invisible width extracted from the ratio of measured Z($\to ll$) + jets and Z($\to \nu\nu$) + jets using LEP's measured Z($\to ll$) partial width

- Comparable precision w.r.t. LEP combination

- $\Gamma_{inv} = 523 \pm 3(\mathrm{stat}) \pm 16(\mathrm{syst})$ MeV
  - muon/electron ID: 2%(1%)
  - jet energy scale: 1.8%





Conclusion

- Presented wide range of the V + jets measurements from CMS
  - Extended to extreme phase spaces in Z + jets
    → High and low Z p_{T} region
    → Collinear Z emission
    → Invisible Z boson decay

- Run 2 statistics allows for precise measurements allowing to better probe MC generator performances

- In general, overall good agreement over NLO predictions

  → especially for state-of-the-art predictions