Drell-Yan Measurements at CMS

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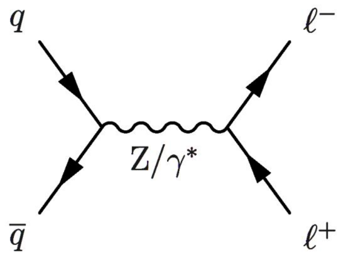
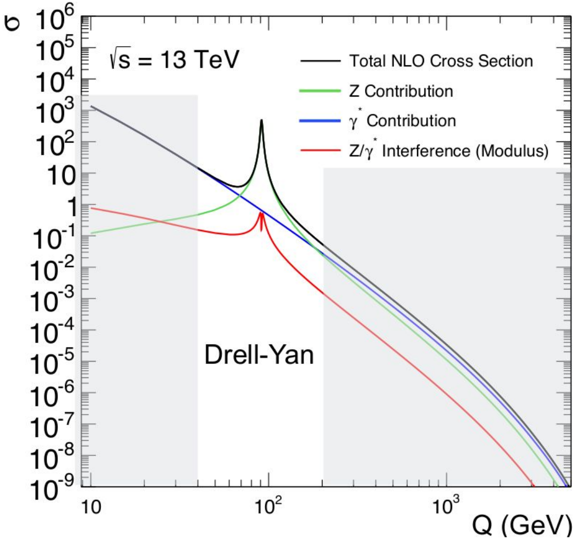
Introduction

- Drell-Yan (DY) process is one of the best understood processes at hadron colliders
  - Precisely measured using clean signatures from leptonic final states
  - Available of many theoretical calculations to describe the process
- The DY measurements at LHC are important:
  - Provide rigorous tests of theoretical predictions
  - Measure weak mixing angle
  - Constrain parton distribution functions (PDFs)
  - Probe existence of new heavy gauge bosons
- CMS DY measurement results at 13 TeV:
  - CMS-SMP-20-003: Transverse momentum of lepton pairs ($p^T_{\ell\ell}$) in different dilepton mass ($m_{\ell\ell}$) ranges
  - JHEP 08 (2022) 063: Forward-backward asymmetry
  - JHEP 12 (2019) 061: Differential Drell-Yan cross section as a function of dilepton rapidity and transverse momentum
  - JHEP 12 (2019) 059: Differential Drell-Yan cross section as a function of dilepton mass





Theoretical predictions

- FEWZ: fixed-order calculation at NNLO in QCD + NLO in EW
- amc@NLO (MG5_aMC) + Pythia8: ME (NLO upto 2 jets) + Pythia8 parton shower model
- CASCADE 3: Z + 0 (1) jet at NLO from MG5_aMC, initial state parton shower from TMD+PB and final state parton shower + hadronization + QED FR from Pythia6
- GENEVA: NNLO + higher-order resummation (NNLL or N^3LL on jettiness or q_T variable)
- MiNNLO: NNLO ME and Pythia8 parton shower
- POWHEG: NLO in QCD
- ArTeMiDe: Analytical prediction, NNLO TMD (N^3LL)

Dilepton invariant mass

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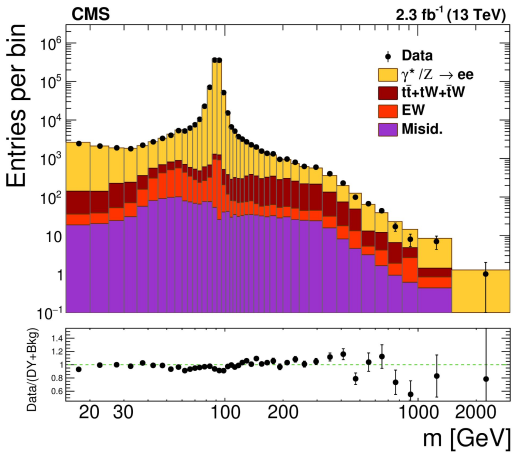
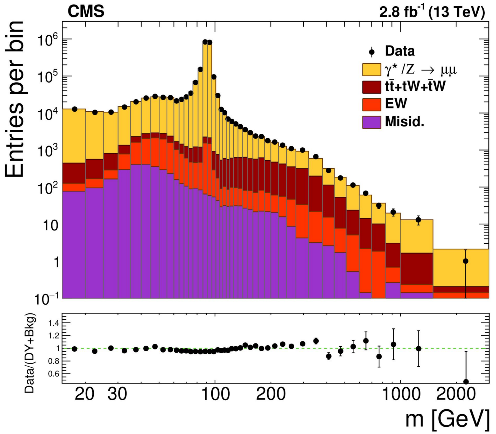
- Measure differential cross section as a function of dilepton invariant mass, $d\sigma/dm$
  - Provide test of perturbative calculations and understanding of DY backgrounds in SM measurements and searches
  - Constrain PDF
- Measured in dielectron and dimuon channels with p_T > 25 GeV and $|\eta|$ < 2.5
- Good agreement between data and predictions over wide mass range 15 to 3000 GeV





Dilepton invariant mass (cont.)

- Differential cross section in full space (corrected for FSR)
- Good agreement between data and prediction from FEWZ
- Photon-induced contributions has sizeable effect in the high mass region

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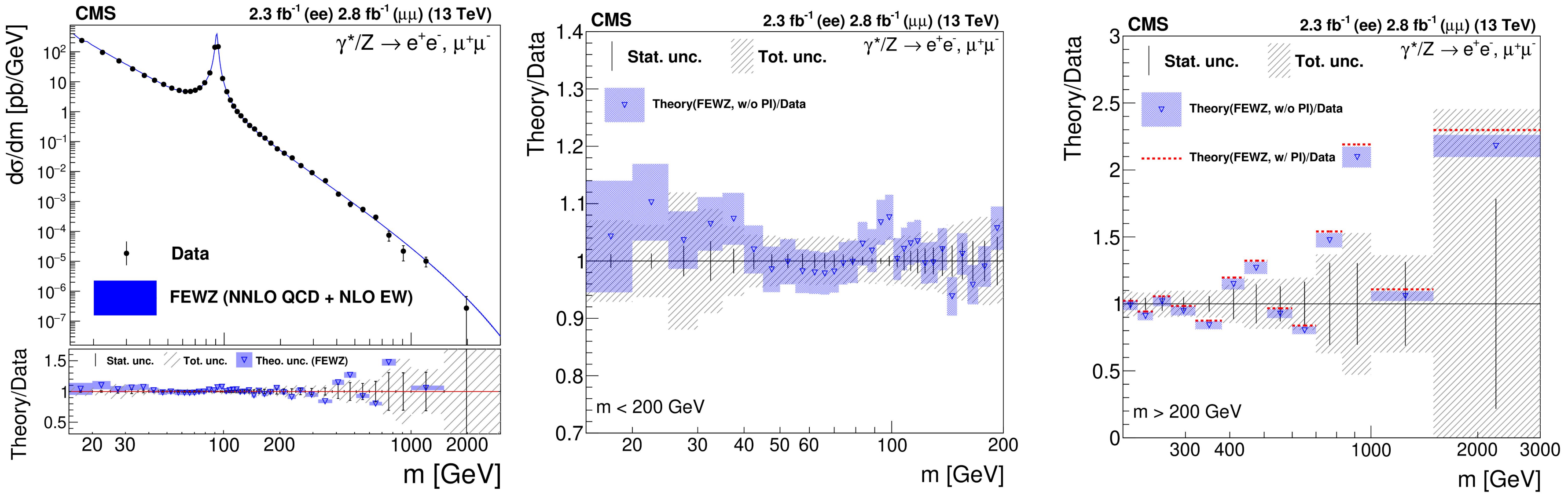
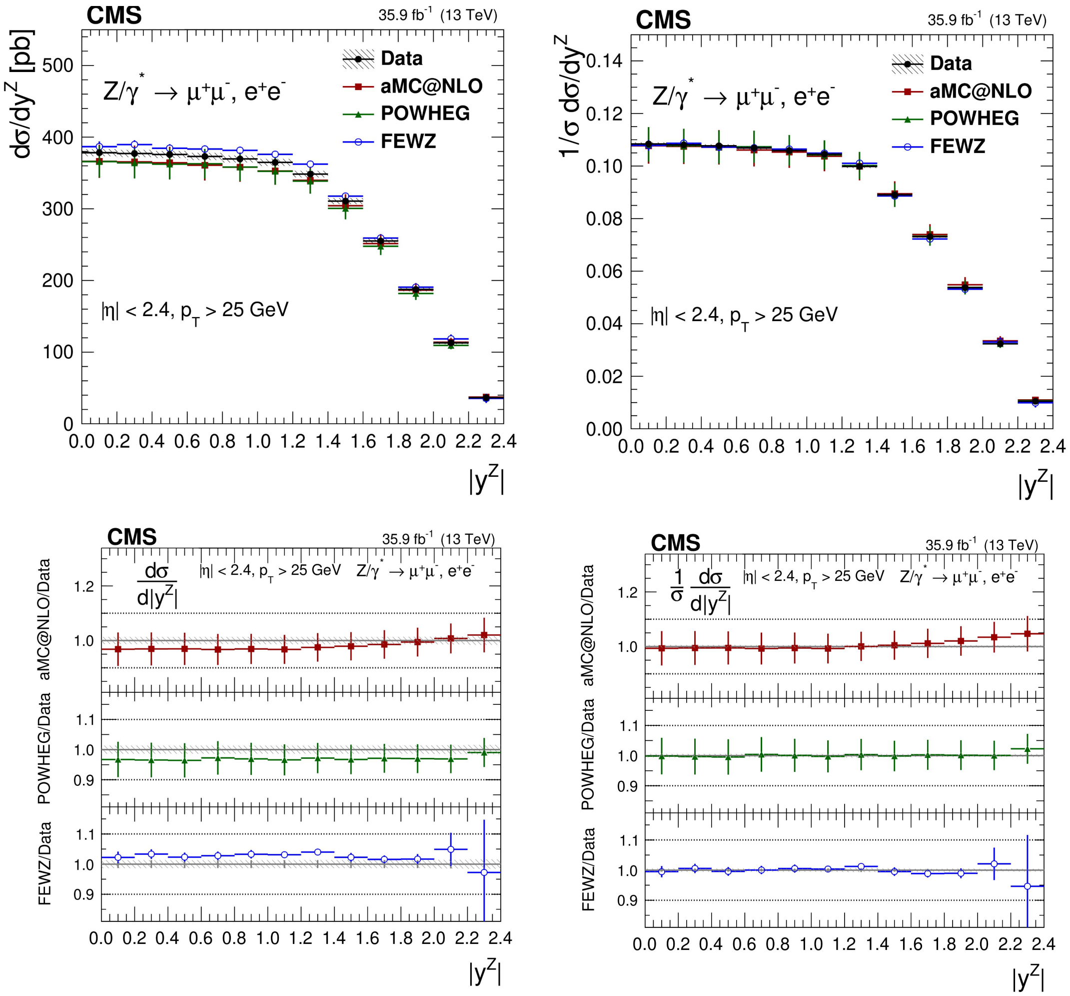


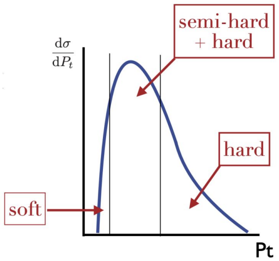
Rapidity (y^Z) distribution

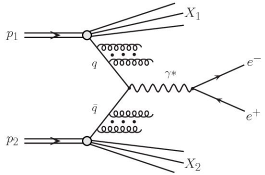
- Provide constraints to light quark and gluon PDF
- Leptons $|\eta| < 2.4$ and $p_T > 25$ GeV, $76 < m_{\ell\ell} < 106$
- amc@NLO and POWHEG agree with data within uncertainties
- FEWZ overestimates data by ~5%



Dilepton transverse momentum

- Dilepton transverse momentum measurement provides insights about soft QCD radiation and hard scattering processes
  - High p_T dominated by hard quark-gluon scattering and described by fixed-order pQCD
  - Low p_T governed by the radiation and intrinsic p_T of the initial-state parton. Soft-gluon resummation is required
- Accurate theoretical prediction of p_T distribution is crucial for precise W mass measurement → important to validate theoretical tools to describe p_T
- Measure p_T distributions at different mass and rapidity ranges to understand QCD effects at different mass scales and phase spaces





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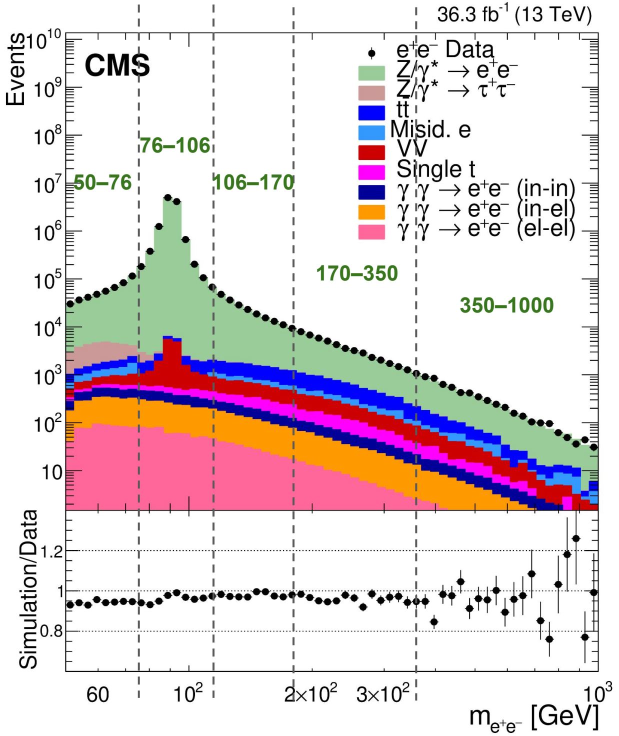
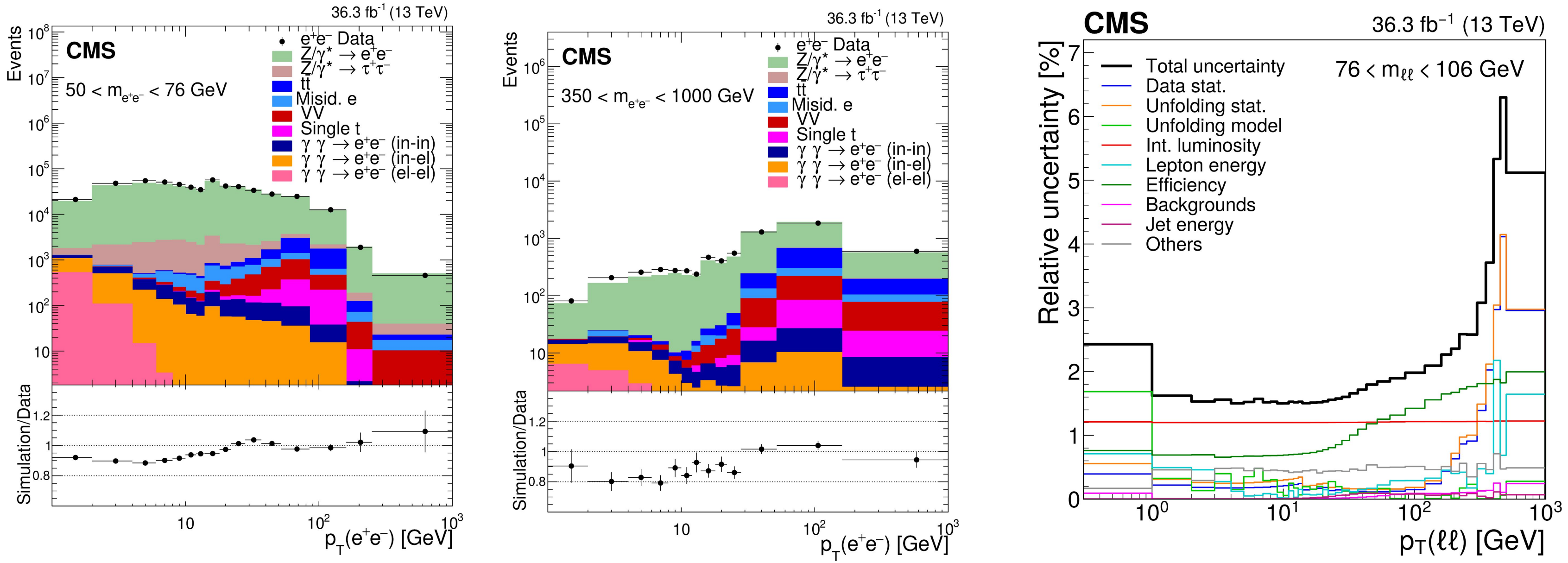


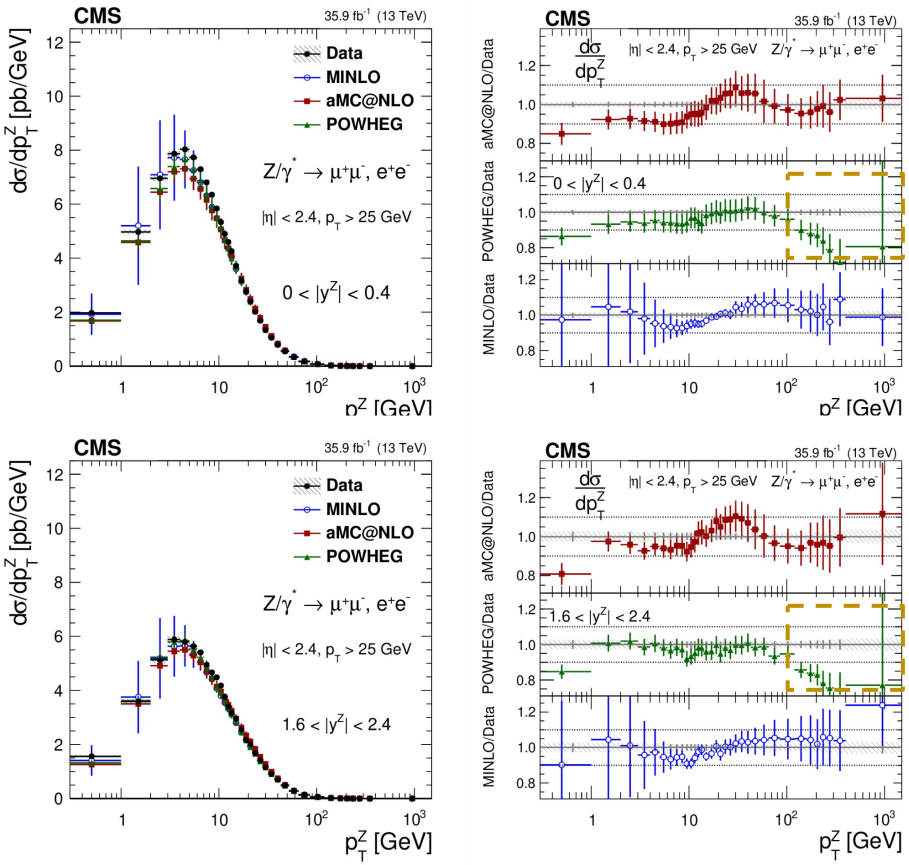
Dilepton transverse momentum measurement

- Selection:
  - Lepton: p_T > 25 GeV, $|\eta|$ < 2.4
  - Jet (for measurement with jets): p_T > 30 GeV, $|\eta|$ < 2.4
- The measurement is almost background free
- Precision is limited by lepton efficiency, luminosity and unfolding



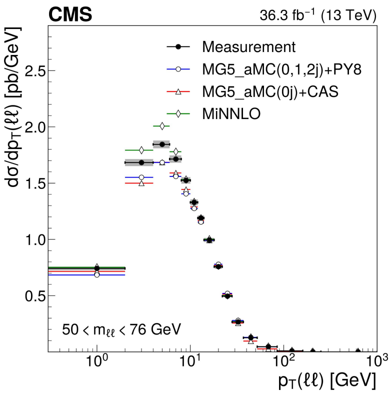
p_T at different rapidity ranges

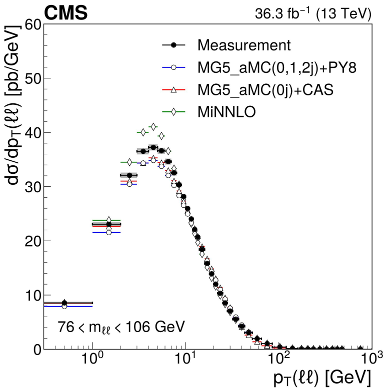
- Data are compared to predictions using parton shower model
- Generally agree with data within uncertainties except for POWHEG in $p_T^Z > 100$ GeV
- MiNLO provides the best description of data

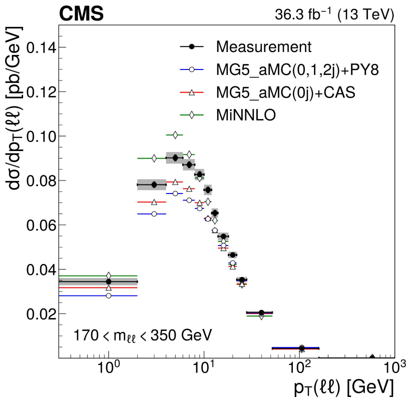


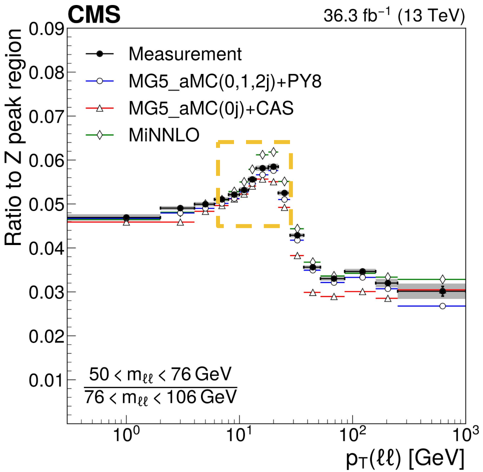
Dilepton transverse momentum at different mass ranges

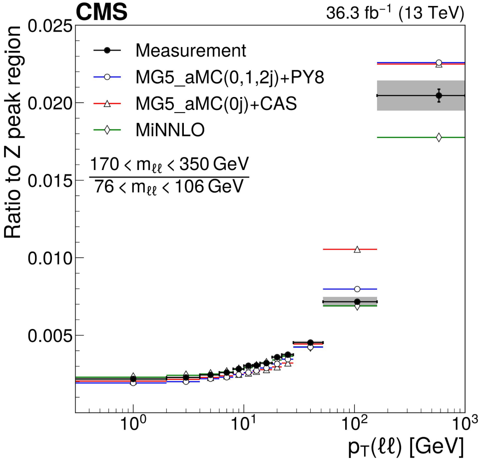
- Peak positions (~4-6 GeV) and rising shape do not change with $m_{\ell\ell}$
- Broader distribution when $m_{\ell\ell}$ increases
- Increasing ratio in lowest $m_{\ell\ell}$ range is due to lepton final state QED radiations (migration from Z peak to lower masses)



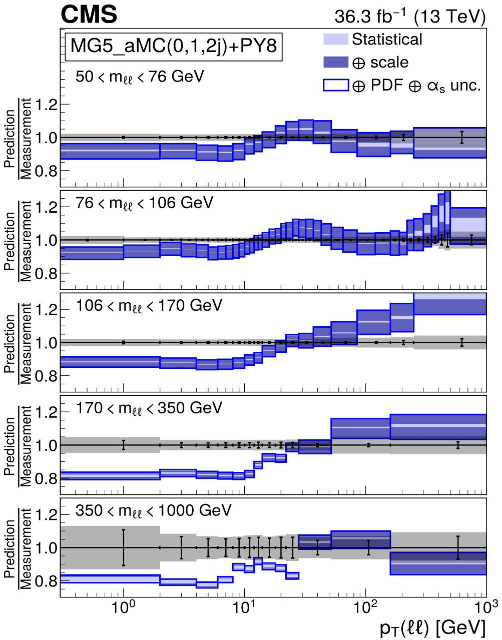


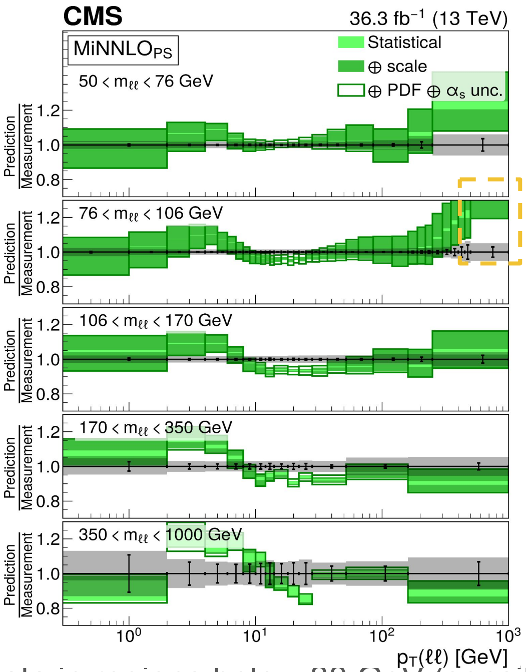


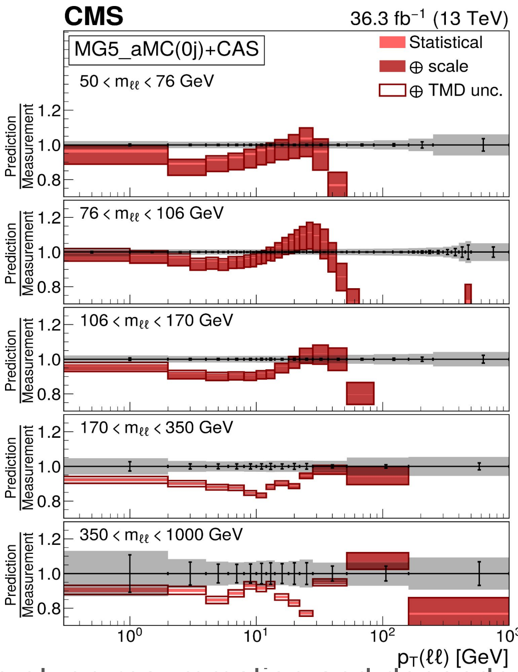




Dilepton transverse momentum at different mass ranges (cont.)

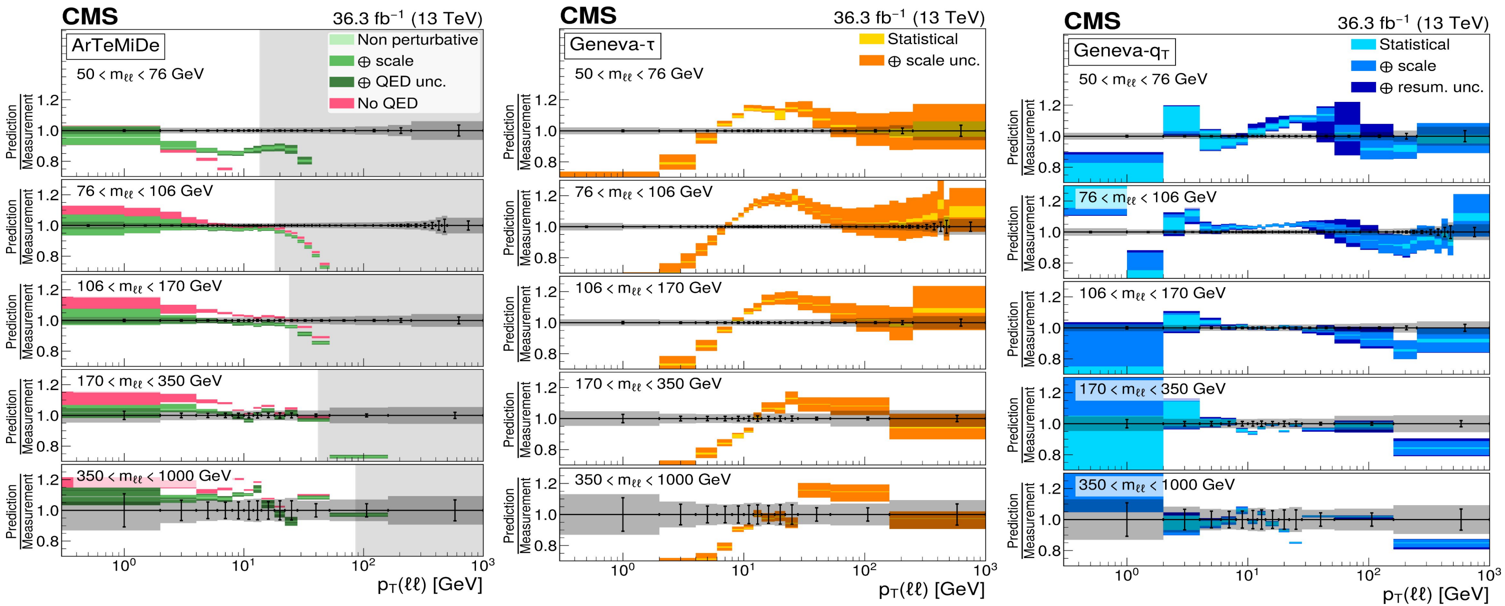






- MG5_aMC+PY8 underestimates data in regions below 30 GeV (sensitive to gluon resummation and dependent on tunes). The effect increases with $m_{\ell\ell}$
- Best global description of data from MiNNLO$_{PS}$ except above 400 GeV, for $m_{\ell\ell}$ around the Z boson peak
- CASCADE: better agreement with data at low p_T regions, lower than data by 5-10% at medium regions and fail to describe data at high p_T (missing higher order calculations)

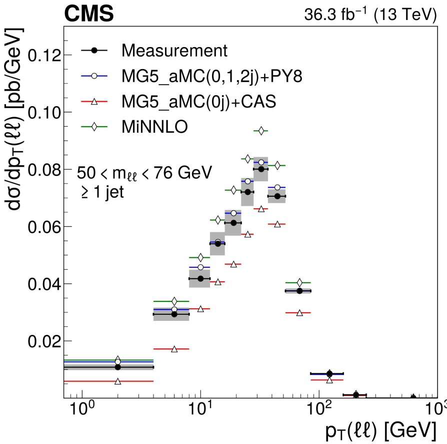
Dilepton transverse momentum at different mass ranges (cont.)

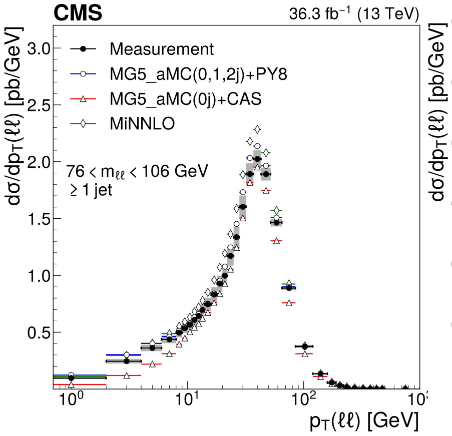


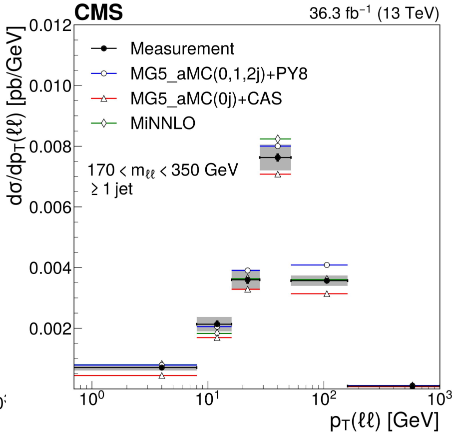
- Data are well-described by ArTeMiDe predictions in low p_T regions ($p_T^{\ell\ell} < 0.2\ m_{\ell\ell}$) except the highest mass bin.
    - Excellent agreement with data for regions under Z peak since use TMD fitted on previous DY measurements at Z boson peak
- GENEVA-τ fails to describe data at p_T < 40 GeV (might be related to the choice of α_s)
- Significant improvement with GENEVA-q_T (q_T resummation at N^3LL)

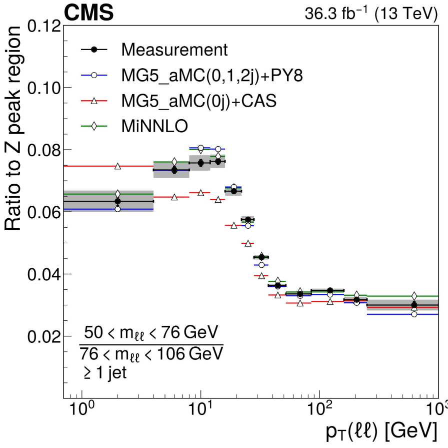
Dilepton transverse momentum with jet requirement

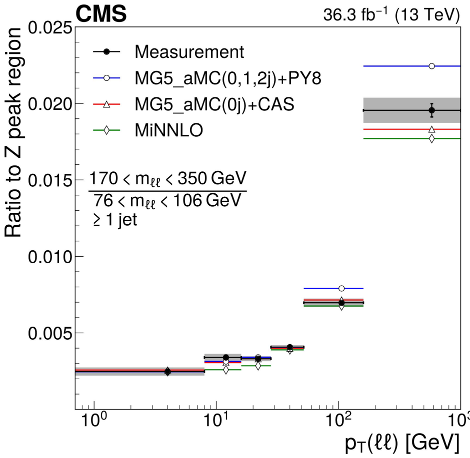
- Complementary way to investigate initial state QCD radiation with jet requirement (at least one jet with p_T > 30 GeV)
- $p_T^{\ell\ell}$ is broaden with more hadronic activities than a single jets
- Low p_T sensitive to multiple hard QCD radiation
- Peak position is dictated by jet p_T requirement of greater than 30 GeV
- Rising and falling shape variations at different $m_{\ell\ell}$ ranges are similar to the inclusive case



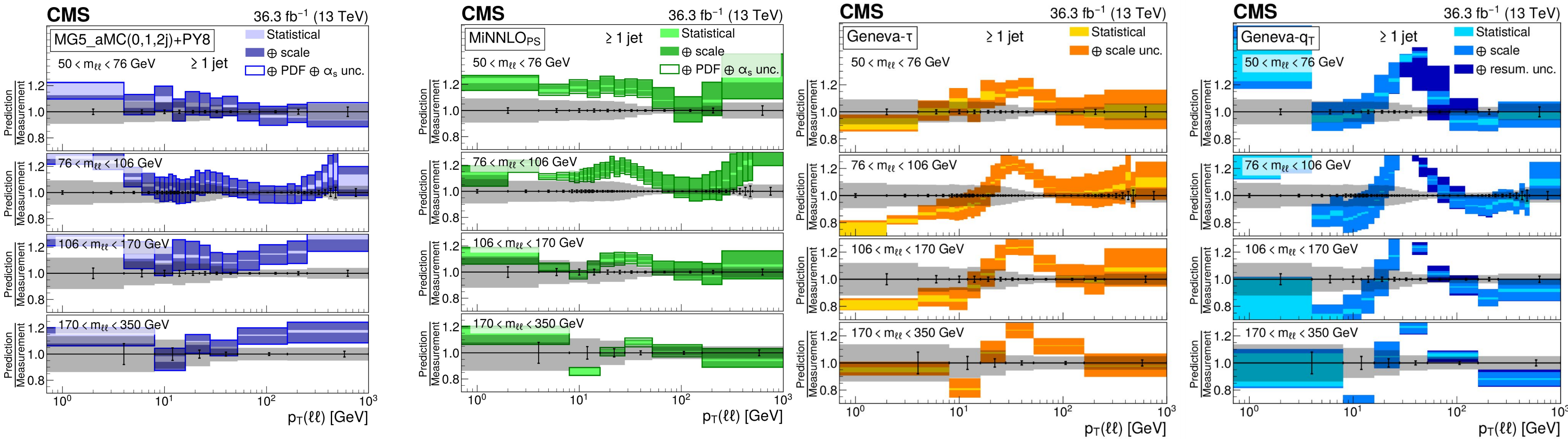








Dilepton transverse momentum with jet requirement (cont.)



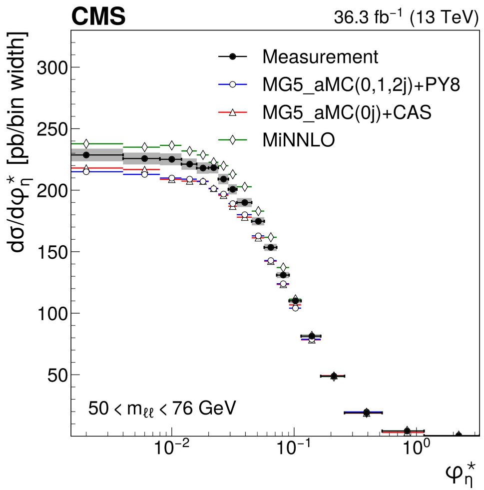
- MG5_aMC+Pythia8 and $\mathrm{MiNNLO_{PS}}$ generally describe data. MiNNLO is better to describe low p_T shape
- Similar prediction over data ratio for two GENEVA predictions (since q_T resummation applied to 0-jettiness case only)

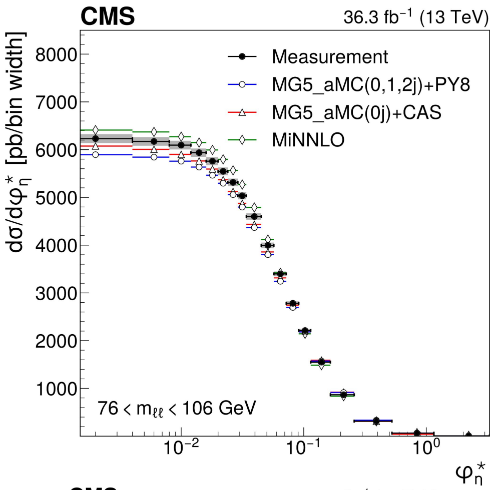
ϕ_η* results

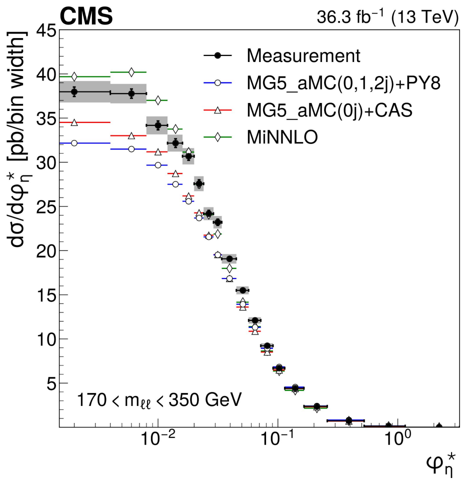
$$\phi^*_\eta = \tan\left(\frac{\pi - \Delta\phi}{2}\right)\,\sin(\theta^*_\eta)$$

$$\cos(\theta^*_\eta) = \tanh\left(\frac{\Delta\eta}{2}\right)$$

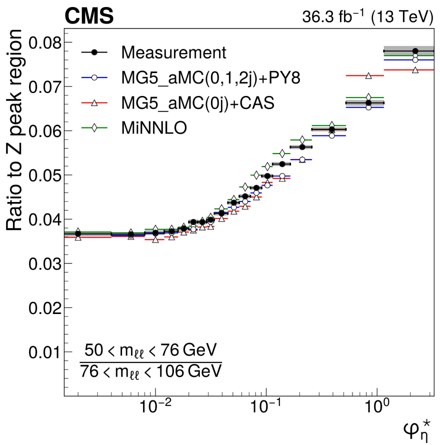
$$\phi^*_\eta \sim p_{\mathrm{T}}^{\mathrm{Z}}/m_{\ell\ell}.$$

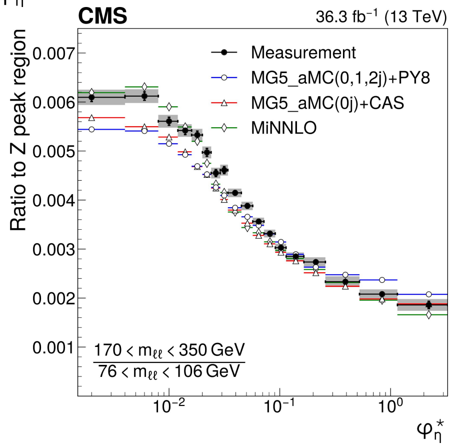




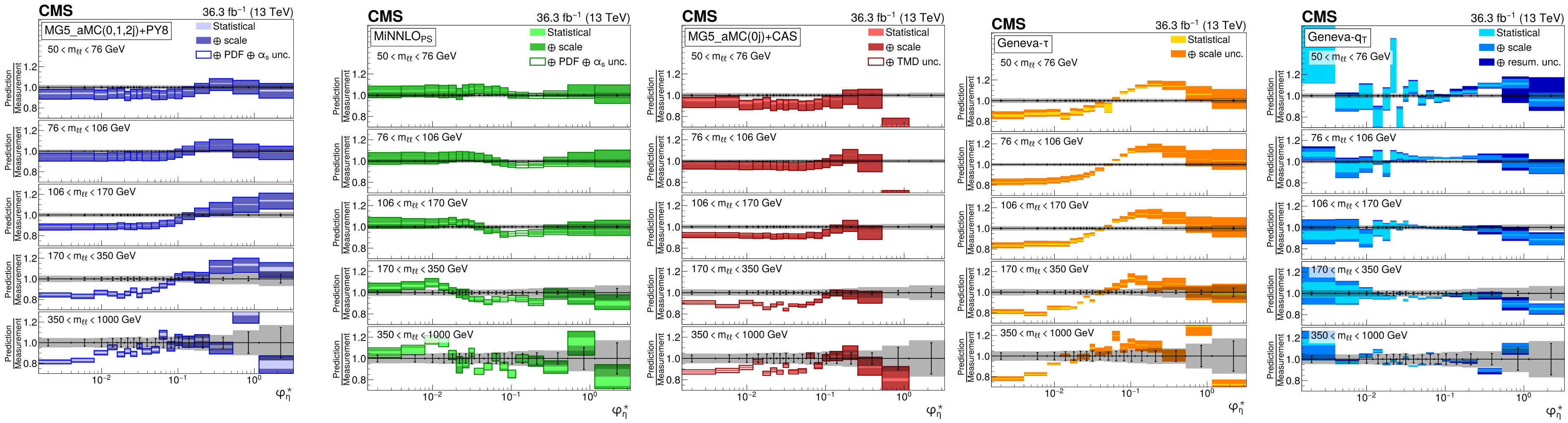


- Fall more rapidly with increasing $m_{\ell\ell}$
- Lepton direction is much less affected by QED FSR radiation → migration from Z peak to the lower mass bin is not visible





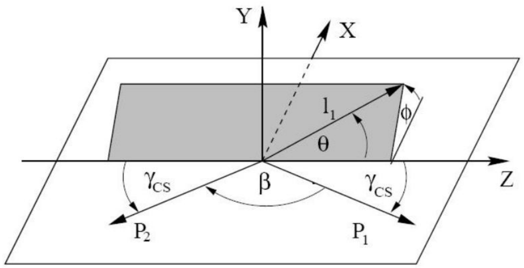
ϕ_η^* results (cont.)



- MG5_aMC + PYTHIA 8: underestimates data in the region sensitive to gluon resummation (ϕ_η^*< 0.1 on Z boson mass peak)
- MiNNLO: best globally description of data
- MG5_aMC + CASCADE: good agreement with data shape ϕ_η^* < 0.1 for all mass ranges
- GENEVA-q_T improves predictions to data with respect to GENEVA-τ

Forward-backward asymmetry (A_{FB})

- Interesting property of the DY process originated from vector and axial-vector couplings of EWK bosons to fermions
  - Sensitive to weak mixing angle and new physics (Z')
  - A_{FB} results provide data to constraint PDF
- A_{FB} depends strongly on $m_{\ell\ell}$ and $y_{\ell\ell}$
- Defined based on the angle θ^* of the negative lepton in the Collins-Soper frame and diluted due to ambiguity of the direction of incoming quark



$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$

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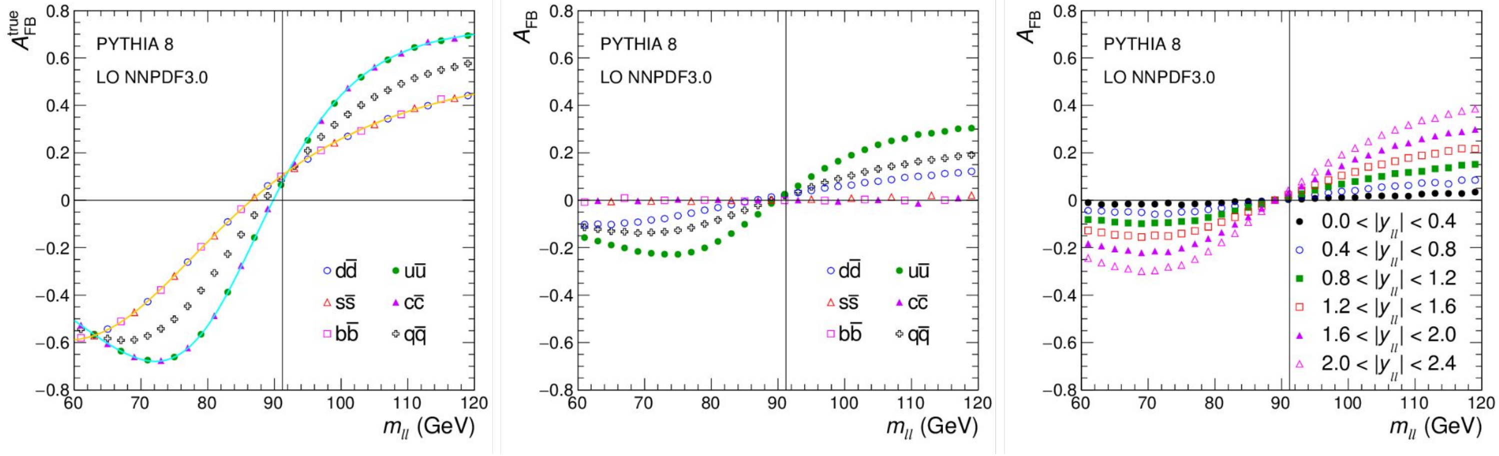


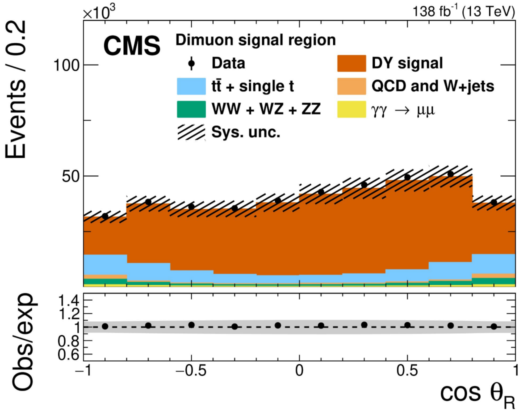
Forward-backward asymmetry (cont.)

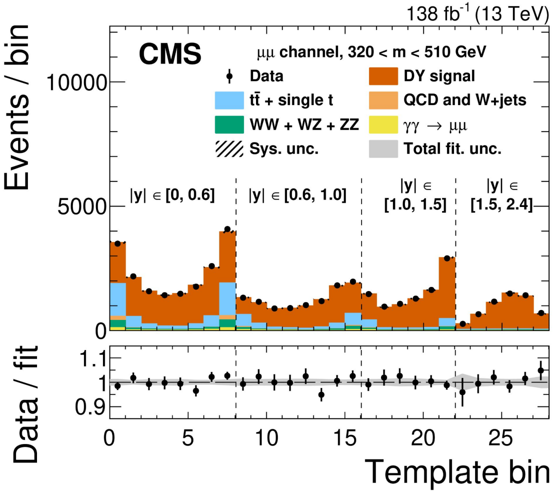
JHEP 08 (2022) 063
CMS-SMP-21-002

$$\frac{d\sigma}{d\cos\theta} \propto \frac{3}{8}\left[1+\cos^2\theta + \frac{A_0}{2}\left(1-3\cos^2\theta\right) + A_4\cos\theta\right] \quad \frac{3}{8}A_4 = A_{FB}$$

- Derived using template fits to data
- Three templates: leading order symmetric, next-leading-order symmetric and asymmetric
- A_0 and A_{FB} are defined by linear coefficients
- Dilution effect is corrected in the template fitting

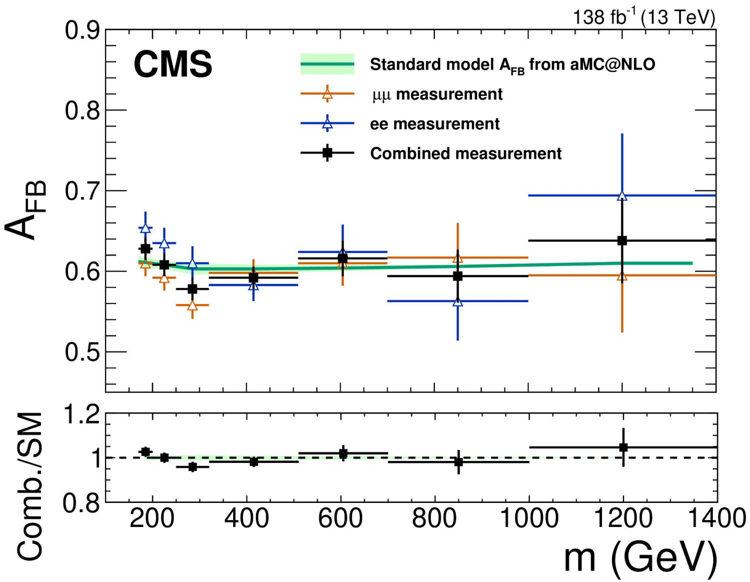
	A_{FB}
Electrons	0.628 ± 0.008 (stat) ± 0.007 (syst)
Muons	0.602 ± 0.006 (stat) ± 0.007 (syst)
Combined	0.612 ± 0.005 (stat) ± 0.007 (syst)
amc@NLO Pred.	0.608 ± 0.006

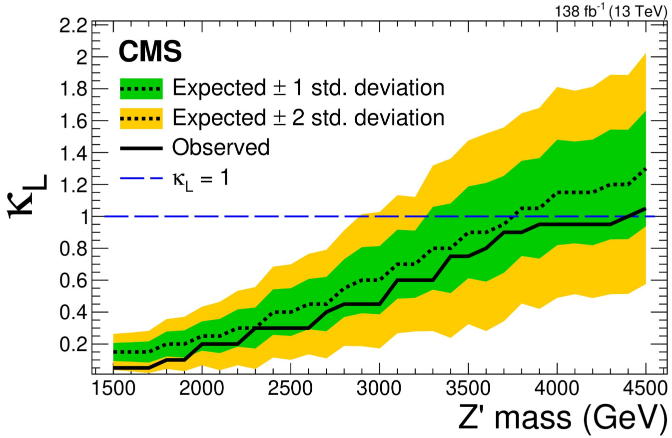




Forward-backward asymmetry (cont.)

JHEP 08 (2022) 063
CMS-SMP-21-002





$m_{Z'}$ > 4.4 (3.7) TeV at 95% CL with κ_L = 1

- No significant deviation from SM predictions
- Small difference between electron and muon results
  - Mostly from three low mass bins
  - ~2.4σ in the inclusive measurement

- Existence of heavy gauge bosons, Z', changes the asymmetry well below their masses → derive limits on Z' mass
  - Model dependent (depends on couplings of Z')
  - Sequential standard model (same couplings between SM Z and Z')

Summary

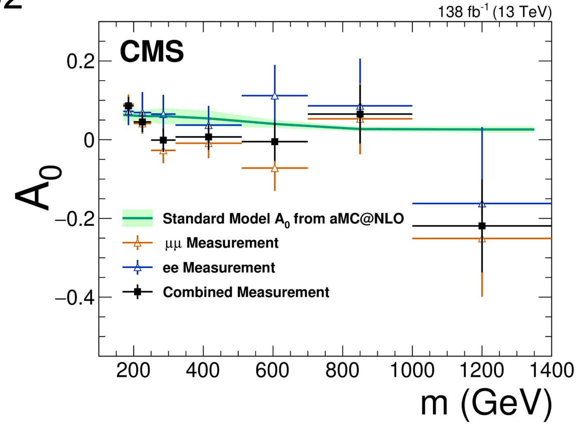
- CMS collaboration has performed comprehensive measurements of the DY process at 13 TeV
- The differential cross section as a function of dilepton invariant mass is measured over a wide mass range from 15 – 3000 GeV and well described by FEWZ
- Dilepton transverse momentum is studied at different dilepton masses to understand the soft QCD radiation and hard scattering in the DY process at different mass scales
  - The results are compared to various predictions using different approaches for soft-gluon resummation
  - Generally, they agree with data in their range of validity
  - MiNNLO provides the best description of data globally
  - The predictions based on TMD approach also describe data well in the regions dominated by soft initial state radiation
- The measured forward-backward asymmetry agrees with SM prediction

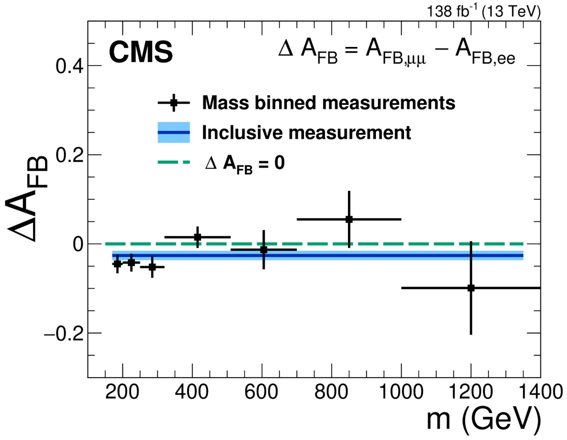
Backups

Forward-backward asymmetry

JHEP 08 (2022) 063
SMP-21-002

Source	Unc. on A_{FB} ($\times 10^{-3}$)	Frac. of total sys. unc. on A_{FB}	Unc. on ΔA_{FB} ($\times 10^{-3}$)	Frac. of total sys. unc. on ΔA_{FB}
PDFs	8.1	47%	0.8	1%
MC and MisID backgrounds stat. unc.	4.1	12%	6.8	42%
$\alpha_S + \mu_F/\mu_R$ scales	3.3	8%	3.2	9%
DY cross section	3.0	7%	0.9	1%
Pileup	2.8	5%	3.8	13%
Fiducial correction	2.7	5%	<0.1	$<1\%$
$t\bar{t}$ cross section	2.7	5%	0.1	$<1\%$
DY p_T correction	2.1	3%	0.8	1%
$e\mu$ shape corrections	1.8	2%	0.4	$<1\%$
Integrated luminosity	1.2	1%	1.0	1%
Electron identification/isolation	1.0	1%	2.7	6%
Electron MisID normalization	0.9	1%	4.3	17%
Electron MisID shape	0.8	$<1\%$	2.6	6%
b tagging uncertainty	0.8	$<1\%$	0.3	$<1\%$
p_T^{miss} uncertainties	0.7	$<1\%$	0.5	$<1\%$
Muon identification/isolation	0.6	$<1\%$	1.2	1%
Muon MisID shape	0.5	$<1\%$	0.6	$<1\%$
$\gamma\gamma$ cross section	0.4	$<1\%$	0.6	$<1\%$
Muon MisID normalization	0.4	$<1\%$	0.1	$<1\%$
Electron trigger	0.4	$<1\%$	1.2	1%
Diboson cross section	0.2	$<1\%$	0.1	$<1\%$
Electron reconstruction	0.2	$<1\%$	0.7	$<1\%$
Muon momentum scale	0.1	$<1\%$	0.1	$<1\%$
Electron momentum scale	0.1	$<1\%$	0.1	$<1\%$
Muon trigger	0.1	$<1\%$	0.1	$<1\%$





p_T^Z uncertainties