Measurement of the Drell-Yan transverse momentum dependence over a wide mass range with CMS

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Bruxelles, Belgium

EOS Equinox meeting

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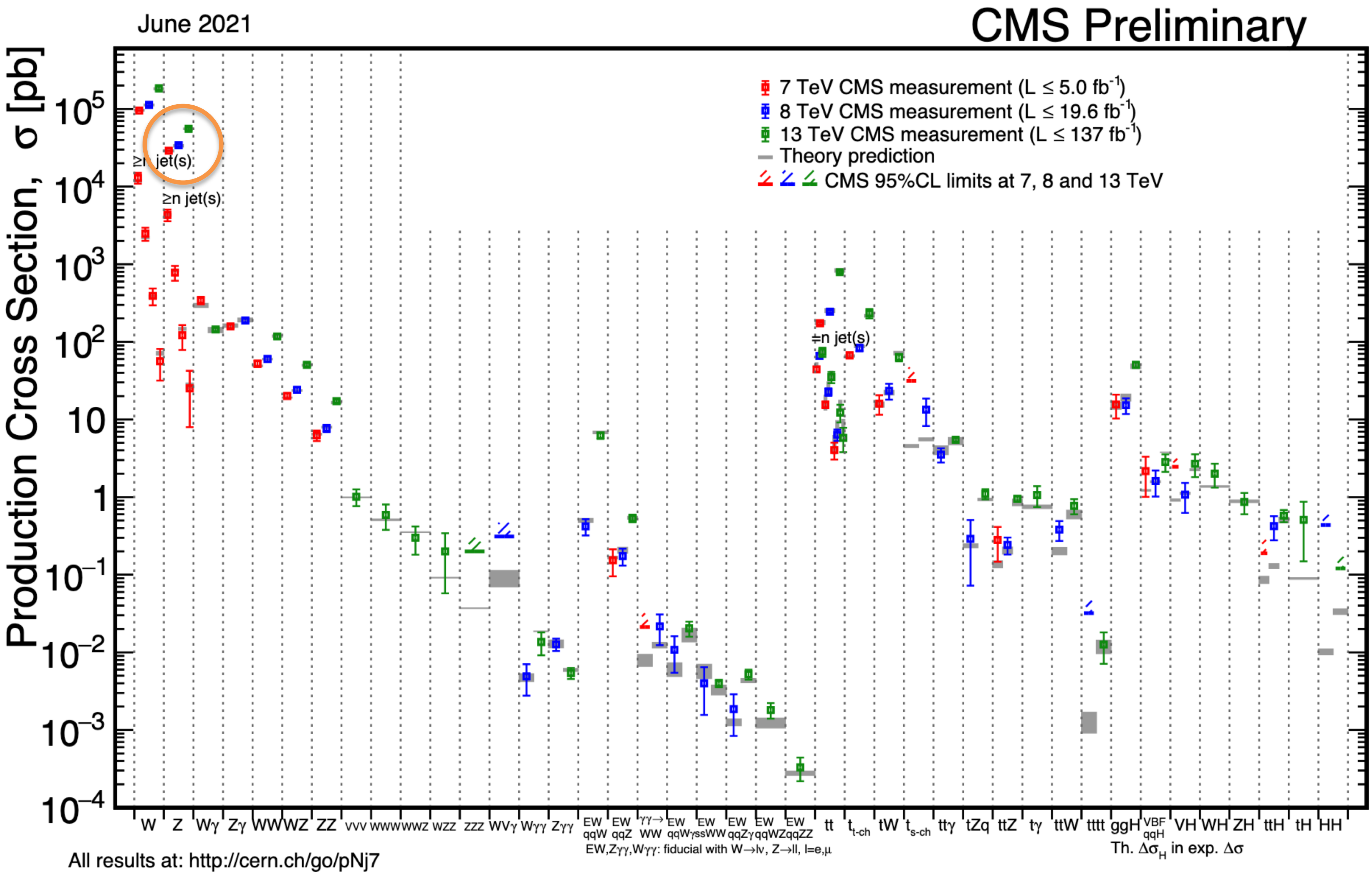


Content

PAS-SMP-20-003

36.3 fb^{-1}

"Measurement of mass dependence of the transverse momentum of Drell Yan lepton pairs in proton-proton collisions at √s=13 TeV" CMS-PAS-SMP-20-003

Available on the CERN CDS information server **CMS PAS SMP-20-003**

CMS Physics Analysis Summary

Contact: cms-pag-conveners-smp@cern.ch 2021/04/15

Measurement of mass dependence of the transverse momentum of Drell Yan lepton pairs in proton-proton collisions at $\sqrt{s} = 13$ TeV

The CMS Collaboration

Abstract

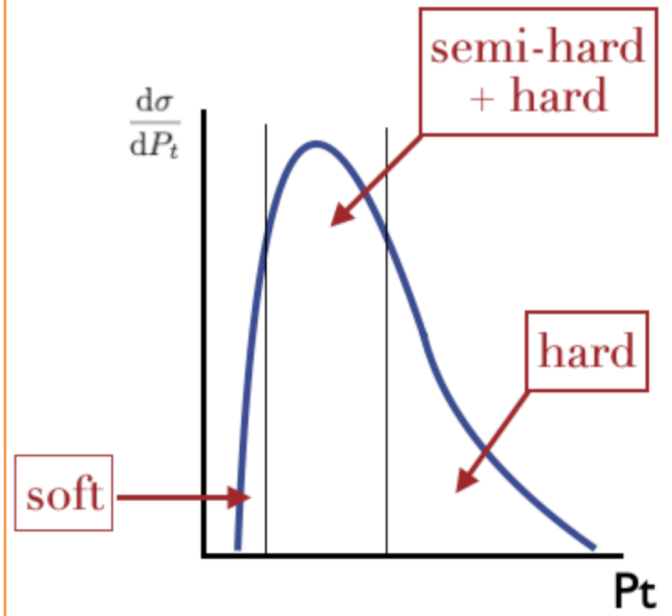
The double differential cross sections of the Drell-Yan lepton pair ($\ell^+\ell^-$, electron or muon) production, as a function of its invariant mass $m_{\ell\ell}$, transverse momentum $p_T(\ell\ell)$, and φ^* are measured. The φ^* observable is highly correlated with $p_T(\ell\ell)$ and is used to probe the low $p_T(\ell\ell)$ region in a complementary way. Drell-Yan masses up to 1 TeV are investigated. Additionally, a measurement is performed requiring at least one jet in the final state. To benefit from partial cancellation of the systematic uncertainty, the ratios of the differential cross sections in $p_T(\ell\ell)$ and φ^* for the $m_{\ell\ell}$ bins around the Z mass peak over the one on the Z mass peak are presented. The collected data correspond to an integrated luminosity of 36.3 fb^{-1} of proton-proton collisions recorded with the CMS detector at the LHC at the center-of-mass energy of 13 TeV in 2016. Measurements are compared to state-of-the-art predictions based on perturbative quantum chromodynamics including soft gluon resummation.

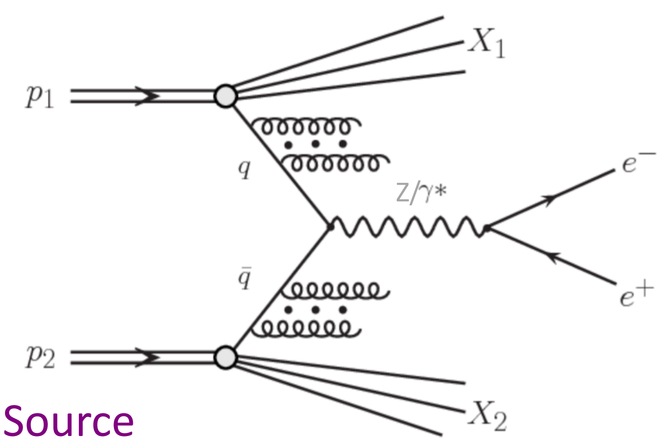
- → CMS measurement done by our group lead by Prof. Laurent Favart
  - → Preliminary results presented in a PAS
  - → Final publication coming soon.
- → PhD thesis of Louis Moureaux, defended (private) this week.
  - → Additional material from his thesis showing comparison of the results to different generators

All CMS public results: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMP

Introduction

- → Processes involving Z/γ* boson productions are one of the best understood processes at hadron colliders
  - → Z->ll, (l=e,μ) are among the cleanest final states experimentally
    - → Allows probing various QCD effects by studying kinematics precisely
      - → Different regions probing pQCD as well as npQCD effects
        - → High p_T part described by fixed order QCD (available up to NNLO)
        - → Low p_T and transition is the challenge
    - → Used to estimate the (multi-)jet model uncertainties
    - → Can serve as background for other measurements as well as BSM searches.

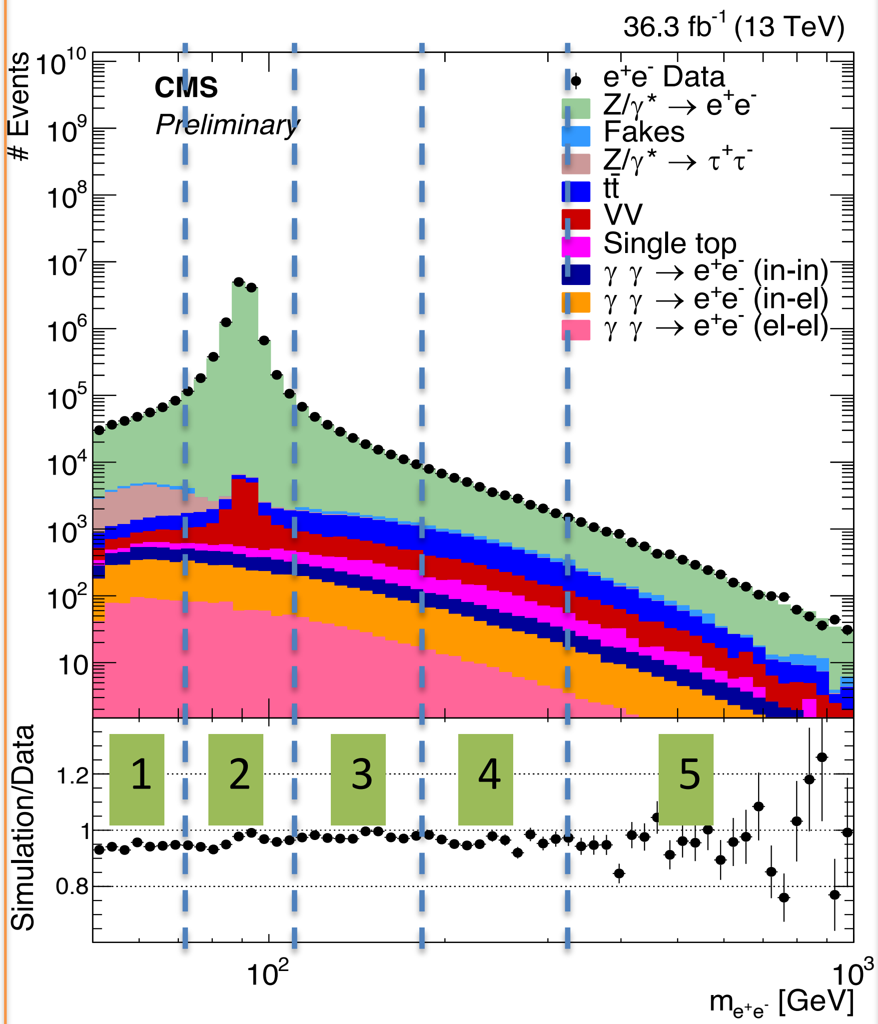




Source

They provide stringent tests of our calculations based on SM

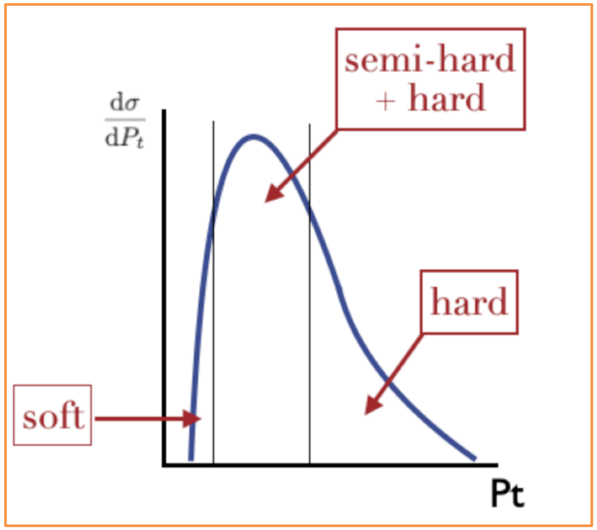
Introduction



→ Measure the p_T in masses out of the Z peak

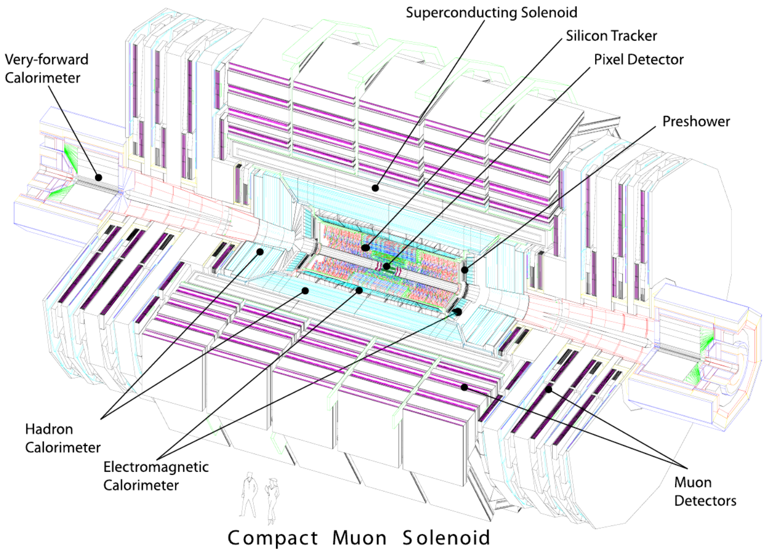
→ Observe dependence on the scale $\mu \sim m$

→ Test models based on the Pythia parton shower as well as models with improved resummation techniques (TMD, NNLL + ME)



Event Selection and Phase-Space Definition

→ Using events recorded in 2016 by the CMS detector
  → Single and double lepton (e or μ) triggers
  → Opposite-sign di-lepton pairs with
    → $p_T\,(l_1)>25$ GeV, $p_T\,(l_2)>20$ GeV $|\eta|< 2.4$
    → Selection criteria to choose "good" lepton candidates



→ Unfolded to the same "fiducial" phase-space
  → To correct for detector effects, selection efficiencies
    → Relies on the simulation of detector
  → "Stable" leptons dressed with photons in $\Delta R(l,\gamma)<0.1$
  → $p_T\,(l_1)>25$ GeV, $p_T\,(l_2)> 20$GeV $|\eta|< 2.4$

Detector-level distributions: background control

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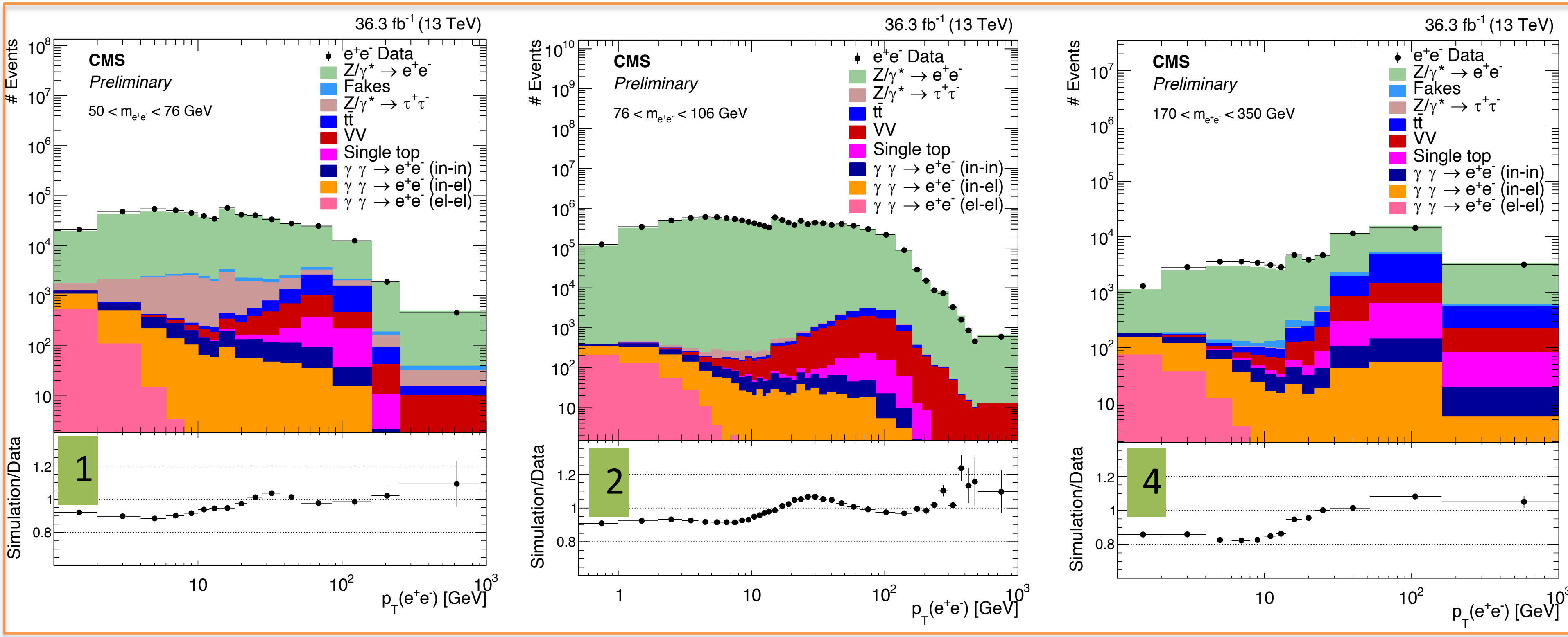


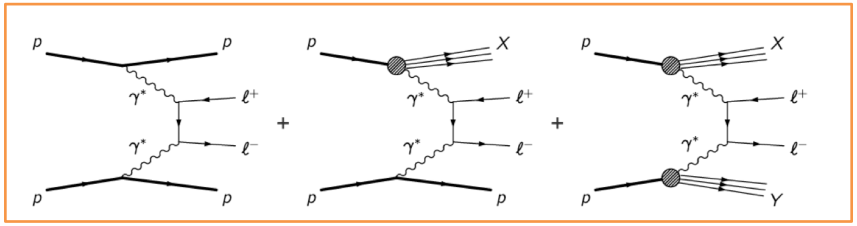
→ tt in high mass, suppressed by vetoing events with b jets (important for high p_T)

→ γγ -> l^+l^-, for elastic and inelastic cases separately (important for low p_T)

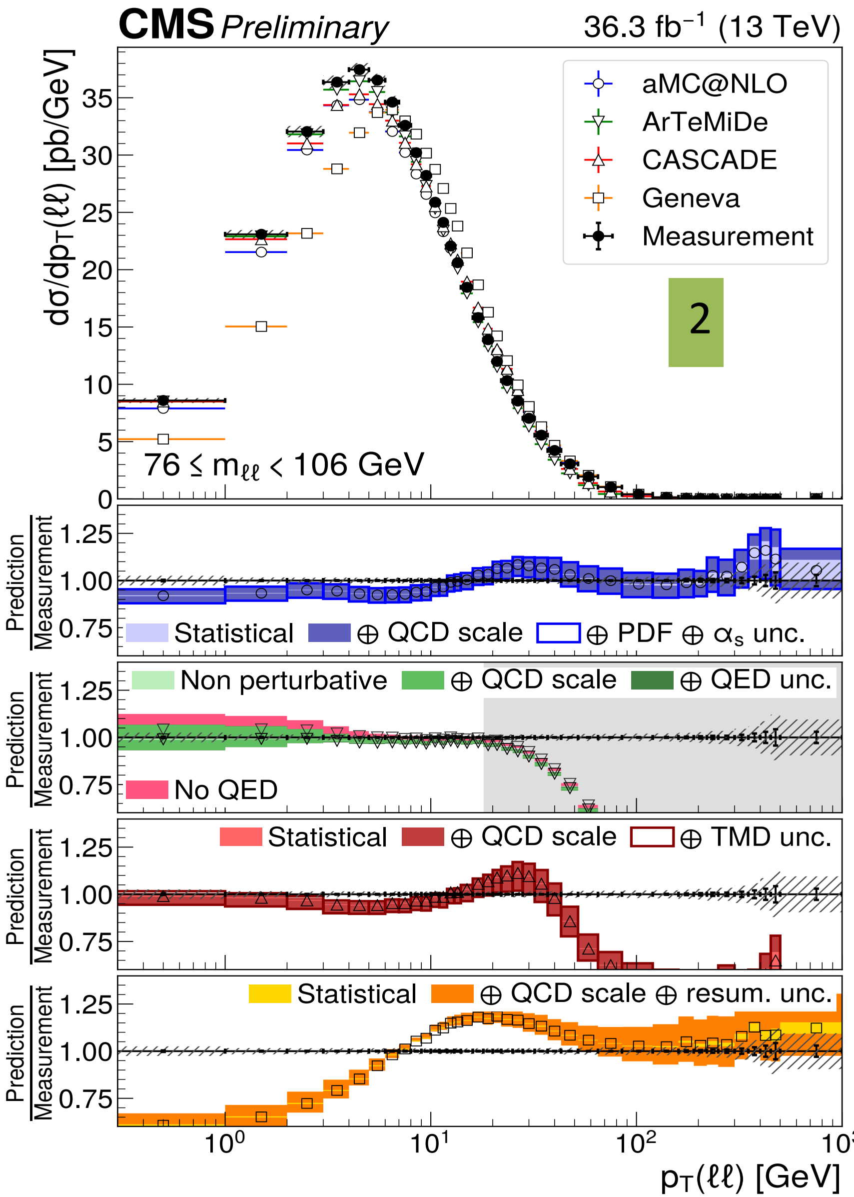
→ Hadrons misidentified as electrons are estimated using a data-driven method.

→ The measurement is ~background free

→ Background contamination increases for off shell with increasing p_T



Comparison to models



- → Measurement results are compared with:
  - → ME + PS approach
    - → MG5_amc@NLO + Pythia 8 @NLO up to 2 partons + PS
  - → TMD approach (PDF (x,k_T,Q^2))
    - → CASCADE (amc@NLO+ PBTMD) + Pythia6 for FS and hadronization
      - → Tuned to Hera data only.
    - → Analytic calculation from ArTeMiDe TMD based (TMDs at NNLO +N^{3}LL)
      - → Tuned on DY p_T (using LHC data too)
      - → Limited to ~m_{ll} *x* 0.2
  - → Resummation
    - → GENEVA, NNLO Z+0j ME and resummation at NNLL'$_\tau$
      - → Showered with Pythia8

Consistent with the previous measurement (JHEP 12 (2019) 061) and supersedes it for this distribution

More models…

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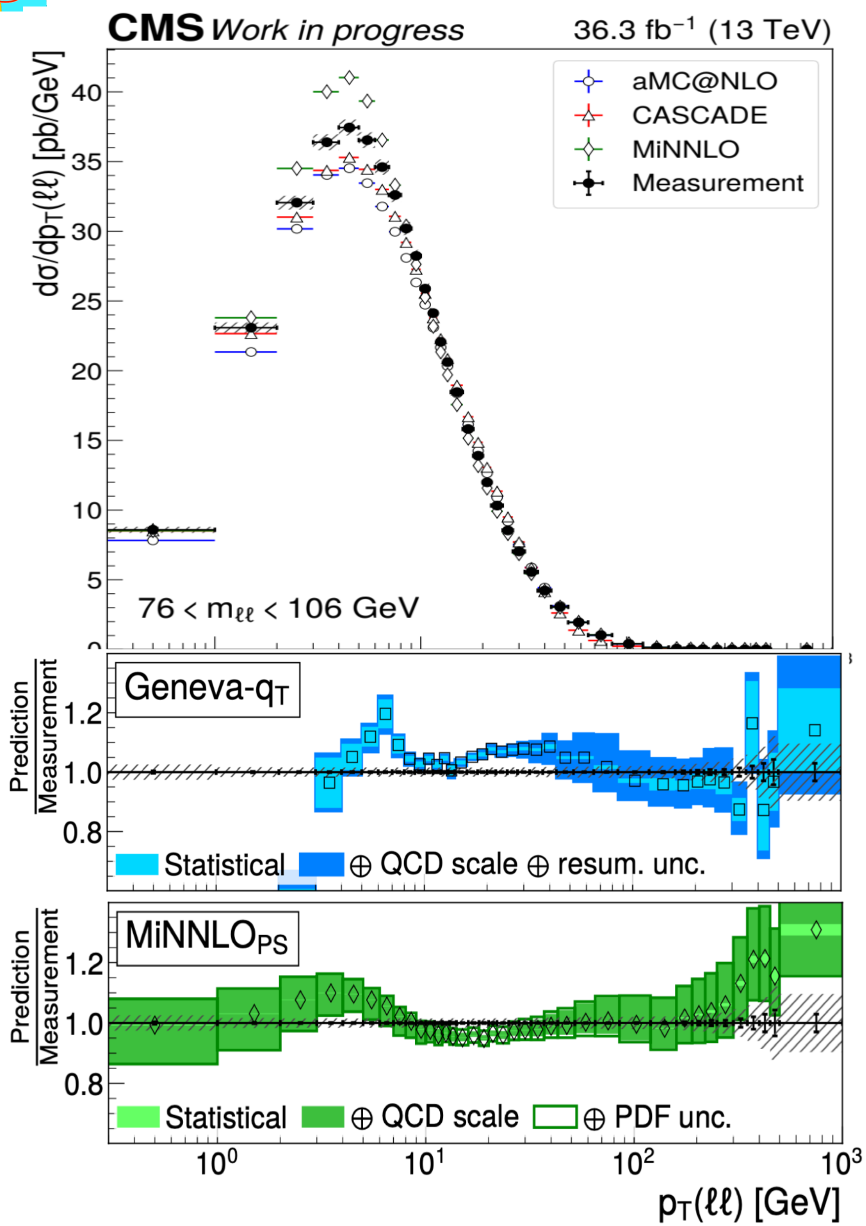

- → Measurement results are compared with:
  - → ME + PS approach:
    - → $MiNNLO_{PS}$
      - → ME at NNLO
      - → Independent treatment of α_s at each vertex
      - → Sudakov form factors used to interpolate between scales
      - → "Photos" used for QED FSR
      - → Pythia 8 for PS matched using Powheg method
  - → Resummation
    - → GENEVA, NNLO Z+0j ME and q_T resummation at NNLL
      - → Showered with Pythia8

Systematic Uncertainties

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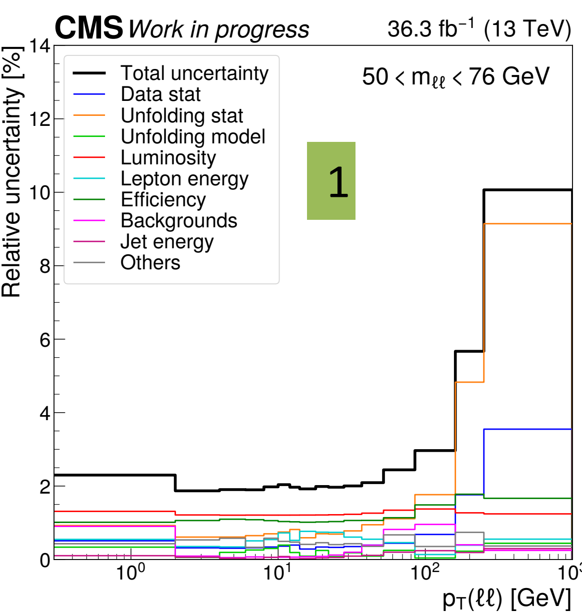
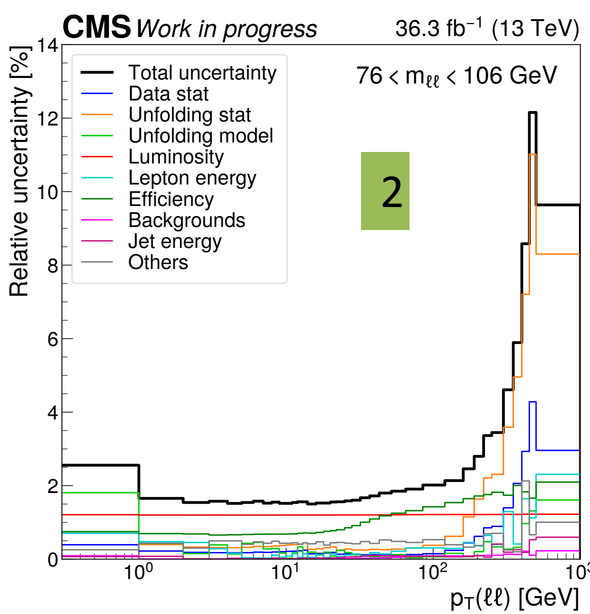
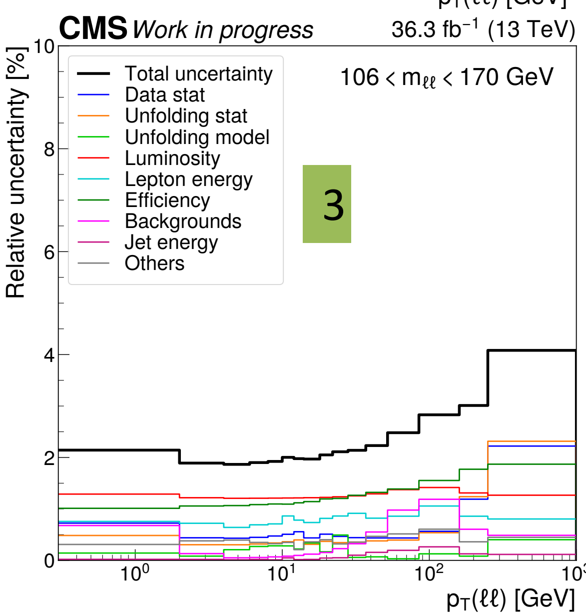
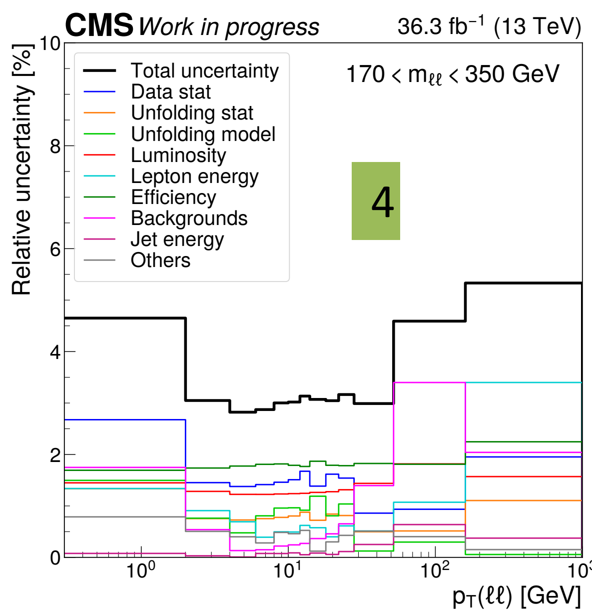
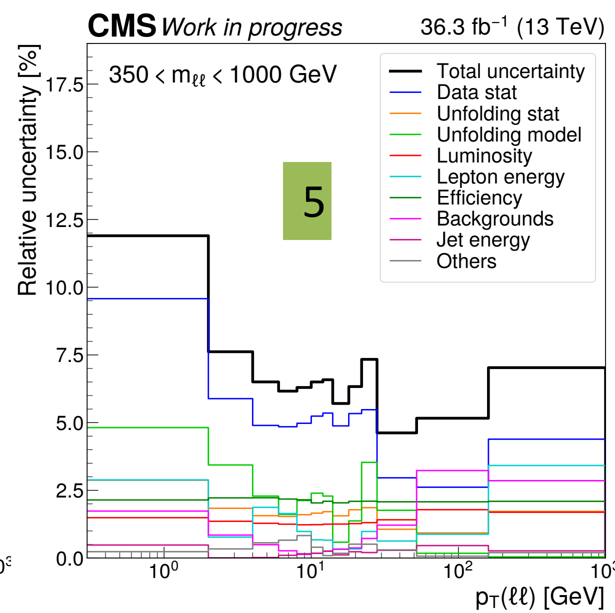




- → Systematic dominated measurement
- → Dominant uncertainties are
  - → lepton id efficiencies
  - → luminosity
    - → Note that the updated luminosity unc. is ~1.2%*
  - → background normalization at high pt.







*: CMS luminosity measurement (2015&2016 data): arXiv:2104.01927

pT over wide mass range

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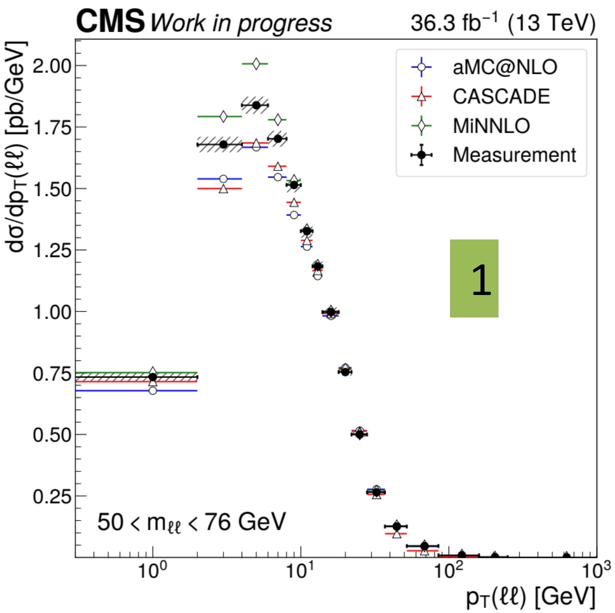
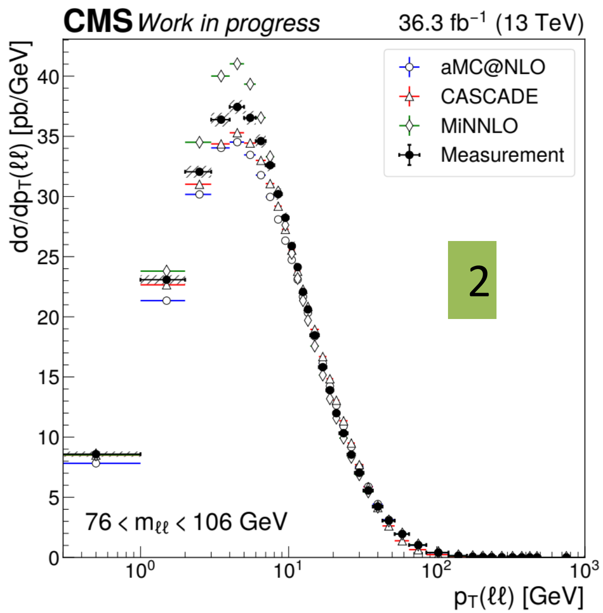
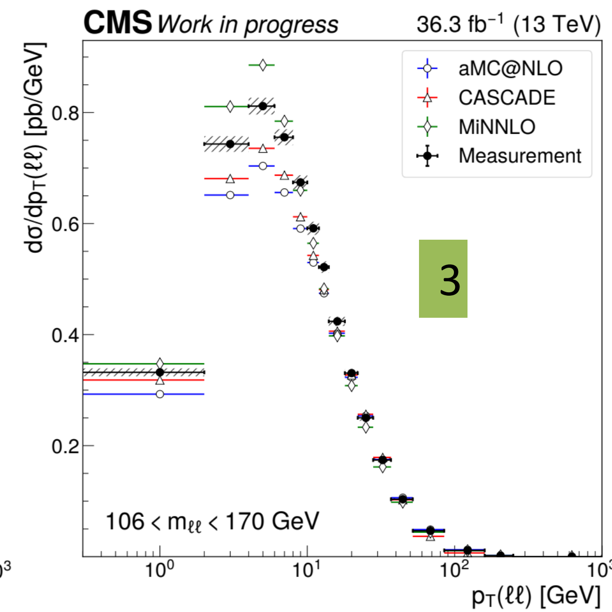
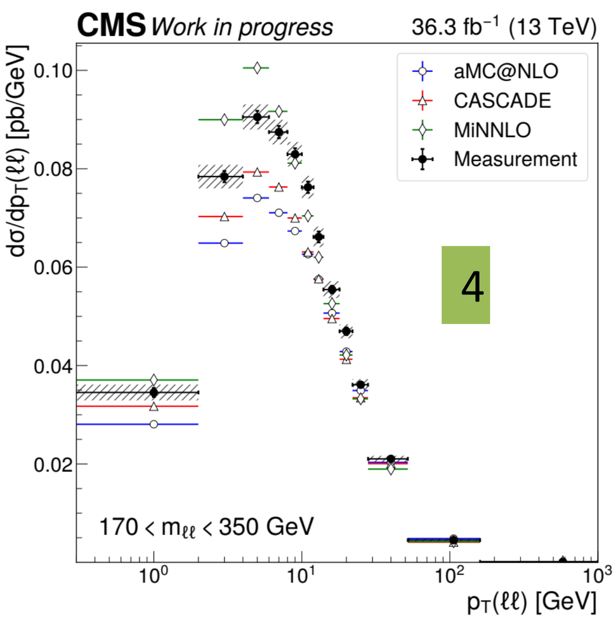
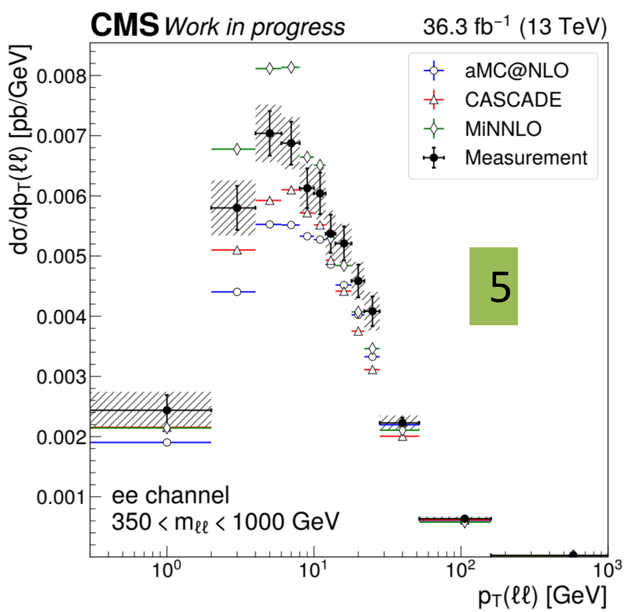


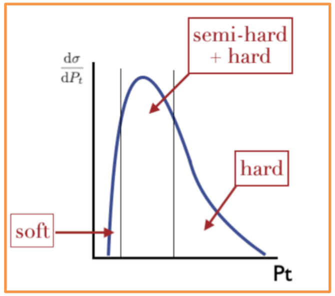






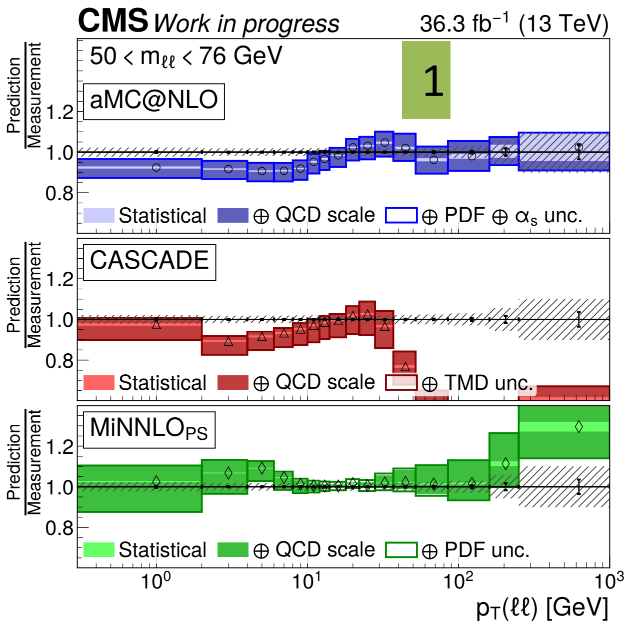


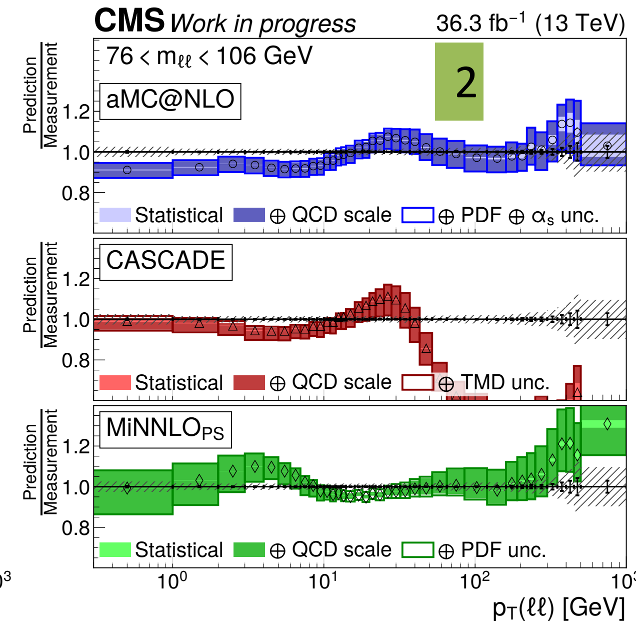
- → Peak is not strongly dependent on mass
- → Choose pT bins to be as-narrow-as-possible
- → Highest mass measurement done only ee due to resolution limitations

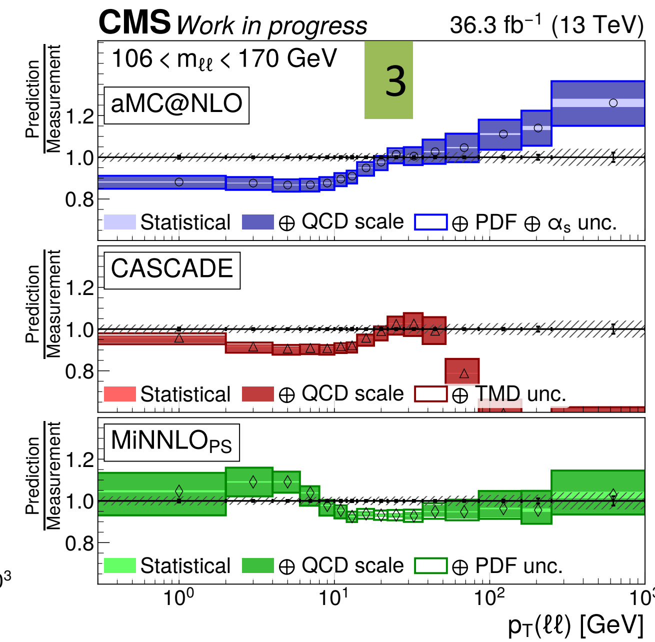


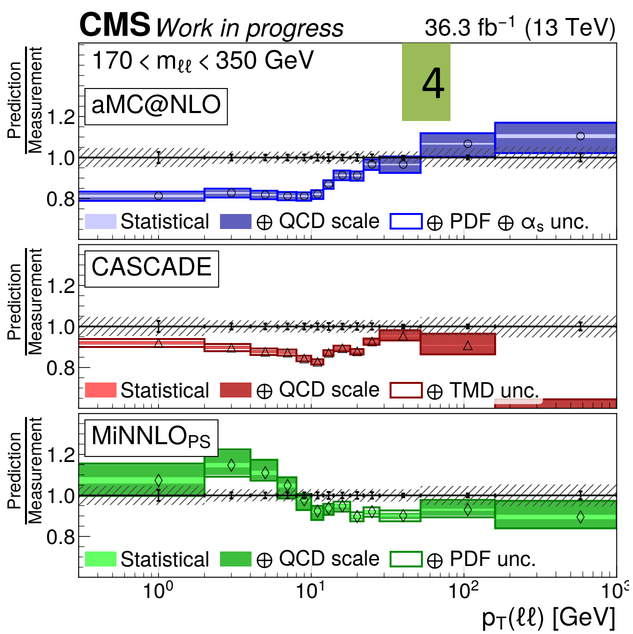
Ratio to predictions

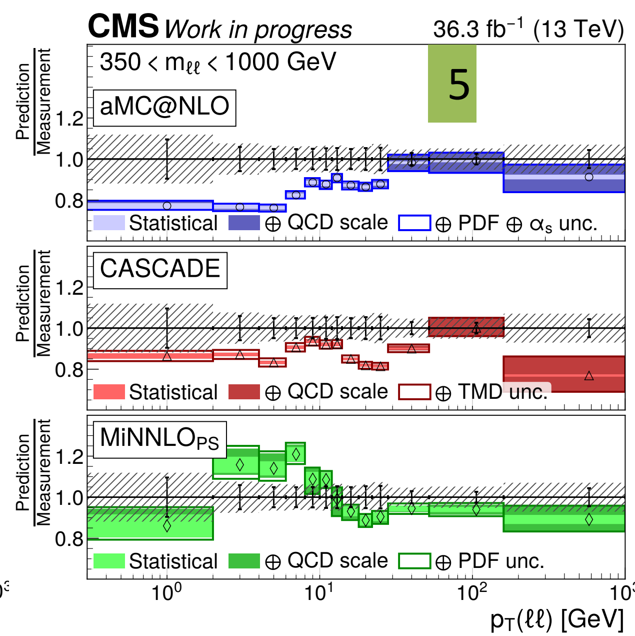
$36.3\ fb^{-1}$











→ amc@NLO+ Pyhthia8 gives overall good description

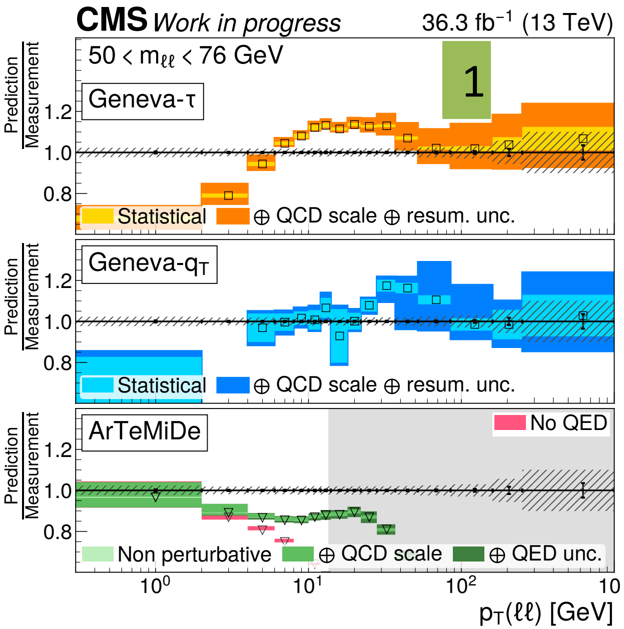
→ Failing to describe the low p_T, failure increasing for higher m(ll)

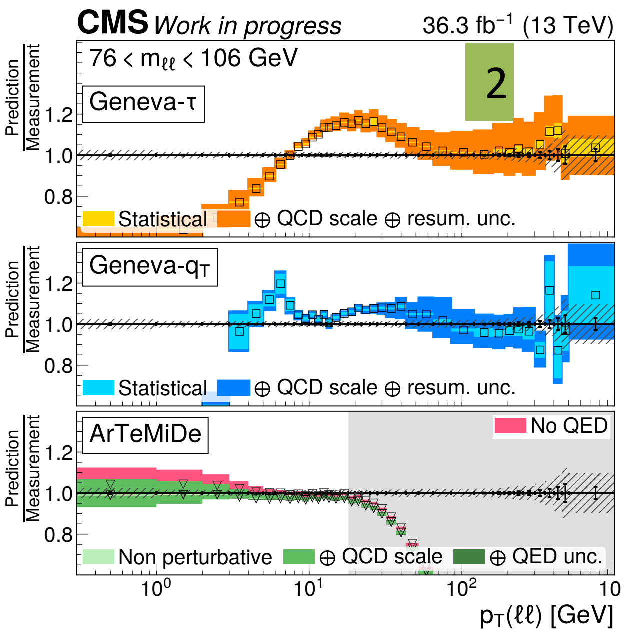
→ Cascade (amc@NLO 0j + PBTMD) describes the low p_T better fails at high p_T due to missing orders in ME

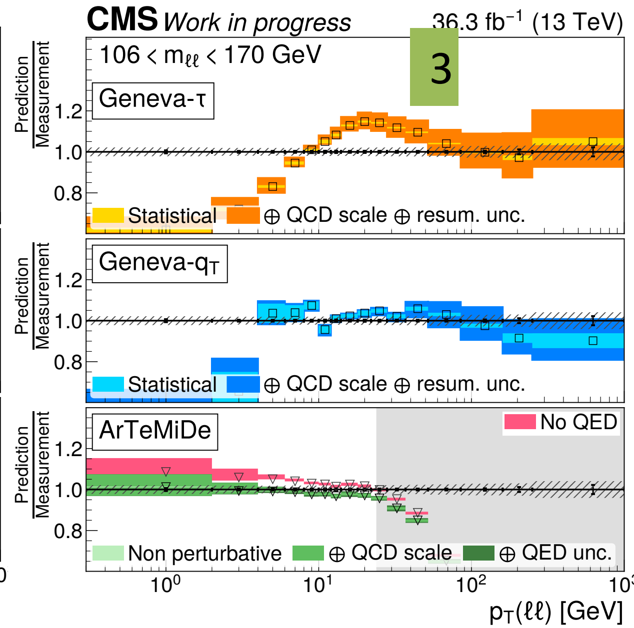
→ $MiNNLO_{PS}$ gives an overall good description.

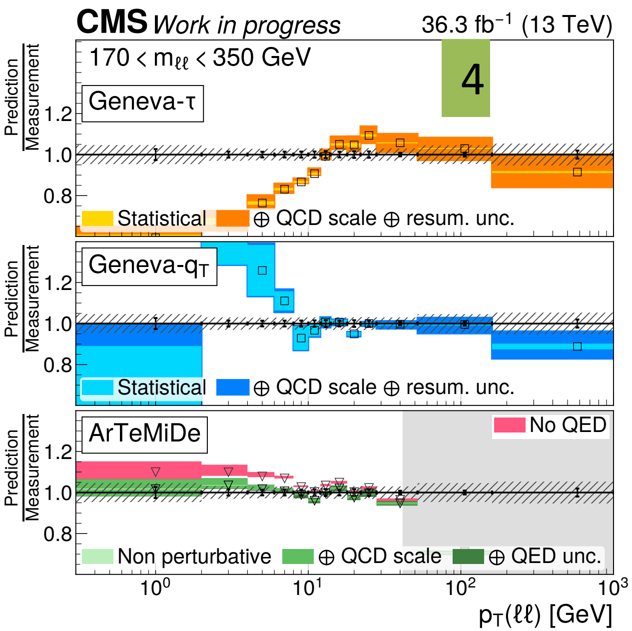
Ratio to predictions

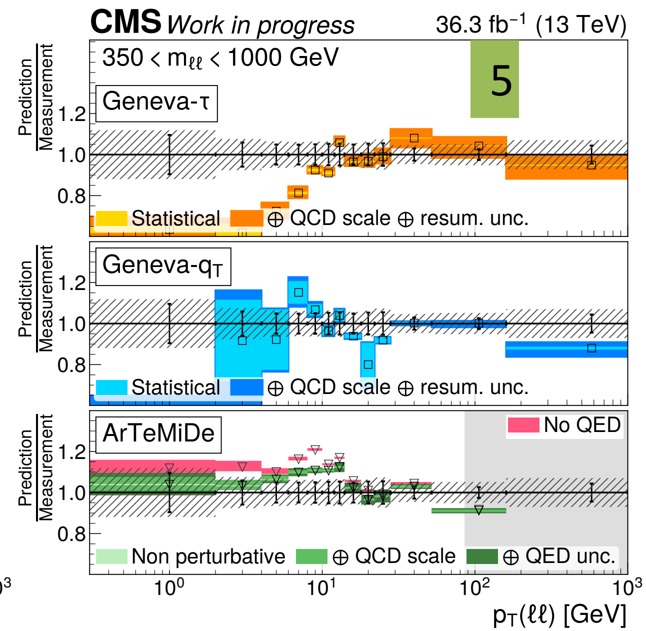
36.3 fb^{-1}





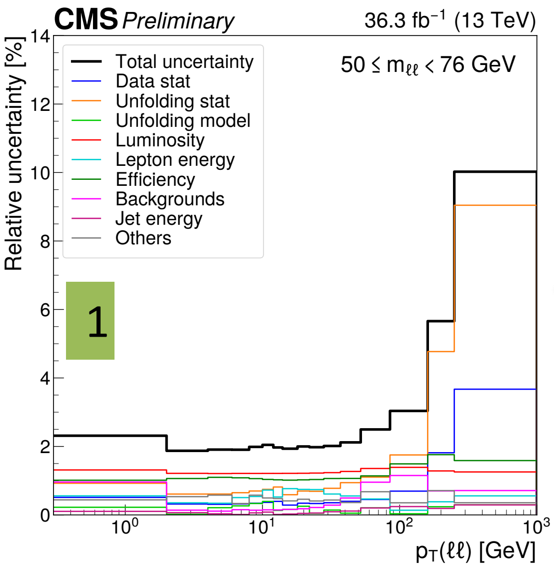


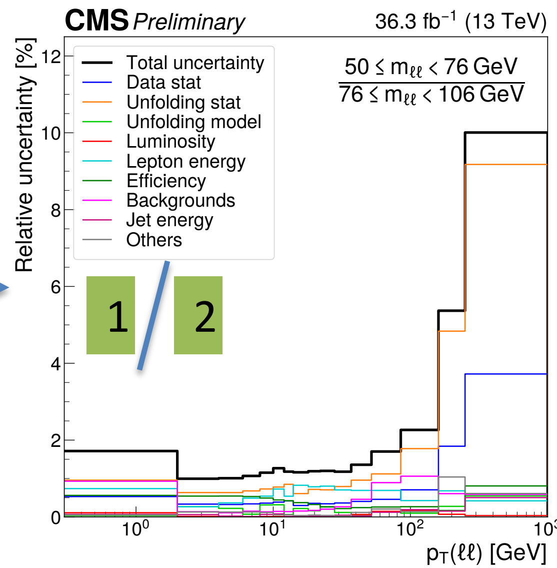


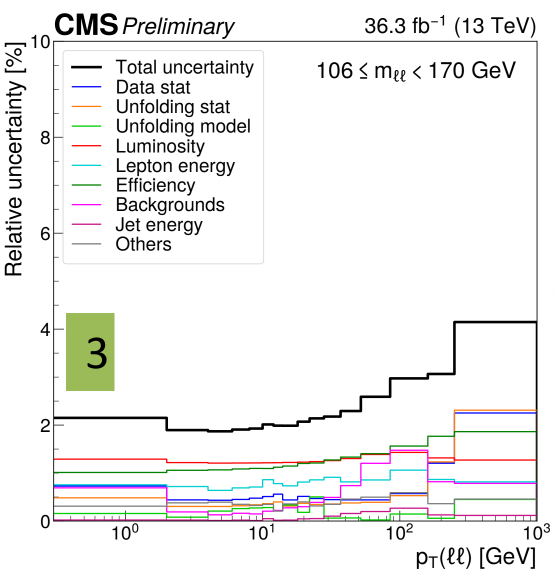


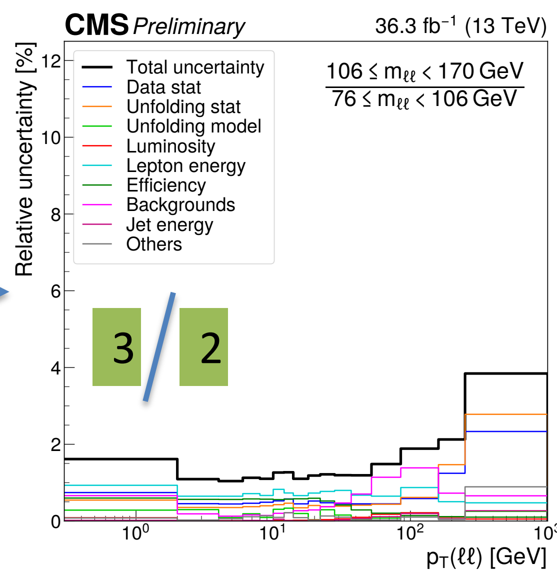
- → GENEVA τ predicts a harder p_T spectrum (α_s choice)
- → GENEVA q_T gives a better description at intermediate/high p_T.
- → ArTeMiDe gives a good description in its validity region

Cross section ratio measurements: motivation





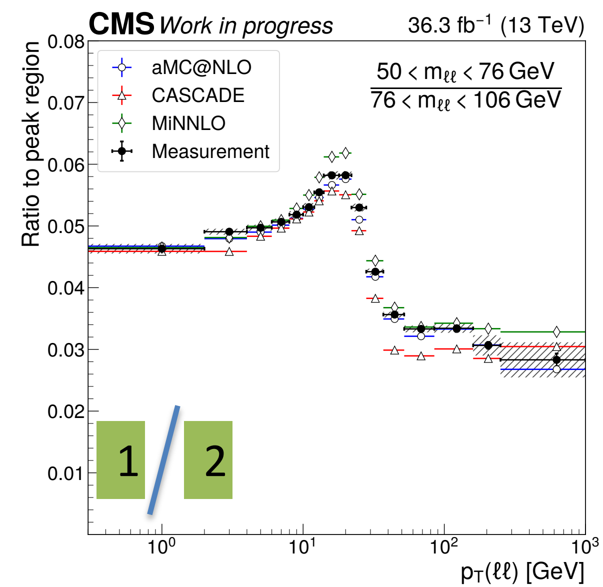


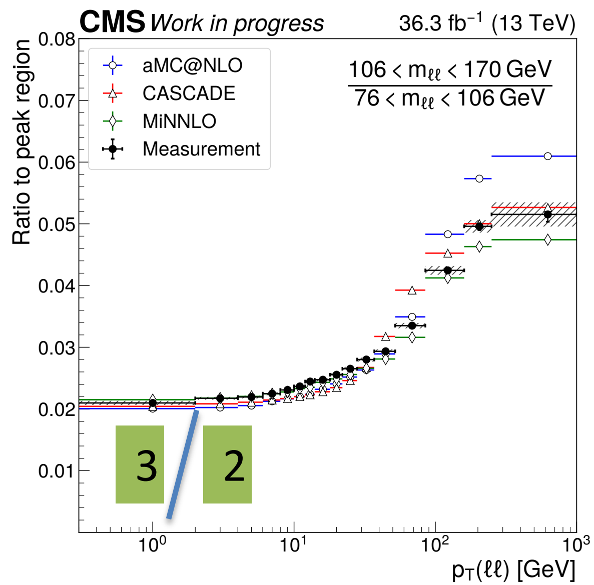


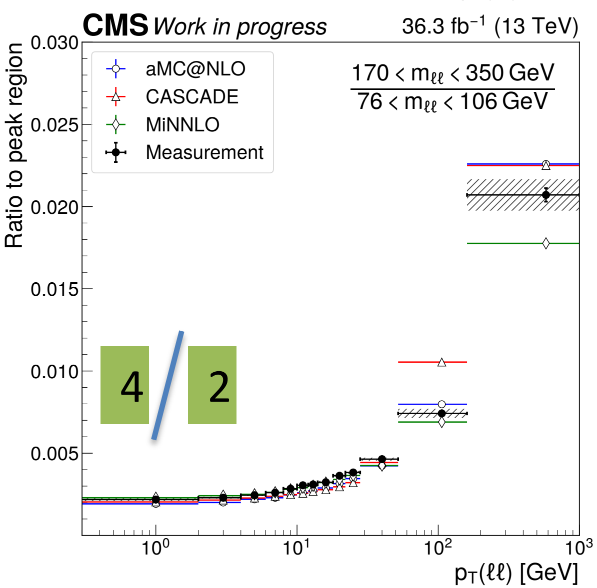
→ Studying ratio of the cross section to on shell:
- → Benefit from (partial to full) cancellation of several systematic sources

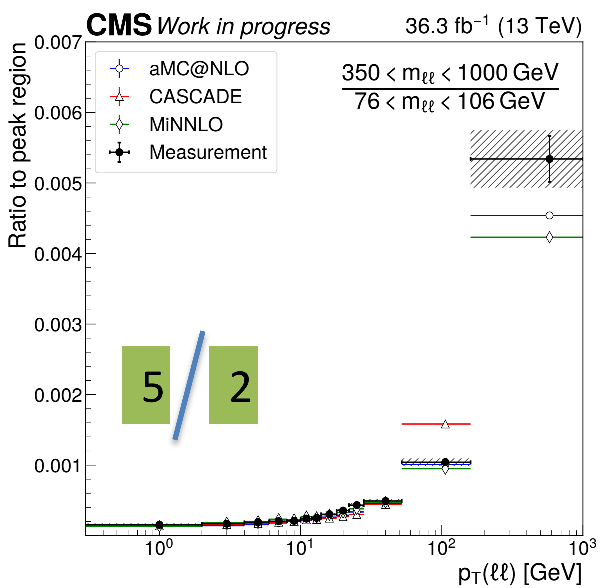
Cross section ratio measurements: results

36.3 fb^{-1}





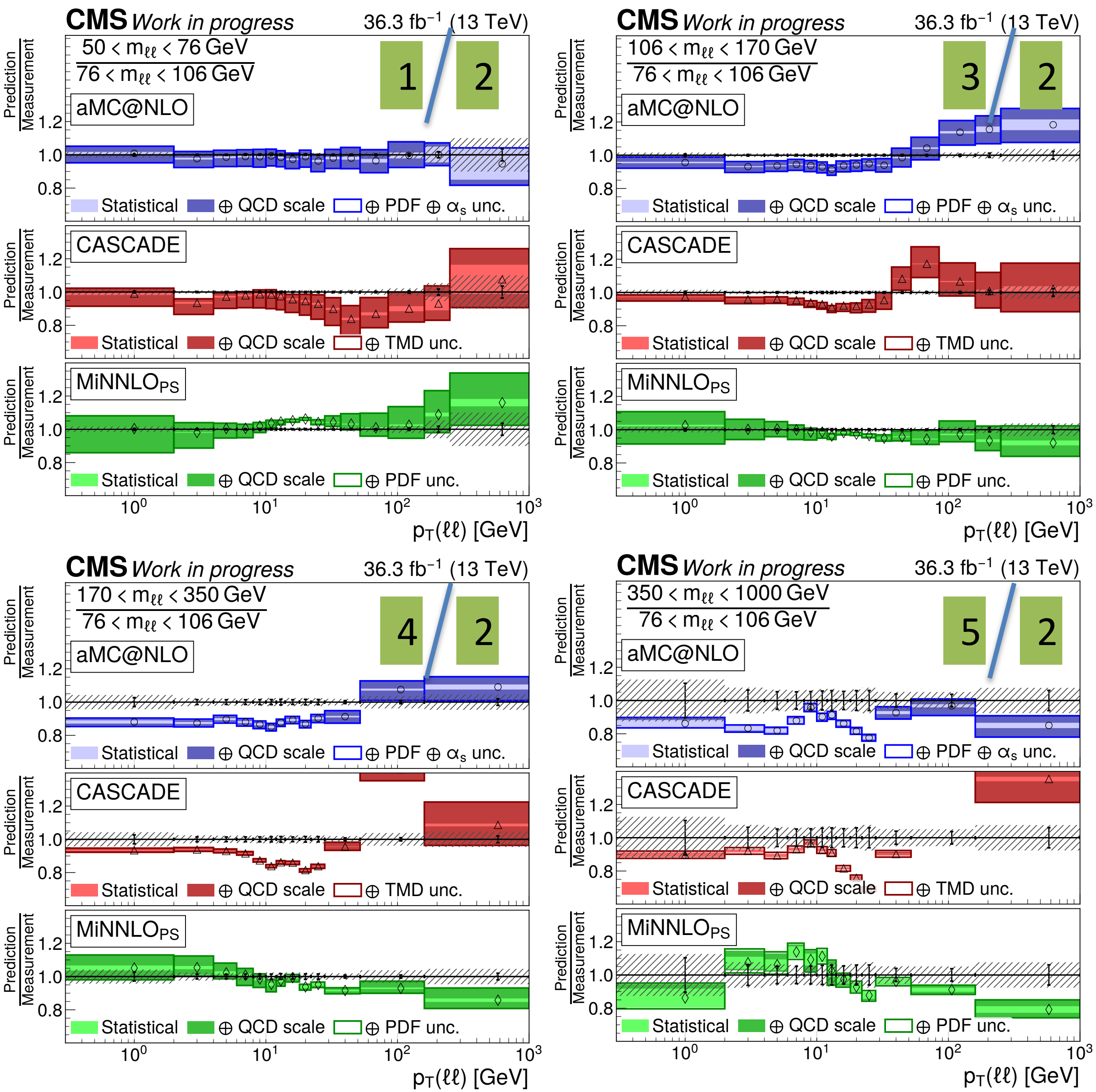




- → Study the evolution with respect to the mass better
- → The "peak" at the low mass is due to QED FSR
  - → A part of the low mass measurement is including the on shell.
- → High p_T cross section increasing with mass
  - → Due to kinematical extension of the phase-space

Ratio to predictions

36.3 fb^{-1}



→ amc@NLO+ Pyhthia8 gives overall good description

→ Failing to describe the low $p_{T,}$ bigger for higher mass ratios.

→ Cascade (amc@NLO 0j + PBTMD) describes the low p_T better, and good description in the high p_T ratio

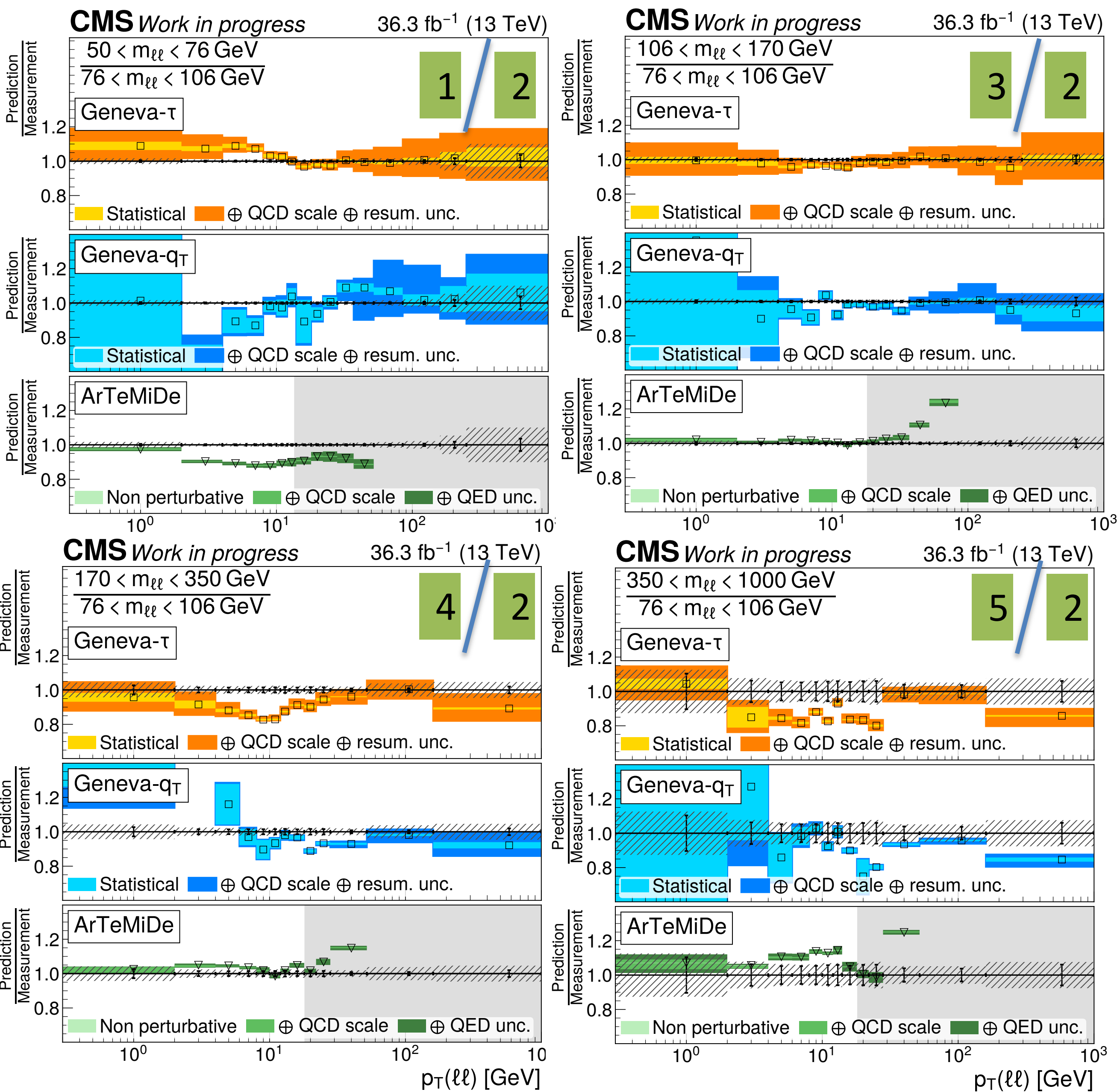
→ Evolution is well described

→ MiNNLO$_{PS}$ gives a very good description of the data

→ Small model uncertainties

Ratio to predictions

36.3 fb^{-1}



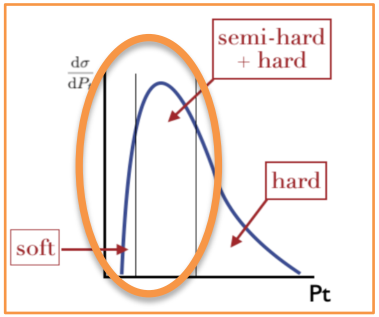
- → ArTeMiDe gives a good description in its validity region
- → GENEVA τ gives a very good description. The effect in absolute cross section (harder p_T spectrum cancels out)
- → GENEVA q_T gives an overall good description, hard to tell for low p_T due to fluctuations

Angular φ^* variable

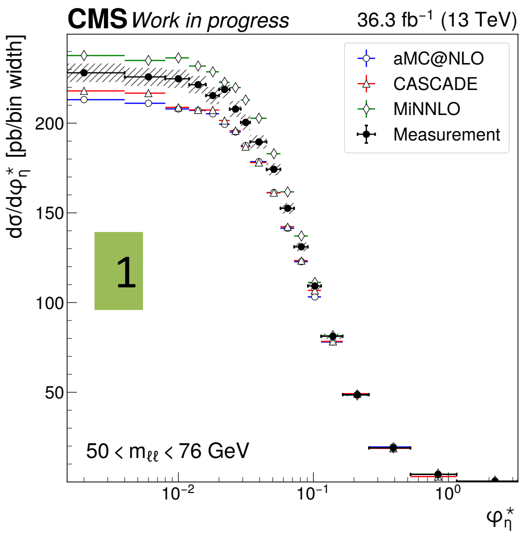
36.3 fb^{-1}

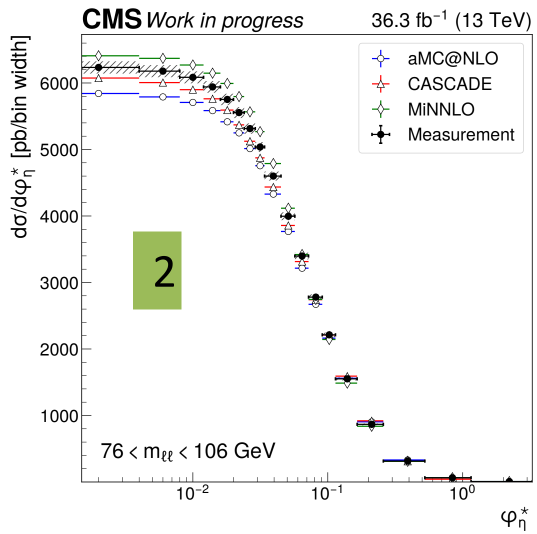
→ Angular variable strongly correlated to p_T

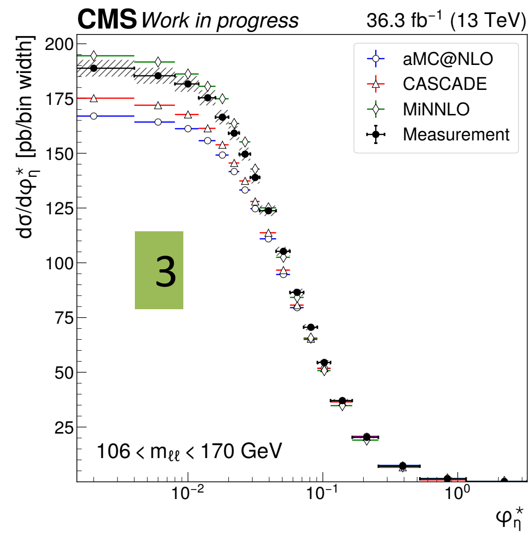
→ Allows studying low p_T in more detail

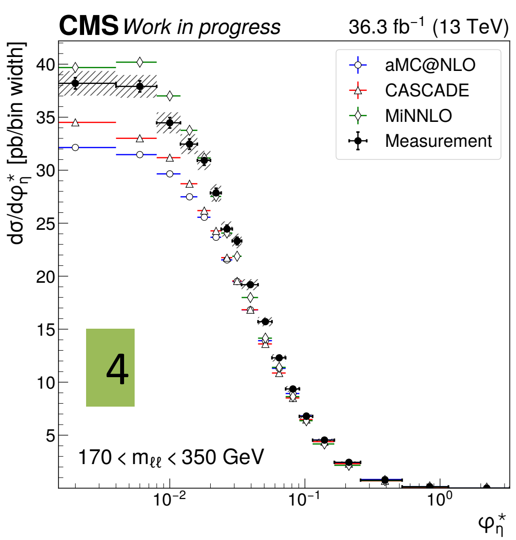


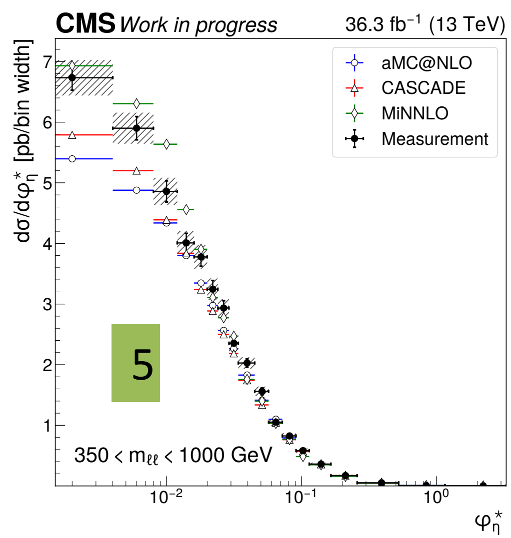
$$\phi^*_\eta = \tan\left(\frac{\pi - \Delta\phi}{2}\right)\sin(\theta^*_\eta), \quad \cos(\theta^*_\eta) = \tanh\left(\frac{\Delta\eta}{2}\right)$$











→ φ^* ratio measurement provides an ultimate precision

→ But, less discrimination between the models

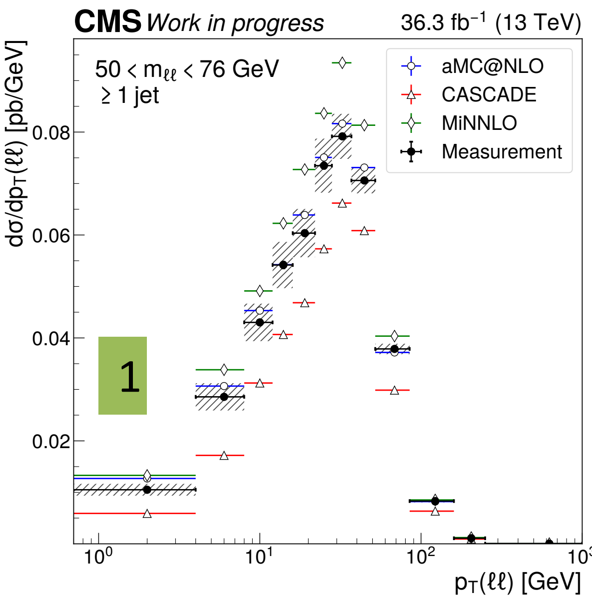
→ *$\varphi^* \sim p_T/m$, the distribution is squeezed to lower values at higher masses*

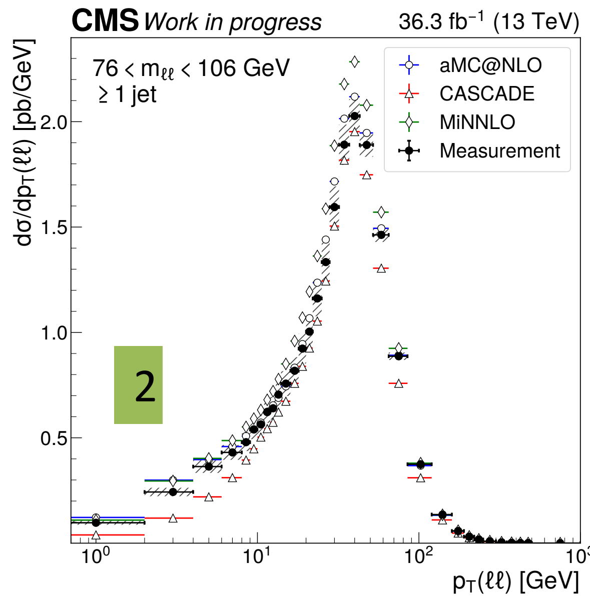
→ Same conclusions as of p_T case.

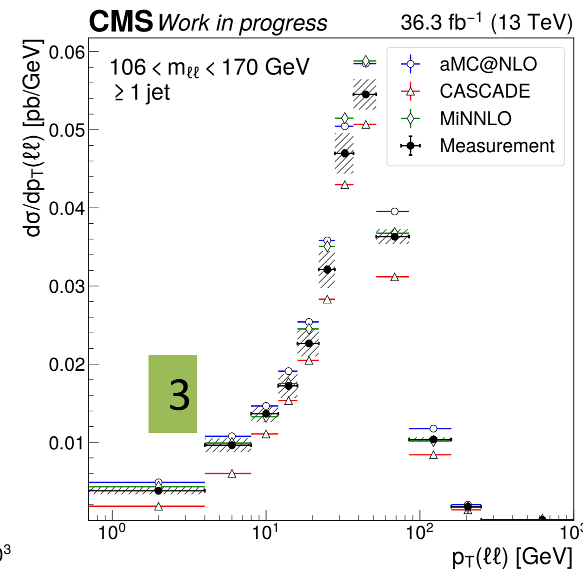
dilepton + >= 1 jet case

36.3 fb^{-1}

→ Measured p_T dependence requiring at least 1 jet with p_T> 30 GeV



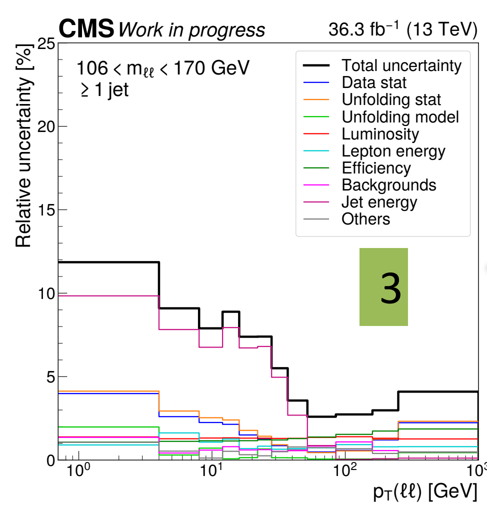


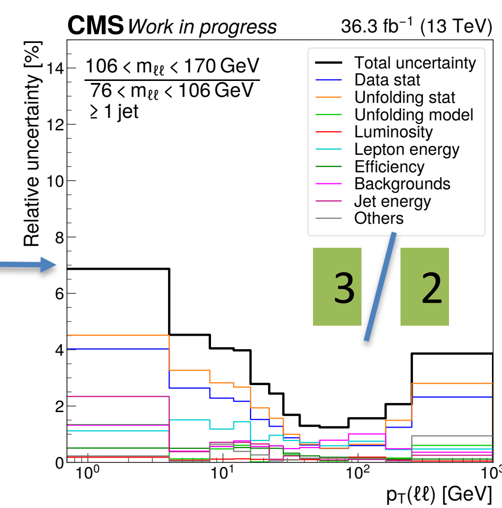


→ possibility of studying multiple gluon emissions away from the non-perturbative region

→ Main systematics is coming from Jet Energy Scale and Corrections

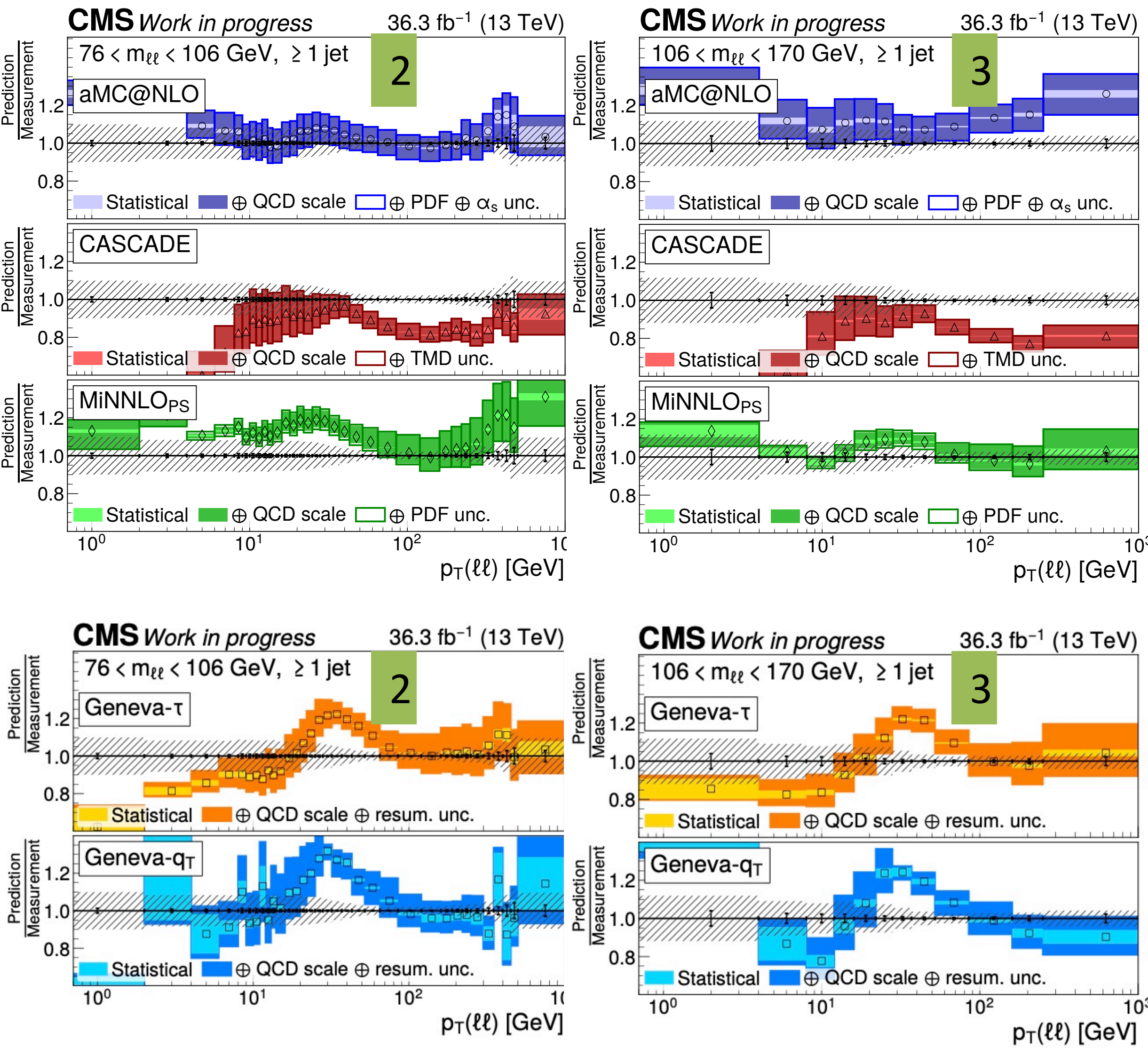
→ Improved by a ratio measurement





dilepton + >= 1 jet case: ratio to predictions

36.3 fb^{-1}



- → Good description by MG5_aMC NLO + Py8 sample
  - → Overshoots the low p_T.
- → Cascade (amc@NLO 1j + PBTMD) fails to describe the regions with Z+ >=2j
  - → Also the region sensitive to MPI. Cascade predictions do not include DPS.

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Summary

→ Presented measurements are an important part of the rich SMP program at CMS.
- → They provide valuable tests of our understanding of the QCD modelling.
  - → While giving an overall description, none of the predictions are able to provide a "perfect" description of the data everywhere.
    - → amc@NLO + PS approach failing at low p_T off shell.
    - → TMD based predictions show a success describing that region.
    - → Motivate an already active theory developments on the approaches discussed.

As usual; more to come; stay tuned!

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMP

Thank you

Backup

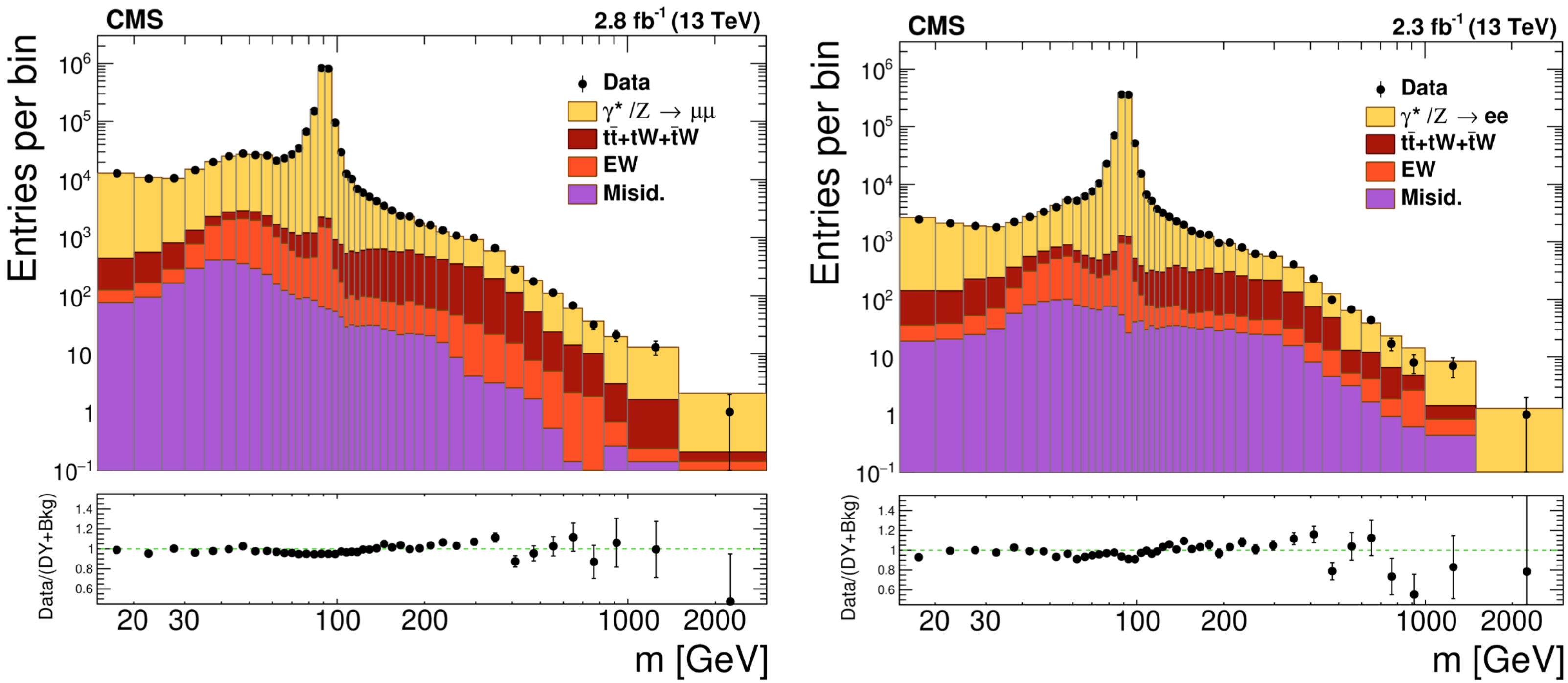
Drell-Yan Mass

JHEP 12 (2019) 059

2.8 (2.3) fb^{-1}

$\mu^+\mu^-$ (e^+e^-); p_T (l) > 25 GeV, $|\eta|<2.4$
15 < M_{ll} < 3000 GeV

Measured differential cross section $d\sigma/dM$



The results are in good agreement with the theoretical predictions of the SM

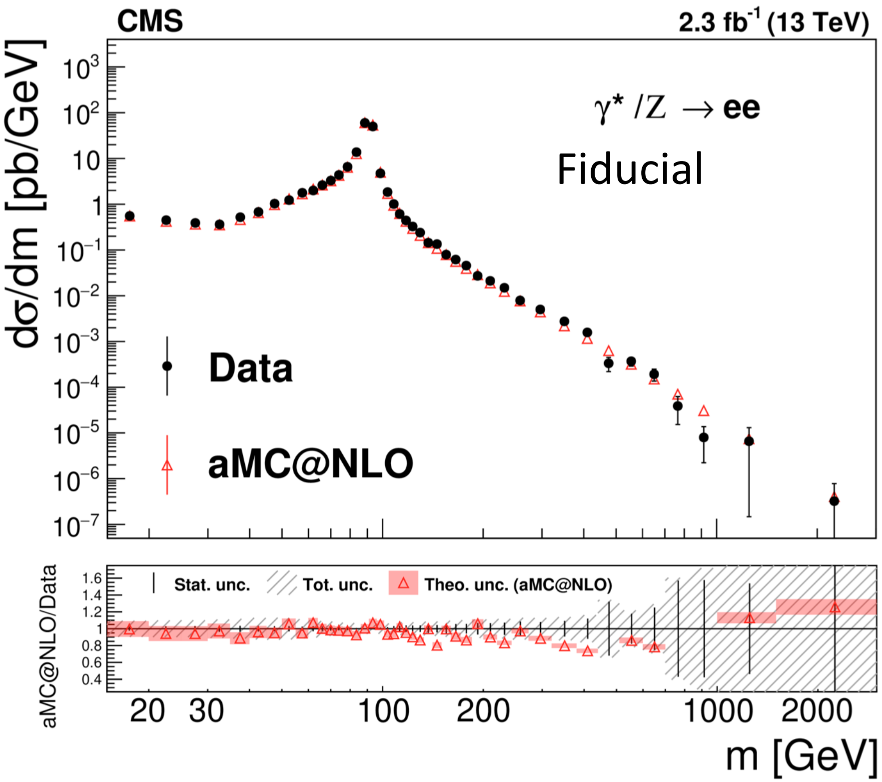
JHEP 12 (2019) 059

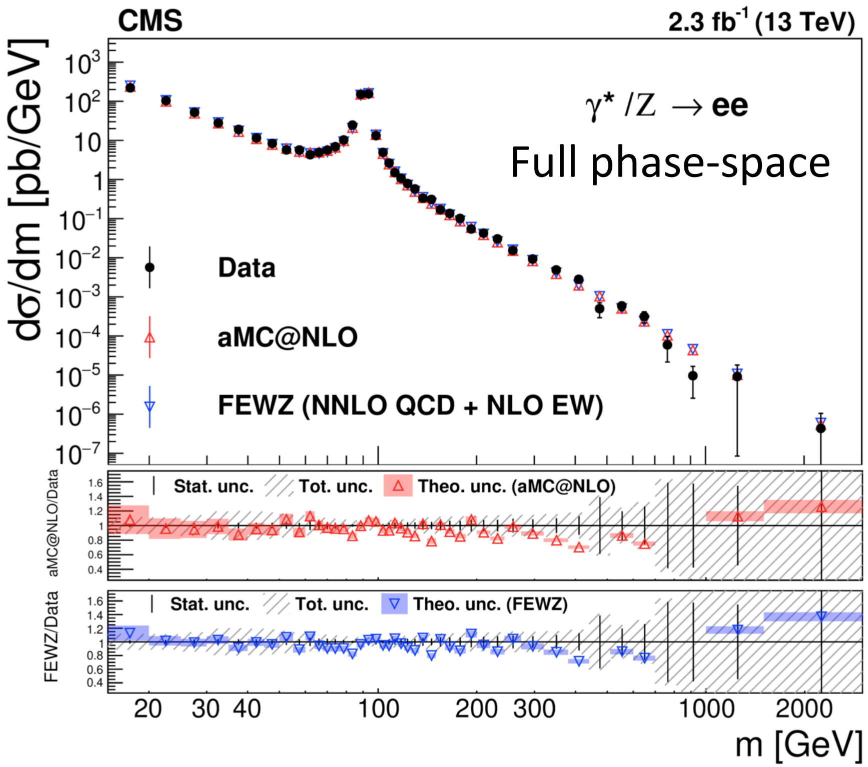
Drell-Yan Mass

2.8 (2.3) fb^{-1}

Unfolded to fiducial space & corrected for acceptance

$\mu^+\mu^-$ (e^+e^-); p_T (l) > 25 GeV, |η|<2.4
15 < M_{ll} < 3000 GeV
Measured differential cross section dσ/dM





Results are in good agreement with the theoretical predictions of the SM

Drell-Yan Measurements

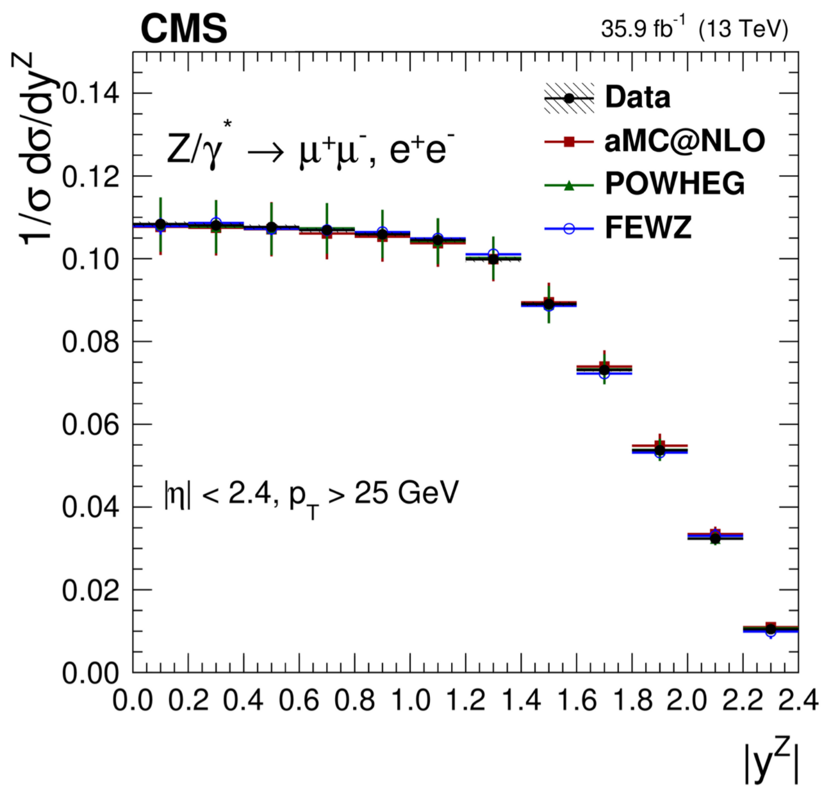
JHEP 12 (2019) 061

35.9 fb^{-1}

Unfolded to fiducial space

$Z \to \mu^+\mu^-$ (e^+e^-); p_T (l) > 25 GeV, $|\eta|<2.4$
76 < M_{ll} < 106 GeV

Measured inclusive cross section as well as (double)differentially (absolute and normalized)
$d\sigma/dp_T$, $d\sigma/d\varphi^*$ also in bins of y(Z)

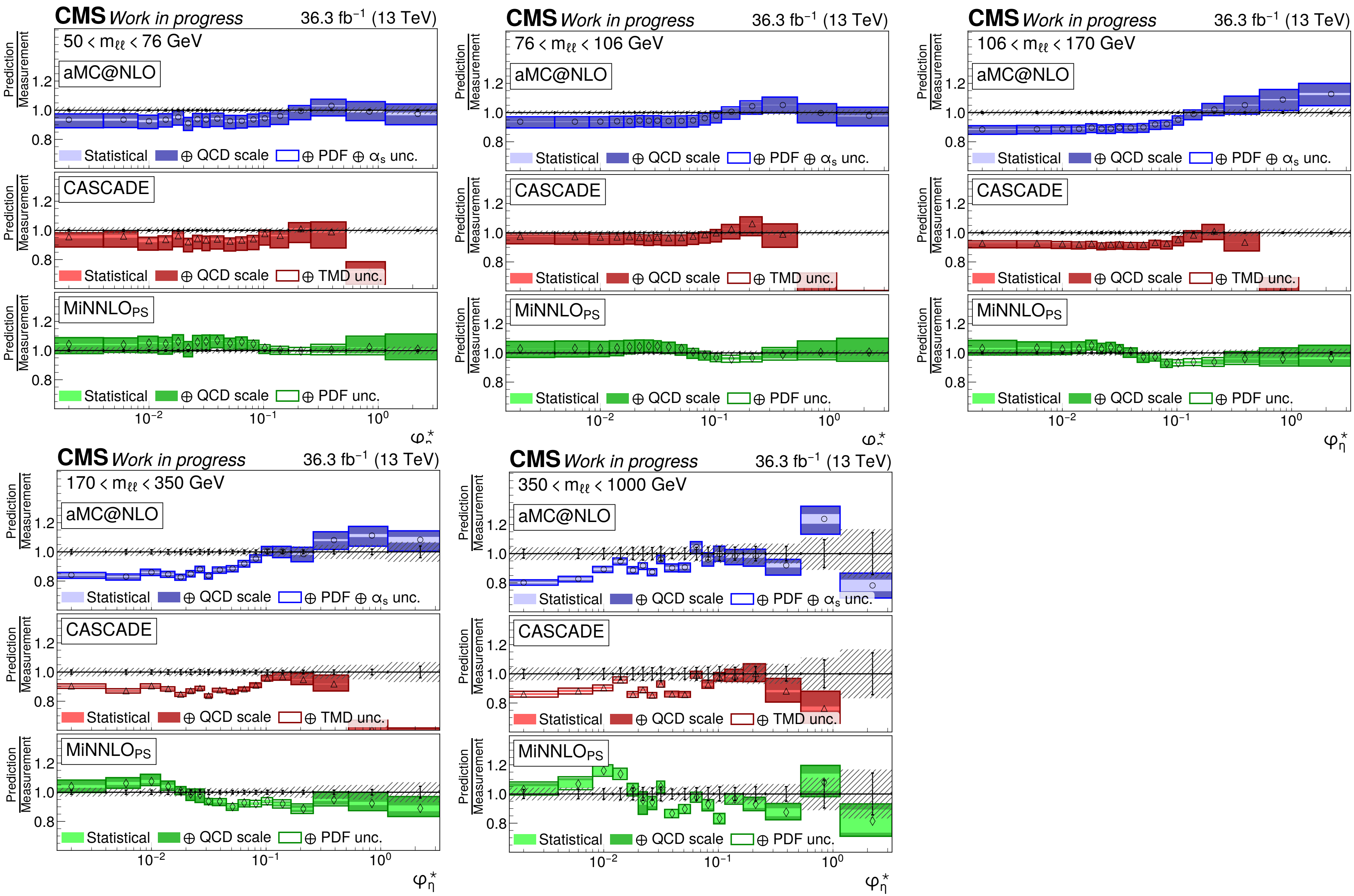


Final state	Data	$Z \to \ell\ell$	Resonant background	Nonresonant background
$\mu\mu$	20.4×10^6	20.7×10^6	30×10^3	41×10^3
ee	12.1×10^6	12.0×10^6	19×10^3	26×10^3

Cross section	$\sigma \mathcal{B}$ [pb]
$\sigma_{Z\to\mu\mu}$	694 ± 6 (syst) ± 17 (lumi)
$\sigma_{Z\to ee}$	712 ± 10 (syst) ± 18 (lumi)
$\sigma_{Z\to\ell\ell}$	699 ± 5 (syst) ± 17 (lumi)

Angular φ^* variable: ratio to predictions

36.3 fb^{-1}



Angular φ^* variable: ratio to predictions

36.3 fb^{-1}