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

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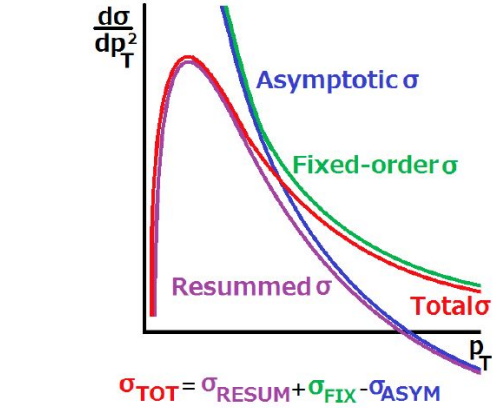
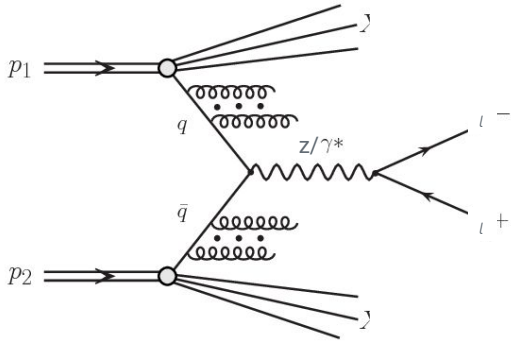
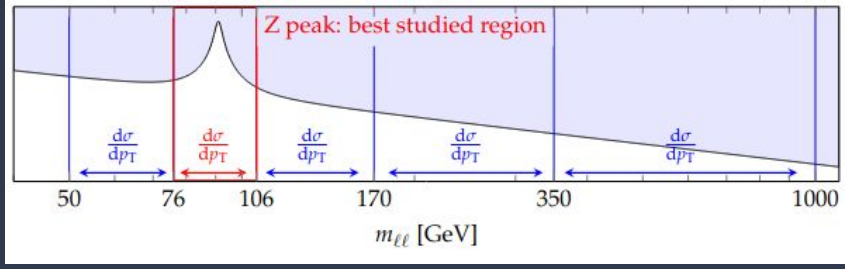
Motivation

- Important insights into the **partonic structure of hadrons** and the **evolution of the parton distribution functions**
- Sensitive to resummation/TMDs in low pT region, pQCD ME for the high pT region and their matching in moderate pT region
  - ➔ tests the **validity of the resummation approach** and the **precision of different predictions**
- **Clean final state** - no QCD final-state radiation, easily measured decay products
- The DY process with one jet - **complementary investigation of the initial-state QCD** radiations, sensitive to **hard QCD radiations and gluon PDF**
- Predictions depend on the factorization and renormalization scales





Introduction



- Results from **CMS-SMP-20-003** publication (arxiv, CMS public page, HepData)
- Analysed data: **2016**
- Luminosity: **36.3 fb^{-1}**
- Five mass bins from **50 to 1000 GeV**
- Di-electron and di-muon channels combined

Event selection:

- Two opposite charged isolated leptons
- Dressed with photons in ΔR (l, γ)< 0.1
- Lepton pT > 25, 20 GeV; $|\eta| < 2.4$

For production in association with at least 1 jet:

- At least one anti-kT jet
- Cone size parameter R = 0.4
- Jet pT >30 GeV; $|y| < 2.4$
- $\Delta R(l, j) > 0.4$

Predictions:

- Test models based on the **ME +** parton shower
- Test the latest models with improved multiple parton emissions (**TMD, NNLL + ME**)

Variables:

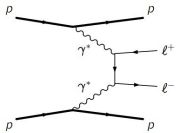
- **pT(*ll*):** sensitive to gluon PDF/TMDs, in many predictions
- **φ*:** based on angular variables only - precise measurements

\+ **Ratios of the cross section in various mass bins over those of Z peak region:** direct probes of evolution between different scales

Backgrounds

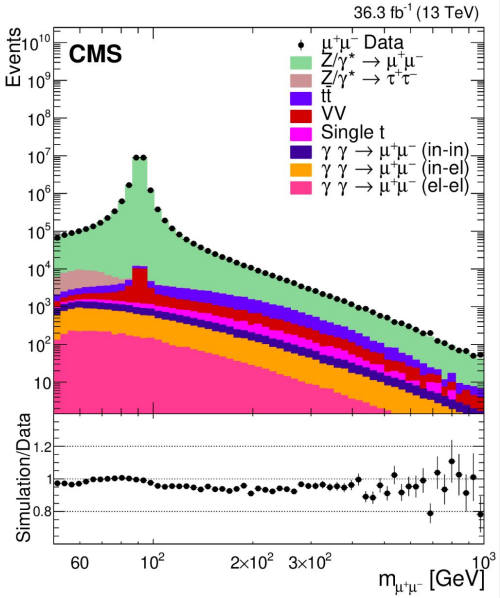
MC background:

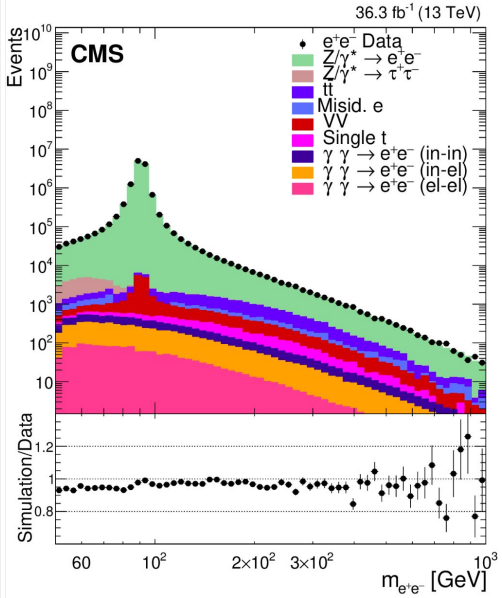
- Top quark pairs that decay into leptons
- Single top production in the t channel, s channel and single top production in association with a W boson
- Production of the Z boson in association with an additional electroweak boson Z or W
- Z/γ* decay in opposite charge τ pairs
- The γγ background process leading to two opposite charged leptons (in-in, in-el, el-el)



Data - driven backround:

- Hadrons misidentified as electrons - estimation based on requiring 2 same sign electrons



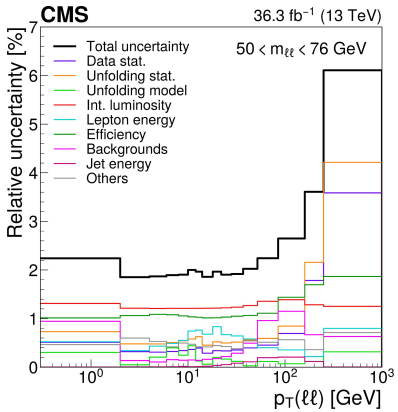


➔ MC corrected to match experimental imperfections

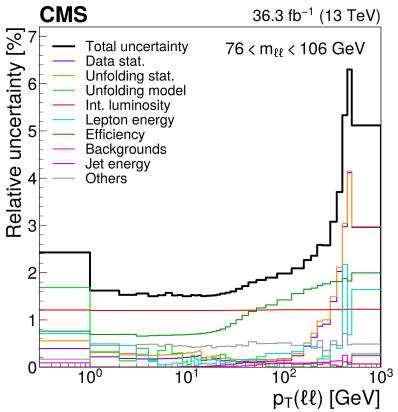
Uncertainties

Uncertainties:

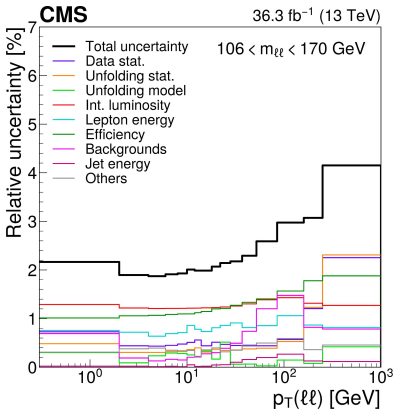
- Total uncertainty **1.5 to 2 %** around the Z peak
- Main source of uncertainties for inclusive measurement:
  - the integrated luminosity measurement
  - the identification and trigger efficiency corrections of the leptons
  - the energy scale of the lepton
- For DY + ≥1 jet case the dominant ones are:
  - jet energy scale
  - the unfolding model



50 - 76 GeV



76 - 106 GeV



106 -170 GeV

➔ For low mass dominant source of uncertainties is luminosity followed by efficiency uncertainties

➔ Low pT region dominated by unfolding model uncertainties at peak and for higher masses

Uncertainties

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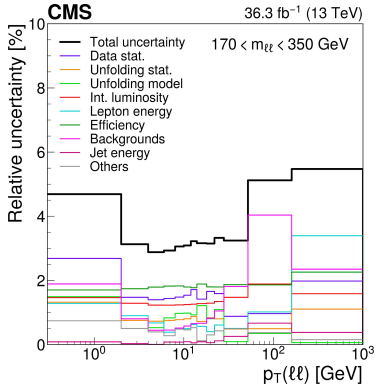
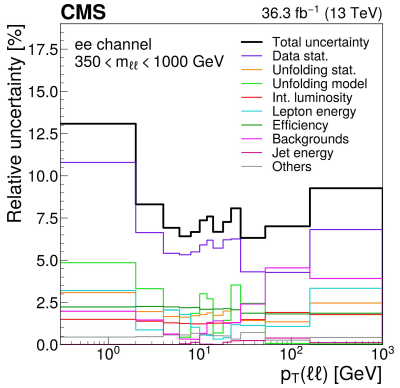


170 - 350 GeV



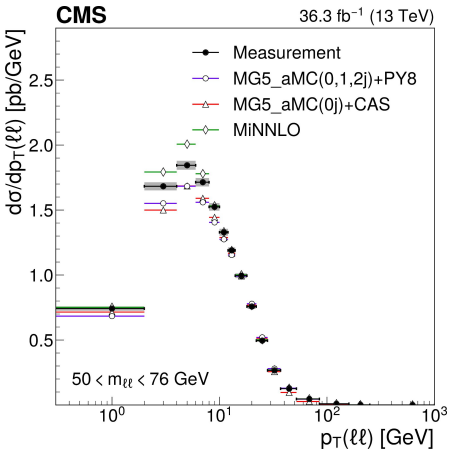
350 - 1000 GeV

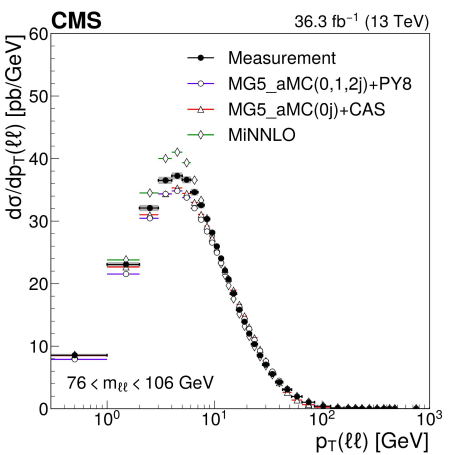
➔ Luminosity also dominant for mass region 170 - 350 GeV

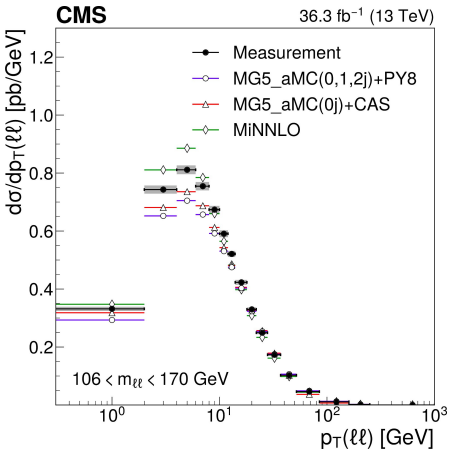
➔ Data statistics dominant in the highest mass bin

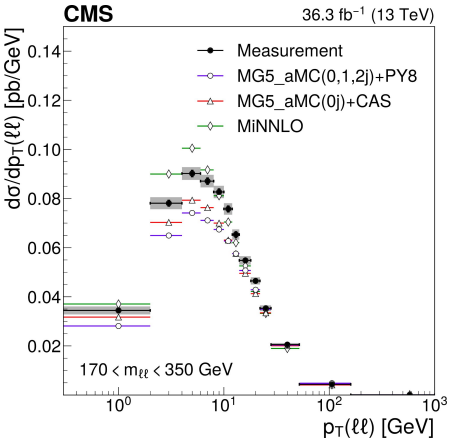
Theoretical predictions

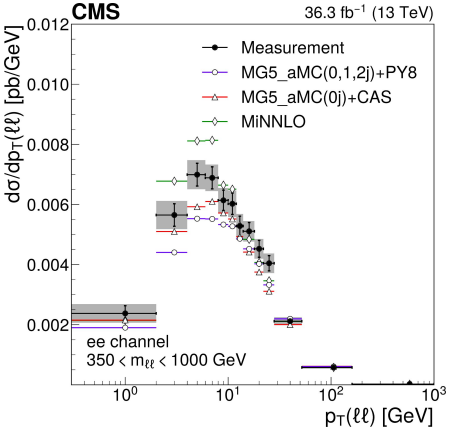
- MADGRAPH_aMC@NLO FxFx
  - Monte-Carlo prediction
  - Interfaced with PYTHIA8 using the CUETP8M1 tune
  - Matrix element at NLO for up to 2 partons
  - The NNPDF3.1 NLO PDF
- MiNNLO
  - Monte-Carlo prediction
  - PYTHIA8 for the parton showers based on the CP5 tune (harder primordial kt)
  - Matrix element at NNLO
  - The NNPDF 3.1 PDF
  - Sudakov form factors are used to interpolate between the scale
- CASCADE
  - Monte-Carlo prediction
  - Parton Branching TMD
  - PYTHIA6
  - Z + 0j or Z + 1j at NLO
- ARTEMIDE
  - Analytical prediction
  - N^3LL + NNLO TMD
  - QED FSR, based on PYTHIA8 (our correction)
- Geneva qT
  - Monte-Carlo prediction
  - qT resummation at N^3LL in the Radish formalism + NNLO
  - PYTHIA8 parton shower
- Geneva τ
  - Monte-Carlo prediction
  - 0-jettiness variable τ_0 resumation - $NNLL'_\tau$ + NNLO
  - PYTHIA8 parton shower











pT(*ll*) results

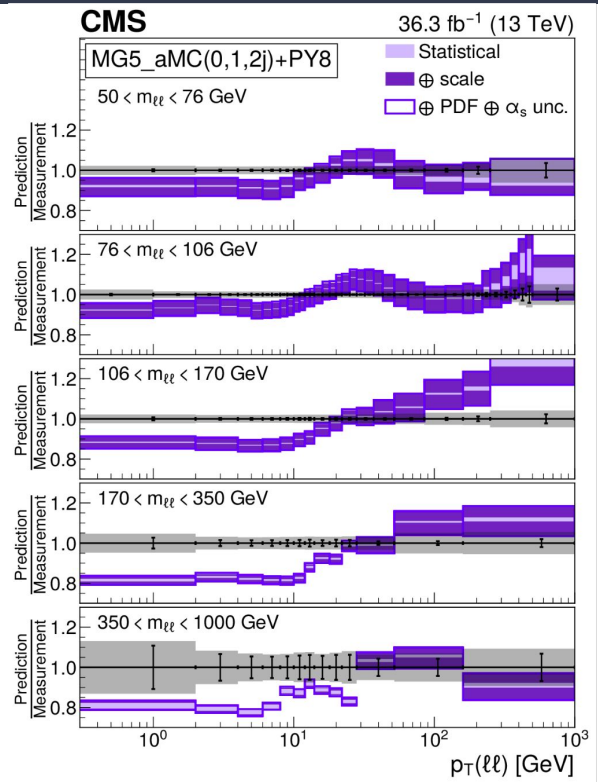
Differential cross section in different mass bins

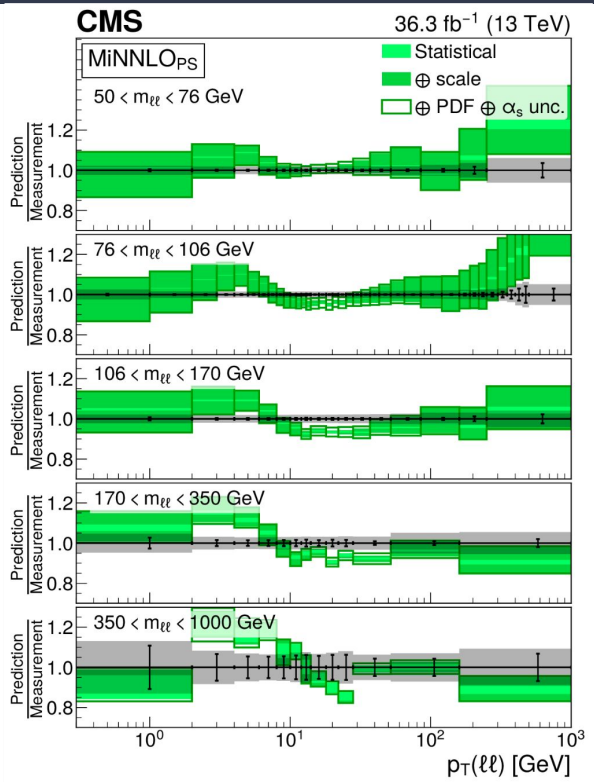
Inclusive

Differential cross section in different mass bins

pT(*ll*) results

Inclusive

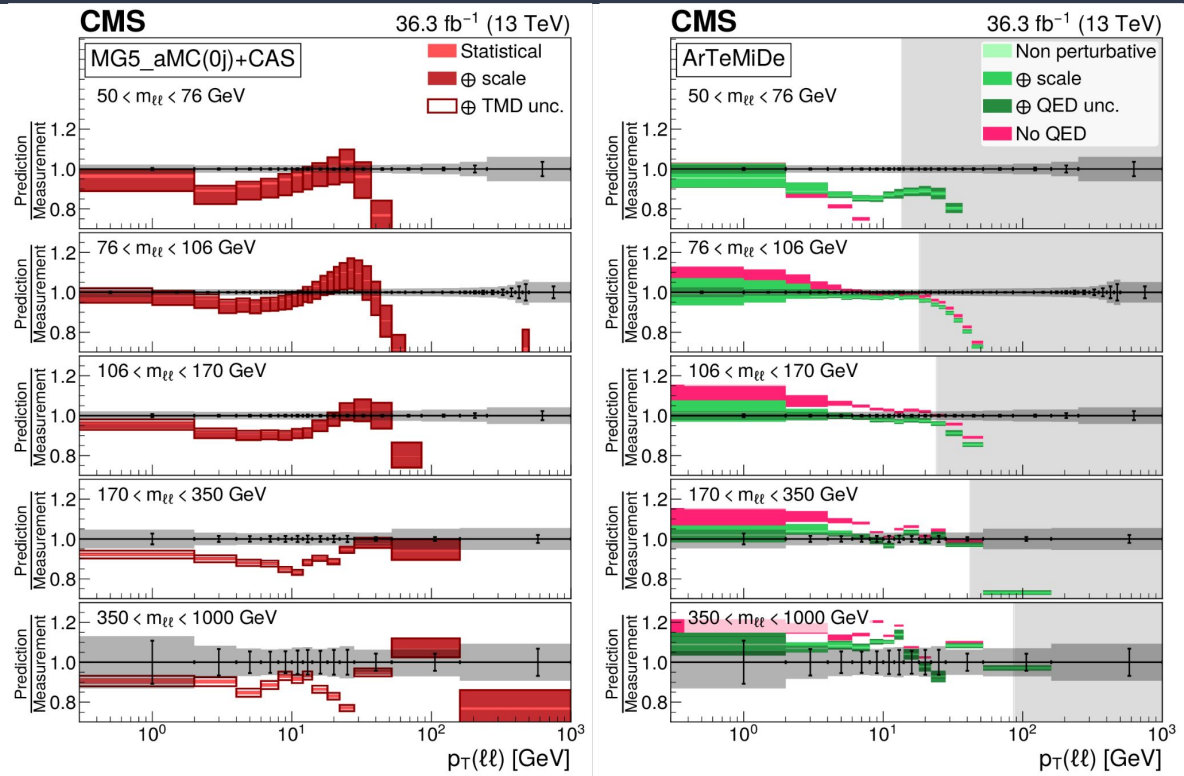




- MG5 aMC + PYTHIA 8:
  - In general, good description of the data
  - Too-small cross section for pT(*ll*) values below 30 GeV - for masses above 170 GeV up to 20% disagreement with data
  - Low pT spectrum is sensitive to the choice of the tuned parameters
  - Disagreement at high pT for high mass bins - higher-order (e.g. NNLO) multiparton predictions
- MiNNLO:
  - The best global description among the predictions shown here
  - Good description of high pT except for pT > 400 GeV in the Z peak region
  - For the medium pT values - PDF uncertainty becomes significant with respect to other model uncertainties

pT(*ll*) results

Inclusive

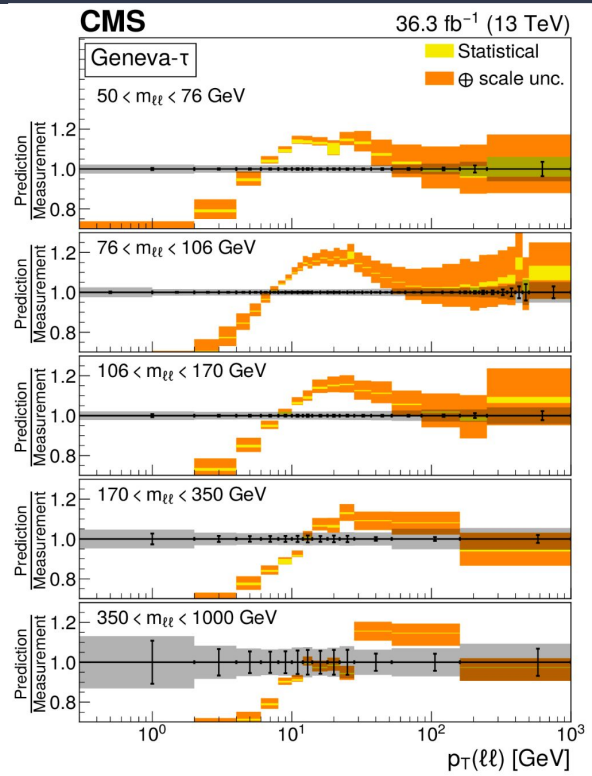


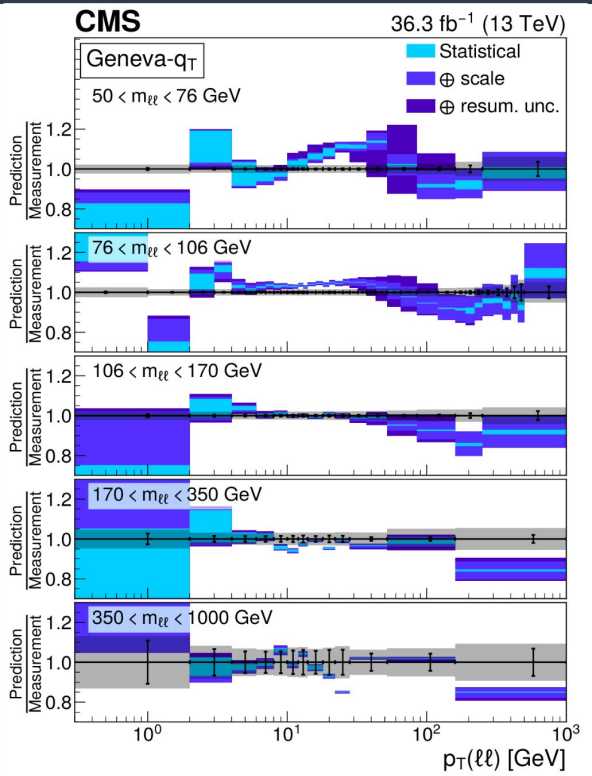
- CASCADE:
  - Better description in the low-pT part for all mass bins
  - For medium pT values - 5 to 10% too low
  - The high pT region - missing higher fixed-order calculations
  - pT regions with good description extend for higher mass bins
- ArTeMiDe:
  - Describes the measurements very well in the range of validity (pT < 0.2 m_{ll})
  - Low-pT region in a very good agreement with data for all mass bins
  - Prediction with and without QED FSR corrections

Differential cross section in different mass bins

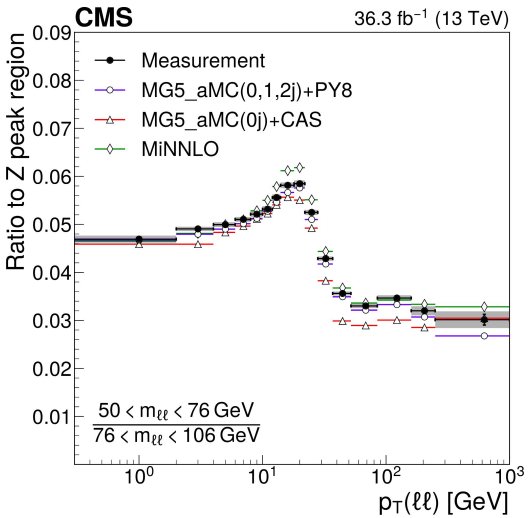
pT(*ll*) results

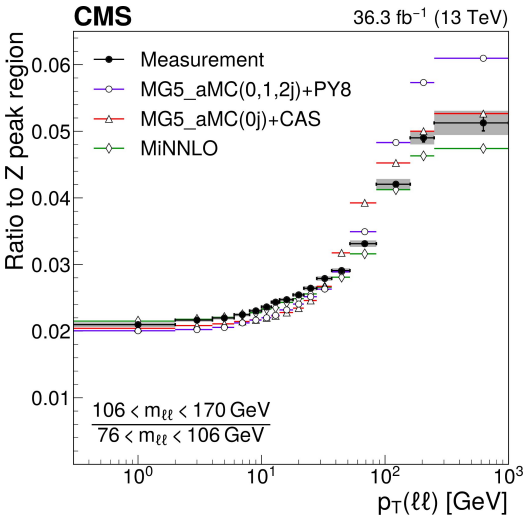
Inclusive

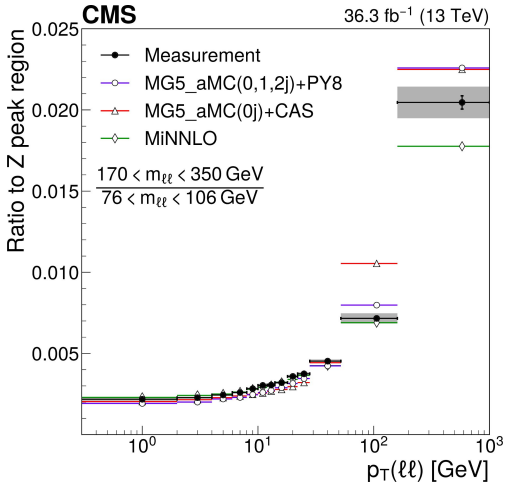


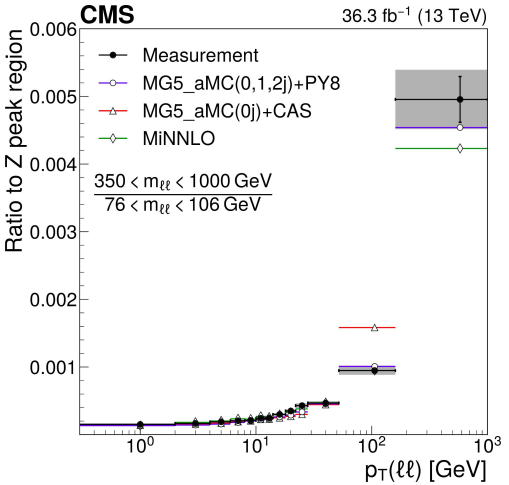


- Geneva τ
  - Does not describe the data well for pT values below 40 GeV
  - Too hard pT spectrum - related to the choice of α_S
  - In high pT region good description - inclusion of NNLO corrections
- Geneva qT
  - Very good description of the data in the whole pT region (except for middle pT values in the lowest mass bin)









pT(*ll*) results

-Ratios-

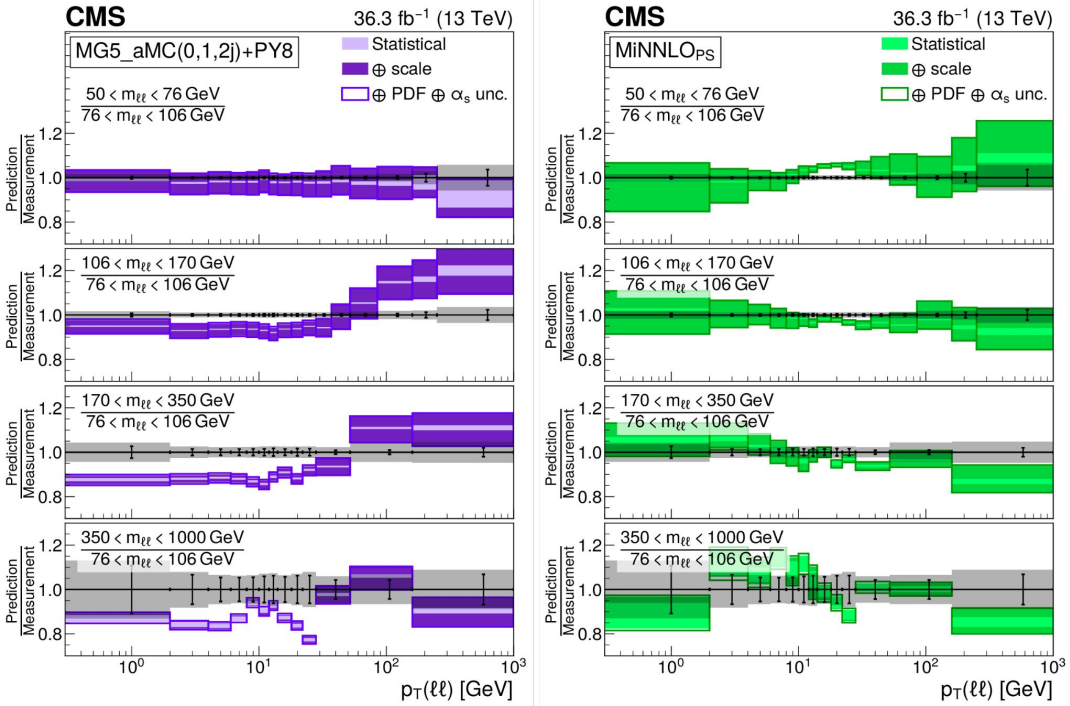
of the differential cross sections for various mass bins to those in the Z mass peak interval

Inclusive

The differential cross sections for various mass bins over those in the Z mass peak interval

pT(*ll*) results –*Ratios*–

Inclusive

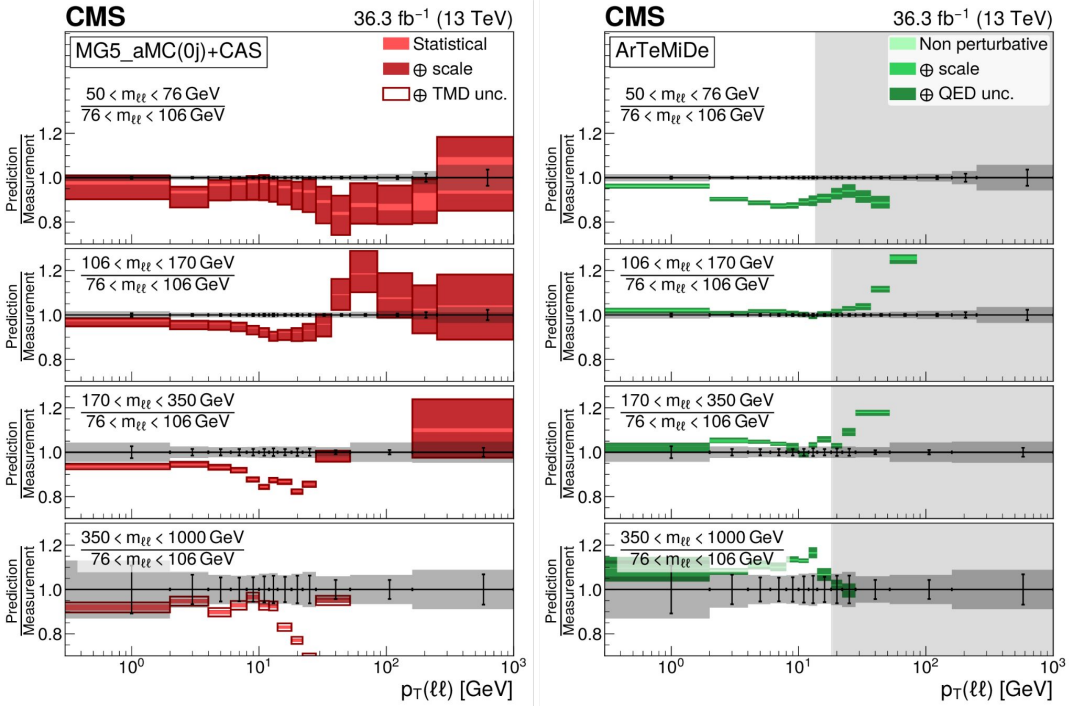


- Probe the QCD evolution between different masses
- Experimental uncertainty goes down to 1.2 % around the Z peak

- MG5 aMC + PYTHIA 8:
  - Great description for low mass
  - Significant disagreement for high masses
- MiNNLO:
  - Best global description
  - Disagreement visible for higher masses and higher pT values

pT(*ll*) results –*Ratios*–

Inclusive

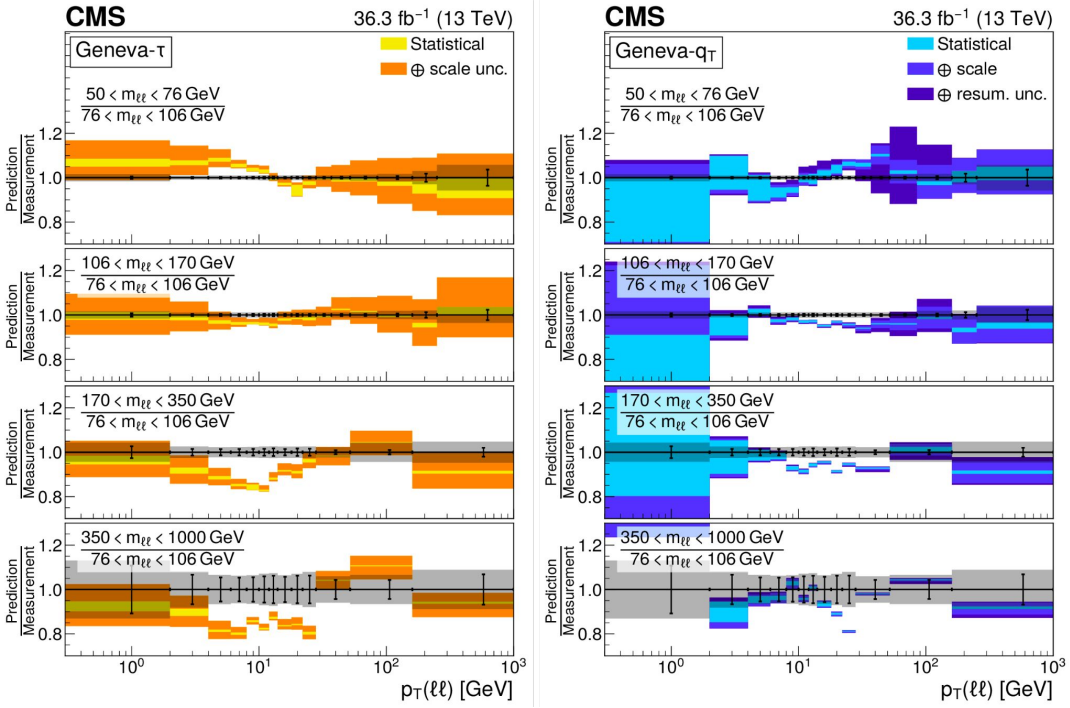


- Probe the QCD evolution between different masses
- Experimental uncertainty goes down to 1.2 % around the Z peak

- CASCADE
  - Good description in the range of validity
- ArTeMiDe
  - Good description for low pT region

pT(*ll*) results –*Ratios*–

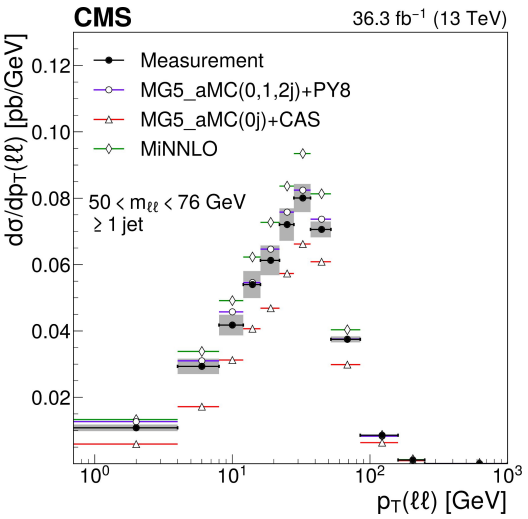
Inclusive

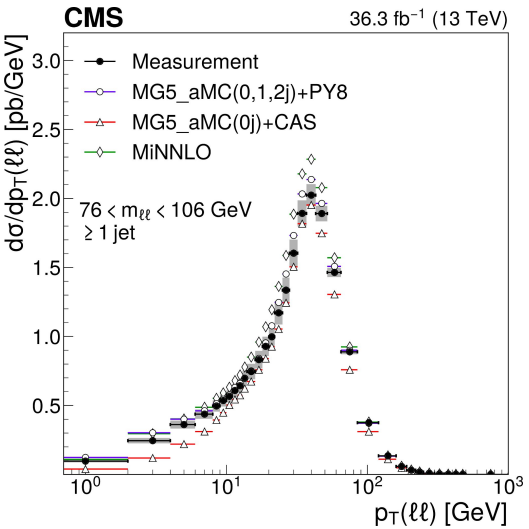


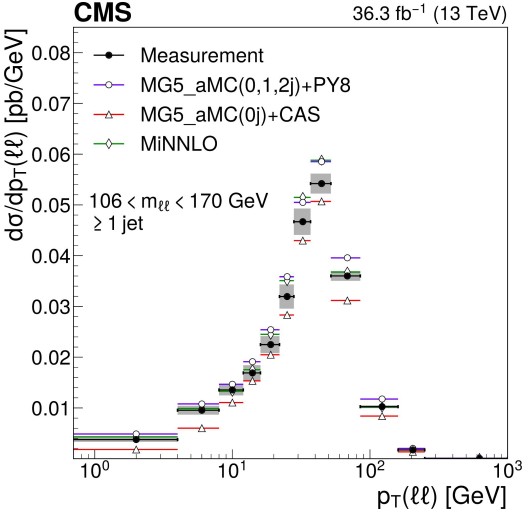
- Probe the QCD evolution between different masses
- Experimental uncertainty goes down to 1.2 % around the Z peak

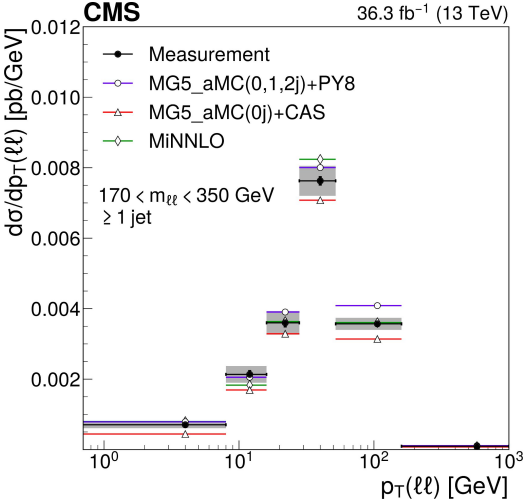
- Geneva τ
  - Very good description of data for mass bin just above the peak
- Geneva qT
  - Good description for high pT region for almost all mass bins

➔ Good description of ratios in the region where it fails to describe well cross sections









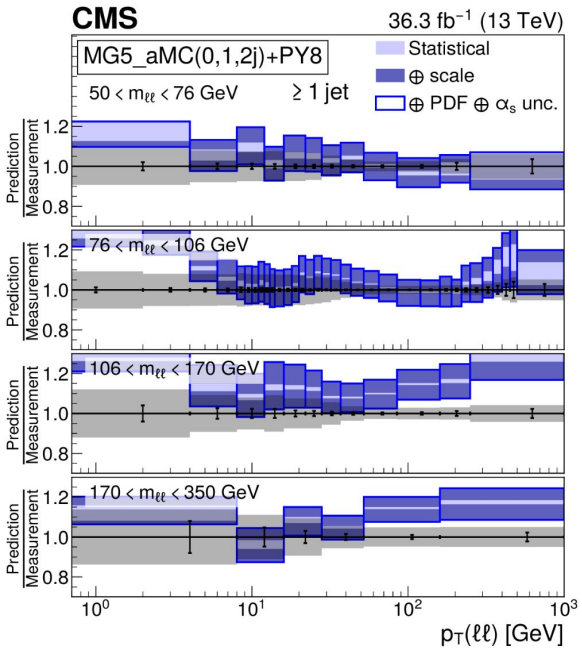
pT(*ll*) results

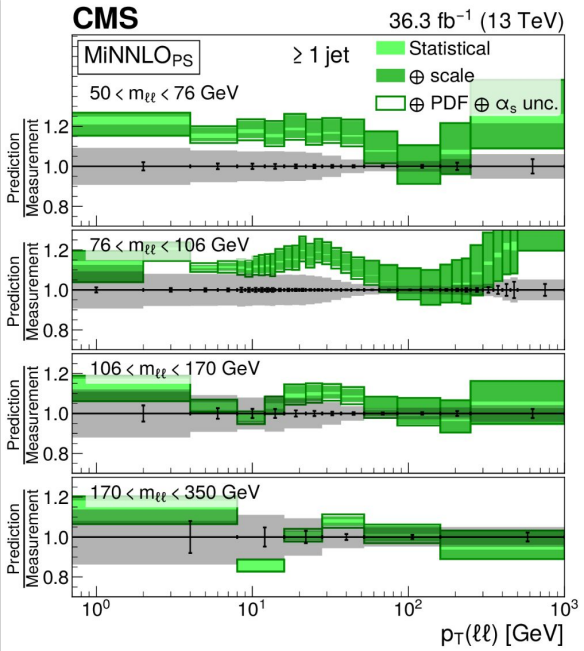
Differential cross section in different mass bins

For one or more jets

pT(*ll*) results

For one or more jets



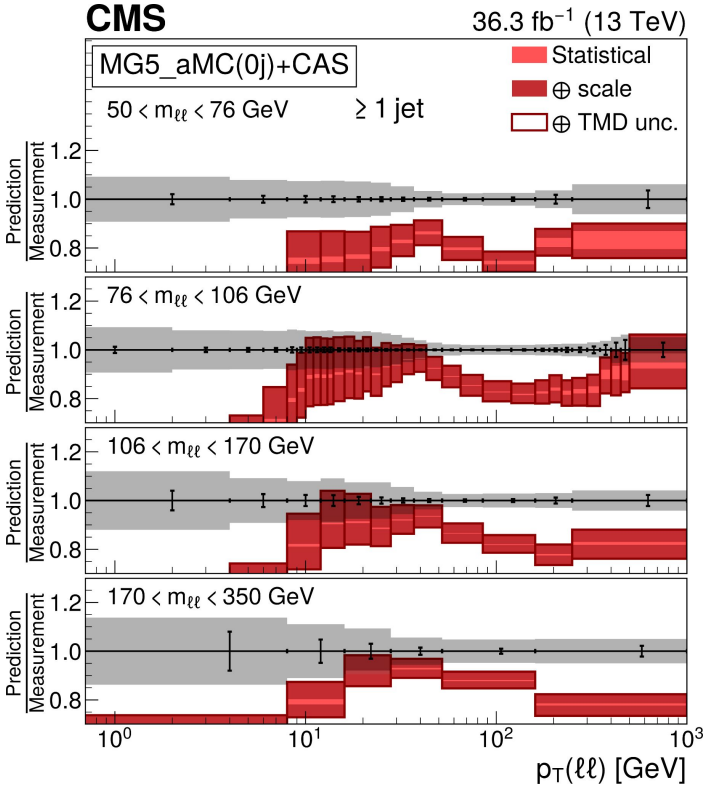


- MG5 aMC + PYTHIA 8:
  - Good description of the data for moderate pT
  - Disagreement for lowest and highest pT bins which goes up to 20% for 106-170 GeV
- MiNNLO:
  - Also for 1 or more jets, best description of the data among shown predictions
  - Larger disagreement with data for all mass bins than for inclusive

Differential cross section in different mass bins

pT(*ll*) results

For one or more jets

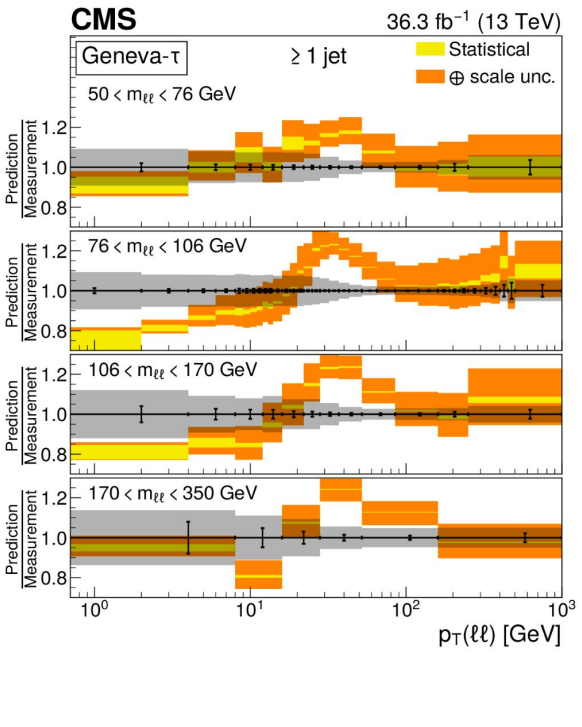


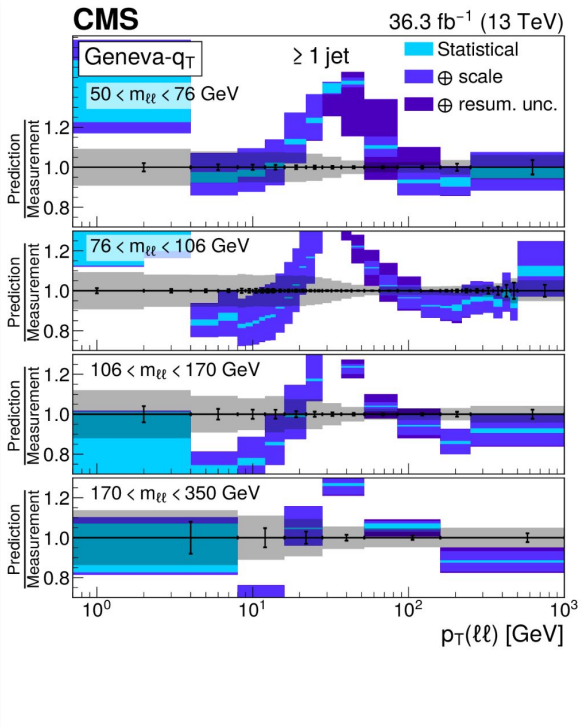
- CASCADE:
  - Missing the contributions from the double parton scattering - the low-pT part is mainly dominated by Z + 2 jet events
  - Multi-jet merging included recently

Differential cross section in different mass bins

pT(*ll*) results

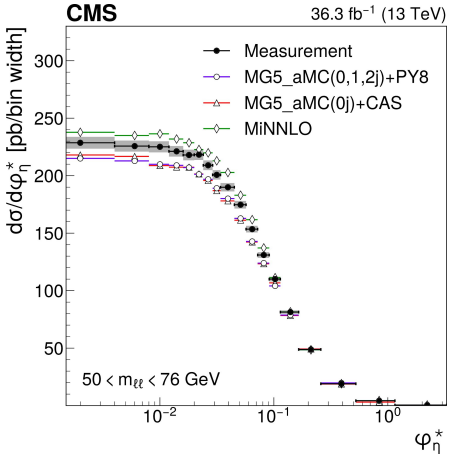
For one or more jets

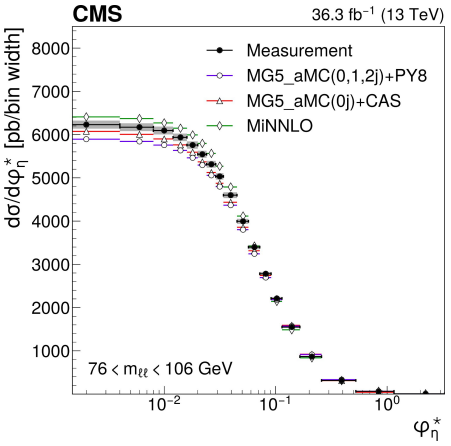


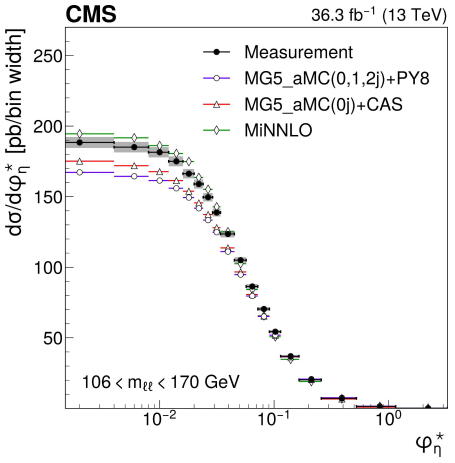


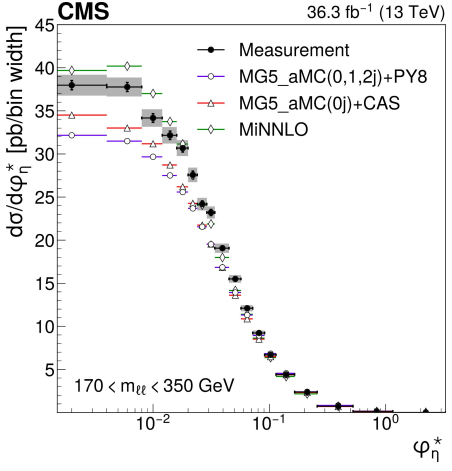
- Similar behaviour for both **GENEVA** predictions - qT resummation is only applied in the 1-jettiness

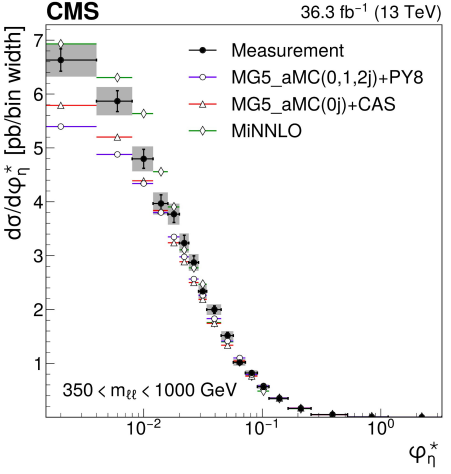
➔ **GENEVA** predicts a too hard pT spectrum, similarly to the 0-jettiness inclusive case











φ^* results

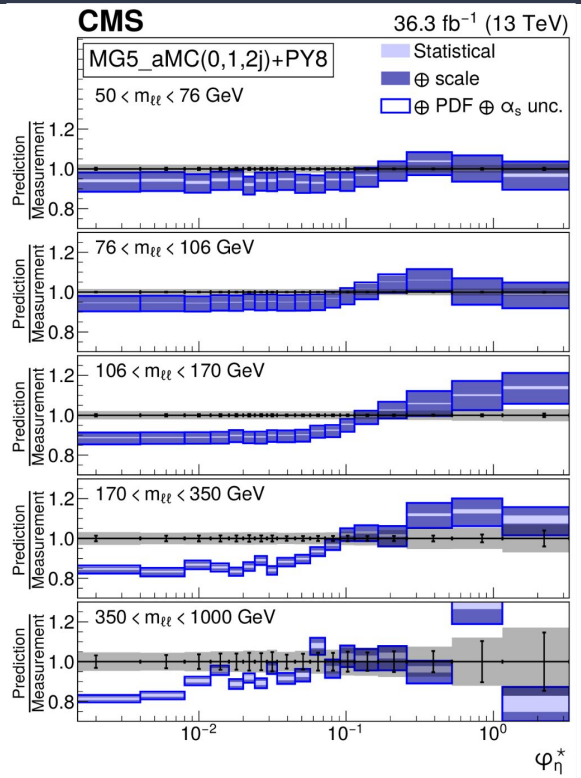
Differential cross section in different mass bins

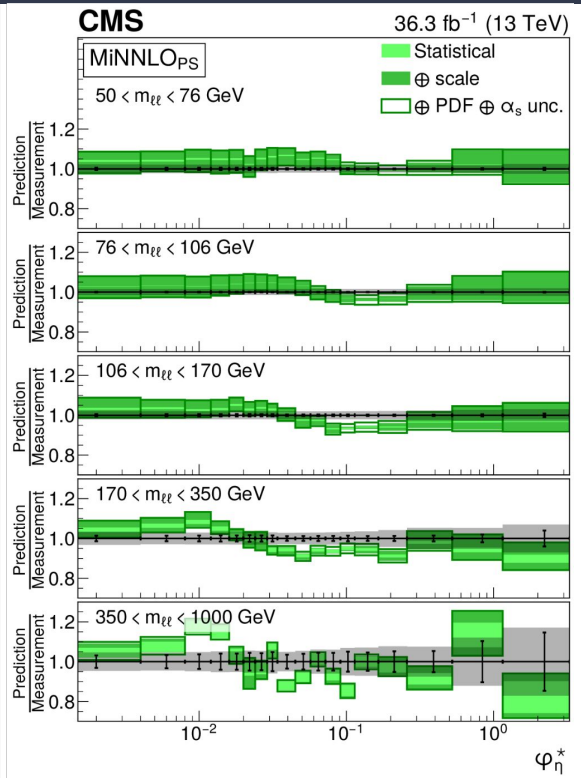
Inclusive

Differential cross section in different mass bins

φ* results

Inclusive

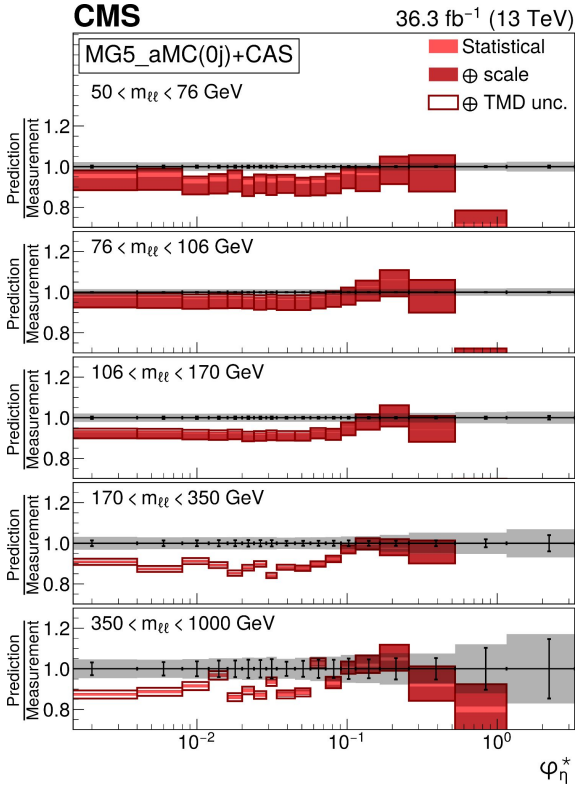




- MG5 aMC + PYTHIA 8:
  - Good description globally
  - Too-small cross section in the region sensitive to gluon resummation - φ* < 0.1 for Z boson mass peak
- MiNNLO:
  - The best global description among the predictions shown here
  - Large φ* are well described in contrast to disagreement noticed for high pT range.
  - Prediction precision of the level of **1.5% in several bins**!

φ* results

Inclusive

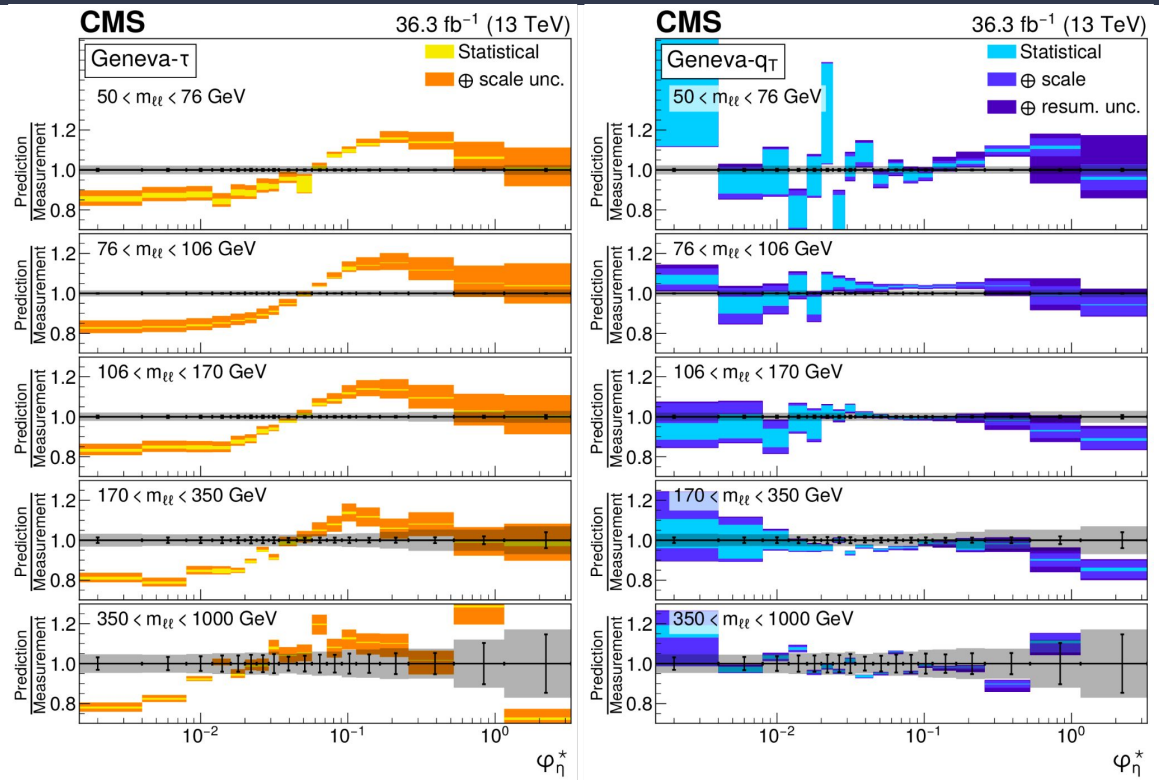


- CASCADE:
  - Describes well φ* < 0.1 region in all mass bins - details of pT distribution are washed out in φ* distribution
  - Good description for Z peak region
  - Underestimates more and more the cross section for higher mass bins

Differential cross section in different mass bins

φ* results

Inclusive



- Geneva qT improves significantly the description with respect to Geneva τ
- The disagreement in low φ* region is improved for three central mass bins
- The discrepancy of GENEVA-qT for low pT range for low mass been and Z boson mass bin is smoothed in φ* - global agreement in all mas bins

Summary

- Precision measurement
- Electron and muon channels were analysed for 2016 data
- Different distributions are measured in several mass bins from 50 do 1000 GeV:
  - Inclusive pT of the pair
  - Inclusive φ*
  - pT of the pair with at least one jet in the final state
- Ratio to the peak region is also measured

- MadGraph sample is within the uncertainties all over the covered phase space, but disagrees with data at low pT — up to 20 %
- MiNNLO has the best overal agreement among all the predictions
- TMD based predictions (Artemide, CASCADE) give better description at low pT . CASCADE describes well the φ* < 0.1 region
- CASCADE gives very nice predictions for moderate PT while it is the only prediction that does not rely on previous DY meaurements.
- Significant improvement in data description for Geneva qT for all the distributions that were shown
- Z + 1 jet region is very sensitive to Z + 2 jets effects, MadGraph and MiNNLO showed best description of the data

Questions?