Measurement of the Drell-Yan transverse momentum dependence over a wide mass range at 13 TeV

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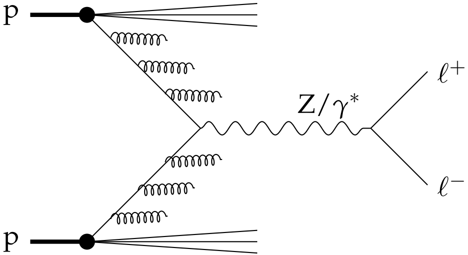
QCD Evolution Workshop
May 10, 2021

CMS and the CERN LHC

Drell-Yan transverse momentum

Transverse momentum of Drell-Yan lepton pairs is a crucial observable



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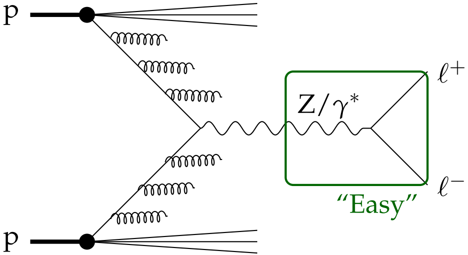

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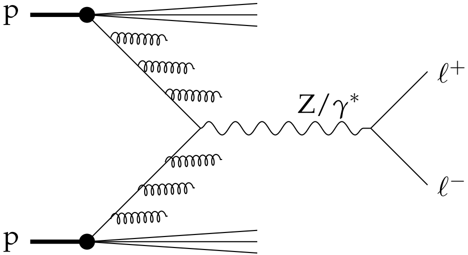

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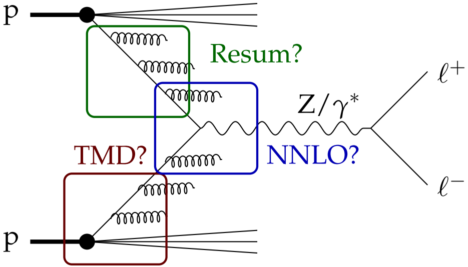

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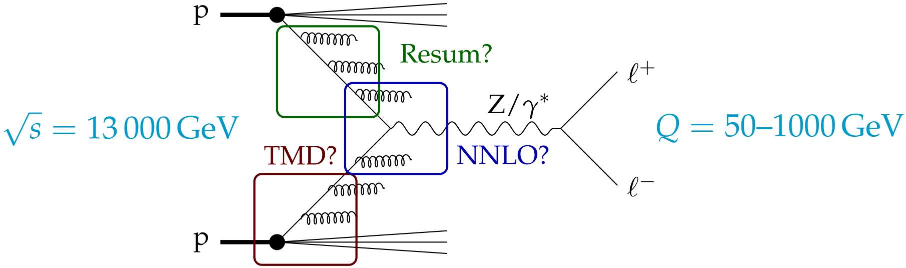
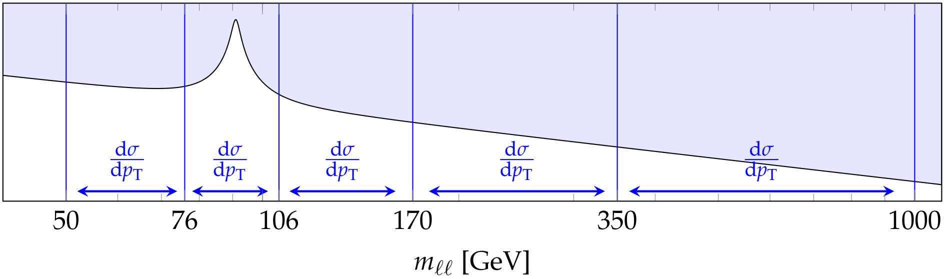


This talk: experimental input from CMS

https://cds.cern.ch/record/2764470/

Observables

We **measure** $p_\mathrm{T}(\ell\ell)$ and $\varphi^* = \tan((\pi - \Delta\phi)/2)\sin(\theta^*_\eta)$ **distributions** in 5 dilepton mass bins, and $p_\mathrm{T}(\ell\ell)$ for ≥ 1 jet in the lower 4 bins:



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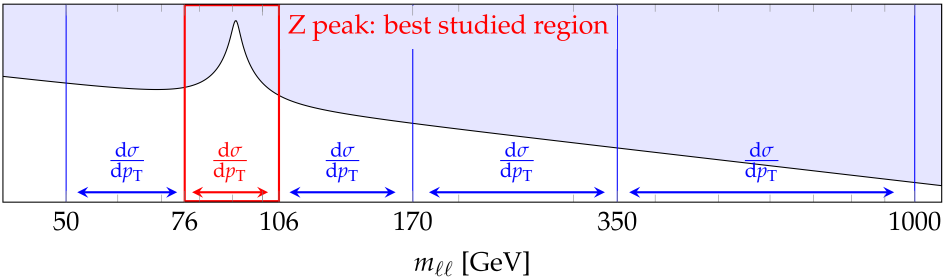

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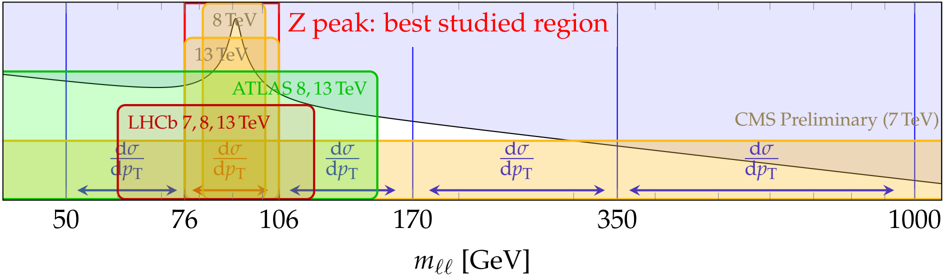

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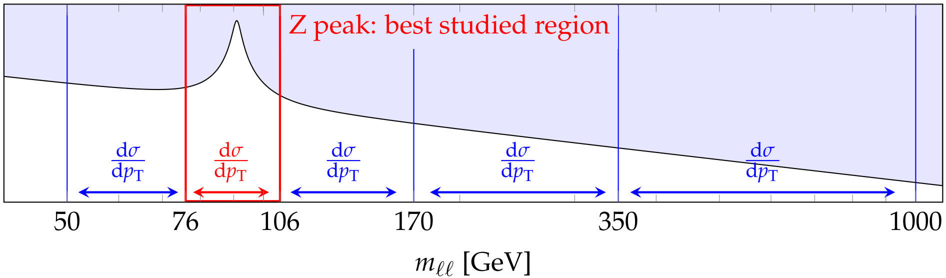
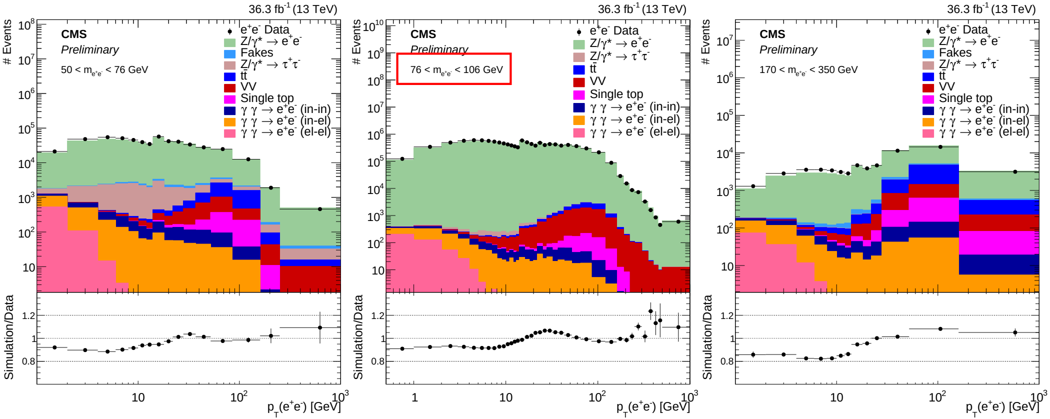


We also measure **ratios** of these quantities with respect to the peak region:

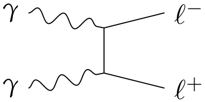
$$\frac{d\sigma}{dX}(m_{\ell\ell}) \Big/ \frac{d\sigma}{dX}(76 < m_{\ell\ell} < 106\,\text{GeV})$$

The ratios probe the $m_{\ell\ell}$ evolution directly.

Detector level distributions



- Almost background free in the Z peak region
- Photon-induced lepton pair production at low p_T
- $t\bar{t}$ production at high mass



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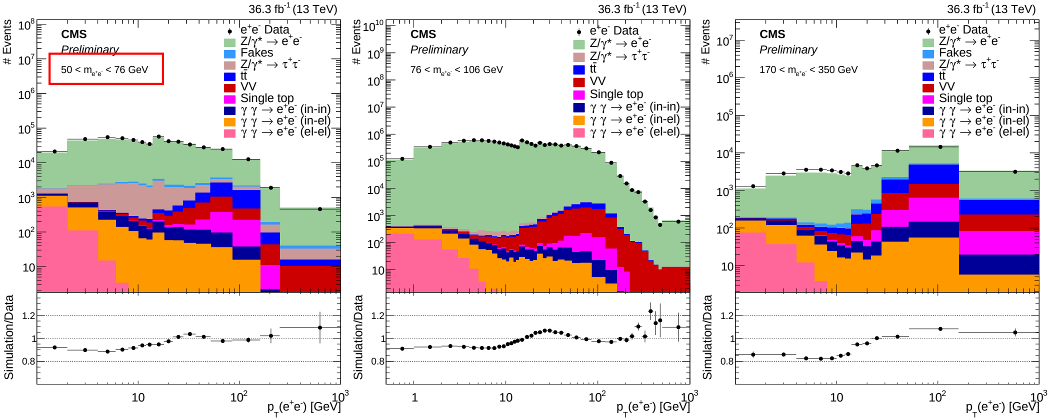

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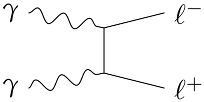

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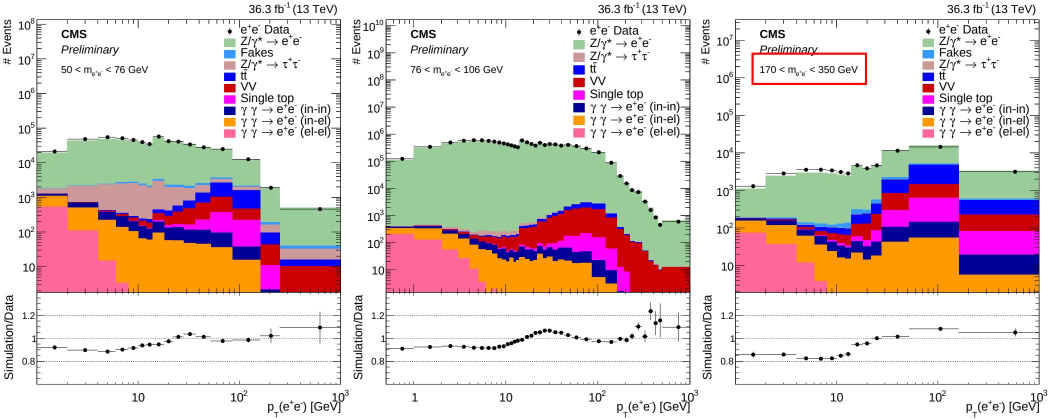

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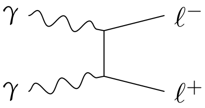


Phase space

The results are unfolded to the following phase space:

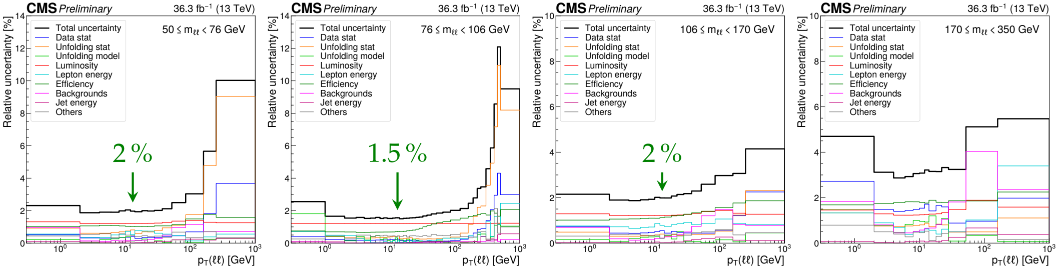
All distributions:

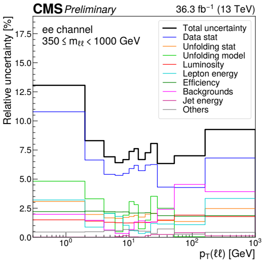
- Two electrons or two muons
- Dressed with photons in $\Delta R(\ell, \gamma) < 0.1$
- $p_{\mathrm{T}} > 25, 20\,\mathrm{GeV}$; $|\eta| < 2.4$

For the cross sections requiring $\geq$ one jet:

- At least one anti-k_{T} jet
- Cone size parameter $R = 0.4$
- $p_{\mathrm{T}} > 30\,\mathrm{GeV}$, $|y| < 2.4$
- Separated from leptons: $\Delta R(\ell, \mathrm{j}) > 0.4$

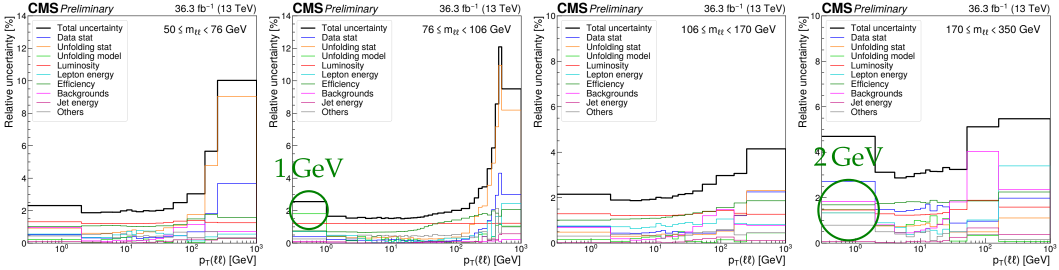
Uncertainties

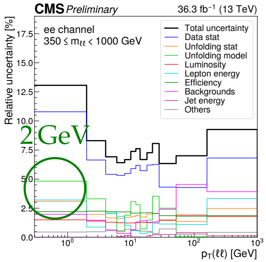




- Total uncertainty 1.5 to 2 % around the Z peak, larger at high p_T and high $m_{\ell\ell}$
- Dominated by systematics up to 350 GeV (except high p_T)

Uncertainties





- Total uncertainty 1.5 to 2 % around the Z peak, larger at high p_T and high $m_{\ell\ell}$
- Dominated by systematics up to 350 GeV (except high p_T)
- Low p_T binning driven by detector resolution (“unfolding model” systematic)

Predictions

MadGraph5_aMC@NLO

Monte-Carlo prediction

Baseline for LHC experiments

$Z + 0, 1, 2$ partons merged at NLO

Pythia8 parton shower

Predictions

MadGraph5_aMC@NLO	arTeMiDe
Monte-Carlo prediction	Analytical prediction
Baseline for LHC experiments	$N^3LL + NNLO$ TMD
$Z + 0, 1, 2$ partons merged at NLO	QED FSR by us, based on Pythia8
Pythia8 parton shower	Valid for $p_T < 0.2 m_{\ell\ell}$
	See talk by I. Scimemi

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MadGraph5_aMC@NLO

Monte-Carlo prediction

Baseline for LHC experiments

$Z + 0$, 1, 2 partons merged at NLO

Pythia8 parton shower

artemide

Analytical prediction

$N^3LL + NNLO$ TMD

QED FSR by us, based on Pythia8

Valid for $p_T < 0.2 m_{\ell\ell}$

See talk by I. Scimemi

CASCADE

Monte-Carlo prediction

Parton Branching TMD

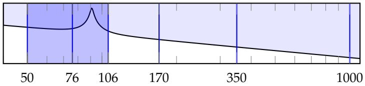
$Z + 0j$ or $Z + 1j$ at NLO,
depending on distribution

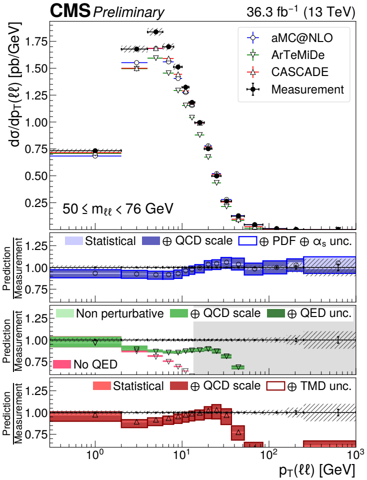
Pythia6 parton shower

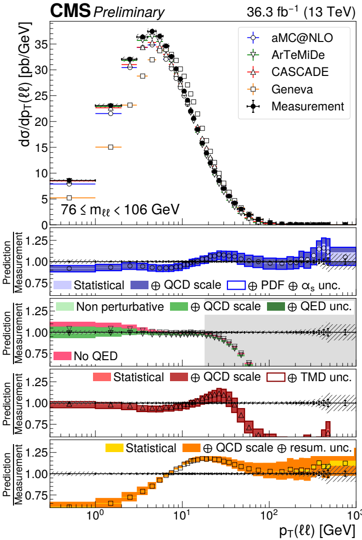
Predictions

MadGraph5_aMC@NLO Monte-Carlo prediction Baseline for LHC experiments $Z + 0, 1, 2$ partons merged at NLO Pythia8 parton shower	**arTeMiDe** Analytical prediction $N^3LL + NNLO$ TMD QED FSR by us, based on Pythia8 Valid for $p_T < 0.2 m_{\ell\ell}$ See talk by I. Scimemi
CASCADE Monte-Carlo prediction Parton Branching TMD $Z + 0j$ or $Z + 1j$ at NLO, depending on distribution Pythia6 parton shower	**Geneva** Monte-Carlo prediction $NNLL'_{\tau} + NNLO$ Pythia8 parton shower

Transverse momentum







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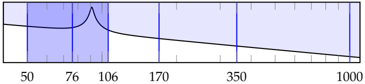

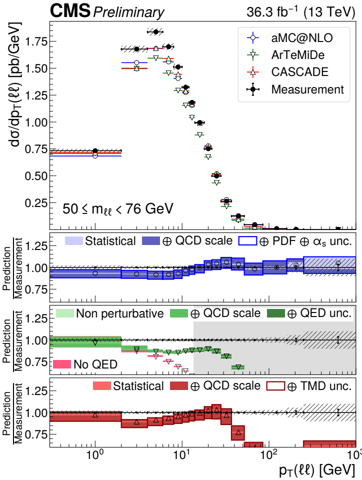

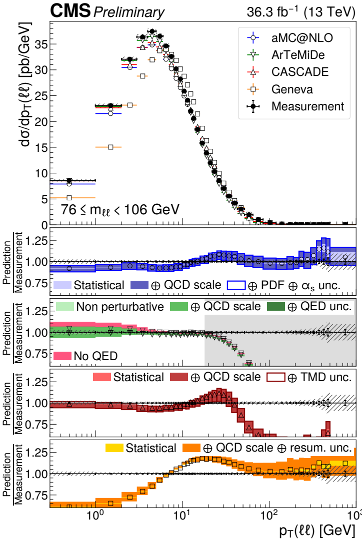

MADGRAPH — LHC baseline

- Globally good description of the data
- Disagreement at low p_T in the region sensitive to resummation

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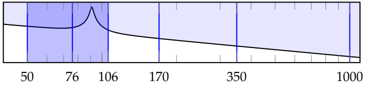
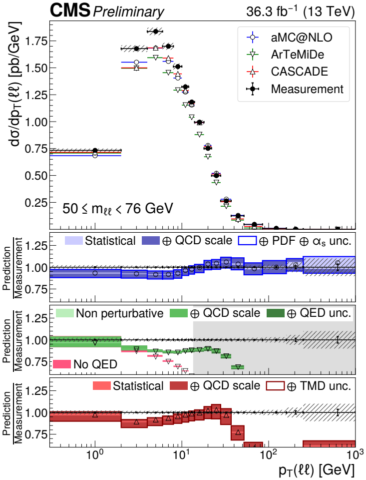
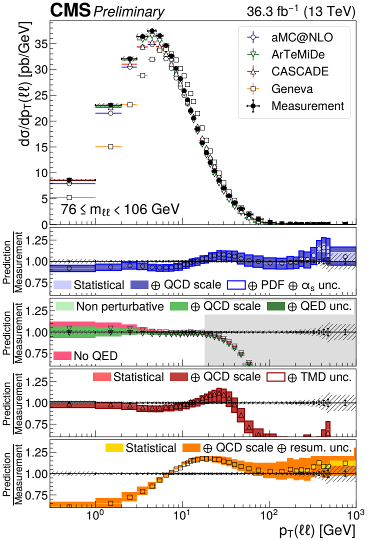






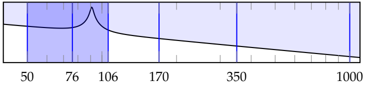
MADGRAPH — LHC baseline

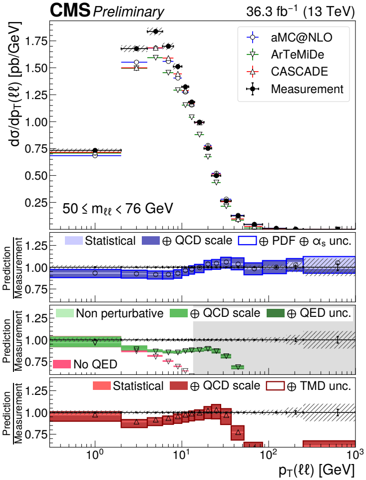
- Globally good description of the data
- Disagreement at low p_T in the region sensitive to resummation

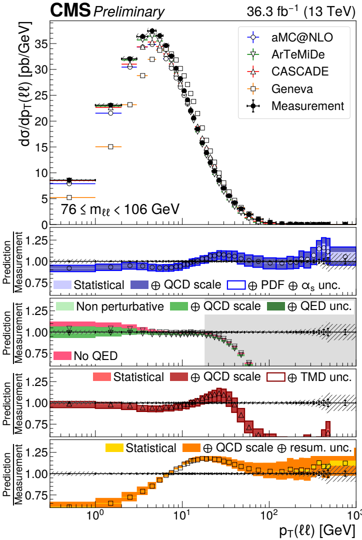
ARTEMIDE — N^{3}LL TMD

- Very good description within its range of validity
- Also shown without QED corrections

Transverse momentum



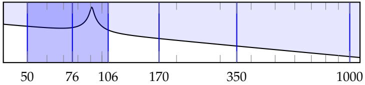


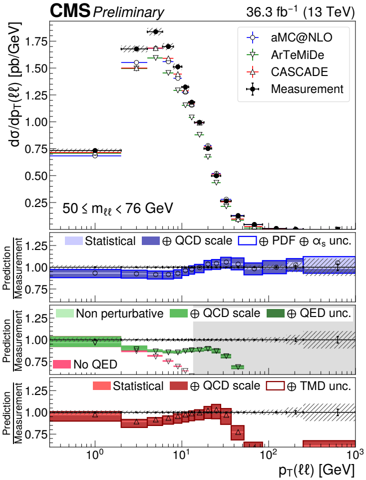


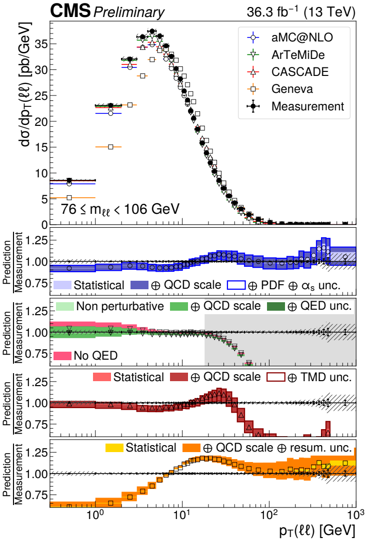
CASCADE — PB TMD + NLO

- PB TMD improve over MADGRAPH for the description of the low p_T part
- High p_T: missing higher orders/jet merging

Transverse momentum







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- PB TMD improve over MADGRAPH for the description of the low p_T part
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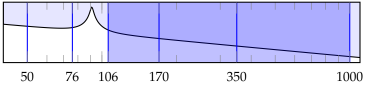
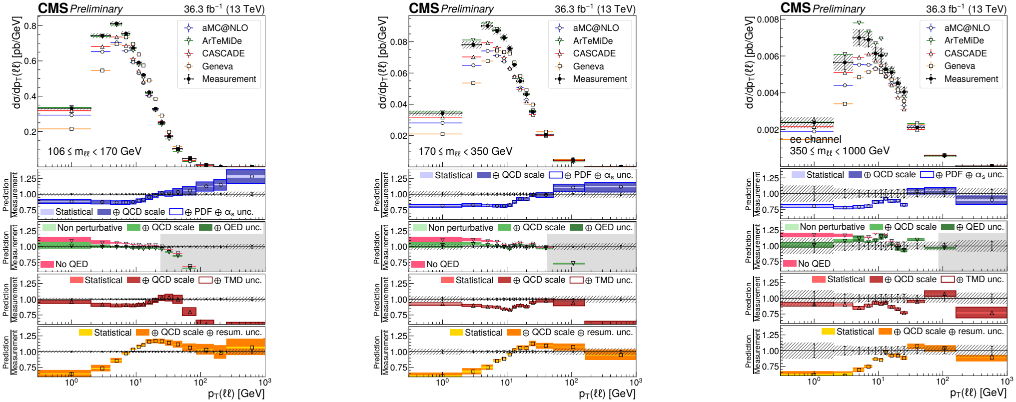
GENEVA — $N^3LL'_\tau + NNLO_\tau$

- The resummed part of the spectrum is too hard due to the choice of α_S
- NNLO works well in the high p_T

Transverse momentum





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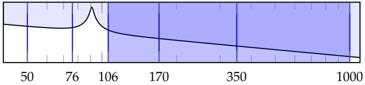
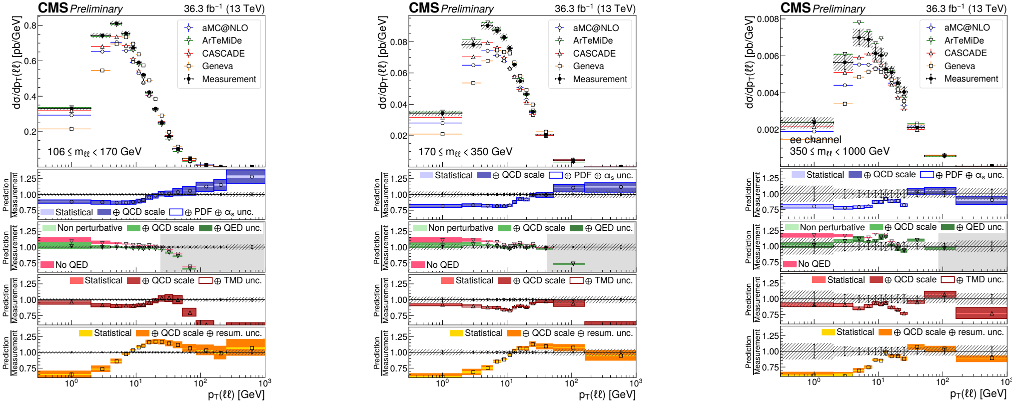


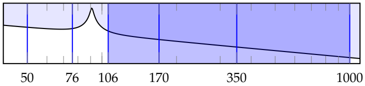


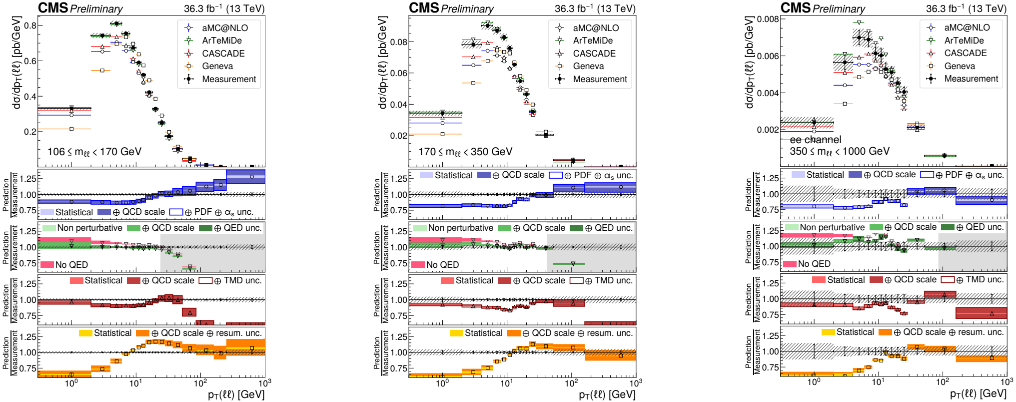
MadGraph

LHC baseline

- Disagreement at low p_T increases with mass
- High p_T works, except just above the peak

Transverse momentum



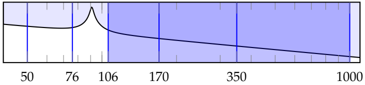


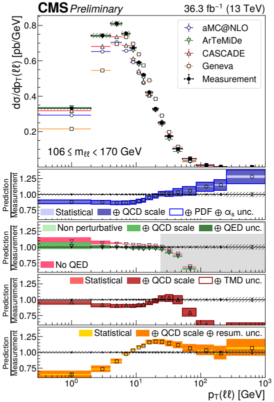
ARTEMIDE

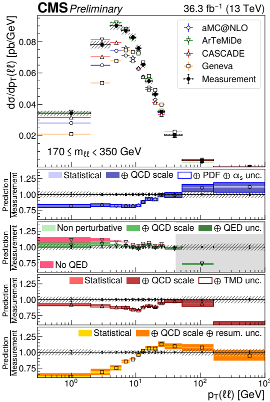
N^{3}LL TMD

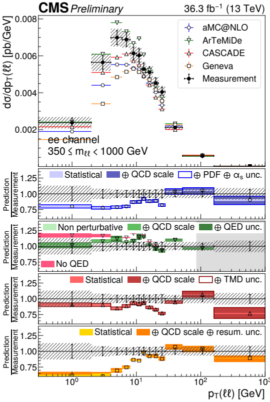
- Very good description over the domain of validity
- QED effects sizeable

Transverse momentum







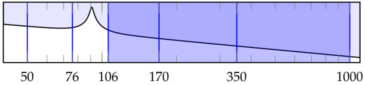


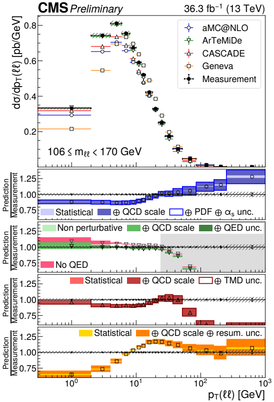
CASCADE

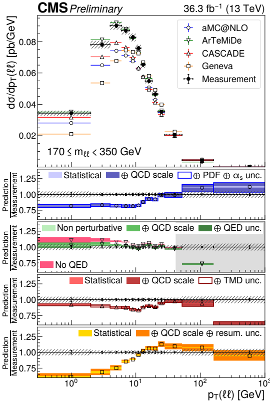
PB TMD + NLO

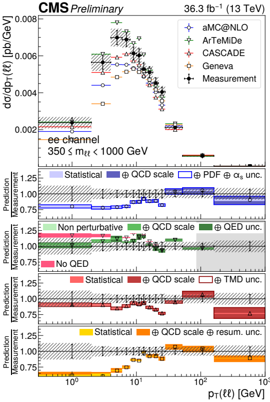
- Better than MadGraph at low p_T
- Inclusive NLO ME gives a good description up to 100 GeV at high mass

Transverse momentum







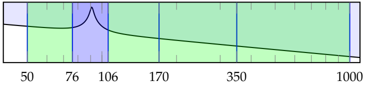


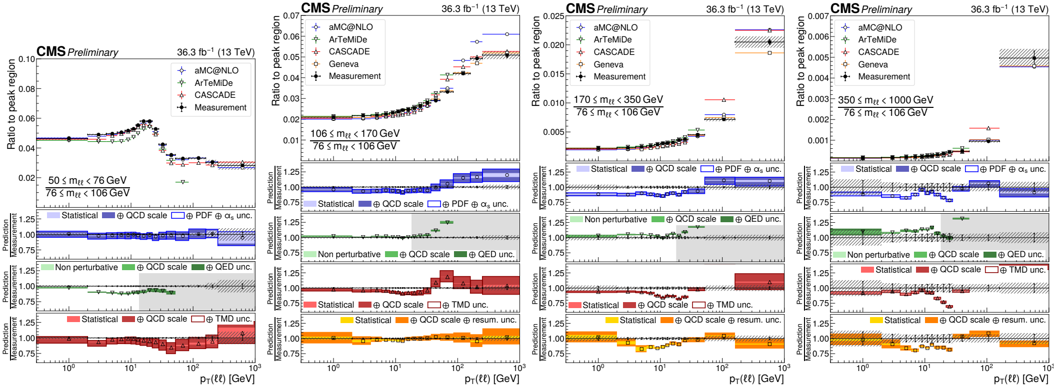
GENEVA

$N^3LL'_\tau + NNLO_\tau$

- Too hard spectrum also at high mass

Transverse momentum ratios



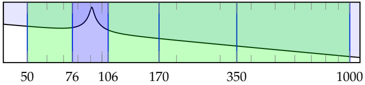


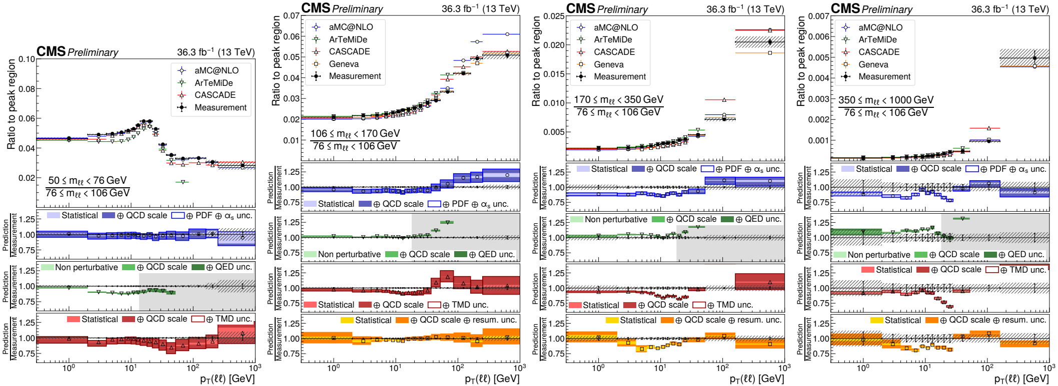
Probe evolution between different masses:

$$\frac{d\sigma}{dX}(m_{\ell\ell}) \Big/ \frac{d\sigma}{dX}(76 < m_{\ell\ell} < 106\,\text{GeV})$$

Experimental uncertainty down to 1.2 % around the Z peak.

Transverse momentum ratios





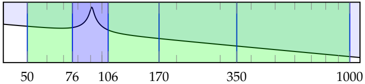
Spectrum becomes harder at high mass

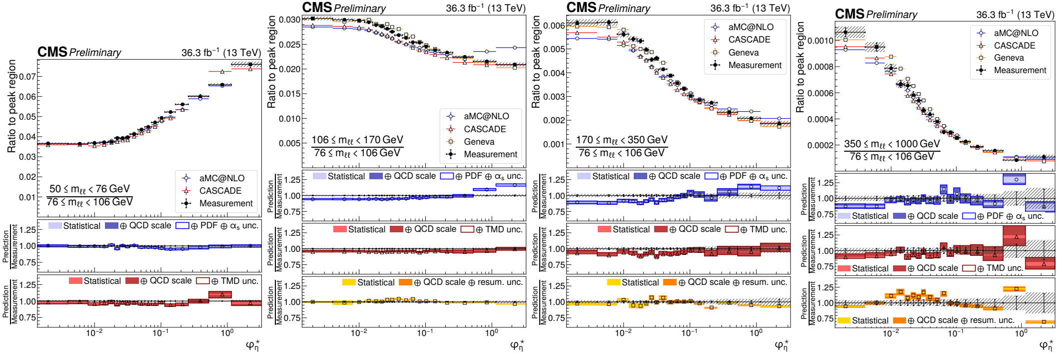
MADGRAPH is perfect in the low mass, fails above the peak

ARTEMIDE and CASCADE work within their range of validity

GENEVA predicts the evolution above the Z peak very well

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

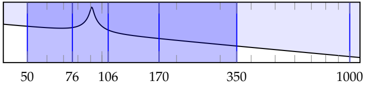


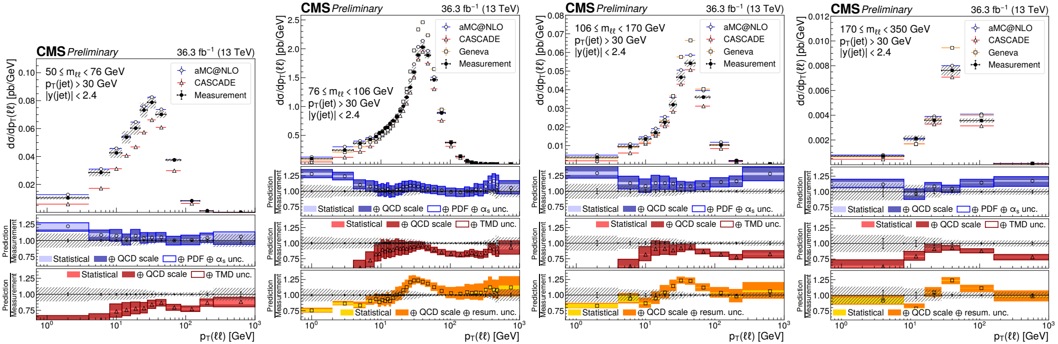


Very precise measurement, uncertainties under 1 %

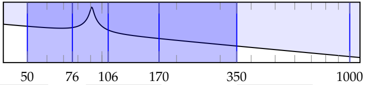
- $\varphi^* \sim p_T(\ell\ell)/m_{\ell\ell}$, high mass spectrum compressed towards the low φ^*
- MadGraph shows a trend at high mass
- CASCADE and Geneva within uncertainties
- Similar to p_T, but less discrimination between models

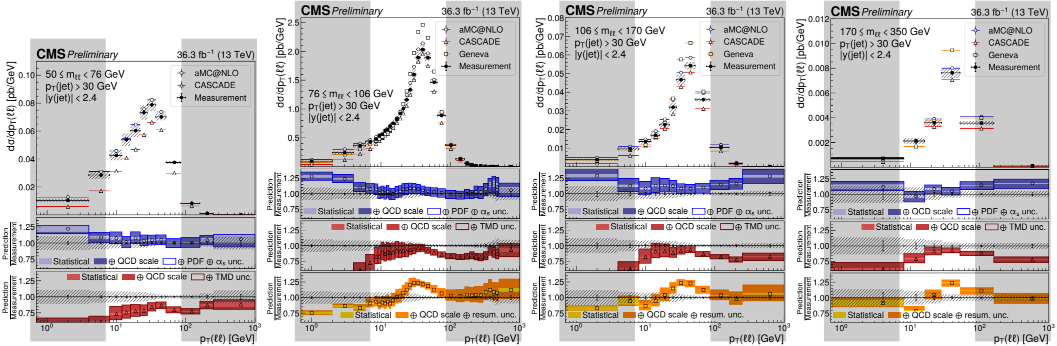
Transverse momentum, at least one jet



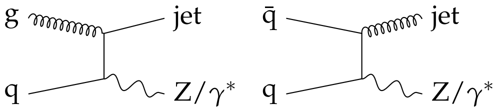


Transverse momentum, at least one jet

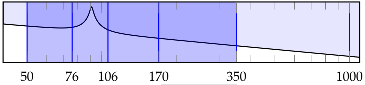


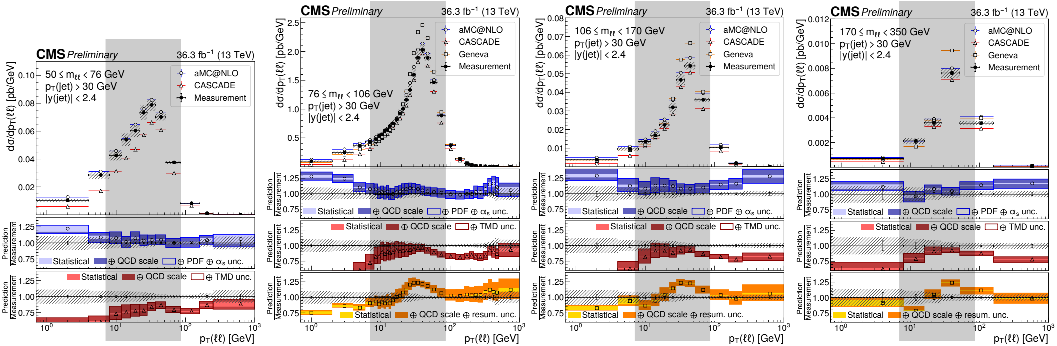


One jet phase space: around 30 GeV

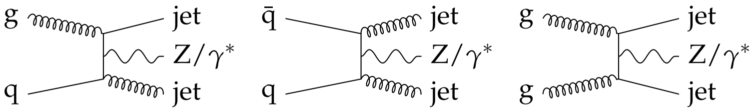


Transverse momentum, at least one jet

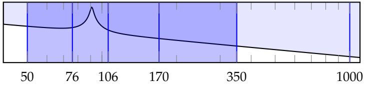


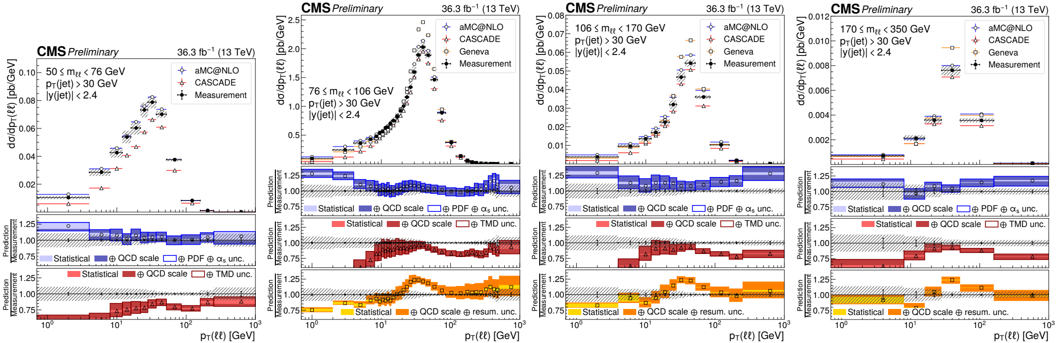


Two (or more) **jets phase space**: low and high p_T



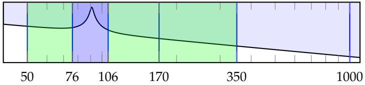
Transverse momentum, at least one jet

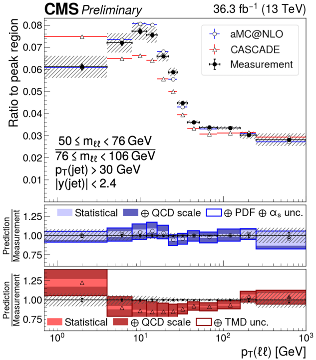


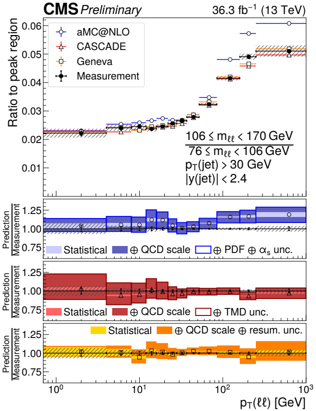


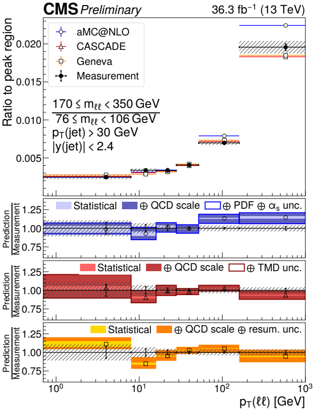
- MADGRAPH within uncertainties, except in the lowest p_T bins and at high p_T in the 106–170 mass bin
- CASCADE Z + 1 jet @NLO fails in the 2 jets the phase space (lacks the gluon-gluon contribution)
- GENEVA similar to the inclusive case

Transverse momentum ratios, at least one jet









- Theory uncertainties dominate, all predictions agree with the data

Summary (1/2)

Precision Drell-Yan measurement from CMS, over a wide mass range

- Three distributions in 5 (4) invariant mass bins:
  - Inclusive $p_{\mathrm{T}}(\ell\ell)$
  - Inclusive φ^*
  - $p_{\mathrm{T}}(\ell\ell)$ with at least one jet
- Probing evolution with differential ratios to the peak region
- $36.3\,\mathrm{fb}^{-1}$ of data at 13 TeV, combining the electron and muon channels
- Unfolded cross sections precise to $\sim 2\,\%$
- Cross section ratios precise to $\sim 1\,\%$

Details, tables... https://cds.cern.ch/record/2764470/

Summary (2/2)

Comparison to four theory predictions

- MadGraph5_aMC@NLO is robust all over the covered phase space, but disagrees with data at low p_T— up to 20 %
- TMD based predictions (arTeMiDe, CASCADE) better at low p_T; merged or NNLO required for high p_T, one jet
- Geneva NNLL$_\tau$ describes neither the p_T nor the φ^* distributions (α_s choice)
- Cross section ratios can be predicted even by models that fail to predict absolute cross section (CASCADE, Geneva)
- $\mathrm{Z} + 1$ jet is very sensitive to $\mathrm{Z} + 2$ jets effects, only MadGraph describes it (with caveats)