Inclusive vector boson measurements at CMS

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Introduction

1. W branching fractions [CMS-PAS-SMP-18-011]

- Precision measurement of W branching fractions to leptons and hadrons
- Test lepton universality
- Comparison to LEP results

2. Drell-Yan p_T over a wide mass range [CMS-PAS-SMP-20-003]

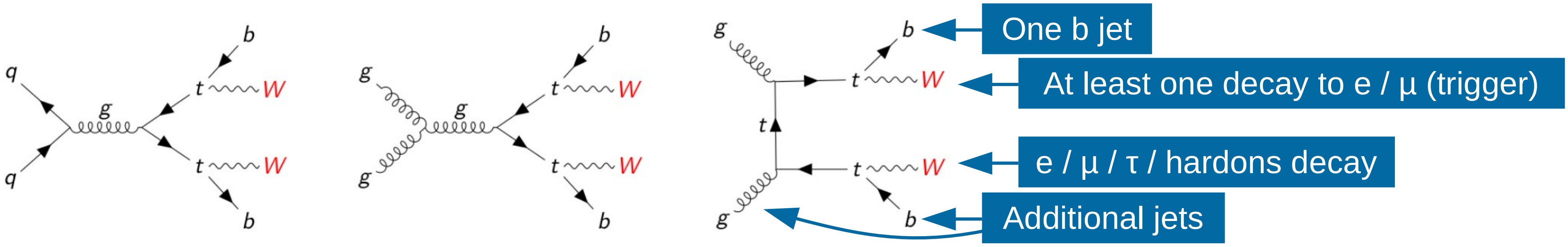
- Precision measurement of the transverse momentum of lepton pairs in Drell-Yan events, for different masses
- Test scale evolution of parton showers and NNLO, NNLL, … predictions
- Probe transverse momentum-dependent parton distributions (TMD)

3. Drell-Yan p_T and rapidity in Z + 1 jet events [CMS-PAS-SMP-19-009]

- Test bench for NNLO Monte-Carlos

1. W branching fractions – Analysis overview

Use top quark production as a W factory:



35.9 fb^{-1} (2016 data) | WW, tW, W+jets also considered | τ efficiency constrained from data

[CMS-PAS-SMP-18-011]

1. W branching fractions – Analysis overview

Use top quark production as a W factory

Split in 30 categories based on decay mode and number of (b-tagged) jets:

	$N_j = 0$	$N_j = 1$	$N_j = 2$	$N_j = 3$	$N_j \geq 4$
$N_b = 0$	$e\tau, \mu\tau$ $e\mu$	$e\tau, \mu\tau,$ $e\mu$	$e\tau, \mu\tau$ $ee, \mu\mu,$ $e\mu$		
$N_b = 1$		$e\tau, \mu\tau$ $e\mu$	$e\tau, \mu\tau$ $ee, \mu\mu, e\mu$	$e\tau, \mu\tau$	 $eh, \mu h$
$N_b \geq 2$			$e\tau, \mu\tau$ $ee, \mu\mu, e\mu$	$e\tau, \mu\tau$	 $eh, \mu h$

Drell-Yan enriched (τ efficiency)

W^+W^-

Main regions: $t\bar{t}$, tW

Additional $t\bar{t}$, tW

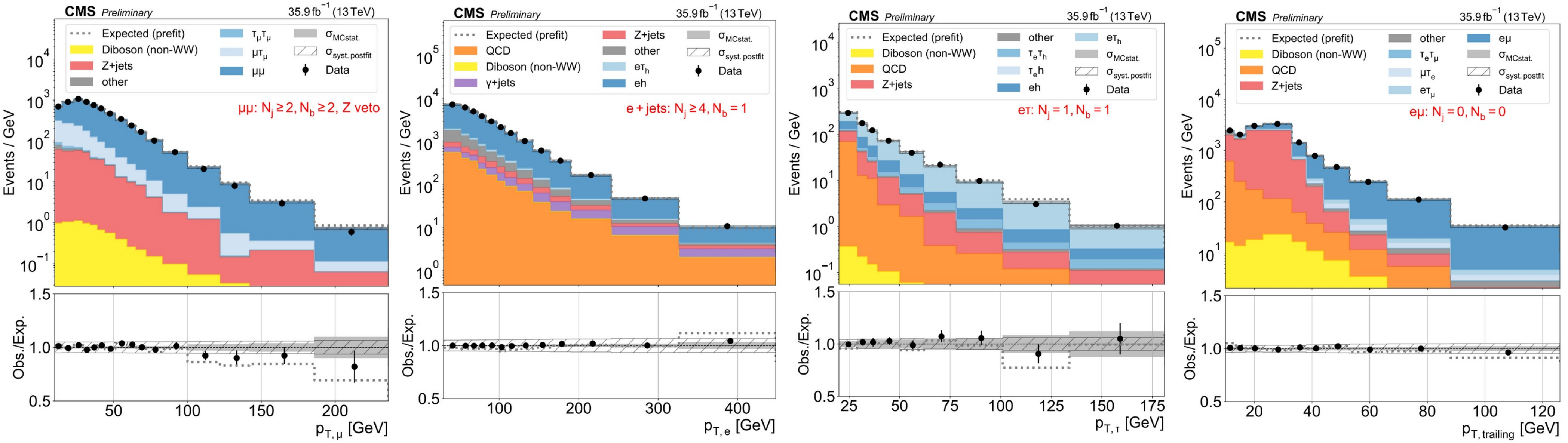
Here τ = reconstructed hadronic τ

1. W branching fractions – Analysis overview

Use top quark production as a W factory

Split in 30 categories based on decay mode and number of (b-tagged) jets

Further refine as a function of p_T to separate $W \to \ell\nu$ from $W \to \tau(\to \ell\nu)\nu$:



[CMS-PAS-SMP-18-011]

1. W branching fractions – Analysis overview

Use top quark production as a W factory

Split in 30 categories based on decay mode and number of (b-tagged) jets

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Fit the branching fractions in all categories simultaneously:

Signals

Backgrounds

$$f_{ij}(\boldsymbol{\beta}) = \sum_{k \in signal} s_{ijk}(\boldsymbol{\beta}, \boldsymbol{\theta}) + \sum_{l \in bckgd} b_{ijl}(\boldsymbol{\theta})$$

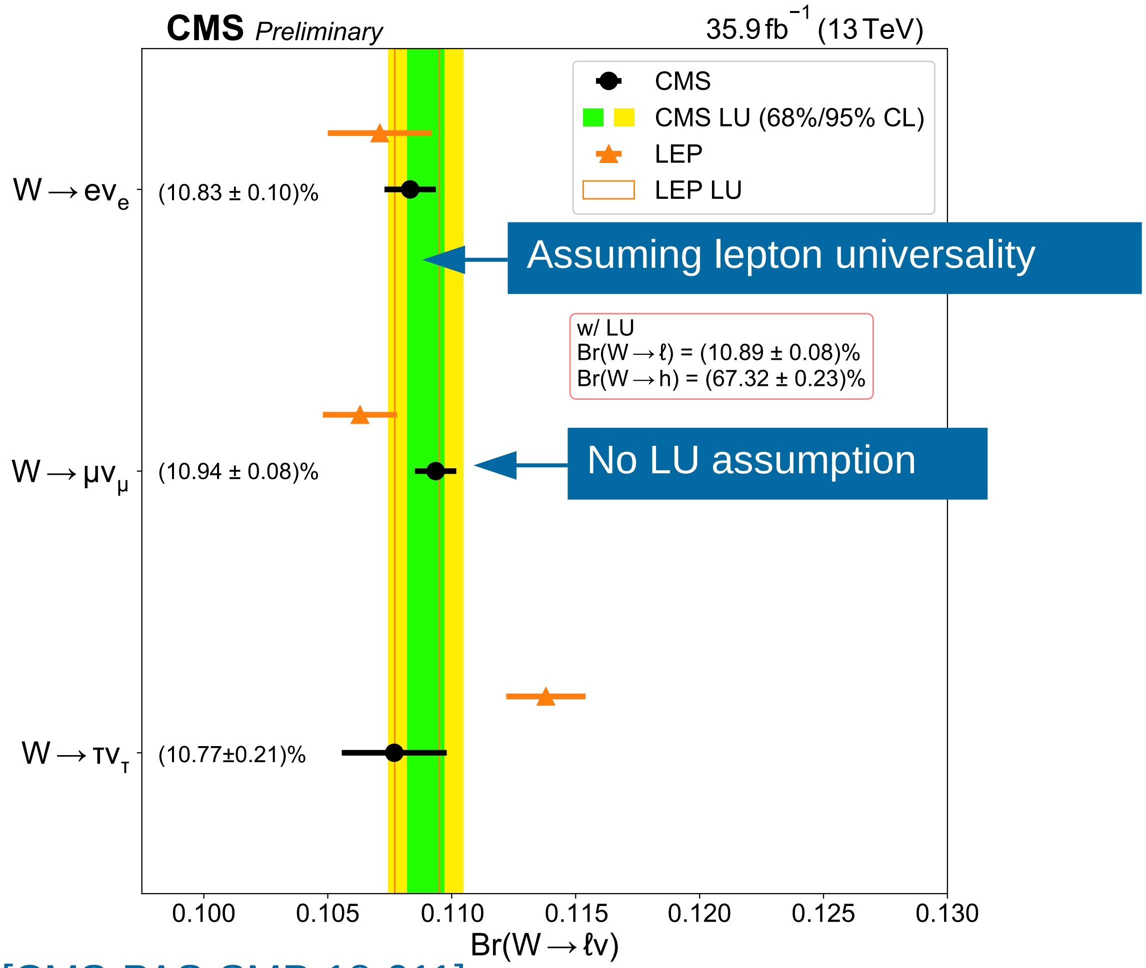
Branching fractions

$$L(\boldsymbol{\beta}, \boldsymbol{\theta}) = \sum_{\text{i}\in\text{channel}} \sum_{\text{j}\in\text{bins}} \left[-y_{ij} \ln f_{ij}(\boldsymbol{\beta}, \boldsymbol{\theta}) + f_{ij}(\boldsymbol{\beta}, \boldsymbol{\theta}) \right] + \sum_{\theta \in \boldsymbol{\theta}} \pi(\theta)$$

Observed yields

[CMS-PAS-SMP-18-011]

1. W branching fractions – Main results



[CMS-PAS-SMP-18-011]

- *Br*(W → eν) and *B*(W → μν) measured to *O*(1%)
- *Br*(W → τν) measured to *O*(2%)
- *Br*(W → h) measured to *O*(0.4%)

- More precise than LEP combination
- Consistent with lepton universality and the Standard Model

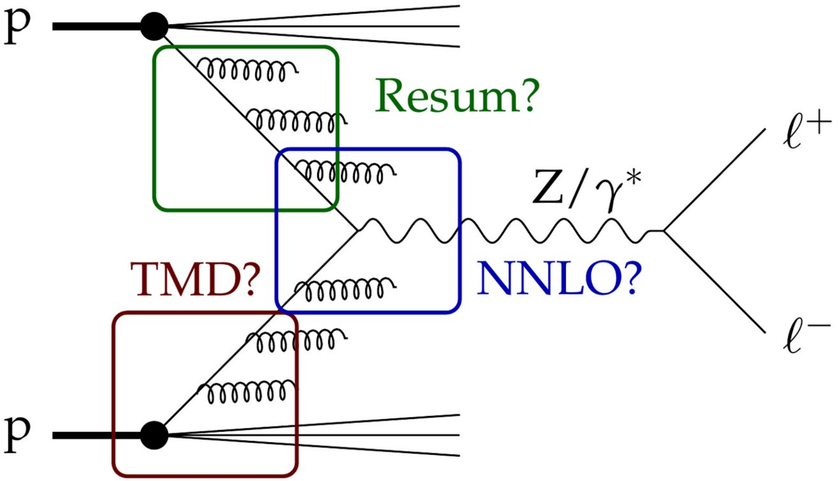
More results:

$R_{\mu/e}$	1.009(9)
$R_{\tau/e}$	0.994(21)
$R_{\tau/\mu}$	0.985(20)
$R_{\tau/\ell}$	1.002(19)

$\sum_{ij} \|V_{ij}\|^2$	1.989(21)
$\|V_{cs}\|$	0.969(11)
$\alpha_s(m_W)$	0.094(33)

2. Drell-Yan p_T over a wide mass range

Predicting QCD initial-state radiation requires advanced theoretical tools:



- e^+e^- or $\mu^+\mu^-$
- $p_T(\ell) > 25, 20$ GeV
- $|\eta(\ell)| < 2.4$
- $50 < m(\ell\ell) < 1000$ GeV
- 36.1 fb^{-1} at 13 TeV
- 2016 data

$p_T(\ell\ell)$ is sensitive to ISR through momentum conservation

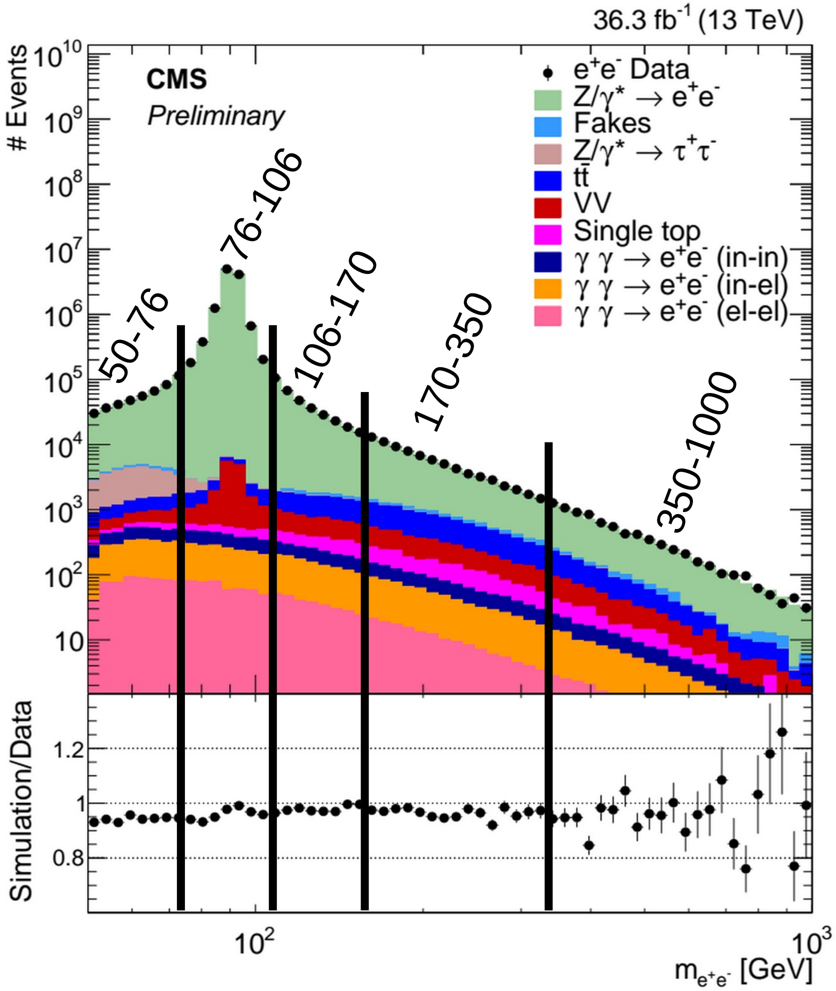
How does it depend on the mass of the Z/γ* ?

[CMS-PAS-SMP-20-003]

See I. Bubanja's poster for details

2. Drell-Yan p_T over a wide mass range

Five mass windows:

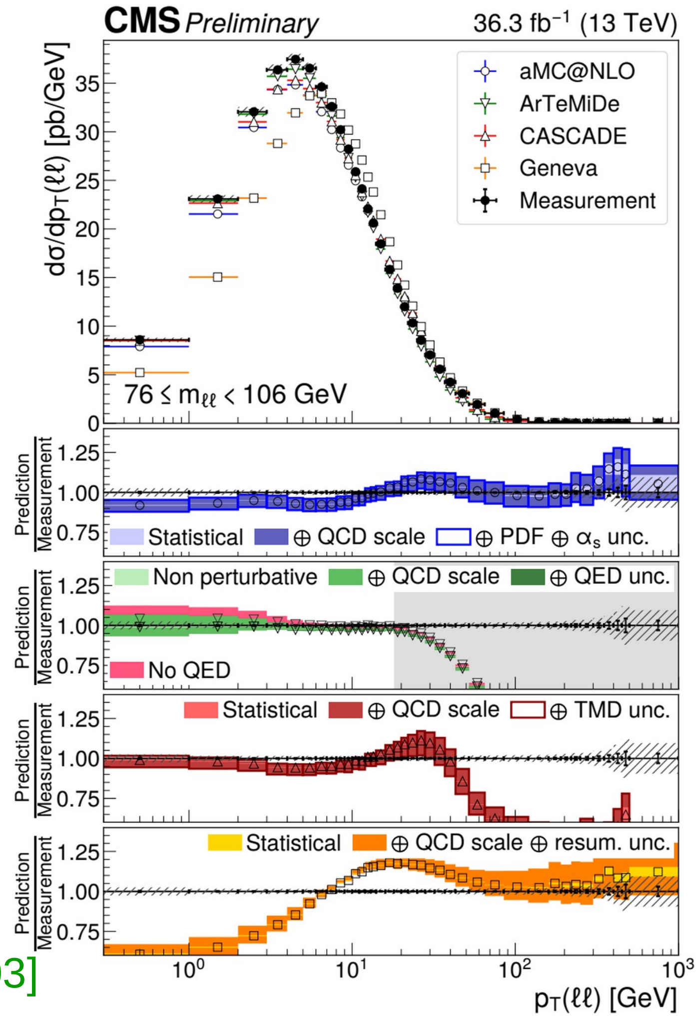


$p_T(\ell\ell)$ distribution measured in each mass window

[CMS-PAS-SMP-20-003]

2. Drell-Yan p_T over a wide mass range

76-106 GeV:
Z peak region



See also 10.1007/JHEP12(2019)061

[CMS-PAS-SMP-20-003]

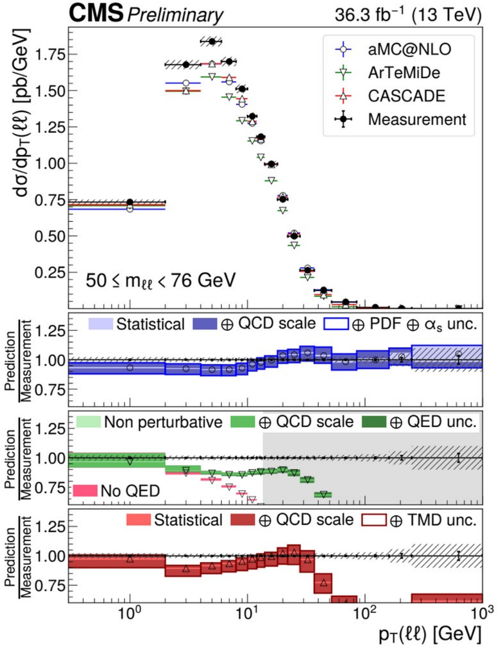
Measurement unfolded to fiducial phase space

Compared to four predictions

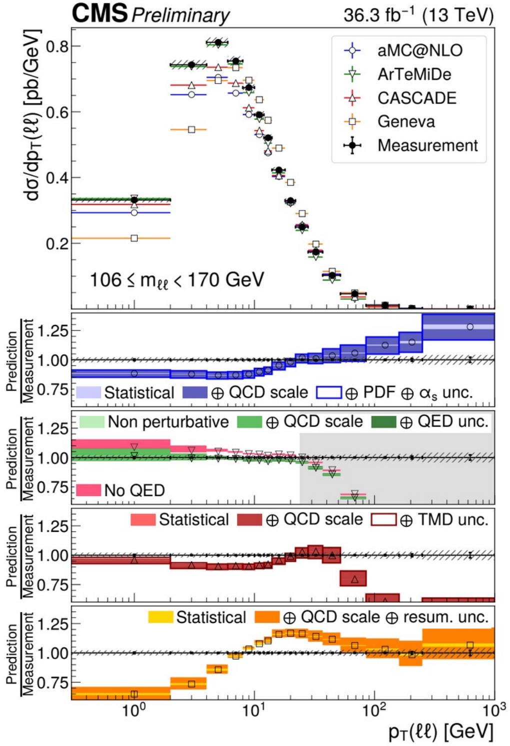
MADGRAPH5_AMC@NLO Monte-Carlo prediction Baseline for LHC experiments $Z + 0, 1, 2$ partons merged at NLO PYTHIA8 parton shower	**ARTEMIDE** Analytical prediction $N^3LL + NNLO$ TMD QED FSR by us, based on PYTHIA8 Valid for $p_T < 0.2 m_{\ell\ell}$
CASCADE Monte-Carlo prediction Parton Branching TMD $Z + 0j$ or $Z + 1j$ at NLO, depending on distribution PYTHIA6 parton shower	**GENEVA** Monte-Carlo prediction $NNLL'_\tau + NNLO$ PYTHIA8 parton shower

2. Drell-Yan p_T over a wide mass range

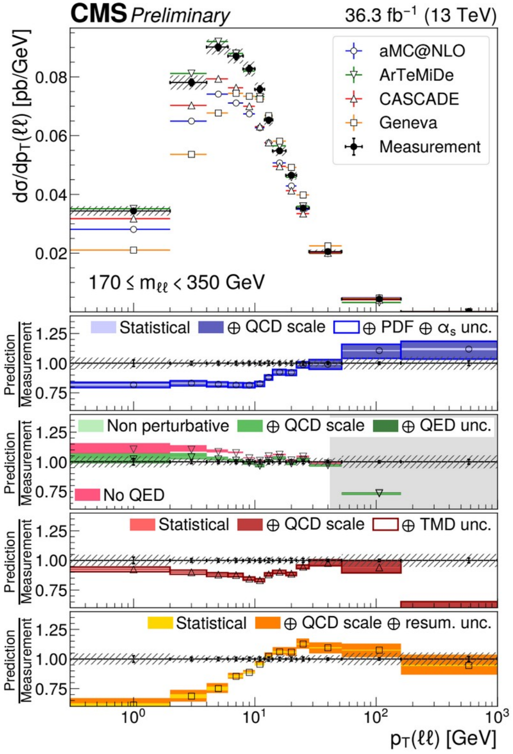
50-76 GeV



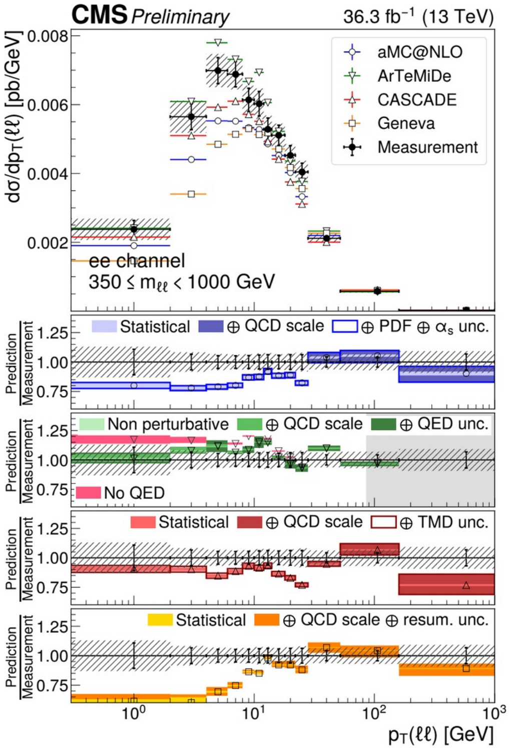
106-170 GeV



170-350 GeV



350-1000 GeV



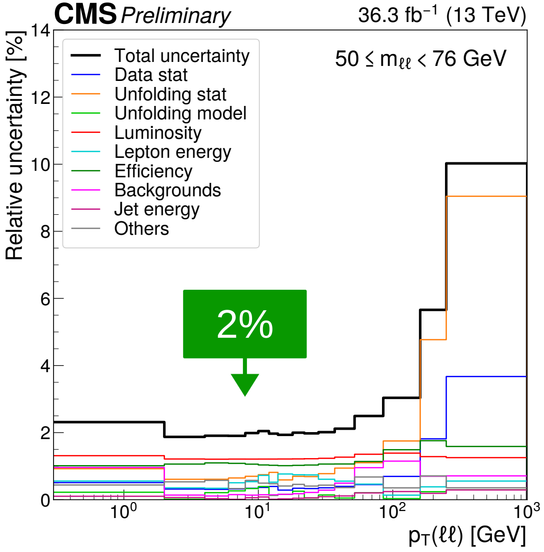
- aMC@NLO does not describe the data at low p_T
- Predictions integrating TMDs provide a better description

[CMS-PAS-SMP-20-003]

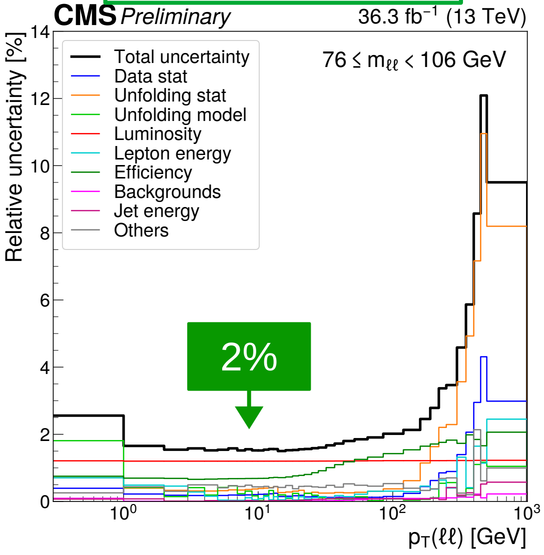
2. Drell-Yan p_T over a wide mass range

Precision measurement:

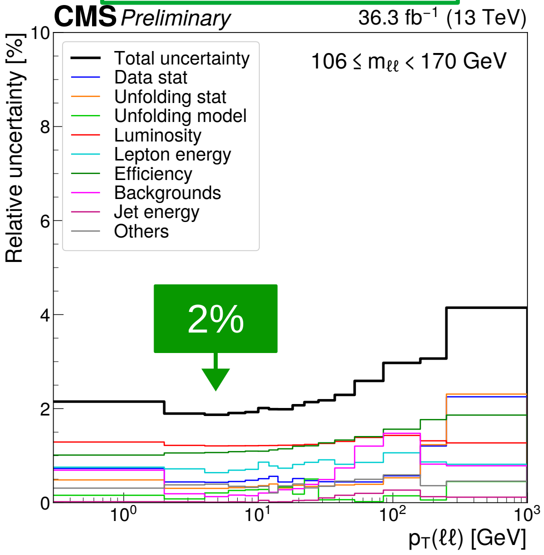
50-76 GeV



76-106 GeV



106-170 GeV



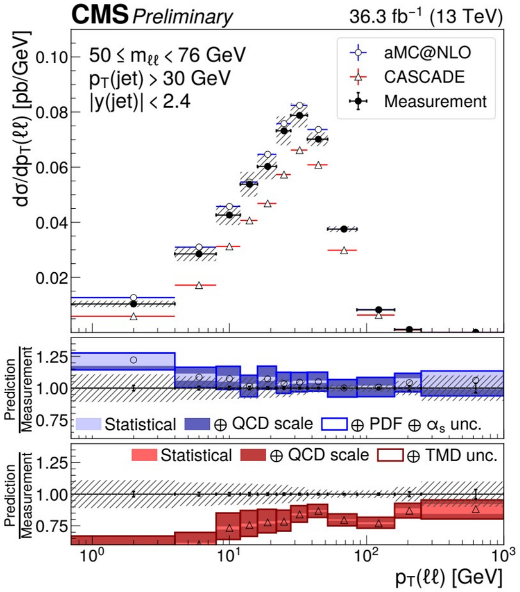
Also provided:

- Ratios with respect to Z peak region: probe evolution directly
- φ* distributions and ratios
- $p_T(\ell\ell)$ distributions and ratios for at least one jet (next slide)

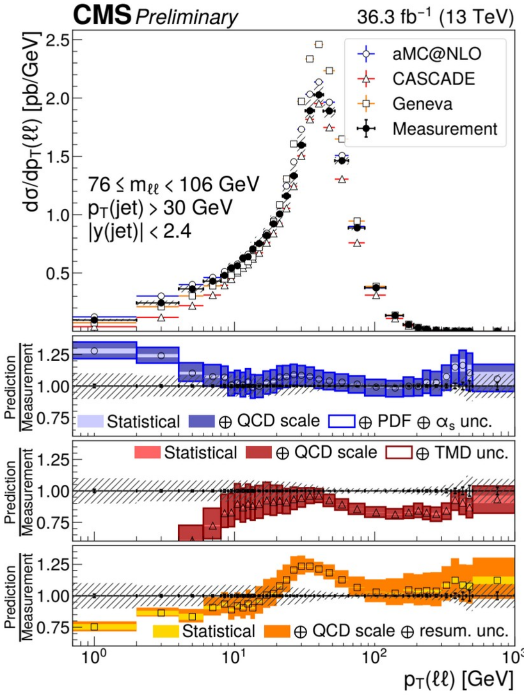
[CMS-PAS-SMP-20-003]

3. Drell-Yan p_T in Z + (≥ 1) jet events

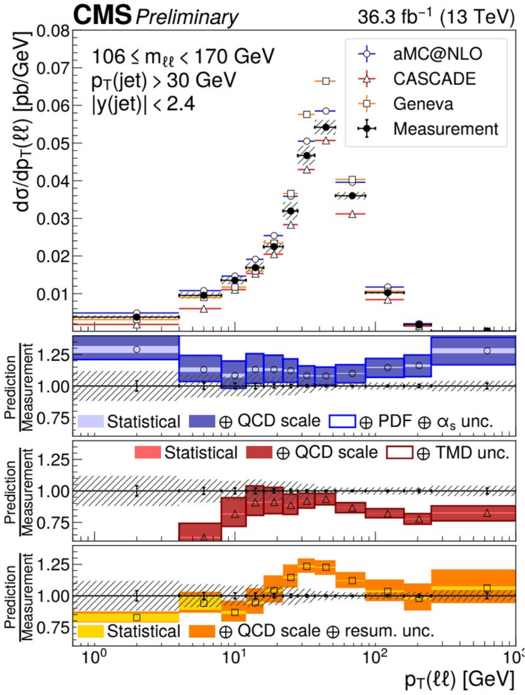
50-76 GeV



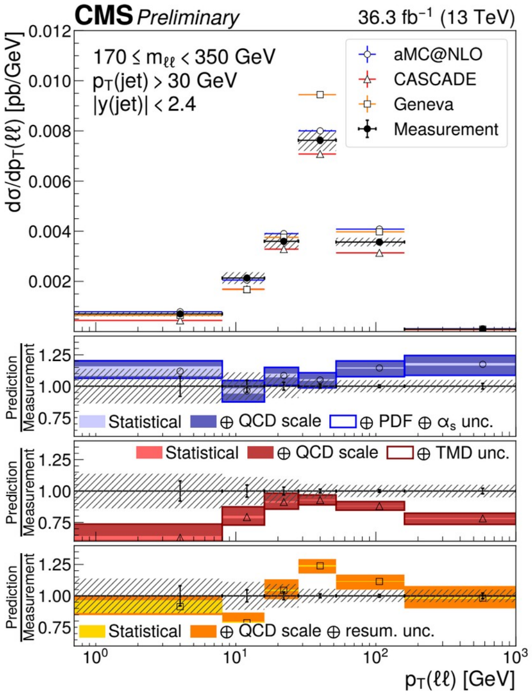
76-106 GeV



106-170 GeV



170-350 GeV



p_T(jet) > 30 GeV

|y(jet)| < 2.4

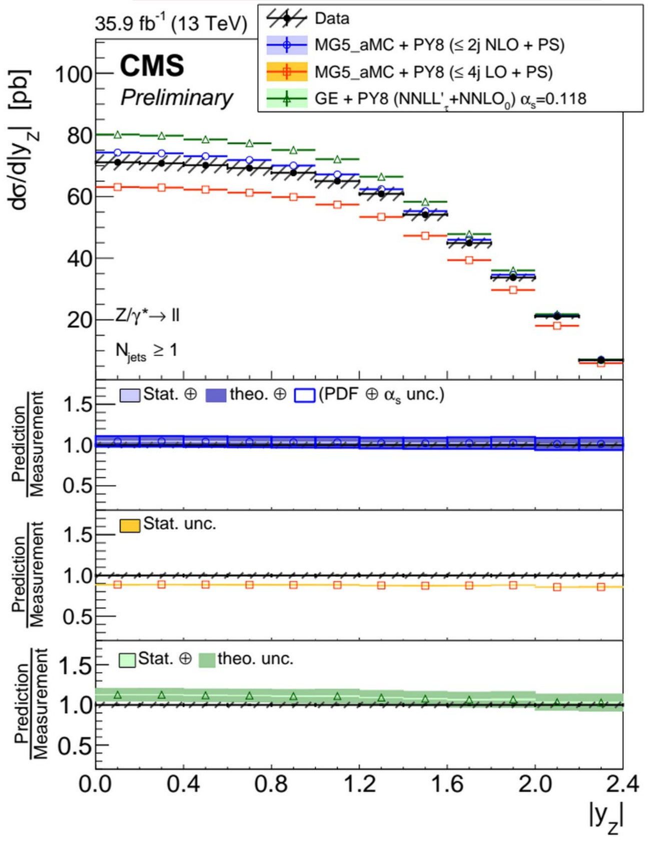
[CMS-PAS-SMP-20-003]

At small and large p_T, events with 2 jets dominate

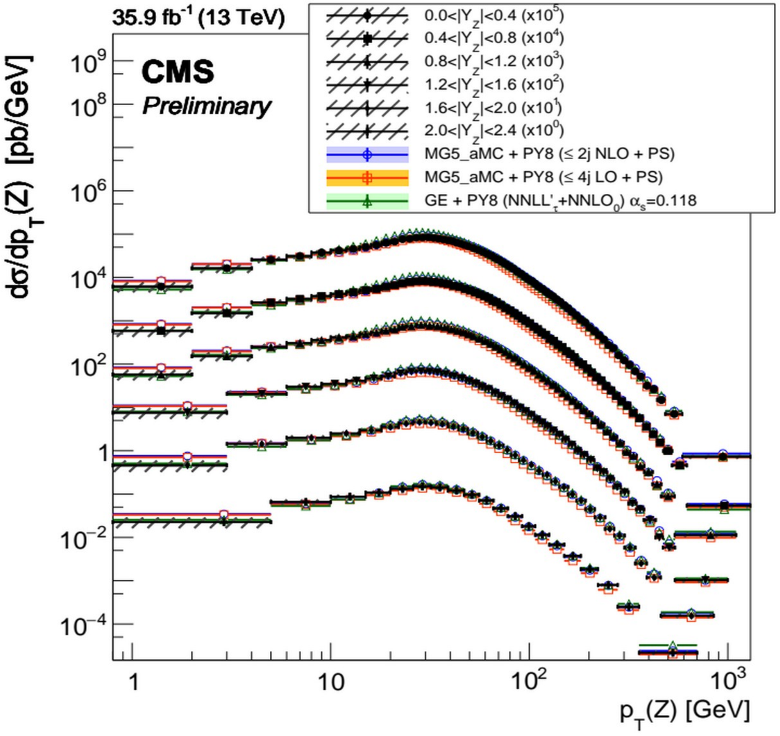
NNLO or $N_{partons}$ merging needed to obtain a complete description

3. Z rapidity in Z + (≥ 1) jet events

Single differential



Double differential



e^+e^- or $\mu^+\mu^-$

$p_T(\ell) > 25/24$ GeV [e/μ]

$|\eta(\ell)| < 2.4$

$71 < m(\ell\ell) < 111$ GeV

$p_T(\text{jet}) > 30$ GeV

$|y(\text{jet})| < 2.4$

35.9 fb^{-1} at 13 TeV

2016 data

See Q. Wang's presentation for more V + jets

[CMS-PAS-SMP-19-009]

Summary

The W and Z bosons are used for precision tests of the SM

In the electroweak sector: W branching fractions

- Measurement using top as a W factory
- Results support lepton flavor universality
- Precision competitive with LEP results

In QCD: Drell-Yan p_T over a wide mass range

- Dilepton invariant mass from 50 to 1000 GeV
- Predictions using TMD PDF describe the data better at low $p_T(\ell\ell)$

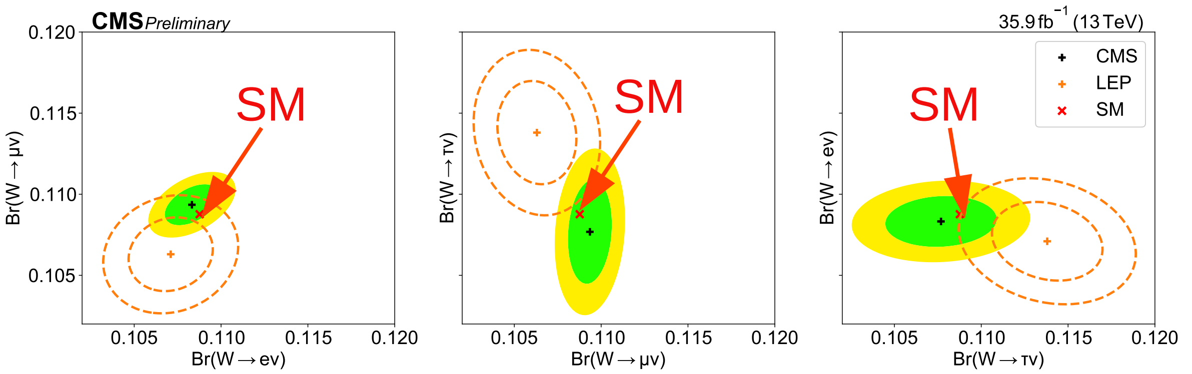
Z kinematics with at least one jet

- Single and double-differential measurements available

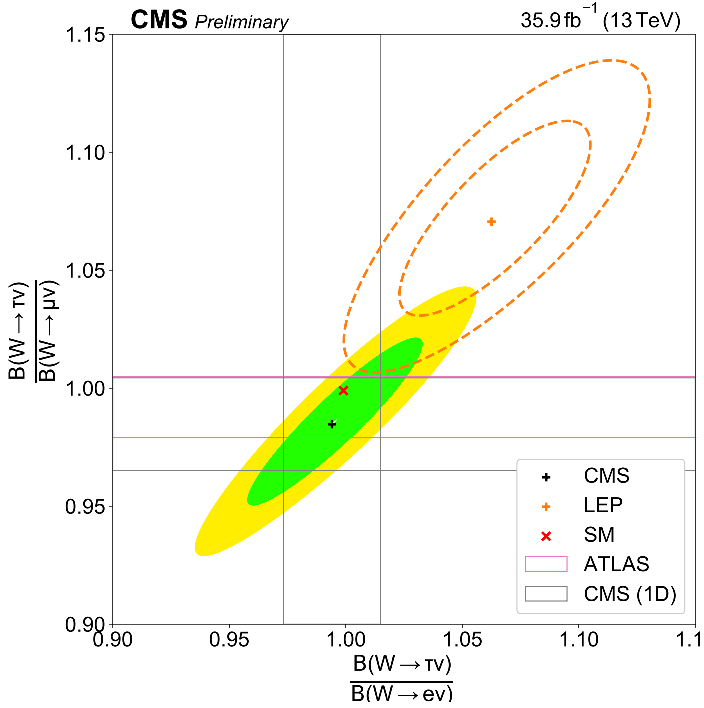
CMS

Compact Muon Solenoid

W branching fractions – More results



	CMS	LEP
$\mathcal{B}(W \to e\overline{\nu}_e)$	$(10.83 \pm 0.01 \pm 0.10)\%$	$(10.71 \pm 0.14 \pm 0.07)\ \%$
$\mathcal{B}(W \to \mu\overline{\nu}_\mu)$	$(10.94 \pm 0.01 \pm 0.08)\%$	$(10.63 \pm 0.13 \pm 0.07)\ \%$
$\mathcal{B}(W \to \tau\overline{\nu}_\tau)$	$(10.77 \pm 0.05 \pm 0.21)\%$	$(11.38 \pm 0.17 \pm 0.11)\ \%$
$\mathcal{B}(W \to h)$	$(67.46 \pm 0.04 \pm 0.28)\%$	–
with LU		
$\mathcal{B}(W \to \ell\overline{\nu})$	$(10.89 \pm 0.01 \pm 0.08)\%$	$(10.86 \pm 0.06 \pm 0.09)\%$
$\mathcal{B}(W \to h)$	$(67.32 \pm 0.02 \pm 0.23)\%$	$(67.41 \pm 0.18 \pm 0.20)\%$



	CMS	LEP	ATLAS
$R_{\mu/e} = \mathcal{B}(W \to \mu\overline{\nu}_\mu)/\mathcal{B}(W \to e\overline{\nu}_e)$	1.009 ± 0.009	0.993 ± 0.019	–
$R_{\tau/e} = \mathcal{B}(W \to \tau\overline{\nu}_\tau)/\mathcal{B}(W \to e\overline{\nu}_e)$	0.994 ± 0.021	1.063 ± 0.027	–
$R_{\tau/\mu} = \mathcal{B}(W \to \tau\overline{\nu}_\tau)/\mathcal{B}(W \to \mu\overline{\nu}_\mu)$	0.985 ± 0.020	1.070 ± 0.026	0.992 ± 0.013
$R_{\tau/\ell}$	1.002 ± 0.019	1.066 ± 0.025	–