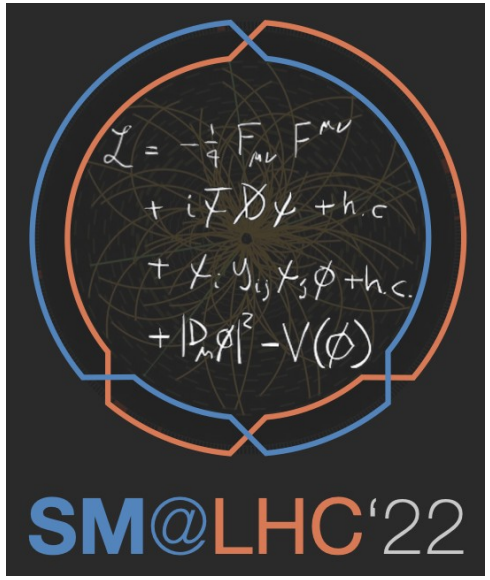


Recent Z Results:

BR→ Invisible, A_{FB}, Forward Production, Mass Dependent p_T

Oz Amram

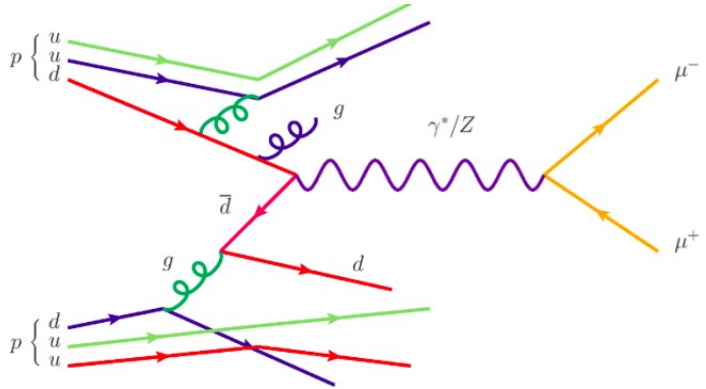
On Behalf of CMS, ATLAS and LHCb Collaborations

JOHNS HOPKINS UNIVERSITY

April 11th, 2022

Z / Drell-Yan at the LHC

- Why study Z at hadron colliders?
  - One of the best understood theoretically and experimentally
  - Precise study of kinematics allows probing of various QCD effects
  - High precision measurements can probe BSM scenarios



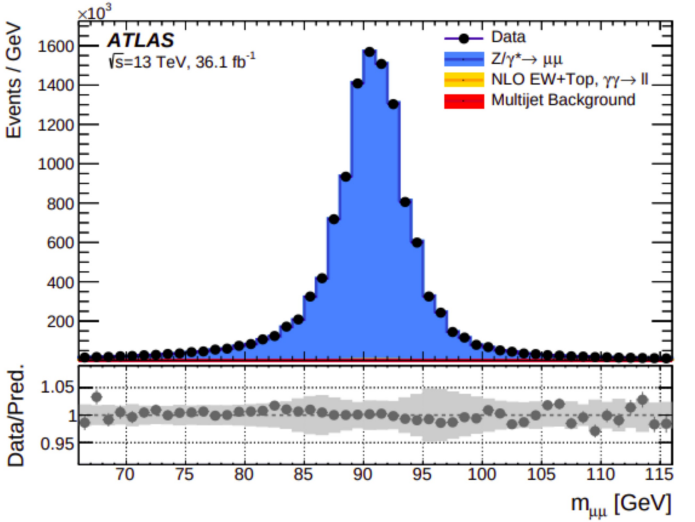
(Source)

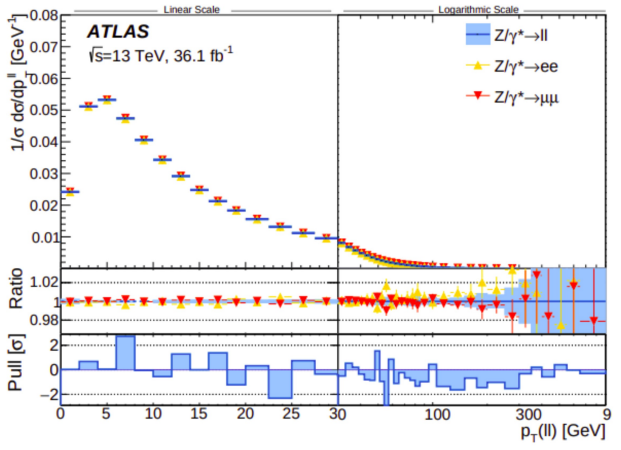
Multiple excellent measurements have been performed at LHC, highlight only a few recent results

Z p_T Spectrum (1/2)

ATLAS

- Measurement of Z p_T and φ_η^* in Z peak region (66 < m < 116 GeV)
- ~32 million Z→$\ell\ell$ events
  - Bkg contribution ~ 0.5%
- ee and μμ channels combined using χ^2 minimization



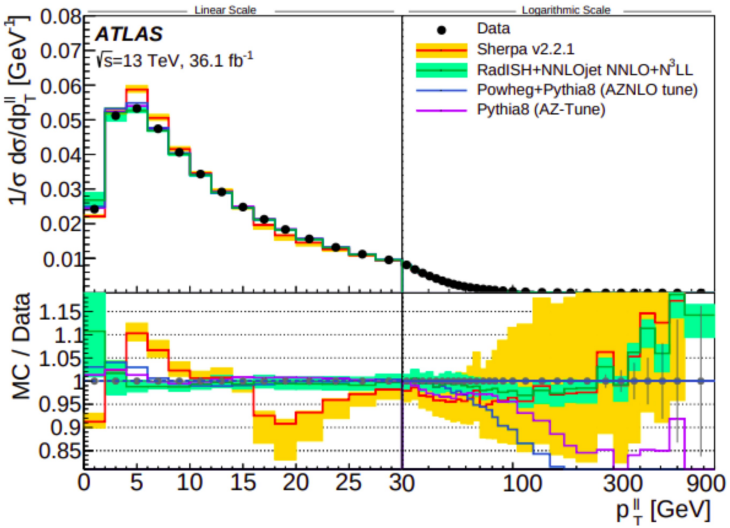


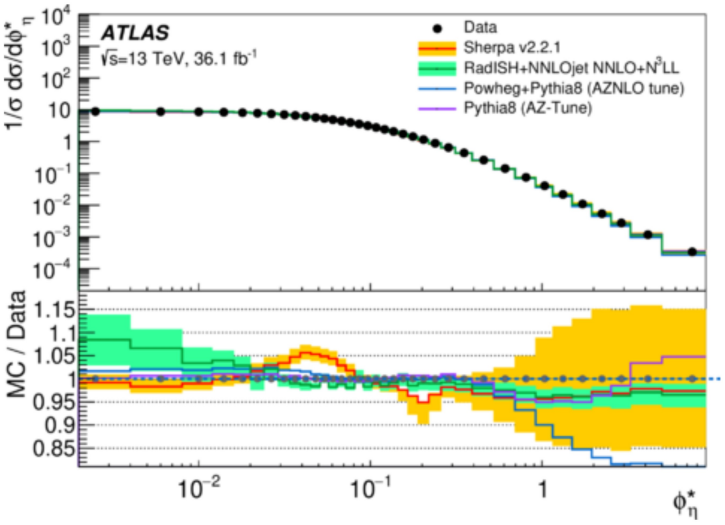
$$\phi_\eta^* = \tan\left(\frac{\pi - \Delta\phi}{2}\right) \times \sin(\theta_\eta^*)\,,$$

Eur. Phys. J. C 80 (2020) 616 (arxiv)

Z p_T Spectrum (2/2)

ATLAS



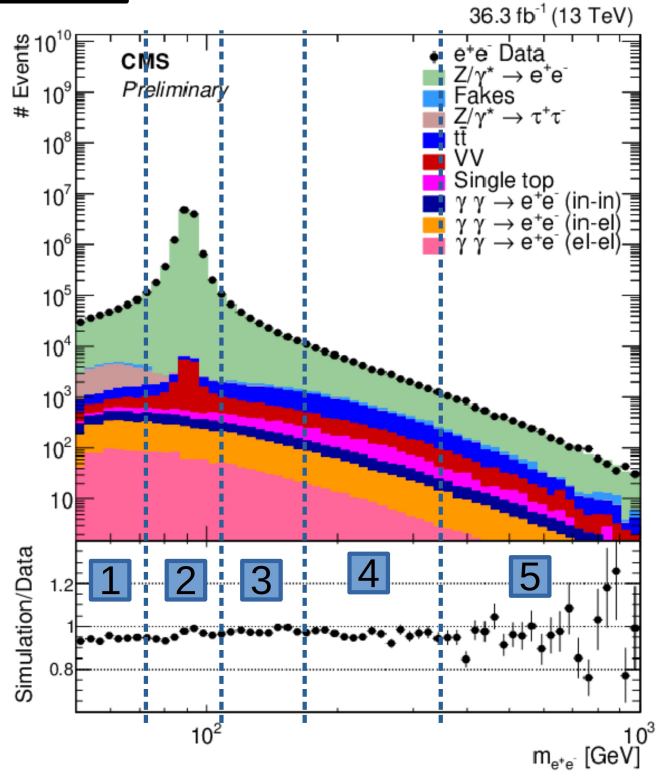


- Unfolded Born-level Z p_T distribution compared to various predictions
  - Sherpa v2.2.1
  - RadISH+NNLOJet NNLO + N^{3}LL
  - Powheg + Pythia8
  - Pythia8 + AZ Tune

Eur. Phys. J. C 80 (2020) 616 (arxiv)

DY p_T over wide mass range (1/3)

CMS



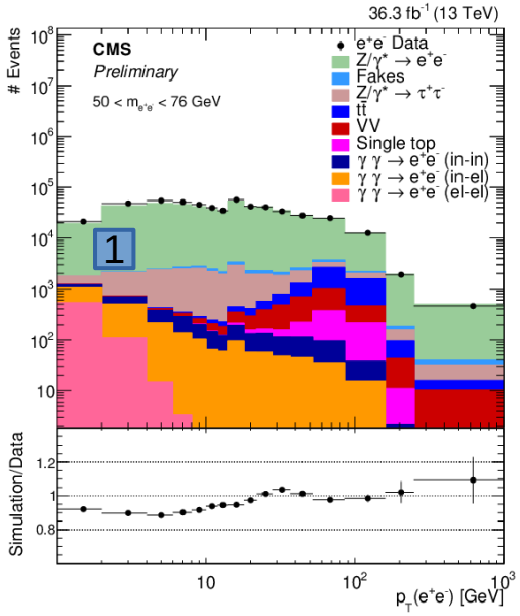
Split into 5 mass bins

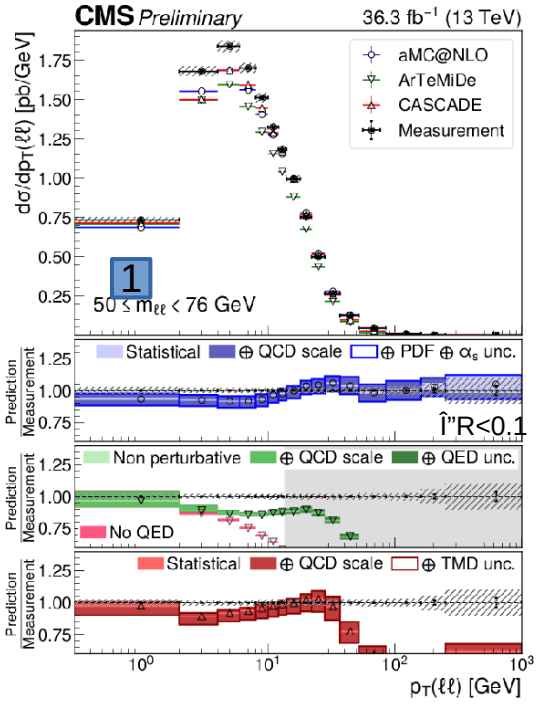
- Measure p_T in masses away from Z peak
  - 5 invariant mass bins
- Observe scale dependence $\mu \sim m$
  - Test agreement of different models (Pythia, TMD, NNLL + ME)
- Anti-btag to veto $t\bar{t}$ events
- Hadrons MisID as electrons estimated using data-driven method

CMS-PAS-SMP-20-003

DY p_T over wide mass range (2/3)

CMS





Measured p_T distribution unfolded to fiducial space using ‘dressed’ (ΔR<0.1) leptons

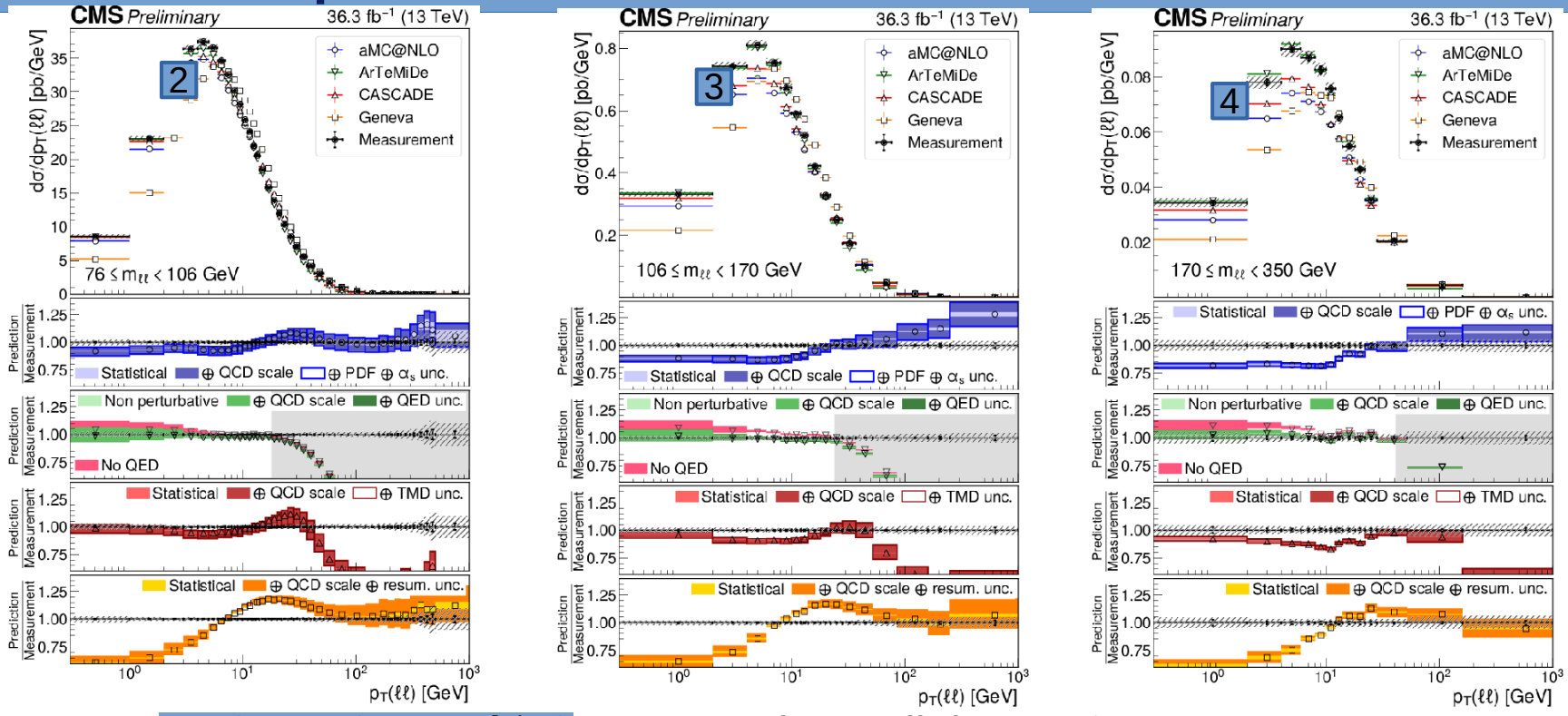
Measurement results are compared with:

- **ME + PS approach**
  - MG5_amc@NLO + Pythia 8 @NLO up to 2 partons + PS
- **TMD approach**
  - CASCADE (amc@NLO+ PBTMD) + Pythia6 for FS and hadronization
  - Analytic calculation from ArTeMiDe TMD based
- **Resummation**
  - GENEVA, NNLO Z+0j ME and resummation at NNLL’$_\tau$

CMS-PAS-SMP-20-003

DY p_T over wide mass range (3/3)

CMS



- **aMC@NLO + Pythia8** gives good overall description
  - Fails at low p_T and high mass
- **ArTeMiDe** gives best description within its region of validity
  - The QED FSR, added to the prediction from amc@NLO, shows the effect of migrations to low mass from the Z peak

CMS-PAS-SMP-20-003

Forward Z Production

LHCb

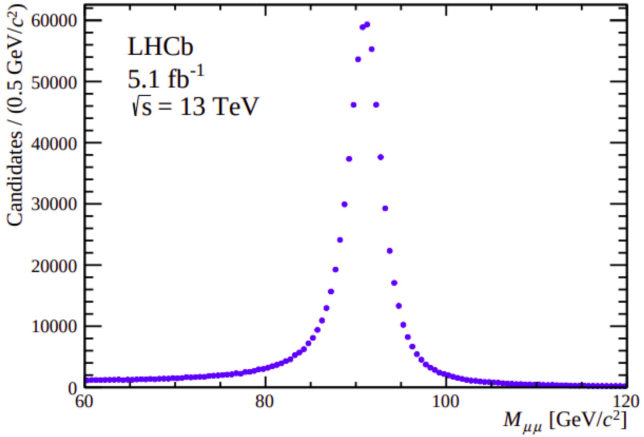
- Forward detector of LHCb allows measurements of Z production at high rapidity

2 < y < 4.5

- Stringent tests of QCD and useful pdf constraints
  - High y → very high or low Bjorken x

$$y = \frac{1}{2} \ln \frac{x_1}{x_2}$$

- Sample of 800k Z→ μμ, 2% bkg contribution
- Two sets of measurements
  - Differential cross section
  - Angular Coefficients



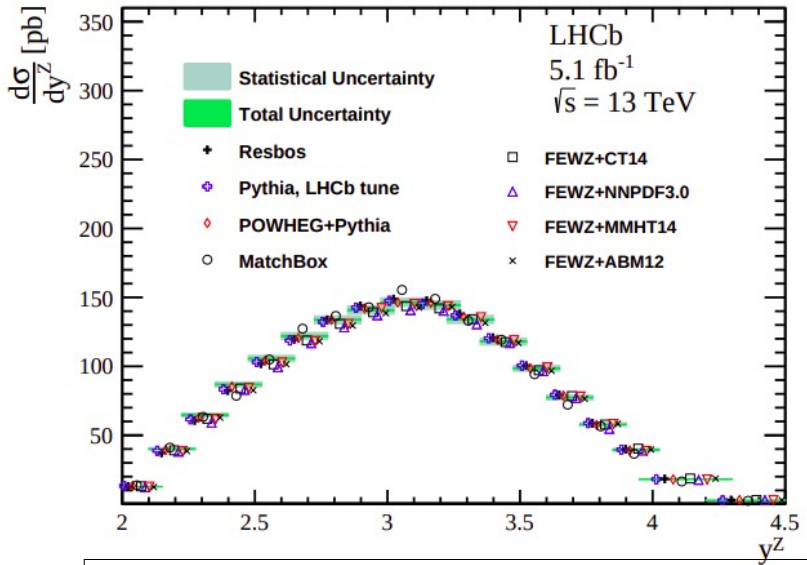
Forward Z: Differential cross sections

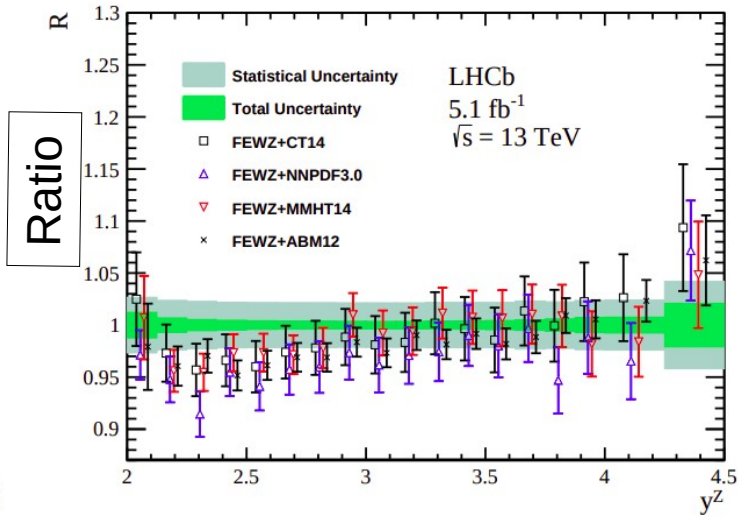
LHCb

- Cross section measured in bins of y, p_T, and φ^*
- Corrected to Born level in QED, allows comparison with theory predictions

Source	$\Delta\sigma/\sigma$ [%]
Statistical	0.11
Background	0.03
Alignment & calibration	-
Efficiency	0.77
Closure	0.06
FSR	0.04
Total Systematic (excl. lumi.)	0.77
Luminosity	2.00
Total	2.15

Lumi and tracking eff. dominant uncs.





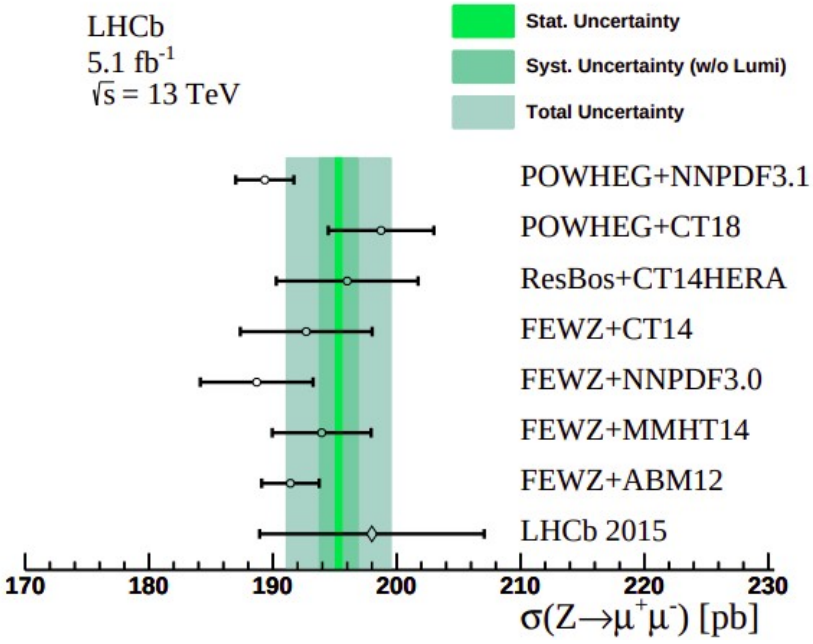
Good agreement overall, slight deficit in lower y region (2 < y < 3)

arXiv: 2112.07458
Submitted to JHEP

Forward Z: Integrated & double differential

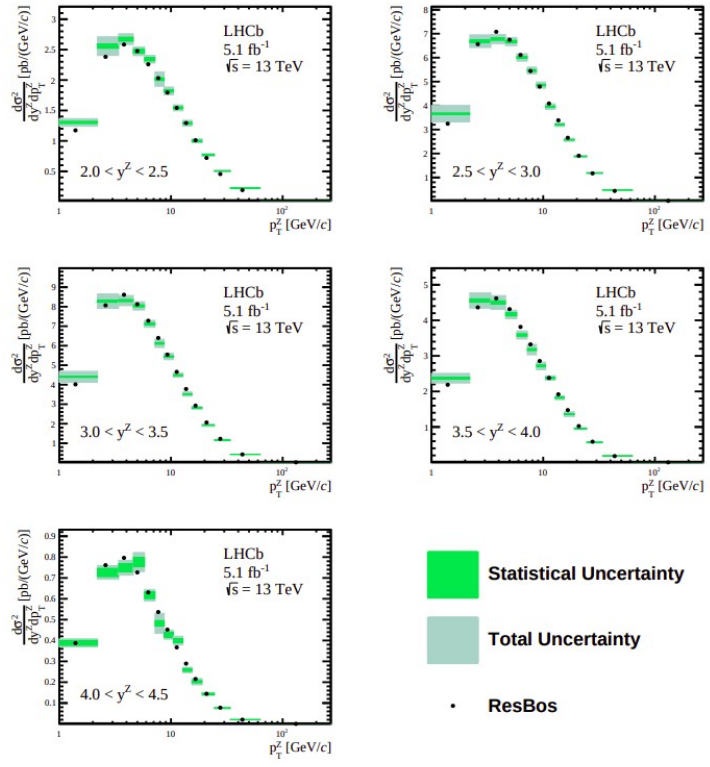
LHCb

Integrated cross section
(in fiducial region)



195.3 ± 0.2 (stat.) ± 1.5 (sys) ± 3.9 (lumi) pb

First double differential cross section
measurement in forward region



arXiv: 2112.07458
Submitted to JHEP

Forward Z: Angular coefficients (1/2)

LHCb

- Further probe of Z production in forward region, angular coefficients of Z boson are measured
  - Similar event selection to cross section analysis

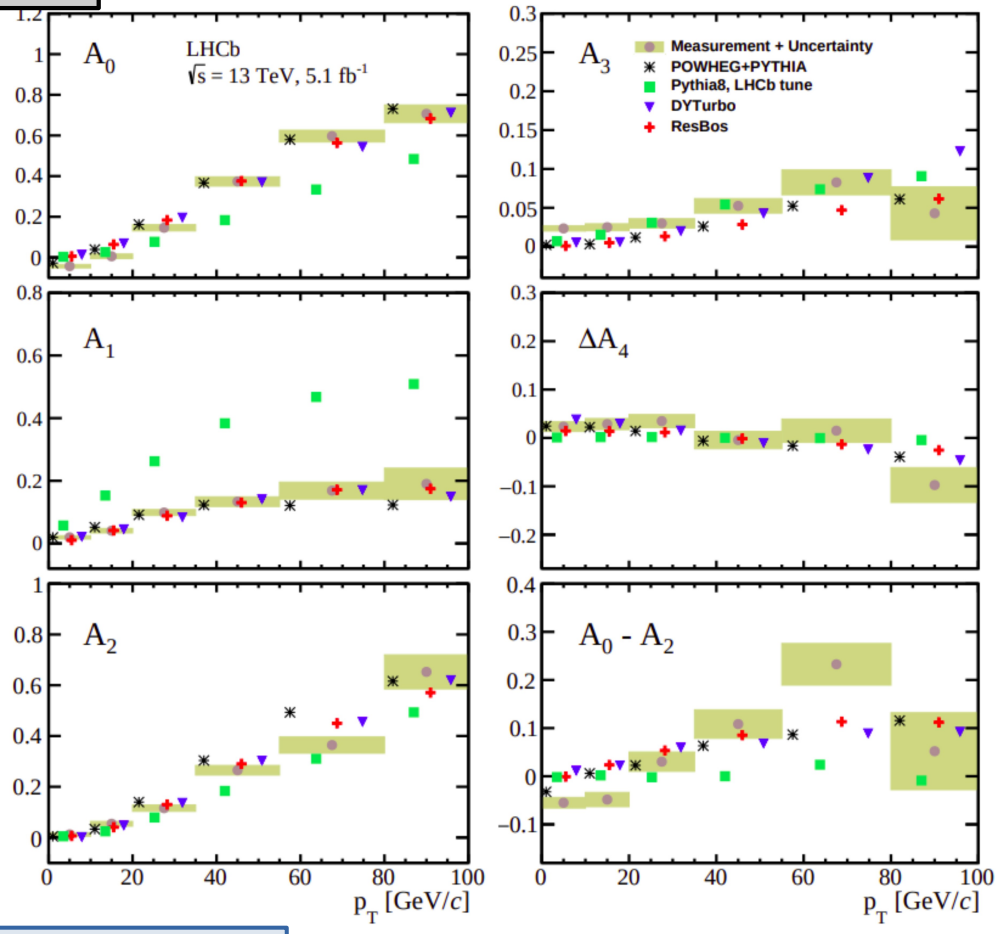
$$\frac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta\mathrm{d}\phi} \propto (1+\cos^2\theta) + \frac{1}{2}A_0(1-3\cos^2\theta) + A_1\sin 2\theta\cos\phi + \frac{1}{2}A_2\sin^2\theta\cos 2\phi$$
$$+A_3\sin\theta\cos\phi + A_4\cos\theta + A_5\sin^2\theta\sin 2\phi + A_6\sin 2\theta\sin\phi + A_7\sin\theta\sin\phi,$$

- $\mathbf{A_4}$ comes from parity violation, sensitive to $\sin^2\theta_w$, not the focus of measurement
- Lam-Tung relation, $\mathbf{A_0} \approx \mathbf{A_2}$, violated at higher orders in QCD
- $\mathbf{A_2}$ sensitive to TMD's, measured in low p_T region with different mass bins
- $\mathbf{A_5}$, $\mathbf{A_6}$, $\mathbf{A_7}$ only have small deviations from zero at NNLO → fixed to zero in fit

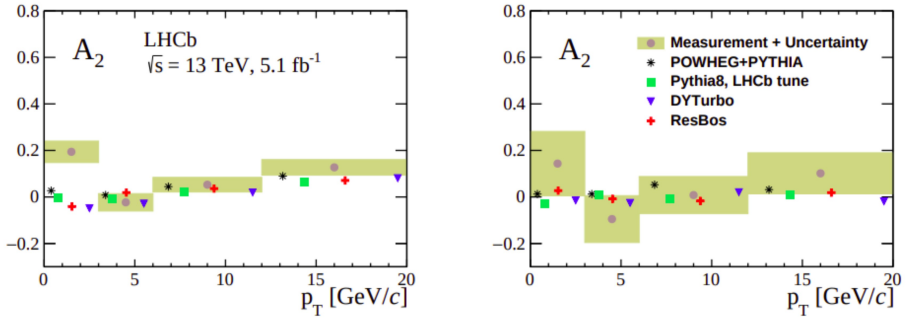
arXiv:2203.01602
Submitted to PRL

Forward Z: Angular coefficients (2/2)

LHCb



Results in low p_T region



- Compared with various predictions:
  - POWHEG+PYTHIA
  - DYTurbo
  - RESBOS
  - PYTHIA8+LHCb tune

arXiv:2203.01602
Submitted to PRL

First measurement of angular coeffs. in forward region!

High mass A_{FB} measurement (1/3)

CMS

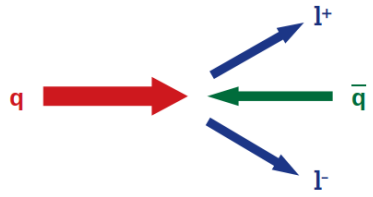
- Forward-backward asymmetry (A_{FB}) results from parity violation
  - Interference from heavy BSM would change A_{FB} at high mass

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

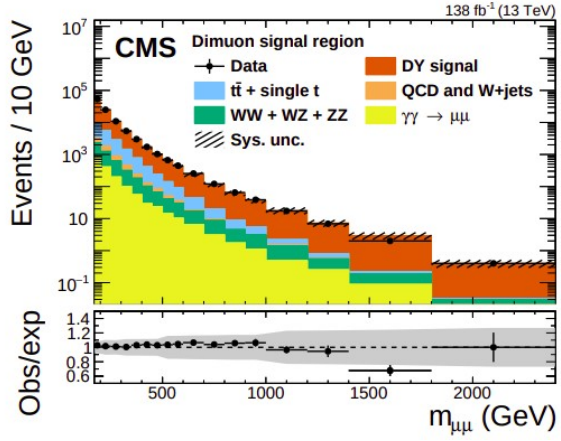
- A_{FB} directly related to A_4 $\quad \frac{3}{8}A_4 = A_{FB}$

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

Quark carries more momentum than anti-quark on avg.



- pp collider → quark vs anti-quark direction only known statistically → **asymmetry diluted**
- Measured via template fitting approach
  - Templates include dilution effect, automatically unfolded
- A_{FB} and A_0 measured for dilepton **masses > 170 GeV**

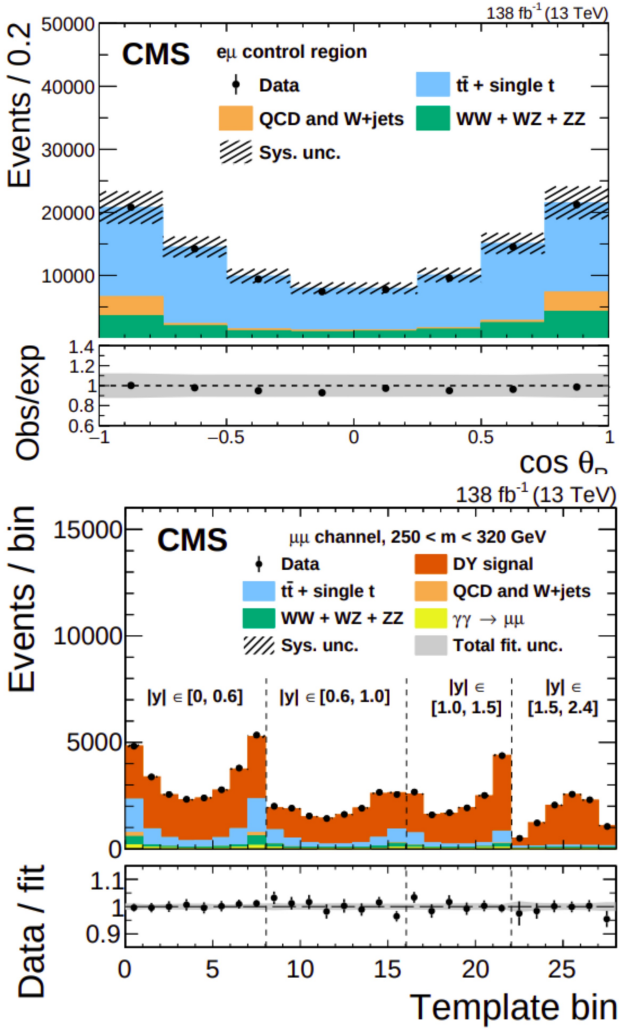


arXiv:2202.12327
Submitted to JHEP

High mass A_{FB} measurement (2/3)

CMS

- $t\bar{t}$ and VV backgrounds using MC, validated in eμ control region
- Hadrons MisID as leptons estimated using data-driven method
- Data fit to templates of $\cos\theta_R$ and rapidity distributions in ee and μμ channels in different mass bins

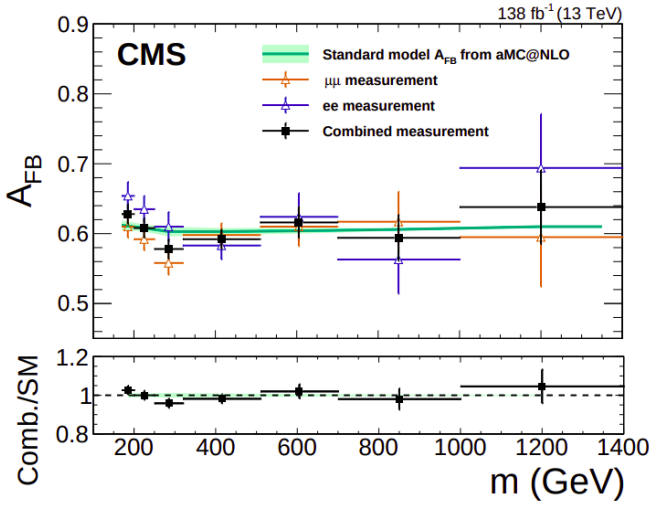


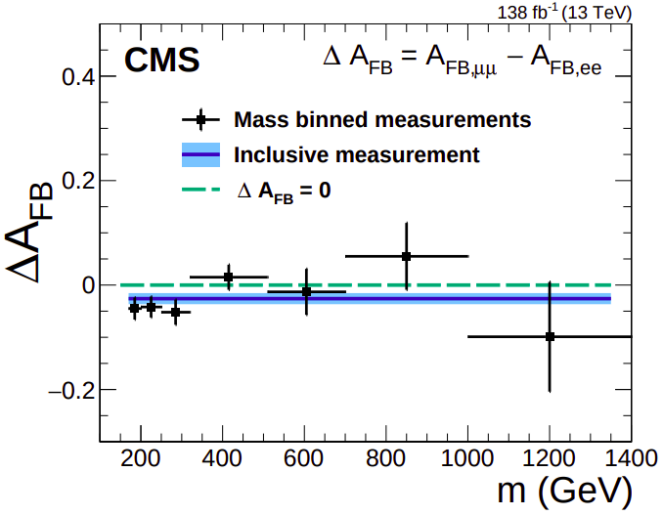
arXiv:2202.12327
Submitted to JHEP

High mass A_{FB} measurement (3/3)

CMS

- Various sets of fits performed
  - ee and μμ fit separately
  - ee and μμ fit with common A_{FB} and A_0 params
  - Test LFU: Fit for ΔA_{FB}(ee, μμ)
    - Slight 2.4σ tension found
- Results used to set limits on Z'_{SSM}
  - $M_{Z'} < 4.4$ TeV excluded @ 95% CL





arXiv:2202.12327
Submitted to JHEP

Z invisible branching ratio (1/2)

CMS

- Z invisible width can be extracted from ratio of Z(νν)+jets to Z(ℓℓ)+jets

$$\Gamma(Z \to \nu\bar{\nu}) = \frac{\sigma(Z+\text{jets})\mathcal{B}(Z \to \nu\bar{\nu})}{\sigma(Z+\text{jets})\mathcal{B}(Z \to \ell\ell)}\Gamma(Z \to \ell\ell)$$

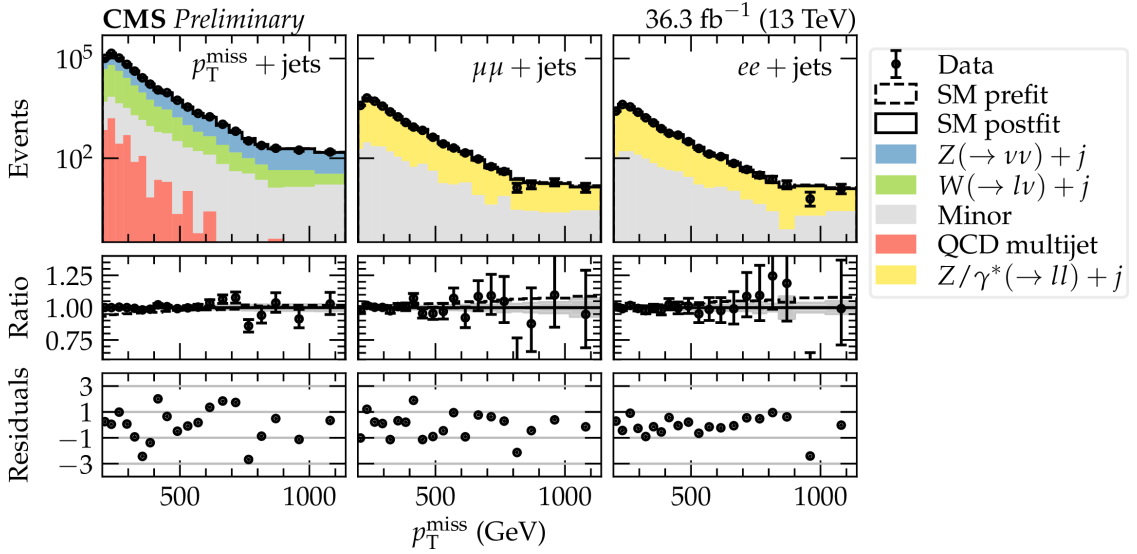
- Simultaneous fit to 3 analysis regions:
  - **Z→νν region**: Jets + $p_{T,miss}$
  - **Z→ℓℓ region**: μμ + jets and ee + jets to select
  - **W+jets Control Region**: μ+$p_{T,miss}$+jets, e+ $p_{T,miss}$+jets, and τ_H+ $p_{T,miss}$+jets

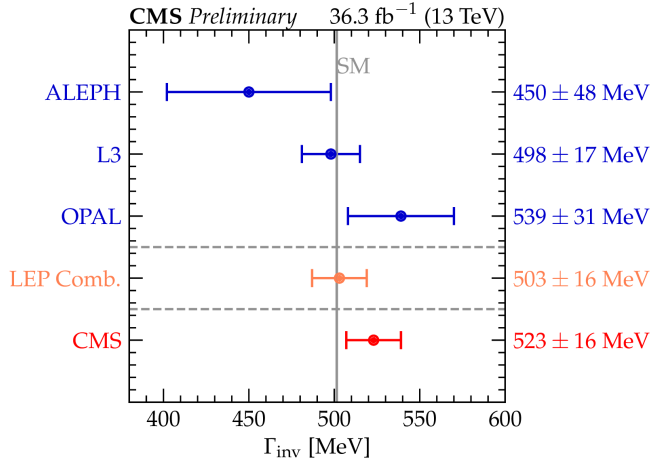
CMS-PAS-SMP-18-014

Z invisible branching ratio (2/2)

CMS

- Events selected in the $p_{T,miss}$>200 GeV region
  - Dileptons from Z decays excluded in $p_{T,miss}$ calculation
- W+jets bkg in SR estimated from CR + transfer factor
- Effect of γ* accounted for and removed





Γ_{inv} =523 ± 3(stat)± 16 (syst) MeV

Single most precise direct measurement to date!

CMS-PAS-SMP-18-014

Conclusions

- Several recent measurements of Z/DY properties have been presented from **ATLAS**, **CMS** **and** **LHCb**
  - **Z p_T distribution**
  - **DY p_T over wide mass range**
  - **Forward Z cross section**
  - **Forward Z angular coefficients**
  - **High mass forward-backward asymmetry**
  - **Z invisible branching ratio**
- Providing valuable tests of QCD modeling
- Precision measurements used as probes of new physics

More exciting results to come, stay tuned!

Backup

List of Analyses Presented

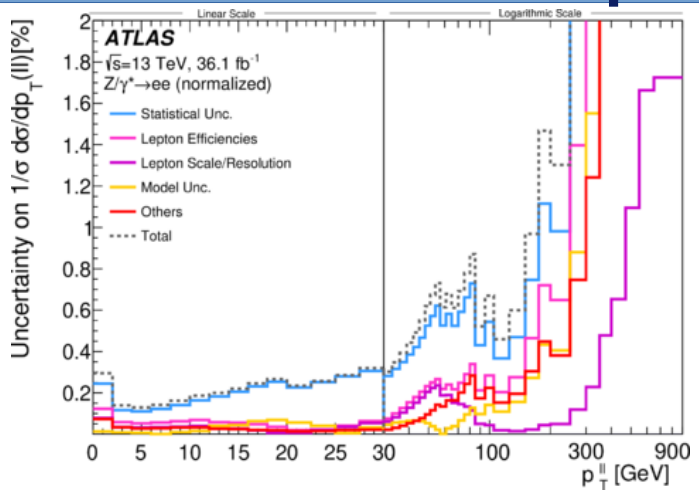
- Measurement of the transverse momentum distribution of Drell-Yan lepton pairs in proton-proton collisions at √s=13 TeV with the ATLAS detector (Eur. Phys. J. C 80 (2020) 616)
- Measurement of mass dependence of the transverse momentum of Drell Yan lepton pairs in proton-proton collisions at √s= 13 TeV (CMS-PAS-SMP-20-003)
- Precision measurement of forward Z boson production in proton-proton collisions at √s= 13 TeV (arXiv:2112.07458)
- First measurement of the $Z \to \mu^+\mu^-$ angular coefficients in the forward region of pp collisions at √s= 13 TeV (arXiv:2203.01602)
- Measurement of the Drell-Yan forward-backward asymmetry at high dilepton masses in proton-proton collisions at √s= 13 TeV (arxiv:2202.12327)
- Precision measurement of the Z invisible width with the CMS experiment in pp collisions at √s= 13 TeV (CMS-PAS-SMP-18-014)

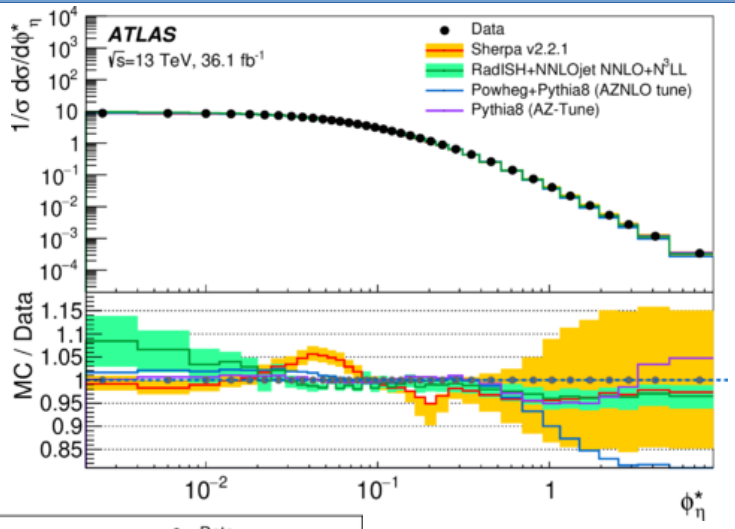
φ_η^*

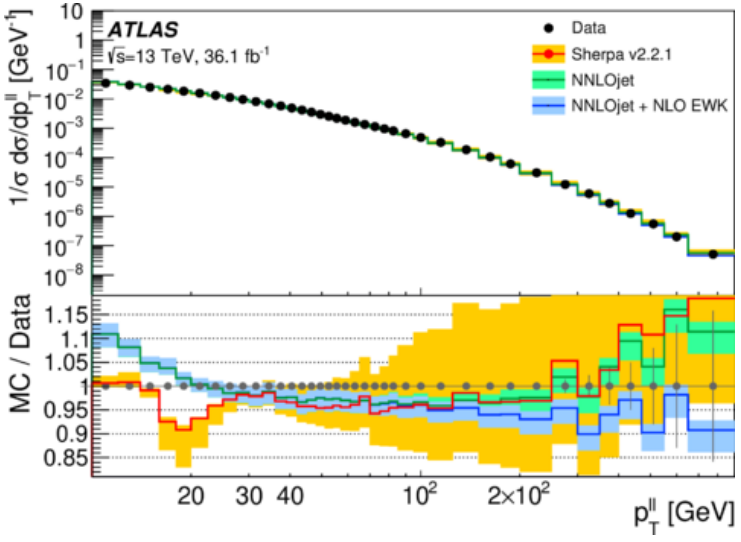
$$\phi_\eta^* = \tan\left(\frac{\pi - \Delta\phi}{2}\right) \times \sin(\theta_\eta^*), \qquad \cos(\theta_\eta^*) = \tanh[(\eta^- - \eta^+)/2]$$

- Measurements at low Z p_T limited by momentum resolution of leptons
- Alternatively use φ_η^* variable
  - Depends only on directions of two leptons → more accurate meassurements
  - Theoretically a little harder to interpret

Z p_T Extra Plots

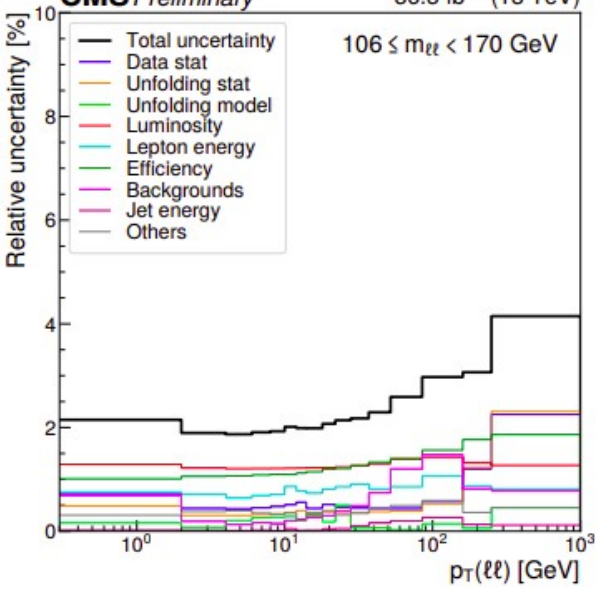


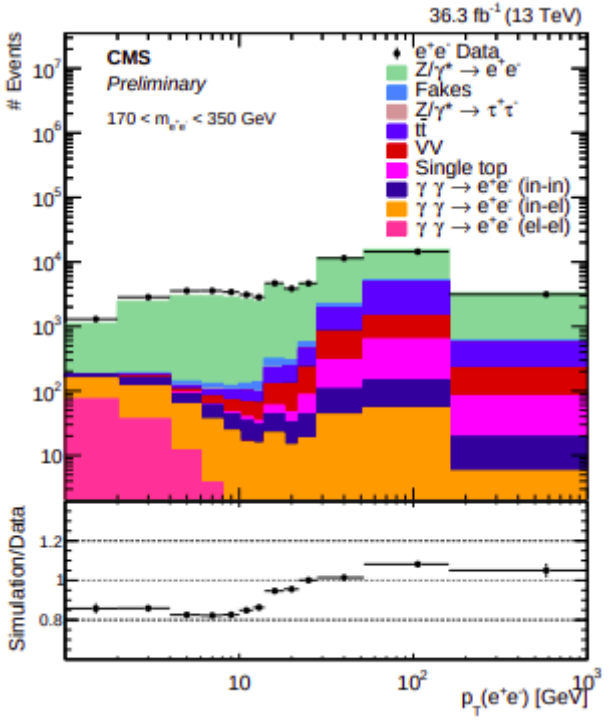


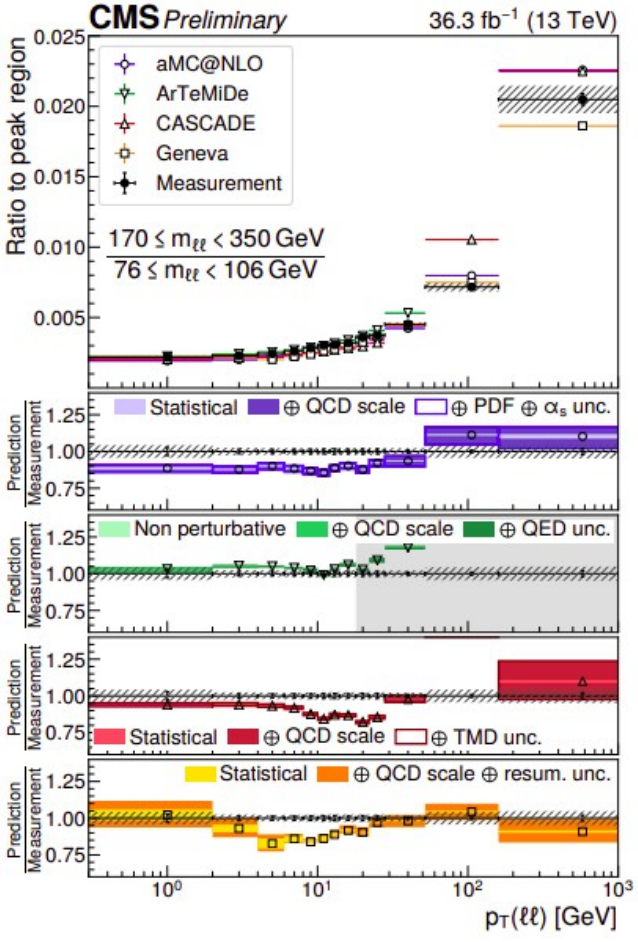


Eur. Phys. J. C 80 (2020) 616 (arxiv)

High Mass p_T Extra Plots

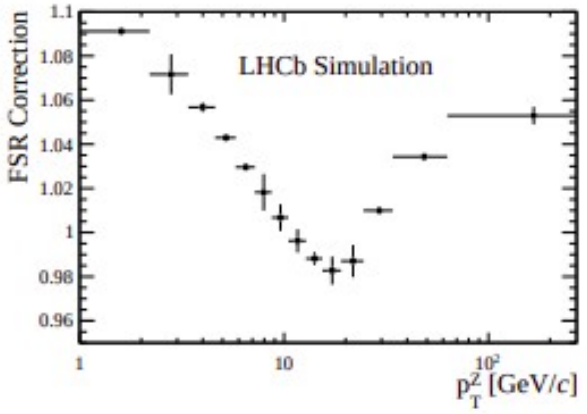




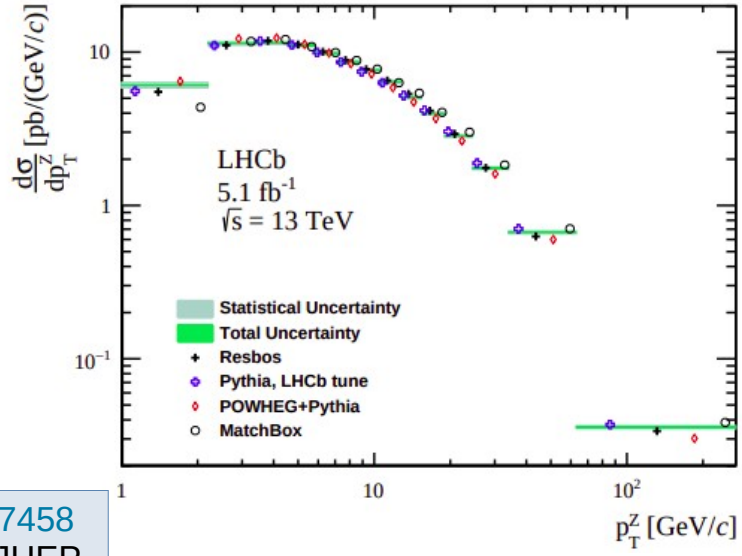


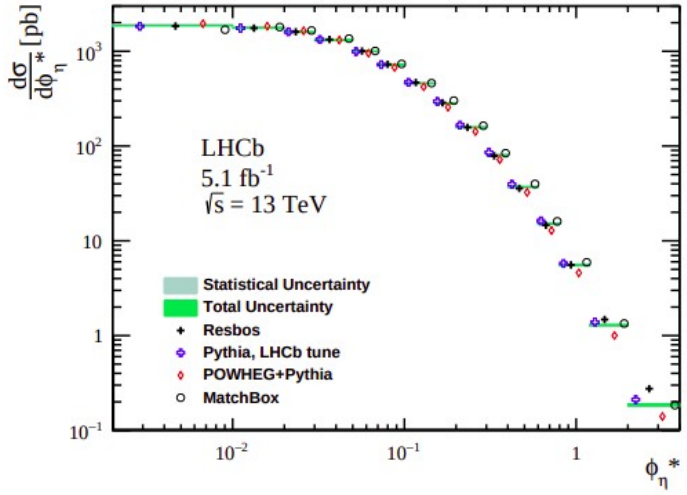
CMS-PAS-SMP-20-003

Forward Z Extra Cross Section Extra Plots



Source	$\Delta\sigma/\sigma$ [%]
Statistical	0.11
Background	0.03
Alignment & calibration	-
Efficiency	0.77
Closure	0.06
FSR	0.04
Total Systematic (excl. lumi.)	0.77
Luminosity	2.00
Total	2.15

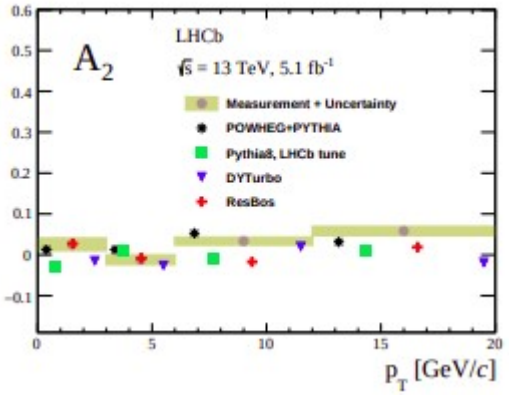




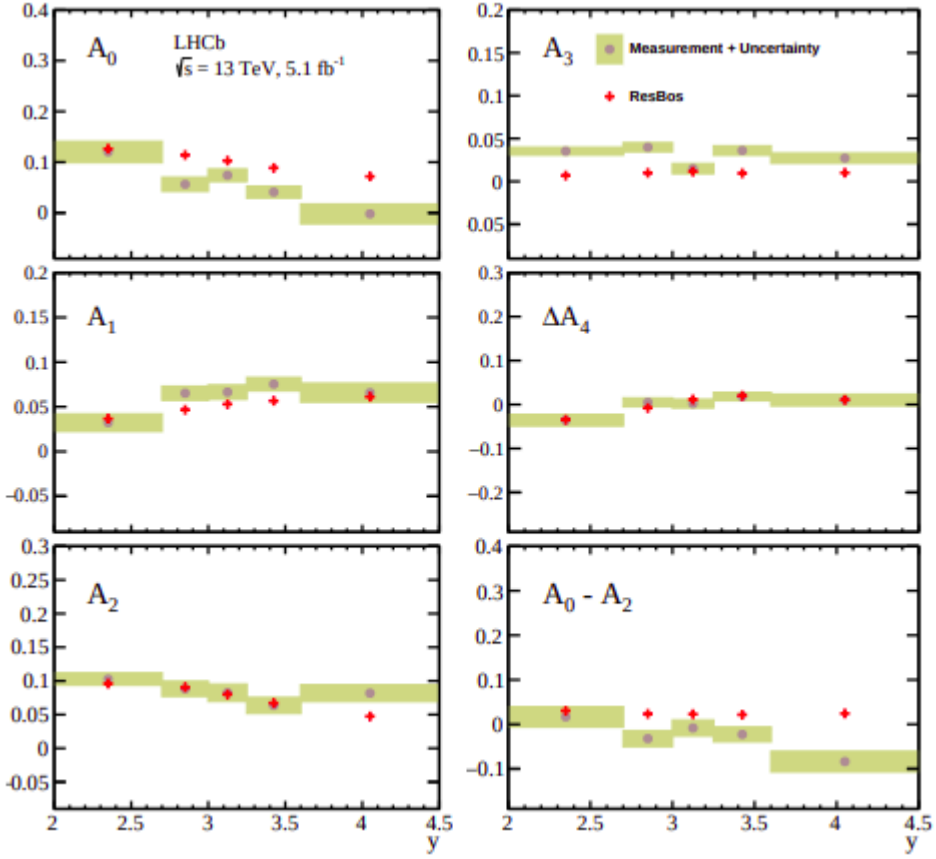
arXiv: 2112.07458
Submitted to JHEP

Forward Z Angular Coeffs. Extra Plots

A_2 in low p_T region

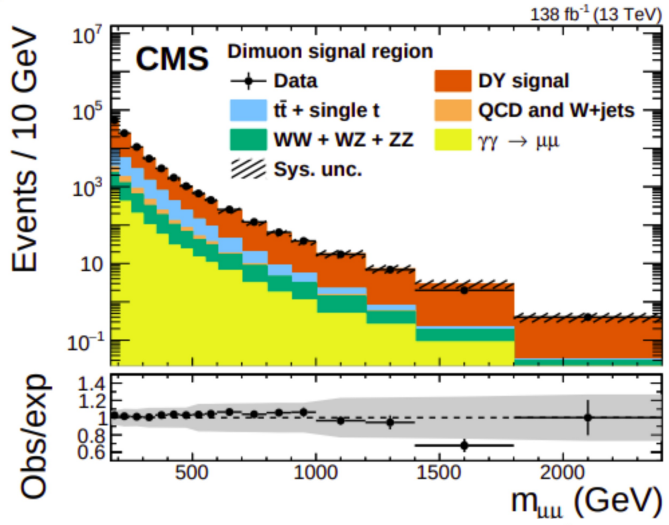


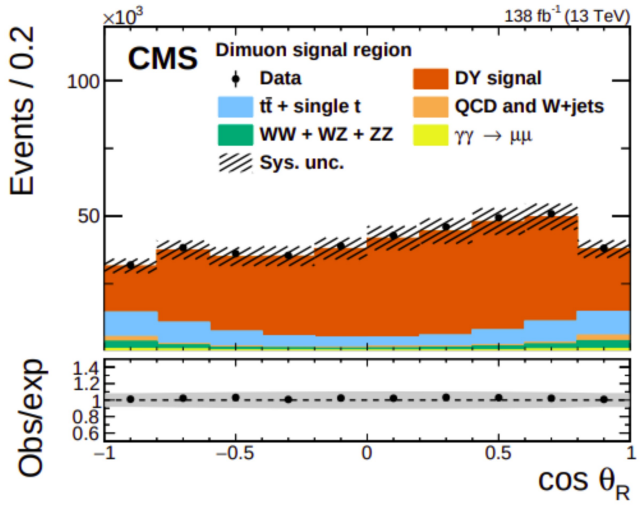
Coeffs. vs. y

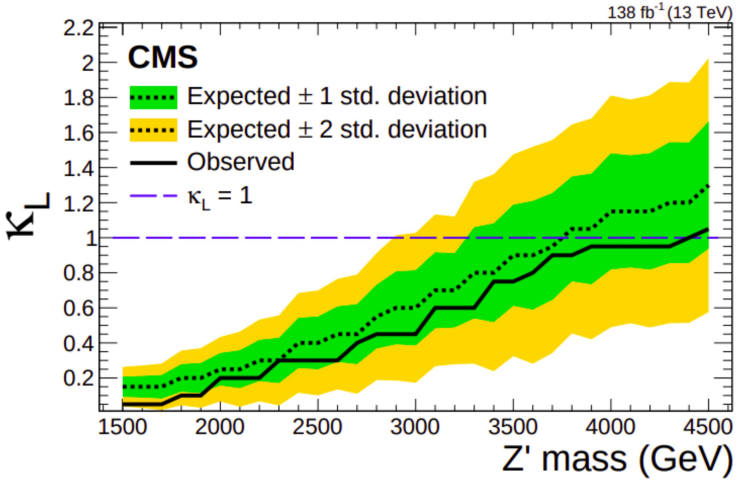


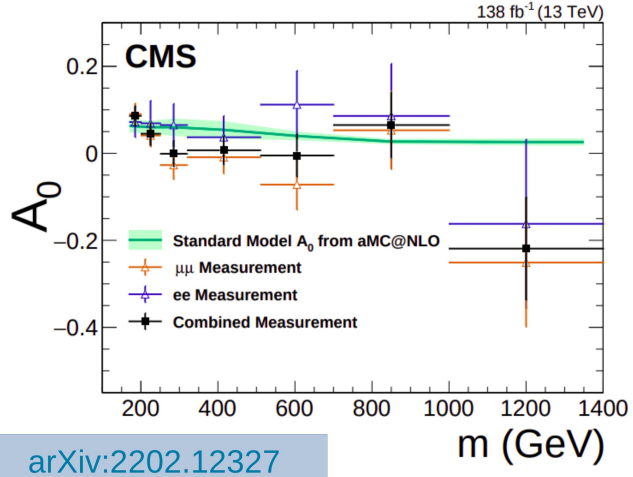
arXiv:2203.01602
Submitted to PRL

DY AFB Extra Plots









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%

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