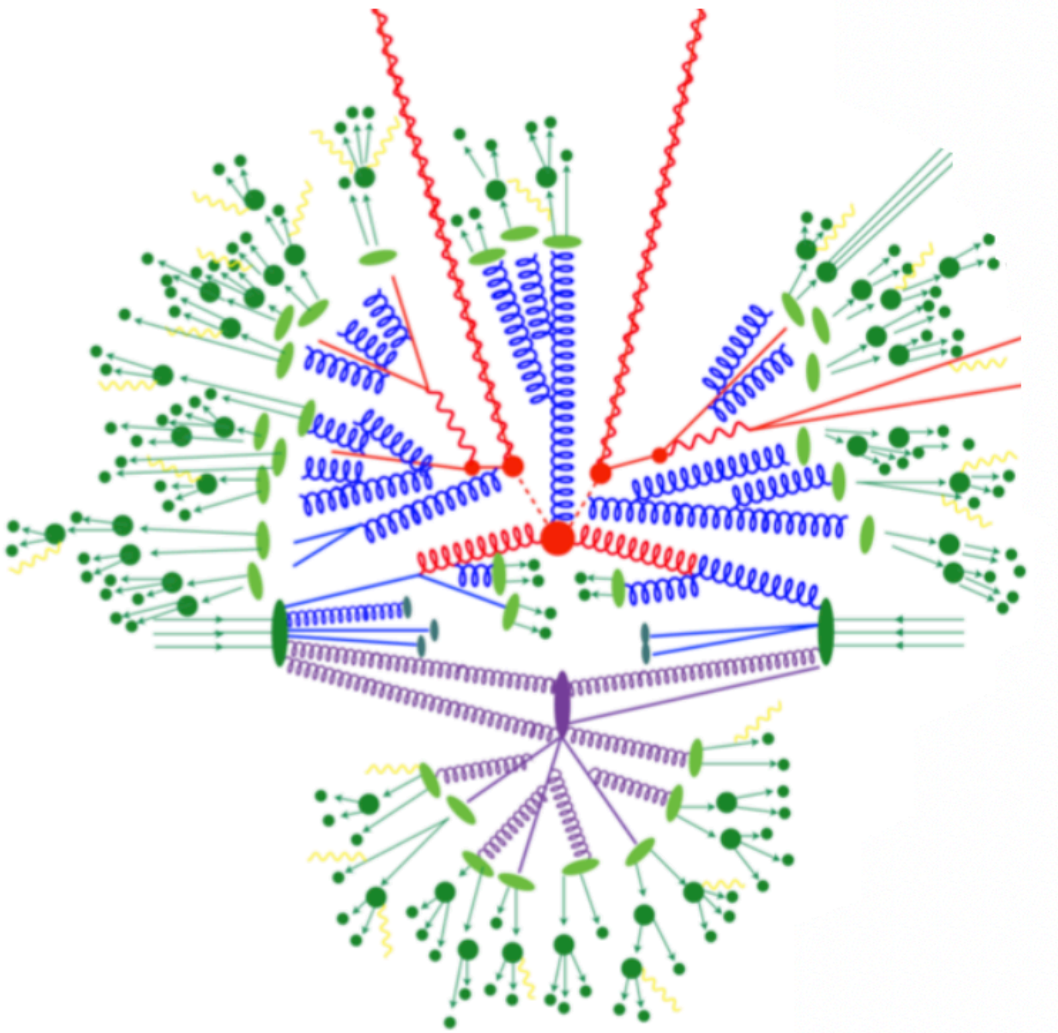
Review of high p_T experimental results (top, W, Z, Higgs) relevant for QCD

Jad Zahreddine (CNRS)

GDR QCD at short distances, June 4th 2021

Review of results



- QCD is complex and abundant: all LHC observables depend on control of QCD

- Important modeling uncertainties in a large amount of SM physics

- Understand QCD background for NP search

- Thanks to F. Balli, N. Berger, R. Camacho, F. Déliot, M. Gouzévitch, L. Fayard, Z. Zhang

Inclusive	W/Z bosons	Top quark	Higgs boson
Event shapes **Radius scan** **Lund Jet Plane**	**Z/y+jet diff XS** **Z p_T** **W/Z production XS** **Determination of PDF**	**Top pair XS** **XS and m_t^{pole}**	**Search for boosted H->bb** **VH modeling uncertainties** **ttH modeling uncertainties**

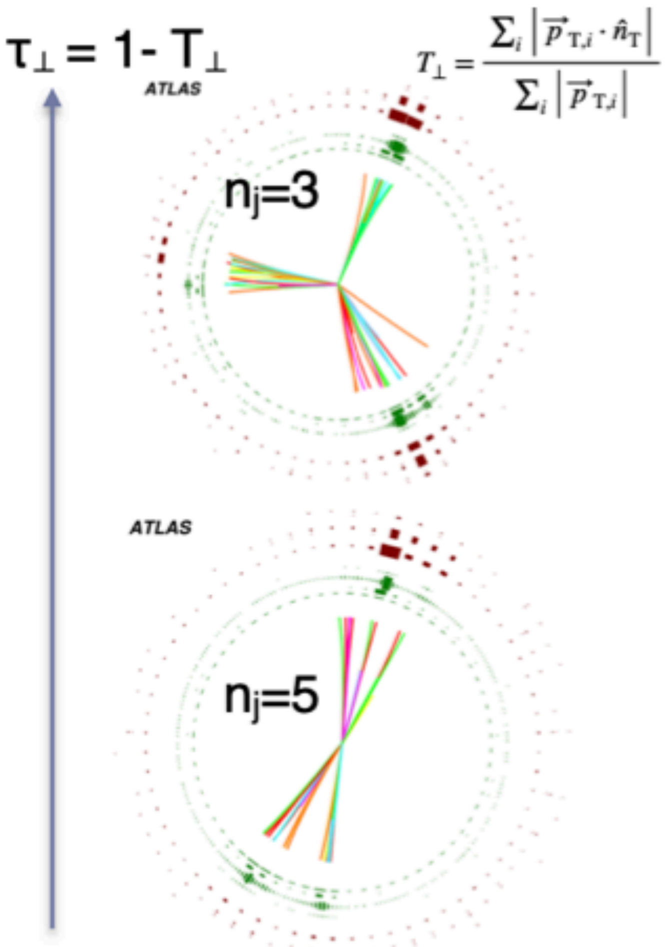
and many more from ATLAS & CMS….

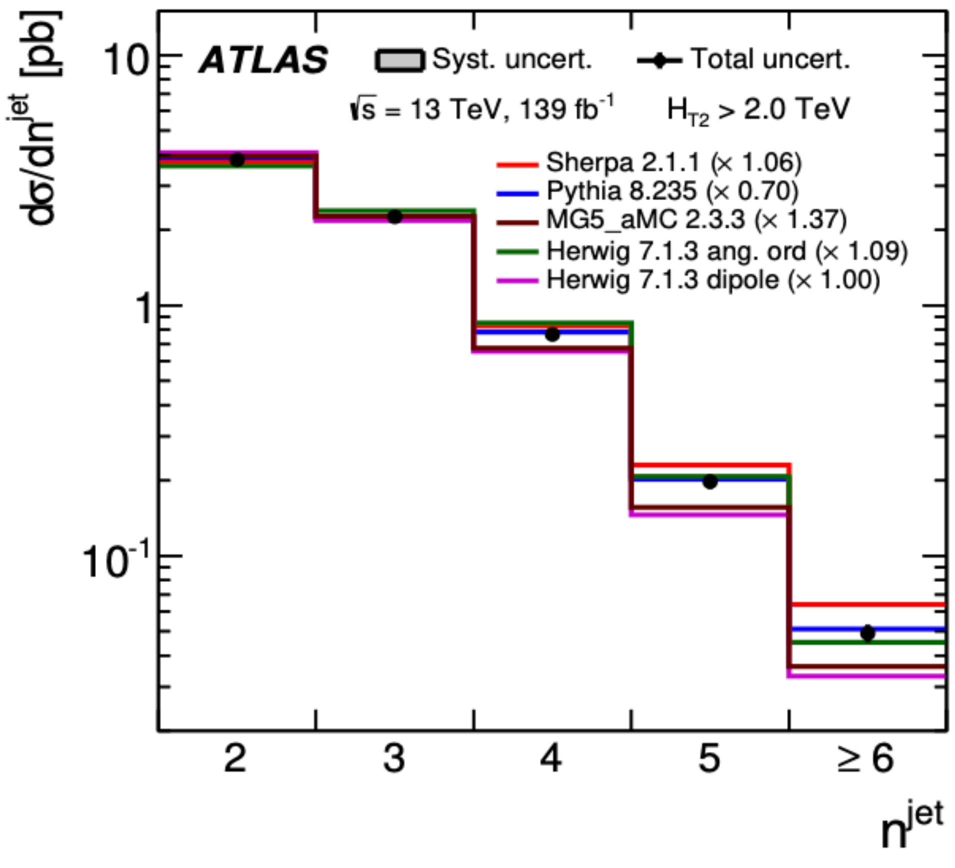
Disclaimer: in this talk, only ATLAS and CMS results are covered, ALICE publication

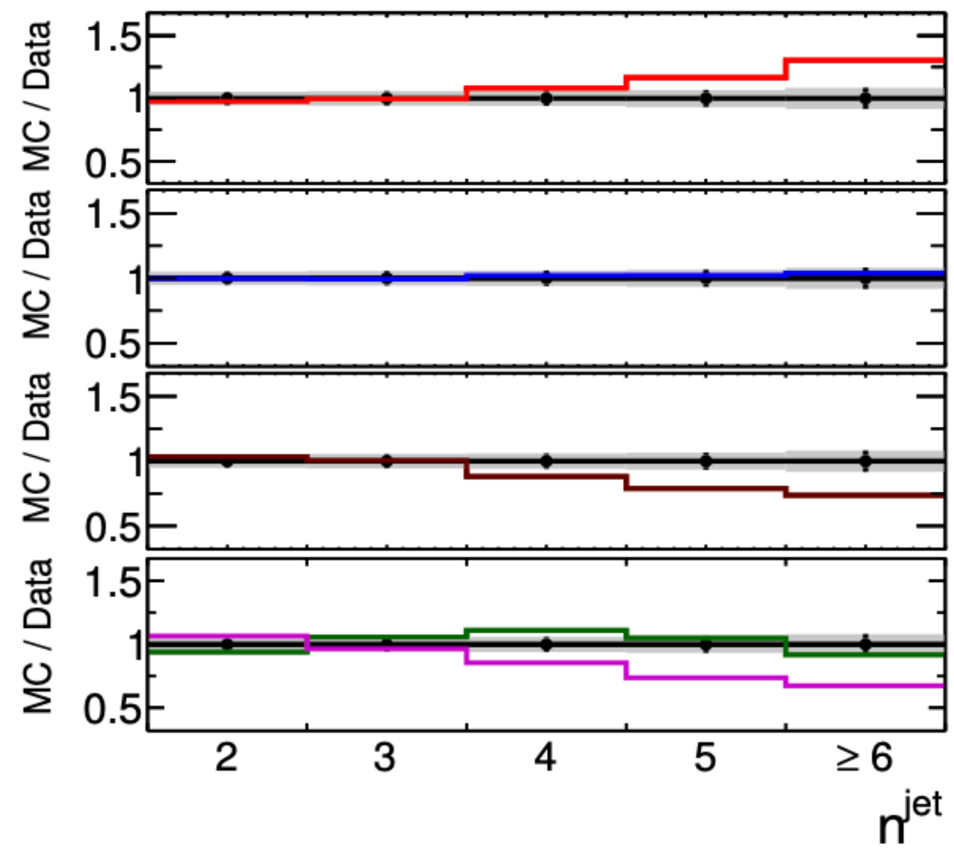
Inclusive

Hadronic energy flow in multi-jet events

JHEP 01 (2021) 188







Hadronic event shapes with jets
- Proxy for energy flow in collision events, provides a test of fixed order calculations, MC modeling, etc.

- Proxy for hard scale: $H_{T2} = p_T^{lead} + p_T^{sublead} > 1$ TeV ($p_T > 100$; $|\eta| < 2.4$)

- Fiducial cross section is measured in three H_{T2} regions

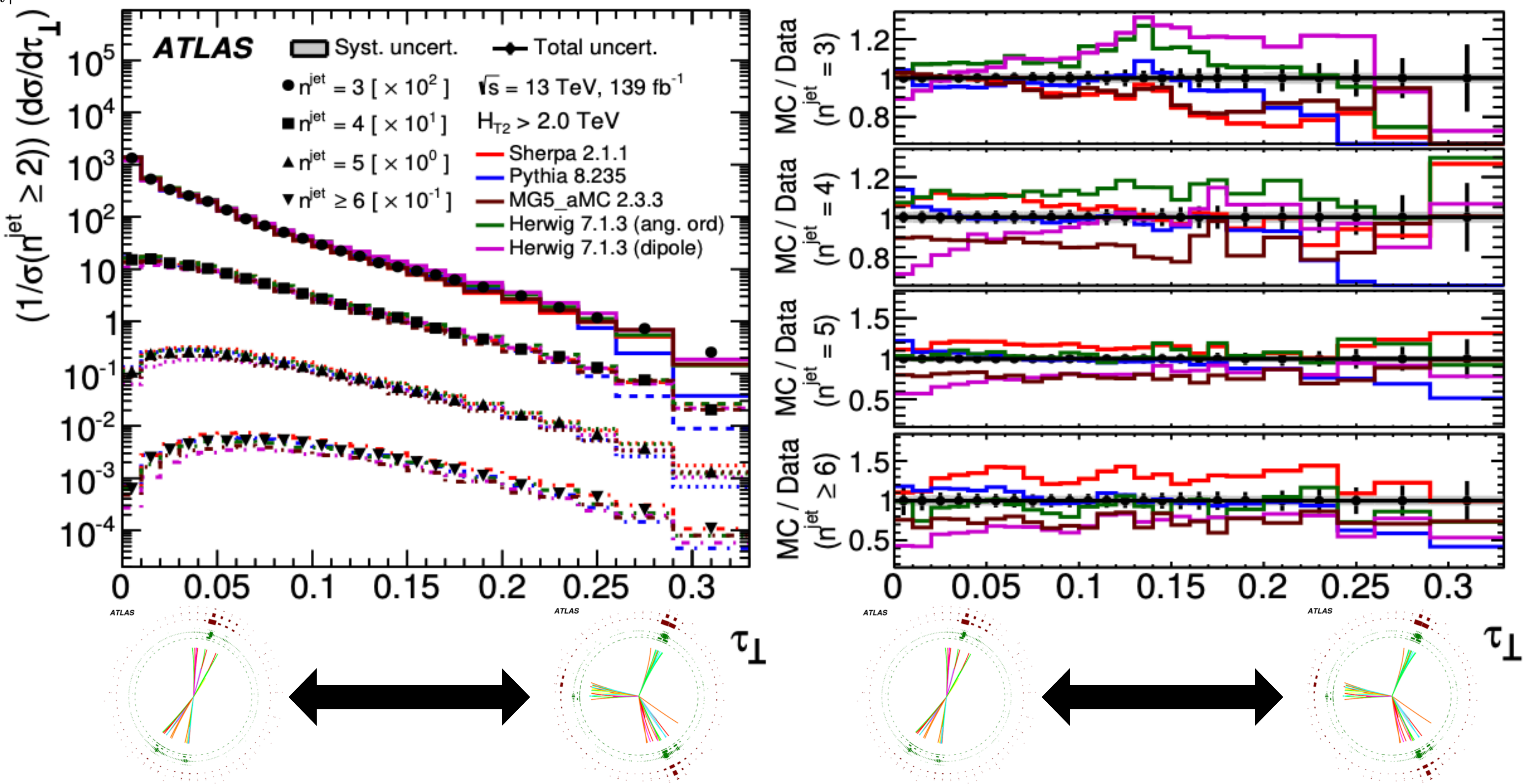
- MC normalized to data to compare the shape of the predictions

- Larger spread at higher n^{jet} (Pythia closest to data)

Hadronic energy flow in multi-jet events

$$T_\perp = \frac{\sum_i |\vec{p}_{\mathrm{T},i} \cdot \hat{n}_\mathrm{T}|}{\sum_i |\vec{p}_{\mathrm{T},i}|}$$

$$\tau_\perp = 1 - T_\perp$$



- Unfolding: differential cross-section as ratio to fiducial cross-section $\sigma(n^{jet} \geq 2)$

- The higher H_{T2}, the less uniform the ratio distribution

- MC underpredicts high H_{T2} and low n^{jet}

- None of the generators gives a good description in full phase space

Radius scan of inclusive jet cross section

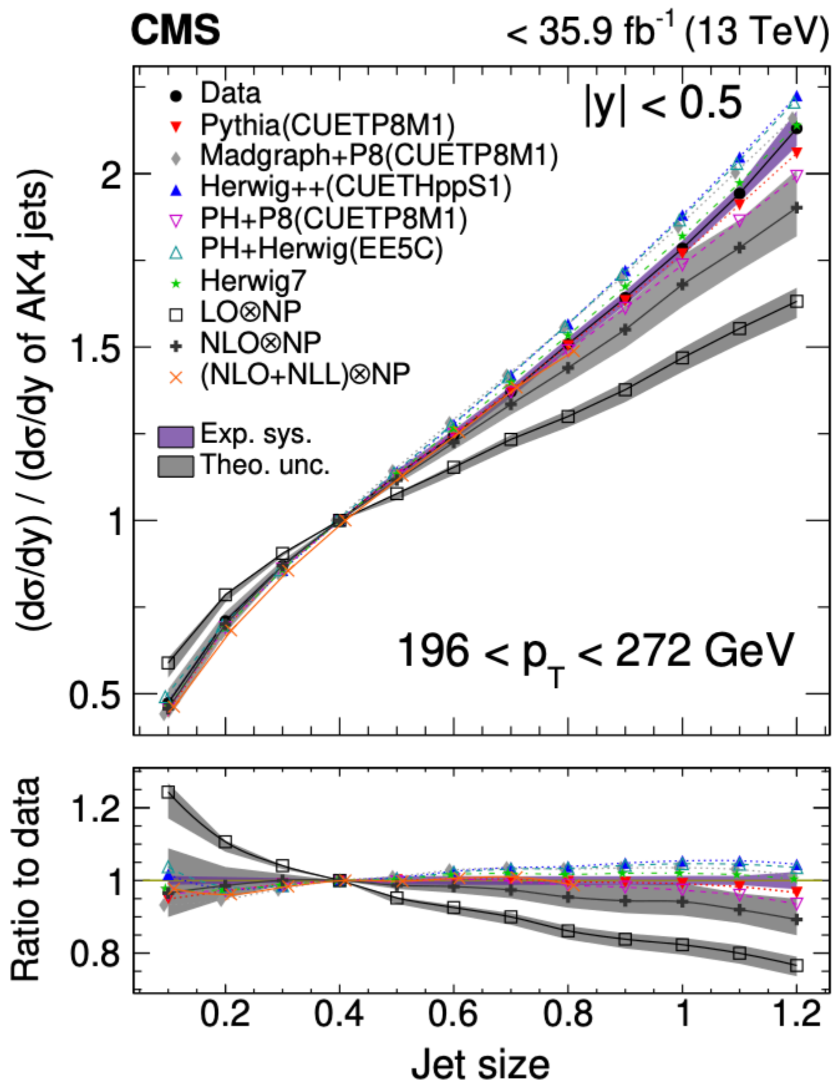
Different distance parameter R is sensitive to different parts of jet formation

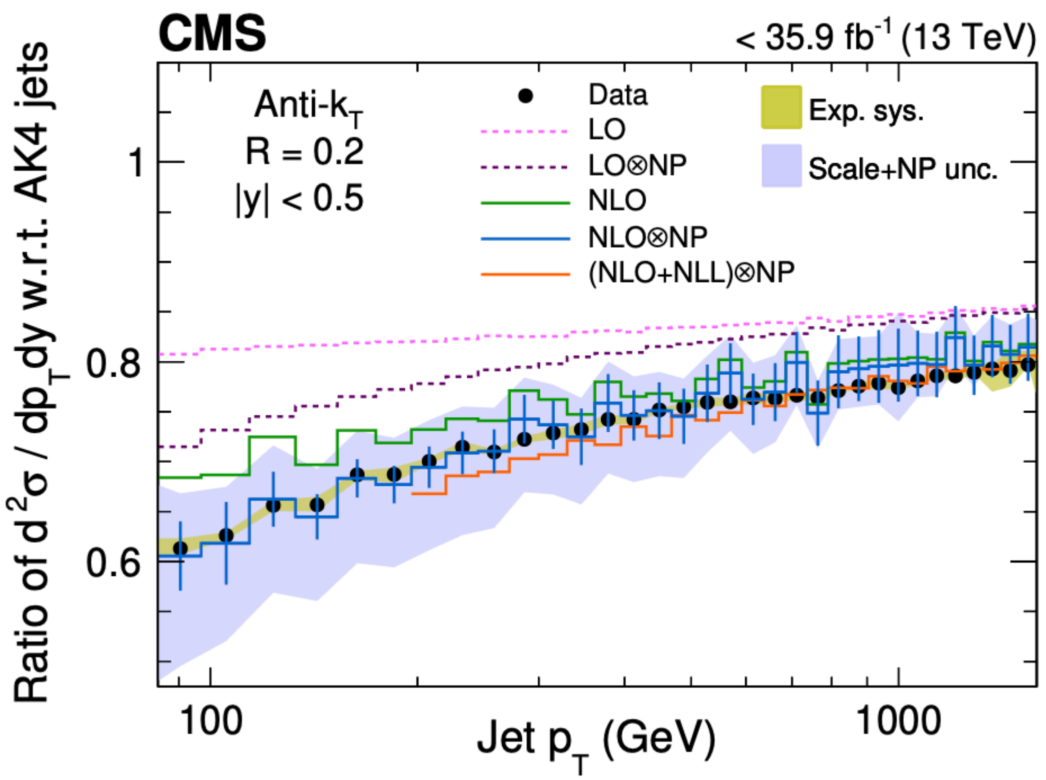
JHEP 12 (2020) 082

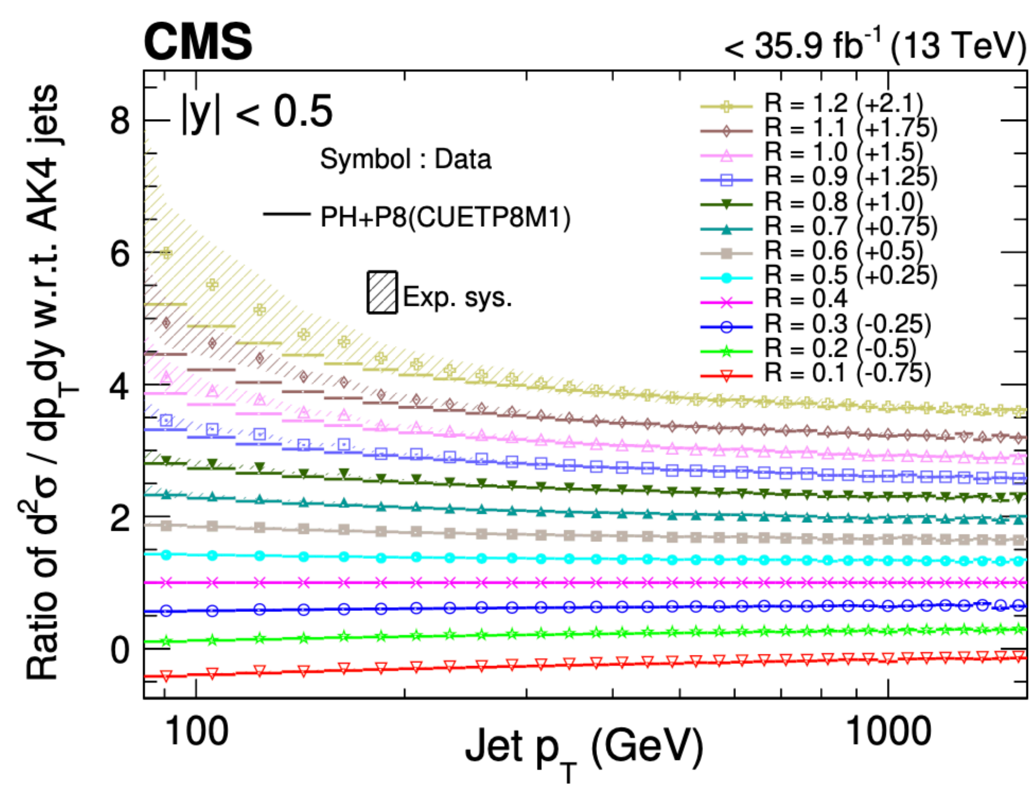
δp_T = "lost" transverse momentum outside jet cone at LO in small radius approximation

R<<1 : $(\delta p_T)_{PS} \sim ln(1/R)$, $(\delta p_T)_{Had} \sim R^{-1}$, $(\delta p_T)_{UE} \sim R^2$

- 2016 data
- PFlow jets with 0.1 < R < 1.2
- Double-differential inclusive jet cross-section ratio







- Unfolding to particle level
- Slope in p_T for large R (underlying event)
- Comparison to LO and NLO predictions

Lund jet plane using charged particles in pp@13TeV

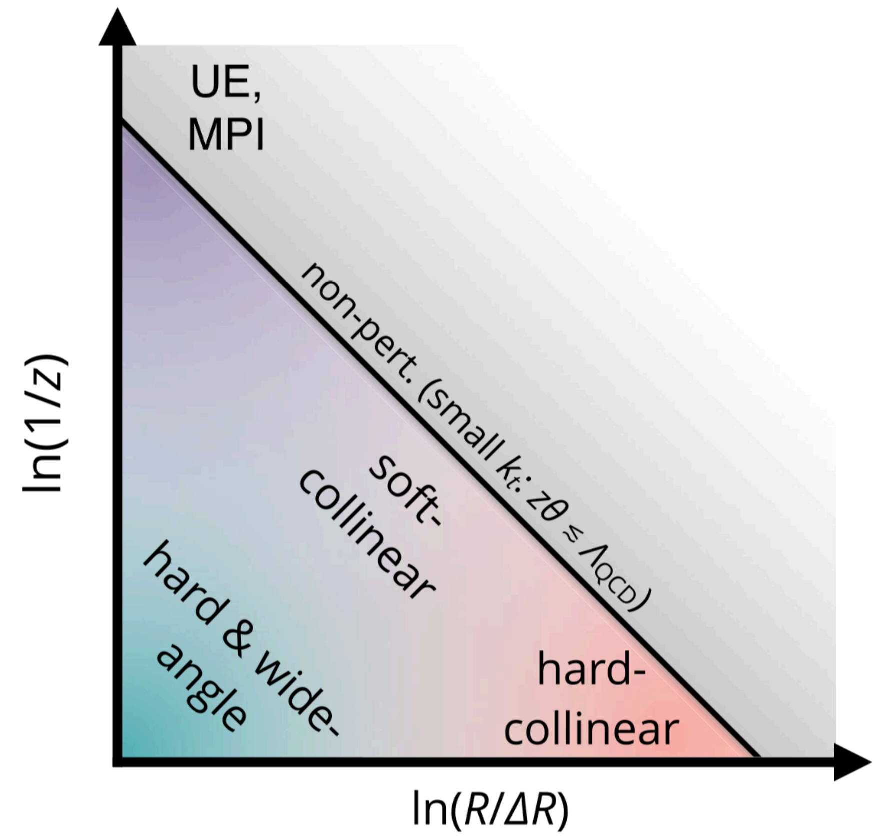
PRL 124, 222002 (2020)

- Lund Jet Plane factorizes QCD effects in jets in a very general fashion

- A jet may be approximated as soft emissions around a hard core which represents the originating quark or gluon

- Emissions may be characterized by
z = relative momentum of emission w.r.t jet core
ΔR = angle of emission relative to the jet core

$$z = \frac{p_{T2}}{p_{T1} + p_{T2}}; \qquad \Delta R = \sqrt{(y_1 - y_2)^2 + (\phi_1 - \phi_2)^2}$$



- Dijet (anti-k_t, R = 0.4) events are selected with $p_T^{(1)}/p_T^{(2)} < 1.5$
- Tracks within ΔR = 0.4 of jet axis are reclustered using C/A algorithm
- The clustering history is examined, z and ΔR obtained for each splitting
- Featuring a flat perturbative region sensitive to PS effects (hard, wide-angle) below the hadronization-sensitive diagonal

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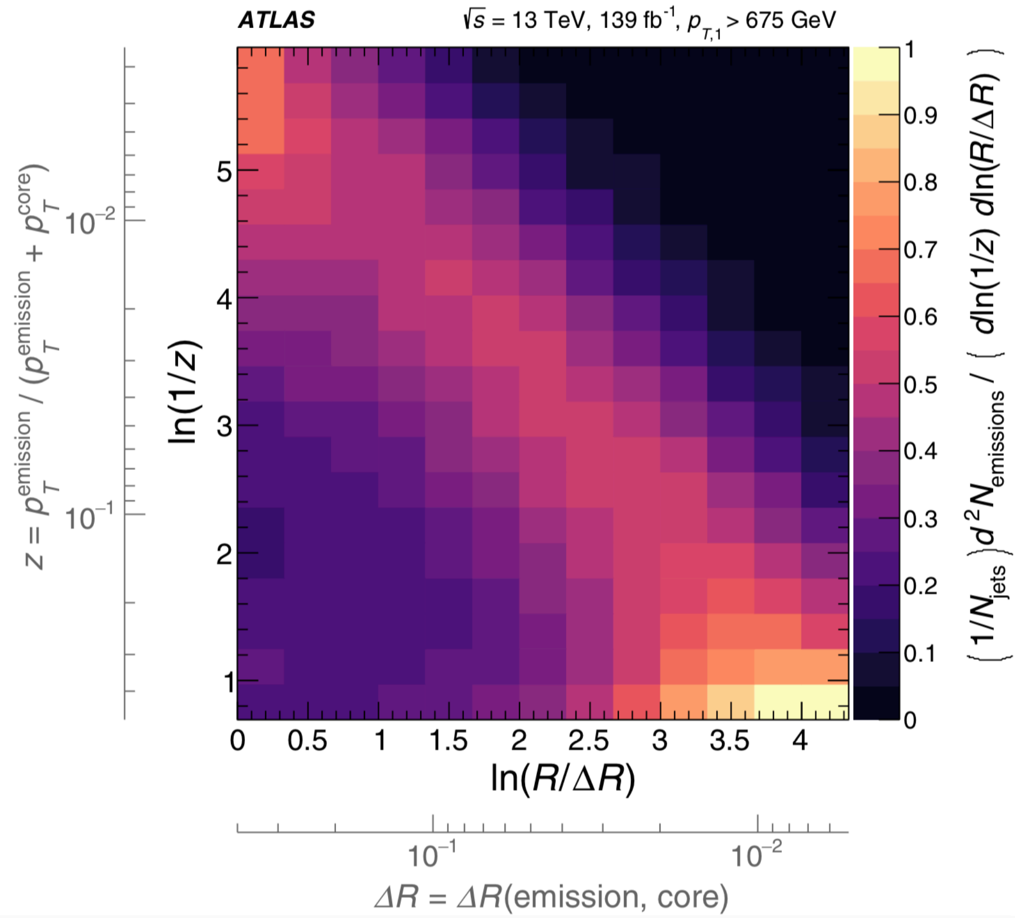

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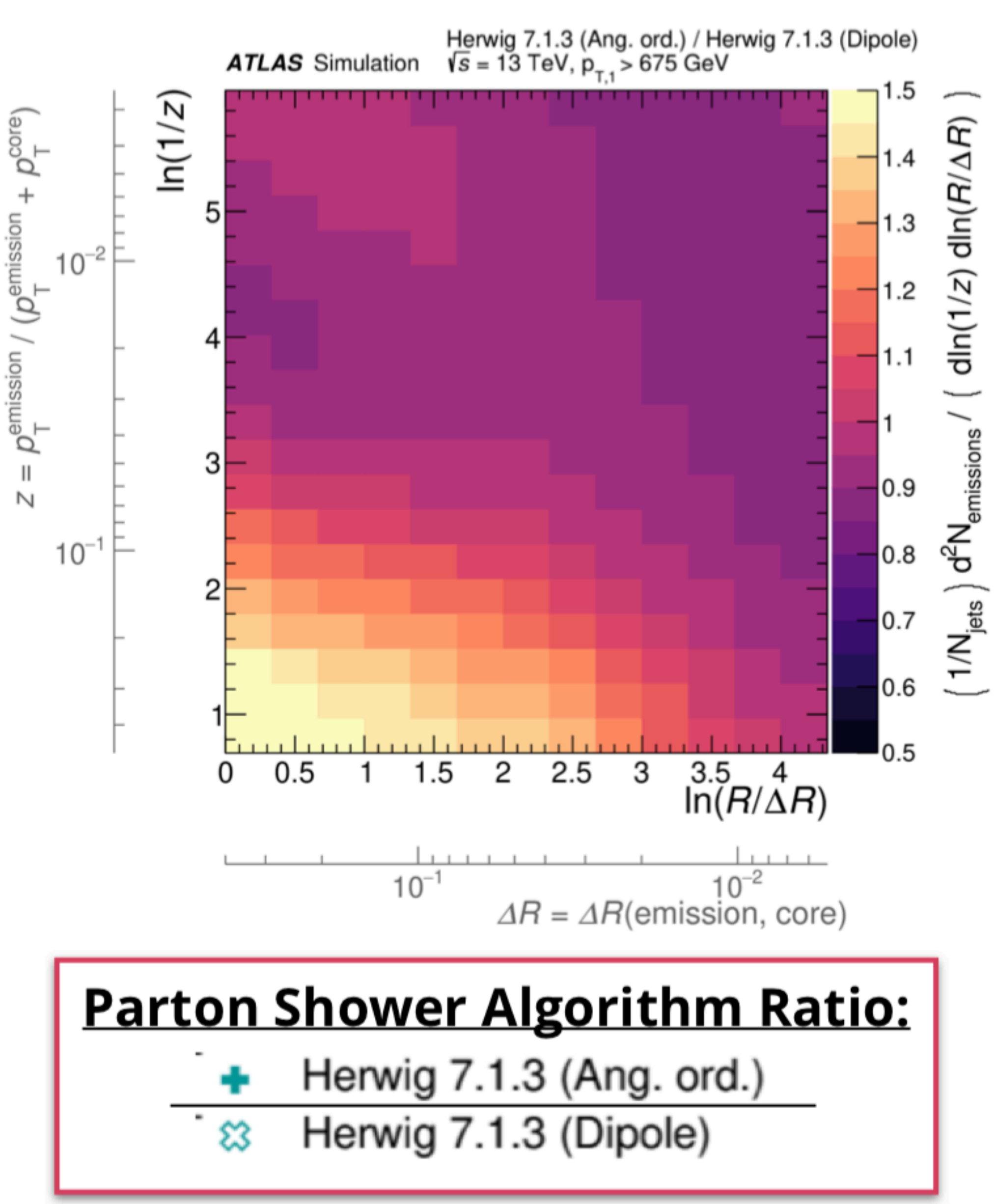
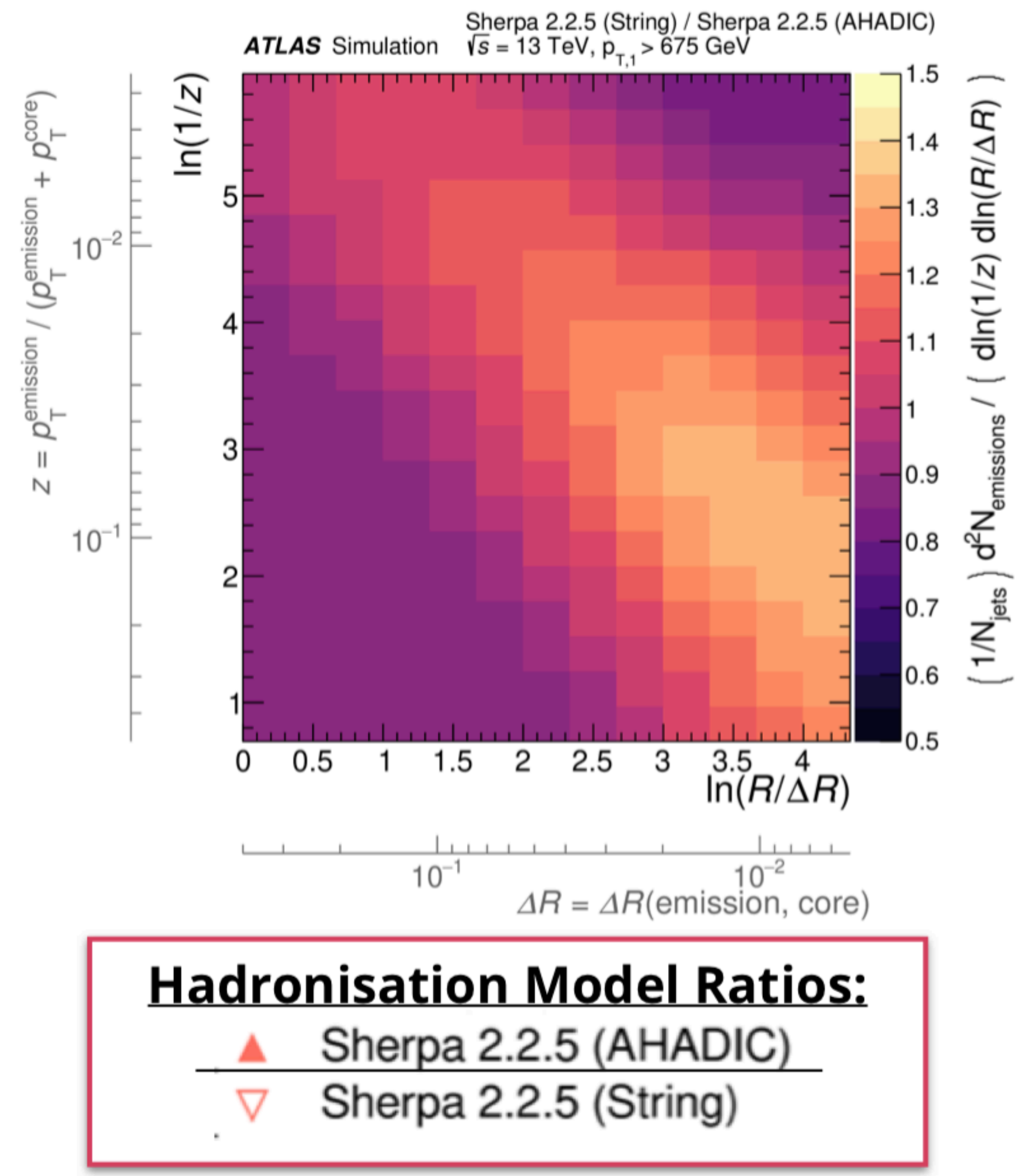
Lund jet plane using charged particles in pp@13TeV

Sensitivity to the ME calculation, parton shower and hadronization models



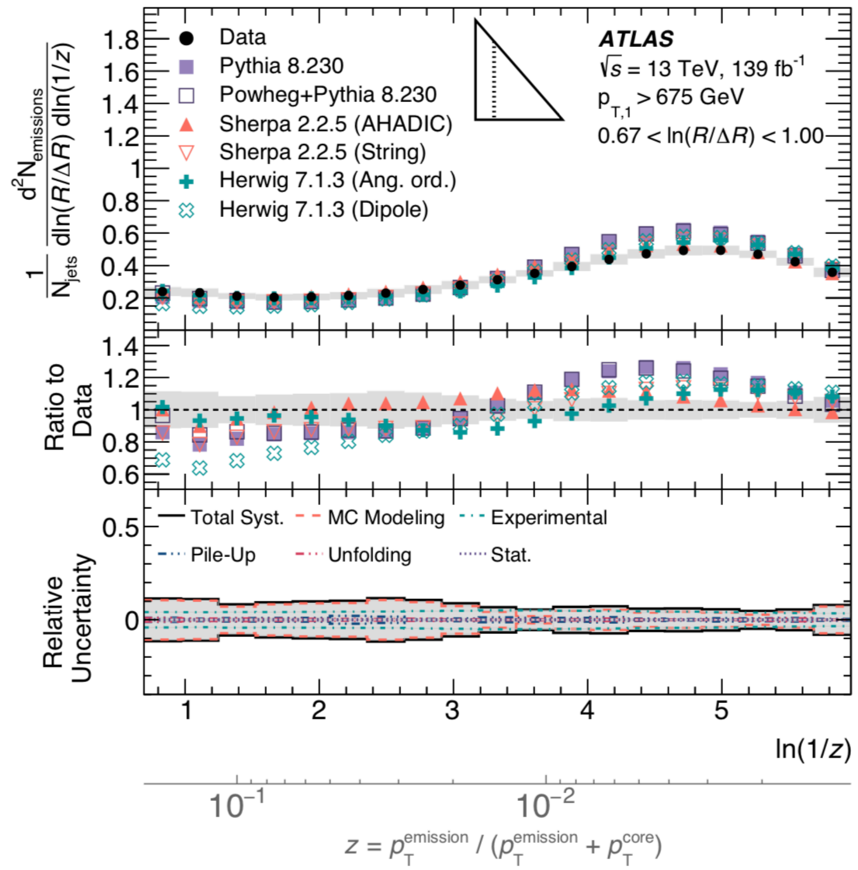


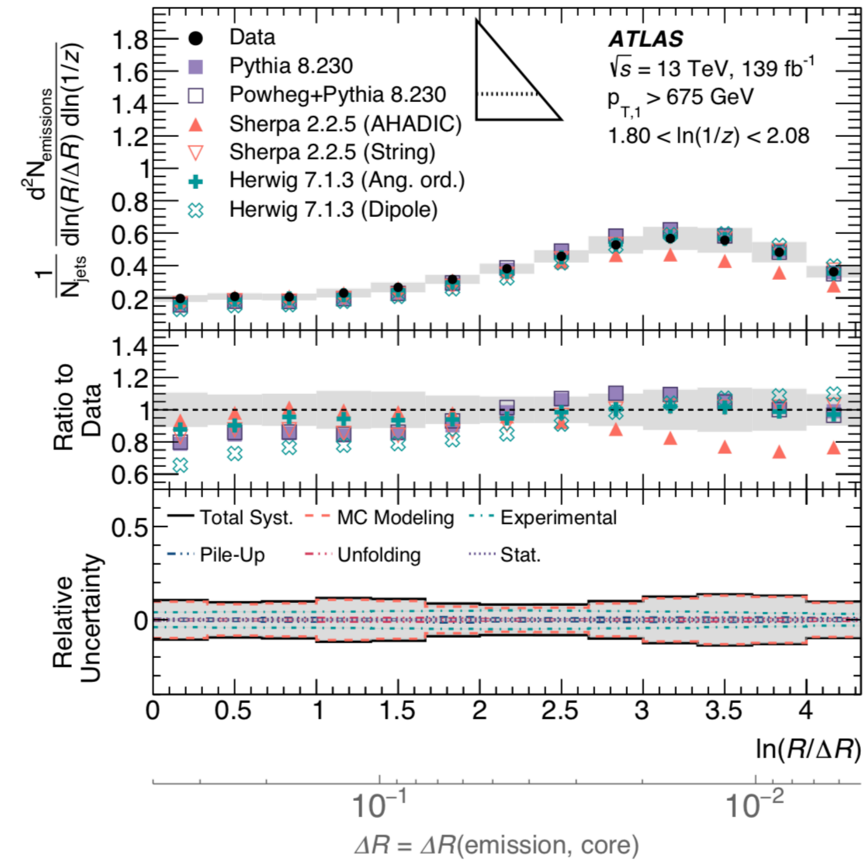
- The plots show the ratios for different shower and hadronization models

- Angle-ordered PS presents more hard, wide angle activity than dipole PS

- String model presents more hard collinear activity than cluster model

Lund jet plane using charged particles in pp@13TeV





- Unfolded LJP data compared to several MC, where a precision of ~10% is achieved, **dominated by MC modeling uncertainties**

- No MC prediction provides an accurate description of all regions

- Herwig with angle-ordered shower gives the best overall agreement, and both Herwig models differ most for hard emissions at wide angles

- Powheg+Pythia differs with Pythia for the hardest, wide-angle emissions, where the ME calculation is relevant

- Possibility to use LJP for jet tagging, MC tuning, α_S measurement

W/Z bosons

Z/γ+jet differential cross section (+ collinear Z emission)

arXiv:2102.02238v1 [hep-ex]

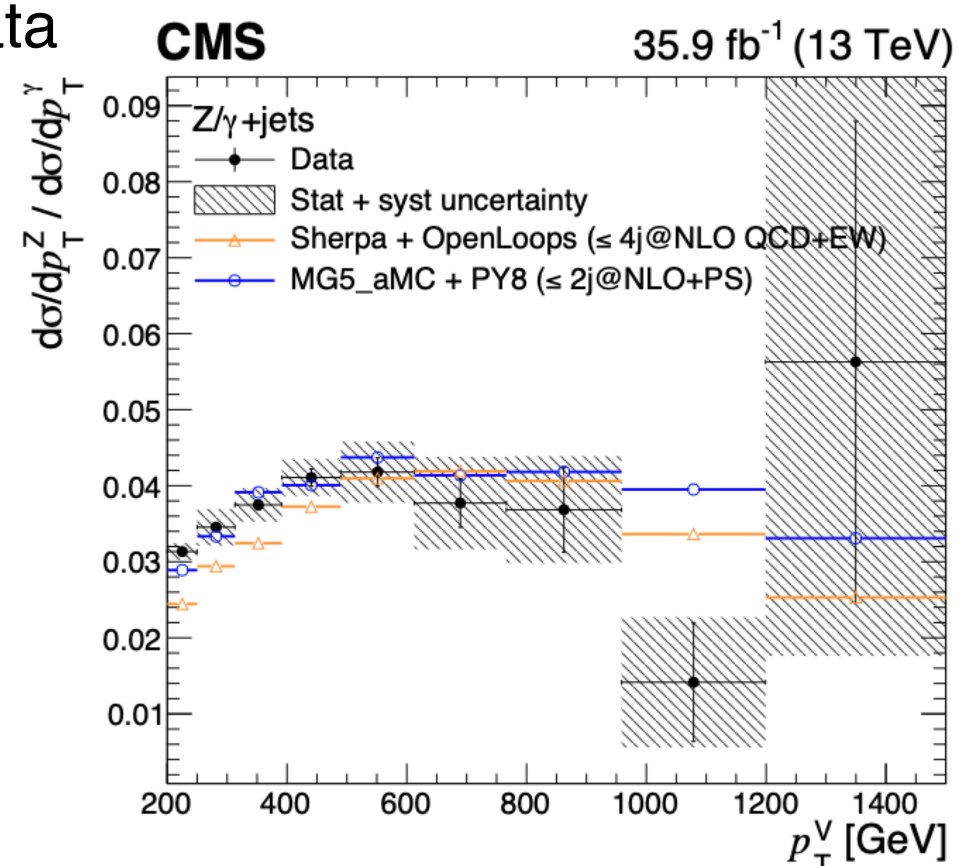
- First differential σ measurement of Z/γ+jets at 13 TeV, and direct measurement of Z emitted collinearly with a jet; $Z \to ll$ & γ at high p_T^V used to estimate $Z \to \nu\nu$ as bkg to searches

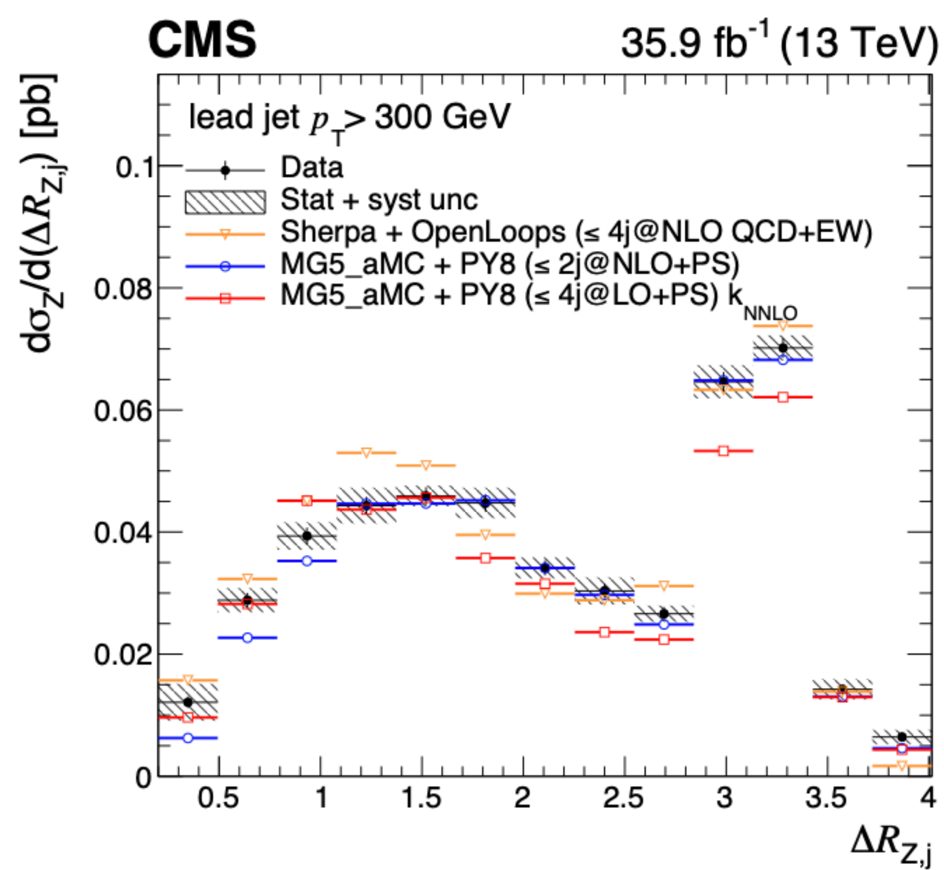
- Z/γ ratio can constrain higher order pQCD as it is sensitive to higher order EW corrections in the high p_T range

- Dominant syst. from μ $(1.7 - 22\%)$ and γ $(0.5 - 8.6\%)$ calibrations (for Z/γ analyses), and bkg estimate $(0.9 - 11\ \%$ for Z emission analysis)

- Unfolded Z/γ σ: NLO Madgraph5 agrees with data in full p_T range

- Unfolded σ_Z vs $\Delta R(Z, jet)$: Z-emission enhanced below 2.5. NLO Madgraph5 mostly agrees with data





Measurement of Z p_T

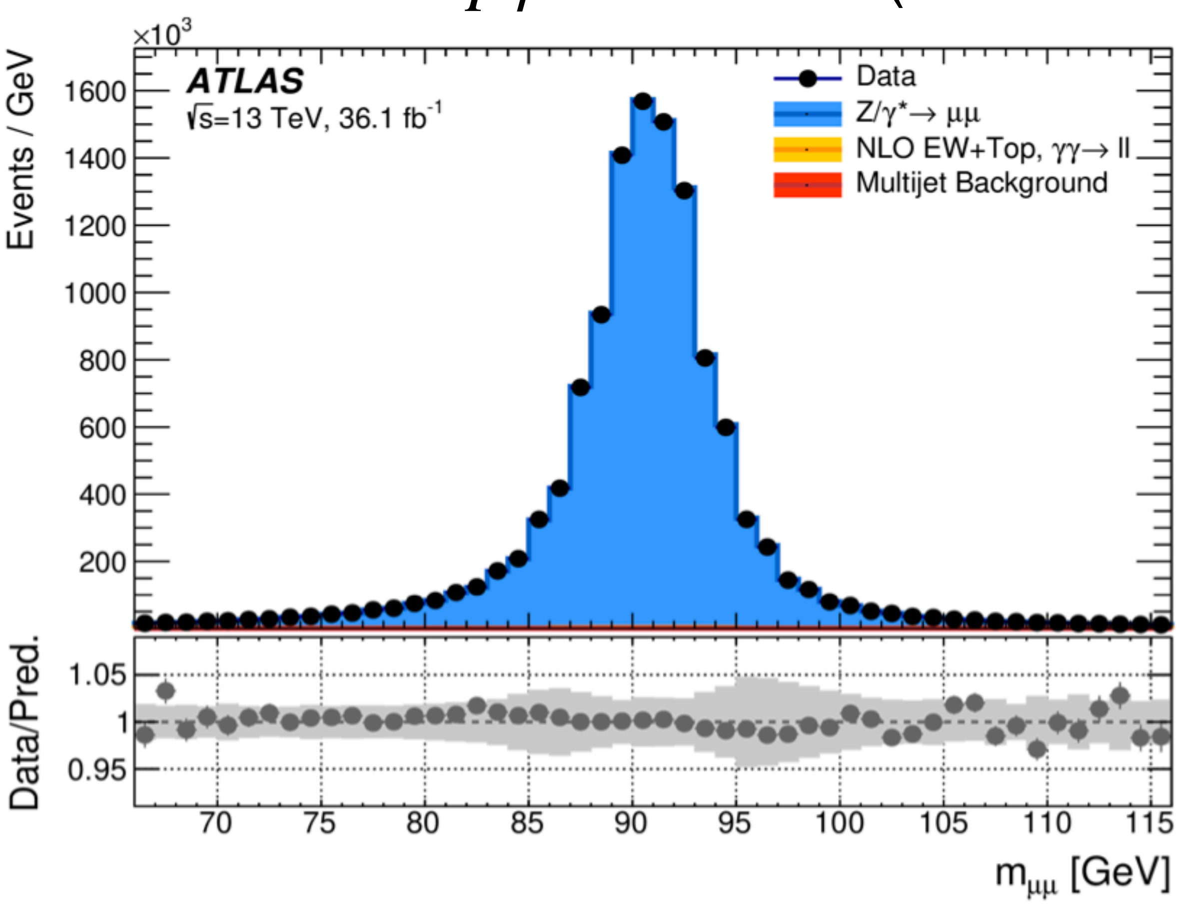
arXiv:1912.02844v2 [hep-ex]

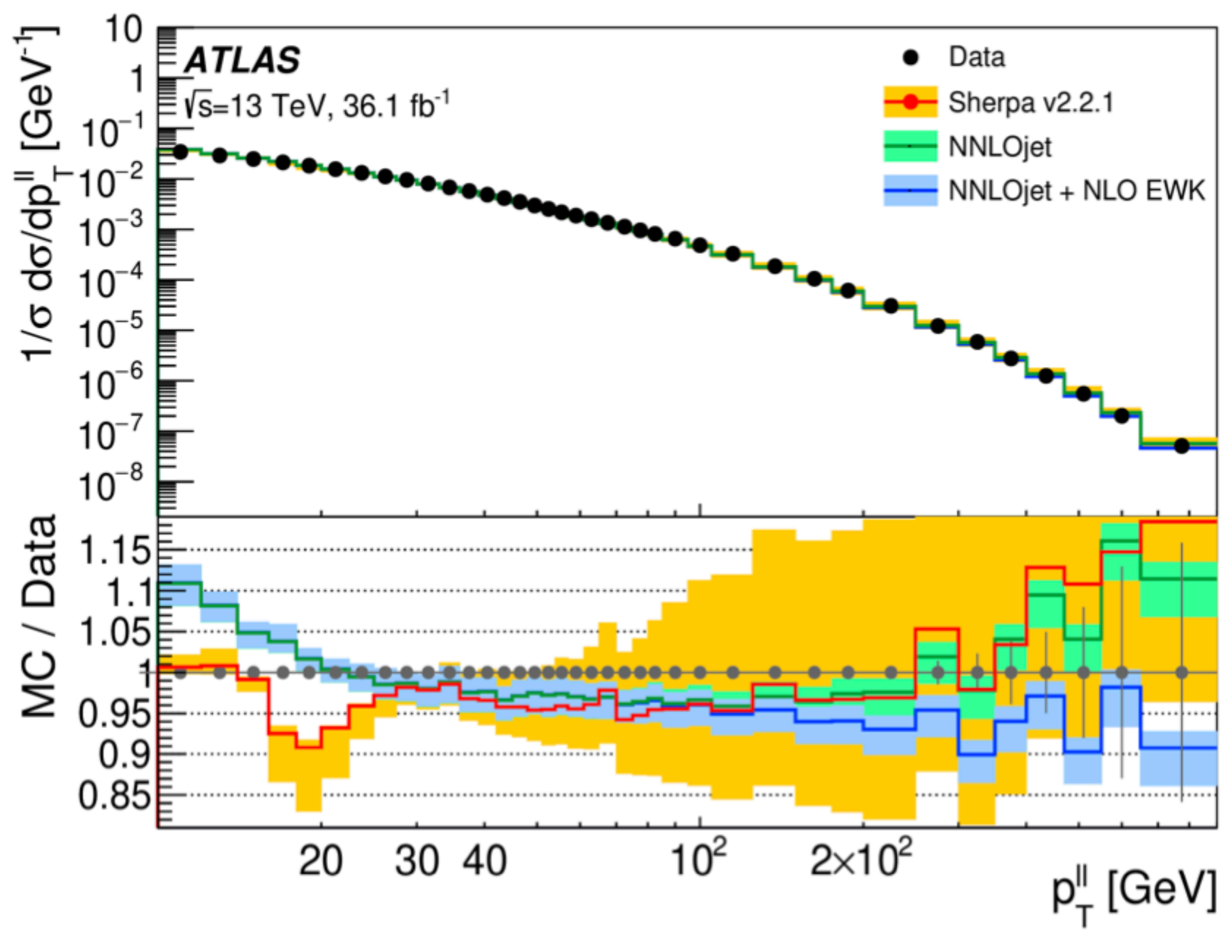
- Probe perturbative QCD at higher $\sqrt{s}$, with different composition of initial states; input to bkg predictions in searches (ex. monojet) and to SM precision measurements (m_W)

- Z inclusive measurement (e and μ channels combined) → very low background (mainly multijet)

- Uncertainty (mostly from lepton calibration) greatly reduced via normalized differential σ, down to 0.2% at low p_T^{ll}

- Impact of EW corrections: NNLOjet with or without NLO EW corrections agrees with unfolded σ from $p_T^{ll} > 20$ GeV (below: deviations due to large log)





Measurement of Z p_T

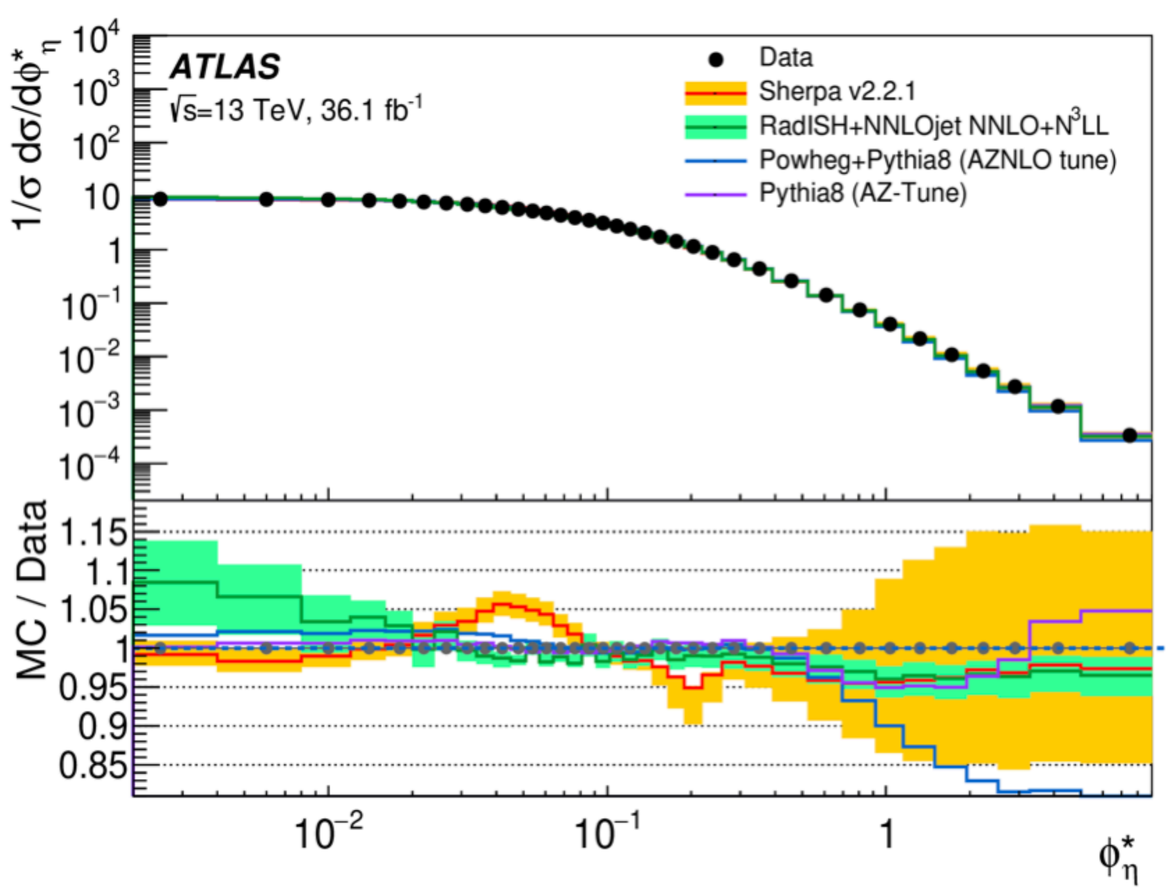
- Alternative observable ϕ^*_η since p_T resolution is limited at low p_T^{ll}

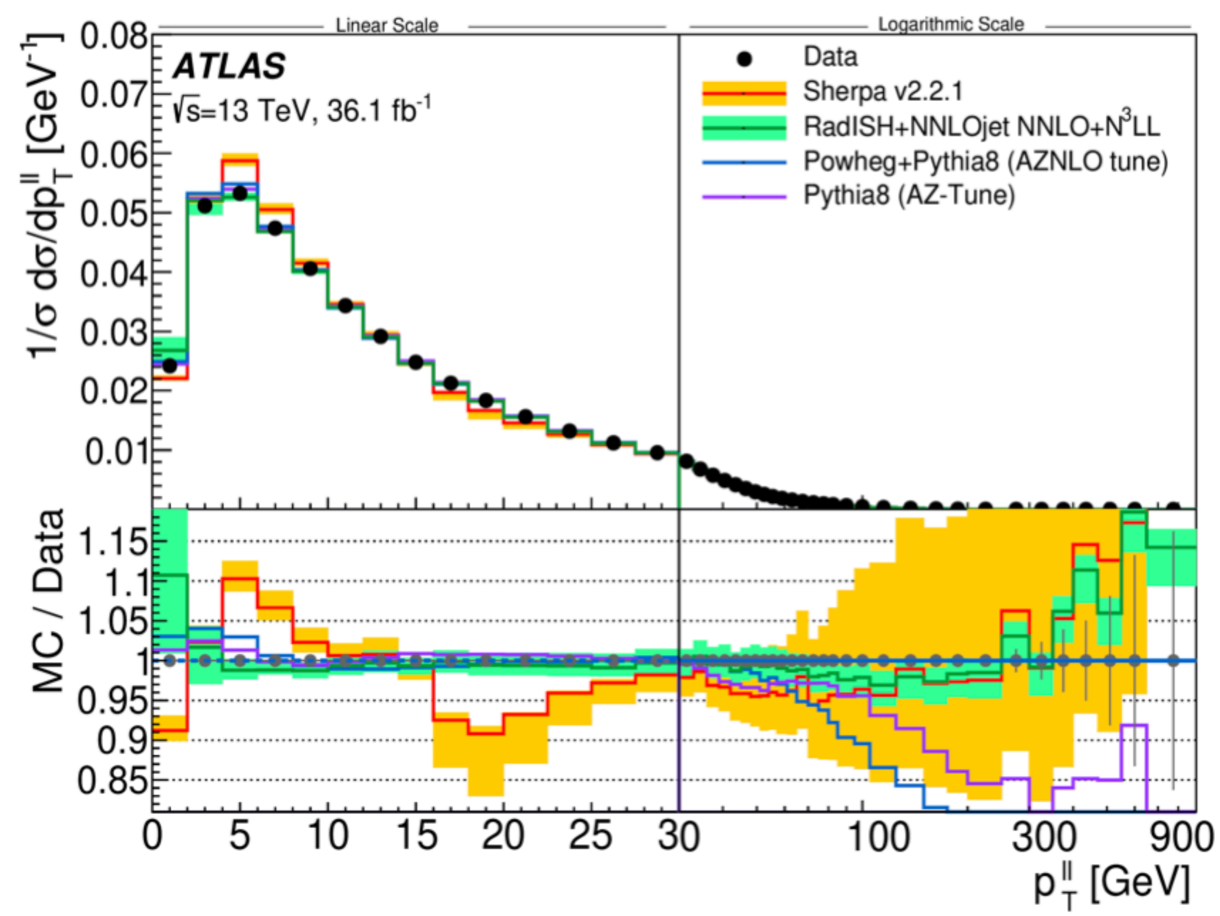
$$\phi^*_\eta = \tan\left(\frac{\pi - \Delta\phi}{2}\right) \times \sin(\theta^*_\eta)$$

- Impact of Parton Shower tunes: **1)** AZ and AZNLO tunes based on 7 TeV data agree within few % at 13 TeV for $p_T^{ll} < 40$ GeV and $\phi^*_\eta < 0.5$. **2)** Low p_T^{ll} (< 25 GeV), Sherpa disagrees, data may be useful in improving PS settings in this regime

- Impact of Matrix Element order: High-p_T^{ll}/ϕ^*_η: Powheg (NLO)and Pythia (LO) miss higher-order ME, while Sherpa with NLO up to 2 partons and LO up to 4 agrees better (worse at low values).

- Impact of resummation: Radish NNLO fixed-order + N³LL resummation agrees best over full spectrum



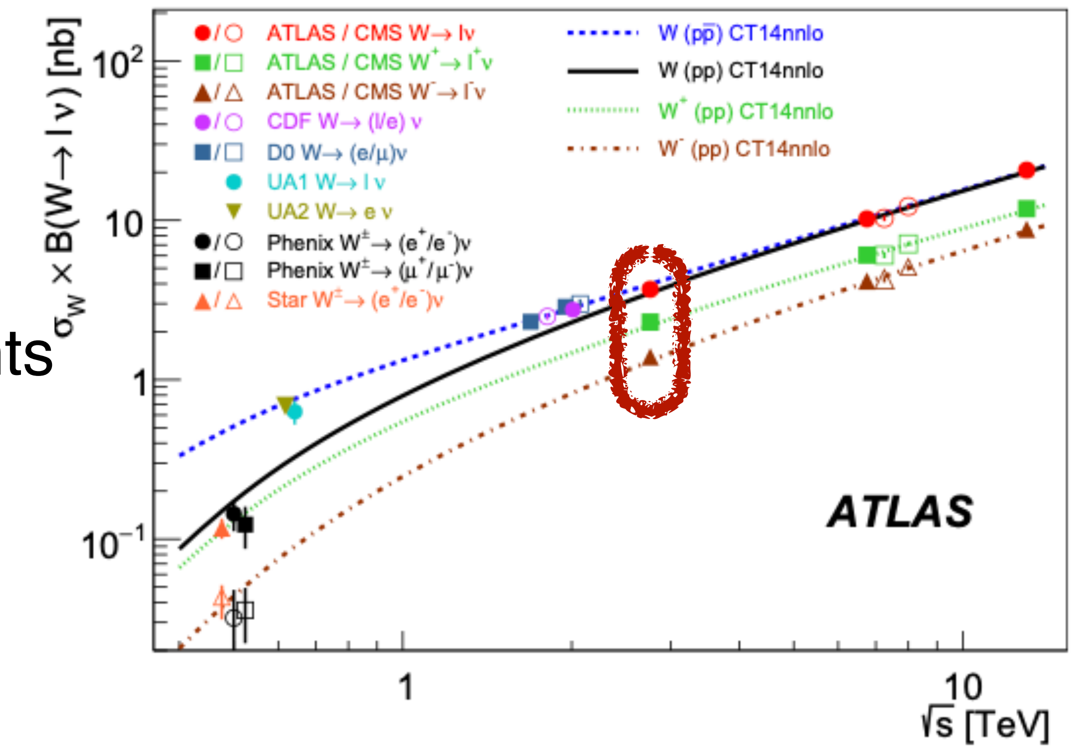


W and Z boson production cross section at low μ

- W/Z production study via Drell Yan

Eur. Phys. J. C 79 (2019) 901

- At lowest order in QCD, production happens as $q\bar{q}^{(\prime)} \rightarrow W/Z$, so precision measurement of these production σ ⟶ better understanding of PDF



- low μ studies also help m_W and $sin^2\theta_W$ measurements

- $\sqrt{s}$ = 2.76 TeV <μ> =0.3, L = 4.0 pb^{-1}

$$\sigma^{\text{tot}}_{W^+\to\ell\nu} = 2312 \pm 26\ (\text{stat.}) \pm 27\ (\text{syst.}) \pm 72\ (\text{lumi.}) \pm 30\ (\text{extr.})\ \text{pb},$$

$$\sigma^{\text{tot}}_{W^-\to\ell\nu} = 1399 \pm 21\ (\text{stat.}) \pm 17\ (\text{syst.}) \pm 43\ (\text{lumi.}) \pm 21\ (\text{extr.})\ \text{pb},$$

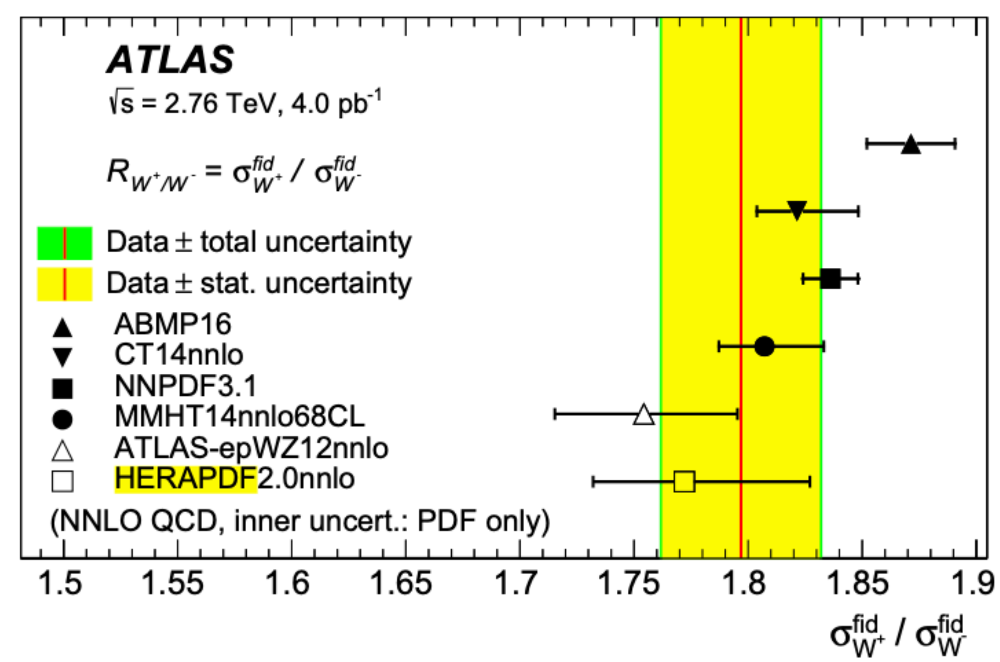
$$\sigma^{\text{tot}}_{Z\to\ell\ell} = 323.4 \pm 9.8\ (\text{stat.}) \pm 5.0\ (\text{syst.}) \pm 10.0\ (\text{lumi.}) \pm 5.5 (\text{extr.})\ \text{pb}.$$

Constrains strange quark distribution

$$R_{W/Z} = 10.95 \pm 0.35\ (\text{stat.}) \pm 0.10\ (\text{syst.});$$

$$R_{W^+/W^-} = 1.797 \pm 0.034\ (\text{stat.}) \pm 0.009\ (\text{syst.}).$$

Constrains valence quark distributions



- Different PDF predictions in good agreement with measurements. Slight tension (less than 2σ) between the data and the prediction using the ABMP16

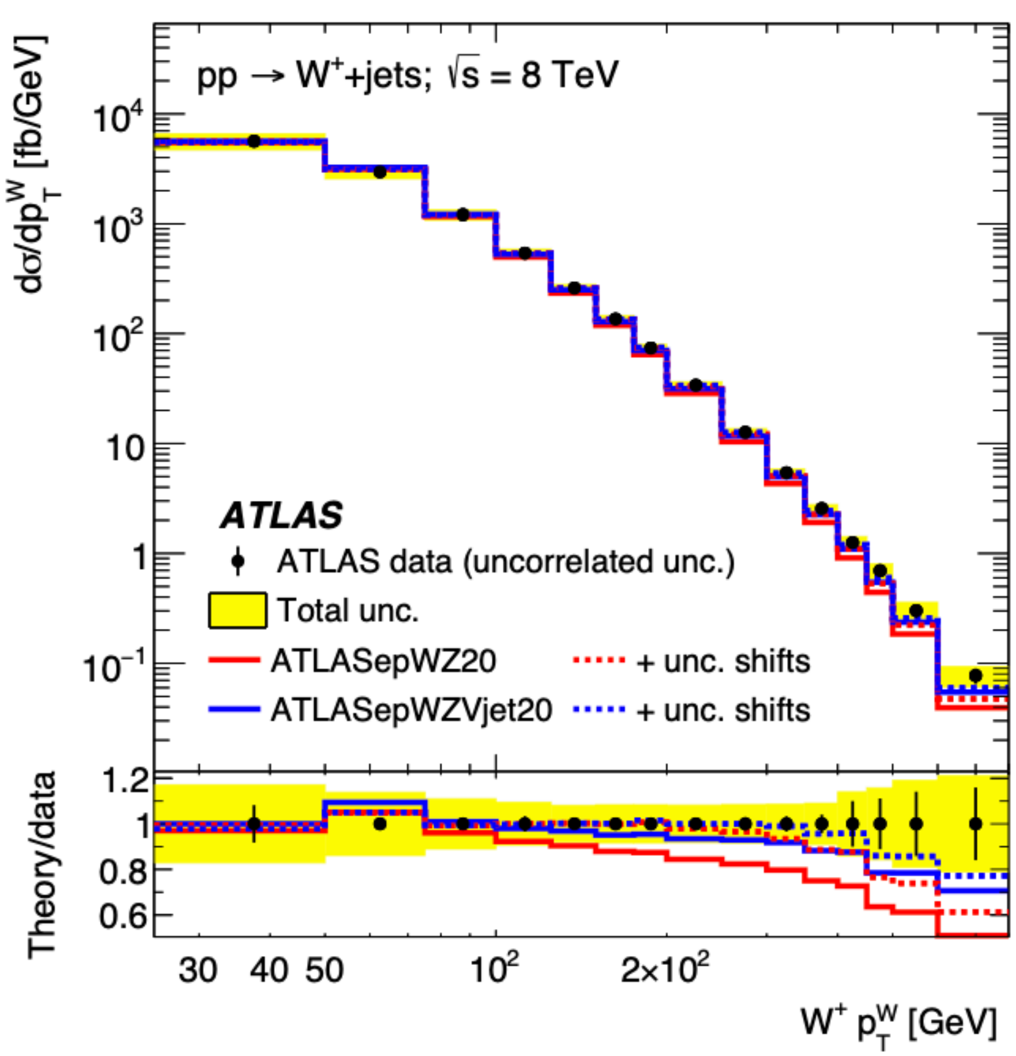
- In terms of charge asymmetry:

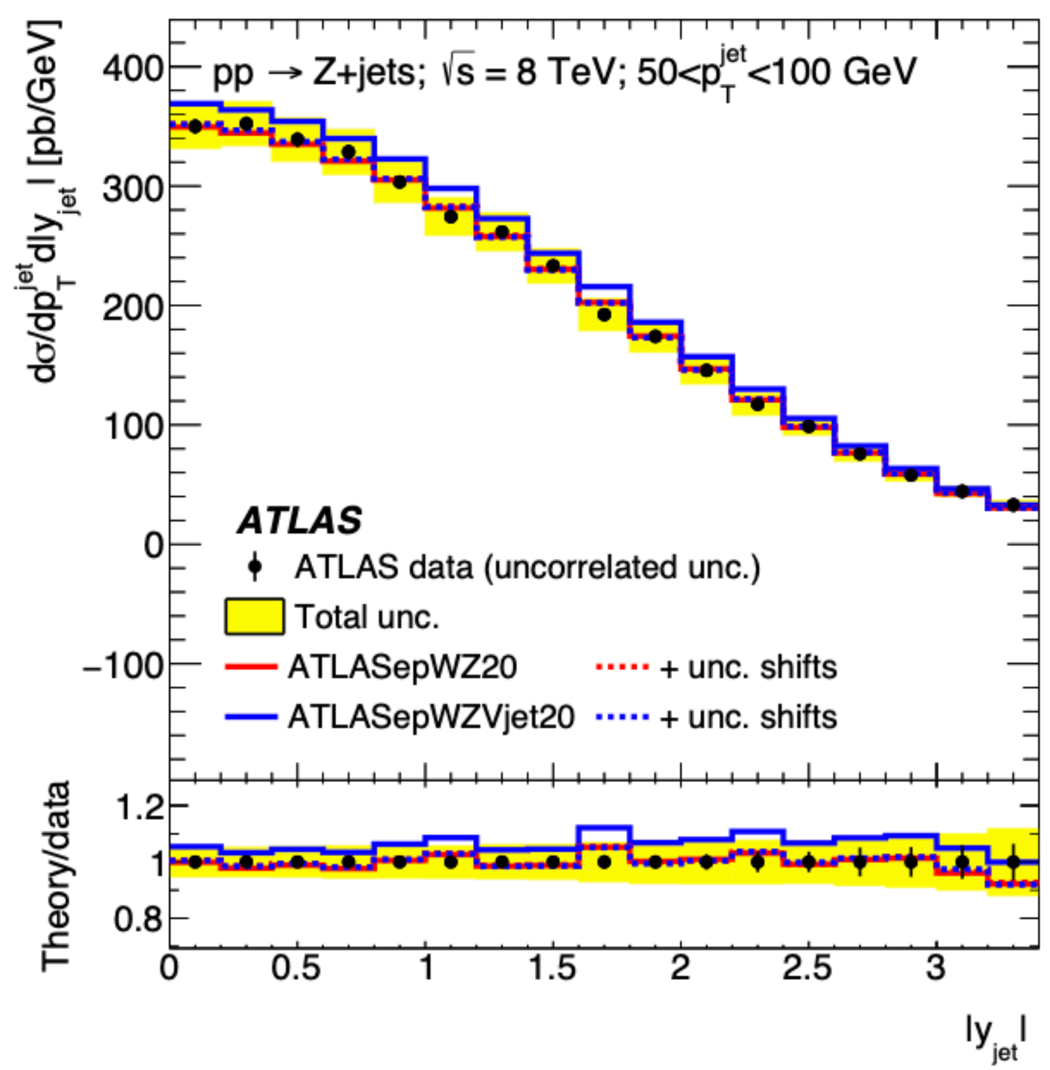
$$A_\ell = \frac{\sigma^{\text{fid}}_{W+} - \sigma^{\text{fid}}_{W-}}{\sigma^{\text{fid}}_{W+} + \sigma^{\text{fid}}_{W-}} = 0.285 \pm 0.009 (\text{stat.}) \pm 0.002 (\text{syst.}).$$

Determination of PDF from V+jets measurements

arXiv: 2101.05095 [hep-ex]

- Carried out a QCD analysis at NNLO (ATLASepWZVjet20)
- Using W/Z(+jets) at 8 TeV as well as W/Z measurements at 7 TeV
- Compared to previous fit, ATLASepWZ20 w/o W/Z+jets
- Both fits include previous HERA data
- Improved description of W p_T with better PDF uncertainties w.r.t previous fit





Determination of PDF from V+jets measurements

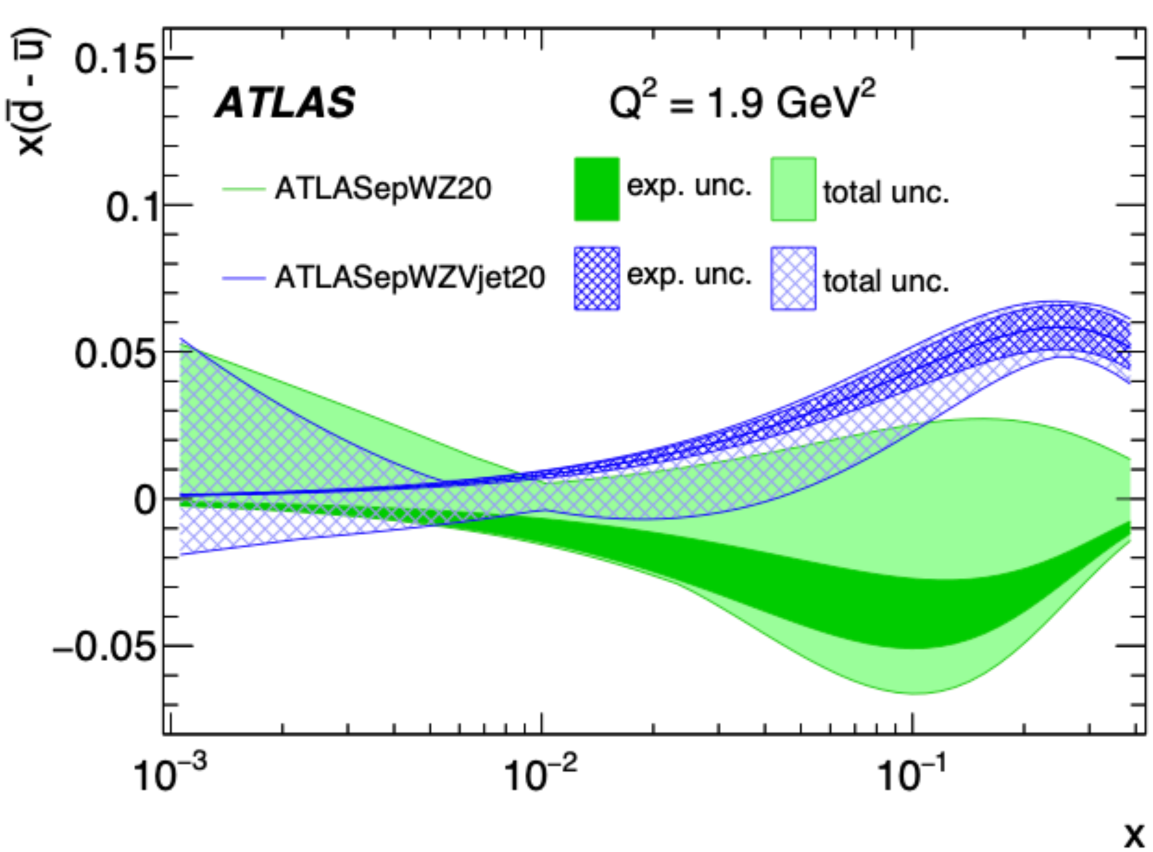
- Improvement of PDF mainly for $\bar{d} - \bar{u}$. Consistent with global fits up to x ~ 0.1, above this x the V+jets is most sensitive and shows different behavior

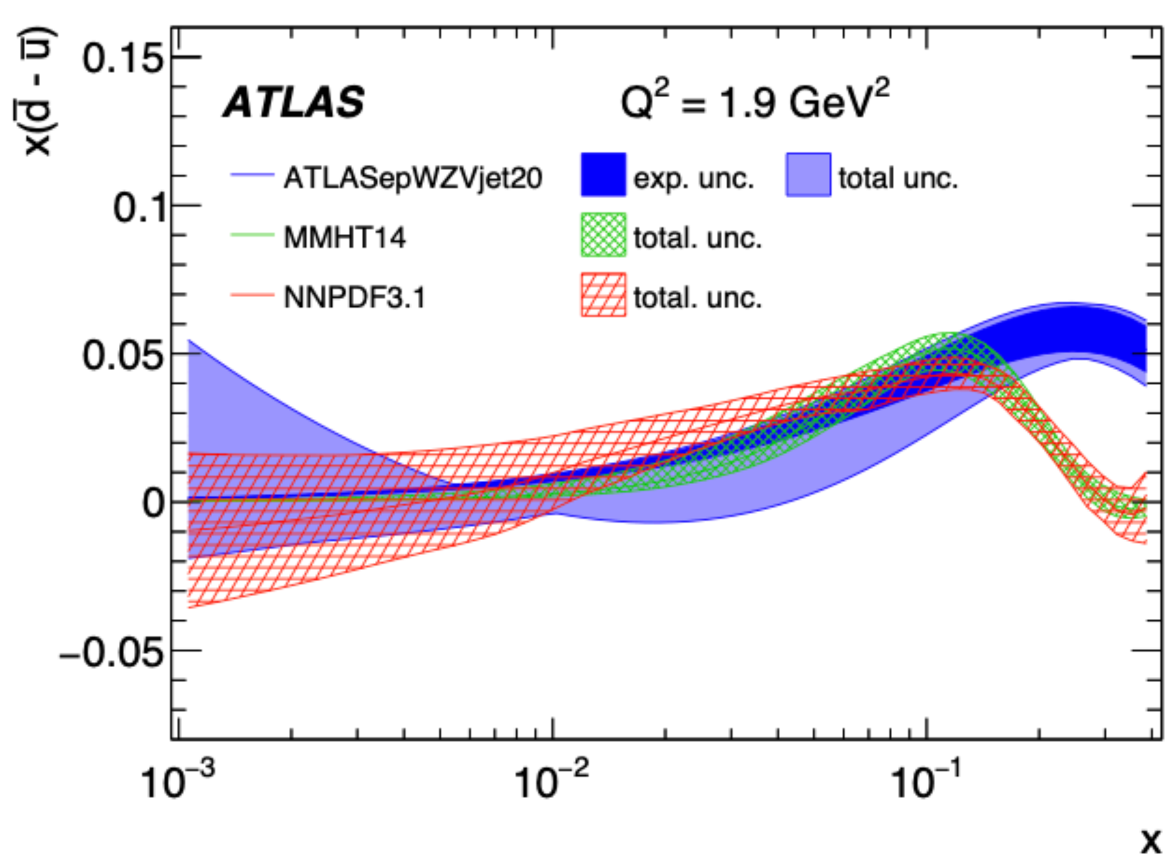
- More precise estimate for strange supression factor ($R_s = \frac{s + \bar{s}}{\bar{d} + \bar{u}}$), especially for x > 0.03

- It is better constrained and falls more steeply at high x

- At low x confirmed unsuppressed strange PDF as observed in previous ATLAS fit.

- ATLAS fits still find a large R_s than global fits, but V+jets data bring them closer to each other





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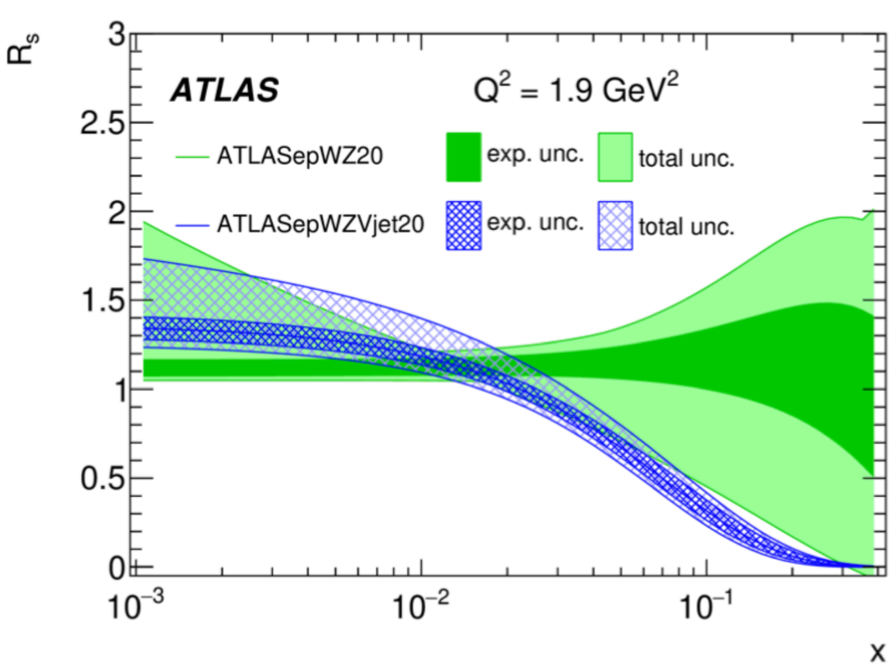

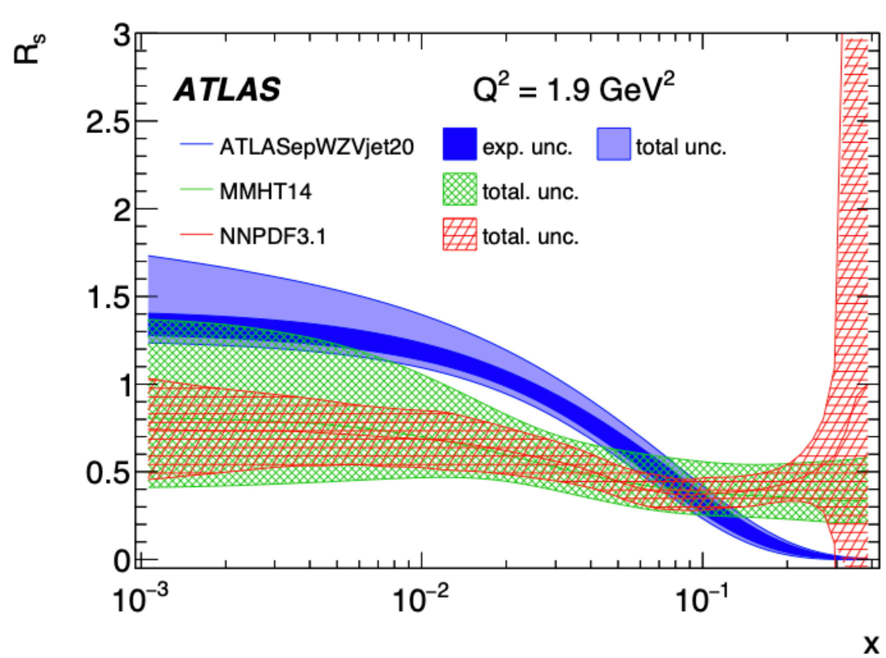

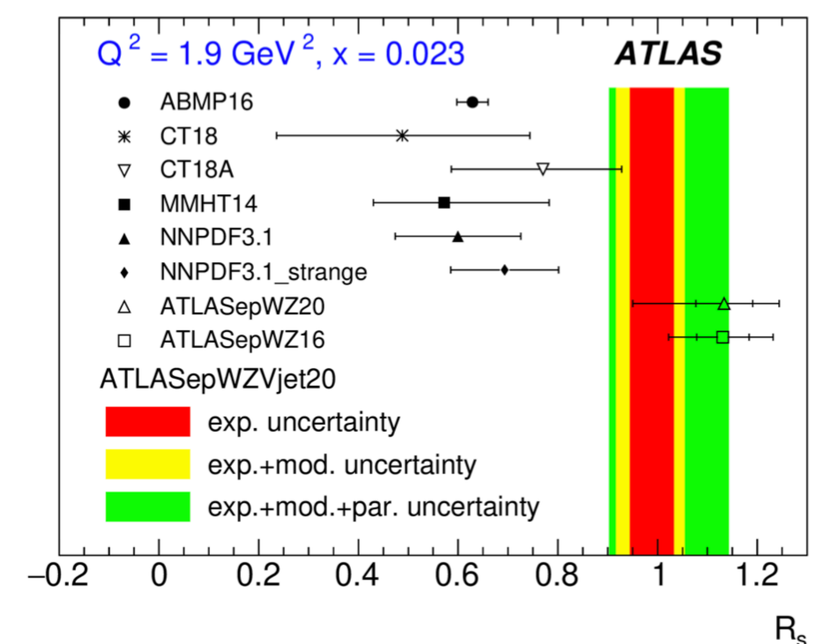

Top quark

Top quark pair cross section

- Absolute and normalized $\sigma(t\bar{t})$ at particle level compared to NLO MC or NNLO predictions for many different variables (top, $t\bar{t}$, jet-related)

- Mismodeling in N_{jets}, p_T and $p_T(t\bar{t})$

- Significant over-prediction of $\sigma(t\bar{t})$ at high p_T observed in CMS analysis targeting the boosted regime

- Consistent with observation of CMS boosted jet mass analysis

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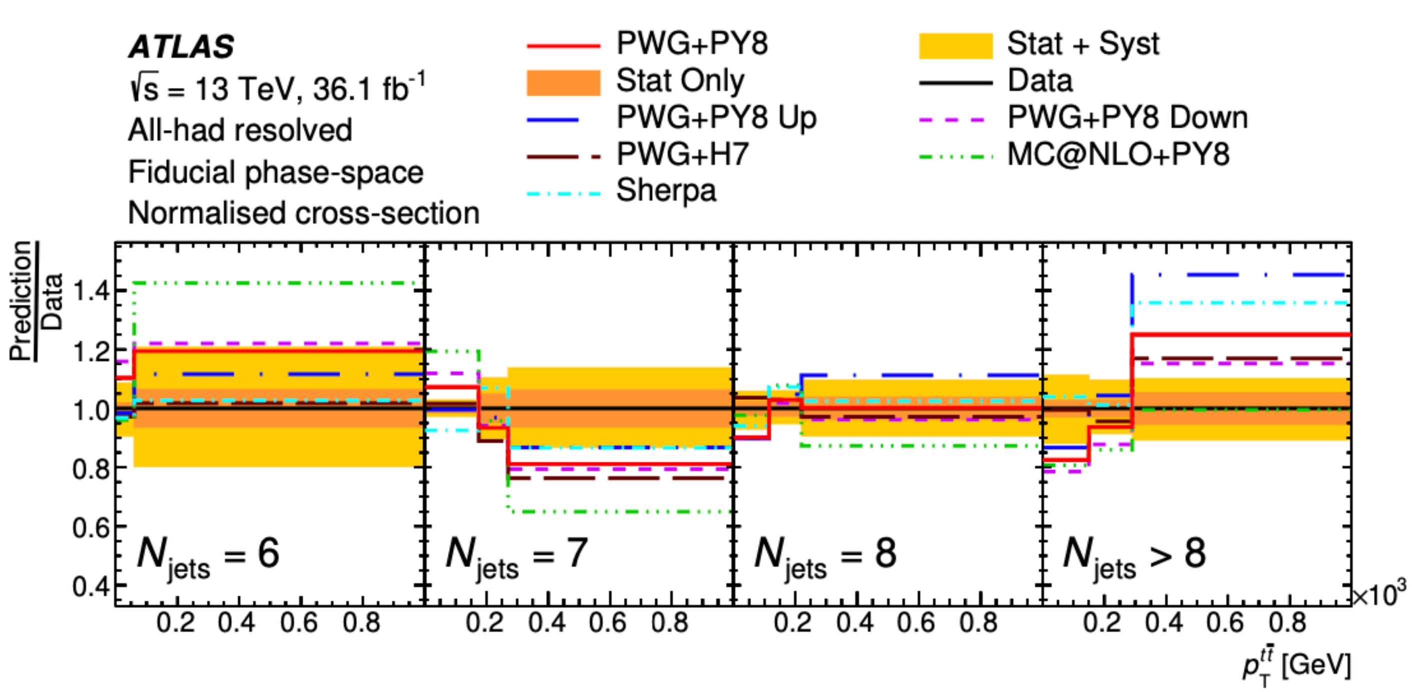

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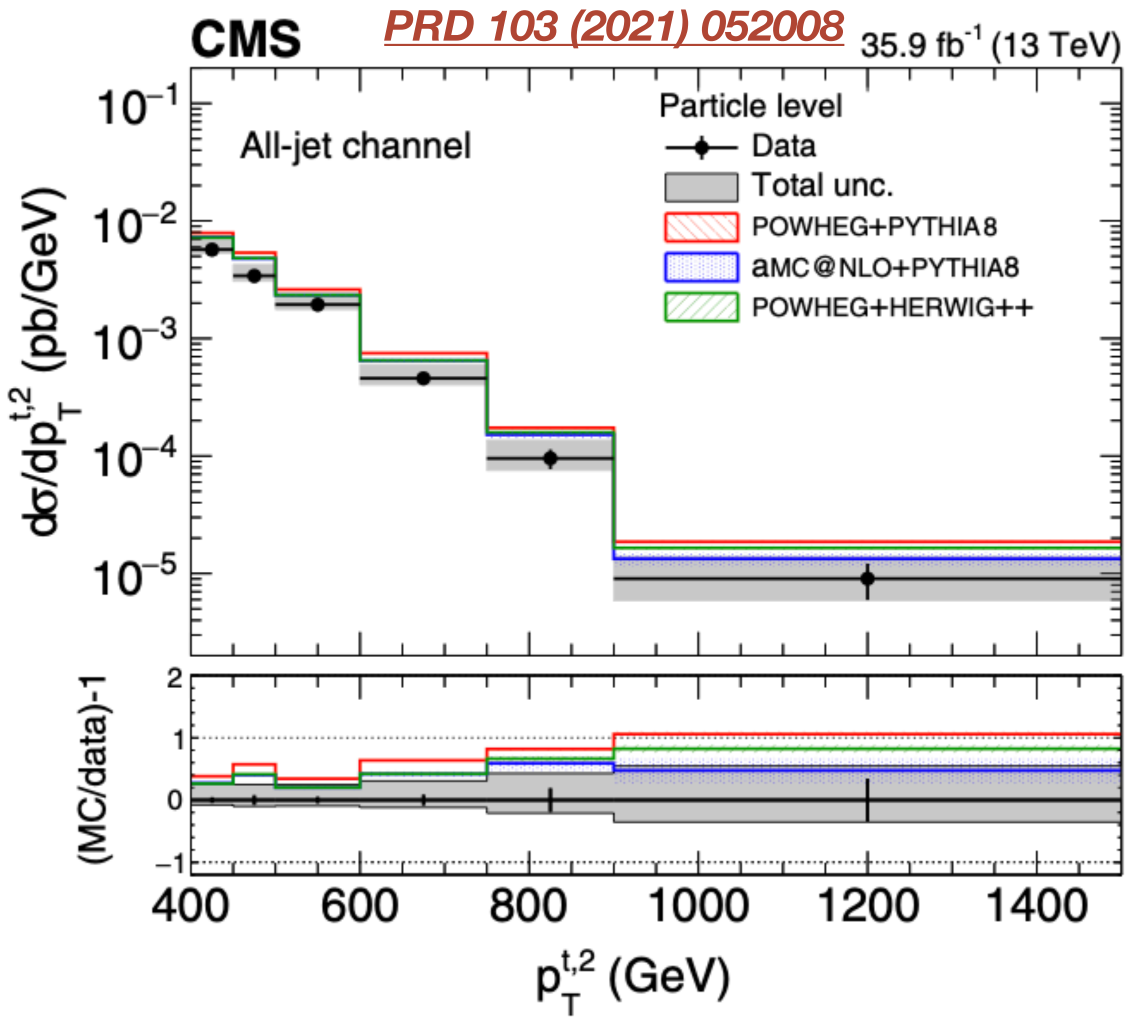

Inclusive/differential σ(tt) at 13 TeV and m_t^{pole}

- $\sigma(t\bar{t})$ measured in eμ channel used to extract m_t^{pole} using NNLO+NNLL predictions

- Most precise $\sigma(t\bar{t})$ at 13 TeV (2.4%) $\longrightarrow m_t^{pole} = 173.1 \pm 2.1$ GeV

- m_t^{pole} precision limited by uncertainties on $t\bar{t}$ modeling dominated by PDFs and QCD scale

- Simultaneous measurement of m_t^{pole}, α_S and PDFs from triple-differential cross section

- Most precise determination of m_t^{pole}: $m_t^{pole} = 170.5 \pm 0.8$ GeV (dominated by scale uncertainties, 0.3 GeV)

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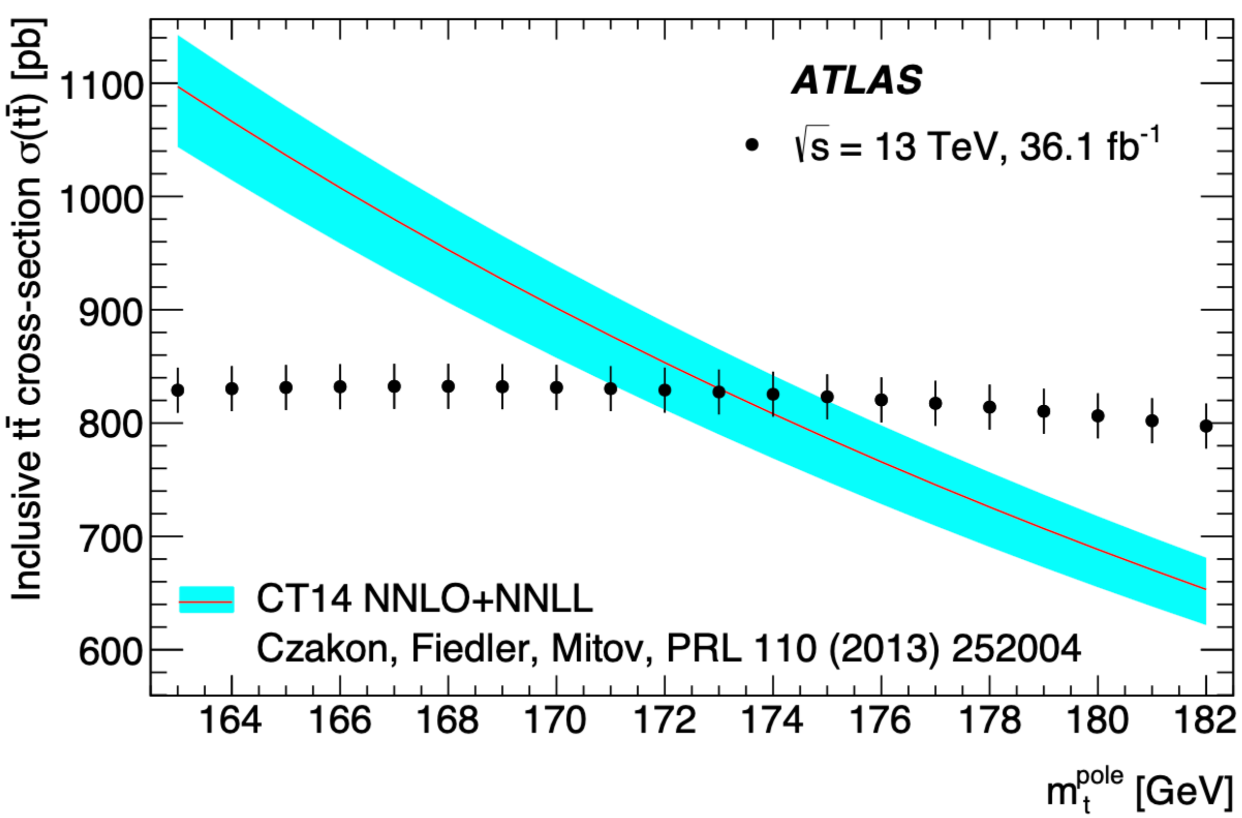

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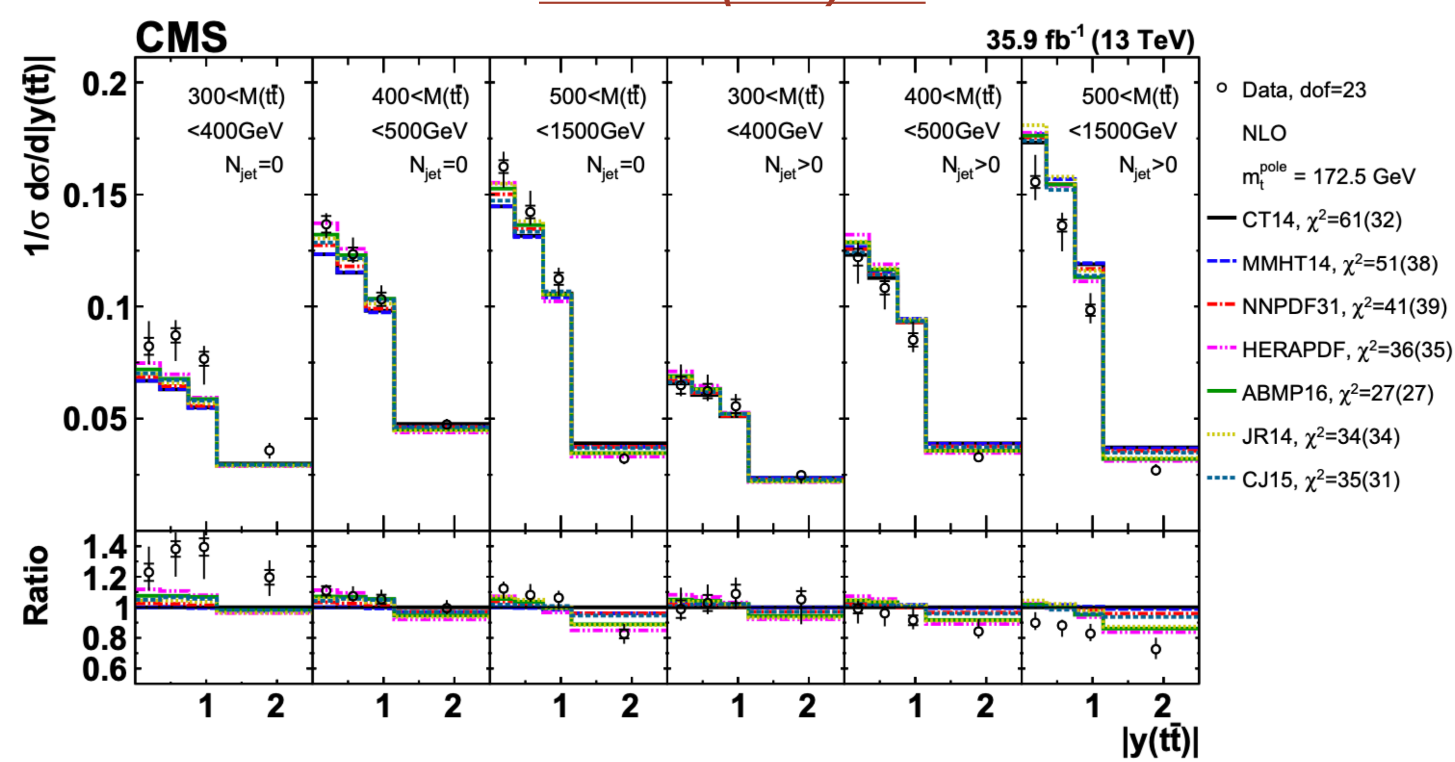


Higgs boson

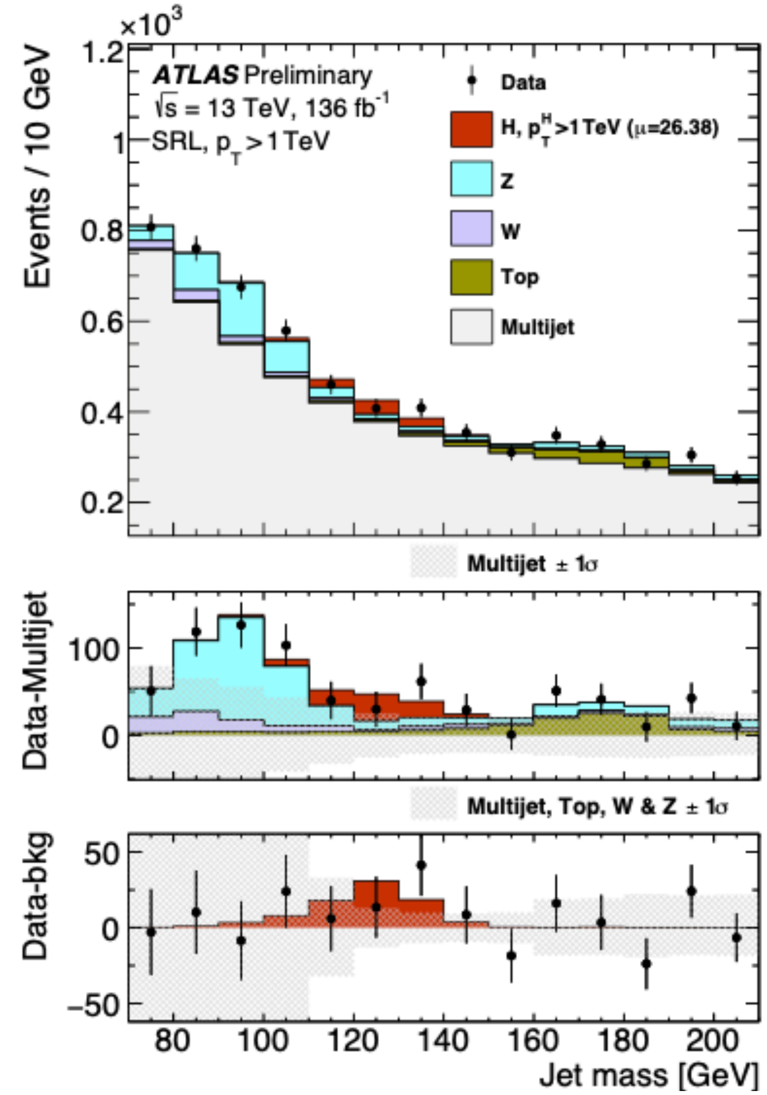
Inclusive search for highly boosted $H \to b\bar{b}$

- Higgs reconstructed as single large-radius jet; leading or subleading p_T jets with two b-tagged track-jets (ATLAS), leading p_T jet passing deep double-b tagger (CMS)

- Dominant background: multijet events modeled by analytic function (ATLAS) or data-driven approach (CMS)

- Fiducial measurements **statistically dominated**

- First look at $p_T^H > 1$ TeV phase space. Results in agreement with SM



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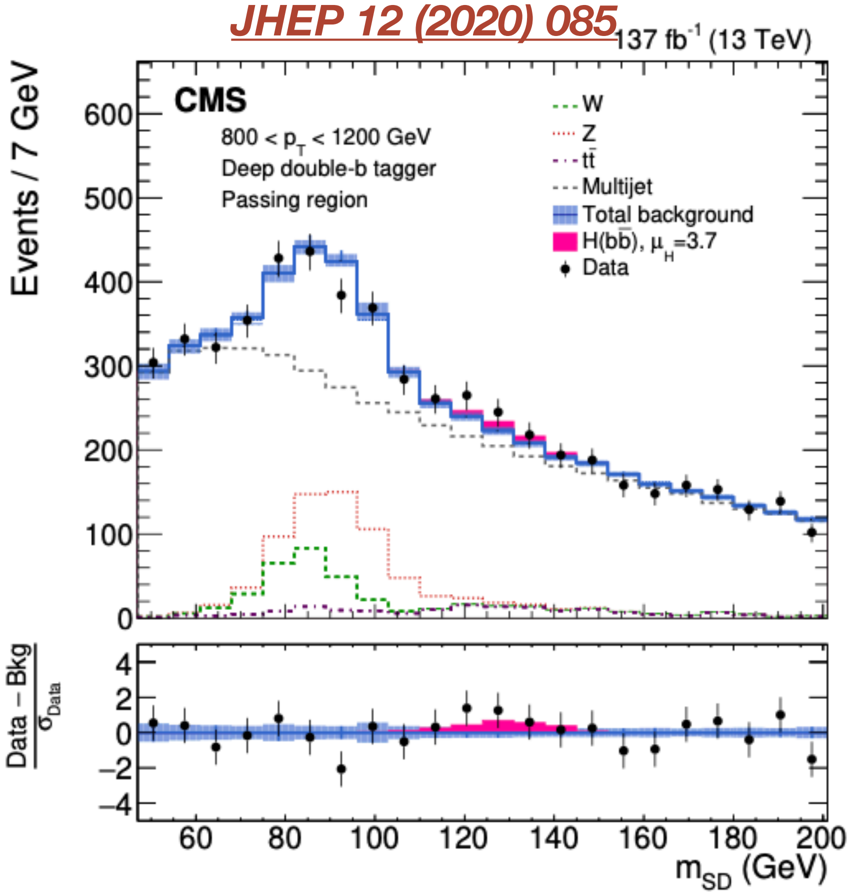
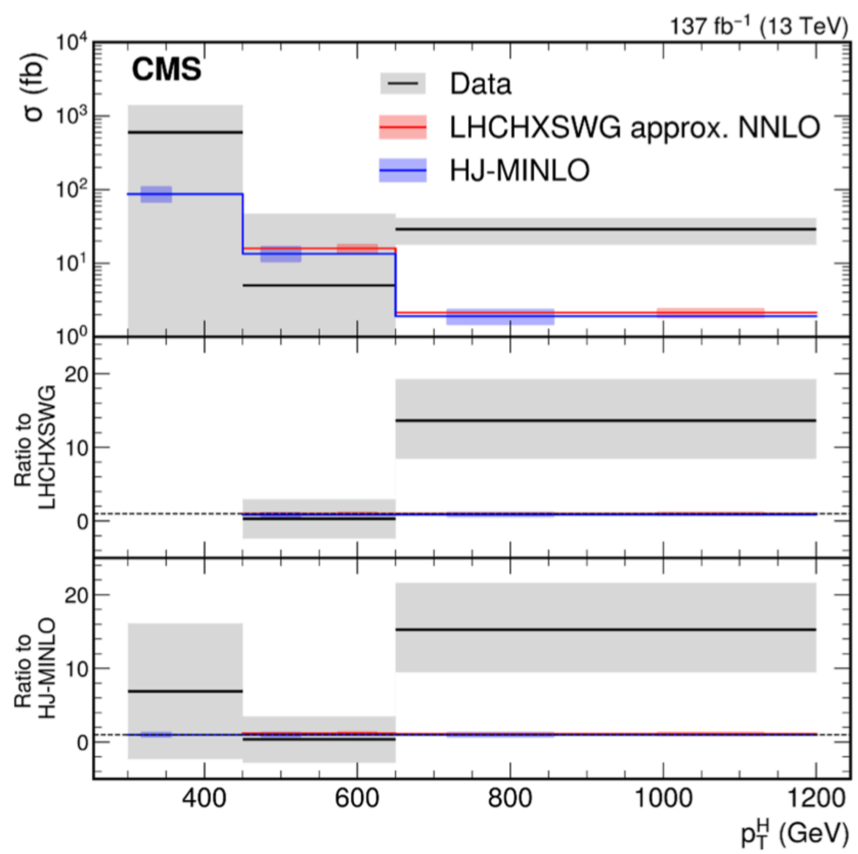
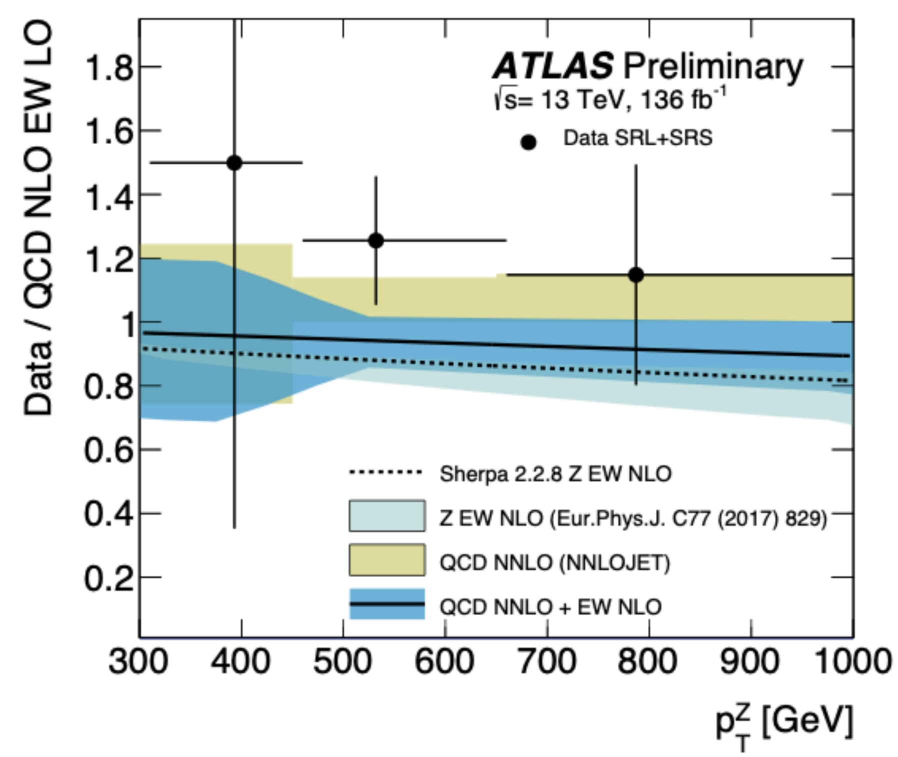






VH modeling uncertainties, VH(bb) case

- Measurements in both resolved and boosted regime

VH (resolved) : bb pair reconstructed as two separate jets — [Eur. Phys. J. C 81 (2021) 178]

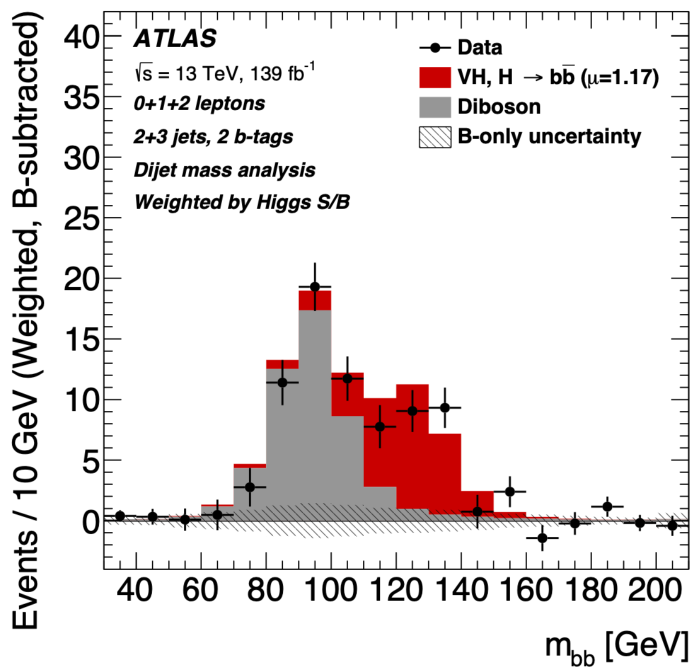
Single STXS bin for $p_T^V > 250$ GeV

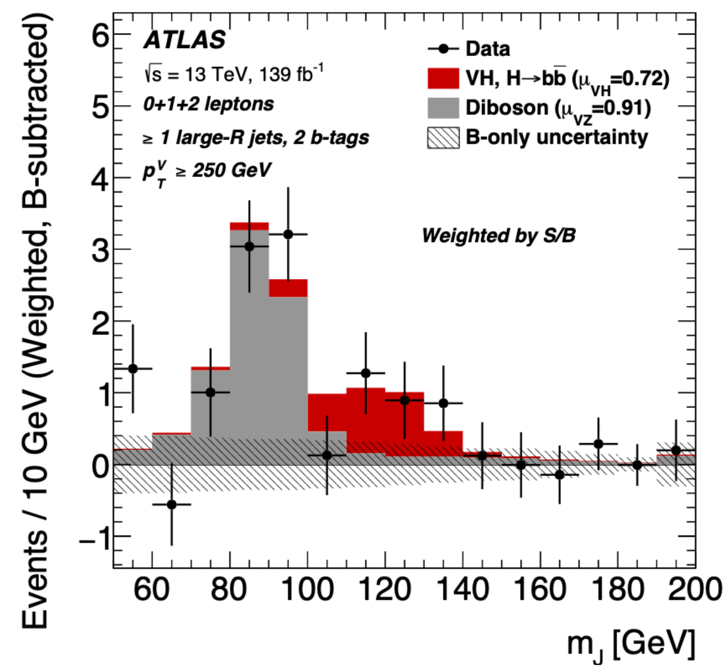
Stat. limited at high p_T^V

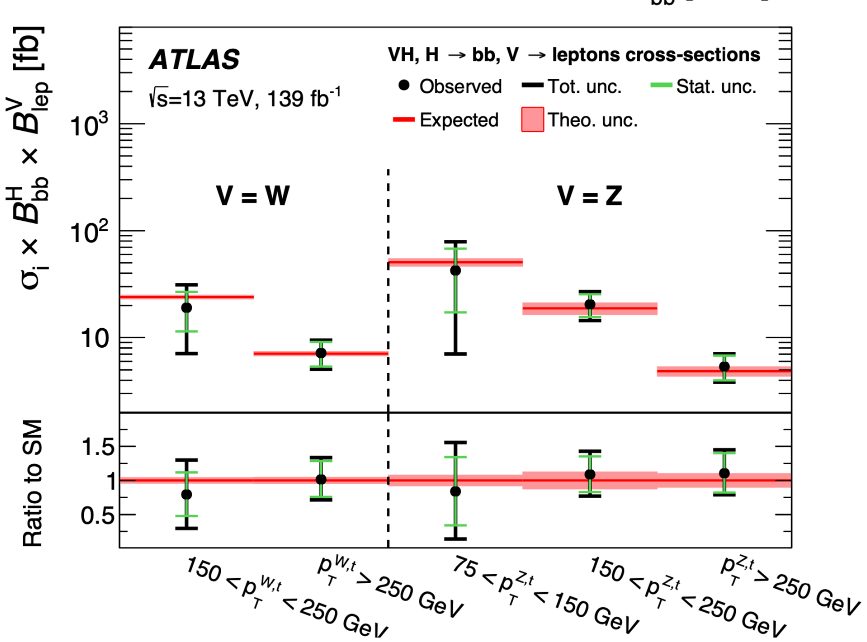
VH (boosted): bb pair reconstructed as a single large-radius jet — [Phys. Lett. B 816 (2021) 136204]

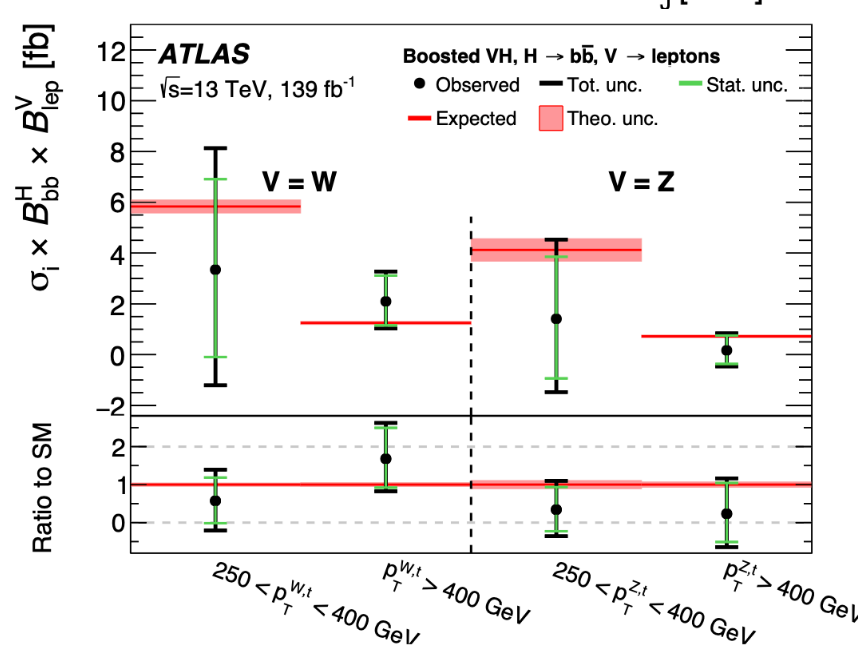
Allows probing phase space $p_T^V > 400$ GeV

Dominated by statistical uncertainty









With present dataset, in high p_T bins:

σ(theory) < σ(stat)

but

σ(theory) ~σ(exp.)

VH modeling uncertainties, VH(bb) case

- With present dataset, in high p_T bins: **σ(theory) < σ(stat)** but **~σ(exp.)**

- For resolved regime, systematic uncertainties affecting the signal modeling:

  ggZH: Large scale uncertainties, this accounts for ~10% of inclusive ZH cross section

  No full NLO calculation available for the foreseeable future

  qqZH: dominated by differences between Pythia and Herwig.

  p_T^V reweighing for EW corrections @ NLO

- For boosted regime, background modeling is most dominant systematic uncertainty (V+hf)

STXS region Process	$p_T^{V,t}$ interval	SM prediction [fb]	Result [fb]	Stat. unc. [fb]	Syst. unc. [fb] Th. sig.	Th. bkg.	Exp.
$W(\ell\nu)H$	150–250 GeV	24.0 ± 1.1	19.0 ± 12.1	± 7.7	± 0.9	± 5.5	± 6.0
$W(\ell\nu)H$	> 250 GeV	7.1 ± 0.3	7.2 ± 2.2	± 1.9	± 0.4	± 0.8	± 0.7
$Z(\ell\ell/\nu\nu)H$	75–150 GeV	50.6 ± 4.1	42.5 ± 35.9	± 25.3	± 5.6	± 17.2	± 19.7
$Z(\ell\ell/\nu\nu)H$	150–250 GeV	18.8 ± 2.4	20.5 ± 6.2	± 5.0	± 2.3	± 2.4	± 2.3
$Z(\ell\ell/\nu\nu)H$	>250 GeV	4.9 ± 0.5	5.4 ± 1.7	± 1.5	± 0.5	± 0.5	± 0.3

Signal	
Cross-section (scale)	0.7% (qq), 25% (gg)
$H \to b\bar{b}$ branching fraction	1.7%
Scale variations in STXS bins	3.0%–3.9% ($qq \to WH$), 6.7%–12% ($qq \to ZH$), 37%–100% ($gg \to ZH$)
PS/UE variations in STXS bins	1%–5% for $qq \to VH$, 5%–20% for $gg \to ZH$
PDF+α_S variations in STXS bins	1.8%–2.2% ($qq \to WH$), 1.4%–1.7% ($qq \to ZH$), 2.9%–3.3% ($gg \to ZH$)

ttH modeling uncertainties, ttW case

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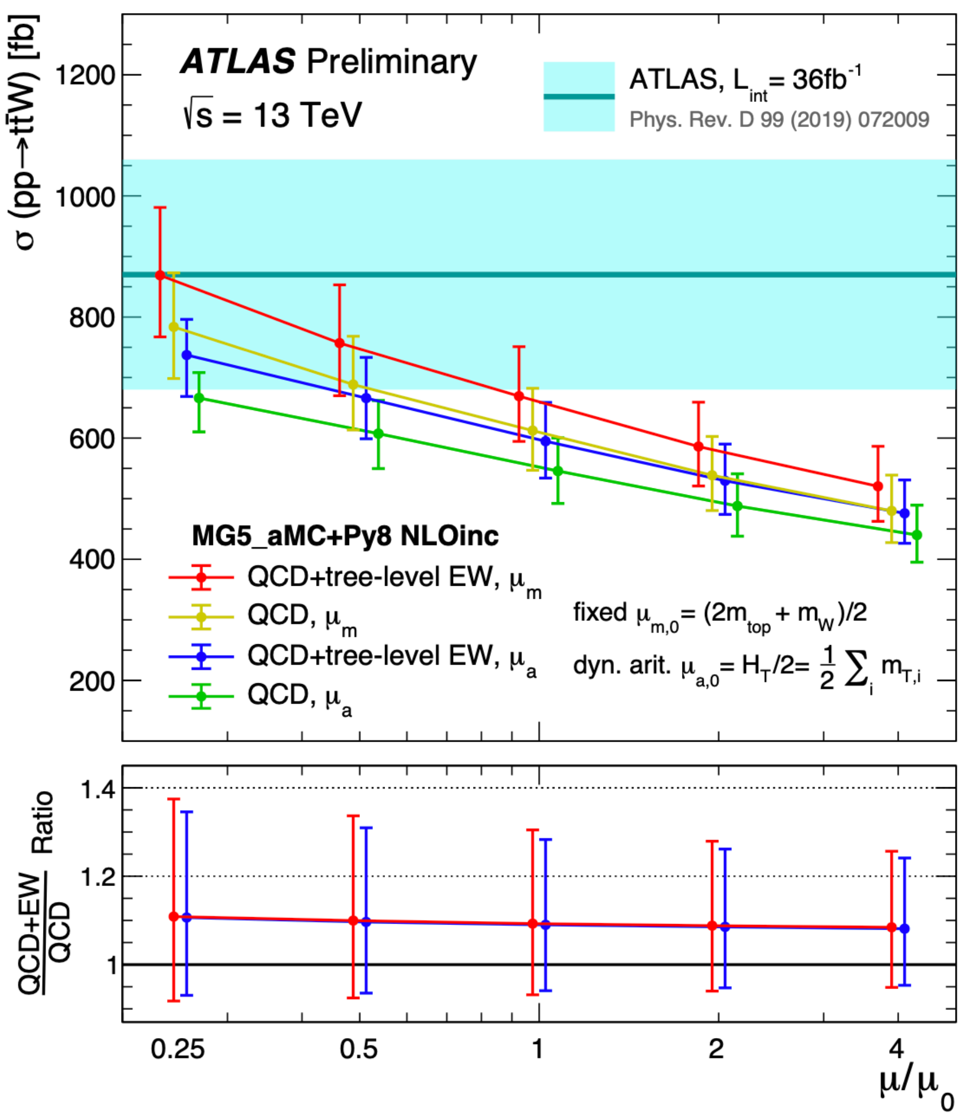
- Several LHC measurements of ttW production rates give values > SM predictions

- From the theoretical point of view, ttW is challenging:
  High order effects are important for ttW production, both in QCD and EW sectors

$$\sigma^{NLO}_{QCD+EW} = \sigma^{NLO}_{QCD} + \delta\sigma_{EW}$$

$$\sigma^{NLO}_{QCD} = \underbrace{\mathcal{O}(\alpha_S^2\alpha)}_{\text{LO QCD}} + \underbrace{\mathcal{O}(\alpha_S^3\alpha)}_{\text{NLO QCD}}$$

$$\delta\sigma_{EW} = \underbrace{\mathcal{O}(\alpha_S^2\alpha^2)}_{\text{NLO EW}} + \underbrace{\mathcal{O}(\alpha^3) + \mathcal{O}(\alpha_S\alpha^3)}_{\text{tree-level EW}} + \underbrace{\mathcal{O}(\alpha^4)}_{\text{negligible}}$$



- Strong dependence on scale choice

- Higher values for fixed scale

- Moving to a lower scale than nominal, increase ~40%

- 10% increase whole range compared to QCD only

- Low scale compatible with latest ATLAS measurement

Conclusion

- A review of different analyses has been presented

- Understanding high p_T QCD is important to SM analyses and for NP searches

- Benefit from theory from different sides

- A lot of work still needs to be done for MC tunings to model higher orders

Backup

W and Z boson production cross section at low μ

- W/Z production study via Drell Yan

- At lowest order in QCD, production happens as $q\bar{q}^{(\prime)} \rightarrow W/Z$, so precision measurement of these production σ ⟶ better understanding of PDF

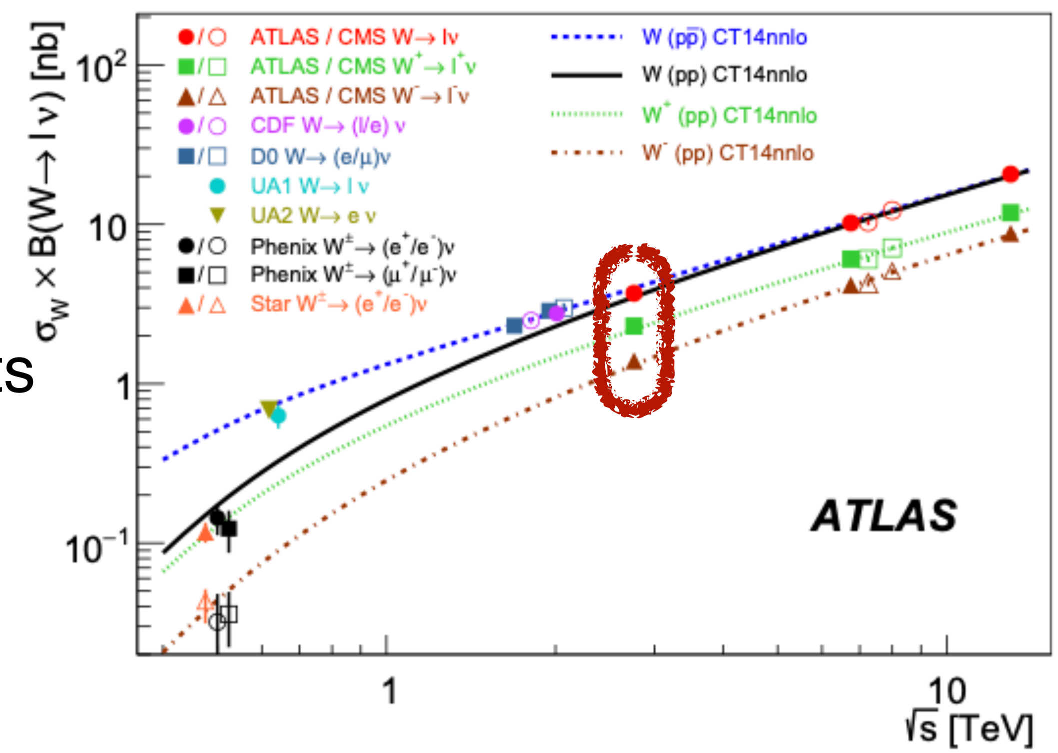
- low μ studies also help m_W and $sin^2\theta_W$ measurements

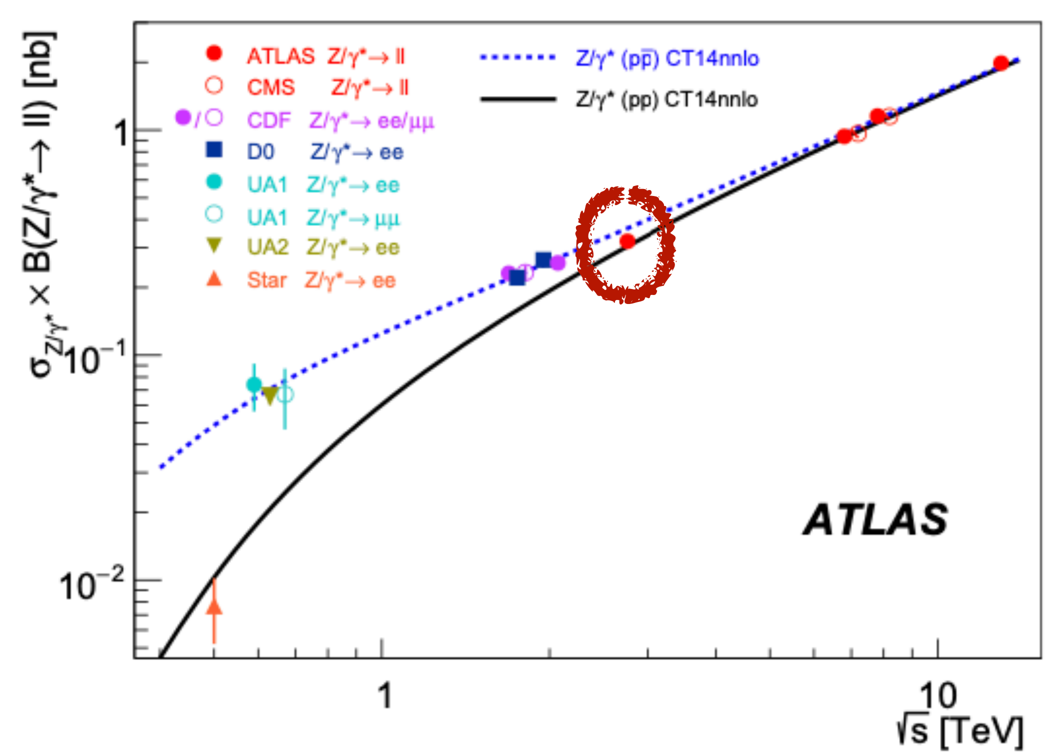
- $\sqrt{s}$ = 2.76 TeV <μ> =0.3, L = 4.0 pb^{-1}

$$\sigma^{\text{tot}}_{W^+\to\ell\nu} = 2312 \pm 26\ (\text{stat.}) \pm 27\ (\text{syst.}) \pm 72\ (\text{lumi.}) \pm 30\ (\text{extr.})\ \text{pb},$$

$$\sigma^{\text{tot}}_{W^-\to\ell\nu} = 1399 \pm 21\ (\text{stat.})\ \pm 17\ (\text{syst.}) \pm 43\ (\text{lumi.}) \pm 21\ (\text{extr.})\ \text{pb},$$

$$\sigma^{\text{tot}}_{Z\to\ell\ell} = 323.4 \pm 9.8\ (\text{stat.}) \pm 5.0\ (\text{syst.}) \pm 10.0\ (\text{lumi.}) \pm 5.5(\text{extr.})\ \text{pb}.$$





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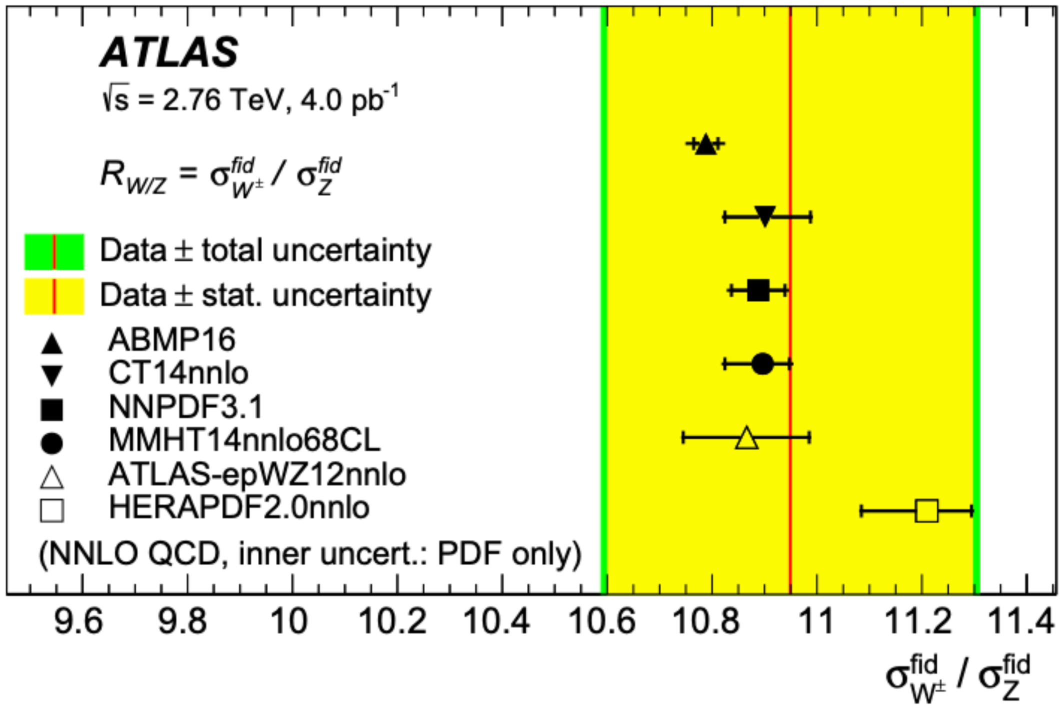
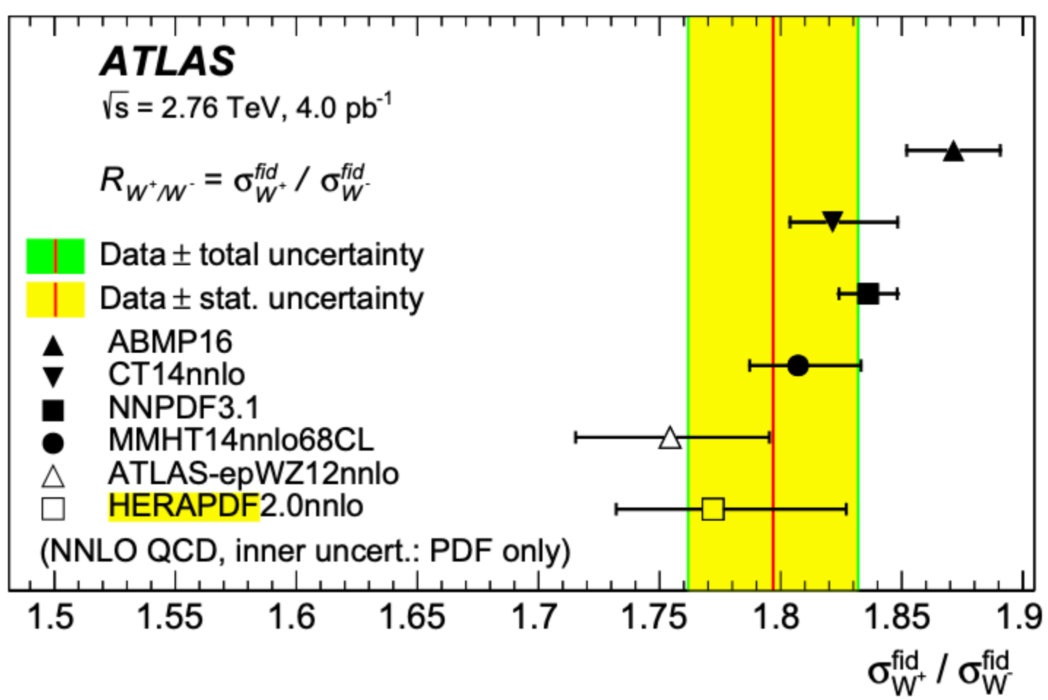


Constrains strange quark distribution

$$R_{W/Z} = 10.95 \pm 0.35\,(\text{stat.}) \,\pm 0.10\,(\text{syst.});$$
$$R_{W^+/W^-} = 1.797 \pm 0.034\,(\text{stat.}) \,\pm 0.009\,(\text{syst.}).$$

Constrains valence quark distributions



- Different PDF predictions in good agreement with measurements. Slight tension (less than 2σ) between the data and the prediction using the ABMP16

- In terms of charge asymmetry:

$$A_\ell = \frac{\sigma^{\text{fid}}_{W+} - \sigma^{\text{fid}}_{W-}}{\sigma^{\text{fid}}_{W+} + \sigma^{\text{fid}}_{W-}} = 0.285 \pm 0.009(\text{stat.}) \pm 0.002(\text{syst.}).$$