Associated production of vector bosons with heavy flavours

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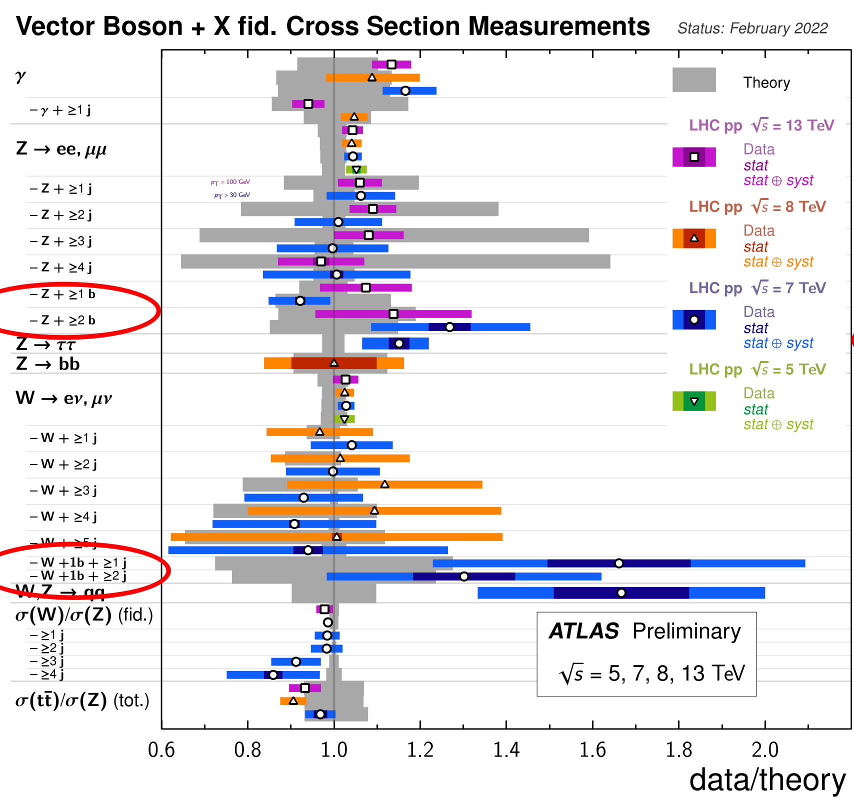
…will concentrate on most recent results

Background

- Associated production of vector bosons with heavy flavour is an important precision test of pQCD in the presence of two mass scales, and can also provide critical information on heavy quark PDFs such as the charm and strange distributions; N.B. NNLO calculations needed for PDF fits
- Can also serve as a background to new physics



Les Houches 2019 precision wishlist (2003.01700)
2021 wishlist in preparation

process	known	desired
$pp \to V$	$N^3LO^{(z\to 0)}_{QCD}$ (incl.) N^3LO_{QCD} (incl., γ^*) $NNLO_{QCD}$ NLO_{EW}	$N^3LO_{QCD} + N^2LO_{EW} + N^{(1,1)}LO_{QCD\otimes EW}$
$pp \to VV'$	$NNLO_{QCD} + NLO_{EW}$ $+ NLO_{QCD}$ (gg channel)	NLO_{QCD} (gg channel, w/ massive loops)
$pp \to V + j$	$NNLO_{QCD} + NLO_{EW}$	hadronic decays
$pp \to V + 2j$	$NLO_{QCD} + NLO_{EW}$ NLO_{EW}	$NNLO_{QCD}$
$pp \to V + b\bar{b}$	NLO_{QCD}	$NNLO_{QCD} + NLO_{EW}$
$pp \to VV' + 1j$	NLO_{QCD} NLO_{EW} (w/o decays)	$NLO_{QCD} + NLO_{EW}$
$pp \to VV' + 2j$	NLO_{QCD}	$NLO_{QCD} + NLO_{EW}$
$pp \to W^+W^+ + 2j$	$NLO_{QCD} + NLO_{EW}$	
$pp \to W^+Z + 2j$	$NLO_{QCD} + NLO_{EW}$	
$pp \to VV'V''$	NLO_{QCD} NLO_{EW} (w/o decays)	$NLO_{QCD} + NLO_{EW}$
$pp \to W^\pm W^+ W^-$	$NLO_{QCD} + NLO_{EW}$	
$pp \to \gamma\gamma$	$NNLO_{QCD} + NLO_{EW}$	
$pp \to \gamma + j$	$NNLO_{QCD} + NLO_{EW}$	→ will add γ+c/b
$pp \to \gamma\gamma + j$	NLO_{QCD} NLO_{EW}	$NNLO_{QCD} + NLO_{EW}$
$pp \to \gamma\gamma\gamma$	$NNLO_{QCD}$	

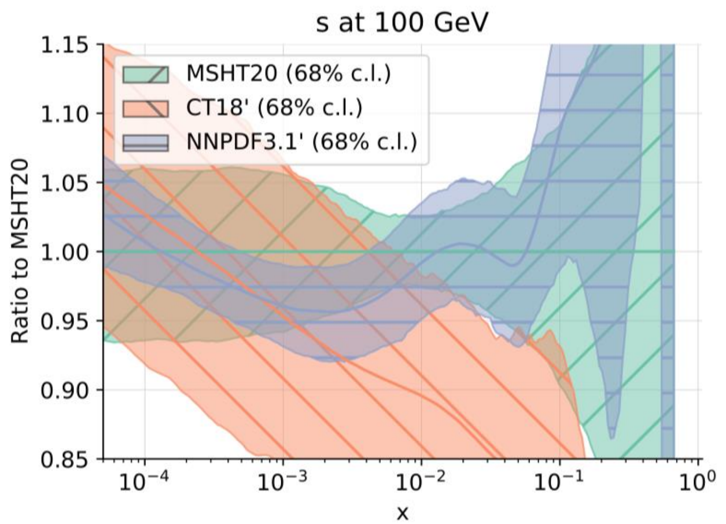
Table I.3: Precision wish list: vector boson final states. $V = W, Z$ and $V', V'' = W, Z, \gamma$. Full leptonic decays are understood if not stated otherwise.

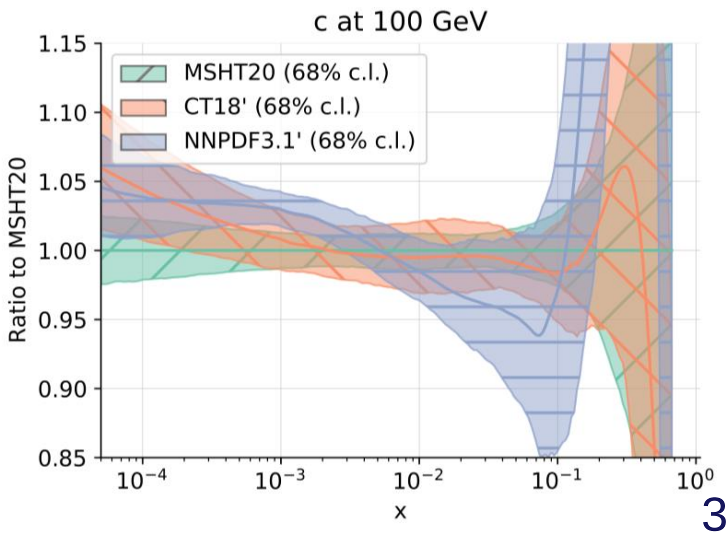
VbB has been known at NLO for some time, and matched to parton showers. WbB known at NLO with up to 3 extra jets. Recently, the two-loop corrections to the WbB amplitude have been calculated (PRL127.012001) Non-planar master integrals still to be calculated.

Strange/charm PDFs

- Consider the strange quark PDF
- There is a large difference between CT18 and CT18A/MSHT20/NNPDF3.1 due almost entirely to the ATLAS 7 TeV W/Z data
- The difference between the W and Z cross sections requires a larger strange quark (s-sbar->Z)
- **All 3 groups fit the ATLAS W/Z data equally poorly**
- Because of its fitting criteria, CT18 does not use the 7 TeV W/Z data for its main fit (but it is in CT18A)
- W+c data offer another window on the strange quark distribution
- NNPDF3.1 has a different charm distribution then CT18/MSHT20, due to its fitting the charm distribution as a free parameter, rather then generating perturbatively through gluon splitting; an intrinsic charm component may be present at high x
- CT has published PDF sets in which an intrinsic component of charm is modeled. The addition of this intrinsic component leads to a small, but noticeable, reduction in global χ^2
- Z+c/γ+c offers another window on the charm quark

PDF4LHC21: arXiv:2203.05506



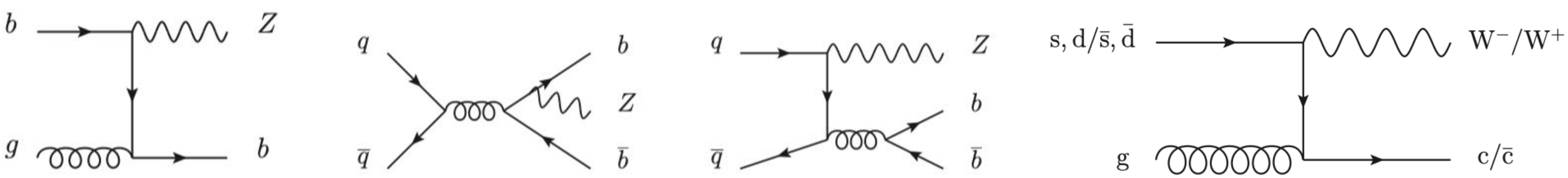


Charm and b quark distributions

- Perturbative view is that c and b quarks are not present in the proton at scales lower then their masses
- They can be produced in the initial state at scales higher then their masses through gluon splitting into quark-antiquark pairs (thus primarily at lower x)
  - only things that drive production (besides the gluon distribution) are the heavy quark mass and the value of $\alpha_s(m_Z)$
- But the proton can also have an intrinsic charm (and bottom for that matter) component through a $|uudc\bar{c}\rangle$ Fock state, primarily at higher x
  - there are models (BHPS, incorporated by the CTEQ group), and increasingly, predictions from lattice gauge theory
- In PDF fits, heavy quarks can be produced through QCD evolution, or through QCD evolution + an intrinsic component through a model (CTEQ), or through a free fit to the heavy quark PDF in a similar manner as for the lighter quarks (NNPDF)

V+HF

- A heavy flavor quark can be present in the initial state or produced through gluon splitting



- The calculation can be performed in a scheme where there are only 4 parton flavours (4FNS) or in which the b-quark is included (5-FNS)
- The kinematics can drive the subprocess for the production, as for example, whether the final state heavy quark (jet) has to pass only some minimum p_T requirement, or whether it has to roughly balance the boson transverse momentum
- If it's the former, then the final state c or b quark is likely to arise through gluon splitting, especially given the additional gluon splittings that may occur in a parton shower (*JHEP* 02 (2018) 059)
    - this effect is more pronounced if there is a hierarchy of scales, i.e. $p_T^{jet} >> p_T^{charm}$ (would be useful to measure differentially in p_T^{jet})

Jet tagging

- There is also the issue of how the heavy flavor jet is tagged; the theory predictions use a flavor tagging k_T jet algorithm in which the distance between pseudo-jets *i* and *j* (d_{ij}) are dependent on the flavour of the considered partons

$$d_{ij} = \frac{\Delta y_{ij}^2 + \Delta \phi_{ij}^2}{R^2} \begin{cases} max\,(k_{\mathrm{T}i}, k_{\mathrm{T}j})^2 & \text{if softer of } i{,}j \text{ is flavored} \\ min\,(k_{\mathrm{T}i}, k_{\mathrm{T}j})^2 & \text{if softer of } i{,}j \text{ is unflavored} \end{cases}$$

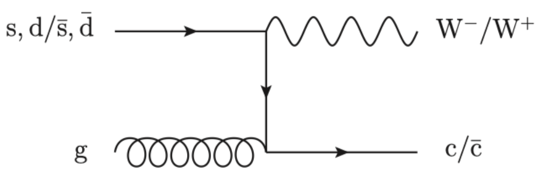
  - the distance to the beam is also flavour-dependent

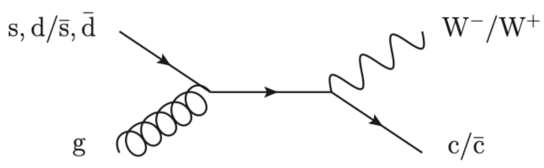
$$d_{i\beta} = \begin{cases} max\,(k_{\mathrm{T}i}, k_{\mathrm{T}\beta}\,(y_i))^2 & \text{if } i \text{ is flavored} \\ min\,(k_{\mathrm{T}i}, k_{\mathrm{T}\beta}\,(y_i))^2 & \text{if } i \text{ is unflavored} \end{cases}$$

- The experimental measurements typically use the anti-k_T jet algorithm with later flavor identification (*Eur.Phys.J.C* 47 (2006) 113)
- The difference between the two may not be small (10-15%)

W+c jets

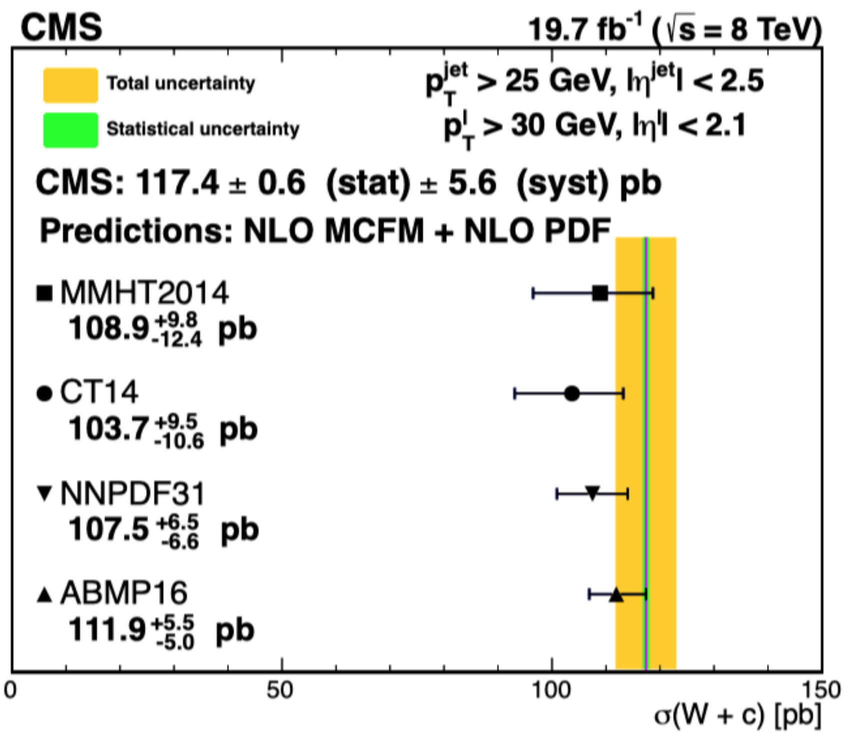
- Measurement carried out inclusively, and differentially as function of p_T and η of lepton

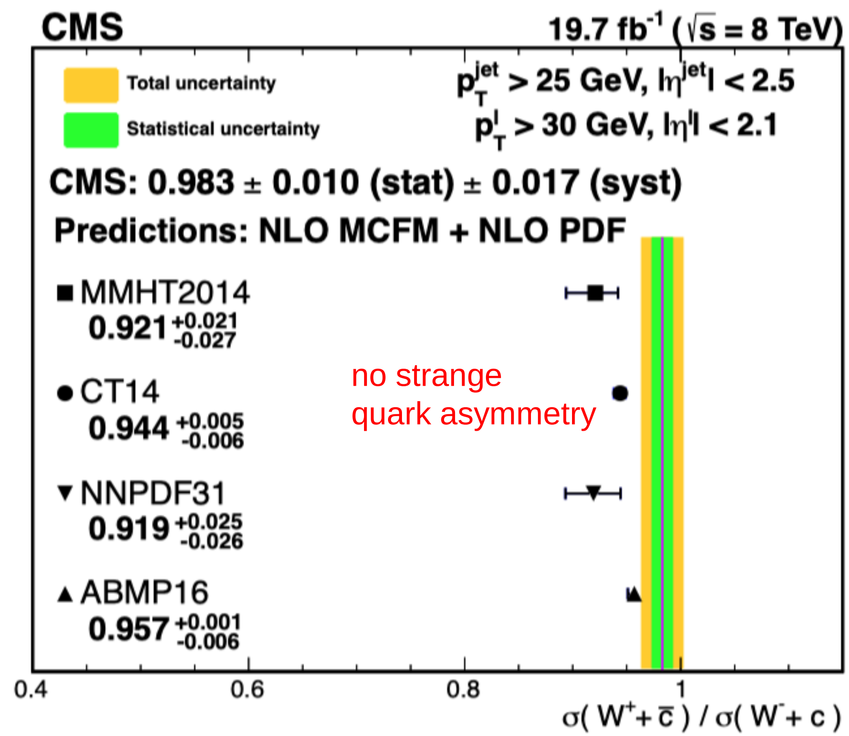




Note: W and c quark should be of opposite sign; SS-OS suppresses contributions from gluon splitting

arXiv:2112.00895 (submitted to EPJC)



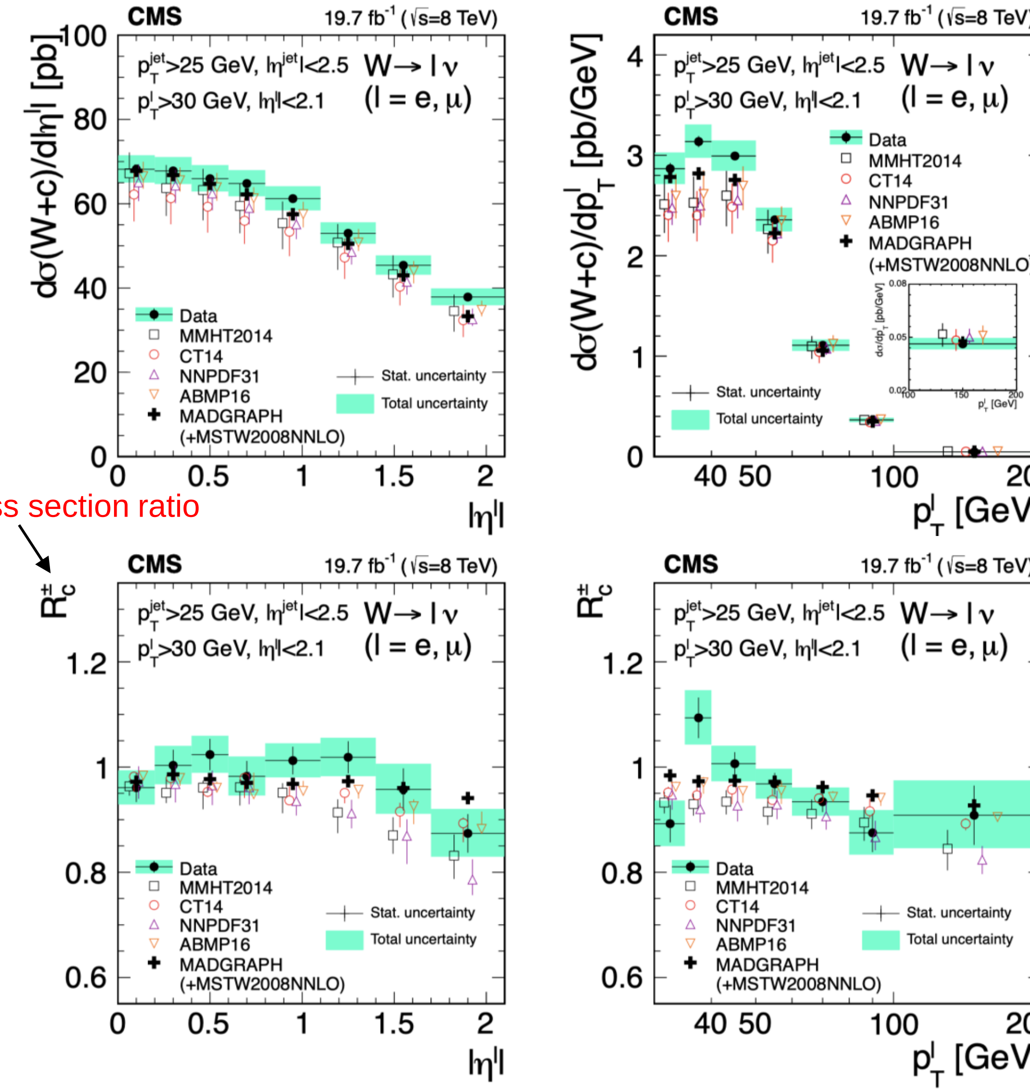


Differential cross sections

- Require an isolated lepton (e or μ) with p_T>30 GeV and $|\eta|$<2.1
- Require a jet with p_T>25 GeV with $|\eta_{jet}|$<2.5. Jets not selected if $\Delta R(jet,l)$<0.5
- Data are larger then (NLO+PS) predictions for lepton p_T less then 65 GeV, but compatible within uncertainties
- NNLO corrections for W+c predicted to be on the order of 5% for lepton p_T less then 60 GeV and about 1% for larger p_T values
  - *JHEP* 06 (2021) 100
- This would improve the level of agreement with the data

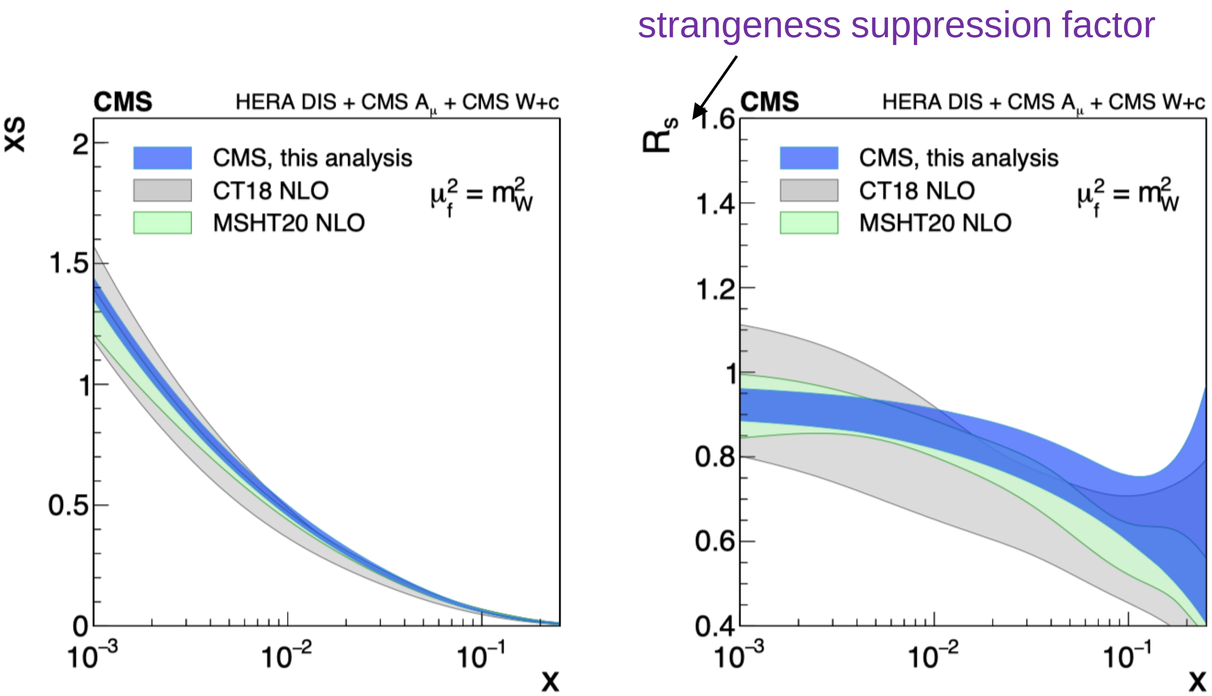
arXiv:2112.00895 (submitted to EPJC)

cross section ratio



(W+c) strange quark PDF

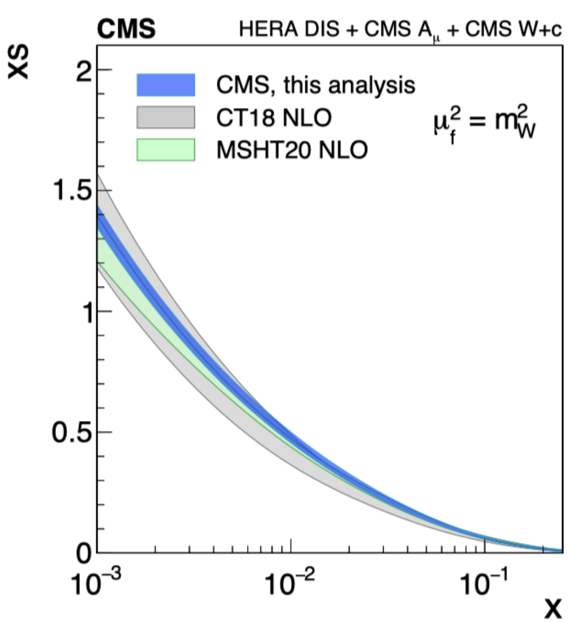
- Derived CMS strange quark consistent with that obtained by CT18 and MSHT20 for x<0.01; somewhat larger at higher x
    - NB: MSHT20 includes ATLAS 7 TeV W/Z data



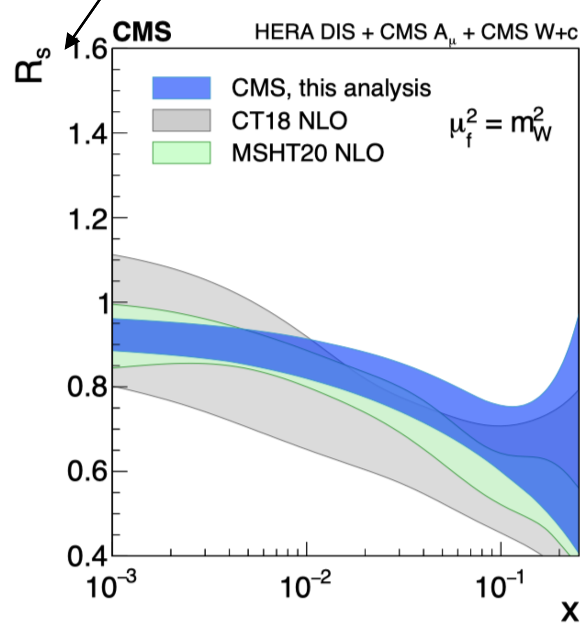
arXiv:2112.00895 (submitted to EPJC)

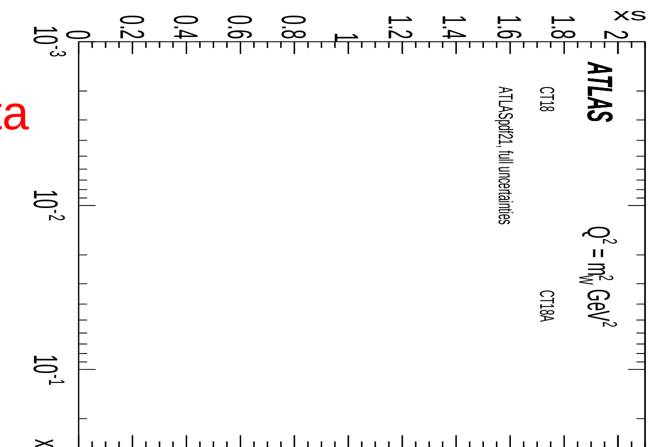
(W+c) strange quark PDF

- Derived CMS strange quark consistent with that obtained by CT18 and MSHT20 for x<0.01; somewhat larger at higher x
  - NB: MSHT20 includes ATLAS 7 TeV W/Z data
- Compare to results from ATLAS PDF21 fit
  - CT18 does not include ATLAS 7 TeV W/Z data, CT18A does

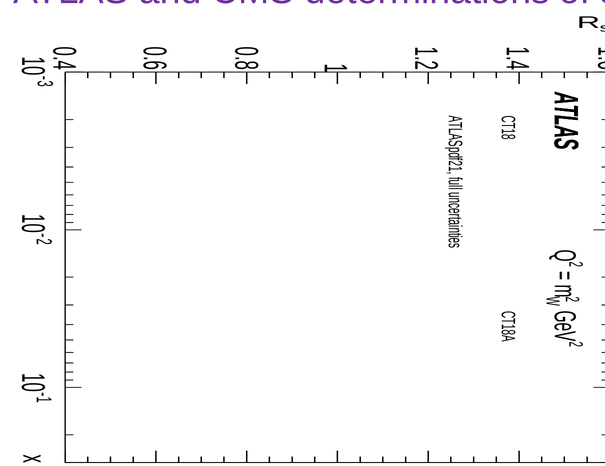


strangeness suppression factor





perhaps more consistency between ATLAS and CMS determinations of s

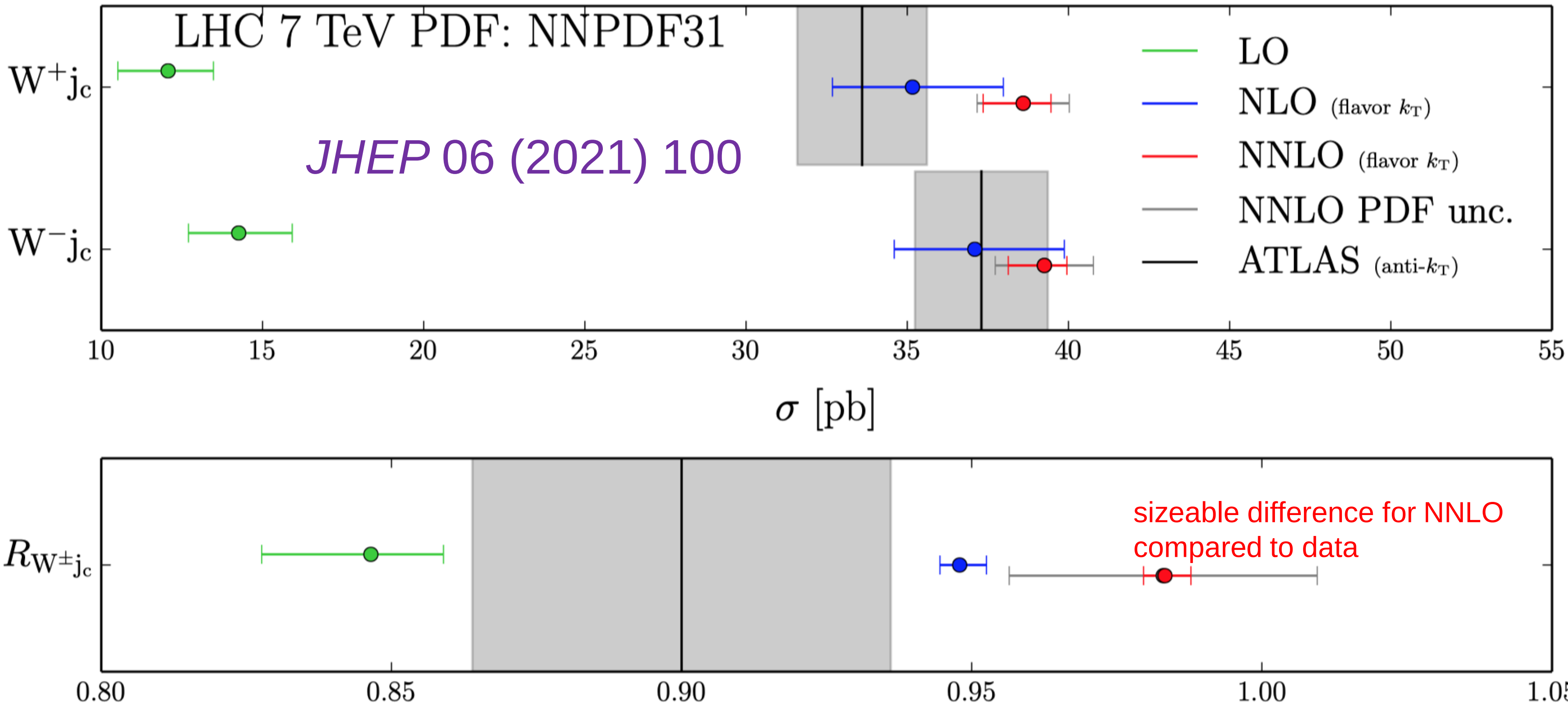


thanks to Francesco Giuli for making the ATLAS plots

arXiv:2112.00895 (submitted to EPJC)

NNLO W+c-jet cross section calculation

- Large reduction in uncertainties from NLO->NNLO
- NNLO scale uncertainties smaller then PDF uncertainties
- NB: the NNLO calculation used flavor tagging for the charm jet; the experimental measurement used the antikT algorithm with later flavor identification; NNLO corrections to subleading CKM-mediated processes not included in this calculation (but are now available)



W+c at NNLO-differential

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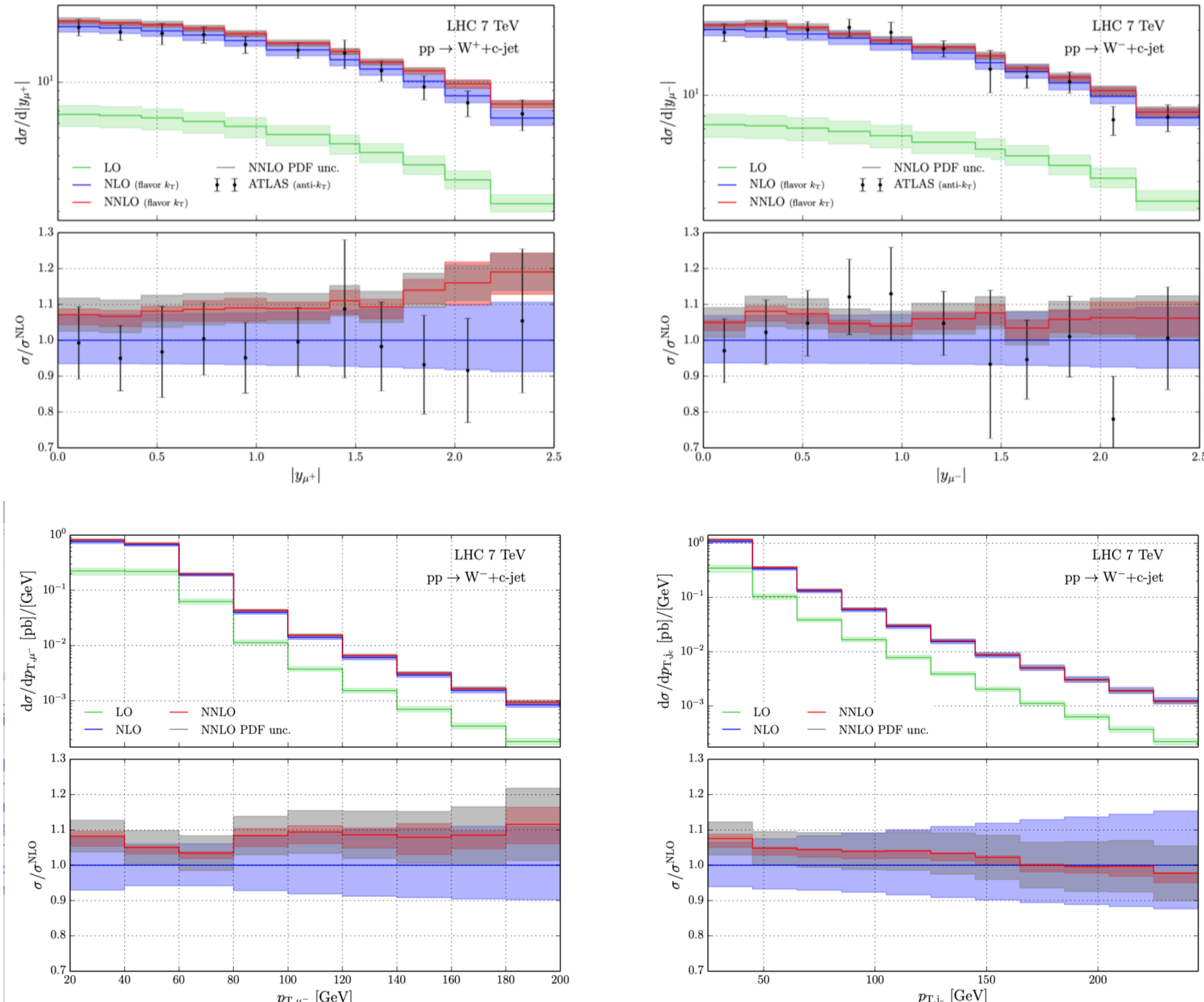

no comparison to data yet (that I know of)

W+c at NNLO

- Ratio plots sensitive to s-$\bar{s}$ asymmetry

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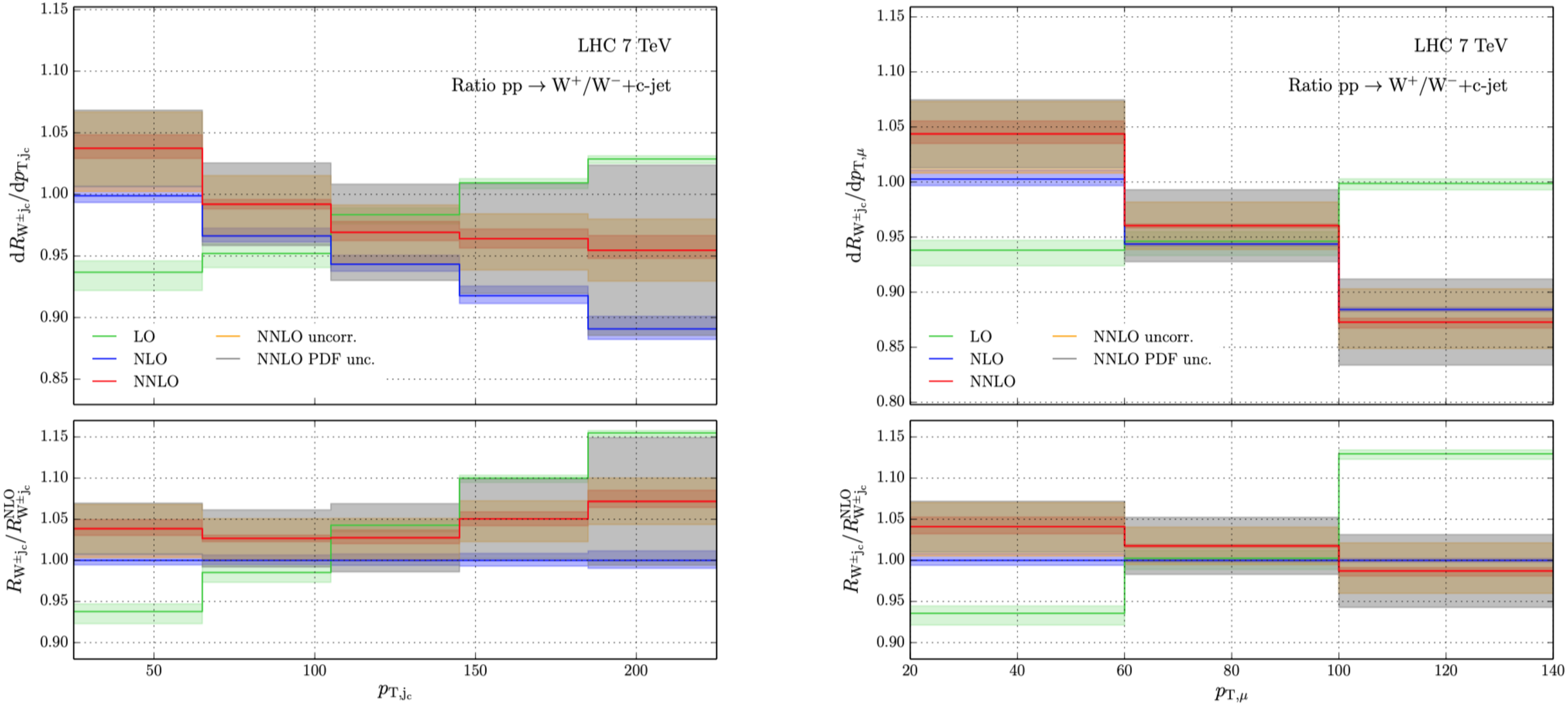
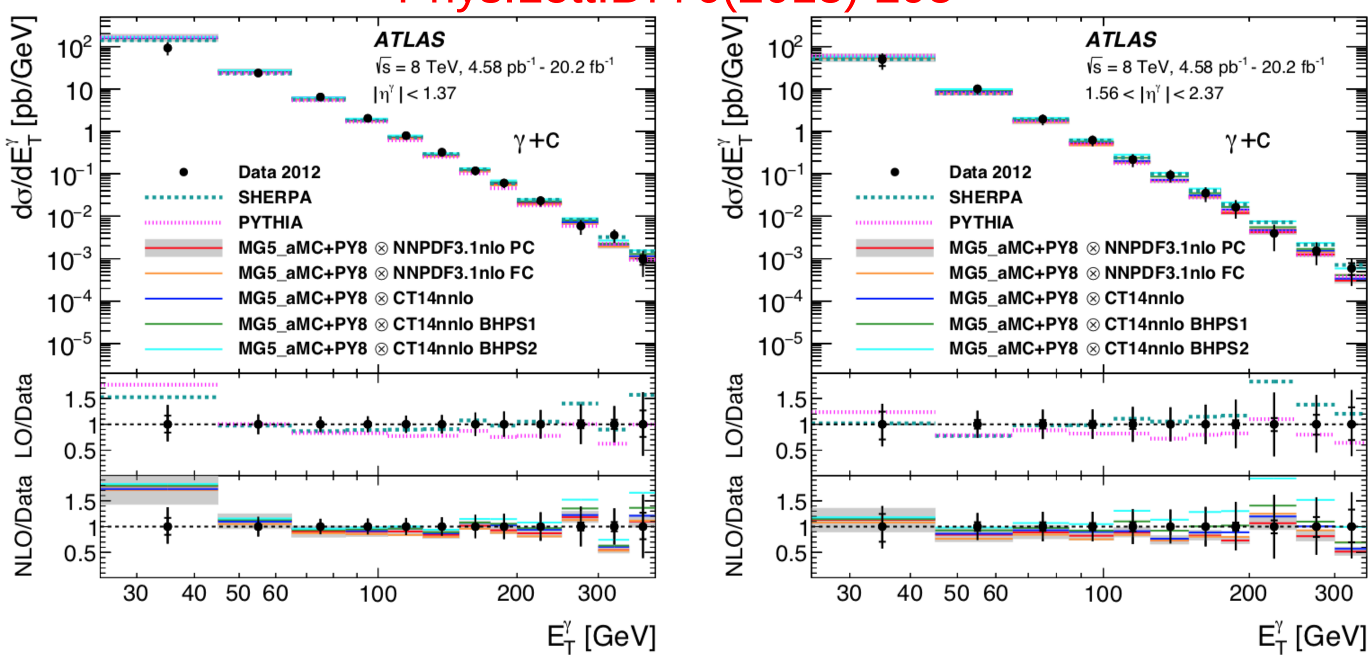


NNLO uncertainties very small; potential for constraining asymmetry

Photon+charm jets

- Photons measured in central and forward rapidity
- Jets are defined with antikT algorithm, R=0.4; p_T^{jet}>20 GeV
  - if jet contains a b-hadron with p_T>5 GeV within ΔR=0.3 of jet, then it is assigned as a b-jet; if there is no b-hadron, but there is a charm hadron, it is assigned as a c-jet
- All predictions agree reasonably well with data (relatively large uncertainties)
- There are differences at high E_T when intrinsic charm included in predictions of similar size to uncertainties
- NNLO predictions would be very useful (have to deal with photon isolation)

Phys.Lett.B776(2018) 295

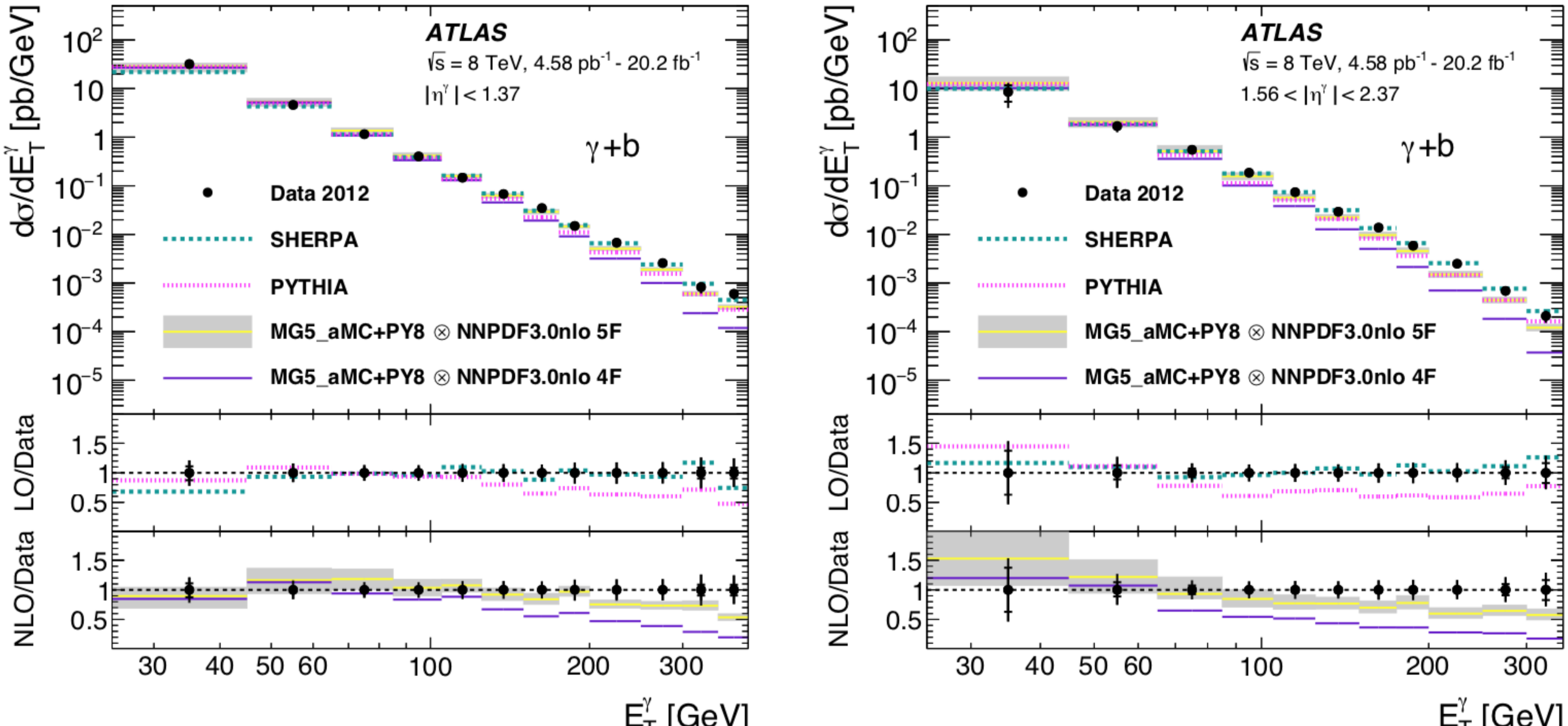


see talk of Hofer on Monday

Photon+b jets

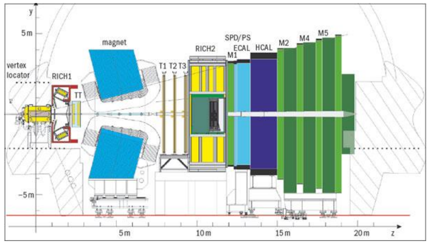
- 5FNS scheme works better then 4FNS scheme
- Best description of the data provided by Sherpa with up to 3 additional partons included in 5FNS scheme
- Again, NNLO would be useful

Phys.Lett.B776(2018) 295



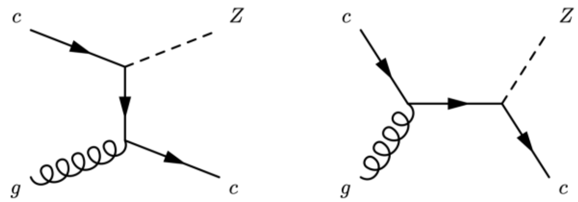
Z+c jets (arXiv:2109.08084)

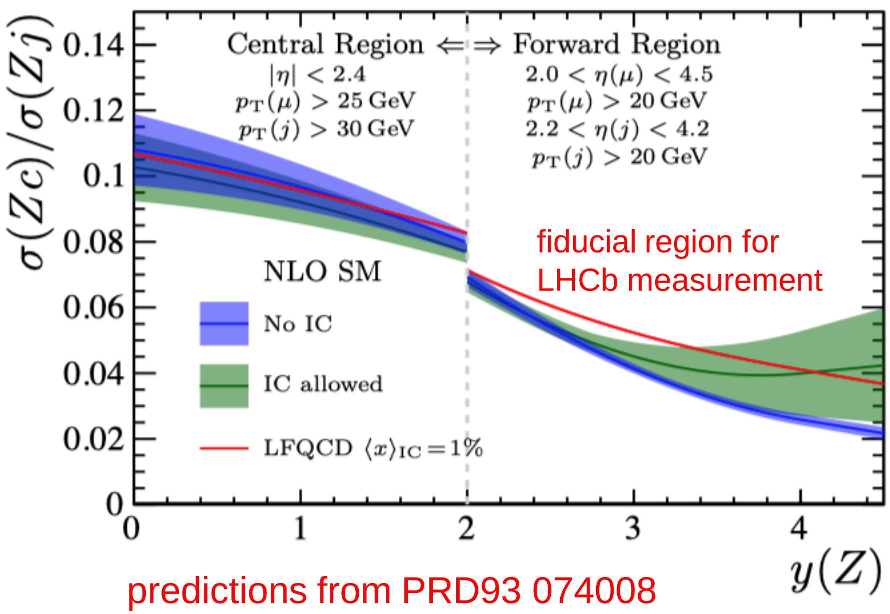
- The forward layout of LHCb makes it particularly sensitive to the presence of any charm component at high x



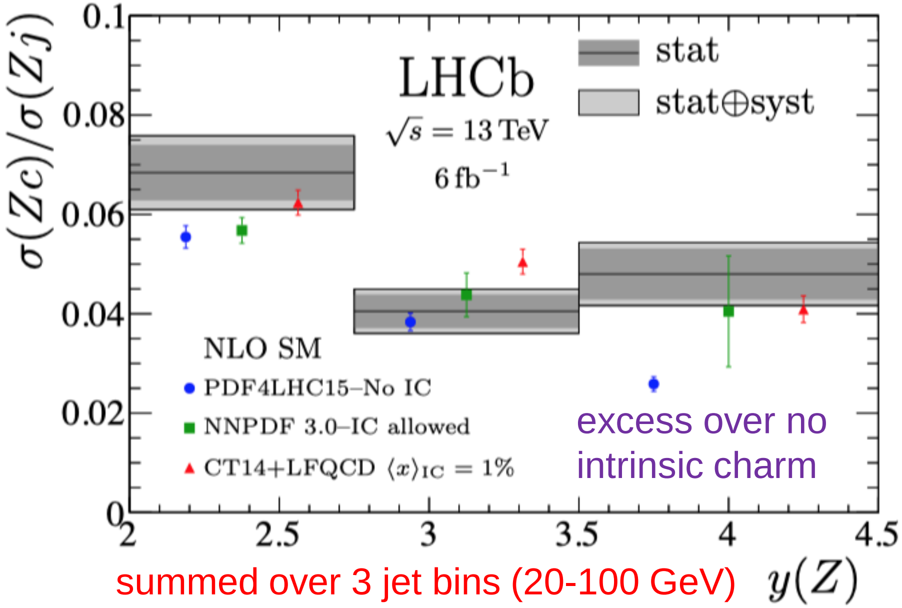
Z bosons	$p_{\mathrm{T}}(\mu) > 20\,\mathrm{GeV}$, $2.0 < \eta(\mu) < 4.5$, $60 < m(\mu^+\mu^-) < 120\,\mathrm{GeV}$
Jets	$20 < p_{\mathrm{T}}(j) < 100\,\mathrm{GeV}$, $2.2 < \eta(j) < 4.2$
Charm jets	$p_{\mathrm{T}}(c\text{ hadron}) > 5\,\mathrm{GeV}$, $\Delta R(j, c\text{ hadron}) < 0.5$
Events	$\Delta R(\mu, j) > 0.5$

- For greater sensitivity, measure the ratio of Zc to Zj





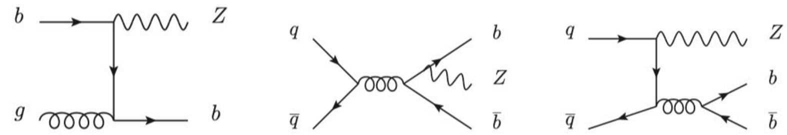
predictions from PRD93 074008



summed over 3 jet bins (20-100 GeV)

Z+b jets

- The b quark is treated as perturbatively produced by all PDF fitting groups; i.e. inside the proton, at higher Q^2 scales, only things that drive it are the b-quark mass and the value of $\alpha_s(m_Z)$
- Also sensitive to final state gluon splitting



- Calculation can be performed either in 4FNS or 5FNS

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- Partial run 2 dataset: 35.6 fb^{-1}
- Z + ≥ 1 or ≥ 2 b jets, b-jet p_T > 20 GeV, |y| < 2.5
- b-jet tagger: ≈ 70% efficiency
- Testing several MC predictions with 4 and 5 FNS: 5FNS includes b quark in PDF

CMS-SMP-20-015 arxiv:2112.09659

- Full run 2 dataset: 137 fb^{-1}
- Z + ≥ 1 or ≥ 2 b jets, b-jet p_T > 30 GeV $|\eta|$ < 2.4
- b-jet tagger: ≈ 50% efficiency (tight WP)

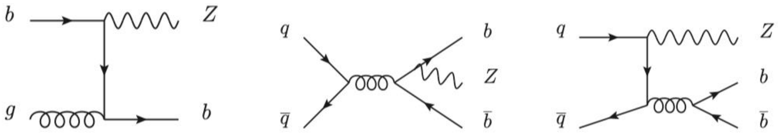
1

Kinematic variable	Acceptance cut
Lepton p_T	$p_T > 27$ GeV
Lepton η	$\|\eta\| < 2.5$
$m_{\ell\ell}$	$m_{\ell\ell} = 91 \pm 15$ GeV
b-jet p_T	$p_T > 20$ GeV
b-jet rapidity	$\|y\| < 2.5$
b-jet–lepton angular distance	$\Delta R(b\text{-jet}, \ell) > 0.4$

Object	Selection
Dressed leptons	p_T (leading) > 35 GeV, p_T (subleading) > 25 GeV, $\|\eta\| < 2.4$
Z boson	$71 < M_{\ell\ell} < 111$
Particle-level bjet	bhadron jet, $p_T > 30$ GeV, $\|\eta\| < 2.4$

Z+b jet

- The b quark is treated as perturbatively produced by all PDF fitting groups; i.e. inside the proton, at higher Q^2 scales only things that drive the PDF are the b-quark mass and the value of $\alpha_s(m_Z)$
- Also sensitive to gluon splitting (and multiplicative factor of parton shower)



- Calculation can be performed either in 4FNS or 5FNS
  - 4FNS underestimates cross section; better agreement with5FNS

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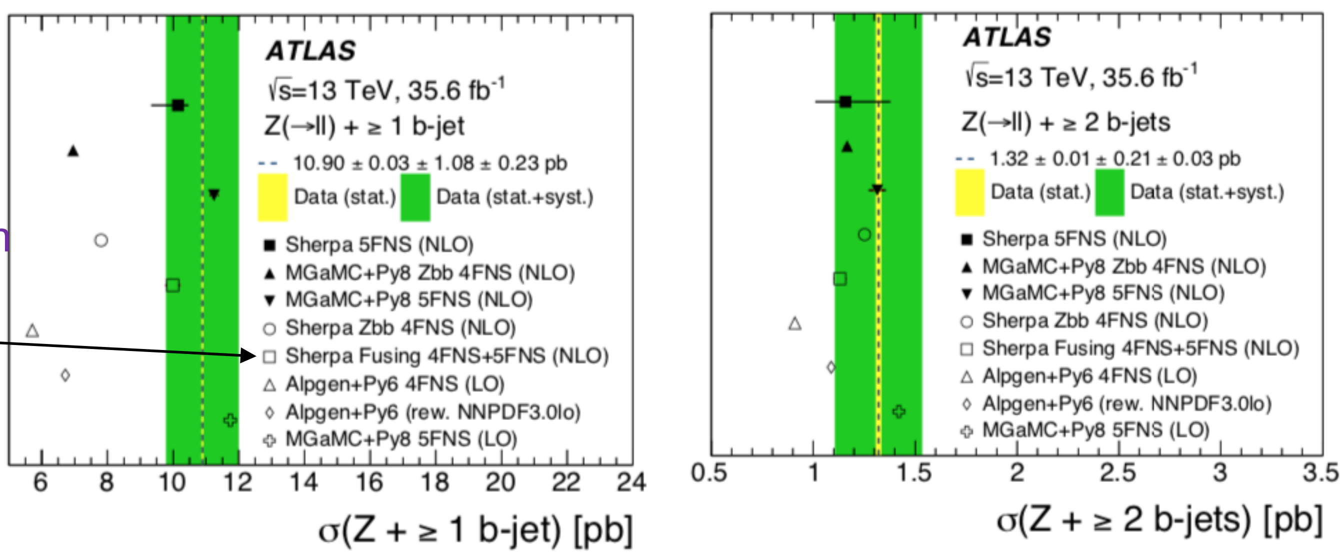

note Fusing prediction of 4FNS+5FNS schemes

Monte Carlo equivalent of FONLL/ ACOT

Most important information comes from differential distributions, though

- NNPDF3.1 PDF is the most up-to-date of the PDFs shown; would be nice to have comparisons of more modern PDFs as well (CT18, MSHT20, NNPDF4.0 (NNPDF3.1’))

arxiv:2112.09659 CMS-SMP-20-015

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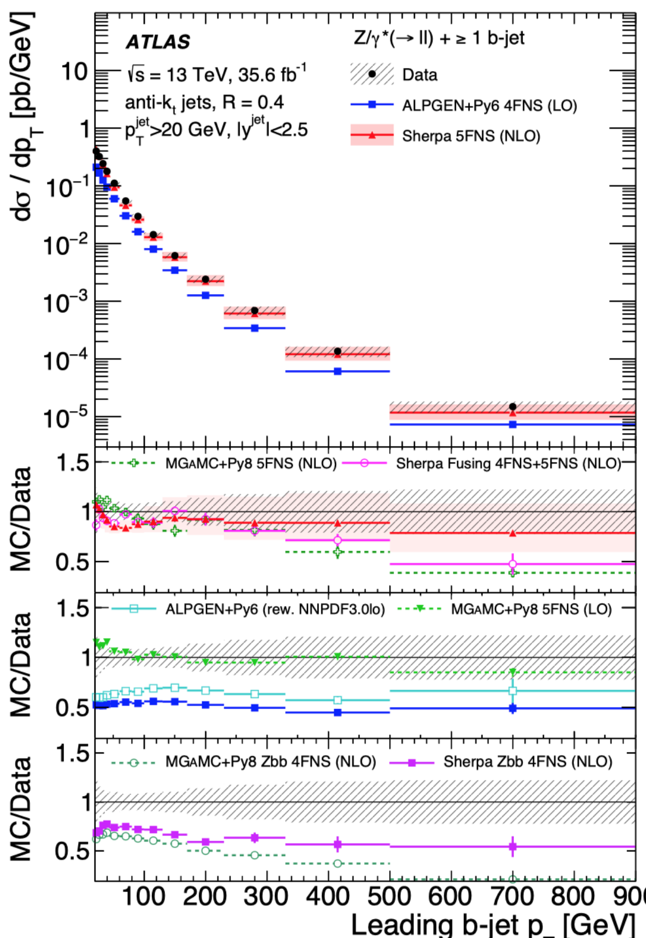
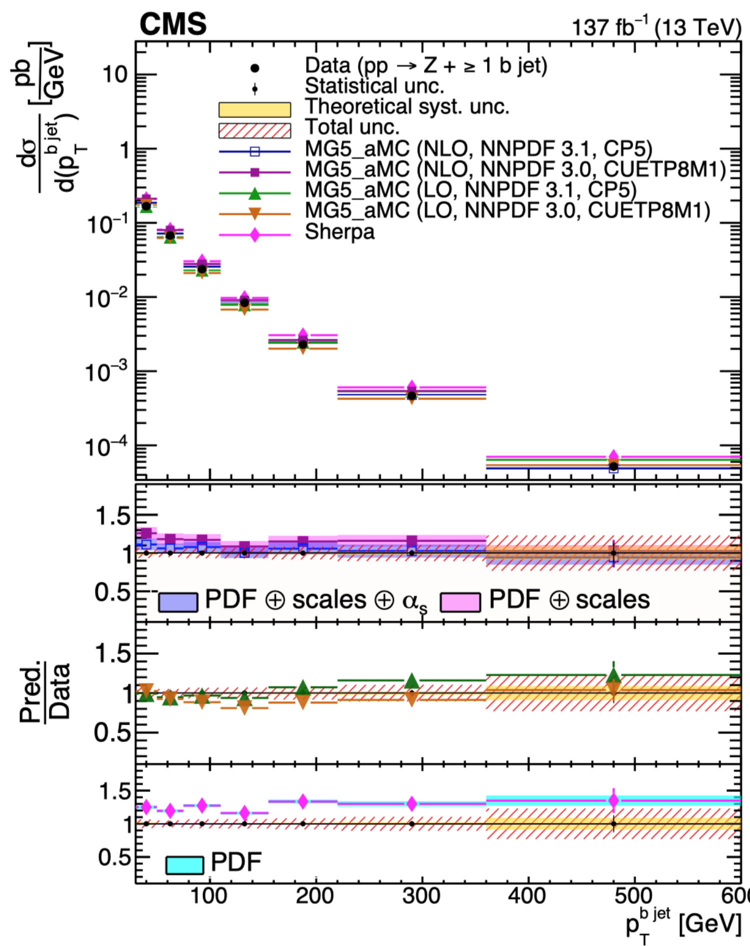


sizeable difference depending on whether massless or massive NLO+PS prediction used



Z+b at NNLO prediction

- Carried out by combining a massless NNLO and a massive NLO computation at order (α_s^3) (arXiv:2005.03016)
  - initial state b-quarks from gluon splitting resummed by PDF evolution; finite b-quark mass effects also incorporated (presumably same could be done for Z+c)
  - note: massless calculation means IR-safe definition of jet flavour must be used; not consistent with experimental choice
  - desired to have data unfolded to level of partonic flavour-kT jets

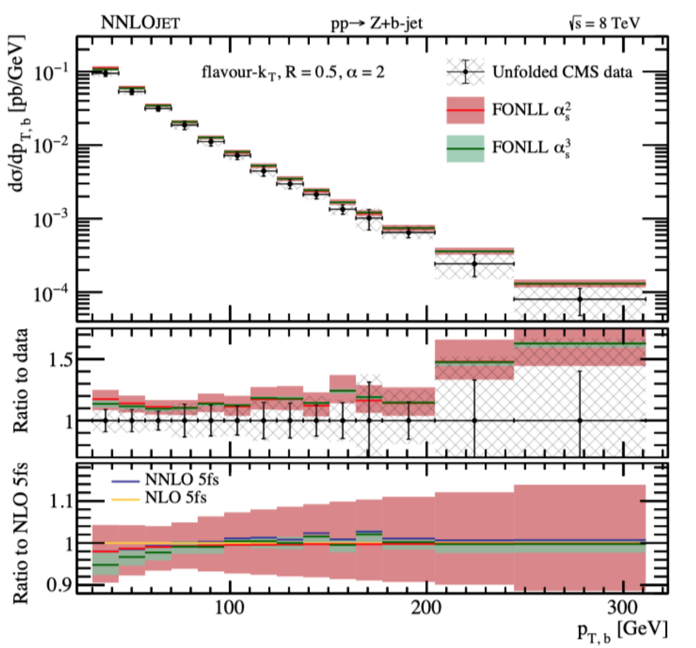


Figure 2: The transverse momentum distribution of the leading flavour-k_T b-jet. The absolute cross-section is shown in the upper panel, the ratio to the unfolded data in the central panel, and the ratio to the NLO 5fs prediction in the lower panel. The shown uncertainty of the FONLL distributions are due to scale variations alone.

large reduction in uncertainty in going from NLO to NNLO

reasonable agreement with data

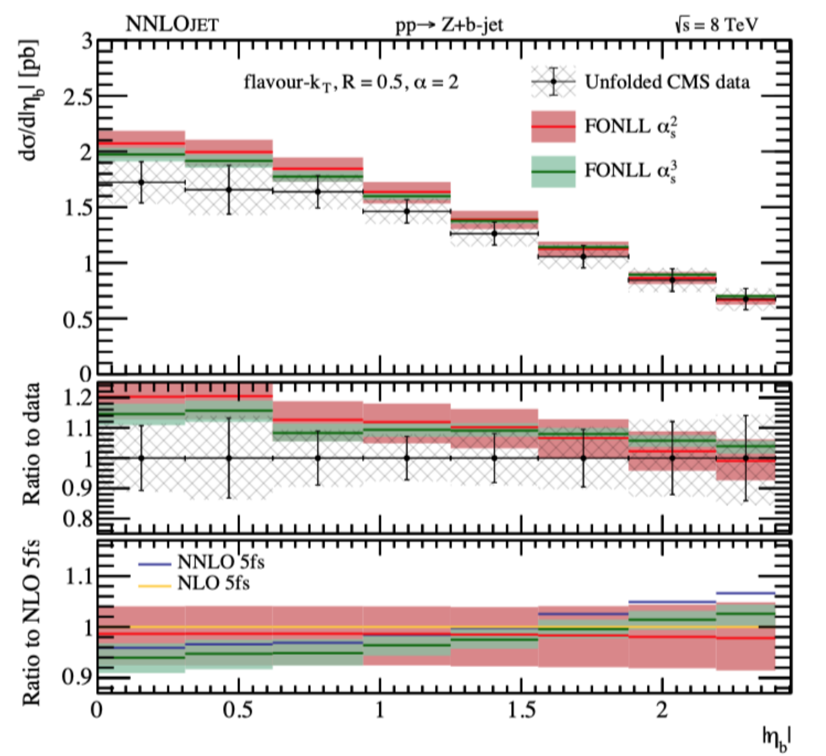


Figure 3: As in Fig. 2, now for the absolute psudorapidity distribution of the leading flavour-k_T b-jet.

Z+>=2 b jets (ΔR_{bb})

- Require at least two b jets
- Small values of ΔR_{bb} sensitive to gluon splitting

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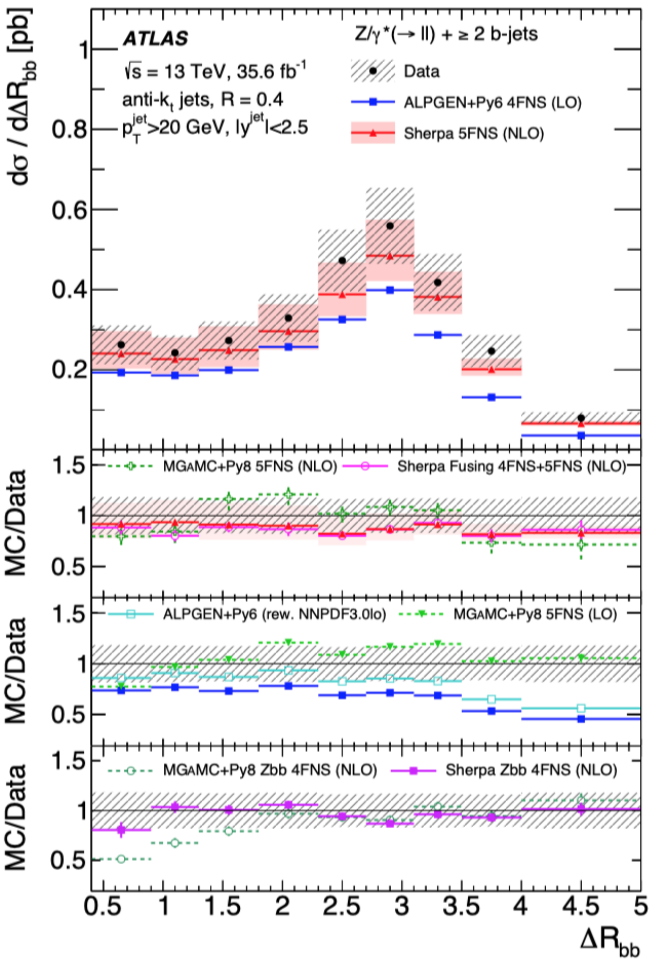
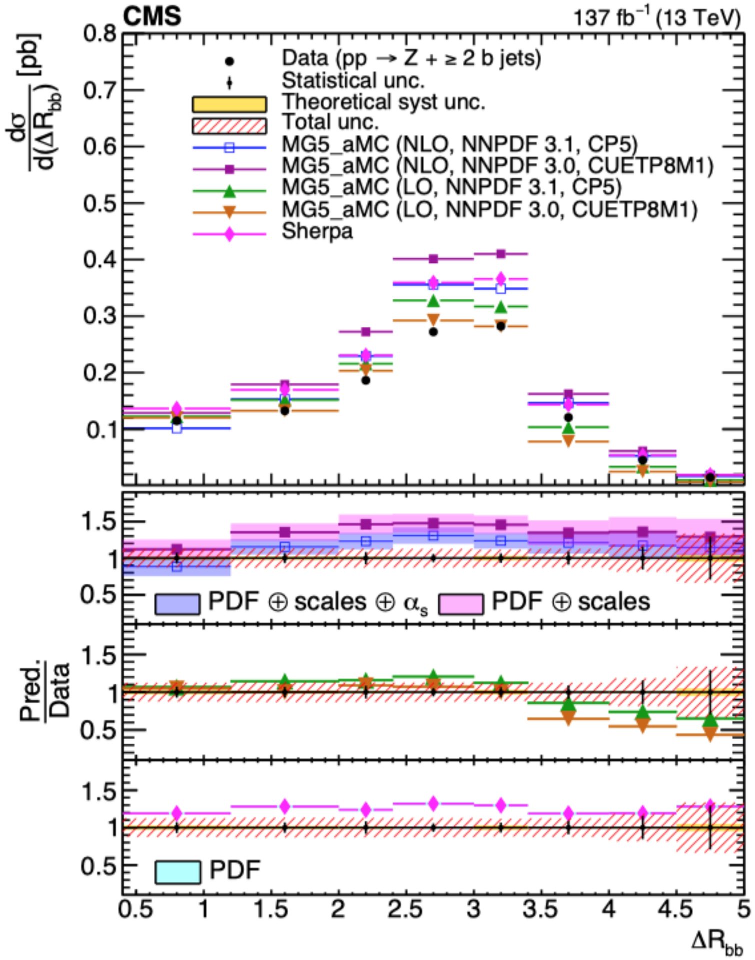
arxiv:2112.09659 CMS-SMP-20-015





Z+>=2 b jets (m_{bb})

- For ATLAS, no MC in agreement for m_{bb}>300 GeV
- For CMS, shapes best described by MG5 NLO

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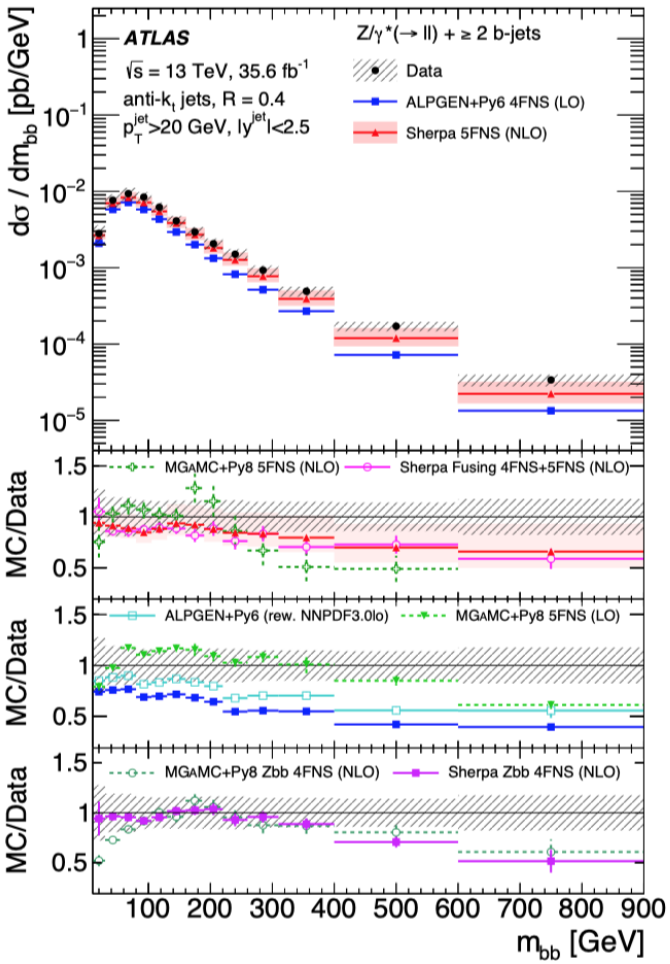

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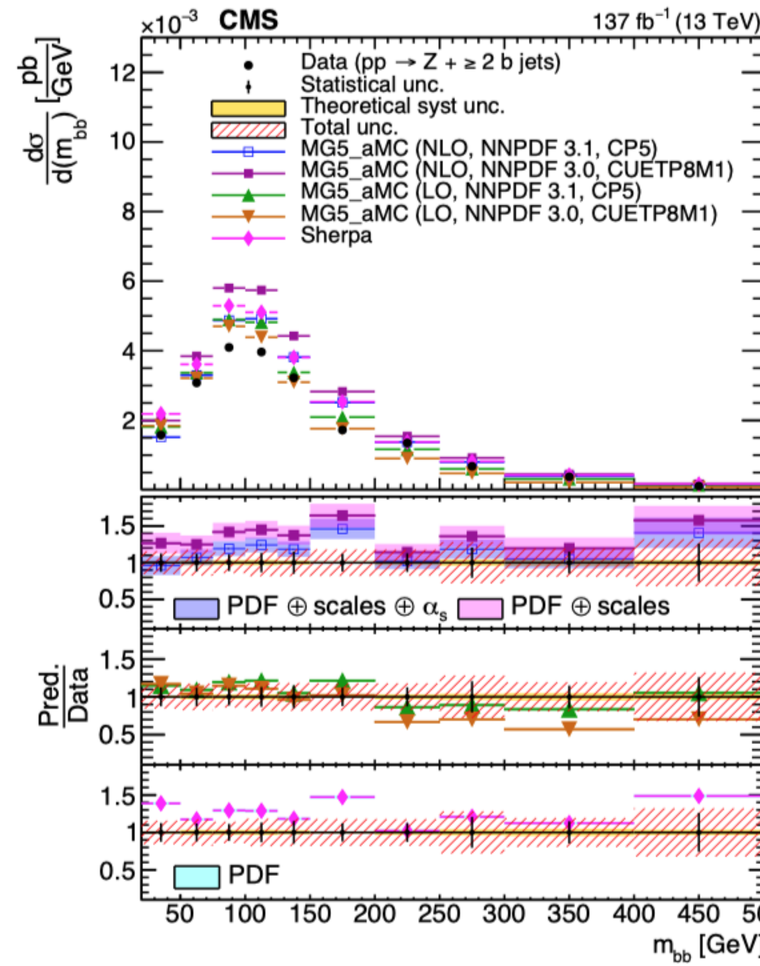


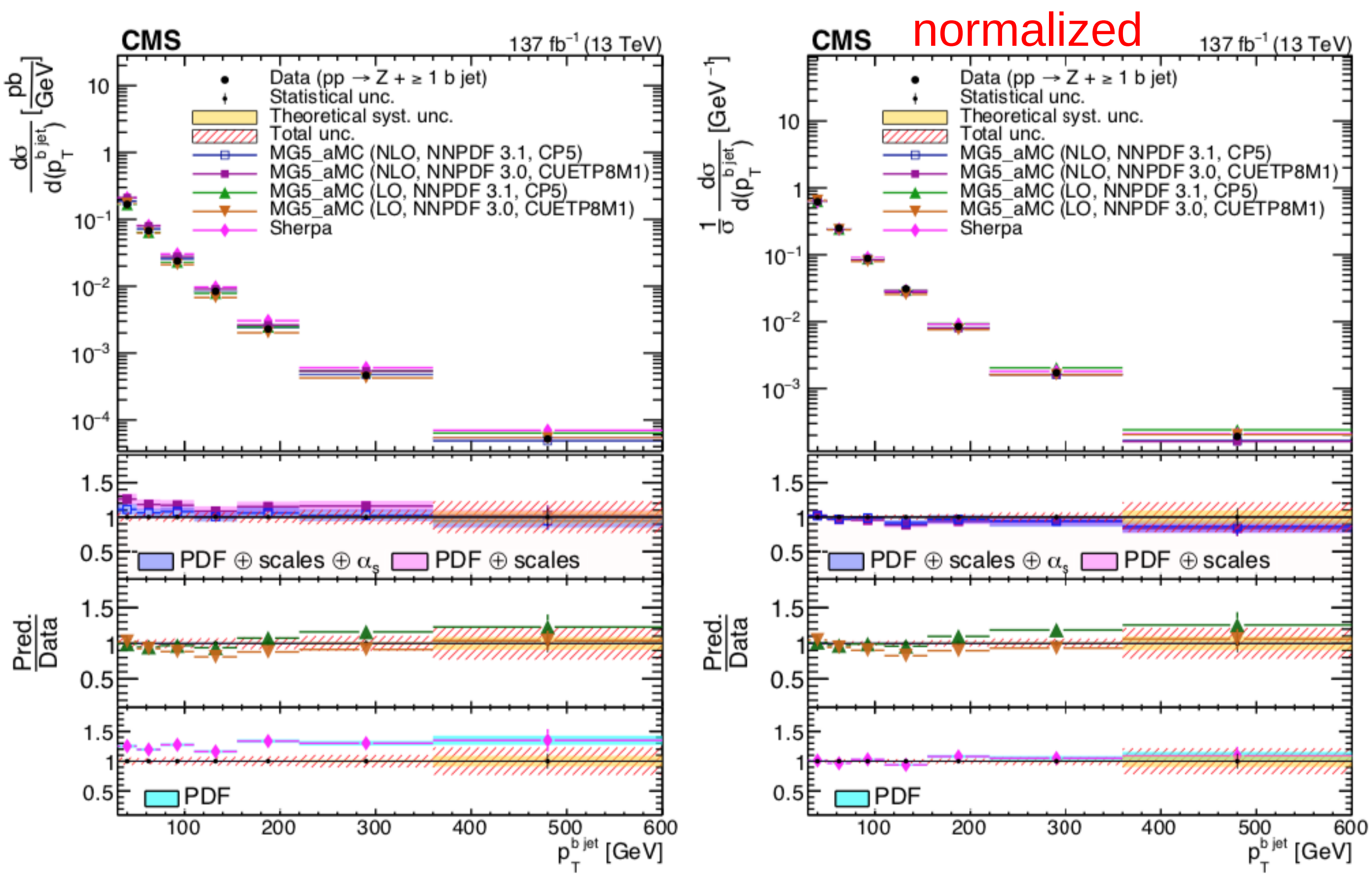
Summary

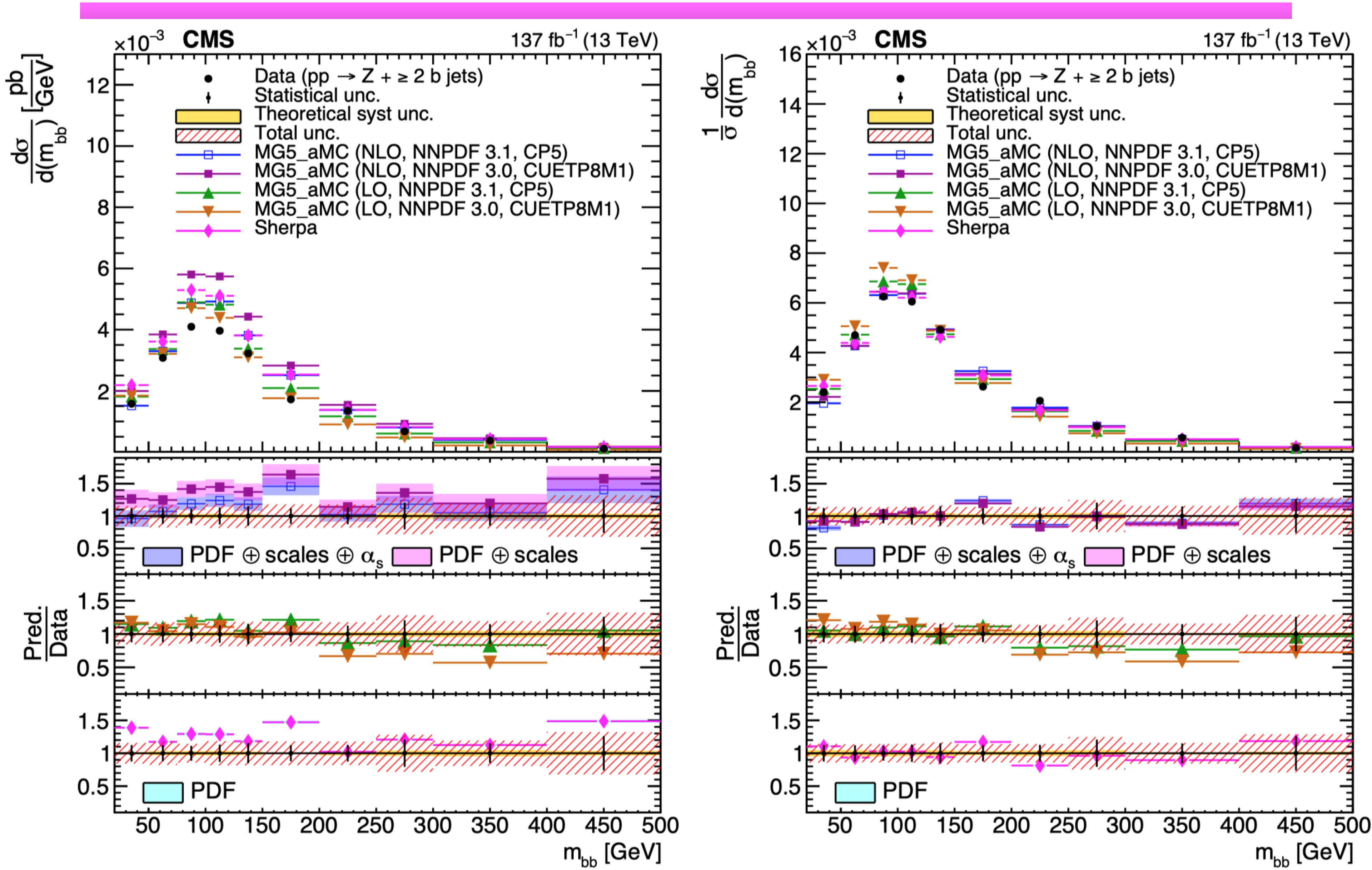
- V+heavy flavor production is a source of very interesting physics at the LHC, with crucial information for heavy flavour PDFs such as strange and charm
- Precision predictions are starting to become available at NNLO, but there is a mis-match between theoretical and experimental jet definitions that needs to be resolved
- Need NNLO predictions for photon+HF (with isolation prescription for the photons)
- Greatest precision of V+HF theory achieved at NNLO, but kinematic cuts make matching to parton showers possibly necessary
  - this is an extremely complex problem, V+j resummation with an extra mass scale thrown in for fun
- NNLO V+HF predictions with fragmentation functions on the way
  - see talk by Czakon earlier today
- Would be nice to have comparisons with more modern PDFs
- We have only just begun to tap the data taken at 13 TeV (->13.6 TeV), and the comparison to precision predictions

Z+b

- Ignore LO predictions; NNPDF3.1 PDF is the most up-to-date of the two PDFs shown; would be nice to have comparisons of more modern PDFs as well (CT18, MSHT20, NNPDF4.0 (NNPDF3.1'))

arxiv:2112.09659 CMS-SMP-20-015





CMS
137 fb^{-1} (13 TeV)
$\times 10^{-3}$
$\frac{d\sigma}{d(m_{bb})}$ [$\frac{pb}{GeV}$]
$\frac{1}{\sigma}\frac{d\sigma}{d(m_{bb})}$
Data (pp → Z + ≥ 2 b jets)
Statistical unc.
Theoretical syst unc.
Total unc.
MG5_aMC (NLO, NNPDF 3.1, CP5)
MG5_aMC (NLO, NNPDF 3.0, CUETP8M1)
MG5_aMC (LO, NNPDF 3.1, CP5)
MG5_aMC (LO, NNPDF 3.0, CUETP8M1)
Sherpa
PDF ⊕ scales ⊕ α_s
PDF ⊕ scales
Pred./Data
PDF
m_{bb} [GeV]