Heavy quarks and W/Z bosons associated production in CMS and constraints on pdf

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on behalf of the CMS collaboration

DIS 2017 Workshop

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Birmingham, UK

Motivation

Heavy quarks and vector bosons associated production

- provides a **precise test** of the QCD and EWK sectors

  $\rightarrow$ matrix element calculation and matching to parton shower
- has **sensitivity** to parton distribution functions

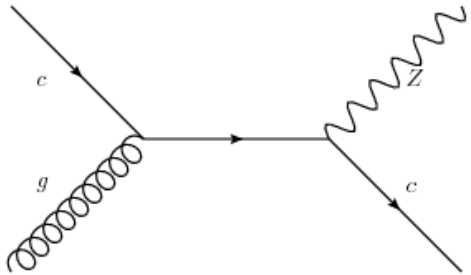
  $\rightarrow$ validation of pdfs determined at lower energies,
  constraints for more precise pdfs extraction
- is an irreducible **background** for other precise measurements and searches for new physics

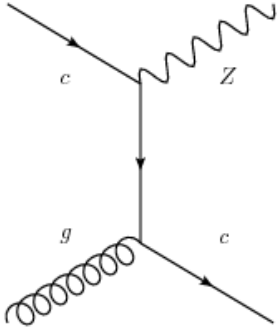
Measurements presented in this talk

- Z + c production at 8 TeV
- W + c production at 7 TeV
- Z + b (b $\bar{b}$) production at 8 TeV
- W + b $\bar{b}$ production at 8 TeV

Z + c associated production at 8 TeV - motivation

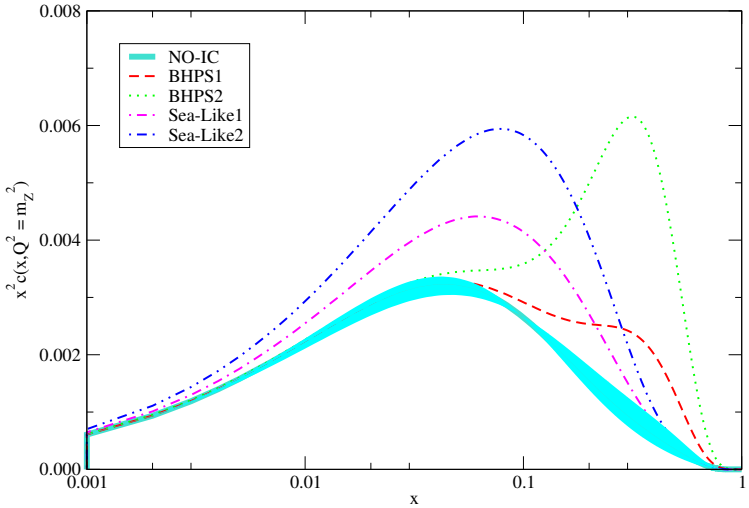
[CMS-PAS-SMP-15-009]





direct probe of the charm content at the **electroweak scale**

search for **intrinsic** charm content



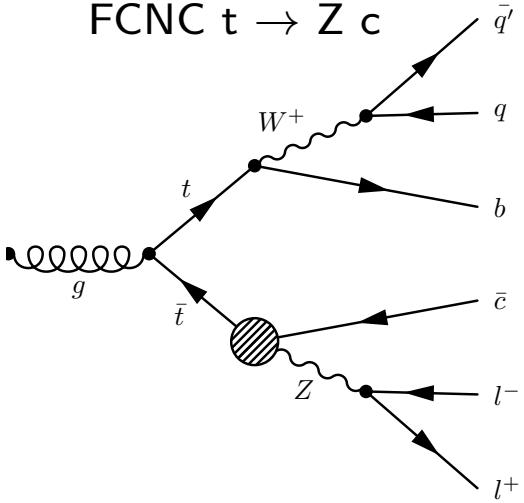
Eur. Phys. J. C 76 (2016) no.3, 105

precision test of the Standard Model:

σ (Z+c+X)/ σ(Z+X) $\sim$ 1% at 8 TeV

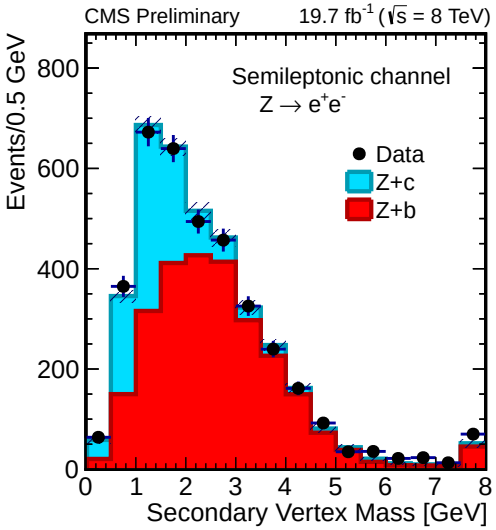
irreducible background to many searches:

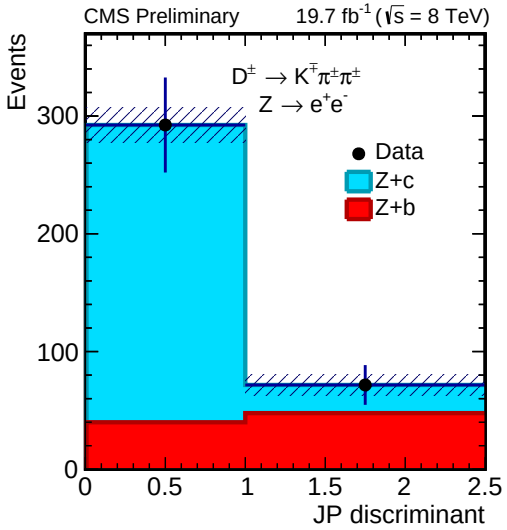
FCNC t $\rightarrow$ Z c

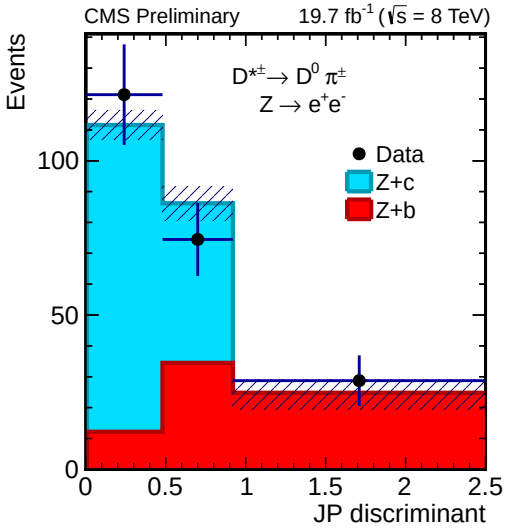


Z + c associated production at 8 TeV - strategy

- 2 isolated high p_T electrons or muons from Z leptonic decay
- at least one c- or b-quark jet identified using **3 different signatures**







semileptonic decay: secondary μ identified among jet constituents

$\to$ **Z+c and Z+b** signal yields extracted from a template fit to the **secondary vertex mass**

$D^\pm \to K^\mp \pi^\pm \pi^\pm$:
3 prong secondary vertex consistent with a $D^\pm$ decay

$D^{*\pm} \to D^0 (\bar{D}^0) \pi_s^\pm$
$D^0 (\bar{D}^0) \to K^\mp \pi^\pm$:
2 prong secondary vertex from a D^0 ($\bar{D}^0$) associated to a primary $D^{*\pm}$ decay

$\to$ **Z+c** signal yield extracted from a template fit to the **jet probability discriminant**

Z + c associated production - inclusive cross sections

- $Z \to l^+ l^-$: 2 leptons with $p_T^l > 20$ GeV, $|\eta^l| < 2.1$, $71 < M_{ll} < 111$ GeV
- at least one c- or b-quark jet with $p_T^{jet} > 25$ GeV, $|\eta^{jet}| < 2.5$, $\Delta R(\text{jet}, l) > 0.5$

  $\sigma(p\ p \to Z + c + X) \times \mathcal{B}(Z \to l^+ l^-) = 8.6 \pm 0.5$ (stat.) ± 0.7 (syst.) pb
  $\sigma(p\ p \to Z + c + X)/\sigma(p\ p \to Z + b + X) = 2.0 \pm 0.2$ (stat.) ± 0.2 (syst.)

  $\to$ 10-15% precision measurement

- **MADGRAPH LO (up to 4 partons at LO) + PS:** cross section and ratio in agreement

  $\sigma(p\ p \to Z + c + X) \times \mathcal{B}(Z \to l^+ l^-) = 8.14 \pm 0.03$ (stat.) ± 0.25 (PDF) pb
  $\sigma(p\ p \to Z + c + X)/\sigma(p\ p \to Z + b + X) = 1.805 \pm 0.006$ (stat.) ± 0.004 (PDF)

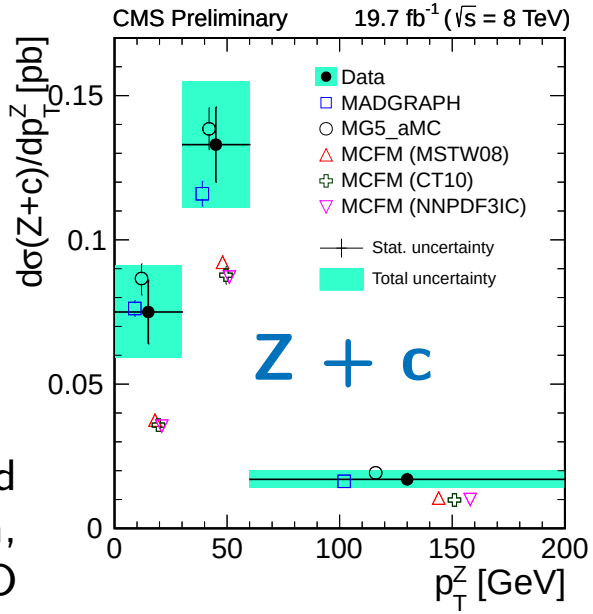
- **MADGRAPH5_AMC@NLO (up to 2 partons at NLO) + PS:**
  cross section slightly higher, ratio in agreement

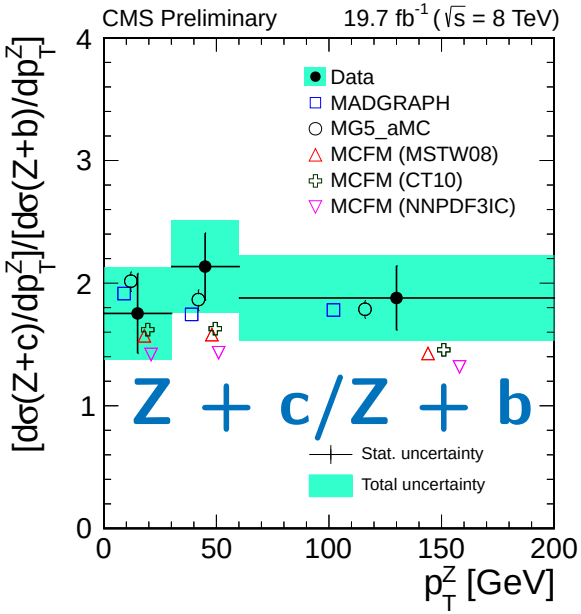
  $\sigma(p\ p \to Z + c + X) \times \mathcal{B}(Z \to l^+ l^-) = 9.47 \pm 0.04$ (stat.) ± 0.15 (PDF) ± 0.50 (scale) pb
  $\sigma(p\ p \to Z + c + X)/\sigma(p\ p \to Z + b + X) = 1.87 \pm 0.07$ (stat.) ± 0.50 (scale)

- **MCFM fixed order NLO + NP corrections:** cross section and ratio significantly smaller
- no significant difference using PDF set with/without intrinsic charm component

Z + c associated production - differential cross sections

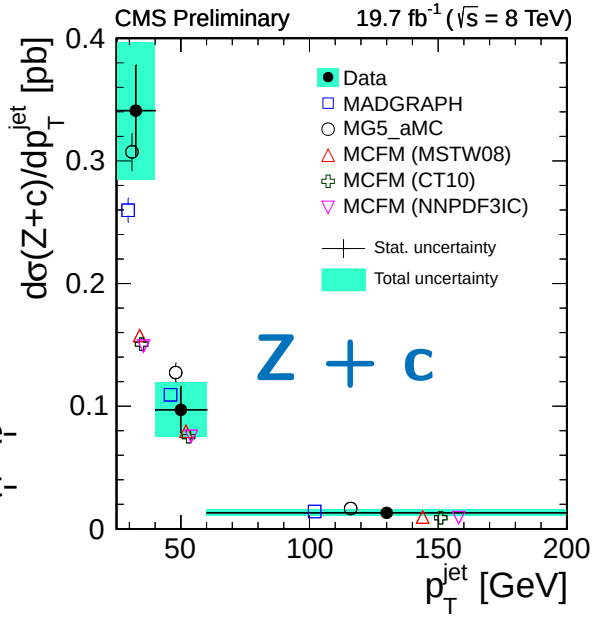
Z boson p_T →

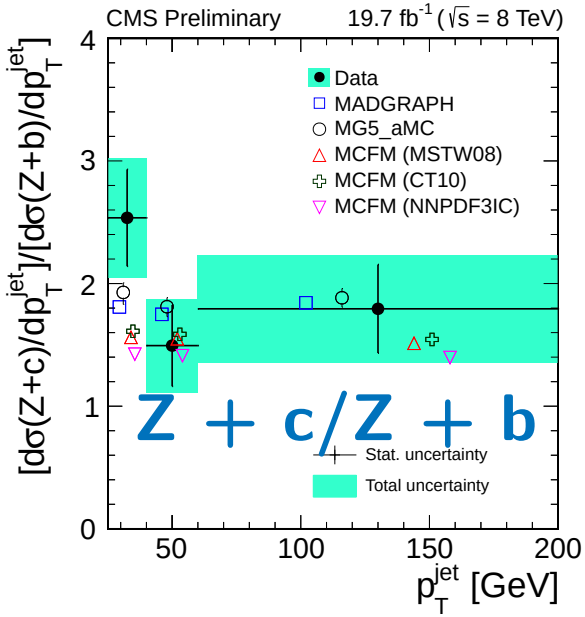




Fixed-order matrix elements matched to parton shower describe the data, both at LO **(MADGRAPH)** and NLO **(MADGRAPH5_AMC@NLO)**

heavy flavor jet p_T →

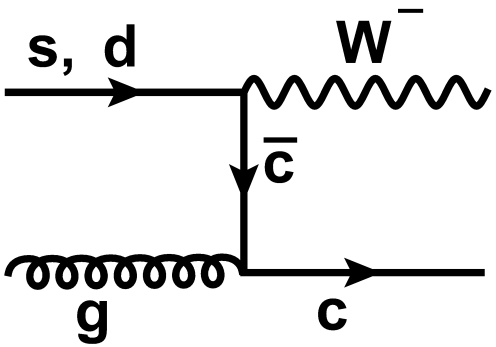


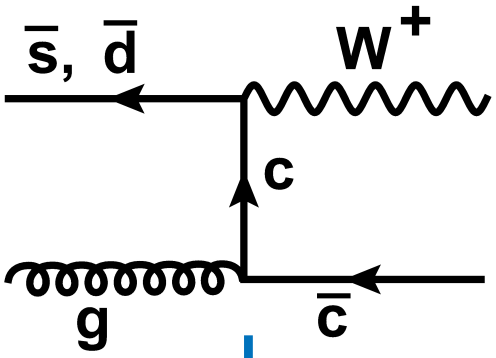


MCFM fixed order NLO predictions underestimate the cross sections, especially in the low p_T region, slightly better agreement for the ratios

W + c associated production at 7 TeV - motivation

[JHEP 1402 (2014) 013]





direct probe of the strange content at the **electroweak scale**

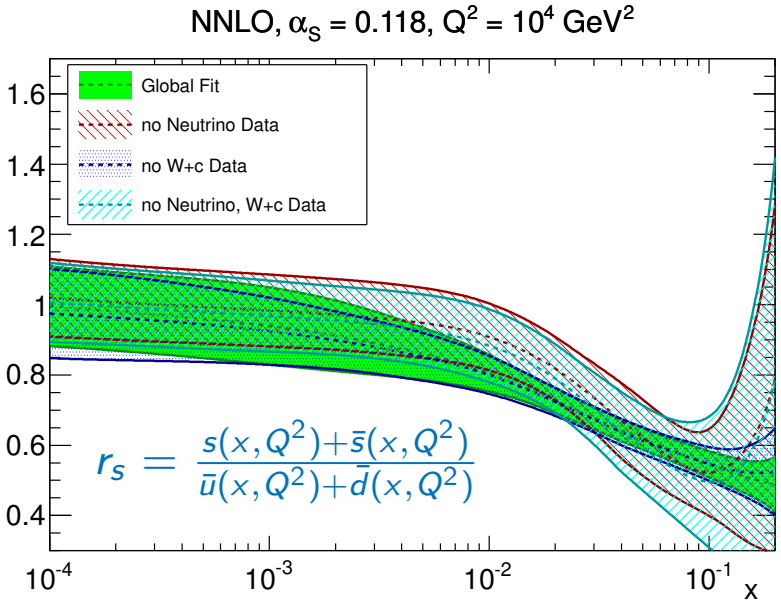
$g\,s \to c\,W^-$, $g\,\bar{s} \to \bar{c}\,W^+$ dominate at LO

$g\,d \to c\,W^-$, $g\,\bar{d} \to \bar{c}\,W^+$ are Cabibbo suppressed

CMS results included into NNPDF3.0

direct probe of a possible s - s̄ asymmetry

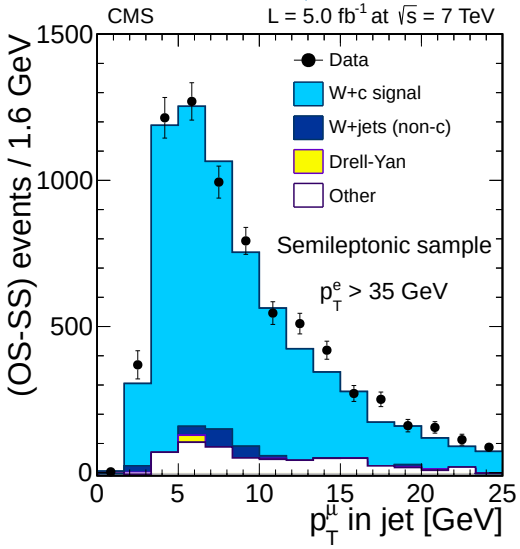
differential cross section versus the rapidity of the lepton from the W decay



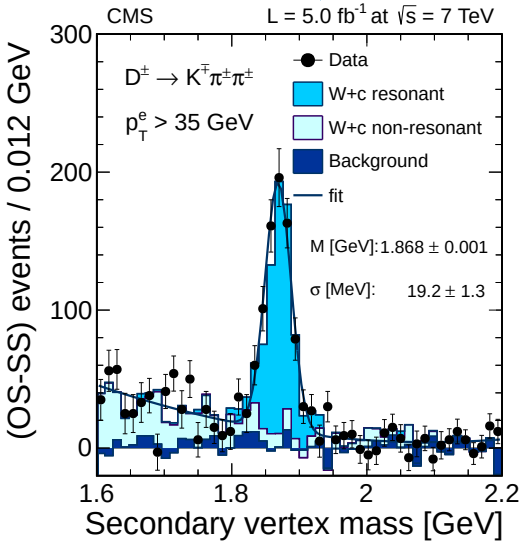
JHEP 1504 (2015) 040 (NNPDF3.0)

W + c associated production at 7 TeV - strategy

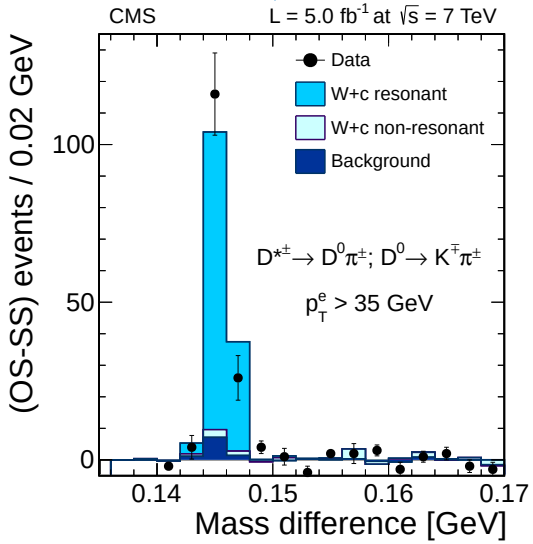
- 1 isolated high p_T electron or muon from W leptonic decay
- transverse mass of the W candidate $M_T > 40$ (55) GeV in the muon (electron) channel
- at least one c-quark jet identified using **3 different signatures**



semileptonic decay: secondary μ identified among jet constituents



$\mathbf{D^\pm \to K^\mp\ \pi^\pm\ \pi^\pm}$**:** secondary vertex mass

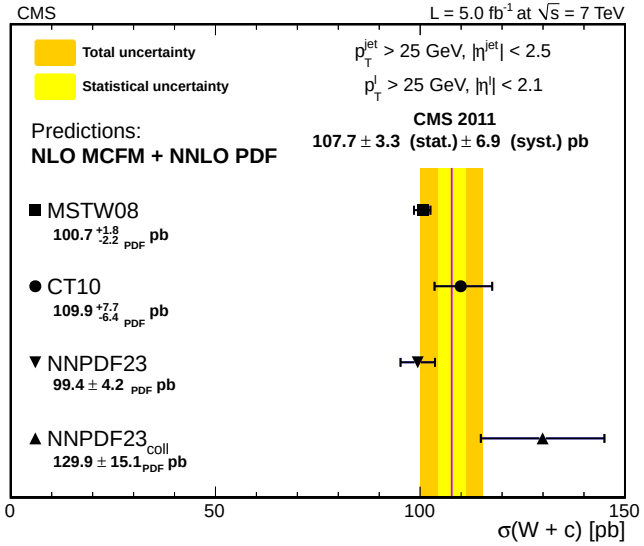


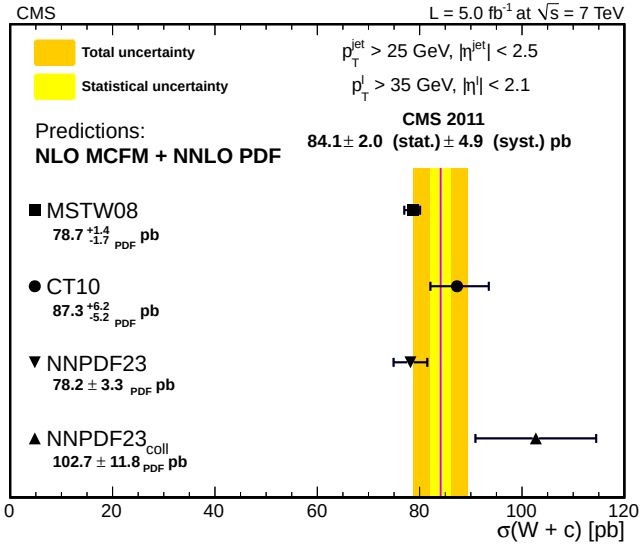
$\mathbf{D^{*\pm} \to D^0\ (\bar{D}^0)\ \pi_s^\pm}$
$\mathbf{D^0\ (\bar{D}^0) \to K^\mp\ \pi^\pm}$**:**
Mass $D^{*\pm}$ - Mass D^0 ($\bar{D}^0$)

Signal: W boson and charm quark with **opposite** charge
Subtraction of the **same** charge W + c contribution
→ distributions **largely dominated by the genuine W+c component**

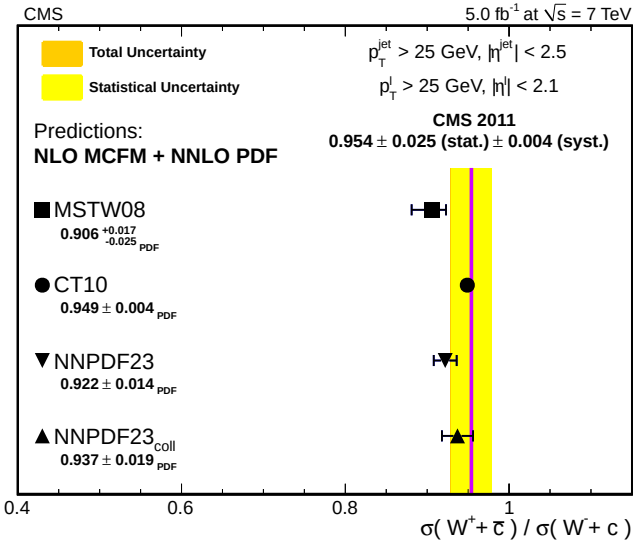
W + c associated production - inclusive cross sections

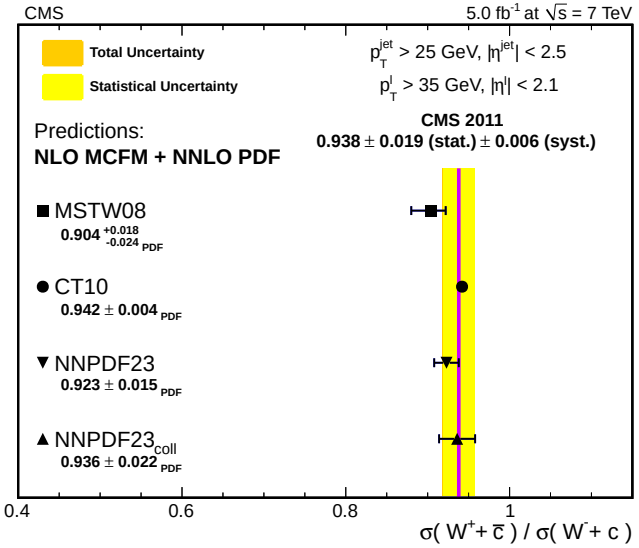
inclusive W + c cross section ($W^+ + \bar{c}$ or $W^- + c$)





cross section ratio $\sigma(W^+ + \bar{c})$ / $\sigma(W^- + c)$





c-quark jet: $p_T > 25$ GeV
$|\eta| < 2.5$

lepton: $p_T > 25$ or 35 GeV
$|\eta| < 2.1$

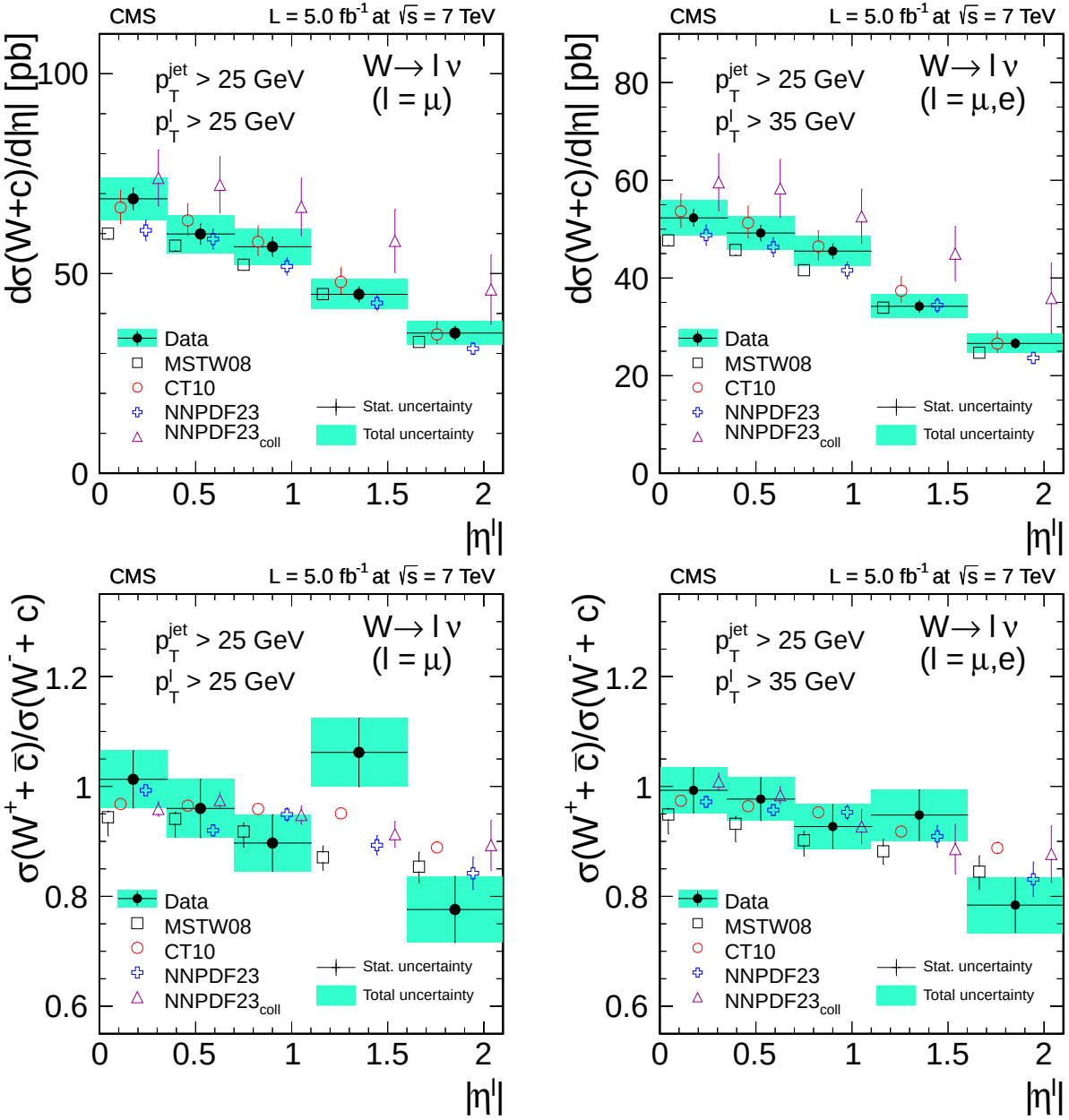
MCFM NLO predictions with different NNLO pdfs

→ **good agreement** for pdfs including neutrino DIS charm data:

MSTW08,CT10,NNPDF23

→ **too large strangeness** content for **NNPDF23coll** which is not including neutrino DIS charm data

W + c associated production - differential cross sections



MCFM NLO predictions with different NNLO pdfs

→ **good agreement** for pdfs including lower energy charm data

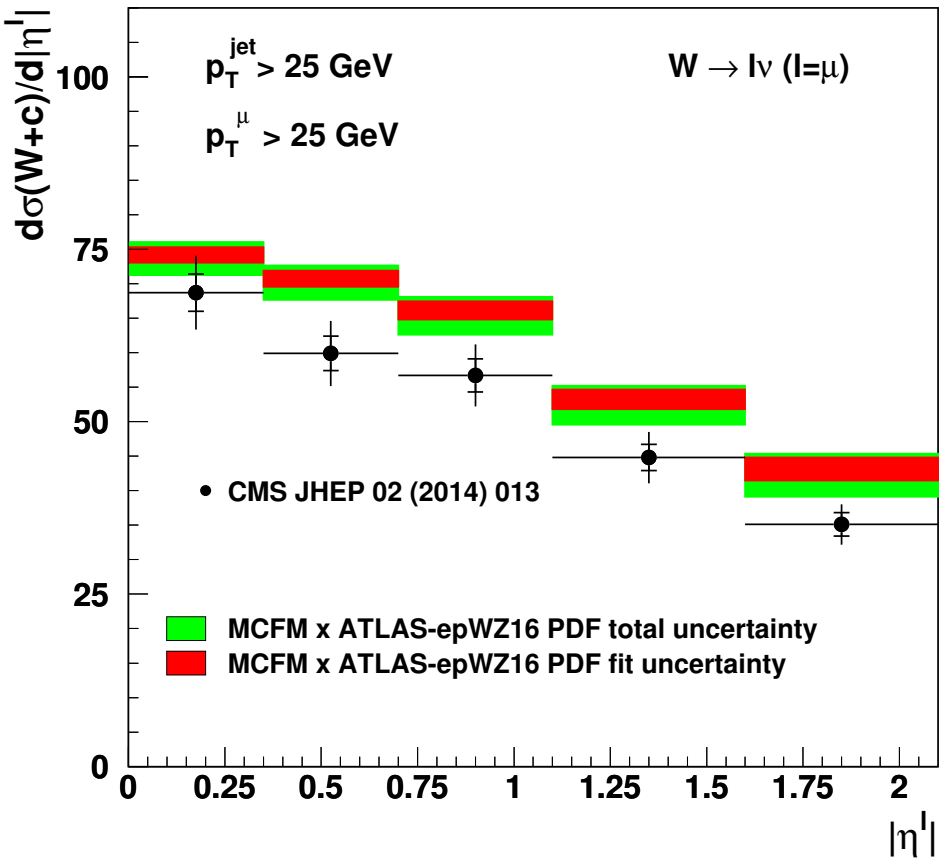
→ **NNPDF23coll** predicts a too large strange contribution

ratio sensitive to both s-s̄ and d-d̄ asymmetry

larger yield for g d → c W$^-$
→ $\sigma(W^+ + \bar{c})/\sigma(W^- + c) < 1$

larger x probed in forward region
→ ratio decreases with η^l as d-d̄ asymmetry larger at large x

W + c associated production - comparison to ATLAS pdfs



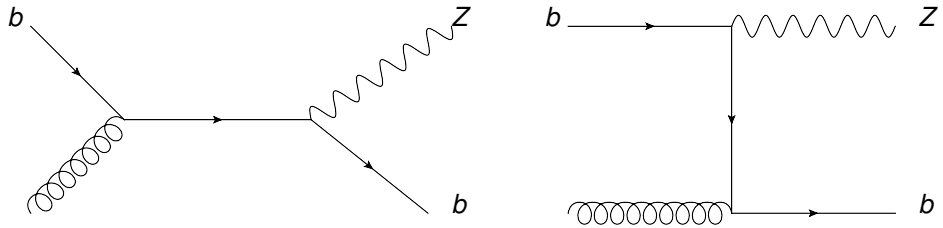
MCFM NLO predictions with NNLO ATLAS-epWZ16 pdfs
arXiv:1612.03016 [hep-ex]

ATLAS-epWZ16 pdfs based on inclusive and differential W and Z cross sections measured by ATLAS at 7 TeV and HERA ep DIS data

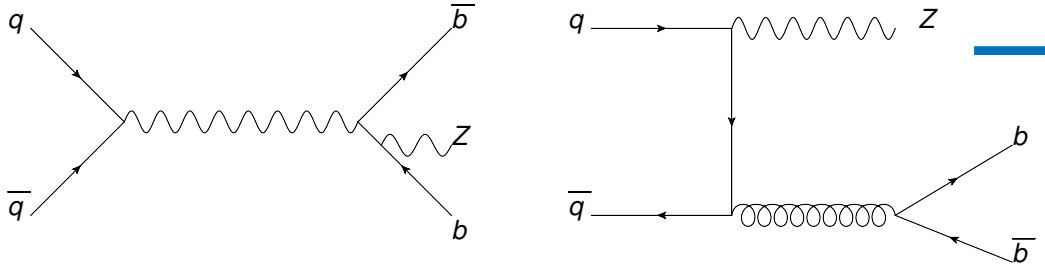
→ **ATLAS-epWZ16 pdfs** predict too large strange contribution when compared to CMS measurement

Z + b (b $\bar{b}$) production at 8 TeV - motivation & selection

[Submitted to Eur.Phys.J.C (2016)]



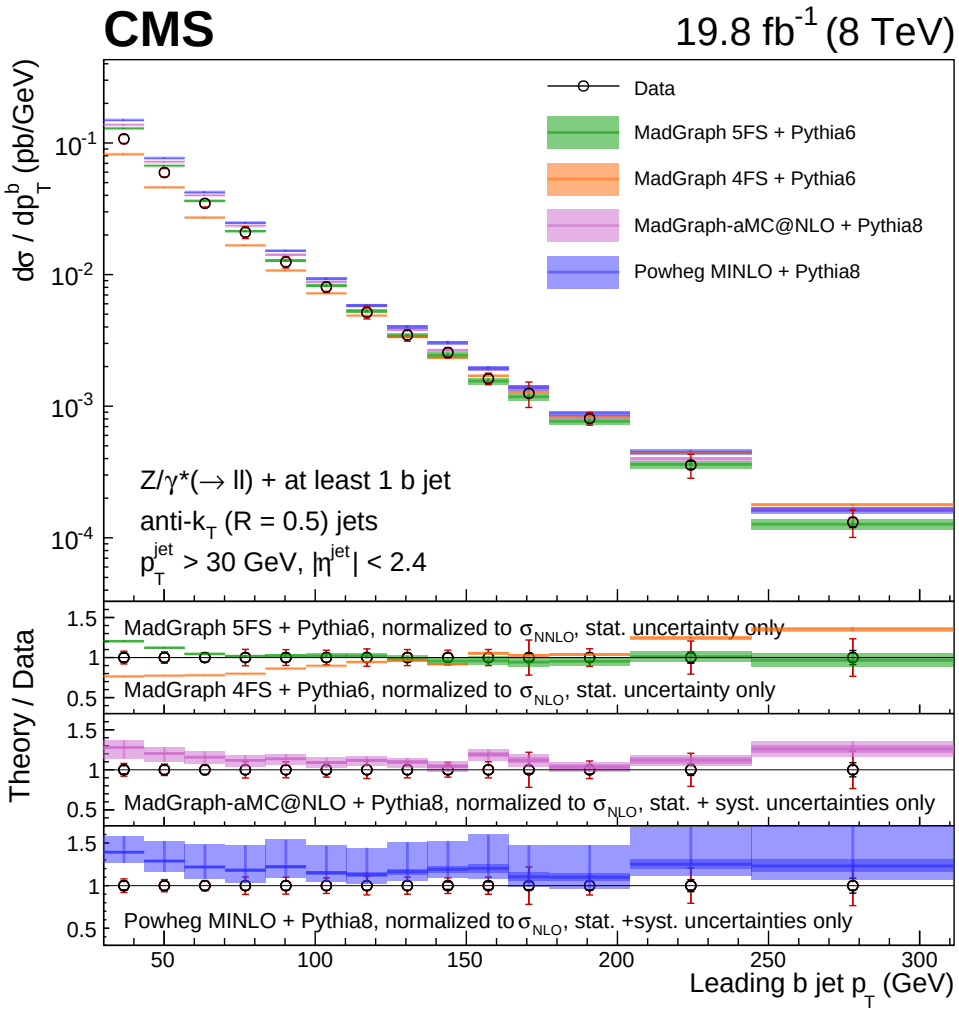
→ **dominant background** in Z + H(b $\bar{b}$) and in several new physics scenarios

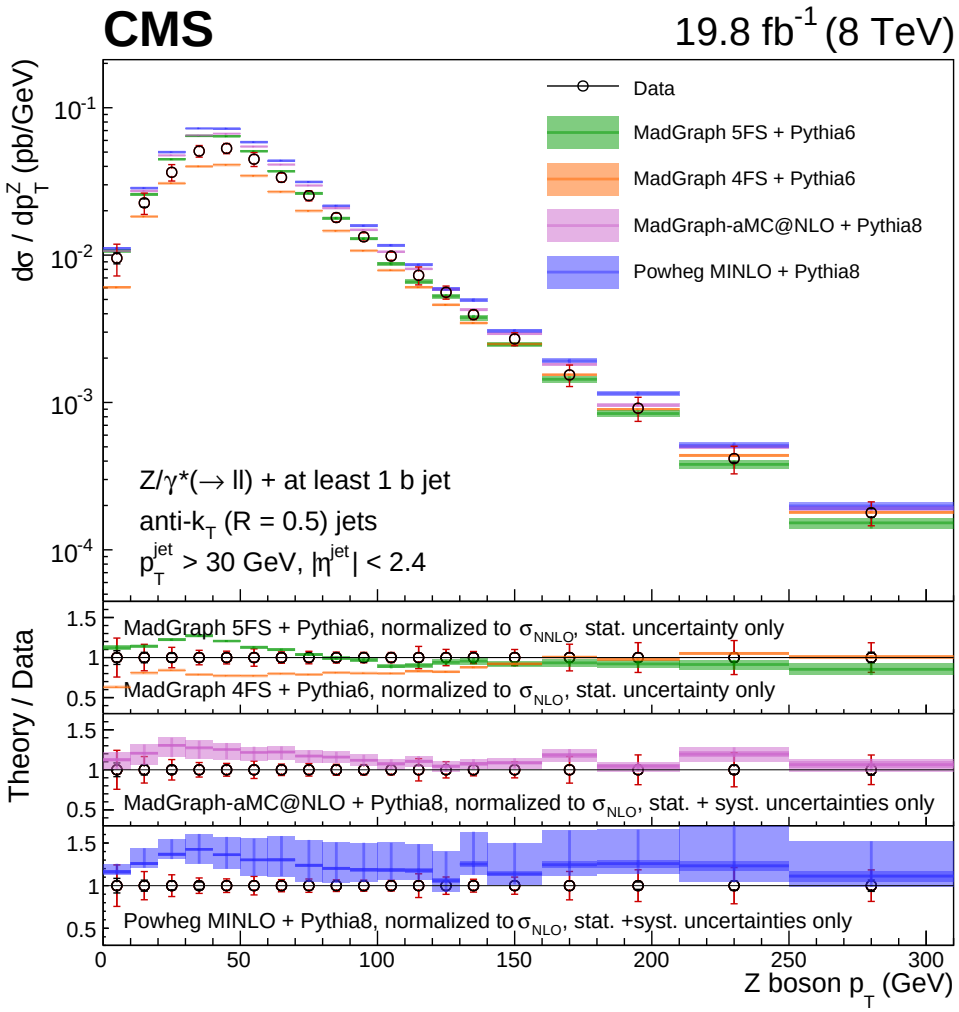


→ **precise test** of different approaches to QCD heavy flavor sector

- **fixed 4 flavor scheme:** g → b $\bar{b}$ absent from pdf, massive b quark in ME
  variable 5 flavor scheme: g → b $\bar{b}$ can contribute to pdf, massless b quark in ME
- **LO** MADGRAPH in **4FS** (MSTW2008) and **5FS** (CTEQ6L1)
  NLO MADGRAPH5_AMC@NLO and POWHEG in **5FS** (NNPDF30)
- 2 leptons with $p_T^l > 20$ GeV, $|\eta^l| < 2.4$, $71 < M_{ll} < 111$ GeV
  at least one b-quark jet with $p_T^{jet} > 30$ GeV, $|\eta^{jet}| < 2.4$

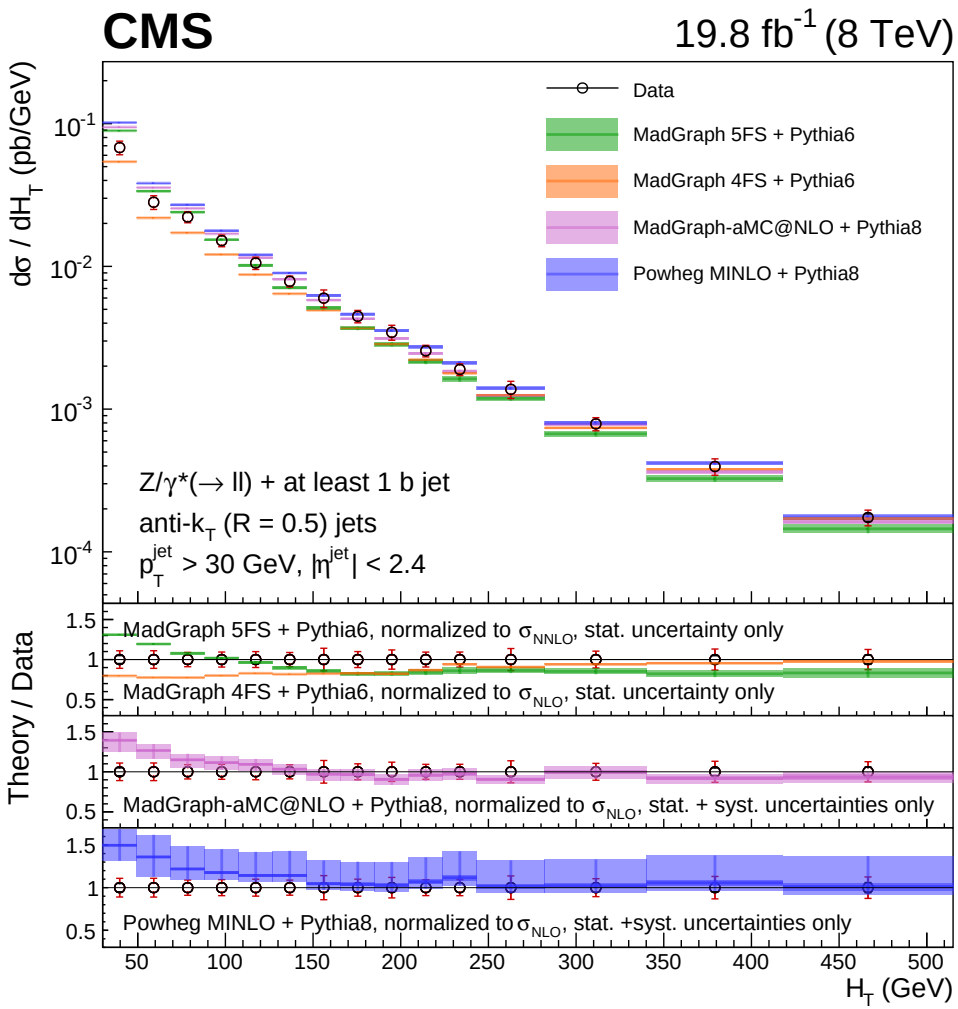
Z + at least one b jet - leading b jet and Z p_T

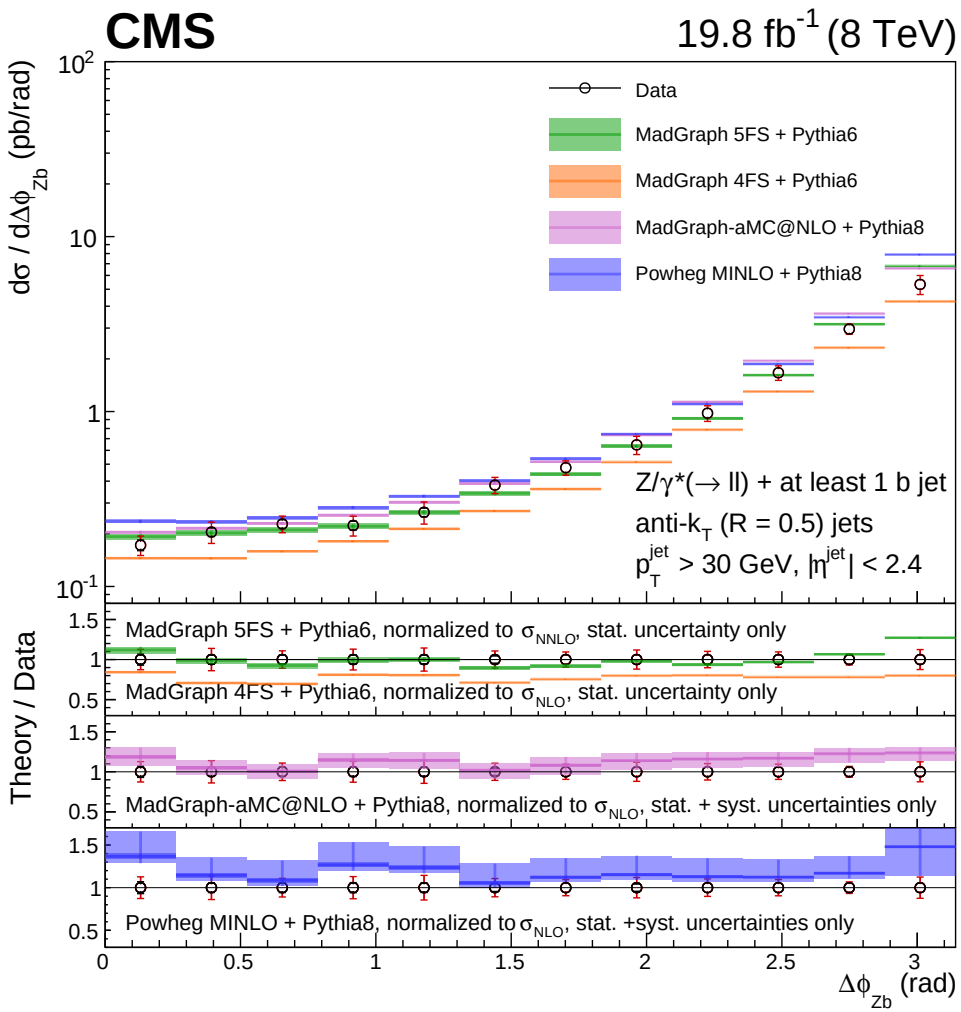




All theoretical predictions show similar agreement with the data and do not succeed to describe the spectra in the low p_T region
$\rightarrow$ need for NLL soft gluon resummation at all orders
difference between the 4 and 5 FS more pronounced at low p_T

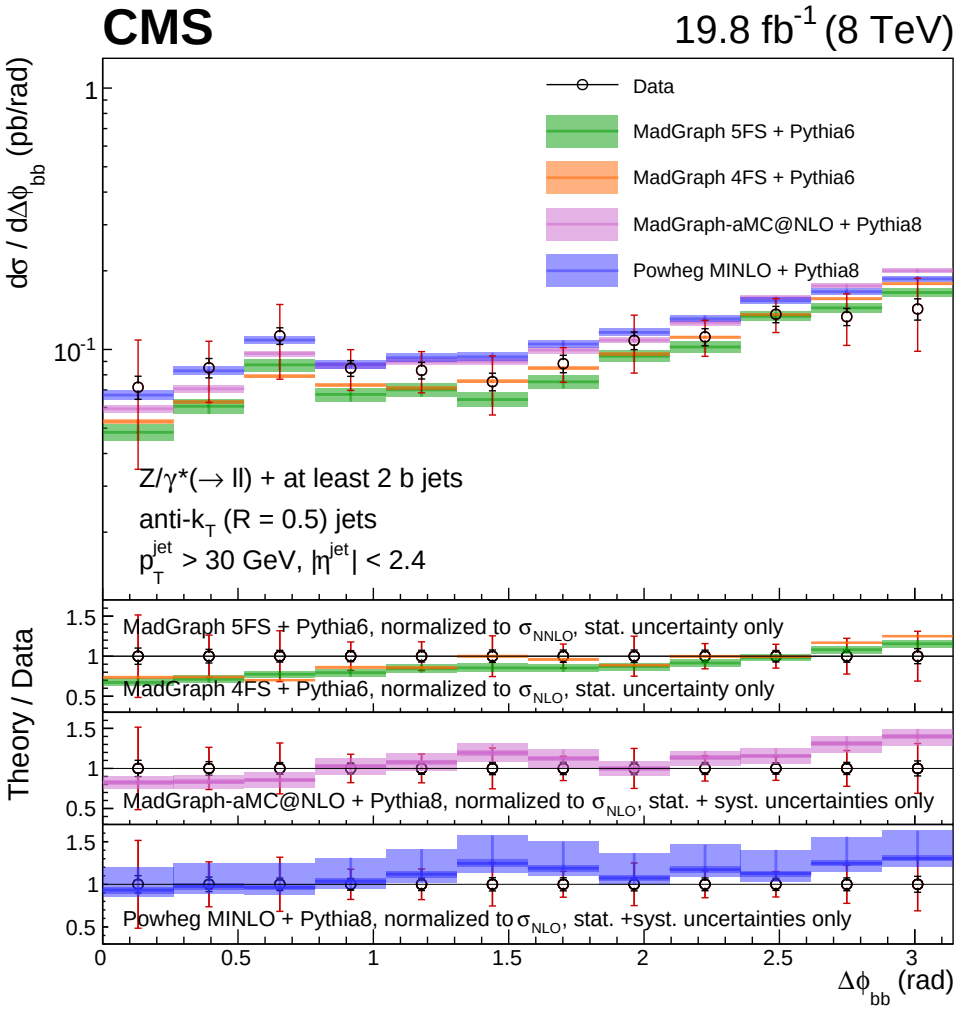
Z + at least one b jet - scalar jet p_T sum and $\Delta\varphi_{Zb}$

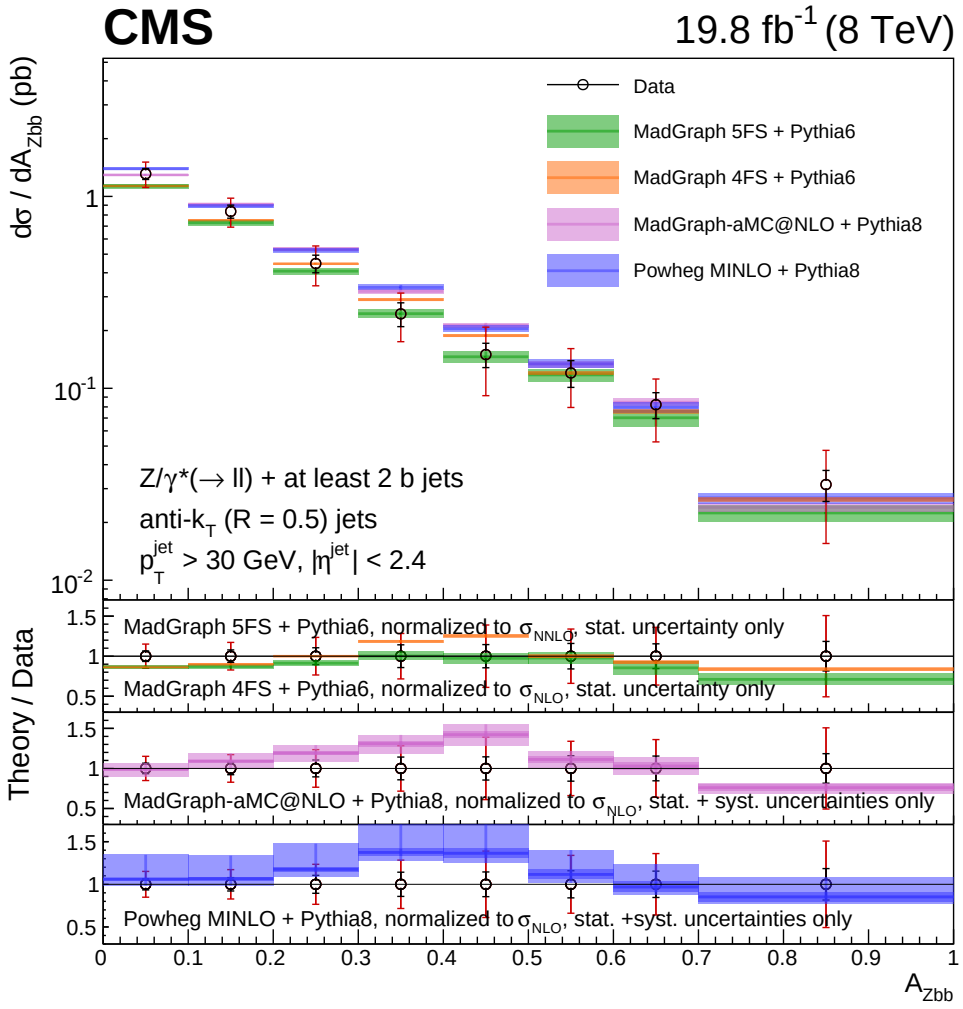




low H_T region more difficult to describe
as well as back-to-back and collinear Z b configurations

Z + at least two b jets - $\Delta\varphi_{b\bar{b}}$ and $A_{Zb\bar{b}}$





$\Delta\varphi_{b\bar{b}}$ shows large decorrelation better described by NLO predictions

$A_{Zb\bar{b}} \sim \Delta$ R (Z, closest b jet) - Δ R (Z, farthest b jet)

few (more) extra radiations $\rightarrow$ (a)symmetric configuration $\rightarrow A_{Zb\bar{b}} \sim 0$ (~ 1)

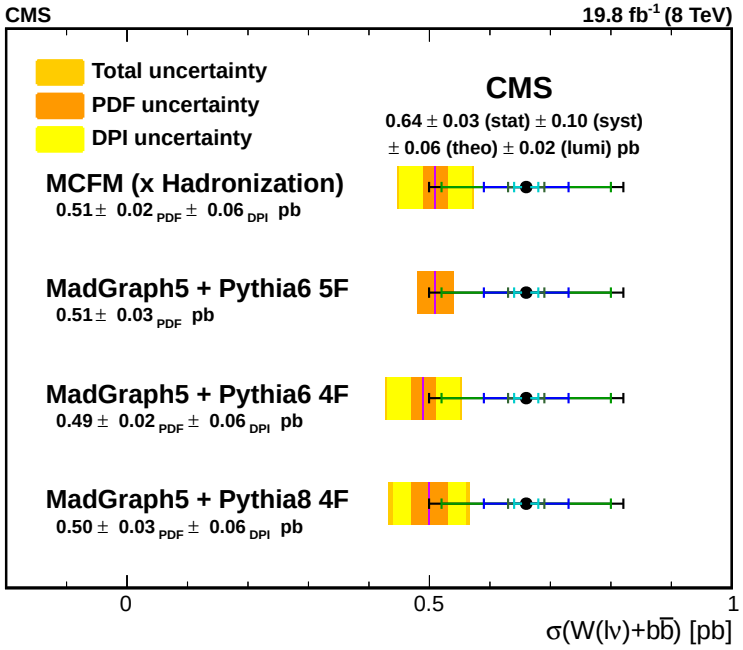
intermediate region more difficult to describe

W + b $\bar{b}$ associated production at 8 TeV

→ **dominant background** in W + H(b $\bar{b}$) and in several new physics scenarios
precise test of different approaches to QCD heavy flavor sector

→ electron or muon from W leptonic decay with $p_T > 30$ GeV and $|\eta| < 2.1$
exactly 2 b-quark jets with $p_T > 25$ GeV and $|\eta| < 2.4$
no other jets with $p_T > 25$ GeV and $|\eta| < 4.7$

σ(p p $\rightarrow$ W(l ν) + b $\bar{b}$) = 0.64 $\pm$ 0.03 (stat) $\pm$ 0.10 (syst) $\pm$ 0.06 (theo) $\pm$ 0.02 (lumi) pb

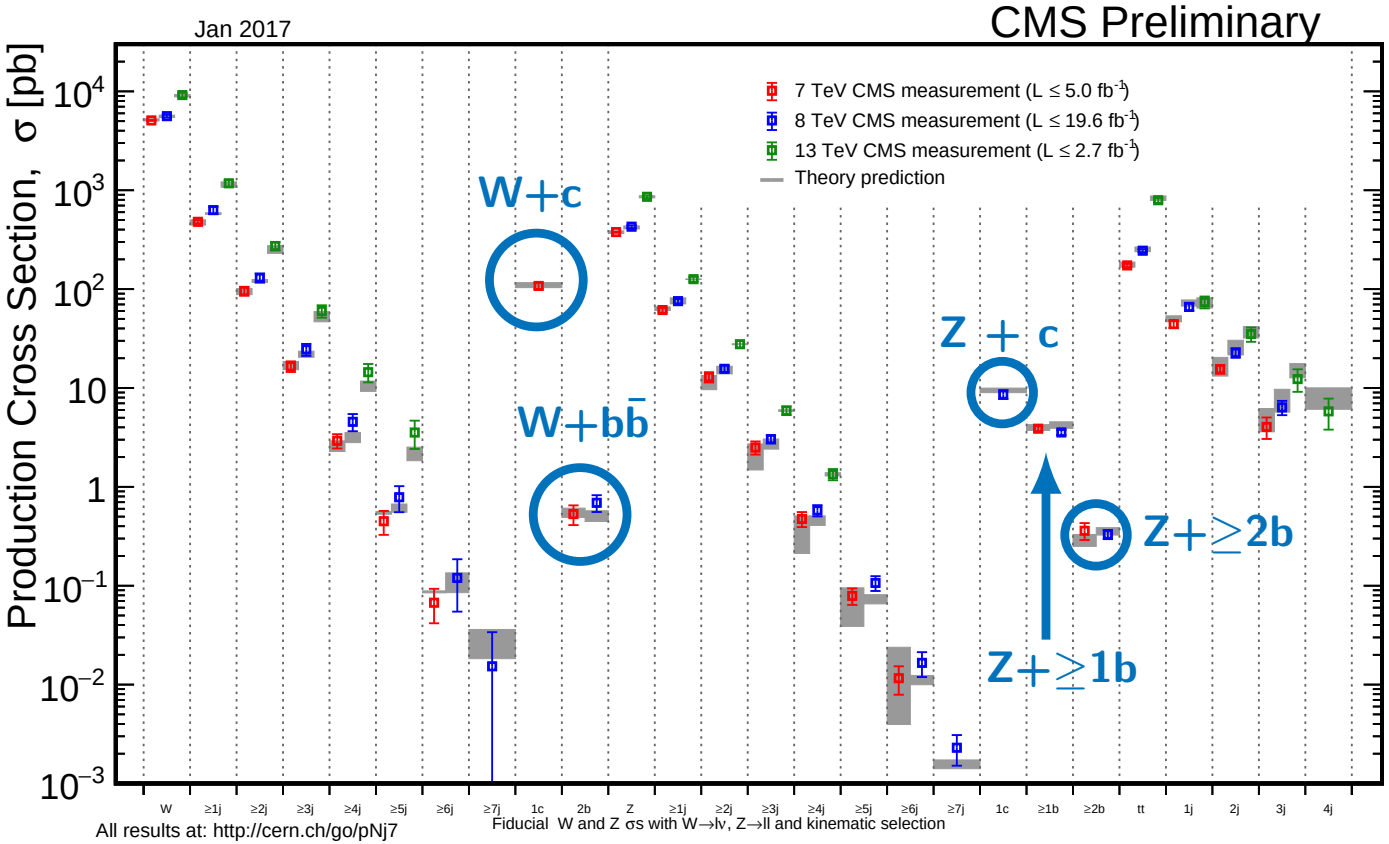


→ comparison to different predictions
NLO MCFM (MSTW2008)
LO MADGRAPH5 + Pythia6 4FS (NNPDF2.3 LO)
+ Pythia6 5FS (CTEQ6L)
+ Pythia8 4FS (NNPDF2.3 LO)

[Eur. Phys. J. C 77 (2017) no.2, 92]

Conclusion

- Heavy quarks and W/Z bosons associated production provides precise test of the QCD and EWK sectors
- They enable to validate pdfs determined at lower energies and provide constraints for more precise pdfs extraction
- Their precise knowledge has an impact on precision Higgs measurements and searches for new physics



Thanks for your attention!

Back up