Associated production of vector bosons and heavy flavours with the CMS experiment

07 September 2023

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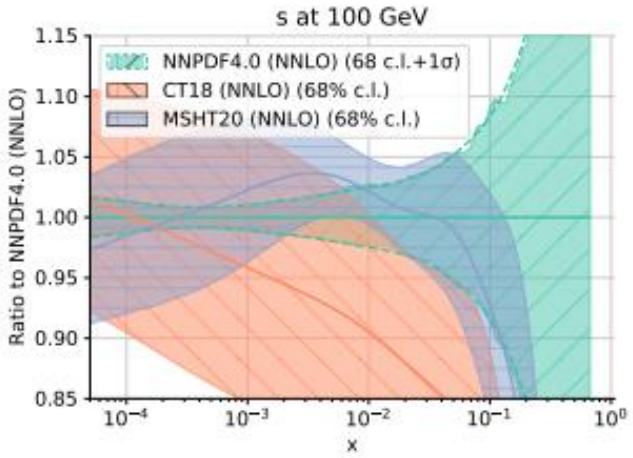
On behalf of the CMS Collaboration

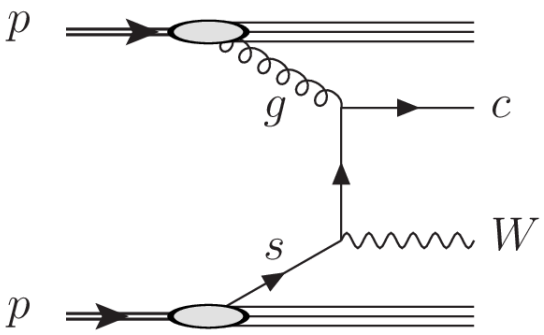
U.S. DEPARTMENT OF ENERGY | Office of Science
Grant DE-SC0023908

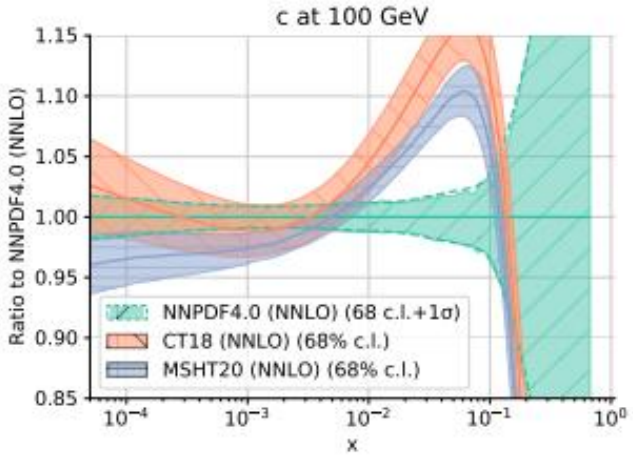
Why Vector boson + heavy flavour (HF) quarks?

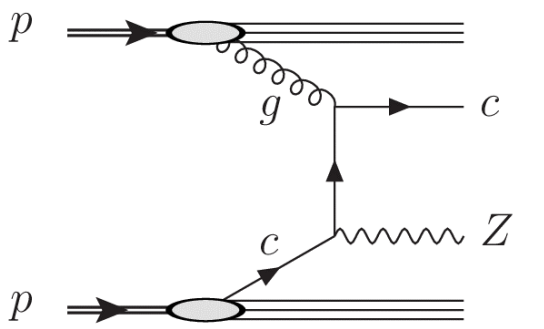
Probes the HF content of the proton PDF

arXiv:2109.02653





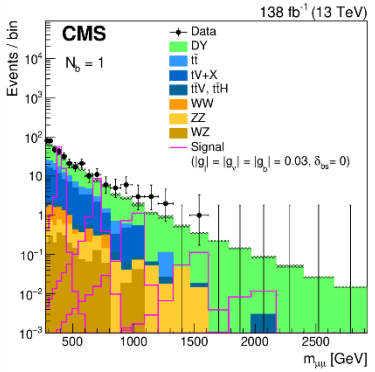


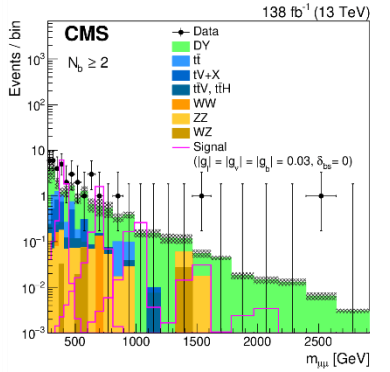


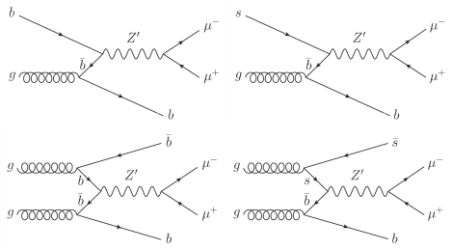
Constrains the V+HF backgrounds

Search for a high-mass dimuon resonance produced in association with b quark

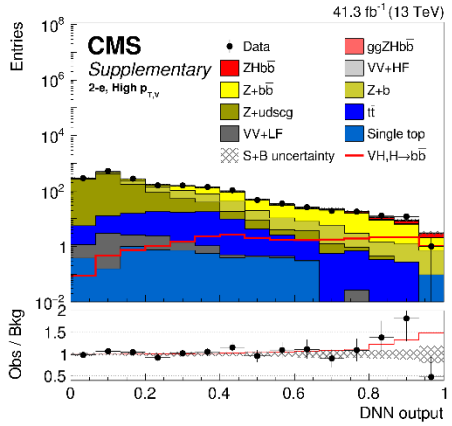
arXiv:2307.08708

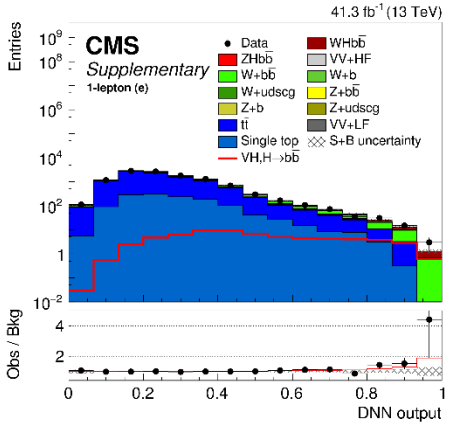




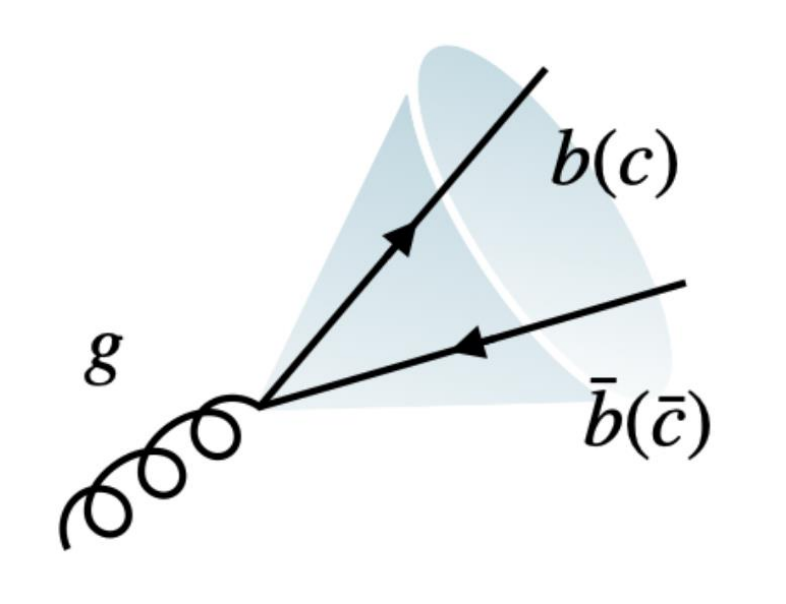


Observation of Higgs boson decay to bottom quarks Phys. Lett. B 778 (2018) 121801





Heavy flavour tagging at CMS



https://cms.cern/news/performance-jet-flavour-algorithms-ml-calibrate-ml-data

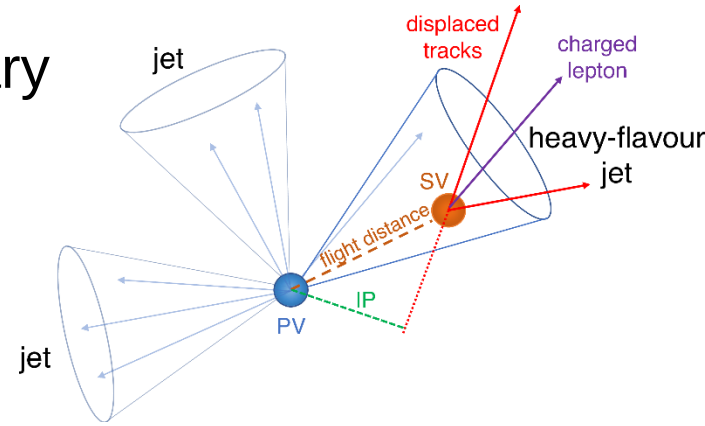
Identification of heavy-flavour jets
JINST 13 (2018) P05011

A new calibration method for c jets
JINST 17 (2022) P03014

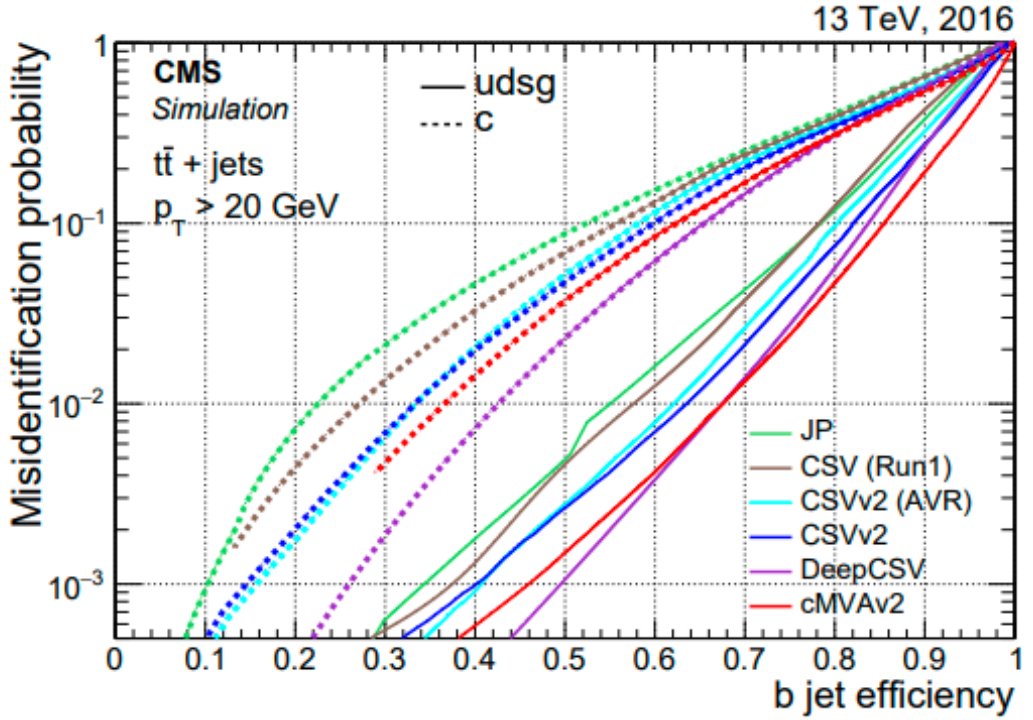
Identification of heavy-flavour jets

JINST 13 (2018) P05011

- Tagging based on Deep Neural Networks and Combined Secondary Vertex tagger (DeepCSV)
- Exploiting combined heavy flavour quark kinematic properties:
  - ✓ Secondary vertex
  - ✓ Impact parameter
  - ✓ Lifetime
  - ✓ Multi-tracking



The DeepCSV is trained for b-jets vs both c- or light- jets

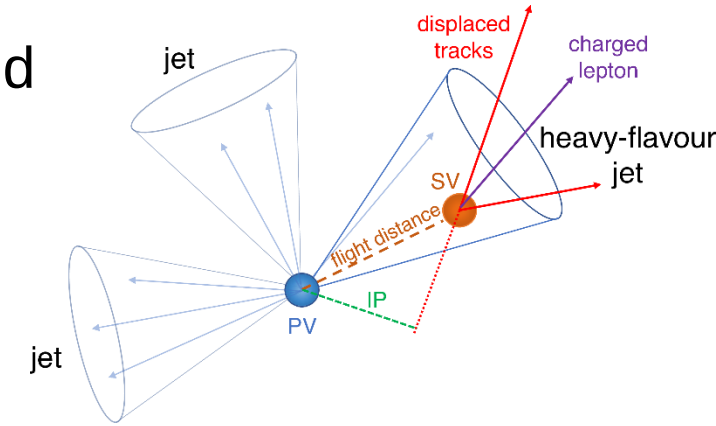


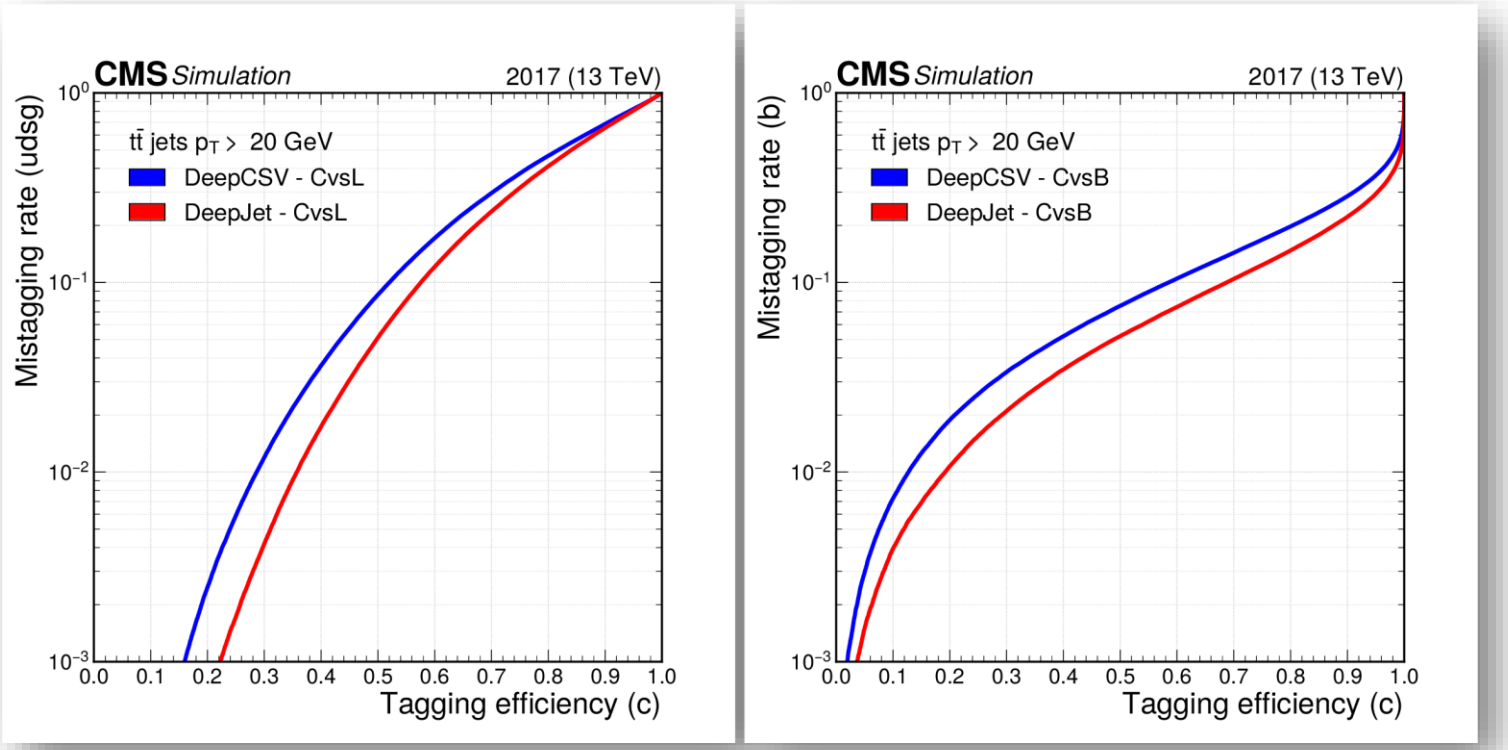
Identification of heavy-flavour jets

JINST 17 (2022) P03014

- Charm jet tagging based b-tagging discrimination in between b and light jets

Tagger	BvsC/L	CvsB	CvsL
DeepCSV	$P(b)+P(bb)$	$\frac{P(c)}{P(c)+P(b)+P(bb)}$	$\frac{P(c)}{P(c)+P(udsg)}$





c-jets are calibrated using W+c events

Selection	Jet yield	c %	b %	udsg %
W+c	362 002	**92.9**	0.957	6.14
$t\bar{t}$	380 366	12.1	**81.0**	6.91
DY + jet	8 509 206	8.87	5.05	**86.1**

Recent results from CMS experiment in pp collisions at $\sqrt{s} = 13$ TeV

W + c quark (2308.02285, Submitted to EPJC)

Z + c jets (JHEP 04 (2021) 109)

Z + b jets (PRD 105 (2022) 092014)

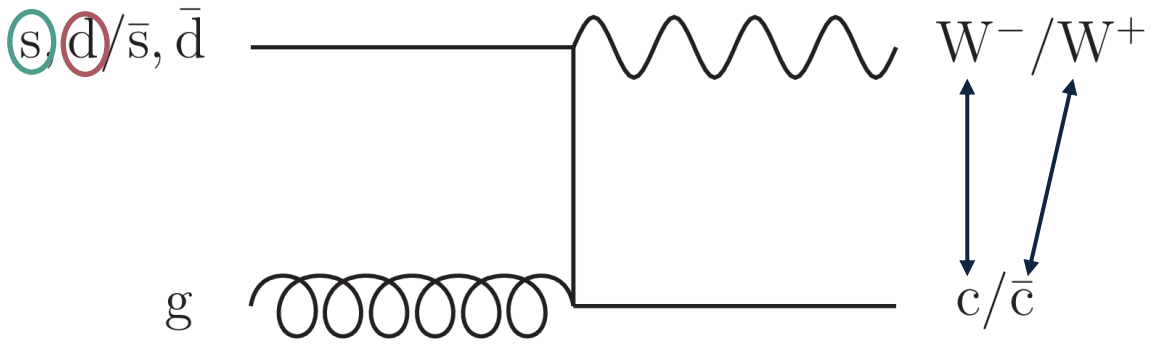
W boson + charm

2308.02285,
Submitted to EPJC

Strange quark content of the proton

+ $s/\bar{s}$ asymmetry

d + g → W + c is Cabibbo supressed



Charm tagging:

- A muon inside the jet (SL channel)
- A displaced secondary vertex inside the jet (SV channel)

Charm charge:

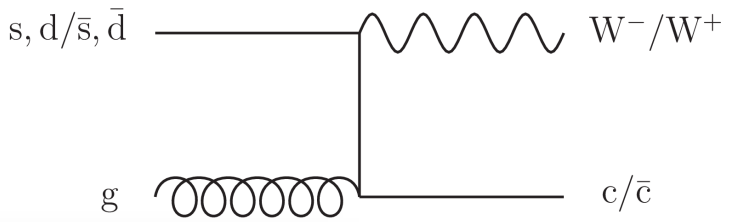
- Muon charge (SL channel)
- Sum of charged of tracks originating from the secondary vertex (SV channel)

- Analysis rely on the correlation between c-jet charge and lepton charge from the W boson leptonic decay: background rejection using SS-OS subtraction

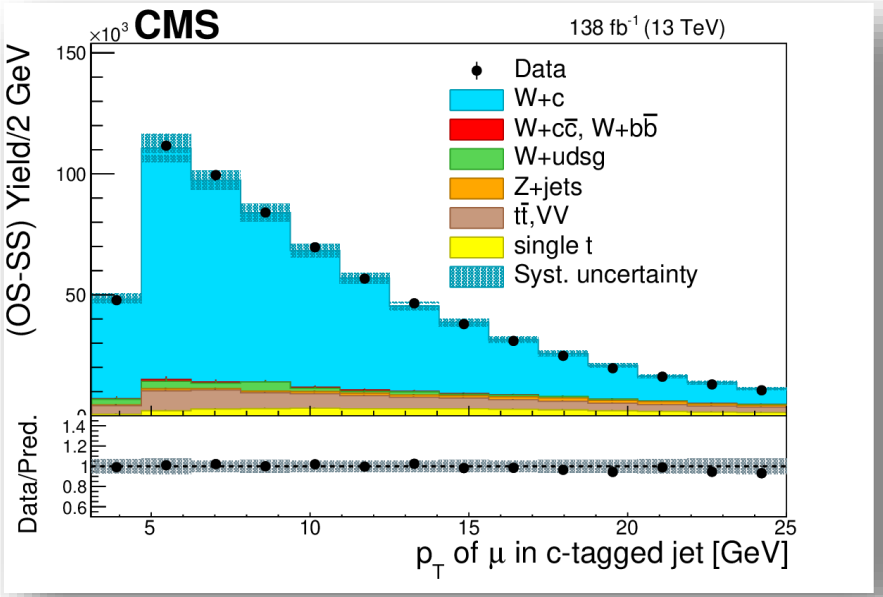
W boson + charm

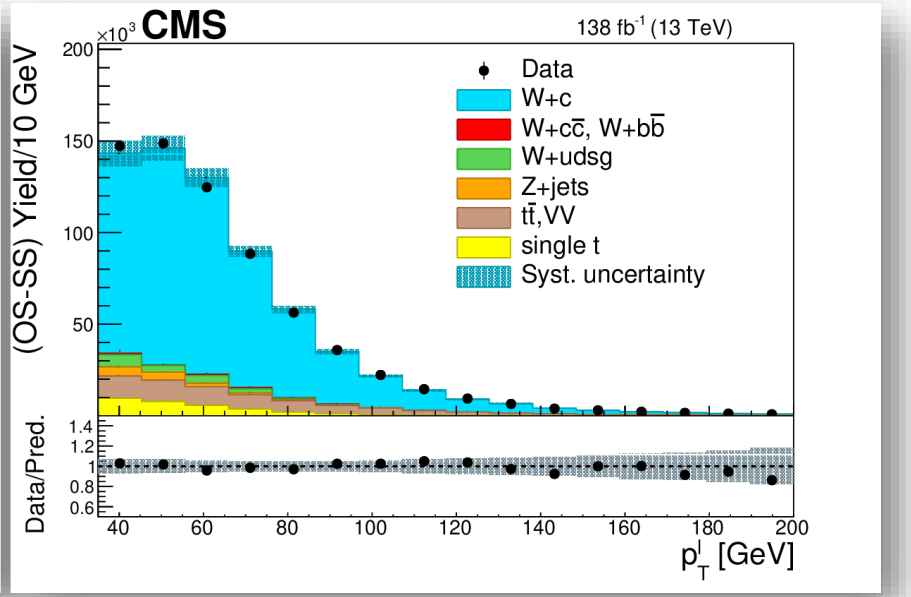
2308.02285,
Submitted to EPJC

SL channel



High event purity (due to a good c-jet charge ID)





SL channel	W+c	W + QQ̄	W + udsg	Z+jets	tt̄	Single t	VV
$W \to e\nu$	81.0 ± 0.6	0.5 ± 0.3	3.1 ± 0.5	0.4 ± 0.1	10.0 ± 0.1	4.4 ± 0.1	0.6 ± 0.1
$W \to \mu\nu$	74.2 ± 0.5	0.5 ± 0.3	2.0 ± 0.4	5.5 ± 0.2	11.6 ± 0.1	5.8 ± 0.1	0.4 ± 0.1

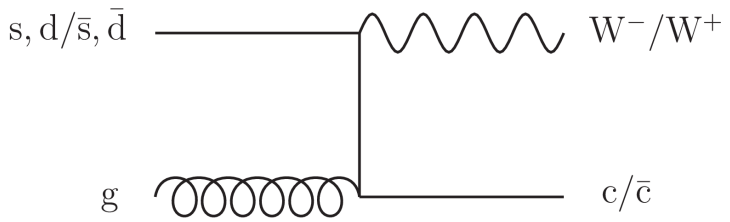
SL channel	Data	Background
$W \to e\nu$	$424\,047 \pm 1286$	$80\,646 \pm 933$
$W \to \mu\nu$	$263\,669 \pm 918$	$68\,108 \pm 917$

Simulated signal and background composition (in %)

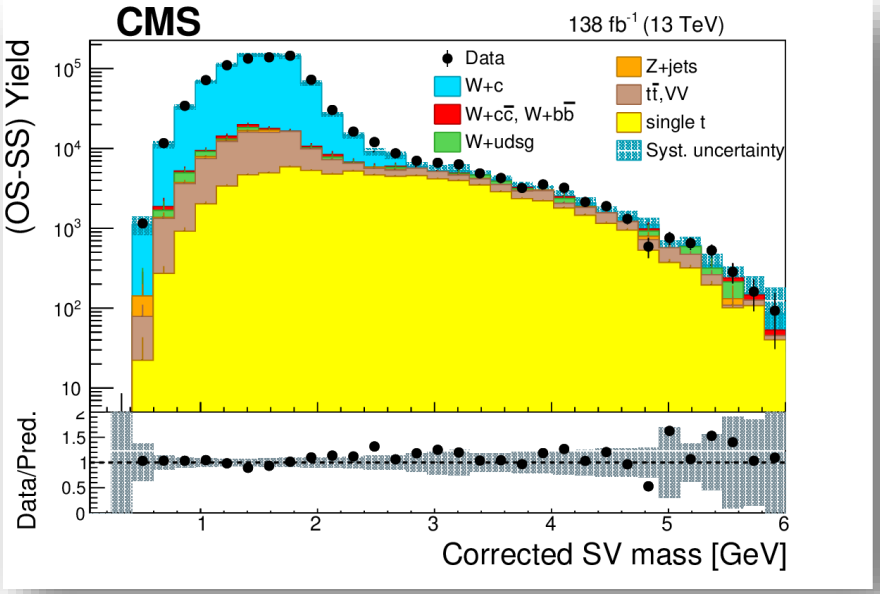
W boson + charm

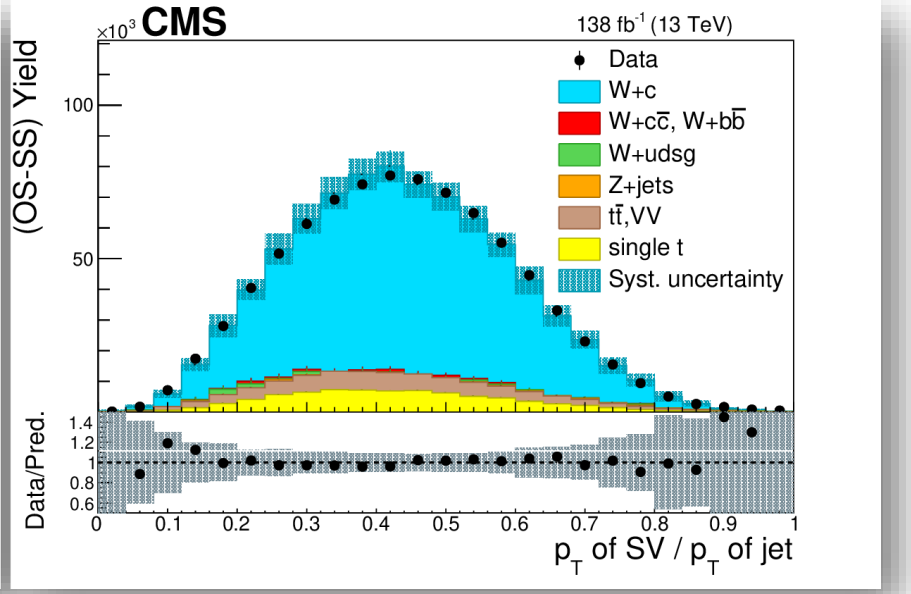
2308.02285,
Submitted to EPJC

SV channel



High event purity (due to a good c-jet charge ID)





SV channel	W+c	W + QQ̄	W + udsg	Z+jets	tt̄	Single t	VV
W → eν	82.1 ± 0.8	0.7 ± 0.4	1.0 ± 0.6	0.1 ± 0.2	7.2 ± 0.1	8.4 ± 0.1	0.5 ± 0.1
W → μν	80.9 ± 0.6	0.7 ± 0.3	0.5 ± 0.4	0.5 ± 0.2	8.0 ± 0.1	8.9 ± 0.1	0.5 ± 0.1

SV channel	Data	Background
W → eν	338 504 ± 1717	60 565 ± 1577
W → μν	494 264 ± 1876	94 356 ± 2002

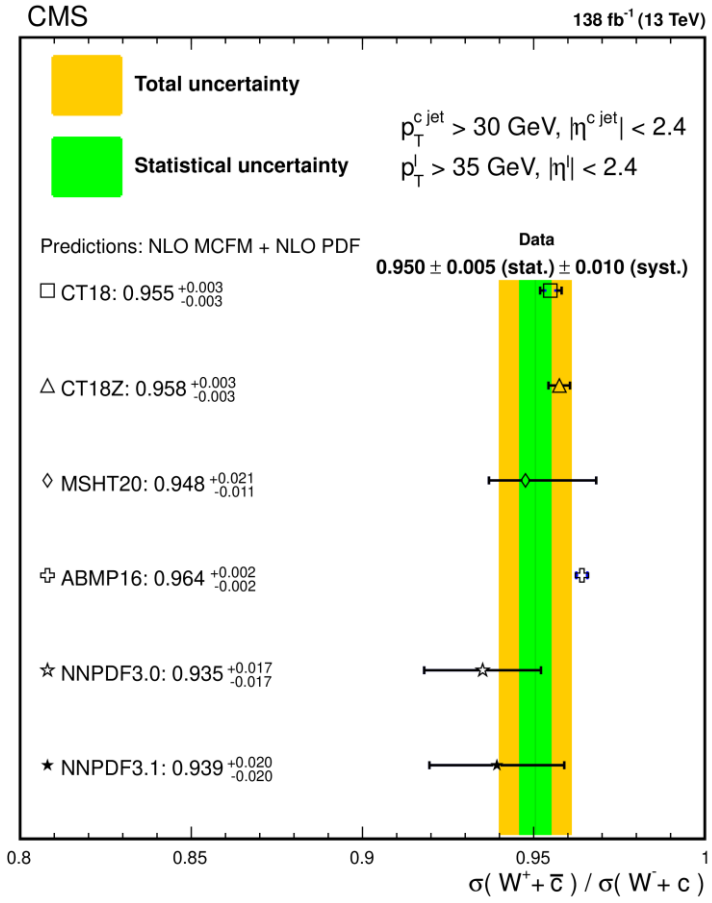
Simulated signal and background composition (in %)

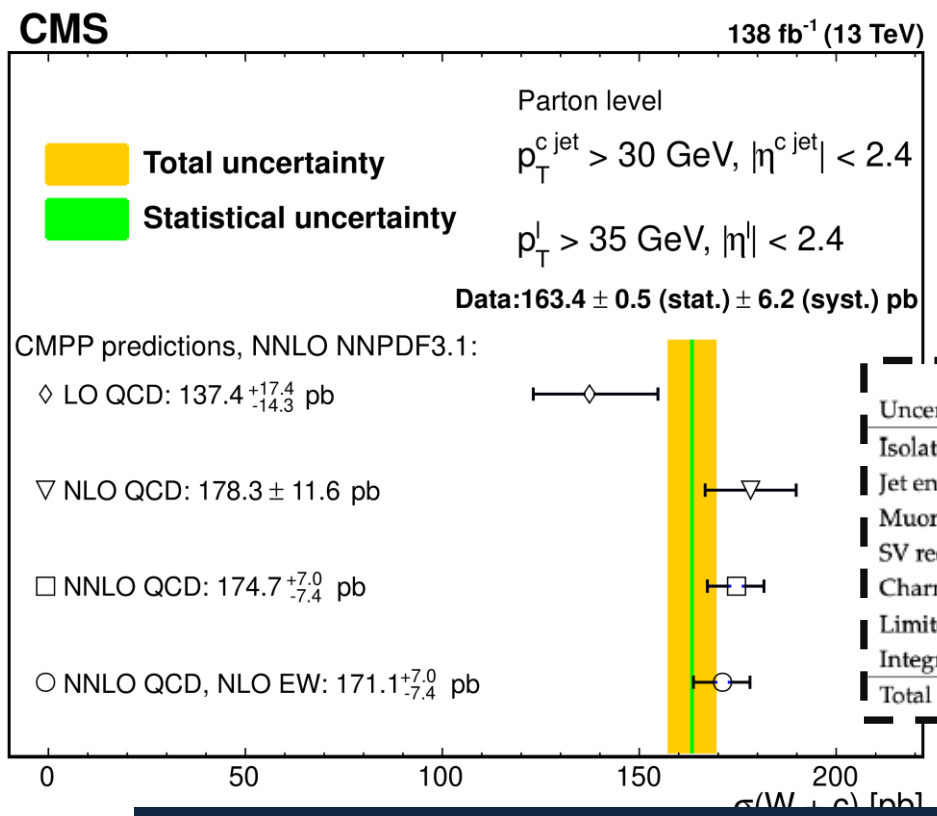
W boson + charm

2308.02285,
Submitted to EPJC

Results

W+c production cross section and $\sigma(W^+ + c)/\sigma(W^- + c)$ cross section ratio with full Run 2 data





Systematics:
Dominated by μ-ID / SV-reco

Uncertainty [%]	SL $W \to e\nu$	SL $W \to \mu\nu$	SV $W \to e\nu$	SV $W \to \mu\nu$
Isolated lepton identification	2	1	2	1
Jet energy scale and resolution	2	2	2	2
Muon in jet identification	3	3	-	-
SV reconstruction	-	-	3	3
Charm fragmentation and decay	2	2	2	2
Limited size of MC samples	1	1	1	1
Integrated luminosity	1.6	1.6	1.6	1.6
Total	5	5	5	5

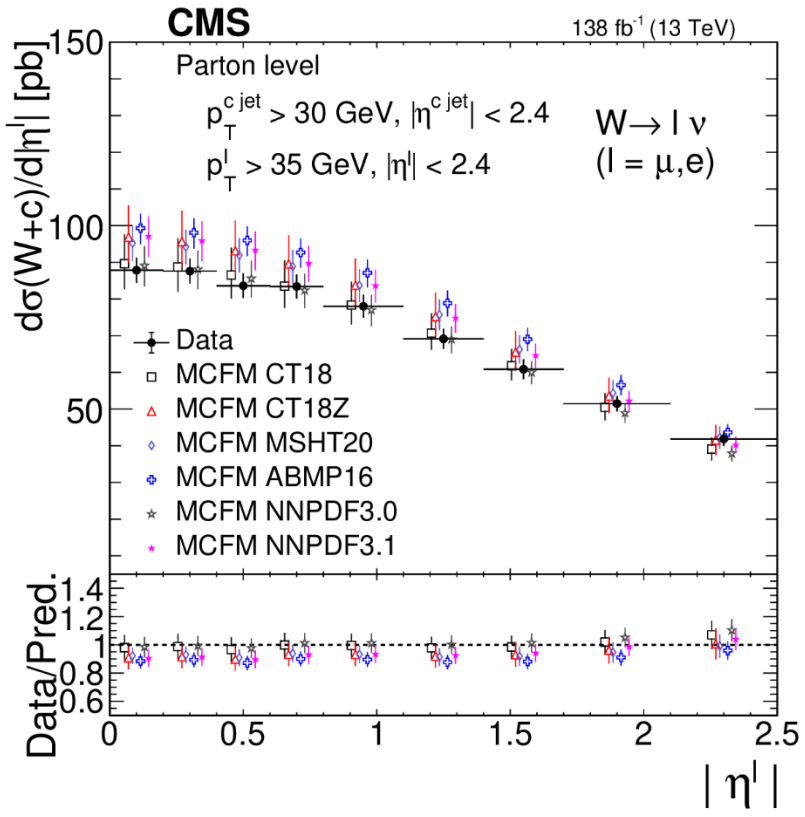
$\sigma(pp \to W + c) = 148.7 \pm 0.4(stat) \pm 5.6(syst)$ pb

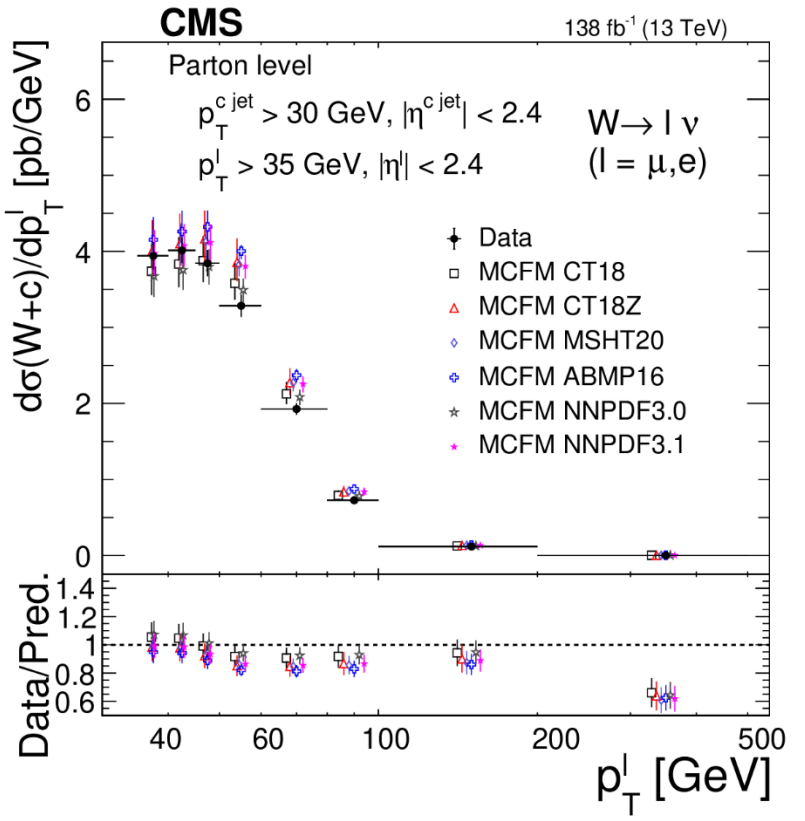
W boson + charm

2308.02285,
Submitted to EPJC

Results

Fiducial and differential unfolded cross section as a function of the pseudorapidity (η) and transverse momentum (pT) of the lepton from the W decay





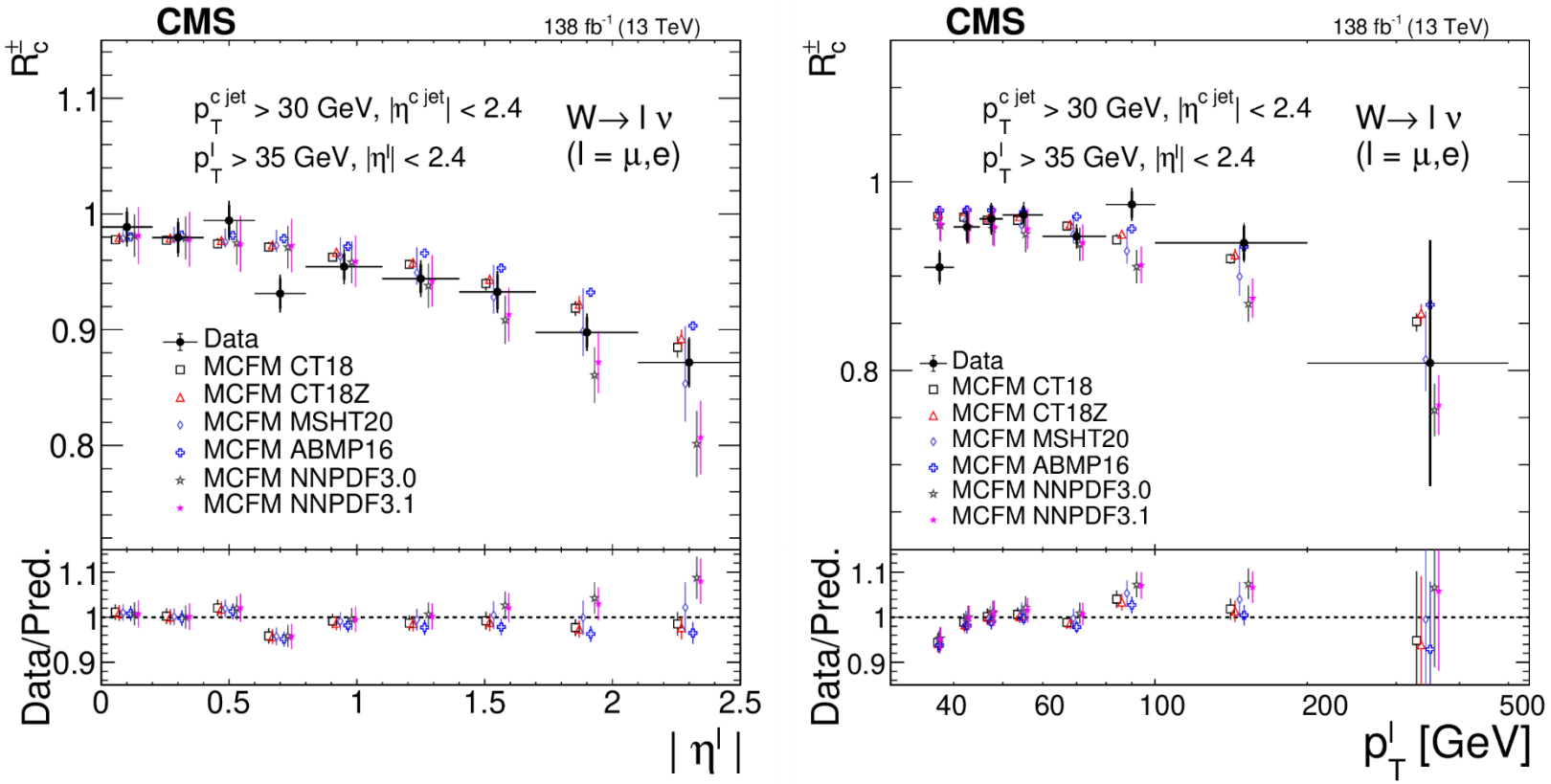
PDF & tune comparison

W boson + charm

2308.02285,
Submitted to EPJC

Results

Highest precision cross section ratio: $R_c^{\pm} = \sigma(W^+ + \bar{c})/\sigma(W^- + c)$ as a function of the pseudorapidity (η) and transverse momentum (pT) of the lepton from the W decay

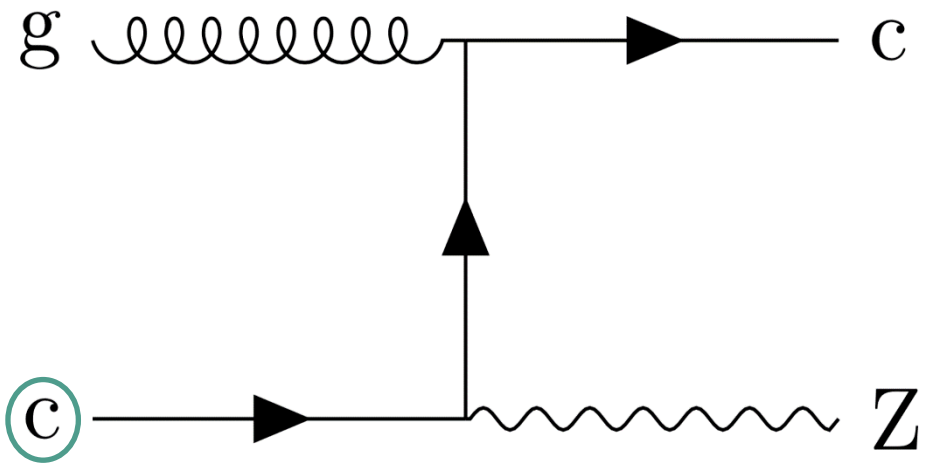


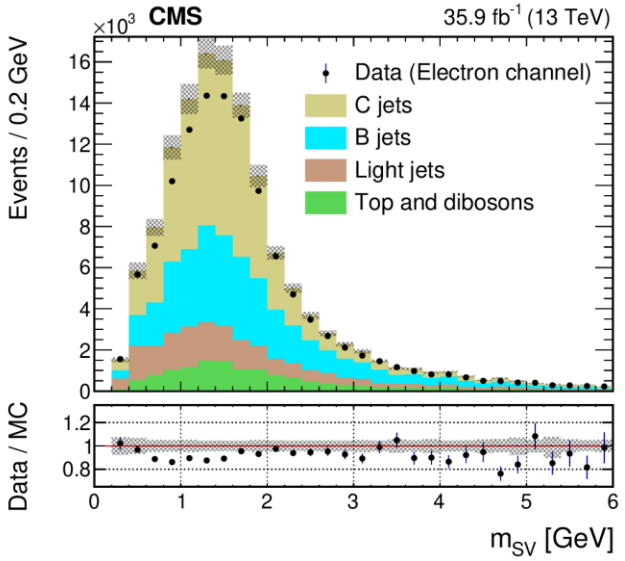
PDF & tune comparison

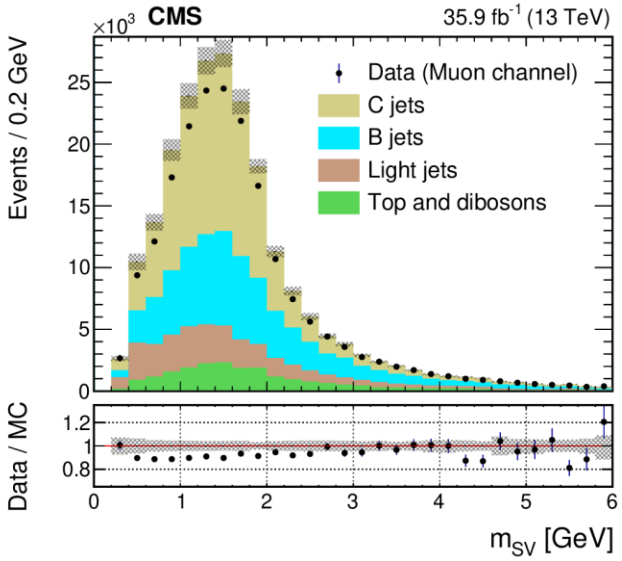
Z boson + charm

JHEP 04 (2021) 109

- **Charm quark content of the proton**
- Measurement of total and differential distributions of Z+c using 2016 data







Strategy:

Charm contribution obtained fitting templates of Z+c, Z+b and Z+light-jet contributions to the sec. vertex mass

Z boson + charm

JHEP 04 (2021) 109

Results

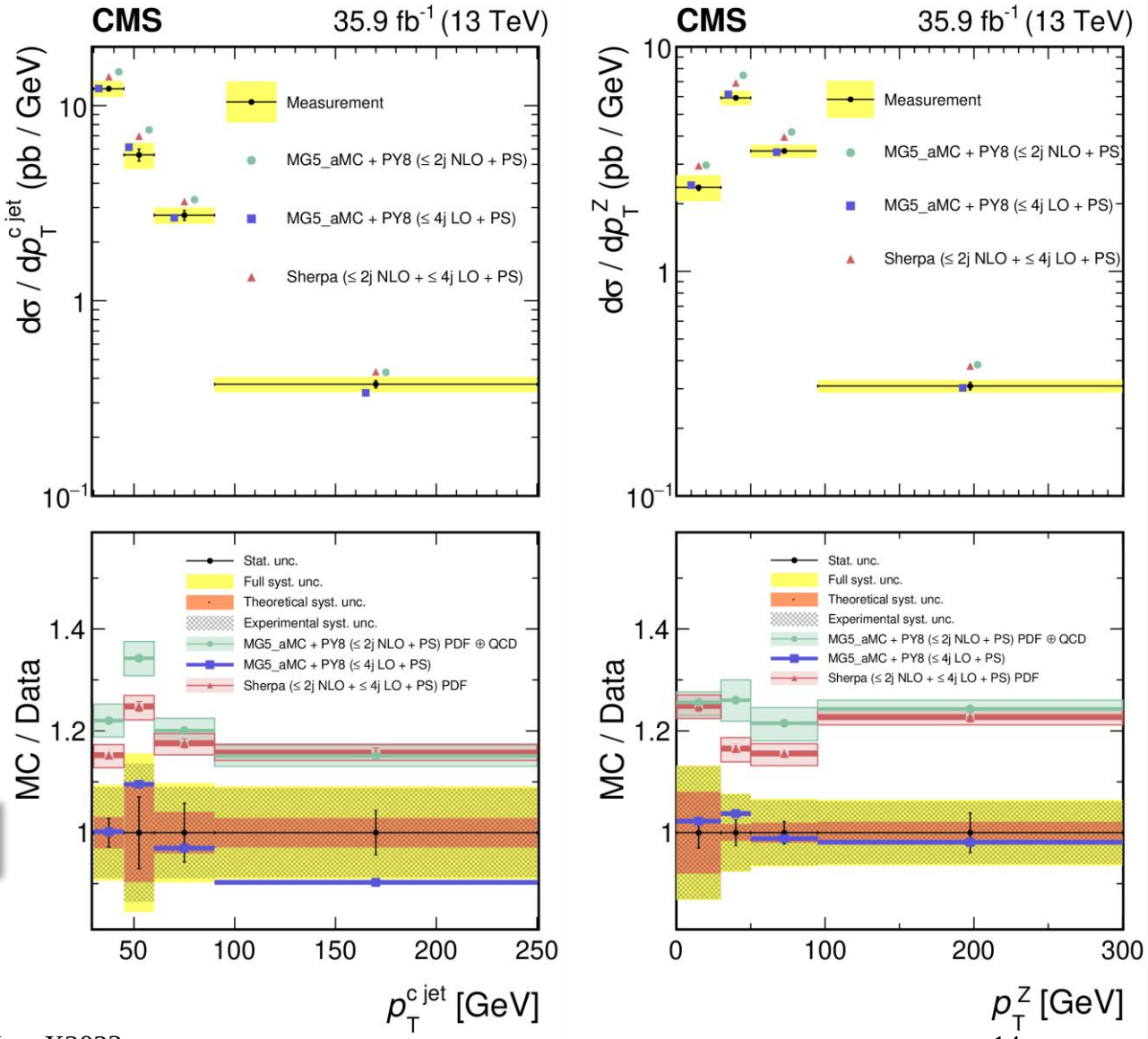
Good agreement with MG5_aMC **LO**

Sherpa & MG5_aMC **NLO** overestimate xsec

c-tagging and JEC are the largest systematics

Channel	QCD (%)	PDF (%)	c tag/mistag (%)	JER (%)	JES (%)	Pileup (%)	Top Pair (%)	ID\Iso (%)	$\mathcal{L}$ (%)	MC stat. (%)
$\mu\mu, p_T^{c\,jet}$	5.5	0.5	4.2	3.9	4.8	1.5	0.6	1.0	2.5	4.2
$\mu\mu, p_T^{Z}$	1.9	0.5	4.2	1.1	3.9	1.6	0.8	1.0	2.5	3.1
ee, $p_T^{c\,jet}$	6.4	0.6	4.2	3.1	6.4	3.0	0.7	2.6	2.5	6.3
ee, p_T^{Z}	2.6	0.5	4.1	1.1	4.8	1.8	0.6	2.6	2.5	3.8

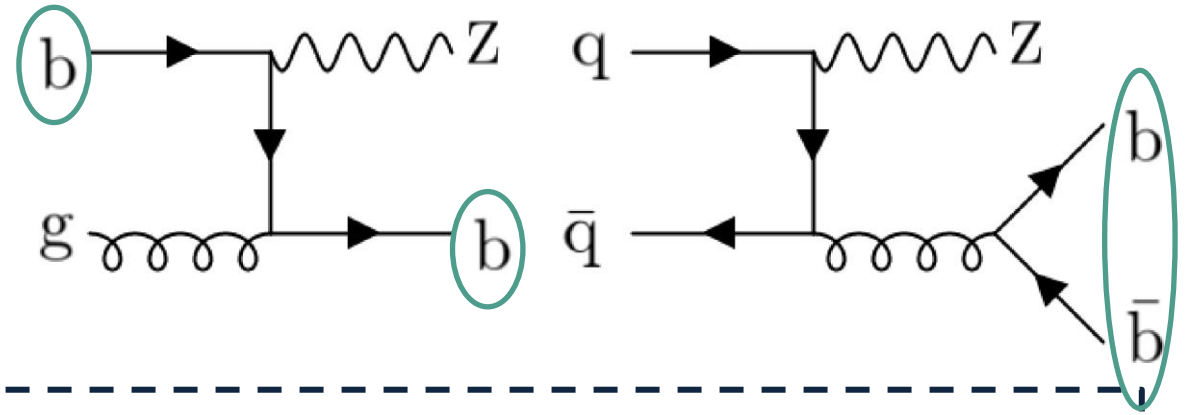
σ = 405.4 ± 5.6(stat) ± 24.3(exp) ± 3.7(theo) pb

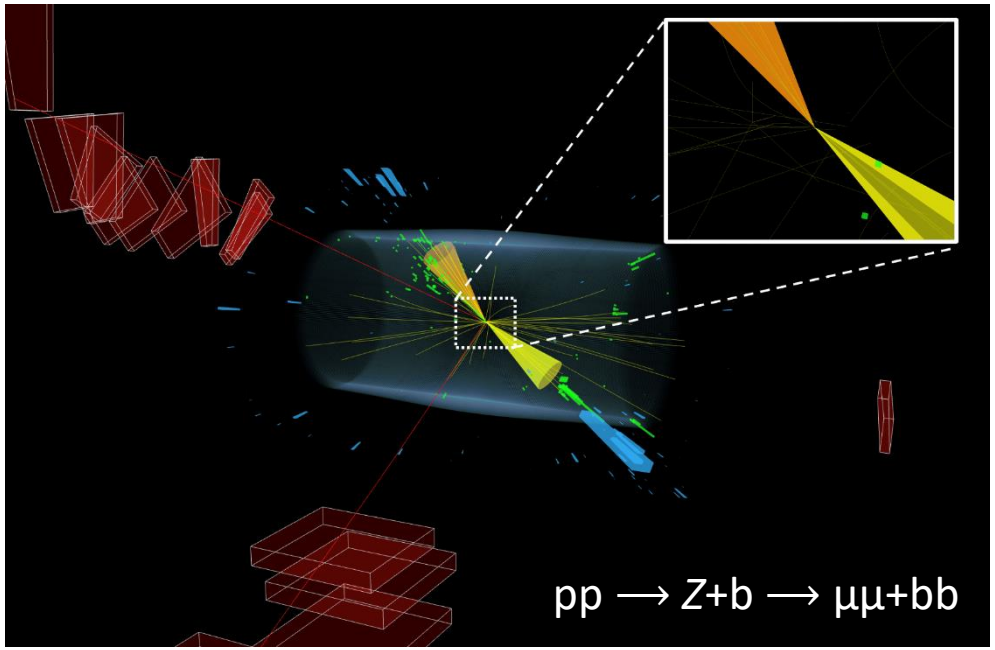


Z boson + b-quark(s)

PRD 105 (2022) 092014

- **4FS vs 5FS: experimental test of the beaty dynamics in the proton**
- Test of pQCD with HF: gluon splitting, quark mass effects, NLO effects





https://cms.cern/news/z-and-b

Strategy:

- Unfolded differential spectra of Z(ll)+(>0),(>1) bjets and ratios
- Standard Z(ll)+jets kinematic cuts + b-jet tagging

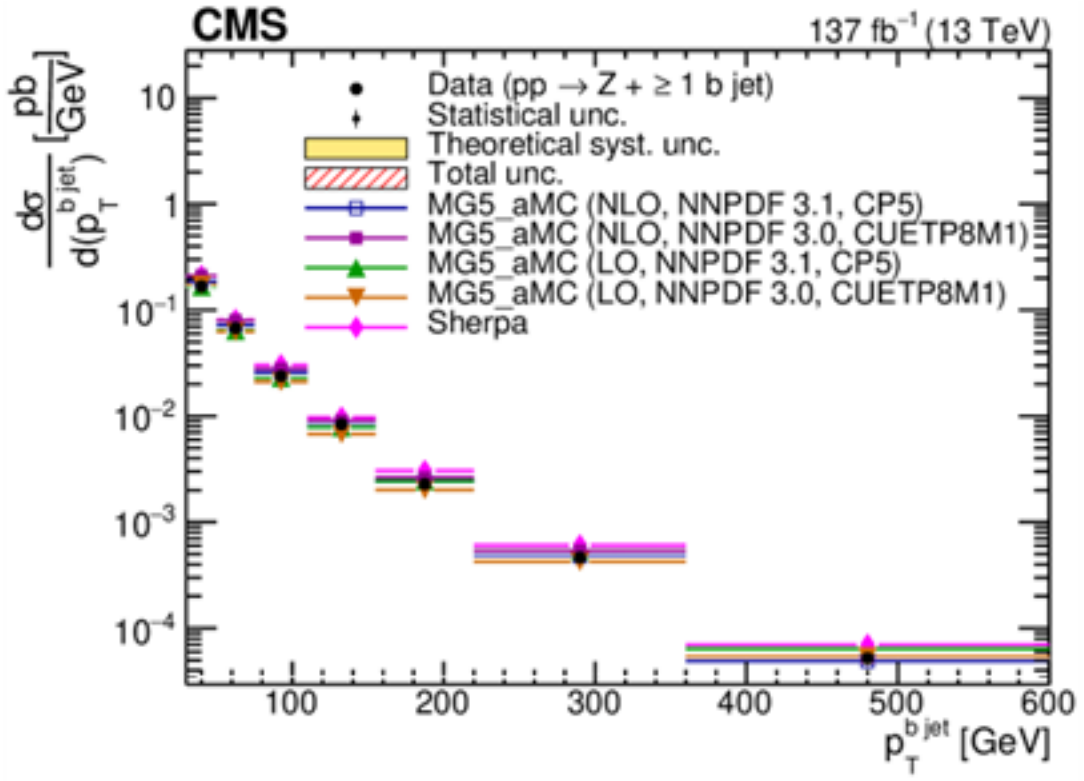
Z boson + b-quark(s)

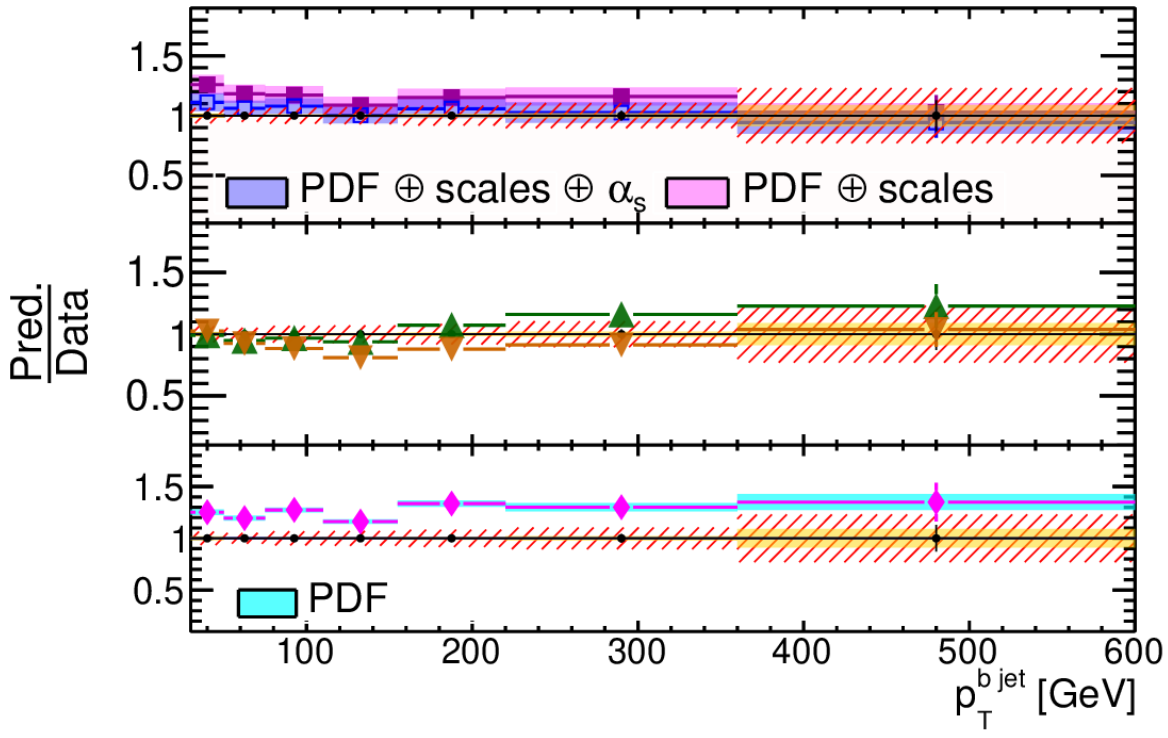
PRD 105 (2022) 092014

Theory: Madgraph LO, NLO w/NNPDF30/31 + CP5tune and Sherpa NLO

Results (≥1 b-jet)

Testing pQCD with leading b-jet transverse momentum





good description of data by MG5_aMC(LO)

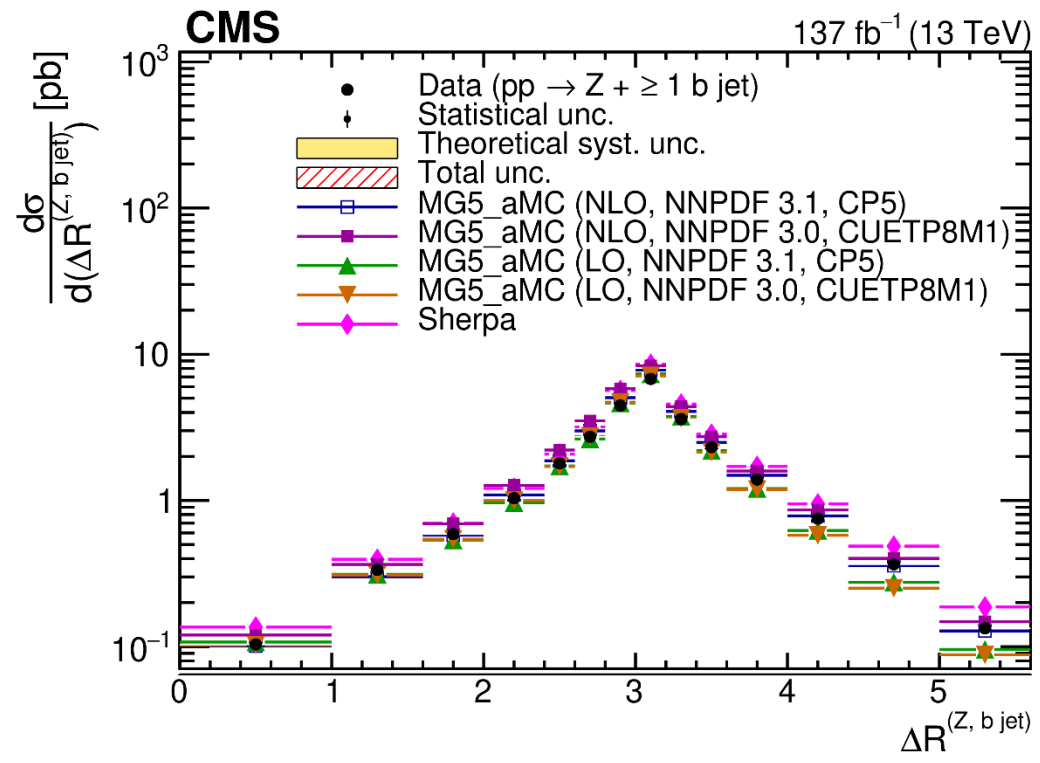
Z boson + b-quark(s)

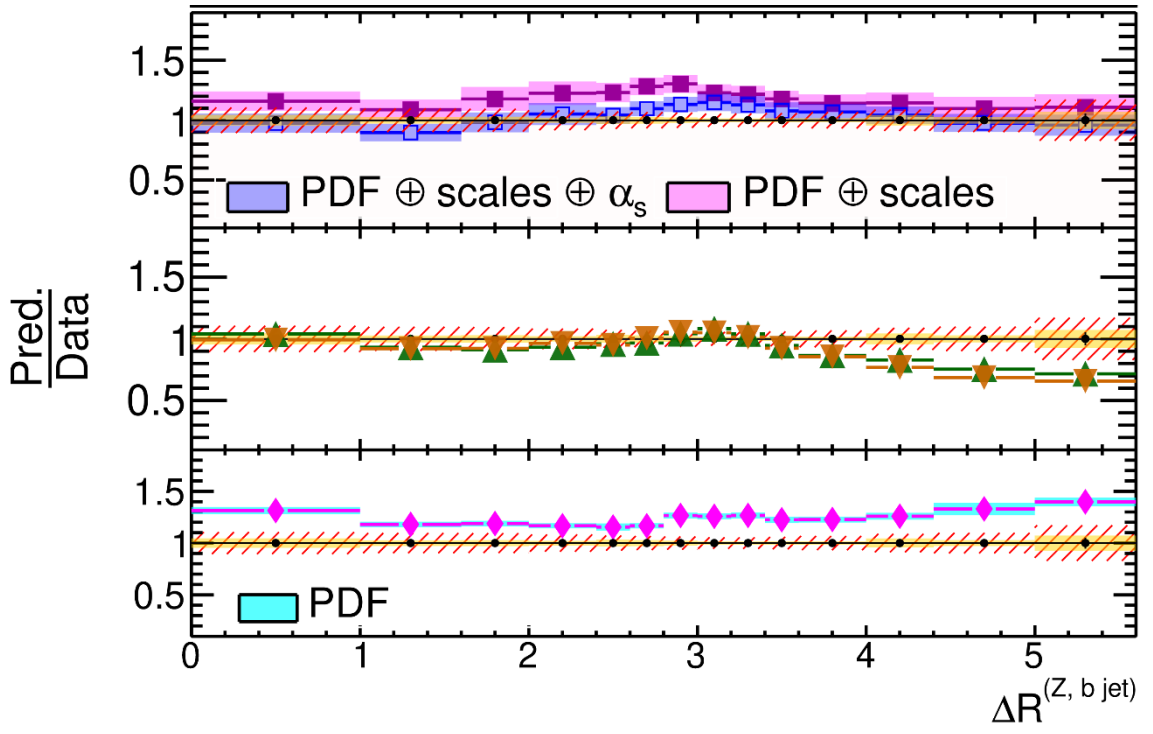
PRD 105 (2022) 092014

Theory: Madgraph LO, NLO w/NNPDF30/31 + CP5tune and Sherpa NLO

Results (≥1 b-jet)

Testing pQCD with dR between Z boson and b-jet (sensitive to NLO corrections)





But do not completely describe the shapes of some kinematic observables

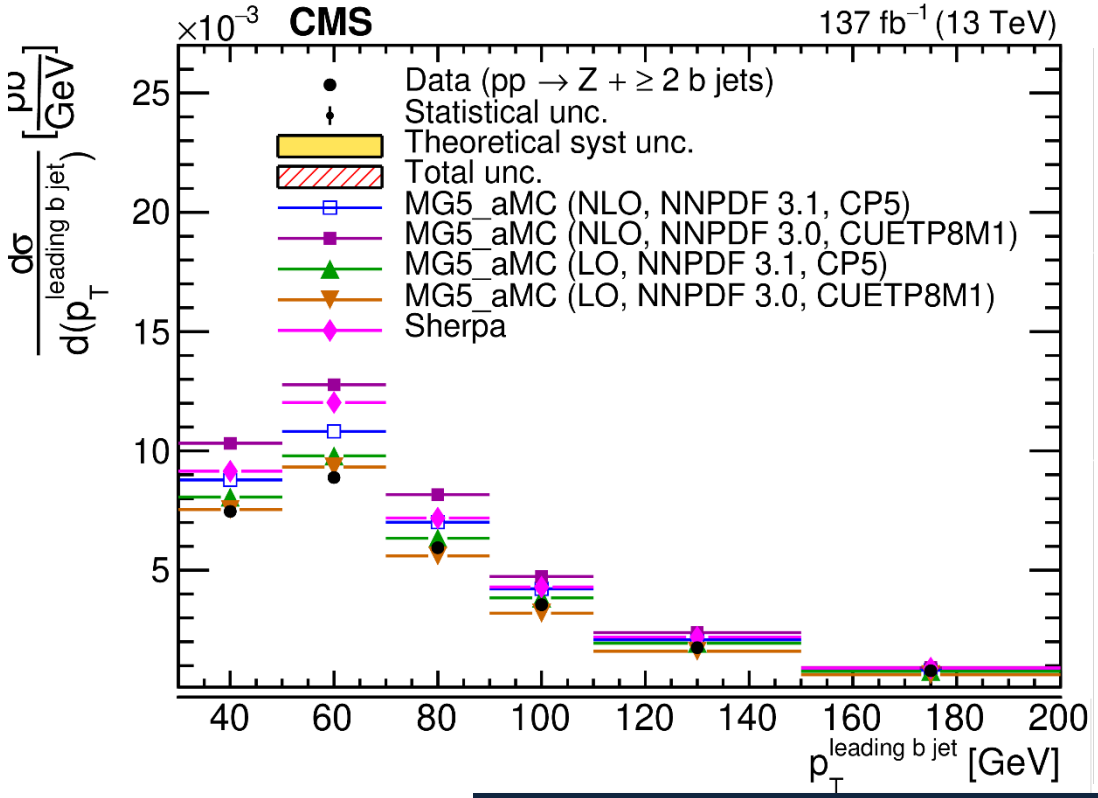
Z boson + b-quark(s)

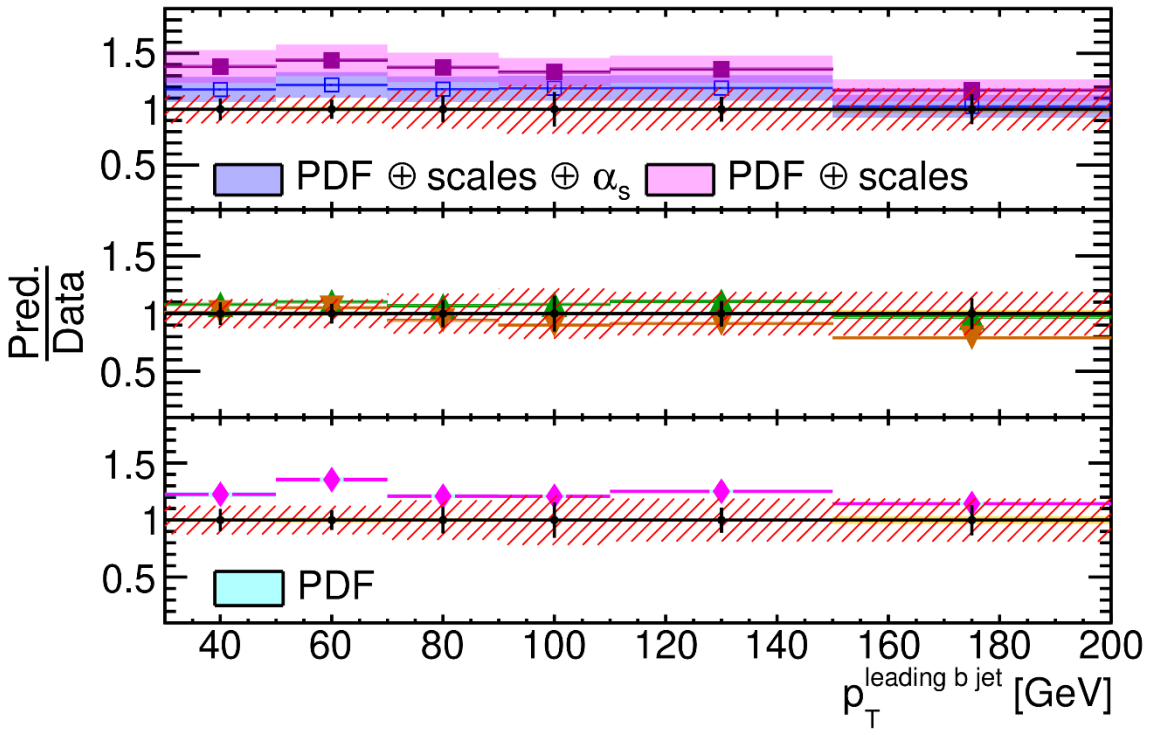
PRD 105 (2022) 092014

Theory: Madgraph LO, NLO w/NNPDF30/31 + CP5tune and Sherpa NLO

Results (≥2 b-jet)

Testing pQCD with leading b-jet transverse momentum





good description of data by all generators

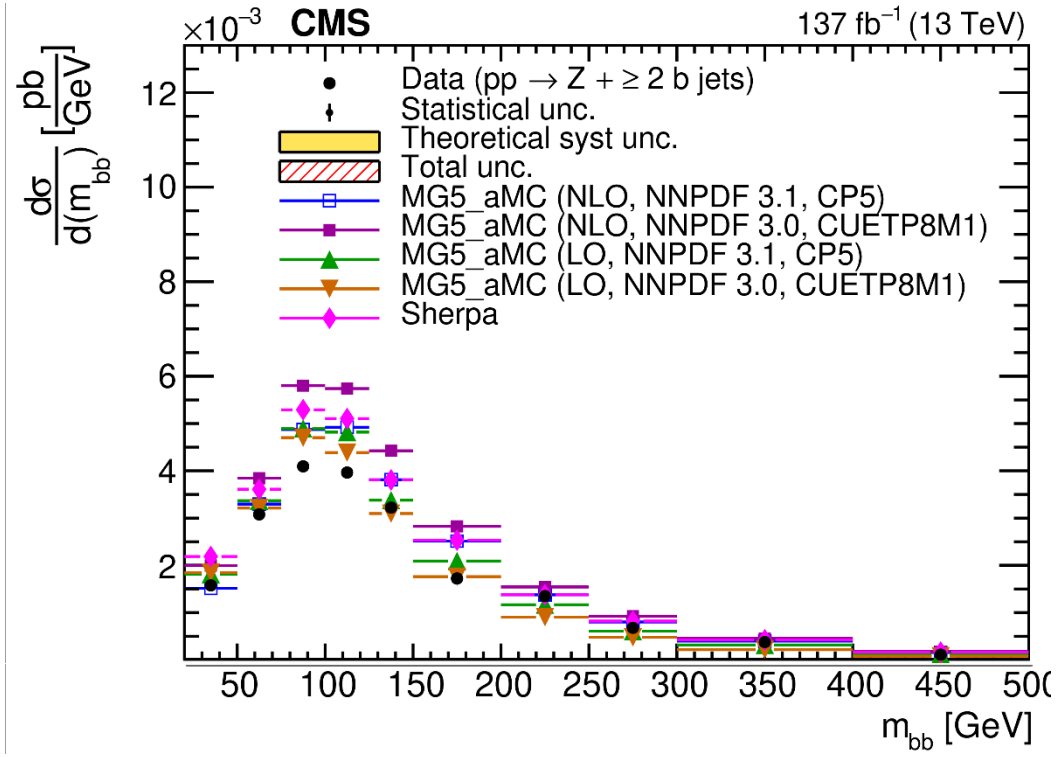
Z boson + b-quark(s)

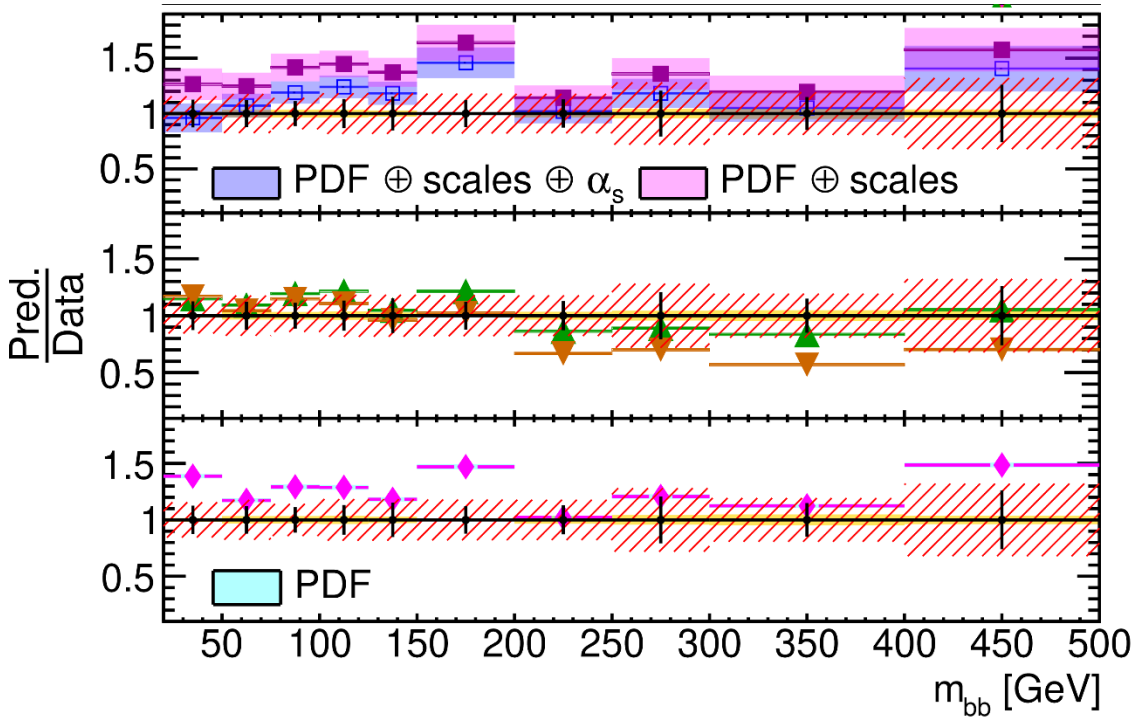
PRD 105 (2022) 092014

Theory: Madgraph LO, NLO w/NNPDF30/31 + CP5tune and Sherpa NLO

Results (≥2 b-jet)

bb and Zbb invariant masses important in searches for resonances and new particles





No deviation with respect to the Standard Model

Z boson + b-quark(s)

PRD 105 (2022) 092014

Theory: Madgraph LO, NLO w/NNPDF30/31 + CP5tune and Sherpa NLO

Results (≥2 b-jet)

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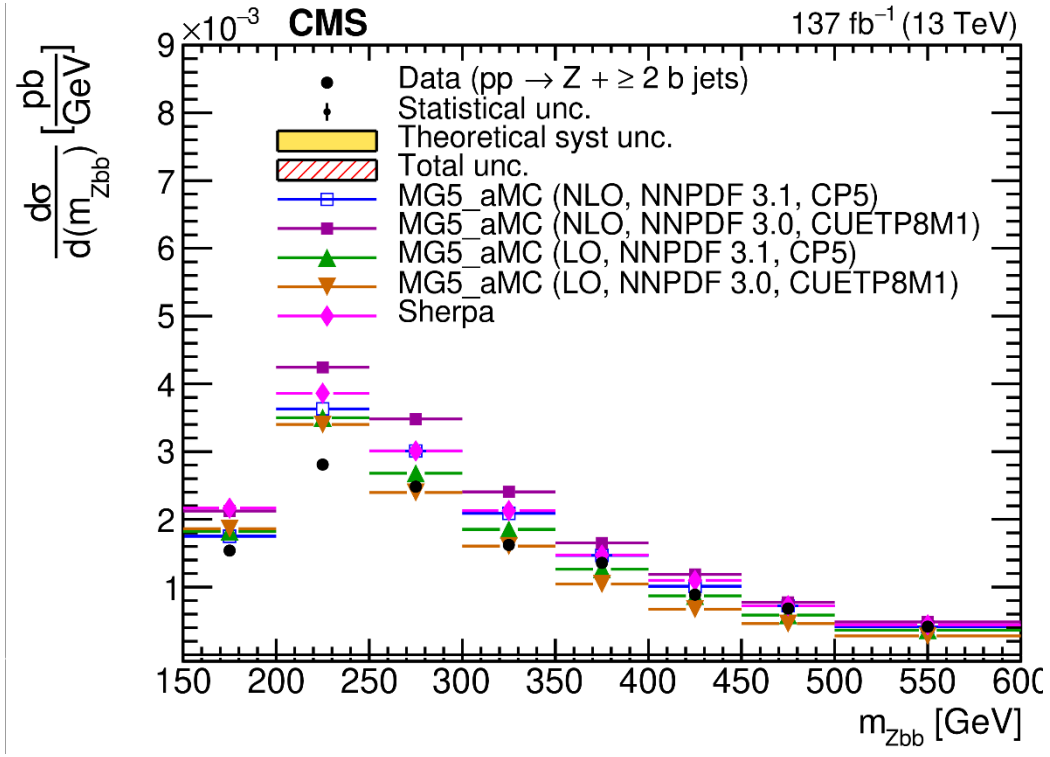
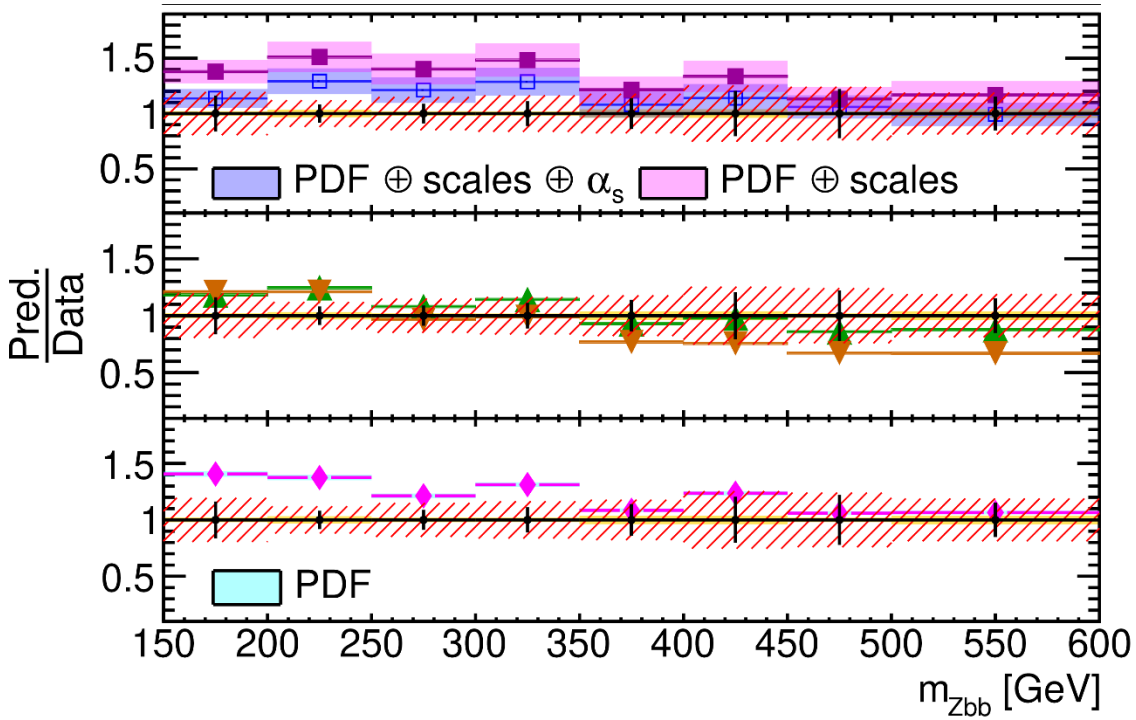




No deviation with respect to the Standard Model

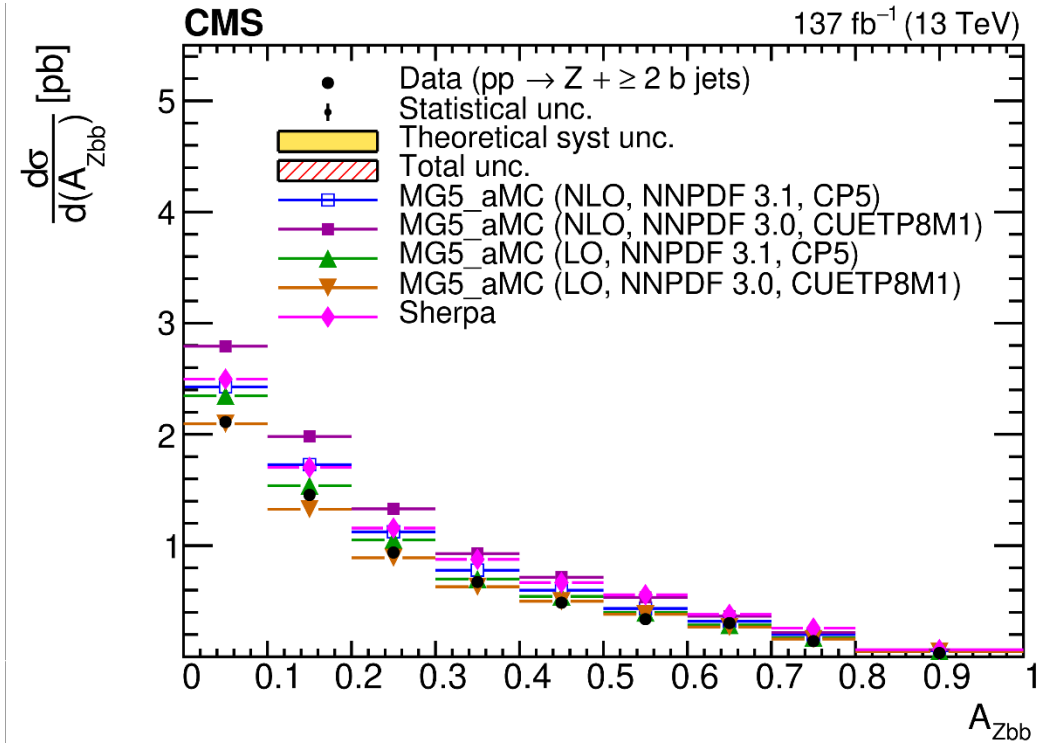
Z boson + b-quark(s)

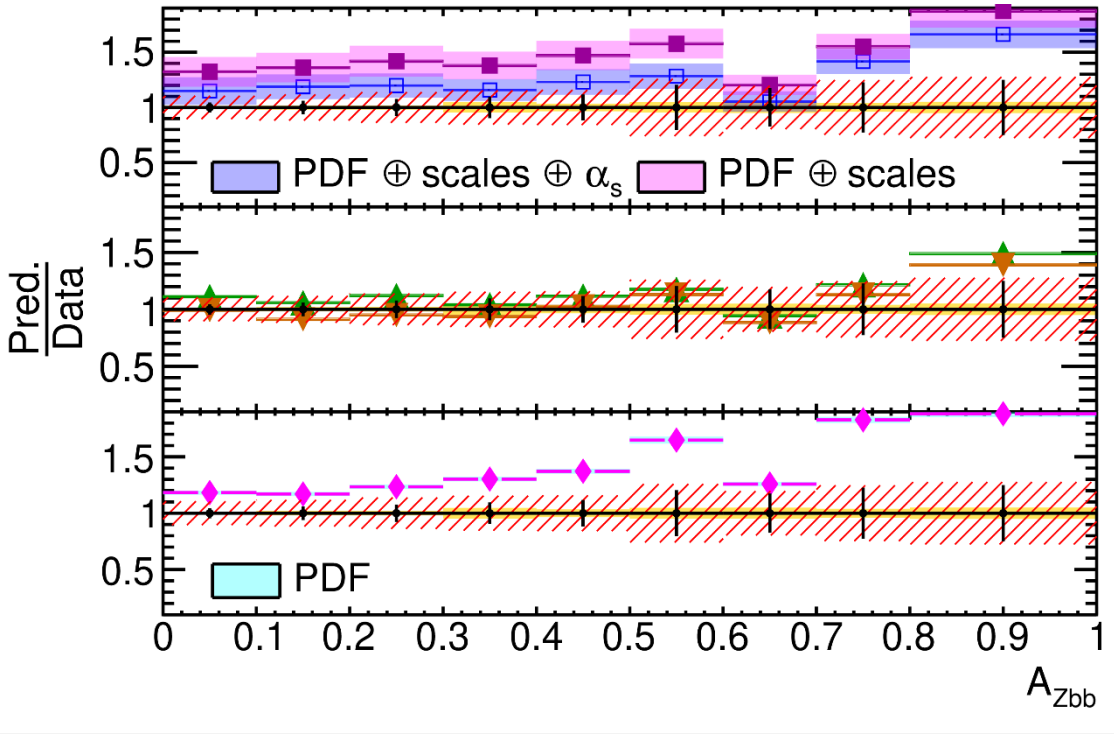
PRD 105 (2022) 092014

Theory: Madgraph LO, NLO w/NNPDF30/31 + CP5tune and Sherpa NLO

Results (≥2 b-jet)

QCD test with asymmetries and soft radiation $A_{Zbb} = \frac{max\Delta R_{ZB} - min\Delta R_{ZB}}{max\Delta R_{ZB} + min\Delta R_{ZB}}$





A→1: emission of additional group radiation (not described by any prediction)

Summary

- Recent 13 TeV CMS measurements of W+c, Z+b, and Z+c have been presented: many interesting results improving our understanding of pQCD
- Results of differential cross-sections have enabled the extraction of information related to PDFs, NNLO precision, and strange quark sea
- In general, there is good agreement with NLO predictions. However, there is a minor tension observed in the case of Z+c, where the predictions overestimate the data by ~20%

Thank You for your attention!

Backup

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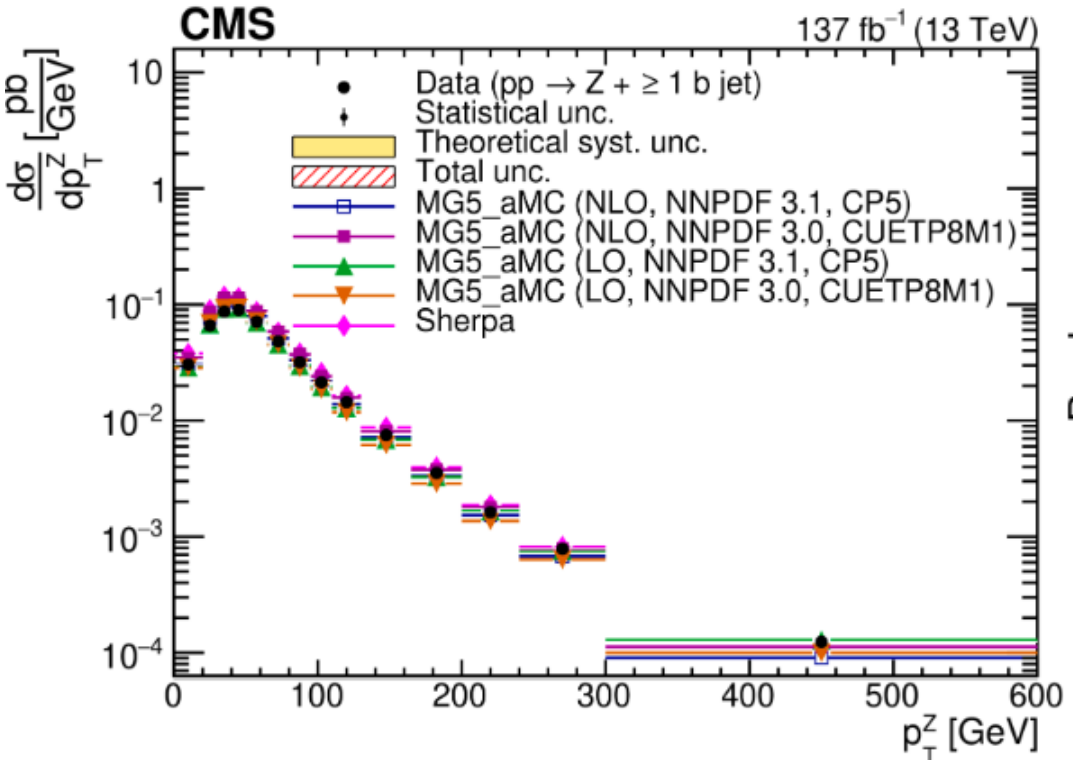
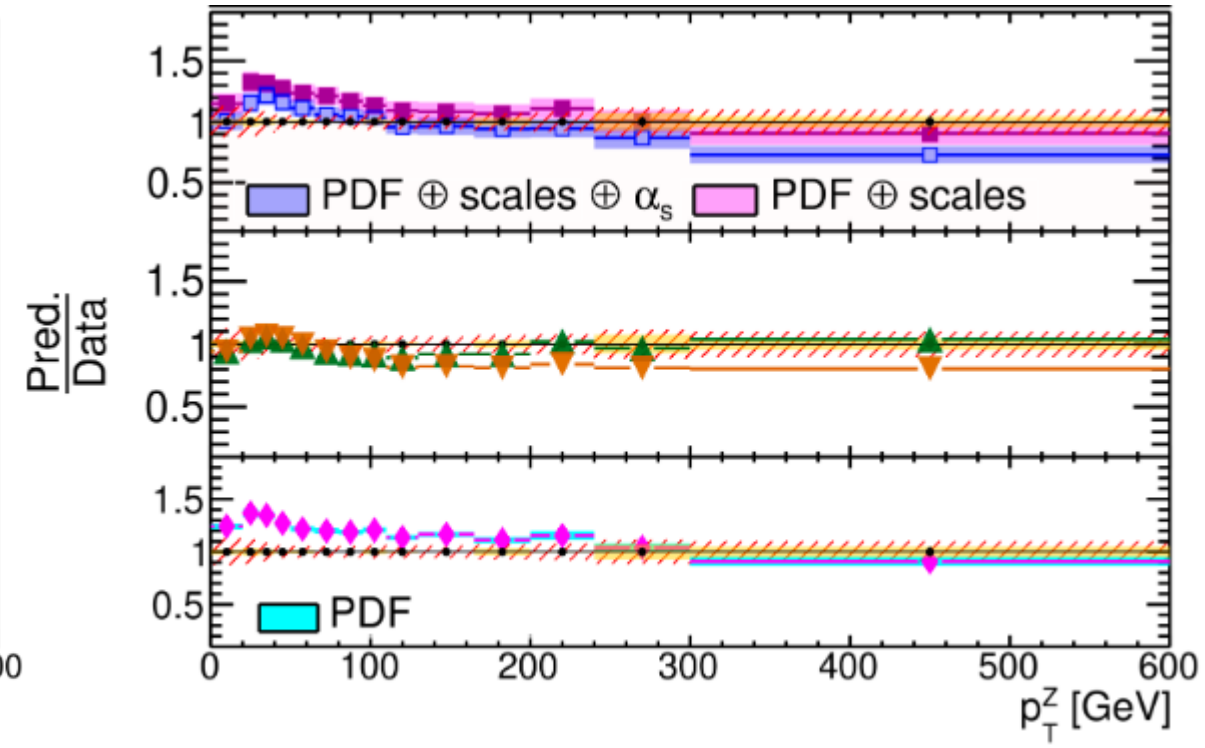
Results

Testing pQCD with Z boson transverse momentum





good description of data by MG5_aMC(LO)