

UNIVERSITÀ  
DEGLI STUDI  
DI TRIESTE

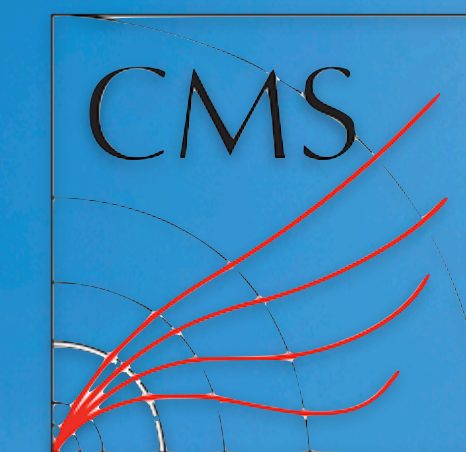
*13<sup>th</sup> QCD@LHC Workshop*

# Associated production of heavy flavours and vector bosons at the LHC

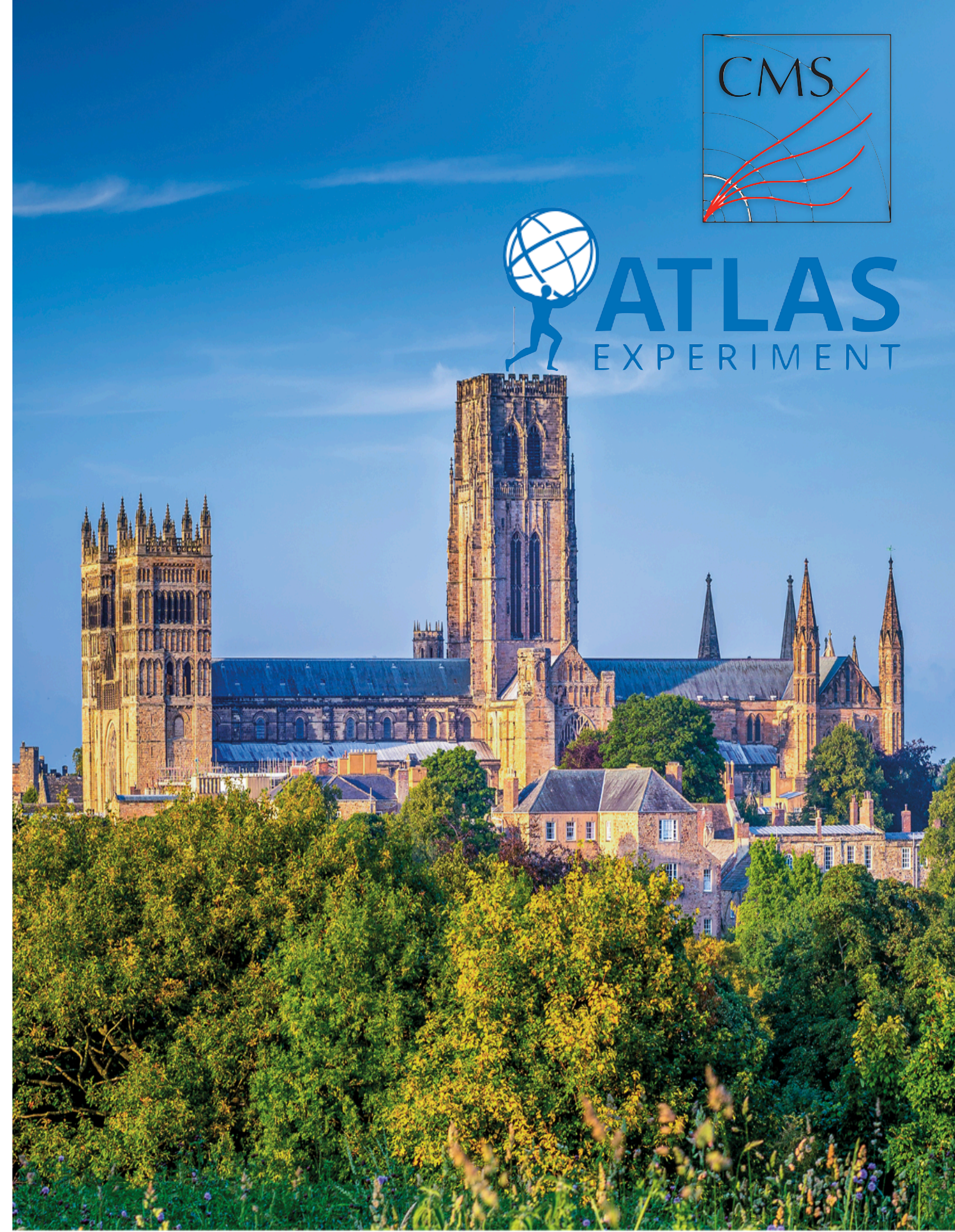
*IPPP, Durham, September 8<sup>th</sup>, 2023*

## Vieri Candelise

*on behalf of the CMS & ATLAS Collaboration*



ATLAS  
EXPERIMENT



# Outline

Phenomenology of  $V+HF$  at the LHC

Heavy flavours tagging performances in ATLAS & CMS

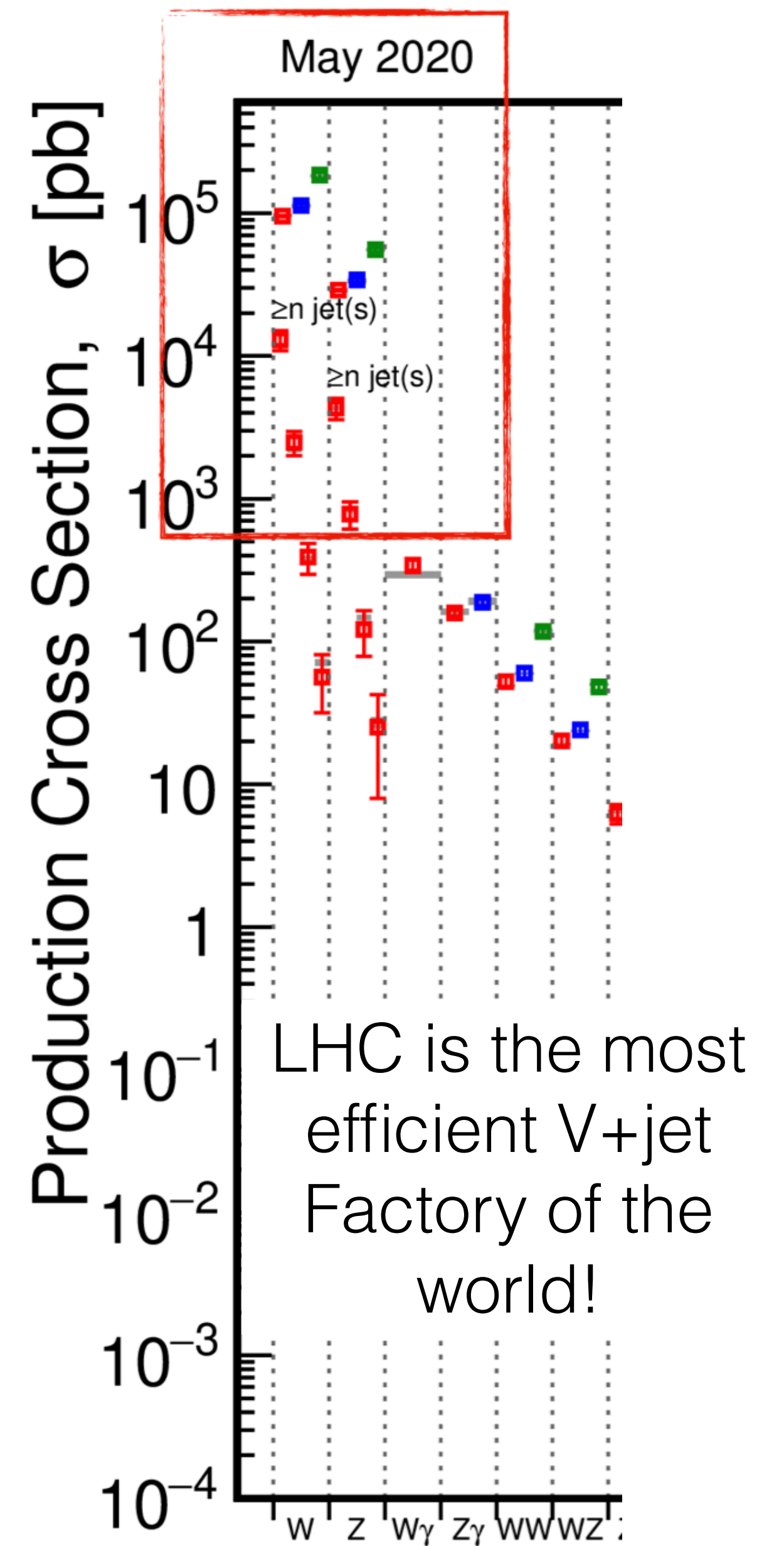
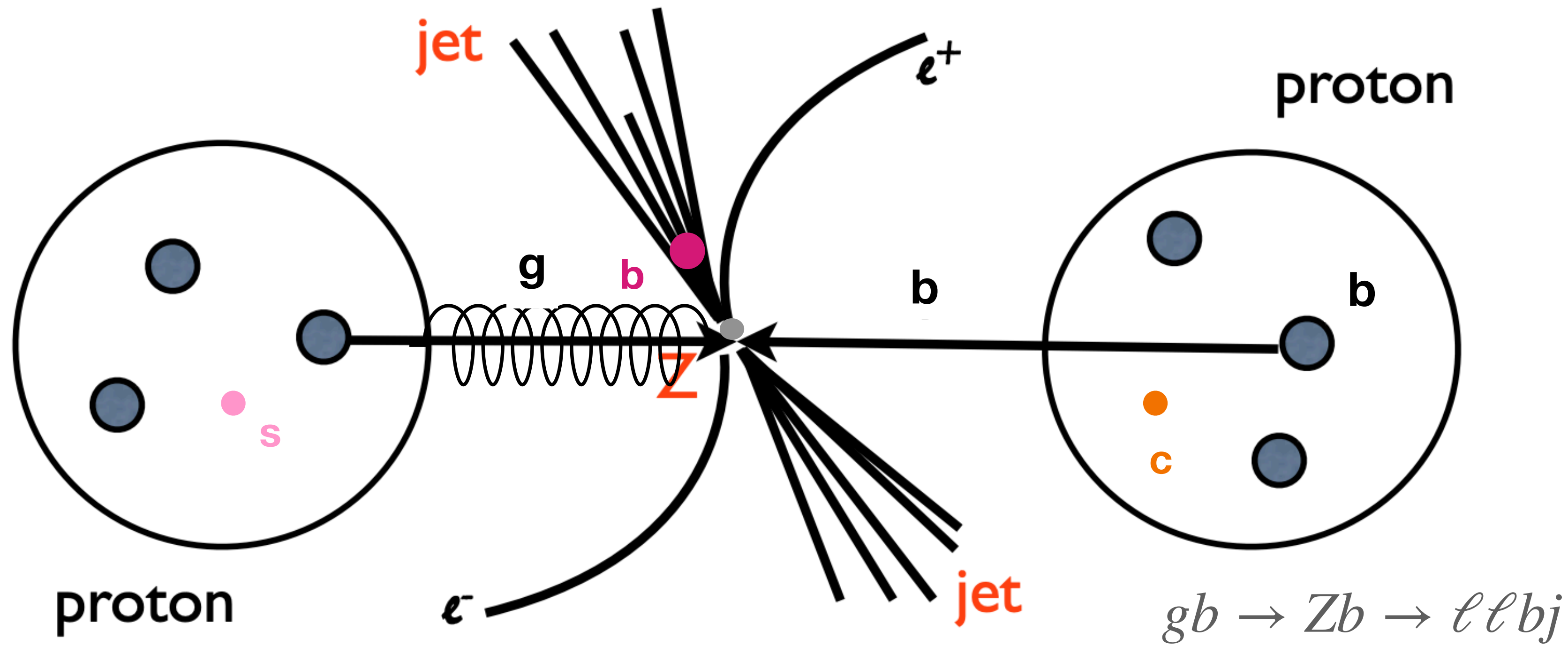
Selected results at  $\sqrt{s} = 13$  TeV in ATLAS & CMS

- Z+b-jets (ATLAS & CMS)
- W+c-jets (CMS), W+c-hadrons (ATLAS)
- Z+c (CMS)

Summary, conclusions and perspectives



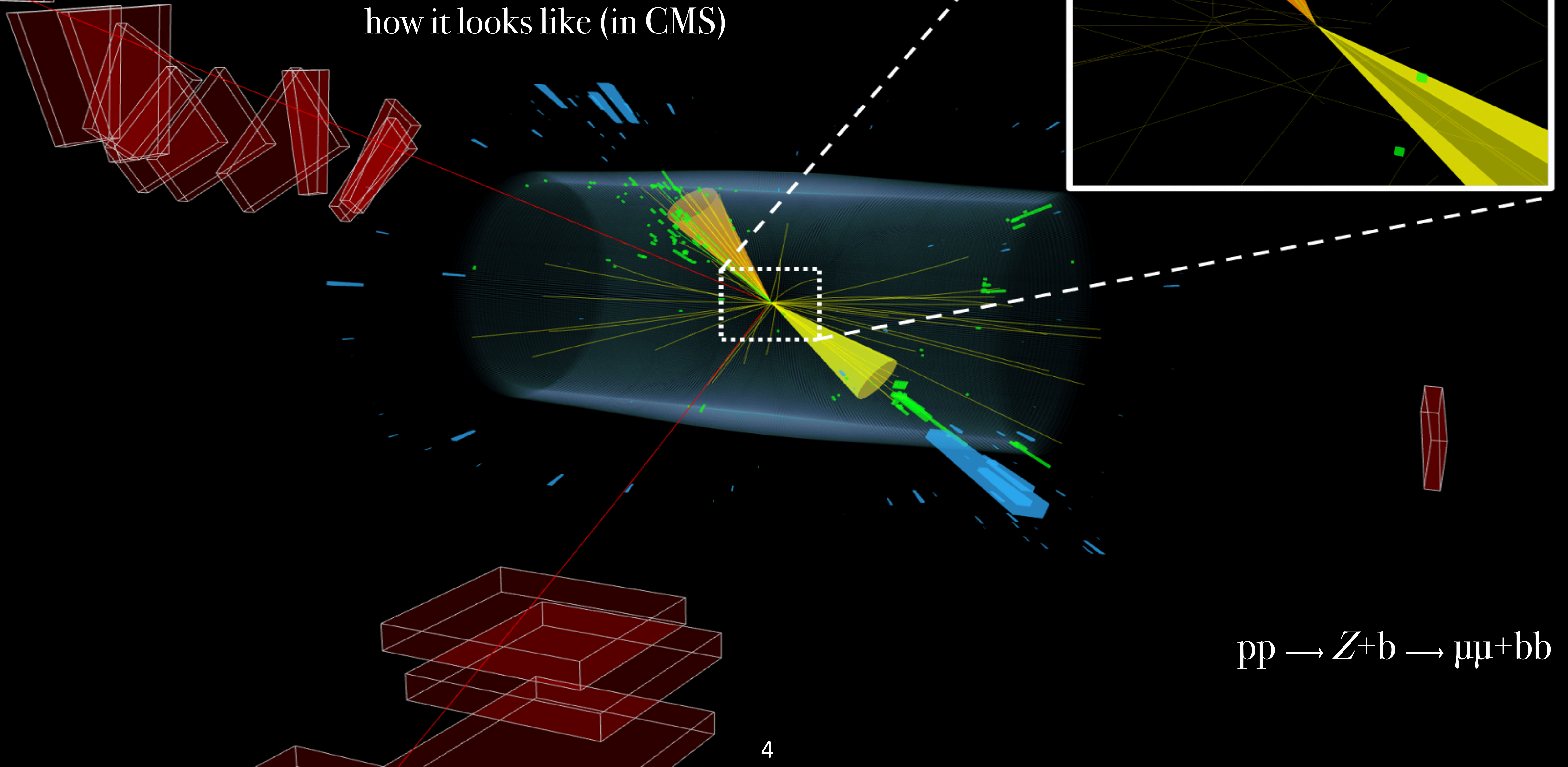
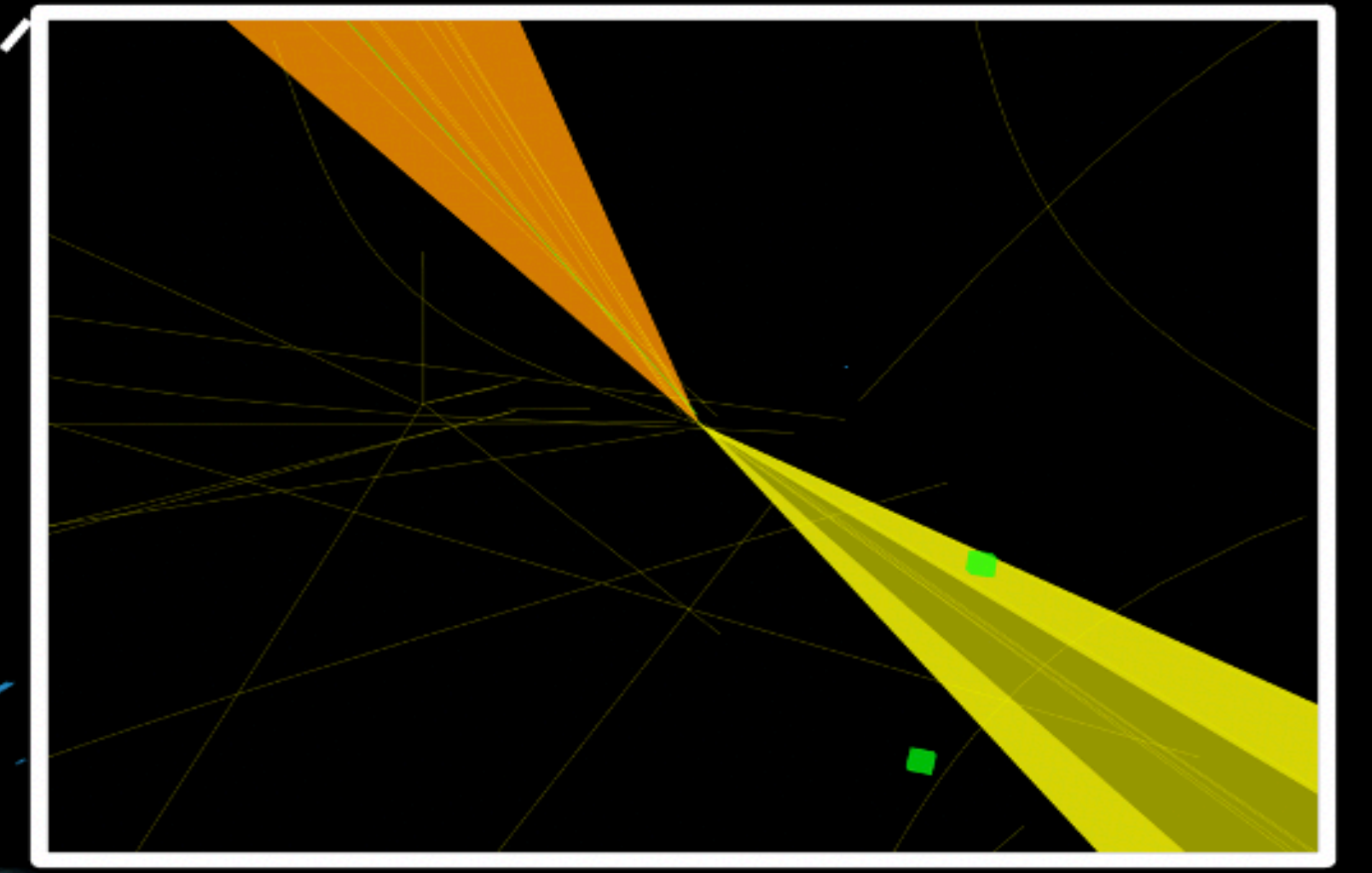
# Phenomenology of V+HF physics



- Precision tests of the SM: differential xsecs, EW couplings, phase space
- Modeling: critical test for Higgs physics with b-jets ( $H \rightarrow bb$ ,  $ttH$ ...)
- Searches: new resonances in  $VH(bb)$ ,  $bb/cc$  resonances, susy, 2HDM ...
- Precision QCD: constrain PDFs, quark sea, NNLO precision, HF proton dynamics (intrinsic charm, nFS)

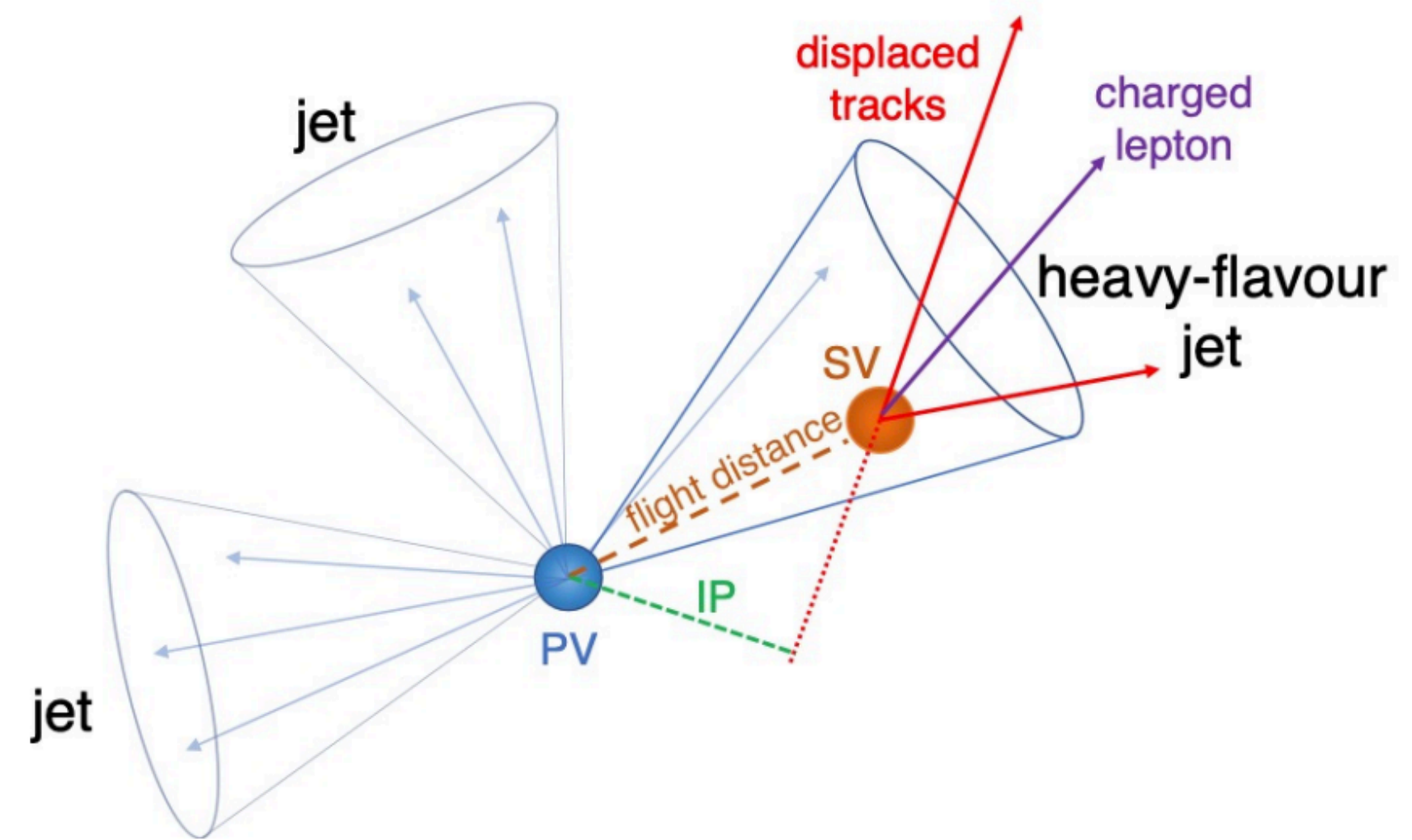
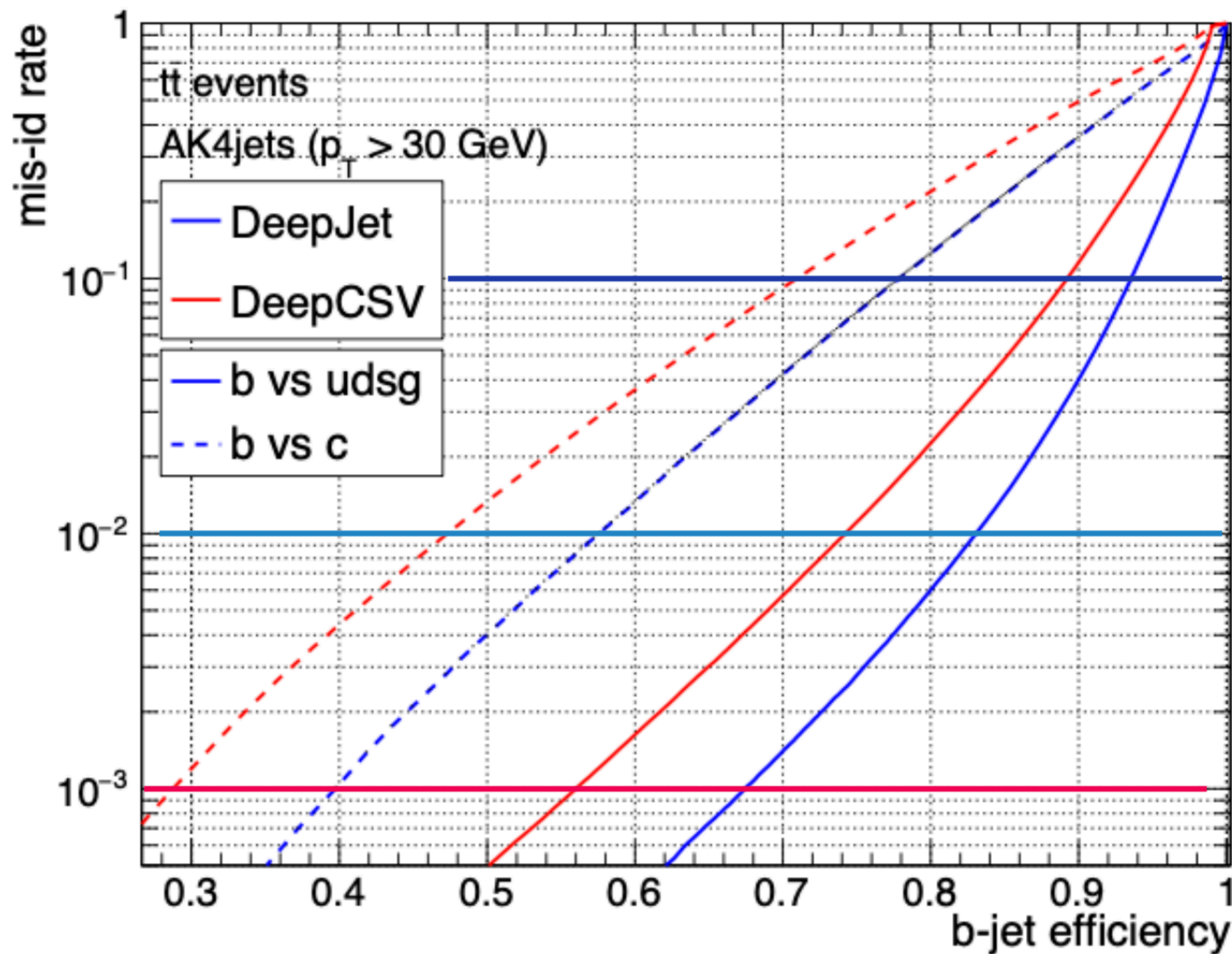
# Phenomenology of V+HF physics

how it looks like (in CMS)



$$pp \rightarrow Z+b \rightarrow \mu\mu+bb$$

# Heavy flavour tagging at CMS

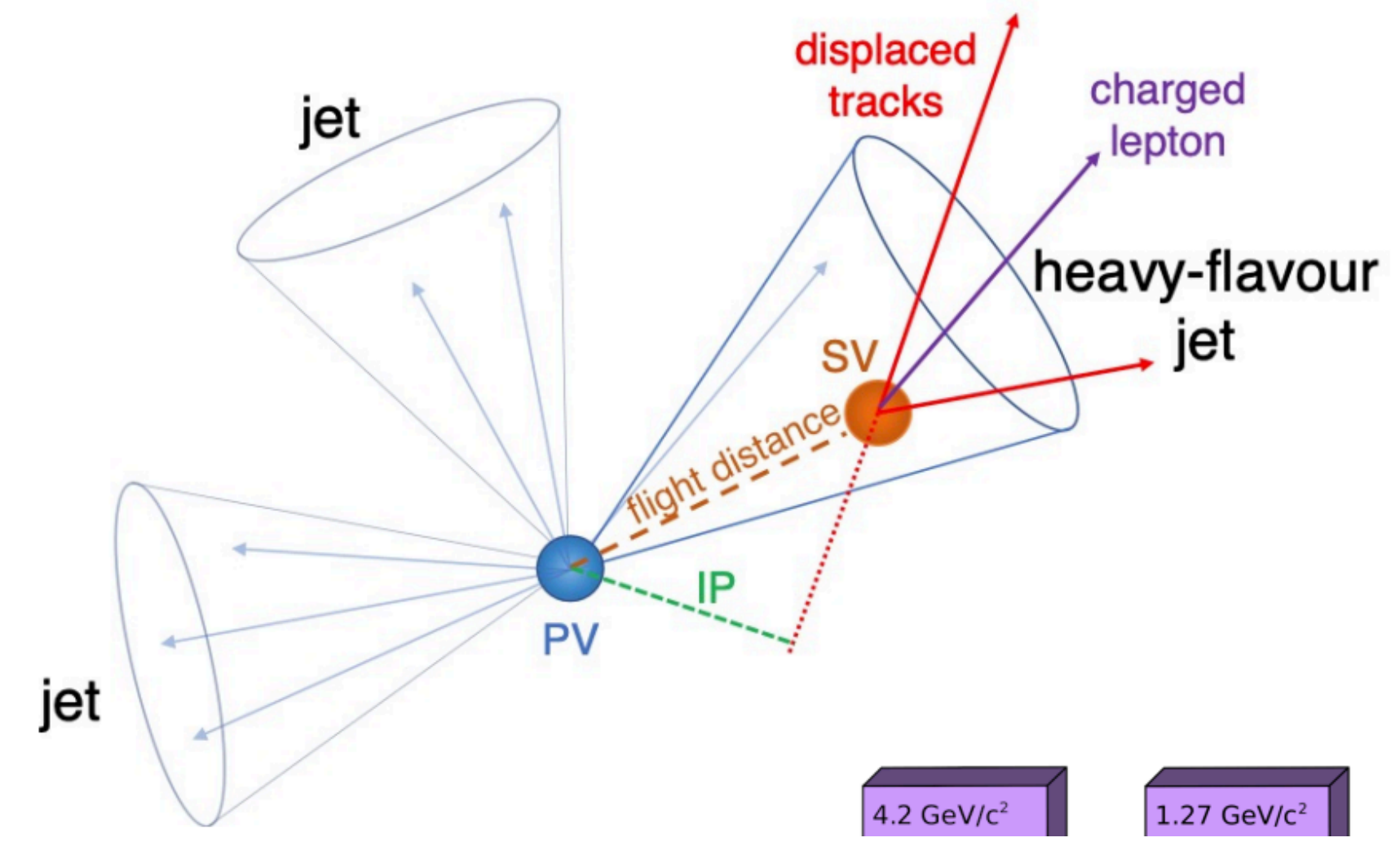


tagging based on DeepNN

exploiting combined b quarks kinematic properties (secondary vertices, impact parameter, lifetime, track multi.)

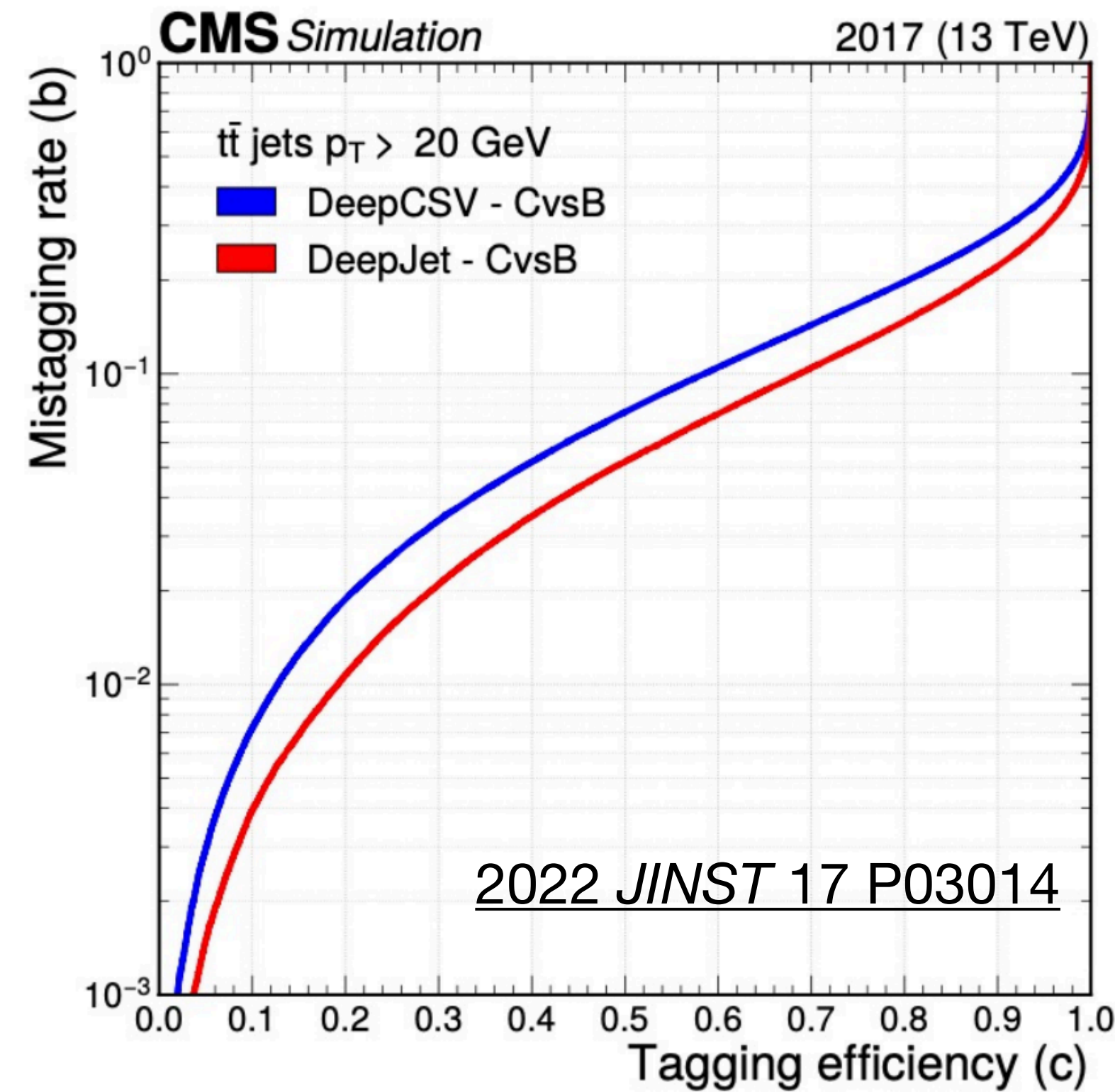
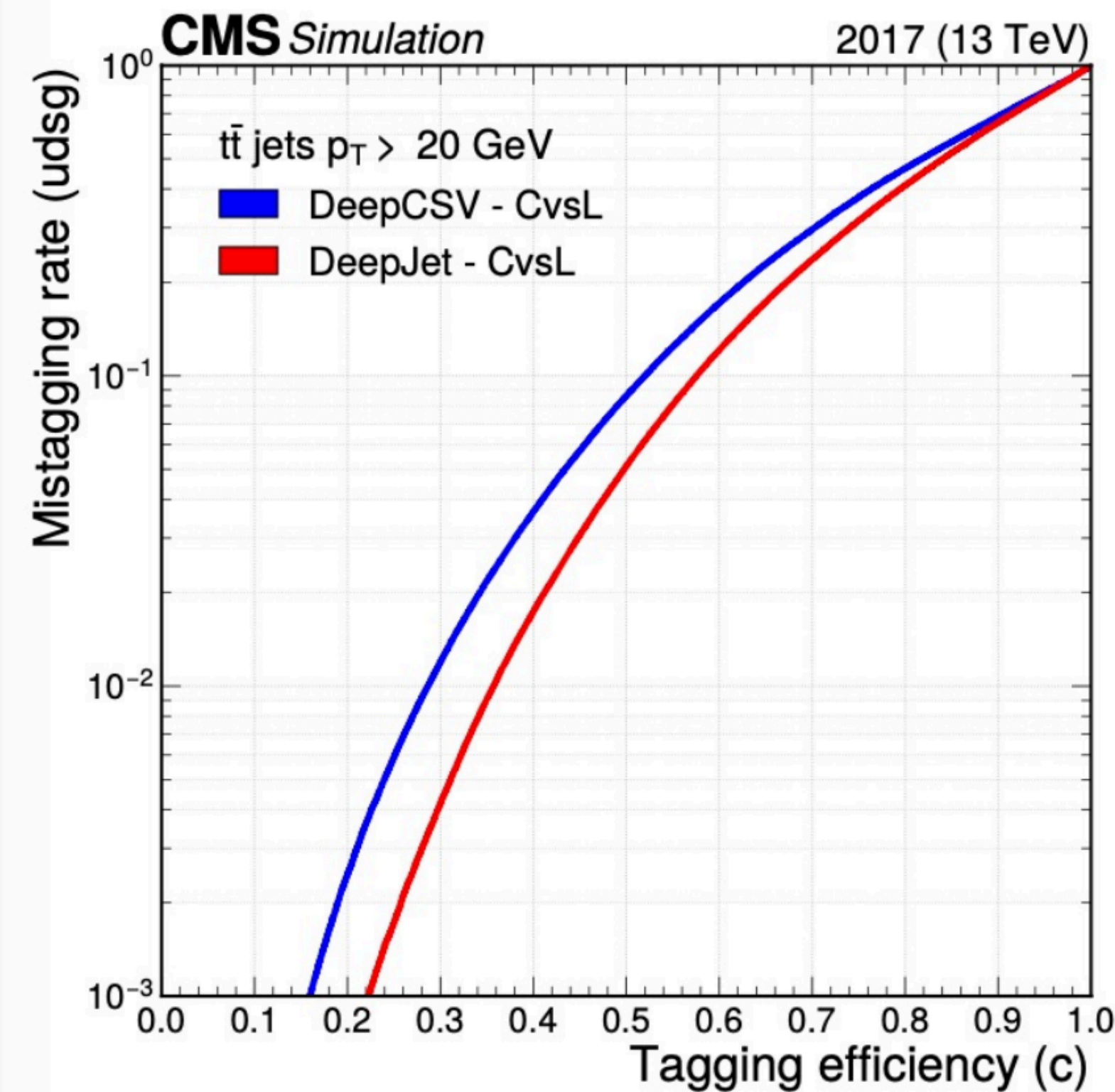
set WP for b- and c-tagging efficiencies and mistag rate

# Heavy flavour tagging at CMS



tagging based on DeepNN

exploiting combined b quarks kinematic properties (secondary vertices, impact parameter,



c-tagging based on b-tagging discrimination in between b and lights

WP	DeepCSV					DeepJet				
	CvsL cut	CvsB cut	c eff.	b eff.	udsg eff.	CvsL cut	CvsB cut	c eff.	b eff.	udsg eff.
Loose	0.064	0.313	91.4%	35.0%	90.0%	0.038	0.246	94.4%	35.0%	90.0%
Medium	0.153	0.363	57.7%	25.0%	25.0%	0.099	0.325	63.7%	25.0%	25.0%
Tight	0.405	0.288	34.2%	20.0%	3.00%	0.282	0.267	40.3%	20.0%	3.00%

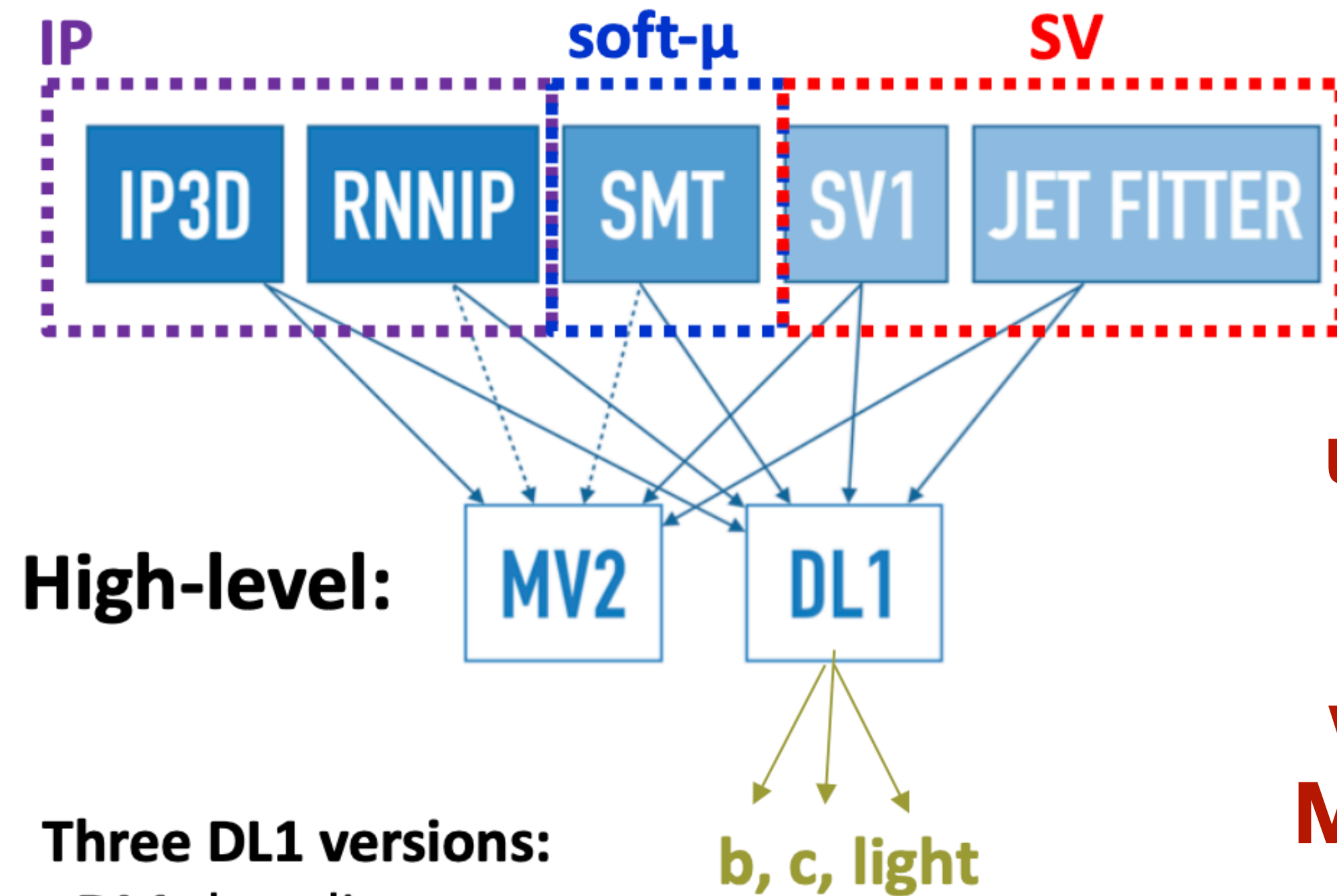
# Heavy flavour tagging at ATLAS

EPJ C 79 (2019) 970

EPJ C (2022)

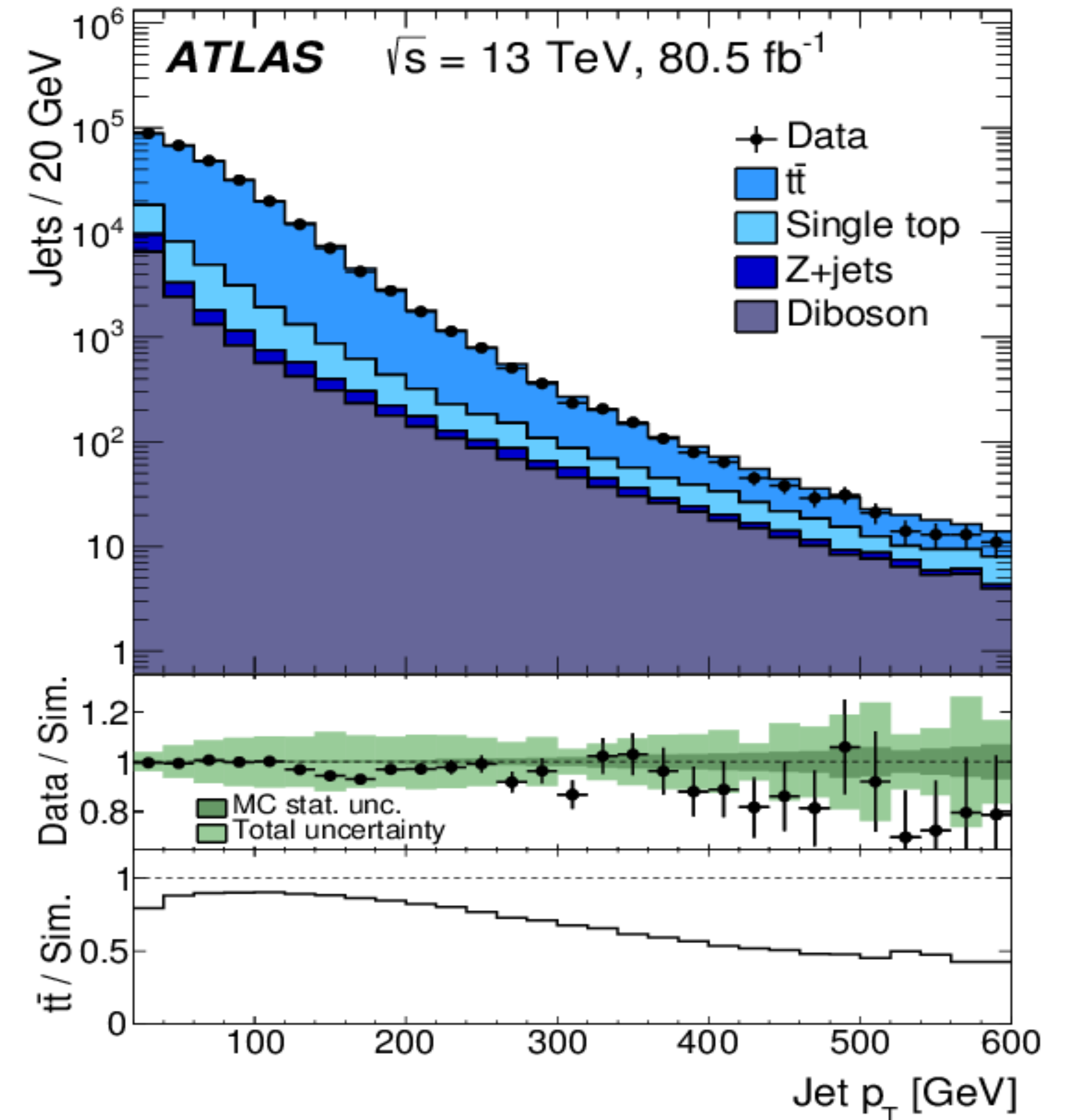
outputs from low-level - track-based algorithms based on different b/c-quark kinematics used as inputs to a higher-level tagger **DL1**

DNN used to combine the outputs

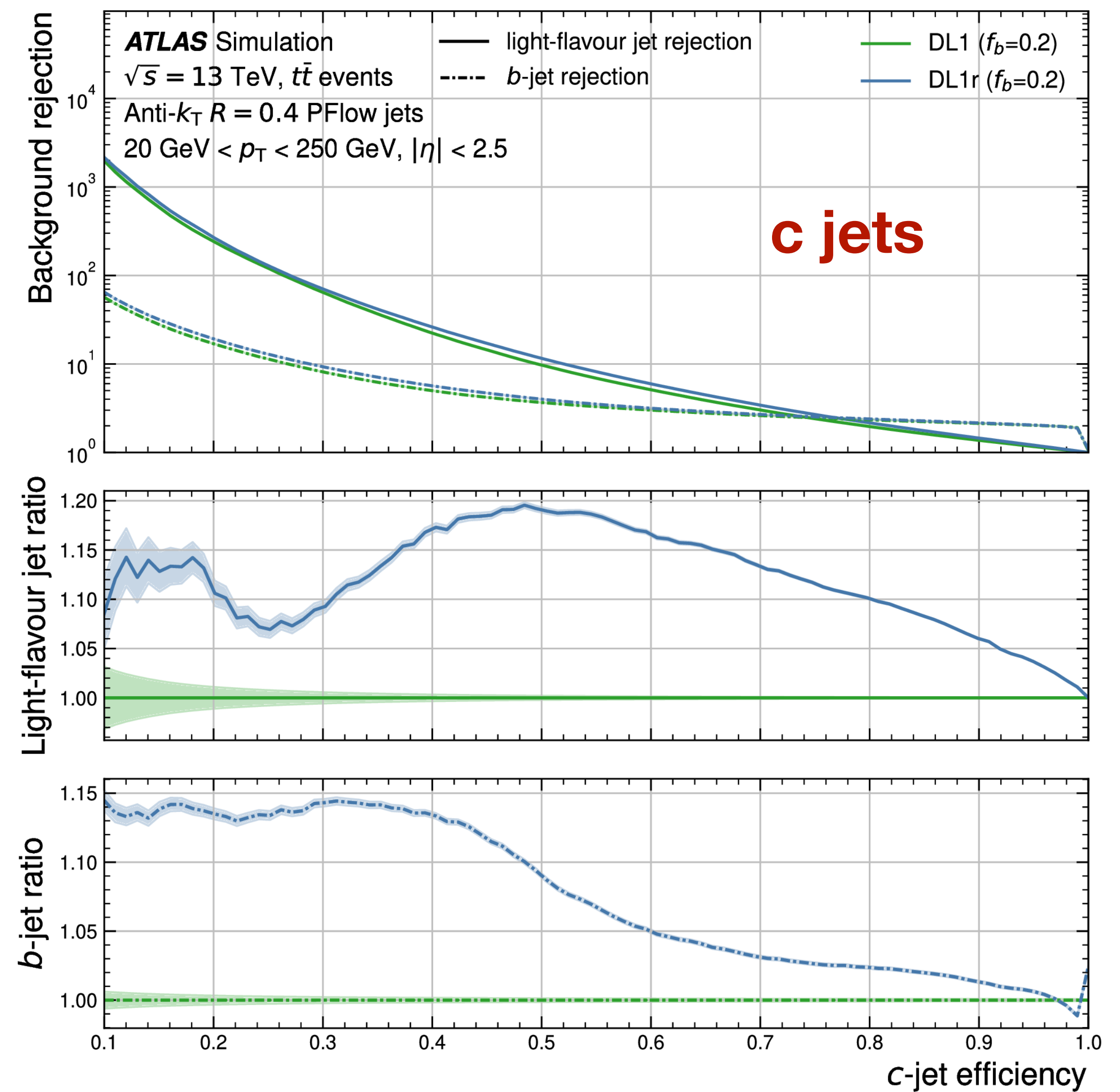
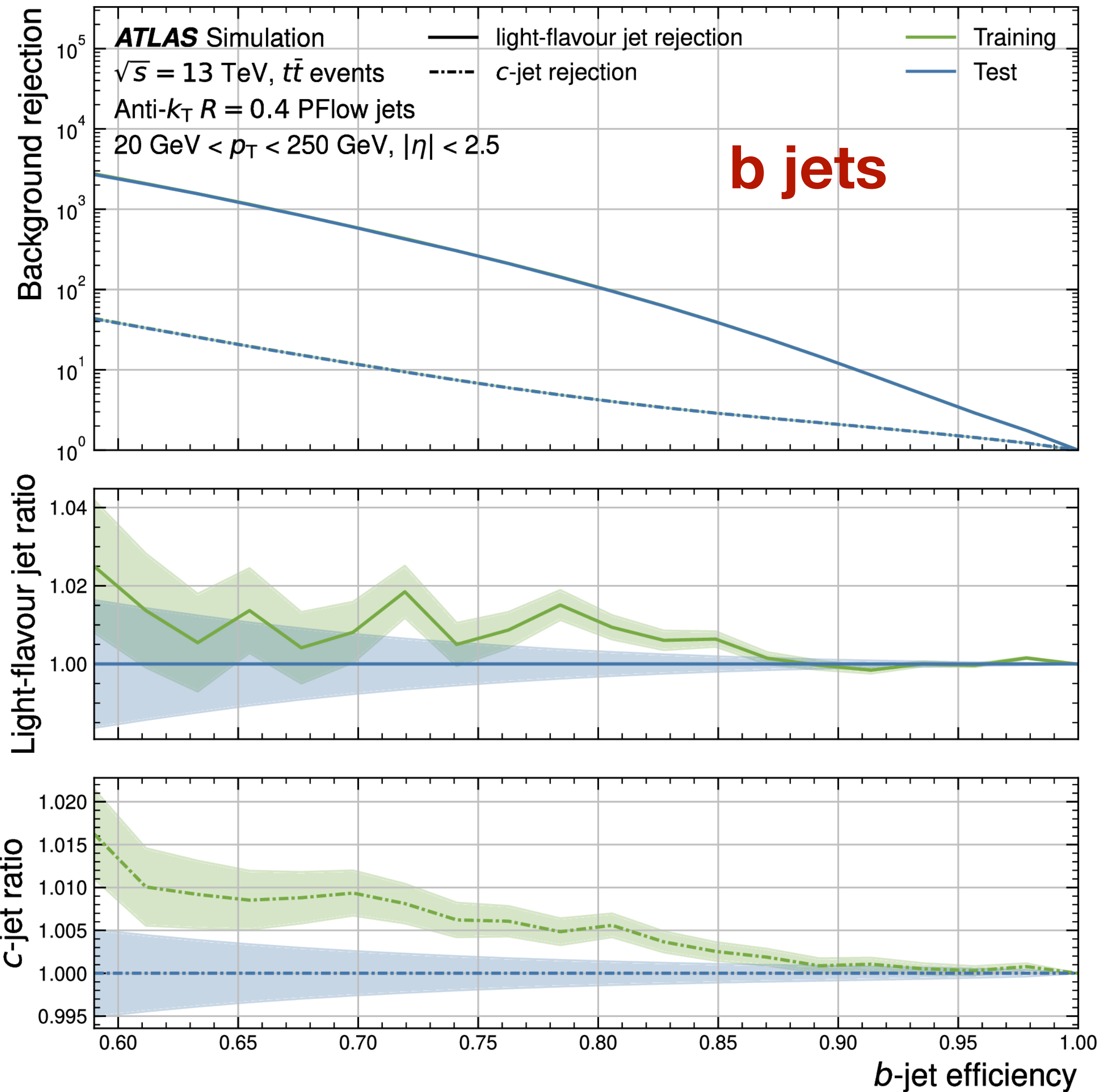


up to 10%  
better

w.r.t. 2016  
MVA tagger



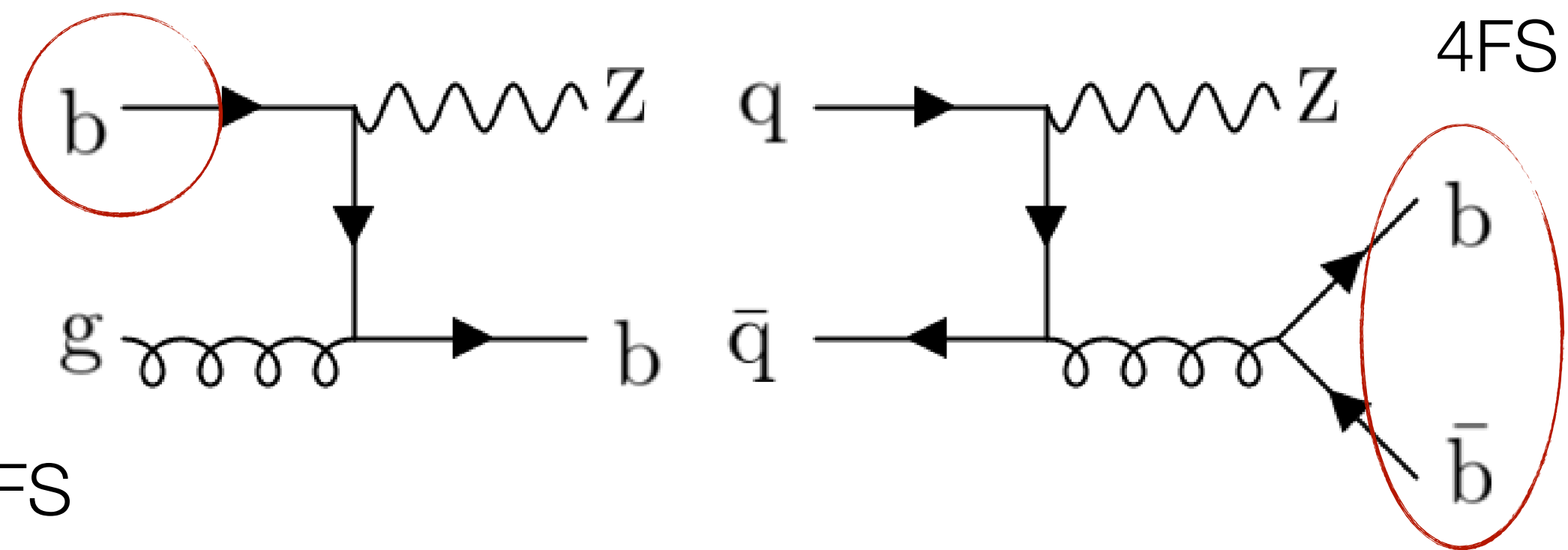
# Heavy flavour tagging at ATLAS





# Associated $Z$ boson and beauty at 13 TeV with CMS

physics



5FS

4FS vs 5Fs: experimental test of the beauty dynamics in the proton

critical test of pQCD with HF: gluon splitting, quark mass effects, NLO effects

crucial for modeling of  $H \rightarrow bb$  observables,  $VH$ ,  $Z'$  searches

**Deep neural network-based b-tagging** reaching 70% efficiency mistag rate  $c$ -quark and light  $\sim 10\%$  and  $\sim 1\%$

backgrounds

top quarks  $\rightarrow$  data driven

light, charm jets  $\rightarrow$  control regions

multiboson + others  $\rightarrow$  MC

strategy

Unfolded differential spectra for  $Z(\ell) + (>0)$ ,  $(>1)$  b-jets and ratios

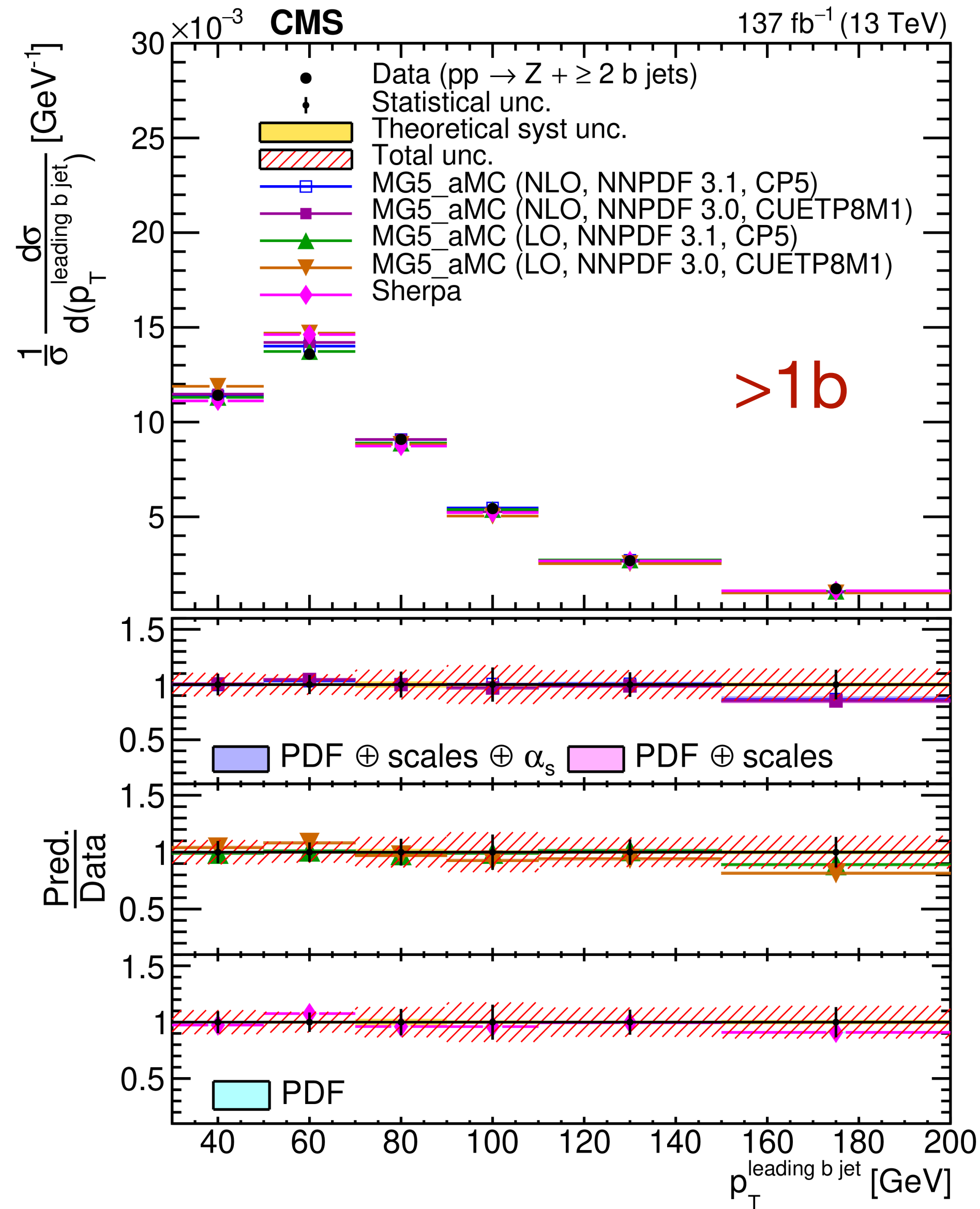
usual  $Z(\ell)$ +jets kinematic cuts + b-tagging

Exploring the  $Zbb$  phenomenology over a vast set of observables

Predictions at LO and NLO, 4F and 5F by MadGraph5\_aMC@NLO and Sherpa

# Associated Z boson and beauty at 13 TeV with CMS

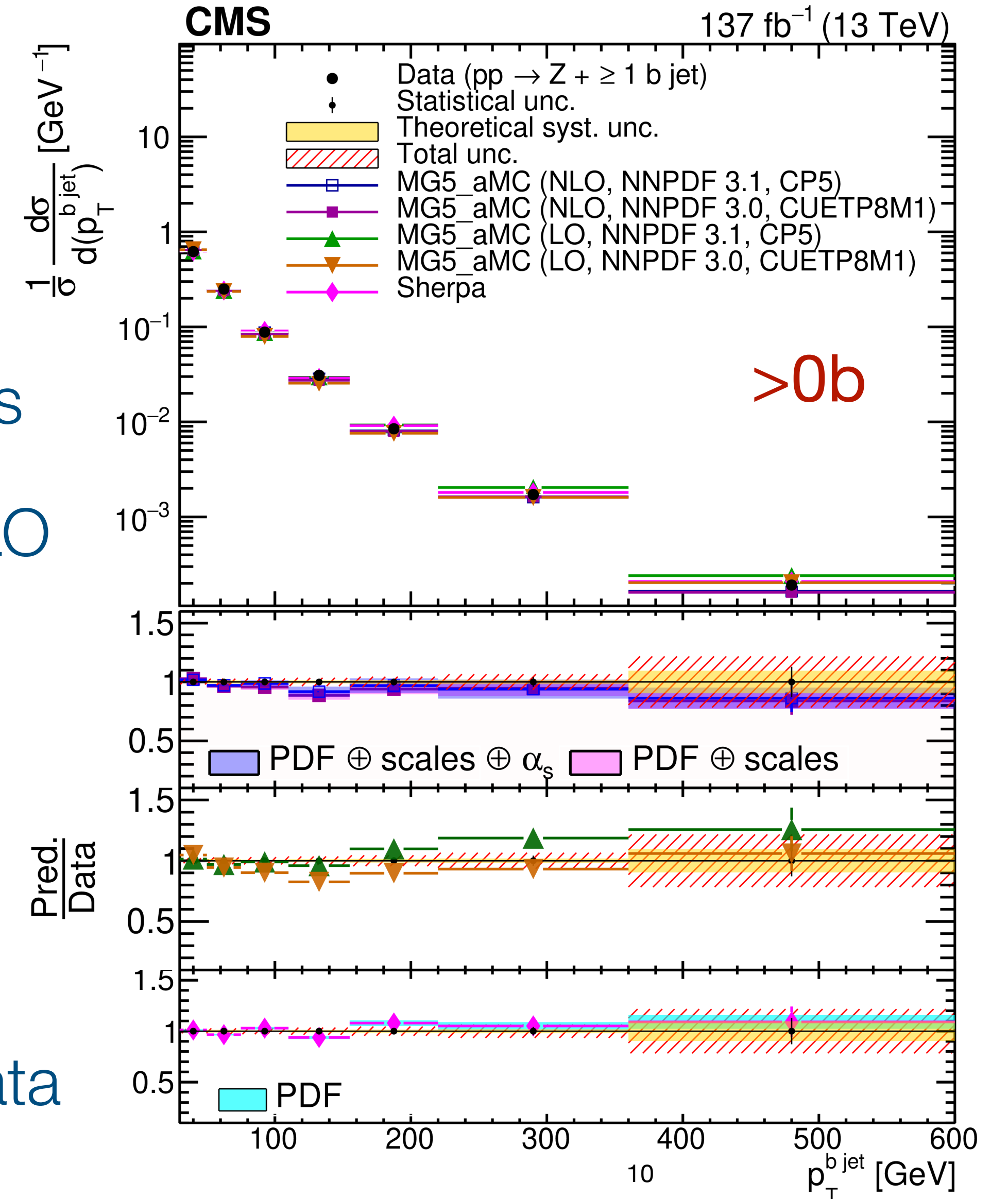
testing pQCD: leading b-jet  $p_T$  differential spectra



theory predictions

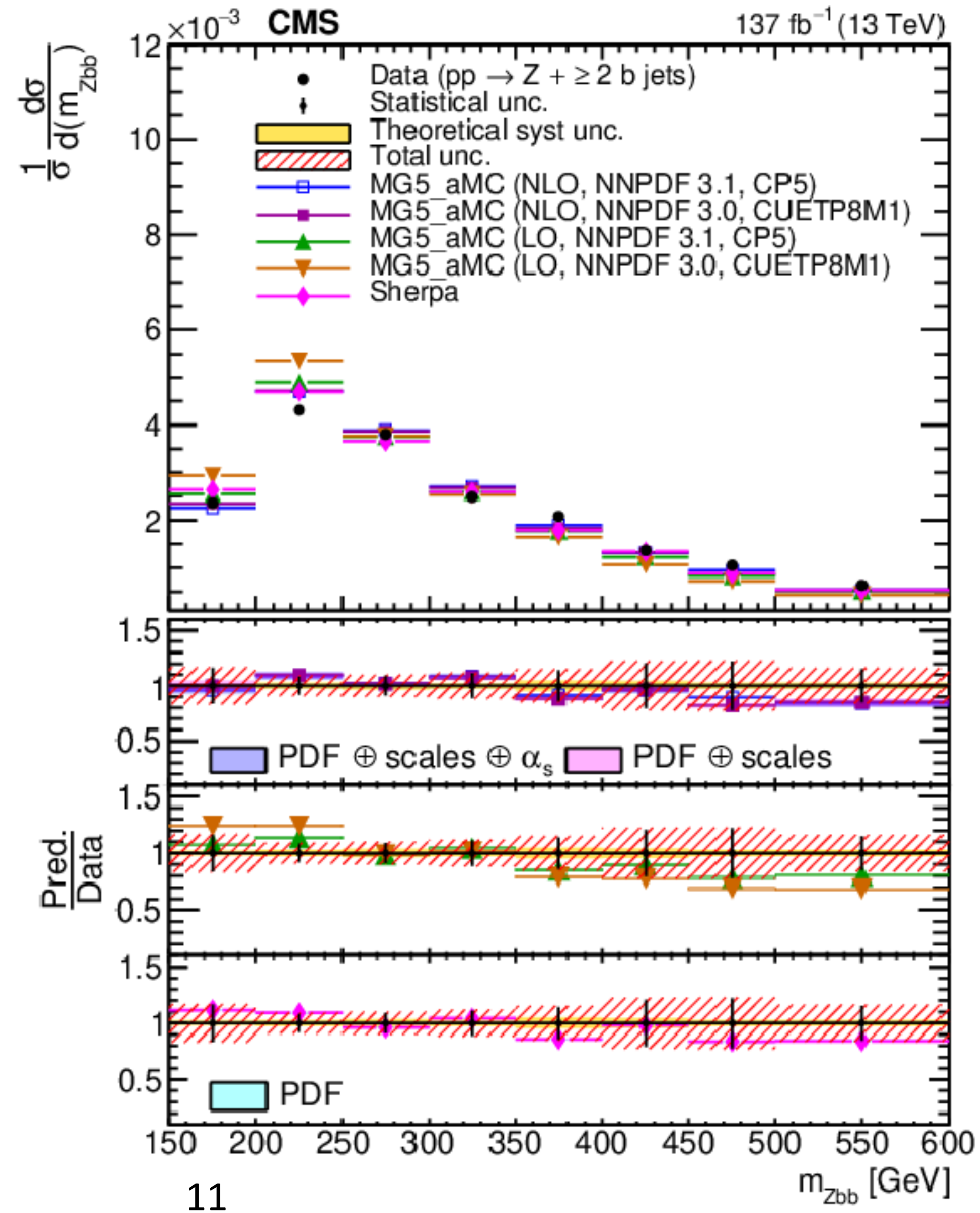
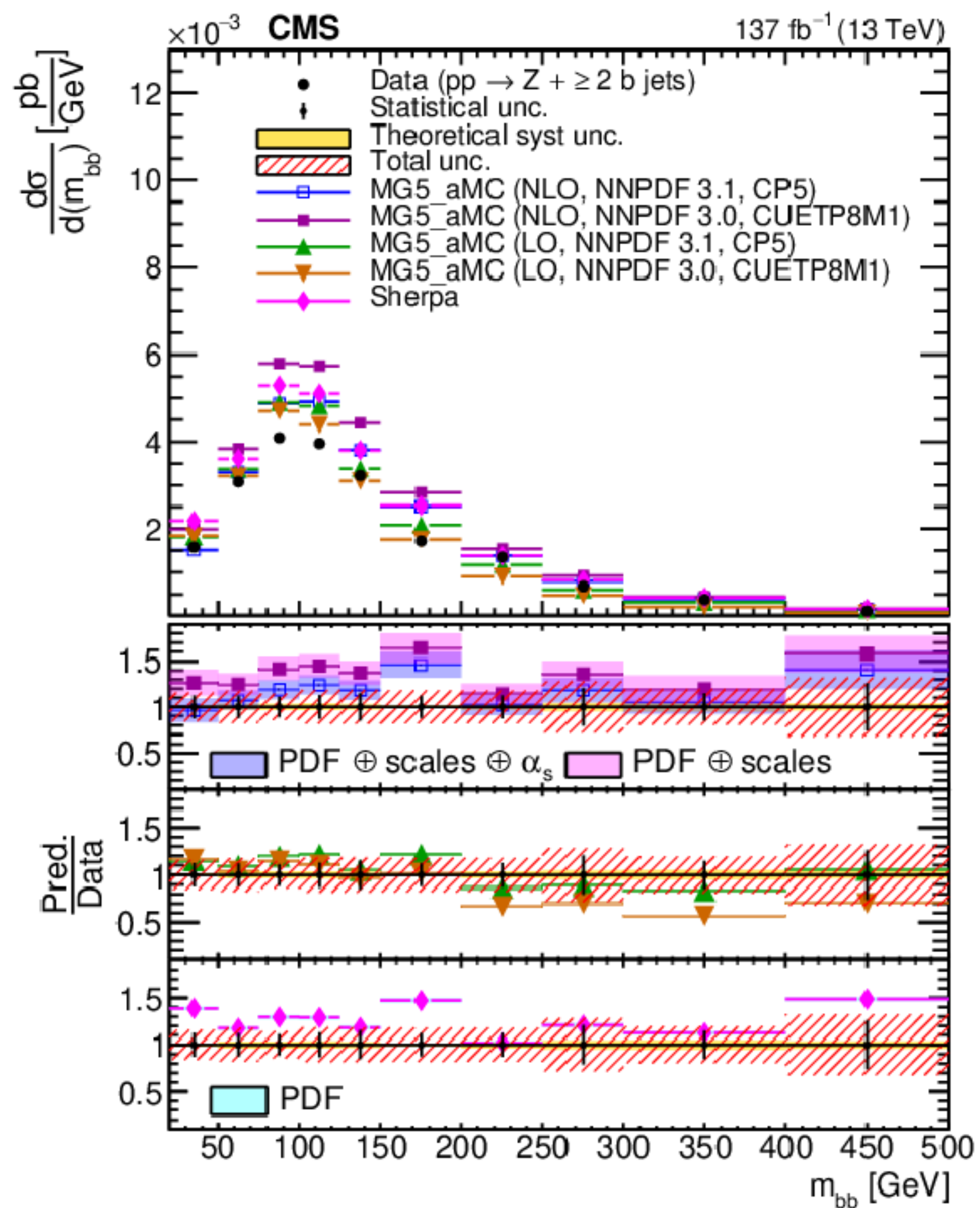
Madgraph LO, NLO  
w/NNPDF30/31  
+CP5tune and  
Sherpa NLO

very good  
description of data



# Associated Z boson and beauty at 13 TeV with CMS

new physics searches for resonances structures in invariant mass

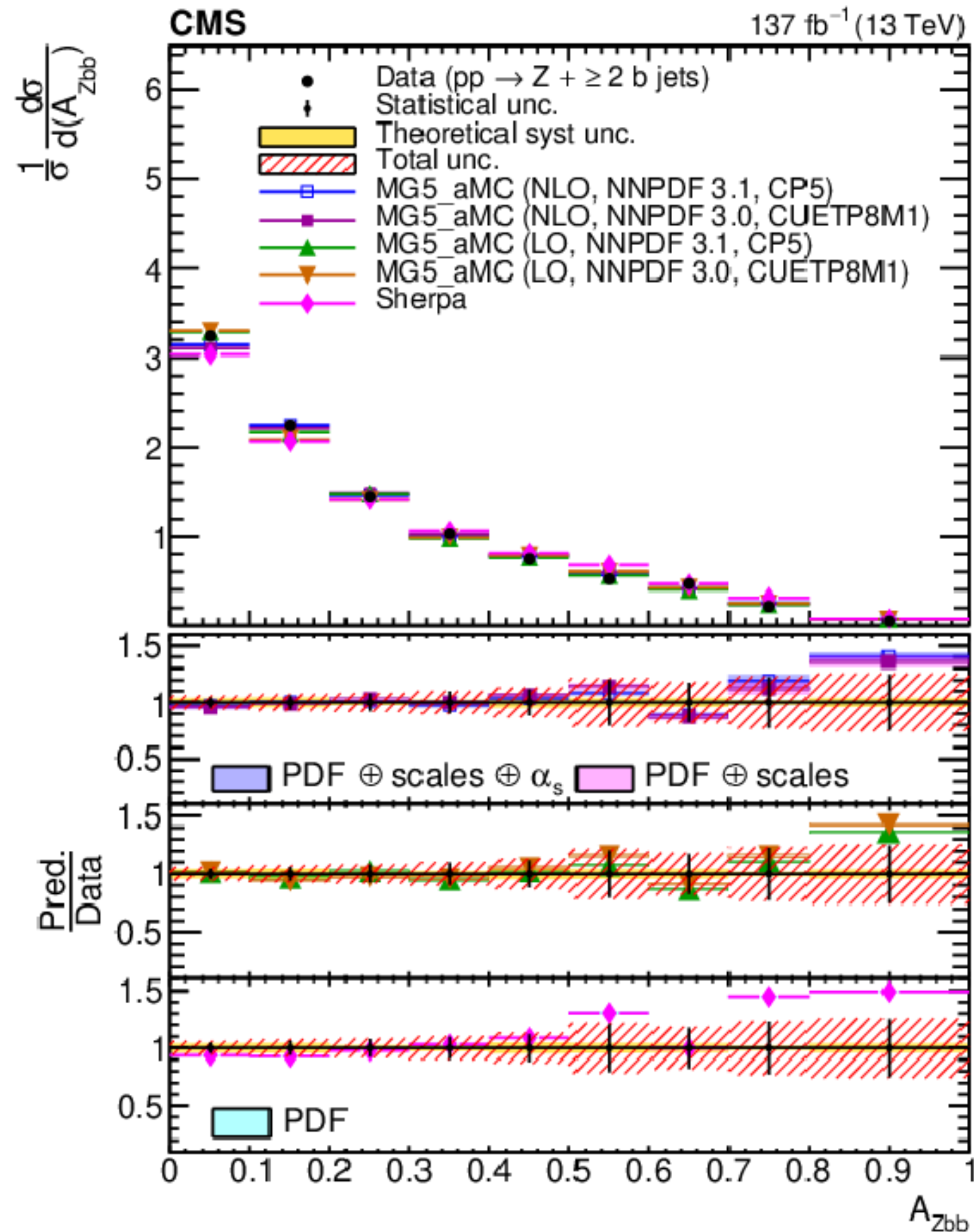


bb and Zbb  
invariant masses  
important in  
searches for  
resonances and  
new particles

no  
deviations  
w.r.t. the SM

# Associated Z boson and beauty at 13 TeV with CMS

## QCD tests with asymmetries and soft radiations



$$A_{ZBB} = \frac{\max \Delta R_{ZB} - \min \Delta R_{ZB}}{\max \Delta R_{ZB} + \min \Delta R_{ZB}}$$

A(Zbb) → 1  
 Emission of additional  
 gluon radiation in the  
 final state (A<sub>Zbb</sub> ≠ 0)

test gluon  
 density and  
 gluon radiation  
 effects in  
 pQCD

A(Zbb) → 0:  
 2 b-jets emitted symmetrically with respect to Z direction

A → 1 not described by any prediction

# Associated Z boson and beauty at 13 TeV with ATLAS

*JHEP 07 (2020) 044*

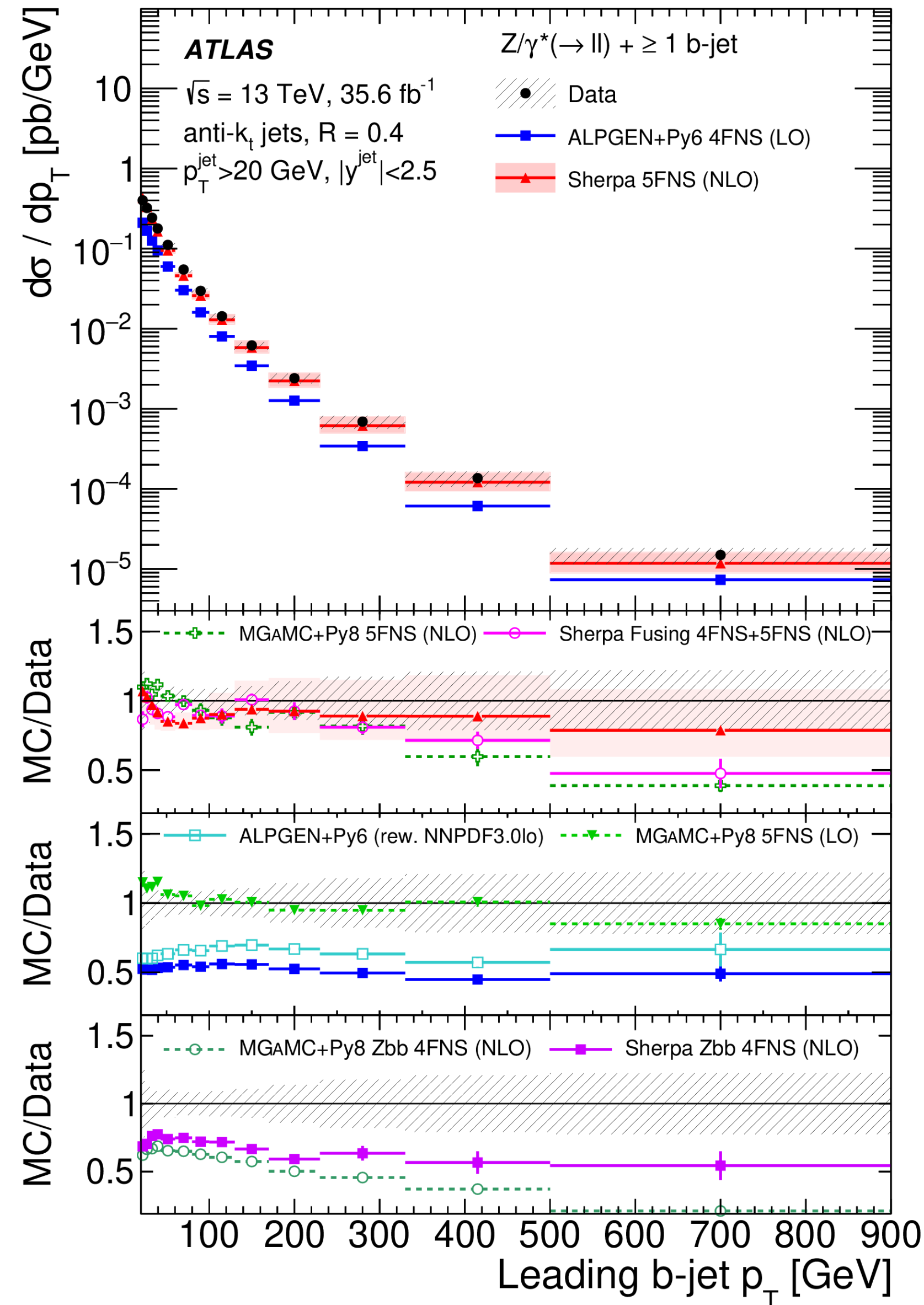


discriminate the effect of the b quark PDF of the proton (5/4-FS)

important test of pQCD: gluon splitting, HF mass, NLO effects

crucial background for  $VH \rightarrow b\bar{b}l\bar{l}$ ,  $V'$

combined MVA-based b-tagging reaching 70% efficiency for high pt jets  
mistag rate c-quarks and light 8% and 0.26%

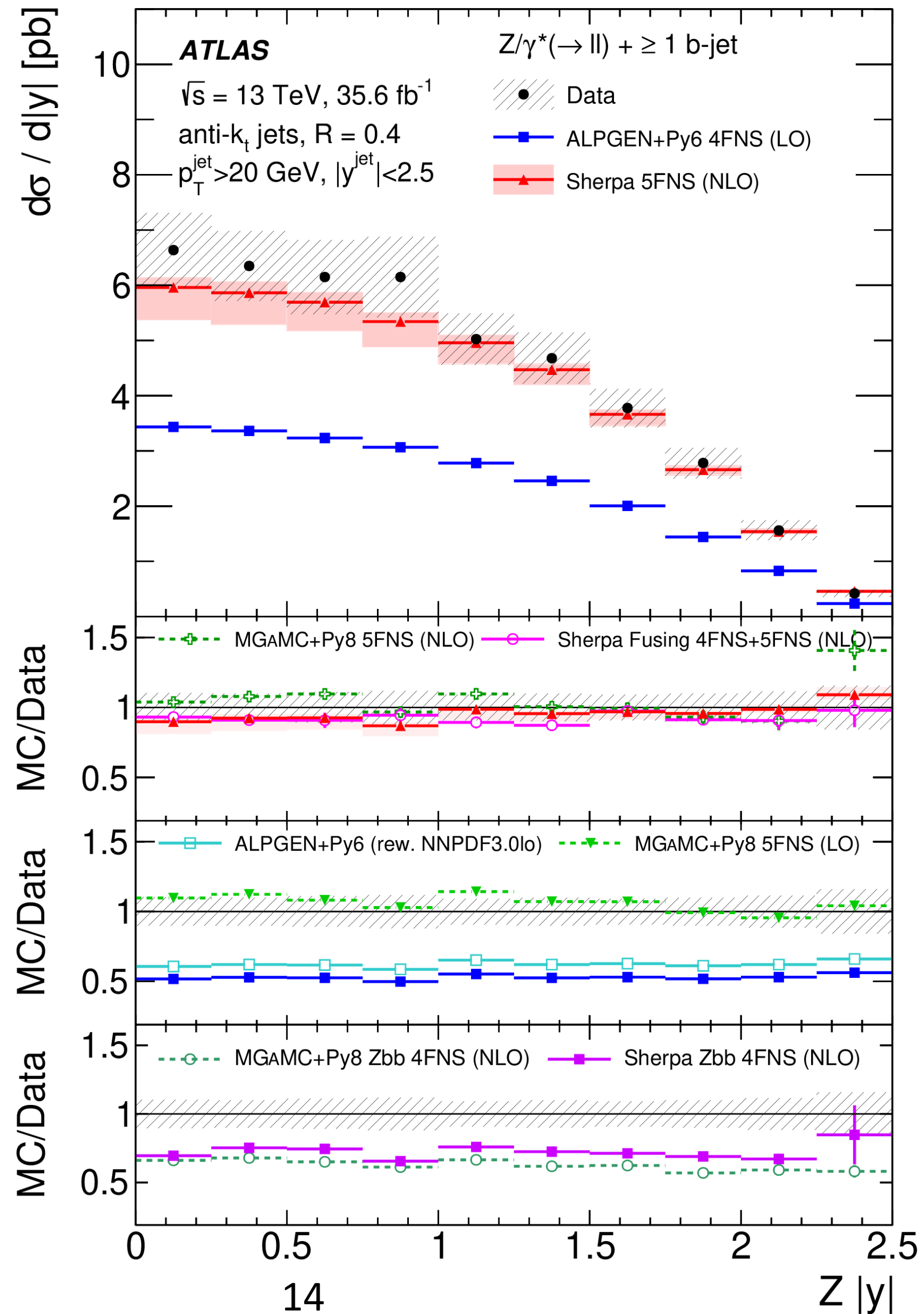
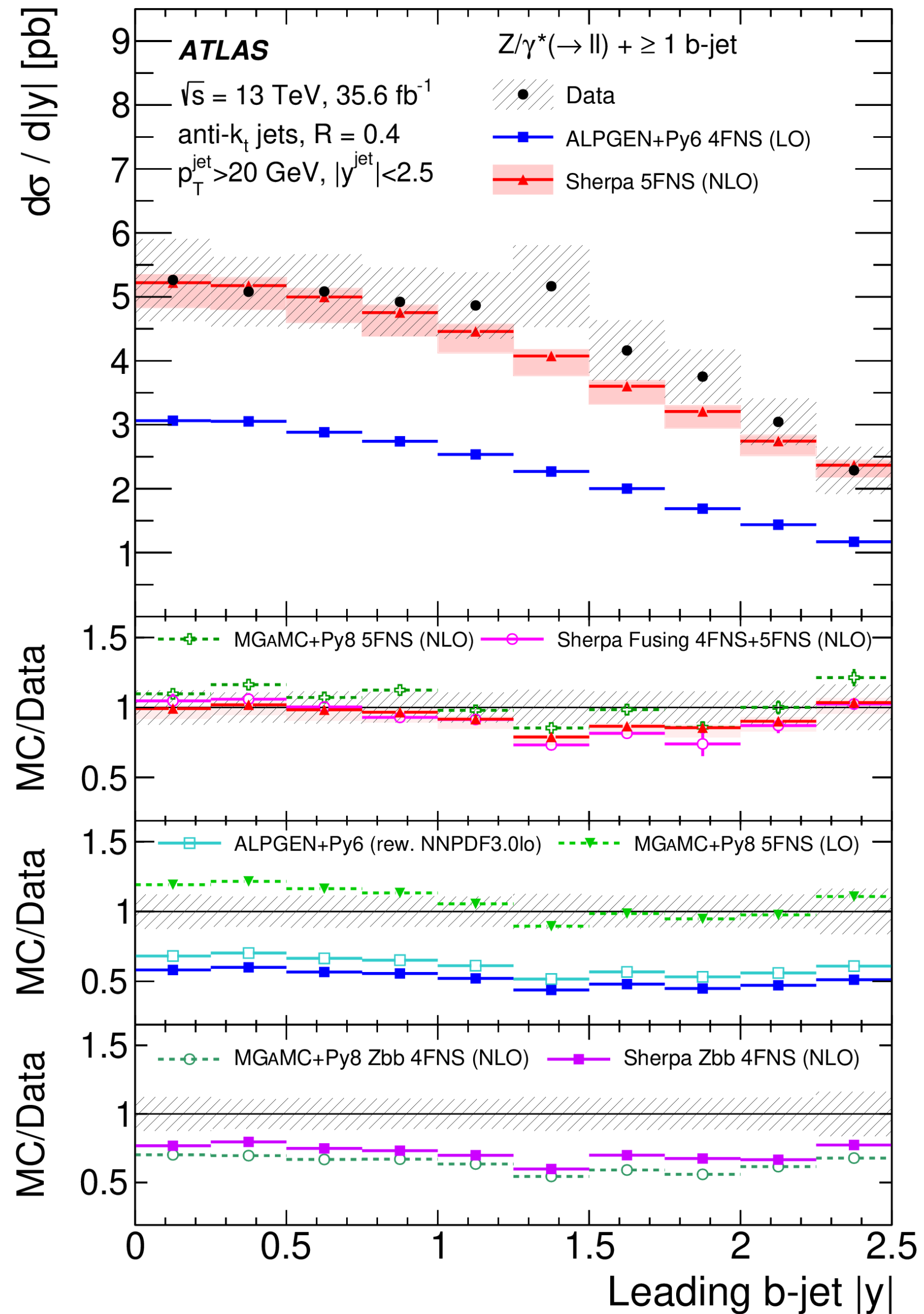


**new Sherpa  
4F+5F @ NLO  
prediction  
tested for the  
first time!**

**all 4F  
prediction  
underestimate  
the Z+1b xsec**

**fuse approach  
fails to  
describe the  
high pT tail**

# Associated Z boson and beauty at 13 TeV with ATLAS



**rapidity of the  
b and the Z**

**very good  
agreement  
with NLO 5F  
and 4+5**

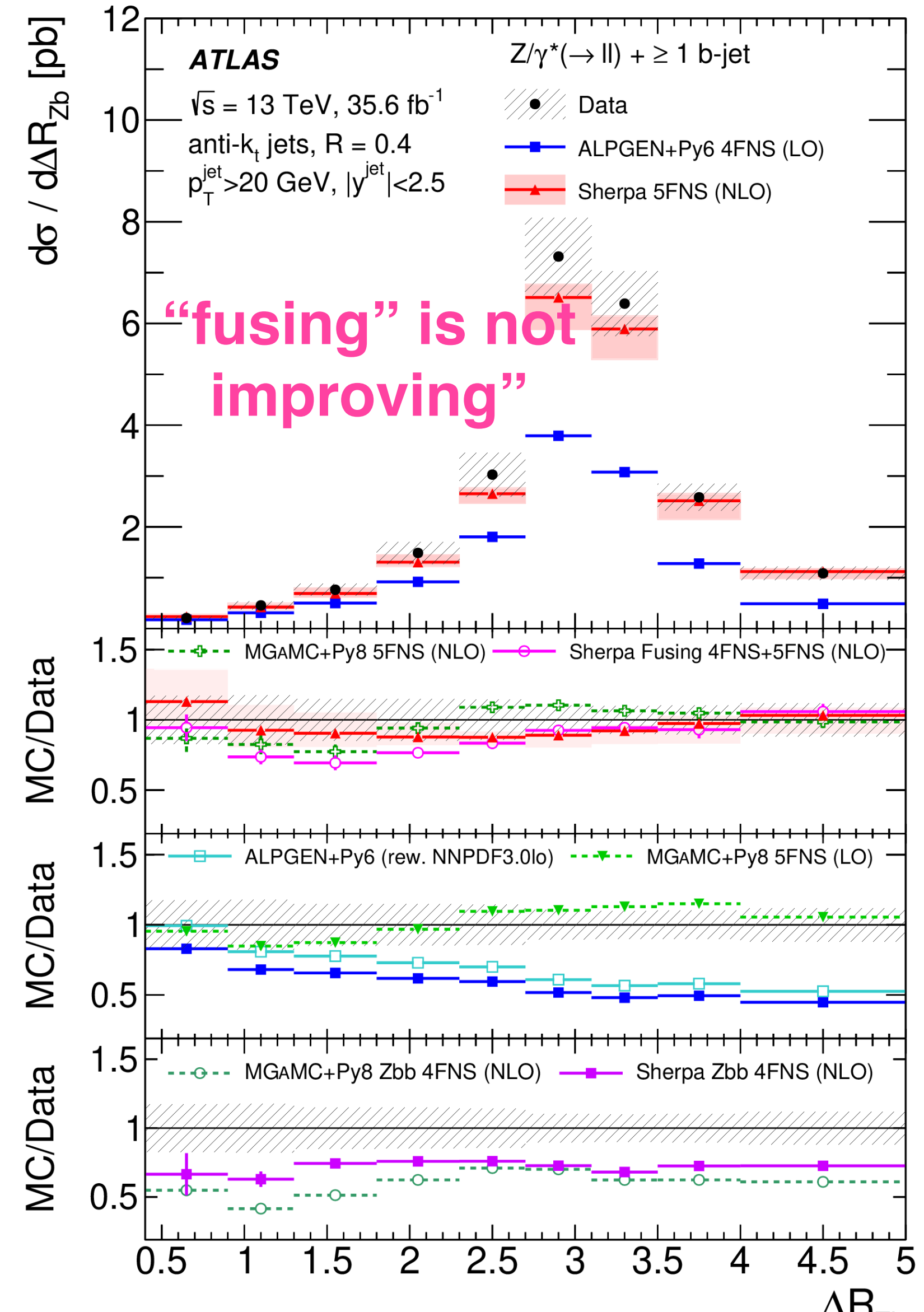
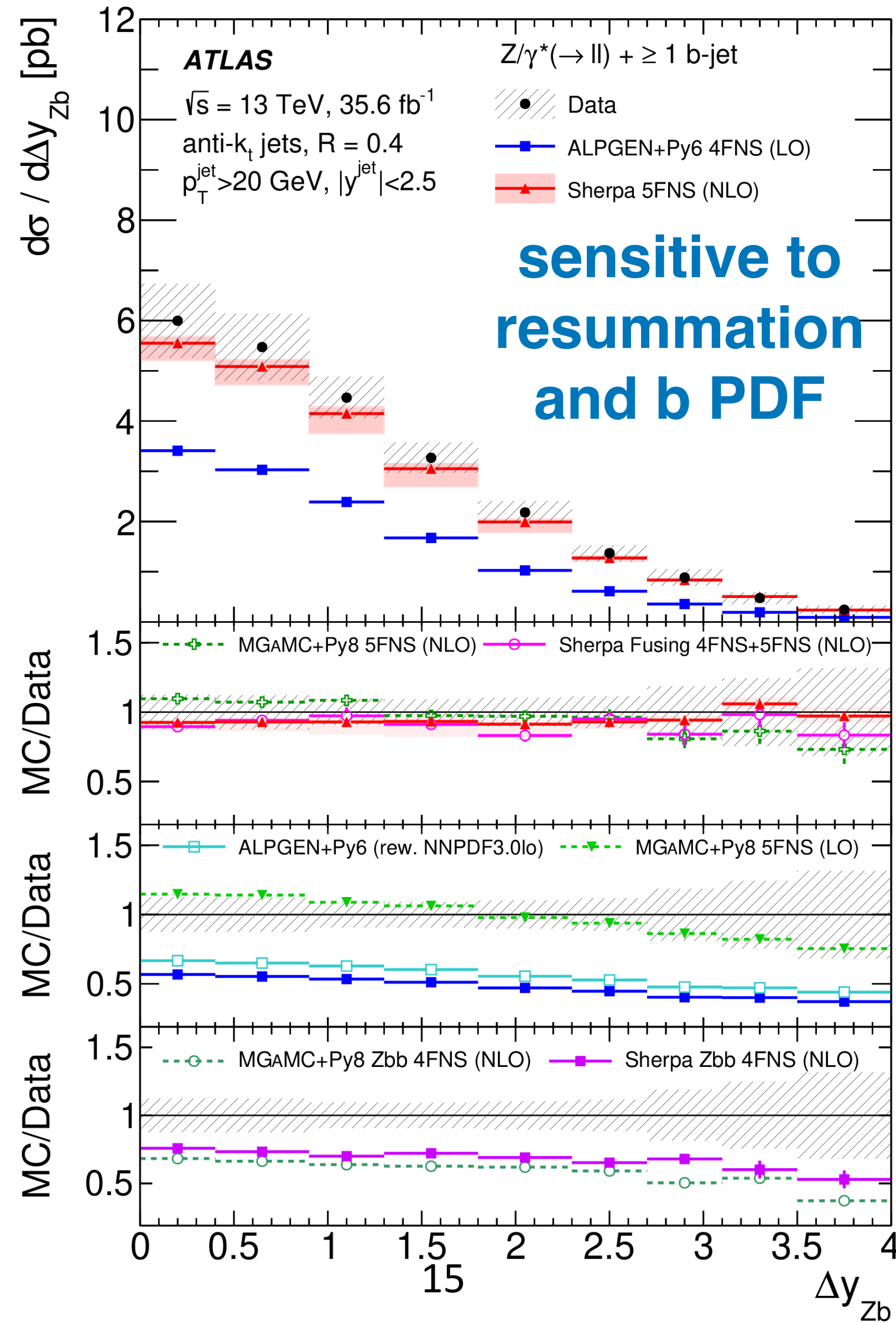
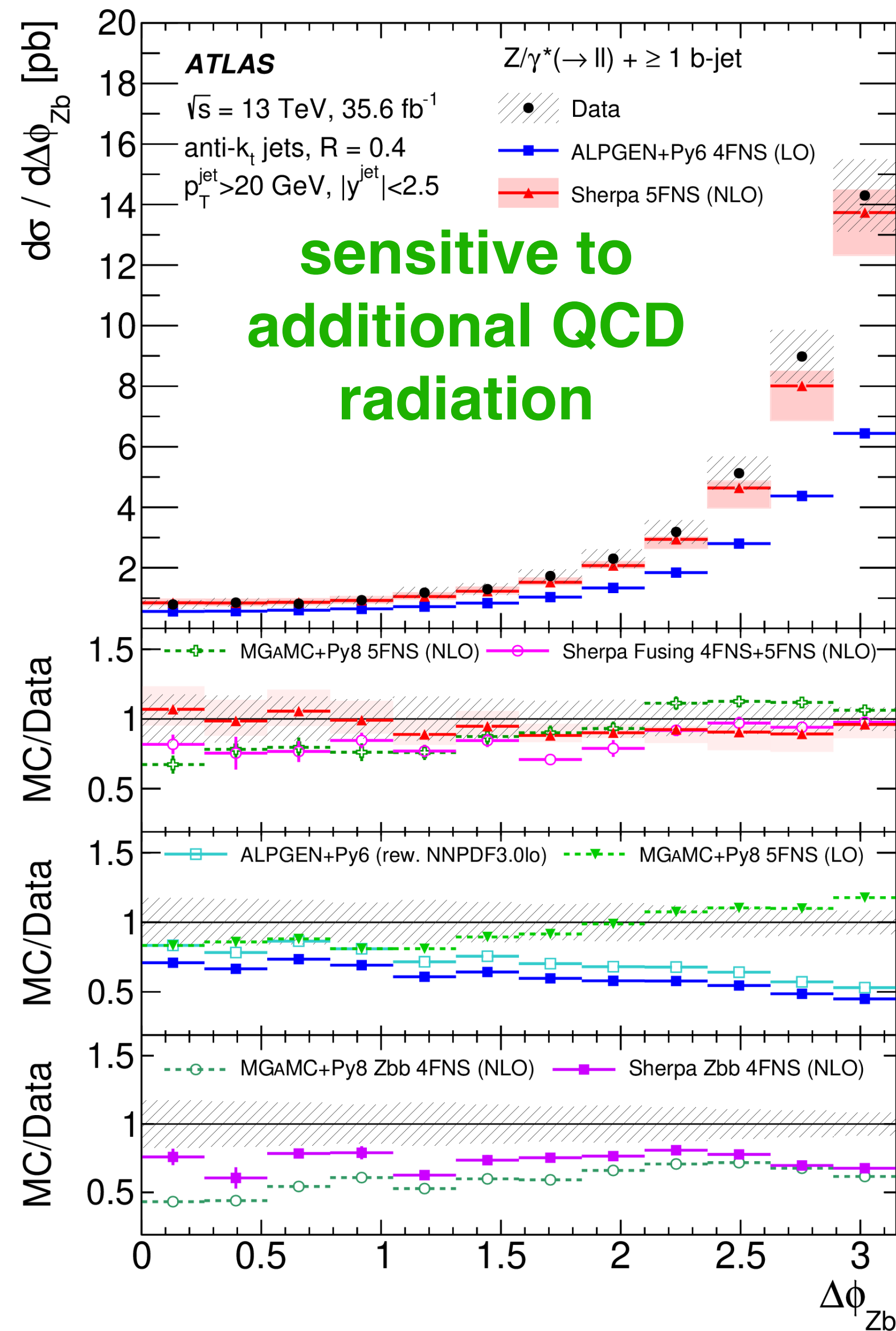
**interesting  
trend in the b  
rapidity 1-2.5**

**all other  
predictions  
underestimate  
data**

# Associated Z boson and beauty at 13 TeV with ATLAS

## resummation and soft QCD

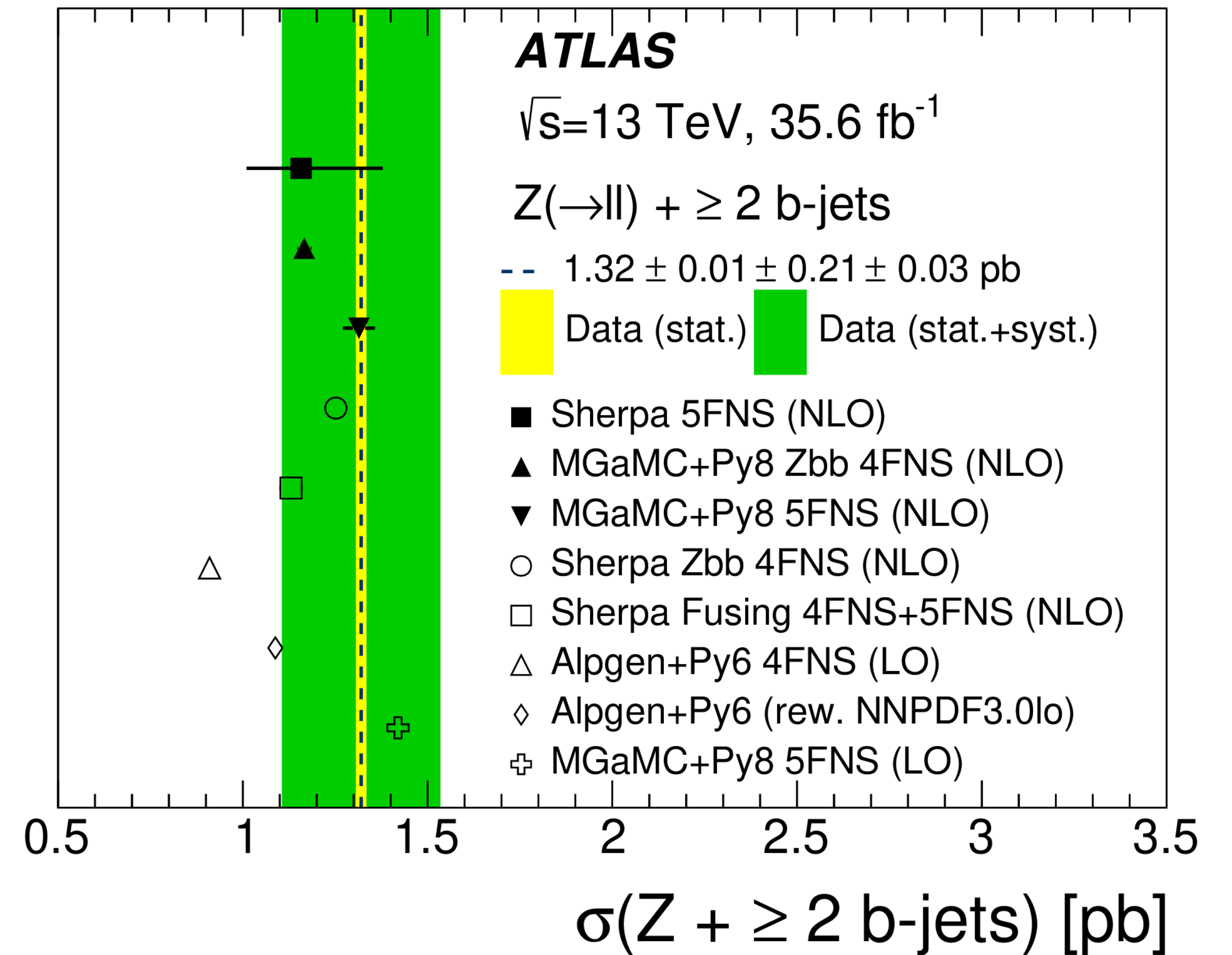
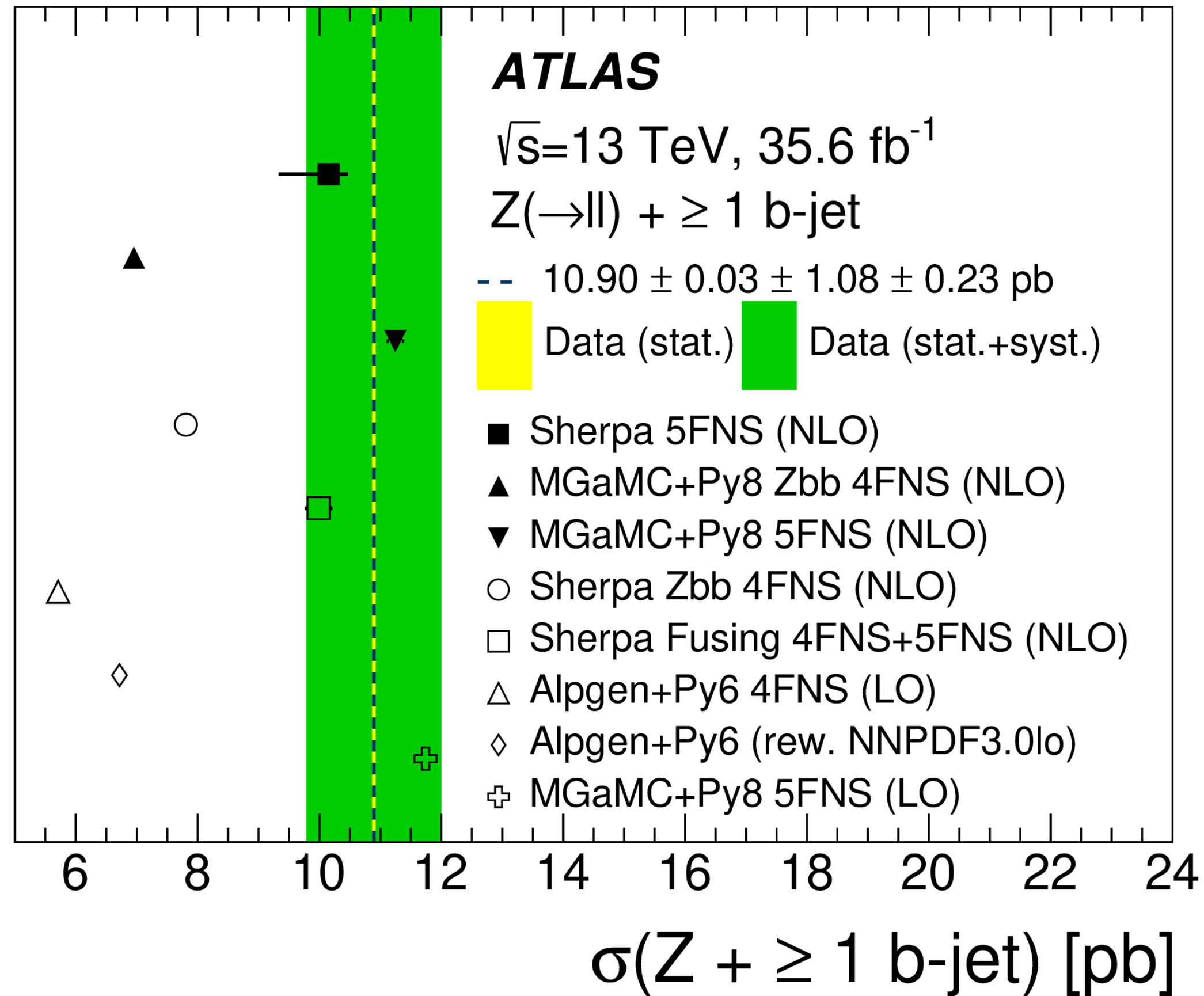
*JHEP 07 (2020) 044*



# Associated $Z$ boson and beauty at 13 TeV with ATLAS

inclusive cross section and flavour schemes

*JHEP 07 (2020) 044*

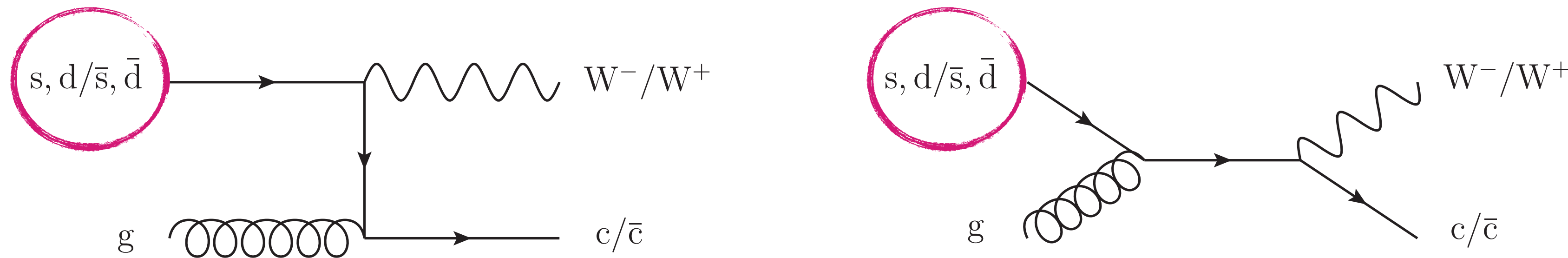


**5FS with either MG or Sherpa gives the best prediction**

**4FS with either MG or Sherpa generally underestimates the xsec**



# Associated $W$ boson and charm-jets at 13 TeV with CMS



*CMS-PAS-SMP-21-005*

$W+c$  production cross section  
and  $\sigma(W^+ + c)/\sigma(W^- + c)$  cross  
section ratio @13 TeV with full Run  
2 data

insight on the strange content of the proton: strange PDF and  $s/\bar{s}$  asymmetry

$d + g \rightarrow W + c$  is Cabibbo suppressed

test strangeness suppression  $R[s(x)] = \frac{s(x) + \bar{s}(x)}{u(x) + \bar{u}(x)}$

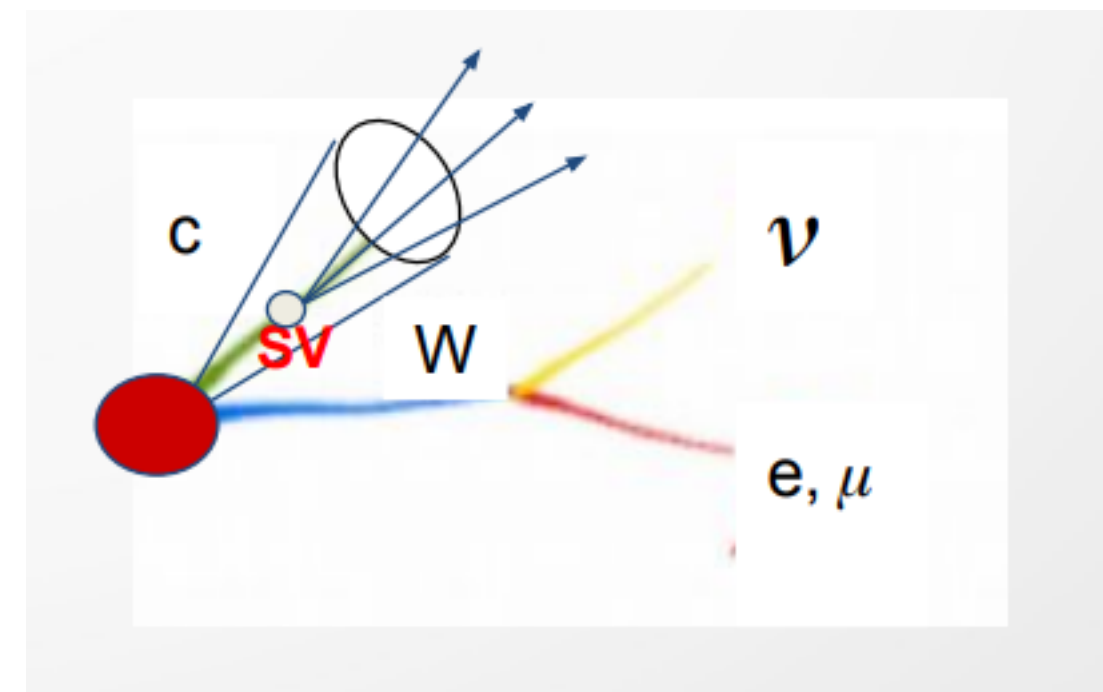
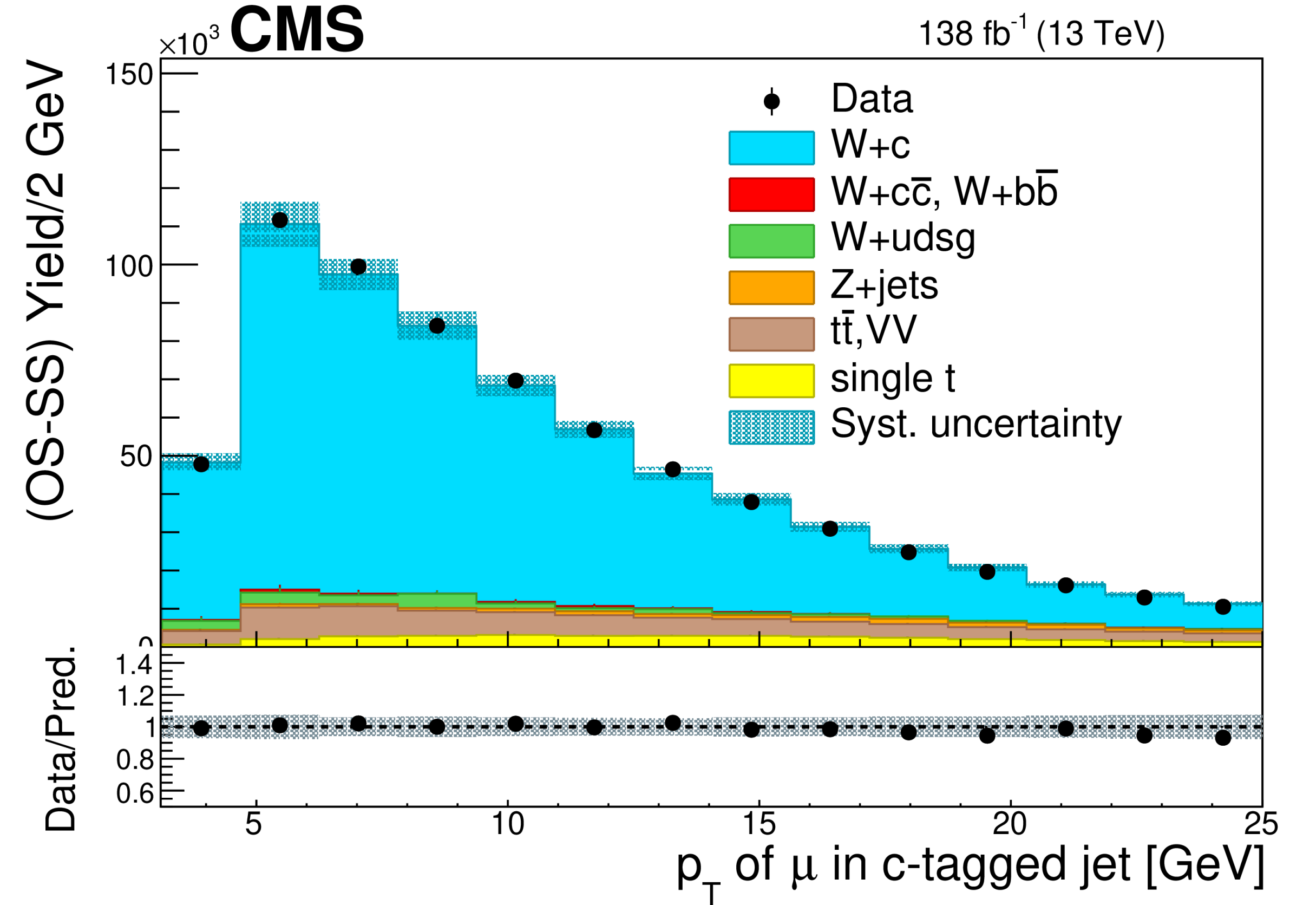
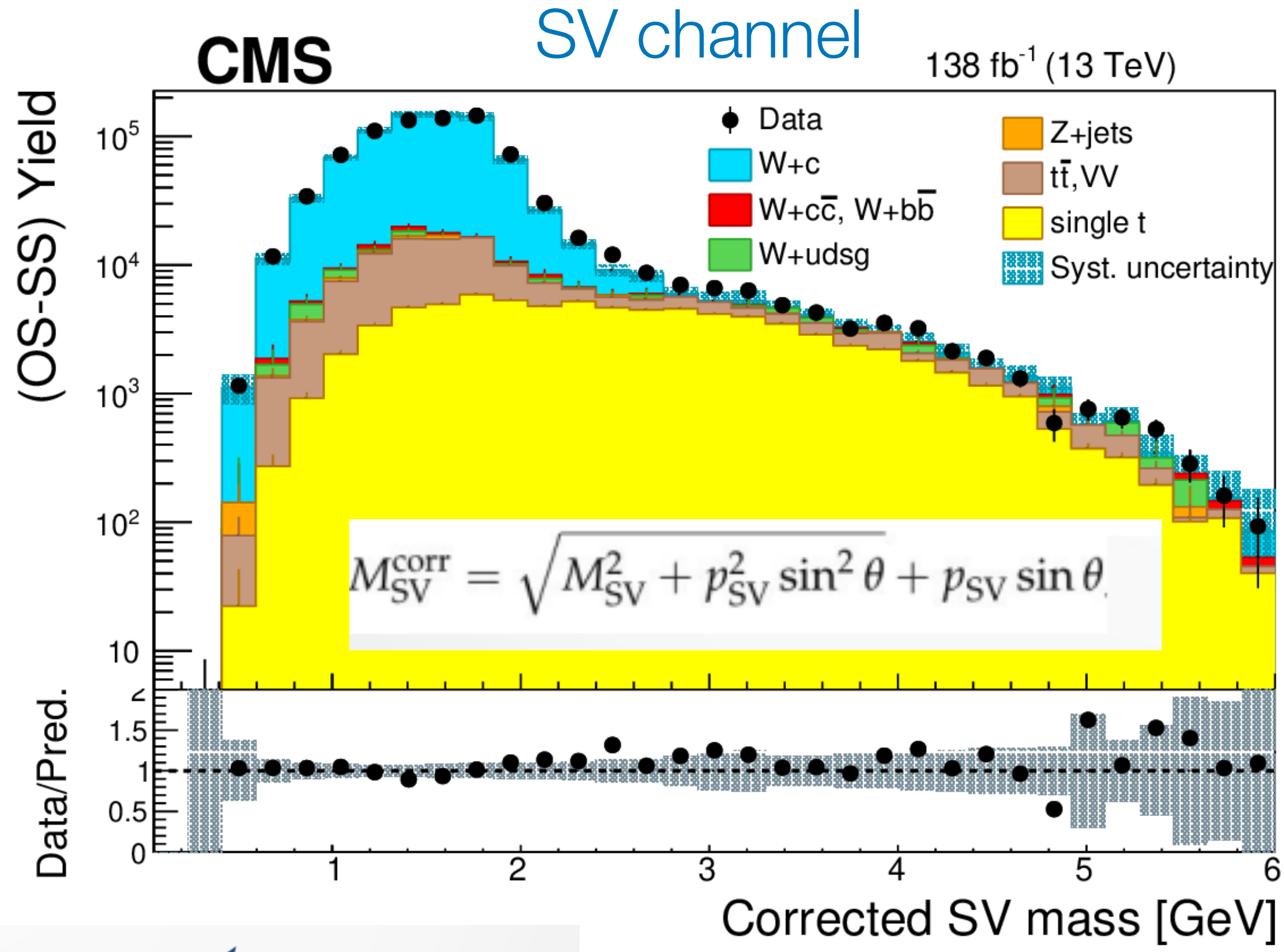
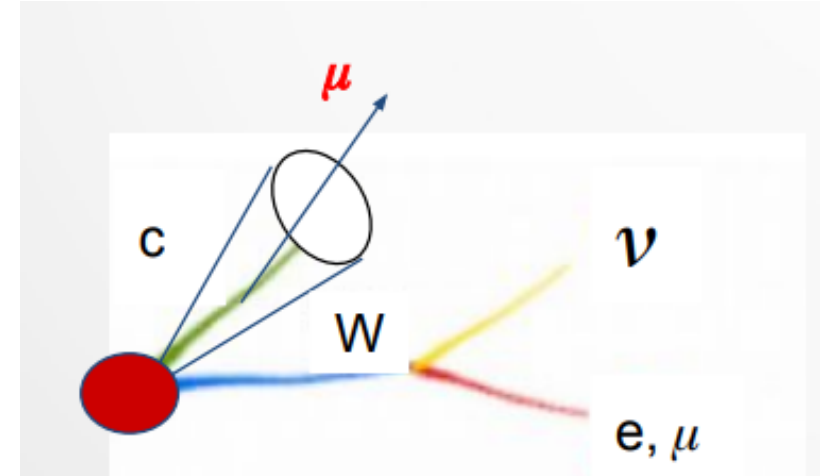
- Fiducial and differential unfolded cross section as a function of the pseudorapidity  $\eta^\ell$  and transverse momentum ( $p_T^\ell$ ) of the lepton from the  $W$  decay compared to NNLO
- In  $W+c$  events, the electric charge of the  $W$  is opposite to the charge of the  $c$  quark (OS) - where charge is identified with the  $\mu$  inside the jet) -> background rejection using same SS-OS subtraction

Charm tagging:

a muon inside the jet (SL channel) +  
a displaced secondary vertex inside the  
jet (SV channel)

4 exclusive categories (SV/SL)  
combined

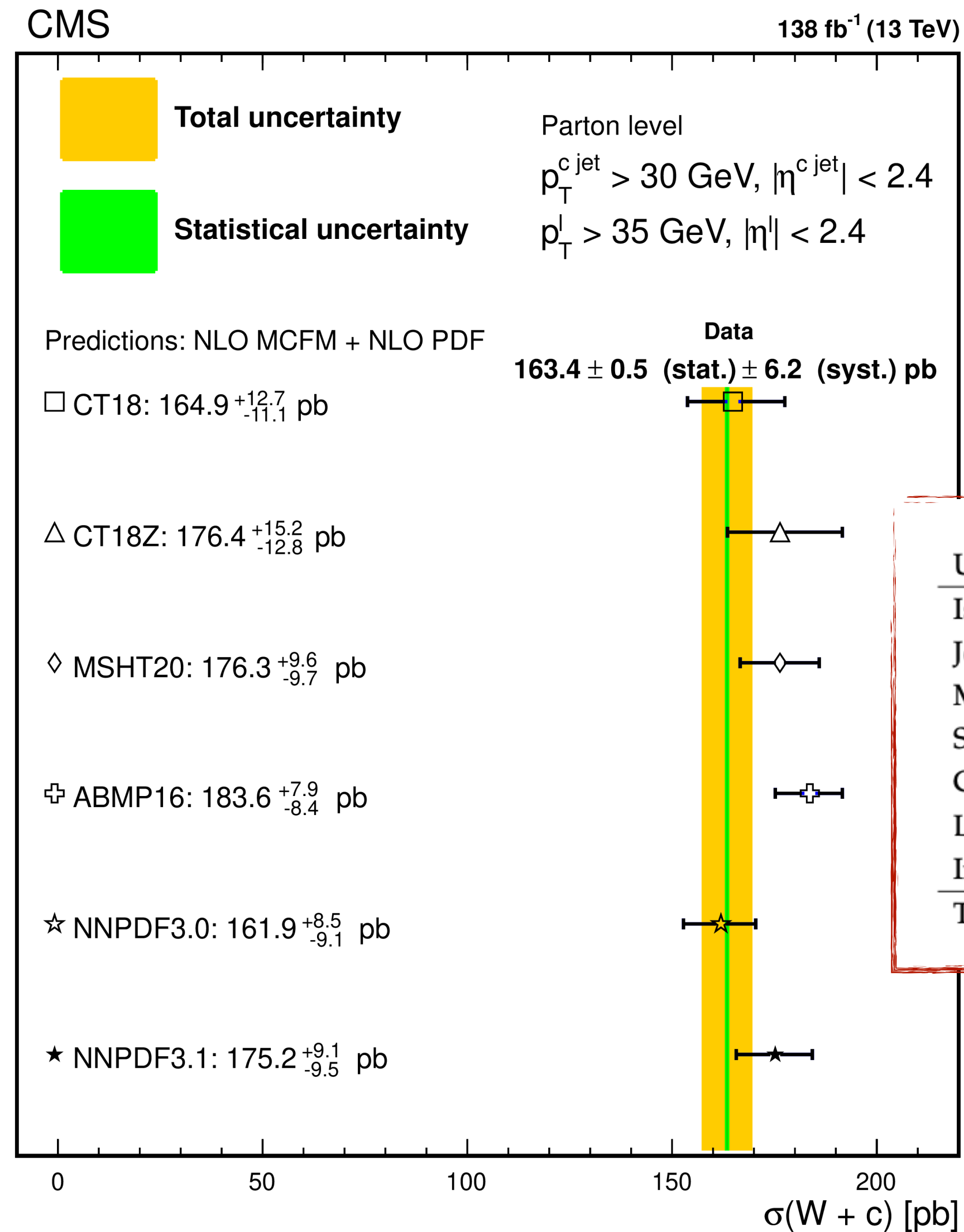
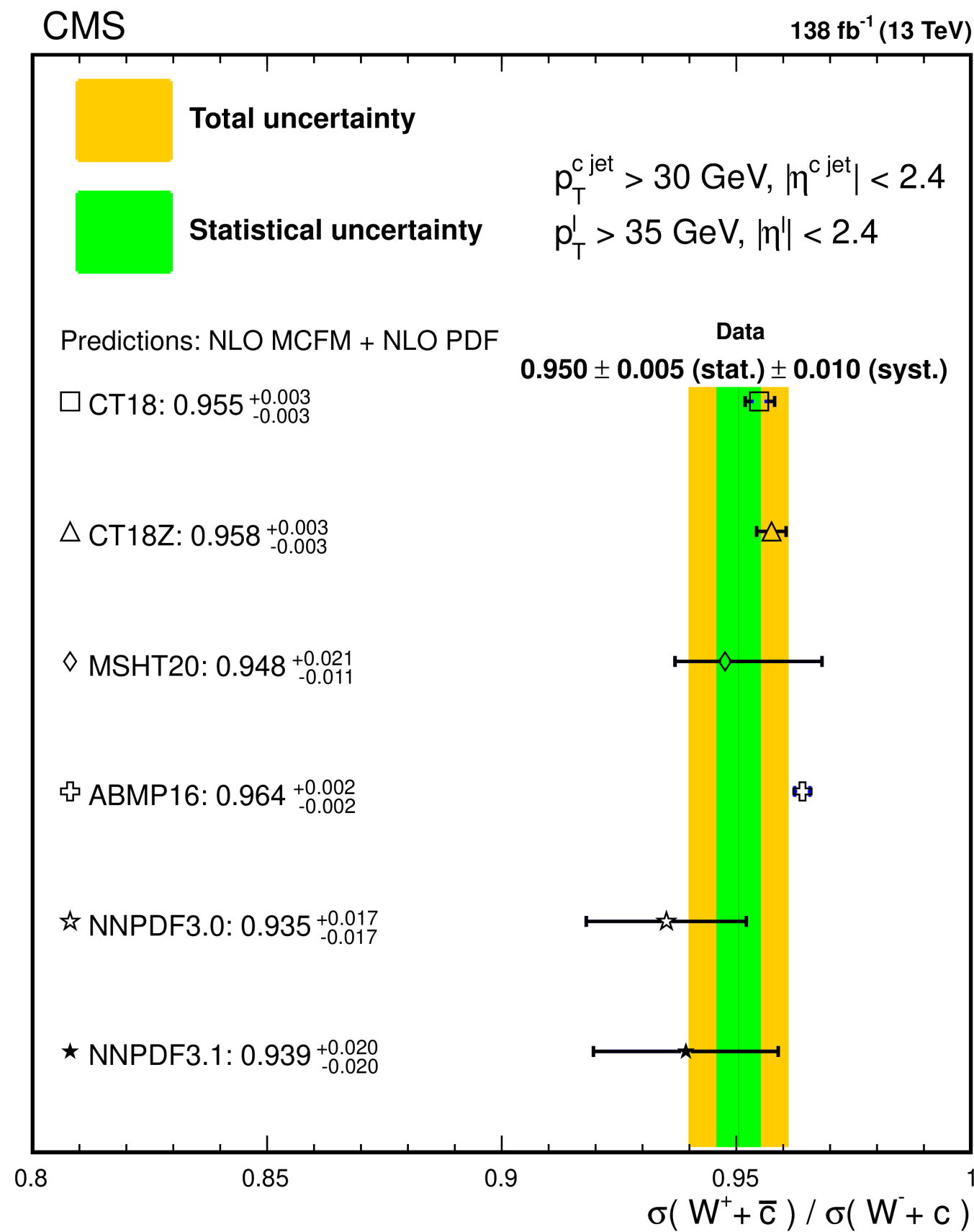
# Associated $W$ boson and charm-jets at 13 TeV with CMS



**SV**

SV Channel	W+c	W + Q $\bar{Q}$	W + udsg	Z+jets	t $\bar{t}$	single top	VV
W $\rightarrow$ e $\nu$	82.1 $\pm$ 0.8	0.7 $\pm$ 0.4	1.0 $\pm$ 0.6	0.1 $\pm$ 0.2	7.2 $\pm$ 0.1	8.4 $\pm$ 0.1	0.5 $\pm$ 0.1
W $\rightarrow$ $\mu\nu$	80.9 $\pm$ 0.6	0.7 $\pm$ 0.3	0.5 $\pm$ 0.4	0.5 $\pm$ 0.2	8.0 $\pm$ 0.1	8.9 $\pm$ 0.1	0.5 $\pm$ 0.1

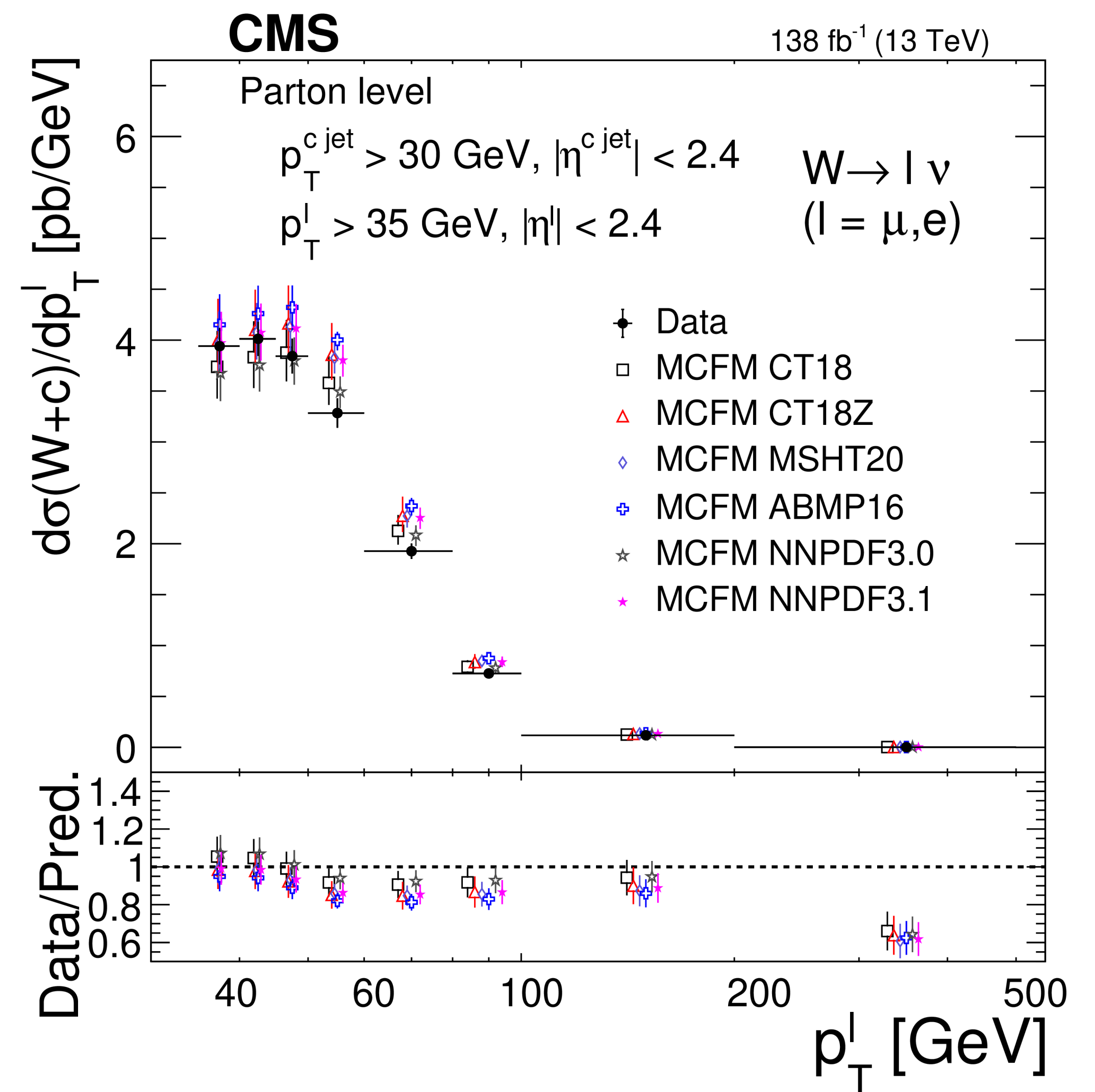
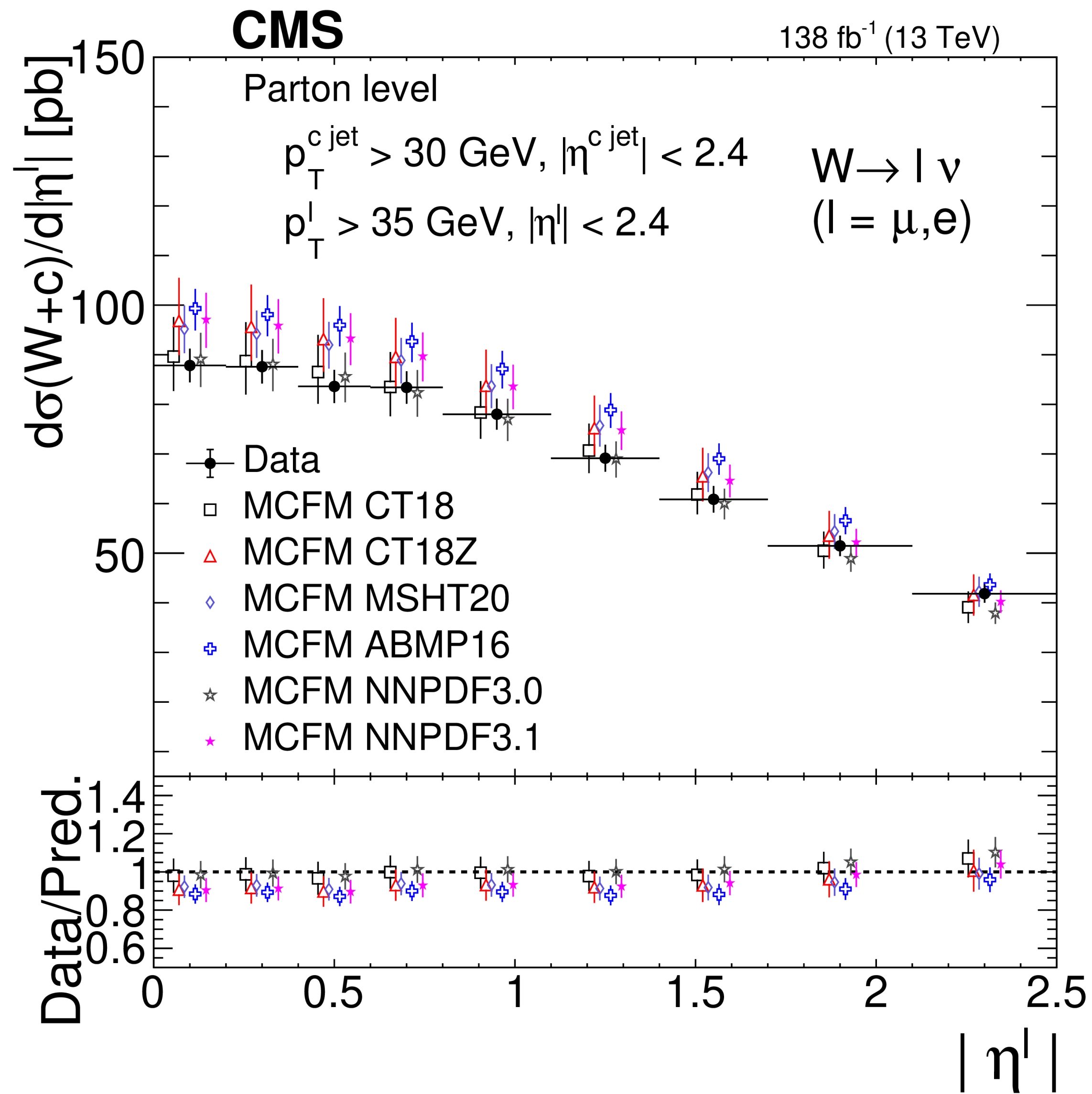
# Associated $W$ boson and charm-jets at 13 TeV with CMS



Uncertainty [%]	SL	SL	SV	SV
	$W \rightarrow e\nu$	$W \rightarrow \mu\nu$	$W \rightarrow e\nu$	$W \rightarrow \mu\nu$
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
<b>Total</b>	<b>5</b>	<b>5</b>	<b>5</b>	<b>5</b>

$$\sigma(pp \rightarrow W + c) = 148.7 \pm 0.4(\text{stat}) \pm 5.6(\text{syst}) \text{ pb}$$

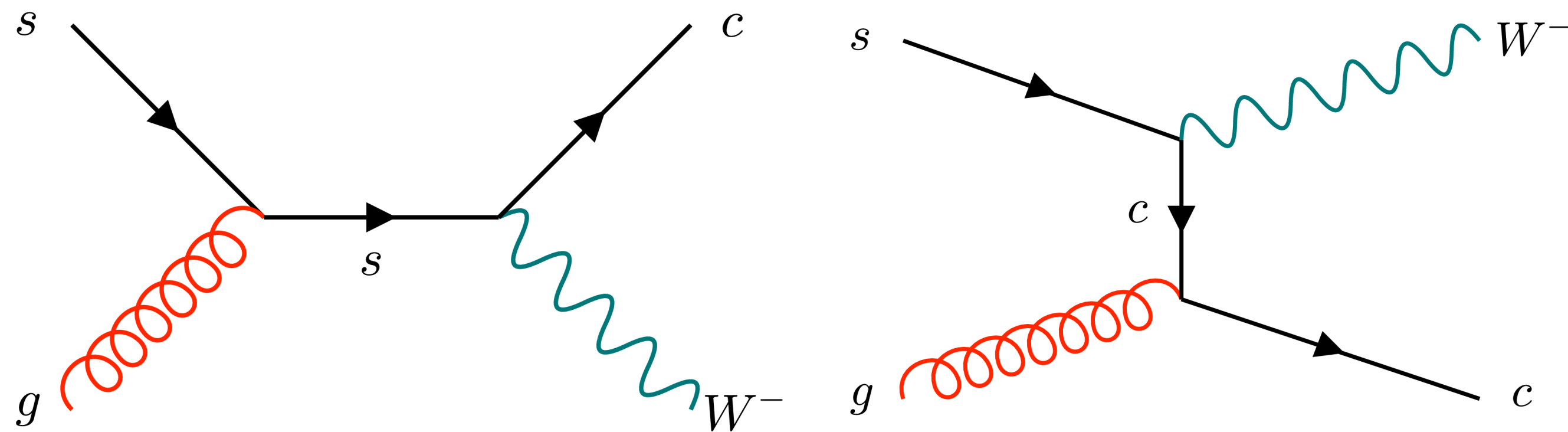
# Associated $W$ boson and charm-jets at 13 TeV with CMS



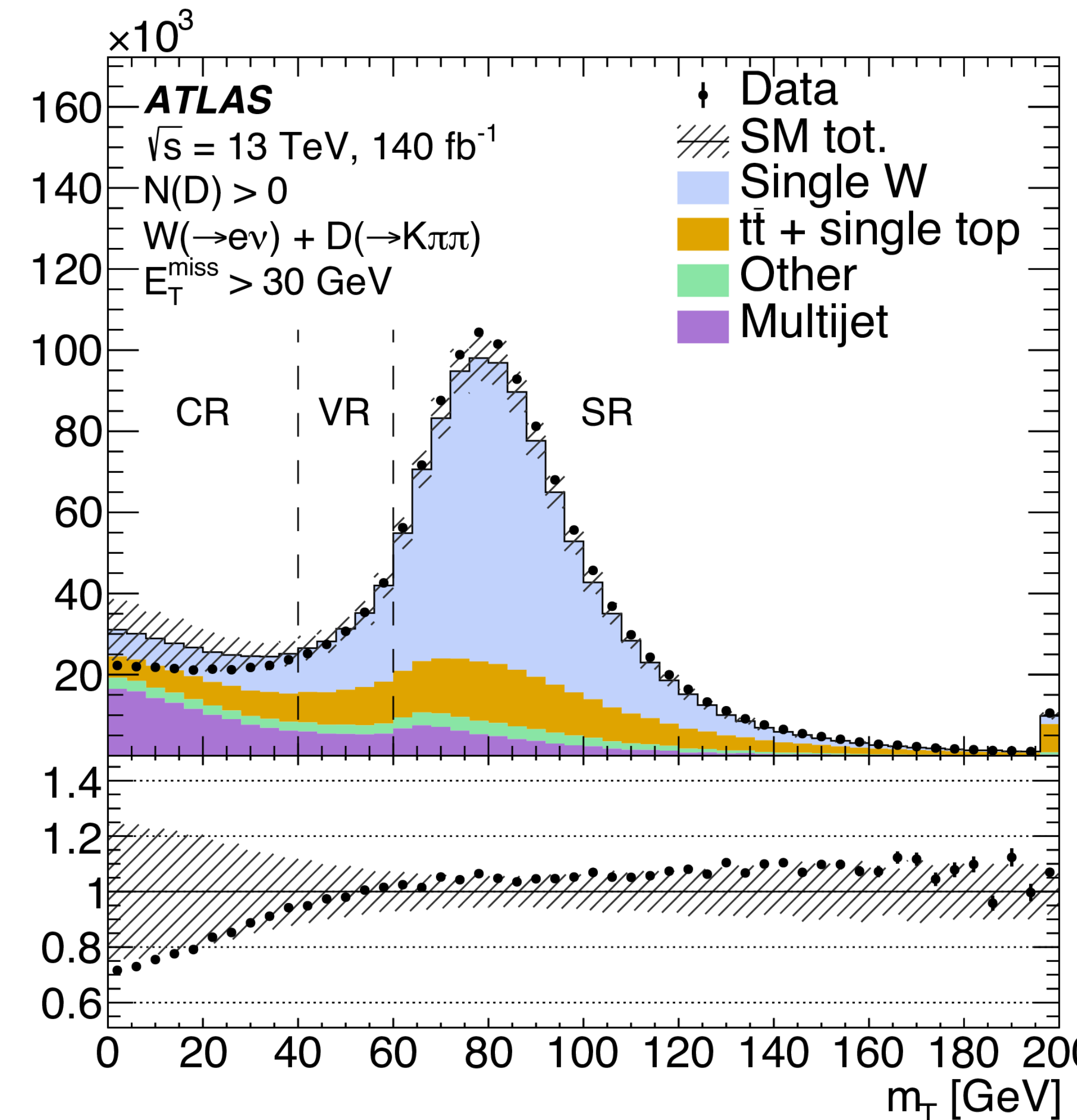
PDF comparison including s/sbar asymmetry

# Associated $W$ boson and charm-hadrons at 13 TeV with ATLAS

[Phys. Rev. D 108 \(2023\) 032012](#)



Entries / (4 GeV)



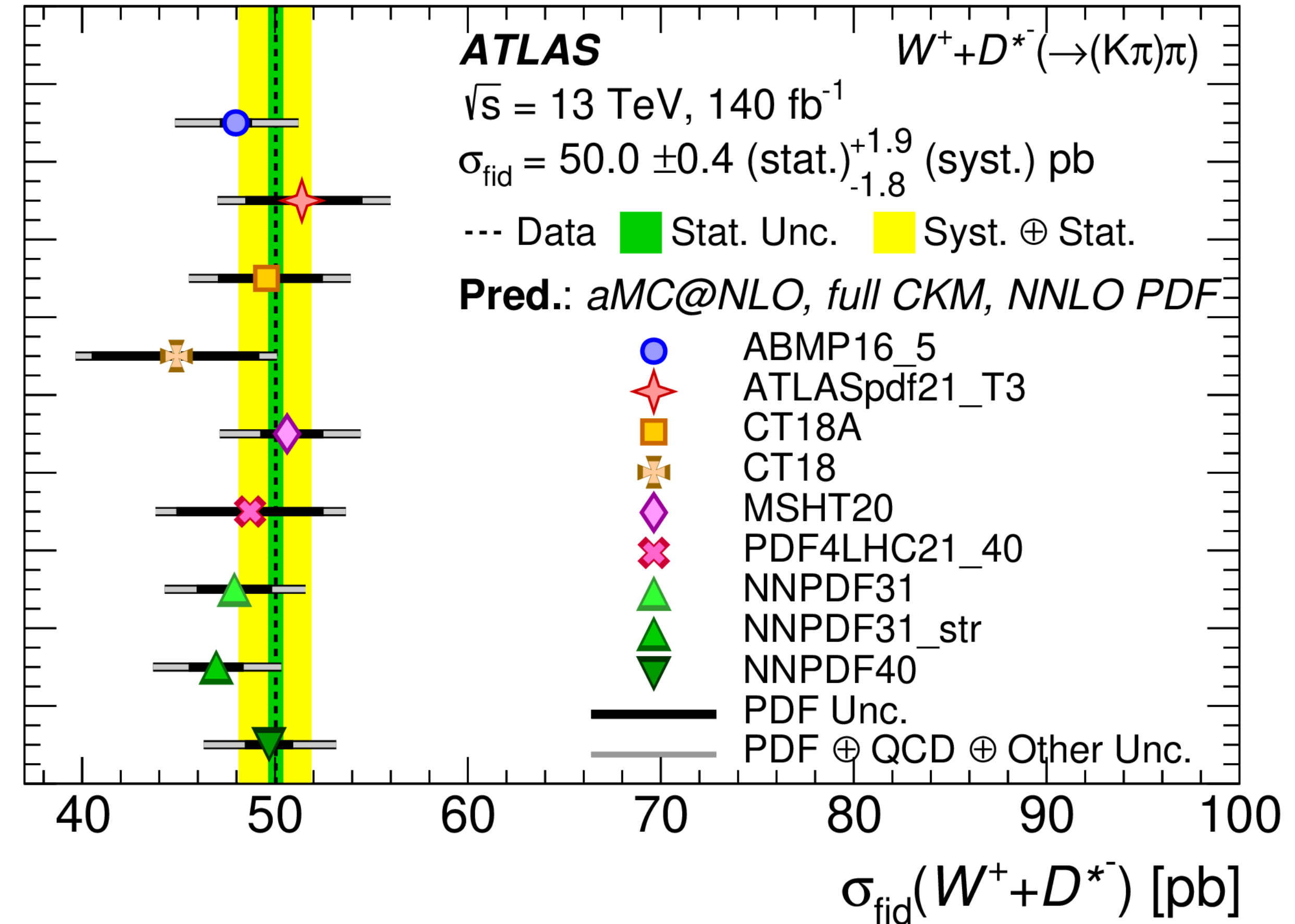
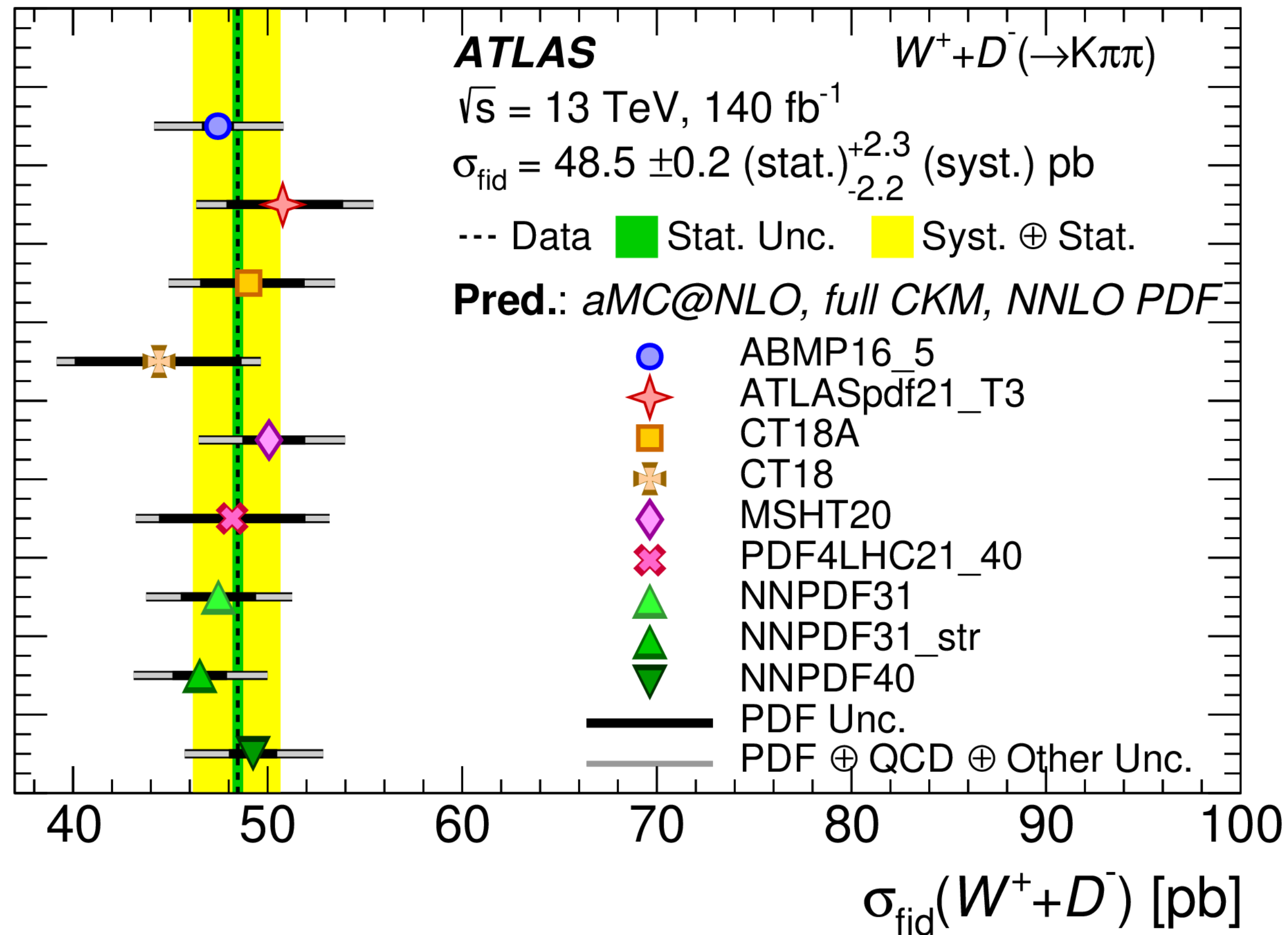
- $W(\rightarrow e\nu/\mu\nu) - D^+ \rightarrow K\pi\pi - D^{*+} \rightarrow D^0\pi^+ \rightarrow (K^-\pi^+)\pi^+$
- Classification of events to opposite- and same- sign (OS/SS) W/D candidates
- only OS pairs are expected at LO
- background dose not discriminate charge  $\rightarrow$  signal extracted by OS - SS candidates
- Measurement of fiducial and differential  $W+D^{(*)}$  cross sections
- Full Run-2 with single lepton triggers

Cross section ratio  $R_c$  also measured

# Associated $W$ boson and charm-hadrons at 13 TeV with ATLAS

*Phys. Rev. D 108 (2023) 032012*

PDF comparison: very nice agreement

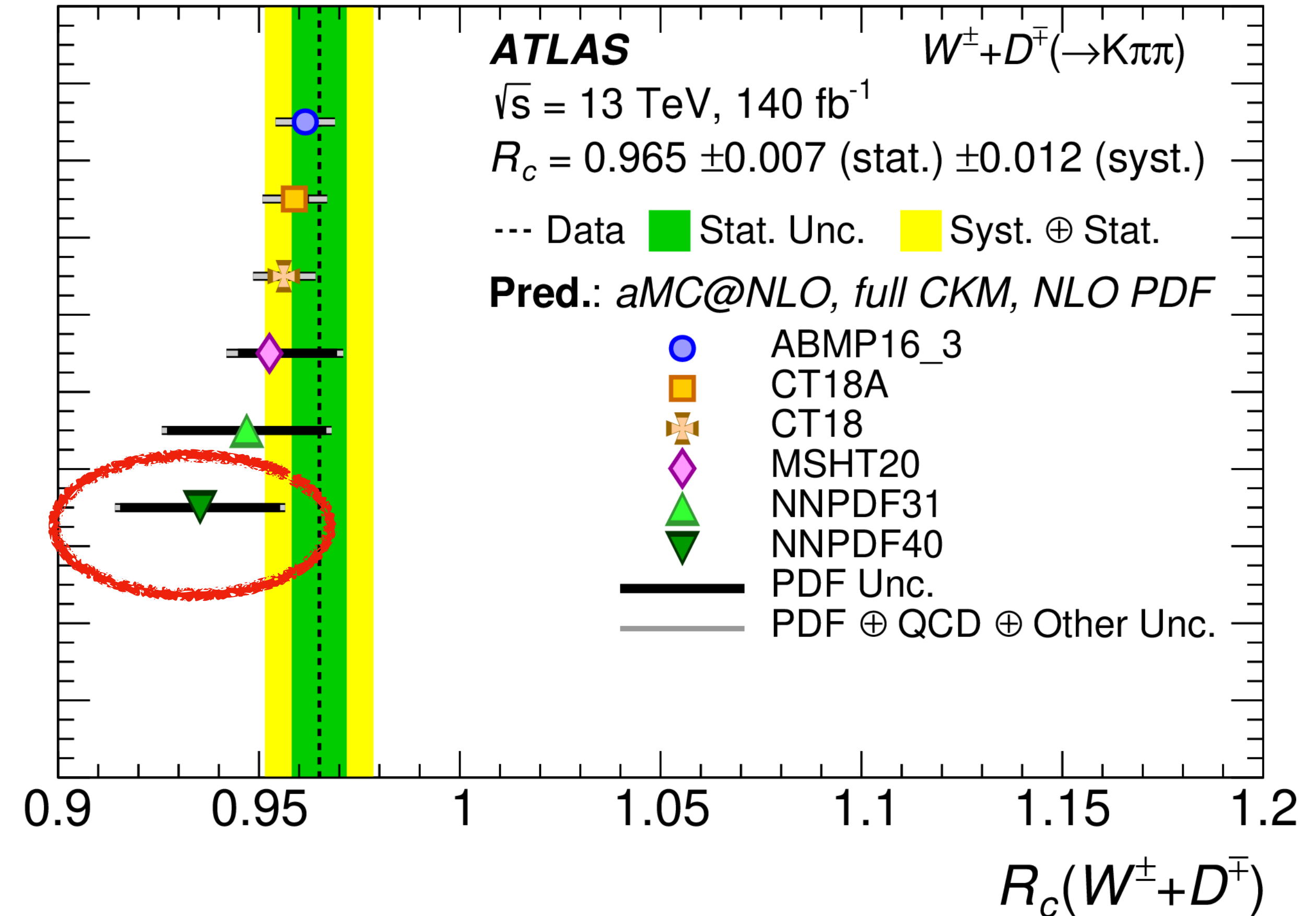
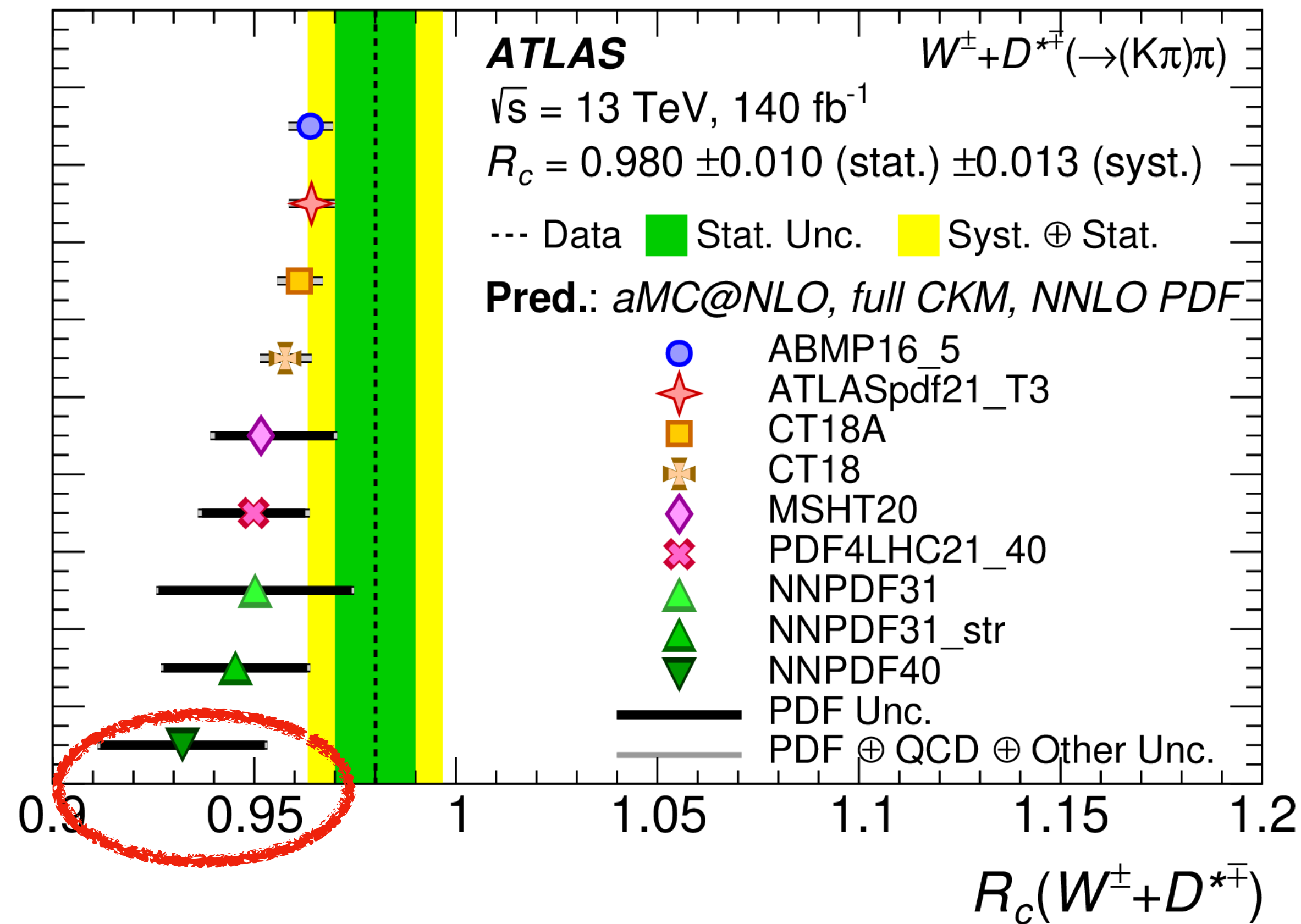


sensitive to the strange sea

# Associated $W$ boson and charm-hadrons at 13 TeV with ATLAS

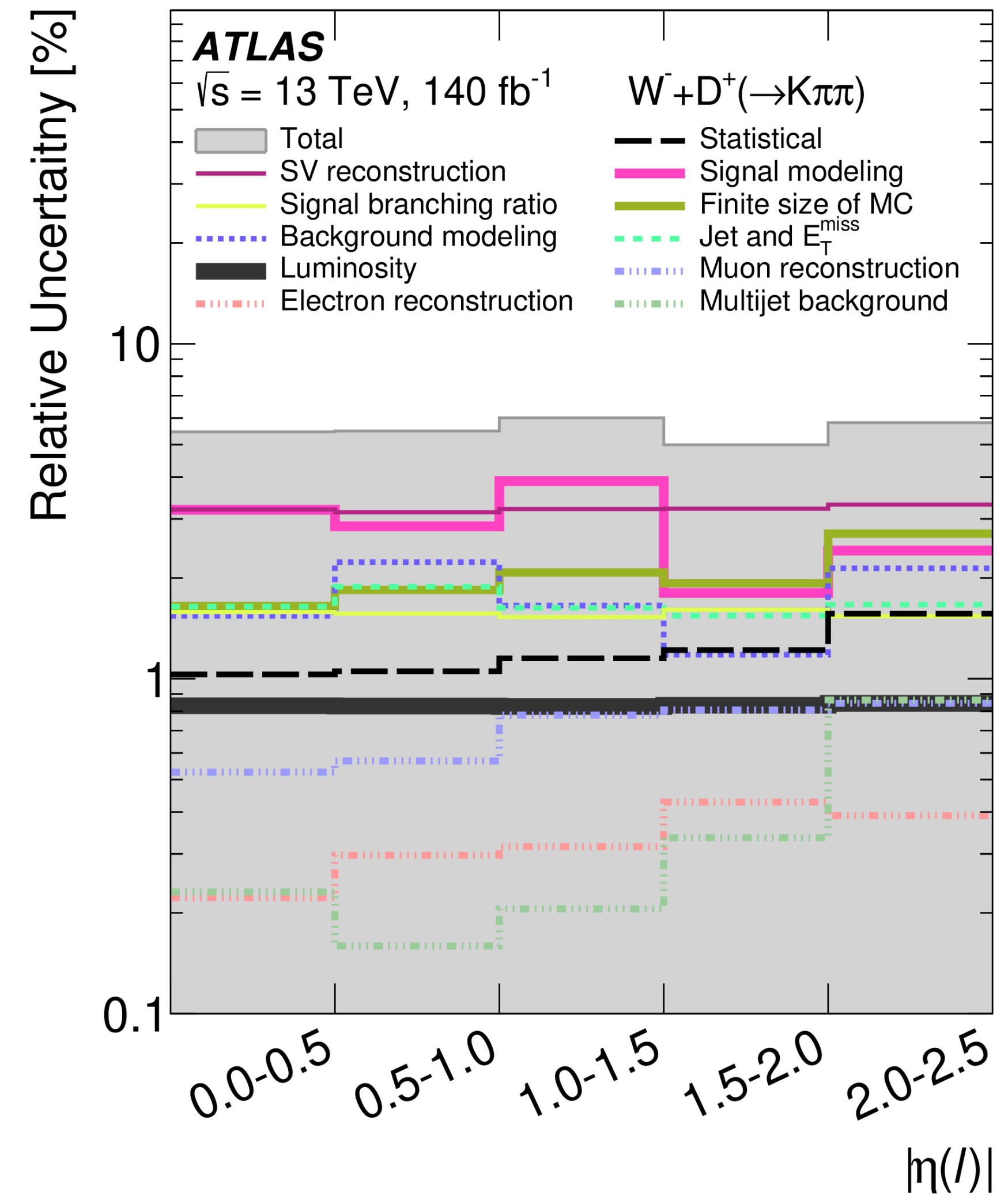
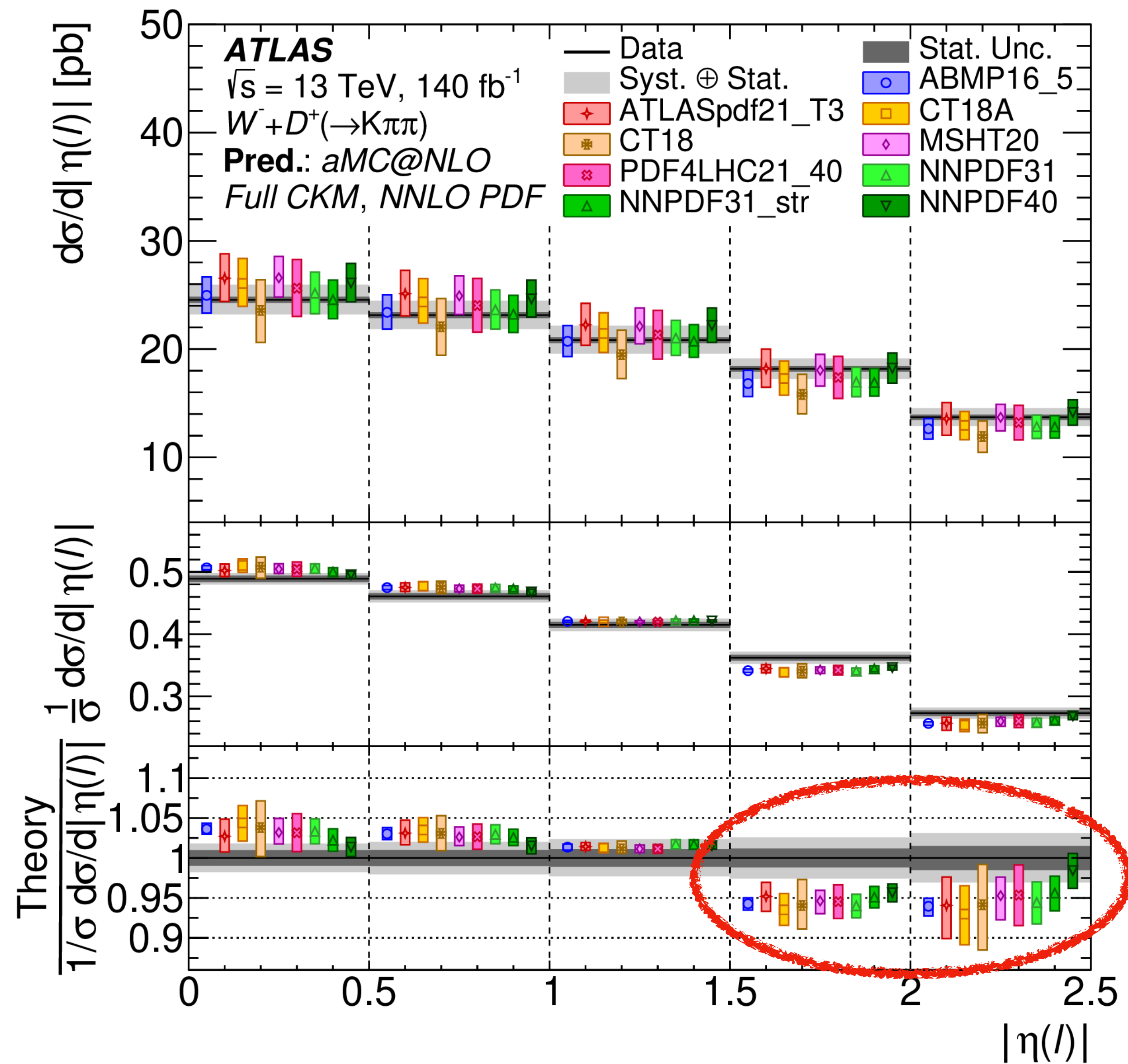
*Phys. Rev. D 108 (2023) 032012*

sensitive to strange/antistrange asymmetry



# Associated $W$ boson and charm-hadrons at 13 TeV with ATLAS

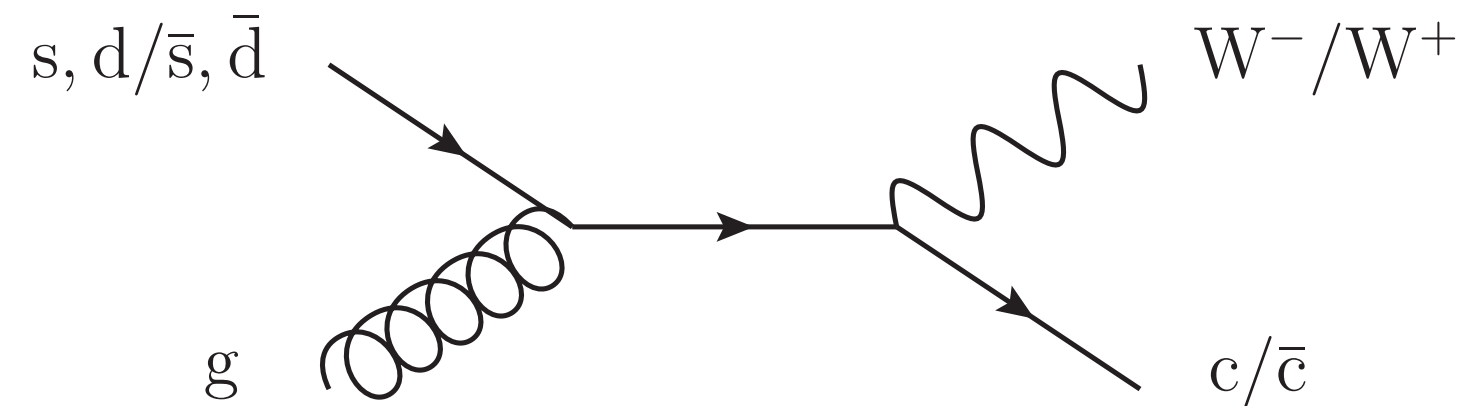
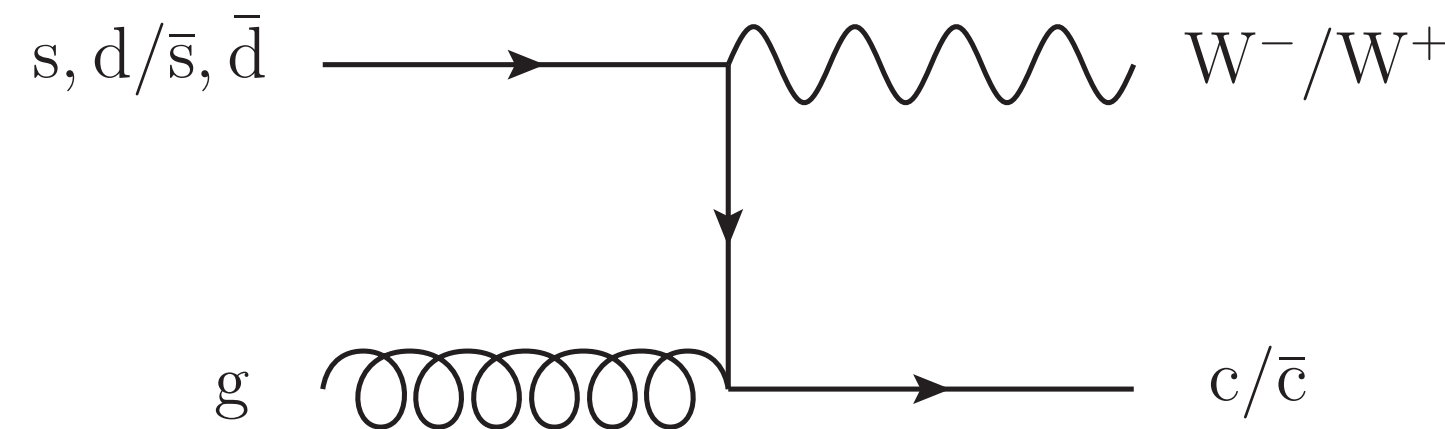
*Phys. Rev. D 108 (2023) 032012*





# Associated Z boson and charm at 13 TeV with CMS

## Phenomenology of Z+c events

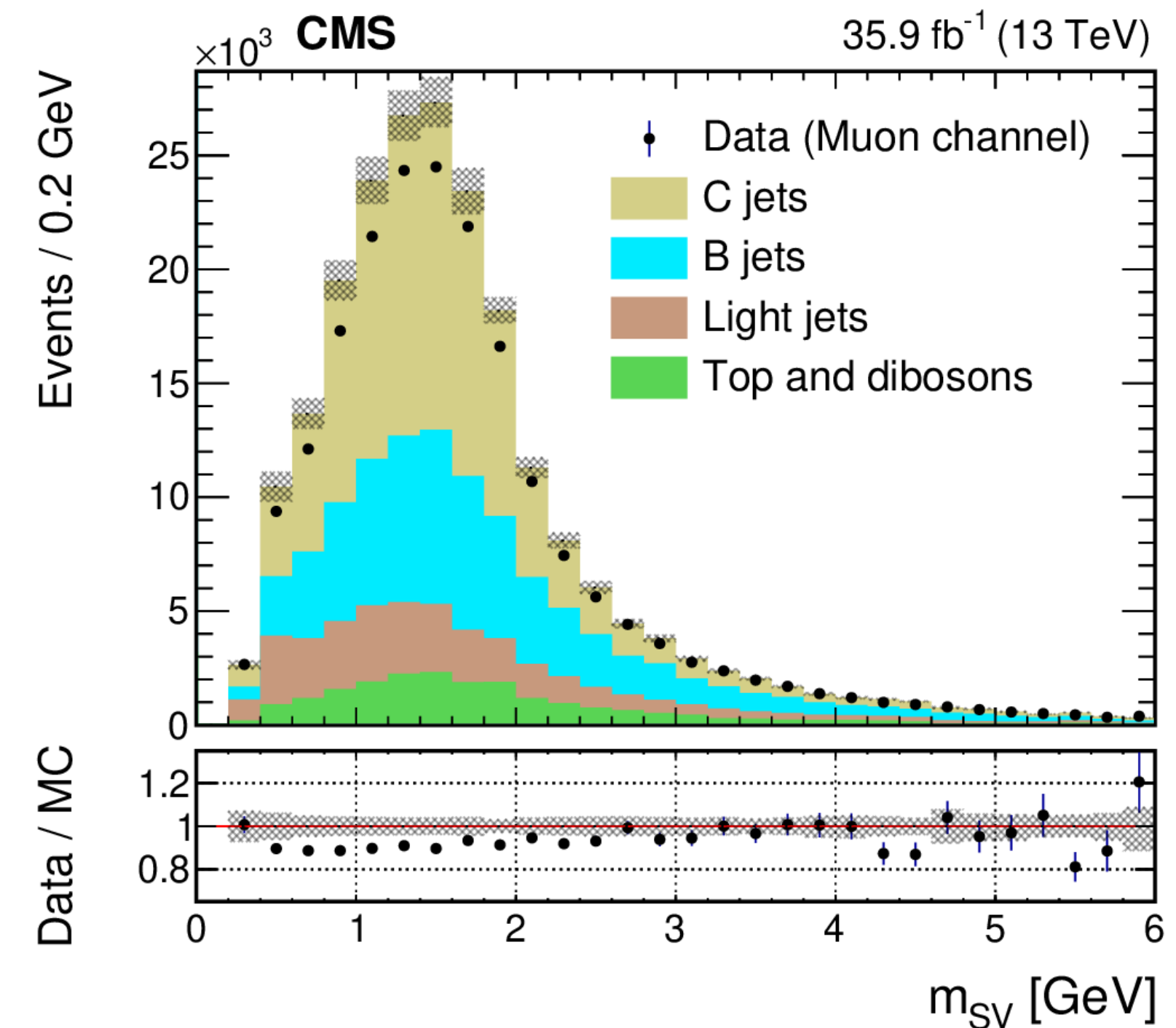
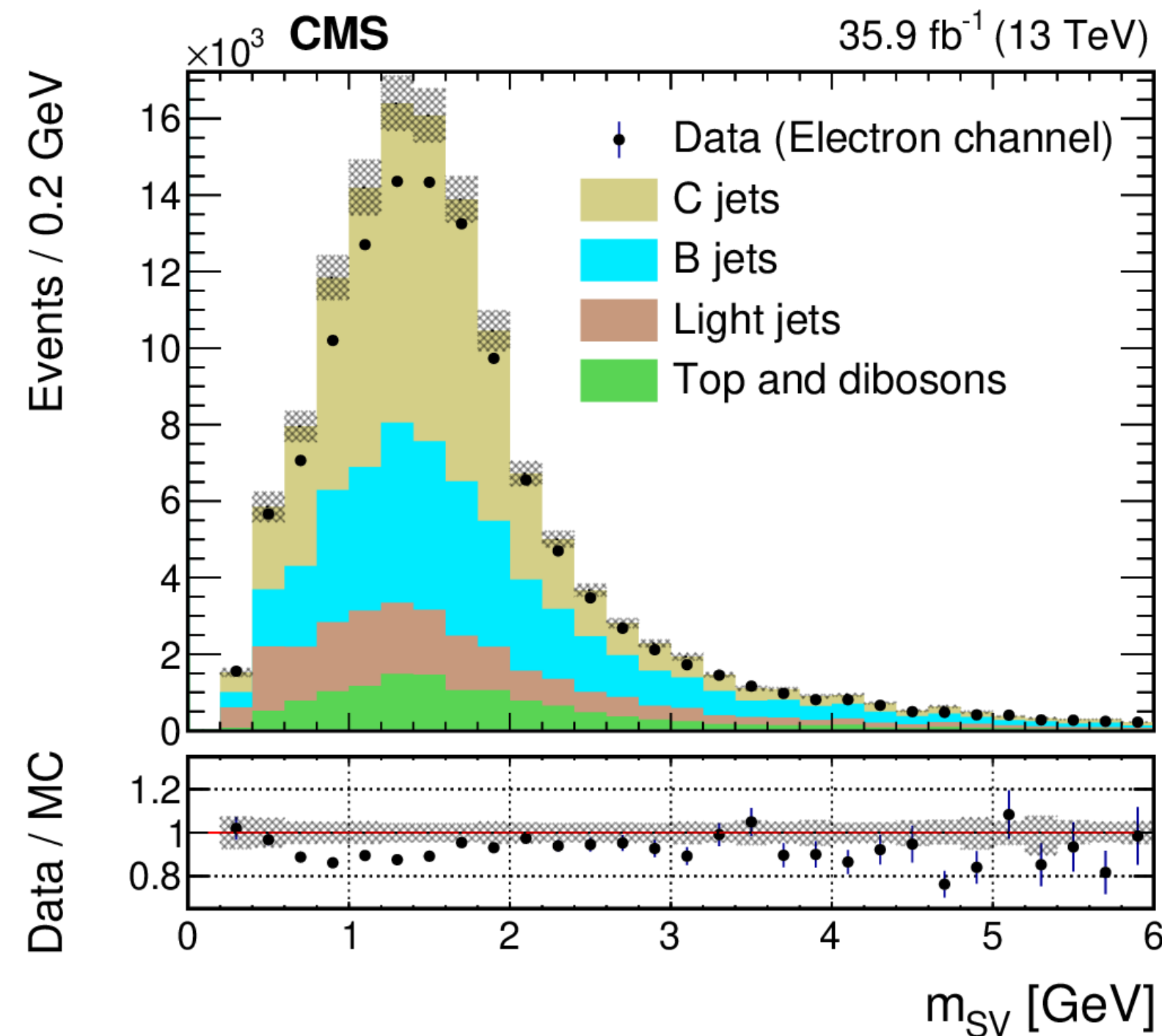


Measurement of total and differential distributions of Z+c spectra using 2016 data, in both electron and muon Z decay channels

flavour composition corrected by MC scale factors

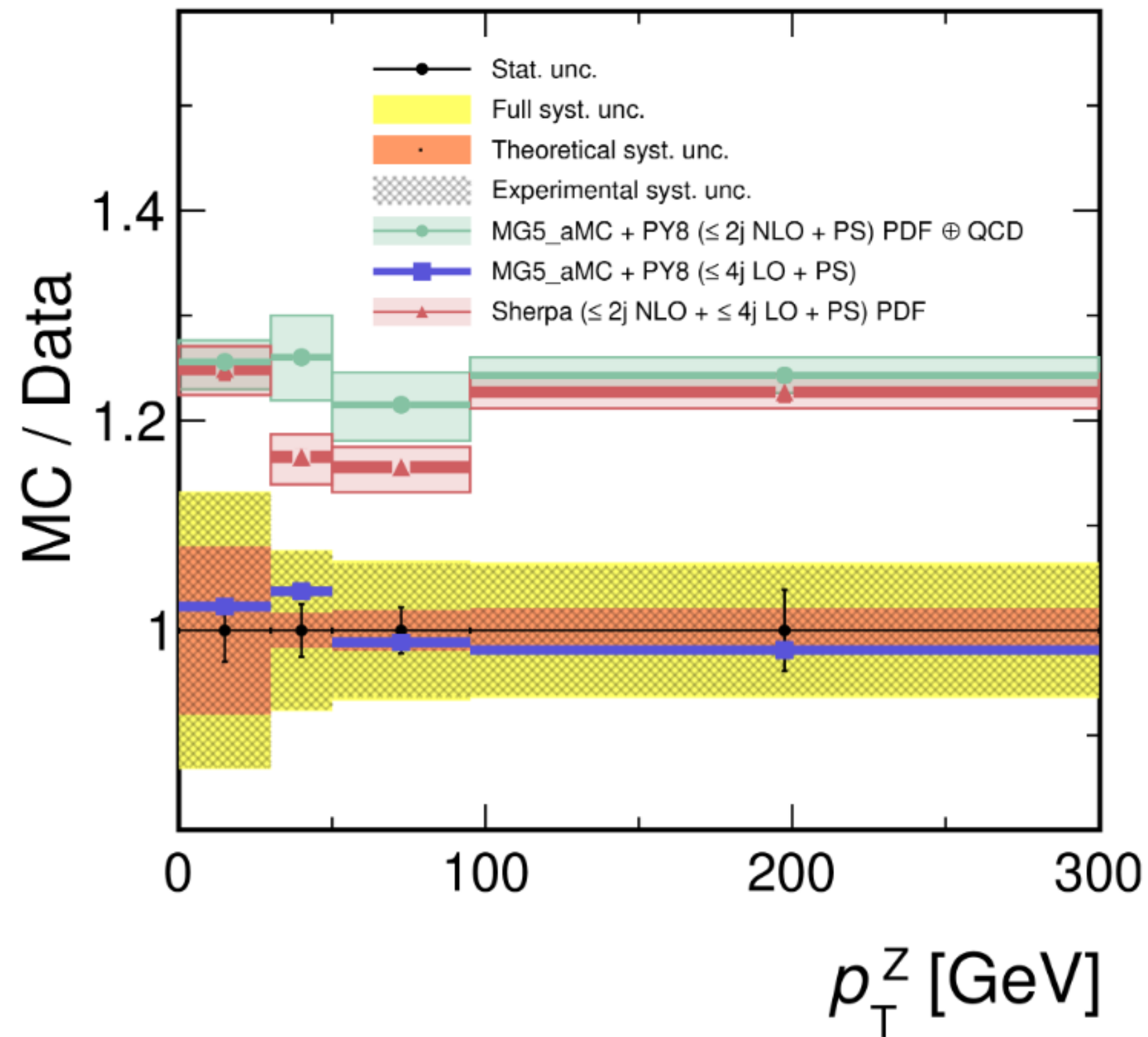
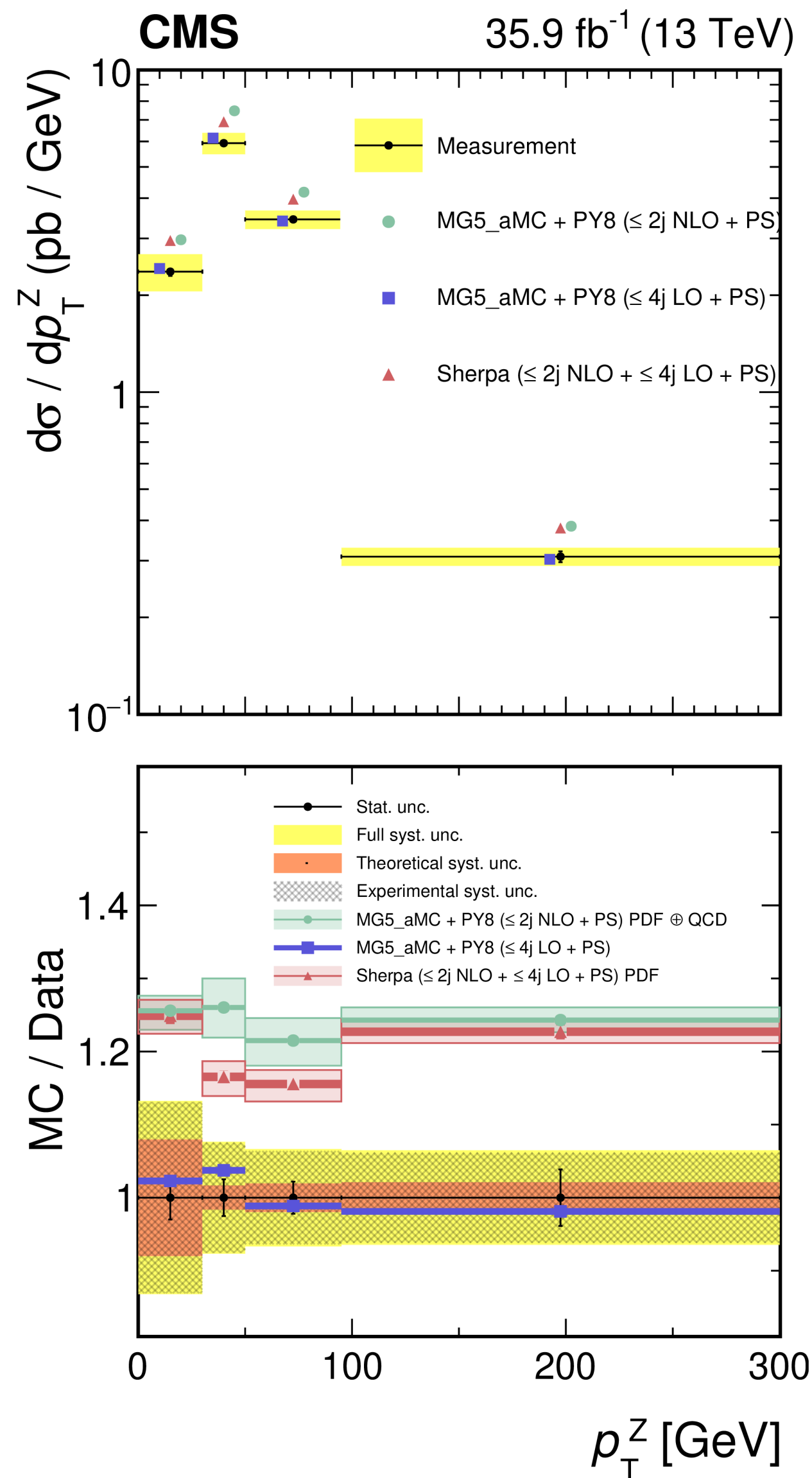
c-tagging and JEC are the largest systematics

charm contribution obtained fitting templates of Z+c, Z+b and Z+light-jet contributions to the secondary vertex mass



# Associated Z boson and charm at 13 TeV with CMS

## Differential cross sections



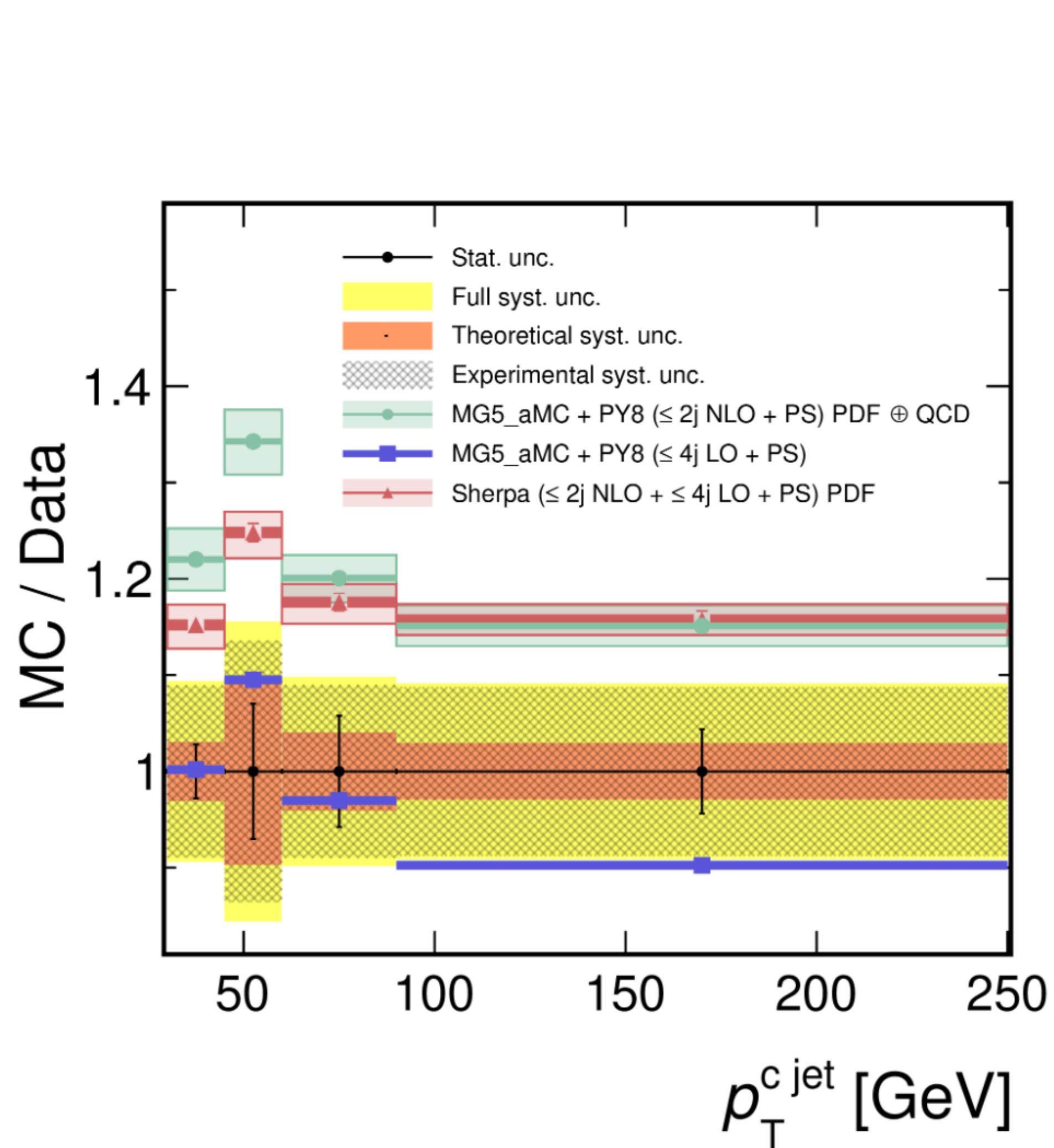
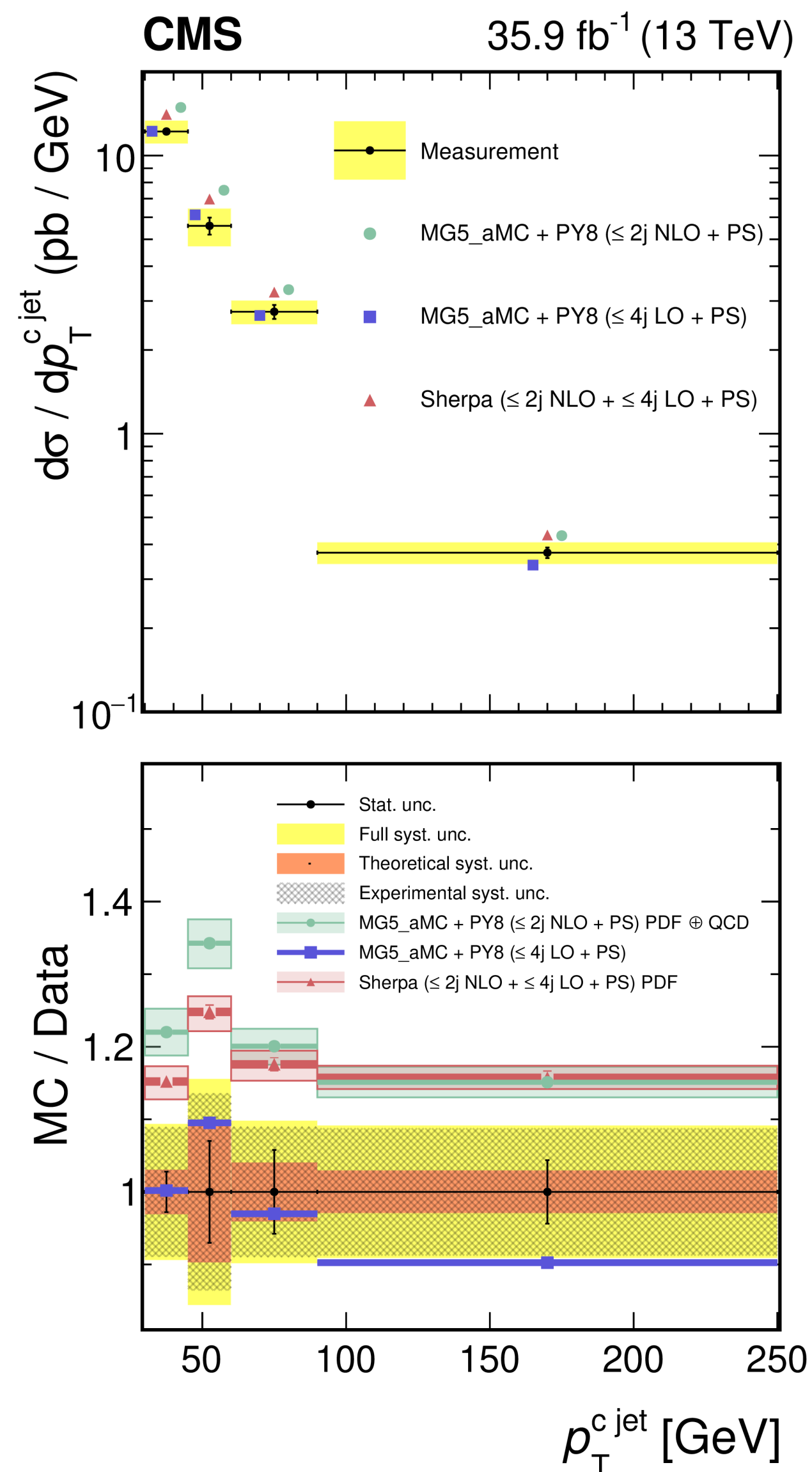
- MG5\_aMC + PY8 ( $\leq 2j$  NLO + PS)
- MG5\_aMC + PY8 ( $\leq 4j$  LO + PS)
- ▲ Sherpa ( $\leq 2j$  NLO +  $\leq 4j$  LO + PS)

Good agreement with  
MG5\_aMC **LO**

SHERPA and MG5\_aMC  
**NLO** overestimate xsec

# Associated Z boson and charm at 13 TeV with CMS

## Differential cross sections

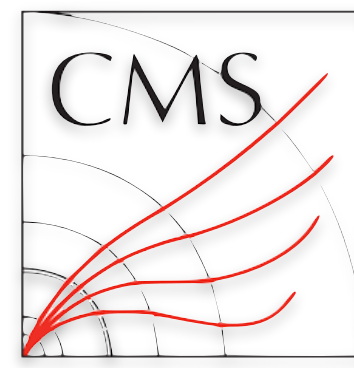


- MG5\_aMC + PY8 ( $\leq 2j$  NLO + PS)
- MG5\_aMC + PY8 ( $\leq 4j$  LO + PS)
- ▲ Sherpa ( $\leq 2j$  NLO +  $\leq 4j$  LO + PS)

Good agreement with  
MG5\_aMC **LO**

SHERPA and MG5\_aMC  
**NLO** overestimate xsec

# Conclusions



- Recent 13 TeV ATLAS&CMS measurements of  $W+c$ ,  $W+D$ ,  $Z+b$ ,  $Z+c$  unfolded spectra have been presented: many interesting results improving our knowledge of pQCD and th. predictions
- Results of differential cross sections allows to extract information on PDFs, NNLO precision, strange quark sea
- General very good agreement over NLO predictions. Some minor tension on  $Z+c$  where predictions overestimate data by  $\sim 20\%$  (CMS) in  $Z+b$  spectra (ATLAS) and  $W+D$  (ATLAS)

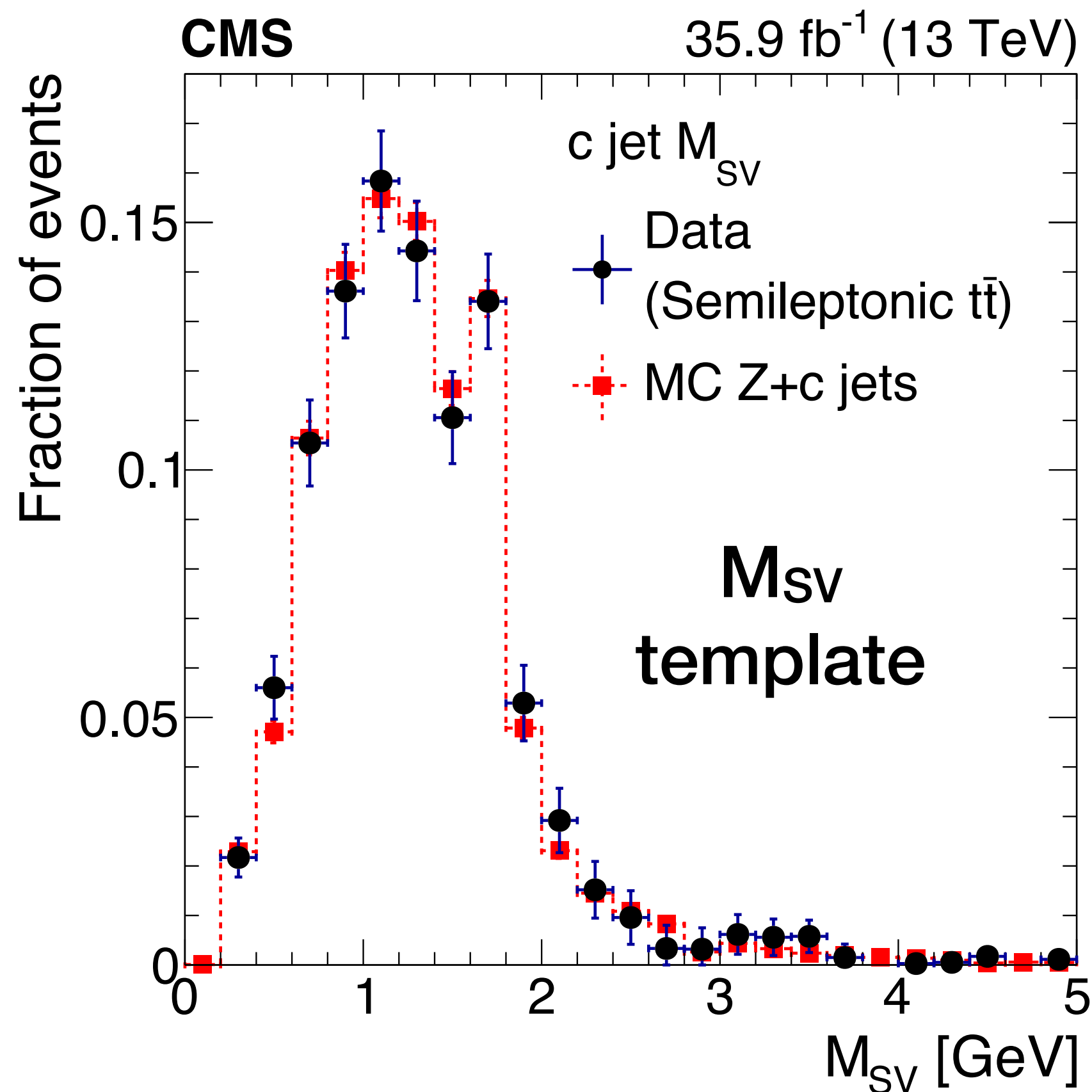
*...what's next?*

- $V+HF$  phase space extensively tested over many interesting observables. Missing the inclusion of new FS strategy and solve the comparison between 4F and 5F, also new direction with TMD possible
- Much more to come...  $W+bb$ ,  $V+b/c$  ratio, photon+ $b/c$ , Higgs+ $b/c$ , new predictions, flavour schemes, TMDs and much more!

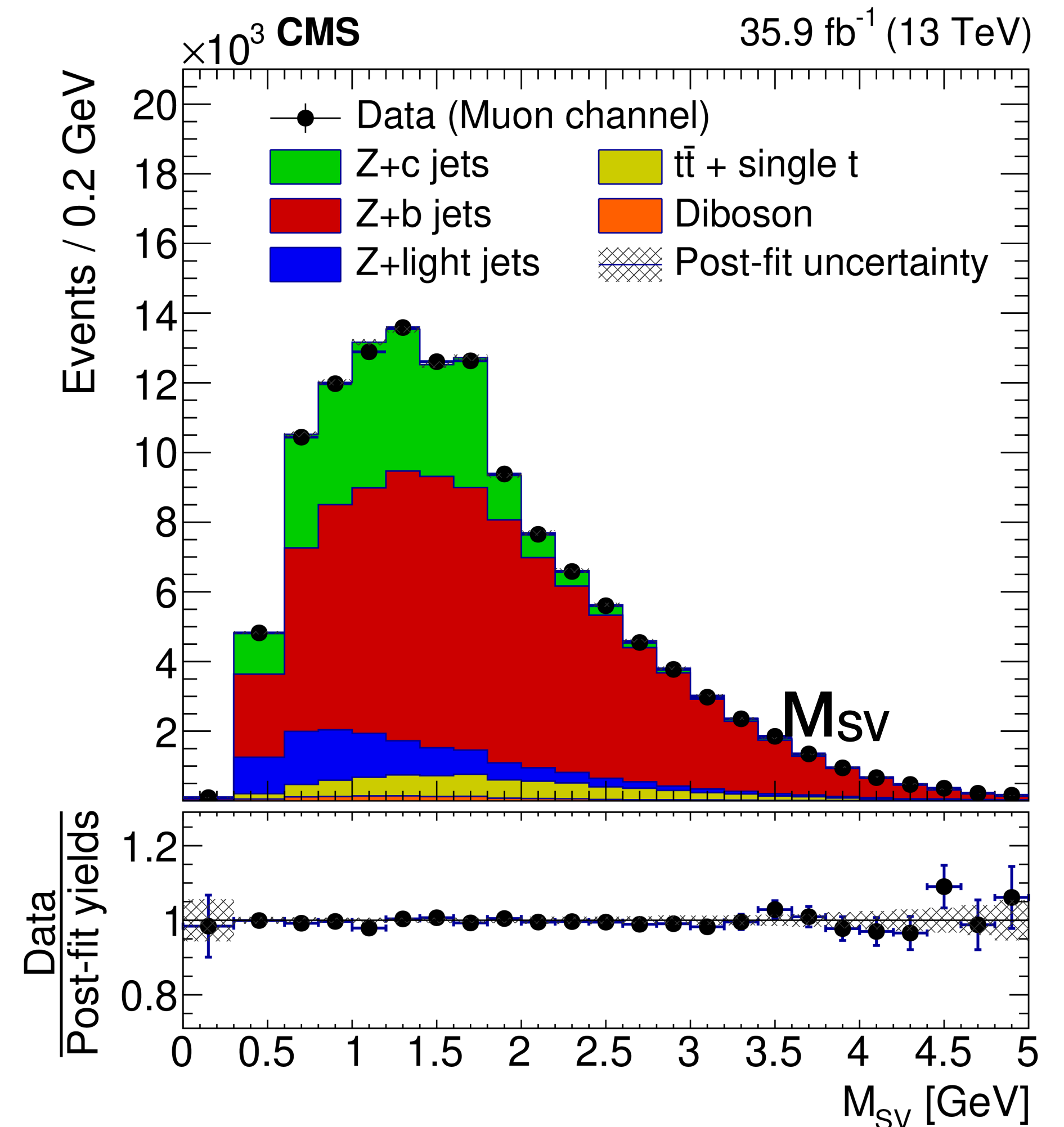
backup

# Ratios of $Z+b/Z+c$ , $Z+b/Z+j$ and $Z+c/Z+j$

- pp collisions @13 TeV, 35.9 fb<sup>-1</sup> data (2016)  
reduce impact of several systematic uncertainties
- Important test of pQCD, background to ZH production
- Measured inclusive and differential cross-section as function of  $p_T$  jet and  $p_T(Z)$  compared to LO and NLO QCD predictions

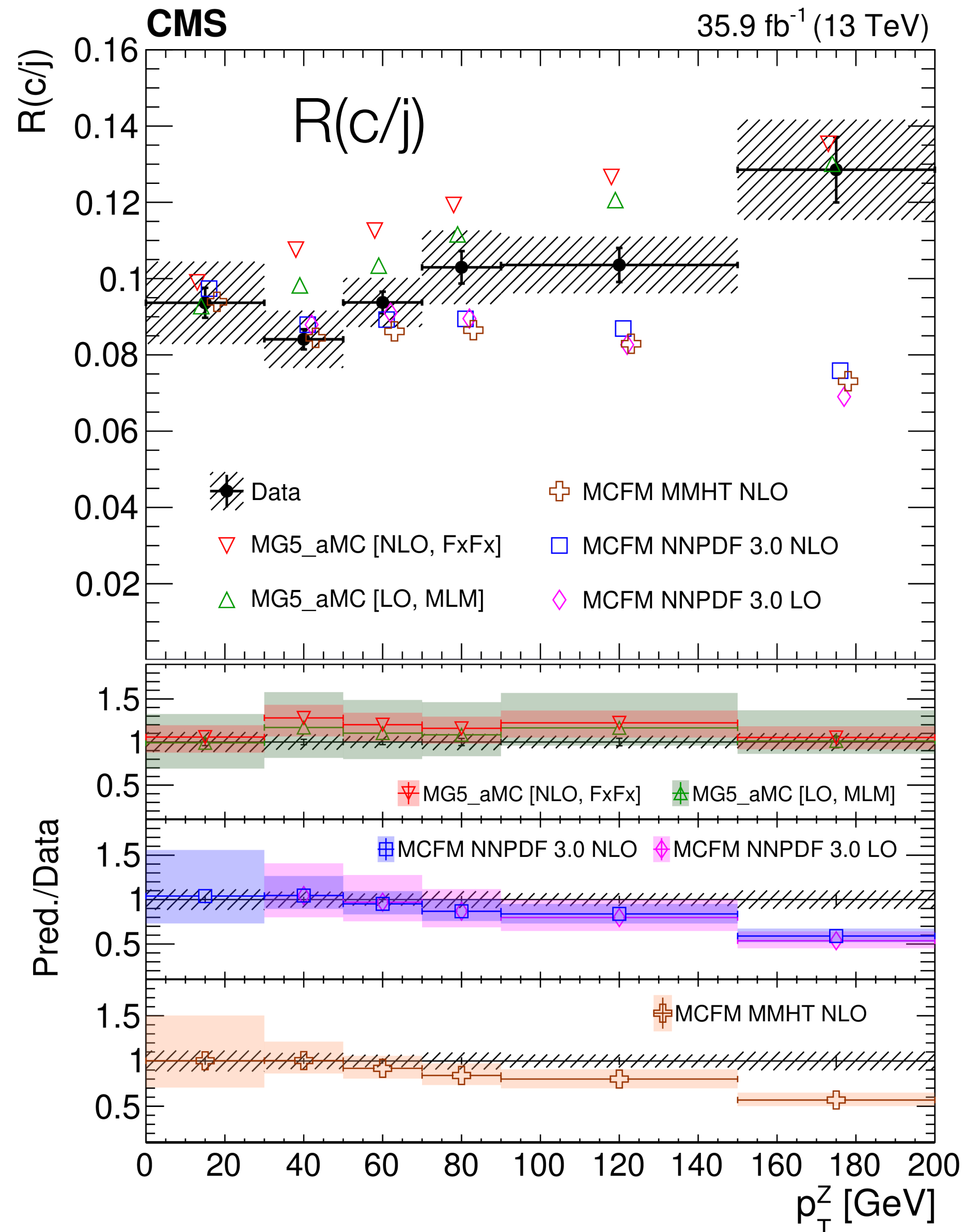


- Secondary vertex mass template from MC (c-jet) or data (b-jet) fitted to observation  $\rightarrow$  Z + c and Z + b event yield



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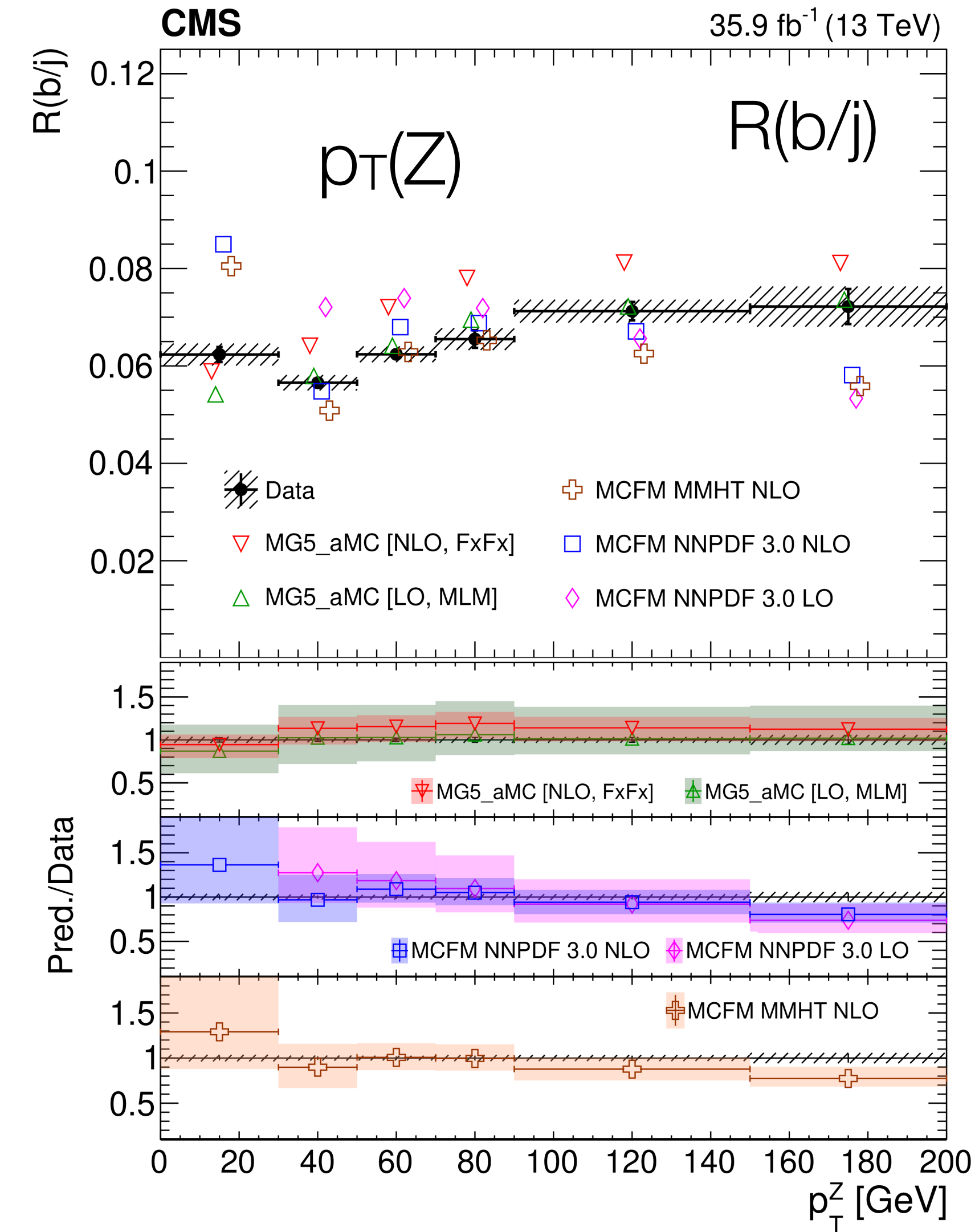
# Ratios of $Z+b/Z+c$ , $Z+b/Z+j$ and $Z+c/Z+j$



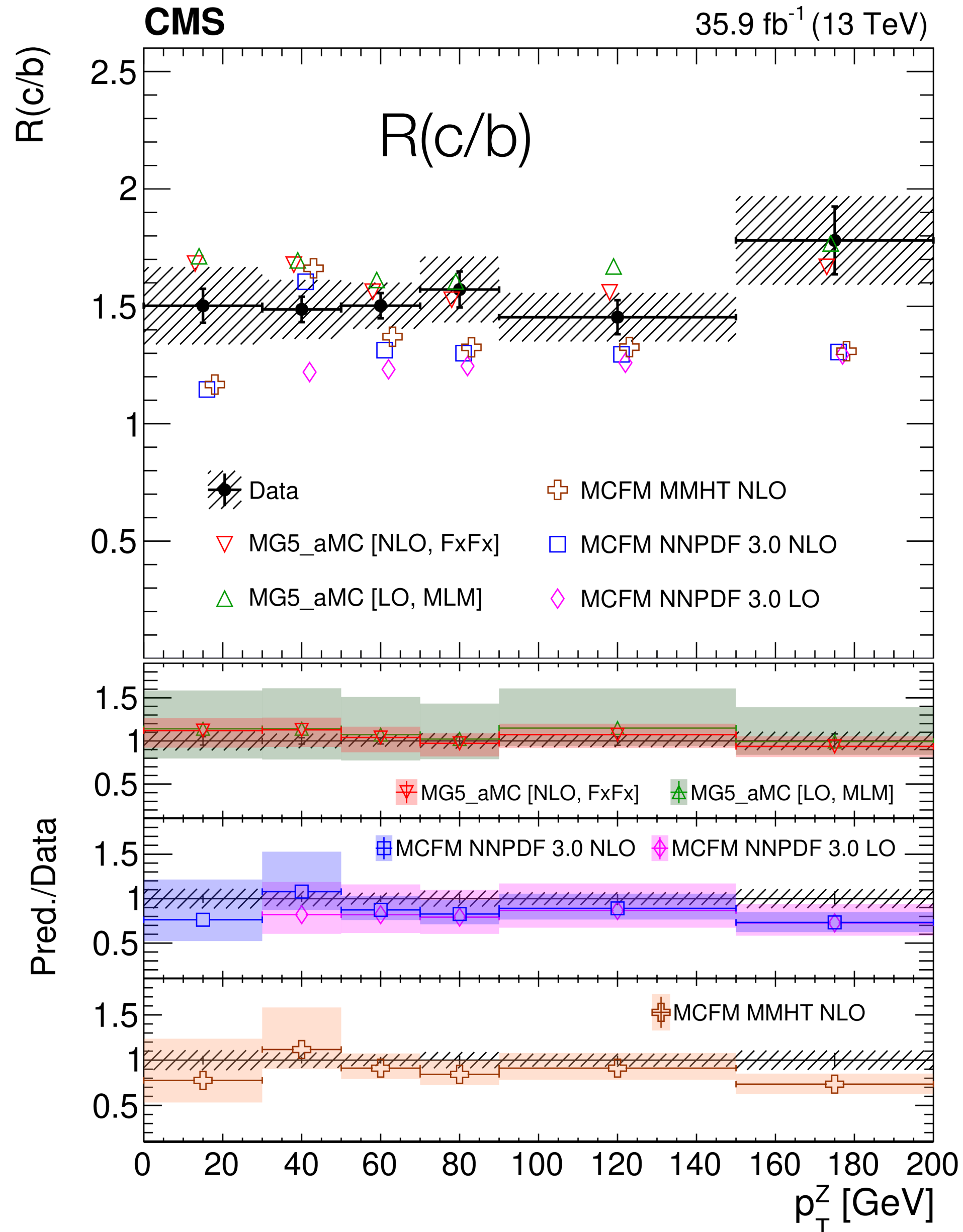
NLO MG5\_aMC (NNPDF) and LO MG5\_aMC (NNPDF) predictions higher but compatible with data in most bins

For  $R(c/j)$  deviations more pronounced, data better described at LO

LO MCFM, NLO MCFM (NNPDF), NLO MCFM (MMHT): prediction for  $R(c/j)$  and  $R(b/j)$  disagree with data at high  $p_T(Z)$



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# Status of theoretical calculations

- **MadGraph5\_aMC@NLO** (ME) + **PYTHIA8** / **HERWIG** (PS)
  - **LO**: up to 4 partons, kT-MLM matching
  - **NLO**: up to 2 partons, FxFx merging
- **Powheg** (ME) + PYTHIA8 (PS) up to NLO
- **Sherpa** (ME + PS) up to NLO
- **Geneva** 1.0-RC2 (ME) + PYTHIA8 (PS):
  - **NNLO** DY production + NNLL higher order resummation
  - Only for Z+jets processes
- **MCFM (ME)**
  - Z/W+1 jet NNLO calculations

NNPDF PDFs  
available at LO and  
NLO

MMTH PDF set at  
NLO

several (CP5)  
PYTHIA8 tunes

- **HF treatment**

- 4FS, b mass and 4 PDFs
- 5FS b mass=0 and 5 PDFs

Samples	0 j	1 j	2 j	3 j	4 j	> 4 j
LO MG5_aMC	LO	LO	LO	LO	LO	PS
NLO MG5_aMC/Powheg	NLO	NLO	NLO	LO	PS	PS
Geneva	NLO	NLO	LO	PS	PS	PS
Z/W+1 jet @ NNLO	-	NNLO	NLO	LO	-	-

# Heavy flavor tagging at collider



CERN-CMS-DP-2017-005

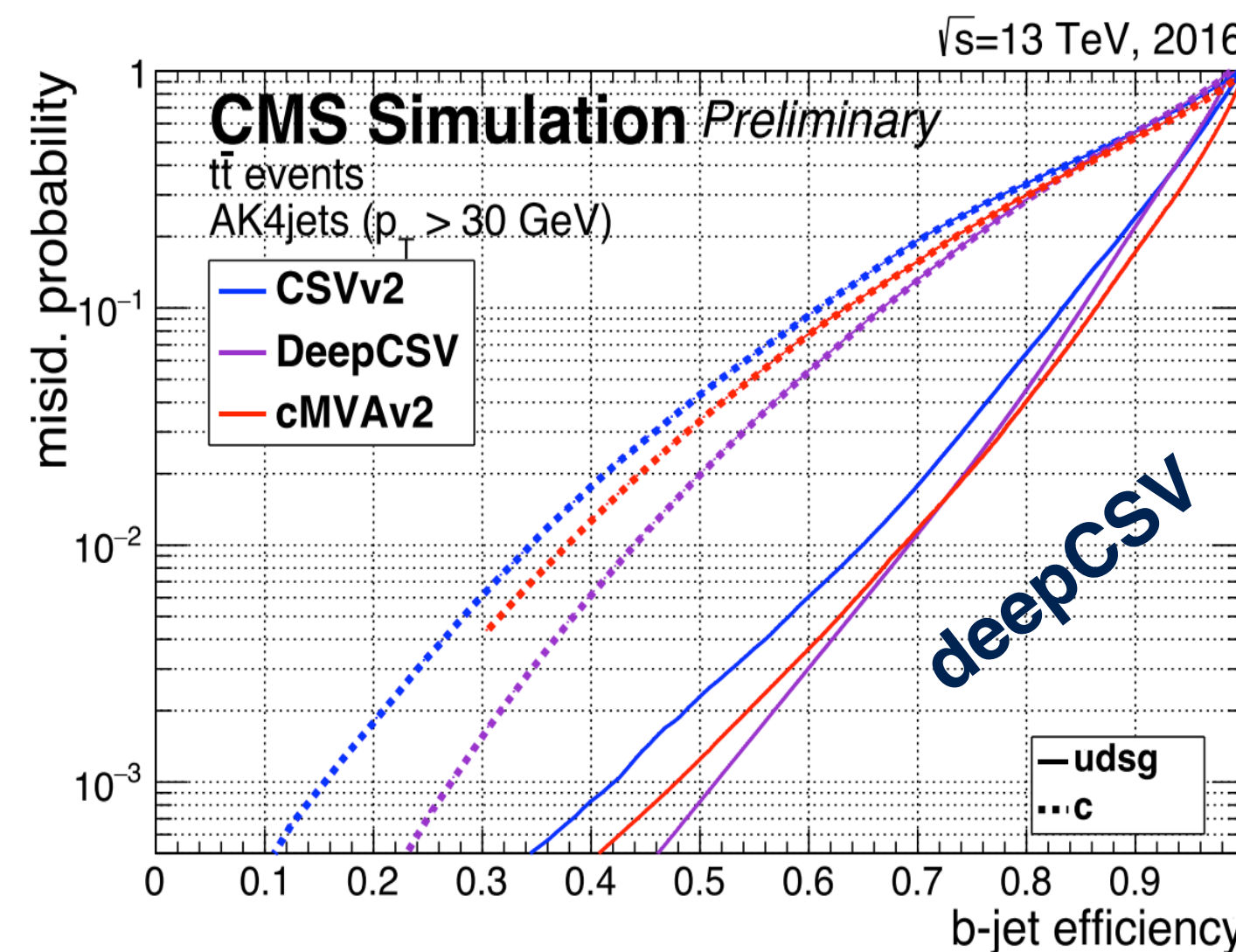
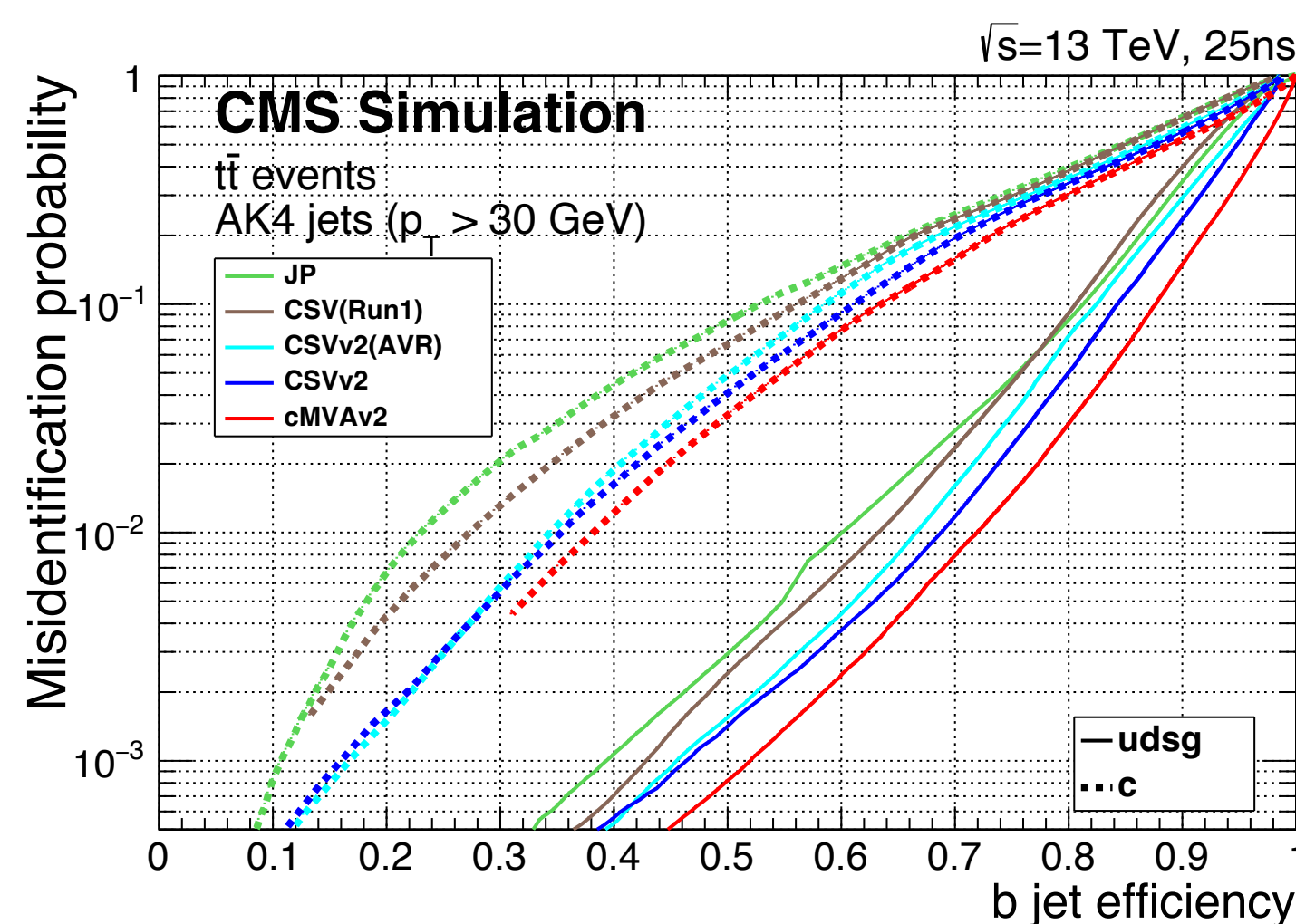
CMS-PAS-BTV-15-001

- several taggers:
  - Jet Probability: likelihood that jets is coming from primary vertex using tracks
  - Combined (CSV): combination of displaced tracks with SV info associated to the jet using an MVA
  - **CSVv2** evolution of CSV using neural networks
- *cMVAv2* combines all the taggers

Tagger	operating point	discriminator value	$\epsilon_b$ (%)
JetProbability (JP)	JPL	0.245	$\approx 82$
	JPM	0.515	$\approx 62$
	JPT	0.760	$\approx 42$
Combined Secondary Vertex (CSVv2)	CSVv2L	0.460	$\approx 83$
	CSVv2M	0.800	$\approx 69$
	CSVv2T	0.935	$\approx 49$
Combined MVA (cMVAv2)	cMVAv2L	-0.715	$\approx 88$
	cMVAv2M	0.185	$\approx 72$
	cMVAv2T	0.875	$\approx 53$

**deepCSV**: based on CSVv2

+ more charged particles, based on deep NN

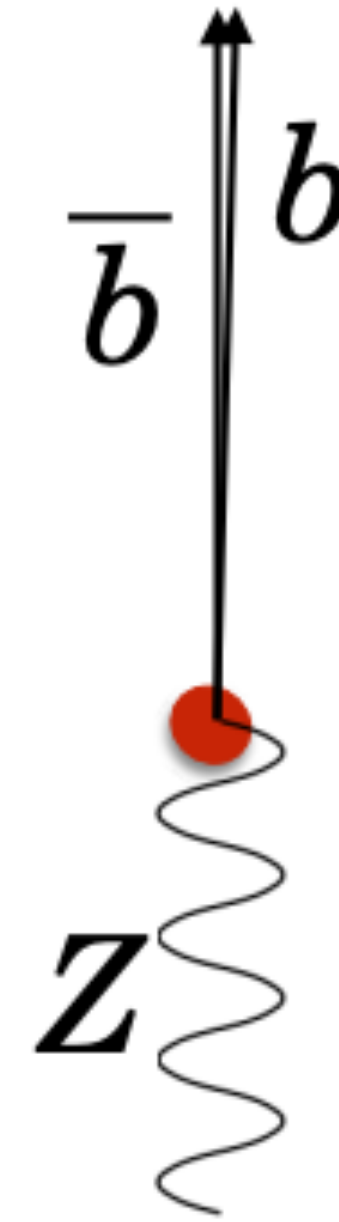
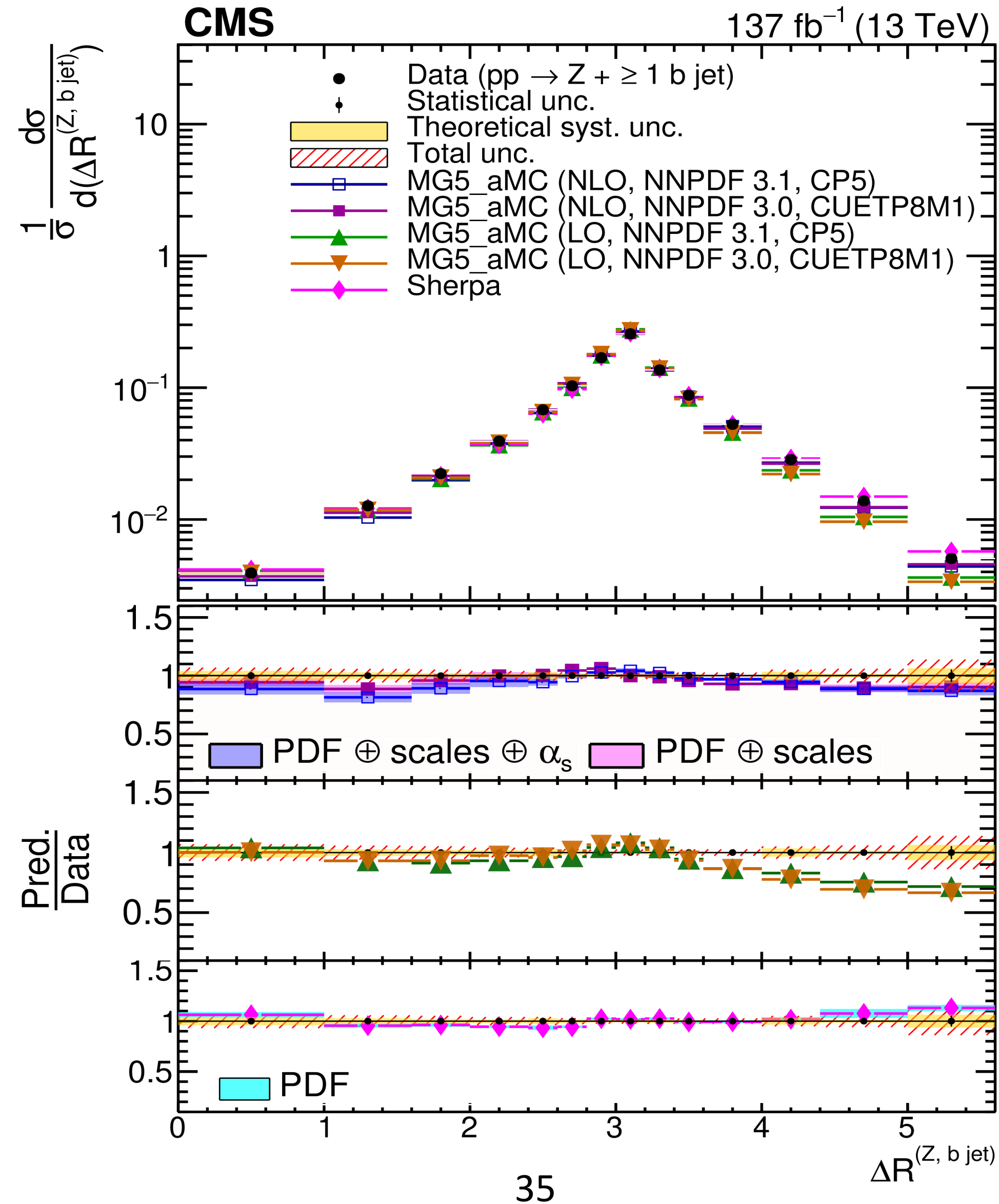
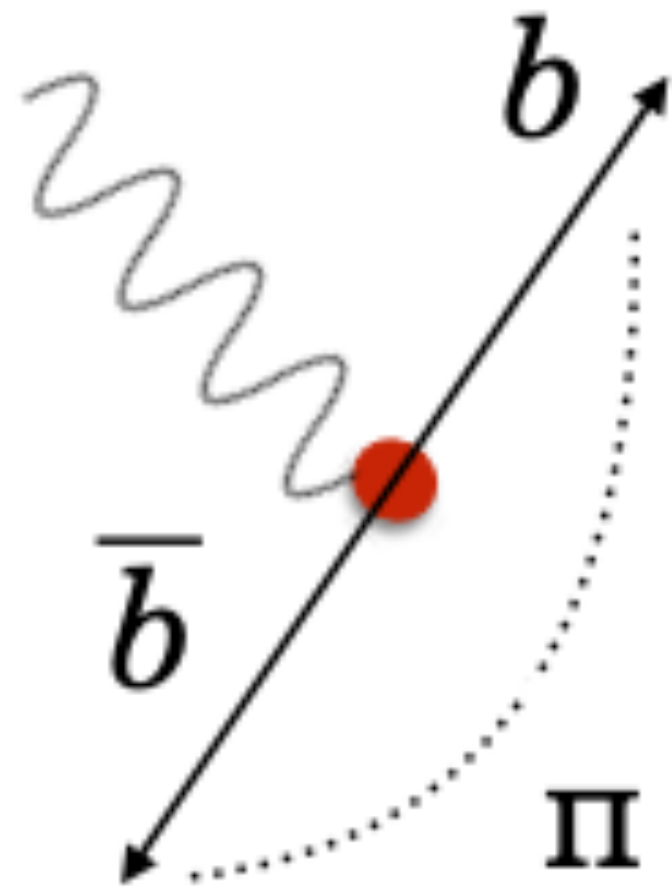


*improves  
 ~4% the b-  
 tag  
 efficiency  
 with a  
 mistag rate  
 of 0.1%*

# Associated Z boson and beauty at 13 TeV with CMS

## Zb kinematics and angles

very good agreement over the full  $\Delta R$  range within the uncertainties



NLO is essential to describe large  $\Delta R$  values

overall good agreement

# Associated $W$ boson and charm-hadrons at 13 TeV with ATLAS

*Phys. Rev. D 108 (2023) 032012*

