QCD aspects in V+jets measurements at the LHC

Resumption, Evolution, Factorization 2020

Virtual Conference, 08/12/2020

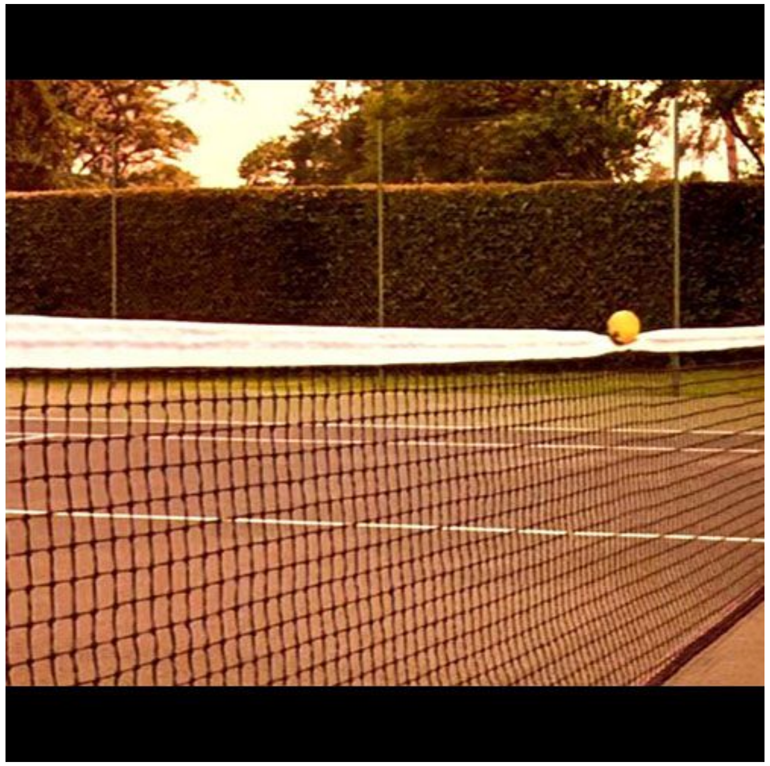
Vieri Candelise (*University of Trieste & INFN Trieste*)

Outline

- V+Jets Physics: Phenomenology at the LHC

- Recent LHC results in three sets:

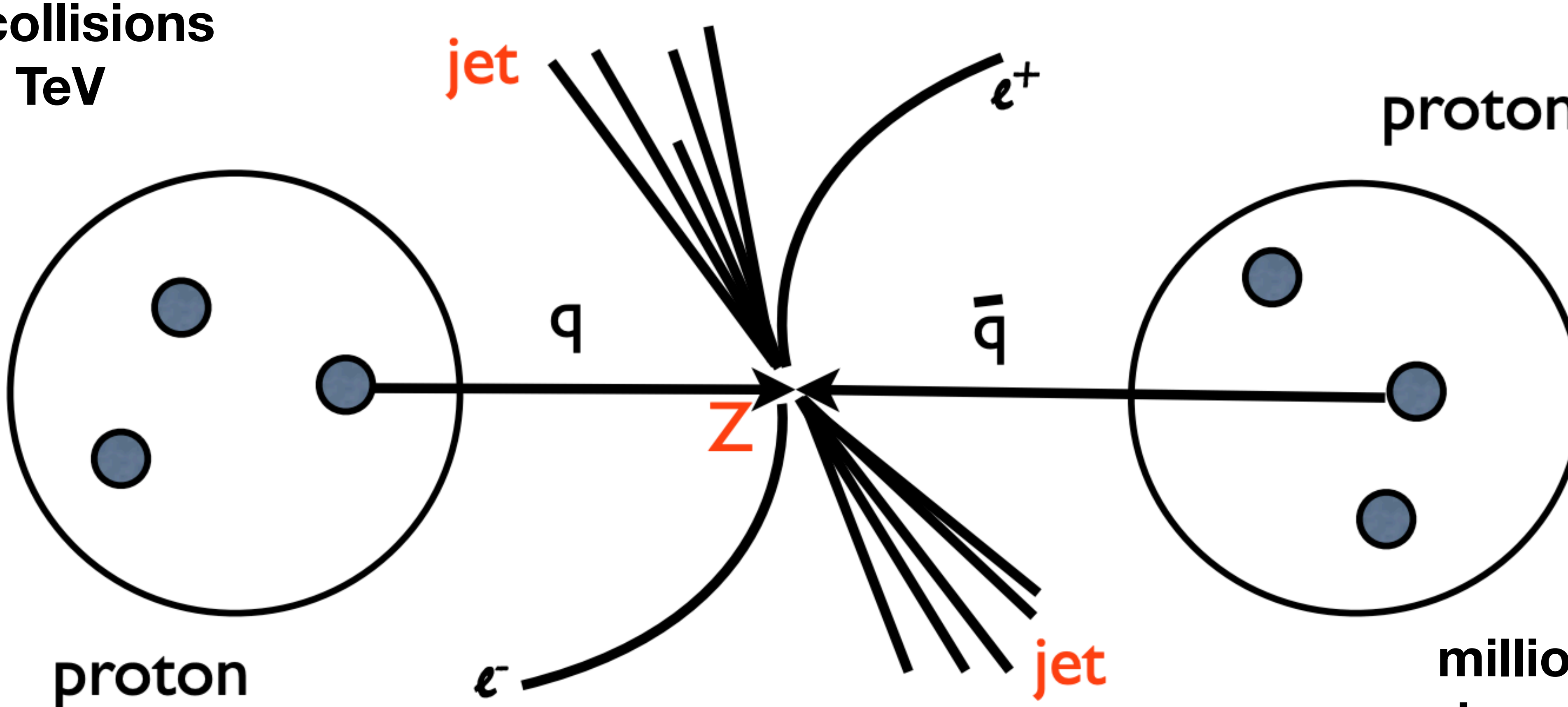
1. Recent results on V+Jets measurements
2. Tuning & PS in V+Jets
3. LHC-EW: Jets & bosons



- Summary, conclusions and perspectives

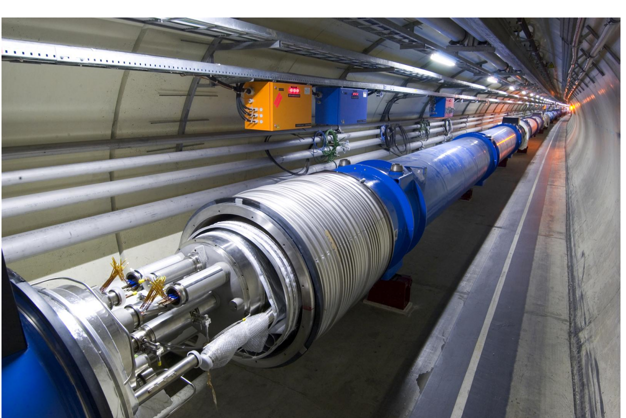
Phenomenology of W and Z bosons at LHC

LHC pp collisions
@ 13 TeV

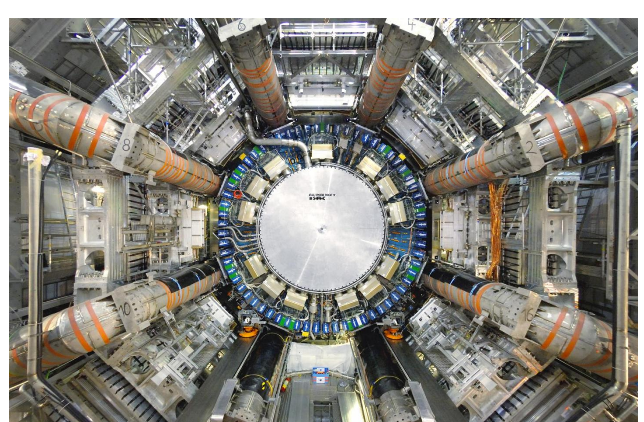


millions of W/Z boson events recorded

2.06 x 10^{34} $cm^{-2}s^{-1}$,

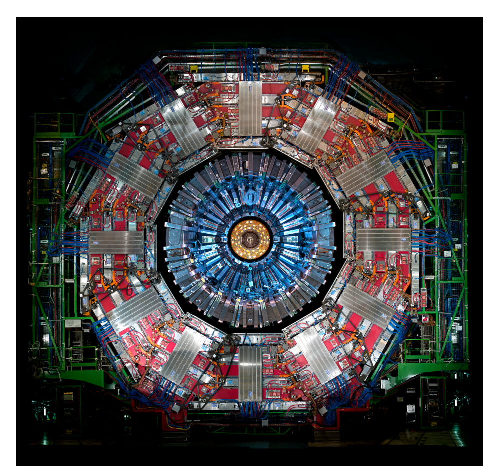


ATLAS

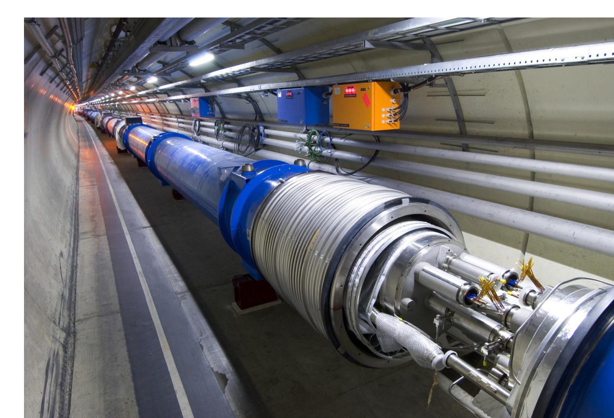


recorded 189.3 fb^{-1}

CMS



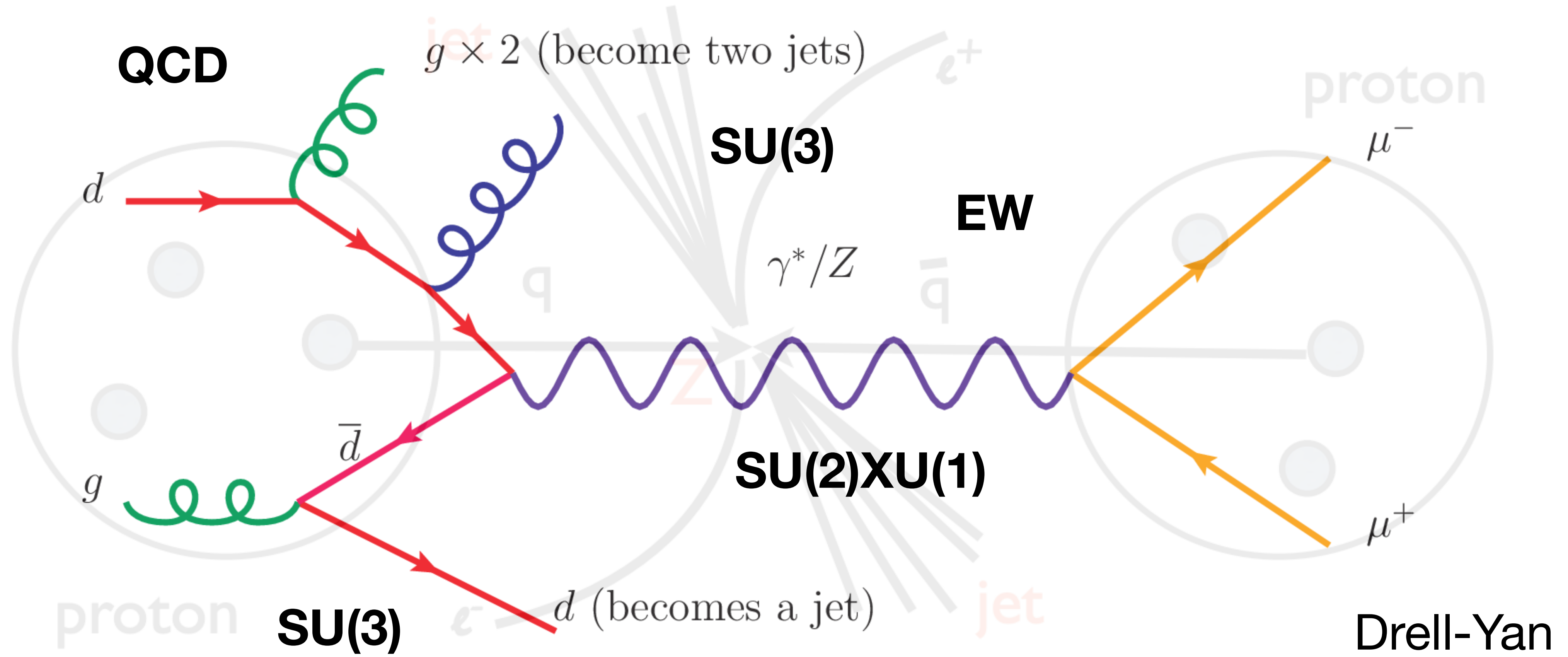
x2 design luminosity!



Phenomenology of W and Z bosons at LHC

LHC is the most efficient V+Jet Factory of the world!

it's the perfect experimental ground field to test the SM!



Jets are the experimental signatures of quarks and gluons, QCD
V bosons are the expression of the EWK interactions…

- **x** QCD modelling plays a prime role: impact of the initial state (PDF, resummation, α_S, scales)
- **x** Open phenomenology: V+jets/HF, multiboson interactions, EW production (VBF/VBS)…
- **x** Precision tests of the SM with W/Z: quark sea, hadronization effects, constrain PDFs
- **x** Data-driven way to “tune” our simulation and improve perturbative calculations

DISCLAIMER!

V+Jets physics at the LHC is a factory of scientific results… a lot of amazing publications are available!

what comes next is my *personal overview* of the *most recent V+Jets results at 13 TeV focusing on QCD aspects* *(especially observables sensitive to resummation, hadronization)* from ATLAS and CMS

enjoy!

you can have a look at the full Standard Model gallery of results from the two experiments here:

https://twiki.cern.ch/twiki/bin/view/AtlasPublic

http://cms-results.web.cern.ch/cms-results/public-results/publications/SMP/index.html

Selected Results

part 1

W and Z plus jets

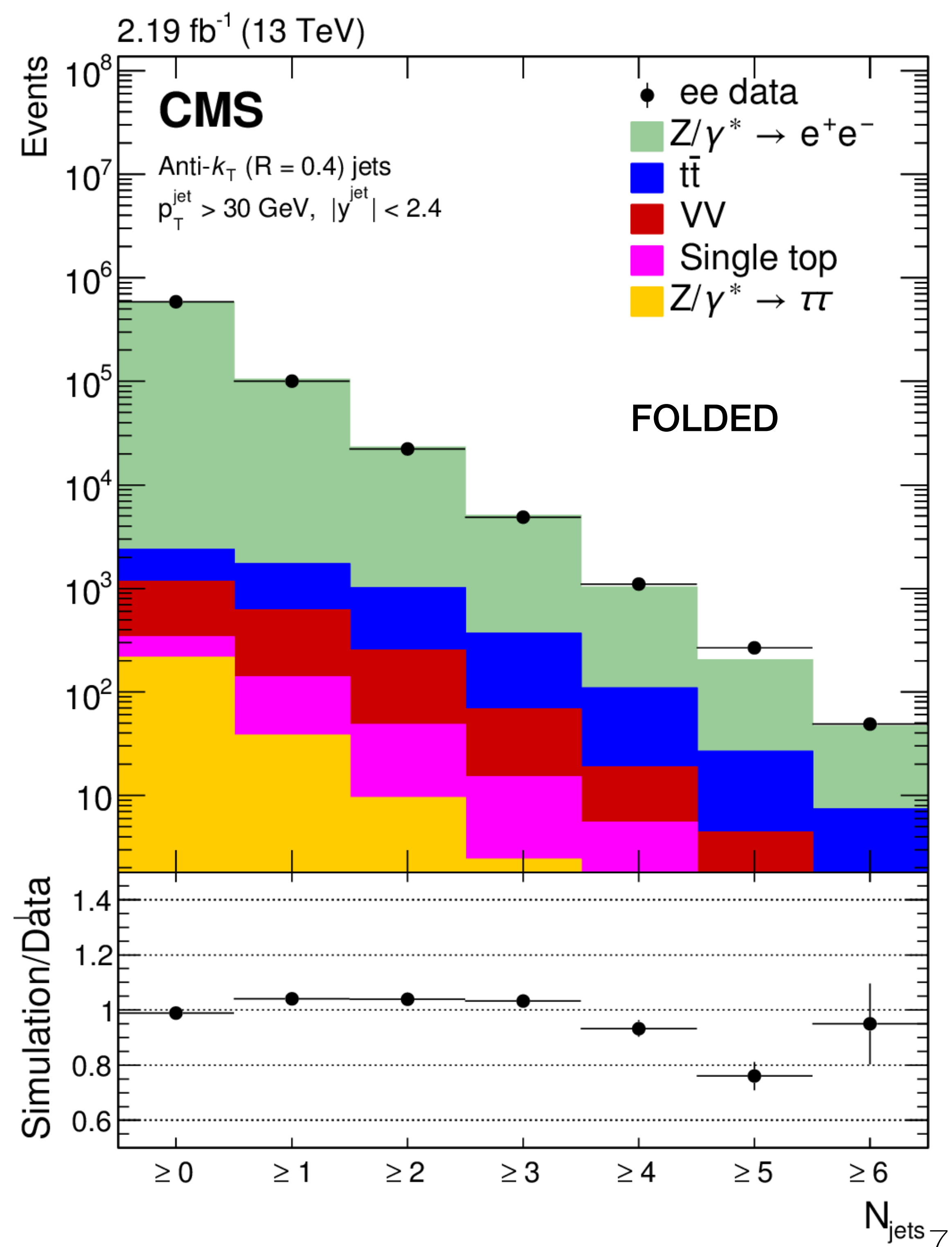
CMS @ 13 TeV

Associated production of Z and jets

pp collisions @13 TeV, 2.2 fb^{-1} data (2015)

[Eur. Phys. J. C 78 (2018) 965]

- Correction for detector resolution (unfolding)
- Dominant background: tt (data-driven estimation)
- Other backgrounds: from MC
- Differential cross-section as a function of Z boson p_T, jet p_T and η, pTbalance, jet-Z balance (JZB)



Jets

anti-kT $(R = 0.4)$

$p_T(j) > 30\ GeV$

$|\eta| < 2.4$

$\Delta R(jet, l) > 0.4$

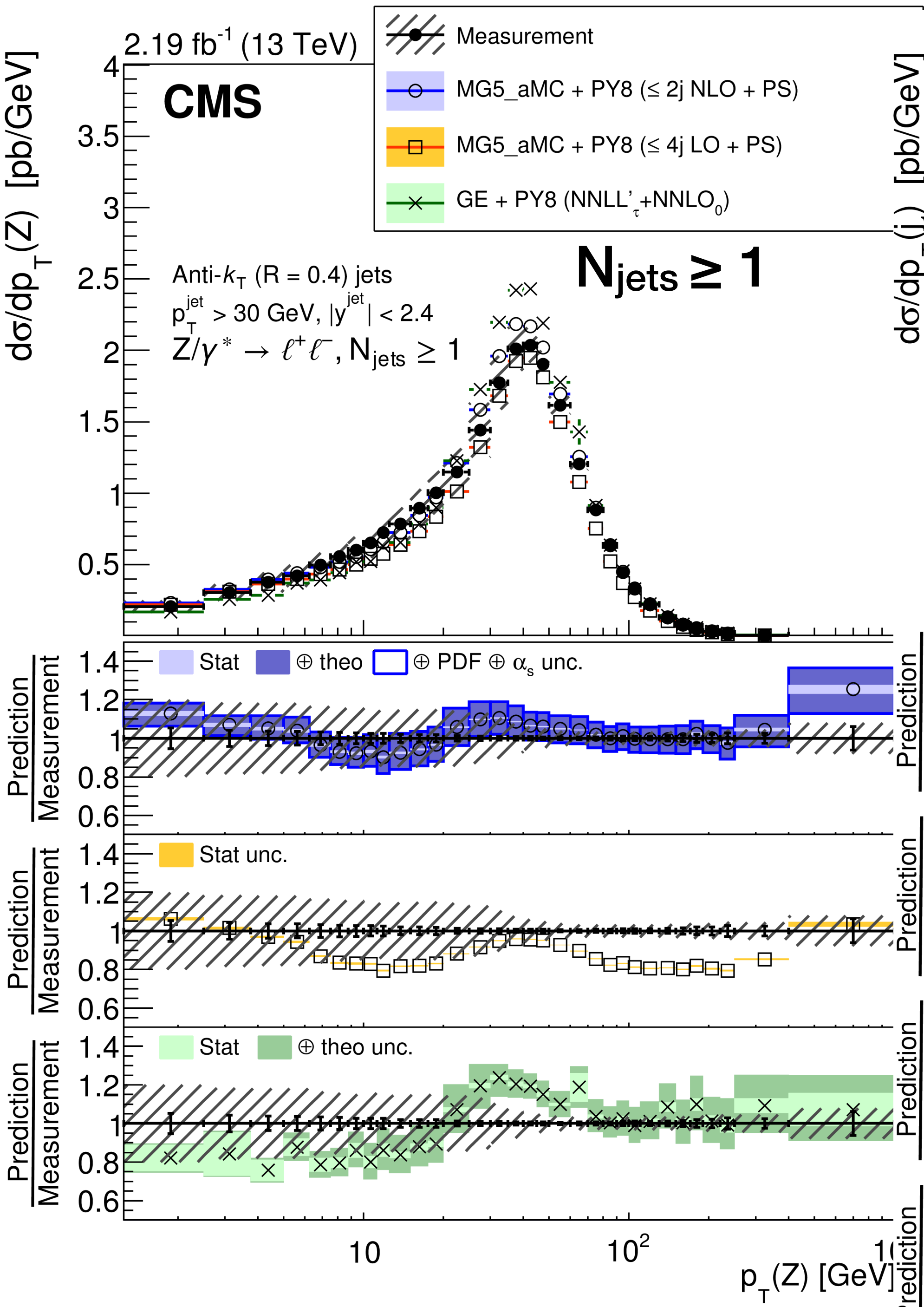
Leptons

$p_T(l) > 20$ GeV

$|\eta| < 2.4$

$M_{ll} = 91 \pm 20$ GeV

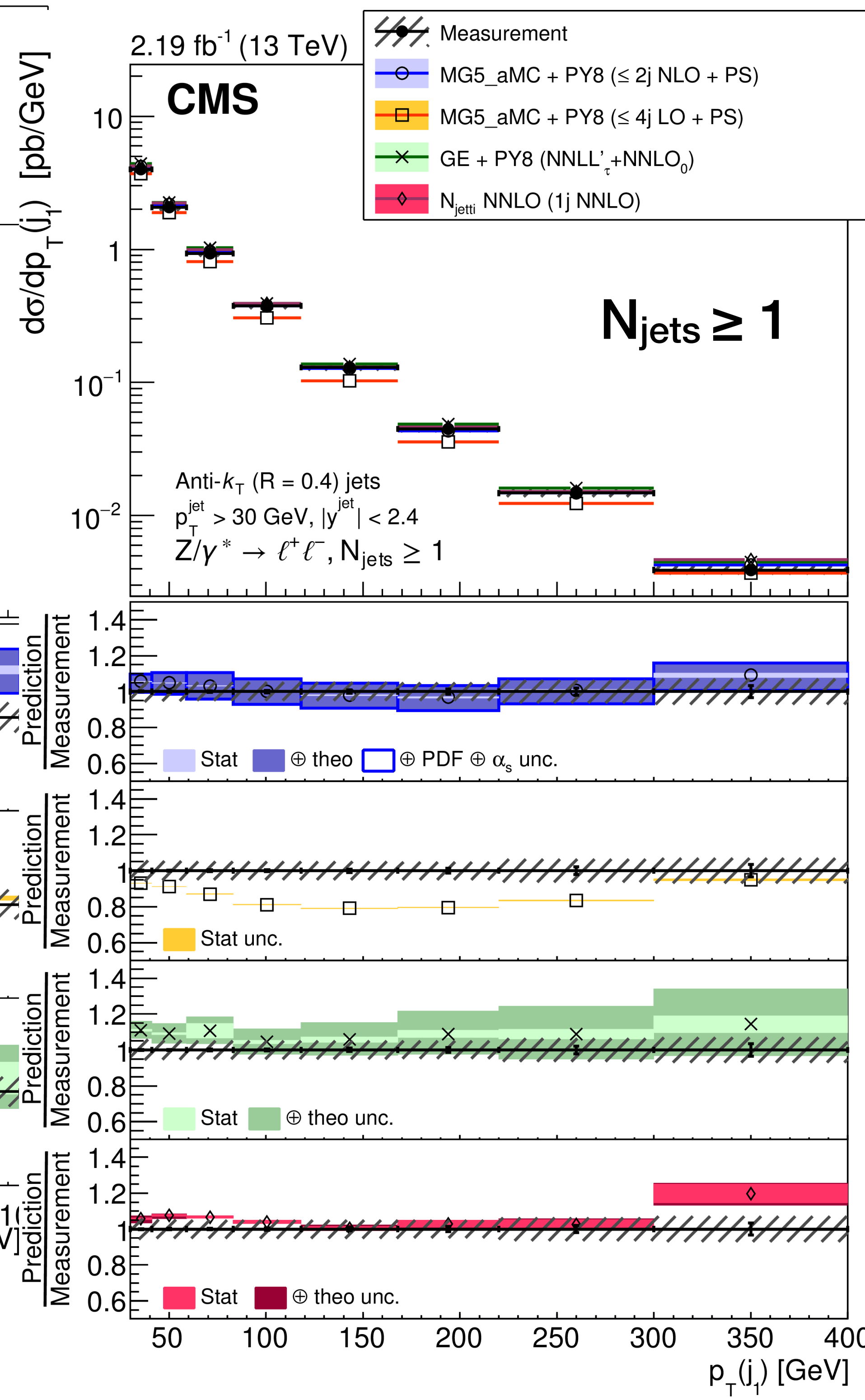
p_T (Z)



Geneva:

shape of p_T (leading j) well modelled. H_T underestimated. p_T (Z) well modelled except for the central region

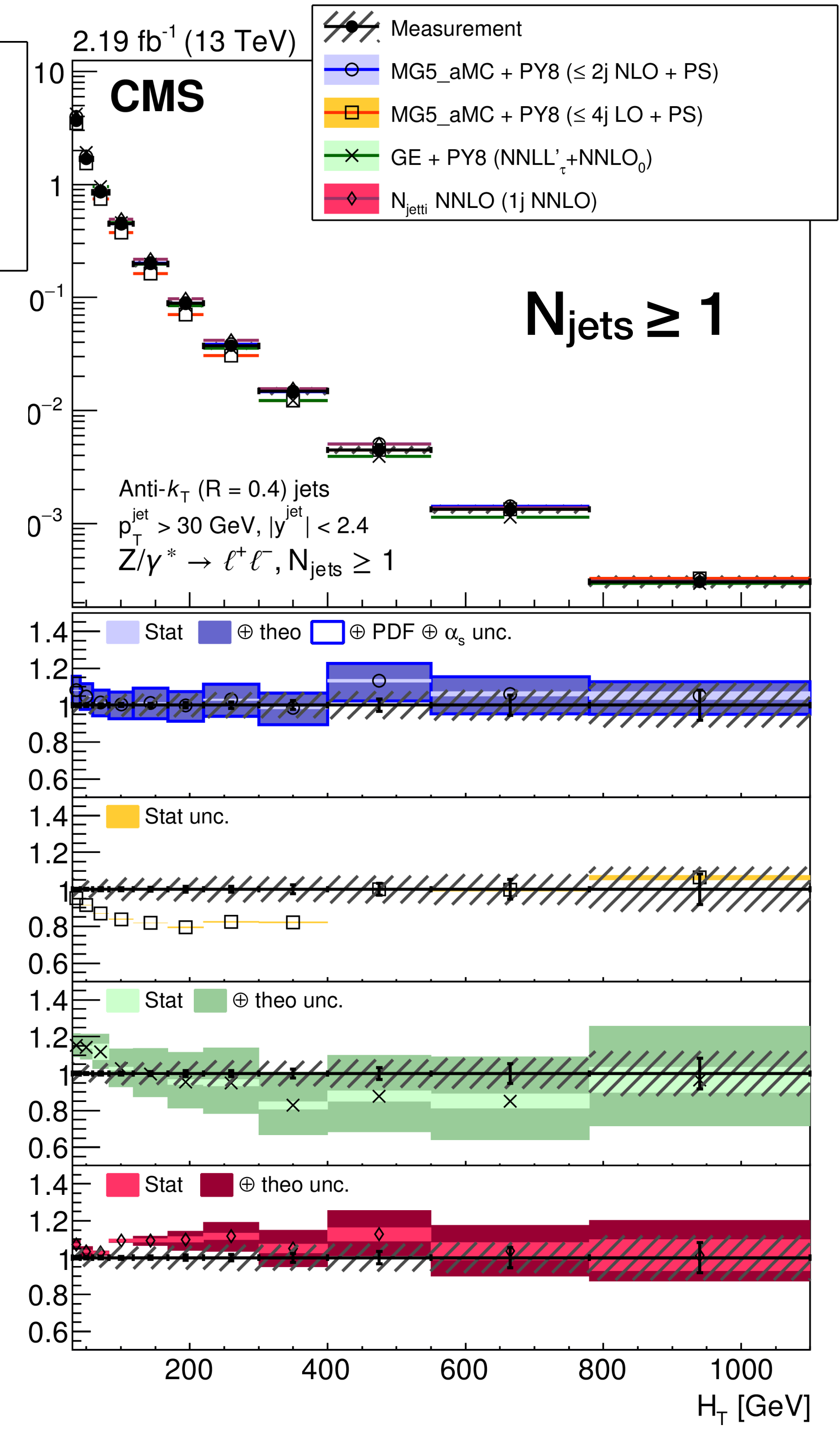
lead jet p_T



NLO MG5_aMC + **Z+1j@NNLO**

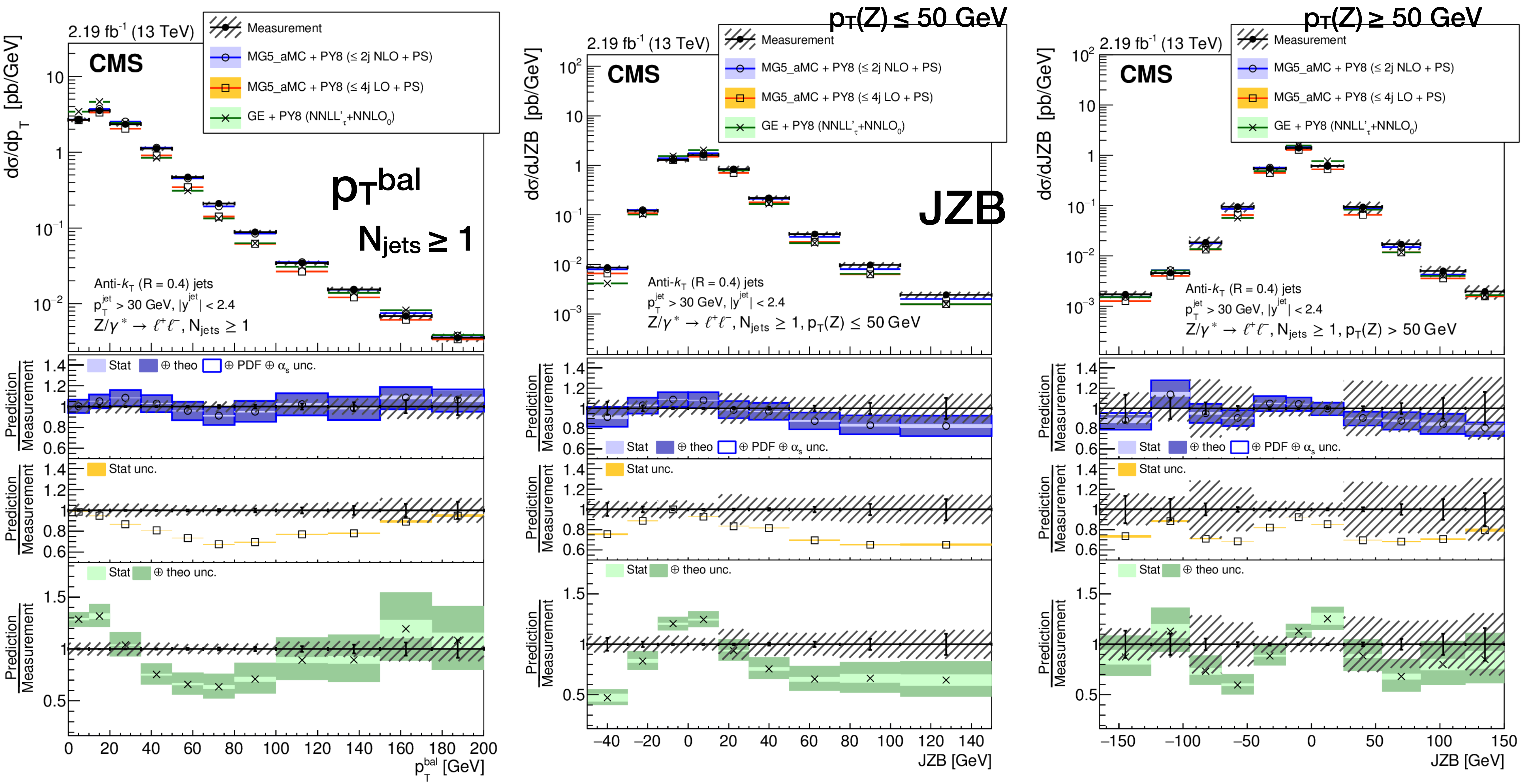
good description of the observables

H_T



LO MG5_aMC

significant disagreement with data



Imbalance due to:

1. Activity in forward region (dominant).
2. Gluon radiation in central region.

NLO MG5_aMC: good agreement with data.

LO MG5_aMC + **Geneva**: discrepancies with data.
LO accuracy for 2 partons in final state.

Observables

$$p_T^{bal} = |p_T(Z) + \sum_{jets} p_T(j_i)|$$

$$\mathrm{JZB} = |\sum_{jets} p_T(j_i)| - |p_T(Z)|$$

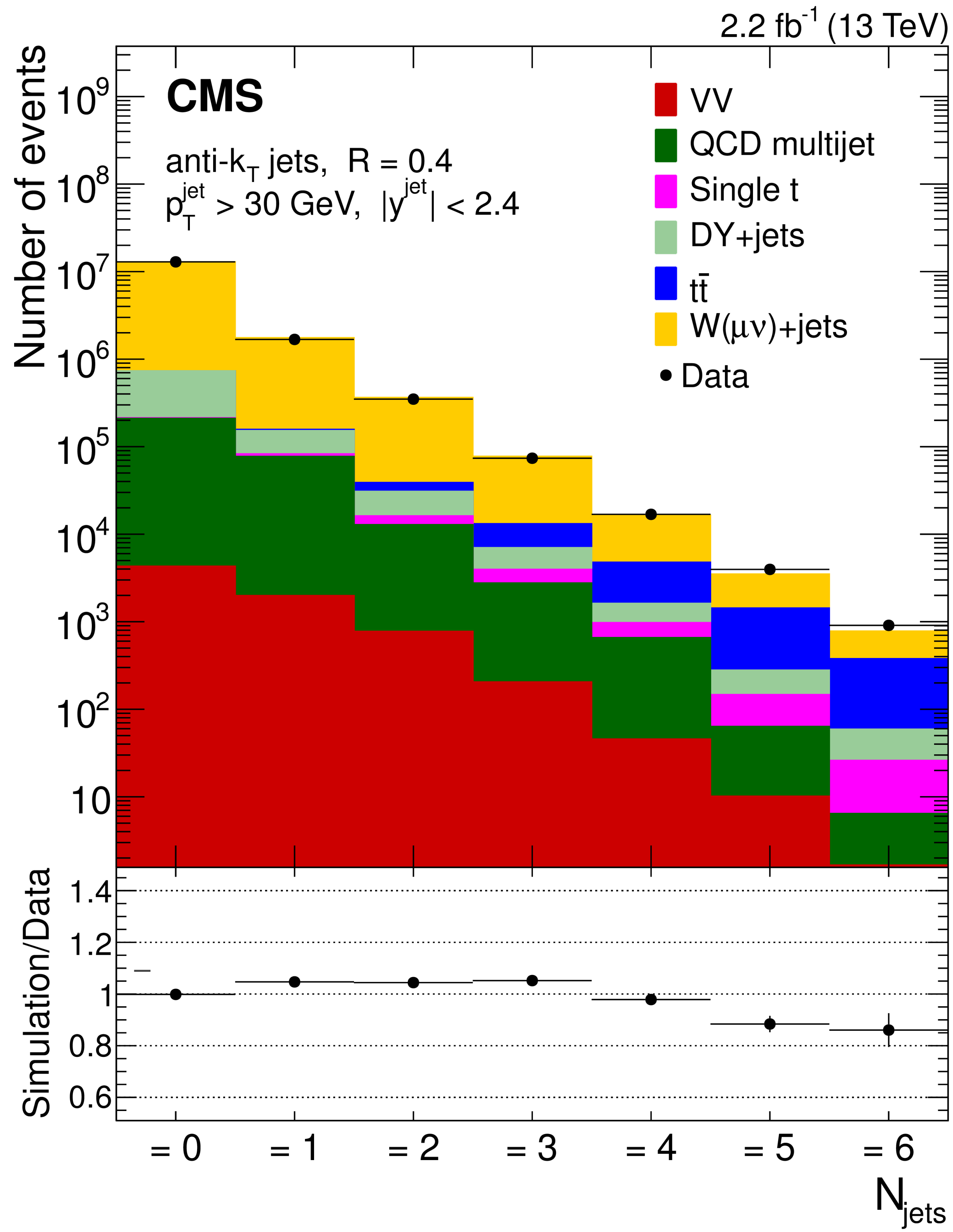
CMS @ 13 TeV

Associated production of W and jets

pp collisions @13 TeV, 2.2 fb^{-1} data (2015)

Phys. Rev. D 96 (2017) 072005

- Detector resolution corrected (unfolding)
- Dominant background: tt production (data-driven estimation)
- Other backgrounds: MC and data driven (QCD)
- Differential cross-section as a function of N_{jets}, jet p_T and η, jets H_T, angular correlations between muon and jets



Jets

anti-kT $(R = 0.4)$

$p_T(j) > 30$ GeV

$|\eta| < 2.4$

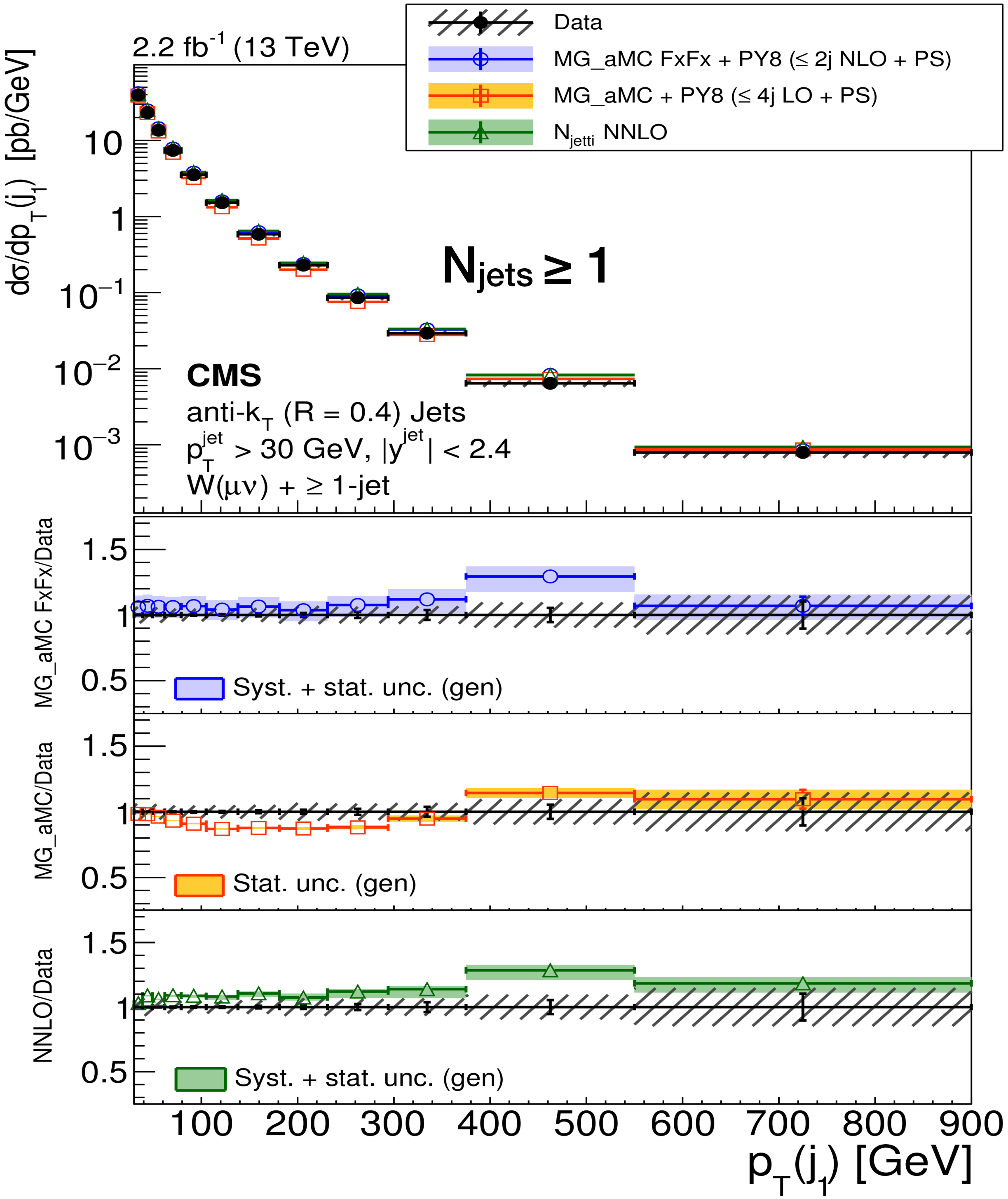
$\Delta R(jet, \mu) > 0.4$

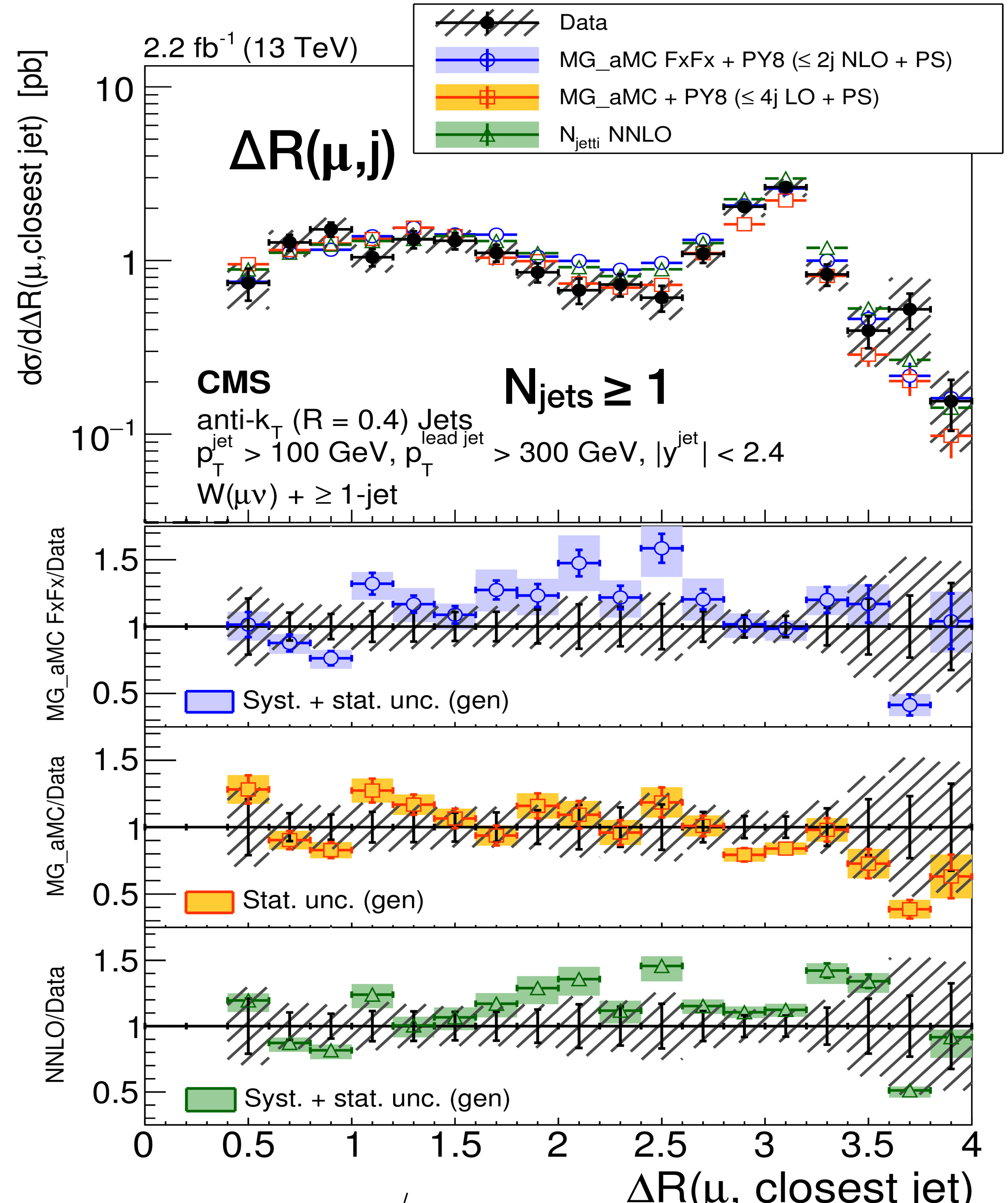
Muon

$p_T(\mu) > 25$ GeV

$|\eta| < 2.4$

$M_T > 50$ GeV

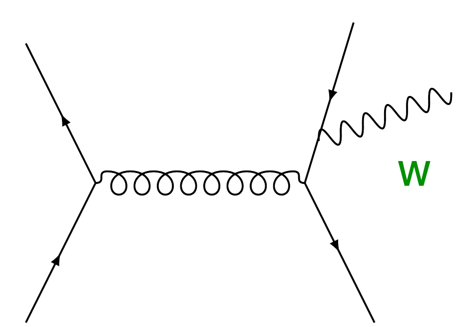




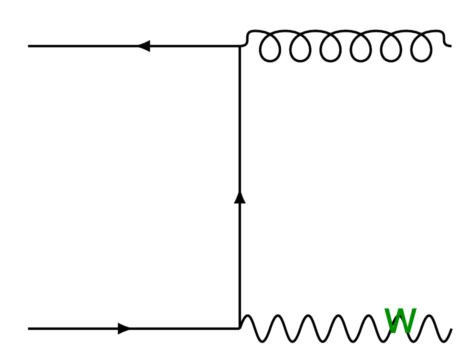
LO MG5_aMC: **underestimate** at low p_T

NLO MG5_aMC + **W+1j@NNLO**: **good description**

ΔR small



ΔR large



ΔR: sensitive to EW radiative production of W boson

Selected Results

part II

W and Z plus heavy flavours

Z plus b quarks @ 13 TeV

ATLAS @ 13 TeV

new!

JHEP 07 (2020) 44

Inclusive unfolded Z+≥1 b-jet and Z+≥2 b-jets x-sections

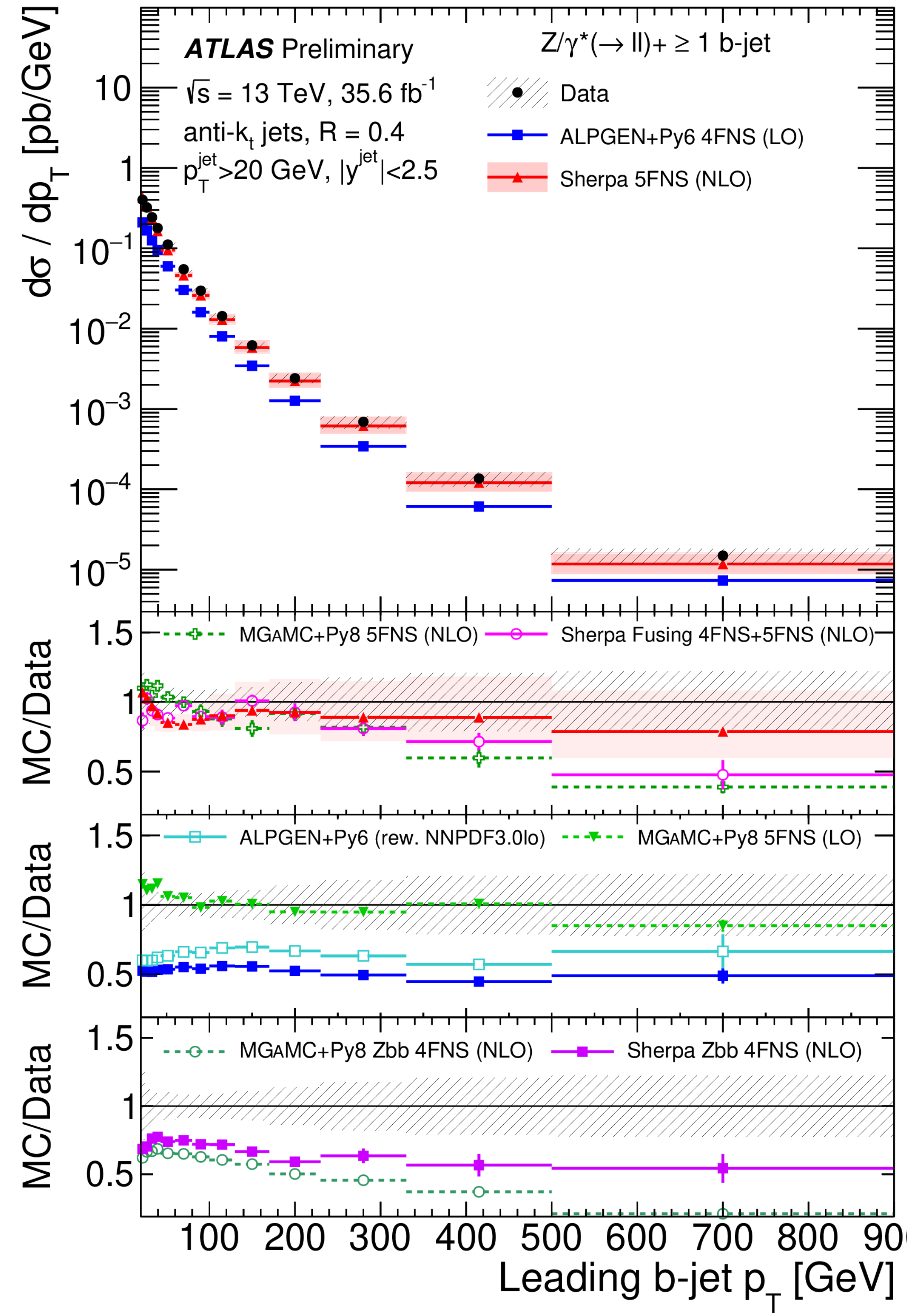
discriminate the effect of the b quark PDF of the proton (5/4-FS)

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

crucial background for VH->bbll, V'

combined MVA-based b-tagging reaching 70% efficiency for high pt jets

mistag rate c-quarks and light 8% and 0.26%

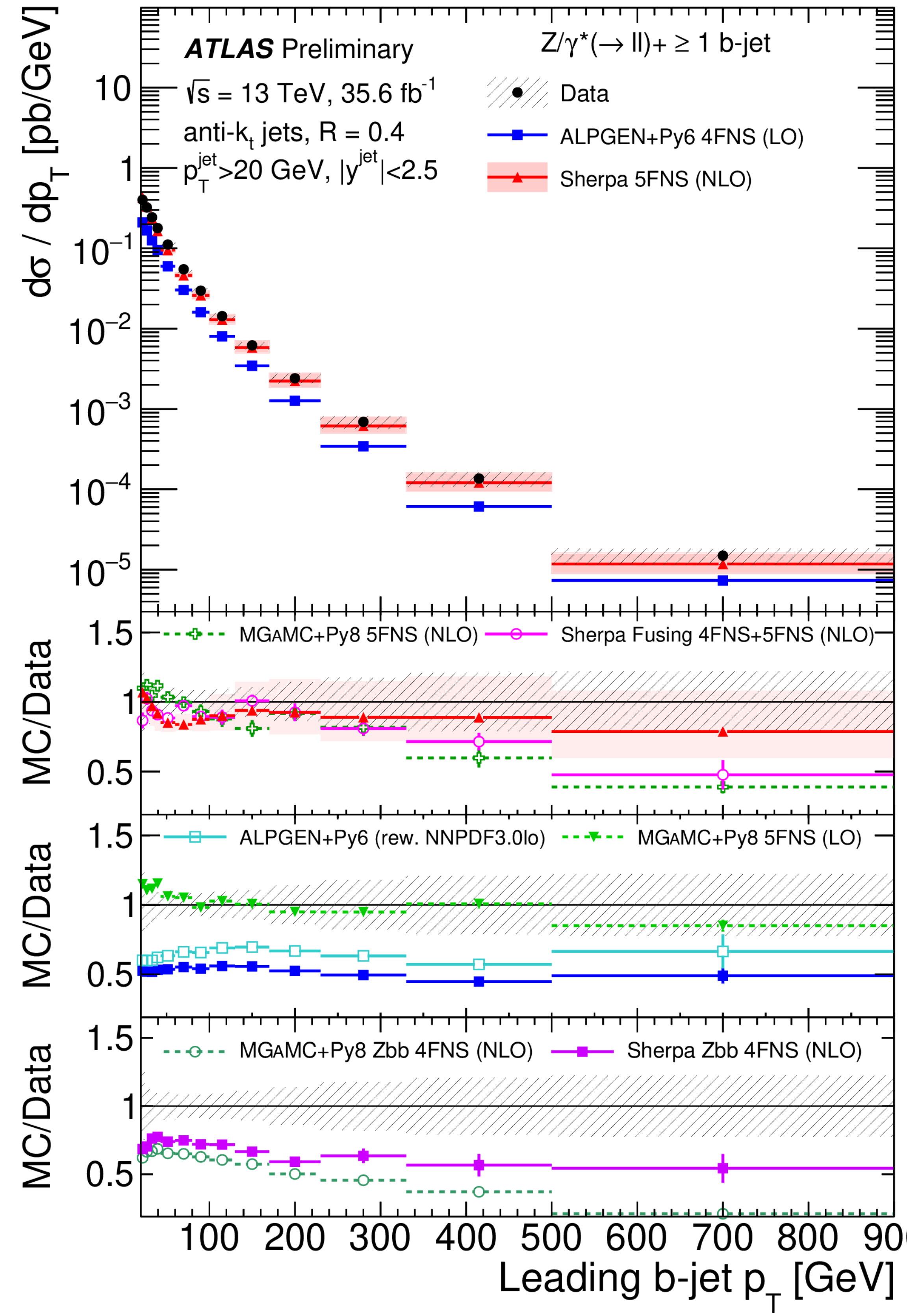


Z plus b quarks @ 13 TeV

new!

JHEP 07 (2020) 44

Inclusive unfolded Z+≥1 b-jet and Z+≥2 b-jets x-sections



- **best agreement for SHERPA 5FNS, not confirmed by SHERPA FUSING 4+5FNS**
- **MGAMC+PY8 5FNS (LO, ME 4p)** better than MGAMC+PY8 5FNS (NLO, ME 1p only), where additional hard radiation is simulated only via PS
- NLO 4FNS ZBB SHERPA and MGAMC+PY8 show a softer leading b-jet p_T
- the inclusive LO 4FNS ALPGEN well describes data

ATLAS @ 13 TeV

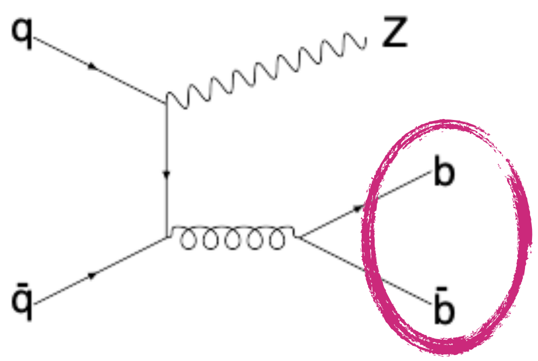
Z plus b quarks @ 13 TeV

new!

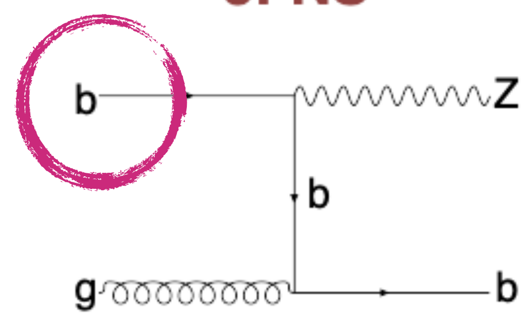
JHEP 07 (2020) 44

Inclusive unfolded Z+≥1 b-jet and Z+≥2 b-jets x-sections

4FNS

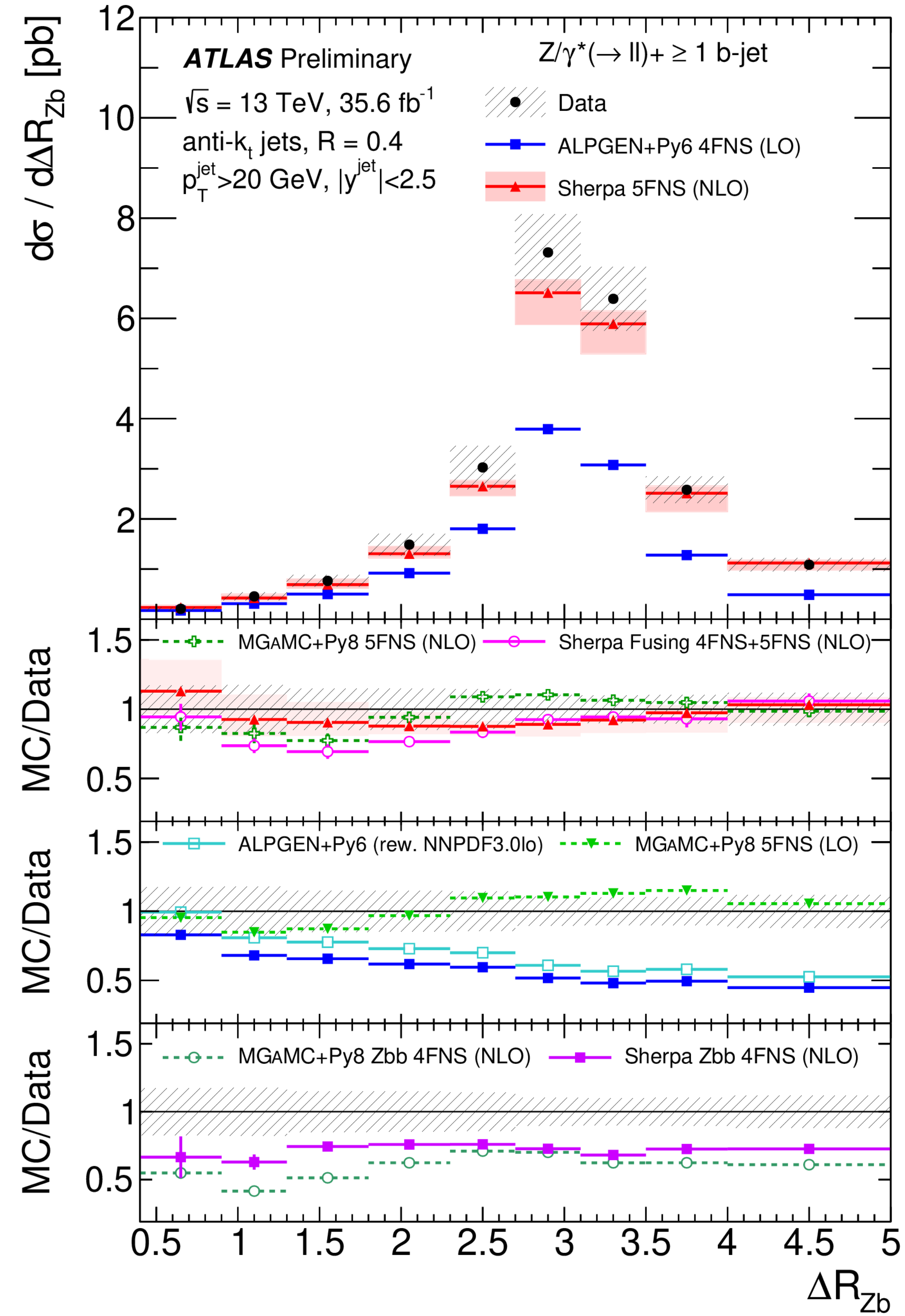


5FNS



- **good description for SHERPA 5FNS, and SHERPA FUSING 4+5FNS (*)**
- all other predictions exhibit a smaller rapidity separation
- different predictions for LO ALPGEN using different PDFs (small effect)

(*) “Fusing” ME at NLO for up to 2 partons, and ME at LO for up to 3 partons. It includes both Z + bb events generated in the 4FNS at NLO with massive b-quarks, and Z+jets events generated in the 5FNS at NLO. Phys. Rev. D 100 (2019) 014011



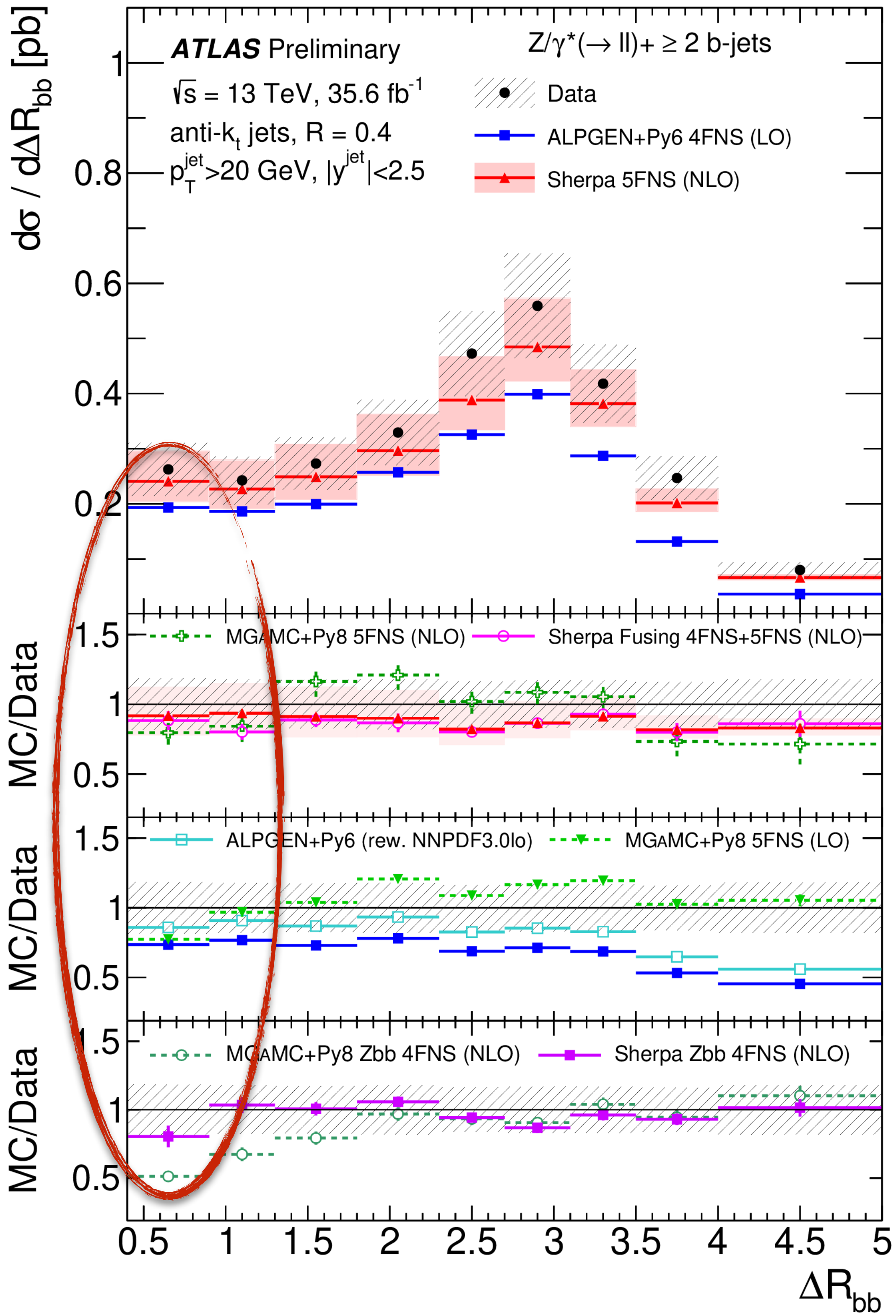
ATLAS @ 13 TeV

Z plus b quarks @ 13 TeV

new!

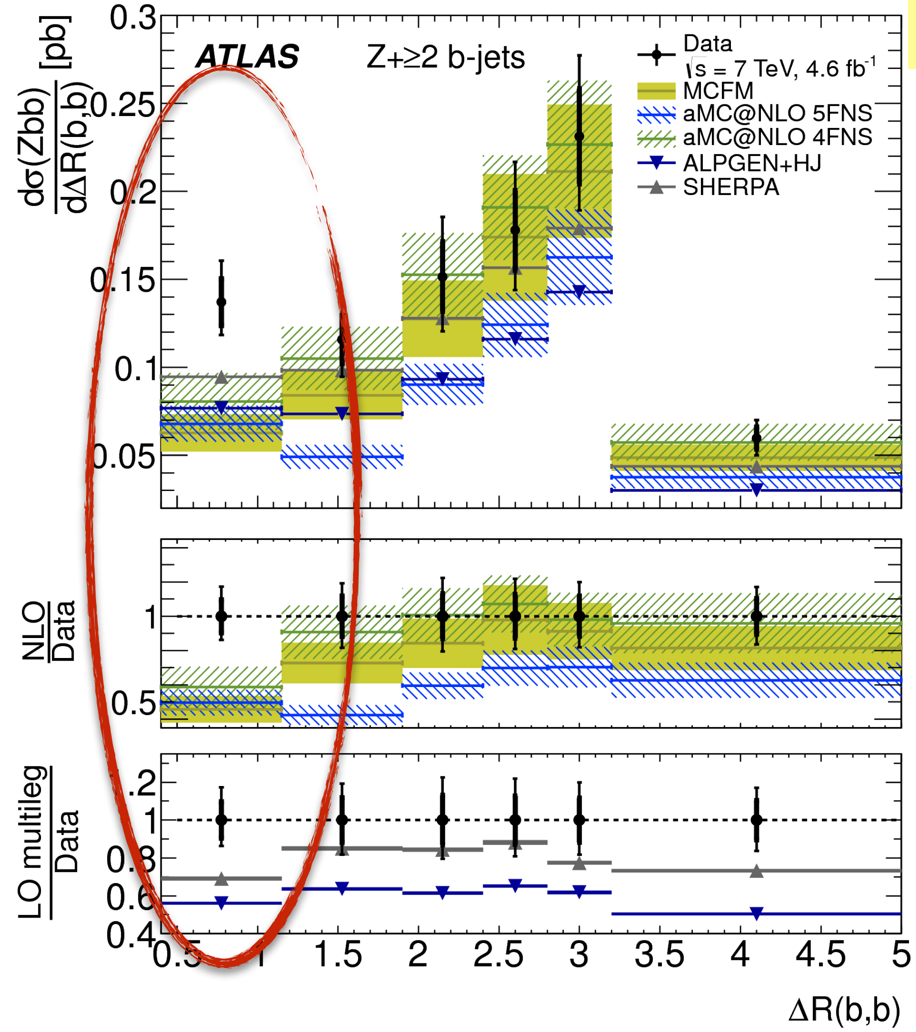
JHEP 07 (2020) 44

ΔR$_{bb}$ sensitive to the Z+bb production mechanisms



Low ΔR$_{bb}$ sensitive to gluon splitting in b-quaks

JHEP10(2014)141



13 TeV
vs
7 TeV

- SHERPA NLO MCs in better agreement with data wrt 7 TeV results (SHERPA LO)
- mismodelling by MGAMC+PY8 ZBB 4FNS in the phase space dominated by g→bb

CMS @ 13 TeV

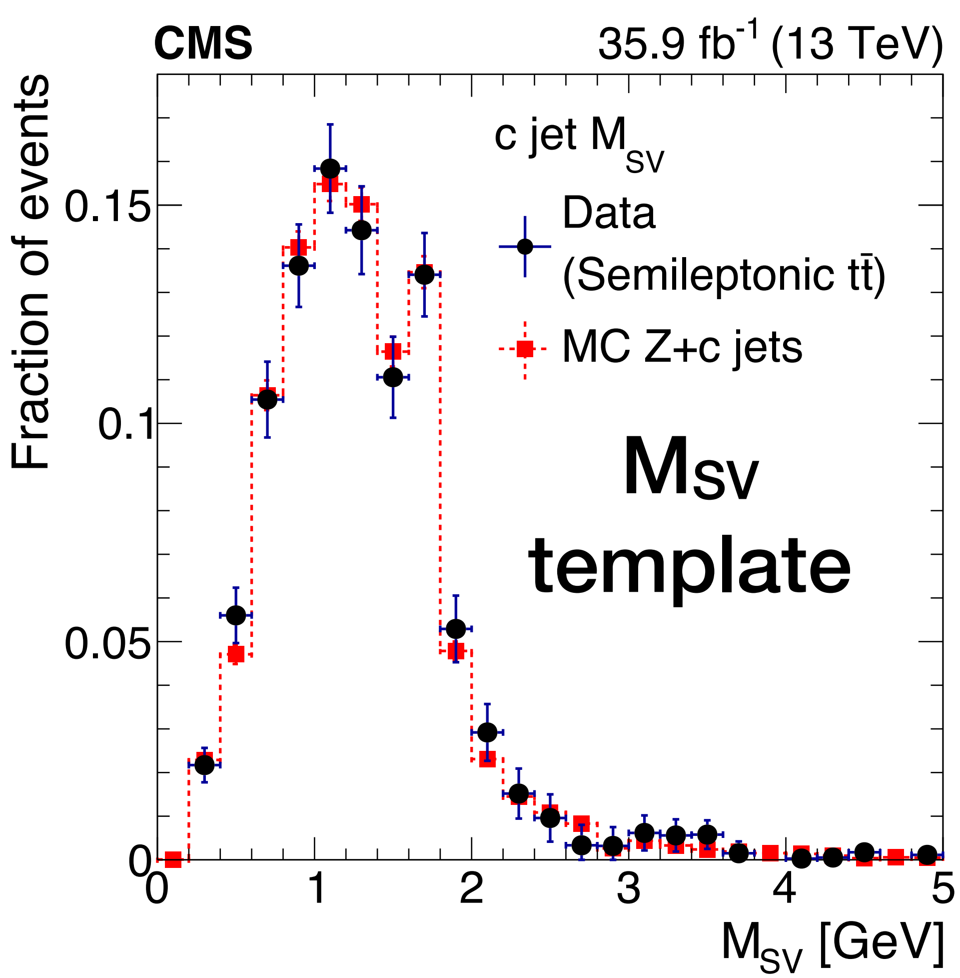
Z+b/Z+c, Z+b/Z+j and Z+c/Z+j

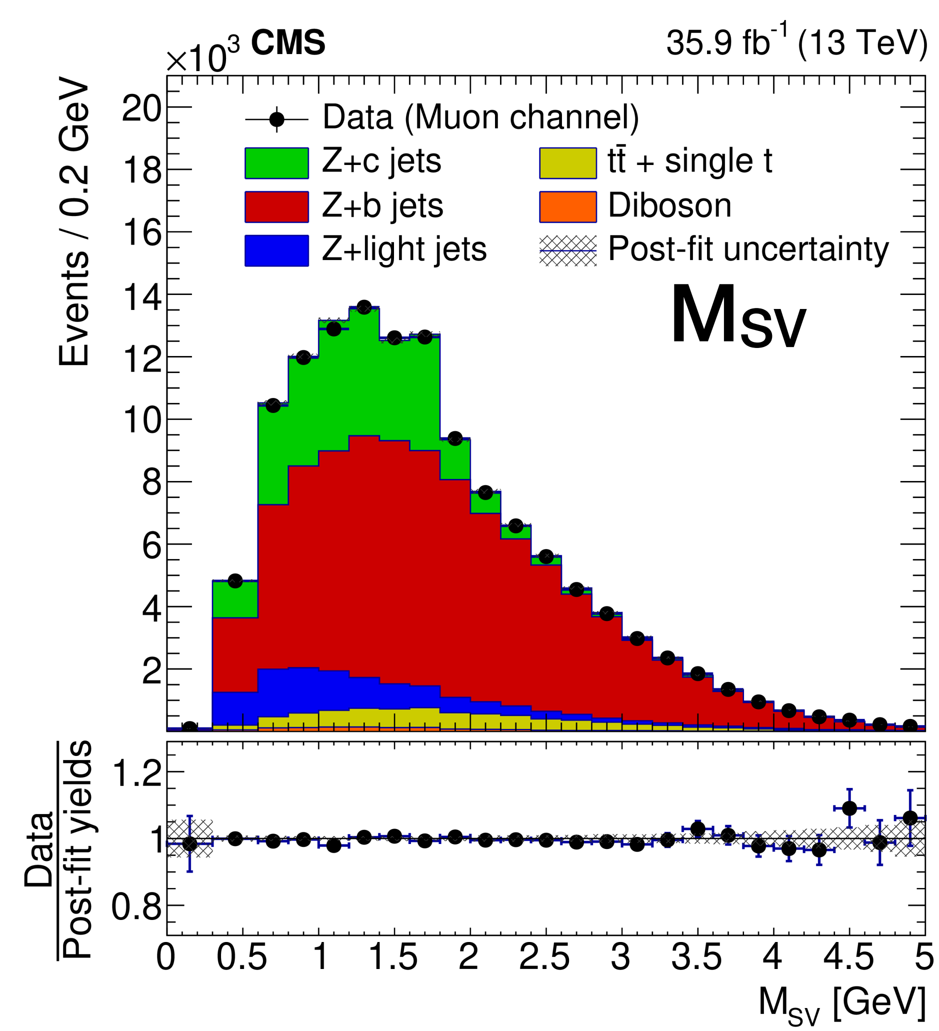
new!

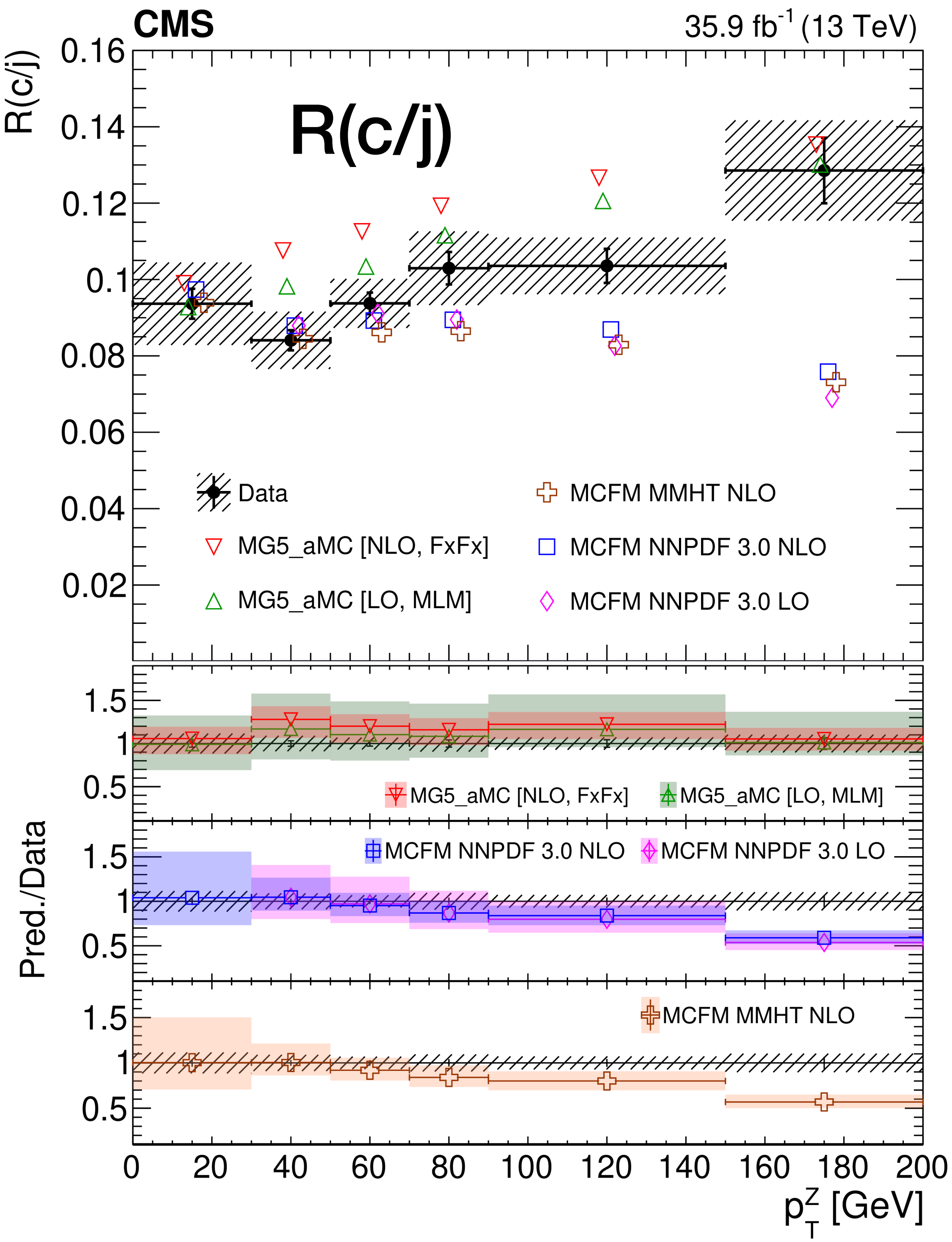
Phys. Rev. D 102 (2020) 032007

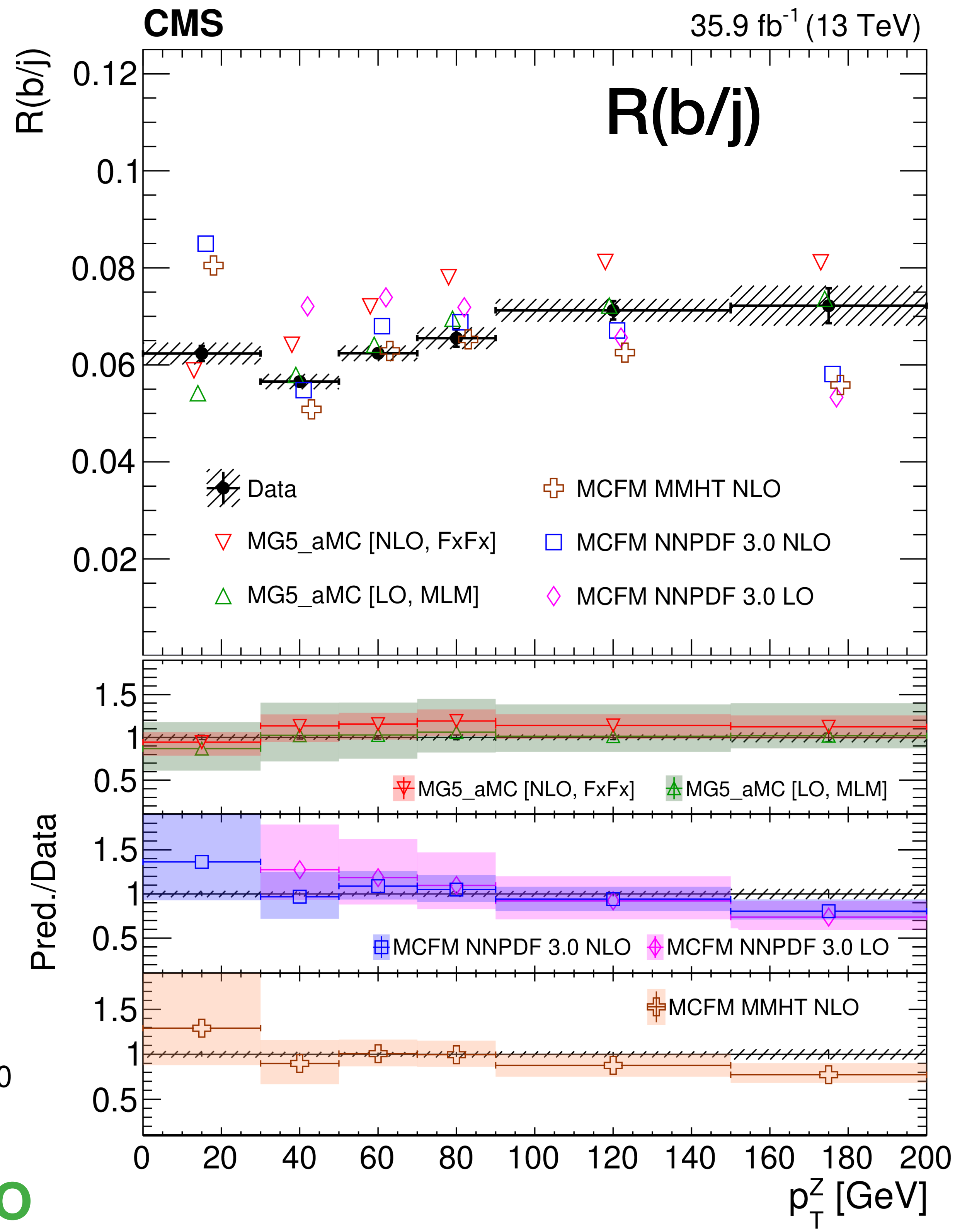
- pp collisions @13 TeV, 35.9 fb^{-1} data (2016)
- Ratios of unfolded cross sections: σ(Z + b/c) / σ(Z + jets) and σ(Z + c) / σ(Z + b) → reduce impact of several systematic uncertainties
- Important test of pQCD, background to ZH production
- Measured inclusive and differential cross-section as function 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 → Z + c and Z + b event yield







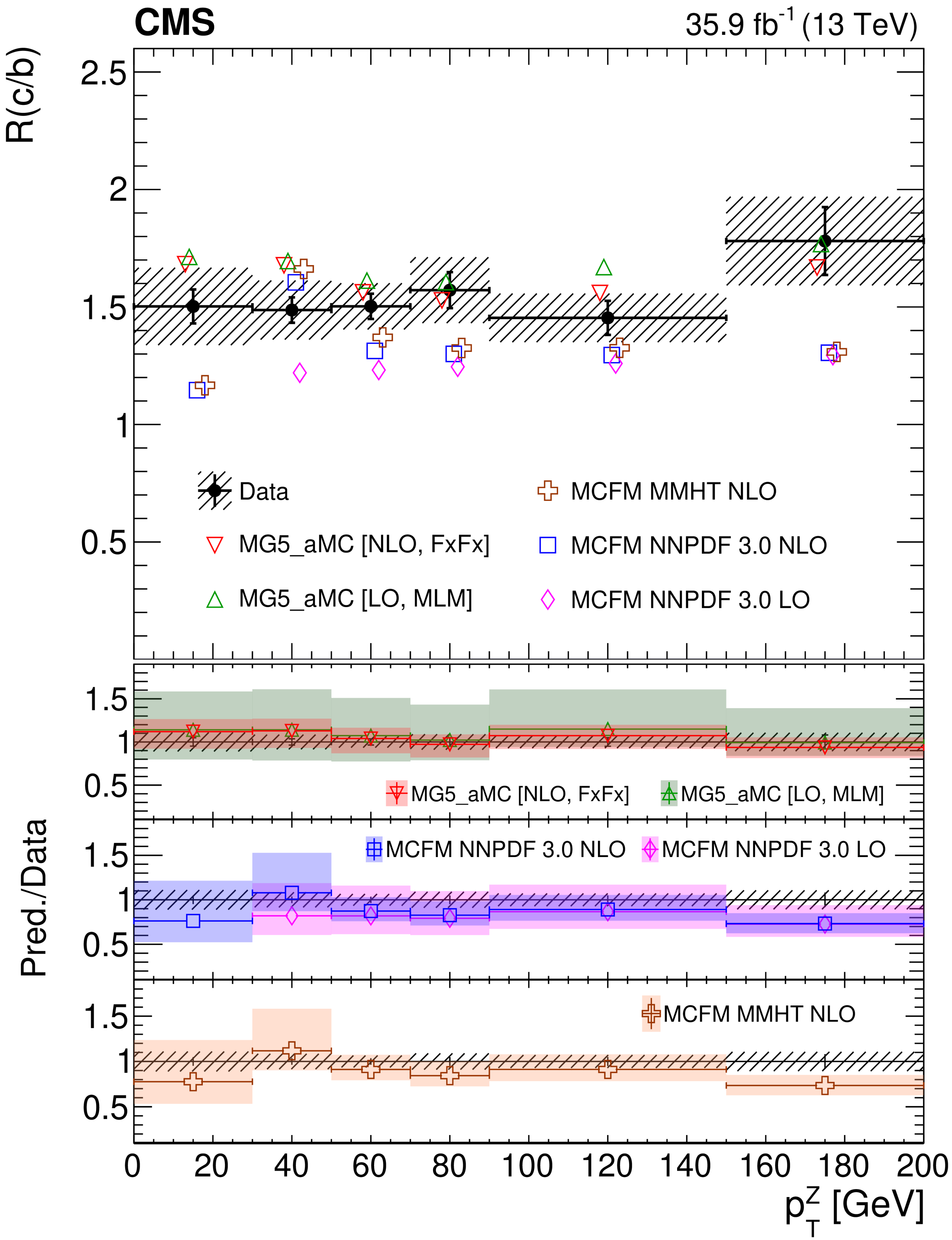


$p_T(Z)$

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 $p_T(Z)$**



R(c/b)

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 $p_T(Z)$**

Phys. Rev. D 102 (2020) 032007

Selected Results

part III

The role of PS and tuning in V+Jets

CMS

Hadronization & Tuning

CMS delivered a set of Pythia8 Tunes for Run2, tested over a wide variety of physics scenarios (including V+jets!)

https://arxiv.org/pdf/1903.12179.pdf

Tunes are extracted by fitting observables sensitive to UE Charged-particle multiplicity and charged-particle scalar-p_T sum (p_T^{sum}) densities

Parameter description	Range considered
MPI threshold [GeV], pT0Ref, at $\sqrt{s} = \sqrt{s_0}$	1.0–3.0
Exponent of $\sqrt{s}$ dependence, ϵ	0.0–0.3
Matter fraction contained in the core	0.1–0.95
Radius of the core	0.1–0.8
Range of color reconnection probability	1.0–9.0

parametrize the dependence of the predictions in bin i on the tuning parameters

Value of the measured observable in bin i

$$\chi^2(p) = \sum_{\mathrm{O}_j} \sum_i \frac{(f_{i,\mathrm{O}_j}(p) - R_{i,\mathrm{O}_j})^2}{\Delta^2_{i,\mathrm{O}_j}}$$

Observables

Total experimental uncertainty of R_i

CMS

Hadronization & Tuning

CMS delivered a set of Pythia8 Tunes for Run2, tested over a wide variety of physics scenarios (including V+jets!)

https://arxiv.org/pdf/1903.12179.pdf

CP1: NNPDF3.1 PDF set at LO, with α_s values used for simulation of MPI, hard scattering, FSR, and ISR equal to, respectively, 0.13, 0.13, 0.1365, and 0.1365

CP2: same as CP1 but with α_s values all equal to 0.13

CP3: NNPDF3.1 PDF set at NLO, with α_s all equal to 0.118

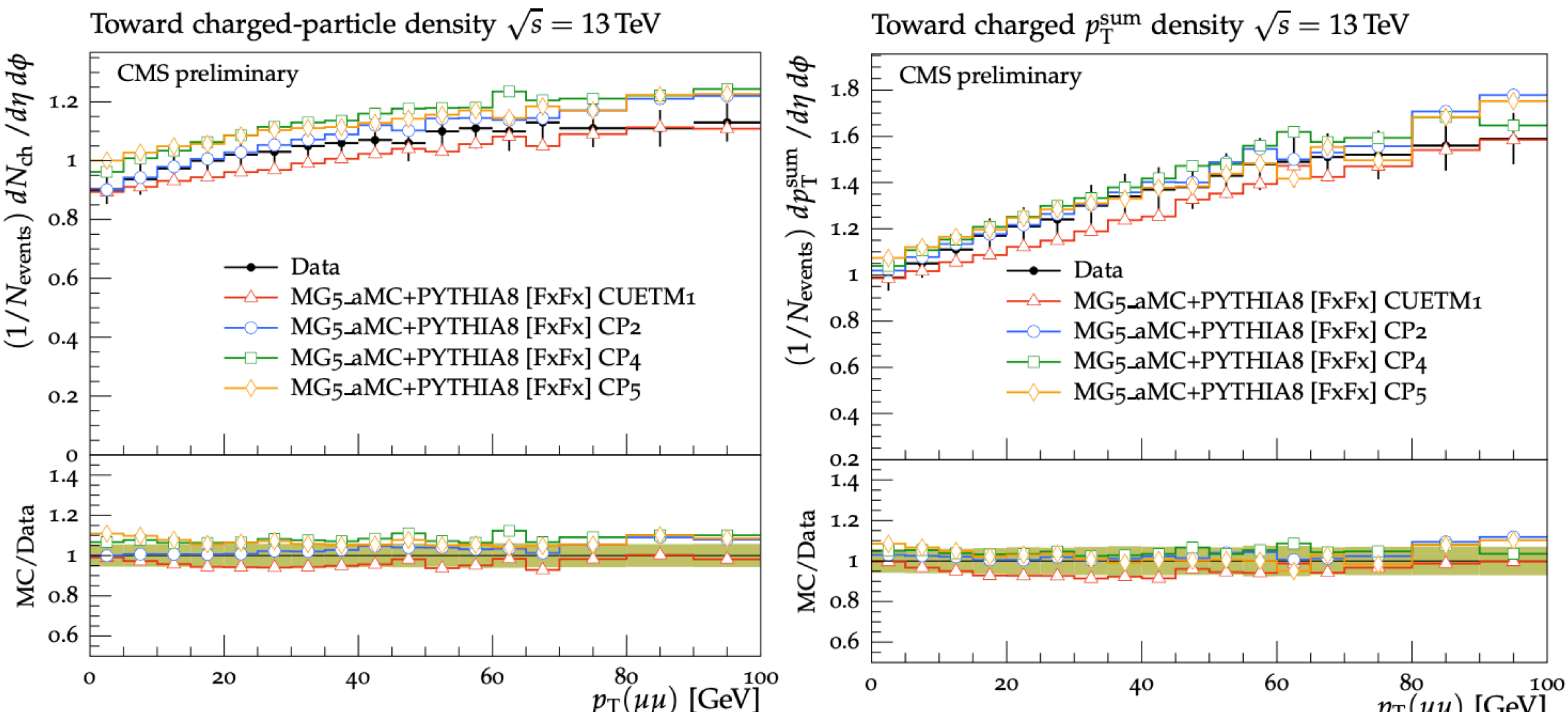
CP4: NNPDF3.1 PDF set at NNLO, same values of α_s as CP3

CP5: same settings as CP4, but with ISR emissions ordered according to rapidity

PROFESSOR for fitting and RIVET for validation

Validation with Underlying Event in Z+Jets

UE in Z+jets matrix element generation made by madgraph_aMC@NLO [FxFx]



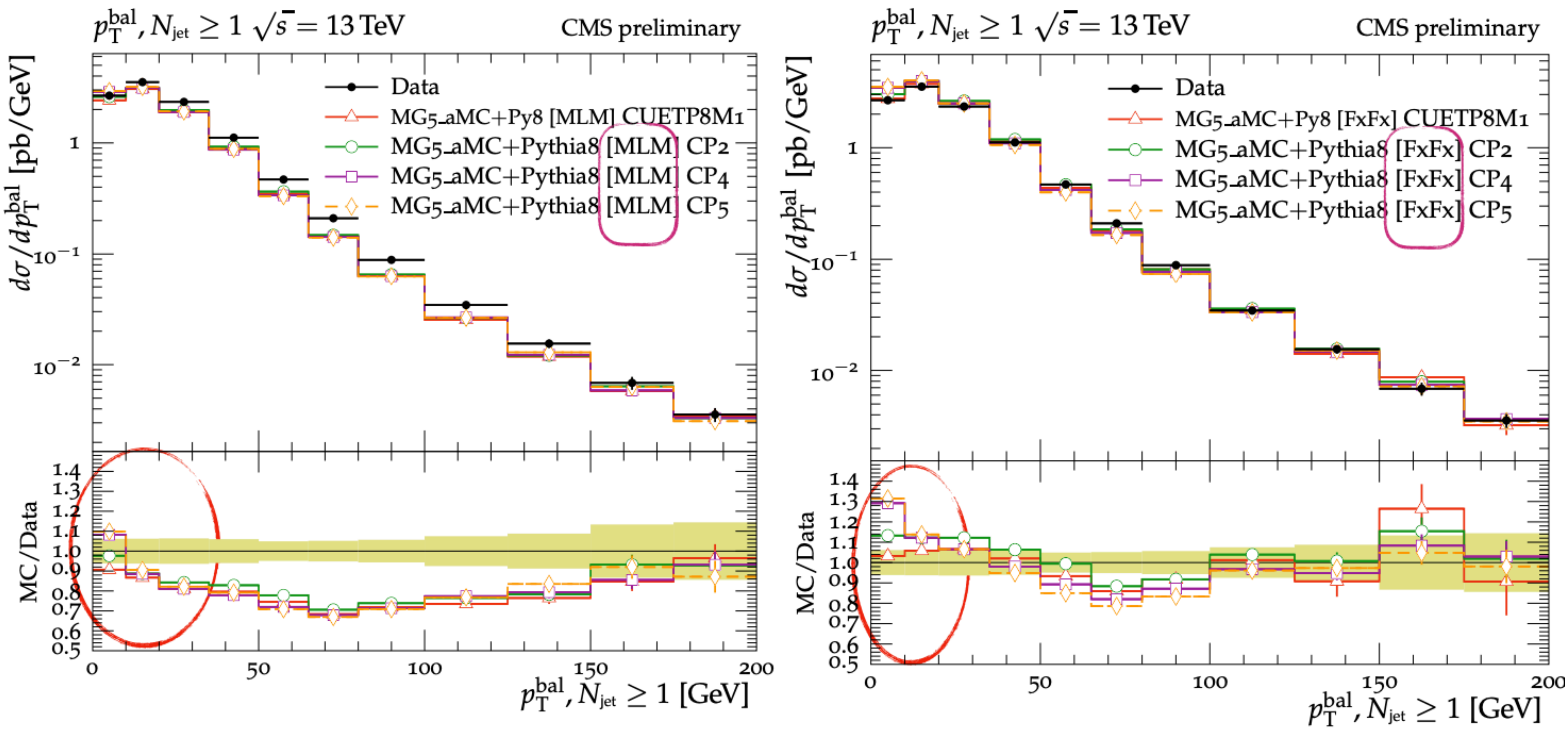
pT(μ)>20/10 GeV
|Mμμ-91| < 20 GeV
eta < 2

old-Monash based tune CUETPM1 not able to describe the Z
CP5 gives the average best description in all regions
all tunes describe data

Validation with hard QCD in V+Jets

hard QCD: Z+jets events with jet pt>30 GeV

matrix element generation made by madgraph_aMC@NLO[FxFx and MLM]

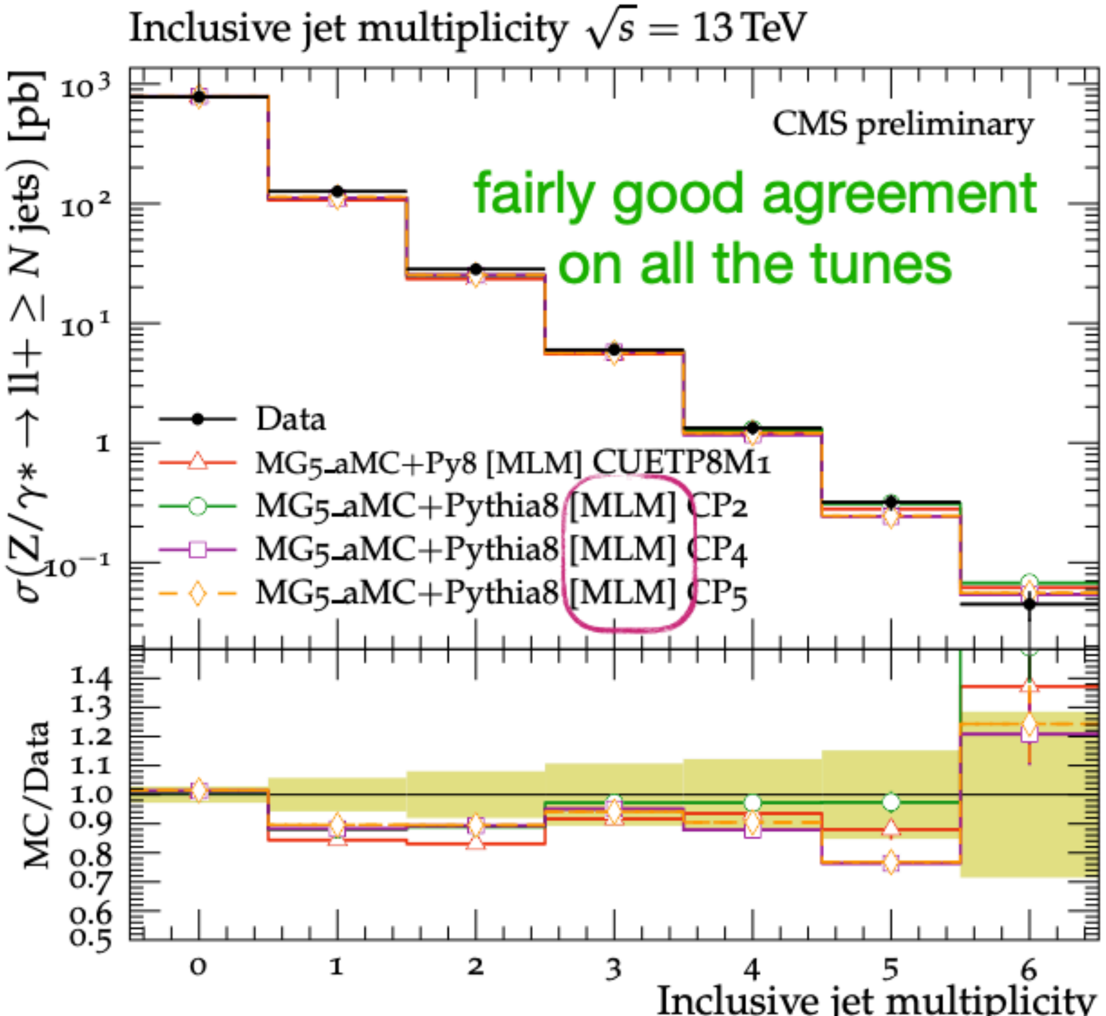


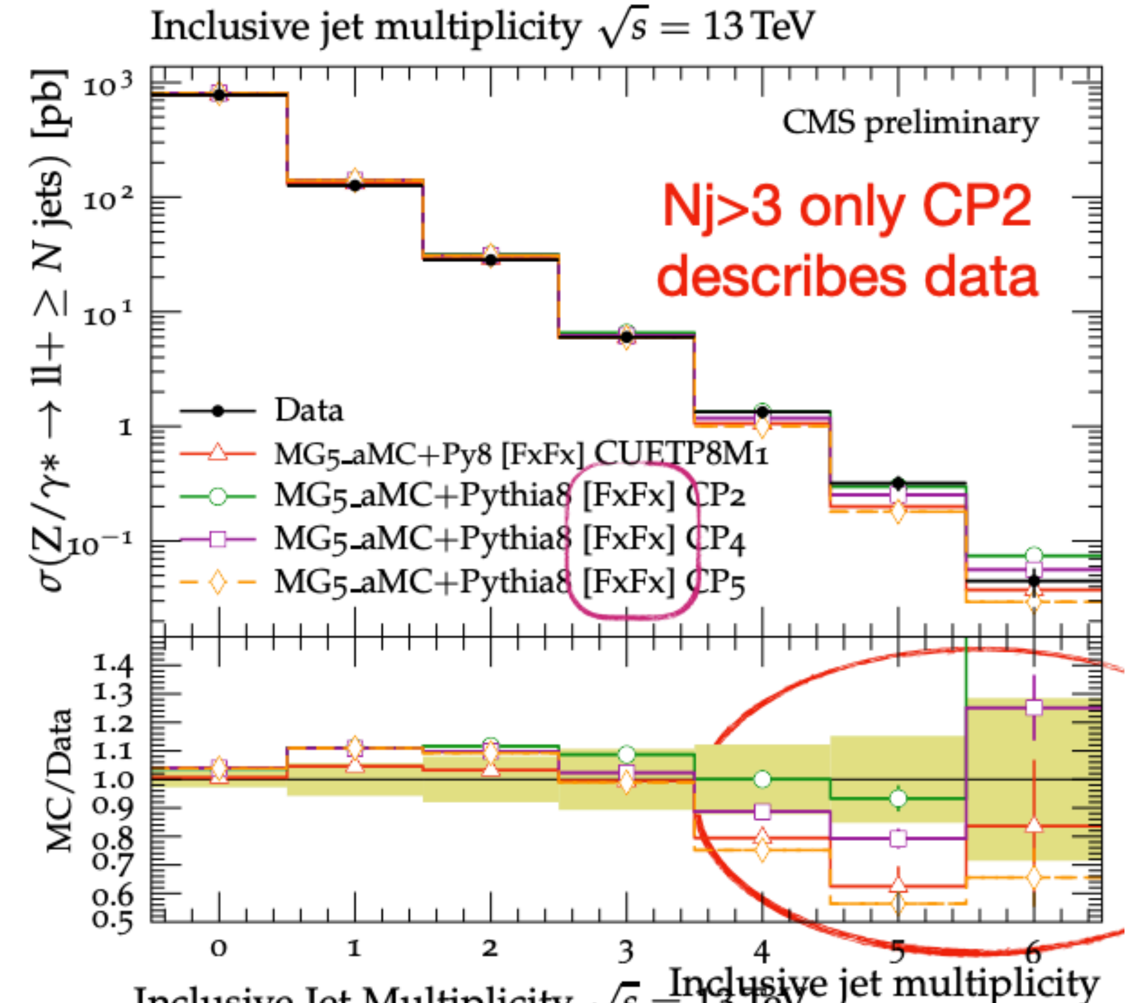
Z-J balance: hadronic activity not clustered in jets generate imbalance

(!) Only below 20 GeV we see differences among tunes

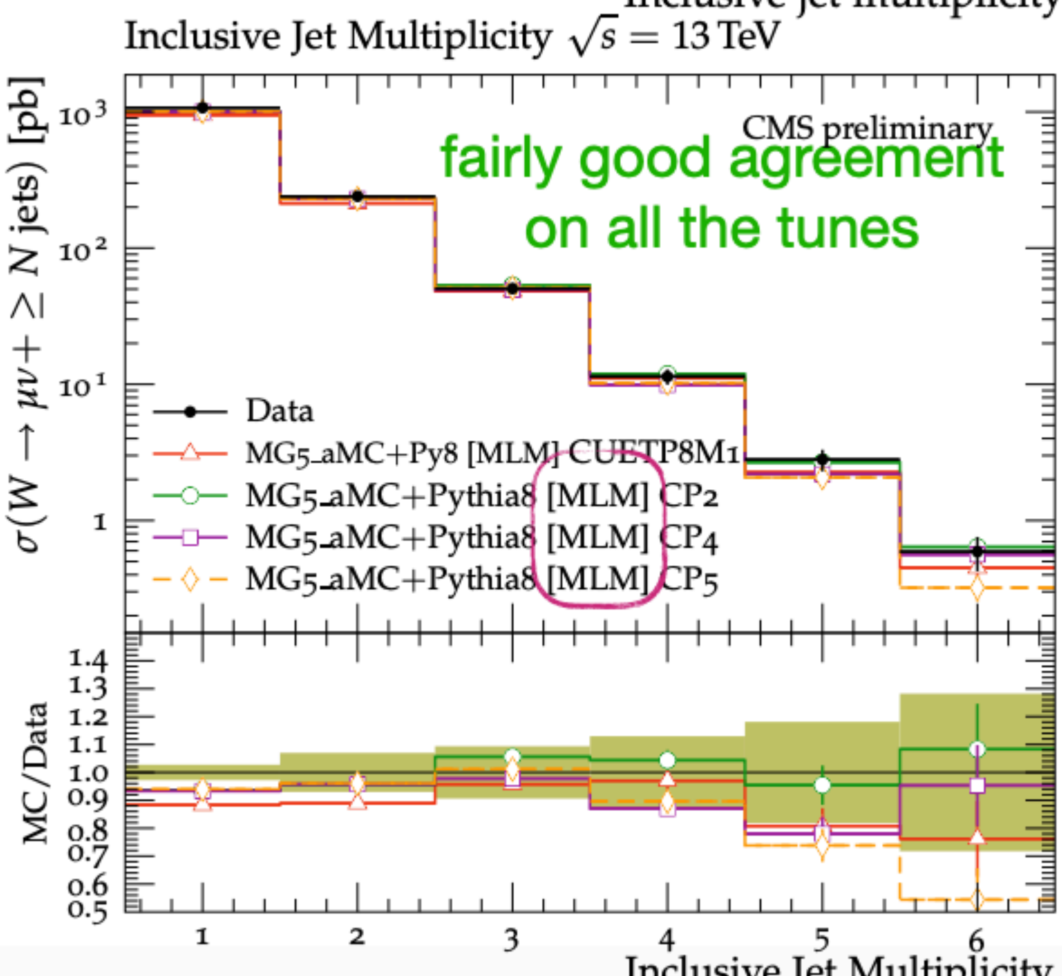
$$p_T^{bal} = |p_T(Z) + \sum_{jets} p_T^j|$$

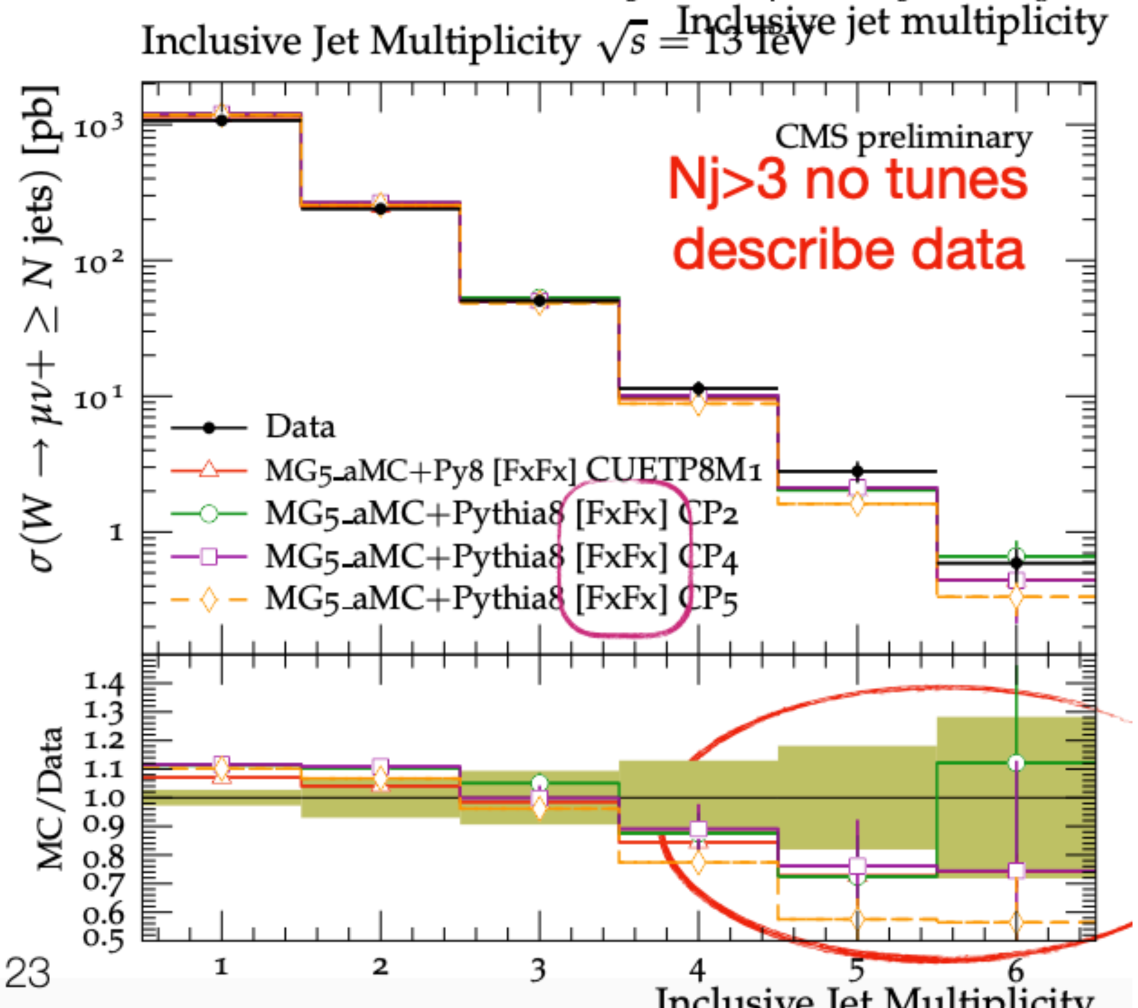
Inclusive Multiplicity in Z+jets





Inclusive Multiplicity in W+jets





The V+jet LHC Electroweak Working Group

Common effort across LHC experiment to deliver results on V+Jets topologies

Contents

Three main projects

Topical workshops organized periodically

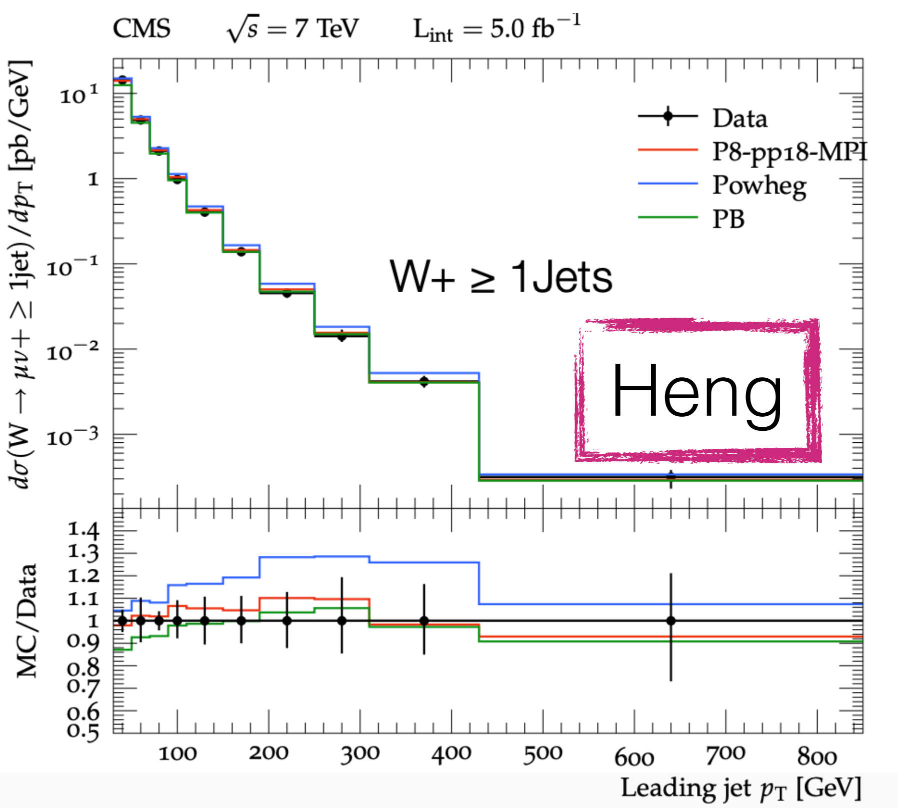
Yellow-report document in preparation

ATLAS	Eram Rizvi and <u>Benjamin Nachman</u>
CMS	Vieri Candelise, Mikko Voutilainen (NEW), Hannes Jung
LHCb	Stephen Farry and Will Barter
ALICE (NEW)	James Mulligan (NEW) and Nima Zardoshti (NEW)
THEORY	Marek Schoenherr

Some recent benchmark comparisons results

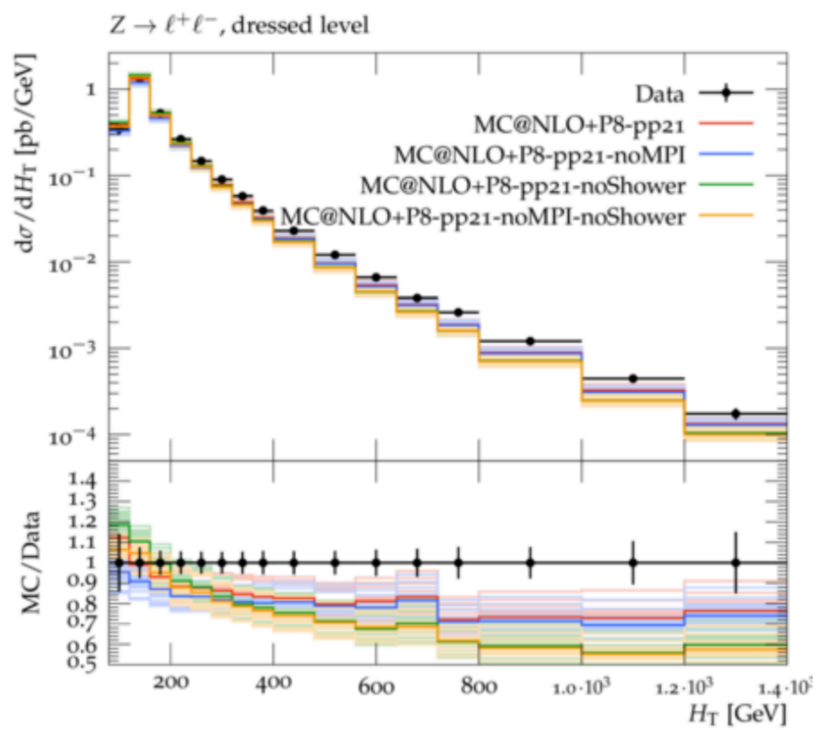
LHCEW

$W/Z + jets$ PB

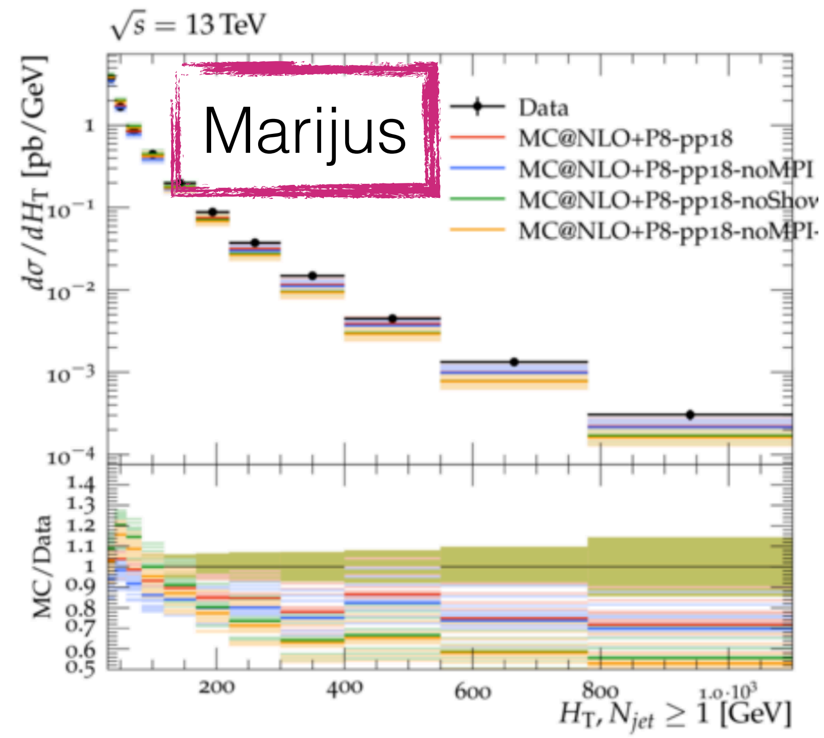


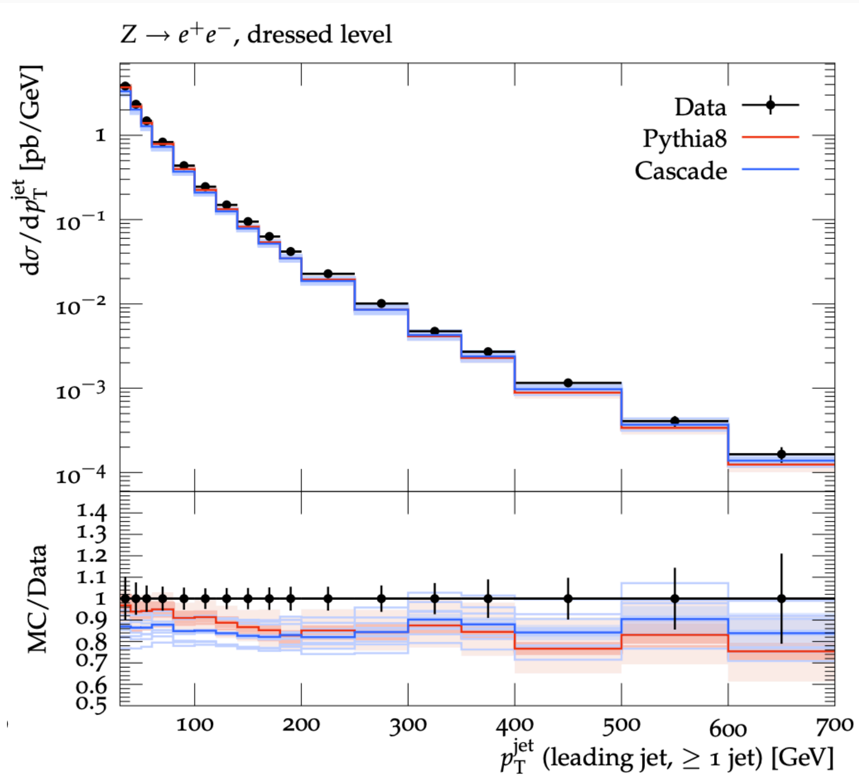
$W/Z + jets$ PS

ATLAS_2017_I1514251



CMS_2018_I1667854

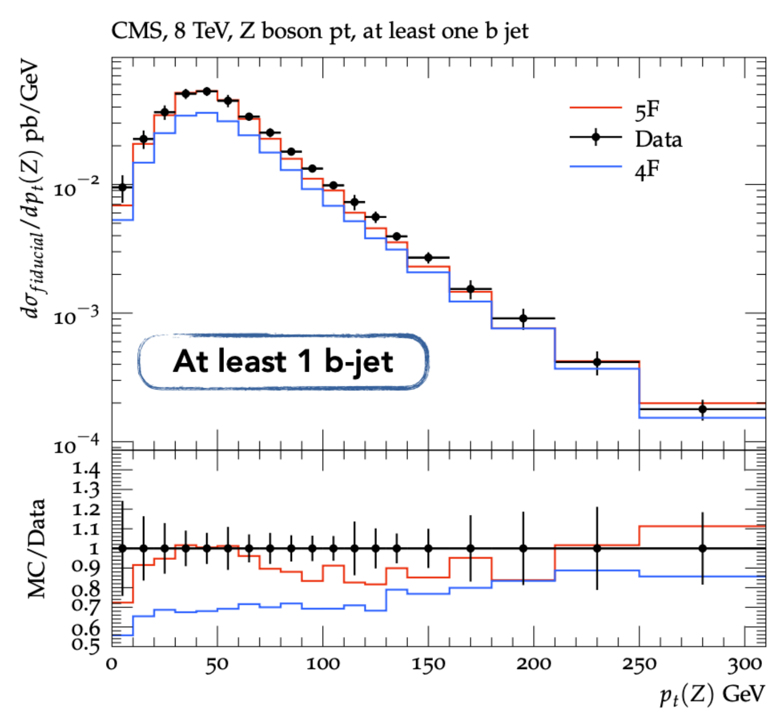


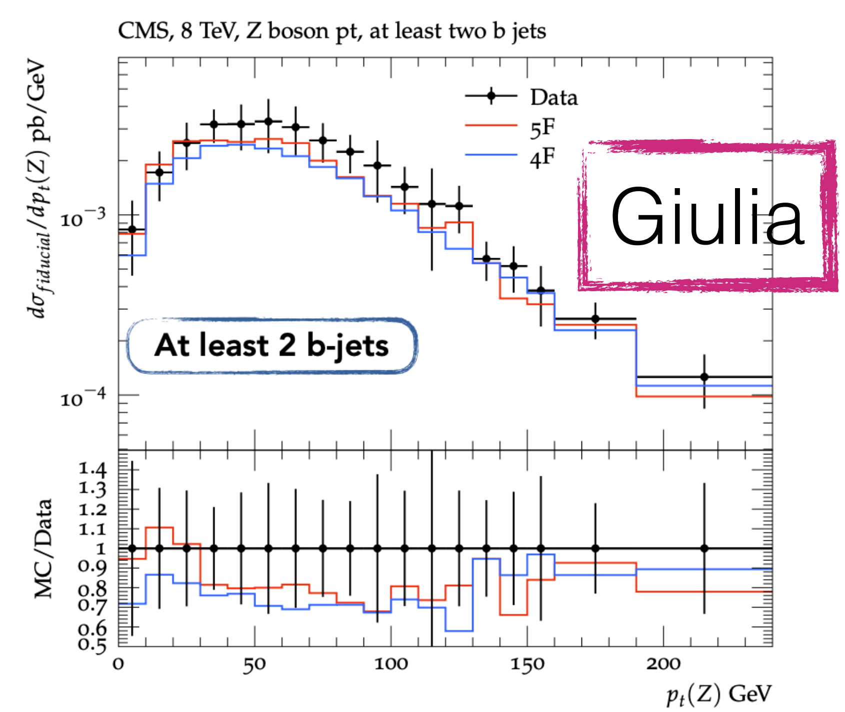


[work in progress!]

$Z + b\bar{b}$ TMD

Directly sensitive to the b quarks PDF and the initial-state gluon splitting





Summary and conclusions

- LHC is a V+jet factory: a rich QCD phenomenology can be explored with experimental data
- QCD can be tested up to NNLO exploiting generators with different calculation *philosophy*
- Several new measurements at 13 TeV with V+Jets and V+HF - Outstanding precision is achieved by experiments
- A lot is ongoing and the best is yet to come… stay tuned!!

Present and future of V+Jets at LHC

(my personal view!)

- ☹ Making experimental SM analyses up to publication is super hard and takes a longer time than searches: we need to find more manpower and be attractive for PhD students!

- ☺ After years of no striking hints of BSM, LHC experimental community started looking at SM results again with more and more interest

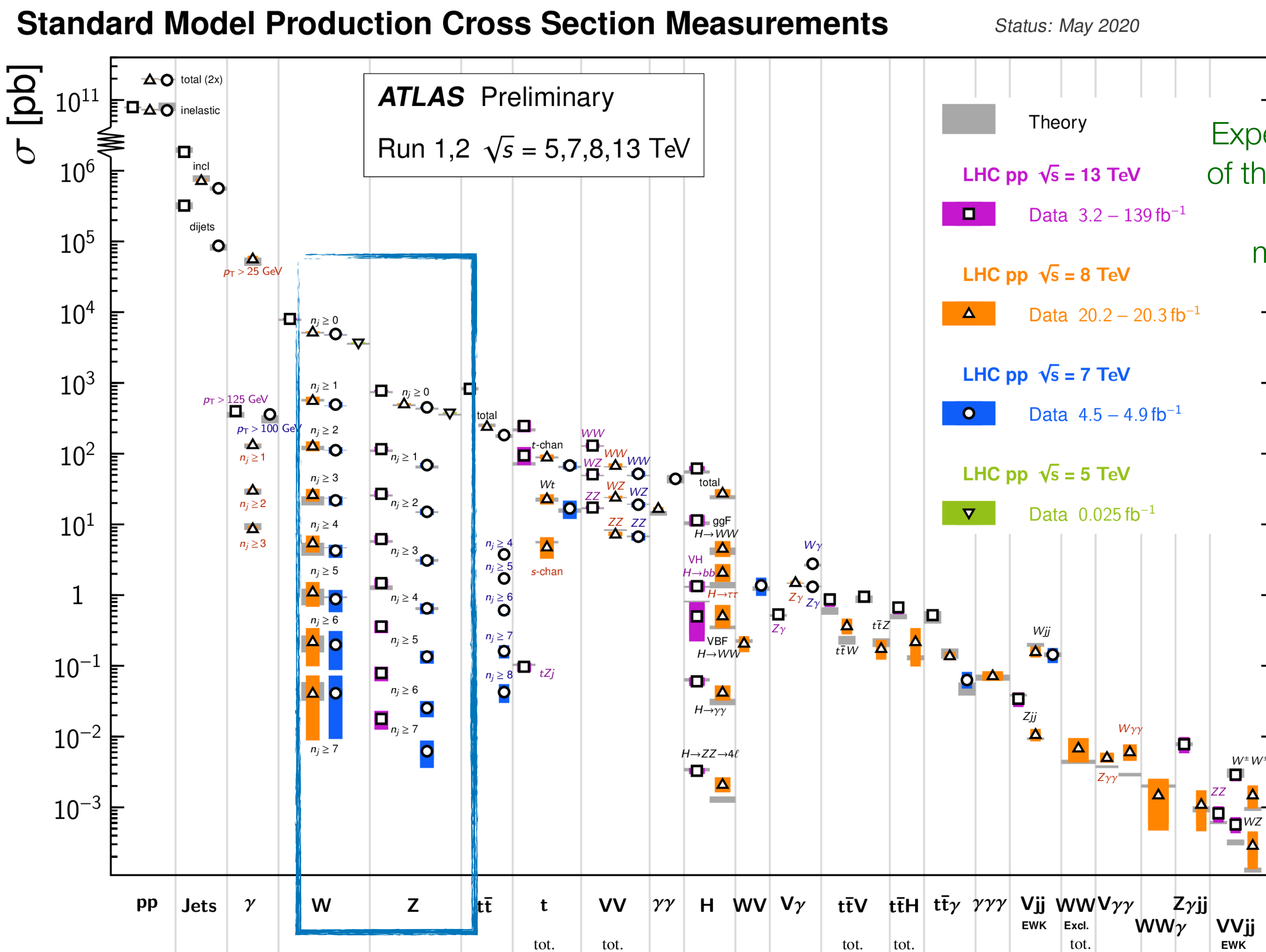
- ☹ Rivet routines we need to raise awareness on their importance. That's our tool to play with phenomenology!

- ☺ The LHC Electroweak Working Group has an important and strong multi-group structure and it has dedicated V+Jets conveners: huge potential to be exploited!

- ☺ TMDs recently demonstrated their crucial role for future comparisons in V+jets and H+jets

- ☹ Photon plus jets is a huge missing in this picture, and we can do a lot of QCD with photon plus N jets and HF backup

Standard Model measurements in 2020

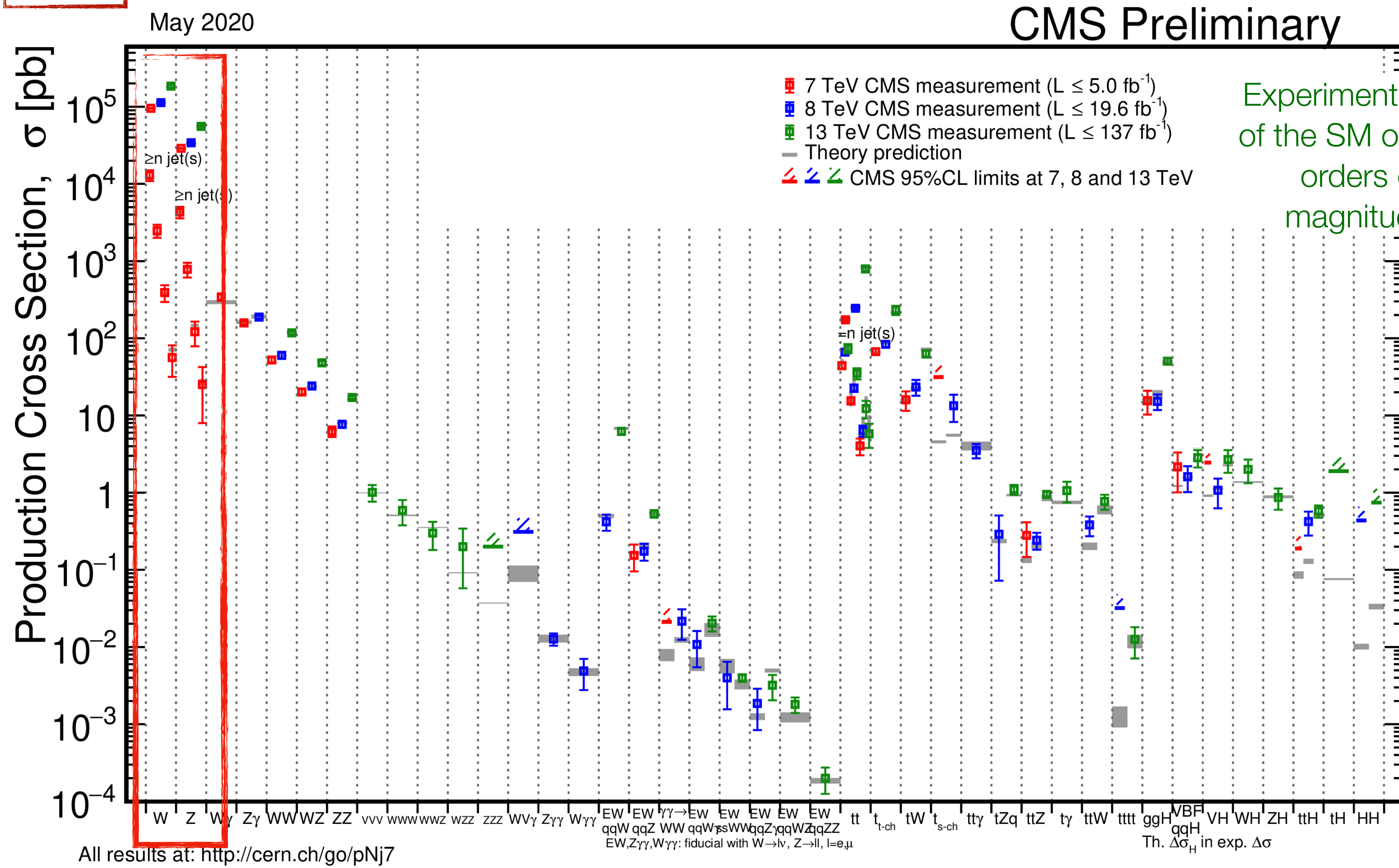


Experimental test of the SM over 15 orders of magnitude!

ATLAS

Standard Model measurements in 2020

CMS



Experimental test of the SM over 15 orders of magnitude!

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

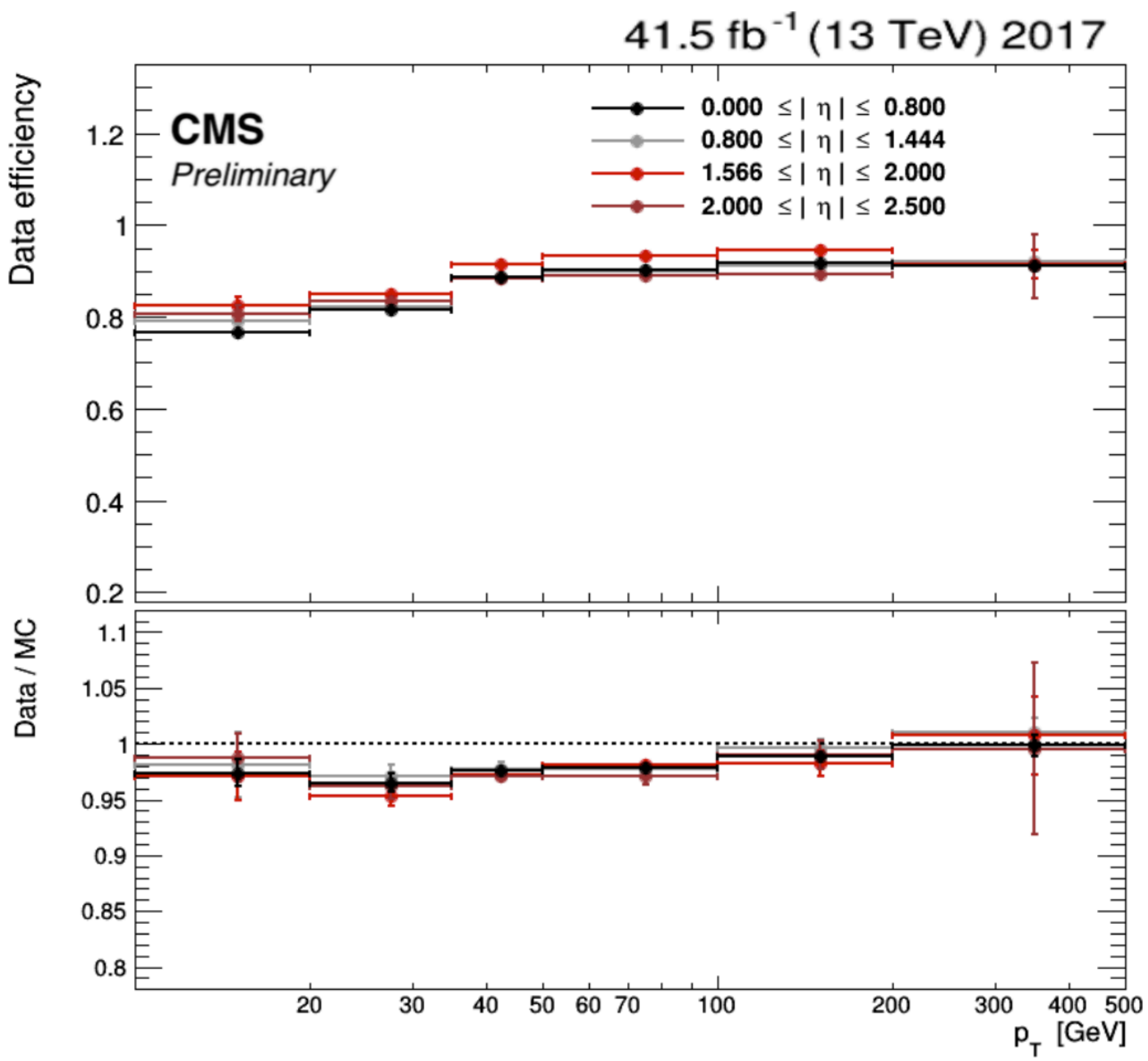
several (CP5) PYTHIA8 tunes

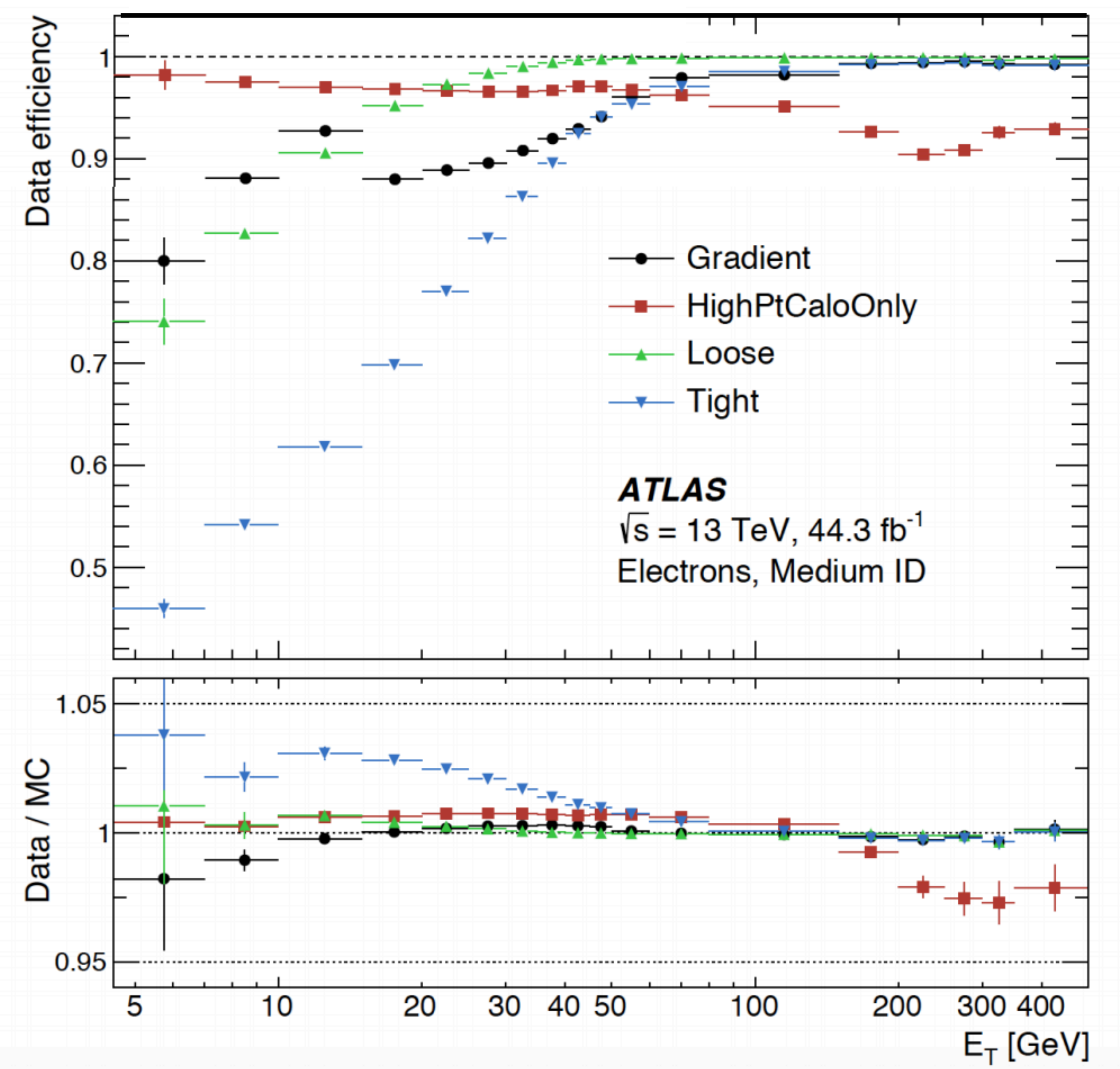
- **HF treatment**
  - 4FS, b mass and 4 PDFs
  - 5FS b mass=0 and 5 PDFs

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	-	-

How all of this is possible

precision SM tests, differential spectra and sensitivity to very rare processes are possible exploiting the ATLAS and CMS excellent detector performances

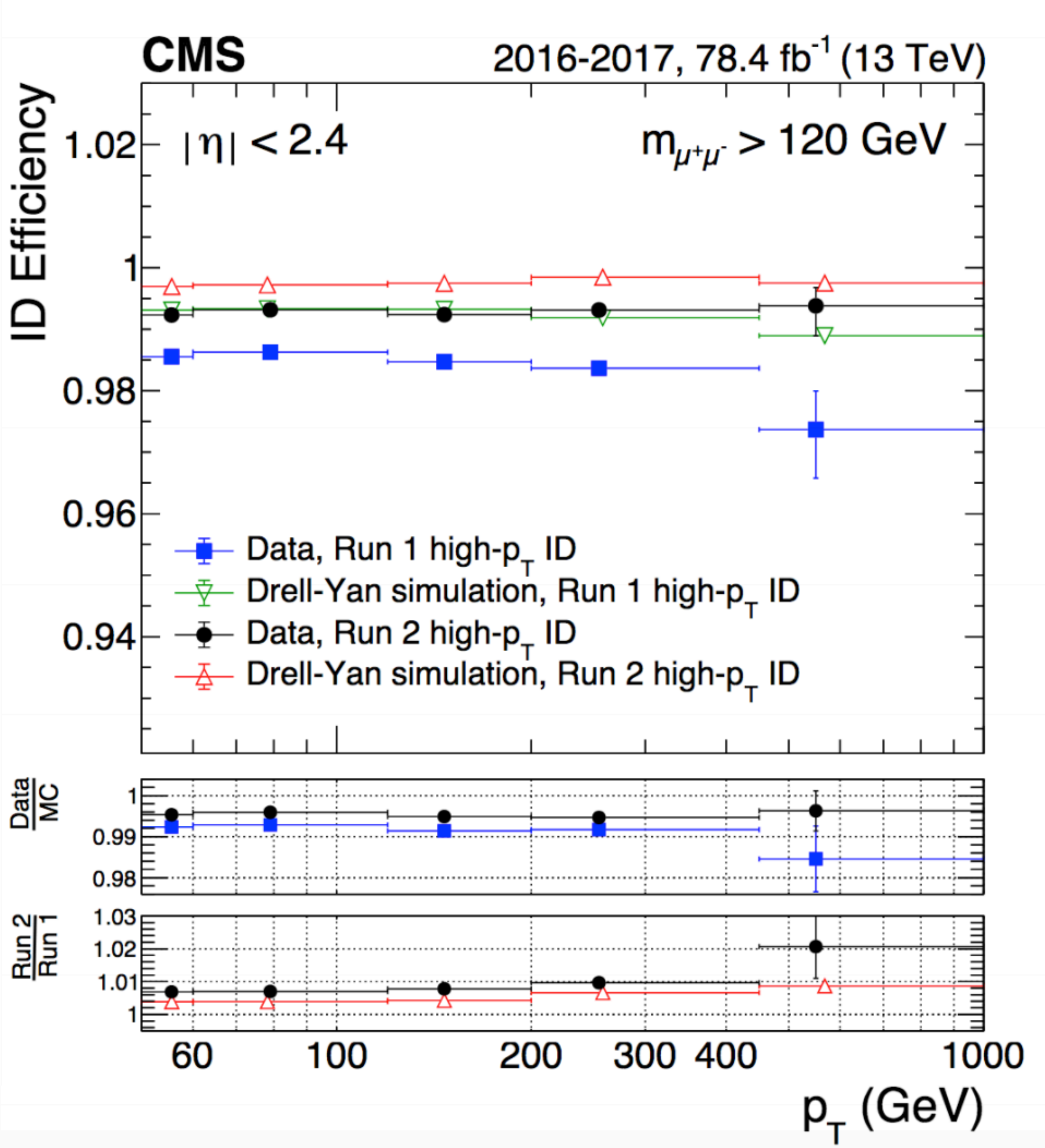


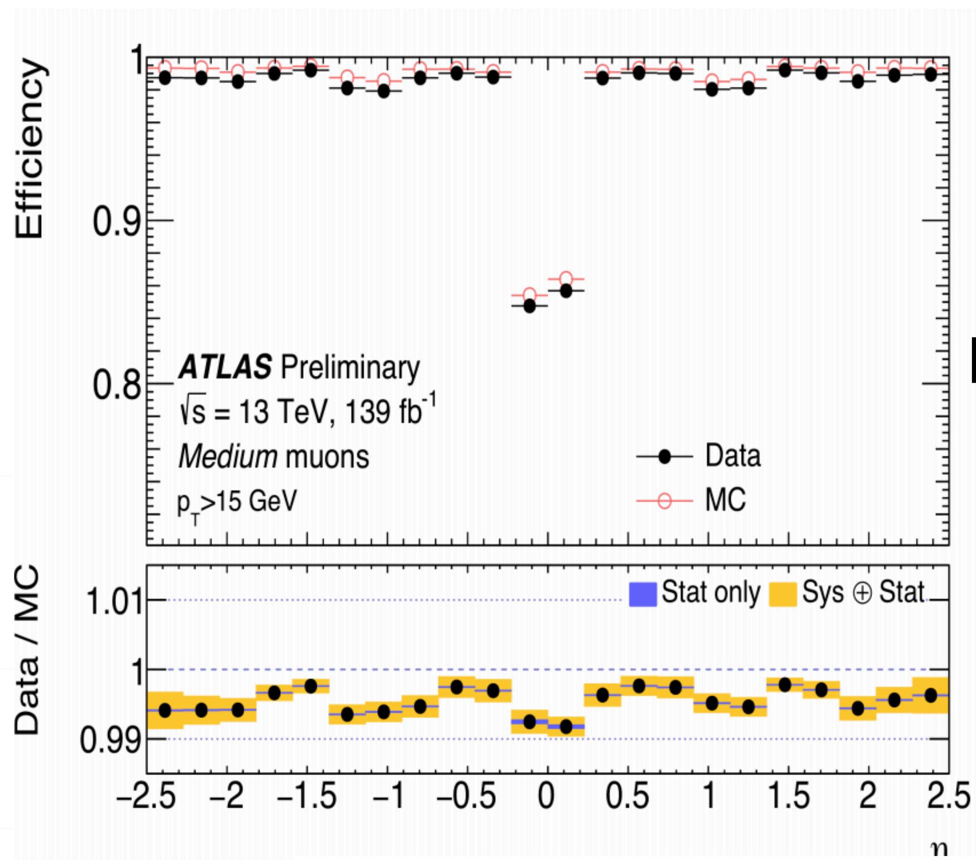


Electrons identification with $Z \to e^+e^-$ and $J/\psi \to e^+e^-$

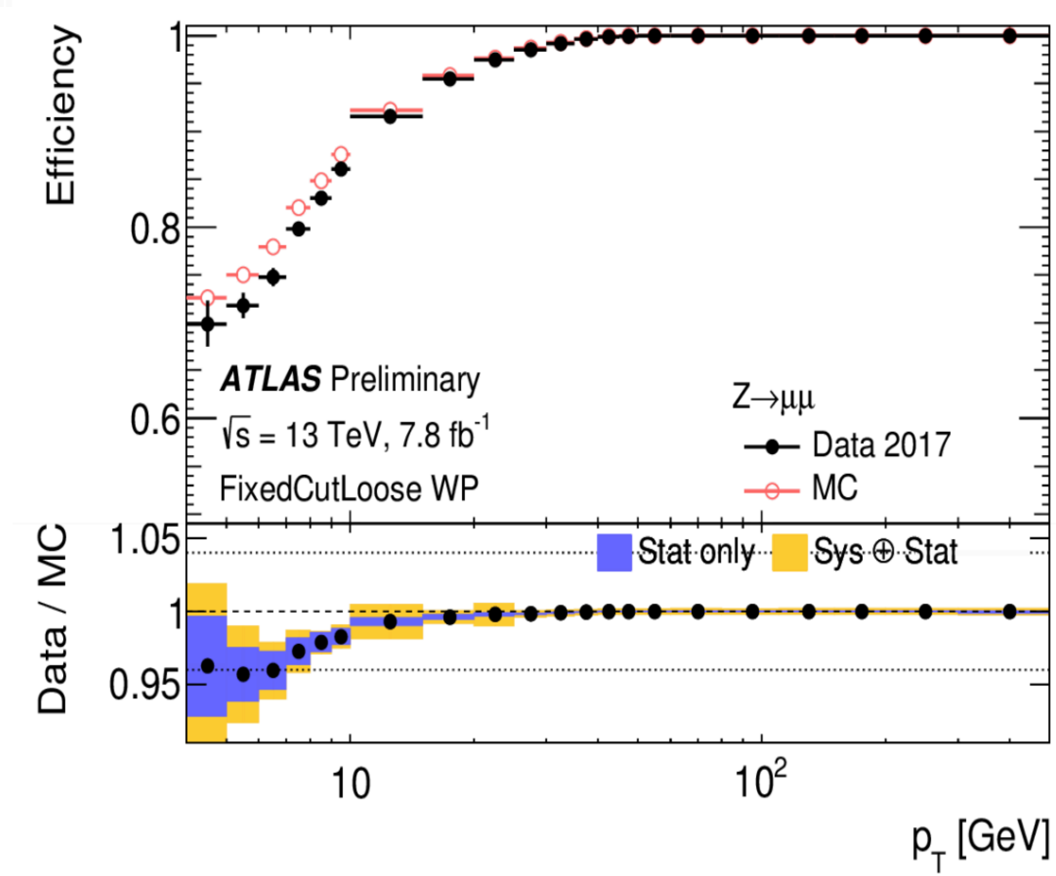
both ATLAS and CMS achieve sub-% precision

How all of this is possible





Muons Reconstruction and Isolation efficiency

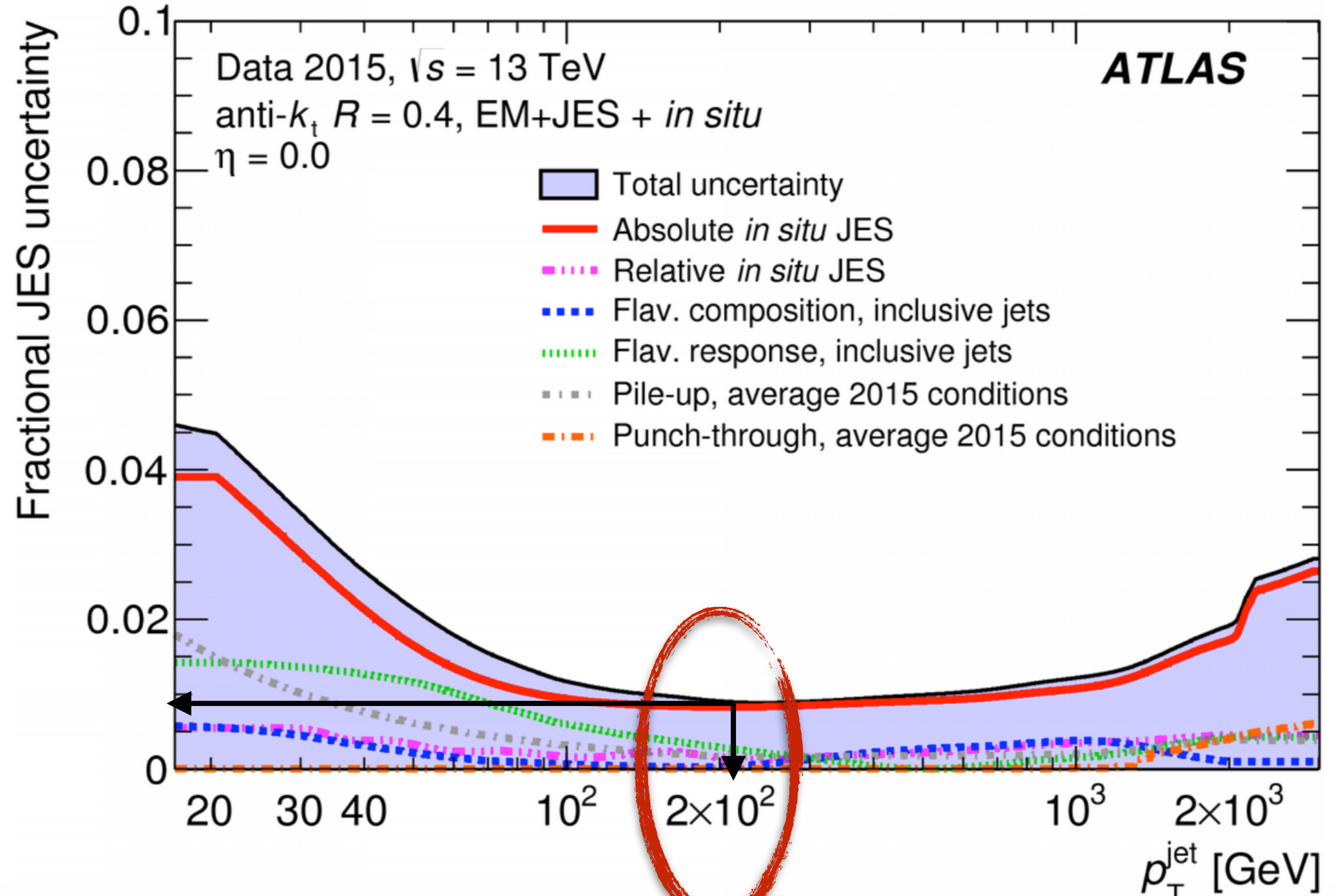


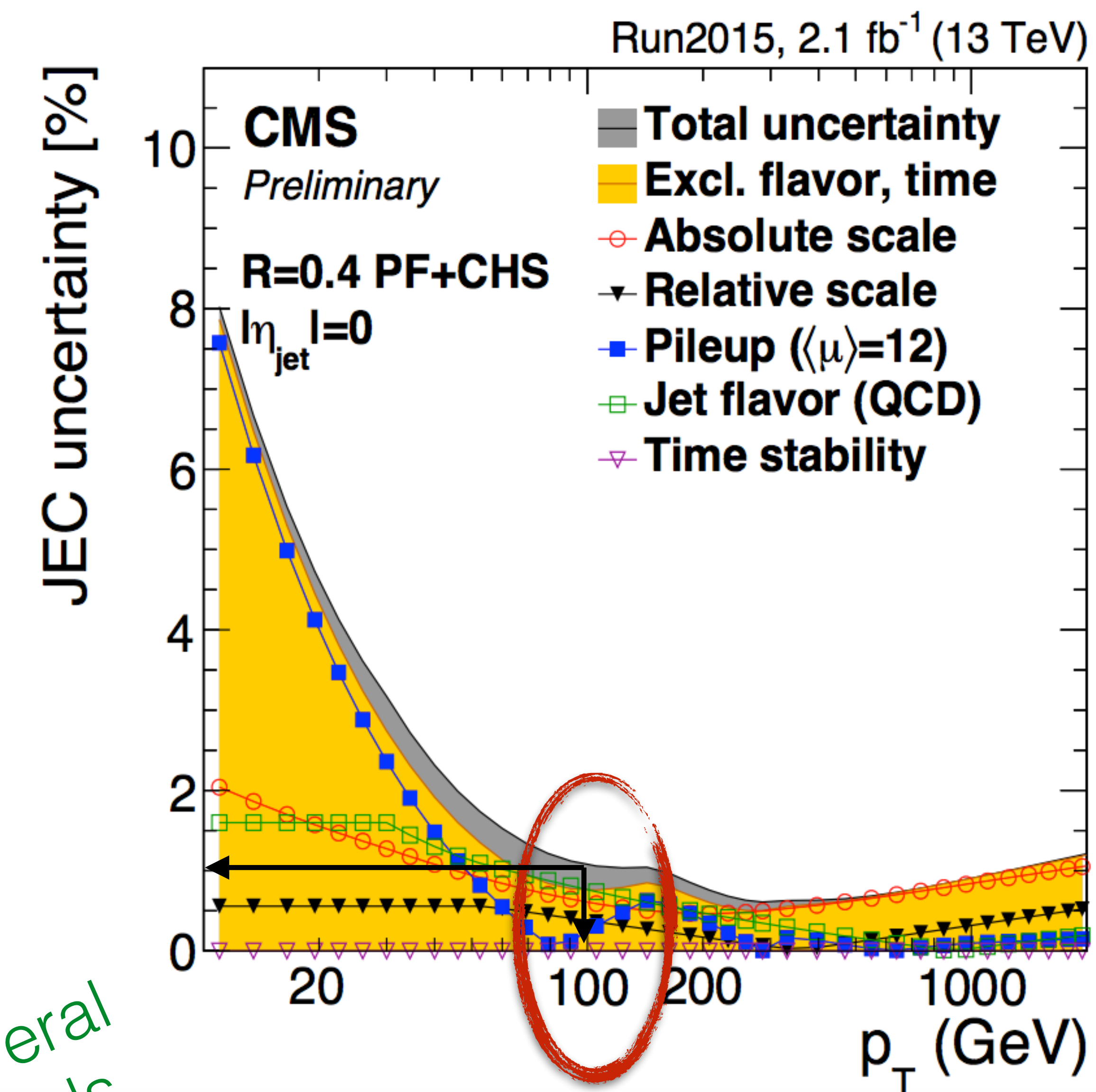
Muons identification with $Z \to e^+e^-$ up to 1 TeV

Outstanding precision

How all of this is possible

ATLAS ← both deliver jet energy corrections → **CMS**





<u>Correct for</u>

- Pile-Up
- Jet Flavor Composition
- Absolute/Relative Scale

thanks to several in-situ methods

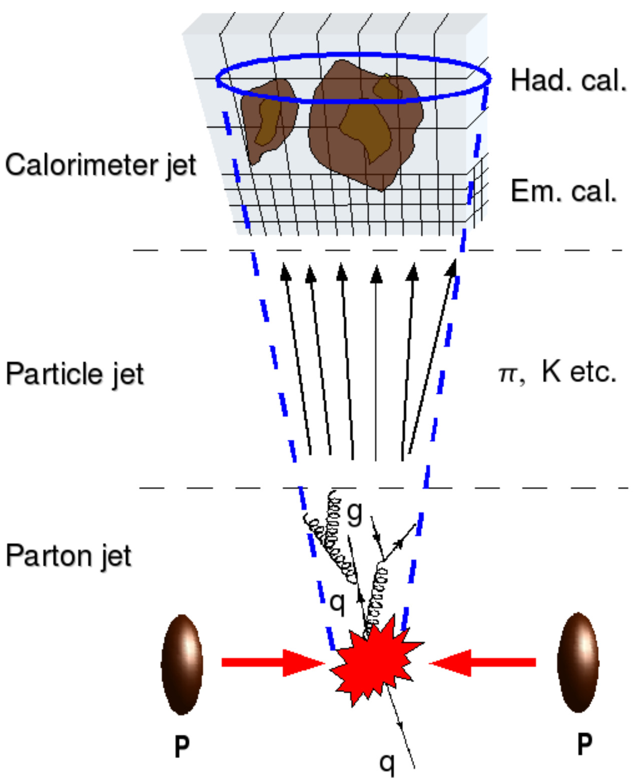
Less than 2% in the region p_T > 100 GeV!

LHCb: ~10-15% for p_T of 10–100 GeV

Jet Reconstruction: Strategy

ATLAS

topological calorimeter-cell **clusters**



anti-k$_T$ clustering algorithm
(infrared and collinear safe)

ATLAS/CMS: R=0.4 (Run II)

LHCb: R=0.5

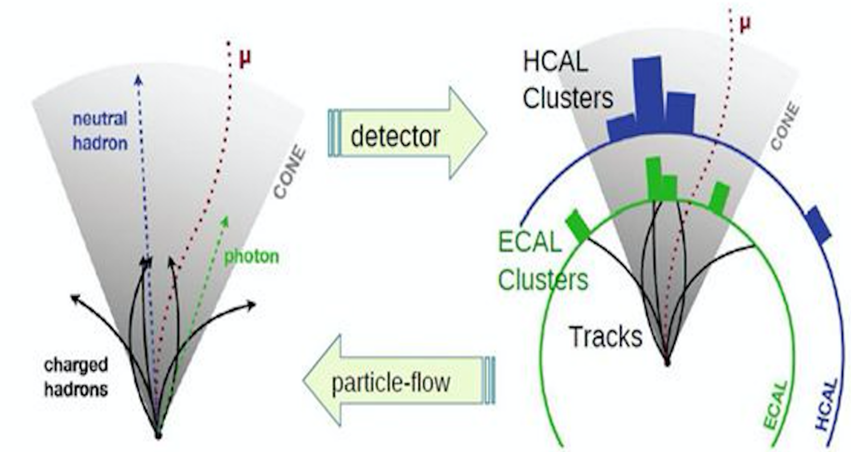
$$d_{ij} = \min(k_{ti}^{2p}, k_{tj}^{2p}) \frac{\Delta_{ij}^2}{R^2}$$

$$d_{iB} = k_{ti}^{2p},$$

← → ↓

CMS

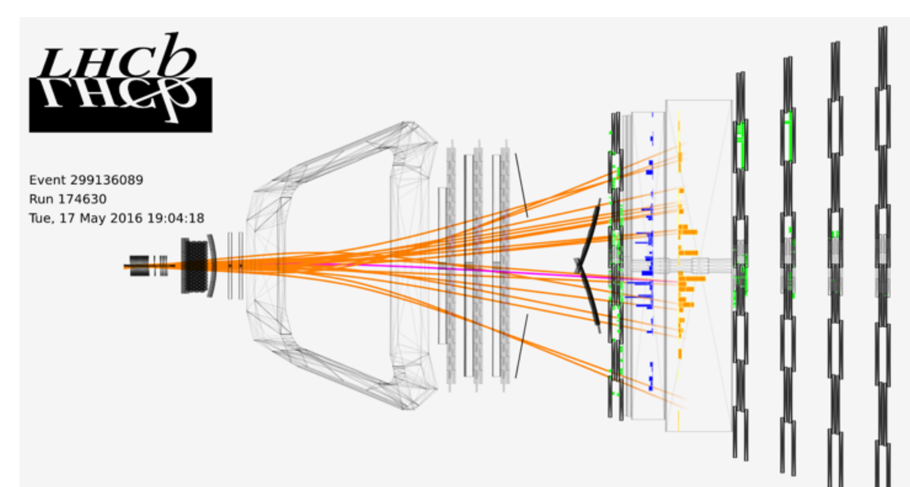
particle-flow



uses all the sub-detectors information to reconstruct objects

LHCb

$(2 < \eta < 5)$



LHCb acceptance forward direction

Particle Flow

calo cell E$_T$~10 GeV saturation

↓

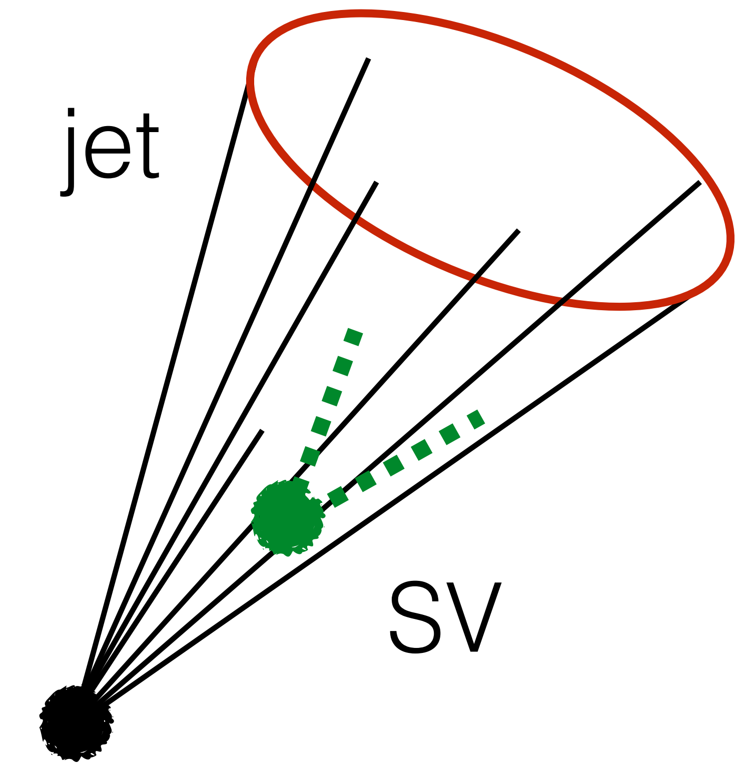
use the precise tracking information → use particles! (Λ,Ks,π,..)

Heavy flavor tagging at collider

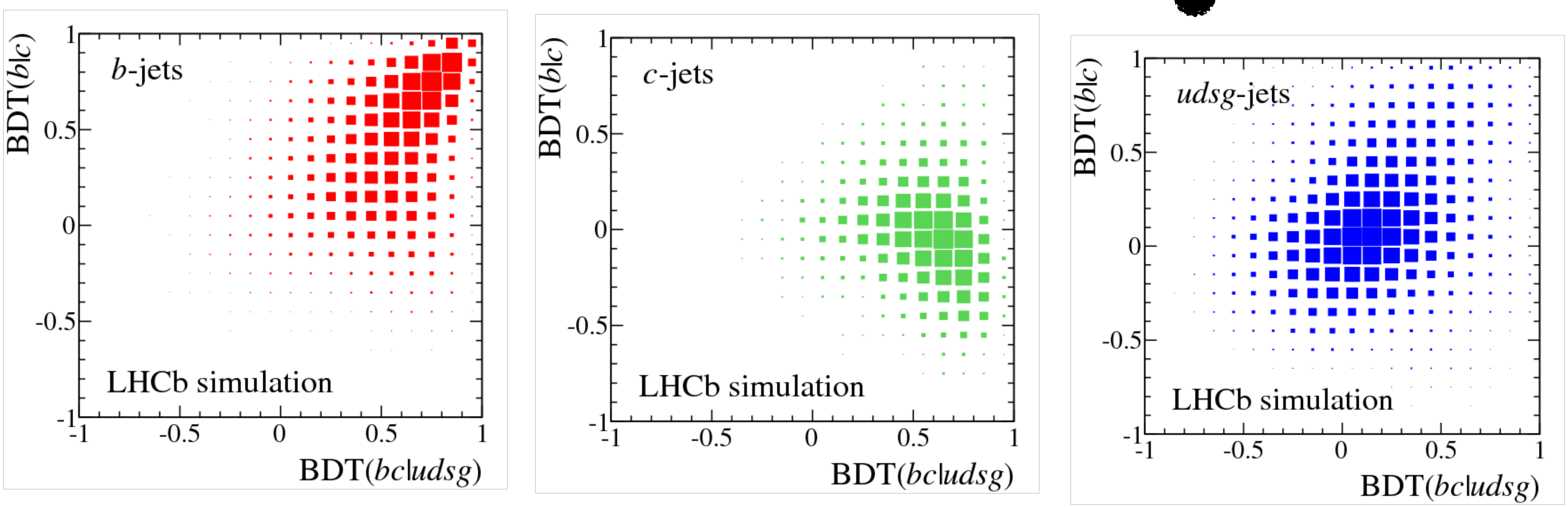
recipe

JINST 10 (2015) P06013

- reconstruct jets with the anti-kT05 algorithm
- tagging using b- and c- inclusive tagger
- reconstruct the two-body vertices in the event
- merge SV n-body by linking tracks and vertices associated
- associate vertices/jets requiring ΔR(SV, jet) < 0.5



BDT trained on SV/j properties to separate **heavy**/**light**



light-jet mistag rate < 1% for b-tag efficiency of 65% and c-tag efficiency of 25%

Heavy flavor tagging at collider

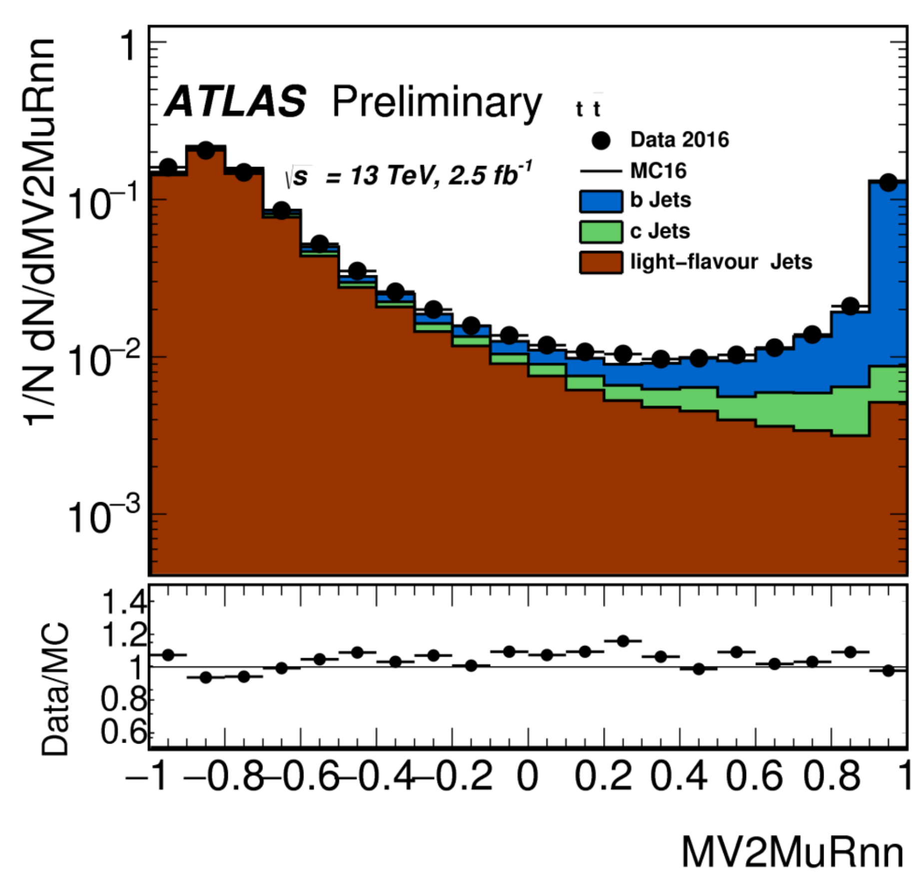
ATL-PHYS-PUB-2017-013
ATLAS-FTAG-2017-003

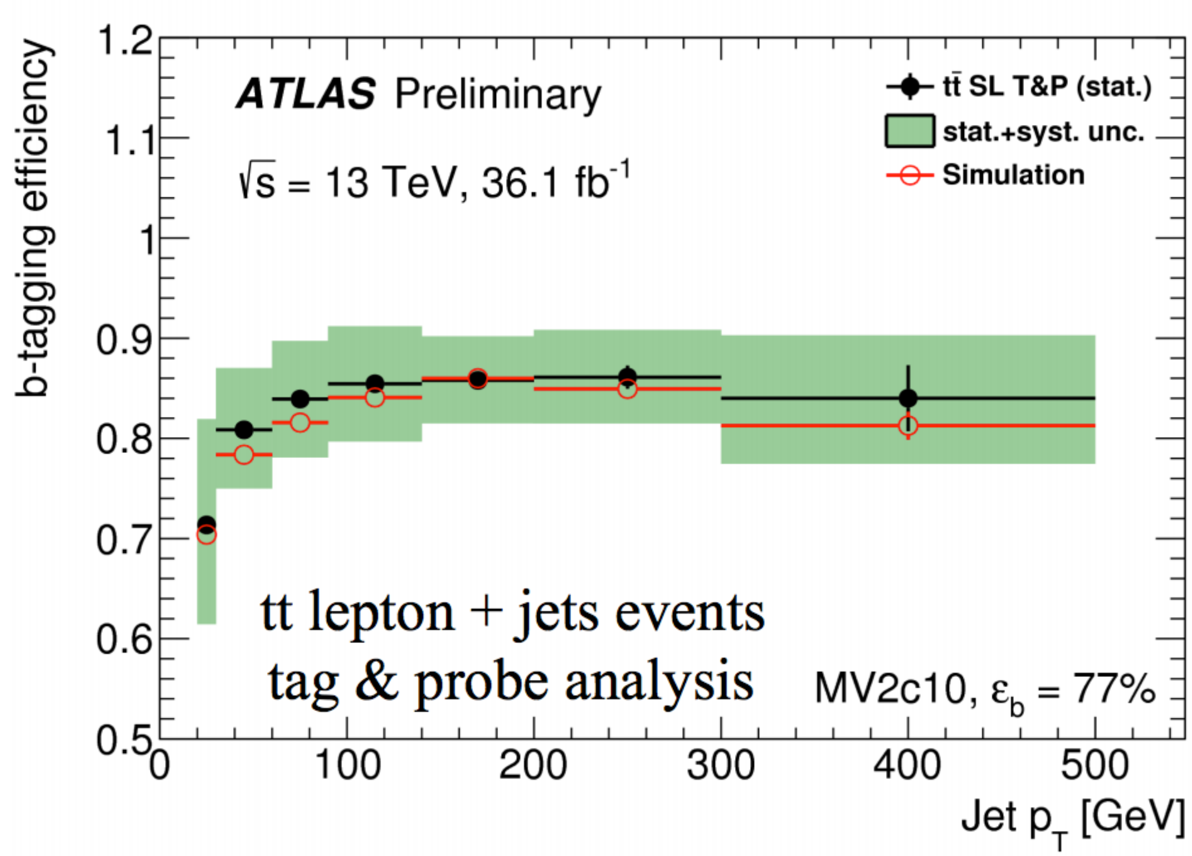
- several taggers:
  - track based (impact parameter tag)
  - soft muon (discriminate μ from b decays)
  - vertex based
- high-level taggers: MVA using all the information available to maximize the b-tag performance

→ BDT — trained on top + Z'bb events (*hybrid training*)

→ Deep Learning Neural Network

combine inputs from track, particle and vertex-based physics taggers using multivariate classifier





b-tag efficiency of 77% and c-tag efficiency of 25%

mistag rate of light flavored jets using dijet events with negative tag

< 2% under pT = 1 TeV

Heavy flavor tagging at collider

CERN-CMS-DP-2017-005

CMS-PAS-BTV-15-001

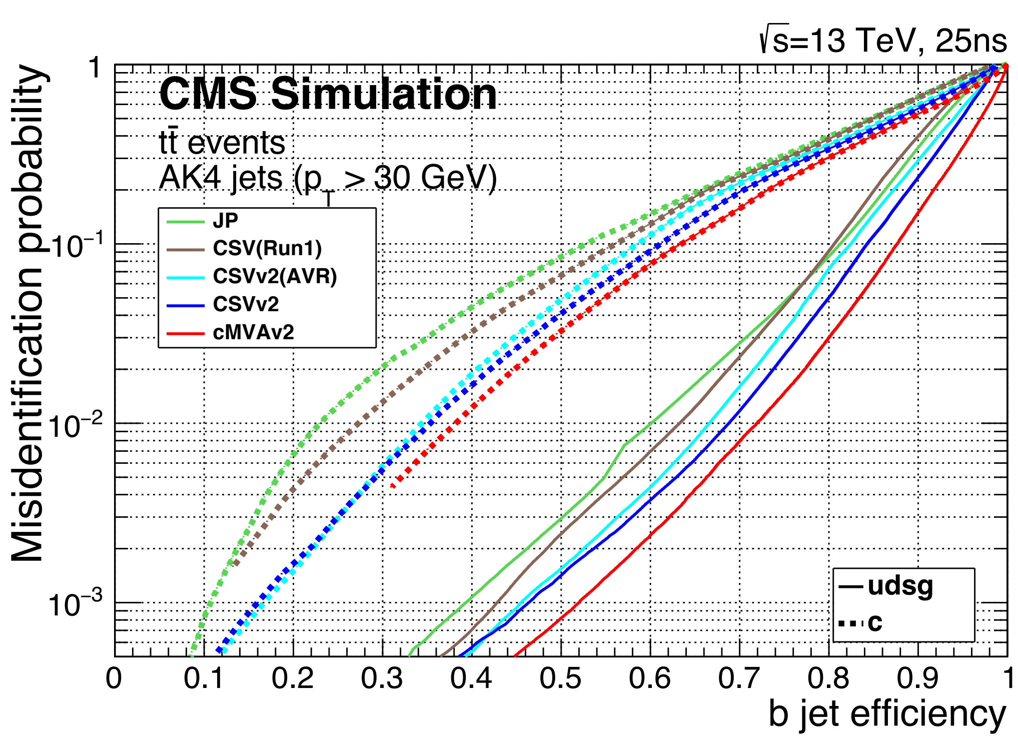
- several taggers:
  - Jet Probability: likelihood that jets is coming from primary vertex using tracks
  - Combined (CSV): combination of displaced tracks with SV info associated to the jet using an MVA
  - **CSVv2** evolution of CSV using neural networks

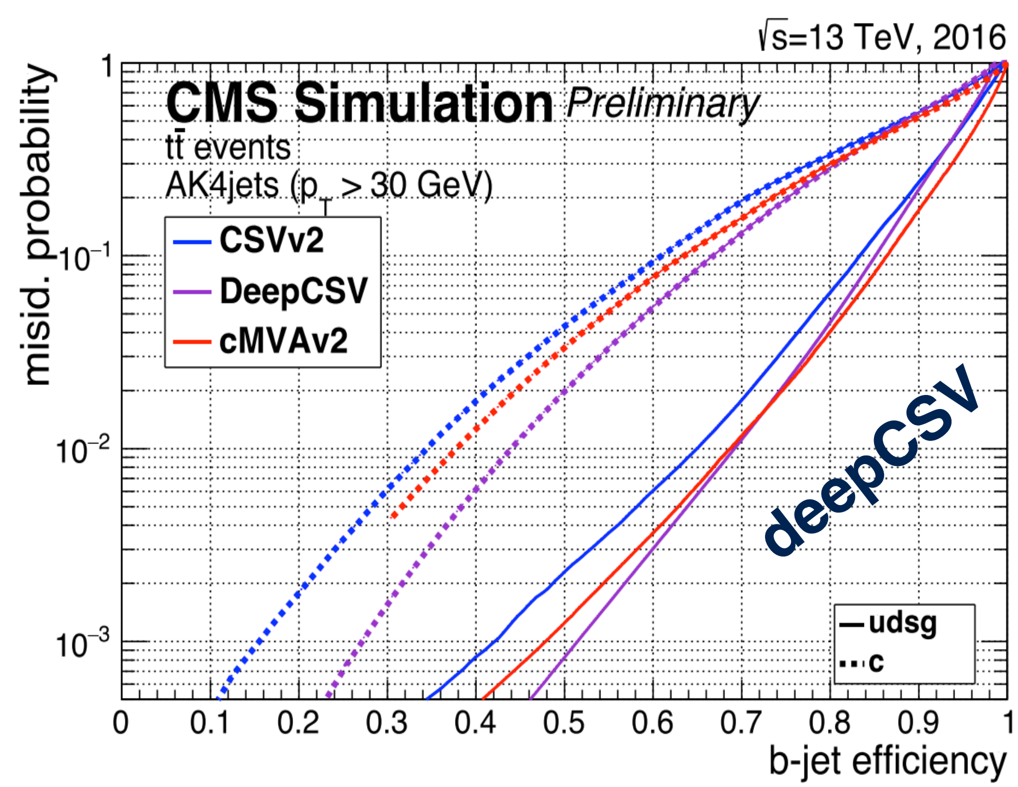
    cMVAv2 combines all the taggers

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

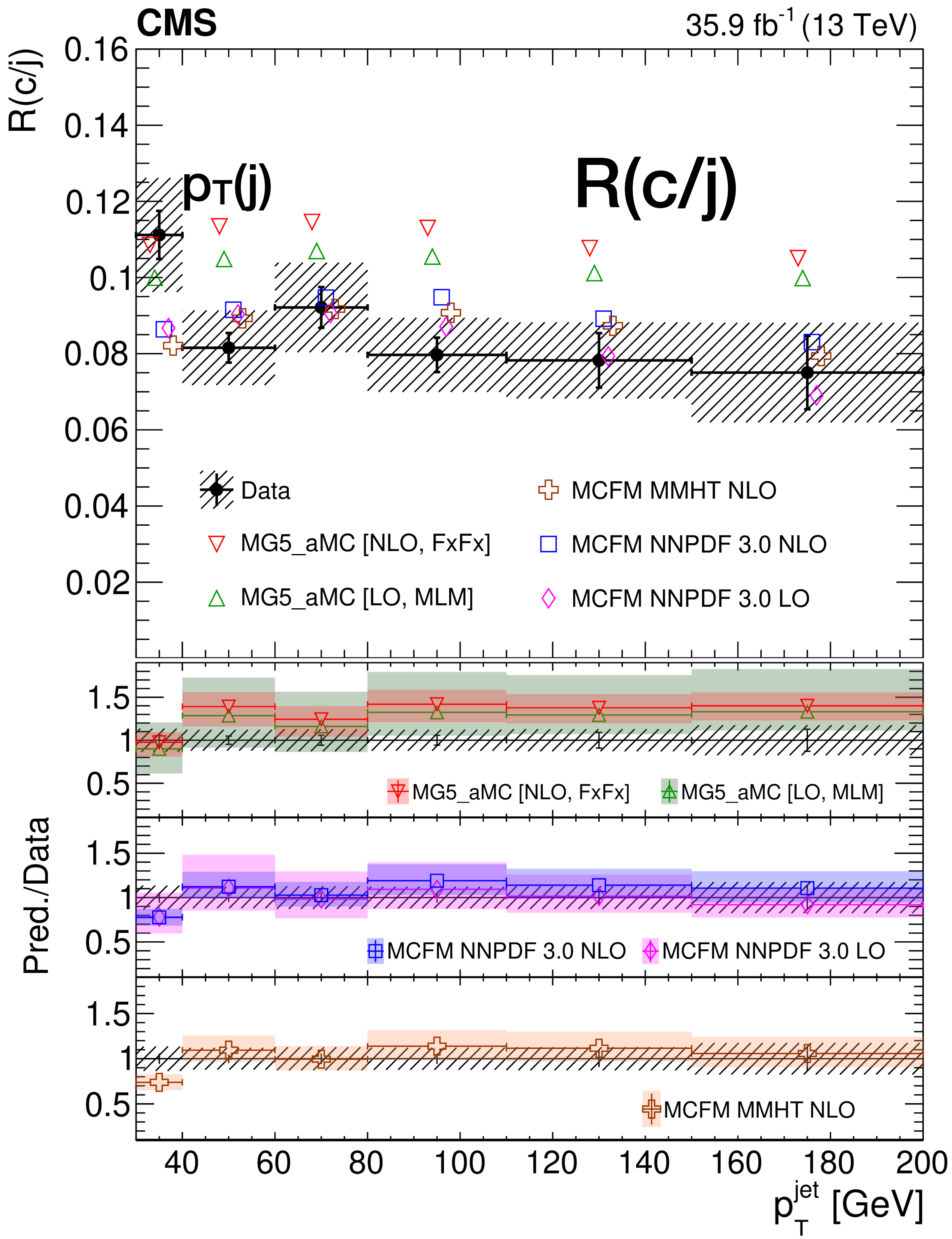
- **deepCSV**: based on CSVv2

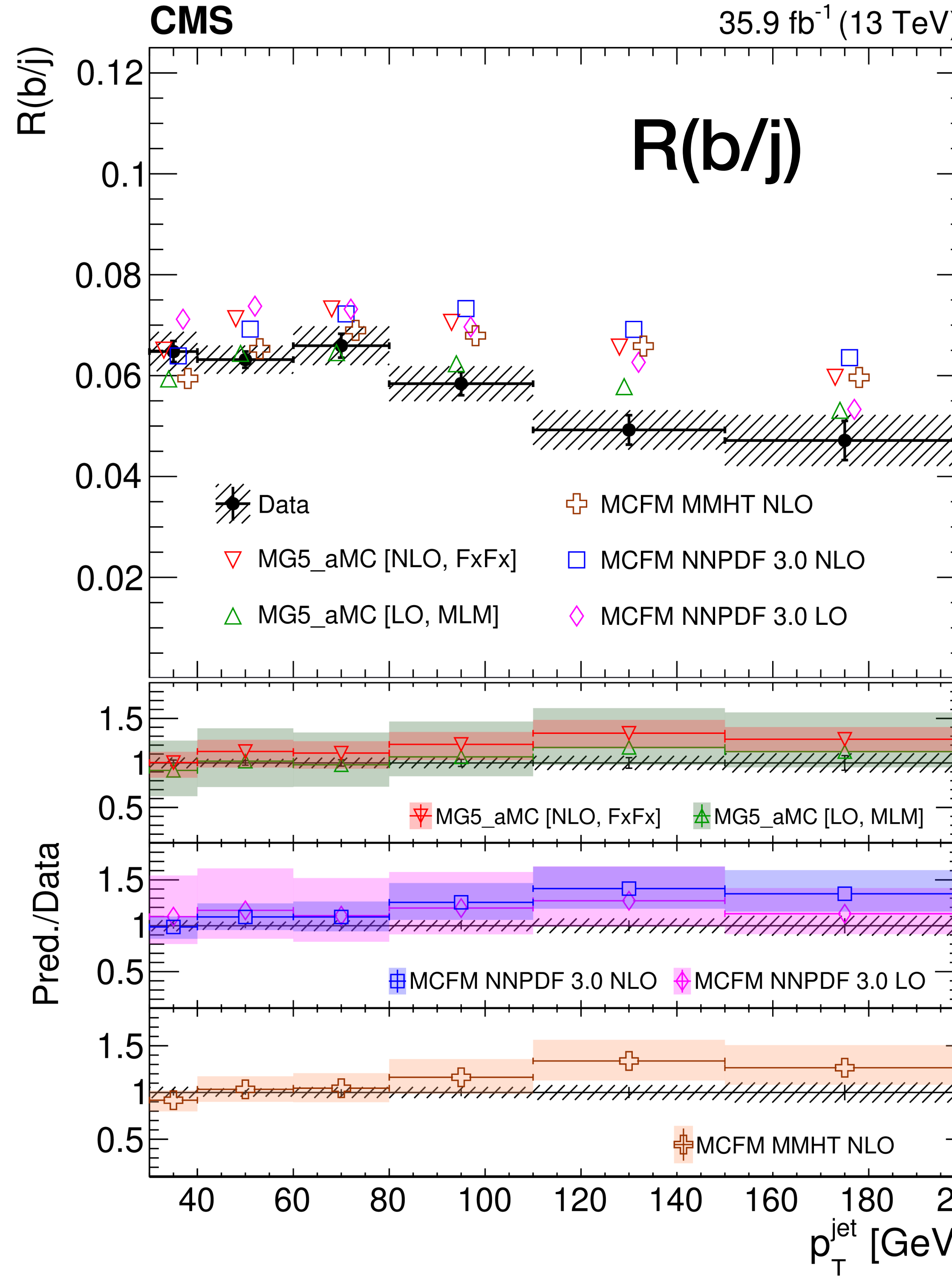
  + more charged particles, based on deep NN





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

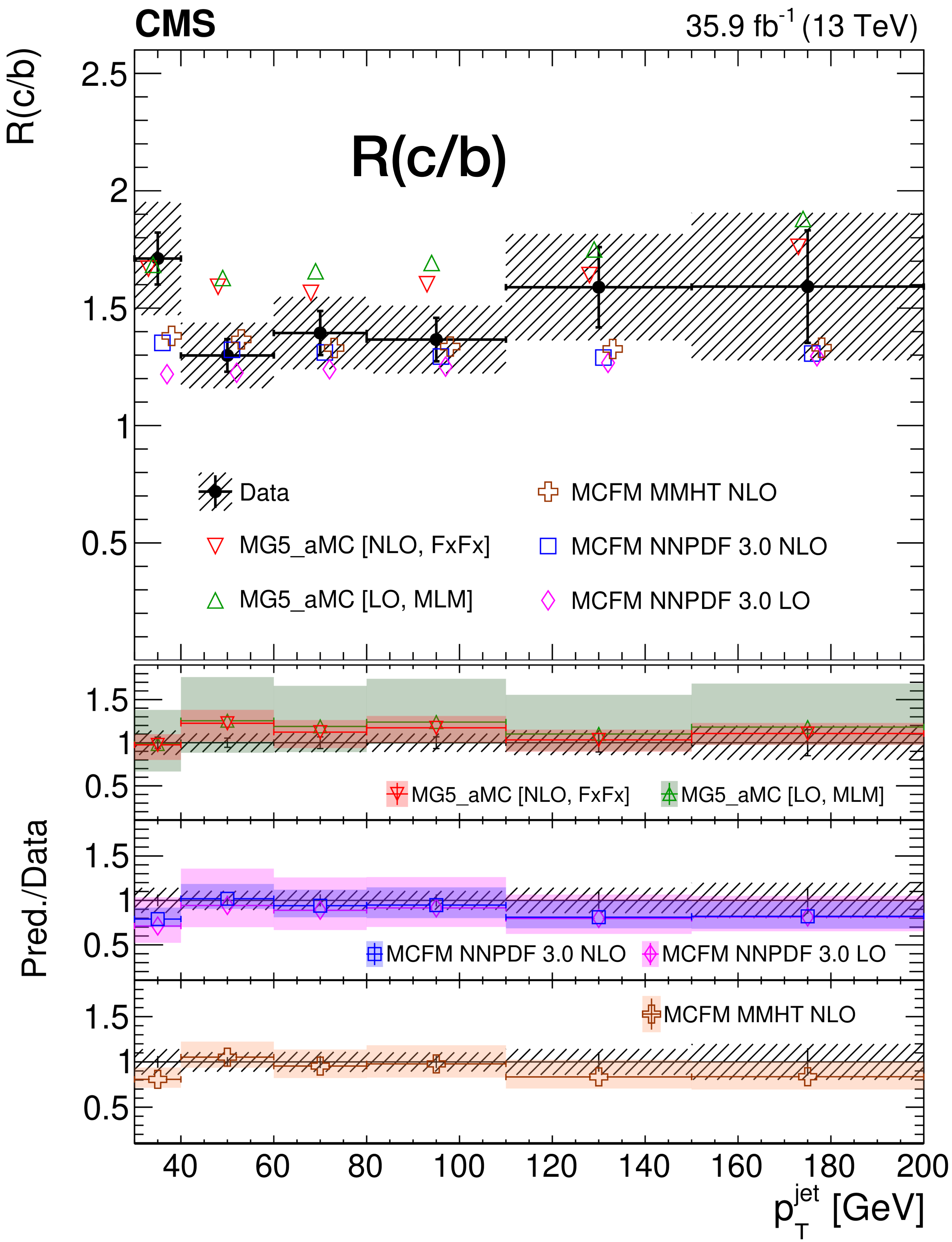




NLO MG5_aMC (NNPDF) and LO MG5_aMC (NNPDF) predictions **higher but compatible with data** in most bins

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

LO MCFM, NLO MCFM (NNPDF), NLO MCFM (MMHT): predictions **compatible** with data



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RESUM
REF

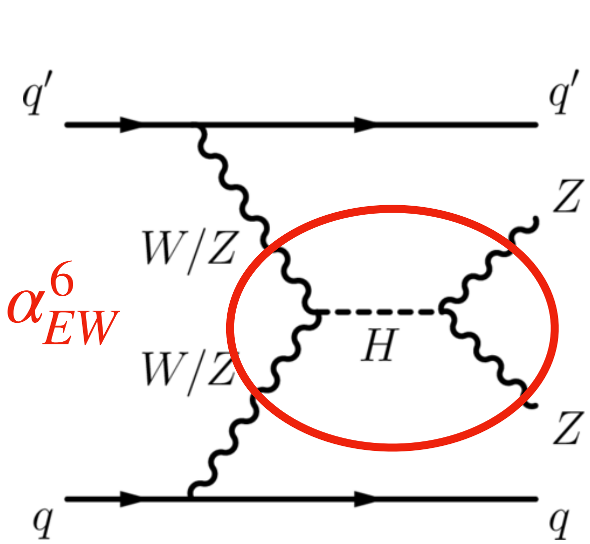
ATLAS @ 13 TeV
CMS @ 13 TeV
~140 fb^{-1}

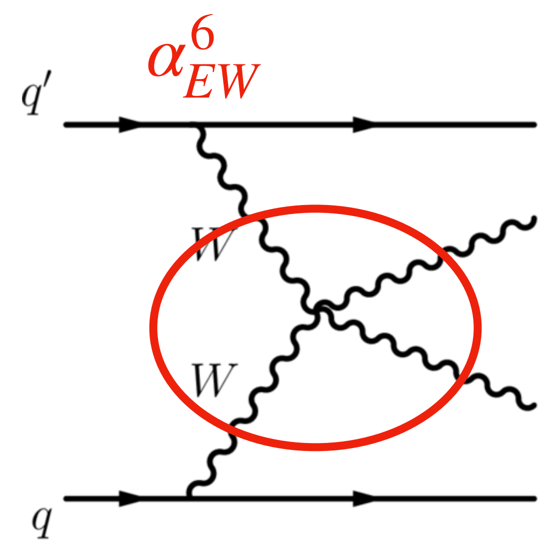
Electroweak ZZ+JJ

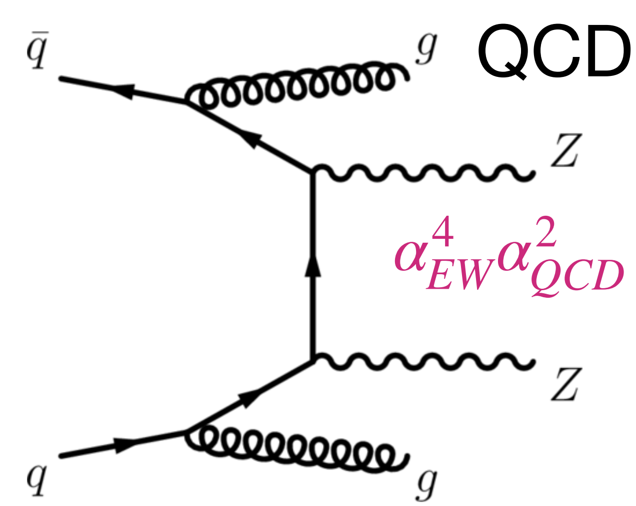
new!

arXiv:2004.10612
arXiv:2008.07013
submitted to PLB
submitted to Nature Physics

first observation





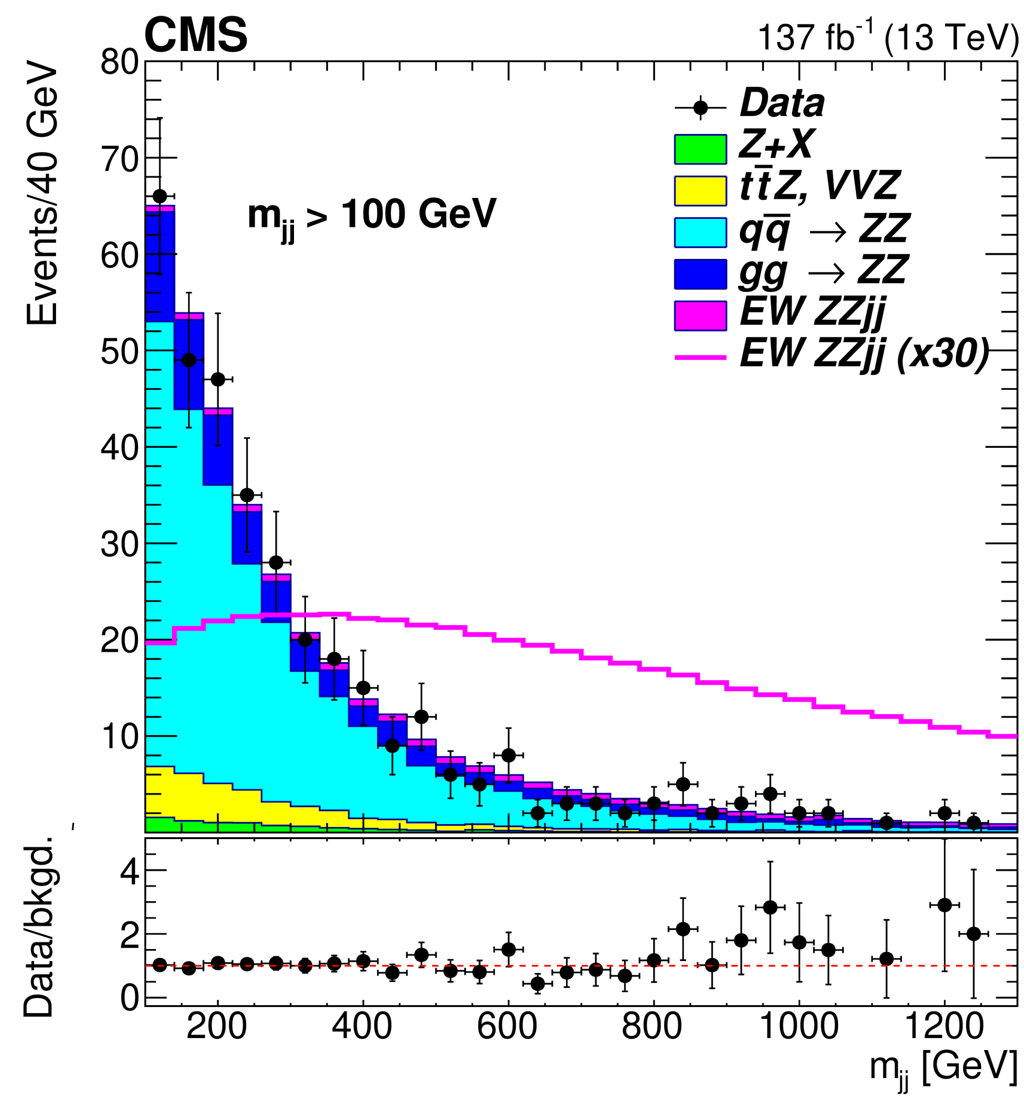


accessing the nature of electroweak symmetry breaking

ZZ+JJ is a rare process: α_{EW}^6 - important test of the SM

testing anomalous quartic gauge couplings also possible

- final state with $4\ell + jj$ (e/μ)
- VBS sub-region with $\Delta\eta, m_{jj}$ cuts
- MVA/MELA to discriminate EW signal
- SM prediction: $\sigma = 1.14 \pm 0.021$ fb



ATLAS @ 13 TeV

Z plus b quarks @ 13 TeV

new!

✦ **8 Theoretical predictions:**

compared with unfolded cross-section results and normalised to their own cross-section

- **LO vs NLO**
- **4FNS vs 5FNS**

Generator	$N_{\text{max}}^{\text{partons}}$ NLO	$N_{\text{max}}^{\text{partons}}$ LO	FNS	PDF set	Parton Shower
		Z+jets (including $Z+b$ and $Z+bb$)			
SHERPA 5FNS (NLO)	2	4	5	NNPDF3.0nnlo	SHERPA
SHERPA FUSING 4FNS+5FNS (NLO)	2	3	5 (*)	NNPDF3.0nnlo	SHERPA
ALPGEN + PY6 4FNS (LO)	-	5	4	CTEQ6L1	PYTHIA v6.426
ALPGEN + PY6 (rew. NNPDF3.0lo)	-	5	4	NNPDF3.0lo	PYTHIA v6.426
MGAMC + PY8 5FNS (LO)	-	4	5	NNPDF3.0nlo	PYTHIA v8.186
MGAMC + PY8 5FNS (NLO)	1	-	5	NNPDF3.0nnlo	PYTHIA v8.186
		$Z+bb$			
SHERPA ZBB 4FNS (NLO)	2	-	4	NNPDF3.0nnlo	SHERPA
MGAMC + PY8 ZBB 4FNS (NLO)	2	-	4	NNPDF3.0nnlo	PYTHIA v8.186

SHERPA FUSING with mixed approach for 4FNS+5FNS

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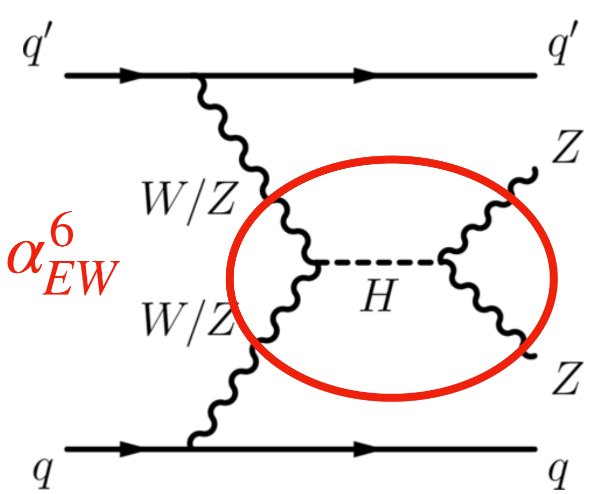
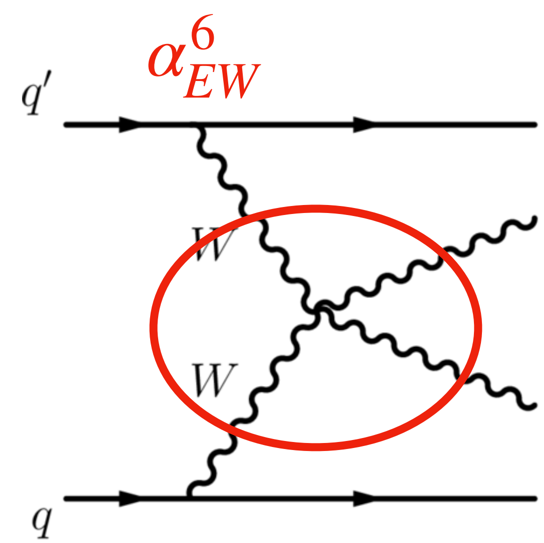
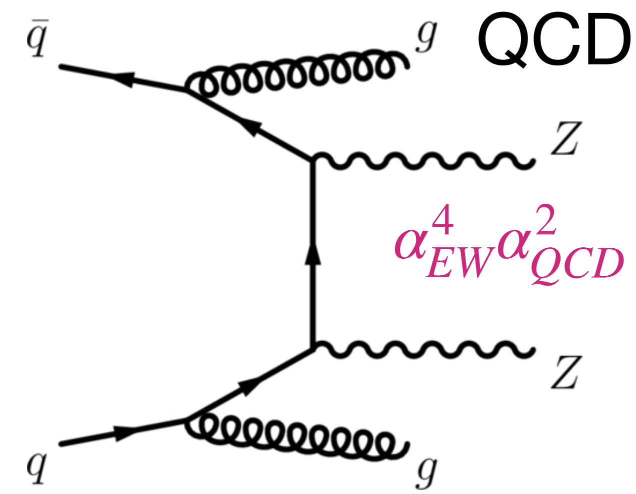




QCD-induced



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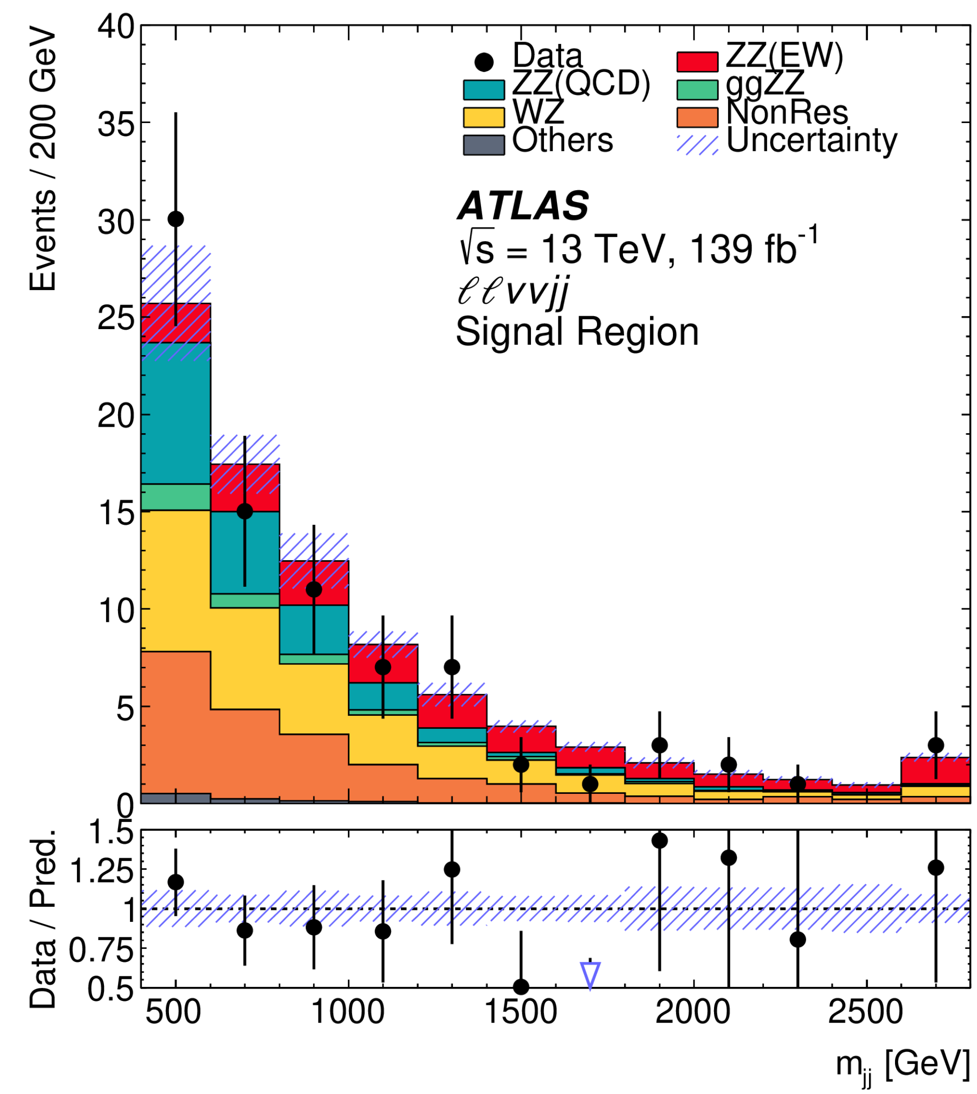


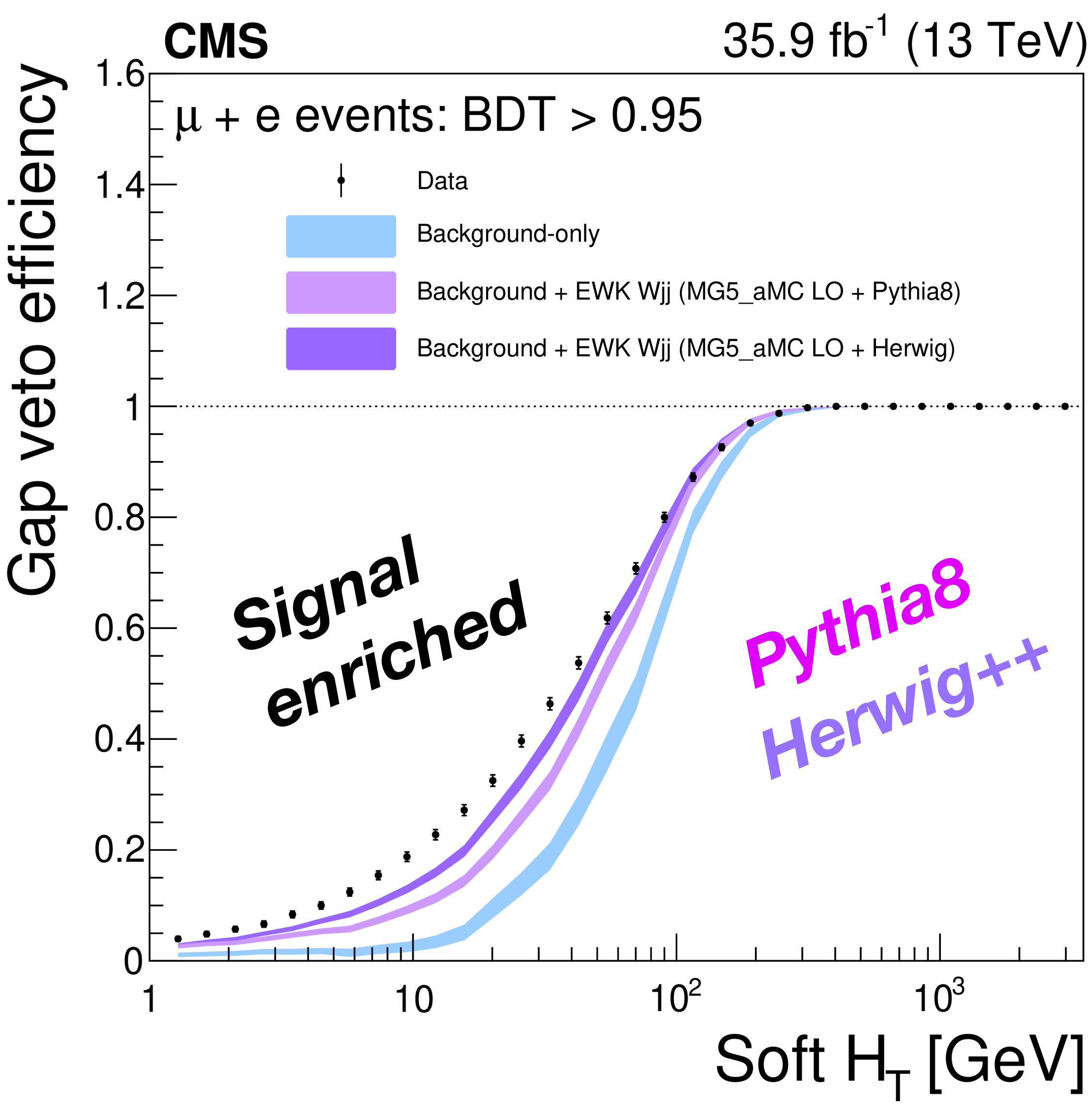
Rapidity Gap in VBF topologies

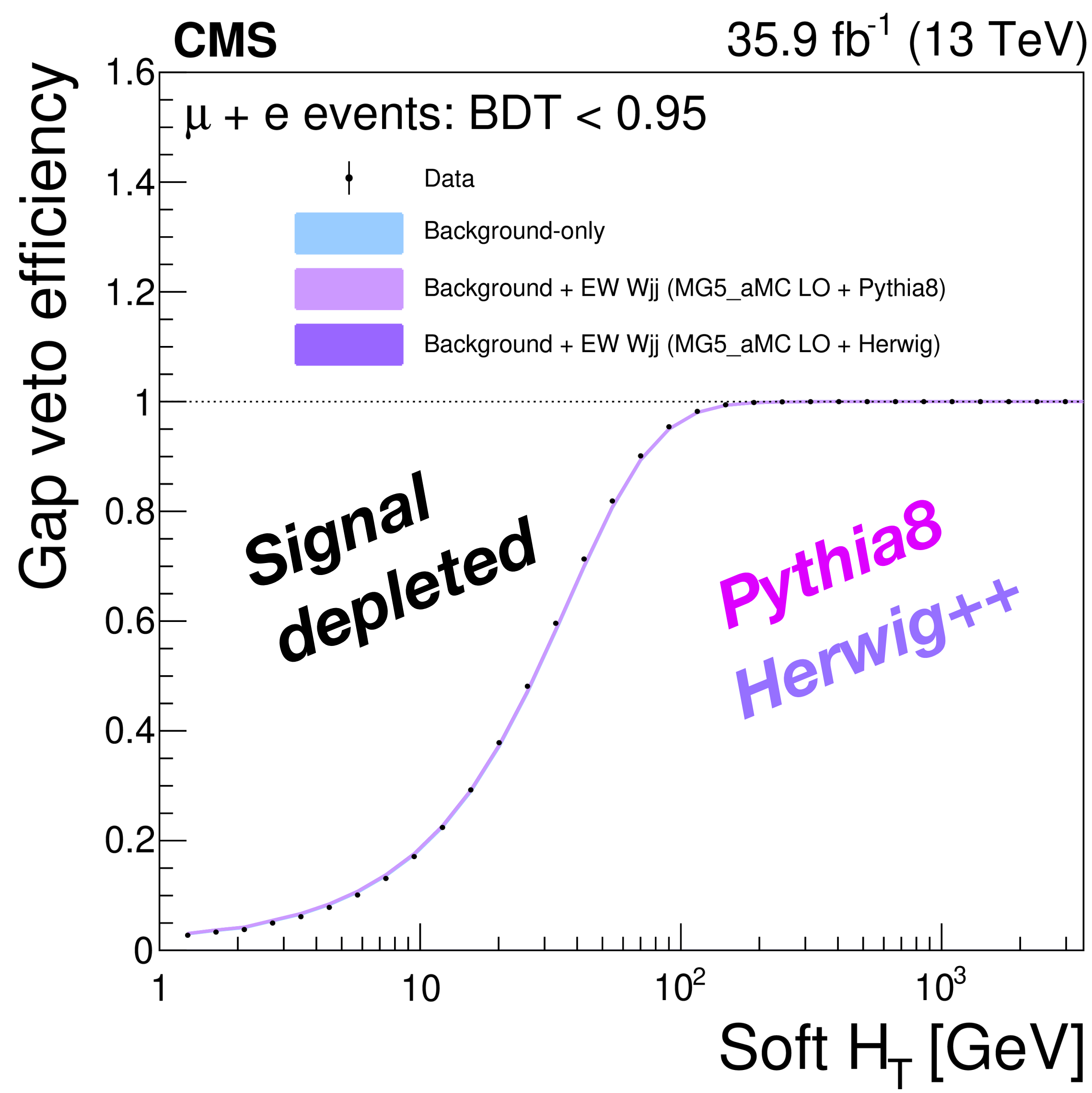
CMS @ 13 TeV

Rapidity Gap

- Low hadronic activity expected in ΔηJJ region due to pure EW nature of interaction
- No color flow between the two tagged highly separated jets

additional jets produced and generated by the Parton Shower (Pythia and Herwig++) → powerful test of the Parton Shower model in Generators





→ Pythia not describing the rapidity gap

→ good agreement

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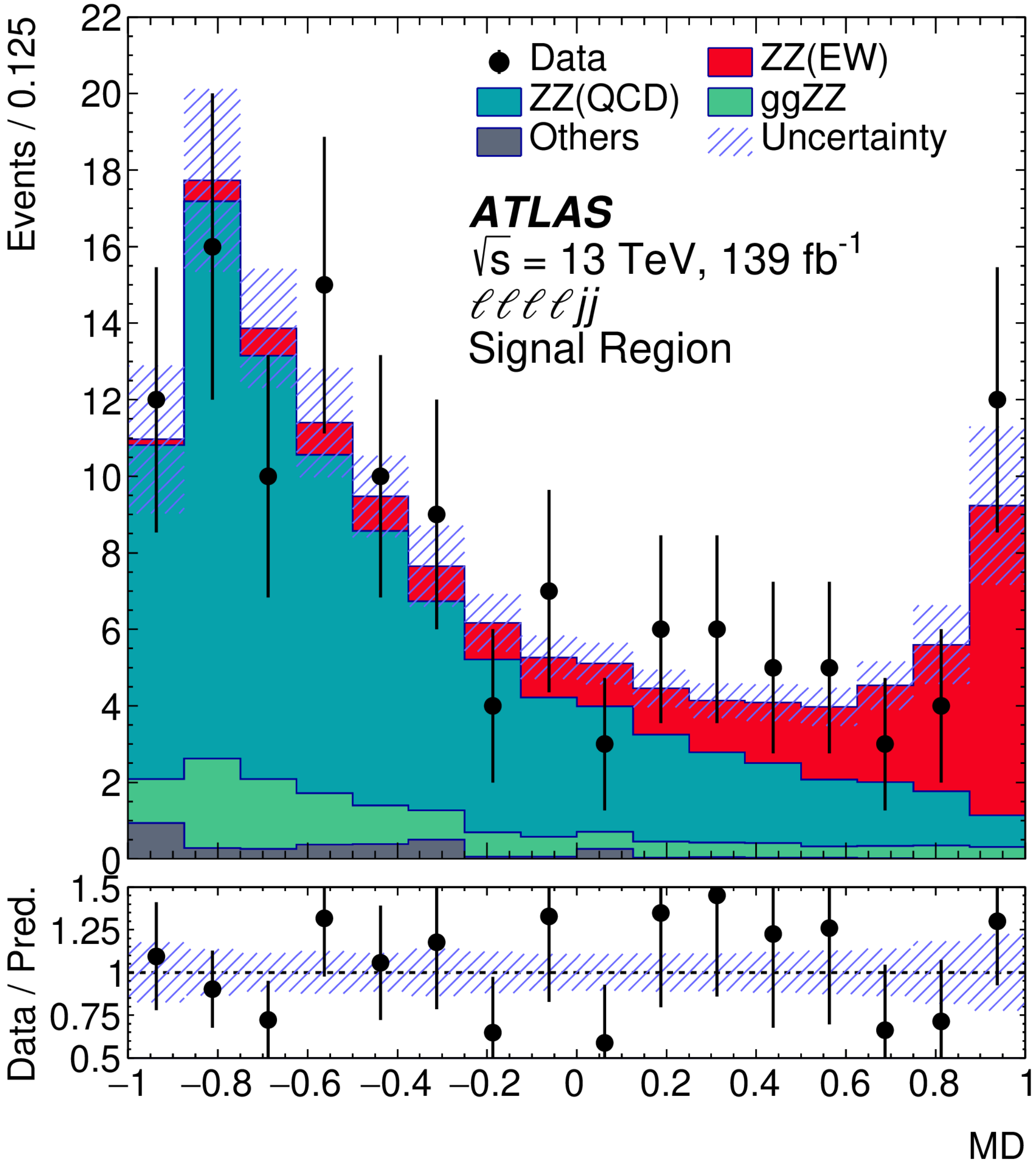

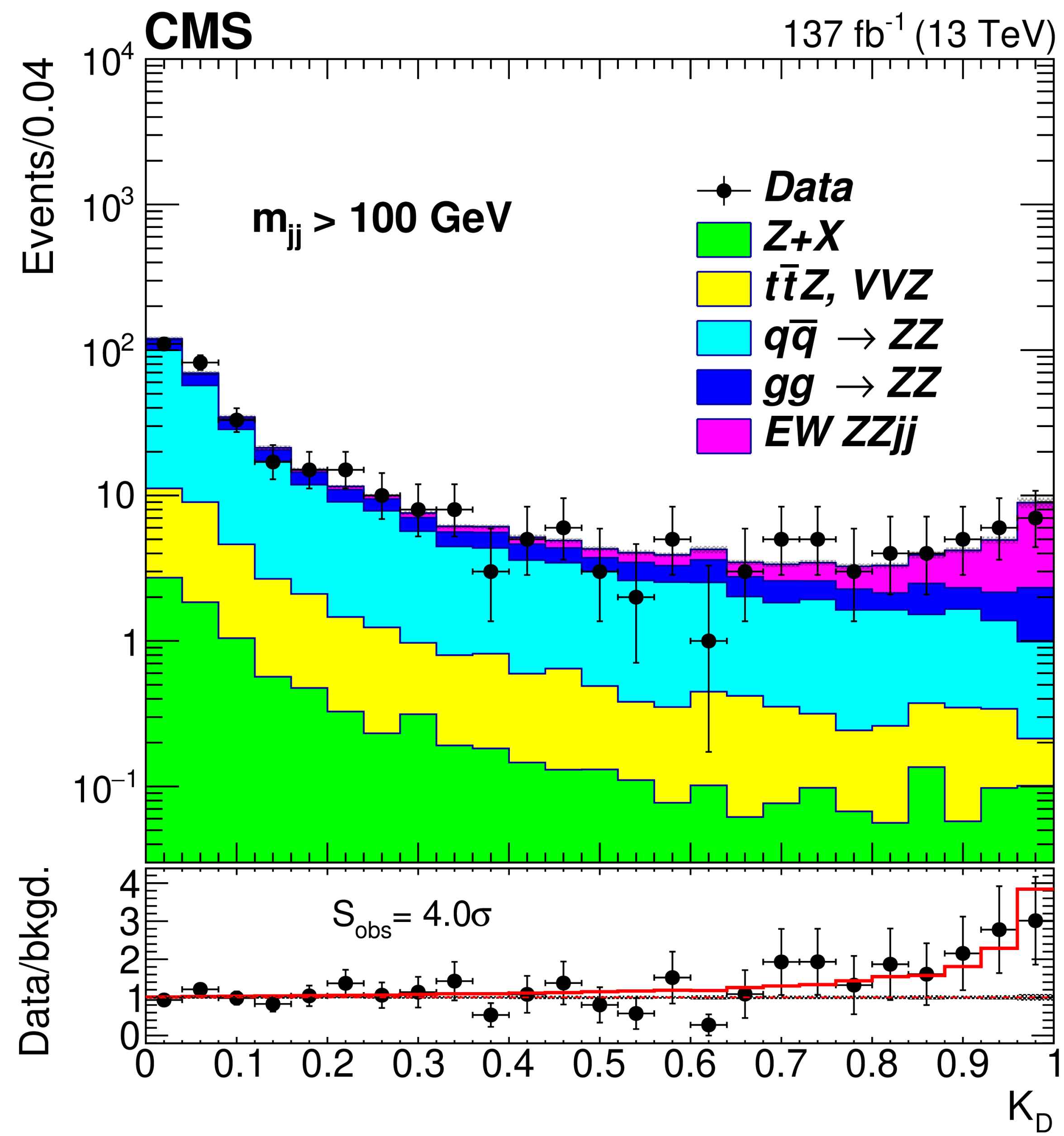

ATLAS: σ obs.(exp) =5.5 (3.9)

CMS: σ obs.(exp) = 4.0 (3.5)