Results on vector bosons production with jets at CMS

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on behalf of the CMS collaboration

Low-x 2021, Isola d'Elba

30/09/2021

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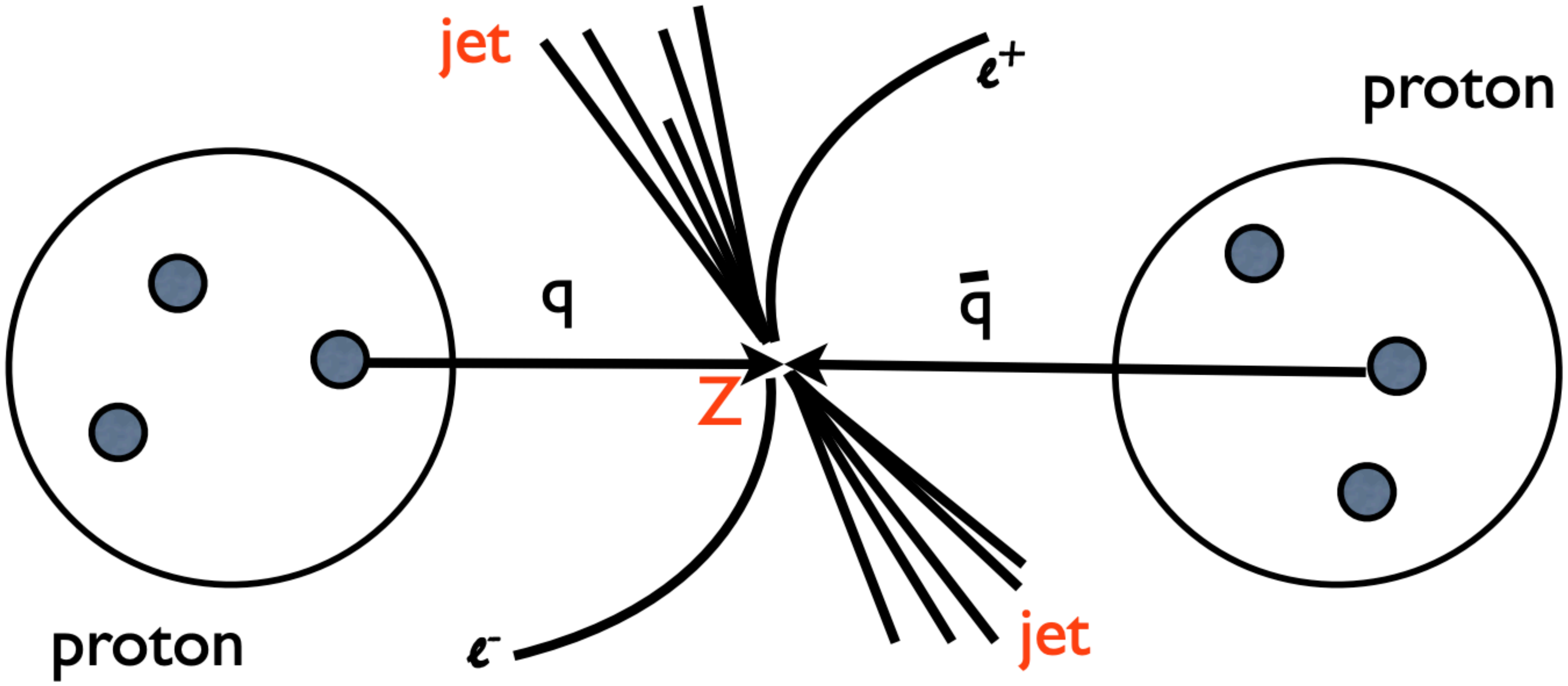
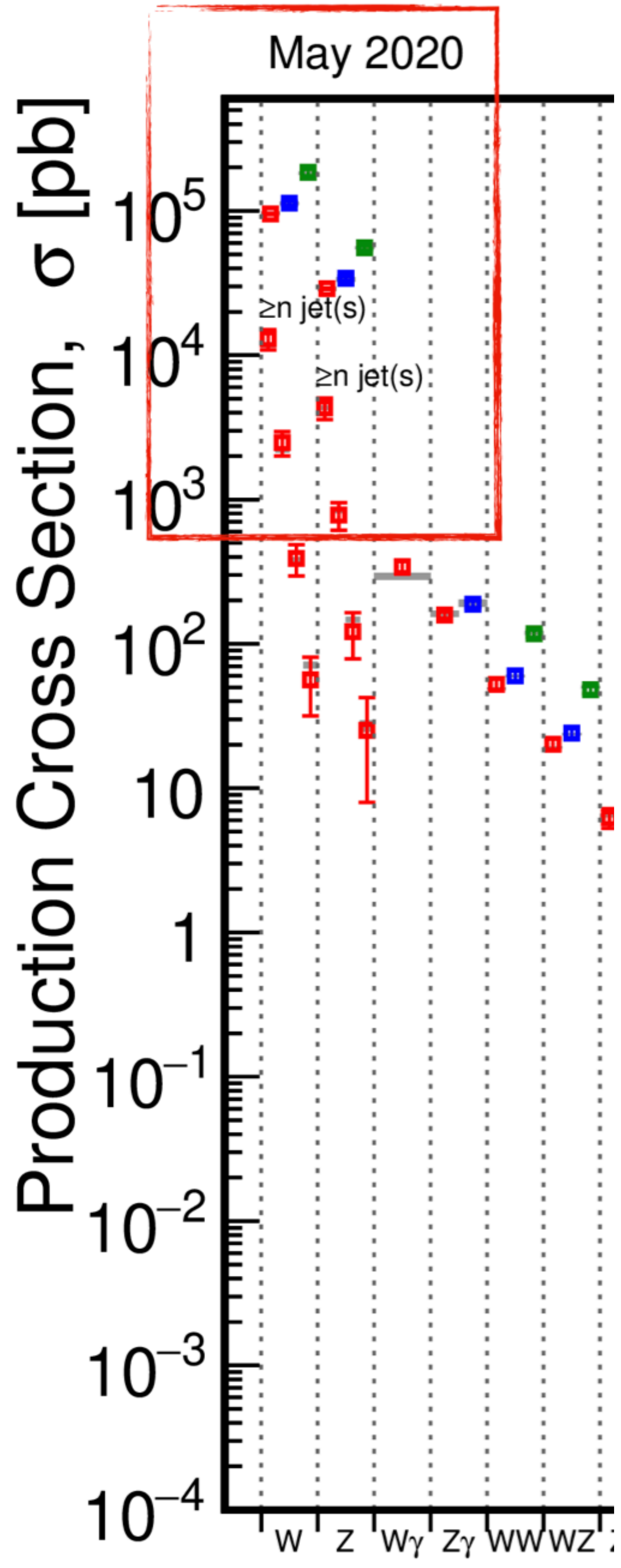
UNIVERSITÀ DEGLI STUDI DI TRIESTE

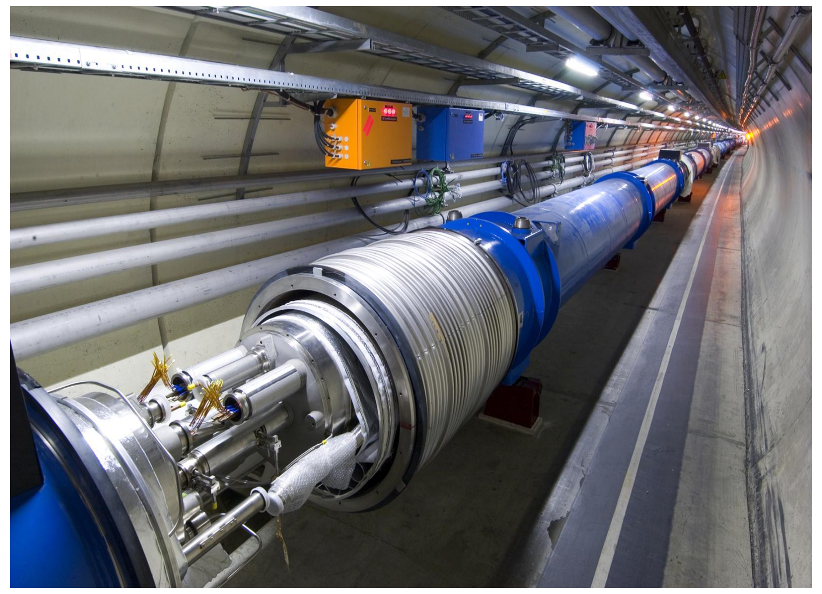
Outline

- V+jets Physics: Phenomenology at the LHC
- New results on dedicated aspects of V+jets physics at CMS
  - **Topology**: collinear, azimuthal Z+jets at 13 TeV
  - **Flavour**: Z boson and b quarks at 13 TeV
  - **Precision**: Z+jets to extract the Z invisible width
- Summary, conclusions and perspectives

Phenomenology of V+jets at the LHC



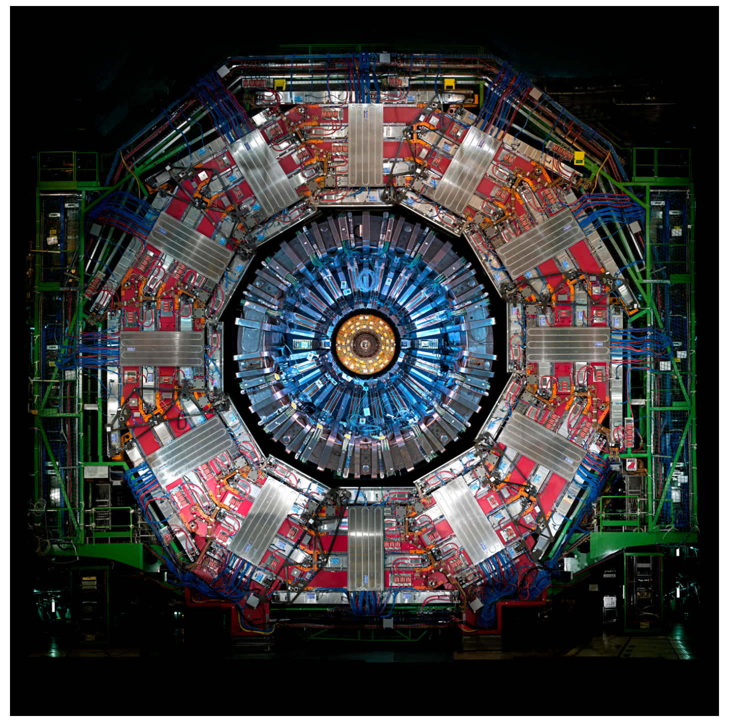




LHC
pp collisions @ 13 TeV

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

x2 design luminosity!

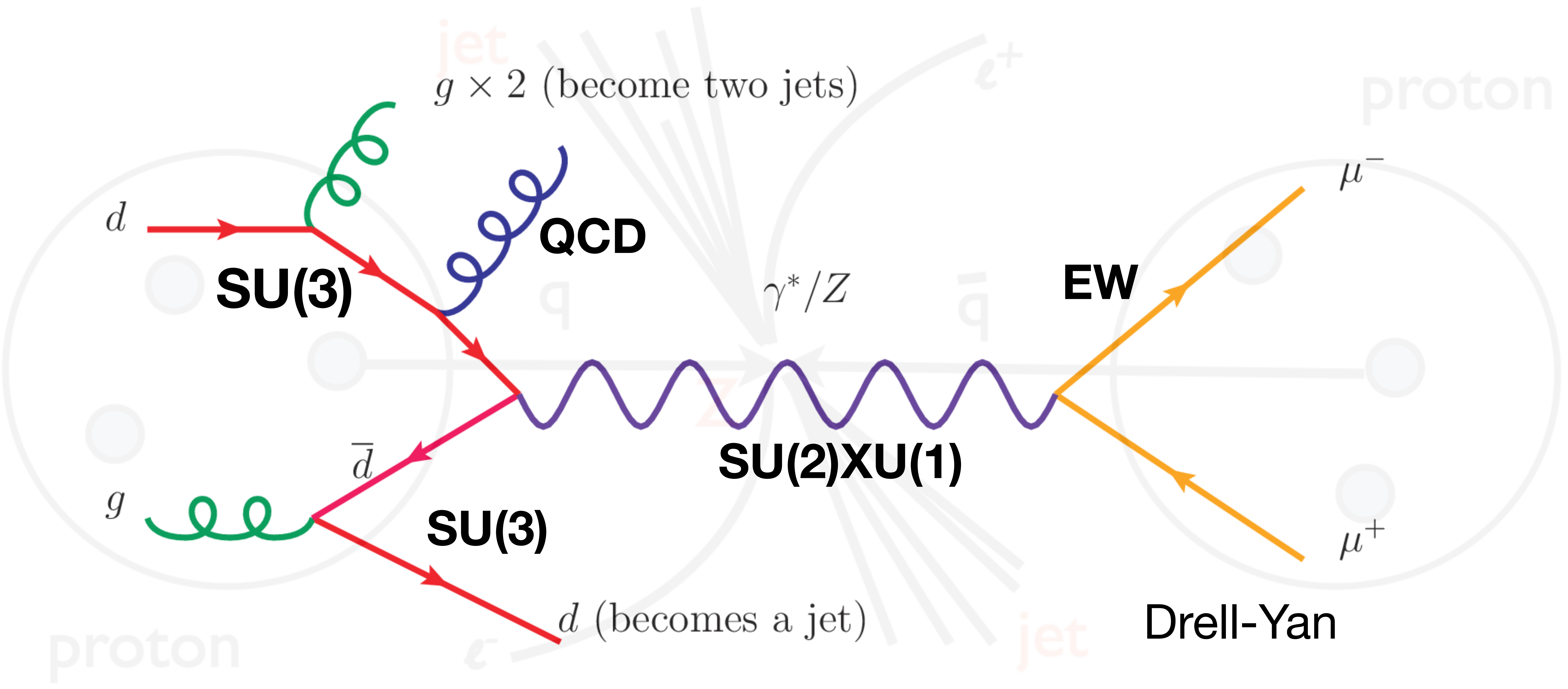


CMS

recorded
189.3 fb^{-1}

millions of W/Z boson events recorded

Phenomenology of V+jets at the LHC



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

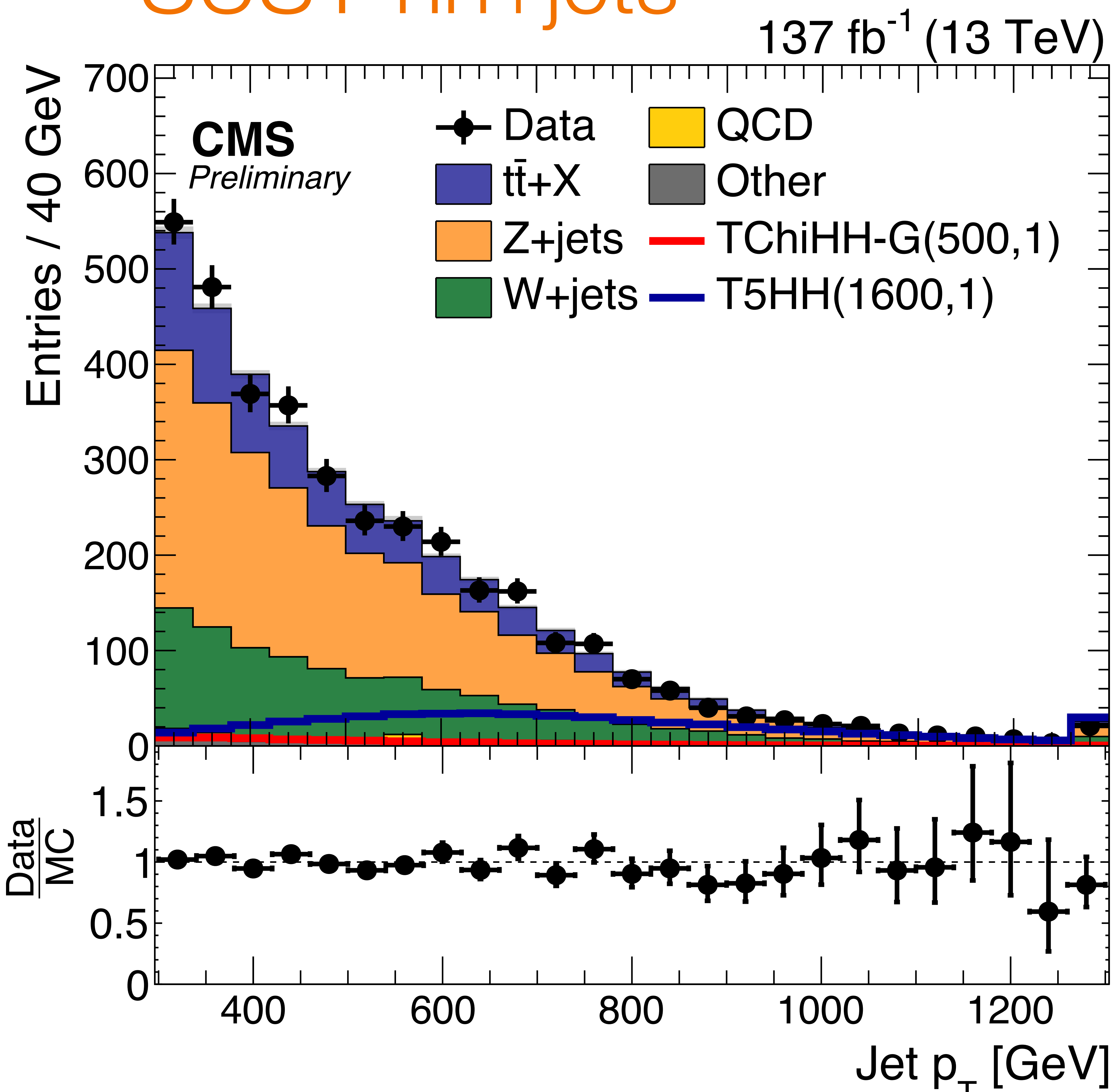
LHC is the most efficient V+jet Factory of the world!

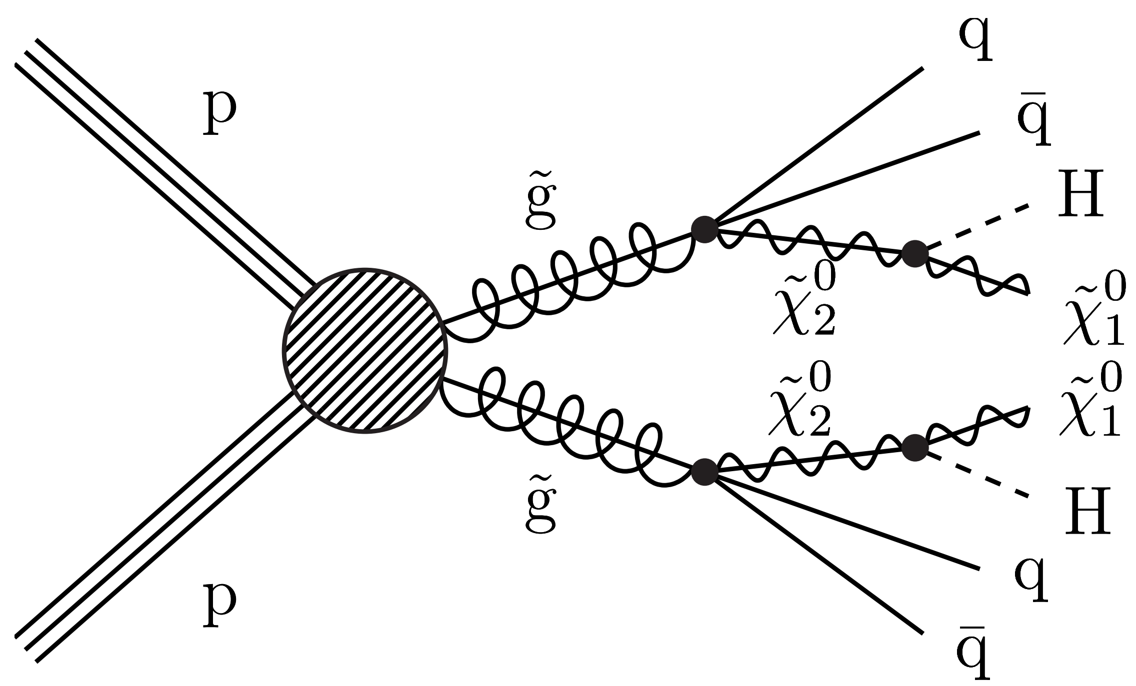
- Data-driven way to "tune" our simulation and improve perturbative calculations
- QCD modelling plays a prime role: impact of the initial state (PDF, resummation, α_S, scales)
- Open phenomenology: V+jets/HF, multiboson interactions, EW production (VBF/VBS)…
- Precision tests of the SM with W/Z: quark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

Phenomenology of V+jets at the LHC

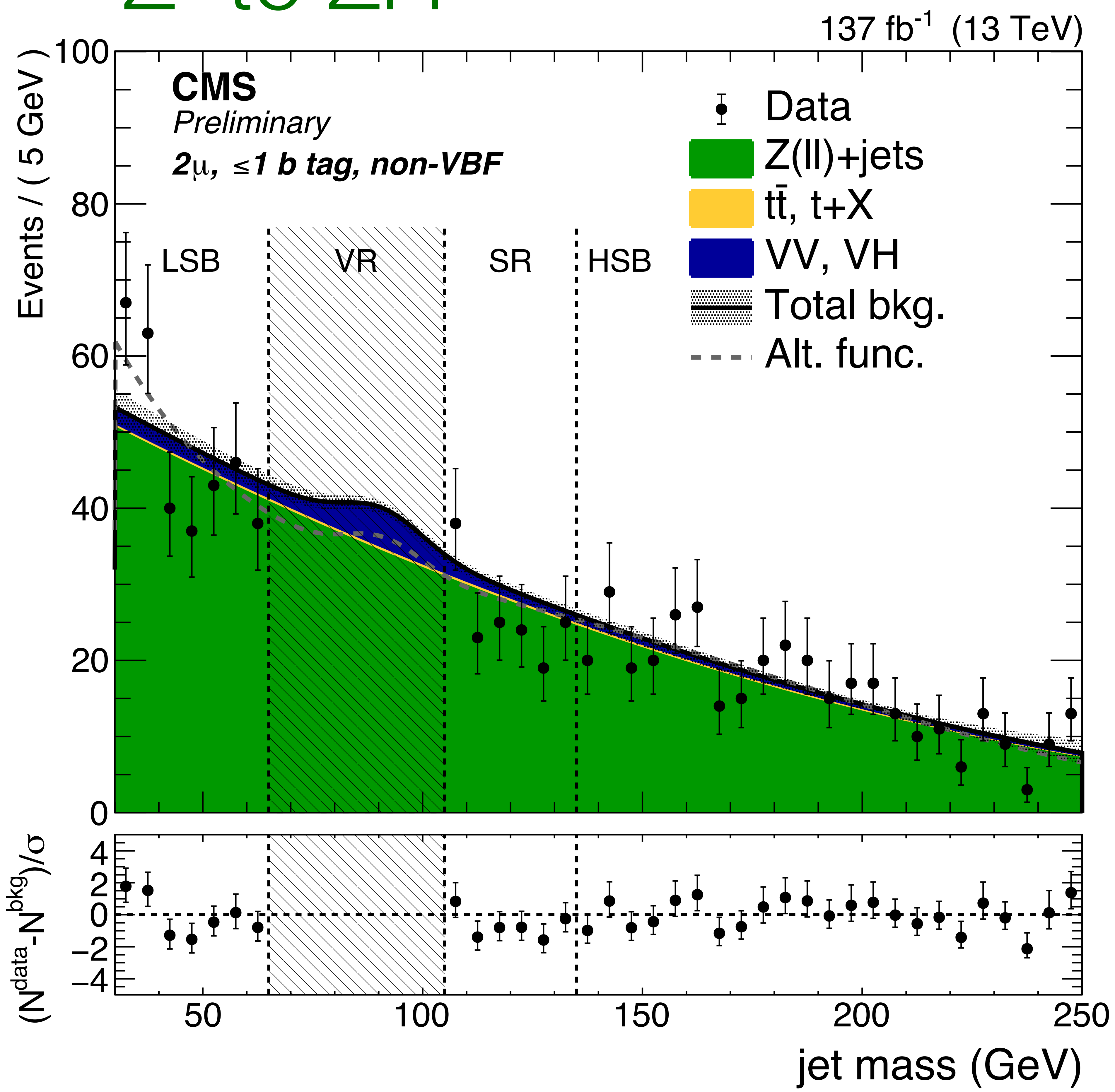
Z+jets is often the primary background in many **BSM searches**…

SUSY hh+jets





Z' to ZH



…and in the SM Higgs (ZH, HH), top, precision physics (W mass)

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* from CMS

enjoy!

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

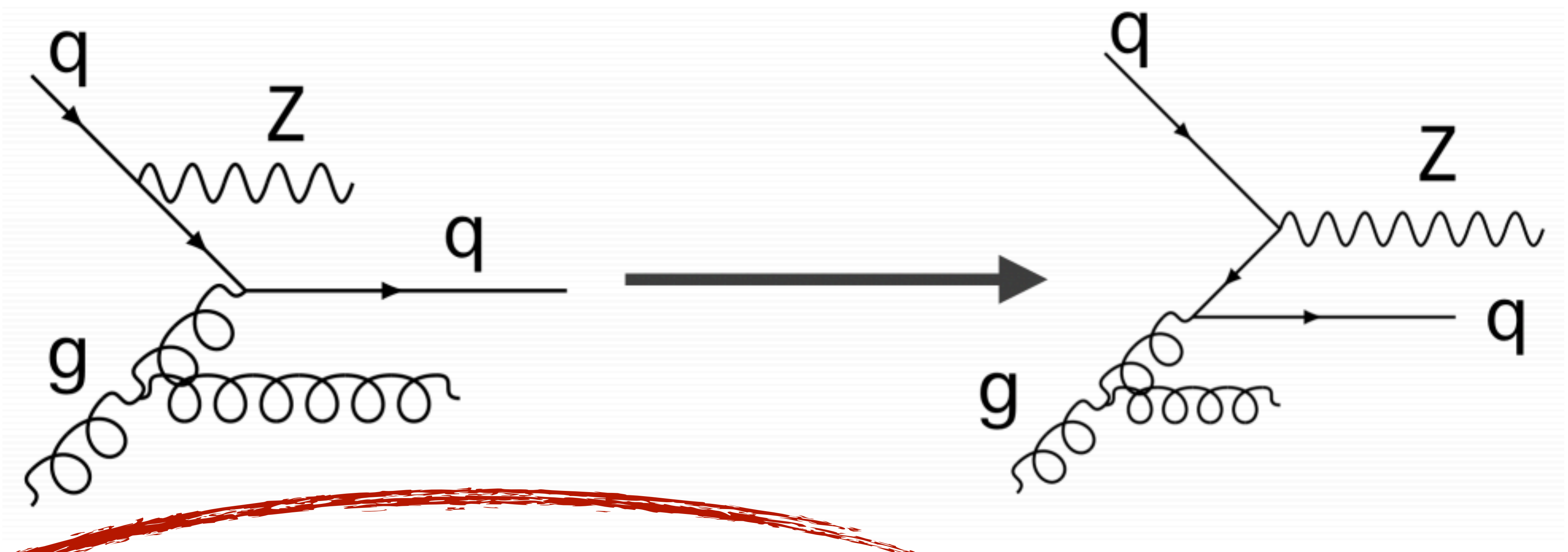
http://cms-results.web.cern.ch/cms-results/public-results/publications/SMP/index.html

Azimuthal correlations in Z+jets

CMS-PAS-SMP-21-003

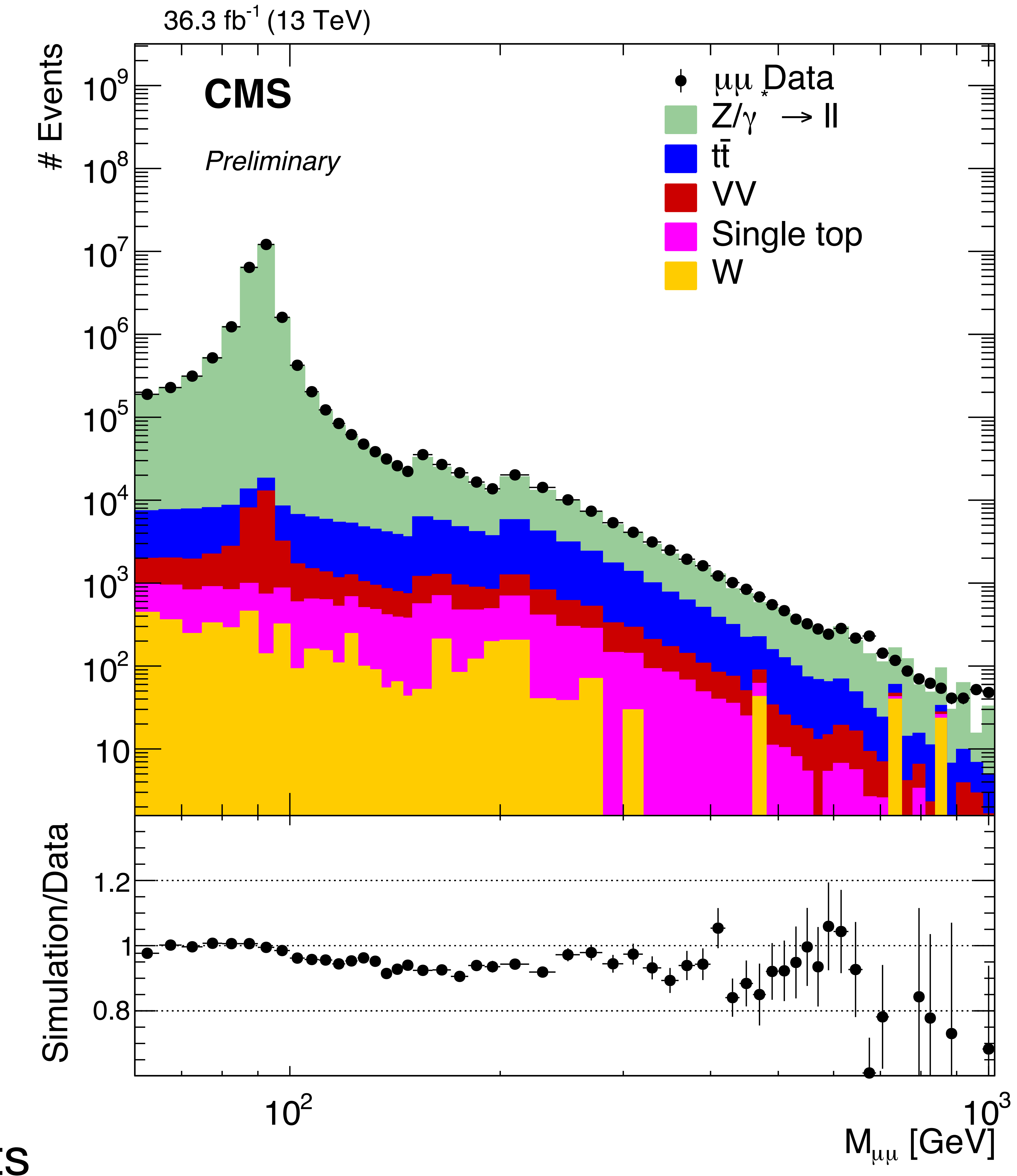
Crucial for deep understanding and modeling of QCD interactions.

- Sensitive to higher-order corrections and soft gluon resummation.



high Z p_T, Z+jet production is dominant with significant corrections coming from QCD.

low Z p_T, the jet production is the dominant process, and the Z boson appears as a higher order EW correction.



dilepton

$p_T(\mu 1) > 25$ GeV, $p_T(\mu 2) > 20$ GeV, $|\eta| < 2.4$

$|M(\mu 1,\mu 2) - M_Z| < 15$ GeV

tight PF relative isolation

jets

AK4PF chs jets

$\Delta R(l, \text{jets}) > 0.4$

Azimuthal correlations in Z+jets

$p_T(Z) < 10$GeV

unfolded differential cross sections

MADGRAPH5 aMC@NLO + pythia8

- NLO matrix element up to 2 partons
- FxFx jet merging
- NNPDF3.0 NLO PDF, CUETP8M1 Pythia8 tune

MCatNLO-CA3 (Z+1) NLO

- Fixed-order perturbative QCD calculation at NLO (2->Z+1)
- PB-NLO-set2 NLO PDF.

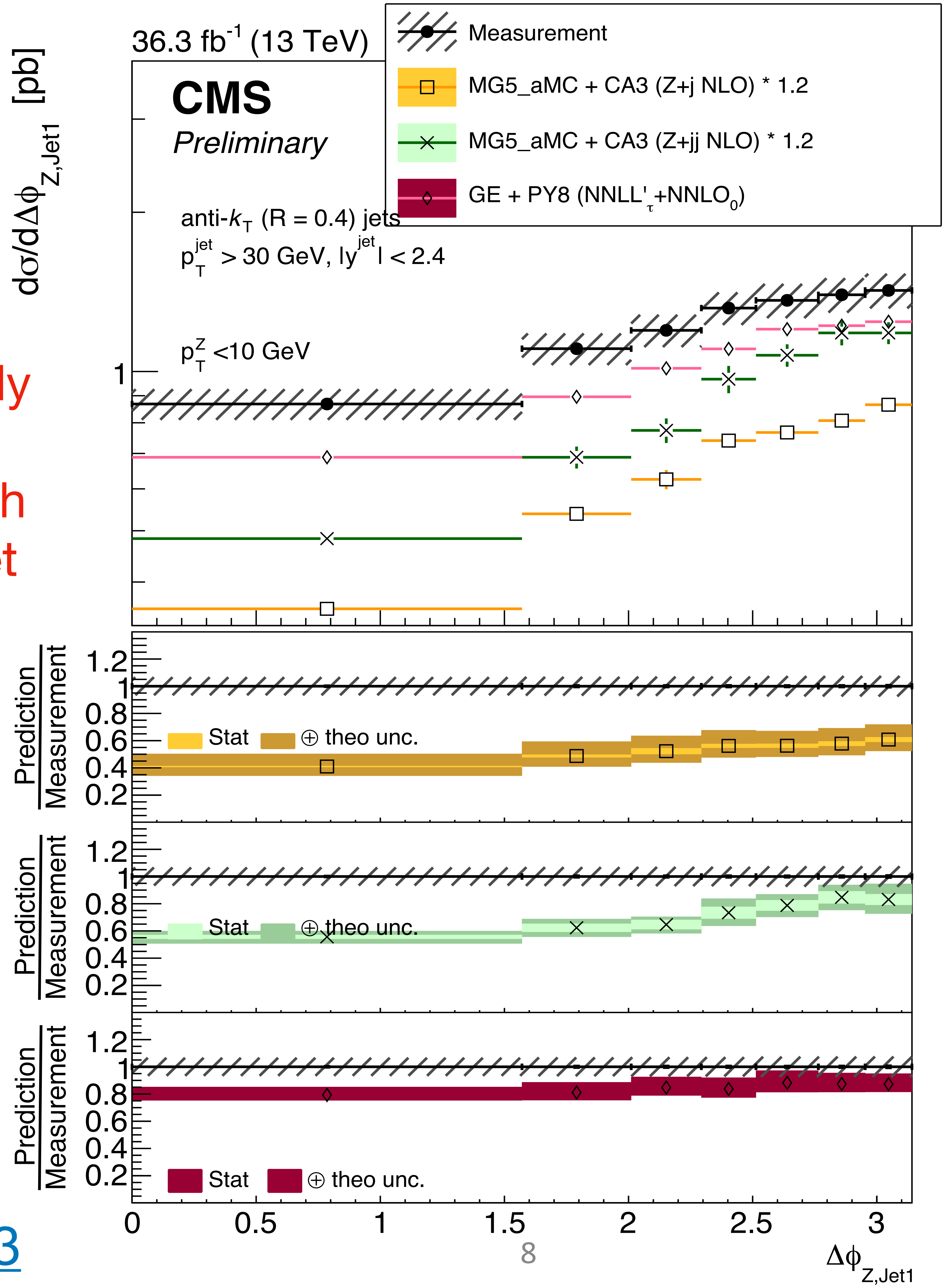
MCatNLO-CA3 (Z+2) NLO

- Fixed-order perturbative QCD calculation at NLO (2->Z+2)
- PB-NLO-set2 NLO PDF

GENEVA NNLO

- Resummed NNLO+NNLL’ calculations for inclusive Z production at NNLO
- NNPDF 3.1, CUETP8M1 Pythia8 tune

Z boson is only weakly correlated with the leading jet



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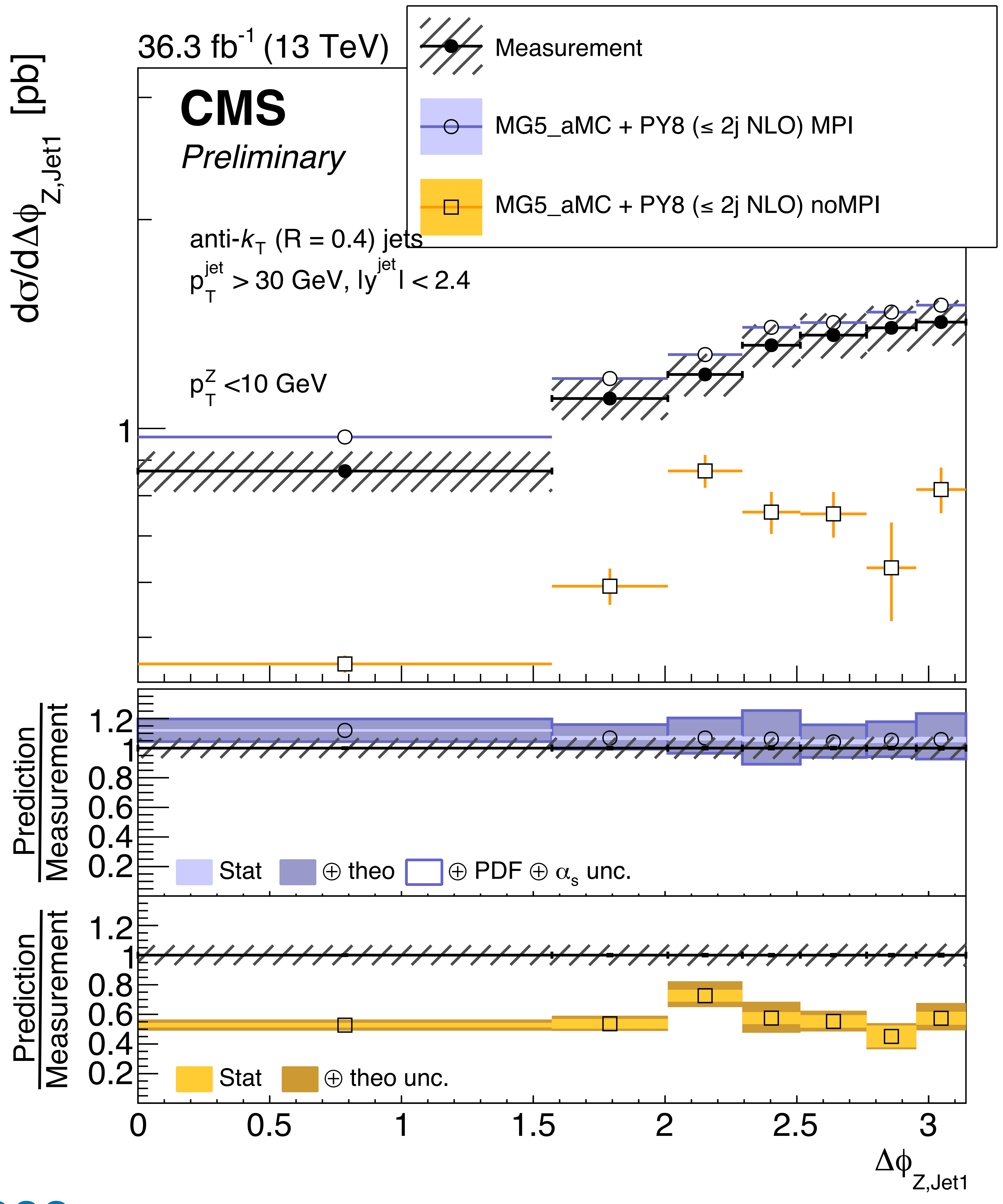
Multi-parton interaction contribution is about 40%



CMS-PAS-SMP-21-003

Azimuthal correlations in Z+jets

pT(Z) >= 100 GeV

unfolded differential cross sections

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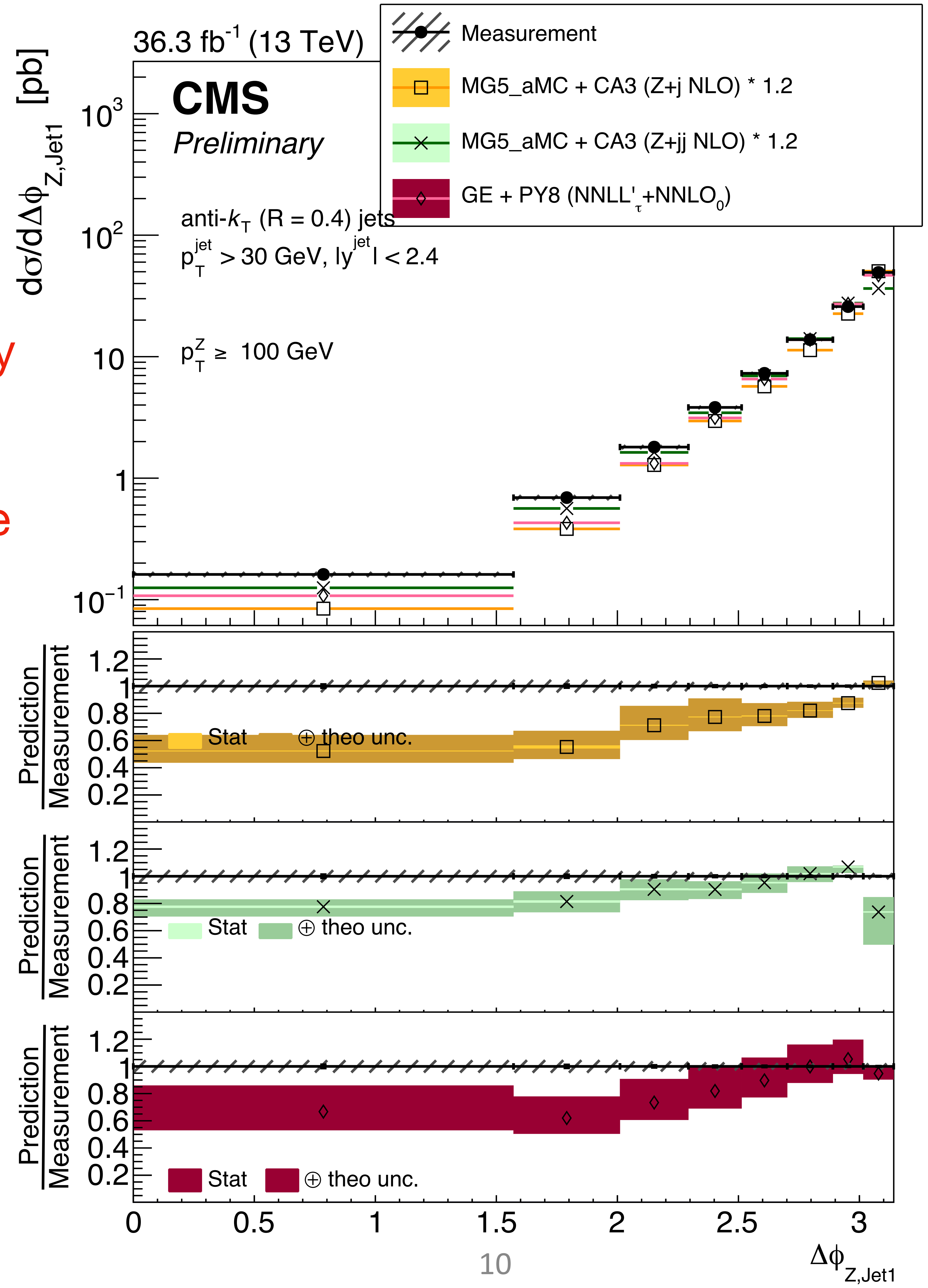
Z boson is highly correlated with the leading jet, and peaks in the back-to-back region.



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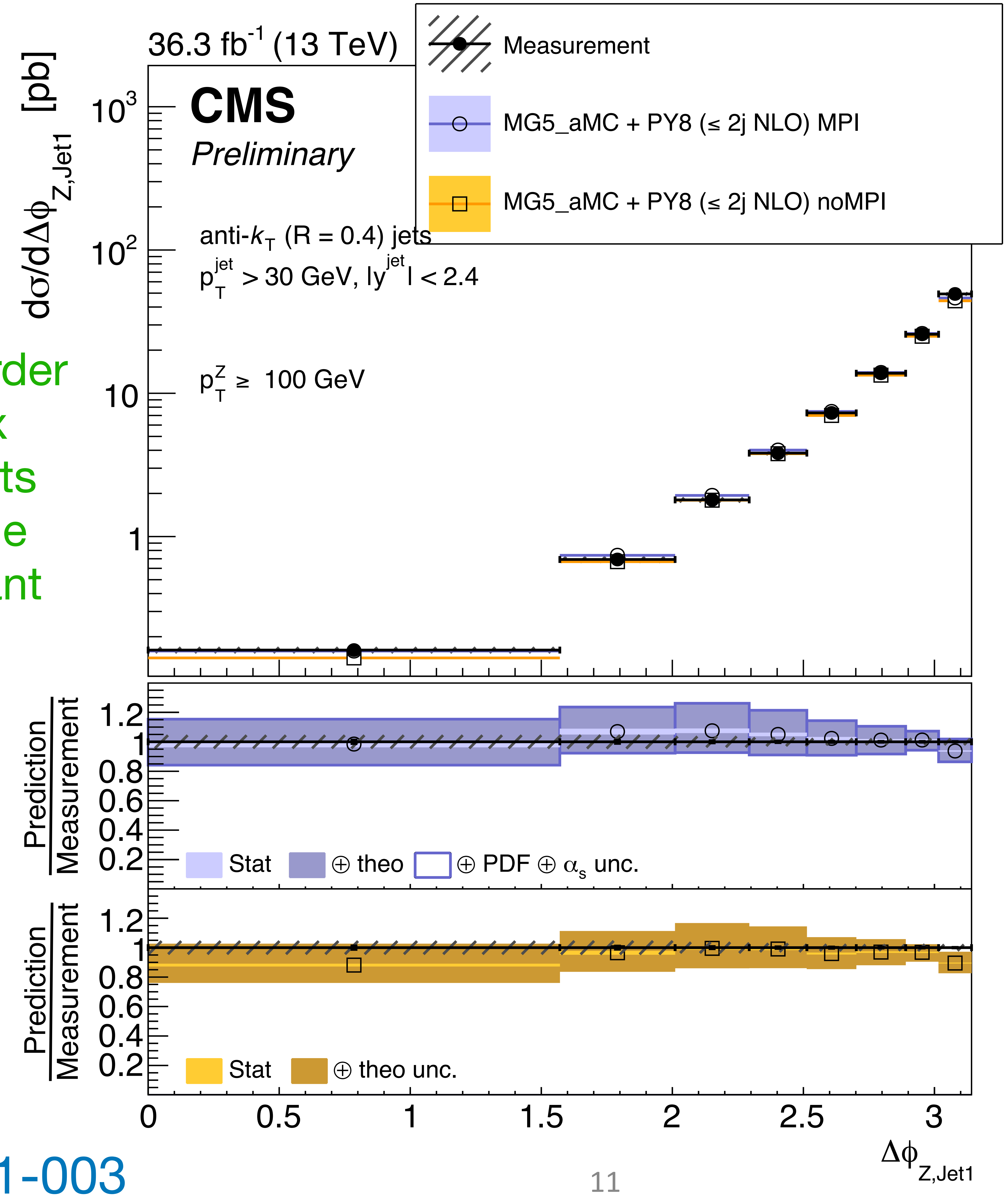
higher order matrix elements become important



CMS-PAS-SMP-21-003

CMS-PAS-SMP-20-015

Associated production of Z and b quarks

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’

Deep neural network-based b-tagging reaching 70% efficiency mistag rate c-quark and light ~10% and ~1%

backgrounds

top quarks -> data driven

light, charm jets -> control regions

multiboson + others -> MC

strategy

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

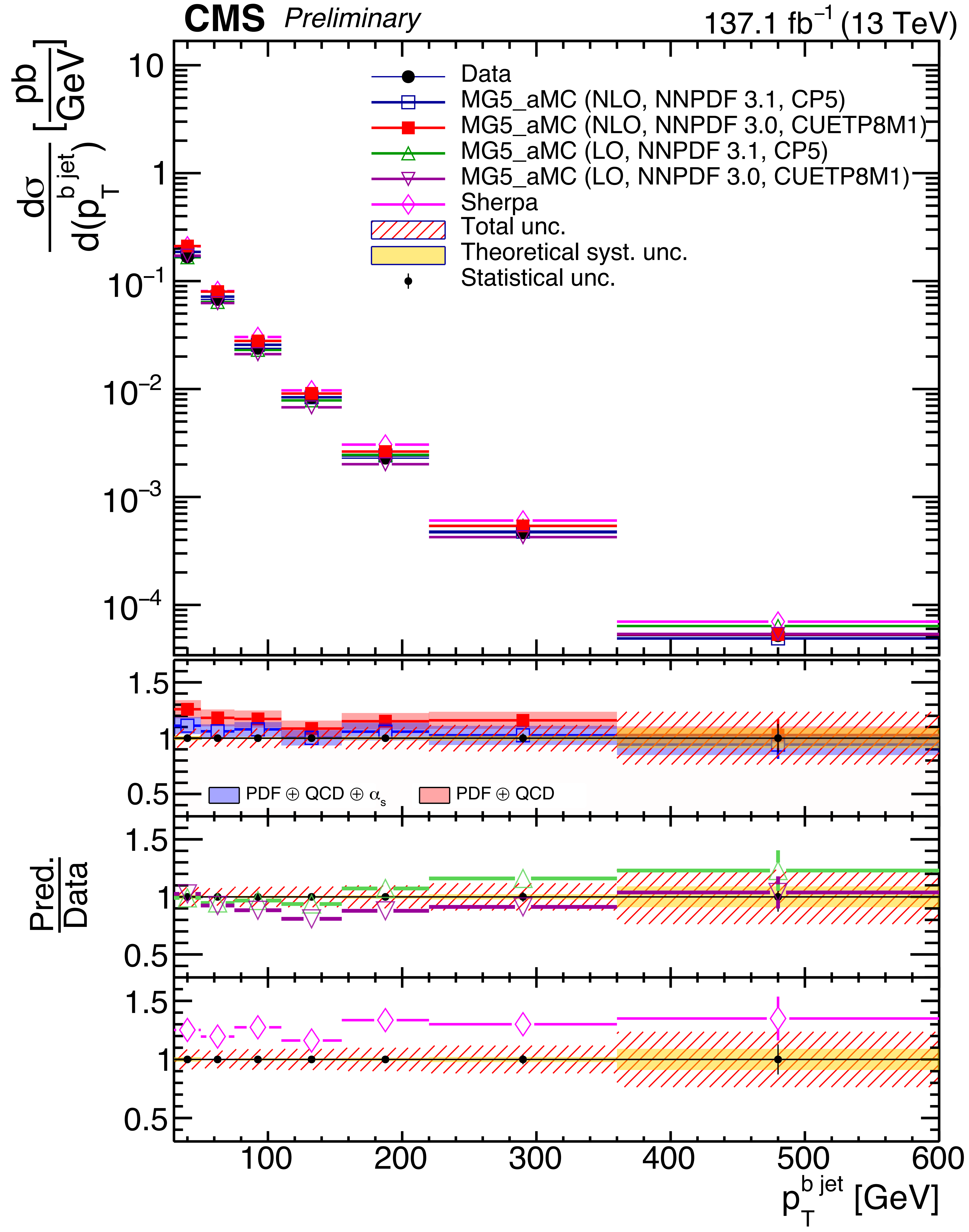
usual Z(ll)+jets kinematic cuts + b-tagging

Exploring the Zbb phenomenology over a vast set of observables

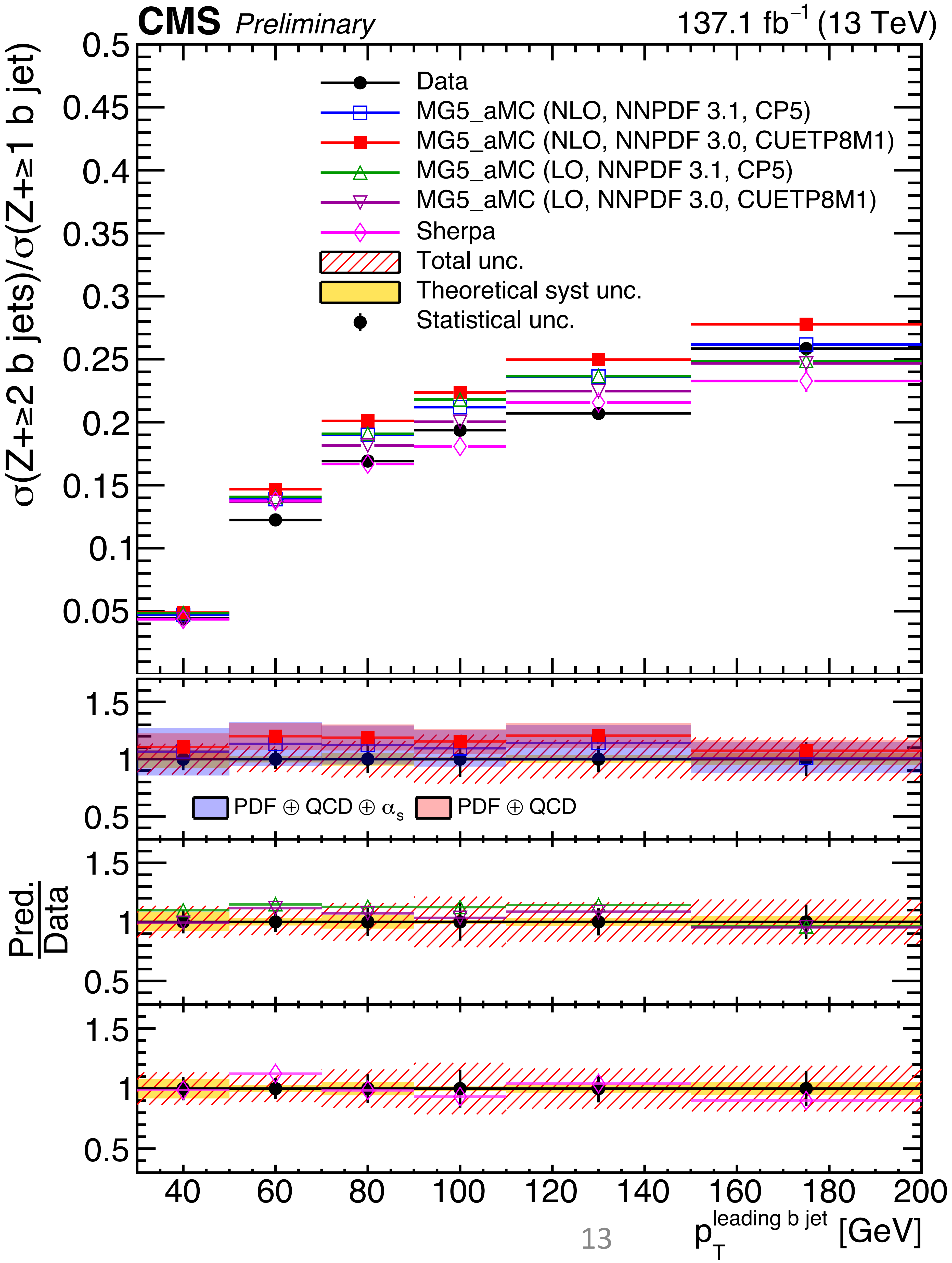
Predictions at LO and NLO, 4F and 5F by MadGraph5_aMC@NLO and Sherpa

CMS-PAS-SMP-20-015

Associated production of Z and b quarks



leading b-jet p_T and ratio >0b/>1b, test pQCD



CMS-PAS-SMP-20-015

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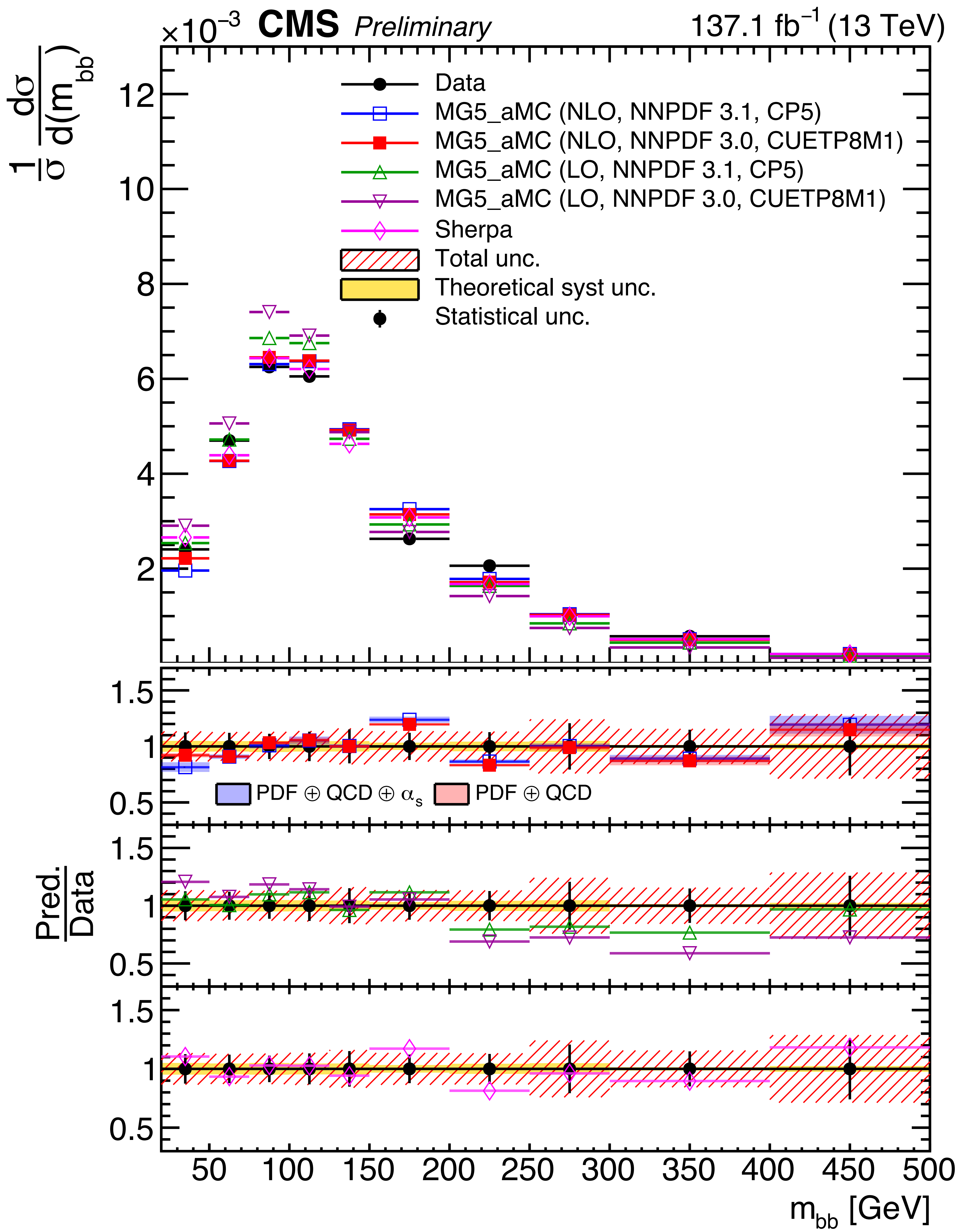
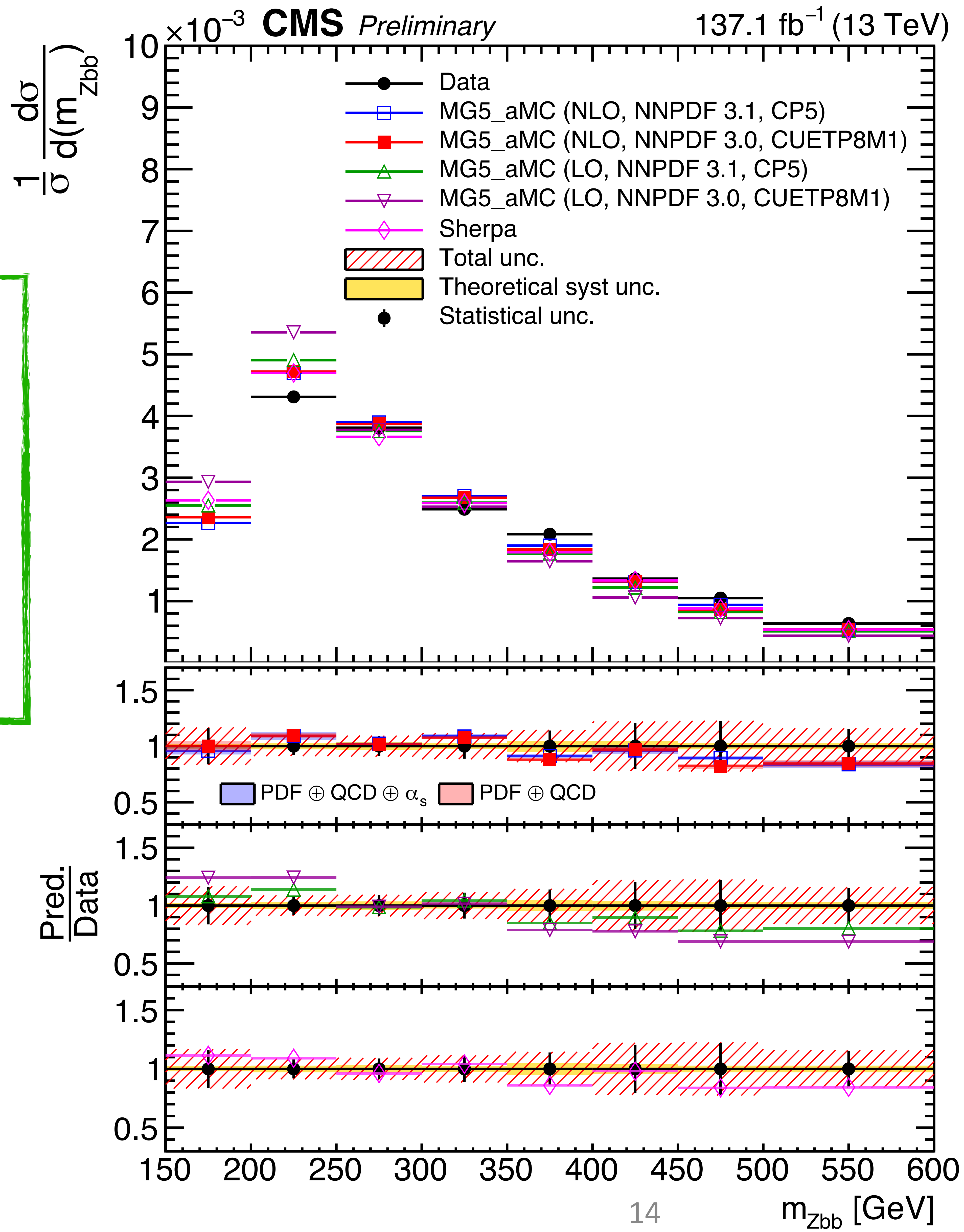


bb and Zbb invariant masses important in searches for resonances

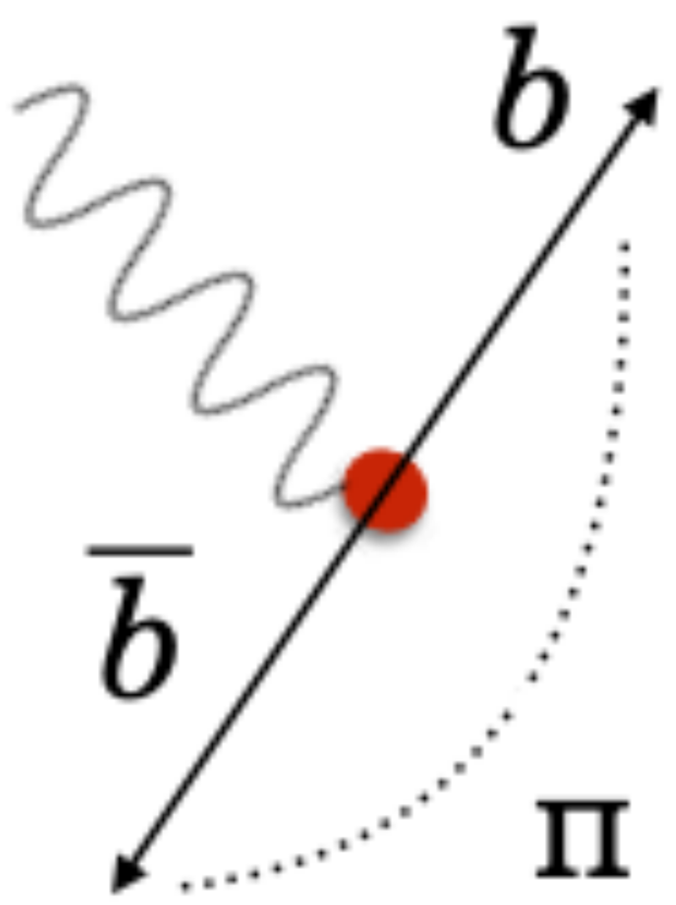
<u>no deviations w.r.t. the SM</u>

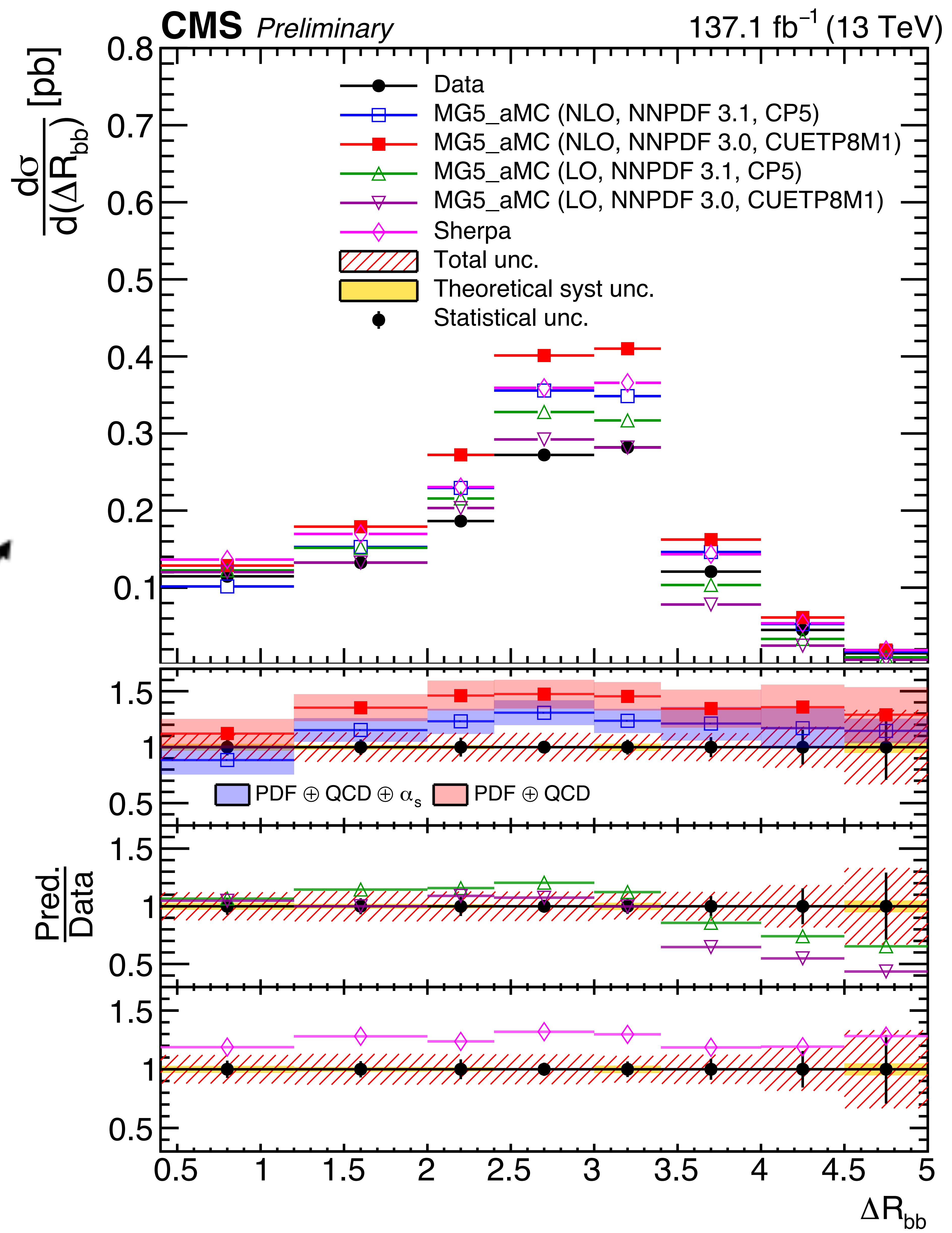


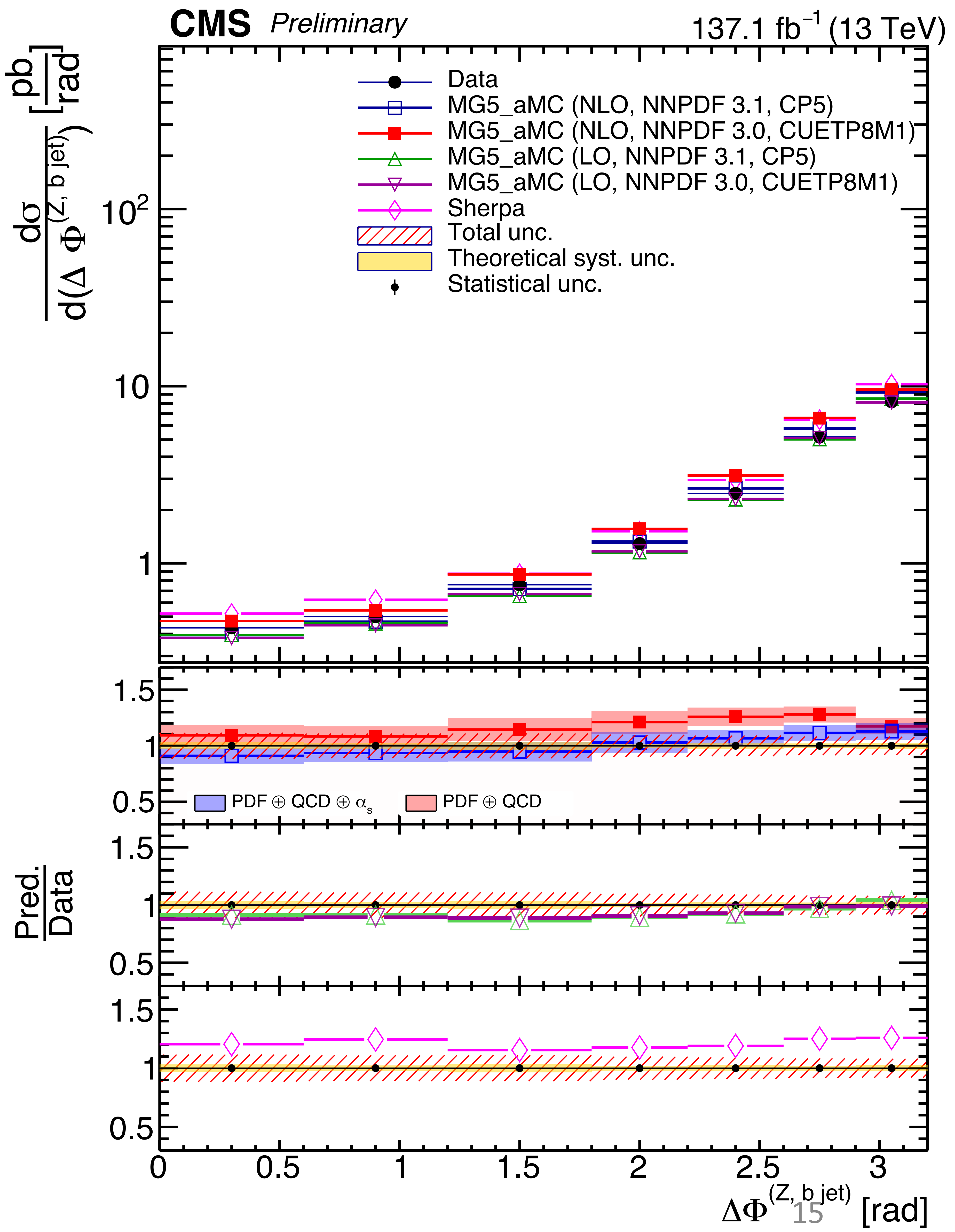
CMS-PAS-SMP-20-015

Associated production of Z and b quarks

very good agreement over the full ΔR range within the uncertainties



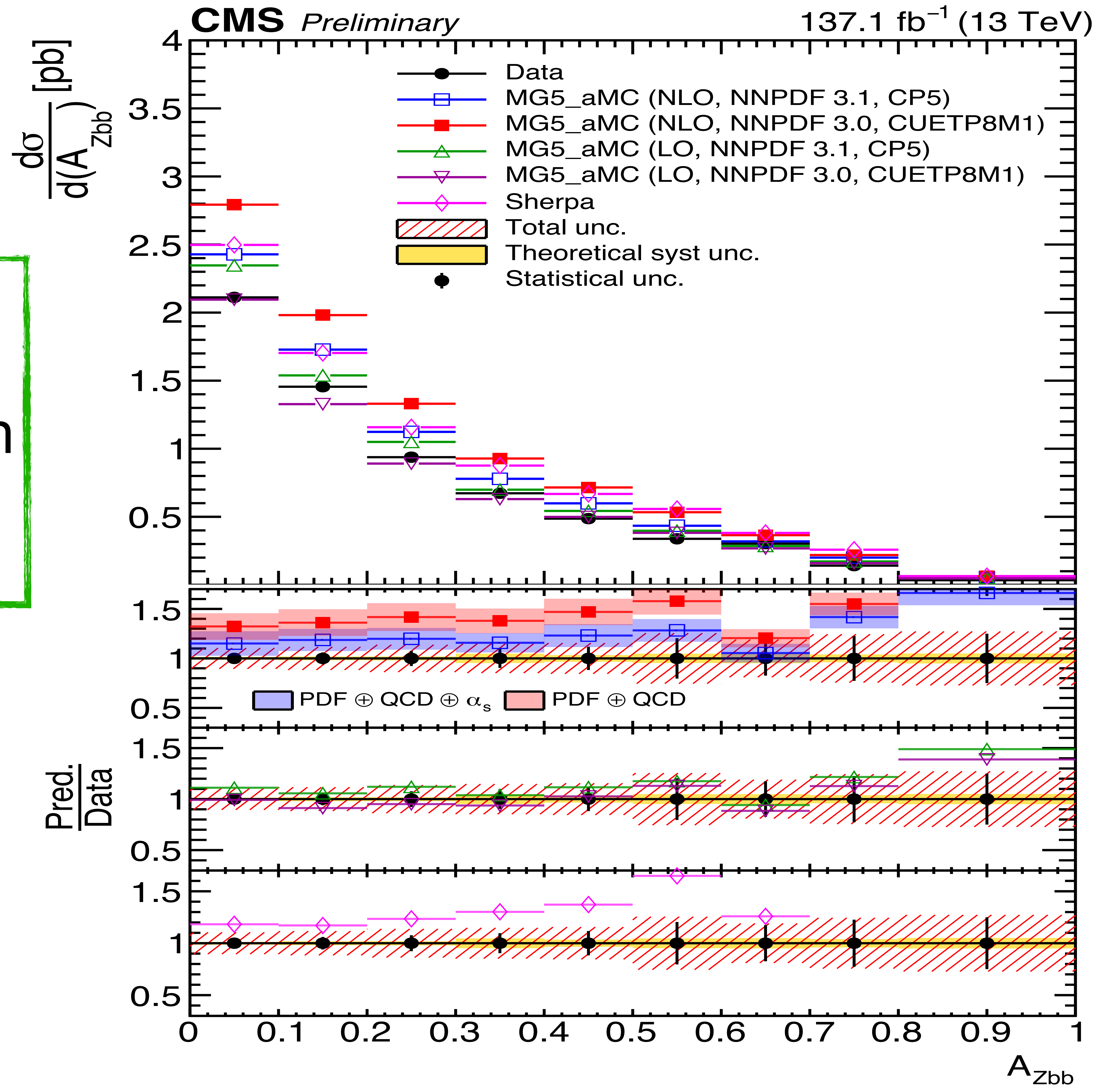




overall good agreement

CMS-PAS-SMP-20-015

Associated production of Z and b quarks



test gluon density and gluon radiation effects in pQCD

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

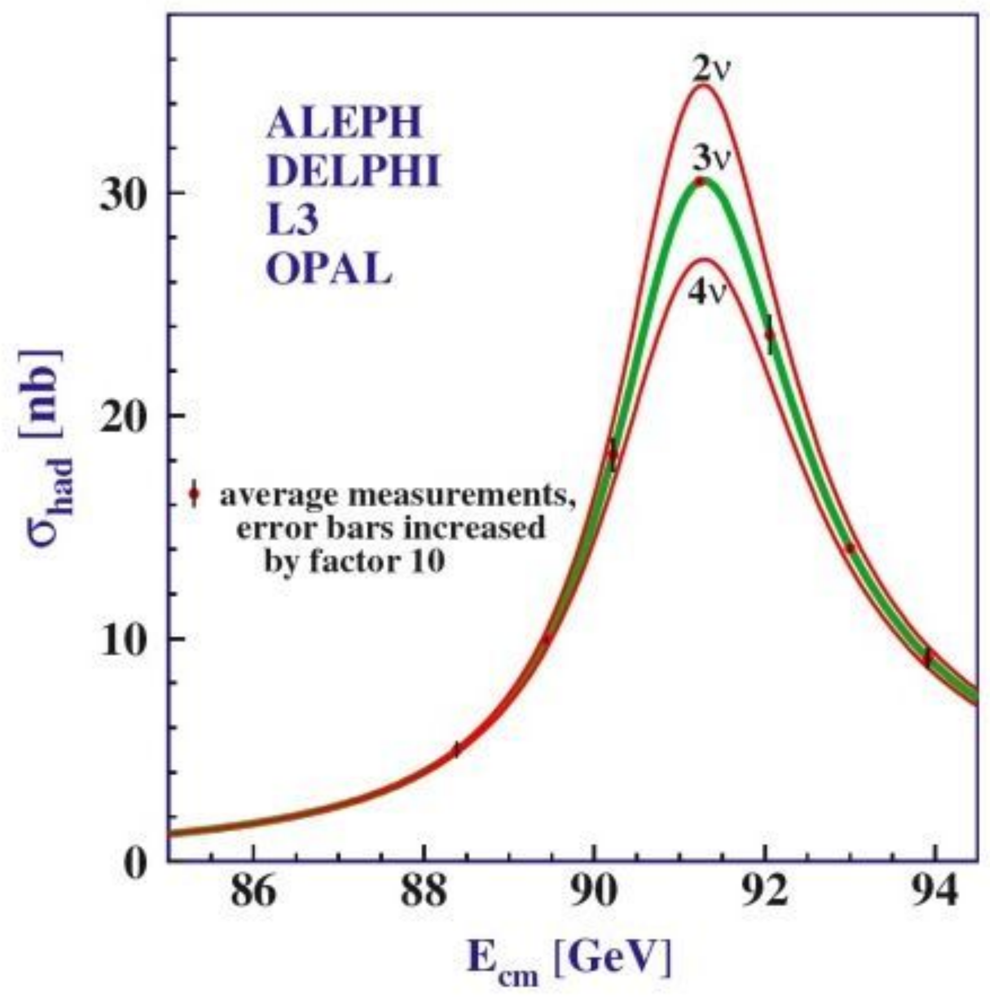
A-> not described by any prediction

A(Zbb) -> 1
Emission of additional gluon radiation in the final state ($A_{Zbb} \neq 0$)

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

Precision invisible Z width with Z+jets

CMS-PAS-SMP-18-014



$$\Gamma(Z \to \nu\bar{\nu}) = \frac{\sigma(Z+\text{jets})\mathcal{B}(Z \to \nu\bar{\nu})}{\sigma(Z+\text{jets})\mathcal{B}(Z \to \ell\ell)}\Gamma(Z \to \ell\ell)$$

BACK TO THE FUTURE

Z invisible width extracted from the ratio of measured Z(ll)+jets and Z(nn)+jets using LEP's measured Z->ll partial widths

- use the "monojet" dark matter strategy as a way to make a precision SM measurement
- first measurement of the Z invisible width at any hadronic collider
- aim to reach LEP's level of precision

Analysis in a nutshell:

W+jets and QCD estimated from data

γ^* interference term estimated using MadGraph and accounted for

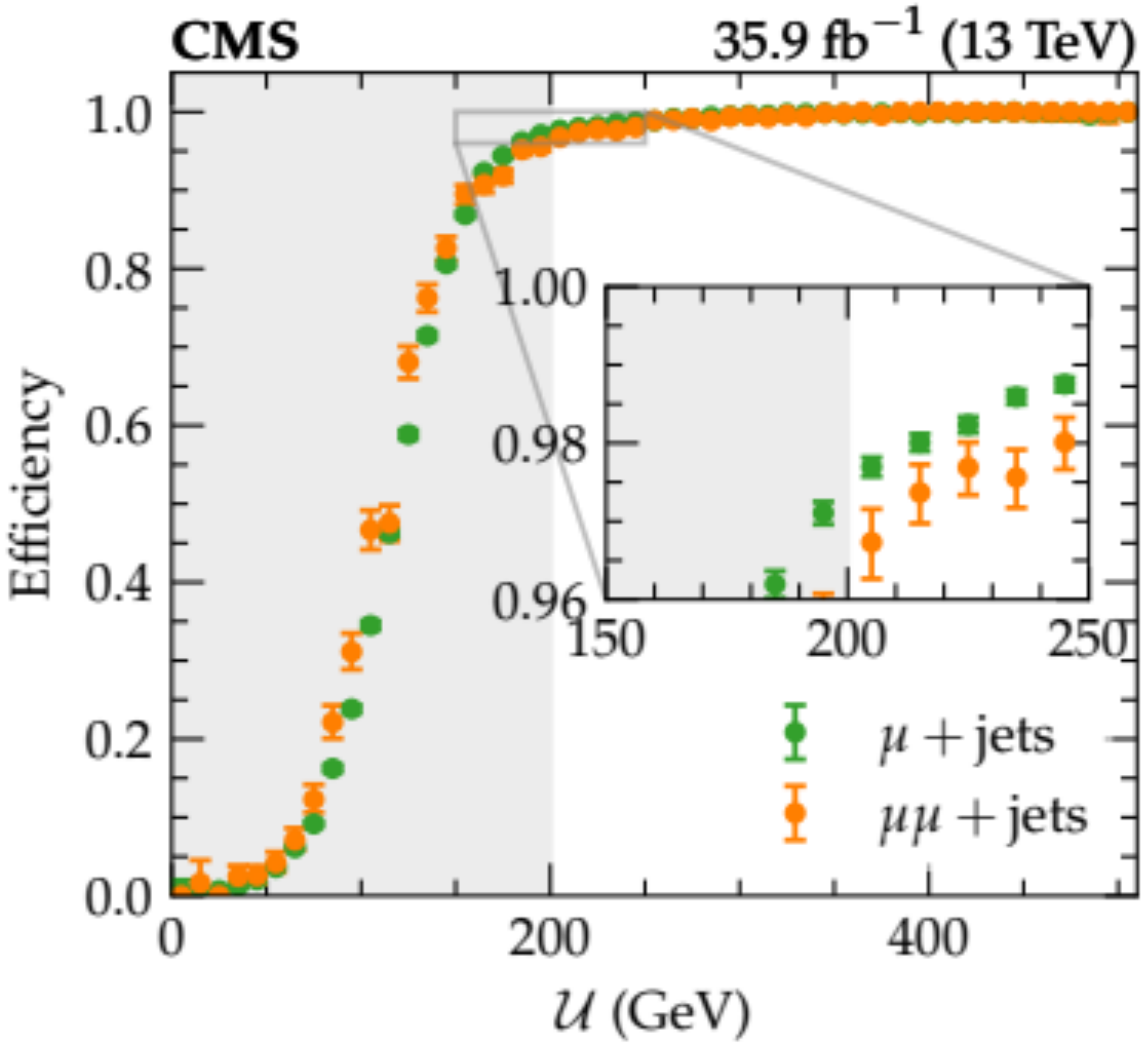
Invisible width extracted from simultaneous fit between jets+MET, ll+jets, l+jets

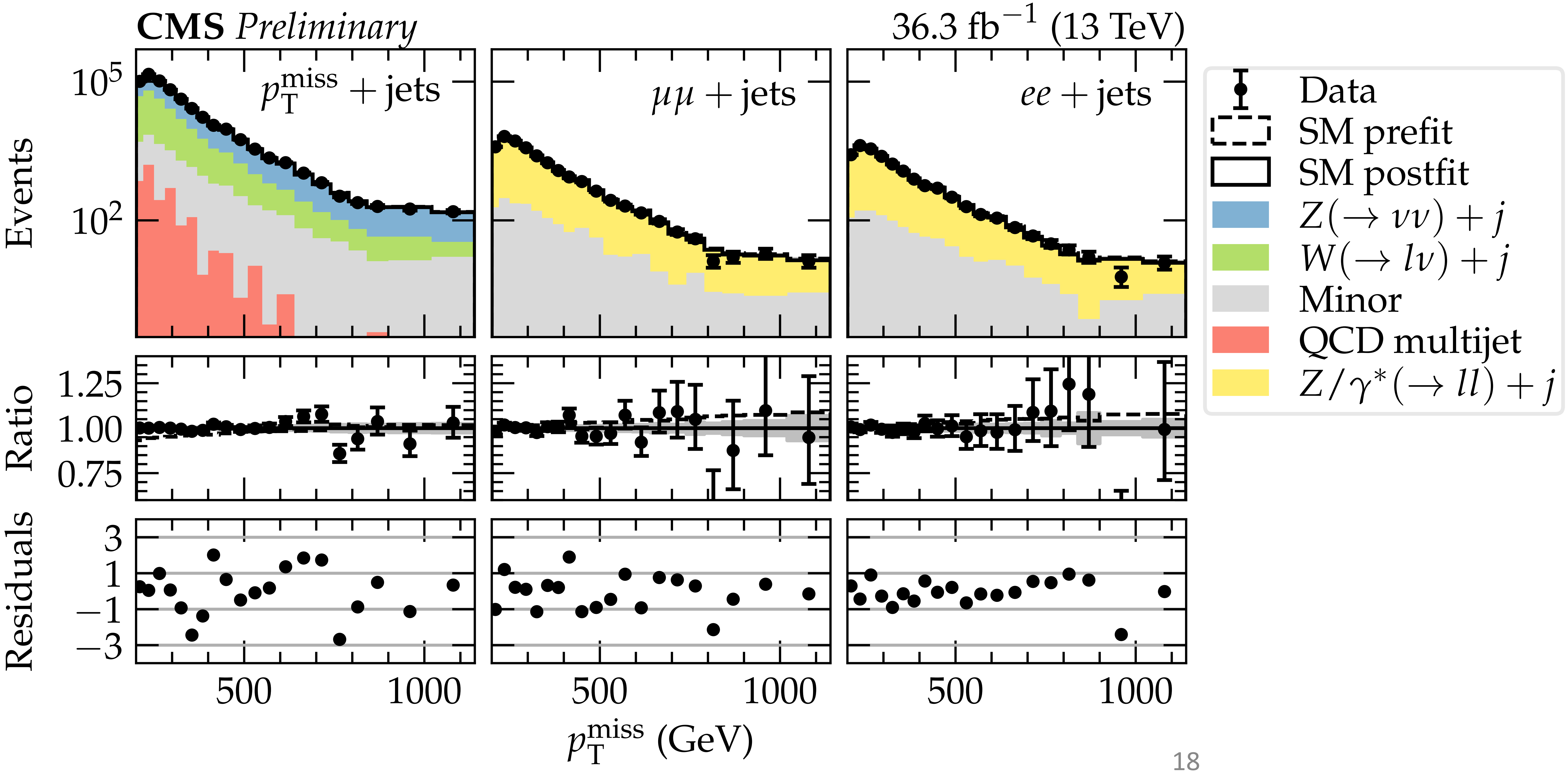
V+jets simulation corrected with NNLO QCD+NLO EWK k-factors

Precision invisible Z width with Z+jets

signal: MET trigger + $\not{p}_T$ > 200 GeV & η<2.4, $p_{T\,(J1)}$ >200 GeV & η<2.4

7 CR selections for bkgs: single/double e/μ, single tau, QCD, Jet-MET





Precision invisible Z width with Z+jets

Simultaneous likelihood fit strategy to extract the invisible width

$$\mathcal{L}(n_j, n_\ell, n_{\ell\ell} | r, r_Z, r_W, \boldsymbol{\theta}) =$$

$$\text{Poisson}\left(n_j \,\middle|\, r \cdot r_Z \cdot s_{Z,j}(\boldsymbol{\theta}) + r_W \cdot b_{j,W}(\boldsymbol{\theta}) + b_{\text{bkg.},j}(\boldsymbol{\theta})\right) \quad \text{Jets+MET}$$

$$\text{Poisson}\left(n_\ell \,\middle|\, r_W \cdot b_{\ell,W}(\boldsymbol{\theta}) + b_{\text{bkg.},\ell}(\boldsymbol{\theta})\right) \quad \text{Single lepton}$$

$$\text{Poisson}\left(n_{\ell\ell} \,\middle|\, r_Z \cdot s_{Z,\ell\ell}(\boldsymbol{\theta}) + \sqrt{r_Z} \cdot s_{\text{int.},\ell\ell} + s_{\gamma^*,\ell\ell}(\boldsymbol{\theta}) + b_{\text{bkg.},\ell\ell}(\boldsymbol{\theta})\right) \quad \text{Double lepton}$$

$$\cdot\, p(\tilde{\boldsymbol{\theta}}, \boldsymbol{\theta})$$

$$\Gamma(Z \to \nu\bar{\nu}) = \frac{\sigma(Z+\text{jets}) \cdot B(Z \to \nu\bar{\nu})}{\sigma(Z+\text{jets}) \cdot B(Z \to \ell\ell)} \Gamma(Z \to \ell\ell)$$

$$= \frac{\varepsilon_{\ell\ell} A_{\ell\ell}}{\varepsilon_{\nu\nu} A_{\nu\nu}} \frac{r \cdot r_Z \cdot s_{Z,j}(\boldsymbol{\theta})}{r_Z \cdot s_{Z,\ell\ell}(\boldsymbol{\theta})} \Gamma(Z \to \ell\ell)$$

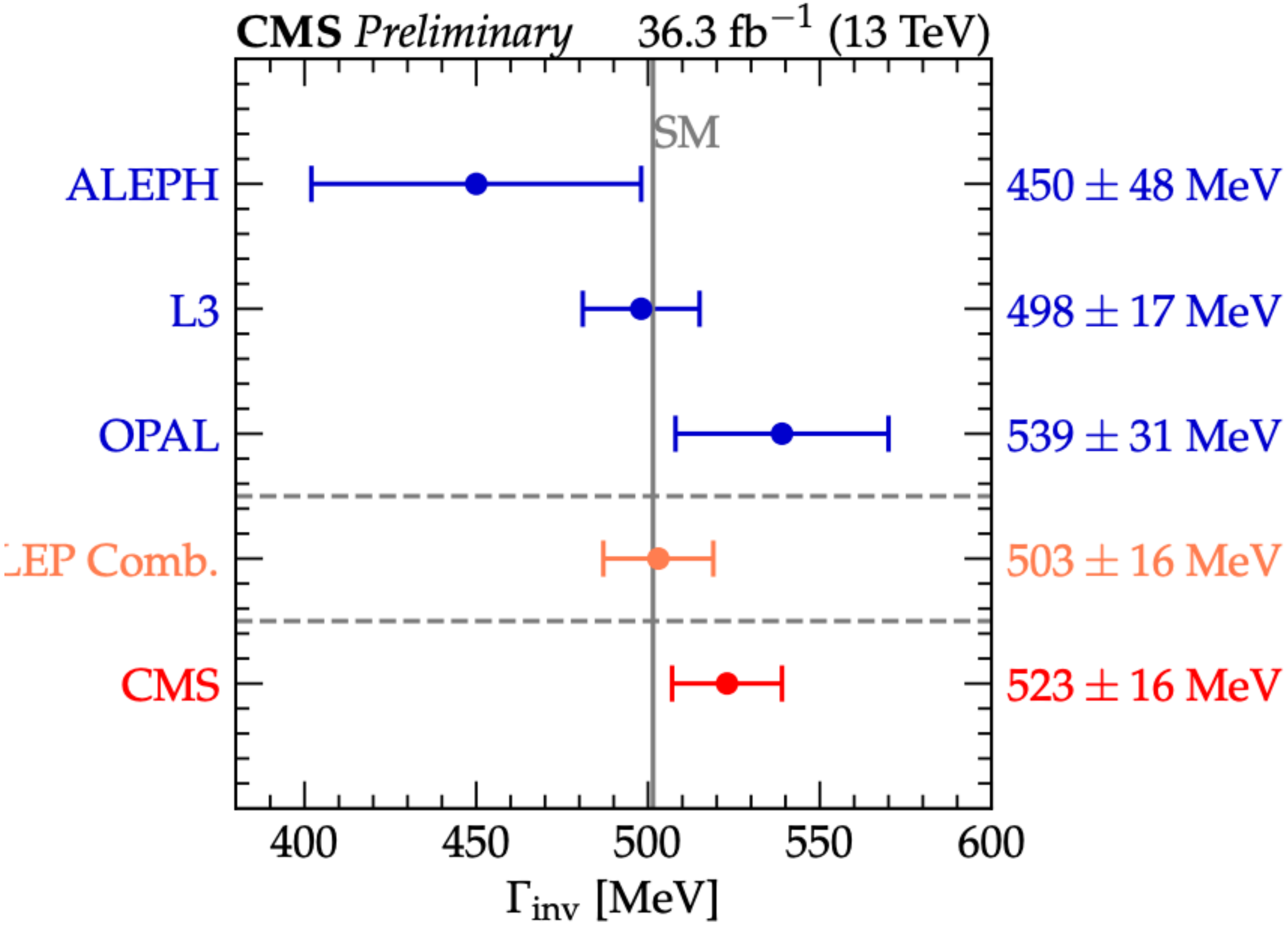
$$= r \frac{\varepsilon_{\ell\ell} A_{\ell\ell}}{\varepsilon_{\nu\nu} A_{\nu\nu}} \frac{s_{Z,j}(\boldsymbol{\theta})}{s_{Z,\ell\ell}(\boldsymbol{\theta})} \Gamma(Z \to \ell\ell).$$

$$r_{\text{inv}} \equiv r = \frac{\Gamma(Z \to \text{inv})}{\Gamma_{\text{MC}}(Z \to \text{inv})}$$

main systematics:

- μ/e ID 2%(1%)
- Jet Scale 1.8%
- trigger eff. 0.7%

Precision invisible Z width with Z+jets



comparable precision w.r.t. LEP combination!

first Z invisible width measurement at hadron colliders

$$\Gamma_{inv} = 523 \pm 3\,(\text{stat}) \pm 16\,(\text{syst})\,\text{MeV}$$

Present and future of V+Jets at LHC

The V+jets physics is a super-rich and growing field in HEP experiments

- After years of no striking hints of BSM, LHC experimental community started looking at SM precision again with more and more interest and ideas
- Impressive set of results from CMS on large variety of topologies, new ideas coming up more and more, new predictions, new approaches: space for creativity
- Still open opportunities: γ+jets is a huge missing in this picture, and we can do a lot of QCD with it… we are working on it!
- New era of theory predictions and high precision (NNLO, TMDs, PB, FSs) will expand the V+jets physics reach even further

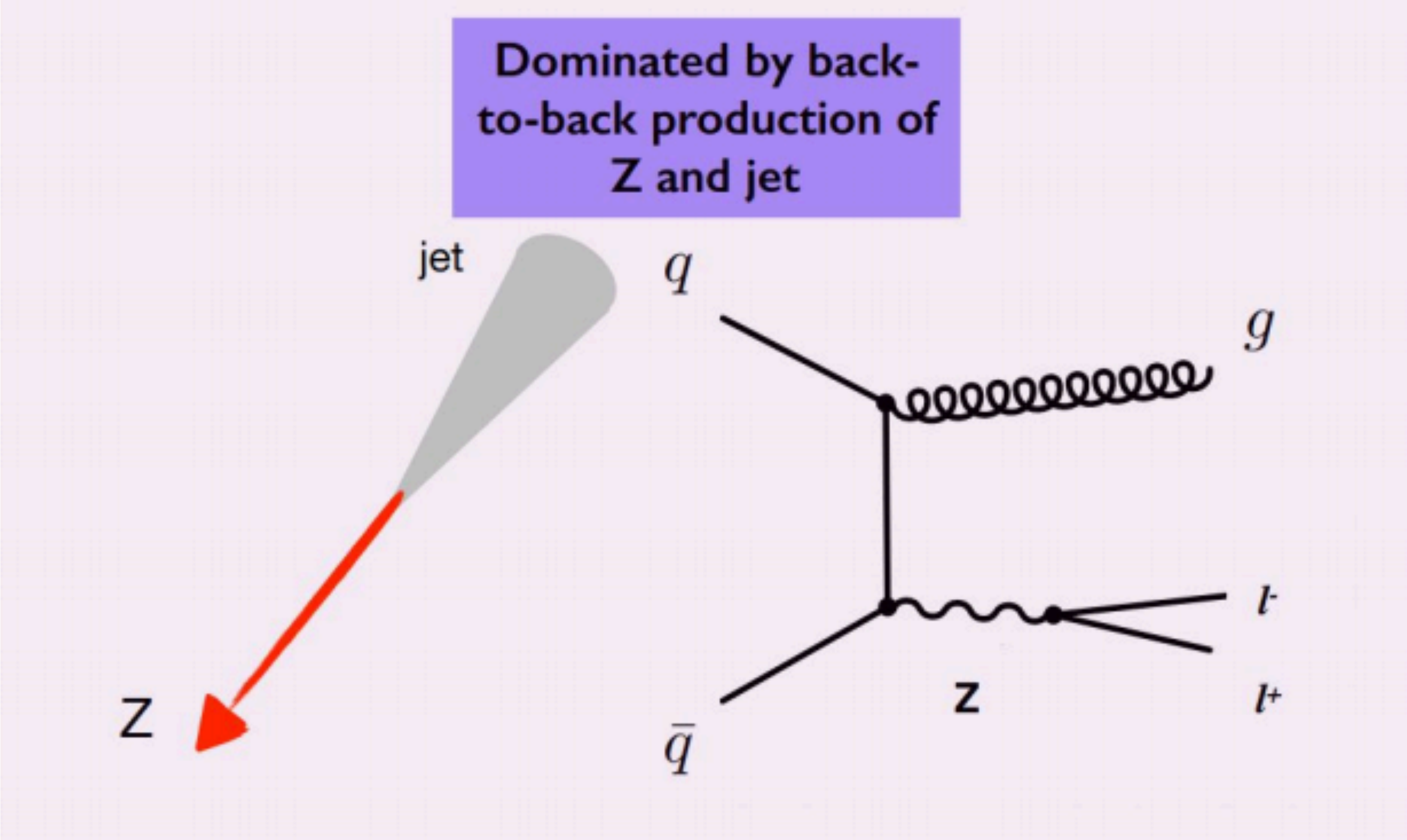
A lot more is coming soon exploiting full Run2 13 TeV data: W+c, W+b, Z+c, γ+HF… stay tuned!

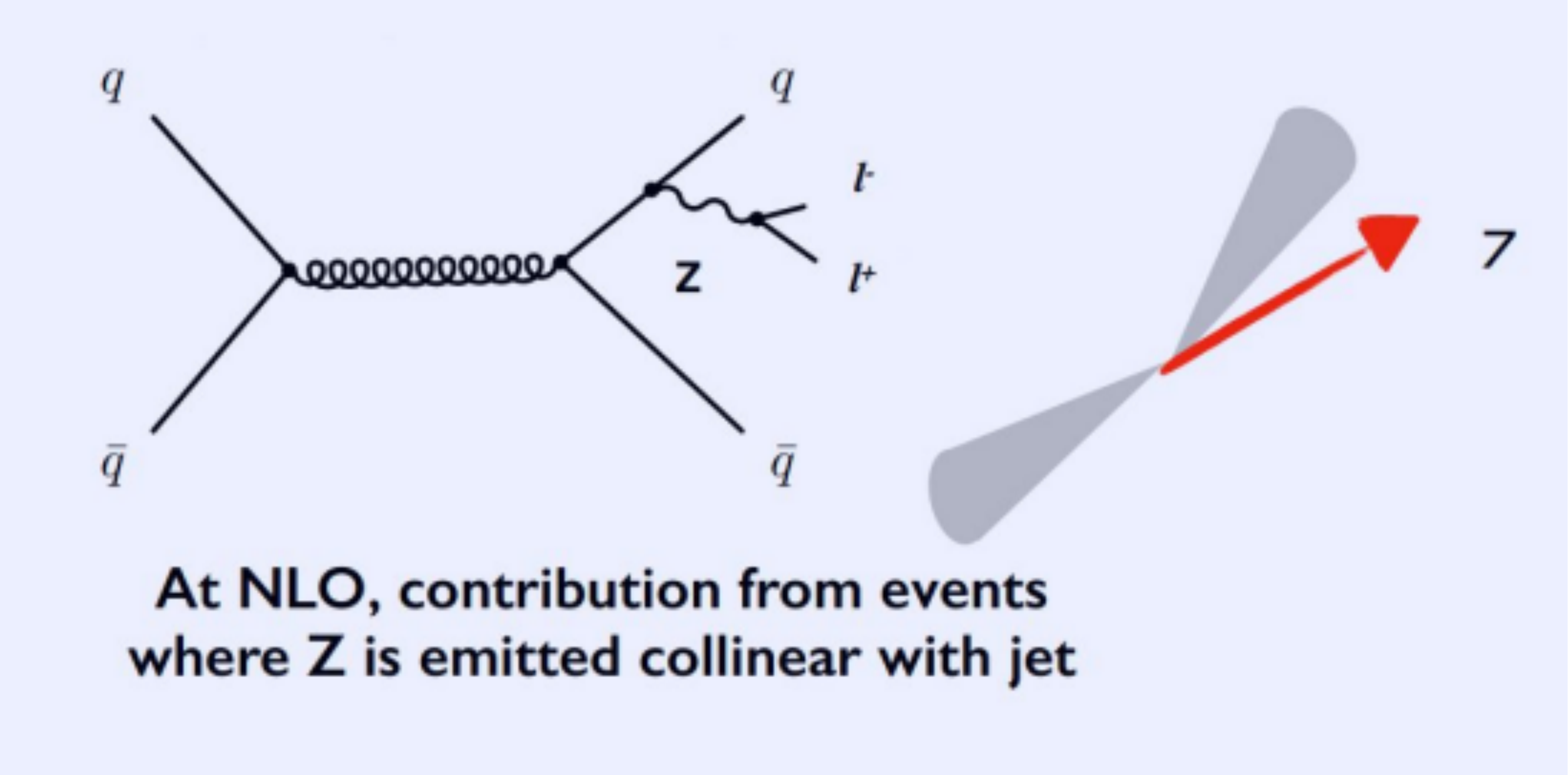
backup

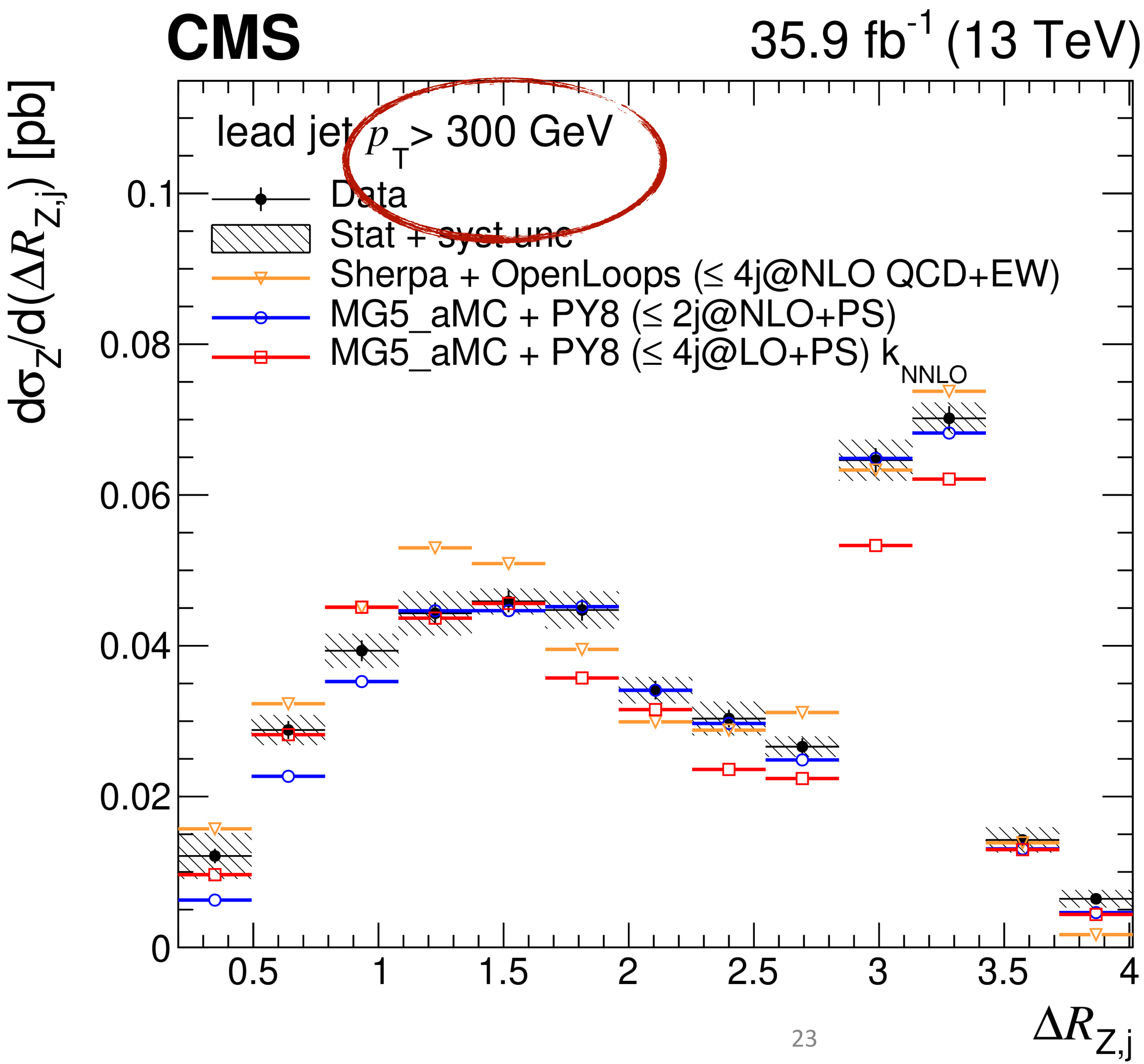
Collinear Z emission

JHEP 05 (2021) 285

First study of collinear emission of Z at the LHC







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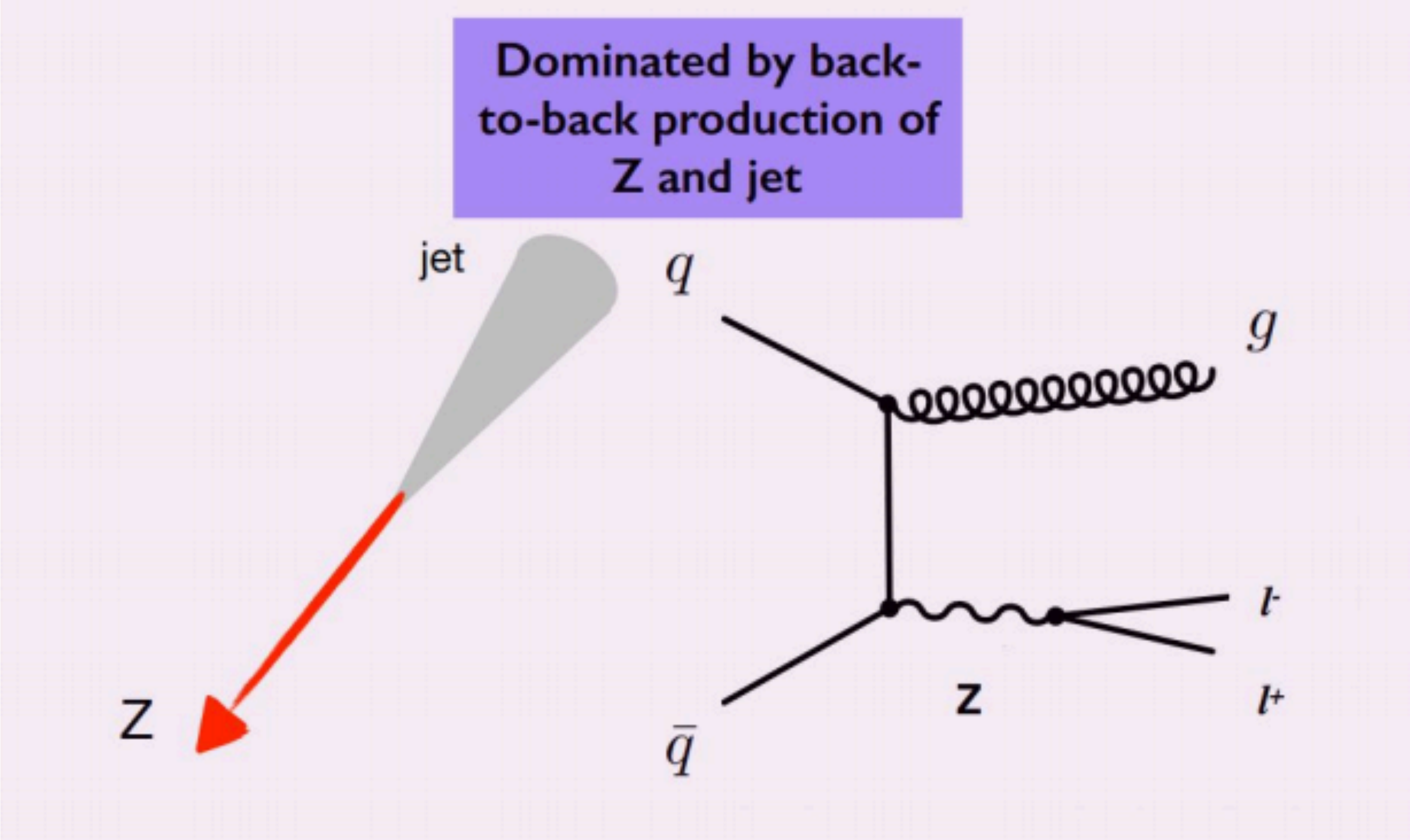

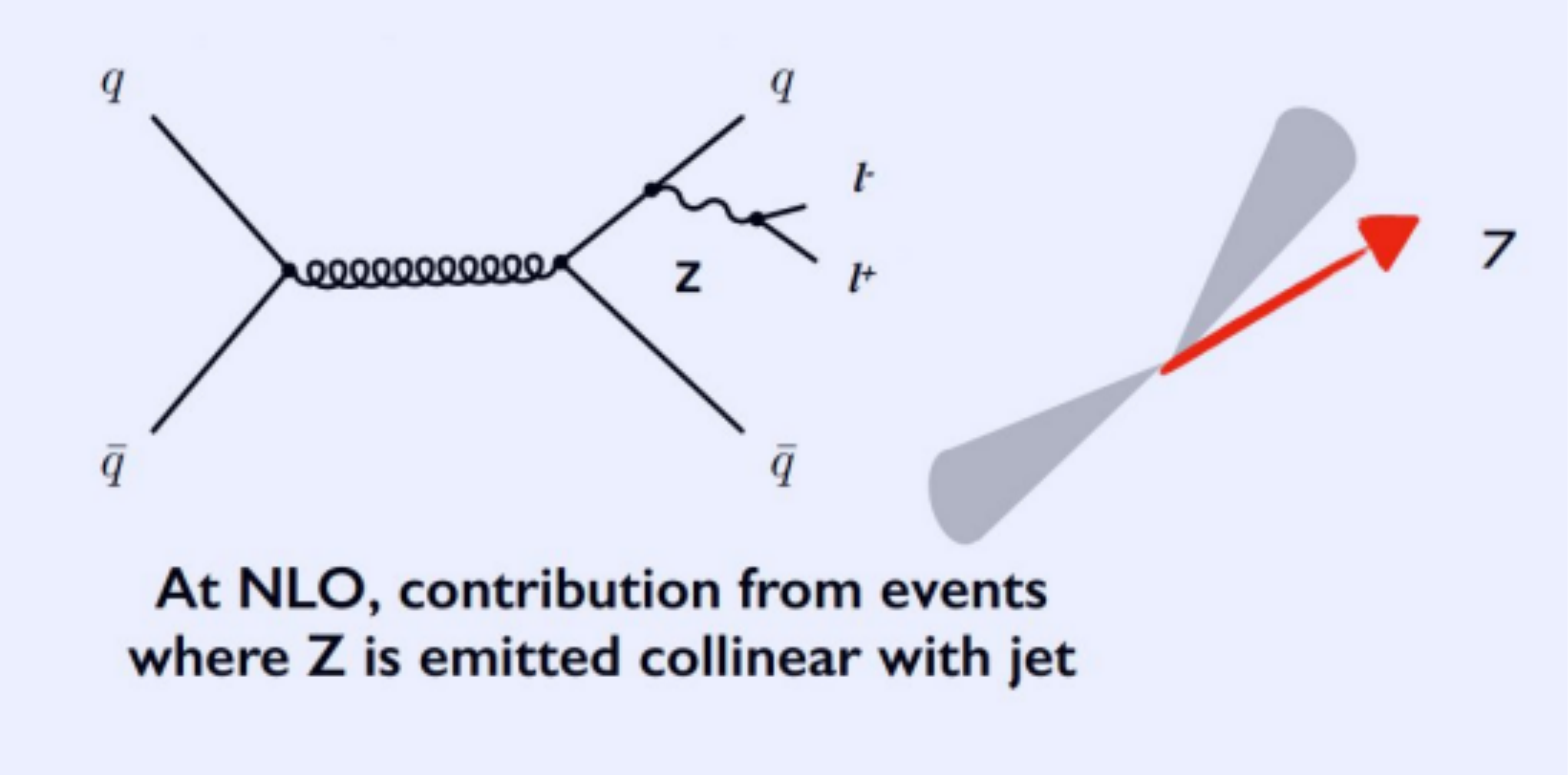

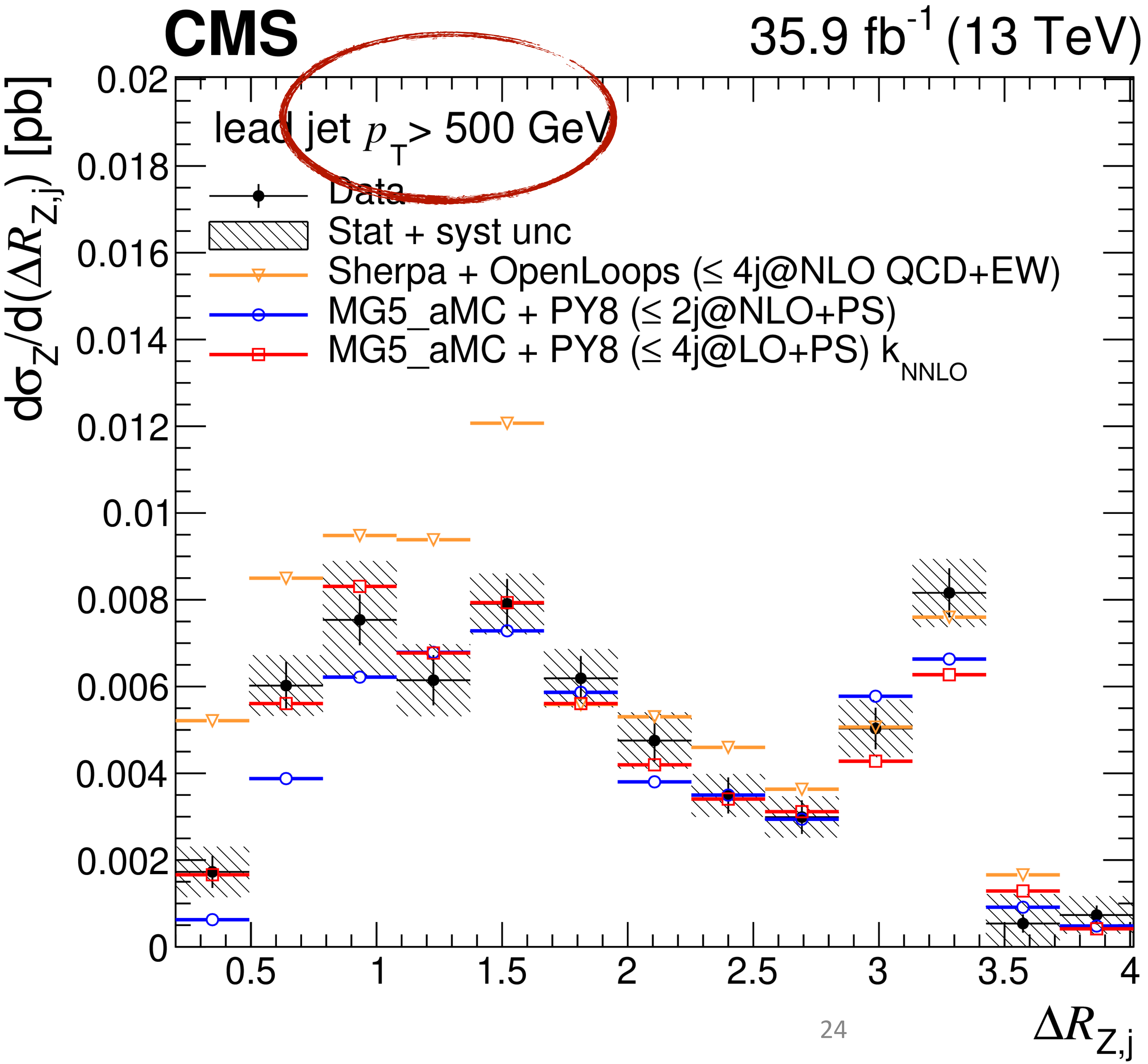

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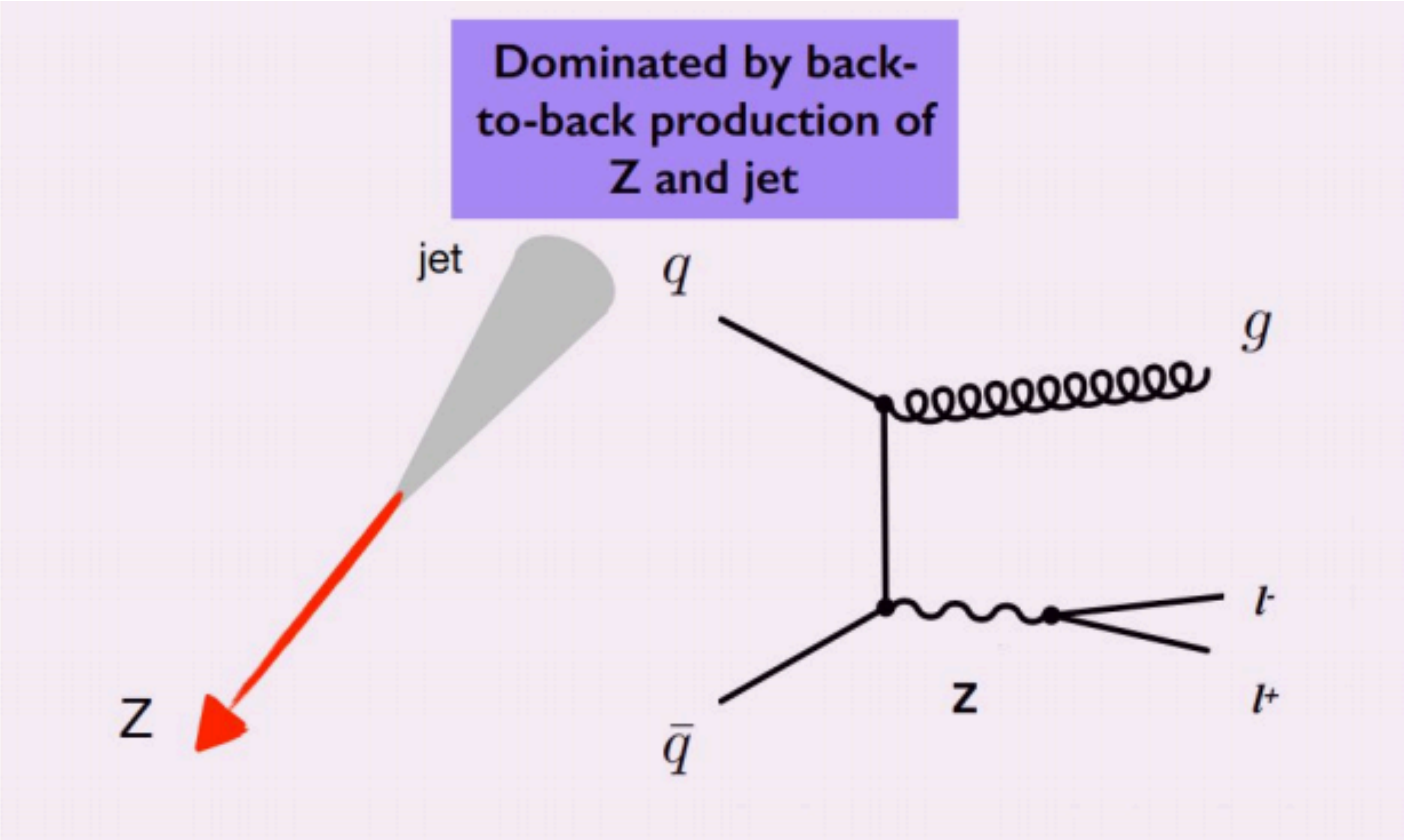
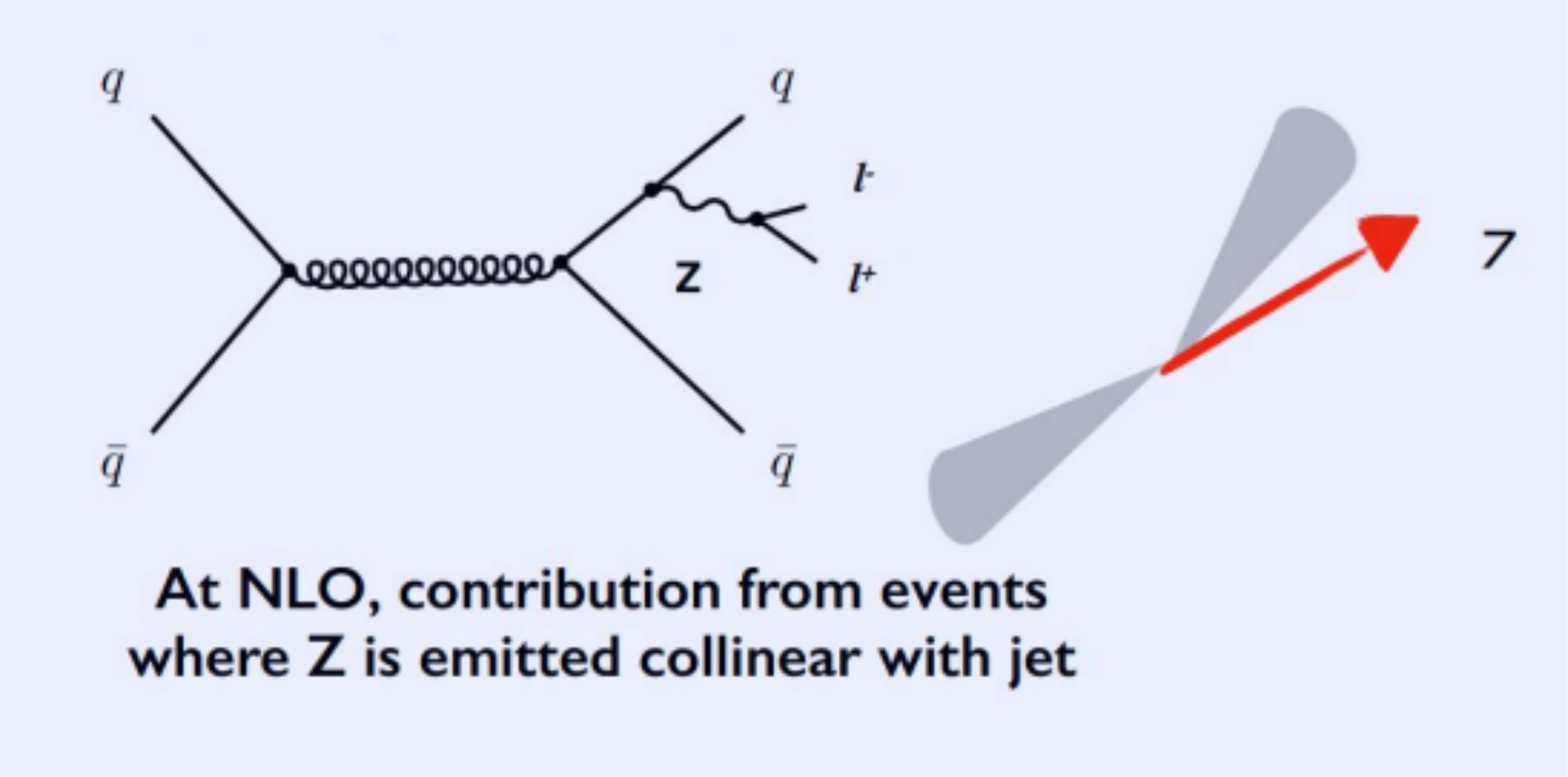
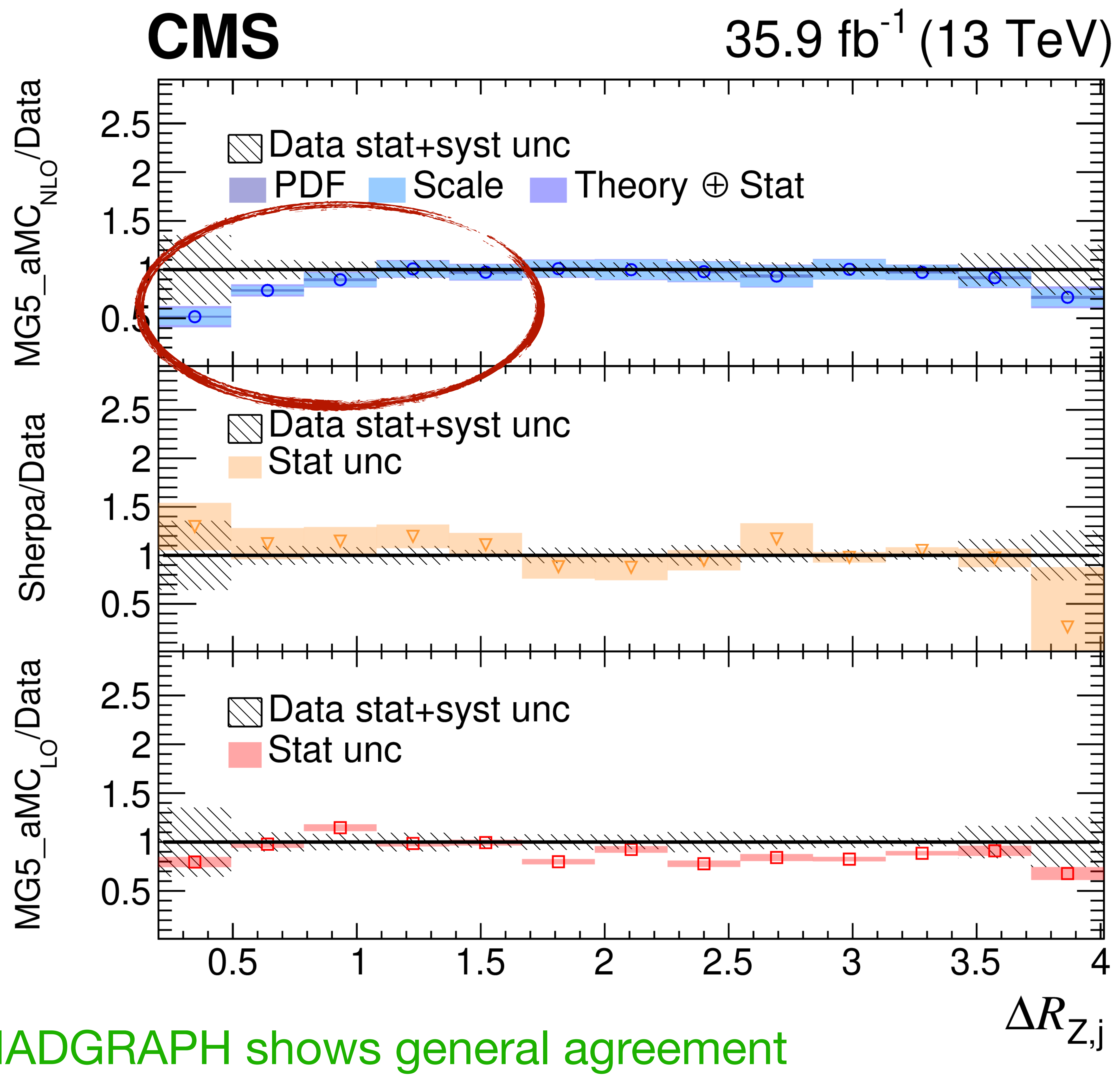






NLO MADGRAPH shows general agreement

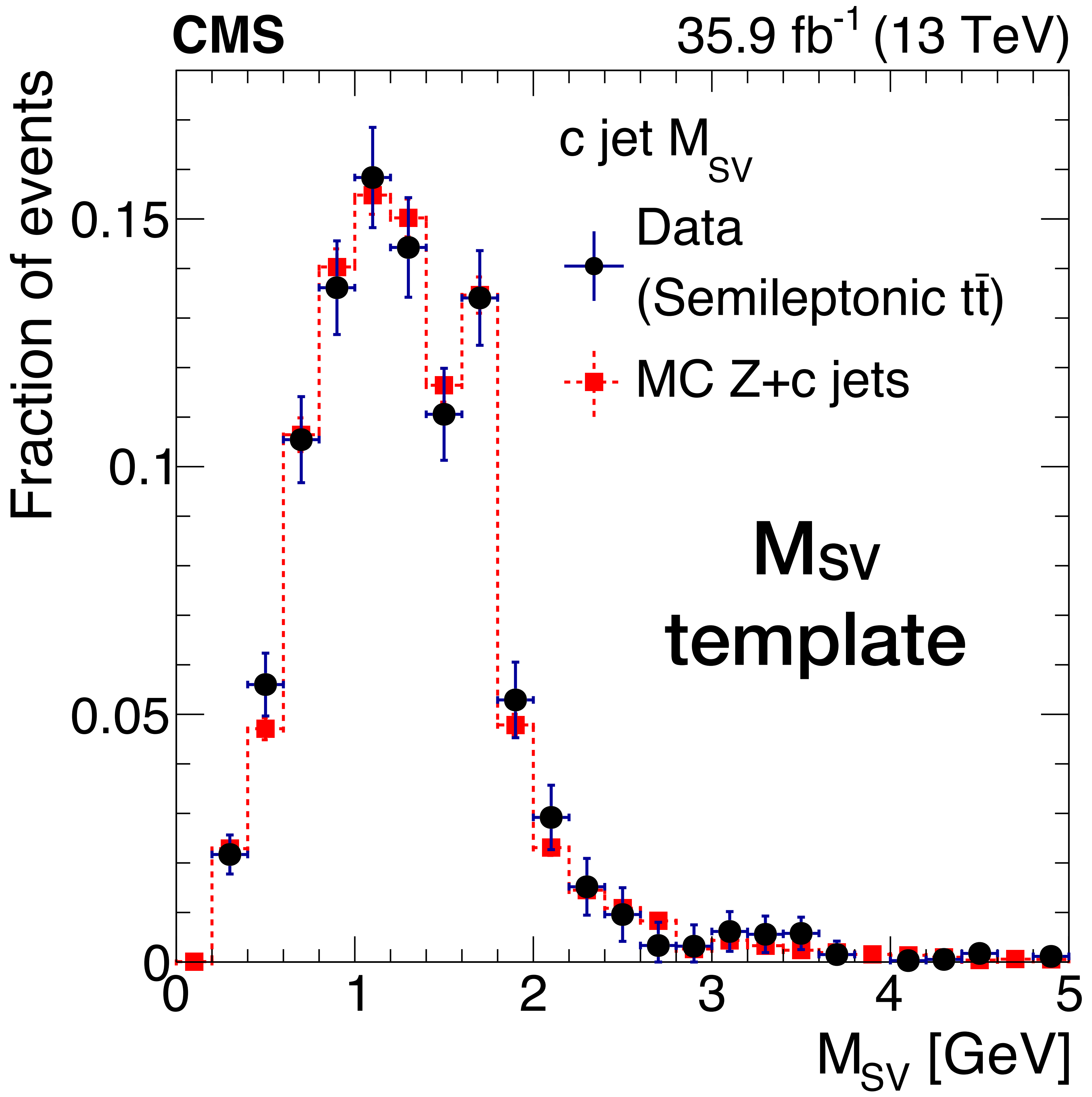
mismodelling at ΔR(Z,J) below 0.8, dominated by events with the mission of a Z boson in close proximity to a jet

Phys. Rev. D 102 (2020) 032007

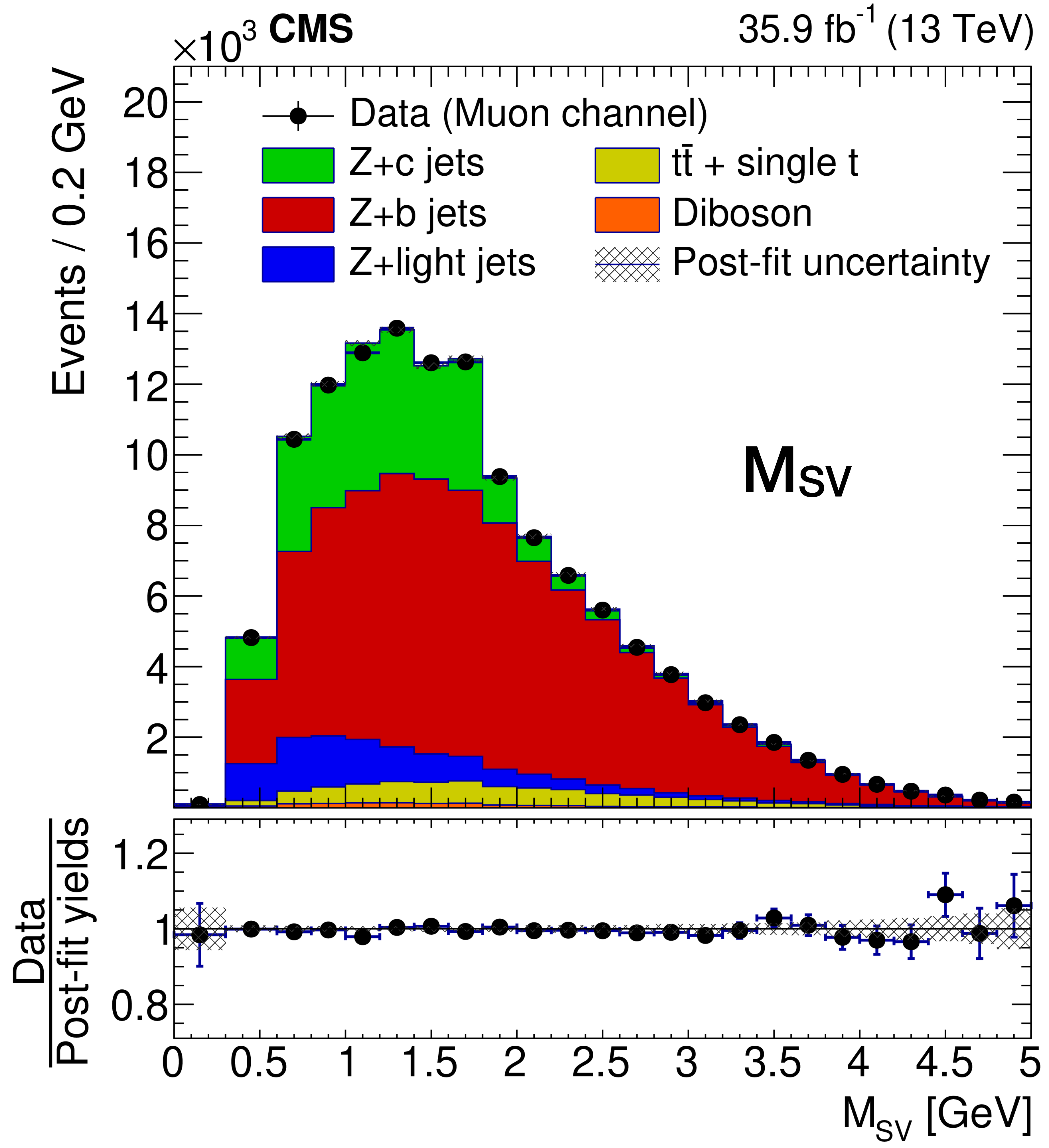
Z+b/Z+c, Z+b/Z+j and Z+c/Z+j

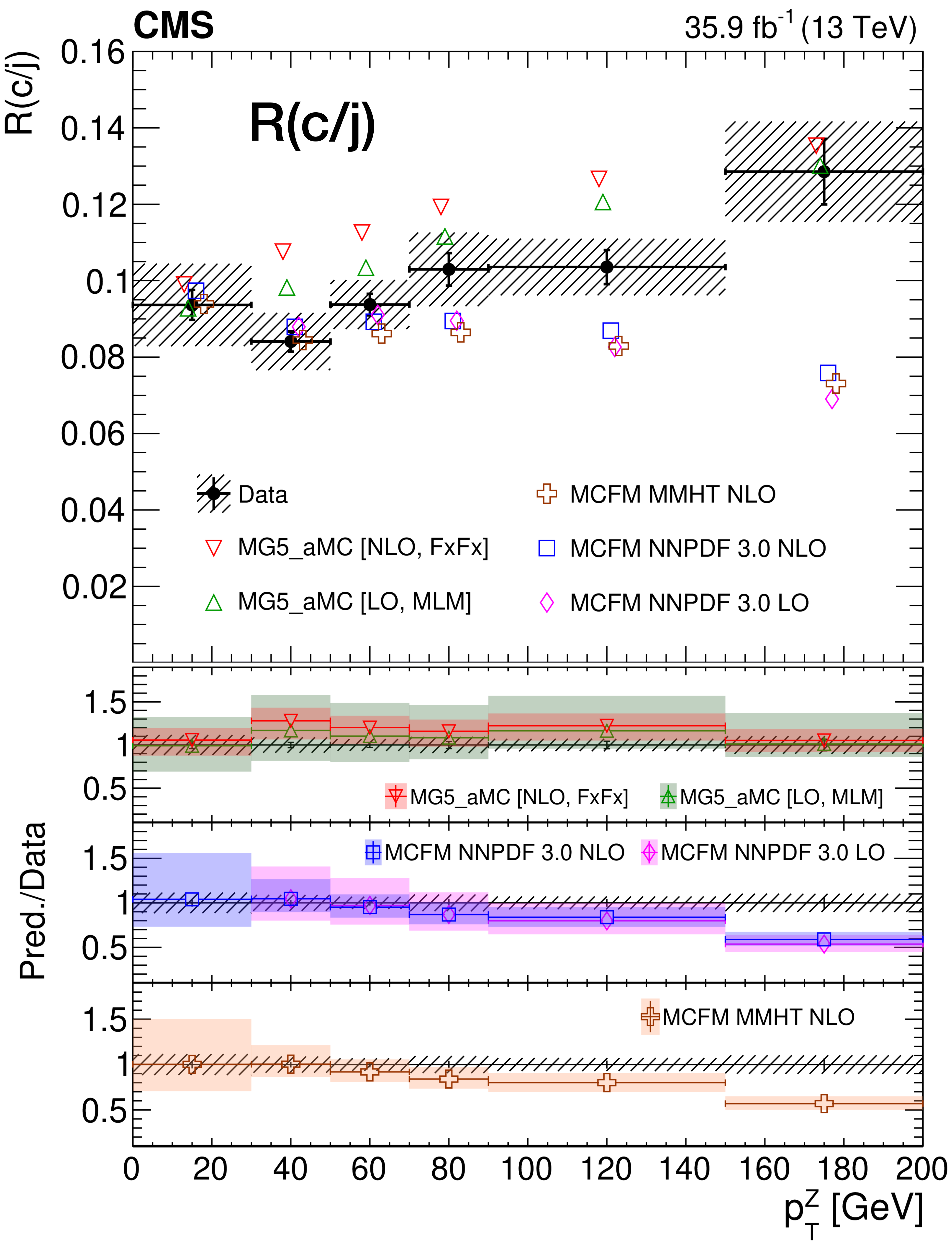
- pp collisions @13 TeV, 35.9 fb^{-1} data (2016)
  reduce impact of several systematic uncertainties
- Important test of pQCD, background to ZH production
- Measured inclusive and differential cross-section as function of p_T jet and $p_T(Z)$ compared to LO and NLO QCD predictions

- σ(Z+b/c) / σ(Z+jets) and σ(Z+c) / σ(Z+b)



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

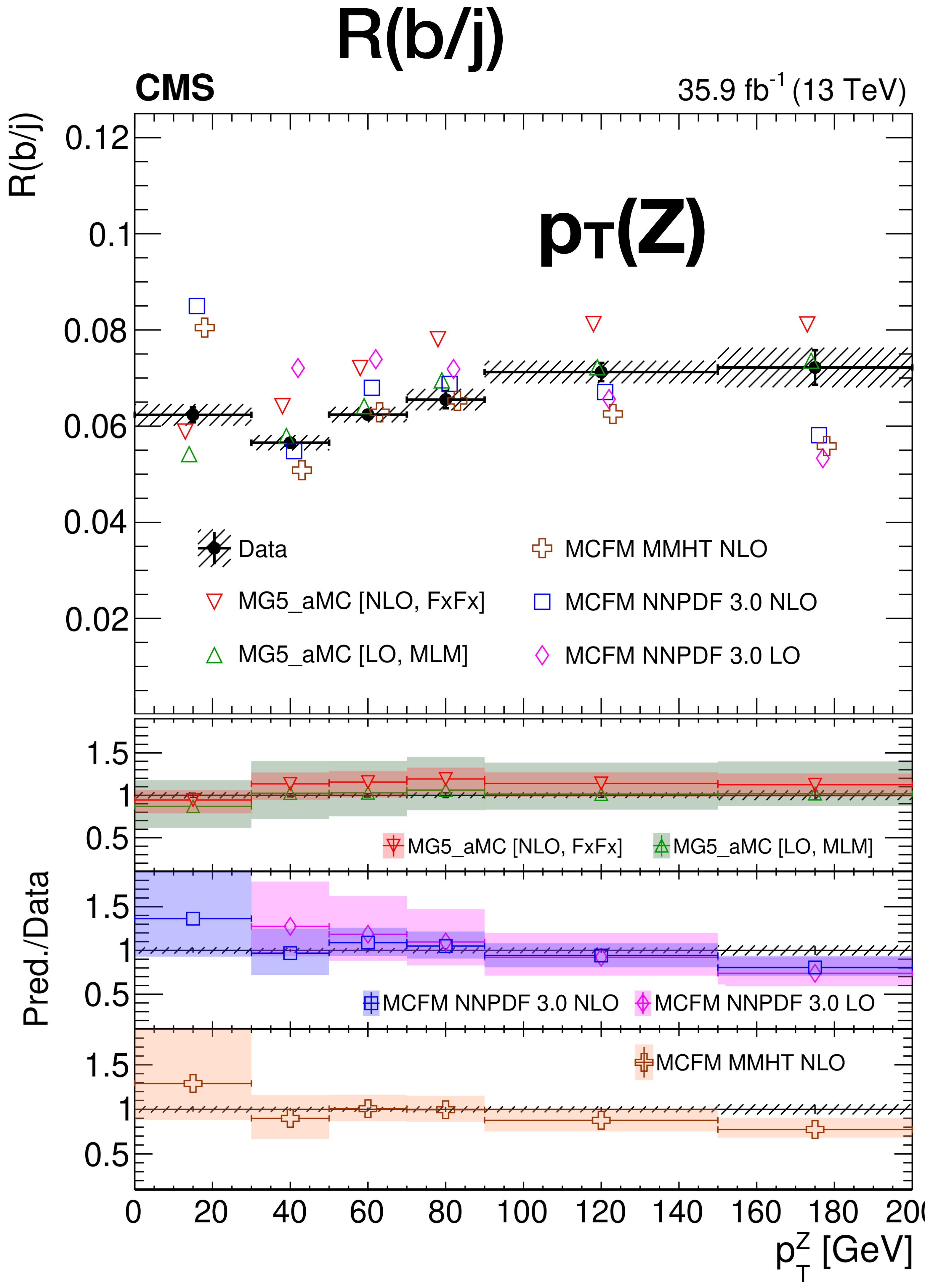


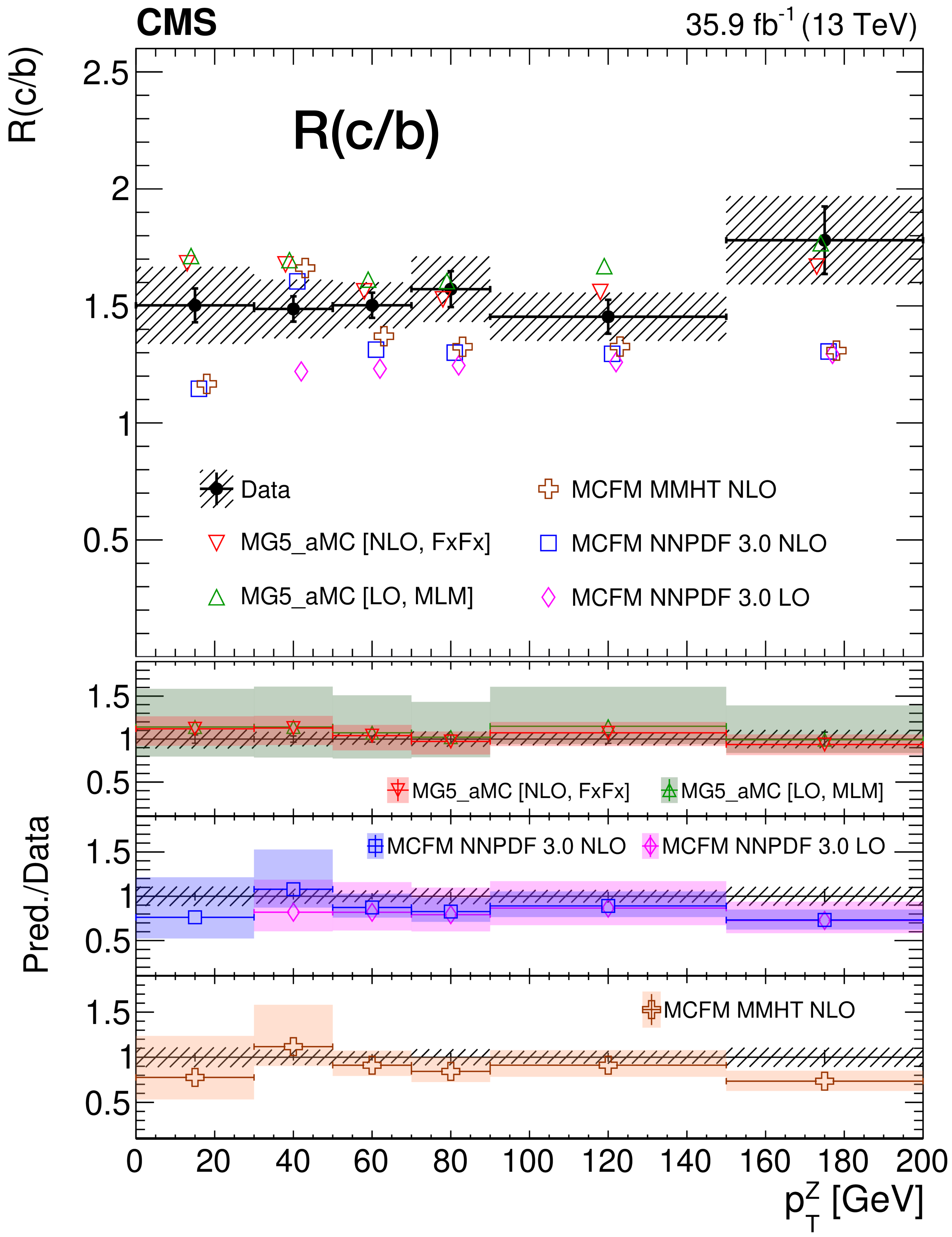


NLO MG5_aMC (NNPDF) and **LO MG5_aMC (NNPDF)** predictions **higher but compatible with data** in most bins

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 $p_T(Z)$**



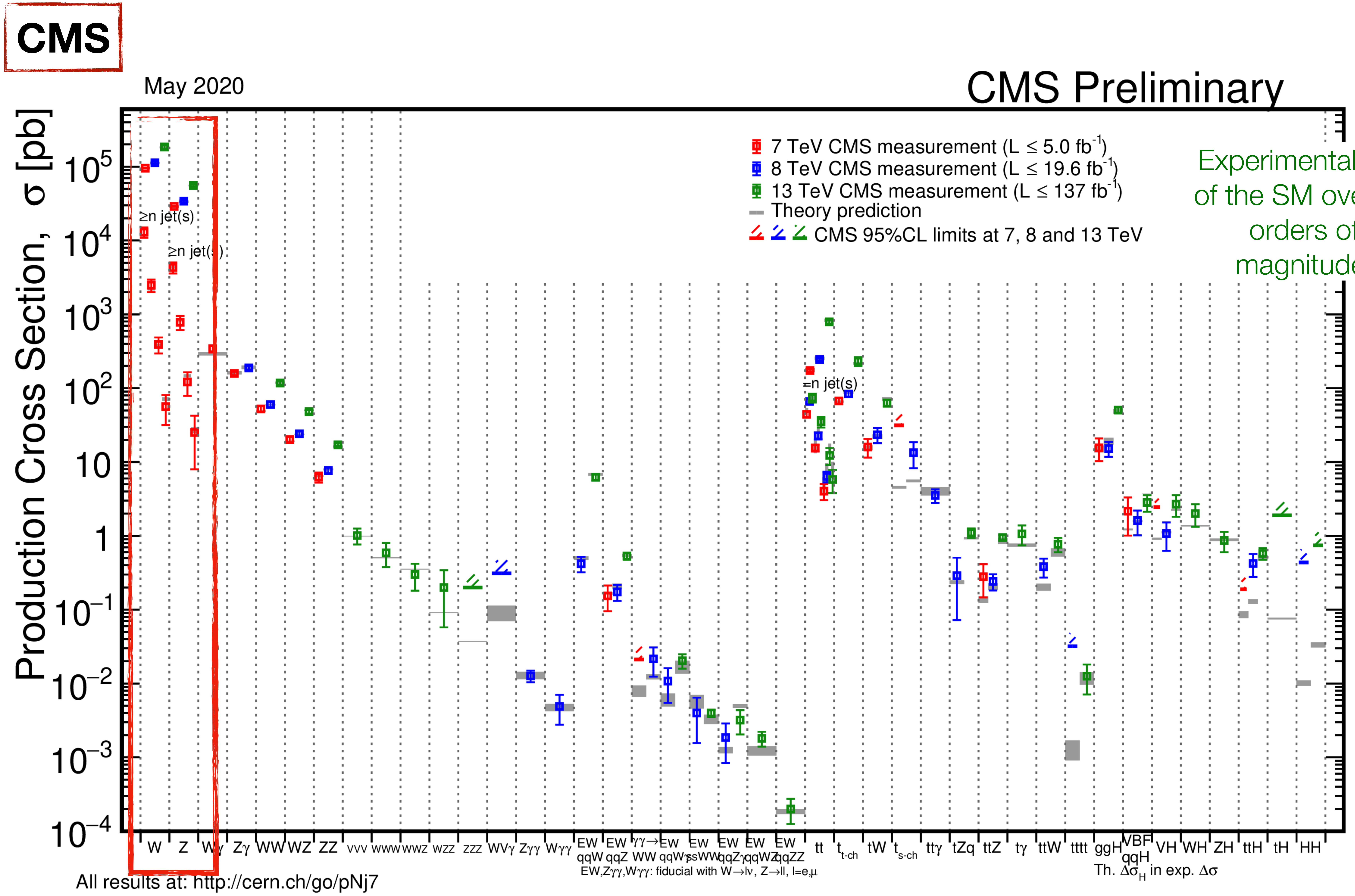


NLO MG5_aMC (NNPDF) and **LO MG5_aMC (NNPDF)** predictions **higher but compatible with data** in most bins

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 $p_T(Z)$**

Standard Model measurements in 2020



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

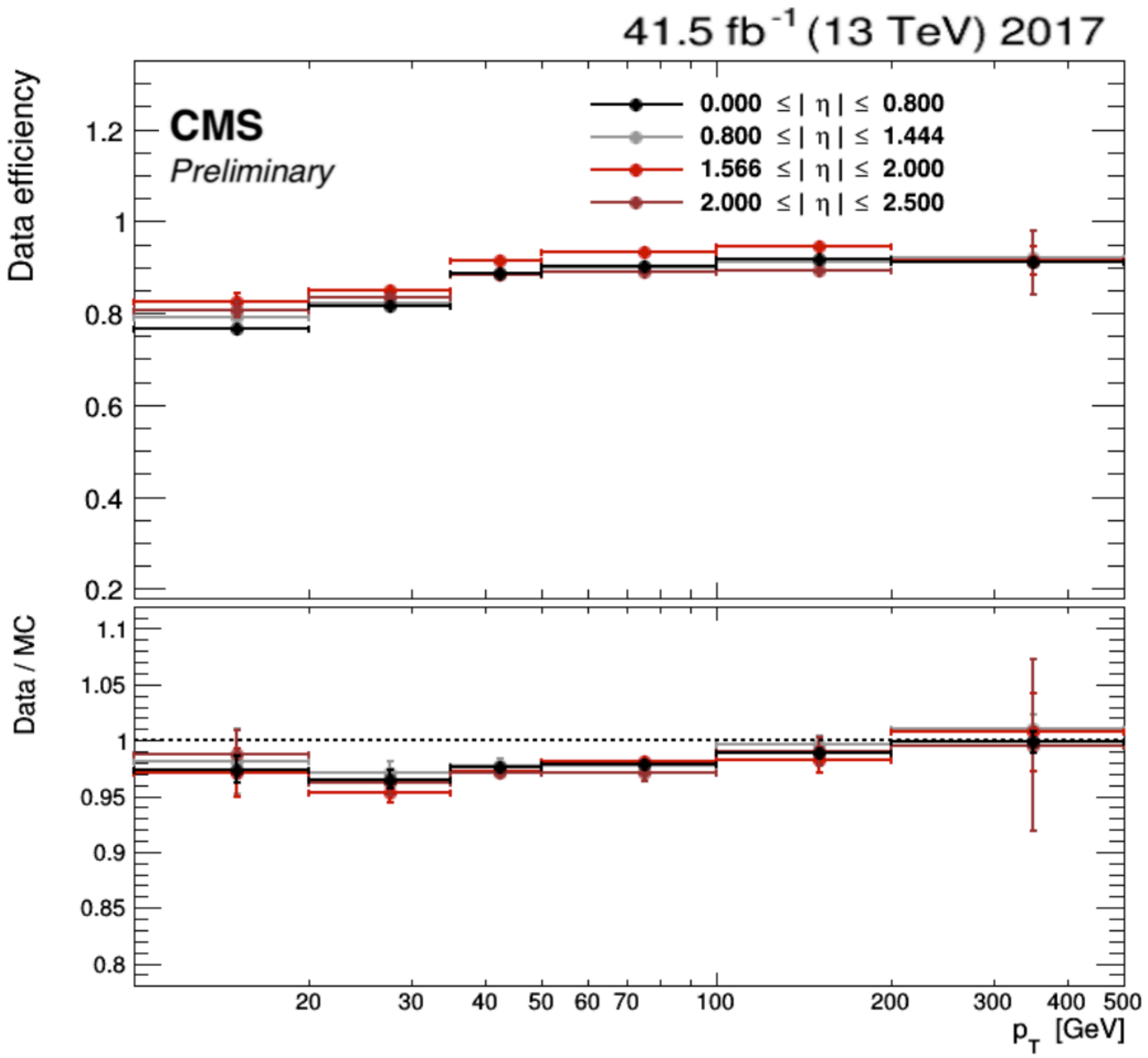
several (CP5) PYTHIA8 tunes

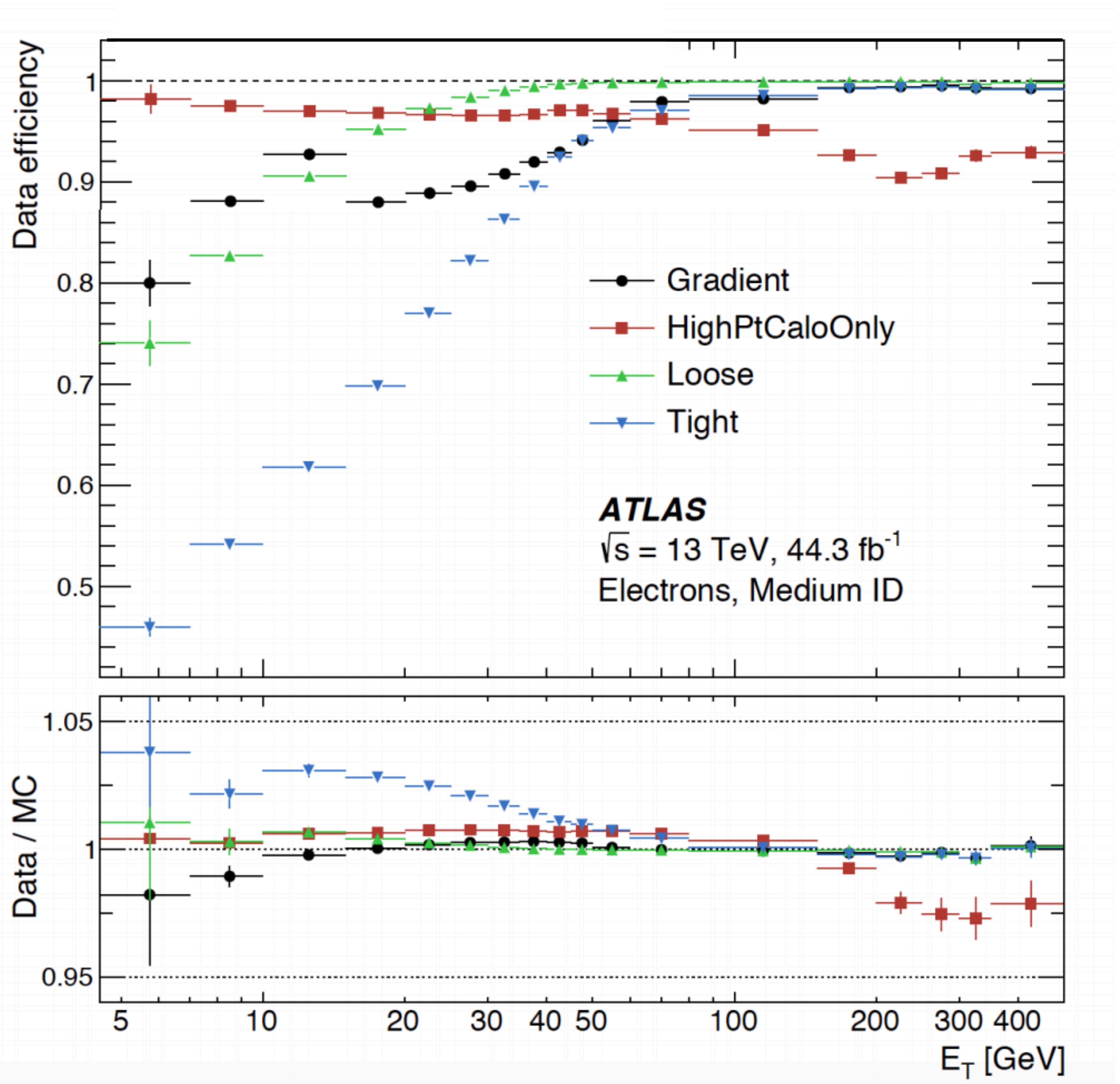
- **HF treatment**
  - 4FS, b mass and 4 PDFs
  - 5FS b mass=0 and 5 PDFs

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

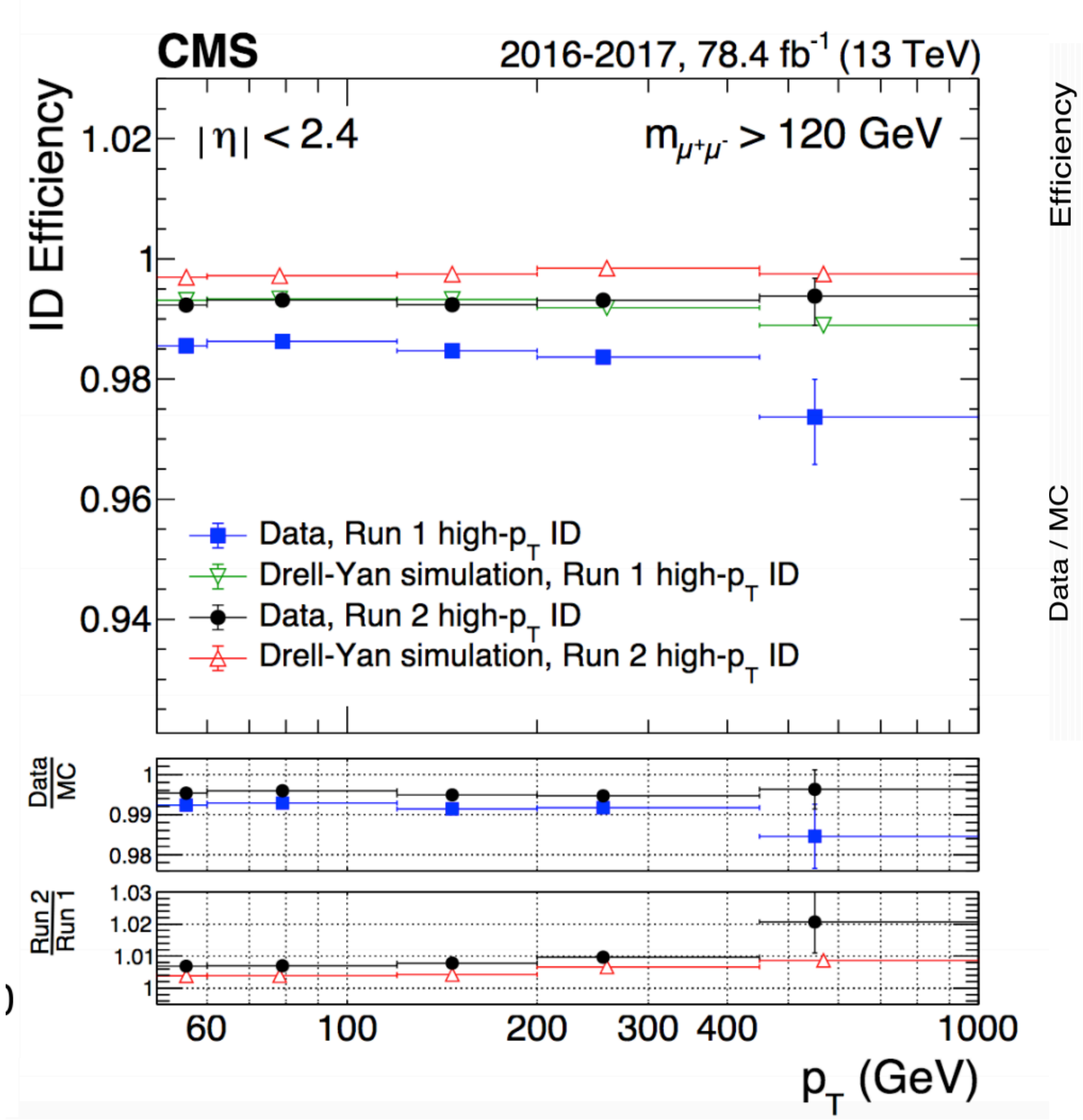




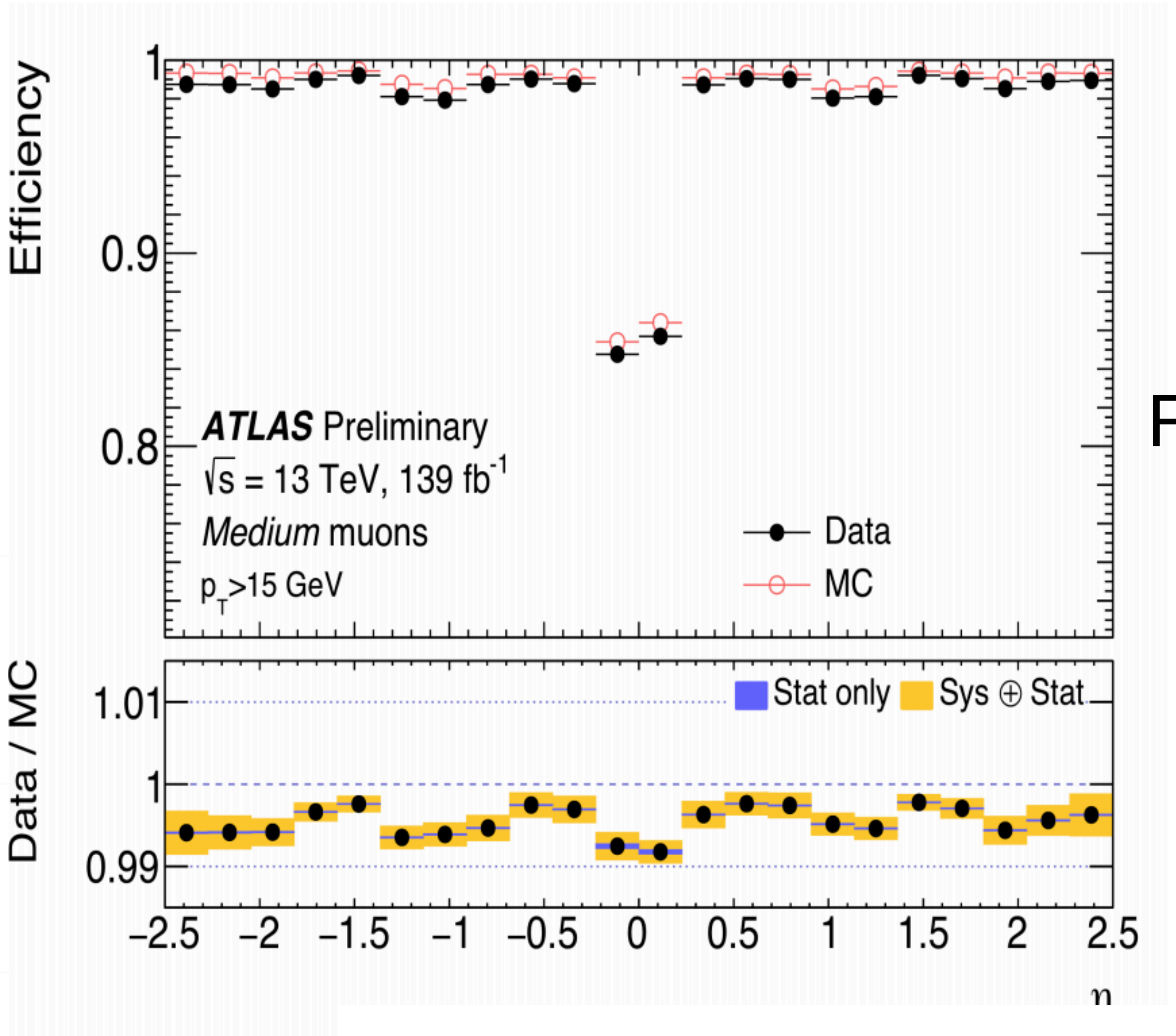
Electrons identification with $Z \rightarrow e^+e^-$ and $J/\psi \rightarrow e^+e^-$

both ATLAS and CMS achieve sub-% precision

How all of this is possible

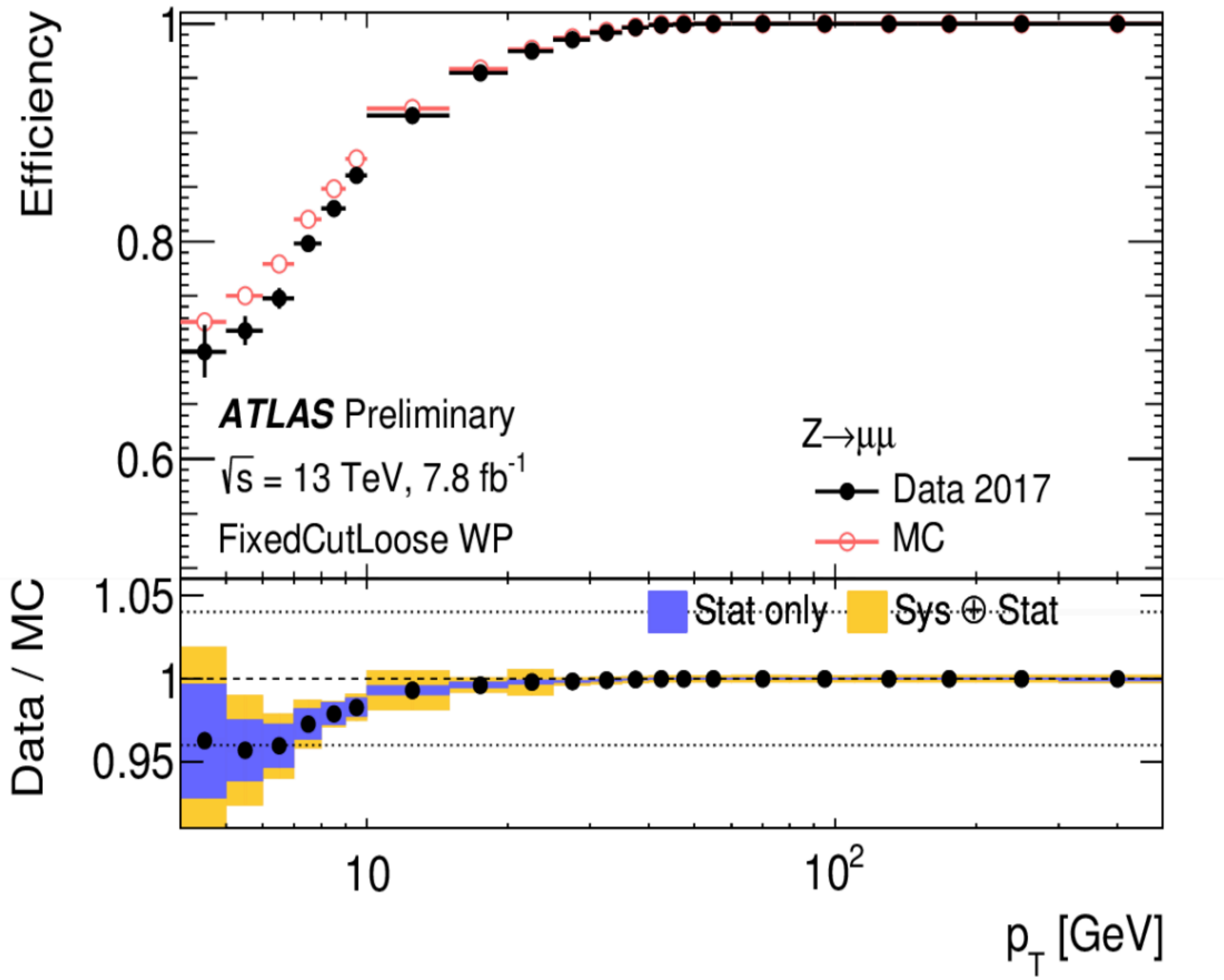


Muons identification with $Z \to e^+e^-$ up to 1 TeV



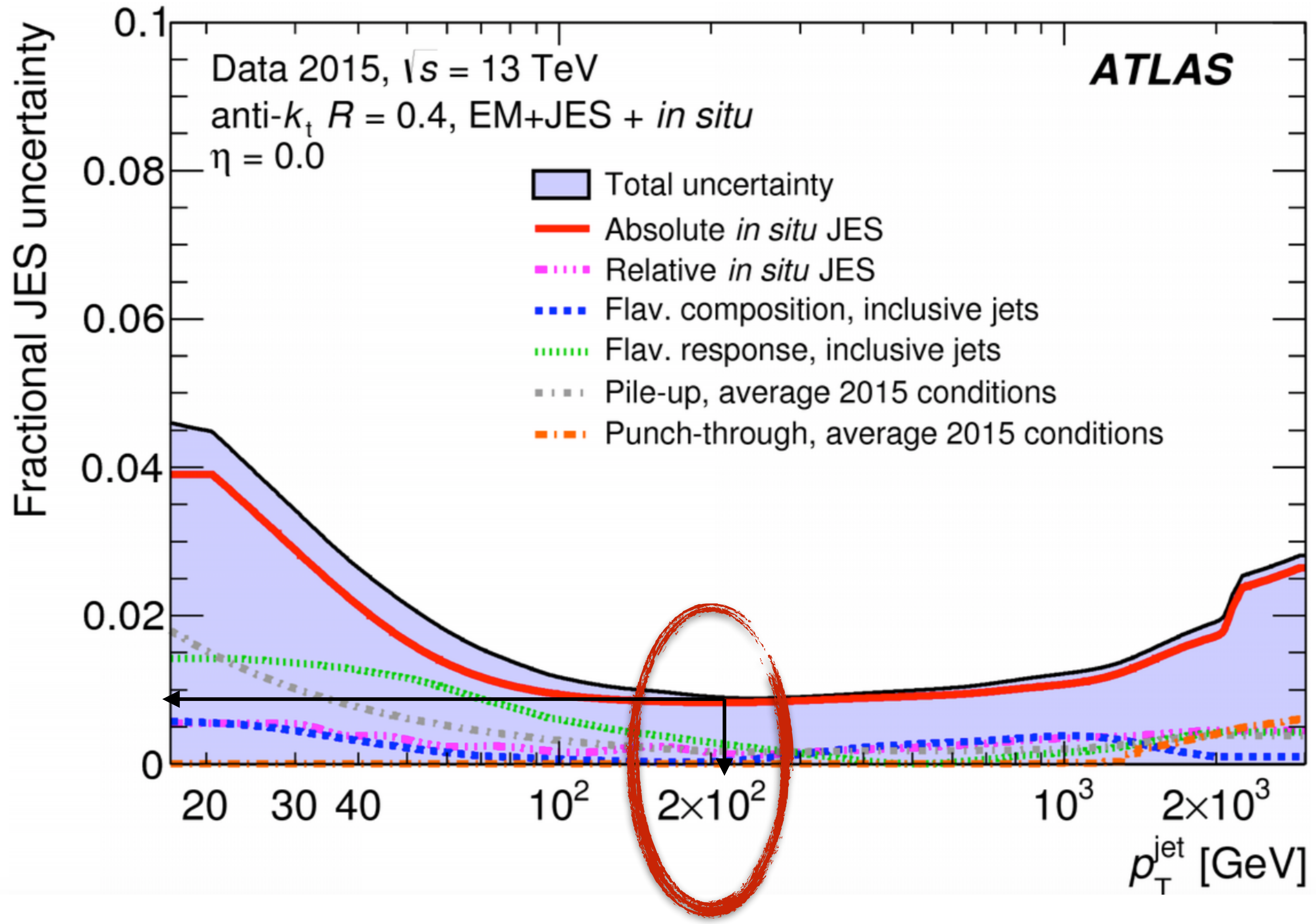
Muons Reconstruction and Isolation efficiency

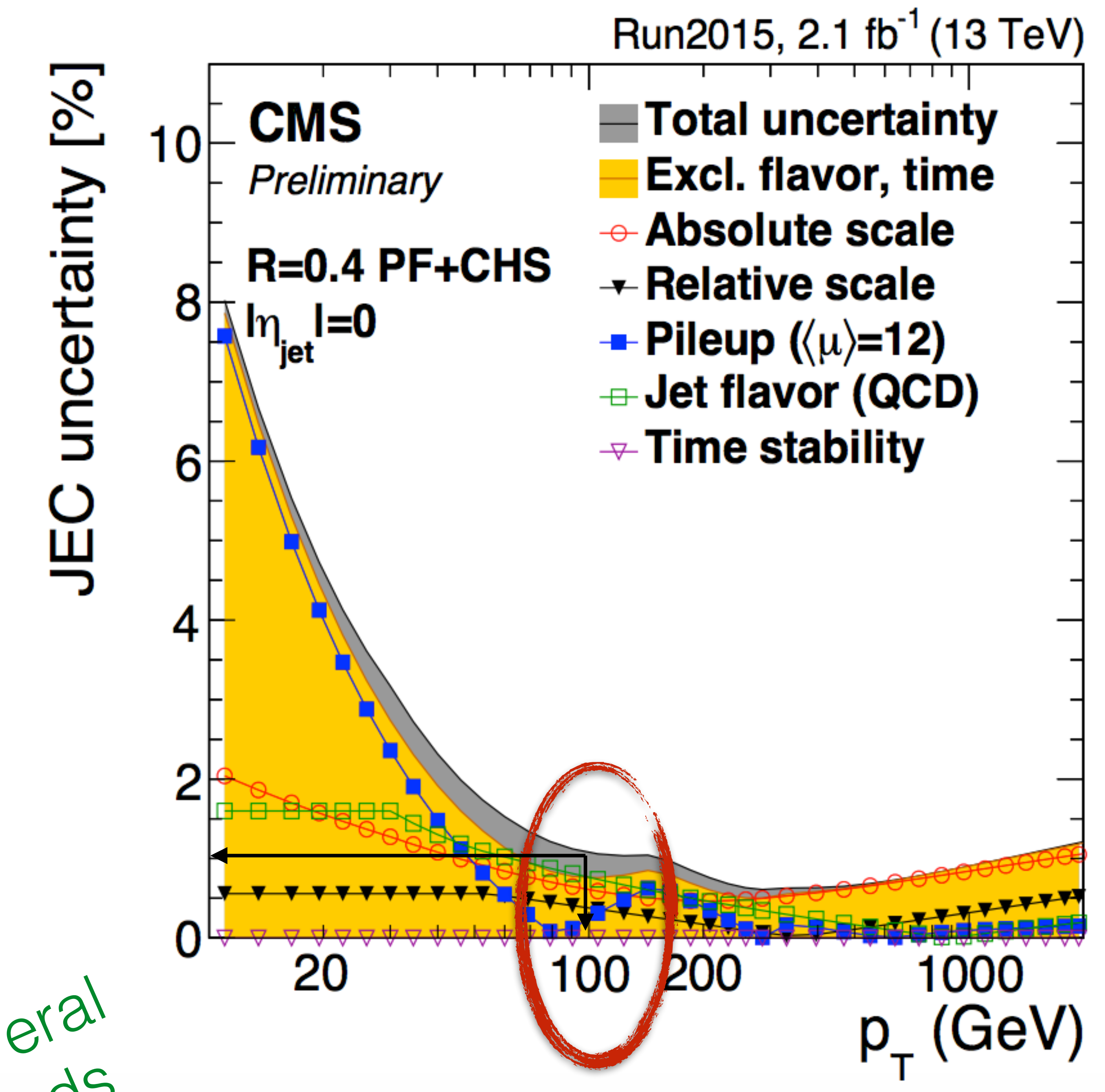
Outstanding precision



How all of this is possible

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





Correct for

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

thanks to several in-situ methods

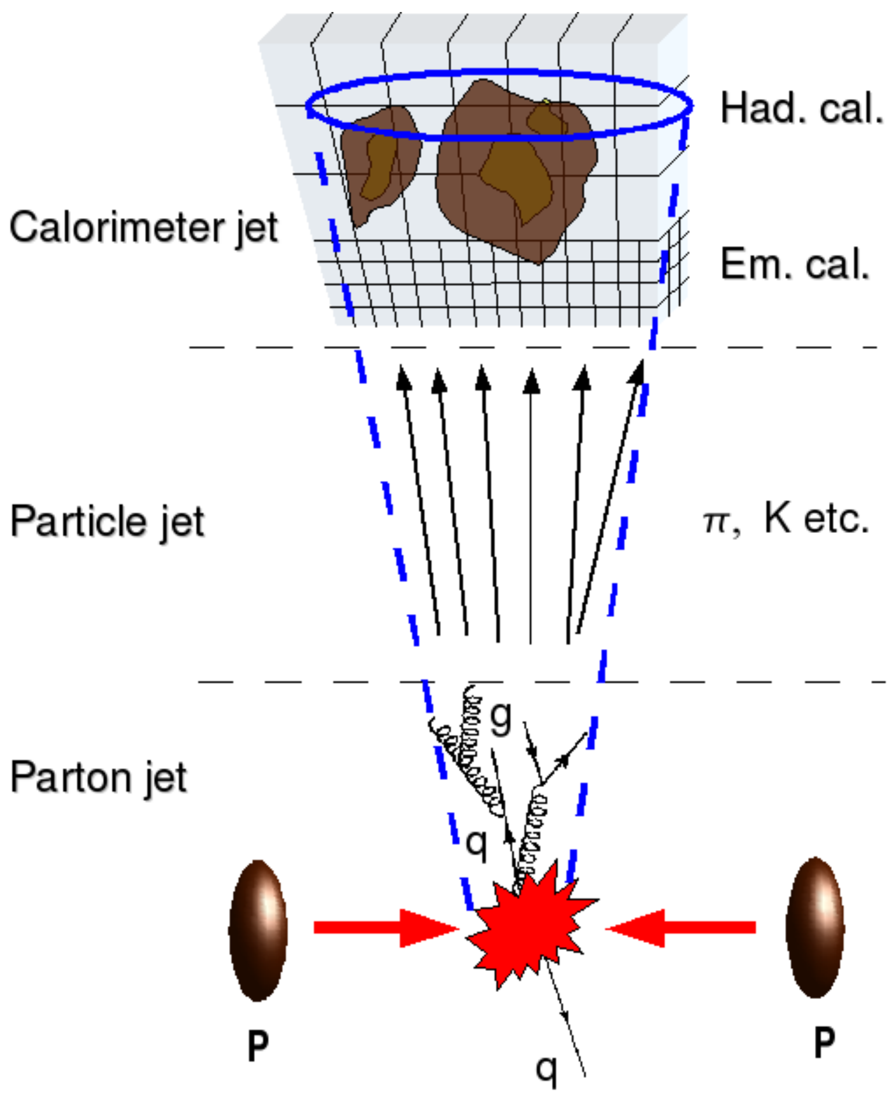
Less than 2% in the region $p_T > 100$ GeV!

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)

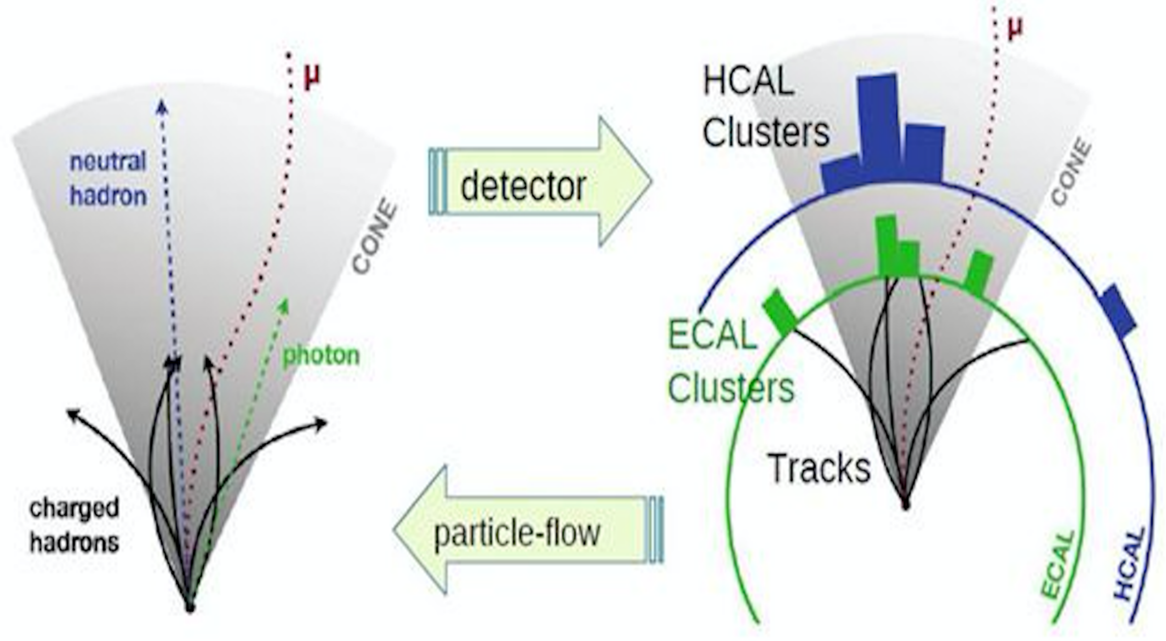
LHCb: R=0.5

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

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

CMS

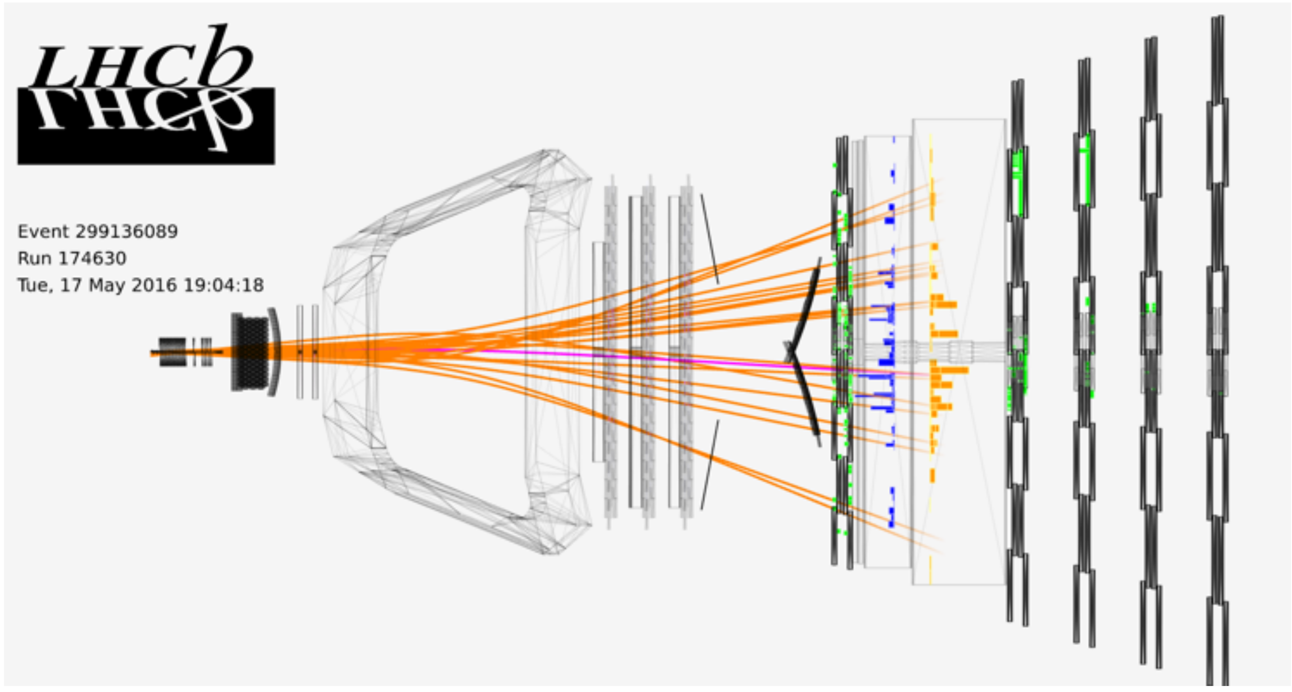
particle-flow



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

↓

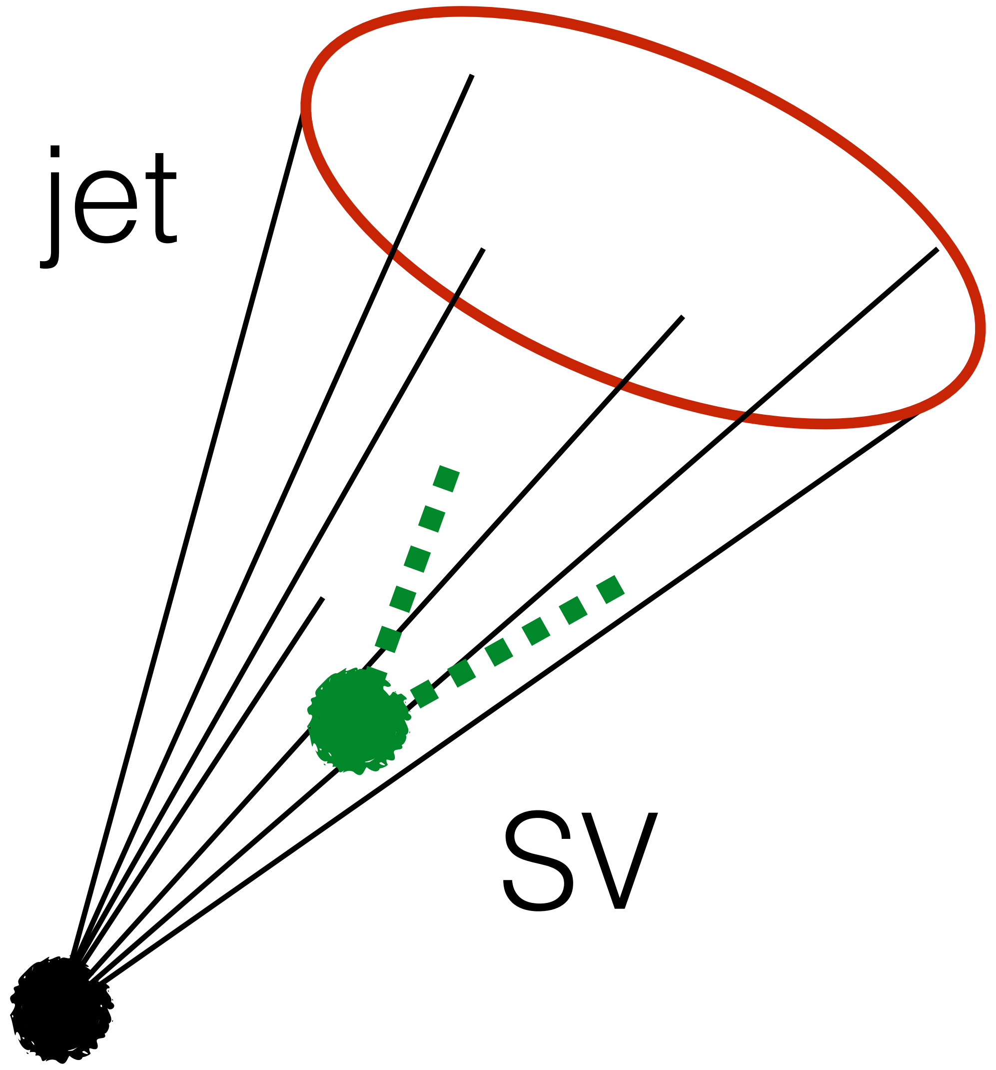
use the precise tracking information → use particles! (Λ,Ks,π,..)

Heavy flavor tagging at collider

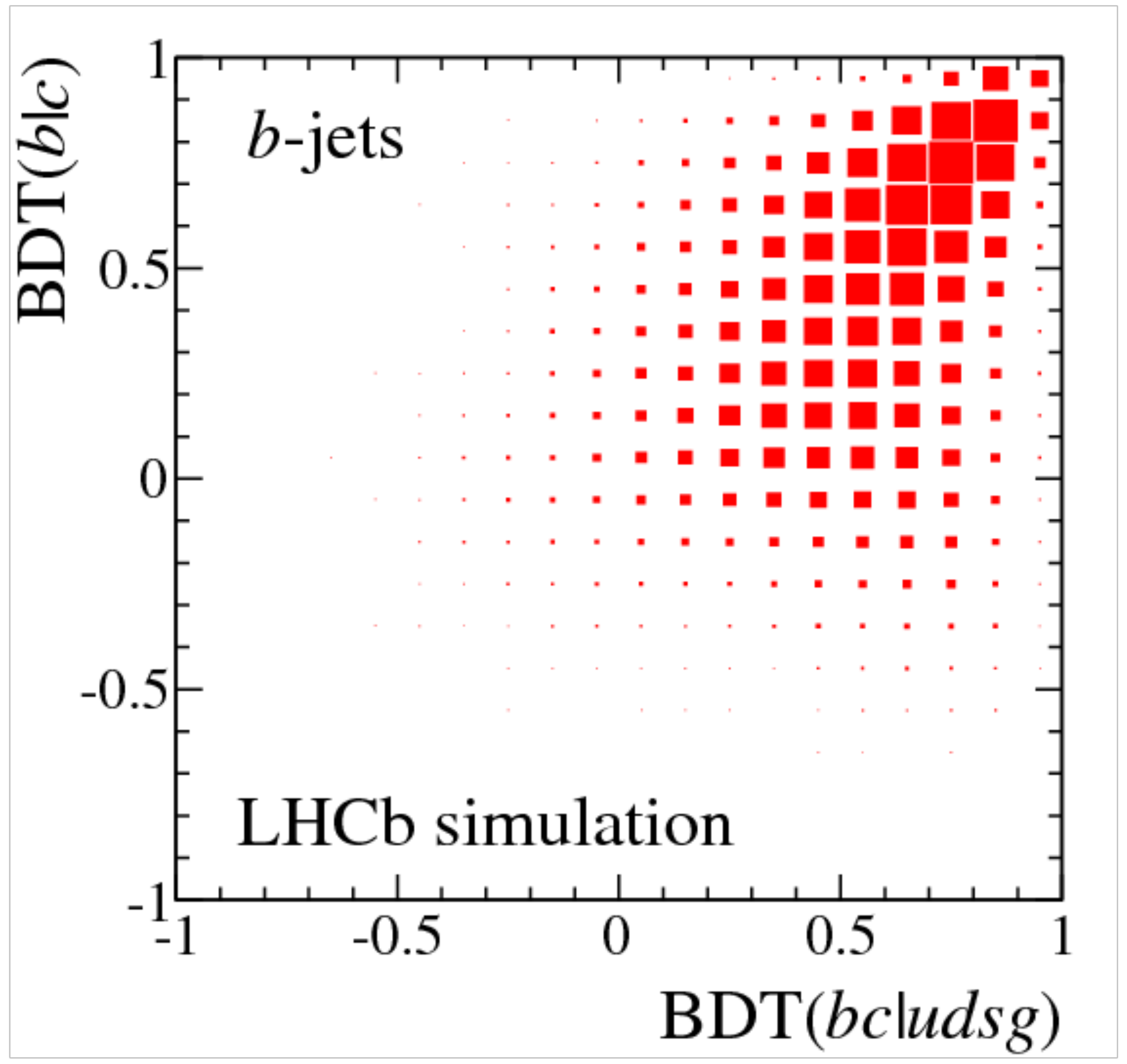
recipe

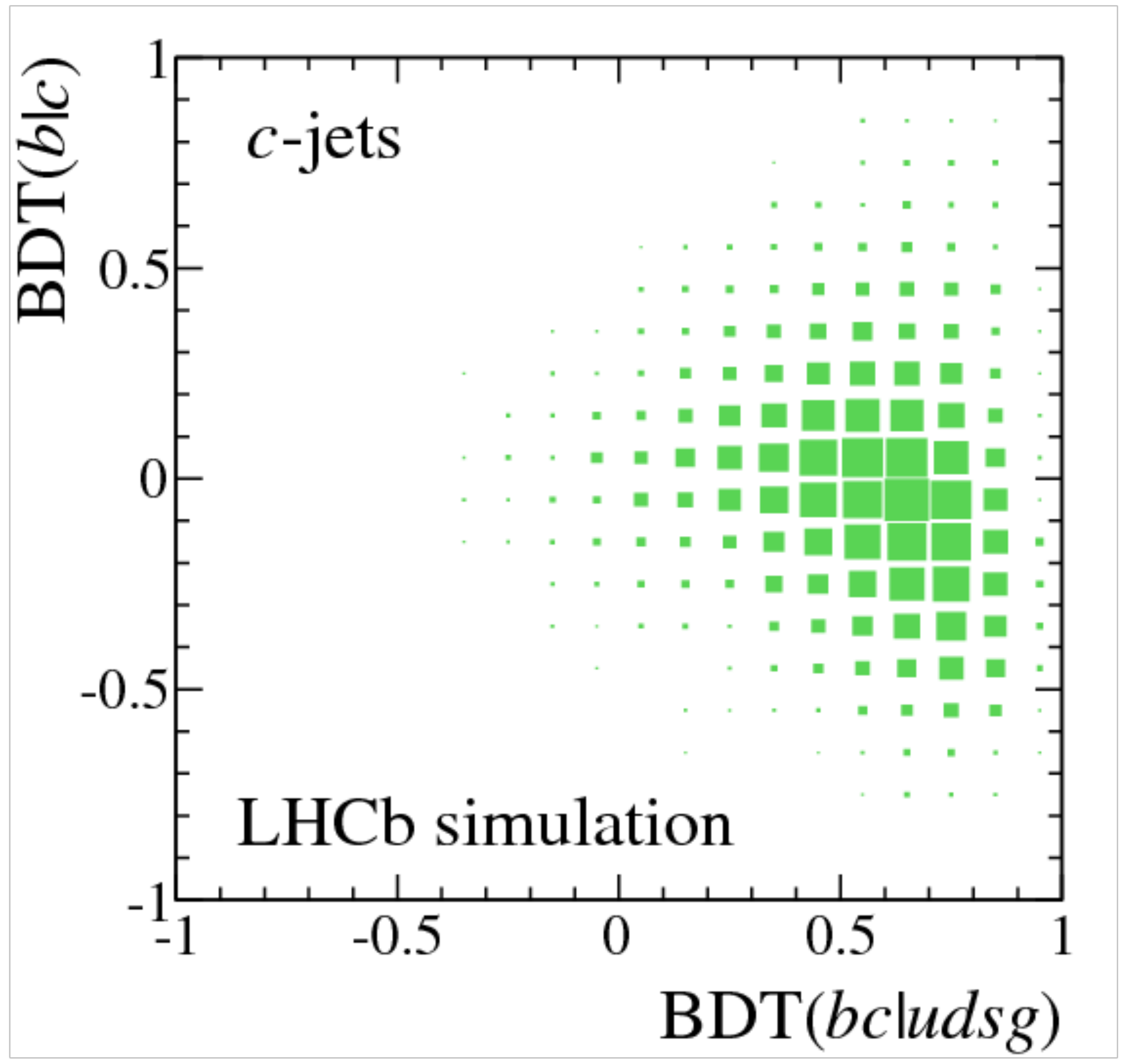
JINST 10 (2015) P06013

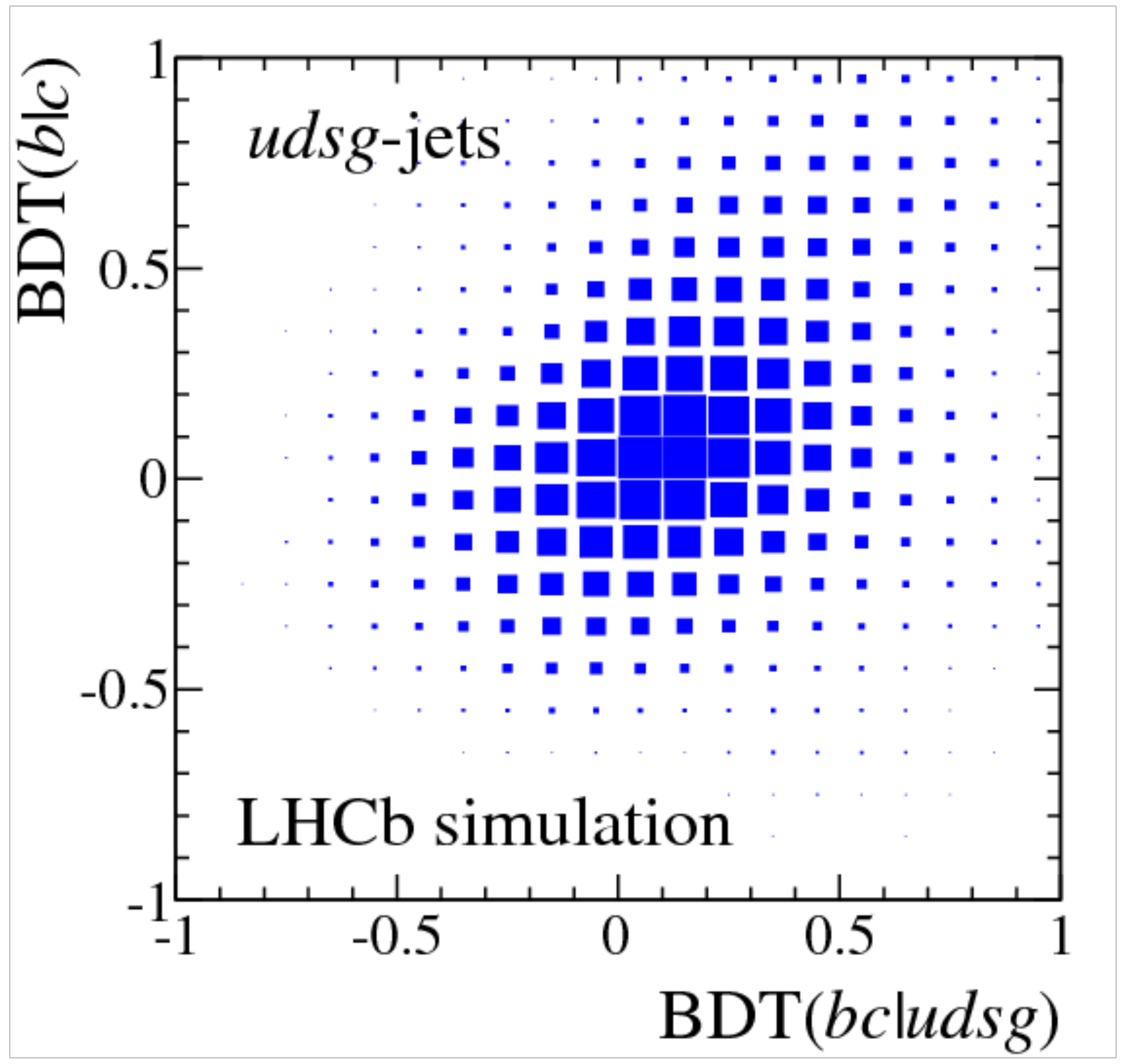
- reconstruct jets with the anti-kT05 algorithm
- tagging using b- and c- inclusive tagger
- reconstruct the two-body vertices in the event
- merge SV n-body by linking tracks and vertices associated
- associate vertices/jets requiring ΔR(SV, jet) < 0.5



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

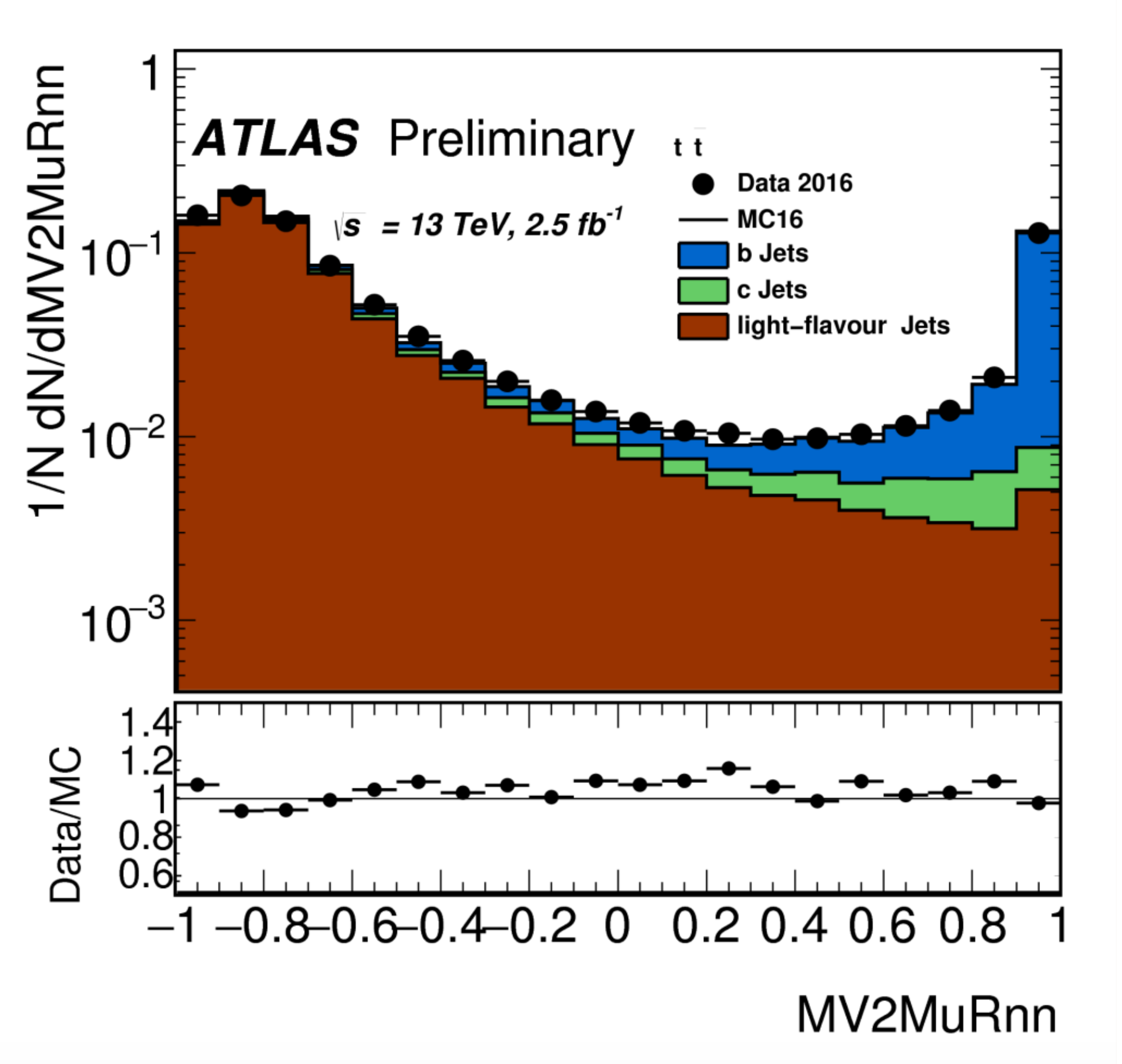
- several taggers:
  - track based (impact parameter tag)
  - soft muon (discriminate μ from b decays)
  - vertex based
- high-level taggers: MVA using all the information available to maximize the b-tag performance

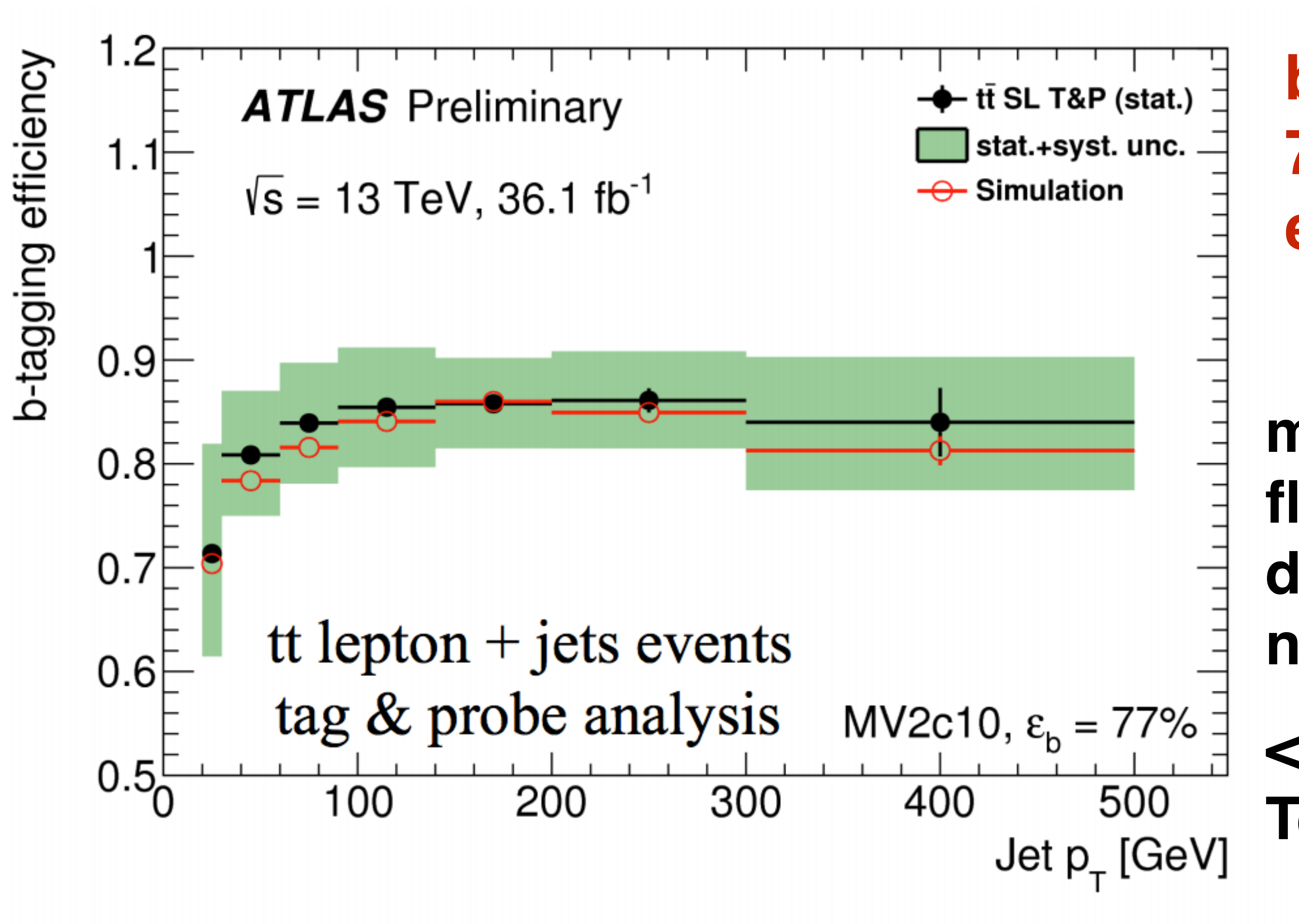
BDT — trained on top + Z'bb events (*hybrid training*)

Deep Learning Neural Network

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

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

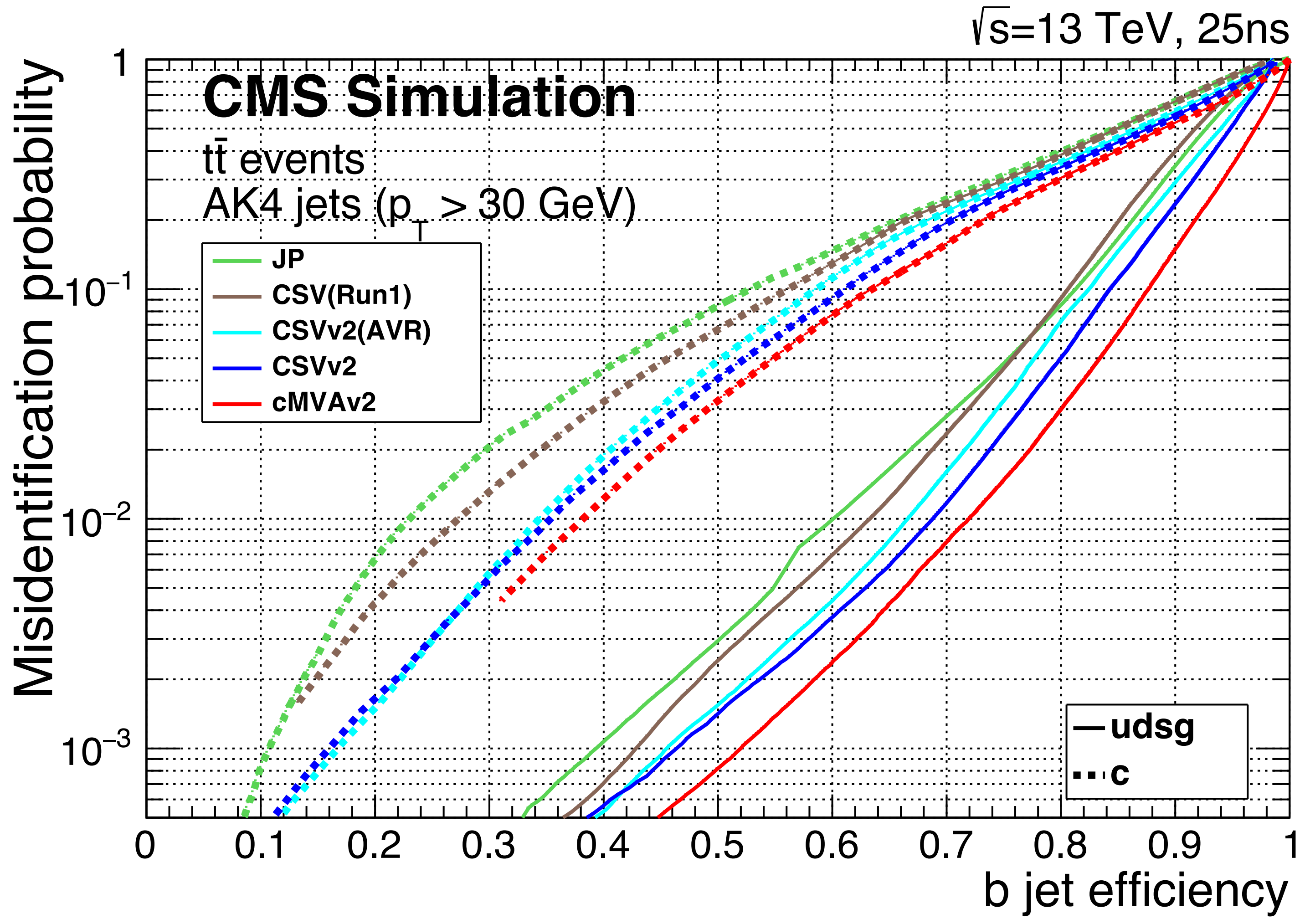
- several taggers:
  - Jet Probability: likelihood that jets is coming from primary vertex using tracks
  - Combined (CSV): combination of displaced tracks with SV info associated to the jet using an MVA
  - **CSVv2** evolution of CSV using neural networks

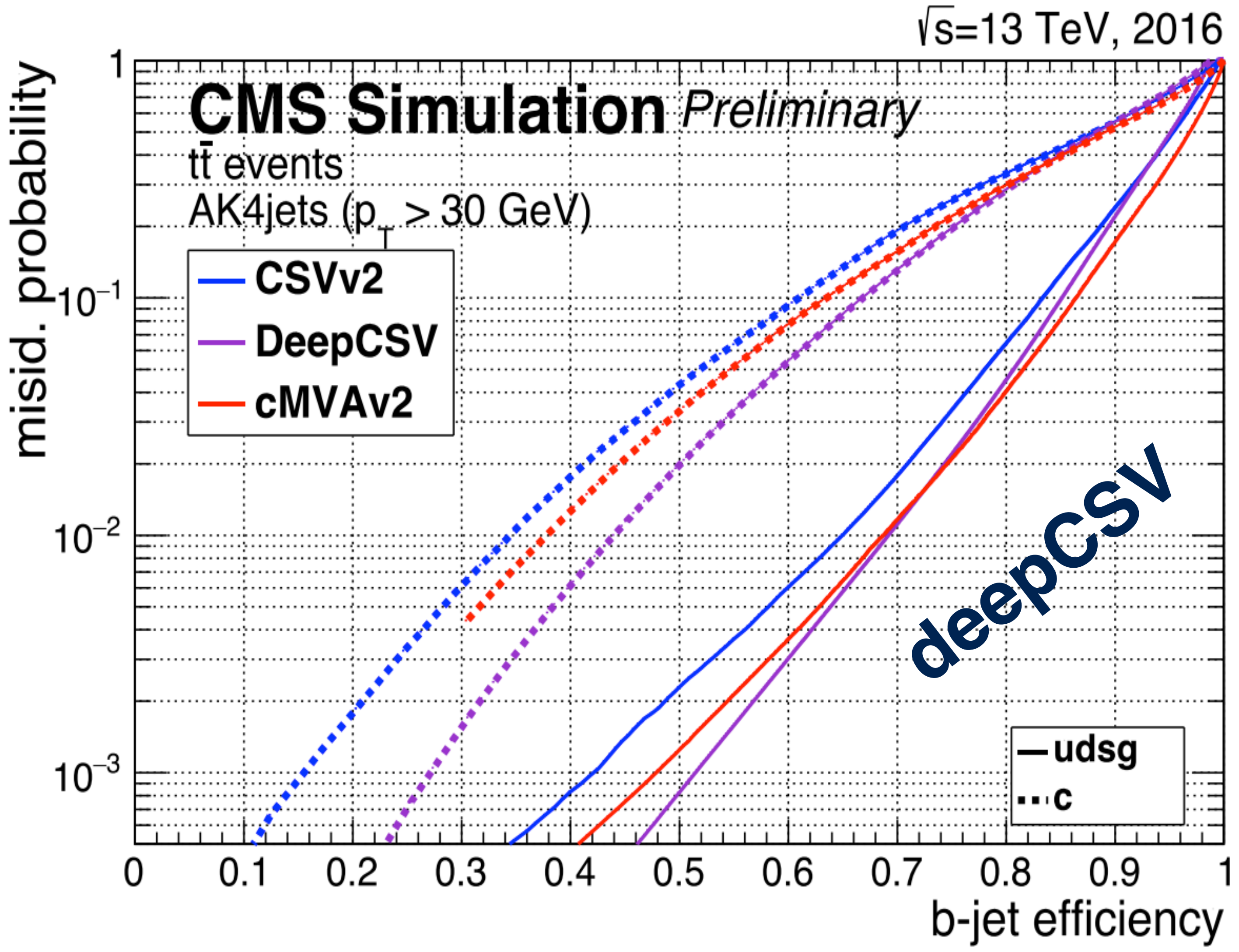
    cMVAv2 combines all the taggers

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%