Heavy flavor jet production & substructures

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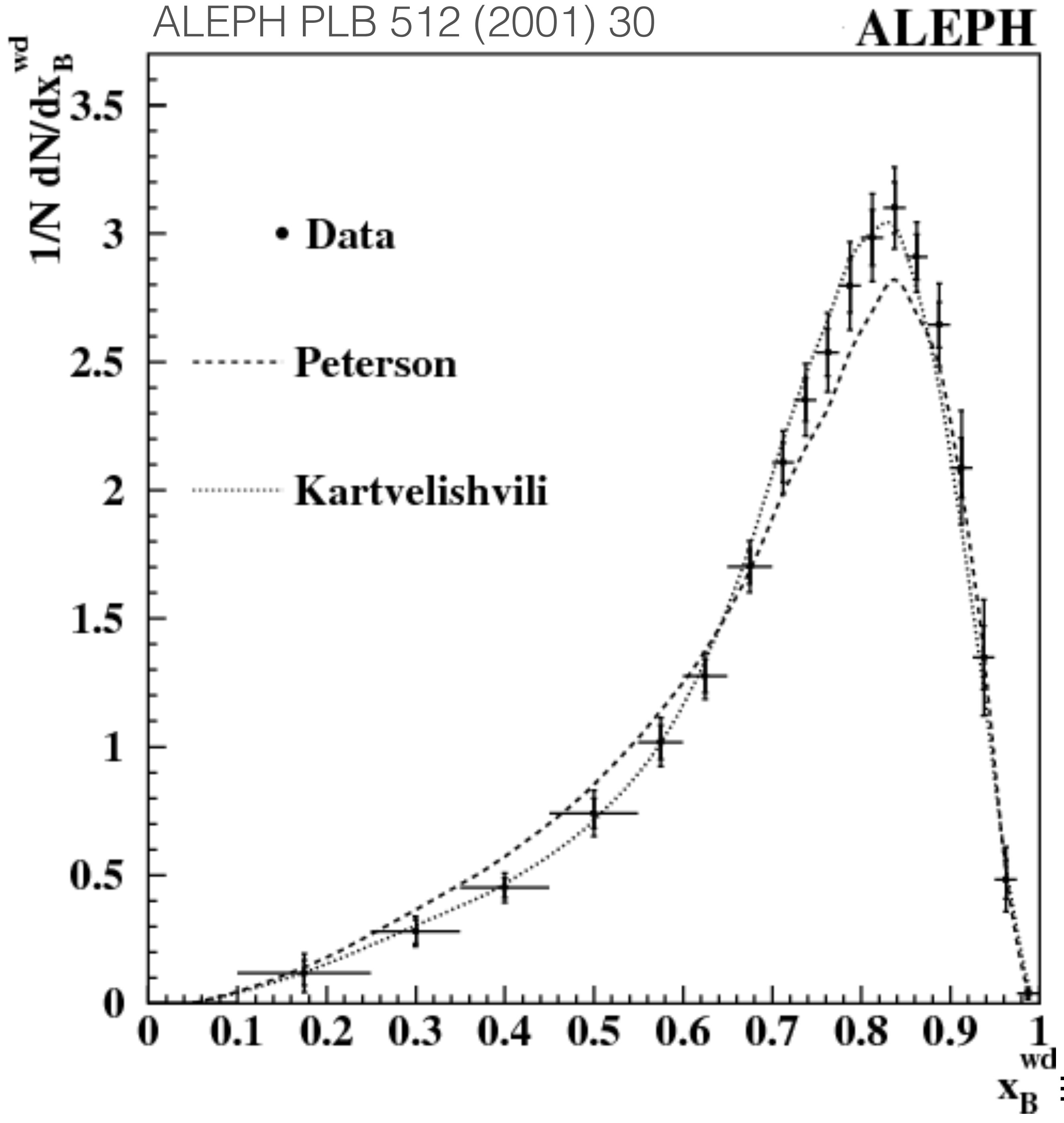
Why heavy flavor jets?

Heavy quarks play a special role in HEP
- Clean signature of heavy particle decays
- Calculable in pQCD up to hadronization

Heavy quarks fragment differently than light ones
- High z: take a larger fraction of the jet energy
- Large angle: Collinear radiation is suppressed

Measurements of heavy flavor jet production & substructure
- Essential input for many processes in the SM & beyond
- Provide stringent tests of pQCD & hadronization
- Interesting probes of nuclear effects in heavy ions

ALEPH PLB 512 (2001) 30



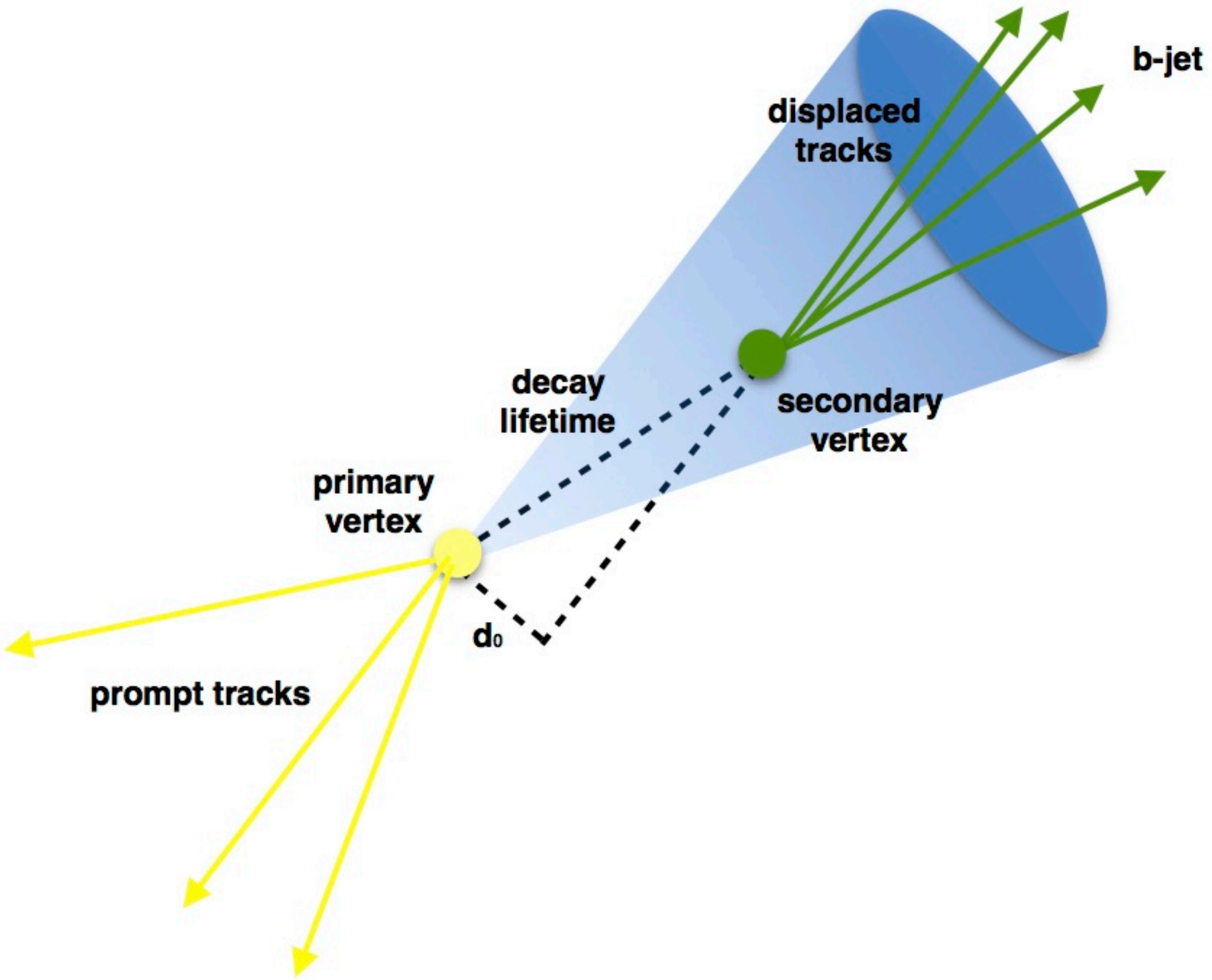
$x_B^{wd} \equiv \frac{E_{hadron}}{E_{beam}}$

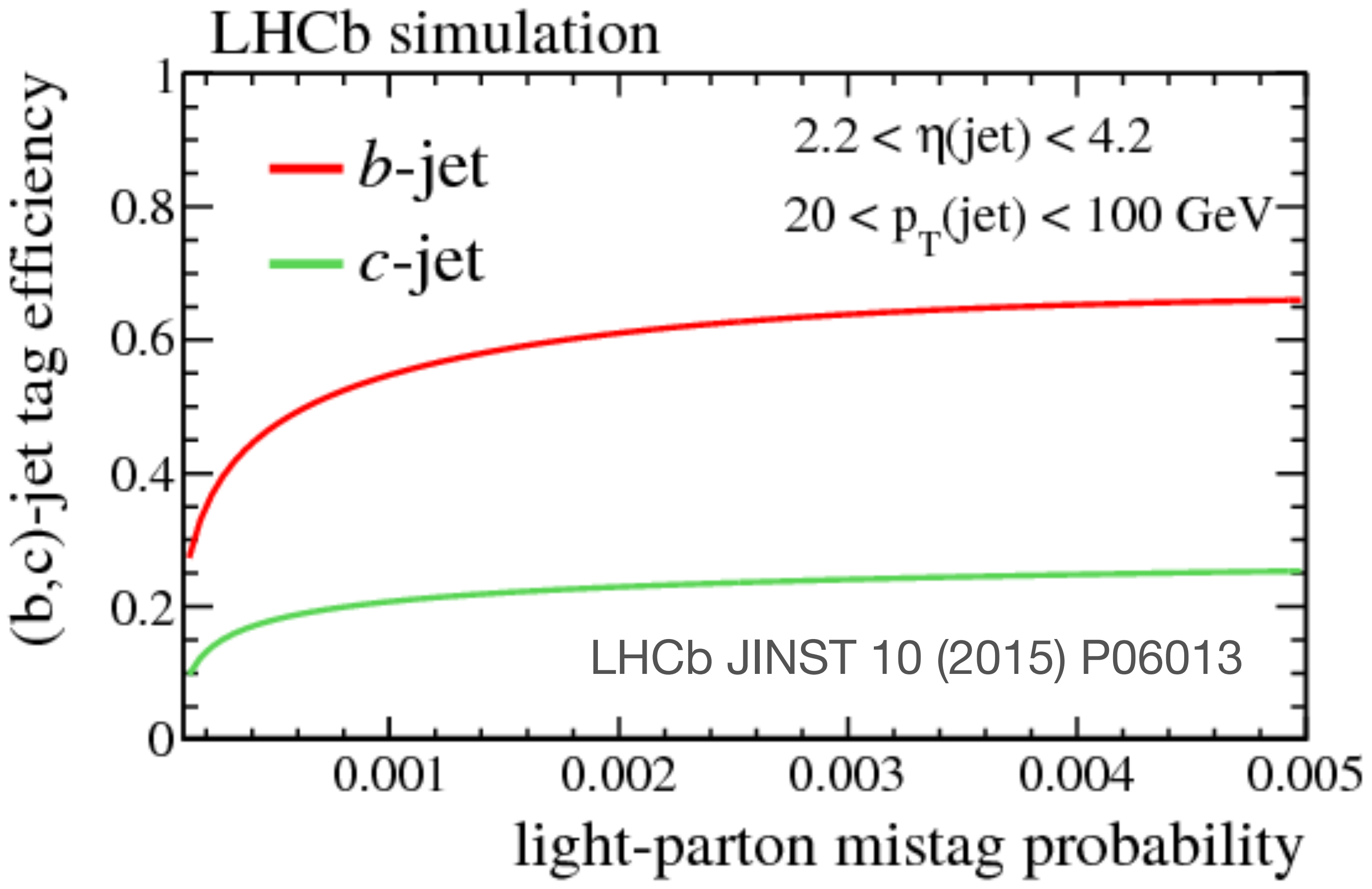
b-hadron fragmentation at LEP

This talk:
✓Flavor tagging methodology
✓Cross sections of heavy quark jets
✓Associated production: boson+Q
✓Fragmentation & substructure
◉Not covered: Nuclear effects

Heavy flavor tagging

Flavor tagging based on lifetime: displaced vertices & track info, often combined with lepton info





Recent developments use more info w/ increasingly sophisticated ML architectures

Qu & Gouskos PRD 101 (2020) 056019, ATL-PHYS-PUB-2022-027

Besides b-tagging

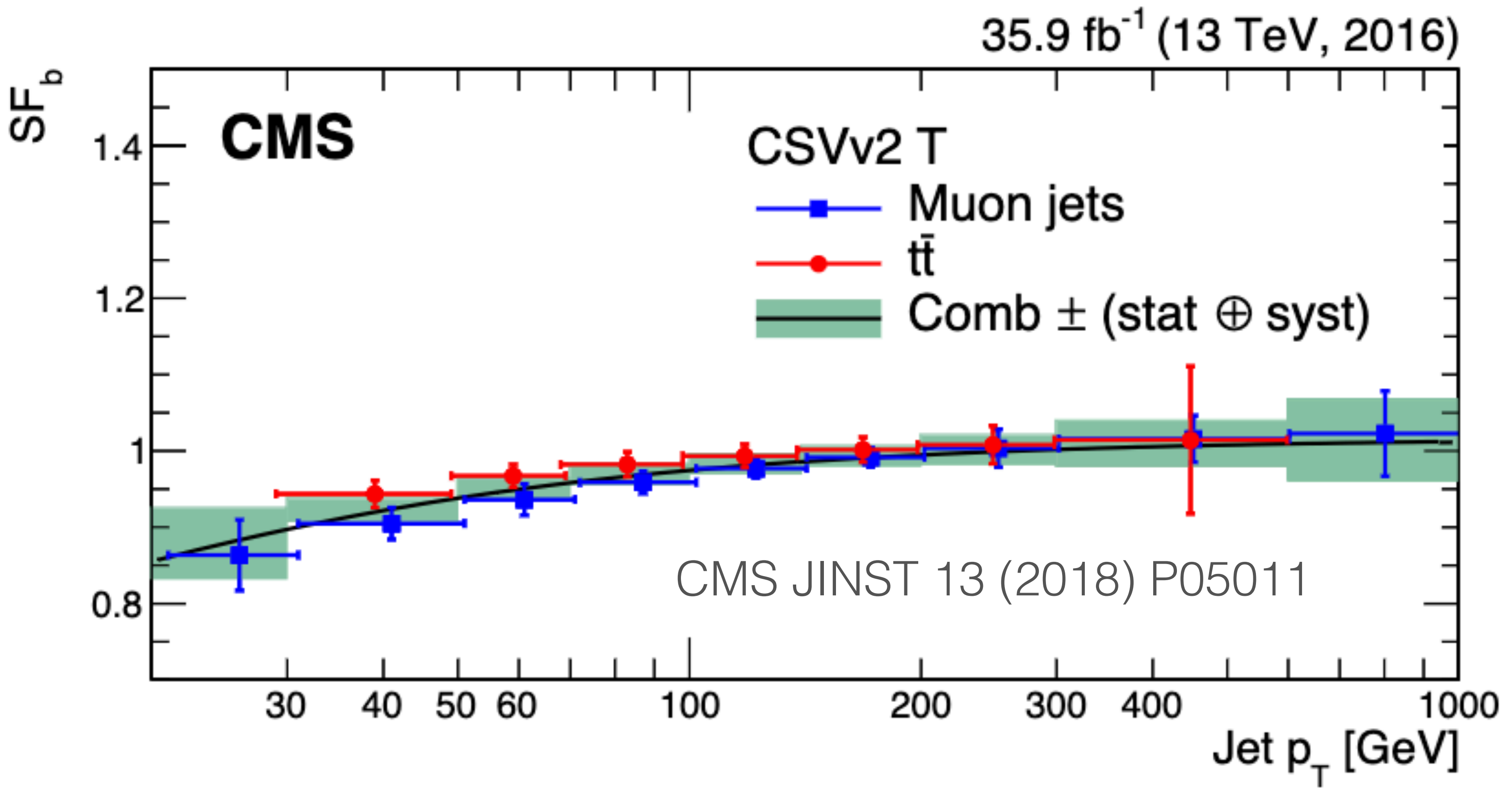
- Charm-jet tagging
- Tagging of boosted objects, e.g., H → bb

LHCb JINST 17 (2022) P02028
CMS JINST 17 (2022) P03014

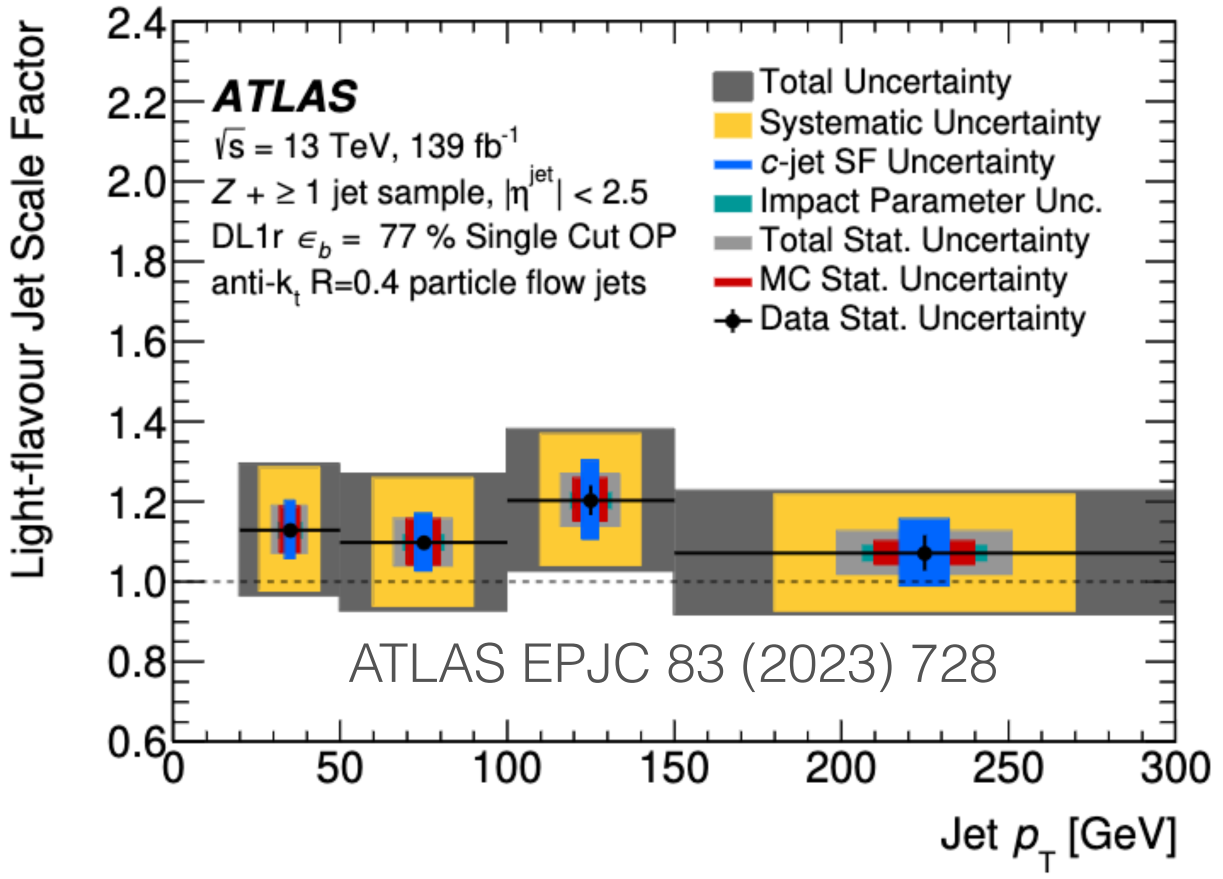
ATLAS EPJC 79 (2019) 836
CMS-PAS-BTV-22-001

Tagging is only half the job
Also need in-situ methods for tag & mistag efficiency

b-tag efficiency scale factors

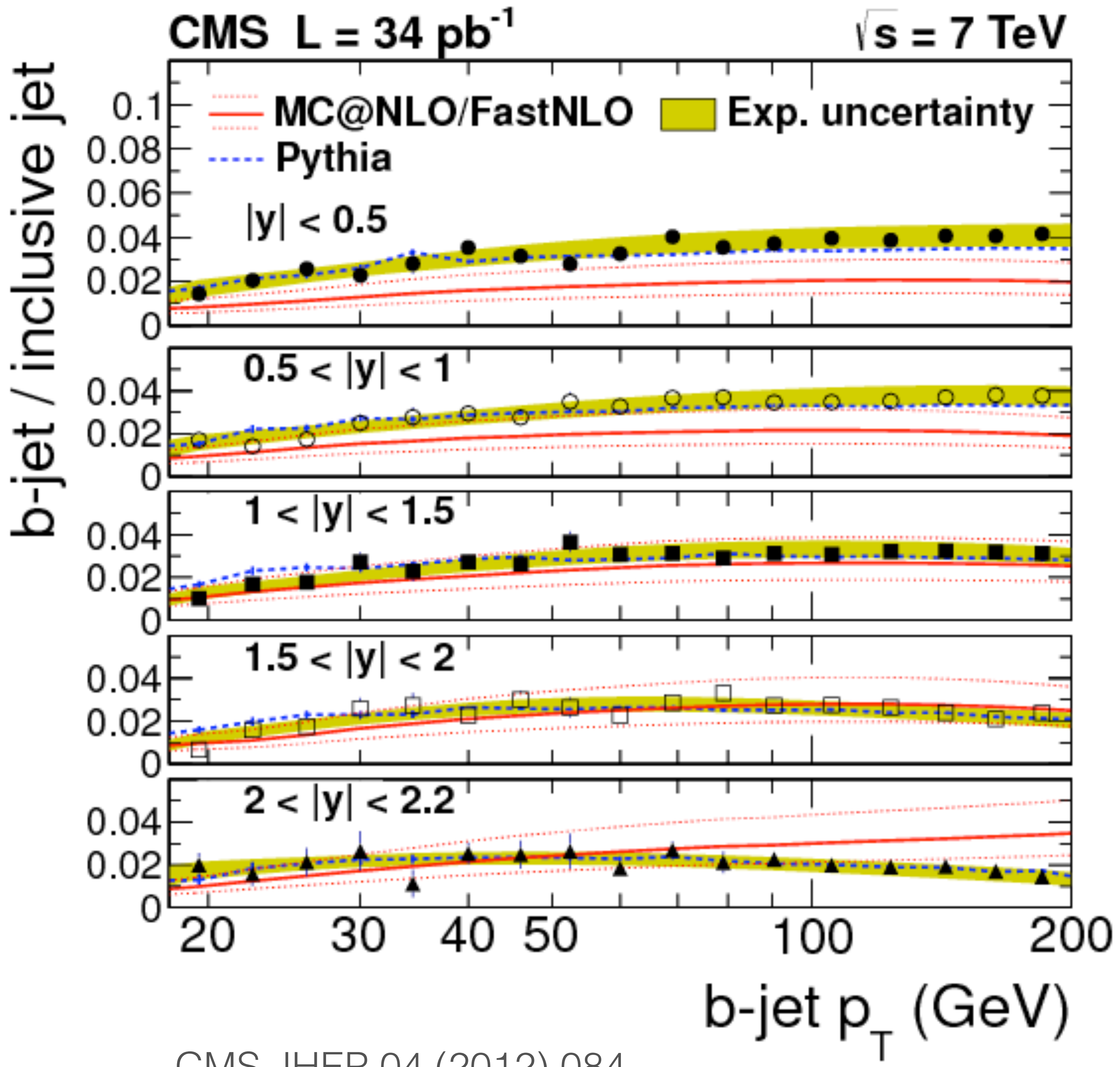


light jet mistag scale factors

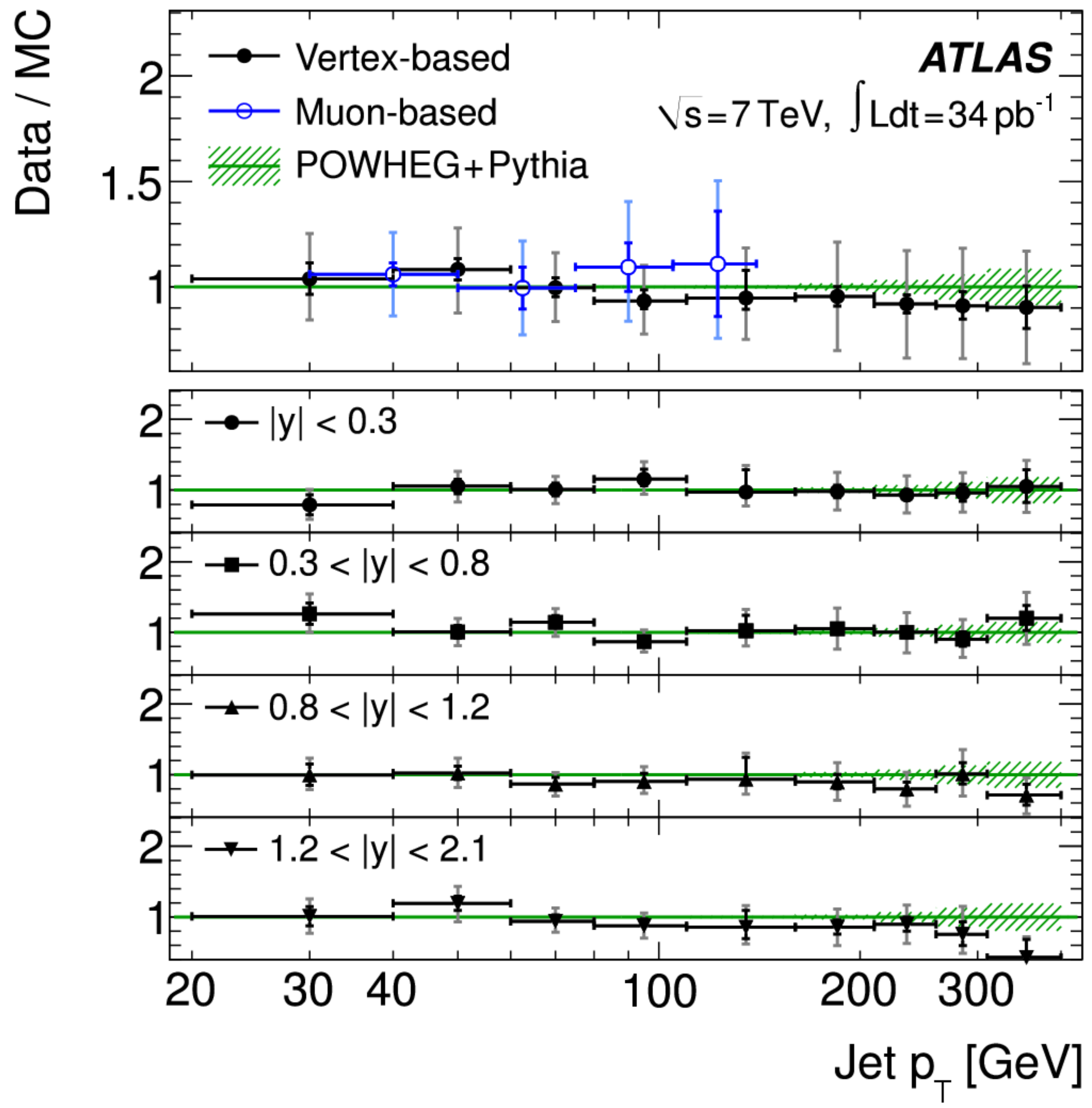


The basics: inclusive b-jet cross section

Measured by ATLAS and CMS in Run 1 @ 7 TeV



CMS JHEP 04 (2012) 084

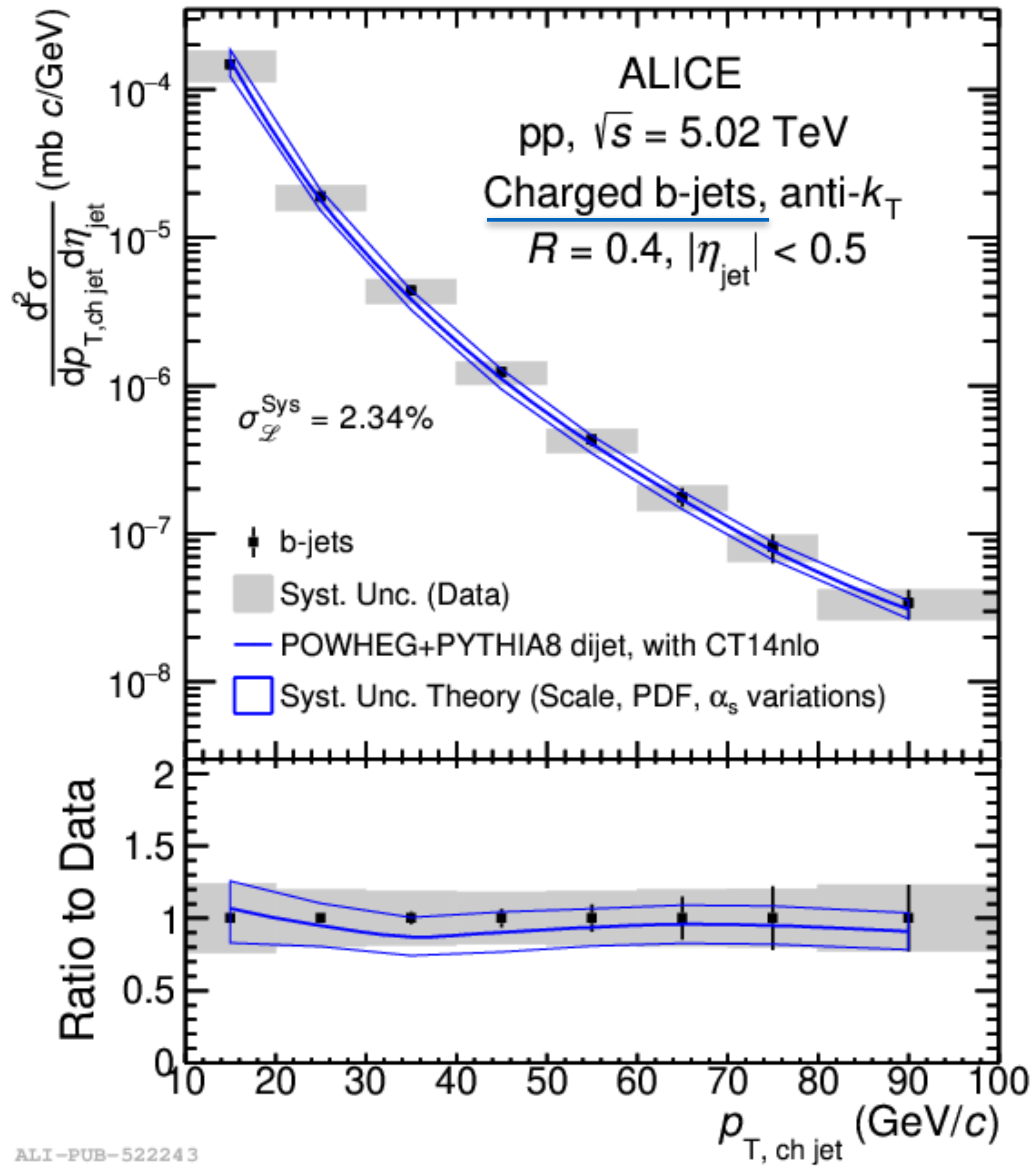


ATLAS EPJC 71 (2011) 1846

Consistent w/ NLO + parton shower MC generators
Powheg matches *y* dependence better than MC@NLO
No measurements yet at top energy / luminosity

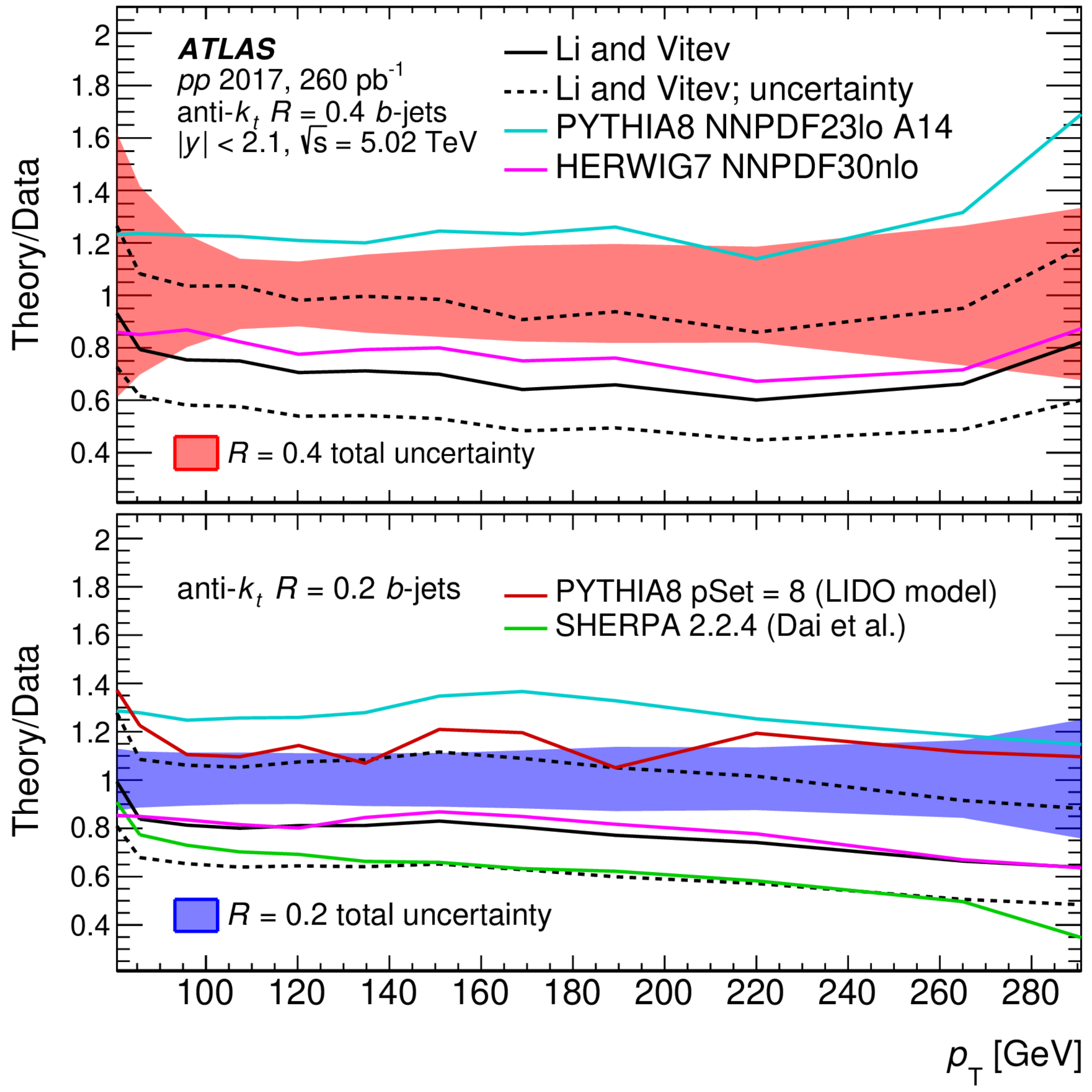
b-jet x-section @ 5 TeV

Well described by POWHEG+P8



ALICE JHEP 01 (2022) 178

Compatible w/ soft-collinear effective theory



ATLAS EPJC 83 (2023) 438

Also x-sections in pp & PbPb @ 2.76 TeV, as well as pPb @ 5.02 GeV

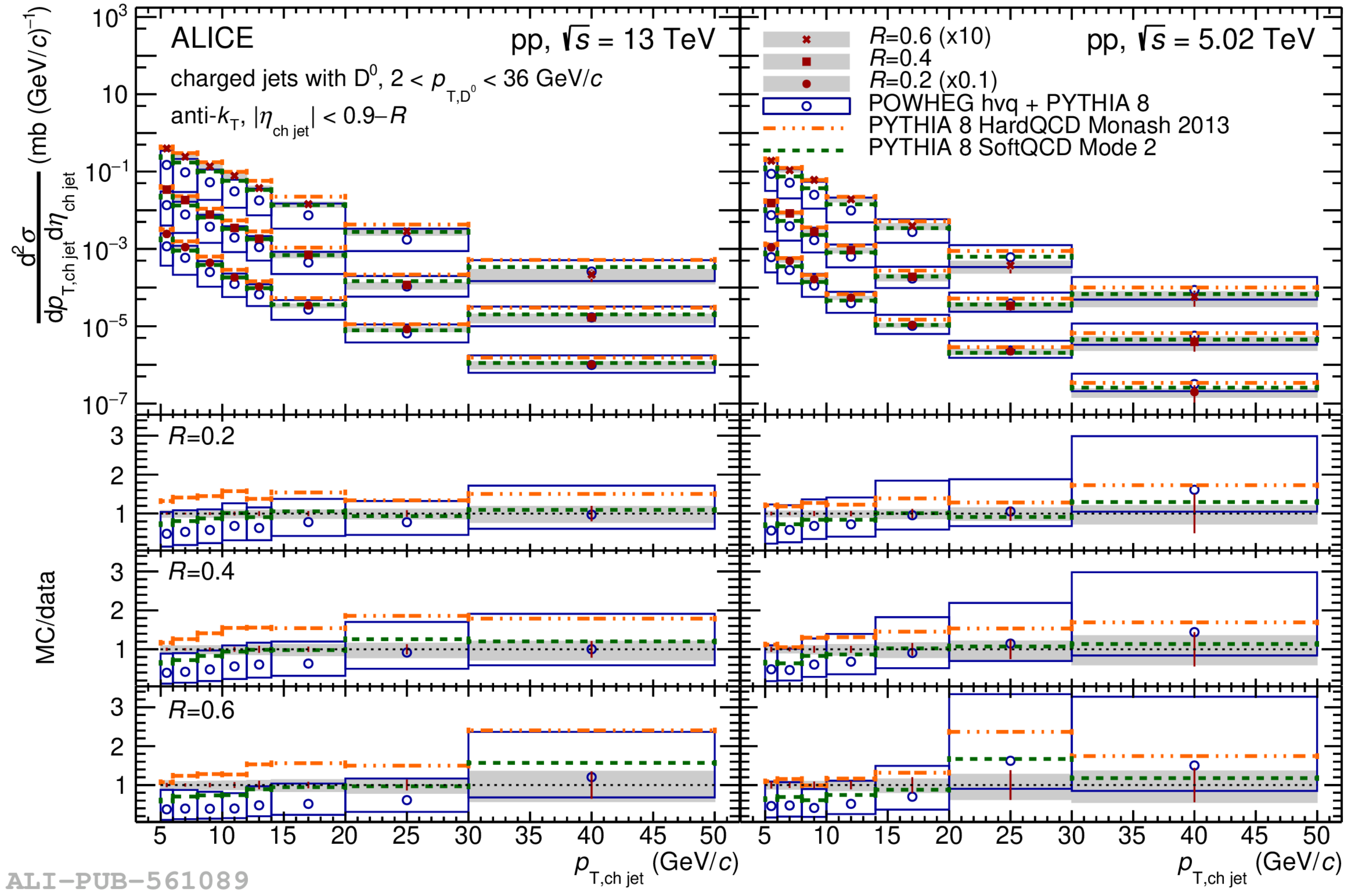
CMS PRL 113 (2014) 132301
CMS PLB 754 (2016) 59

Charm jet cross-section

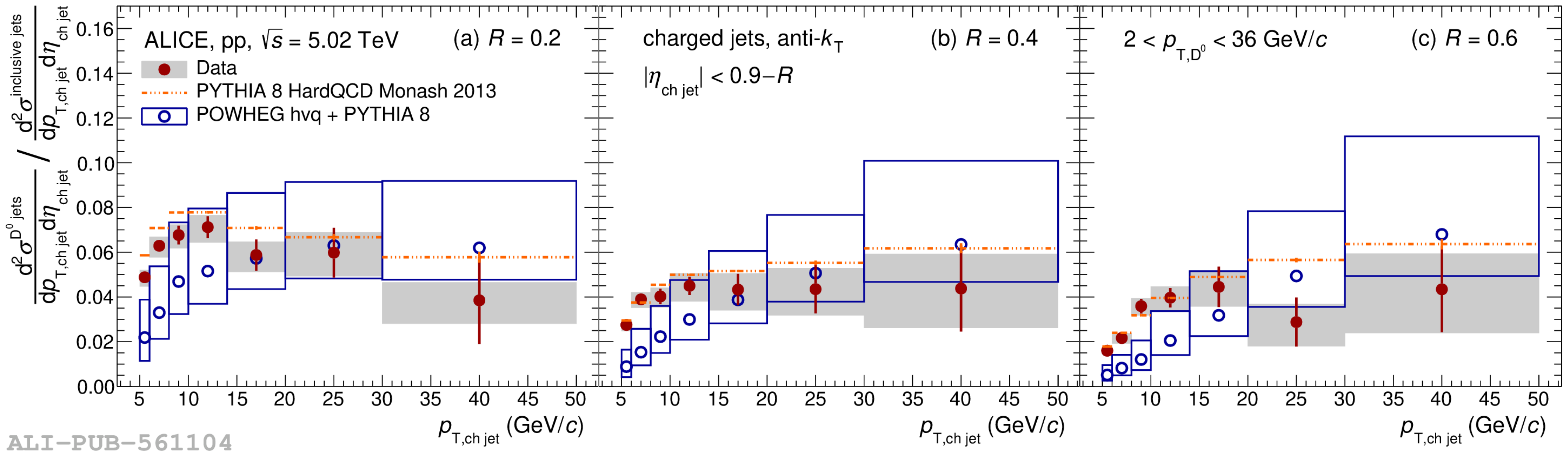
ALICE JHEP 06 (2022) 133

charm / light

D0-jet x-section at 13 & 5 TeV



D0-jet / inclusive-jet for different R @ 5 TeV



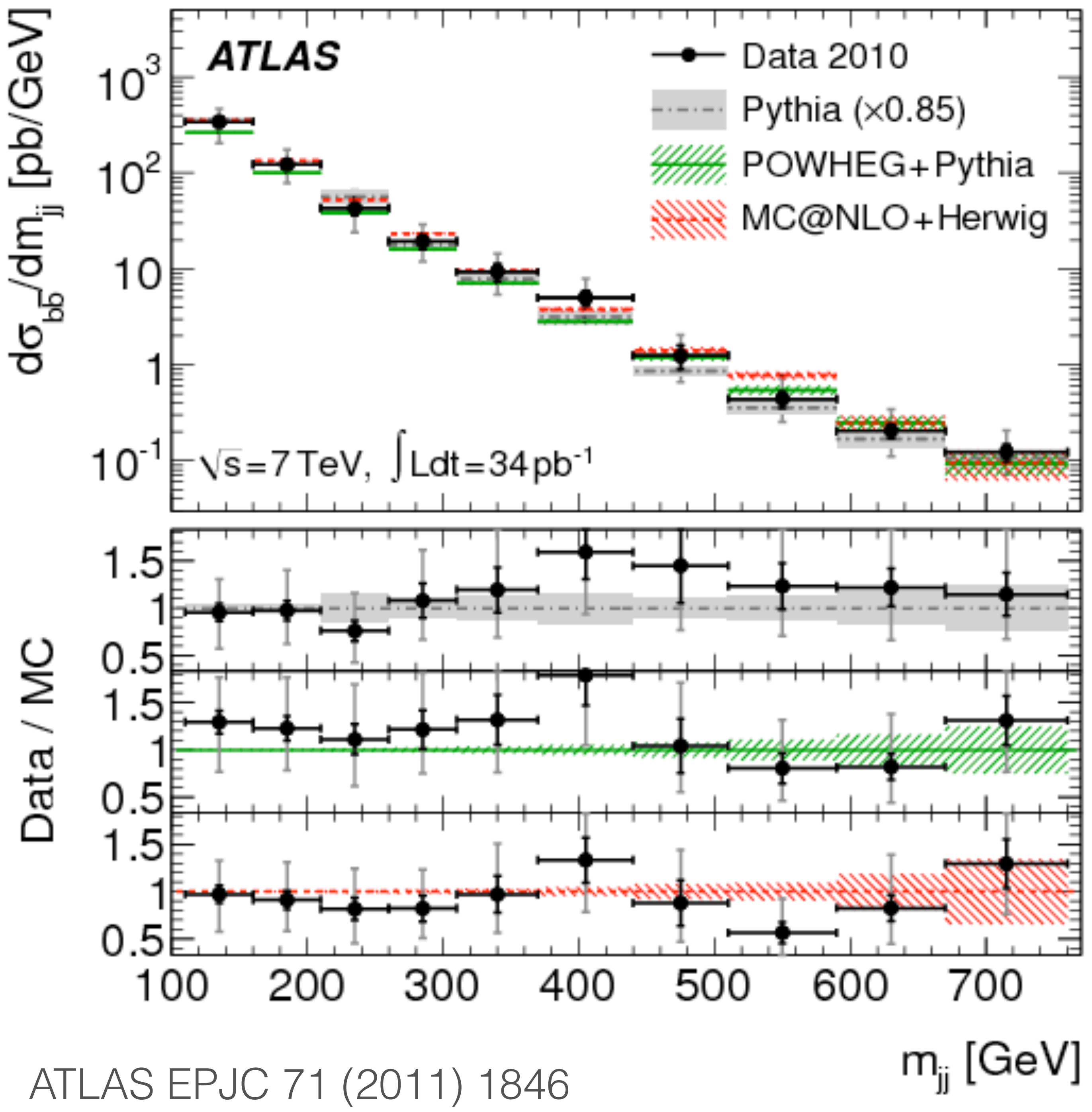
Reasonable theory description,
tension at low p_T where mass effects are relevant?

Also: Inclusive c-jet x-section @ 2.76 & 5 TeV CMS PLB 772 (2017) 306

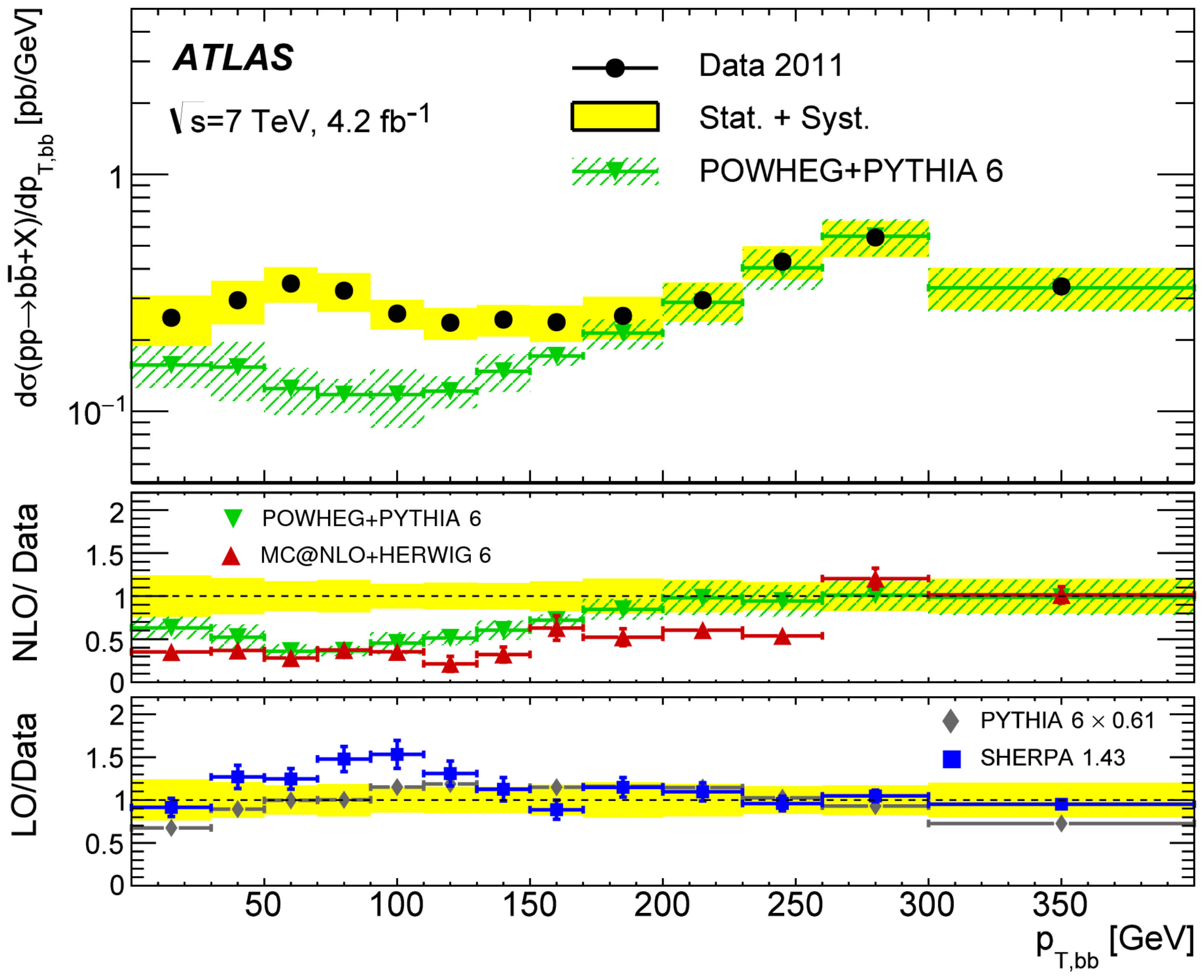
bb (resolved)

Pair production is important to test modeling of different heavy flavor production processes

Event selection	
Leading jet	$p_T > 270$ GeV and $\|\eta\| < 3.2$
2 *b*-jets selection	$p_T > 20$ GeV and $\|\eta\| < 2.5$
	2 *b*-jets separated by $\Delta R > 0.4$



ATLAS EPJC 71 (2011) 1846



ATLAS EPJC 76 (2016) 670

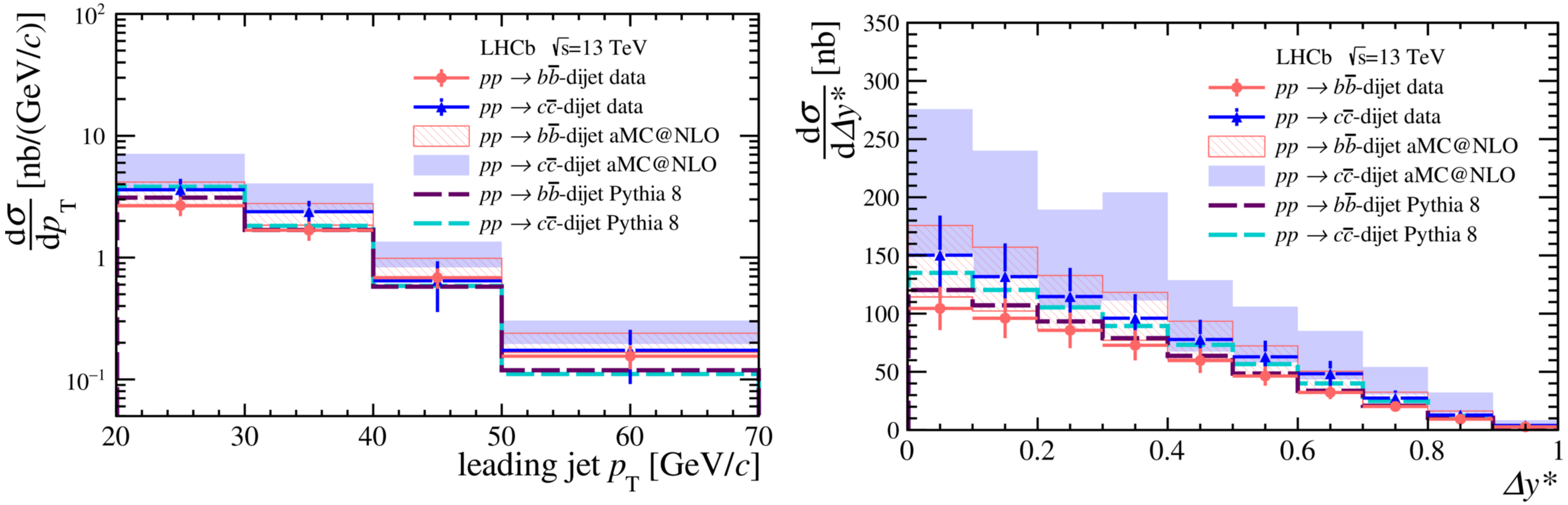
1st measurement broadly consistent w/ NLO

Poor description by NLO+PS when you push the kinematics
e.g., at low $p_{T,bb}$, where flavor excitation contributes

Also: b-dijet p_T balance at 5.02 TeV CMS JHEP 03 (2018) 181
dijet flavor composition at 7 TeV ATLAS EPJC 73 (2013) 2301

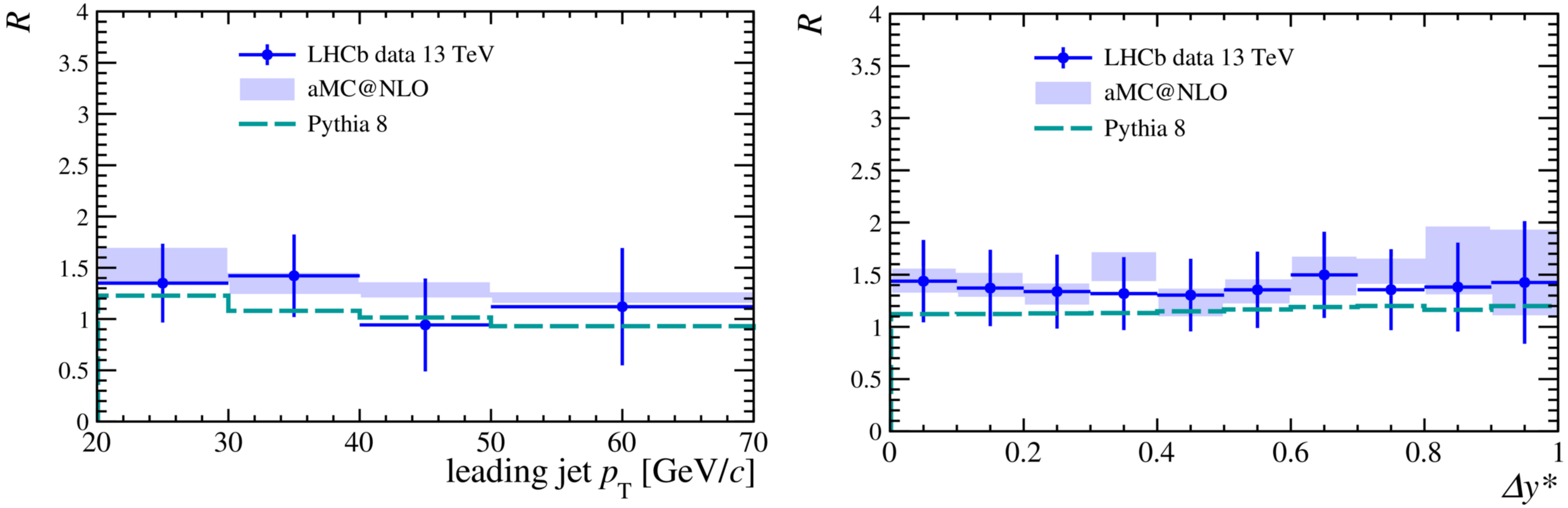
Forward bb and cc

LHCb JHEP 02 (2021) 023



Cross-sections at lower edge of theory uncertainty bands

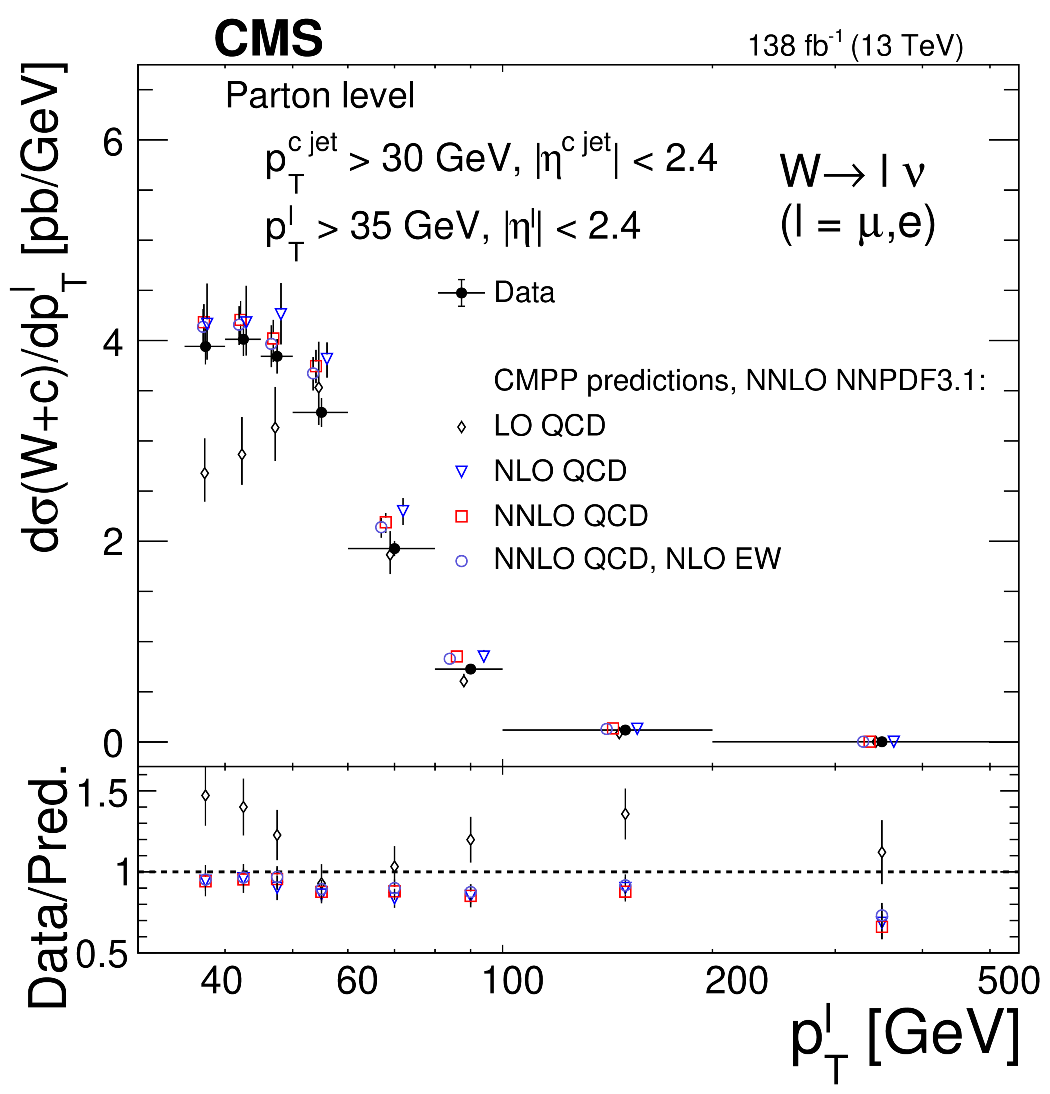
$R \equiv cc/bb$

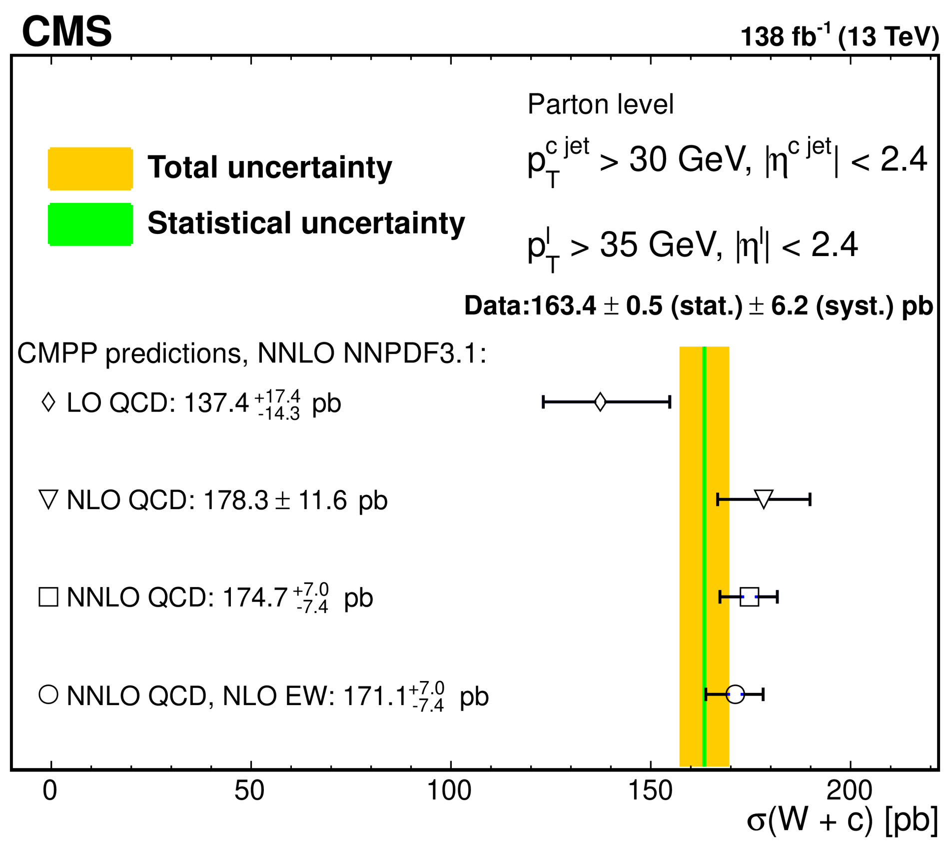


Excellent agreement of aMC@NLO w/ cc:bb

W+charm

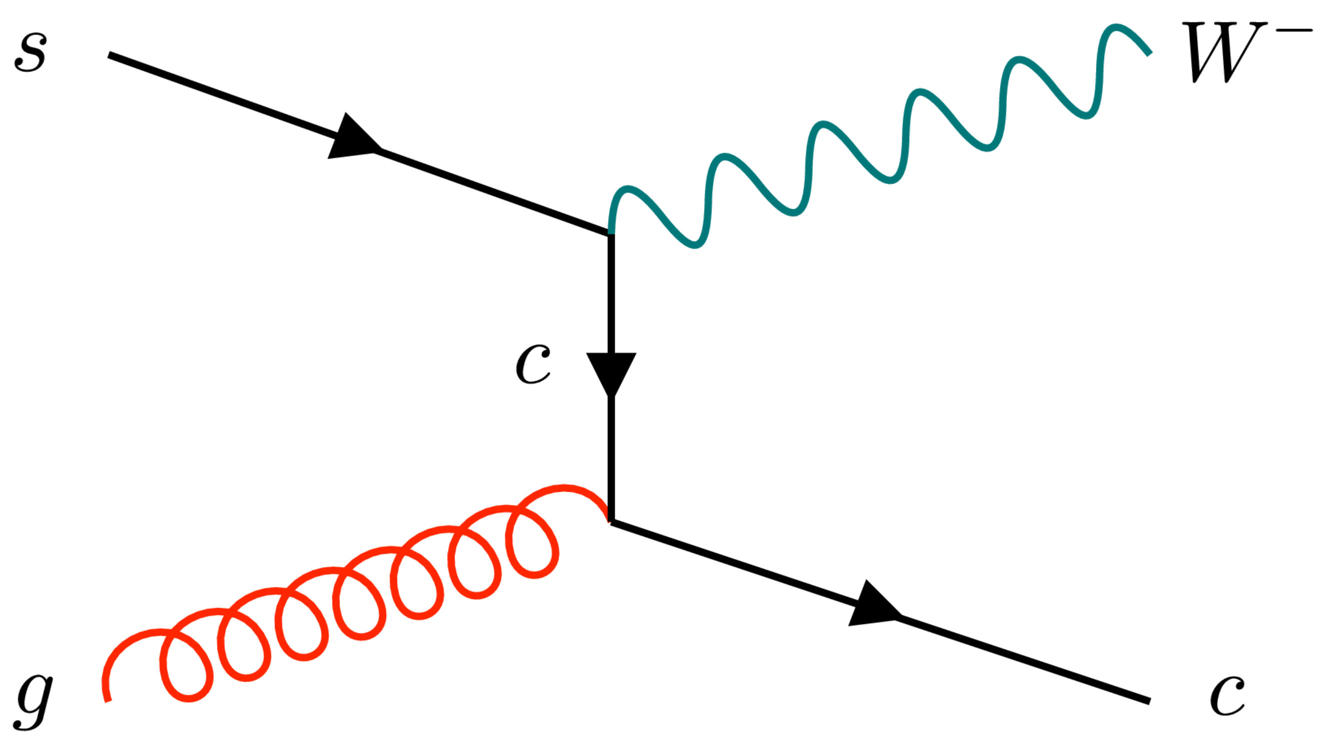
x-section vs FO pQCD





CMS EPJC 84 (2024) 027

Probes *s* quark PDF

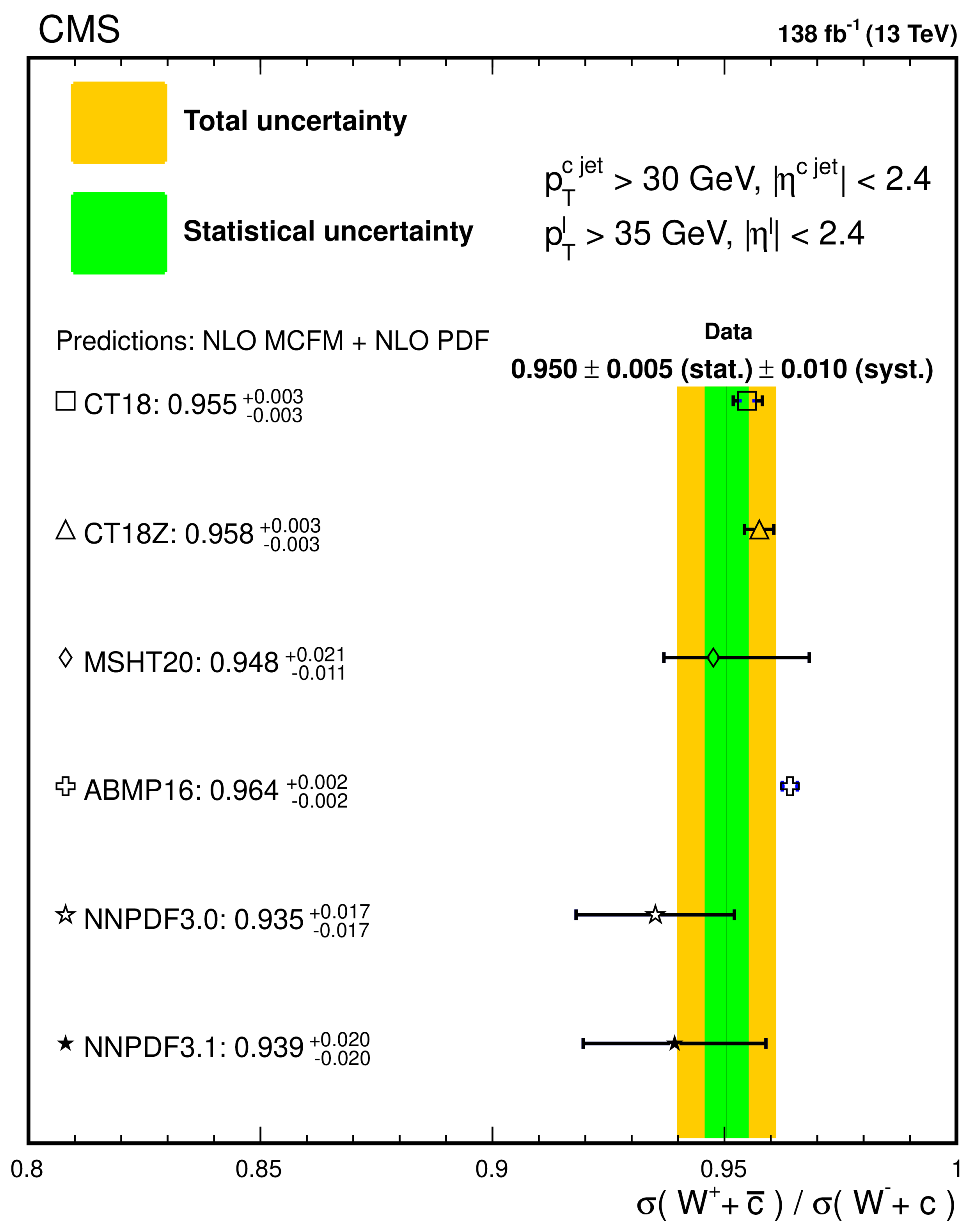


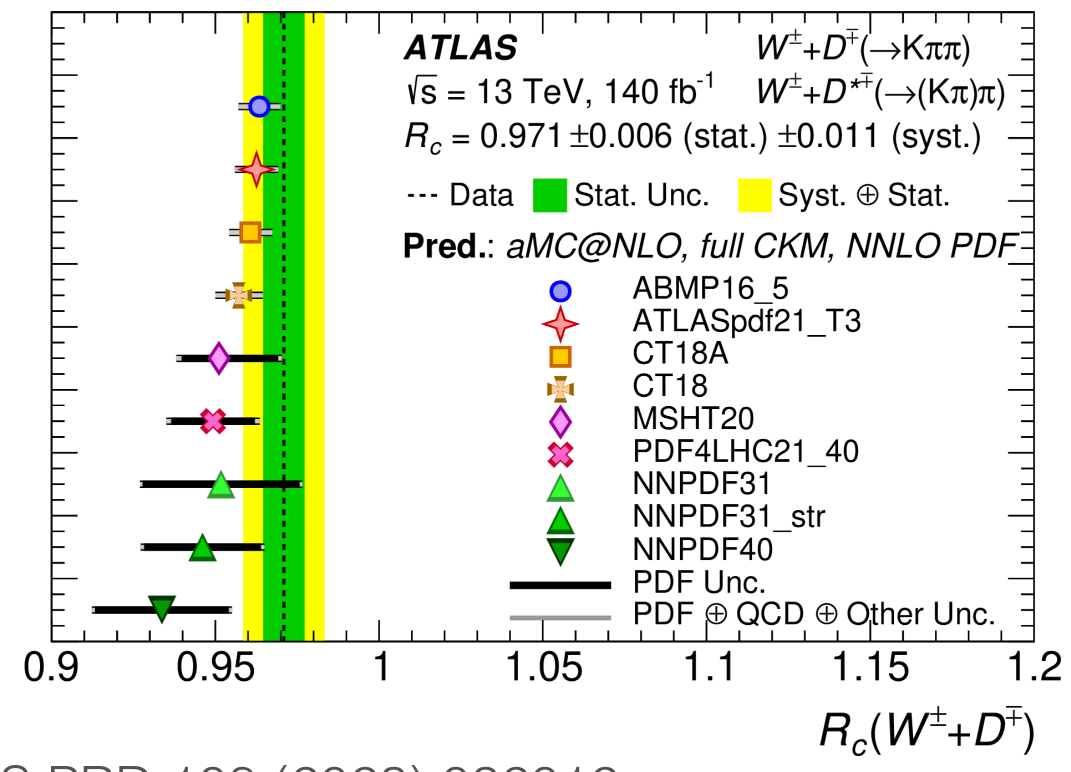
CMS measures c-jets w/ displaced vertices & muons
ATLAS uses exclusive c-hadrons w/o explicit jet reco
$t\bar{t}$ rejected requiring opposite sign for W & c-hadron

CMS: $R_c = 0.950 \pm 0.005 \pm 0.010$
ATLAS: $R_c = 0.971 \pm 0.006 \pm 0.011$

- Cross section consistent w/ pQCD (NNLO)
- Strong constraints on the strange quark sea

R_C vs PDF global fits

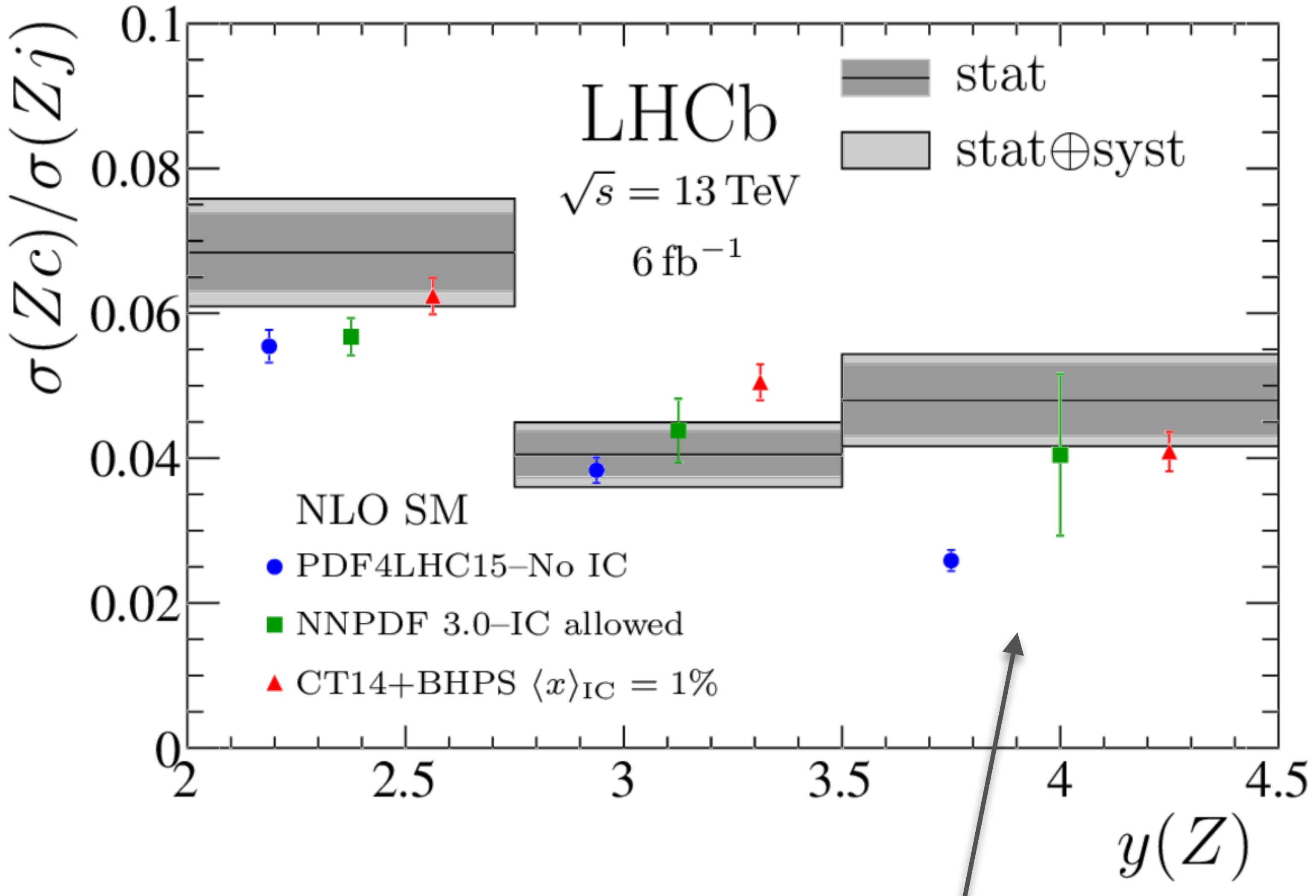




ATLAS PRD 108 (2023) 032012

Z+charm

Forward rapidity

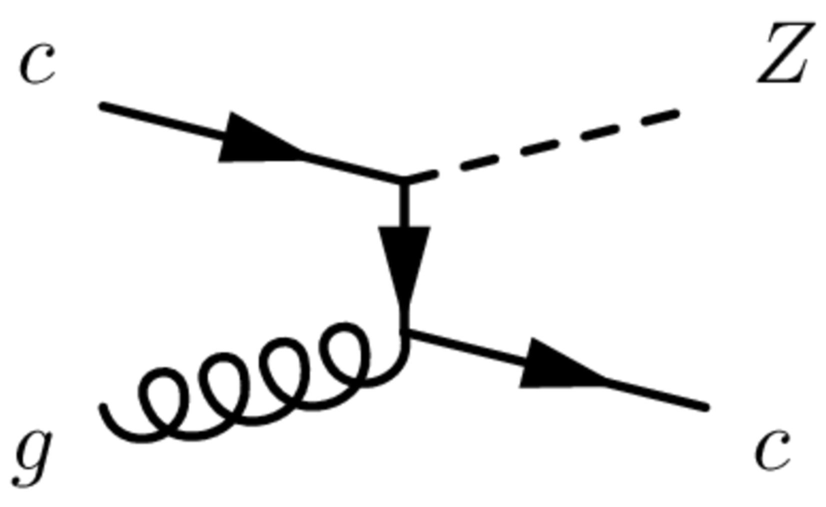


charm / inclusive

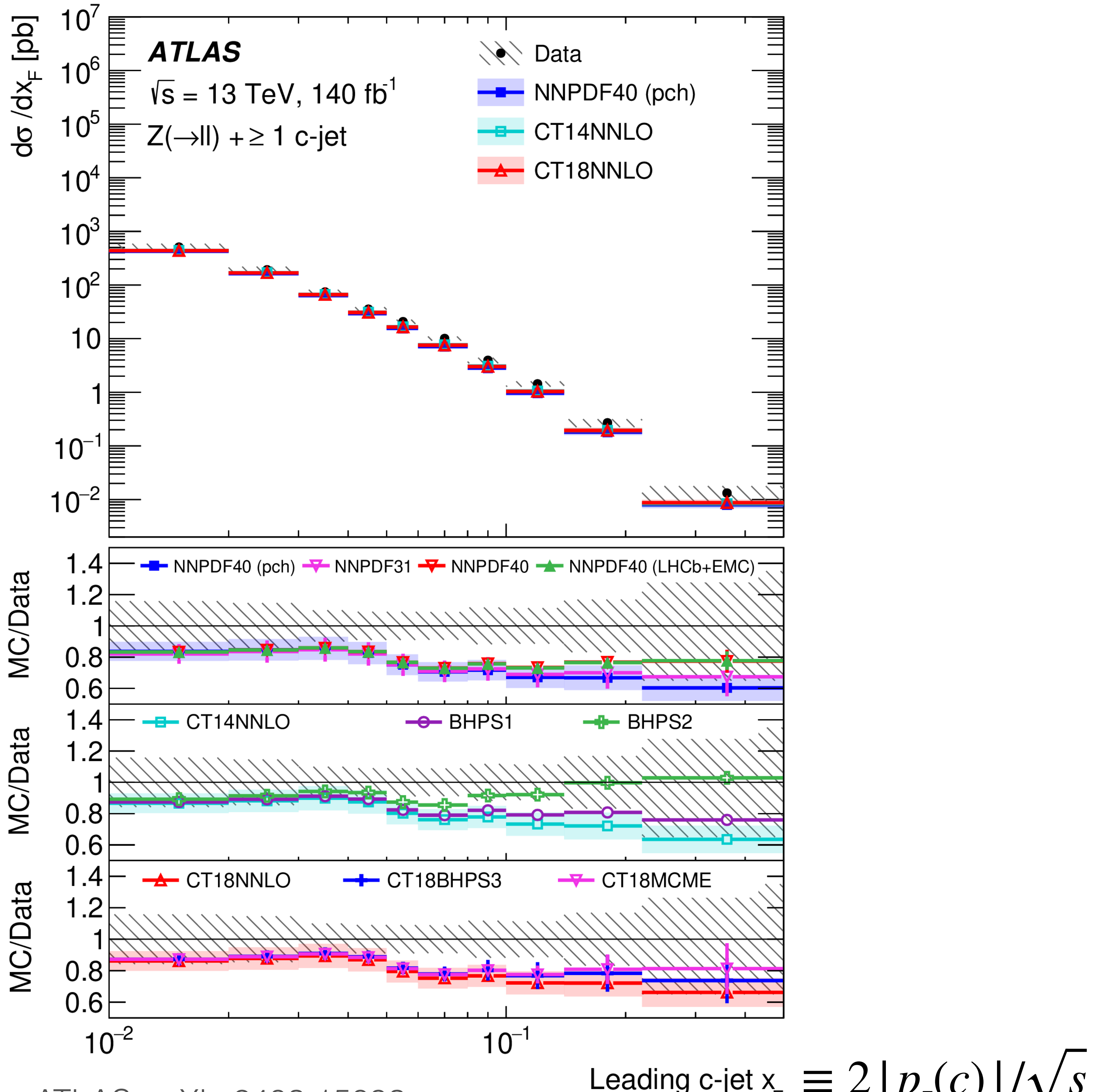
LHCb PRL 128 (2022) 082001

Most forward data strongly favor intrinsic charm

Probes intrinsic charm



Mid-rapidity

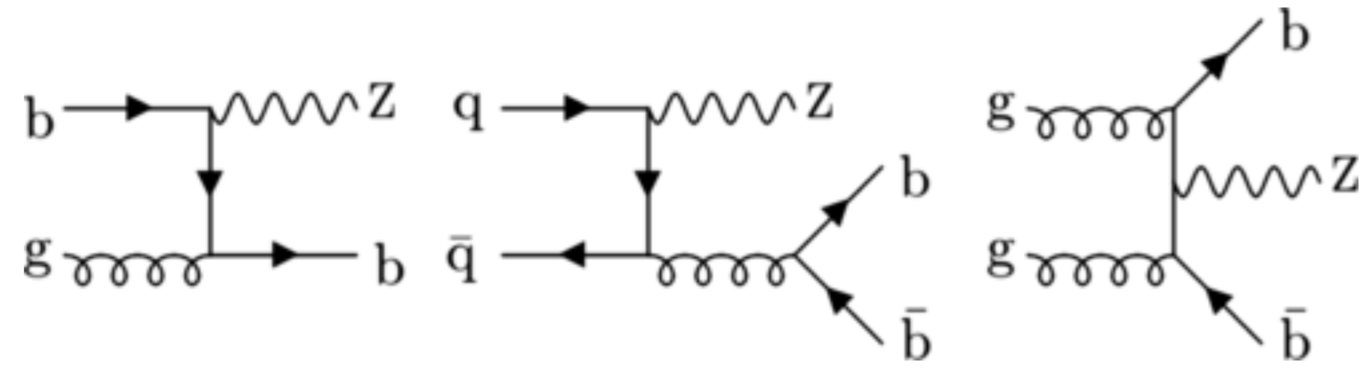


ATLAS, arXiv:2403.15093

MadGraph/aMC@NLO + various PDFs
w/ different intrinsic charm contribution
→ poor agreement at large c-jet x_F

Also CMS Z+c: JHEP 04 (2021) 109

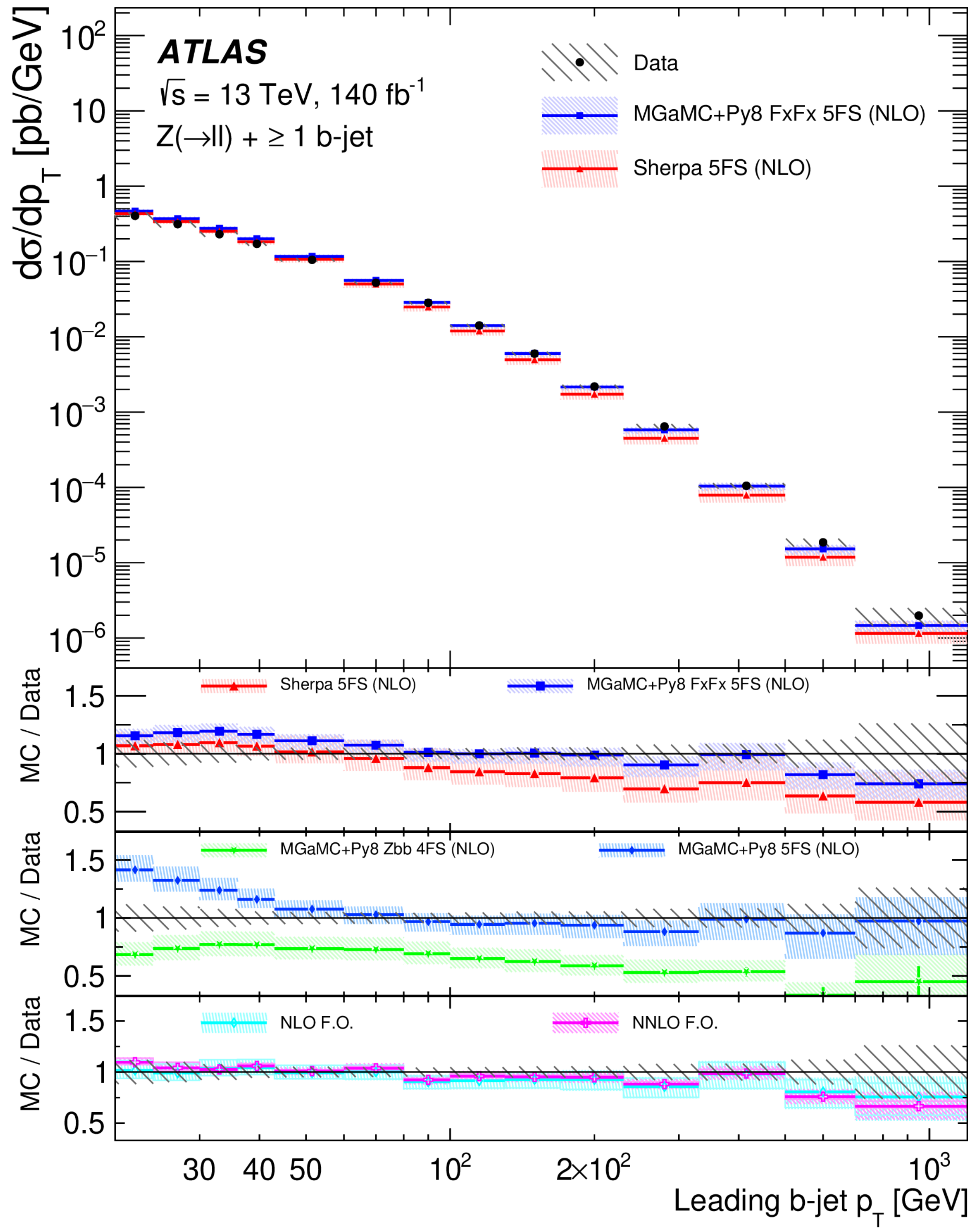
Z+b-jet(s)



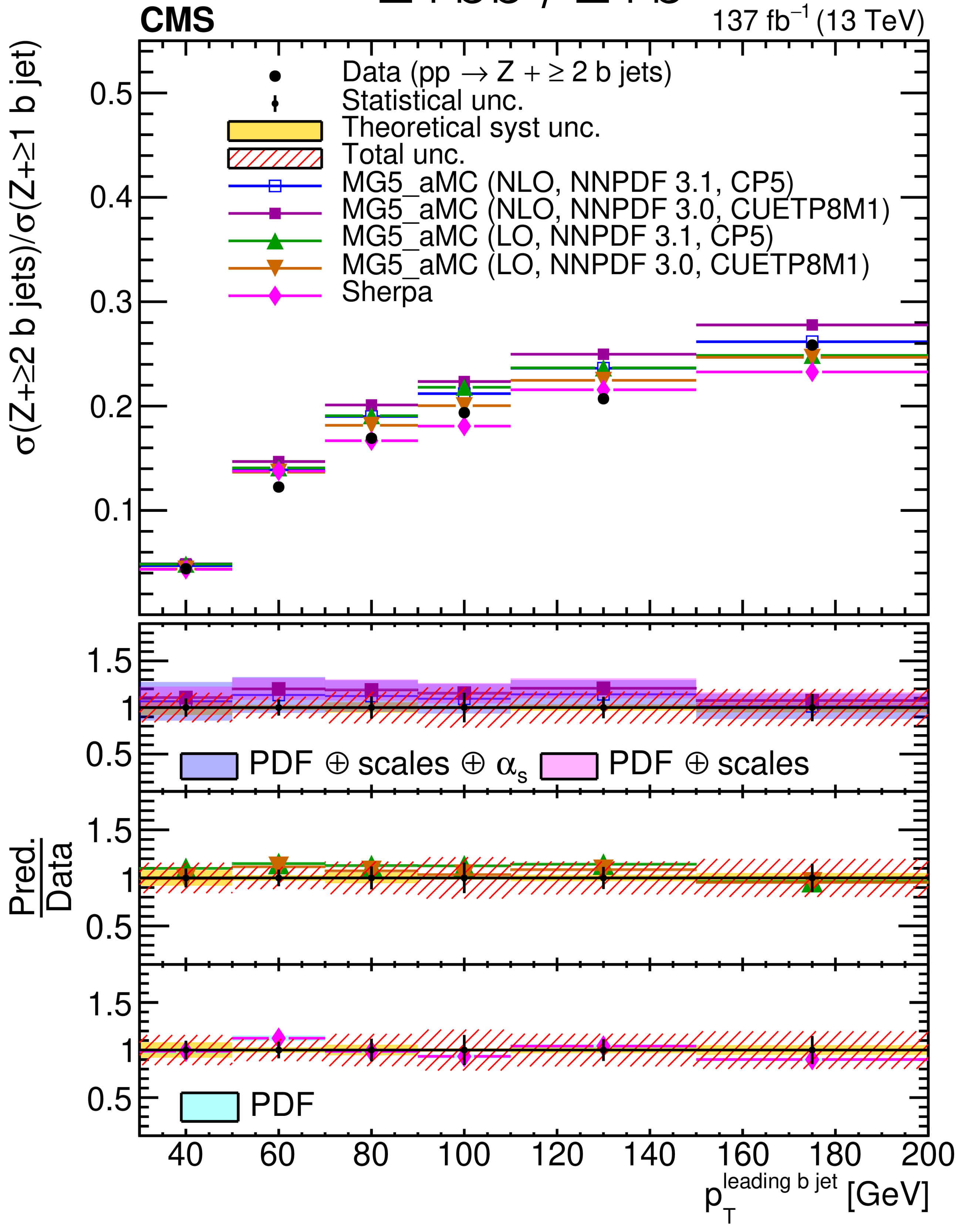
Several processes w/ different kinematics of bb in final state
Z+bb is a key background for HZ

ATLAS PRD 108 (2023) 012022
CMS PRD 105 (2022) 092014

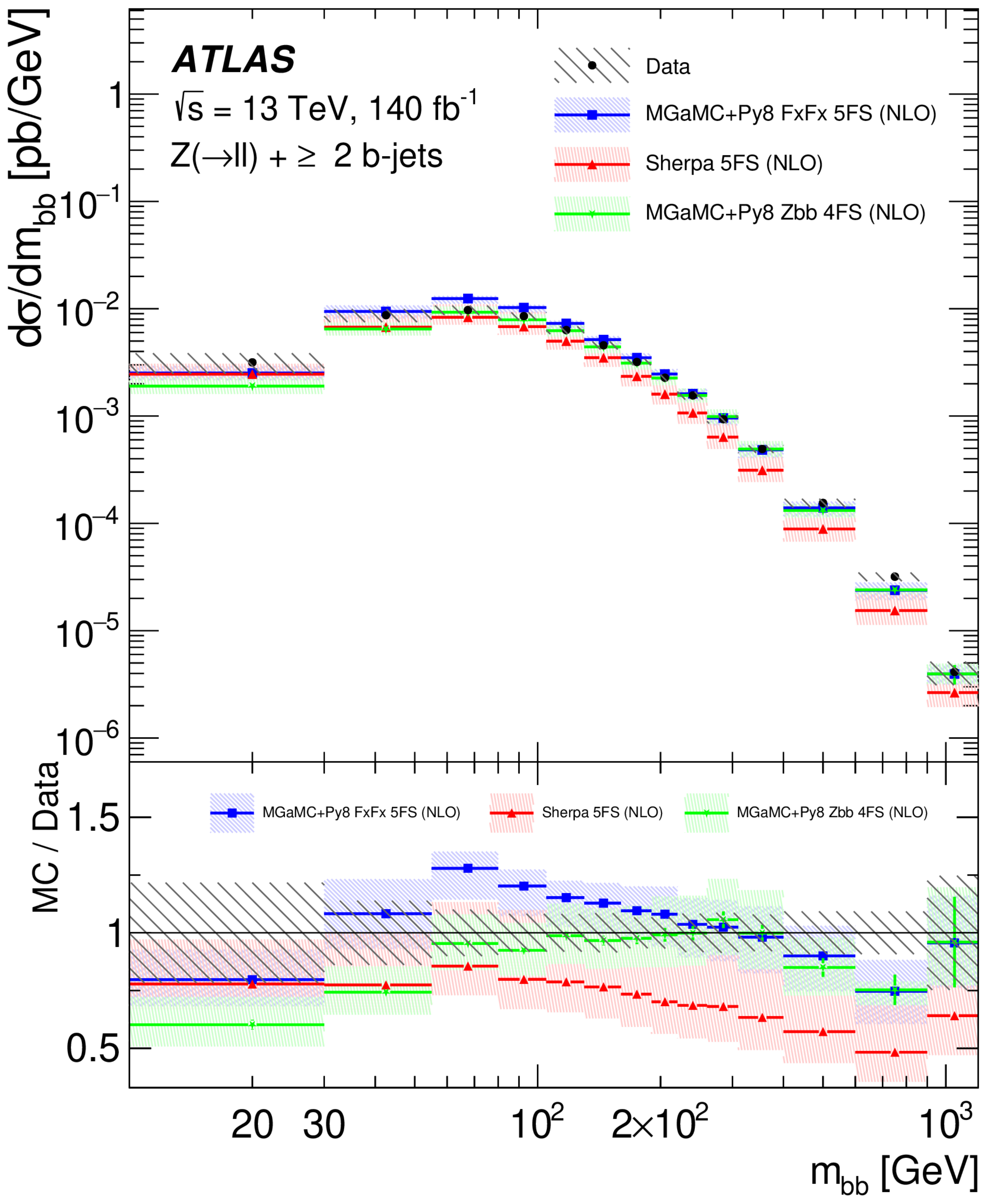
Z+b x-section



Z+bb / Z+b



Z+bb kinematic distribution

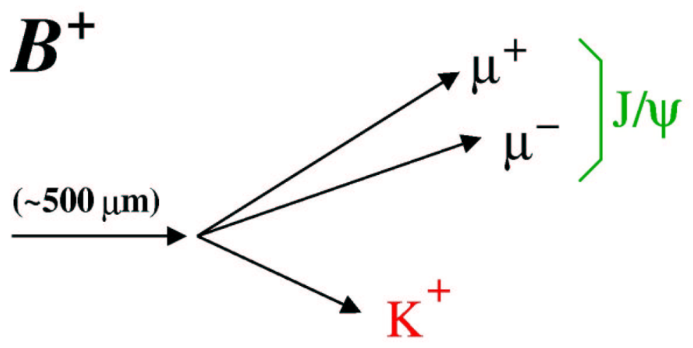


x-section discriminates btwn
4 flavor & 5 flavor schemes

Generators describe Z+bb / Z+b x-section, but have more trouble w/ kinematic distributions

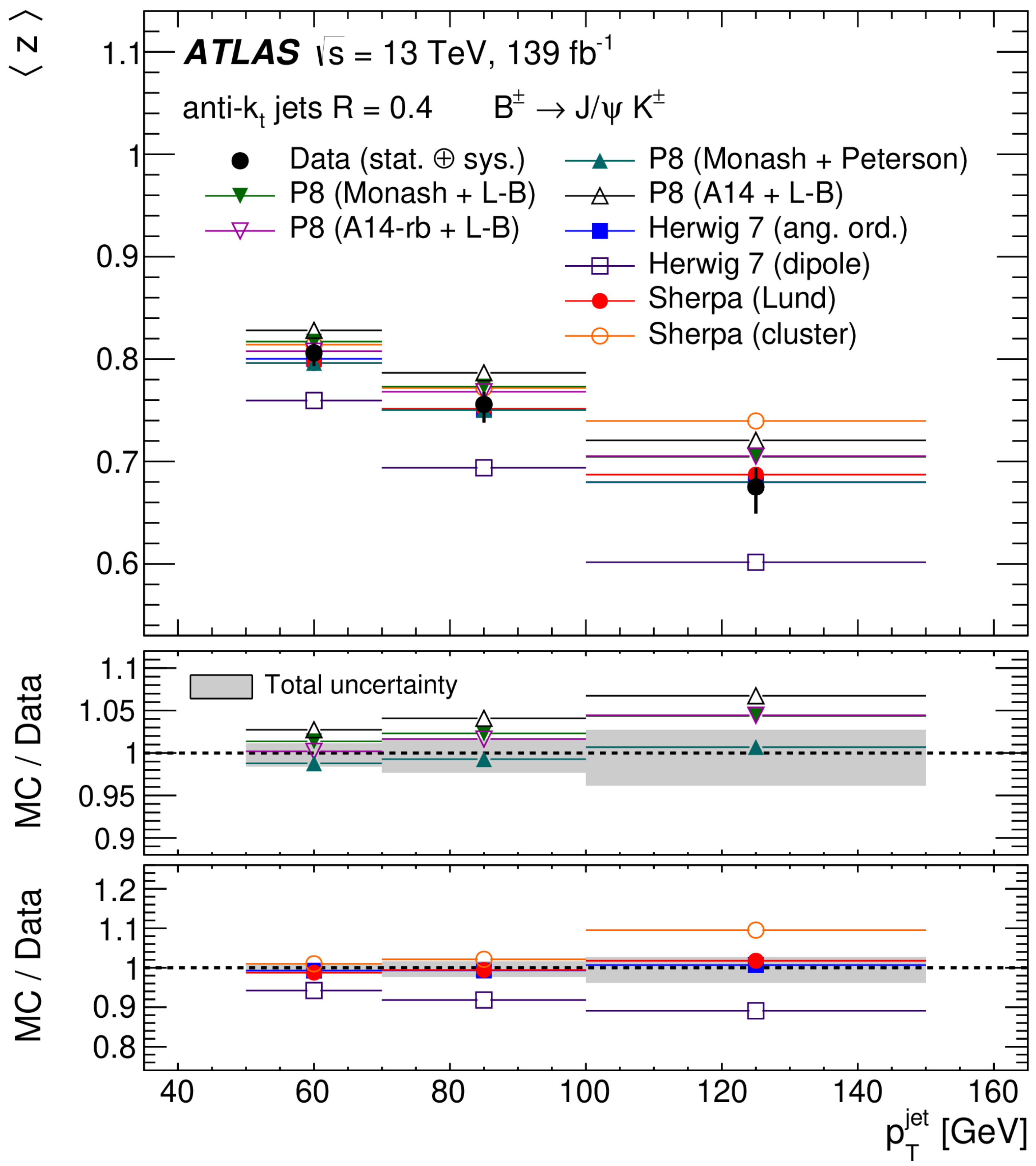
b-jet fragmentation w/ exclusive B+

ATLAS JHEP 12 (2021) 131

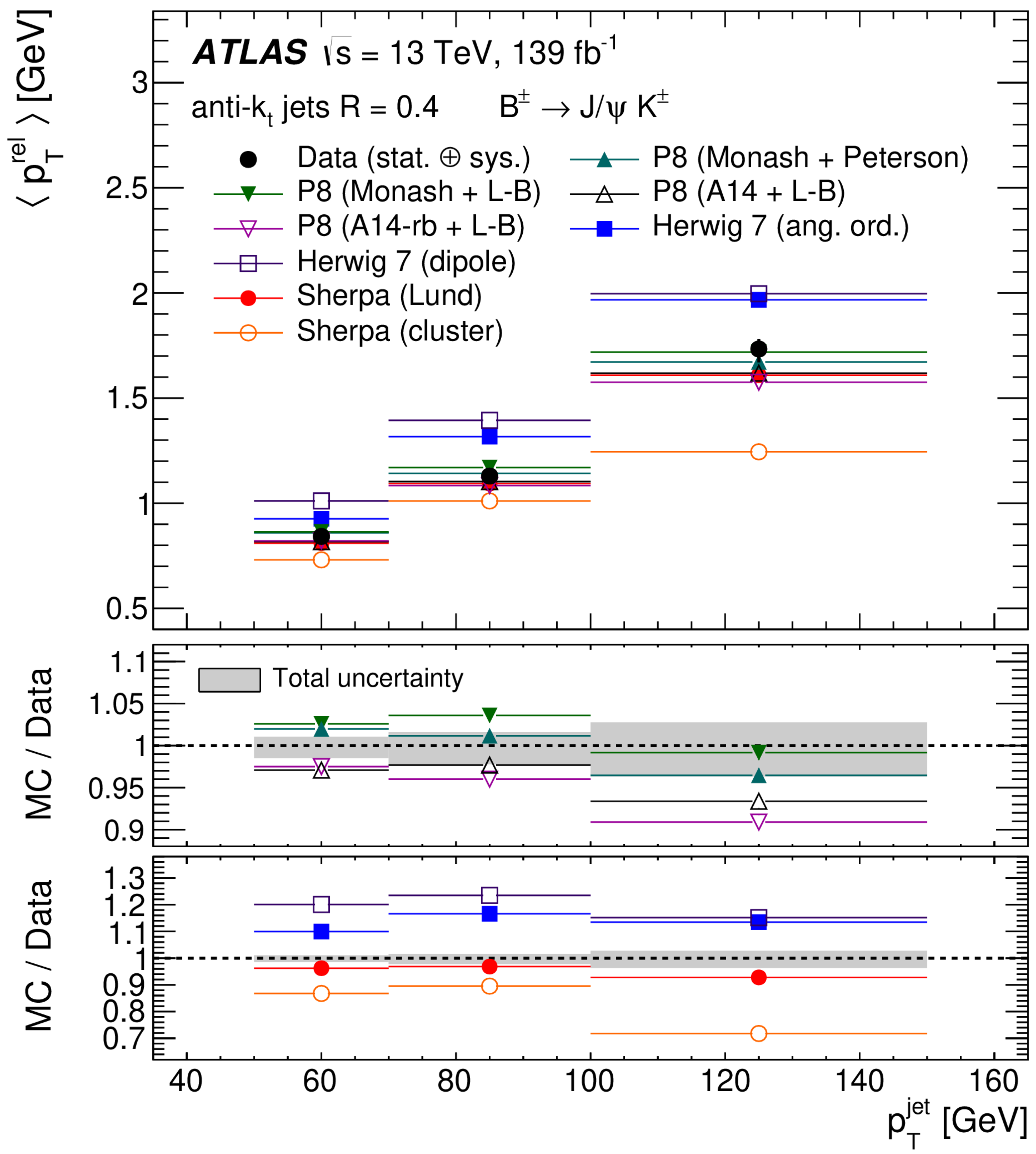


- b-hadron FF a key uncertainty, e.g., for top mass
- Still based on LEP data, universality assumed

longitudinal



transverse



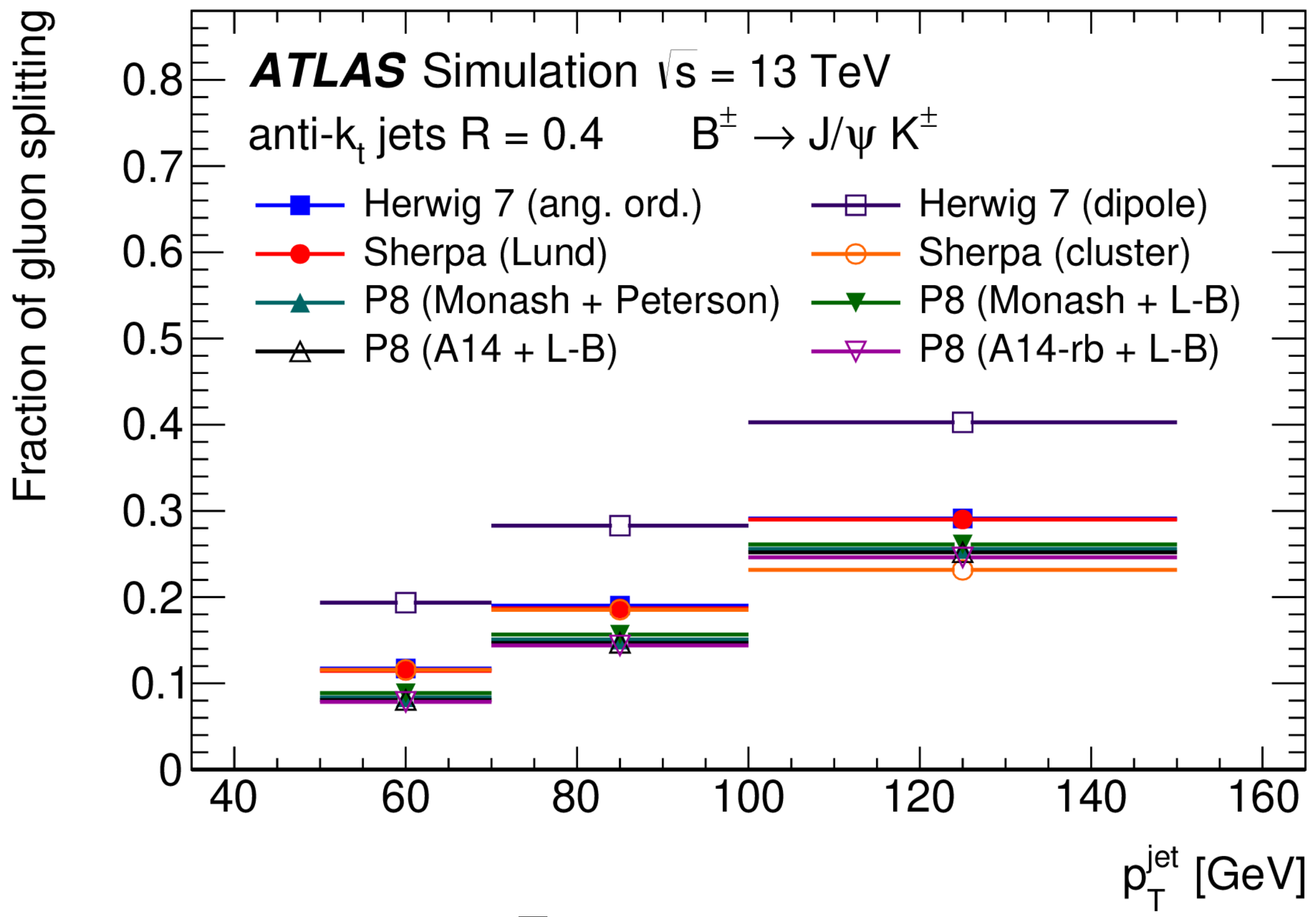
b-hadron fragmentation parameterization (Pythia8)

- Lund-Bowler with r_b = 0.855 vs. 1.05 (“A14-rb”)
- Peterson vs. Lund-Bowler (r_b = 0.855)

Hadronization & parton shower models

- String hadronization: Pythia8, Sherpa
- Cluster hadronization: Herwig7, Sherpa
- p_T ordered: Pythia8
- angular ordered: Herwig7
- dipole: Herwig7,Sherpa

Gluon splitting plays a key role:



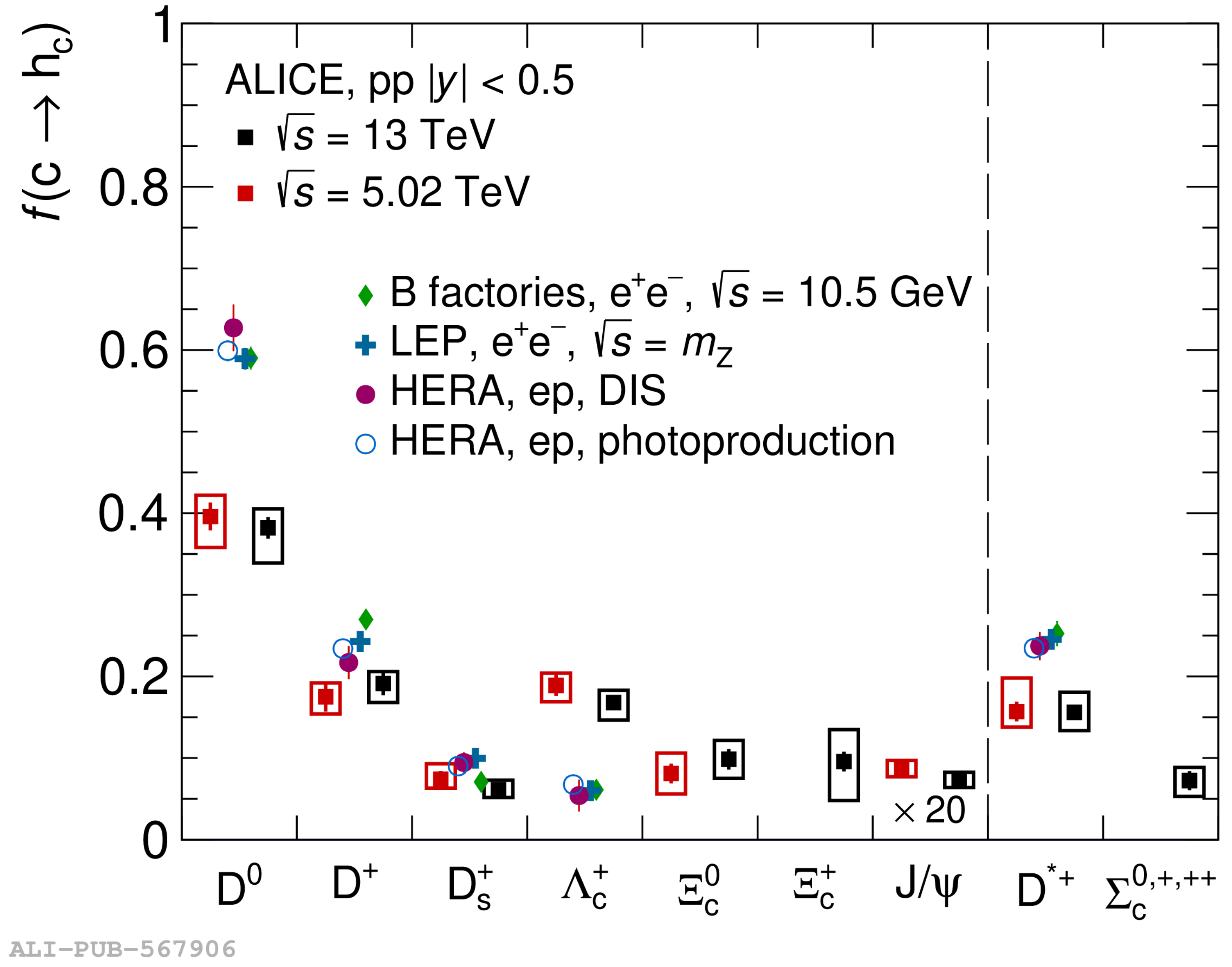
- Universality of b-hadron fragmentation appears to hold;
- String-based models give a good description of the data

See also b-fragmentation in $t\bar{t}$: ATLAS PRD 106 (2022) 032008, CMS-PAS-18-012

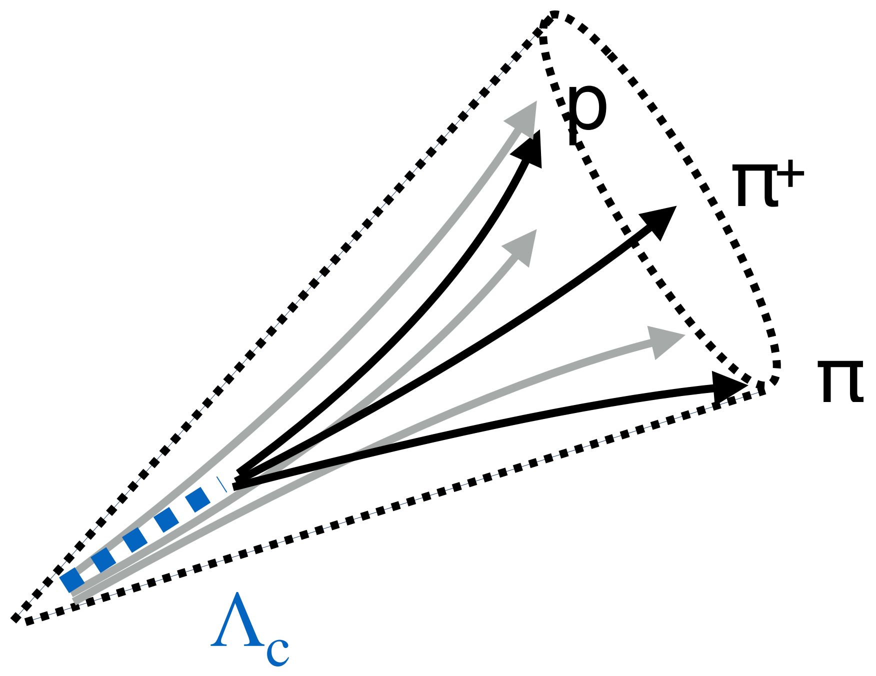
Fragmentation of charm jets

Hadron species dependence of fragmentation accessible in the charm sector

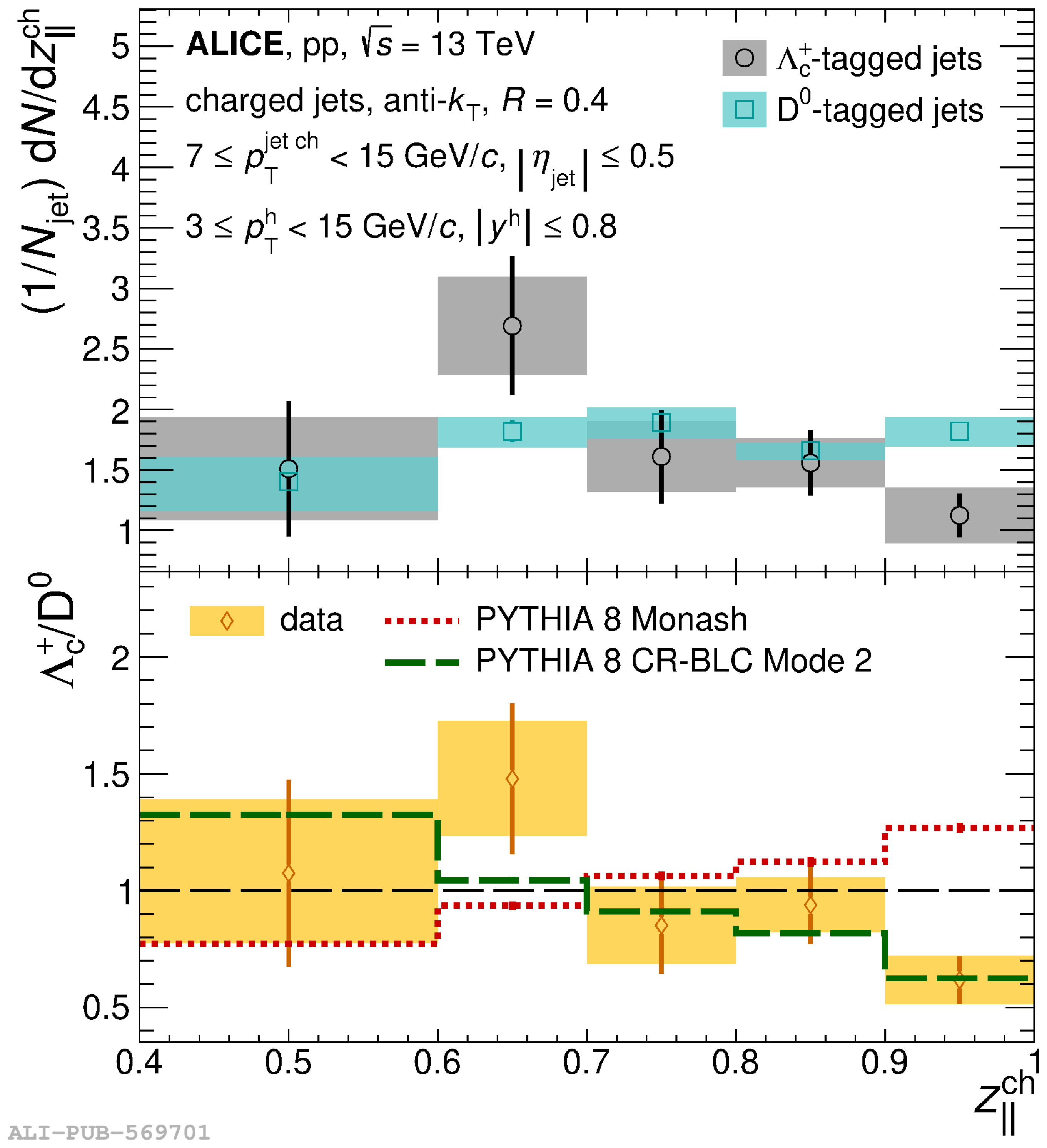
ALICE JHEP 12 (2023) 086



Universality of charm fragmentation known to broken:
Λ_c/D^0 quite different in pp vs. e+e-, ep



ALICE PRD 109 (2024) 072005, ALICE JHEP 06 (2023) 133

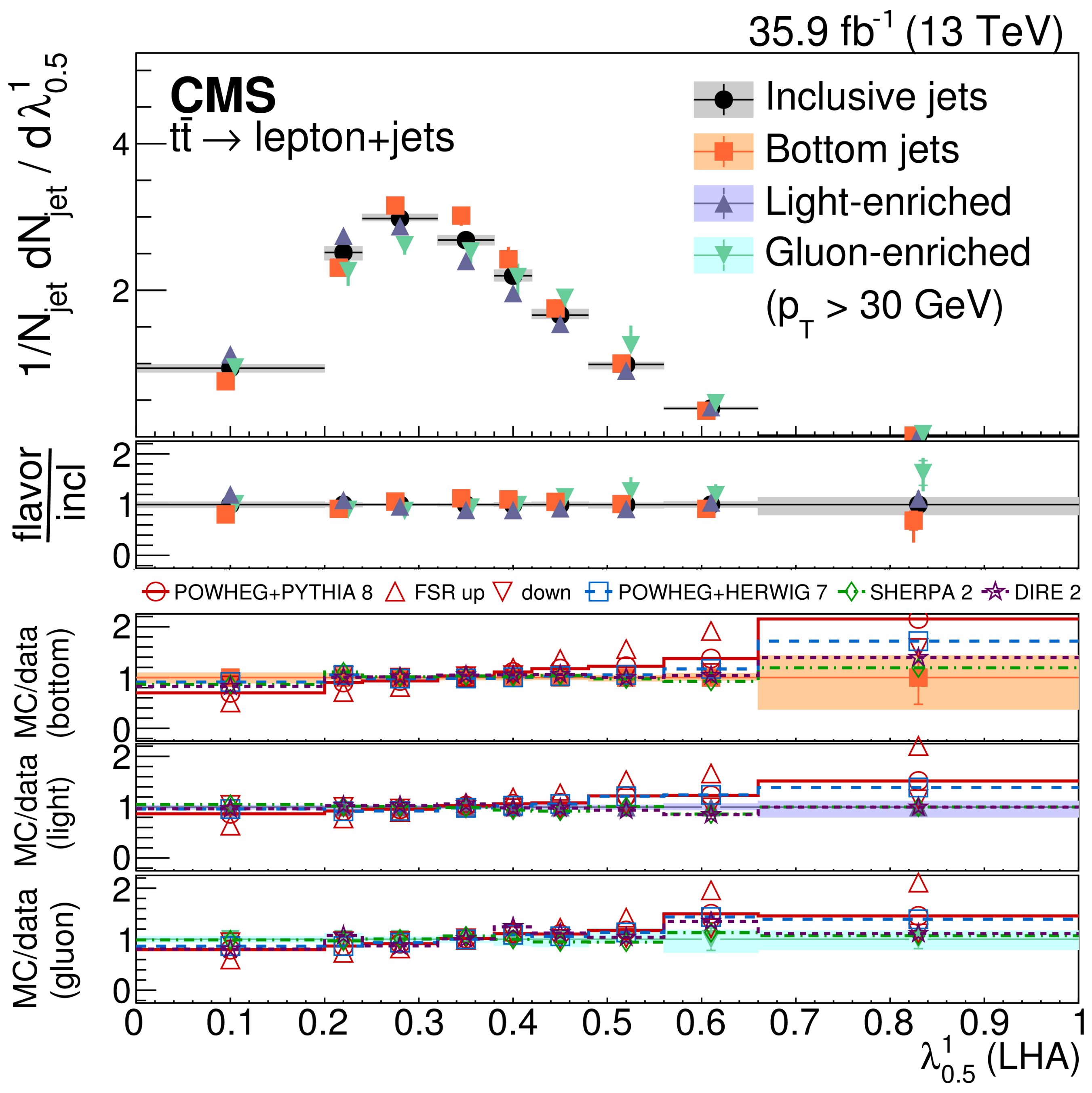


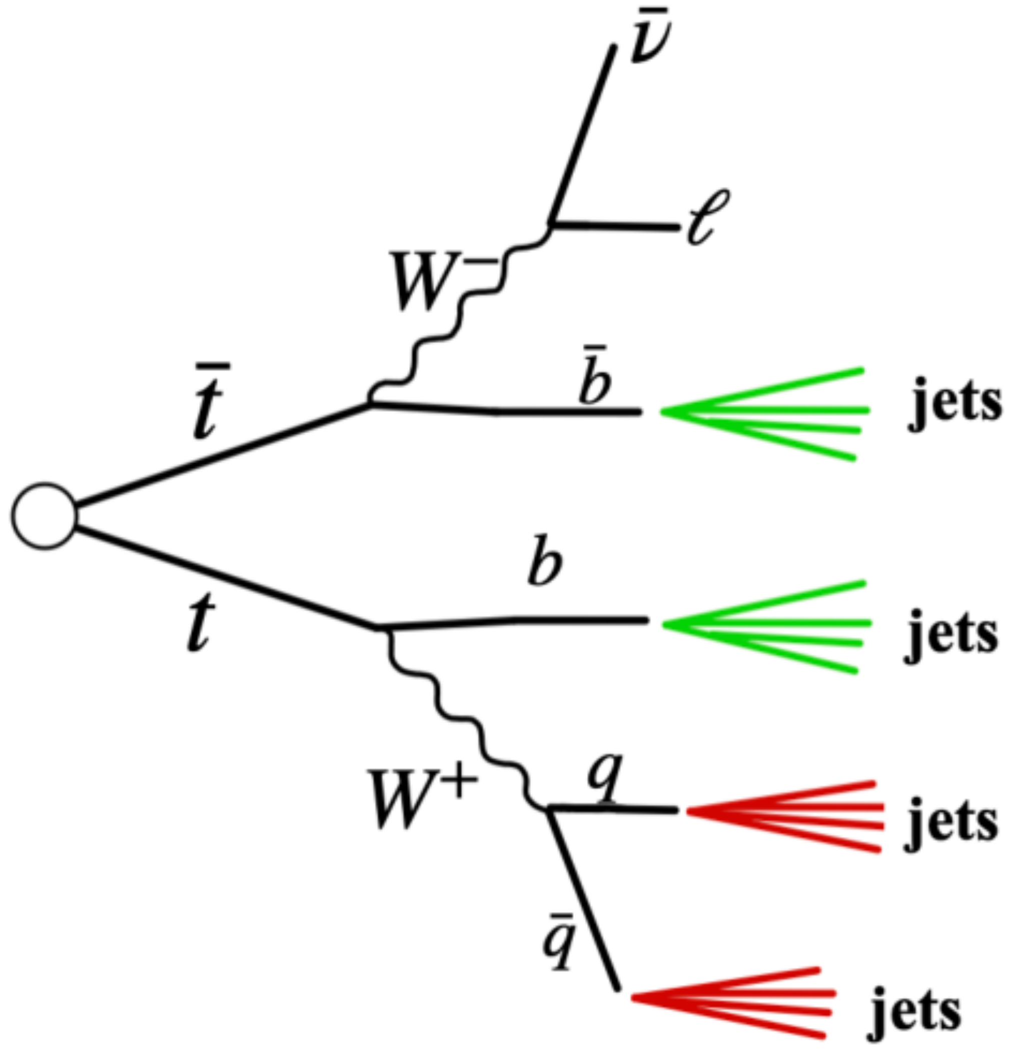
Λ_c well described by model w/ color reconnection beyond leading color approximation

See also D*-jet FF: ATLAS PRD 85 (2012) 052005

b-jet substructure in $t\bar{t}$

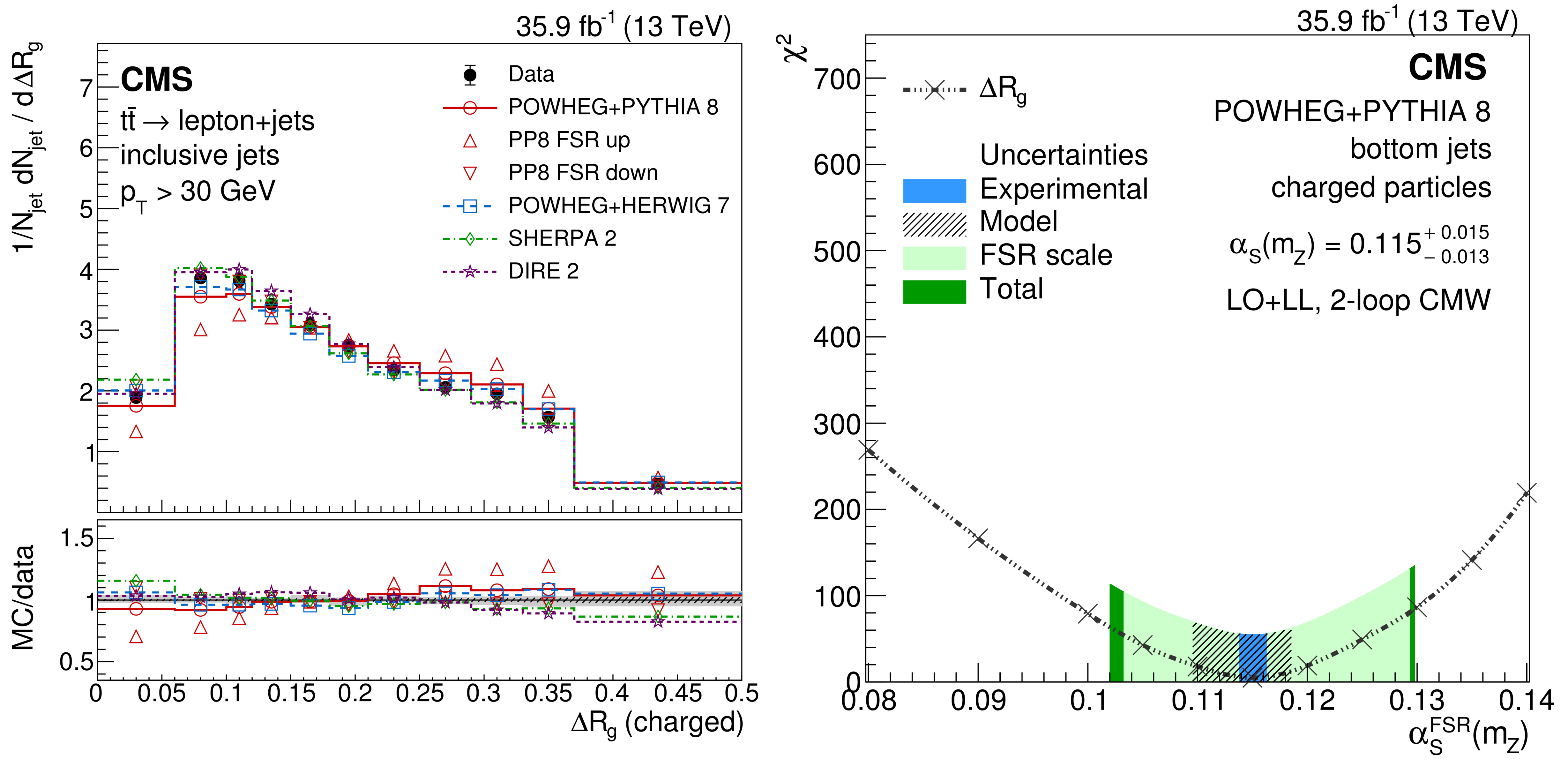
Variety of substructure variables compared to jets of all flavors





$t\bar{t} \rightarrow$lepton+jets

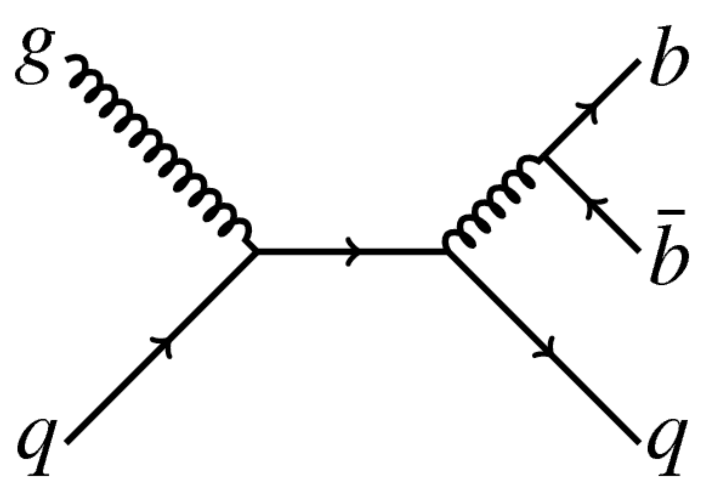
Groomed jet radius used to extract α_s



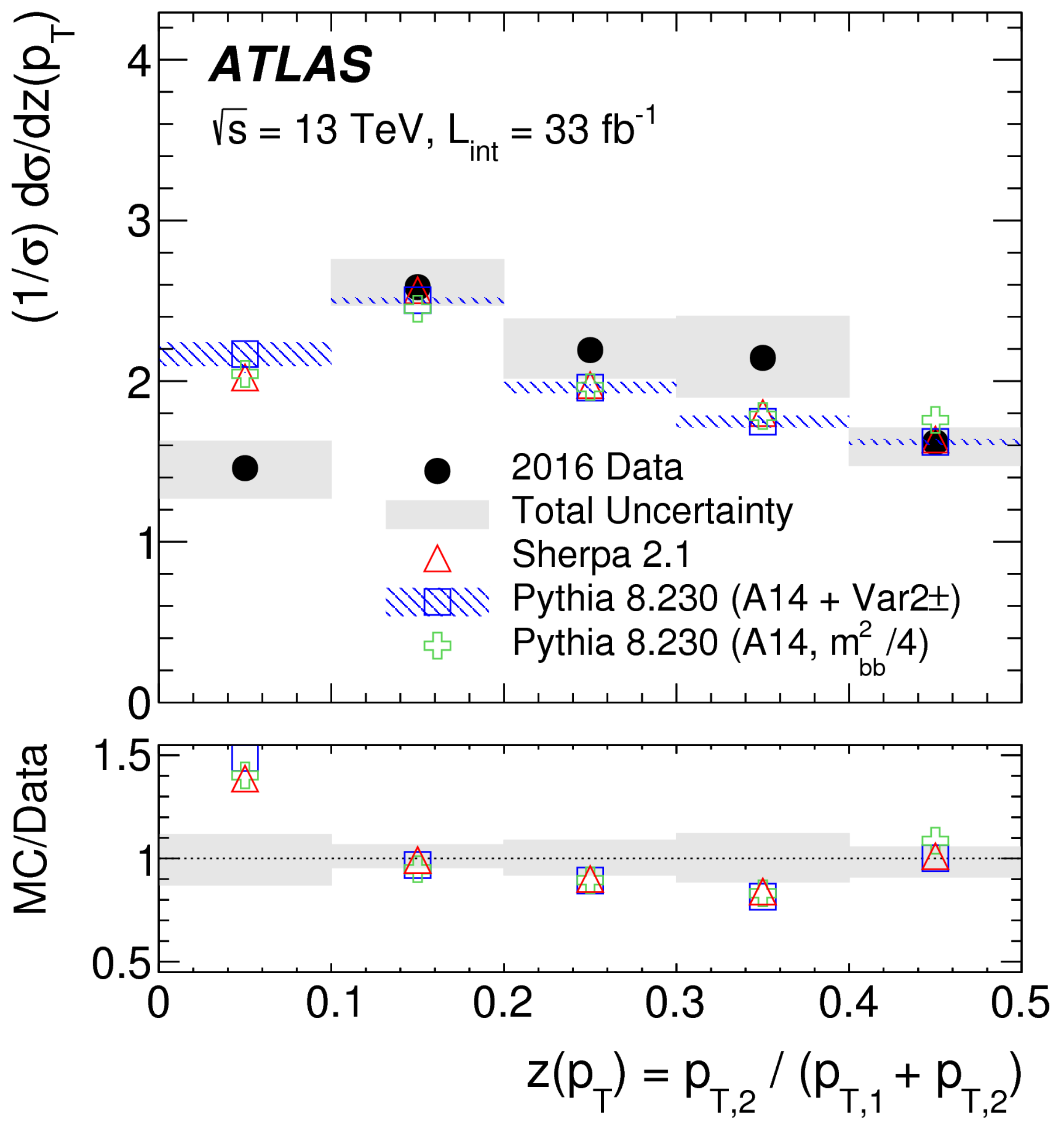
Limited by FSR scale uncertainty of LL parton showers
Expect improvement from top decays at H.O.
w/ multiple emissions & NLL parton showers

b-jet substructure: g→ bb

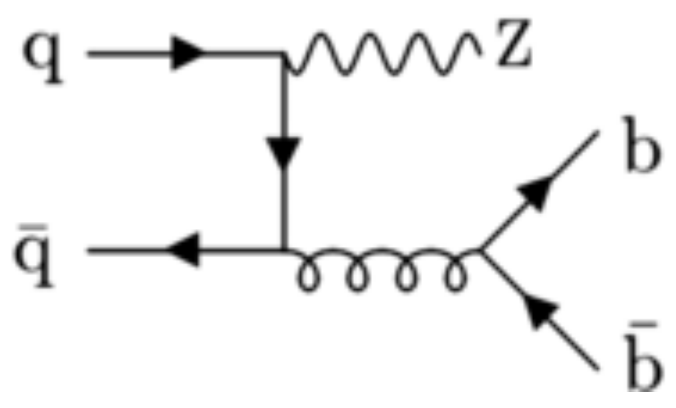
Collinear splitting of gluons to heavy quarks accessed w/ jet substructure
- Measured via large-R jets (R=1.0) w/ track jets (R=0.2) inside
- Crucial background for boosted processes, notably H → $b\bar{b}$



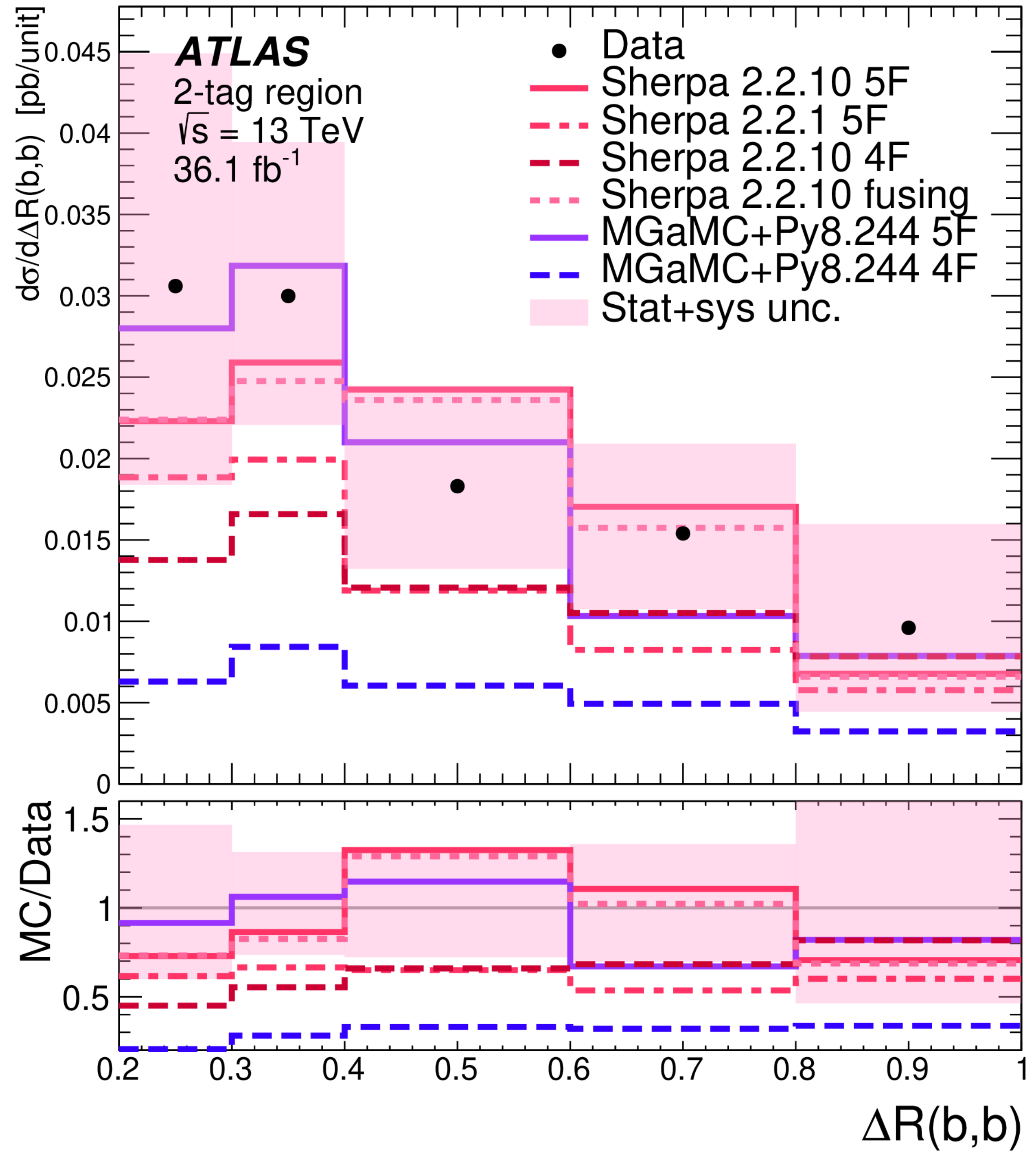
Inclusive large-R jets, p_T > 450 GeV



Poor description in some kinematic regions, e.g., for the most p_T asymmetric splittings



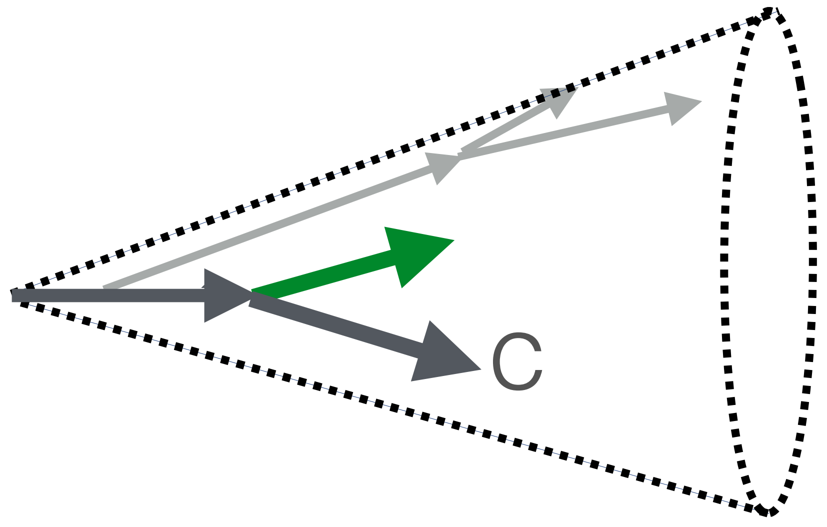
Z+bb-tagged large-R jet, p_T > 200 GeV



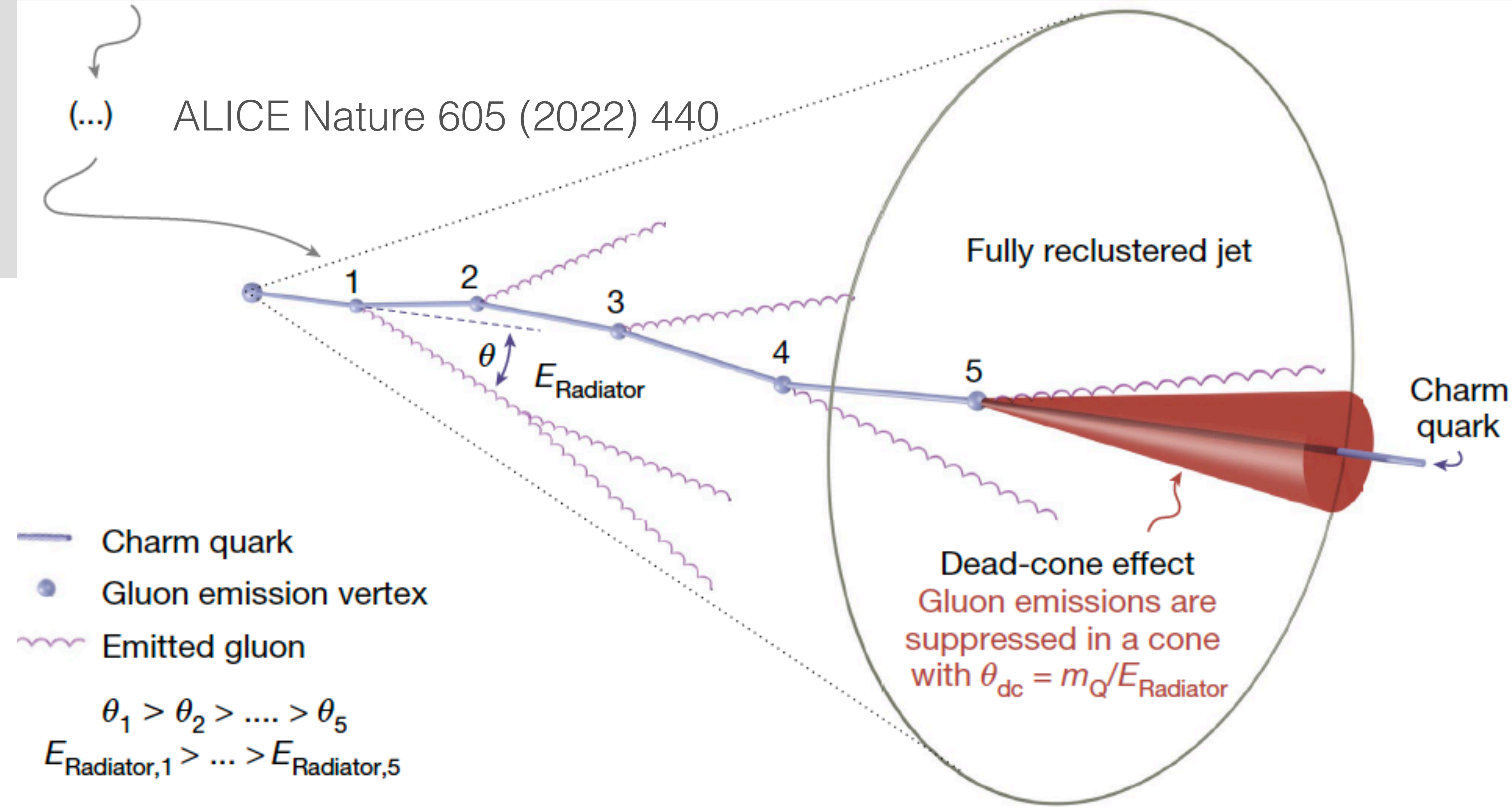
Clear preference for 5 flavor scheme, in this kinematic regime

Related: J/ψ-in-jets LHCb PRL 118 (2017) 192001, CMS PLB 825 (2022) 136842

charm-jet substructure & the dead cone

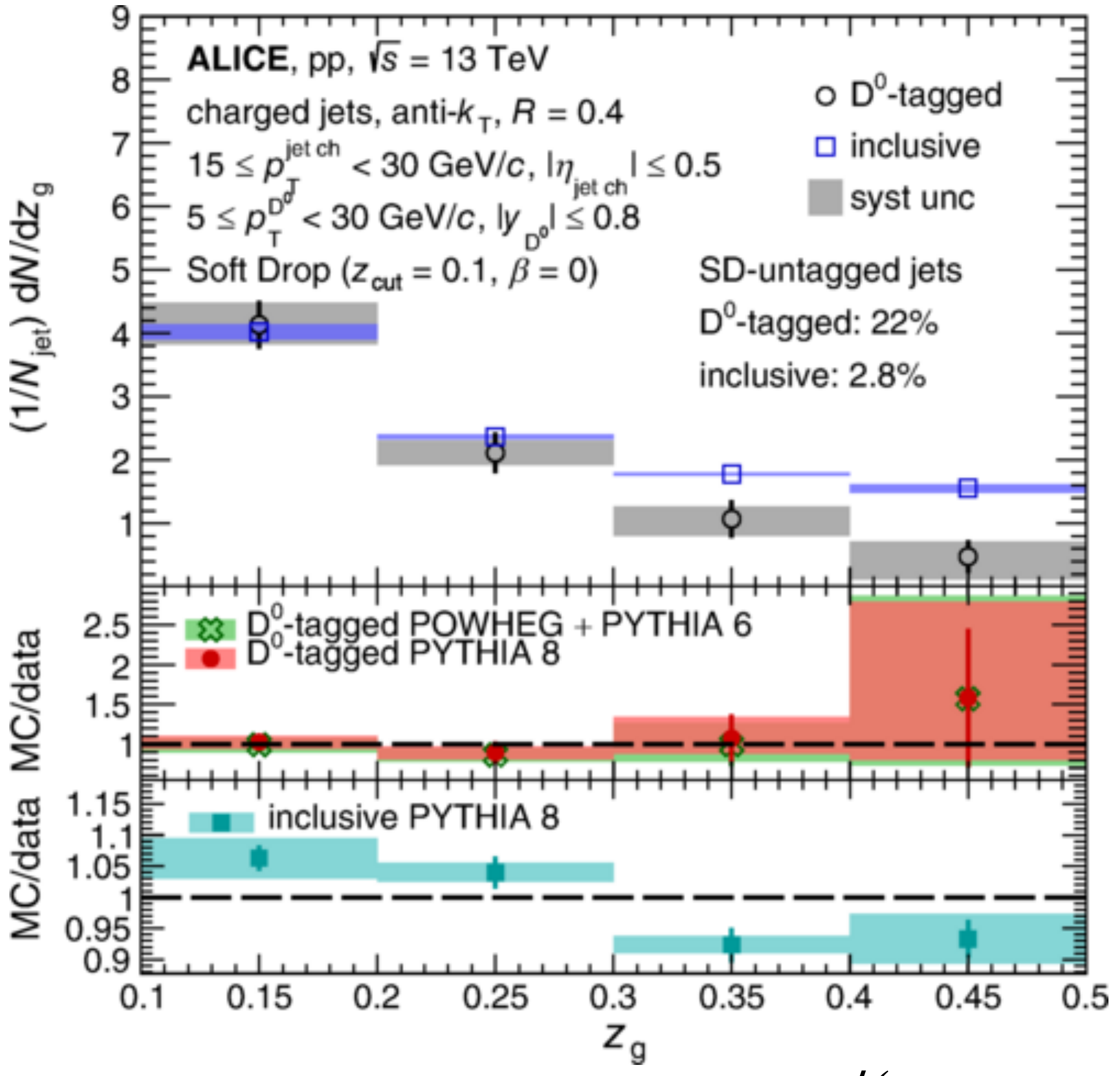


Heavy quark “dead cone” in charm jets
→ Gluon emission suppressed for $\theta = m_c/E$



Standard soft drop declustering

Iterative declustering used to access all c→g splittings

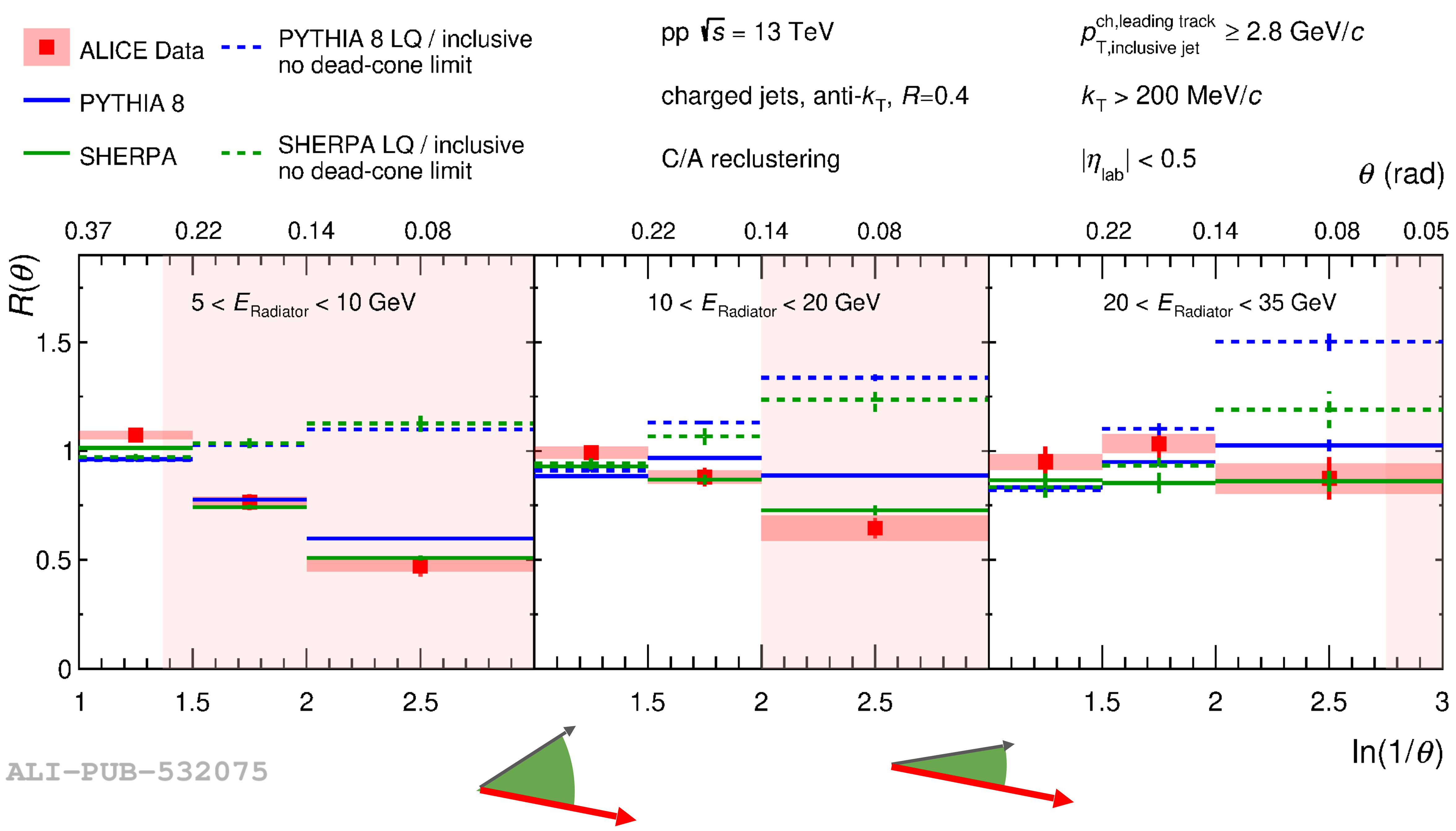


$\equiv p_{\mathrm{T},2}/(p_{\mathrm{T},1} + p_{\mathrm{T},2})$

Compared to inclusive jets, charm jets have:

- Less p_T symmetric splittings
- Higher rate of single prongs

$\frac{\text{charm jet}}{\text{inclusive jet}}$



Deficit of small angle radiation observed at low charm E
Well reproduced by generators

ALICE PRL 131 (2023) 192301

Conclusions

- Single and double b-jet & c-jet cross sections
  - Generally compatible w/ generators, but some tensions, e.g, for extreme kinematics
  - Still room for more precise measurements, e.g., at high p_T
- Associated production
  - Important to test pQCD & constrain background processes
  - Constrain strange sea & intrinsic charm content of proton
- Jet fragmentation of b-hadrons & c-hadrons
  - Precise data constrain b-hadron fragmentation & showering model
  - c-jet fragmentation w/ different hadron species valuable for hadronization models
- Heavy quark-jet substructure
  - Direct measurements of mass-dependent gluon radiation (dead cone)
  - Able to probe interesting dynamics such as collinear gluon splitting

This is an active area of study
→should anticipate more interesting results from LHC expt's in the near future