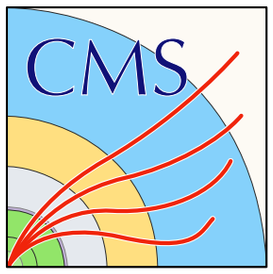
V + heavy flavour @ LHC

Sebastien Prince, McGill University
on behalf of the ATLAS and CMS collaborations

HF@LHC 17



McGill

Outline

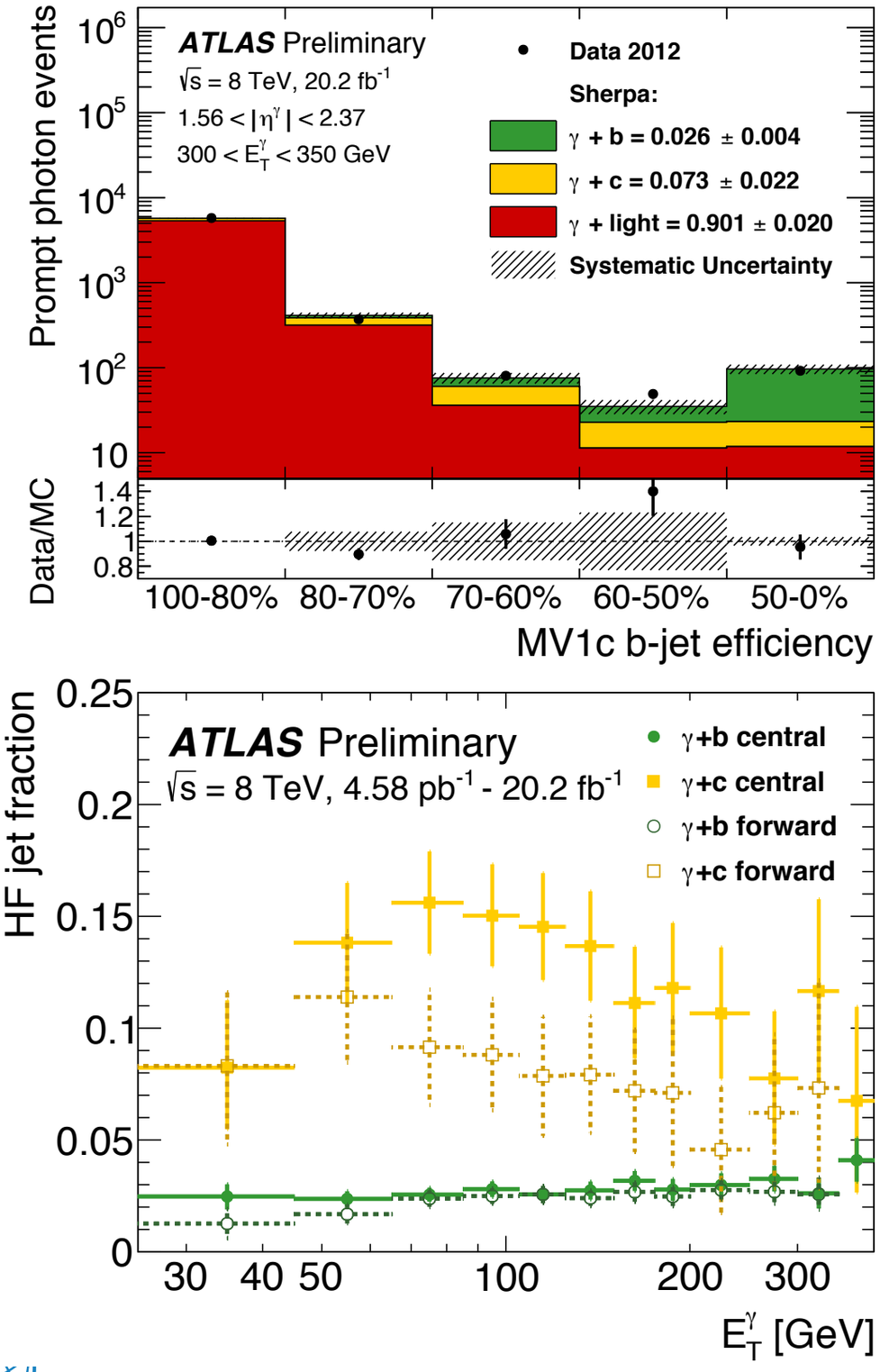
- V+HF cross section measurements presented at this workshop **last year** https://conference.ippp.dur.ac.uk/event/516/
  - ATLAS Z+b(b), W+b(b), W+c @ 7 TeV
  - CMS Z+b(b), W+$b\bar{b}$, W+c @ 7 TeV
- This talk covers the measurements made public **since last year**
  - ATLAS γ+b, γ+c @ 8 TeV
  - CMS Z+b(b), Z+c, W+$b\bar{b}$ @ 8 TeV

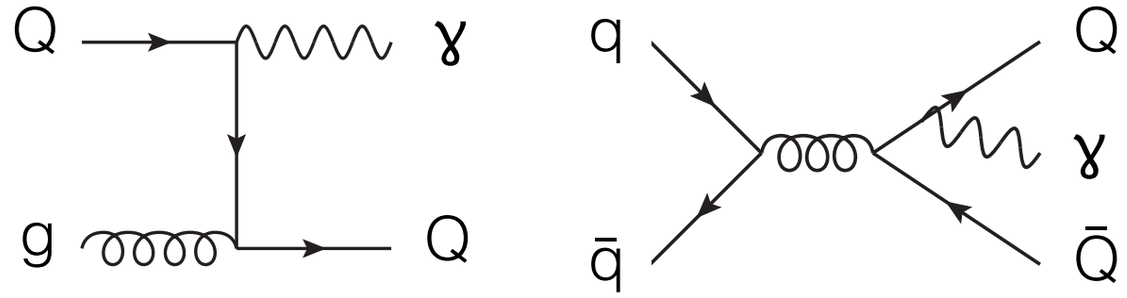
Physics motivation

- Test of pQCD
  - **New topologies**
  - **4-flavour** scheme vs **5-flavour** scheme (4F vs 5F)
- Sensitive to **b- and c-PDF**
- V + HF processes background to Higgs measurements and to various searches
- 8 TeV might be better than 13 TeV to probe high x values

ATLAS γ+b, γ+c @ 8 TeV

γ+b, γ+c

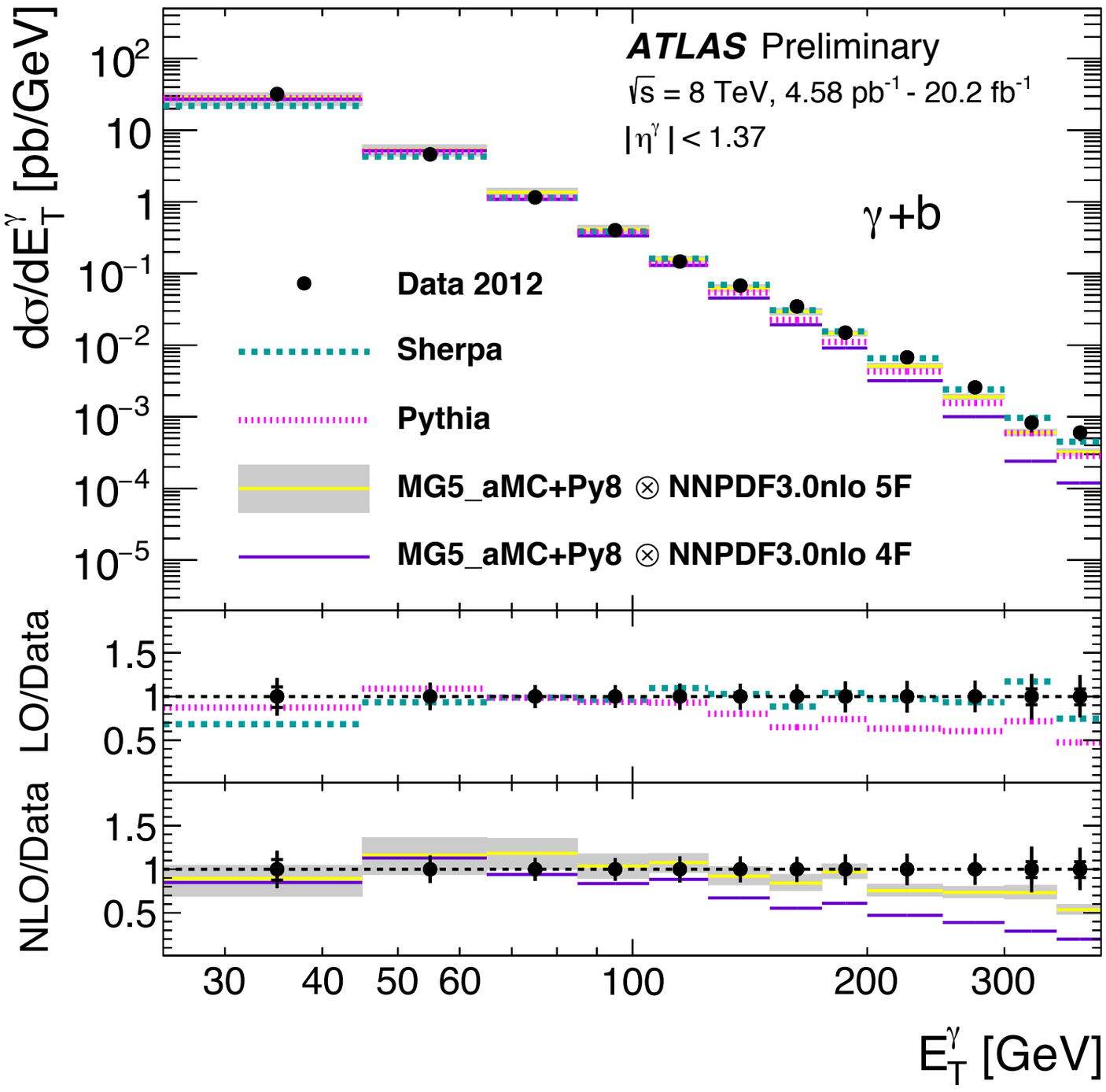




CERN-EP-2017-217

- **p+p→γ+b** and **p+p→γ+c**
  - Fiducial differential cross sections as a function of $\mathbf{E_T^{\gamma}}$ in **two $\mathbf{|\eta^{\gamma}|}$ regions**
  - Fiducial region:
    - Isolated photon:
      $E_T > 25$ GeV and $|\eta| < 1.37$ or $1.56 < |\eta| < 2.37$
    - One b- or c-jet (anti-kt R=0.4):
      $p_T > 20$ GeV and $|\eta| < 2.5$
    - Angular separation: $\Delta R_{\gamma\text{-jet}} > 1$
  - Also ratio of central / forward $|\eta^{\gamma}|$ regions
- Both signals **simultaneously** extracted from fit to the MV1c b-tagging discriminant
  - Correlates the two measurements

γ+b: E_T^{γ} cross section



- Predictions

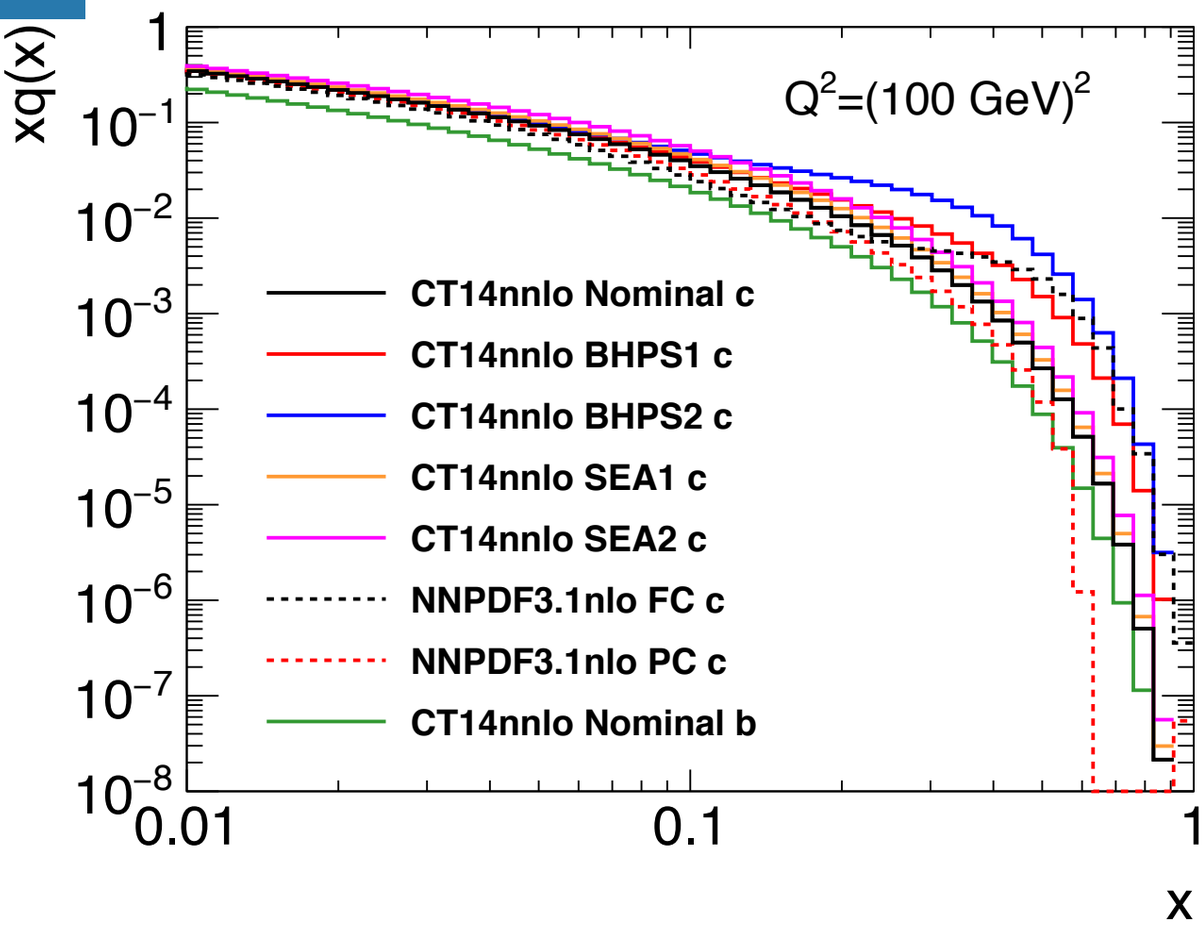
  - Sherpa 1:
    LO 2→2,3,4,5 in massive 5F
  - Pythia 8:
    LO 2→2 in 5F
  - Madgraph5_aMC@NLO + Pythia 8:
    NLO in 4F and 5F

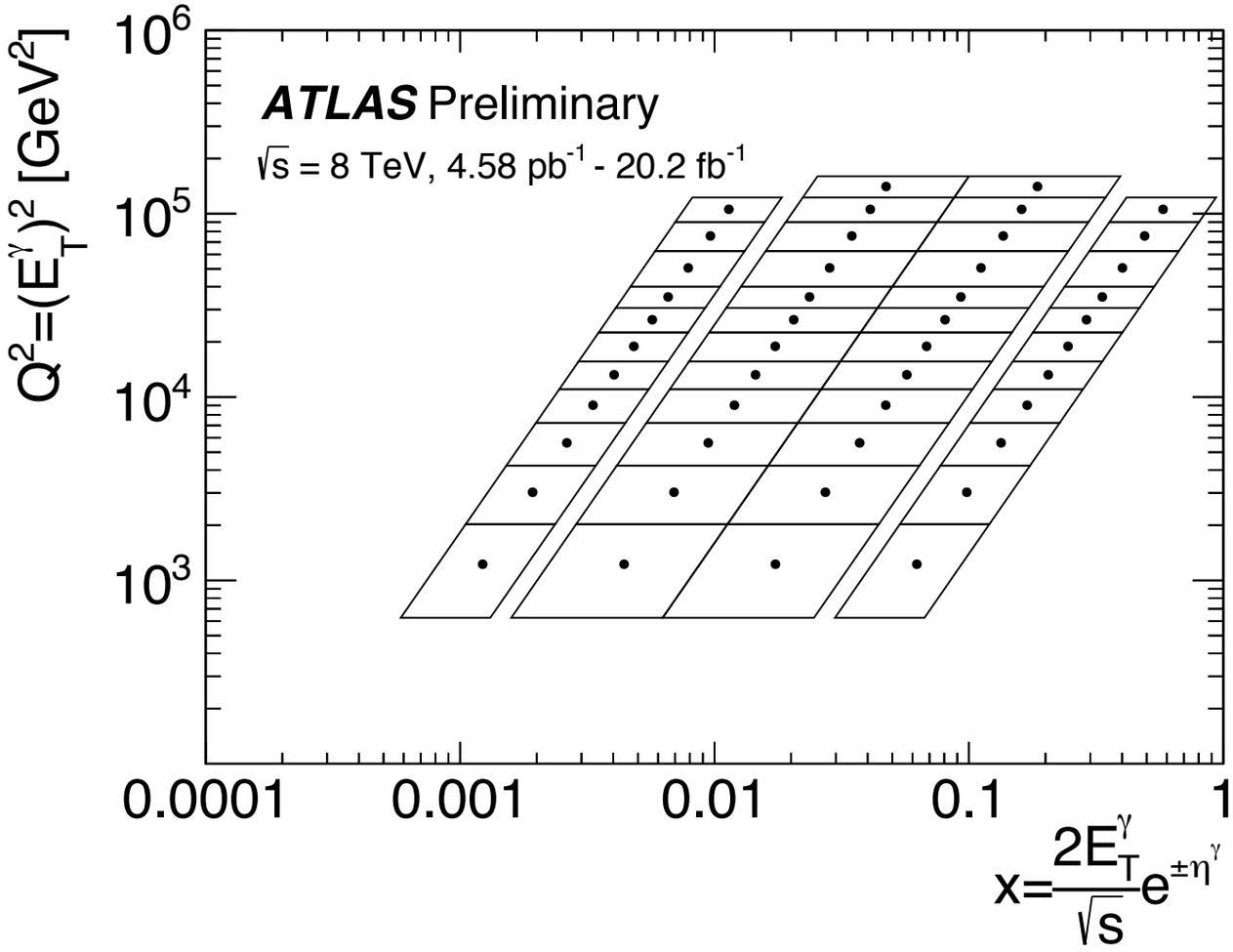
- Better agreement from 5F NLO than 4F NLO

  - Still, **both underestimate data at high E_T**, where gluon-splitting dominates

- Best agreement from Sherpa

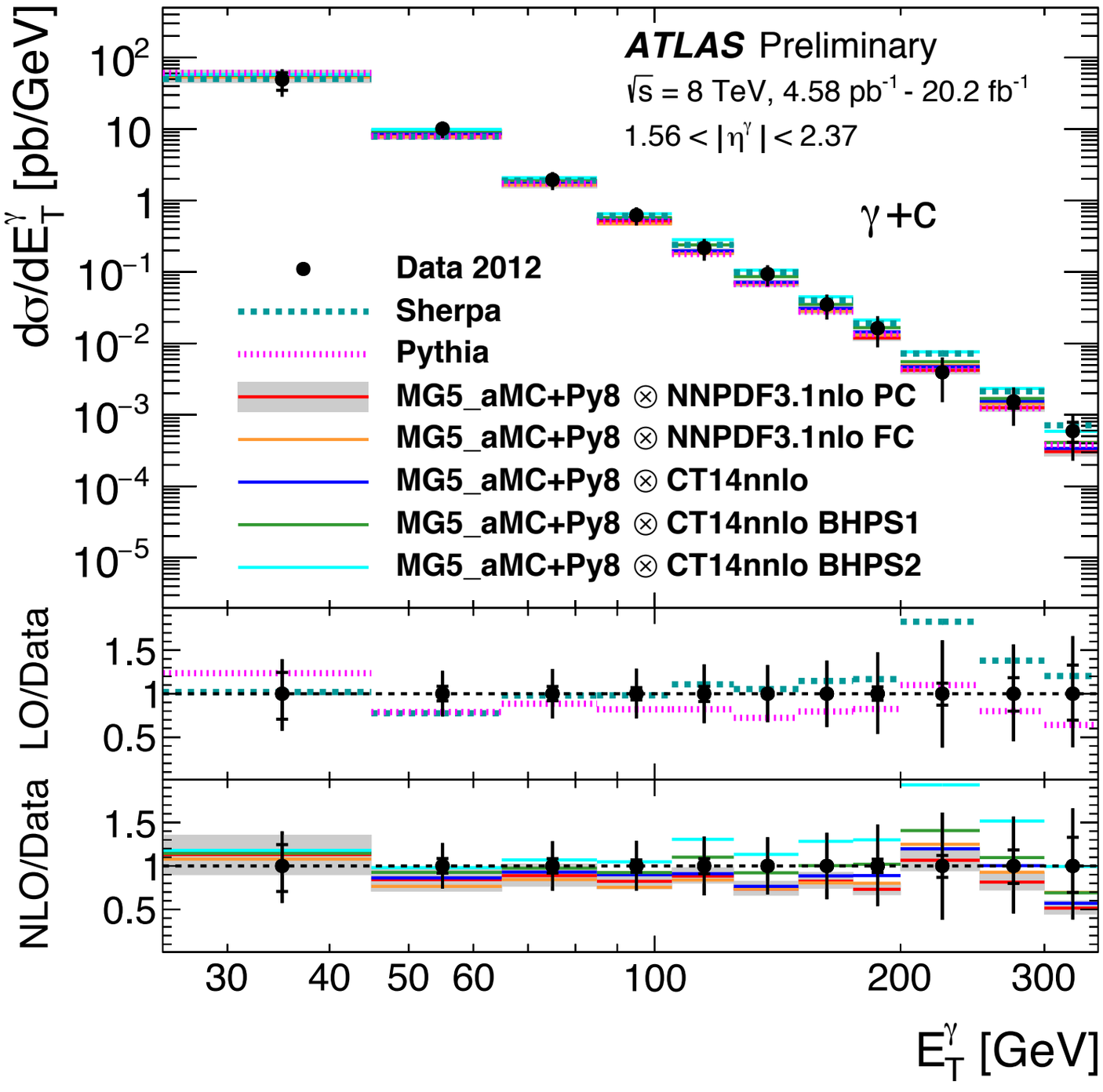
Intrinsic charm





- Intrinsic charm: non-perturbative charm (non PC) component in proton
  - $c(x,Q=m_c) \neq 0$
  - Different parameterization: valence-like (BHPS), sea-like (SEA), fitted to data (FC)
- Would be manifest at large E_T^γ and large $|\eta^\gamma|$

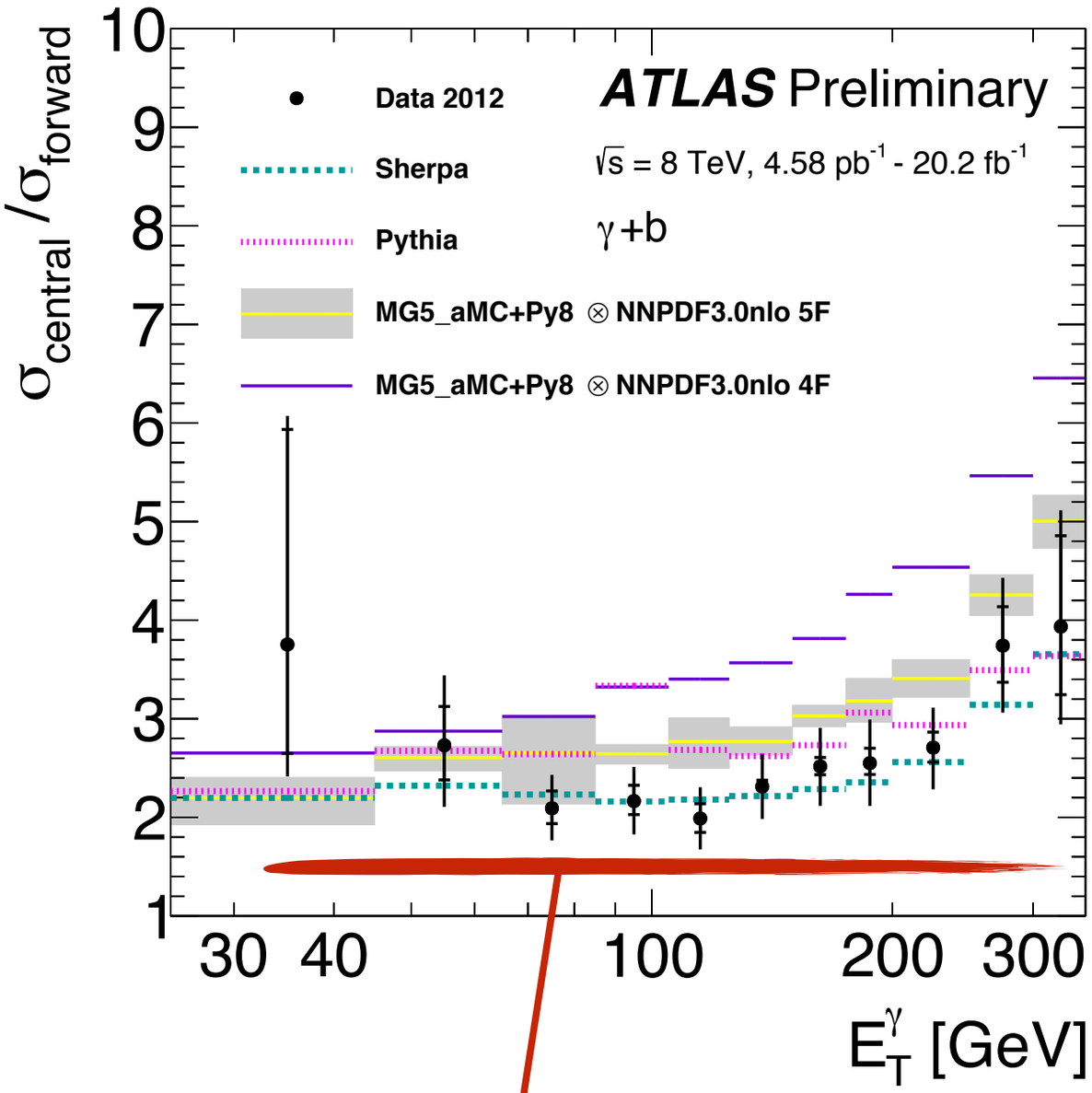
γ+c: E_T^{γ} cross section



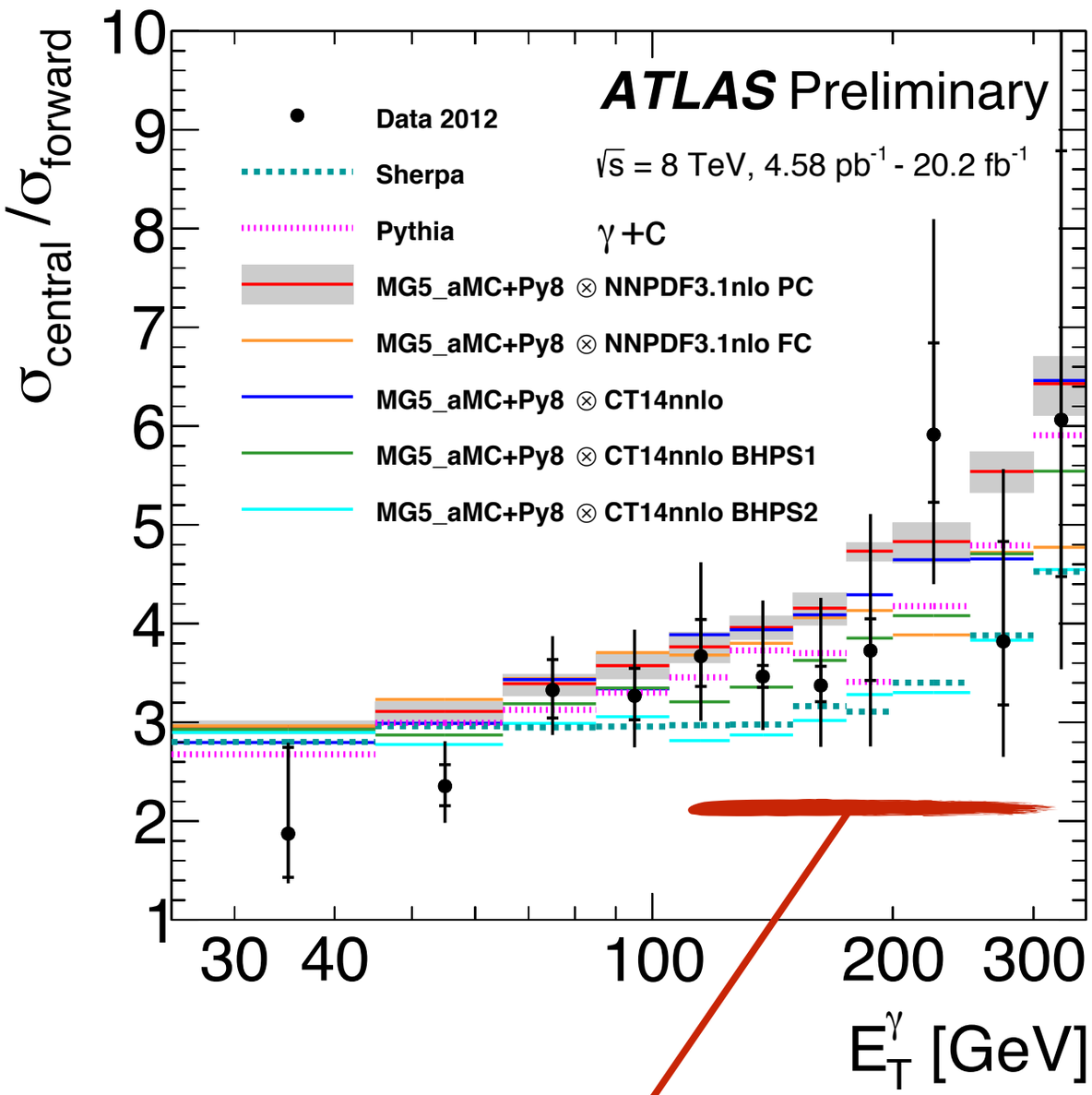
- Predictions:
  - Sherpa 1:
    LO 2→2,3,4,5 in massive 5F
  - Pythia 8:
    LO 2→2 in 5F
  - Madgraph5_aMC@NLO + Pythia 8:
    NLO (5F) with PDFs including intrinsic charm contributions (FC, BHPS1,2)

- γ+c:
  Larger measurement **uncertainties** than γ+b
- Agreement will all predictions, within uncertainties
- BHPS2, containing large intrinsic charm contributions, **deviates from nominal predictions** at high E_T

γ+b, γ+c cross-section ratios



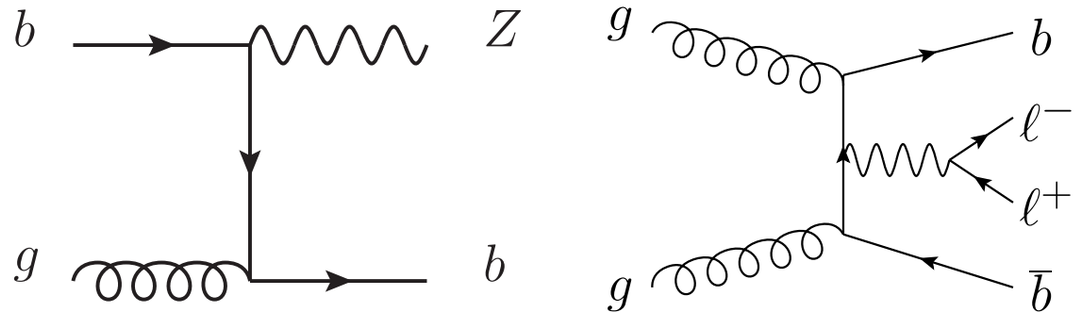
Sherpa again provides best description of the data



Data falls in-between predictions with and without intrinsic charm, but agrees with all predictions given the uncertainties

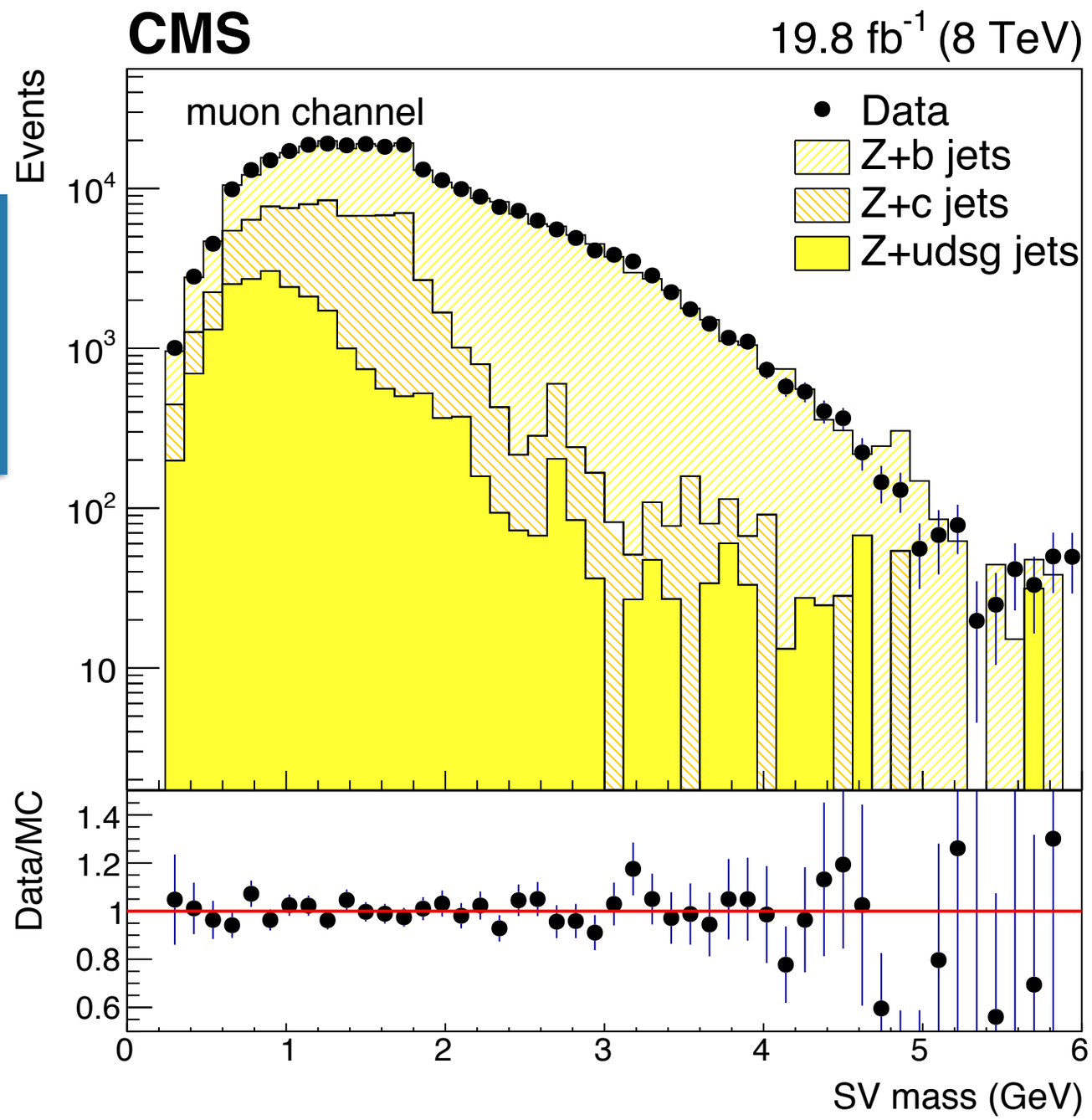
CMS Z+b(b) @ 8 TeV

Z+b(b)



arXiv:1611.06507

- **p+p → Z(→$\ell\bar{\ell}$)+b(b)**
  - Fiducial differential cross sections, with following observables:
    - Z+b:
      p_T^{bjet}, $|\eta|^{bjet}$, p_T^Z, H_T, $\Delta\phi_{Zb}$
    - Z+bb:
      $p_T^{leading\ bjet}$, $p_T^{subleading\ bjet}$, p_T^Z,
      M_{bb}, M_{Zbb}, $\Delta\phi_{bb}$, ΔR_{bb}, ΔR_{Zb}^{min}, A_{Zbb}
  - Fiducial region:
    - Two electrons or muons:
      $p_T > 20$ GeV and $|\eta| < 2.4$,
      within 20 GeV of Z mass window
    - One or two b-jets (anti-kt R=0.5):
      $p_T > 30$ GeV and $|\eta| < 2.4$
    - Angular separation: $\Delta R_{\ell\text{-jet}} > 0.5$
  - Also Z+b / Z+jets ratio
- Signal extracted by fitting the jet secondary vertex mass



Z+b: p_T^Z cross section

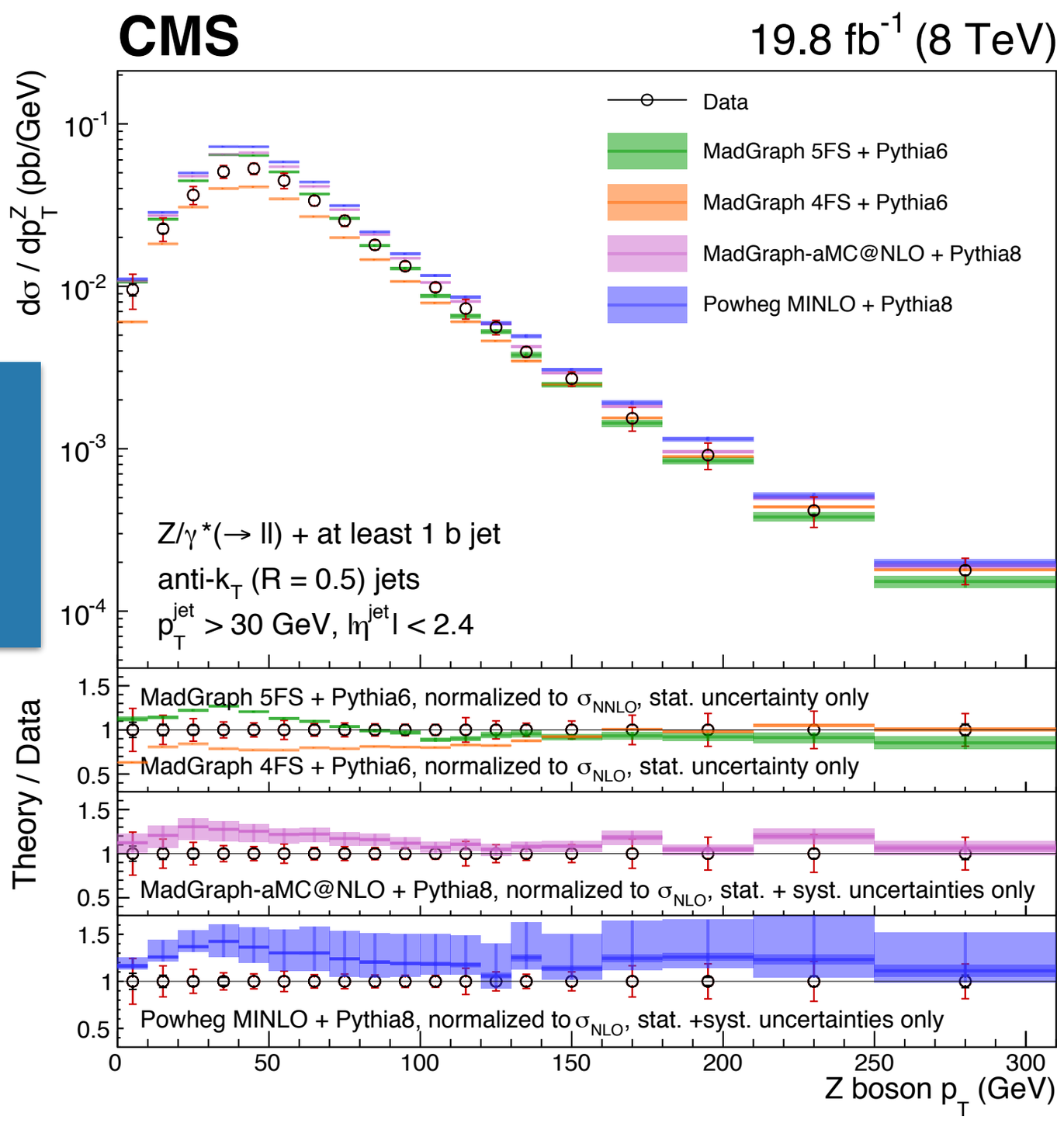
- p_T^Z and p_T^{bjet} sensitive to **PDF** and **flavour scheme**

- Predictions:

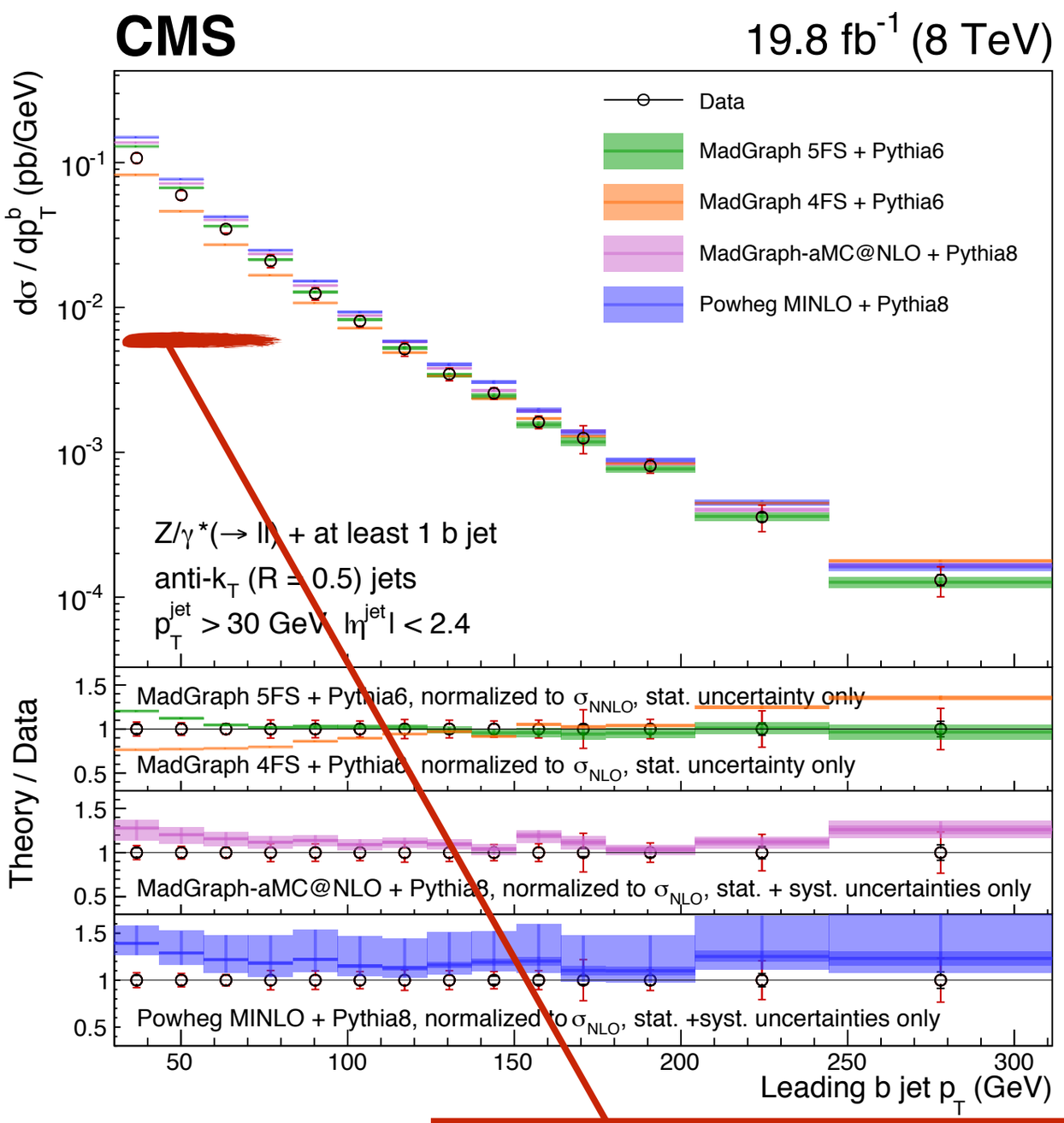
  - LO Madgraph5 + Pythia 6:
    2→2,3,4,5 in 4FS and 5FS
  - NLO Madgraph5_aMC@NLO + Pythia 8 (5FS):
    FxFx-merged samples of 0, 1 and 2 partons
  - NLO Powheg + Pythia 8 (5FS):
    Scale choice based on MINLO

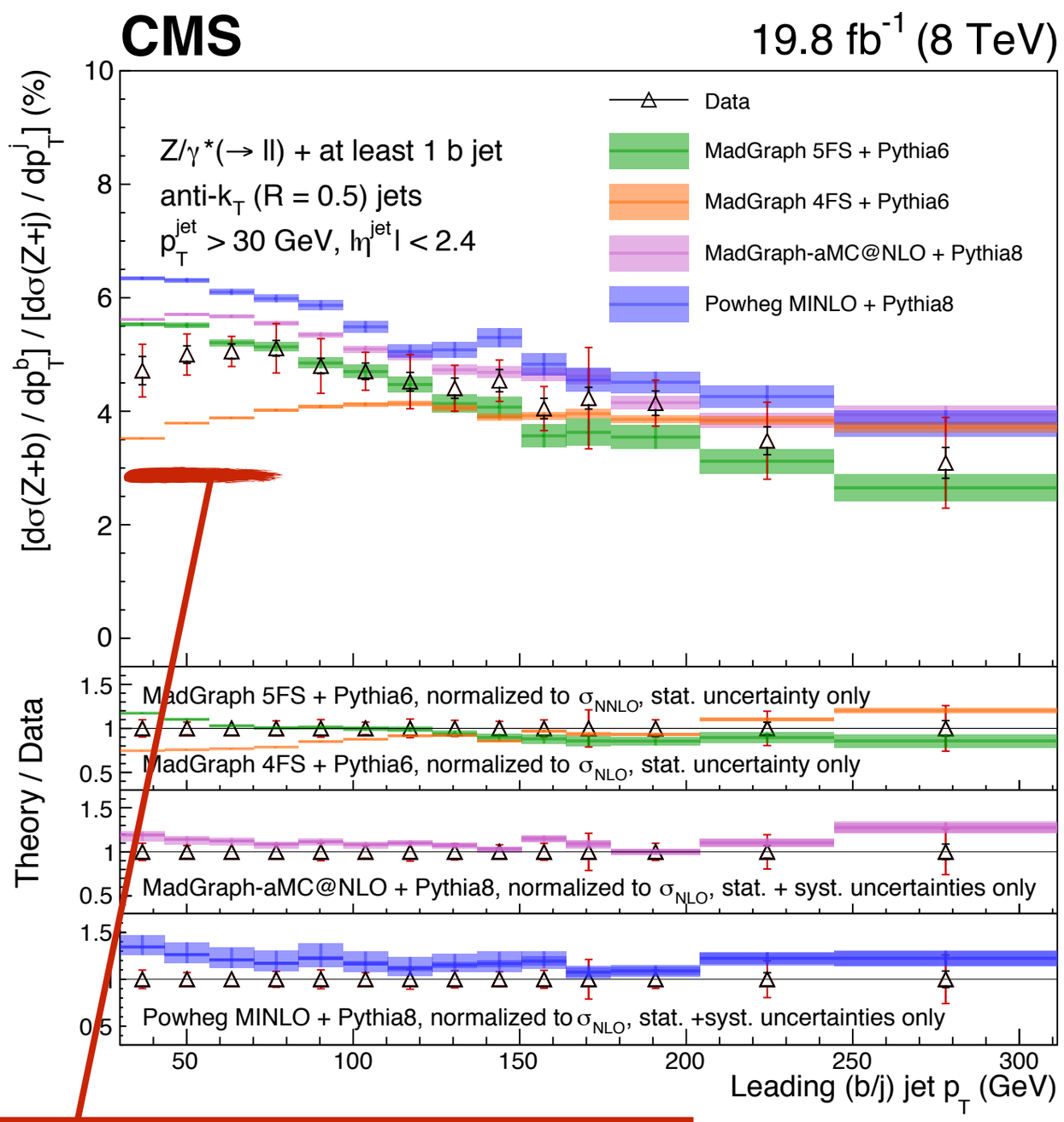
- LO and NLO Madgraph show overall good agreement

- **Better shape** description by Madgraph **4FS** than 5FS **below 130 GeV**



Z+b: p_T^{bjet} cross section

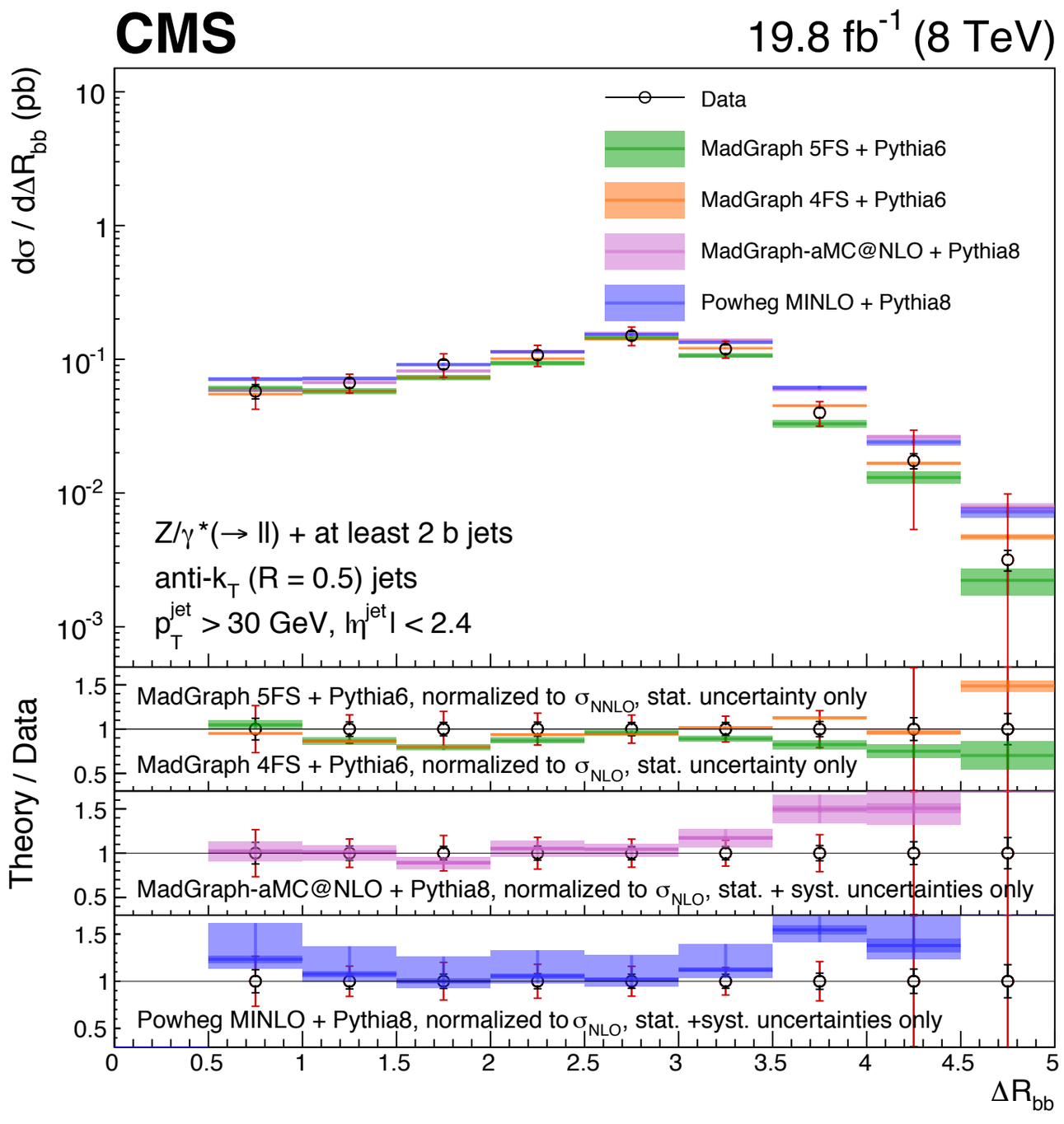




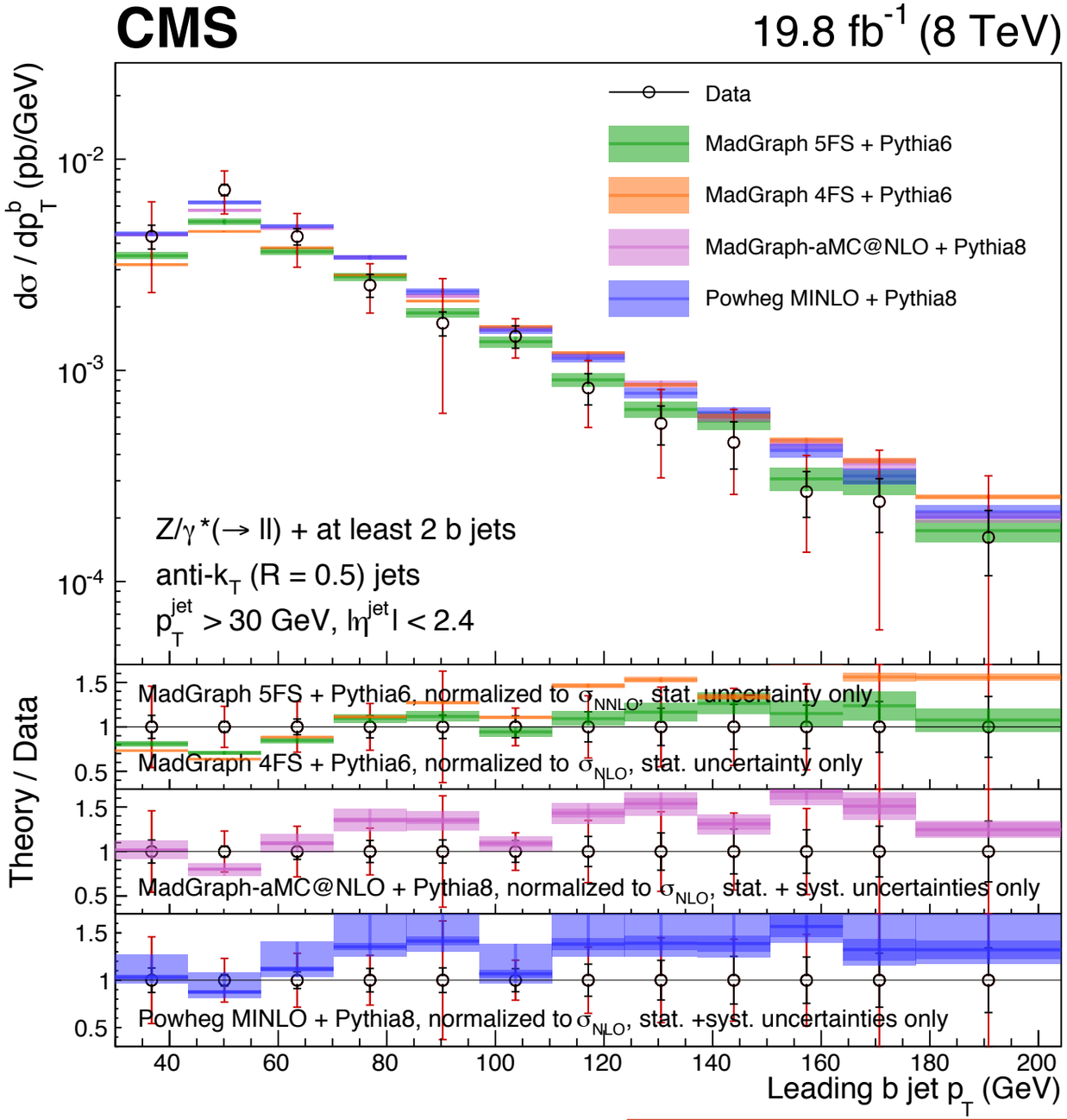
Below 80 GeV, Madgraph 4FS underestimates, while Powheg overestimates

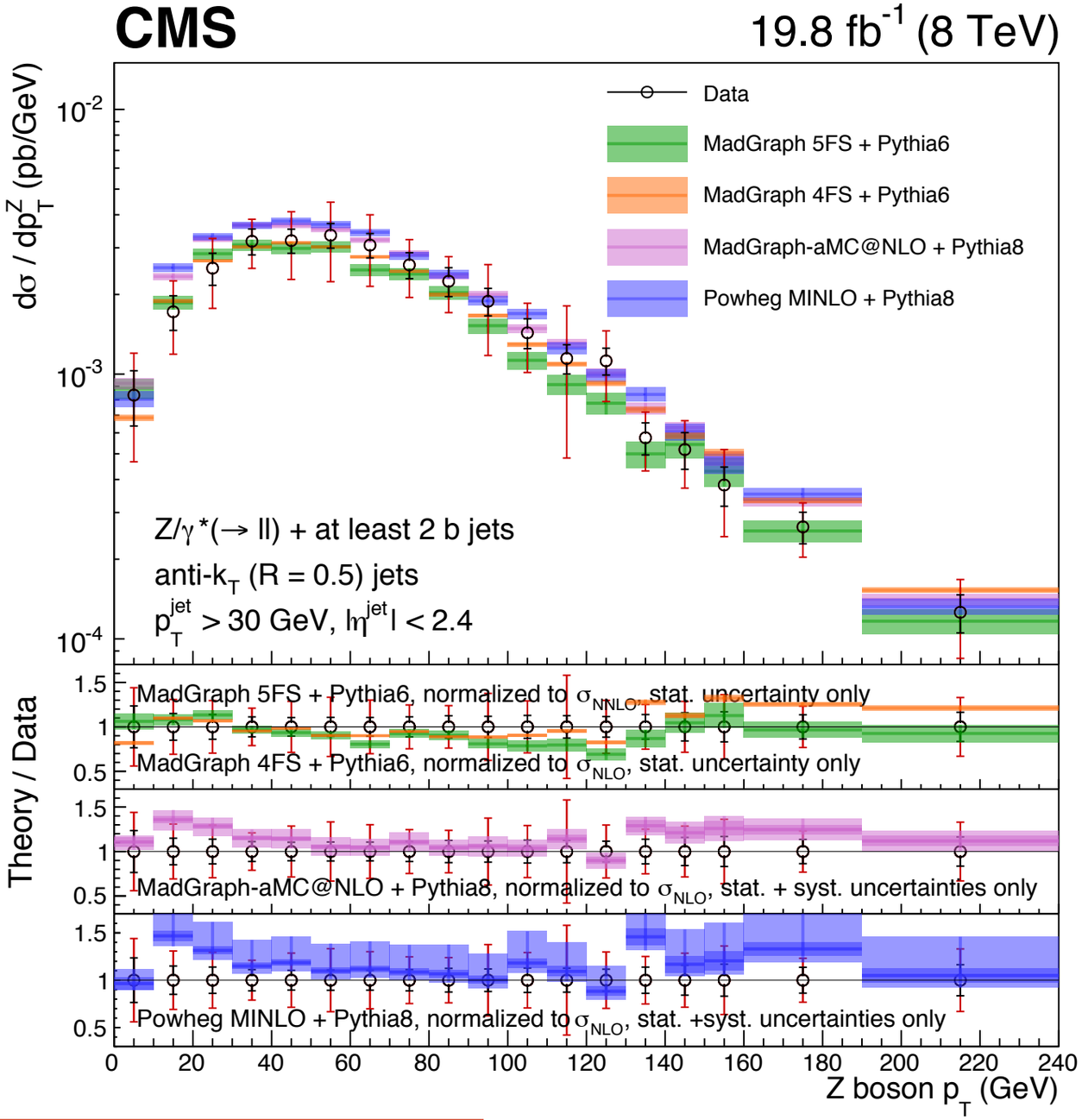
Z+bb: ΔR_{bb} cross section

- ΔR_{bb} sensitive to **bb production mechanism**
  - Small values: gluon-splitting
  - Large values: hard process
- Z+bb:
  Larger experimental **uncertainties** than Z+b
- Agreement will all predictions, within uncertainties
  - Similar for other Z+bb observables



Z+bb: $p_T^{\text{leading bjet}}$, p_T^{Z} cross sections

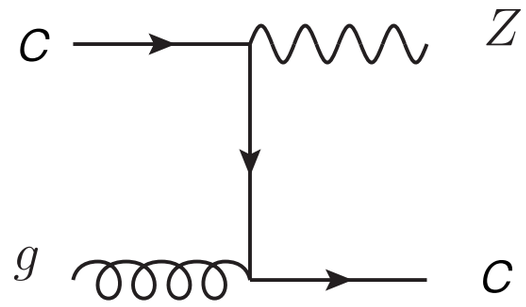




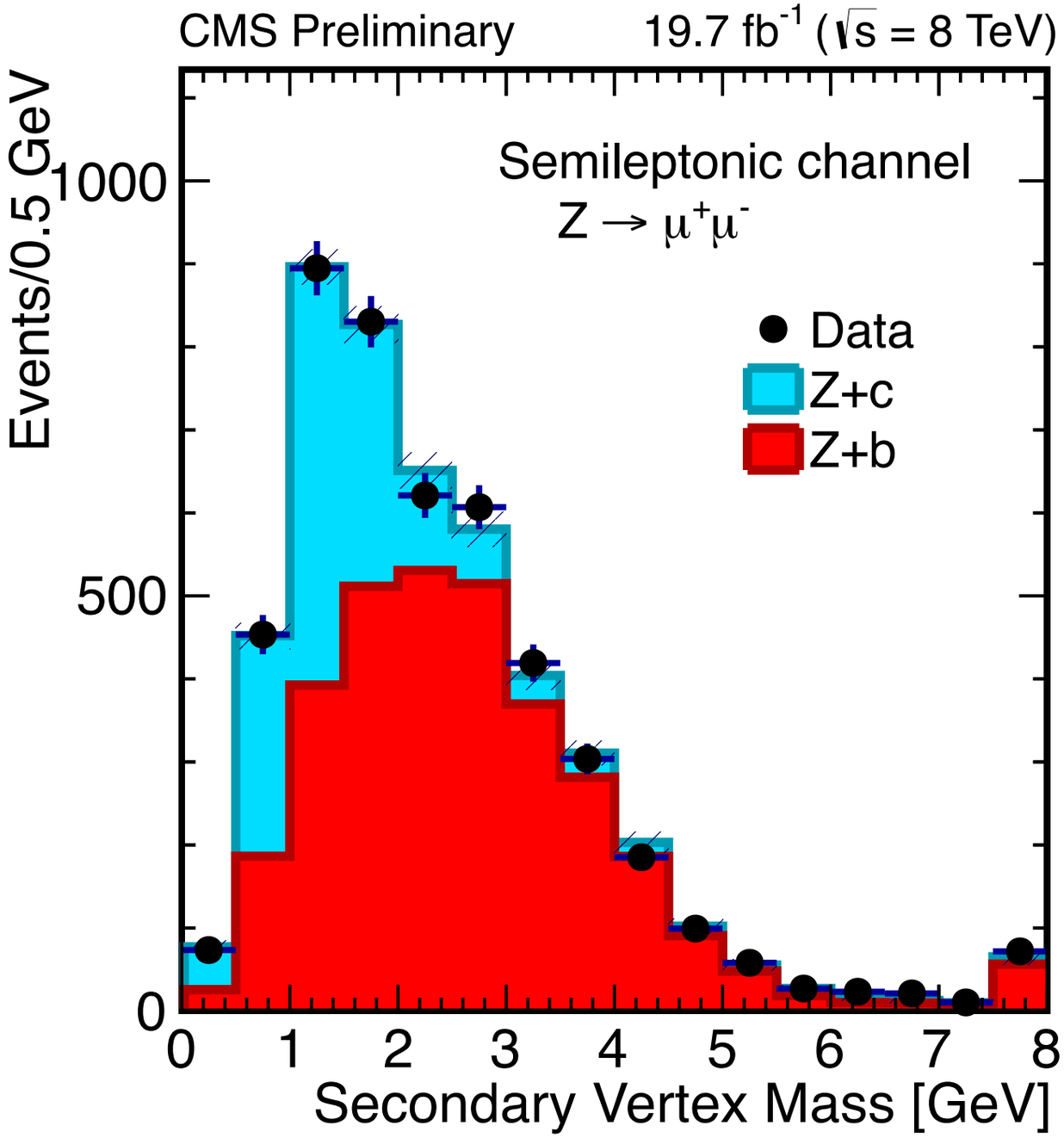
Agreement with all predictions, within uncertainties

CMS Z+c @ 8 TeV

Z+c

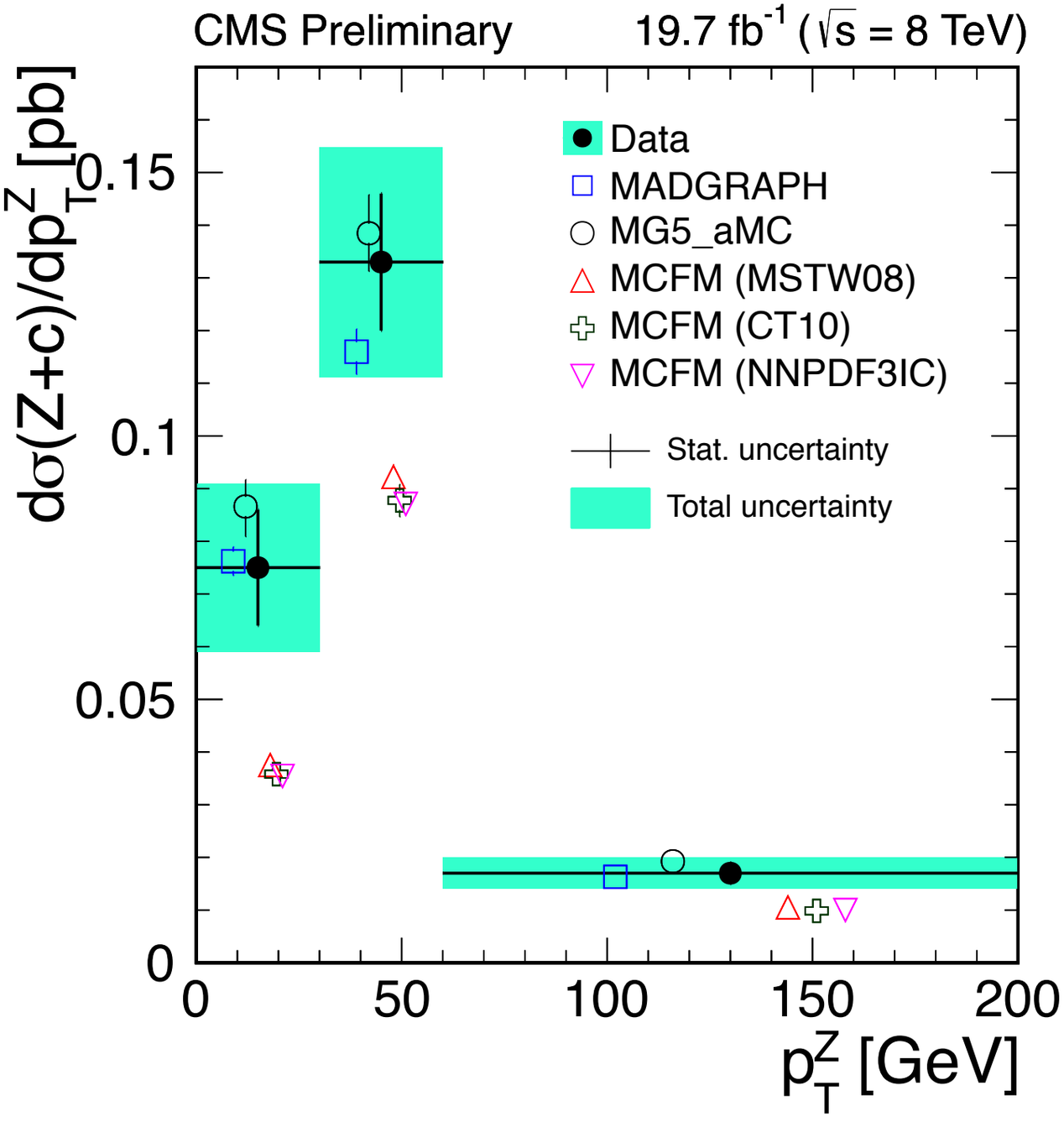


CMS-PAS-SMP-15-009



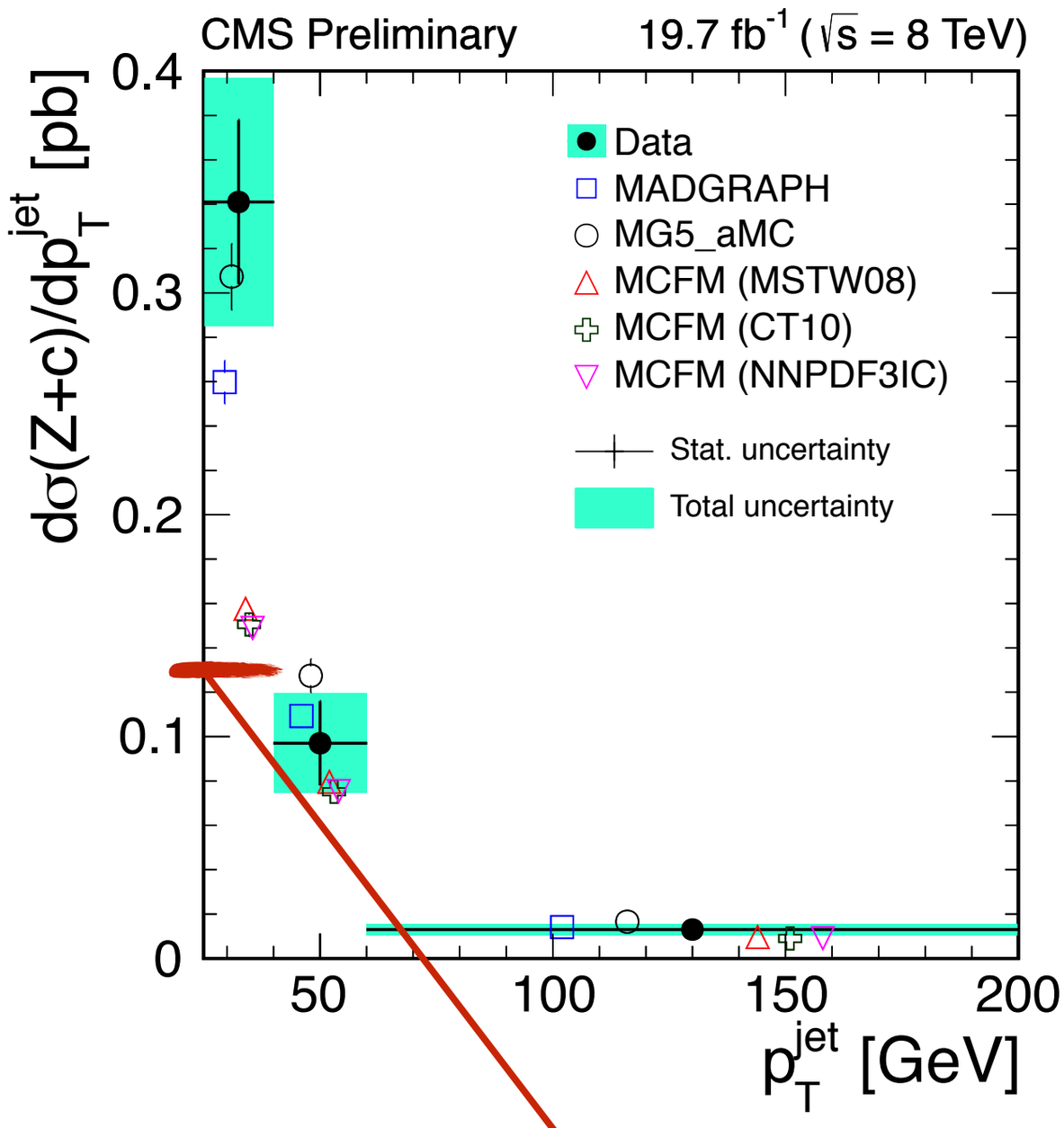
- **p+p → Z(→ℓℓ̄)+c**
  - Fiducial differential cross sections as function of p_T^Z, p_T^{jet}
  - Fiducial region:
    - Two electrons or muons:
      $p_T > 20$ GeV and $|\eta| < 2.1$,
      within 20 GeV of Z mass window
    - One c-jet (anti-kt R=0.5):
      $p_T > 25$ GeV and $|\eta| < 2.5$
    - Angular separation: $\Delta R_{\ell\text{-jet}} > 0.5$
  - Also Z+c / Z+b ratio
- Differential signal extracted from fit to jet secondary vertex mass for semileptonic decays

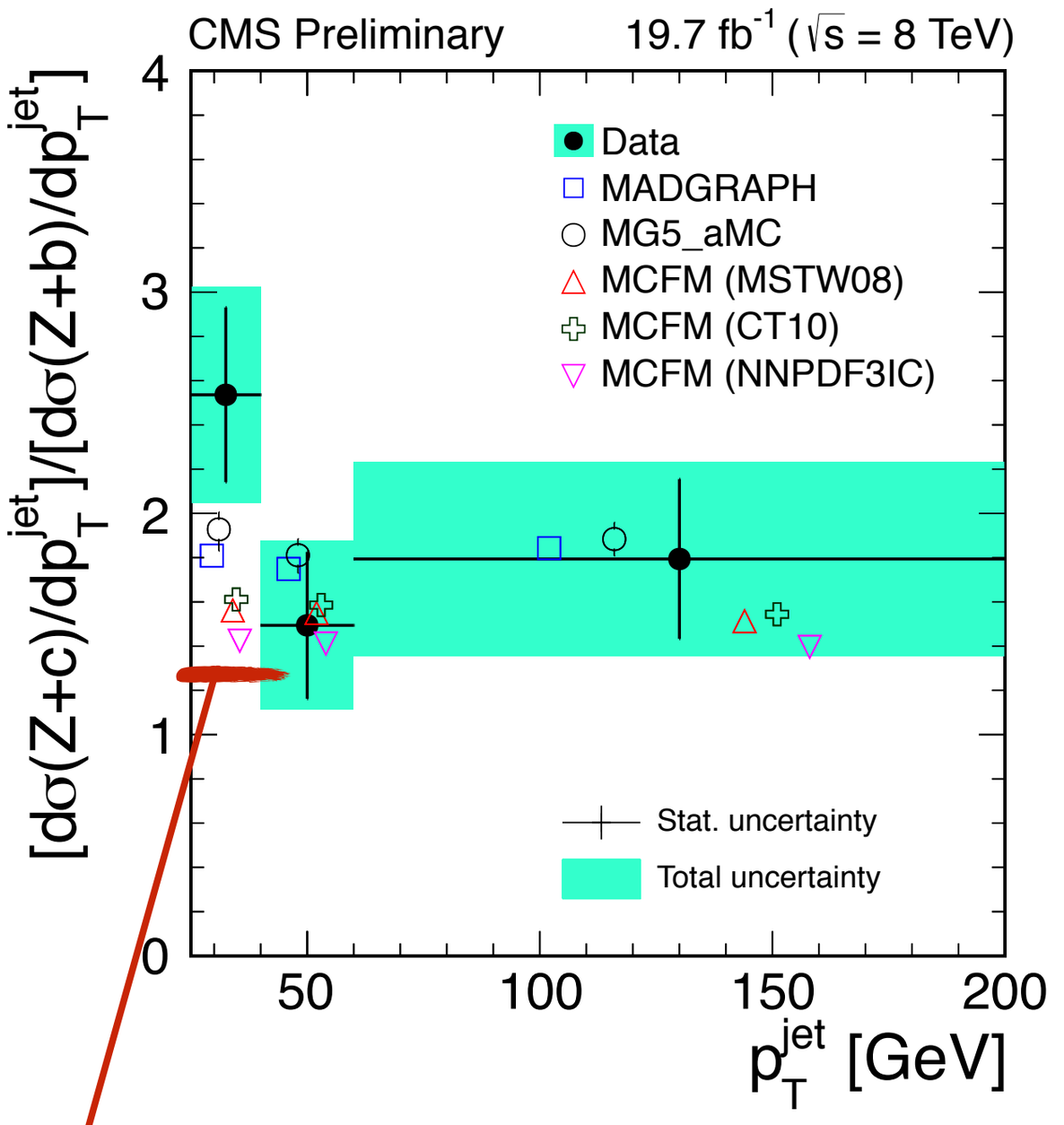
Z+c: p_T^Z cross section



- Predictions:
  - LO Madgraph5 + Pythia 6: 2→2,3,4,5
  - NLO Madgraph5_aMC@NLO + Pythia 8: FxFx-merged samples of 0, 1 and 2 partons
  - NLO MCFM 7 with different PDFs: Parton-level corrected for hadronization
- Madgraph predictions in agreement with data
- **MCFM underestimates** the data, no matter the PDF
- Intrinsic charm effects **beyond measurement range**

Z+c: p_T^{jet} cross section

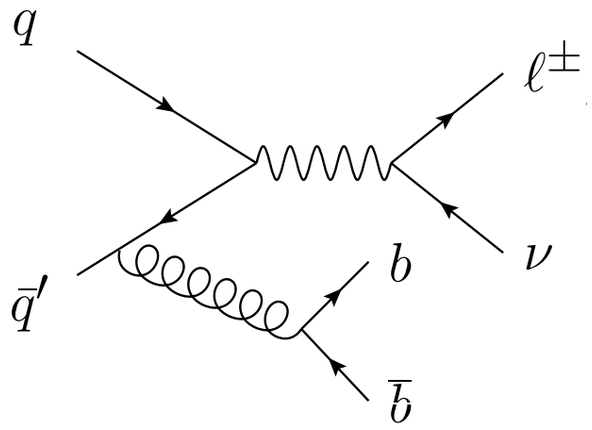




First bin underestimated by nearly all predictions

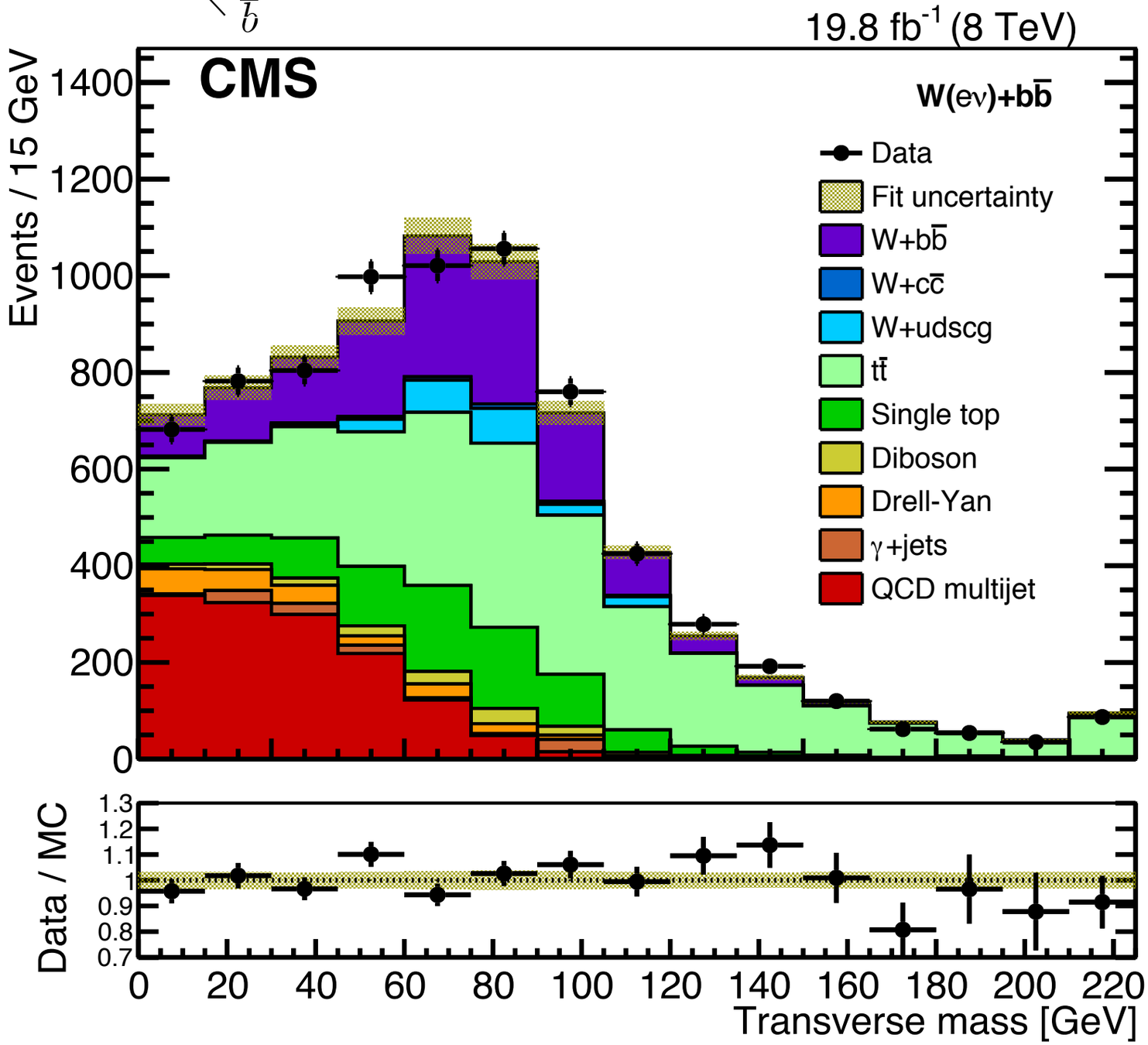
CMS W+$b\bar{b}$ @ 8 TeV

W+b$\bar{b}$



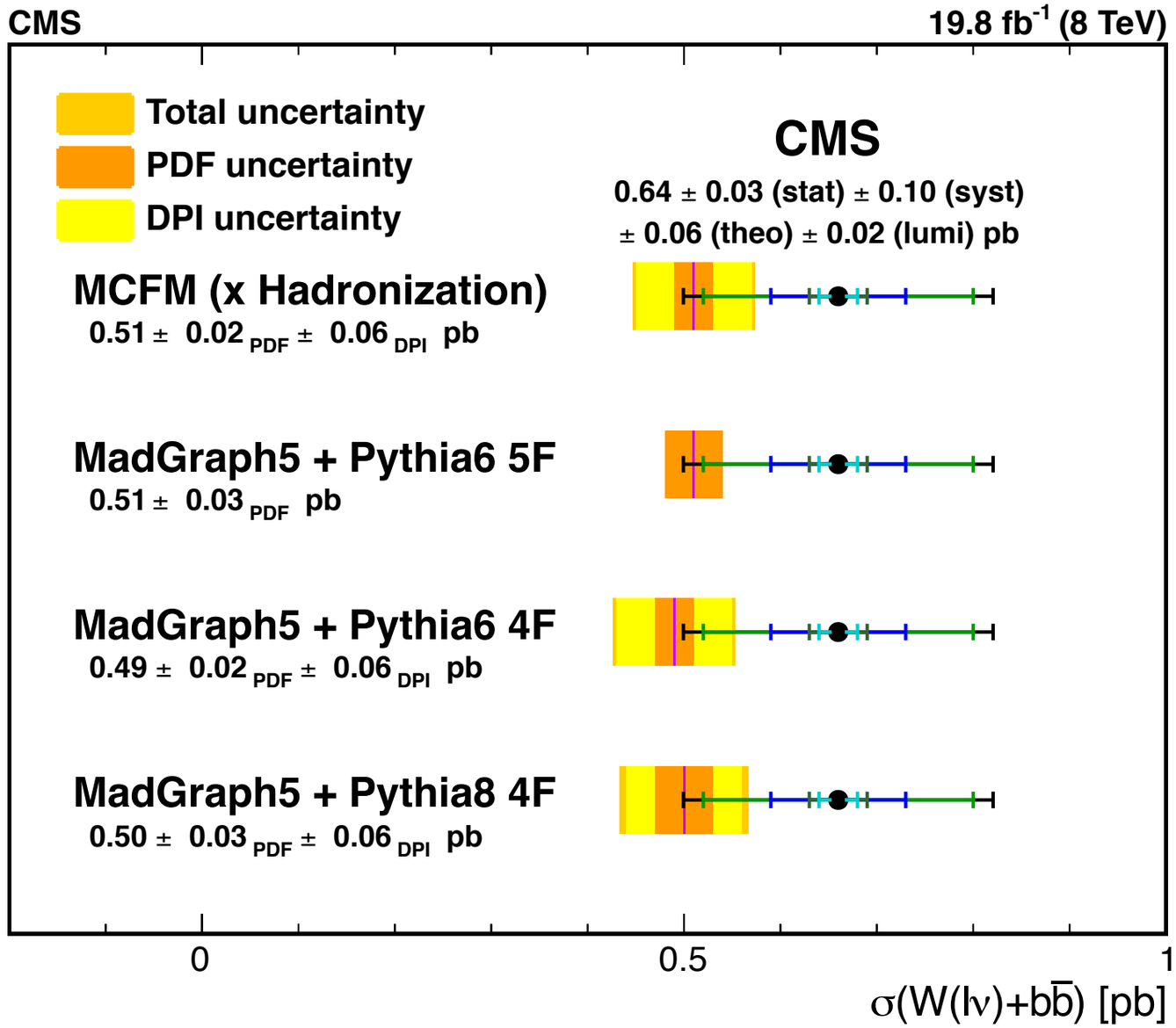
arXiv:1608.07561
EPJC 77 (2017) 92

- **p+p → W(→ℓν)+bb̄**
  - Fiducial integrated cross section
  - Fiducial region:
    - Exactly one muon or electron: pT > 30 GeV and |η| < 2.1
    - Exactly two b-jets (anti-kt R=0.5): pT > 25 GeV and |η| < 2.4
    - Angular separation: ΔRℓ-jet > 0.5
  - Signal extracted from fit to the transverse mass of the W boson
  - Electron and muon channels **combined** for final results



W+bb̄: cross section

- Reduced relative uncertainty compared to 7 TeV measurement
  - σ(pp → W + bb) × B(W → μν) = 0.53 ± 0.05 (stat) ± 0.09 (syst) ± 0.06 (theo.) ± 0.01 (lumi) pb
- Predictions:
  - NLO MCFM 7: Parton-level + hadronization
  - LO Madgraph5 + Pythia 6 and 8: in 5F and 4F
- Good agreement with theory, **within 1σ**



Conclusion

- Extensive **kinematic** description of V+HF at 8 TeV:
  CMS Z+b(b)

- Three measurements sensitive to the **b-PDF** and to **4F vs 5F**:
  ATLAS γ+b and CMS Z+b(b) and W+$b\bar{b}$

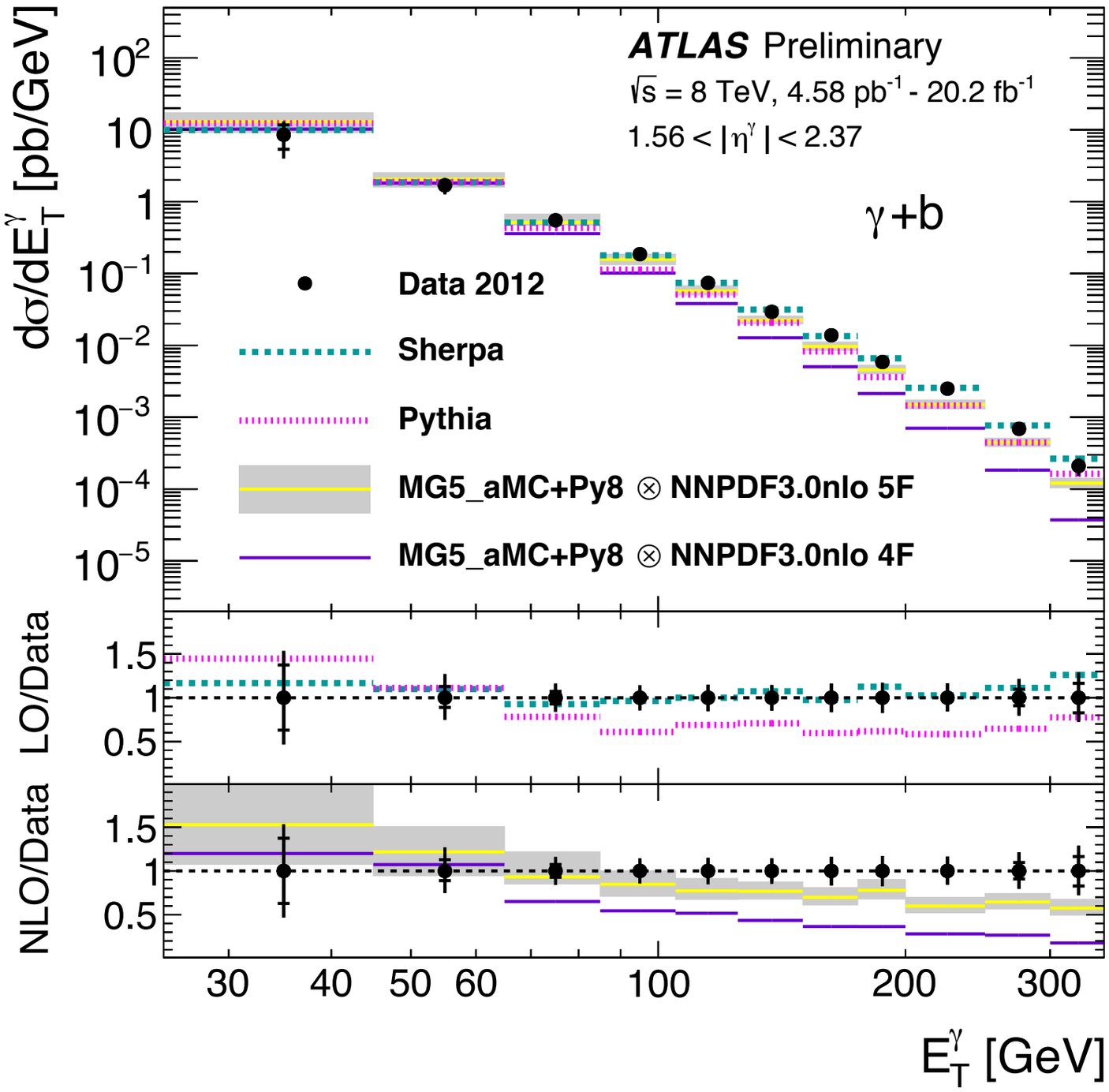
- Two measurements probing the **c-PDF** and **intrinsic charm**:
  ATLAS γ+c and CMS Z+c

- Overall good agreement with theory predictions, but with some discrepancies

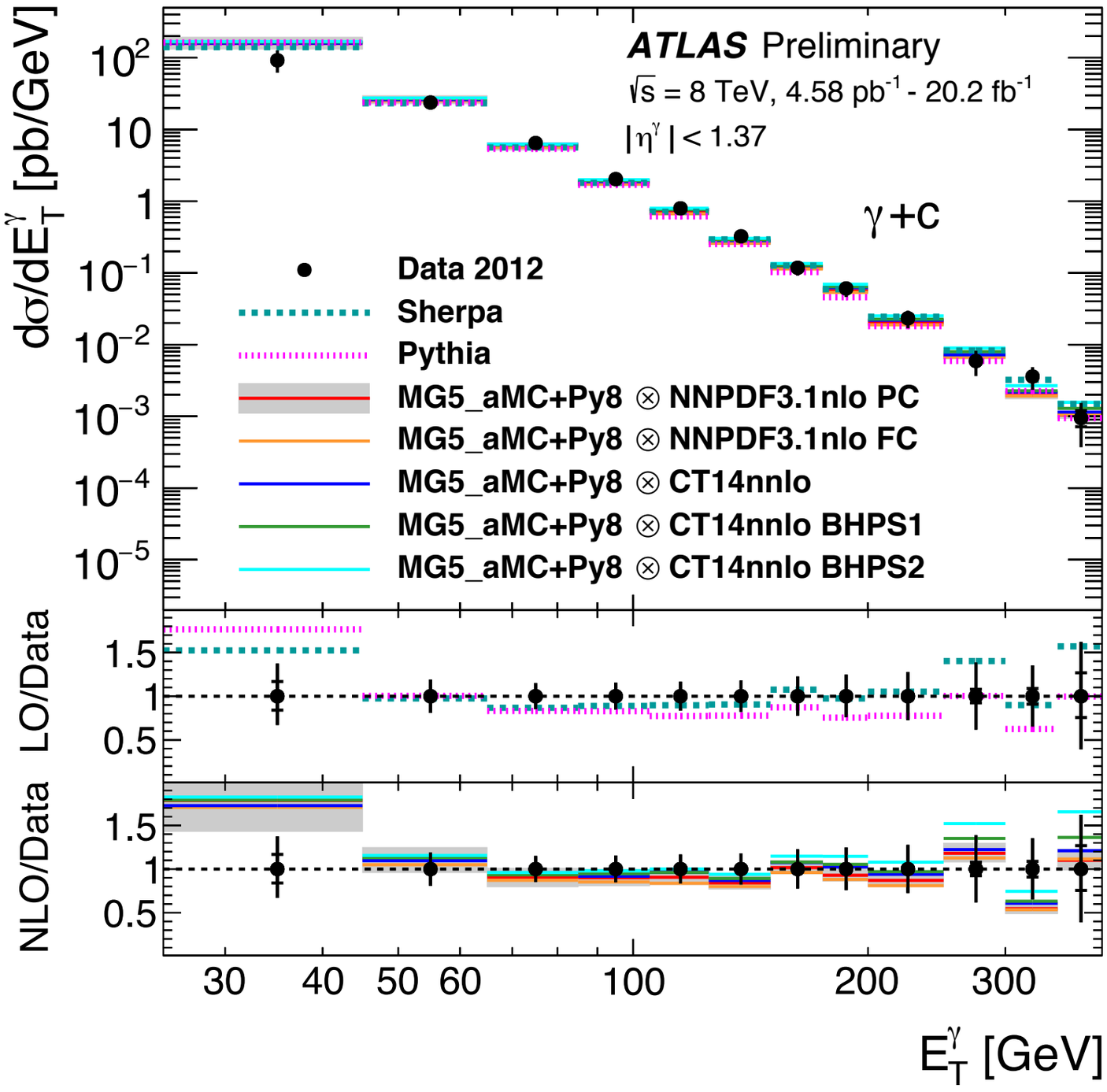
  - Hopefully these measurements can help theory developments

Backup

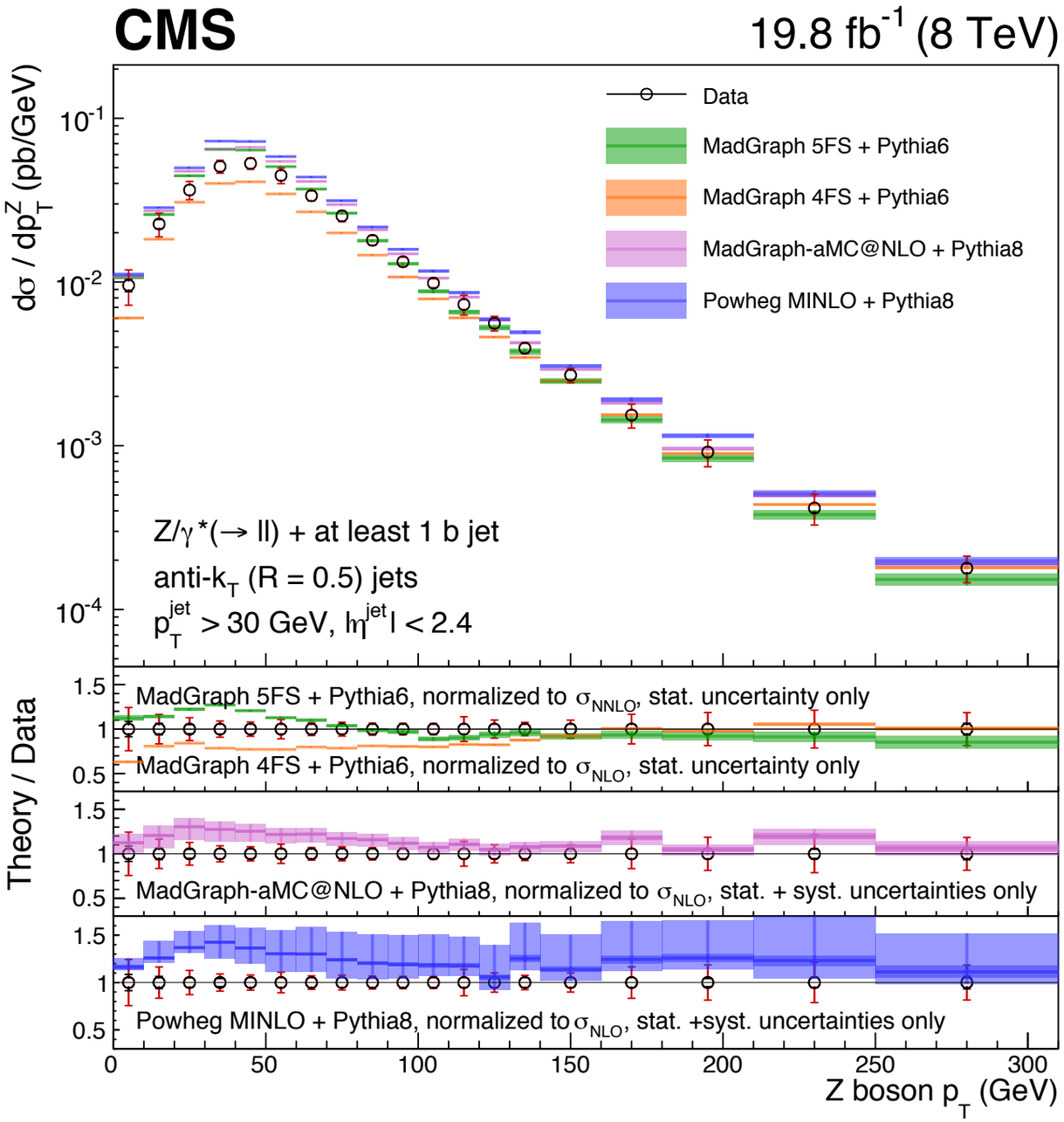
γ+b: E_T^{γ} cross section, forward region

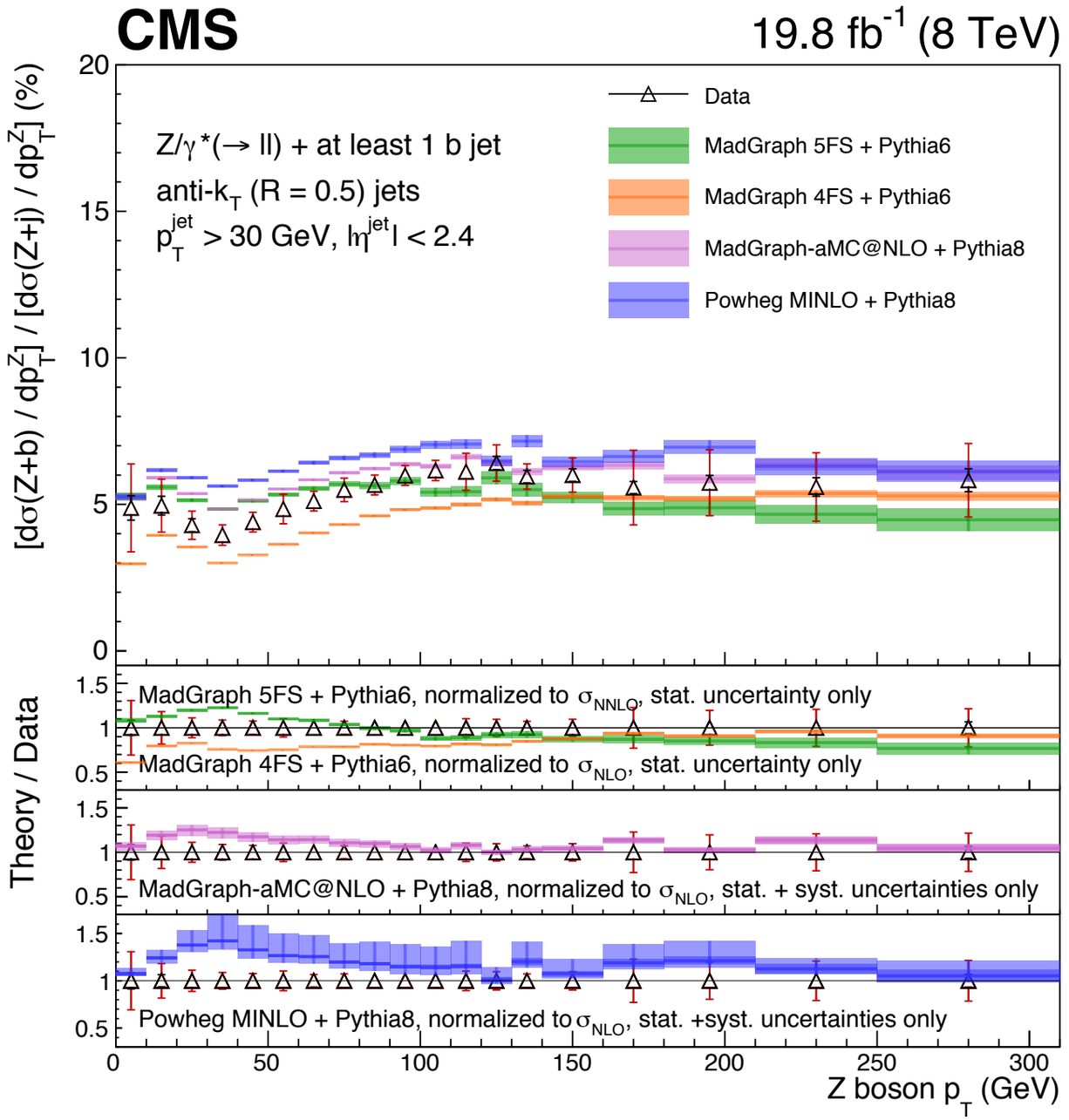


γ+c: E_T^{γ} cross section, central region

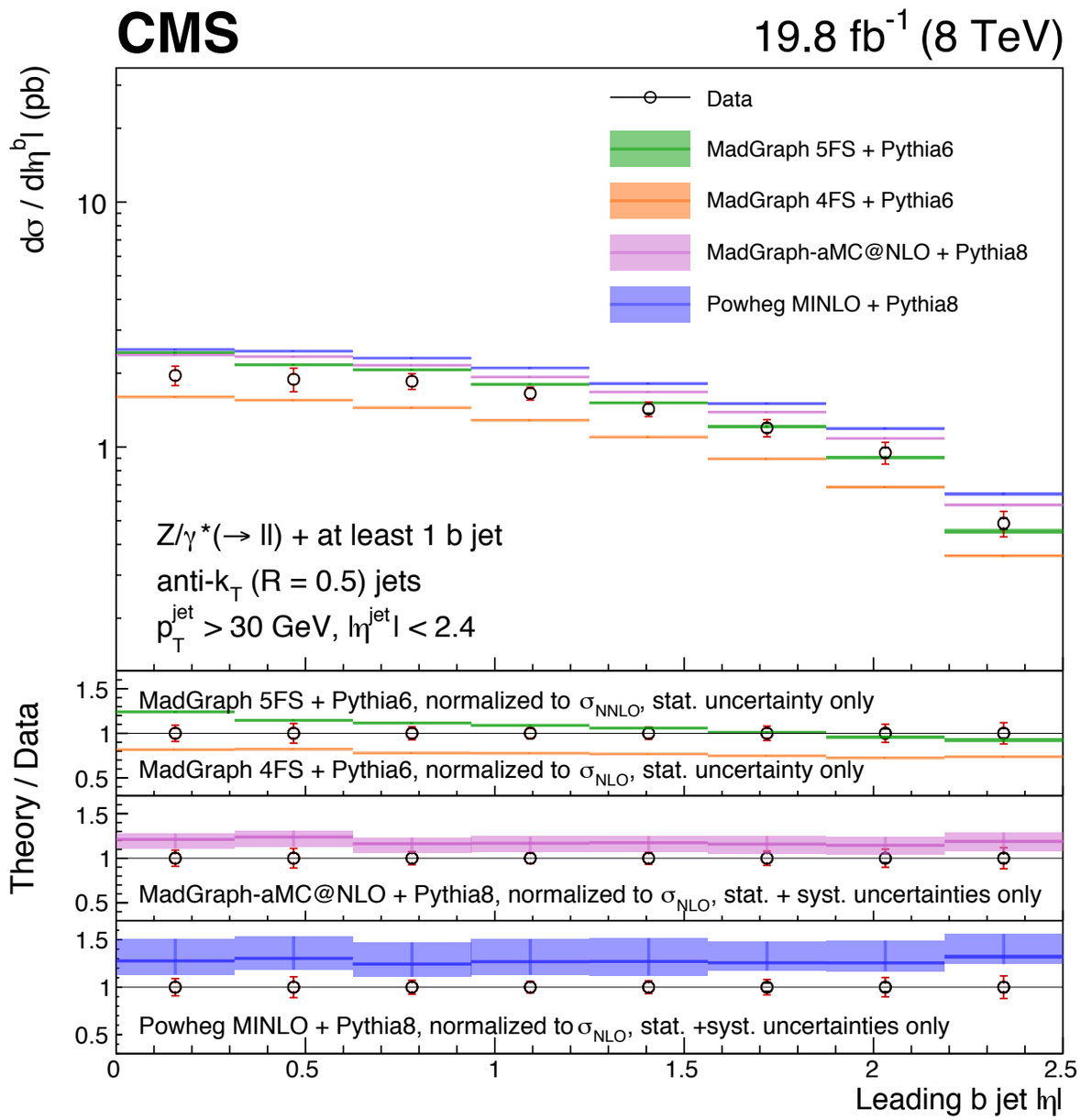


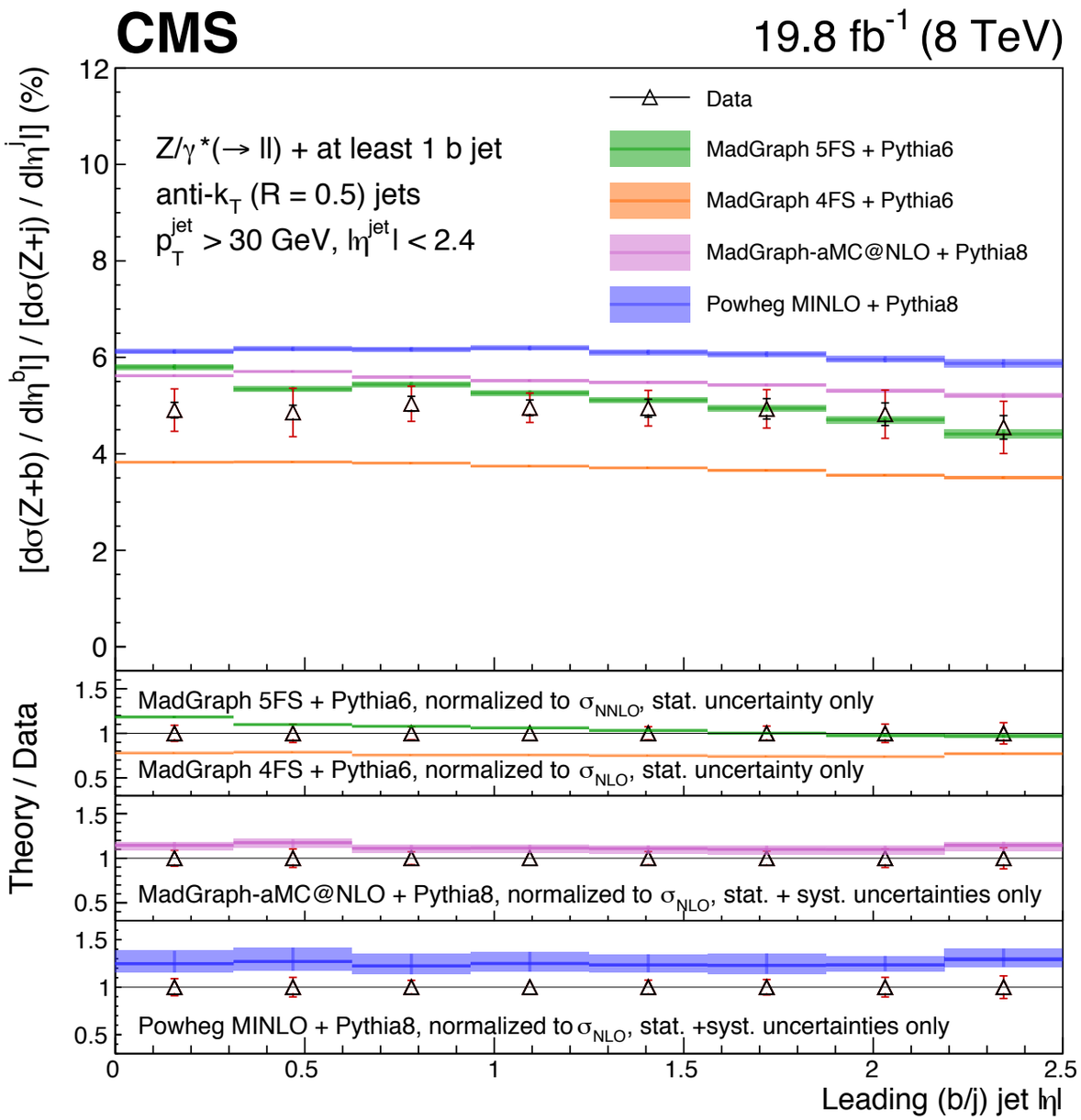
Z+b: p_T^Z cross section, ratio



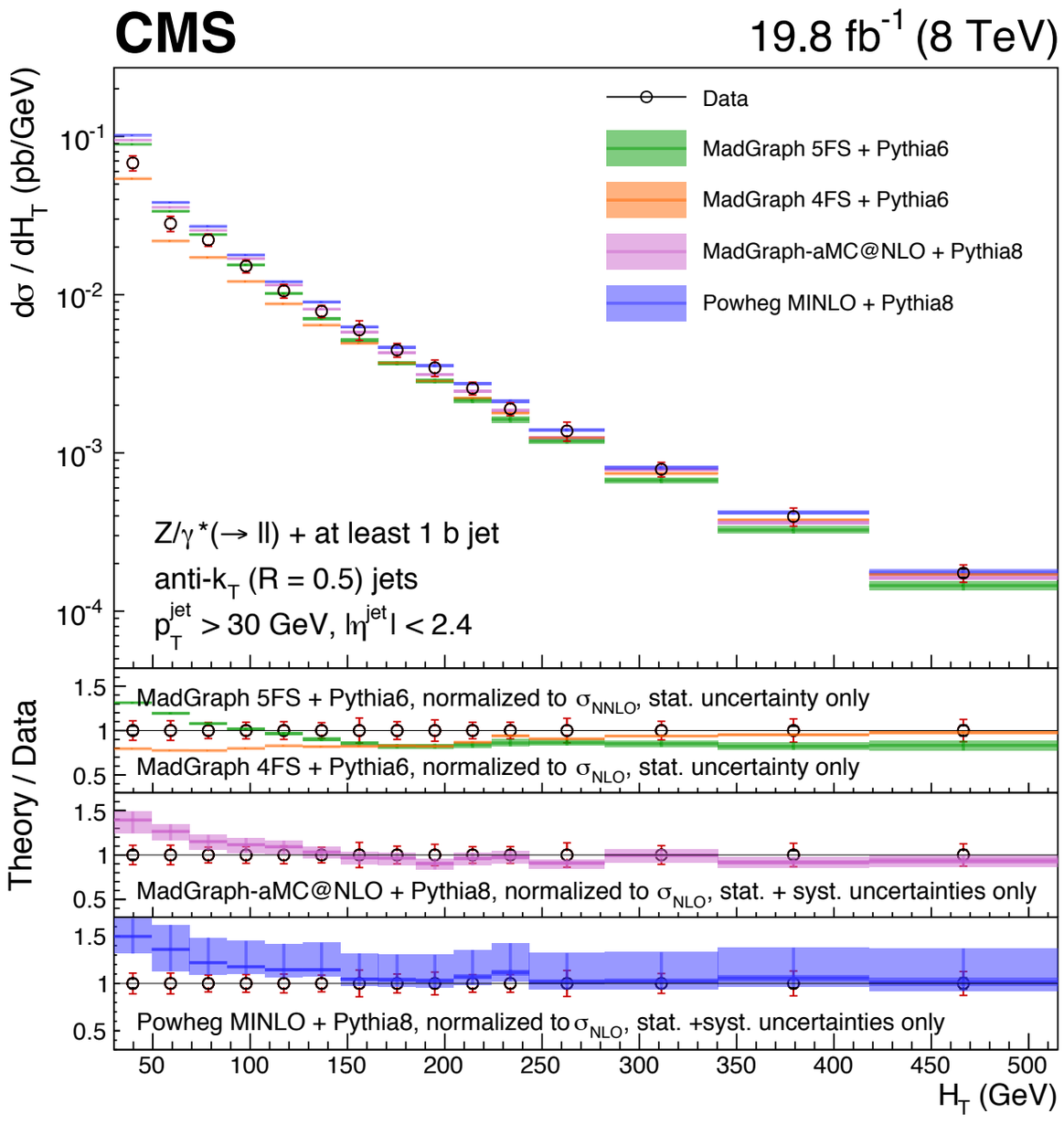


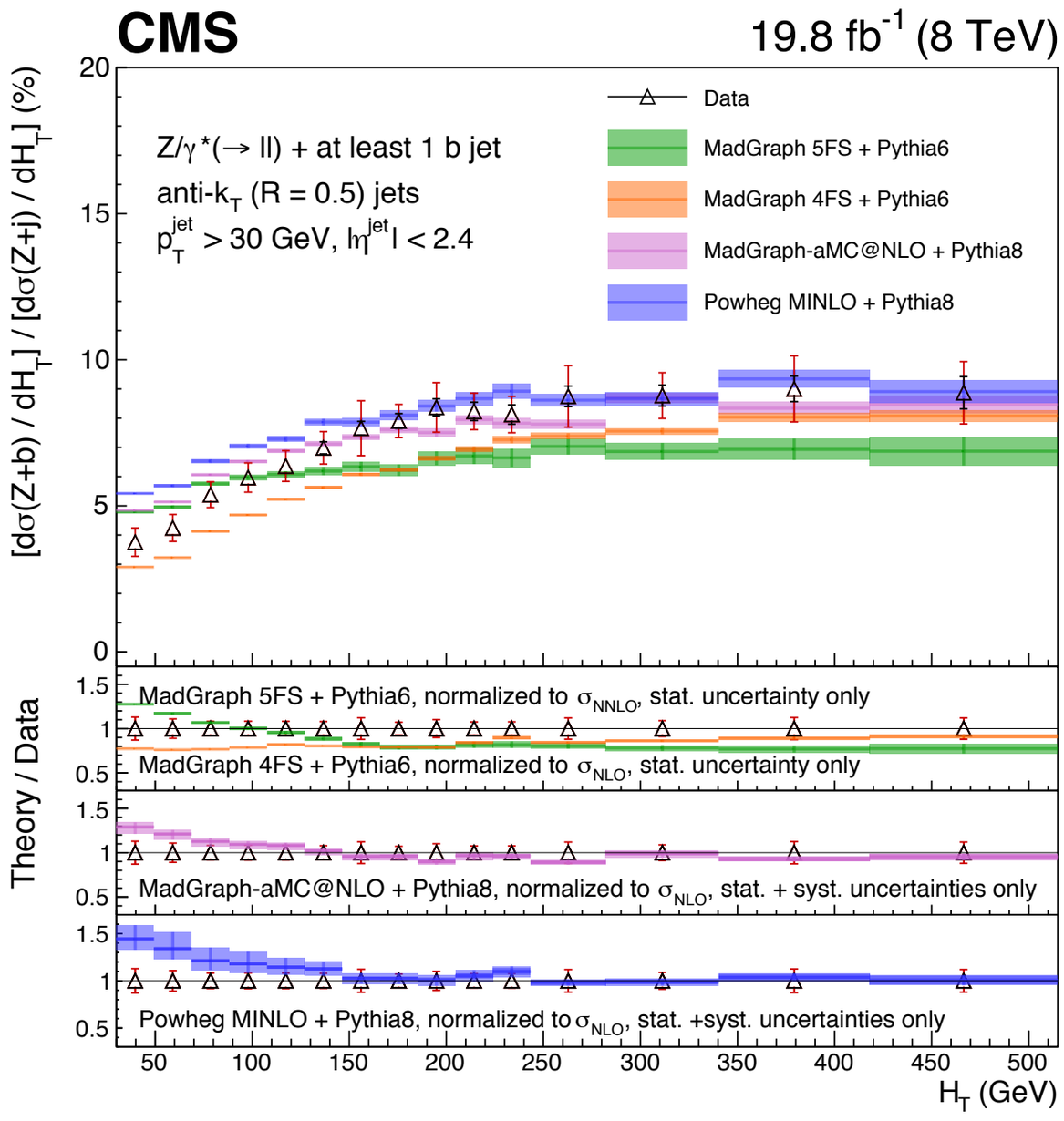
Z+b: $|\eta|^{bjet}$ cross section, ratio



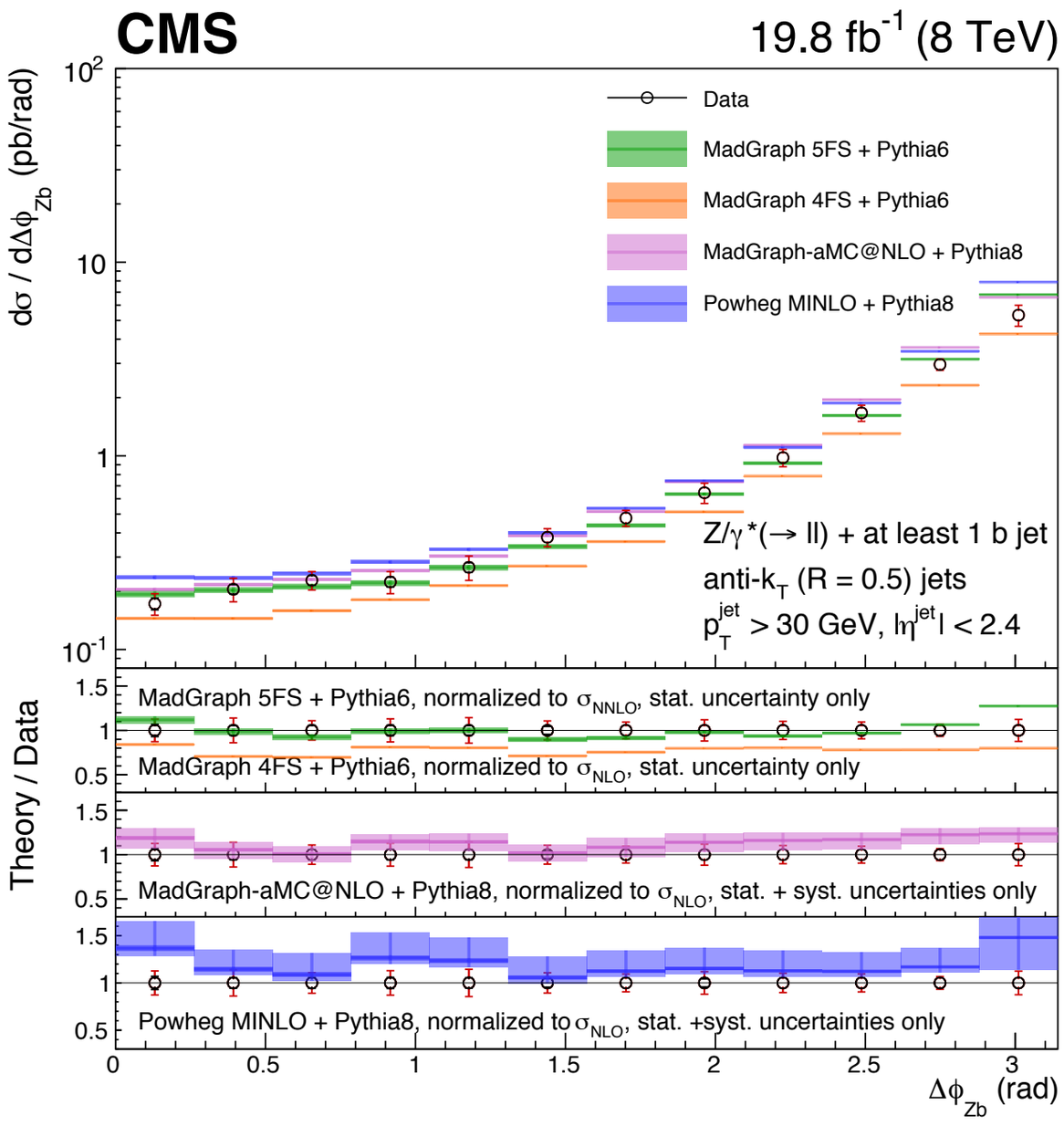


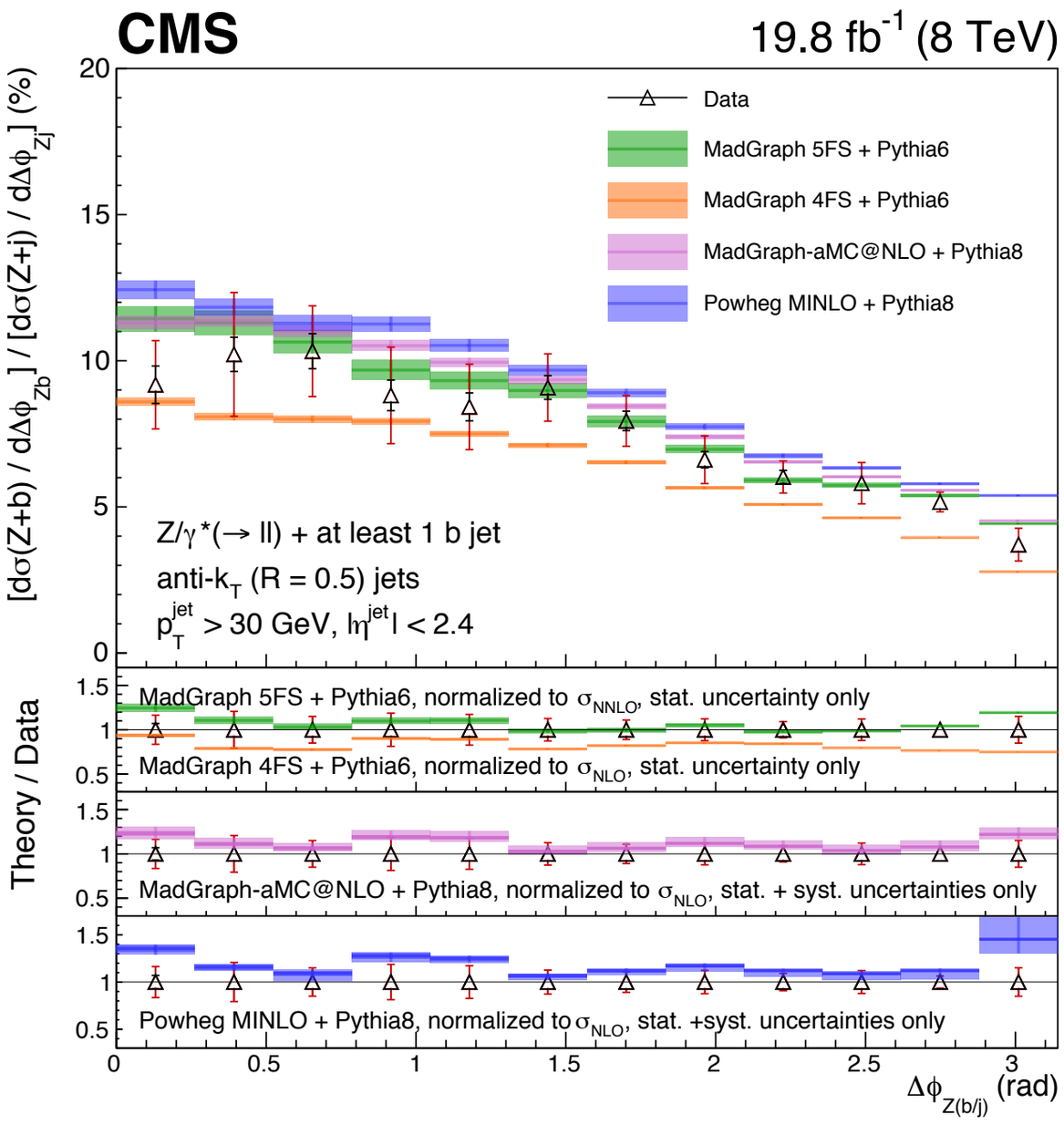
Z+b: H_T cross section, ratio



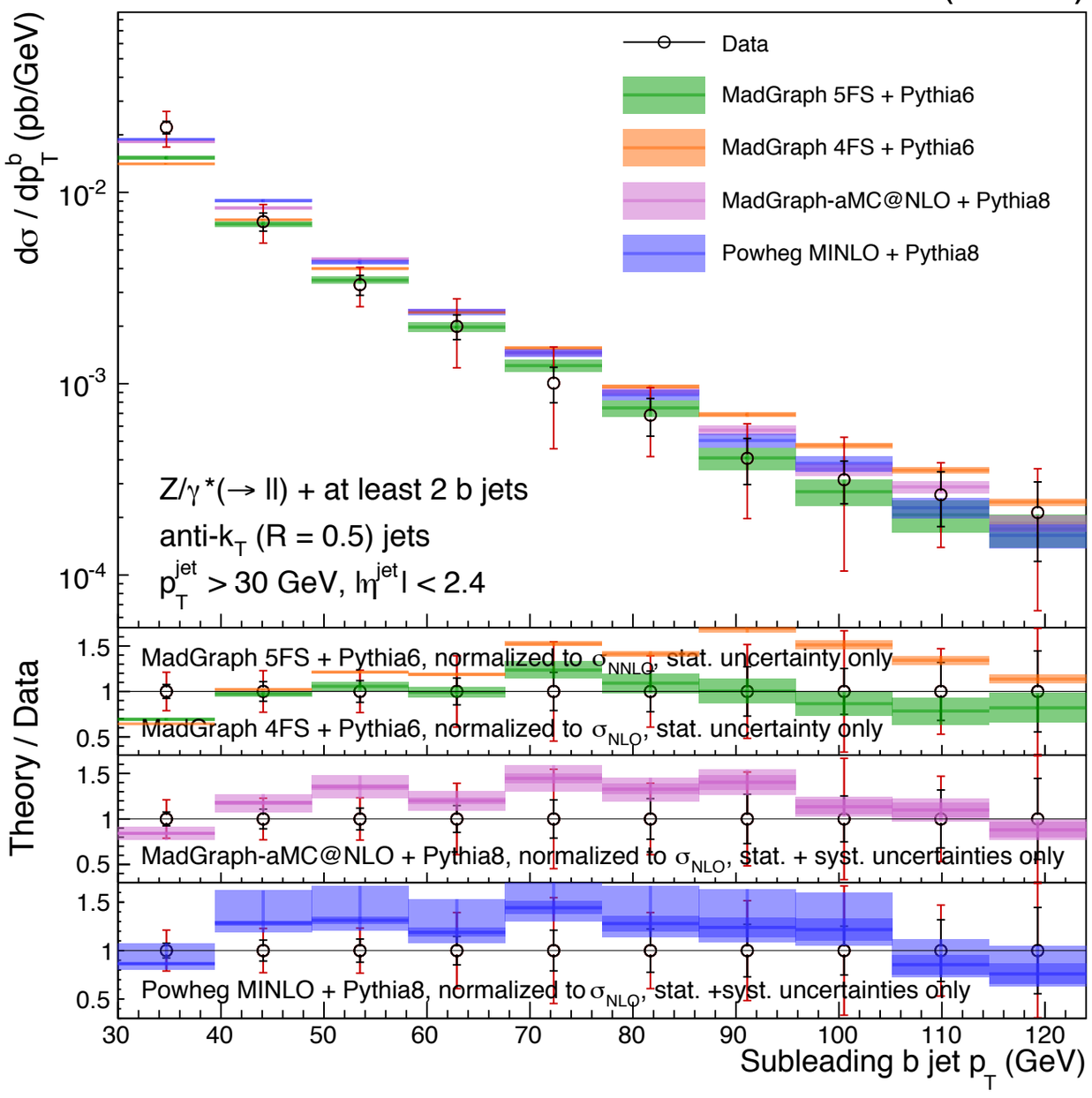


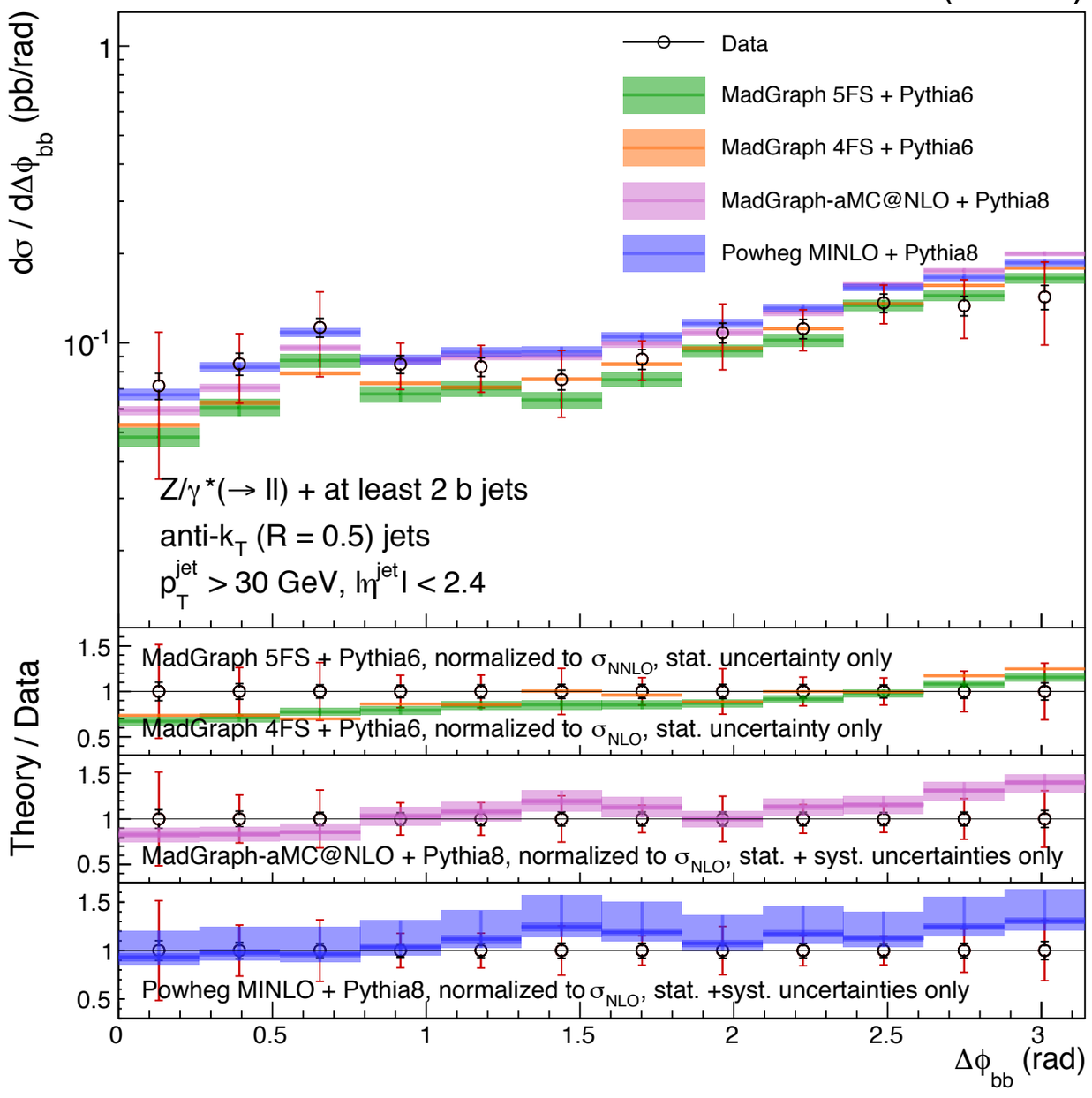
Z+b: $\Delta\phi_{Zb}$ cross section, ratio



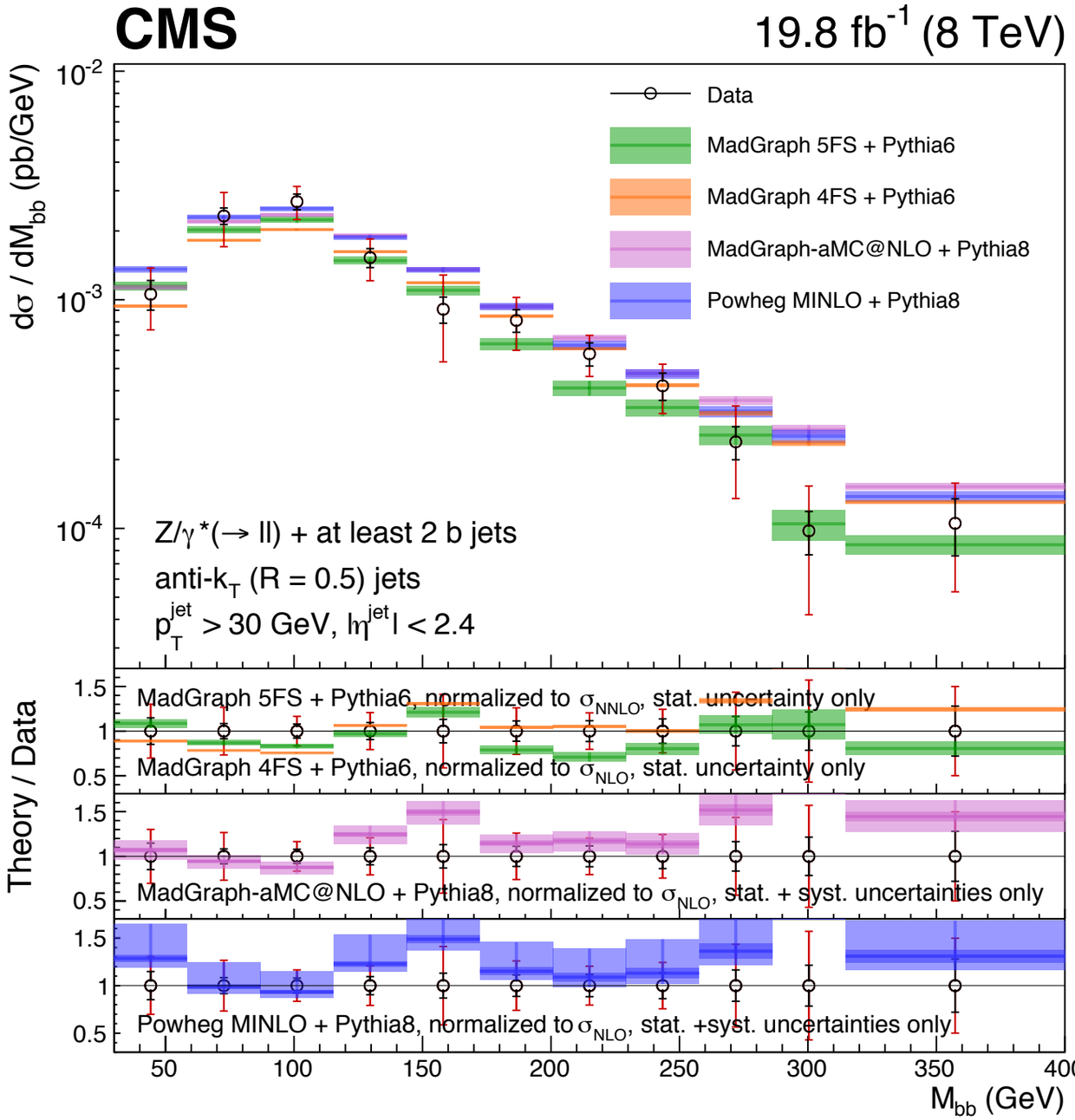


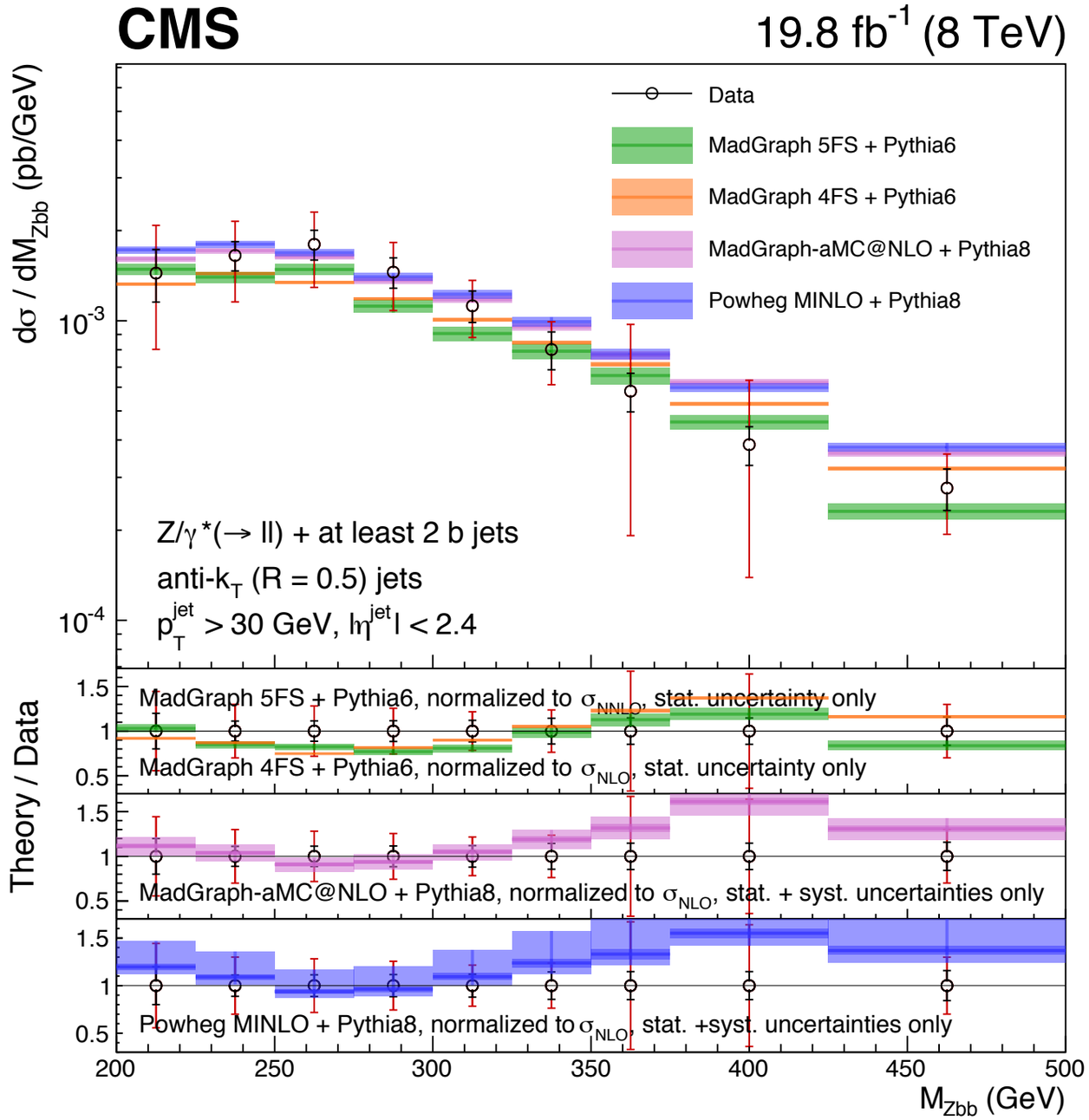
Z+bb: p_T subleading bjet , $\Delta\phi_{bb}$ cross sections



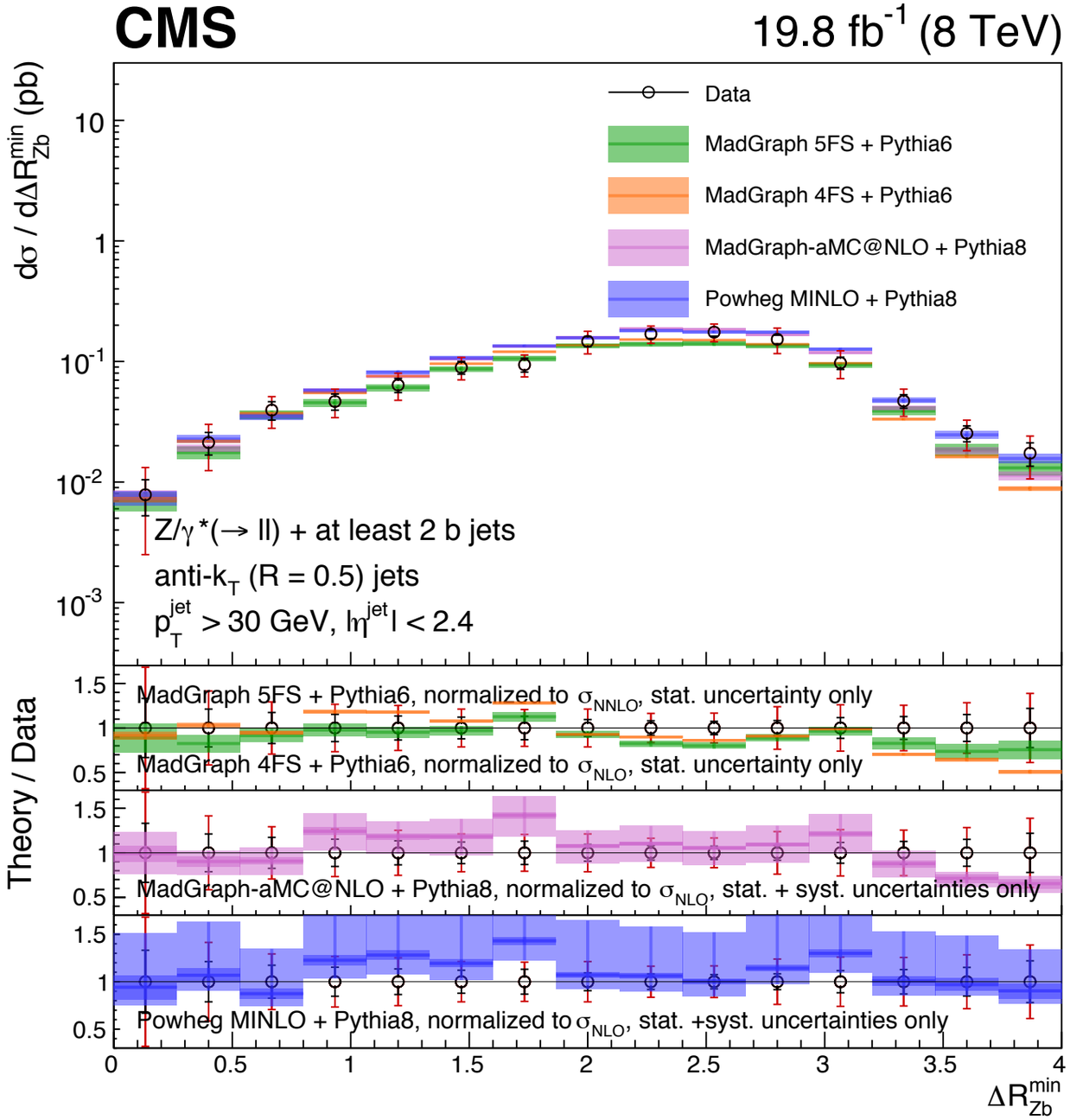


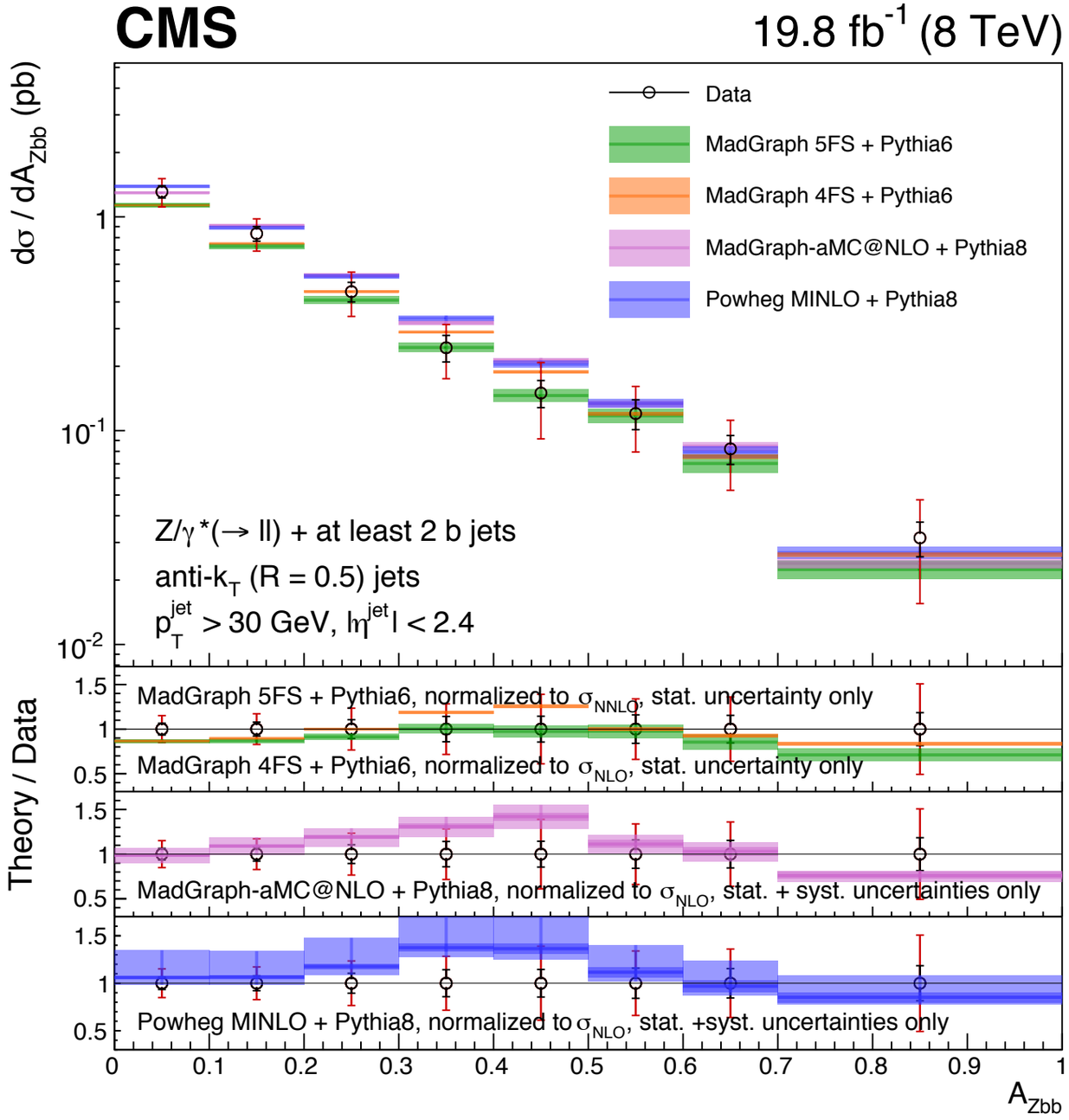
Z+bb: M_{bb}, M_{Zbb} cross sections





Z+bb: ΔR_{Zb}^{min}, A_{Zbb} cross sections





Z+c: p_T^Z cross section, ratio