RHIC $\sqrt{s} = 200$ GeV PYTHIA 8 Tune

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Introduction

Tuning task force charged with determining a "STAR/RHIC tune" for the PYTHIA 8 event generator

- "Primary" focus on p+p 200 GeV energy (mid-rapidity) - "Base tune"
- Addendums: p+p 510 GeV; Forward rapidity tune(?)

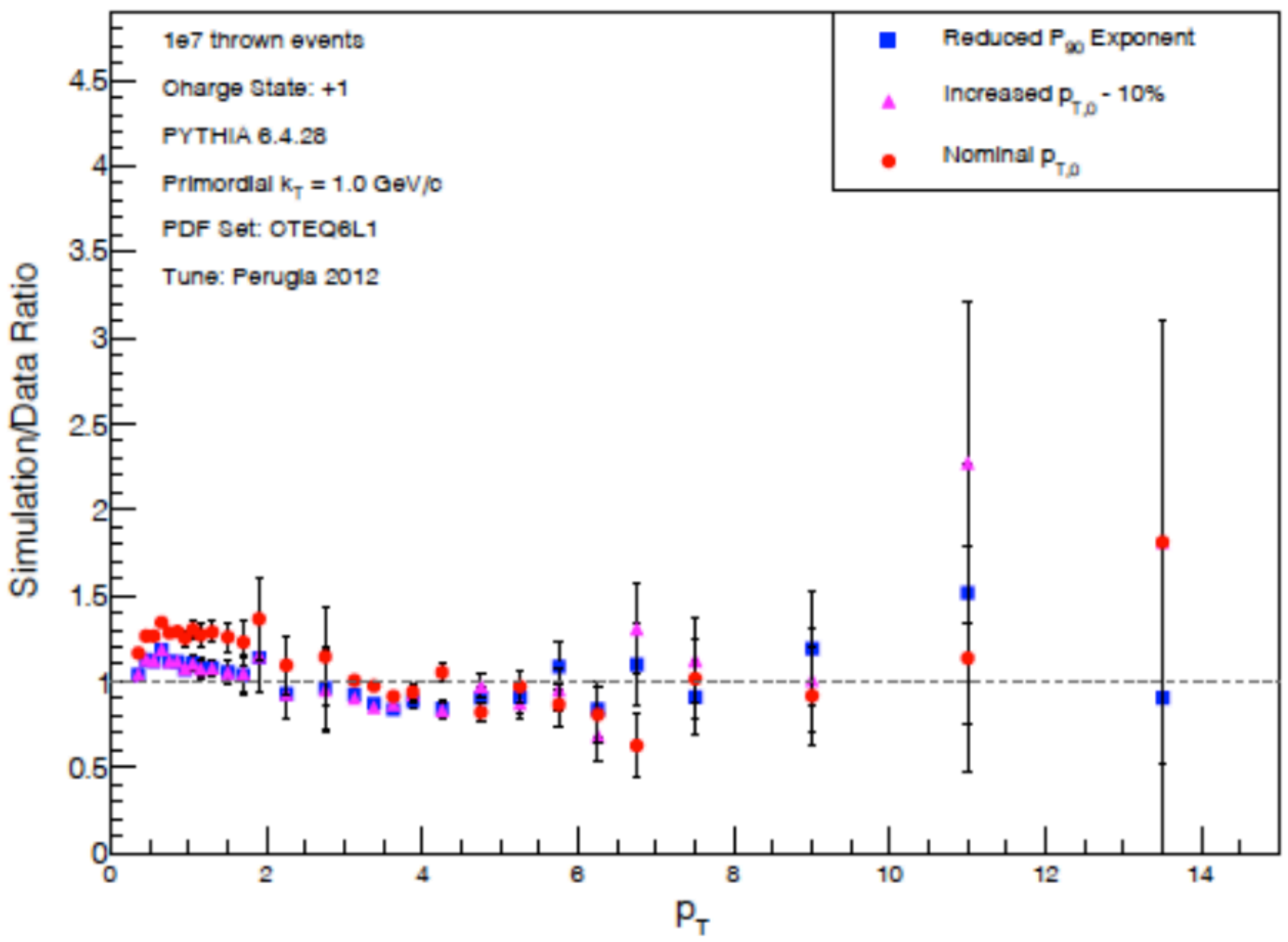
Lessons from PYTHIA 6 STAR tune

- Tuning of the $p_{T,0}$ regularization extrapolation parameter

PYTHIA 8 tune strategy

- Tune on top of Monash tune
- Utilize Professor tuning toolkit

$$p_{T,0} = p_{T,0}^{Ref} \cdot \left(\frac{\sqrt{s}}{\sqrt{s_{Ref}}}\right)^{PARP(90)}$$



What to Expect

1) **Brief overview of tuning technicalities**
2) **Base tune to mid-rapidity 200 GeV data**
3) **Forward rapidity tune**
4) **Jets/p+p 510 GeV (Next talk)**

Observables+Tune-ables

==========Legend===========

Green = RIVET done and tested

Red = RIVET needs work/testing

Black = No current RIVET/HepData available

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Mid-rapidity:

- Single particle spectra + proton/pion ratio (https://arxiv.org/pdf/0808.2041.pdf, https://www.hepdata.net/record/ins930463)
- Jet mass (paper in collab.-wide review)
- Jet sub-structure (https://arxiv.org/pdf/2003.02114.pdf)
- Underlying event (https://arxiv.org/pdf/1912.08187.pdf)
- Drell-Yan (https://arxiv.org/pdf/1805.02448.pdf Tables XII + XIII) **RIVET: PHENIX_2019_I1672015**
- Preliminary jet cross section @ 200 GeV

Heavy Flavor:

- Open Charm spectra (https://arxiv.org/pdf/1204.4244.pdf, https://arxiv.org/pdf/1404.6185.pdf)
- Heavy flavor decayed electron pt spectra (https://arxiv.org/pdf/1102.2611.pdf, https://arxiv.org/pdf/1102.2611.pdf)

p+p @ 510 GeV:

- Jet cross section (https://drupal.star.bnl.gov/STAR/blog/zchang/run12-pp510-jet-cross-seciton-preliminary-plot)
- Z pT spectrum (https://drupal.star.bnl.gov/STAR/files/Fazio_DNP_Fall_OCT2020_v6.pdf)

Forward Physics:

- Charged particle rapidity dependence (https://arxiv.org/pdf/1011.1940.pdf)
- p/K/pi spectra at forward rapidities (https://arxiv.org/pdf/hep-ex/0701041.pdf)
- Identified hadron cross-section (https://arxiv.org/pdf/0908.4551.pdf)
- Proton/Pion ratio (https://arxiv.org/pdf/0910.3328.pdf)
- Drell-Yan (https://arxiv.org/pdf/1805.02448.pdf Tables XII + XIII) **RIVET: PHENIX_2019_I1672015**
- Jet energy @ 500 GeV (https://www.sciencedirect.com/science/article/pii/S0370269315007522?via%3Dihub)

$$p_{T,0} = p_{T,0}^{Ref} \cdot \left(\frac{\sqrt{s}}{\sqrt{s}_{Ref}}\right)^{PARP(90)}$$

Similar $p_{T,0}$ tuning strategy as PYTHIA 6

- ecmPow (equiv. to PARP(90))
- Or $p_{T,0}^{Ref}$ (equiv. to PARP(82), no extrapolation)
- Which is better...

Additional proton overlap function tuning

- expPow; 2nd-order effect w.r.t. $p_{T,0}$

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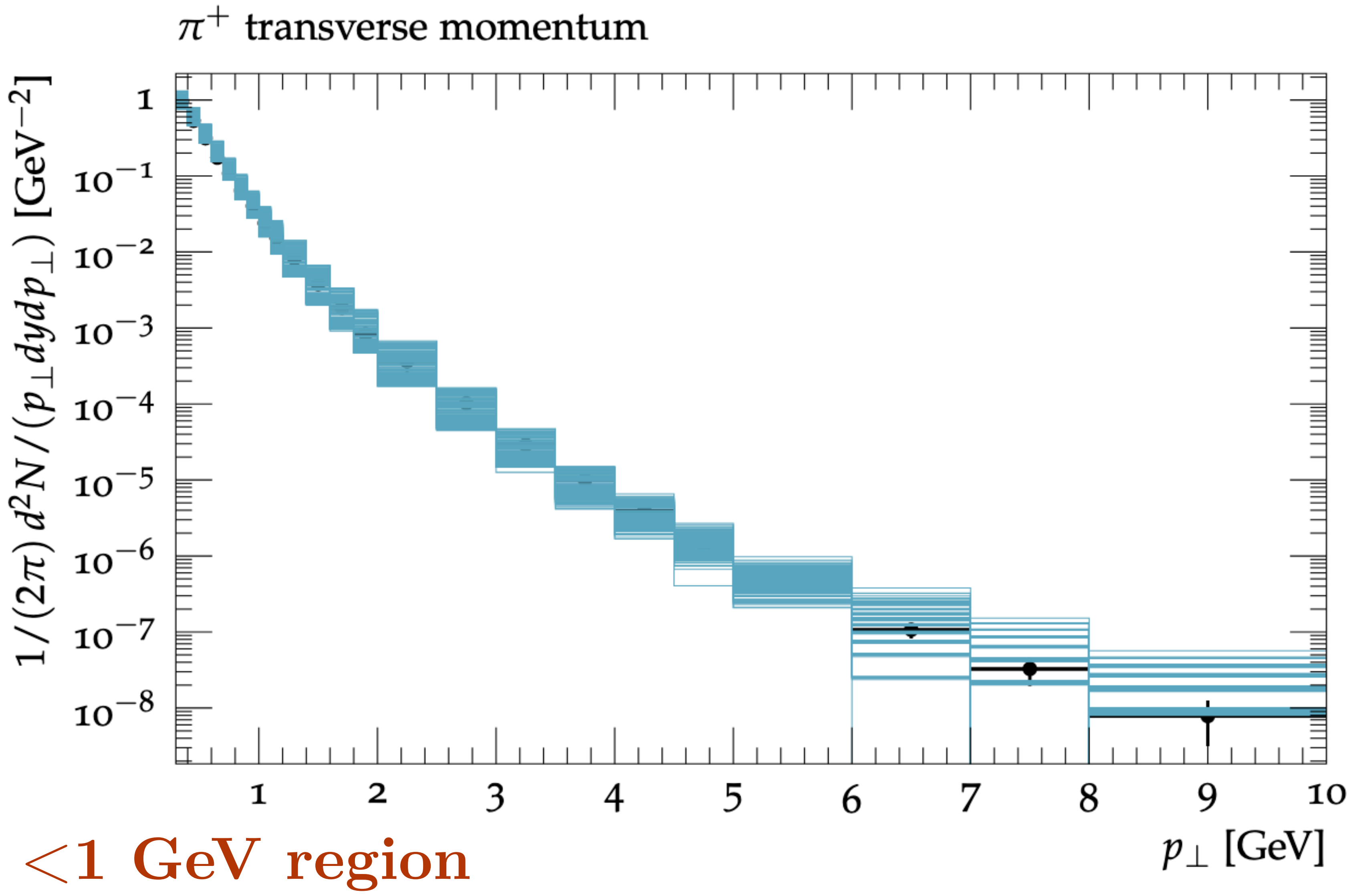
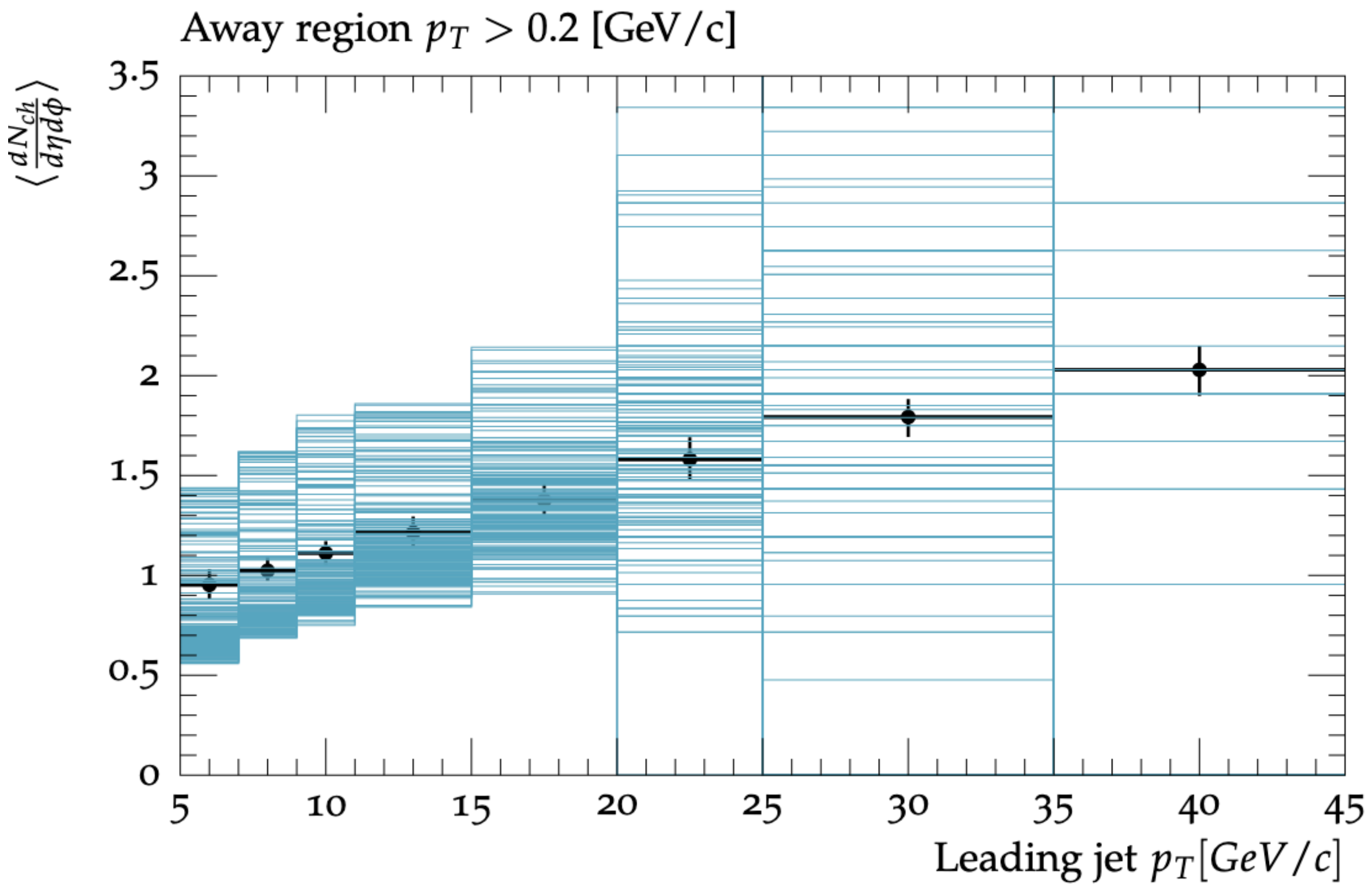
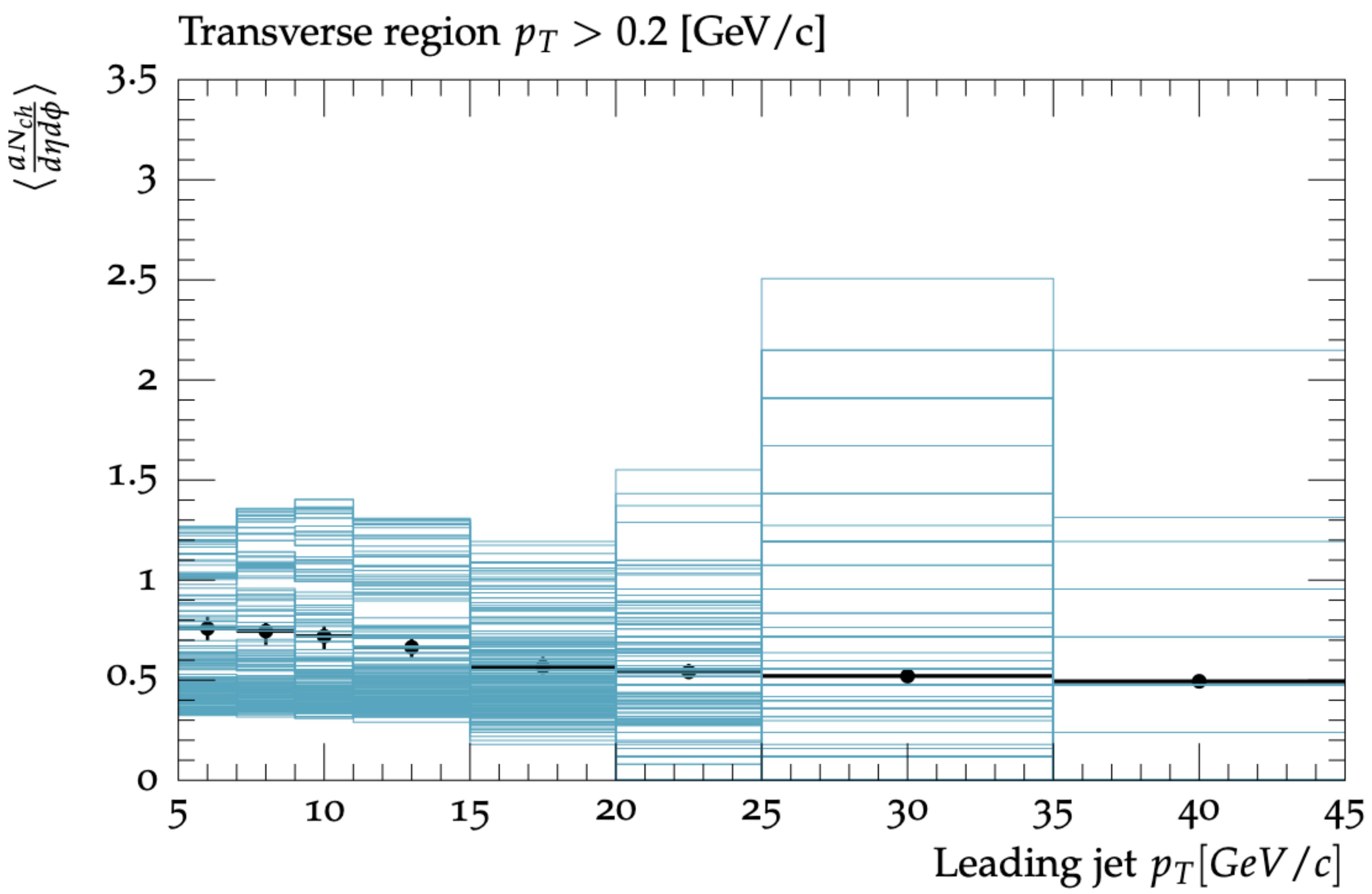
Sensitivities

Each blue line corresponds to variation of tune-able values - 200 in total(some data points completely buried)



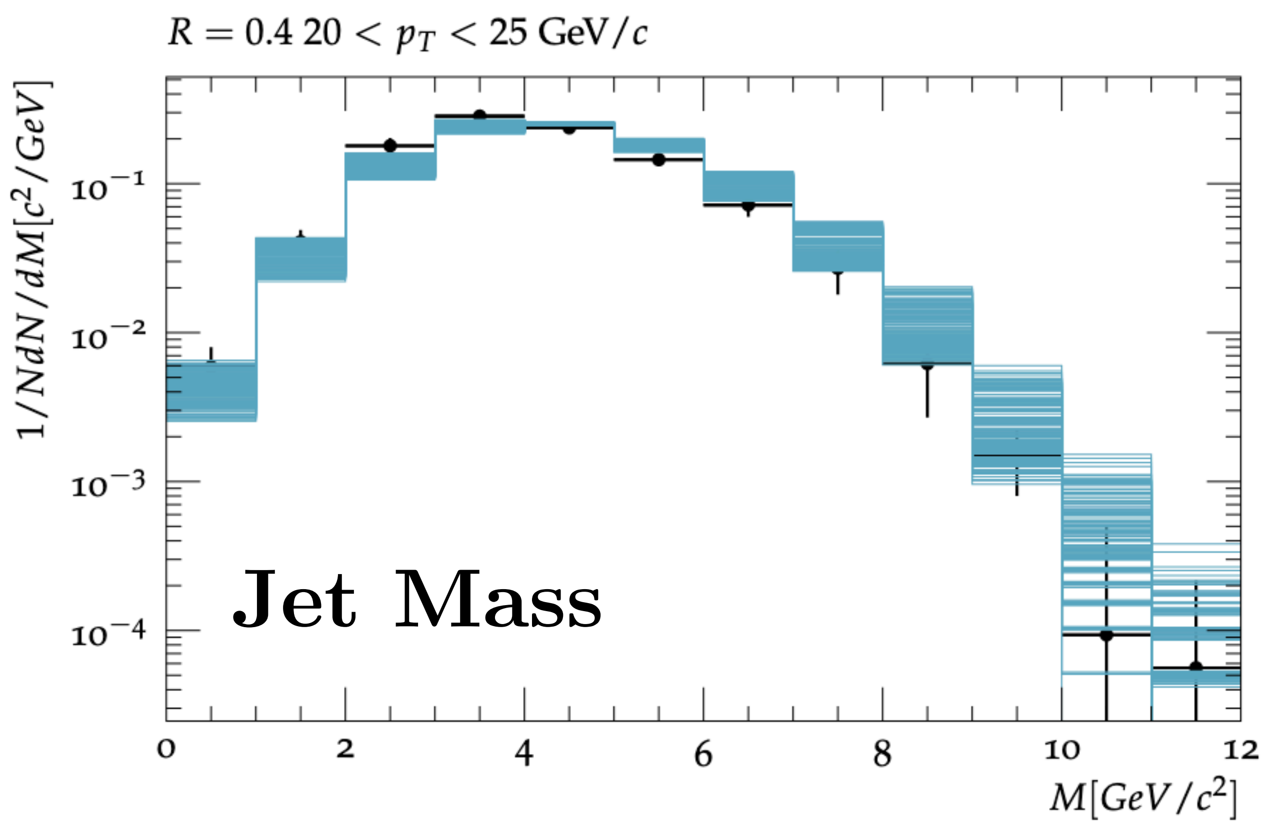




<1 GeV region
not used

Pion spectra (1-10 GeV) and underlying event (trans.+away) expected to have largest sensitivities to $p_{T,0}$

- However, other observables (jet quantities) also have sig. sensitivity (more later)



Disclaimer: Somewhat biased selection of representative plots

Sensitivities (All UE)

Each blue line corresponds to variation of tune-able values - 200 in total(some data points completely buried)

Base Tune Results

Note: Low stat. regions not used in tune currently

Base tune with emcPow and expPow variables:

- Using all mid-rapidity observables (χ^2/NDOF = 382/324); Low stat.+outside env. points removed
- emcPow = 0.177 (Monash default = 0.215)
- expPow = 1.36 (Monash default = 1.85)

General takeaway: Tune procedure works, improvement of MC agreement in all mid-rapidity observables (aside from kaons/protons)

Comparisons to PYTHIA 6 Tune

*Calculated

$$p_{T,0} = p_{T,0}^{Ref} \cdot \left(\frac{\sqrt{s}}{\sqrt{s}_{Ref}}\right)^{PARP(90)}$$

PYTHIA	PDF	pT,0	expPow	PARP(90)/ ecmPow	PARP(82)/pT0Ref (7 TeV)
6	CTEQ6L1	1.35*	-	0.213	2.65
8	NNPDF2.3	1.22*	1.36	0.177	2.28

Monash default for ecmPow= 0.215

Comparable $p_{T,0}$ extrapolations between PYTHIA 8/6 tunes

emcPow vs. $p_{T,0}^{Ref}$

pT0Ref(1.37)+expPow(1.43) χ2/ndof = 370/324

ecmPow(0.177)+expPow(1.36) χ2/ndof = 382/324

No significant difference in pT0Ref/ecmPow central value when tuning without expPow

Pion spectra incrementally improved with pT0Ref; UE with ecmPow...

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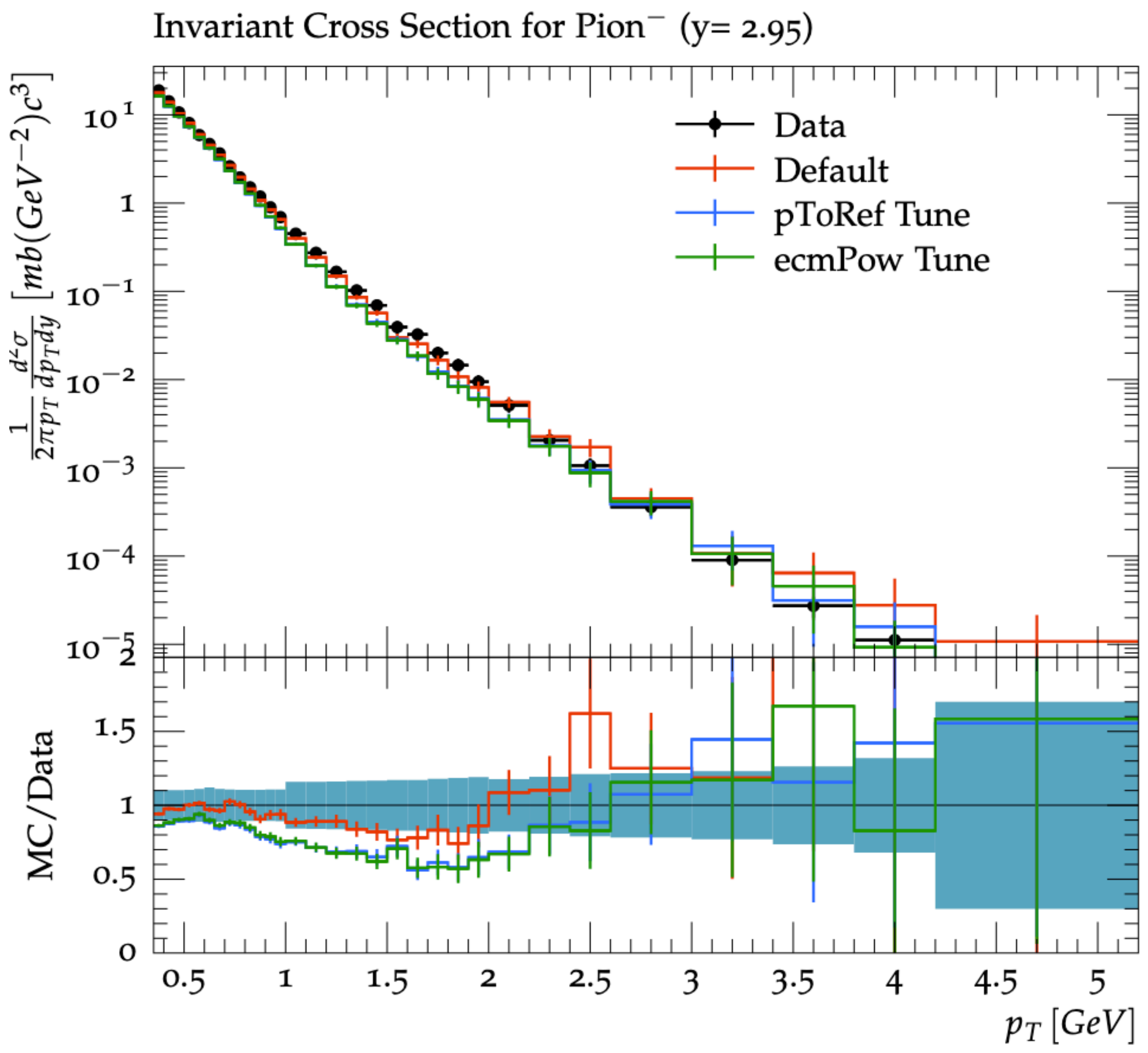
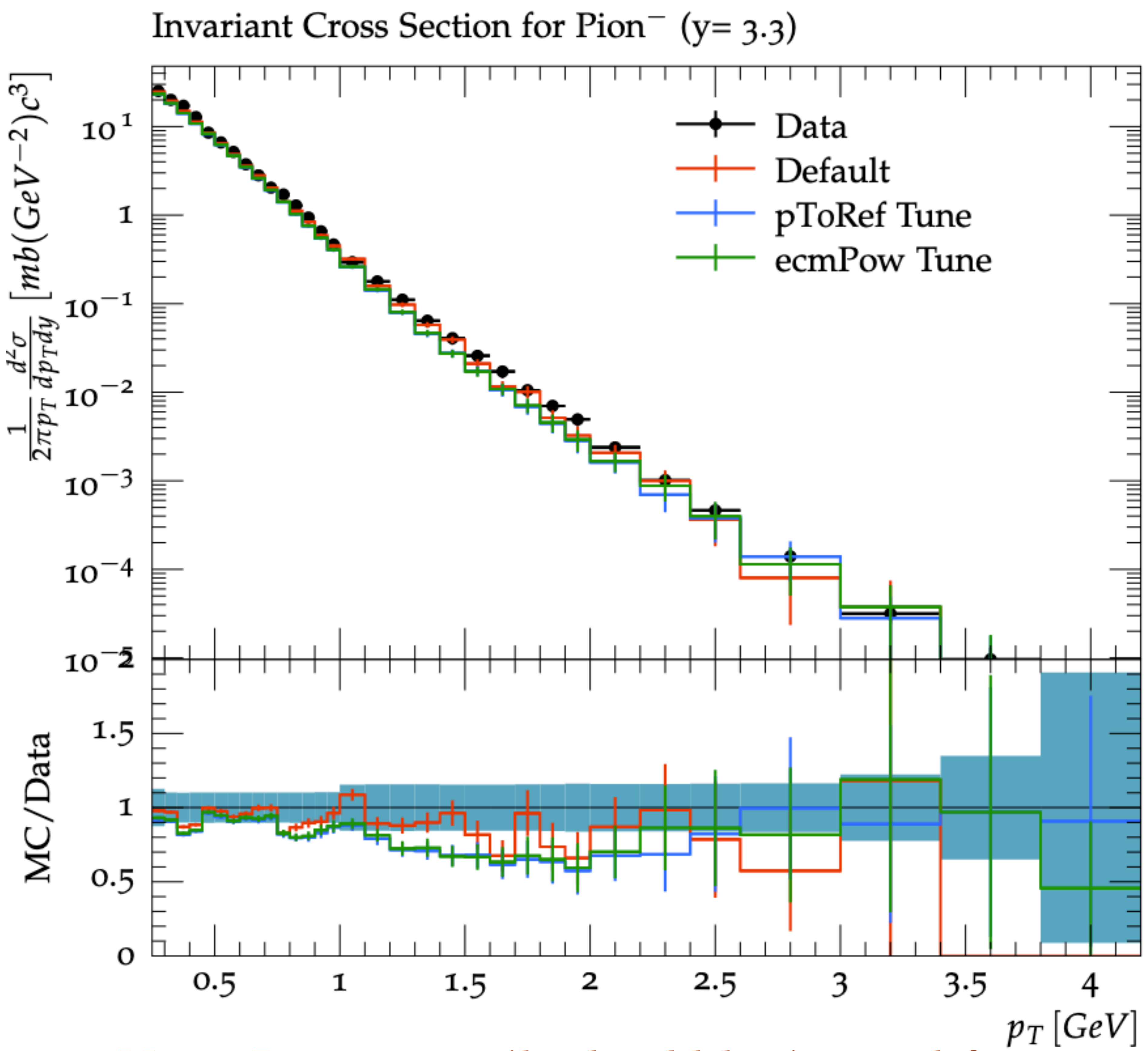
Base Tune for Forward Pion Spectra





Note: Low stat. tails should be ignored for now

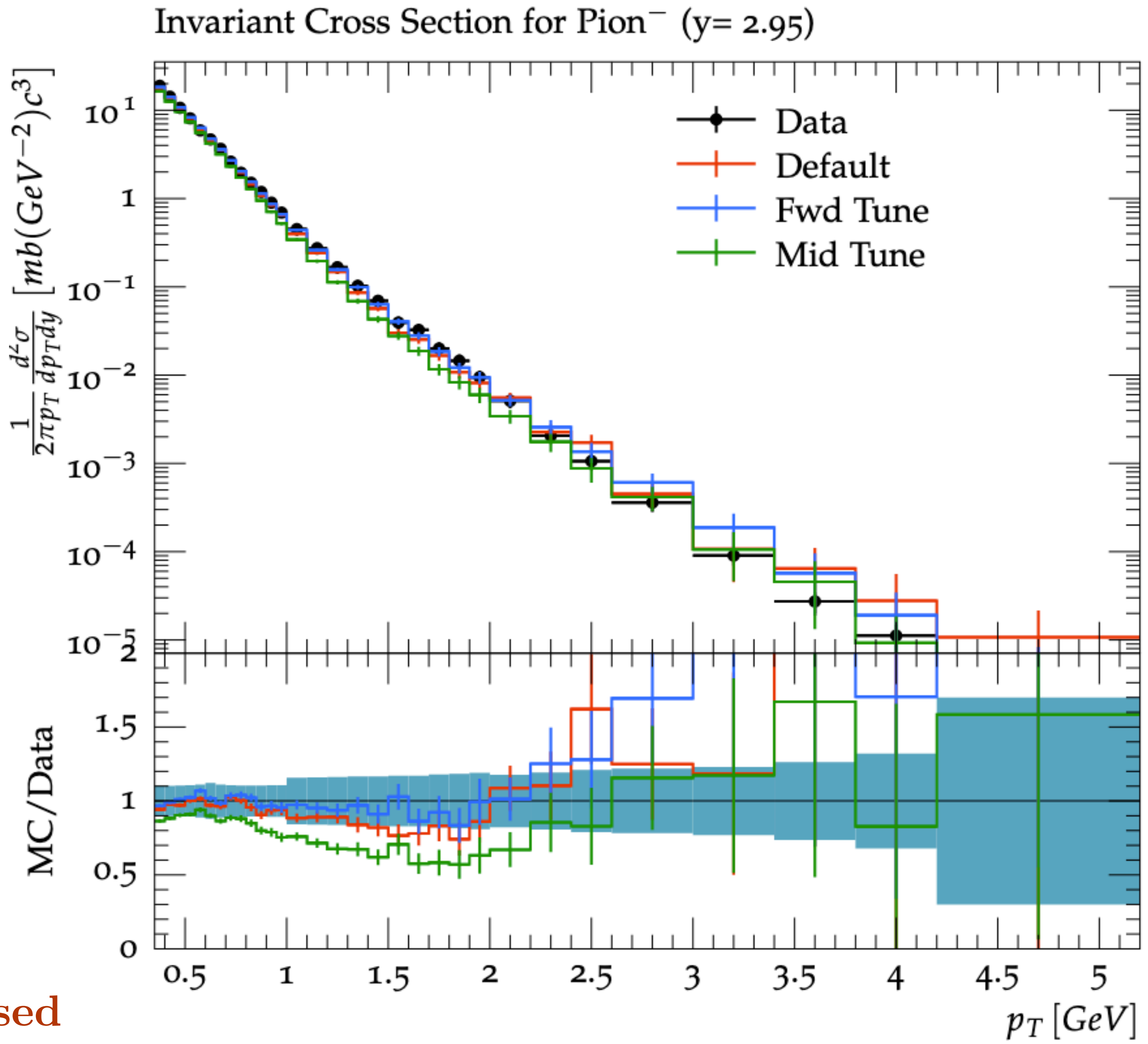
Mid-rapidity tune does worse than default Monash! (expected?)

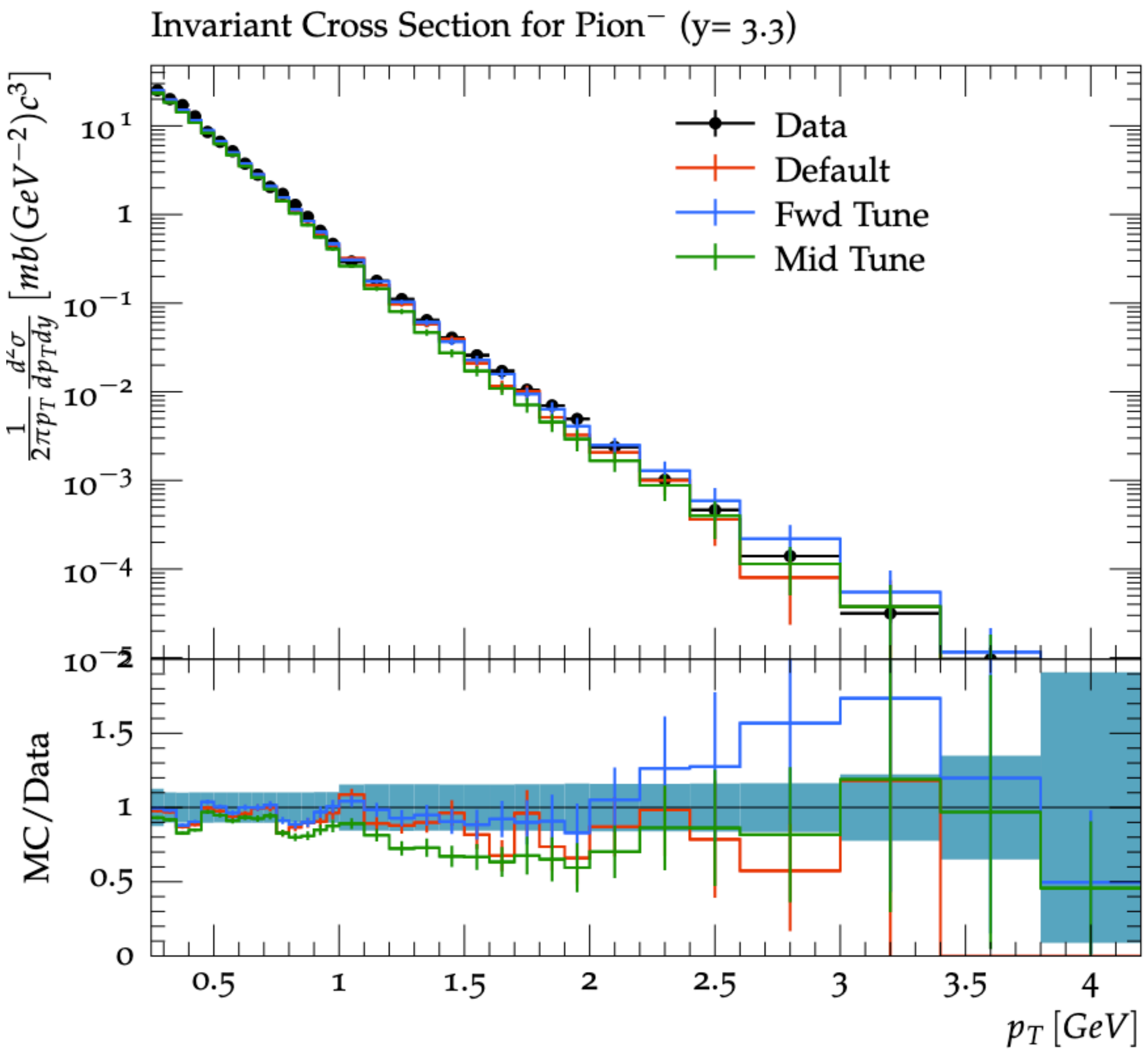
No difference between tuned MPI variables

BRAHMS Data: https://arxiv.org/pdf/hep-ex/0701041.pdf

Forward Tune

Note: Low stat. tails should be ignored for now





<0.7 GeV region not used

Forward pions (>0.7 GeV) only: ecmPow(0.229)+expPow(1.61) $\chi2/\text{ndof} = 49/92$

- Mid.: ecmPow(0.177)+expPow(1.36); Monash default: ecmPow= 0.215

Re-tuning can recover MC description, but not practical

- Other tuning variables (simultaneous tune)? E.g., Intrinsic kT, coupling to ISR, ...?

Conclusions

Tuning the MPI-related parameters in general produces better description to mid-rapidity observables

- Some small variations with ecmPow vs. pT0Ref @ 200 GeV; Good global tune to mid-rapidity with either variable

Mid-rapidity-tuned PYTHIA 8 does not describe forward pion spectra

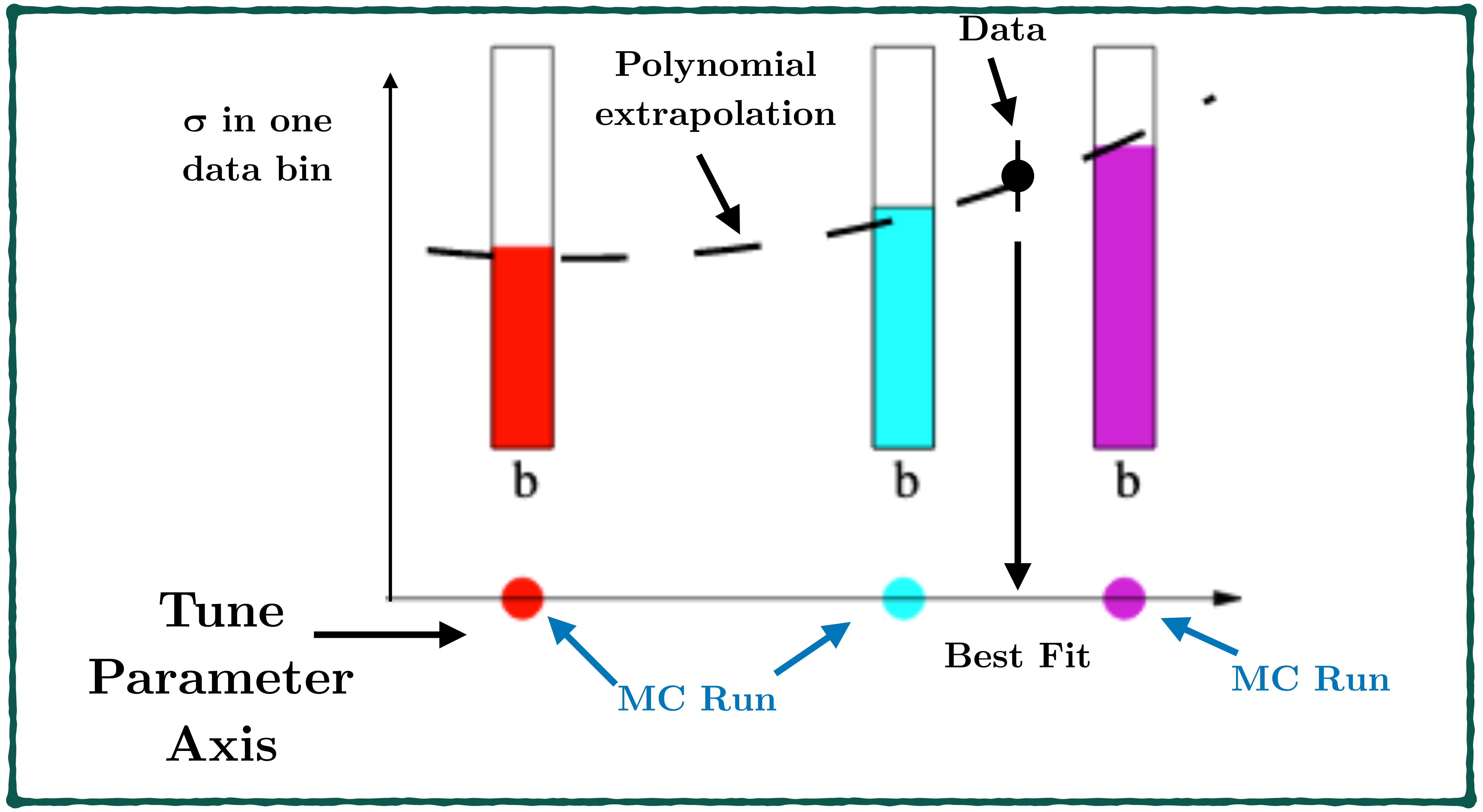
- Actually worse than default Monash
- Re-tune to only forward pions produces a good description of data but not practical
- Other variables to tune for forward rapidity?

BACKUP

Tuning Methodology

Parametrization-based tuning methodology: *Professor* toolkit (professor.hepforge.org)

- Polynomial parameterization of MC variation response + χ^2 min. w.r.t. data



p ≡ tunable parameter space

$$\mathrm{MC}_b(\boldsymbol{p}) \approx f^{(b)}(\boldsymbol{p}) = \alpha_0^{(b)} + \sum_i \beta_i^{(b)} p'_i + \sum_{i \le j} \gamma_{ij}^{(b)} p'_i p'_j$$

MC response in *one* data bin b

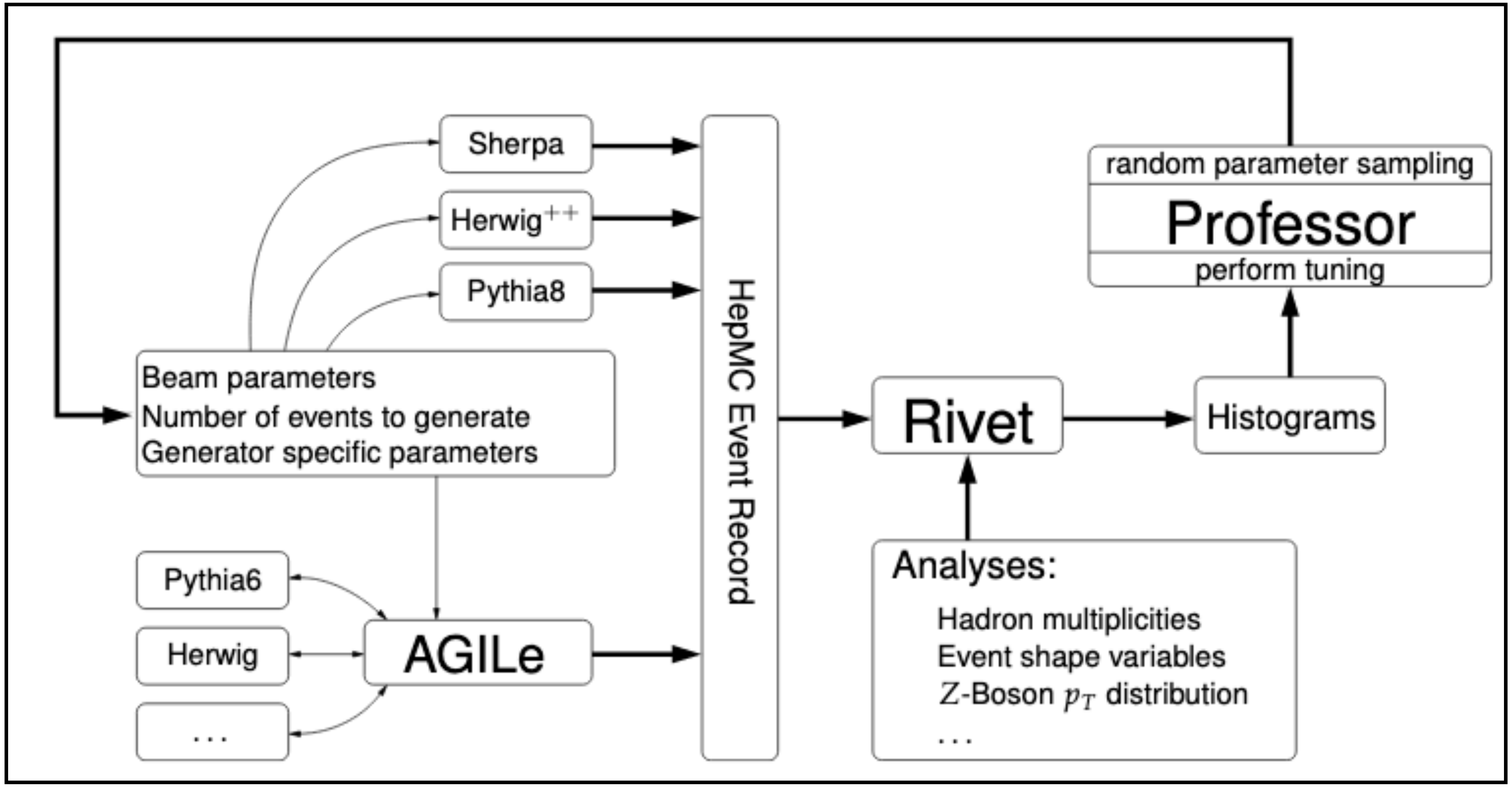
$$\chi^2(\boldsymbol{p}) = \sum_{\mathcal{O}} w_{\mathcal{O}} \sum_{b \in \mathcal{O}} \frac{(f^{(b)}(\boldsymbol{p}) - \mathcal{R}_b)^2}{\Delta_b^2}$$

Minimize weighted chi2 w/ parameterization

Professor+PYTHIA6 Tune: https://doi.org/10.1140/epjc/s10052-009-1196-7
CMS PYTHIA6,8 Herwig++ Tune: https://doi.org/10.1140/epjc/s10052-016-3988-x
CMS Herwig 7 Tune: arXiv:2011.03422

Tuning Methodology Cont.

A little more technical view....



https://professor.hepforge.org/diplomathesis_h_schulz.pdf

RIVET needed for Professor method

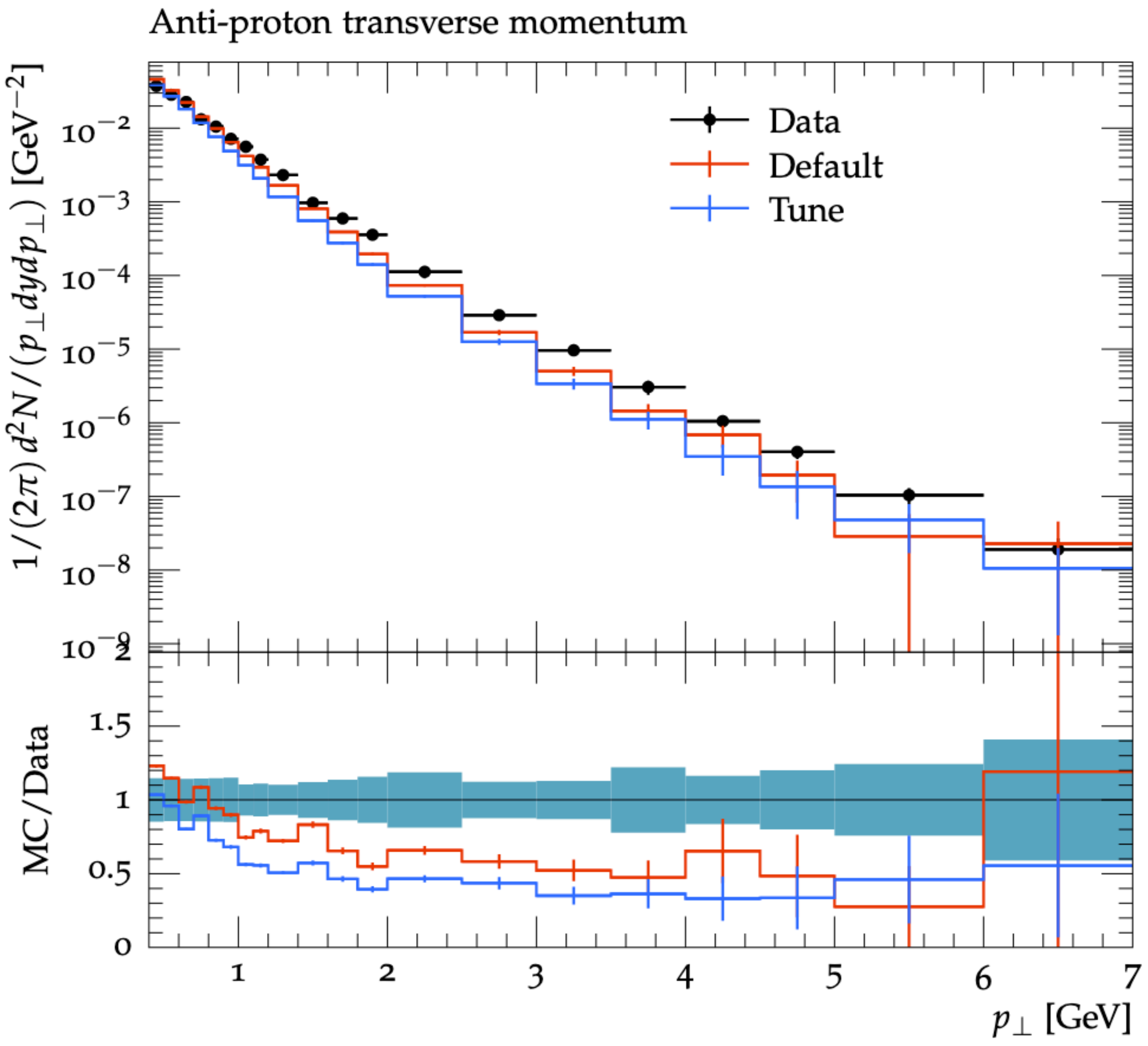
"The Rivet toolkit (Robust Independent Validation of Experiment and Theory) is a system for validation of Monte Carlo event generators."

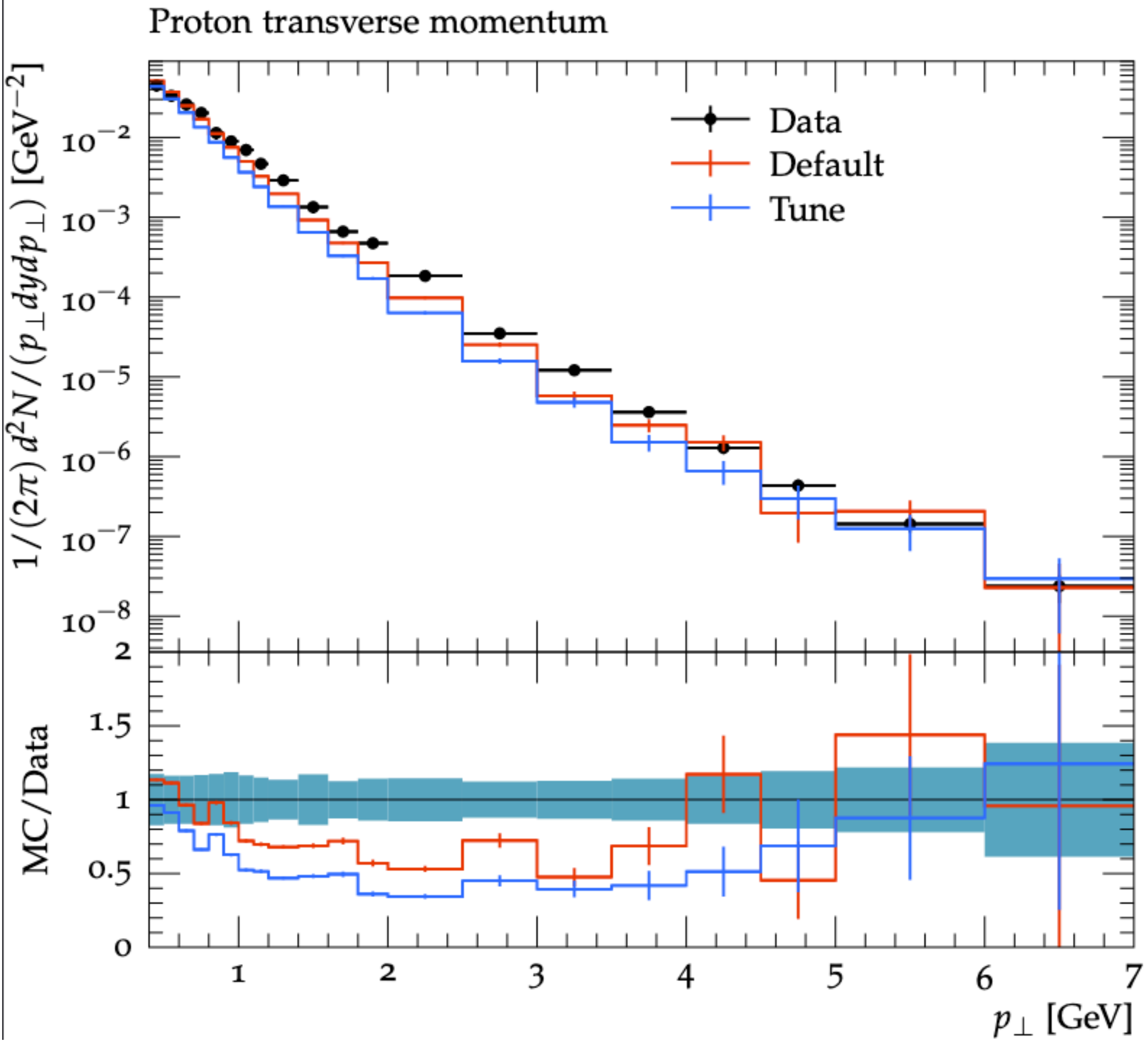
I.e., a generator-agnostic analysis code package that reproduce physics "measurements" on HepMC data

→ Compare to real data

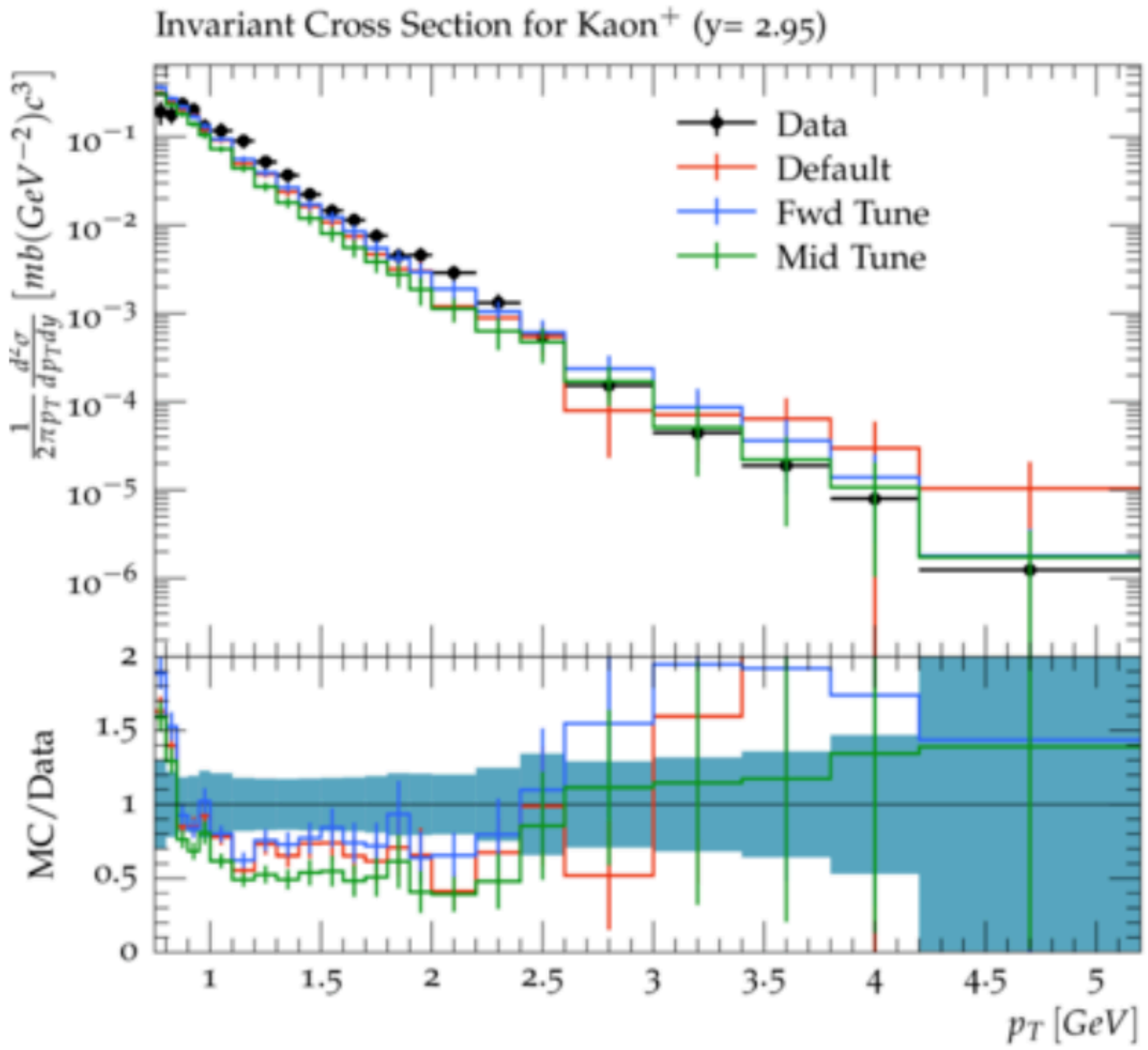
rivet.hepforge.org

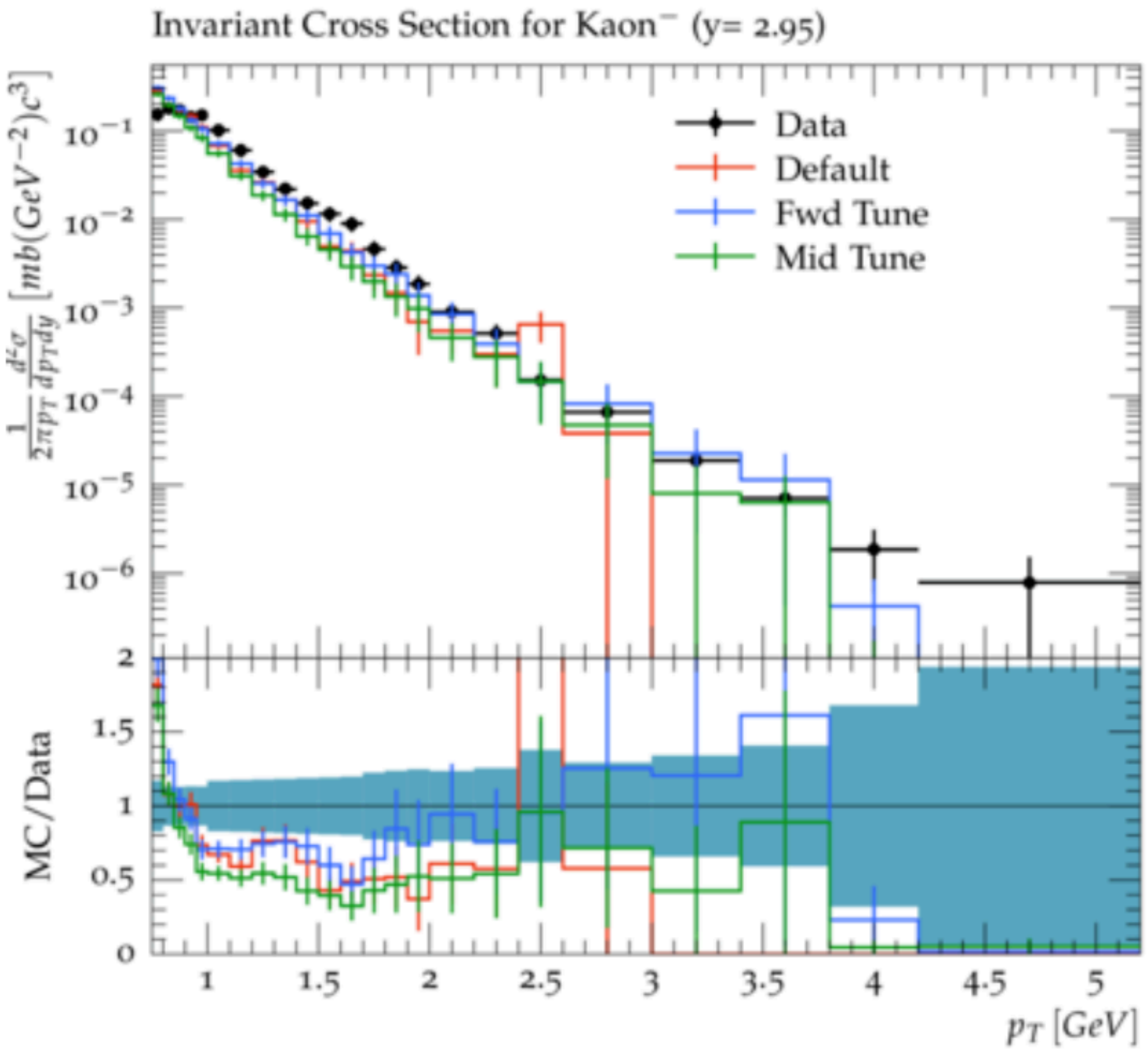
Protons @ Mid-Rapidity





PID @ Forward-Rapidity





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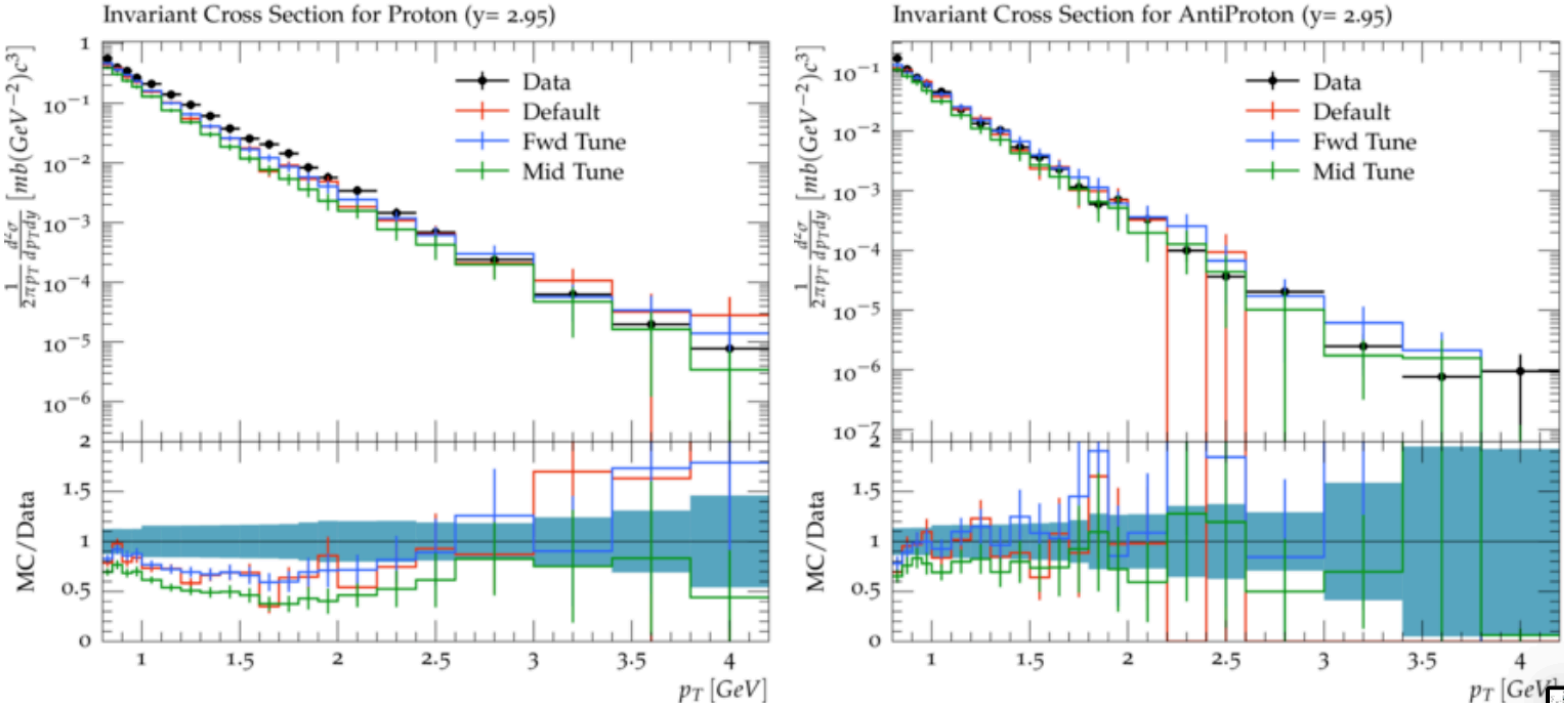

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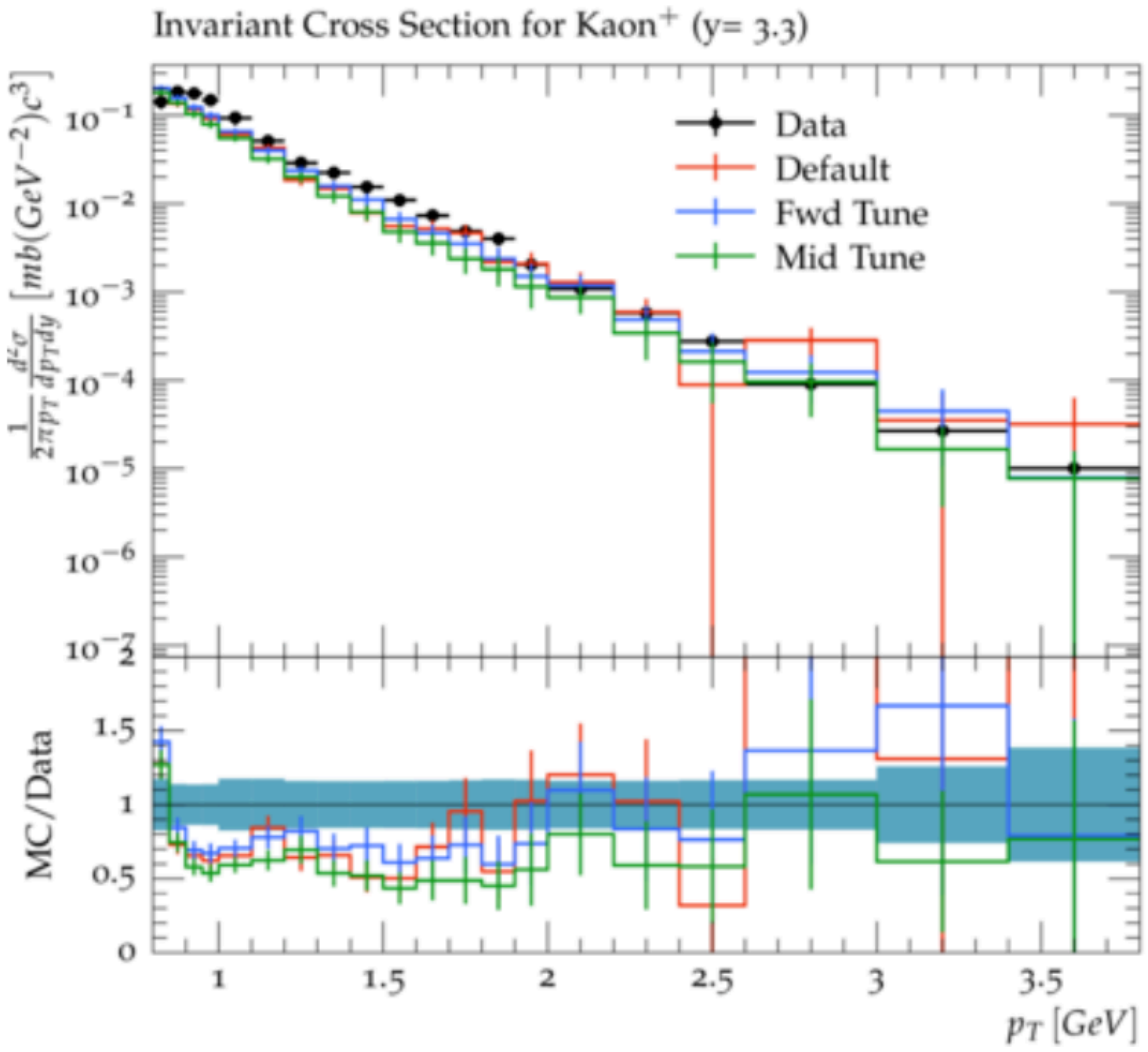
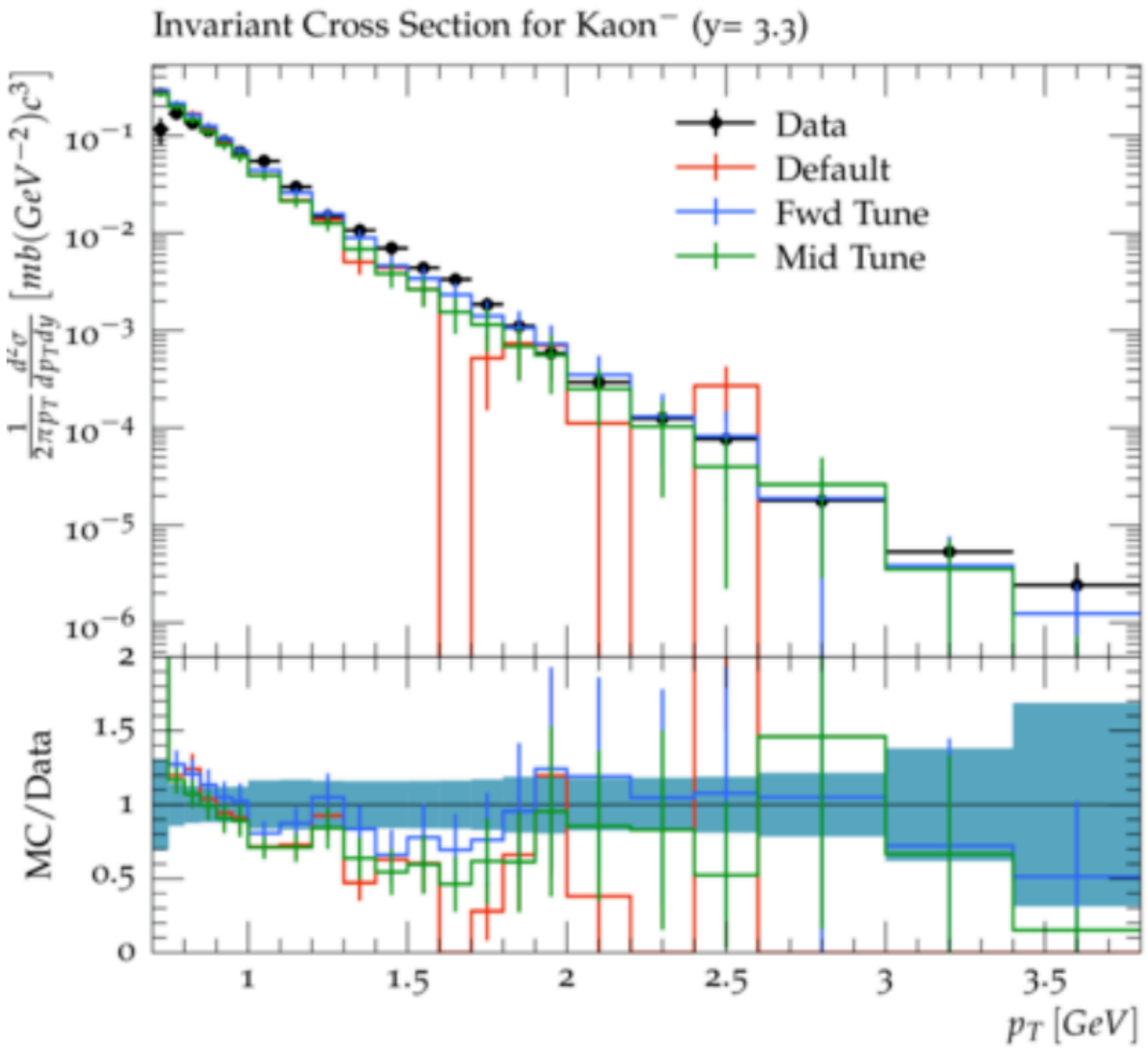
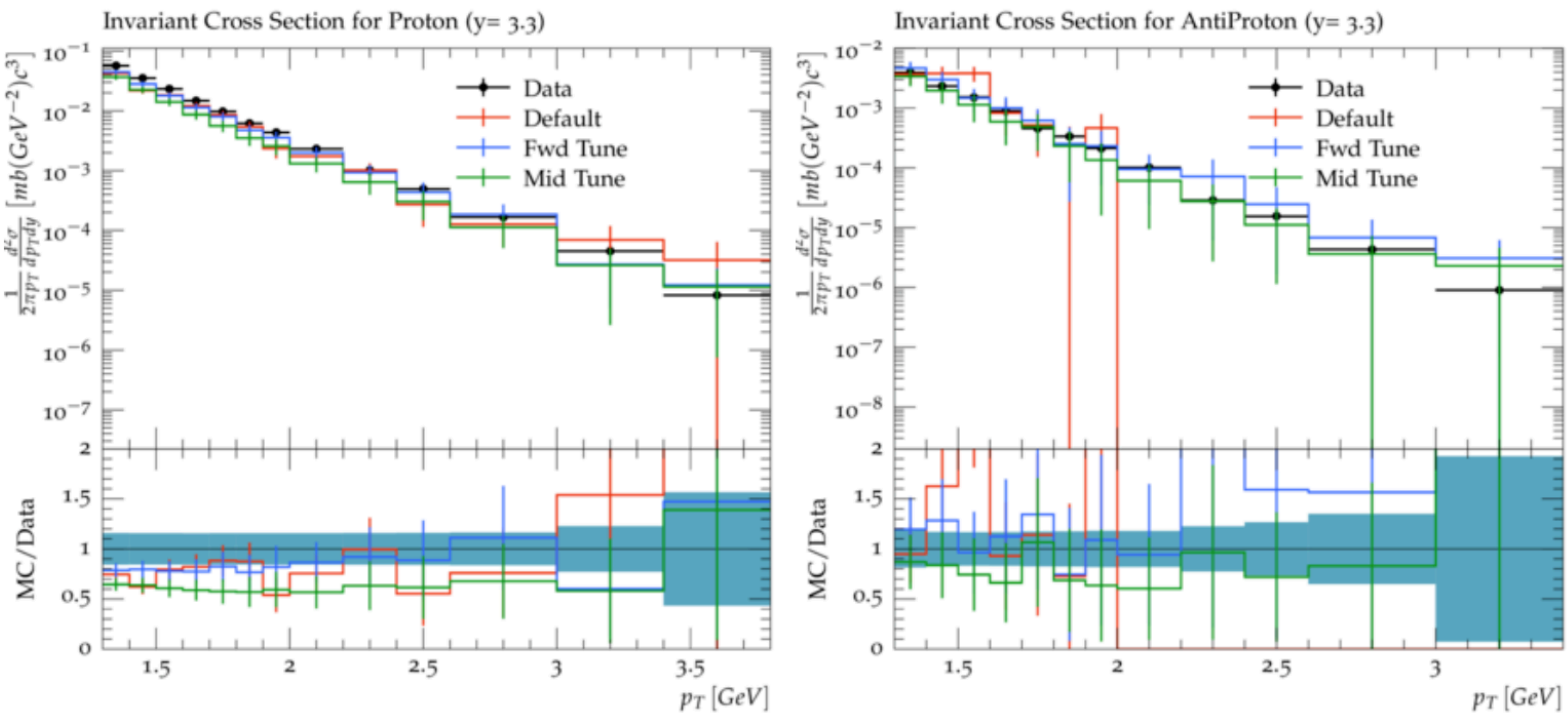




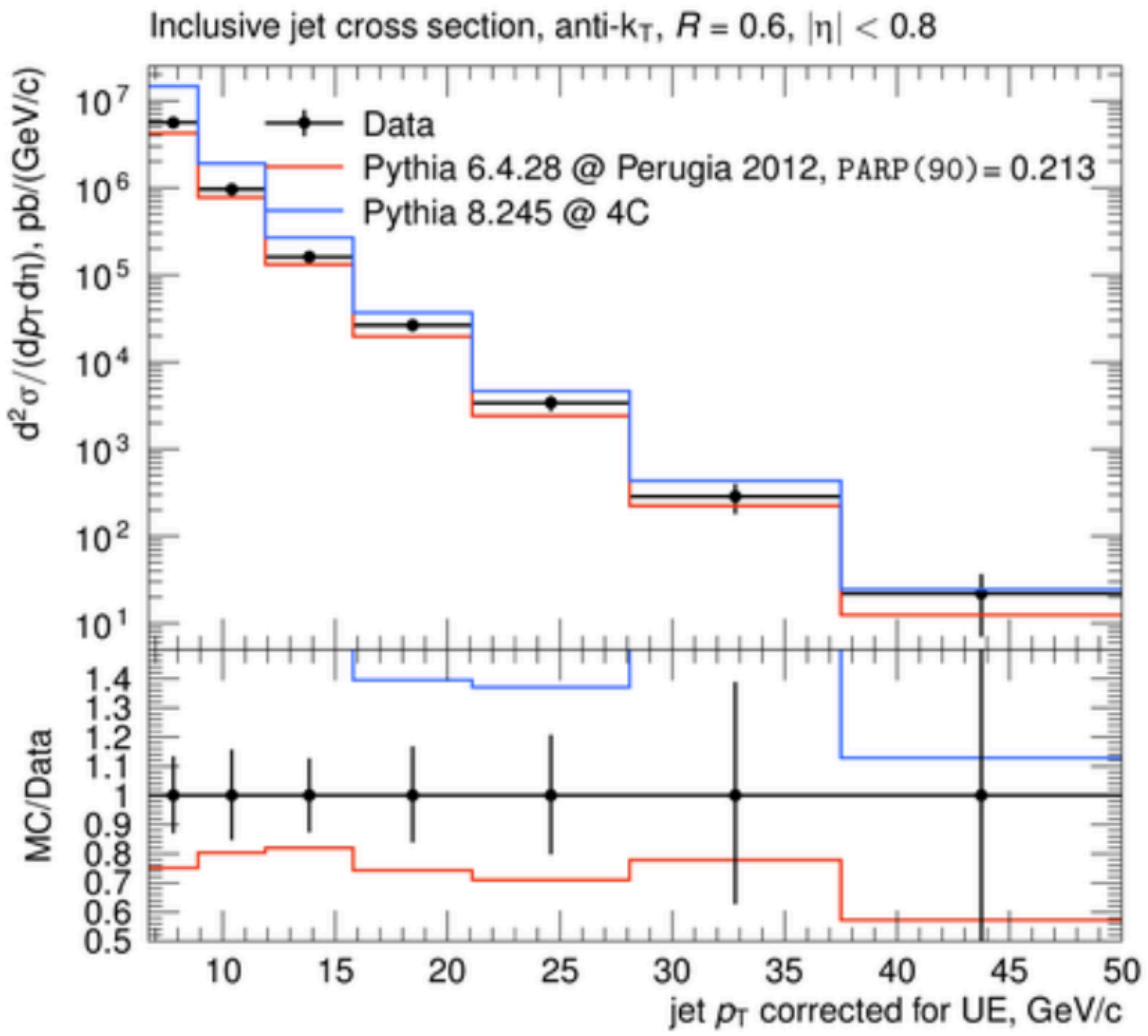
PID @ Forward-Rapidity

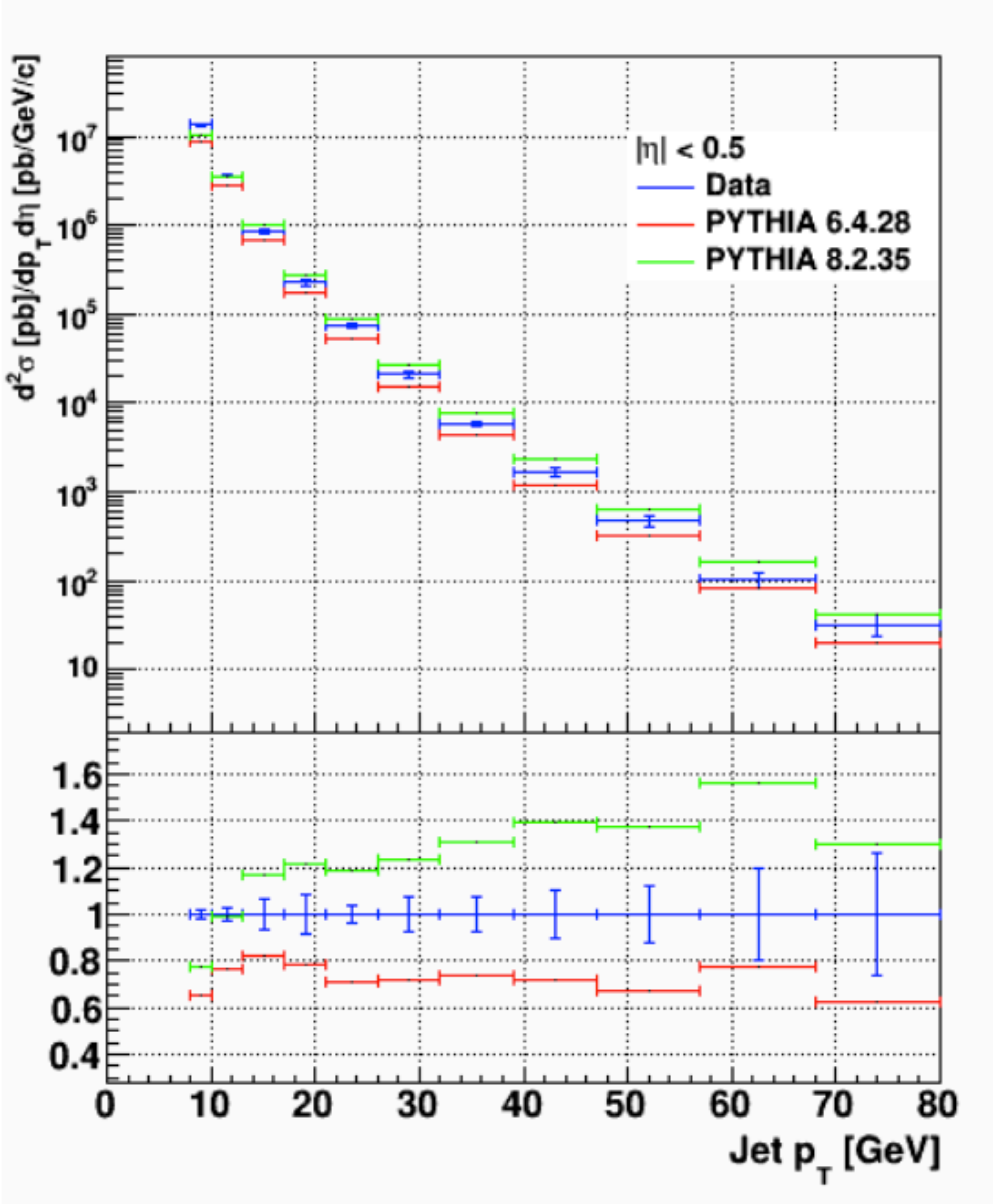


p+p 510 GeV Jet Spectra

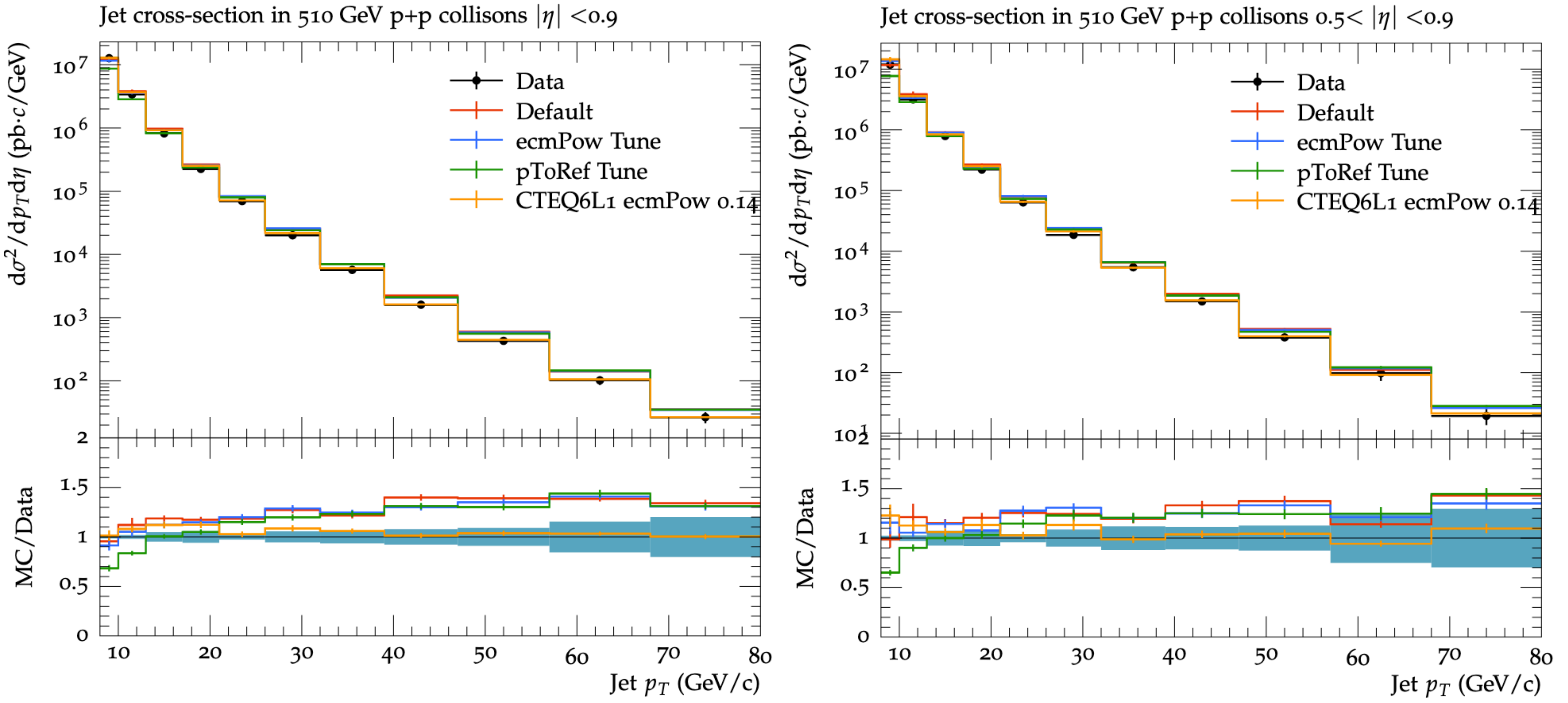
In general default PYTHIA 8 seems to over-predict the data while PYTHIA 6 (STAR tune) under-predicts

- Due to proton PDFs (NNPDF vs. CTEQ6L1)?
- Also seen with 200 GeV jets
- Note both analyses corrected for UE





p+p 510 GeV Jet Spectra



Tuned PYTHIA 8 slightly modified from default

- Directly tuned pT0Ref does worse at low pT (would need sequential tuning to get new extrapolation factor?)

PYTHIA 8 w/ CTEQ6L1+tune (same pT0 as PYTHIA 6 tune) reasonably reproduces scale and shape