Overview Working Group for Light Hadron Production (WG3)

FLArE WG Meeting

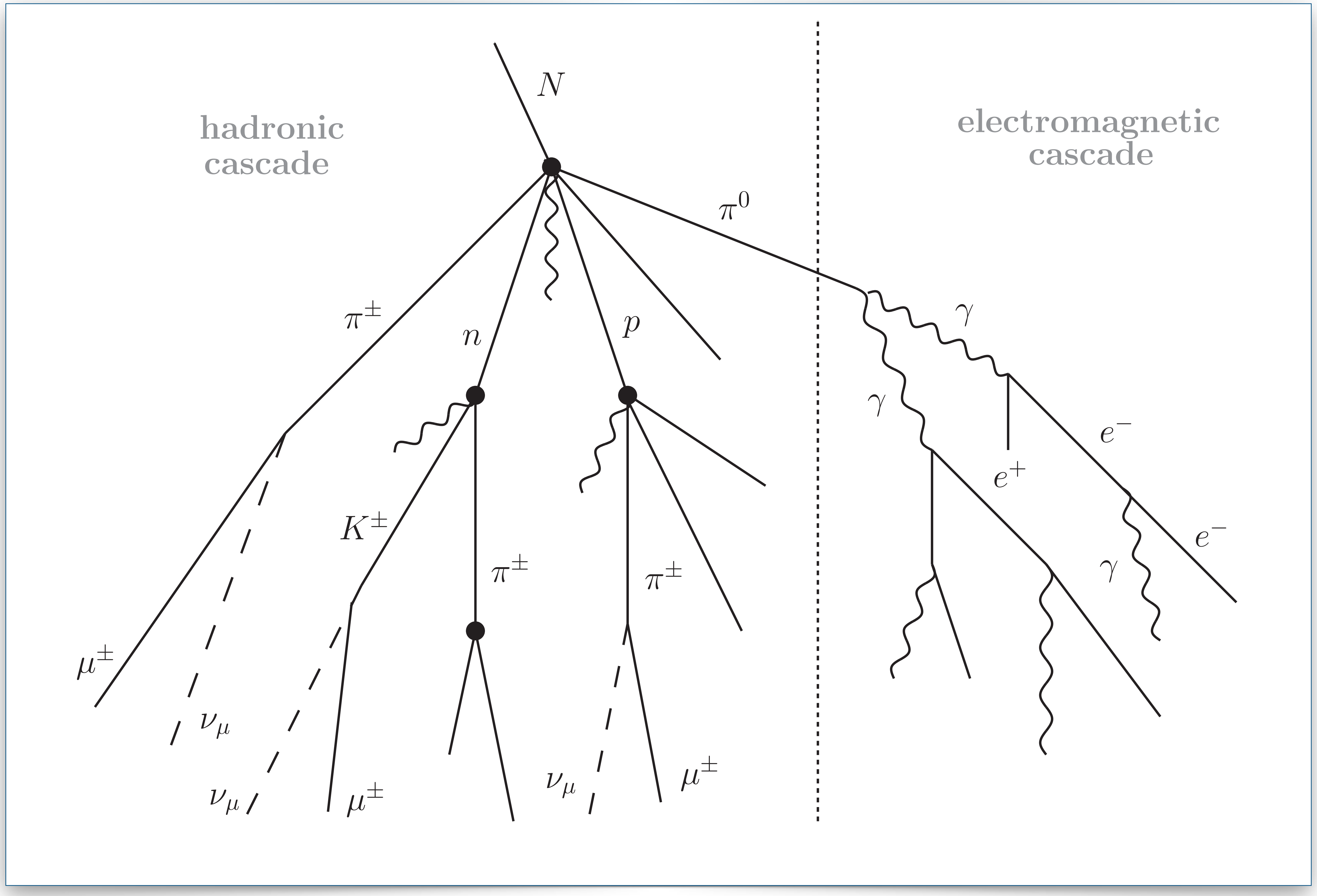
Dennis Soldin

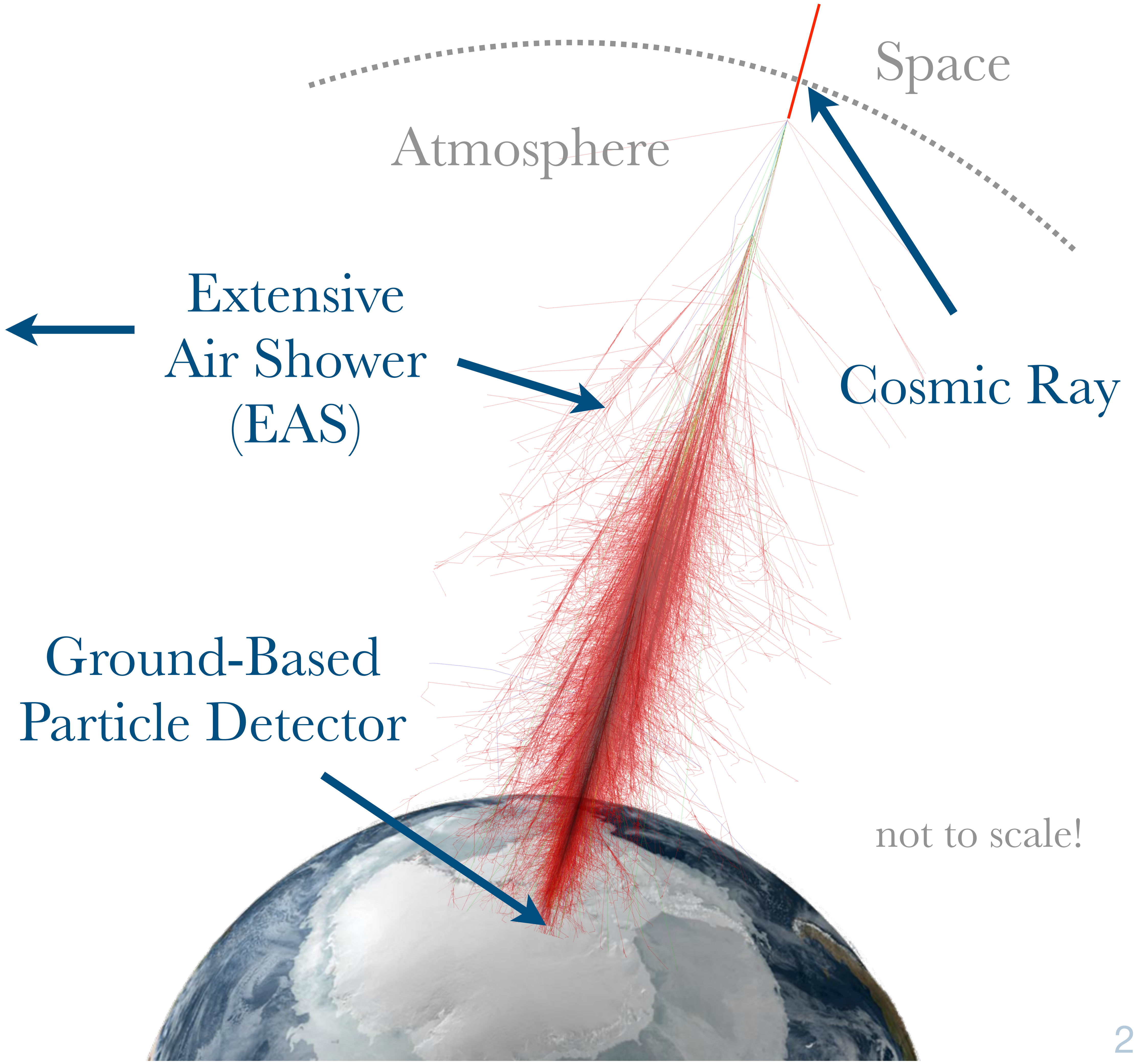
Outline

- Why is it interesting to study light hadron (pion/kaon) production at the FPF?
- How can FPF experiments contribute to understand light hadron production?
- What detector specifications would be needed…?
- Disclaimer I
  - I will not talk about charm neutrino production which is also highly relevant for astroparticle physics, i.e. dominant background for astrophysical neutrino searches
  - Please refer to FPF WG 2 (charm production)…
- Disclaimer II
  - I am not an experimentalist!
  - I will only discuss a physics-motivated "wish list" from a theoretician's point of view!

Motivation I

- Large motivation to study light hadron production at the FPF arises from observations of extensive air showers (EAS)





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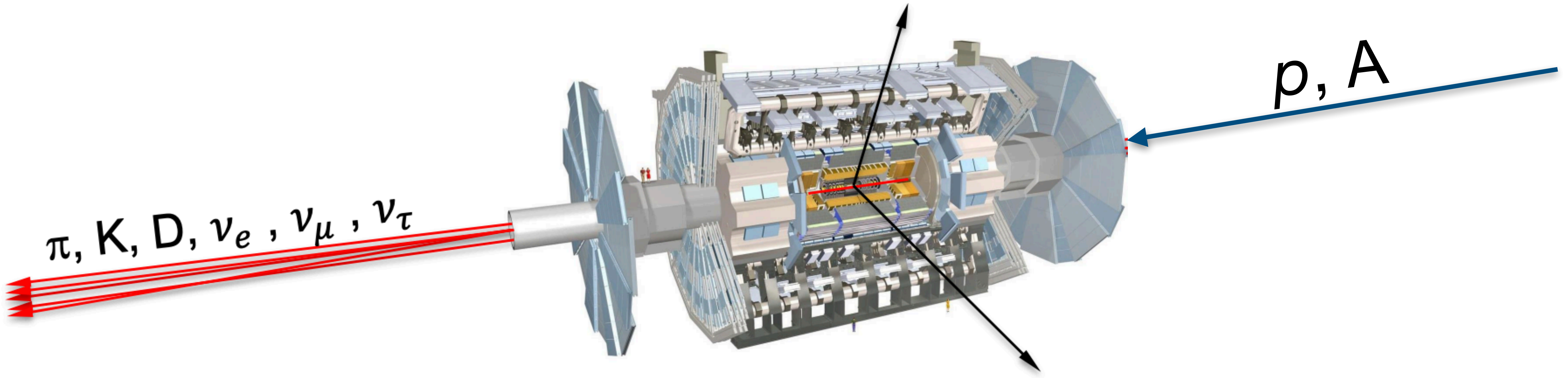
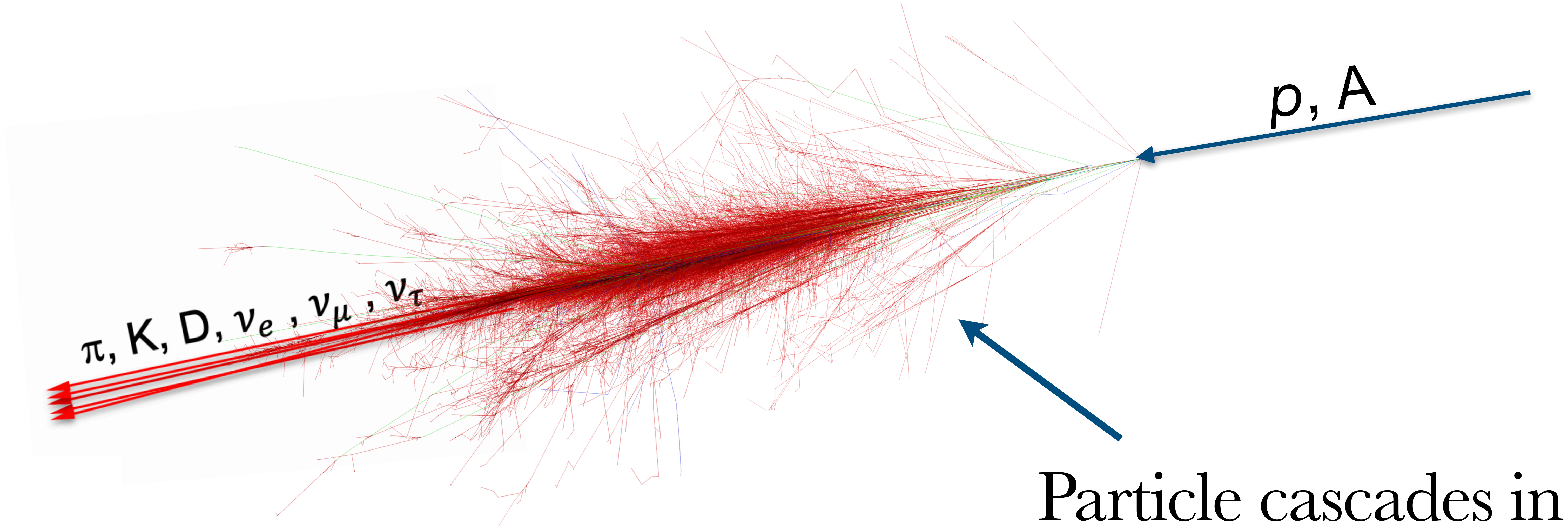
- <u>LHC:</u>



- <u>EAS:</u>

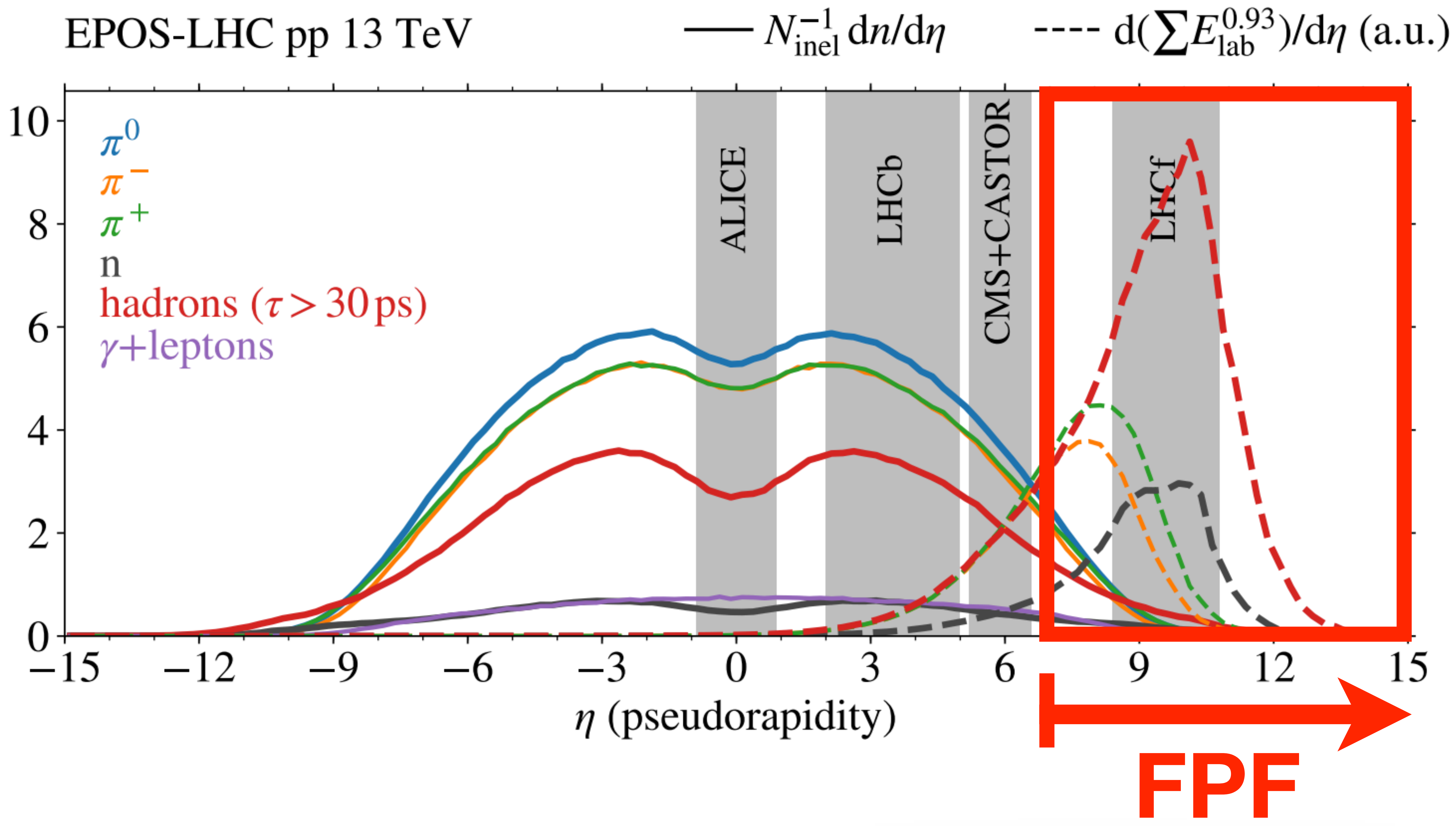


Particle cascades in the atmosphere initiated by high-energy cosmic rays

Motivation I

- Extensive air showers:
  - Particle production in the far-forward region
  - Low momentum transfer
  - Non-perturbative regime
  - Complex particle composition
  - Energies range over many orders of magnitude
- Modeling of particle interactions based on phenomenological models developed for EAS simulations

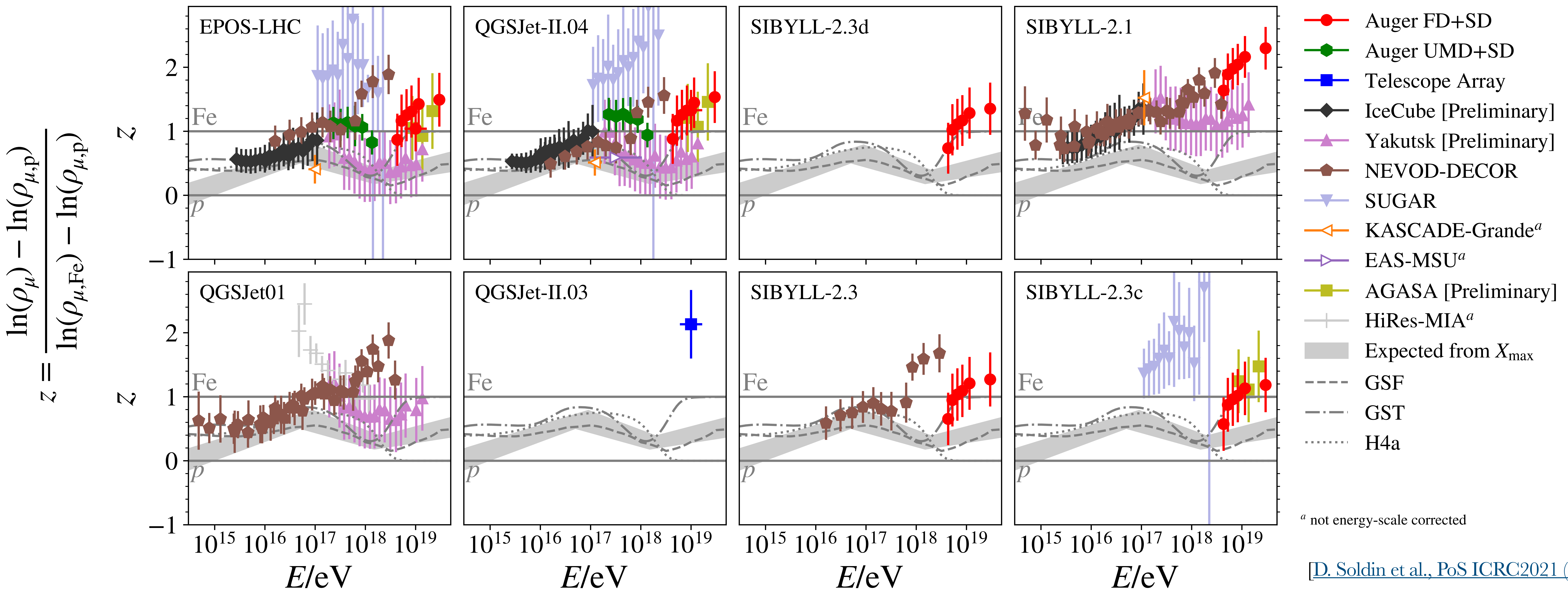
[J. Albrecht et al., Astrophys. Space Sci. 367 (2022)]



FPF will provide unique opportunities to test /constrain hadronic interaction models

Motivation I

- Large discrepancies between data and MC observed in extensive air showers (EAS)



[D. Soldin et al., PoS ICRC2021 (2021) 349]

- Muon measurements and models indicate composition heavier than iron at high energies!

Motivation I

Muon Puzzle

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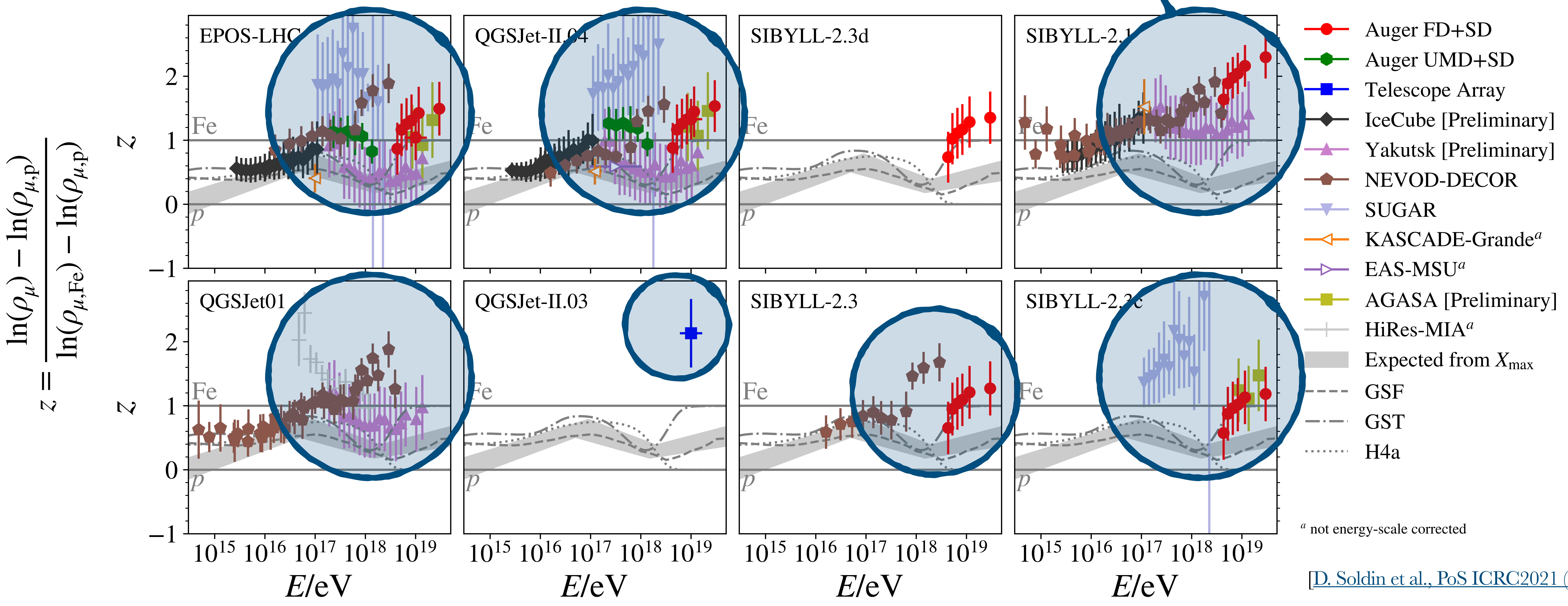


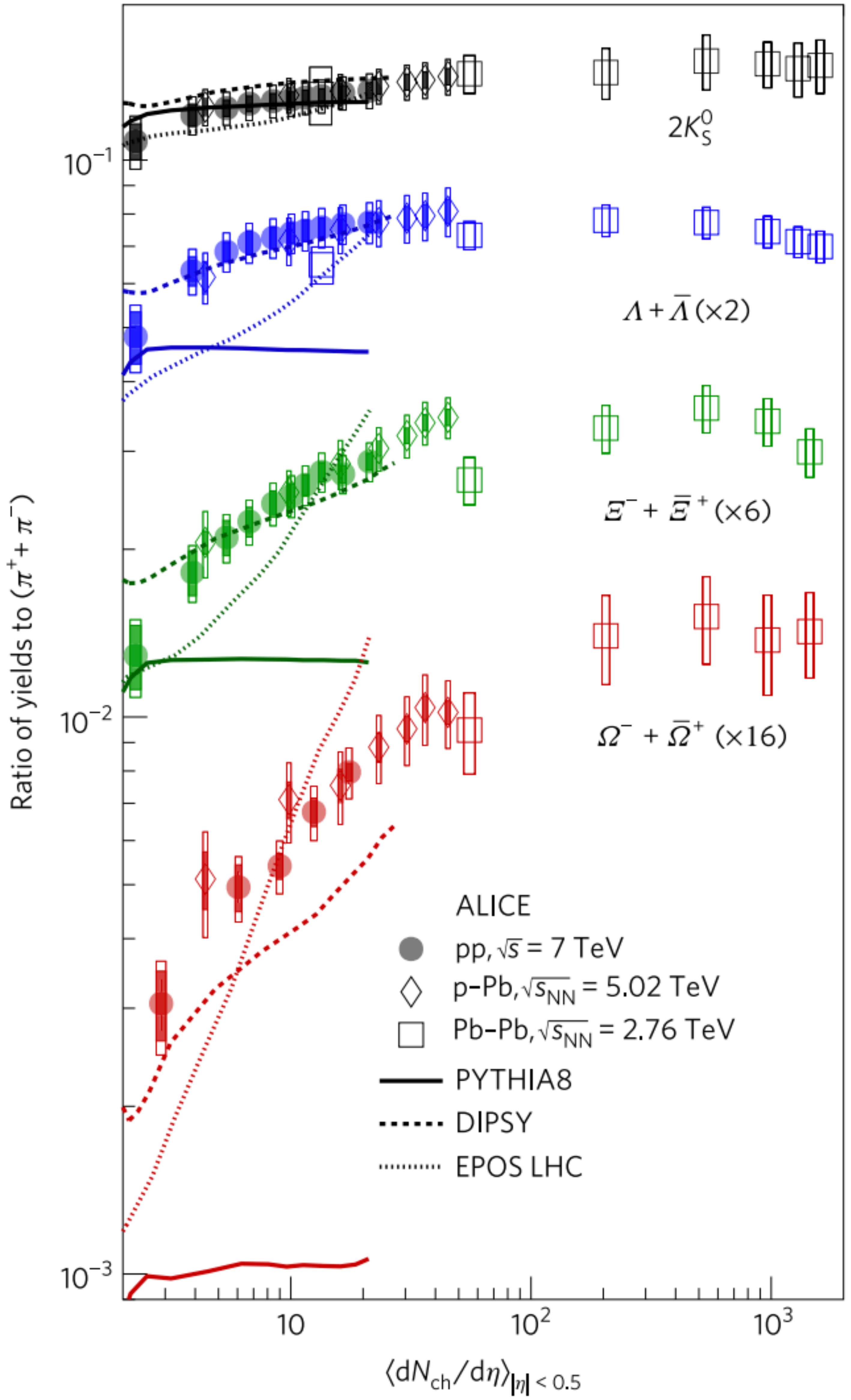
[D. Soldin et al., PoS ICRC2021 (2021) 349]

- Muon measurements and models indicate composition heavier than iron at high energies!

Motivation II

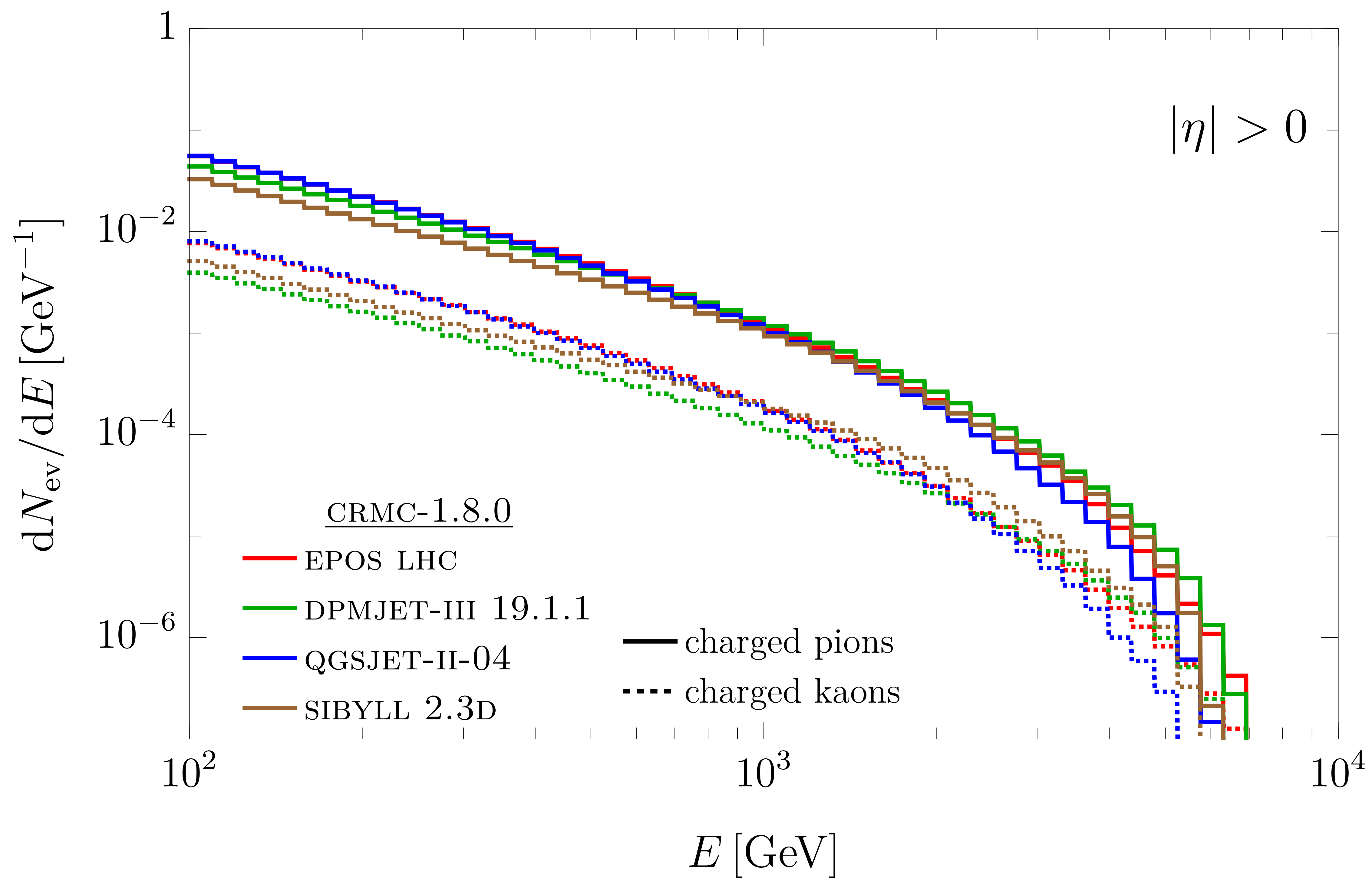
- Evidence for strangeness enhancement reported by ALICE
- Universal enhancement of strangeness production in high-multiplicity events at mid-rapidity ($|y| < 2$)
- Depends on the multiplicity of the event at mid-rapidity, not on the details of the collision system!
- Can this effect also be seen in hadrons produced at forward rapidities?
- Possible explanation for the Muon Puzzle in EAS…
- <u>FPF provides unique opportunities for testing the forward rapidity region!</u>

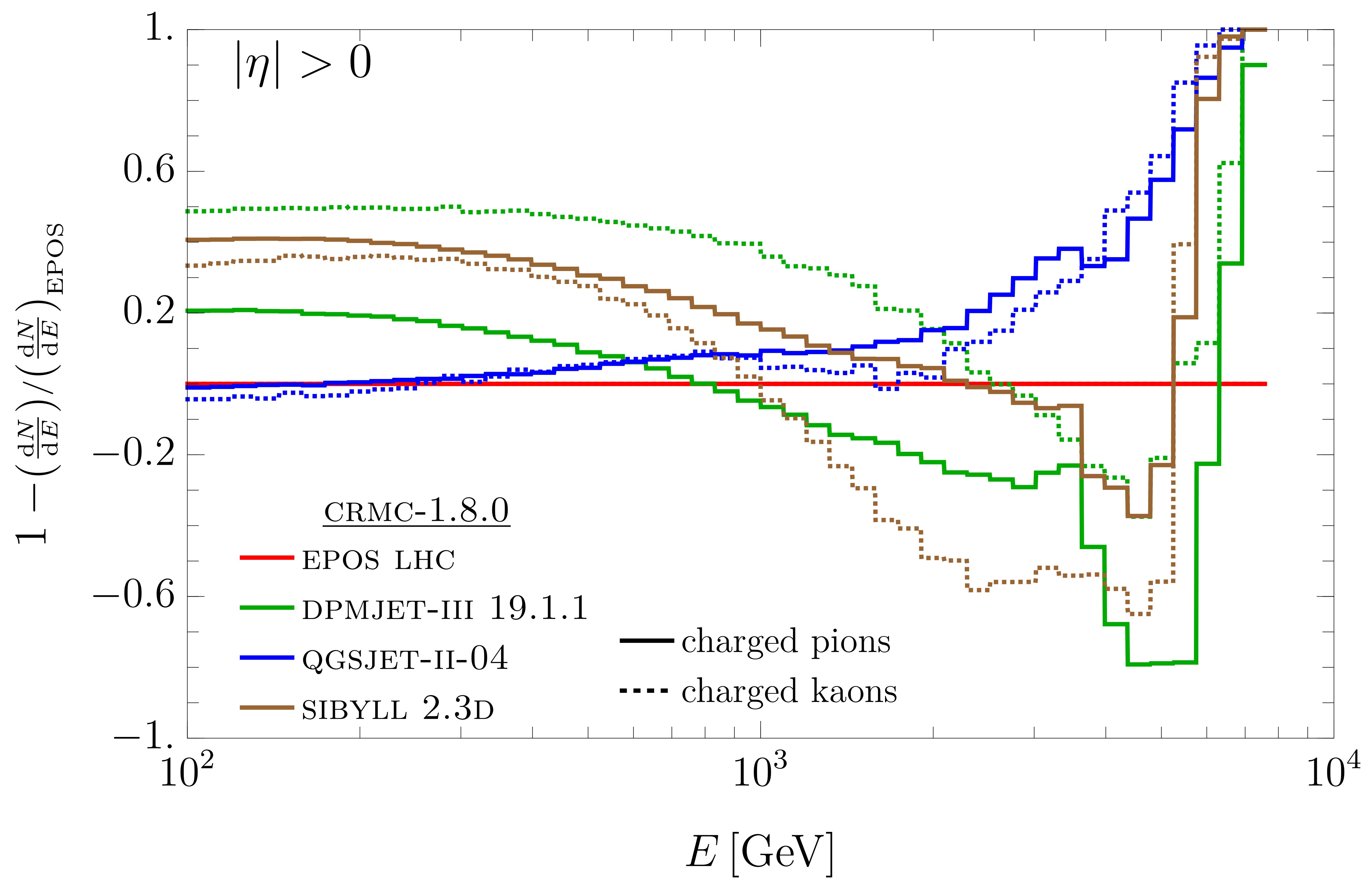
[J. Adam et al. (ALICE), Nature Phys. 13, 535 (2017)]



WG3 Science Topics I

- <u>Goal: constrain pion/kaon production in hadronic interaction models</u>
  - Example: $|\eta| > 0$ (all hadrons)





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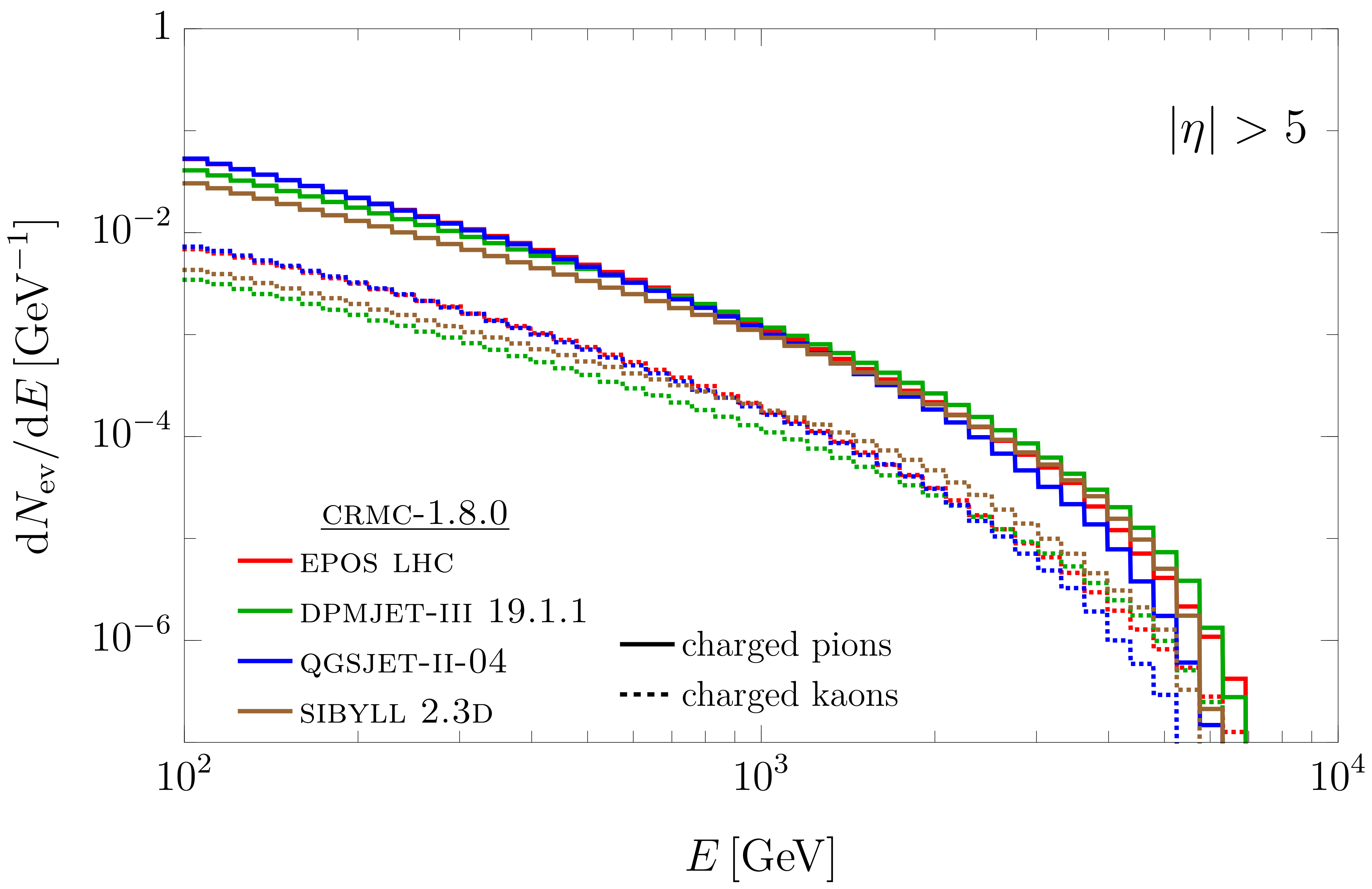
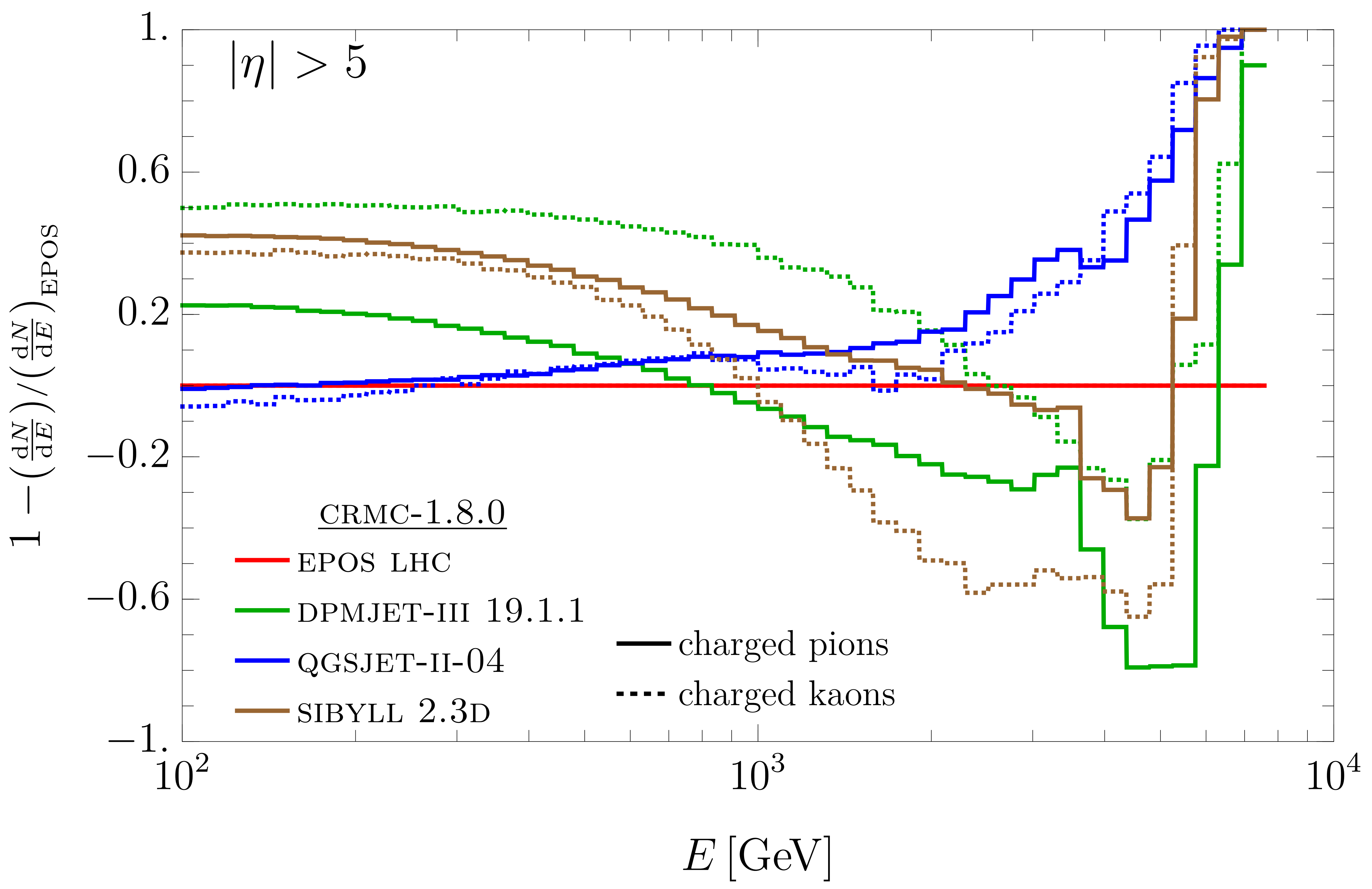
  - Example: $|\eta| > 5$ (intermediate range)





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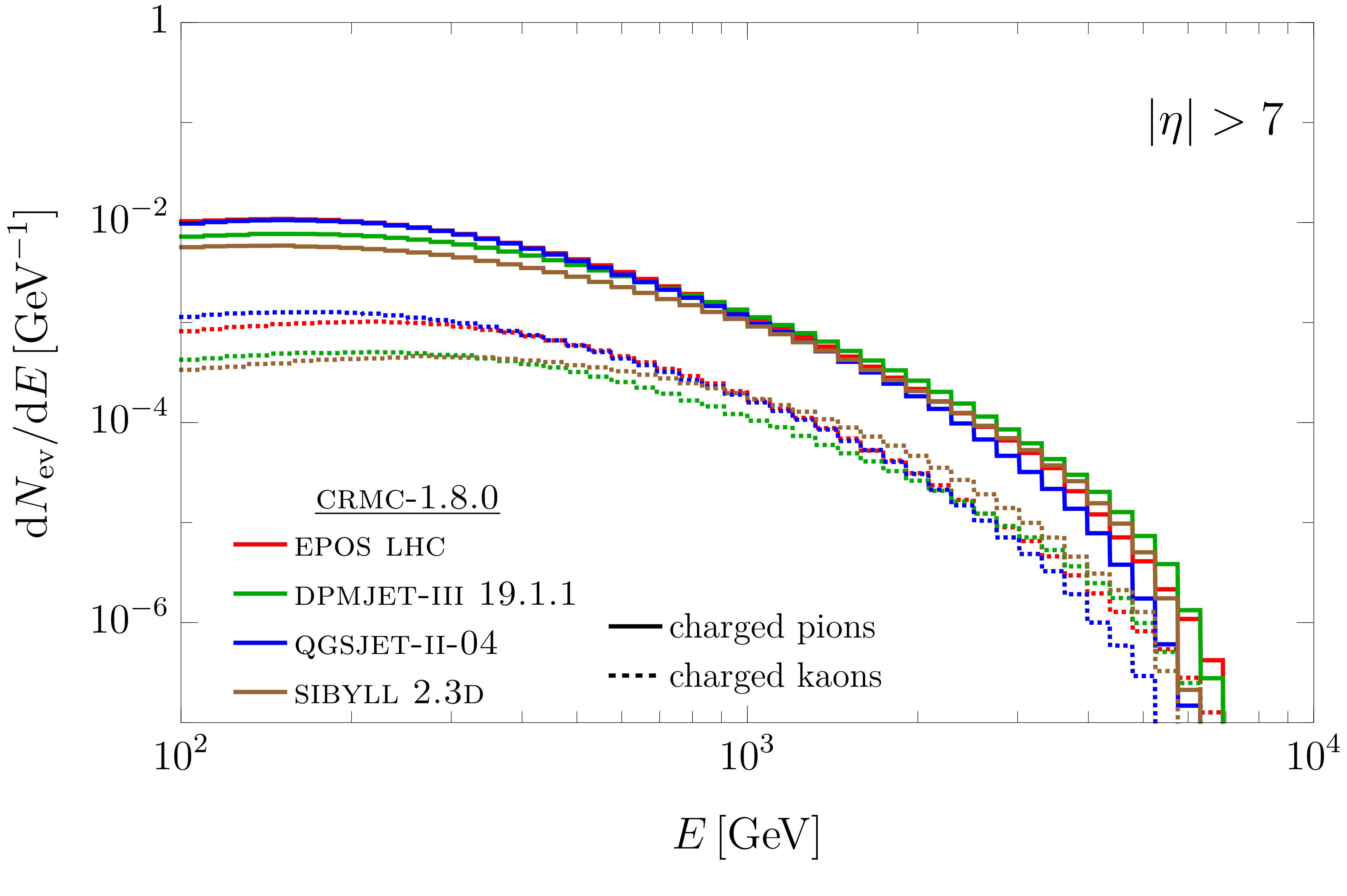
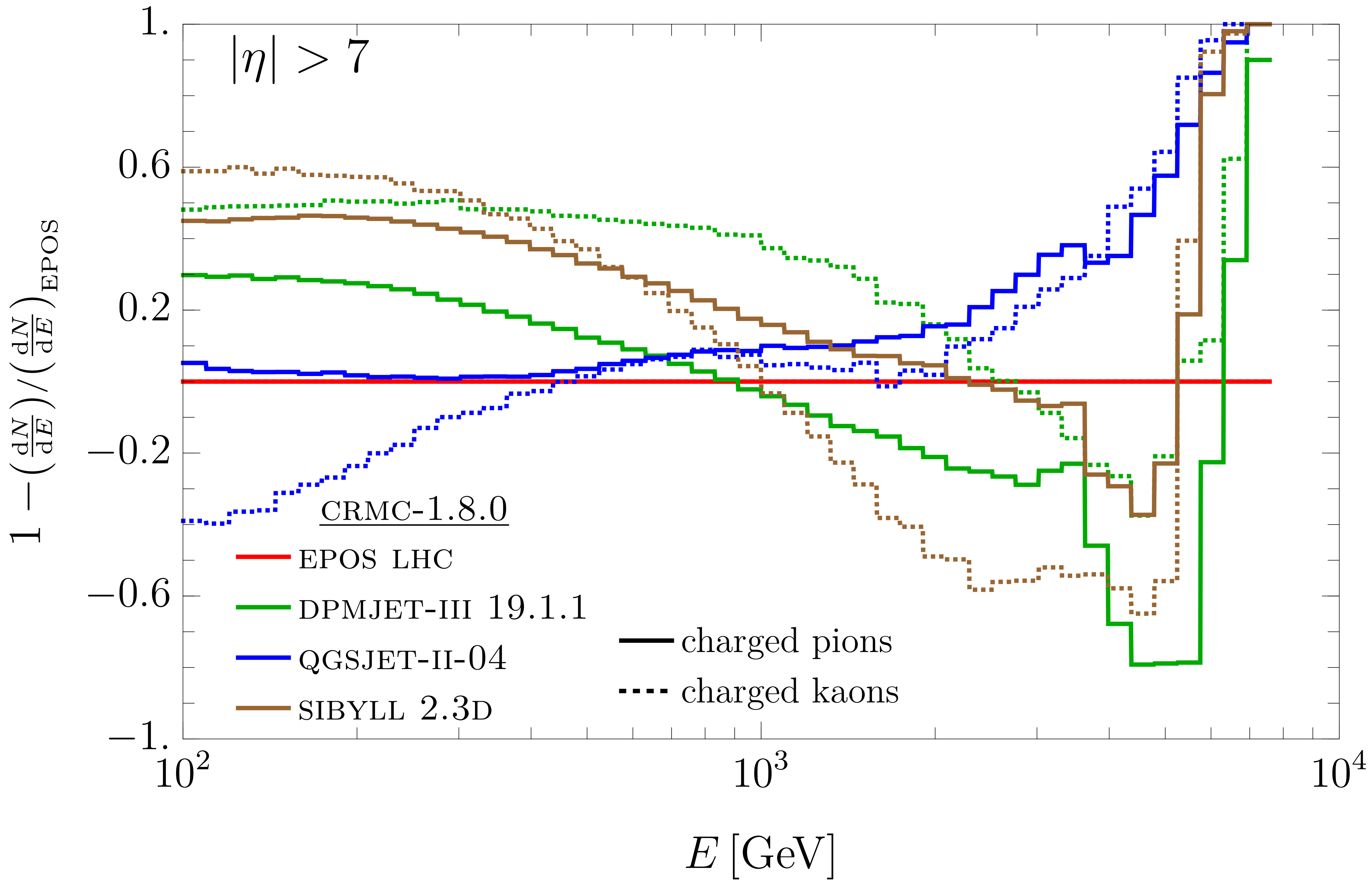
  - Example: $|\eta| > 7$ (FPF range)





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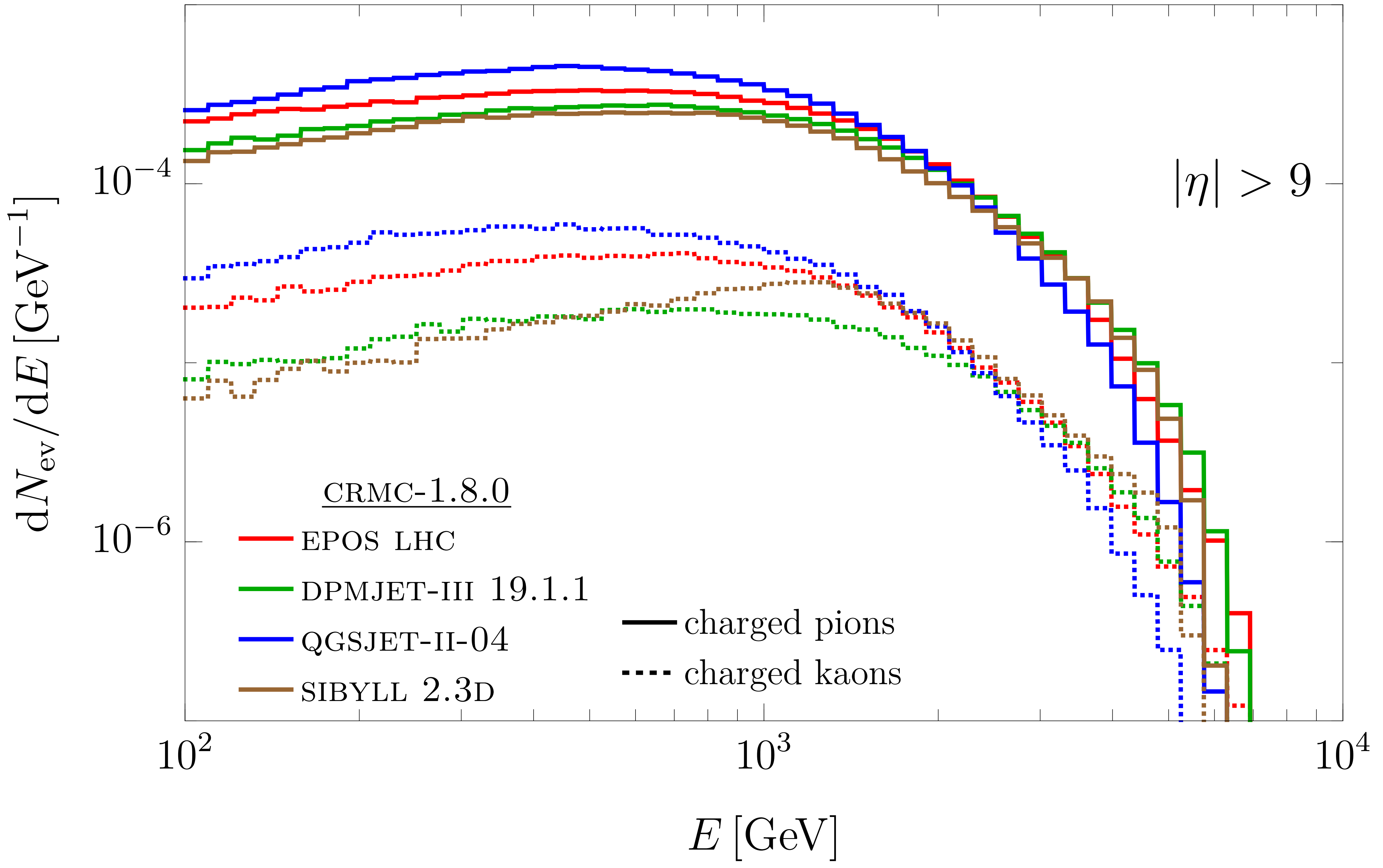
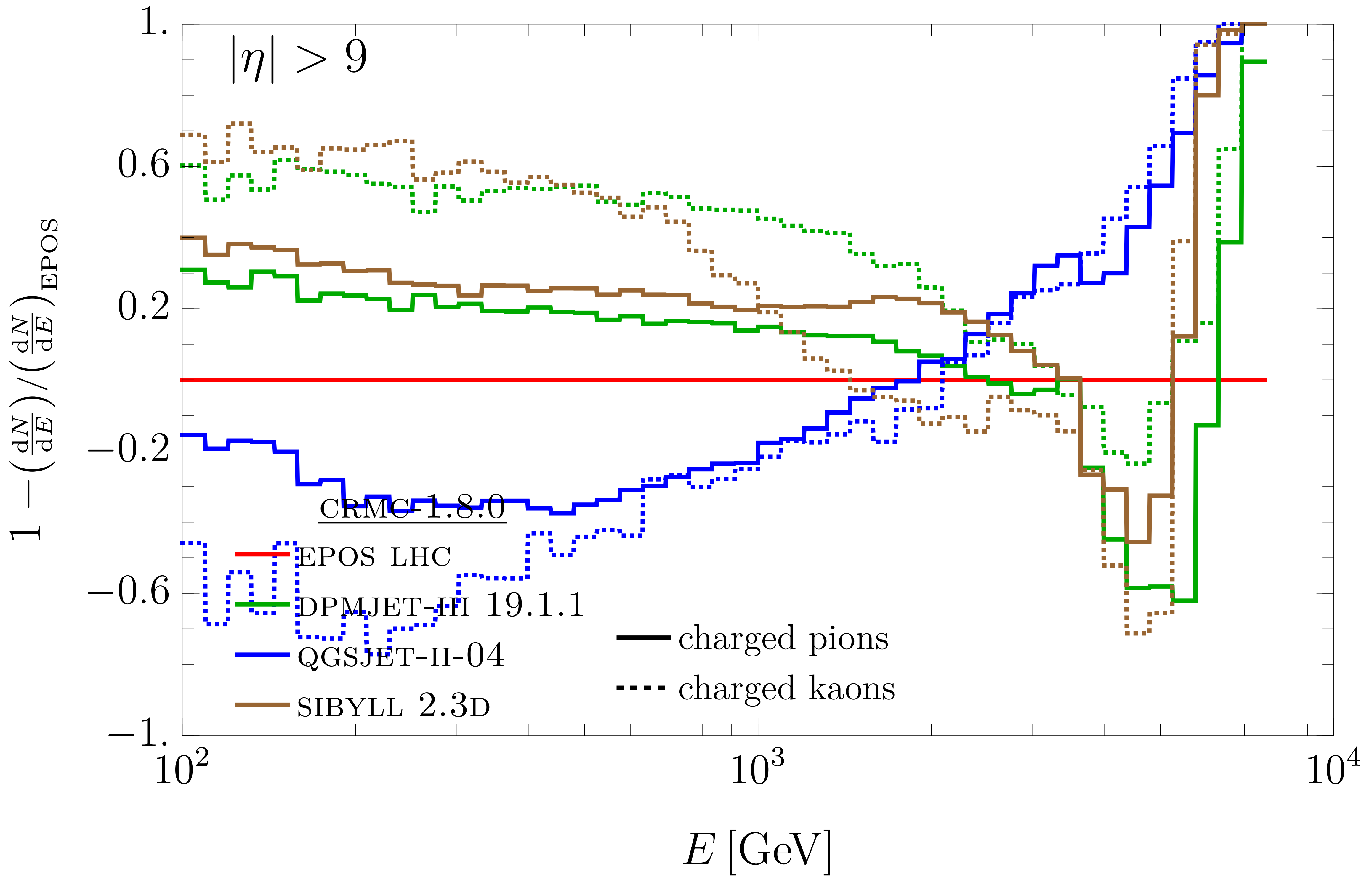
  - Example: $|\eta| > 9$ (far-forward range)



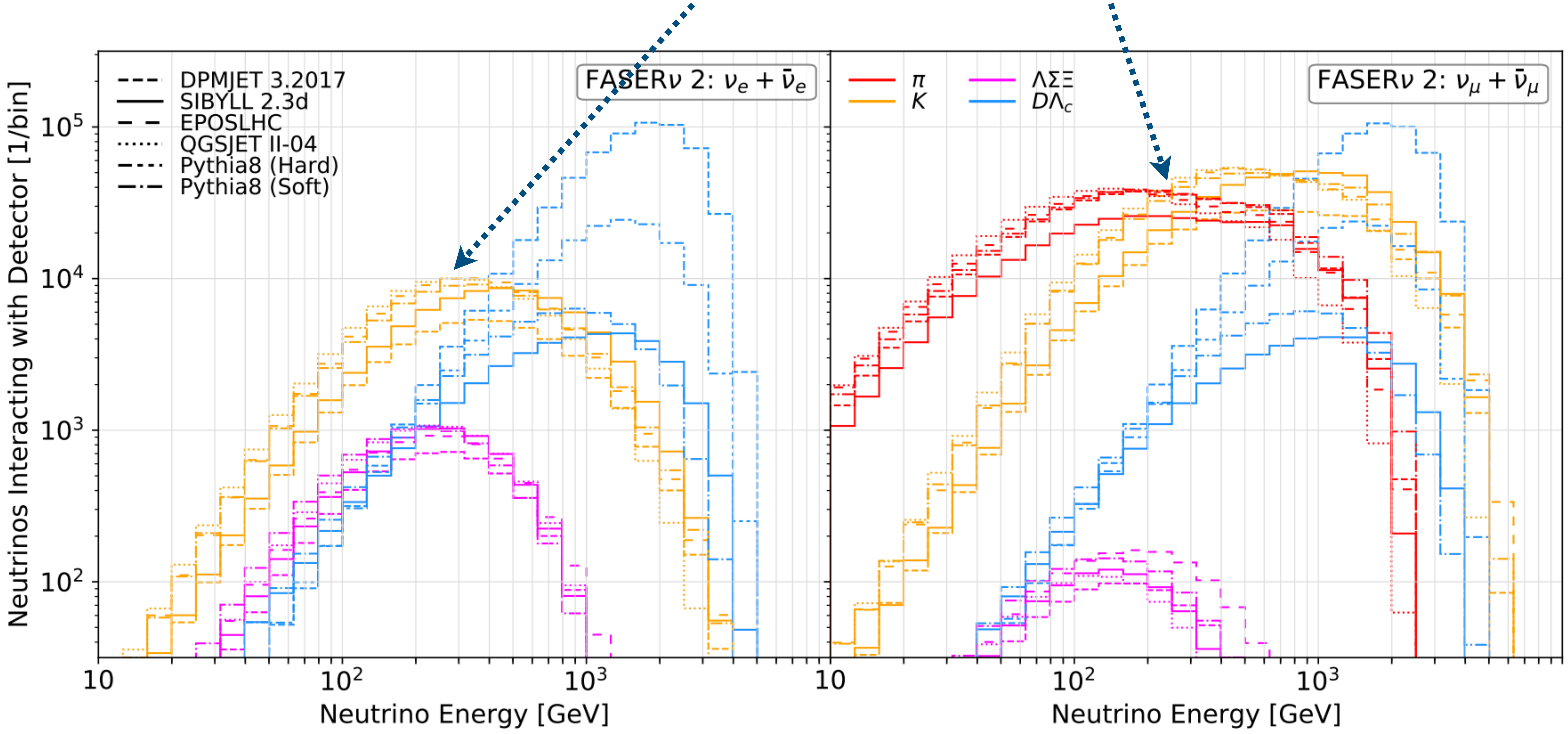


WG3 Science Topics I

- How to use neutrino fluxes at the FPF to constrain pion/kaon production?
  - Ratio of electron and muon neutrinos is a proxy for the ratio of charged pions and kaons (see next slide)
    - Particle ID needed, e.g. $\nu_e + \bar{\nu}_e$ vs. $\nu_\mu + \bar{\nu}_\mu$
  - Electron and muon neutrino fluxes populate different energy regions which will help to disentangle them
    - Energy spectrum (also at low energies, see next slide)
  - Neutrinos from pion and kaon decays have different rapidity distributions which will help to disentangle them
    - Rapidity distribution
  - Additional constraints through charge ratio (air shower measurements not sensitive)

WG3 Science Topics I

- Neutrino fluxes at FASERν2: kaons only pions + kaons

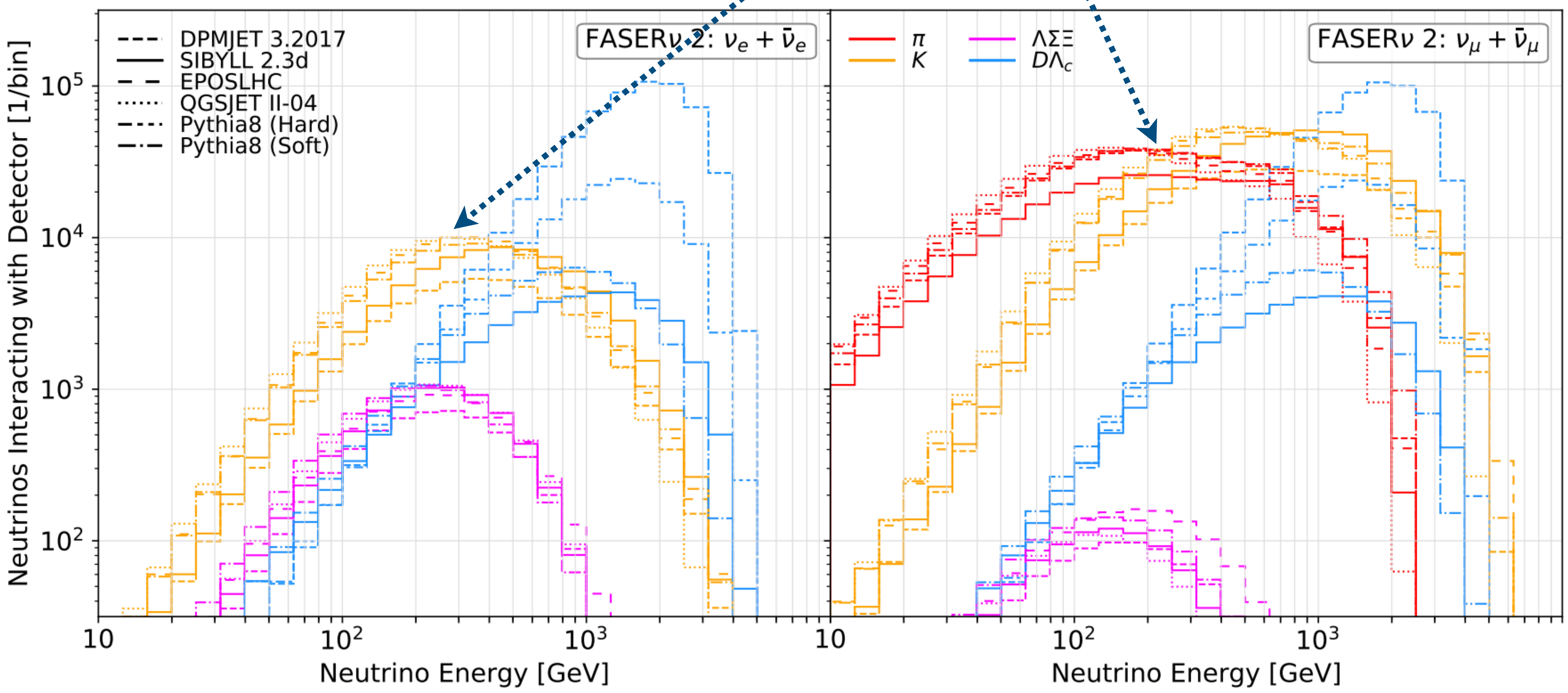


- Predictions differ by a factor of up to 2, much bigger than the anticipated FPF uncertainties

* Simulation code available at: https://github.com/KlingFelix/FastNeutrinoFluxSimulation, see also https://arxiv.org/abs/2105.08270

WG3 Science Topics I

- Neutrino fluxes at FASERν2: low energy region relevant!



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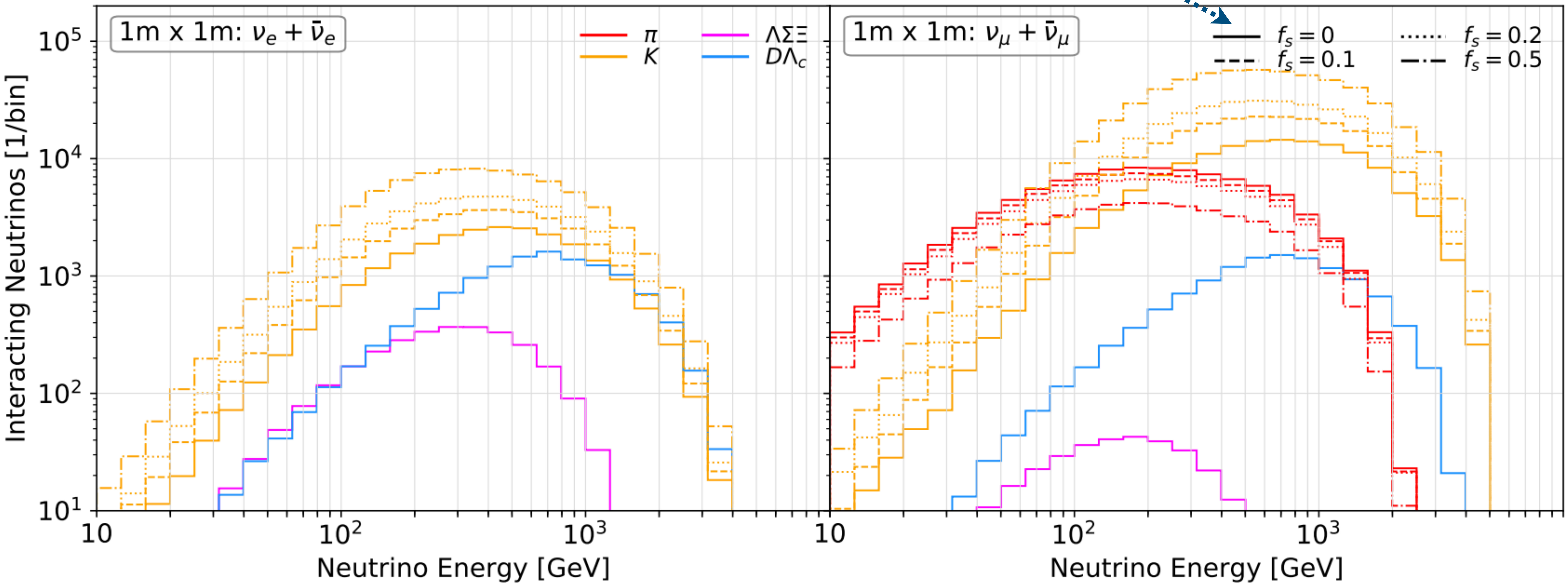
WG3 Science Topics I

- Neutrino fluxes at FLArE: amount of K/π swap



- Example: strangeness enhancement (K/π swap) toy model (baseline: Sibyll 2.3d)

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[L. Anchordoqui et al., JHEAp 34 (2022)]

WG3 Plans

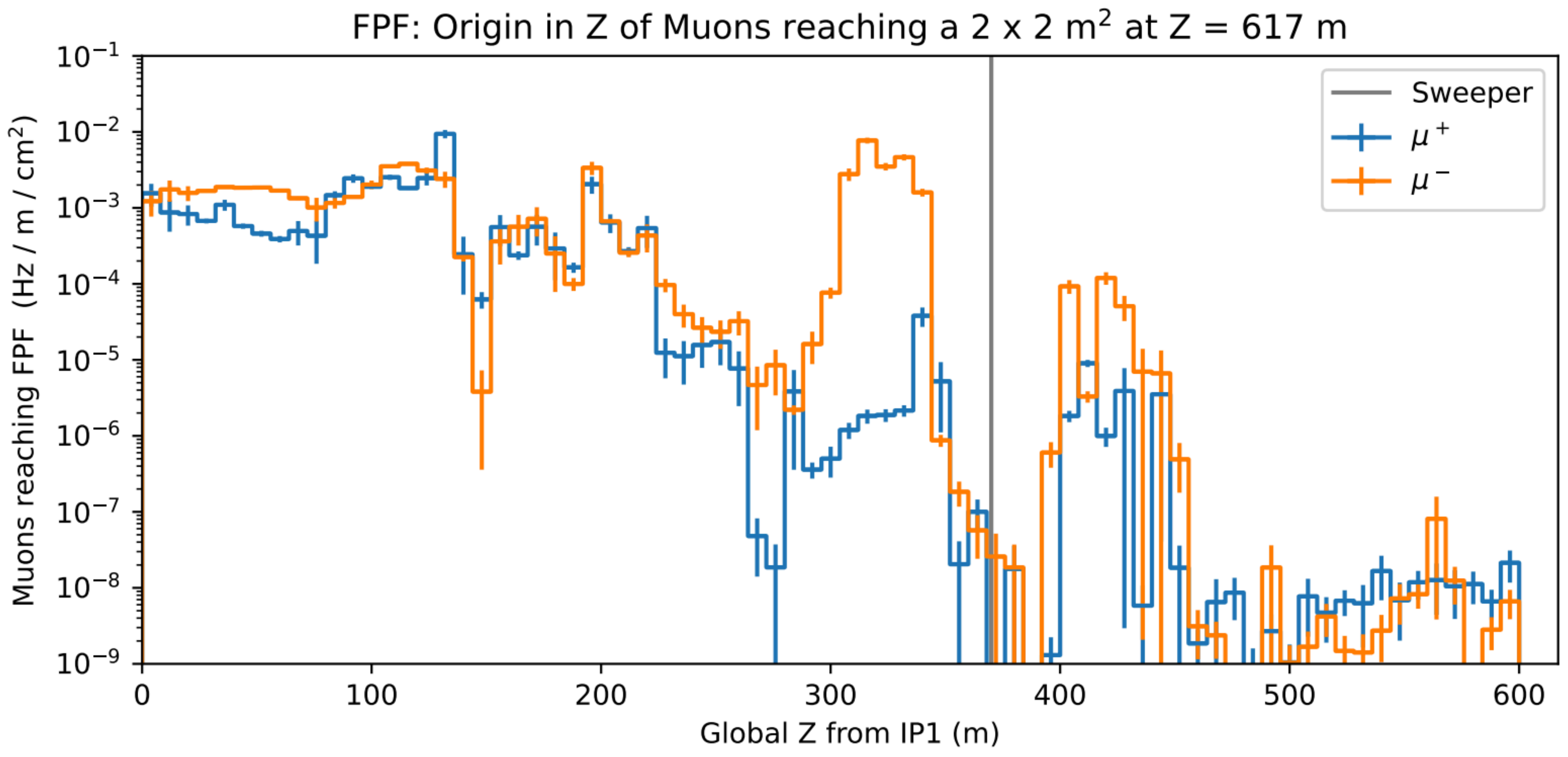
- Comprehensive MC library of event generators / models to be tested:
  - PYTHIA
    - Monash tune
    - Forward physics tune
  - HERWIG/SHERPA
  - DIPSY
  - DPMJet
    - DPMJet-II
    - DPMJet-III
  - QGSJet
    - QGSJet-II.04
    - QGSJet-III (?)
  - EPOS
    - EPOS-LHC
    - EPOS-LHCr (?)
    - ~~EPOS 3~~
    - EPOS 4 (?)
  - Sibyll
    - Sibyll-2.1
    - Sibyll-2.3
      - ρ^0-enhancement
      - Baryon enhancement
      - pi-K swap model
      - Manshanden-Sigl-Garzelli model

WG3 Plans

- Current status:
  - We're in the process of contacting all model authors at the moment
  - Production of comprehensive MC library (partially) in progress
  - WG3 report to be prepared:
    - Detailed model comparisons
      - Energy spectra
      - Rapidity spectra
      - K/pi ratios (?)
      - More..?
    - Recommendations / benchmark models for FPF science
    - Discussion: How to treat model uncertainties for FPF measurements?
  - This effort needs some coordination with WG2 (e.g. some models include charm)

WG3 Science Topics II

- Muon fluxes at the FPF:
  - Large muon flux at the FPF, e.g. ~1 Hz per cm^2 in FASER
  - Challenging to study as the origin of production is uncertain…
  - BDSIM/Geant4 simulations available, including full muon history (L. Nevay)
  - Open questions:
    - Can we use muons to study light hadron production?
    - Can we measure the muon charge ratio?
    - Can we measure muon cross-sections?
    - What can we learn from muon fluxes measured at FASER and SND@LHC?
  - Dedicated studies of the muon yield at the FPF (incl. full muon history) needed!



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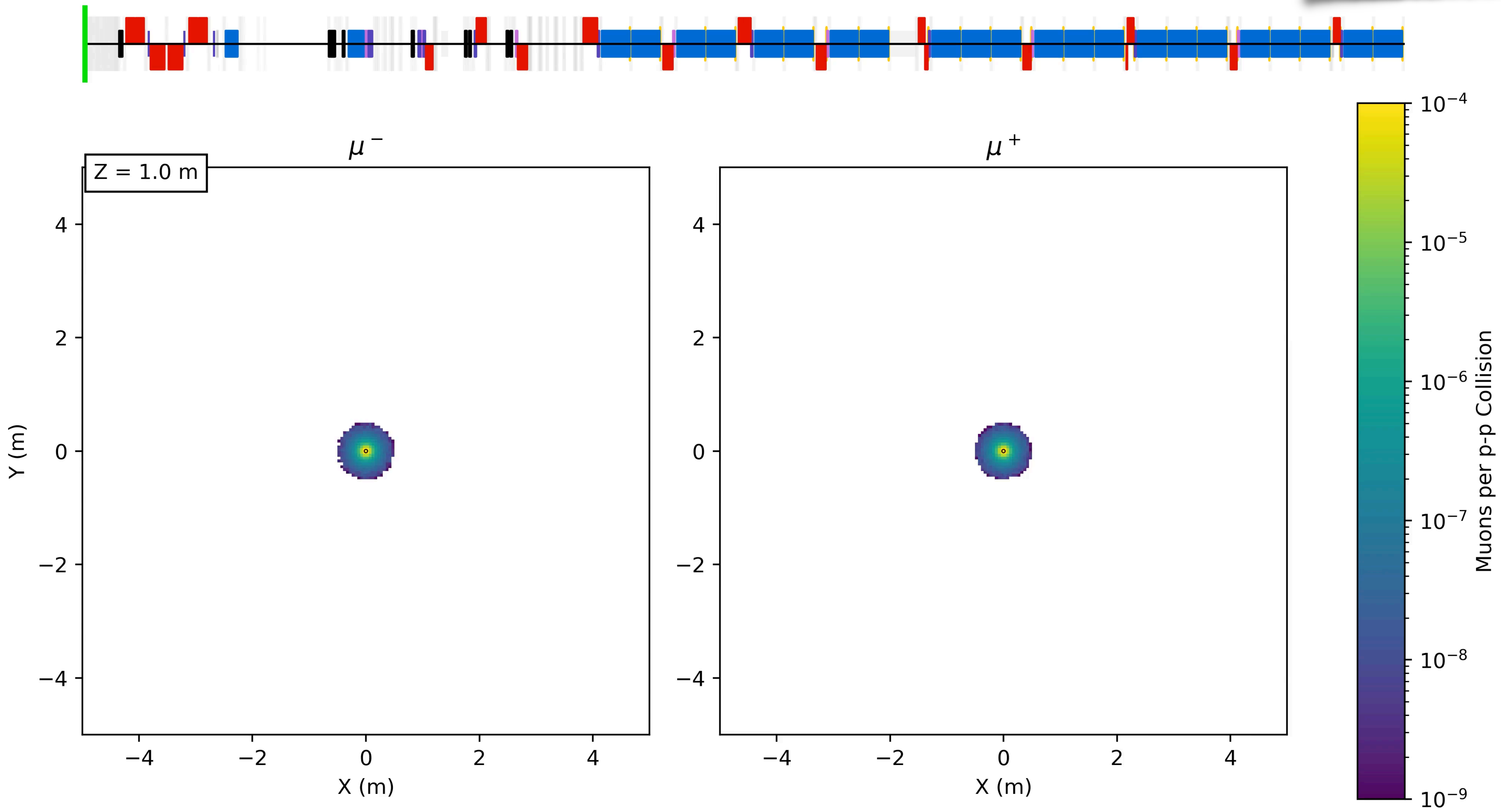
- Muon fluxes at the FPF:

Credit: L. Nevay



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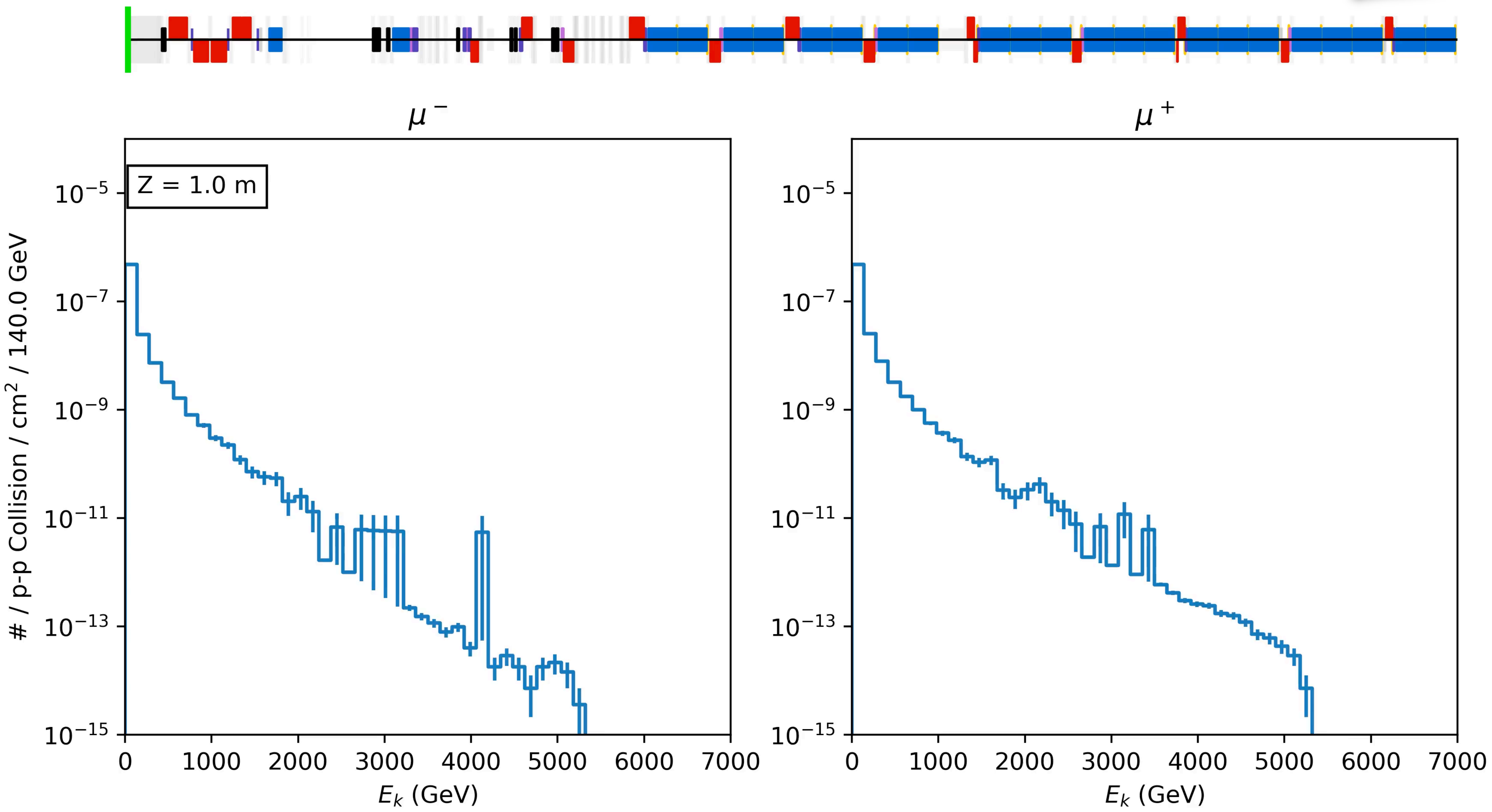

Summary & Discussion

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  - Ratio of electron and muon neutrinos is a proxy for the ratio of charged pions and kaons
    - Particle ID needed, e.g. $\nu_e + \bar{\nu}_e$ vs. $\nu_\mu + \bar{\nu}_\mu$ ← requirement
  - Electron and muon neutrino fluxes populate different energy regions which will help to disentangle them
    - Energy spectrum ← best possible resolution
  - Neutrinos from pion and kaon decays have different rapidity distributions which will help to disentangle them
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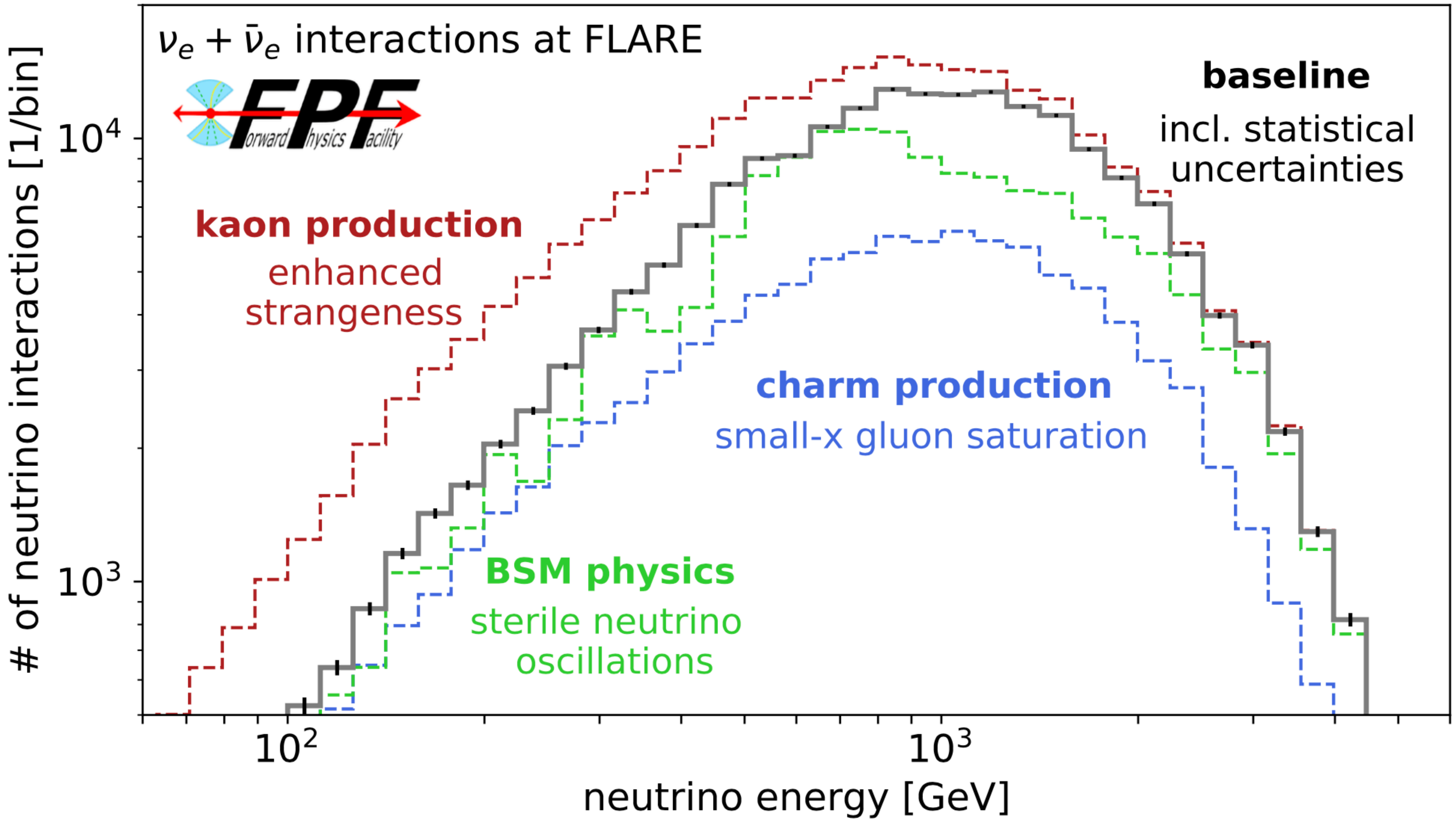
Thanks!

Forward Physics Facility

WG3 Science Topics I



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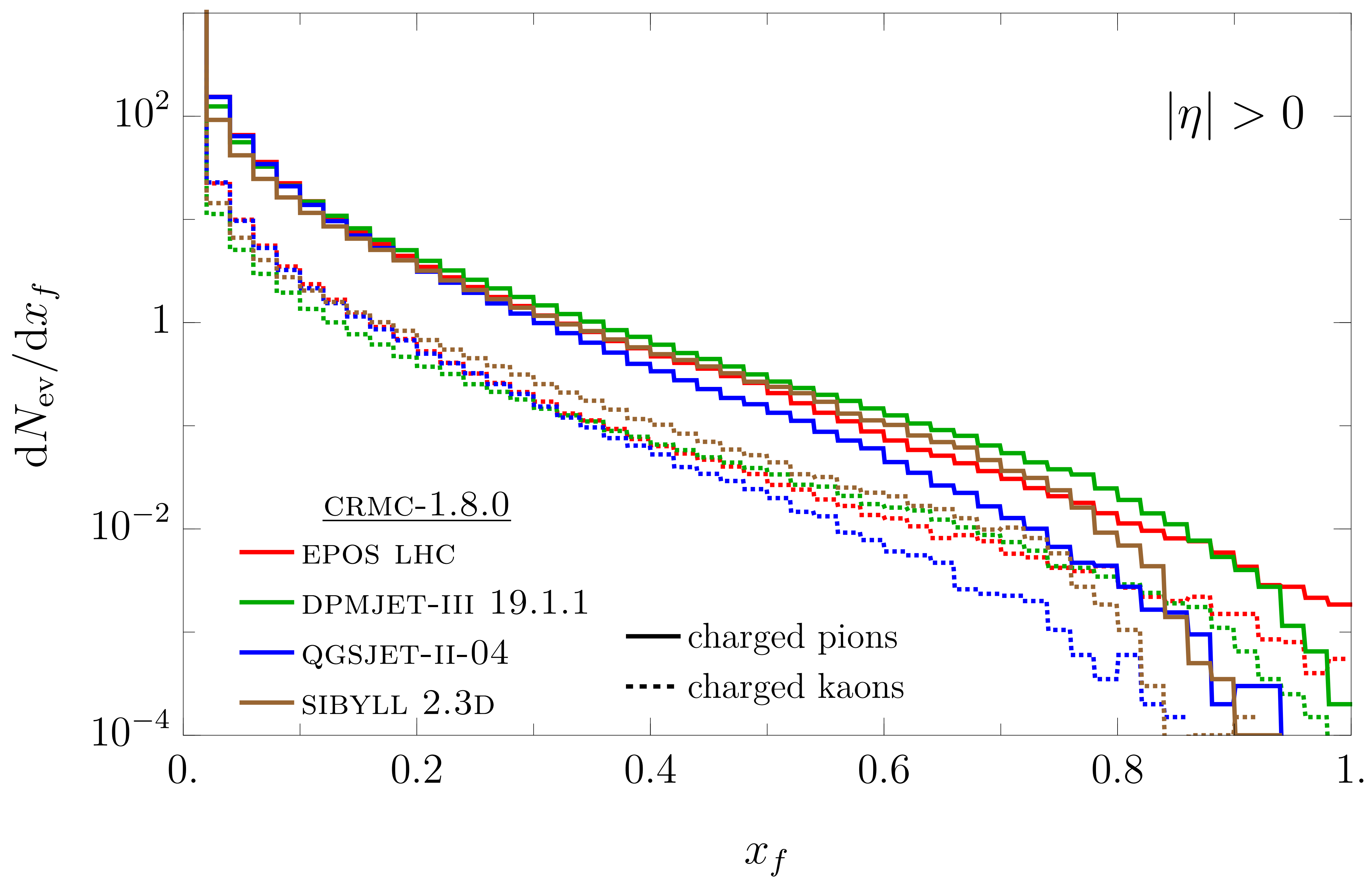

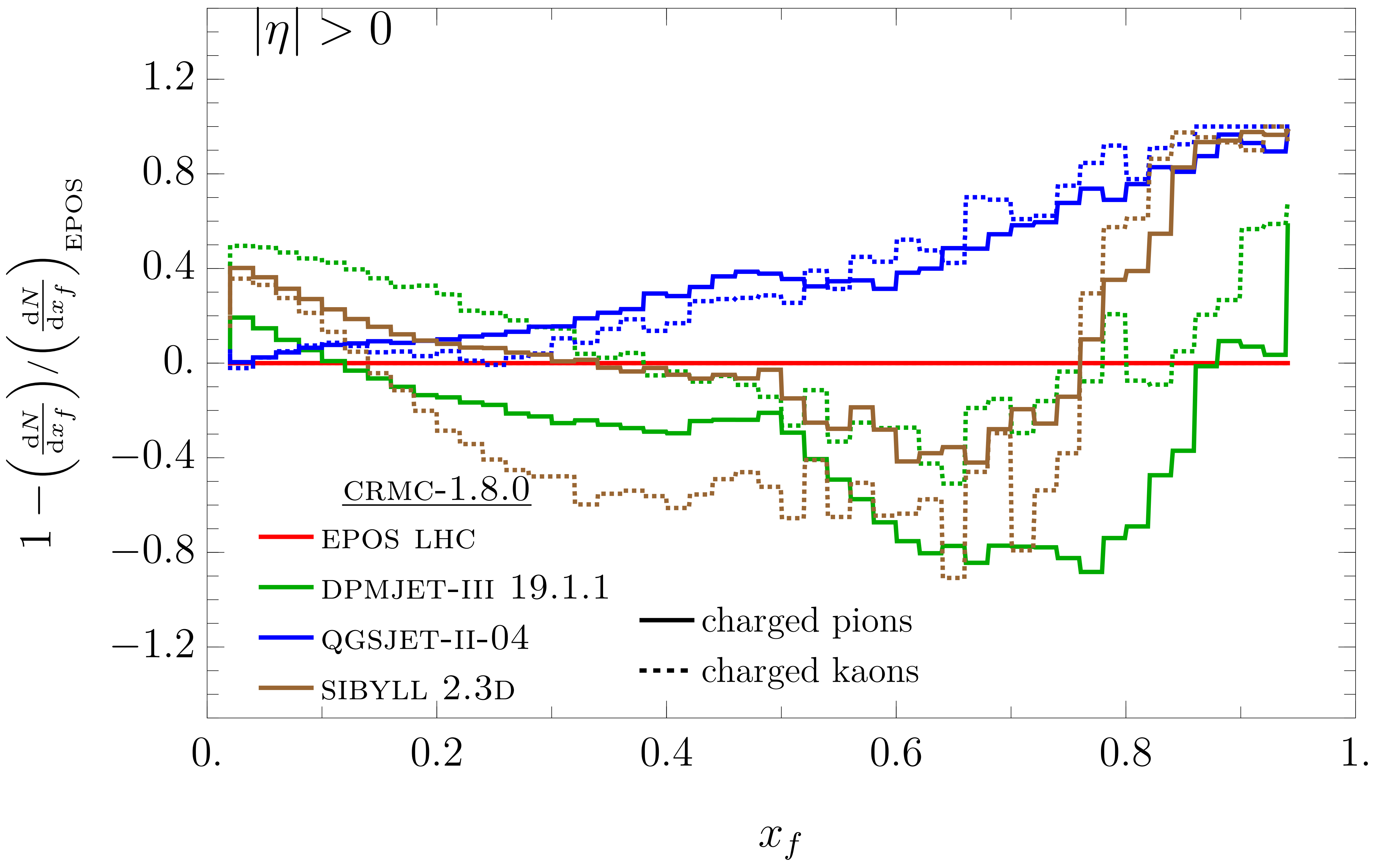

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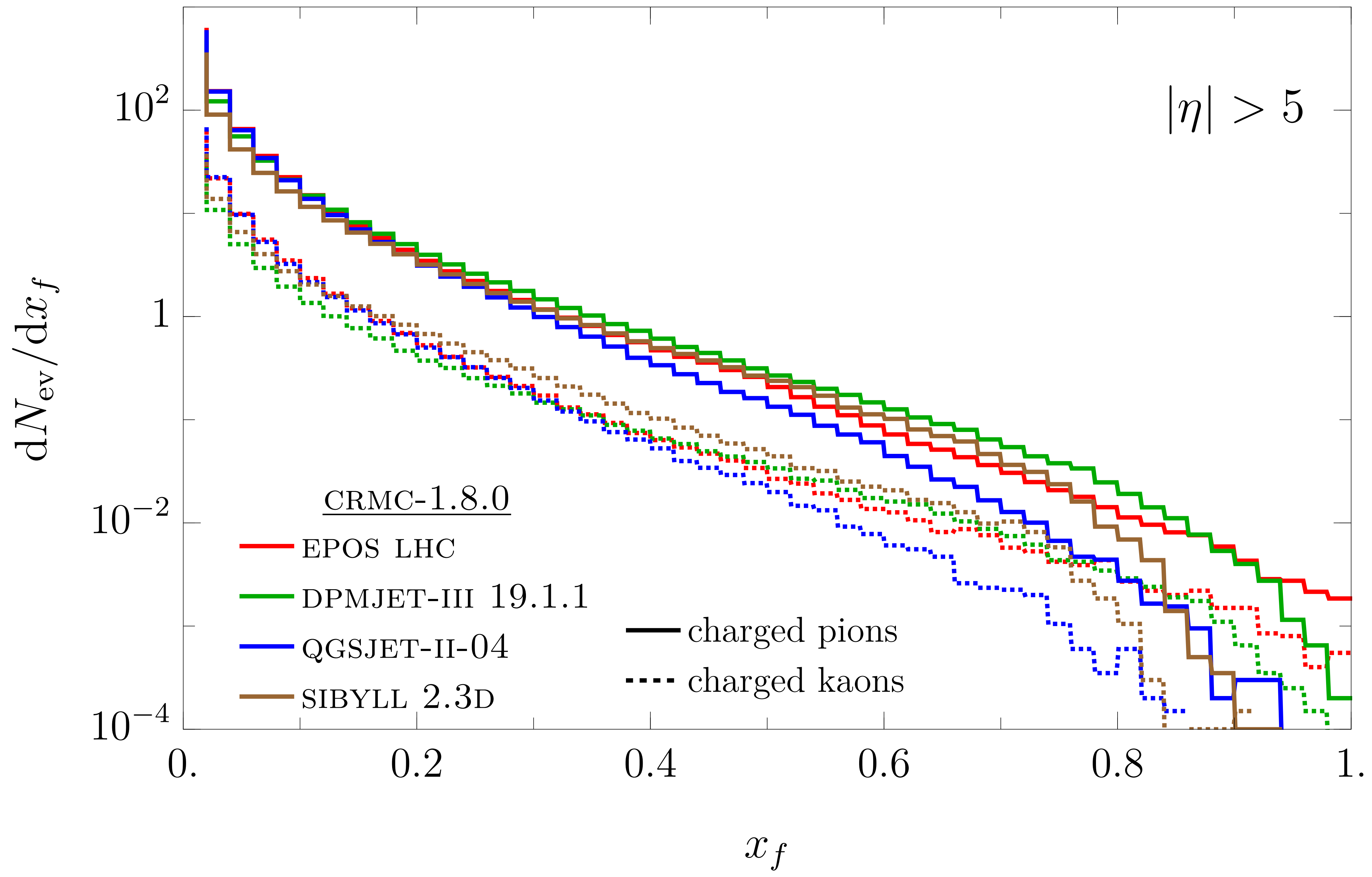

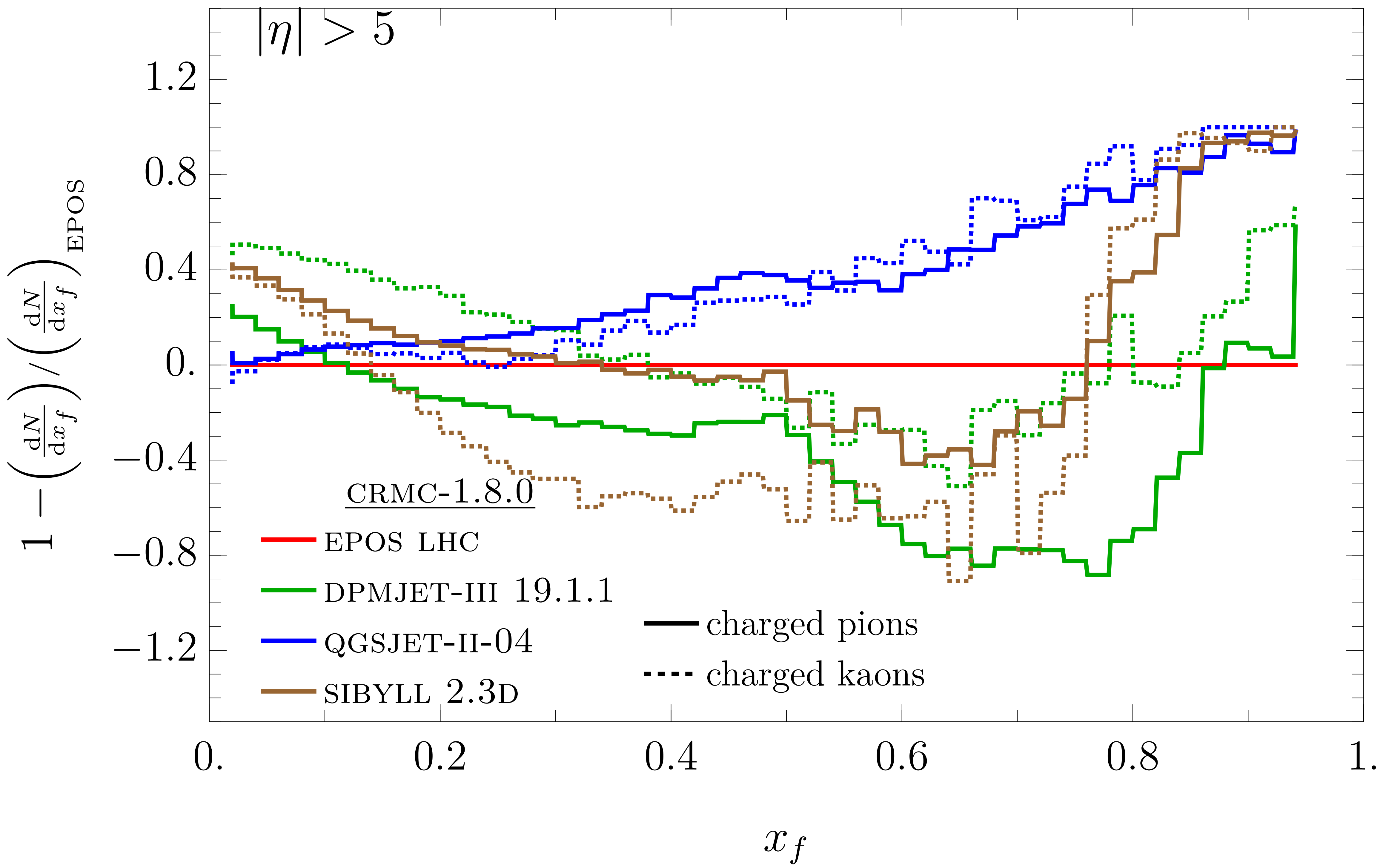

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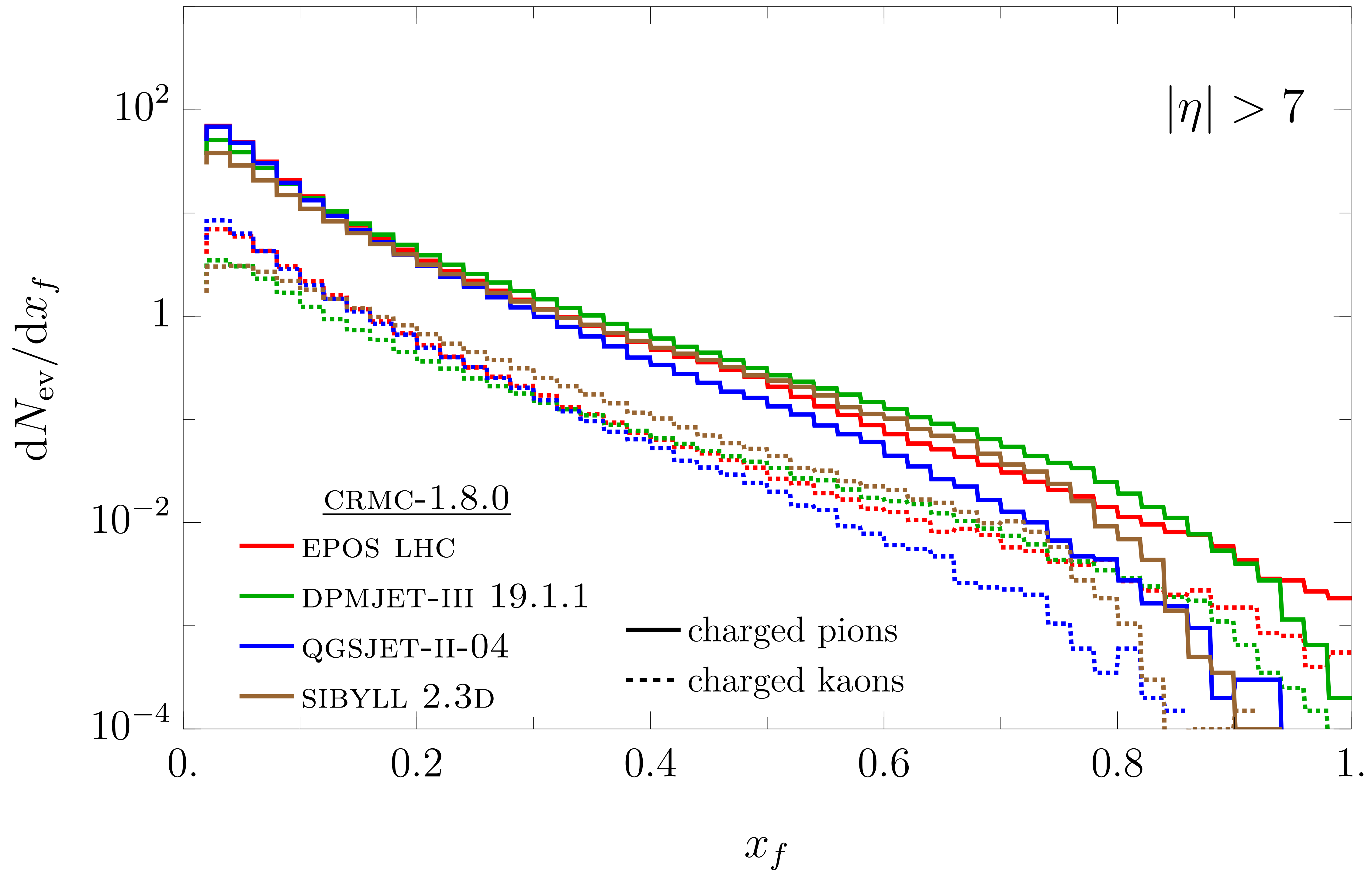

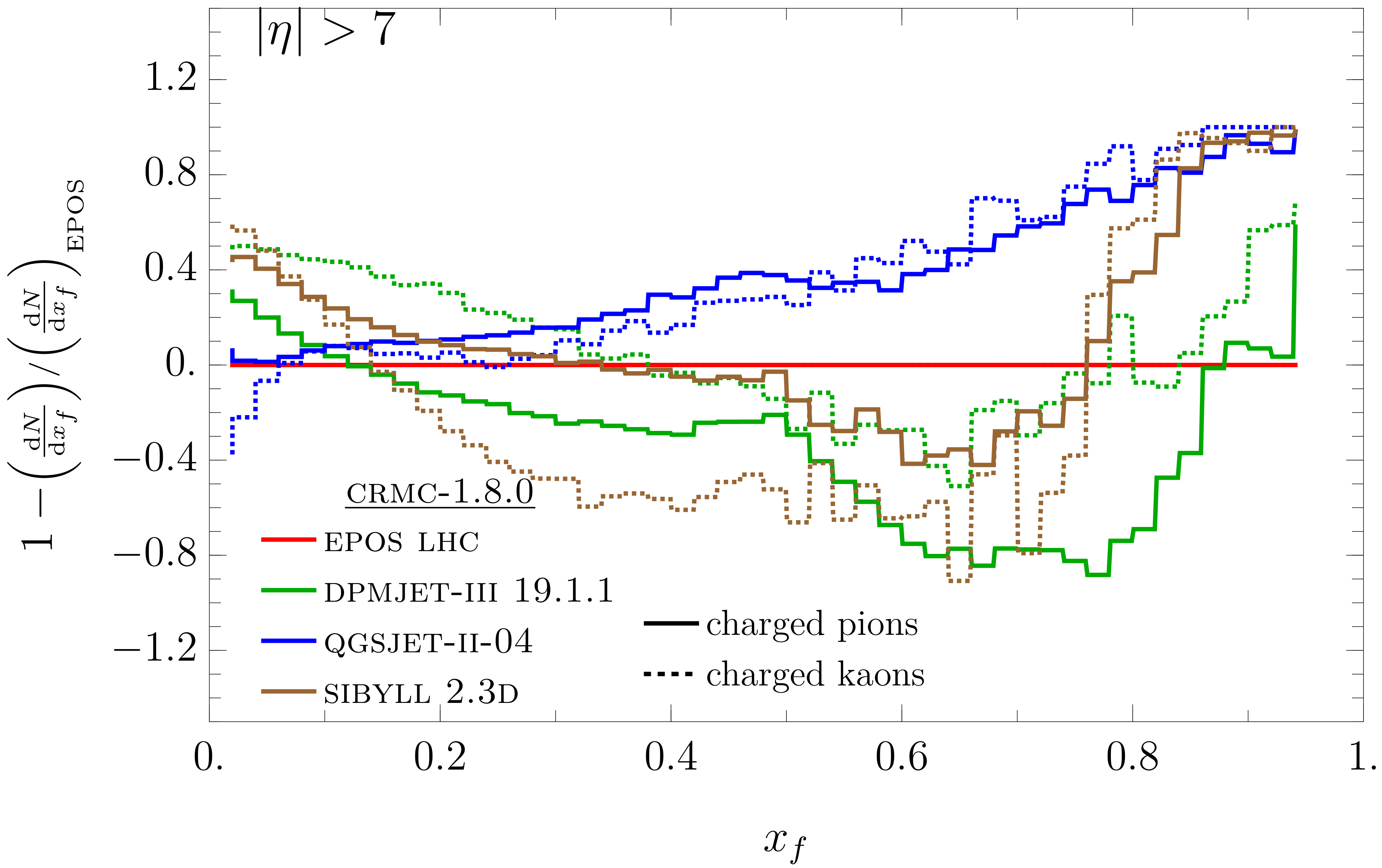

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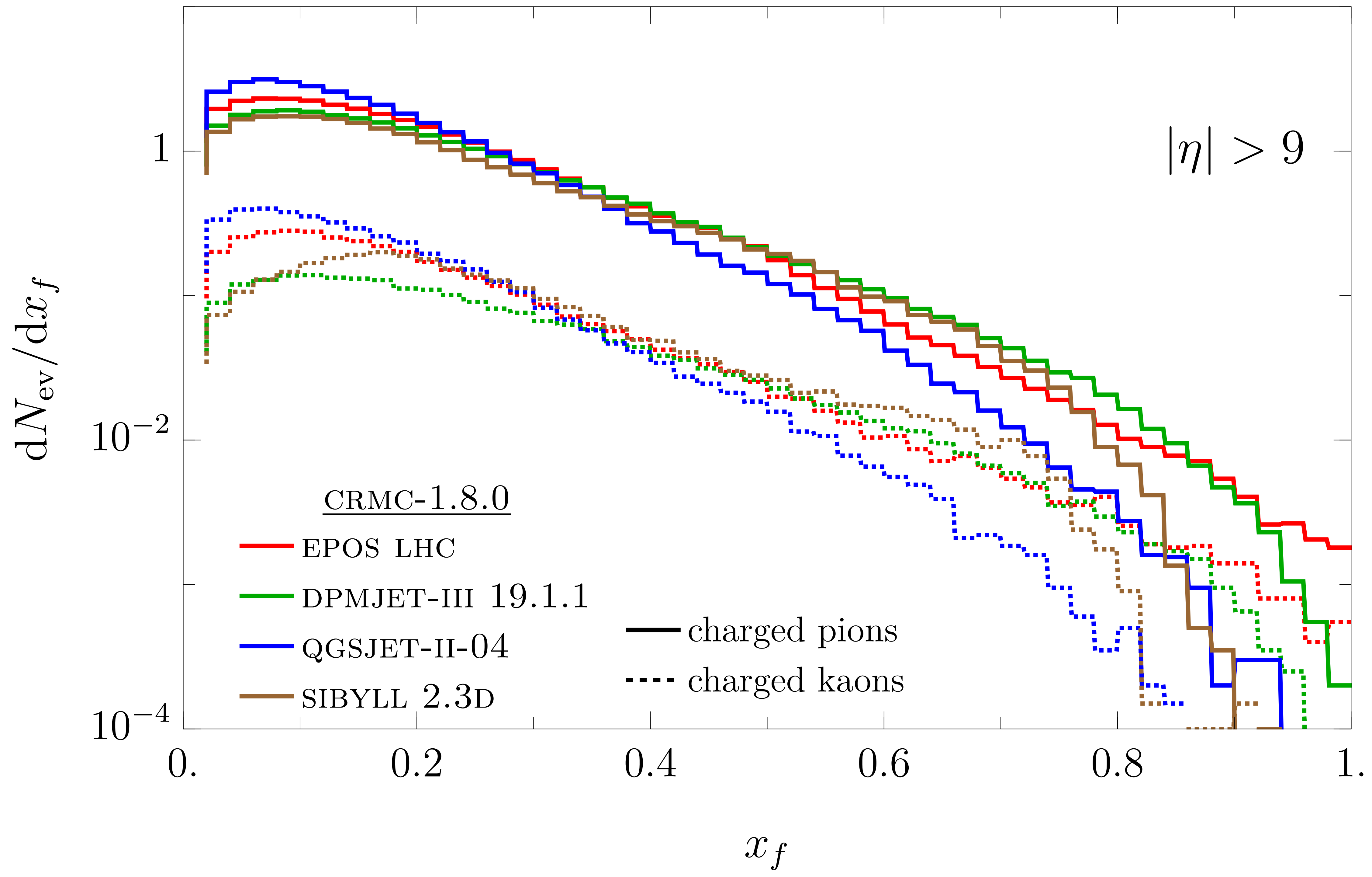
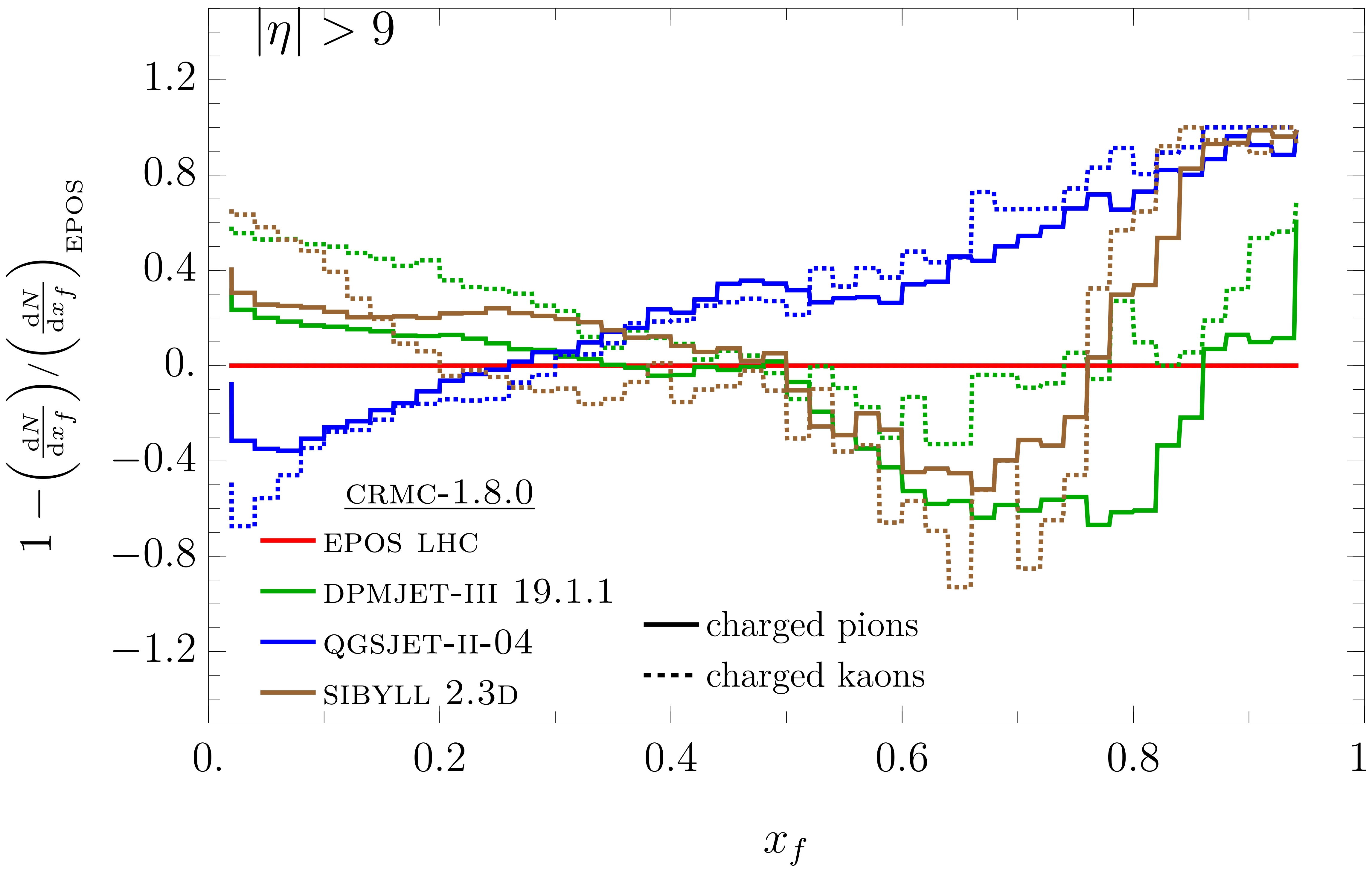
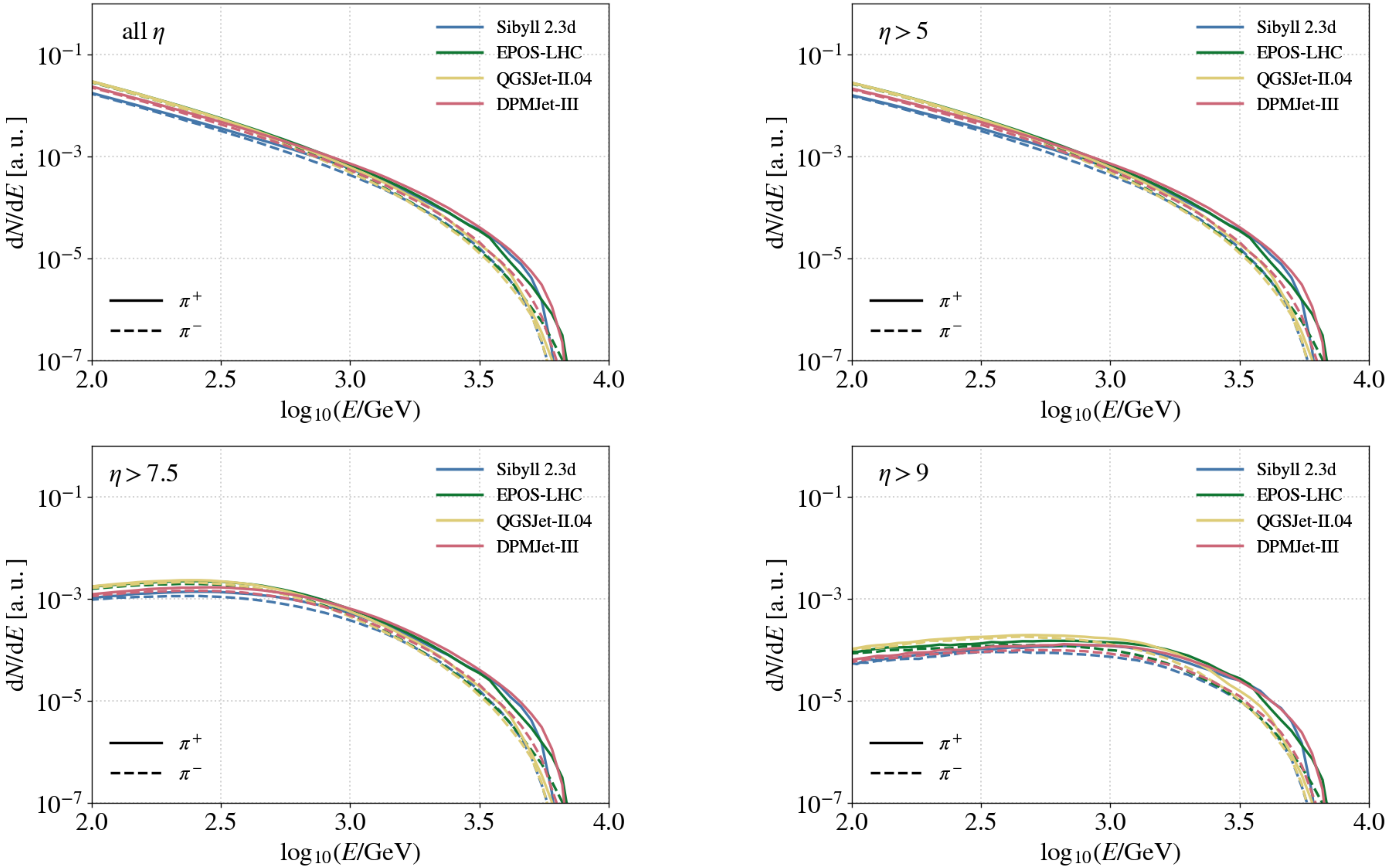




Energy (Charged Pions)

Many thanks to J. Soriano & F. Riehn!



Model Ratios (Charged Pions)

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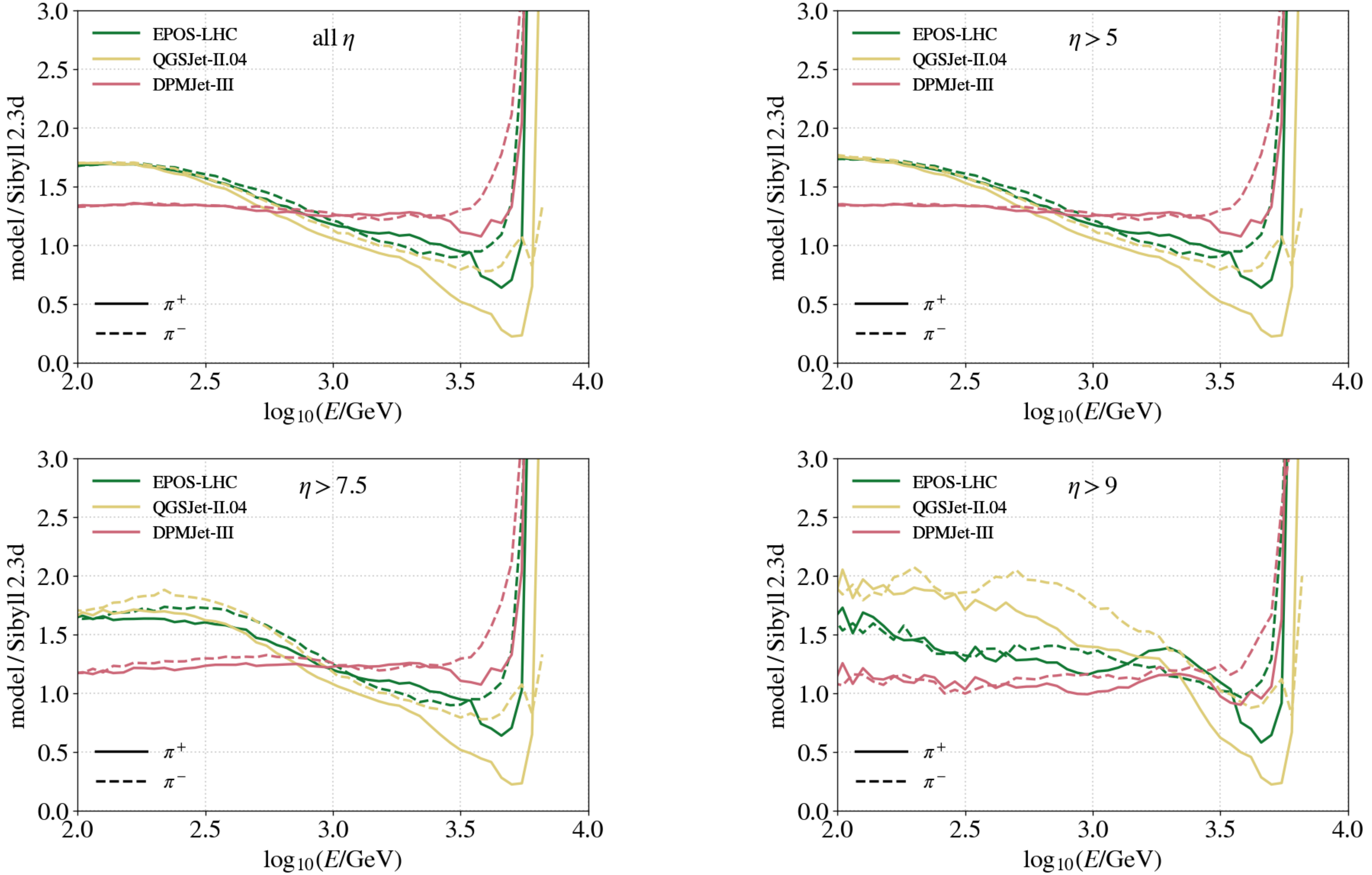

Energy (Charged Kaons)

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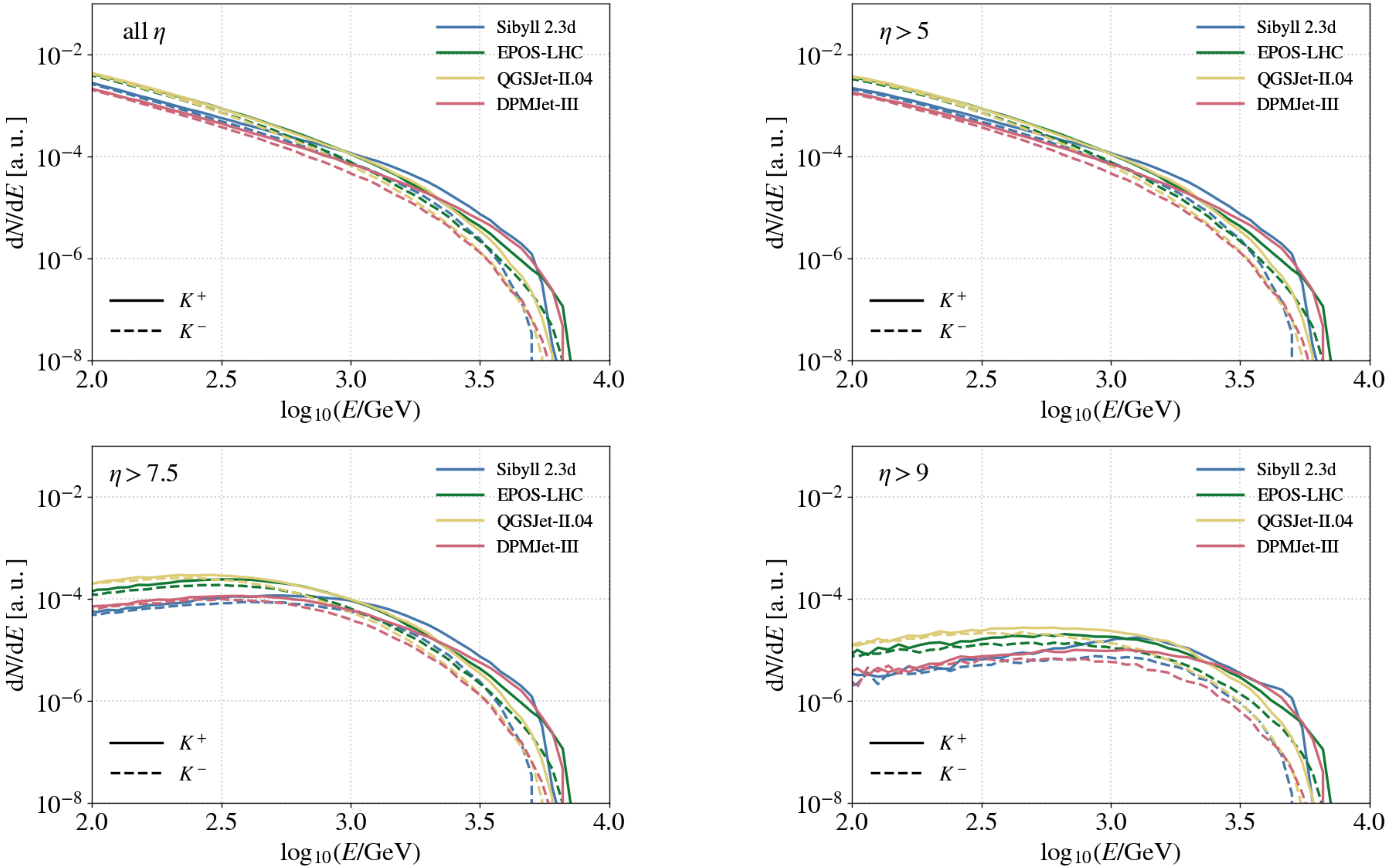

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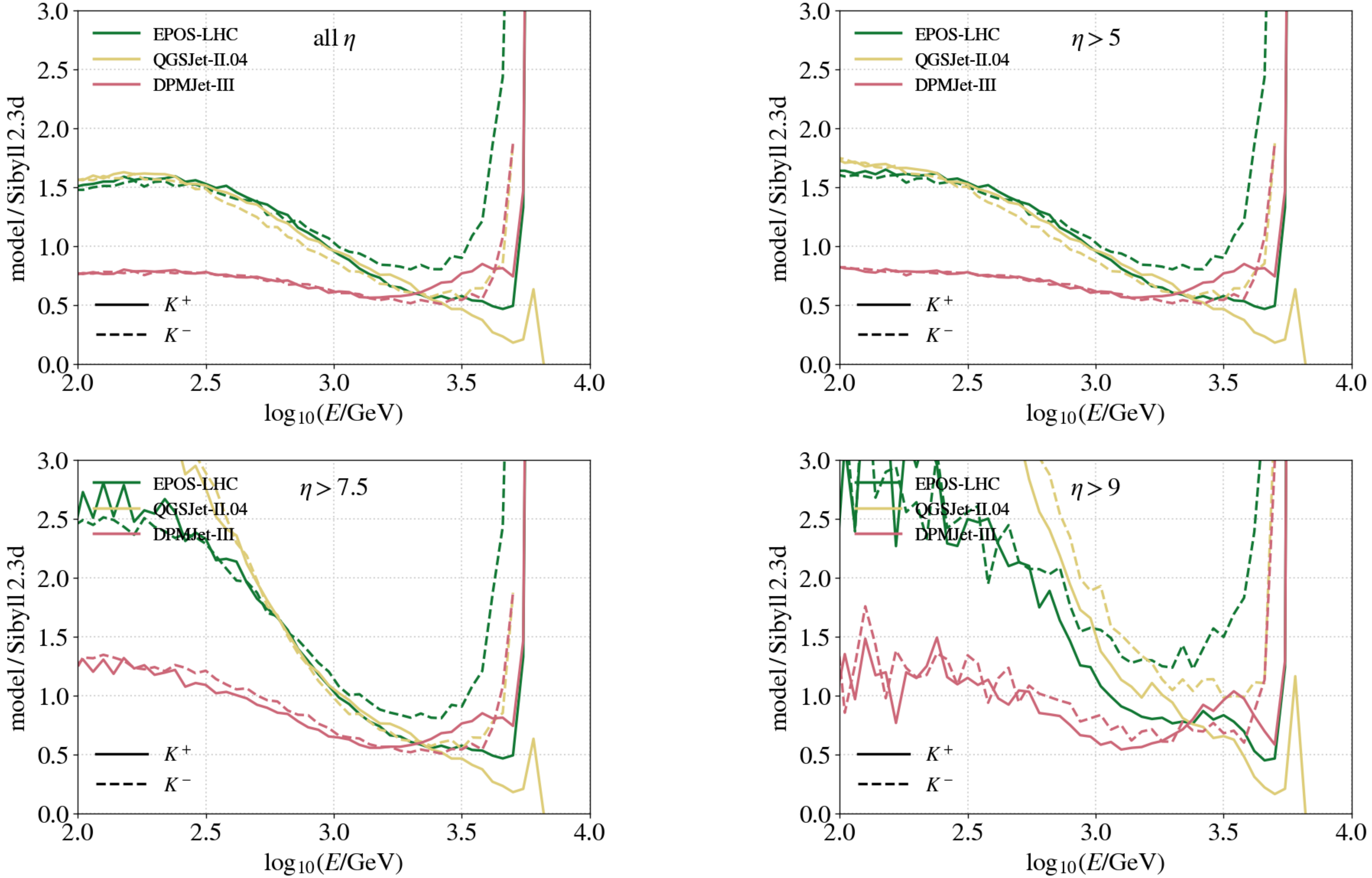

Feynman-x (Charged Pions)

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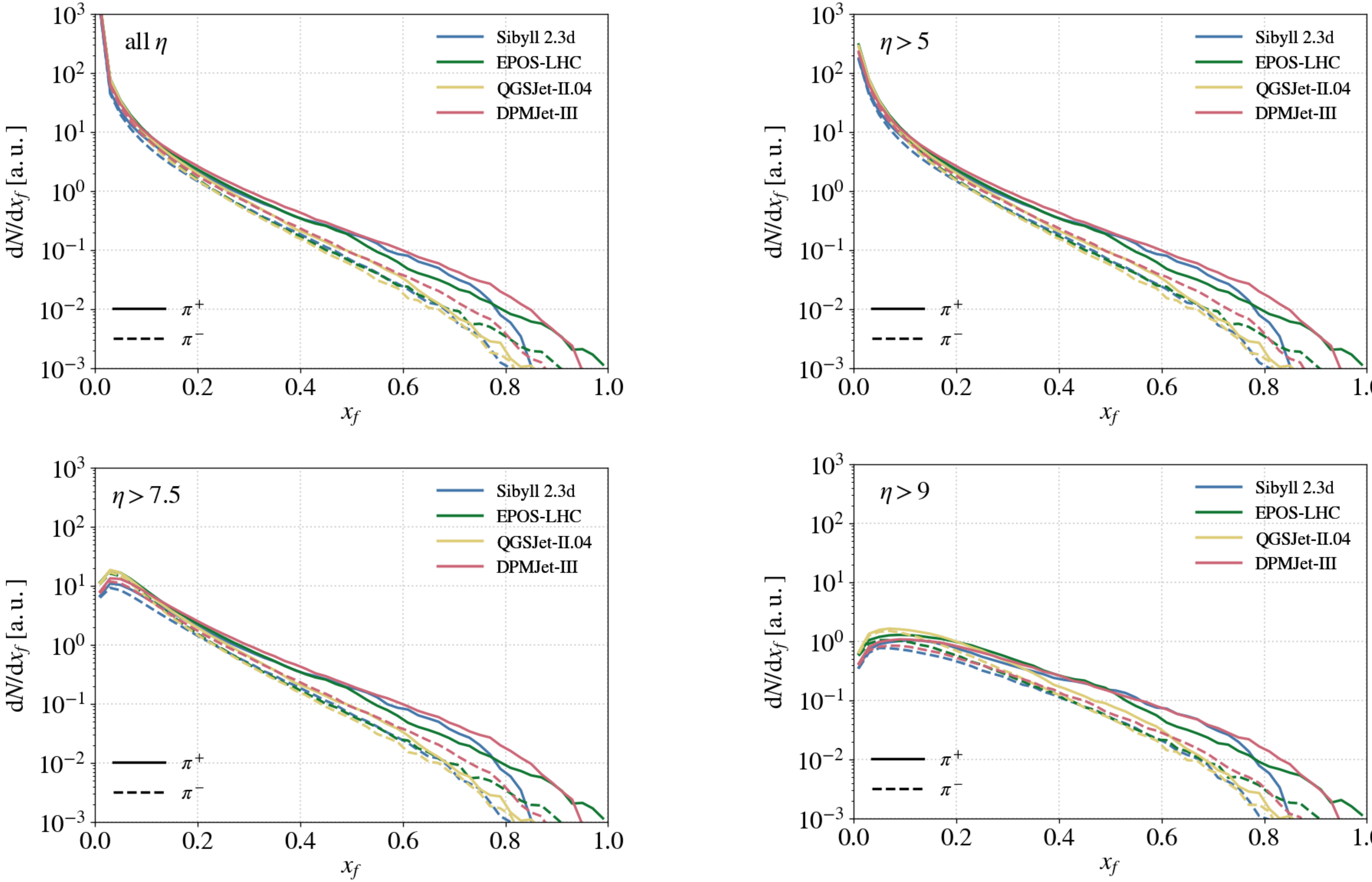

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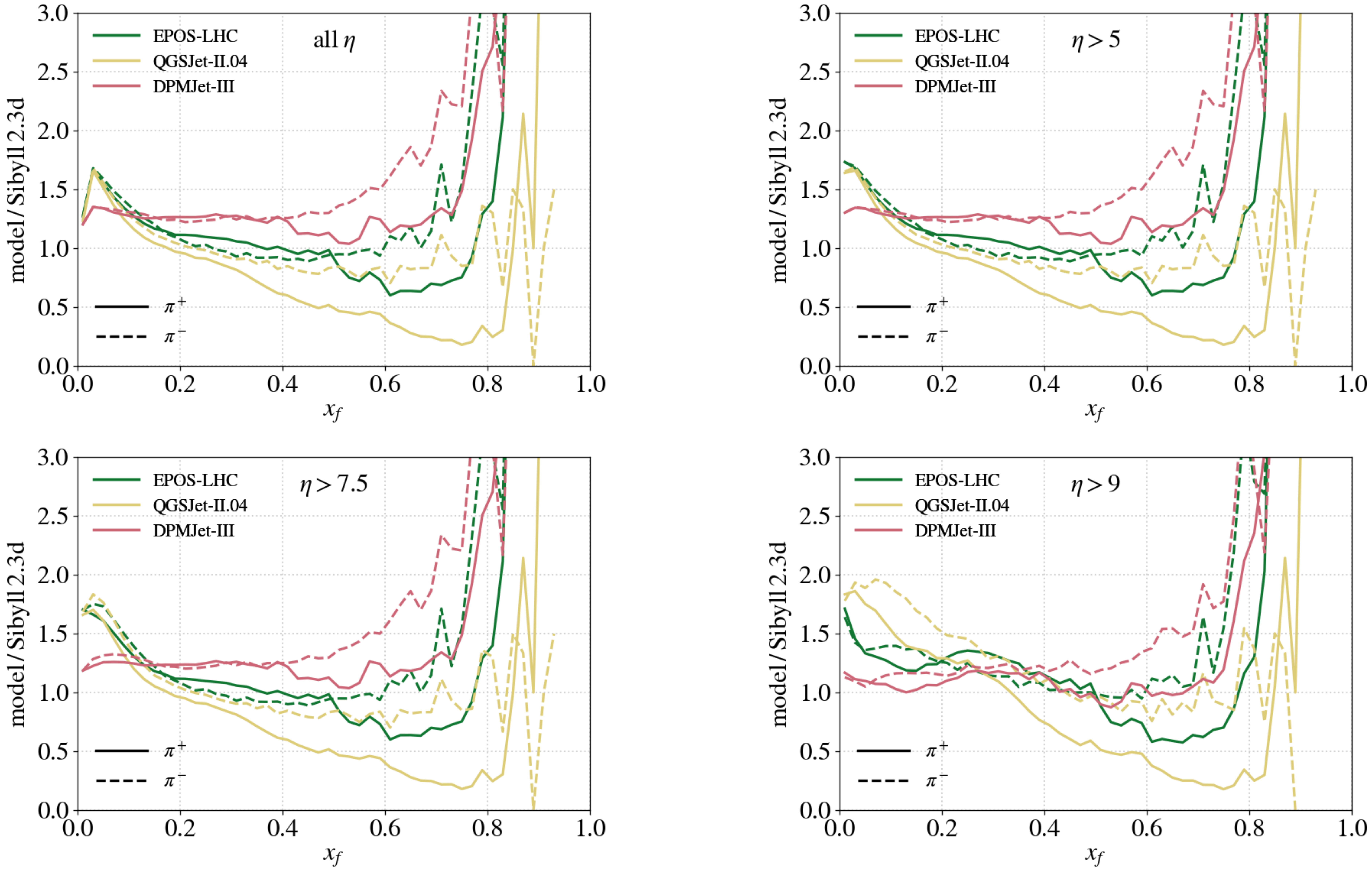

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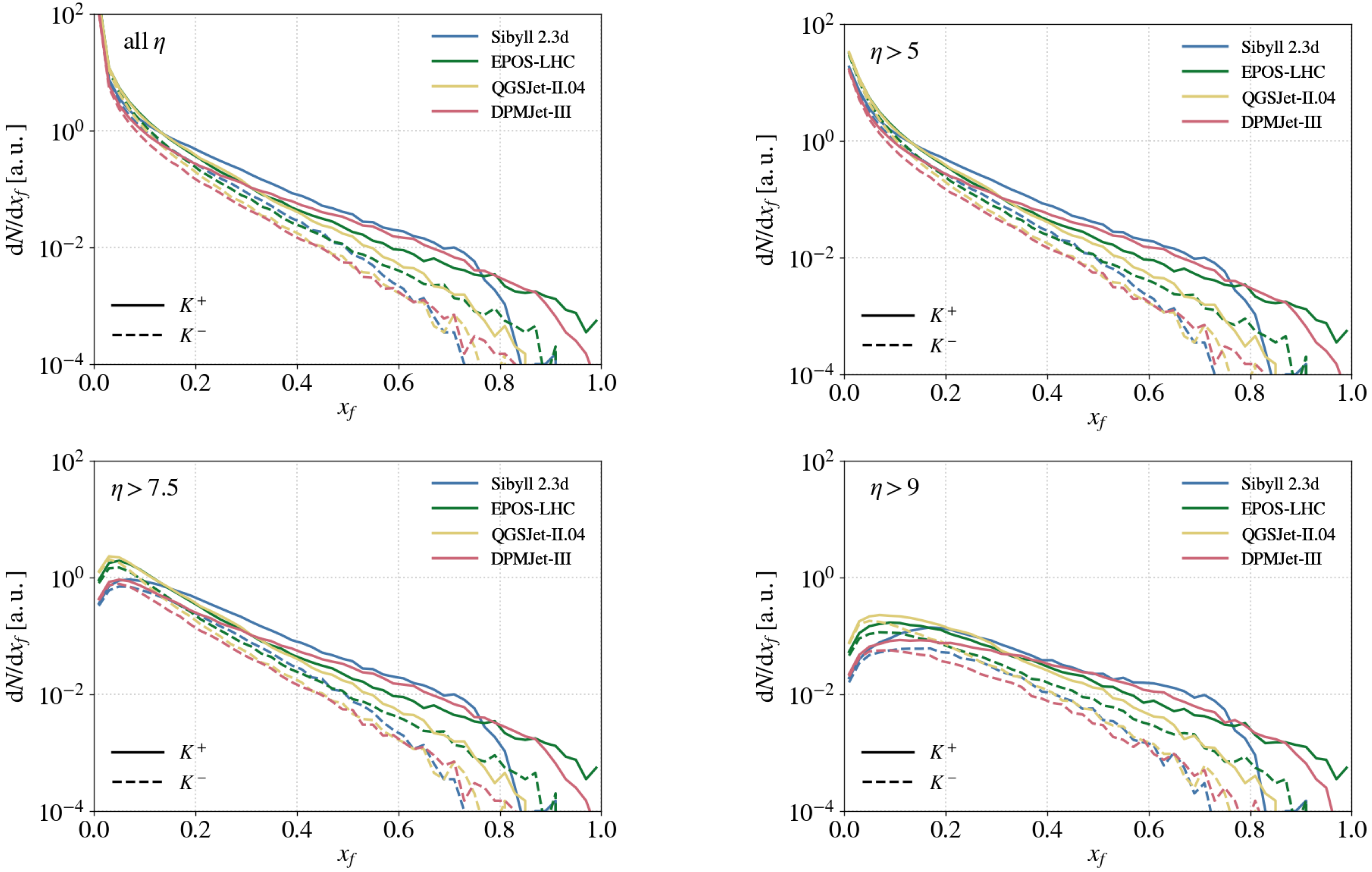

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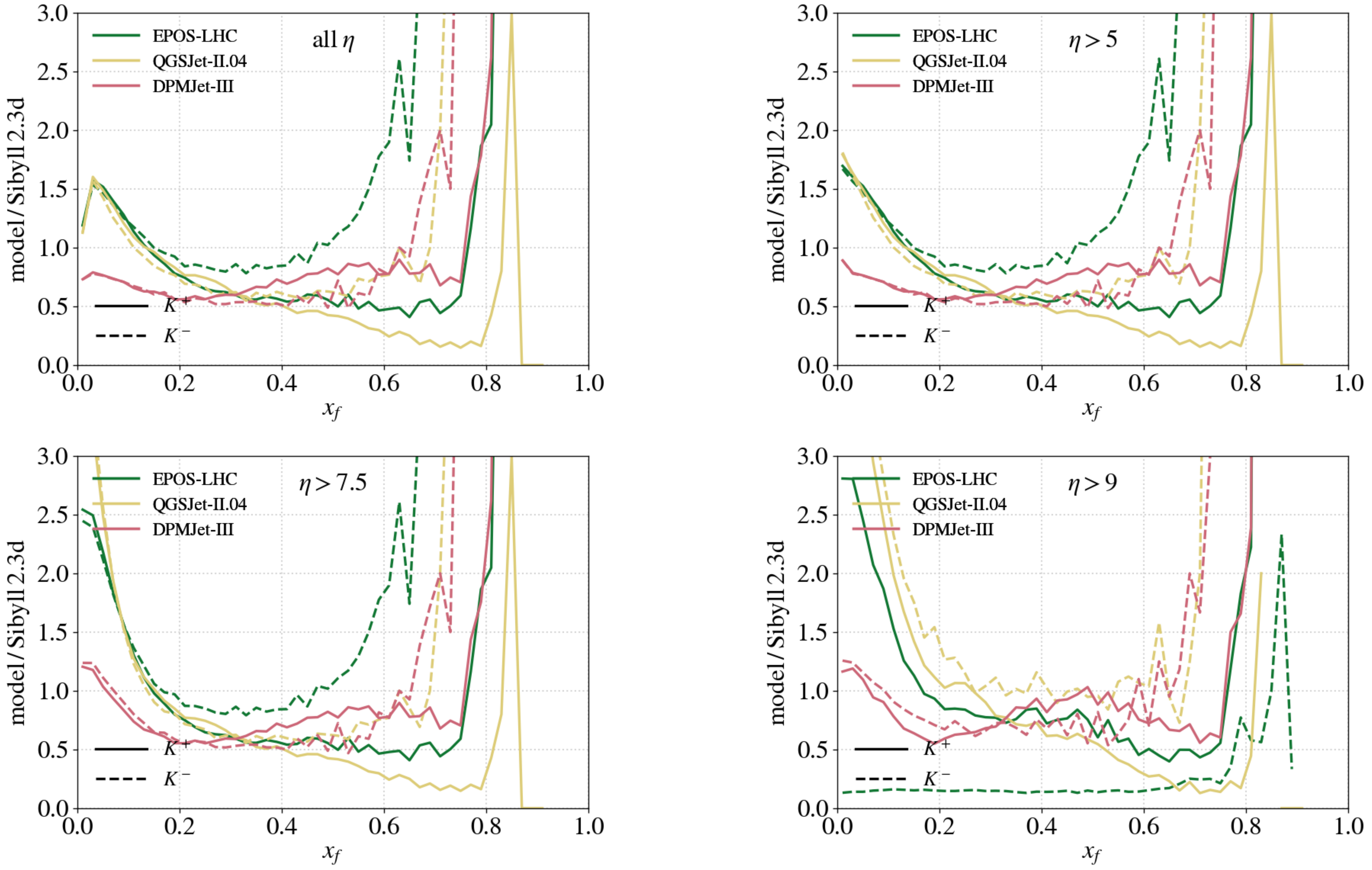
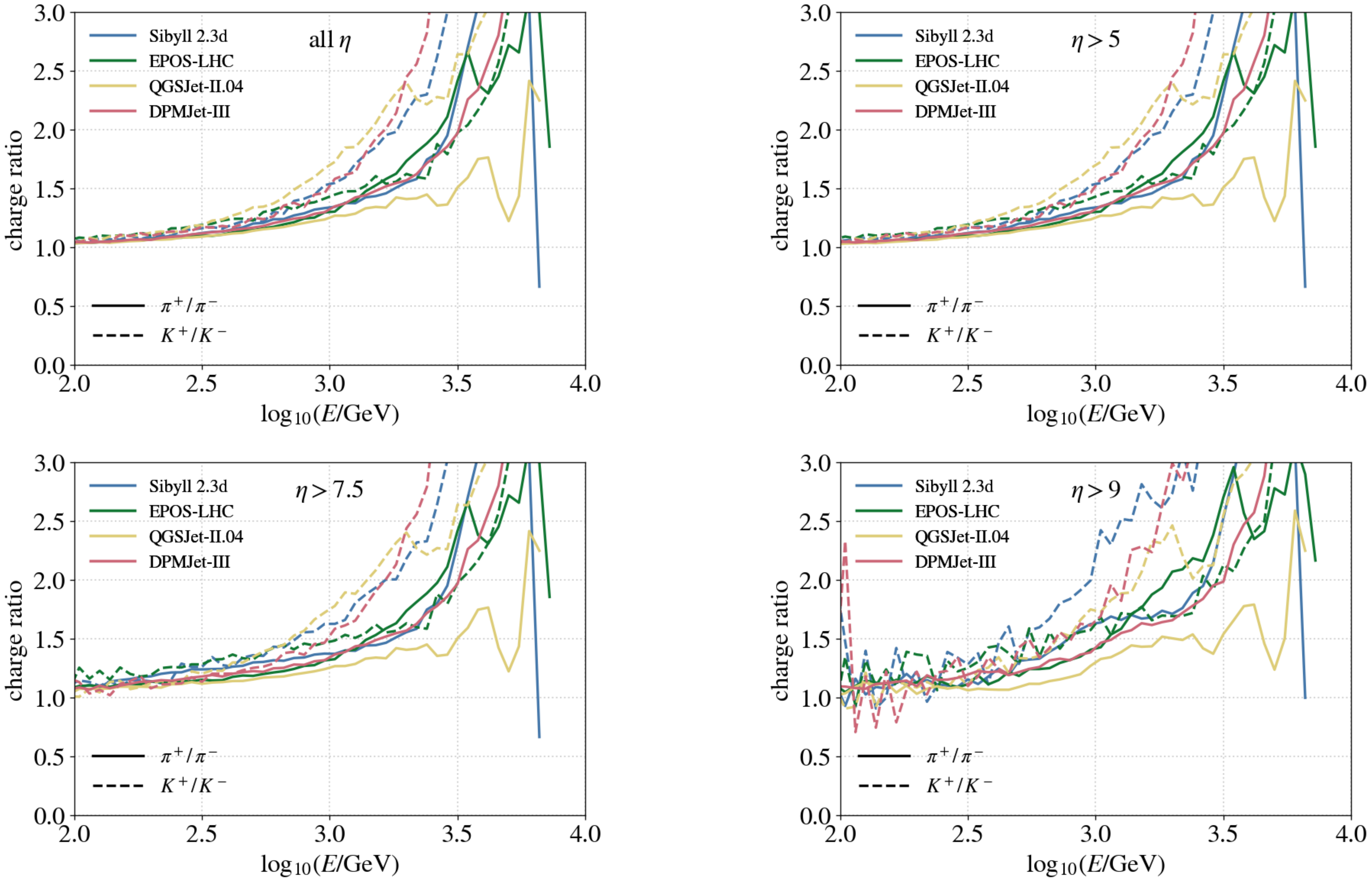
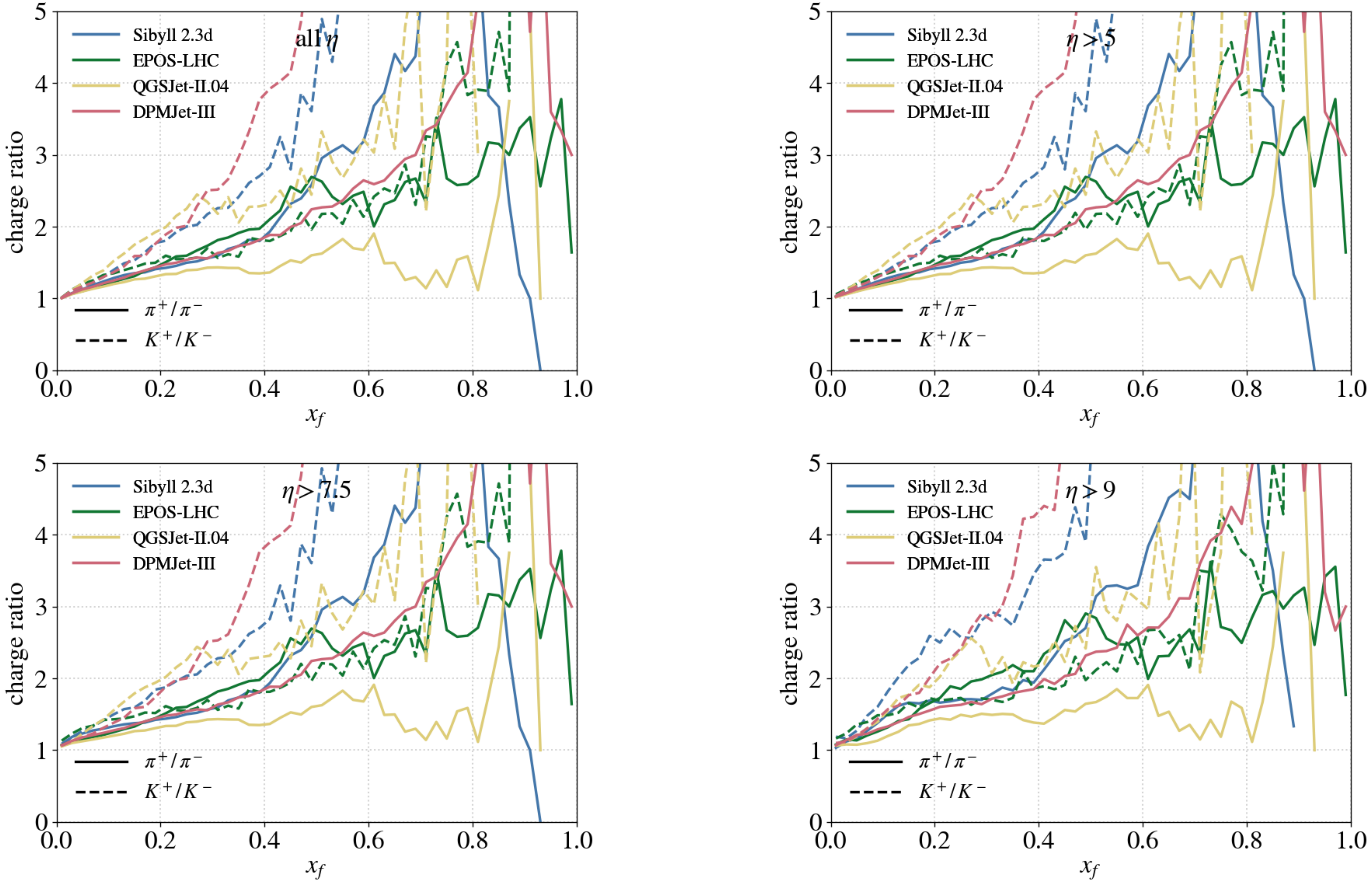


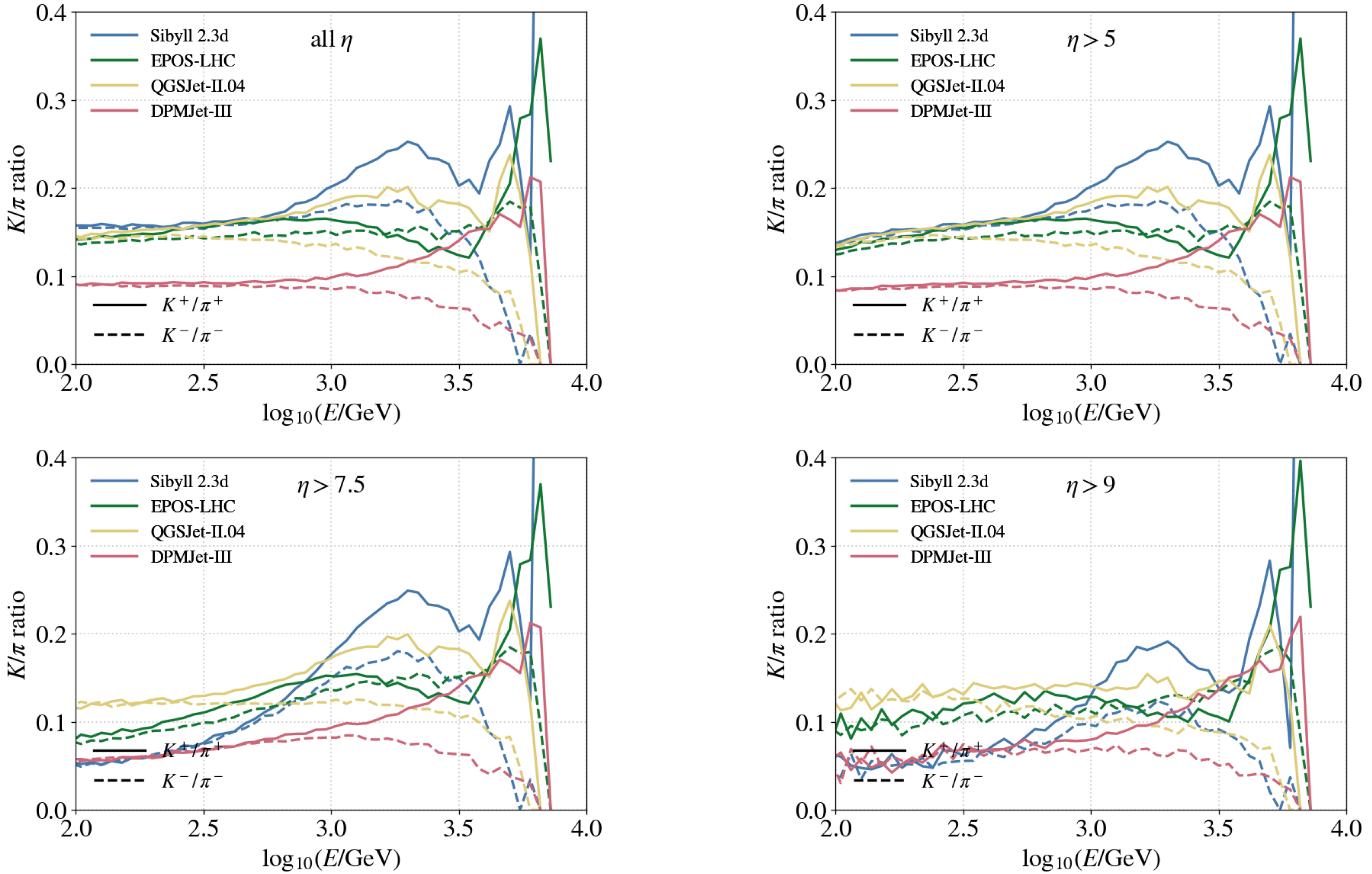
Charge Ratios vs. Energy



Charge Ratios vs. Feynman-x



K/π Ratios vs. Energy



K/π Ratios vs. Feynman-x