Investigating muon content in extensive air showers using Pythia 8

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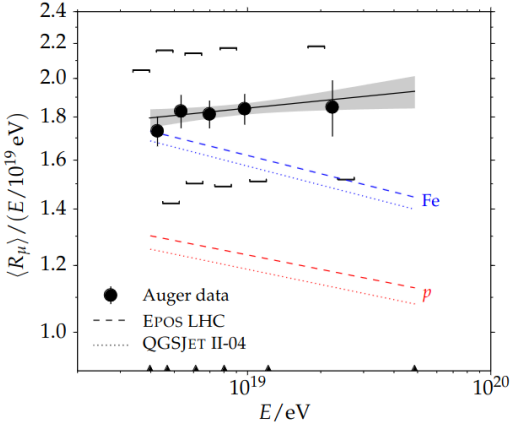
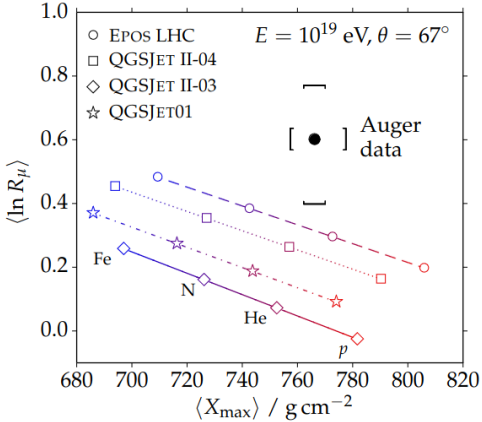
German Research Foundation

Muon puzzle: significant muon discrepancy between air shower simulations and experimental measurements from the TeV scale, increasing with energy





Phys. Rev. D 91, 032003 (2015)

Pythia 8

- general purpose hadronic interaction model
- well-tailored for LHC experiments
  - ↳ good description of e^+e^-, pp, $\bar{p}p$, pPb and PbPb interactions

Incomplete data description

- strangeness enhancement and ridge effect at high multiplicity
- baryon enhancement in charm and bottom production
- forward particle spectra

Limitations for air shower applications

- only for high-energy interactions
- initialized for fixed energy and beam
- only $e^{\pm}$,$\mu^{\pm}$,p,$\bar{p}$,n,$\bar{n}$ beams (not hA or AA!)

↓

need for nuclear interaction extension

Pythia 8.3.07+

`PythiaCascade` wrapper class

- ↳ simplified model unrelated to Angantyr
- ↳ fixed-target hA collisions and decays
- ↳ $E^{\text{hadron}}_{\text{kin, min}} = 0.2\,\text{GeV}$

Angantyr model

- nuclear geometry given by Glauber model
- stack individual nucleon-nucleon sub-collisions and hadronize them together

Pythia 8.3.12

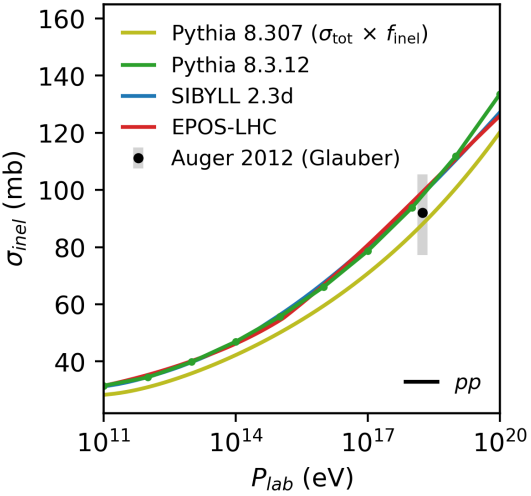
Angantyr model update

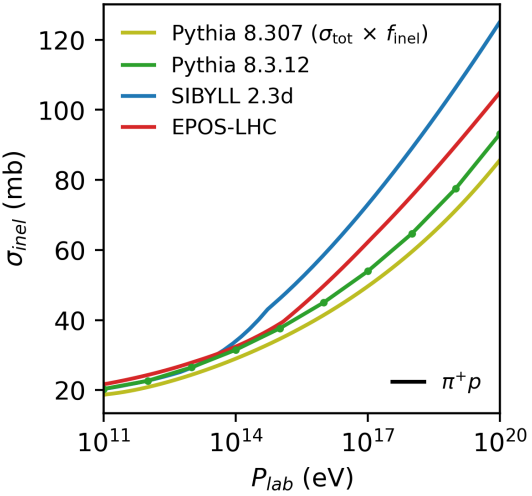
- ↳ variable energy and beam on an event-by-event basis

↓

tabulate σ_{tot} and σ_{inel} for combination of (projectile, target, $E_{lab} \leftrightarrow E_{CM}$)

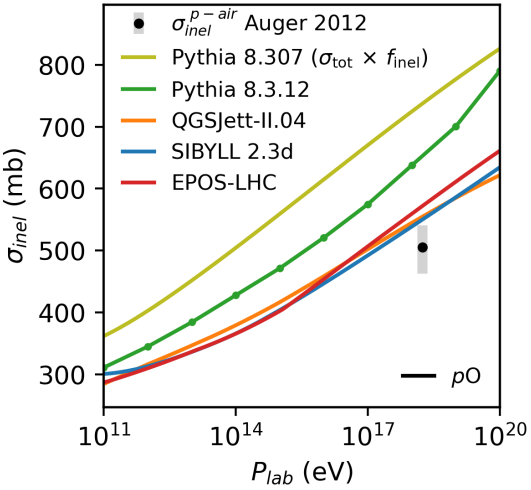
σ_{inel} of (p, p) and (π^+, p)

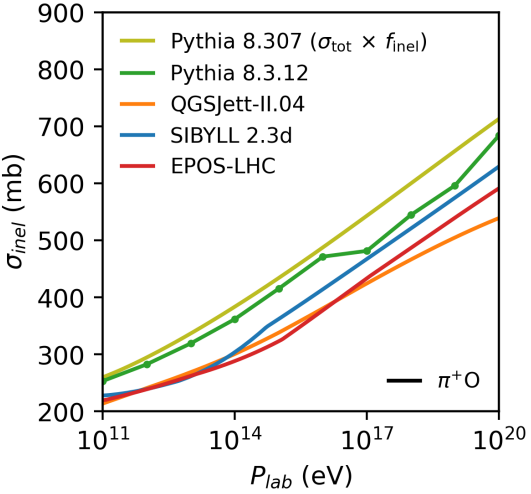




continuation of EPJ Web of Conferences, 05010 (2023)

σ_{inel} of (p, ^{14}N), (p, ^{16}O) and (π^+, ^{16}O)





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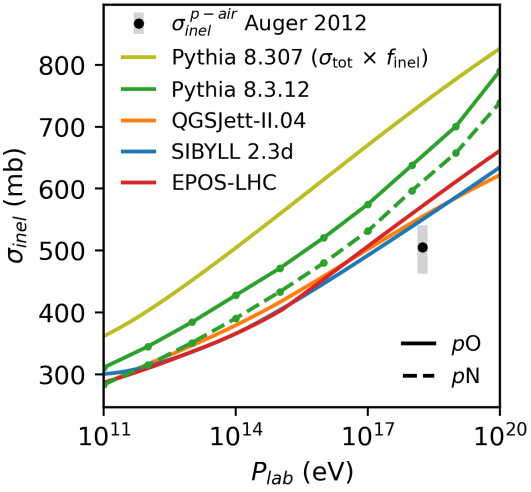
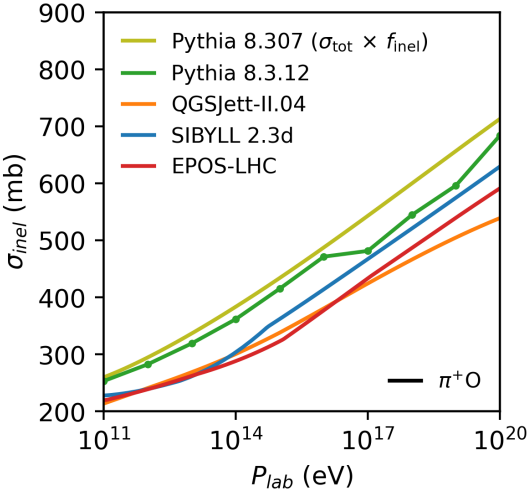
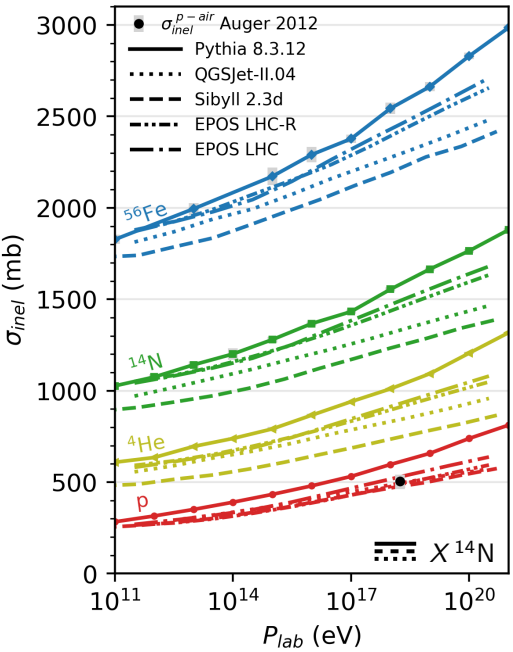




continuation of EPJ Web of Conferences, 05010 (2023)

σ_{inel} of (p, ^{14}N), (^{4}He, ^{14}N), (^{14}N, ^{14}N) and (^{56}Fe, ^{14}N)



Corsika 8 + Pythia 8.3.07

- tracking done by Corsika 8
- interactions/decays performed by the `PythiaCascade` class
  - ↳ provide collision $\sigma(hA)$,
  - ↳ perform an hA collision,
  - ↳ perform an h decay

Corsika 8 + Pythia 8.3.12

- tracking done by Corsika 8
- calls Pythia for pp, Angantyr for hA/AA
- new energy and beam switching features
  - ↳ single Pythia instance
  - ↳ perform (proj, target, $E_{lab/CM}$) collisions on event-by-event basis
- interpolate from $\sigma_{tot}/\sigma_{inel}$ tables
- semi-superposition model for AA
  - ↳ as used with Sibyll 2.3d
- fast simulations thanks to reuse files

As previously discussed by Peter Skands[1] and Fares Djama[2], Pythia 8 can be tuned to accelerator dataset to better describe specific science cases.

↳ Monash tune
↳ ATLAS tunes
↳ forward physics tune

ongoing efforts towards a fixed-target tune
↳ **Pythia 8 Wuppertal tune**

beam remnant
- `BeamRemnants:dampPopcorn`
- `BeamRemnants:popcornRate`
- `BeamRemnants:companionPower`

colour reconnection
↳ help for the baryon description

- set `MultipartonInteractions:ecmRef`
  ↳ $p_{T,0}^{\mathrm{Ref}} = p_{T,0}(E_{\mathrm{CM}}^{\mathrm{Ref}})$
- fix parameters step-by-step
  ↳ pp
  ↳ $\pi^{\pm}$p
  ↳ $\pi^{\pm}$A[a]
  ↳ pA

[1] Soft QCD talk from Monday
[2] ATLAS talk from Tuesday

[a] A from the CNO group

NA49

- hadron production in pp @ 158 GeV/c[a] [b]
  - ↳ $\pi^{\pm}$, p, $\overline{\text{p}}$, n

[a] Eur. Phys. J. C 45, 343–381 (2006)
[b] Eur. Phys. J. C 65, 9–63 (2010)

NA61/SHINE

- hadron production in pp @ [20, 31, 40, 80, 158] GeV/c[a]
- hadron production in $\pi^{\pm}$C @ [158, 350] GeV/c[b]
  - ↳ $\pi^{\pm}$, $\text{K}^{\pm}$, p, $\overline{\text{p}}$

[a] Eur. Phys. J. C 77, 671 (2017)
[b] Phys. Rev. D 107, 062004 (2023)

NA8

- soft $\pi^{\pm}$p and pp elastic scattering @ [30:345] GeV[a]

[a] Nucl. Phys. B 217, 285-335 (1983)

E104

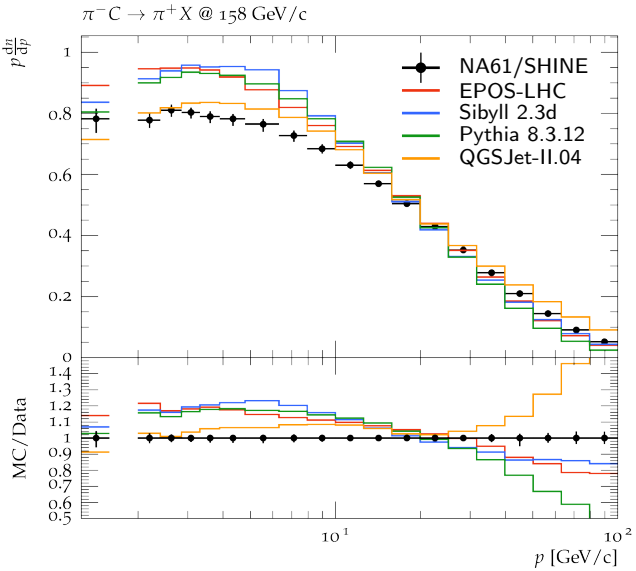
- σ_{tot} in $\pi^{\pm}$p, K$^{\pm}$p, pp, $\bar{\text{p}}$p @ [23:208] GeV/c[a]
- σ_{tot} in $\pi^{\pm}$p, K$^{\pm}$p, pp, $\bar{\text{p}}$p @ [200:370] GeV/c[b]

[a] Phys. Lett. B 61, 303-308 (1976)
[b] Phys. Lett. B 80, 423-427 (1979)

Rivet plug-in

↳ NA61/SHINE publication[3]

- fixed-target collisions
  - ↳ π^-C interactions
  - ↳ $p_z(\pi^-) = 158$, 350 GeV/c
- hadron production spectra
  - ↳ $p\frac{dn}{dp}$ distributions
  - ↳ π^+, π^-, K^+, K^-, p and $\overline{p}$
  - ↳ (+ K^0_s, Λ, $\overline{\Lambda}$)



[3] Phys. Rev. D 107, 062004 (2023)

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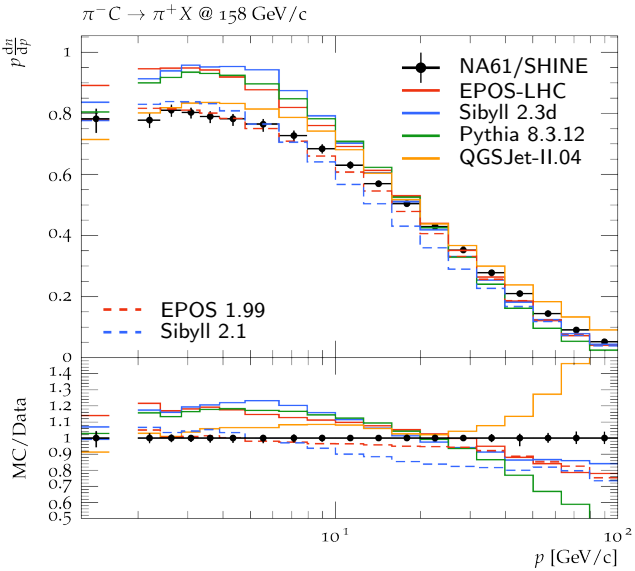


[3] Phys. Rev. D 107, 062004 (2023)

Corsika 8 + Pythia 8.3

and

Pythia 8.3 + Chromo
Pythia 8.3 + MCEq

fast simulation of dE/dX tables via Chromo
needed for MCEq

↓

Corsika 8 showers and **MCEq** leptons fluxes with Pythia 8.3 (Angantyr)

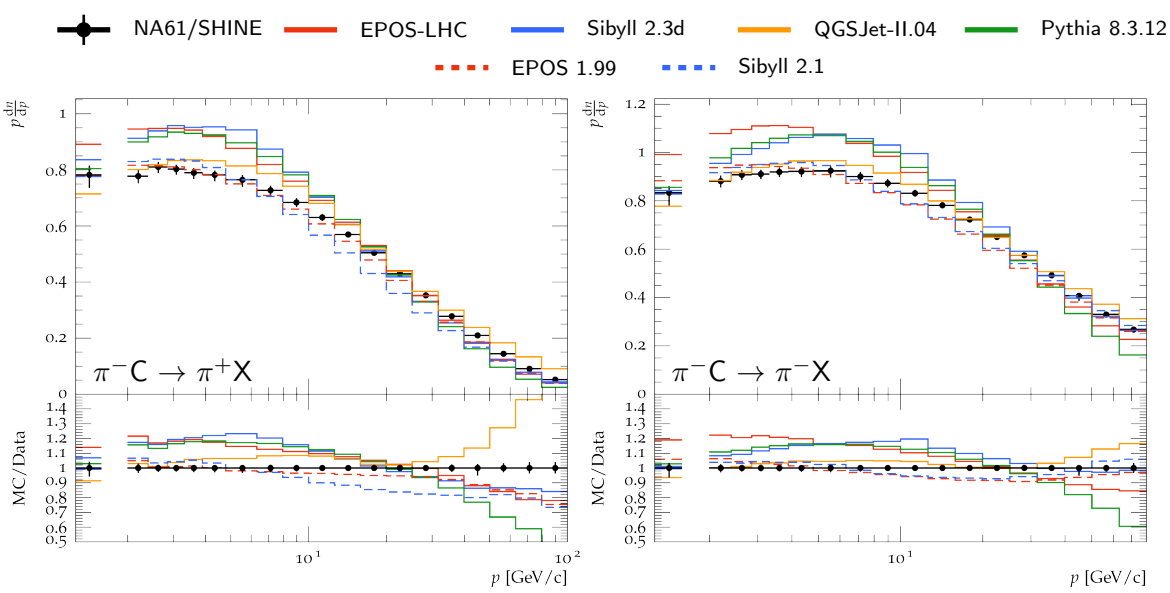
+

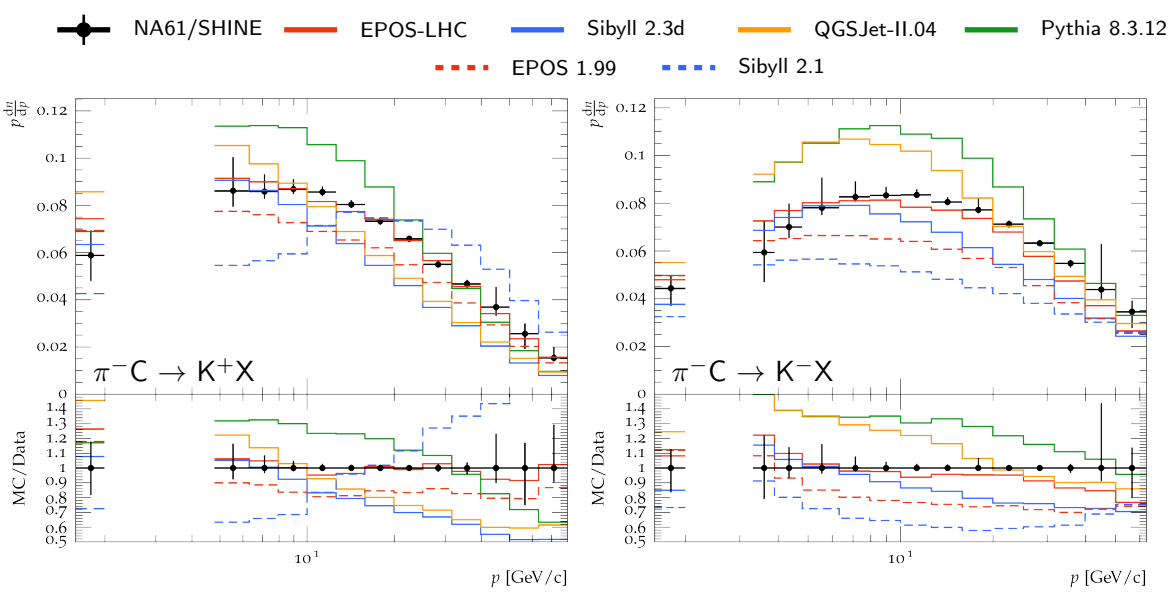
Pythia 8 Wuppertal tune

Global tune for air shower

- tune using air shower observables and accelerator datasets
  - ↳ muonic shower properties ($N_\mu(E)$, $\sigma(n_\mu, R_\mu, ...)$
  - ↳ electromagnetic shower properties (N_e, X_{max}, $\sigma(X_{max})$, ...)
  - ↳ cross-sections inferred from X_{max} distribution tail
  - ↳ mass composition of cosmic rays
- discussed at the workshop on the tuning of hadronic interaction models[4]
  - ↳ workshop report to be release soon

[4] took place in 22-25 January 2024 in Wuppertal


NA61/SHINE
EPOS-LHC
Sibyll 2.3d
QGSJet-II.04
Pythia 8.3.12
EPOS 1.99
Sibyll 2.1
$p\frac{d\eta}{dp}$
$\pi^-C \to \pi^+X$
$\pi^-C \to \pi^-X$
MC/Data
p [GeV/c]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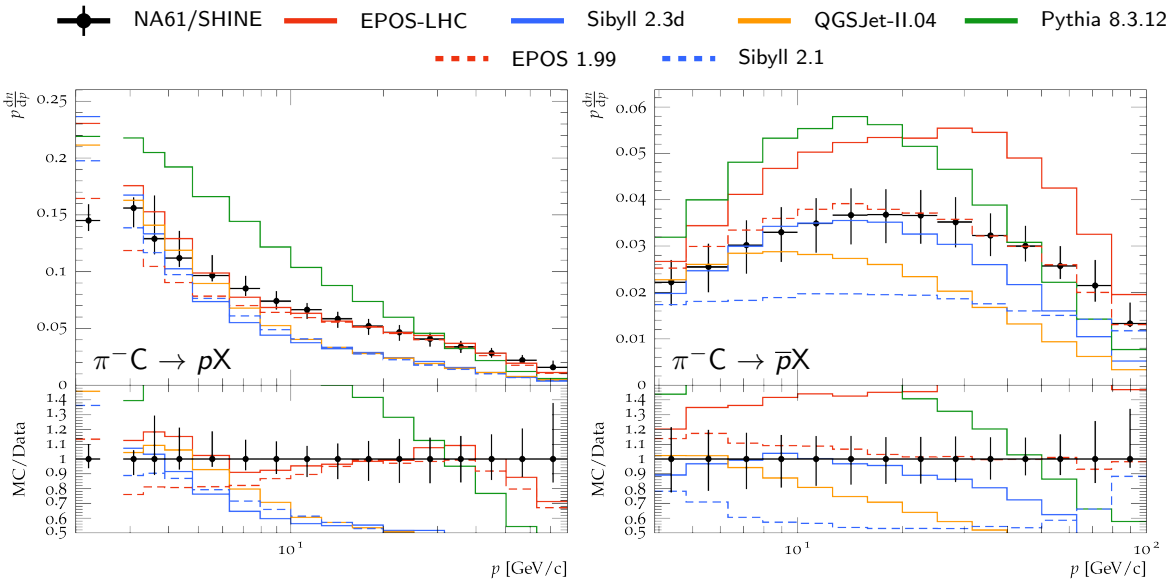
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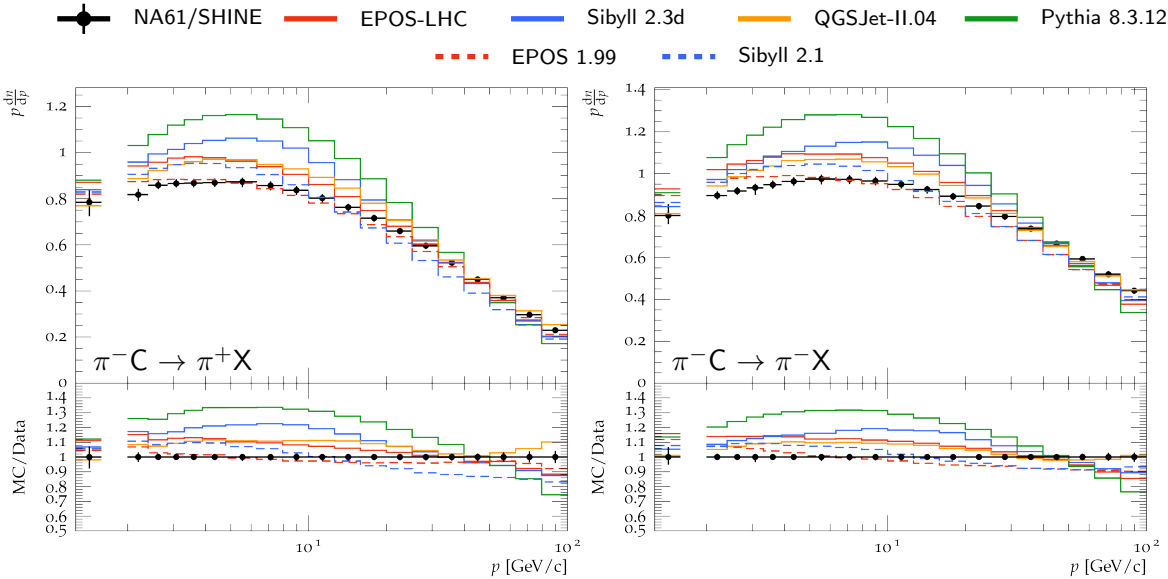
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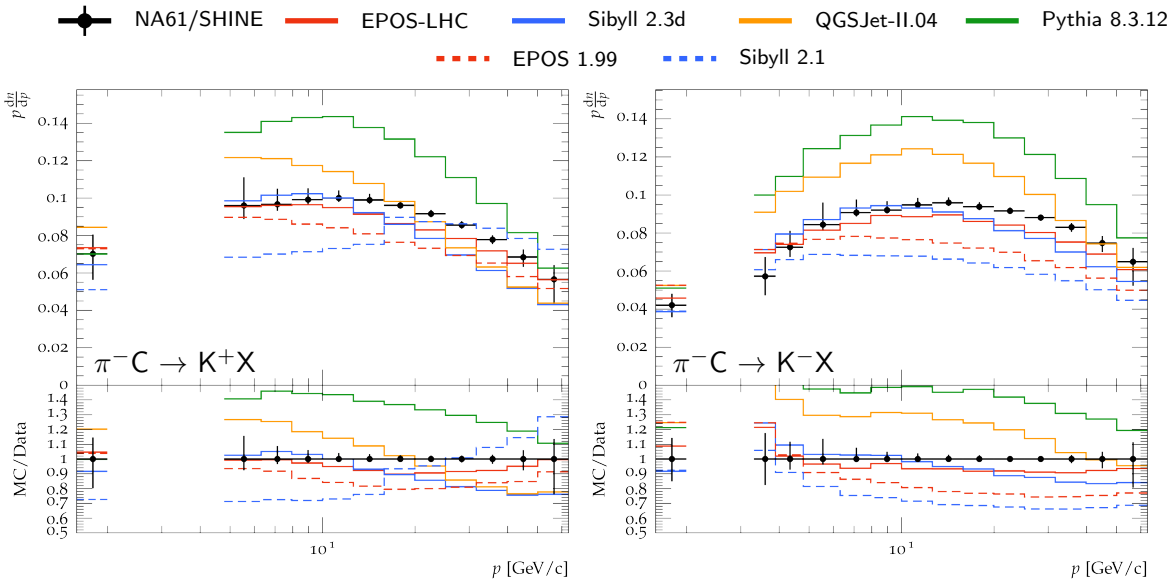
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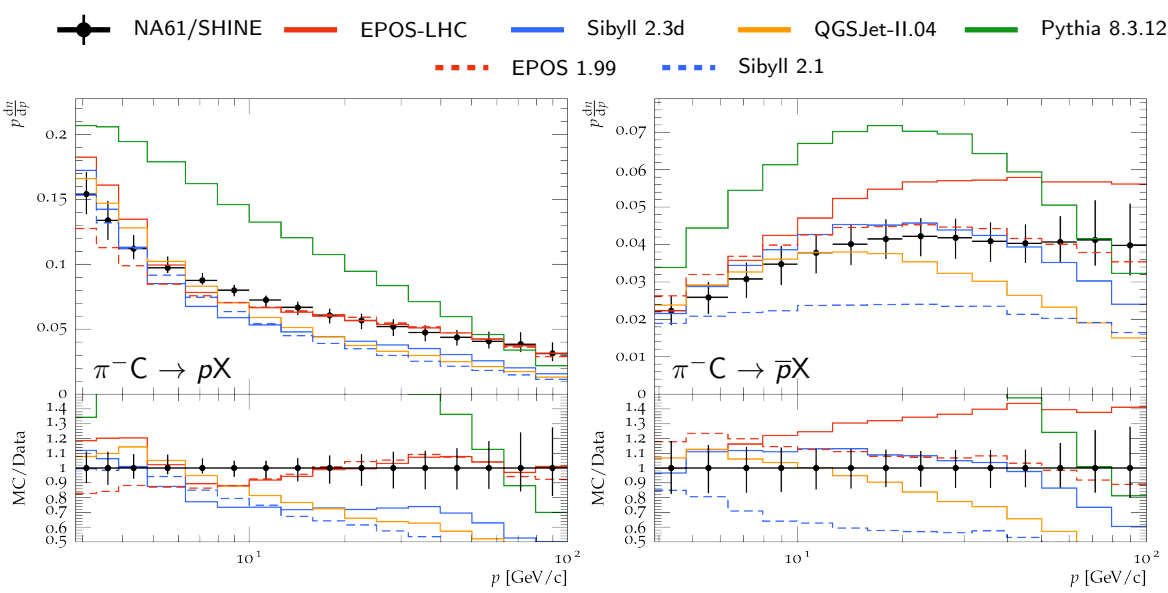
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