The anti-proton and positron cosmic ray fluxes

and

Hadronic Cross Sections.

Paolo Lipari, INFN Roma “Sapienza”

Meeting: “Hadronic cross sections:
Physics case from Cosmic Rays”

Torino 6th - 7th july 2015

Prediction of the spectra of anti-protons
and positrons from the "conventional mechanism"

[Hadronic interactions of Cosmic Rays (CR)
in the interstellar medium].

Step 1: Measure the spectra of CR near the Earth.

Step 2: Correct for Solar Modulation effects
to obtain the spectra in interstellar space

Step 3: Assume that these "local" CR spectra
are present in the entire Galaxy.

Step 4: Model the interaction to compute
injection spectra of positrons + anti-protons.

Step 5: "Propagate" the injection spectra.

Important open question:

Production of secondaries
inside (or close) to the sources

This contribution has been assumed
as negligible in most (or all) of discussions here

$$q_j(E, \vec{x}, t) = q_j^{(\mathrm{ism})}(E, \vec{x}, t) + q_j^{(\mathrm{sources})}(E, \vec{x}, t)$$

Hypothesis:

Local Spectra = Spectra in the entire Galaxy

Expected for nuclear component
(p, He, Nuclei, pbar, ...)

NOT expected for electrons and positrons.

Questions accessible to experimental verification
via gamma, radio astronomy.

Calculation of the injection spectra:

$$n_A(E) \simeq \frac{4\pi}{\beta c}\,\phi_A(E)$$

$$q_j(E,\vec{x},t) \;=\; n_{\rm target}(\vec{x}) \sum_{\rm A} \int_E^\infty dE_0\, n_{\rm A}(E_0,\vec{x},t)\,\beta\,c \sum_{{\rm A}_t} f_{{\rm A}_t}\,\sigma_{{\rm AA}_t}(E_0)\,\frac{dN(E,E_0)}{dE}\bigg|_{{\rm AA}_t\to j}$$

Dominant source of positrons:

$$\pi^+ \to \mu^+ + \nu_\mu \to [e^+\ \nu_e\ \overline{\nu}_\mu] + \nu_\mu$$

Additional sources [kaon decay]

$$K^+ \to e^+ + \nu_e + \pi^\circ$$

$$K^+ \to \mu^+ + \nu_\mu \to [e^+\ \nu_e\ \overline{\nu}_\mu] + \nu_\mu$$

$$K^+ \to \mu^+ + \nu_\mu + \pi^\circ \to [e^+\ \nu_e\ \overline{\nu}_\mu] + \nu_\mu + \pi^\circ$$

$$K^+ \to \pi^+ + \pi^\circ \to \nu_\mu \to e^+$$

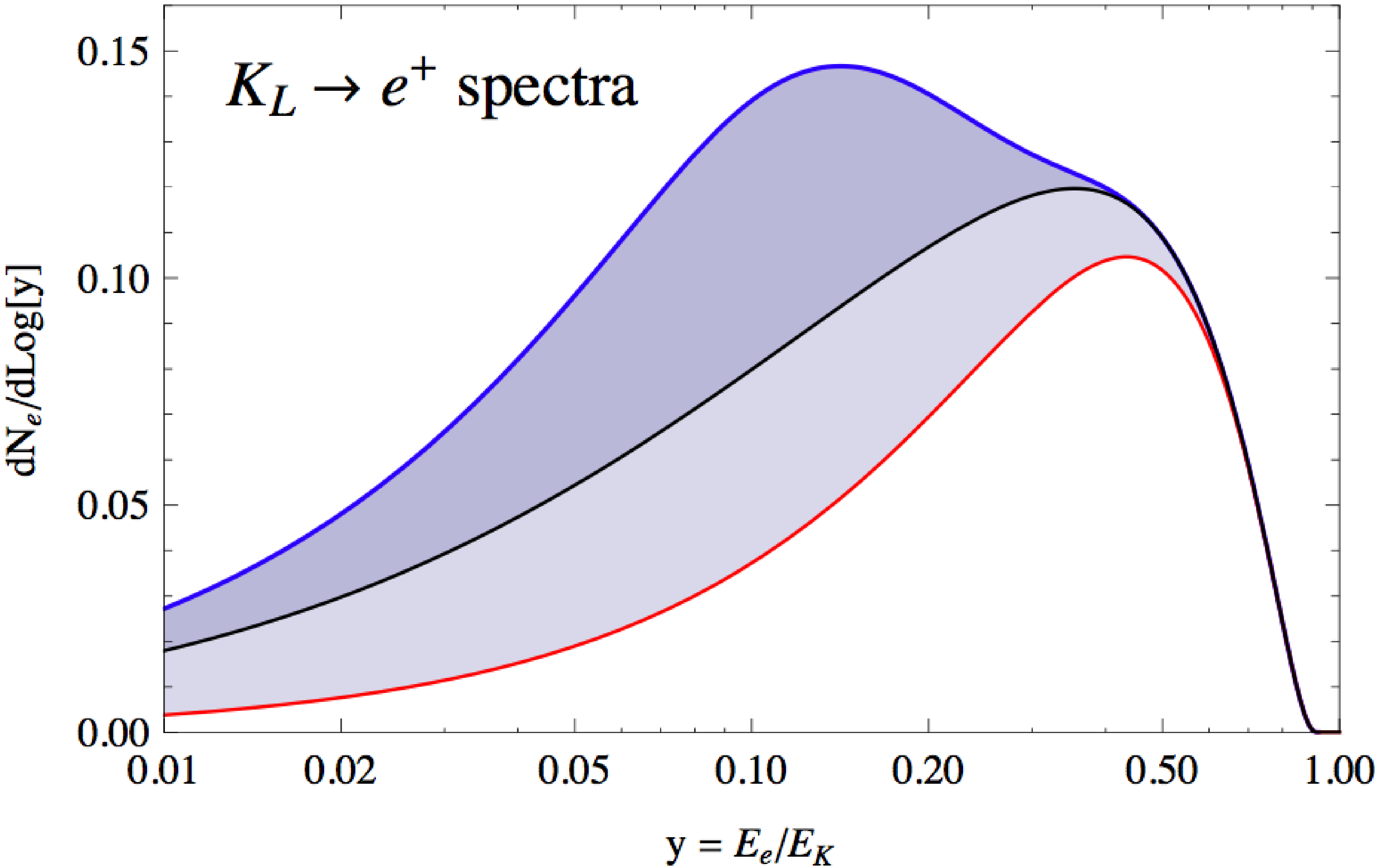
$$K^+ \to \pi^+ + \pi^\circ + \pi^\circ \to e^+ + \ldots$$

$$K^+ \to \pi^+ + \pi^+ + \pi^- \to e^+ + \ldots$$

$$K_L \to \pi^- + e^+ + \nu_e$$

$$K_L \to \pi^- + \mu^+ + \nu_\mu \to \pi^- + [e^+\ \nu_e\ \overline{\nu}_\mu] + \nu_\mu$$

$$K_L \to \pi^+ + \pi^\circ + \pi^\circ \to e^+ + \ldots$$


$K_L \to e^+$ spectra
0.15
0.10
0.05
0.00
$dN_e/dLog[y]$
0.01
0.02
0.05
0.10
0.20
0.50
1.00
$y = E_e/E_K$

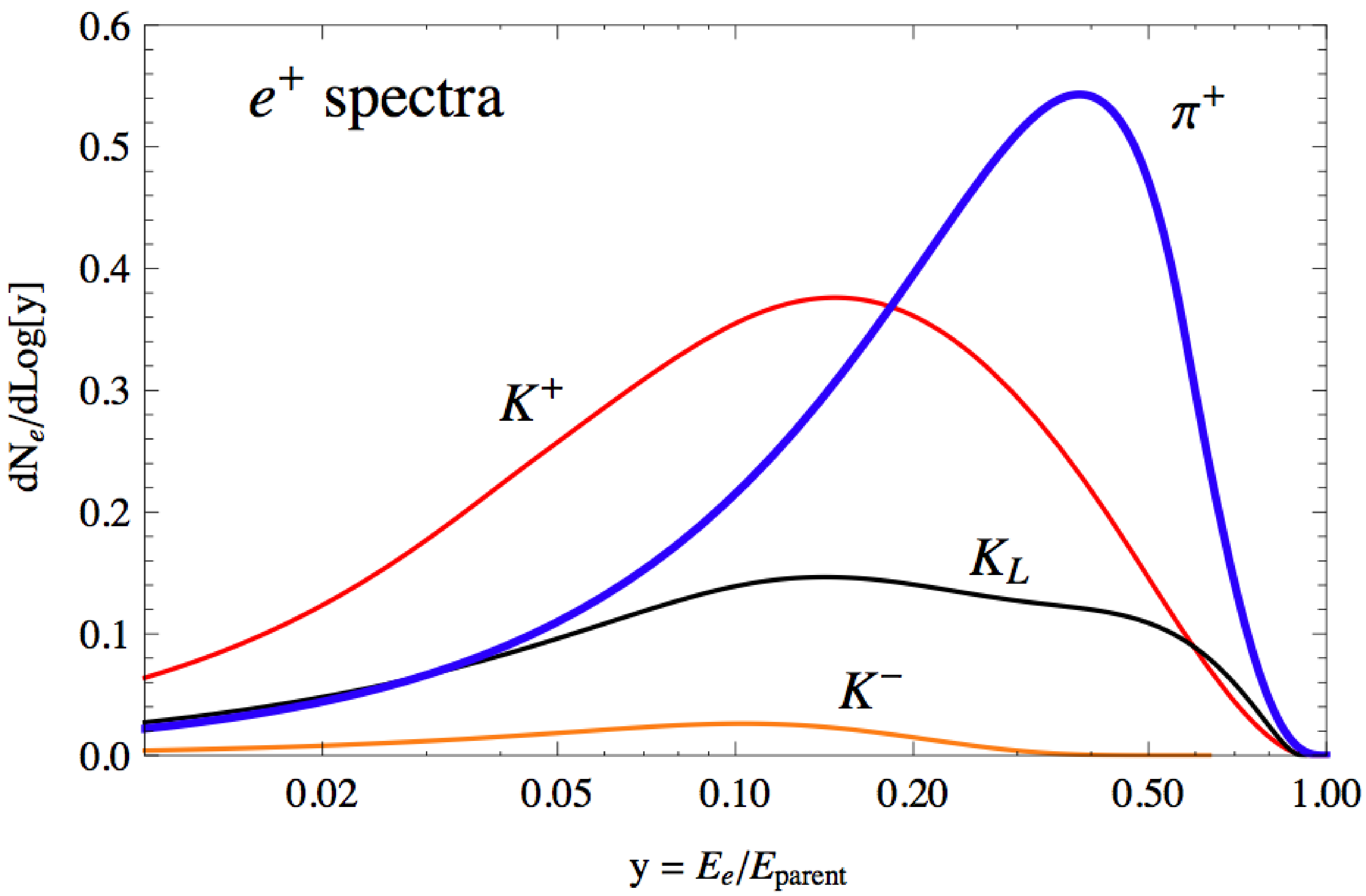
$$\frac{\langle N_{e^+} \rangle}{\pi^+ \text{ decay}} = 1.000 \qquad \frac{\langle Ee^+ \rangle}{E_{\pi^+}} = 0.264$$

$$\frac{\langle N_{e^+} \rangle}{K^+ \text{ decay}} = 1.055 \qquad \frac{\langle Ee^+ \rangle}{E_{K^+}} = 0.158$$

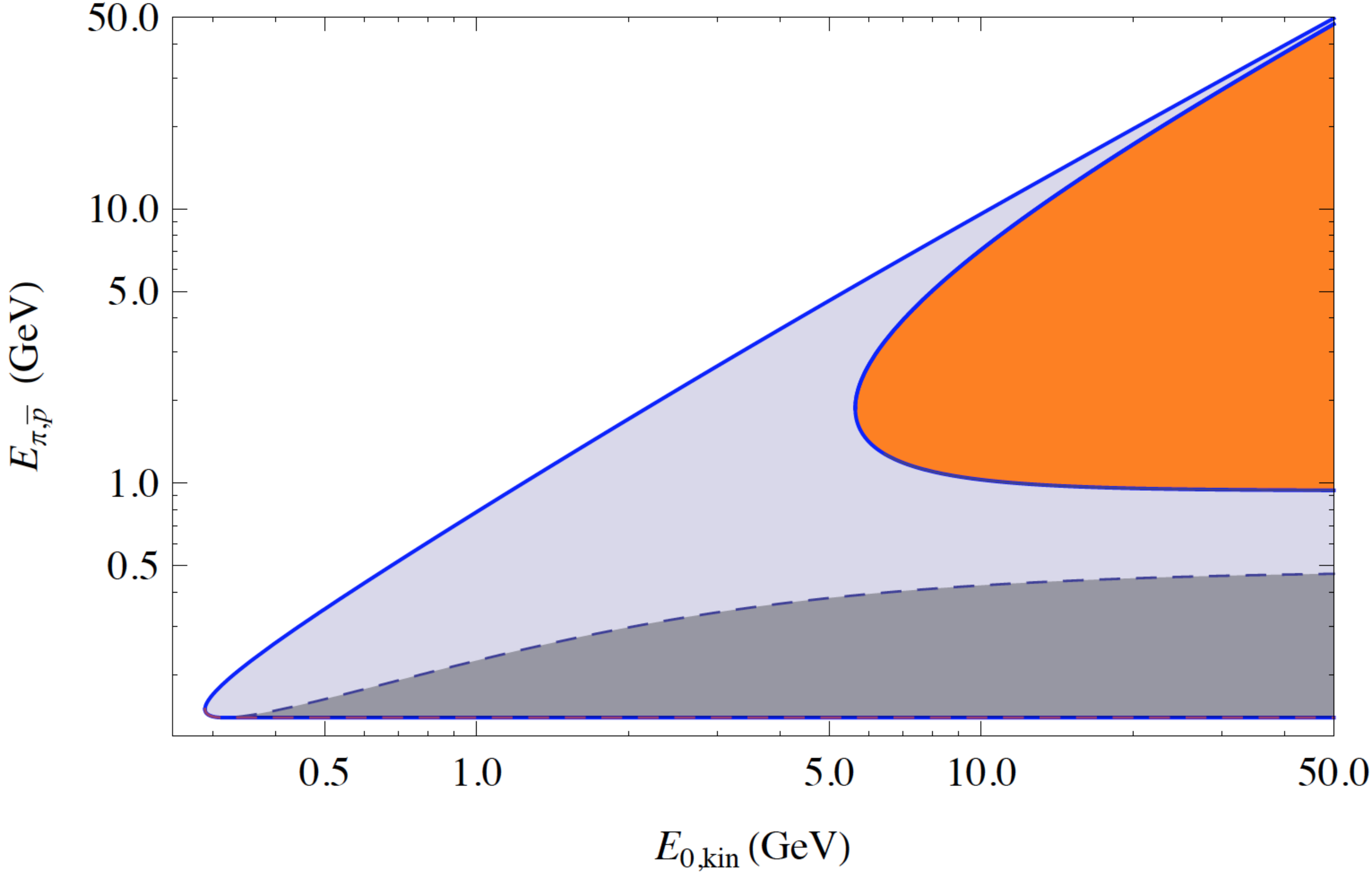
$$\frac{\langle N_{e^+} \rangle}{K_L \text{ decay}} = 0.455 \qquad \frac{\langle Ee^+ \rangle}{E_{K_L}} = 0.083$$

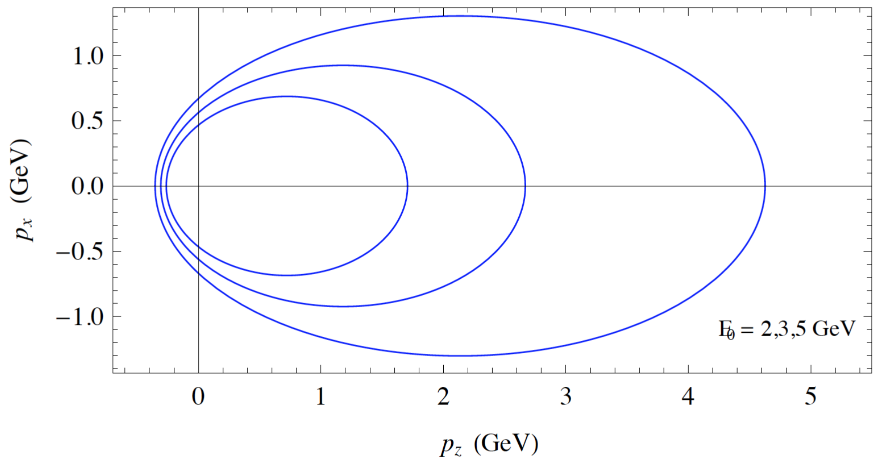
$$\frac{\langle N_{e^+} \rangle}{K^- \text{ decay}} = 0.055 \qquad \frac{\langle Ee^+ \rangle}{E_{K^-}} = 0.004$$

Positron spectra in Meson decay:



Kinematics of production for pions and anti-protons

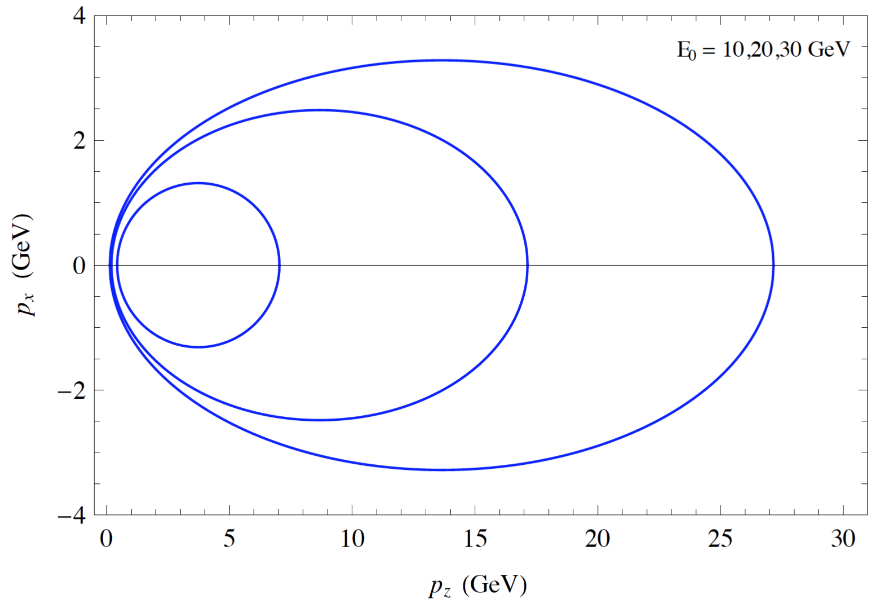




Pion production

kinematical
allowed region

(backward production)

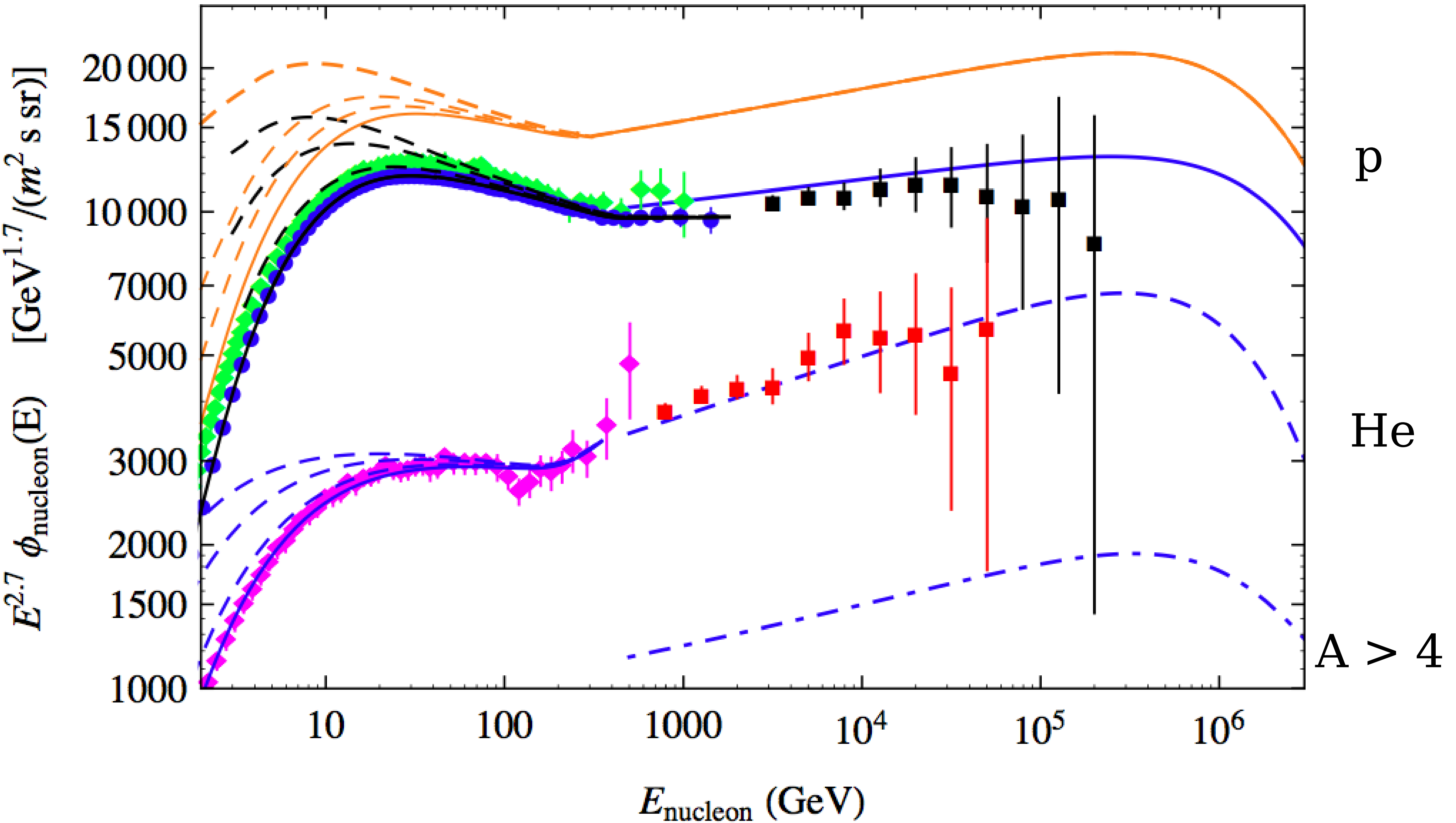


anti-proton production

Always forward

Strong suppression of low
energy anti-protons

Nucleon Fluxes



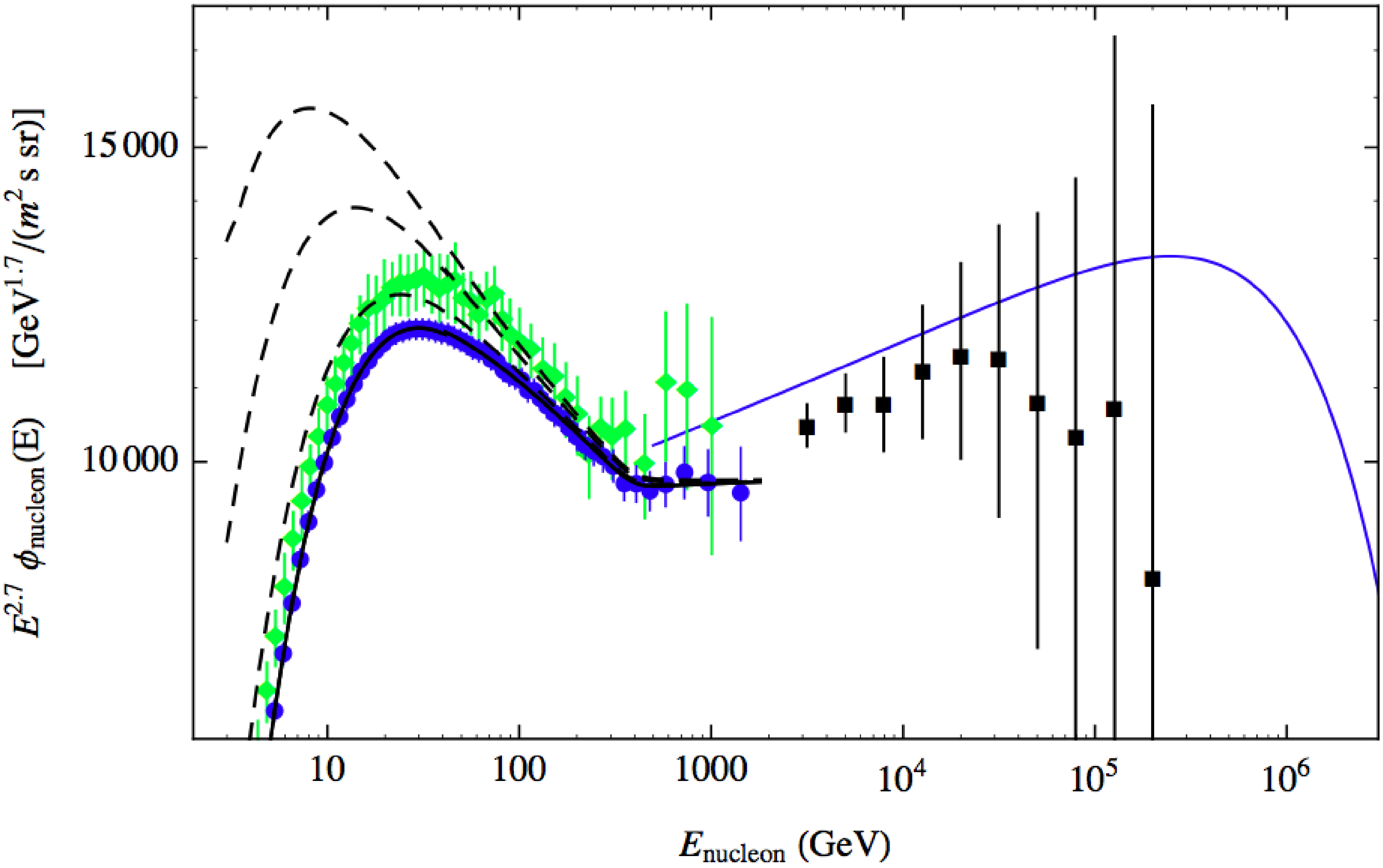
Observed flux, LIS spectrum

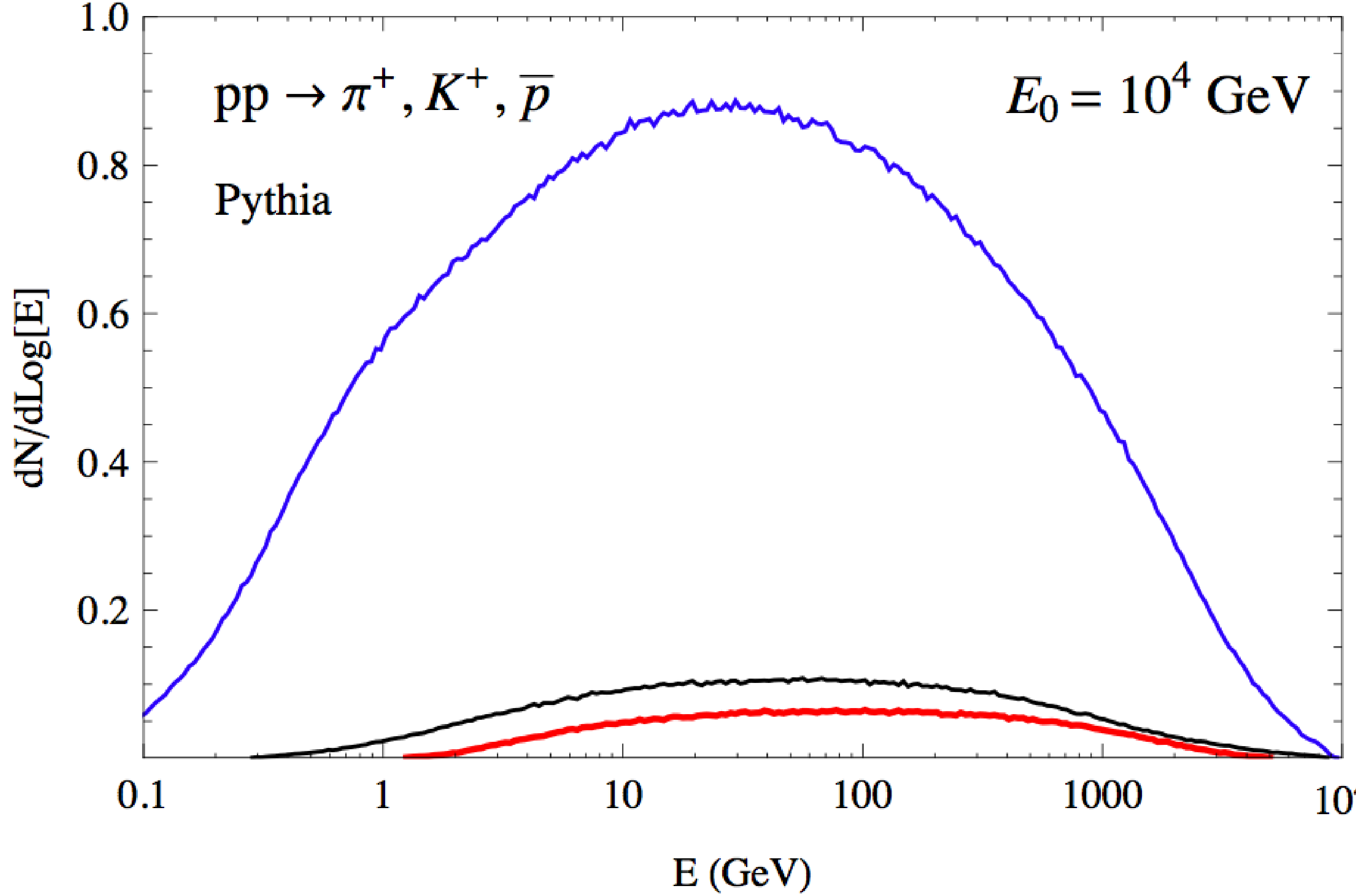
$$n_A(E, \vec{x}_\odot) = \frac{4\,\pi}{\beta\,c}\left\{\hat{H}^{-1}(t) \otimes \phi_A(E,t)\right\}$$

High energy approximation

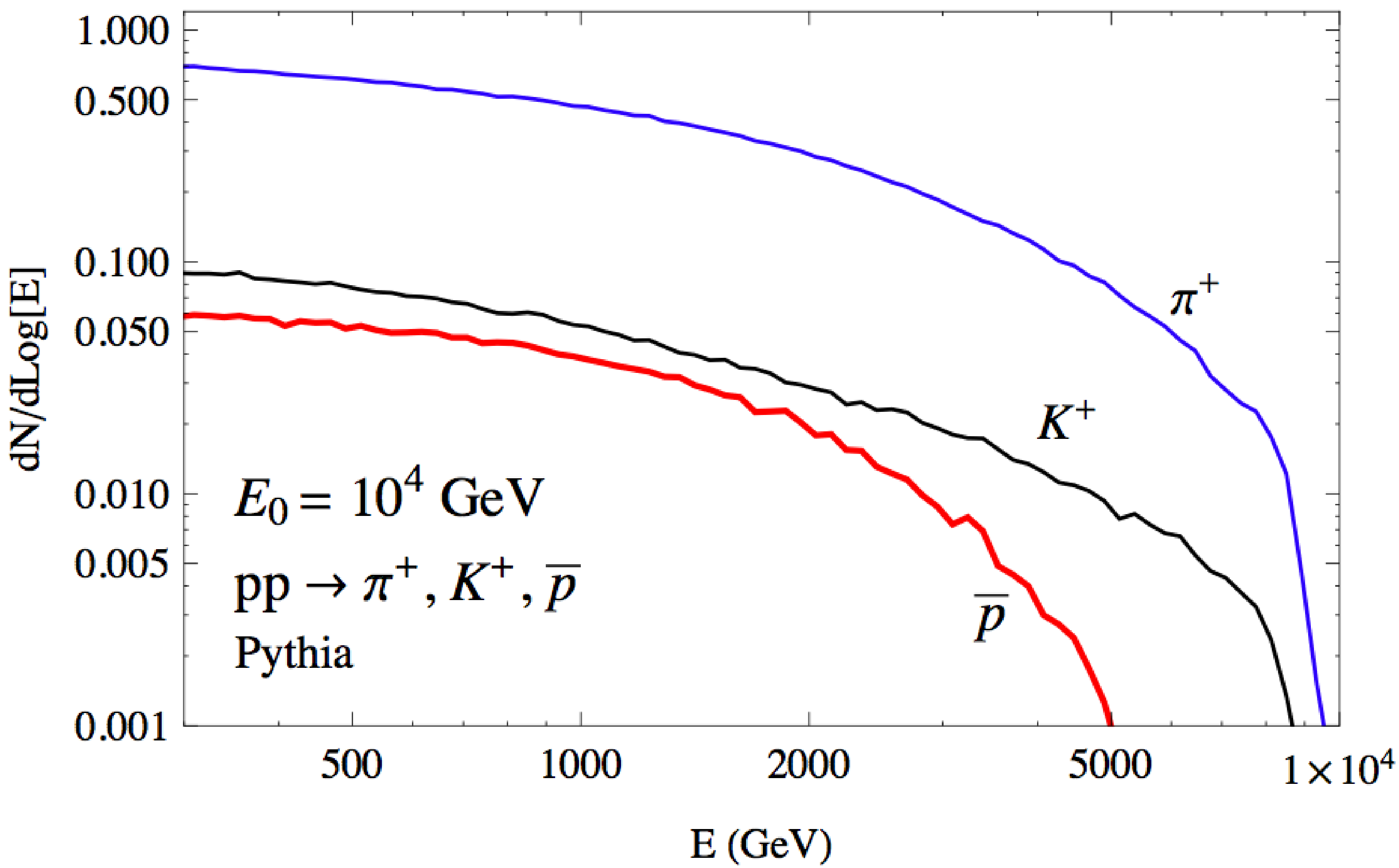
$$n_A(E, \vec{x}_\odot) \simeq \frac{4\,\pi}{\beta\,c}\phi_A(E)$$

Proton Flux


15 000
10 000
$E^{2.7}\ \phi_{nucleon}(E)\quad [GeV^{1.7}/(m^2\ s\ sr)]$
10
100
1000
10^4
10^5
10^6
$E_{nucleon}$ (GeV)

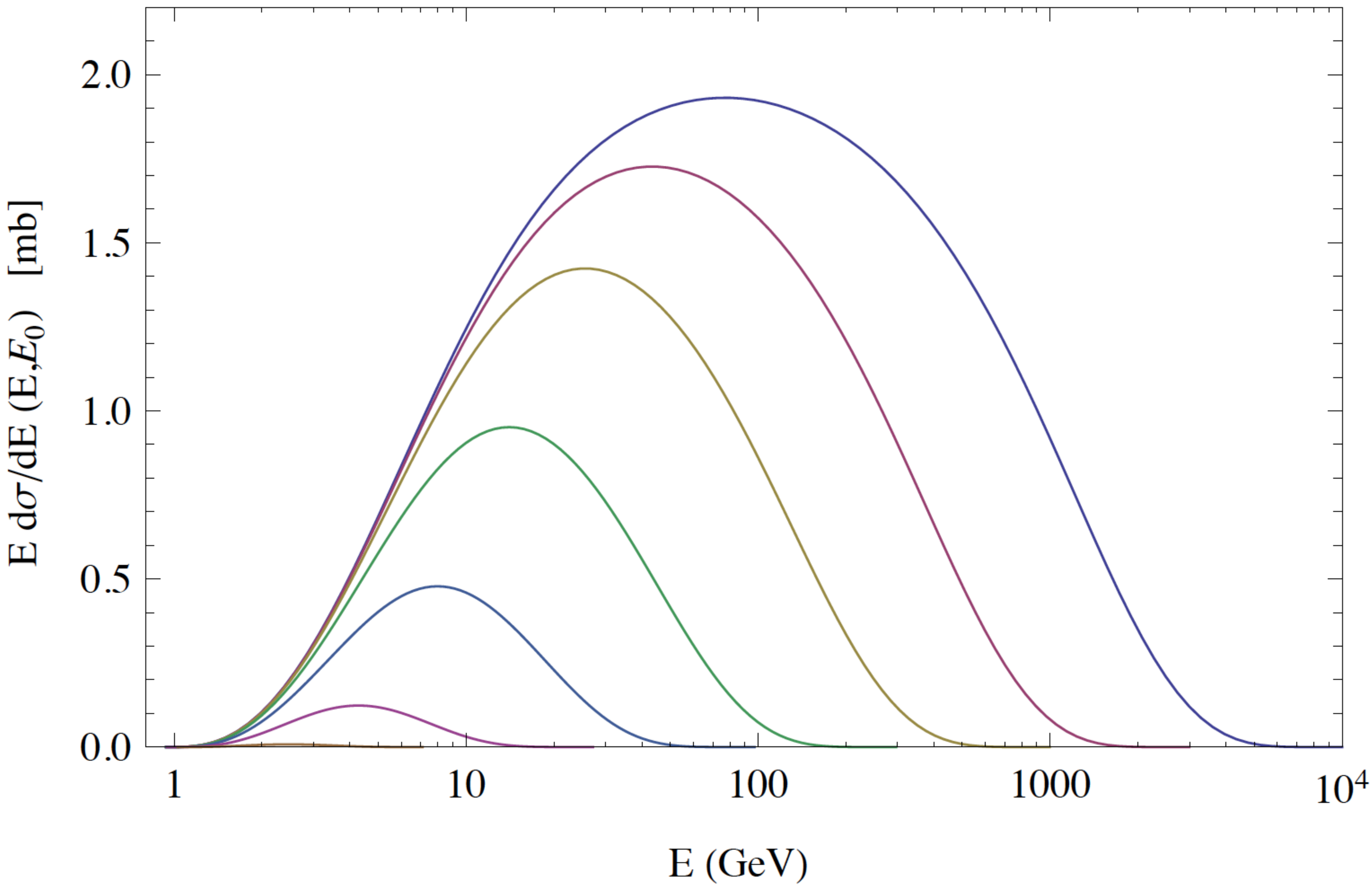


$pp \to \pi^+, K^+, \overline{p}$
$E_0 = 10^4$ GeV
Pythia
dN/dLog[E]
E (GeV)
1.0
0.8
0.6
0.4
0.2
0.1
1
10
100
1000
10^4

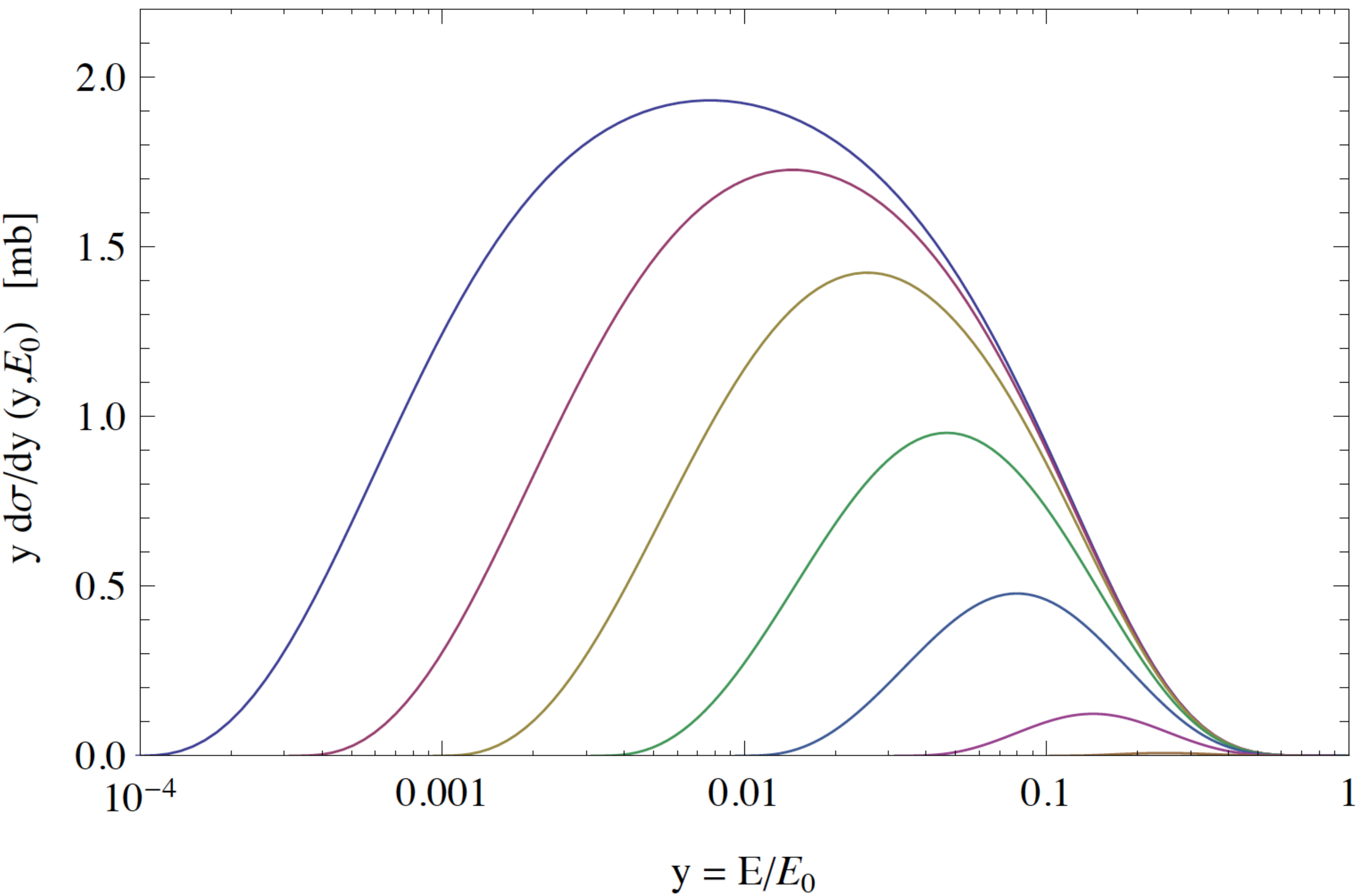


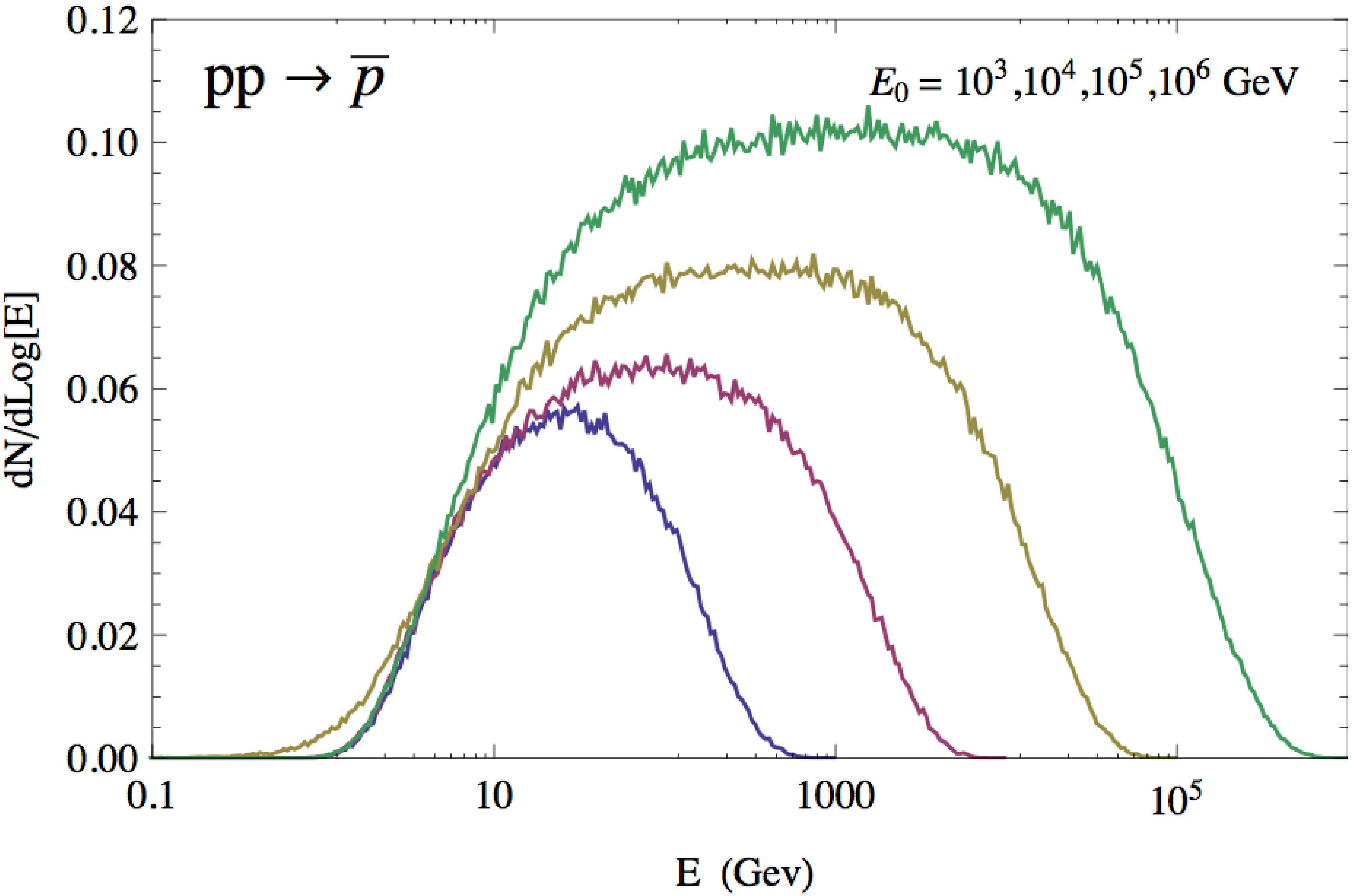
1.000
0.500
0.100
0.050
0.010
0.005
0.001
dN/dLog[E]
500
1000
2000
5000
1×10^4
E (GeV)
π^+
K^+
$\overline{p}$
$E_0 = 10^4$ GeV
pp $\rightarrow \pi^+, K^+, \overline{p}$
Pythia

Anti-proton model (asymptotically scaling)

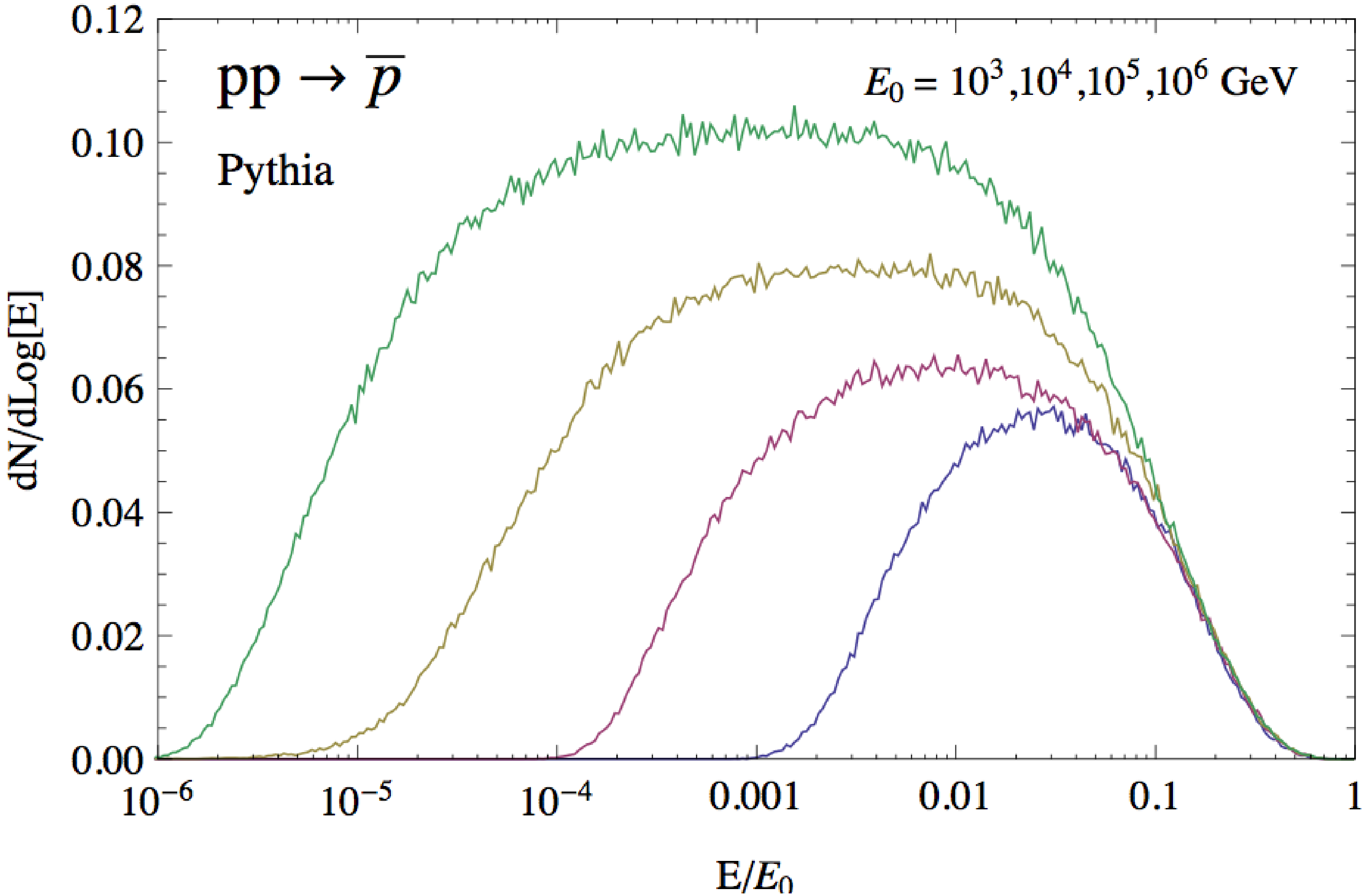


Anti-proton model (asymptotically scaling)

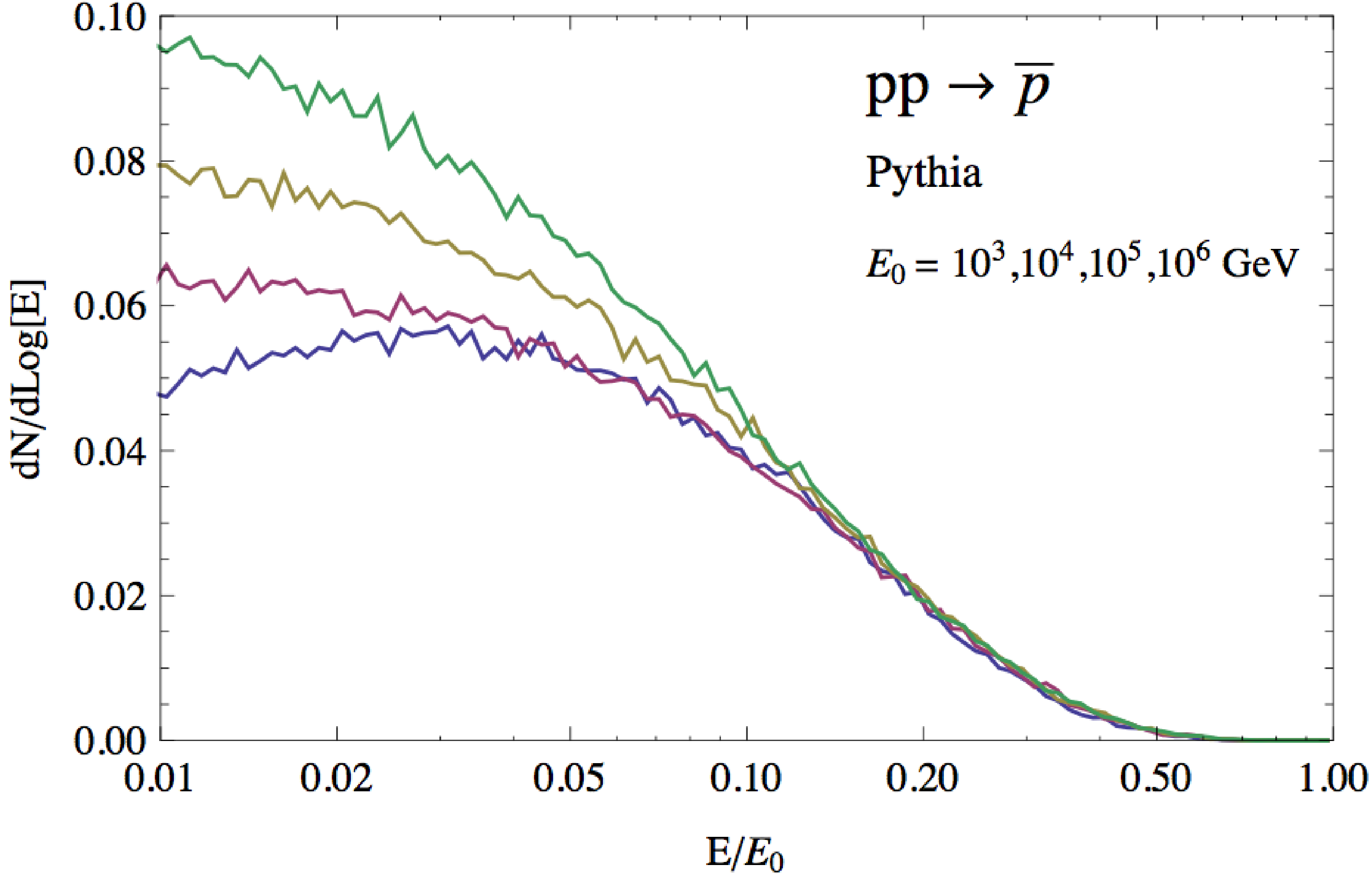




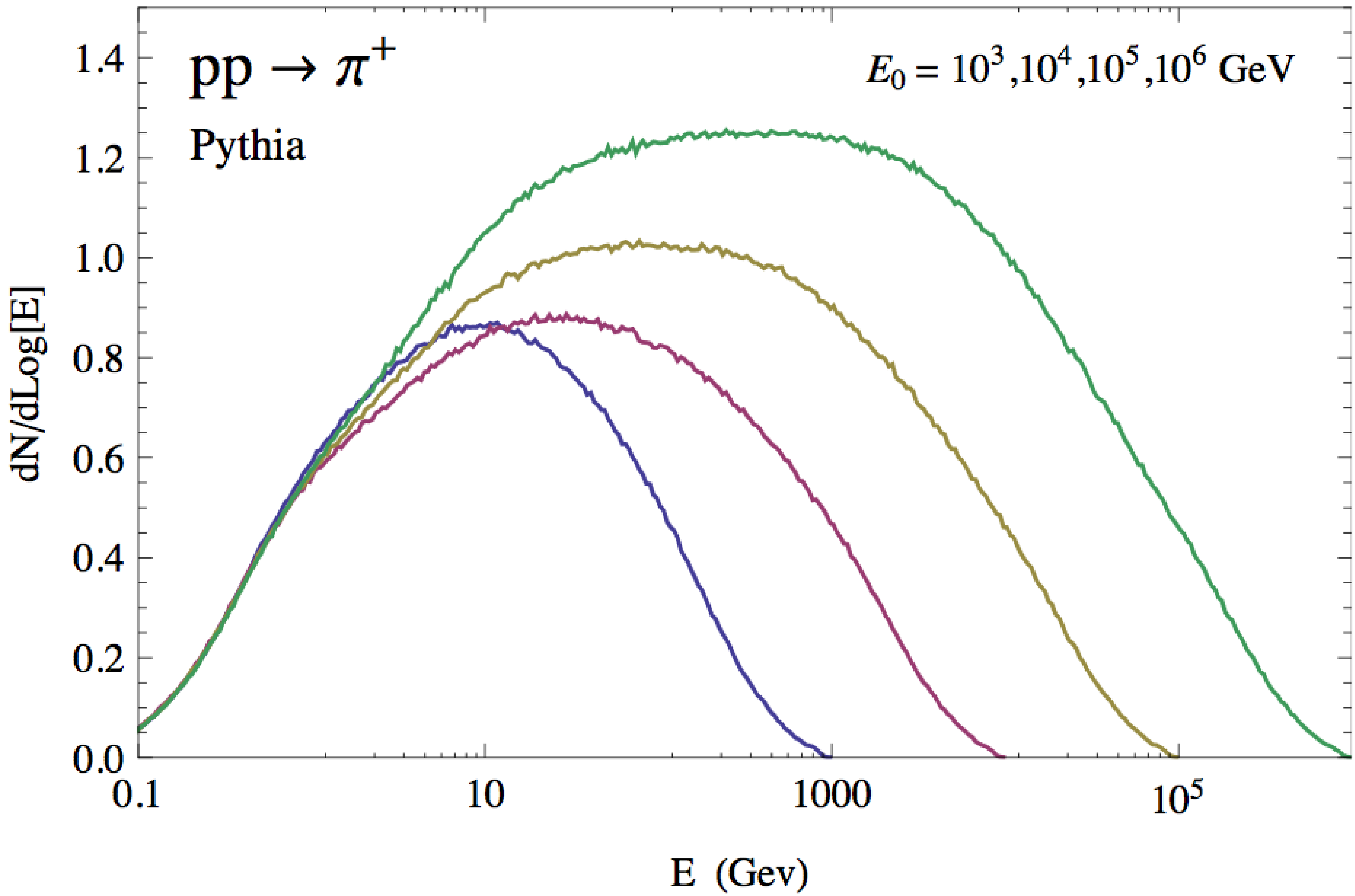
$pp \to \overline{p}$
$E_0 = 10^3, 10^4, 10^5, 10^6$ GeV
dN/dLog[E]
E (Gev)
0.00
0.02
0.04
0.06
0.08
0.10
0.12
0.1
10
1000
10^5



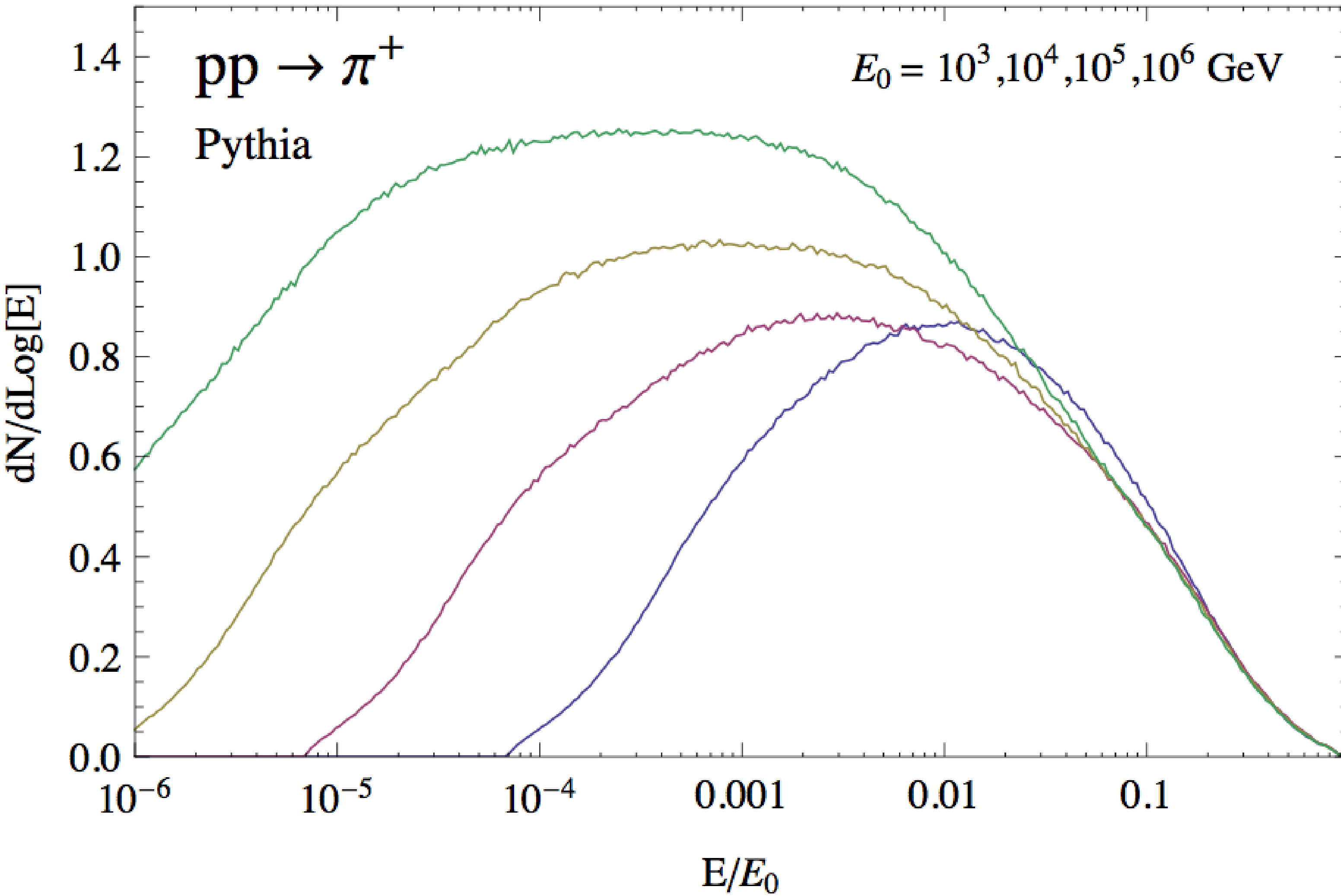
pp → $\overline{p}$
Pythia
$E_0 = 10^3, 10^4, 10^5, 10^6$ GeV
dN/dLog[E]
0.12
0.10
0.08
0.06
0.04
0.02
0.00
10^{-6}
10^{-5}
10^{-4}
0.001
0.01
0.1
1
E/E_0



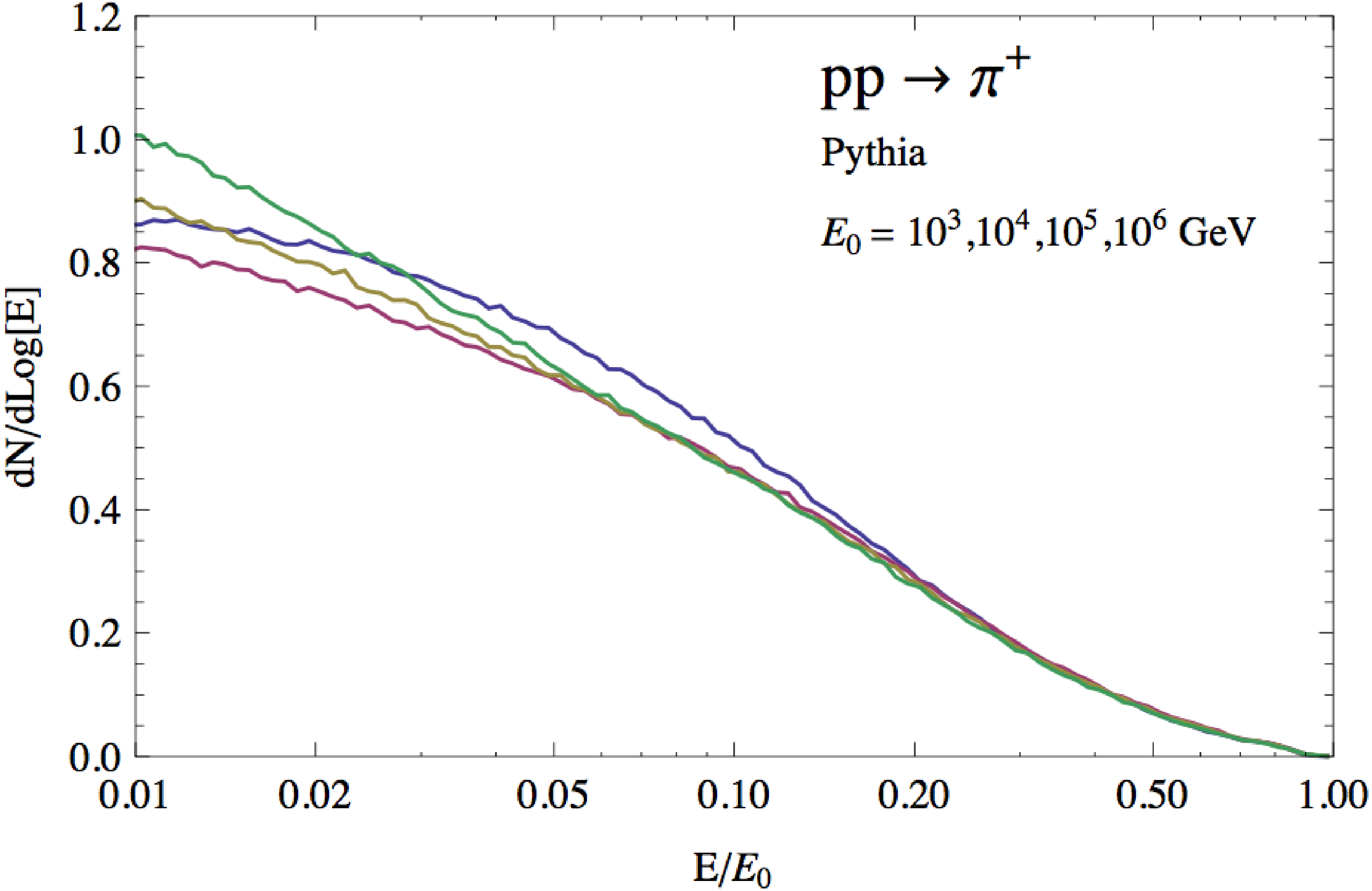
$pp \to \overline{p}$
Pythia
$E_0 = 10^3, 10^4, 10^5, 10^6$ GeV
dN/dLog[E]
E/E_0
0.10
0.08
0.06
0.04
0.02
0.00
0.01
0.02
0.05
0.10
0.20
0.50
1.00



pp → π+
Pythia
E0 = 10^3,10^4,10^5,10^6 GeV
dN/dLog[E]
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0.1
10
1000
10^5
E (Gev)



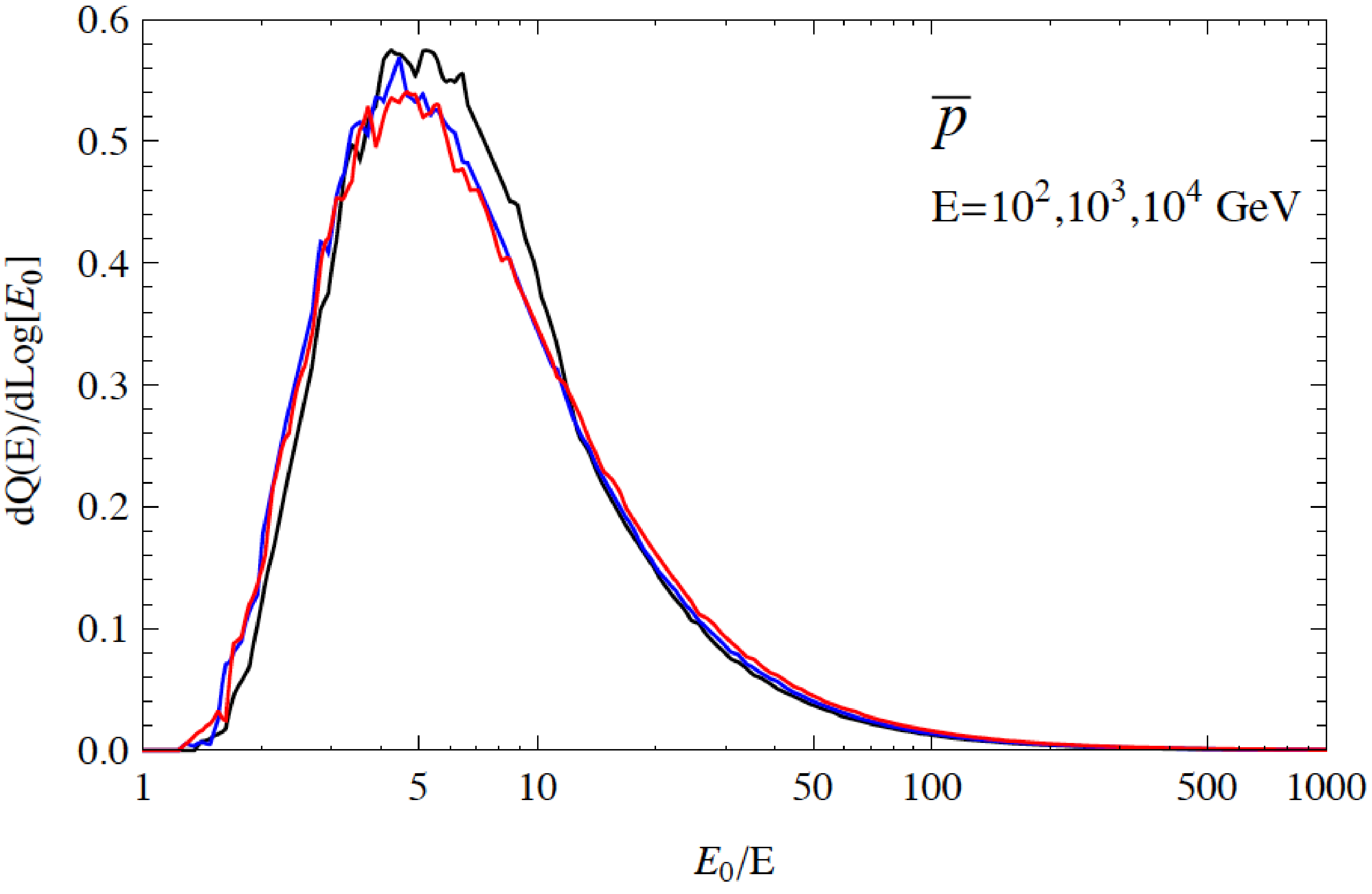
$pp \to \pi^+$
Pythia
$E_0 = 10^3, 10^4, 10^5, 10^6$ GeV
dN/dLog[E]
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
10^{-6}
10^{-5}
10^{-4}
0.001
0.01
0.1
1
E/E_0



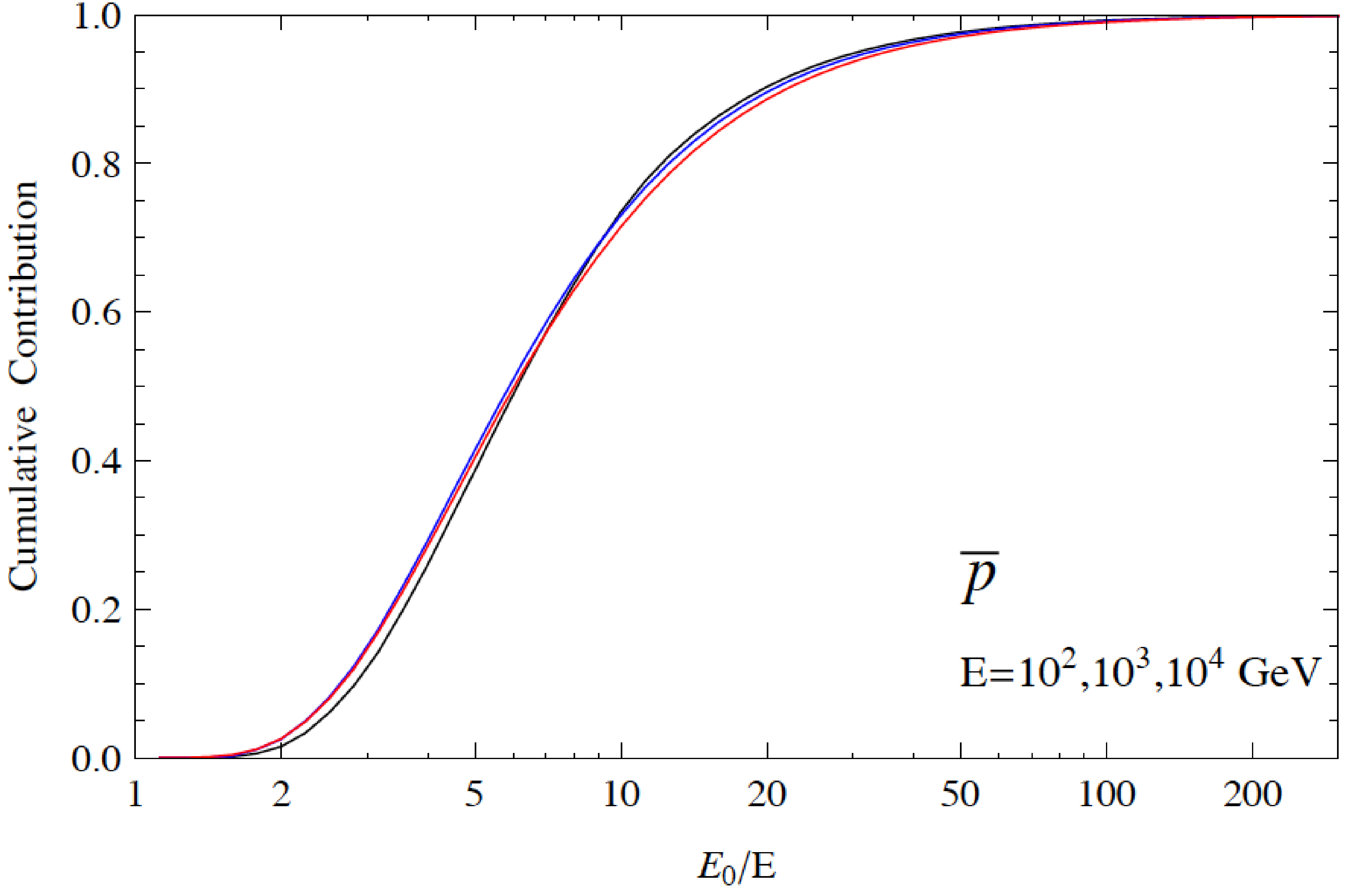
$pp \to \pi^+$
Pythia
$E_0 = 10^3, 10^4, 10^5, 10^6$ GeV
dN/dLog[E]
E/E_0
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0.01
0.02
0.05
0.10
0.20
0.50
1.00

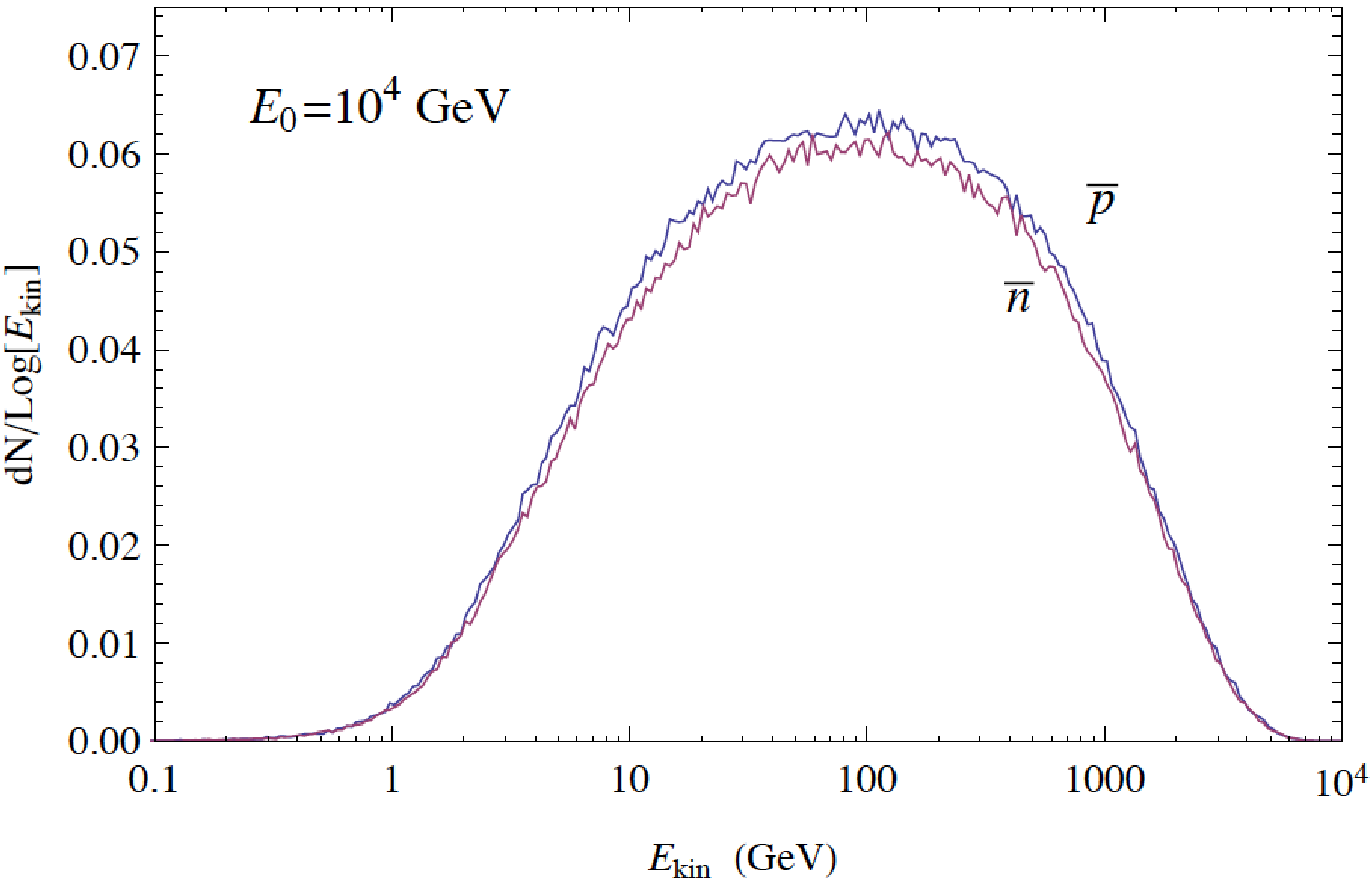
Response function for anti-proton production.
[Primary particle energy that contributes
to the flux at energy E]

$$q_j^{(\mathrm{ism})}(E,\vec{x},t) = \sum_A \int dE_0 \; n_A(E_0,\vec{x},t) \; n_{\mathrm{ism}}(\vec{x}) \, \beta c \, \frac{d\sigma_{A\to j}}{dE}(E,E_0)$$



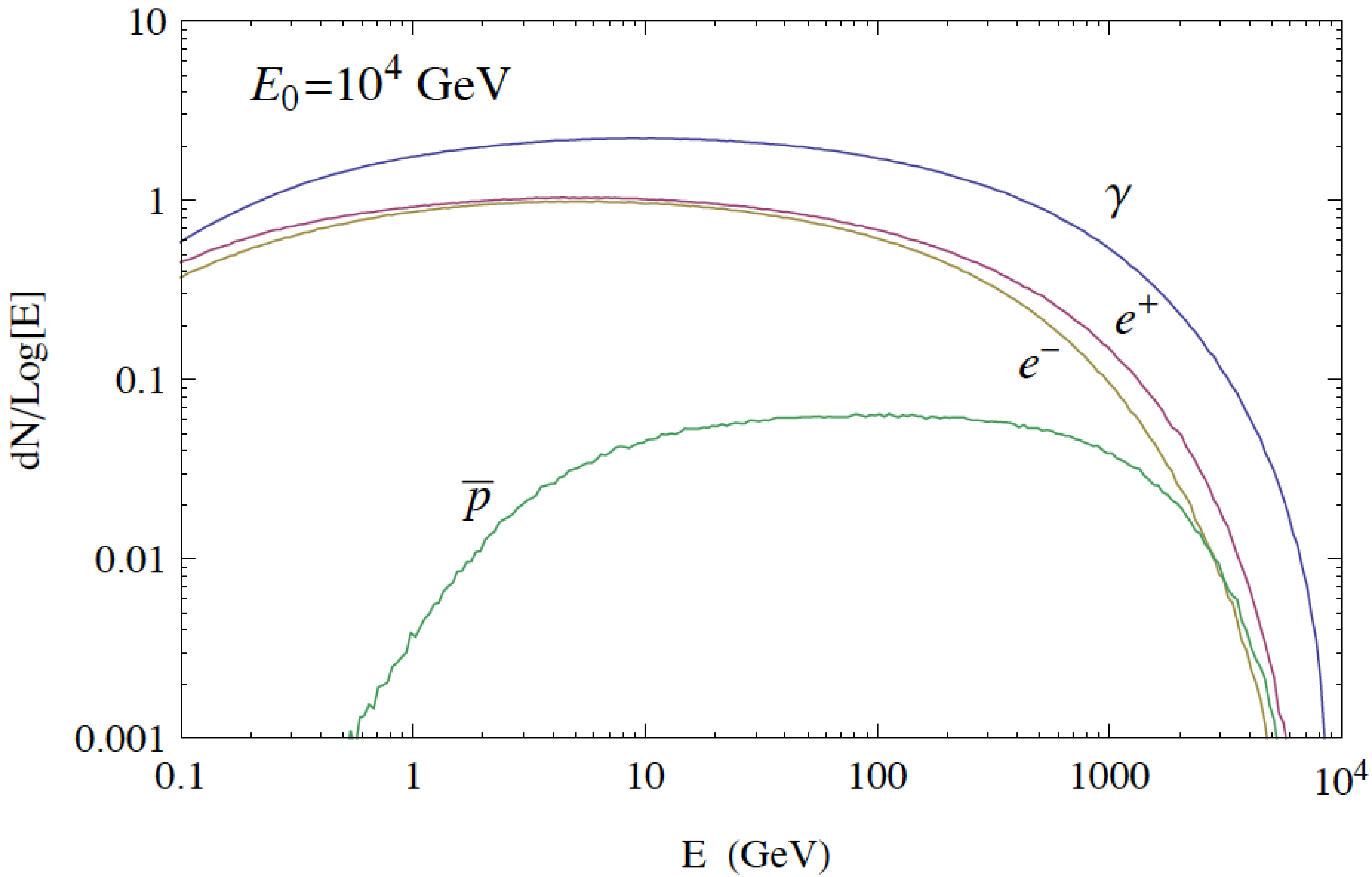
Cumulative Response function

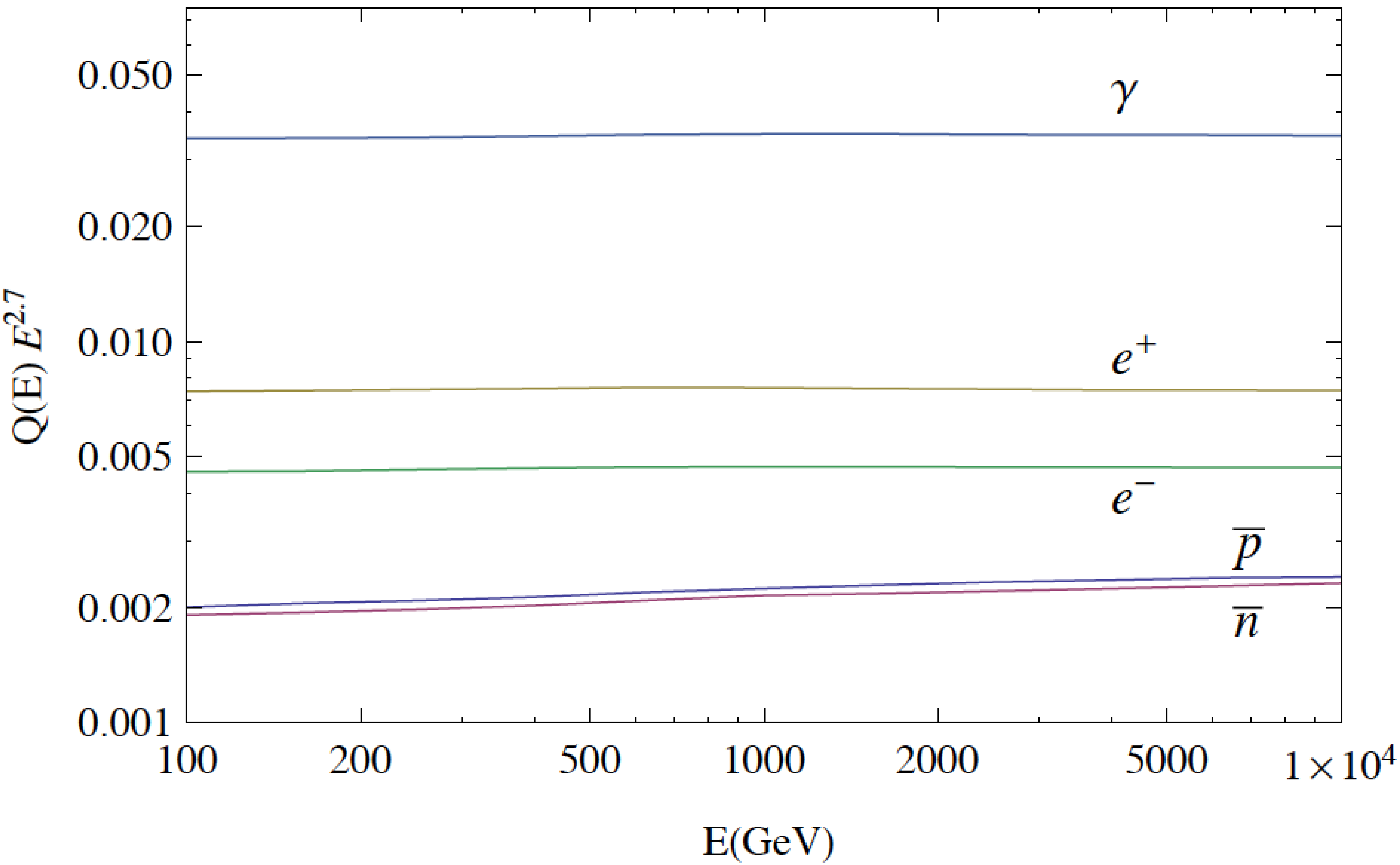




$E_0 = 10^4$ GeV
$\overline{p}$
$\overline{n}$
dN/Log[E_{kin}]
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.00
0.1
1
10
100
1000
10^4
E_{kin} (GeV)

Production of different particles





Q(E) $E^{2.7}$
0.050
0.020
0.010
0.005
0.002
0.001
100
200
500
1000
2000
5000
1×10^4
E(GeV)
γ
e^+
e^-
$\overline{p}$
$\overline{n}$

Nuclear effects:

$p\ p$

$p\ \mathrm{A}$

$\mathrm{A}_1\ \mathrm{A}_2$

$p\ \mathrm{A}$

$$1 \leq N_{\mathrm{target}} \leq A$$

$$\sigma_{p\mathrm{A}} = \sum_{N} \sigma_{N}$$

Glauber theory

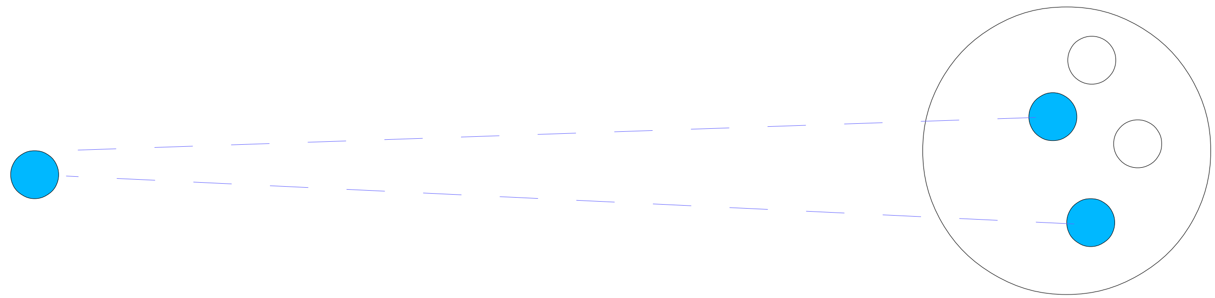
$$P(N) = \frac{\sigma_{N}}{\sigma_{p\mathrm{A}}}$$

Laboratory frame:

$$\left[\frac{dN}{dE}\right]_{pp}$$

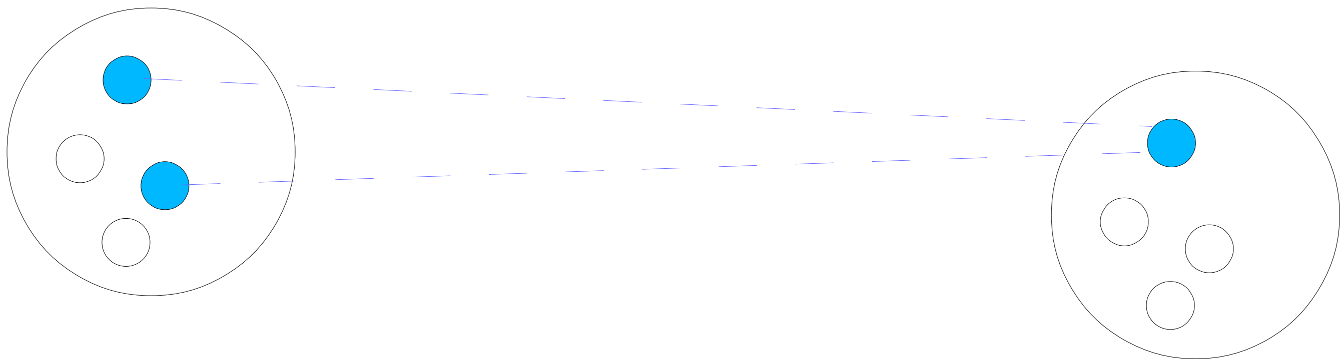
$$\left[\frac{dN}{dE}\right]_{\mathrm{A}p}$$

Spectra moderately softer
in projectile hemisphere



$$\left[\frac{dN}{dE}\right]_{\mathrm{A}\ p} \simeq \langle N_{\mathrm{A}} \rangle \left[\frac{dN}{dE}\right]_{pp}$$

$$\mathrm{A}_1 \ \mathrm{A}_2$$



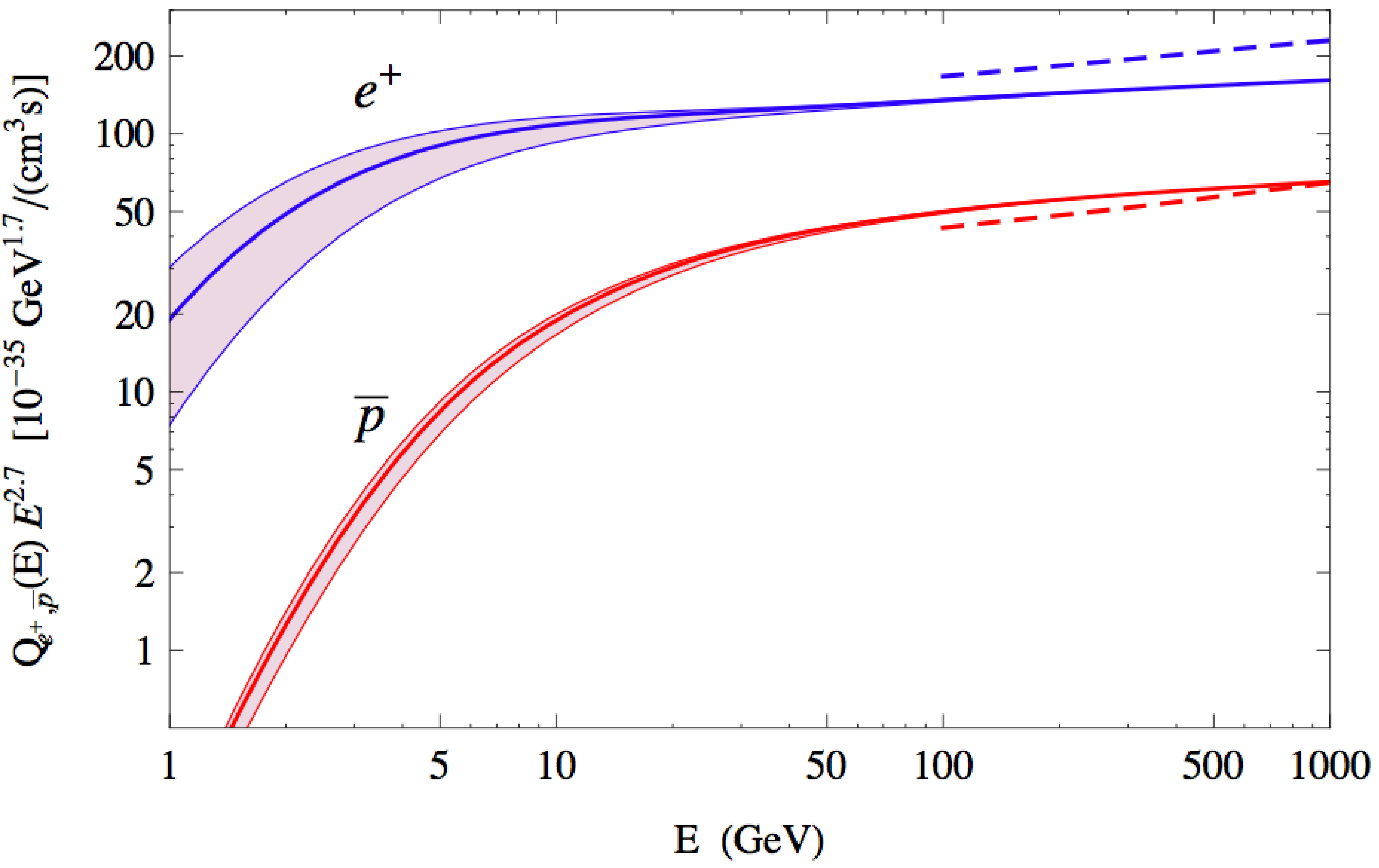
Decomposition of the cross section into partial cross sections

$$1 \leq N_{\mathrm{projectile}} \leq \mathrm{A}_1$$

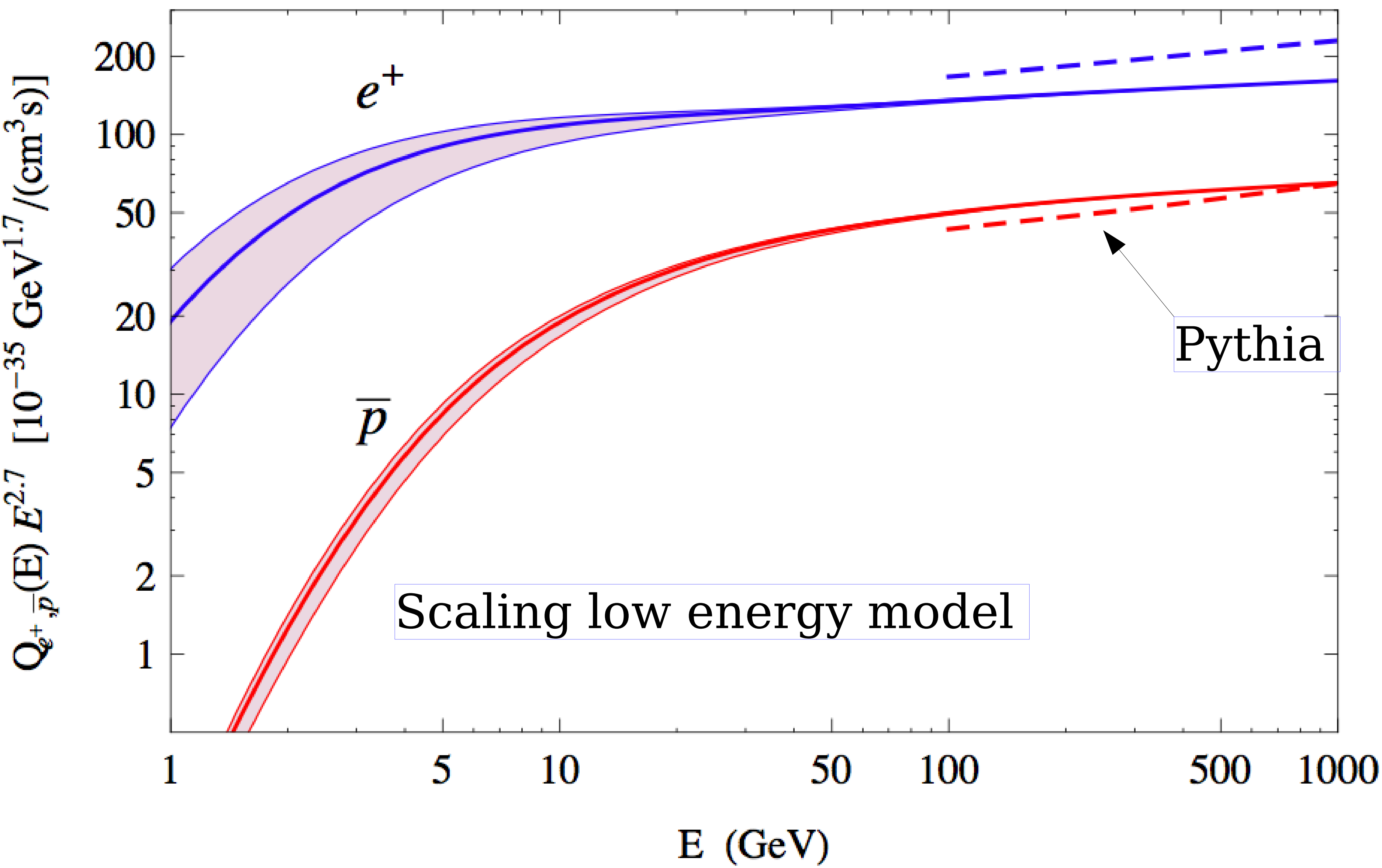
$$1 \leq N_{\mathrm{target}} \leq \mathrm{A}_2$$

$$\left[\frac{dN}{dE}\right]_{\mathrm{A}_1\ \mathrm{A}_2} \simeq \langle N_{\mathrm{A}_1}\rangle \left[\frac{dN}{dE}\right]_{p\mathrm{A}_2}$$

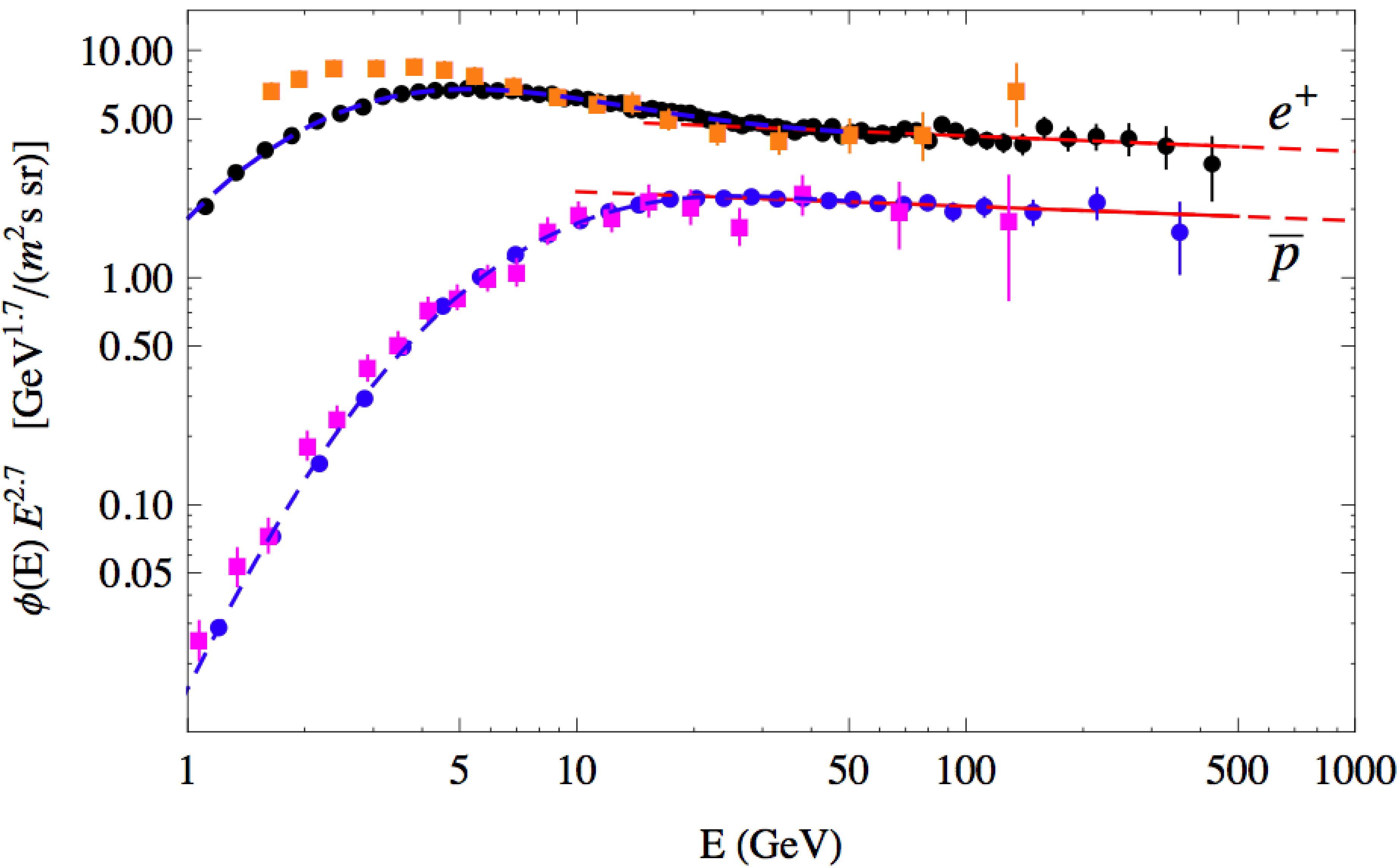
Injection Spectra of positrons and anti-protons



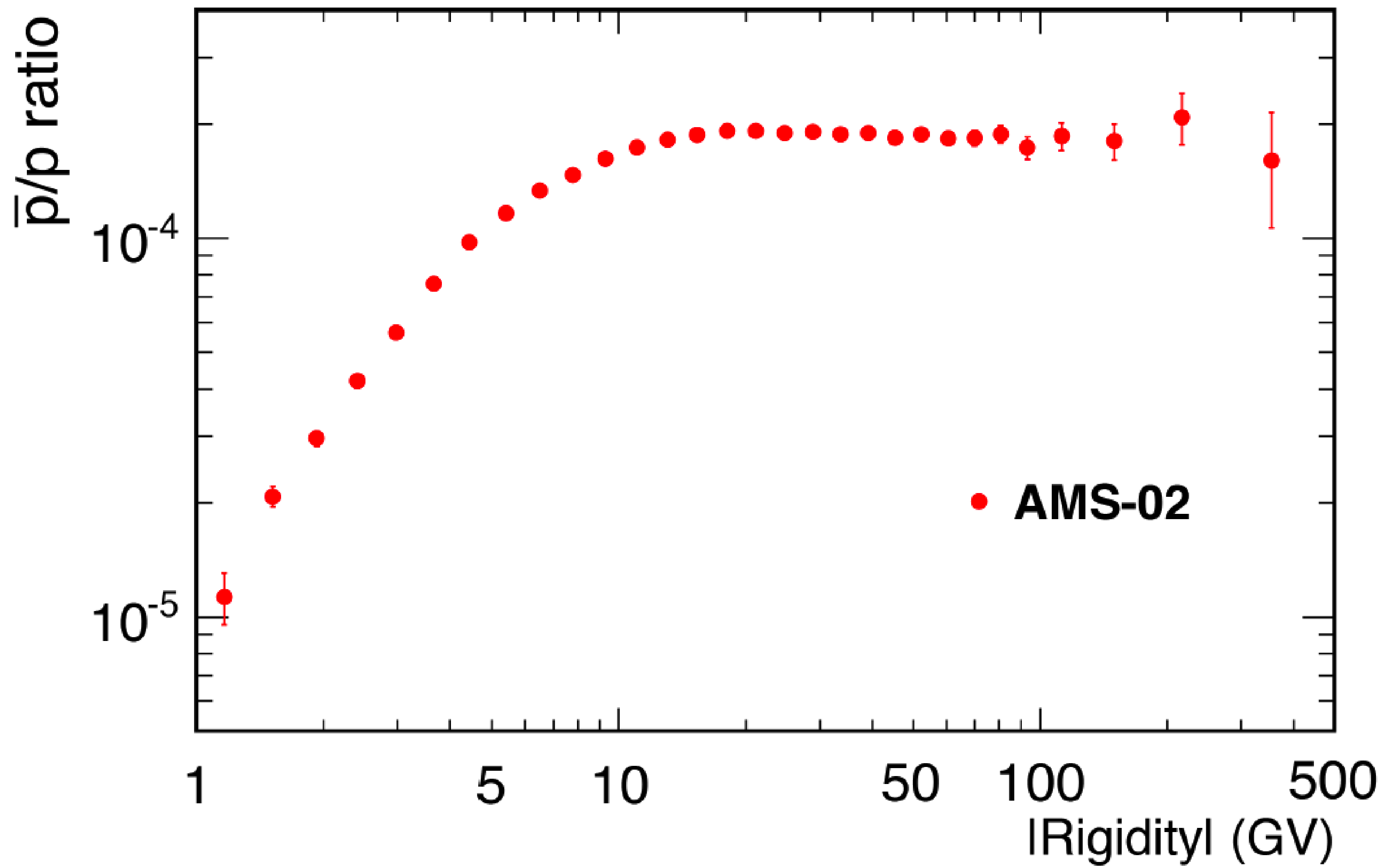
Injection Spectra of positrons and anti-protons



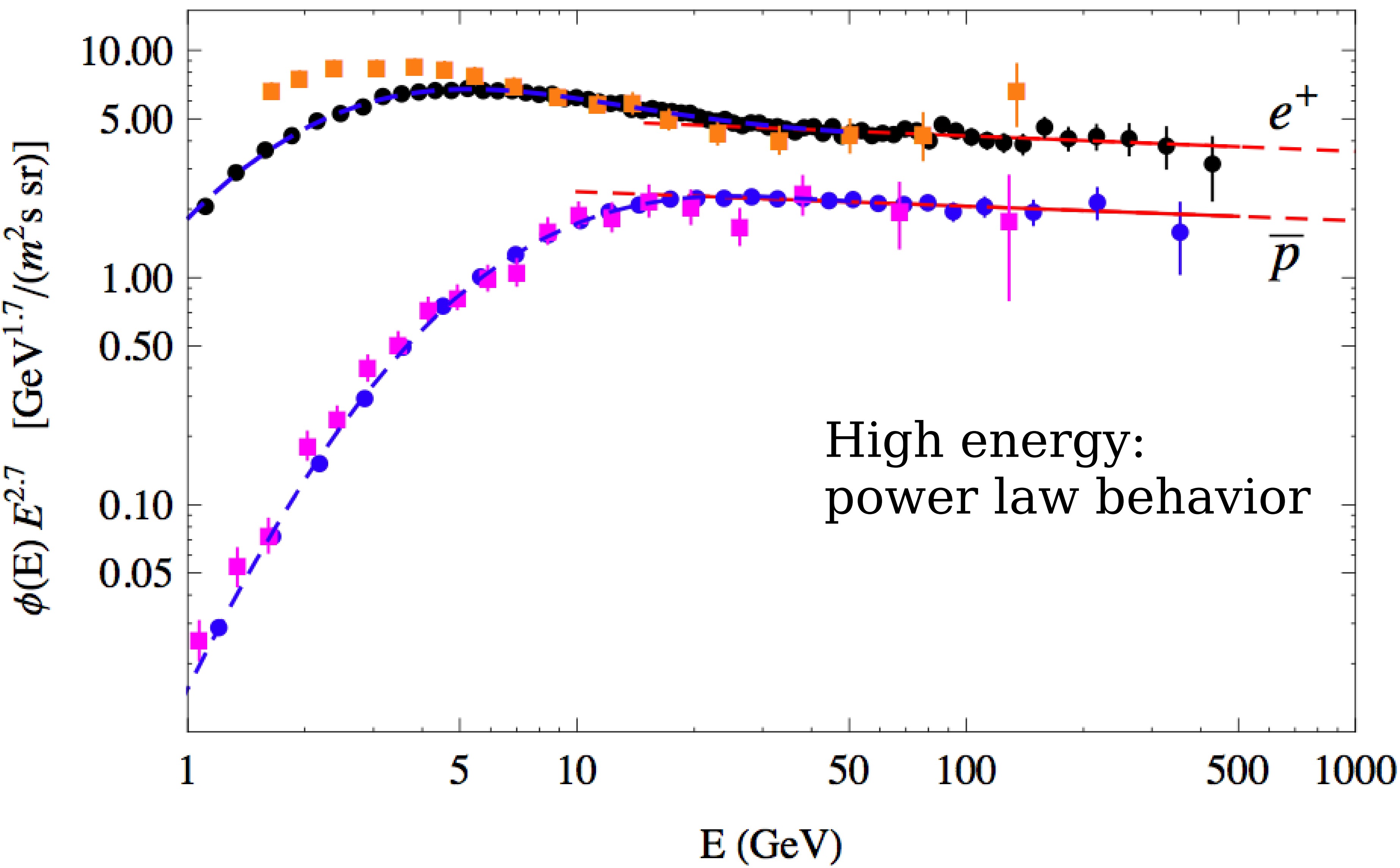
Anti-proton and Positron Cosmic Ray Fluxes



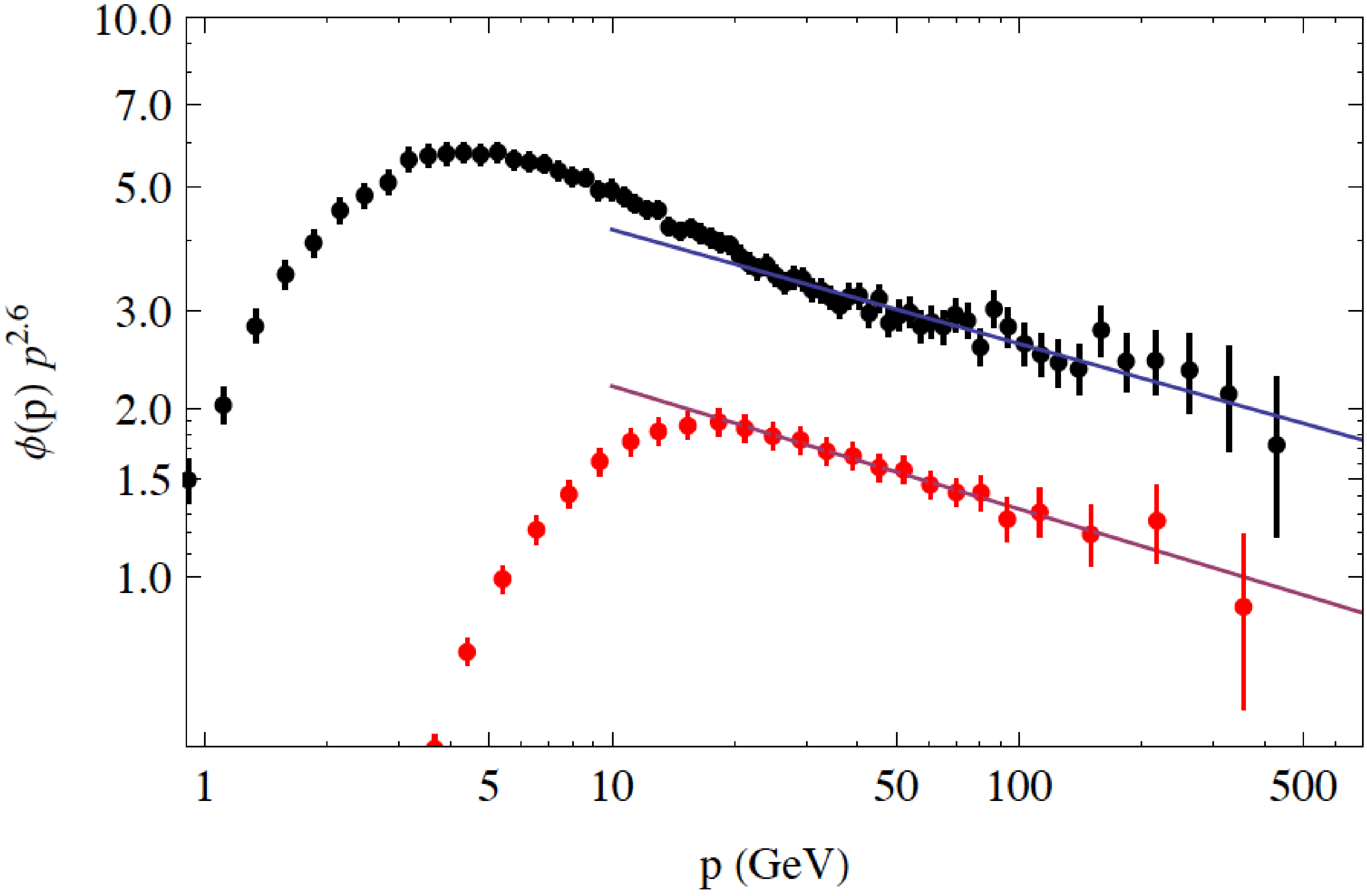
AMS $\bar{p}/p$ results



Anti-proton and Positron Cosmic Ray Fluxes

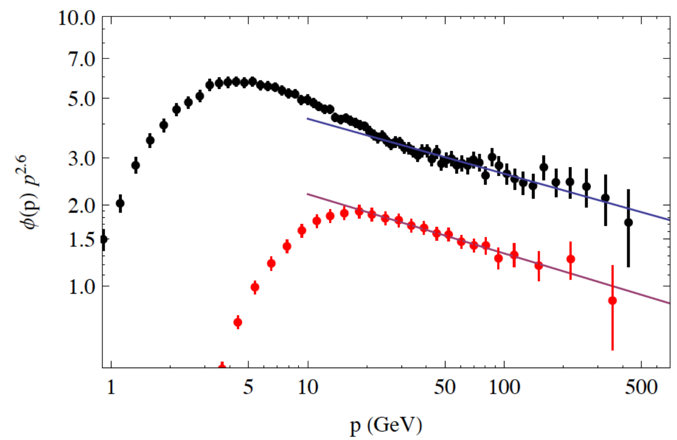


Fluxes of positrons and Anti-protons



$$\phi_j(E) = K_j \; E^{-\alpha}$$

$E > 20$ GeV



$$\chi^2_{\min} = 1.70 \quad (15\text{d.o.f.})$$

$$\alpha \simeq 2.82 \pm 0.02$$

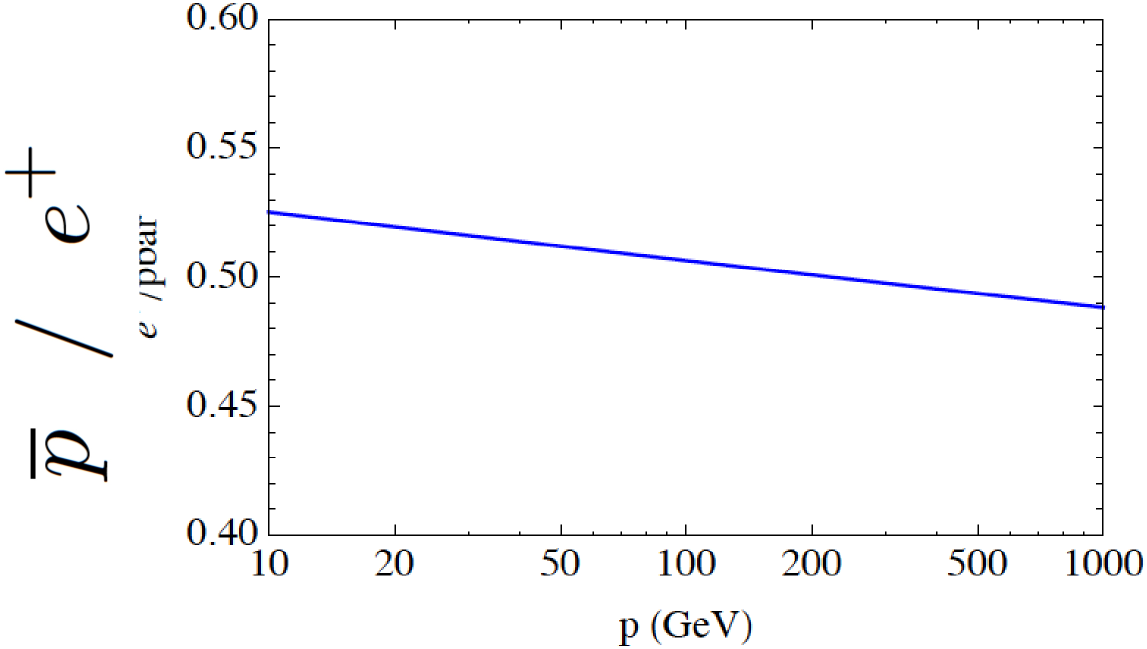
$\bar{p}$

$$\chi^2_{\min} = 18.21 \quad (37\text{d.o.f.})$$

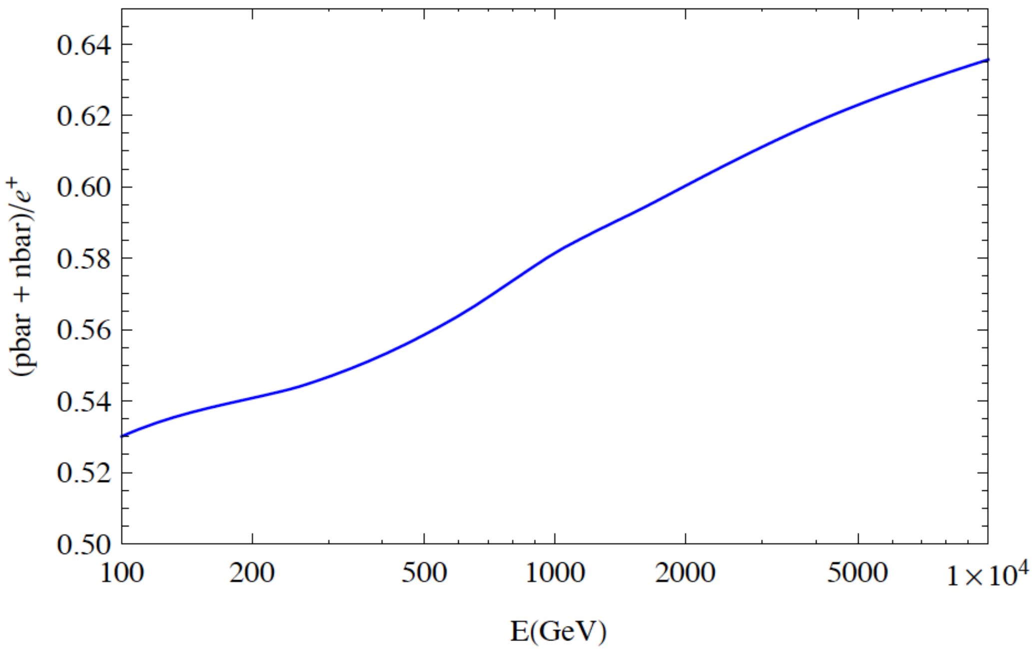
$$\alpha \simeq 2.80 \pm 0.01$$

e^+

Ratio antiproton / positron

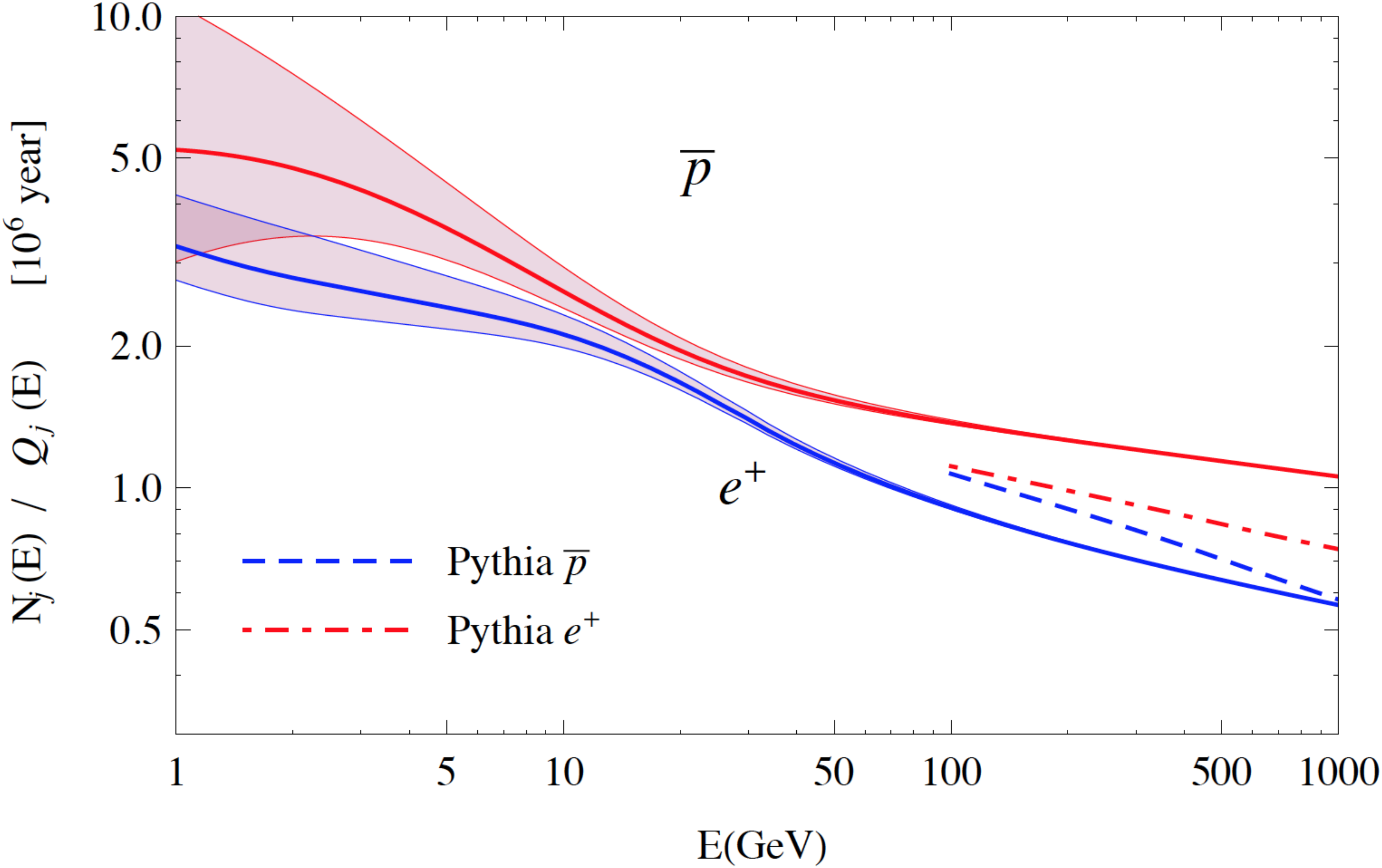


Data



Injection

Ratio Flux / Injection



In the “Conventional Model”
the similarity of the positron and anti-proton fluxes
is simply a *coincidence.*

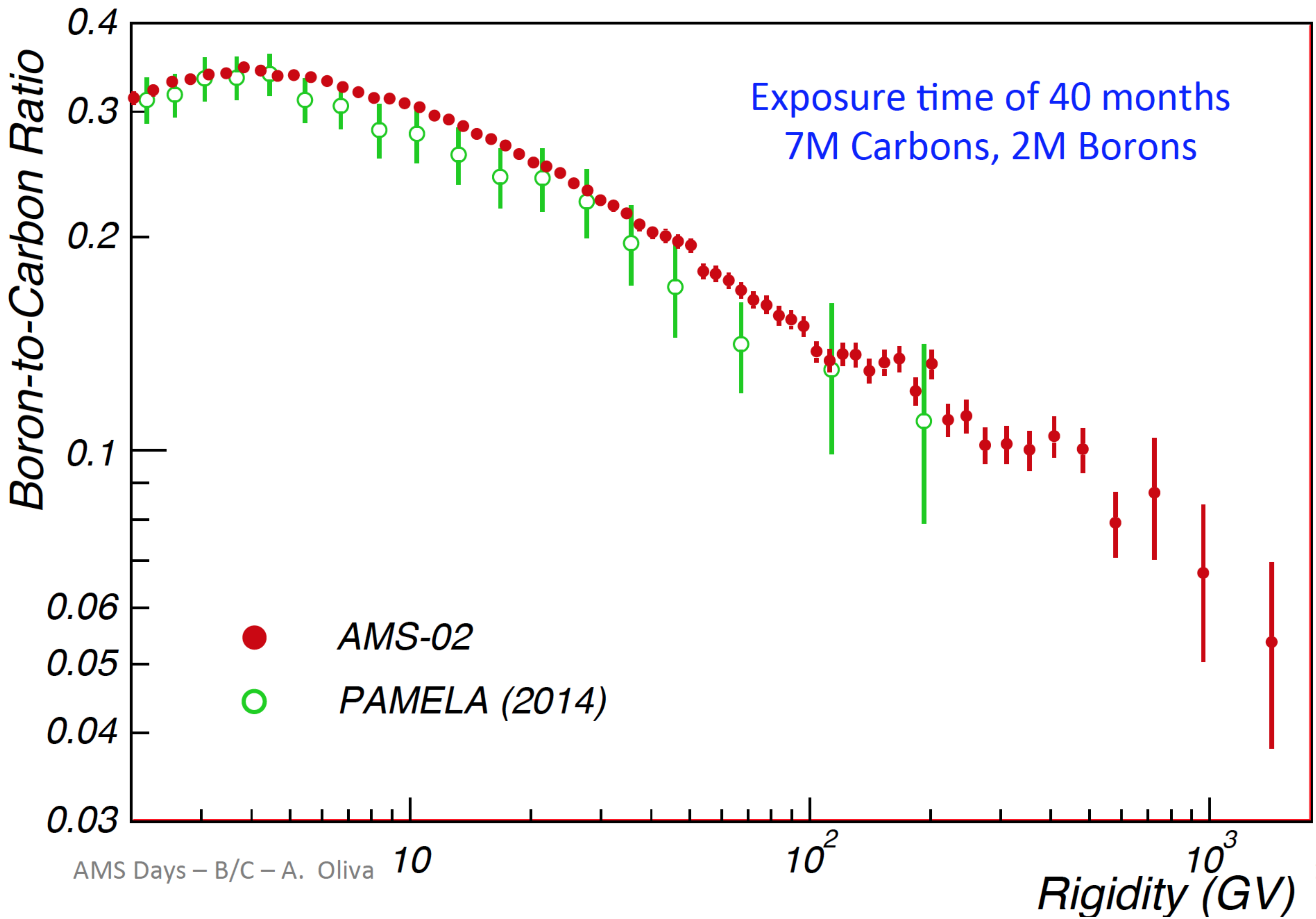
The propagation of electrons/positrons
and protons/anti-protons/nuclei
is considered as very different

$$\frac{\phi_{\overline{p}}(E)}{q_{\overline{p}}(E)} \propto E^{-\delta}$$

$$\frac{\phi_{e^+}(E)}{q_{e^+}(E)} \propto E^{-(1 \oplus \delta)}$$

$$\frac{\phi_{e^+}(E)}{q_{e^+}(E)} \propto E^{-1}$$

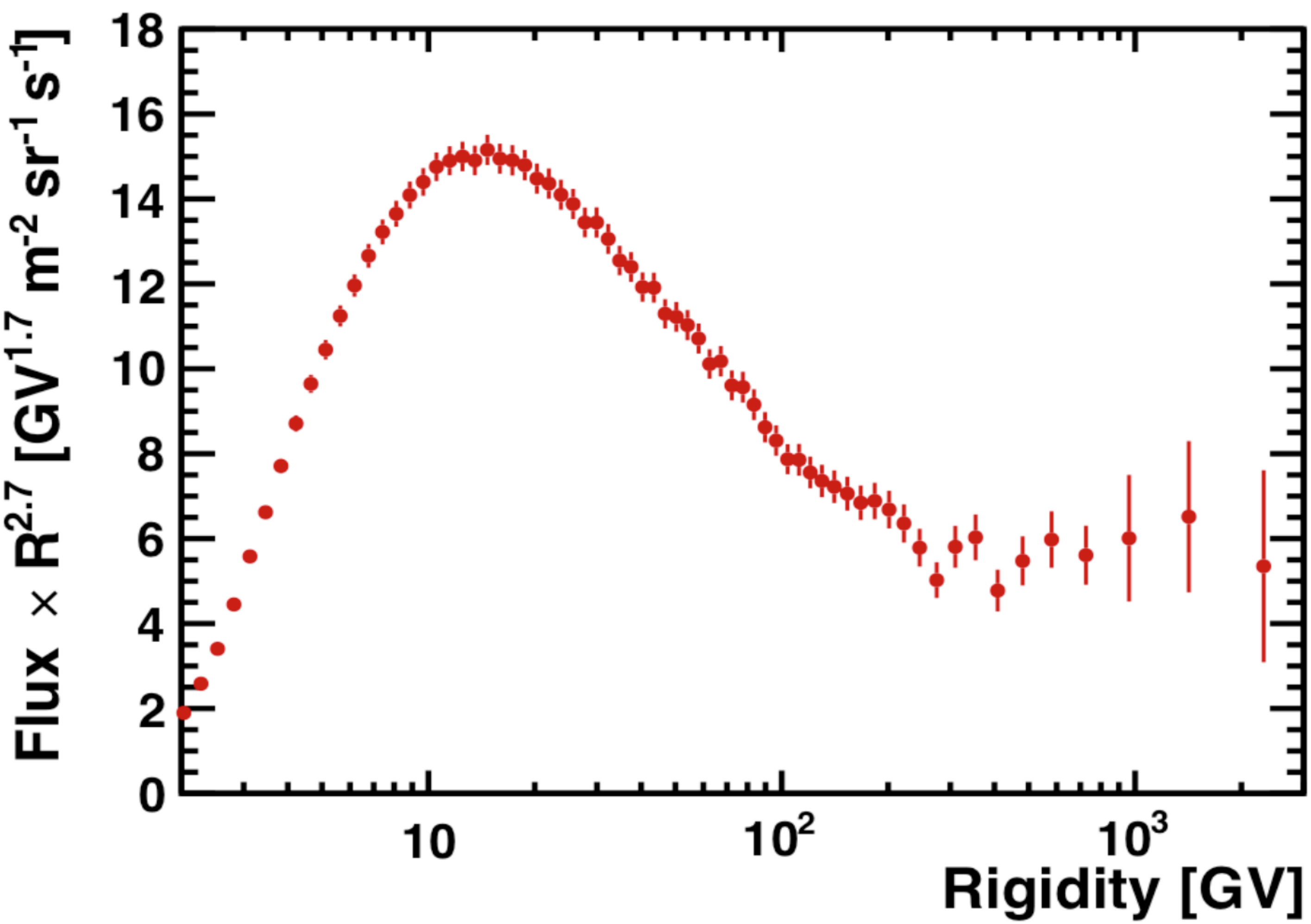
B/C Ratio



Exposure time of 40 months
7M Carbons, 2M Borons
Boron-to-Carbon Ratio
0.4
0.3
0.2
0.1
0.06
0.05
0.04
0.03
AMS-02
PAMELA (2014)
10
10^2
10^3
Rigidity (GV)

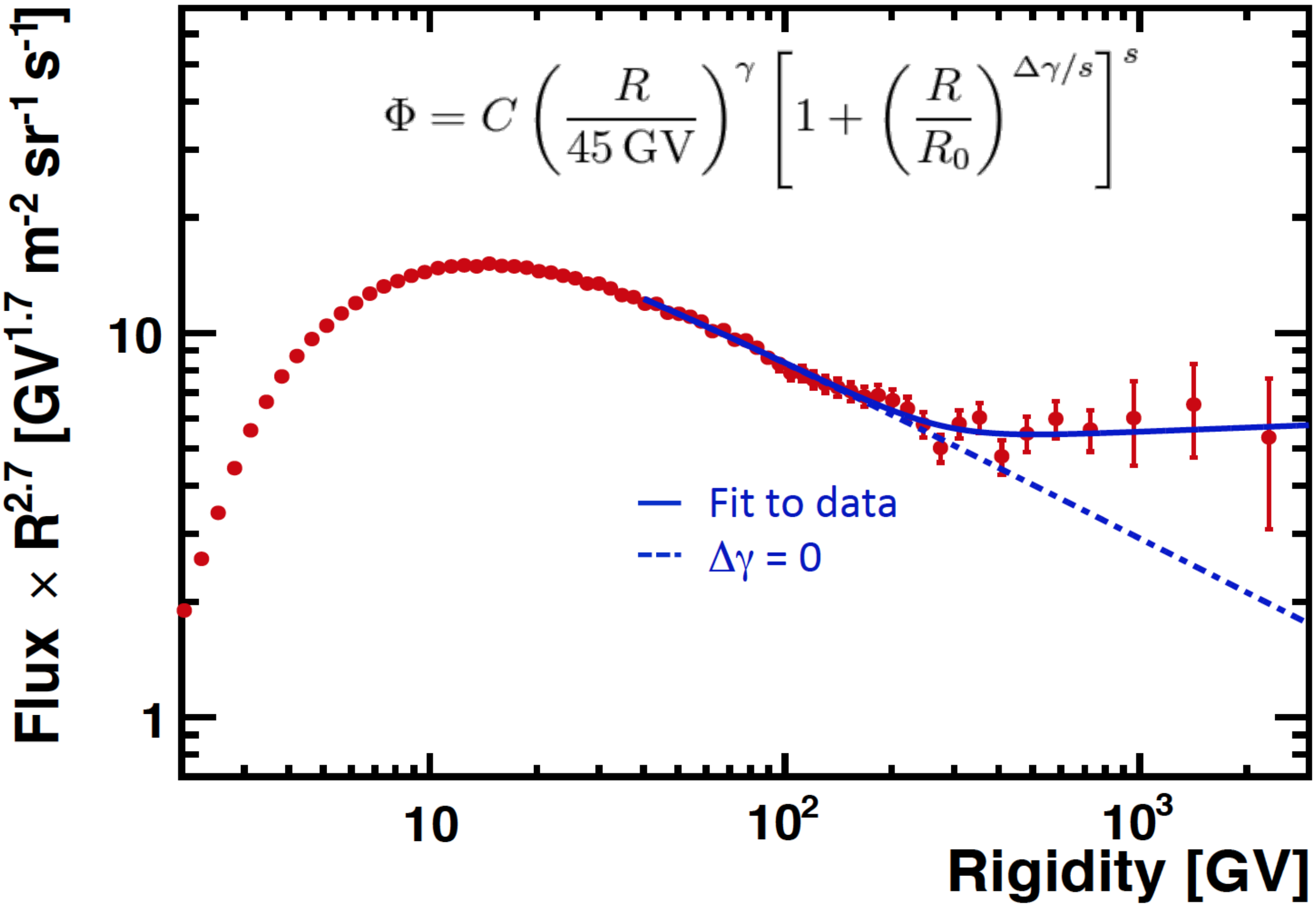
Lithium flux

- Combined result with total errors (Inner+L1 below 800 GV, Full Span above):



Fit of Lithium flux

Same model as the one used for proton and helium (double power law with smooth transition) between 45 GV and 3 TV:

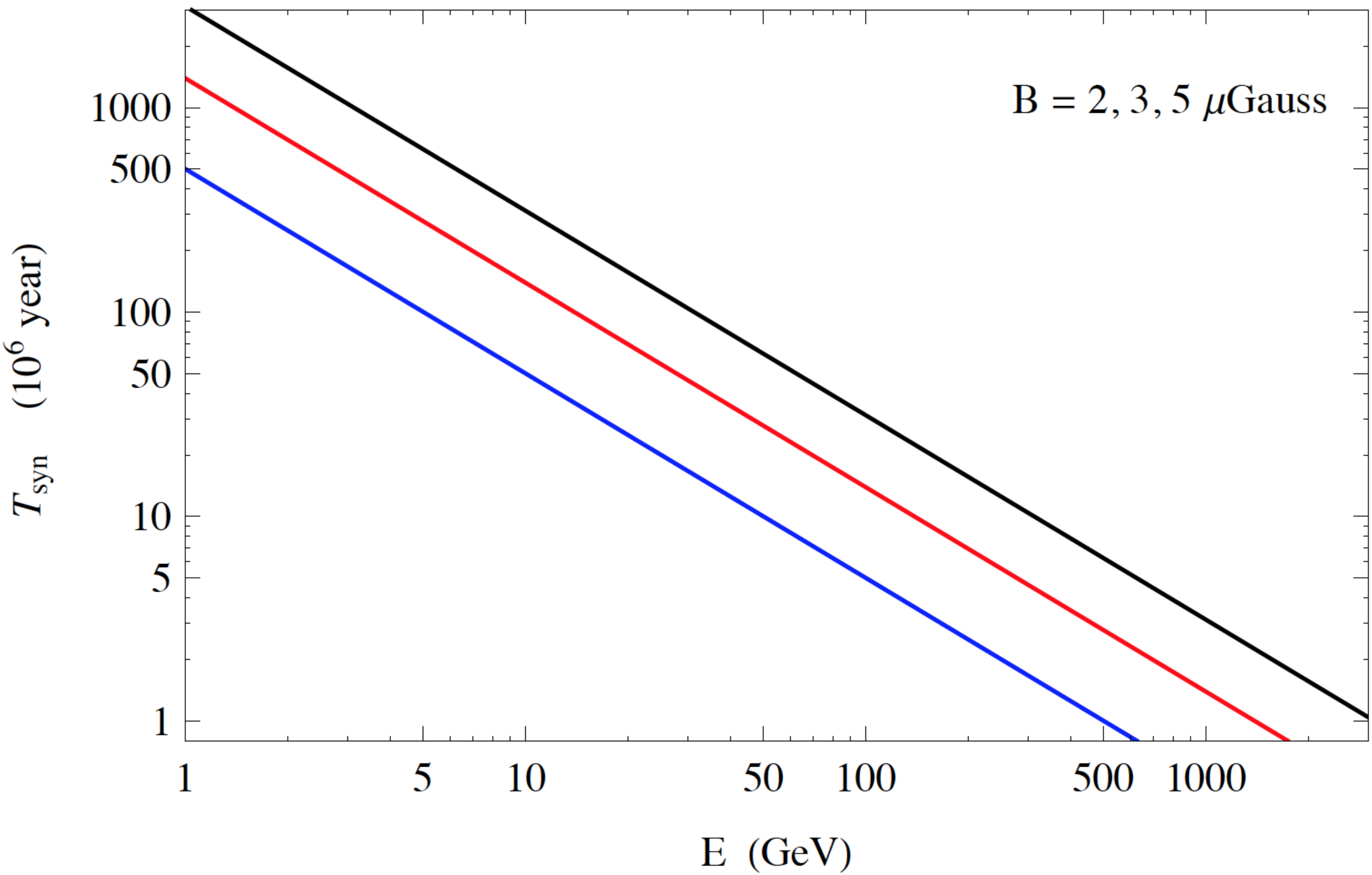


→ Change of slope at the same range than for the one found for Proton and Helium.

Energy losses for Electrons and Positrons:

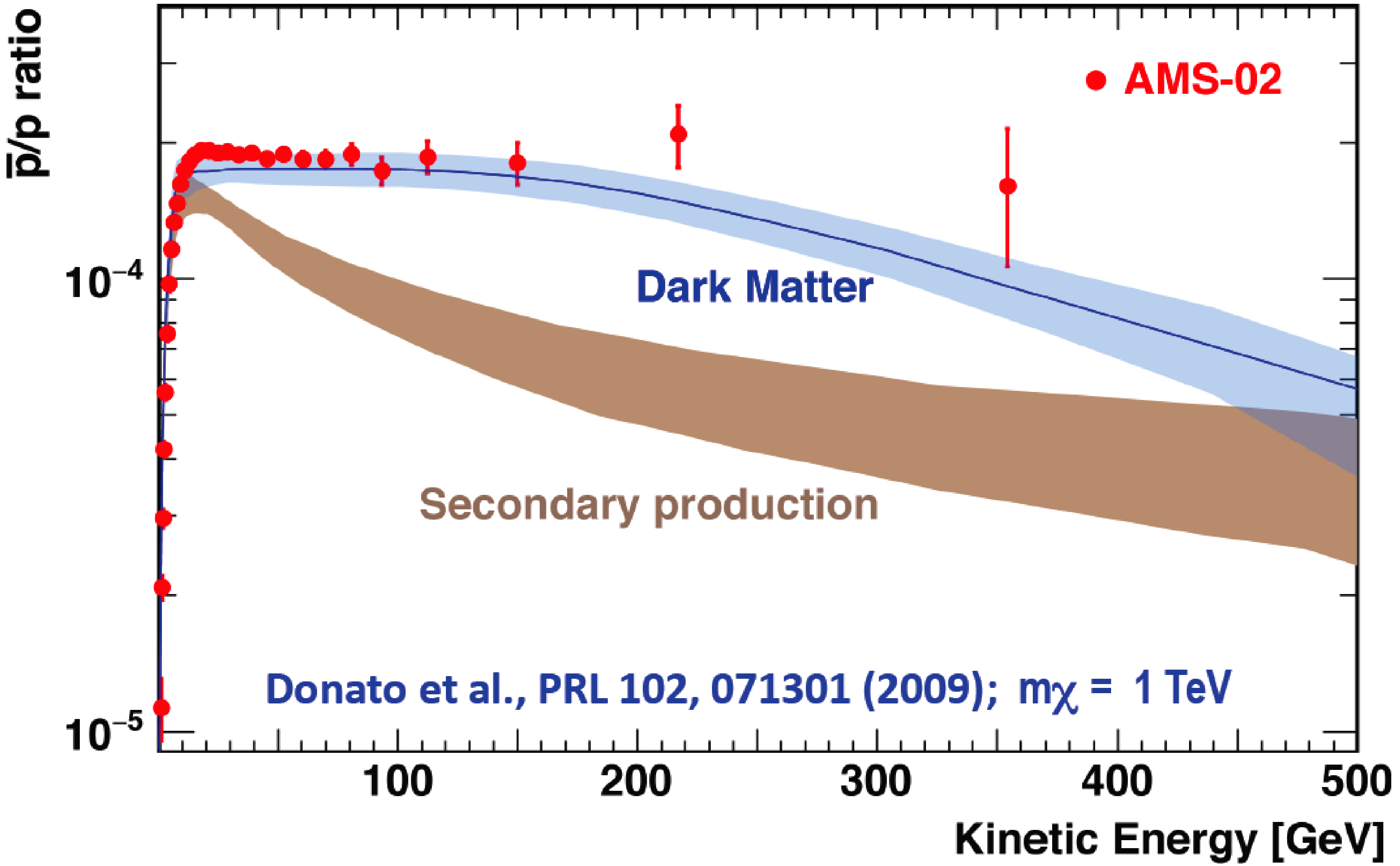
$$- \left. \frac{dE}{dt} \right|_{\rm syn} = \frac{4}{3}\, \sigma_{\rm Th}\, c\, \frac{B^2}{8\pi}\, \frac{E^2}{m^2}$$

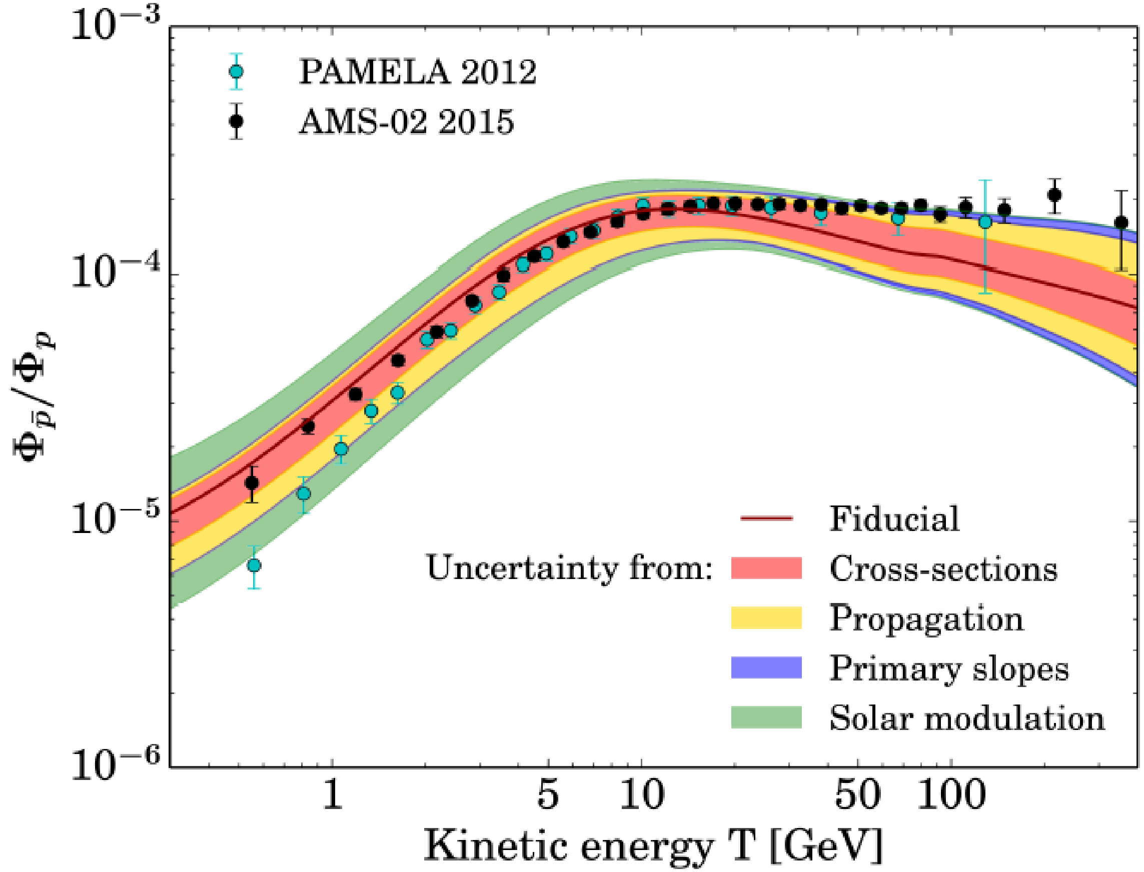
$$T_{\rm syn} = \frac{E}{|dE/dt|} = \frac{1.2514 \times 10^4 \ {\rm Myr}}{E_{\rm GeV}\ B^2_{\mu {\rm G}}}$$



B = 2, 3, 5 μGauss
1000
500
100
50
10
5
1
T syn (10^6 year)
1
5
10
50
100
500
1000
E (GeV)

AMS $\bar{p}/p$ results and modeling

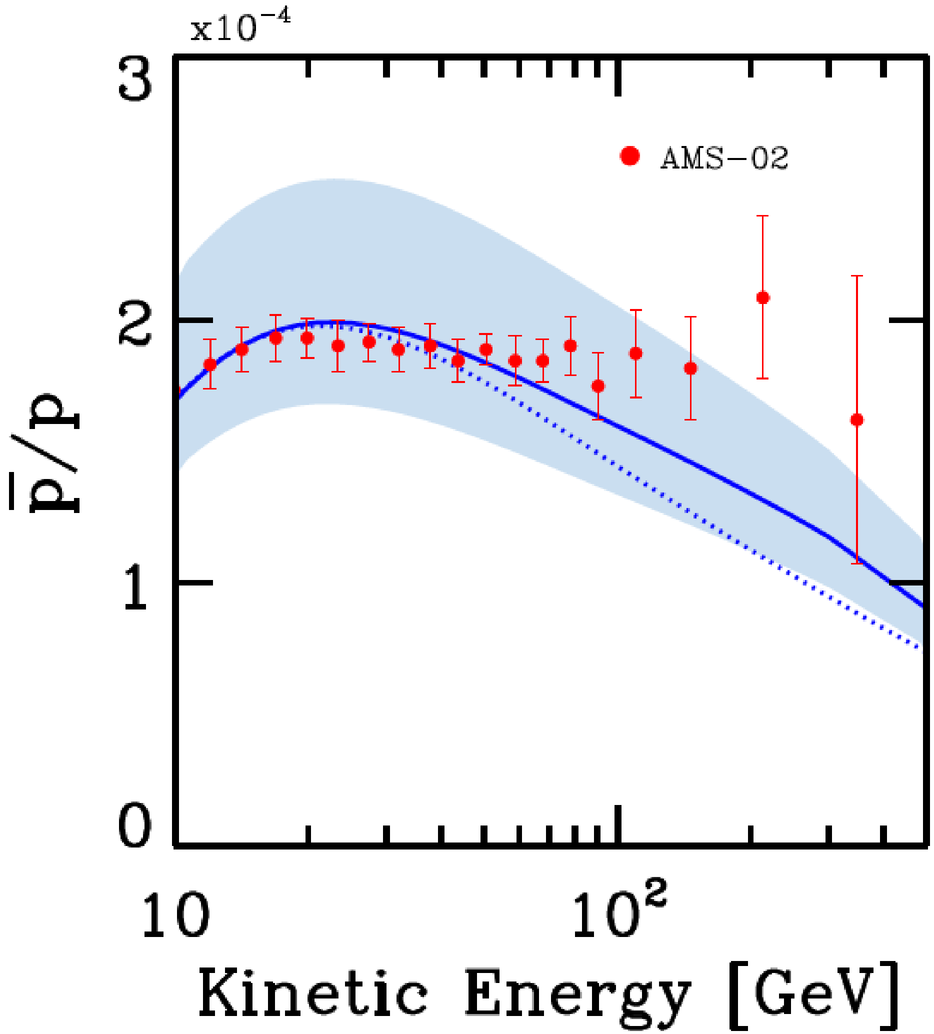




AMS-02 antiprotons, at last!

Secondary astrophysical component and immediate implications for Dark Matter

Gaëlle Giesen[a*], Mathieu Boudaud[b], Yoann Génolini[b], Vivian Poulin[b,c], Marco Cirelli[a], Pierre Salati[b], Pasquale D. Serpico[b]



Secondary antiprotons as a Galactic Dark Matter probe

Carmelo Evoli[a] Daniele Gaggero[b] Dario Grasso[c]