PRODUCTION OF SECONDARY PARTICLES IN THE GALAXY

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4th International Workshop on QCD Challenges from pp to AA collisions

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arXiv:1802.03030, Phys. Rev. D (2018) 97, 103019

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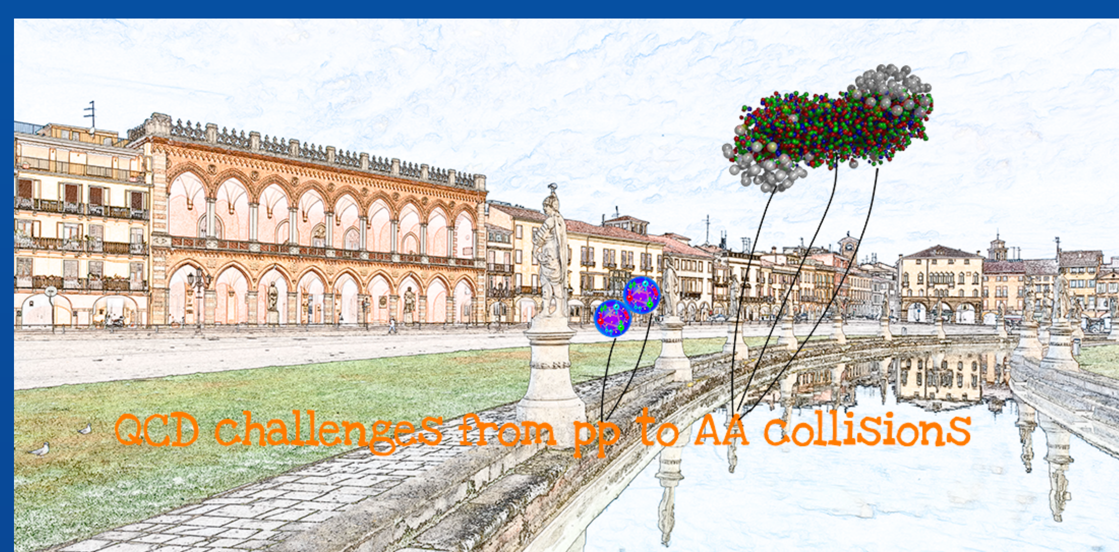

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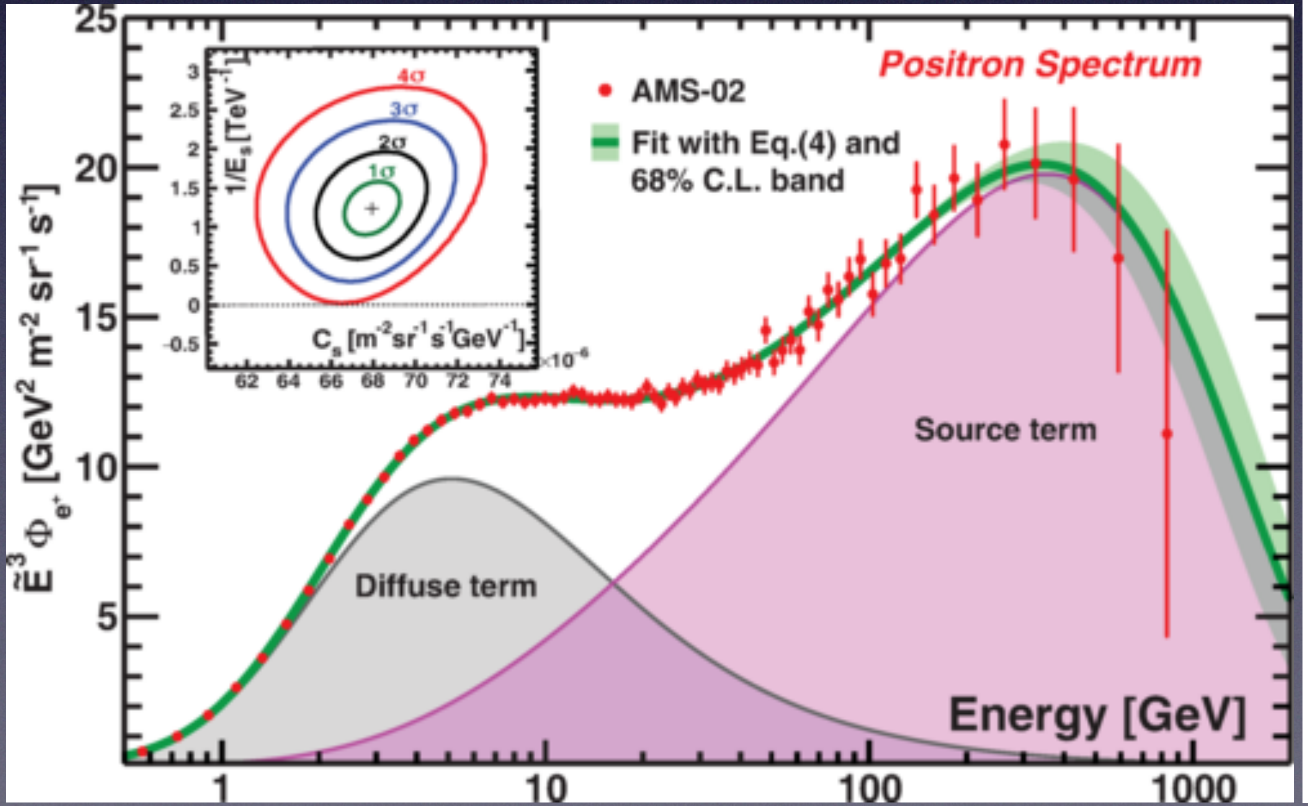
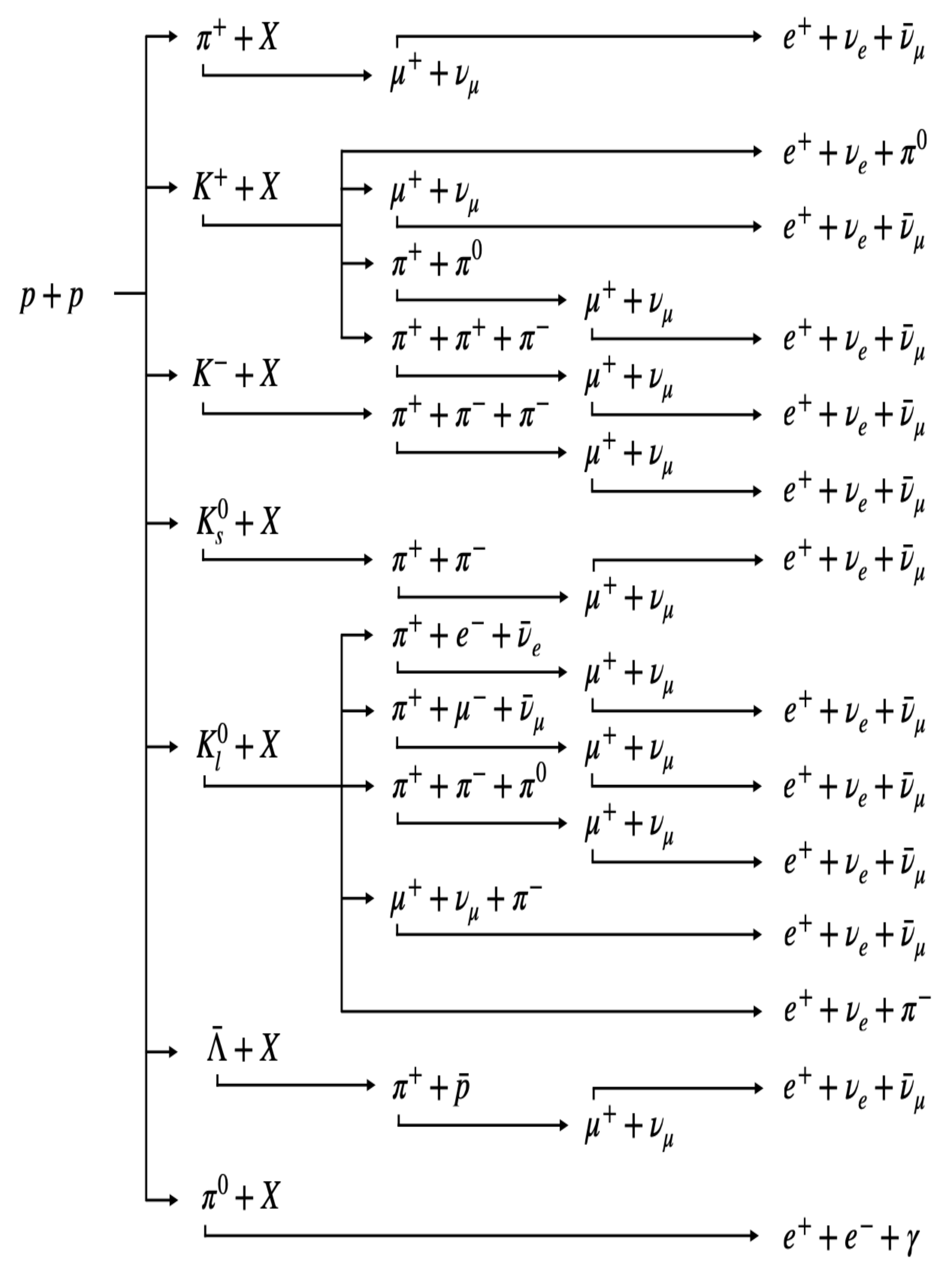
1. Secondary positrons

The journey started with the attempt, shared by many, to interpret the e^+ data.

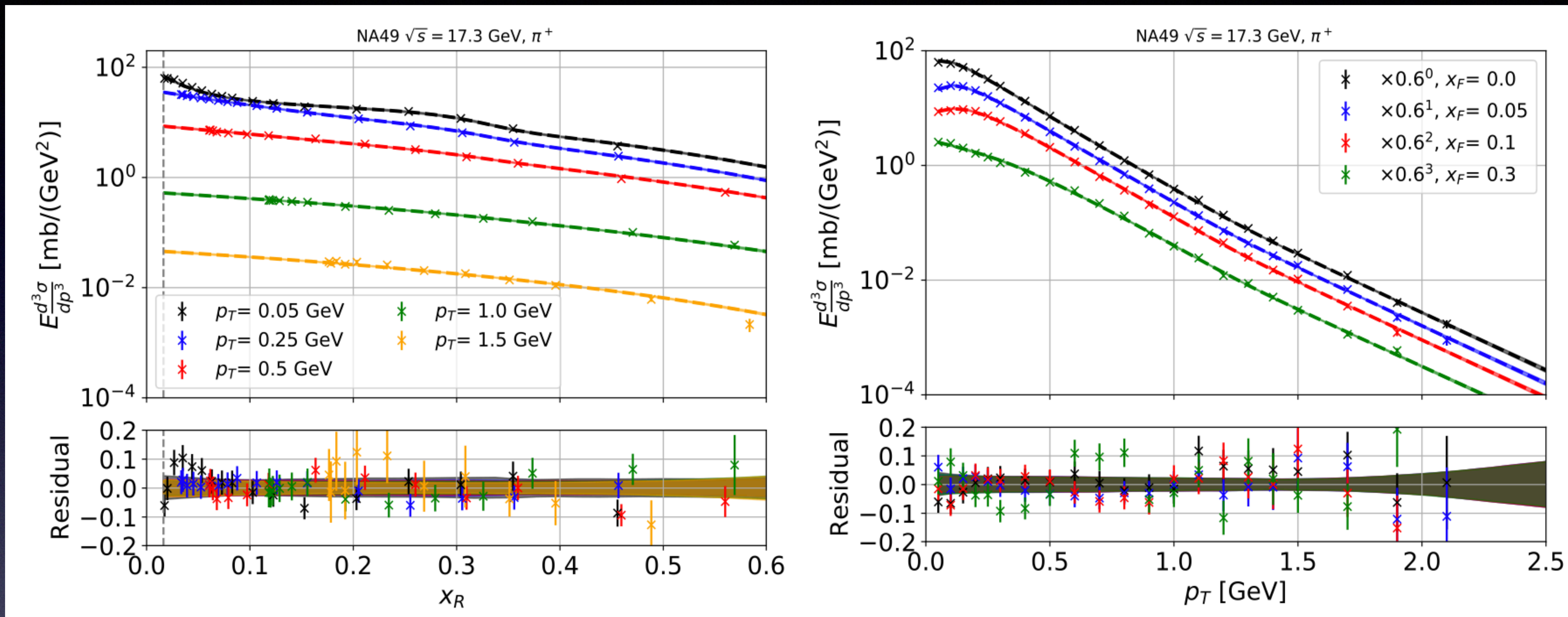
- AMS-02 positron flux measures → secondary + primary contribution.
- $$q(T_{e^+}) = \sum_{i,j} 4\pi\, n_{\mathrm{ISM},j} \int dT_i\, \phi_i(T_i) \frac{d\sigma_{ij}}{dT_{e^+}}(T_i, T_{e^+})$$
- Previous $d\sigma(p + H \to e^{\pm} + X)$ predictions affected by factor 2 of uncertainty.



AMS-02 Collab, PRL122(2019)



2. Fit to π^+ data



- Total uncertainties between 5 and 10%. $\sqrt{s}$ = 5-50 GeV relevant.
- Integrating the σ_{inv} over the solid angle and combining the result with the π^+ decay, we obtain the $\frac{d\sigma_{ij}}{dT_{e^+}}(T_i, T_{e^+})$ from π^+.

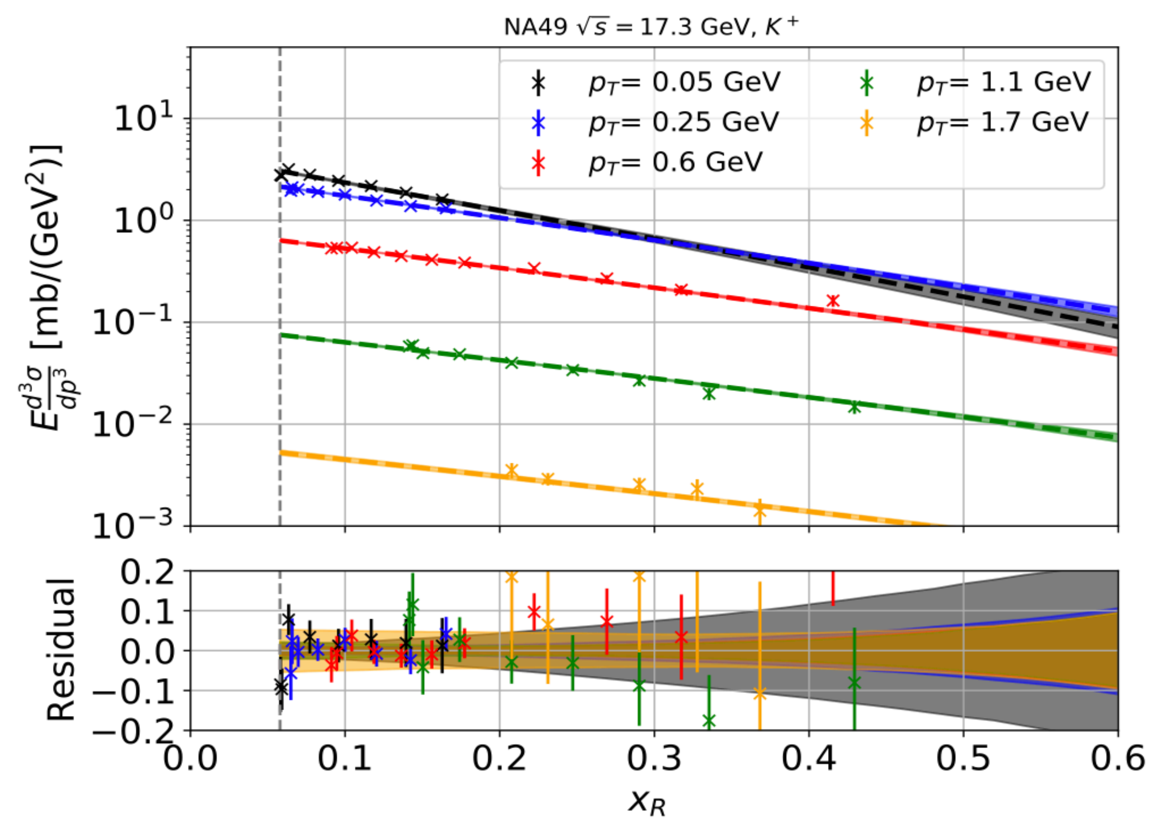
Experiment	$\sqrt{s}$ [GeV]		σ_{inv}	n	Ref.
NA49	17.3	$(\pi^\pm, K^\pm)$	$\surd$	-	[67, 76]
ALICE	900	$(\pi^+, K^\pm)$	$\surd$	-	[77]
CMS	900, 2760, 7000, 13000	$(\pi^\pm, K^\pm)$	$\surd$	-	[78, 79]
Antinucci	3.0, 3.5, 4.9, 5.0, 6.1, 6.8	$(\pi^\pm)$	-	$\surd$	[80]
	2.8, 3.0,3.2, 5.3, 6.1, 6.8	(K^+)	-	$\surd$	[80]
	4.9, 5.0, 6.1, 6.8	(K^-)	-	$\surd$	[80]
NA61/SHINE	6.3, 7.7, 8.8, 12.3, 17.3	$(\pi^\pm, K^\pm)$	-	$\surd$	[68]

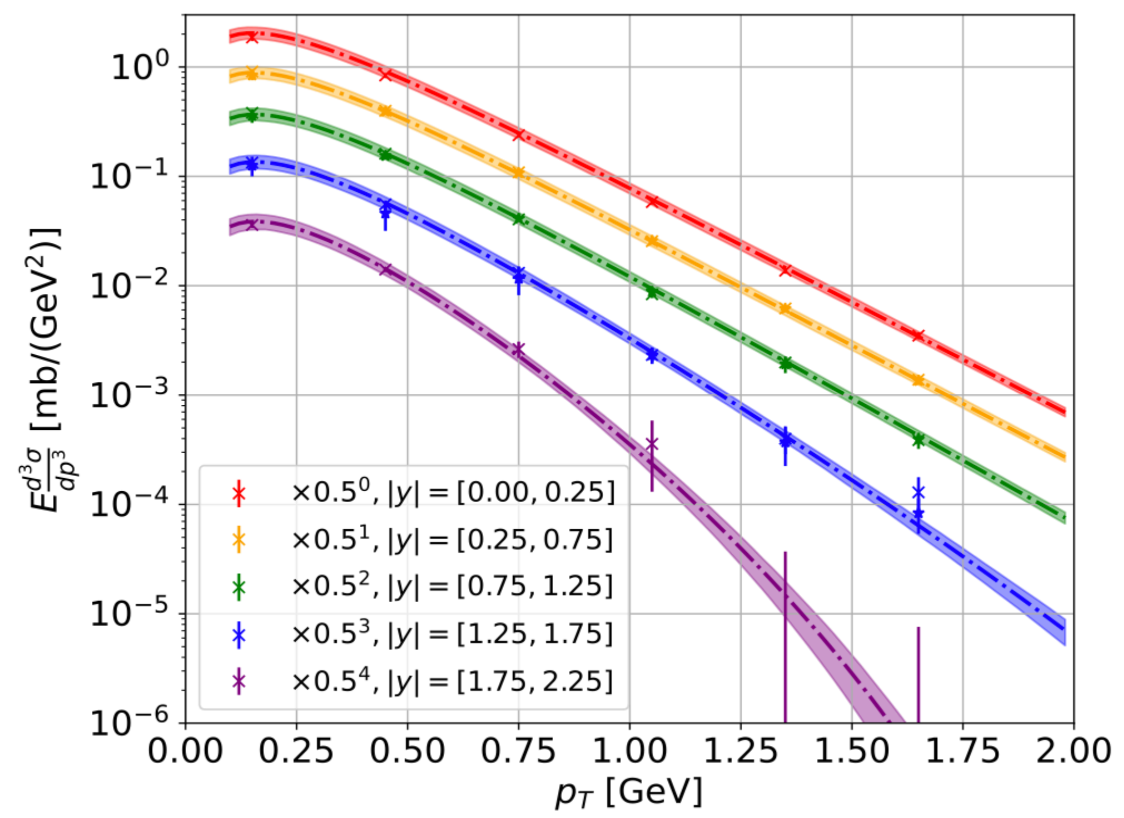
3. Other channels

We also have to consider the π^+ created from weak decays of strange particles and not included in π^+ dataset, that are:

- $K^{\pm}$: fit on available data.
- K^0_S: fit on available data.
- K^0_L: rescaled contribution from K^0_S.
- $\bar{\Lambda}$, Σ and Ξ: rescaled contribution from the Λ.

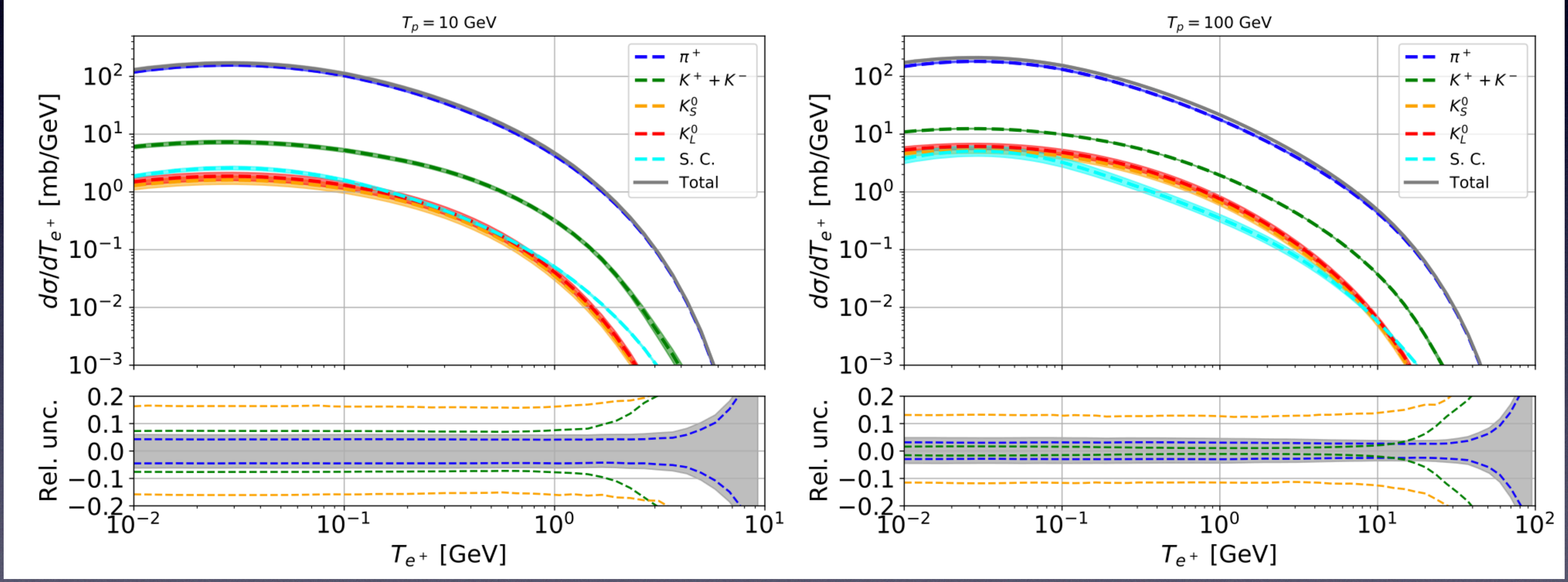
In the end we also consider the contribution from π^0 to the e^+ yield by multiplying the charged pions cross sections by a normalization factor connected to the multiplicity of π^+, π^0.





4. Results on the e^+ production cross section

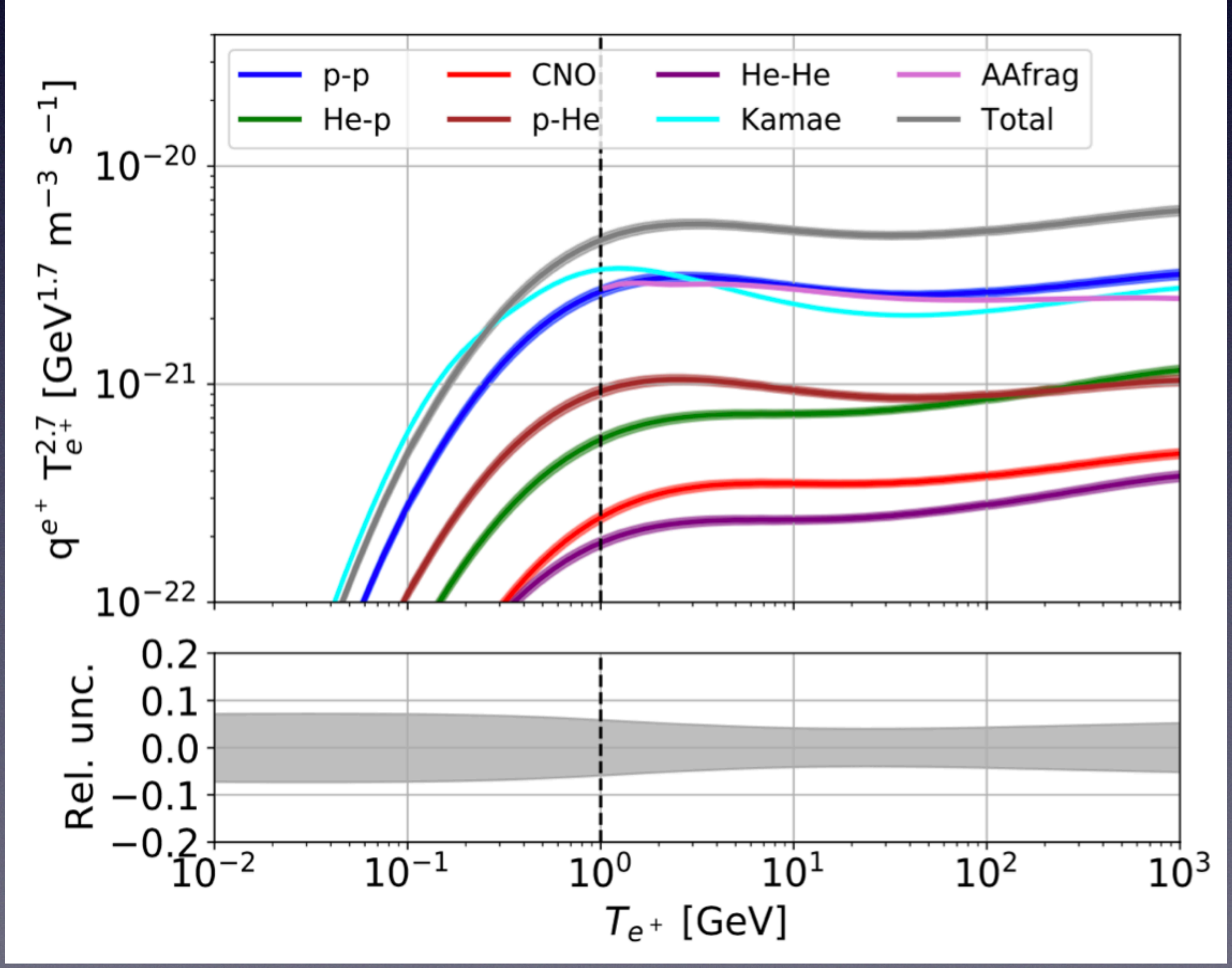
- The π^+ channel dominates the total cross section, being about 10 times higher than the K^+ channel.
- Positron production from K_S^0, K_L^0, and subdominant channels are all contributing at a few % level.
- The main comment to these results is the smallness of the uncertainty with which we determine $d\sigma/dT_{e^+}$. At 1σ the uncertainty band around the best fit is 5% to 8% at all T_p energies.



In the Galaxy, nuclei interactions (p + A, A + p, and A + A) give a significant contribution to the production of secondary particles. We use the data of NA49 for the production of π^+ in p+C collisions at $\sqrt{s}$ =17.3 GeV and NA61 data at $\sqrt{s}$ =7.7 GeV for the other channels.

4. Results on the e^+ production cross section

- The *q(E)* is predicted with a remarkably small uncertainty, ranging from 5% to 8% depending on the energy.
- The channels involving He, both projectile and target, constitute 30-40% of the total spectrum depending on the positron energy.
- The heavier primary CNO nuclei contribute a non negligible few percent at the AMS-02 energies.

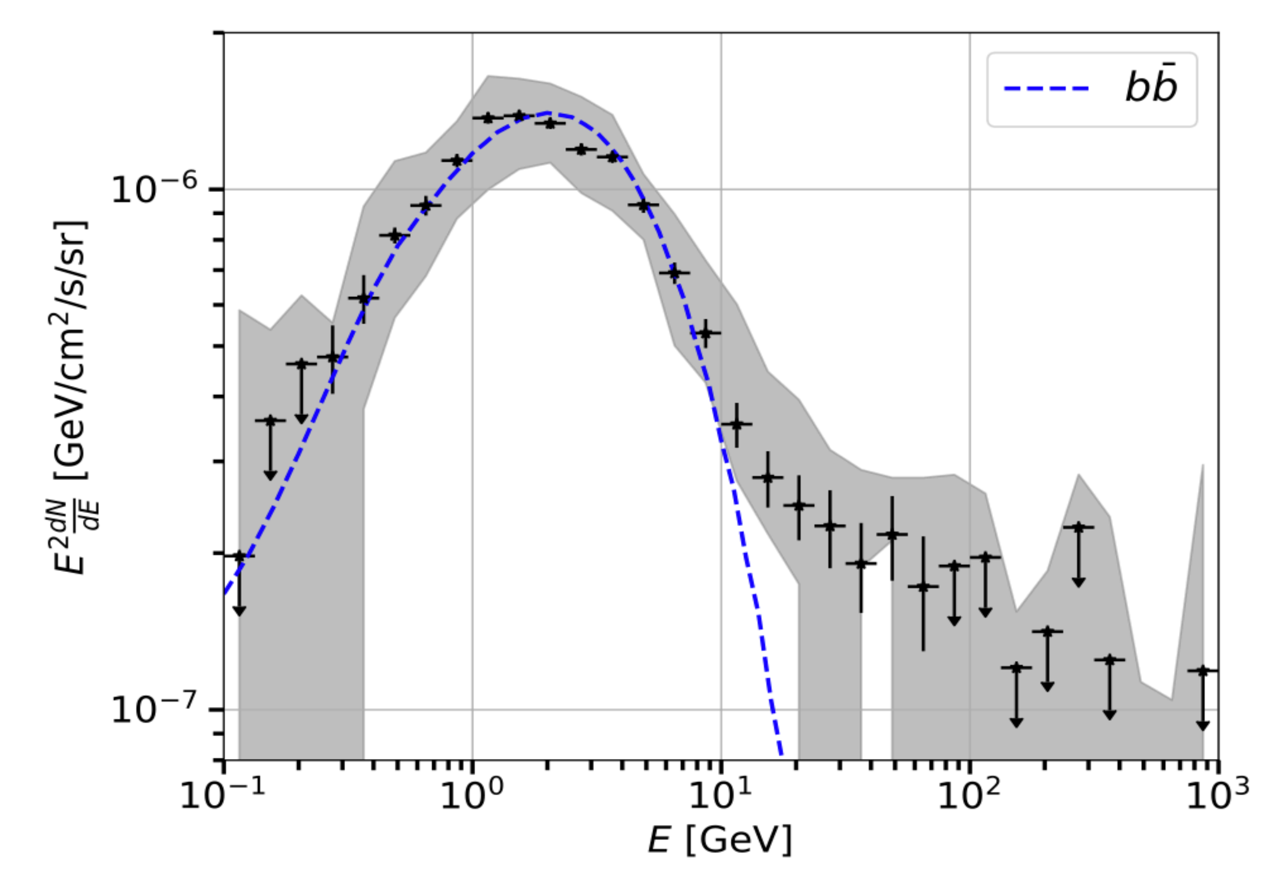


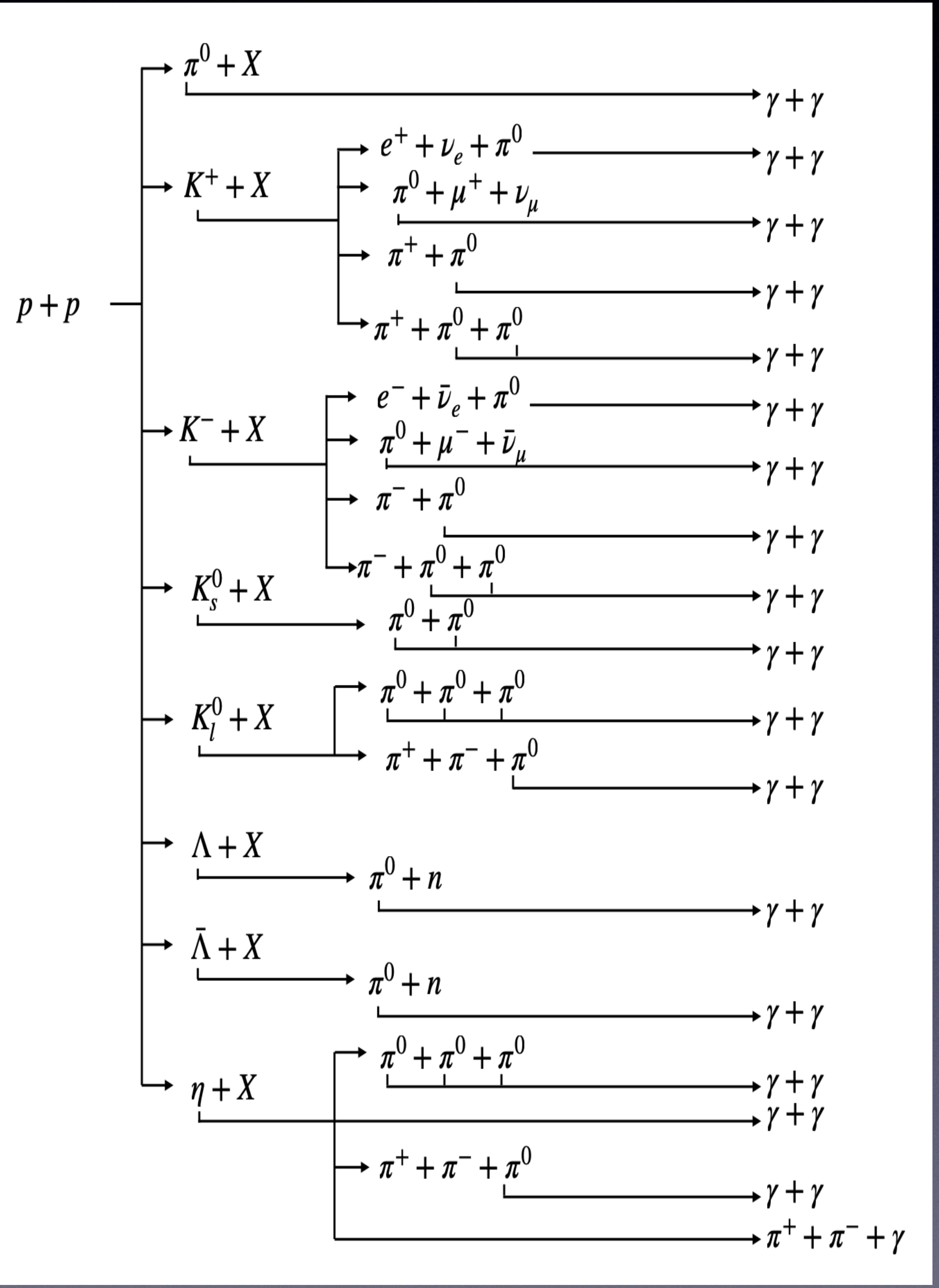
- Including all the production and decay channels, the total $d\sigma/dT_{e^\pm}(i+j \to e^\pm + X)$ is predicted from 10 MeV up to tens of TeV of $e^\pm$ energy (https://github.com/lucaorusa/positron_electron_cross_section).
- Future measurements of pion production in the p+He could help to improve the predictions for nuclei channels.

5. Diffuse γ-ray emission

Most of the γ rays detected by Fermi-LAT are produced by the Galactic insterstellar emission.

- γ-ray production cross section $\sigma(p+p \rightarrow \gamma + X)$ are needed.
- Uncertainties comparable or greater than the Fermi-LAT statistical errors undermine the study of the Galactic interstellar emission.
- Galactic Center: a significant excess of γ-ray has been observed and discussed controversially.

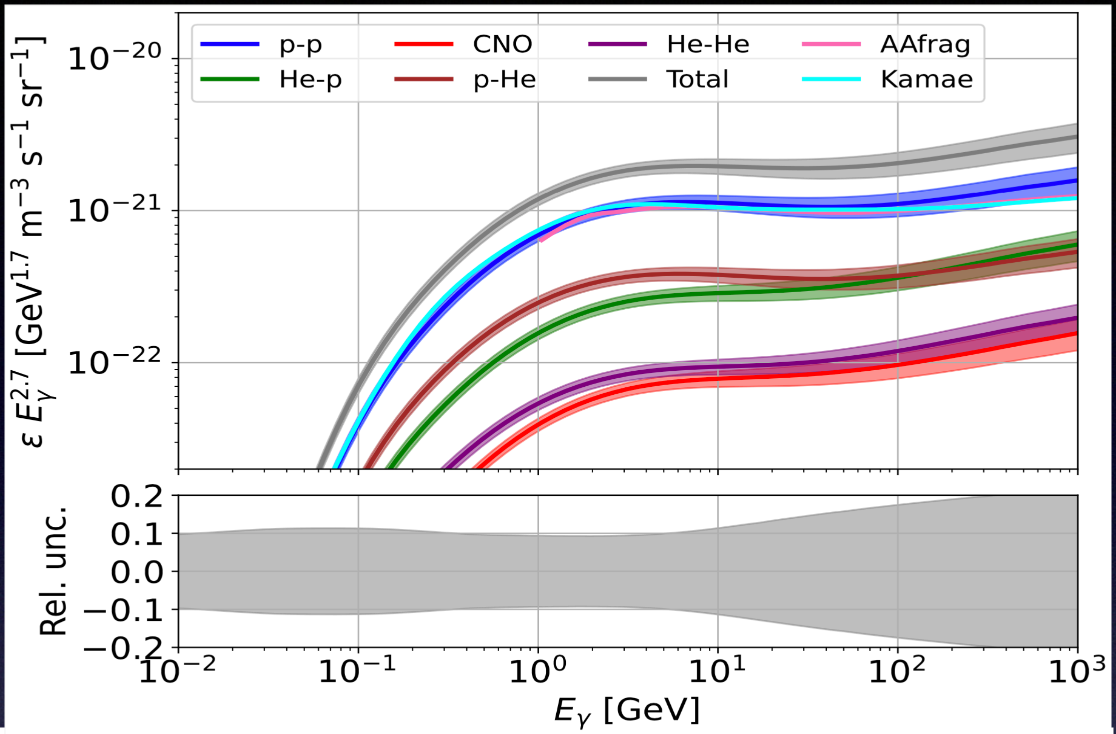


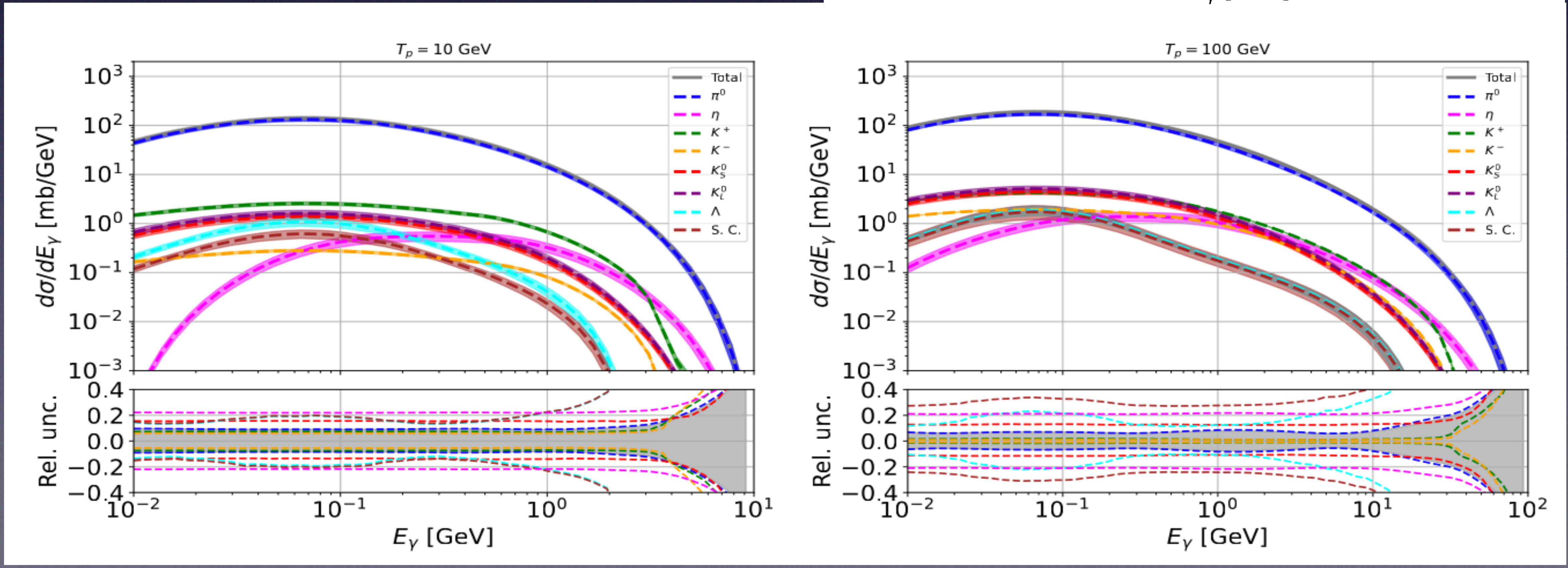


Di Mauro et al., Phys. Rev. D 103, 123005 (2021)

6. Results on the γ-ray production cross section

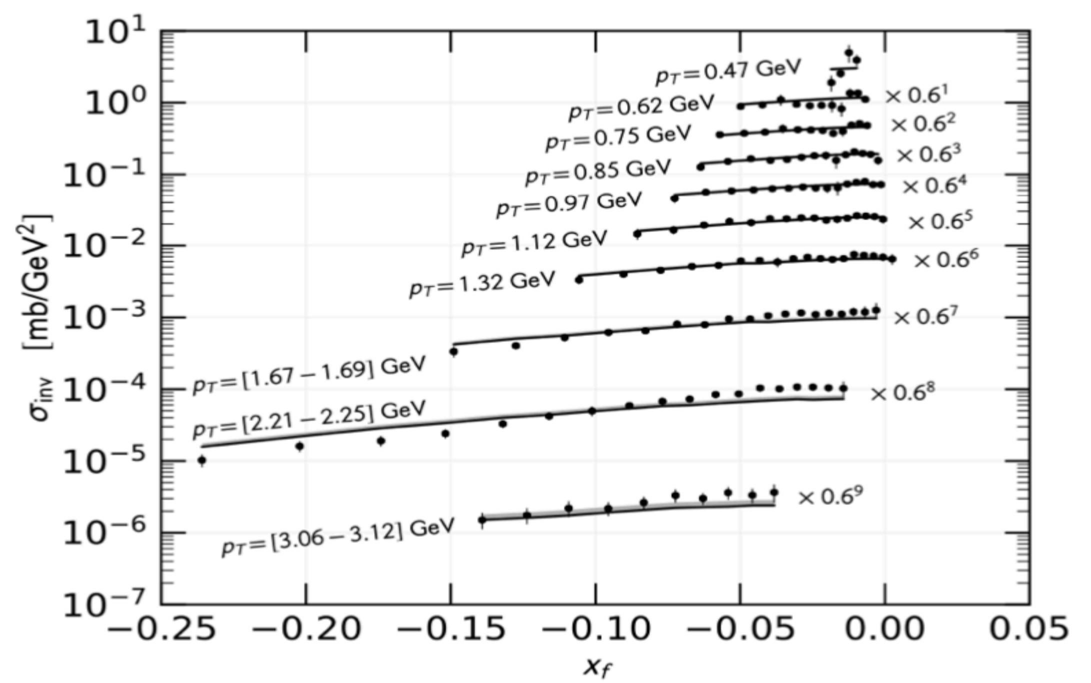
- The π^0 channel dominates the total cross section, with final uncertainty spans from 6% to 20% at different T_p and E_γ (https://github.com/lucaorusa/gamma_cross_section).
- New data from colliders are needed: Lorenz invariant cross section for π^0 productions (pT < 1 GeV, in $\sqrt{s}$ = 5-50 GeV). Same for He target. Even better data with the inclusive γ-ray production cross section.

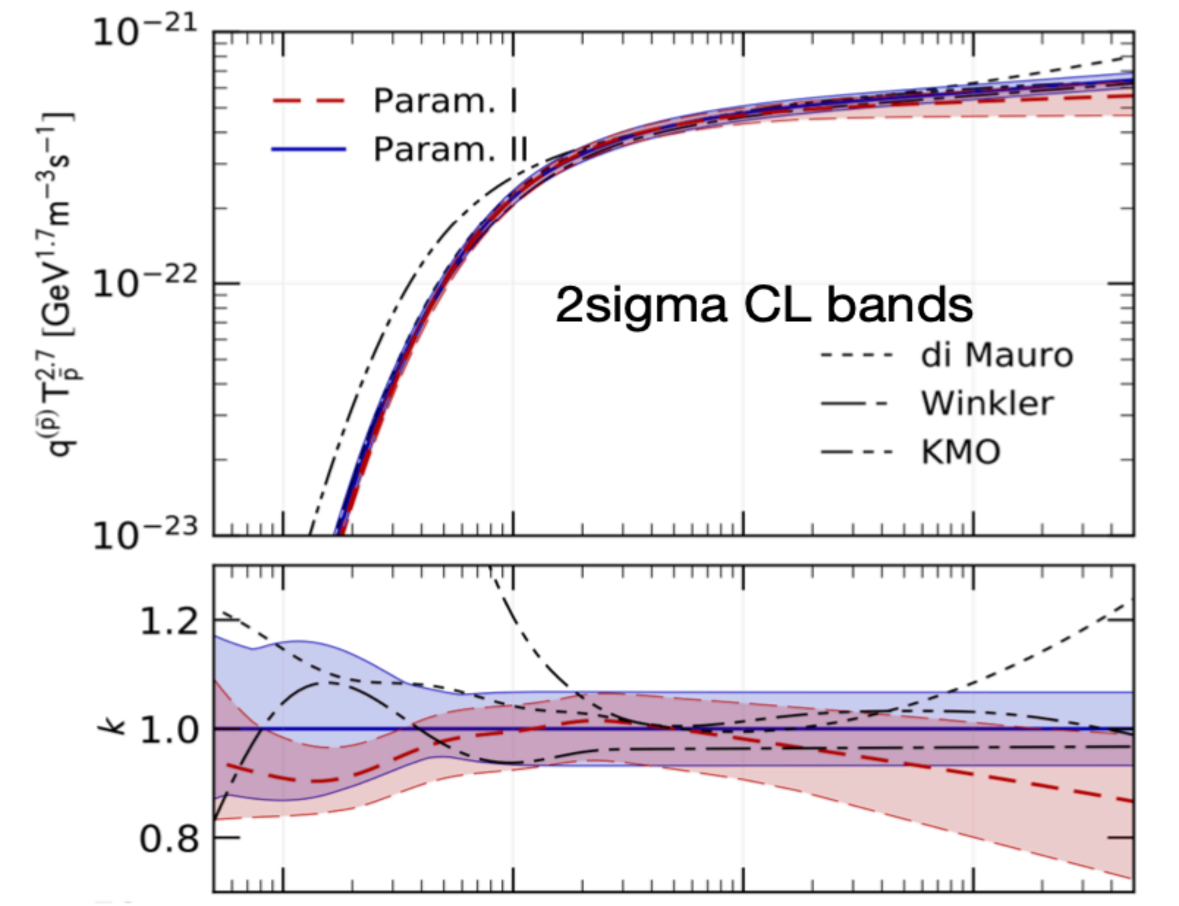


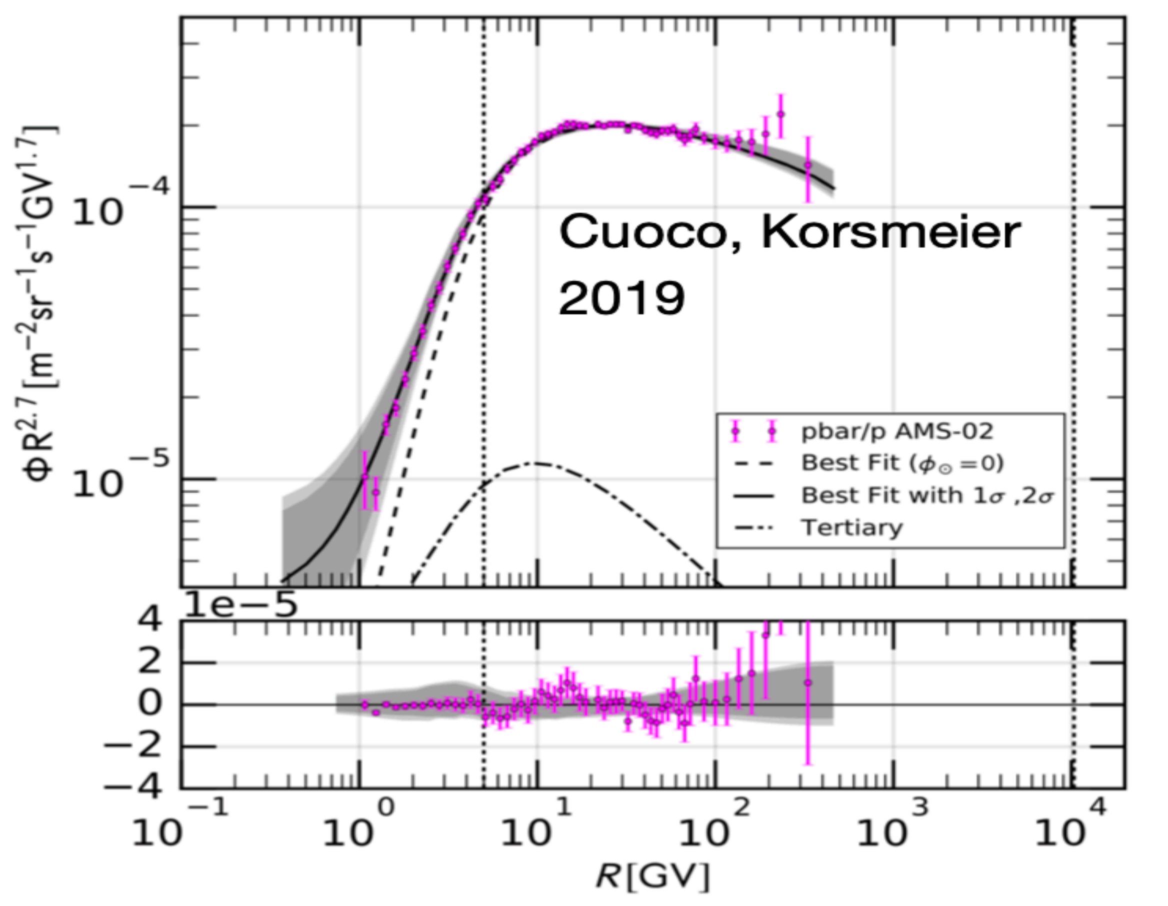


7. Antiprotons

- For $\bar{p}$ the AMS-02 data reach a precision of about 3-6%.
- This is particularly relevant for CR physics and searches for DM signals.
- $\bar{p}$ data between 10-1000 GeV —> $\sqrt{s}$ = 5-50 GeV.
- The prompt $p+p$ channel has an uncertainty between 10-15%.
- The uncertainty for the He part is about 15-20% (fit at LHCb data).

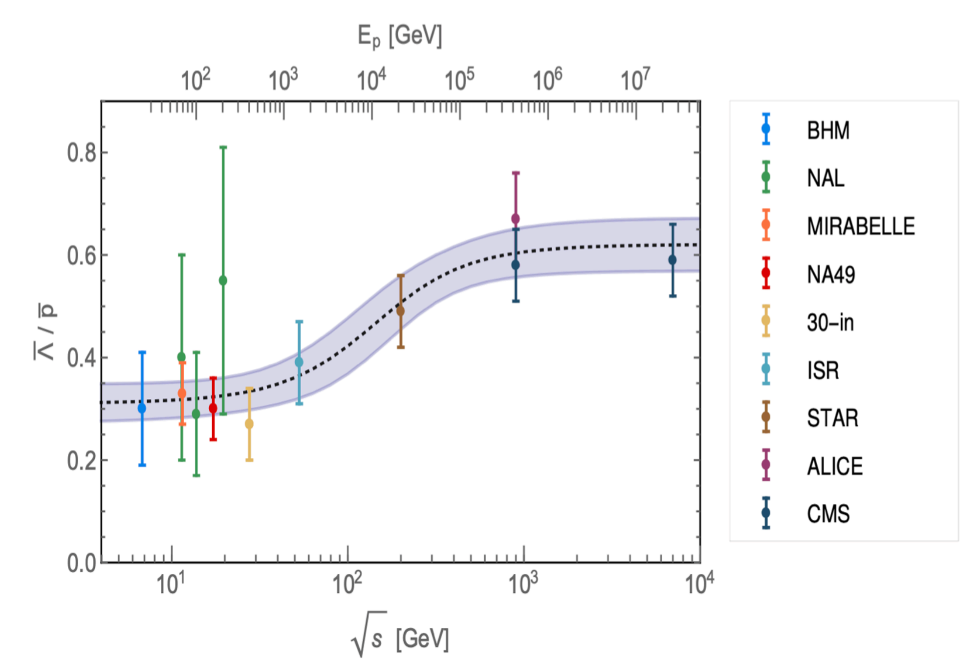


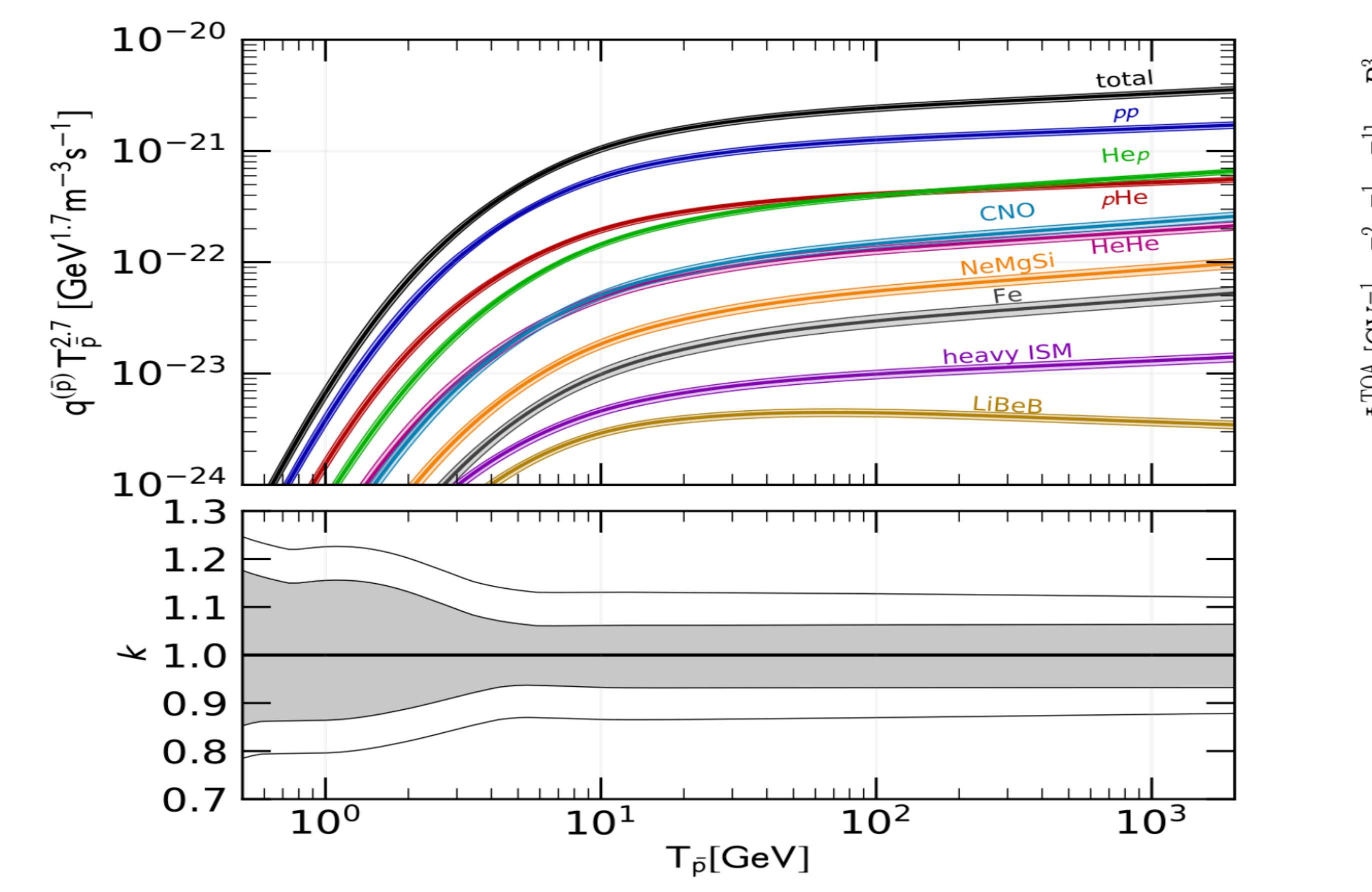


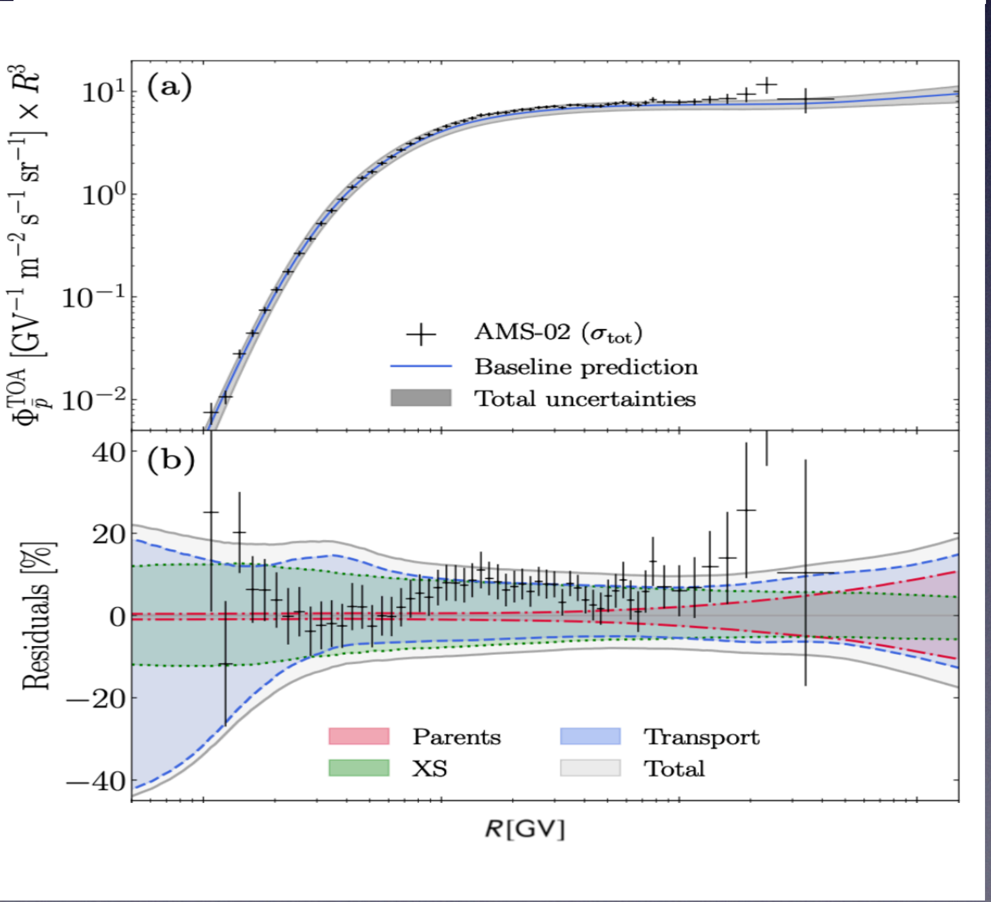


8. Results on the antiproton production cross section

- $p+p \to \bar{n}+X \to \bar{p}+Y$ usually taken equal to $p+p \to \bar{p}+Y$
- NA49 found an isospin asymmetry at of 20-30% at x_F=0.
- Hyperons usually taken as a rescaling of the prompt channel (30-40%) and uncertainty of 20-30%.
- The first and most important point is a measurement of $\bar{n}$.
- Uncertainties for the prompt $p+p \to \bar{p}+X$ and $p+p \to \bar{n}+X$ should reach the level of 5% (similar for the Helium part).







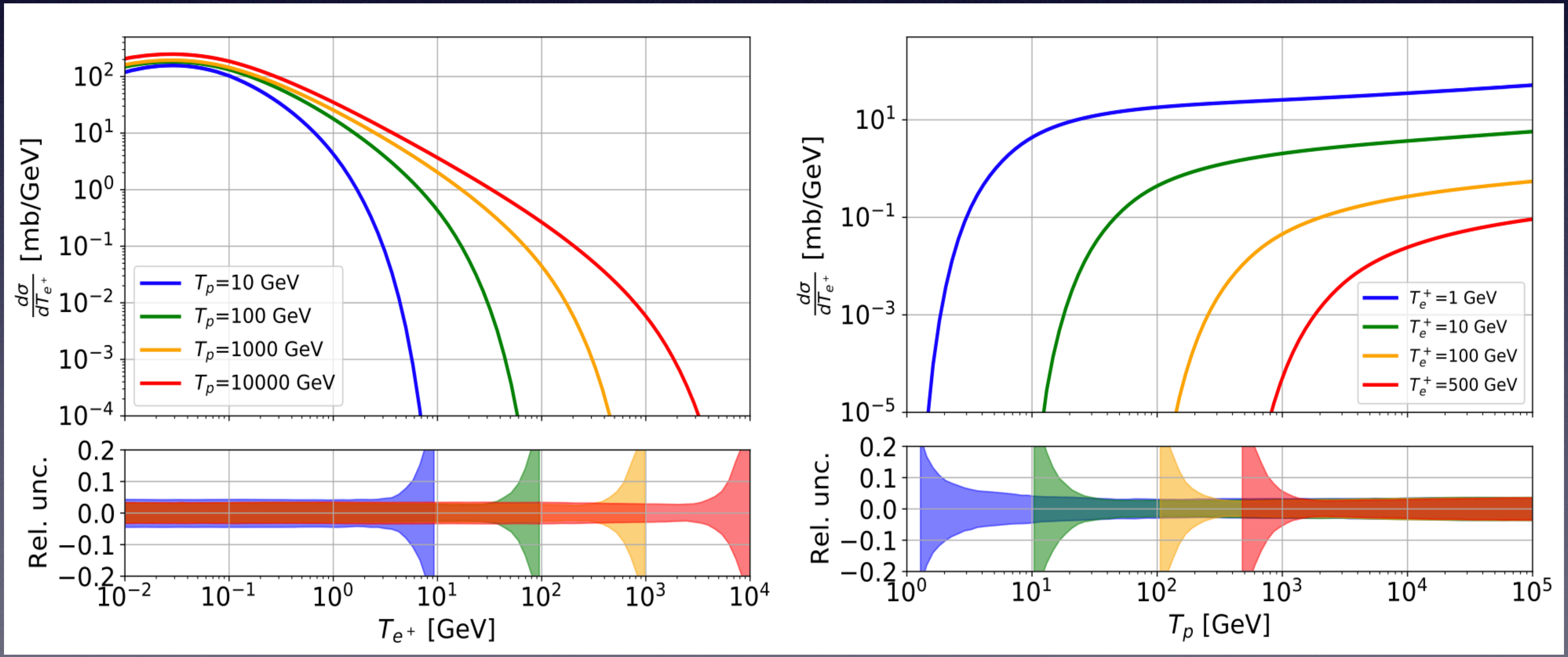
9. Backup

- $\sigma_{\rm inv} = \sigma_0(s)\, c_1 \left[F_p(s, p_T, x_R) + F_r(p_T, x_R)\right] A(s)$
- $F_p(s, p_T, x_R) = (1 - x_R)^{c_2} \exp(-c_3\, x_R)\, p_T^{c_4} \times \exp\left[-c_5 \sqrt{s/s_0}^{\,c_6} \left(\sqrt{p_T^2 + m_\pi^2} - m_\pi\right)^{c_7 \sqrt{s/s_0}^{\,c_6}}\right]$
- $F_r(p_T, x_R) = (1 - x_R)^{c_8} \times \exp\left[-c_9\, p_T - \left(\frac{|p_T - c_{10}|}{c_{11}}\right)^{c_{12}}\right] \times \left[c_{13} \exp(-c_{14}\, p_T^{c_{15}} x_R) + c_{16} \exp\left(-\left(\frac{|x_R - c_{17}|}{c_{18}}\right)^{c_{19}}\right)\right]$
- $A(s) = \frac{1 + \left(\sqrt{s/c_{20}}\right)^{c_{21} - c_{22}}}{1 + \left(\sqrt{s_0/c_{20}}\right)^{c_{21} - c_{22}}} \left(\sqrt{\frac{s}{s_0}}\right)^{c_{22}}$

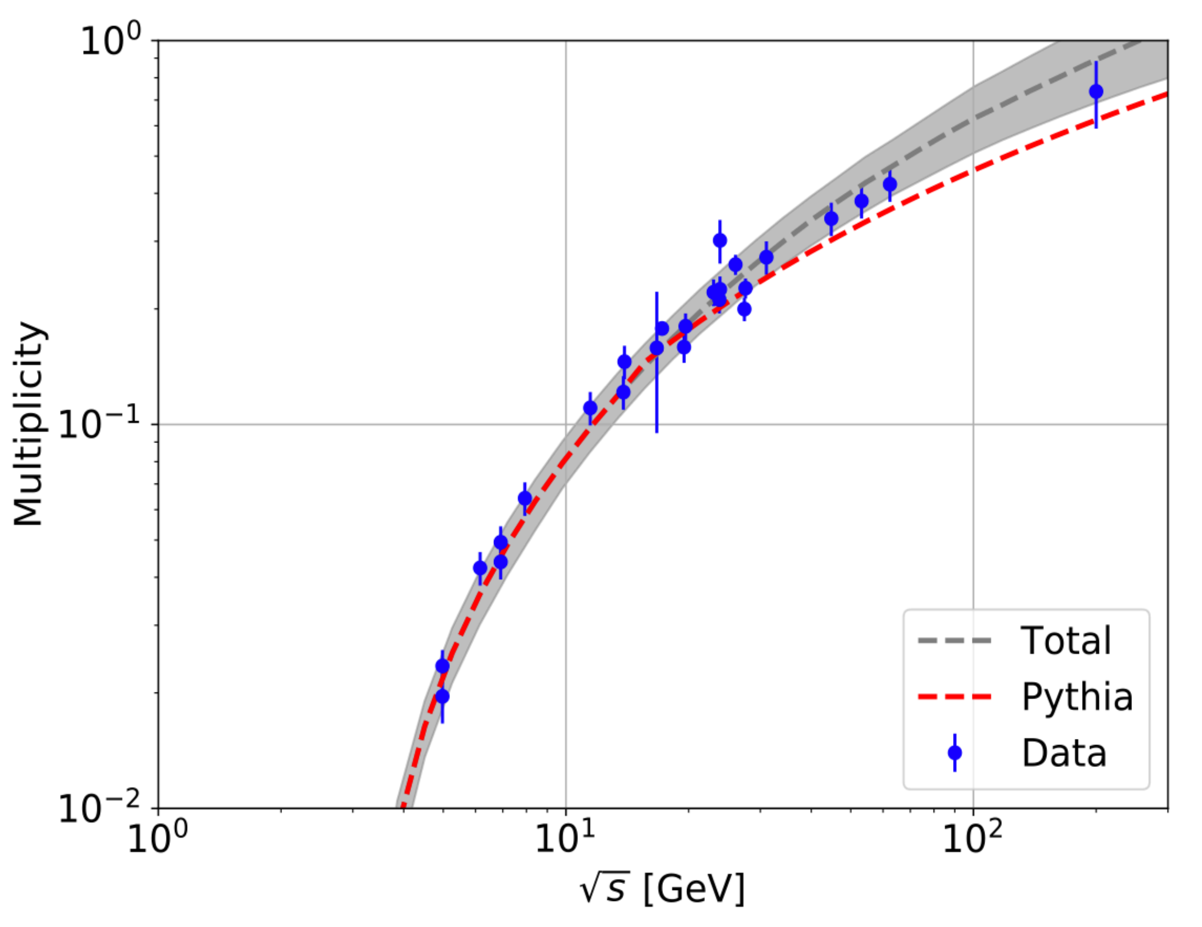
	π^+	π^-	K^+	K^-
$\chi^2_{\rm NA49}$/d.o.f.	338/263	287/290.	146/151	197/151
χ^2_{n}/d.o.f.	189/129	169/96	160/102	135/100
$\chi^2_{\rm ALICE}$	77 (33)	-	42 (27)	36 (27)
$\chi^2_{\rm CMS}$	100 (88)	154 (88)	77 (68)	54 (68)
$\chi^2_{\rm NA61, Antinucci}$	10 (12)	15 (12)	39 (11)	44 (9)
$\chi^2_{\rm tot}$/d.o.f.	527/392	456/386	306/253	332/251

9. Backup

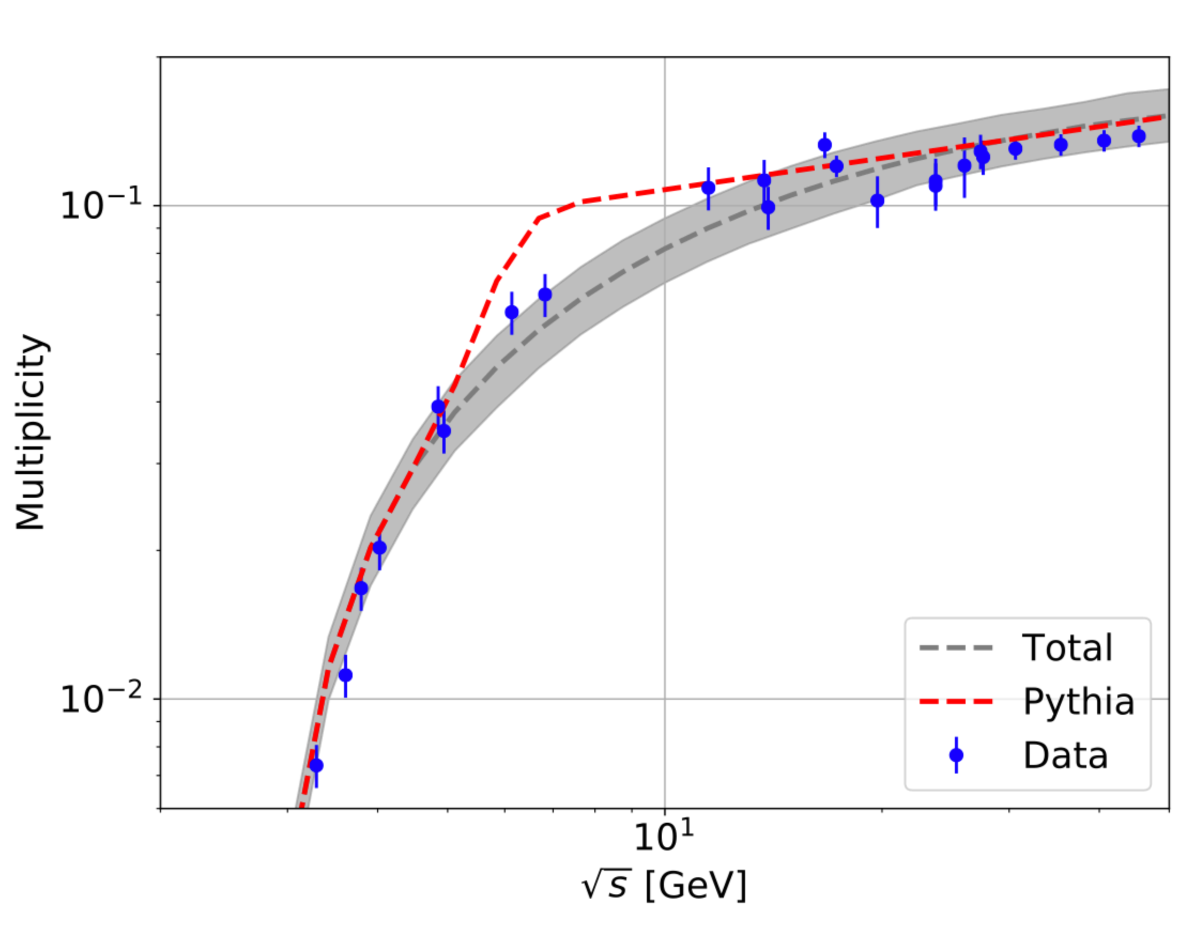
- The uncertainties are about 5% for almost all T_{e^+}.
- The relative uncertainty increases above 20% when approaching the maximum energy, that has a negligible impact on the final uncertainty.
- The results of this Section already hint at the final result. The by far dominant contribution of e^+ production in $p + p$ collisions comes from π^+.



9. Backup

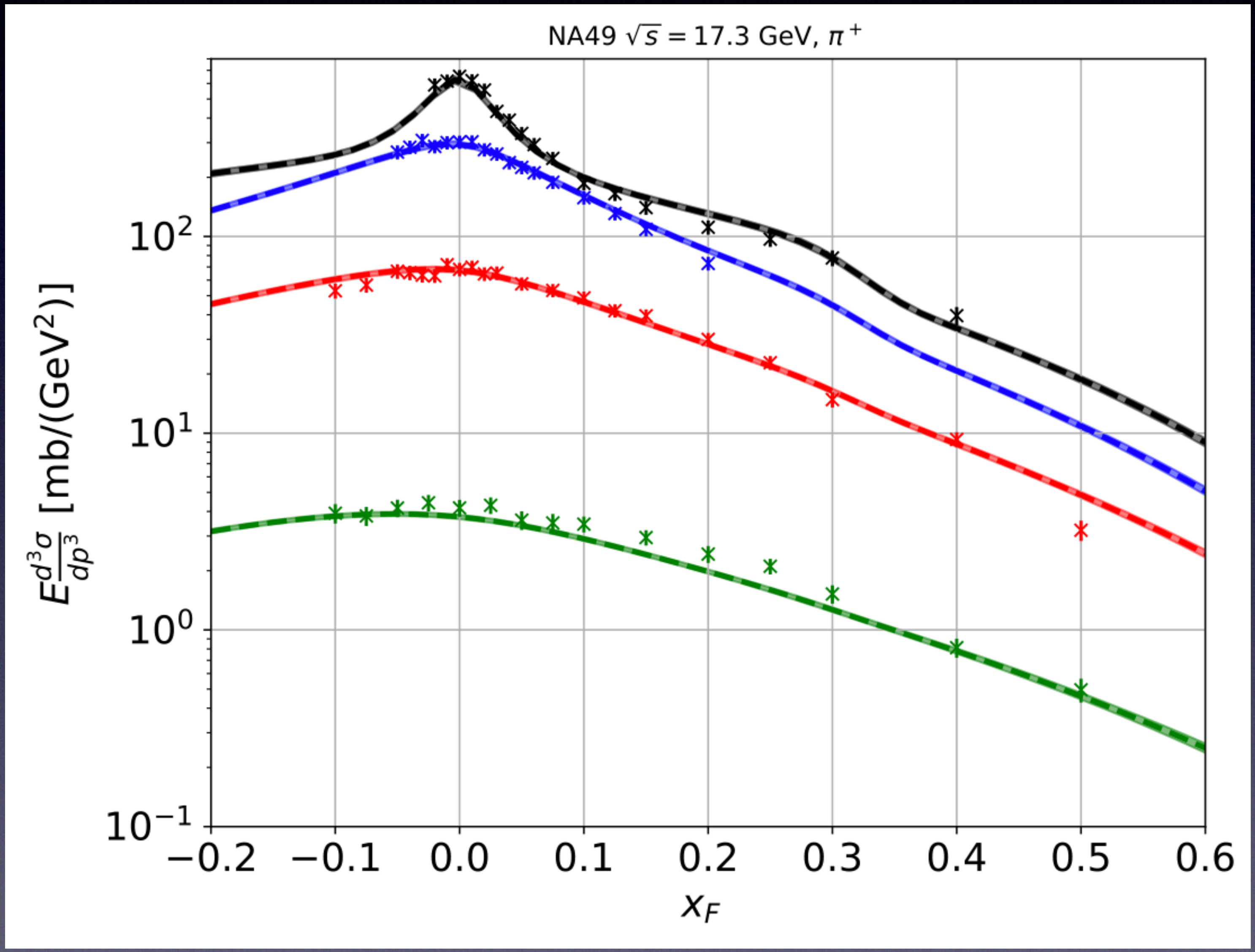


Multiplicity
$\sqrt{s}$ [GeV]
Total
Pythia
Data

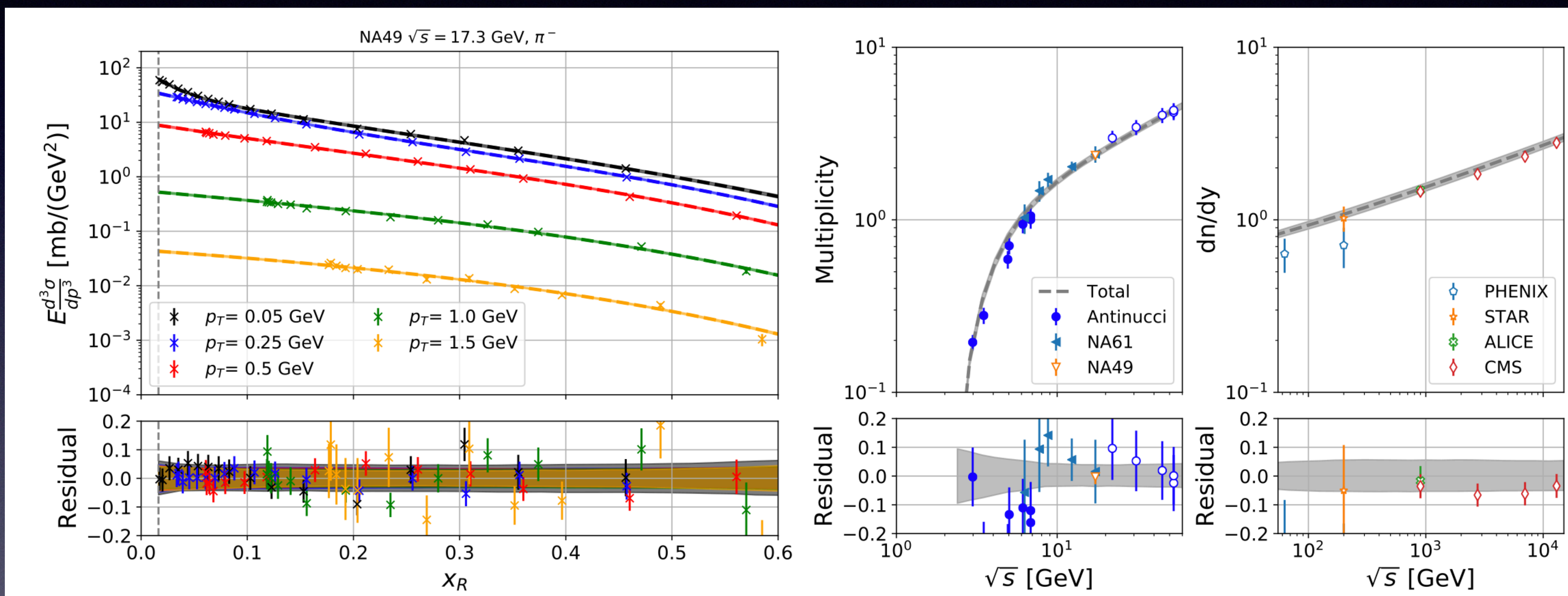


Multiplicity
$\sqrt{s}$ [GeV]
Total
Pythia
Data

9. Backup

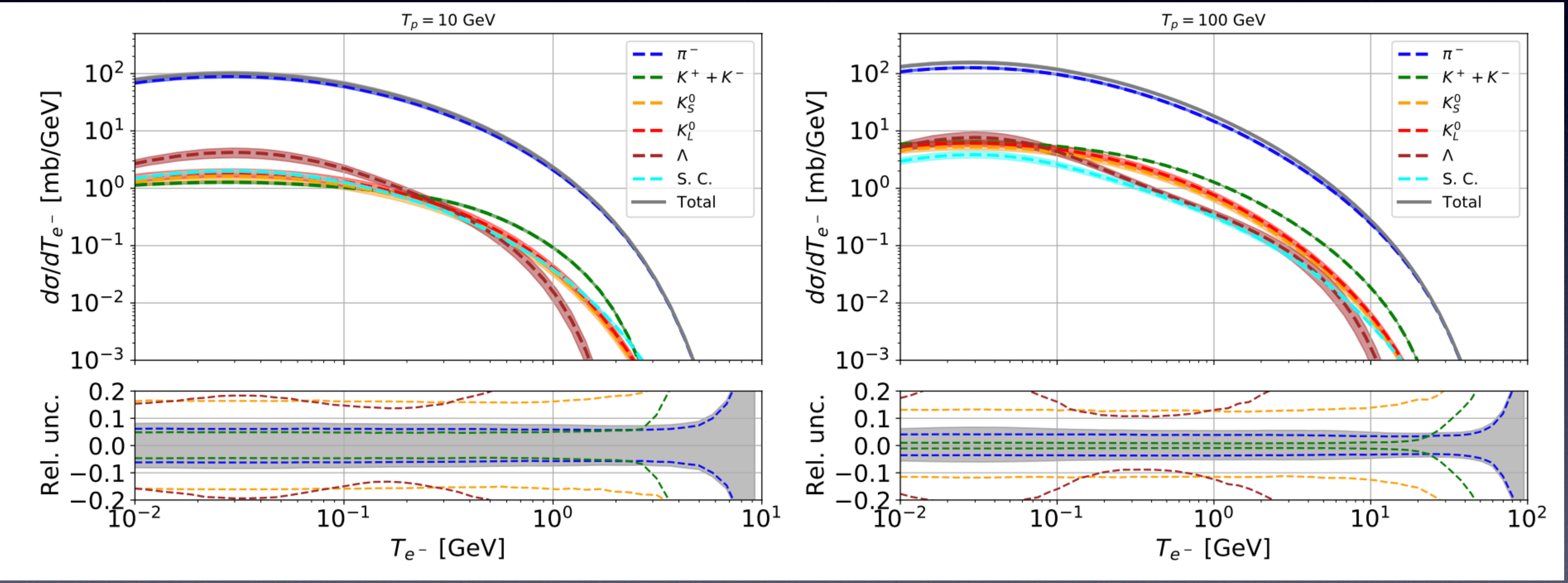


NA49 $\sqrt{s} = 17.3$ GeV, π^+
$E\frac{d^3\sigma}{dp^3}$ [mb/(GeV^2)]
10^{-1}
10^0
10^1
10^2
−0.2
−0.1
0.0
0.1
0.2
0.3
0.4
0.5
0.6
x_F



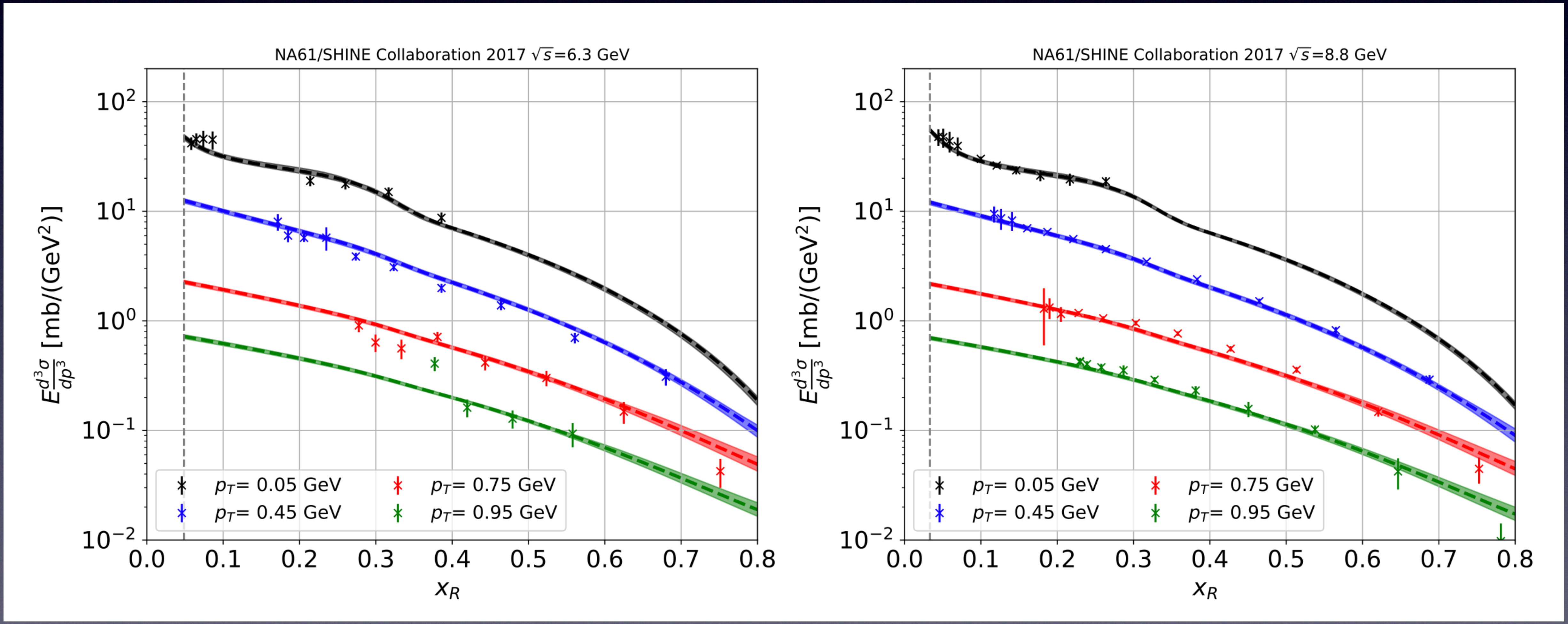
NA49 $\sqrt{s}$ = 17.3 GeV, π^-
$E\frac{d^3\sigma}{dp^3}$ [mb/(GeV^2)]
p_T= 0.05 GeV
p_T= 0.25 GeV
p_T= 0.5 GeV
p_T= 1.0 GeV
p_T= 1.5 GeV
Residual
x_R
Multiplicity
Total
Antinucci
NA61
NA49
dn/dy
PHENIX
STAR
ALICE
CMS
$\sqrt{s}$ [GeV]

9. Backup



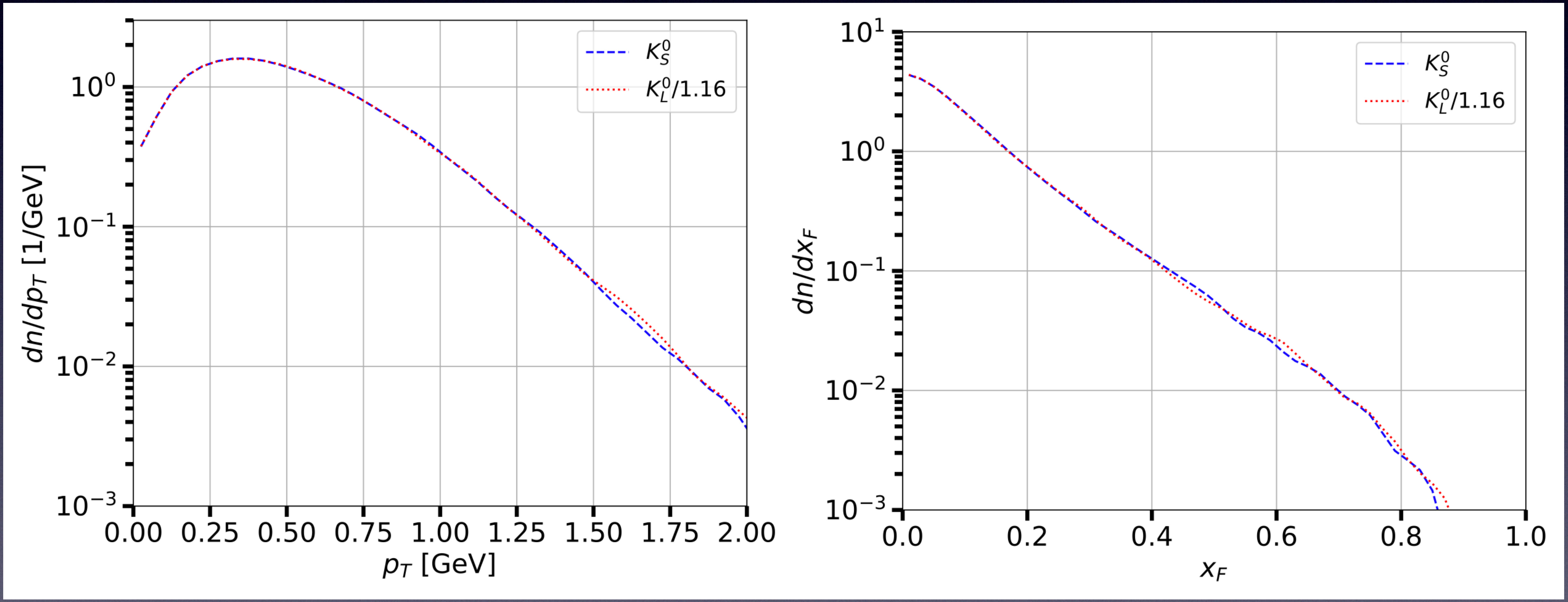
$T_p = 10$ GeV
$T_p = 100$ GeV
$d\sigma/dT_{e^-}$ [mb/GeV]
Rel. unc.
T_{e^-} [GeV]
π^-
$K^+ + K^-$
K_S^0
K_L^0
Λ
S. C.
Total

10. Backup



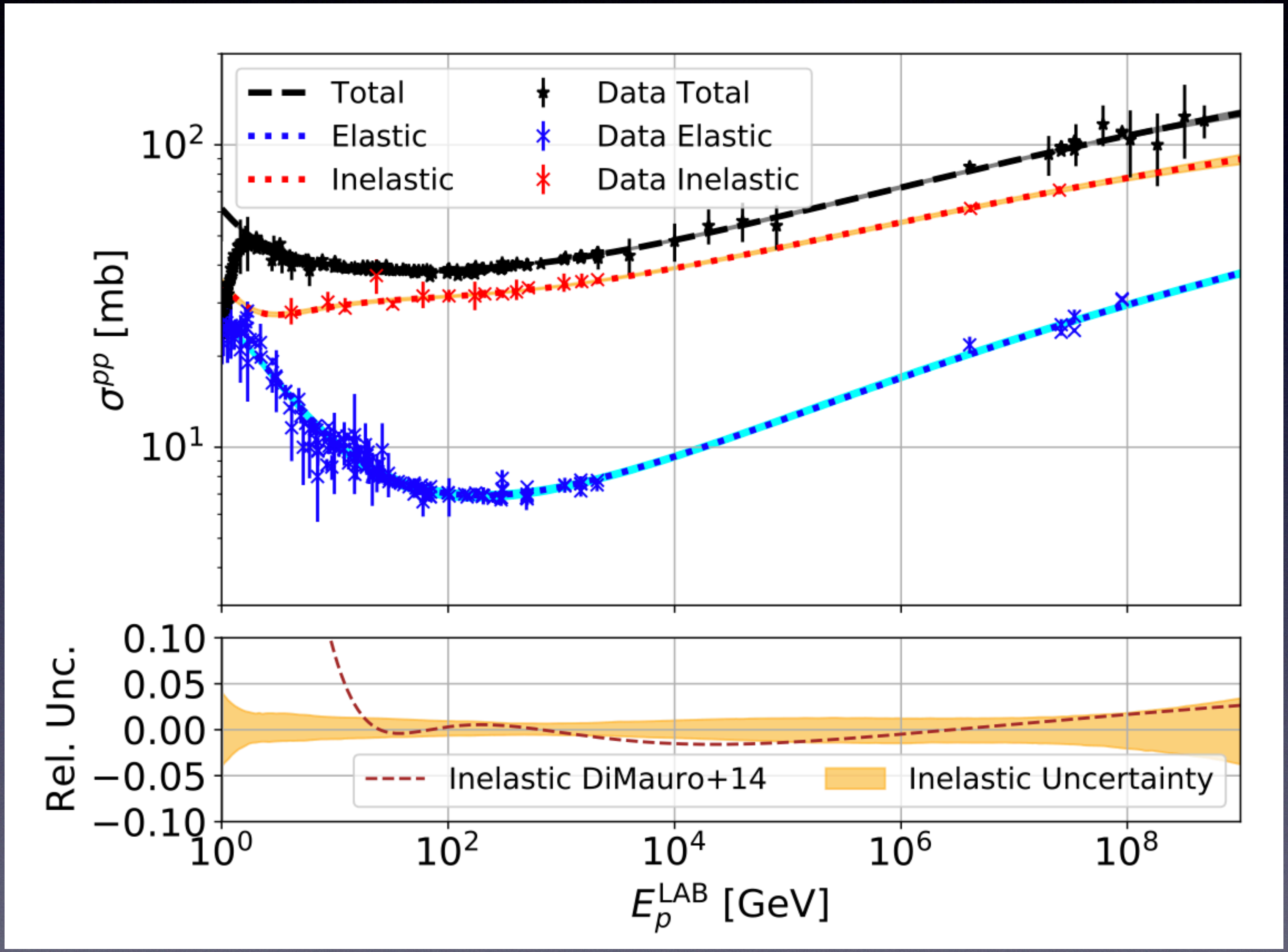
NA61/SHINE Collaboration 2017 √s=6.3 GeV
NA61/SHINE Collaboration 2017 √s=8.8 GeV
$E\frac{d^3\sigma}{dp^3}$ [mb/(GeV^2)]
x_R
p_T= 0.05 GeV
p_T= 0.45 GeV
p_T= 0.75 GeV
p_T= 0.95 GeV

10. Backup



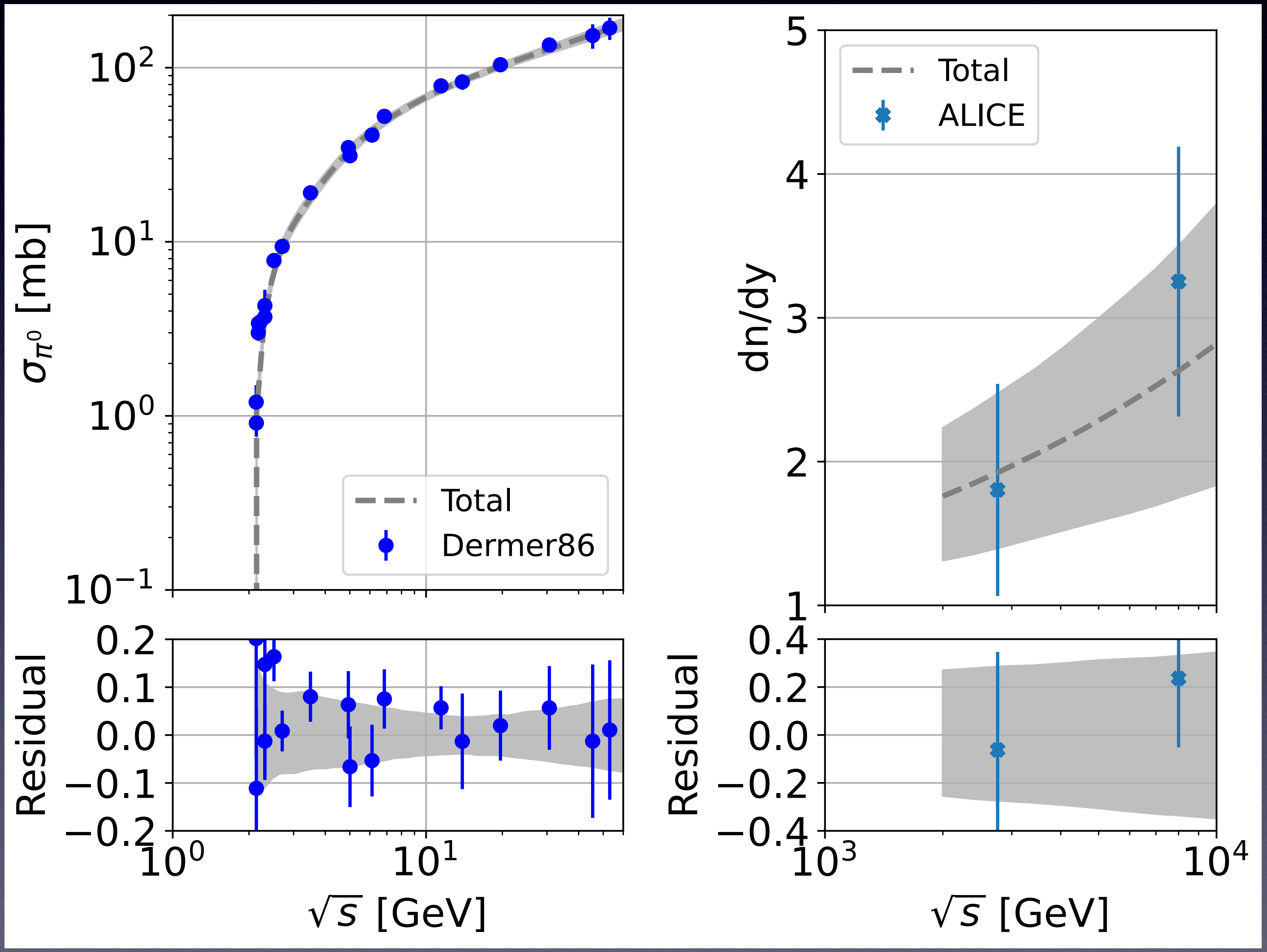
K_S^0
$K_L^0/1.16$
10^0
10^{-1}
10^{-2}
10^{-3}
dn/dp_T [1/GeV]
0.00 0.25 0.50 0.75 1.00 1.25 1.50 1.75 2.00
p_T [GeV]
K_S^0
$K_L^0/1.16$
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
dn/dx_F
0.0 0.2 0.4 0.6 0.8 1.0
x_F

10. Backup



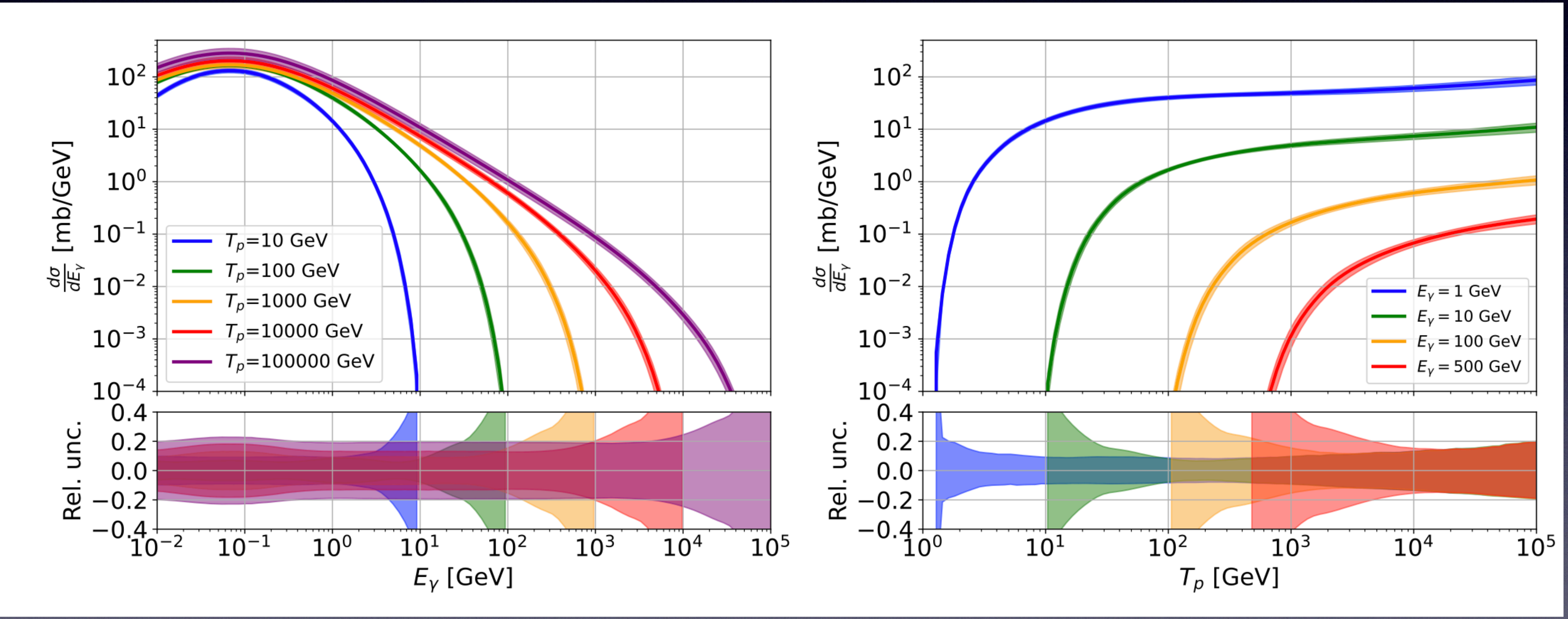
Total
Elastic
Inelastic
Data Total
Data Elastic
Data Inelastic
10^2
10^1
σ^{pp} [mb]
0.10
0.05
0.00
−0.05
−0.10
Rel. Unc.
Inelastic DiMauro+14
Inelastic Uncertainty
10^0
10^2
10^4
10^6
10^8
E_p^{LAB} [GeV]

9. Backup



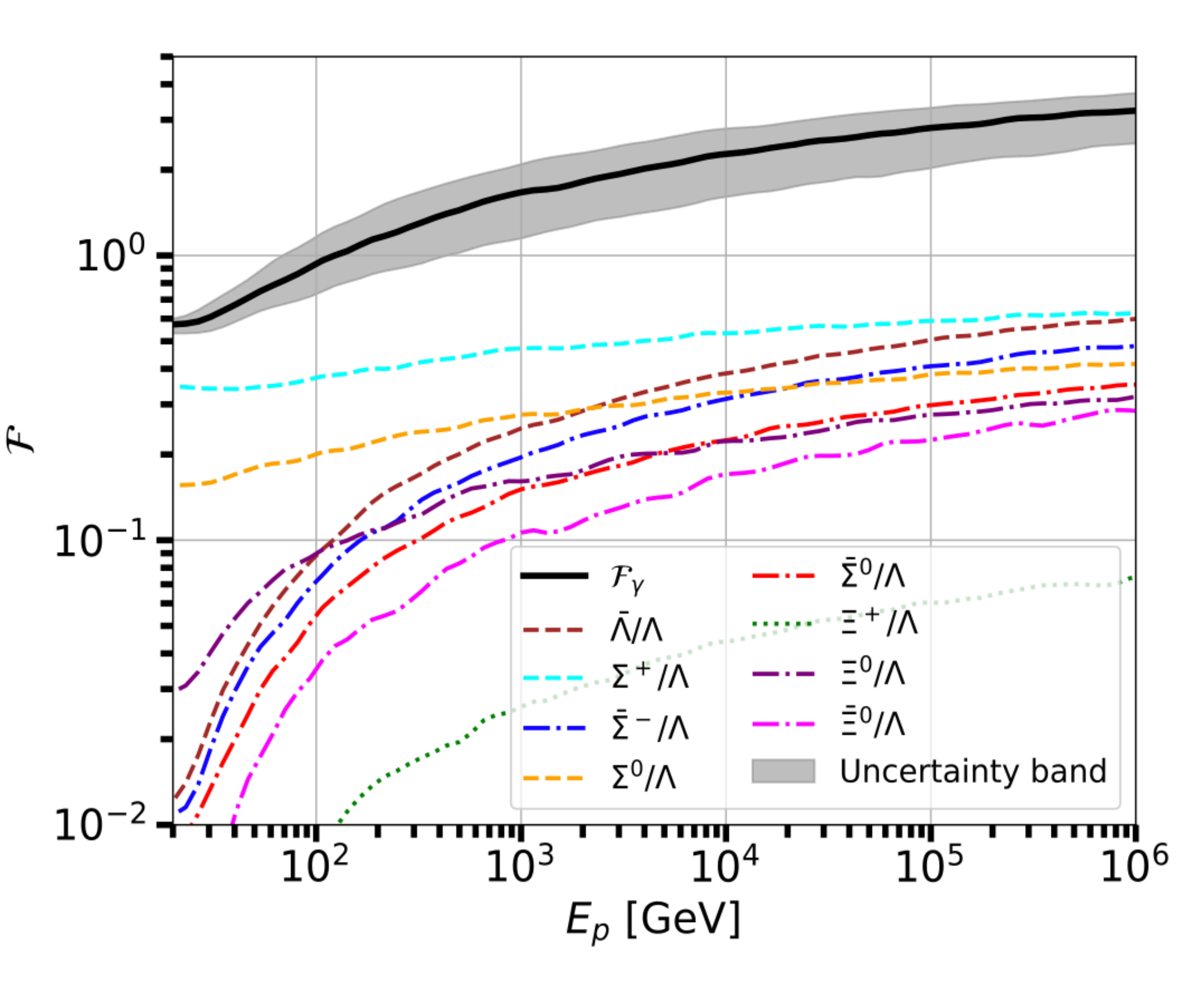
10^2
10^1
10^0
10^{-1}
σ_{π^0} [mb]
Total
Dermer86
Residual
0.2
0.1
0.0
−0.1
−0.2
10^0
10^1
$\sqrt{s}$ [GeV]
5
4
3
2
1
dn/dy
Total
ALICE
Residual
0.4
0.2
0.0
−0.2
−0.4
10^3
10^4
$\sqrt{s}$ [GeV]

9. Backup

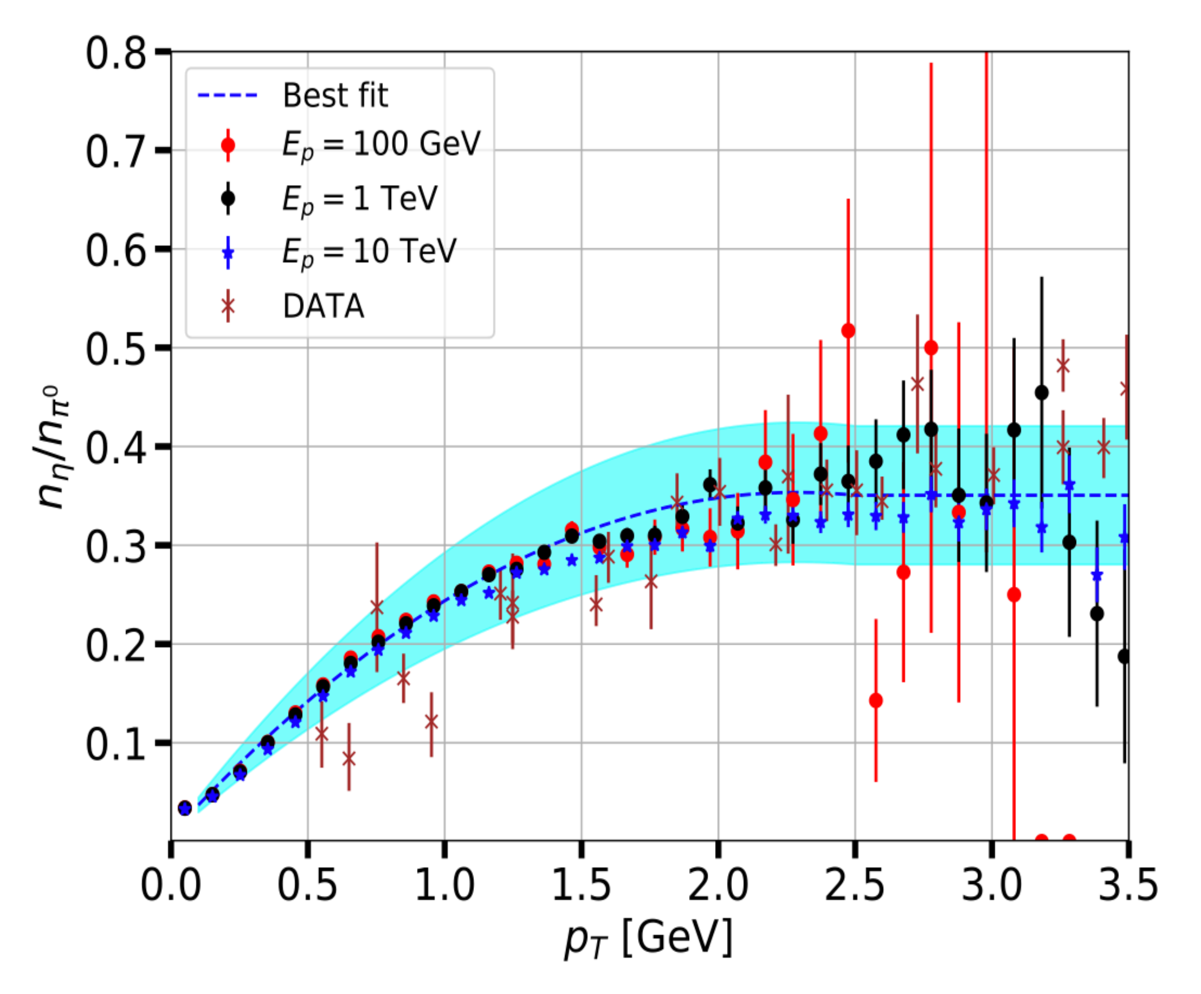


$\frac{d\sigma}{dE_\gamma}$ [mb/GeV]
T_p=10 GeV
T_p=100 GeV
T_p=1000 GeV
T_p=10000 GeV
T_p=100000 GeV
Rel. unc.
E_γ [GeV]
$E_\gamma = 1$ GeV
$E_\gamma = 10$ GeV
$E_\gamma = 100$ GeV
$E_\gamma = 500$ GeV
T_p [GeV]

9. Backup

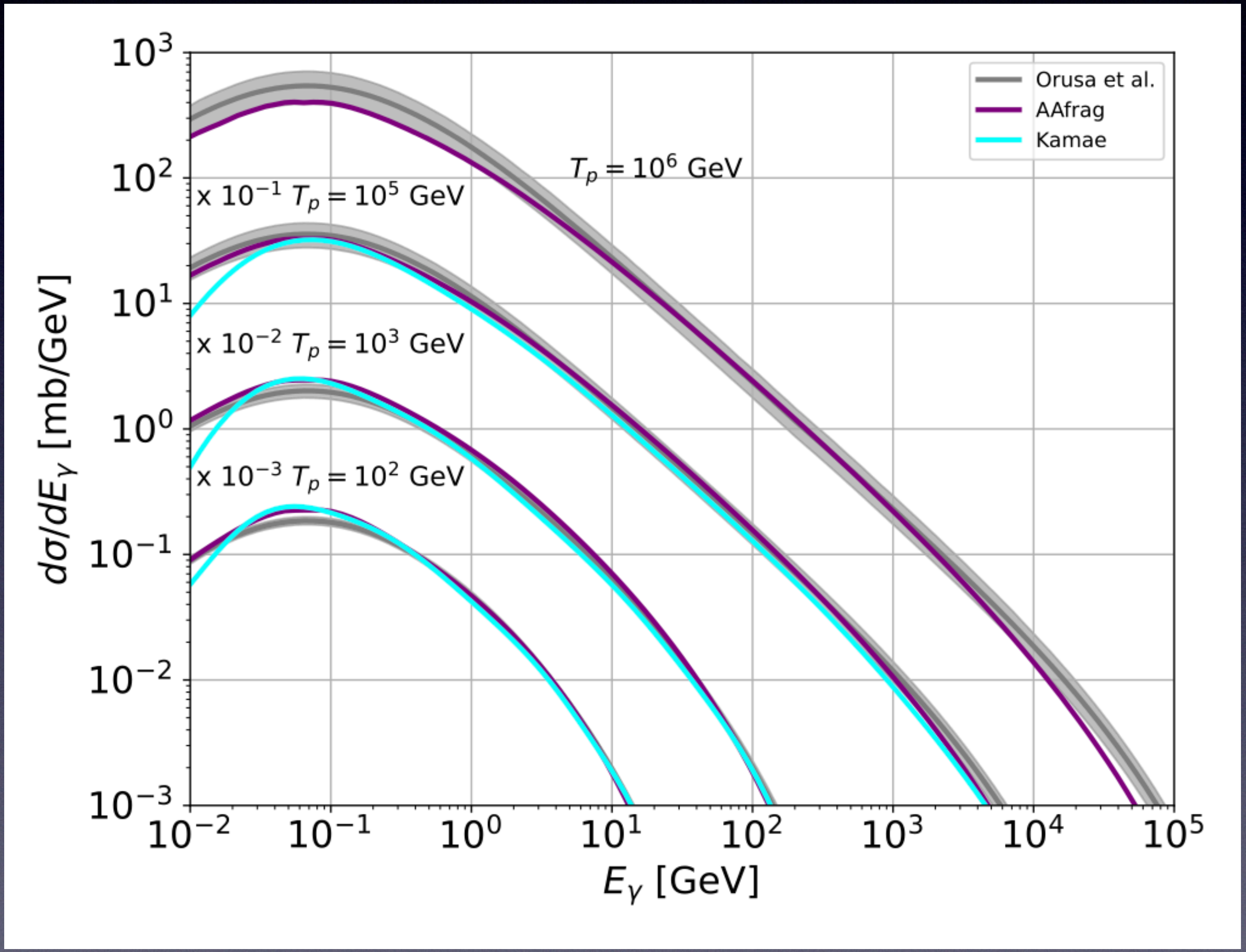


$\mathcal{F}$
E_p [GeV]
$\mathcal{F}_\gamma$
$\bar{\Lambda}/\Lambda$
Σ^+/Λ
$\bar{\Sigma}^-/\Lambda$
Σ^0/Λ
$\bar{\Sigma}^0/\Lambda$
Ξ^+/Λ
Ξ^0/Λ
$\bar{\Xi}^0/\Lambda$
Uncertainty band



n_η/n_{π^0}
p_T [GeV]
Best fit
E_p = 100 GeV
E_p = 1 TeV
E_p = 10 TeV
DATA

9. Backup



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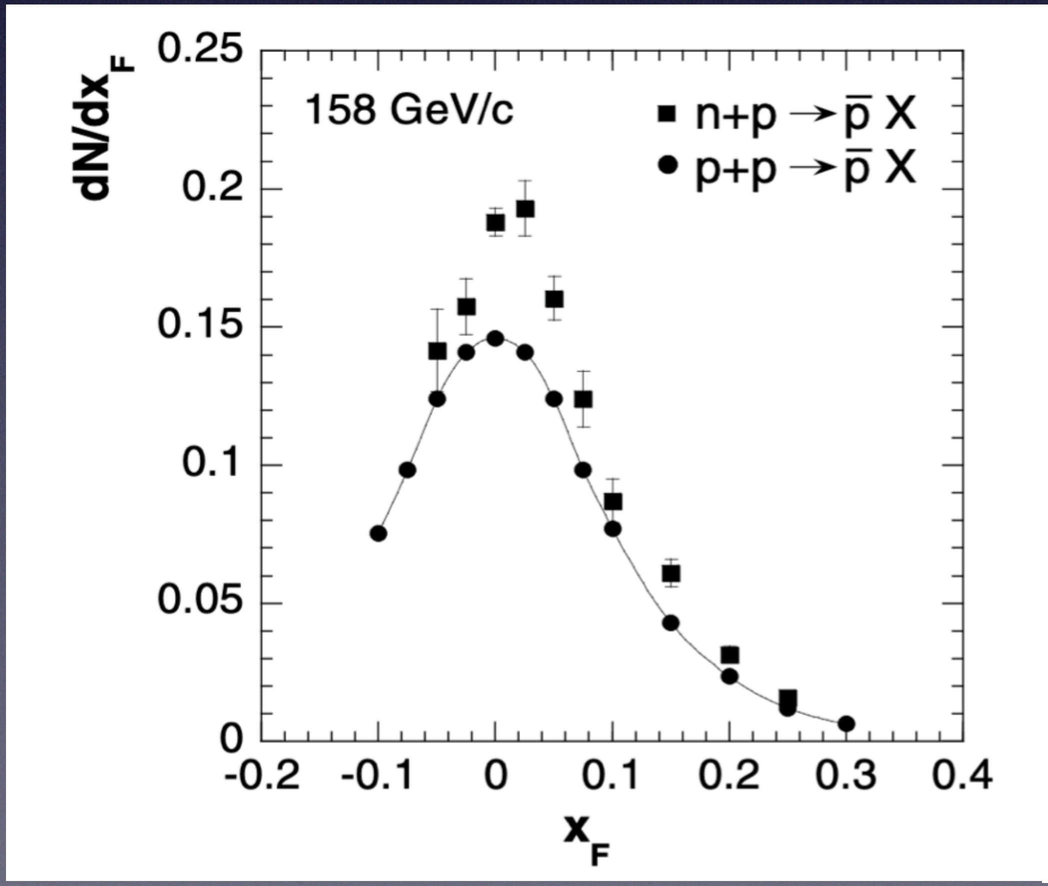
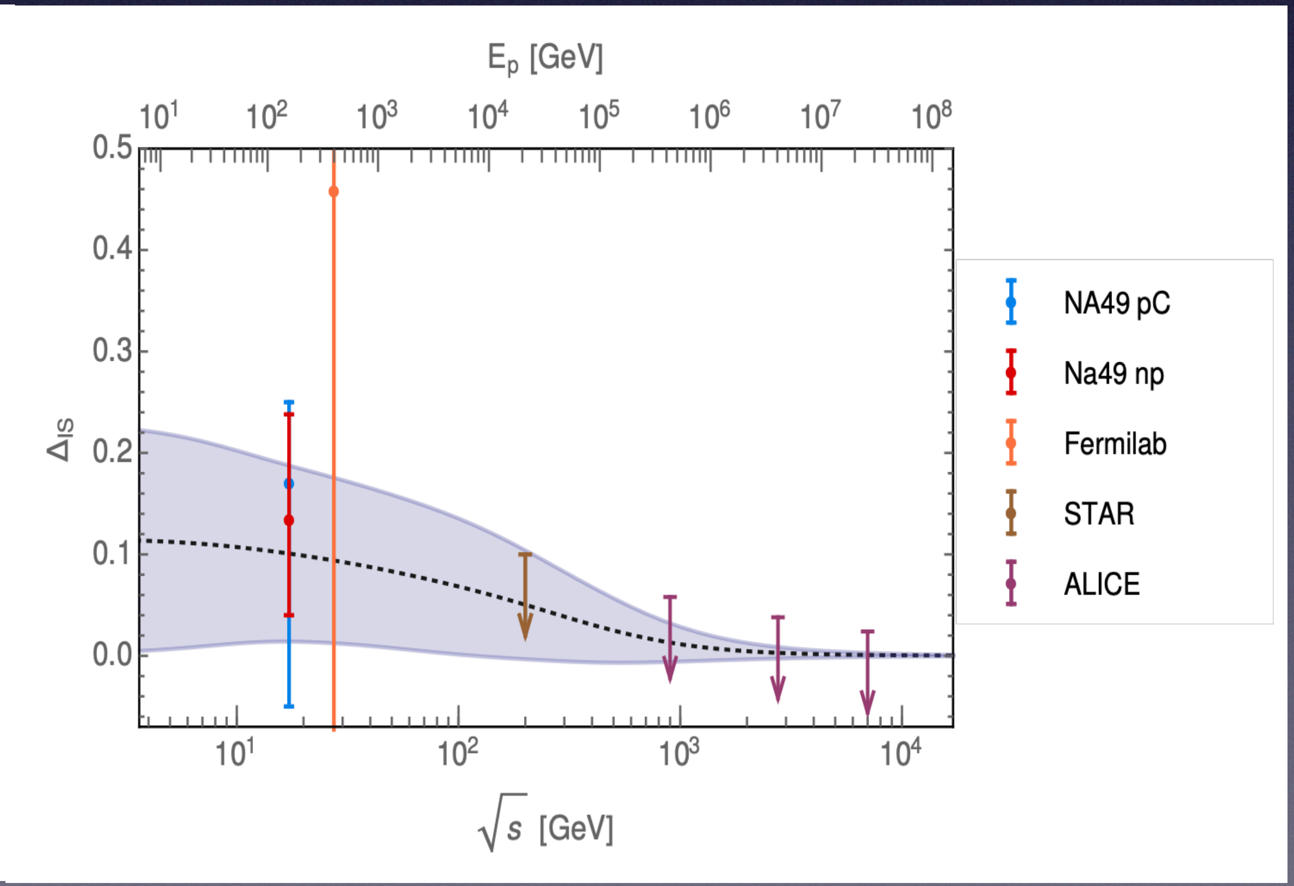
AAfrag
Kamae
$T_p = 10^6$ GeV
x 10^{-1} $T_p = 10^5$ GeV
x 10^{-2} $T_p = 10^3$ GeV
x 10^{-3} $T_p = 10^2$ GeV
$d\sigma/dE_\gamma$ [mb/GeV]
E_γ [GeV]

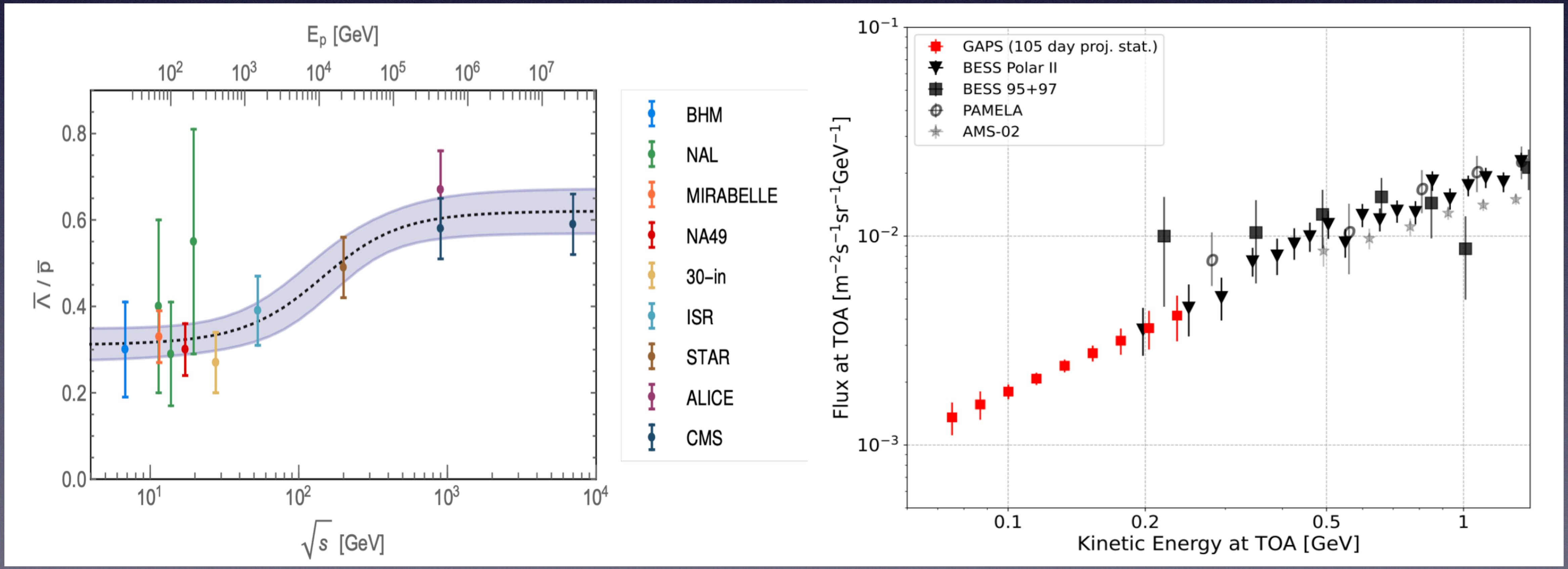
- $p + p \to \bar{n} + X \to \bar{p} + Y$ usually taken equal to $p + p \to \bar{p} + Y$
- NA49 found an isospin asymmetry at of 20-30%.
- This is the main source of uncertainty in antiproton production cross sections.
- On a Monte Carlo point of view Pythia produce same amount of $\bar{n}$ and $\bar{p}$ while others (Herwig) a different amount.
- The first and most important point is a measurement of $\bar{n}$.
- Uncertainties for the prompt $p + p \to \bar{p} + X$ and $p + p \to \bar{n} + X$ should reach the level of 5% (similar for the Helium part).





9. Backup

- Hyperons usually taken as a rescaling of the prompt channel (30-40%) and uncertainty of 20-30%.
- This contribution has an uncertainty of about 20-30%(subdominant uncertainty of about 5-10%).
- New measurements from NA61 and LHCb.
- GAPS will measure with the best sensitivity ever the antiproton cosmic flux below 1 GeV of kinetic energy.
- This energy range is very important for understanding the CR propagation and solar modulation effects.



Charged particles (nuclei, isotopes, leptons, antiparticles) diffusing in the galactic magnetic field

- Observed at Earth with E~ 10 MeV/n – 103 TeV/n
- PRIMARIES: directly produced in their sources (Supernova remnants (SNR), pulsars, dark matter annihilation, …)
- SECONDARIES: produced by spallation reactions of primaries on the interstellar medium (ISM), made of H and He

ACCELERATION

- SNR are considered the powerhouses for CRs (They can accelerate particles at least up to 102 TeV)

PROPAGATION

- CRs are diffused in the Galaxy galactic magnetic field (μG)
- Primaries: produced in the sources (SNR and Pulsars)
- H, He, CNO, Fe; e-, e+; possibly e+, p-, d- from Dark Matter annihilation
- Secondaries: produced by spallation of primary CRs (p, He,C, O, Fe) on the interstellar medium (ISM): Li, Be, B, sub-Fe, [...], (radioactive) isotopes ; e+, p-, d-

- Diffusion: D(x,R) a priori usually assumed isotropic in the Galaxy: $D(R) = D_0 R^\delta$ (R=pc/Ze)
- D_0 and δ usually fixed by B/C
- Energy losses: Synchrotron on the galactic B; full relativistic inverse Compton scattering on photon fields (stellar, CMB, UV, IR)
- Solution of the eq: semi-analytic (Maurin+ 2001, Donato+ 2004, ...), USINE codes or fully numerical: GALPROP, DRAGON codes
- Geometry of the Galaxy: cylinder with height L ~ kpc
- Fragmentation cross section uncertainties currently prevent a better understanding of CR propagation.
- They matter in both directions: as a loss term for progenitors, as a source term for daughters

$$\frac{\partial \psi_i(\boldsymbol{x}, p, t)}{\partial t} = q_i(\boldsymbol{x}, p) + \boldsymbol{\nabla} \cdot (D_{xx} \boldsymbol{\nabla} \psi_i - \boldsymbol{V} \psi_i) + \frac{\partial}{\partial p} p^2 D_{pp} \frac{\partial}{\partial p} \frac{1}{p^2} \psi_i - \frac{\partial}{\partial p} \left(\frac{\mathrm{d}p}{\mathrm{d}t} \psi_i - \frac{p}{3} (\boldsymbol{\nabla} \cdot \boldsymbol{V}) \psi_i \right) - \frac{1}{\tau_{f,i}} \psi_i - \frac{1}{\tau_{r,i}} \psi_i .$$

9. Backup

- Among all cosmic rays, secondaries are the most interesting for DM searches.
- In particular antiprotons, positrons, gamma rays and neutrinos are the most studied. Antinuclei are also considered because the DM production should exceed the secondary one at low energy.