Antiproton production cross section for cosmic ray

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Phys.Rev. D90 (2014) 085017

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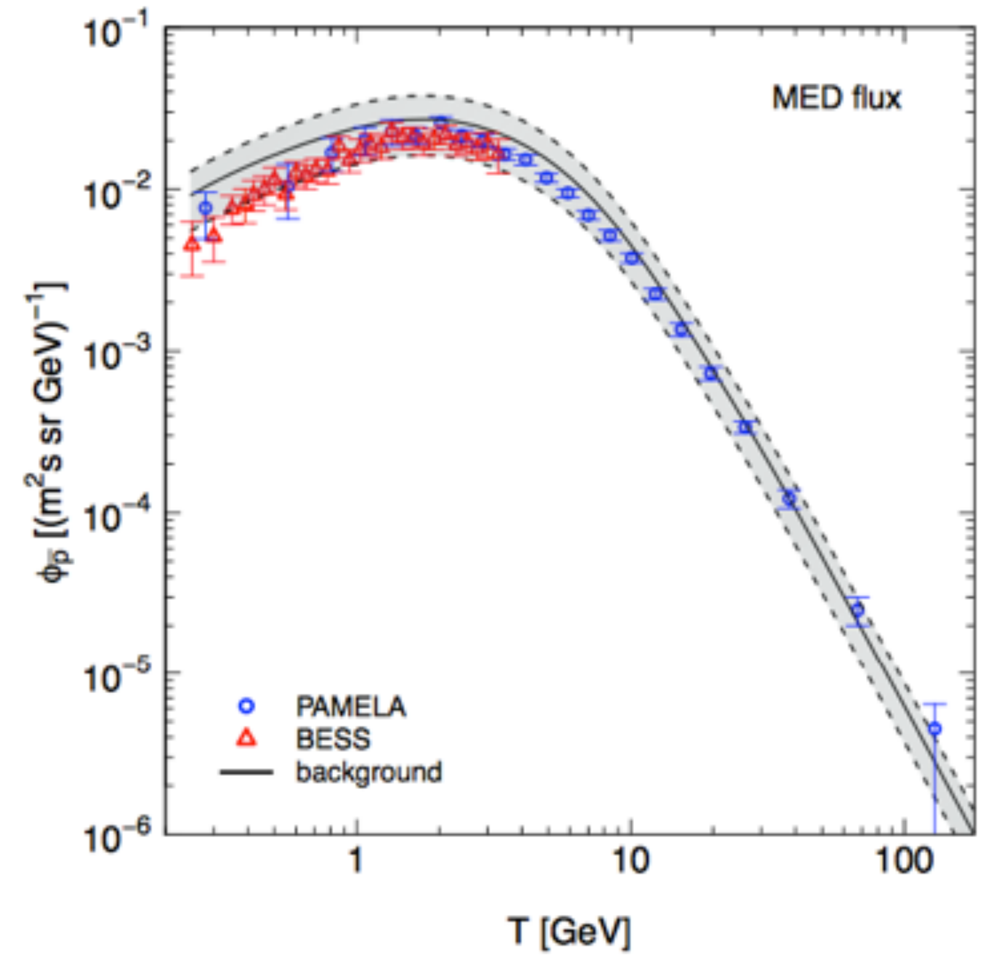
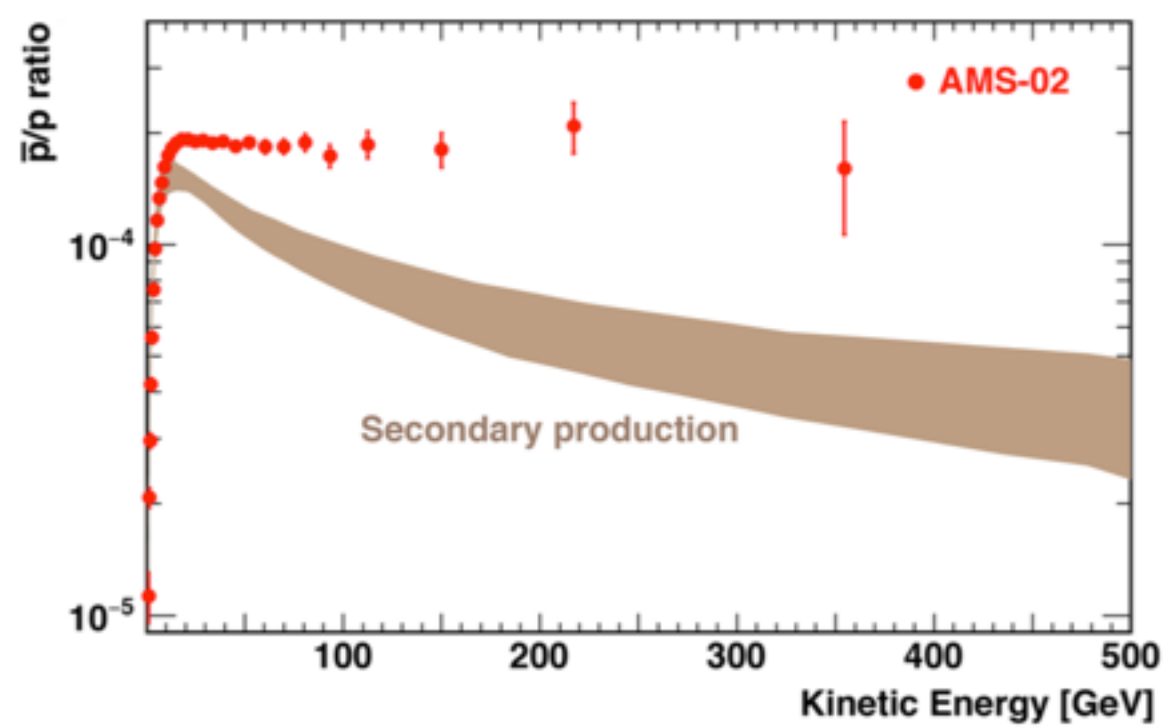
The p-He cross section measurement: a physics case from cosmic rays. Turin 6-7 July 2015

MOTIVATIONS 1

- Antiprotons one of the most powerful tool for astroparticle physics.
- A low fraction of antimatter is present cosmic rays (about anti-p/p$\sim 10^{-4}$)
- Research activities on antiprotons have been of central importance for the search of dark matter and to constrain the parameters of propagation.
- The bulk of the Pamela flux is consistent with a purely secondary origin (e.g. Donato et al. PRL 2009).
- New measure released by AMS-02.
- Is there an extra component in the data?

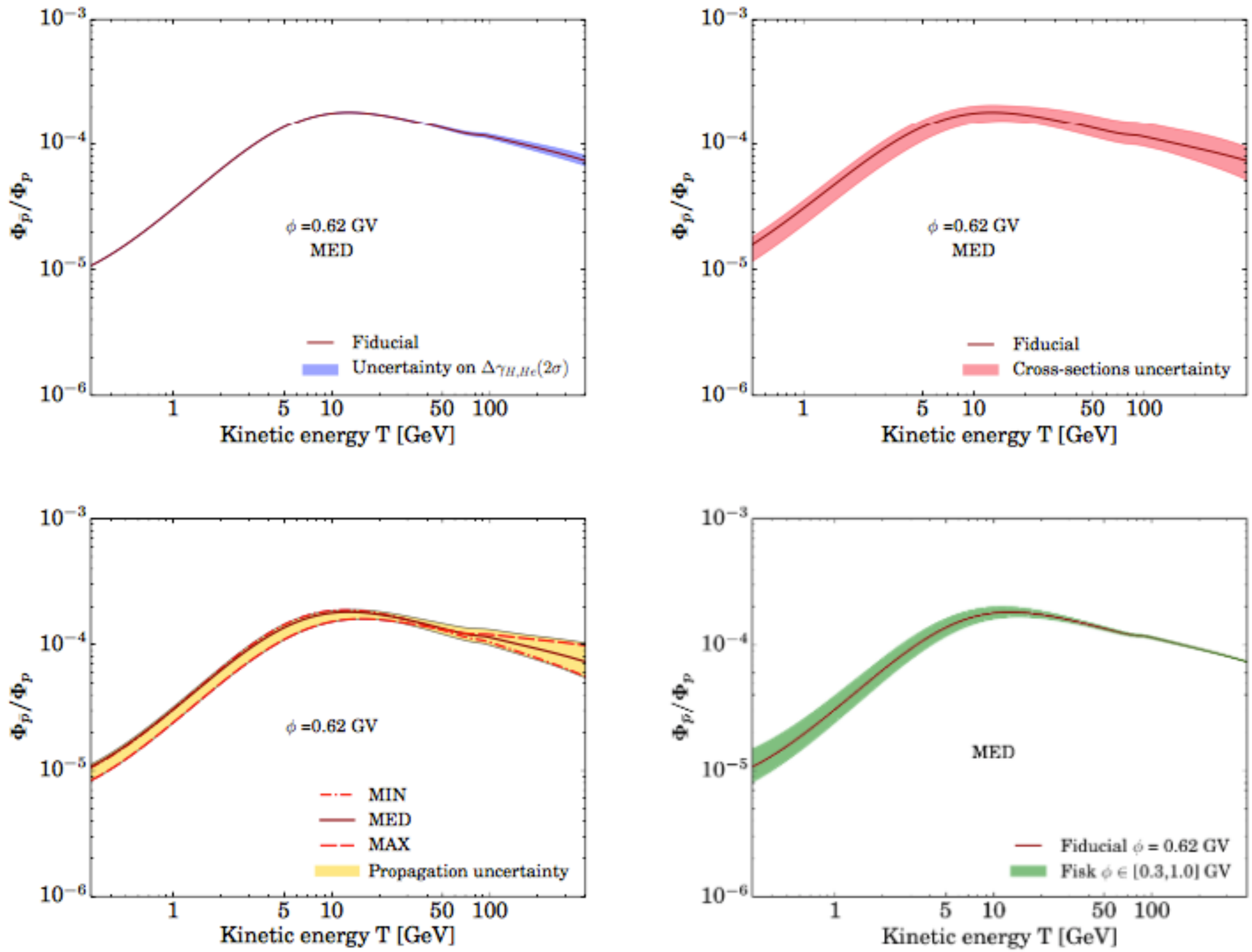




Donato et al. Phys. Rev. Lett. 102 (2009) 071301
Fornengo et al. JCAP 1404 (2014) 003

http://www.ams02.org/2015/04/ams-days-at-cern-and-latest-results-from-the-ams-experiment-on-the-international-space-station/

MOTIVATIONS 2



Giesen et al. arXiv:1504.04276

MOTIVATIONS 3

- The process giving rise to secondary antiprotons is the spallation reaction of CRs (p and He) with ISM (H and He).
- The uncertainties on the production cross sections were estimated to be ~ 25% (e.g. Donato et al. ApJ. 563:172-184,2001) and already is identified as the limiting factor in theoretical predictions
- The latest re-evaluation of the antiproton production yield in pp collisions are Duparry et al. 2004 and Tan & Ng 1983 parameterization despite being derived with really old data sets (sixties and seventies.).
- Two more experimental datasets have become available: the BRAHMS data and the NA49 results collected at the CERN Super Proton Synchrotron (SPS).

Donato et al. Phys. Rev. Lett. 102 (2009) 071301
Fornengo et al. JCAP 1404 (2014) 003

http://www.ams02.org/2015/04/ams-days-at-cern-and-latest-results-from-the-ams-experiment-on-the-international-space-station/

ANTI-PROTON SOURCE TERM

- Antiproton CRs produced for the spallation reaction of primary CRs with the ISM.
- CR protons interact with the interstellar medium (ISM) and may produce secondary antiprotons.
- Different channels are involved, with the dominant one being the CR proton flux collisions with the target hydrogen gas (pp).

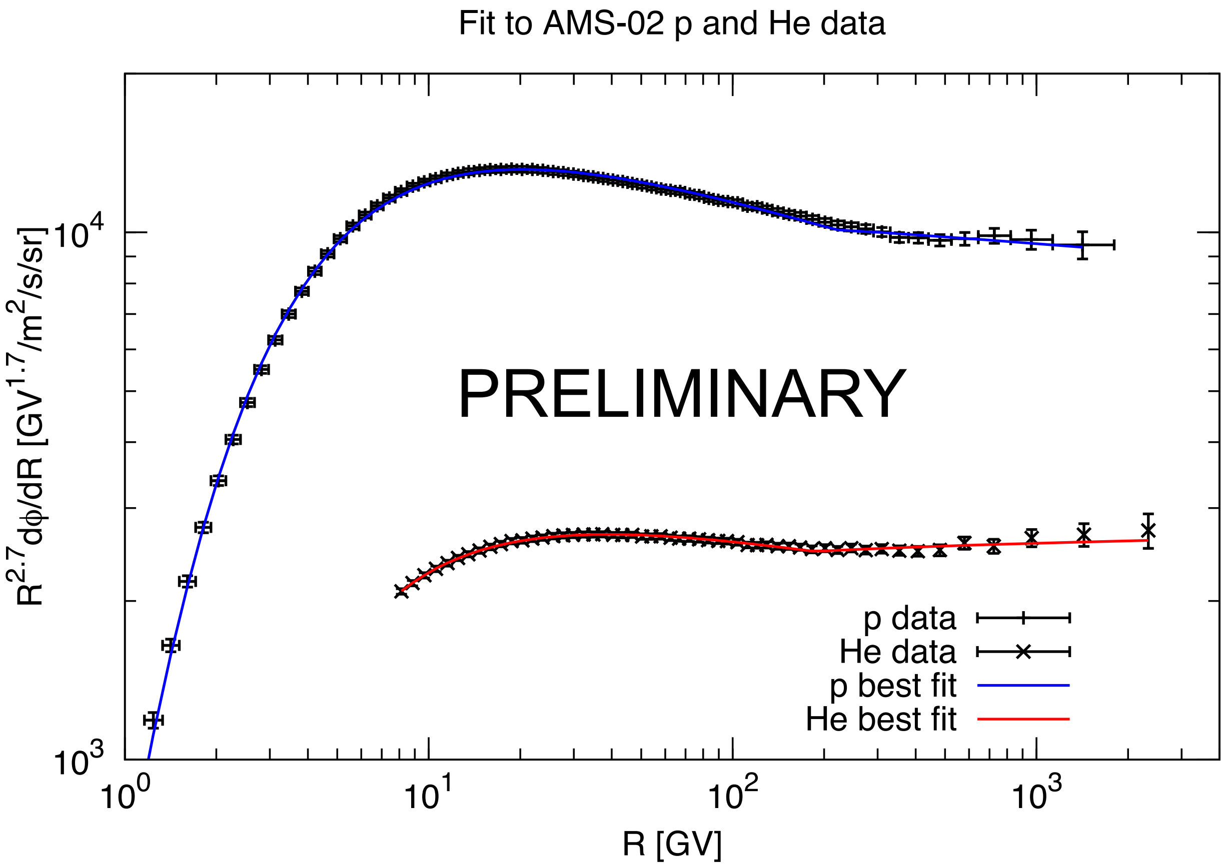
$(p/He_{CR}/A_{CR}) + (H_{ISM}/He_{ISM}/A_{ISM}) \longrightarrow$ anti-p X

$$q_{\bar{p}}^{pp}(E_{\bar{p}}) = \int_{E_{\rm th}}^{+\infty} \frac{d\sigma_{p\,p\to\bar{p}}}{dE_{\bar{p}}}(E_p, E_{\bar{p}}) n_H (4\pi\Phi_p(E_p))dE_p$$

1 2 3 4

1. $E_{th}=7m_p$
2. Antiproton cross section
3. Density of the ISM $\mathrm{H{:}He{:}C}=1{:}0.1{:}5\times10^{-4}\ \mathrm{cm}^{-3}$
4. Flux of incoming cosmic rays.

PRIMARY CRS

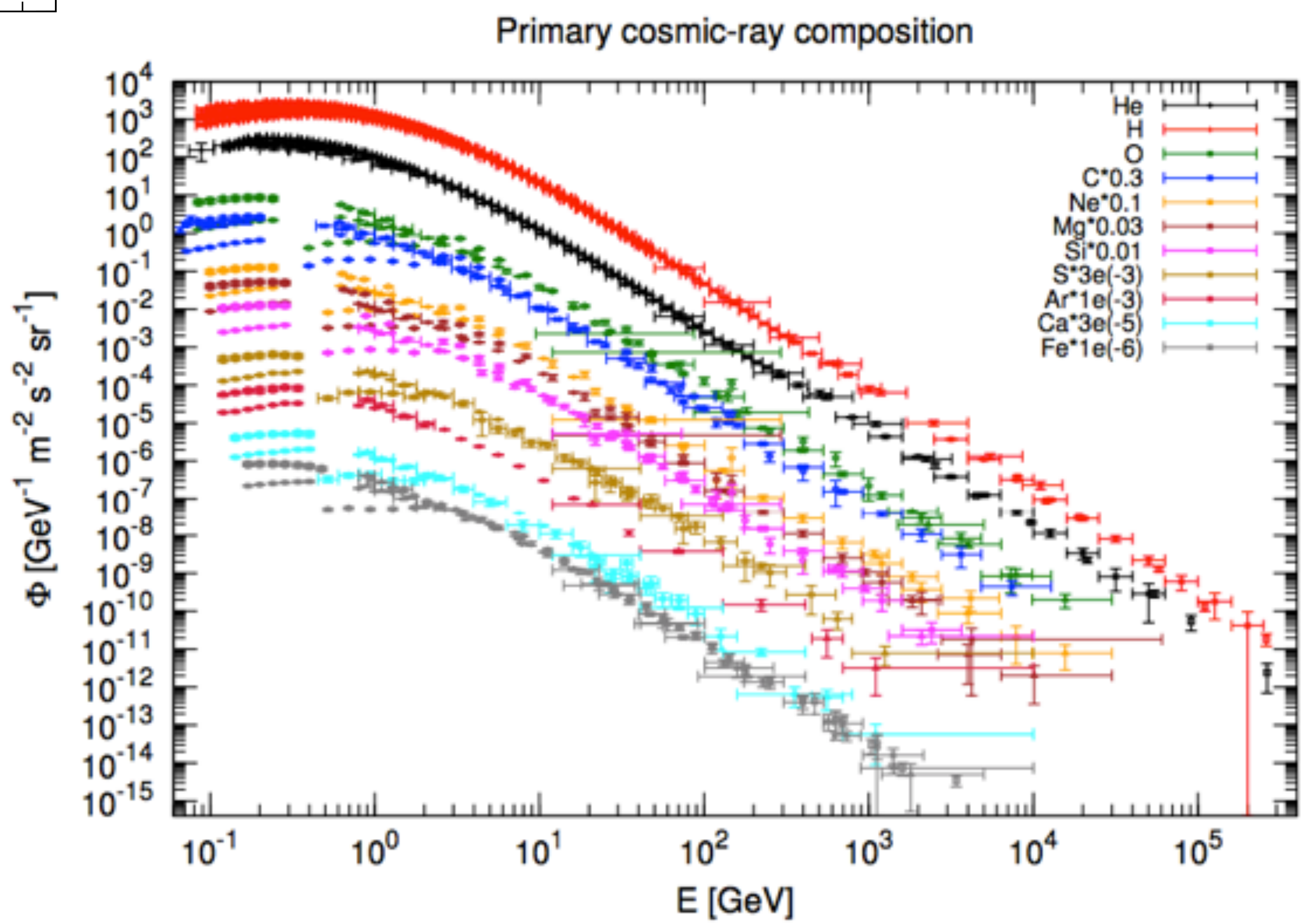


Di Mauro et al. 2015 in preparation

$$\Phi = A\beta^P R_{\rm break}^{-P_1+P_2} R^{-P_2}$$

Proton flux about a factor of 20 larger than He nucleus flux

Nuclei heavier than He contribute with a few % to primary CRs.



Di Mauro PhD thesis

HELIUM AND NUCLEI CHANNELS

Nuclei heavier than protons and helium only contribute at a few percent level thus playing a very marginal role

Reactions involving helium (p-He, He-p, He-He) represent a sizable fraction of the total yield, easily reaching ~50% at low energies.

However, for processes involving helium nuclei no data is available. Very little data are present only for heavier nuclei.

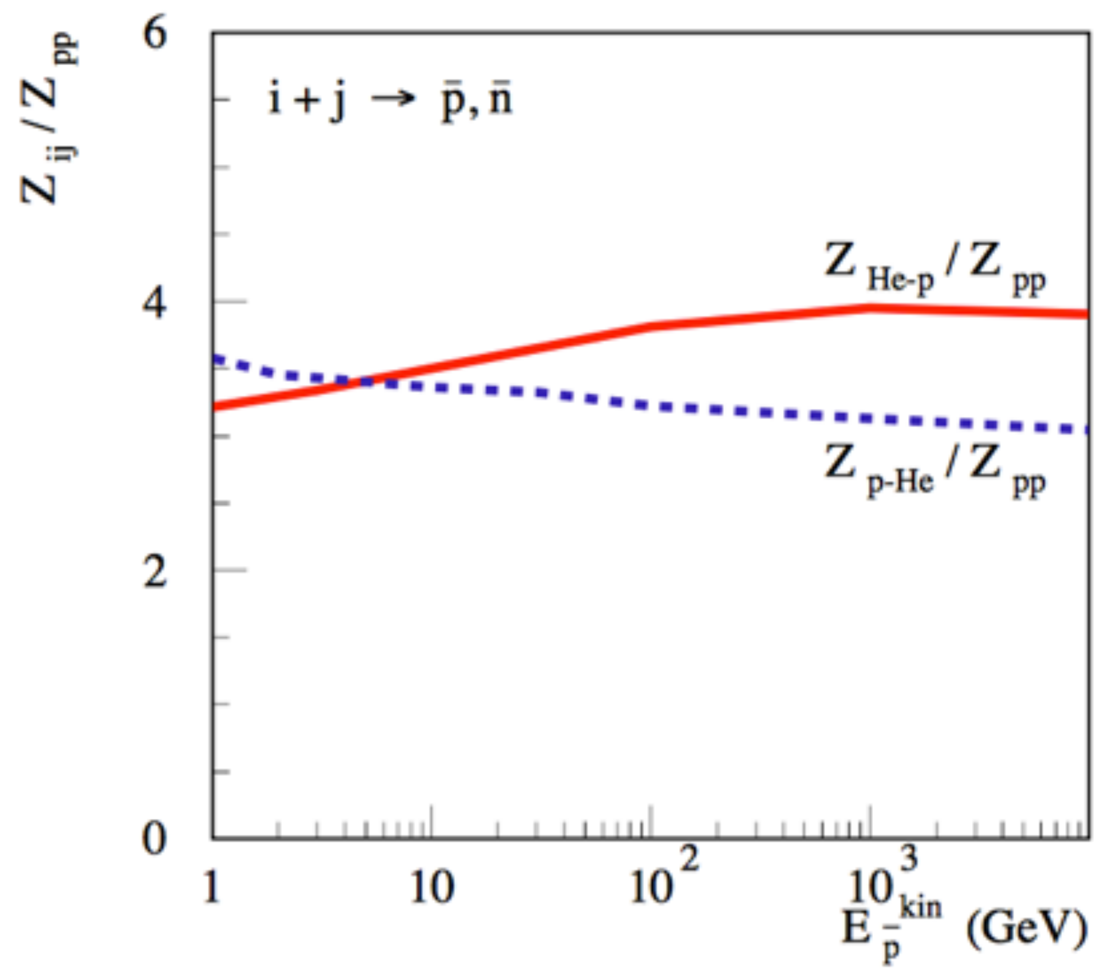
One possible strategy to deduce cross sections for reactions involving helium is to constrain those of nuclear species for which some data are available, and extrapolate from heavier species to lighter ones.

The most recent dedicated studies were performed on the basis of the Monte Carlo (MC) model DTUNUC, EPOS-LHC and QGSJET-II- 04.

$$Z_{\bar{p}}^{ij}(E_{\bar{p}}, \alpha) = \int_0^1 dz\, z^{\alpha-1} \frac{d\sigma^{ij\to\bar{p}}(E_{\bar{p}}/z, z)}{dz}$$

$$Q_{\rm tot}/Q_{\rm pp} = 0.12(T_{\bar{p}}/{\rm GeV})^{-1.67} + 1.78$$

Moskalenko, A.et al. APJ. 565, 280 (2002),

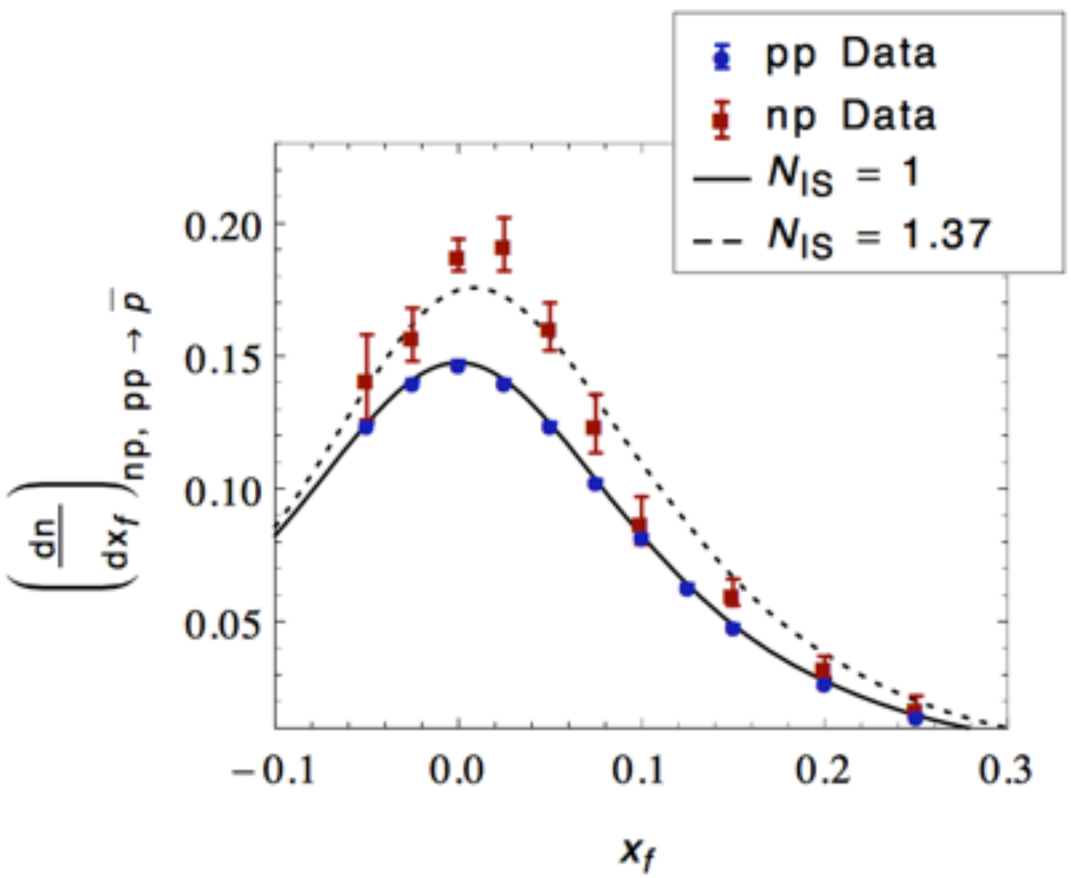


M. Kachelriess et al. ApJ 803 (2015) 2, 54

ANTI-PROTONS FROM ANTI-NEUTRON CHANNEL

- The second most important process is antineutron channel.
- Standard assumption in cosmic ray physics $\sigma_{pp\to\bar{n}} = \kappa\sigma_{pp\to\bar{p}}$ with k=1
- However, NA49 collaboration has reported an isospin-dependence of secondary yields in np and pp collisions: in pp reactions, there is a significant preference of the positively charged p ant-n combination over anti-p n.

$$(p/He_{CR}/A_{CR}) + (H_{ISM}/He_{ISM}/A_{ISM}) \longrightarrow \text{anti-}p\ X$$



k =1.3±0.2

Kappl and Winkler 2014 k =1.37±0.06

Fischer et al., Heavy Ion Phys. 17 (2003)

ANTI-PROTON CHANNELS

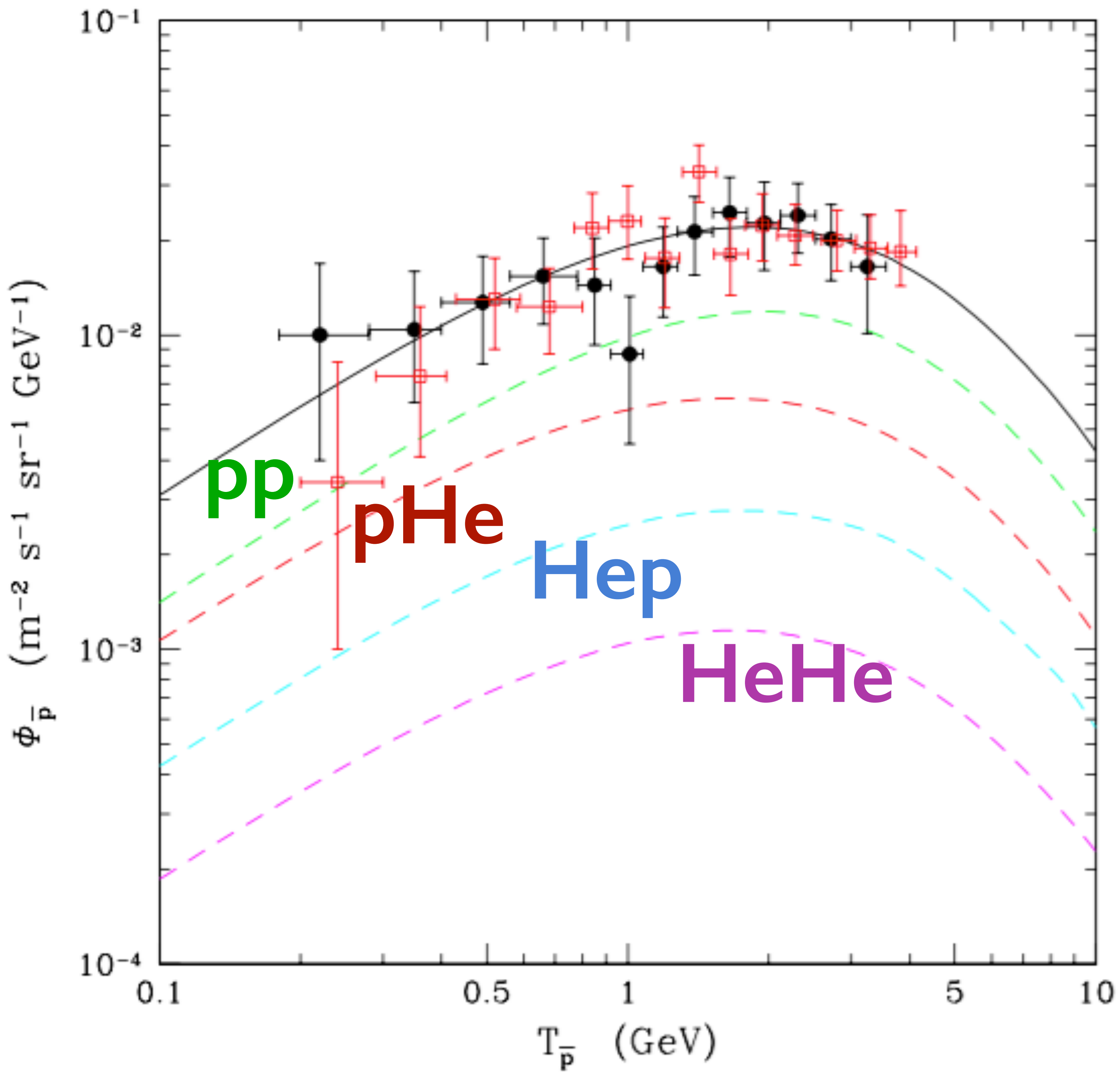
M. Kachelriess et al.
ApJ 803 (2015) 2, 54

- The principal channel for the production of anti-protons CRs is the interaction of primary proton CRs with the hydrogen nuclei of the ISM.
- The second most important process, about of the same order of the previous one, is the interaction of primary He CRs with ISM hydrogen and primary helium CRs with ISM hydrogen.
- Finally all the channels involving nuclei is at most a few % of the p_{CR}-H_{ISM} channel.

	n_{ism}	Φ_{CR}	CS	q	ratio
p_{CR}-H_{ISM}	0.9	1	1	0.90	**55%**
p_{CR}-He_{ISM}	0.1	1	3.2	0.32	**20%**
He_{CR}-H_{ISM}	0.9	0.05	3.7	0.18	**11%**
He_{CR}-He_{ISM}	0.1	0.05	11	0.06	**4%**
A_{CR}-H_{ISM}	0.9	0.01	10	0.09	**6%**
A_{CR}-He_{ISM}	0.1	0.01	35	0.04	**3%**

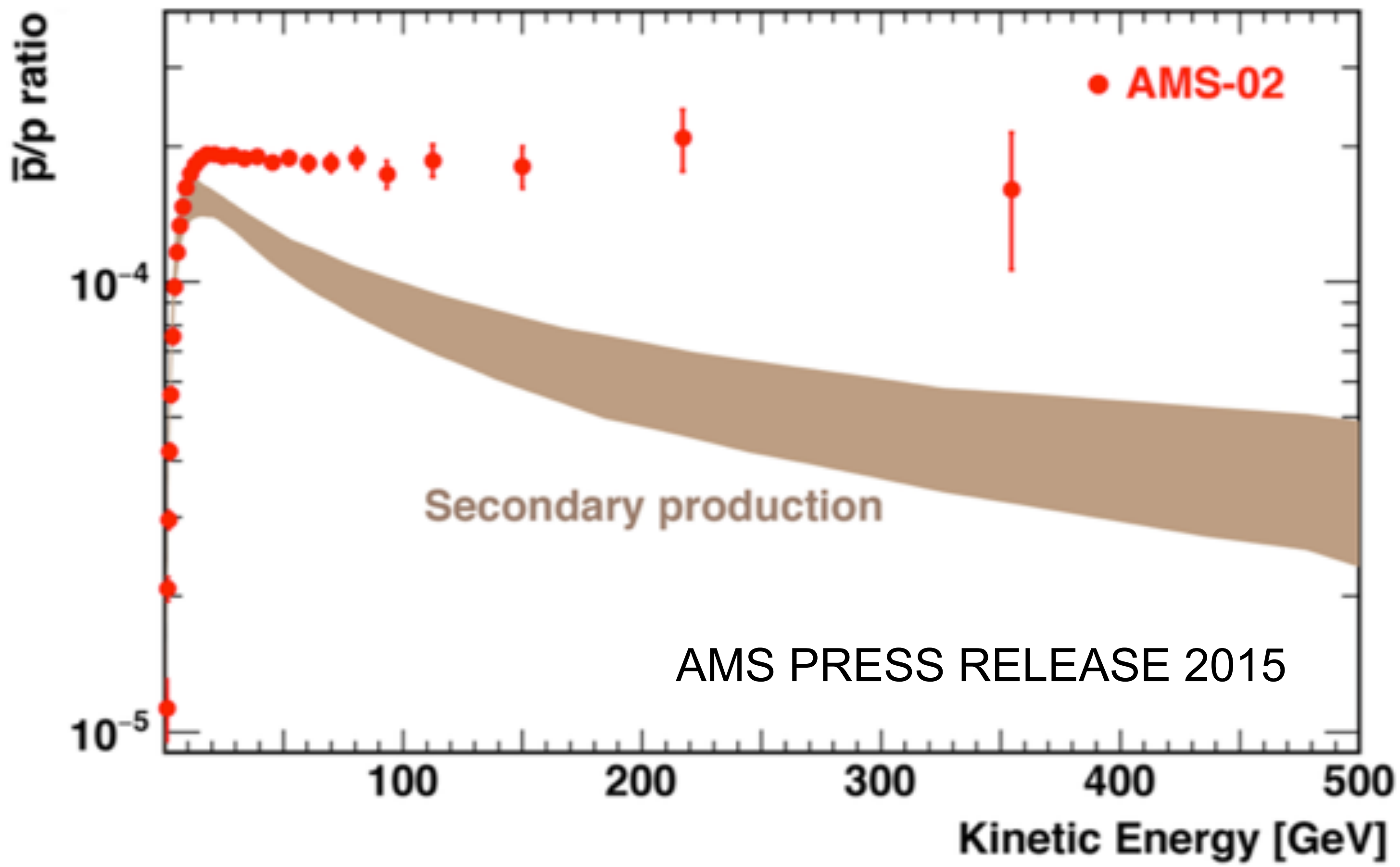
$$(p/He_{CR}/A_{CR}) + (H_{ISM}/He_{ISM}/A_{ISM}) \longrightarrow \text{anti-p } X$$

ANTI-PROTON CHANNELS



Donato et al. ApJ 563 (2001) 172-184

ENERGETICS OF ANTI-P CRS



CR ISM —> anti-p X

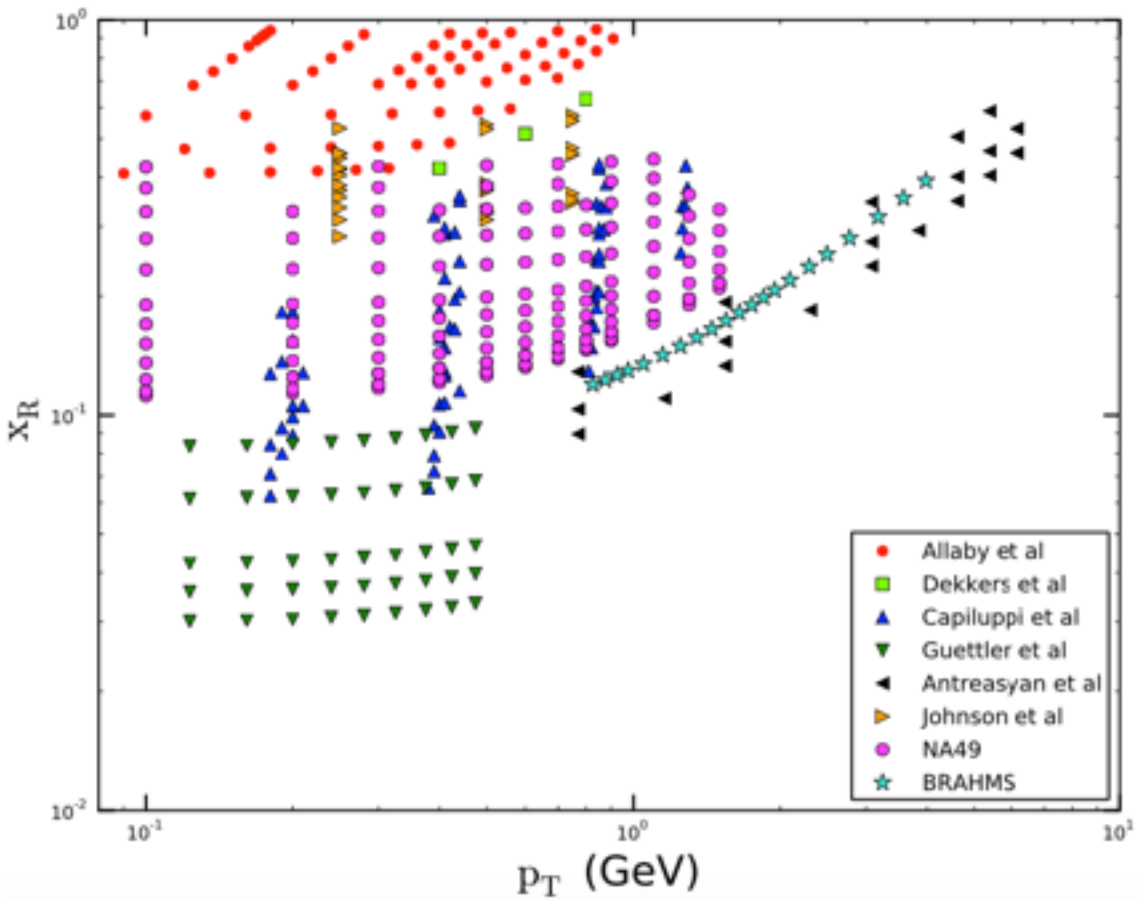
LAB FRAME

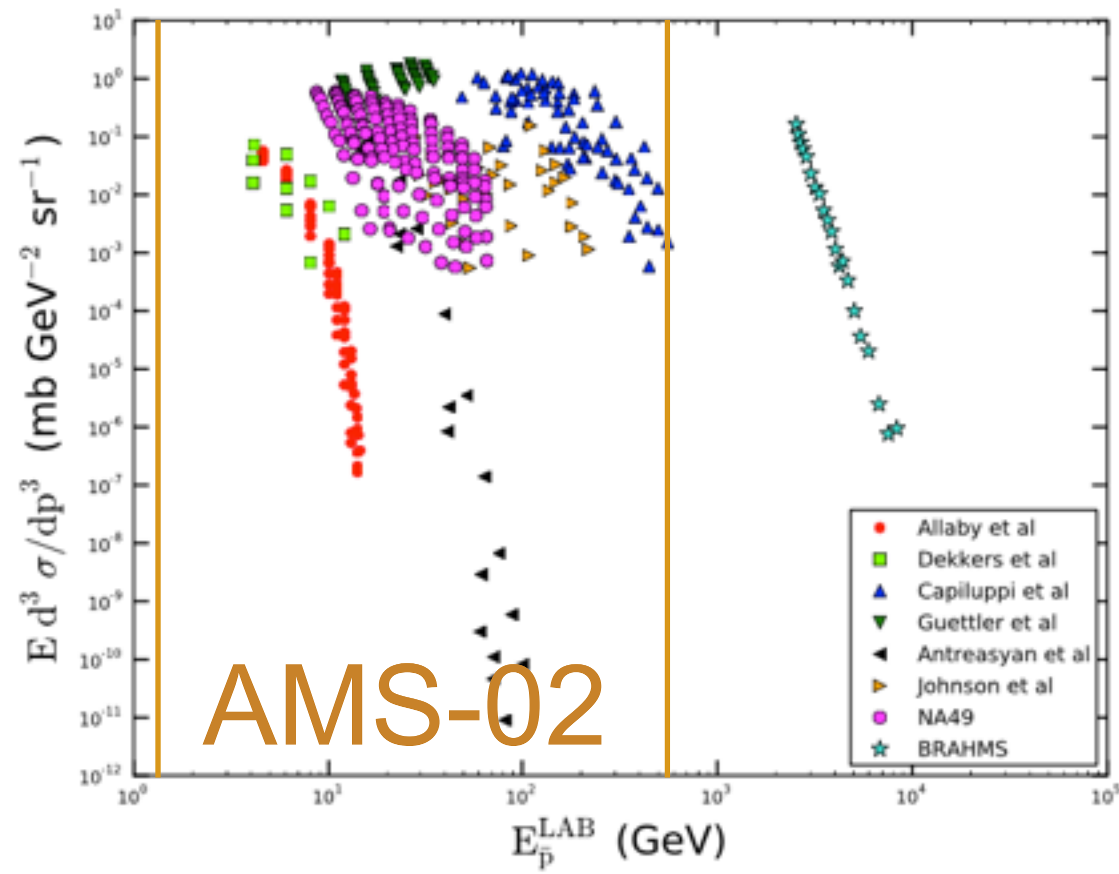
100-5000 GeV

10-500 GeV

$$\sqrt{s} = \sqrt{2m_p(E_p + m_p)}$$ = 15-100 GeV

EXPERIMENTAL SITUATION





Experiment	$\sqrt{s}$ (GeV)	p_T (GeV)	x_R
Dekkers *et al*, CERN 1965 [18]	6.1, 6.7	$(0., 0.79)$	$(0.34, 0.65)$
Allaby *et al*, CERN 1970 [19]	6.15	$(0.05, 0.90)$	$(0.40, 0.94)$
Capiluppi *et al*, CERN 1974 [20]	23.3, 30.6, 44.6, 53.0, 62.7	$(0.18, 1.29)$	$(0.06, 0.43)$
Guettler *et al*, CERN 1976 [21]	23.0, 31.0, 45.0, 53.0, 63.0	$(0.12, 0.47)$	$(0.036, 0.092)$
Johnson *et al*, FNAL 1978 [22]	13.8, 19.4, 27.4	$(0.25, 0.75)$	$(0.31, 0.55)$
Antreasyan *et al*, FNAL 1979 [23]	19.4, 23.8, 27.4	$(0.77, 6.15)$	$(0.08, 0.58)$
BRAHMS, BNL 2008 [13]	200	$(0.82, 3.97)$	$(0.11, 0.39)$
NA49, CERN 2010 [14]	17.3	$(0.10, 1.50)$	$(0.11, 0.44)$

FRAMEWORK

LAB experiments measure the Lorentz invariant distribution function

$$f(a+b \to c+X) = E_c \frac{d^3\sigma}{dp_c^3} = \frac{E_c}{\pi} \frac{d^2\sigma}{dp_L dp_T^2} = \frac{d^2\sigma}{\pi dy dp_T^2}$$

The differential cross section is then obtained in the following way:

$$\frac{d\sigma_{pp\to\bar{p}}}{dE_{\bar{p}}}(E_p, E_{\bar{p}}) = 2\pi p_{\bar{p}} \int_{\vartheta_{\min}}^{\vartheta_{\max}} E_{\bar{p}} \frac{d^3\sigma}{dp_{\bar{p}}^3} d(-\cos\vartheta)$$

$$q_{\bar{p}}^{pp}(E_{\bar{p}}) = \int_{E_{\rm th}}^{+\infty} \frac{d\sigma_{pp\to\bar{p}}}{dE_{\bar{p}}}(E_p, E_{\bar{p}}) n_H (4\pi\Phi_p(E_p)) dE_p$$

We considered all the cited experiments in the center-of-mass frame considering the following parameters:

$$\{s, p_T, x_R\}$$

METHOD

1) We derive the Lorentz- invariant distribution function with the following chi-square function:

$$\chi^2(\mathbf{C}) = \chi^2_{\rm stat}(\mathbf{C}) + \chi^2_{\rm sys}$$

$$\chi^2_{\rm sys} = \sum_{k=1}^{L} \frac{(\omega_k - 1)^2}{\epsilon_k^2}$$

$$\chi^2_{\rm stat}(\mathbf{C}) = \sum_{k=1}^{L} \sum_{i_k} \frac{(\omega_k f_{i_k} - F(s_{i_k}, x_{R_{i_k}}, p_{T_{i_k}}, \mathbf{C}))^2}{\omega_k^2 \sigma_{i_k}^2}$$

Renormalization parameter

Systematic overall scale error

Data errors

Fit function parameters

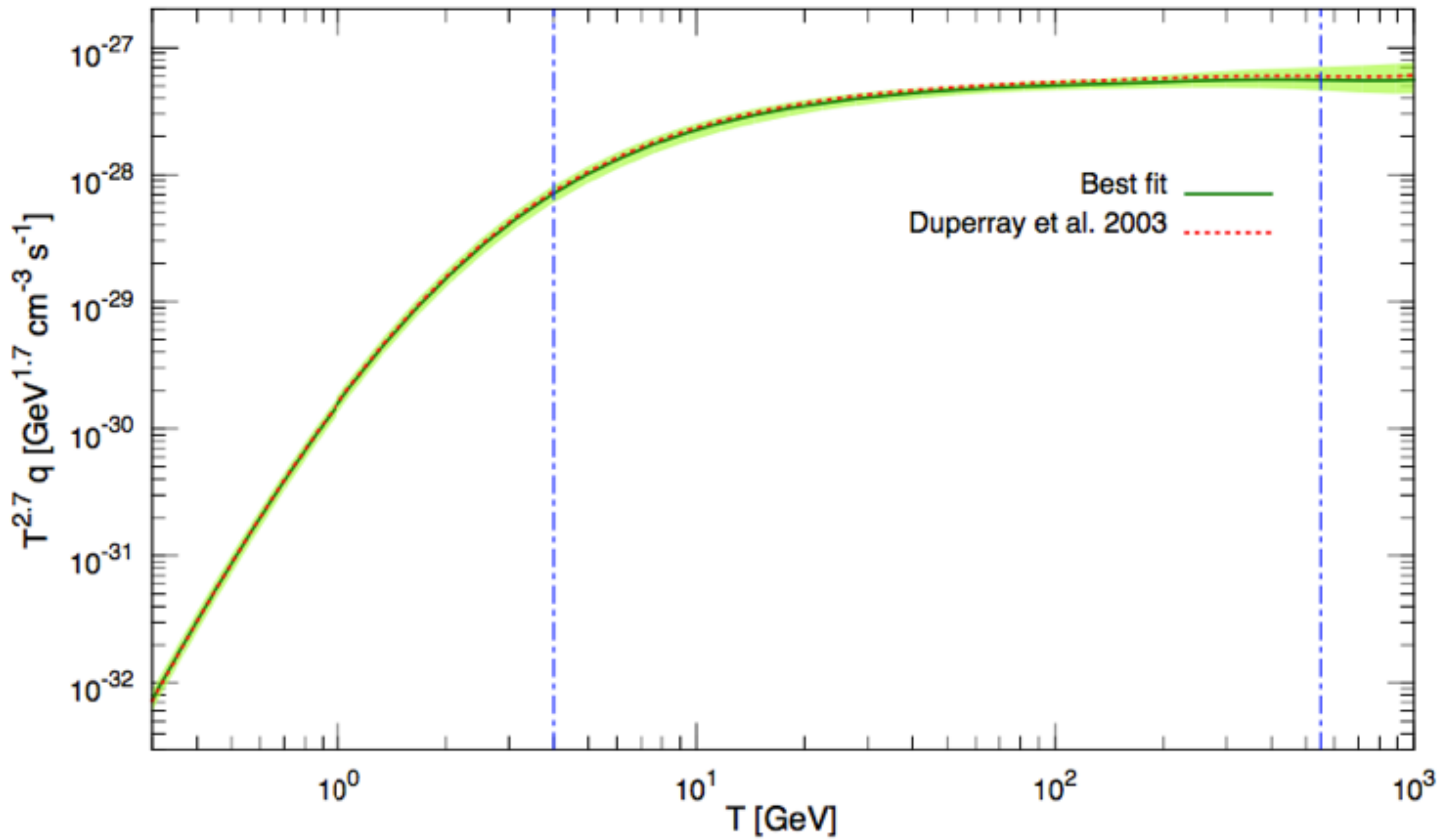
2) We also use a completely data driven method using a spline interpolation of the data, which only requires a smooth, piecewise functional dependence.

The interpolations were performed by means of the Python routine SmoothBivariateSpline contained in the scipy library, choosing piecewise cubic polynomials as in- terpolating functions.

We use this method as a crosscheck in the range of validity of data

VALIDATION OF THE METHOD

- In order to validate our method we take into account the same dataset as in Duperray 2003 and using their same fitting function we perform a fit to cross section data.
- We find the same values as in Duparray et al. 2003 and the source term is consistent with the one found with Duparray values.

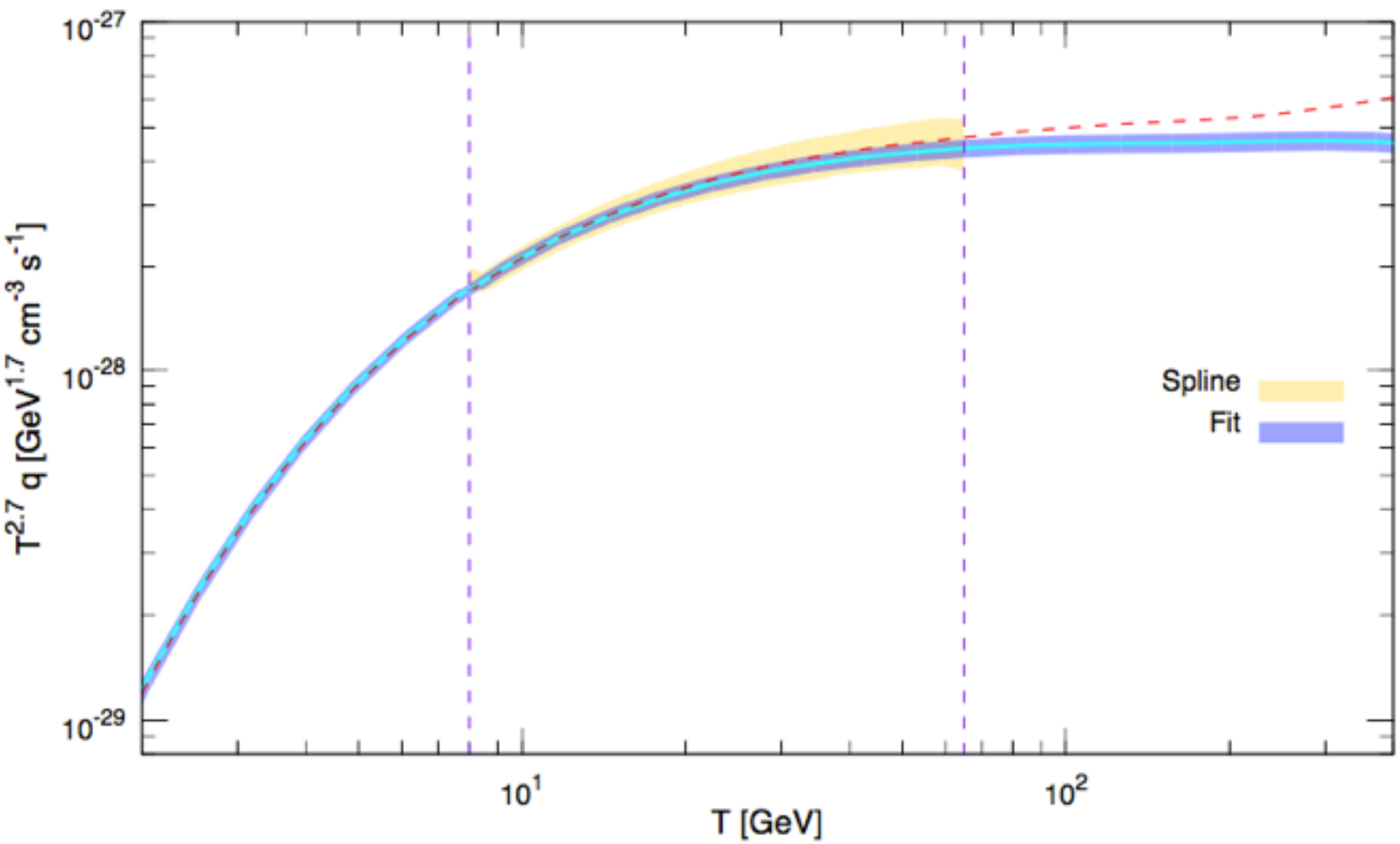


R. Duperray et al. Phys.Rev. D68 2003

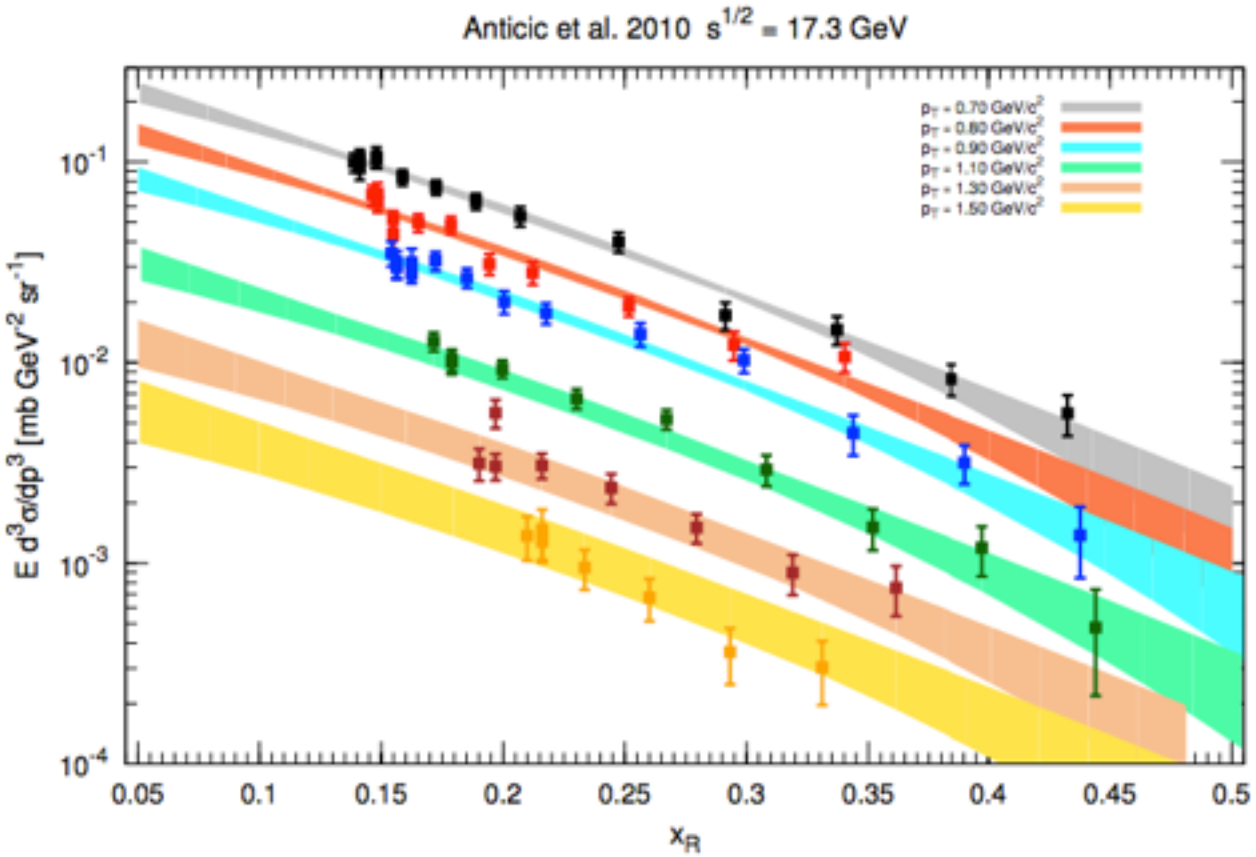
ANALYSIS ON NA49 DATA

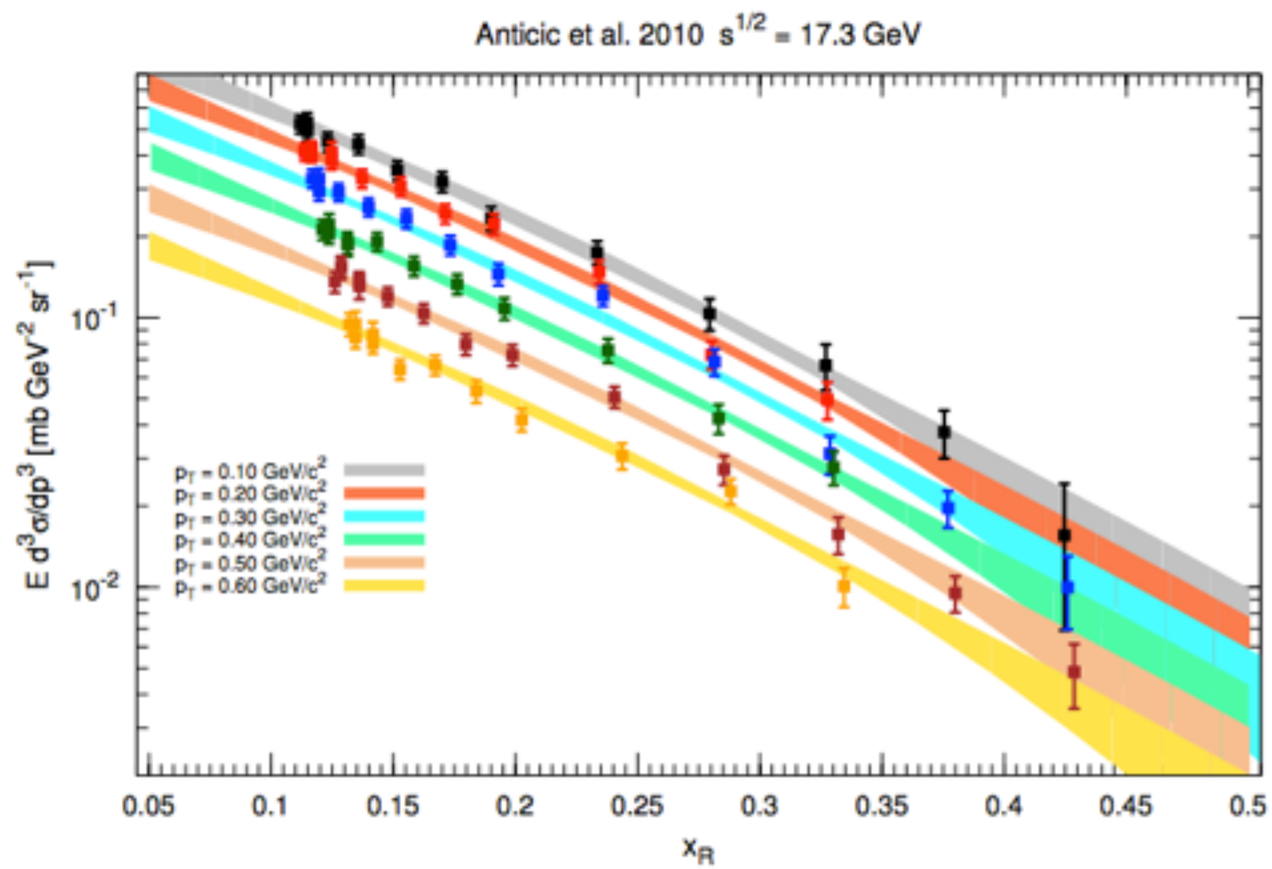
$$E\frac{d^3\sigma}{dp^3} = \sigma_{\rm in}(s)(1-x_R)^{C_1}e^{-C_2 x_R} \left[C_3\, e^{-C_4 p_T} + C_5\, e^{-C_6 p_T^2}\right]$$

$$\chi^2_\nu = 1.3 \text{ for } 137 \text{ degrees of freedom}$$



NA49 COMPARISON





GLOBAL ANALYSIS

$$E\frac{d^3\sigma}{dp^3} = \sigma_{\text{in}}(s)(1-x_R)^{C_1}e^{-C_2 x_R}$$
$$\left[C_3(\sqrt{s})^{C_4}e^{-C_5 p_T} + C_6(\sqrt{s})^{C_7}e^{-C_8 p_T^2}\right]$$

$$\chi^2_\nu = 4.16$$

$$E\frac{d^3\sigma}{dp^3} = \sigma_{\text{in}}(s)(1-x_R)^{C_1}e^{-C_2 x_R}\left|\left[C_3(\sqrt{s})^{C_4}e^{-C_5 p_T} + \right.\right.$$
$$\left.\left.C_6(\sqrt{s})^{C_7}e^{-C_8 p_T^2} + C_9(\sqrt{s})^{C_{10}}e^{-C_{11} p_T^3}\right]\right|, \qquad (1$$

$$\chi^2_\nu = 3.30$$

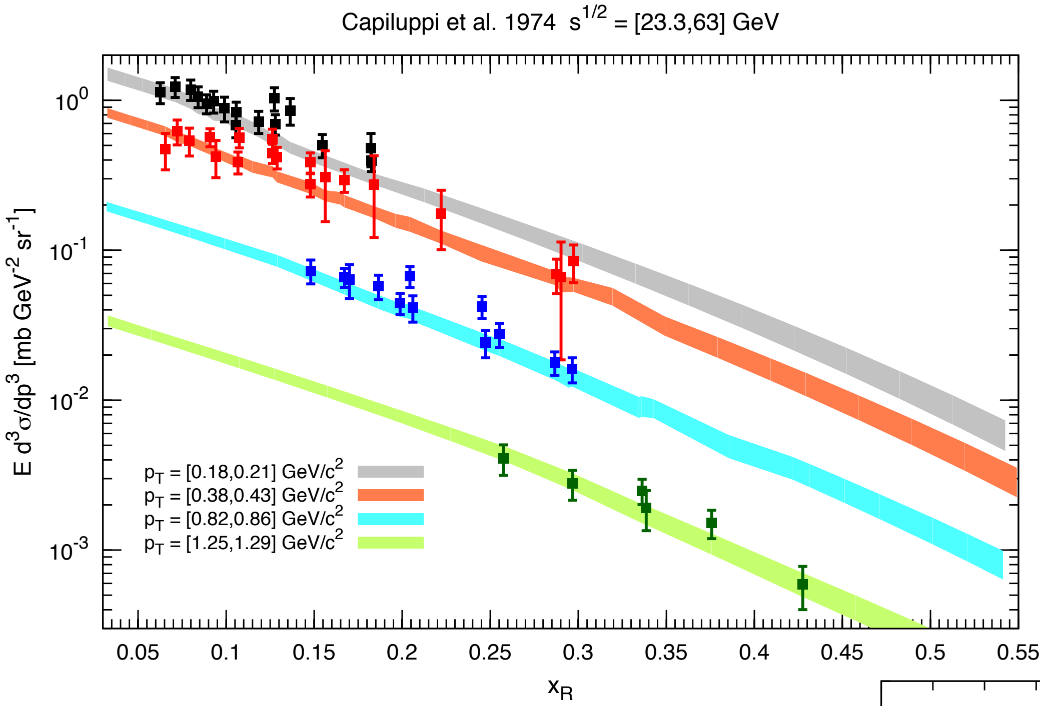
Renormalization factors:

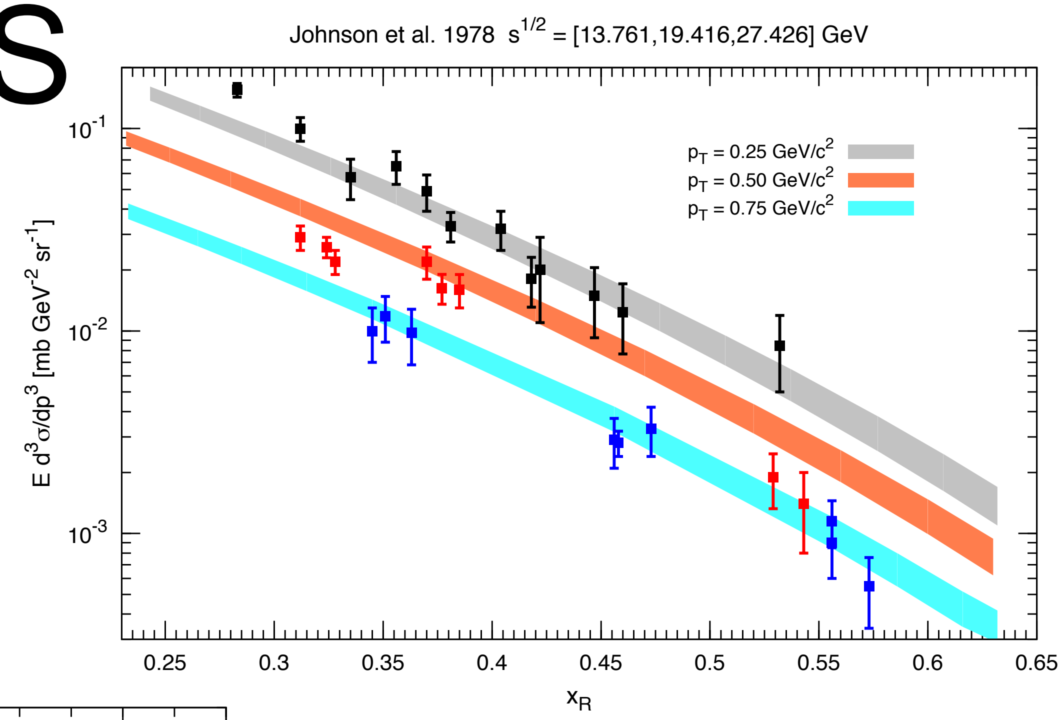
NA49

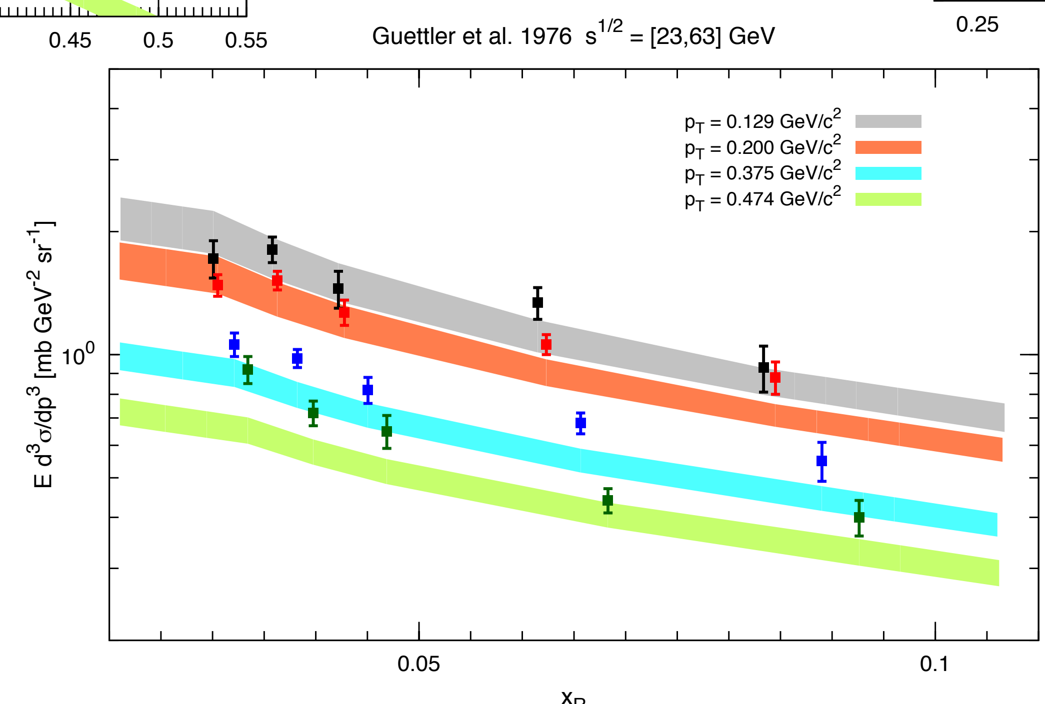
$$\{0.87, 1.04, 1.16, 0.98, 0.95, 1.13, 1.02, 1.16\}$$

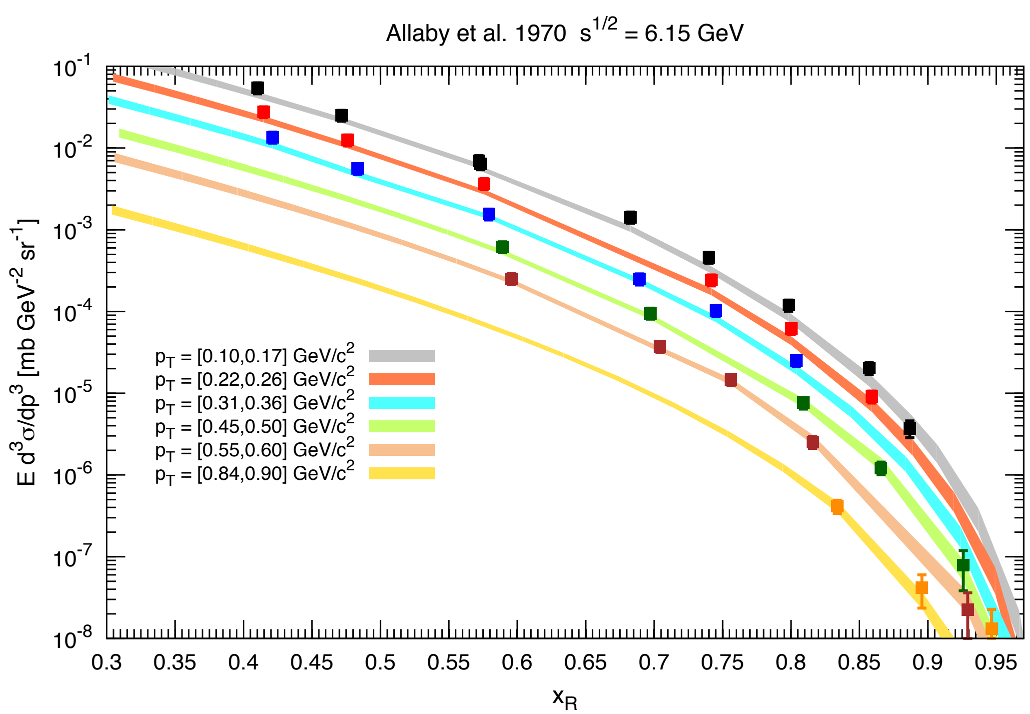
Brahms

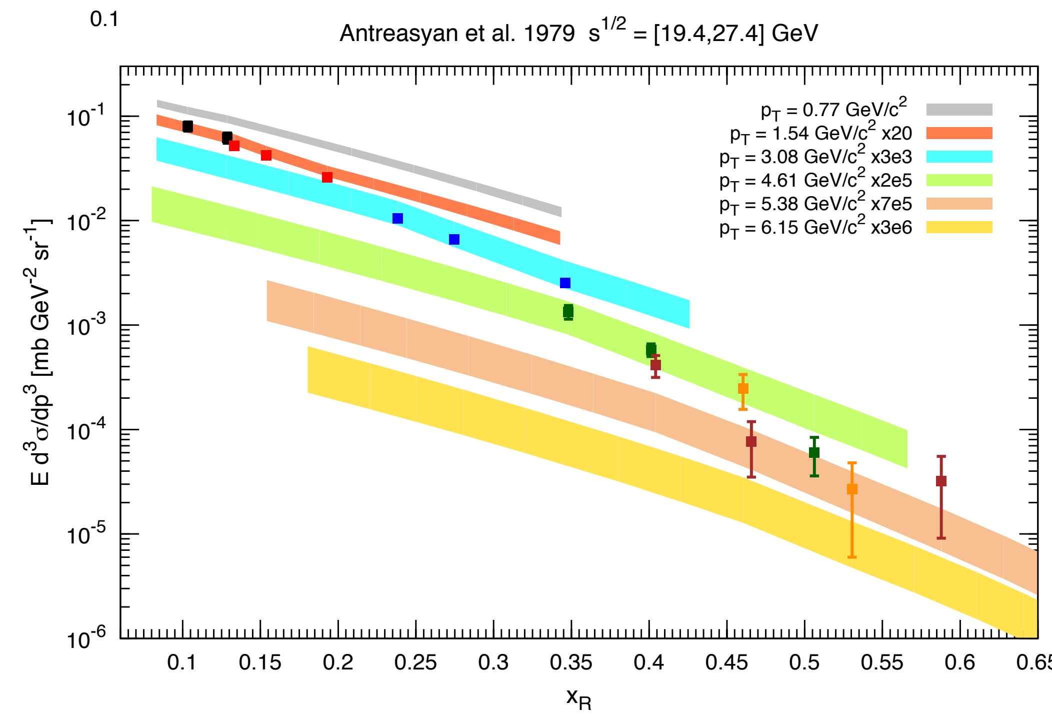
RESULTS 1


Capiluppi et al. 1974 $s^{1/2}$ = [23.3,63] GeV
p_T = [0.18,0.21] GeV/c^2
p_T = [0.38,0.43] GeV/c^2
p_T = [0.82,0.86] GeV/c^2
p_T = [1.25,1.29] GeV/c^2
E $d^3\sigma/dp^3$ [mb GeV^{-2} sr^{-1}]
x_R

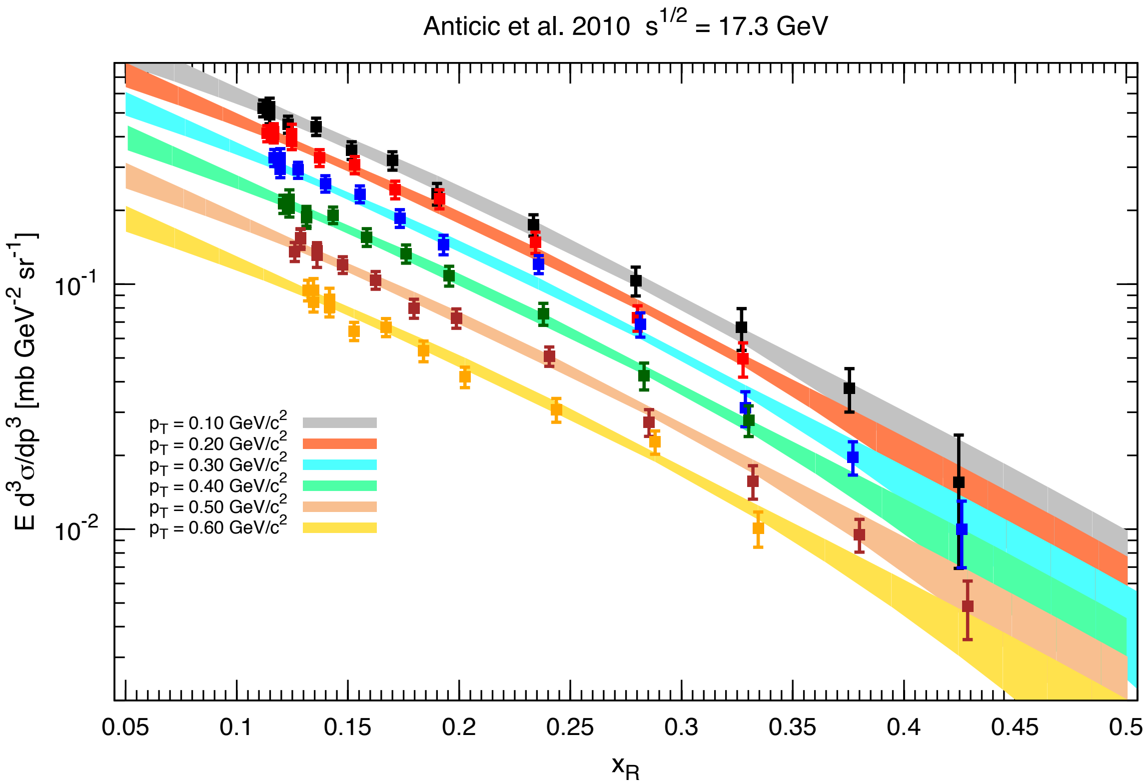

Johnson et al. 1978 $s^{1/2}$ = [13.761,19.416,27.426] GeV
p_T = 0.25 GeV/c^2
p_T = 0.50 GeV/c^2
p_T = 0.75 GeV/c^2
E $d^3\sigma/dp^3$ [mb GeV^{-2} sr^{-1}]
x_R


Guettler et al. 1976 $s^{1/2}$ = [23,63] GeV
p_T = 0.129 GeV/c^2
p_T = 0.200 GeV/c^2
p_T = 0.375 GeV/c^2
p_T = 0.474 GeV/c^2
E $d^3\sigma/dp^3$ [mb GeV^{-2} sr^{-1}]
x_R

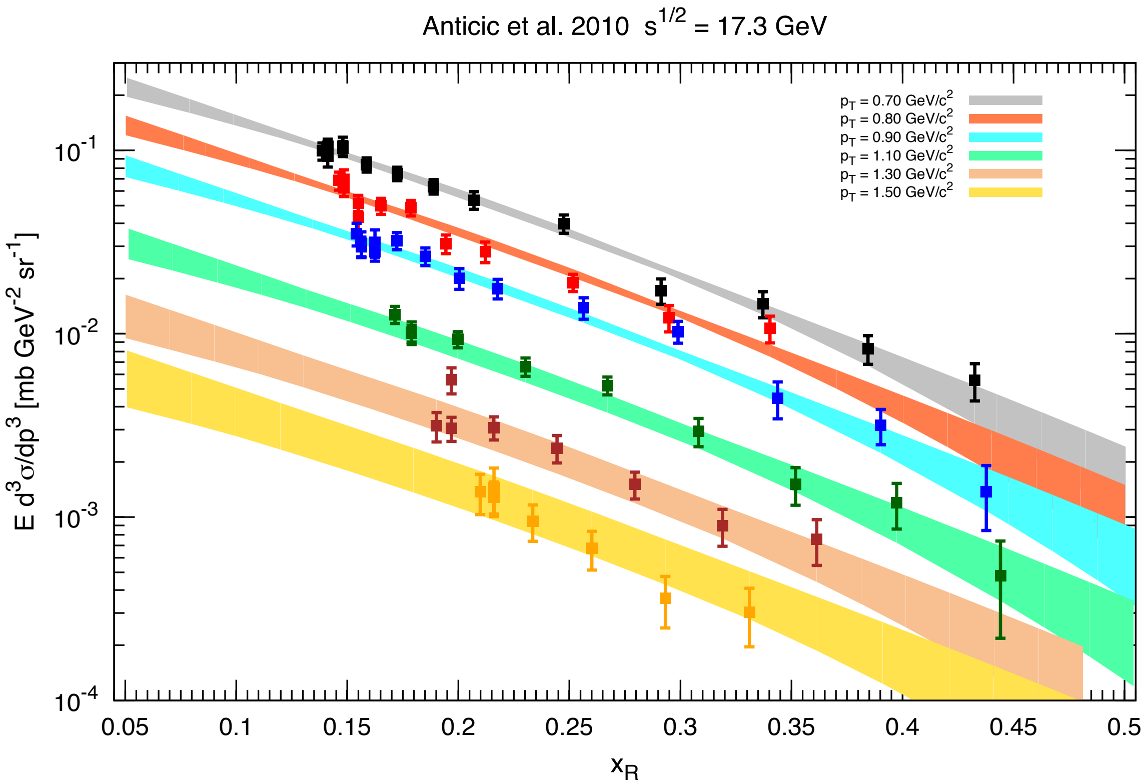

Allaby et al. 1970 $s^{1/2}$ = 6.15 GeV
p_T = [0.10,0.17] GeV/c^2
p_T = [0.22,0.26] GeV/c^2
p_T = [0.31,0.36] GeV/c^2
p_T = [0.45,0.50] GeV/c^2
p_T = [0.55,0.60] GeV/c^2
p_T = [0.84,0.90] GeV/c^2
E $d^3\sigma/dp^3$ [mb GeV^{-2} sr^{-1}]
x_R


Antreasyan et al. 1979 $s^{1/2}$ = [19.4,27.4] GeV
p_T = 0.77 GeV/c^2
p_T = 1.54 GeV/c^2 x20
p_T = 3.08 GeV/c^2 x3e3
p_T = 4.61 GeV/c^2 x2e5
p_T = 5.38 GeV/c^2 x7e5
p_T = 6.15 GeV/c^2 x3e6
E $d^3\sigma/dp^3$ [mb GeV^{-2} sr^{-1}]
x_R

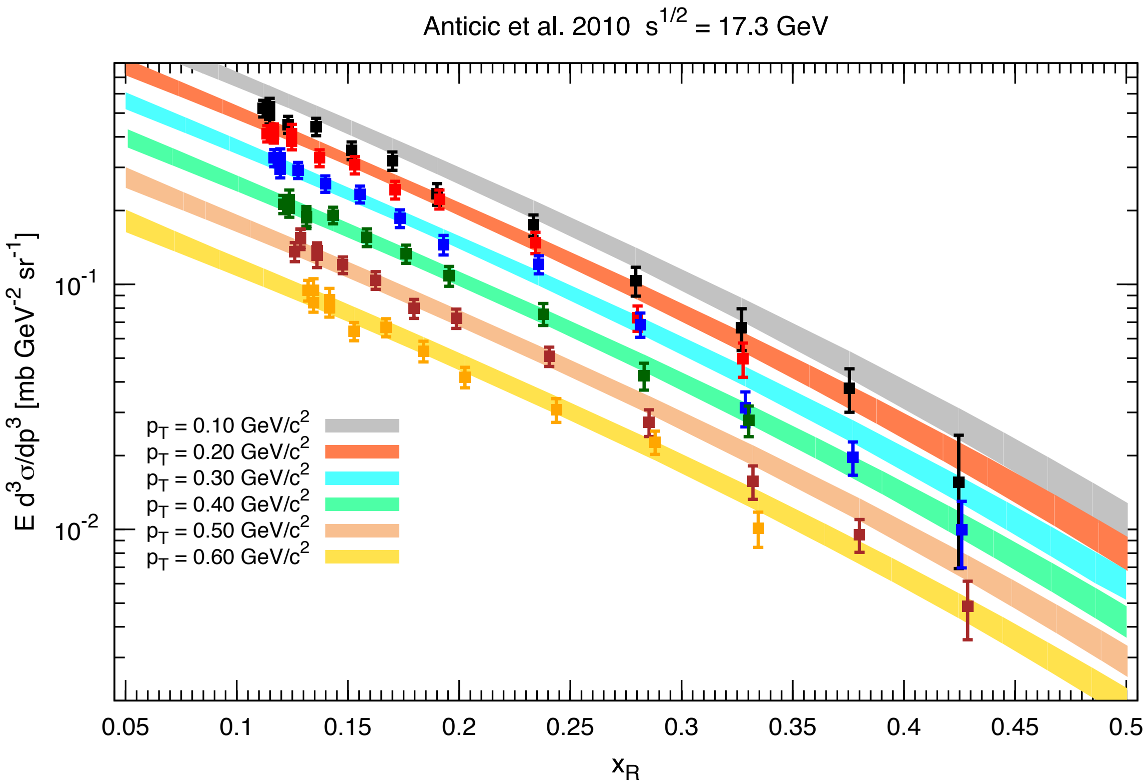
RESULTS 2



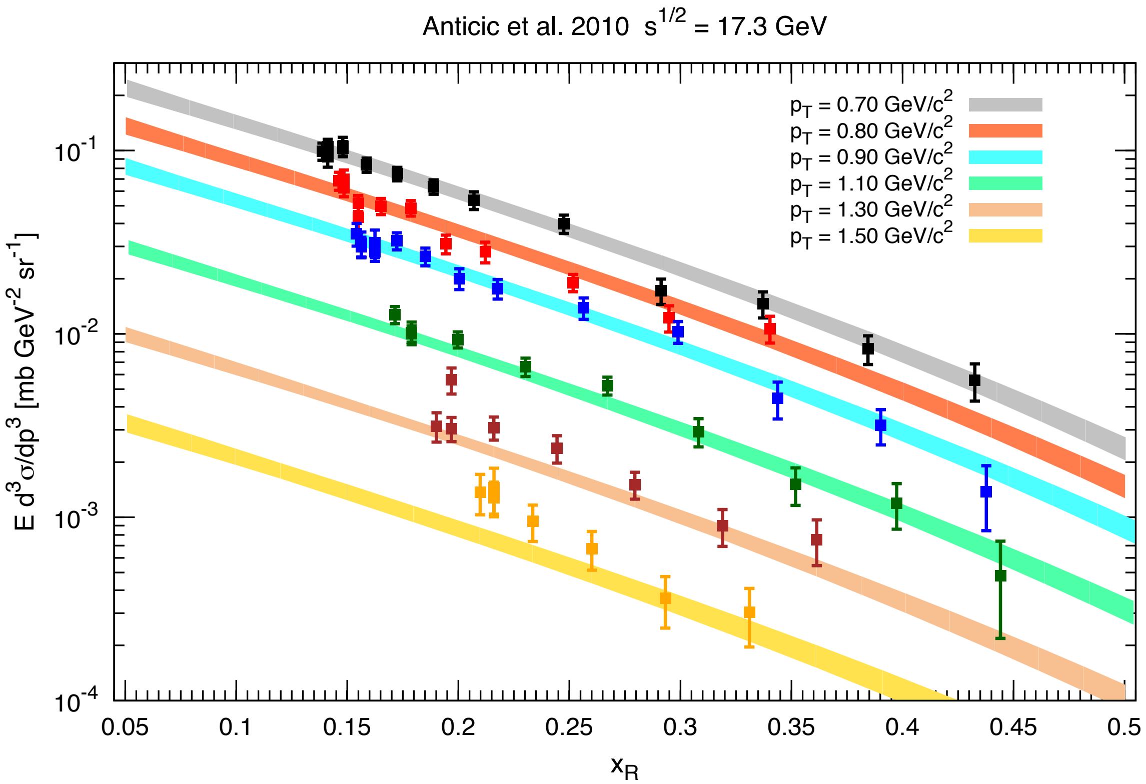
Anticic et al. 2010 $s^{1/2}$ = 17.3 GeV
p_T = 0.10 GeV/c^2
p_T = 0.20 GeV/c^2
p_T = 0.30 GeV/c^2
p_T = 0.40 GeV/c^2
p_T = 0.50 GeV/c^2
p_T = 0.60 GeV/c^2
E $d^3\sigma/dp^3$ [mb GeV^{-2} sr^{-1}]
x_R



Anticic et al. 2010 $s^{1/2}$ = 17.3 GeV
p_T = 0.70 GeV/c^2
p_T = 0.80 GeV/c^2
p_T = 0.90 GeV/c^2
p_T = 1.10 GeV/c^2
p_T = 1.30 GeV/c^2
p_T = 1.50 GeV/c^2
E $d^3\sigma/dp^3$ [mb GeV^{-2} sr^{-1}]
x_R



Anticic et al. 2010 $s^{1/2}$ = 17.3 GeV
p_T = 0.10 GeV/c^2
p_T = 0.20 GeV/c^2
p_T = 0.30 GeV/c^2
p_T = 0.40 GeV/c^2
p_T = 0.50 GeV/c^2
p_T = 0.60 GeV/c^2
E $d^3\sigma/dp^3$ [mb GeV^{-2} sr^{-1}]
x_R



Anticic et al. 2010 $s^{1/2}$ = 17.3 GeV
p_T = 0.70 GeV/c^2
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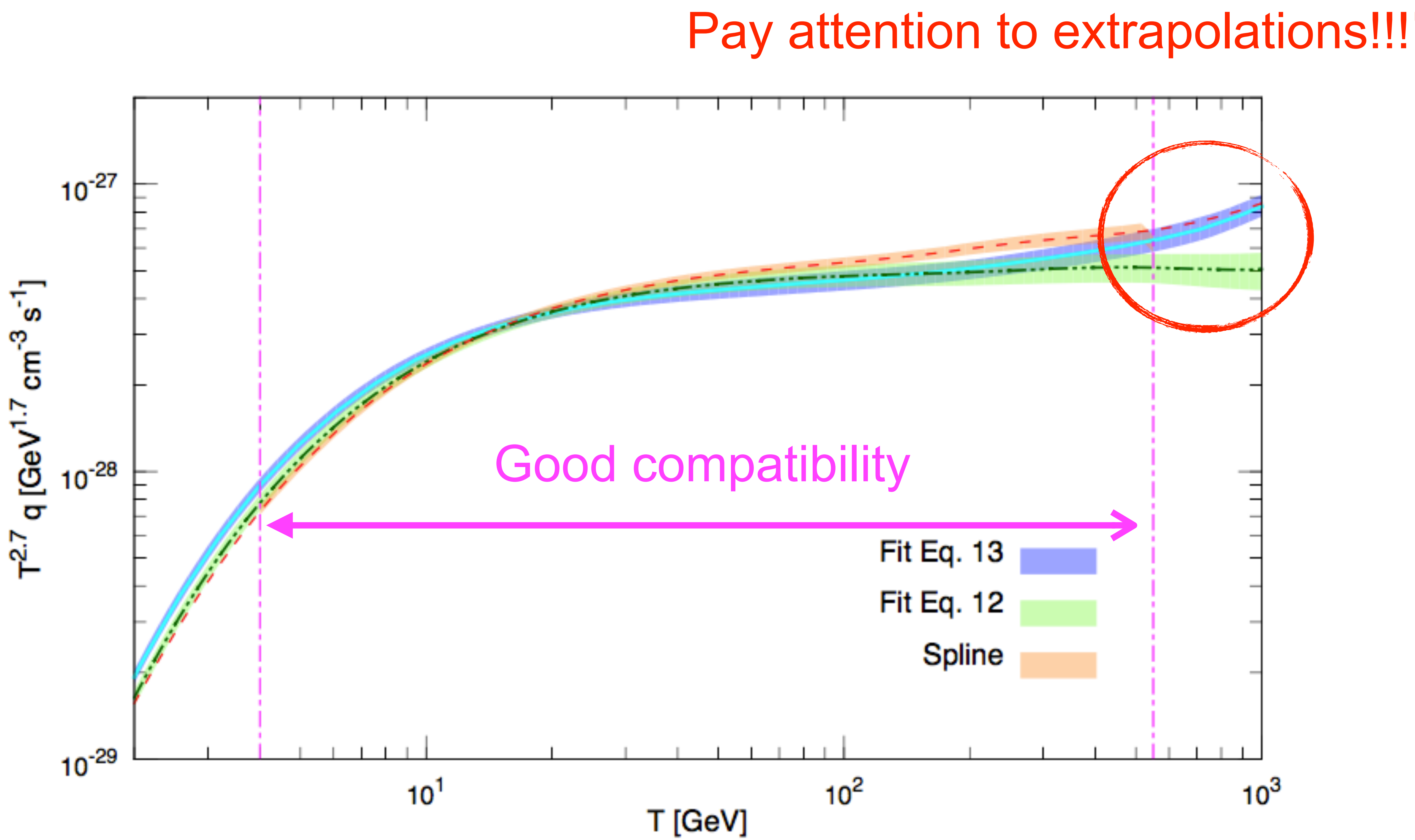
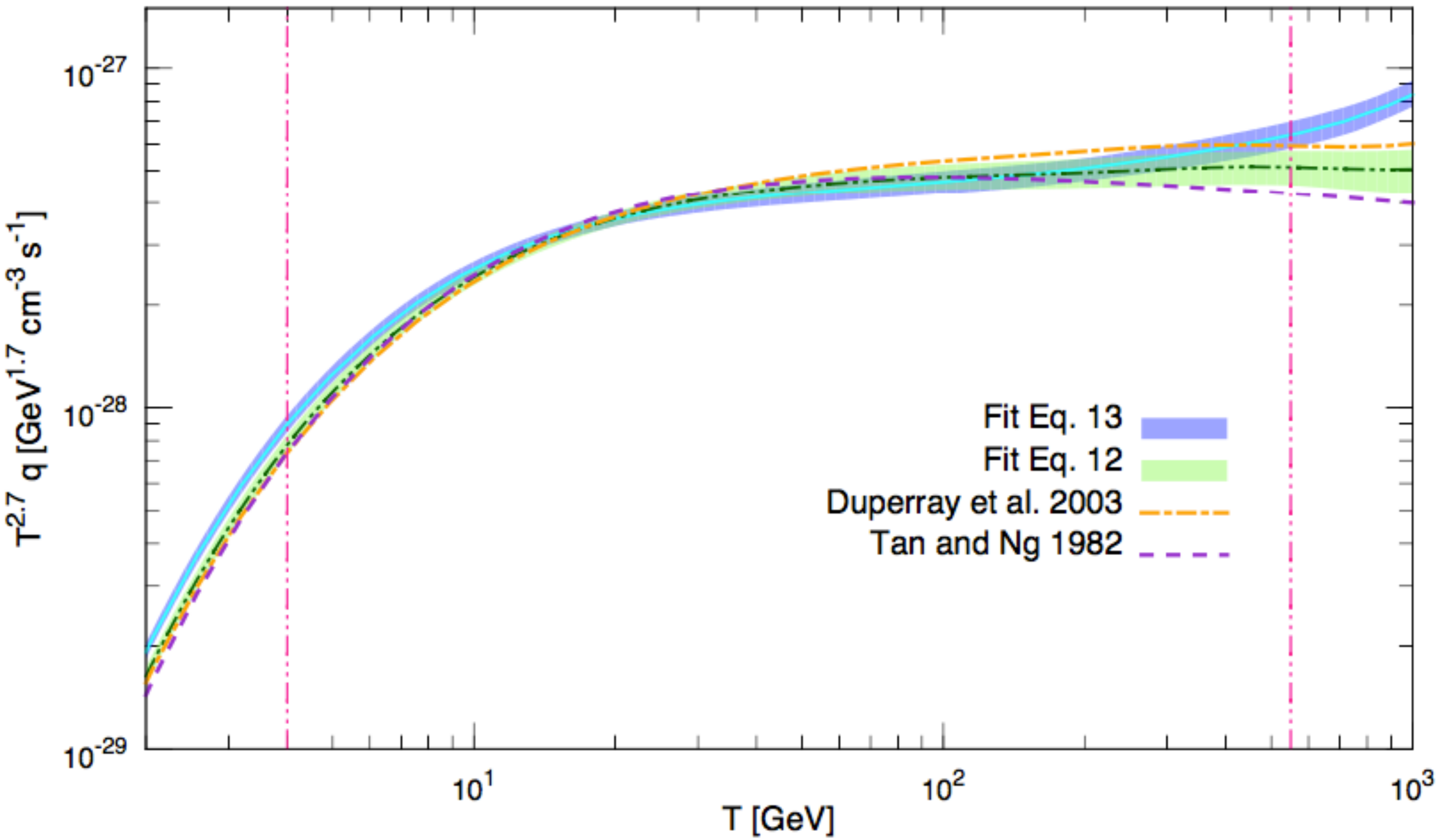
p_T = 0.90 GeV/c^2
p_T = 1.10 GeV/c^2
p_T = 1.30 GeV/c^2
p_T = 1.50 GeV/c^2
E $d^3\sigma/dp^3$ [mb GeV^{-2} sr^{-1}]
x_R

COMPARISON OF DIFFERENT FUNCTIONS

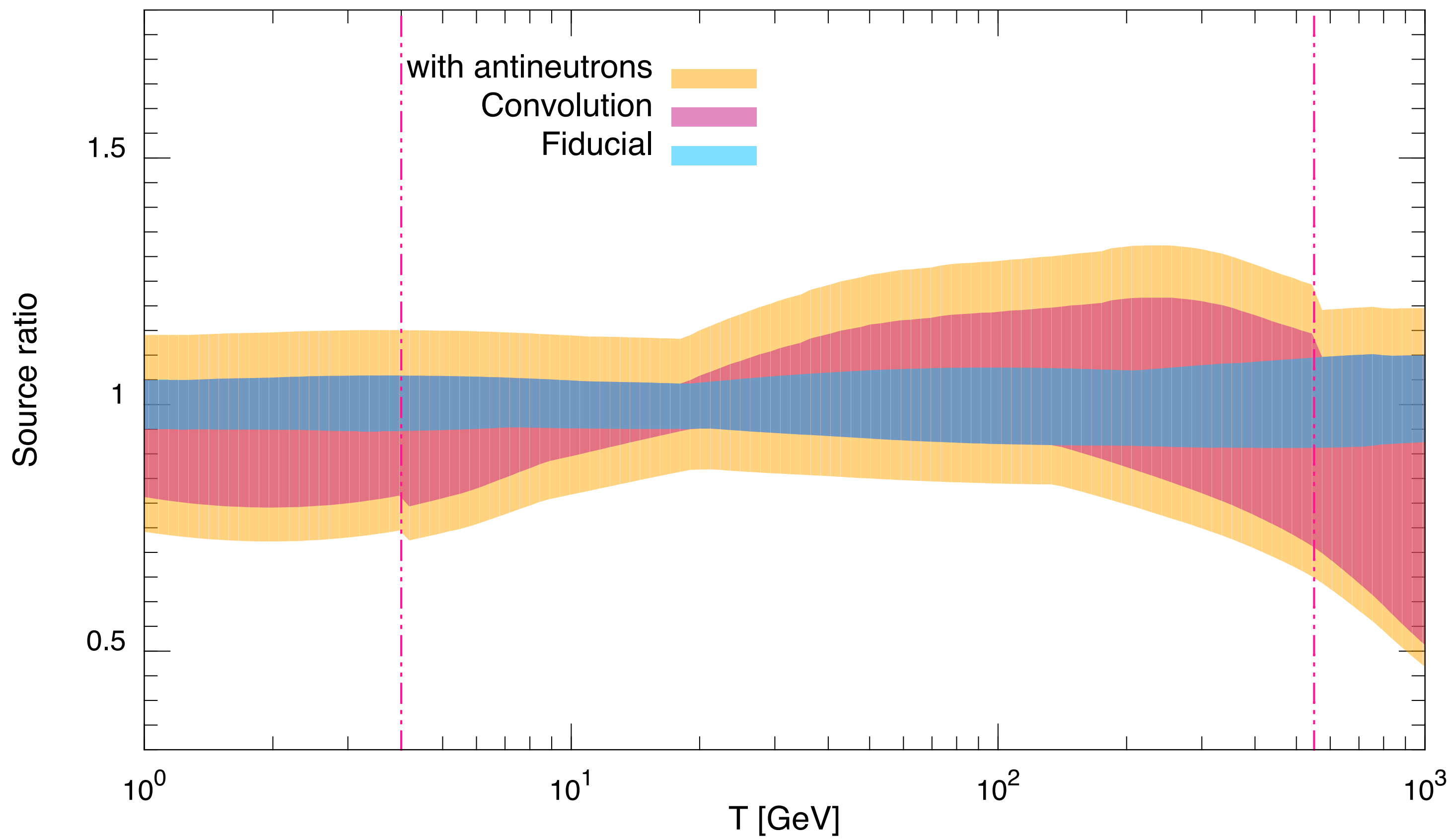


COMPARISON WITH DUPERRAY 2003 AND TAN AND NG 1983

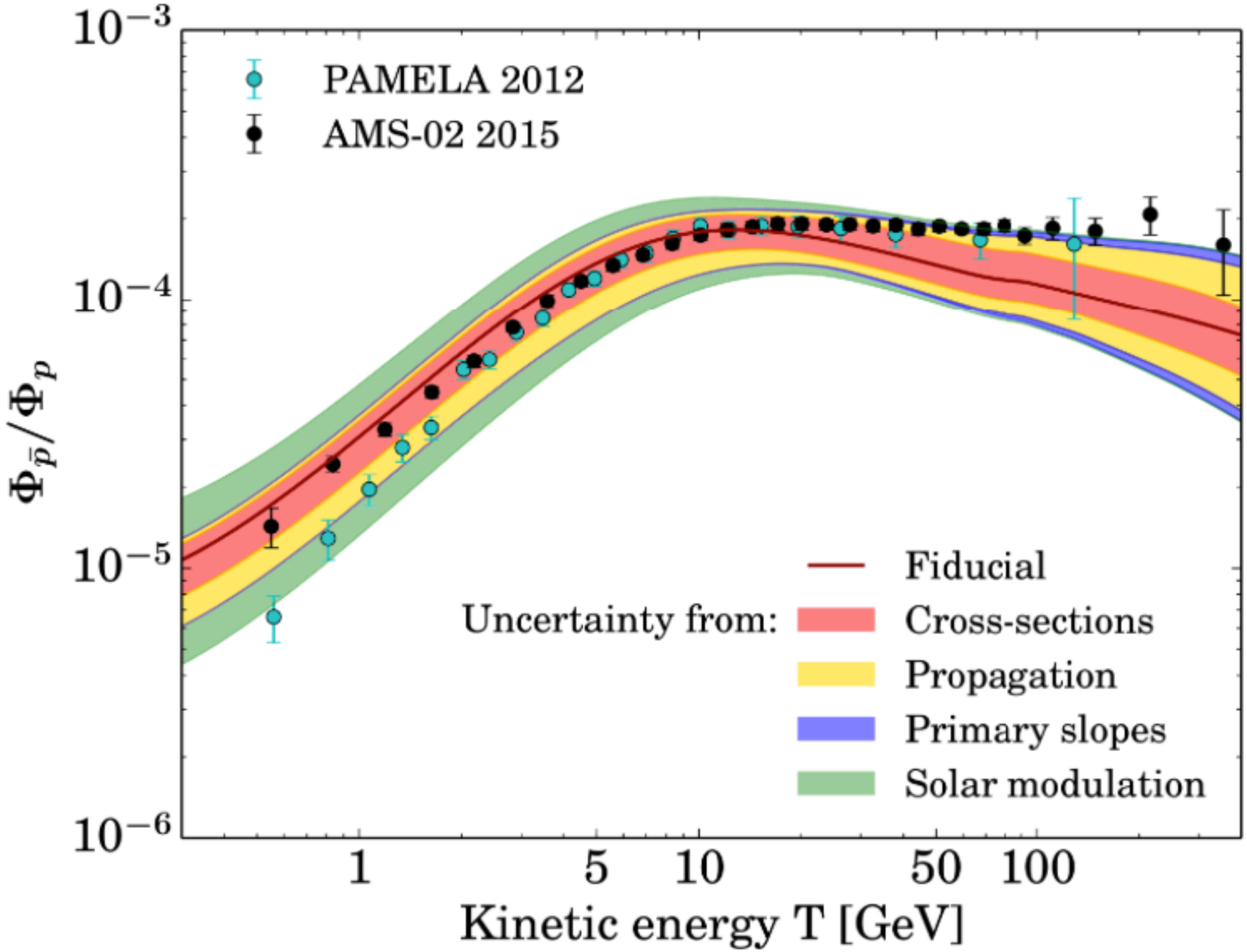


UNCERTAINTIES

- In the data energy range uncertainties for the pp channel about 10−15%.
- At higher energies extrapolations lead to errors larger than ~ 50% at 1 TeV.
- The antiproton yield from pp scattering include the antineutron decay contribution —> isospin dependence.
- A significant contribution to the cosmic antiproton flux is due to the reactions involving helium nuclei. The relevant cross sections have NEVER been measured.
- These uncertainties will continue imposing non-negligible limitations on the interpretation of cosmic antiproton data.
- As a side-effect, it appears unlikely that any definite conclusion for dark matter indirect detection could be drawn from a relatively featureless “excess” in the antiproton yield.



II ANTI-P AND AMS-02 DATA 2



SEE ALSO MARTIN'S TALK

Giesen et al. arXiv:1504.04276

CONCLUSIONS

- In the data energy range the antiproton production uncertainties for the pp channel can be as high as 10−15%.
- At higher energies, we have shown that our knowledge is much worse, with extrapolations leading to errors larger than ~ 50% at 1 TeV.
- The antiproton yield from pp scattering include the antineutron decay contribution —> isospin dependence. Uncertainty 10-20%.
- A significant contribution to the cosmic antiproton flux is due to the reactions involving helium nuclei. The relevant cross sections have NEVER been measured.
- **These uncertainties will continue imposing non-negligible limitations on the interpretation of cosmic antiproton data.**
- **Uncertainties of antiproton/proton AMS-02 are of the order of 5-15% while uncertainties on cross section is of the order of 25%.**
- As a side-effect, it appears unlikely that any definite conclusion for dark matter indirect detection could be drawn from a relatively featureless “excess” in the antiproton yield

BACKUP SLIDES