Galactic cosmic rays:
The need for cross section data

An experiment proposal: p-He scattering

Workshop on

The p-He cross section measurement:
a physics case from cosmic rays

Torino, 6/7.07.2015

Fiorenza Donato
Dipartimento di Fisica, Università di Torino & INFN, Sezione di Torino

WELCOME in

TORINO!!

Thanks to all of you for coming!

Thanks to INFN

This workshop is the evolution of a seed idea launched at the INFN **"What Next"** general meeting, Rome, May 2014…

… followed by discussions with many of you, meetings, seminars at various Commissioni Scientifiche Nazionali (CSN3, CSN1, CSN4*,CSN2*), informal meetings, seminars, NPQCD…

Thanks in particular to the INFN Torino section

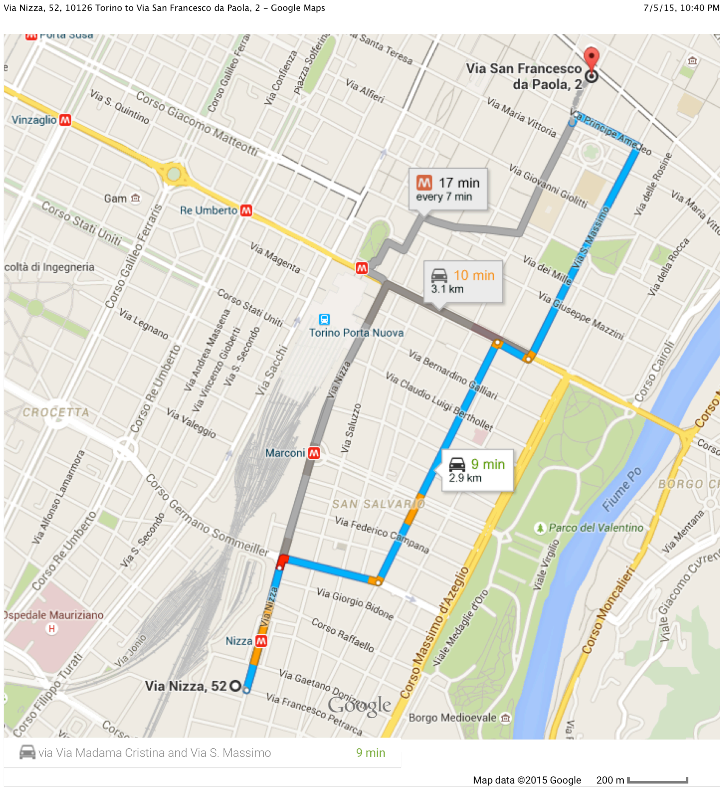
We warmly thank the MBC of Turin University for hosting our workshop

Practical details

- Coffee breaks are served in the courtyard
- Lunch is offered by INFN in the courtyard
- Dinner at 20.30: “La via del Sale”

  Via San Francesco da Paola, 2

If you want to come, sign in.



Via Nizza, 52, 10126 Torino to Via San Francesco da Paola, 2 - Google Maps

7/5/15, 10:40 PM

via Via Madama Cristina and Via S. Massimo 9 min

Map data ©2015 Google 200 m

This is a workshop: let's try to understand together

In the following, only a few and incomplete guidelines to the

p-He → p-, e+, γ, d-

cross section physics case

GALACTIC COSMIC RAYS

are charged particles (nuclei, isotopes, leptons, antiparticles) diffusing in the galactic magnetic field (+Gamma-rays) observed at Earth with E~ 10 MeV/n - 10^3 TeV/n

1. SOURCES

PRIMARIES: directly produced in their sources

SECONDARIES: produced by spallation reactions of primaries on the interstellar medium (ISM)

2. ACCELERATION

SNR are considered the powerhouses for CRs.
They can accelerate particles at least up to 10^2 TeV

3. PROPAGATION

CRs are diffused in the Galaxy by the inhomogeneities of the galactic magnetic field.

\+ loose/gain energy with different mechanisms

CRs production and propagation history

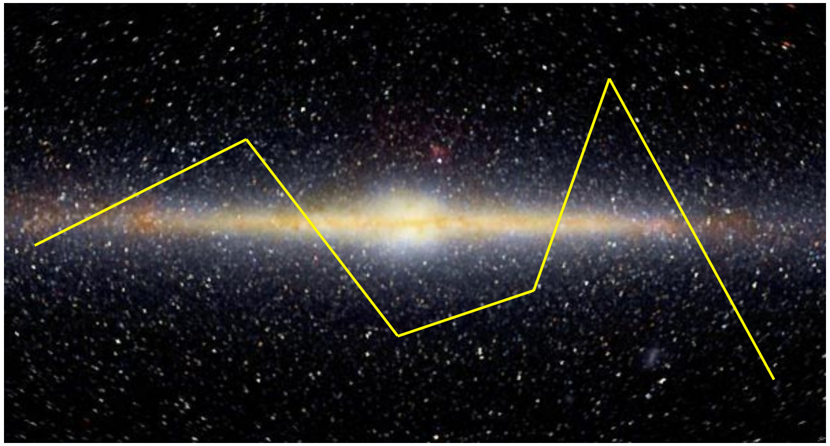
Charged nuclei - isotopes – antinuclei - leptons

1. Synthesis and acceleration

- Are SNR the accelerators?
- How are SNR distributed?
- What is the abundance at sources?
- Are there exotic sources out of the disc?

2. Transport in the Milky Way

- Diffusion by galactict B inhom.
- electromagnetic losses
  - ionization on neutral ISM
  - Coulomb on ionized plasma
- Convection
- Reacceleration



4. Solar Modulation

- Force field approximation?
- Charge-dependent models?

3. Nuclear interactions CRs&ISM:

- Production of secondary nuclei
- Destruction of nuclei on the ISM

Cosmic antiprotons

Antiprotons are produced in the Galaxy by **inelastic scattering**
of cosmic proton and He (p/He~5)
(and marginally heavier nuclei)
off the ISM (90% H and 10% He): **secondary antiprotons**.

These antiprotons would be the background to
an exotic component due to

dark matter annihilation

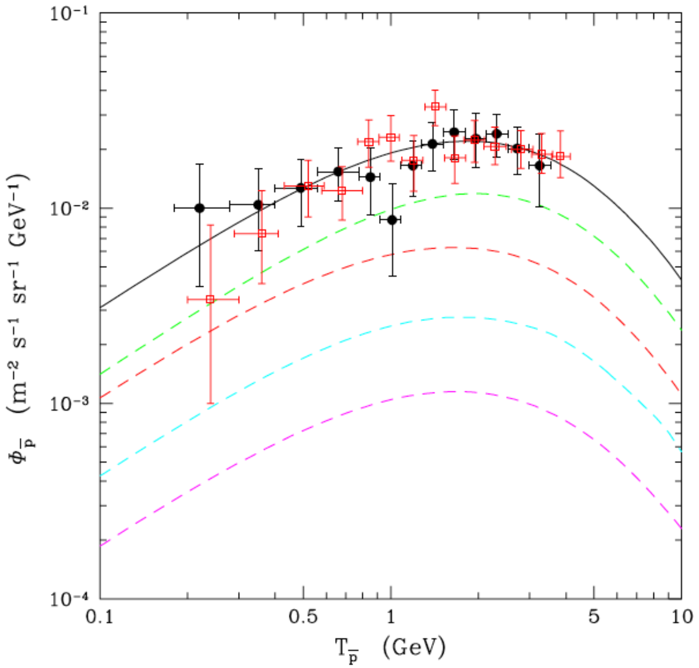
in the galactic halo (**primary antiprotons**).

N. B. Thousands of cosmic antiprotons have already been
detected by balloon-borne (Bess, Caprice,…)
or satellite experiments (Pamela), and AMS-01,
and 290000 (out of 54 billion events) from AMS-02 on the ISS

Secondary antiprotons in cosmic rays (CR)

Produced by spallation reactions on the interstellar medium (ISM)

$$\left.\begin{array}{l} p_{CR} + H_{ISM} \\ p_{CR} + He_{ISM} \\ He_{CR} + H_{ISM} \\ He_{CR} + He_{ISM} \end{array}\right\} \bar{p} + X$$

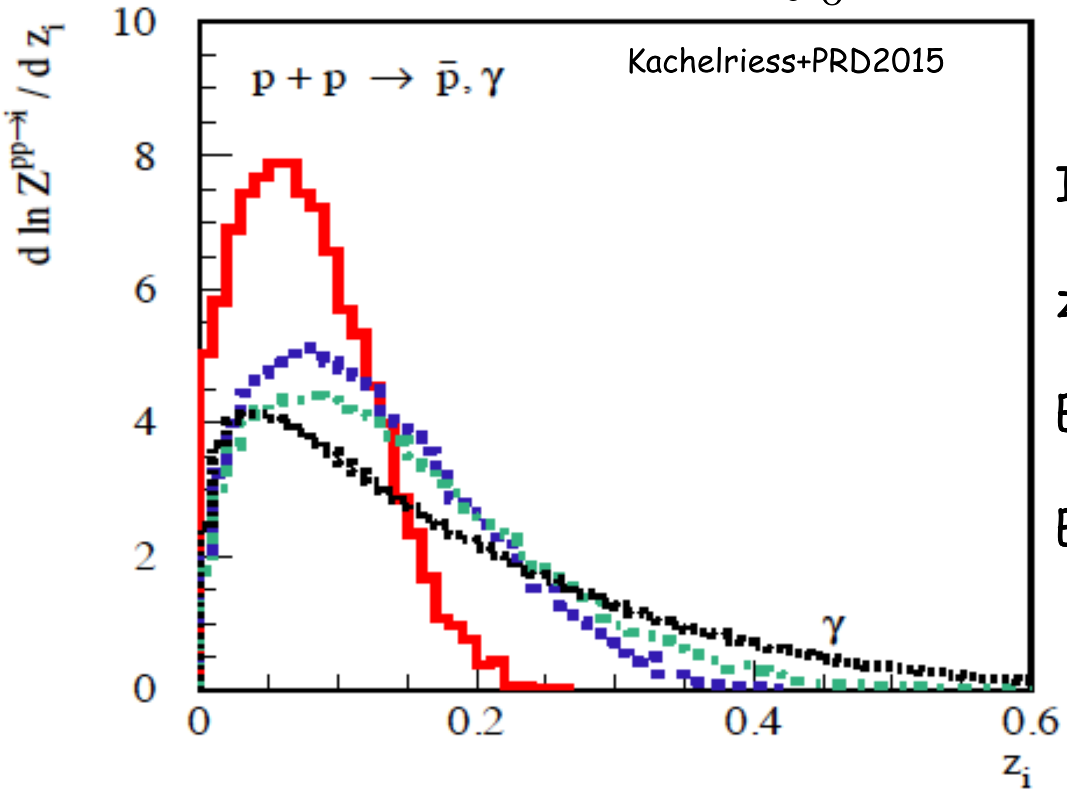


The only measured cross section is p-p → $\bar{p}$ + X

ALL CROSS SECTIONS INVOLVING He (projectile or target) ARE DERIVED FROM DATA on other nuclei, and for limited energies

Protons → antiprotons

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



$$I_i(E) = K_i\, E^{-\alpha_i}$$

I(E) is the incoming CR spectrum

z= E_pbar/E_p

E_pbar = 1, 3, 10 GeVs

E_γ = 10 GeV

The bulk of antiprotons is produced by protons with kinetic energy 10-30 times greater
Gamma rays are more spread on proton energies

Partial contributions from CR nuclei

Kachelriß+2015

$$\epsilon^{\bar{p}}_{ij}(E_{\bar{p}}) = \frac{q^{ij}_{\bar{p}}(E_{\bar{p}})}{q^{pp}_{\bar{p}}(E_{\bar{p}})}$$

$$q^{ij}_{\bar{p}}(E_{\bar{p}}) = n_j \int_{E_{\rm thr}(E_{\bar{p}})}^{\infty} dE \, \frac{d\sigma^{ij\to\bar{p}}(E,E_{\bar{p}})}{dE_{\bar{p}}} \, I_i(E)$$

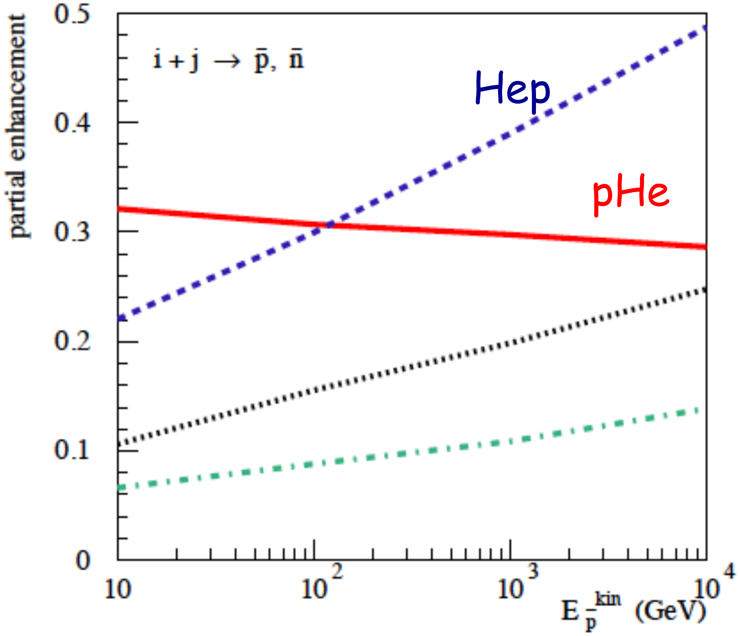
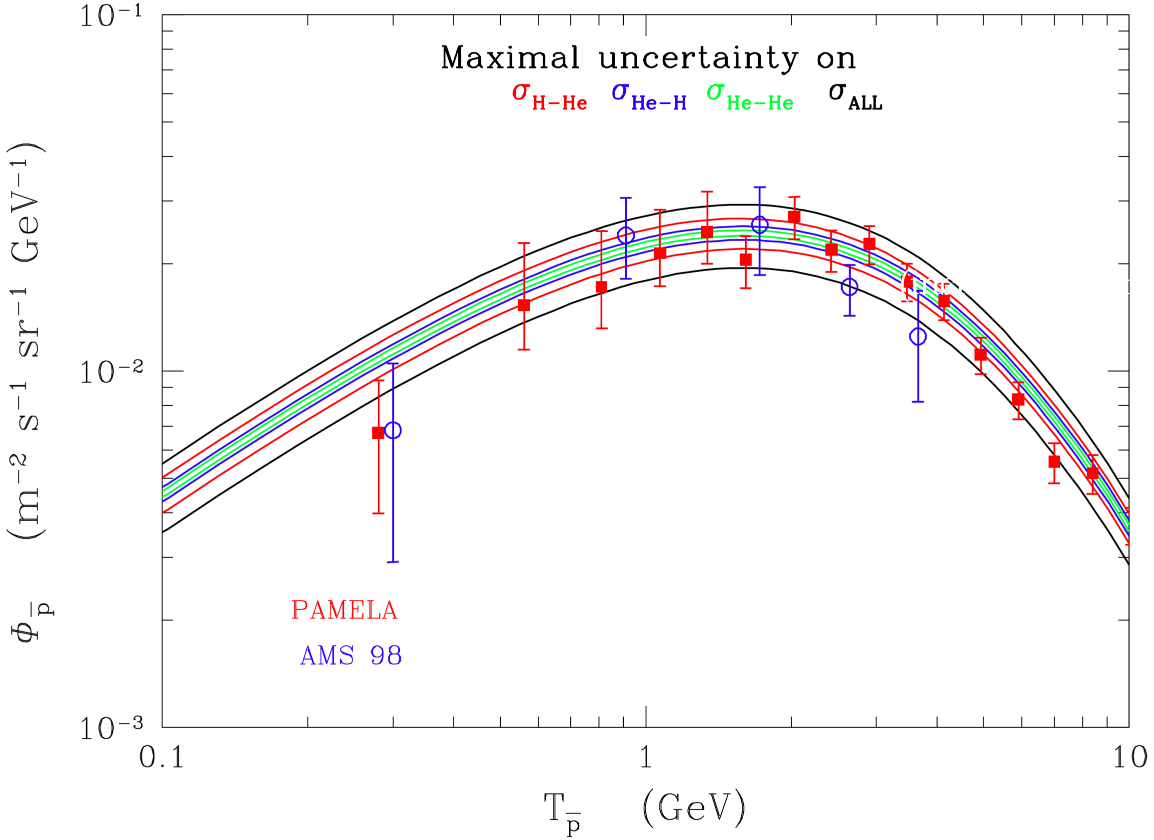


FIG. 8.— Energy dependence of partial contributions $\epsilon^{\bar{p}}_{ij}(E_{\bar{p}})$ to the nuclear enhancement factor from different interaction channels: pHe (solid, red), He p (dashed, blue), He He (dot-dashed, green), and all others (dotted, black); the CR composition given in Table 2 is used.

Uncertainties on the antiproton flux from **nuclear cross sections**

(Model from Donato et al. ApJ 2001, PRL 2009)



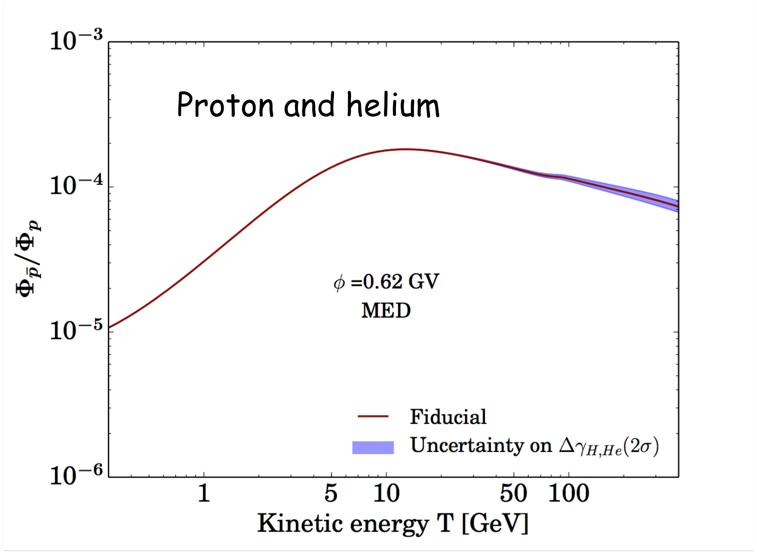
- pp: Tan& Ng
- H-He, He-H, He-He: DTUNUC MC
- Functional form for the cross section derived from other reactions

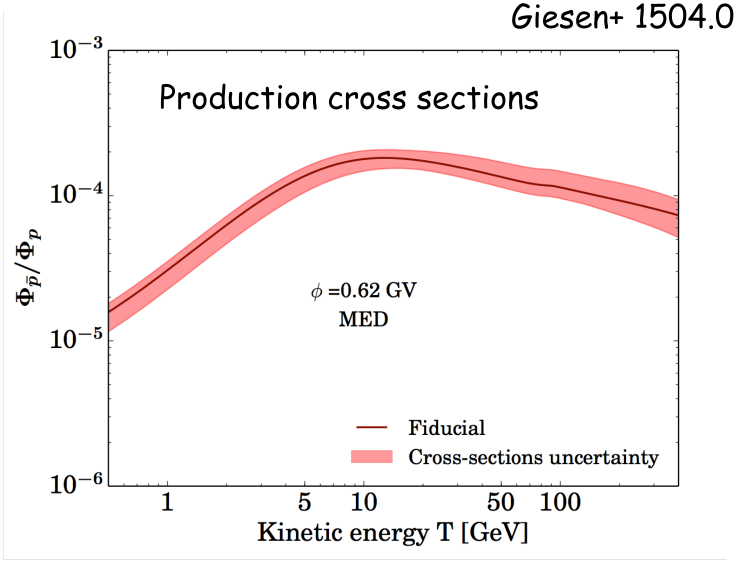
Maximal uncertainty from p-He cross sections: 20-25%!

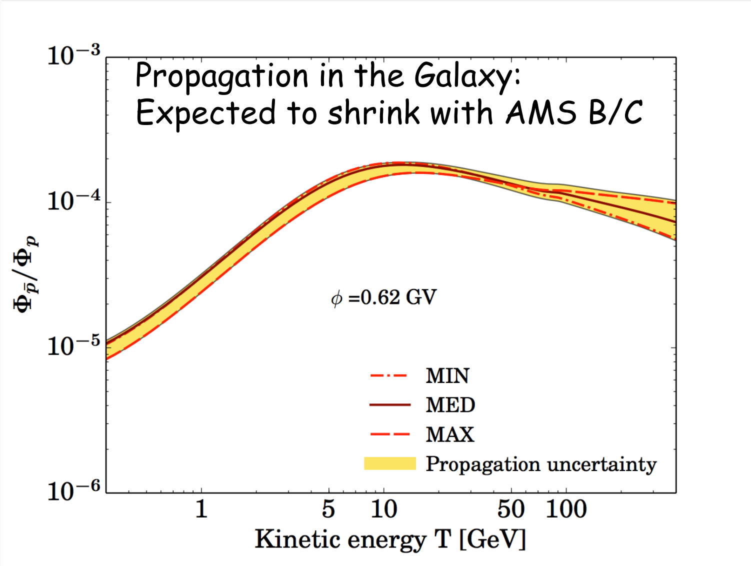
Data from AMS-02 on cosmic antiprotons at <~10% accuracy

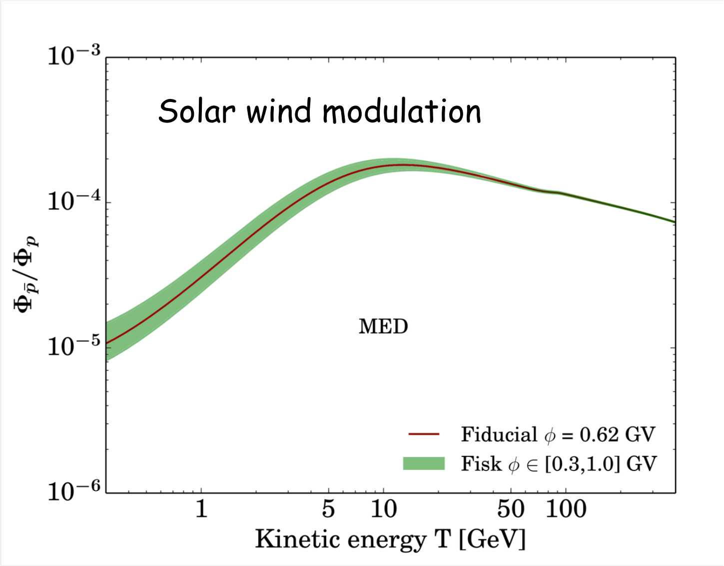
Secondary antiprotons: theoretical uncertainties

Giesen+ 1504.04276


Proton and helium

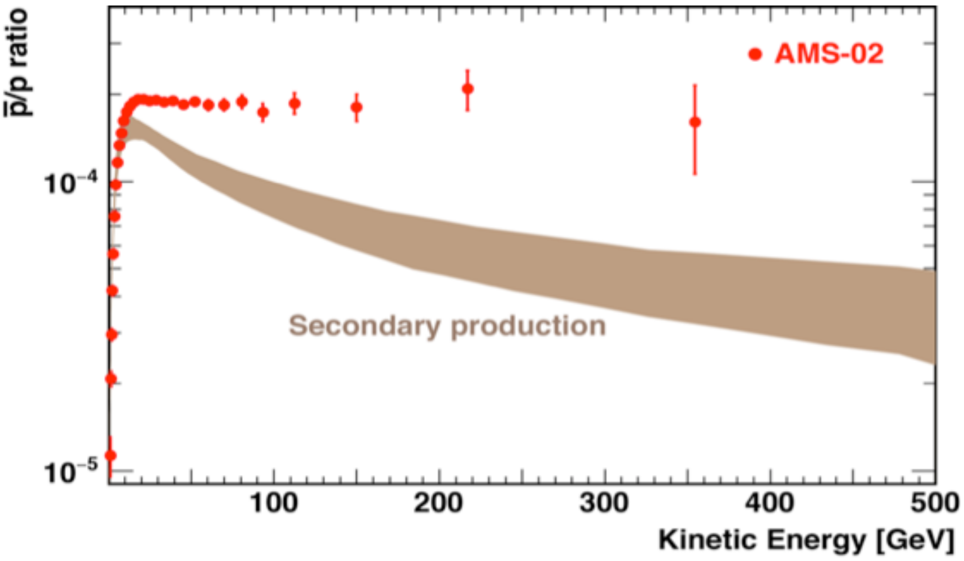

Production cross sections


Propagation in the Galaxy:
Expected to shrink with AMS B/C

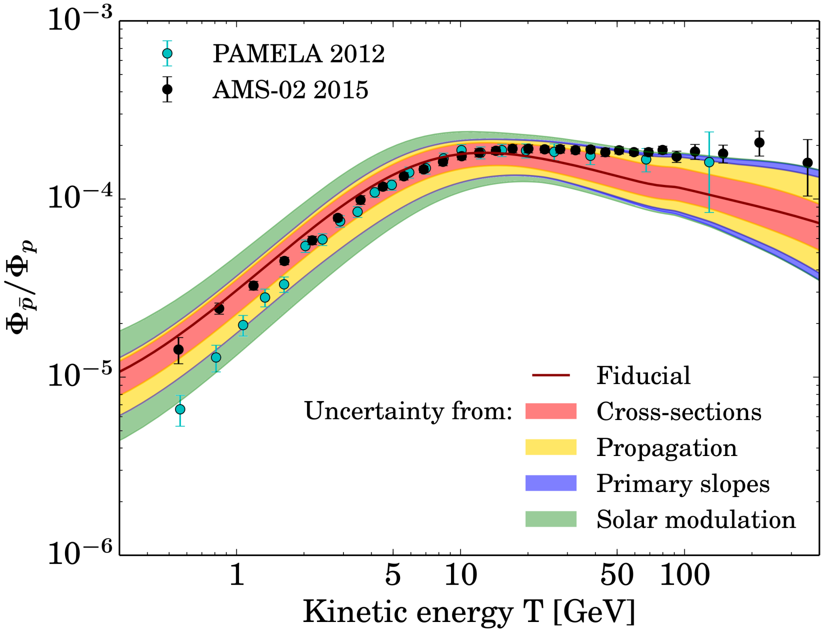

Solar wind modulation

Prediction and AMS data

AMS Coll., Cern 15.04.2015



Giesen+ 1504.04276



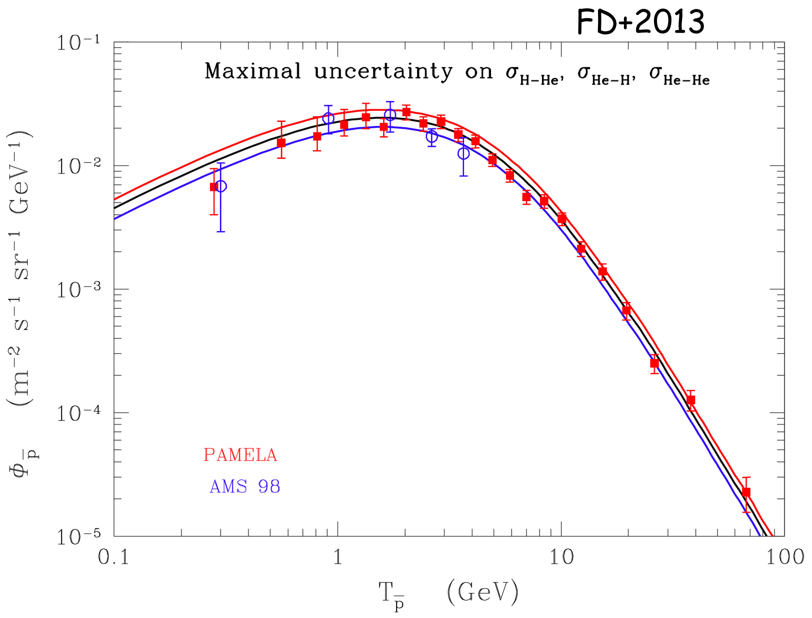
Very recent AMS-02 results up to 450 GeV
Can be explained by secondary production in the Milky Way,
considering several theoretical uncertainties

Reactions involving helium & higher energies

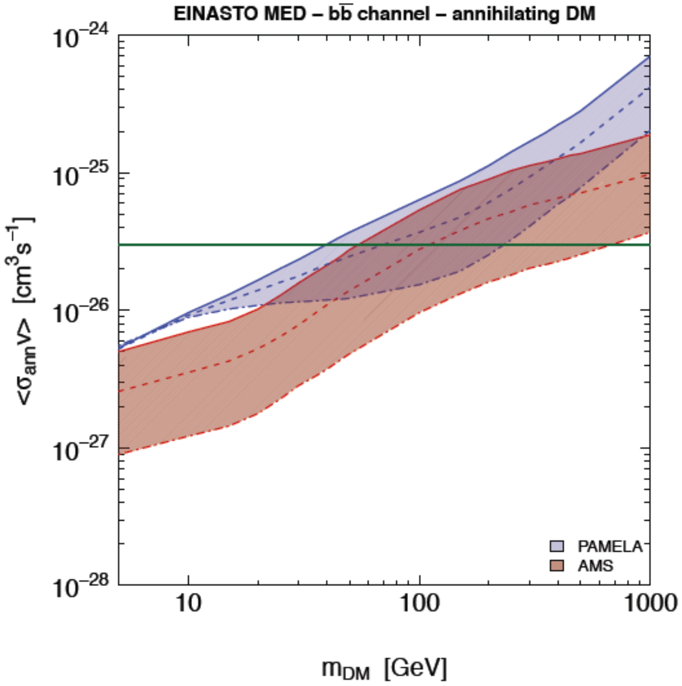
Uncertainties due to helium reactions range 40-50% on Secondary CR flux

Effect of cross section uncertainty on DARK MATTER interpretation

Fornengo, Maccione, Vittino JCAP2014



FD+2013

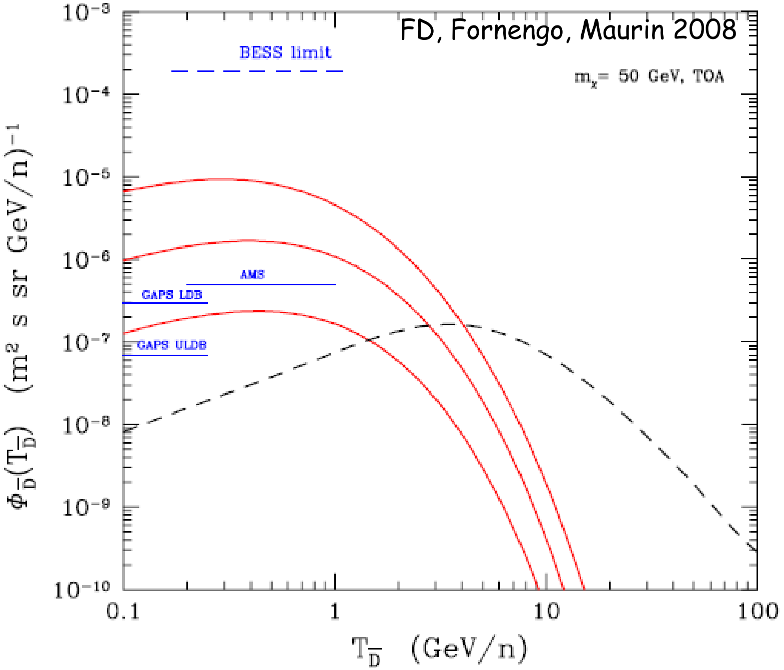


AMS-02 will provide data with much higher precision up to hundreds of GeV!!! Their interpretation risks to be seriously limited by nuclear physics

COSMIC ANTIDEUTERONS

FD, Fornengo, Maurin PRD 2001; 2008; Kadastik, Raidal, Strumia PLB2010; Ibarra, Wild JCAP2013;
Fornengo, Maccione, Vittino JCAP 2013; …

In order for fusion to take place, the two antinucleons must have low kinetic energy



Kinematics of **spallation** reactions prevents the formation of very low antiprotons (antineutrons).

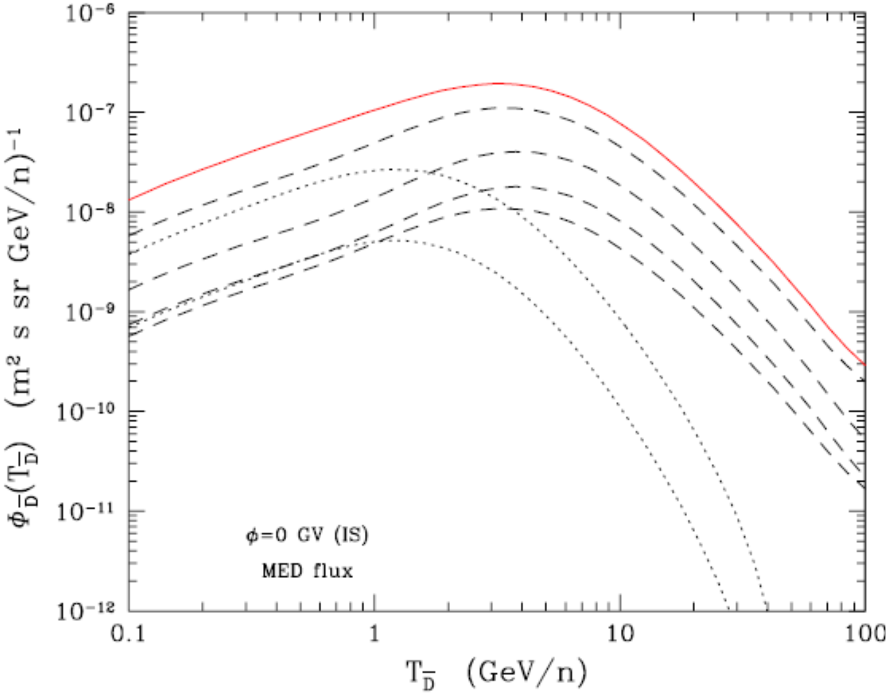
At variance, **dark matter** annihilate almost at rest

N.B: Up to now, NO ANTIDEUTERON has been detected yet.
Several expriments are on the road: AMS/ISS, BESS-Polar, GAPS …

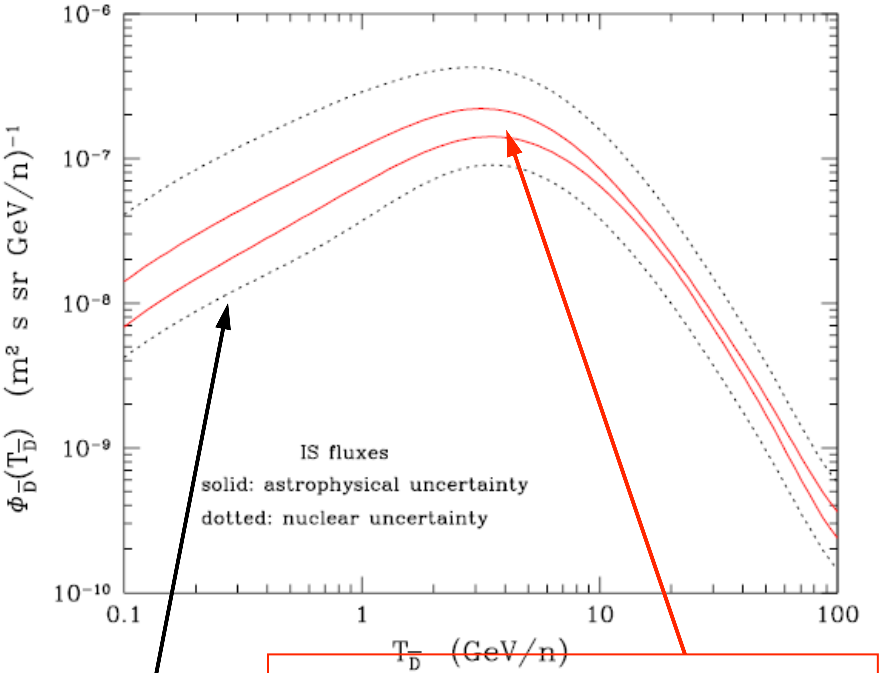
Secondary antideuterons

FD, Fornengo, Maurin PRD 2008

Contributions to secondaries



p-p, p-He,
He-H, He-He
H- pbar, He-pbar



Propagation uncertainties
Compatibility with B/C

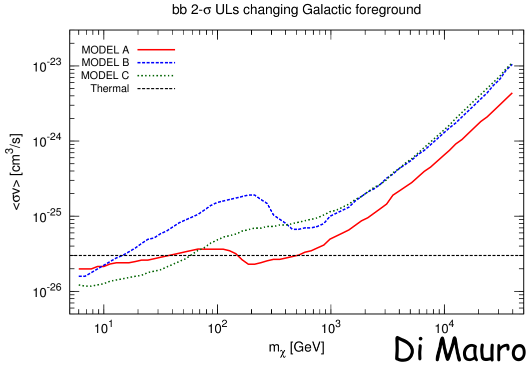
Nuclear uncertainties
Production cross sections & P_{coal}
Production from antiprotons
Non-annihilating cross sections

$p+He \rightarrow \pi^0 \rightarrow 2\gamma$: galactic foreground in the Fermi-LAT data

Contextually to p+He→ antiprotons, it would be of very interesting to measure also the photons (**gamma rays**) coming from the hadronization processes via π^0 decay.

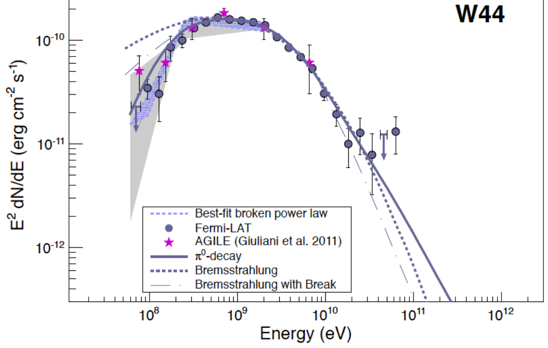
This process occurs in the galactic disk and enters the calculation of the galactic emission, crucial for understanding:

1. DARK MATTER annihilation
   (Galaxy, dwarf spheroidal galaxies, ..)
2. ORIGIN of COSMIC RAYS
   galaxy emission, SNRs, ..



Di Mauro & FD 2015

Fermi-LAT Coll. 2013



The astrophysics of cosmic rays is entering an era of remarkable **precision** (AMS-02, Fermi-LAT,…)

Data on nuclei, isotopes, antimatter, leptons and gamma-rays will need **complex modeling** for their interpretation:

1. The accelerators of cosmic rays
2. The propagation in the Galaxy
3. The nuclear processes: from the highest nuclei (i.e. nichel) to light antimatter one needs total inelastic, production, inelastic non-annihilating **cross sections**, … which are **modeled** according to LAB experiments…**if any…**

Focusing on cosmic antimatter

ANTIMATTER (**antiproton**, positrons, antideuterons)
in cosmic rays is a clue ingredient in order to:

1. Test the galactic propagation models (fixed, i.e., by B/C)

2. Search for (or set limits) to **dark matter** annihilating in the halo of the Milky Way

Propagation uncertainties are now confined to ~20%,
and will be significantly reduced by
AMS-02 data on B/C and other nuclear species.

DATA in space → DATA at Cern?

Cosmic **antiproton** data are expected with few% errors
while nuclear physics may bring uncertainties ~ 50%
to the predicted cosmic flux

The **lack of data** on several lab cross section puts serious limits in the interpretation of forthcoming cosmic ray data

A direct measurement of **ANTIPROTON**, together with **γ,e^+, D^-**,.. production from **p-He** seems to me mandatory in order to interpret unambiguously future cosmic ray data.

May we also improve in nuclear physics modelings,
non perturbative QCD, etc?

No conclusions!
Let's think about:

- Is the physics case p+He→ p-, e+, γ **worth** to be pursued within our community, and w.r.t. funding agencies?
- If yes, what should be done from the **theory** side?
  And from the **experimental** side?
- The accelerator data (cross sections) needed to properly model the galactic cosmic ray data would make up a **HUGE experimental program**
- ……

BACKUP SLIDES

The role of helium nuclei

Kachelriess, Moskalenko & Ostapchenko 2015

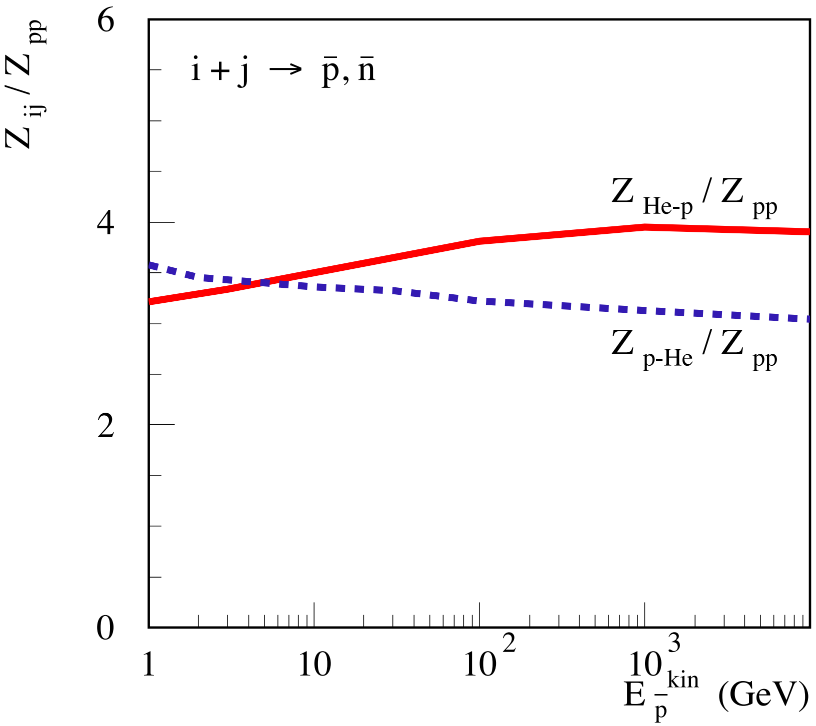


FIG. 7.— Energy dependence of the enhancement of the Hep (solid, red) and pHe (dashed, blue) contributions to the antiproton spectrum, relative to the pp-case, $Z_{\bar{p}}^{ij}(E_{\bar{p}}, \alpha)/Z_{\bar{p}}^{pp}(E_{\bar{p}}, \alpha)$ (plotted as a function of $E_{\bar{p}}^{\mathrm{kin}}$), for $\alpha = 2.6$.

X-sec uncertainties: impact on GCR model parameters

(Slide from D. MAURIN)

Input

X-sections

Minimisation

Propagation model: free parameters δ, K_0, V_a

GCR data: B/C data from HEAO-3 (1979)

Output

Best-fit parameters

Maurin, Putze & Derome, A&A **516**, 67(2010)

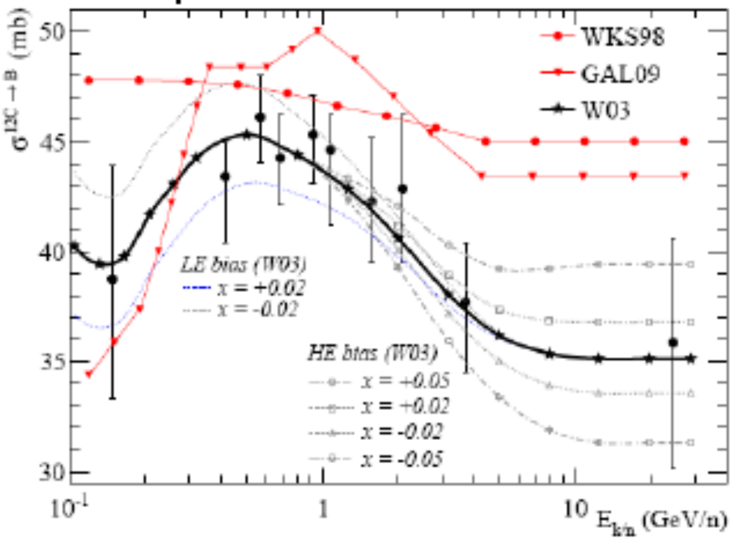
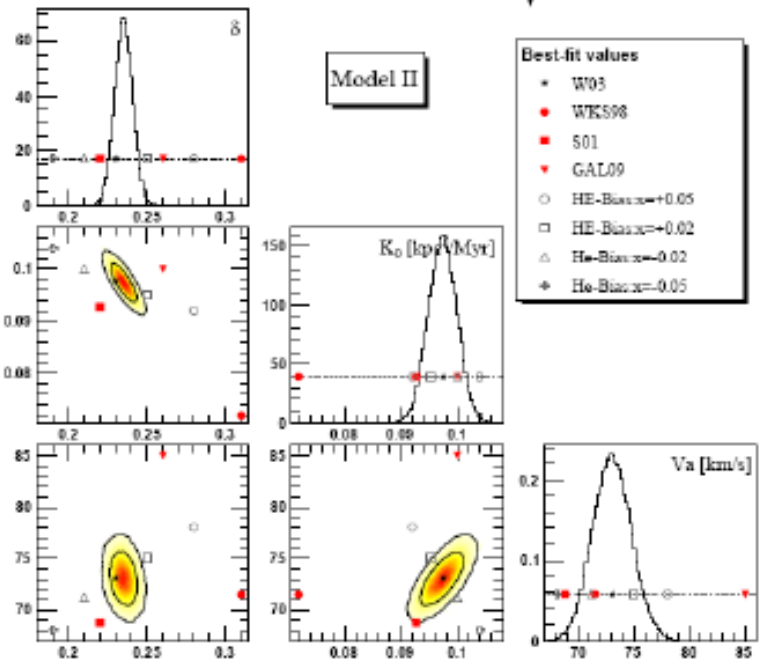


Fig. 3. Production cross-section for $^{12}C+H\to^{10,11}B$ (adapted from Webber et al. 2003). The standard sets are shown as solid lines (WKS98: red dots; GAL09: red down triangles; W03: black stars), and the biased sets in dotted ($|x| = 0.02$) and dashed ($|x| = 0.05$) lines.



- W03 and WKS98 are parameterisations of the same 'data' (energy bias)
- GAL09: modern nuclear codes normalised to LANL database [Moskalenko & Mashnik, astro-ph/0306367]

→ Systematics uncertainties (from X-sec) > statistical uncertainties (from GCR data)

… and AMS-02 is at least 100 better than HEAO-3!

Inelastic cross sections ($\sigma_R = \sigma^{tot} - \sigma^{tot}_{ela}$)

(Slide from D. MAURIN)

- Bradt & Peters (1950)

$$\sigma_R = \pi r_0^2 (A^{1/3}_{proj} + A^{1/3}_{cible} - b_0)^2$$

- Letaw *et al.* (1970-2000): accuracy <2% for 2<Z<30 and E>300MeV/n

S.Barshay & al, Phys.Lett **51B**, 5 (1974)
J.R.Letaw & al, ApJSS **51**, 271 (1983)
R.Silberberg & C.H Tsao, Phys.Rep. **191**, 351 (1990)
L.Sihver & al, Phys.Rev.C **47**, 1225 (1993)
H.P.Wellish & D.Axen, Phys.Rev.C **54**, 1329 (1996)
R.Silberberg & al, ApJ **501**, 911 (1998)
C.H.Tsao & al, ApJ **501**, 920 (1998)

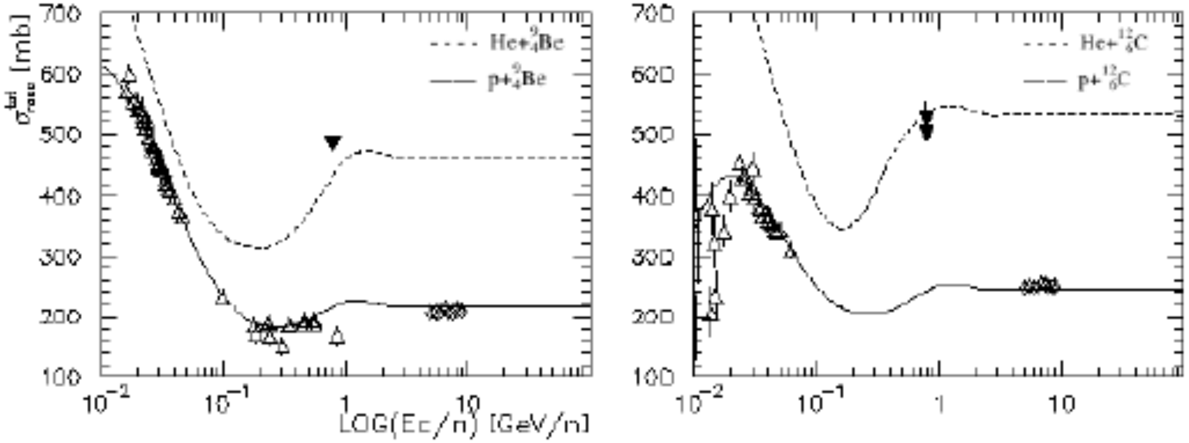
$$\sigma_R(E_k) = \sigma_R^{HE} \left[1 - 0.62 \exp(-E_k/200) \sin(10.9 E_k^{-0.28})\right] \ (mb)$$

$$\sigma_R^{HE} = 45 A^{0.7} \left[1 + 0.016 \sin(5.3 - 2.63 \ln A)\right] \ (mb)$$

- Tripathi *et al.* (~2000): ~ or better (at low E) than Letaw *et al.*, valid for all N+N reaction!

R.K.Tripathi & al, NASA, Technical Paper **3621**, (1997)
R.K.Tripathi & al, NASA, Technical Paper **3656**, (1997)
R.K.Tripathi & al, NASA, Technical Paper **209726**, (1999)

$$\sigma_R = \pi r_0^2 \left(A^{1/3}_{proj} + A^{1/3}_{cible} + \delta_E\right)^2 \left(1 - R_c \frac{B}{E_{cm}}\right) X_m$$



Data from compilations:
Bobchenko 79, Tanihata 85,
Bauhoff 86, Carlson 96

→ Tripathi *et al.* is the one generally used in the field

Production cross sections (straight-ahead approx.)

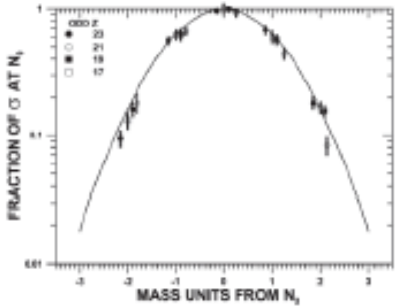
$$\boxed{\int_0^\infty n_{\rm H}\, v' N^k(T')\sigma^{kj}(T,T')dT' = \int_0^\infty n_{\rm H}\, v' N^k(T')\sigma^{kj}(T)\delta(T-T')dT' = n_{\rm H}\, v N^k(T)\sigma^{kj}(T)}$$

Slide from
D. MAURIN

R.Silberberg & C.H.Tsao, ApJSS **25**, 315 (1973)
R.Silberberg & C.H.Tsao, ApJSS **35**, 129 (1977)
R.Silberberg & C.H.Tsao, ApJSS **35**, 137 (1977)
R.Silberberg & al, ApJSS **58**, 877 (1985)
R.Silberberg & C.H Tsao, Phys.Rep. **191**, 351 (199
L.Sihver & al, Phys.Rev.C **47**, 1225 (1993)
C.H.Tsao & al, Phys.Rev.C **47**, 1257 (1993)
C.J.Waddington, ApJ **470**, 1218 (1996)
R.Silberberg & al, ApJ **501**, 911 (1998)
C.H.Tsao & al, ApJ **501**, 920 (1998)
C.H.Tsao & al, ICRC **26**, HE.1.1.04 (1999)

- **Semi-empirical approach** [Silberberg et Tsao]
  - for any Proj. + Targ. → Frag.
  - better than Webber if extrapolation (Z>30)

- **Empirical approach** [Webber et al.]
  - for Proj. + H/He → Frag.
  - better than Silberberg on 'data' (Z<30)



P.Ferrando & al, Phys.Rev.C **37**, 1490 (1988)
W.R.Webber, J.C.Kish, D.A.Schrier, Phys.Rev C 4
W.R.Webber & al, ApJ **508**, 940 (1998-a)
W.R.Webber & al, ApJ **508**, 949 (1998-b)
W.R.Webber & al, Phys.Rev.C **58**, 3539 (1998-c)
W.R. Webber et al., ApJSS 144, 153 (2003)

- **More recent empirical codes**
  - EPAX2 *http://www-w2k.gsi.de/hellstr/asp/gsi/epaxv21m.asp*
  - PHITS *phits.jaea.go.jp*

- **Microscopic description**
  - LAQGSM (Los Alamos Quark Gluon String Model)
  - NUCFRG2 (semi-empirical abrasion-ablation model)

L.W.Townsend & al, NASA, Technical Paper **3310**, (1993)
F.A.Cucinotta, NASA, Technical Paper **3354**, (1993)
J.P.Bondorf & al, Phys.Rep. **257**, 133 (1995)
J.W.Wilson & al, NASA, Technical Paper **3533**, (1995)
F.A.Cucinotta & al, NASA, Technical Paper **3594**, (1996)
C.R.Ramsey & al, Phys.Rev.C **57**, 982 (1998)
Zeitlin et al., Phys. Rev. C **77**, 034605 (2008)
Zeitlin et al., AdSR **46**, 728 (2010)
Zeitlin et al., Phys. Rev. C **83**, 034909 (2011)

→ Webber *et al.* is the one generally used in the field (but for Z<3 nuclei) with claimed uncertainties <10% (fragments from Li → O) or <20% (from Fe)

NB: it is not straightforward to go from nuclear data/models to X-sec for GCRs

Transport equation in diffusion models

Diffusion Convection

$$-\vec{\nabla}\left[K\vec{\nabla}N^j(E) - \vec{V}_c N^j(E)\right] - \Gamma^j N^j$$

$$-\frac{(\vec{\nabla}.\vec{V}_c)}{3}\frac{\partial}{\partial E}\left[\frac{p^2}{E}N^j(E)\right] = Q^j(E) +$$

$$\frac{\partial}{\partial E}\left[-b_{\rm tot}(E)N^j(E) + \beta^2 K_{pp}\frac{\partial N^j(E)}{\partial E}\right]$$

Eneegy losses (EM) Reacceleration

Destruction on ISM

CR sources: primaries, **secondaries (spallations)**

1. DESTRUCTION: $\Gamma = n_{ISM} v \sigma_R$, $\sigma_R = \sigma^{tot} - \sigma^{tot}_{el}$
2. SOURCES: $\bar{Q}^j \equiv q_0^j Q(E)\hat{q}_i + \sum_k^{m_k>m_j} \tilde{\Gamma}^{kj} N_i^k(0)$

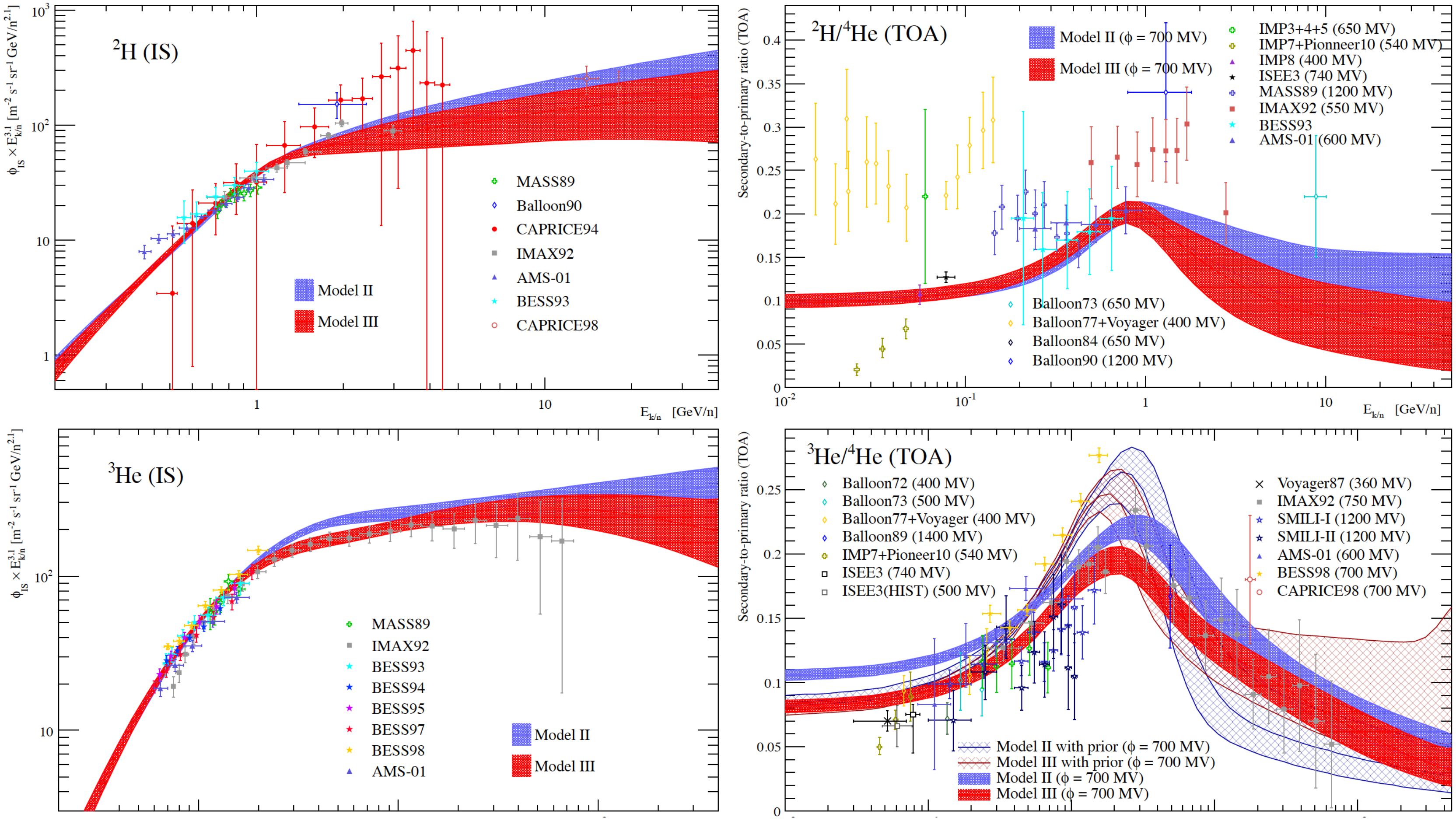
Primary production in SNR

Secondary production by fragmentation of heavier nuclei

Z<=2 Nuclei

Coste, Derome, Maurin, Putze A&A 2012

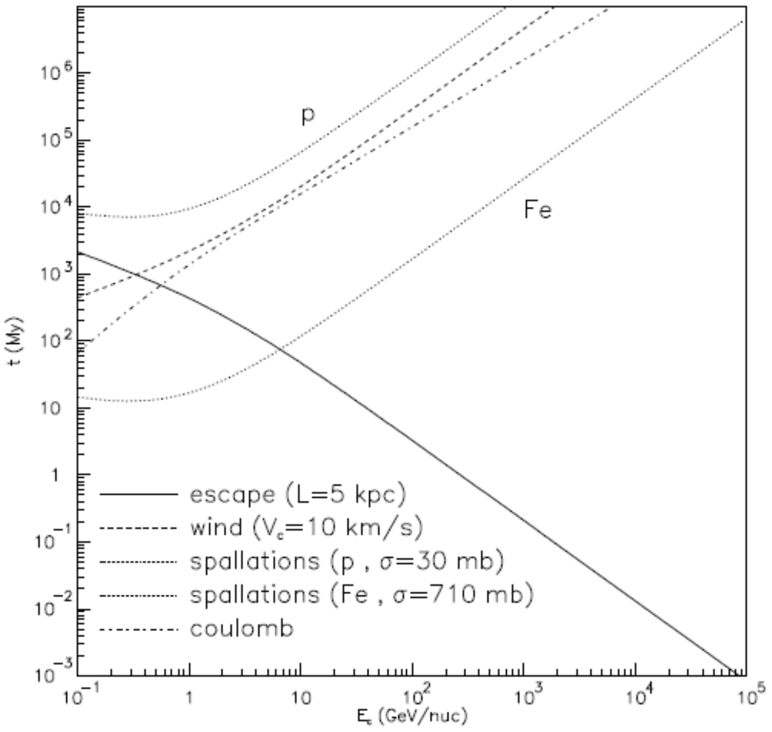
^{1}H, ^{2}H, ^{3}He, ^{4}He almost as powerful as B/C
Noticeable effort on reliable cross sections

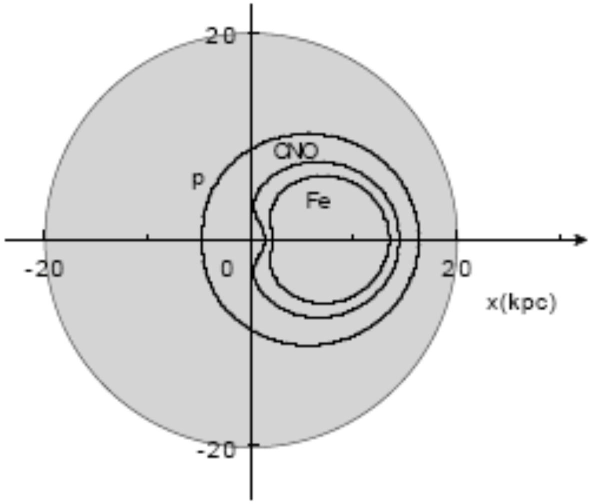


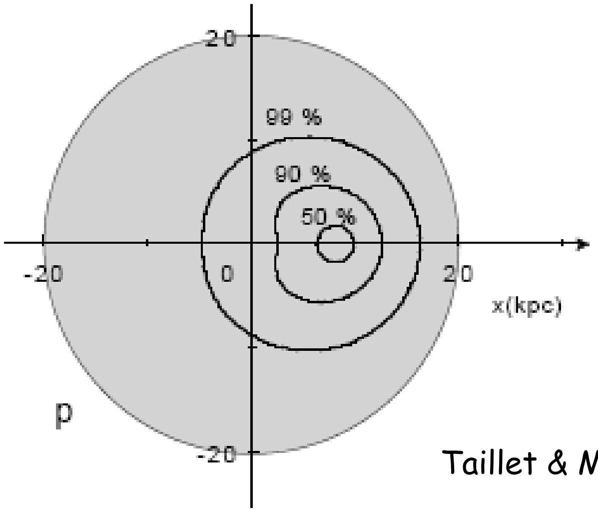
Characteristic times and distances

The smaller the time,
the most effective the process is

Protons: escape E > 1 GeV
convection and e.m. losses E<1 GeV,
Iron: escape E > 1 GeV
Spallations E<10 GeV/n





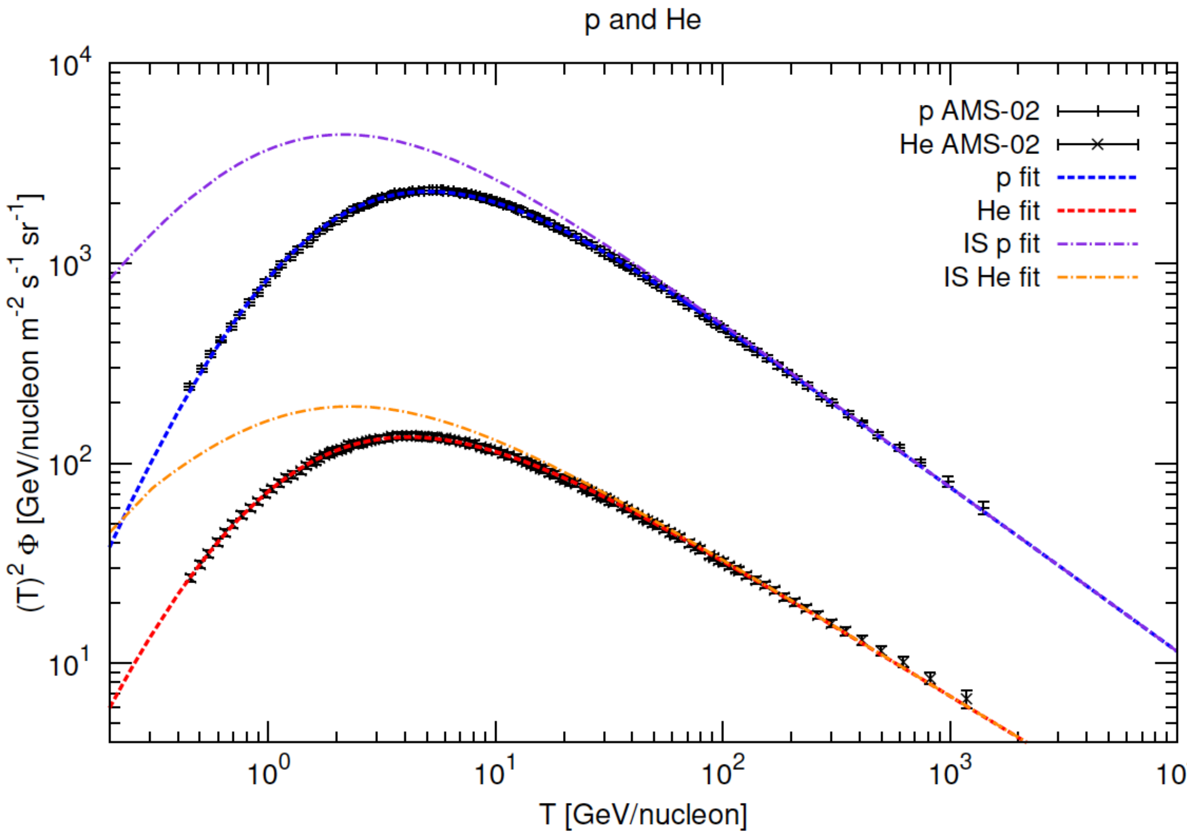


Fe more local than p

90% p from 5-6 kpc

Taillet & Maurin A&A 2003

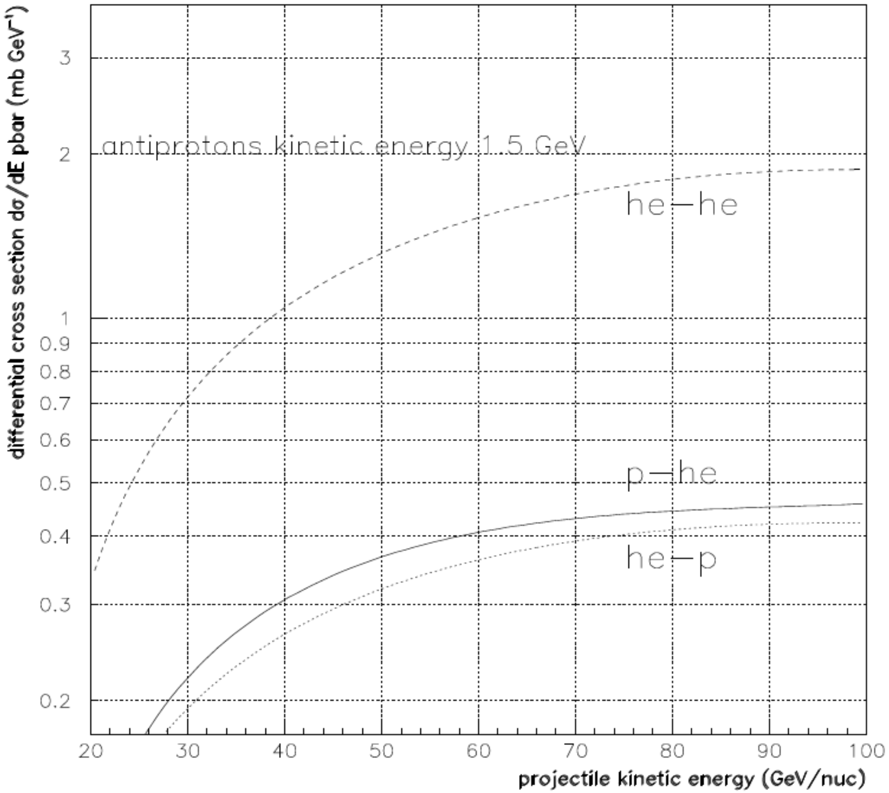
Antiproton source: p and He fluxes



Cosmic p and He experimental data from AMS02 (2013).

Excellent fit → <u>negligible uncertainty</u> due to this entry

Differential antiproton cross section



Given that:

1. In the ISM n_H=0.9/cm^3, n_{He}=0.1/cm^3,
2. the cosmic p flux is ~ 10 higher than He

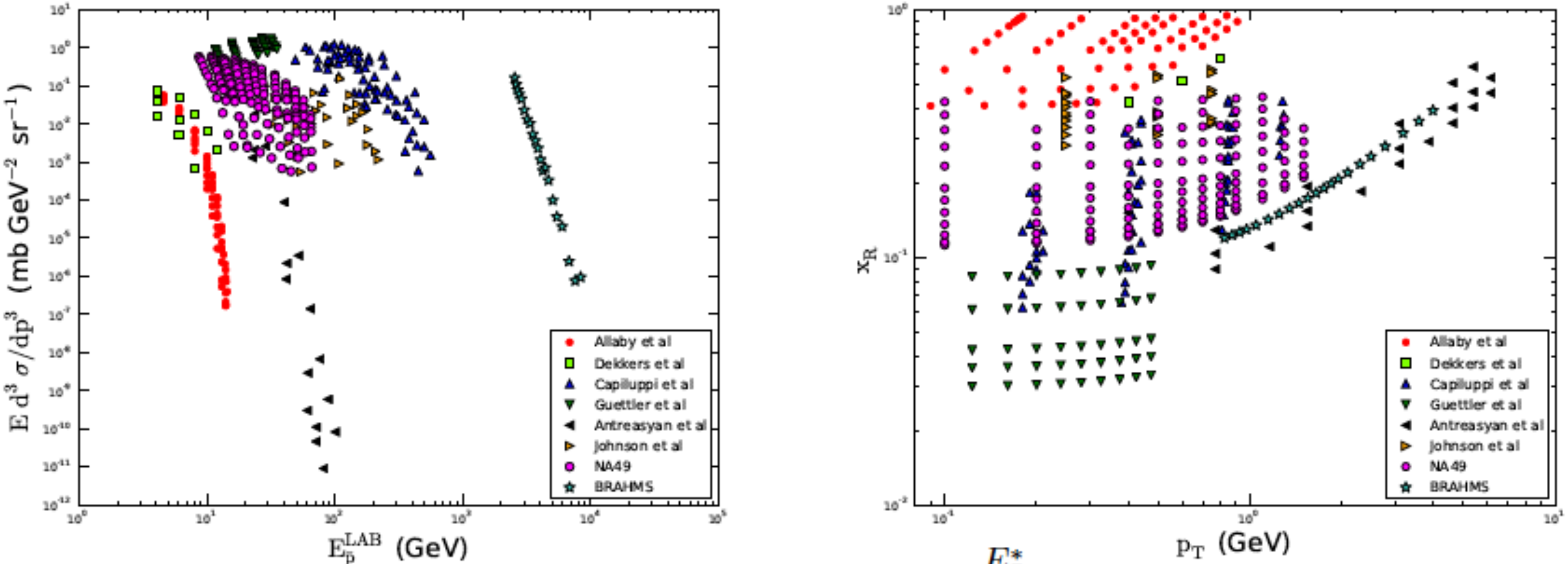
→ the main production channel involving He is p_{CR}-He_{ISM}

New analysis of p-p→pbar data

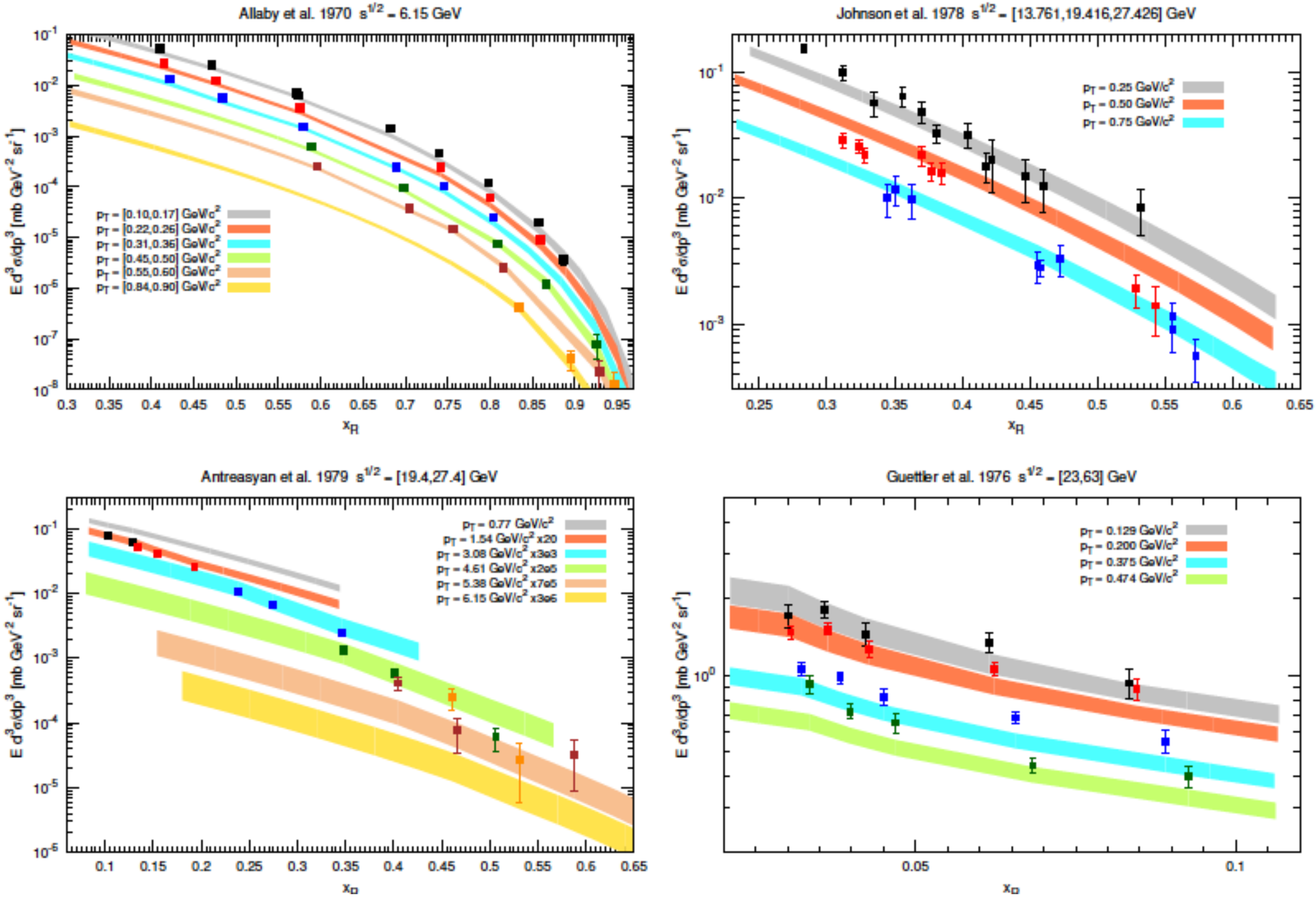
Di Mauro, FD, Goudelis, Serpico PRD 2014, 1408.0288; Kappl, Winkler 1408.0299

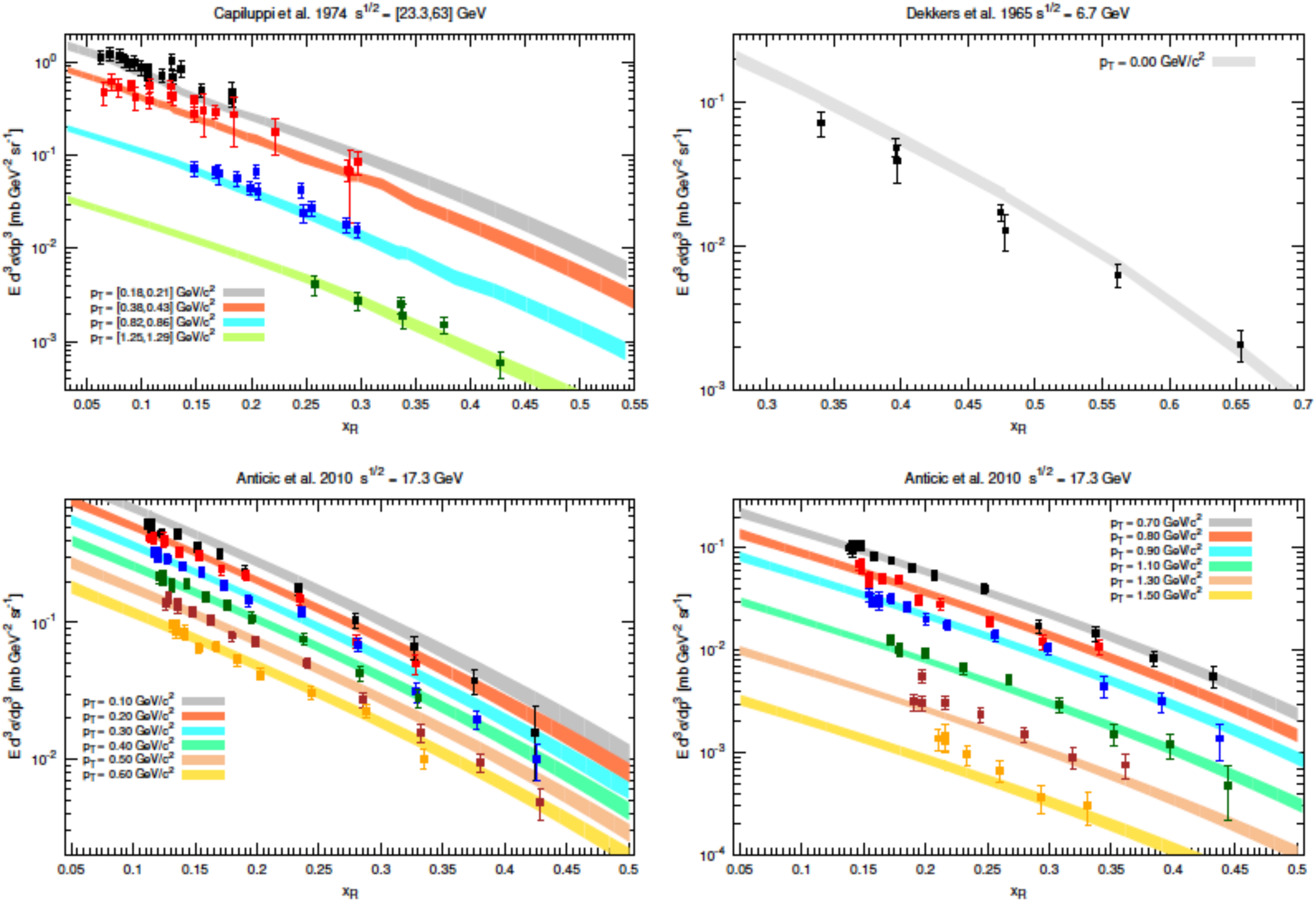
$$q_{\bar{p}}^{pp}(E_{\bar{p}}) = \int_{E_{\rm th}}^{+\infty} \frac{d\sigma_{p\,p\to\bar{p}}}{dE_{\bar{p}}}(E_p, E_{\bar{p}})\, n_H (4\pi\Phi_p(E_p))\, dE_p$$

Existing data



$$x_R = \frac{E^*_{\bar{p}}}{E^*_{\bar{p},\rm max}}$$


Allaby et al. 1970 $s^{1/2}$ = 6.15 GeV
$E\,d^3\sigma/dp^3$ [mb GeV^{-2} sr^{-1}]
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
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
0.3 0.35 0.4 0.45 0.5 0.55 0.6 0.65 0.7 0.75 0.8 0.85 0.9 0.95
x_R
Johnson et al. 1978 $s^{1/2}$ = [13.761,19.416,27.426] GeV
$E\,d^3\sigma/dp^3$ [mb GeV^{-2} sr^{-1}]
10^{-1}
10^{-2}
10^{-3}
p_T = 0.25 GeV/c^2
p_T = 0.50 GeV/c^2
p_T = 0.75 GeV/c^2
0.25 0.3 0.35 0.4 0.45 0.5 0.55 0.6 0.65
x_R
Antreasyan et al. 1979 $s^{1/2}$ = [19.4,27.4] GeV
$E\,d^3\sigma/dp^3$ [mb GeV^{-2} sr^{-1}]
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
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
0.1 0.15 0.2 0.25 0.3 0.35 0.4 0.45 0.5 0.55 0.6 0.65
x_R
Guettler et al. 1976 $s^{1/2}$ = [23,63] GeV
$E\,d^3\sigma/dp^3$ [mb GeV^{-2} sr^{-1}]
10^{0}
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
0.05
0.1
x_R



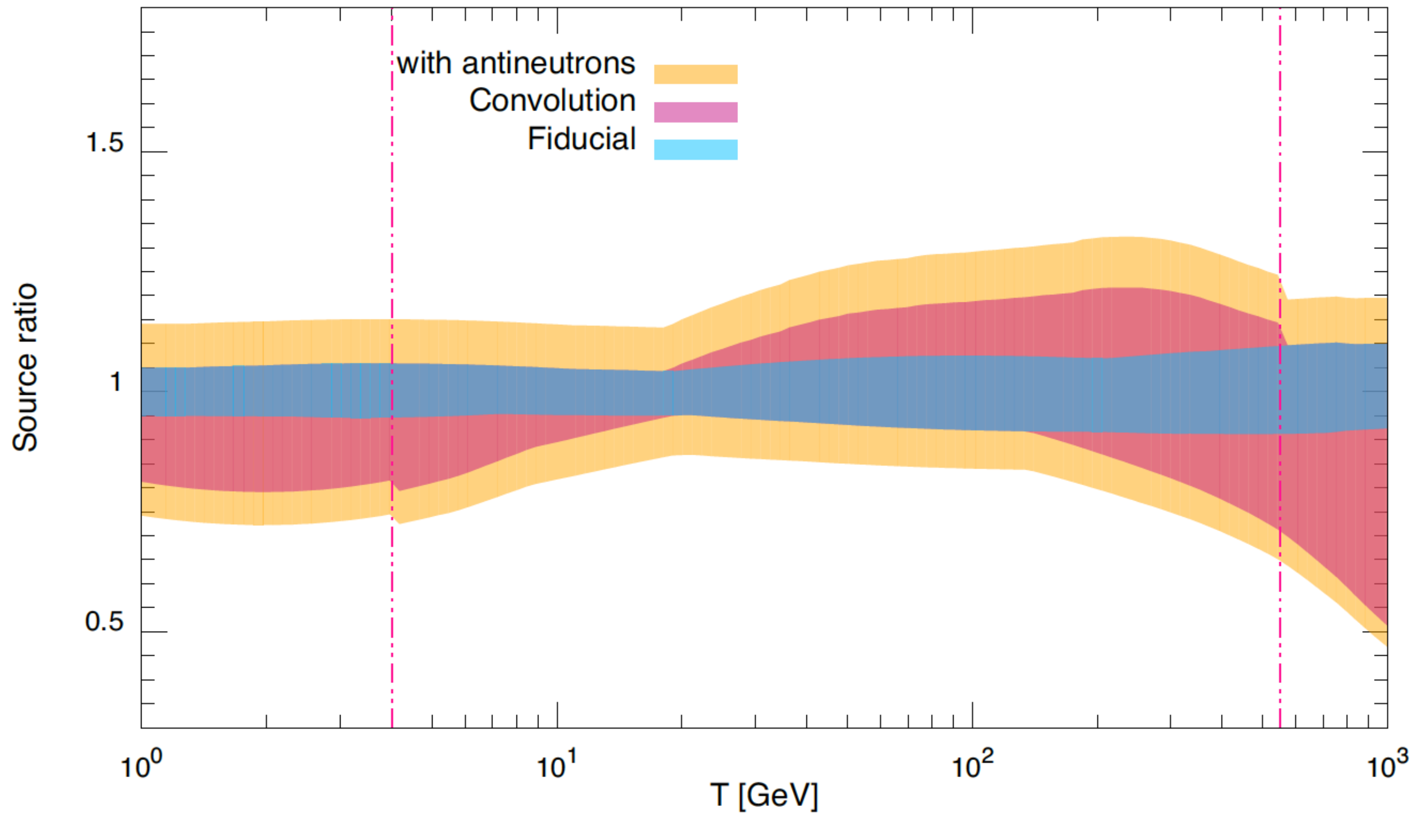
Capiluppi et al. 1974 $s^{1/2}$ = [23.3,63] GeV

Dekkers et al. 1965 $s^{1/2}$ = 6.7 GeV

Anticic et al. 2010 $s^{1/2}$ = 17.3 GeV

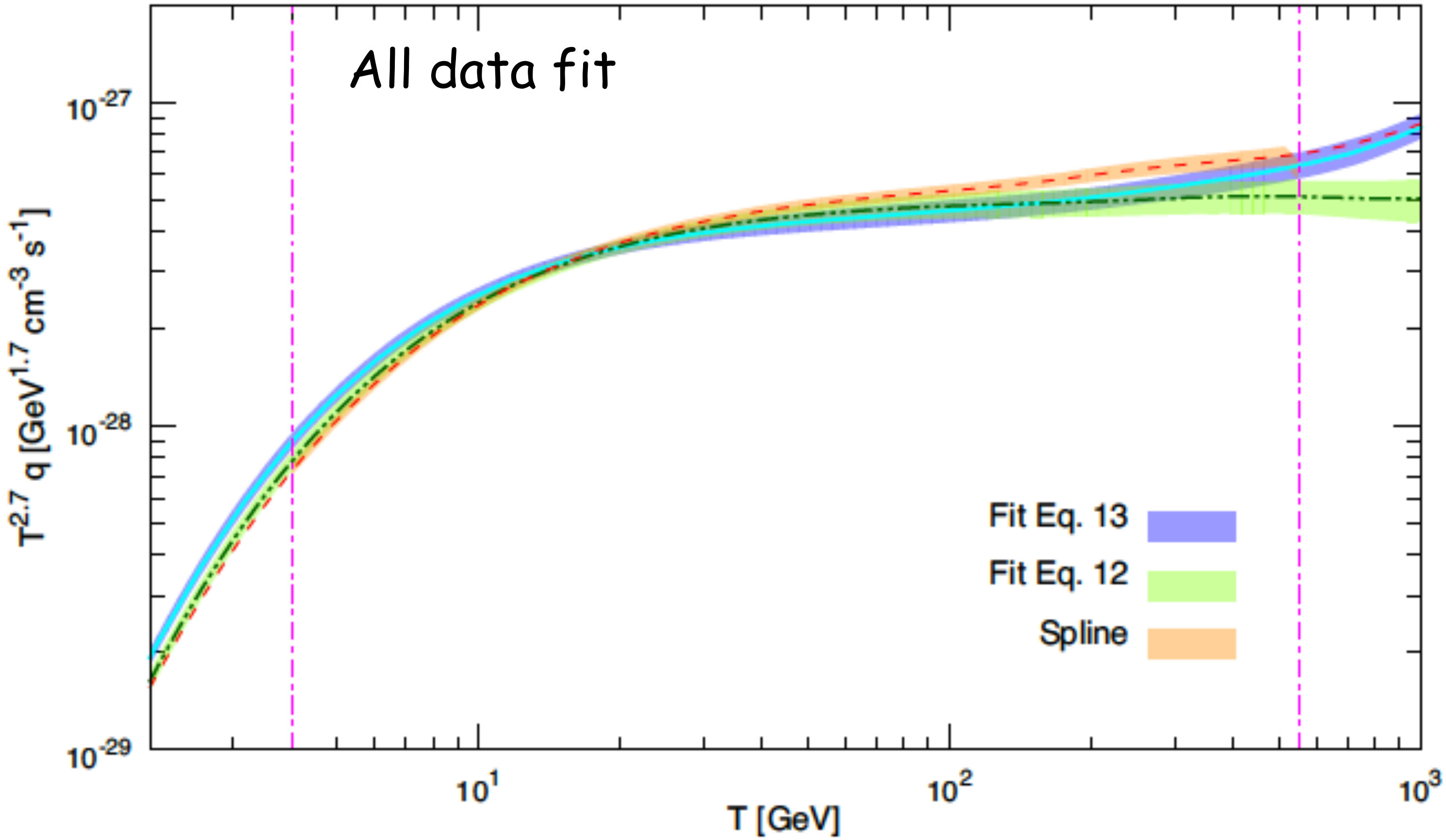
Anticic et al. 2010 $s^{1/2}$ = 17.3 GeV

Uncertainties due p-p scattering



Uncertainties in the pbar production spectrum from p-p scattering are at least 10%.
Conservative: 20% at low energies (GeV) up to 50% (TeV)
(data expected at least up to ~ 500 GeV)

Antiproton source spectrum from p-p channels



$$E\frac{d^3\sigma}{dp^3} = \sigma_{\rm in}(s)(1-x_R)^{C_1} e^{-C_2 x_R} \left[C_3(\sqrt{s})^{C_4} e^{-C_5 p_T} + C_6(\sqrt{s})^{C_7} e^{-C_8 p_T^2}\right]. \qquad (12)$$

$$E\frac{d^3\sigma}{dp^3} = \sigma_{\rm in}(s)(1-x_R)^{C_1} e^{-C_2 x_R} \left|[C_3(\sqrt{s})^{C_4} e^{-C_5 p_T} + C_6(\sqrt{s})^{C_7} e^{-C_8 p_T^2} + C_9(\sqrt{s})^{C_{10}} e^{-C_{11} p_T^3}]\right|, \qquad (13)$$

Different analytical functions give similar chi2, but different extrapolation out of validity ranges → uncertainties at low and high energies

GAPS prototype flight

P. von Doetinchem et al. 1307.3538