Understanding production cross sections for galactic cosmic rays

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Cosmic Rays (CRs) in the Galaxy

Primaries = produced in the sources:

Nuclei: H, He, CNO, Fe; e-, (e+) in SNR (& pulsars)

e^+, p^+, d^+ from Dark Matter annihilation

Secondaries = NOT present in sources, produced by **spallation** of primary CRs (p, He, C, O, Fe) on the interstellar medium (ISM)

Nuclei: LiBeB, sub-Fe; e^+, p^+, d^+; ...

All species propagate in the Galaxy, dominated by diffusion on the magnetic fields and/or by intense energy losses (leptons)

Primaries = present in sources:

Nuclei: H, He, CNO, Fe; e-, (e+) in SNR (& pulsars)

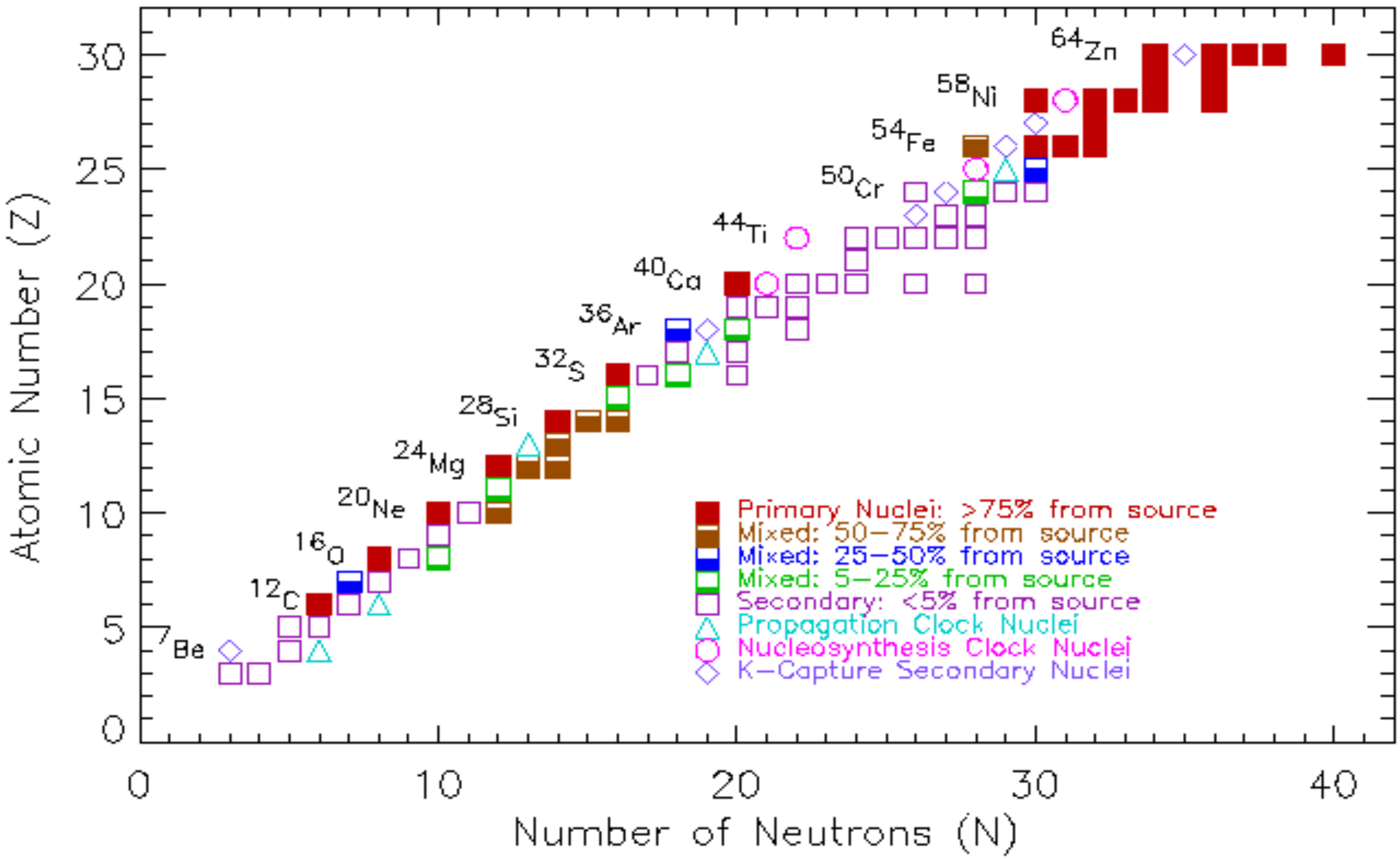
e^+, p^+, d^+ from Dark Matter annihilation

Secondaries = NOT present in sources, thus produced by

spallation of primary CRs (p, He, C, O, Fe) on ISM

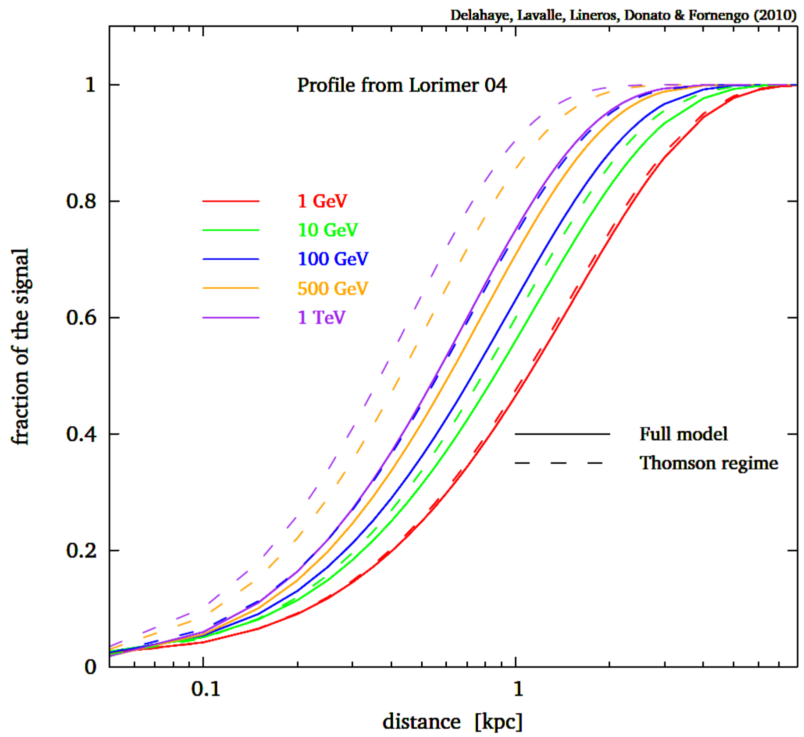
Nuclei: LiBeB, sub-Fe, … ;

e^+, p^+, d^+; … from inelastic scatterings

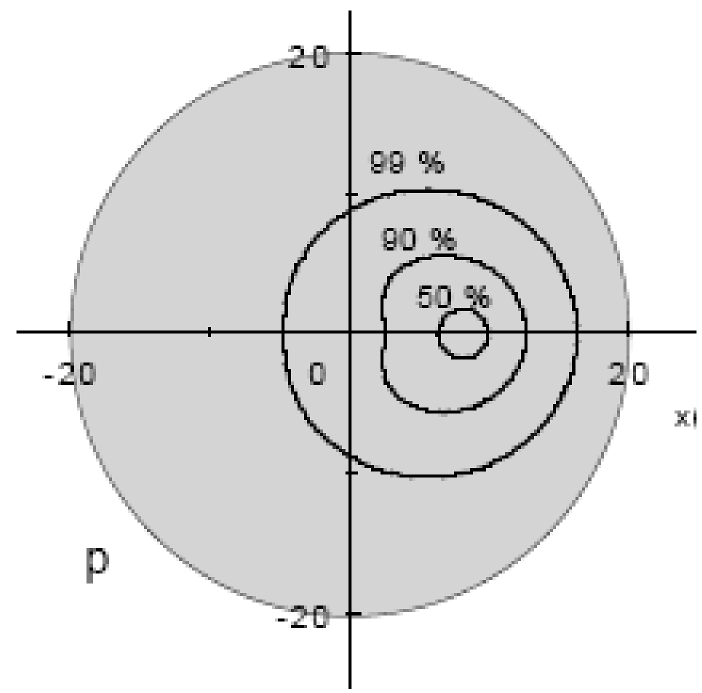


CRs arriving at the Earth

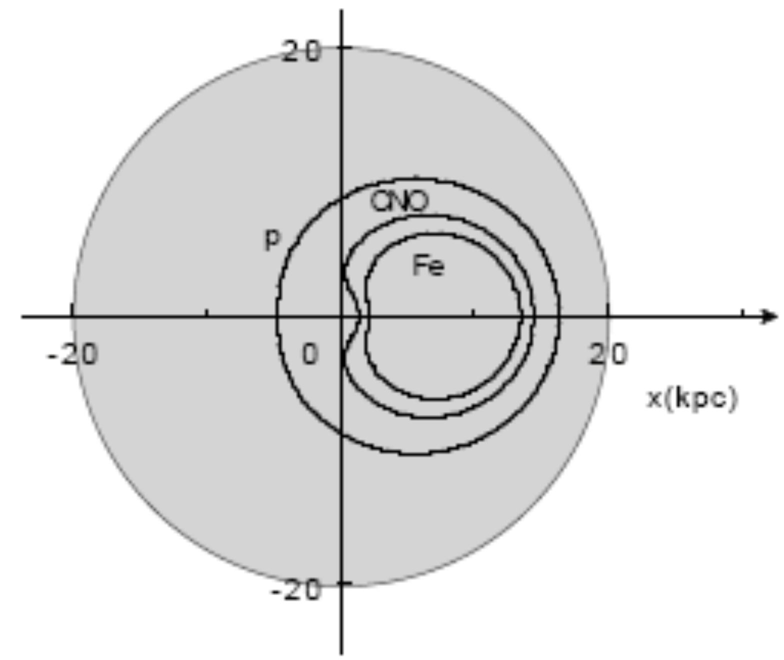
Electrons



Protons (~antiprotons)



Nuclei



Energetic electrons are quite **local** due to **radiative cooling**
Stable hadrons arrive at Earth from farther places, depending on **spallations** on the interstellar medium (ISM: H, He)

Different species trace different galactic environments

Transport equation in diffusion models for flux (intensity) $N^j(E)$

$\Gamma^j = \Gamma^{j,\mathrm{inel}} + \Gamma^{j,\mathrm{rad}}$

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

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

Primary production
(SNR, PSR, DM)

$$\bar{Q}^j \equiv q_0^j Q(E)\hat{q}_i + \sum_k^{m_k>m_j}\tilde{\Gamma}^{kj}N_i^k(0)$$

Secondary production
by fragmentation

$$b_{\mathrm{tot}} = b_{\mathrm{loss}} + b_{\mathrm{reac}}$$

$$b_{\mathrm{loss}}(E) = \left(\frac{dE}{dt}\right)_{\mathrm{Ion}} + \left(\frac{dE}{dt}\right)_{\mathrm{Coul}} + \left(\frac{dE}{dt}\right)_{\mathrm{Adiab}}$$

It is a second order differential equation in space and in energy

Secondary fluxes are grossly proportional to their production cross section

Production cross sections in the galactic cosmic ray modeling

H, He, C, O, Fe,... are present in the supernova remnant surroundings, and directly accelerated into the the interstellar medium (ISM)

All the other nuclei (Li, Be, B, p-, and e+, gamma, ...) are produced by spallation of heavier nuclei with the atoms (H, He) of the ISM

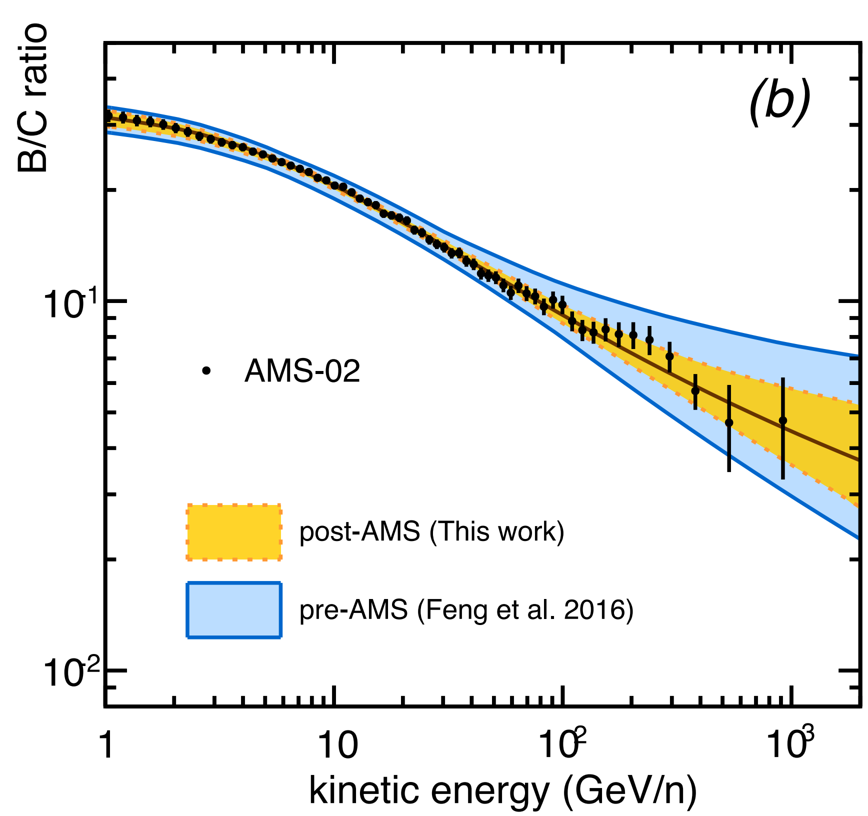
We need all the cross sections σ^{kj} - from Nichel down to proton - for the production of the j-particle from the heavier k-nucleus scattering off the H and He of the ISM

Remarkable for DARK MATTER signals is productions of: antiproton, antideuteron, positron and gamma rays.

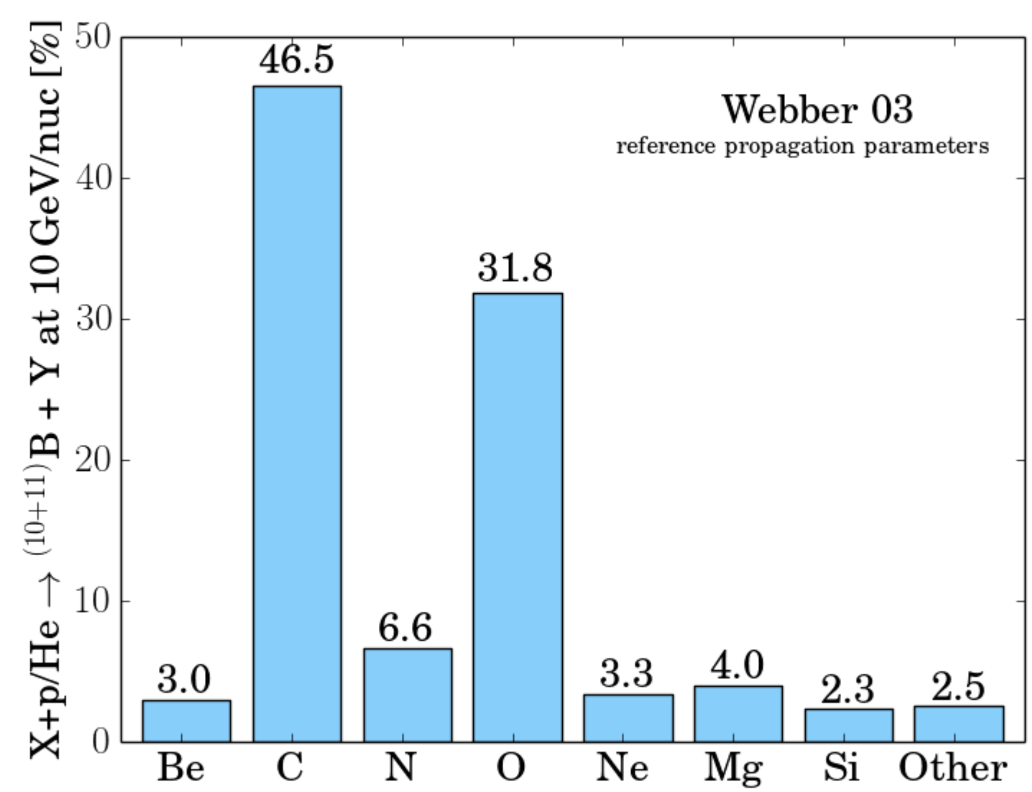
Boron-to-Carbon: a standard candle for fixing GALACTIC PROPAGATION

- Li, Be, B are produced by fragmentation of heavier nuclei (mostly C, N, O) on H and He: production cross sections
- B/C is very sensitive to **propagation effects**, kind of standard candle

Tomassetti, Feng, Oliva PRD 2017



Genolini, Putze, Serpico, Salati 2015



See talk by A. Oliva

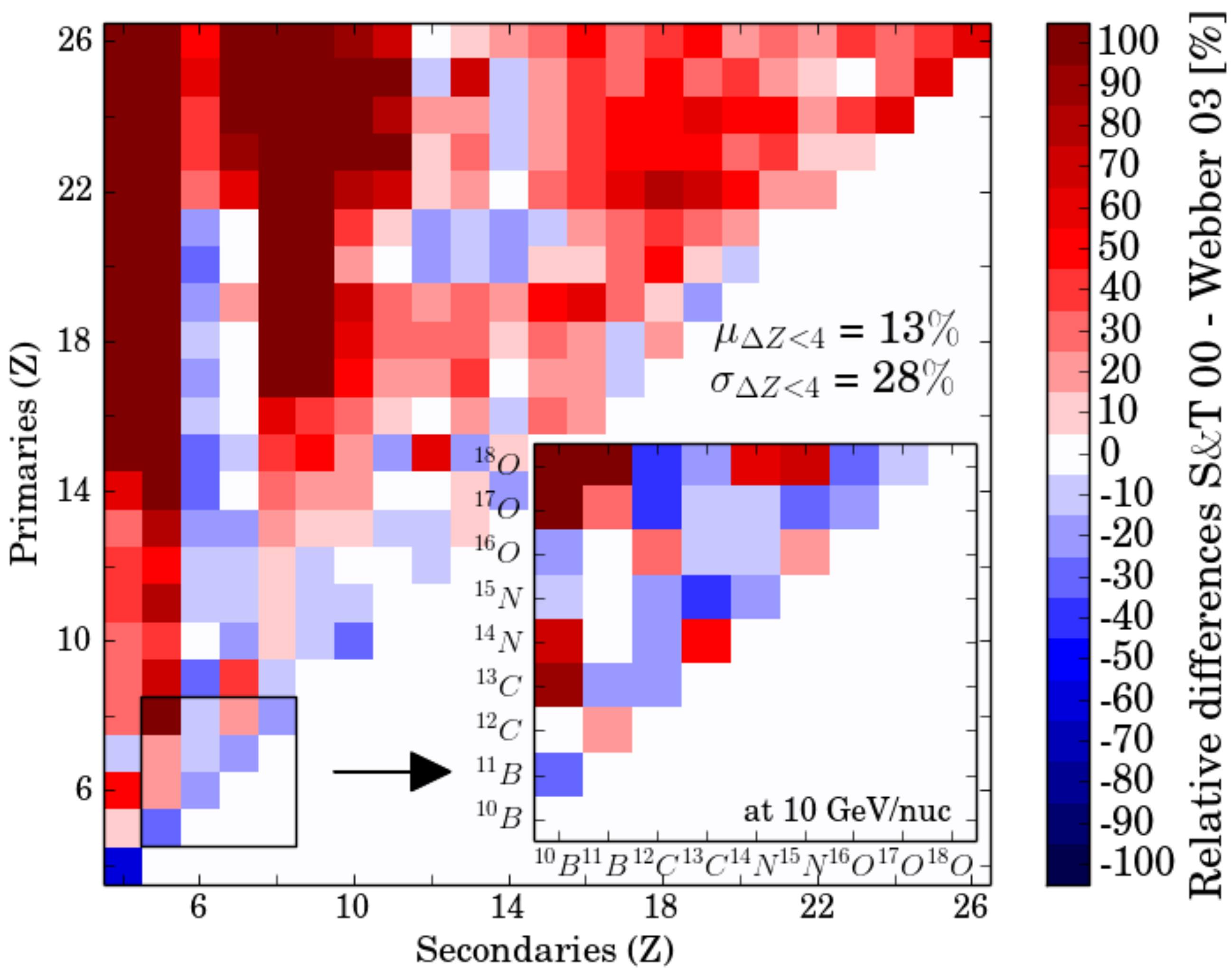
B/C (AMS, PRL 117, 2016) does not show features at high energies

At first order, we understand B/C within Fermi acceleration and isotropic diffusion.

Getting the cross sections

Several approaches are attempted: direct fit to the data, **if data exist;** analytic parameterizations (interpolations, then extrapolations), Monte Carlo.

Genolini, Putze, Serpico, Salati 2015



Differences are larger for Z-projectile and Z-fragment are >> 1

These cross sections are often small, have few or no data, so different empirical models give different results

Blu-red imply strong biases

Current status and desired accuracy of the isotopic production cross sections relevant to astrophysics of cosmic rays I. Li, Be, B, C, N

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(Dated: March 14, 2018)

1803.04685

- Ranking of the most important cross sections for the production of Li, Be, B, C, N

- Propagation of uncertainties

Reaction $a+b\rightarrow c$	Flux impact f_{abc} [%] min	mean	max	σ [mb] range	Data	σ^c/σ
$\sigma(^{12}\mathrm{C}+\mathrm{H}\rightarrow{}^{6}\mathrm{Li})$	11.0	**13.6**	16.0	14.0	✓	
$\sigma(^{16}\mathrm{O}+\mathrm{H}\rightarrow{}^{6}\mathrm{Li})$	11.0	**13.5**	16.0	13.0	✓	
$\sigma(^{12}\mathrm{C}+\mathrm{H}\rightarrow{}^{7}\mathrm{Li})$	10.0	**11.9**	14.0	12.6	✓	
$\sigma(^{16}\mathrm{O}+\mathrm{H}\rightarrow{}^{7}\mathrm{Li})$	9.6	**11.3**	13.0	11.2	✓	
$\sigma(^{11}\mathrm{B}+\mathrm{H}\rightarrow{}^{7}\mathrm{Li})$	3.00	**3.52**	4.00	21.5	✓	
$\sigma(^{13}\mathrm{C}+\mathrm{H}\rightarrow{}^{7}\mathrm{Li})$	2.00	**2.39**	2.80	22.1		
$\sigma(^{16}\mathrm{O}+\mathrm{He}\rightarrow{}^{6}\mathrm{Li})$	2.00	**2.38**	2.80	20.6		
$\sigma(^{7}\mathrm{Li}+\mathrm{H}\rightarrow{}^{6}\mathrm{Li})$	2.30	**2.35**	2.40	31.5	✓	
$\sigma(^{12}\mathrm{C}+\mathrm{He}\rightarrow{}^{6}\mathrm{Li})$	1.90	**2.33**	2.70	21.6		
$\sigma(^{15}\mathrm{N}+\mathrm{H}\rightarrow{}^{7}\mathrm{Li})$	1.90	**2.27**	2.60	18.6	✓	
$\sigma(^{12}\mathrm{C}+\mathrm{He}\rightarrow{}^{7}\mathrm{Li})$	1.70	**2.04**	2.40	19.4		
$\sigma(^{16}\mathrm{O}+\mathrm{He}\rightarrow{}^{7}\mathrm{Li})$	1.70	**2.00**	2.30	17.8		
$\sigma(^{24}\mathrm{Mg}+\mathrm{H}\rightarrow{}^{6}\mathrm{Li})$	1.70	**1.98**	2.30	12.6		
$\sigma(^{13}\mathrm{C}+\mathrm{H}\rightarrow{}^{6}\mathrm{Li})$	1.60	**1.97**	2.30	17.8		
$\sigma(^{24}\mathrm{Mg}+\mathrm{H}\rightarrow{}^{7}\mathrm{Li})$	1.50	**1.74**	2.00	11.4		
$\sigma(^{10}\mathrm{B}+\mathrm{H}\rightarrow{}^{6}\mathrm{Li})$	1.40	**1.64**	1.90	20.0		
$\sigma(^{14}\mathrm{N}+\mathrm{H}\rightarrow{}^{6}\mathrm{Li})$	1.40	**1.62**	1.90	13.0	✓	
$\sigma(^{15}\mathrm{N}+\mathrm{H}\rightarrow{}^{6}\mathrm{Li})$	1.30	**1.60**	1.90	12.8	✓	
$\sigma(^{12}\mathrm{C}+\mathrm{H}\rightarrow{}^{11}\mathrm{B})$	1.20	**1.38**	1.60	30.0	✓	1.8
$\sigma(^{7}\mathrm{Be}+\mathrm{H}\rightarrow{}^{6}\mathrm{Li})$	1.20	**1.34**	1.50	21.0		
$\sigma(\mathbf{^{12}C+H\rightarrow{}^{11}C})$	1.10	**1.24**	1.40	26.9	✓	n/a
$\sigma(^{14}\mathrm{N}+\mathrm{H}\rightarrow{}^{7}\mathrm{Li})$	0.95	**1.13**	1.30	9.3	✓	
$\sigma(^{56}\mathrm{Fe}+\mathrm{H}\rightarrow{}^{7}\mathrm{Li})$	0.00	**0.94**	1.90	[0.0, 23.0]		
$\sigma(^{56}\mathrm{Fe}+\mathrm{H}\rightarrow{}^{6}\mathrm{Li})$	0.00	**0.94**	1.90	[0.0, 22.0]		
$\sigma(^{16}\mathrm{O}+\mathrm{H}\rightarrow{}^{11}\mathrm{B})$	0.80	**0.90**	1.00	18.2	✓	1.5
$\sigma(^{11}\mathrm{B}+\mathrm{H}\rightarrow{}^{6}\mathrm{Li})$	0.71	**0.84**	0.97	5.0	✓	
$\sigma(^{28}\mathrm{Si}+\mathrm{H}\rightarrow{}^{6}\mathrm{Li})$	0.00	**0.80**	1.60	[0.0, 13.0]		
$\sigma(^{10}\mathrm{B}+\mathrm{H}\rightarrow{}^{7}\mathrm{Li})$	0.70	**0.80**	0.90	10.0		
$\sigma(^{28}\mathrm{Si}+\mathrm{H}\rightarrow{}^{7}\mathrm{Li})$	0.00	**0.71**	1.40	[0.0, 11.0]		
$\sigma(^{16}\mathrm{O}+\mathrm{H}\rightarrow{}^{15}\mathrm{N})$	0.57	**0.64**	0.71	34.3	✓	1.8
$\sigma(^{12}\mathrm{C}+\mathrm{H}\rightarrow{}^{10}\mathrm{B})$	0.53	**0.64**	0.74	12.3	✓	1.1
$\sigma(^{20}\mathrm{Ne}+\mathrm{H}\rightarrow{}^{6}\mathrm{Li})$	0.00	**0.63**	1.30	[0.0, 13.0]		
$\sigma(\mathbf{^{16}O+H\rightarrow{}^{13}O})$	0.55	**0.63**	0.71	30.5	✓	n/a
$\sigma(^{16}\mathrm{O}+\mathrm{H}\rightarrow{}^{10}\mathrm{B})$	0.50	**0.60**	0.70	10.9	✓	
$\sigma(^{11}\mathrm{B}+\mathrm{He}\rightarrow{}^{7}\mathrm{Li})$	0.52	**0.60**	0.69	33.2		
$\sigma(\mathbf{^{16}O+H\rightarrow{}^{15}O})$	0.51	**0.57**	0.63	30.5	✓	n/a
$\sigma(^{20}\mathrm{Ne}+\mathrm{H}\rightarrow{}^{7}\mathrm{Li})$	0.00	**0.56**	1.10	[0.0, 11.0]		
$\sigma(^{16}\mathrm{O}+\mathrm{H}\rightarrow{}^{7}\mathrm{Be})$	0.37	**0.45**	0.54	10.0	✓	
$\sigma(\mathbf{^{16}O+H\rightarrow{}^{11}C})$	0.40	**0.45**	0.50	9.1		n/a
$\sigma(^{56}\mathrm{Fe}+\mathrm{He}\rightarrow{}^{7}\mathrm{Li})$	0.00	**0.44**	0.88	[0.0, 97.0]		
$\sigma(^{56}\mathrm{Fe}+\mathrm{He}\rightarrow{}^{6}\mathrm{Li})$	0.00	**0.44**	0.88	[0.0, 95.0]		
$\sigma(^{7}\mathrm{Li}+\mathrm{He}\rightarrow{}^{6}\mathrm{Li})$	0.42	**0.43**	0.45	52.2		
$\sigma(^{13}\mathrm{C}+\mathrm{He}\rightarrow{}^{7}\mathrm{Li})$	0.34	**0.41**	0.48	34.2		
$\sigma(^{12}\mathrm{C}+\mathrm{H}\rightarrow{}^{7}\mathrm{Be})$	0.34	**0.41**	0.48	9.7	✓	
$\sigma(^{16}\mathrm{O}+\mathrm{H}\rightarrow{}^{13}\mathrm{C})$	0.36	**0.41**	0.46	17.5	✓	1.2
$\sigma(^{24}\mathrm{Mg}+\mathrm{He}\rightarrow{}^{6}\mathrm{Li})$	0.33	**0.39**	0.46	22.5		
$\sigma(^{15}\mathrm{N}+\mathrm{He}\rightarrow{}^{7}\mathrm{Li})$	0.33	**0.39**	0.45	28.6		
$\sigma(\mathbf{^{7}Li+H\rightarrow{}^{6}He})$	0.00	**0.38**	0.76	[0.0, 10.0]		n/a
$\sigma(^{11}\mathrm{B}+\mathrm{H}\rightarrow{}^{10}\mathrm{B})$	0.29	**0.35**	0.40	38.9	✓	
$\sigma(^{24}\mathrm{Mg}+\mathrm{He}\rightarrow{}^{7}\mathrm{Li})$	0.29	**0.34**	0.40	20.3		
$\sigma(^{13}\mathrm{C}+\mathrm{He}\rightarrow{}^{6}\mathrm{Li})$	0.28	**0.34**	0.40	27.5		
$\sigma(\mathbf{^{56}Fe+H\rightarrow{}^{6}He})$	0.00	**0.29**	0.57	[0.0, 6.9]		n/a

Reaction $a+b\rightarrow c$	Flux impact f_{abc} [%] min	mean	max	σ [mb] range	Data	σ^c/σ
$\sigma(^{16}\mathrm{O}+\mathrm{H}\rightarrow{}^{7}\mathrm{Be})$	17.0	**17.6**	19.0	10.0	✓	
$\sigma(^{12}\mathrm{C}+\mathrm{H}\rightarrow{}^{7}\mathrm{Be})$	15.0	**15.9**	17.0	9.7	✓	
$\sigma(^{12}\mathrm{C}+\mathrm{H}\rightarrow{}^{9}\mathrm{Be})$	8.80	**9.27**	9.80	6.8	✓	
$\sigma(^{16}\mathrm{O}+\mathrm{H}\rightarrow{}^{9}\mathrm{Be})$	5.00	**5.34**	5.60	3.7	✓	
$\sigma(^{16}\mathrm{O}+\mathrm{He}\rightarrow{}^{7}\mathrm{Be})$	2.70	**2.87**	3.00	14.7		
$\sigma(^{28}\mathrm{Si}+\mathrm{H}\rightarrow{}^{7}\mathrm{Be})$	2.60	**2.77**	2.90	10.8		
$\sigma(^{24}\mathrm{Mg}+\mathrm{H}\rightarrow{}^{7}\mathrm{Be})$	2.50	**2.65**	2.80	10.0		
$\sigma(^{12}\mathrm{C}+\mathrm{He}\rightarrow{}^{7}\mathrm{Be})$	2.30	**2.48**	2.60	13.7		
$\sigma(^{11}\mathrm{B}+\mathrm{H}\rightarrow{}^{9}\mathrm{Be})$	2.30	**2.36**	2.50	10.0	✓	
$\sigma(^{12}\mathrm{C}+\mathrm{H}\rightarrow{}^{10}\mathrm{Be})$	2.00	**2.16**	2.30	4.0	✓	
$\sigma(^{14}\mathrm{N}+\mathrm{H}\rightarrow{}^{7}\mathrm{Be})$	2.00	**2.12**	2.20	10.1	✓	
$\sigma(^{20}\mathrm{Ne}+\mathrm{H}\rightarrow{}^{7}\mathrm{Be})$	1.60	**1.73**	1.90	[7.4, 9.7]		
$\sigma(^{10}\mathrm{B}+\mathrm{H}\rightarrow{}^{9}\mathrm{Be})$	1.60	**1.62**	1.70	13.9		
$\sigma(^{12}\mathrm{C}+\mathrm{He}\rightarrow{}^{9}\mathrm{Be})$	1.40	**1.45**	1.50	9.6		
$\sigma(^{12}\mathrm{C}+\mathrm{H}\rightarrow{}^{11}\mathrm{B})$	1.30	**1.43**	1.60	30.0	✓	1.8
$\sigma(^{15}\mathrm{N}+\mathrm{H}\rightarrow{}^{9}\mathrm{Be})$	1.20	**1.29**	1.40	7.3	✓	
$\sigma(\mathbf{^{12}C+H\rightarrow{}^{11}C})$	1.20	**1.28**	1.40	26.9	✓	n/a
$\sigma(^{16}\mathrm{O}+\mathrm{H}\rightarrow{}^{10}\mathrm{Be})$	1.20	**1.27**	1.40	2.2	✓	
$\sigma(^{11}\mathrm{B}+\mathrm{H}\rightarrow{}^{10}\mathrm{Be})$	1.10	**1.21**	1.30	12.9	✓	
$\sigma(^{11}\mathrm{B}+\mathrm{H}\rightarrow{}^{7}\mathrm{Be})$	0.99	**1.16**	1.30	[3.6, 4.5]	✓	
$\sigma(^{15}\mathrm{N}+\mathrm{H}\rightarrow{}^{7}\mathrm{Be})$	1.10	**1.15**	1.20	5.4	✓	
$\sigma(^{13}\mathrm{C}+\mathrm{H}\rightarrow{}^{9}\mathrm{Be})$	0.96	**1.03**	1.10	6.7	✓	
$\sigma(^{28}\mathrm{Si}+\mathrm{H}\rightarrow{}^{9}\mathrm{Be})$	0.91	**0.96**	1.00	4.5	✓	
$\sigma(^{10}\mathrm{B}+\mathrm{H}\rightarrow{}^{7}\mathrm{Be})$	0.93	**0.95**	0.98	6.9	✓	
$\sigma(^{24}\mathrm{Mg}+\mathrm{H}\rightarrow{}^{9}\mathrm{Be})$	0.89	**0.94**	0.99	4.3		
$\sigma(^{16}\mathrm{O}+\mathrm{H}\rightarrow{}^{11}\mathrm{B})$	0.87	**0.94**	1.00	18.2	✓	1.5
$\sigma(^{56}\mathrm{Fe}+\mathrm{H}\rightarrow{}^{7}\mathrm{Be})$	0.11	**0.92**	1.70	[0.6, 11.0]		
$\sigma(^{16}\mathrm{O}+\mathrm{He}\rightarrow{}^{9}\mathrm{Be})$	0.82	**0.87**	0.92	5.4		
$\sigma(^{13}\mathrm{C}+\mathrm{H}\rightarrow{}^{7}\mathrm{Be})$	0.71	**0.76**	0.81	4.1	✓	
$\sigma(^{20}\mathrm{Ne}+\mathrm{H}\rightarrow{}^{9}\mathrm{Be})$	0.68	**0.72**	0.76	4.3		
$\sigma(^{12}\mathrm{C}+\mathrm{H}\rightarrow{}^{10}\mathrm{B})$	0.59	**0.64**	0.68	12.3	✓	1.1
$\sigma(^{16}\mathrm{O}+\mathrm{H}\rightarrow{}^{10}\mathrm{B})$	0.56	**0.60**	0.65	10.9	✓	
$\sigma(^{9}\mathrm{Be}+\mathrm{H}\rightarrow{}^{7}\mathrm{Be})$	0.59	**0.59**	0.60	10.6	✓	
$\sigma(^{28}\mathrm{Si}+\mathrm{He}\rightarrow{}^{7}\mathrm{Be})$	0.53	**0.56**	0.60	19.8		
$\sigma(^{56}\mathrm{Fe}+\mathrm{H}\rightarrow{}^{9}\mathrm{Be})$	0.06	**0.53**	1.00	[0.4, 7.5]		
$\sigma(^{24}\mathrm{Mg}+\mathrm{He}\rightarrow{}^{7}\mathrm{Be})$	0.47	**0.50**	0.52	16.8		
$\sigma(\mathbf{^{16}O+H\rightarrow{}^{11}C})$	0.43	**0.47**	0.50	9.1		n/a
$\sigma(^{16}\mathrm{O}+\mathrm{H}\rightarrow{}^{15}\mathrm{N})$	0.41	**0.44**	0.47	34.3	✓	1.8
$\sigma(^{56}\mathrm{Fe}+\mathrm{He}\rightarrow{}^{7}\mathrm{Be})$	0.05	**0.41**	0.77	[2.4, 43.0]		
$\sigma(\mathbf{^{16}O+H\rightarrow{}^{15}O})$	0.37	**0.39**	0.42	30.5	✓	n/a
$\sigma(^{27}\mathrm{Al}+\mathrm{H}\rightarrow{}^{7}\mathrm{Be})$	0.30	**0.38**	0.45	[5.3, 8.9]		
$\sigma(^{14}\mathrm{N}+\mathrm{H}\rightarrow{}^{9}\mathrm{Be})$	0.35	**0.37**	0.39	2.1	✓	
$\sigma(^{11}\mathrm{B}+\mathrm{He}\rightarrow{}^{9}\mathrm{Be})$	0.35	**0.37**	0.38	14.0		
$\sigma(^{13}\mathrm{C}+\mathrm{H}\rightarrow{}^{10}\mathrm{Be})$	0.33	**0.37**	0.40	5.9	✓	
$\sigma(^{23}\mathrm{Na}+\mathrm{H}\rightarrow{}^{7}\mathrm{Be})$	0.30	**0.35**	0.41	[5.8, 8.6]		
$\sigma(^{11}\mathrm{B}+\mathrm{H}\rightarrow{}^{10}\mathrm{B})$	0.33	**0.35**	0.37	38.9	✓	
$\sigma(^{25}\mathrm{Mg}+\mathrm{H}\rightarrow{}^{7}\mathrm{Be})$	0.29	**0.34**	0.40	[5.6, 8.8]		
$\sigma(^{12}\mathrm{C}+\mathrm{He}\rightarrow{}^{10}\mathrm{Be})$	0.31	**0.34**	0.36	5.6		
$\sigma(^{14}\mathrm{N}+\mathrm{He}\rightarrow{}^{7}\mathrm{Be})$	0.32	**0.34**	0.36	14.4		
$\sigma(^{20}\mathrm{Ne}+\mathrm{He}\rightarrow{}^{7}\mathrm{Be})$	0.28	**0.30**	0.32	[12.0, 15.0]		
$\sigma(^{22}\mathrm{Ne}+\mathrm{H}\rightarrow{}^{7}\mathrm{Be})$	0.22	**0.25**	0.28	[4.7, 6.4]		
$\sigma(^{10}\mathrm{B}+\mathrm{He}\rightarrow{}^{9}\mathrm{Be})$	0.25	**0.25**	0.26	19.6		
$\sigma(^{26}\mathrm{Mg}+\mathrm{H}\rightarrow{}^{7}\mathrm{Be})$	0.21	**0.25**	0.29	[4.7, 7.2]		
$\sigma(\mathbf{^{16}O+H\rightarrow{}^{9}Li})$	0.23	**0.24**	0.26	0.3	✓	n/a

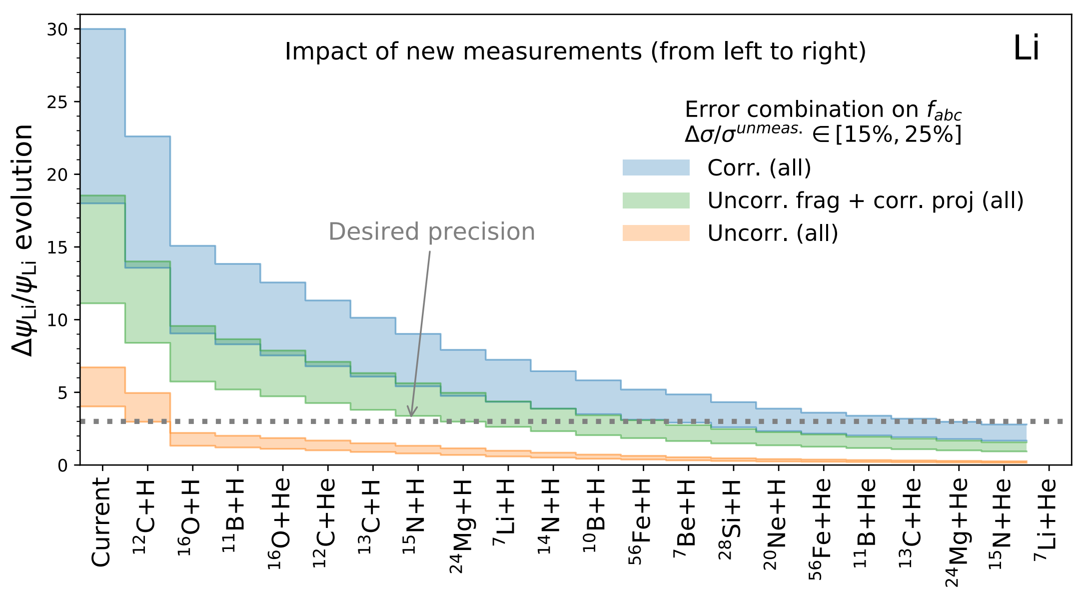
# of channels	in range	contribution [%]
13	[1%,100%]	82.2
25	[0.1%,1%]	7.7
110	[0.01%,0.1%]	3.8
346	[0.001%,0.01%]	1.3
526	[0.0001%,0.001%]	0.2
2340	[0.0%,0.0001%]	0.0

Channel	min	**mean**	max
$^{12}\mathrm{C}\rightarrow{}^{11}\mathrm{B}$	30.8	**32.7**	35.3
$^{16}\mathrm{O}\rightarrow{}^{11}\mathrm{B}$	16.2	**17.7**	18.8
$^{12}\mathrm{C}\rightarrow{}^{10}\mathrm{B}$	9.04	**9.95**	10.9
$^{16}\mathrm{O}\rightarrow{}^{10}\mathrm{B}$	7.64	**8.17**	8.68
$^{12}\mathrm{C}\rightarrow{}^{11}\mathrm{B}\rightarrow{}^{10}\mathrm{B}$	2.07	**2.16**	2.26
$^{16}\mathrm{O}\rightarrow{}^{12}\mathrm{C}\rightarrow{}^{11}\mathrm{B}$	1.60	**1.96**	2.34
$^{16}\mathrm{O}\rightarrow{}^{15}\mathrm{N}\rightarrow{}^{11}\mathrm{B}$	1.29	**1.69**	2.04
$^{24}\mathrm{Mg}\rightarrow{}^{11}\mathrm{B}$	1.51	**1.59**	1.69
$^{20}\mathrm{Ne}\rightarrow{}^{11}\mathrm{B}$	1.26	**1.32**	1.39
$^{14}\mathrm{N}\rightarrow{}^{11}\mathrm{B}$	1.00	**1.32**	1.66
$^{28}\mathrm{Si}\rightarrow{}^{11}\mathrm{B}$	0.85	**1.29**	1.66
$^{16}\mathrm{O}\rightarrow{}^{11}\mathrm{B}\rightarrow{}^{10}\mathrm{B}$	1.03	**1.17**	1.26
$^{16}\mathrm{O}\rightarrow{}^{13}\mathrm{C}\rightarrow{}^{11}\mathrm{B}$	0.54	**1.15**	1.62
$^{16}\mathrm{O}\rightarrow{}^{14}\mathrm{N}\rightarrow{}^{11}\mathrm{B}$	0.68	**0.83**	0.92
$^{24}\mathrm{Mg}\rightarrow{}^{10}\mathrm{B}$	0.66	**0.75**	0.84
$^{16}\mathrm{O}\rightarrow{}^{12}\mathrm{C}\rightarrow{}^{10}\mathrm{B}$	0.51	**0.59**	0.69
$^{16}\mathrm{O}\rightarrow{}^{15}\mathrm{N}\rightarrow{}^{10}\mathrm{B}$	0.50	**0.59**	0.68
$^{20}\mathrm{Ne}\rightarrow{}^{10}\mathrm{B}$	0.47	**0.54**	0.63
$^{28}\mathrm{Si}\rightarrow{}^{10}\mathrm{B}$	0.32	**0.53**	0.67
$^{14}\mathrm{N}\rightarrow{}^{10}\mathrm{B}$	0.39	**0.50**	0.65
$^{56}\mathrm{Fe}\rightarrow{}^{11}\mathrm{B}$	0.11	**0.49**	1.10
$^{16}\mathrm{O}\rightarrow{}^{13}\mathrm{C}\rightarrow{}^{10}\mathrm{B}$	0.12	**0.32**	0.50
$^{16}\mathrm{O}\rightarrow{}^{14}\mathrm{N}\rightarrow{}^{10}\mathrm{B}$	0.26	**0.31**	0.36
$^{24}\mathrm{Mg}\rightarrow{}^{12}\mathrm{C}\rightarrow{}^{11}\mathrm{B}$	0.21	**0.22**	0.25
$^{56}\mathrm{Fe}\rightarrow{}^{10}\mathrm{B}$	0.00	**0.21**	0.71
$^{20}\mathrm{Ne}\rightarrow{}^{12}\mathrm{C}\rightarrow{}^{11}\mathrm{B}$	0.19	**0.20**	0.22
$^{14}\mathrm{N}\rightarrow{}^{12}\mathrm{C}\rightarrow{}^{11}\mathrm{B}$	0.14	**0.20**	0.25
$^{13}\mathrm{C}\rightarrow{}^{11}\mathrm{B}$	0.15	**0.18**	0.24
$^{28}\mathrm{Si}\rightarrow{}^{12}\mathrm{C}\rightarrow{}^{11}\mathrm{B}$	0.10	**0.18**	0.21
$^{25}\mathrm{Mg}\rightarrow{}^{11}\mathrm{B}$	0.14	**0.17**	0.19
$^{32}\mathrm{S}\rightarrow{}^{11}\mathrm{B}$	0.09	**0.14**	0.17
$^{26}\mathrm{Mg}\rightarrow{}^{11}\mathrm{B}$	0.11	**0.13**	0.14
$^{27}\mathrm{Al}\rightarrow{}^{11}\mathrm{B}$	0.08	**0.12**	0.16
$^{24}\mathrm{Mg}\rightarrow{}^{16}\mathrm{O}\rightarrow{}^{11}\mathrm{B}$	0.10	**0.12**	0.13
$^{24}\mathrm{Mg}\rightarrow{}^{23}\mathrm{Na}\rightarrow{}^{11}\mathrm{B}$	0.10	**0.11**	0.14
$^{20}\mathrm{Ne}\rightarrow{}^{15}\mathrm{N}\rightarrow{}^{11}\mathrm{B}$	0.09	**0.11**	0.12
$^{24}\mathrm{Mg}\rightarrow{}^{11}\mathrm{B}\rightarrow{}^{10}\mathrm{B}$	0.10	**0.11**	0.11
$^{20}\mathrm{Ne}\rightarrow{}^{16}\mathrm{O}\rightarrow{}^{11}\mathrm{B}$	0.09	**0.10**	0.12

Invaluable theoretical and experimental work to do for a correct understanding of precise CR data

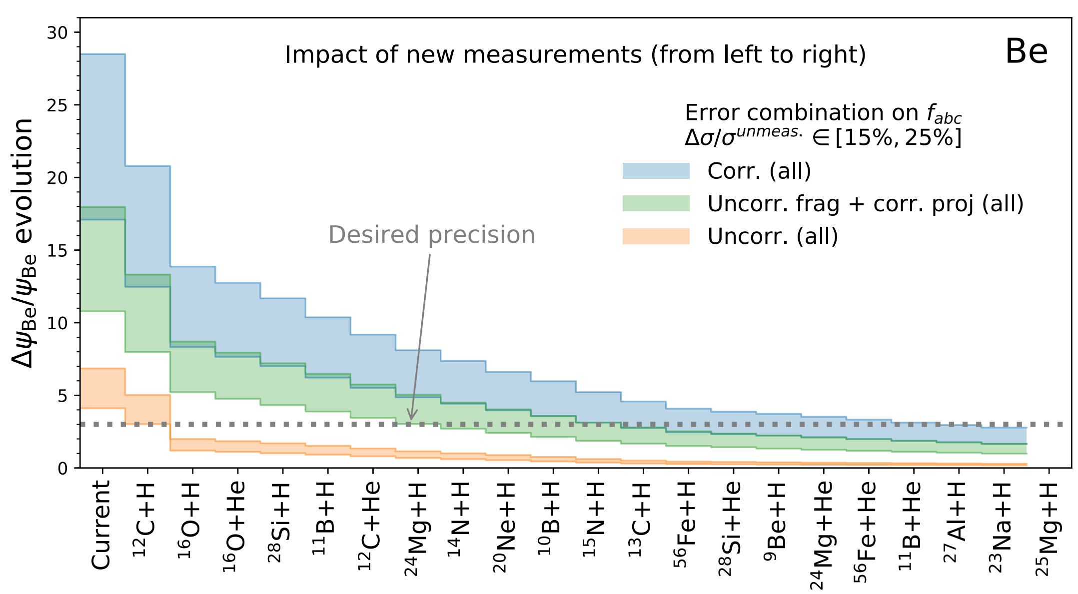
The necessary cross sections to measure

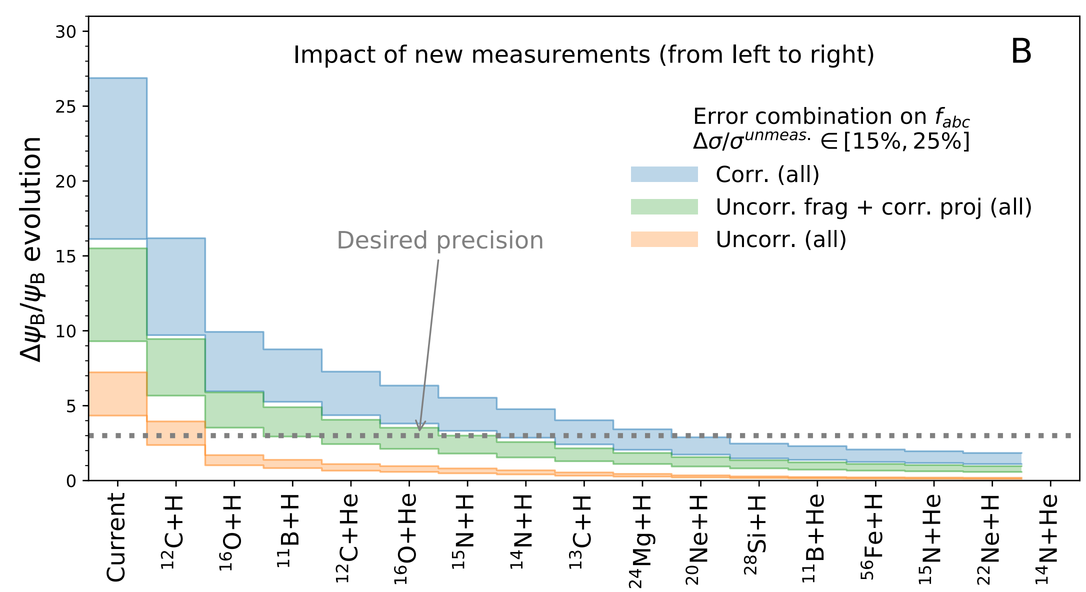
Genolini, Maurin, Moskalenko, Unger 1803.04685

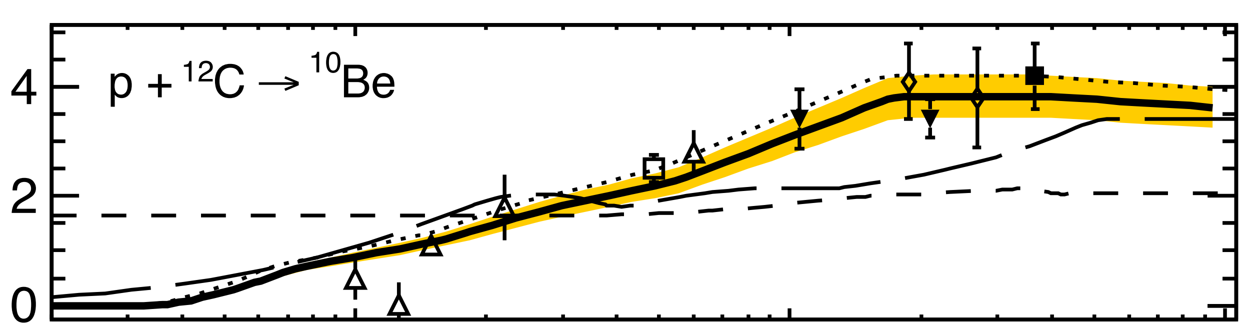


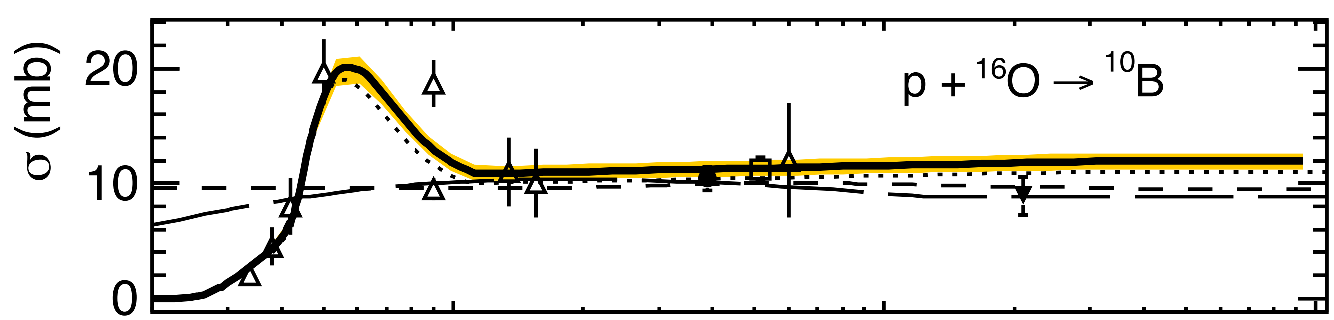
Evolution of the error on the calculated Li, Be, B as if new reactions were measured with perfect accuracy

The way in which errors are computed is relevant









Tomassetti 2016

High energy experiments contribution to the CR and dark matter physics

The antiproton production case is the most challenging.

$$q_{\bar{p}} = \int_{E_{threshold}}^{+\infty} \boxed{\frac{d\sigma_{p(He)\ ISM \to \bar{p}}}{dE_{\bar{p}}}(E_{p(He)}, E_{\bar{p}})} n_{ISM}(4\pi\Phi_p(r, E_{p(He)}))dE_{p(He)}$$

$E_{threshold}$ = 7m_p (for H target), 4m_p (for He target)

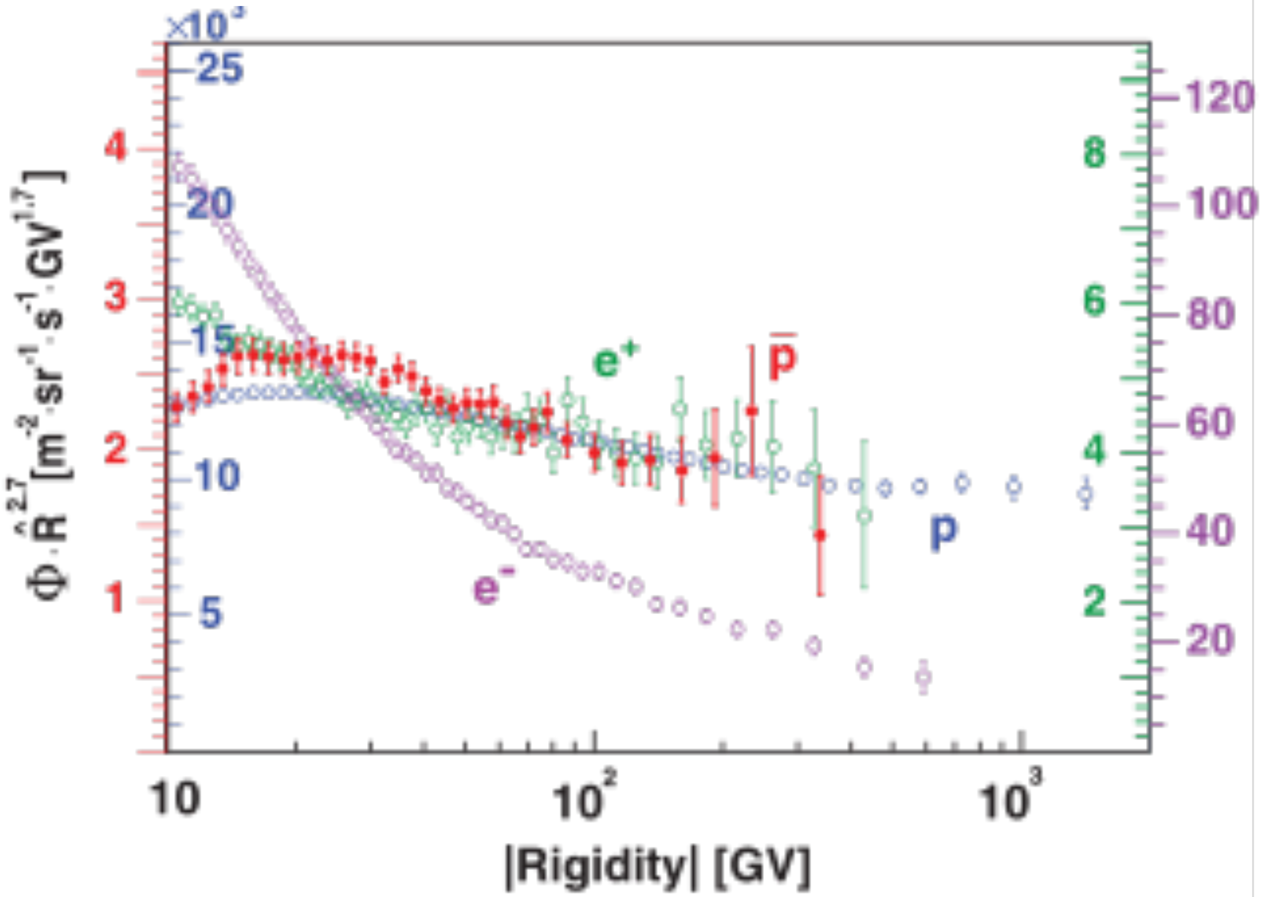
NEEDED:

1. New data for p-He → antiproton + X
2. A further determination of p-p → antiproton + X

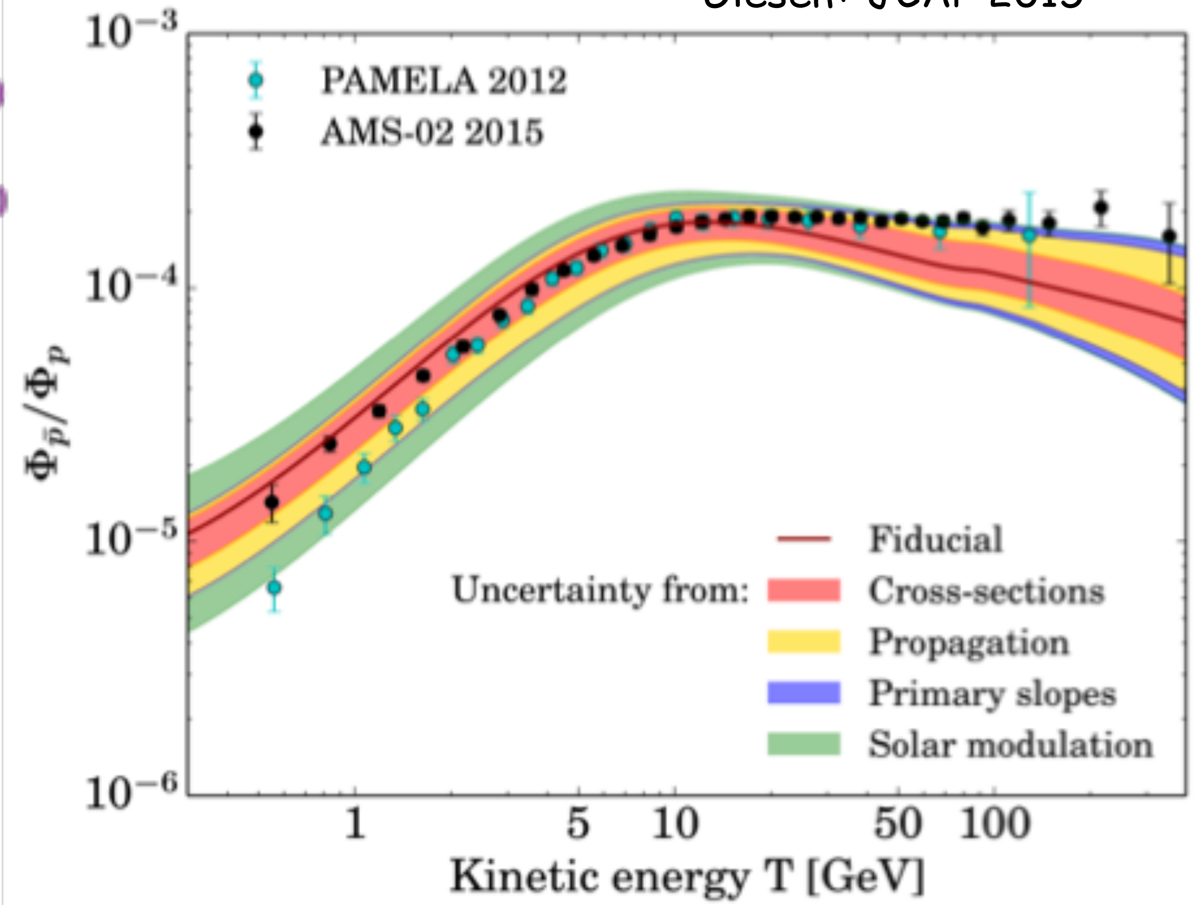
- data points falling in ~ 0.1-400 GeV antiproton energy →
  proton beam ~ 10 GeV - TeV
- errors < 10%
- determination of the role of neutrons at % level (NA49 found an isospin depedence σ(pp→n-)= 1.5 σ(pp→p-)

Antiproton data

AMS Coll., PRL 2016



Giesen+ JCAP 2015



AMS-02 results from below GeV up to 400 GeV
Could be explained by secondary production in the Milky Way

The most relevant theoretical uncertainty is due to production CROSS SECTIONS

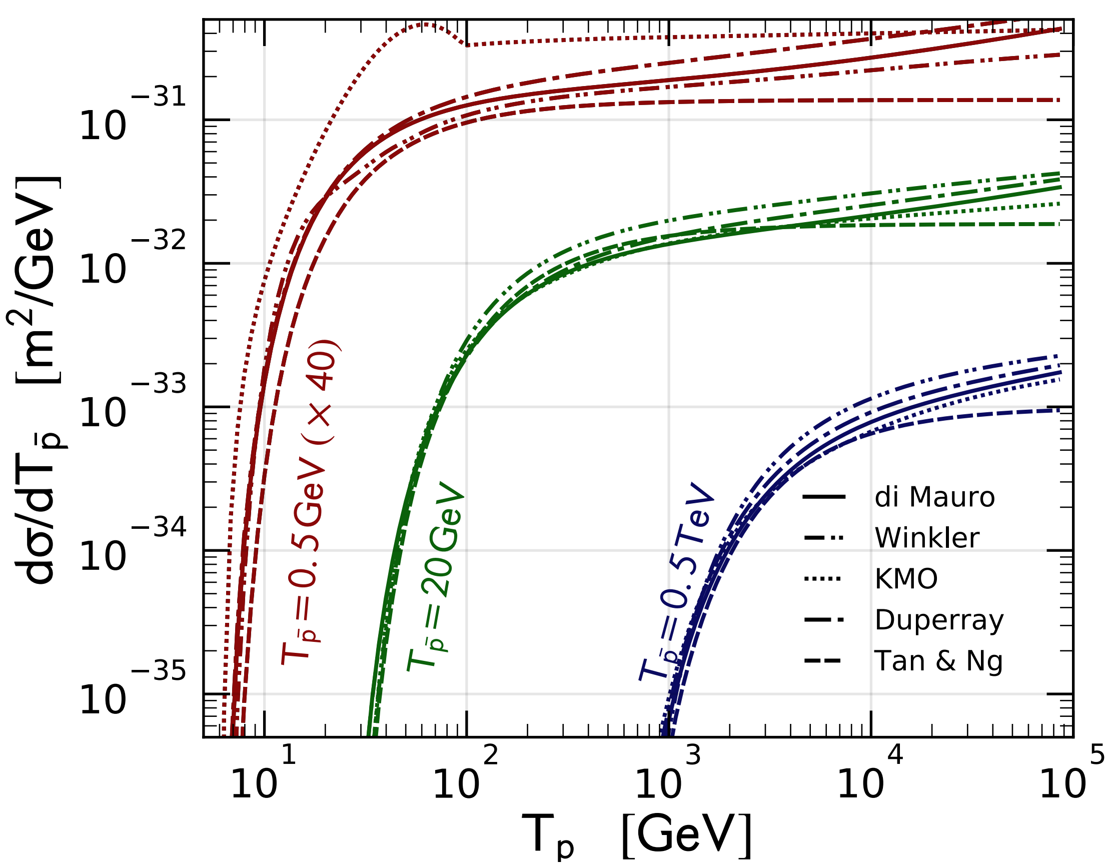
Antiproton production cross sections

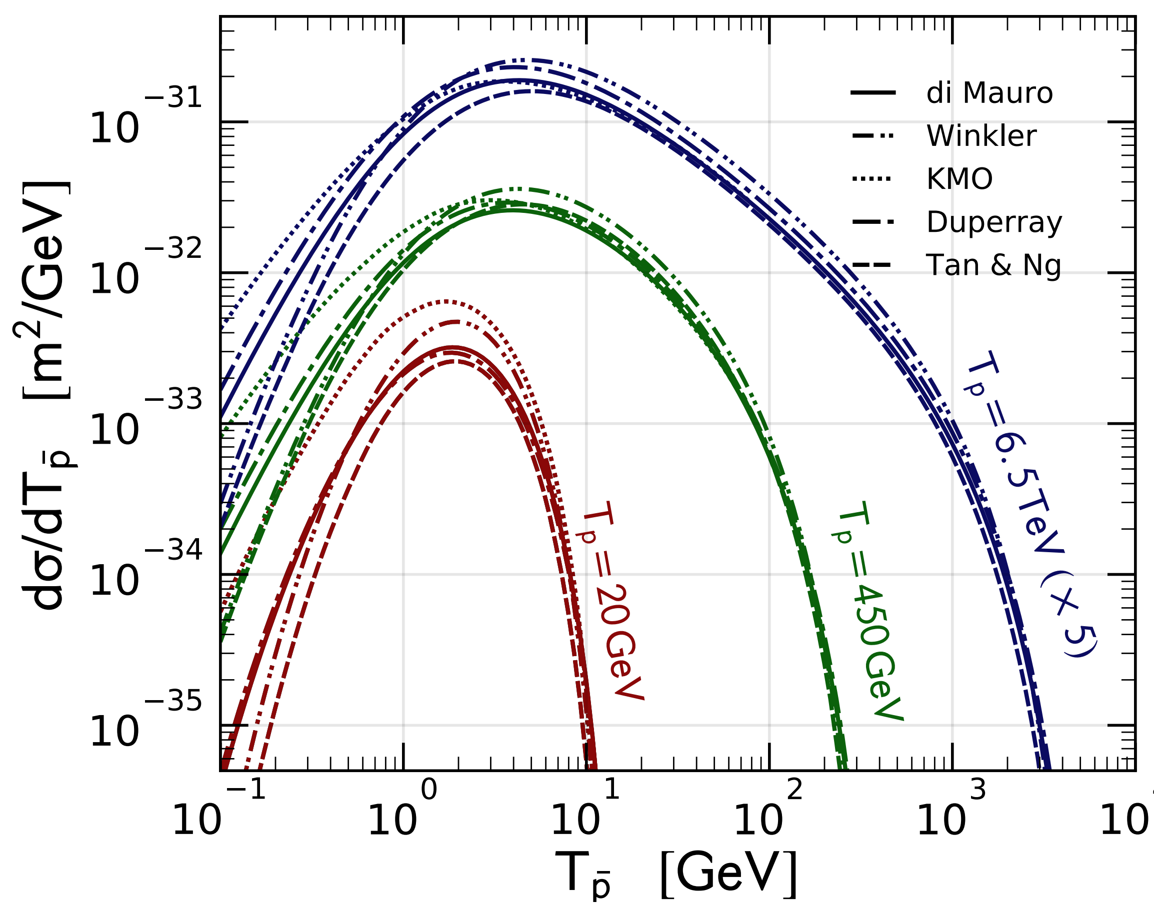
FD, Korsmeier, Di Mauro PRD 2017

$$q_{ij}(T_{\bar{p}}) = \int_{T_{\rm th}}^{\infty} dT_i \; 4\pi \, n_{{\rm ISM},j} \, \phi_i(T_i) \, \frac{d\sigma_{ij}}{dT_{\bar{p}}}(T_i, T_{\bar{p}})$$

Source term

i, j = proton, helium
(both in the CRs and in the ISM)

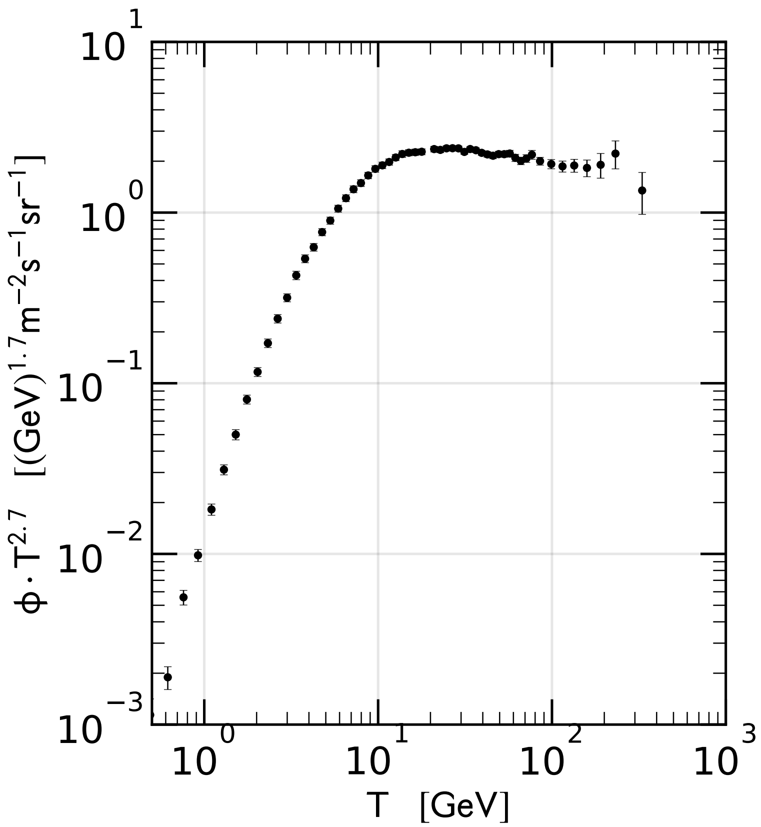




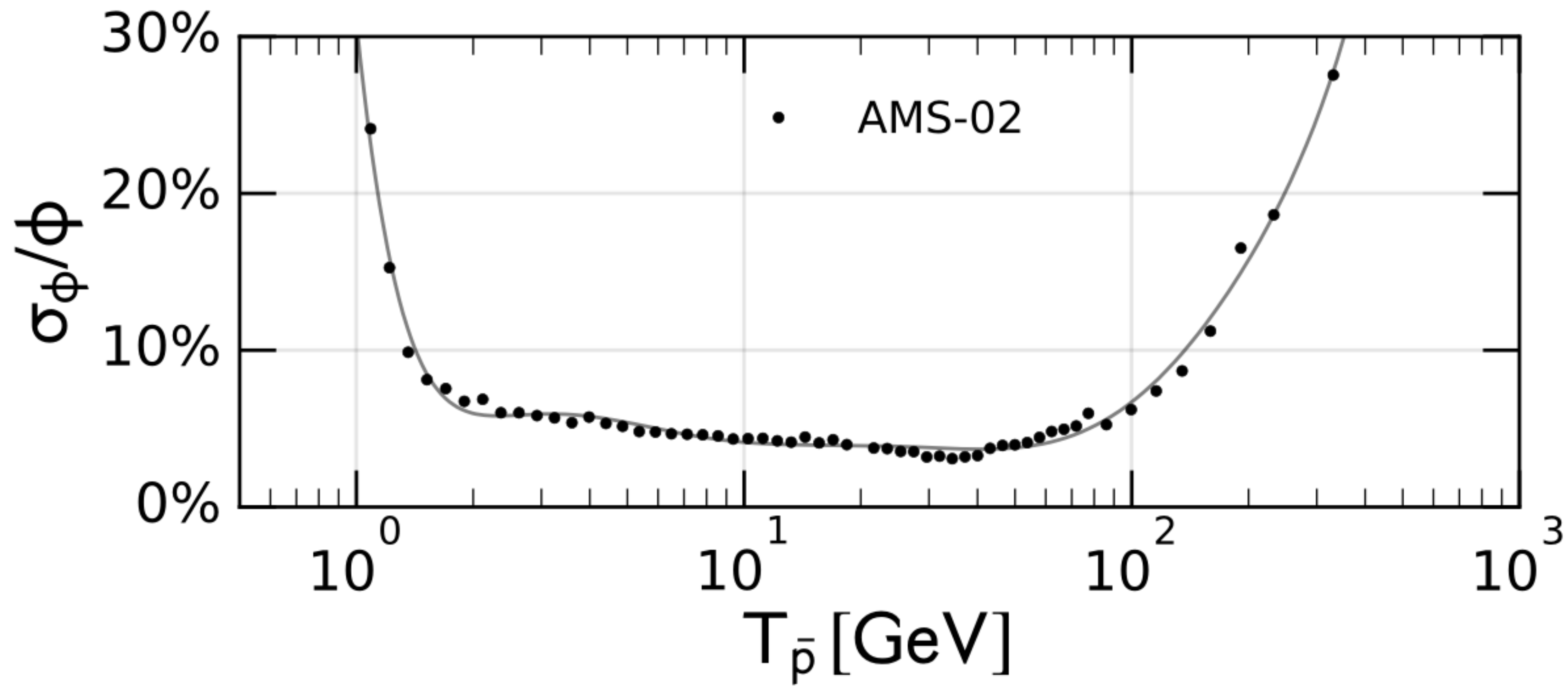
- Reasonable agreement for 10 GeV <T <100 GeV
- Deviations for T<10 GeV

Requirement on the phase space for the pp→pX cross section

FD, Korsmeier, Di Mauro PRD 2017



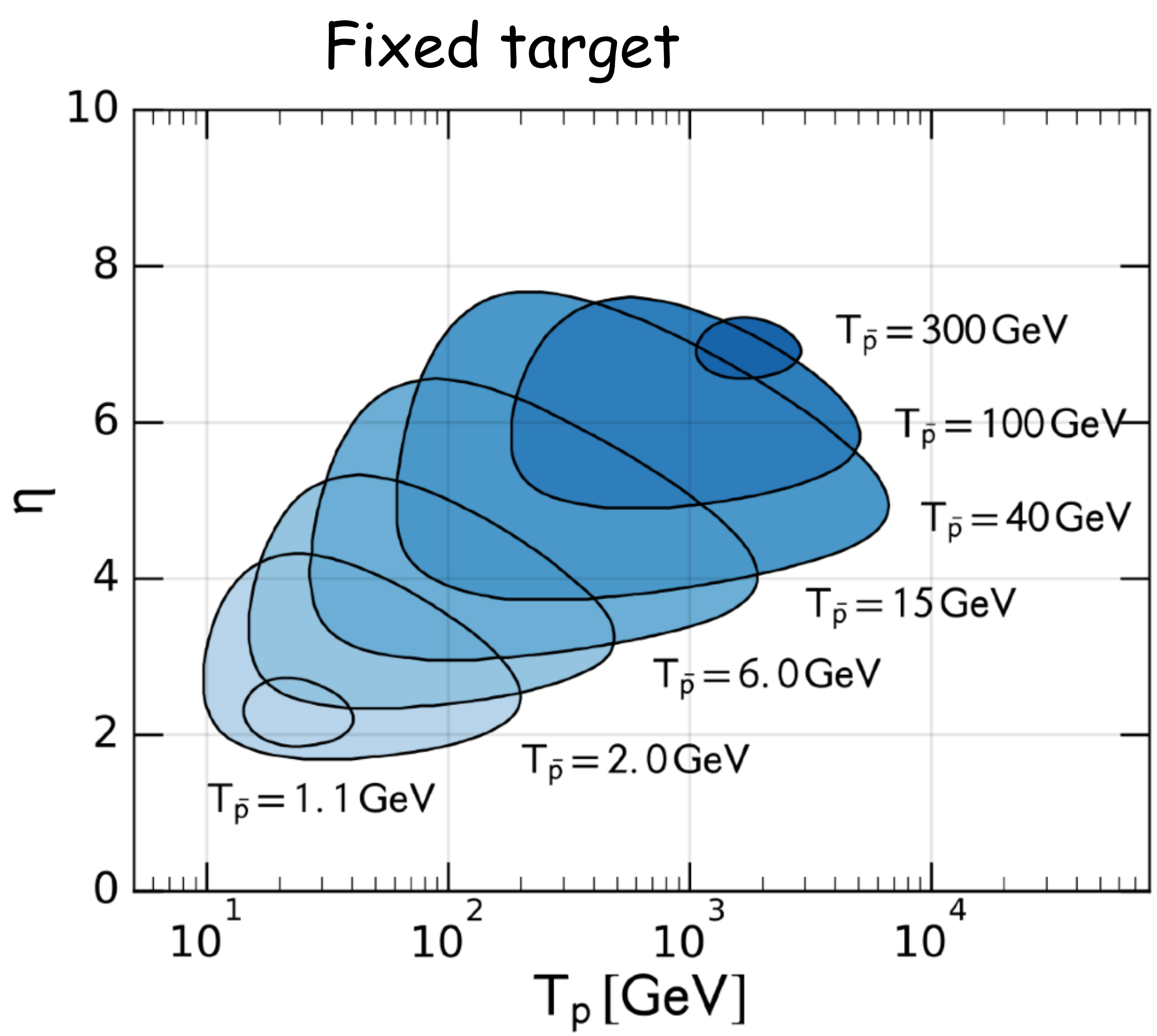
M. Aguilar et al., 2016. DOI: 10.1103/PhysRevLett.117.091103

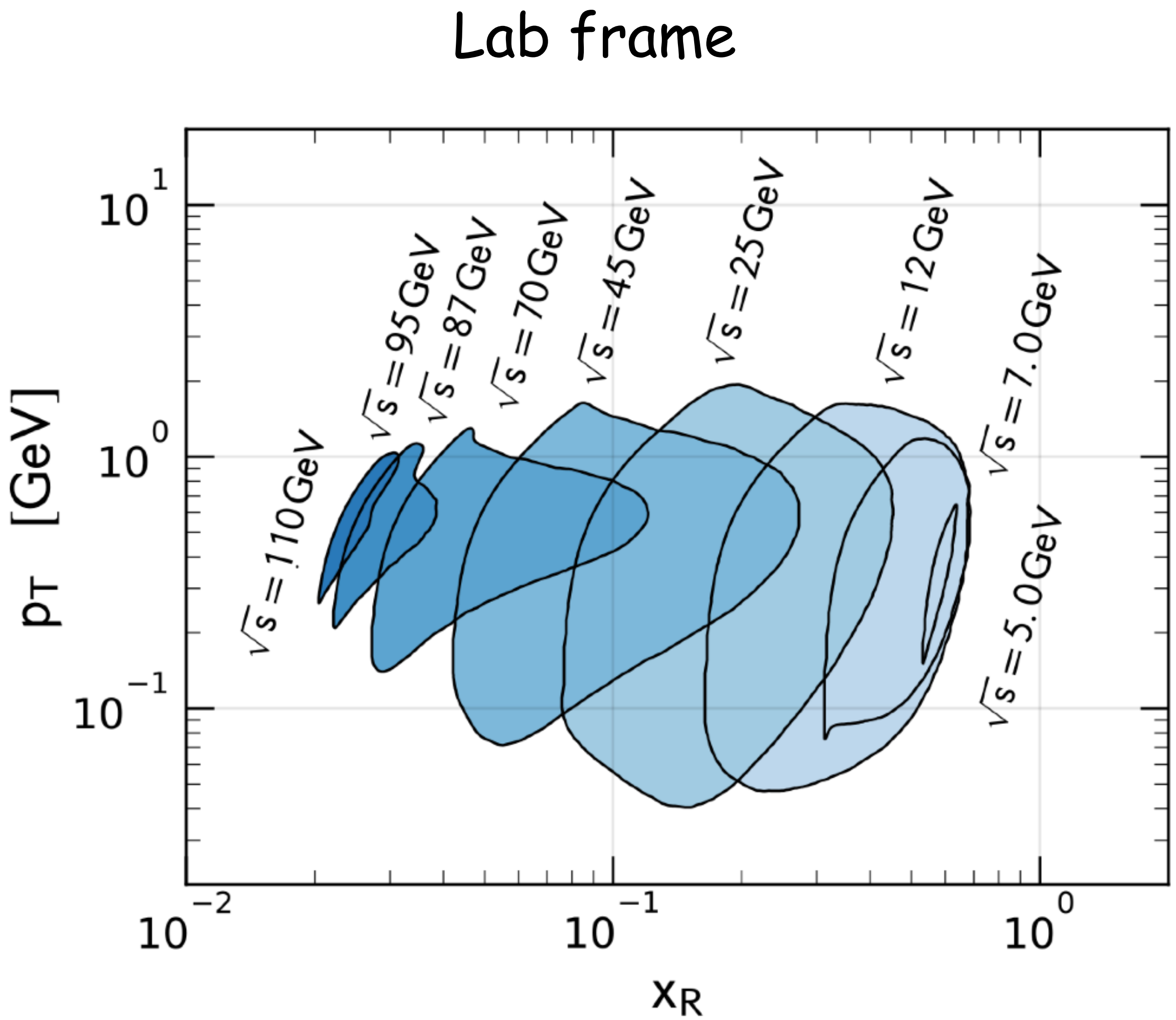


Which level of accuracy on cross sections do we need in order to match (not exceed) the accuracy in CR data?

Bias towards AMS-02 data

Parameter space to be covered



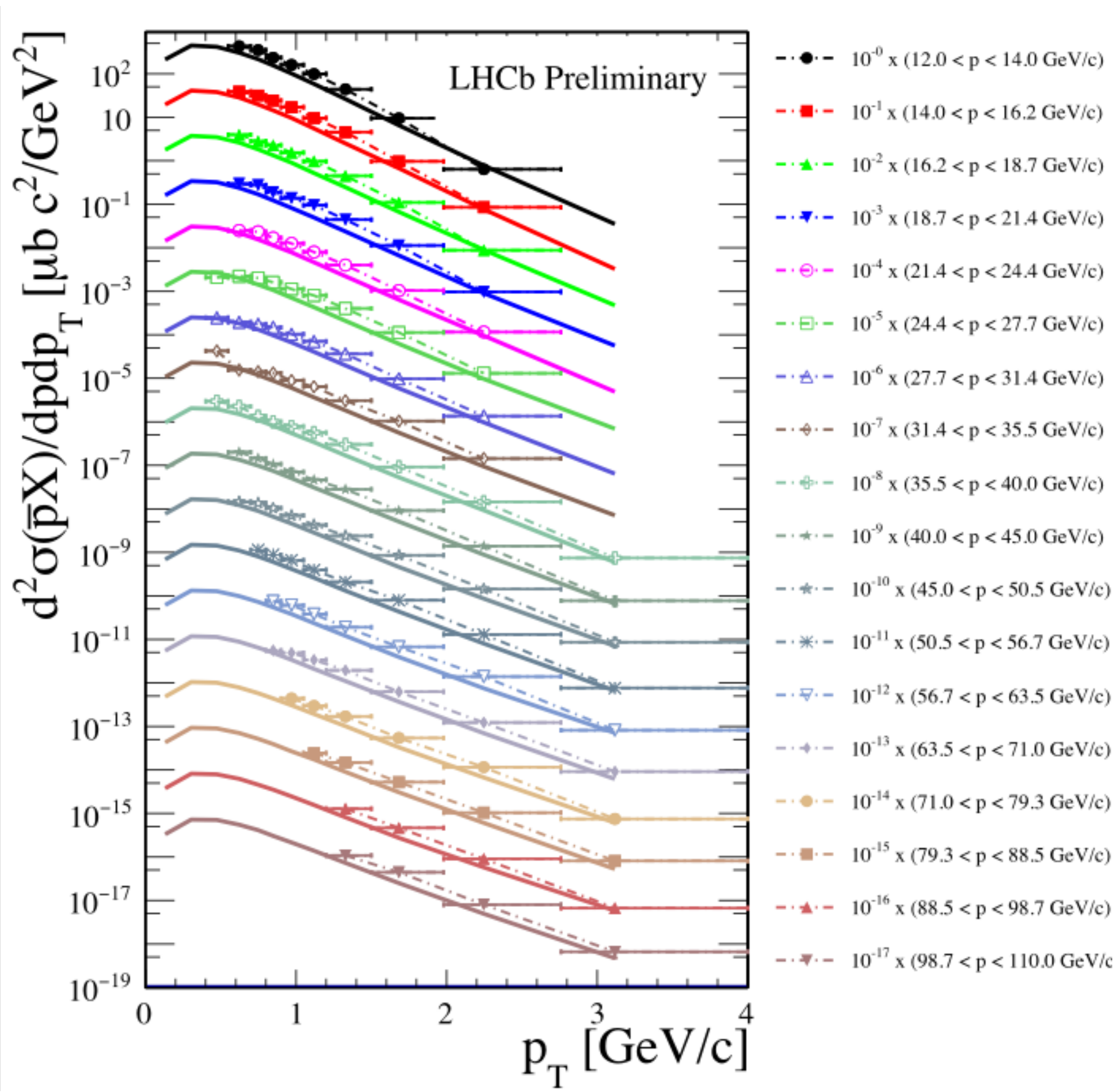


AMS02 accuracy is reached if pp→pbar cross section is measured with 3% accuracy inside the regions, 30% outside.

LHCb pHe —> p^{-}X cross section data

G Graziani for LHCb, Moriond 2017

First data ever has been collected by LHCb in fixed target mode



Result for **prompt** production (excluding weak decays of hyperons)

The total inelastic cross section is also measured to be

$$\sigma_{inel}^{\mathrm{LHCb}} = (140 \pm 10)\ \mathrm{mb}$$

The EPOS LHC prediction

[T. Pierog at al, Phys. Rev. C92 (2015), 034906]

is 118 mb, ratio is 1.19 ± 0.08.

Run at 4 TeV p beam energy is under analysis by the collaboration

New fixed-target data for the antiproton XS

pp —> pbar+X

NA61 (Aduszkiewicz Eur. Phys. J. C77 (2017))

$\sqrt{s}$=7.7, 8.8, 12.3 and 17.3 GeV

T_p = 31, 40, 80, 158 GeV

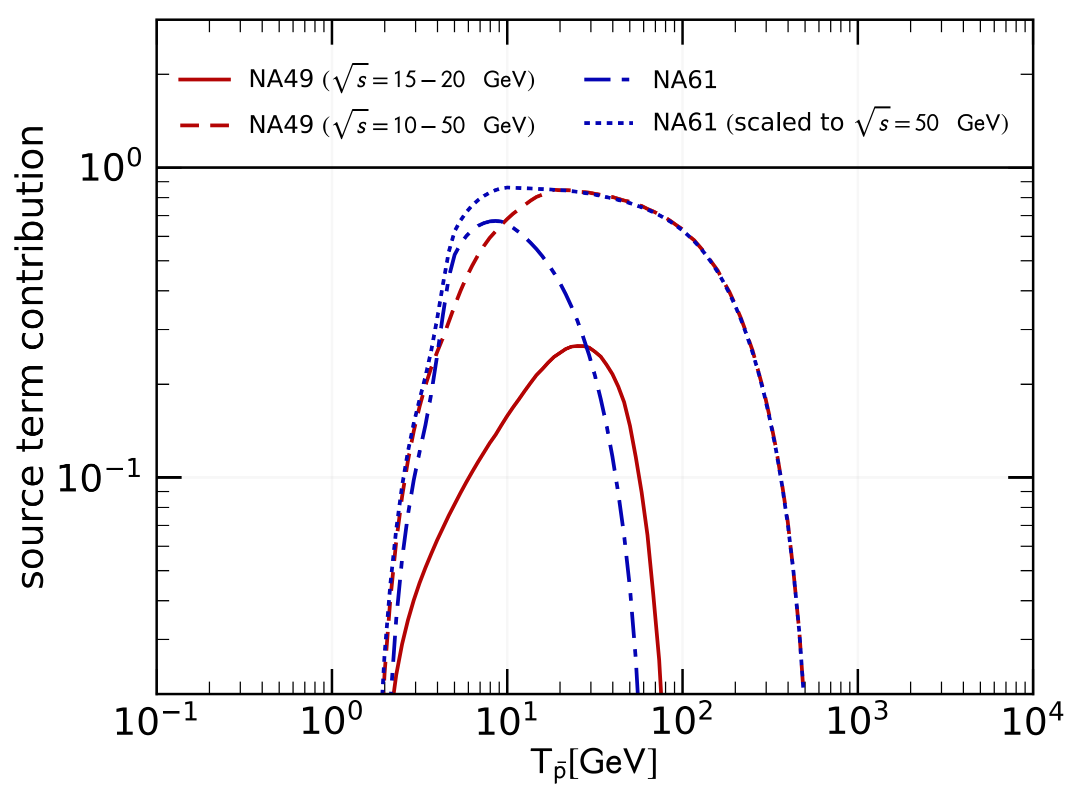
pHe —> pbar + X

LHCb (Graziani et al. Moriond 2017)

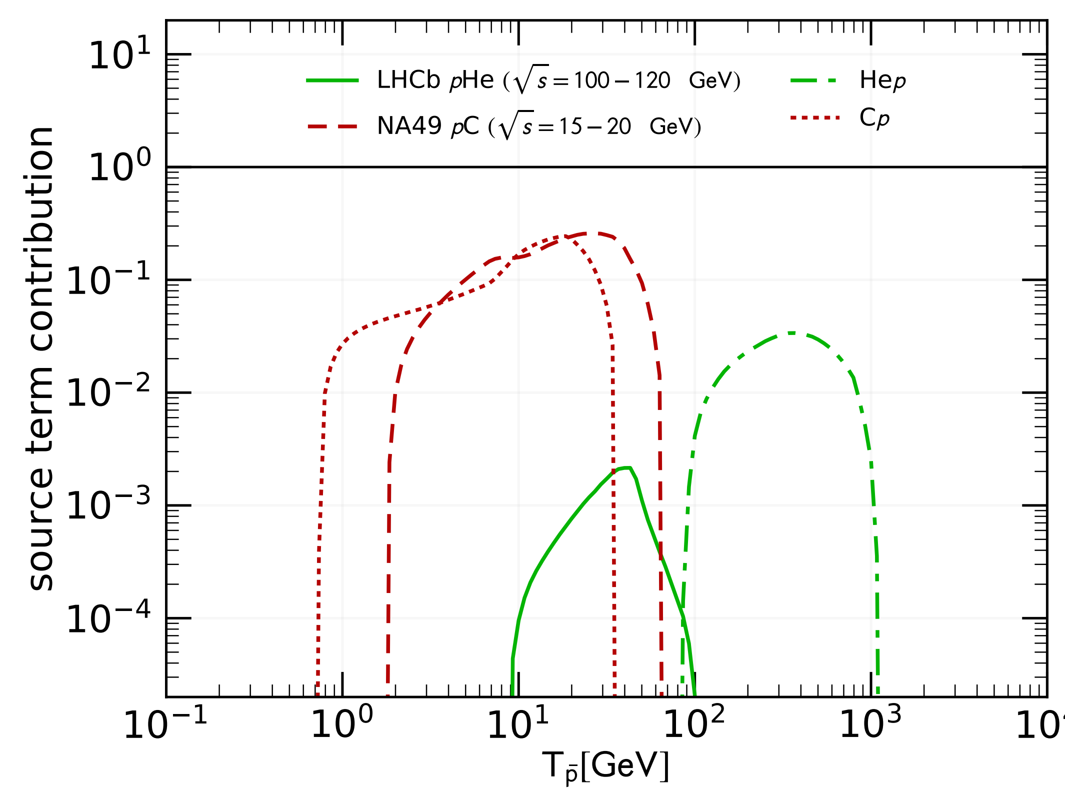
$\sqrt{s} = 110$ GeV

T_p = 6.5 TeV

Fraction of the pp source term covered by the kinematical parameters space



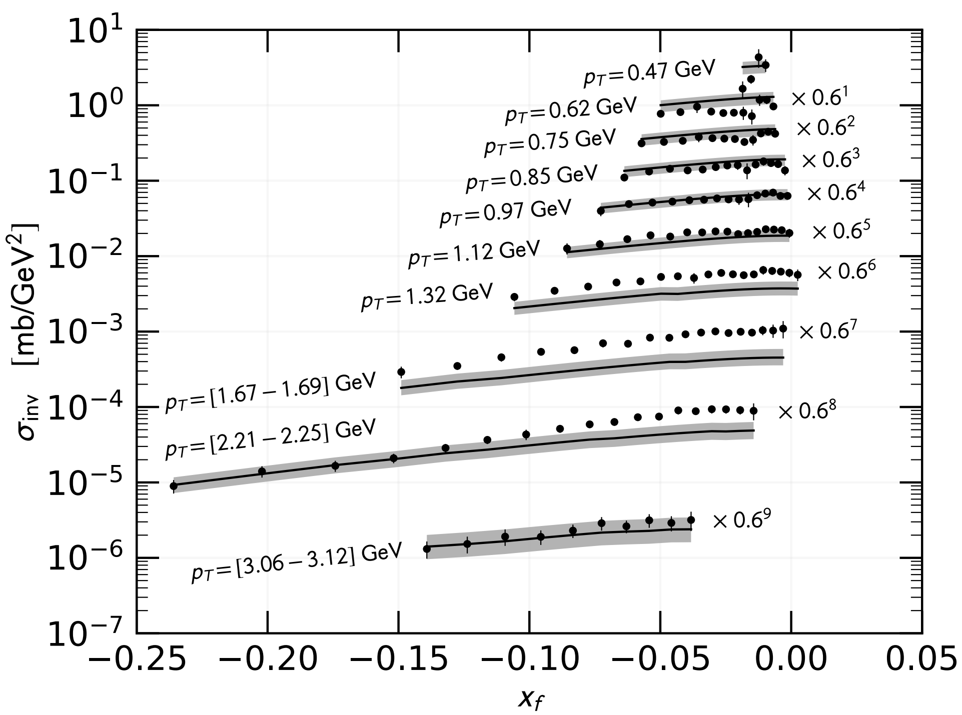
Fraction of the p-nucelus source term covered by the kinematical parameters space

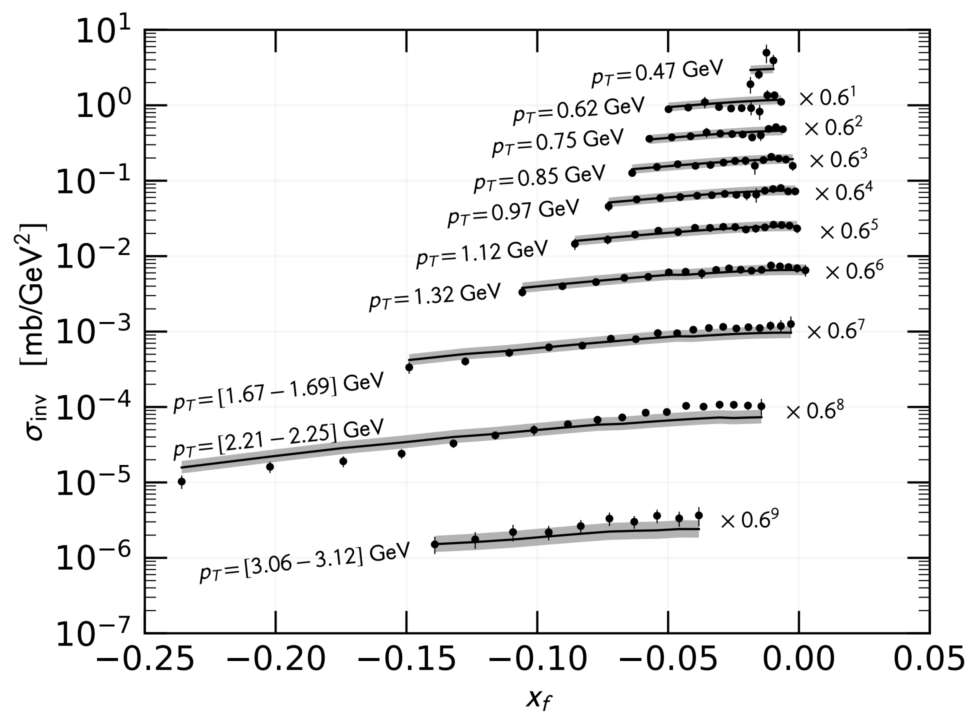


New high energy data analysis

Korsmeier, FD, Di Mauro, 1802.03030, PRD in press

1. Fit to NA61 pp —> pbar + X data
2. Calibration of pA XS on NA49 pC —> pbar + X data
3. Inclusion of LHC pHe —> pbar + X data

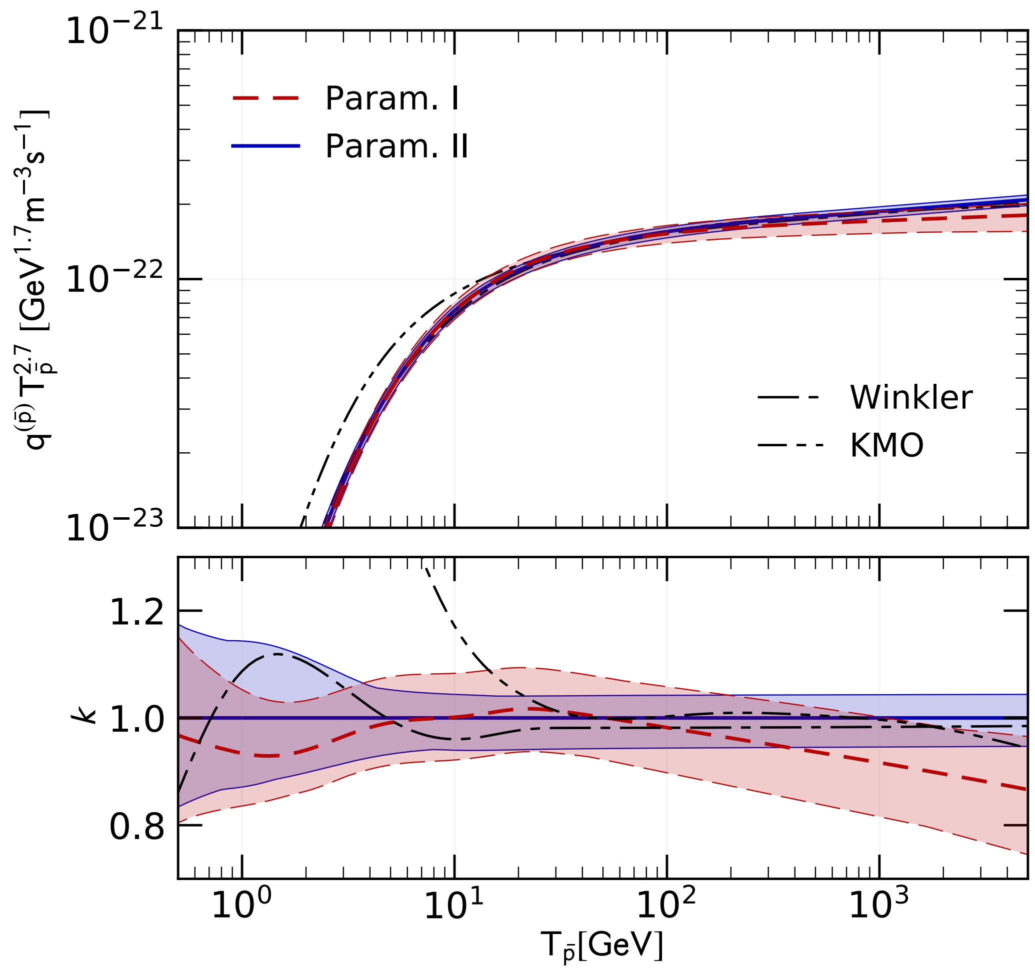


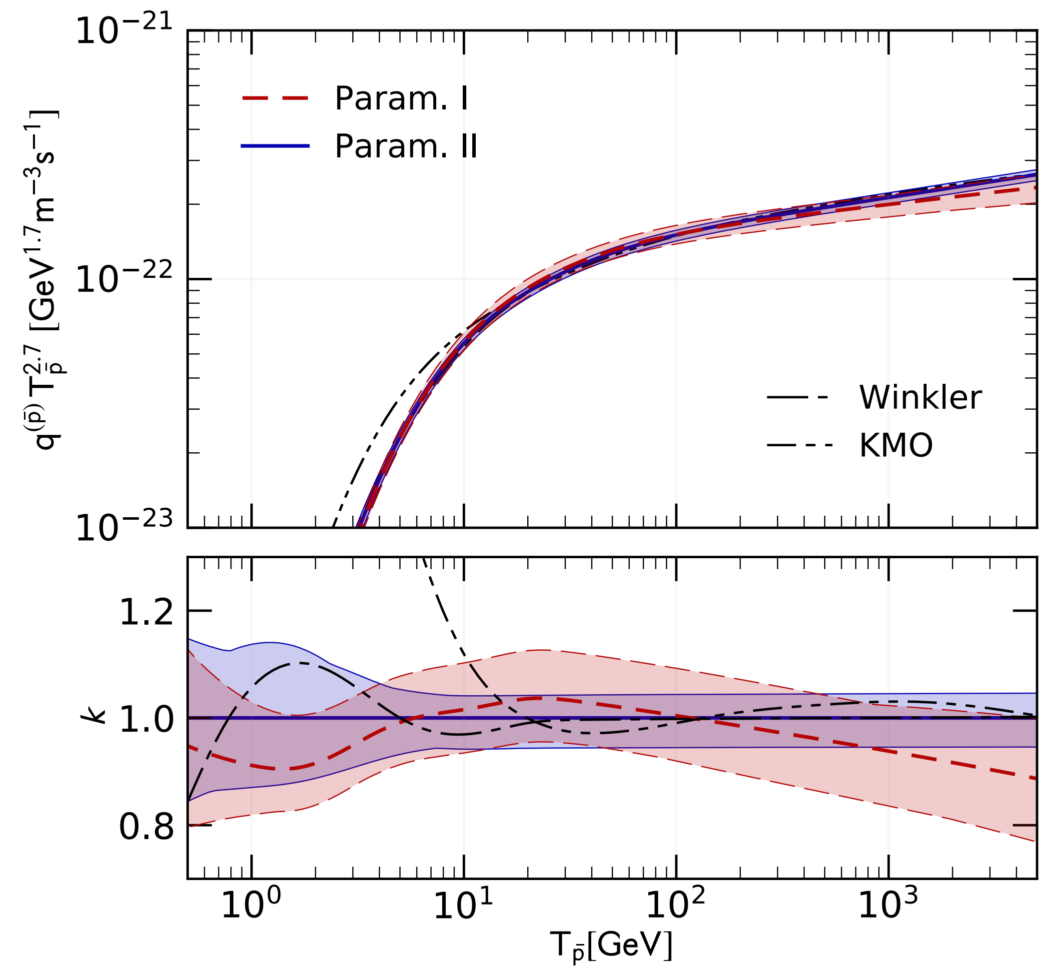


LHCb data agree better with one of the two pp parameterizations.
They select the high energy behavior of the Lorentz invariant cross section

The antiproton source spectrum

Korsmeier, FD, Di Mauro, 1802.03030, PRD in press





Param II is preferred by the fits.

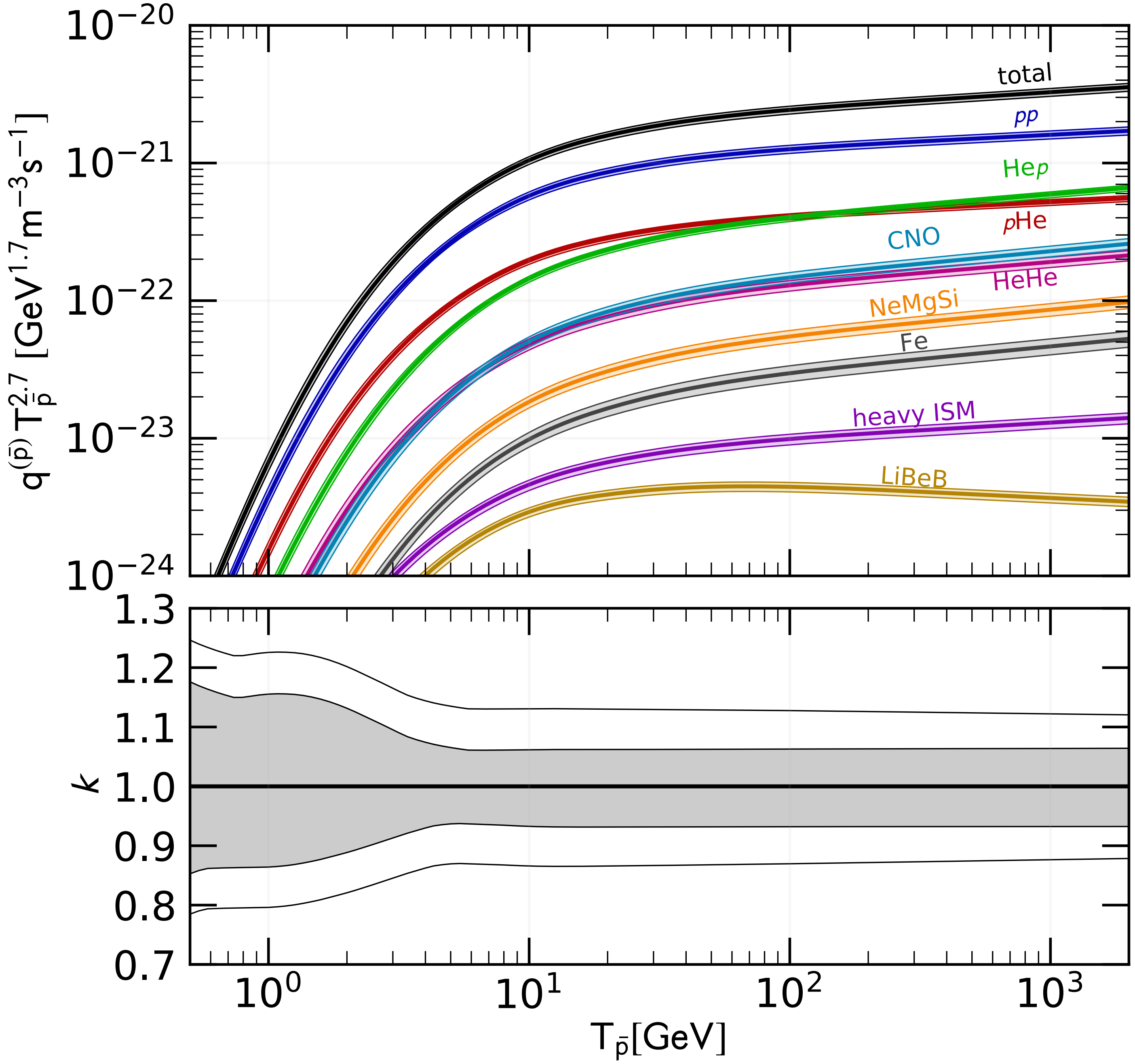
The effect of LHCb data is to select a h.e. trend of the pbar source term.

A harder trend is preferred.

Uncertainties still range about 10-15%, and increase at low energies.

Effects on the total pbar production

Korsmeier, FD, Di Mauro, 1802.03030, PRD in press



with uncertainties in the hyperon correction and isospin violation

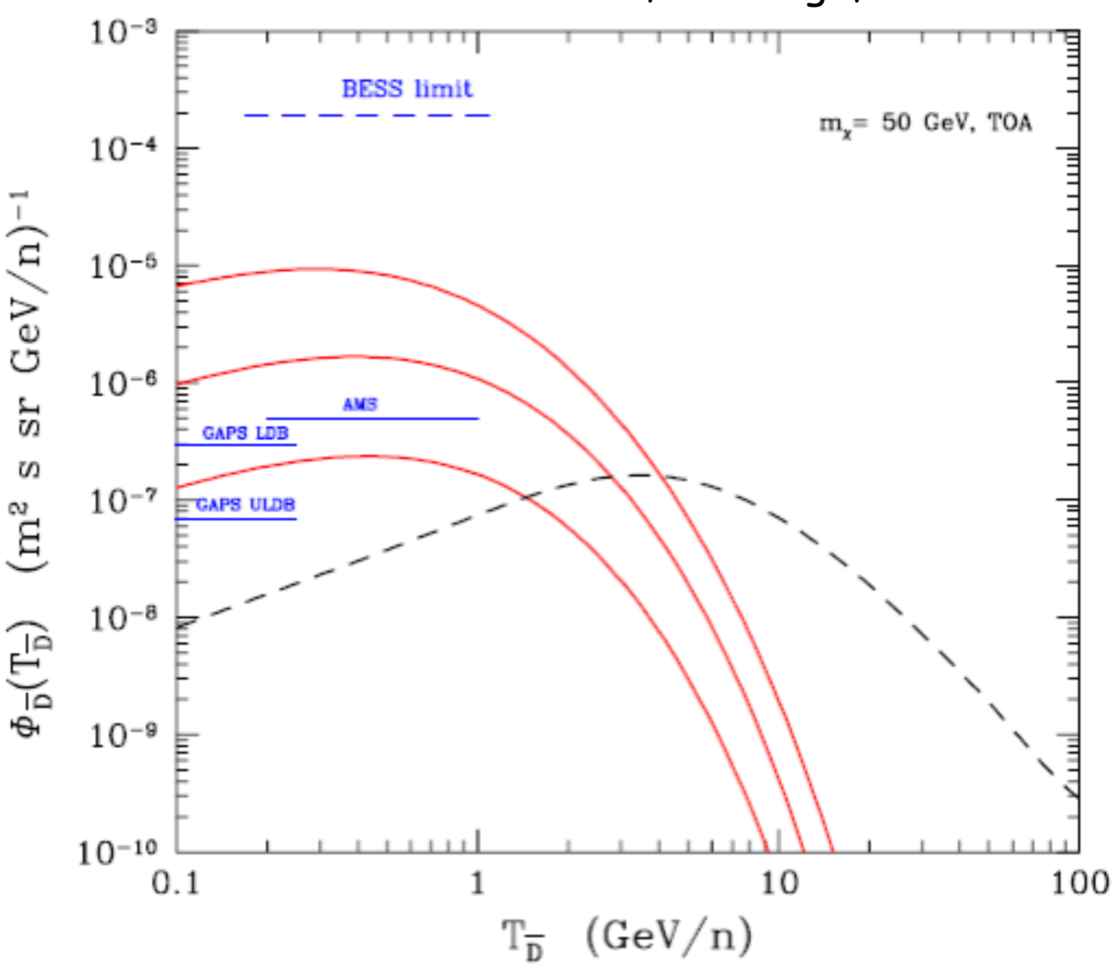
The antiproton source term - is affected by uncertainties of +- 10% from cross sections. Higher uncertainties at very low energies

COSMIC ANTIDEUTERONS

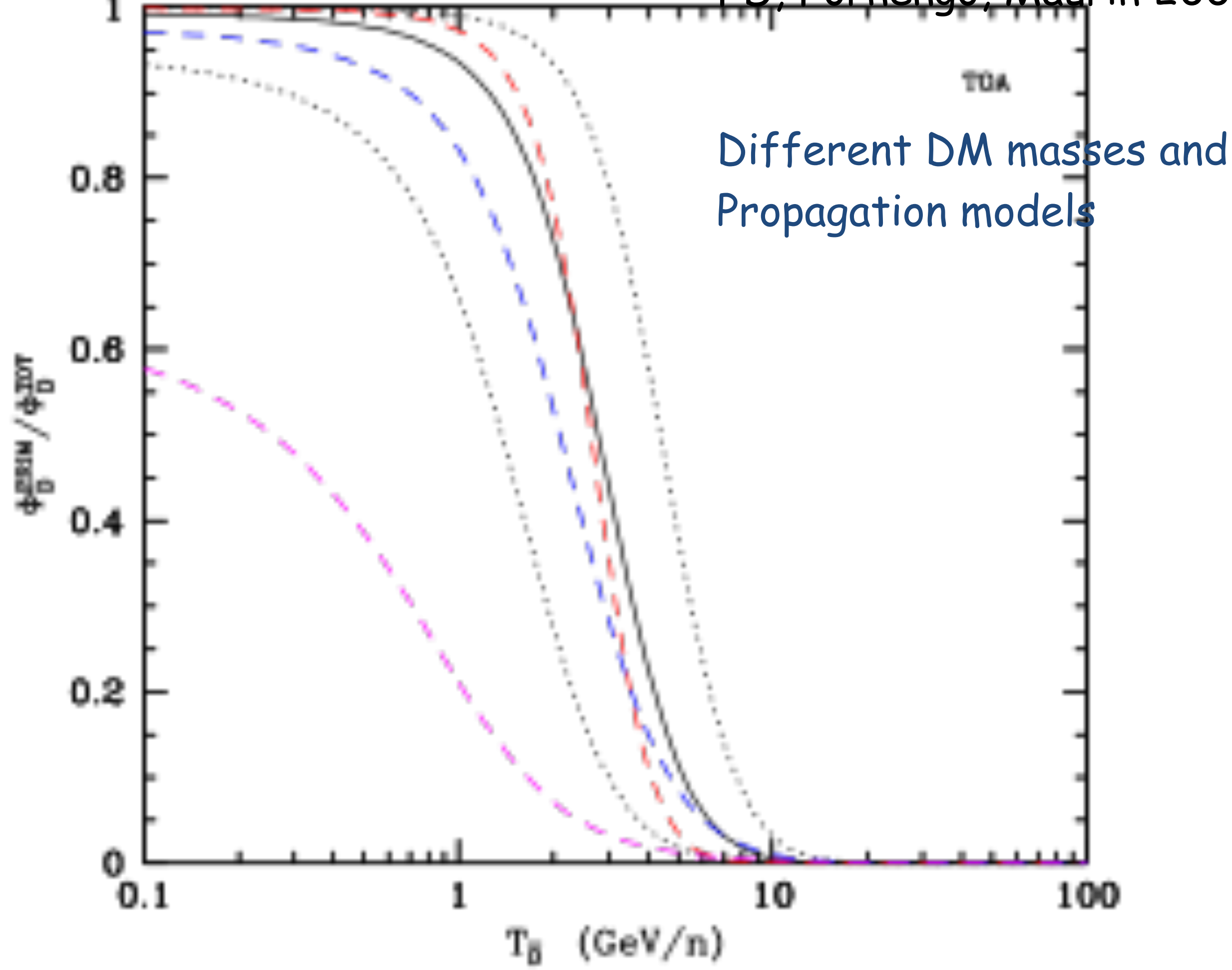
FD, Fornengo, Salati 2000;IFD, Fornengo, Maurin PRD 2008; 2008; Kadastik, Raidal, Strumia PLB 2010; Ibarra, Wild JCAP 2013; Fornengo, Maccione, Vittino JCAP 2013; Aramaki et al, Phys. Rep. 2015

In order for fusion to take place, the antiproton and antineutron must have low kinetic energy

FD, Fornengo, Salati 2000



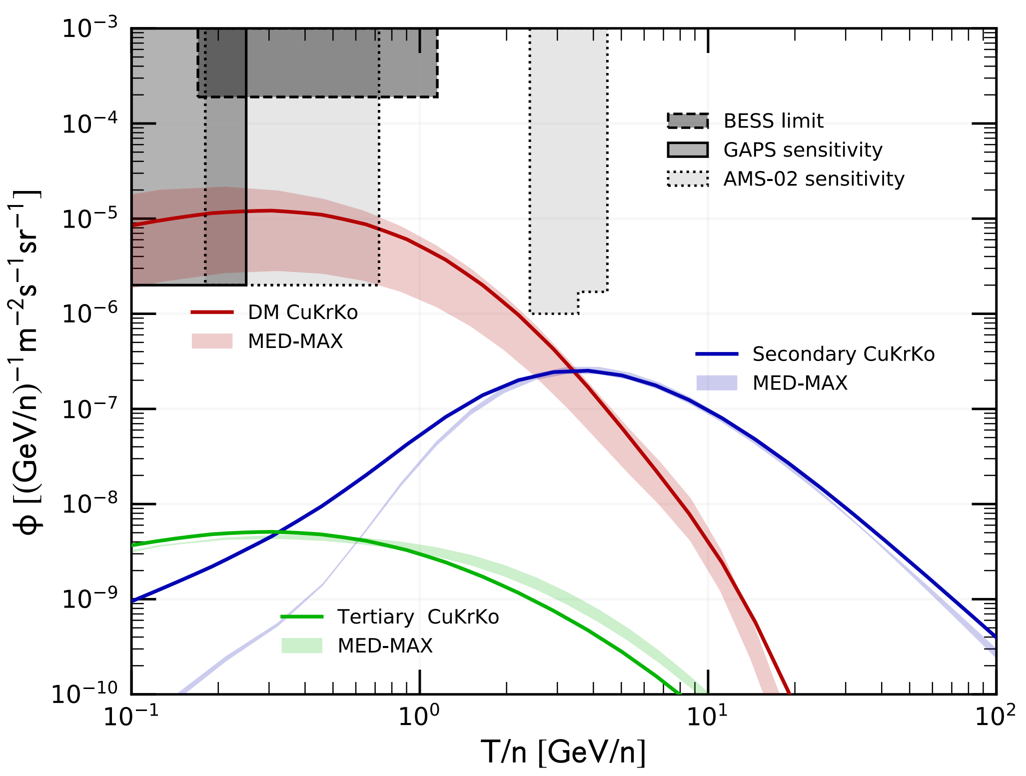
FD, Fornengo, Maurin 2008



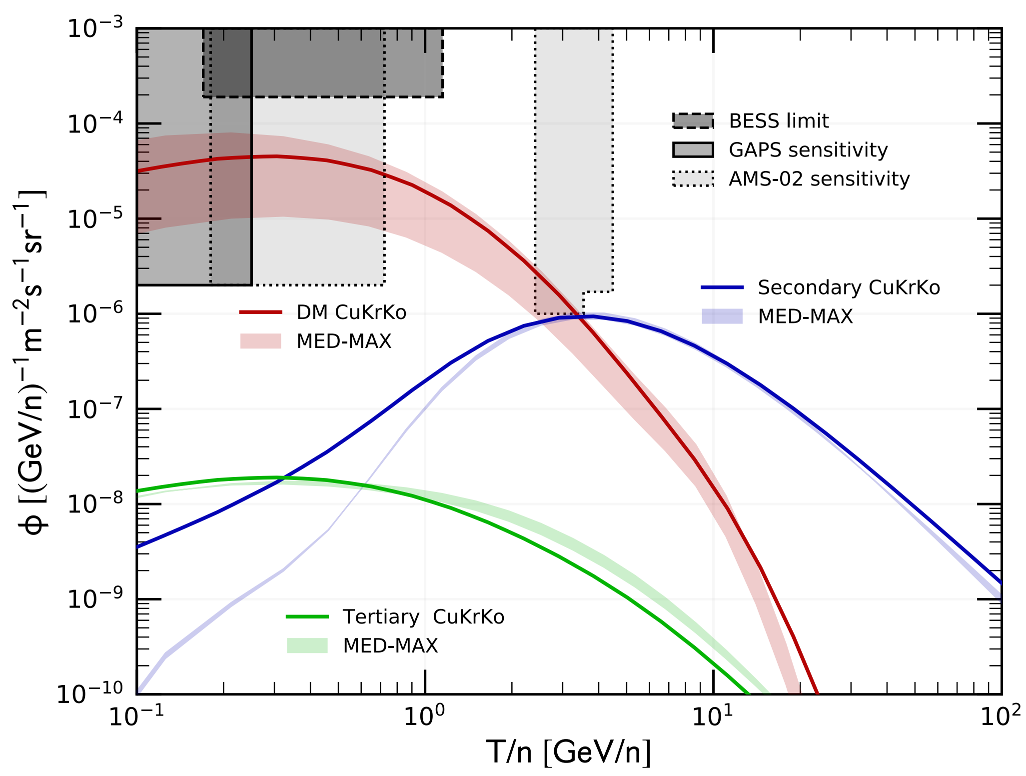
Possible **antideuteron** verification of Dark Matter hint in antiprotons

FD, Fornengo, Korsmeier, PRD 2018

P_{coal} = 124 (62) MeV



P_{coal} = 248 (124) MeV

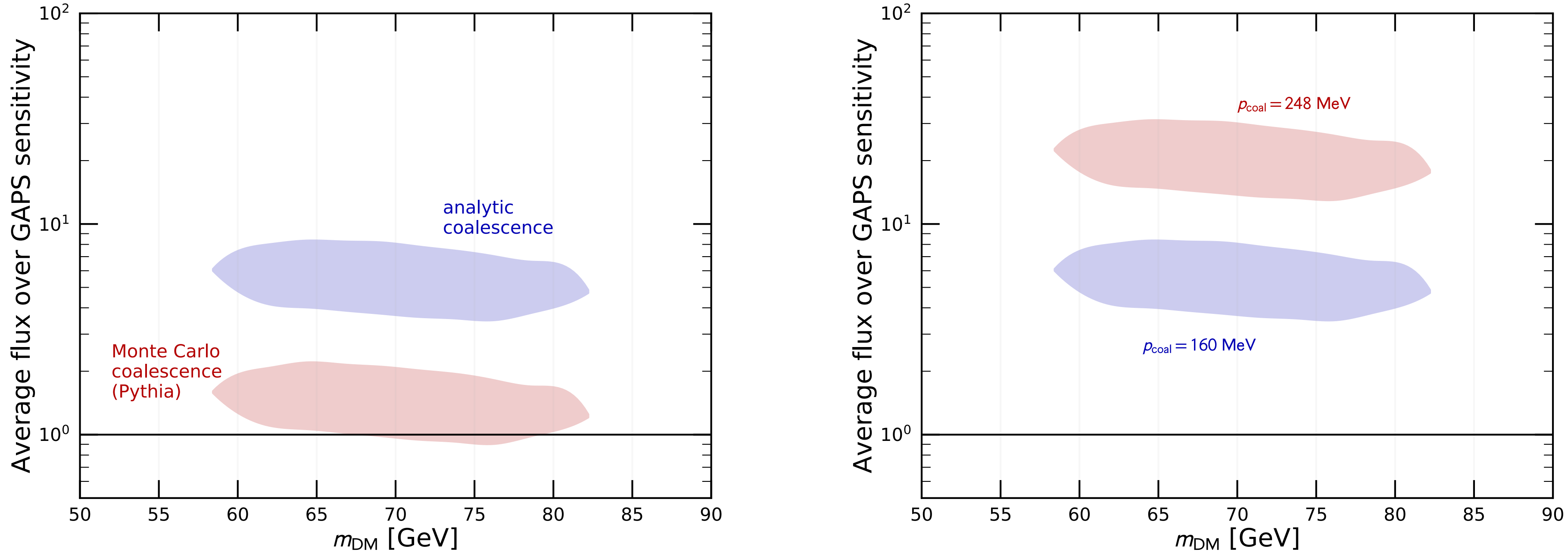


DM antiprotons possibly hidden in AMS data are potentially testable by AMS and GAPS

Uncertainties on the detection predictions

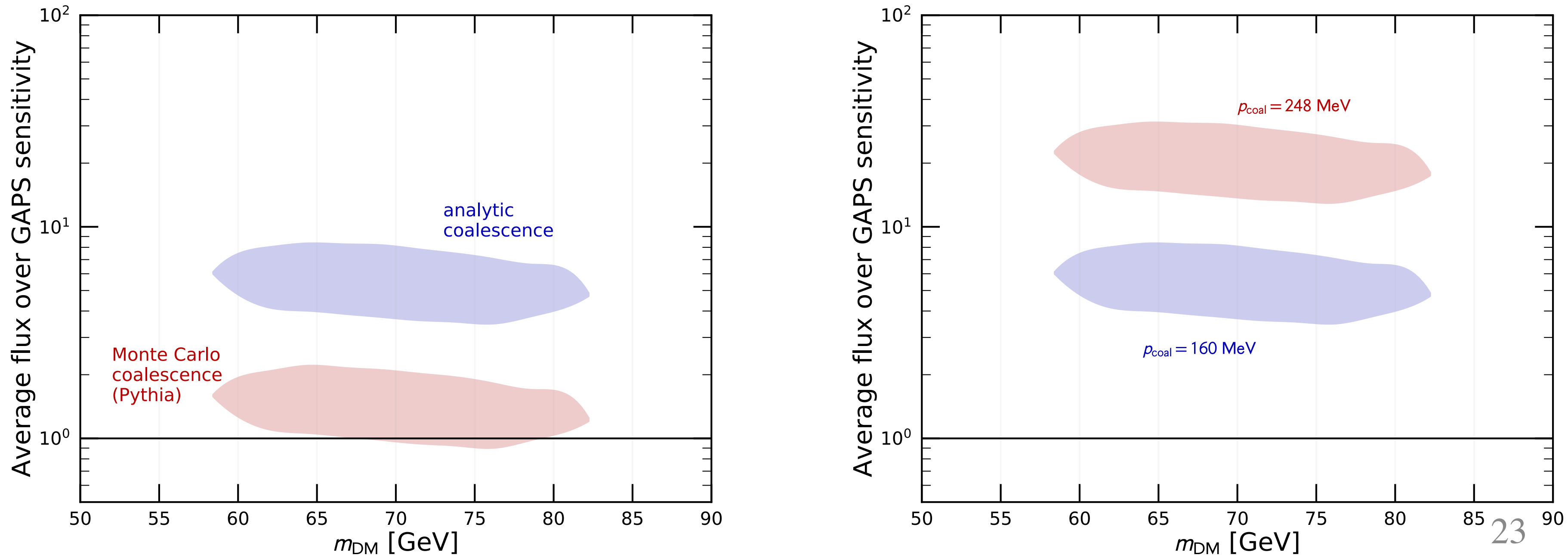
FD, Fornengo, Korsmeier, 1711.08465 subm. PRD

Coalescence Model:
a factor > 10
(does not affect pbar flux



(a) Coalescence model (b) Coalescence momentum

Propagation models:
a factor > 10
(affects pbar flux)



Conclusions

- The AMS data induce a remarkable progress in understanding our Galaxy. Its data reach unprecedented precision (few %).

- The production cross sections for secondary nuclei are often the main source of theoretical uncertainty

- High energy physics is addressing new data at the service of high precision cosmic ray data

- Improvements in calculations of the nuclear cross sections will certainly remain data driven in the near future

Experiments and beam time

In an experiment one single projectile can give several fragments measured

$$\left(\frac{\Delta\psi^{\rm sec}}{\psi^{\rm sec}}\right)_{ab} = \frac{1}{\sqrt{N}}\,\mathcal{C}_{ab}$$

For example, to achieve flux uncertainty of <0.5 %
C+H and O+H require N=5.2 10^4 and 3.9 10^ 4 interactions

Genolini+2018

General idea for matching the accuracy

- Determine the contribution to the antiproton source spectrum from the whole parameter space

$$\{\sqrt{s}, x_{\mathrm{R}}, p_{\mathrm{T}}\} \qquad \{T, T_{\bar{p}}, \cos(\theta)\}$$

- Assign the maximal uncertainty that the cross section should have in orc to address the following requirements:

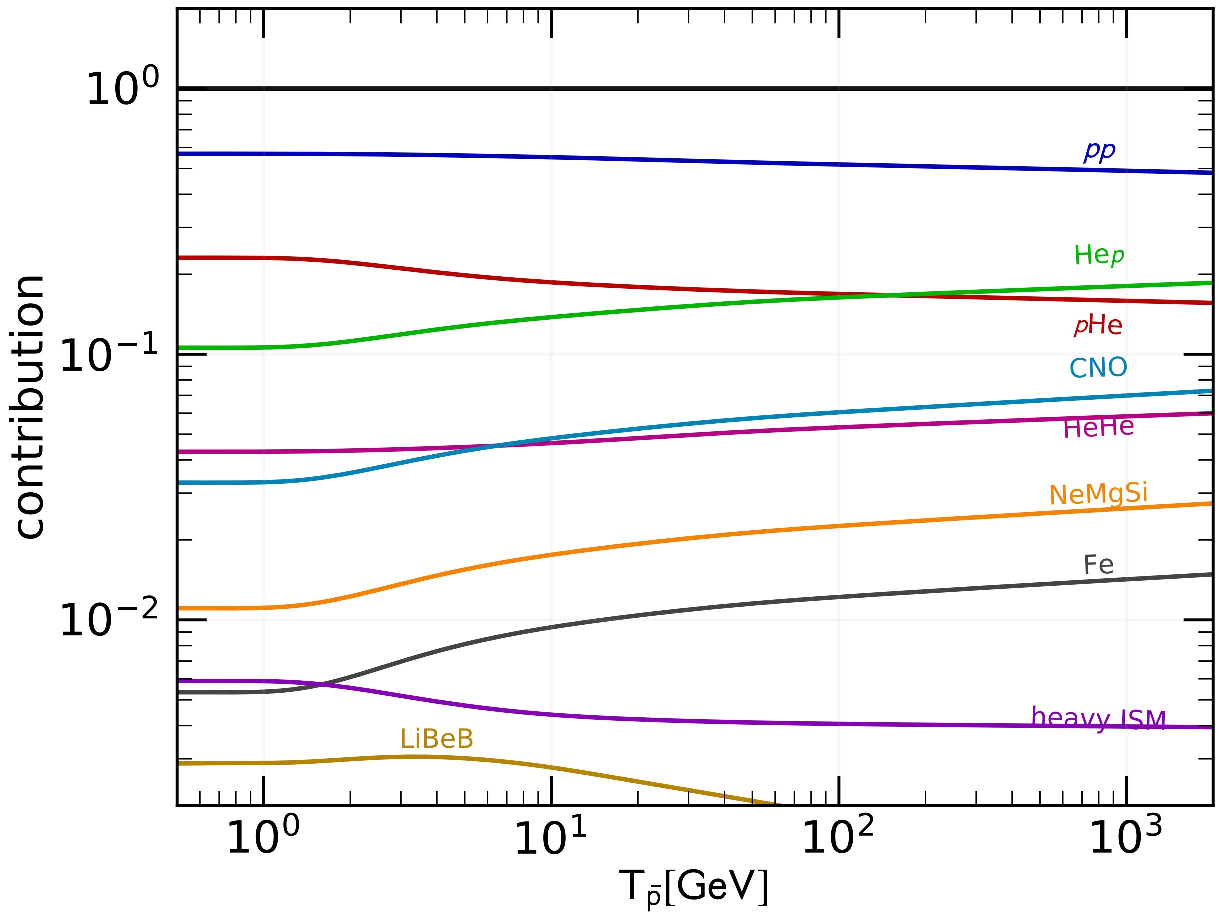
1. The total uncertainty shall match the AMS-02 accuracy
2. The parameter space with larger contribution to the source spectrum, should have the smaller uncertainties in the cross section measurements

$$\frac{d\sigma}{dT_{\bar{p}}}(T, T_{\bar{p}}) = 2\pi p_{\bar{p}} \int_{-1}^{1} d\cos(\theta)\ \sigma_{\mathrm{inv}}$$

$$= 2\pi p_{\bar{p}} \int_{-\infty}^{\infty} d\eta\ \frac{1}{\cosh^2(\eta)}\ \sigma_{\mathrm{inv}} \qquad \eta = -\ln\left(\tan\left(\frac{\theta}{2}\right)\right)$$

Nuclei contributions to antiprotons

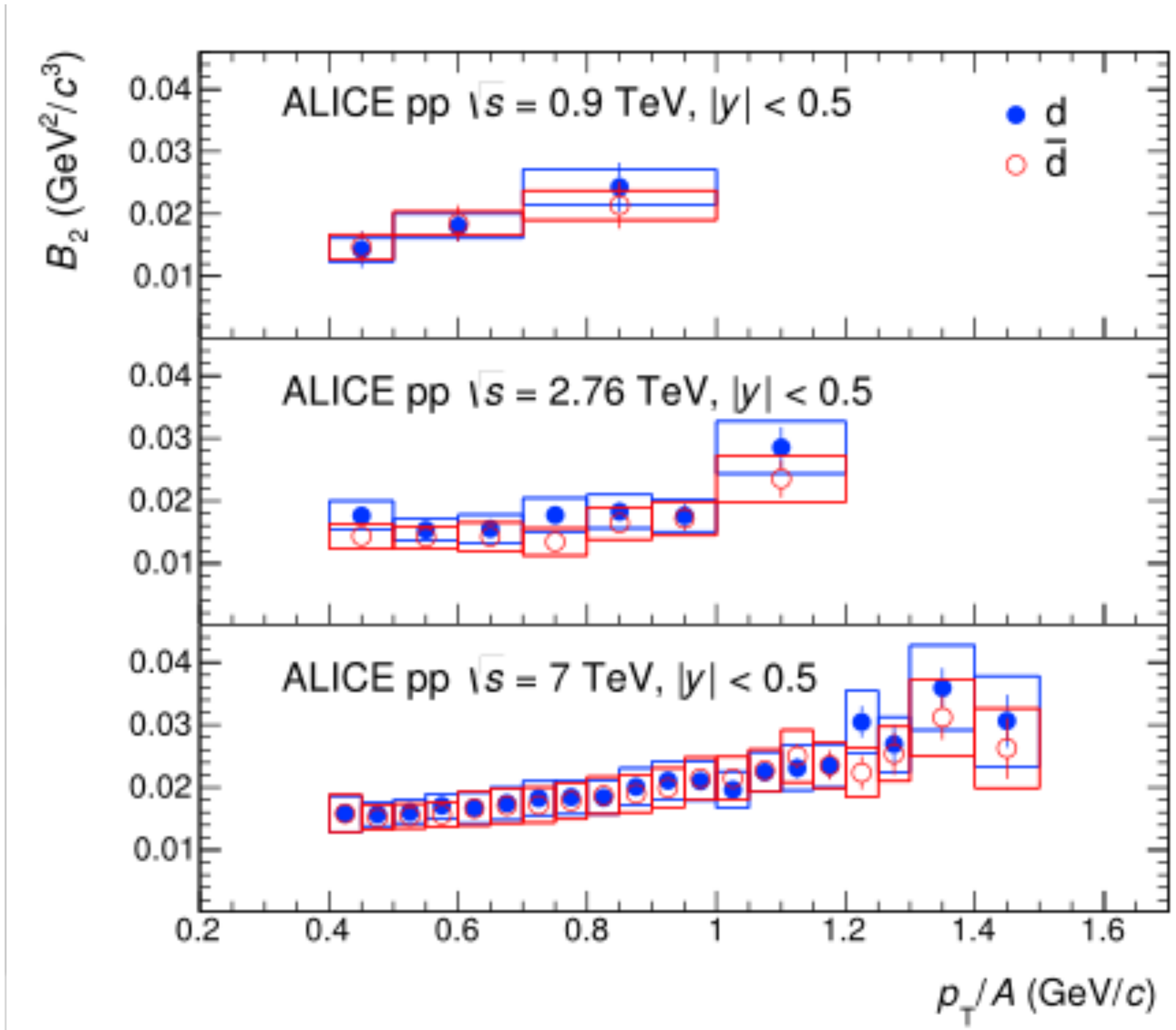
Relevant contribution of the different channels to the total production of antiprotons in the Galaxy (CR-ISM)

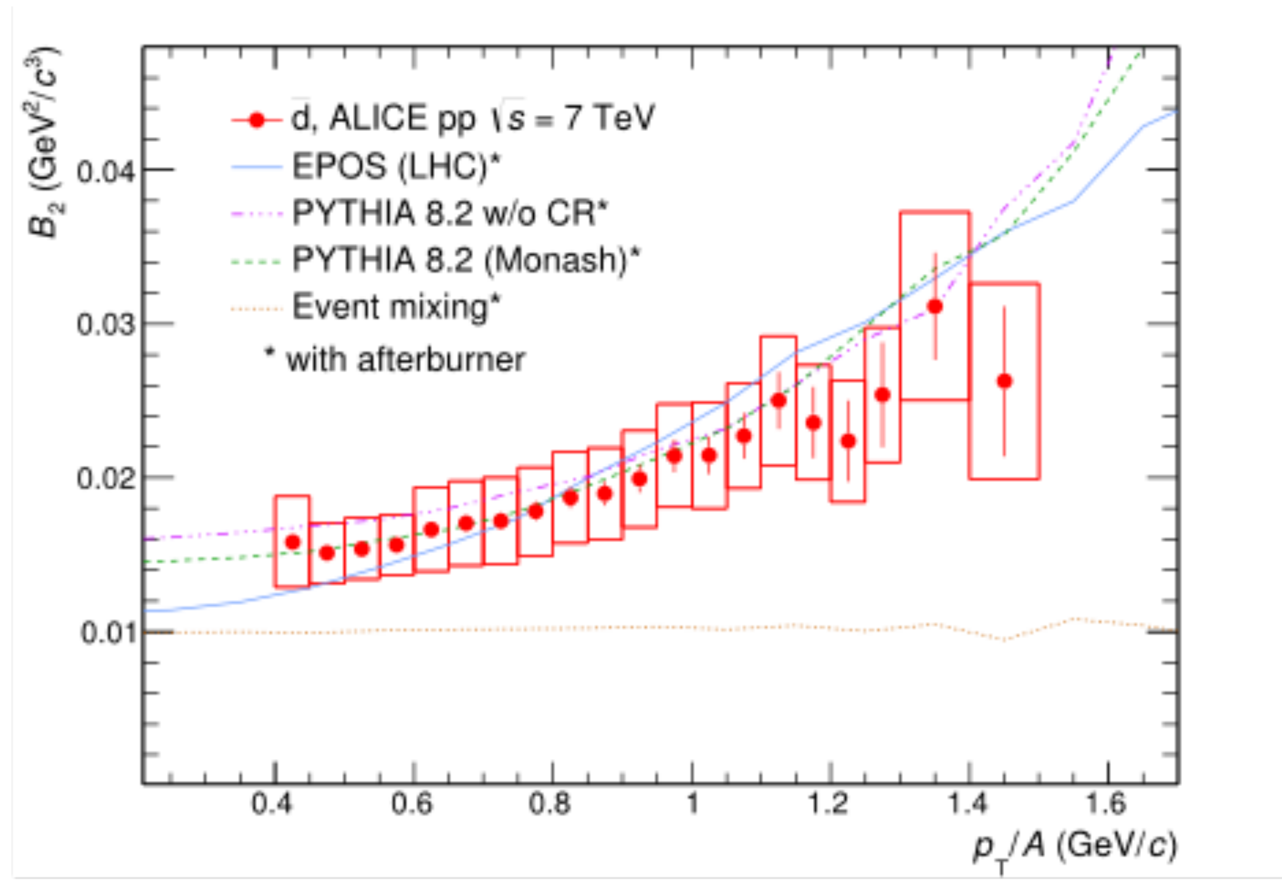


The channels involving He - both CR and ISM target - contribute 30-40% to the antiproton source in the Galaxy

Contribution from ALICE

Alice Coll. 1709.08522, sub. PRC





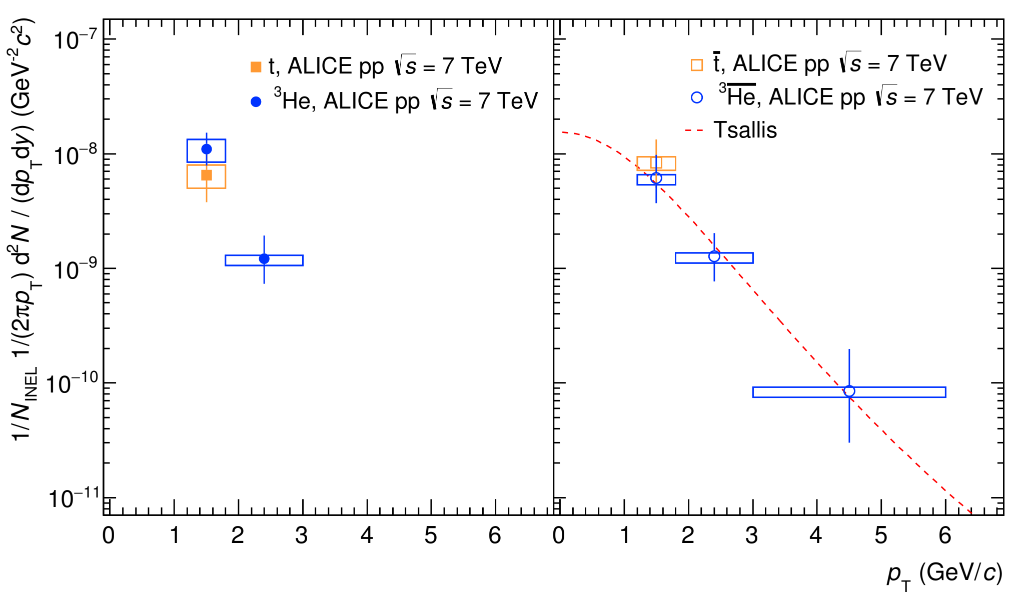
Coalescence parameter measured also at LHC energies

Anithelium $^3\overline{\text{He}}$ production

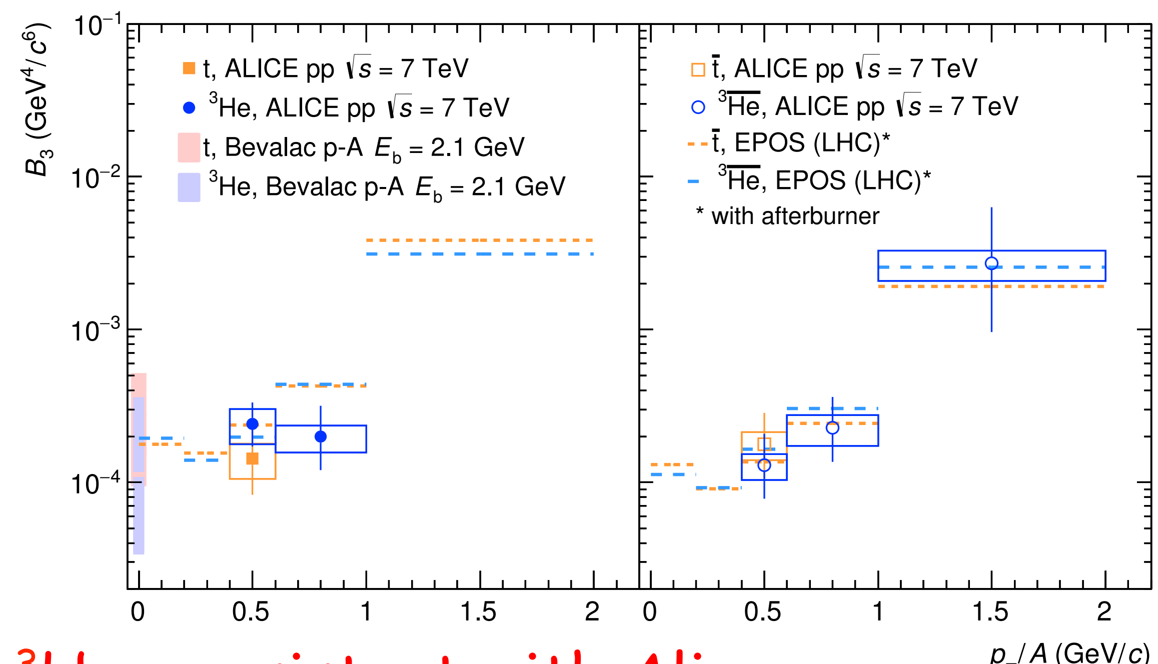
First data at LHC/Alice, Alice Coll. 1709.08522, subm. PRC

Data at $\sqrt{s} = 0.9,\ 2.76 \text{ and } 7 \text{ TeV}$

Invariant yields



Coalescence parameter



Previous data from Bevalac on ^{3}He, consistent with Alice.
Measured a p_T dependence, but non very relevant in the Galaxy (see inv. yield)
P_{coal} greater (122 MeV vs 98 MeV) than in previous estimations → $(p_{coal})^6$