Antiproton cosmic rays: Has dark matter been detected?

Pierre Salati – LAPTh & Université Savoie Mont Blanc

Outline

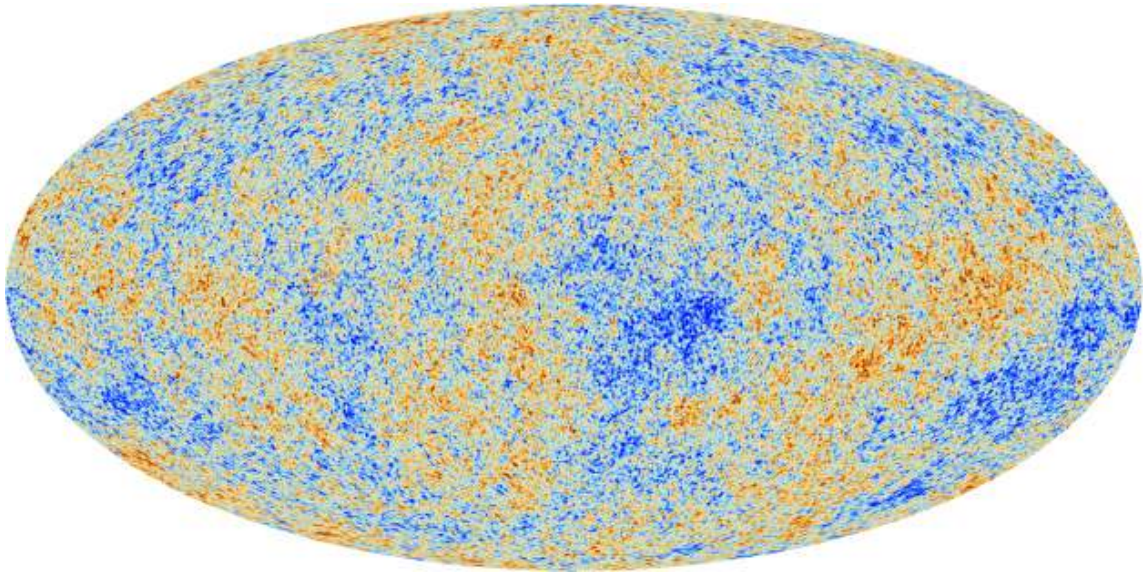
1) Cosmic rays as an indirect probe for dark matter

2) A new estimate of the antiproton background

3) Limits on DM properties – a status report

June 3, 2015: The Spacetime Odyssey Continues – Nordita @ Piperska Muren, Stockholm

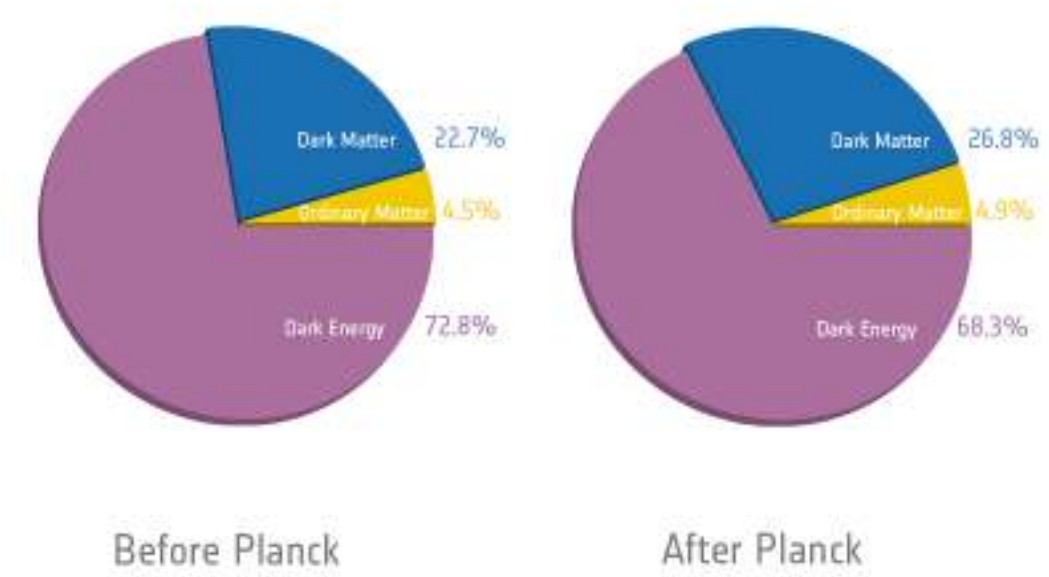
1) Cosmic rays as an indirect probe for dark matter



- Dark matter is also detected at cosmological scales.
- This component contributes substantially to the mass of the universe.
- Last but not least, its nature is unknown.

$$\Omega_{\rm DM} h^2 = 0.1196 \pm 0.0031$$

Anisotropies in the cosmic micro-wave background (CMB)



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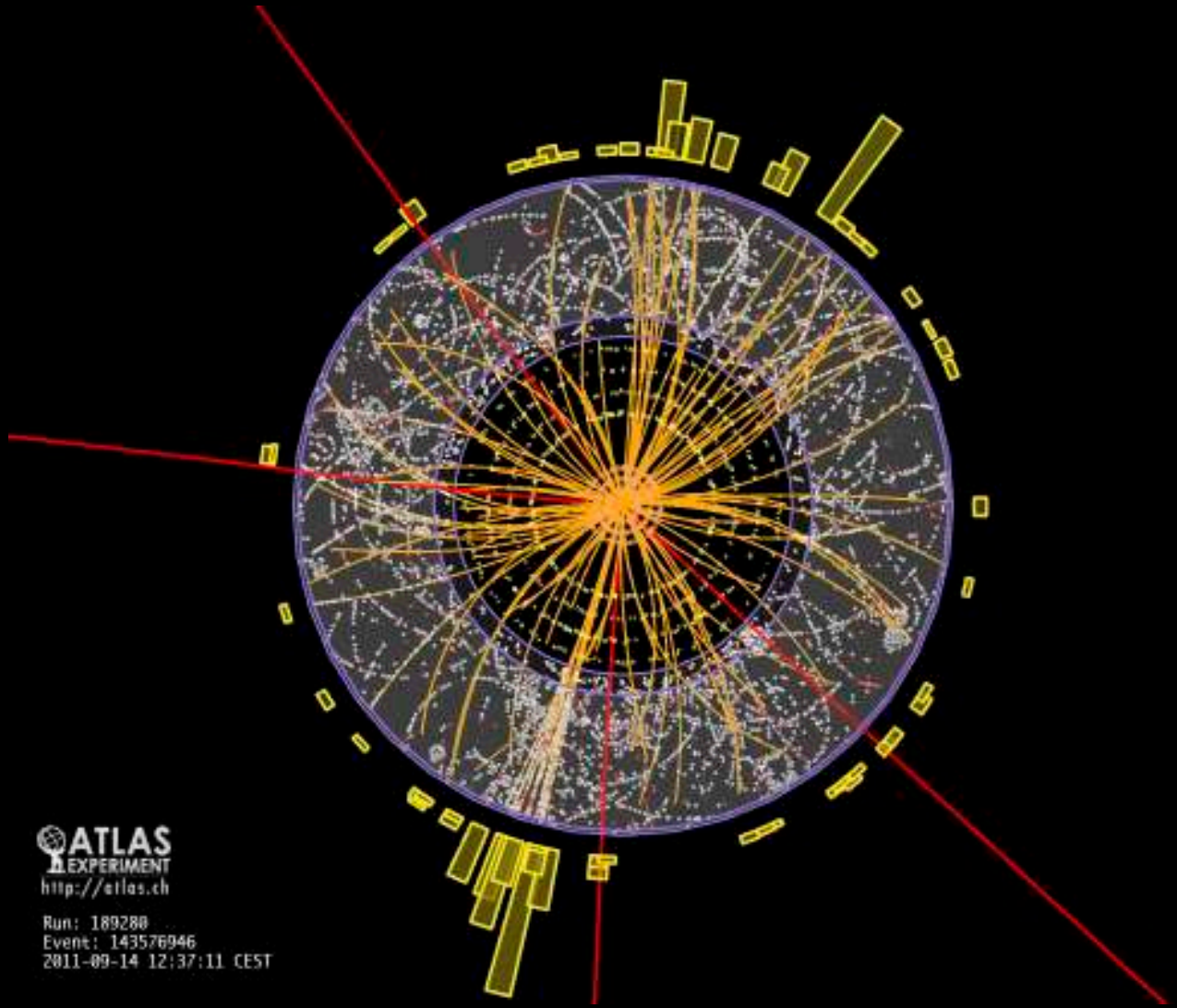
A plethora of DM candidates have been proposed

$\Downarrow$

Weakly interacting massive particles – WIMPs

- predicted by most BSM extensions
- stable by conservation of a quantum number
- 10 to 10^4 times more massive than the proton
- no electric charge – neutral species
- weak interactions like neutrinos
- produced during the Big-Bang
- relic abundance compatible with Planck

A plethora of DM candidates have been proposed



A pletho proposed

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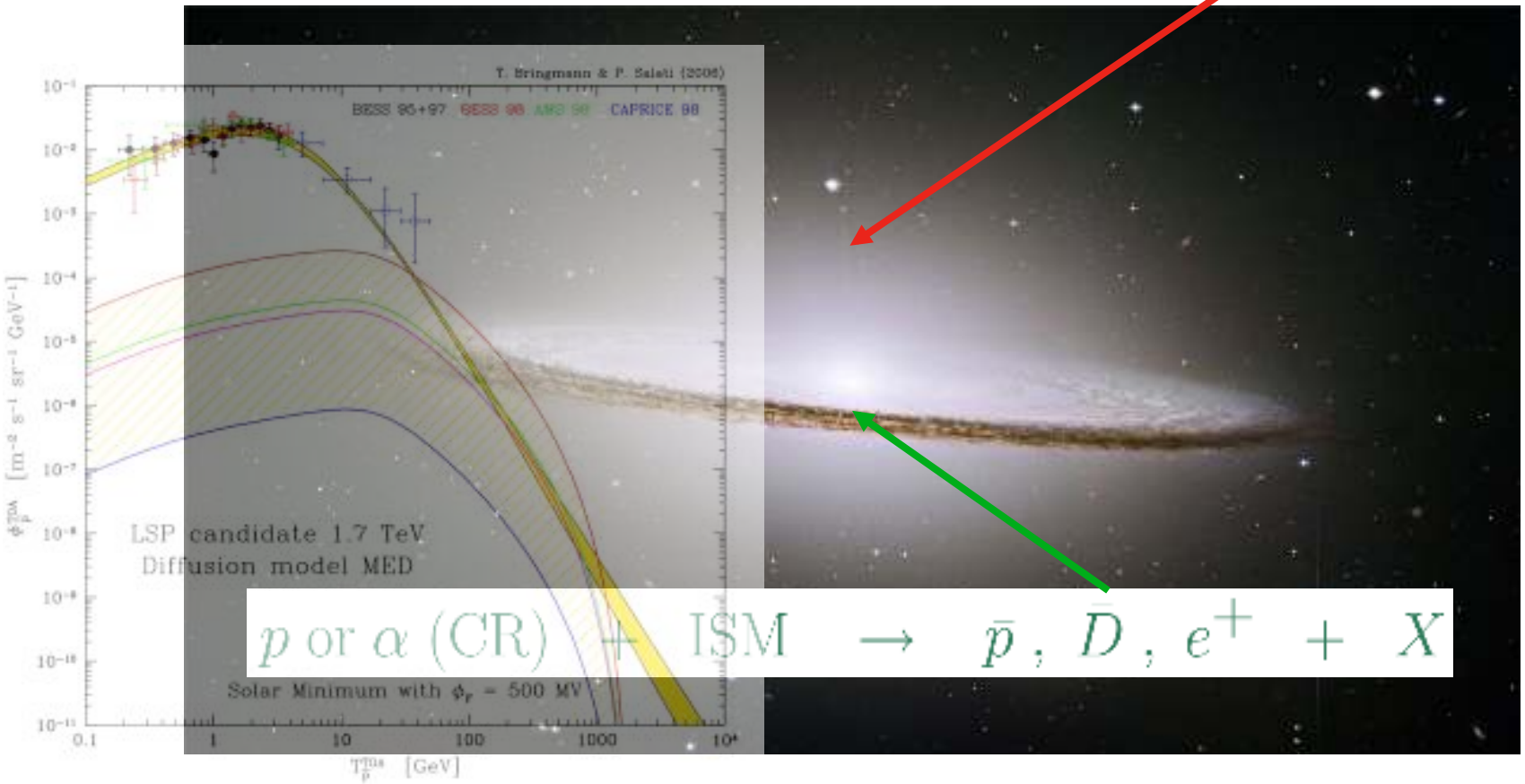
1) Cosmic rays as an indirect probe for dark matter

• Indirect Detection – WIMPs continuously annihilate and produce SM particles such as gamma-rays, neutrinos, but also rare antimatter species like positrons, antiprotons and even antideuterons.

$$\chi + \chi \to q\bar{q}, W^+W^-, \ldots \to \boxed{\gamma,\ \bar{p},\ \bar{D},\ e^+,\ \nu's}$$



AMS Collaboration
CERN, Geneva, 15 April 2015

"AMS Days at CERN" and Latest Results from the AMS Experiment on the International Space Station

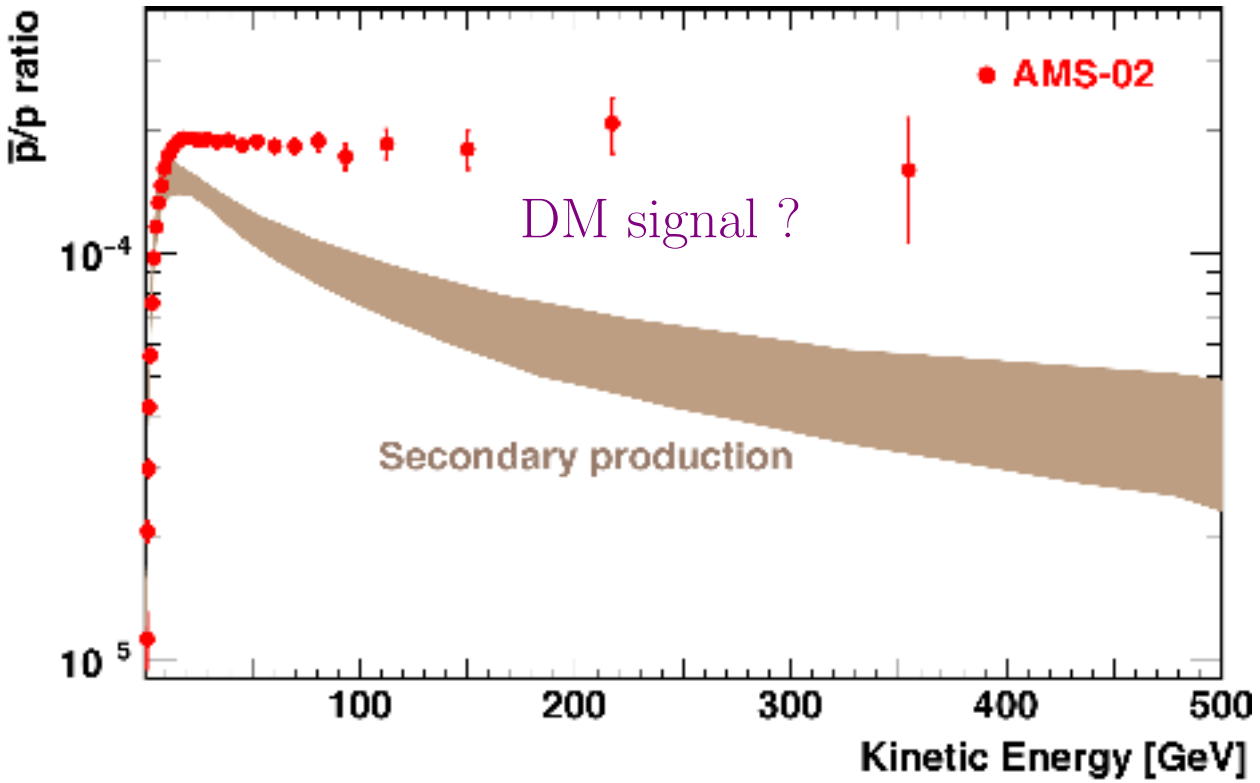


Figure 1. Antiproton to proton ratio measured by AMS. As seen, the measured ratio cannot be explained by existing models of secondary production.

Has an antiproton excess been discovered ?

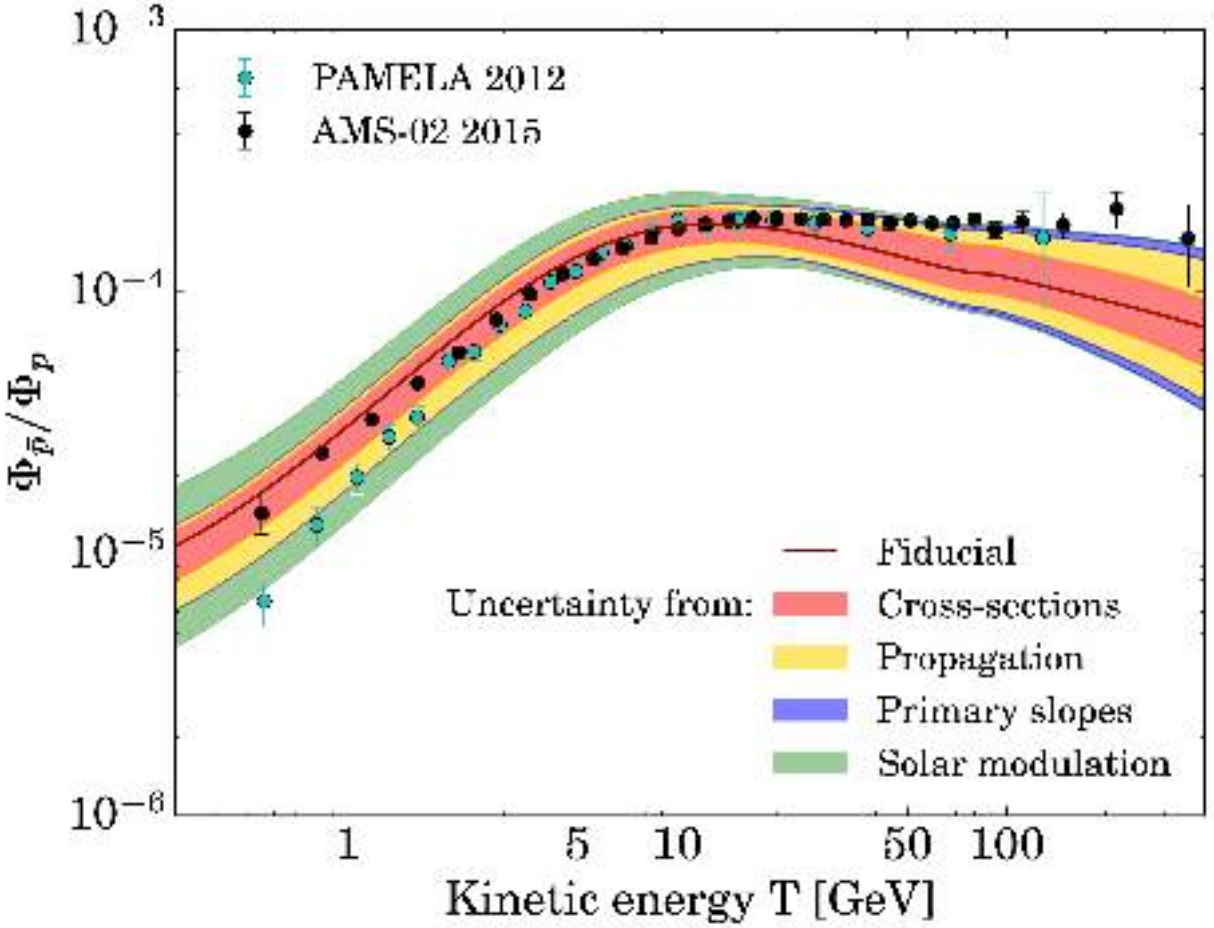
AMS Collaboration

CERN, Geneva, 15 April 2015

"AMS Days at CERN" and Latest Results from the AMS Experiment on the International Space Station

Backgrounds to a putative DM signal need to understood

Production cross sections – solar modulation – cosmic ray propagation



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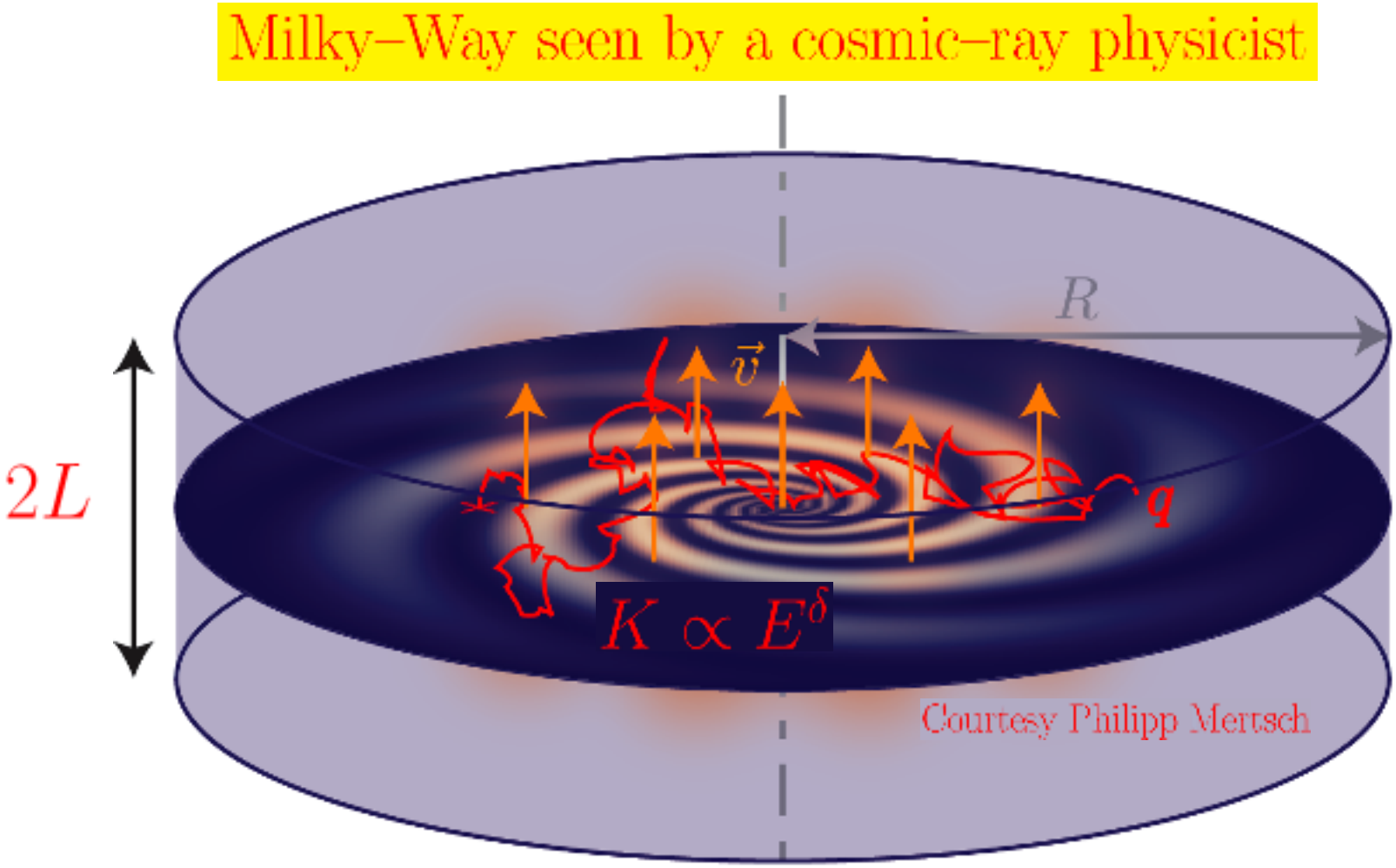

Cosmic rays propagate inside a diffusive halo

D. Maurin, R. Taillet, F. Donato, P. Salati, A. Barrau and G. Boudoul, *Galactic cosmic ray nuclei as a tool for astroparticle physics*, [astro-ph/0212111].

Antiprotons Production in the Galaxy

• **Secondary** antiprotons are produced through the spallations of cosmic–ray protons and He nuclei on the interstellar material.

$$p\,(\mathrm{CR}) \;+\; H\,(\mathrm{ISM}) \;\rightarrow\; \bar{p} \;+\; X$$

$$\Downarrow$$

$$q_{\bar{\mathrm{p}}}^{\mathrm{sec}}(r, E_{\bar{\mathrm{p}}}) \;=\; 4\pi \int_{E_{\mathrm{p}}^{0}}^{+\infty} \frac{d\sigma_{\mathrm{pH}\rightarrow\bar{\mathrm{p}}}}{dE_{\bar{\mathrm{p}}}} \left\{E_{\mathrm{p}} \rightarrow E_{\bar{\mathrm{p}}}\right\} n_{\mathrm{H}}\, \Phi_{\mathrm{p}}(r, E_{\mathrm{p}})\, dE_{\mathrm{p}}$$

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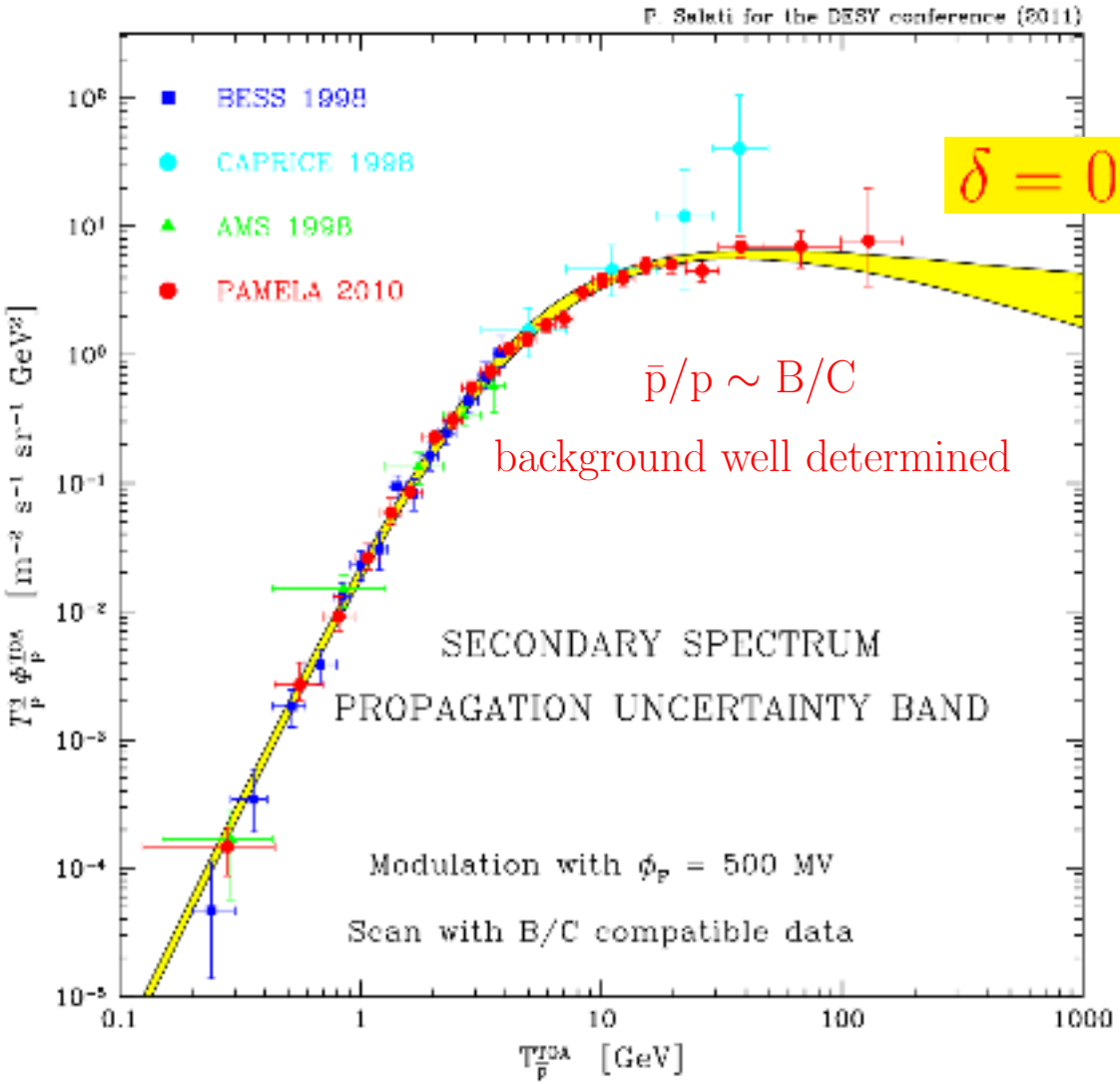
Reduced CR uncertainties for the antiproton background

best DM probe



$\delta = 0.46$ to 0.85

$\bar{p}/p \sim B/C$

background well determined

2008 background calculation

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New developments since 2008

– CR p and He fluxes measured with improved accuracy.

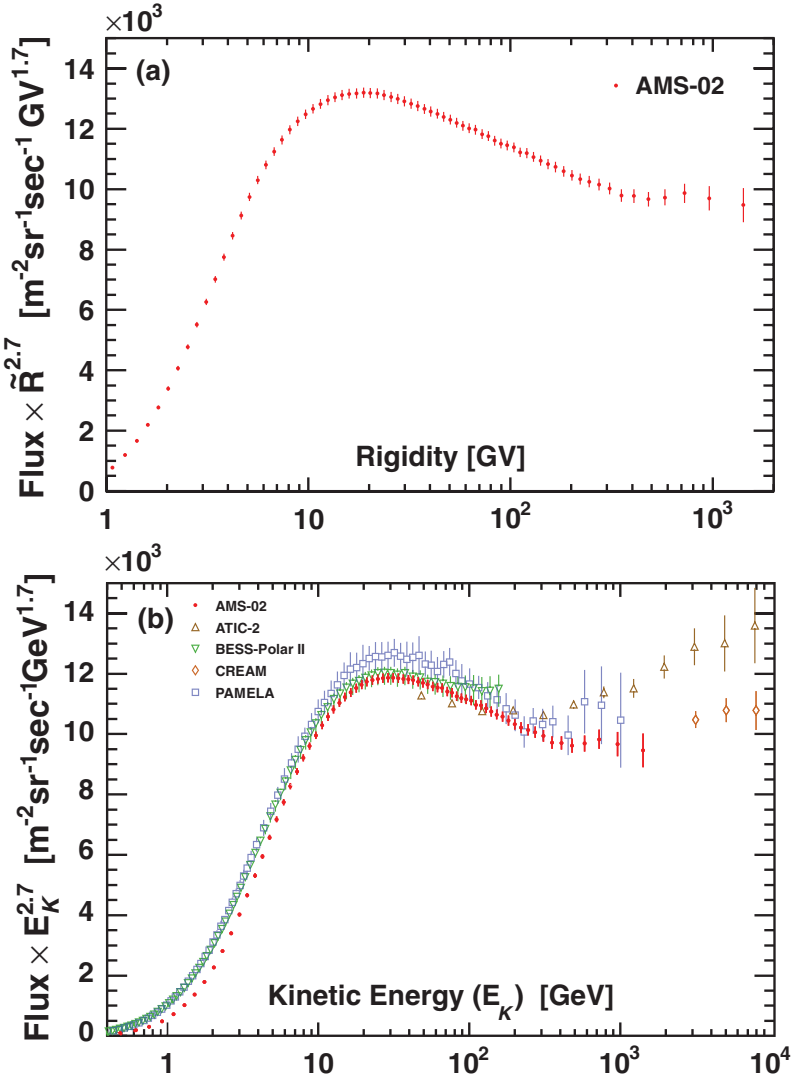
$$\Phi^{\mathrm{sec}}_{\bar{\mathrm{p}}}(E_{\bar{\mathrm{p}}}) \;\propto\; q^{\mathrm{sec}}_{\bar{\mathrm{p}}}(E_{\bar{\mathrm{p}}}) \;\propto\; \Phi_{\mathrm{p}}(E_{\mathrm{p}} \sim 10 \times E_{\bar{\mathrm{p}}})$$

$$\Downarrow$$

$$\bar{\mathrm{p}}/\mathrm{p}(E) \;\propto\; \Phi_{\mathrm{p}}(\sim 10 \times E)/\Phi_{\mathrm{p}}(E) \;\propto\; 10^{-\alpha}$$

$\bar{\mathrm{p}}/\mathrm{p}$ depends on the CR proton spectral index α

Precision Measurement of the Proton Flux in Primary Cosmic Rays from Rigidity 1 GV to 1.8 TV with the Alpha Magnetic Spectrometer on the International Space Station



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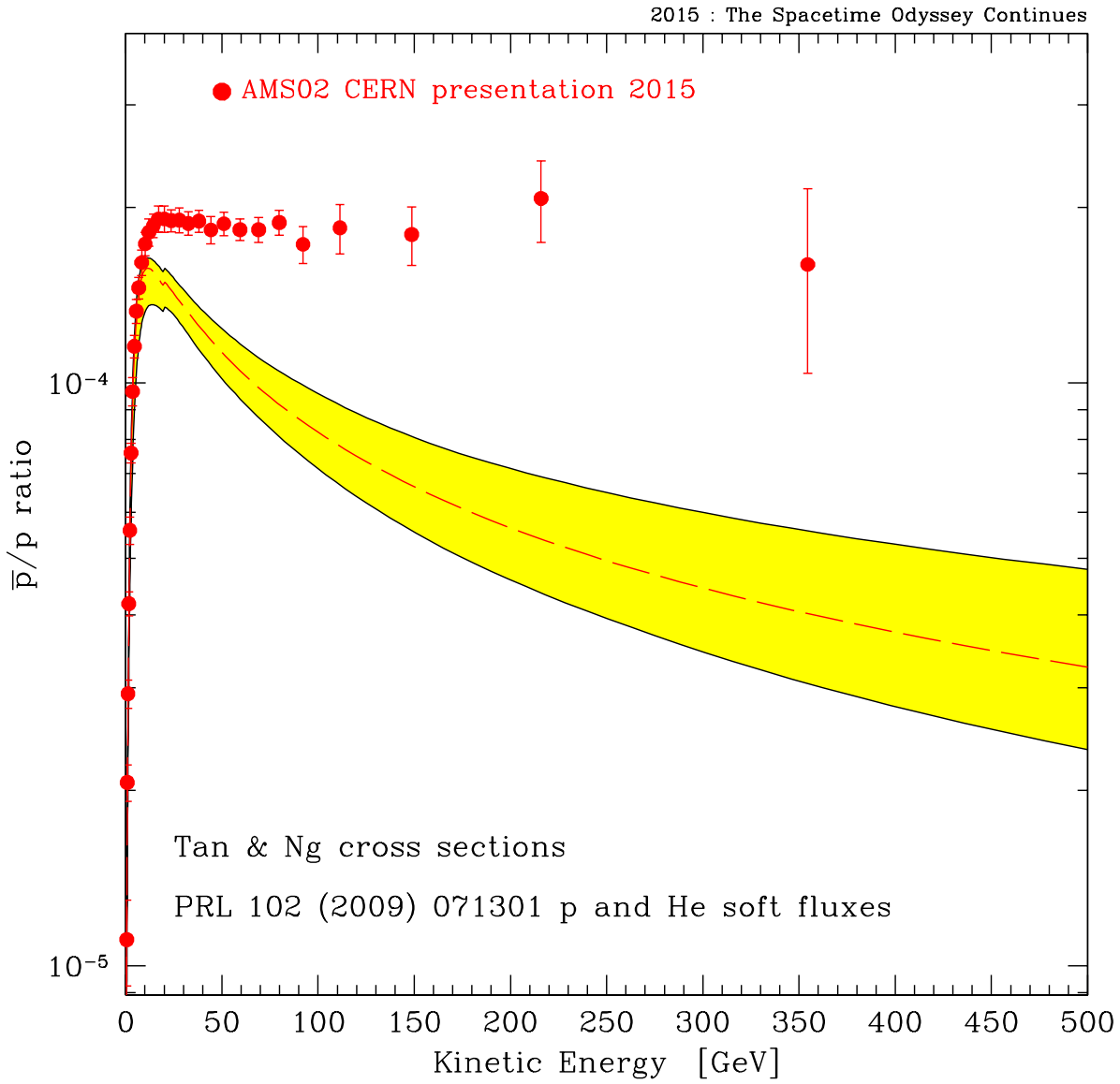

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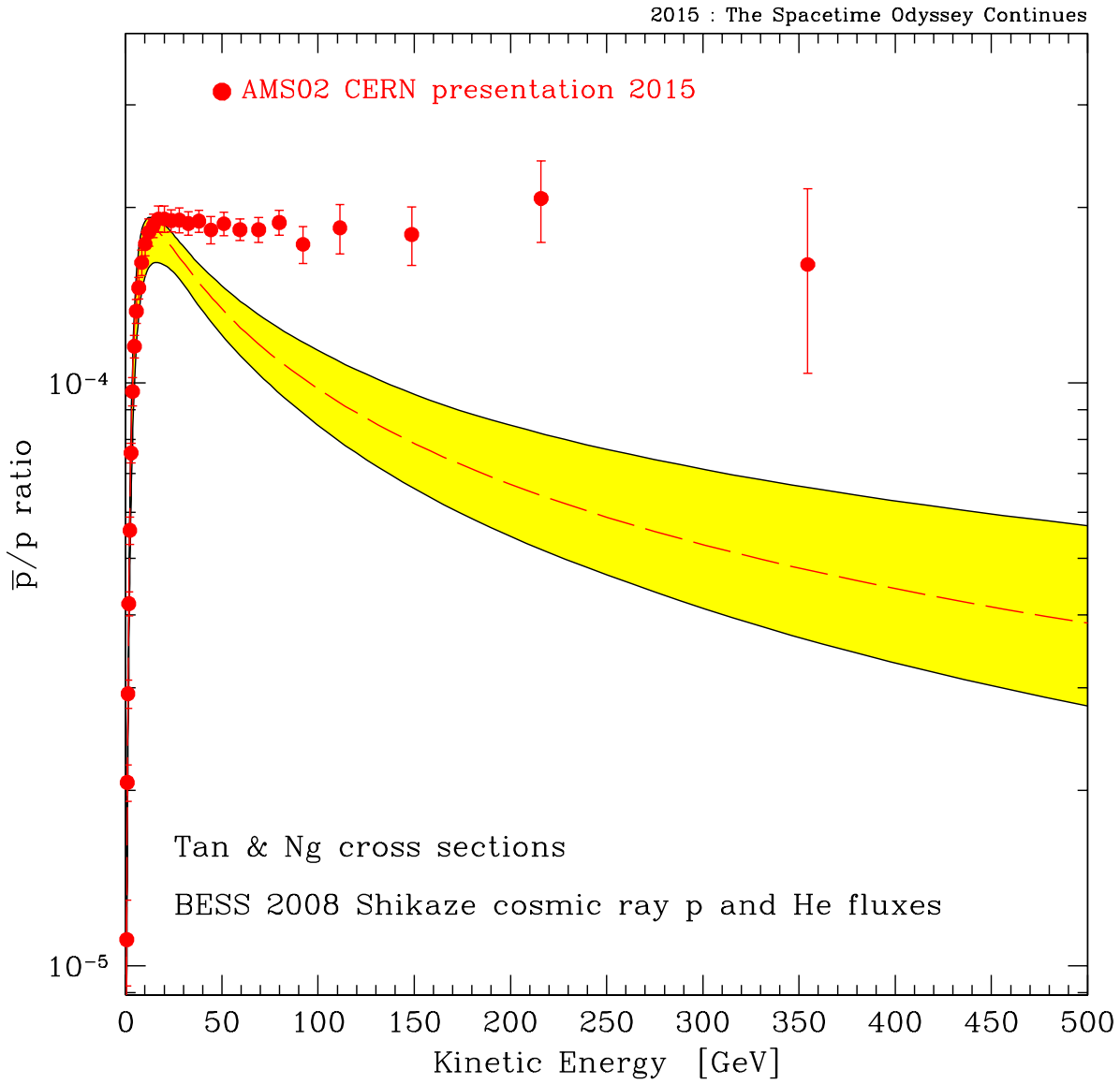

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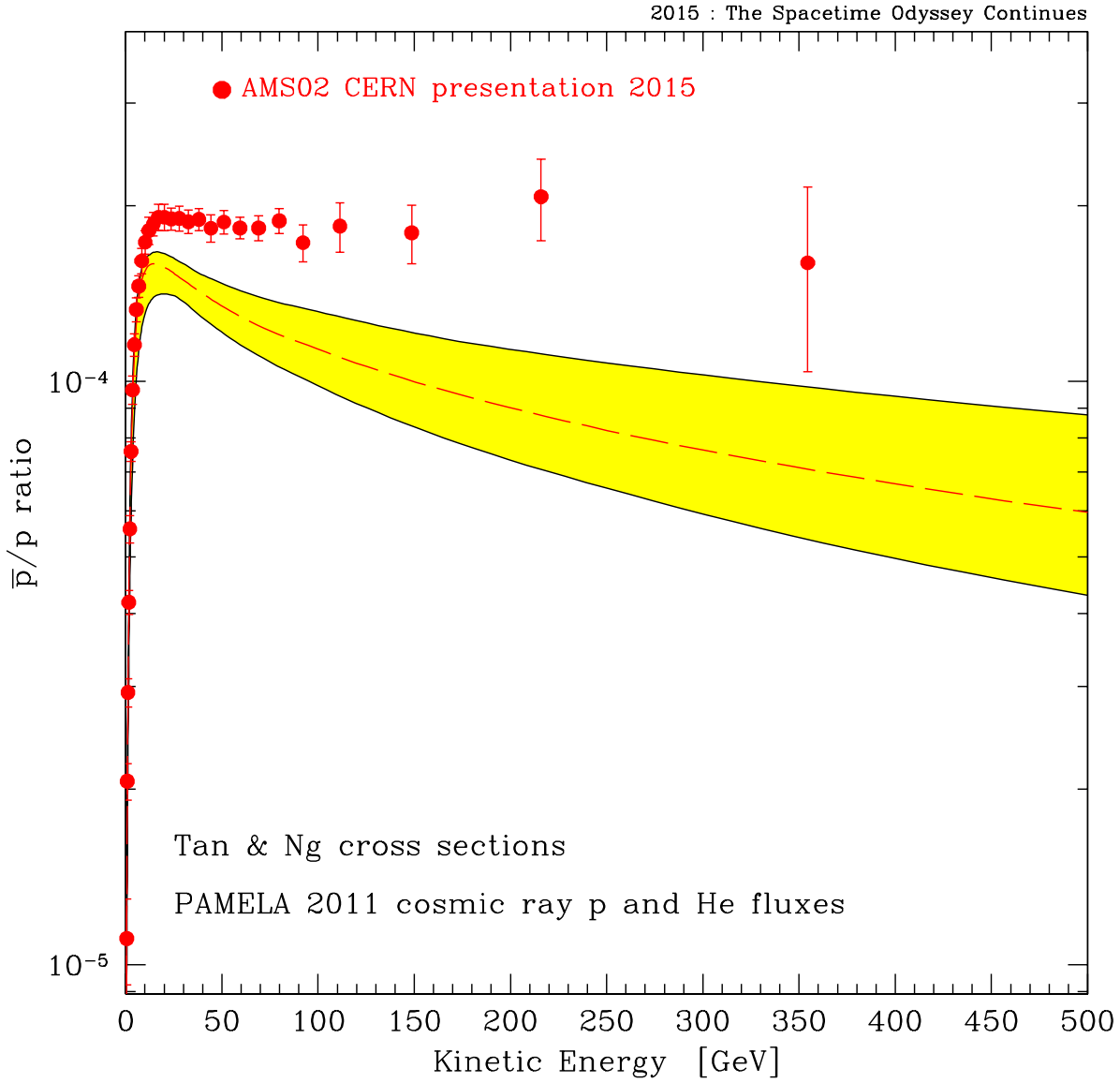

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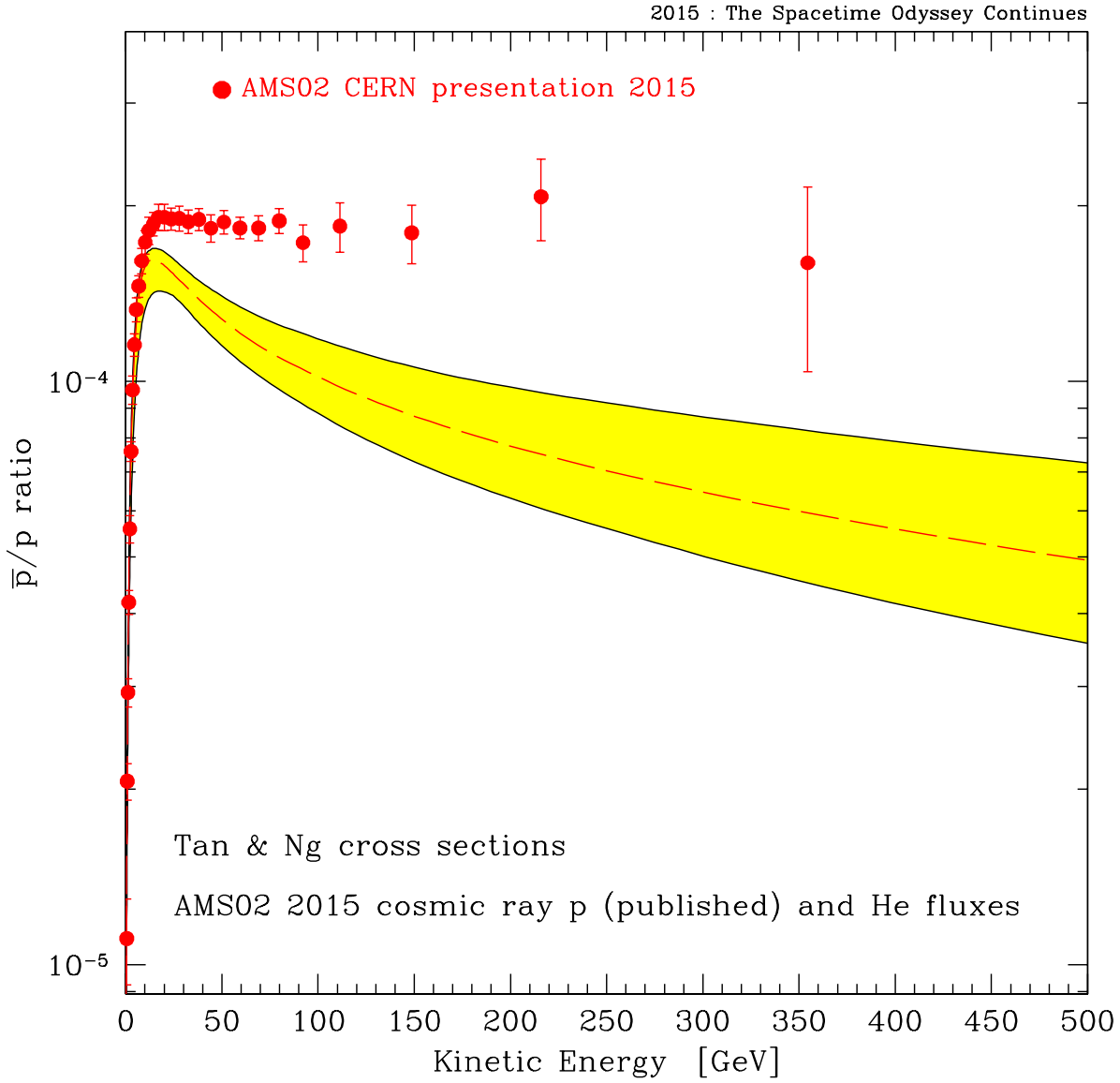

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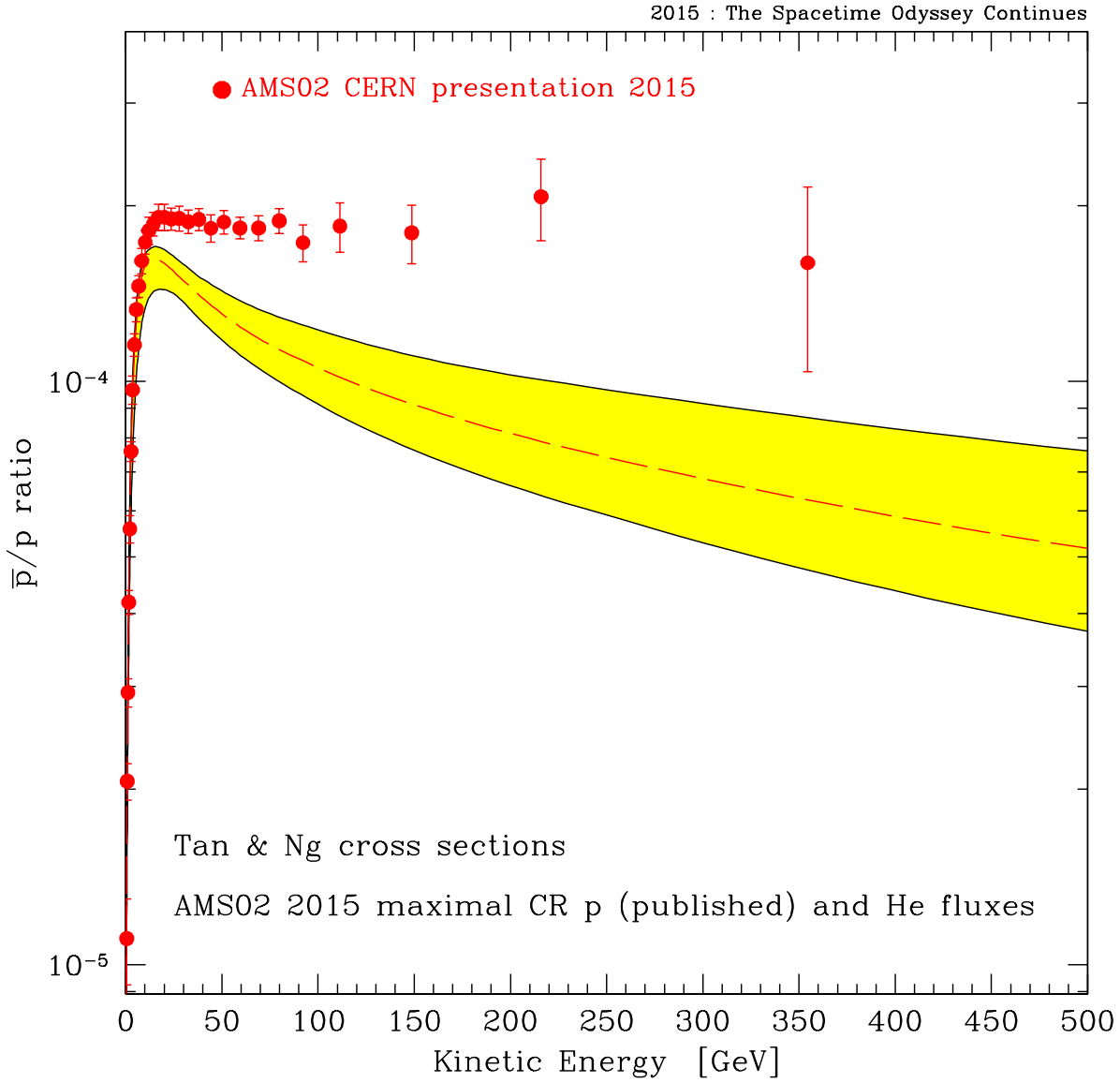

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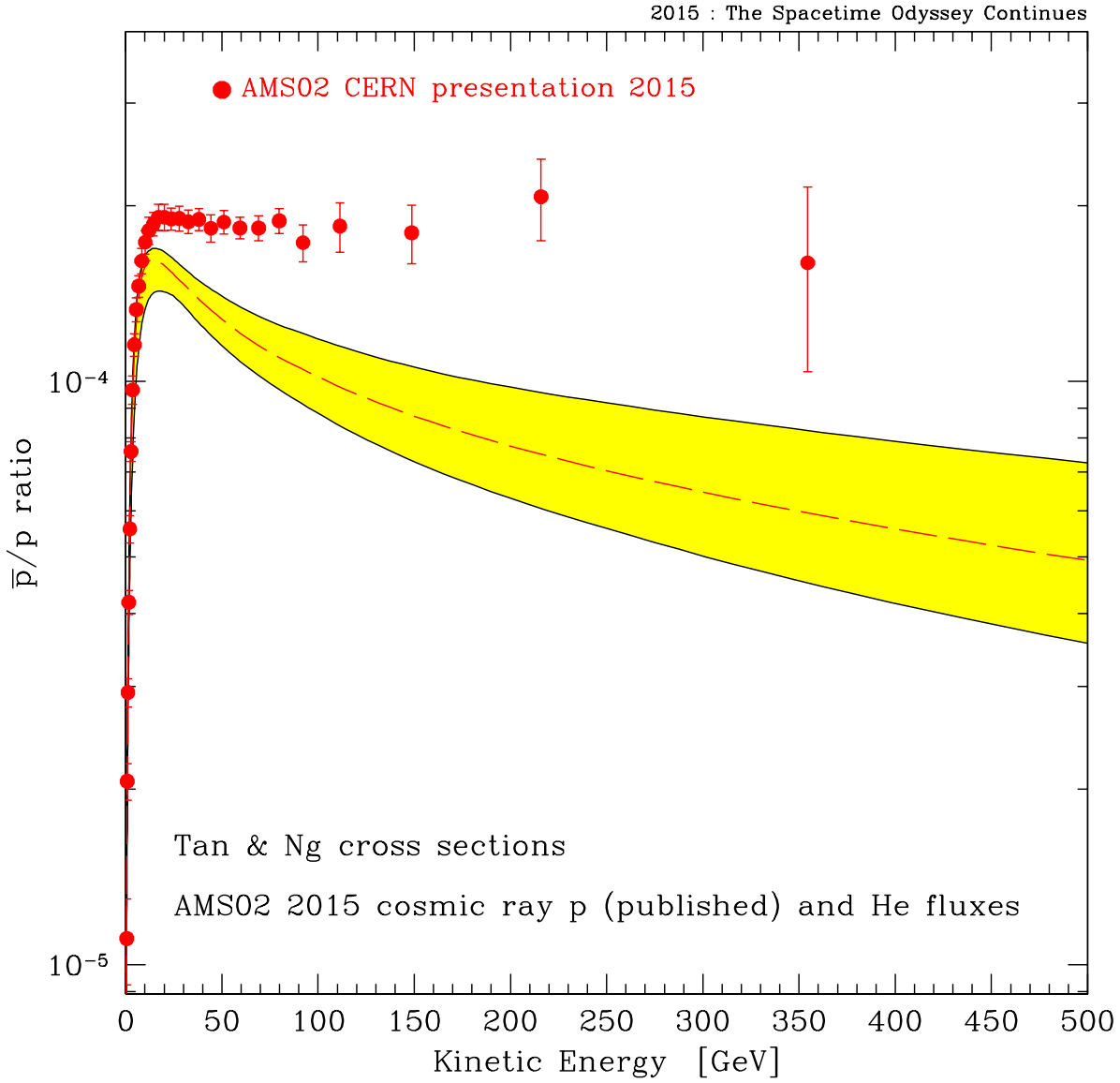

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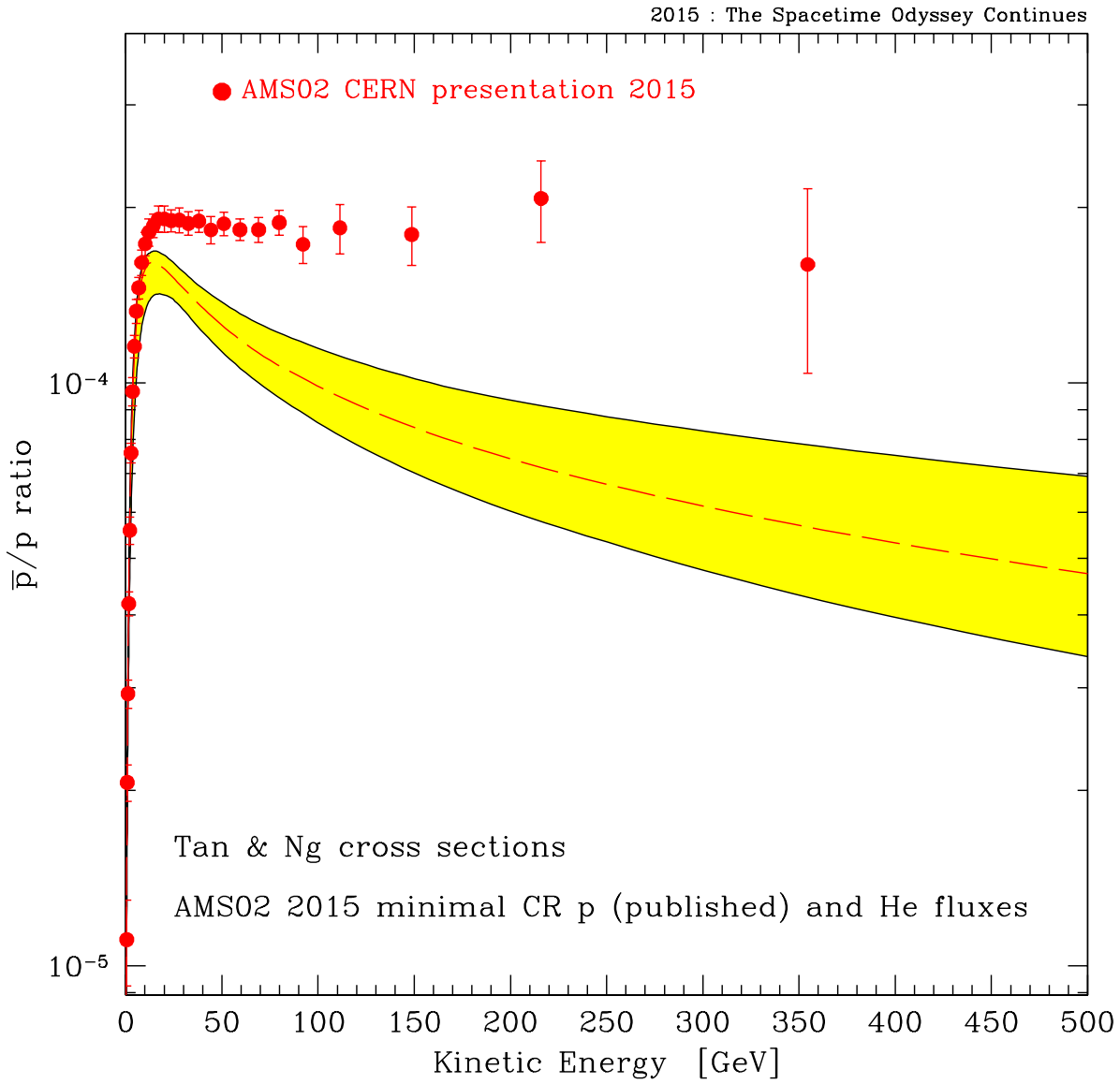

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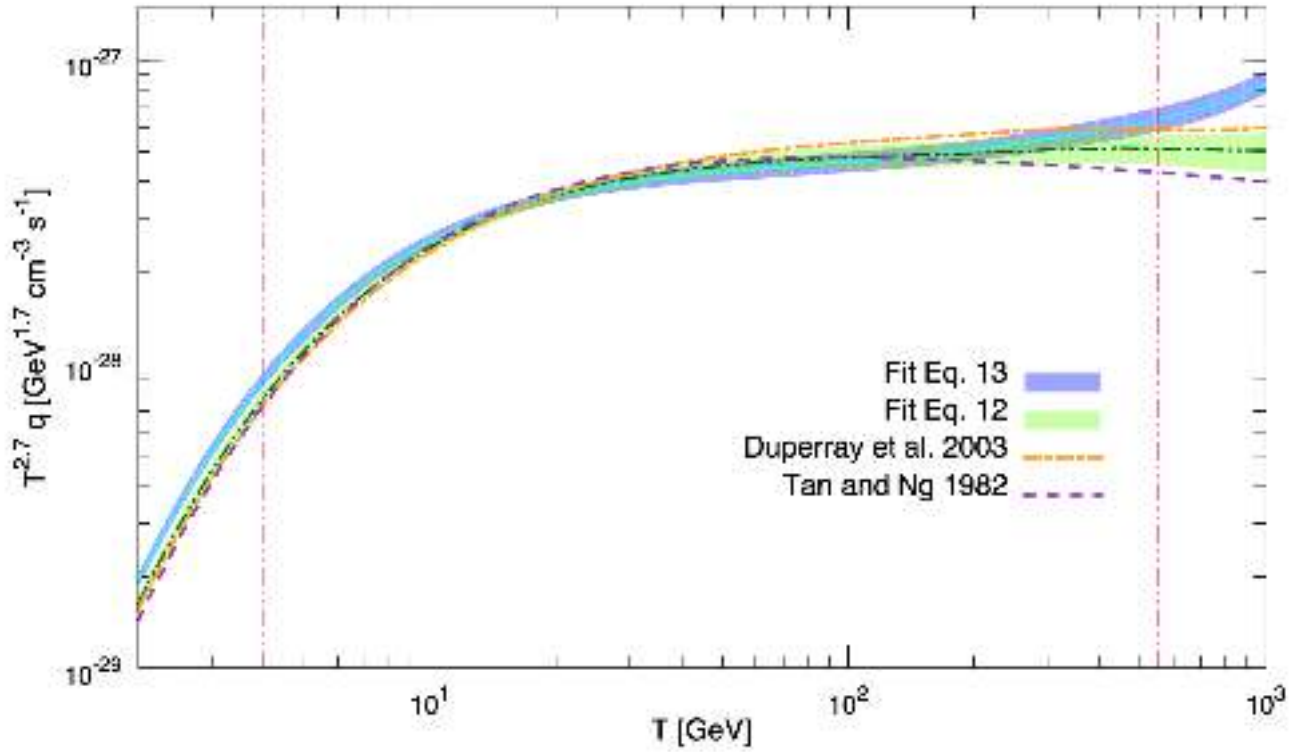

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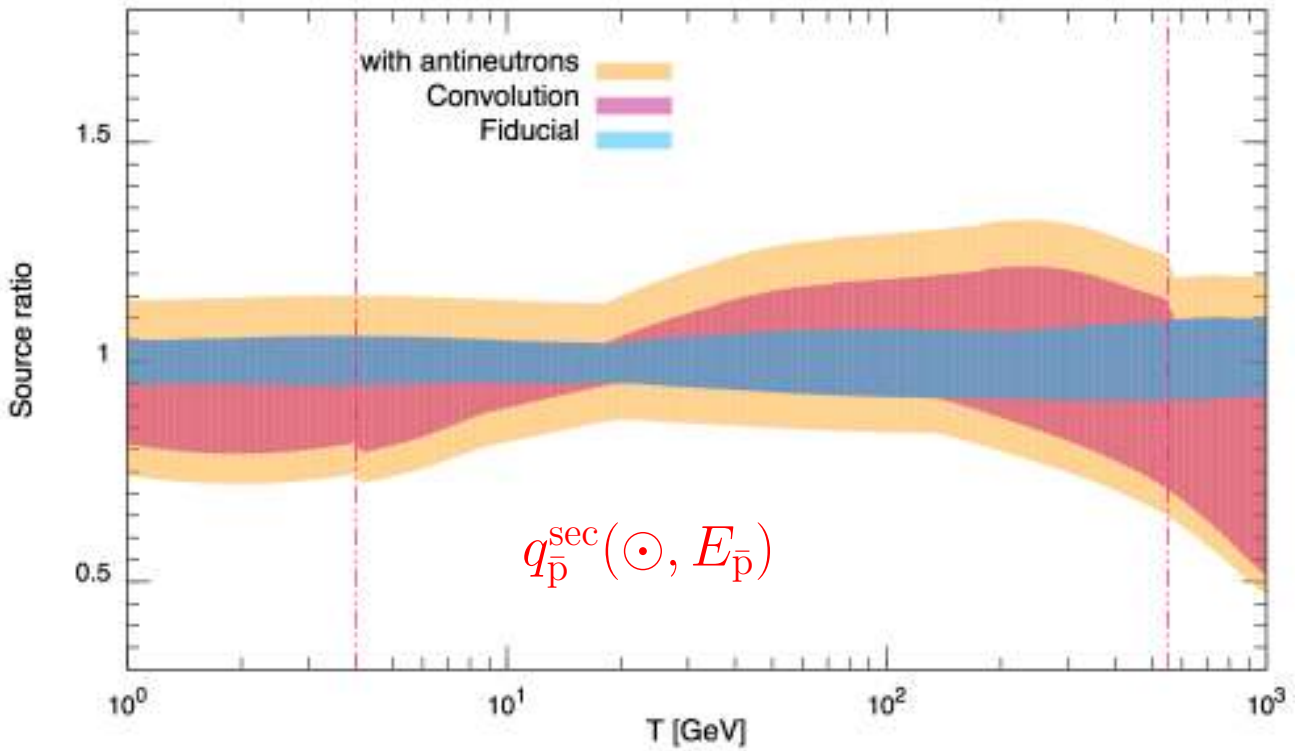
A new evaluation of the antiproton production cross section for cosmic ray studies

Mattia di Mauro[1,2], Fiorenza Donato[1], Andeas Goudelis[2], Pasquale Dario Serpico[2]

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

C_1 (error)	C_2 (error)	C_3 (error)	C_4 (error)	C_5 (error)	C_6 (error)	C_7 (error)	C_8 (error)
4.499(0.040)	3.41(0.11)	0.00942(0.00083)	0.445(0.027)	3.502(0.018)	0.0622(0.0086)	-0.247(0.049)	2.576(0.027)



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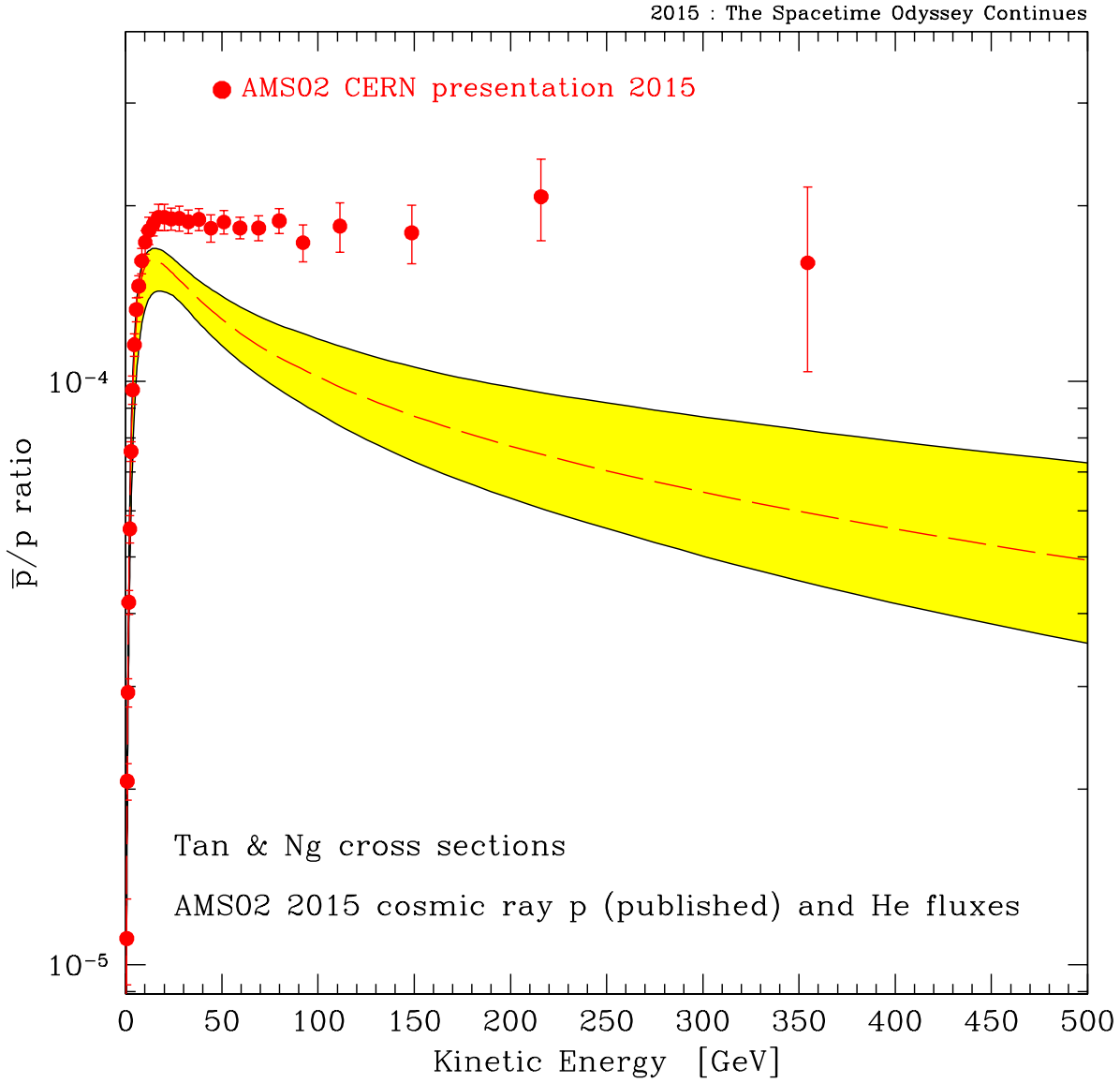

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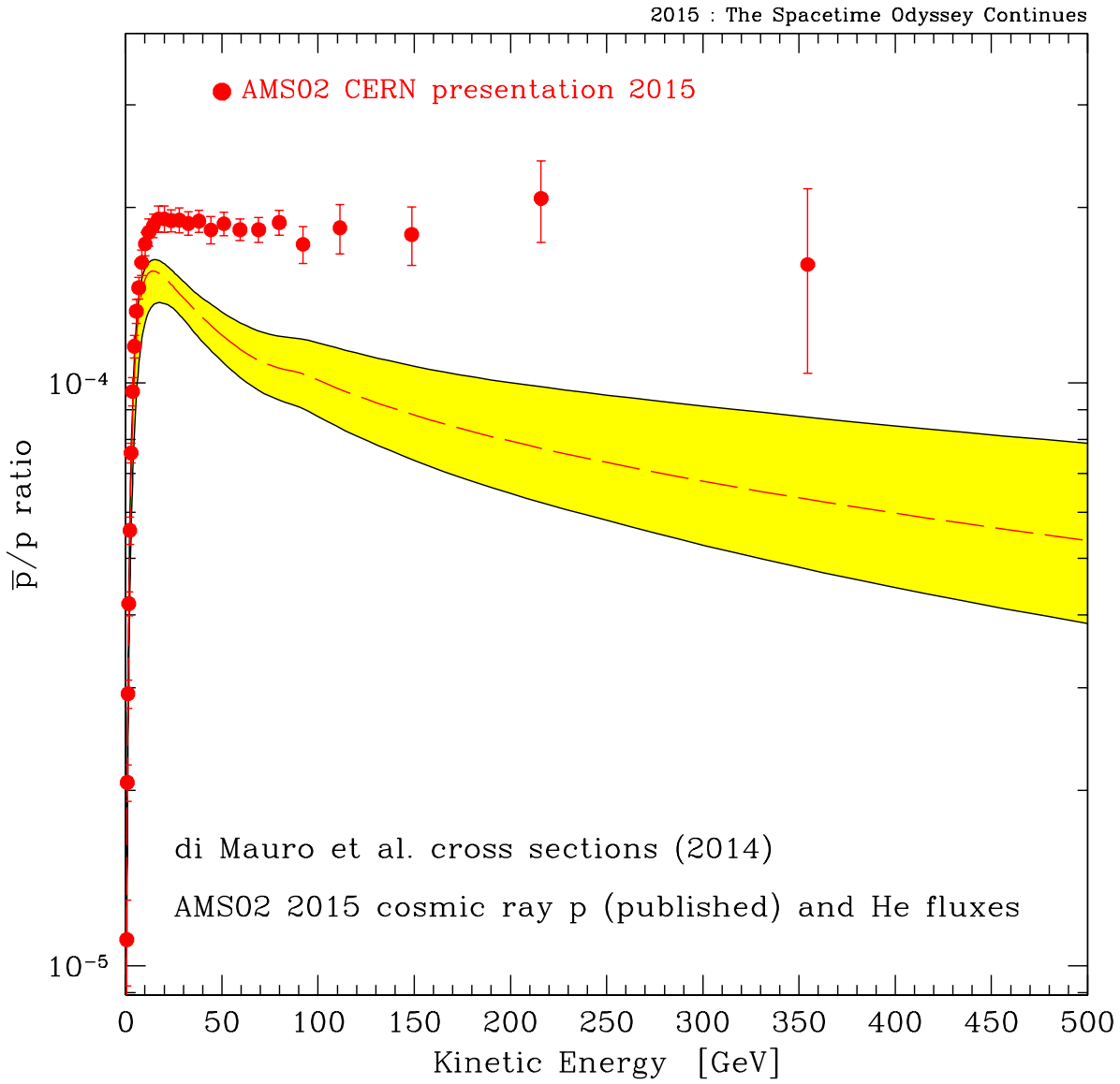

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New developments since 2008

– Proton collisions yield more antineutrons than antiprotons.

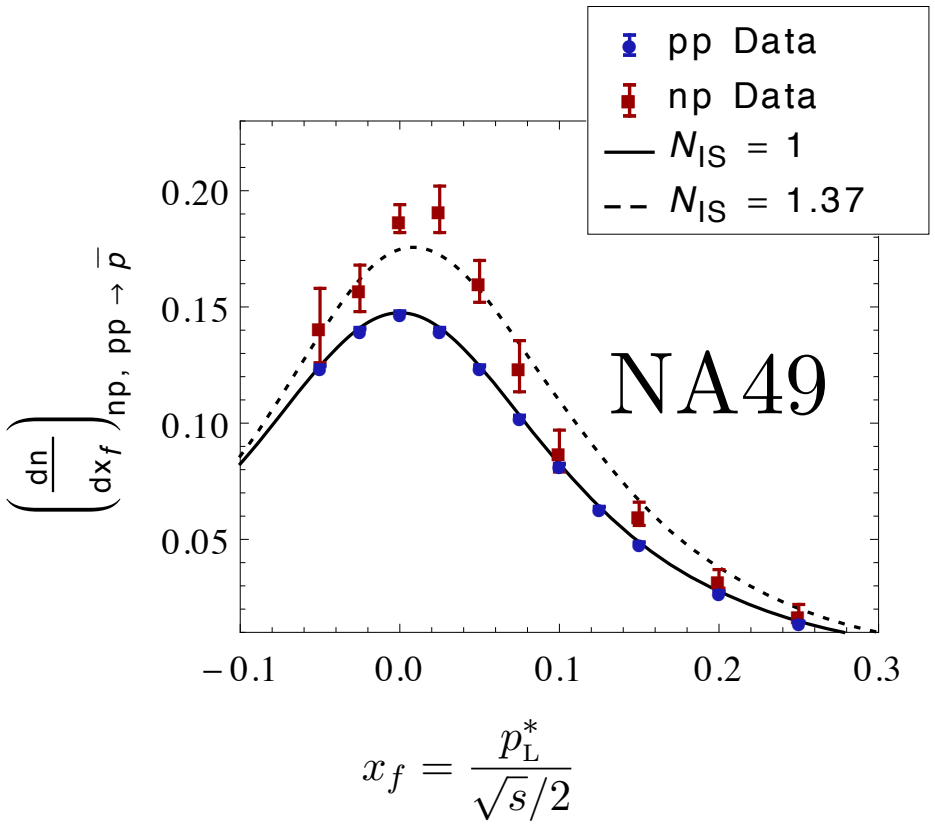
$$d\sigma_{\mathrm{pp}\rightarrow\bar{\mathrm{n}}}/dE_{\bar{\mathrm{p}}} \equiv d\sigma_{\mathrm{pn}\rightarrow\bar{\mathrm{p}}}/dE_{\bar{\mathrm{p}}}$$

$$\Downarrow$$

$$d\sigma_{\mathrm{pp}\rightarrow\bar{\mathrm{n}}}/d\sigma_{\mathrm{pp}\rightarrow\bar{\mathrm{p}}} \simeq 1.3$$

The Cosmic Ray Antiproton Background for AMS-02

Rolf Kappl[a], **Martin Wolfgang Winkler**[b]



NA49 Collaboration, H. Fischer, Heavy Ion Phys. **17** (2003), 369–386

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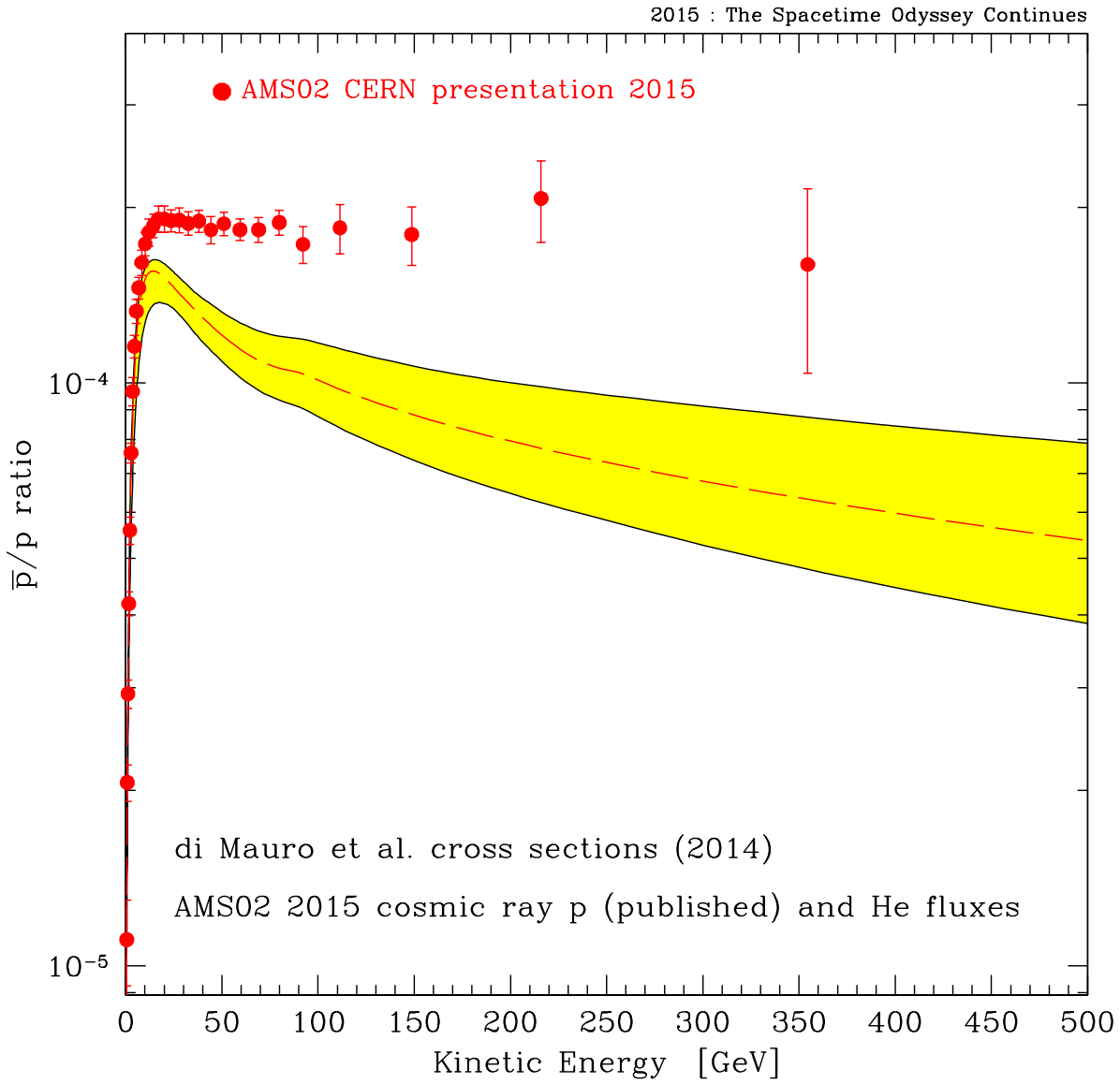

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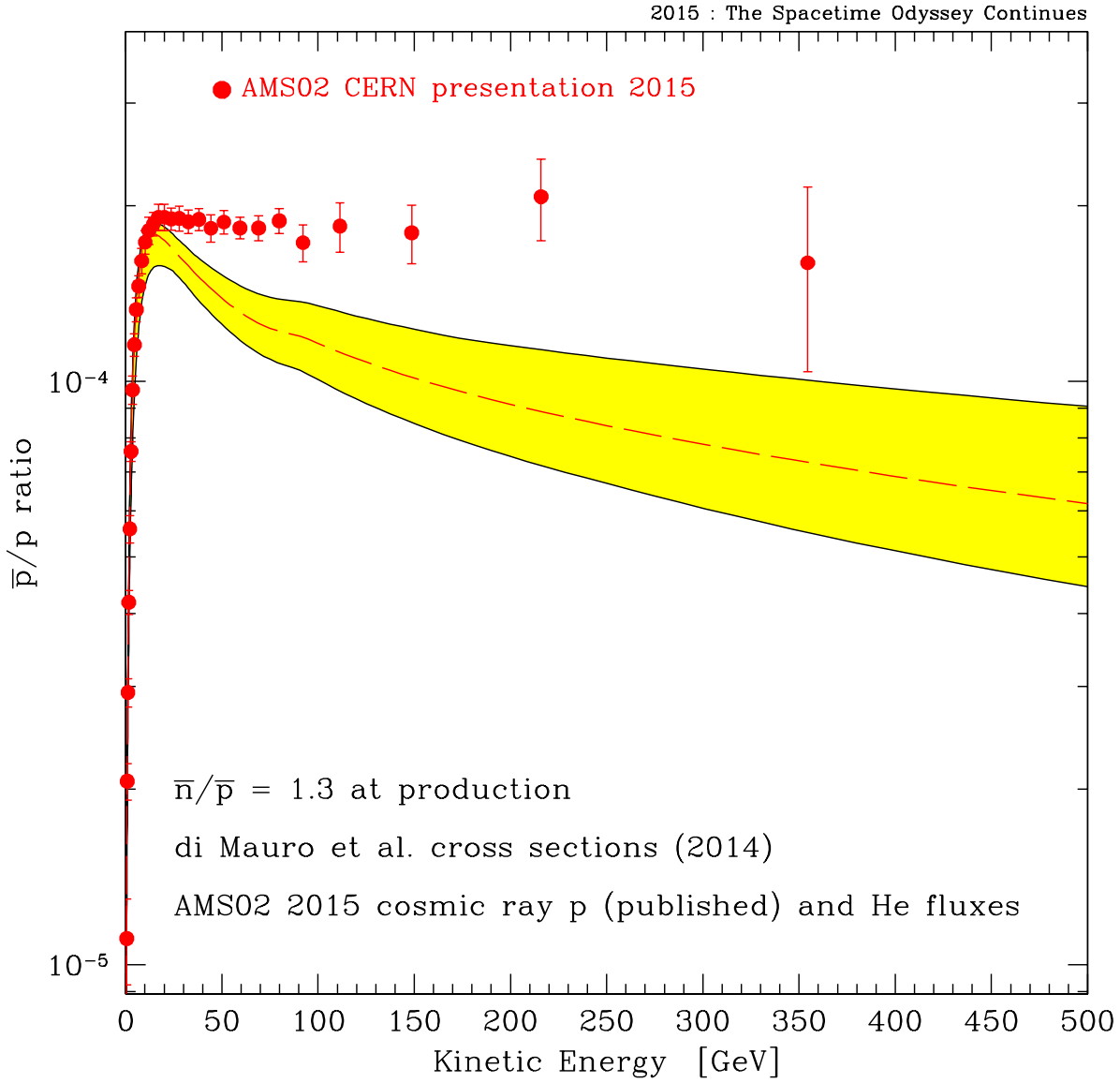

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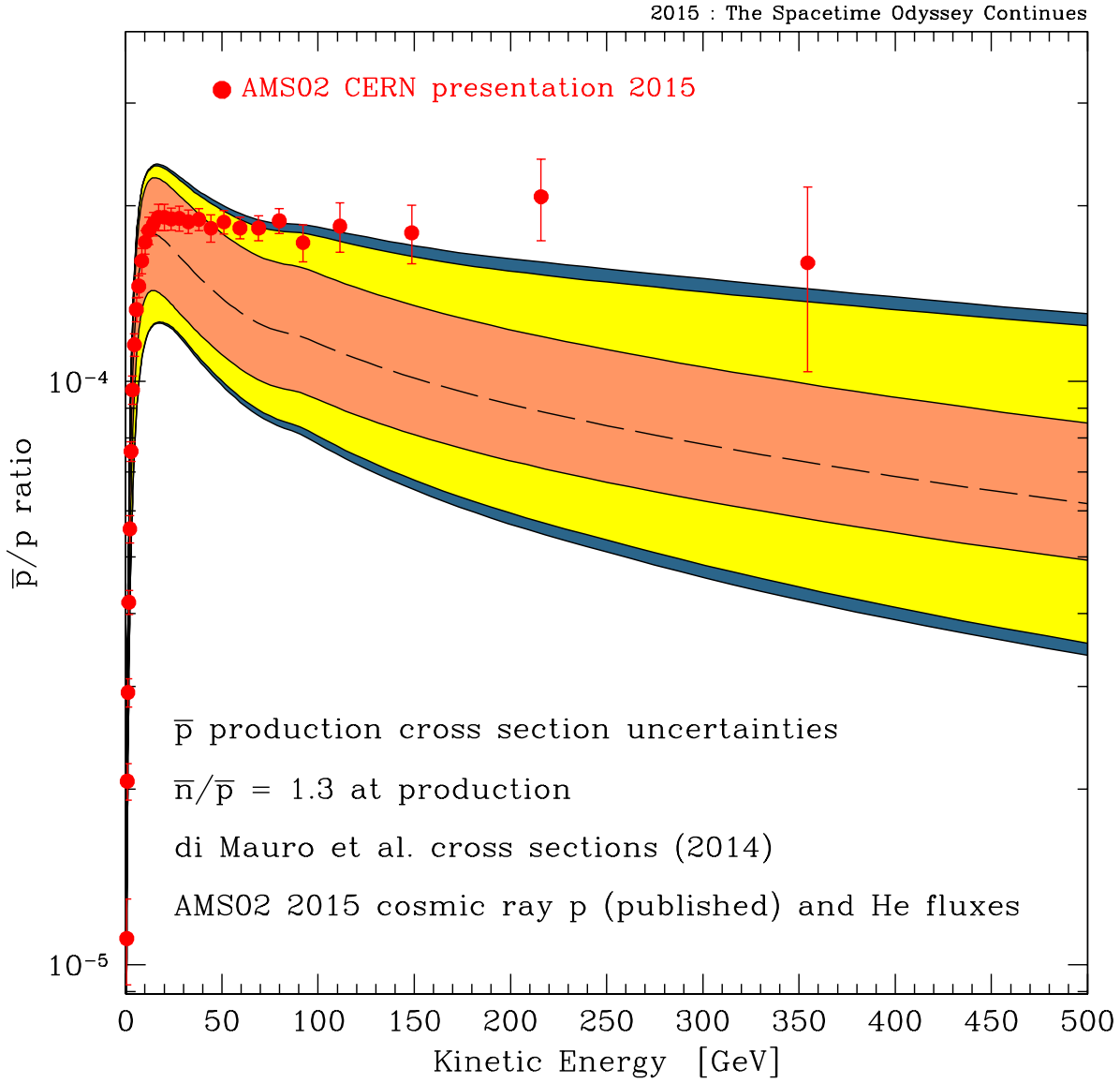
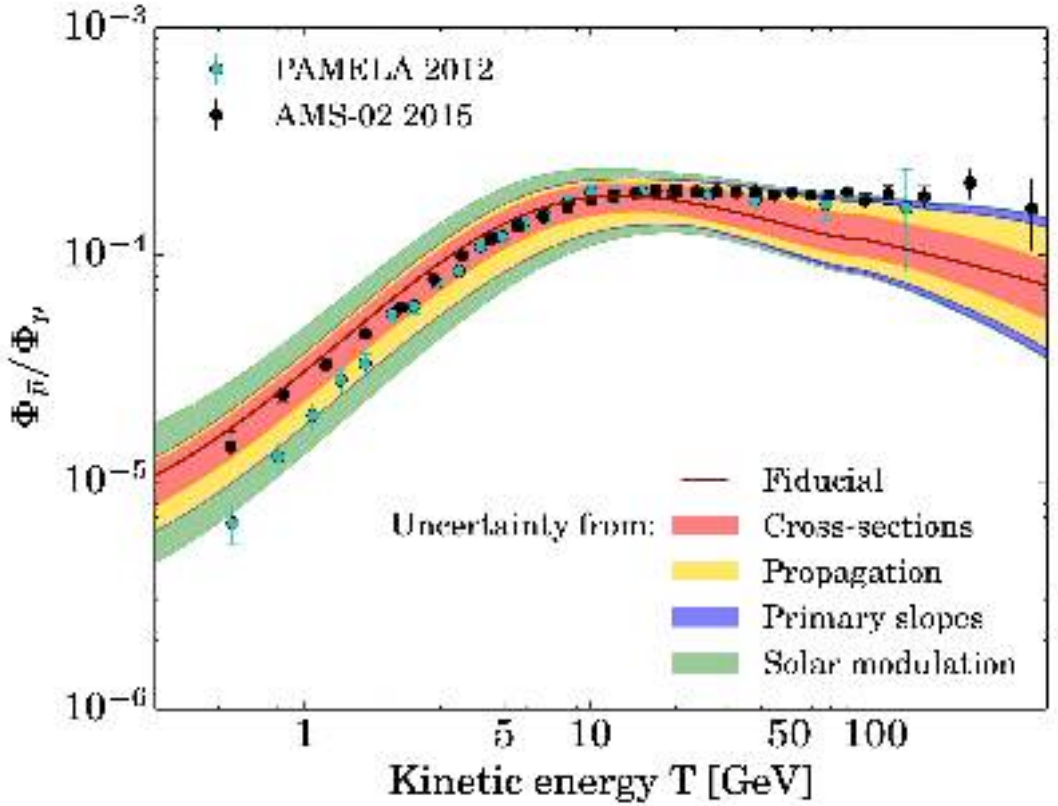


New developments since 2008

Antiproton data are compatible with the background

No $\bar{p}$ excess



But measurements are on the upper side

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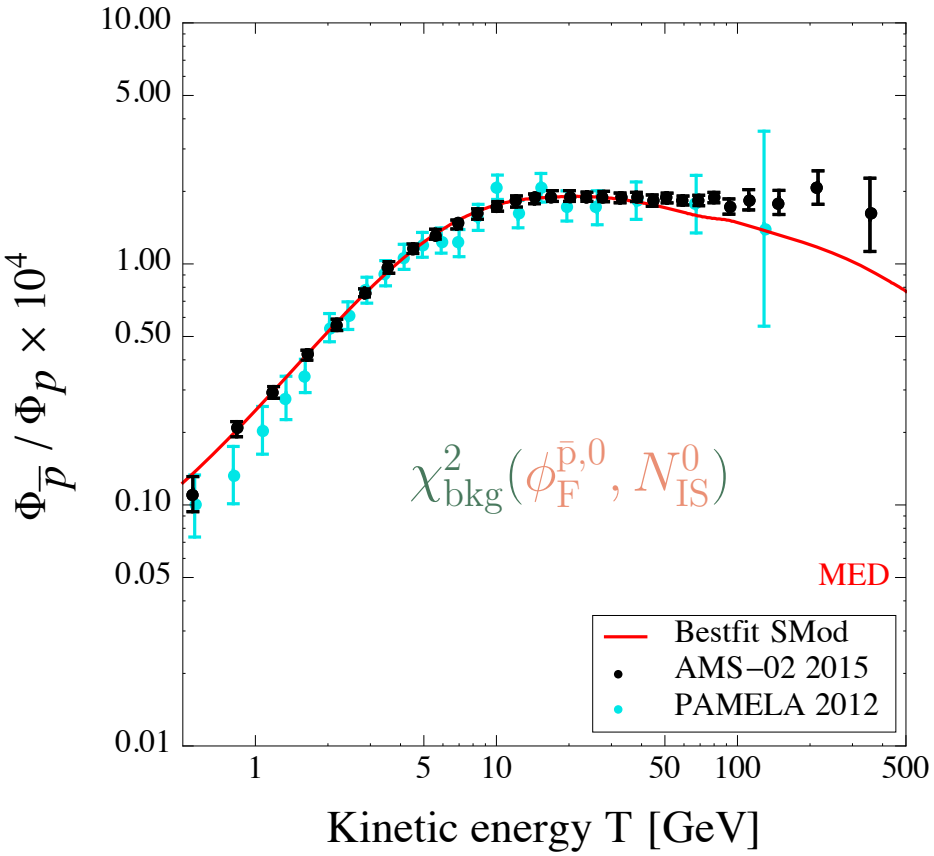
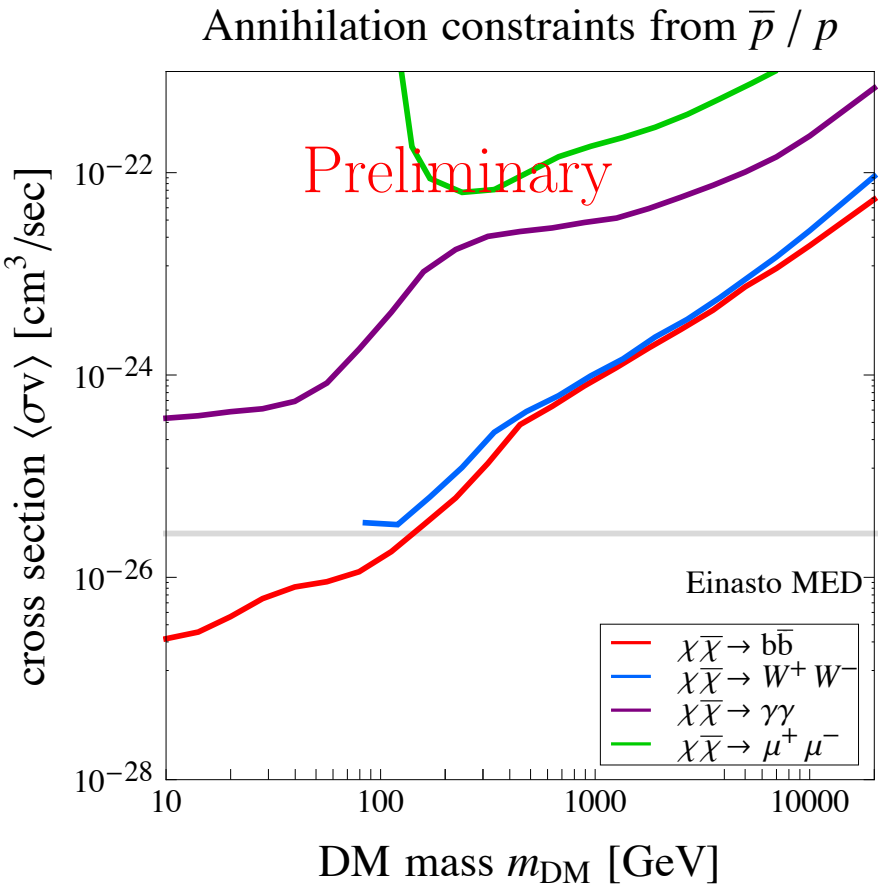
Case	δ	K_0 [kpc^2/Myr]	L [kpc]	V_C [km/s]	V_a [km/s]
max	0.46	0.0765	15	5	117.6
med	0.70	0.0112	4	12	52.9
min	0.85	0.0016	1	13.5	22.4



New limits can be set on DM properties

Treat $\phi_{\rm F}^{\bar{\rm p}}$ and $N_{\rm IS} = \bar{\rm n}/\bar{\rm p}$ as nuisance parameters

$$\chi^2(m_{\rm DM}, \langle\sigma v\rangle, \phi_{\rm F}^{\bar{\rm p}}, N_{\rm IS}) - \chi^2_{\rm bkg}(\phi_{\rm F}^{\bar{\rm p},0}, N_{\rm IS}^0) \leq 4$$



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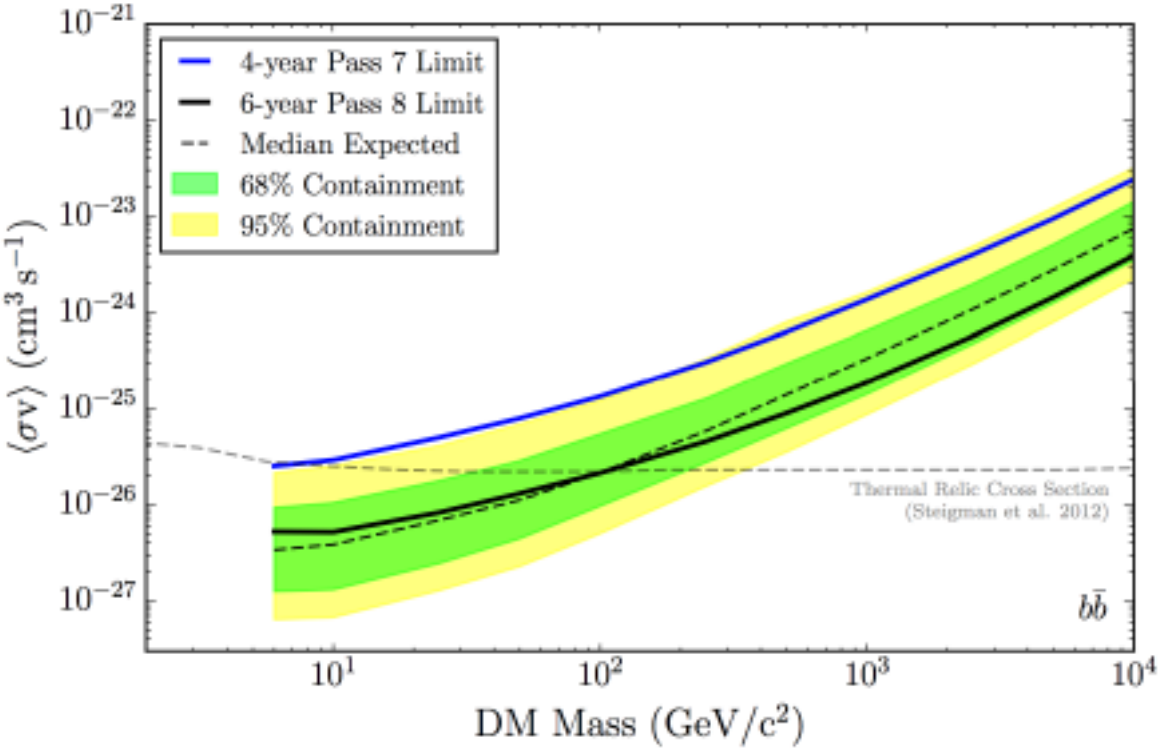

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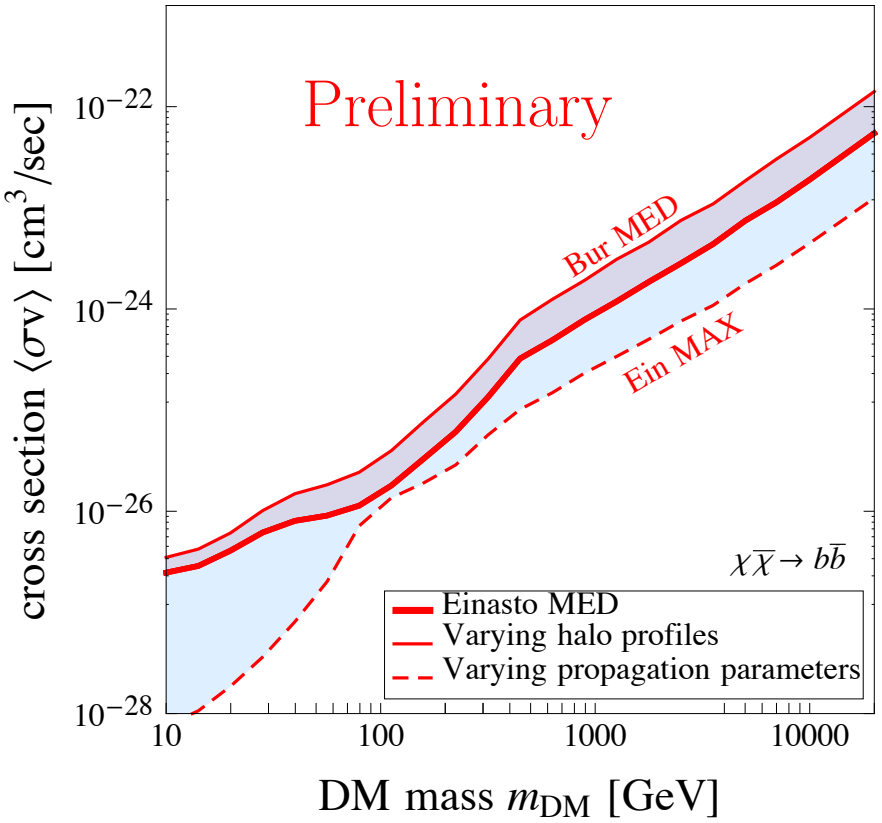
Astrophysical uncertainties on the constraints



New limits can be set on DM properties

Closing thoughts

• Dark Matter indirect detection is a powerful probe provided that **astrophysical backgrounds** are well determined.

$$\Downarrow$$

Cosmic ray propagation & X-sections

• The antiproton background has been increasing somewhat since 2008...

(i) harder CR proton and He spectra,

(ii) increased $\bar{n}/\bar{p}$ ratio at production,

(iii) better determination of the cross-section uncertainties.

• The AMS-02 antiproton measurements are of exquisite quality. They are – at that stage – compatible with the background although at the upper limit of what is expected.

• To decide whether a signal is hidden inside the AMS-02 $\bar{p}/p$ data, CR propagation needs to be better constrained and the antiproton production cross-sections should be more accurately measured.

Future CR measurements are a gold mine to be exploited