

AMS-02 antiprotons are consistent with a secondary astrophysical origin

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IFT - UAM/CSIC

arXiv:1906.07119

MB, Y. Génolini, L. Derome, J. Lavalley, D. Maurin,
P. Salati and P. D. Serpico

The Delta Rana warship firing a beam of jacketed antiprotons and positrons - Star Trek



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secondary antiprotons



State of the art:

- Data (AMS-02)
 - CR fluxes: H, He, C, O (acceleration) *PRL 114 171103 (2015), PRL 119 251101 (2017)*
 - CR ratio: B/C (transport) *PRL 117 231102 (2016)*
- Models
 - CR transport in the Galaxy *Derome+(2019), Génolini+(2019)*
 - antiprotons production cross sections (XS) *Winkler(2016), Korsmeier+(2018)*

⇒ **prediction of the secondary antiprotons flux**

v.s.

AMS-02 antiprotons *PRL 117 091103 (2016)*

Do secondary antiprotons explain the AMS-02 data?

Preamble: data vs model

- χ^2 : quadratic distance between data and model

$$\chi^2 = \sum_{i,j} x_i (\mathcal{C}^{-1})_{ij} x_j \quad x_i = \text{data}_i - \text{model}_i$$

Preamble: data vs model

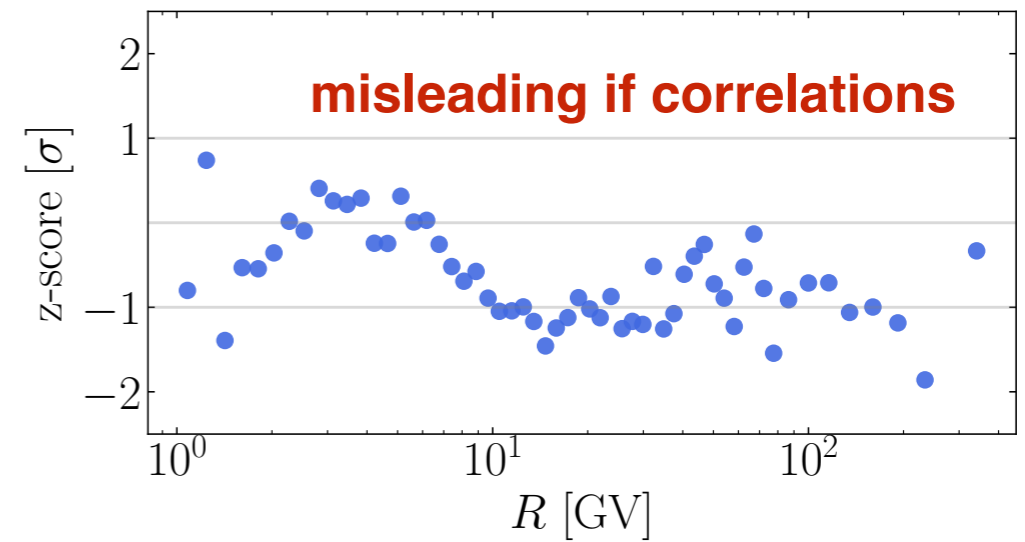
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- **Visual inspection**

- standard z-score $z_i = x_i / \sigma_i$



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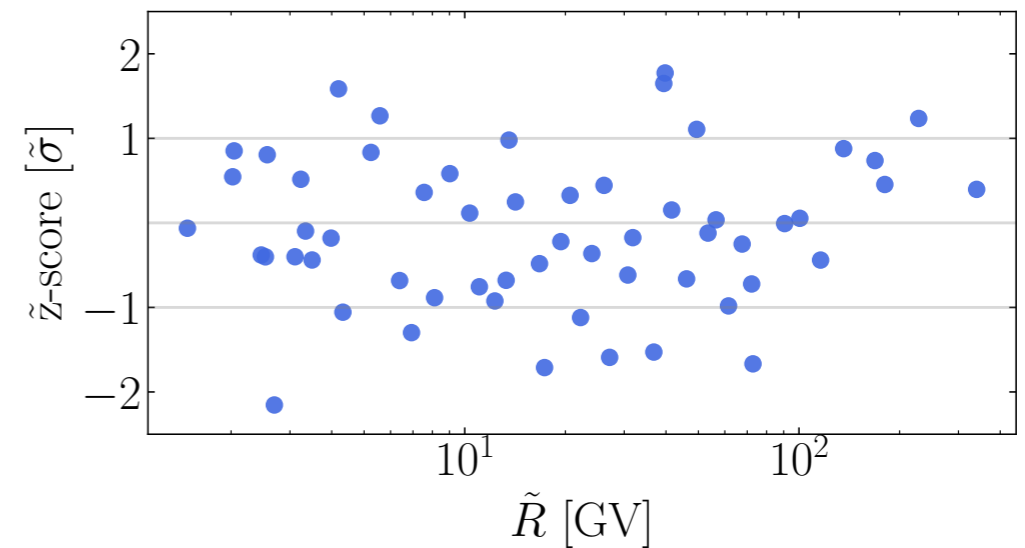
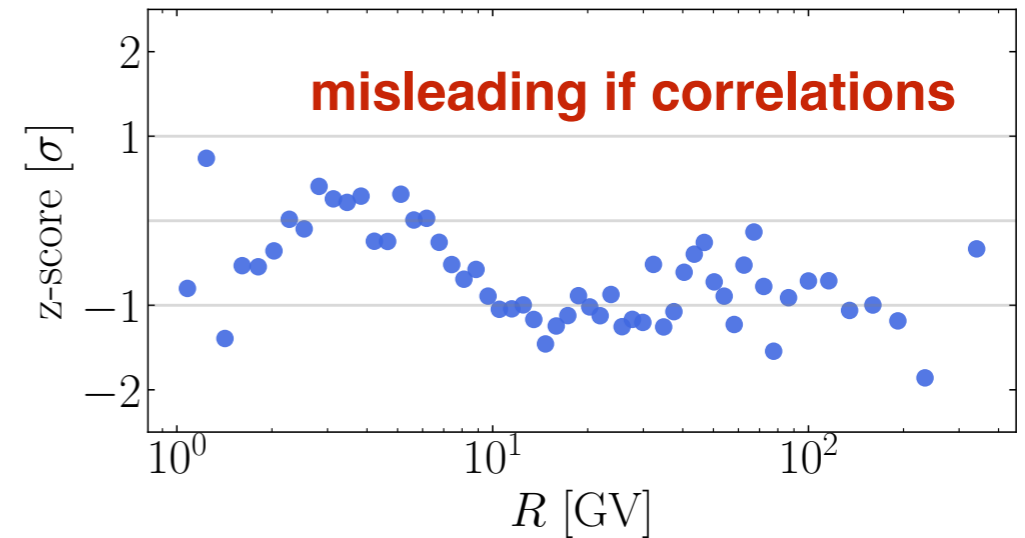
- standard z-score $z_i = x_i / \sigma_i$
- rotated z-score (diagonal in new basis)

$$\tilde{x}_i = U_{ij} x_j, \quad \tilde{\mathcal{C}} = U \mathcal{C} U^T$$

$\tilde{\mathcal{C}}$ is diagonal with elements $\tilde{\mathcal{C}}_{ii} = \tilde{\sigma}_i^2$

$$\tilde{z}_i = \tilde{x}_i / \tilde{\sigma}_i$$

$$\chi^2 = \sum_i \tilde{z}_i^2 \quad \tilde{R}_i = \sum_j U_{ij}^2 R_j, \quad \tilde{R}_i \simeq R_i$$



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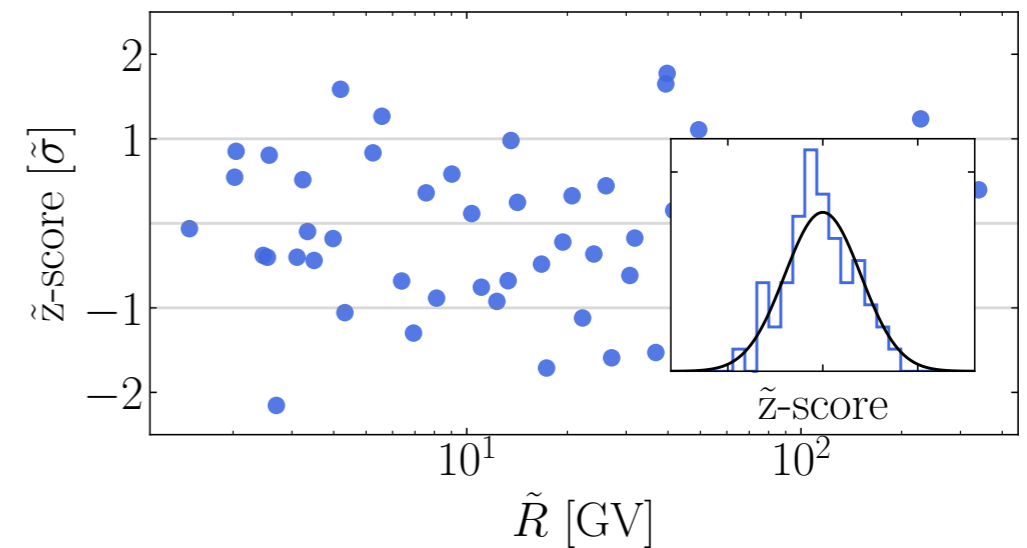
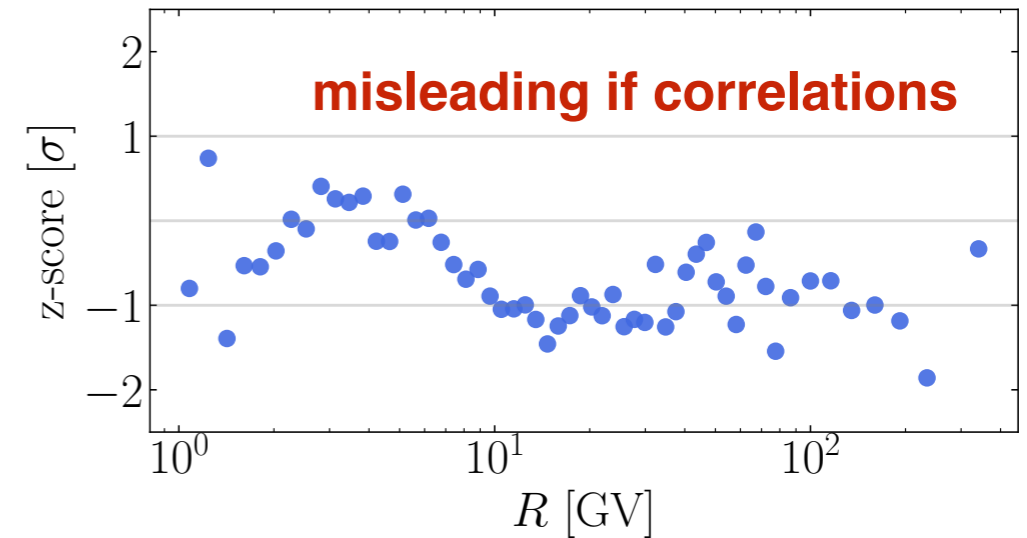
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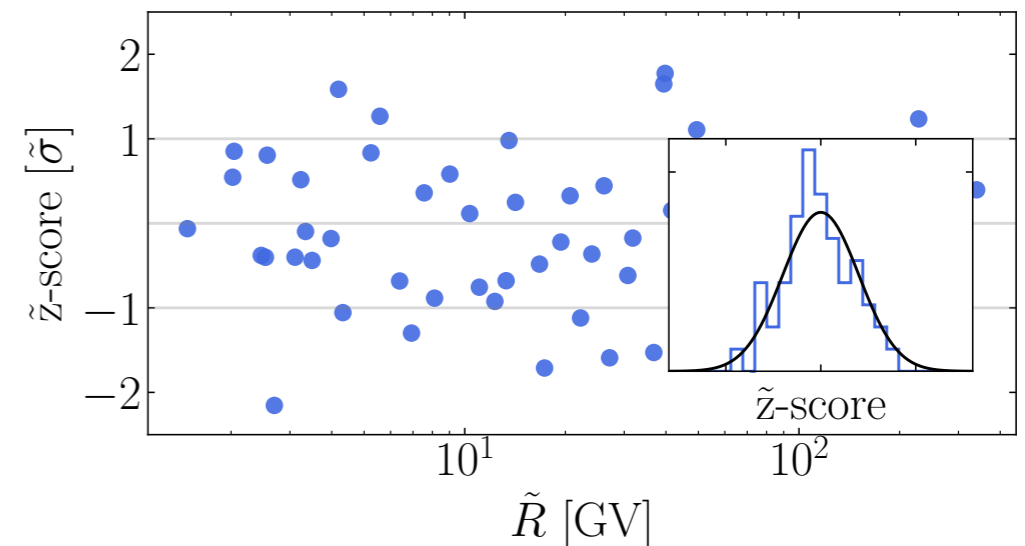
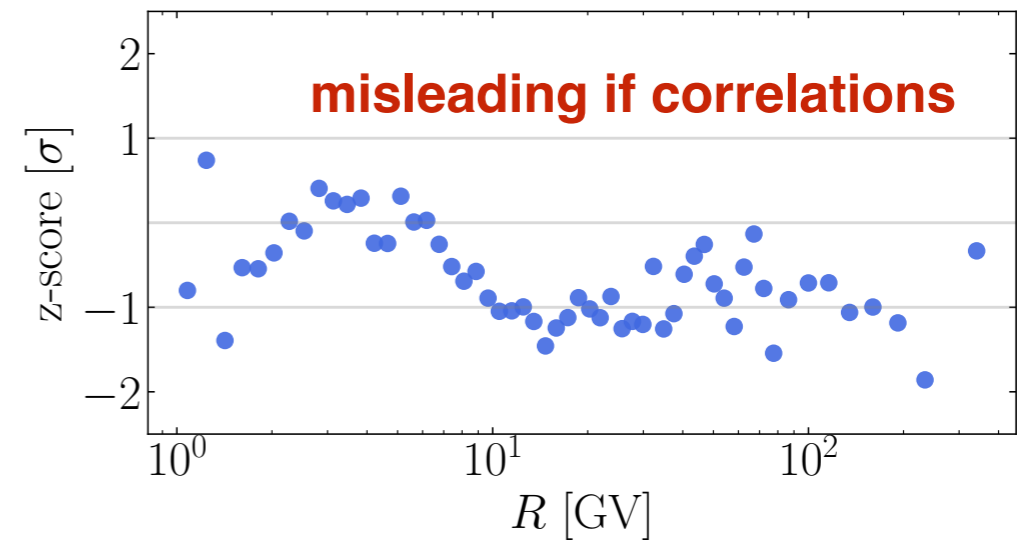
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• Statistical test

- χ^2 test
 - Kolmogorov-Smirnov (KS) test
 - etc.
- } \Rightarrow **p-value**



how consistent are the data with the model?

- 
- A futuristic spaceship is shown in the upper right quadrant, emitting a powerful blue energy beam that illuminates the scene. The background is a dark space filled with stars, and a planet's horizon is visible on the left side. The text is overlaid on the right side of the image.
- 1. Theoretical prediction**
 2. Uncertainties
 3. Statistical test

Production XS: prompt antiprotons

$$\frac{d\sigma_{ij}}{dT_{\bar{p}}}(T_i, T_{\bar{p}}) = p_{\bar{p}} \int d\Omega \sigma_{\text{inv}}^{ij}(T_i, T_{\bar{p}}, \theta),$$

Lorentz invariant XS

$$\sigma_{\text{inv}} = E \frac{d^3\sigma}{d^3p}(\sqrt{s}, x_{\text{R}}, p_T), \quad x_{\text{R}} = \frac{E^*}{E_{\text{max}}^*}$$

- ***p-p interactions:***

$$p + p \longrightarrow \bar{p} + X$$

data: NA49, BRAHMS, Dekkers+(1965)

+ NA61/SHINE: $\sqrt{s} = 7.7, 8.8, 12.3$ and 17.3 GeV ($T_p = 31, 40, 80$ and 158 GeV) *Aduszkiewicz+(2017)*

model: functional form of σ_{inv} from *Winkler(2016)*

\Rightarrow **parametrisation:** II from *Korsmeier+(2018)*

[M. Korsmeier Wen. 16:45]

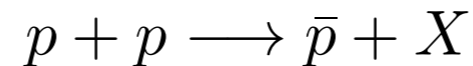
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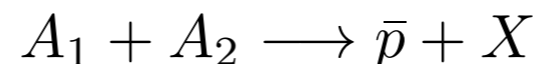
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⇒ **parametrisation:** II from *Korsmeier+(2018)*

[M. Korsmeier Wen. 16:45]

- ***nucleus-nucleus interactions:***



data: NA49: $p + C \longrightarrow pbar + X$, $\sqrt{s} = 17.3$ GeV ($T_p = 158$ GeV) *Anticic+(2010)*

LHCb: $p + He \longrightarrow pbar + X$, $\sqrt{s} = 110$ GeV ($T_p = 6.5$ TeV) *Aaij+(2018)*

[G. Graziani Fri. 9:50]

model: functional form of the nucleon scaling $f^{A_1 A_2}(\sqrt{s}, x_F)$ from *Winkler(2016)*

⇒ **parametrisation:** B from *Korsmeier+(2018)*

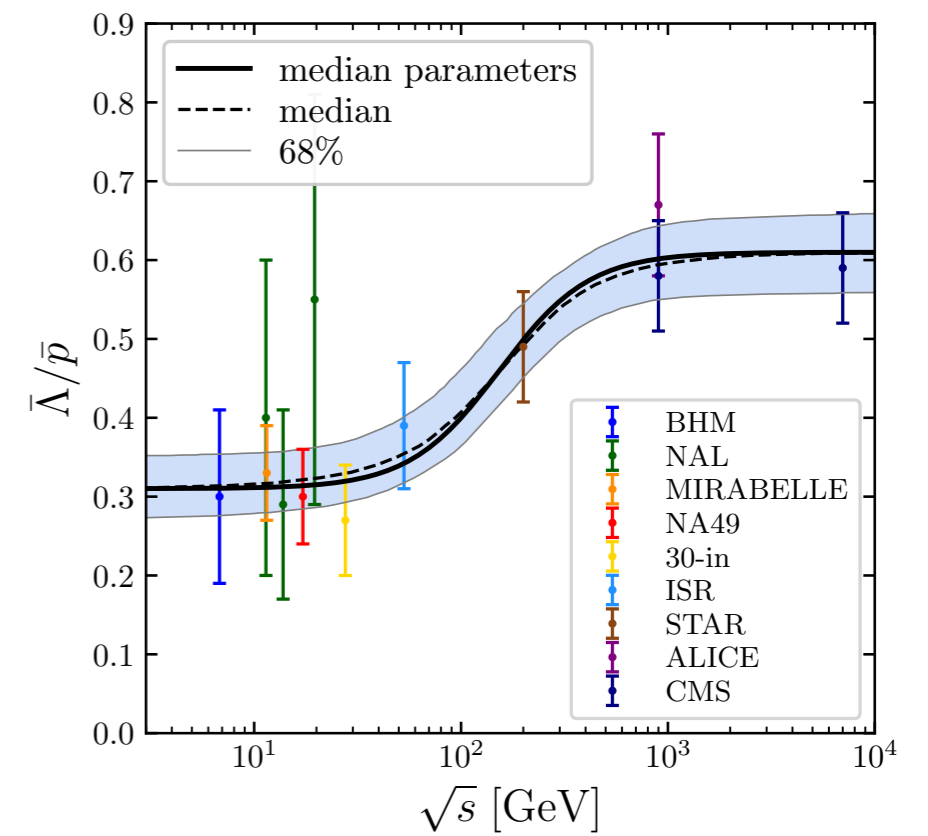
[M. Korsmeier Wen. 16:45]

Production XS: antihyperons and antineutrons

- **Antihyperons decay:** $p + p \longrightarrow \{\bar{\Lambda}, \bar{\Sigma} \longrightarrow \bar{p}\} + X$

Parametrisation from *Winkler(2016)*

$$\Delta_{\Lambda}(\sqrt{s}) = (0.81 \pm 0.04)(\bar{\Lambda}/\bar{p})$$



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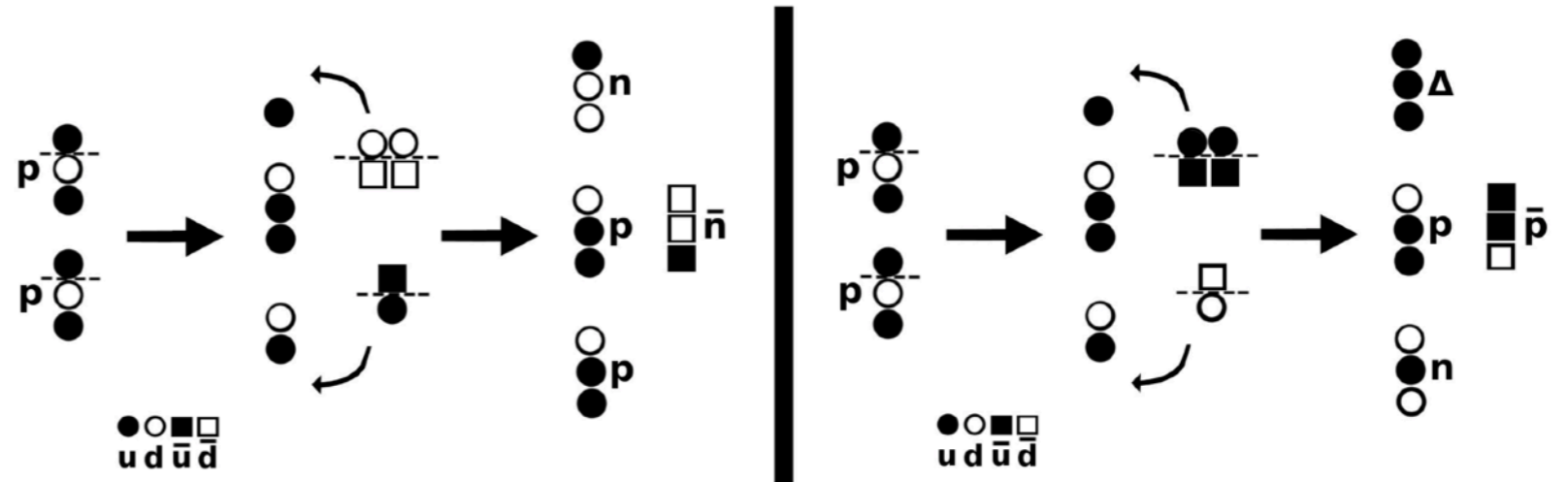
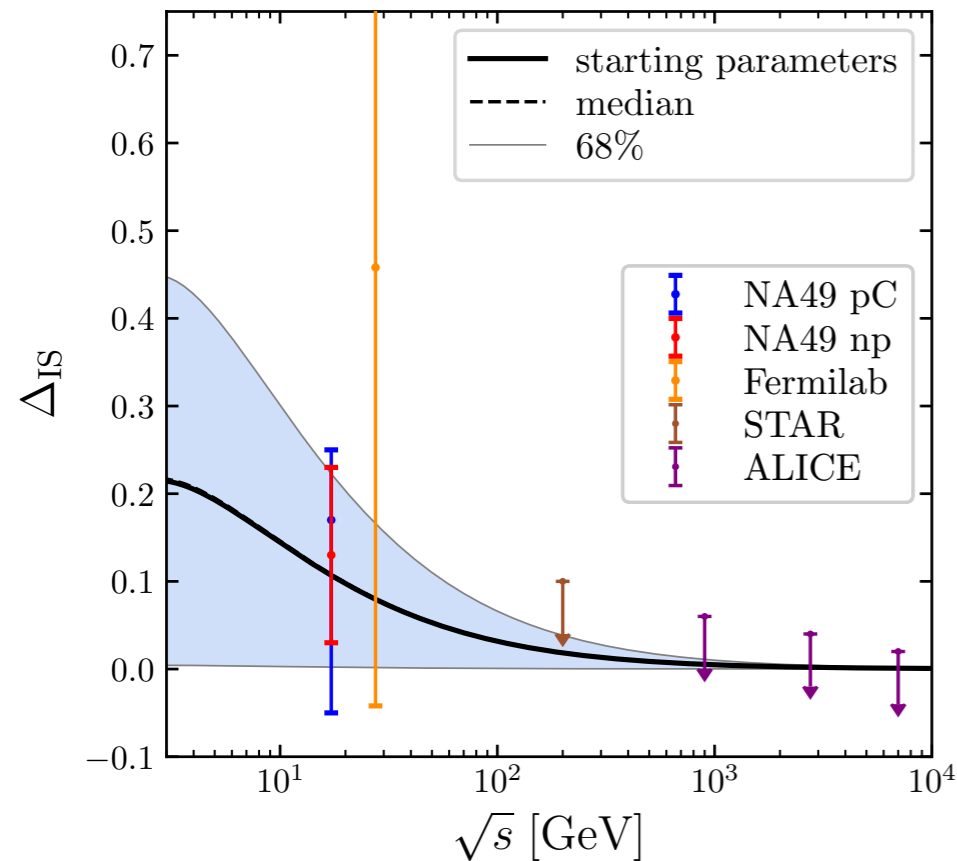
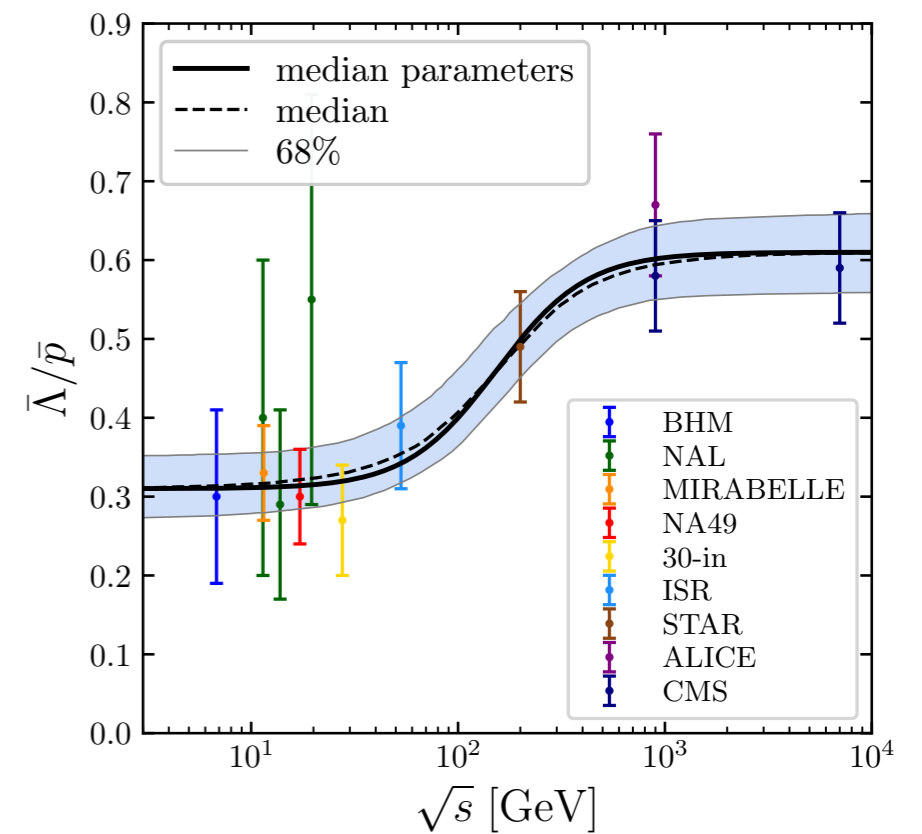
Parametrisation from *Winkler(2016)*

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- **Antineutrons decay:** $p + p \longrightarrow \{\bar{n} \longrightarrow \bar{p}\} + X$

Isospin asymmetry: $\sigma_{pn \rightarrow \bar{p}} > \sigma_{pp \rightarrow \bar{p}} \Rightarrow \sigma_{pp \rightarrow \bar{n}} > \sigma_{pp \rightarrow \bar{p}}$

(*NA49 Anticic+(2010), Winkler(2016)*)



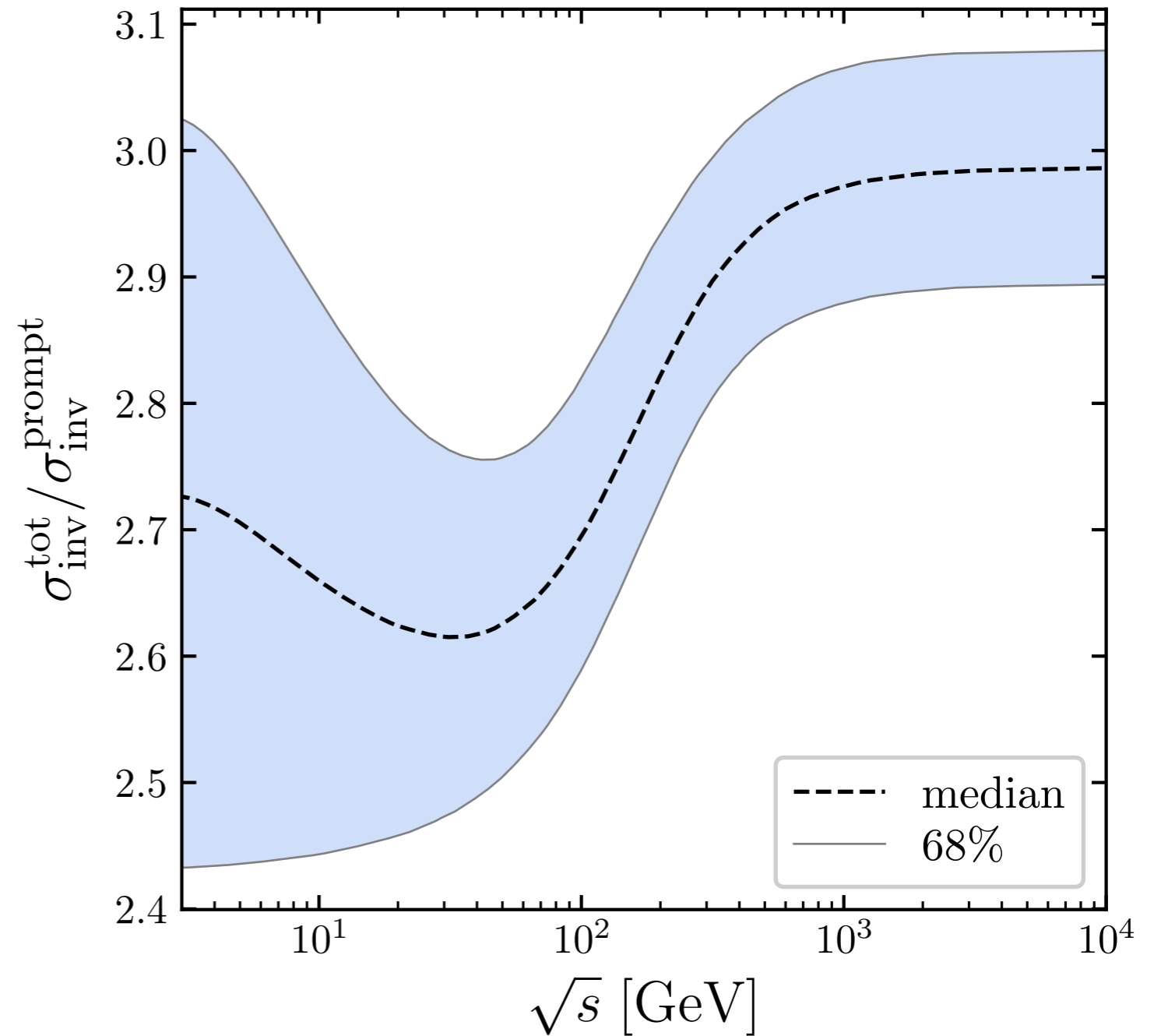
Courtesy M. Winkler

$$\Delta_{\text{IS}} = \frac{\sigma_{pp \rightarrow \bar{n}}}{\sigma_{pp \rightarrow \bar{p}}} - 1$$

$$\Delta_{\text{IS}}(\sqrt{s}) = c_0(x + c_2)^{c_3} \exp(-x/c_1), \quad x = \log(\sqrt{s})$$

Total production XS

$$\sigma_{\text{inv}}^{\text{tot}} = \sigma_{\text{inv}}(2 + \Delta_{\text{IS}} + 2\Delta_{\Lambda})$$



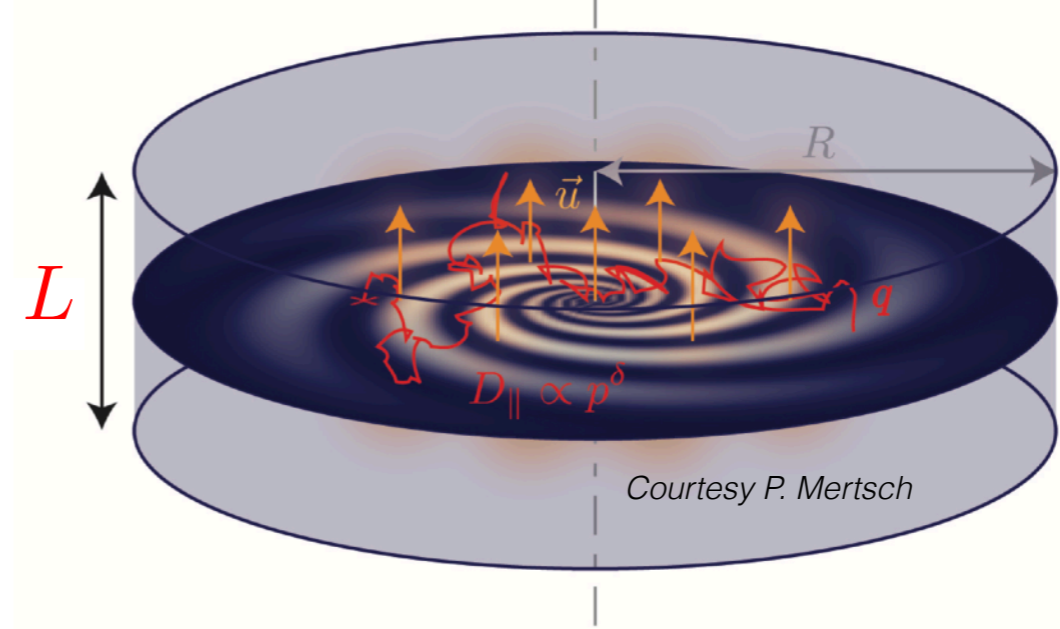
- 20 - 50% correction wrt standard calculations assuming isospin symmetry ($\Delta_{\text{IS}} = 0$)
- energy dependent feature
- 5 - 10% uncertainties

CRs transport in the Galaxy

- **Two-zone diffusion model**

Galactic disc - $h \sim 100$ pc
stars, gas and dust

Magnetic halo - $1 \lesssim L \lesssim 20$ kpc
diffusion zone of the model



$$\begin{aligned}
 - \vec{\nabla}_{\mathbf{x}} \left\{ K(E) \vec{\nabla}_{\mathbf{x}} \psi_{\alpha} - \vec{V}_c \psi_{\alpha} \right\} + \frac{\partial}{\partial E} \left\{ b_{\text{tot}}(E) \psi_{\alpha} - \beta^2 K_{pp} \frac{\partial \psi_{\alpha}}{\partial E} \right\} + \sigma_{\alpha} v_{\alpha} n_{\text{ism}} \psi_{\alpha} + \Gamma_{\alpha} \psi_{\alpha} \\
 = q_{\alpha} + \sum_{\beta} \left\{ \sigma_{\beta \rightarrow \alpha} v_{\beta} n_{\text{ism}} + \Gamma_{\beta \rightarrow \alpha} \right\} \psi_{\beta}
 \end{aligned}$$

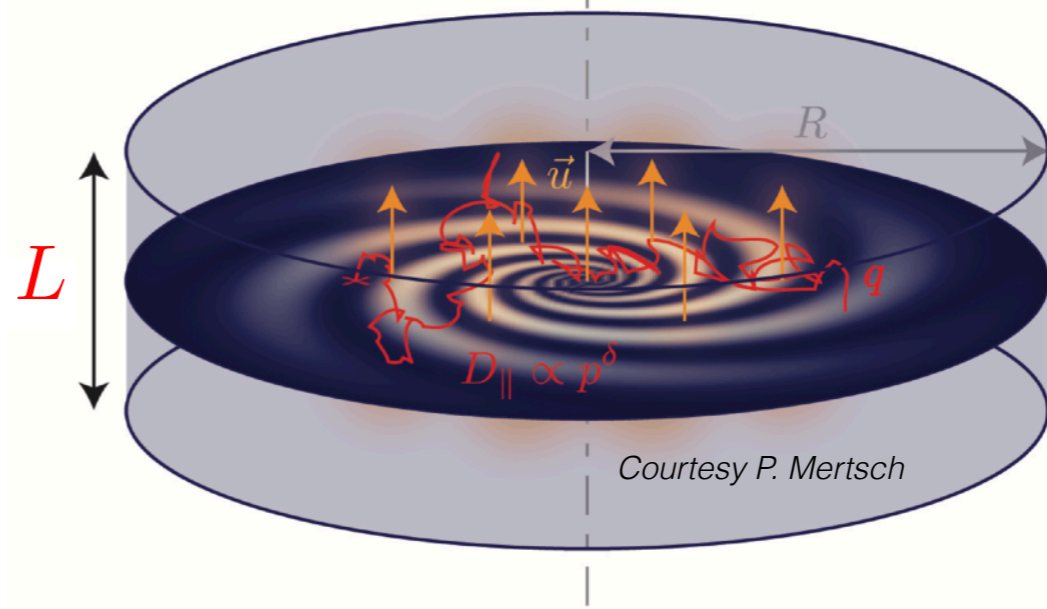
Semi-analytical method implemented in **USINE v3.5** <https://dmaurin.gitlab.io/USINE/> Maurin(2018)

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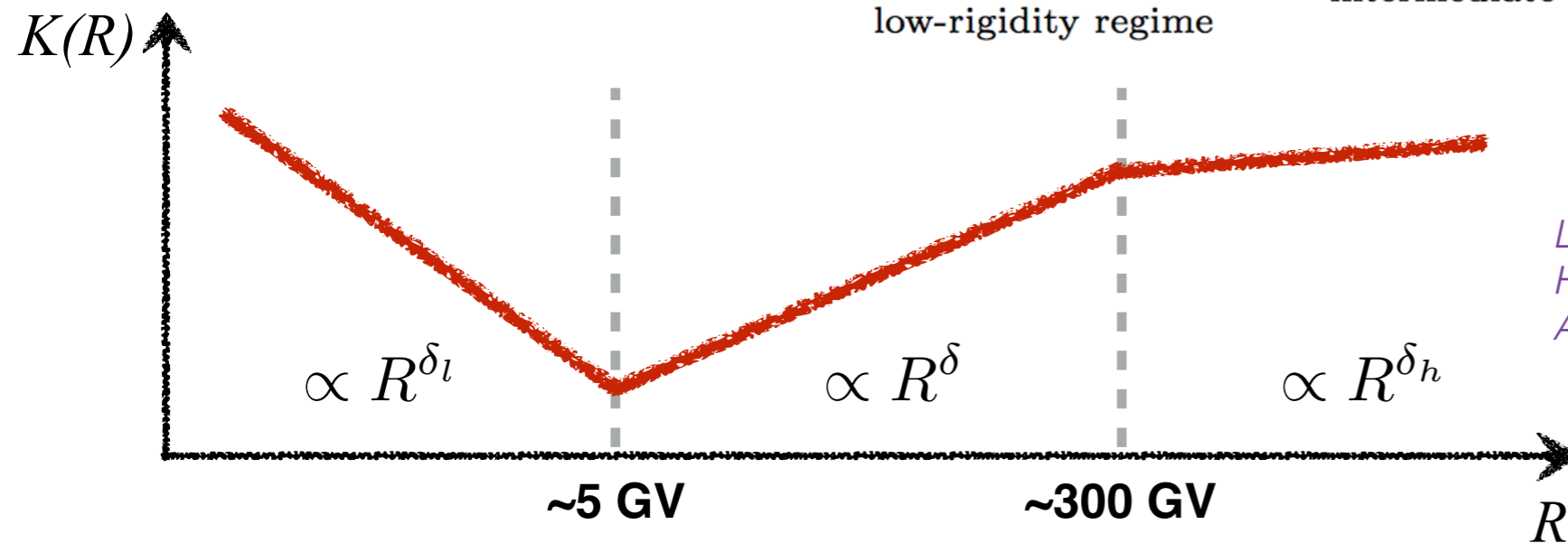


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- **2-break diffusion coefficient**

$$K(R) = \underbrace{\beta^{\eta}}_{\text{non-relativistic regime}} K_{10} \underbrace{\left\{ 1 + \left(\frac{R}{R_l} \right)^{\frac{\delta_l - \delta}{s_l}} \right\}^{s_l}}_{\text{low-rigidity regime}} \underbrace{\left\{ \frac{R}{(R_{10} \equiv 10 \text{ GV})} \right\}^{\delta}}_{\text{intermediate regime}} \underbrace{\left\{ 1 + \left(\frac{R}{R_h} \right)^{\frac{\delta - \delta_h}{s_h}} \right\}^{-s_h}}_{\text{high-rigidity regime}}$$



Low R: Yan+(2004), Putsin+(2005)
High R: Génolini+(2017), Tomassetti(2012),
Aloisio+(2015)

New benchmark models

Fitting B/C cosmic-ray data in the AMS-02 era: a cookbook

Model numerical precision, data covariance matrix of errors, cross-section nuisance parameters, and mock data

L. Derome^{1*}, D. Maurin^{1**}, P. Salati^{4***},
M. Boudaud^{2†}, Y. Génolini^{3‡}, and P. Kunzé¹

Derome+(2019)

BASELINE



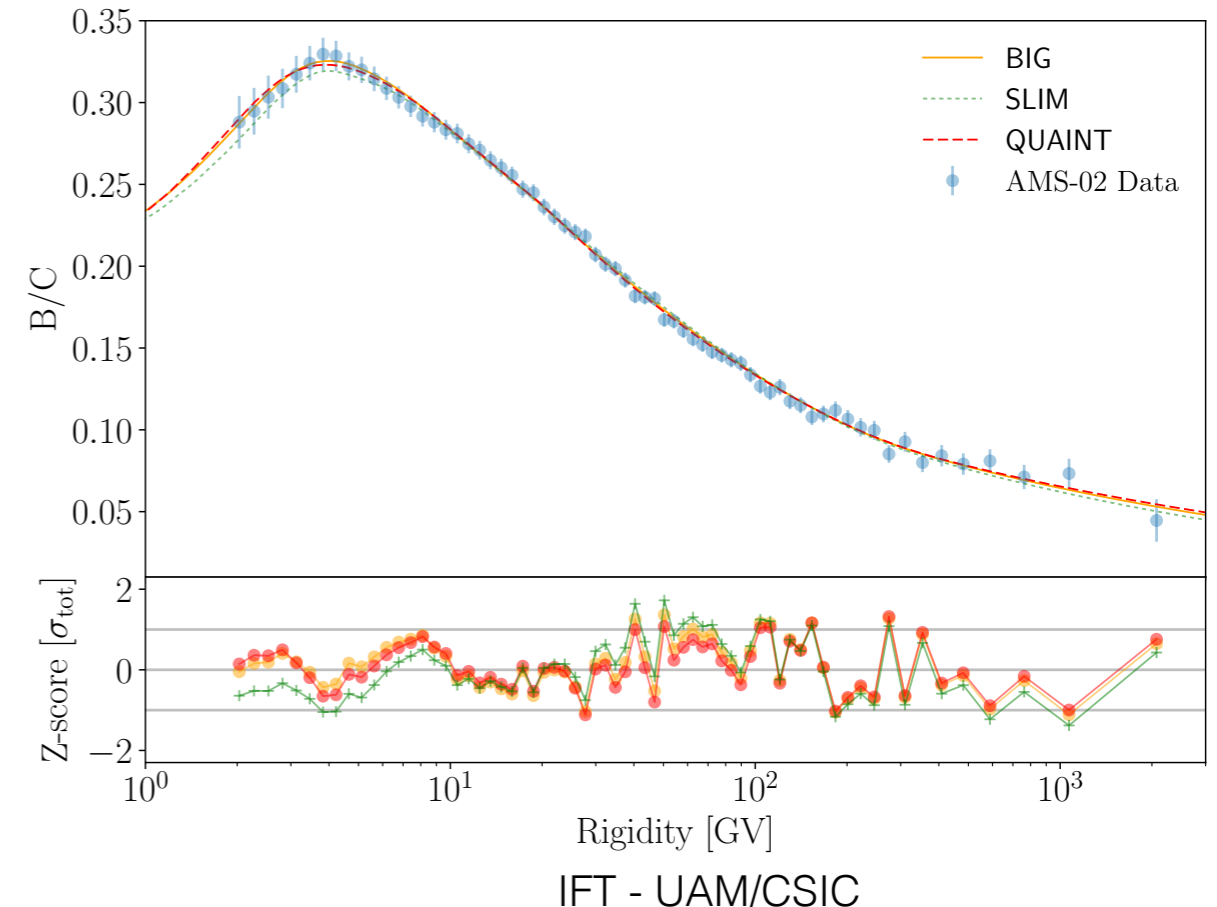
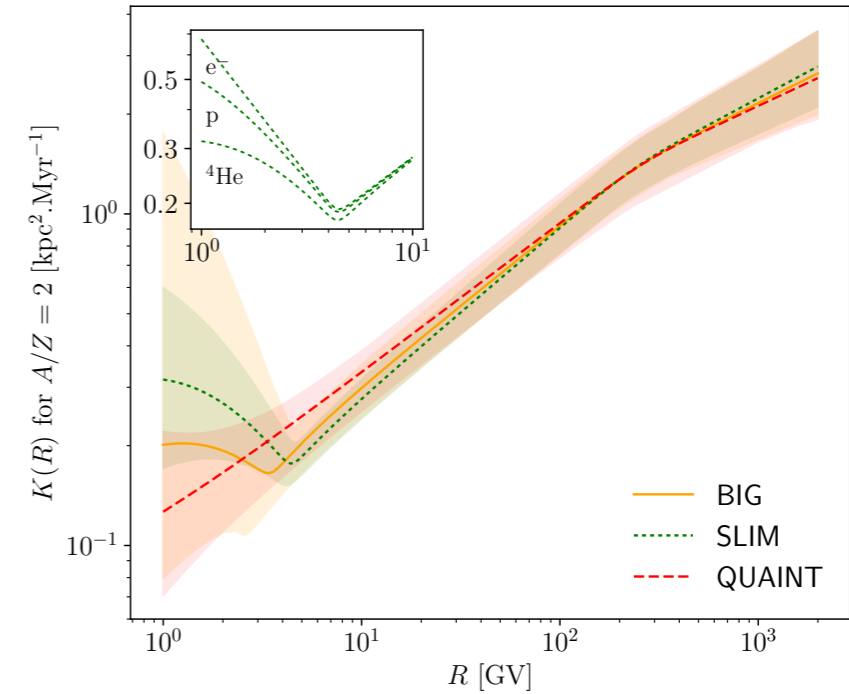
Courtesy Y. Génolini

| Parameters | BIG | SLIM | QUAINT |
|---|---|---|---|
| χ^2/dof | 61.7/61 = 1.01 | 61.8/63 = 0.98 | 62.1/62 = 1.00 |
| Intermediate-rigidity parameters | | | |
| K_{10} [kpc ² Myr ⁻¹] | 0.30 ^{+0.03} _{-0.04} | 0.28 ^{+0.02} _{-0.02} | 0.33 ^{+0.03} _{-0.06} |
| δ | 0.48 ^{+0.04} _{-0.03} | 0.51 ^{+0.02} _{-0.02} | 0.45 ^{+0.05} _{-0.02} |
| Low-rigidity parameters | | | |
| V_c [km s ⁻¹] | 0 ^{+7.4} | N/A | 0.0 ⁺⁸ |
| V_A [km s ⁻¹] | 67 ⁺²⁴ ₋₆₇ | N/A | 101 ⁺¹⁴ ₋₁₅ |
| η | 1 (fixed) | 1 (fixed) | -0.09 ^{+0.35} _{-0.57} |
| δ_l | -0.69 ^{+0.61} _{-1.26} | -0.87 ^{+0.33} _{-0.31} | N/A |
| R_l [GV] | 3.4 ^{+1.1} _{-0.9} | 4.4 ^{+0.2} _{-0.2} | N/A |
| High-rigidity break parameters (nuisance parameters) | | | |
| Δ_h | 0.18 | 0.19 | 0.17 |
| R_h [GV] | 247 | 237 | 270 |
| s_h | 0.04 | 0.04 | 0.04 |

Cosmic-ray transport from AMS-02 boron to carbon ratio data: Benchmark models and interpretation

Y. Génolini,^{1,*} M. Boudaud,^{2,†} P.-I. Batista,³ S. Caroff,⁴ L. Derome,⁵ J. Laval,^{6,‡} A. Marcowith,⁶ D. Maurin,⁵ V. Poireau,⁷ V. Poulin,⁶ S. Rosier,⁷ P. Salati,⁸ P.D. Serpico,^{8,§} and M. Vecchi^{3,9}

Génolini+(2019)



New benchmark models

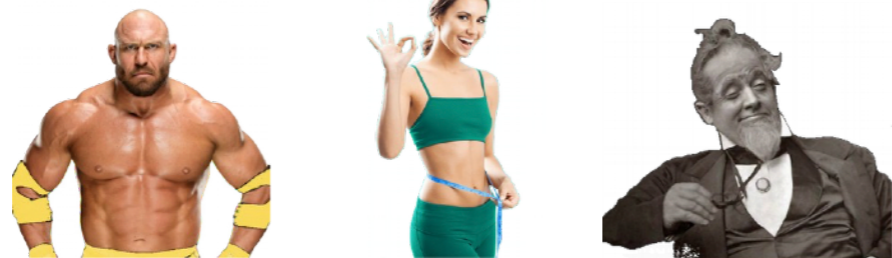
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Derome+(2019)

BASELINE



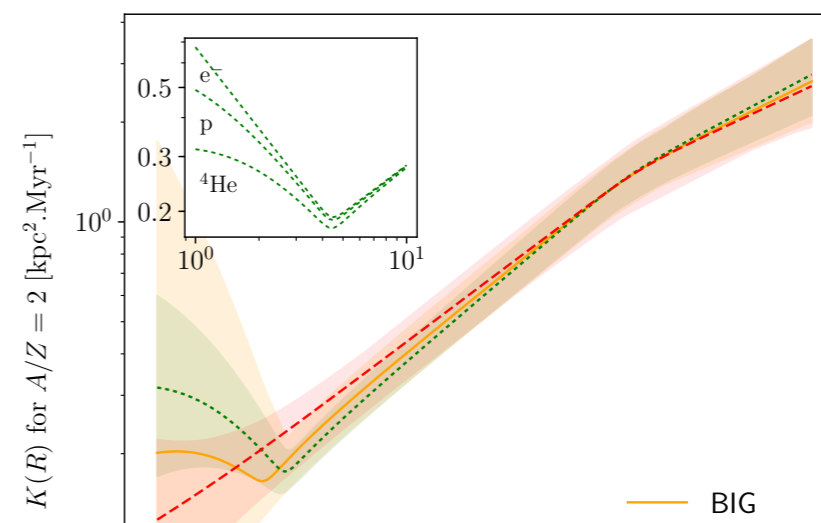
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Génolini+(2019)



Subtleties of the fitting procedure

Derome+(2019)

- **AMS-02 uncertainties**

Errors are dominated by systematics
⇒ model for the covariance matrix of errors

- **Theoretical uncertainties**

⇒ nuisance parameters

- Solar modulation: force field approximation
- Production XS: NSS method for $\sigma^{12\text{C} \rightarrow 11\text{B}}$

[Y. Génolini Wen. 16:15]

K
 δ
 V_c
 V_A
 η
 δ_1
 R_1
 Δ
 R_{11}
 s_h

0.04 0.04 0.04

10^0 10^1 10^2 10^3

Rigidity [GV]

Antiprotons parents: combined fit of AMS-02 H, He, C and O

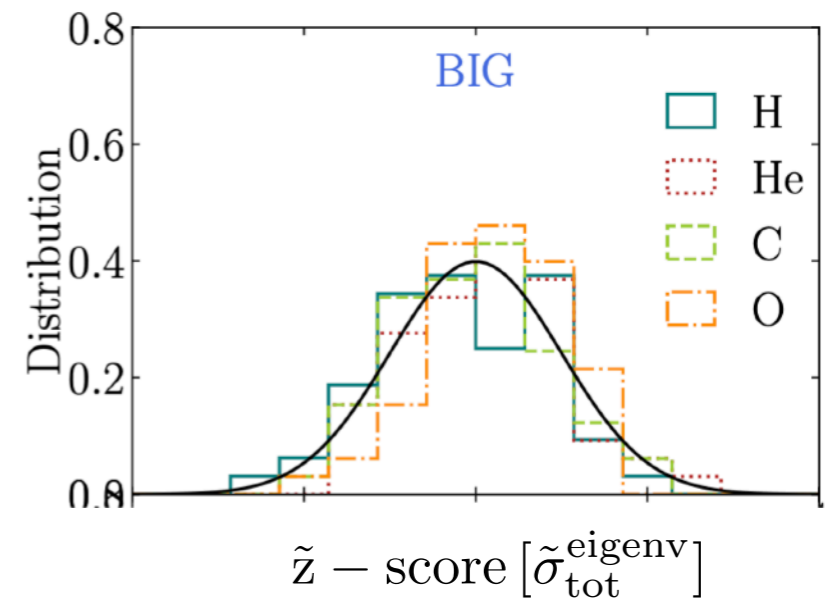
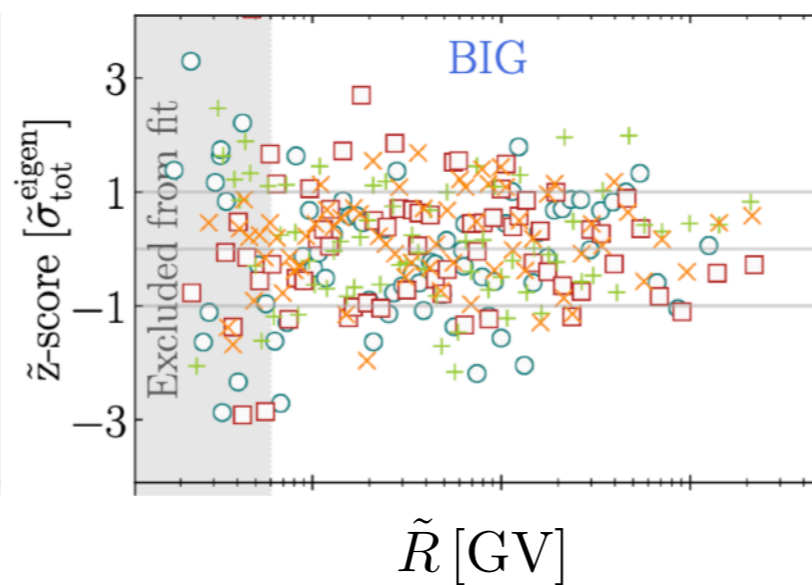
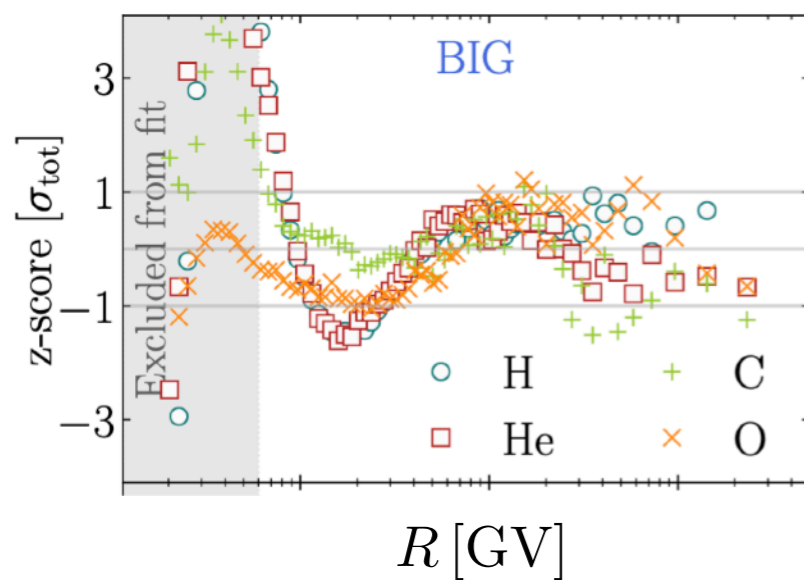
PRL 114 171103 (2015), PRL 119 251101 (2017)

- most abundant CRs \Rightarrow main pbar parents
- spectrum at source: $q(R) = q_0 R^{-\alpha}$
- $T_n > 6$ GeV/n: pbar production threshold

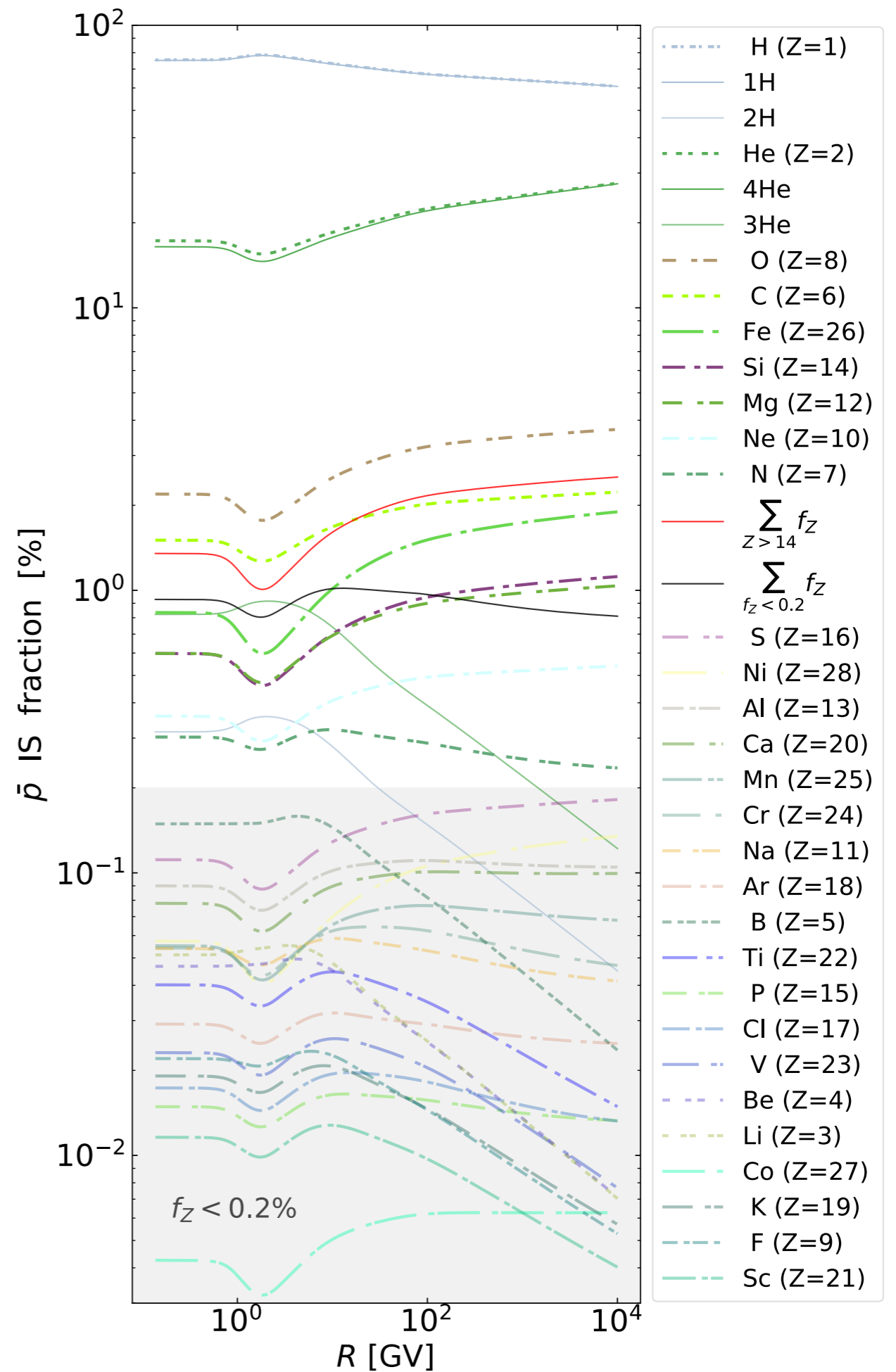
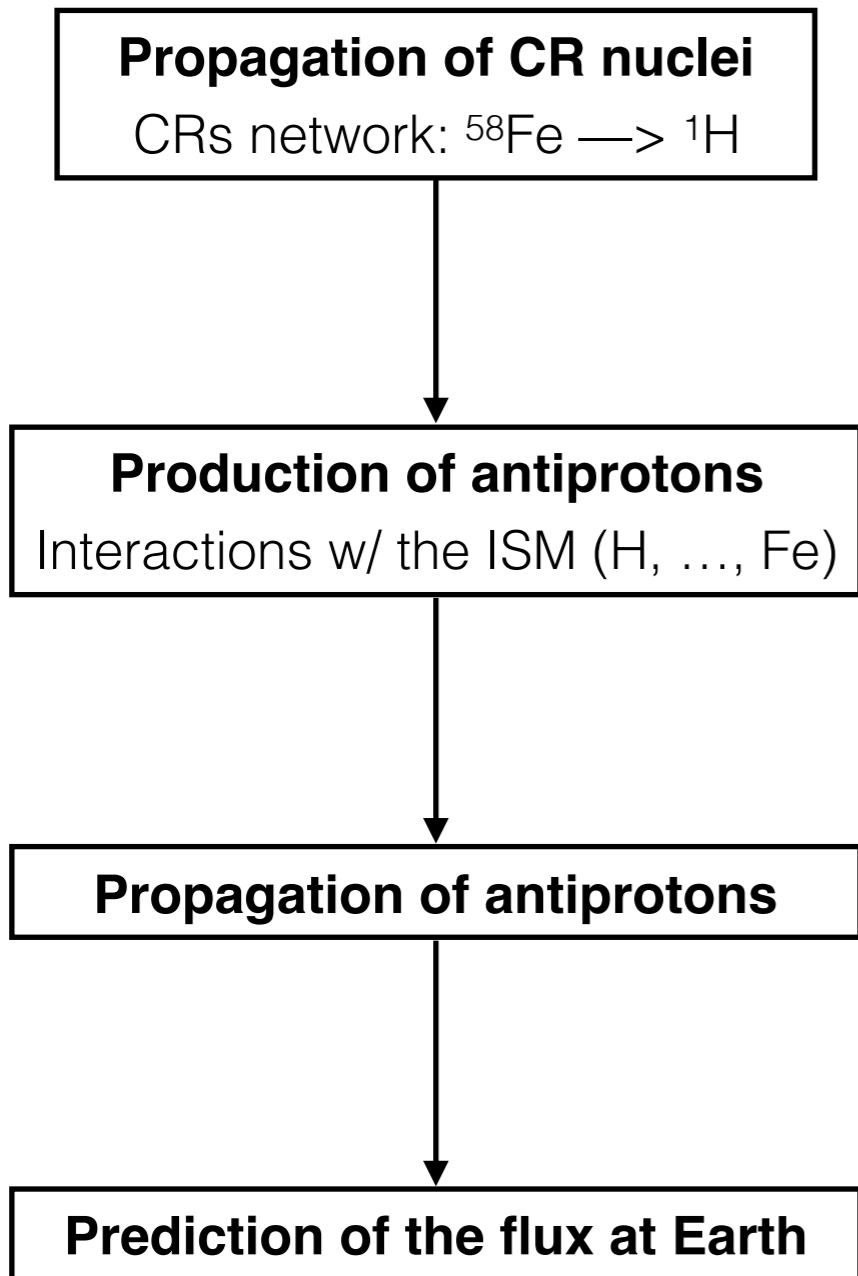
Free parameters

| Source | High energy break |
|---|---|
| $\alpha_{\text{H}}, \alpha_{\text{He}}, \alpha_{Z>2},$ $q_{\text{H}}, q_{\text{He}}, \dots, q_{\text{Si}}$ | $\delta_{\text{h}}, R_{\text{h}}, s_{\text{h}}$ |

$$\chi_{\text{dof}}^2 = 0.90$$



Antiprotons flux calculation



Secondary antiprotons prediction

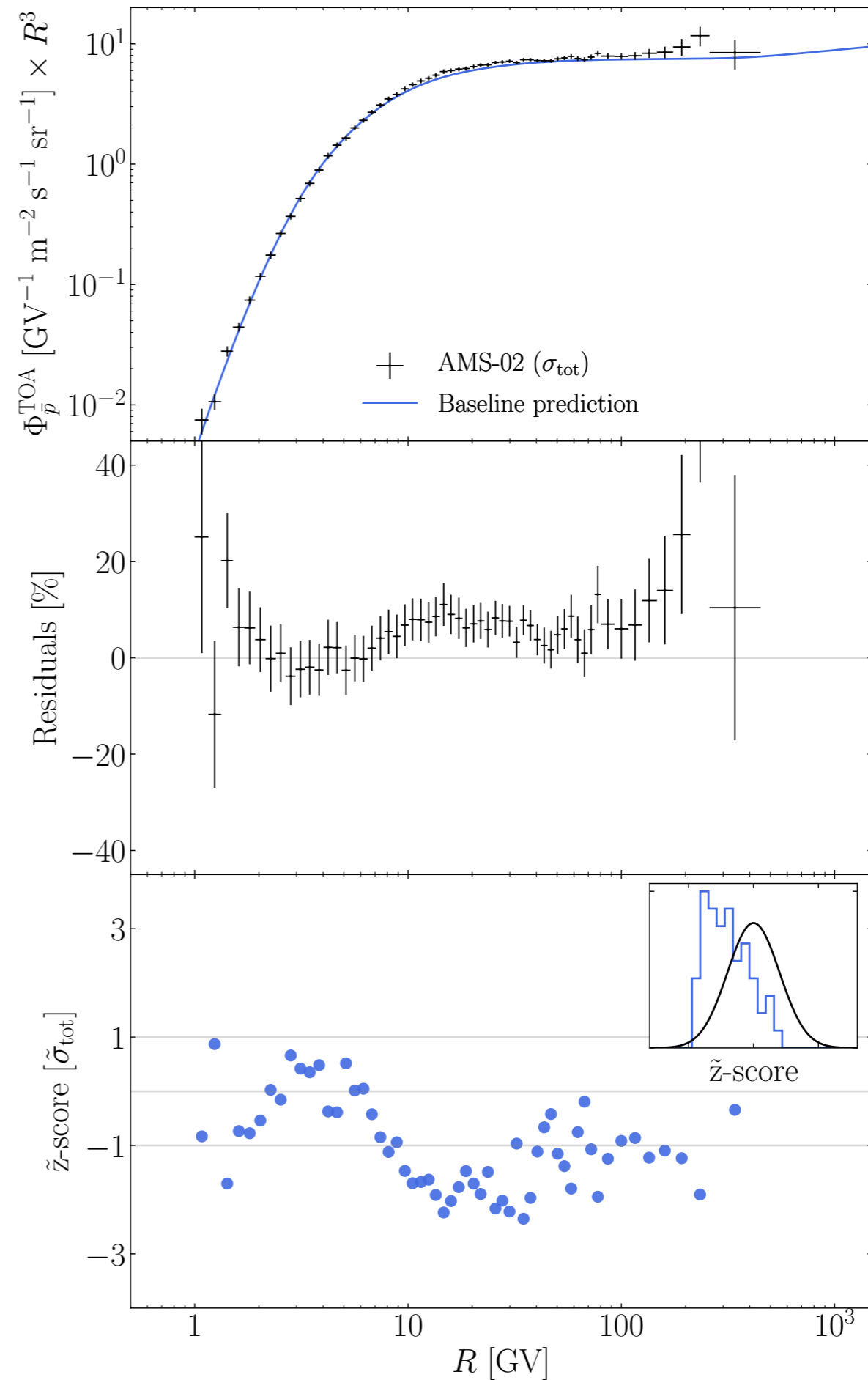
⇒ prediction of the antiprotons flux
(not a fit)

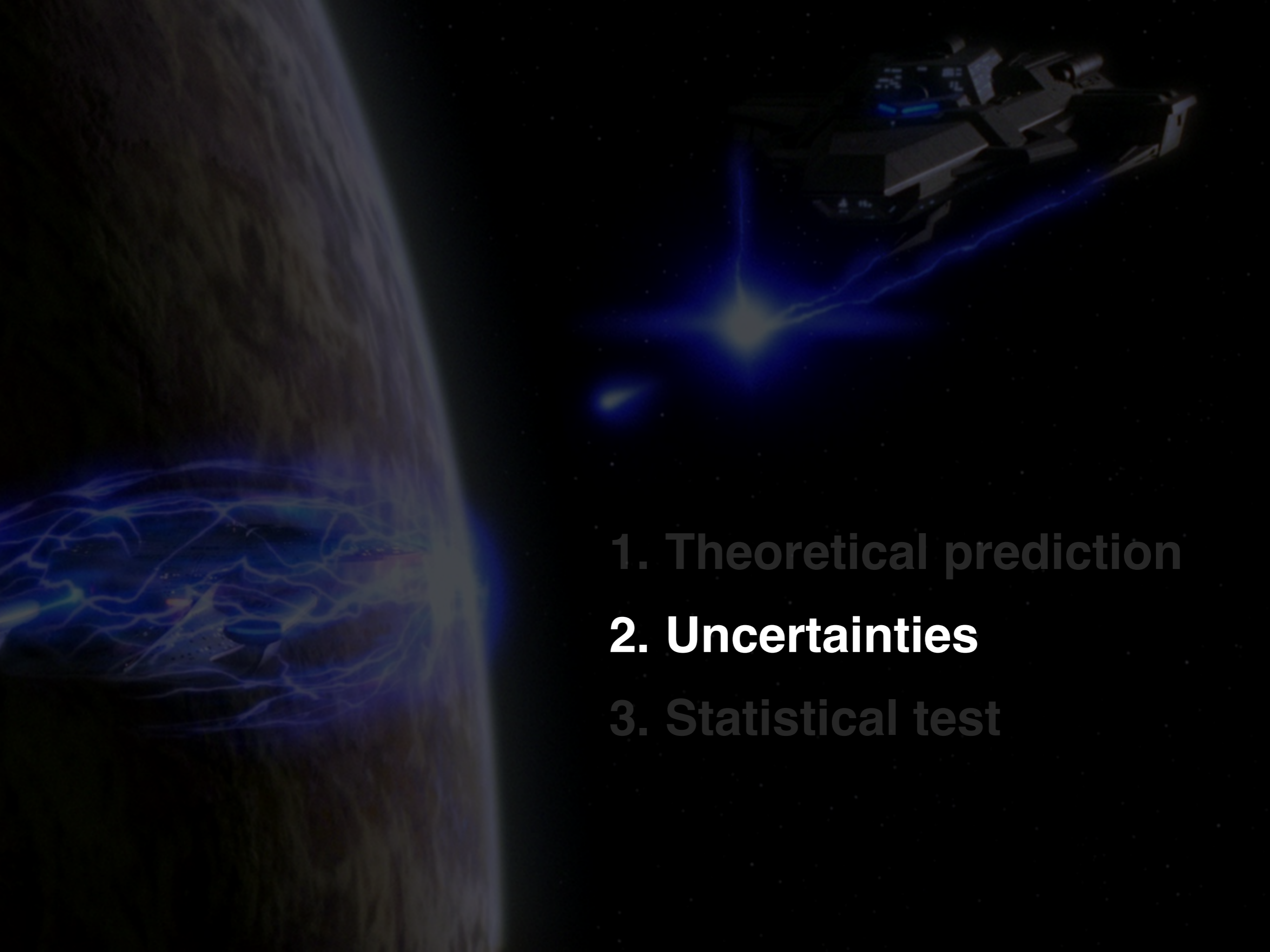


Is there an excess?

Wait, because:

- no model uncertainties
- no correlation in AMS-02 data





1. Theoretical prediction
- 2. Uncertainties**
3. Statistical test

Model uncertainties

- Production XS (fit collider data): 13 parameters
- Transport (fit B/C): 7 parameters
- Parents (fit H, He, C and O): 10 parameters

Correlation between parameters (covariance matrix)

⇒ MC method to propagate the uncertainties:

1. draw from covariance matrix of best-fit parameters 10000 pbar predictions for each source of uncertainties (XS, Transport, Parents)
2. determine the 1σ confidence intervals

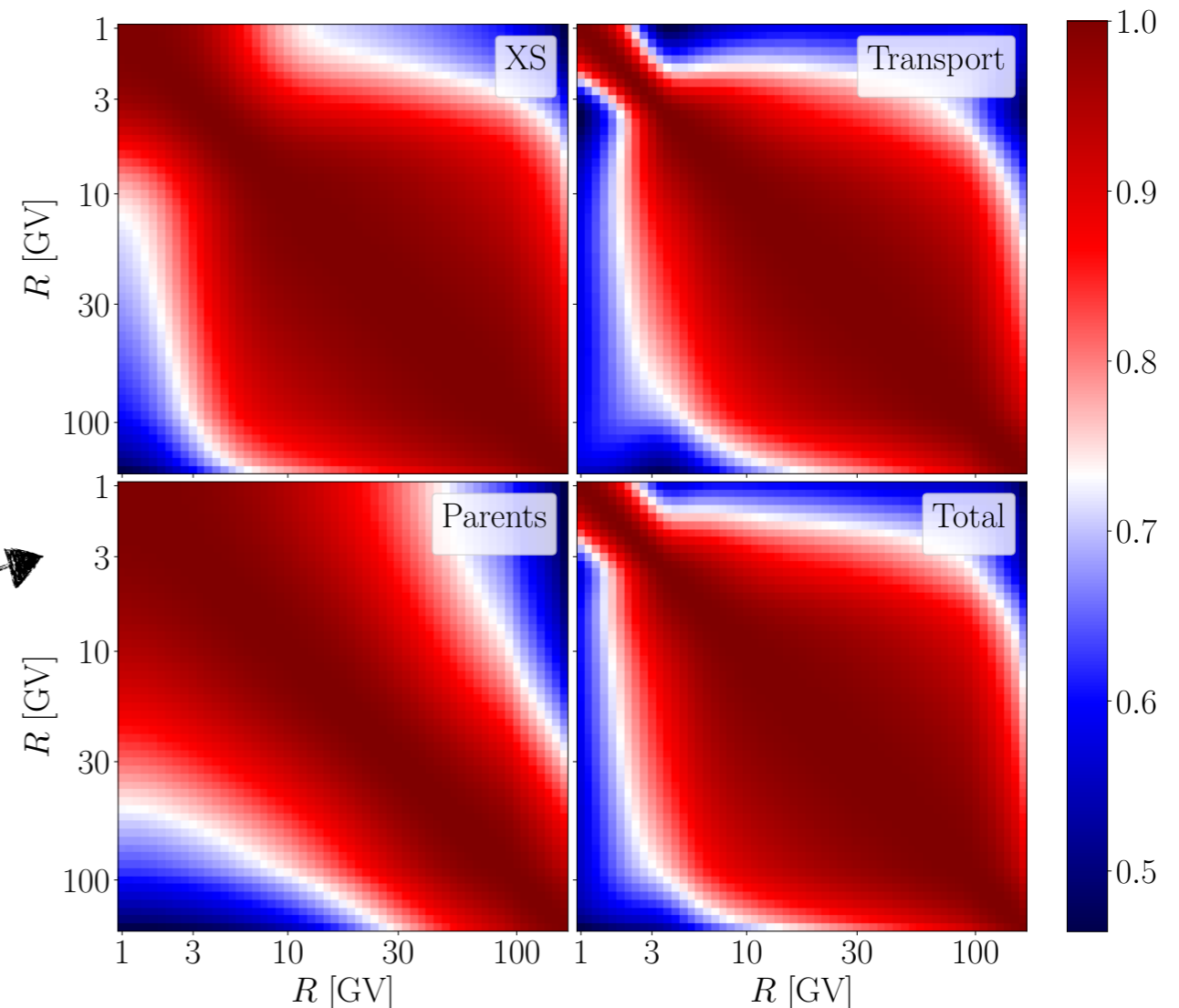
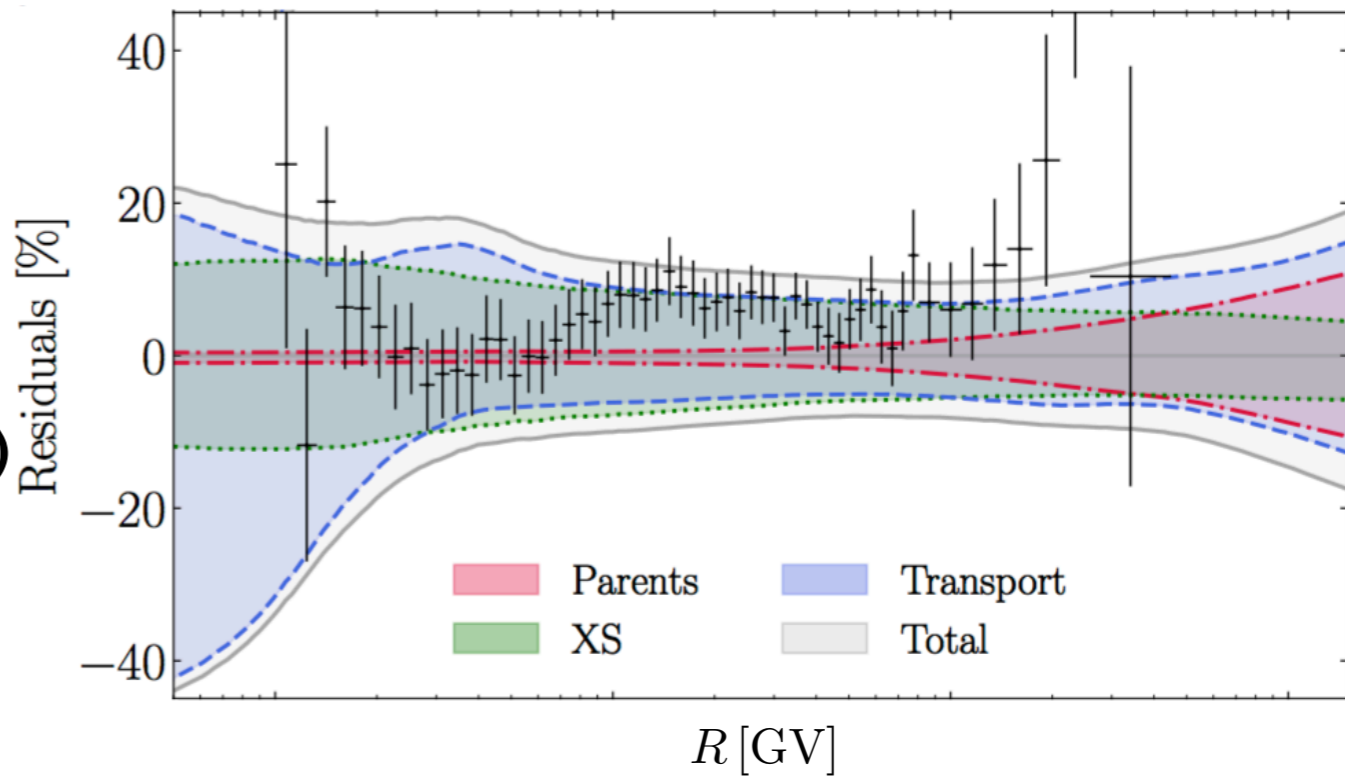
Covariance matrix of model uncertainties

$a \in (\text{XS, Transport, Parents})$

$$C_{ij}^a = \frac{1}{N} \sum_{n=1}^N (\Phi_{i,n}^a - \mu_i^a) (\Phi_{j,n}^a - \mu_j^a)$$

μ_i^a : mean prediction at the rigidity bin i

$$c_{ij}^\alpha = \frac{C_{ij}^\alpha}{\sqrt{C_{ii}^\alpha} \sqrt{C_{jj}^\alpha}} : \text{associated correlation matrix}$$



Data uncertainties

PRL 117 091103 (2016)

AMS-02 antiprotons uncertainties (from publication)

- broken-down uncertainties
(Cut-off, Sel., Templ., XS, Unf., Scale, Acc)
- no covariance matrix of errors

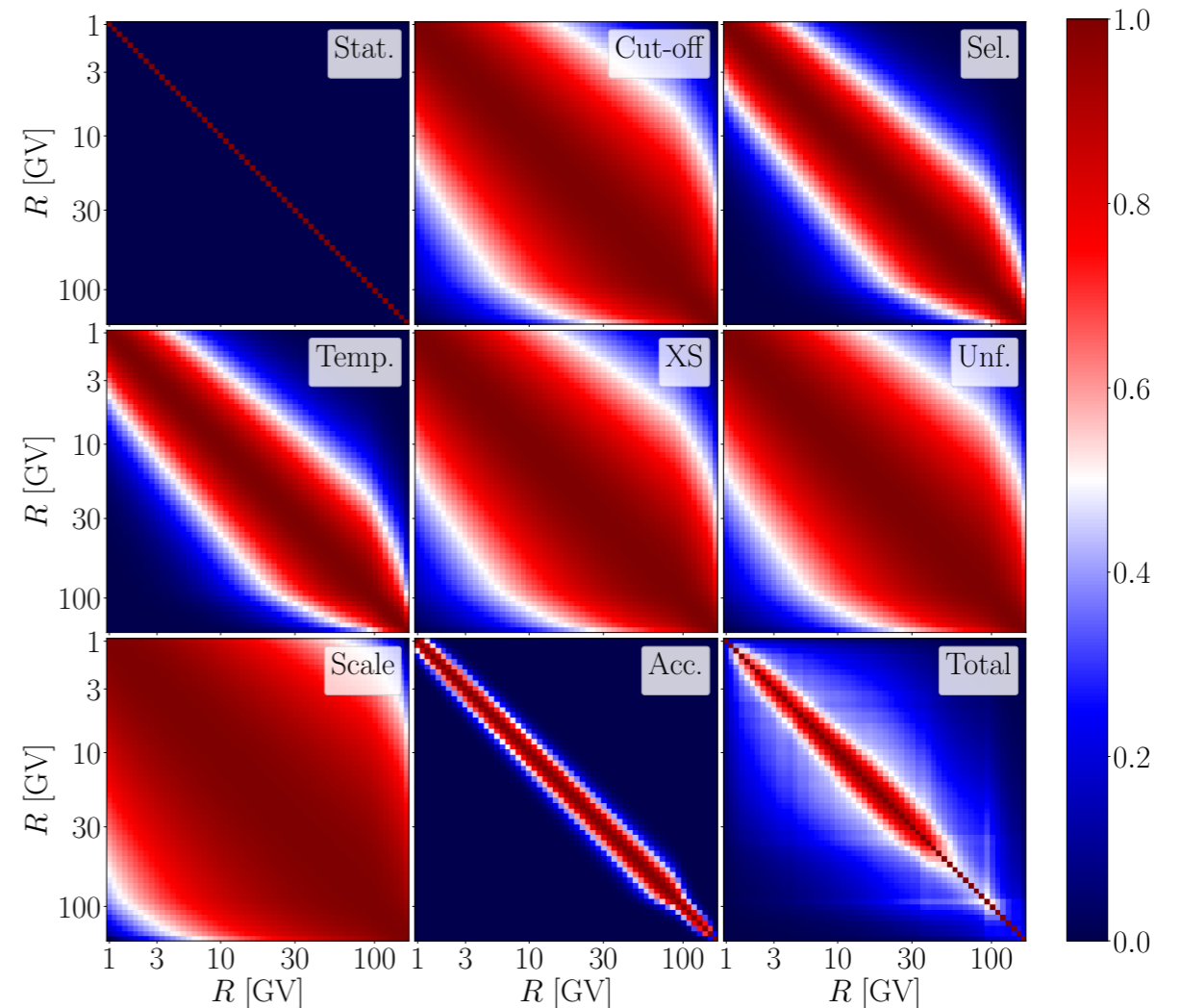
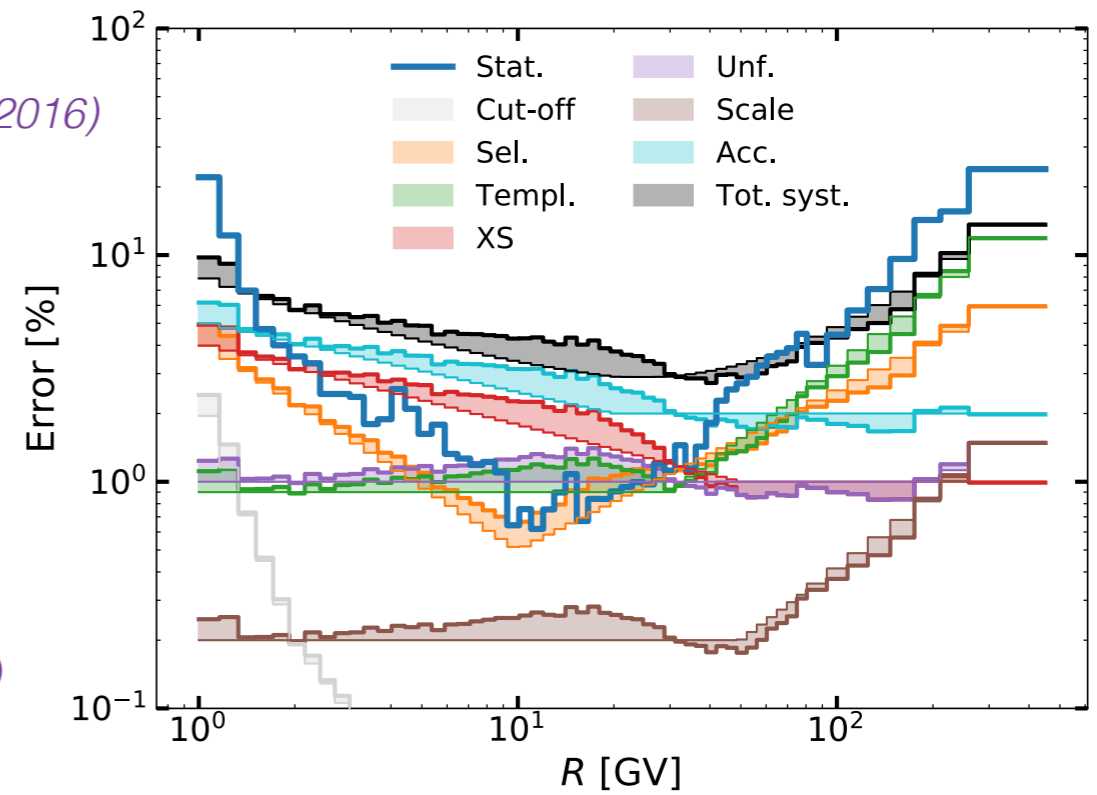
Covariance matrix of data uncertainties *Derome+(2019)*

$\alpha \in (\text{Cut-off, Sel., Templ., XS, Unf., Scale, Acc})$

$$(C^\alpha)_{ij} = \sigma_i^\alpha \sigma_j^\alpha \exp\left(-\frac{1}{2} \frac{(\log_{10}(R_i/R_j))^2}{(l_\rho^\alpha)^2}\right)$$

Correlation length

| | |
|----------------|-----|
| Scale | 4.0 |
| Unf. | 1.0 |
| Acc. | 0.1 |
| Cut-off | 1.0 |
| Sel. | 0.5 |
| Templ. | 0.5 |
| XS | 1.0 |



Secondary antiprotons prediction

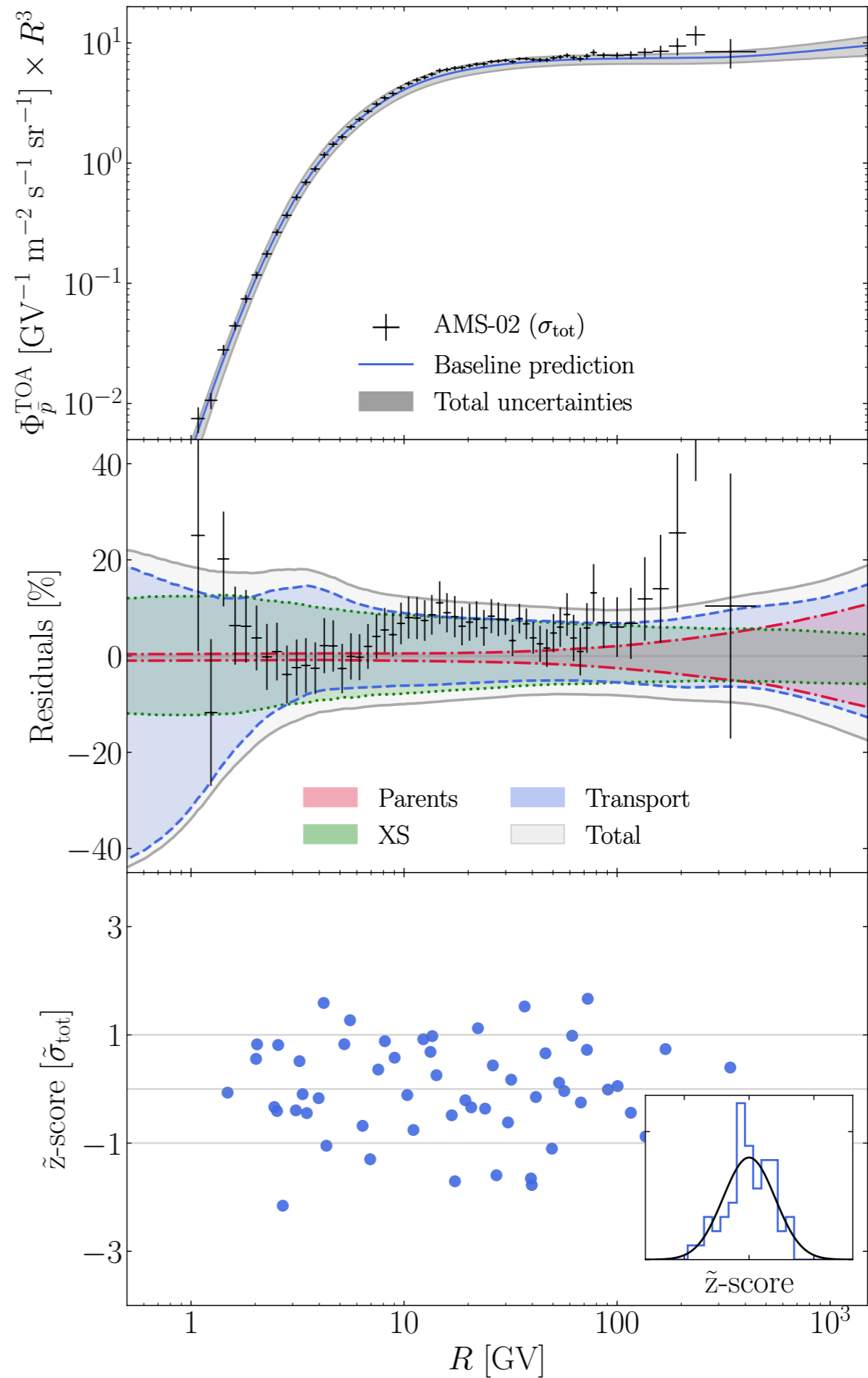
⇒ prediction of the antiprotons flux
(not a fit)

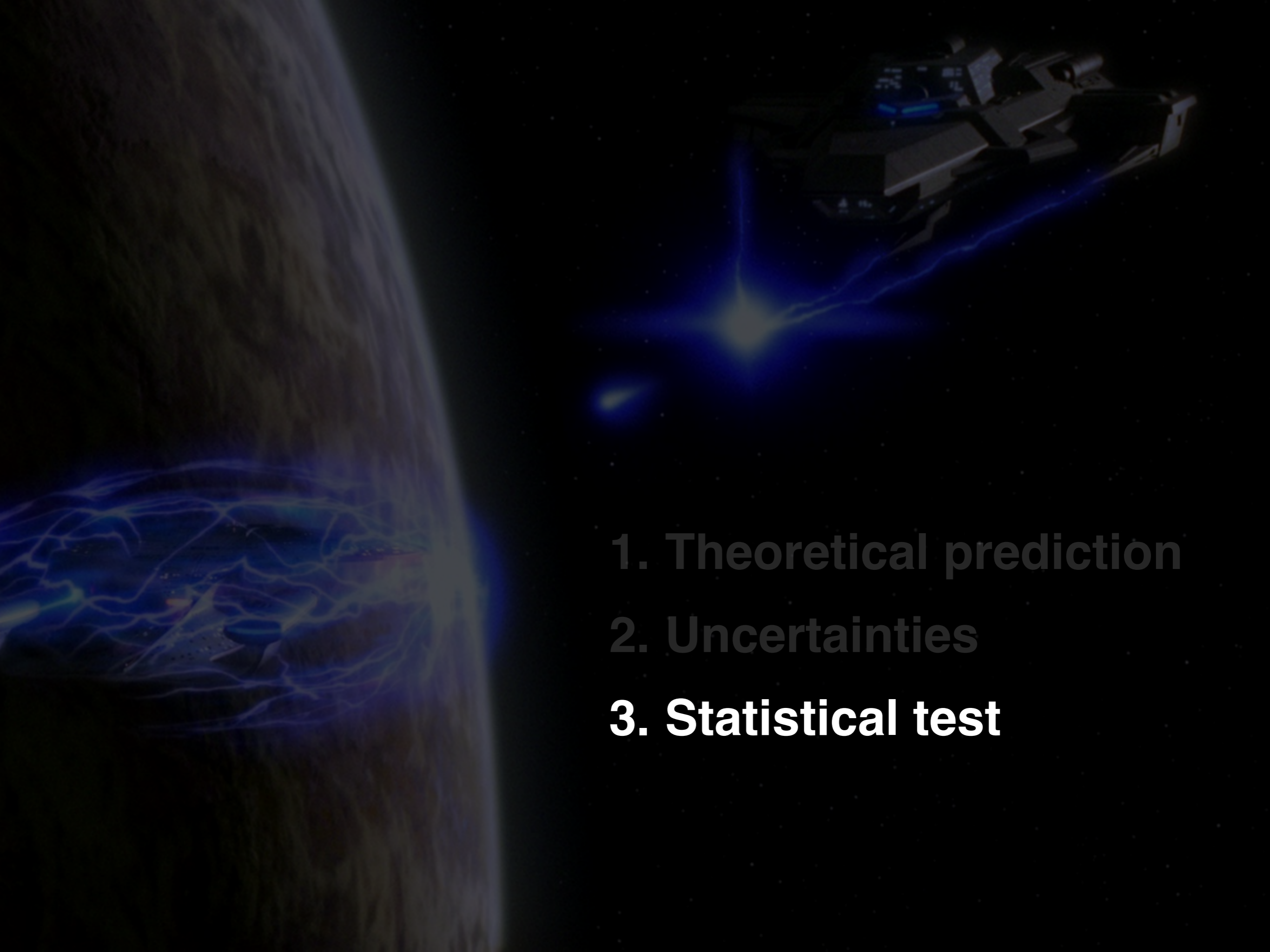


Is there an excess?

model uncertainties

correlation in AMS-02 data





1. Theoretical prediction
2. Uncertainties
- 3. Statistical test**

Statistical test

$$\chi^2 = \sum_{i,j} x_i (\mathcal{C}^{-1})_{ij} x_j,$$

$$x_i = \text{data}_i - \text{model}_i$$

$$\mathcal{C} = \mathcal{C}^{\text{data}} + \mathcal{C}^{\text{model}}$$

| Error considered | χ^2/dof | p-value (χ^2 -test) |
|--|---------------------|------------------------------|
| $\mathcal{C}^{\text{data}} + \mathcal{C}^{\text{model}}$ | 0.77 | 0.90 |

Good agreement
between data and model

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Good agreement
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Limitation of χ^2 -test in this context

- Relies on the notion of degrees of freedom which is not well defined when correlations matter
- Does not assess a possible overestimate of errors

Statistical test

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| Error considered | χ^2/dof | p-value (χ^2 -test) | p-value (KS-test) |
|--|---------------------|---------------------------|-------------------|
| $\mathcal{C}^{\text{data}} + \mathcal{C}^{\text{model}}$ | 0.77 | 0.90 | 0.86 |

Good agreement
between data and model



Limitation of χ^2 -test in this context

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Kolmogorov-Smirnov (KS-test)

- Does not rely on the notion of degrees of freedom
- Assesses a possible overestimate of errors

Statistical test

$$\chi^2 = \sum_{i,j} x_i (\mathcal{C}^{-1})_{ij} x_j,$$

$$x_i = \text{data}_i - \text{model}_i$$

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| Error considered | χ^2/dof | p-value (χ^2 -test) | p-value (KS-test) |
|--|---------------------|---------------------------|-------------------|
| $\mathcal{C}^{\text{data}} + \mathcal{C}^{\text{model}}$ | 0.77 | 0.90 | 0.86 |

Good agreement
between data and model

| | | | |
|---|------|------|------|
| $\mathcal{C}^{\text{data}}$ | 0.85 | 0.79 | 0.97 |
| σ_{stat} and $\mathcal{C}^{\text{model}}$ | 1.32 | 0.05 | 0.99 |

\Rightarrow AMS-02 data are consistent with secondary antiprotons

Conclusion robust wrt:

- statistical test (χ^2 vs KS)
- error mismodelling of model or data

Summary

Prediction (not a fit) of the secondary antiprotons flux from the state of the art:

- Data (AMS-02)
 - CR fluxes: H, He, C, O *PRL 114 171103 (2015), PRL 119 251101 (2017)*
 - CR ratio: B/C *PRL 117 231102 (2016)*
- Models
 - CR transport in the Galaxy *Derome+(2019), Génolini+(2019)*
 - antiprotons production cross sections (XS) *Winkler(2016), Korsmeier+(2018)*

⇒ **AMS-02 data are consistent with secondary antiprotons**

Summary

Prediction (not a fit) of the secondary antiprotons flux from the state of the art:

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⇒ **AMS-02 data are consistent with secondary antiprotons**

Thank you for your attention!

Questions?

Back up

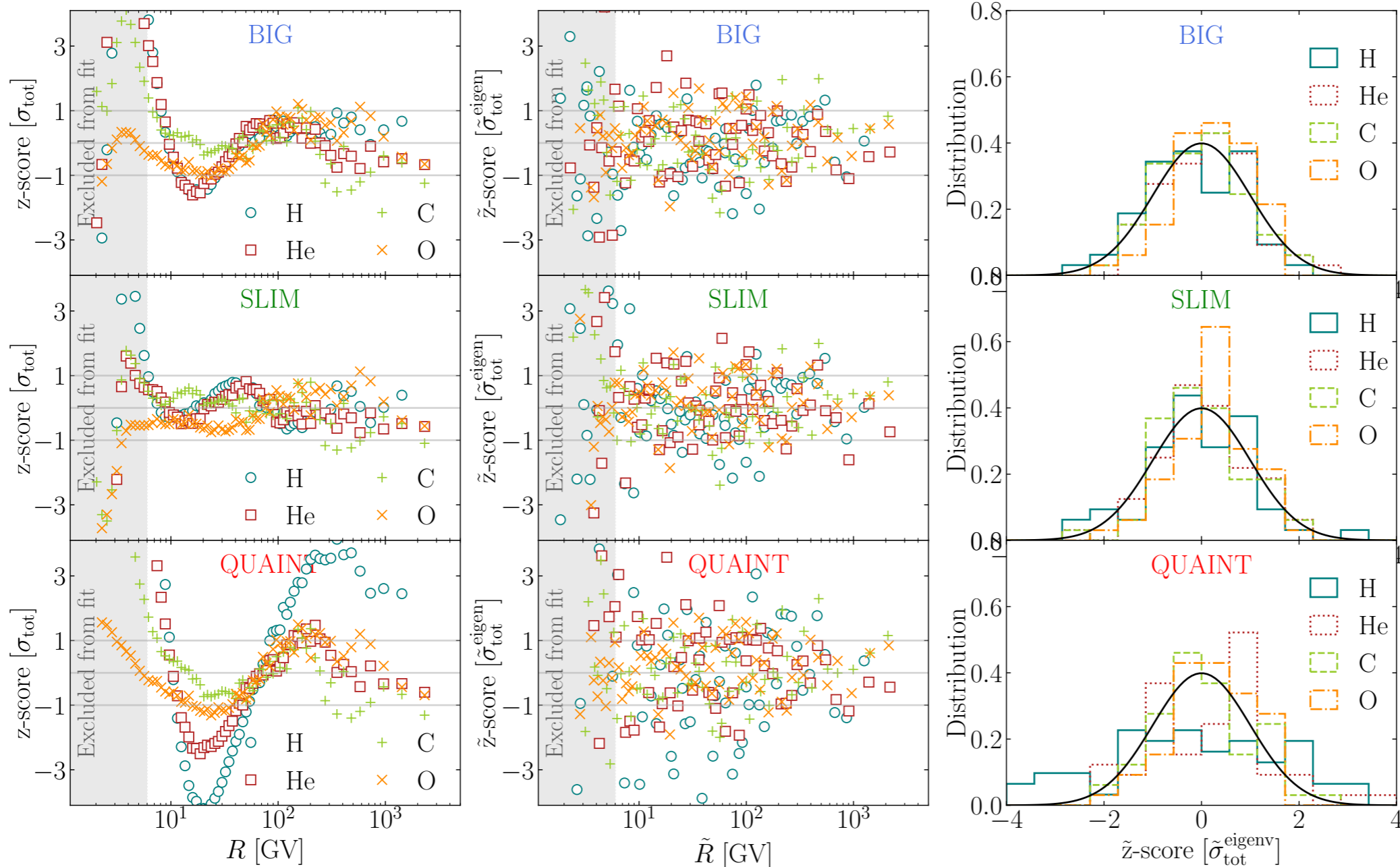
Antiprotons parents: combined fit of AMS-02 H, He, C and O

PRL 114 171103 (2015), PRL 119 251101 (2017)

- most abundant CRs \Rightarrow main pbar parents
- spectrum at source: $q(R) = q_0 R^{-\alpha}$
- $T_n > 6$ GeV/n: pbar production threshold

Free parameters

| Source | High energy break |
|--|----------------------|
| $\alpha_H, \alpha_{He}, \alpha_{Z>2},$ $q_H, q_{He}, \dots, q_{Si}$ | δ_h, R_h, s_h |



Antiprotons parents: heavy species

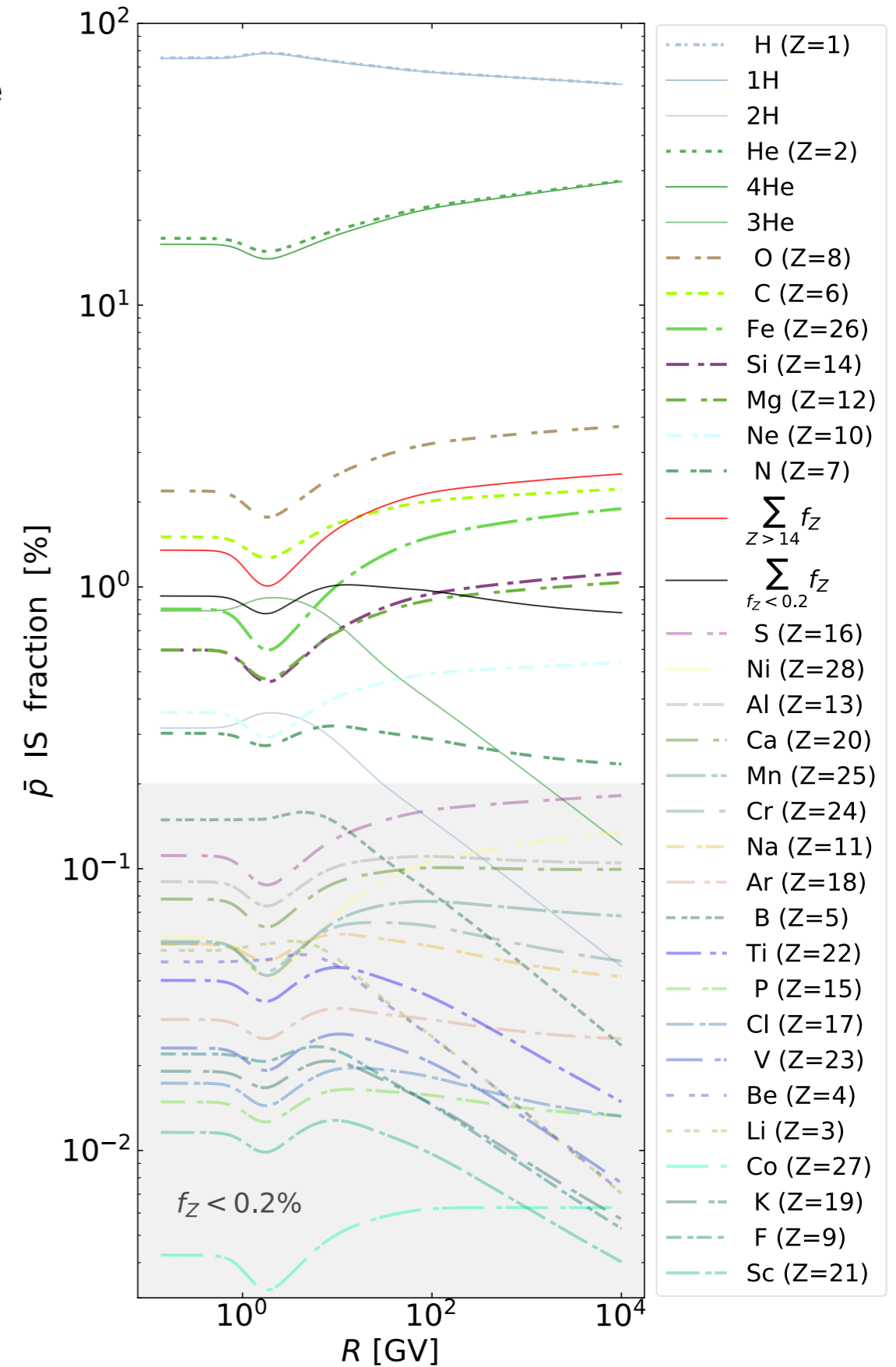
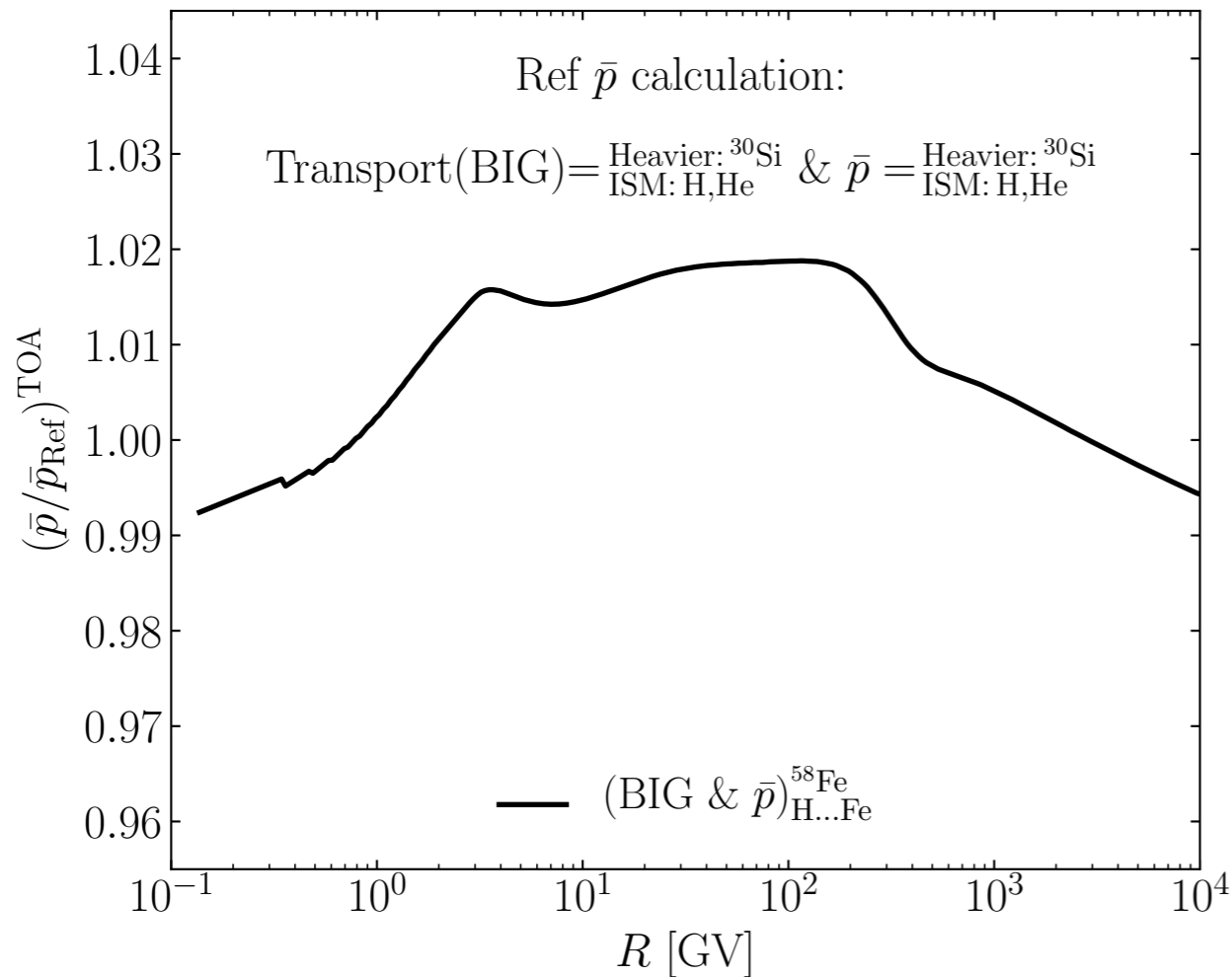
Reference

- CRs network: $^1\text{H} \rightarrow ^{30}\text{Si}$
 - ISM: H, He
- \Rightarrow fast calculation

Heavier species

- CRs network: $^1\text{H} \rightarrow ^{58}\text{Fe}$
 - ISM: $\text{H} \rightarrow \text{Fe}$
- \Rightarrow slow calculation

- 3% correction wrt standard calculation
 - peculiar energy dependent feature
- \Rightarrow correction included in the following



Statistical test

$$\chi^2 = \sum_{i,j} x_i (\mathcal{C}^{-1})_{ij} x_j, \quad x_i = \text{data}_i - \text{model}_i$$

$$\mathcal{C} = \mathcal{C}^{\text{data}} + \mathcal{C}^{\text{model}}$$

| Error considered | χ^2/dof | p-value (χ^2) | p-value (KS) |
|----------------------------|--|----------------------|----------------------|
| data uncertainties only | σ_{stat} | 23 | 0 |
| | σ_{tot} | 1.69 | 8.3×10^{-4} |
| | $\mathcal{C}^{\text{data}}$ | 0.84 | 0.79 |
| data + model uncertainties | σ_{stat} and $\mathcal{C}^{\text{model}}$ | 1.32 | 0.05 |
| | σ_{tot} and $\mathcal{C}^{\text{model}}$ | 0.37 | 1.0 |
| | $\mathcal{C}^{\text{data}}$ and $\mathcal{C}^{\text{model}}$ | 0.77 | 0.90 |

$$\left(\sigma_{\text{tot}} = \sqrt{\sigma_{\text{stat}}^2 + \sigma_{\text{syst}}^2} \right)$$



Limitation of χ^2 -test in this context

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- Does not assess a possible overestimate of errors

Kolmogorov-Smirnov (KS-test)

- Does not rely on the notion of degrees of freedom
- Assesses a possible overestimate of errors