# AMS-02 ANTIPROTONS ARE CONSISTENT WITH A SECONDARY ASTROPHYSICAL ORIGIN

**arXiv:1906.07119**

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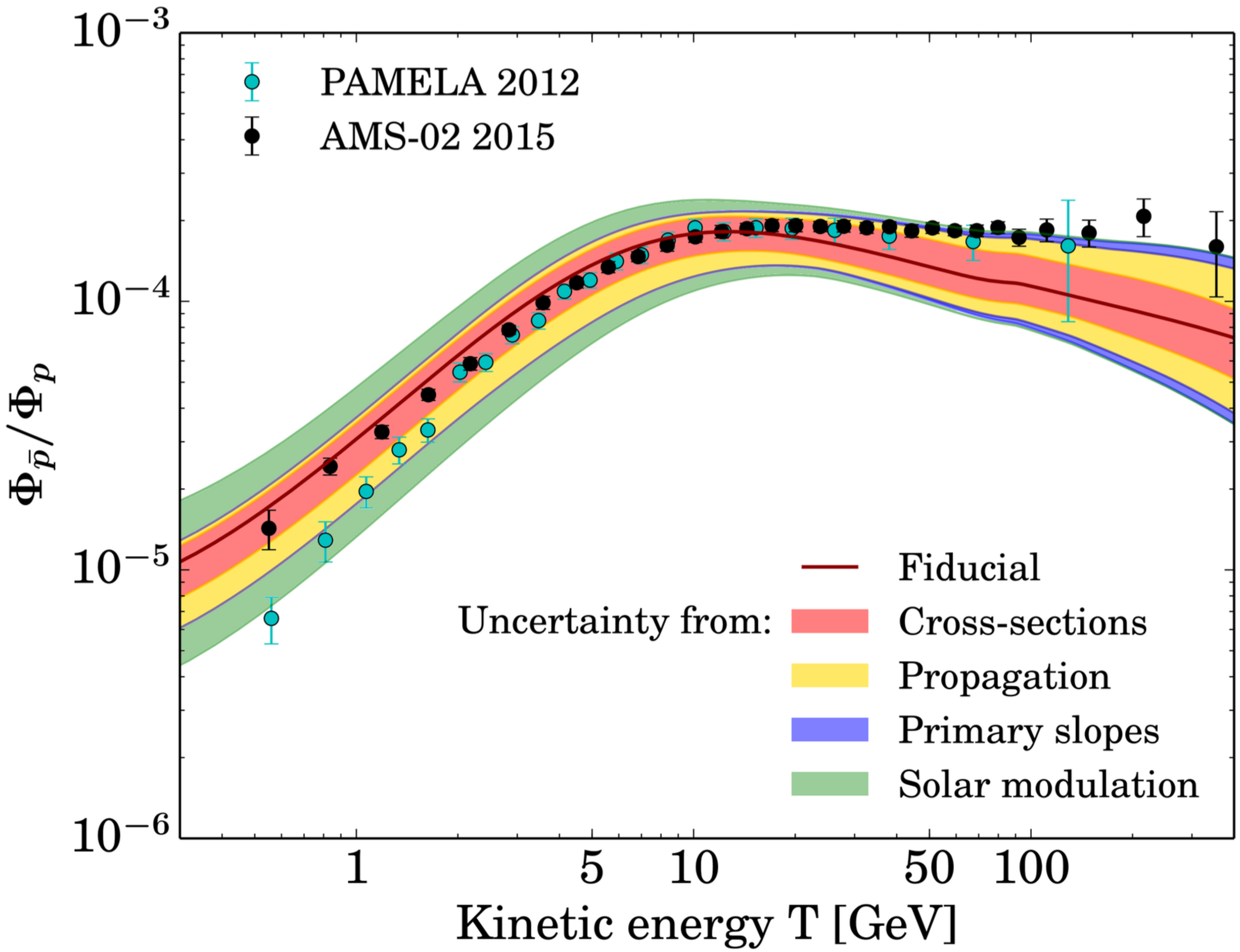
# Secondary antiprotons: a new prediction

**2015:** AMS-02 antiprotons, at last! Secondary astrophysical component and immediate implications for DM

*Giesen+(2015) arXiv:1504.04276*




# Secondary antiprotons: a new prediction

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**New inputs since 2015**

| DATA | MODEL |
|---|---|
| **AMS-02**<br>• pbar flux<br>• H, He, C, N, O fluxes<br>(most abundant CRs ⟹ main pbar parents)<br>• B/C ratio (CR tranport)<br>• **Systematic errors**<br>AMS-02 collaboration does not provide the covariance matrix of errors<br>⟹ homemade covariance matrix based on the description of systematics in AMS-02 papers | **CR transport**<br>New models from AMS-02 B/C (Génolini et al.)<br>• QUAINT: historical model diff/conv/reac<br>• SLIM: pure diffusion w/ 2 breaks in the diff. coef.<br>• BIG: diffusion/convection/reacceleration + 2 breaks in the diffusion coef.<br>(QUAINT, SLIM) ⊂ BIG |
| **Production XS**<br>• **NA61**: p+p —> pbar + X<br>$\sqrt{s}$ = 7.7, 8.8, 12.3 and 17.3 GeV<br>Tp = 31, 40, 80 and 158 GeV<br>• **LHCb**: p+He —> pbar + X<br>$T_p$ = 6.5 TeV | **Production XS**<br>• Prompt pbar in pp reactions<br>New parametrisations of the Lorentz invariant production XS<br>$\sigma_{inv} = Ed^3\sigma/dp^3$<br>*Winkler+(2016), Korsmeier+(2018)*<br>• Antihyperons ($\Delta_\Lambda$) and isospin asymmetry ($\Delta_{IS}$)<br>New energy dependant ($\sqrt{s}$) parametrisations |

# Production XS

- **Prompt pbar in pp reactions (p + p —> pbar + X)**
  Parametrisation II from *Korsmeier+(2018)*
  - functional form of $\sigma_{inv}(\sqrt{s}, x_R, p_T)$ from *Winkler+(2016)*
  - updated parameters using NA49, NA61, BRAHMS, Dekkers+(1965) *Korsmeier+(2018)*

- **Prompt pbar in AA reactions ($A_1$ + $A_2$—> pbar + X)**
  Parametrisation B from *Korsmeier+(2018)*
  - functional form of the nucleon scaling $f^{A1A2}(\sqrt{s}, x_F)$ from *Winkler+(2016)*
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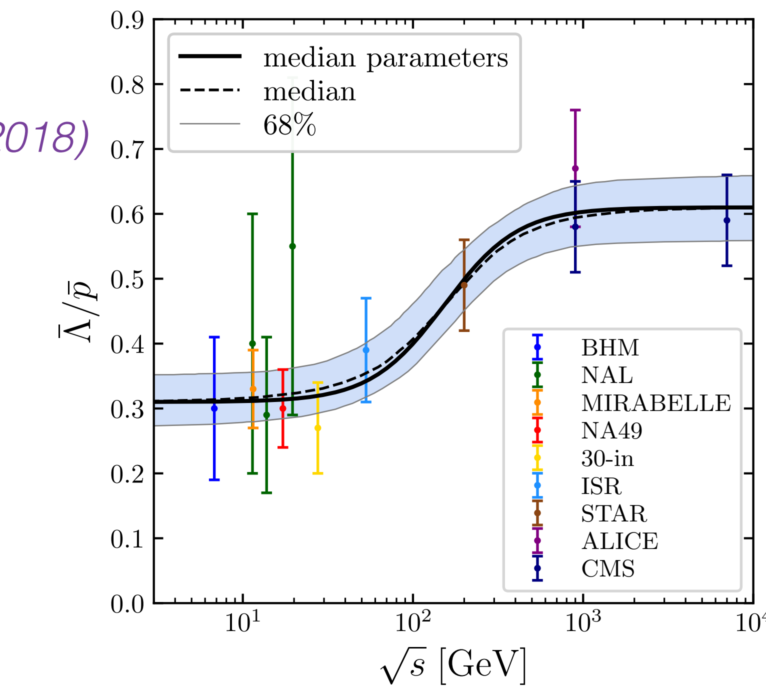
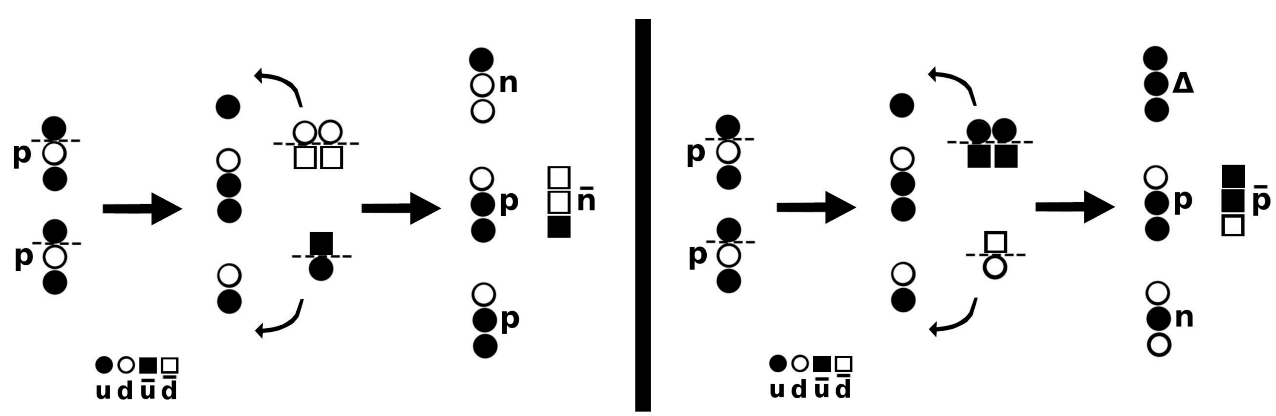


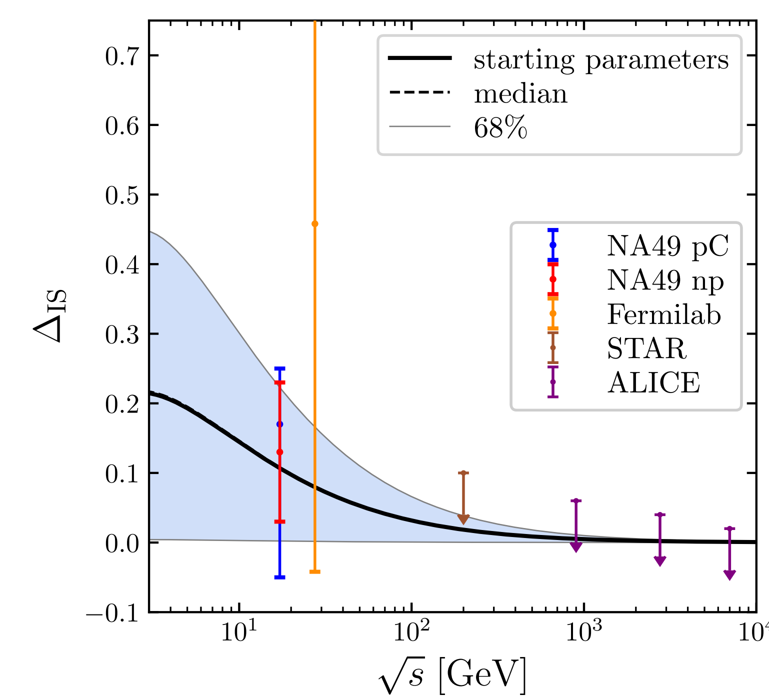

- **Antihyperons correction (p + p —> X + [($\Lambda$bar, Σbar) —> pbar])**
  Parametrisation of $\Delta_\Lambda(\sqrt{s})$ from *Winkler+(2016)*

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

- **Isospin asymmetry correction (p + p —> X + [nbar—> pbar])**
  We introduce the following parametrisation to reproduce the results of *Winkler+(2016)*

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



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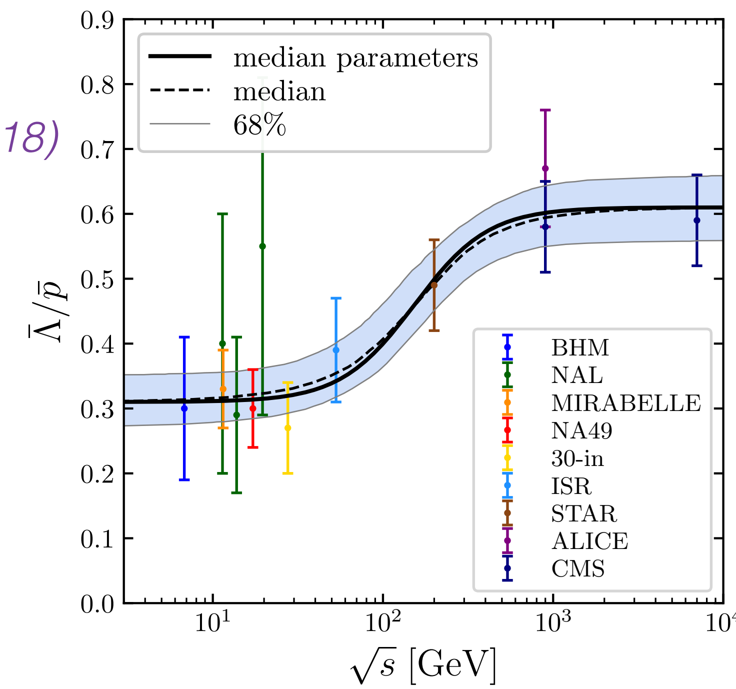


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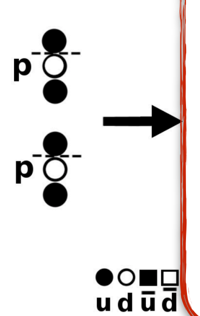
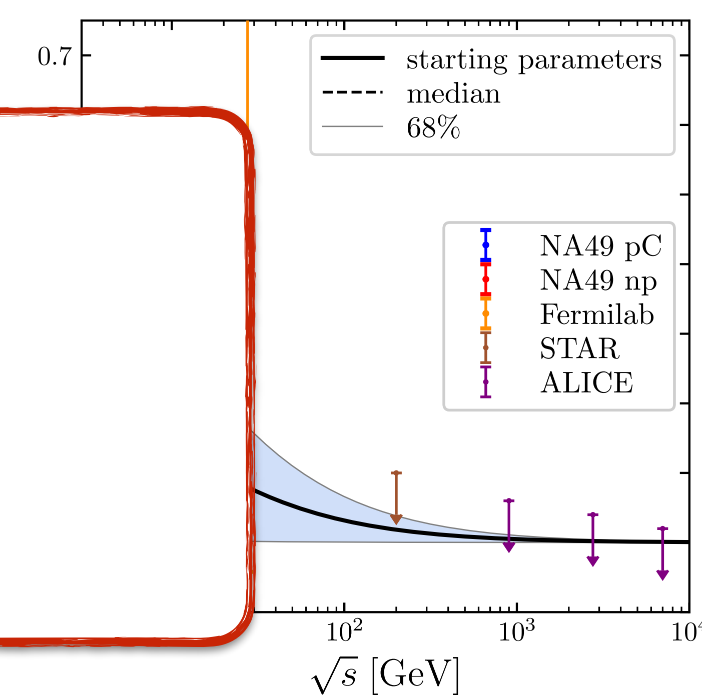
$$\Delta_{\mathrm{IS}}(\sqrt{s})$$




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



# A model for the covariance matrix of AMS-02 errors

- **Covariance matrix (see David's talk)**
  Coefficient corresponding to the uncertainty $\alpha$ (Acc., Unf., Trig., etc.)

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

- **$\chi^2$ calculation**
  Quadratic distance between model and data:

$$\chi^2 = \sum_{i,j} x_i \left(\mathcal{C}^{-1}\right)_{ij} x_j \equiv \mathbf{x}^{\mathrm{T}}\mathcal{C}^{-1}\mathbf{x} \qquad x_i = \mathrm{data}_i - \mathrm{model}_i$$

- **Visual inspection**
  - Standard z-score
    Misleading when correlations between data points

$$z_i = x_i/\sqrt{\mathcal{C}_{ii}}$$

  - Rotated z-score

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

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

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

$$\chi^2 = \sum_i \tilde{z}_i^2$$

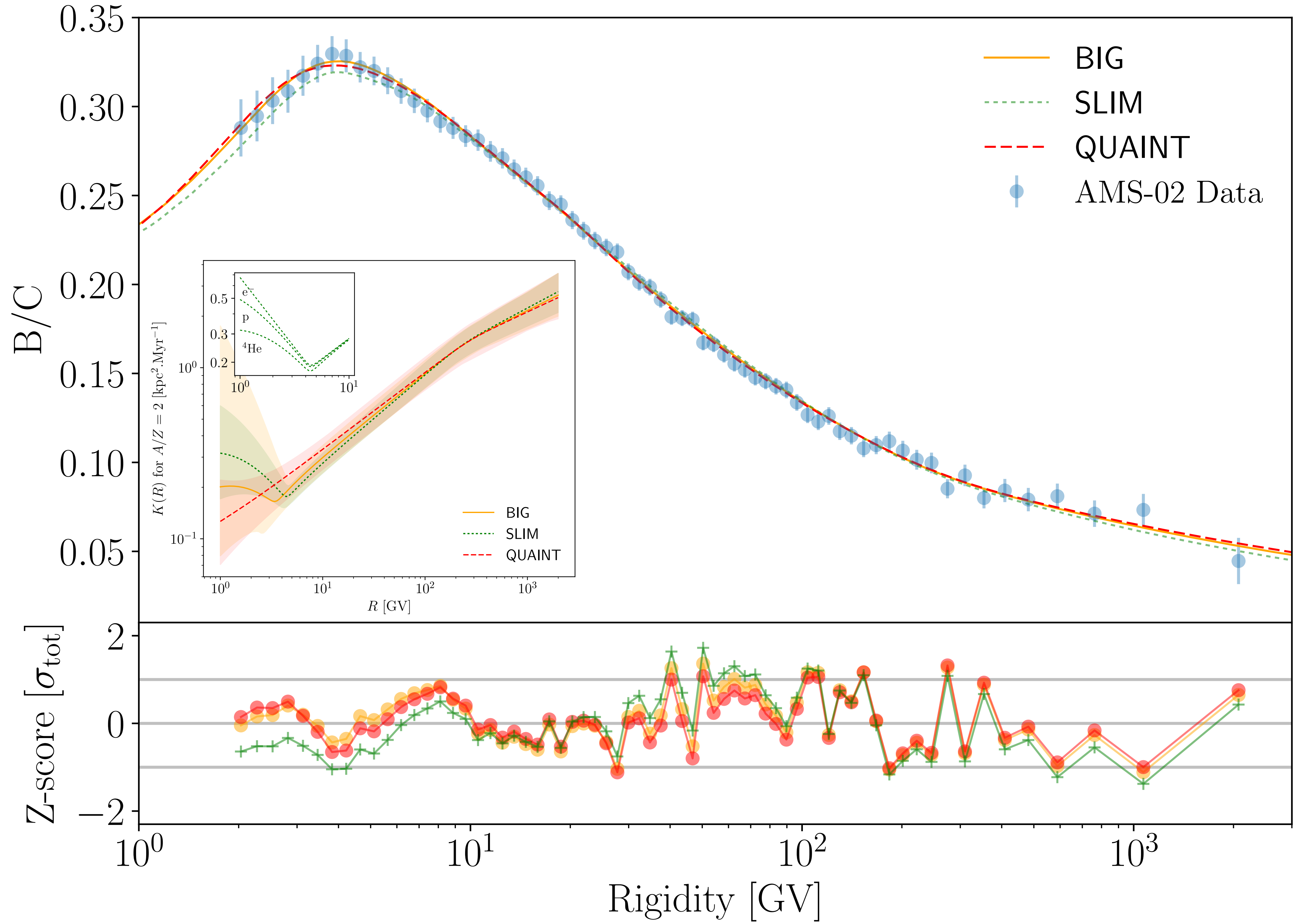
Rotated rigidity

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

# Model of CR transport

**New models from AMS-02 B/C (see Yoann's talk)**

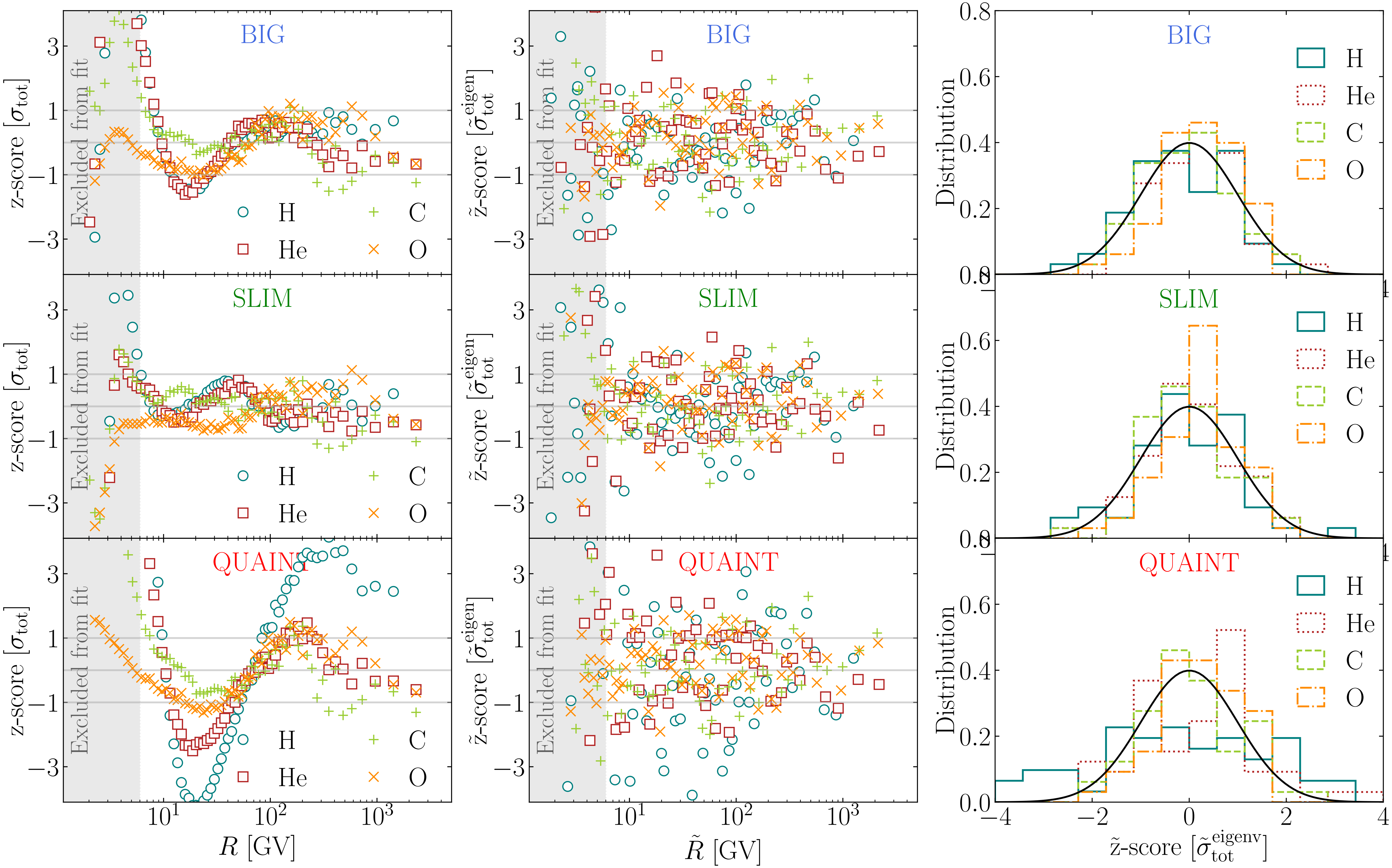
- QUAINT: historical model diff/conv/reac
- SLIM: pure diffusion w/ 2 breaks in the diff. coef.
- BIG: diffusion/convection/reacceleration + 2 breaks in the diffusion coef. **(BASELINE)**



# Antiproton parents

**Combined fit of AMS-02 H, He, C and O**

Most abundant CRs $\Longrightarrow$ main pbar parents



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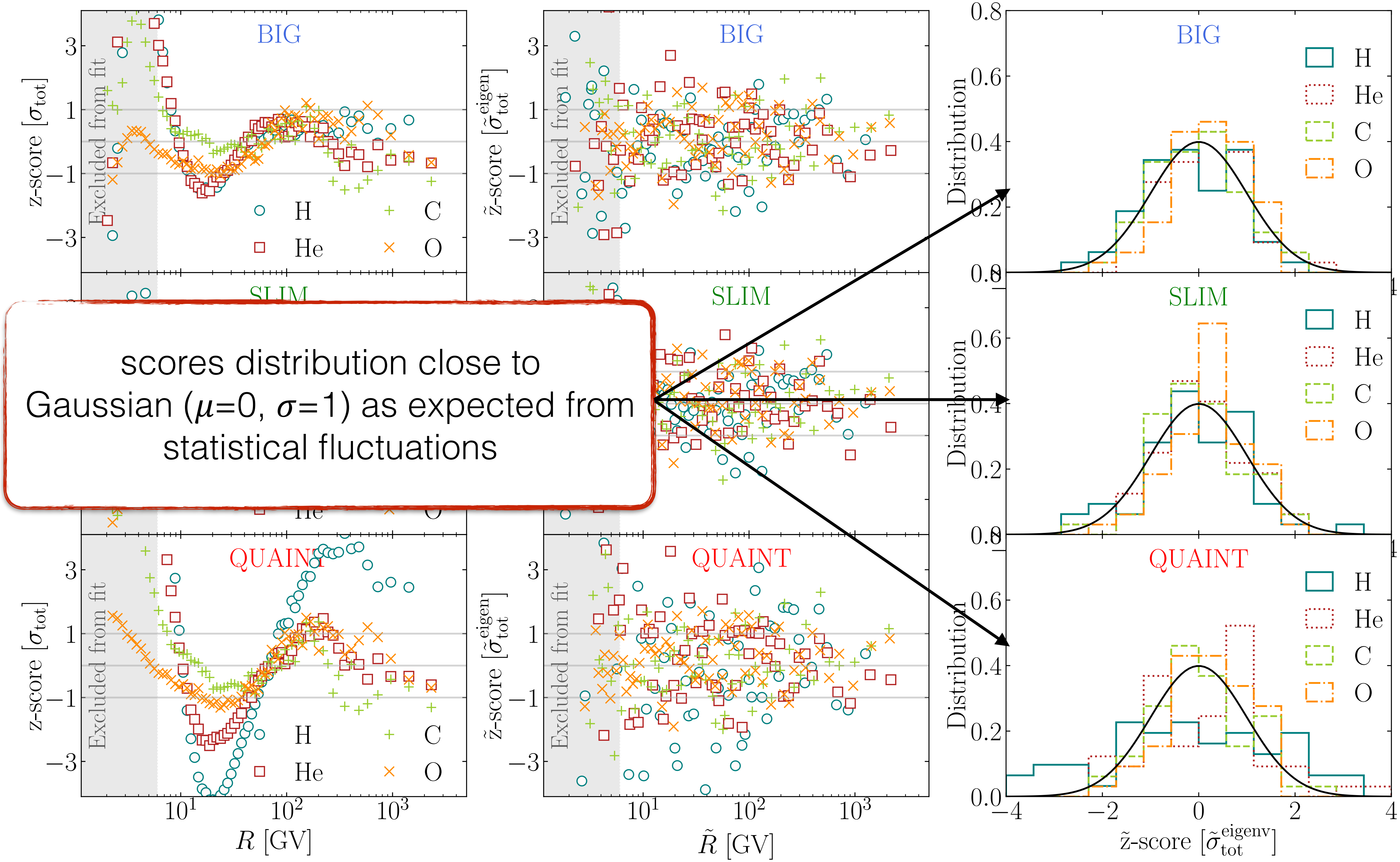
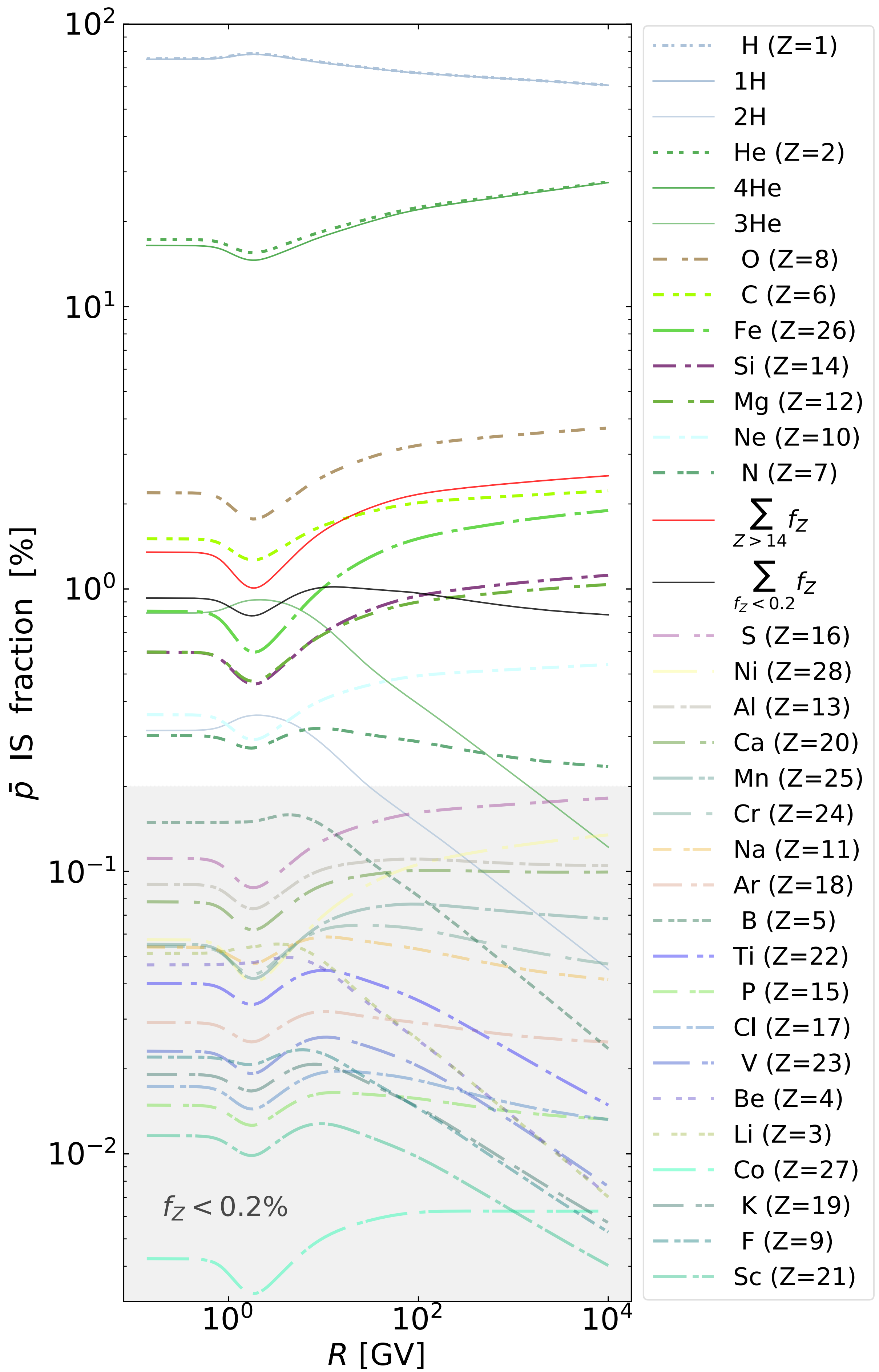
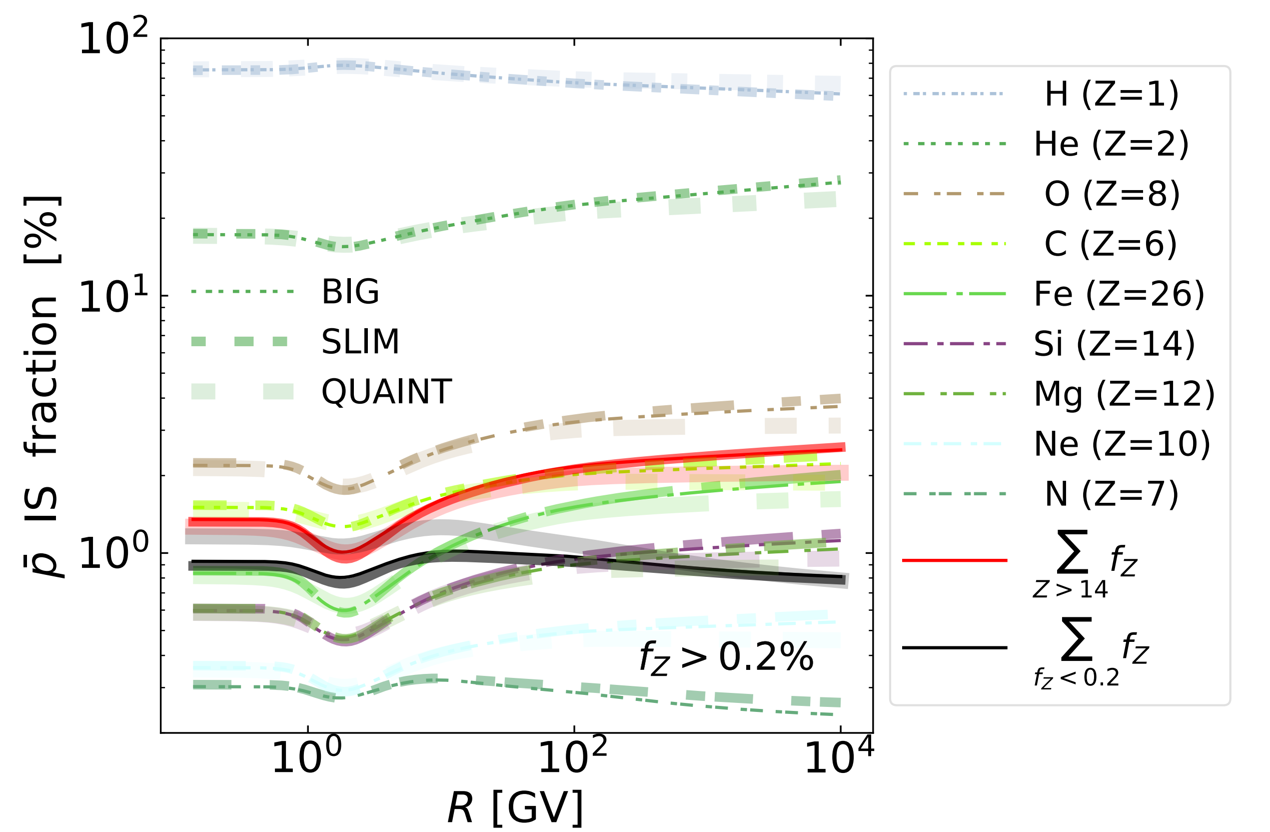


# Ranking parents contributions



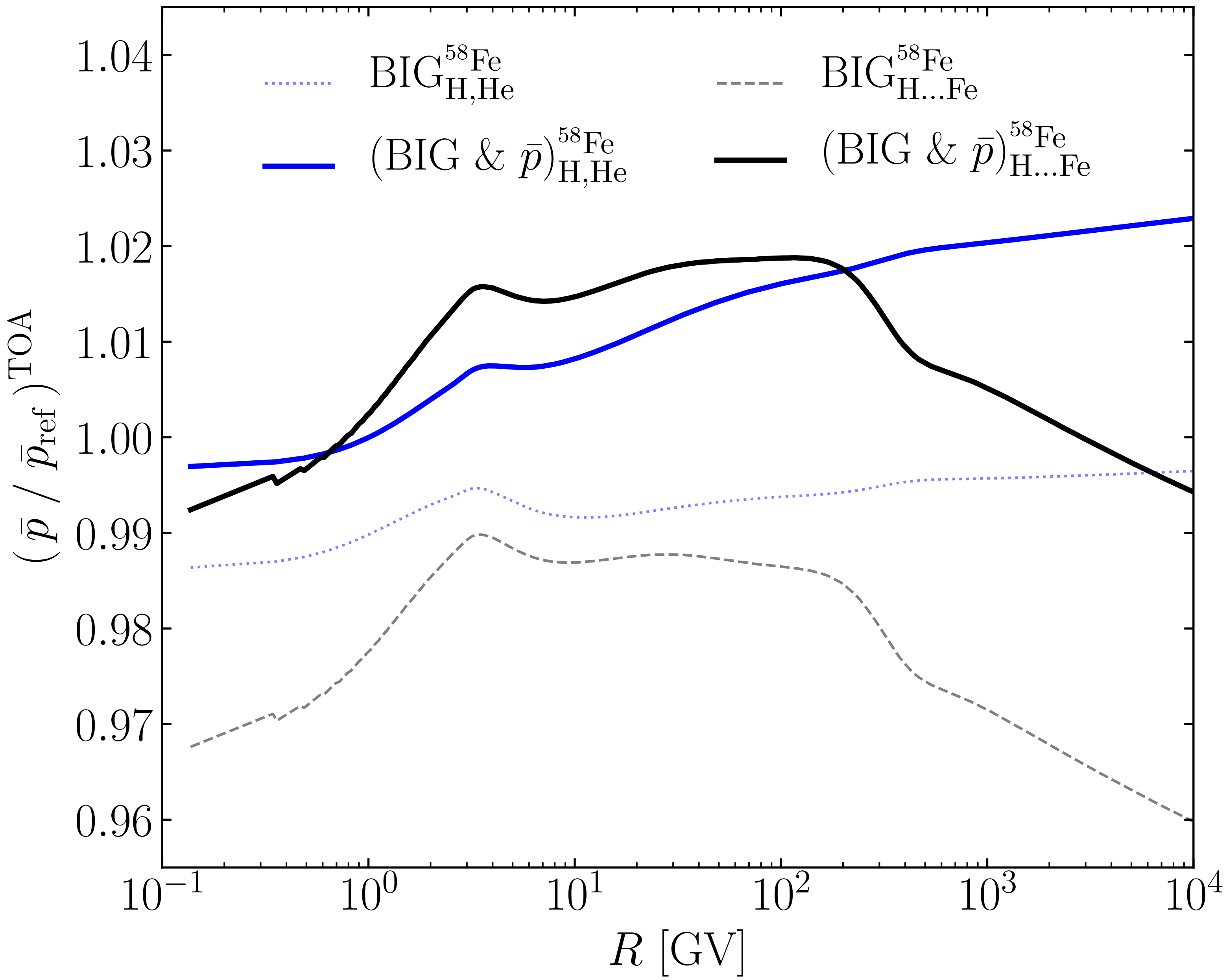
# Heavy parents, heavy species in the ISM

**Fast calculation (ref)**

- pbar and B/C parents: H … $^{30}$Si
- ISM species: H, He

**Full (slow) calculation**

- pbar and B/C parents: H … $^{58}$Fe
- ISM species: H…Fe




We rescale our pbar prediction by the **black solid** line to account for heavy species in the ISM

# Propagation of uncertainties

**Uncertainties on parameters entering:**

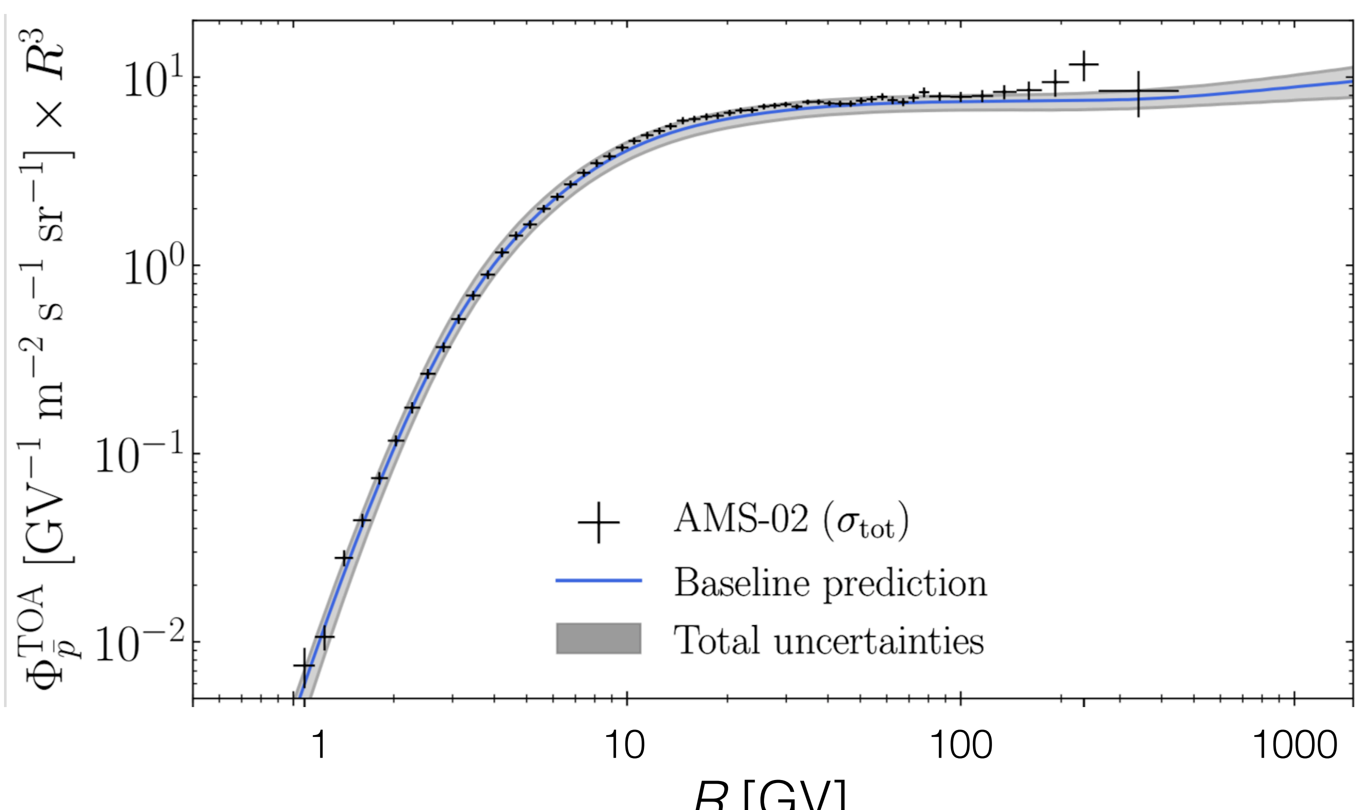
- Production XS (fit collider data)
- Transport (fit B/C)
- Parents (fit H, He, C and O)

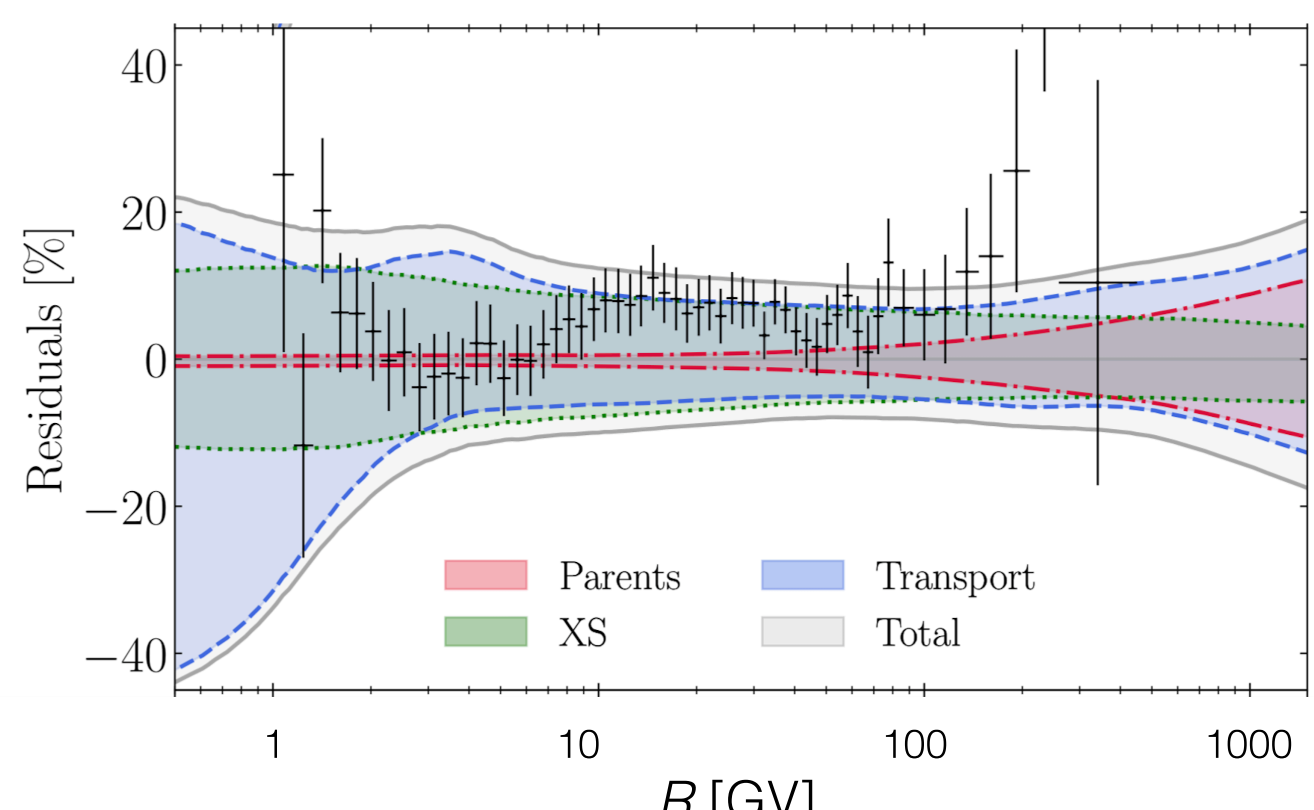
**Assume parameter distribution is Gaussian**

$\Longrightarrow$ use the covariance matrix of errors to propagate uncertainties and their correlations

**In practice**

1. Draw randomly 10000 pbar predictions from the covariance matrix for each source of uncertainties (XS, Transport, Parents)
2. Determine the $1\sigma$ confidence intervals



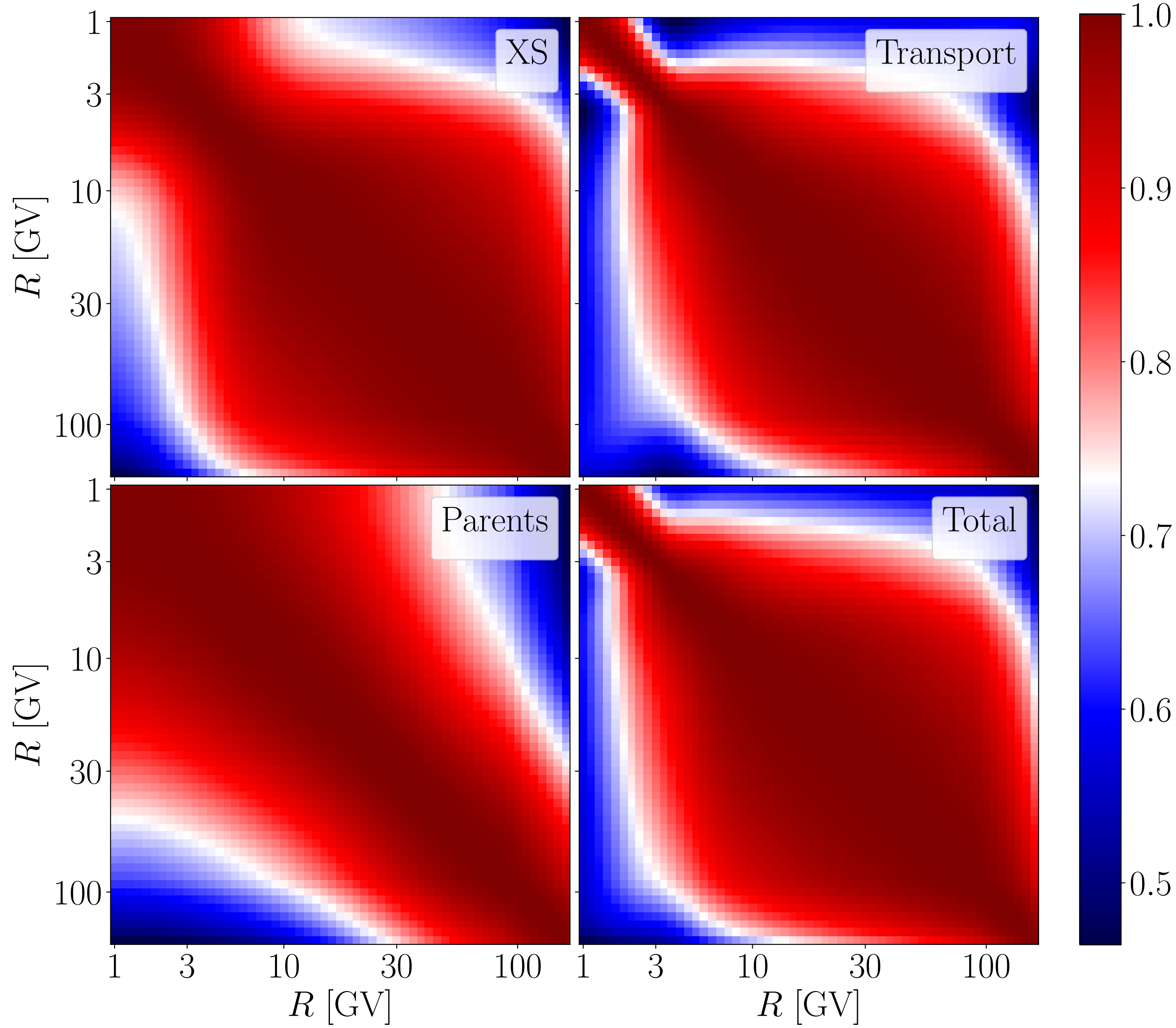
# Covariance matrix of model uncertainties

- For the source of uncertainty a ∈ (XS, Transport, Parents)

$$\mathcal{C}_{ij}^{\mathrm{a}} = \frac{1}{N}\sum_{n=1}^{N}\left(\Phi_{i,n}^{\mathrm{a}} - \mu_i^{\mathrm{a}}\right)\left(\Phi_{j,n}^{\mathrm{a}} - \mu_j^{\mathrm{a}}\right)$$

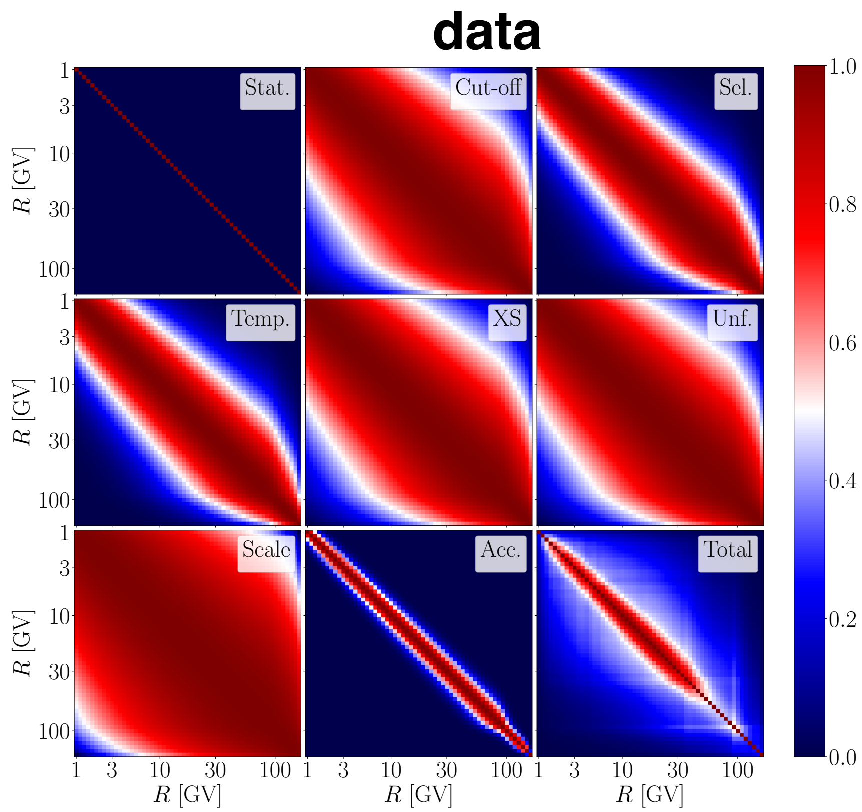
$\mu_i^{\mathrm{a}}$ mean prediction at the energy bin $i$

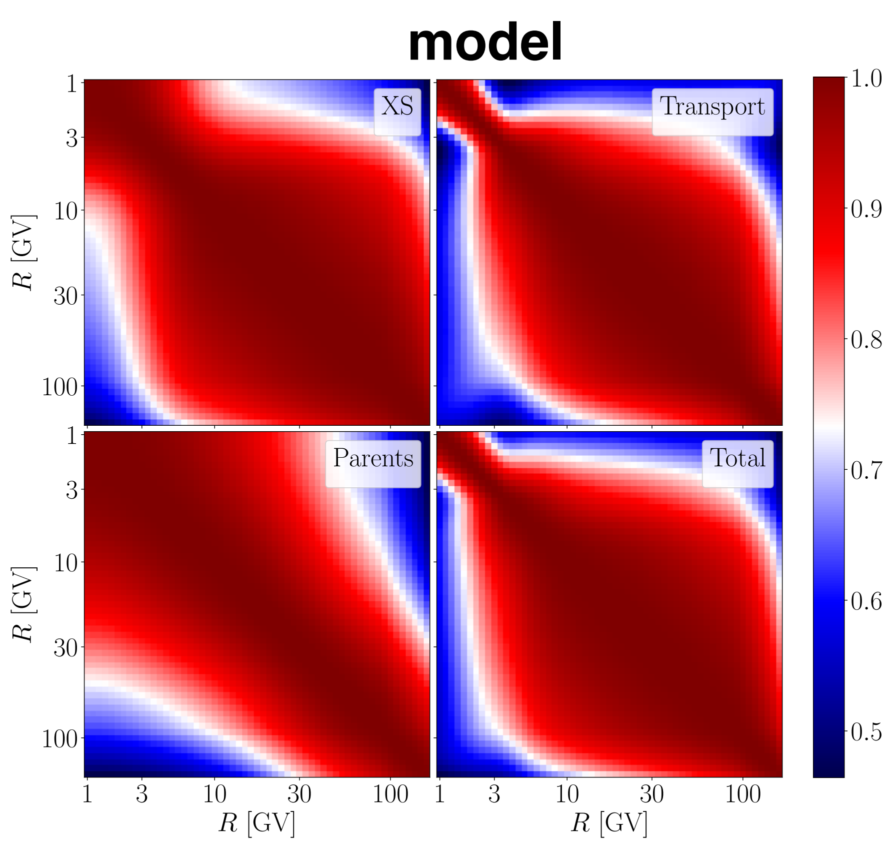
- Associated correlation matrix: $\mathrm{c}_{ij}^{\alpha} = \frac{\mathcal{C}_{ij}^{\alpha}}{\sqrt{\mathcal{C}_{ii}^{\alpha}}\sqrt{\mathcal{C}_{jj}^{\alpha}}}$

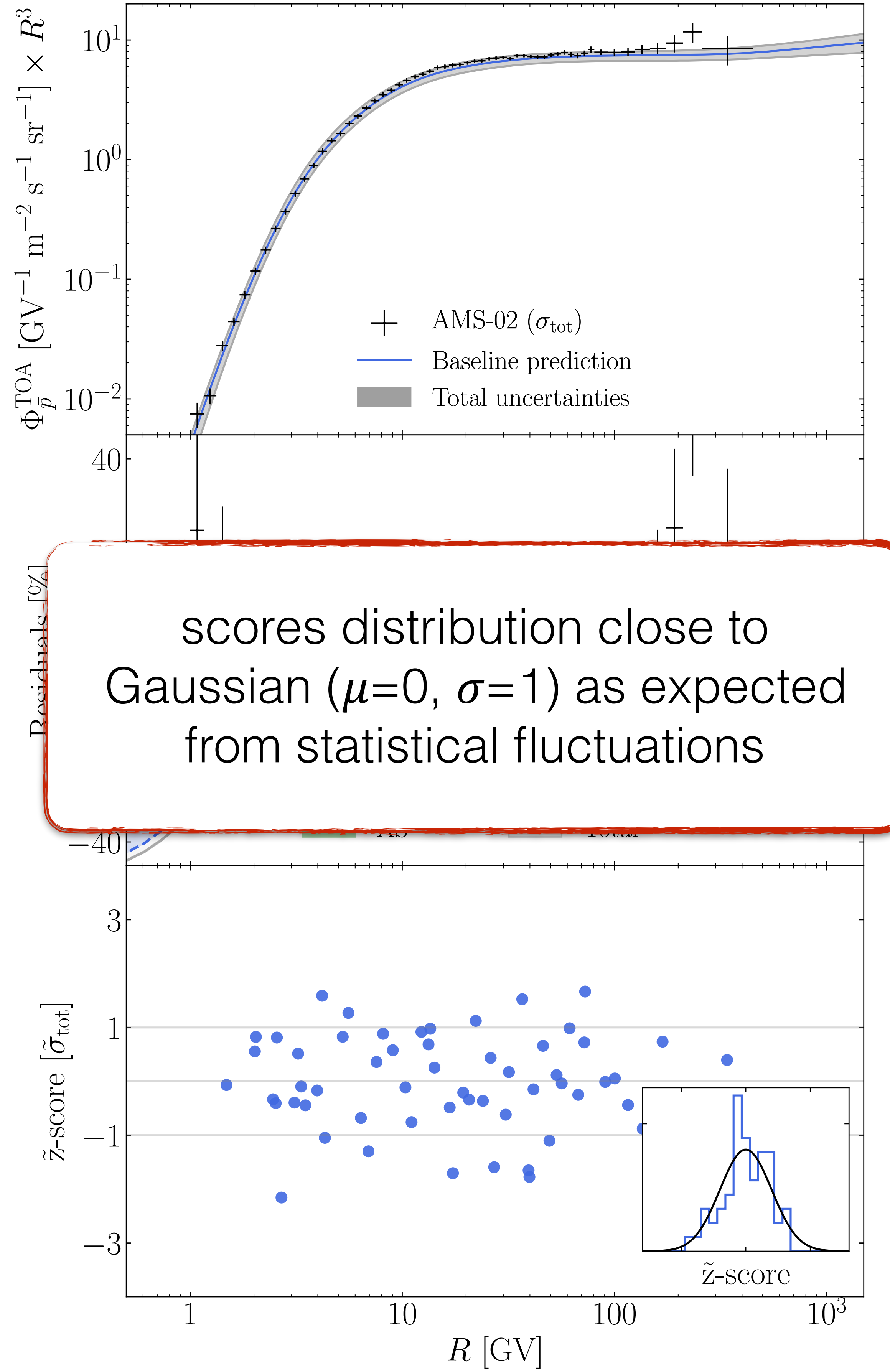


# Prediction vs AMS-02: visual inspection

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




scores distribution close to Gaussian ($\mu$=0, $\sigma$=1) as expected from statistical fluctuations

# Statistical test: $\chi^2$ vs Kolmogorov-Smirnov (KS)

$$\chi^2 = \sum_{i,j} x_i \left(\mathcal{C}^{-1}\right)_{ij} x_j, \qquad x_i = \mathrm{data}_i - \mathrm{model}_i \qquad \mathcal{C} = \mathcal{C}^{\rm data} + \mathcal{C}^{\rm model}$$

$\sqrt{\sigma^2_{\rm stat}+\sigma^2_{\rm syst}} \longrightarrow$

| Error considered | $\chi^2$/dof | p-value ($\chi^2$) | p-value (KS) |
|---|---|---|---|
| $\sigma_{\rm stat}$ | 23 | 0 | 0 |
| $\sigma_{\rm tot}$ | 1.69 | $8.3 \times 10^{-4}$ | 0 |
| $\mathcal{C}^{\rm data}$ | 0.84 | 0.79 | 0.98 |
| $\sigma_{\rm stat}$ and $\mathcal{C}^{\rm model}$ | 1.32 | 0.05 | 0.99 |
| $\sigma_{\rm tot}$ and $\mathcal{C}^{\rm model}$ | 0.37 | 1.0 | 0.04 |
| $\mathcal{C}^{\rm data}$ and $\mathcal{C}^{\rm model}$ | 0.77 | 0.90 | 0.27 |

**$\chi^2$-test**

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

**KS-test**

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

**(i)** No model uncertainty + data uncertainty: good agreement for both KS and $\chi^2$

**(ii)** Model uncertainty + data statistics only: KS: good agreement, $\chi^2$ marginally consistent ($2\sigma$)

**(iii)** Model uncertainty + data uncertainty: good agreement for both KS and $\chi^2$

- **AMS-02 data are consistent w/ a pure secondary origin**
- **Conclusion robust wrt error mismodelling of model or data**

# Conclusion

**Prediction of the pbar flux computed from external data (not a fit)**

- Use the latest constraints on transport parameters from AMS-02 B/C
- Propagate all the uncertainties (and their correlation) to the pbar flux prediction
- Account for correlated errors in pbar data

**AMS-02 data are consistent w/ a pure secondary origin**

- Conclusion robust wrt the statistical test used ($\chi^2$-test or KS-test)
- Conclusion robust wrt error mismodelling of model or data

*Thank you for your attention!*
*Questions?*