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

L. Derome[1], D. Maurin[1], P. Salati[2], M. Boudaud[3], Y. Génolini[4], P. Kunzé[1]

1 LPSC, Université Grenoble Alpes, CNRS/IN2P3, 53 avenue des Martyrs, 38026 Grenoble, France

2 LAPTh, Université Savoie Mont Blanc & CNRS, 74941 Annecy Cedex, France

3 LPTHE, SorbonneUniversité & CNRS, 4 Place Jussieu, 75252 Paris Cedex 05, France

4 Service de Physique Théorique, Université Libre de Bruxelles, Boulevard du Triomphe, CP225, 1050 Brussels, Belgium

Work based on :

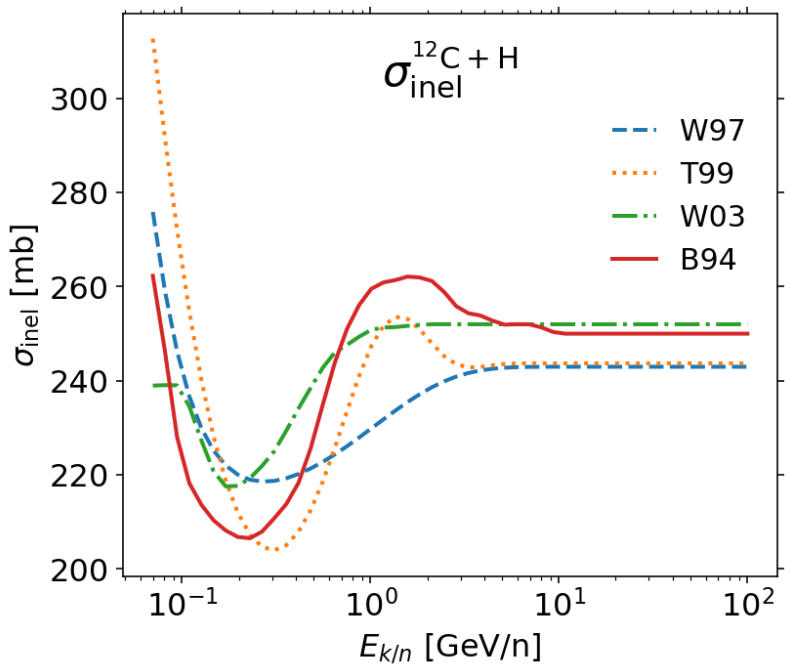
Fitting B/C cosmic-ray data in the AMS-02 era: a cookbook
Astronomy & Astrophysics, 627, A158 (2019)
L. Derome, D. Maurin, P. Salati, M. Boudaud, Y. Génolini and P. Kunzé

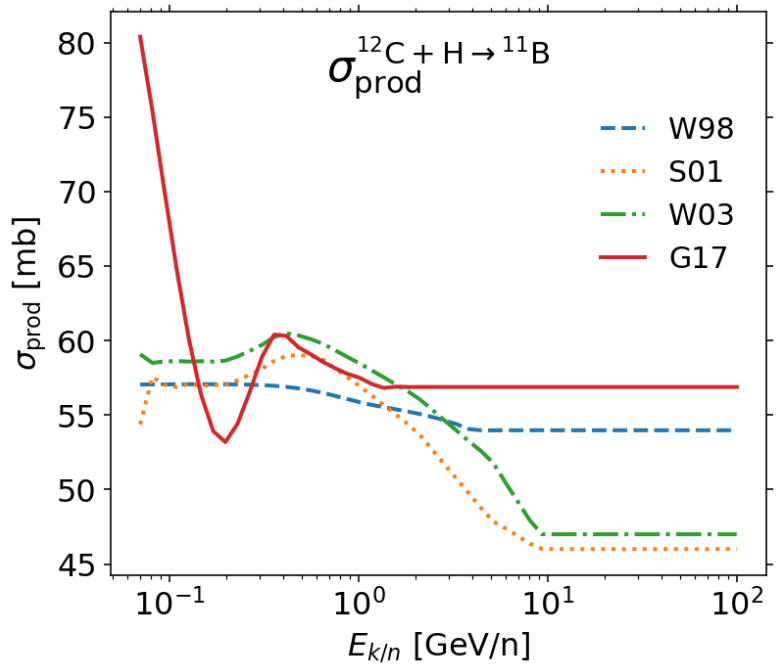
- New generation of experiments (AMS-02, …): percent-level precision, systematic-dominated data.
- Methods used to constrain models with these data should be updated:
  - improved model precision:
    - Boundary condition
    - Stability of numerical solution
  - Handling of cross-section uncertainties
  - Handling of systematics errors from experimental data

} This presentation

Nuclear Cross Sections

- Major ingredient in the modelling of GCR nuclei:
  - Inelastic cross sections: sink term for both primaries and secondaries.
  - Production cross sections: source term for secondaries.
- Several parameterisations of the reactions, based on experimental data, available:
  - Inelastic: Barashenkov [B94], Wellisch [W97], Tripathi [T99], Weber [W03]
  - Production: Weber [W98], Soutoul 01 [S01], Weber [W03], Galprop [G17]

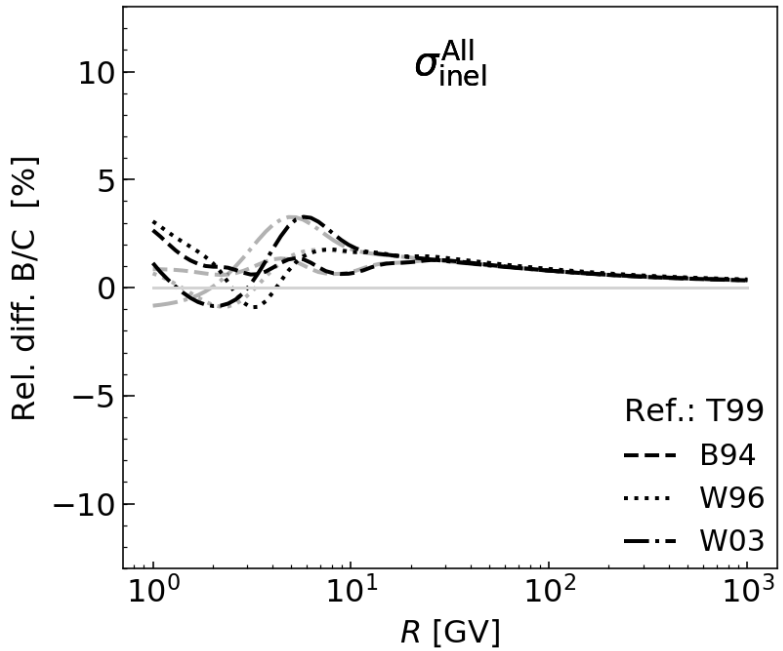


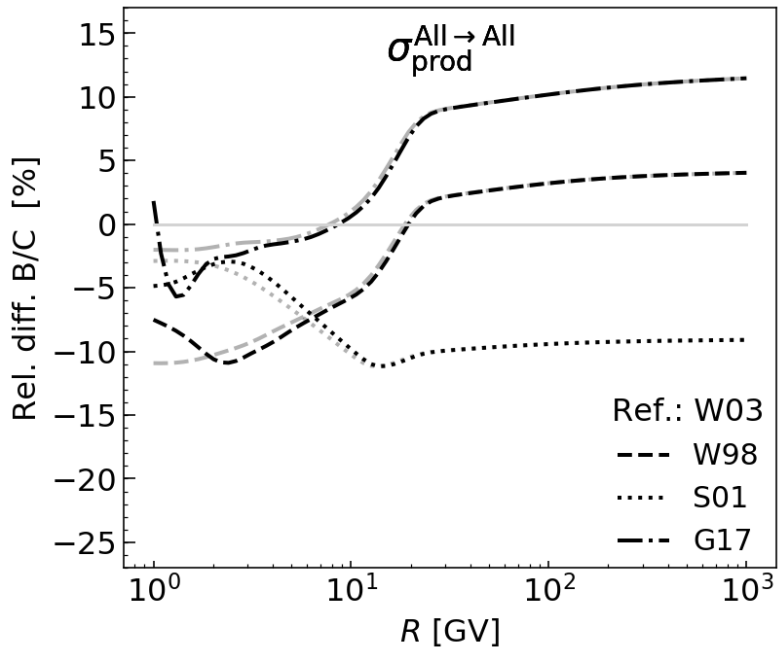


Nuclear Cross Sections

- Major ingredient in the modelling of GCR nuclei:
  - Inelastic cross sections: sink term for both primaries and secondary.
  - Production cross sections: source term for secondaries.
- Several parameterisations of the reactions, based on experimental data, available:
  - Inelastic: Barashenkov [B94], Wellisch [W97], Tripathi [T99], Weber [W03]
  - Production: Weber [W98], Soutoul 01 [S01], Weber [W03], Galprop [G17]
- Impact on B/C ratio larger than data precision

Impact on B/C ratio:

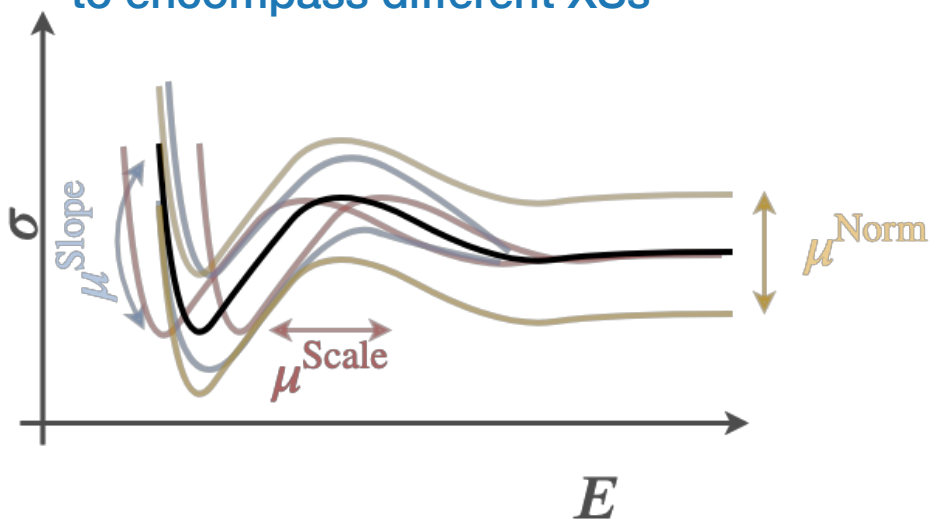




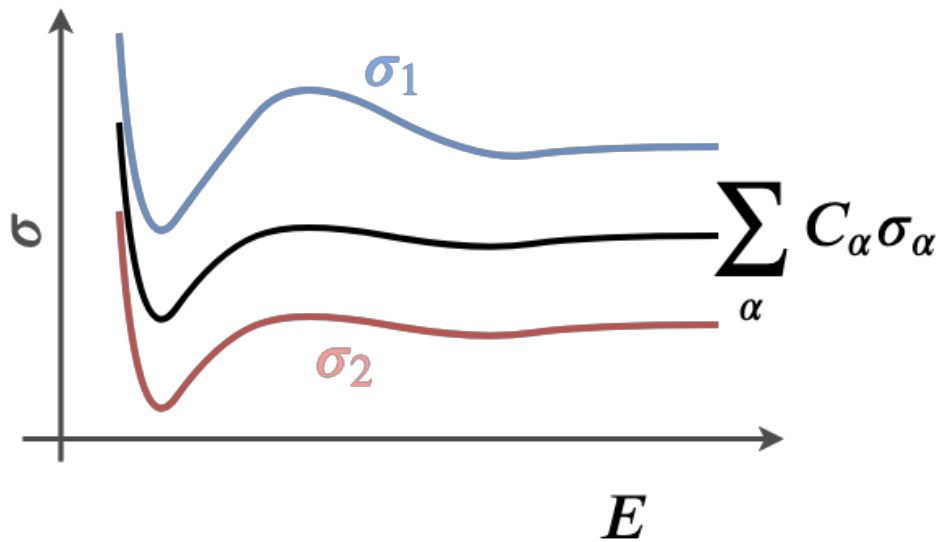
Nuclear Cross Sections

2 approaches to implement cross-section systematics:

- Norm Scale Slope (NSS)
  - Simple transformations from reference XS.
  - 3 Nuisance parameters with gaussian distribution and with ranges chosen to encompass different XSs



- Linear Combination (LC)
  - Linear combination of available XSs.
  - Nuisance parameters C_α with a flat distribution.
  - Can fully recover each XSs parametrisation



- Cross Sections considered (not the all network):
  - $\sigma_{\text{Inel.}}$ for B, C, O
  - $\sigma_{\text{Prod.}}$ for C $\rightarrow$ ^{10,11}B and O $\rightarrow$ ^{10,11}B,
- In total: 14-20 nuisance parameters used to handled cross-section systematics

Propagation Models

- 2 configurations :
  - Model A (diffusion + reacceleration + convection aka QUAINT):

$$K(R) = \beta^{\eta_t} K_0 \left(\frac{R}{1\ \mathrm{GV}}\right)^{\delta}$$ + reacceleration (V_a) + convection (V_c)

5 free parameters

  - Model B (pure diffusion aka SLIM):

$$K(R) = \beta K_0 \left(\frac{R}{1\ \mathrm{GV}}\right)^{\delta} \left(1 + \left(\frac{R_l}{R}\right)^{(\delta+\delta_l)/s_l}\right)^{s_l}$$

4 free parameters

- Mock Data (1000) generated with statistical errors around reference models for A and B.
- Fit of the mock data, two cases considered:
  - Unbiased: $\sigma_{\mathrm{Inel.,\ Prod.}}(\mathrm{Fit}) = \sigma_{\mathrm{Inel.,\ Prod.}}(\mathrm{Gen.})$ (Inel.: W97, Prod.: G17)
  - Biased: $\sigma_{\mathrm{Inel.,\ Prod.}}(\mathrm{Fit})$ (Inel.: T99, Prod.: W03) $\neq \sigma_{\mathrm{Inel.,\ Prod.}}(\mathrm{Gen.})$

Unbiased

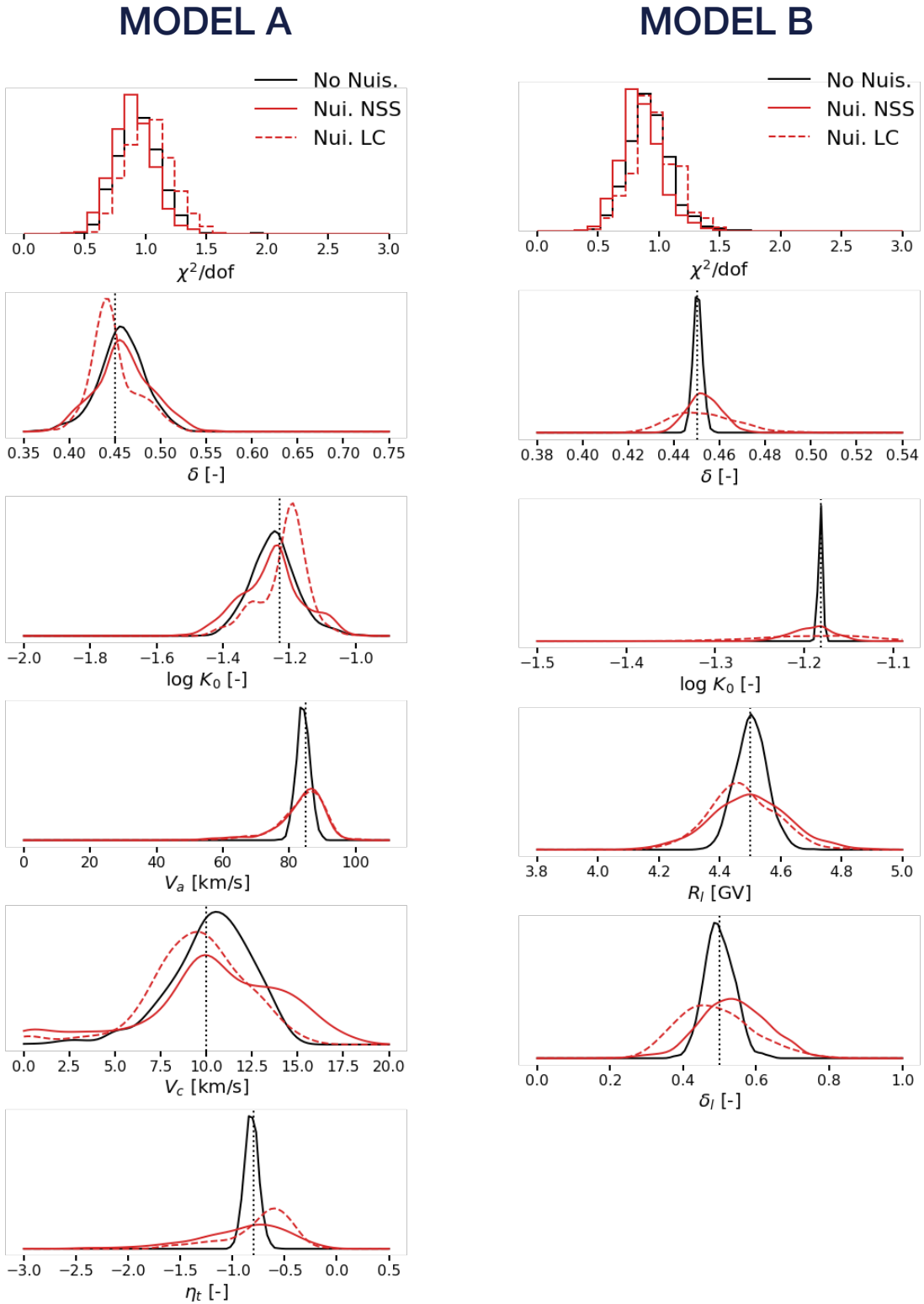
$$\sigma(\text{Gen.}) = \sigma(\text{Fit})$$

No nuisance (black):

- $\chi^2/\text{dof} \sim 1$
- no bias w.r.t parameters values of the models (vertical dashed lines)

With nuisances NSS (—) and LC (--):

- $\chi^2/\text{dof} \sim 1$
- Larger errors (systematic from XS now included in the errors from the fit)



Biased

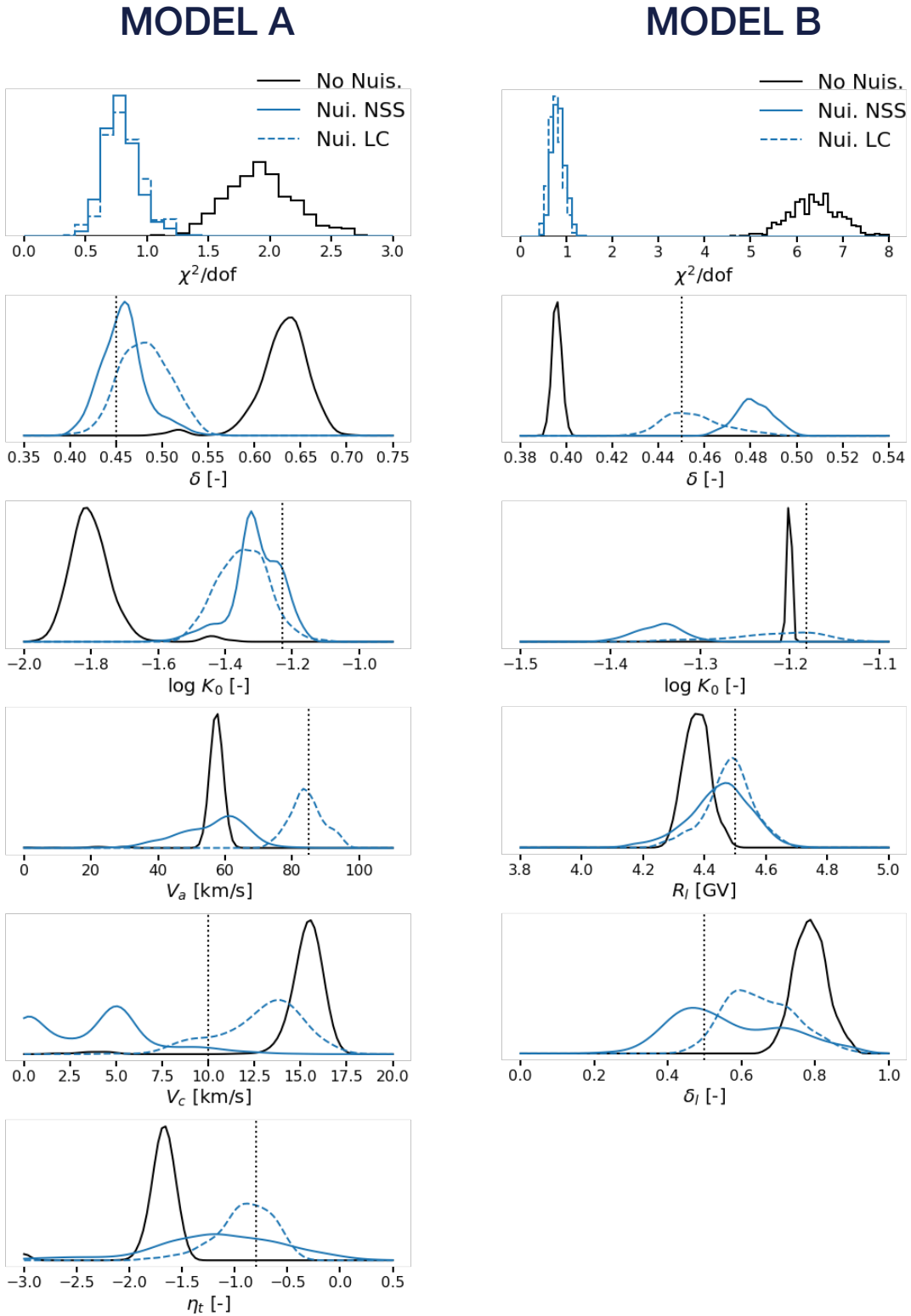
$\sigma(\text{Gen.}) \neq \sigma(\text{Fit})$

No nuisance (black):

- Large χ^2/dof
- Biased best fits w.r.t to parameters values (vertical dashed lines)

With nuisances NSS (—) and LC (--):

- good χ^2/dof recovered
- Reduced biases on the parameter distributions
- Better results for LC than for NSS as expected.



Systematic errors on Data

AMS02 B/C:

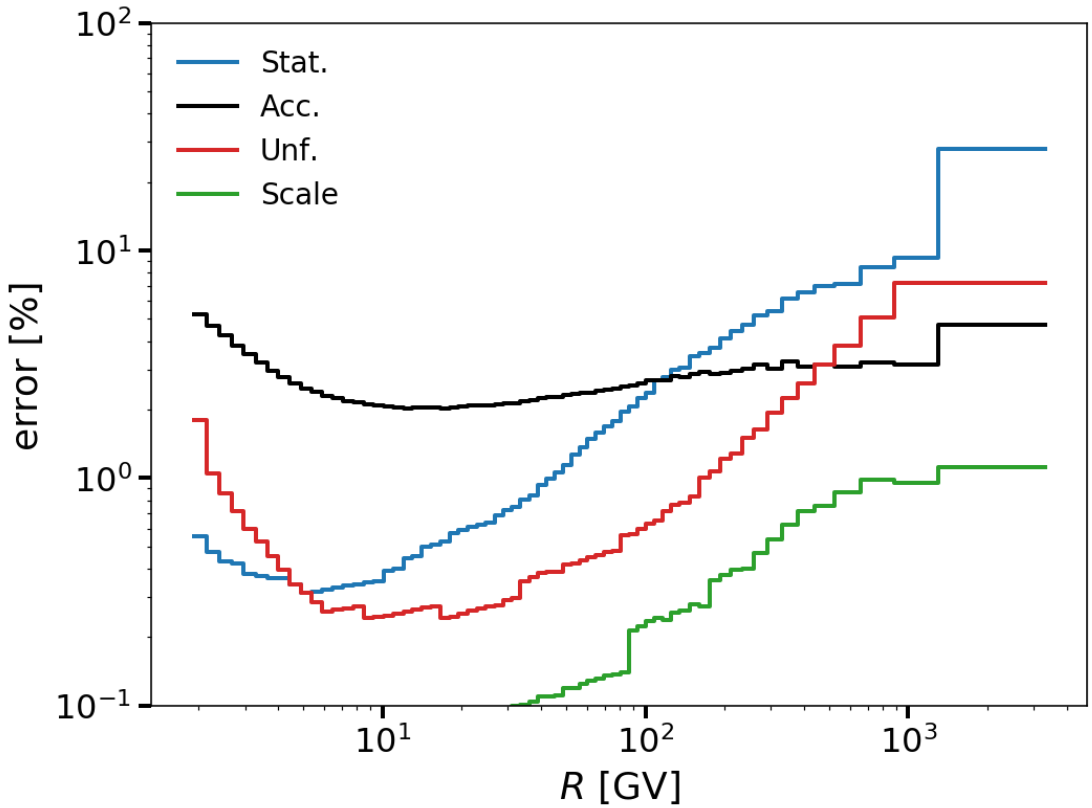
- Dominated by systematic Acceptance error up to 100 GV
- No covariance matrix provided to account for bin-to-bin correlation of systematic errors.
- Model guessed for the covariance matrices (α = Stat., Acc., Unf., Scale):

$$(C^{\alpha}_{\mathrm{rel}})_{ij} = \sigma^{\alpha}_{i}\sigma^{\alpha}_{j} \exp\left(-\frac{1}{2}\frac{(\log_{10}(R_i/R_j))^2}{(l^{\alpha}_{\rho})^2}\right)$$

where:

- σ^{α}_{i} is the error from AMS
- l^{α}_{ρ} is the correlation length in unit of decade of rigidity.

AMS errors for B/C from PRL 120, 021101 (2018)



- $l_{\rho}^{\mathrm{Stat.}} = 0$
- $l_{\rho}^{\mathrm{Unf.}} = 0.5$
- $l_{\rho}^{\mathrm{Scale}} = \infty$
- $l_{\rho}^{\mathrm{Acc.}} = 0.01 \ldots 3$

How the choice of $l_{\rho}^{\mathrm{Acc.}}$ impact the best fit values ?

Systematic errors on Data

AMS02 B/C:

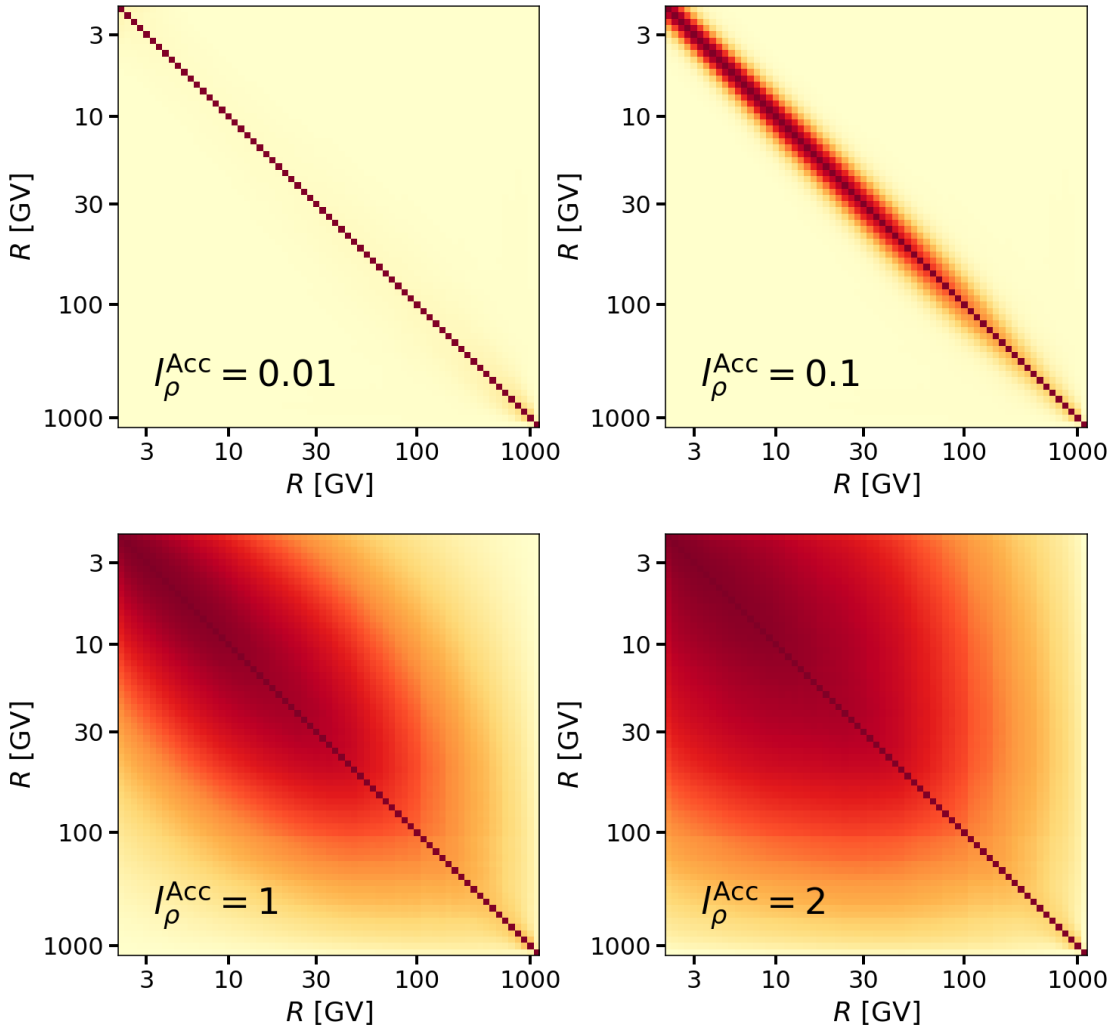
- Dominated by systematic Acceptance error up to 100 GV
- No covariance matrix provided to account for bin-to-bin correlation of systematic errors.
- Model guessed for the covariance matrices (α = Stat., Acc., Unf., Scale):

$$(C^{\alpha}_{\mathrm{rel}})_{ij} = \sigma^{\alpha}_{i}\sigma^{\alpha}_{j}\exp\left(-\frac{1}{2}\frac{(\log_{10}(R_i/R_j))^2}{(l^{\alpha}_{\rho})^2}\right)$$

where:

- σ^{α}_{i} is the error from AMS
- l^{α}_{ρ} is the correlation length in unit of decade of rigidity.

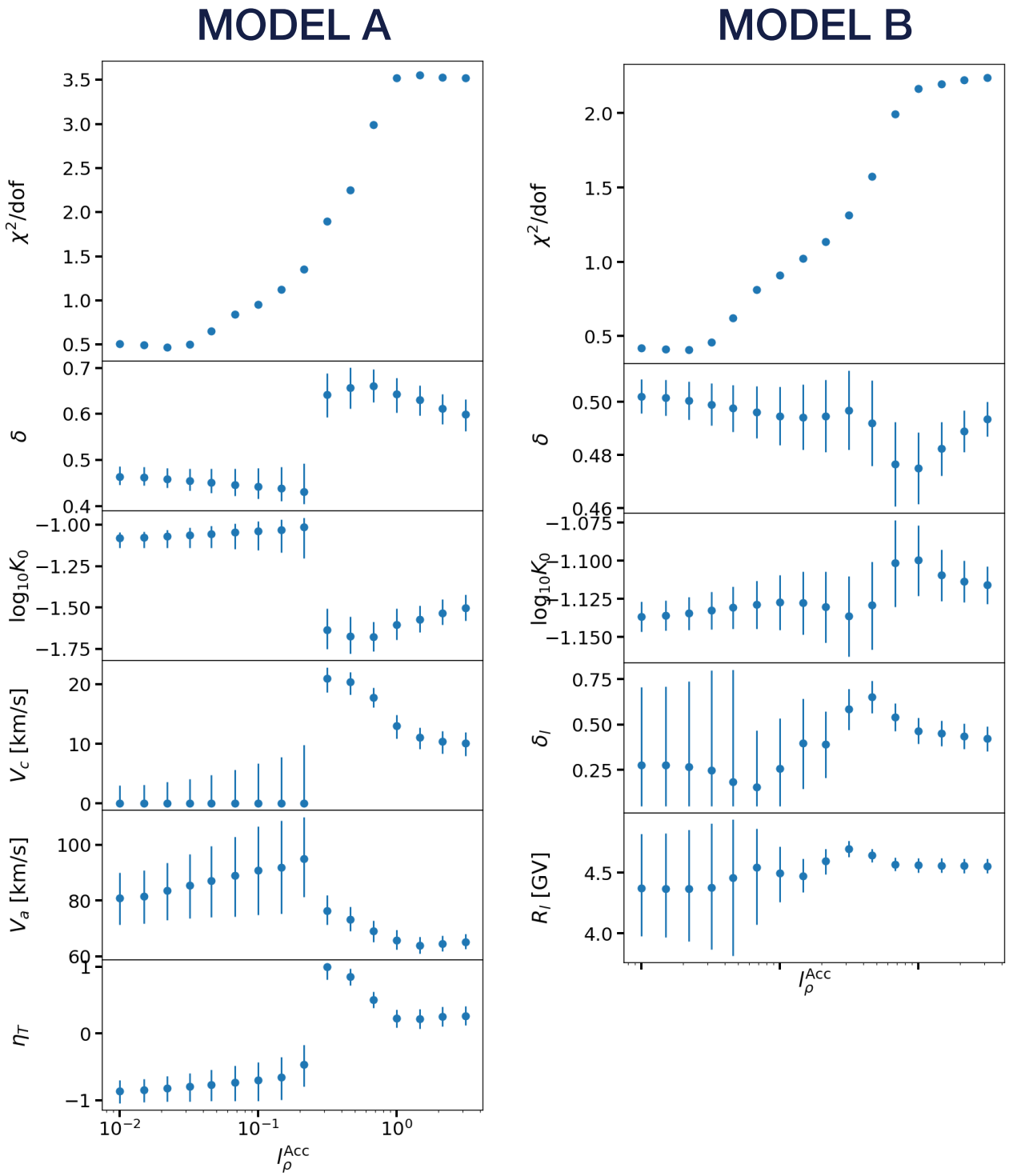
Total correlation matrix



AMS-02 B/C fit

AMS B/C fit results as a function of $l_\rho^{\text{Acc.}}$:

- χ^2/dof from 0.5 to 3.5
- Large best-fit values and errors dependence:
  - Model A: 2 different regimes for low $l_\rho^{\text{Acc.}}$ and high $l_\rho^{\text{Acc.}}$
  - Model B: Less dependence for values. Still large dependence for errors.

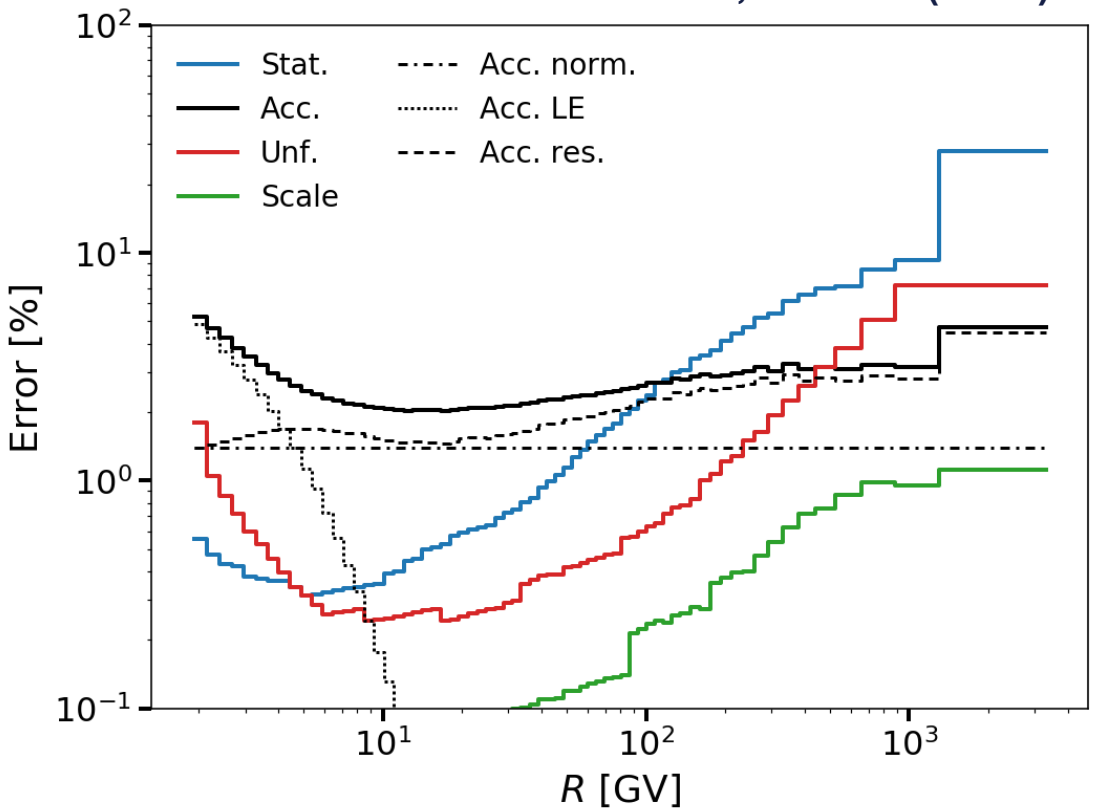


Systematic errors on Data

Acceptance error handling is critical:

- Sum of different contribution, may have different correlation lengths.
- Split acc. error into 3 contributions:
  - Acc. Norm: Flat normalisation error, related to systematic on survival probability : $l_\rho \sim 1.0$
  - Acc. LE: Low Energy error : $l_\rho \sim .3$
  - Acc. res. : Residual error data/ MC corrections, … $l_\rho = 0.01 \ldots 3$

AMS errors from PRL 120, 021101 (2018)

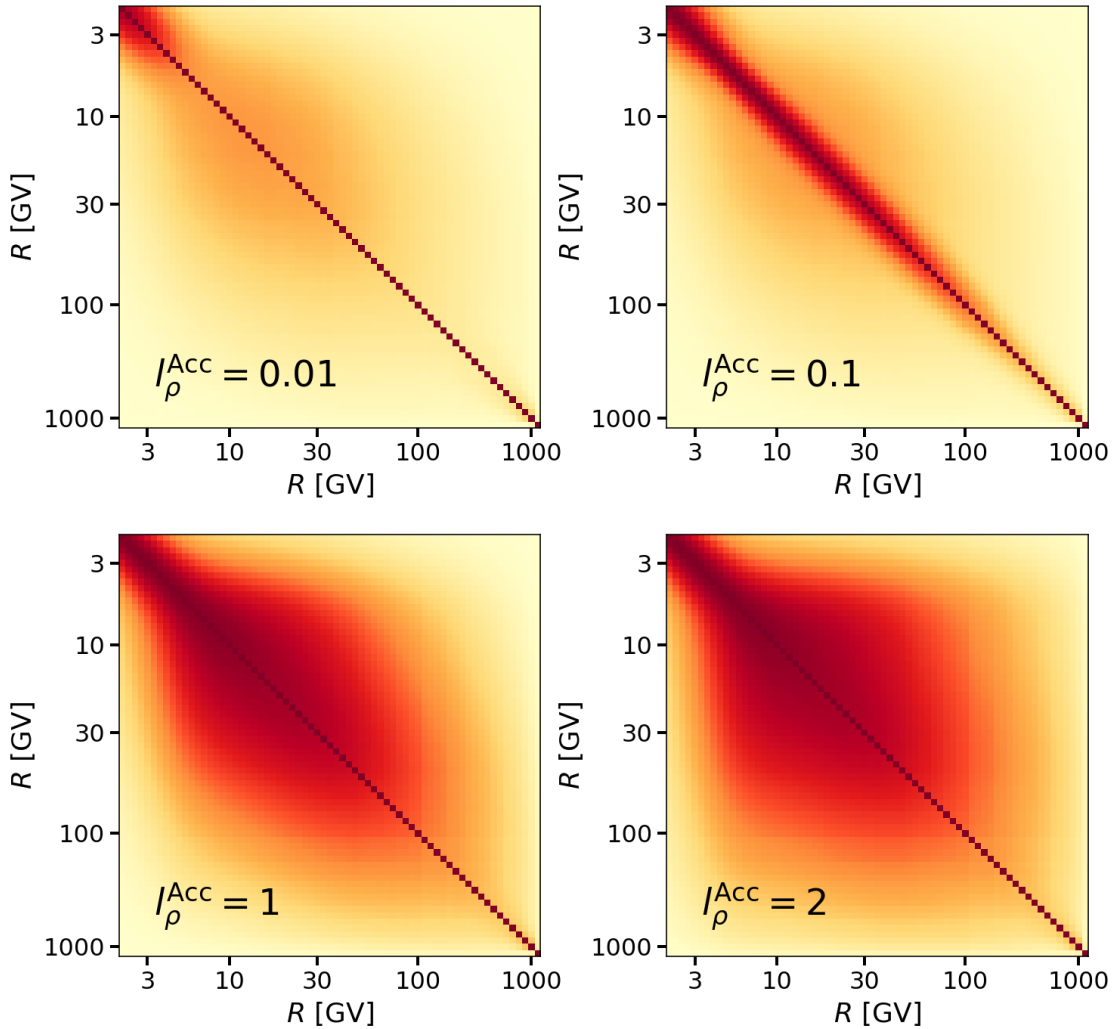


Systematic errors on Data

Acceptance error handling is critical:

- Sum of different contribution, may have different correlation lengths.
- Split acc. error into 3 contributions:
  - Acc. Norm: Flat normalisation error, related to systematic on survival probability : $l_\rho \sim 1.0$
  - Acc. LE: Low Energy error : $l_\rho \sim .3$
  - Acc. res. : Residual error data/ MC corrections, … $l_\rho = 0.01 \ldots 3$

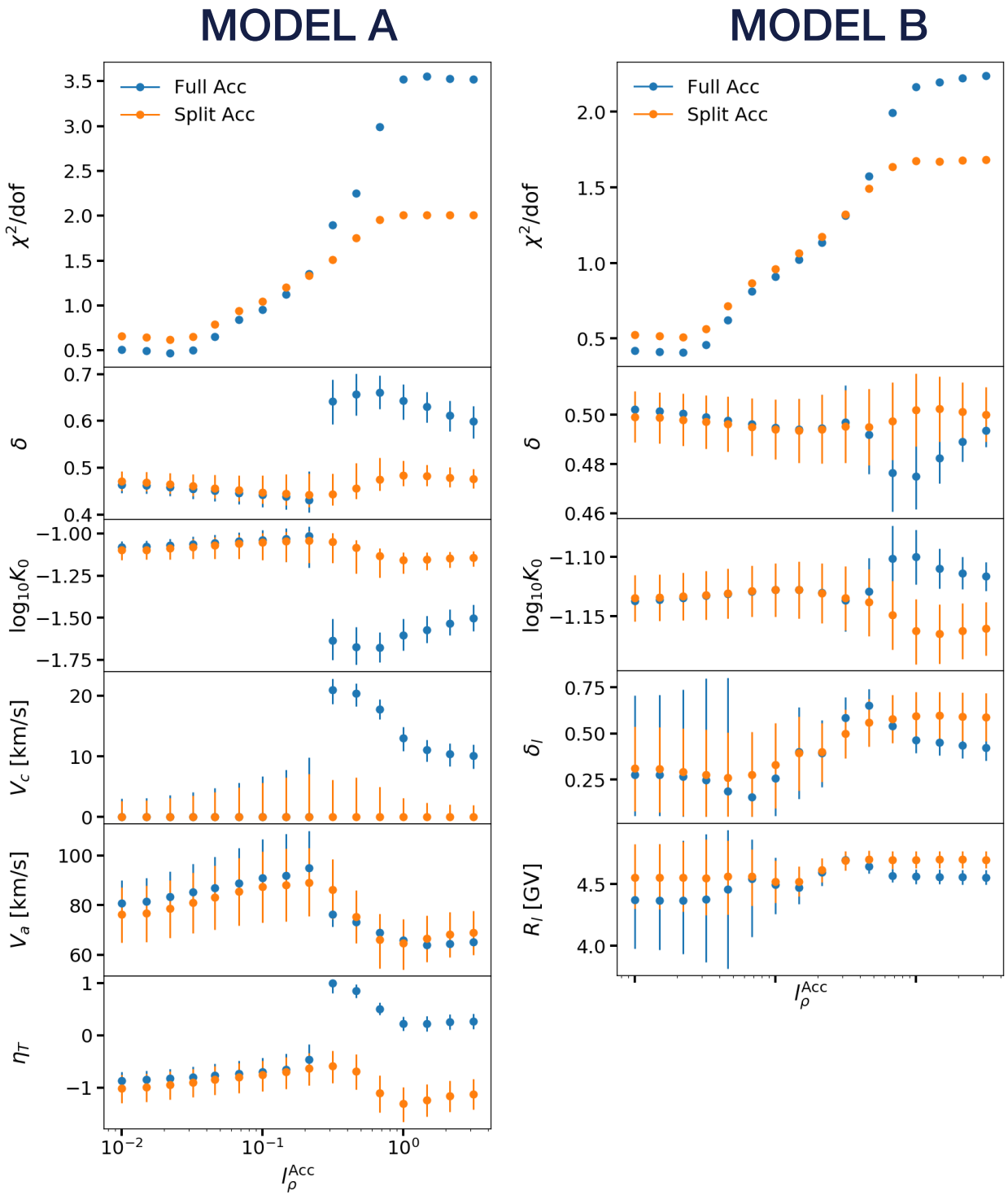
Total correlation matrix



AMS-02 B/C fit

AMS B/C fit results as a function of $l_\rho^{\text{Acc. res.}}$:

- χ^2/dof from 0.7 to 2
- Best-fit values dependence reduced. More stable results for both Model A and B.
- $l_\rho^{\text{Acc.}} = 0.1$ gives $\chi^2/\text{dof} \simeq 1$, stable results and conservative errors.

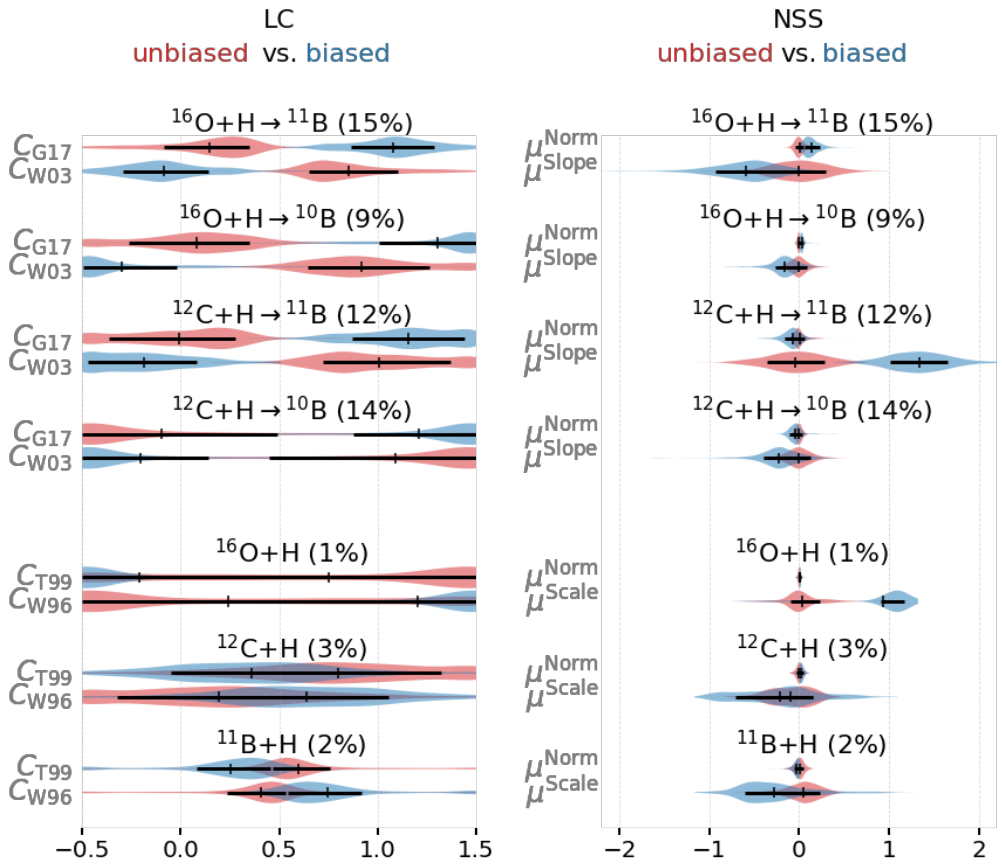


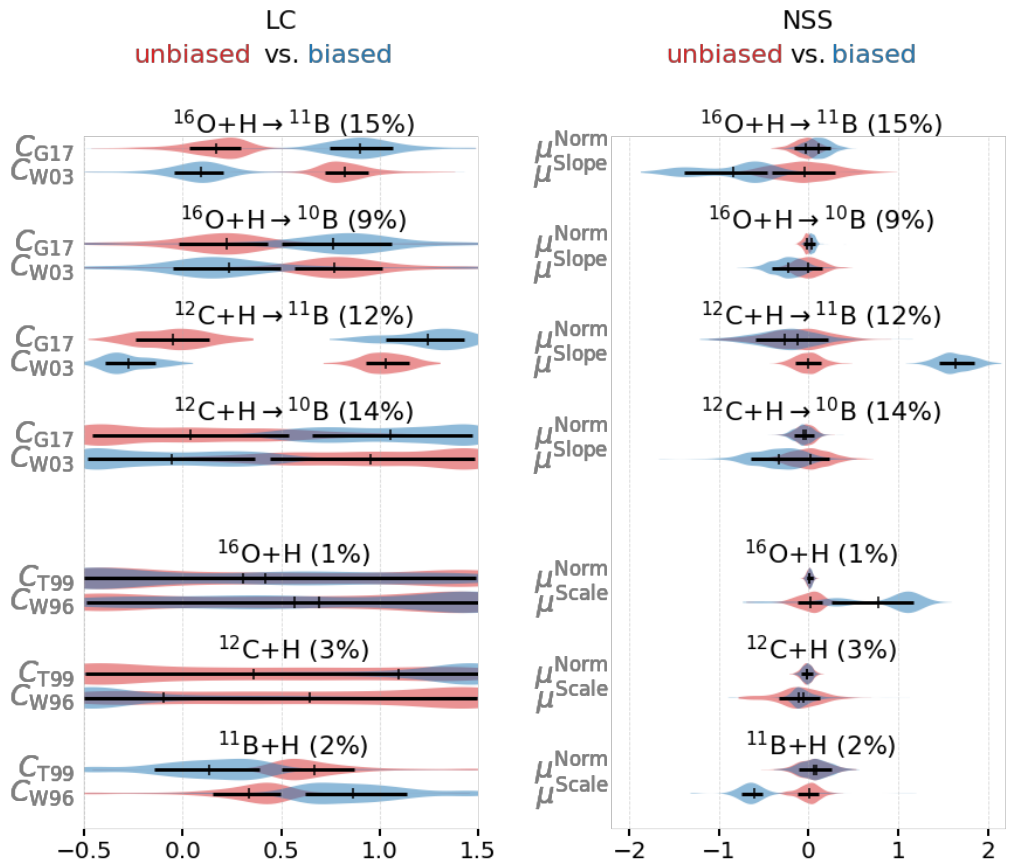
Conclusions

- Production and inelastic nuclear cross-sections can be implemented in the models with nuisances parameters to propagate ‘uncertainties’ and remove biases from wrong cross-sections.
- Handling of systematic on data from AMS-02 requires to model the bin-to-bin correlation for each source of systematics.
- Full description of analyses and results presented here: A&A, 627, A158 (2019)
- All analyses performed with USINE [https://lpsc.in2p3.fr/usine]
- Methodology presented here used in:
  - CRD1b (Thursday, July 25) AMS-02 Antiprotons are Consistent with a Secondary Astrophysical Origin, M. Boudeau
  - CRD6a (Monday, July 29): Cosmic ray transport from AMS-02 B/C data: reference parameters and physical interpretation, Y. Génolini

Backup slides

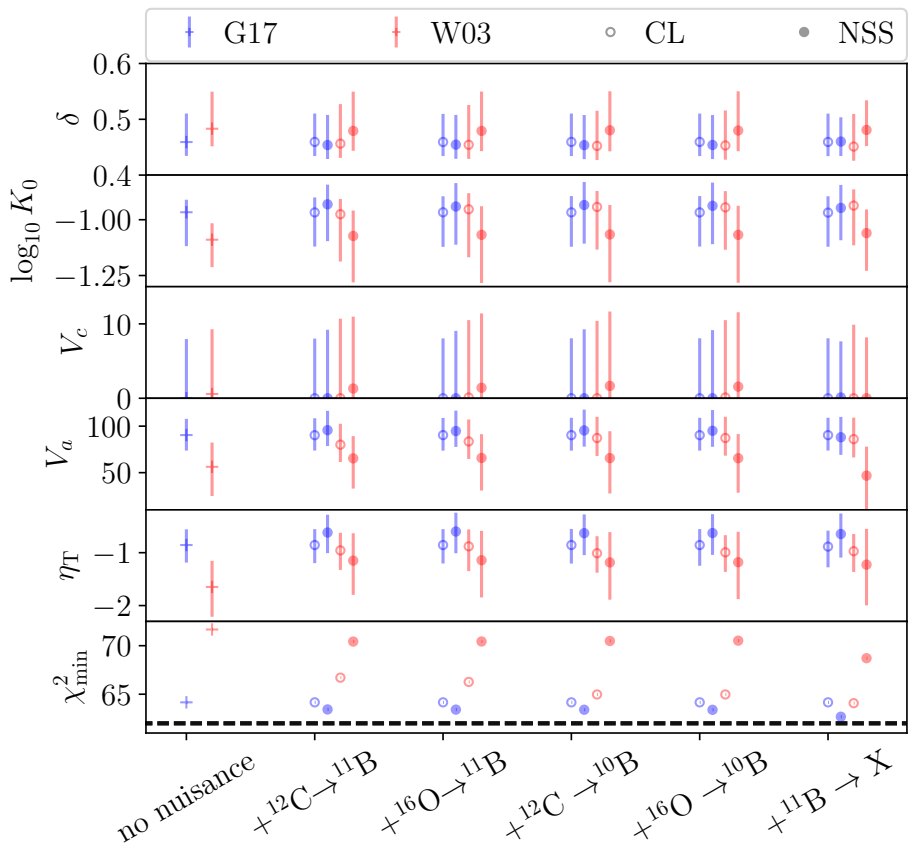
Nuclear Cross-Section



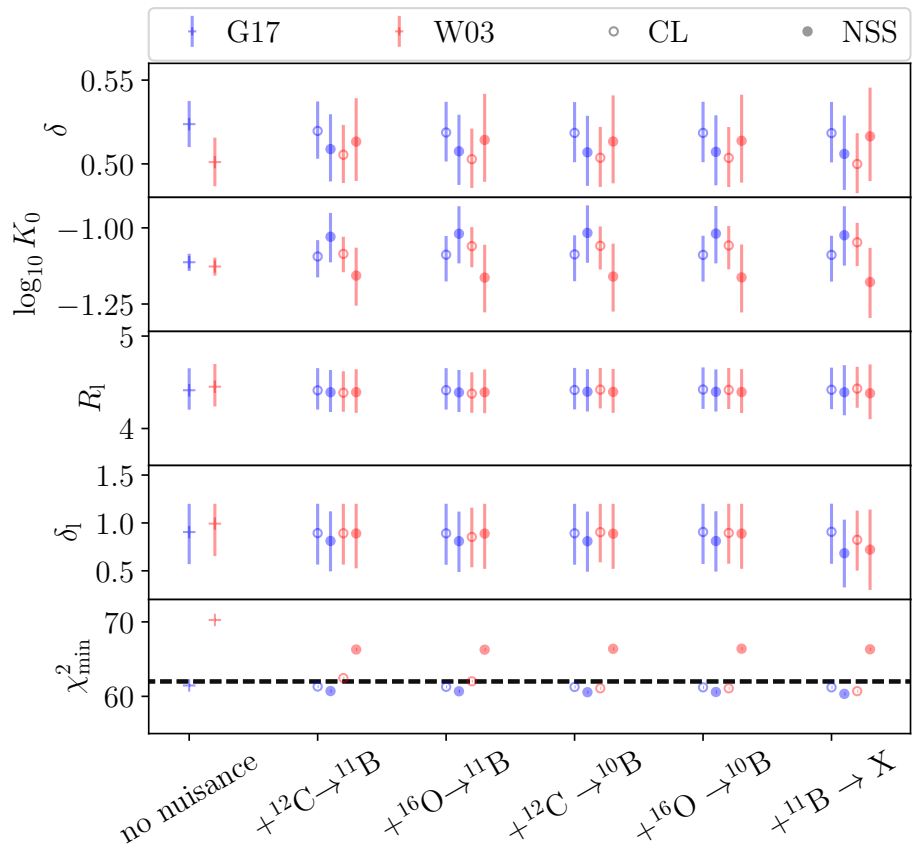


Systematic errors on Data + Nuclear Cross Sections

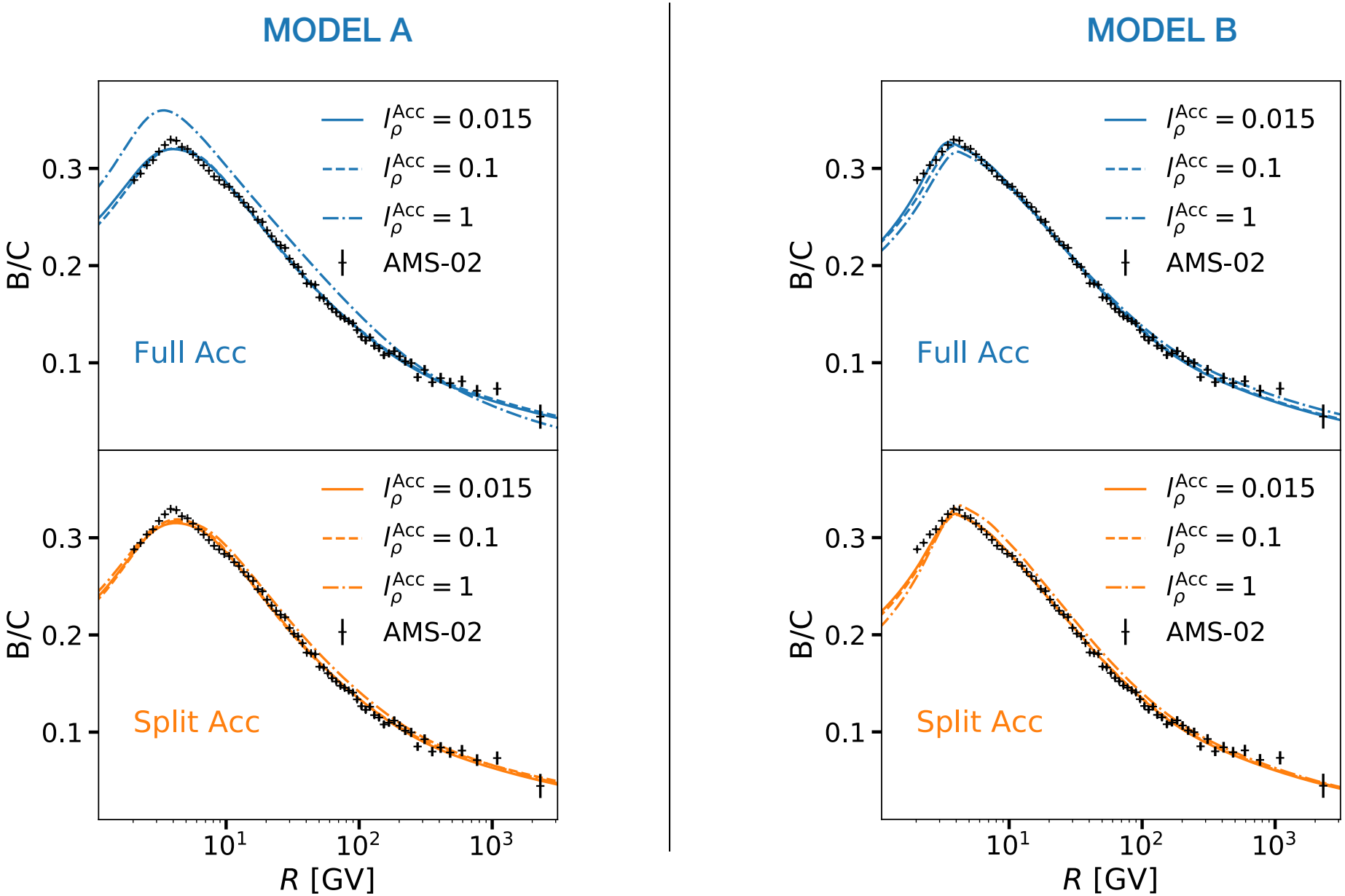
MODEL A



MODEL B



Nuclear Cross-Section



Propagation Models

- 2 configurations :
  - Model A (diff.+reac.+conv. aka QUAINT):

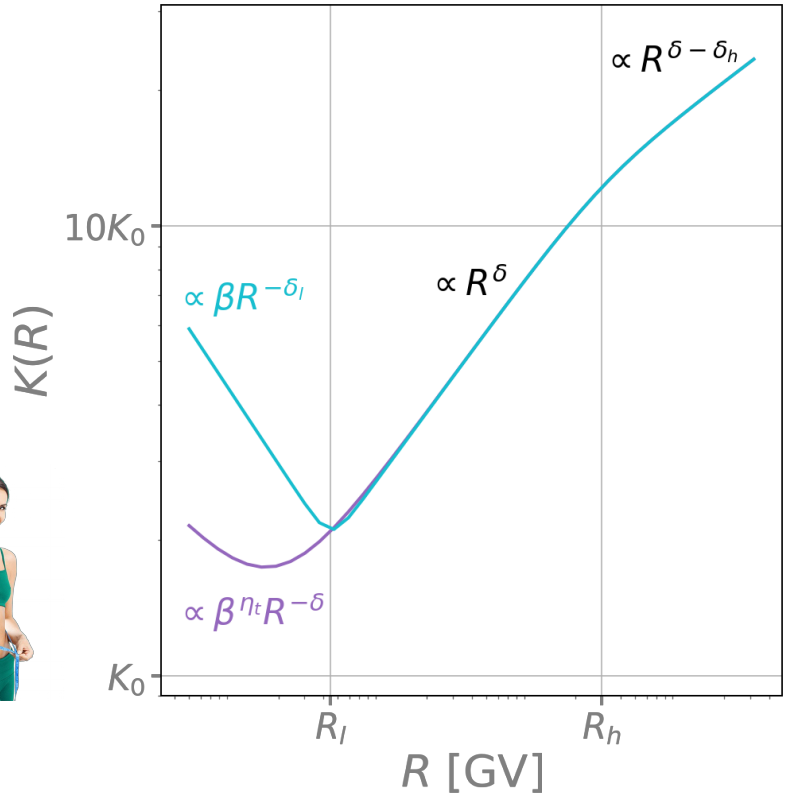
$$K(R) = \beta^{\eta_t} K_0 \left(\frac{R}{1\ \mathrm{GV}}\right)^{\delta} K_{\mathrm{HE}}(R)$$

+ reacceleration (V_a) + convection (V_c)

  - Model B (pure diffusion aka SLIM):

$$K(R) = \beta K_0 \left(\frac{R}{1\ \mathrm{GV}}\right)^{\delta} \left(1 + \left(\frac{R_l}{R}\right)^{(\delta+\delta_l)/s_l}\right)^{s_l} K_{HE}(R)$$

  - Where $K_{HE}(R) = (1 + (R/R_h)^{\delta_h/s_h})^{-s_h}$ (fixed)



- Mock Data generated with statistical errors around reference models for A and B.
- Fit of the mock data, two cases considered:
  - Unbiased: $\sigma_{\mathrm{Inel.,\ Prod.}}(\mathrm{Fit}) = \sigma_{\mathrm{Inel.,\ Prod.}}(\mathrm{Gen.})$ (Inel.: W97, Prod.: G17)
  - Biased: $\sigma_{\mathrm{Inel.,\ Prod.}}(\mathrm{Fit})$ (Inel.: T99, Prod.: W03) $\neq \sigma_{\mathrm{Inel.,\ Prod.}}(\mathrm{Gen.})$

Nuclear Cross Sections

- Major ingredient in the modelling of GCR nuclei:
  - Inelastic cross sections: sink term for both primaries and secondaries.
  - Production cross sections: source term for secondaries.
- Impact on B/C ratio:
  - Inelastic XSs: 3% at ~5 GV, decreases to zero at higher R.
  - Production XSs: ~10% above 20 GV
  - Larger than data precision

Impact on B/C ratio: