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

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Work based on:

Fitting B/C cosmic-ray data in the AMS-02 era: a cookbook
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]
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- Impact on B/C ratio larger than data precision
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 Xs.

- **Linear Combination (LC)**
  - Linear combination of available Xs.
  - Nuisance parameters $C_\alpha$ with a flat distribution.
  - Can fully recover each Xs parametrisation.

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

- 2 configurations:
  - Model A (diffusion + reacceleration + convection aka QUAIN'T):
    \[ K(R) = \beta m_n K_0 \left( \frac{R}{1 \text{ GV}} \right)^{\delta} + \text{reacceleration} \left( V_d \right) + \text{convection} \left( V_c \right) \]
    5 free parameters
  - Model B (pure diffusion aka SLIM):
    \[ K(R) = \beta K_0 \left( \frac{R}{1 \text{ GV}} \right)^{\delta} \left( 1 + \left( \frac{R_l}{R} \right)^{(\delta+\delta_l)\delta_l} \right)^{\delta_l} \]
    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: \( \sigma_{\text{Inel., Prod.}}(\text{Fit}) = \sigma_{\text{Inel., Prod.}}(\text{Gen.}) \) (Inel.: W97, Prod.: G17)
  - Biased: \( \sigma_{\text{Inel., Prod.}}(\text{Fit}) \) (Inel.: T99, Prod.: W03) \( \neq \sigma_{\text{Inel., Prod.}}(\text{Gen.}) \)
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 $\chi^2 / \text{dof}$
- Biased best fits w.r.t to parameters values (vertical dashed lines)

With nuisances NSS (—) and LC (--):
- good $\chi^2 / \text{dof}$ recovered
- Reduced biases on the parameter distributions
- Better results for LC than for NSS as expected.

MODEL A

MODEL B
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 ($\alpha = \text{Stat., Acc., Unf., Scale}$):

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

where:

- $\sigma_i^\alpha$ is the error from AMS
- $l^\alpha_{\rho}$ is the correlation length in unit of decade of rigidity.

How the choice of $l^\alpha_{\rho}$ impact the best fit values?
Systematic errors on Data

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- \(l_\rho^\alpha\) is the correlation length in unit of decade of rigidity.
AMS B/C fit

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

- $\chi^2$/dof from 0.5 to 3.5
- Large best-fit values and errors dependence:
  - Model A: 2 different regimes for low $l^{\text{Acc}}_{\rho}$ and high $l^{\text{Acc}}_{\rho}$
  - 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, ...
    \( l_\rho = 0.01...3 \)
Systematic errors on Data

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  - Acc. res.: Residual error data/ MC corrections, ... $l_\rho = 0.01...3$
AMS B/C fit results as a function of $I^\text{Acc. res.}_\rho$:

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

MODEL A

LC unbiased vs. biased

NSS unbiased vs. biased

MODEL B

LC unbiased vs. biased

NSS unbiased vs. biased
Systematic errors on Data + Nuclear Cross Sections

MODEL A

MODEL B
Nuclear Cross-Section

MODEL A

MODEL B

$B/C$ vs $R$ [GV]

- Full Acc
- Split Acc

$\rho^{\text{Acc}} = 0.015$
$\rho^{\text{Acc}} = 0.1$
$\rho^{\text{Acc}} = 1$

AMS-02
Propagation Models

- 2 configurations:
  - Model A (diff.+reac.+conv. aka QUAINTE):
    \[ K(R) = \beta^{\text{ini}} K_0 \left( \frac{R}{1 \text{ GV}} \right)^{\delta} K_{\text{HE}}(R) \]
    + reacceleration \( \left( V_d \right) \) + convection \( \left( V_c \right) \)
  - Model B (pure diffusion aka SLIM):
    \[ K(R) = \beta K_0 \left( \frac{R}{1 \text{ GV}} \right)^{\delta} \left( 1 + \left( \frac{R_l}{R} \right)^{(\delta+S_l)/S_l} \right)^{S_l} K_{\text{HE}}(R) \]
    \[ K_{\text{HE}}(R) = \left( 1 + \left( R/R_h \right)^{\delta_h/S_h} \right)^{-S_h} \text{ (fixed)} \]

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- Fit of the mock data, two cases considered:
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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 $\sim 5$ GV, decreases to zero at higher $R$.
  - Production XSs: $\sim 10\%$ above 20 GV
  - Larger than data precision