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TTK Institute for Theoretical Particle Physics and Cosmology

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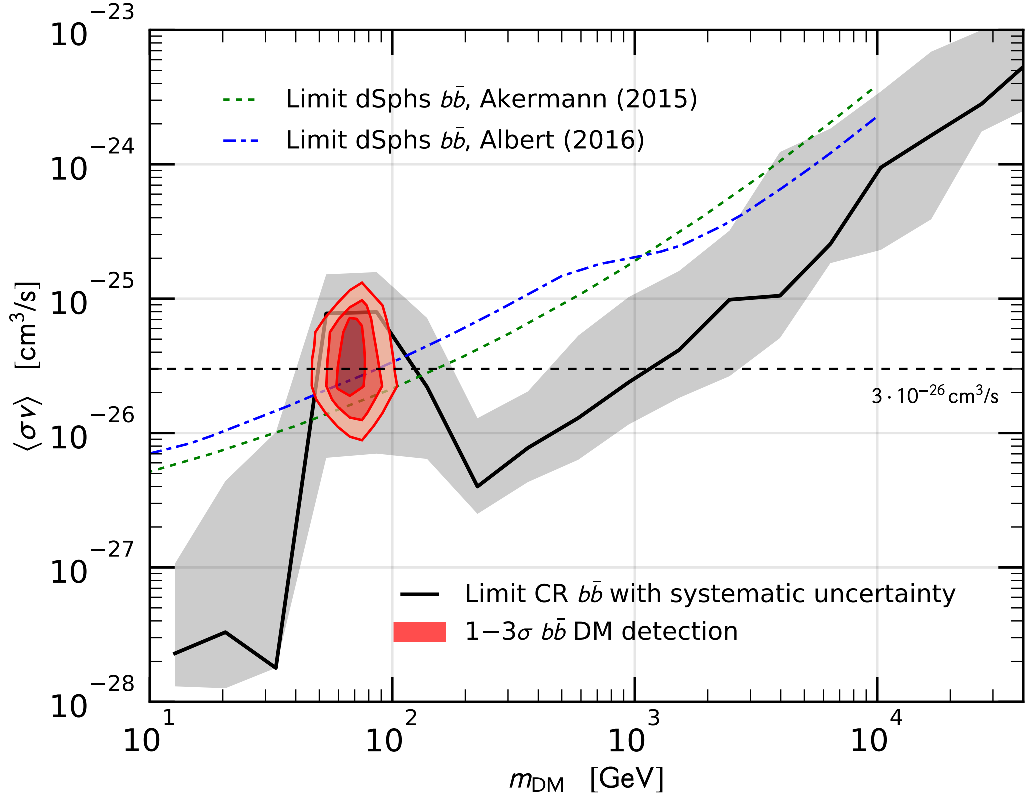
# Scrutinizing the evidence for dark matter in cosmic-ray antiprotons

**Michael Korsmeier**

Based on: Cuoco, Heisig, Klamt, **MK**, Krämer; arXiv:1903.01472

# A hint for DM in cosmic-ray antiprotons?

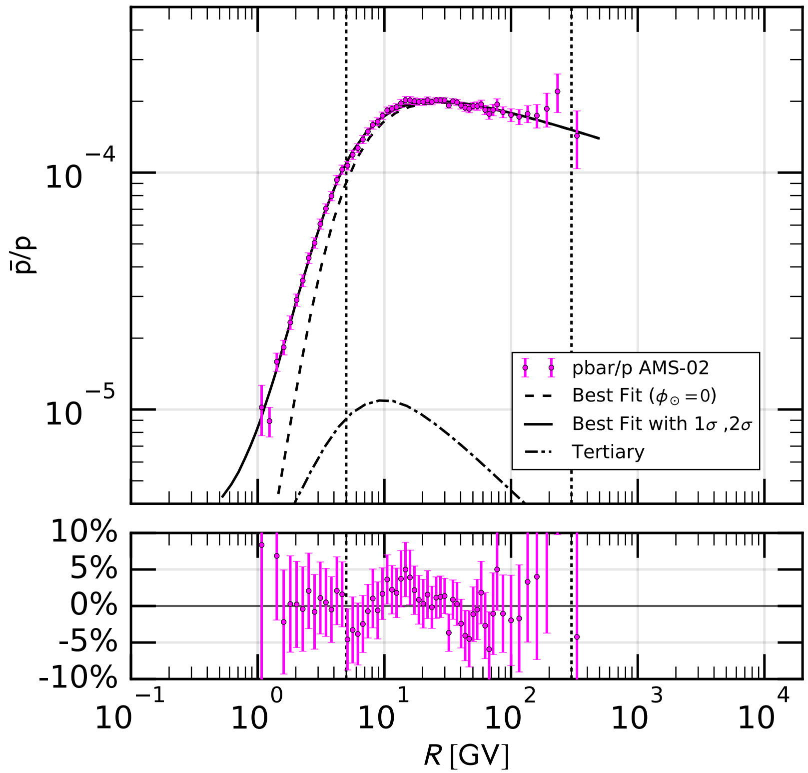



[Cuoco, Krämer, **MK**; 2017]

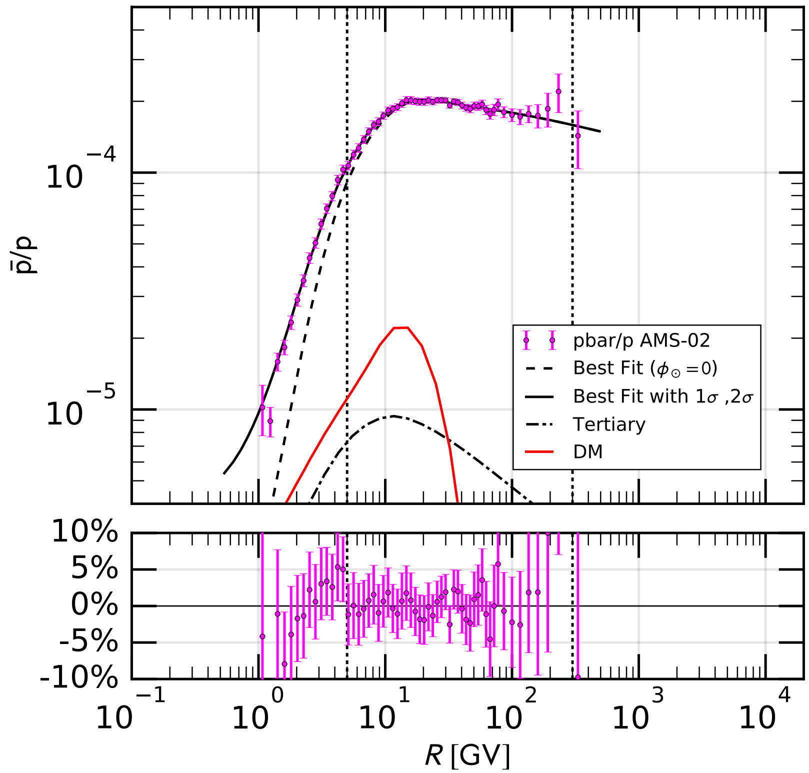
We will address two important sources of systematic uncertainties: the production **cross sections of secondary antiprotons** and **potential correlation in the cosmic-ray data**

# Antiproton spectra of the default setup

**Fit without DM**

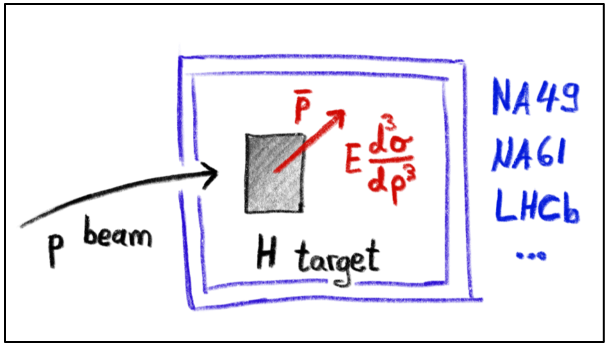



**Fit with DM**

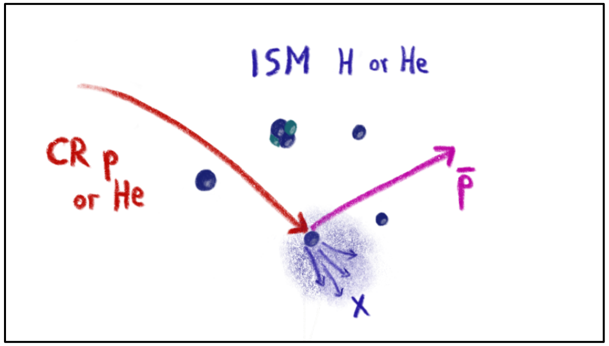



[Cuoco, **MK**, + ; 2019]

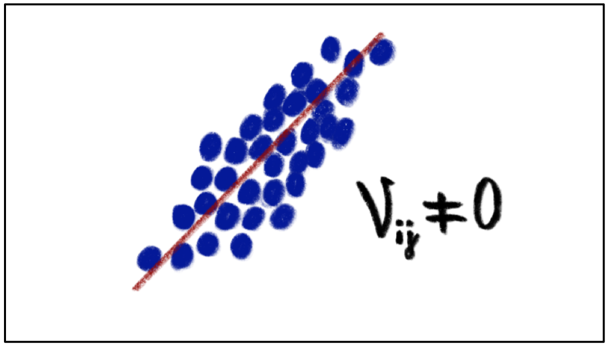
# Outline




- Determination of the antiproton production cross section for cosmic rays and its uncertainty

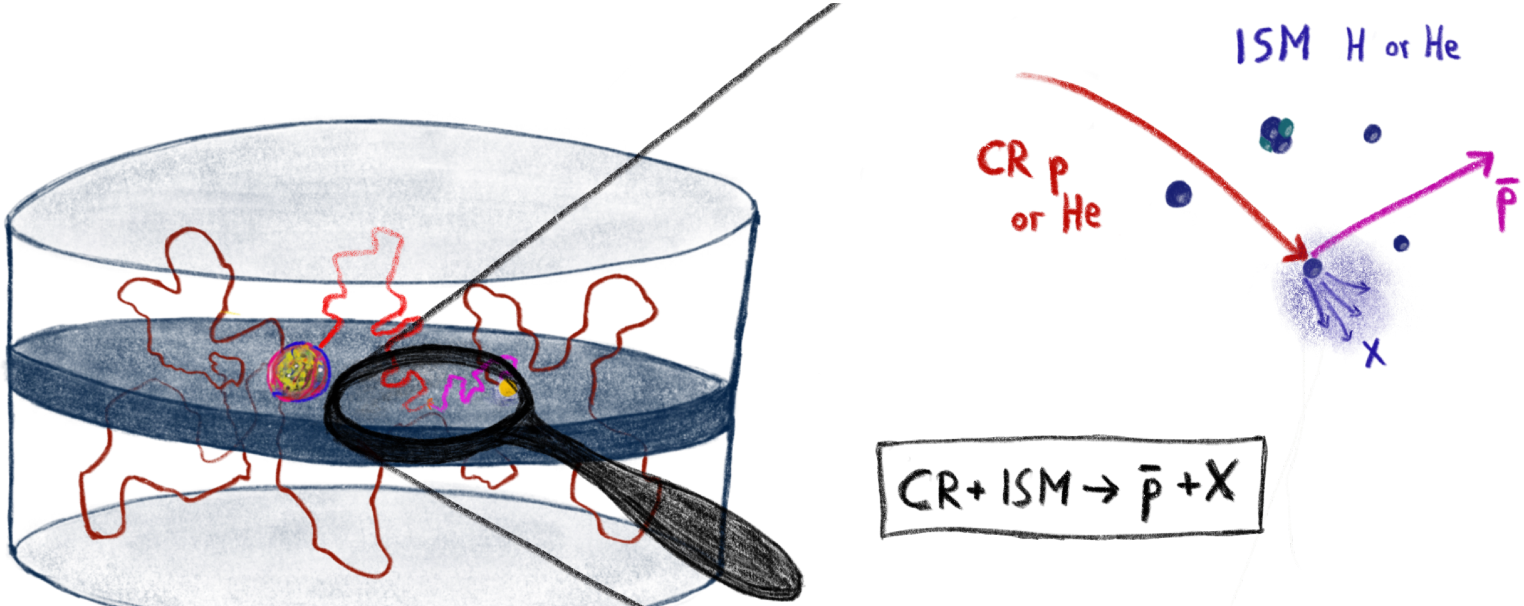



- Impact of the antiproton production uncertainty on CR fits and the search for DM




- Impact of potential correlation in the CR data on CR fits and the search for DM

# Secondary antiprotons in cosmic rays




$$\boxed{\mathrm{CR} + \mathrm{ISM} \rightarrow \bar{p} + X}$$

$$q^{\bar{p}}(T_{\bar{p}}) = \int dT \, 4\pi \, n_{\mathrm{ISM}} \, \phi_{\mathrm{CR}}(T) \, \frac{d\sigma(T, T_{\bar{p}})}{dT_{\bar{p}}}$$

## Antiproton production

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

$$E \frac{d^3\sigma}{dp^3} \sim R(s, x_R) \, (1 - x_R)^{c_1} \, e^{-c_2 p_T} \xrightarrow[\text{+ angular integration}]{\text{Lorentz transformation}} \frac{d\sigma(T, T_{\bar{p}})}{dT_{\bar{p}}}$$

scaling violation

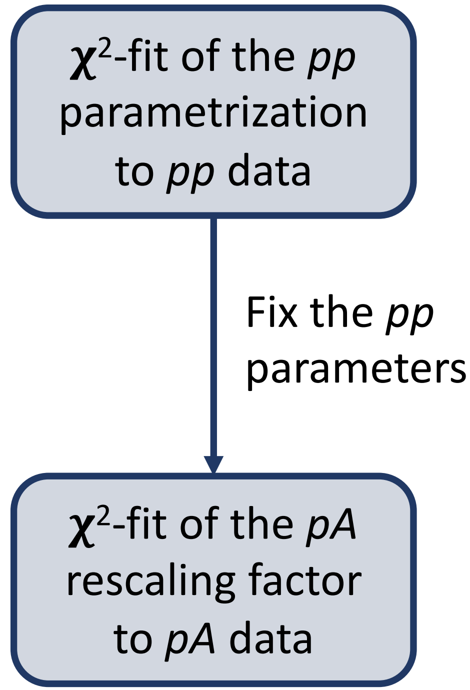
Feynman scaling invarianz

$p_T$ suppression

# Reanalysis of the cross section parametrizations

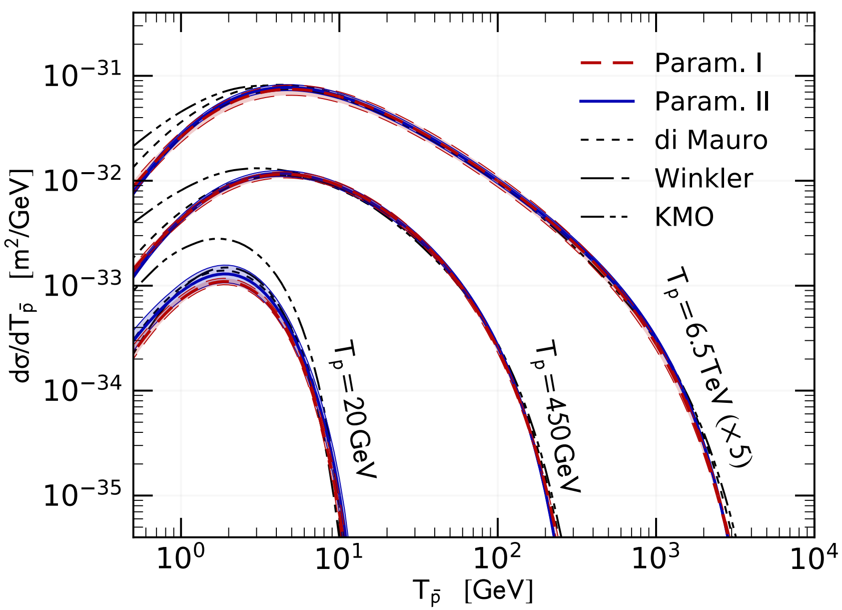
- Fit of two most recent (analytic) parametrizations for antiproton production in *pp* collisions
- Fit of *pA* parametrization by rescaling from *pp*

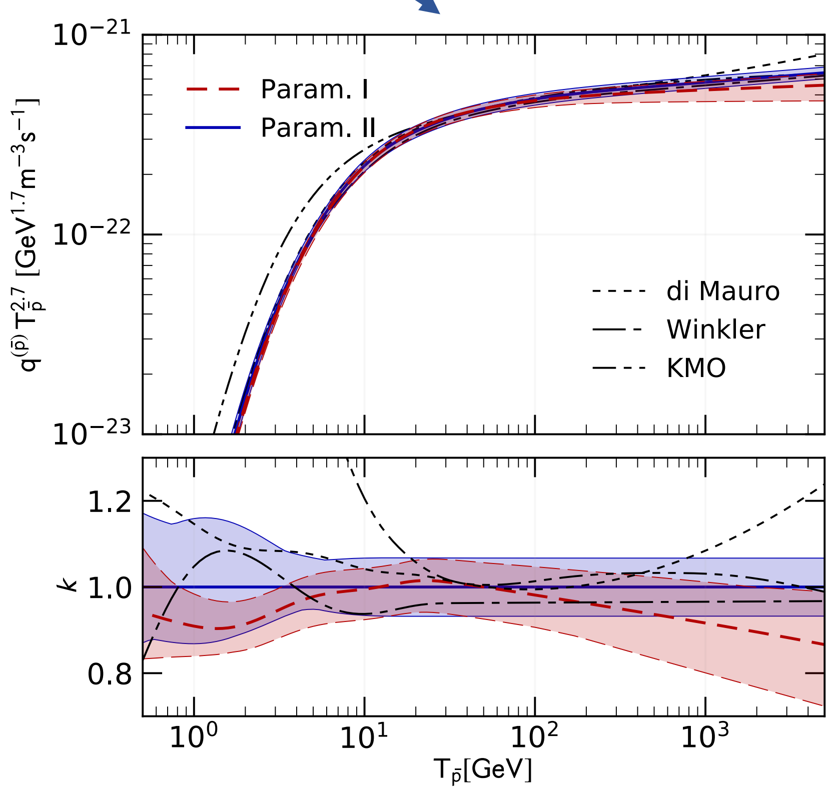
| Experiment | CM-Energy [GeV] | Channel |
|---|---|---|
| NA49 | 17.3 | *pp* |
| NA61 | 7.7, 8.8, 12.3, 17.3 | *pp* |
| Dekkers | 6.1, 6.7 | *pp* |
| | | |
| LHCb | 110 | *p*He |
| NA49 | 17.3 | *p*C |



# Result of the fits to proton-proton data

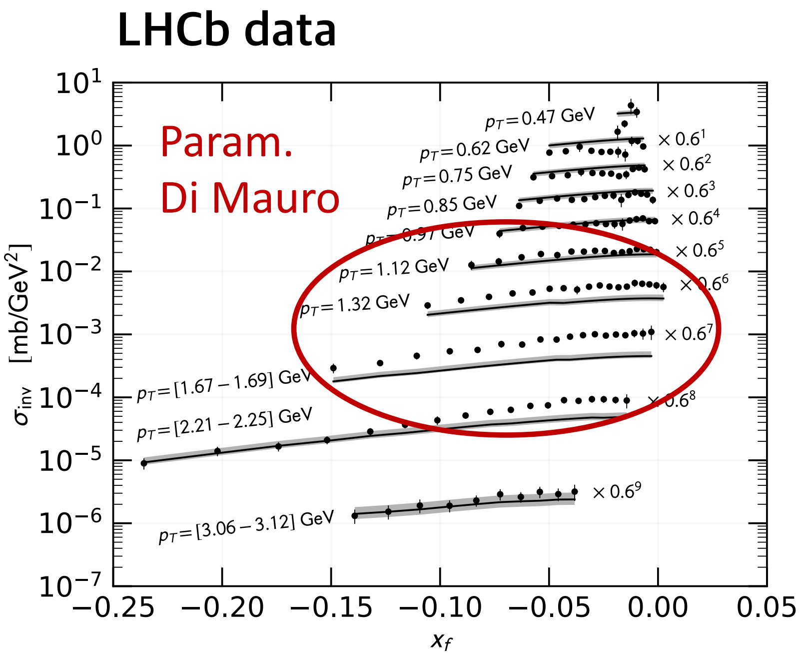
$$q_{ij}(T_{\bar{p}}) = \int_0^\infty dT_i \; 4\pi \, n_{\mathrm{ISM},j} \, \phi_i(T_i) \, \boxed{\frac{d\sigma_{ij}}{dT_{\bar{p}}}(T_i, T_{\bar{p}})}$$

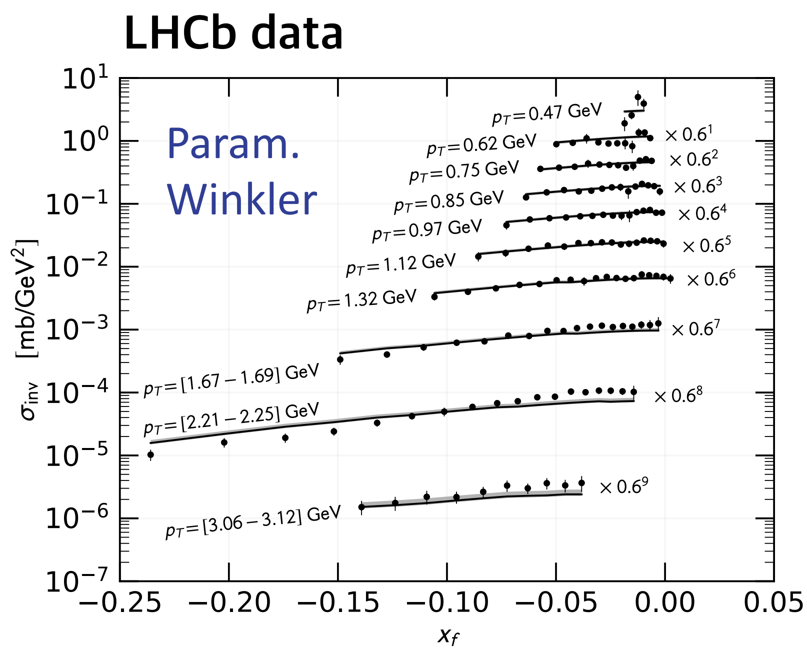



[**MK**, Donato, Di Mauro; 2018]

# Result of the fits to proton-nucleus data



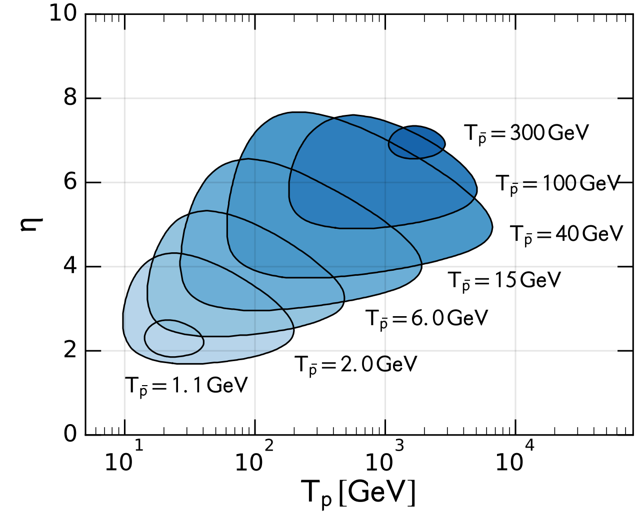

[MK, Donato, Di Mauro; 2018]

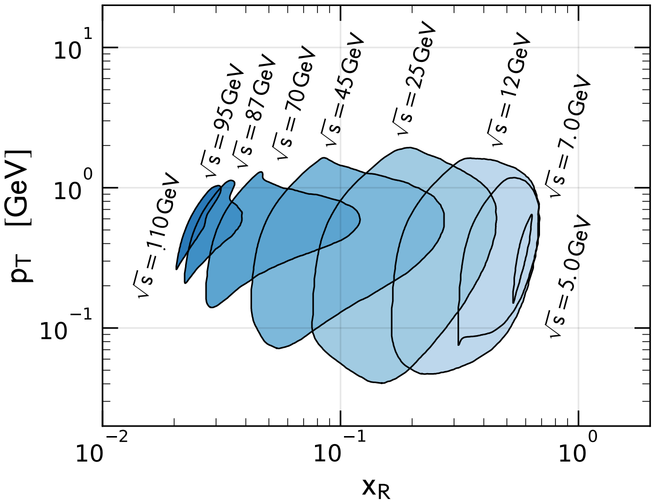
LHCb data show preference for Param. II (Winkler) at (very high) energies of $T_p$ = 6.5 TeV

# How to improve cross section uncertainties?

[Donato, **MK,** Di Mauro; 2017]

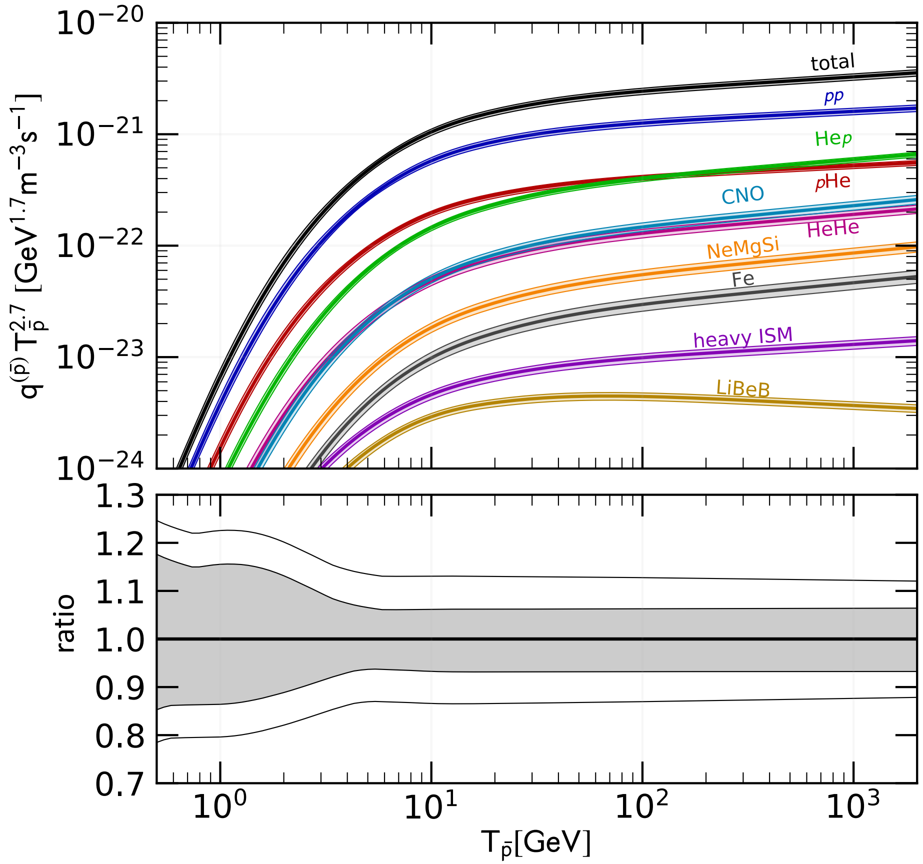
- We provide a guideline for future experiments concerning the most relevant kinematic parameter space
- If the cross sections $E\frac{d^3\sigma}{dp^3}(\sqrt{s}, x_{\mathrm{R}}, p_{\mathrm{T}})$ are known by 3% inside the blue contours we reach AMS-02 accuracy
- **In particular, future measurements at low center-of-mass energies (< 7 GeV) could improve the current uncertainties**



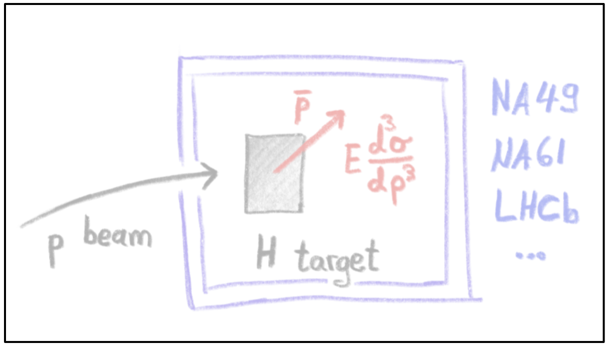
# Antiproton cross sections and GAPS

- Cross section uncertainties in the energy range of AMS-02 are at the level of 10% to 20%
- At low energies the uncertainty of from cross sections increases
- **At GAPS energies there is a significant uncertainty of the source term from cross section normalization and shape**




[MK, Donato, Di Mauro; 2018]

# Outline

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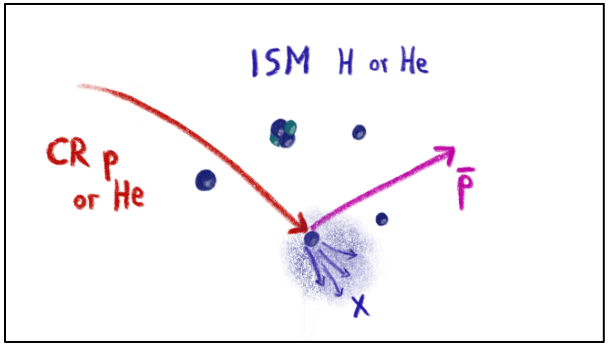
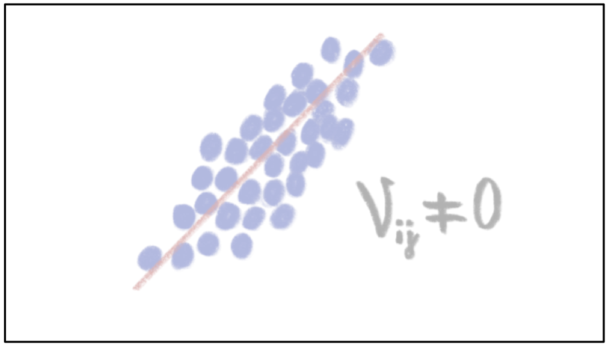



- Impact of the antiproton production uncertainty on CR fits and the search for DM




- Impact of potential correlation in the CR data on CR fits and the search for DM

# Fit setup

- CR data: *p*, He, $\bar{p}$/p (AMS-02 and Voyager)

**Fit Parameters:**

- 2D diffusion halo, cylindrical symmetry → $z_h$
- Broken-power-law injection spectrum → $\gamma_{1,p}$, $\gamma_{1,He}$, $\gamma_{2,p}$, $\gamma_{2,He}$, $R_0$, s
- Power-law diffusion (break at 300 GV) → $D_0$, $\delta$, ($R_D$, $\delta_2$)
- Diffusive reacceleration → $v_A$
- Convection → $v_{0,c}$
- Solar modulation, force-field approximation → $\phi$, $\phi_{\bar{p}}$
- (DM annihilation into a pair of b-quarks) → ($m_{DM}$, $\langle\sigma v\rangle$ )

- Antiproton production cross sections from Part I
- AMS-02 data is fitted to GALPROP model for rigidities above 5 GV

$$\frac{\mathrm{d}\psi}{\mathrm{d}t} = q(\boldsymbol{x},p) + \boldsymbol{\nabla}\cdot(D_{xx}\boldsymbol{\nabla}\psi - \boldsymbol{V}\psi) + \frac{\partial}{\partial p}p^2 D_{pp}\frac{\partial}{\partial p}\frac{1}{p^2}\psi - \frac{\partial}{\partial p}\left(\frac{\mathrm{d}p}{\mathrm{d}t}\psi - \frac{p}{3}\boldsymbol{\nabla}\cdot\boldsymbol{V}\psi\right) - \frac{1}{\tau_f}\psi - \frac{1}{\tau_r}\psi$$

# The default fit setup

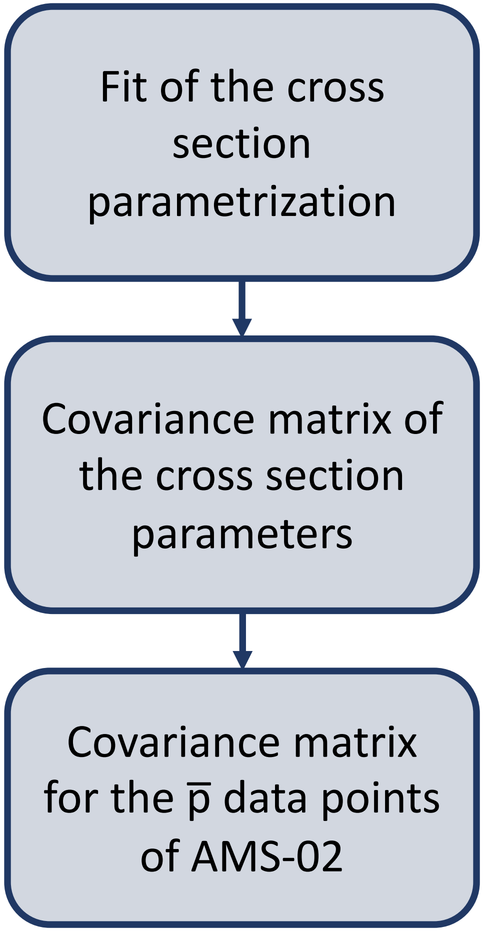
| | $\chi^2$ | | $\Delta\chi^2$ |
|---|---|---|---|
| | no DM | with DM | |
| [Cuoco, Krämer, **MK;** 2017] | 71.0 | 45.6 | 25.4 |
| Restrict data to R < 300 GV | 43.6 | 23.0 | 20.6 |
| Change cross section to Winkler | **35.6** | **22.9** | **12.7** |
| Include data R > 300 GV (include CREAM) + fit of the break in diffusion | 50.7 | 35.6 | 15.1 |

New default setup in Ref. [Cuoco, **MK**, + ; 2019]

A more careful setup (CREAM data, cross section, solar modulation) reduces the significance of the DM signature to a $\Delta\chi^2$ of about 13-15 (~3σ in frequentist interpretation)

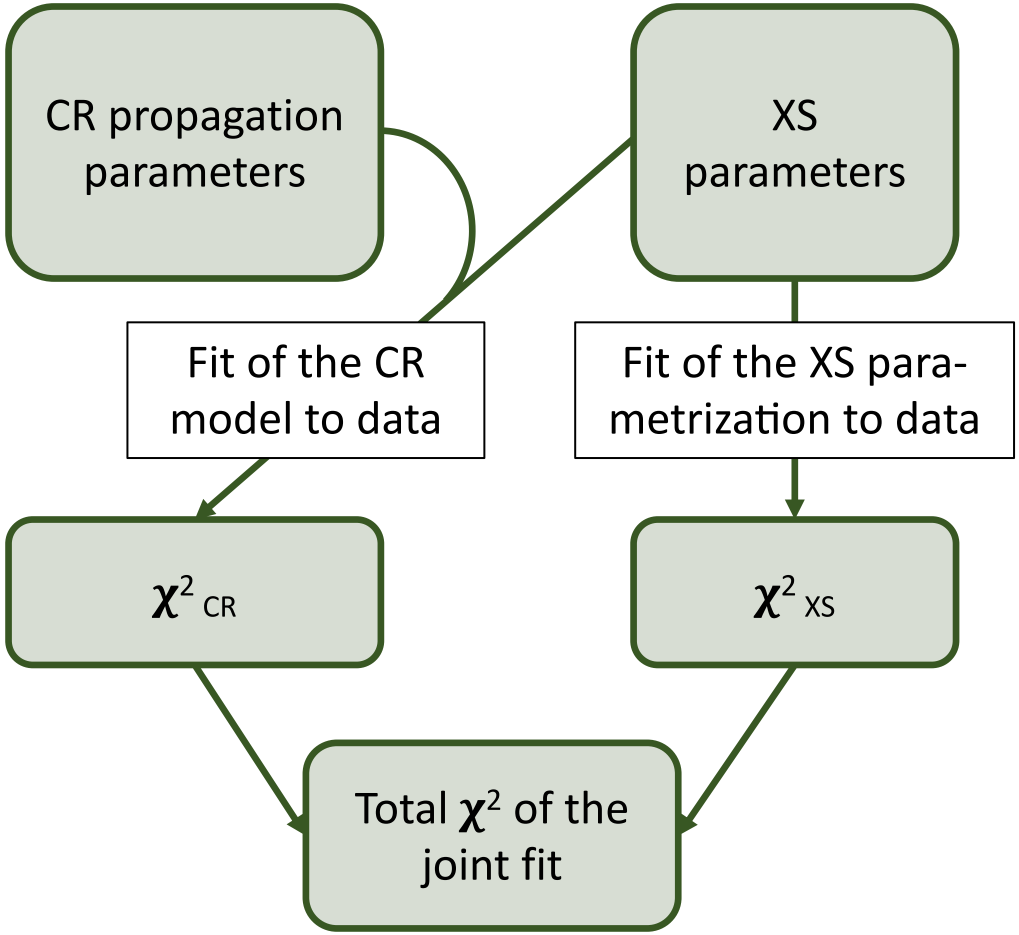
# Treatment of cross section uncertainties

## Covariance matrix approach




Already used in [Reinert, Winkler; 2018]

## Joint fit method



# Joint fit method to CR and XS data

- We use Winkler's cross section and identify the 3 most important parameters which affect the shape of the source term

$$E_{\bar{p}} \frac{\mathrm{d}^3\sigma}{\mathrm{d}p_{\bar{p}}^3}(\sqrt{s}, x_\mathrm{R}, p_\mathrm{T}) = \sigma_\mathrm{in}\, R\, C_1 (1 - x_\mathrm{R})^{C_2} \left[1 + \frac{X}{\mathrm{GeV}}(m_T - m_p)\right]^{\frac{-1}{C_3 X}}$$

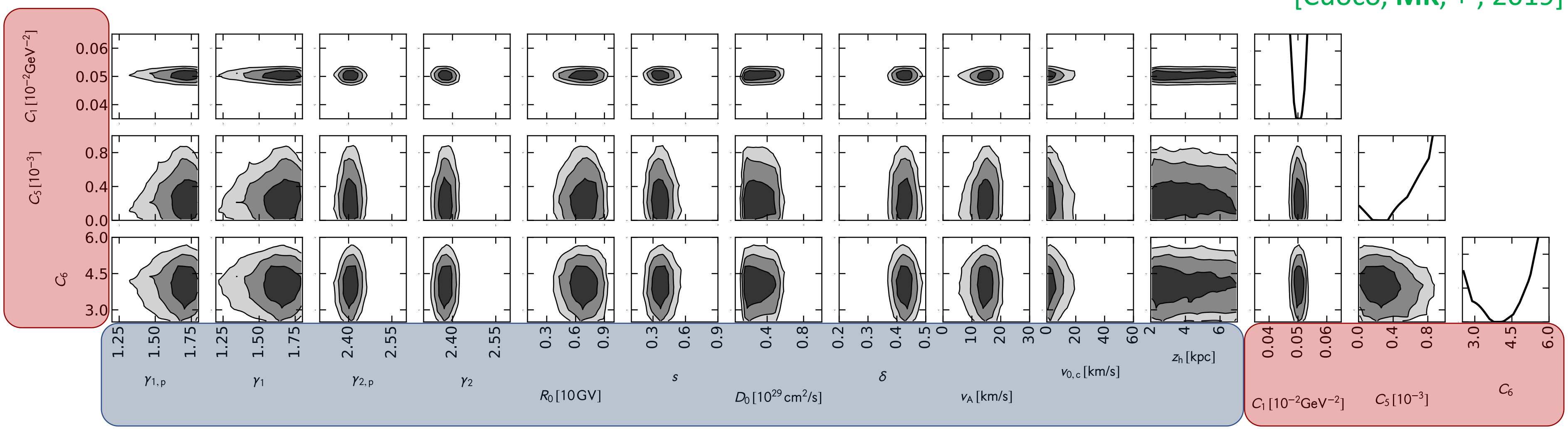
$$R = \begin{cases} \left[1 + C_5 \left(10 - \frac{\sqrt{s}}{\mathrm{GeV}}\right)^5\right] \cdot \exp\left[C_6 \left(10 - \frac{\sqrt{s}}{\mathrm{GeV}}\right)^2 \cdot \ (x_\mathrm{R} - x_{R,\mathrm{min}})^2\right] & , \ \sqrt{s} \leq 10\,\mathrm{GeV} \\ 1 & , \ \mathrm{else} \end{cases}$$

- In total the fit contains 11+3 (CR+XS) parameters

# Joint fit: correlation of parameters

XS parameters

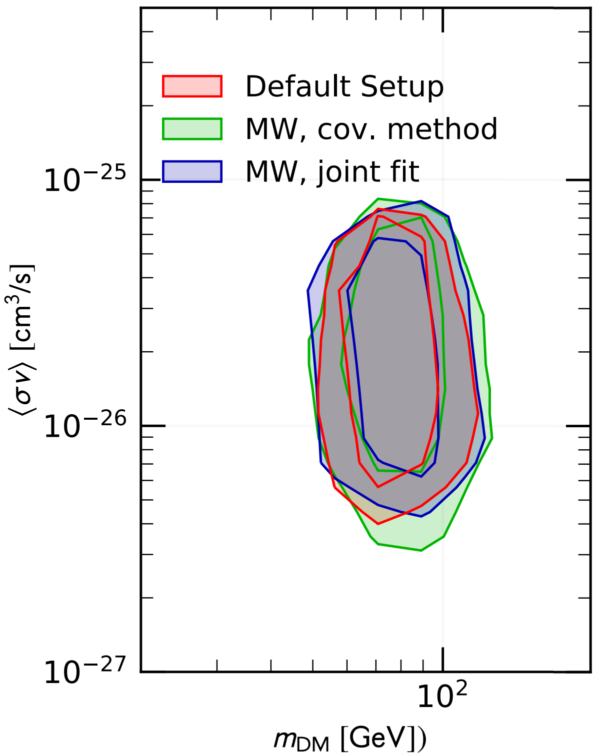
[Cuoco, **MK**, + ; 2019]




CR parameters

The cross section parameters and the cosmic-ray parameters are not (strongly) correlated.

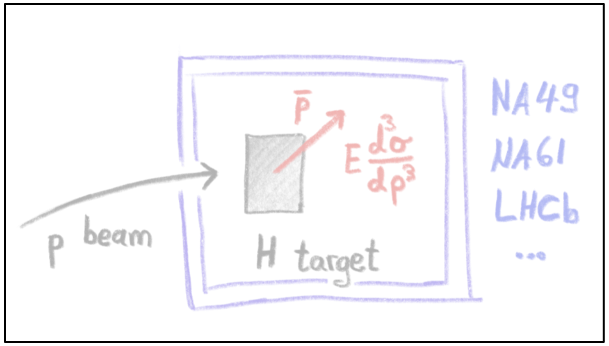
# Cross section uncertainties and the DM hint




| | $\chi^2$ | | $\Delta\chi^2$ |
|---|---|---|---|
| | no DM | with DM | |
| Param. MD | 34.2 | 22.2 | 12.0 |
| **Param. MW** | **35.6** | **22.9** | **12.7** |
| Cov-mat (Param. MD) | 34.2 | 22.0 | 12.2 |
| Cov-mat (Param. MW) | 33.9 | 23.0 | 10.9 |
| Joint fit (Param. MW) | 825.2 | 814.5 | 10.7 |

The significance of DM is only slightly affected by the uncertainty of the antiproton production cross section.

# Outline

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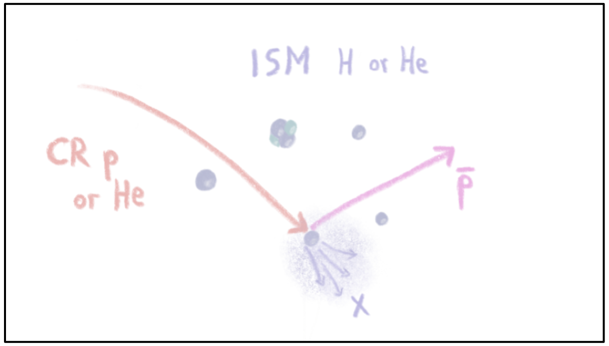
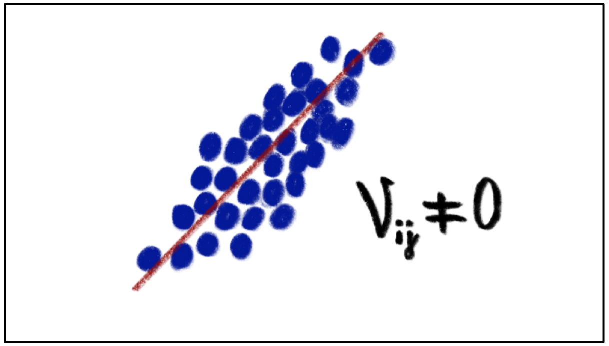
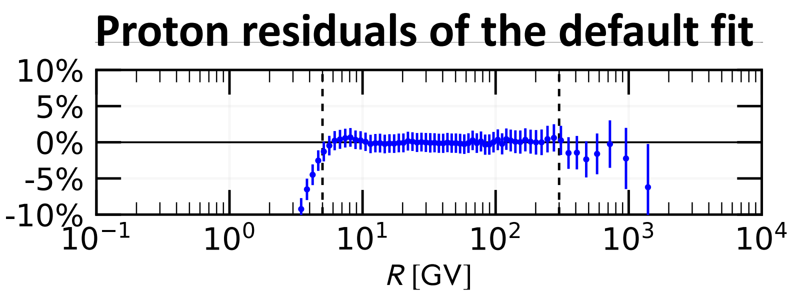



- Impact of the antiproton production uncertainty on CR fits and the search for DM




- Impact of potential correlation in the CR data on CR fits and the search for DM

# Correlation of uncertainties in the CR data?




- AMS-02 data is (mostly) dominated by systematic uncertainties
- Typically residuals of CR fits are not distributed statistically

- Our approach: split the uncertainty in three different categories

$$\mathcal{V} = \mathcal{V}_{\rm stat} + \boxed{\mathcal{V}_{\rm short}} + \boxed{\mathcal{V}_{\rm long}}$$

Has to be modeled and investigated

Normalizations are absorbed by nuisance parameters

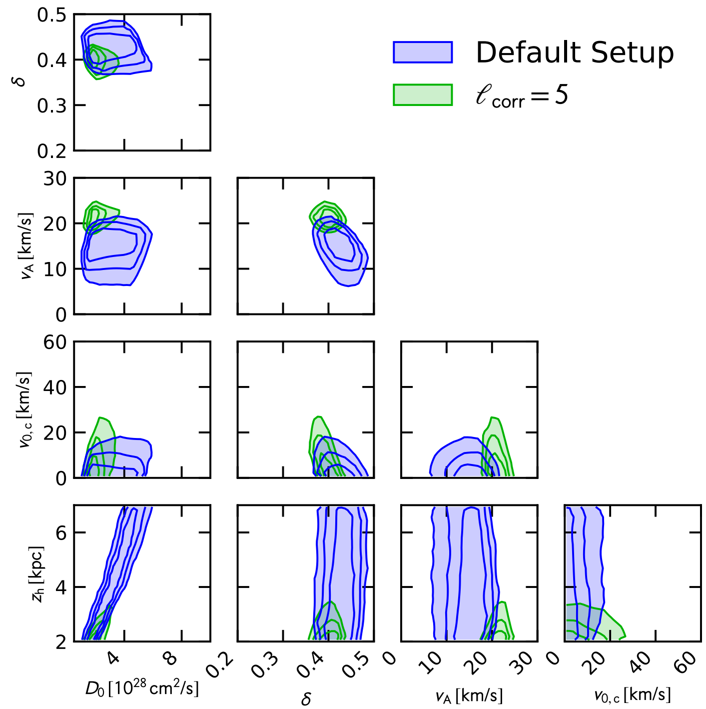
# Benchmark scenarios for correlation

- Data-driven method to estimate a covariance matrix with a short correlation length of neighboring points:
  Choose three benchmark scenarios for $\ell_{\mathrm{corr}}$ of 0, 5, and 10

$$\mathcal{V}_{\mathrm{short},ij} = \exp\left(-\frac{|i-j|^{\alpha}}{{\ell_{\mathrm{corr}}}^{\alpha}}\right) f^2 \sigma_{\mathrm{sys},i}\sigma_{\mathrm{sys},j}$$

Fit of the CR spectra by a smooth function → Use the $\chi^2$ definition of data with the smooth function as likelihood for $\ell_{\mathrm{corr}}$, α, and f → Derive constraints for the correlation matrix

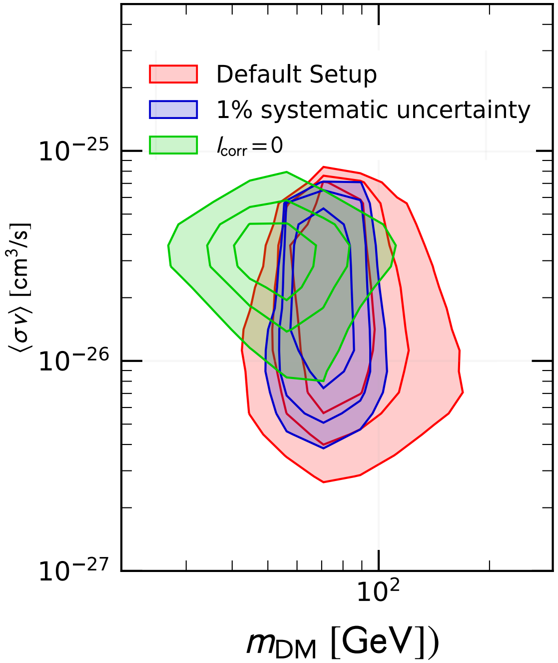
# Effect on the CR propagation parameters




[Cuoco, **MK**, + ; 2019]

A potential correlation could reduce the uncertainties in CR propagation parameters.

# Impact of correlations on the DM search



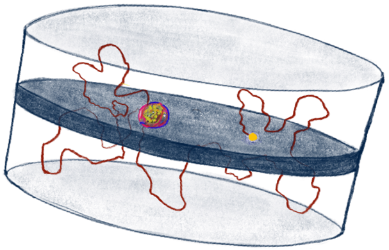

| | $\chi^2$ | | $\Delta\chi^2$ |
|---|---|---|---|
| | no DM | with DM | |
| Data driven, $\ell_{corr} = 0$ | 284.1 | 250.0 | 34.1 |
| Data driven, $\ell_{corr} = 5$ | 250.2 | 232.6 | 17.6 |
| Data driven, $\ell_{corr} = 10$ | 259.3 | 241.3 | 18.0 |

Replacing the systematic uncertainty by correlated uncertainties could potentially increase the significance of the DM hint.

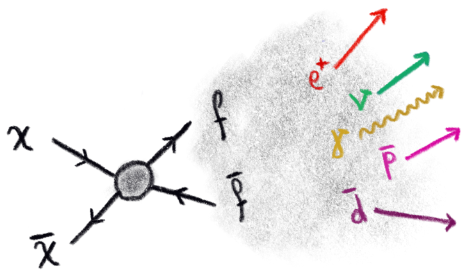
**Note of caution:** Only a covariance matrix provided by the experiments will allow to draw solid conclusion.

# Summary and conclusion

- The antiproton production cross section is an important systematic uncertainty, in particular at the low energies of future GAPS measurements



- Fits of AMS-02 antiproton data are not strongly affected by cross section uncertainties and the parameter spaces of cosmic rays and cross section are not strongly correlated




- Due to increasing precision of cosmic-ray measurements correlations of the data become important and could affect the results

Thank you for your attention!