Dark matter or correlated errors: Systematics of the AMS-02 antiproton excess

based on 2005.04237 *in collaboration with* M. Korsmeier, M.Winkler
and review: 2012.03956

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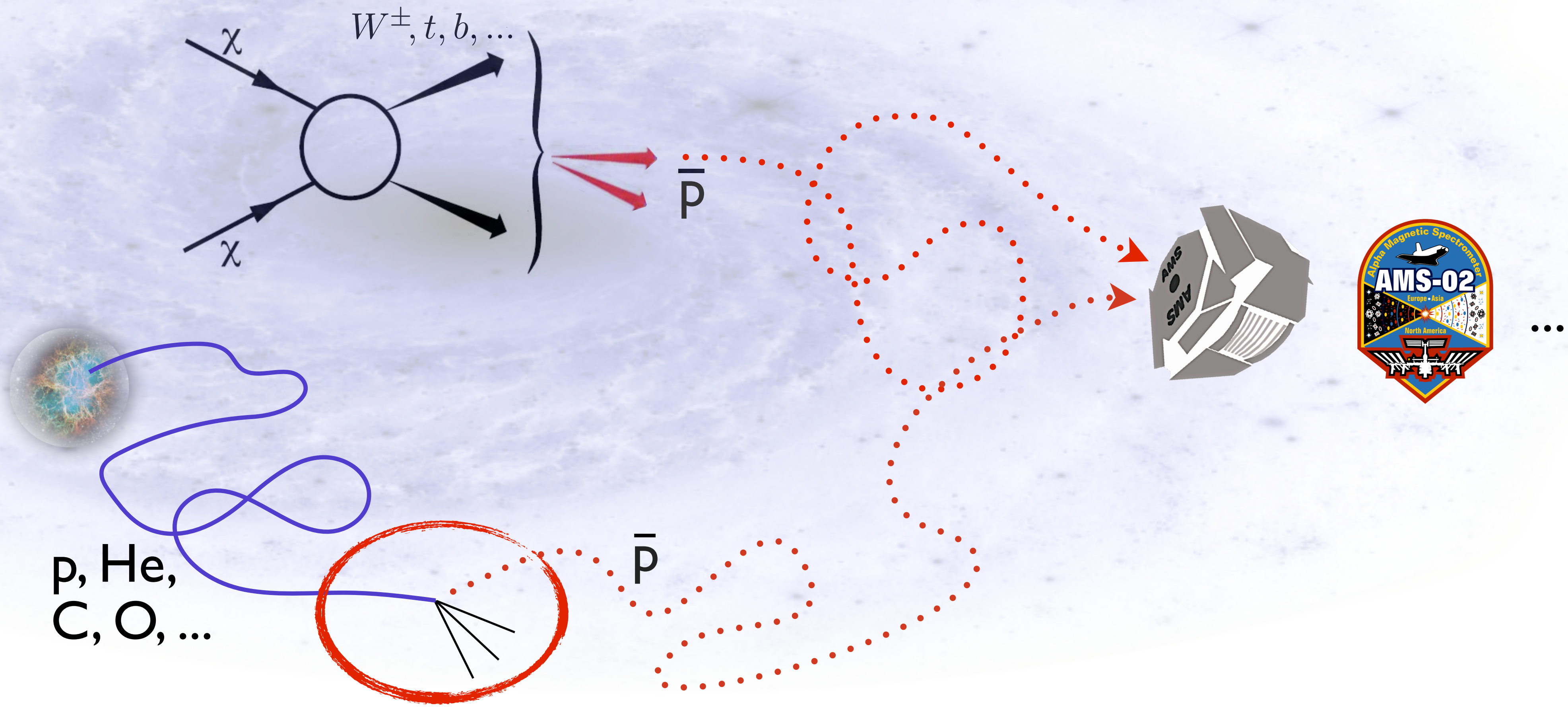
ONLINE ICRC 2021
THE ASTROPARTICLE PHYSICS CONFERENCE
Berlin | Germany
37th International Cosmic Ray Conference
12–23 July 2021

Dark matter indirect detection searches: cosmic rays

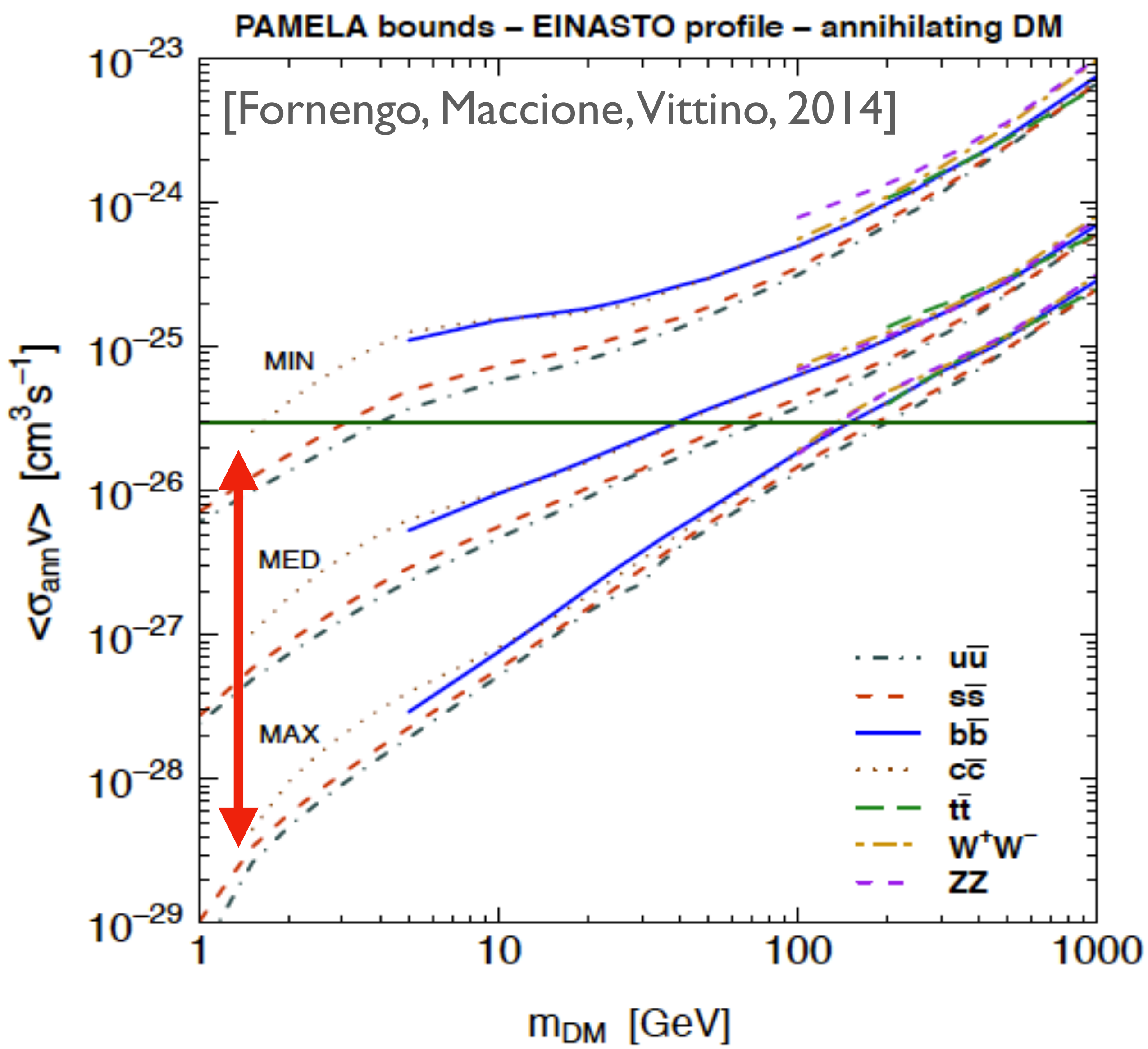
- Cosmic-ray (CR) antiprotons powerful tool for dark-matter searches

Dark matter indirect detection searches: cosmic rays



- Cosmic-ray (CR) antiprotons powerful tool for dark-matter searches
- Bulk of antiprotons consistent with secondary origin from scatterings of primaries off interstellar gas
- Uncertainties from propagation important

Uncertainties in the PAMELA era



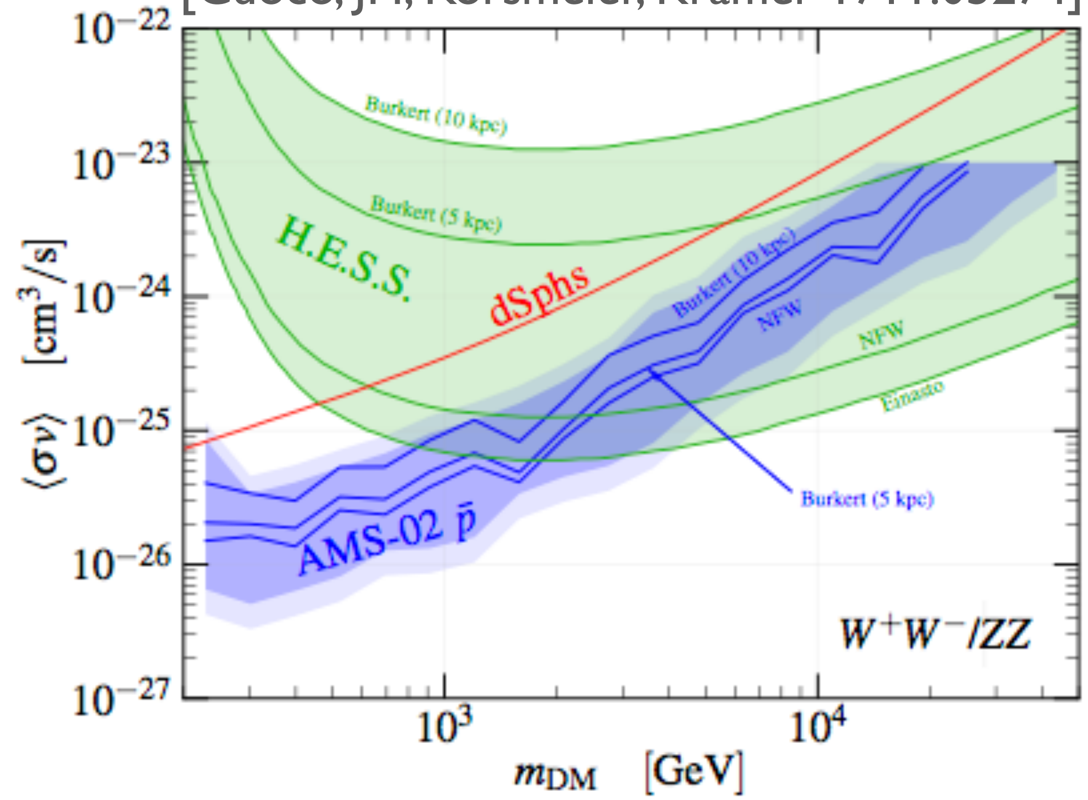
[see also e.g. L. Bergstrom, J. Edsjo, P. Ullio, ApJ,526,215 (1999); F. Donato, N. Fornengo, D. Maurin, P. Salati, PRD69, 063501 (2004); T. Bringmann, P. Salati, PRD75, 083006 (2007); F. Donato, D. Maurin, P. Brun, T. Delahaye, P. Salati, PRL. 102, 071301 (2009); D. Hooper, T. Linden, P. Mertsch, JCAP 1503, 021; V. Pettorino, G. Busoni, A. De Simone, E. Morgante, A. Riotto, W. Xue, JCAP 1410, 078 (2014); M. Boudaud, M. Cirelli, G. Giesen, P. Salati, JCAP1505, 013 (2015); J. A. R. Cembranos, V. Gammaldi, A. L. Maroto, JCAP 1503, 041 (2015); M. Cirelli, D. Gaggero, G. Giesen, M. Taoso, A. Urbano, JCAP 1412, 045 (2014); T. Bringmann, M. Vollmann, C. Weniger, Phys. Rev. D90, 123001 (2014)]

- MIN/MED/MAX scenario: Uncertainties in limits on dark-matter annihilation cross section span ~ 3 orders of magnitude

Uncertainties in the AMS-02 era

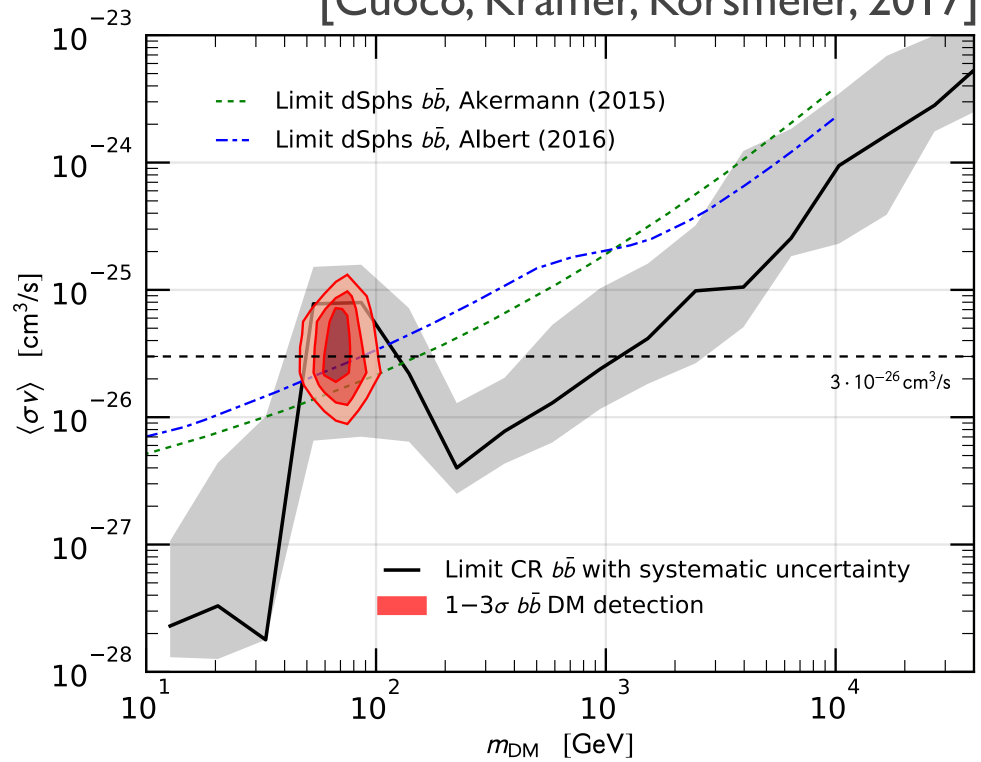
- High precision data (down to few percent uncertainties)
- Exploit precision in joint fit of propagation and dark-matter parameters ⇒ Profiling over the latter

[Cuoco, JH, Korsmeier, Krämer 1711.05274]

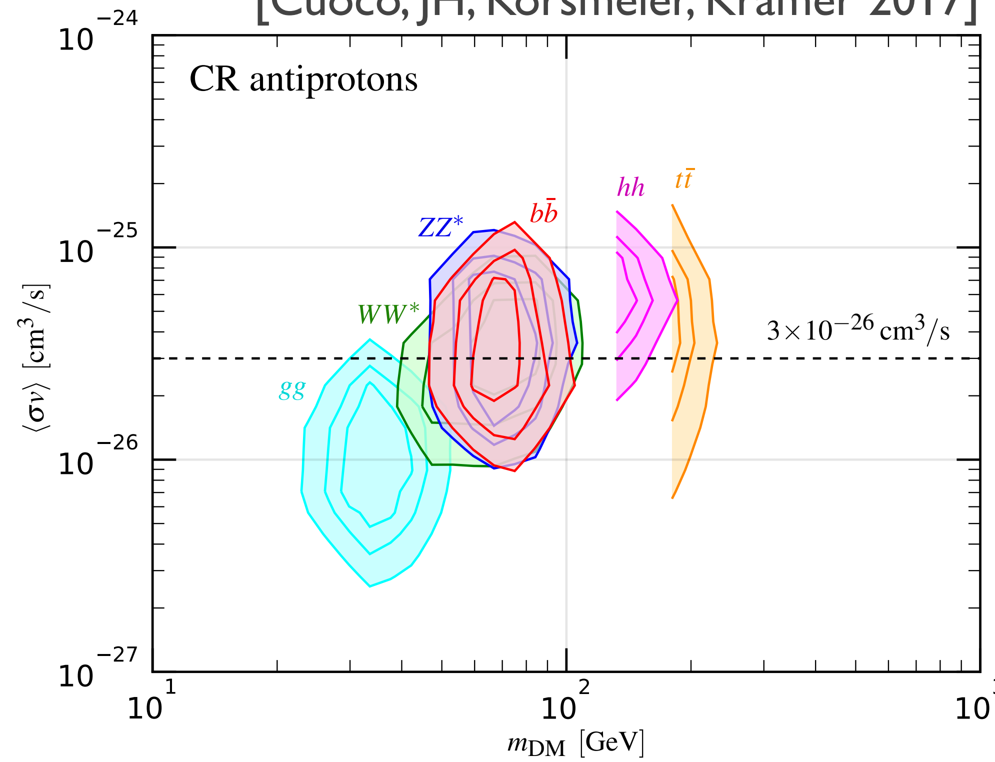


Hint for 100 GeV-ish dark matter

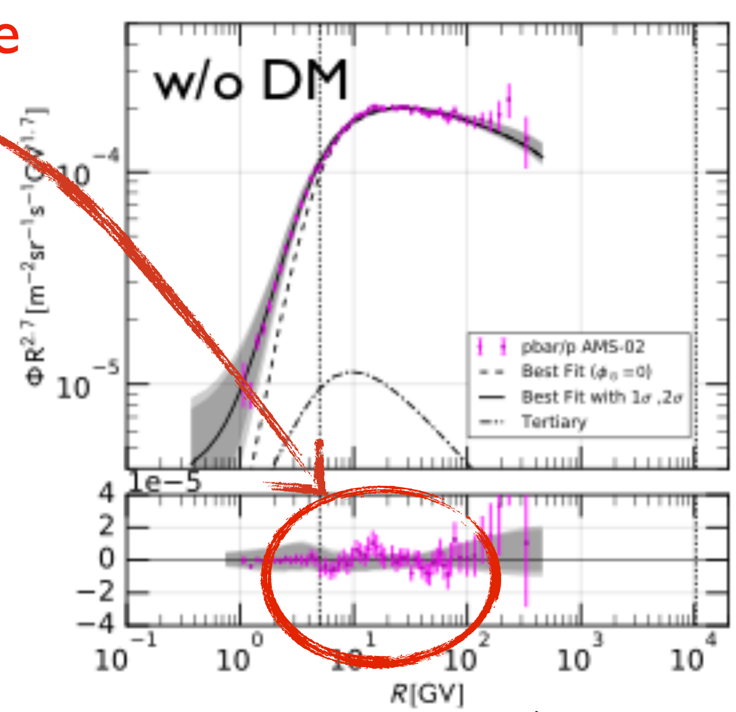
[Cuoco, Krämer, Korsmeier, 2017]

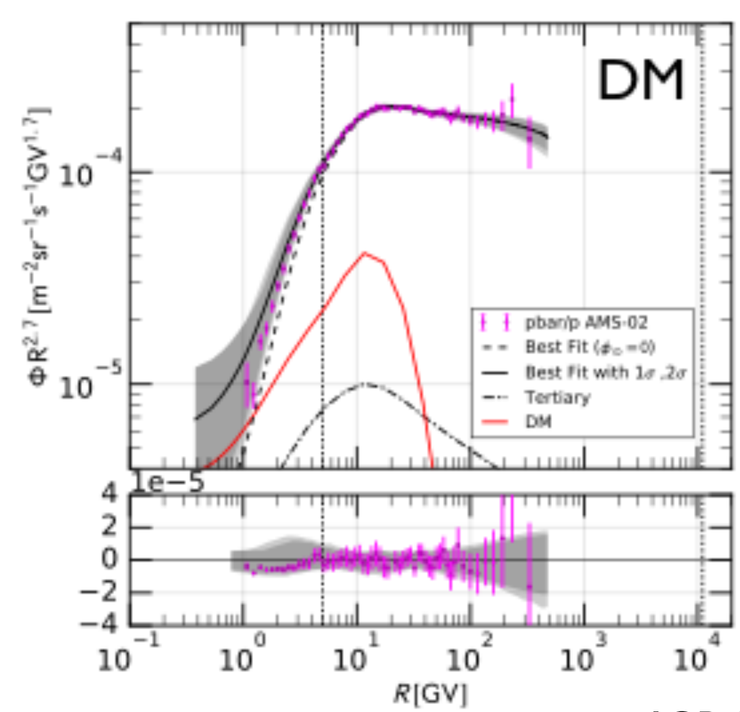


[Cuoco, JH, Korsmeier, Krämer 2017]



Preference from feature around 10-20GV

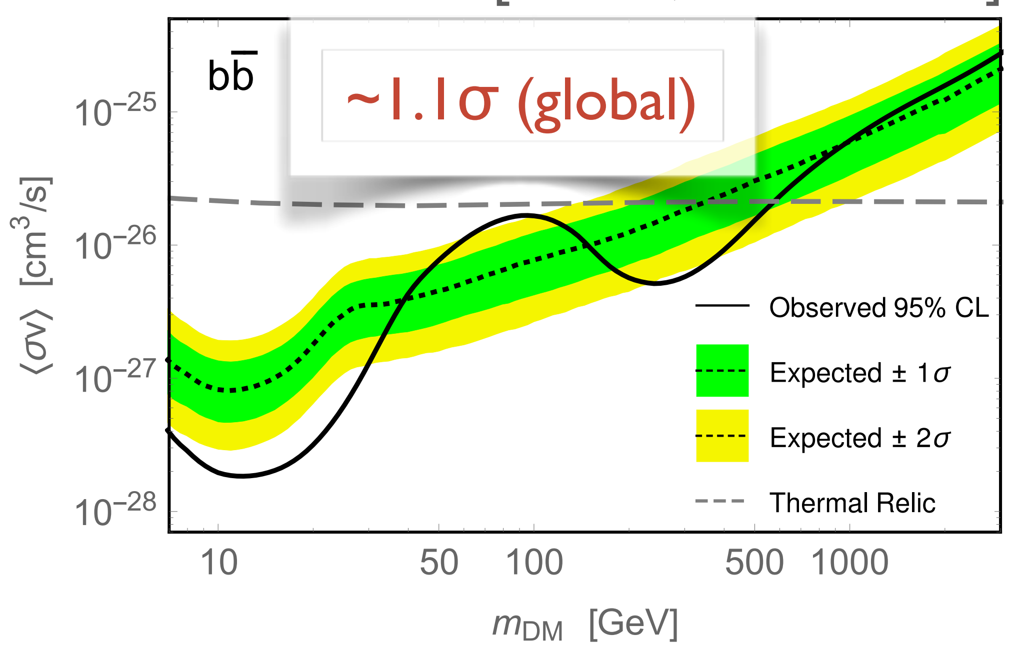




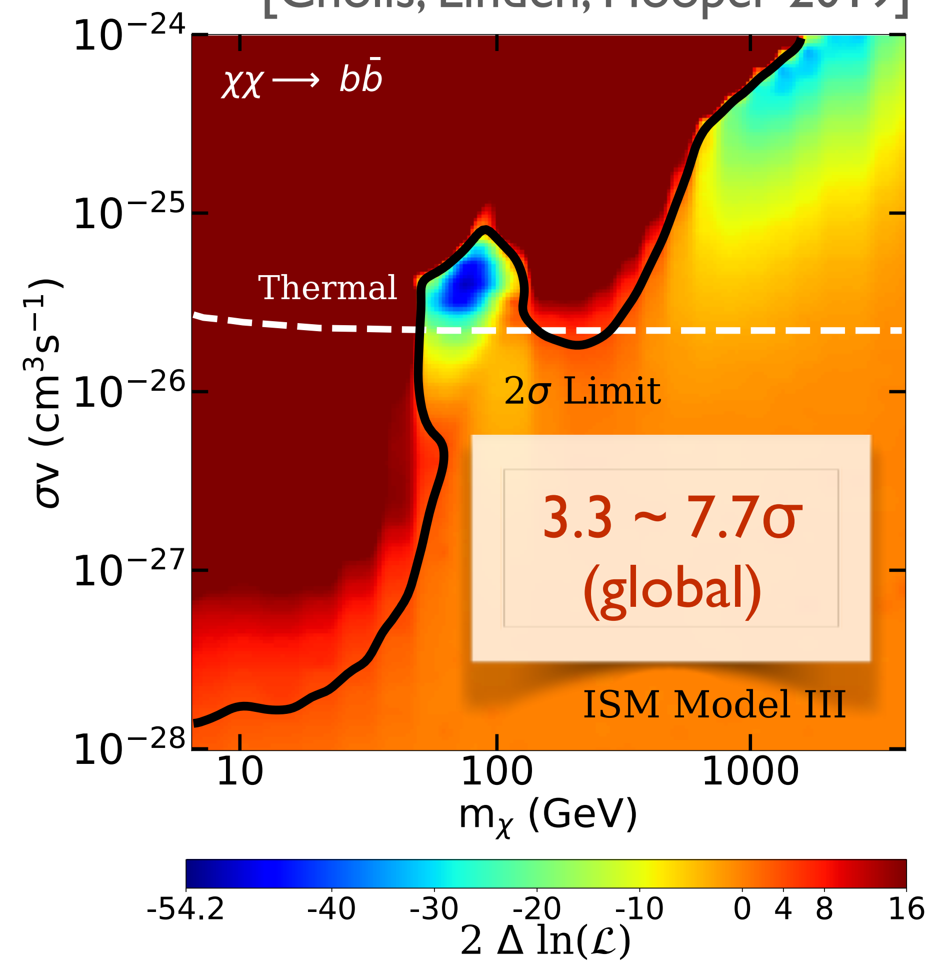
[*see also* Cui, Yuan, Tsai, Fan, 2017]

Hint for 100 GeV-ish dark matter

[Reinert, Winkler 2018]



[Cholis, Linden, Hooper 2019]



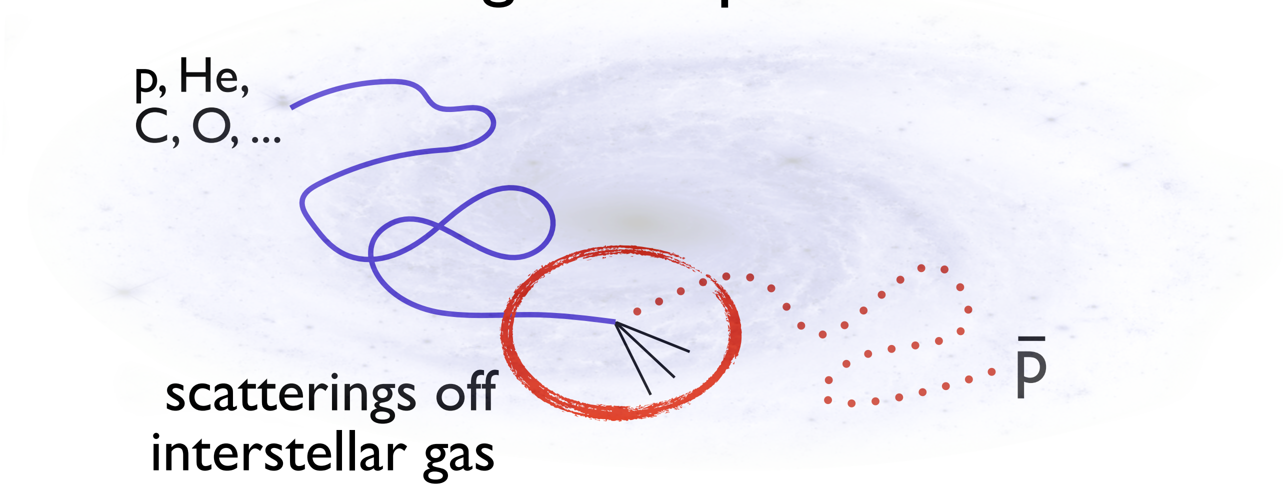
- Agree on dark-matter properties
- Significance highly controversal

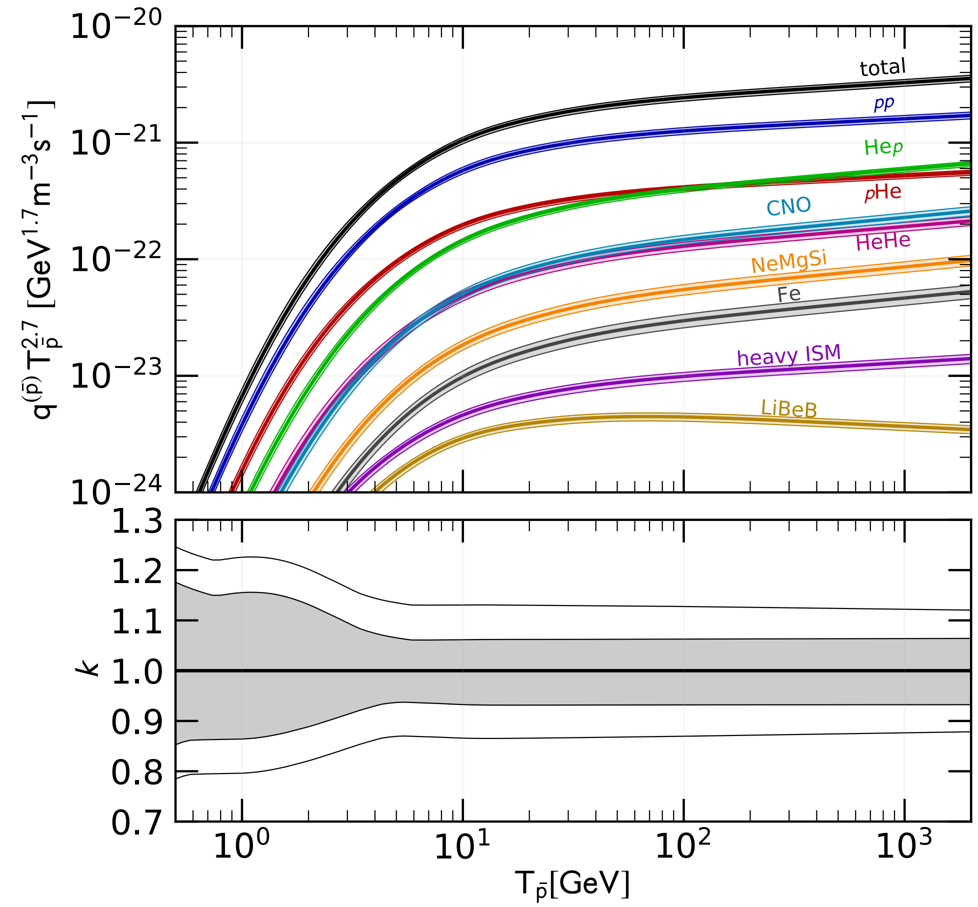
⇒ unaccounted systematic uncertainties

[*see also* Cui, Pan, Yuan, Fan, Zong 2018; Lin, Bi, Yin 2019]

Secondary antiproton cross-section uncertainties

- Enters background prediction:

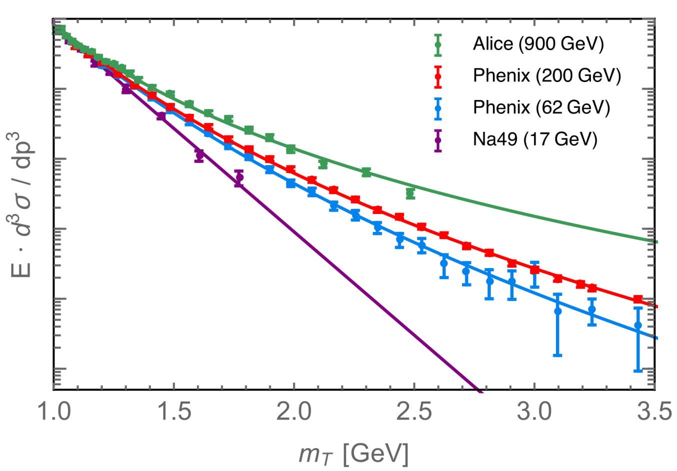




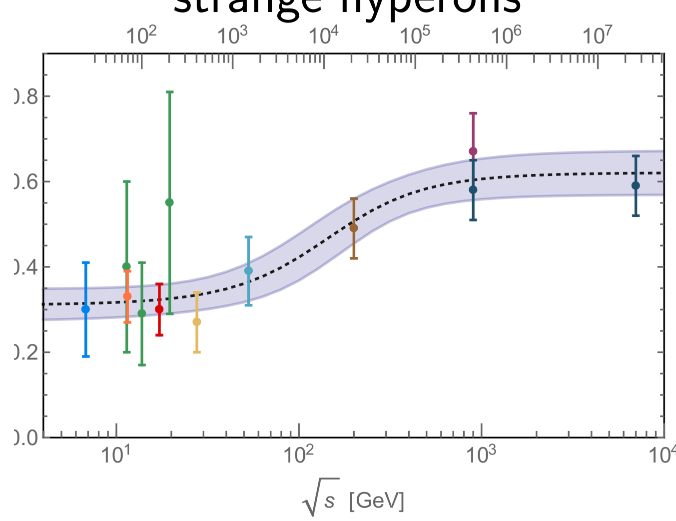
[Korsmeier, Donato, Di Mauro 2018]

- Partly relies on old laboratory data
- Recent progress in modeling:

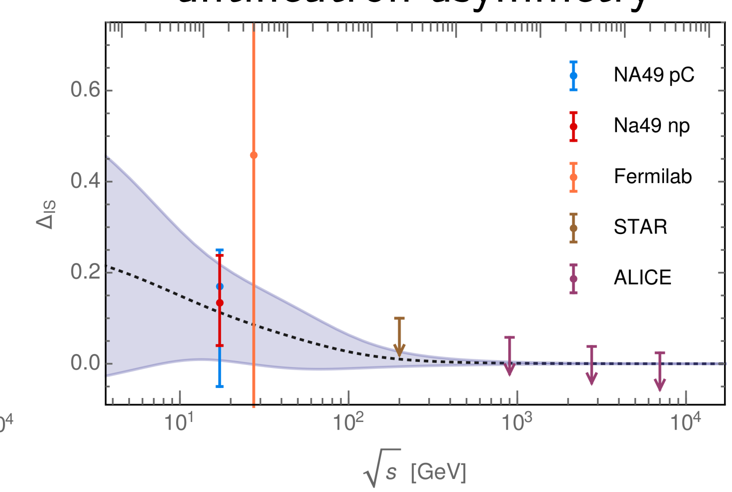
Feynman scaling violation



strange hyperons



antineutron asymmetry



[Winkler 2017]

Secondary antiproton cross-section uncertainties

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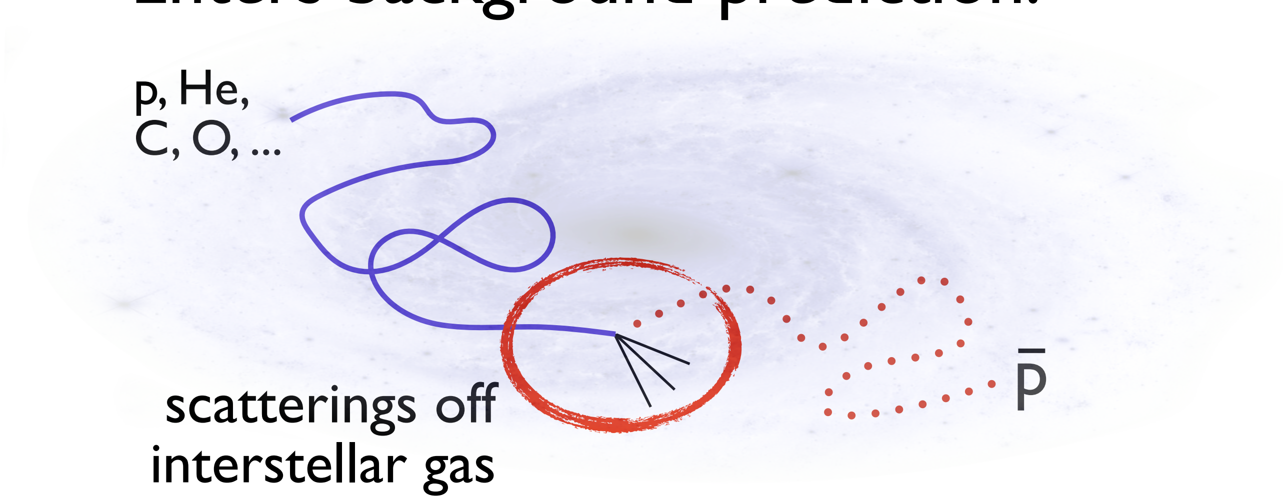
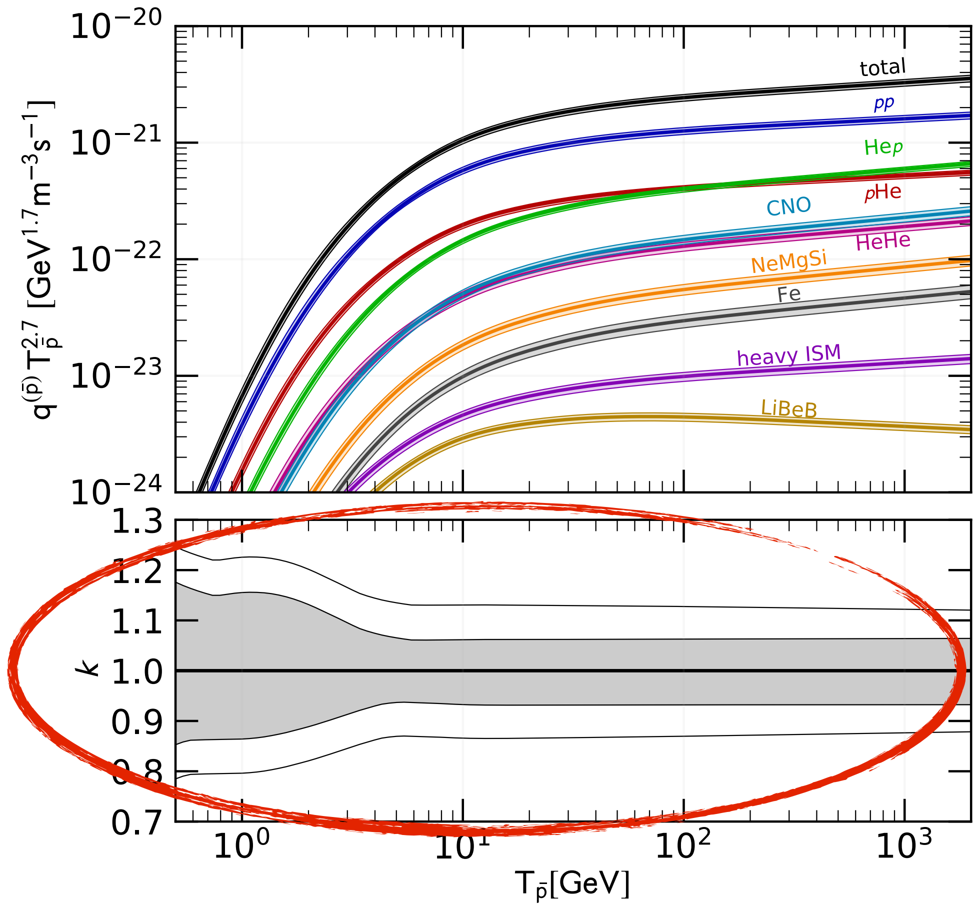
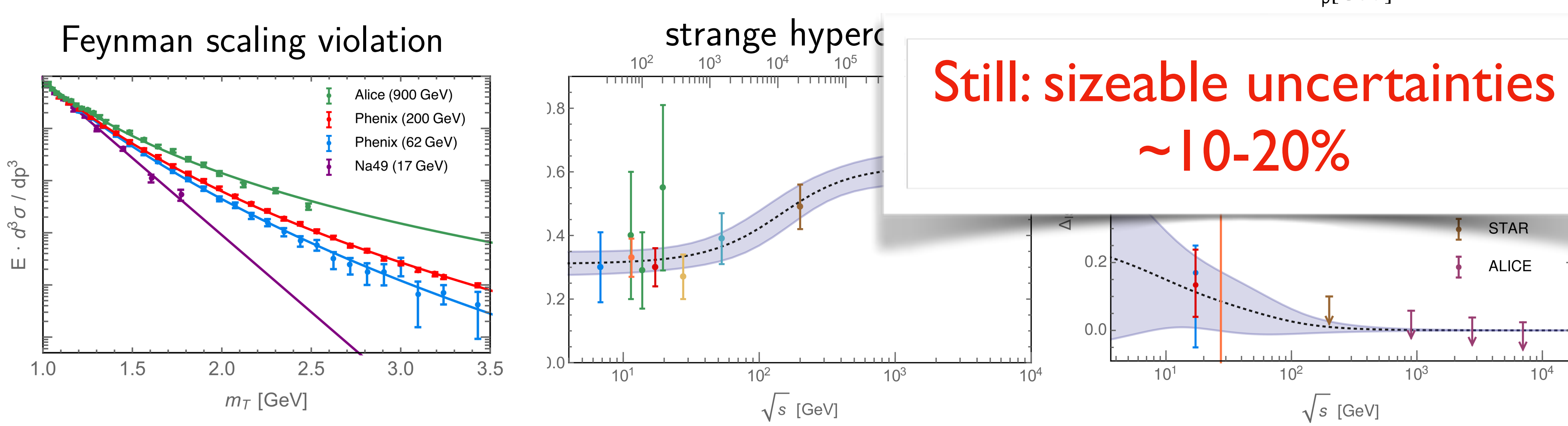




[Korsmeier, Donato, Di Mauro 2018]

- Partly relies on old laboratory data
- Recent progress in modeling:

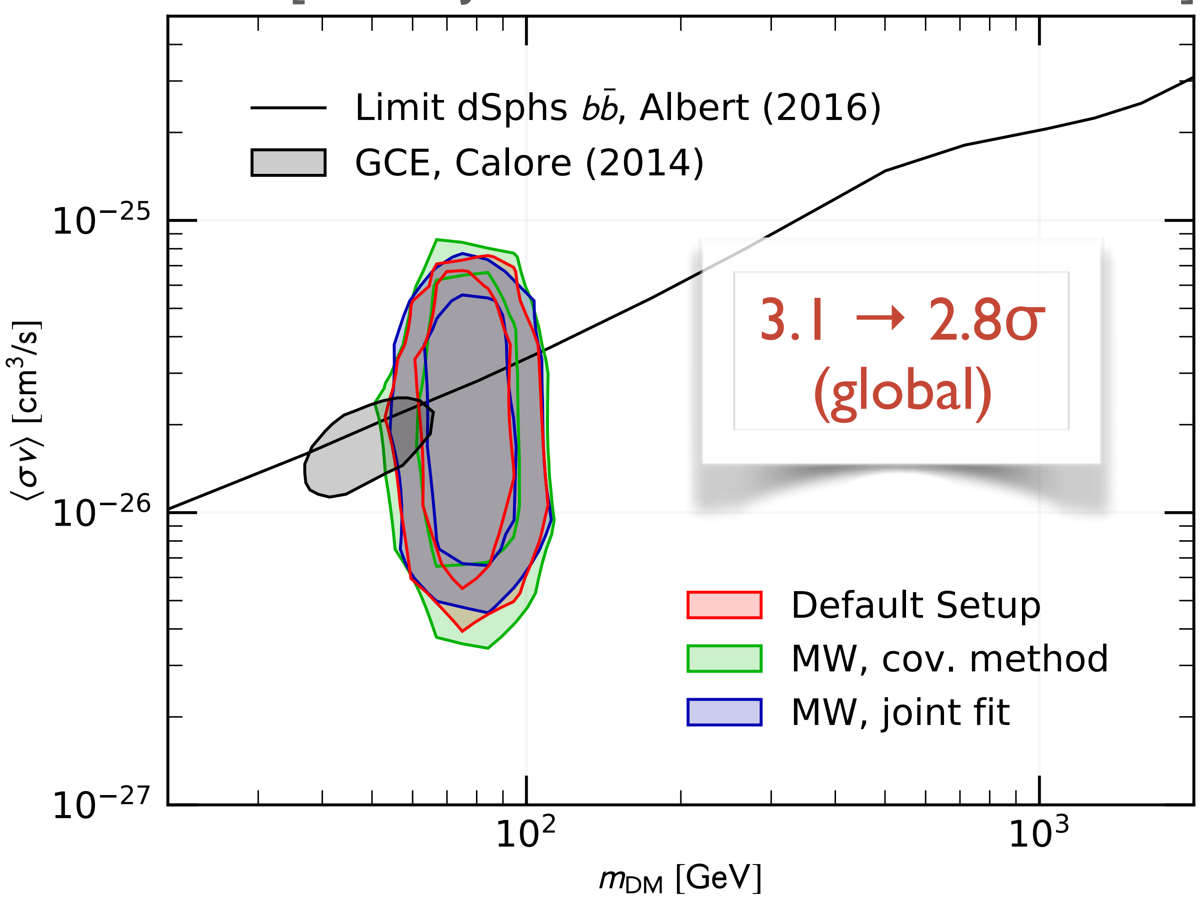


Still: sizeable uncertainties ~10-20%

Secondary antiproton cross-section uncertainties

- Effect on tentative signal moderate:

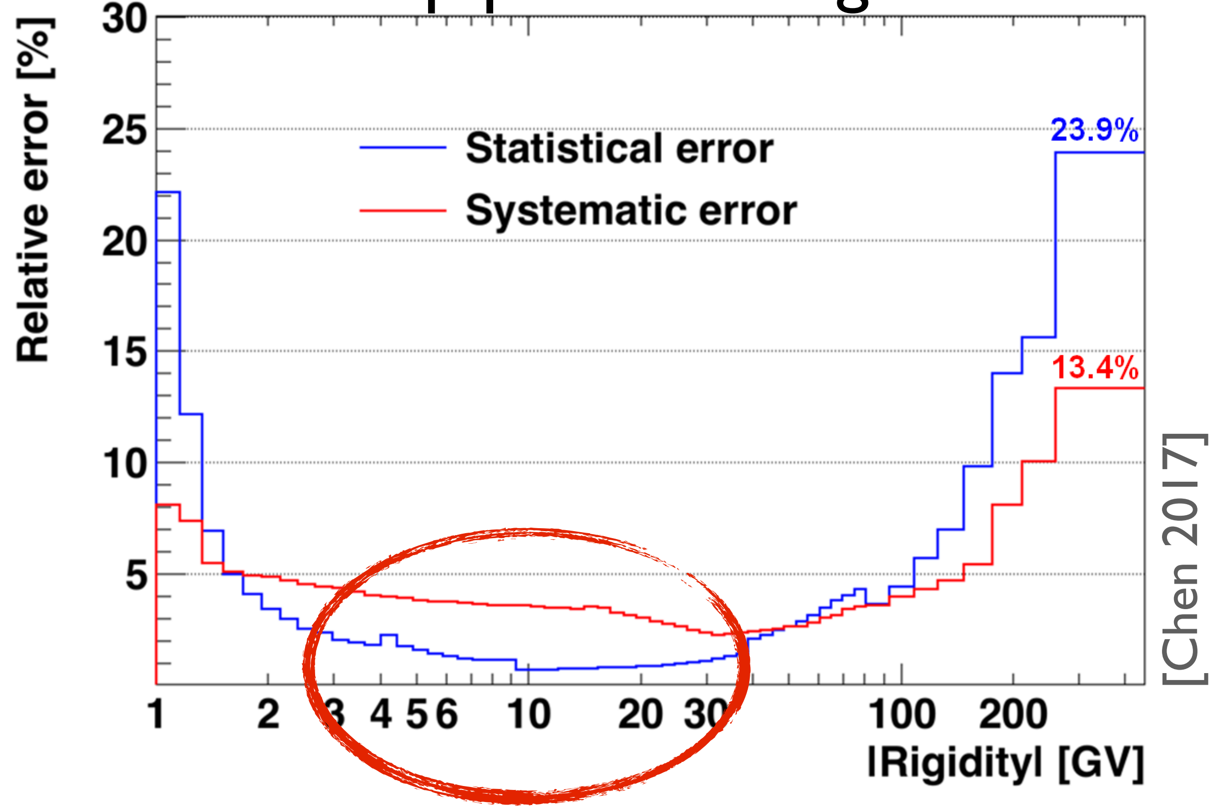
[Cuoco, JH, Klamt, Korsmeier, Krämer 2019]



[Korsmeier, Donato, Di Mauro 2018]

Correlations in AMS-02 uncertainties

AMS-02 p̄/p error budget:

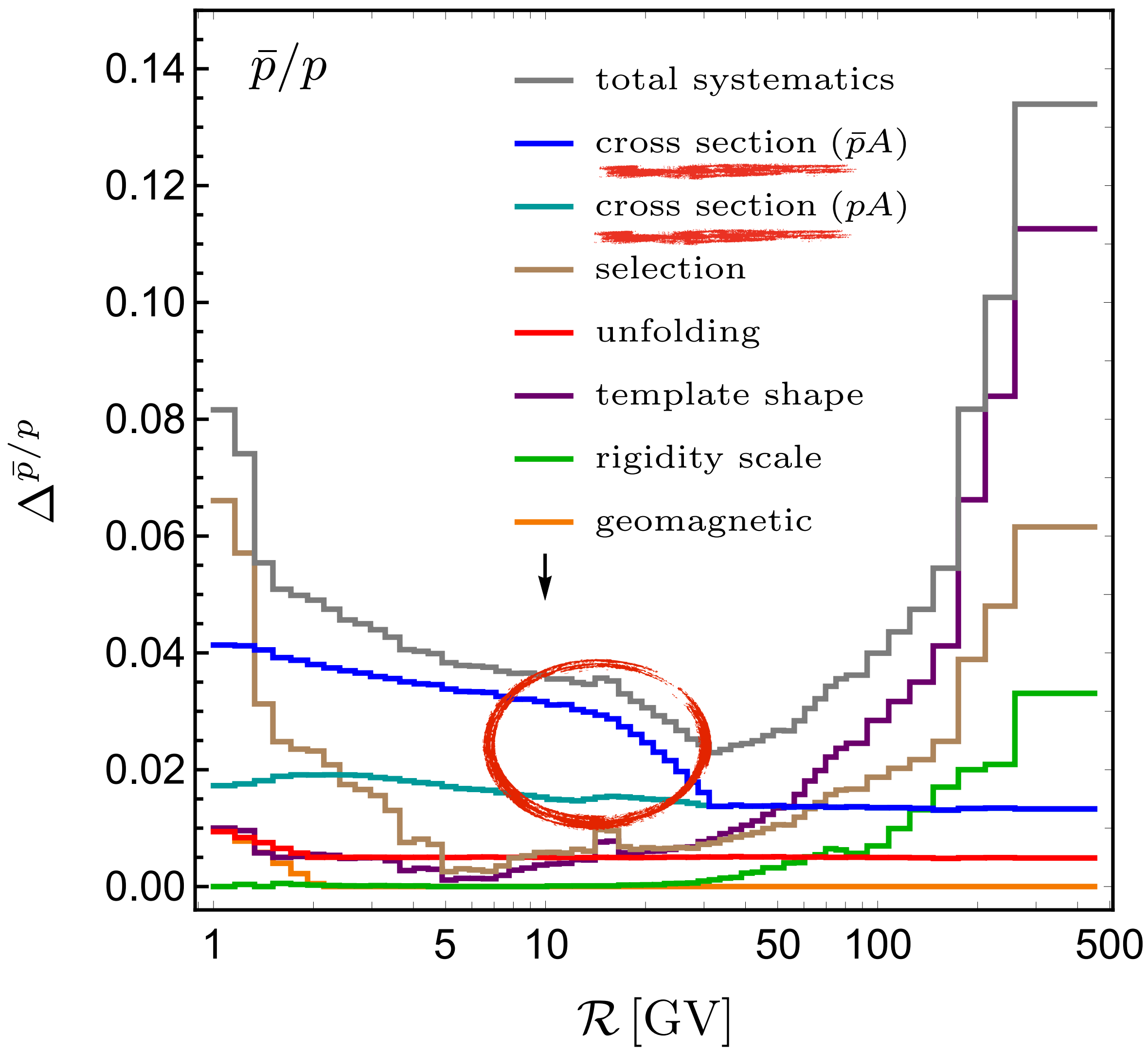


- Systematic uncertainties dominate in relevant region: 5~25GV
- Rel. error around 4%
- No covariance provided by AMS-02, but correlations expected!
  ⇒ Potentially huge effect [Cuoco, JH, Klamt, Korsmeier, Krämer 1903.01472]

Correlations in AMS-02 uncertainties

[JH, M.Korsmeier, M.Winkler, 2005.04237]

- Systematics – split up in sub-contributions: [see also Boudaud *et al.* 1906.07119]



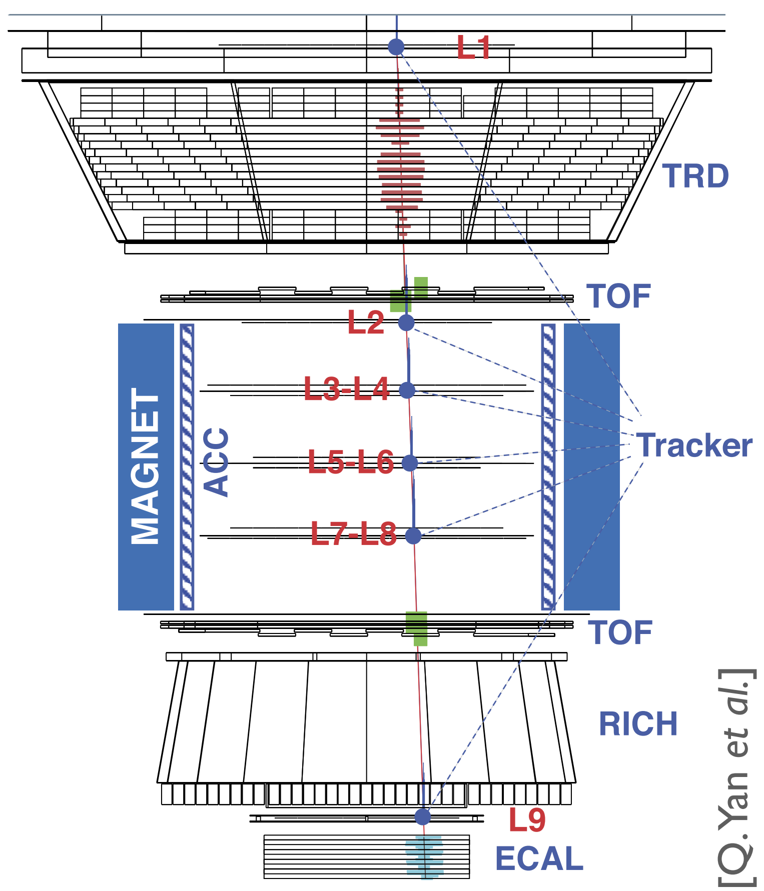
[*Data collected from:*
M. Aguilar *et al.* (AMS) 2016;
P. Zuccon, *Talk at Antideuteron 2019*;
A.I. Chen, *PhD thesis* 2017]

⇒ Investigate dominant ones in detail: CR absorption in detector

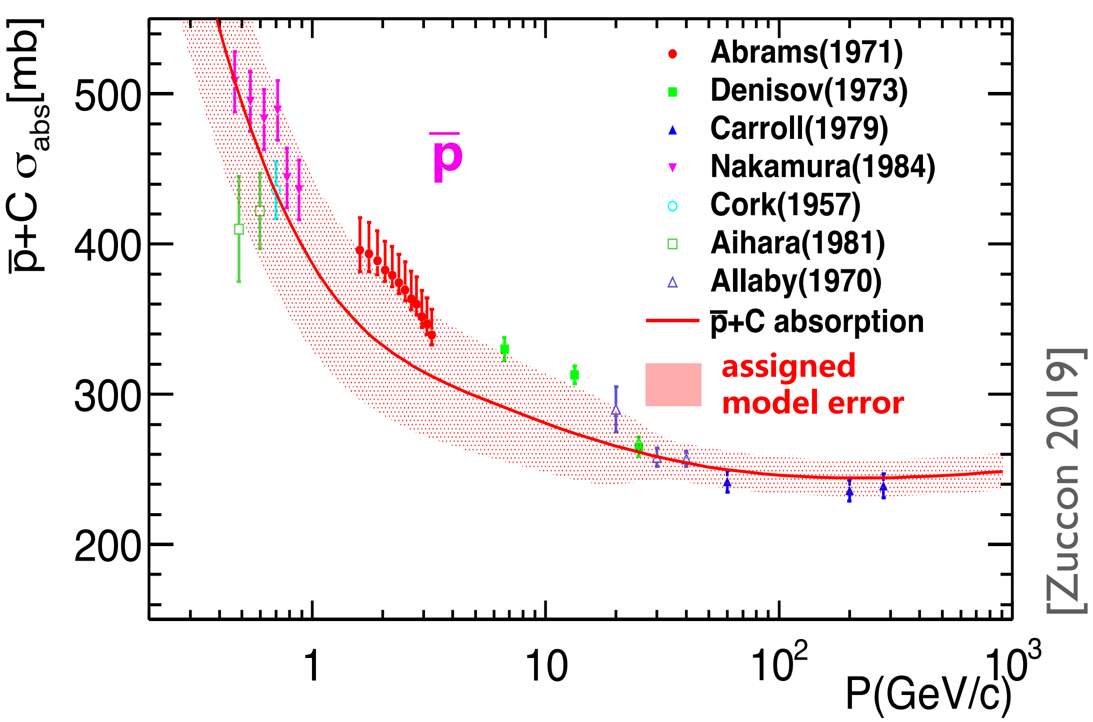
Uncertainties from absorption cross section

[JH, M.Korsmeier, M.Winkler, 2005.04237]

- Reported fluxes corrected by absorption in upper layers
- Detector: ~70% carbon, ~20% aluminum



- $\bar{p}\mathrm{C}$ absorption XS poorly measured
- Error correlations unavailable



Uncertainties from absorption cross section

[JH, M.Korsmeier, M.Winkler, 2005.04237]

- Improved measurements require runs of laboratory experiments
- Employ a theoretical framework for low-energy nucleon-nucleus scattering
- Independent prediction for absorption XS in Glauber-Gribov theory:

$$\sigma_{\rm abs}^{\bar{p}\rm C} = \int {\rm d}^2 b \left(1 - \prod_{i=1}^{12} \left[1 - \sigma_{\bar{p}N_i}(q)\, \mathcal{T}_i(q, \boldsymbol{b})\right]\right) \;+\; \text{inel. screening}$$

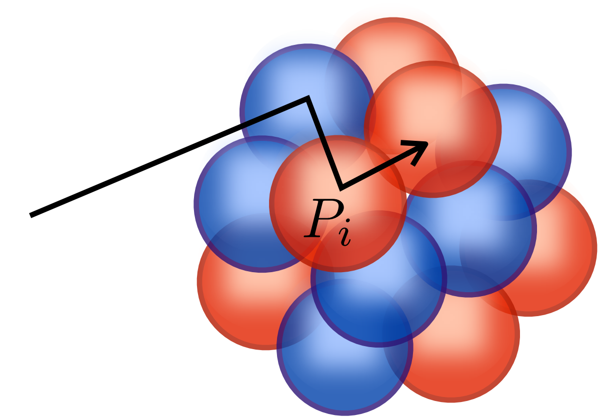
[Glauber 1959; Sitenko 1959; Pumplin, Ross 1968; Gribov 1969; Karmanov, Kondratyuk 1973]

- Links XS to input quantities:

Nucleon-nucleon cross sections

Nuclear densities etc.

- Introduces redundancies to reduce uncertainties and compute correlations via global fit

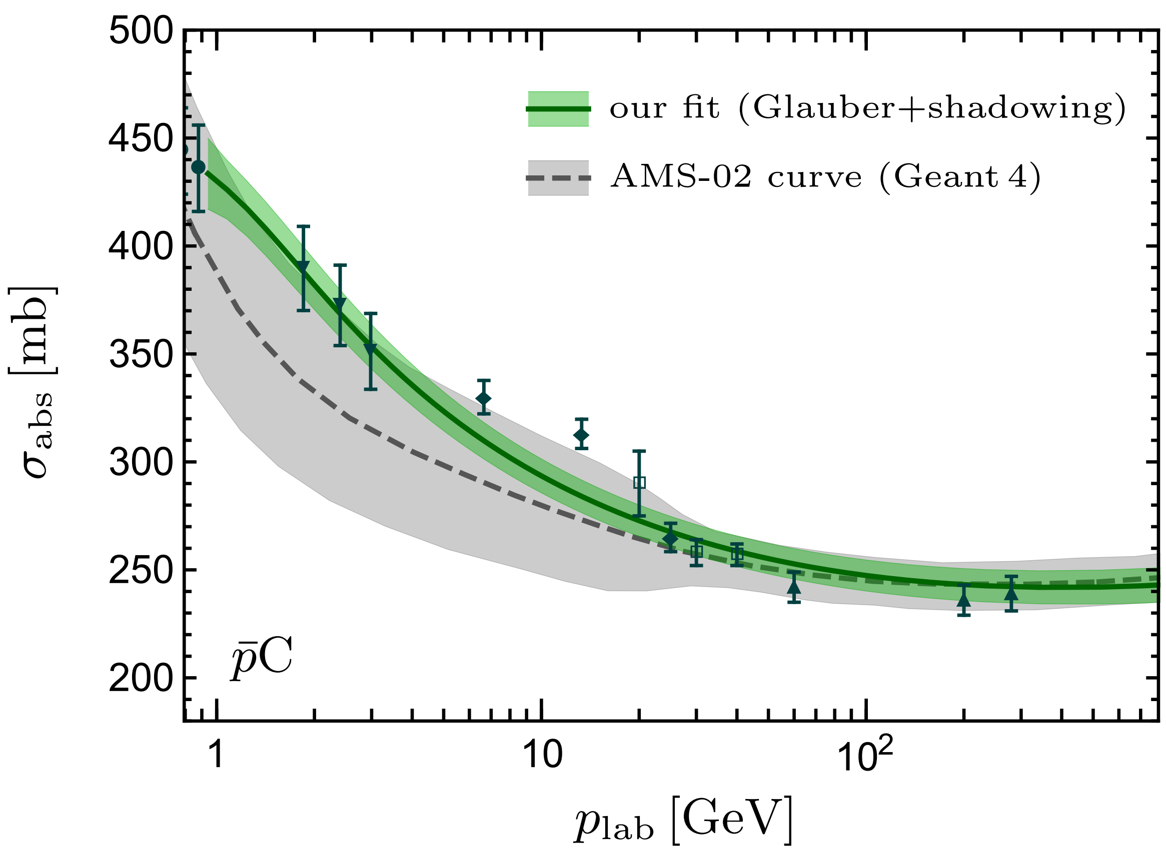


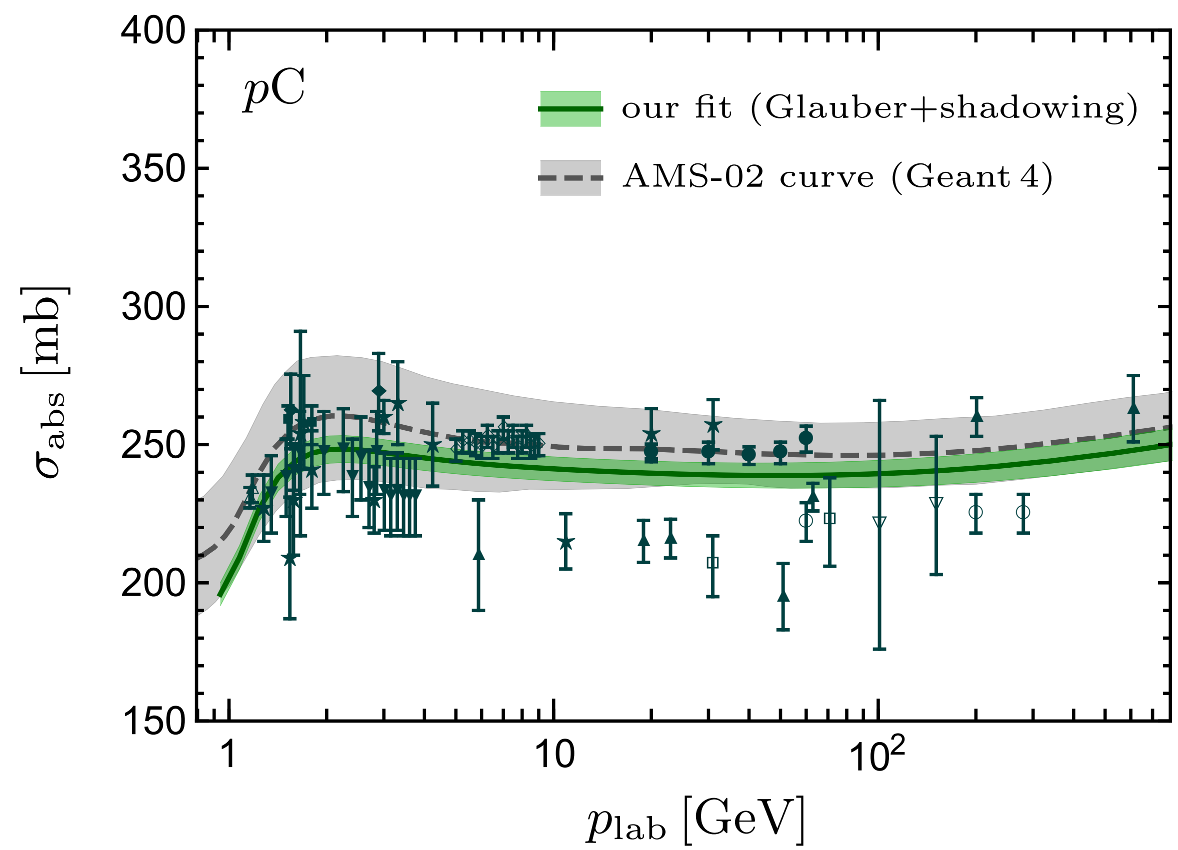
$$P_{\text{at-least-one}} = \left(1 - \prod_{i=1}^{A} \left[1 - P_i\right]\right)$$

Uncertainties from absorption cross section

[JH, M.Korsmeier, M.Winkler, 2005.04237]

- Results of global fits within Glauber-Gribov theory:



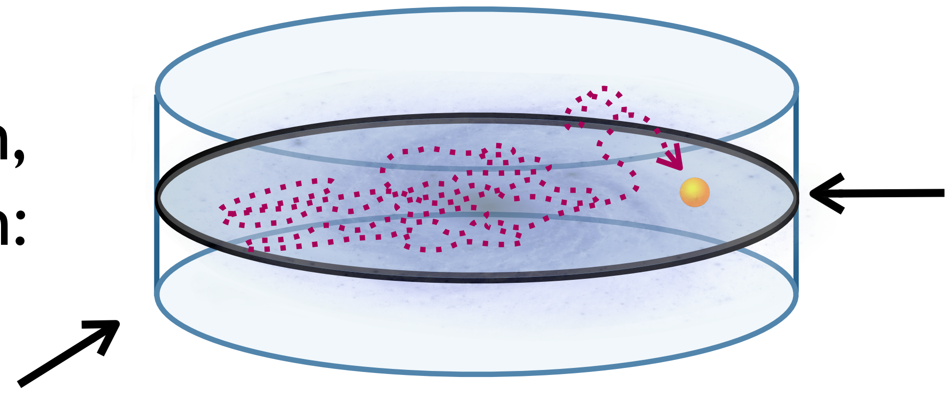


+ correlation matrix!

- Using improved prediction for a reanalysis of fluxes only inside collaboration
  But: Effect of correlations can be studied

Cosmic-ray propagation: numerical setup

spatially constant diffusion, convection, reacceleration:



Setup (joint fit): [similar to Cuoco, JH, Klamt, Korsmeier, Krämer 1903.01472]

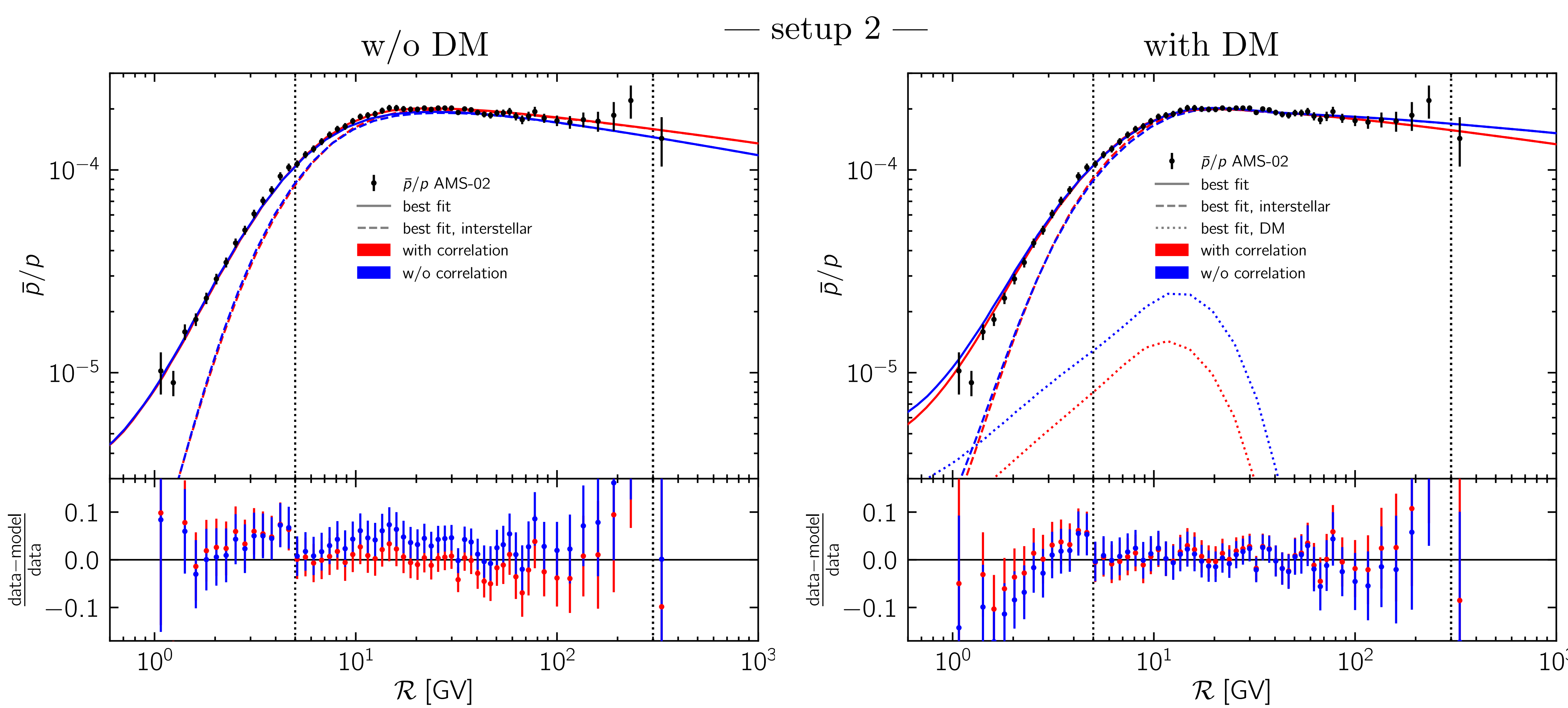
- Joined fit of $\bar{p}/p$, p, He ($\bar{p}$, p, He; see below)
- Model primary spectra with broken power laws
- Diffusion coefficient: $D_{xx} \propto \beta^{\eta} R^{\delta}$ (negative η: ~ low-rigidity break)* [see Boudaud *et al.* 2019]
- Consider convection and reacceleration
- Numerical solution using Galprop [Strong, Moskalenko, Reimer, Ptuskin]

*) as a consequence of damping of small-scale magnetic turbulences
[see e.g. Blasi, Amato, Serpico 2012]

Including full covariance in cosmic-ray fit

[JH, M.Korsmeier, M.Winkler, 2005.04237]

- Perform global cosmic-ray fit with and without dark matter
- Use full covariance for all species (also sub-leading contributions)



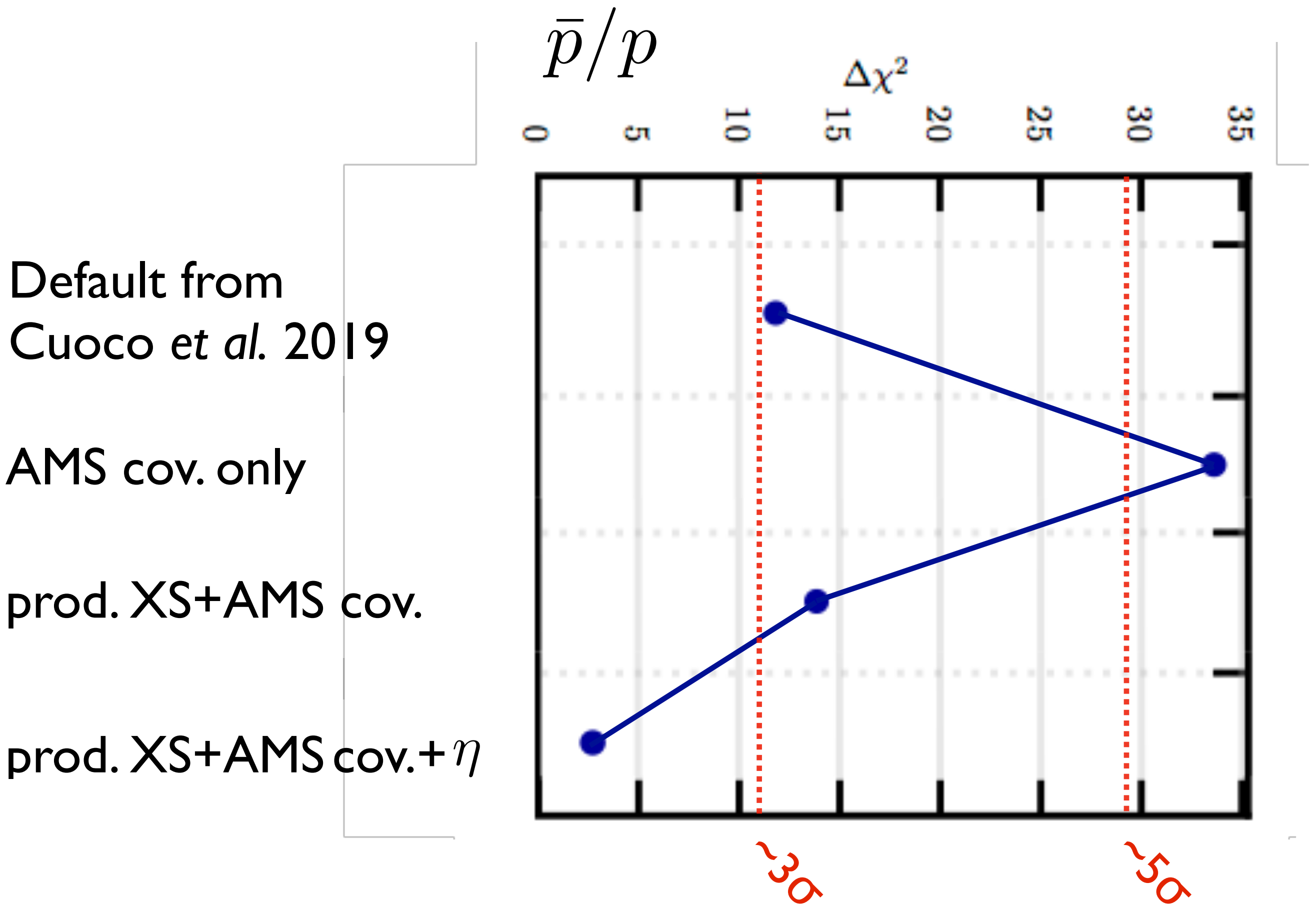
⇒ no significant preference found in data: global significance of 0.5σ *

$*)$ Not fully conclusive: Need to explore

- AMS-02 error correlation
- secondary antiproton production XS uncertainties
- extra parameter (η) in diffusion, $D_{xx} \propto \beta^\eta R^\delta$

to fully absorb the signal.

[*as suggested by recent B/C analyses,* see Génolini *et al.* 2019; Weinrich *et al.* 2020]



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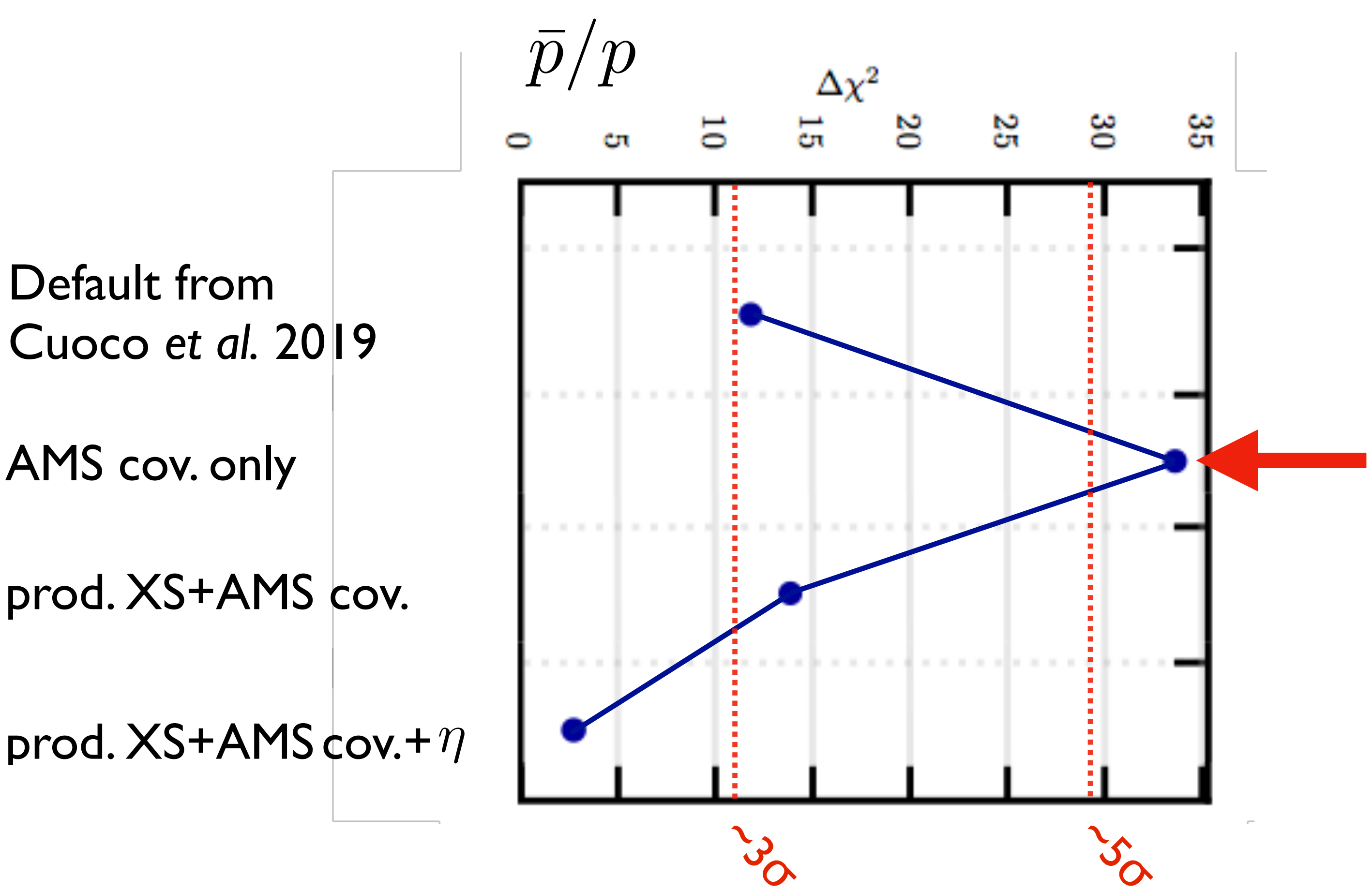

- Significance increases!
- Fit provides less freedom to accommodate features not in line with correlations

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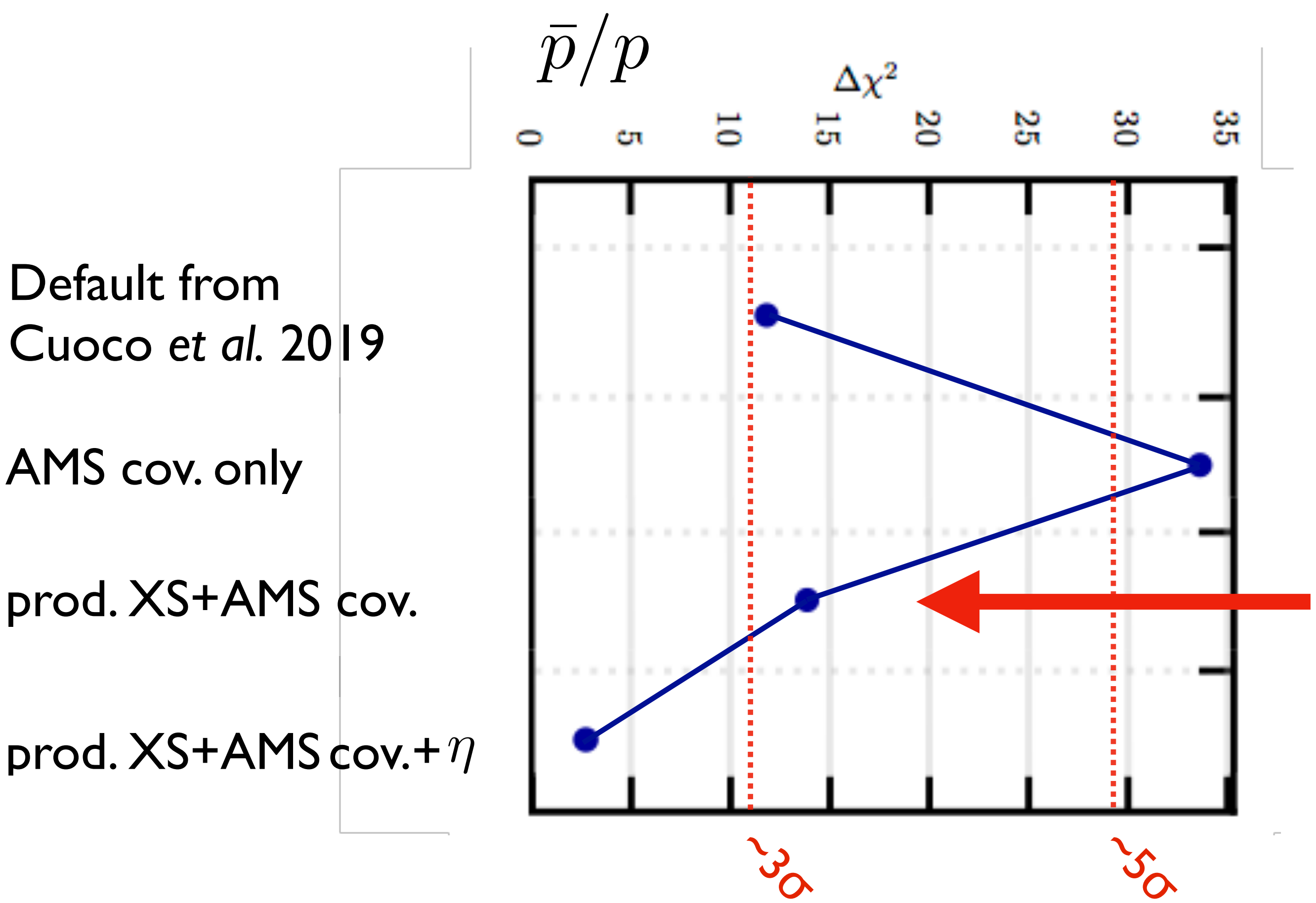

- Back at 3σ-level
- Feature partly absorbed

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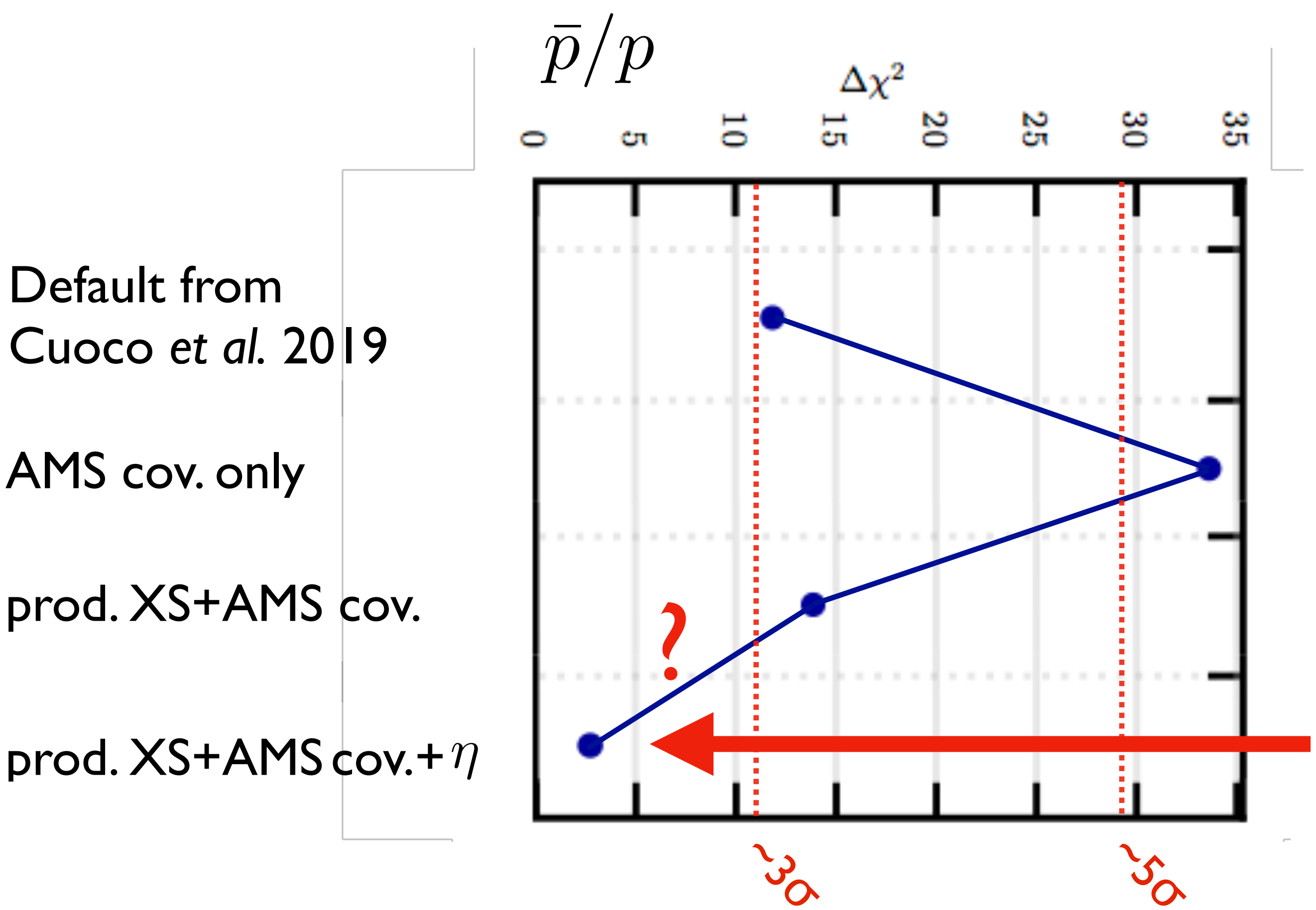

- Only additional freedom in diffusion allows to reconcile tension w/o dark matter

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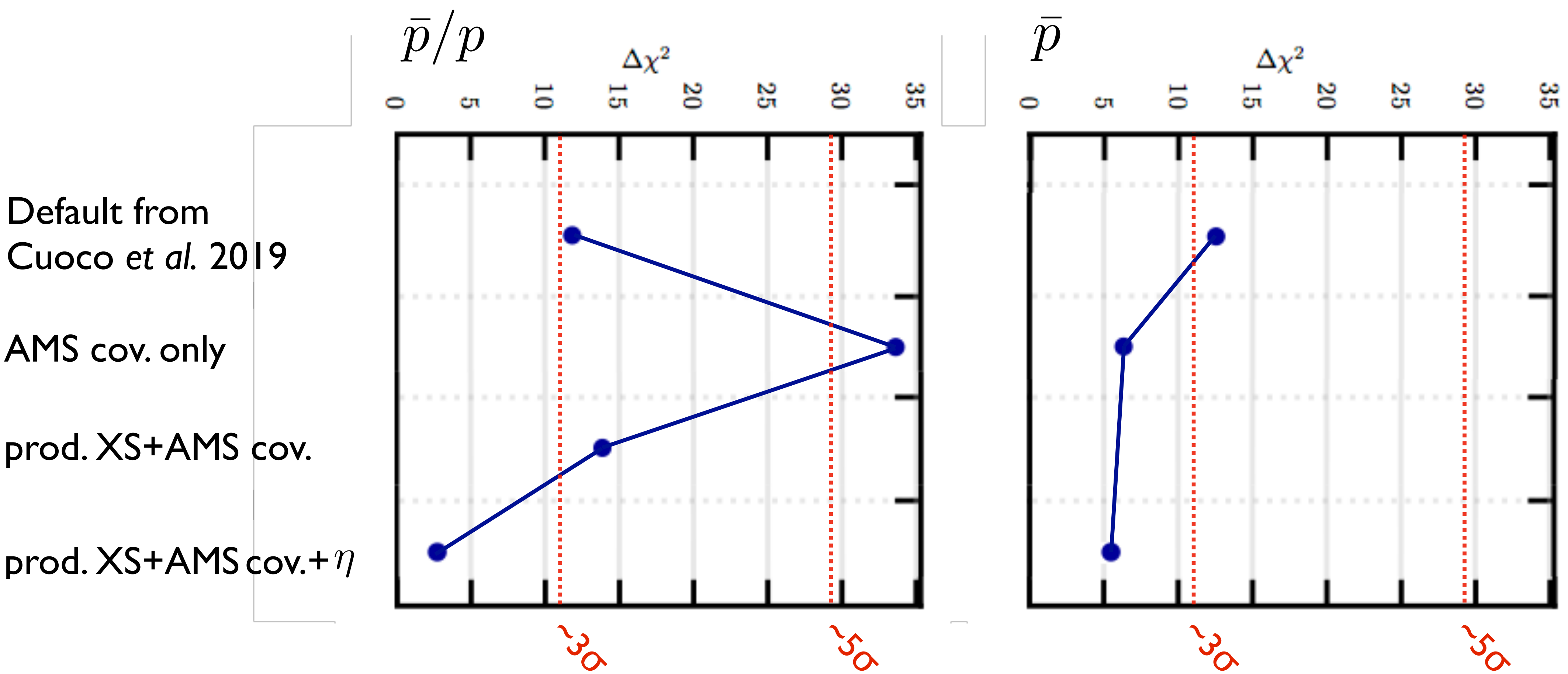

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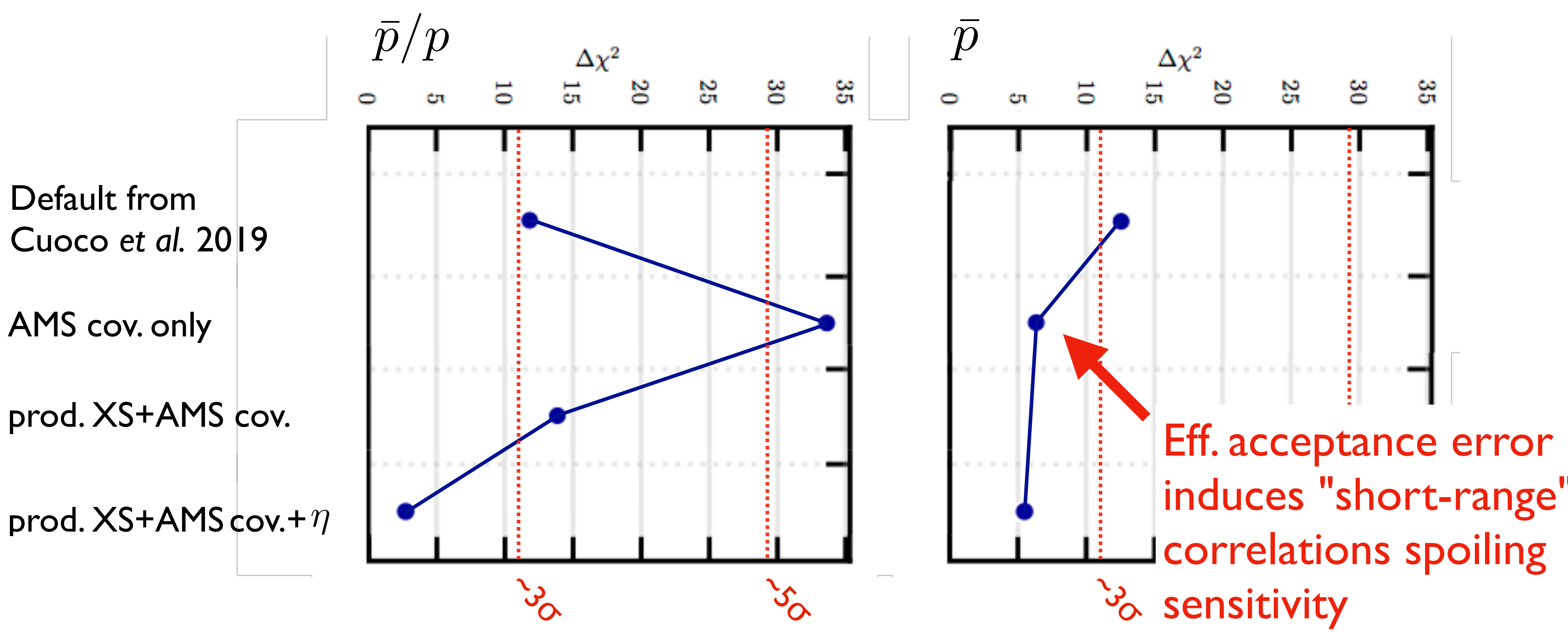
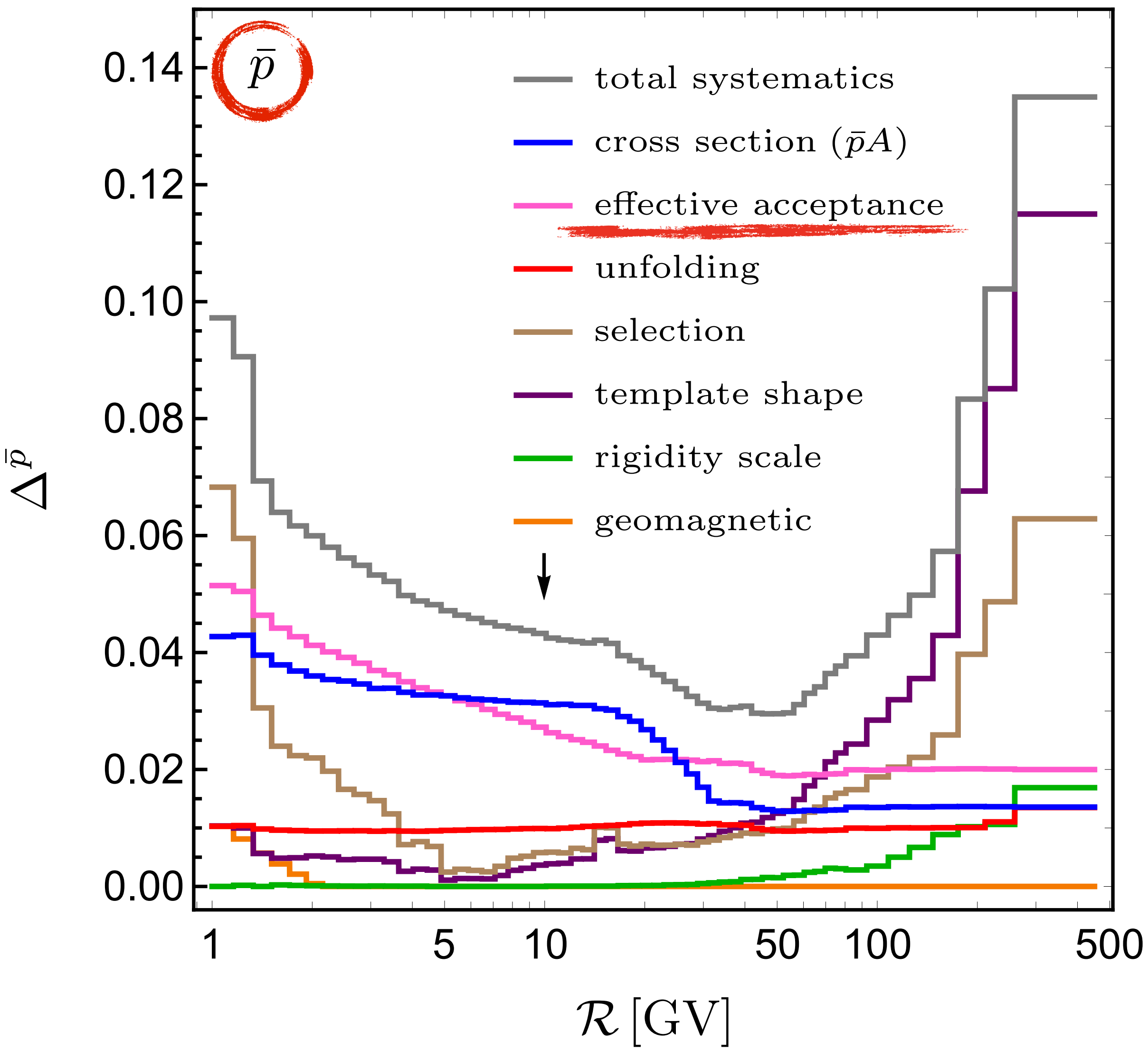


Compute full covariance for all species

[JH, M.Korsmeier, M.Winkler, 2005.04237]

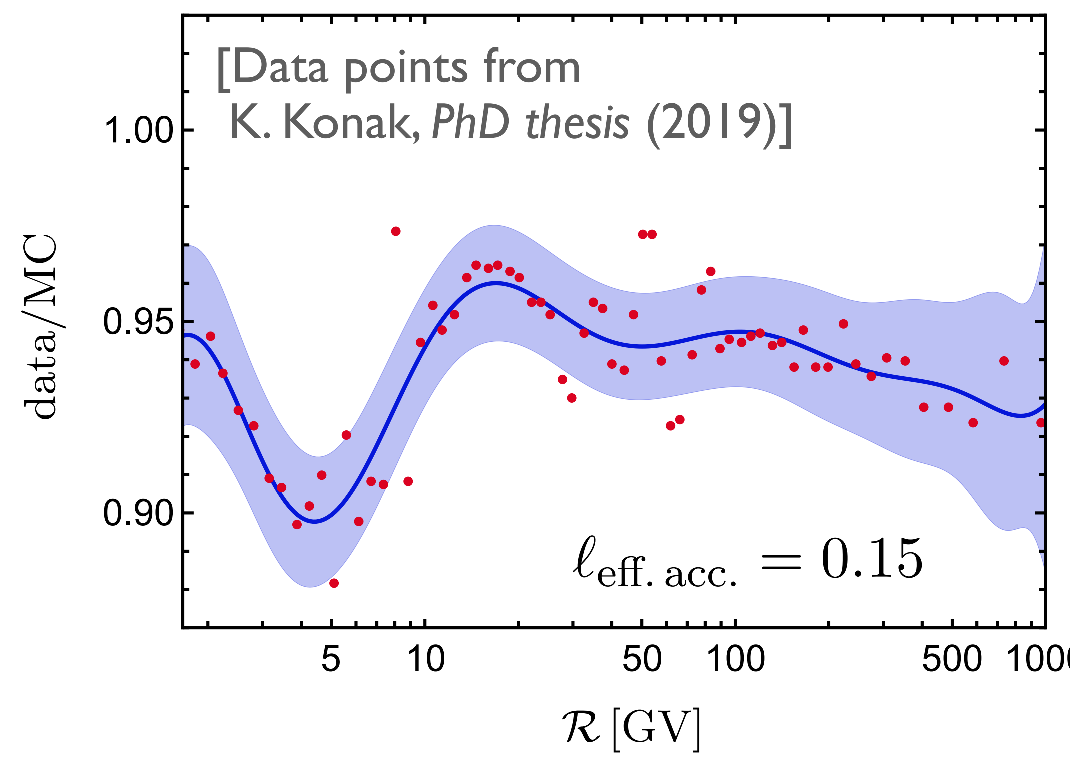
- Considering sub-leading contributions

[similar to Cuoco *et al.* 1903.01472]



$$\left(\rho_a^{\bar{p}}\right)_{ij} = \exp\left[-\frac{1}{2}\left(\frac{\log_{10}(\mathcal{R}_i/\mathcal{R}_j)}{\ell_a}\right)^2\right]$$

Effective acceptance:



[further correlation length taken as estimated in Boudaud *et al.* 1906.07119]

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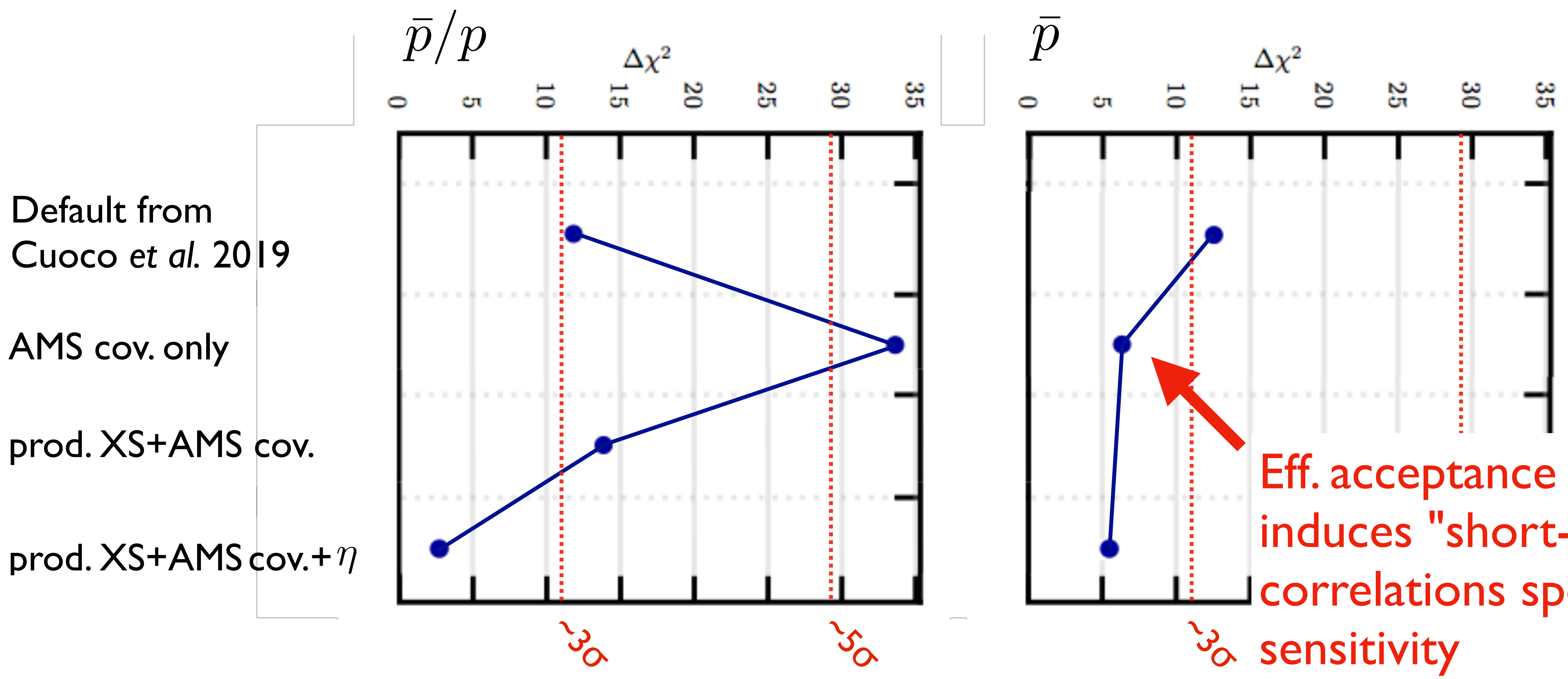
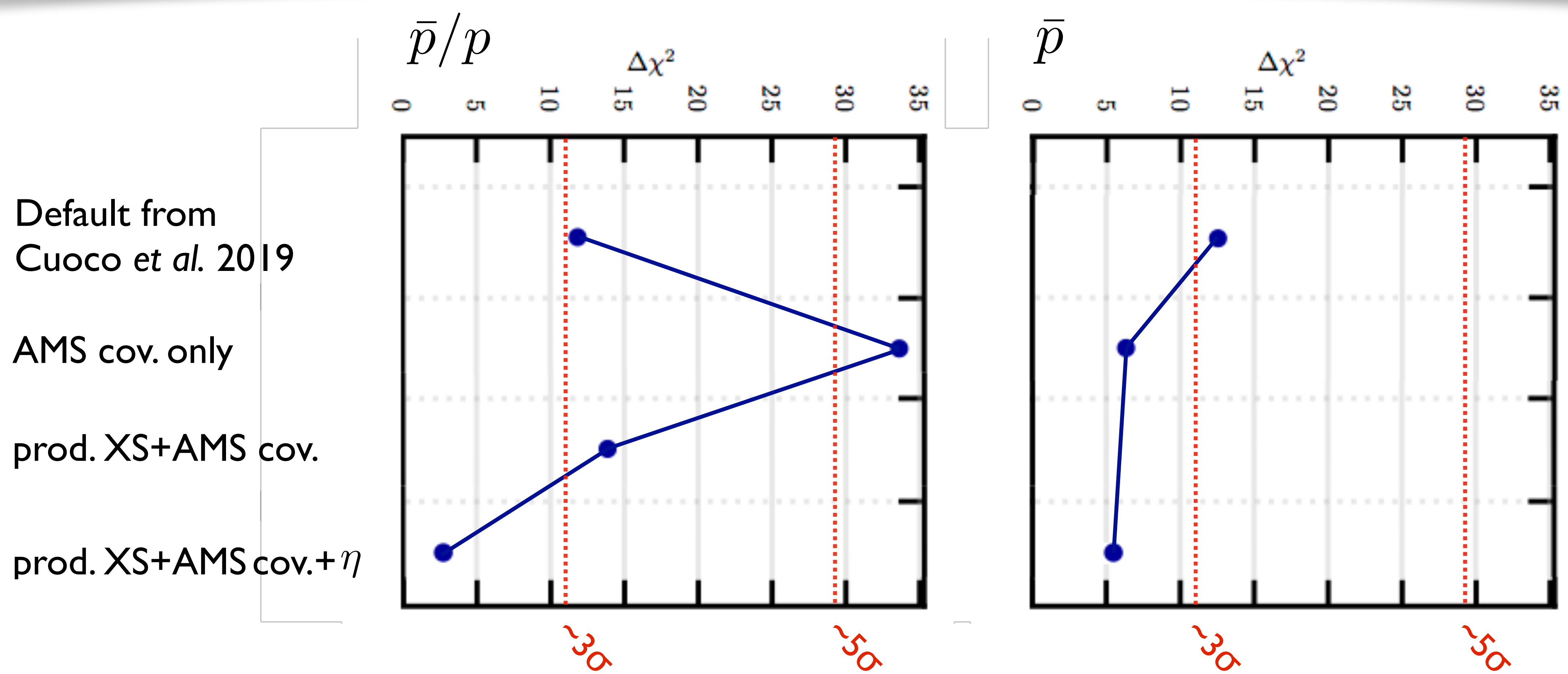


Eff. acceptance error induces "short-range" correlations spoiling sensitivity

Take-home messages:

- Flux ratio more sensitive to spectral features
- Excess sensitive to low-rigidity diffusion model
  Limiting factor: inelastic XS for other species



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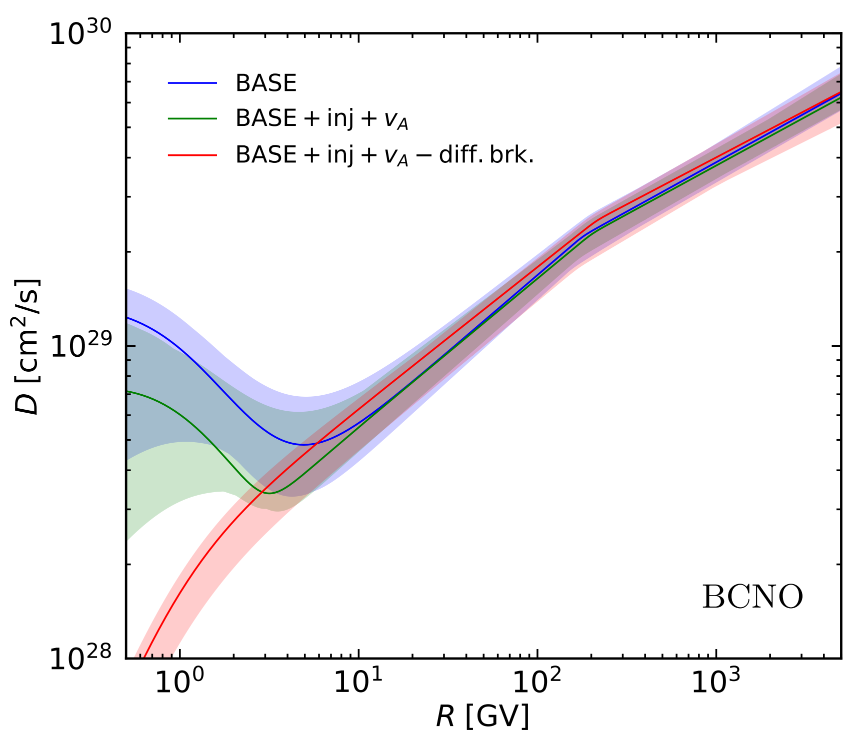
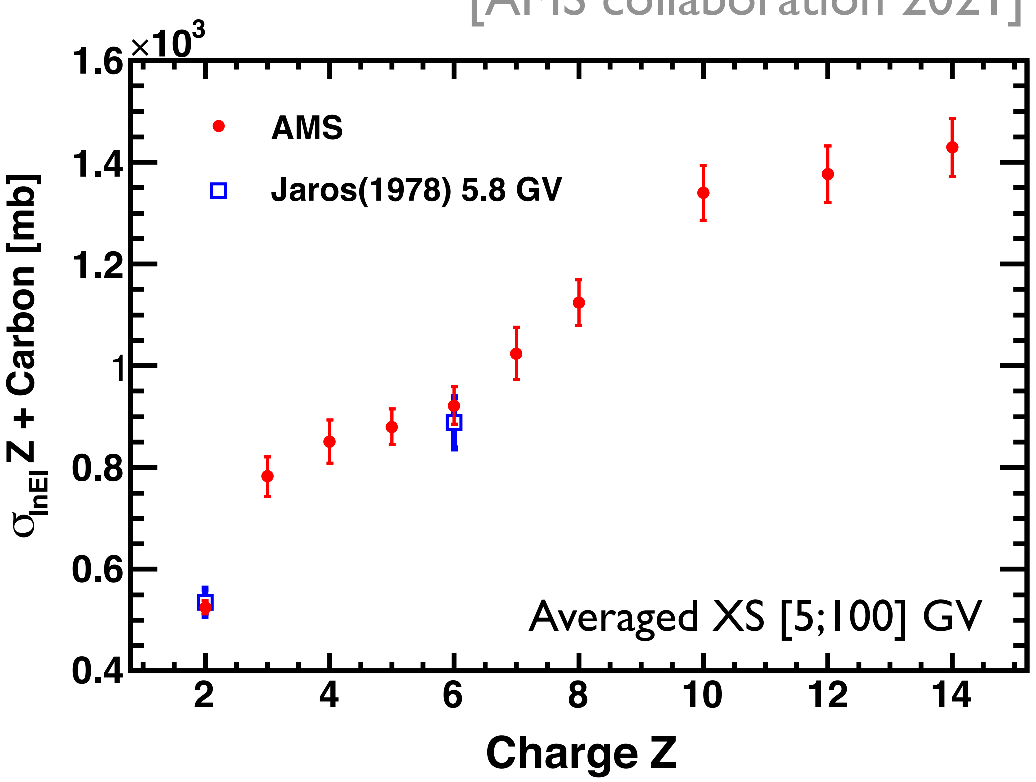
[Korsmeier, Cuoco 2103.09824]



[AMS collaboration 2021]



Conclusions

- With AMS-02, the cosmic-ray precision era has started
- Hint for dark matter around 100GeV, consistent with GCE
- Systematic uncertainties at few % level important
- Antiproton production XS uncertainties
- Correlations in AMS-02 systematics: Potentially large effect
- Computation of absorption XS error ⇒ full covariance
- Knowledge of correlations vital to fully exploit precision
- Signal not robust – decisive: low-rigidity diffusion model
- Uncertainties in nuclear XS limiting factor