
Cosmic-ray antiprotons in the AMS-02 era: A sensitive probe of dark matter

based on [2005.04237](#), [1903.01472](#) and review: [2012.03956](#)

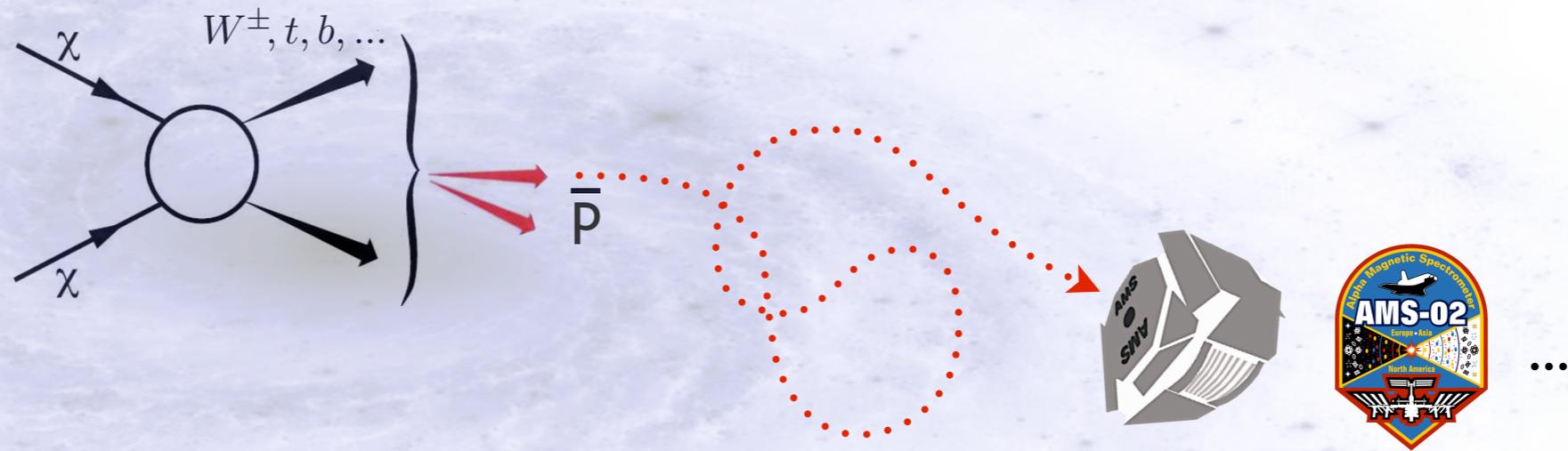
in collaboration with A. Cuoco, L. Klamt, M. Korsmeier, M. Krämer, M. Winkler

Jan Heisig



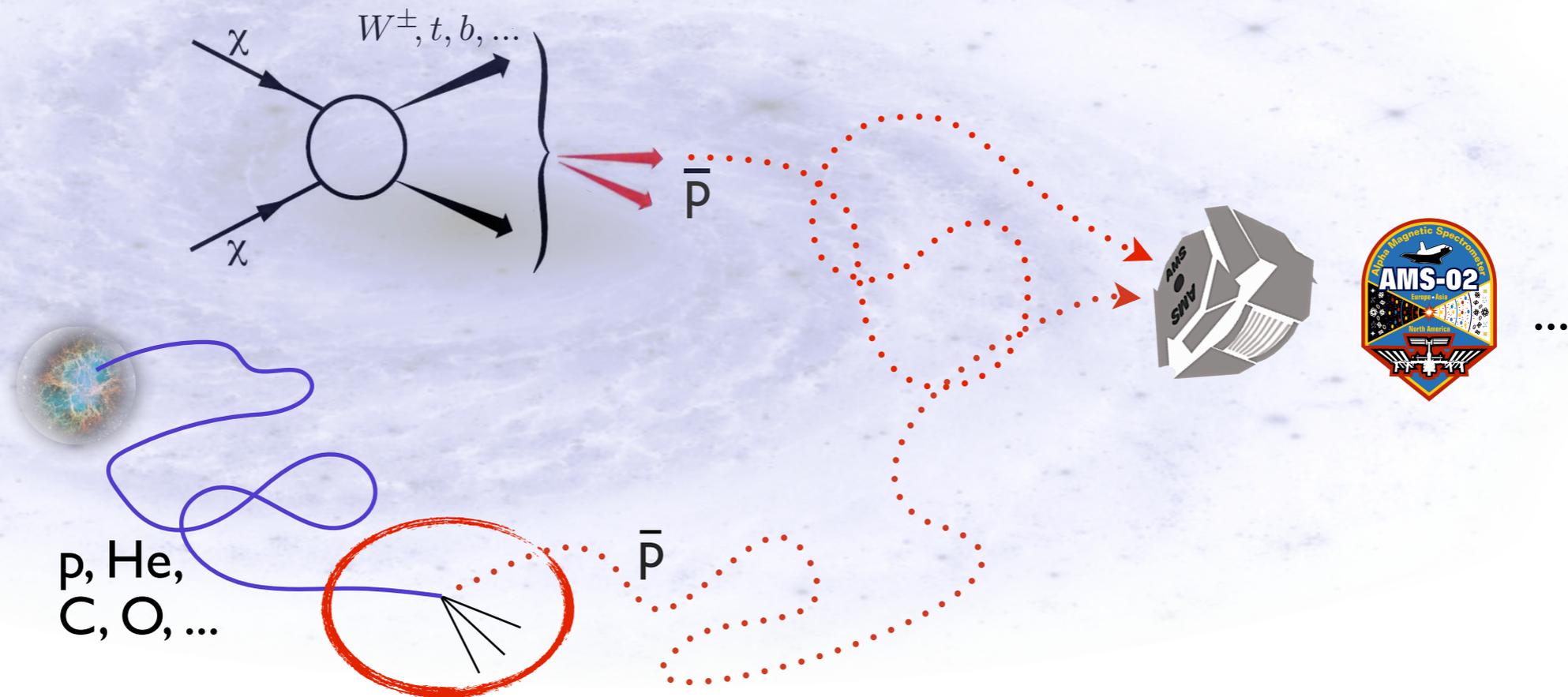
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The UNIVERSITY of OKLAHOMA

Dark matter indirect detection searches: cosmic rays



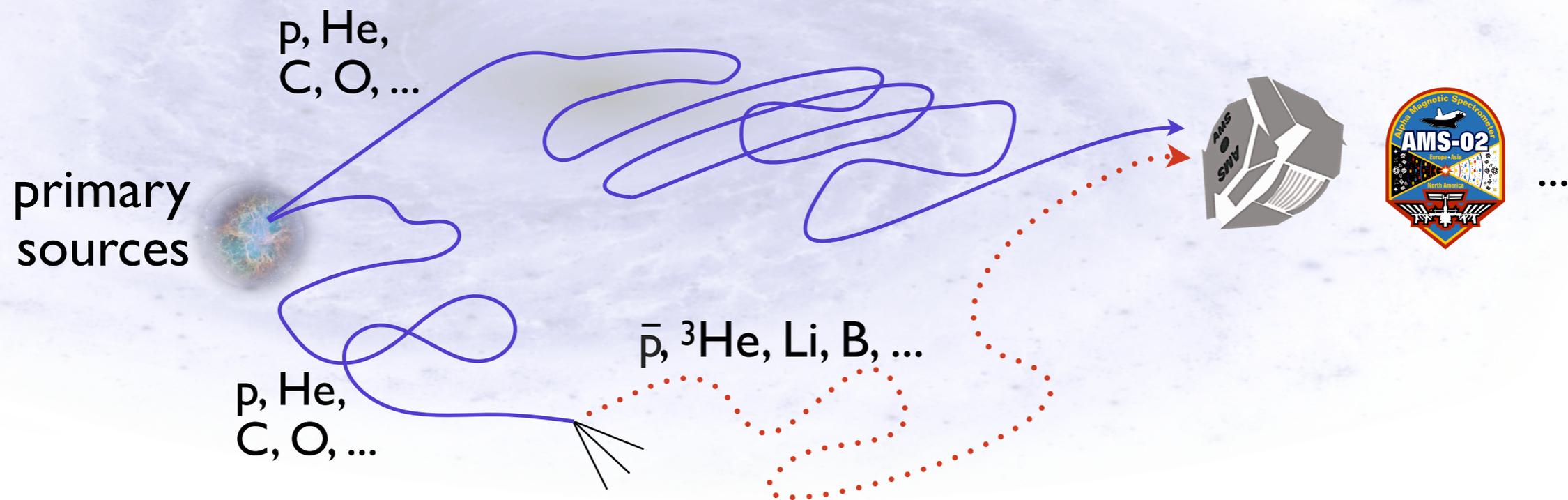
- Cosmic-ray (CR) antiprotons powerful tool for dark-matter searches
- Antimatter: background relatively low

Dark matter indirect detection searches: cosmic rays



- Secondaries from **scatterings off interstellar gas**
- Complicated propagation: Deflected by magnetic clouds
⇒ Diffusive process

Dark matter indirect detection searches: cosmic rays



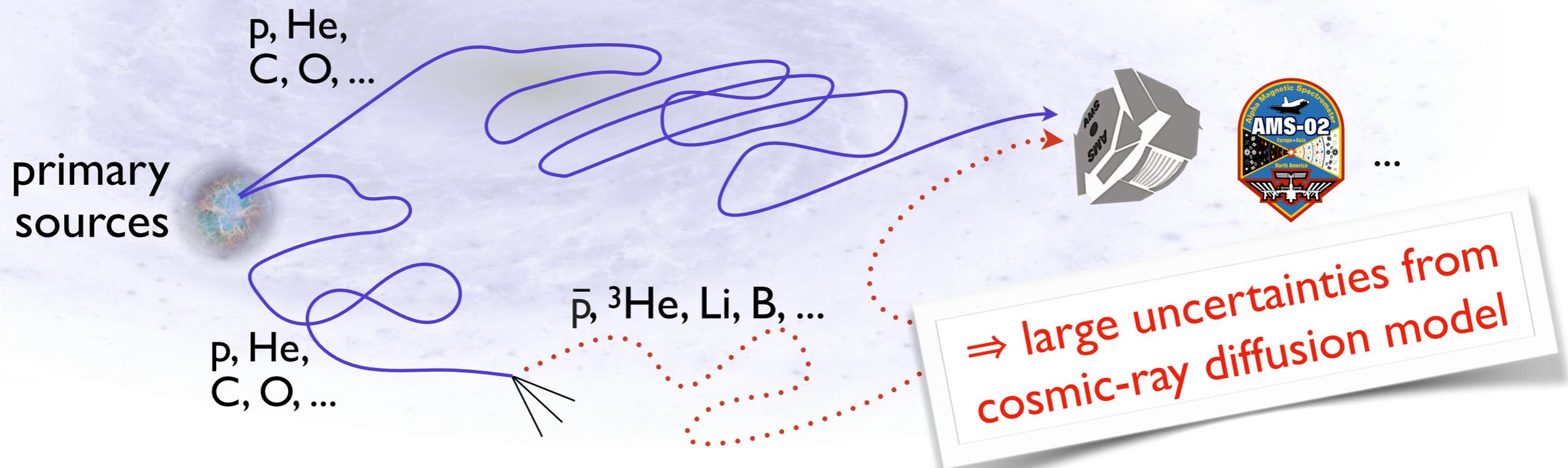
- Sufficiently predictive theory of CR propagation not established
 \Rightarrow Models involve free parameter constraint by observations

- Central: rigidity-dependence of diffusion coefficient $D \propto D_0 R^\delta$

(rigidity = $\frac{\text{momentum}}{\text{charge}}$)

- Secondaries/primaries constrain diffusion: $\frac{\psi_s}{\psi_p} \sim D^{-1} \sim R^{-\delta}$

Dark matter indirect detection searches: cosmic rays



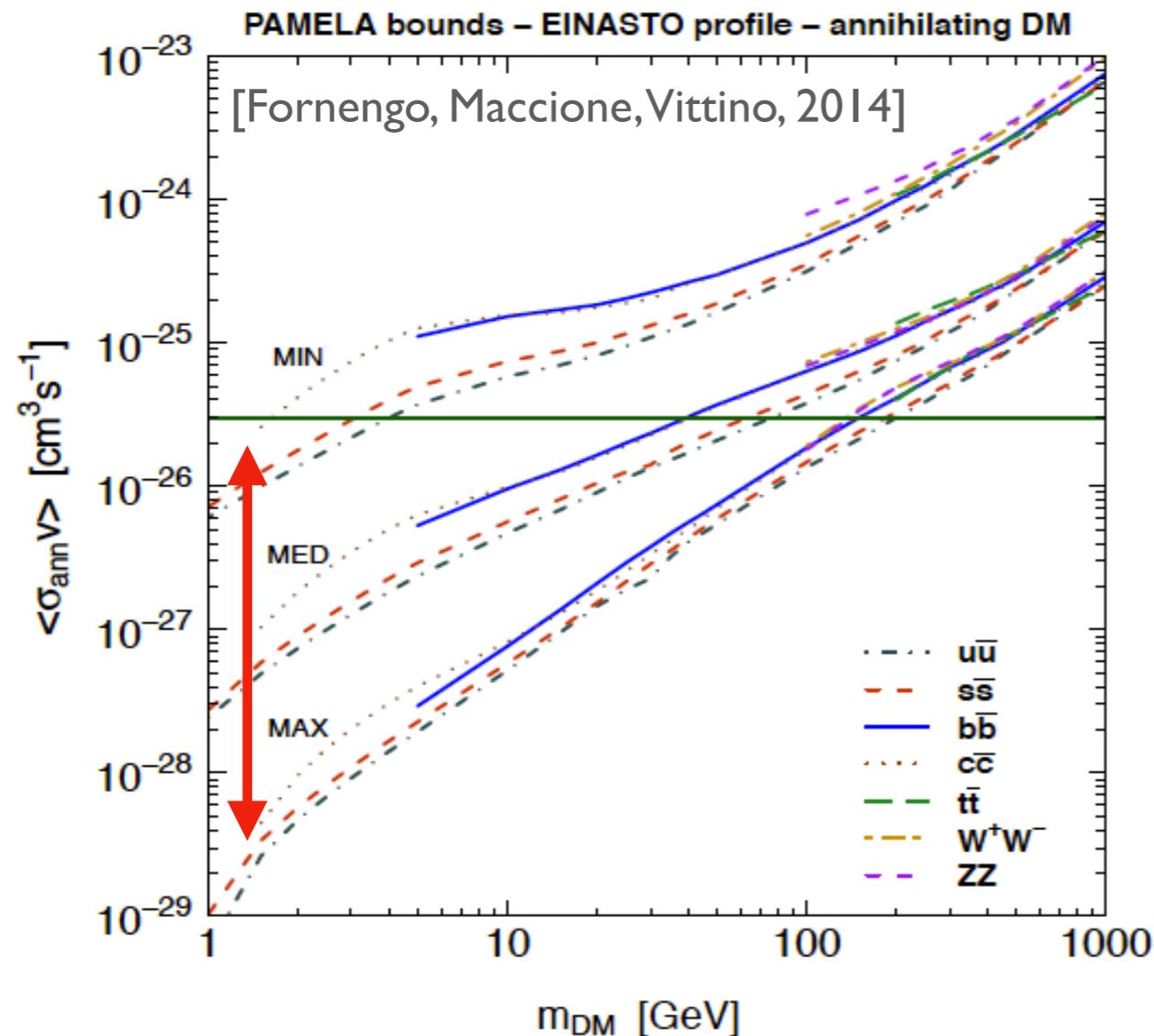
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Uncertainties in the PAMELA era



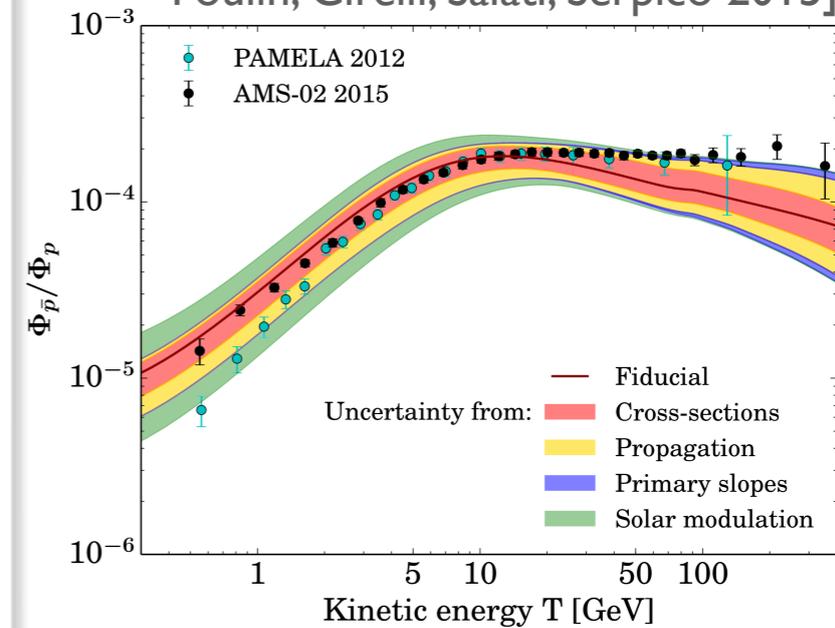
[see also e.g. L. Bergstrom, J. Edsjo, P. Ullio, ApJ, 526, 215 (1999); F. Donato, N. Fornengo, D. Maurin, P. Salati, PRD69, 063501 (2004); T. Bringmann, P. Salati, PRD75, 083006 (2007); F. Donato, D. Maurin, P. Brun, T. Delahaye, P. Salati, PRL. 102, 071301 (2009); D. Hooper, T. Linden, P. Mertsch, JCAP 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, JCAP 1505, 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

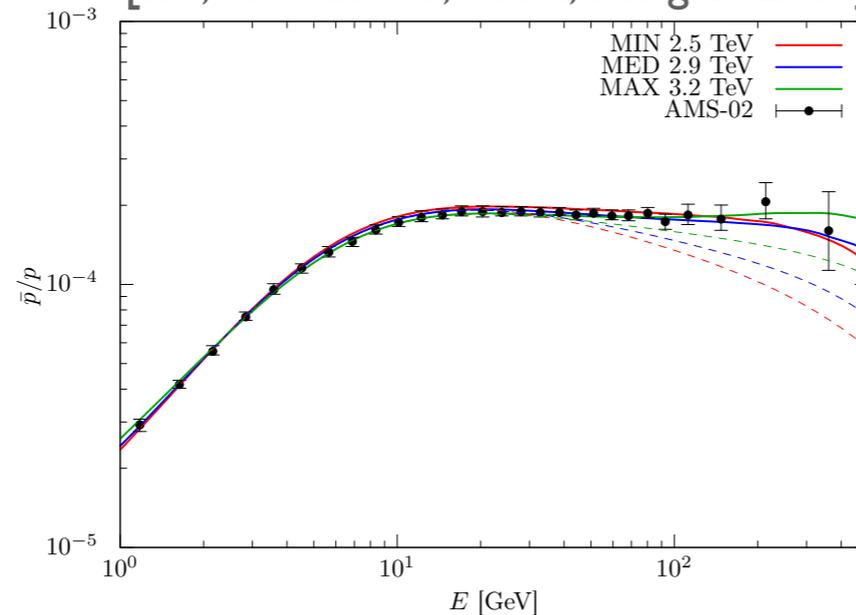
Uncertainties in the AMS-02 era

- High precision data (down to few percent uncertainties)
- Sensitive probe of dark matter
- Need to revise diffusion model

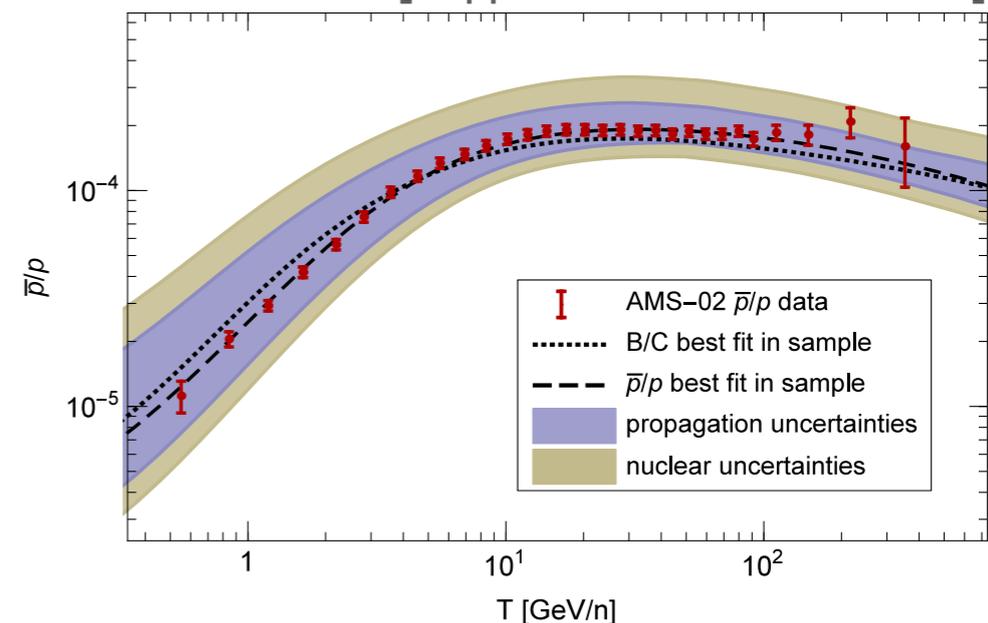
[Giesen, Boudaud, Genolini, Poulin, Cirelli, Salati, Serpico 2015]



[Ibe, Matsumoto, Shirai, Yanagida 2015]



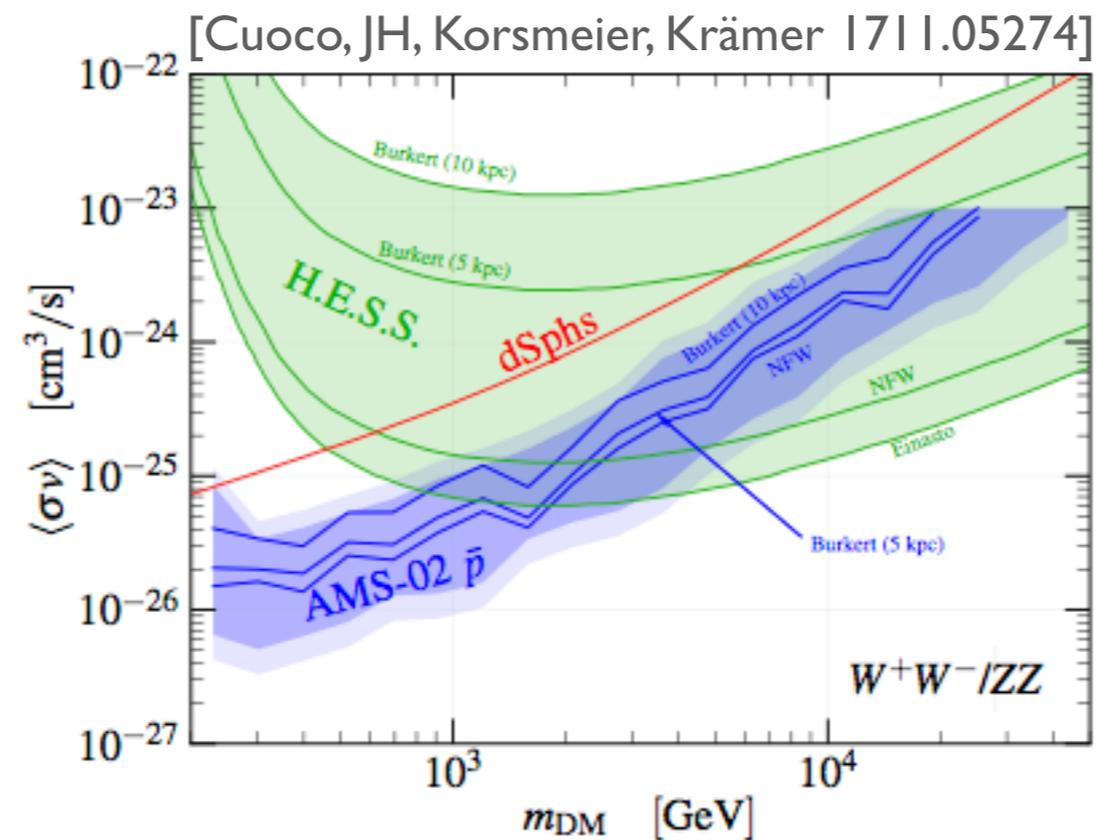
[Kappl, Reinert, Winkler 2015]



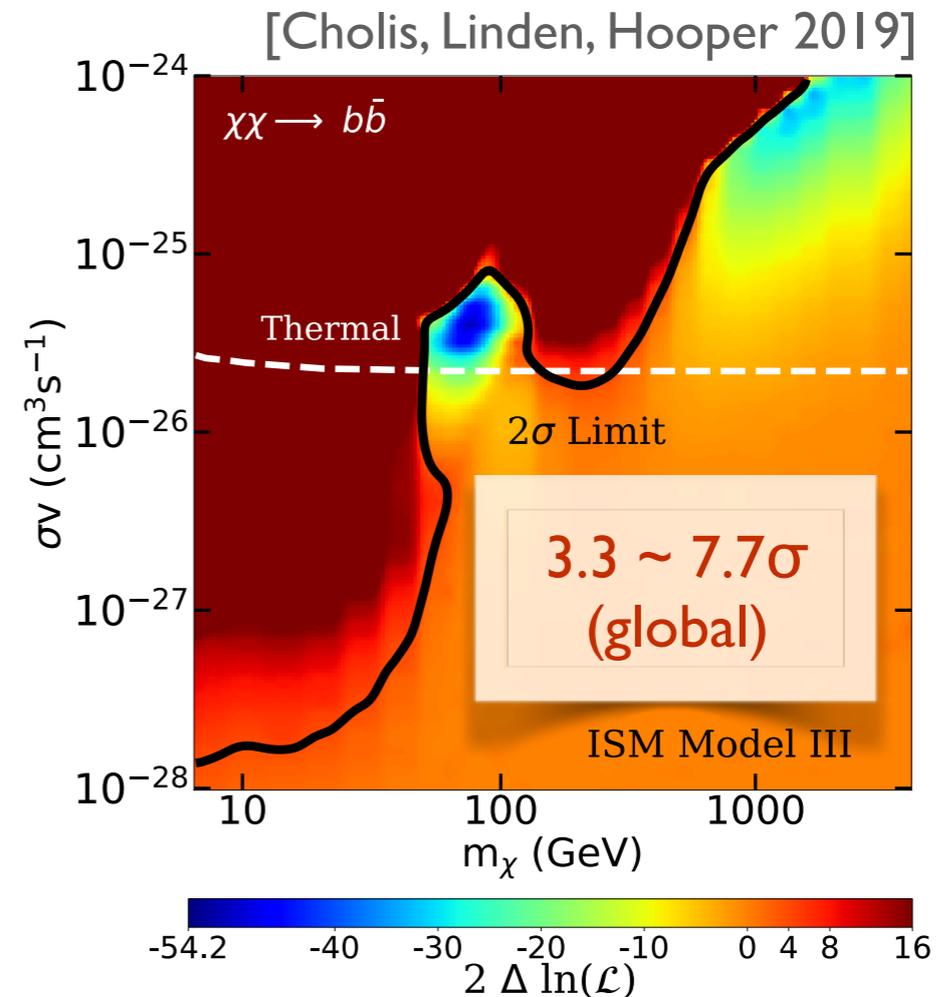
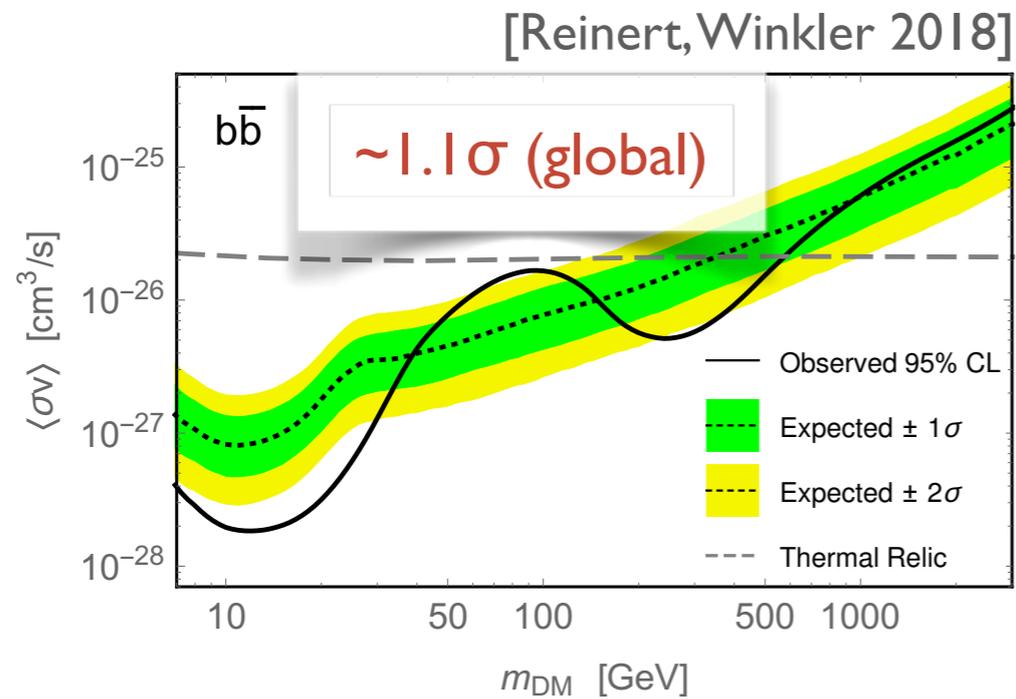
Uncertainties in the AMS-02 era

One way to explore precise data:

- Joint fit of propagation and dark matter parameters
- Profiling over propagation parameters



Hint for 100 GeV-ish dark matter

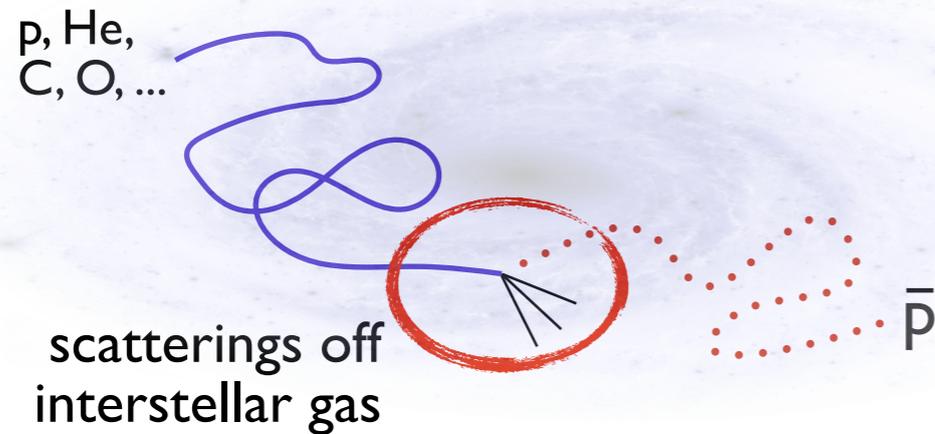


- Agree on dark-matter properties
 - Significance highly controversial
- \Rightarrow unaccounted systematic uncertainties

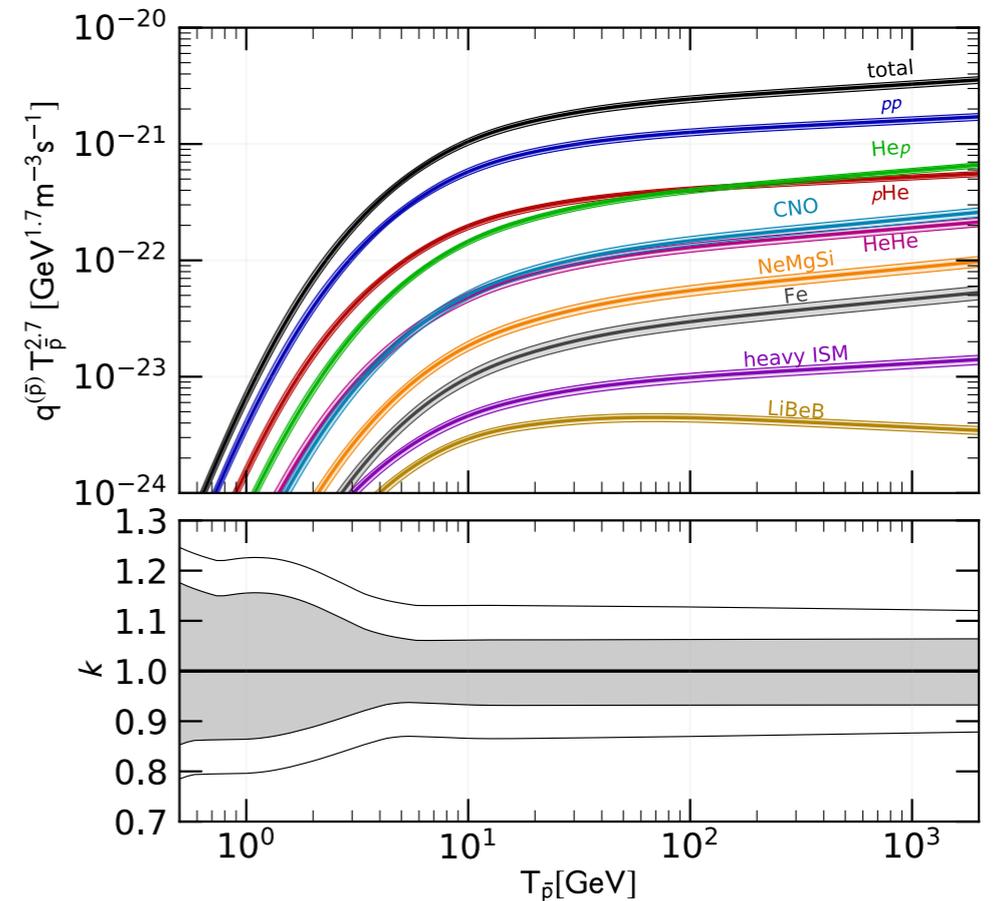
[see also Cui, Pan, Yuan, Fan, Zong 2018;
 Lin, Bi, Yin 2019]

Secondary antiproton cross-section uncertainties

- Enters background prediction:

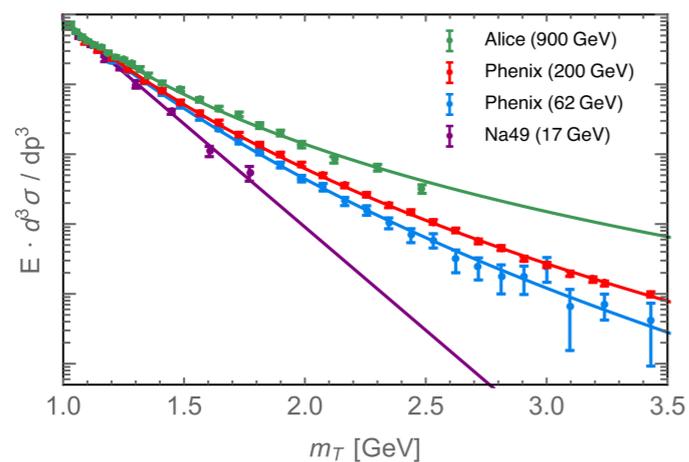


- Partly relies on old laboratory data
- Recent progress in modeling:

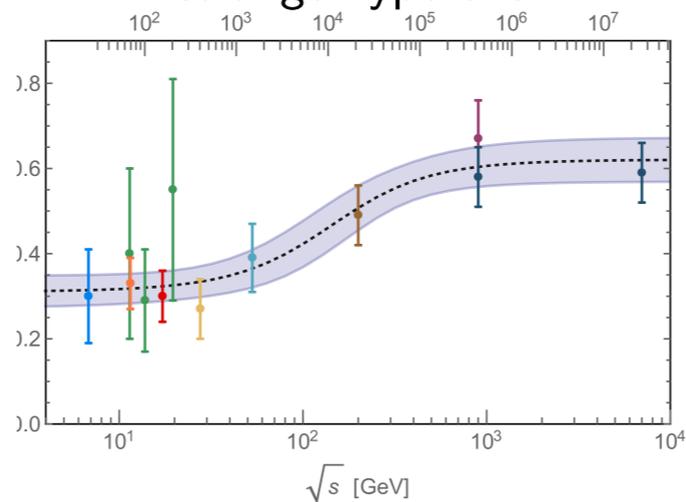


[Korsmeier, Donato, Di Mauro 2018]

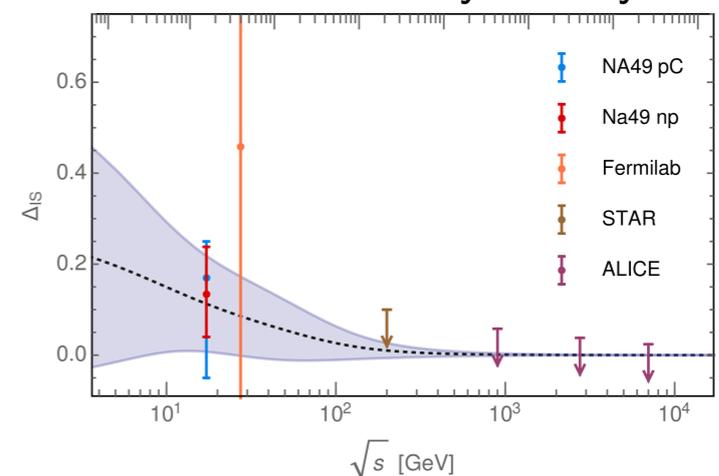
Feynman scaling violation



strange hyperons



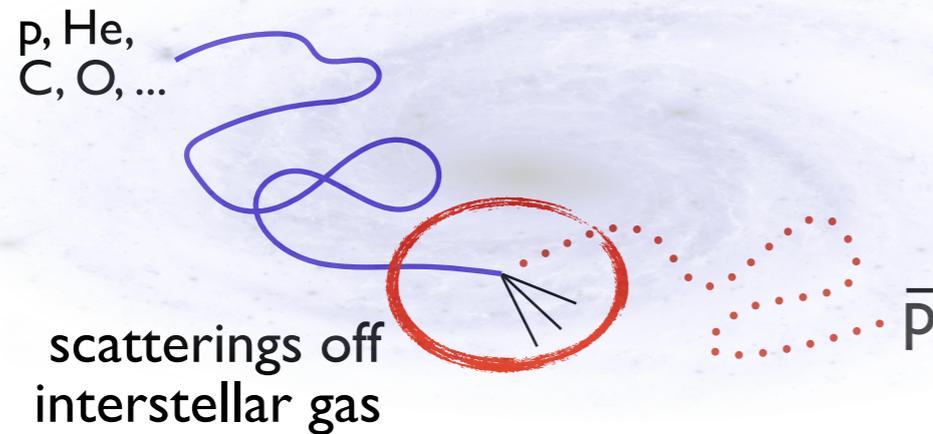
antineutron asymmetry



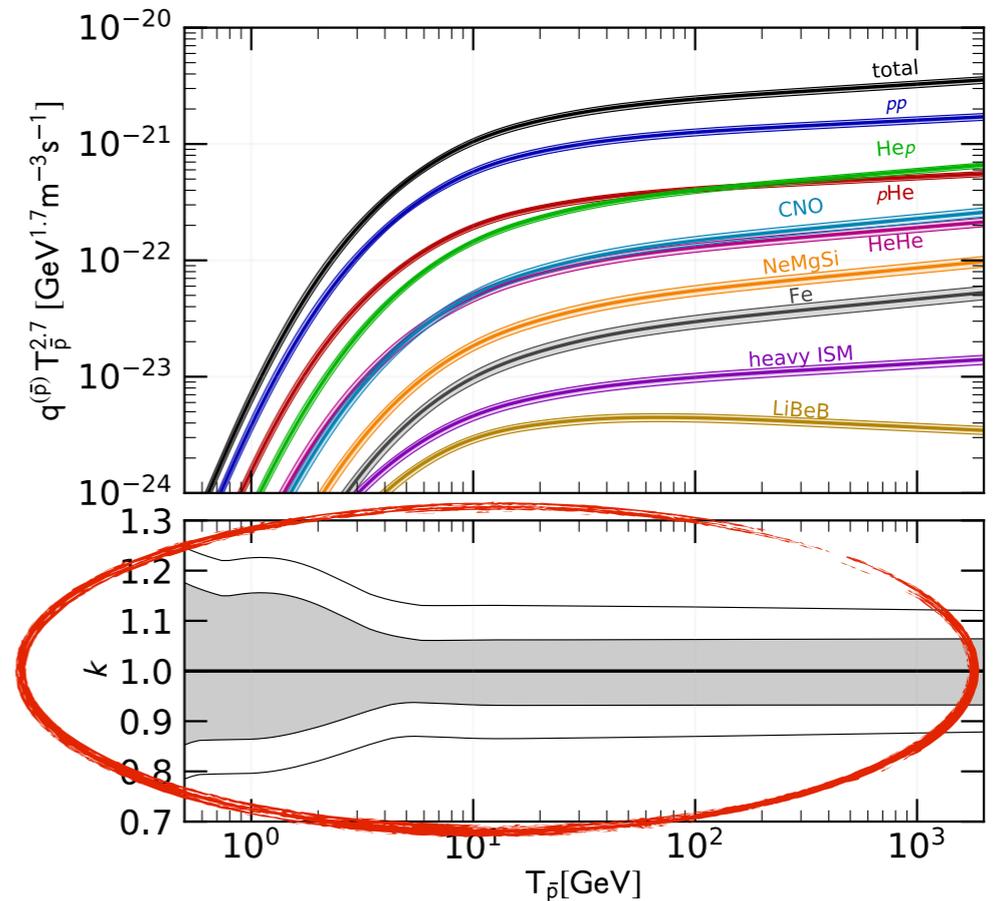
[Winkler 2017]

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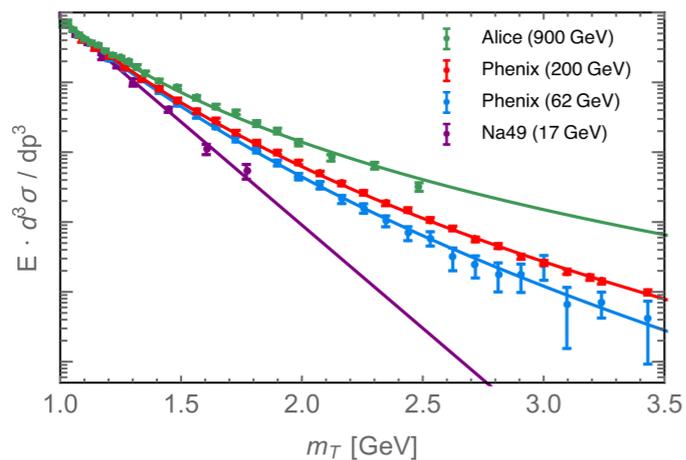


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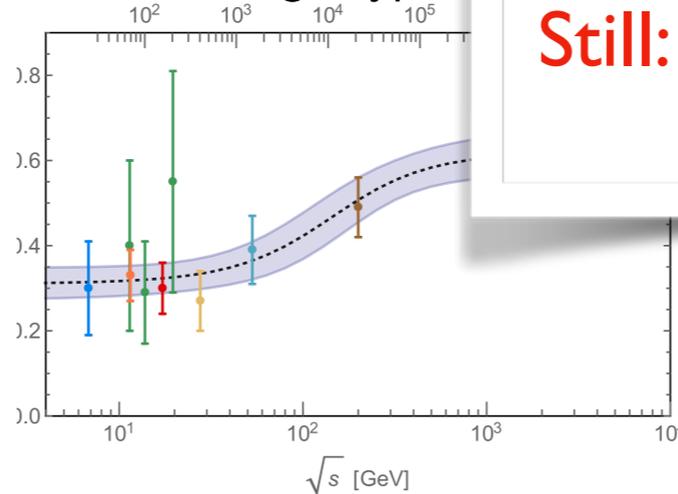


[Korsmeier, Donato, Di Mauro 2018]

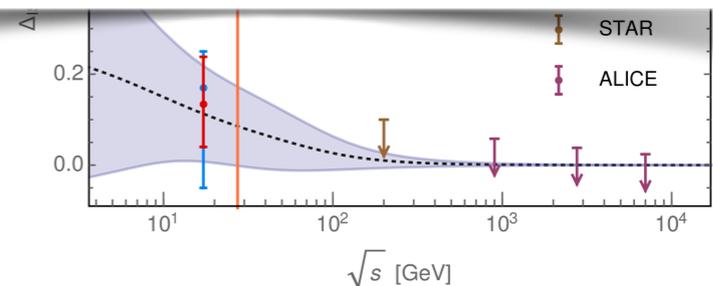
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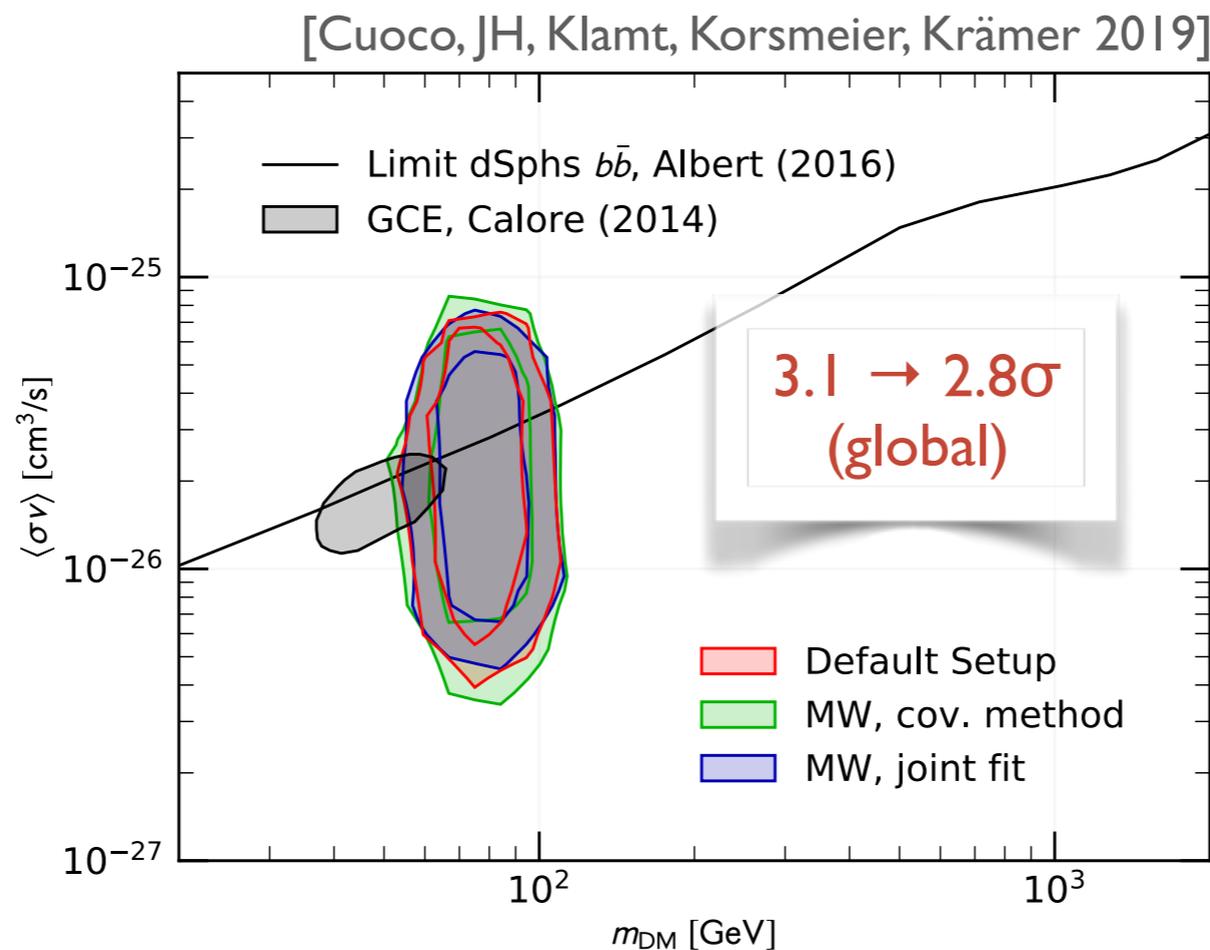
Still: sizeable uncertainties
~10-20%



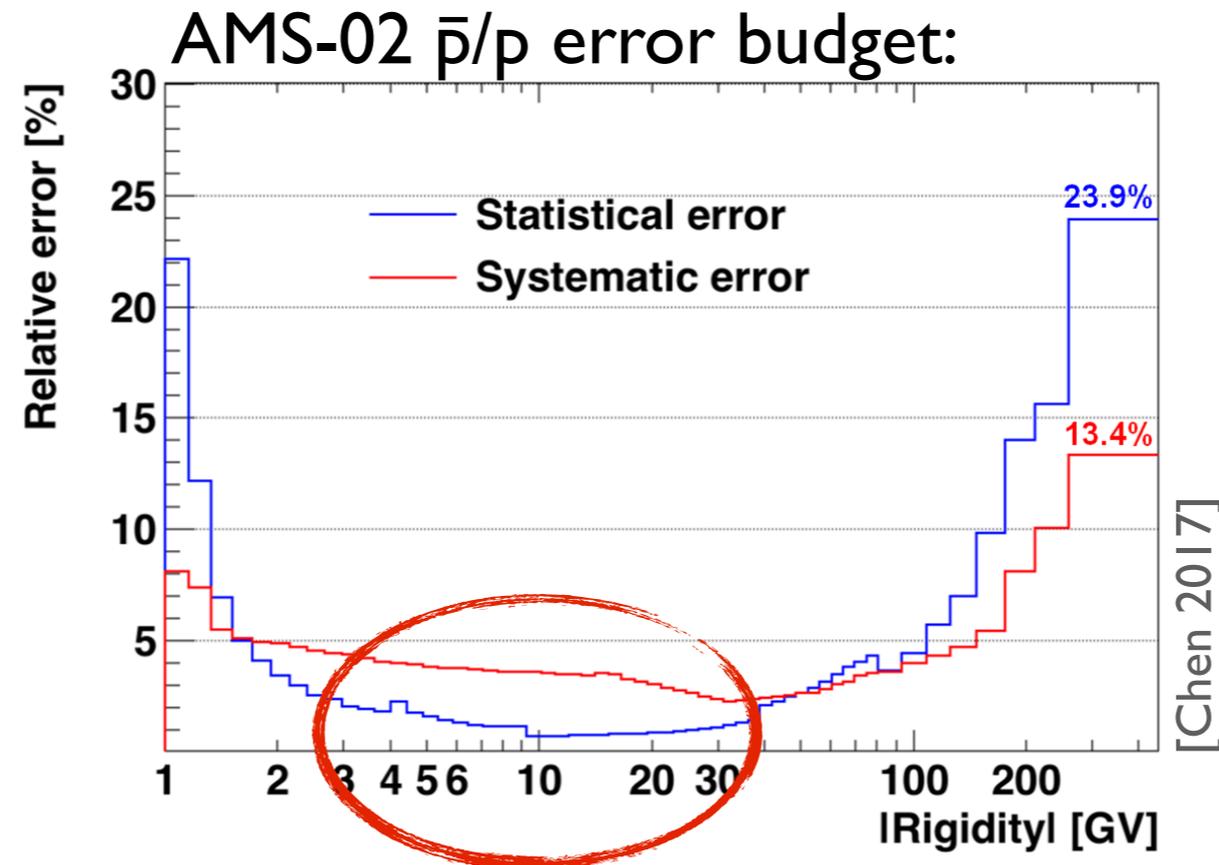
[Winkler 2017]

Secondary antiproton cross-section uncertainties

■ Effect on tentative signal moderate:



Correlations in AMS-02 \bar{p}/p uncertainties

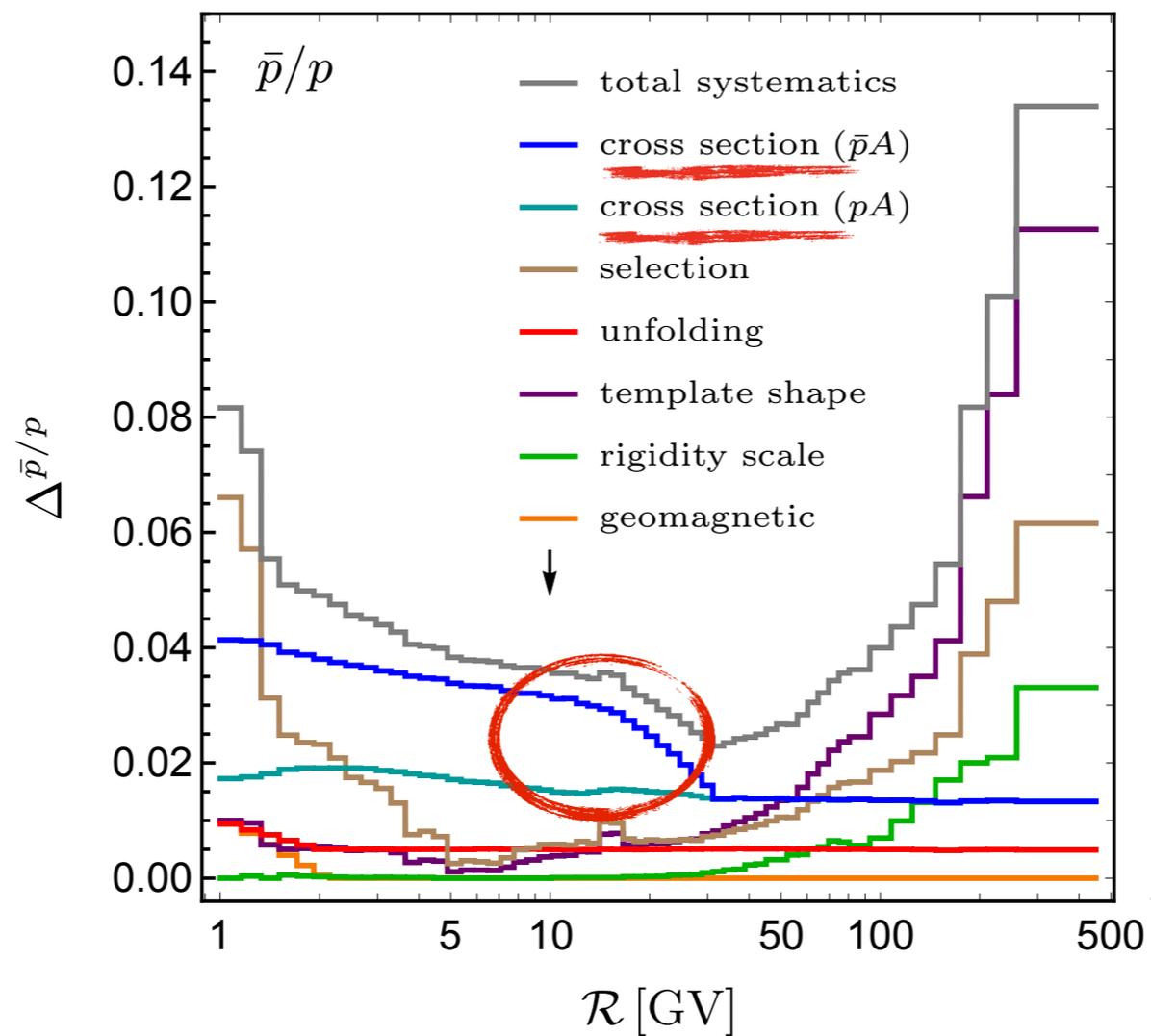


- Systematic uncertainties dominate in relevant region: 5~25GV
- Rel. error around 4%
- No covariance provided by AMS-02, but correlations expected!
⇒ Potentially huge effect [Cuoco, JH, Klamt, Korsmeier, Krämer 1903.01472]

Correlations in AMS-02 uncertainties

[J.H., M.Korsmeier, M.Winkler, 2005.04237]

- Systematics – split up in sub-contributions:



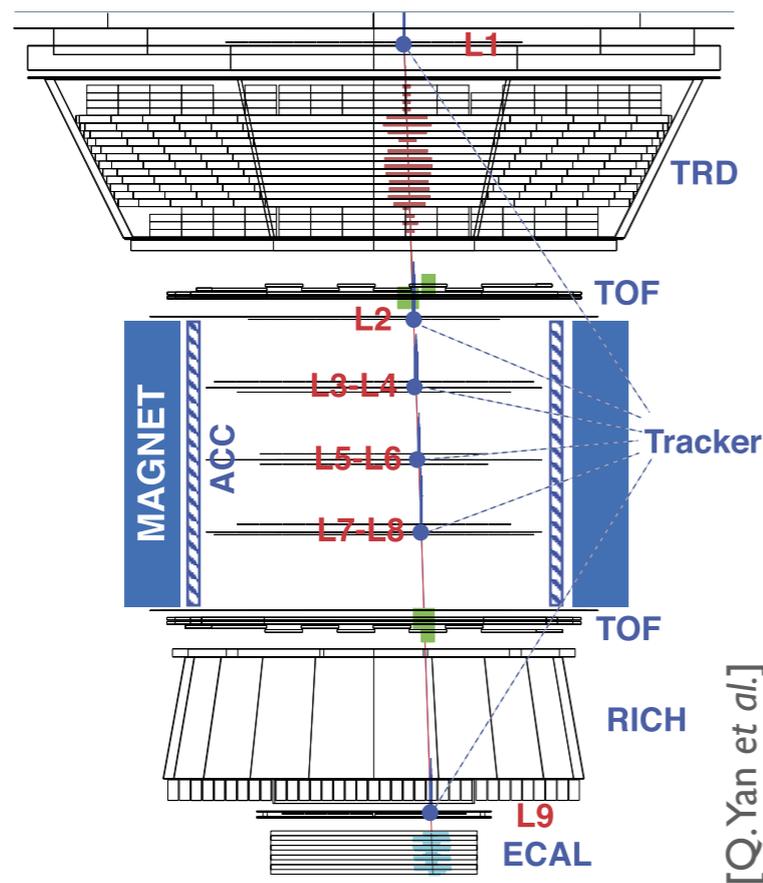
[Data collected from:
M.Aguilar et al. (AMS) 2016;
P.Zuccon, Talk at Antideuteron 2019;
A.I.Chen, PhD thesis 2017]

⇒ Investigate dominant ones in detail: CR absorption in detector

Uncertainties from absorption cross section

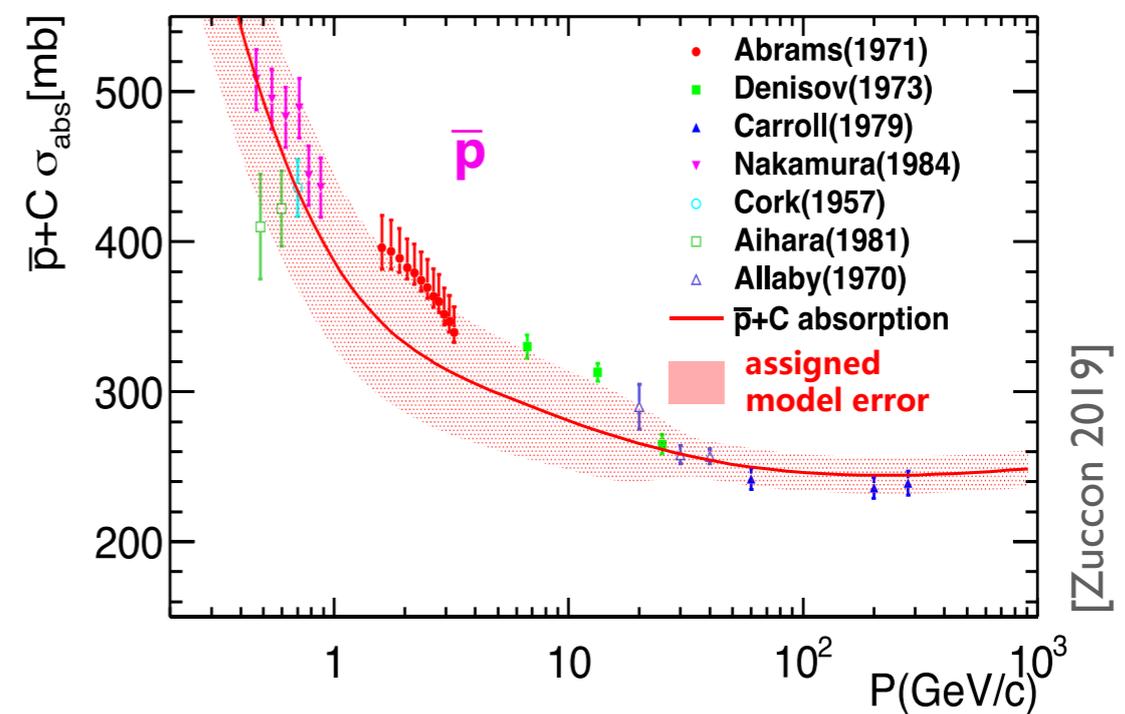
[JH, M.Korsmeier, M.Winkler, 2005.04237]

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



[Q.Yan et al.]

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



[Zuccon 2019]

Uncertainties from absorption cross section

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

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

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

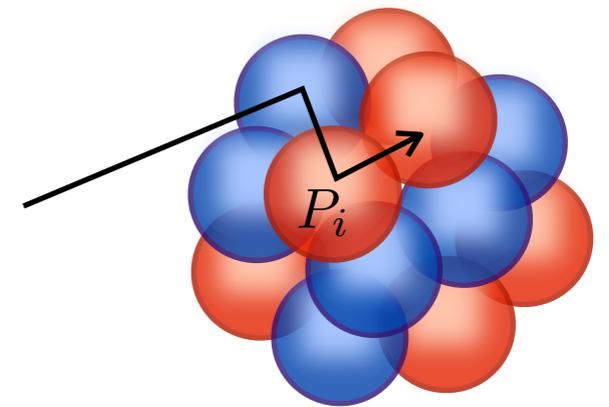
[Glauber 1959; Sitenko 1959; Pumplin, Ross 1968; Gribov 1969; Karmanov, Kondratyuk 1973]

- Links XS to input quantities:

Nucleon-nucleon cross sections

Nuclear densities etc.

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

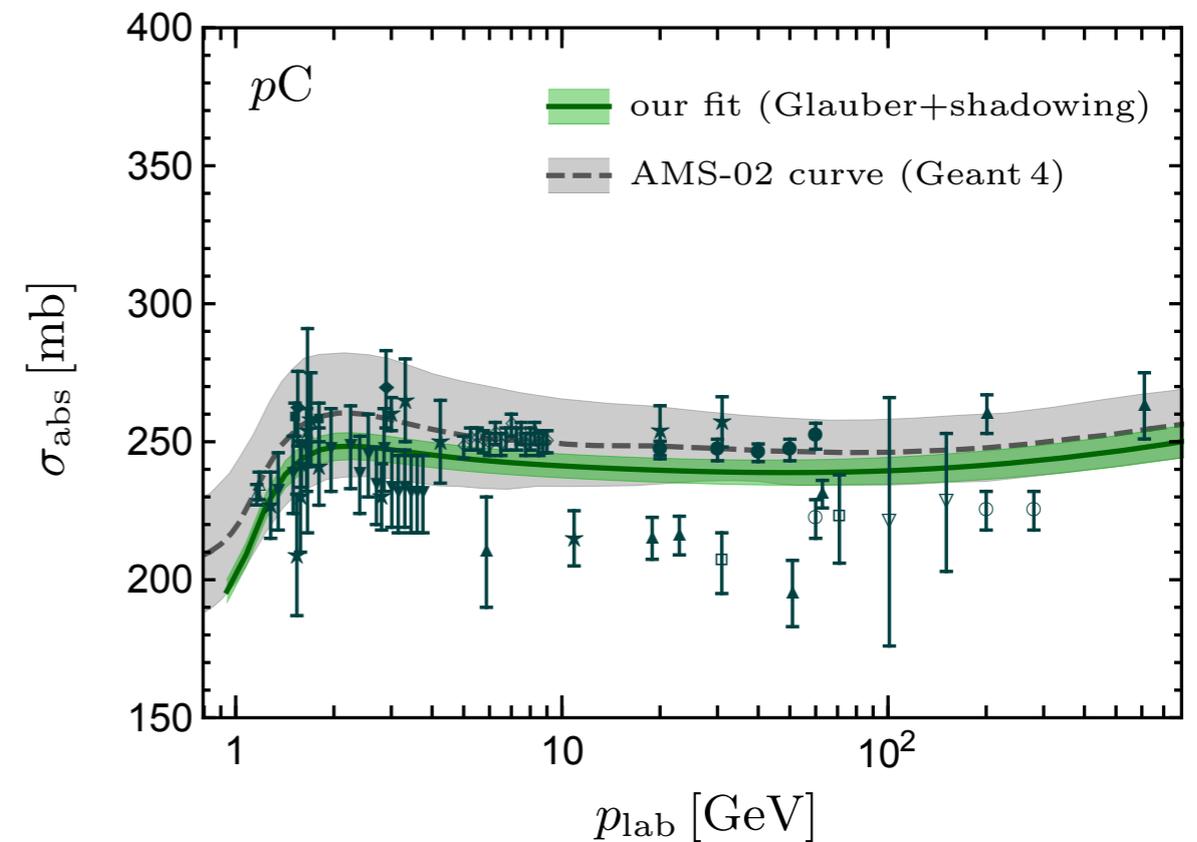
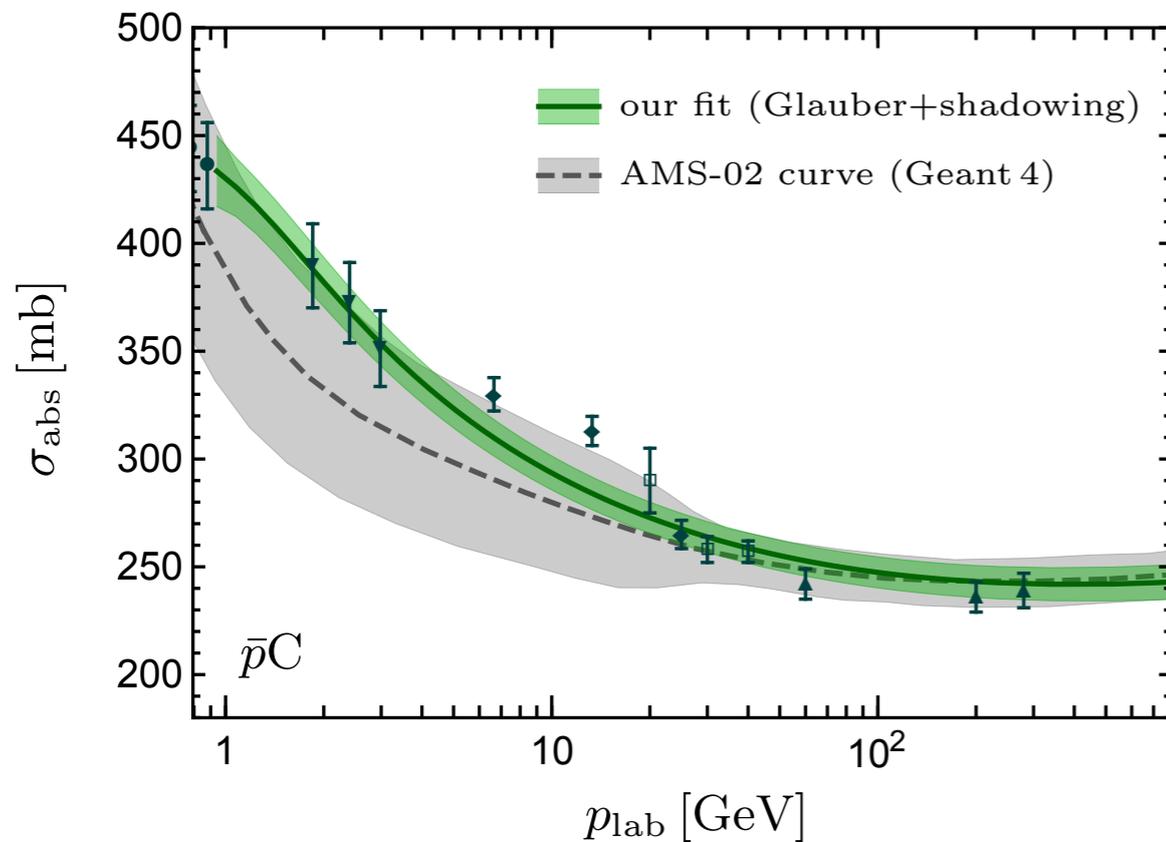


$$P_{\text{at-least-one}} = \left(1 - \prod_{i=1}^A [1 - P_i] \right)$$

Uncertainties from absorption cross section

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

- Results of global fits within Glauber-Gribov theory:



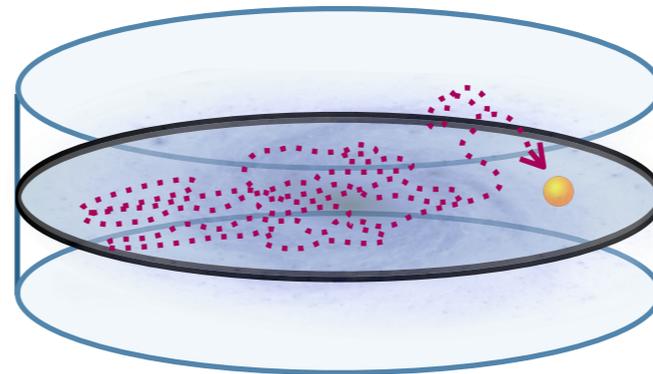
+ correlation matrix!

- 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:

diffusion volume



sources in Galactic plane

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

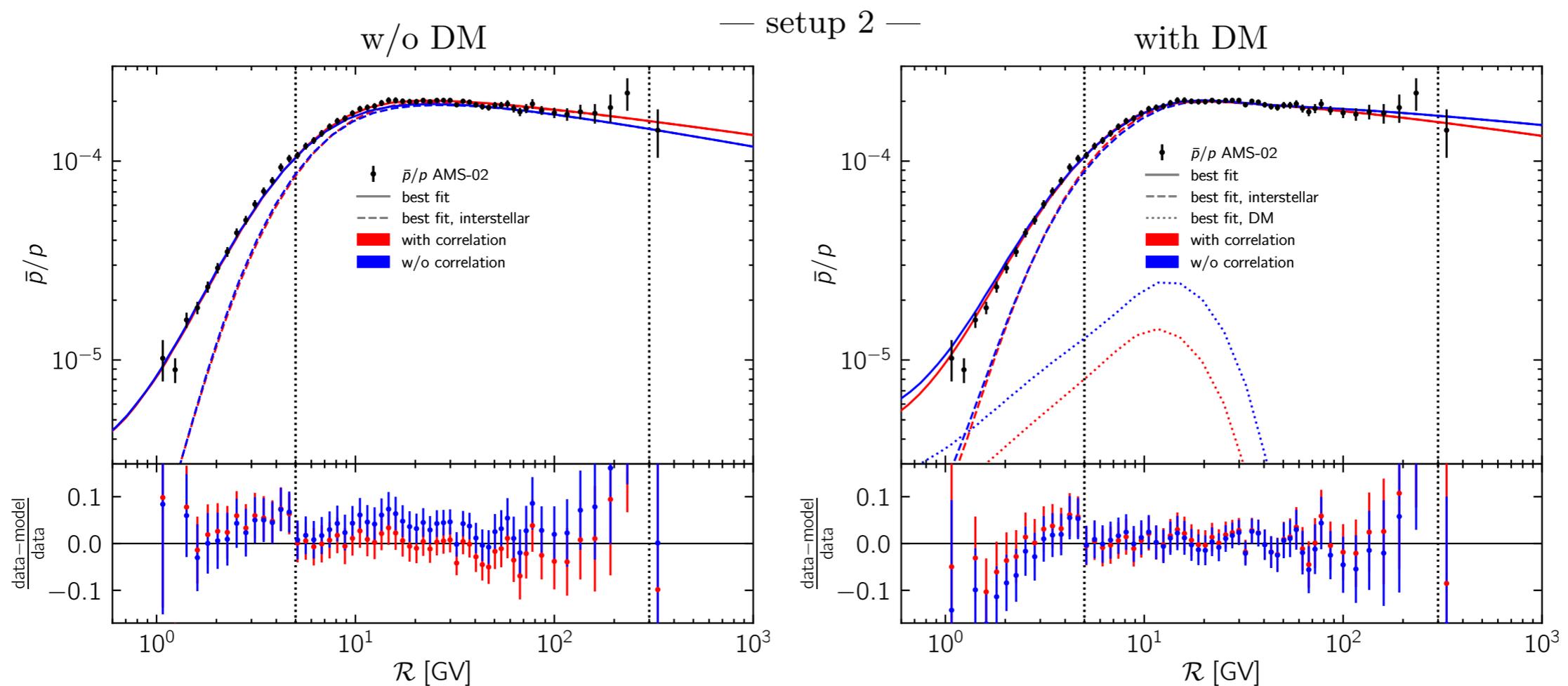
- Joined fit of \bar{p}/p , p , He (\bar{p} , p , He; see below)
- Model primary spectra with broken power laws
- Diffusion coefficient: $D_{xx} \propto \beta^\eta R^\delta$ (negative η : \sim low-rigidity break)*
[see Boudaud et al. 2019]
- Consider convection and reacceleration
- Numerical solution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



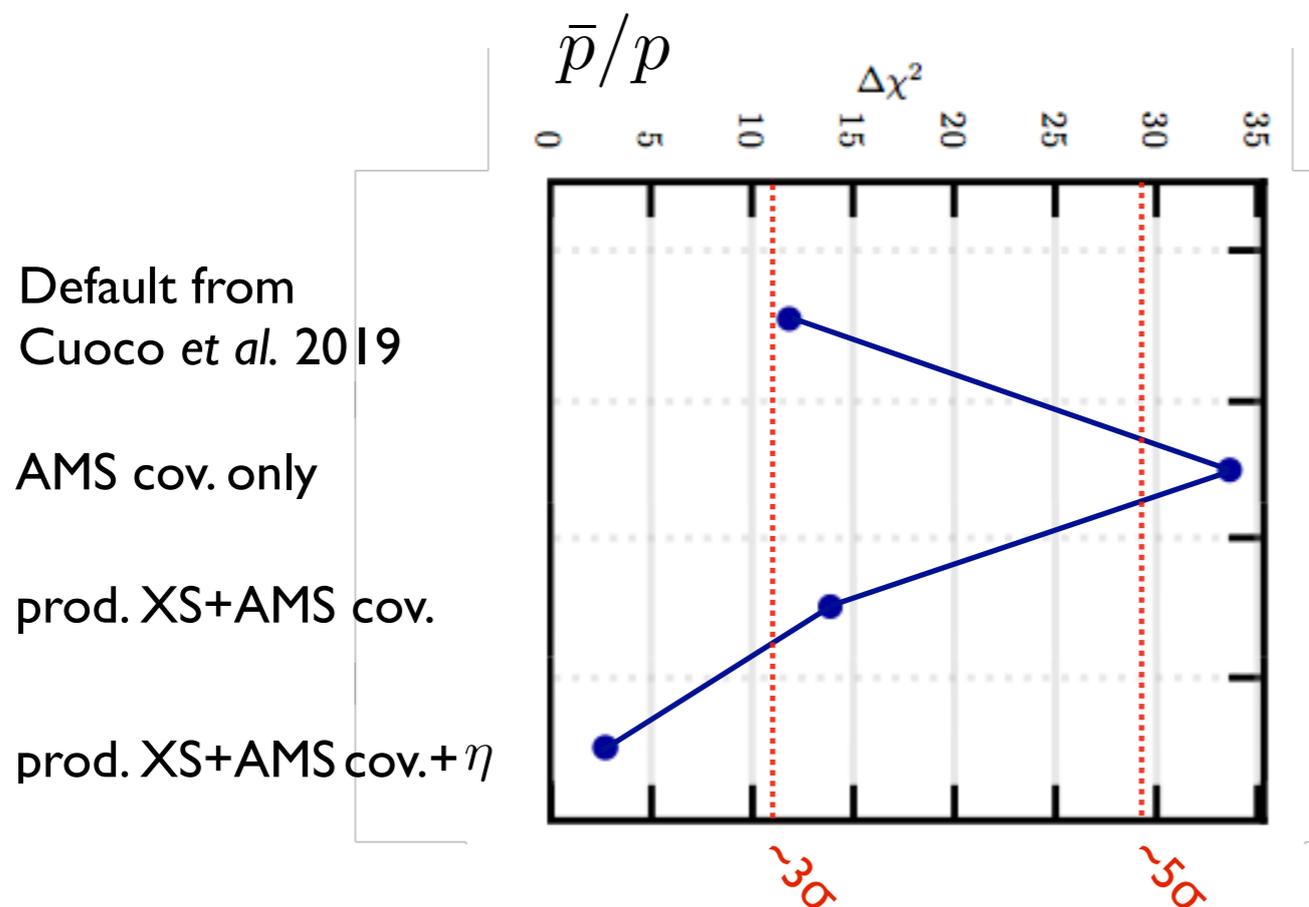
⇒ no significant preference found in data: **global significance of 0.5σ** *

*) 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]

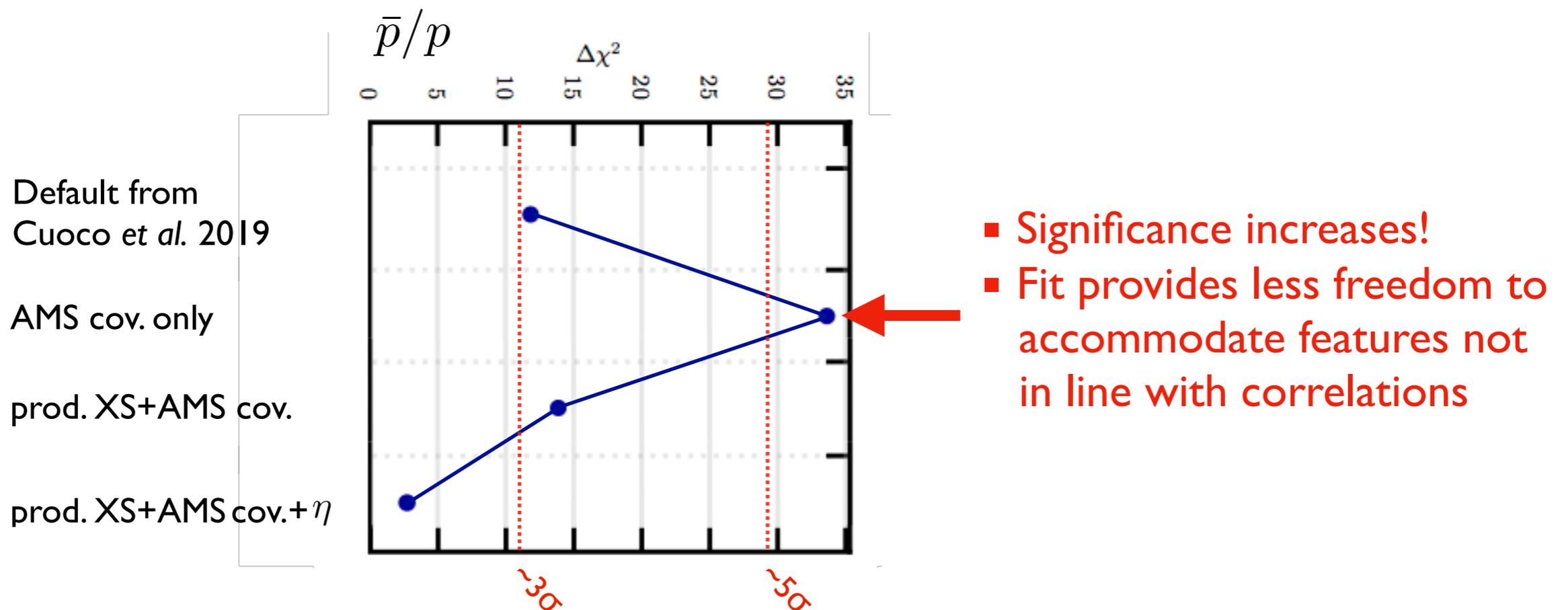


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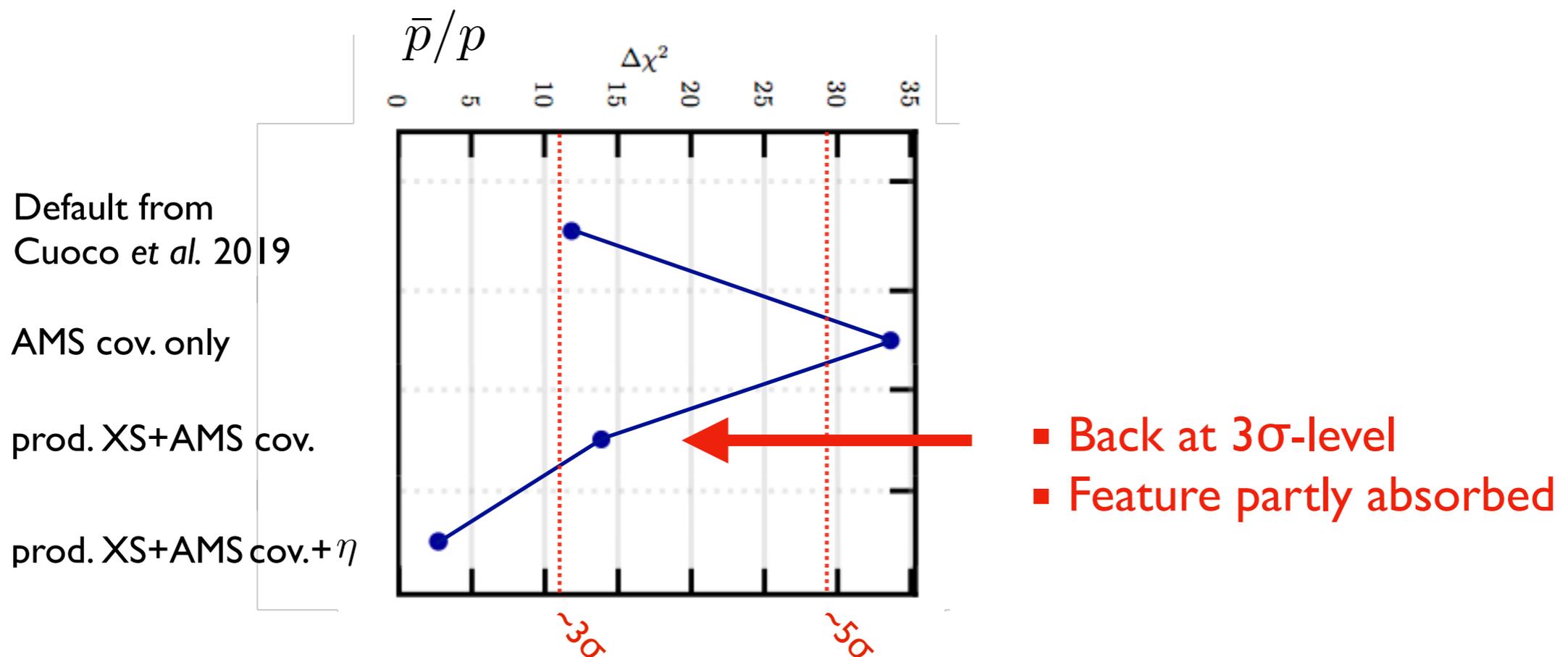
- Significance increases!
- Fit provides less freedom to accommodate features not in line with correlations

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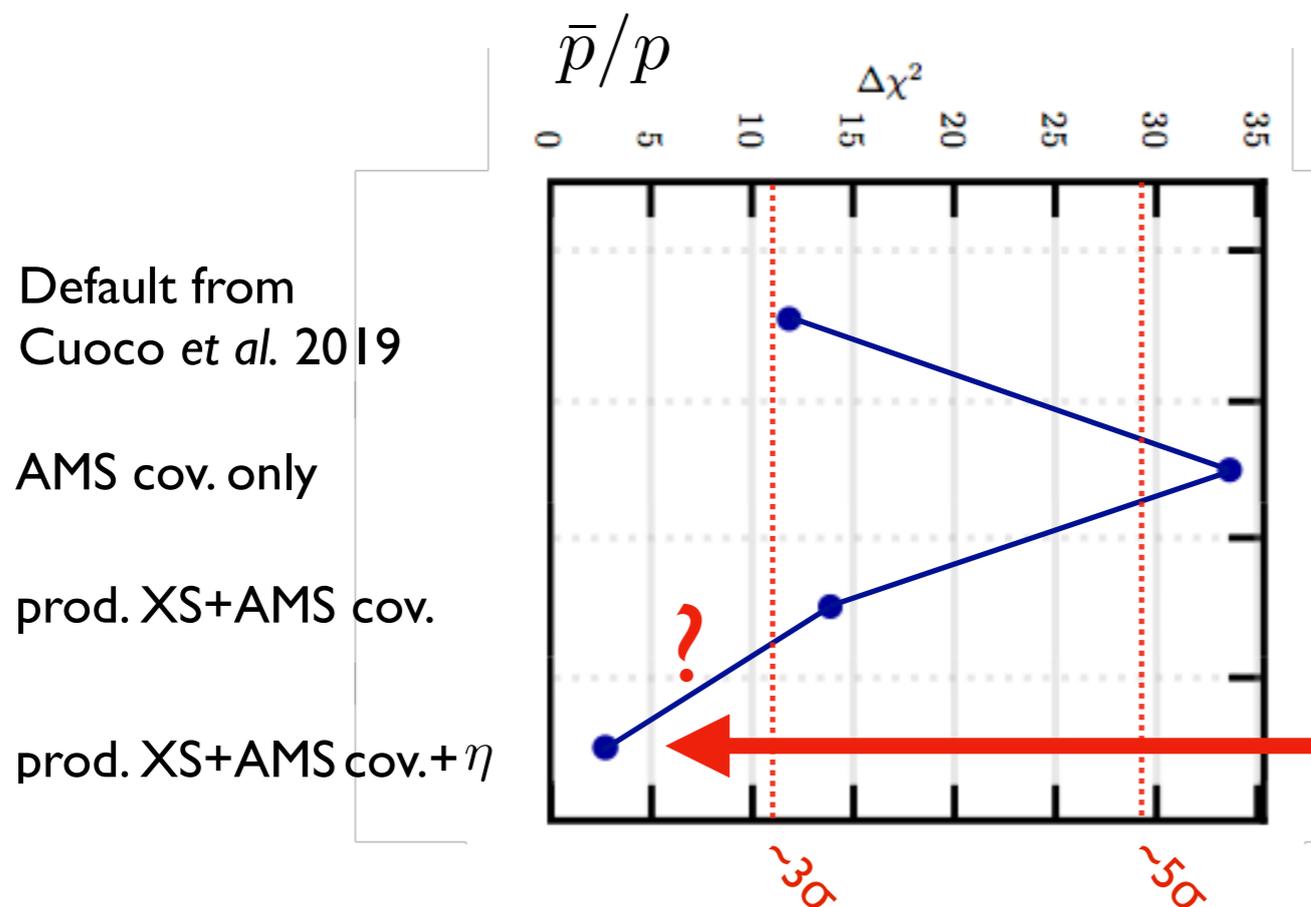
- Back at 3σ -level
- Feature partly absorbed

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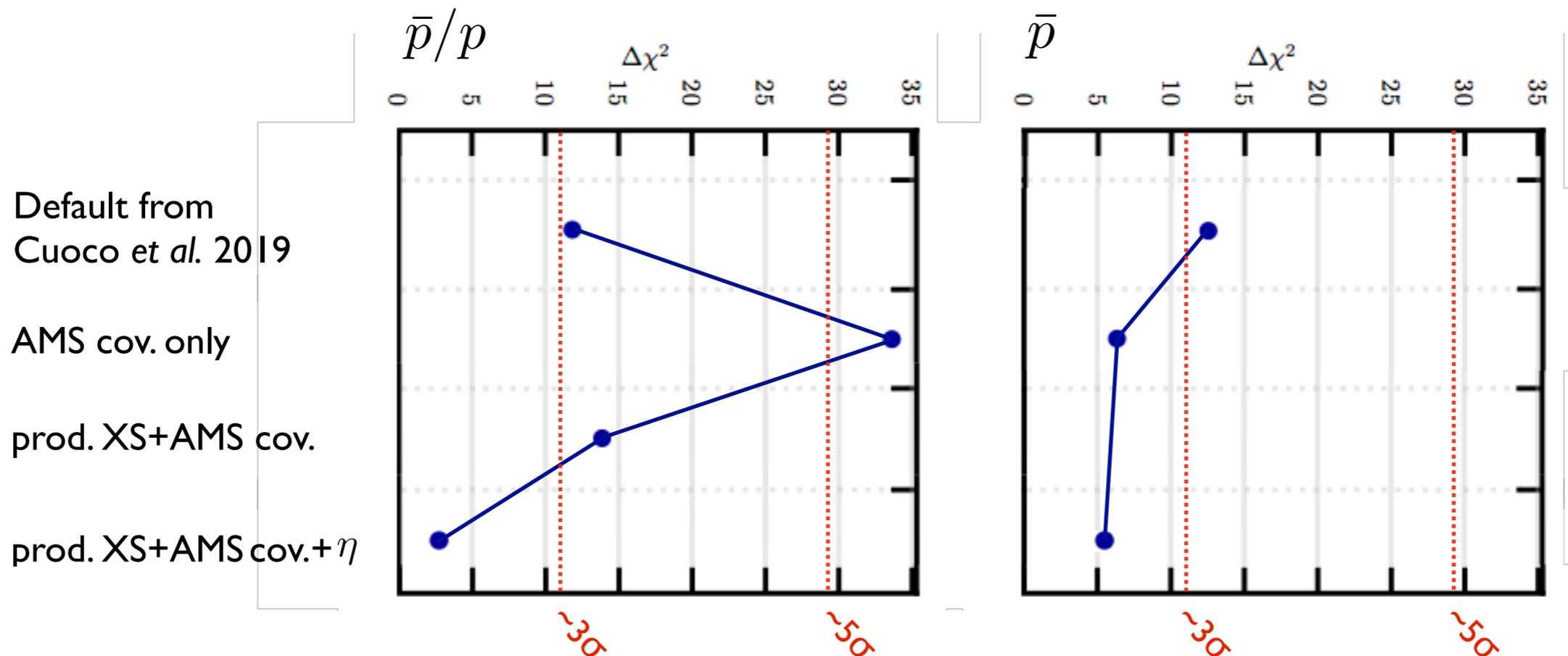
- Only additional freedom in diffusion allows to reconcile tension w/o dark matter

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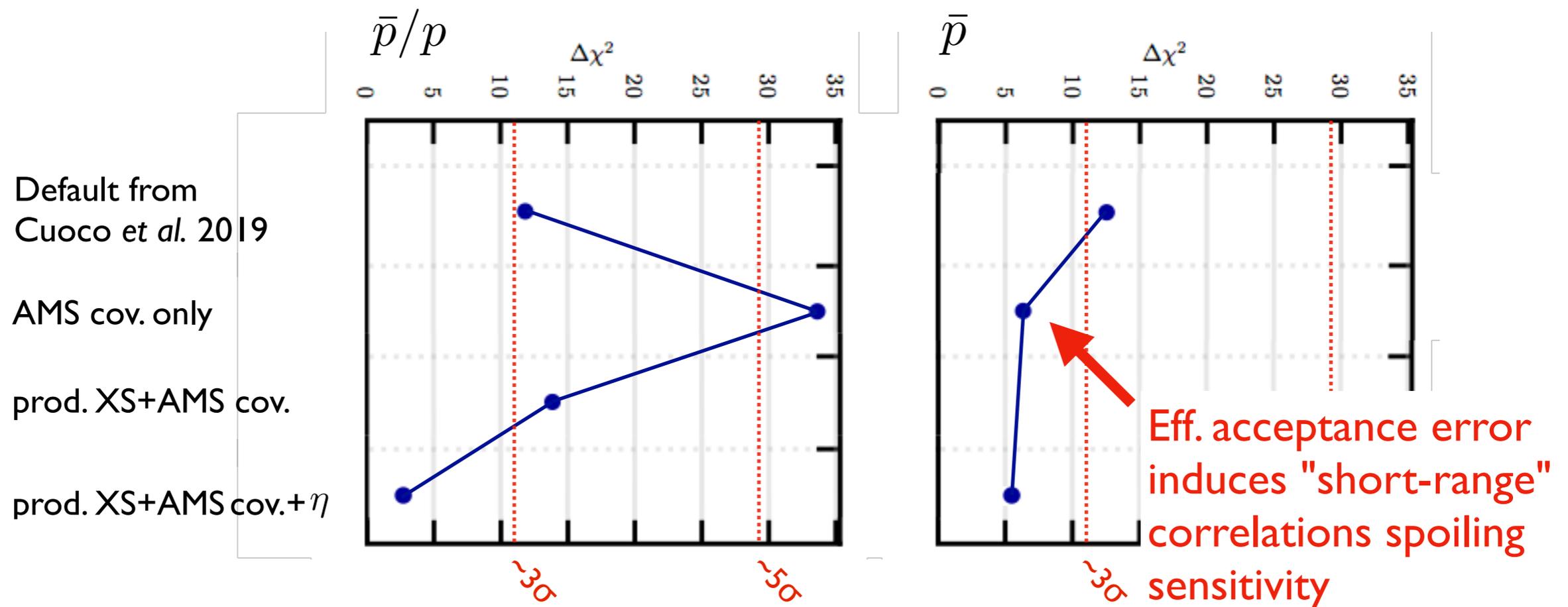


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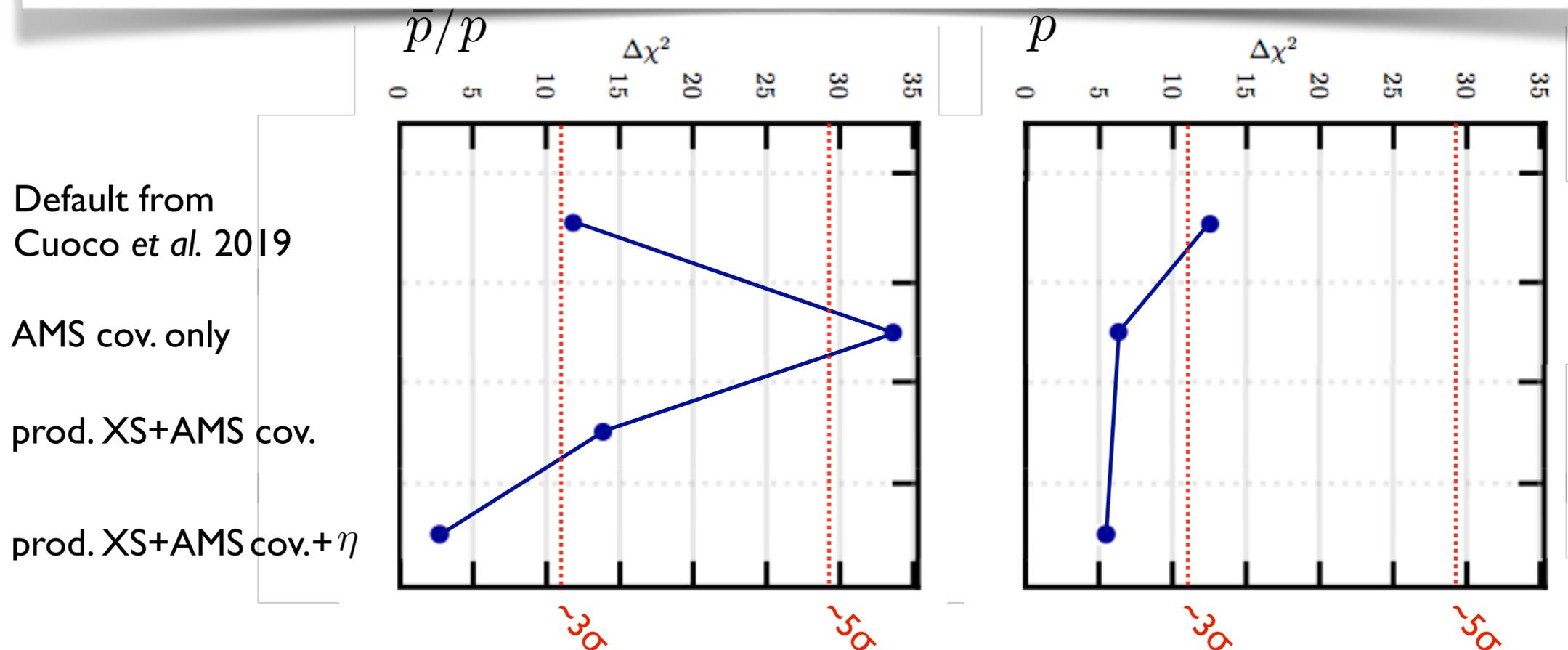


Take-home messages:

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

[see e.g. Korsmeier, Cuoco 2103.09824]

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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 data: Potentially large effect
- Computation of absorption XS error \Rightarrow full covariance
- Knowledge of correlations vital to fully exploit precision
- Signal not robust – decisive: low-rigidity diffusion model
- Uncertainties in nuclear XS limiting factor