Models and Measurements of Antiproton Production for Cosmic-Ray Studies

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Indirect Dark Matter Search with (Galactic) Cosmic-Ray Antiprotons

Is a flux consistent with pure production from CR interactions or are additional exotic sources in the Galaxy, like dark-matter annihilation or decay?

Fig. from AMS Days at CERN 2015

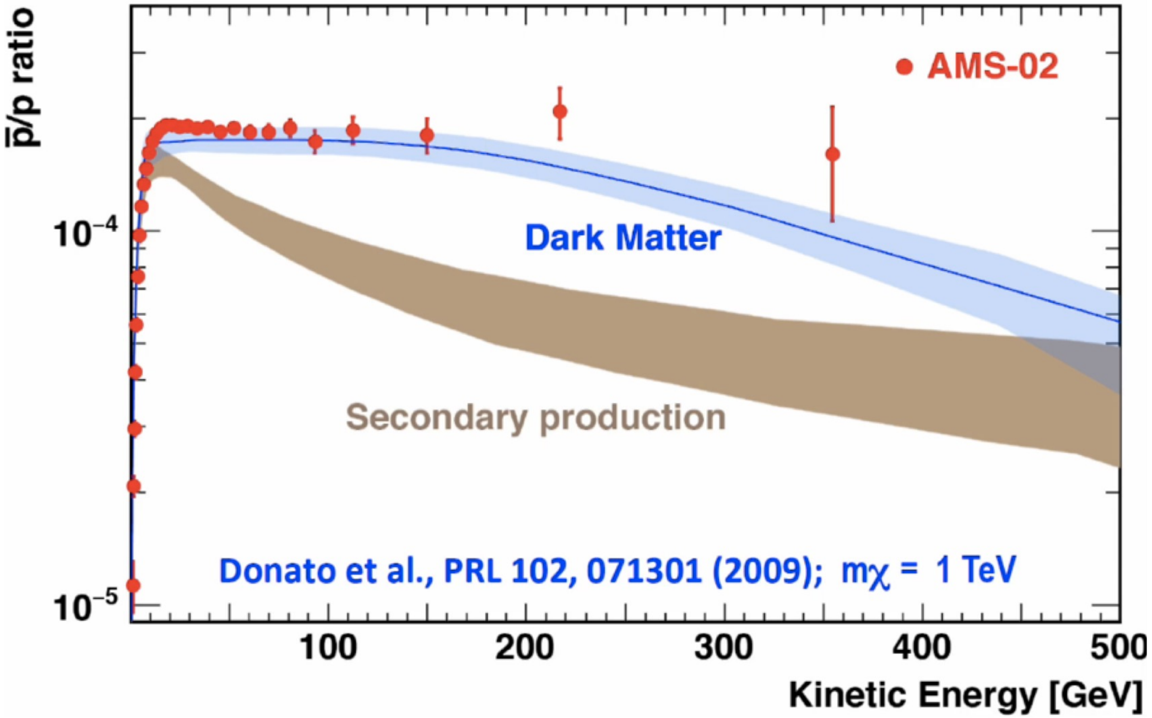
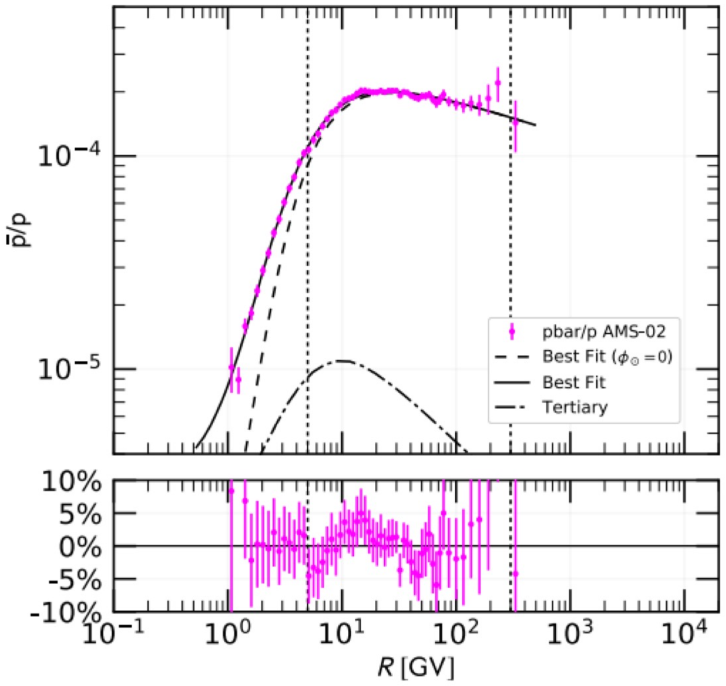


Fig. from J. Heisig arXiv:2012.03956



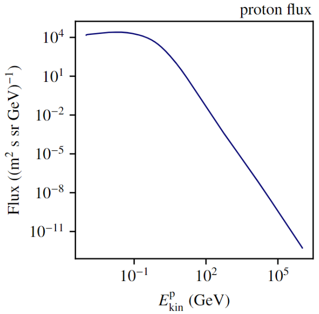
How accurate are our models and where do the differences come from?

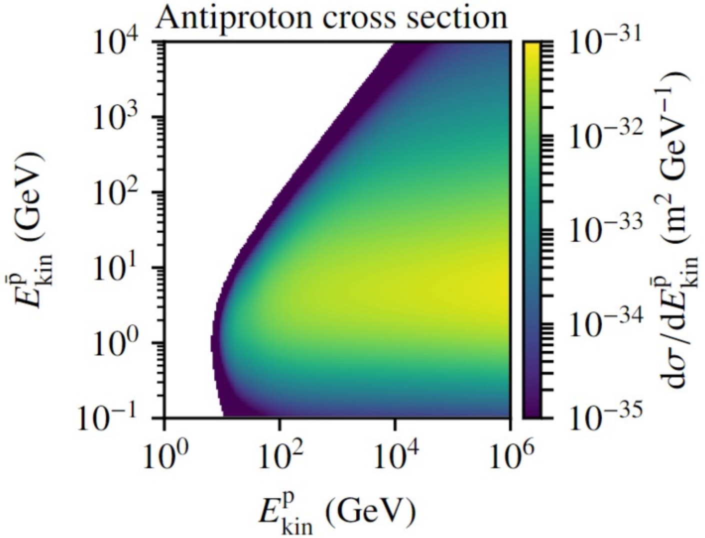
Differences from:

- CR propagation models
- Antiproton-production models

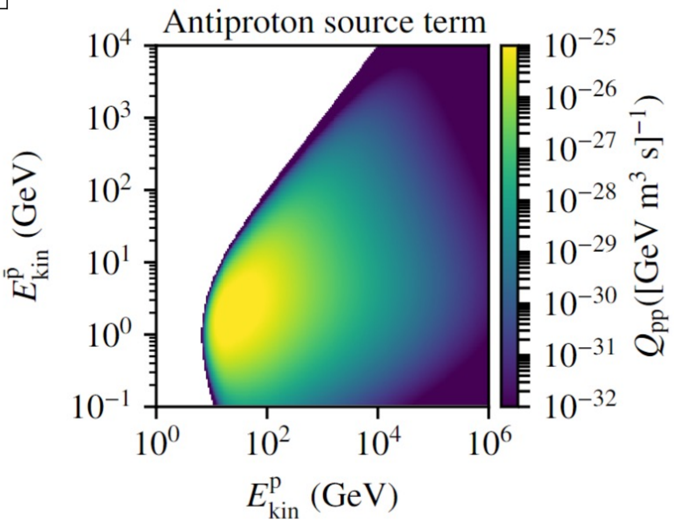
Modeling of Cosmic-Ray Antiprotons

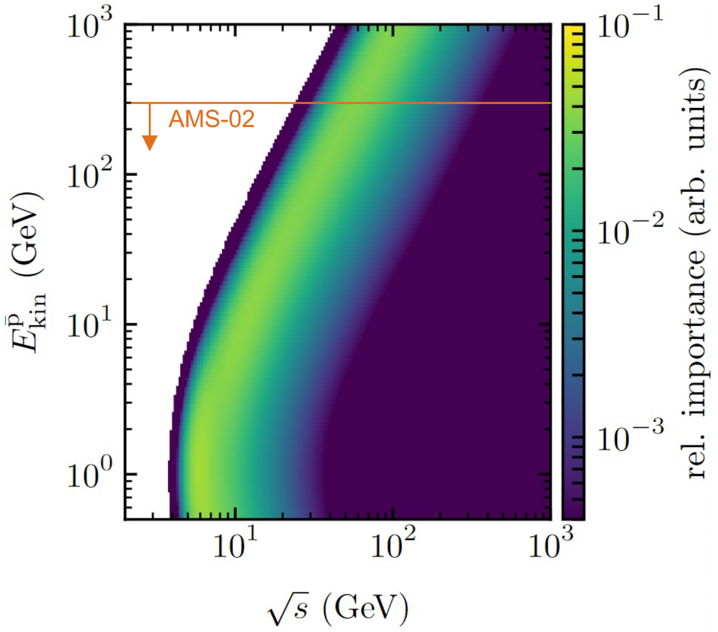
What are the interesting collision energies for production of antiprotons that have energies currently measurable by cosmic-ray experiments?





projectile energy spectra





Most contribution to highest energy bin in AMS-02 data stems from $\sqrt{s}$ = 70 GeV collisions.
($\sqrt{s}$ = 200 GeV contributes 5%, $\sqrt{s}$ = 900 GeV contributes 0.1%, $\sqrt{s} \geq 7$ TeV contributes $\sim 10^{-6}$)

Contributing Antiproton-Production Channels

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

$$p + p \rightarrow \bar{\Lambda} + X \qquad p + p \rightarrow \bar{\Sigma}^- + X$$

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

$$p + He,\ He + p,\ He + He,\ \ldots$$

decreasing availability of data

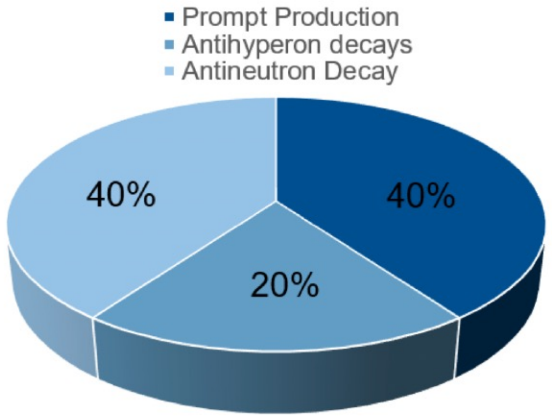
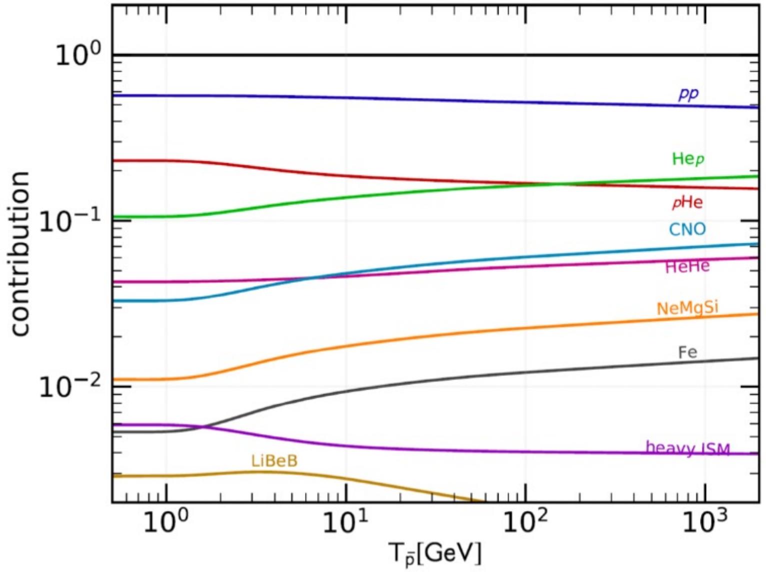


Figure taken from Di Mauro et al., Phys. Rev. D, Vol. 97, 103019 (2018)



We need to model all different contributions accurately in the relevant energy range

Models of Antiproton Production

Different approaches: Multi-purpose event generators vs. phenomenological analytical parametrizations

Event Generators:

- Tuned to a variety of data (not (only) antiproton production)
- Can also be used to describe production of antihyperons and antineutrons
- Different collision systems available in most generators

→ Important for antinuclei studies: Particle correlations in event

$$x_{\mathrm{r}} \equiv E/E_{\max} = \frac{2\sqrt{p_{\mathrm{t}}^2 + m_{\mathrm{p}}^2}}{\sqrt{s}} \cosh y,$$

Analytical Parameterizations:

- Specialized analytical function to describe the invariant production cross section $\sigma_{\mathrm{inv}}^{\bar{p}}(\sqrt{s}, x_R, p_T)$ in pp collisions
- Free model parameters constrained by fitting to experimental data of prompt antiproton production
- Contribution from antihyperons, antineutrons, and heavier collision systems via scaling of the prompt production

→ Better accordance with data expected but requires a suitable analytical function to be found

Analytical Parameterizations for Prompt Antiproton Production (in p-p Collisions)

Two of the most recent parameterizations developed by Di Mauro et al. and Winkler et al.

Di Mauro et al. (*Phy. Rev. D, Vol. 90, 8-085017, 2014*) **(8 free parameters)**

$$\begin{aligned}\sigma_{\rm inv}(\sqrt{s}, x_{\rm R}, p_{\rm T}) &= \sigma_{\rm in}(1-x_{\rm R})^{C_1}\exp(-C_2 x_{\rm R}) \\ &\times \left[C_3\left(\sqrt{s}\right)^{C4}\exp(-C_5 p_{\rm T}) + C_6\left(\sqrt{s}\right)^{C7}\exp\left(-C_8 p_{\rm T}^2\right)\right]\end{aligned}$$

Winkler et al. (*JCAP02(2017)048*) **(6 free parameters)**

$$\sigma_{\rm inv}(\sqrt{s}, x_{\rm R}, p_{\rm T}) = \sigma_{\rm in} R\, C_1 (1-x_{\rm R})^{C_2}\left[1+\frac{X}{\rm GeV}(m_T - m_p)\right]^{-\frac{1}{C_3 X}}$$

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

$$X = C_4 \log^2\left(\frac{\sqrt{s}}{4m_p}\right)$$

Tested Event Generators

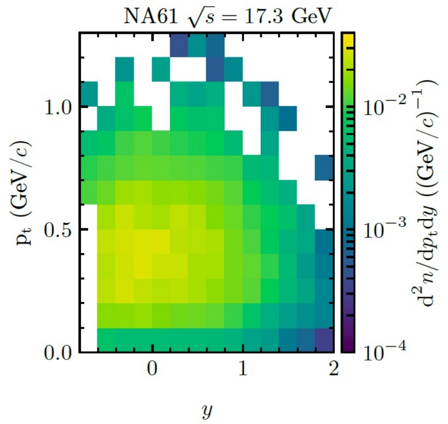
- **EPOS-LHC** (in CRMC) – found by Shukla et al. to be most compatible generator in CRMC
- **EPOS-3**
- **Pythia 8.2.44** (Monash tune) – often used for antinuclei studies
- **GiBUU** (Pythia 6 + add. final state transport) – add. focus on low collision energies

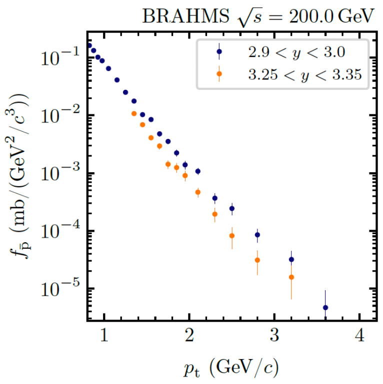
Remark: *Of course very incomplete list, many potentially better candidates not tested …*

(Selection) of Experimental Data on Antiproton Production in p-p Collisions

- Compare antiproton-production models (parameterizations and event generators) to experimental data between $\sqrt{s} = 6$ GeV and $\sqrt{s} = 900$ GeV
- For datasets without separation of antihyperon contribution, we subtract the contribution similar to Winkler et al. JCAP02(2017)048 (assumption: same spectrum from prompt $\bar{\mathrm{p}}$ and from weak decays)
- ~600 data points, 80% below $\sqrt{s} = 20$ GeV

experiment	$\sqrt{s}$ GeV	contribution from antihyperons	phase-space coverage (%)
Dekkers et al. [193]	6.1	included	9.0
	6.7		6.3
NA61 [194]	7.7	excluded	99.6
	8.8		99.3
	12.3		98.8
	17.3		98.0
NA49 [195]	17.3	excluded	98.7
PHENIX [196]	62.4	included†	12.3
	200.0		13.5
BRAHMS [197]	200.0	included	0.2
ALICE [198]	900.0	excluded	11.3





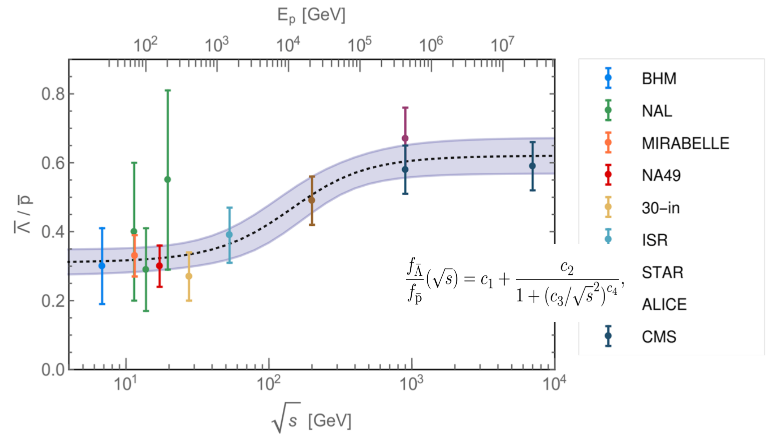


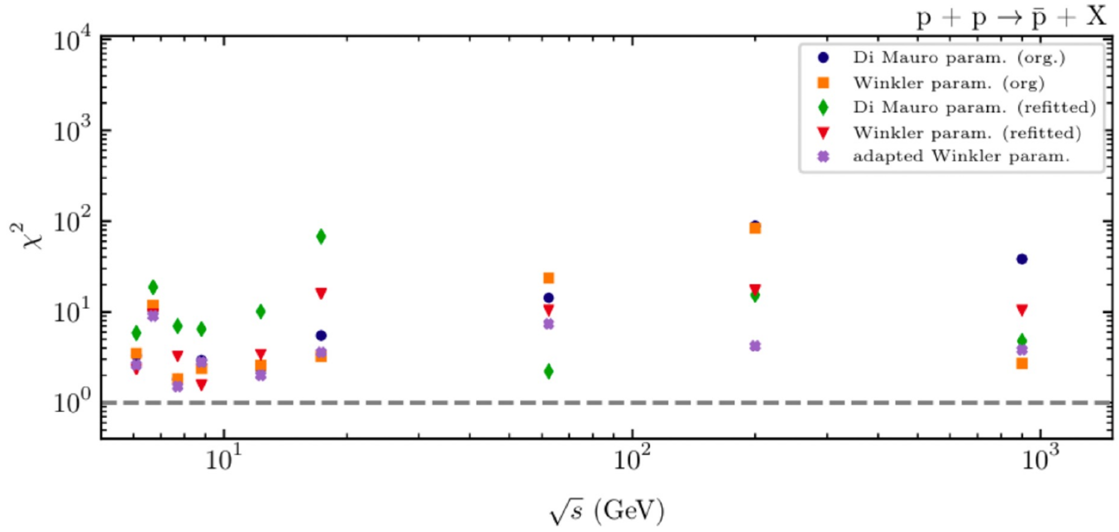
Figure from M. Winkler JCAP02(2017)048

Comparison of Models with Prompt Antiproton Production

Analytical Parameterizations

- Compare original parameterizations and re-fitted parameterizations using all datasets
- Re-fitting yields quite different model parameters → systematic deviations

Metric for quantifying deviations: $\chi^2 \equiv \frac{1}{n.d.f.} \sum_n \frac{f^i_{mod} - f^i_{data}}{\sigma^i_{data}}$

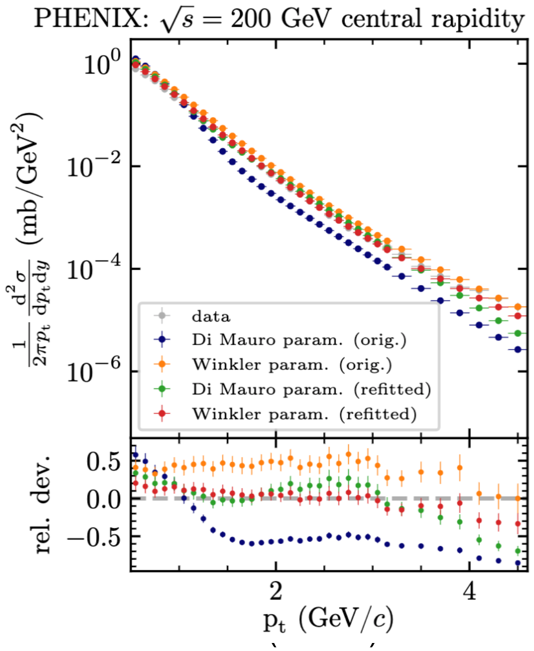


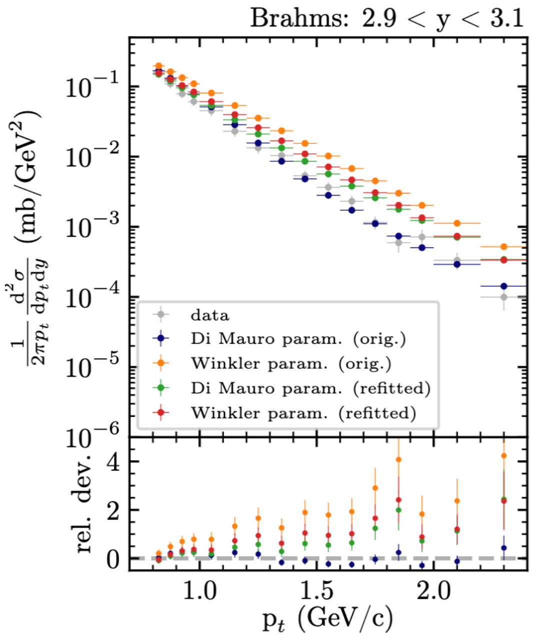
Comparison of Models with Prompt Antiproton Production

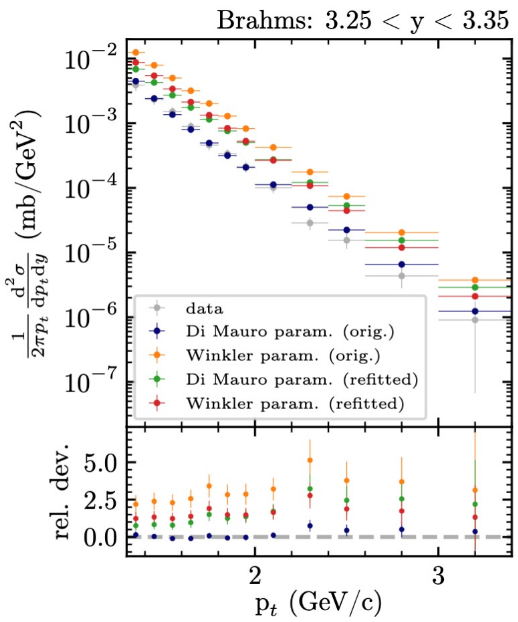
Analytical Parameterizations

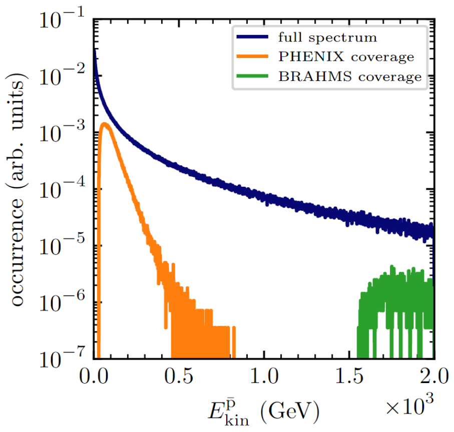
- Rapidity dependence of production mainly determined by low-energy collision data (large phase space coverage and many datapoints)
- Both parameterizations assume collision-energy independent rapiditiy dependence
  → no sufficient simultaneous description of data with different rapidities at small and large $\sqrt{s}$

Increasing rapidity →







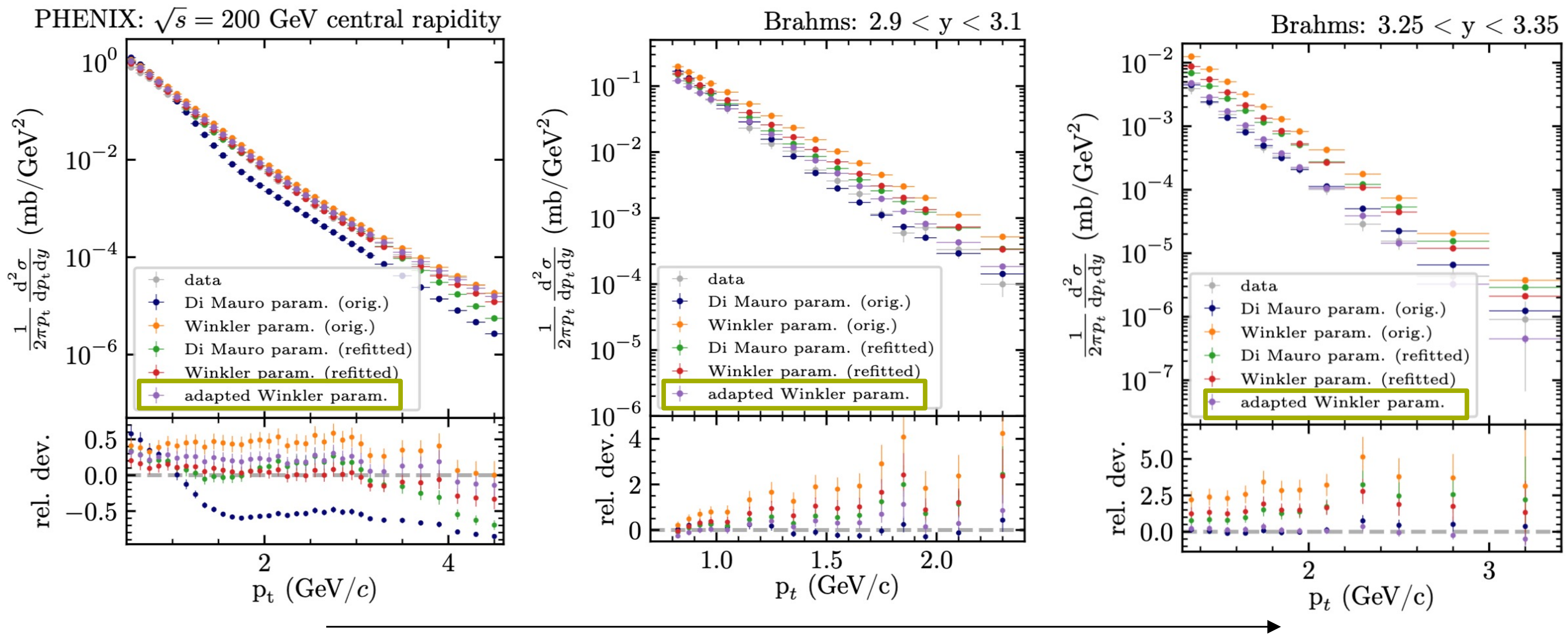


Comparison of Models with Prompt Antiproton Production

(Experimental) Approach

- Adding of an explicit $\sqrt{s}$ dependence of the x_r distribution, e.g. in Winkler model, significantly improves accordance with data:

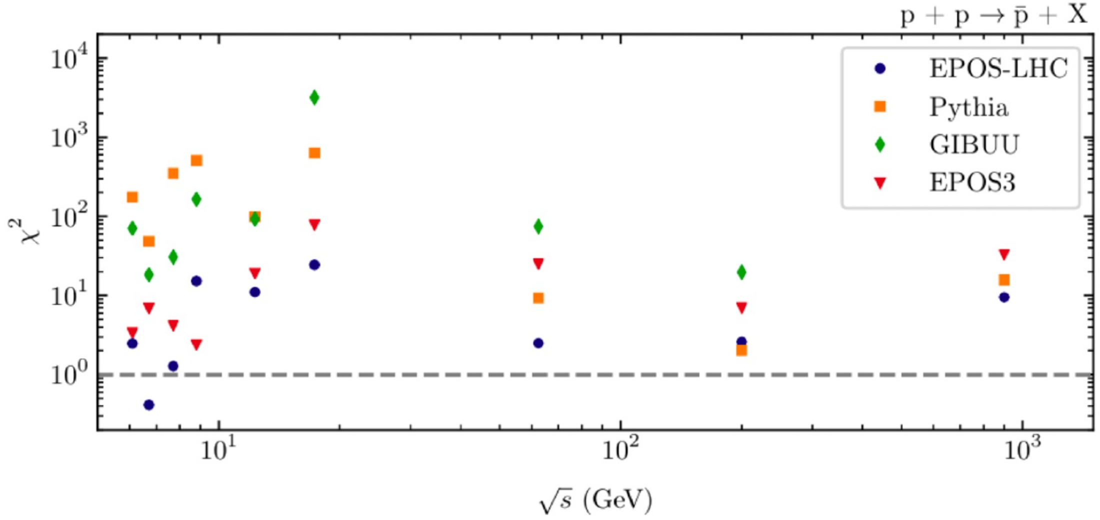
$$(1-x_\mathrm{r})^{C_2} \rightarrow (1-x_\mathrm{r})^{C_2\left(1+C_7 \log^2 \frac{\sqrt{s}}{4m_\mathrm{p}}\right)}$$

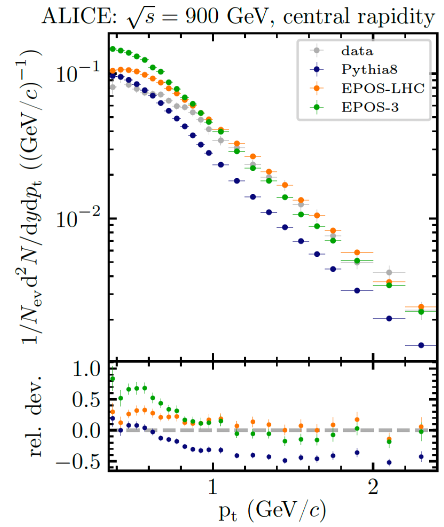


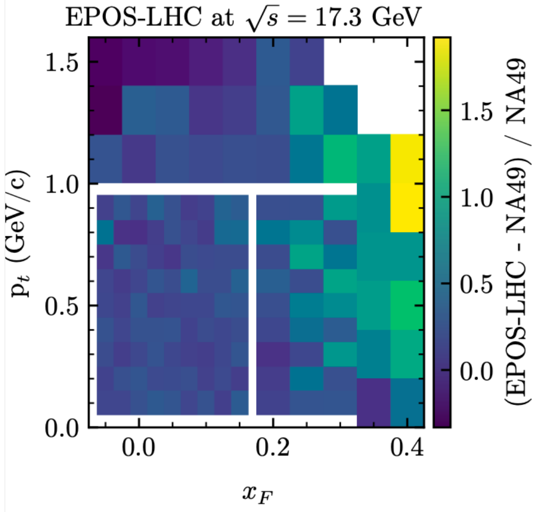
Comparison of Models with Prompt Antiproton Production

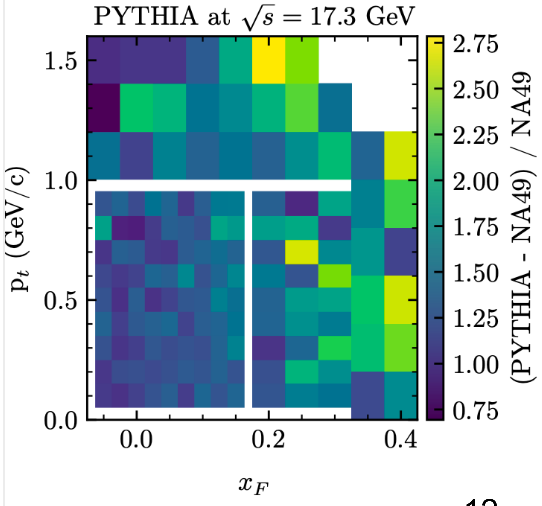
Event Generators

- Overproduce prompt antiprotons, especially at low $\sqrt{s}$
- EPOS-LHC has least deviations overall
- Complete comparison under https://mediatum.ub.tum.de/1659625









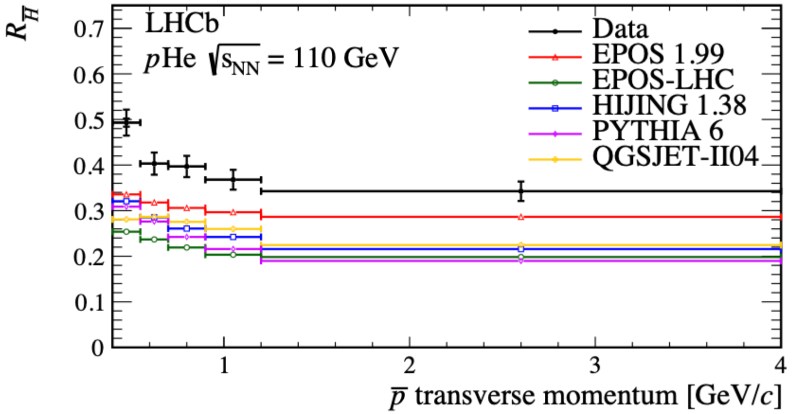
Neither the analytical parameterizations nor the event generators reproduce accurately the measurements
→ Systematic deviations of predicted cosmic-ray antiproton flux

Antiproton Production from Weak Decays

Antihyperons

- Production at all relevant collision energies to be checked as well
- Similar momentum spectrum of prompt $\bar{p}$ and from decays doubtful

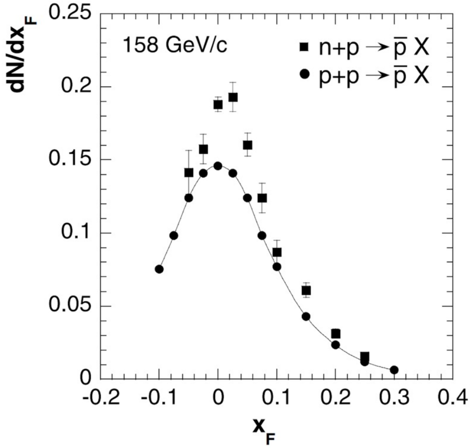
Figure from LHCb, Eur. Phys. J. C (2023) 83:543

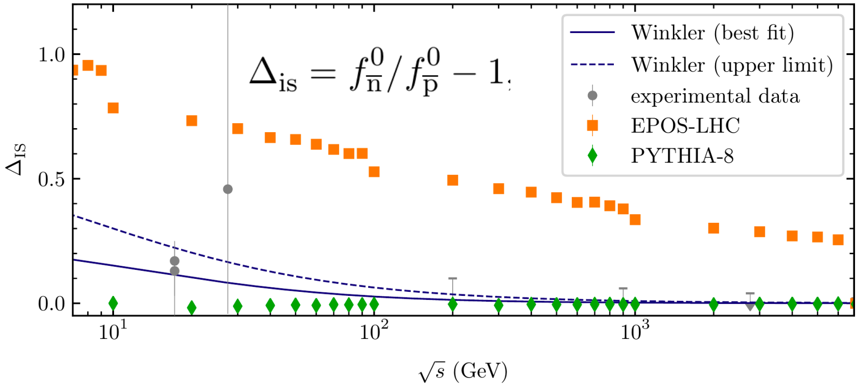


Antineutrons

- Assuming isospin symmetry → equal production
- Isospin asymetric production possible at low collision energies
- Different implementations in event generators (but no tuning)

Figure from NA49, Acta Phys. Hun. Ser. A 17(2003) 369-386



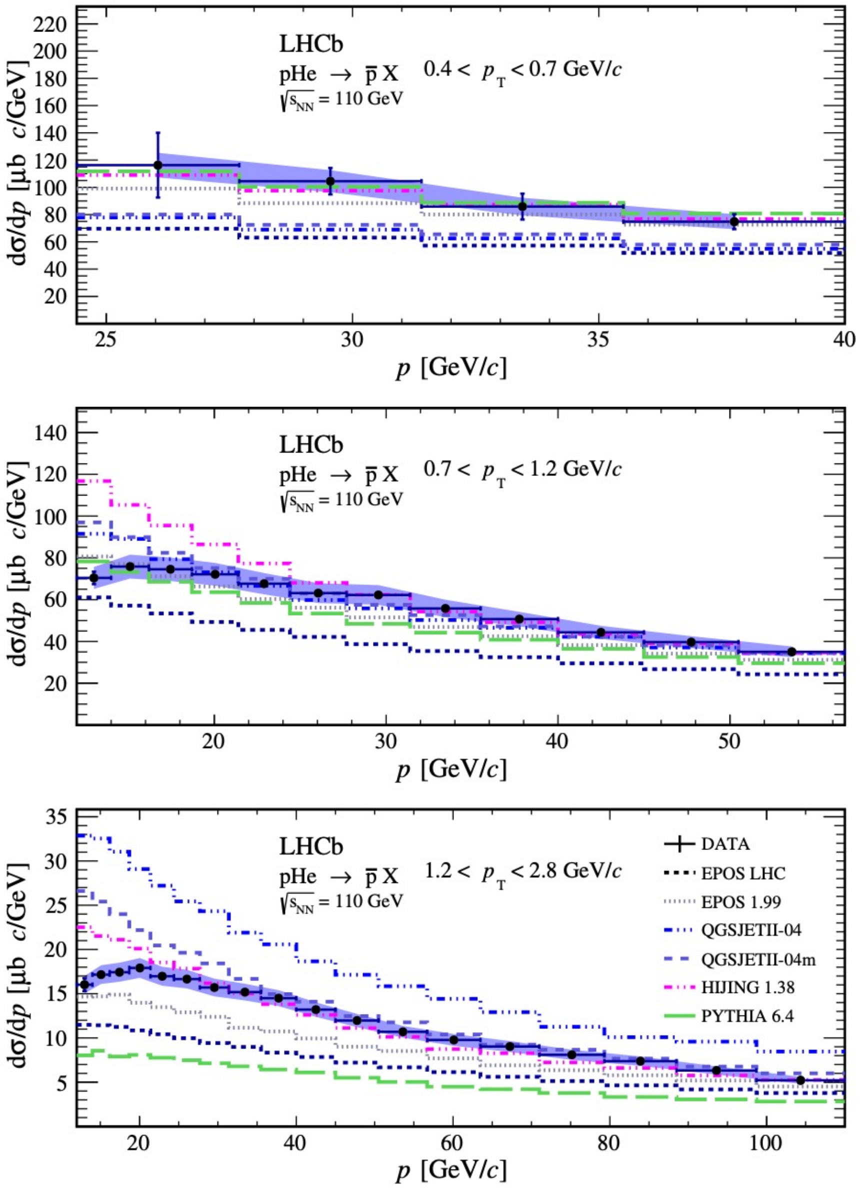


Antiprotons in Light-Ion Collisions

- Experimental data for collisions relevant to CR physics rare (p-He, He-p, He-He)

- Only existing data: LHCb $\sqrt{s} = 110$ GeV p-He
  - Deviations dominated by underlying $\sigma_{pp}^{\bar{p}}$ (e.g. for EPOS-LHC)

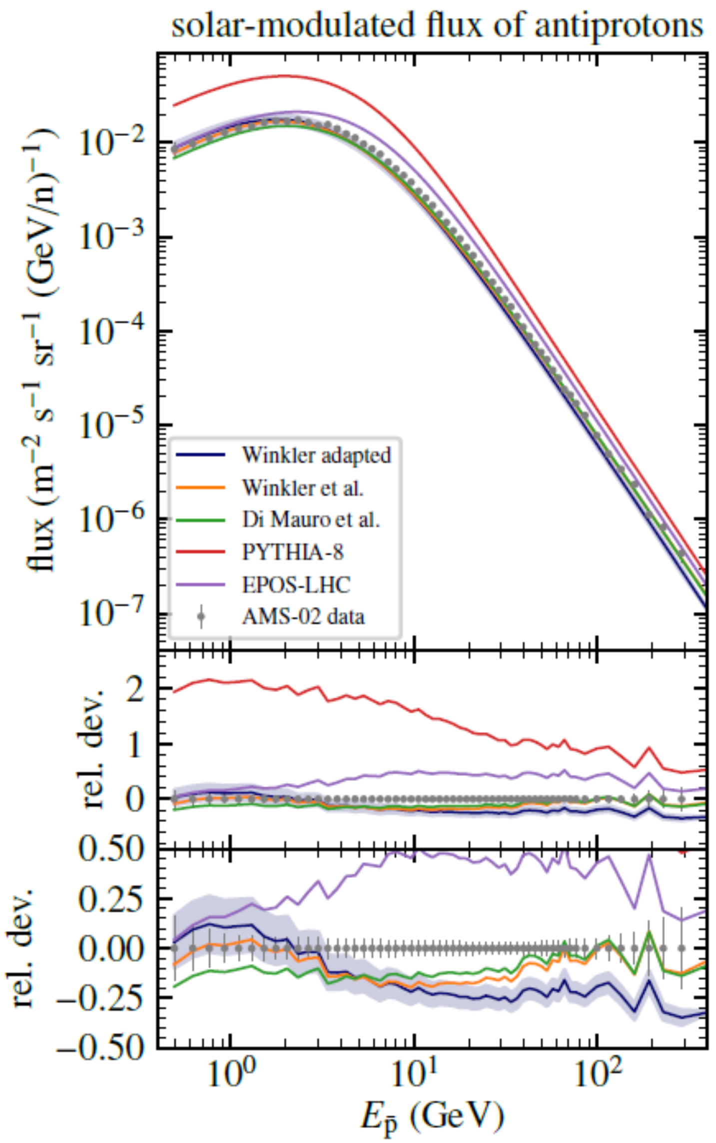
LHCb, Phys. Rev. Lett. 121, 222001



Conclusion and Required Improvements

- No tested model can reproduce accurately antiproton production for collisions relevant for cosmic-ray antiproton production

- Large differences in predicted CR antiproton flux for different production models



Required from modeling:

Tuning on antiproton data is required for reliable flux prediction of cosmic-ray antiprotons

Required from experiments:

Larger rapidity coverage of the data, especially for higher collision energies to constrain collision-energy dependence of rapidity distribution

something missing?

Both: improve also models of antihyperon and antineutron production (e.g. potential isospin asymetric production)

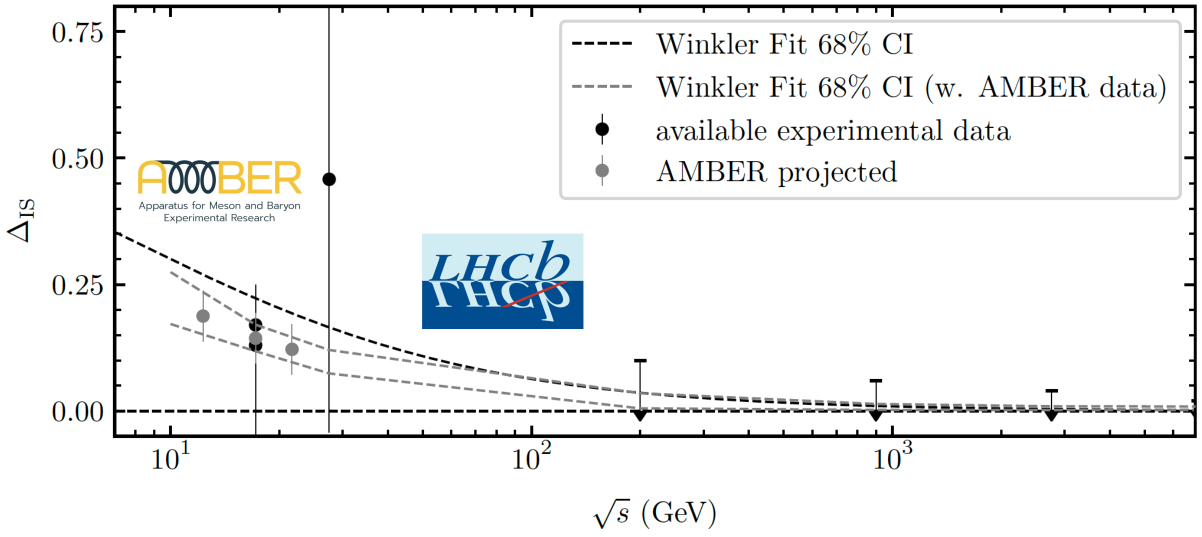
Upcoming Experimental Data

Under analysis

- AMBER p-He $\sqrt{s_{NN}} = [10.7 - 21.7]$ GeV
- LHCb p-He $\sqrt{s_{NN}} = 86$ GeV

Upcoming data taking

- LHCb SMOG 2: p-p, p-D $\sqrt{s_{NN}} = [29 - 110]$ GeV
- AMBER p-p, p-D $\sqrt{s} = [10.7 - 21.7]$ GeV



New data on p-p and investigation of possible isospin asymetry in antiproton and antineutron production using p-p, p-D, p-He

Thank you for your attention!