Deuteron and antideuteron production simulations in cosmic-ray interactions

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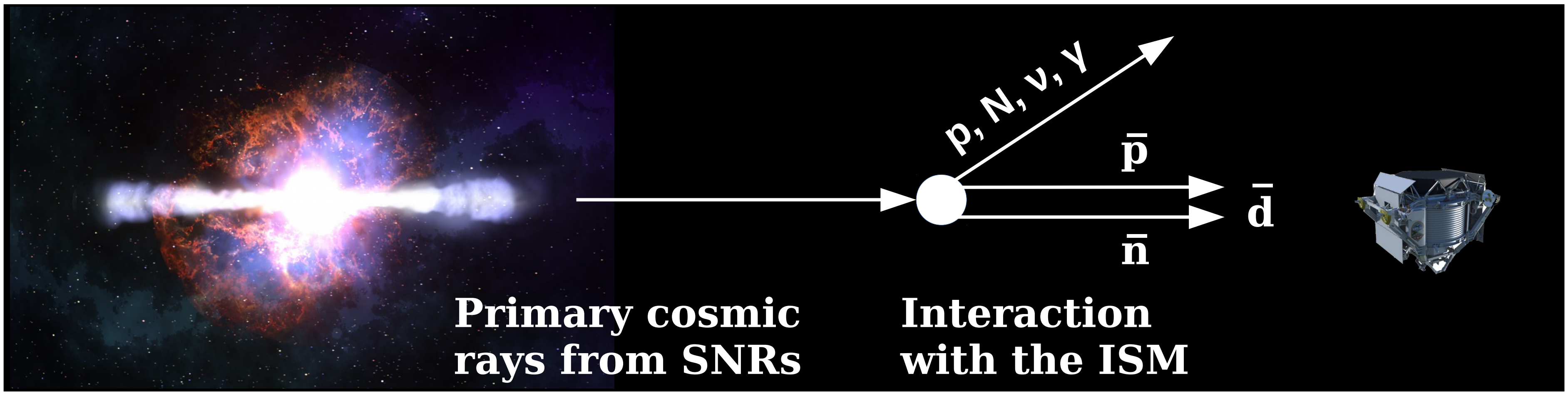
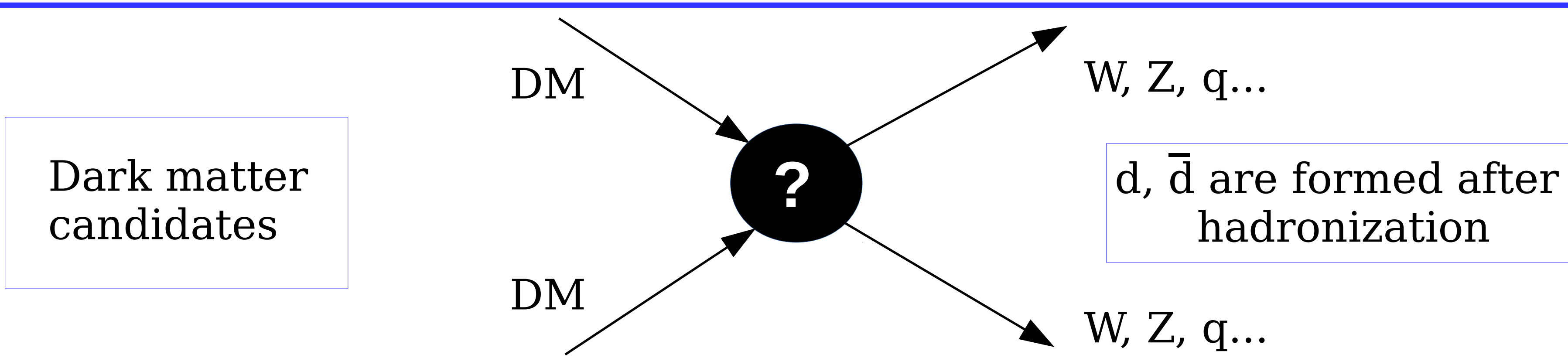
Indirect search for dark matter

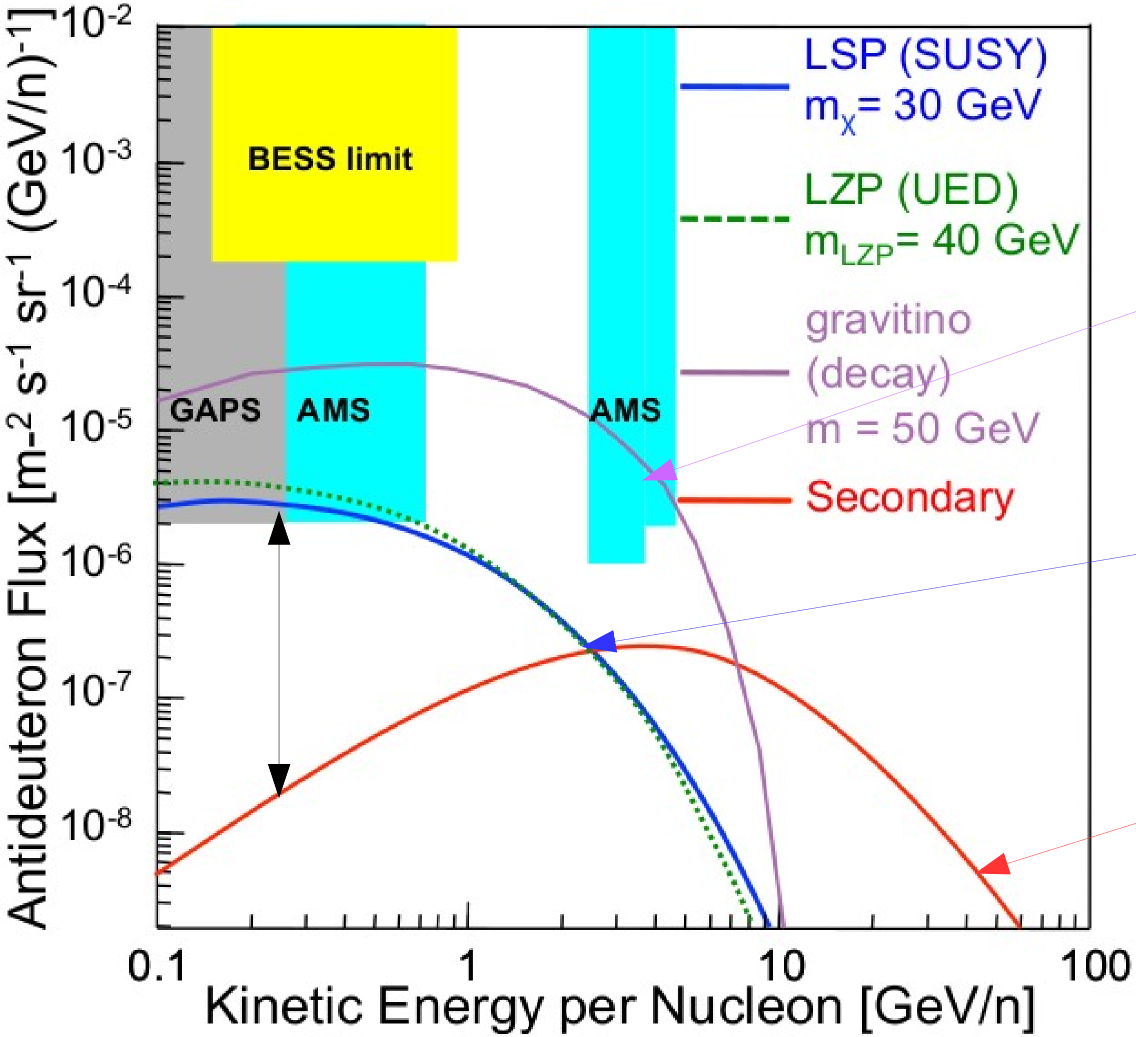
Expected antideuteron production in cosmic-ray interactions



Hypothetical antideuteron cosmic-rays from dark matter



Indirect search for dark matter



Examples of antideuteron signals from dark matter candidates interactions.

Late decays of unstable gravitinos

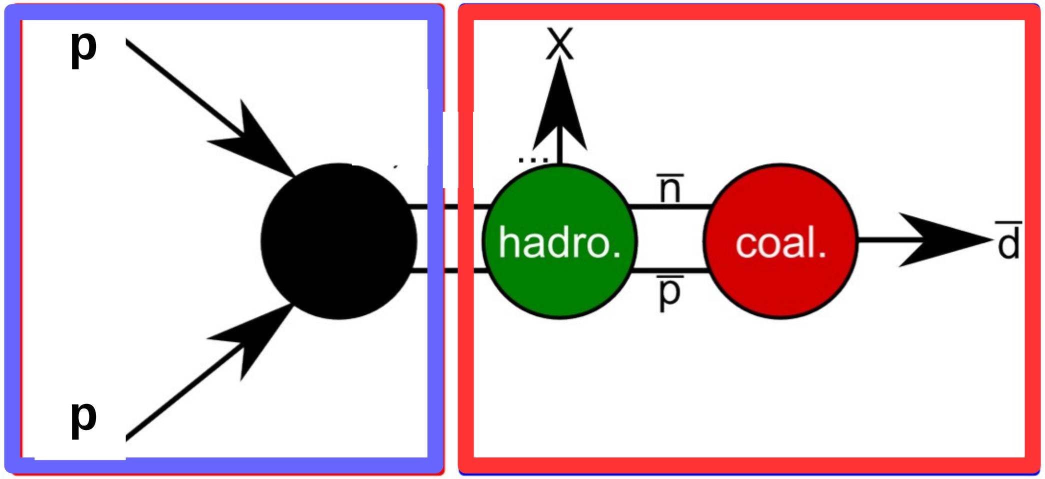
Neutralino:
SUSY lightest supersymetric particle, decay into bb

Astrophysical background:
Cosmic-ray collisions with the interstellar medium

Antideuterons are an important unexplored indirect detection technique.

T. Aramaki et al., Phys. Rept. 618, 1 (2016), arXiv:1505.07785 [hep-ph].

Antideuteron formation model



p+p, p+He, He+p, pbar+p collisions

Coalescence

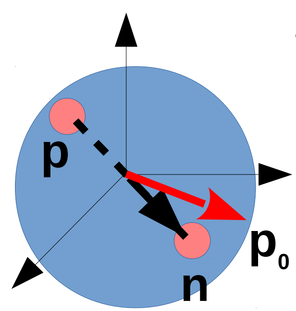
Coalescence Model

Deuterons and antideuterons can be formed by a pair p-n or $\bar{p}$-$\bar{n}$ close in phase space.

$$\gamma_d \frac{d^3N_d}{dp_d^3} = \frac{4\pi}{3} p_0^3 \left(\gamma_p \frac{d^3N_p}{dp_p^3}\right) \left(\gamma_n \frac{d^3N_n}{dp_n^3}\right)$$

$\mathbf{p_0}$ is extracted from this comparison

Collisions are simulated with **Monte Carlo** generators



Afterburner

d and $\bar{d}$ are created from the pairs **event by event**

The results from simulations are compared to data

Generation scheme

Collisions simulations

Monte Carlo Generators

CRMC (Cosmic Ray Monte Carlo) :

- **EPOS-LHC**
- **QGSJETII-04**
- **SYBILL 2.1**

- **Pythia8.205**

- **Geant4.10.02.p02**

Nucleons and antinucleons selection

Only nucleons and antinucleons are selected and saved

ROOT macro: NucFilter.C

Deuteron and antideuteron production

We simulate the coalescence process, calculating the difference in momentum of pairs p-n and pbar-nbar.

If the difference is lower than a free parameter p0, then the pair is transformed into a deuteron or antideuteron accordingly

ROOT class: AntiNucGen.cxx AntiNucGen.h

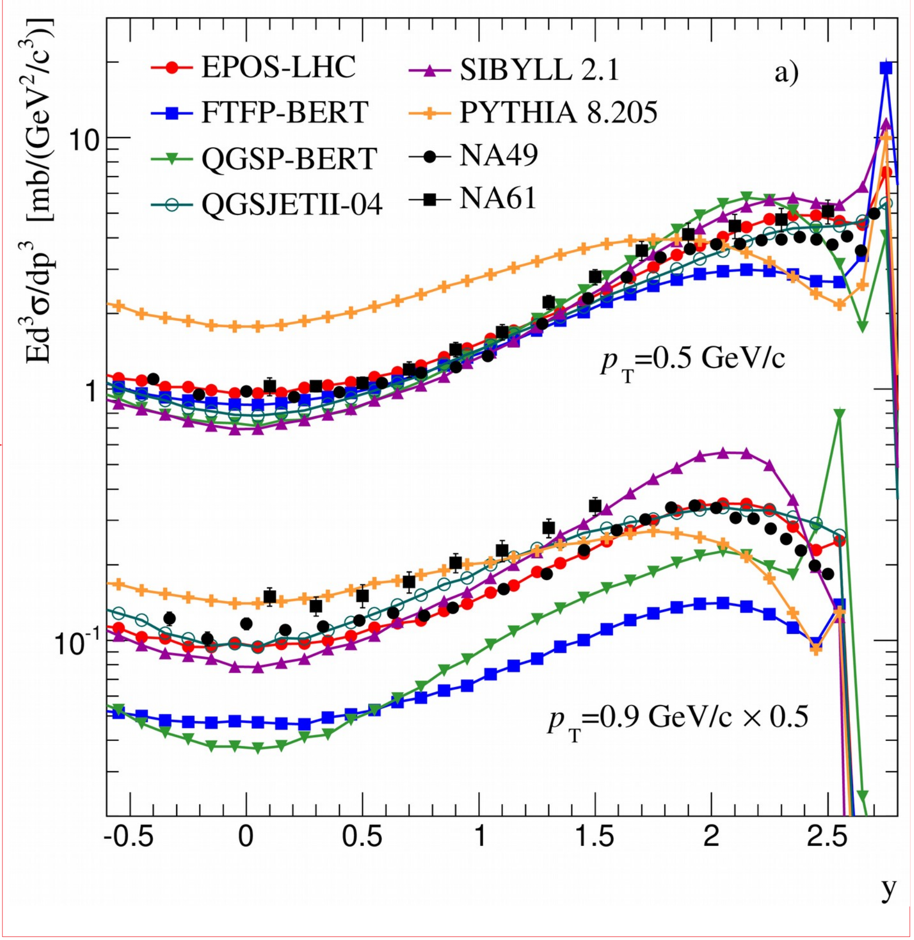
Proton production simulation

- To generate a correct prediction of deuterons using MC, it is necessary to have a proper description of protons.

Experiment or Laboratory	Reference	Collision	Final states	p_{lab} (GeV/c)	$\sqrt{s}$ (GeV)
ITEP[1]	[192]	p+Be	p	10.1	4.5
CERN[1]	[193, 194]	p+p	p, $\bar{p}$	19.2	6.1
		p+Be	p, $\bar{p}$		
CERN[1]	[194]	p+p	p	24	6.8
NA61/SHINE	[195]	p+C	p	31	7.7
	[85]	p+p	p, $\bar{p}$		
NA61/SHINE	[85]	p+p	p, $\bar{p}$	40	8.8
Serpukhov[1]	[196, 197]	p+p	p, $\bar{p}$	70	11.5
	[198]	p+Be	p, $\bar{p}$		
	[199]	p+Al	p, $\bar{p}$		
NA61/SHINE	[85]	p+p	p, $\bar{p}$	80	12.3
CERN-NA49	[82]	p+p	p, $\bar{p}$	158	17.5
	[83]	p+C	p, $\bar{p}$		
CERN-NA61	[85]	p+p	p, $\bar{p}$		
CERN-SPS[1]	[200, 201]	p+Be	p, $\bar{p}$	200	19.4
		p+Al	p, $\bar{p}$		
Fermilab[1]	[202, 203]	p+p	p, $\bar{p}$	300	23.8
		p+Be	p, $\bar{p}$		
Fermilab[1]	[202, 203]	p+p	p, $\bar{p}$	400	27.4
		p+Be	p, $\bar{p}$		
CERN-ISR	[204]	p+p	p, $\bar{p}$	1078	45.0
CERN-ISR	[204]	p+p	p, $\bar{p}$	1498	53.0
CERN-LHCb	[86]	p+He	$\bar{p}$	6.5×10^3	110
CERN-ALICE	[84]	p+p	p, $\bar{p}$	4.3×10^5	900
CERN-ALICE	[84]	p+p	p, $\bar{p}$	2.6×10^7	7000

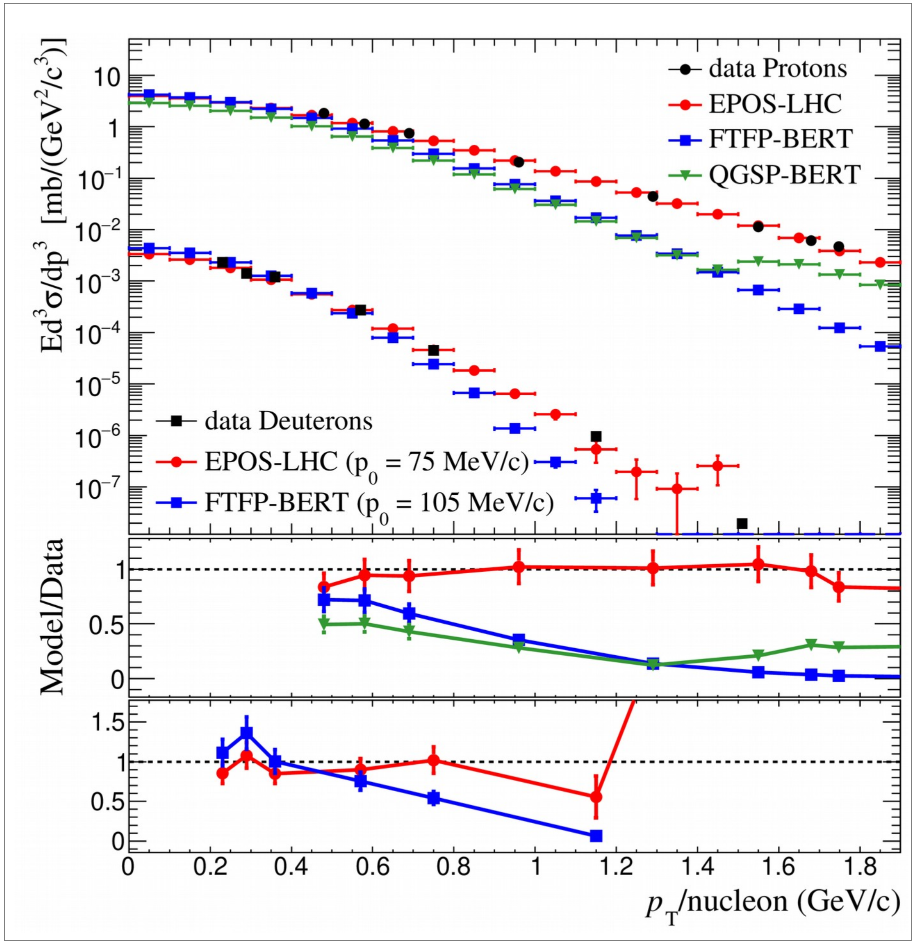
Proton and antiproton data list on p+p and p+A collisions to be compared to simulations. **D. Gomez-Coral et al. Phys. Rev. D 98, 023012 (2018) arXiv:1806.09303 [astro-ph.HE]**

Invariant differential cross section for **protons** in p+p collisions at 158 GeV/c, as function of rapidity



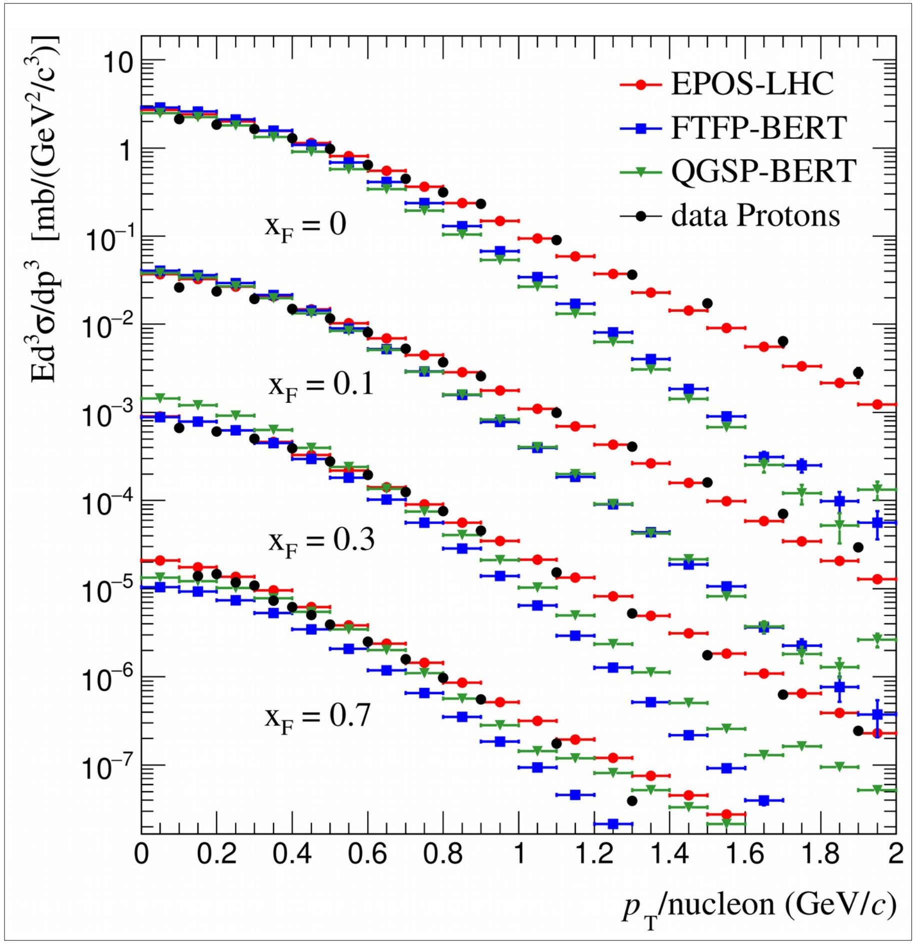
Proton production simulation

p+p at p_{lab} = 70 GeV/c



Invariant differential cross section for **protons** as function of pT. Data from Serpukov.

p+p at p_{lab} = 158 GeV/c



Invariant differential cross section for **protons** as function of pT. Data from NA49.

Antiproton production simulation

- To generate a correct prediction of antideuterons using MC, it is necessary to have a proper description of antiprotons.

Invariant differential cross section for **antiprotons** in p+p collisions at 158 GeV/c, as function of rapidity

Experiment or Laboratory	Reference	Collision	Final states	p_{lab} (GeV/c)	$\sqrt{s}$ (GeV)
ITEP [1]	[192]	p+Be	p	10.1	4.5
CERN [1]	[193, 194]	p+p	p, $\bar{p}$	19.2	6.1
		p+Be	p, $\bar{p}$		
CERN [1]	[194]	p+p	p	24	6.8
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	[85]	p+p	p, $\bar{p}$		
NA61/SHINE	[85]	p+p	p, $\bar{p}$	40	8.8
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		p+Al	p, $\bar{p}$		
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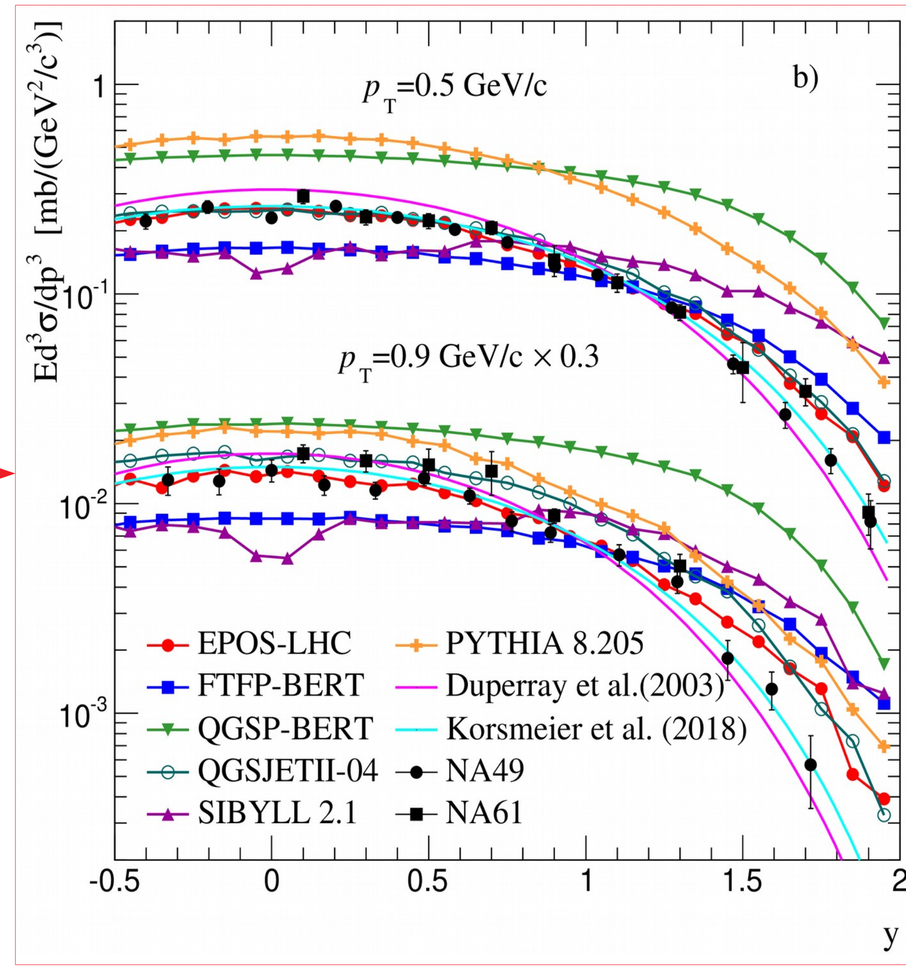
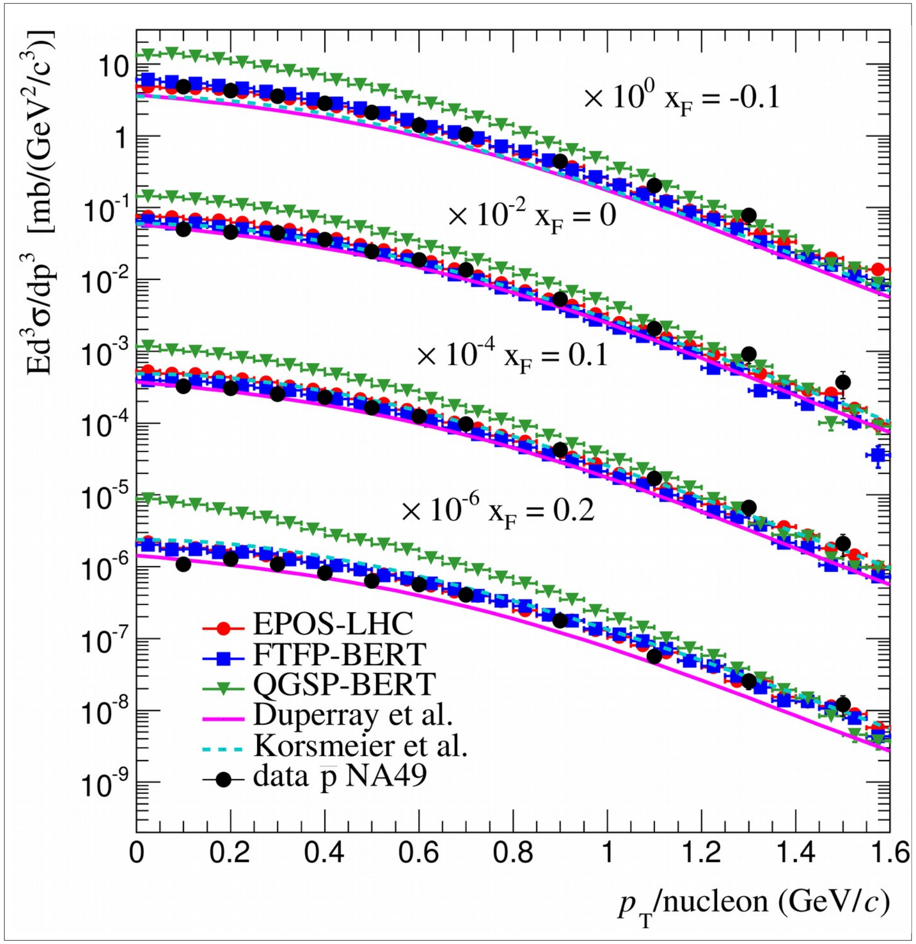


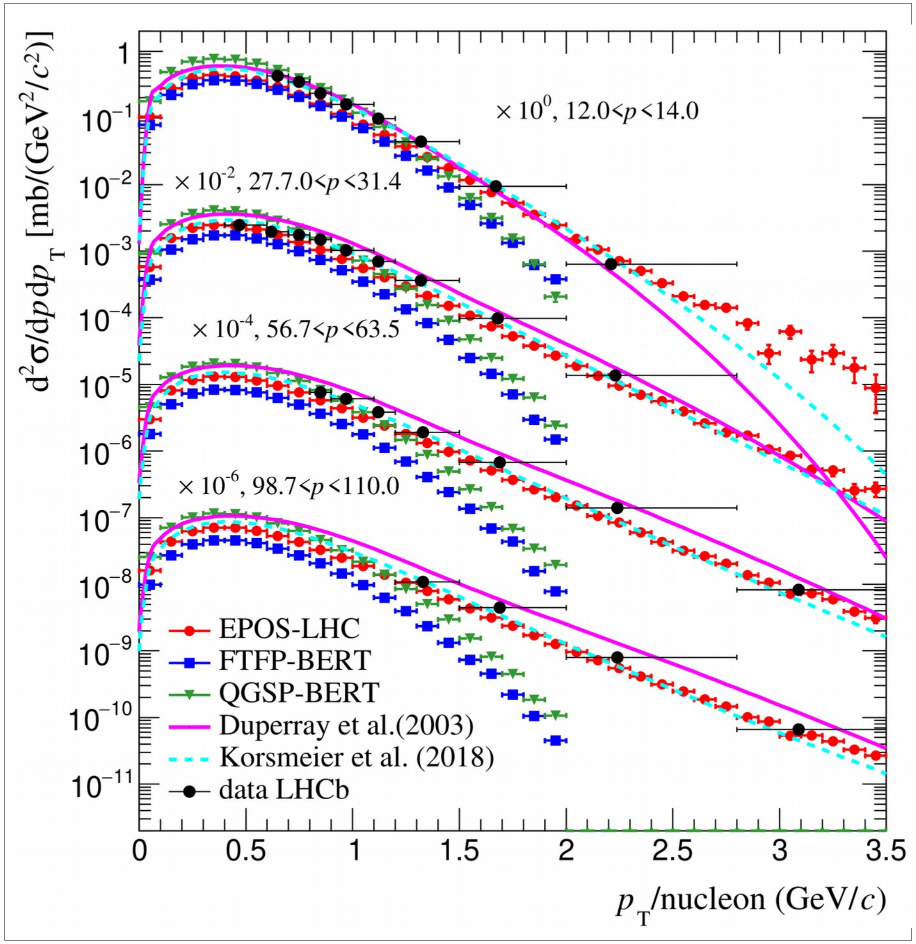
Antiproton production simulation

p+p at p_{lab} = 158 GeV/c



Invariant differential cross section for **antiprotons** as function of pT. Data from NA49.

p+p at √s = 110 GeV/c



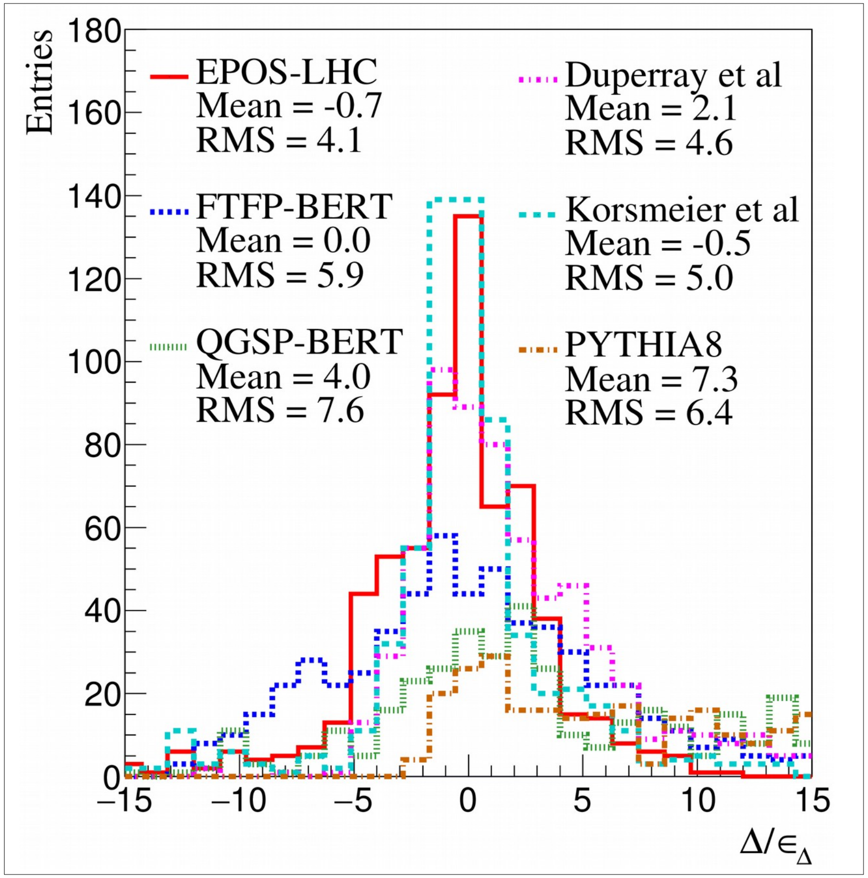
Invariant differential cross section for **antiprotons** as function of pT. Data from LHCb.

(Anti)proton comparison to data

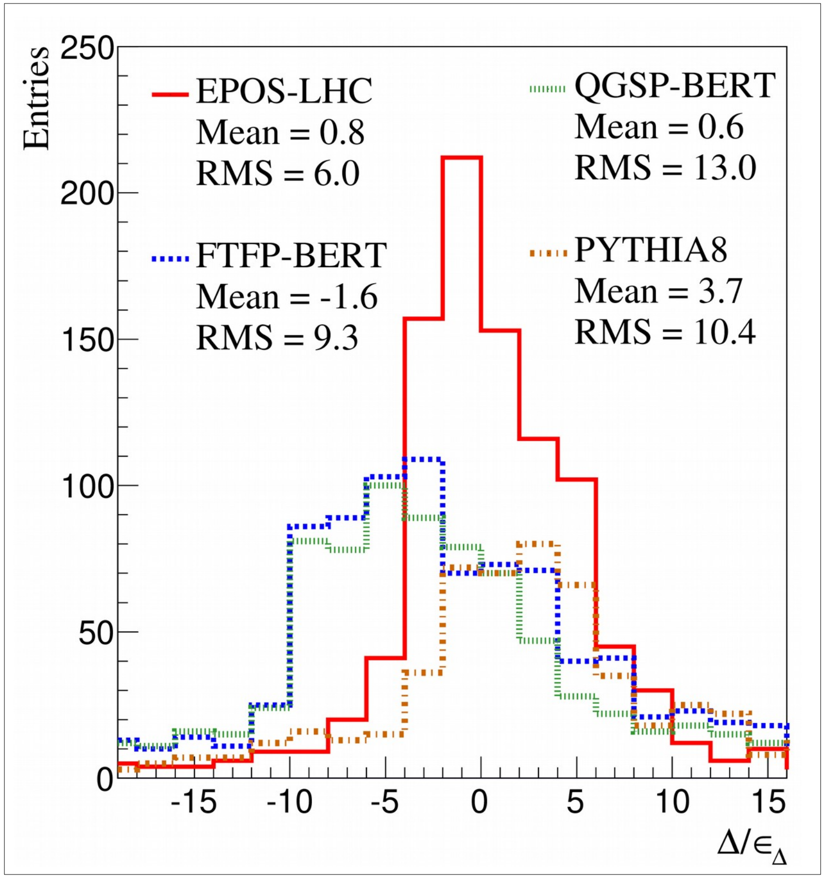
- Simulation is compared to data point by point.
- The most reliable MC model is selected from the comparison to data.

$$\frac{\Delta}{\epsilon_\Delta} = \frac{\left(E\frac{d^3\sigma}{dp^3}^{sim} - E\frac{d^3\sigma}{dp^3}^{data}\right)}{\sqrt{(\epsilon_{sim})^2 + (\epsilon_{data})^2}}$$

antiprotons



protons



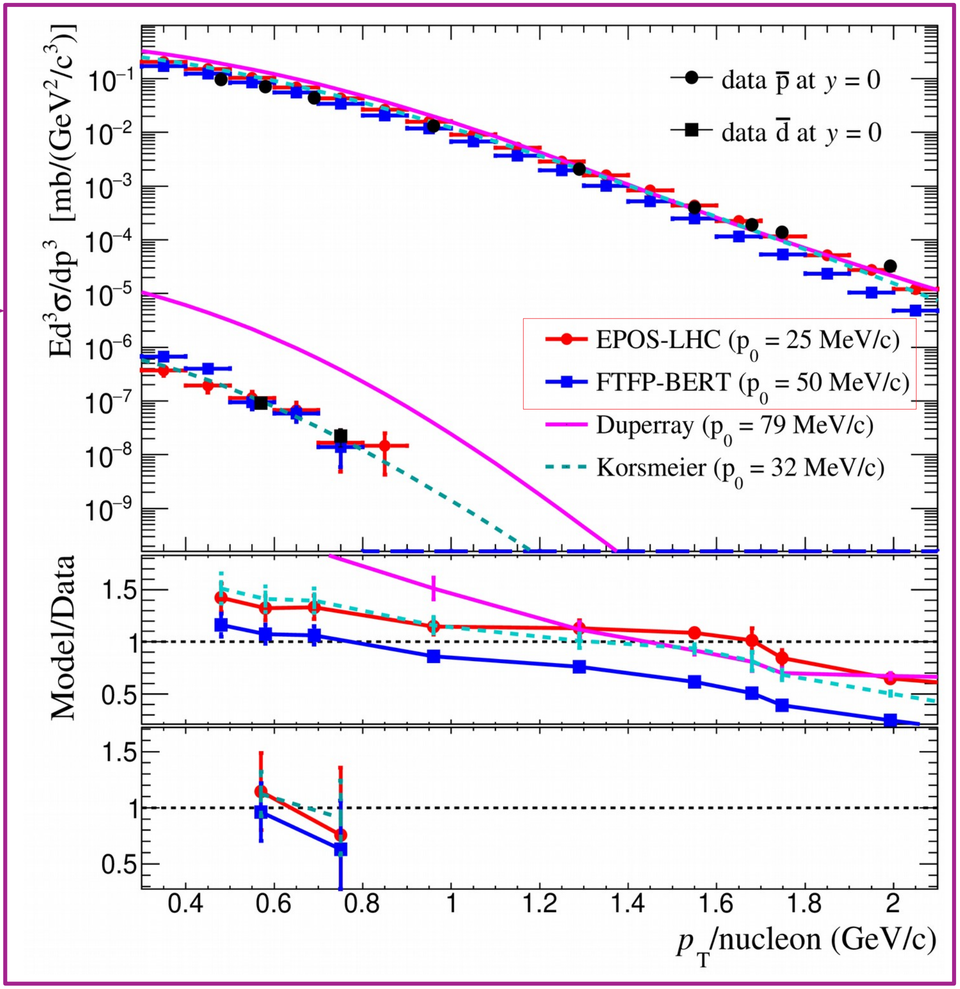
Antideuteron production simulation

- The coalescence momentum (p_0) is determined from the fit of simulations to data.

Experiment or Laboratory	Reference	Collision	p_{lab} (GeV/c)	$\sqrt{s}$ (GeV)	No. of points d	dbar
CERN	[194]	p+p	19	6.15	6	0
CERN	[194]	p+p	24	6.8	4	0
Serpukhov	[198]	p+p	70	11.5	7	2
		p+Be			6	3
CERN-SPS	[200, 205]	p+Be	200	19.4	3	5
		p+Al			3	3
Fermilab	[203]	p+Be	300	23.8	4	1
CERN-ISR	[206, 207, 208]	p+p	1497.8	53	3	8
CERN-ALICE	[155, 209]	p+p	4.3×10^5	900	3	3
CERN-ALICE	[155, 209, 210]	p+p	2.6×10^7	7000	21	20

Deuteron and antideuteron data list on p+p and p+A collisions to be compared to simulations. **D. Gomez-Coral et al. Phys. Rev. D 98, 023012 (2018) arXiv:1806.09303 [astro-ph.HE]**

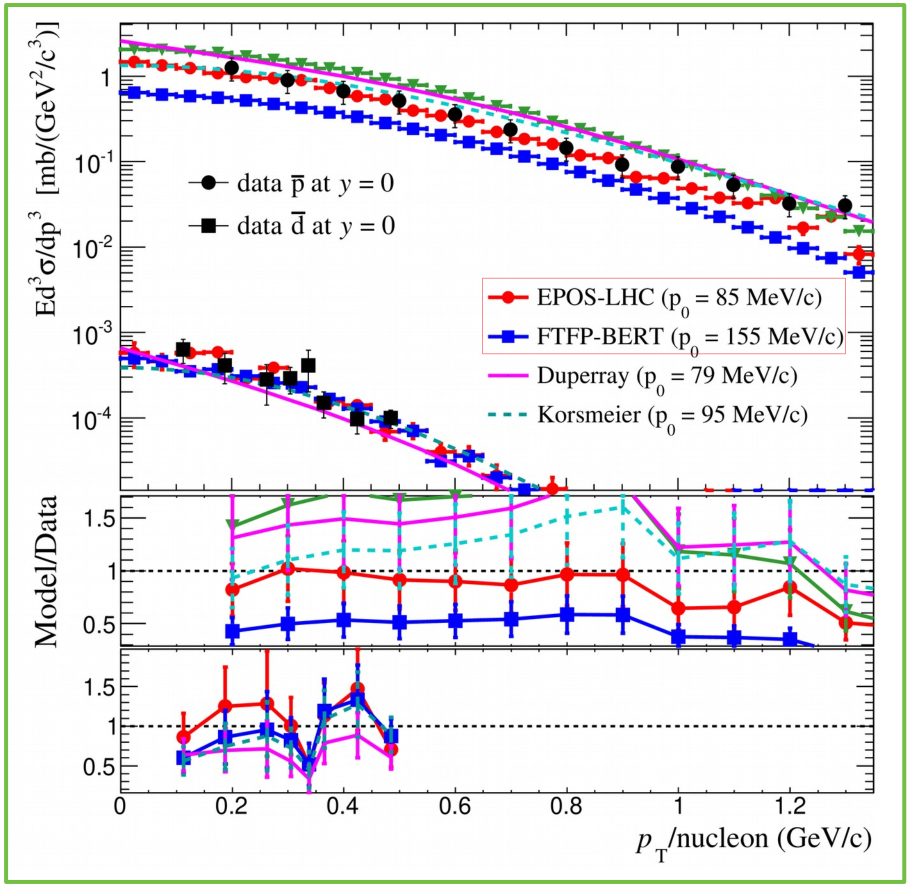
p+p at p_{lab} = 70 GeV/c



Antideuteron invariant differential cross section in p+p collisions at 70 GeV/c, as function of p_T

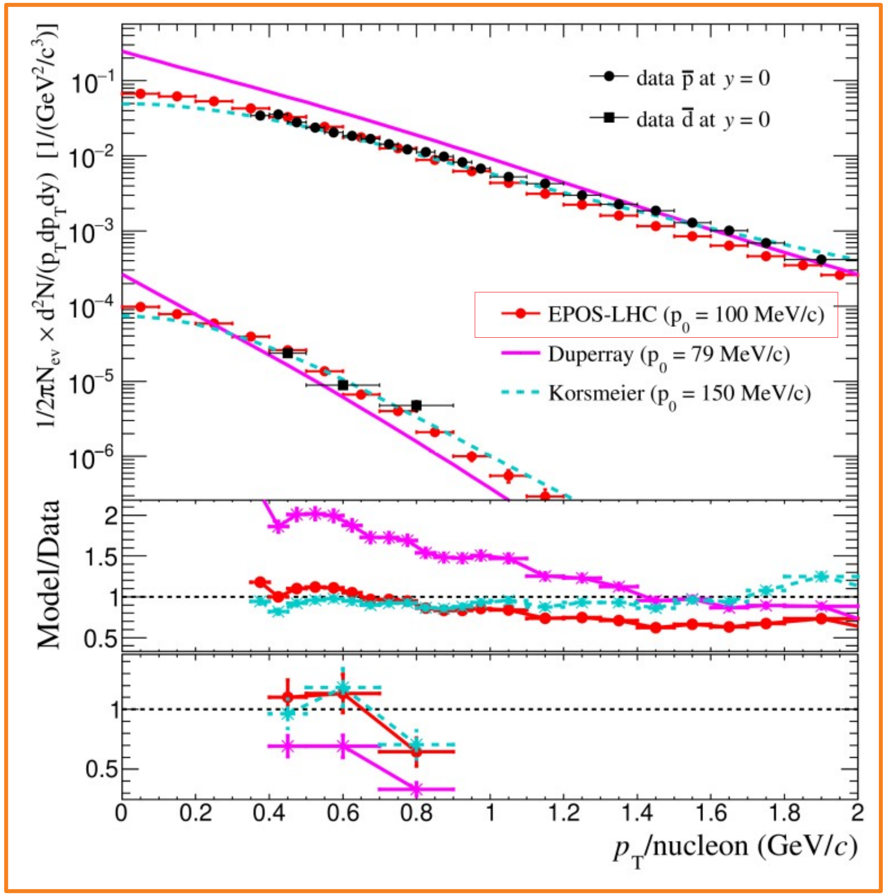
Antideuteron production simulation

p+p at √s = 53 GeV



Antideuteron invariant differential cross section as function of p_T compared to ISR data.

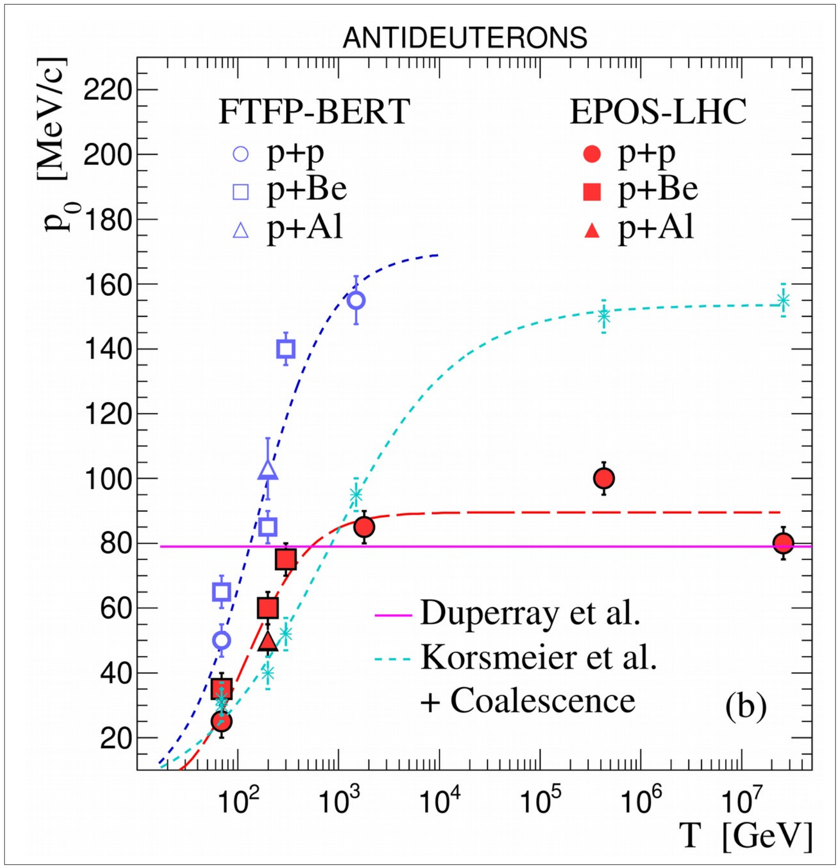
p+p at √s = 900 GeV

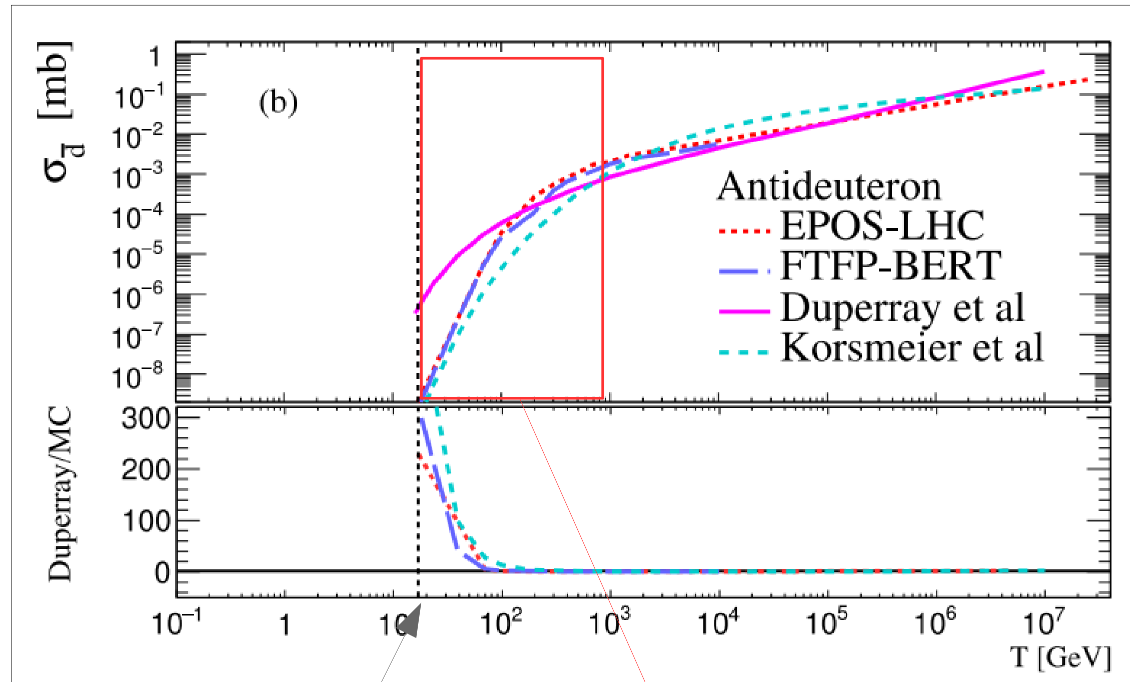


Antideuteron invariant differential cross section as function of p_T compared to ALICE-LHC data.

Antideuteron coalescence momentum (p_0) and cross section

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





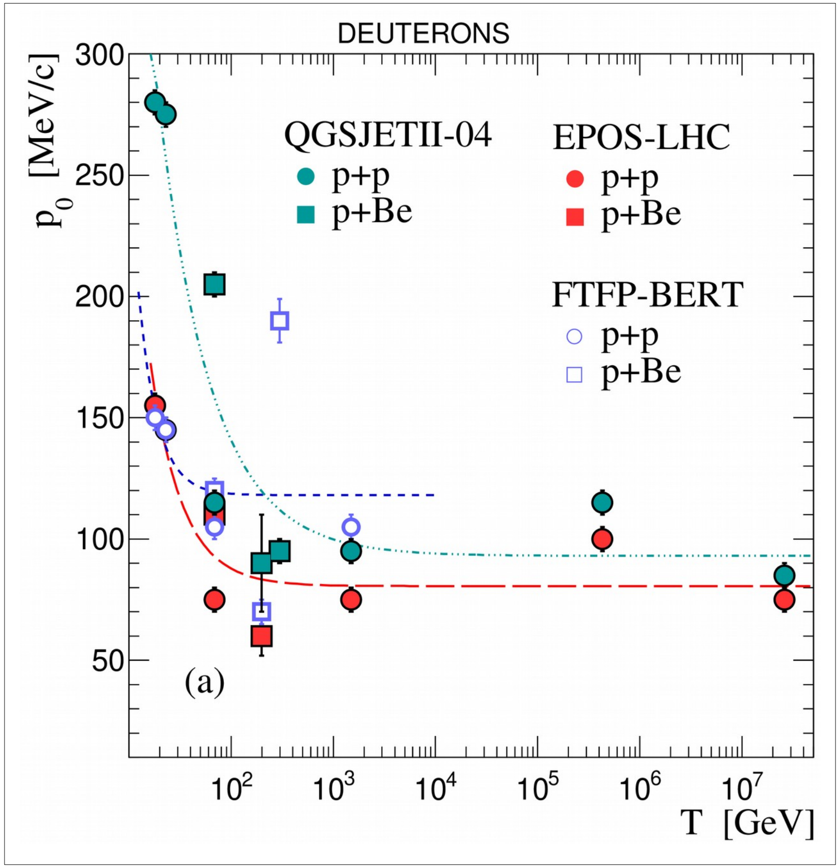
Energy production threshold

- p_0 changes in the energy region of major importance for cosmic ray production.

- p_0 is parameterized as function of the projectile kinetic energy.

$$p_0 = \frac{A}{1 + \exp(B - \ln(\mathrm{T/GeV})/C)}$$

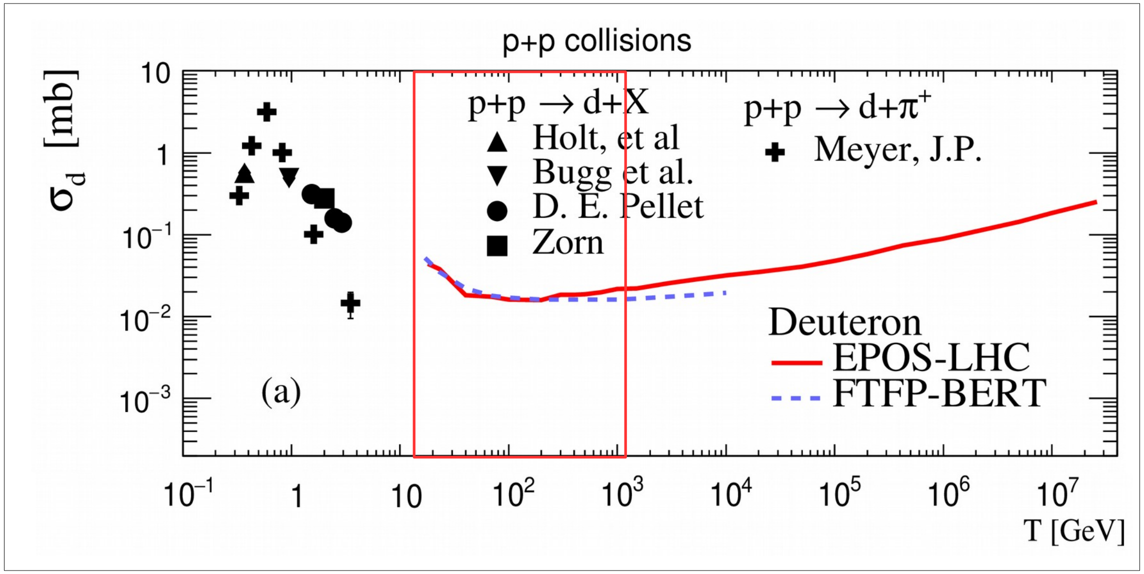
Deuteron coalescence momentum (p_0) and cross section



- p_0 is parameterized as function of the projectile kinetic energy.

$$p_0 = A\left[1 + \exp\left(B - \frac{\ln(\mathrm{T}/\mathrm{GeV})}{C}\right)\right]$$

p+p → X + d



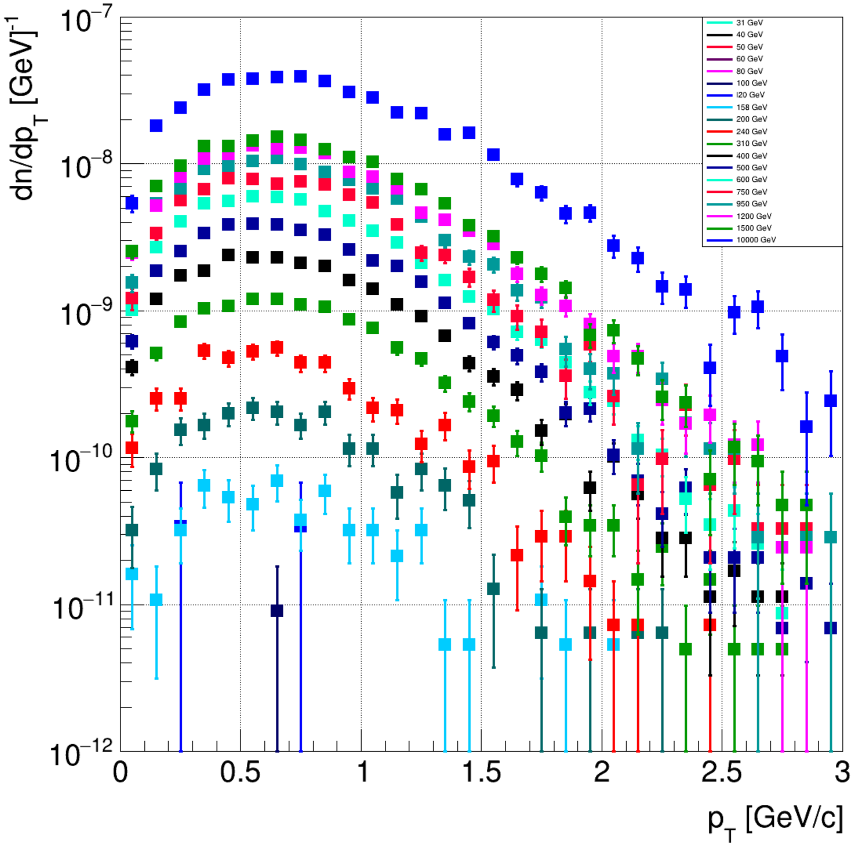
- We found p_0 is similar for p+p and p+Be collisions.

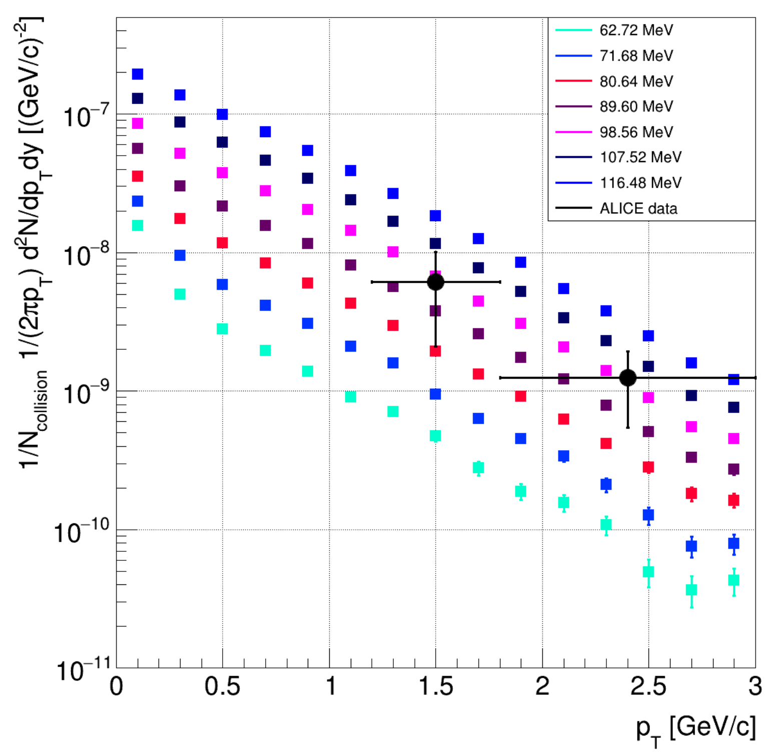
Antihelium production simulation

- MC coalescence is expanded to merge 3 antinucleons from p-p interactions.
- High computing power is required ~ 2000 years so far.

- Using same p_0 as for dbar shows very good agreement with ALICE antihelium-3 data

p+p at √s = 7 TeV



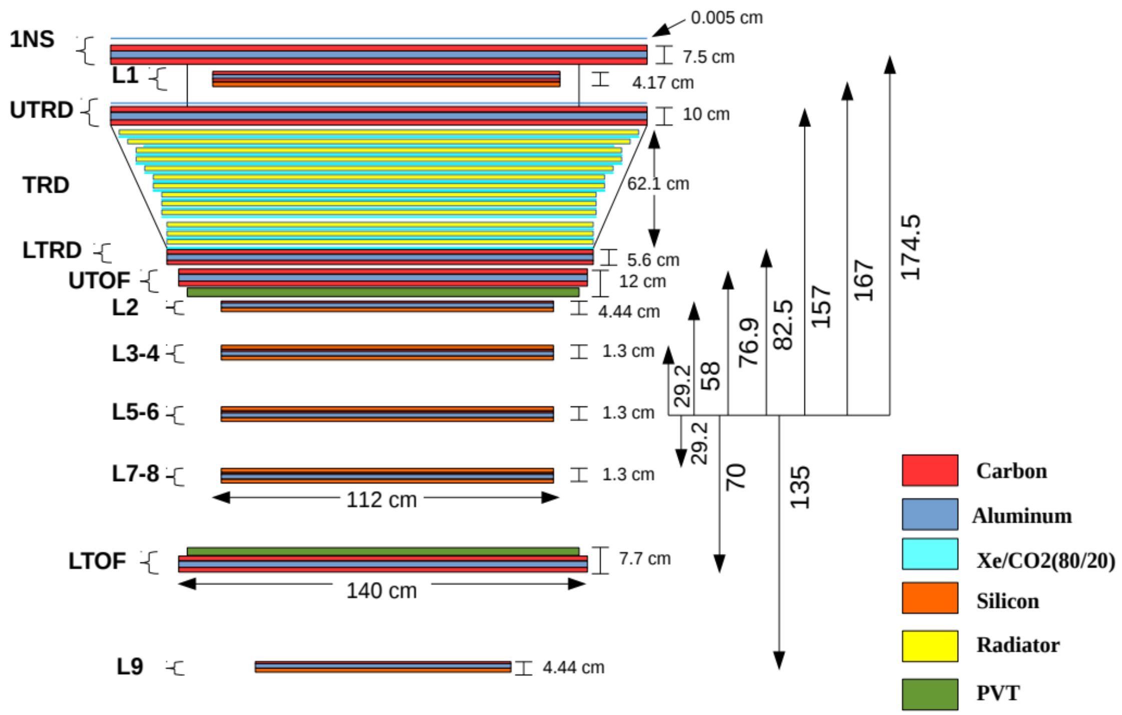


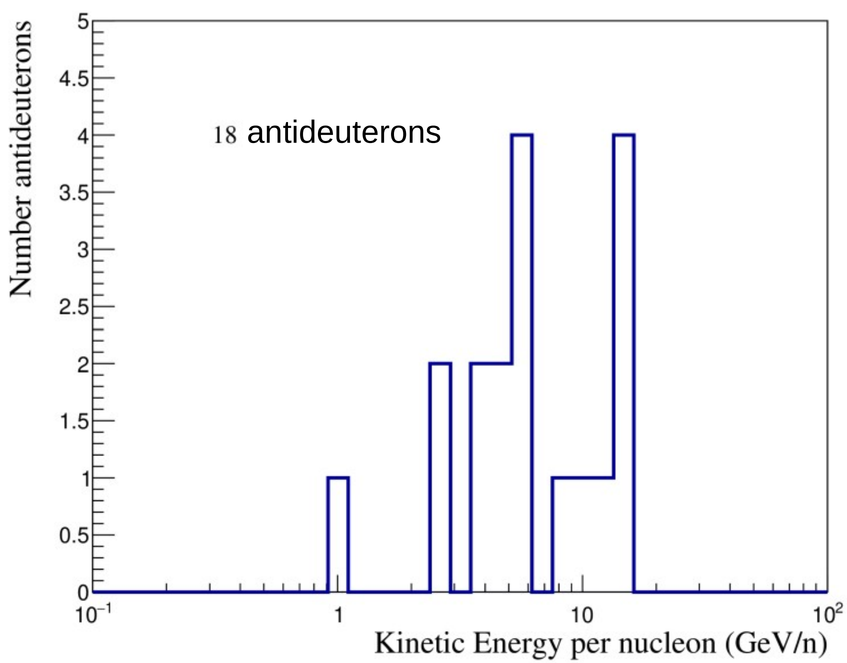
Anirvan Shukla PhD student UH

Antideuteron production in a toy detector geometry

- The coalescence model and the p_0 function are into implemented into Geant4 G4TheoFSGenerator class to simulate antideuteron production.

- Toy AMS-02 geometry.





Summary

- A new study on deuteron and antideuteron production in CRs was presented, using high-energy MC generators (EPOS-LHC) and Geant4.10.02 hadronic models (FTF) along with the coalescence model.

- Simulations were compared to an extensive data set, including new measurements from NA49, NA61 and ALICE-LHC to obtain the coalescence momentum (p_0).

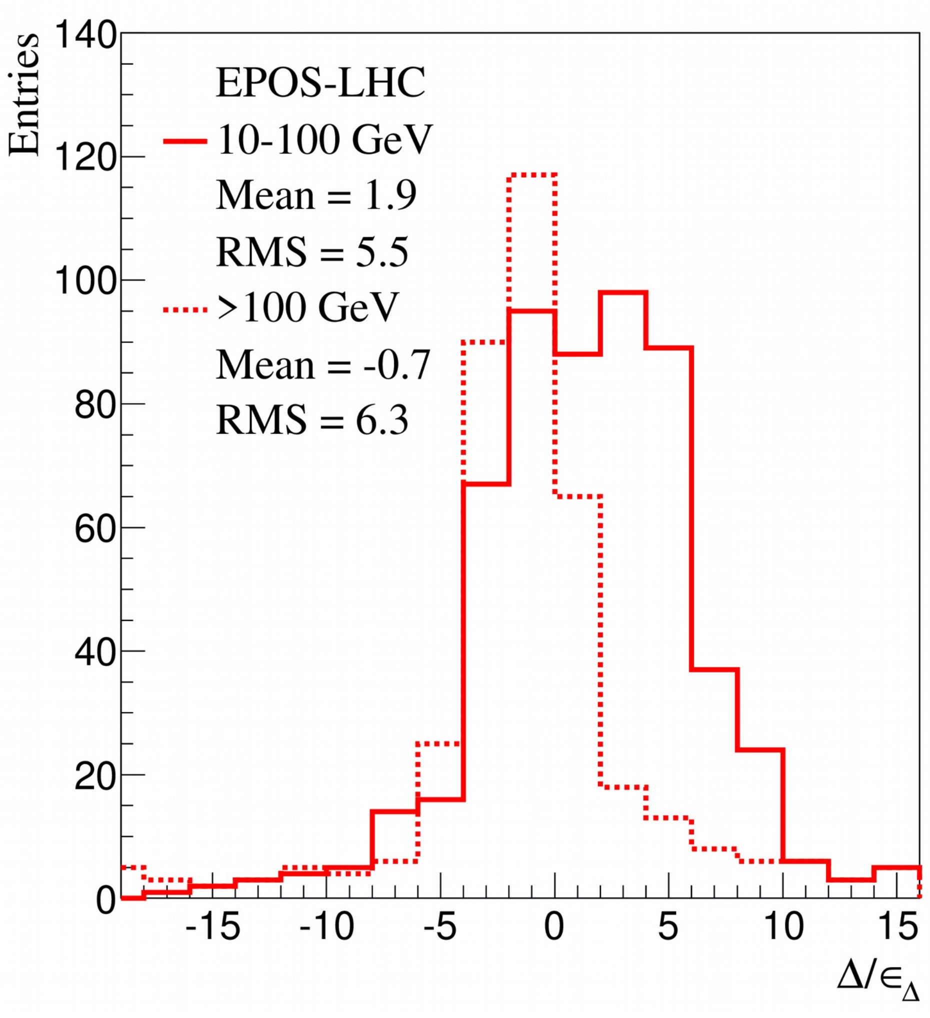
- From the comparison to data, it seems the coalescence momentum (p_0) depends on the collision energy. This dependence has been parameterized. As consequence:

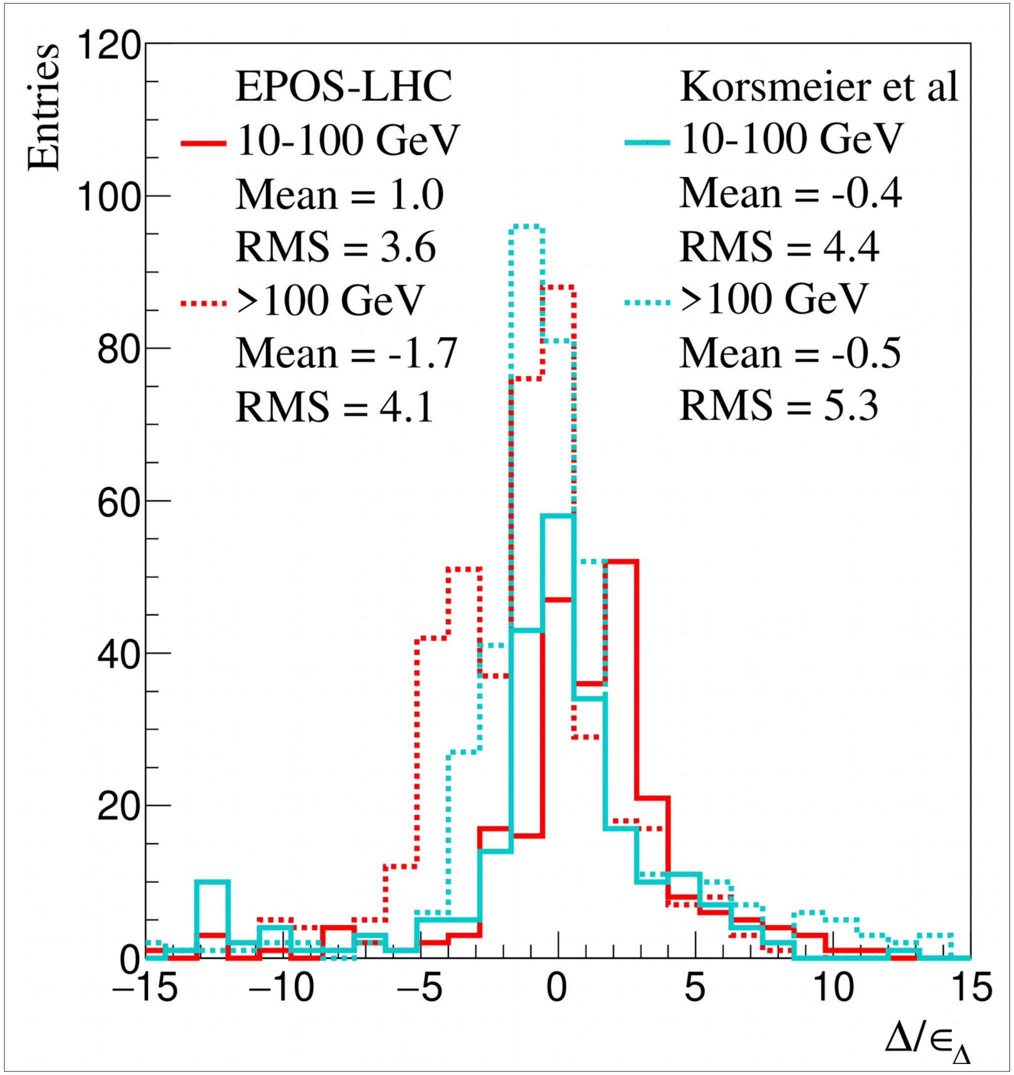
  - Antideuteron production cross section shows important differences with respect to previous calculations in the region of interest for CR antideuteron production, which produces changes in the expected flux.

- We implemented the coalescence model and the p_0 function into Geant4 G4TheoFSGenerator class to generate the antideuterons in a toy geometry detector.

Thank you!

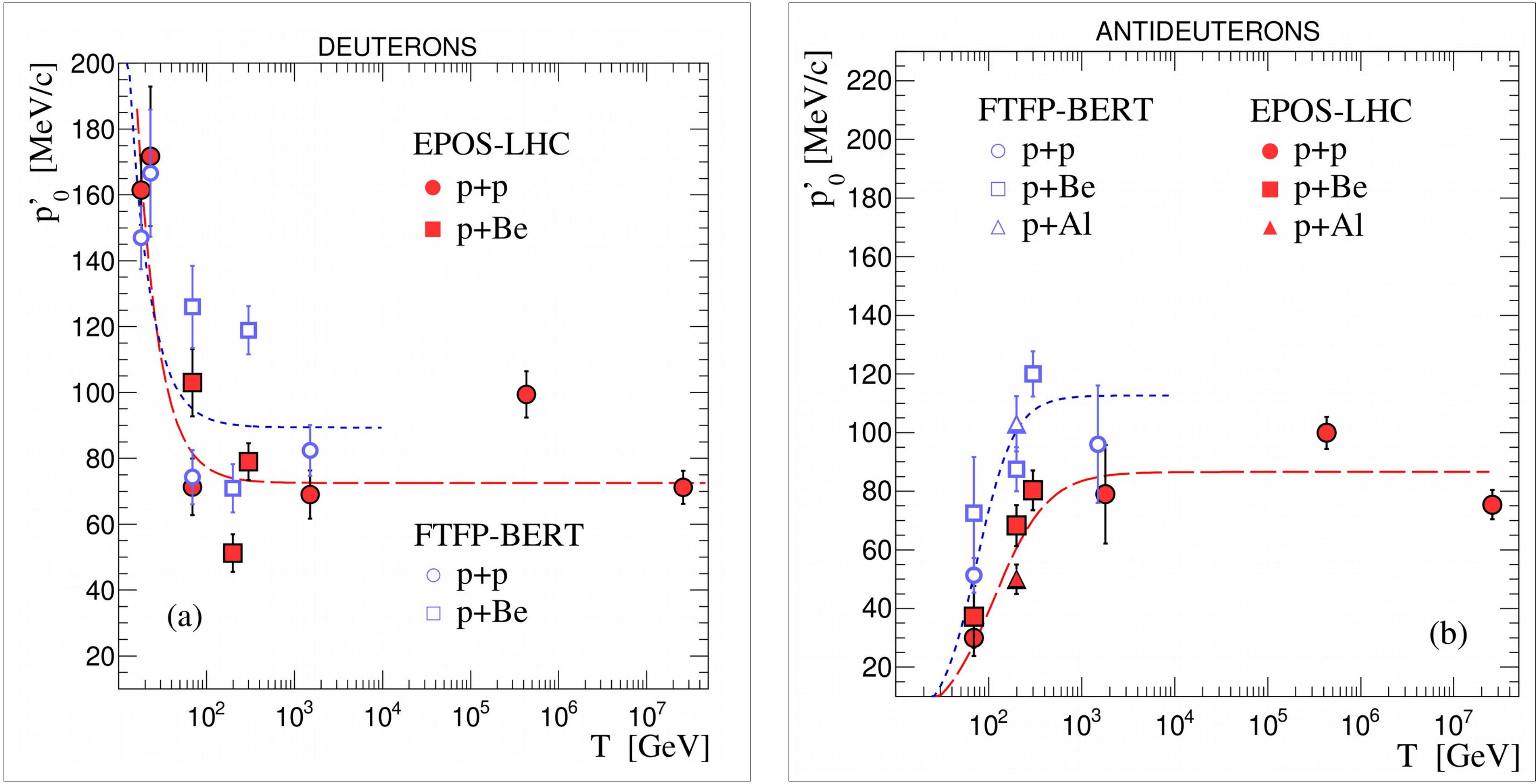
(Anti)proton production simulation





Antiproton mismatch factorization

- Correcting the antiproton mismatch between MC and data, we obtain a redefined p_0



Propagation with Galprop56

$$\frac{\partial f(p,\vec{r},t)}{\partial t} = \vec{\nabla}\cdot\left(D_{xx}(p,\vec{r})\vec{\nabla}f - \vec{V}f\right) + \frac{\partial}{\partial p}p^2 D_{pp}\frac{\partial}{\partial p}\frac{1}{p^2}f$$

$$-\frac{\partial}{\partial p}\left[\dot{p}f - \frac{p}{3}(\vec{\nabla}\cdot\vec{V})f\right] - \frac{1}{\tau_f}f - \frac{1}{\tau_r}f + q(p,\vec{r},t),$$

Antideuteron source term

Set 1 DR
Without convection

z [kpc]	$D_0/10^{28}$ [$cm^2\ s^{-1}$]	δ	V_{alf} [$km\ s^{-1}$]
6	4.37	0.494	7.64

Proton

R1	R2	γ1	γ2	γ3
5.78 GV	304 GV	1.74	2.35	2.178

Helium

R1	R2	γ1	γ2	γ3
5.78 GV	304 GV	1.69	2.29	2.12

T. A. Porter et al., 2017

Set 2 DCR
With convection

z [kpc]	$D_0/10^{28}$ [$cm^2\ s^{-1}$]	δ	V_{alf} [$km\ s^{-1}$]	V_{conv} [$km\ s^{-1}$]	dV/dz_{conv} [$km\ s^{-1}\ kpc^{-1}$]
4	4.3	0.395	28.6	12.4	10.2

Proton

R1	R2	γ1	γ2	γ3
7 GV	360 GV	1.69	2.44	2.28

Helium

R1	R2	γ1	γ2	γ3
7 GV	330 GV	1.71	2.38	2.21

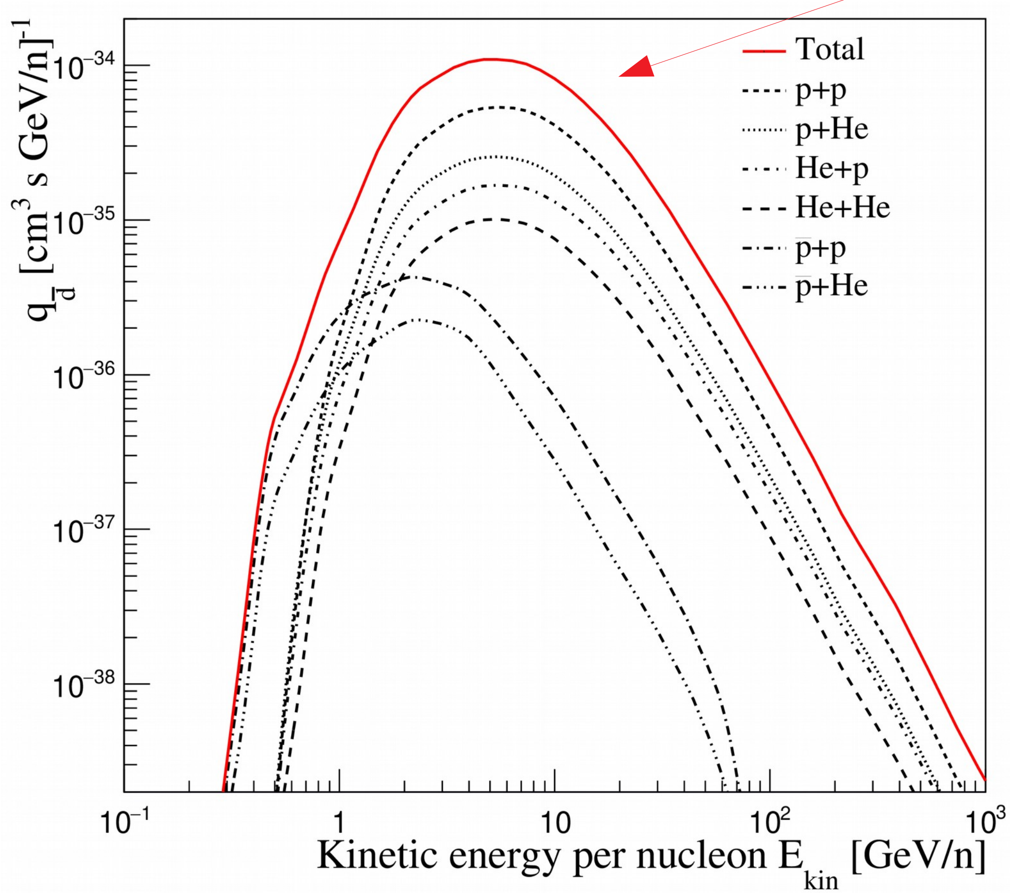
M. J. Boschini et al 2017 PoS(ICRC2017)278

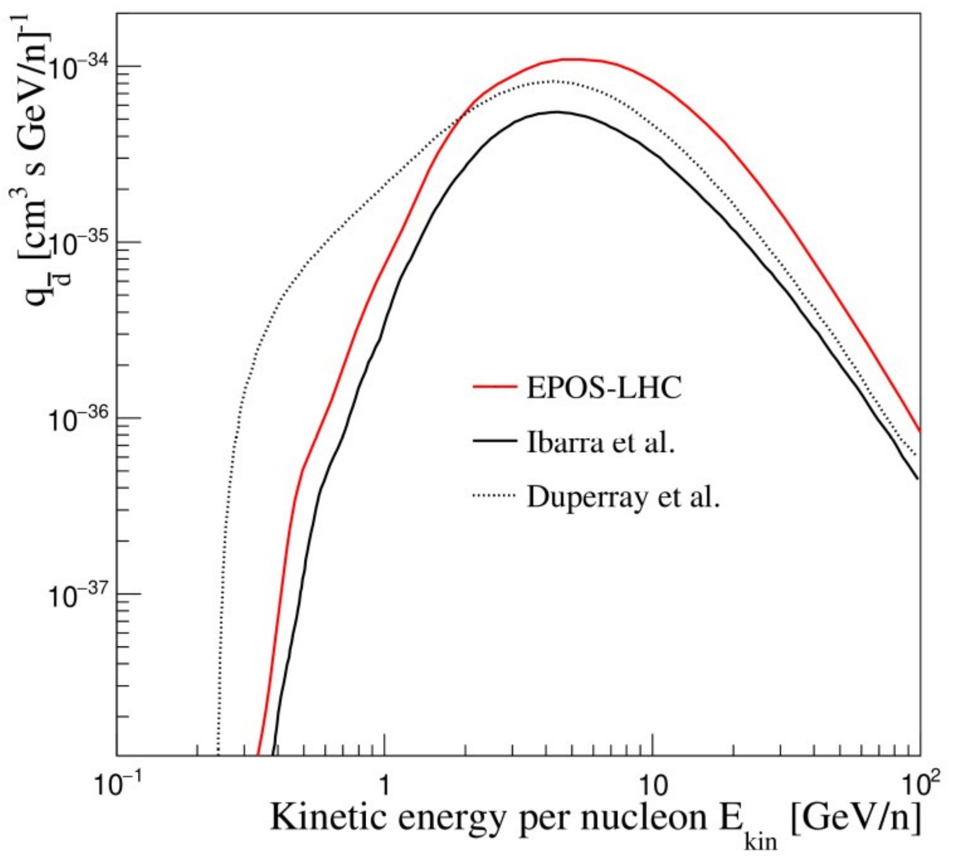
Antideuteron source term

$$q^{sec}_{\bar{d}}(E^{\bar{d}}_{kin}) = \sum_{i=p,He,\bar{p}} \sum_{j=p,He} 4\pi n_j \int_{T_{min}}^{\infty} dT_i \left(\frac{d\sigma}{dE^{\bar{d}}_{kin}}\right)_{ij} \Phi_i(T_i)$$

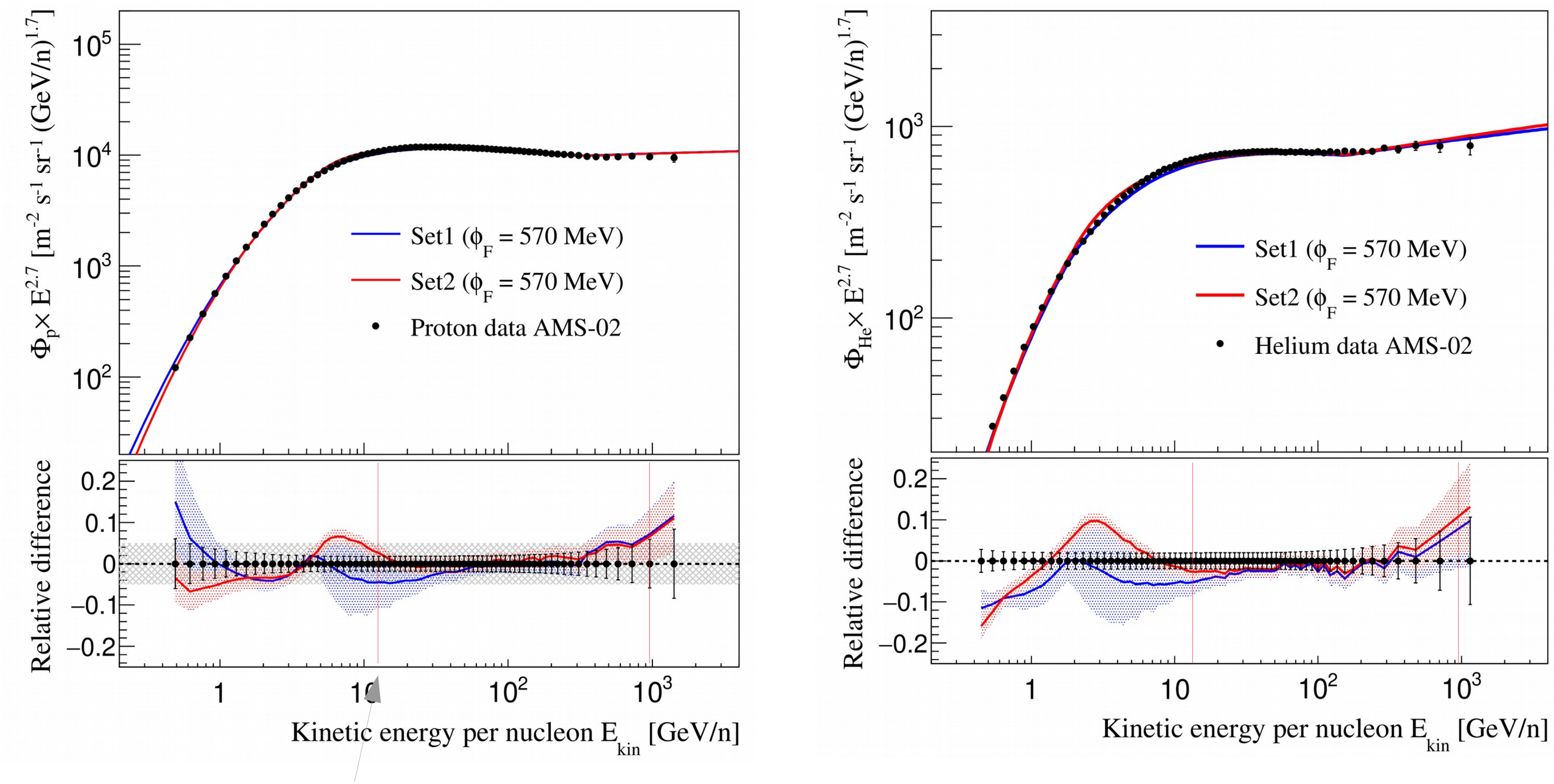
EPOS-LHC cross-section

p, He Fluxes



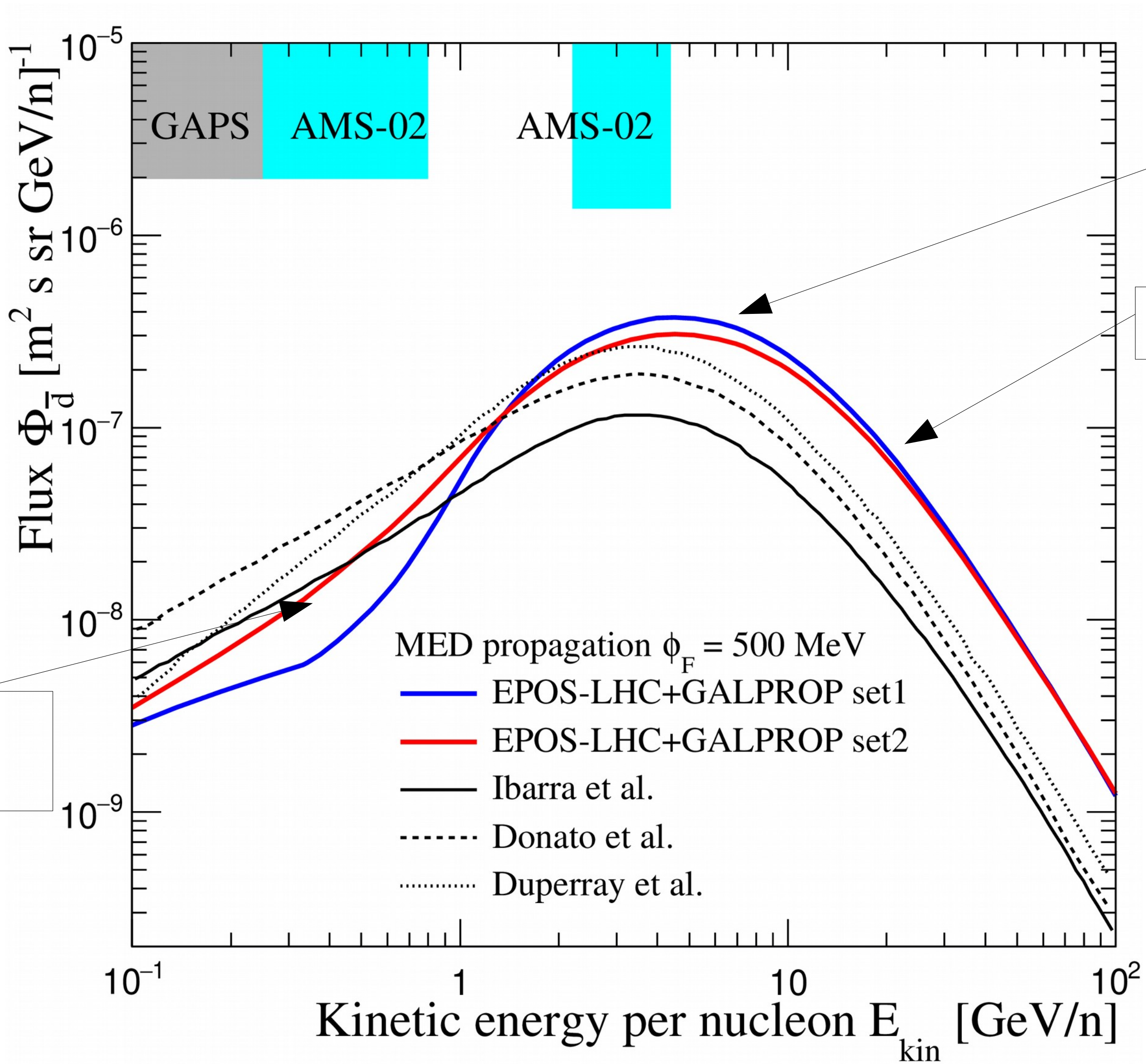


Proton and Helium fluxes



Energy production threshold

Secondary Antideuteron Flux

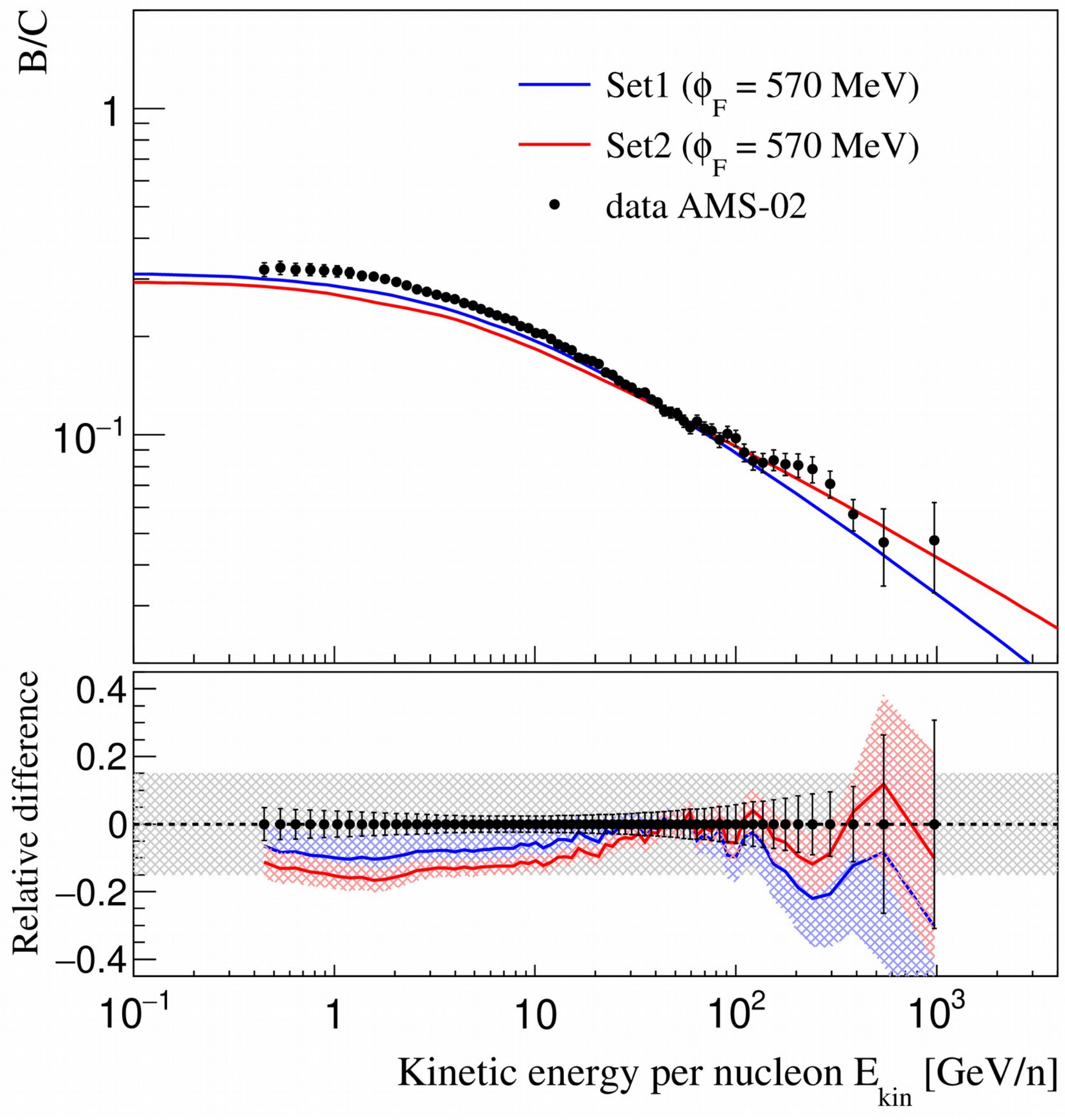


Maximum is shifted.

Increase at high energy.

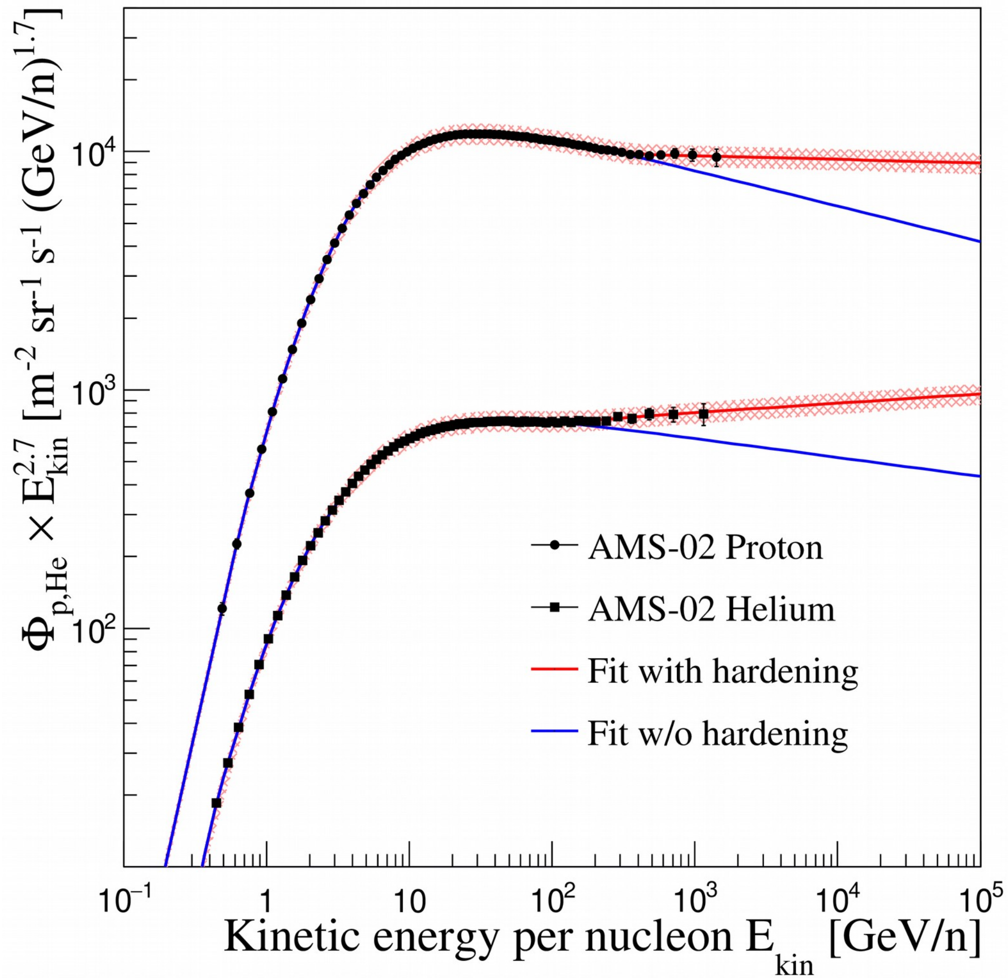
Adiabatic energy loss

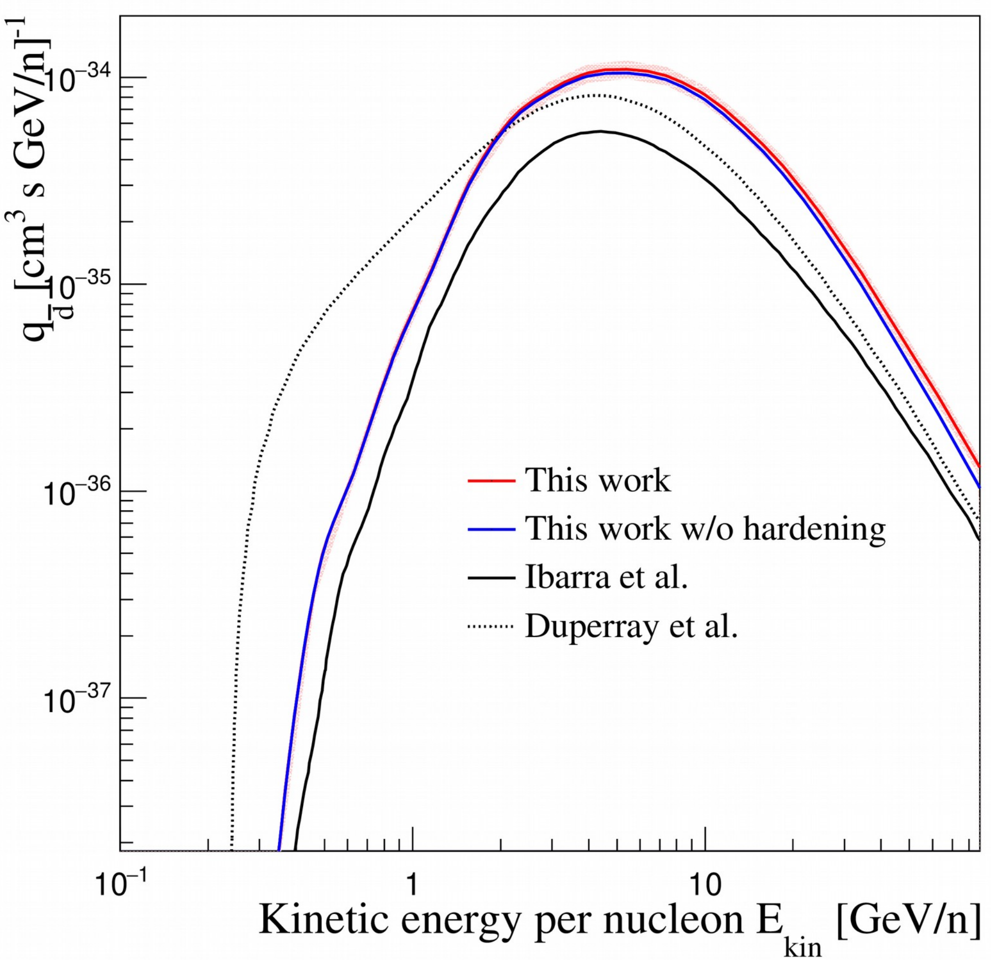
Boron to Carbon ratio



Antideuteron source term

- Proton and helium fluxes with and without hardening are inserted in the convolution.





- Hardening increases dbar flux by less than 10%
- dbar production is higher than in previous works.