Production of light nuclei in p-p collisions and its relevance to the search for dark matter in cosmic rays

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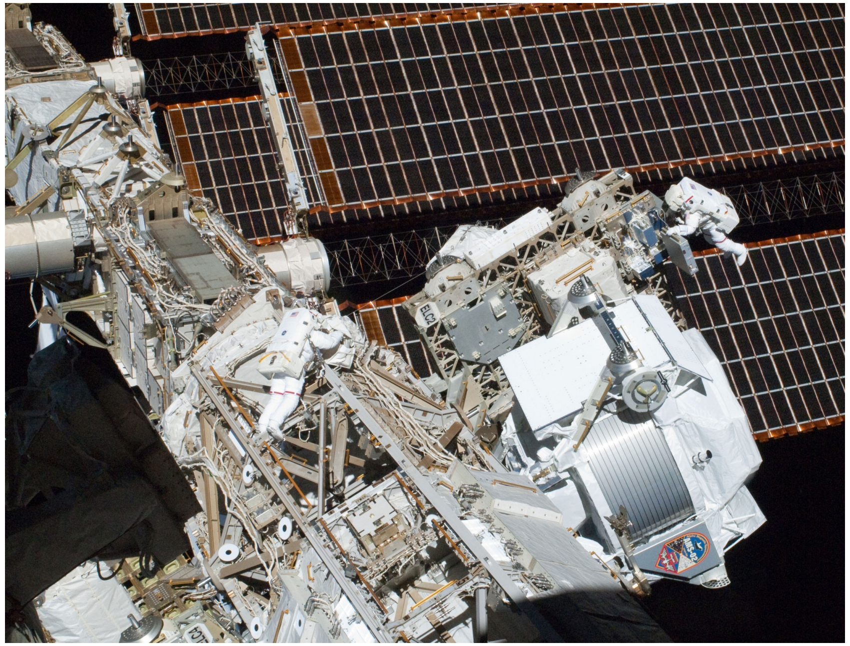
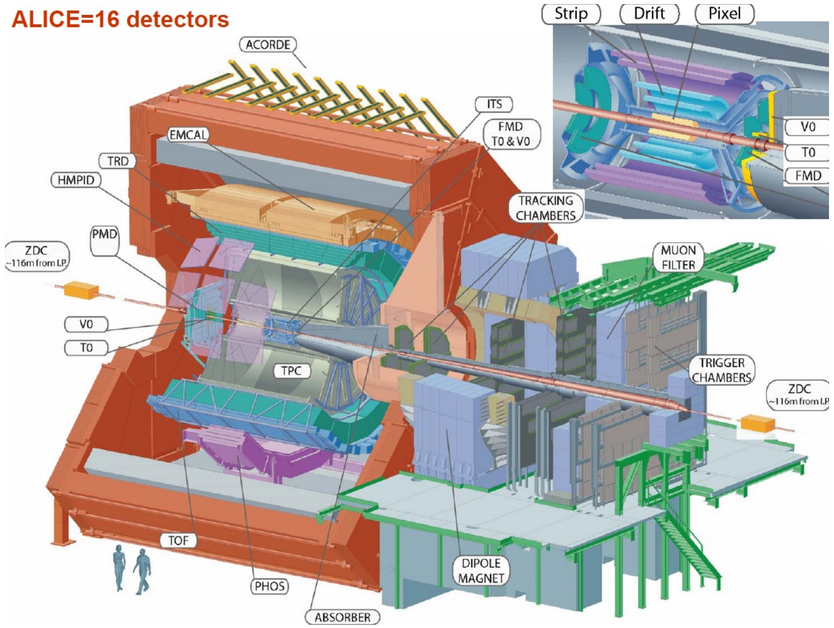
Particles and Fields, SMF
11/05/2021

Antinuclei production studies@IFUNAM



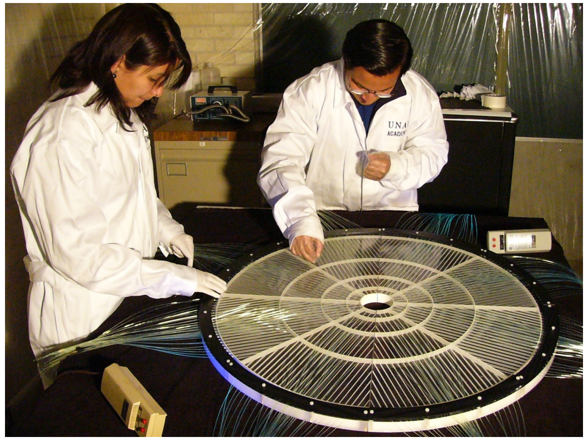
AMS 02

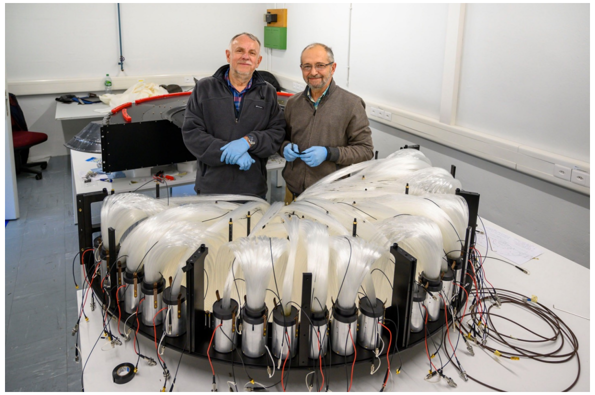


ALICE-LHC

Developing instruments: two decades

AMS-RICH
Aerogel
Characterization
& Aging





ALICE
V0A & V0-plus

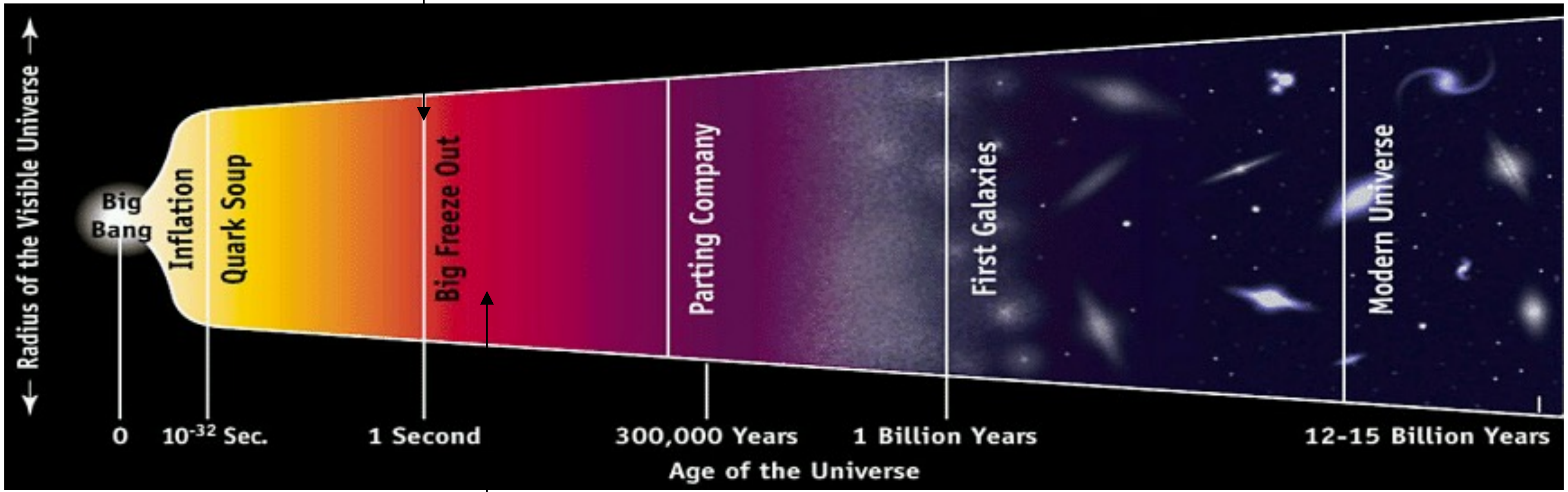
A common scientific interest?

- RPP: B.D. Fields (Illinois) and S. Sarkar (Oxford):
- “BBN still marks the boundary between the established and the speculative in Big Bang cosmology”
- “Speculative BB”: baryogenesis, dark matter…

Can ALICE generate data of interest to AMS02?

HADRONIZATION

Light nuclei



BBNS

BB and LHC: very different time scales

Inter-nuclear cascade:

S. Nagamiya & M. Gyulassy, Adv. In Nucl. Phys, 13(1984)201

($\geq$ 1 A · GeV) collisions and do not result in substantially better agreement with data than statistical models (RA14, TG1–TG7) alone. However, they have provided insight as to rate of approach to thermal equilibrium. A rule of thumb that has emerged from such studies is that after only 3 collisions the form of the distribution, $F^{(1)}_{m,n}$, becomes insensitive to the detailed form of the *NN* cross section. It is, however, essential to include the direct component ($m = n = 1$) through a Fermi momentum-averaged free-space *NN* cross section (TL1, TL2).

Fm,n describes the one-particle distribution of m,n clusters

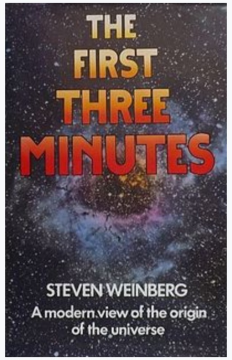
$\lambda \sim 1.4\ (\rho_0/\rho)$ fm < R

Thermodynamic calculations

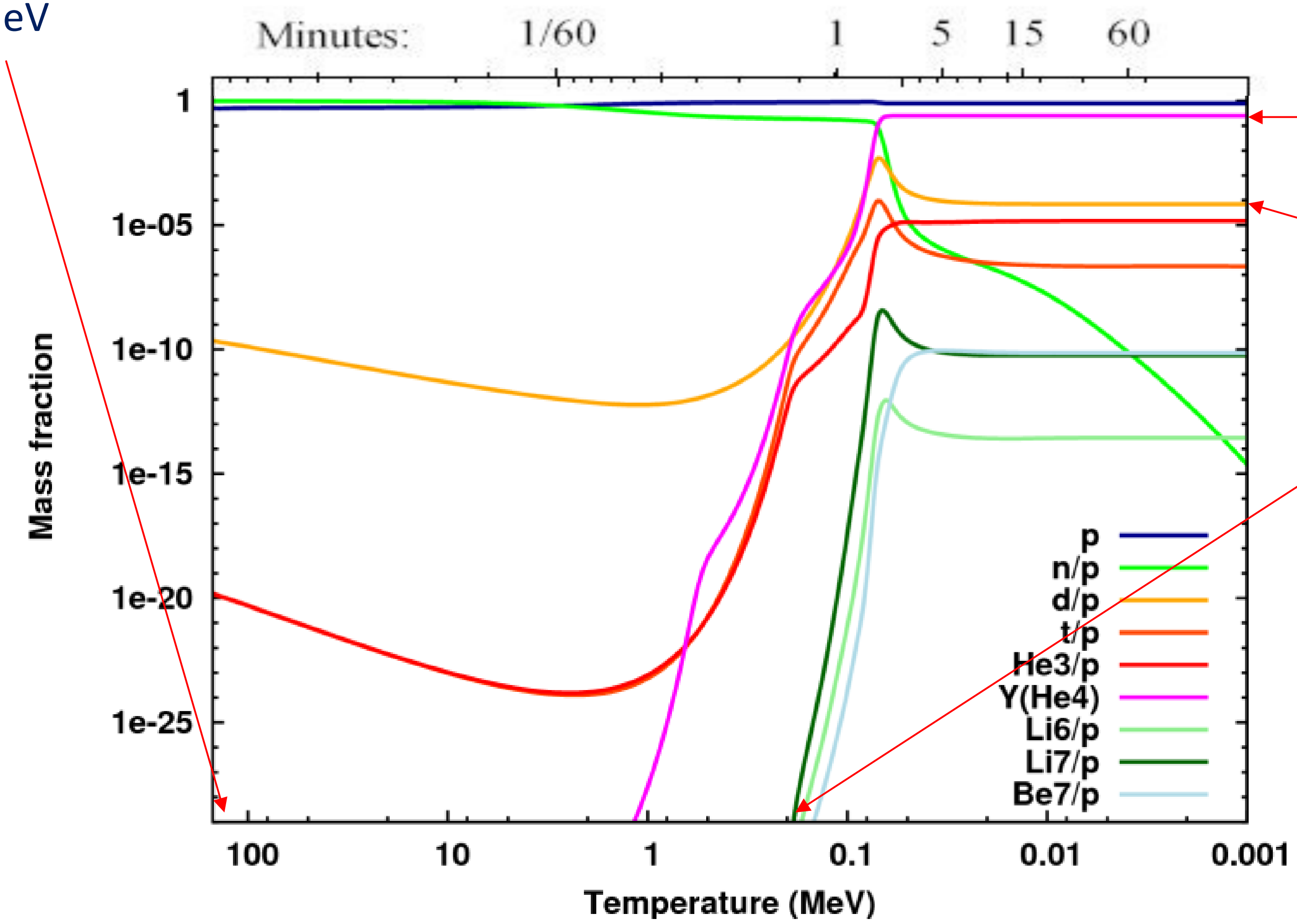
S. Das Gupta and A.Z. Mekjian, Phys. Rep. 72(1981)131

cross section for N + d → n + p + N is of the order of 100 mb [54] so that $\rho_N\langle\sigma V\rangle \sim 2.5\times10^{23}$/sec at normal nuclear matter density. Thus the reaction rate is an order of magnitude greater than the expansion rate 10^{22}/sec. This conclusion is also confirmed in the detailed calculation of ref. [53]. Consequently, an important conclusion can be drawn which is that an equilibrium concentration is achieved in the initial stages of the expansion. The same arguments can be made for the formation of other light composites and it will be found that they are also in chemical equilibrium [17].

BBN à la Wagoner (fusion)



150 MeV



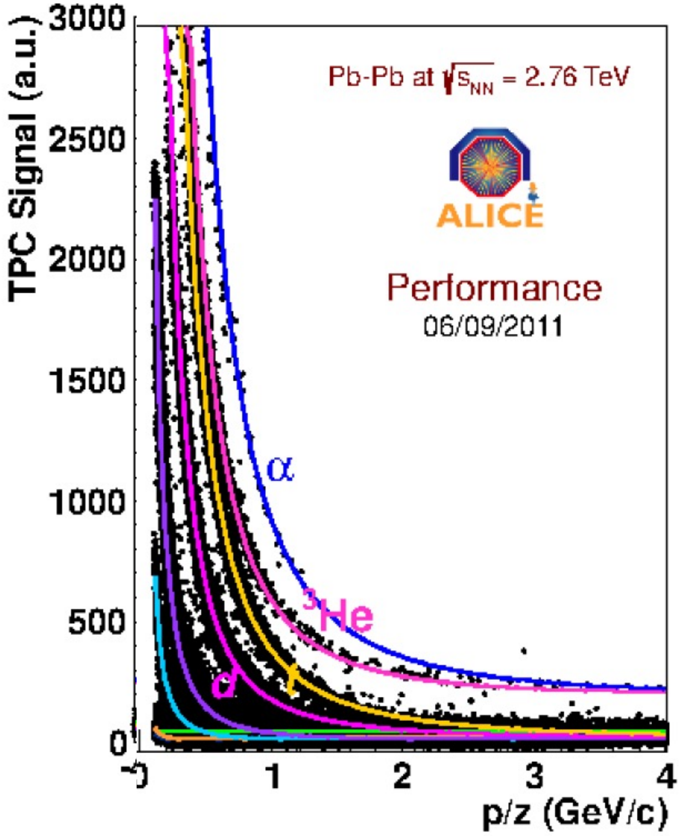
25% α's

25 **d** per millon

α/**d** >> 1

0.1 MeV

But in ALICE, hadronization occurs in 10^{-22} s



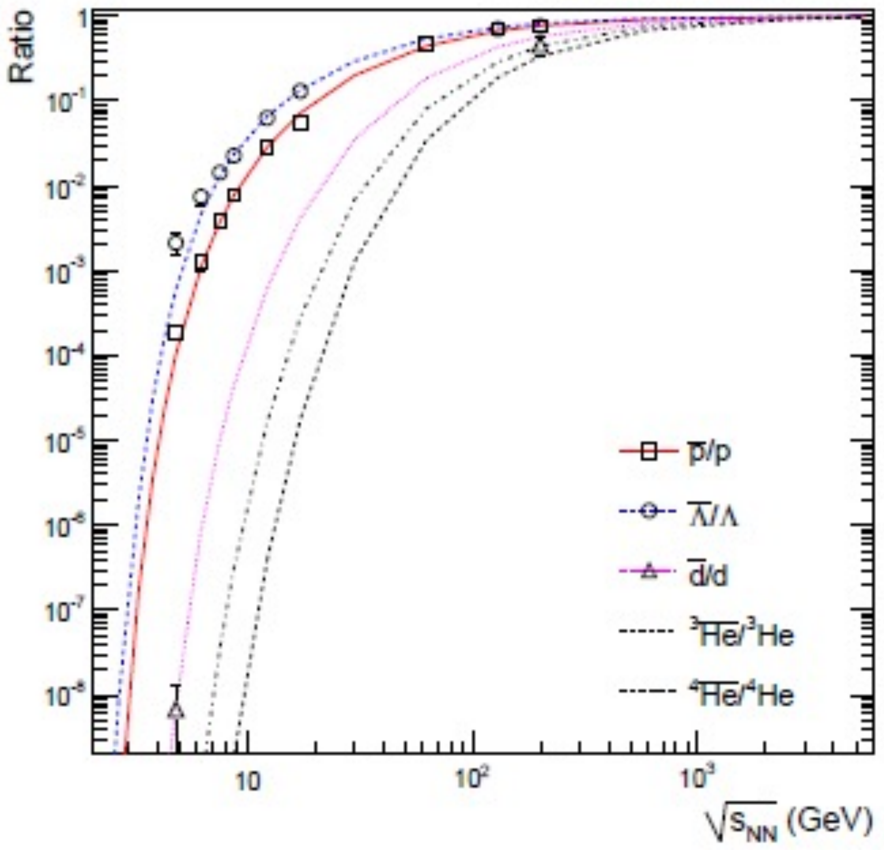
-No time for nuclear **d**'s to fuse

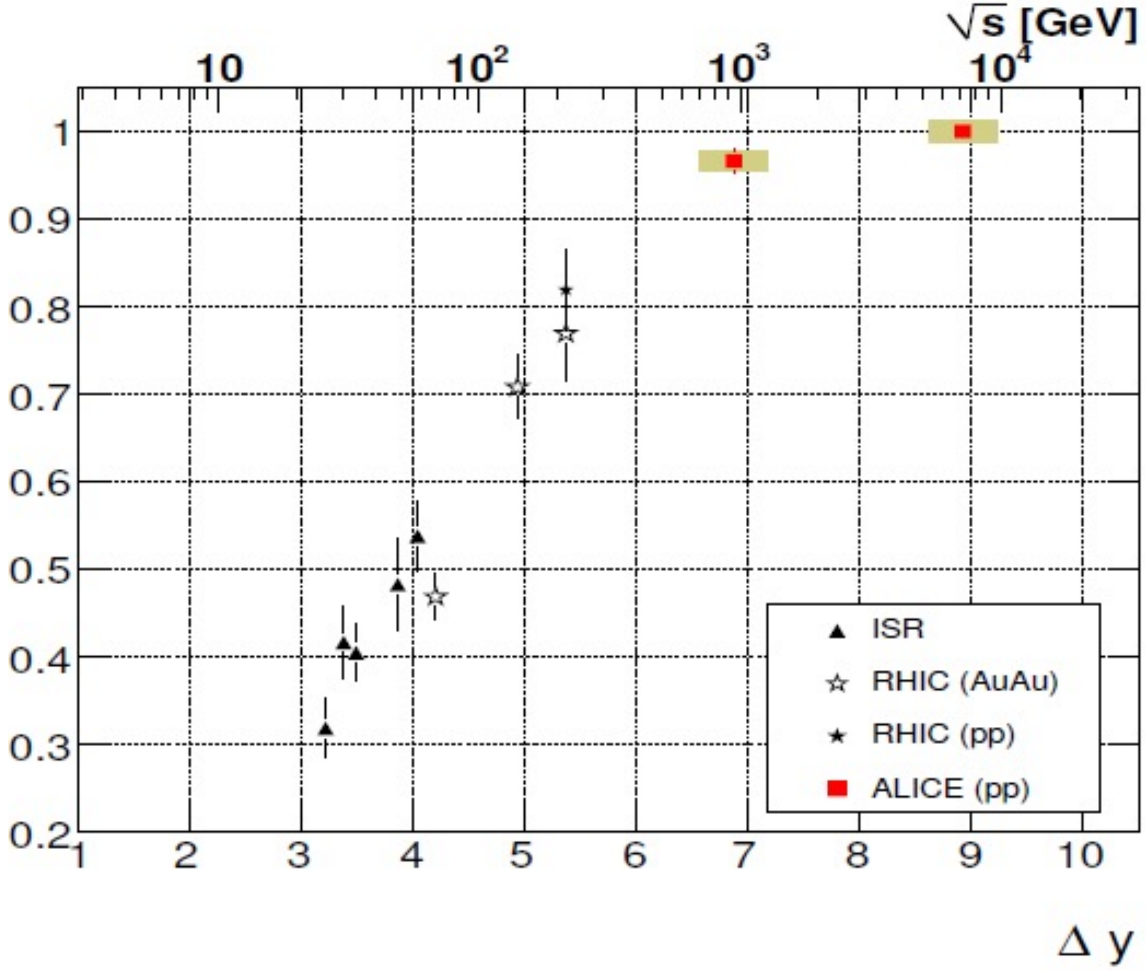
-Only phase space

-Hence, less α's than **d**'s

PHYSICAL REVIEW LETTERS, 105, 7, 2010, 072002

Furhermore, unlike BBN, in ALICE B ≈ 0





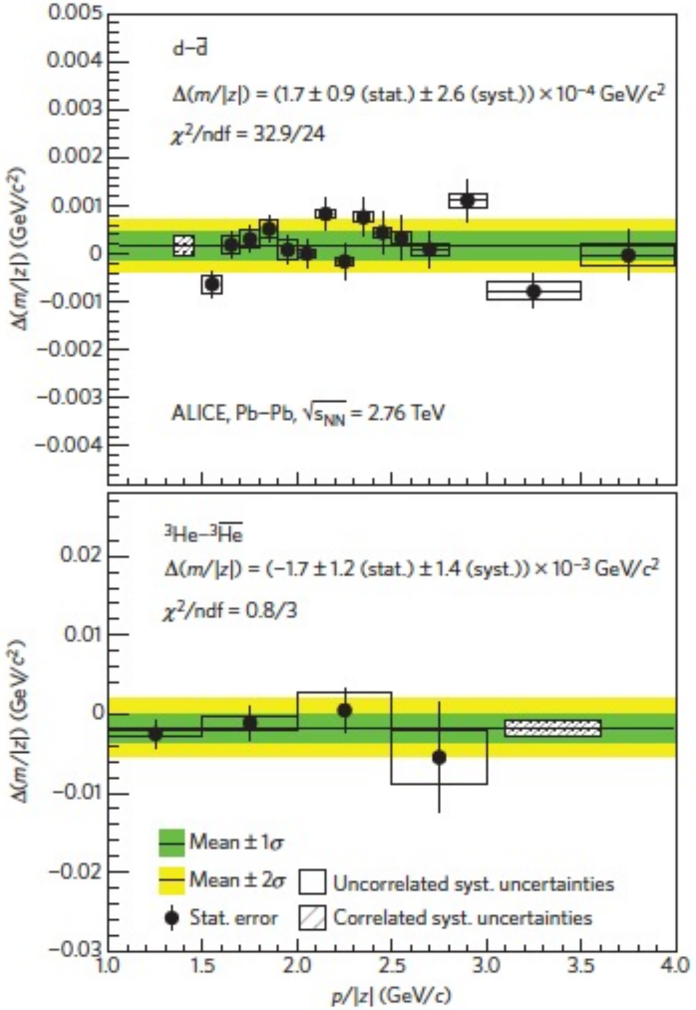
PHYSICAL REVIEW LETTERS, 105, 7, 2010, 072002

ALICE post-hadronization physics is quite relevant

The CPT theorem implies that the difference between the properties of a matter particle and those of its antimatter counterpart is *Completely* described by C-inversion. Since this C-inversion doesn't affect gravitational mass, the CPT theorem predicts that the gravitational mass of antimatter is the same as that of ordinary matter.

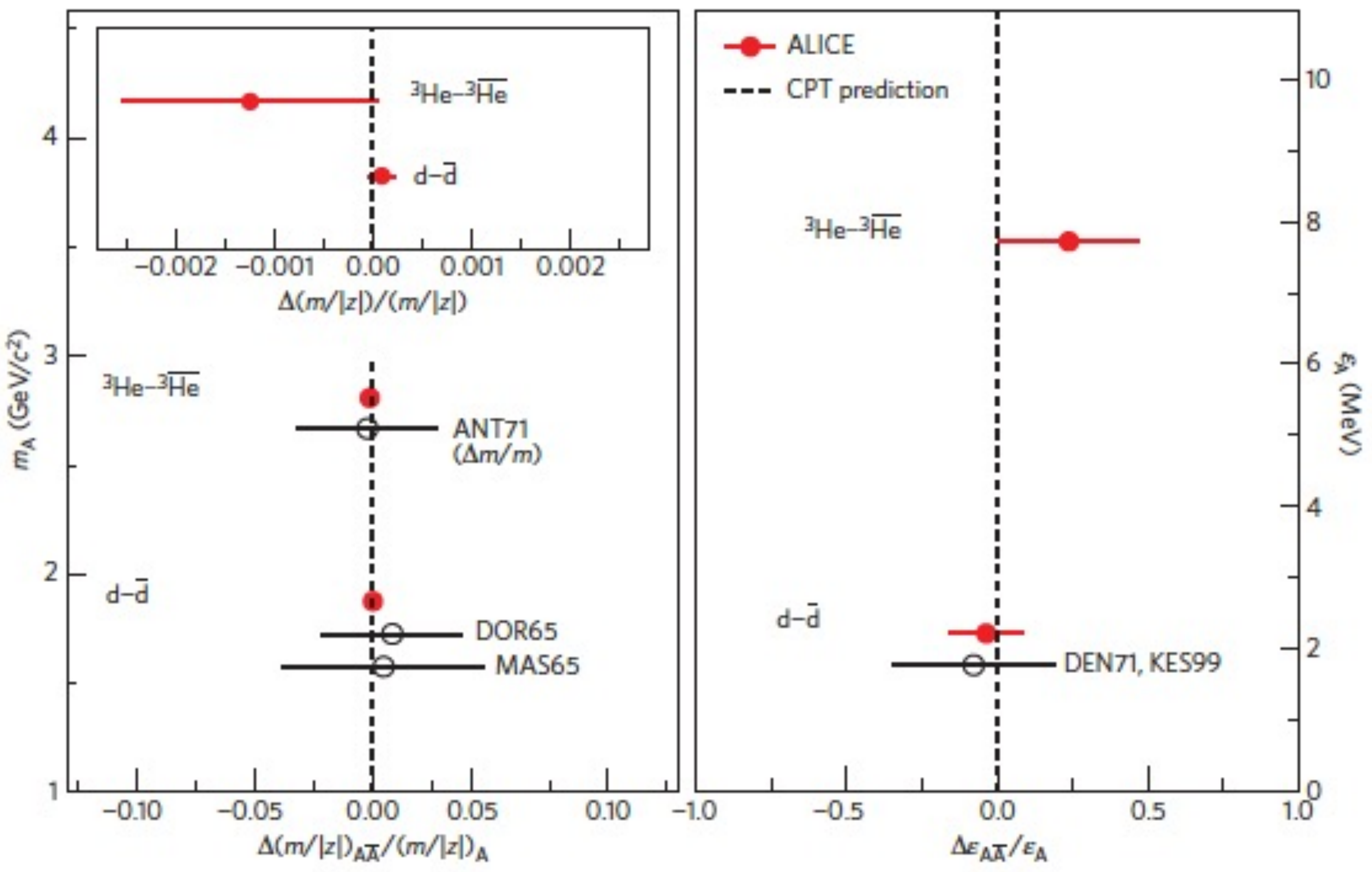
M.J.T.F. Cabbolet,
Annalen der Physik 522(10), 699-738 (2010)

ALICE produced the most sensitive test, so far



nature physics LETTERS
PUBLISHED ONLINE: 17 AUGUST 2015 | DOI: 10.1038/NPHYS3432

Not only mass, binding energy, too.



nature physics
LETTERS
PUBLISHED ONLINE: 17 AUGUST 2015 | DOI: 10.1038/NPHYS3432

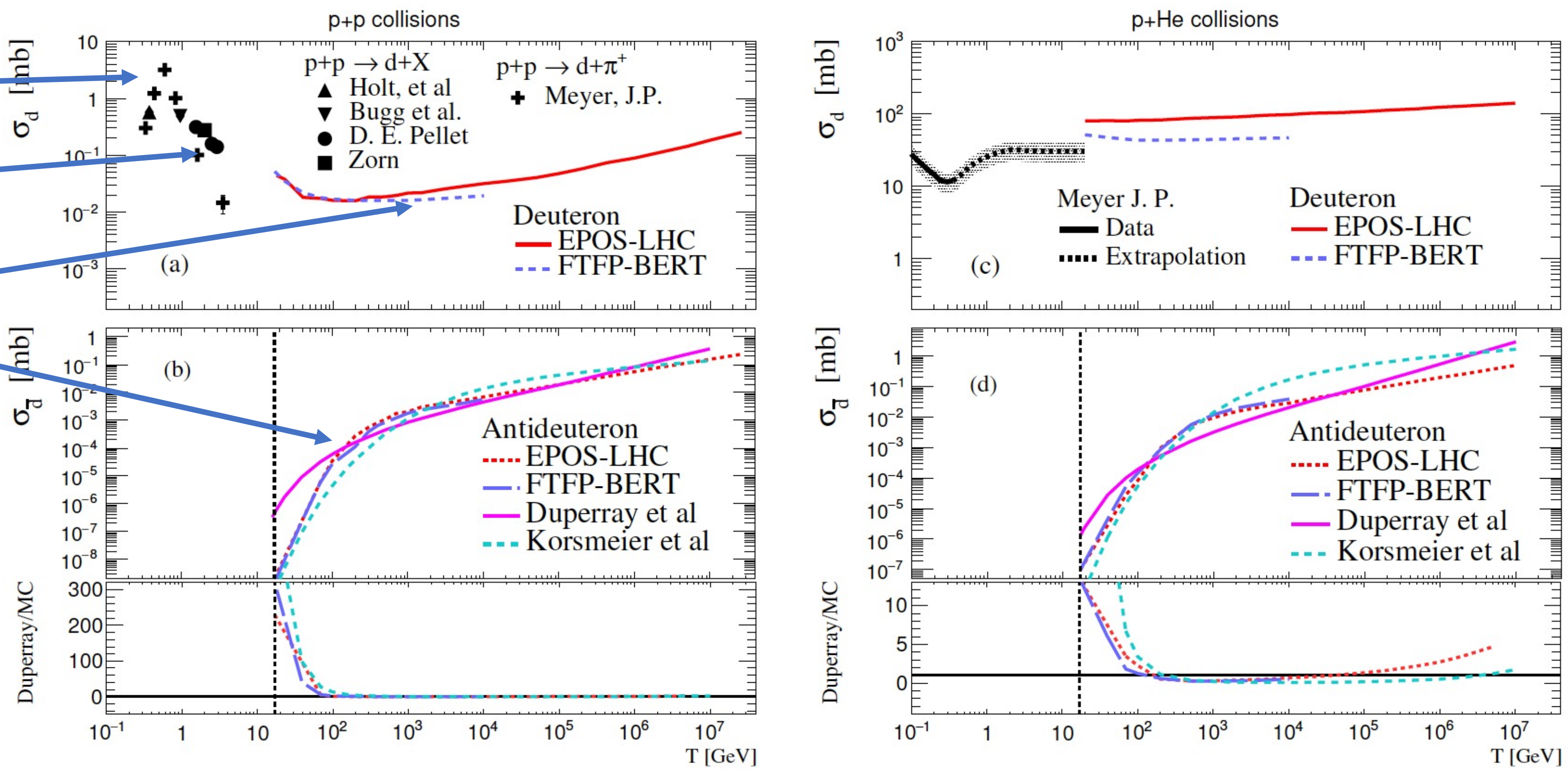
Question: How are **d**'s and $\overline{\mathbf{d}}$'s produced in space?

p + p -> π^+ + d

p + X -> Y + d

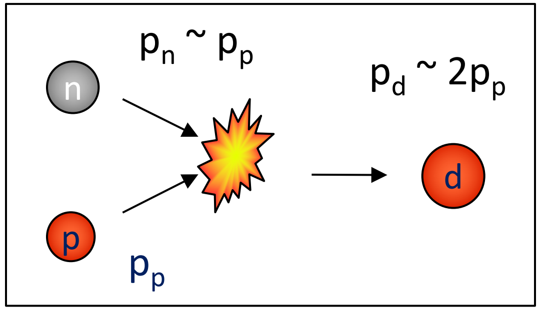
p + p -> x(p+$\bar{p}$+n+$\bar{n}$)+…

"Coalescence"



Coalescence

Phase espace

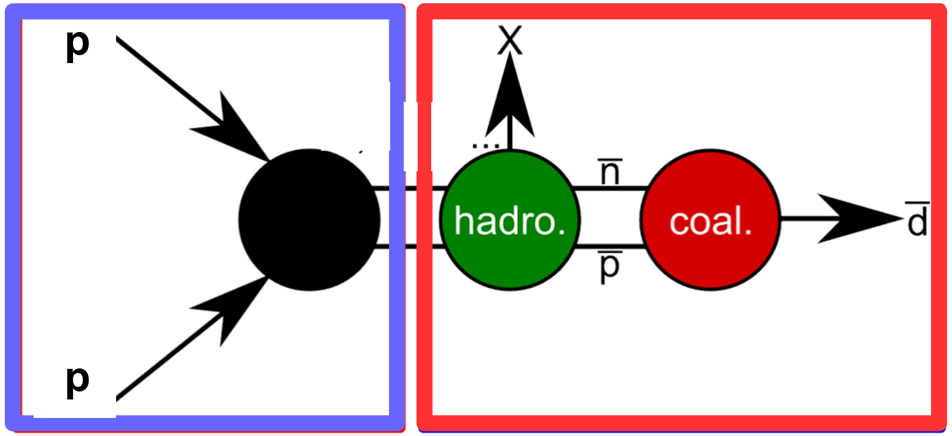


Coalescence parameter

$$E_A \frac{d^3 N_A}{d\vec{p}_A^3} = B_A \left(E_p \frac{d^3 N_p}{d\vec{p}_p^3} \right)^A , \quad \vec{p}_A = A\vec{p}_p$$

Has been measured in Earthly experiments, ALICE

Coalescence and MC simulations



Deuterons & antideuterons created from p-n or $\bar{p}$-$\bar{n}$ pairs, lying close in phase space

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

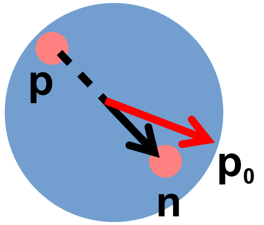
p+p, p+He, p+p

Coalescence

Coalescence radius: $\mathbf{p_0}$, a constant from data

Model collisions from **Monte Carlo** Simulations
Eulogio Serradilla,
PhD Thesis, 2014
&
D. M. Gómez Coral
MSc Thesis, 2014

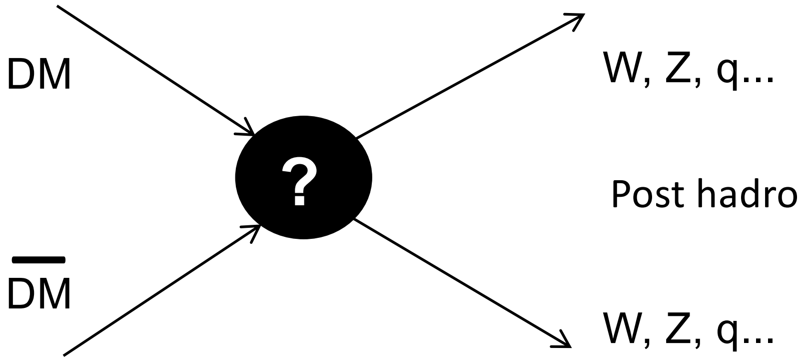
Afterburner



d and $\bar{d}$ are created from nucleon pairs

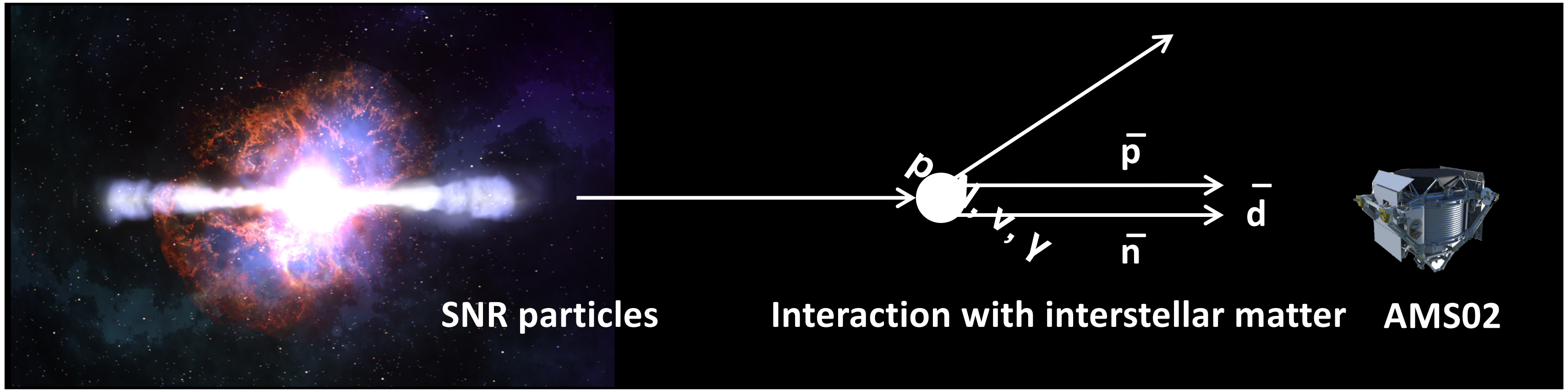
What about AMS02?

Non-SM
particle-antiparticle
annihilation

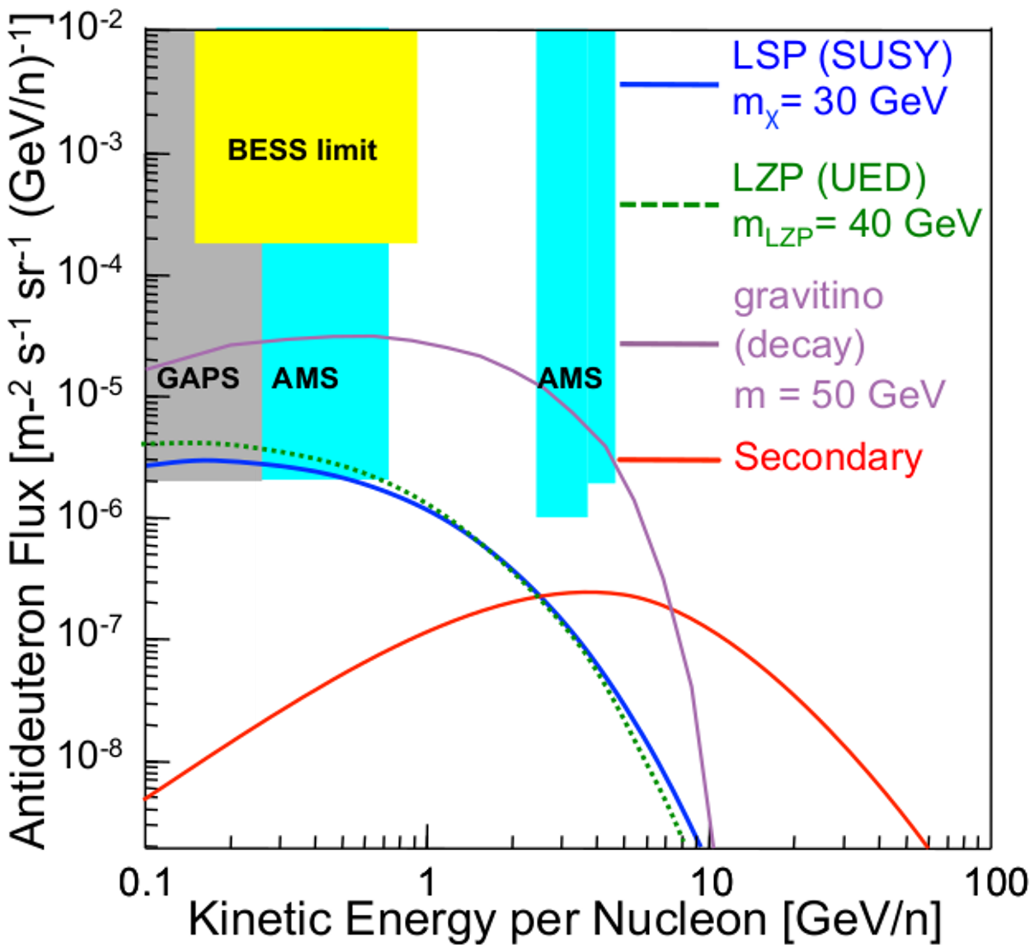


Post hadronization $d,\bar{d}$ pairs

SM d,d-bar background



AMS 02 sensitibity to measure such $\overline{\mathbf{d}}$'s

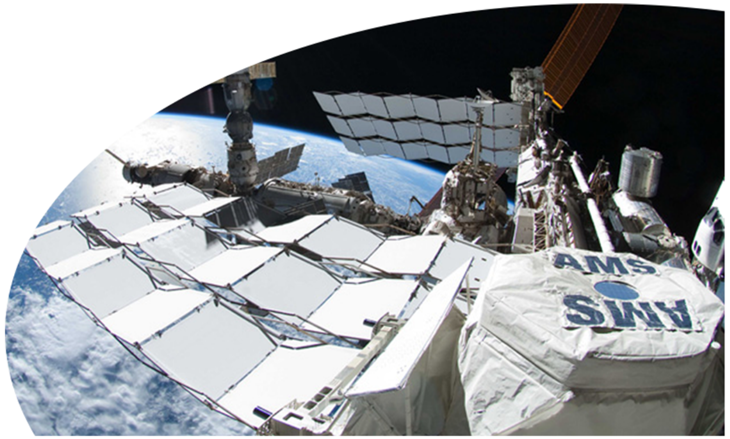


Possible DM signals

Gravitino decay (Super Gravity)

Neutralino (SUSY) & WGUTs

SM background, high energy estimate

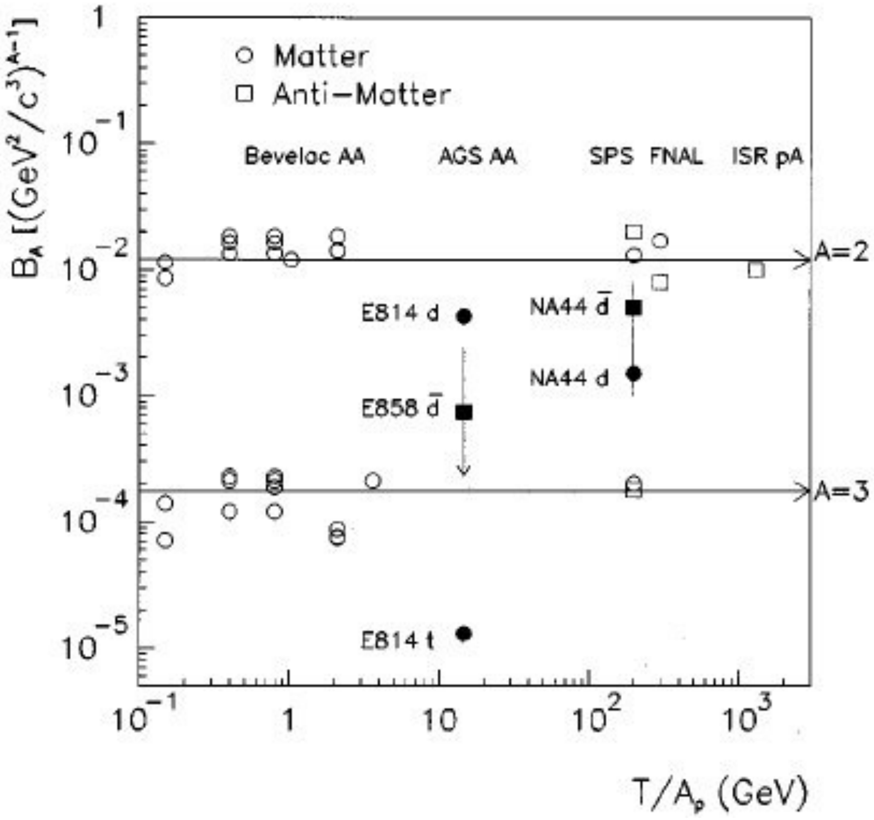


T. Aramaki et al., Phys. Rept. 618, 1 (2016), arXiv:1505.07785 [hep-ph].

SM $\overline{\mathbf{d}}$ background to Dark Matter signals

- High energy approximation (Duperray et al., 2003):
  - Use p and d data to extract an energy-independent $\mathbf{p_0}$
  - Use galactic diffusion equation with measured differential
  x-sections + geometrical limit, and charge symmetry considerations
  for x-section estimates + coalescence (using $\mathbf{p_0}$) to predict $\overline{\mathbf{d}}$ flux.
- Can one do better?: use HEP-MC simulators
  - Fit p at all available energies to choose best MC simulator.
  - Use chosen simulator to extract $\mathbf{p_0}$ values from measured p and **d** spectra.
  - Use these $\mathbf{p_0}$´s in chosen MC with coalescence afterburner to predict $\overline{\mathbf{d}}$ production x-sections
  - Use galactic (+ AMS-02 matter budget) transport MC to predict $\overline{\mathbf{d}}$ flux

Data: from Bevalac to ALICE



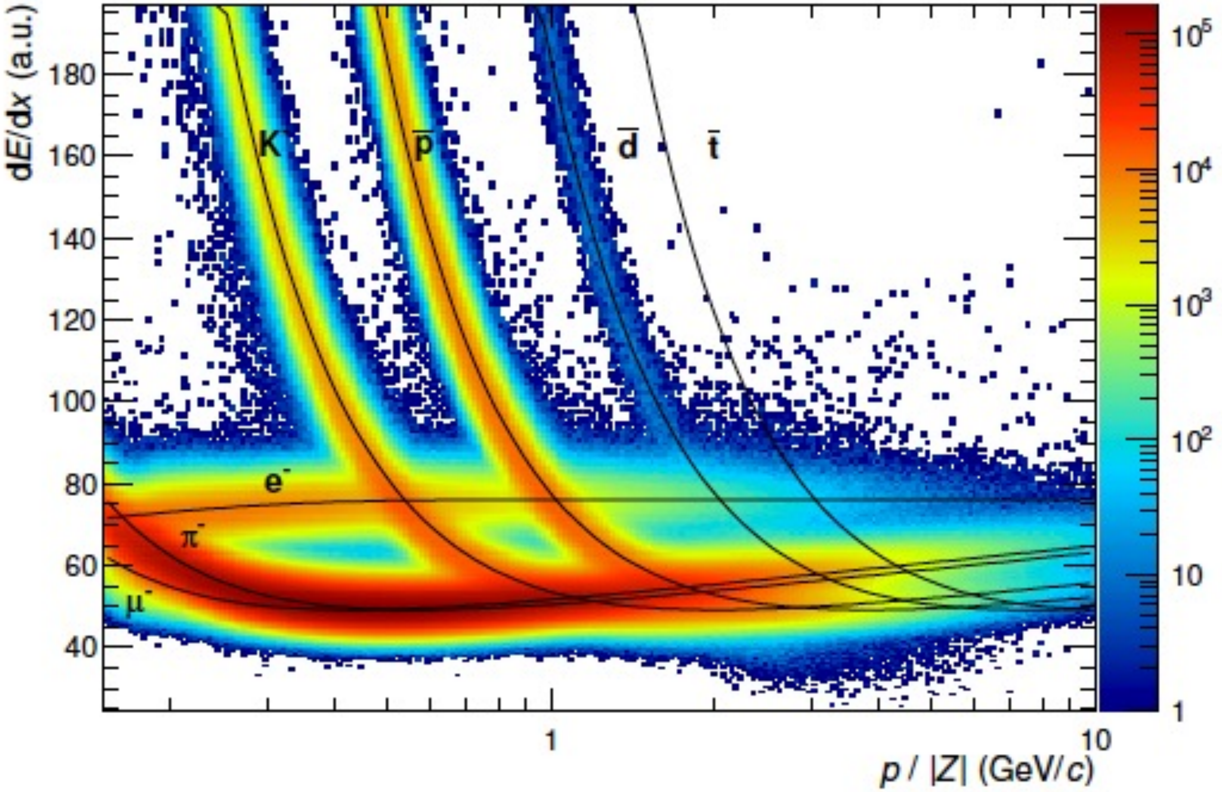
Early data systematics

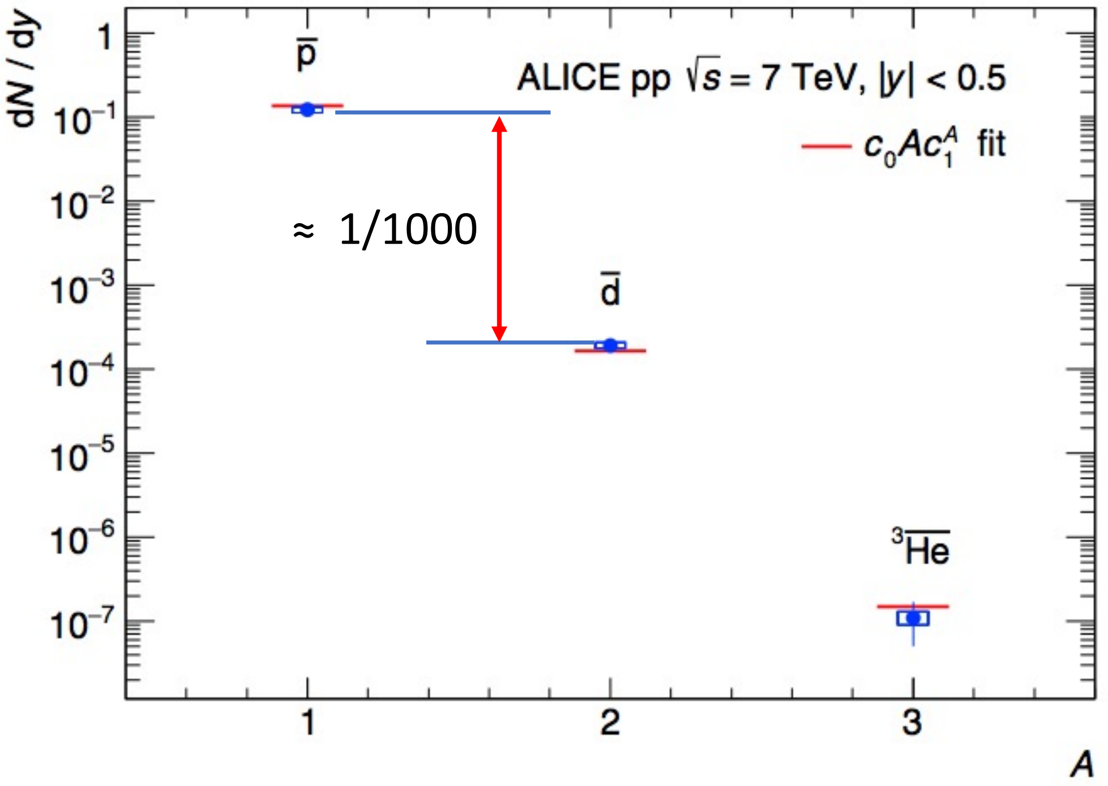
Experiment or Laboratory	Reference	Collision	Final states	p_{lab} (GeV/c)	$\sqrt{s}$ (GeV)
ITEP [1]	[192]	p+Be	p	10.1	4.5
CERN [1]	[193, 194]	p+p	p, $\bar{p}$	19.2	6.1
		p+Be	p, $\bar{p}$		
CERN [1]	[194]	p+p	p	24	6.8
NA61/SHINE	[195]	p+C	p	31	7.7
	[85]	p+p	p, $\bar{p}$		
NA61/SHINE	[85]	p+p	p, $\bar{p}$	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

Updated data list

Eulogio Serradilla, PhD Thesis, 2014

$\overline{\mathrm{d}}$’s produced en p+p @ 0.9 -> 7 TeV

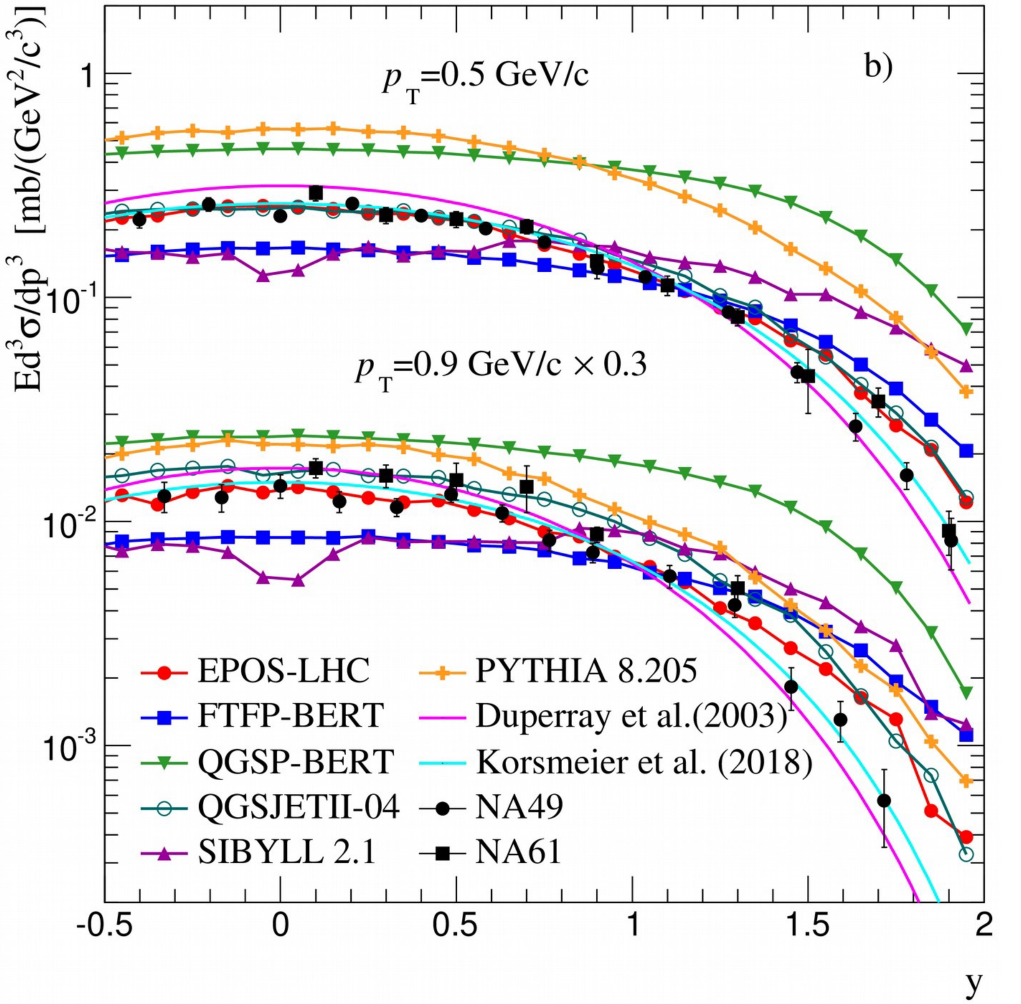




PhD Thesis, Eulogio Serradilla, 2014
Phys. Rev. C 97 (2018) 024615

Remember? less α’s than **d**’s
$\alpha/\overline{\mathrm{d}} \approx 1/10^6$

Best MC for $\overline{p}$'s?



p invariant differential x-section vs rapidity, from p + p @ 158 GeV/c

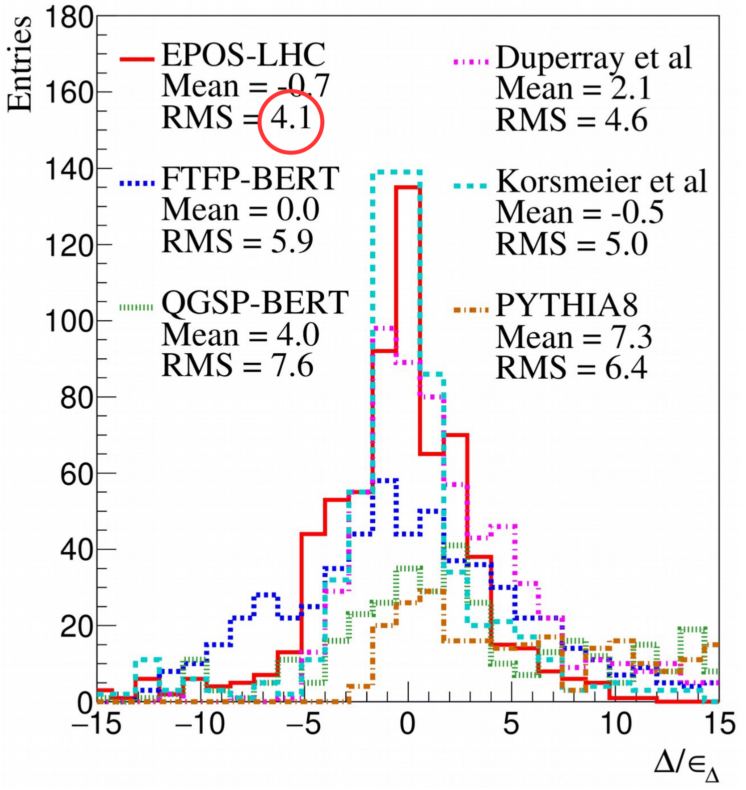
Diego Gómez-Coral, PhD Thesis (2019)

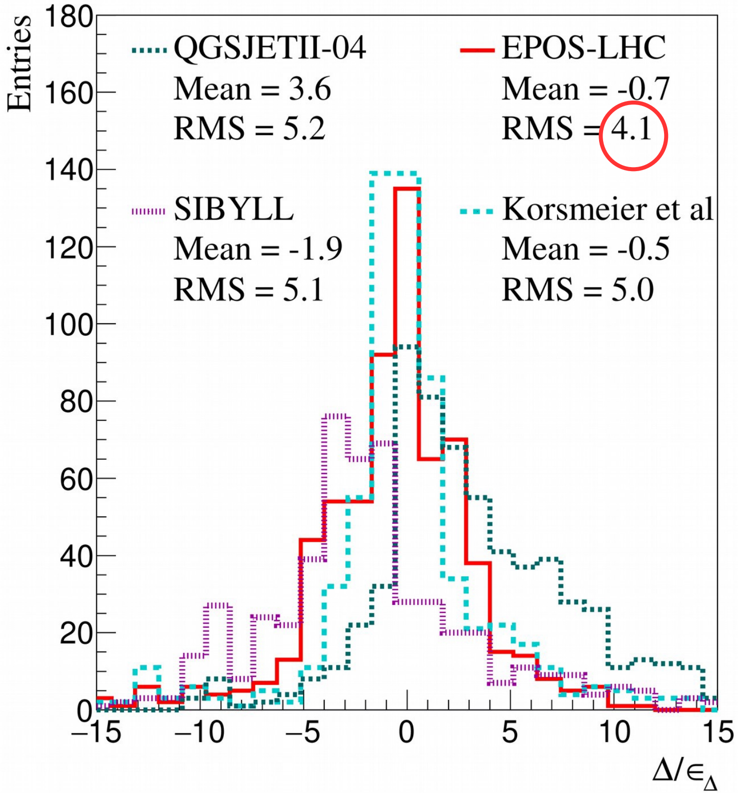
Phys. Rev. D 98, 023012 (2018) arXiv:1806.09303 [astro-ph.HE]

Best fit

Best choice: EPOS-LHC

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

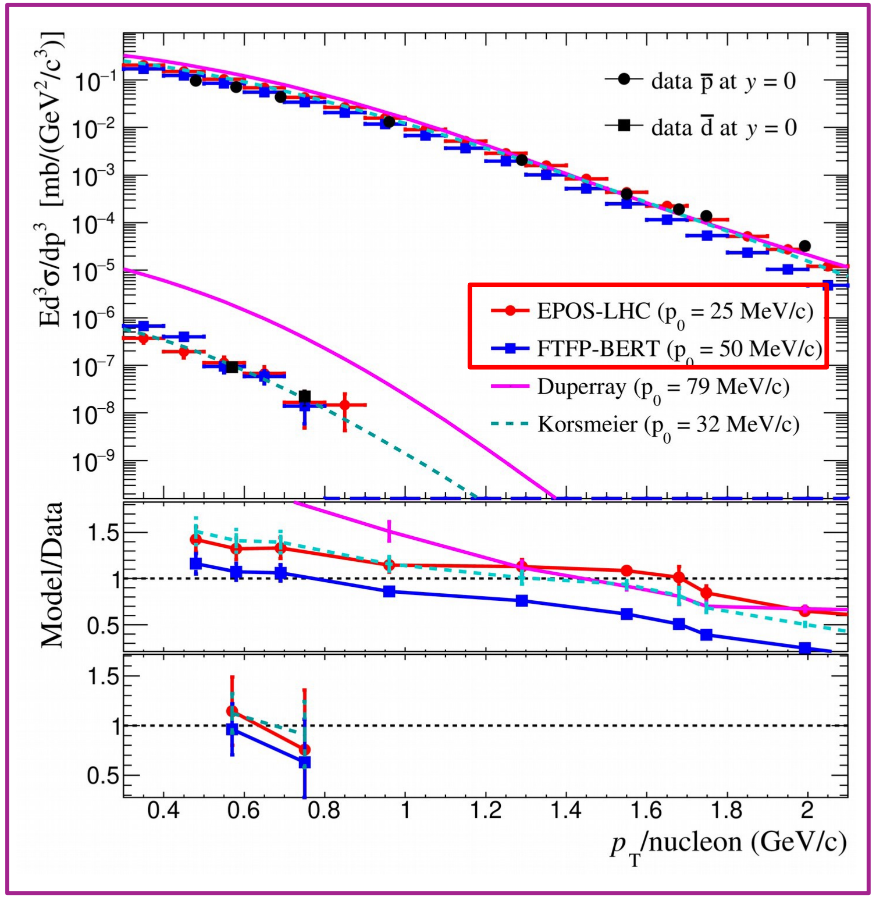




MC $\overline{\mathbf{d}}$'s simulation to extract p_0

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
CERN-SPS	[200, 205]	p+Be	200	19.4	6	3
		p+Be			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

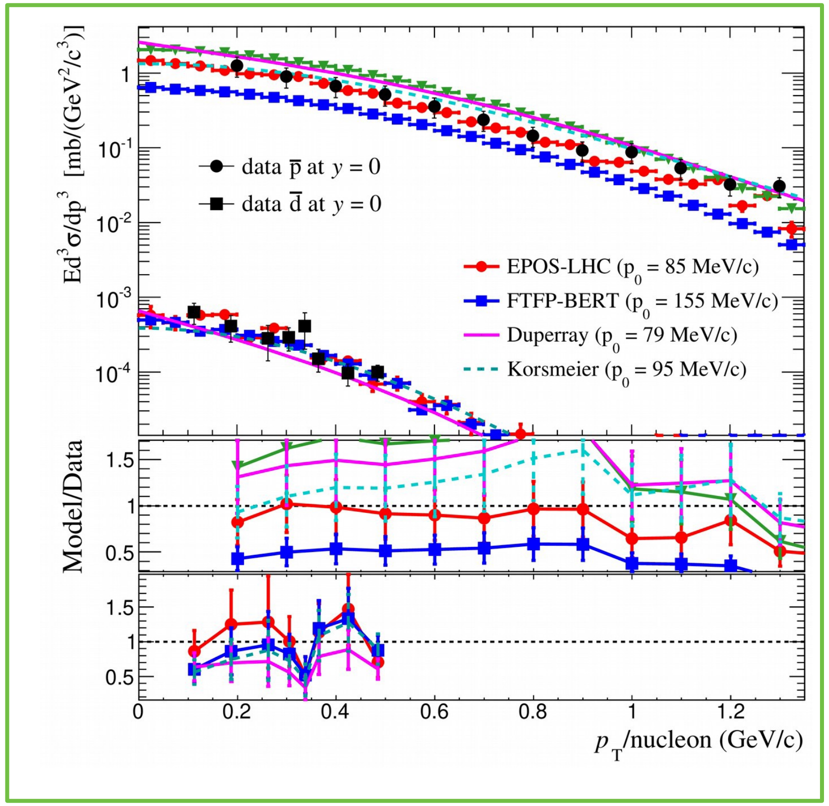
Example: p+p @ √s = 11.5 GeV



d-bar invariant differential x-section vs rapidity, from p + p @ 70 GeV/c

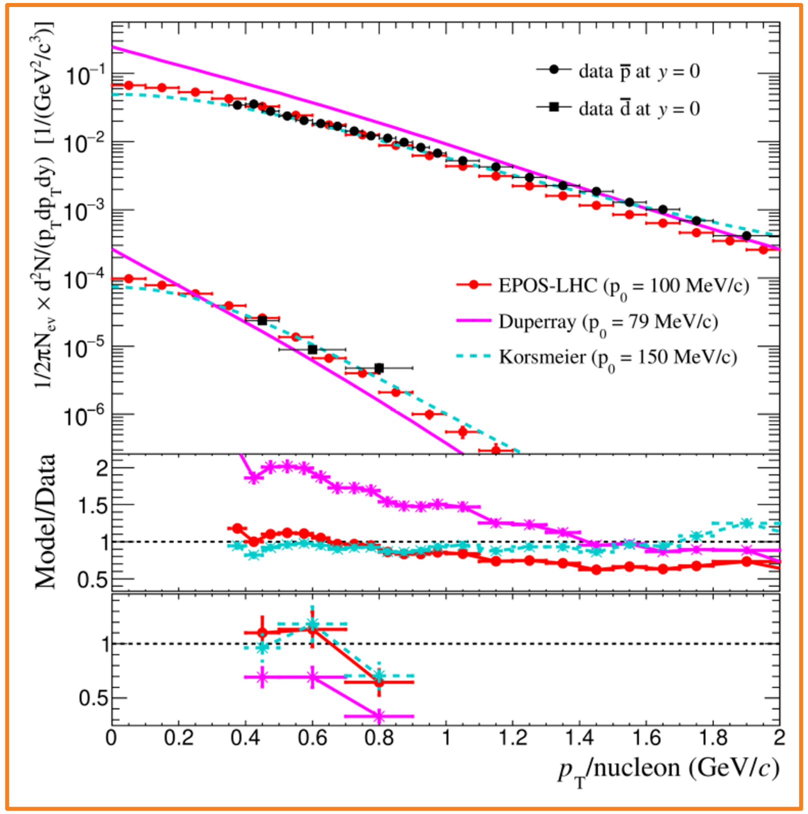
Other energies

p+p @ √s = 53 GeV



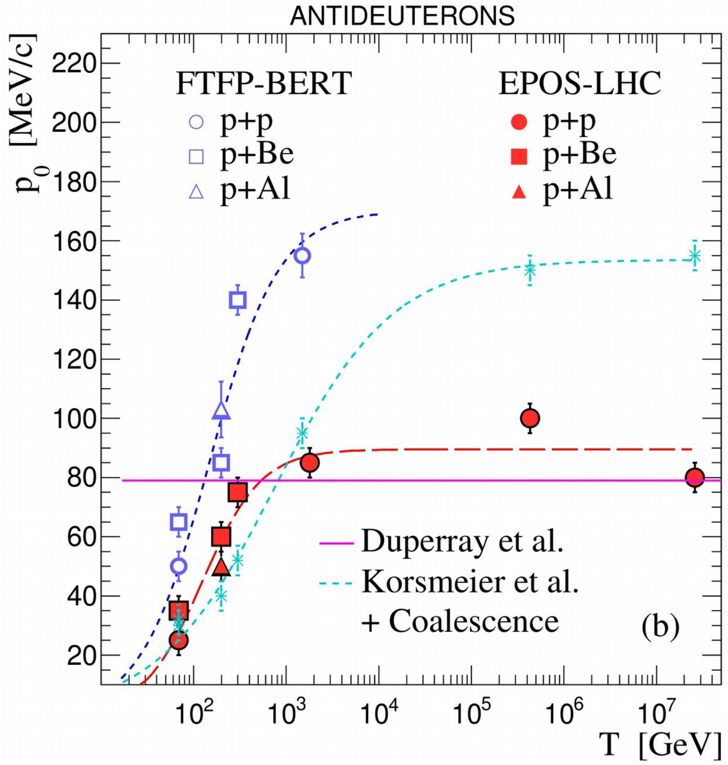
Comparison with ISR data.

p+p @ √s = 900 GeV

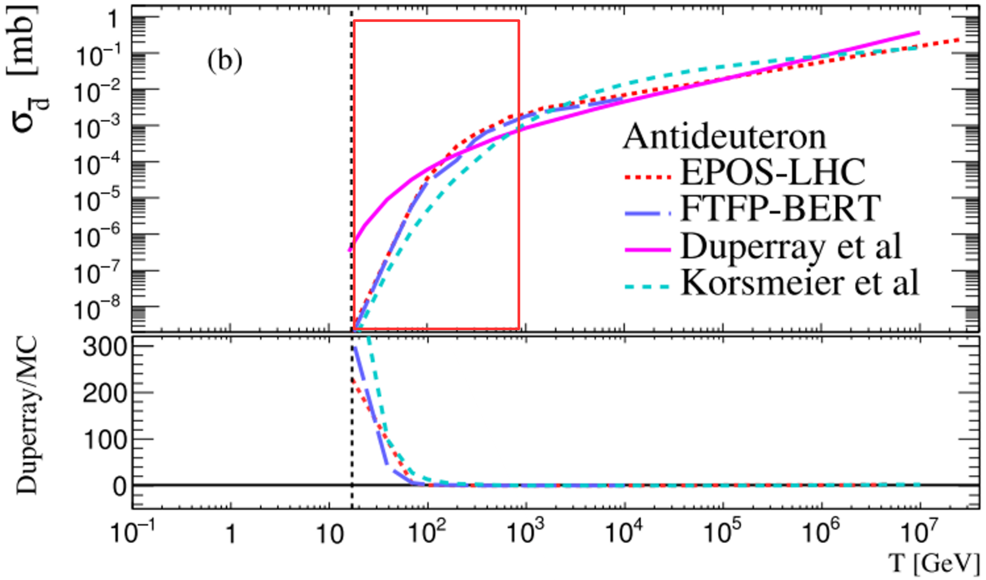


Comparison with ALICE-LHC data.

p_0 and cross sections for $\overline{\mathbf{d}}$, vs energía del proton



p+p → X + d



- p_0 variation occurs @ low T
- p_0 is similar for p+p y p+Be.

- P_0 variation in the region most relevant for CR´s

Galactic Transport Code (GALPROP)

Diffusion-convection and reacceleration

Convection velocity

Reacceleration coefficient

Decay, annihilation, fragmentation

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

Diffusion coefficient

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

Particle density

ISM interactions

Adiabatic processes

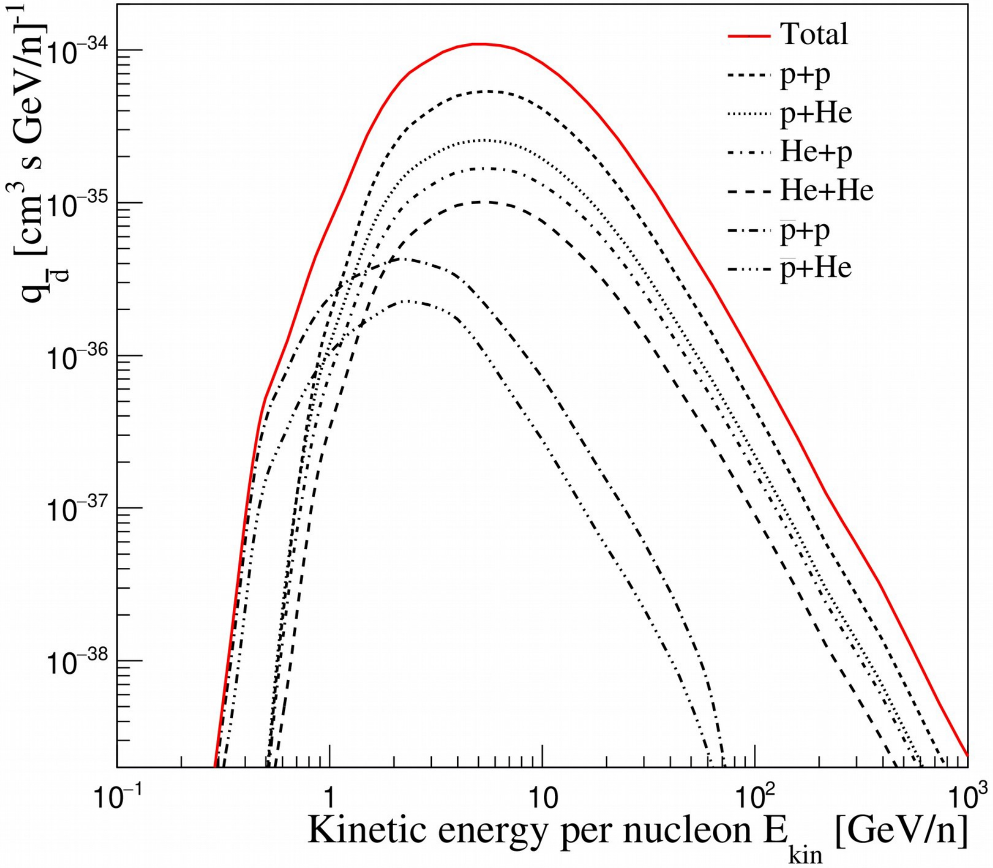
d sources

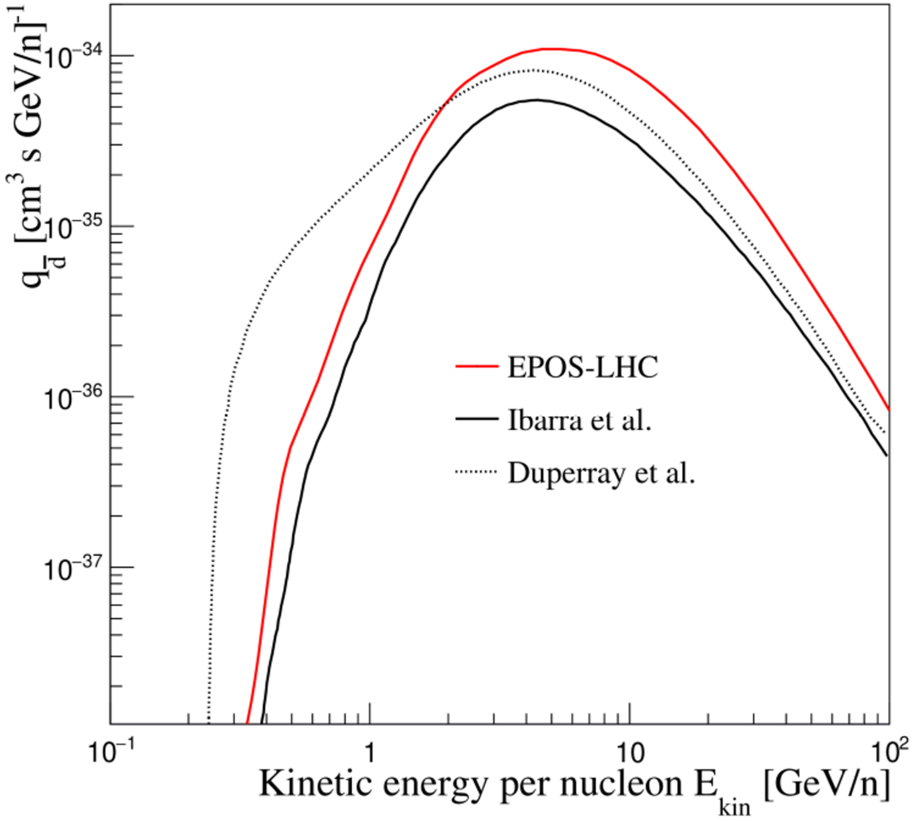
Most significant $\overline{\mathrm{d}}$ sources

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

p, He flux

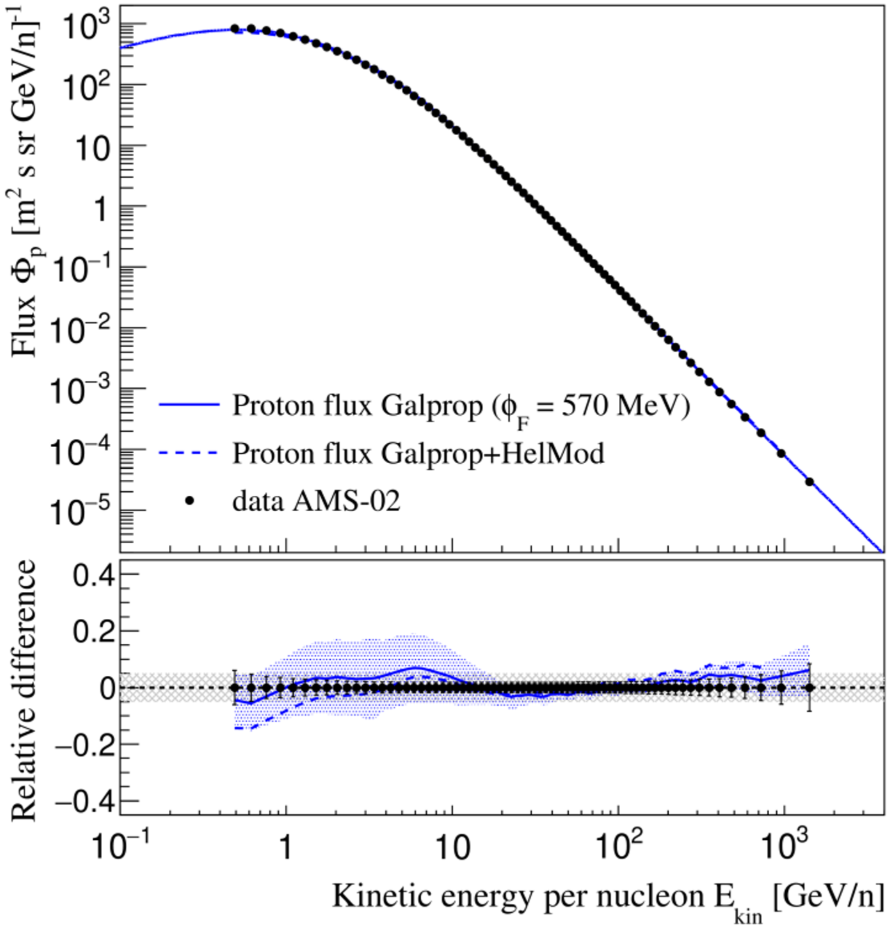
EPOS-LHC
X-section



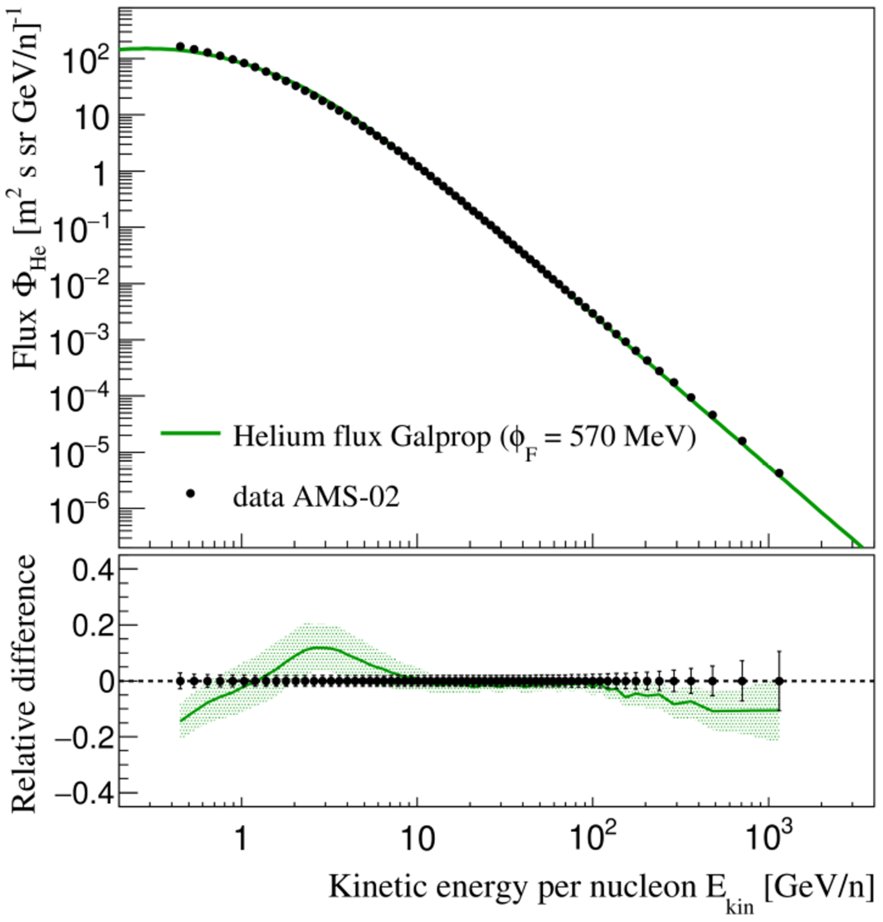


GALPROP is certified for p's and α's

Proton Flux



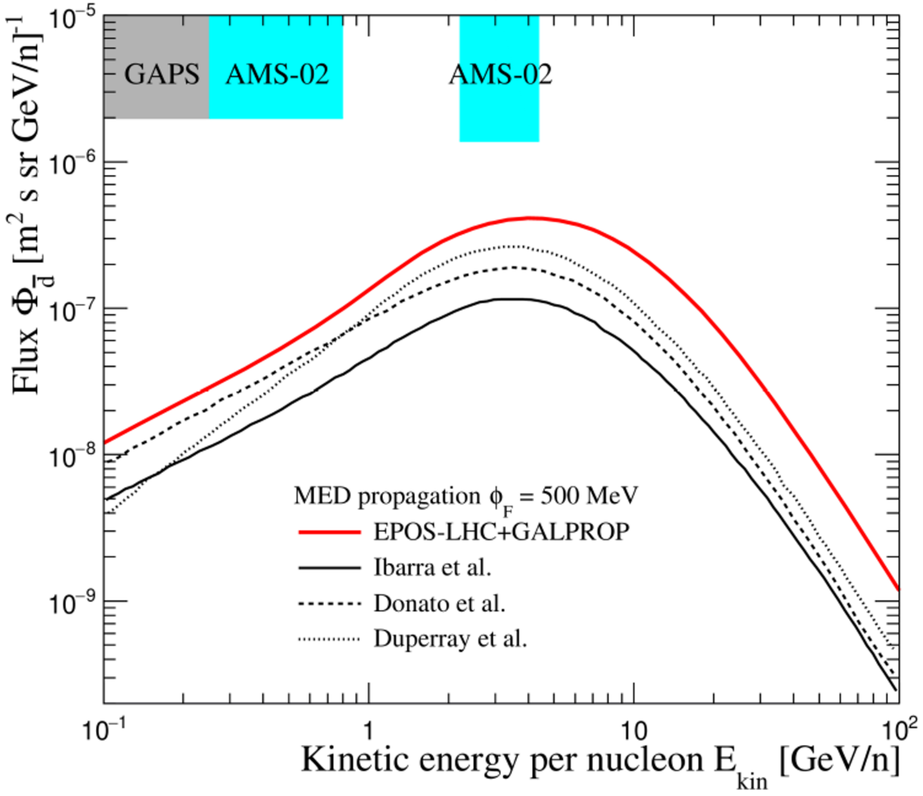
Helium Flux

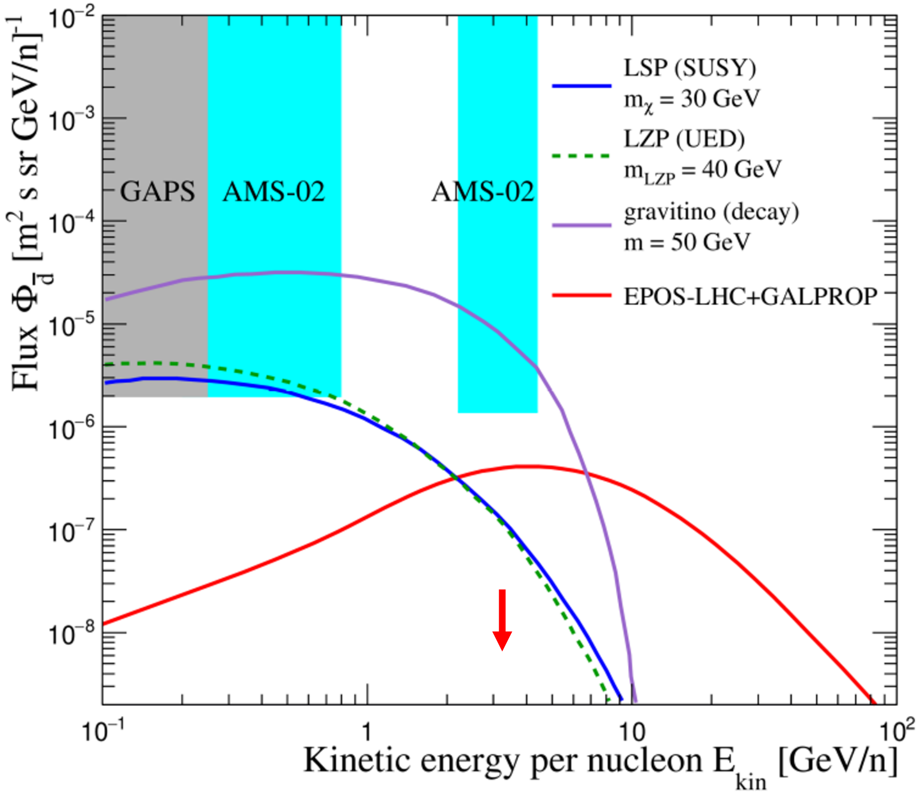


Predicted $\overline{d}$ SM backgound

Maximum is displaced

High Energy component also increased



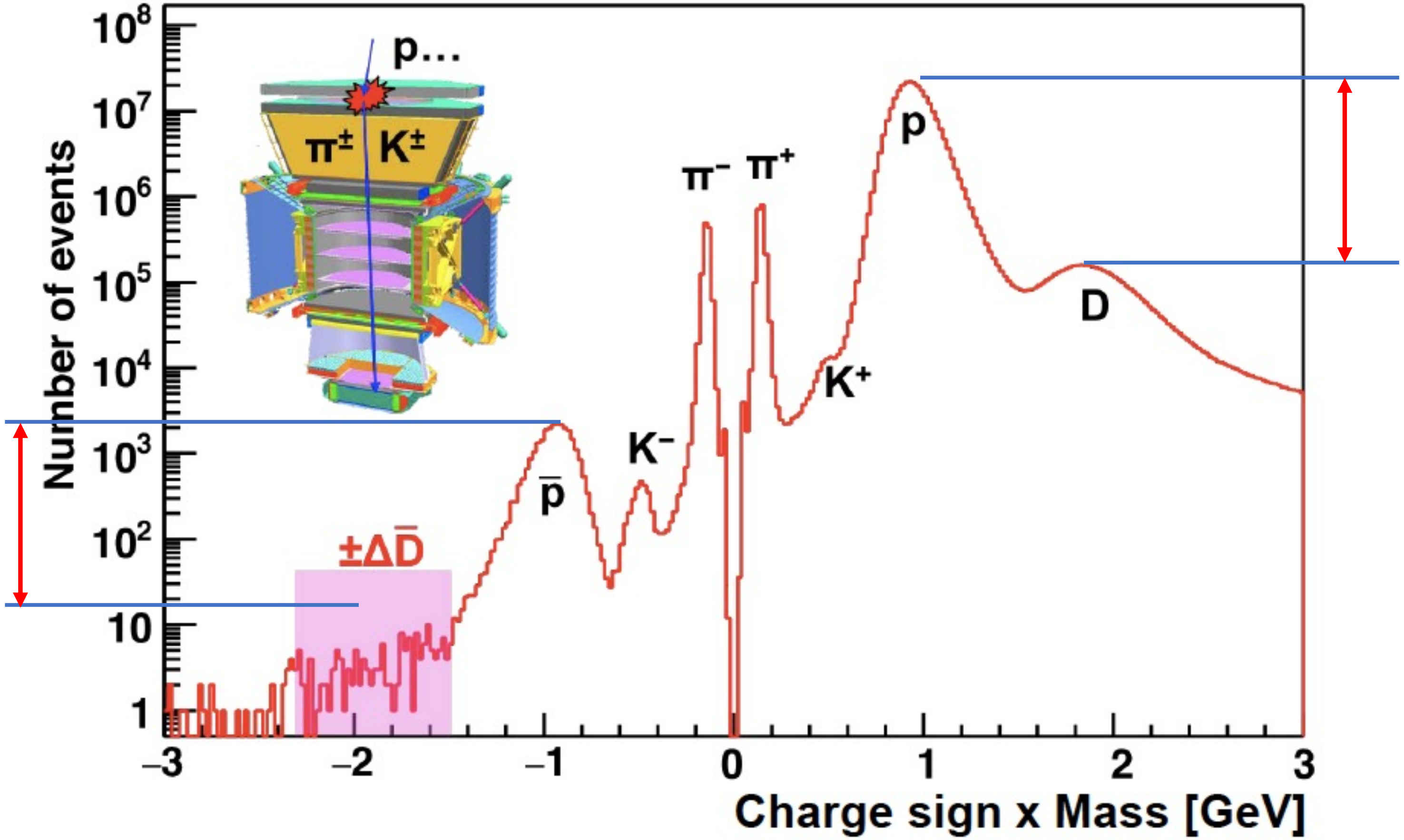


Low energy increment is due to adiabatic processes energy losses

AMS 02 data? (PRELIMINARY)

Status of Anti-Deuteron Analysis

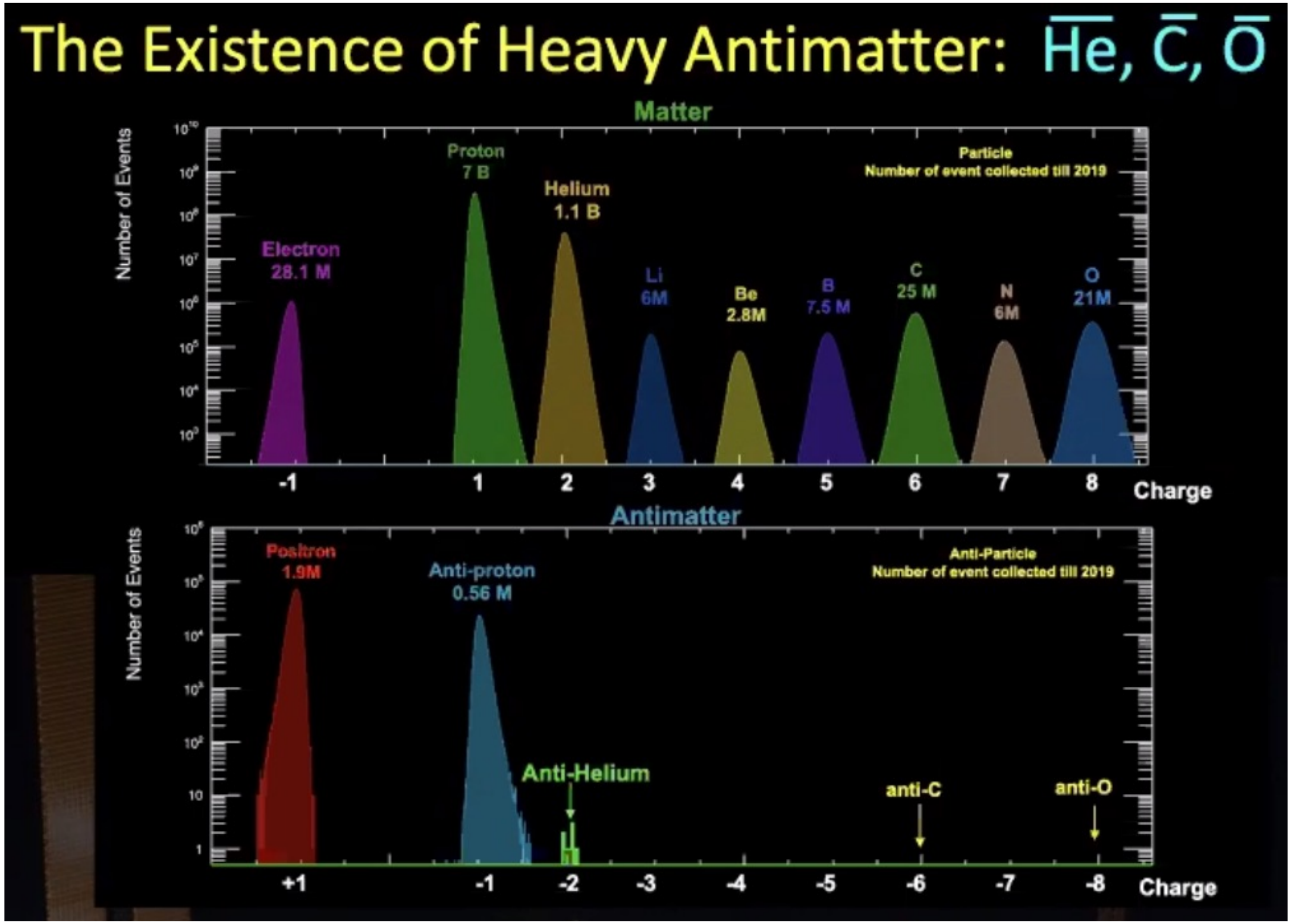
$\bar{d}$'s consistent with background



< 1/200

≈ 1/200

What about $\overline{\text{He}}$'s? (PRELIMINARY)



$\overline{\text{He}}/\bar{d} \gtrsim 1$?

Thanks!