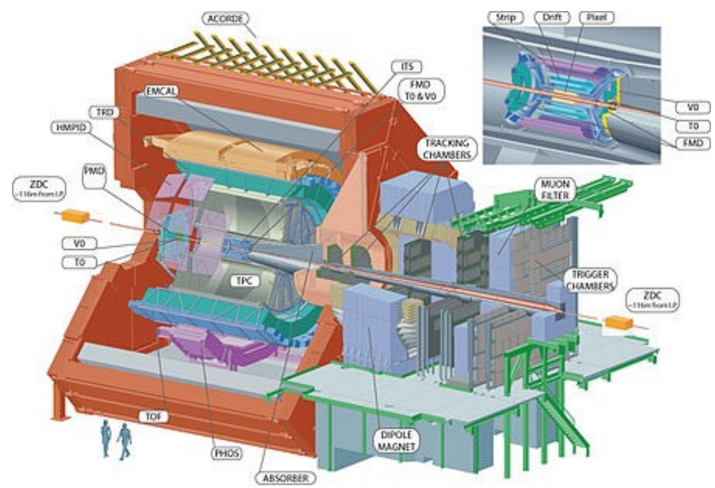
Cosmic rays and the connection to (anti-)nuclei production

Kfir Blum

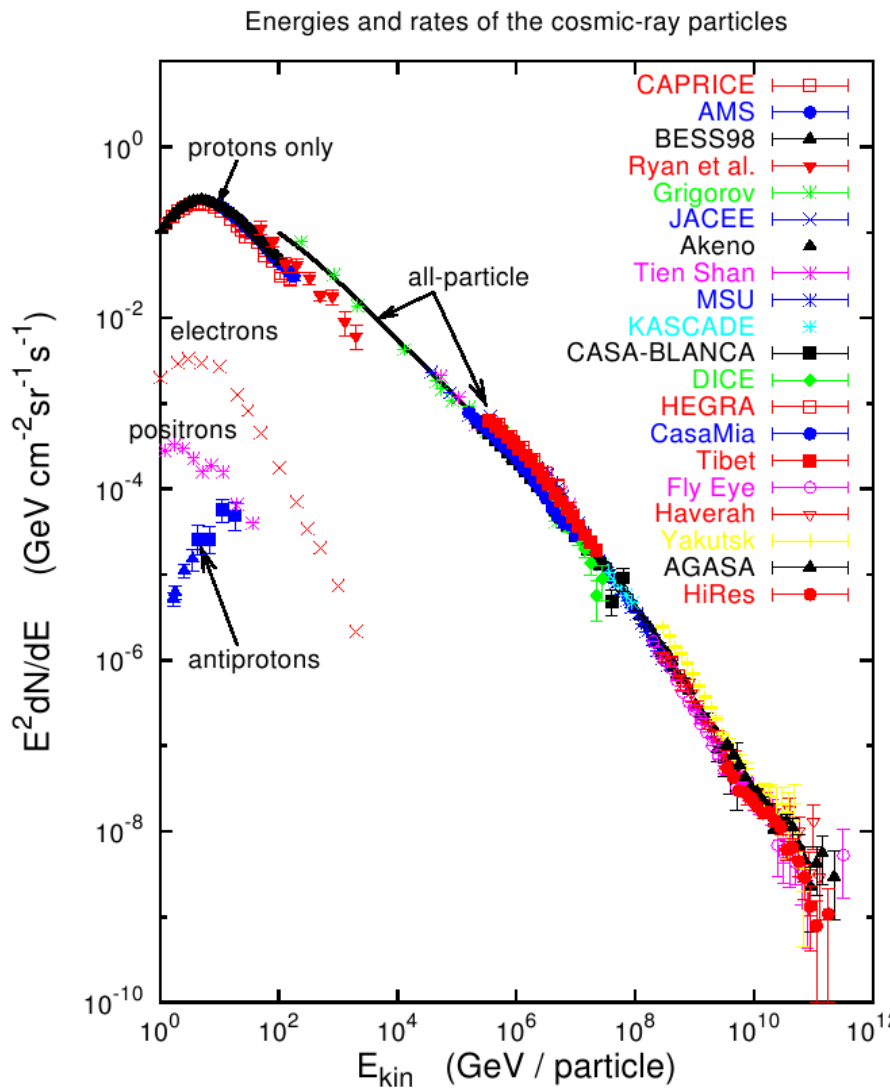
CERN & Weizmann Institute



EMMI workshop, Turin, Nov 7 2017

Cosmic Rays

The Universe is filled with a gas of high-energy particles



Hillas, astro-ph/0607109

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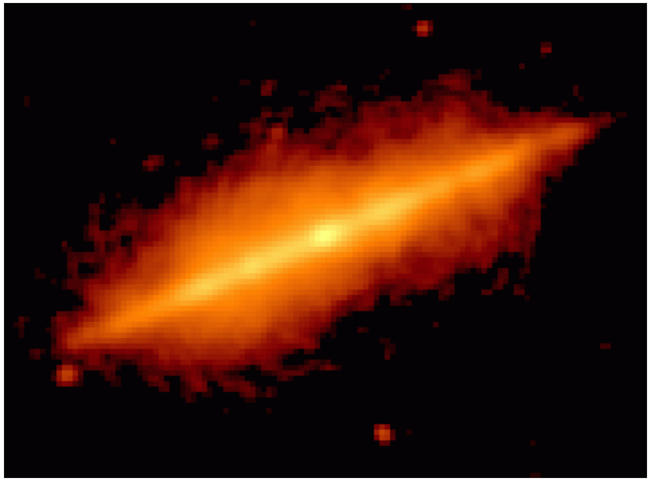
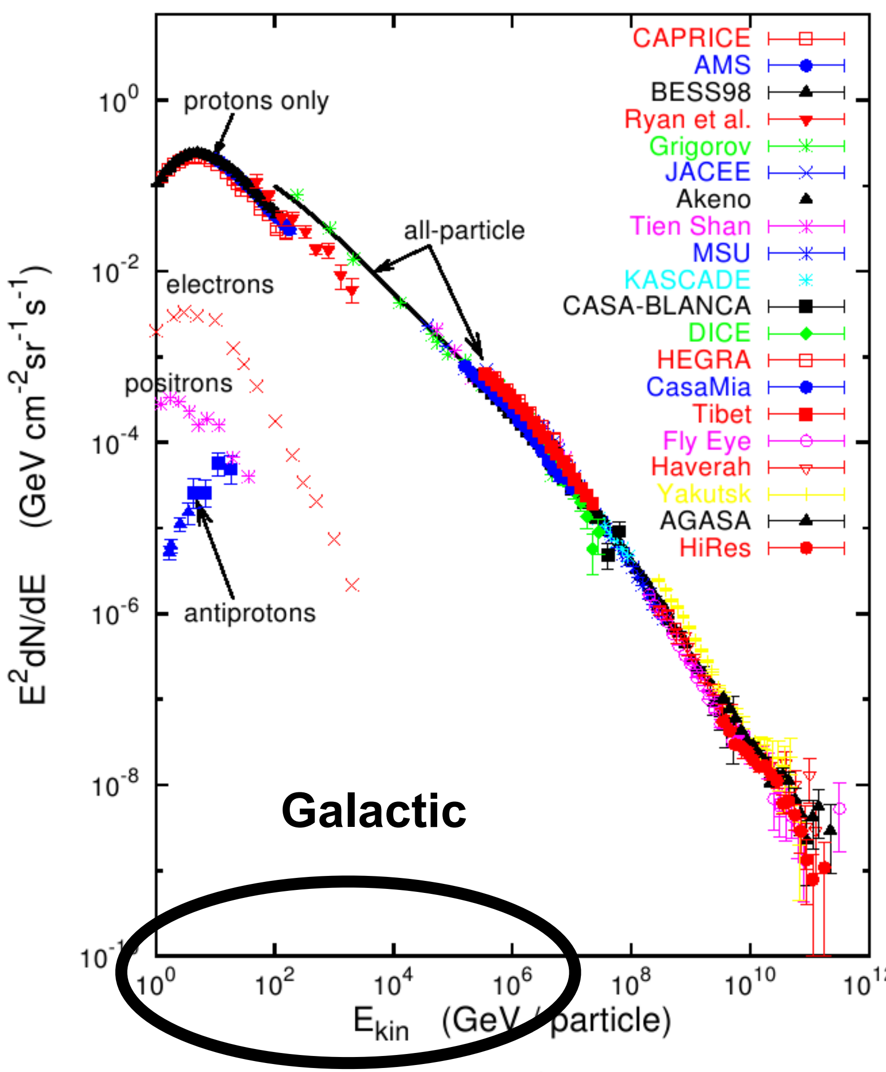


Energies and rates of the cosmic-ray particles



Hillas, astro-ph/0607109

Cosmic Rays

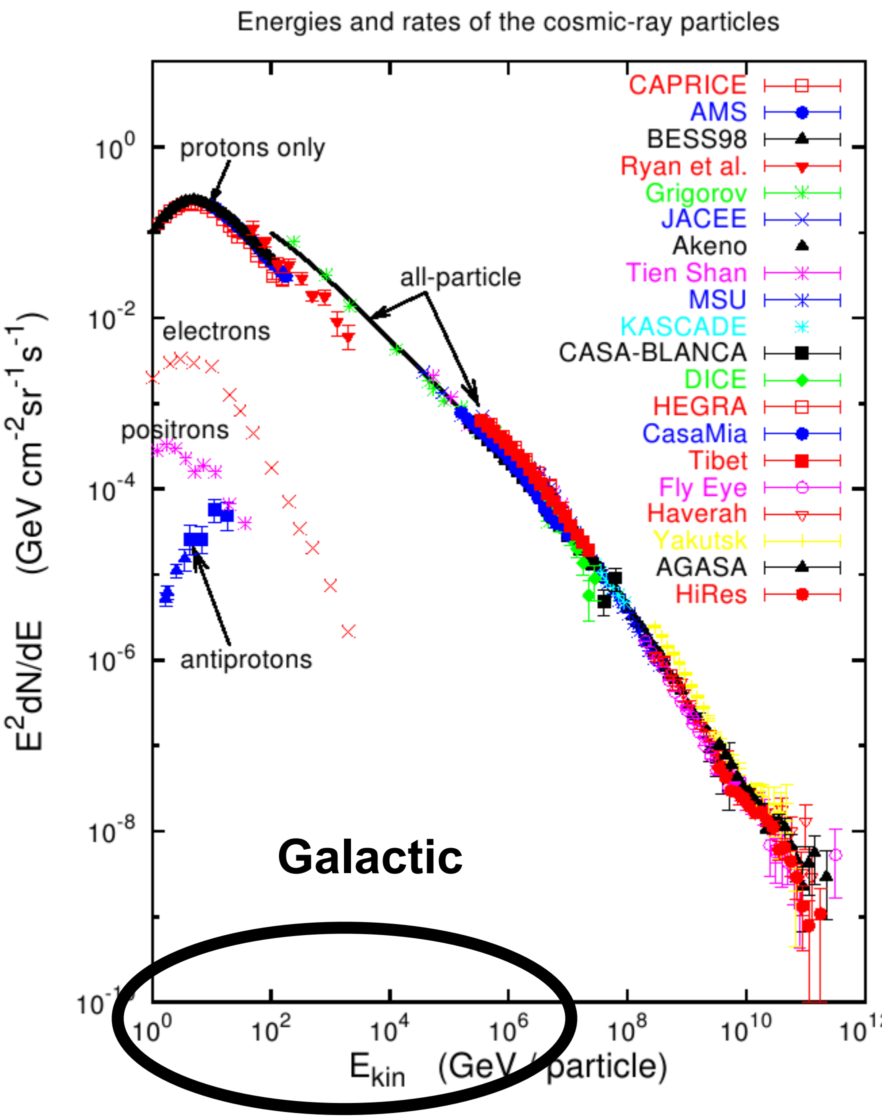
The Universe is filled with a gas of high-energy particles

Where do they come from?

What role do they play in Cosmic evolution?

What role do they play in Galaxy dynamics?

Do they contain hints of exotic high-energy physics?



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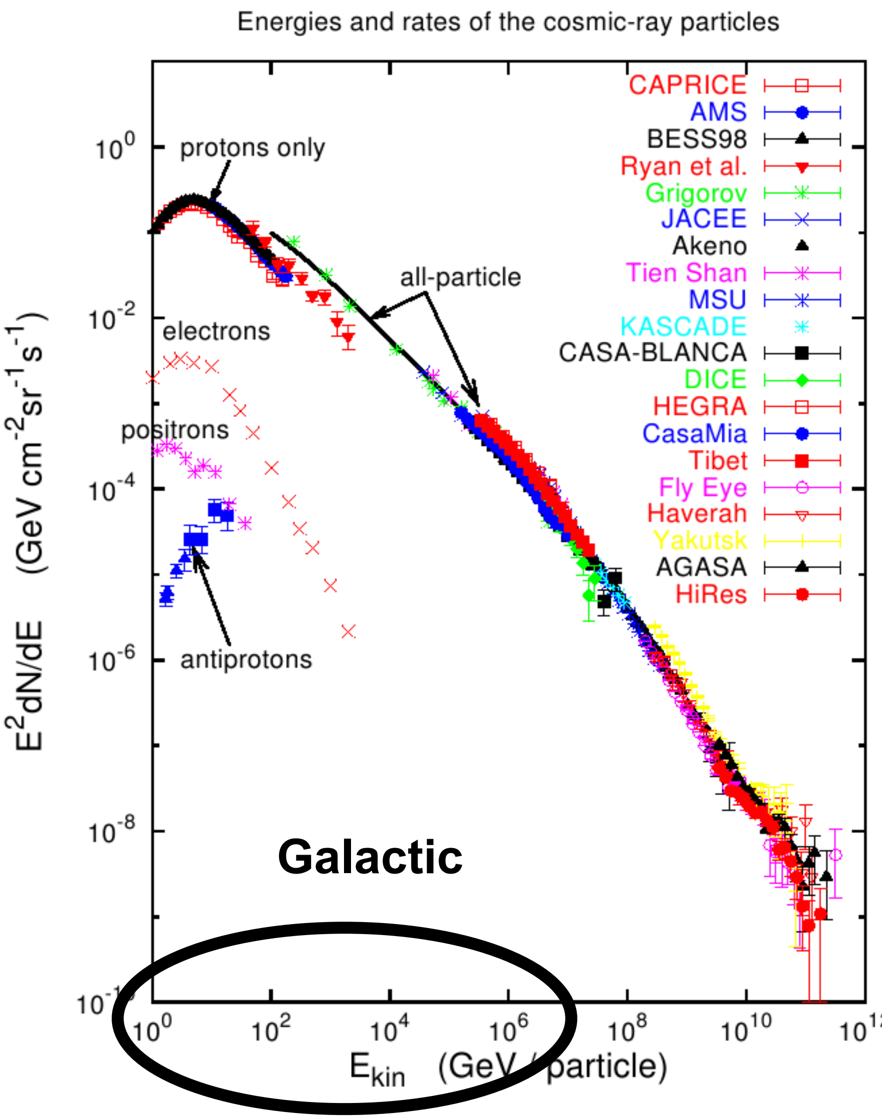
Cosmic Rays

Two basic populations:

1. **primary** (p, He, C, O, Fe, e-,…),

2. **secondary** (B, sub-Fe, pbar, e+,…),



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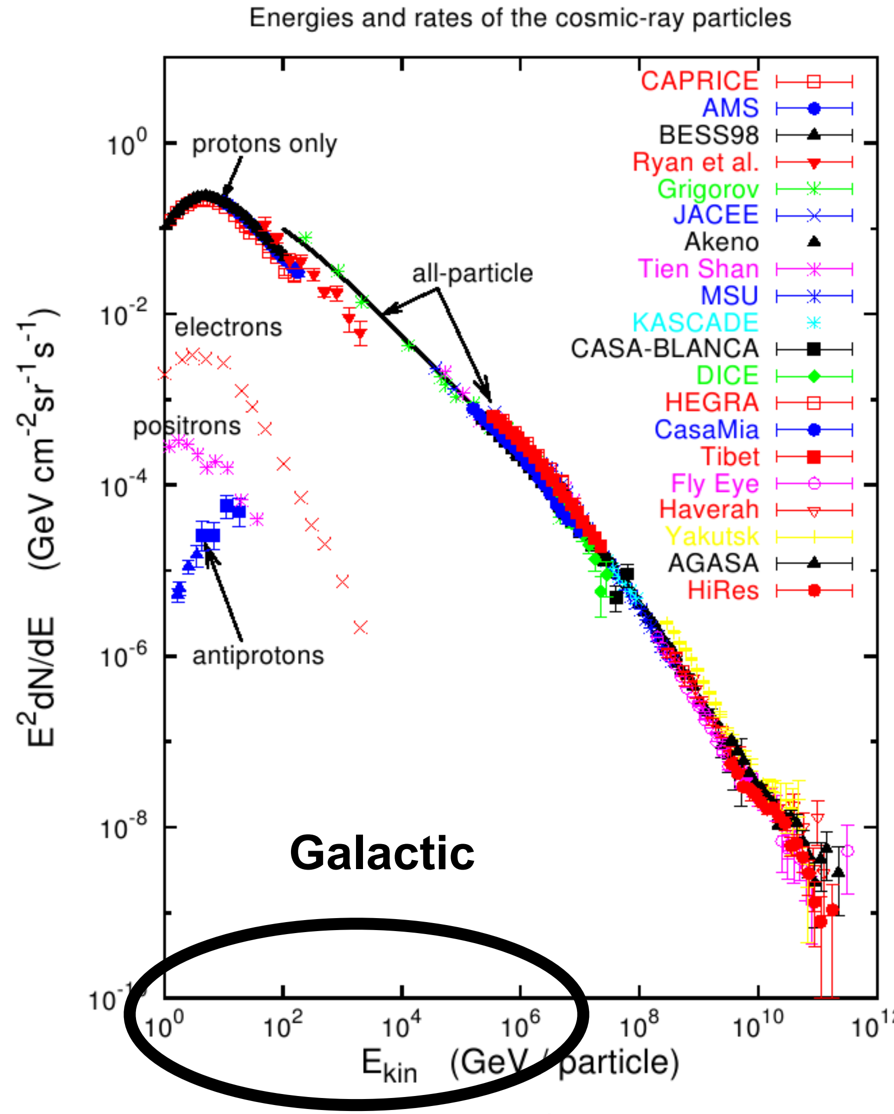

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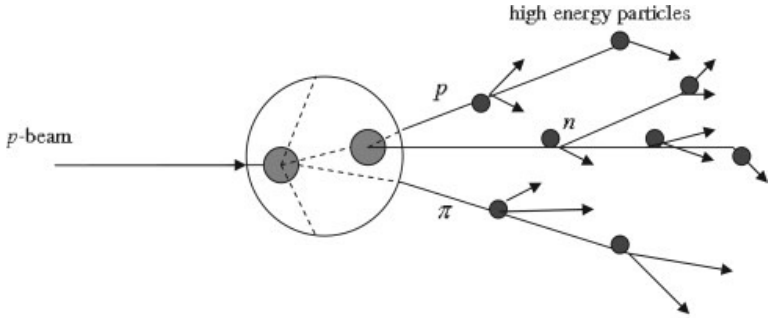

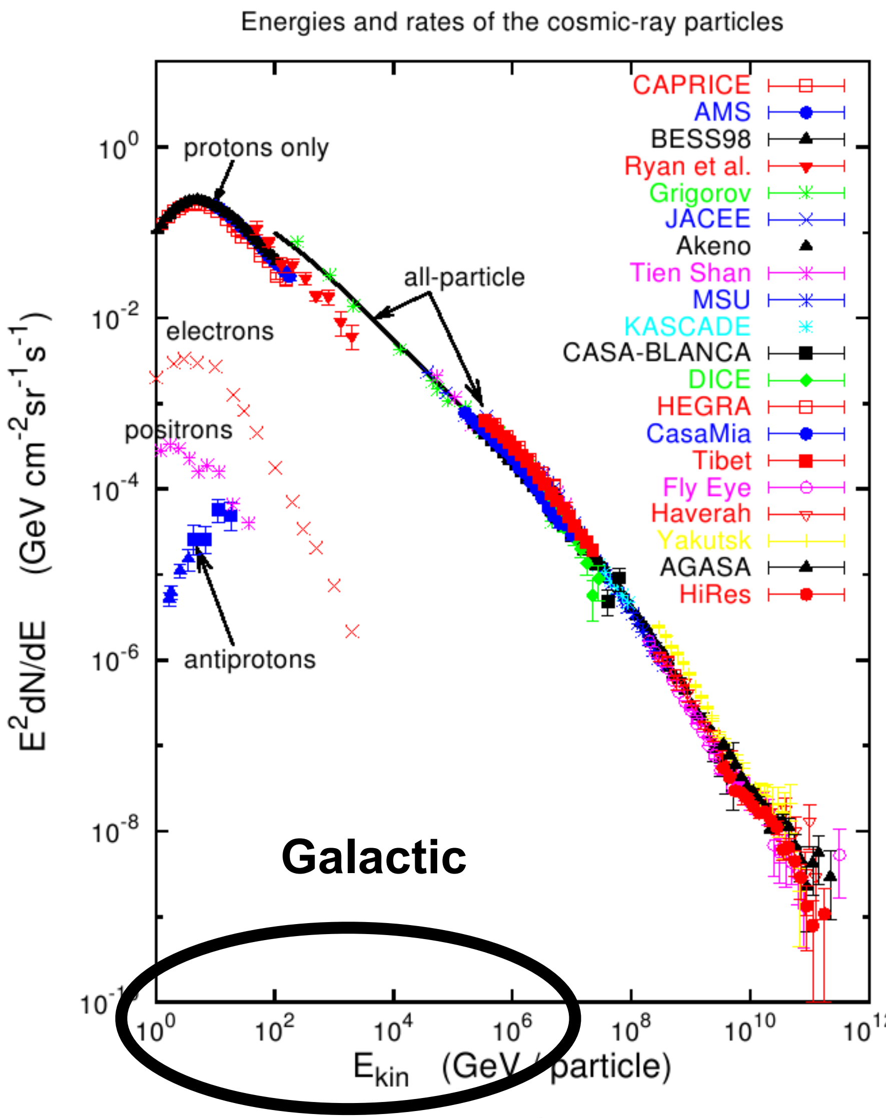

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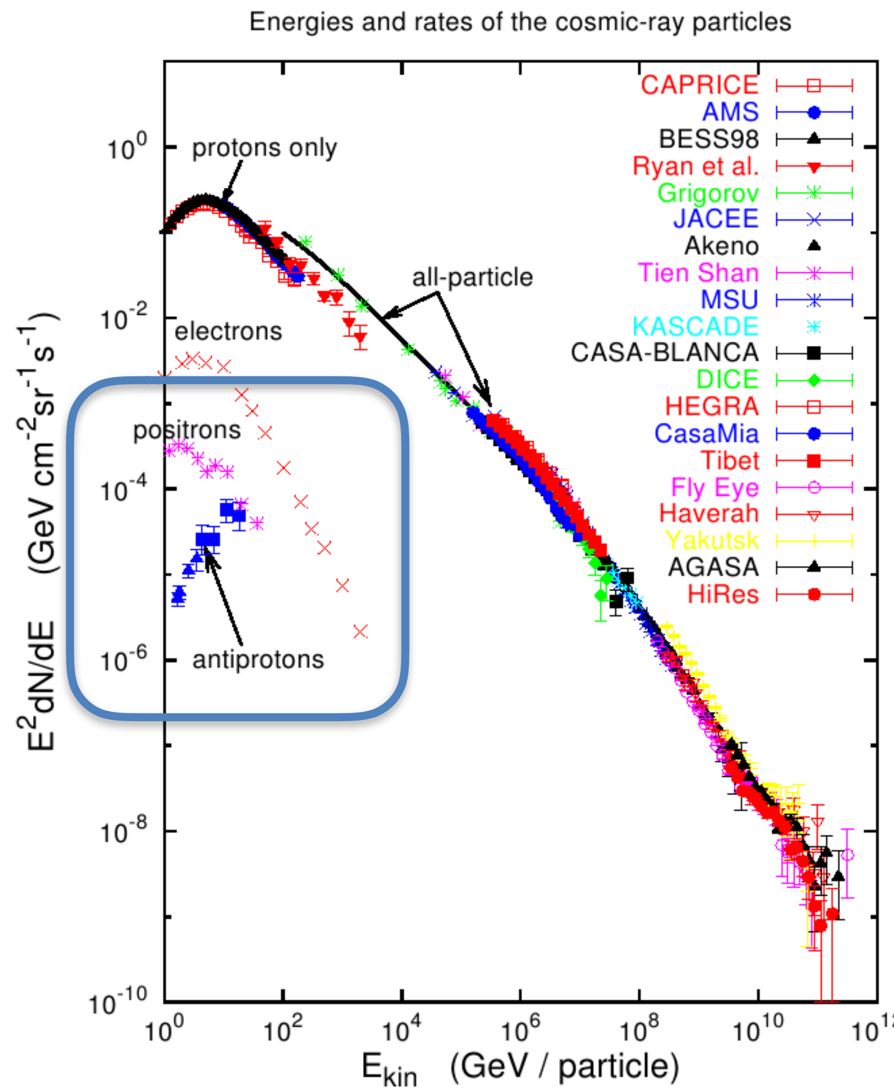
CR antimatter – $\bar{p}$, e^+, $\bar{\mathrm{d}}$, and $\overline{^3\mathrm{He}}$ – long thought a smoking gun of exotic high-energy physics like dark matter annihilation



CR antimatter – $\bar{p}$, e^+, $\bar{\mathrm{d}}$, and $\overline{^3\mathrm{He}}$ – long thought a smoking gun of exotic high-energy physics like dark matter annihilation

A host of experiments out there to detect it.

CR antimatter – $\bar{p}$, e^+, $\bar{\mathrm{d}}$, and $\overline{^3\mathrm{He}}$ – long thought a smoking gun of exotic high-energy physics like dark matter annihilation

Antiprotons

Some confusion in the literature, as to what and how we can calculate.

=> will try to sort this out

Anti-helium, anti-deuterium

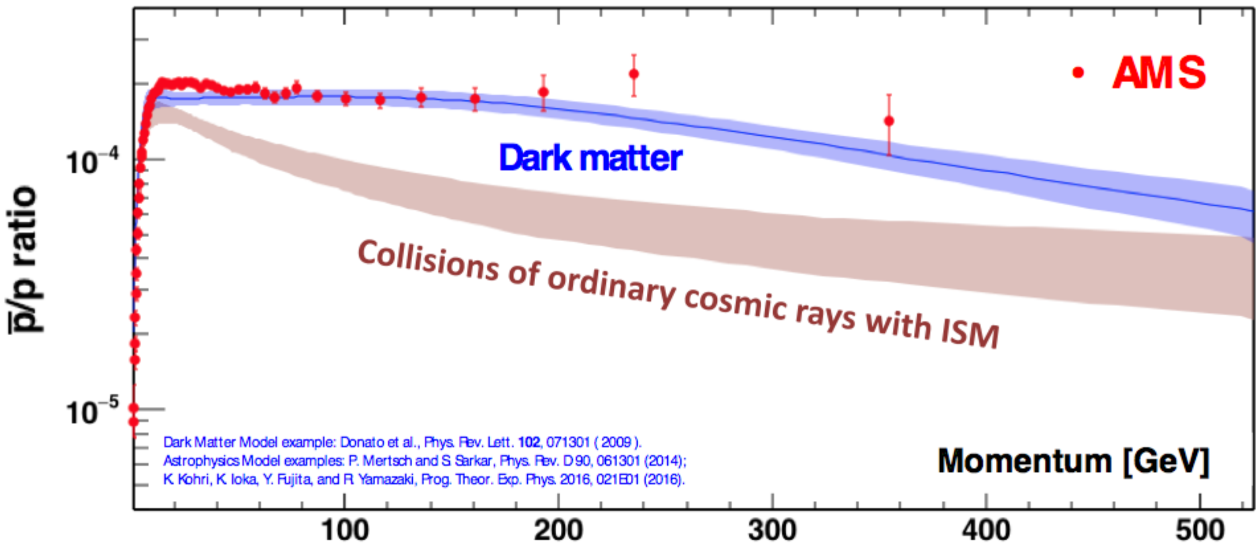
Thought so scarce that a single event would mark new physics.

=> but how does one actually calculate the flux?

will show very **recent progress thanks to the LHC ALICE** collaboration

AMS02, Dec 2016

Antiproton-to-proton ratio



The excess of antiprotons observed by AMS cannot come from pulsars.

It can be explained by Dark Matter collisions or by new astrophysics phenomena

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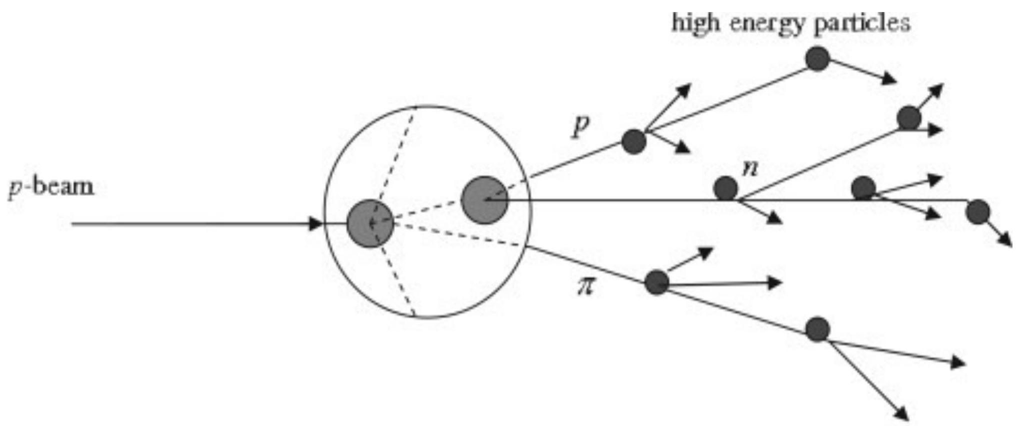
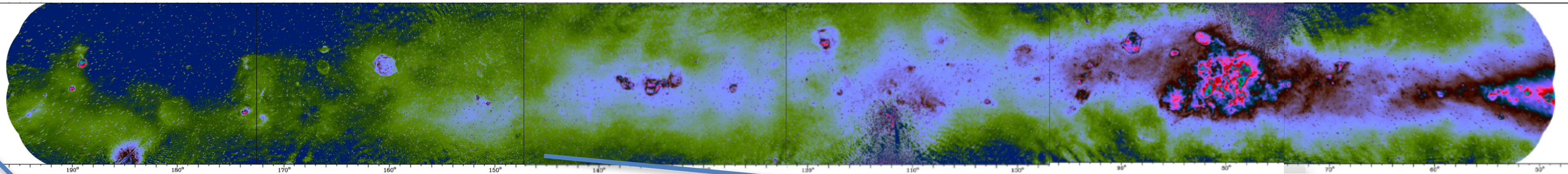
antimatter is produced in collisions of the bulk of the CRs
-- protons and He – with interstellar gas

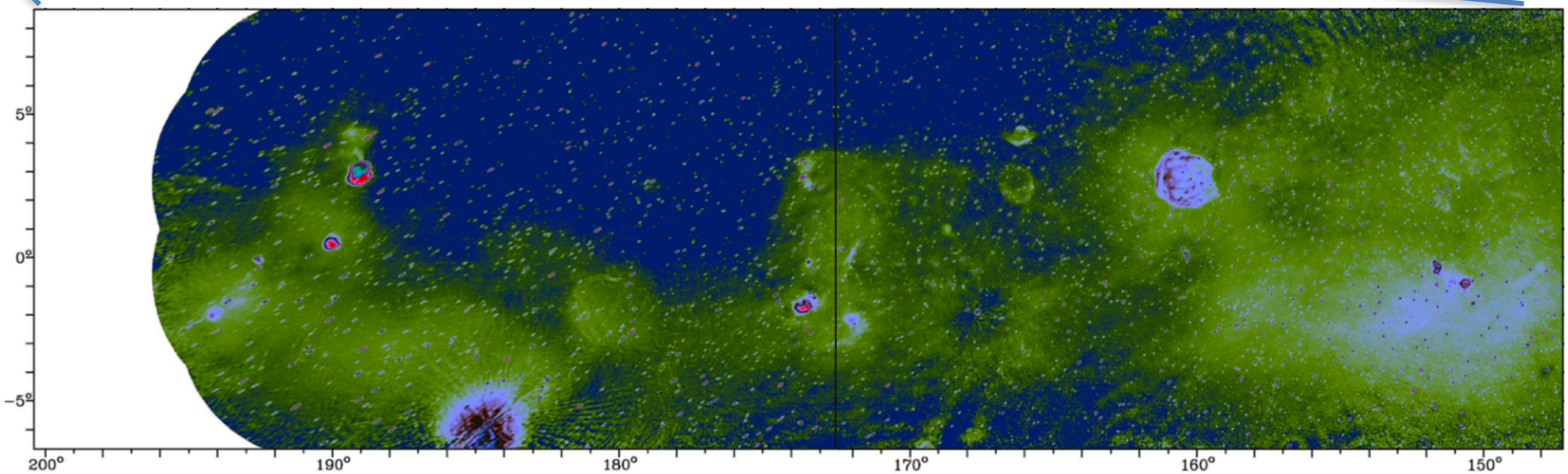
Need to calculate this background to learn about possible exotic sources

Problem: we don't know where CRs come from, nor how long they are trapped in the Galaxy, nor how they eventually escape.

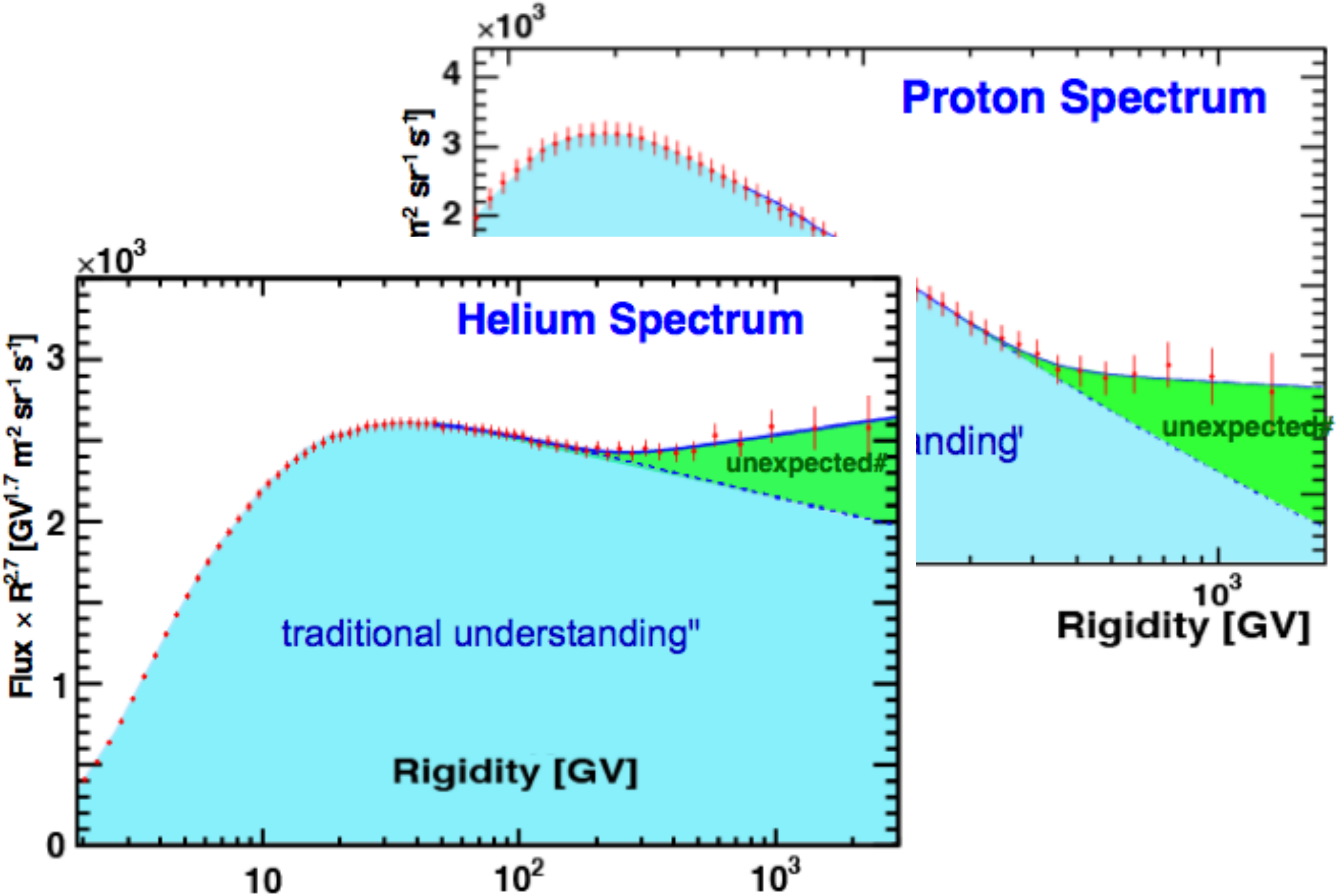


https://arxiv.org/pdf/1708.04316.pdf
408MHz (Canadian Galactic Plane Survey)





S. Schael, **Moriond 2016 for AMS02**



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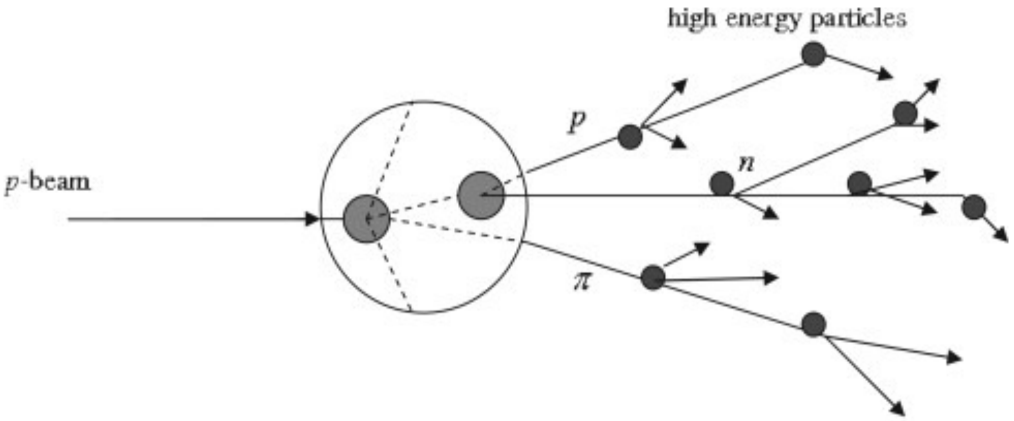

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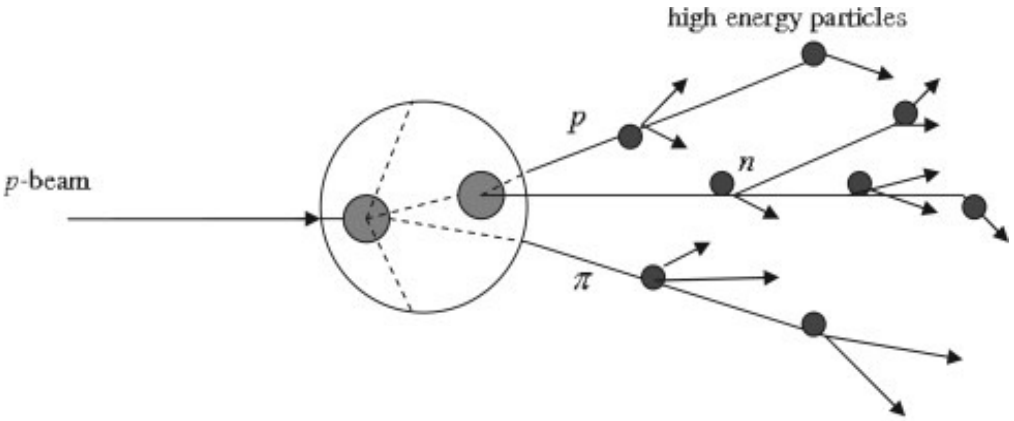
For secondary antimatter we have a handle: particle physics branching fractions

$$\frac{n_a(\mathcal{R})}{n_b(\mathcal{R})} \approx \frac{Q_a(\mathcal{R})}{Q_b(\mathcal{R})}$$



Recipe for an antiproton pie:

$$\frac{n_a(\mathcal{R})}{n_b(\mathcal{R})} \approx \frac{Q_a(\mathcal{R})}{Q_b(\mathcal{R})} \quad \Rightarrow \quad n_{\bar{p}}(\mathcal{R}) \approx \frac{n_{\rm B}(\mathcal{R})}{Q_{\rm B}(\mathcal{R})} Q_{\bar{p}}(\mathcal{R})$$

MNRAS 405 (2010) 1458 Katz, Blum, Morag, Waxman

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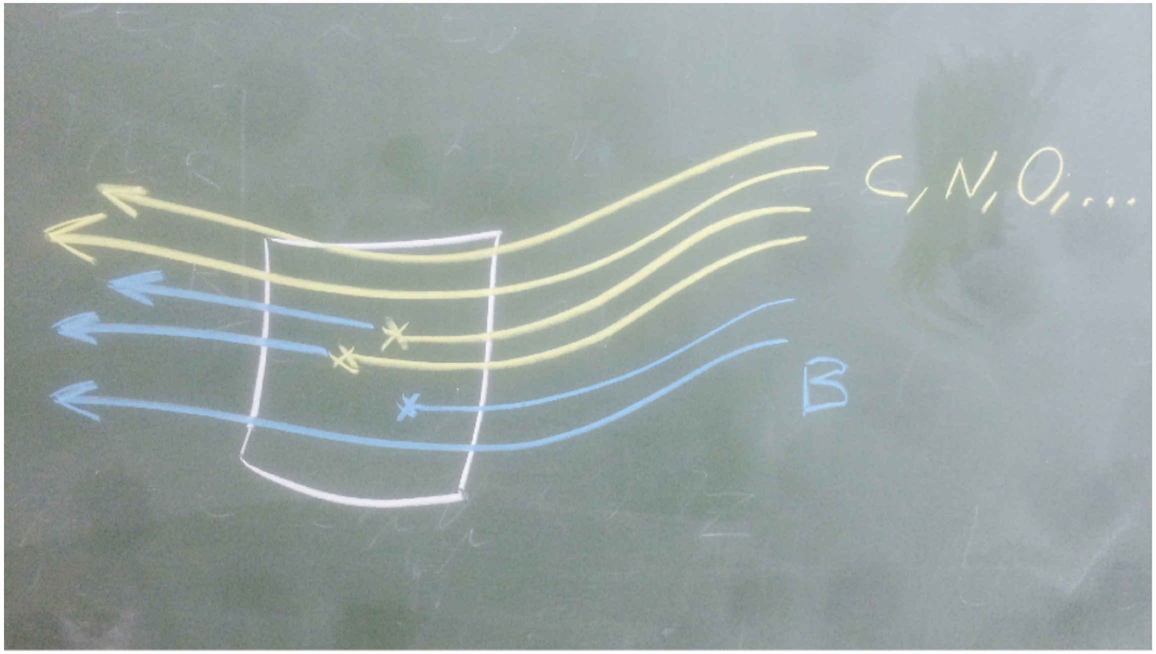
$$Q_a(\mathcal{R}) = \sum_P n_P(\mathcal{R}) \frac{\sigma_{P\to a}(\mathcal{R})}{m} - n_a(\mathcal{R}) \frac{\sigma_a(\mathcal{R})}{m}$$



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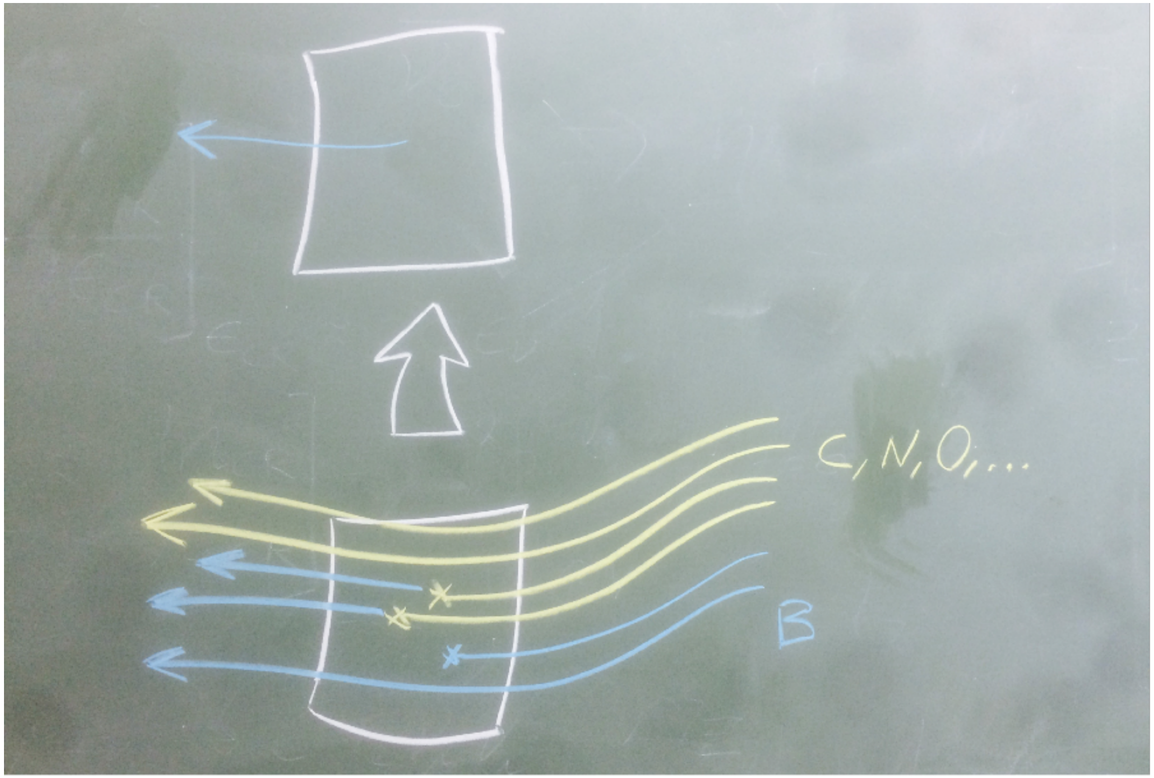

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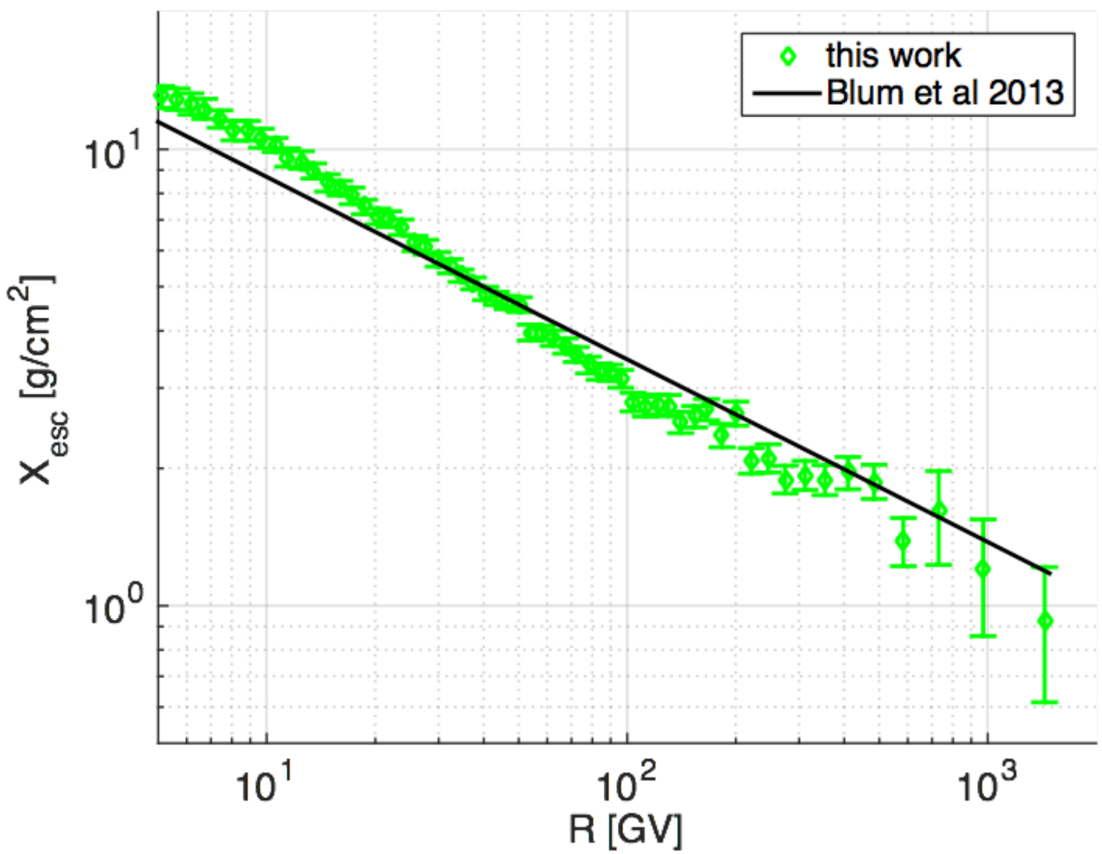
$$X_{\mathrm{esc}}(\mathcal{R}) = \frac{n_{\mathrm{B}}(\mathcal{R})}{Q_{\mathrm{B}}(\mathcal{R})}$$



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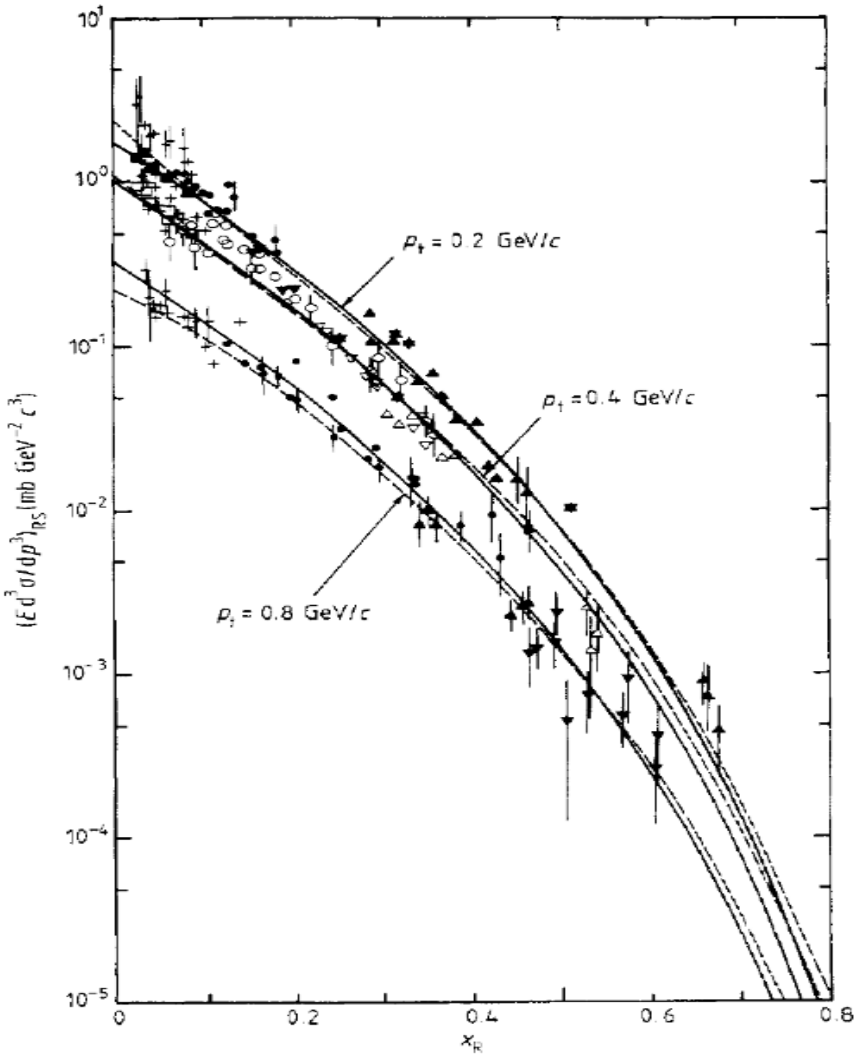

$$\sigma_{p\to\bar{p}}(\mathcal{R}) = \frac{2\int_{\mathcal{R}}^{\infty} d\mathcal{R}_p \, J_p(\mathcal{R}_p) \left(\frac{d\sigma_{pp\to\bar{p}X}(\mathcal{R}_p,\mathcal{R})}{d\mathcal{R}_p} \right)}{J_p(\mathcal{R})}$$

Recipe for an antiproton pie:

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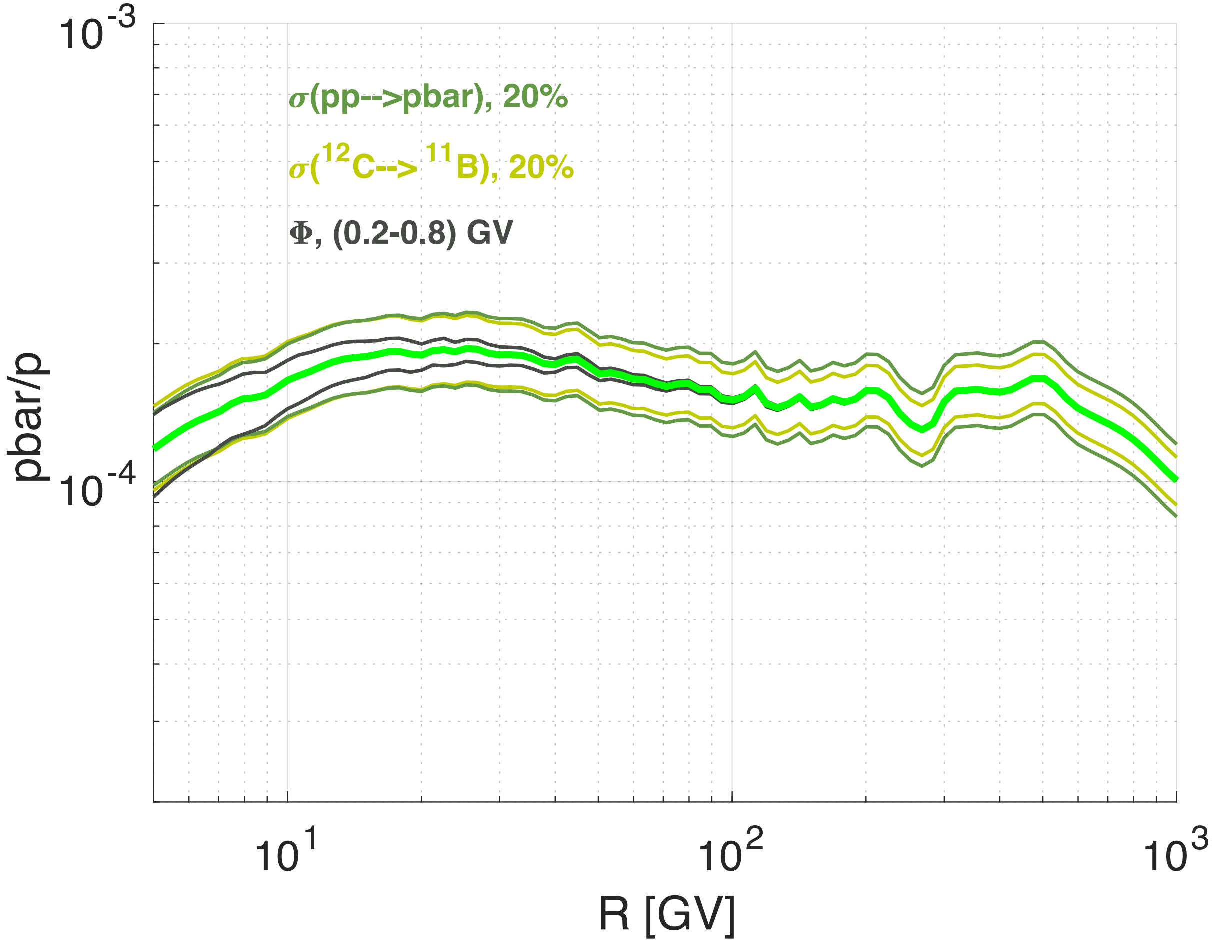

1704.05431, 1709.04953, 1709.06507

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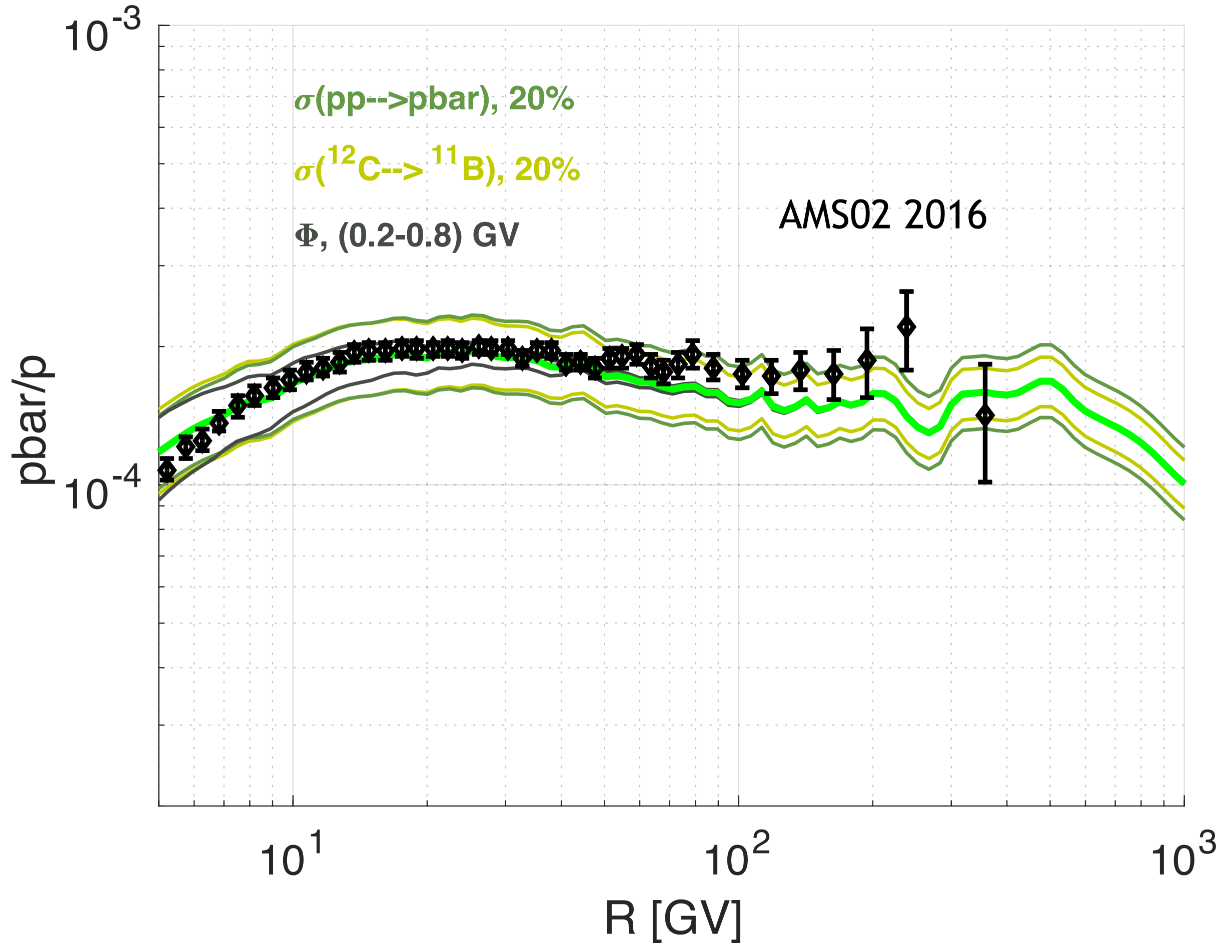

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Antiprotons are secondary.

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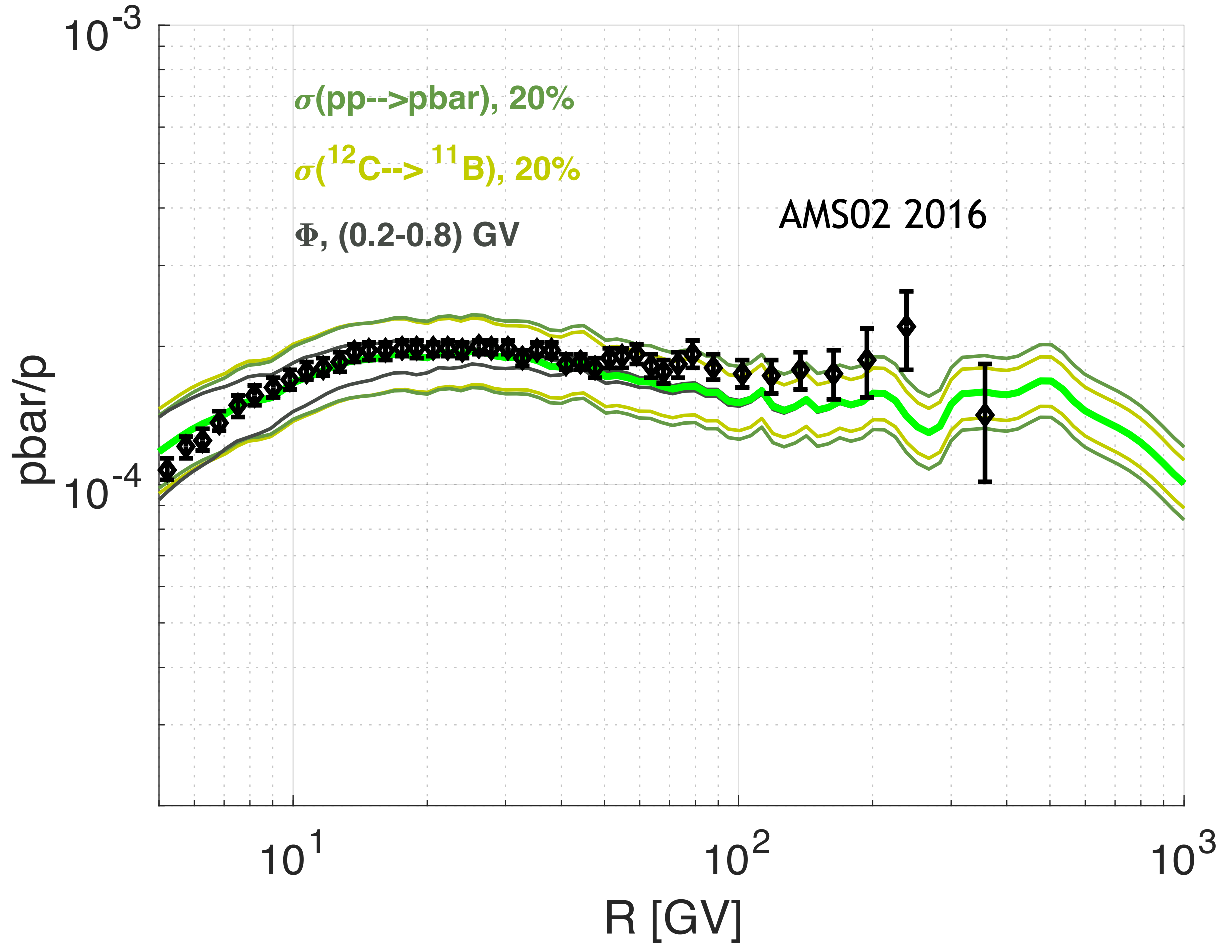

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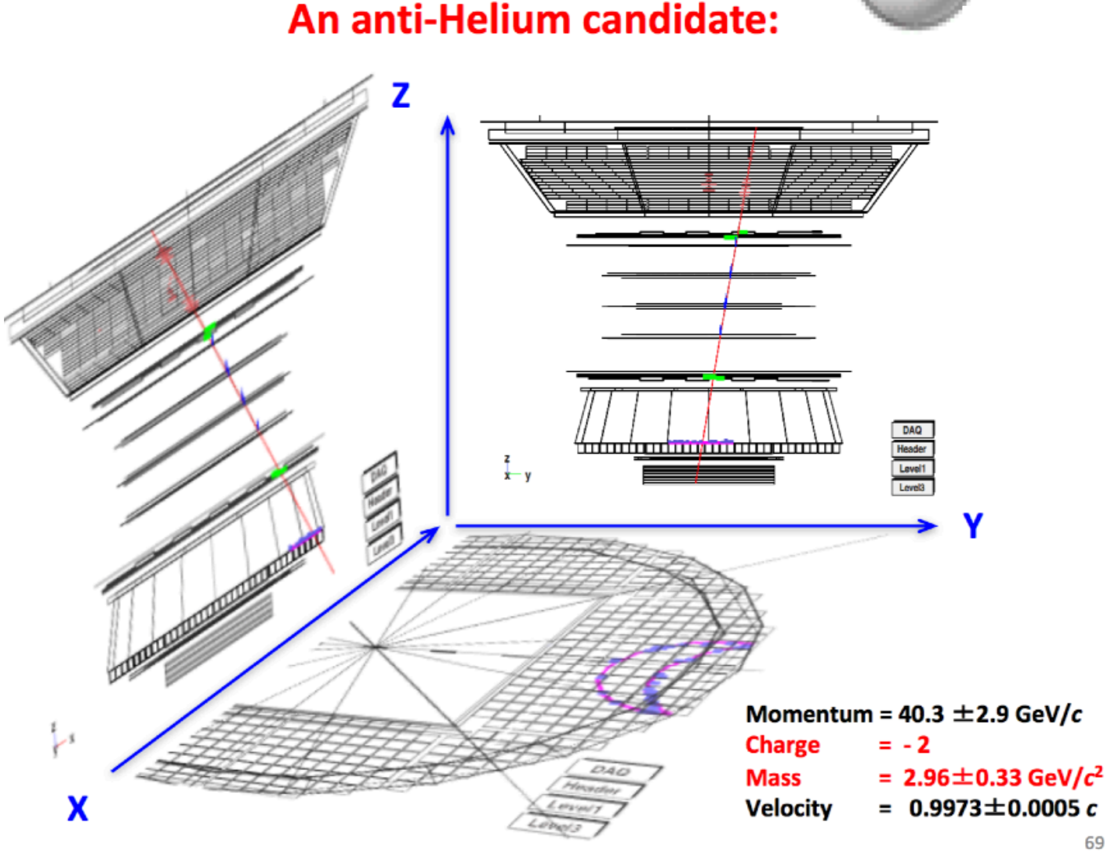
anti He3

anti He3

AMS02, Dec 2016

Handful of events?



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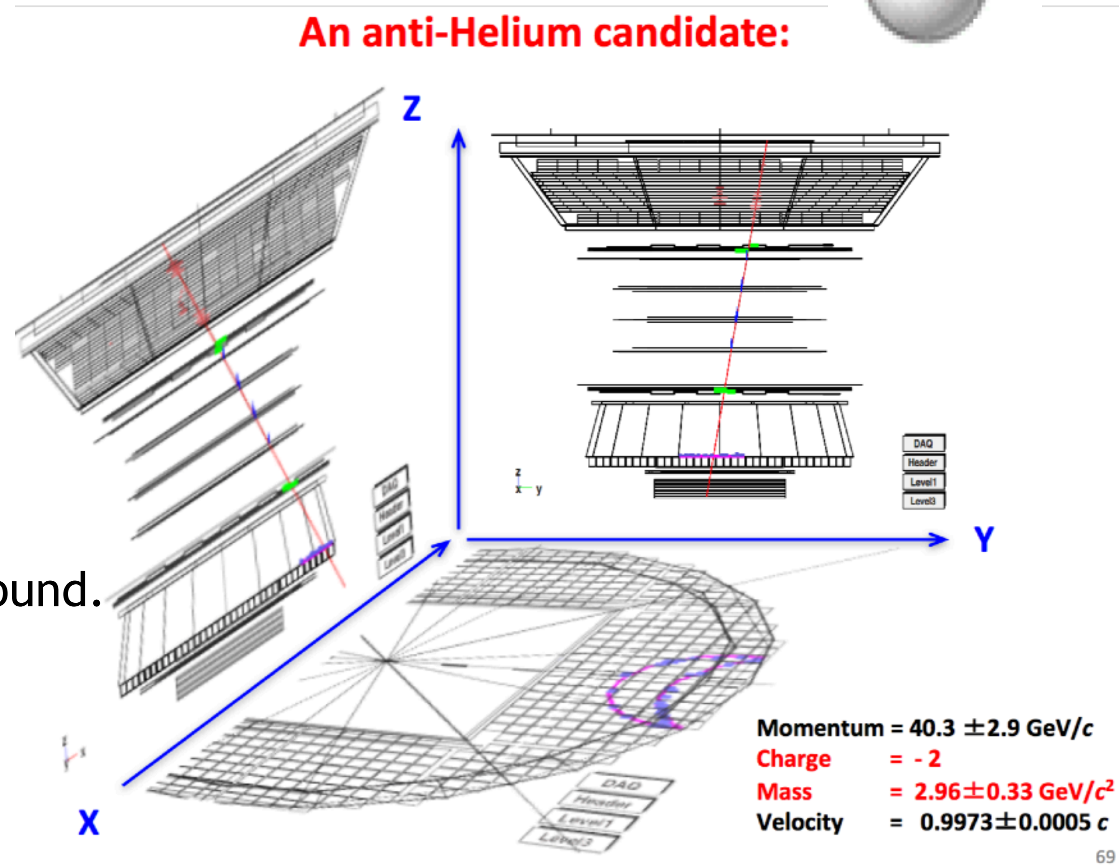

At this point it is not clear
if AMS02 is seeing true CR events,
or some rare experimental background.

Need to reject freak background
events at a level of ~ 1:100M…

We take it as motivation for theory examination of what
the astro anti-He3 flux is.

anti He3

"coalescence":

$$E_A \frac{dN_A}{d^3p_A} = B_A \, R(x) \, \left(E_p \frac{dN_p}{d^3p_p} \right)^A$$

The difficult part is to get the cross section right.

Note: we need pp initial state for astrophysics…

anti He3

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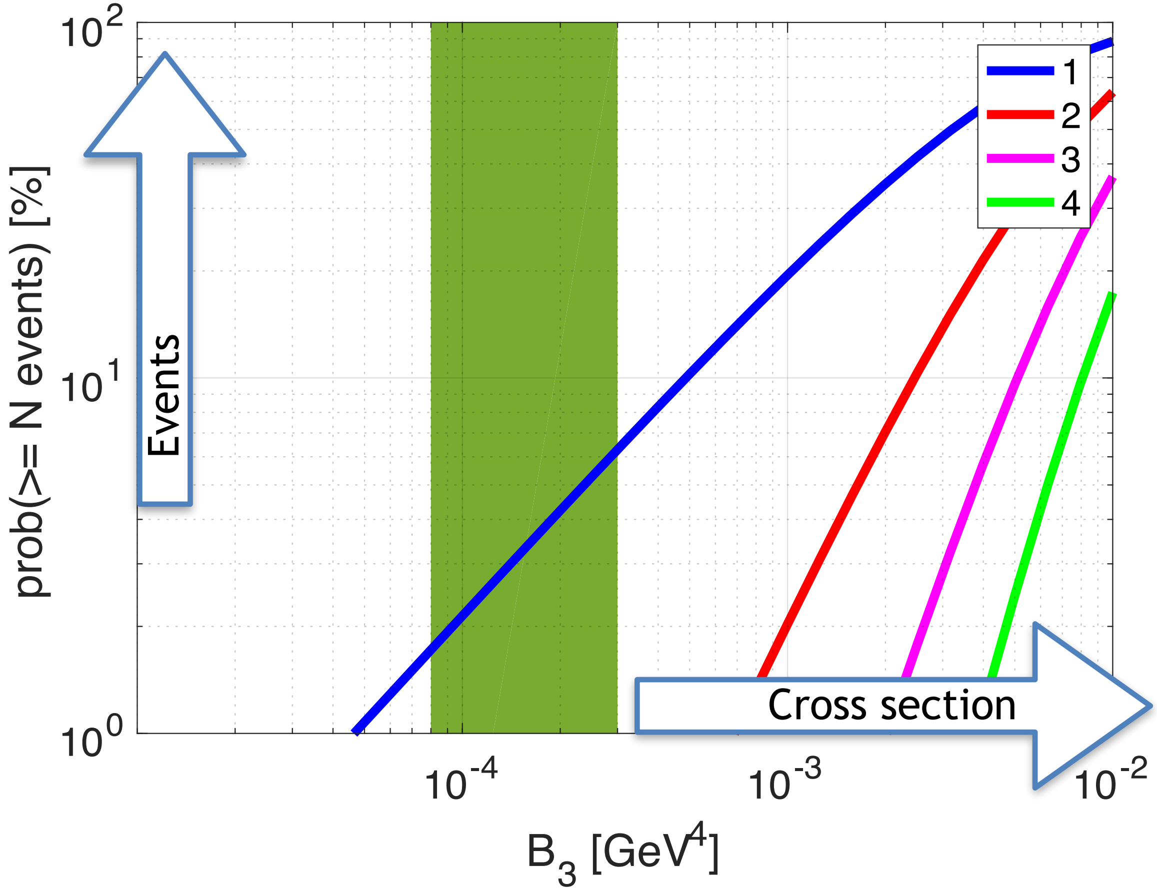
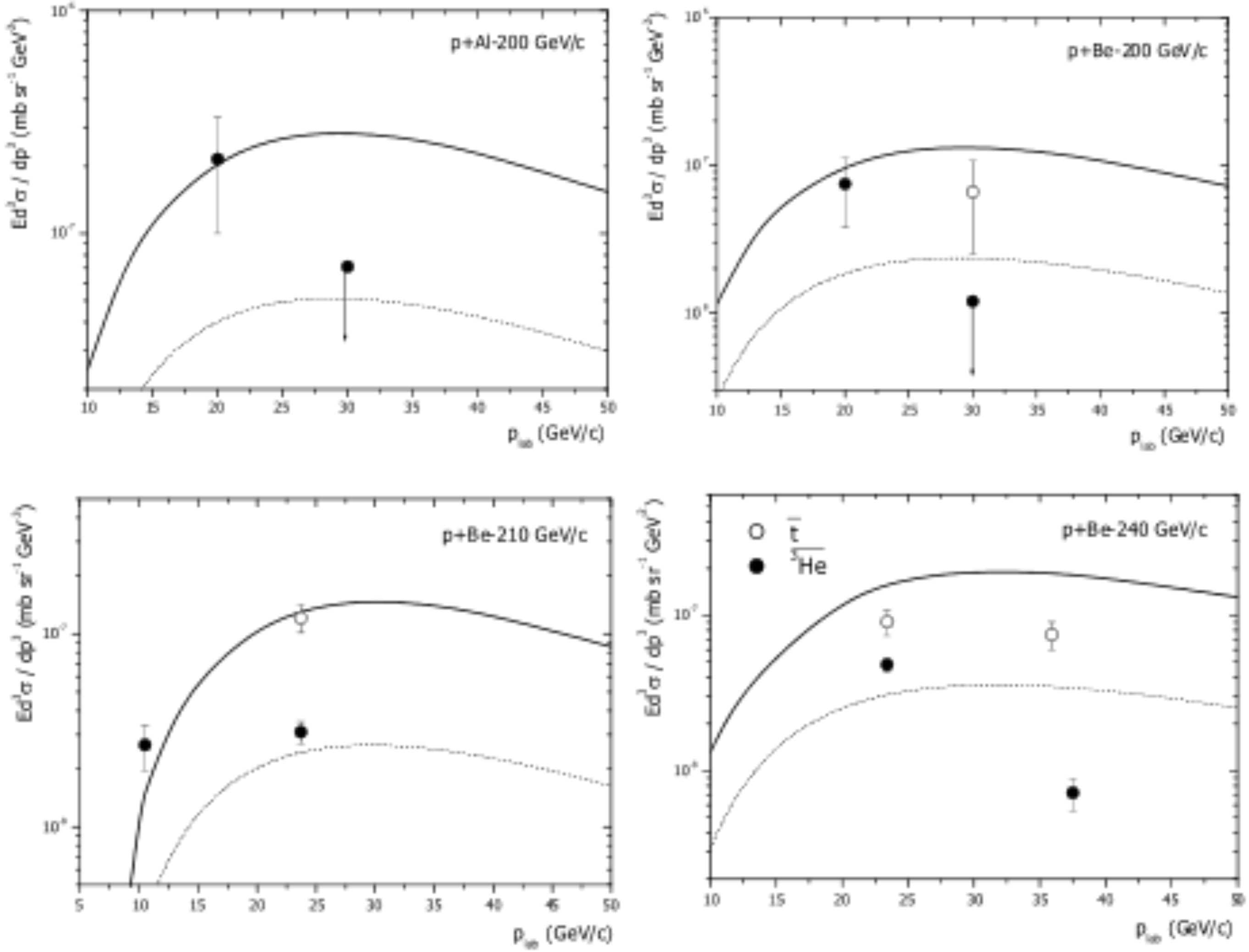
The difficult part is to get the cross section right

We need B_3



Duperray et al, PRD71 083013 (2005), **pA data** from SPS (1980's)

B_3=1.4x10^{-5} GeV^4



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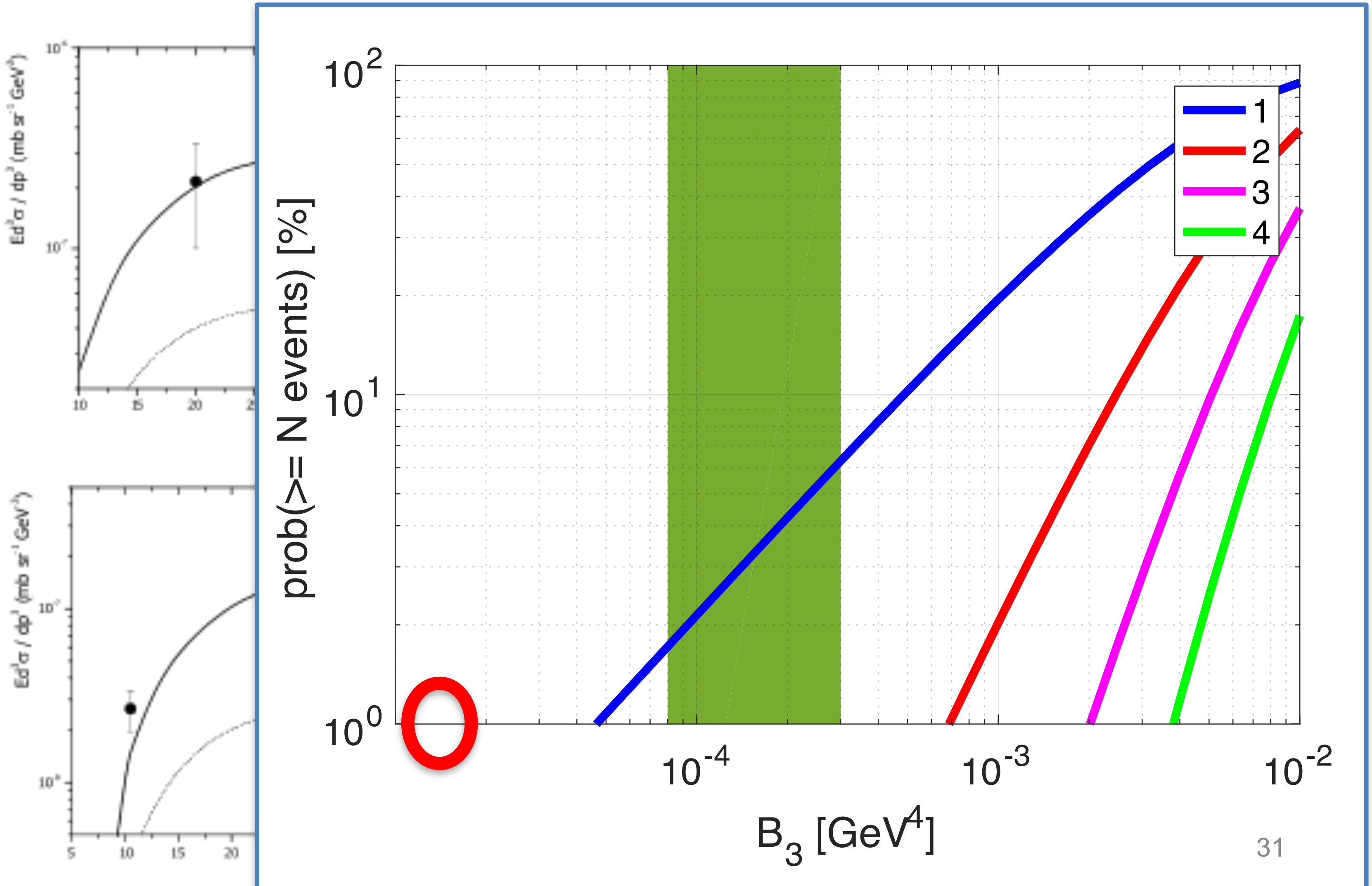
If true, then anti-helium @AMS02 = new physics



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Previous CR literature typically made 2 key assumptions:

1. Same coalescence factor describes He3 and d
2. B_A extracted from pA used directly for pp

Complimentary AA, pA, and related pp data exists elsewhere.

Let's take a step back and try to see the bigger picture

$$E_A \frac{dN_A}{d^3p_A} = B_A\, R(x) \left(E_p \frac{dN_p}{d^3p_p} \right)^A$$

Hadrons emitted from a finite size emission region.
Typical scales O(fm) ~ 1/(100 MeV)

Natural scaling law: $\boxed{B_A \propto V^{1-A}}$

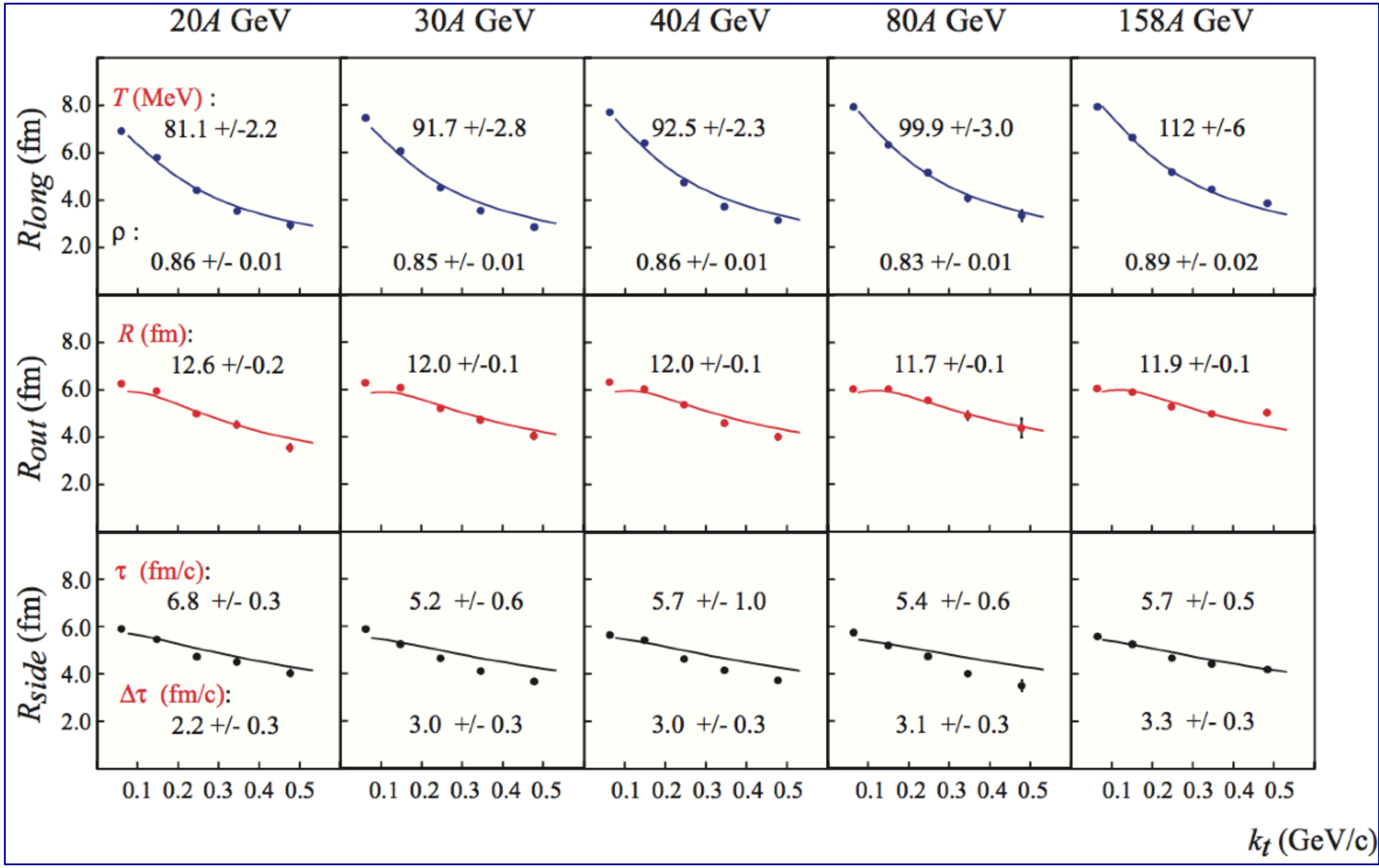
Emission region scale size is probed by two-particle correlations:

Hanbury Brown-Twiss (HBT) data

Scheibl & Heinz, Phys.Rev. C59 (1999) 1585-1602

HBT in heavy ion and pp collisions

Example: CERN SPS, **PbPb** 20, 30, 40, 80, 158A GeV



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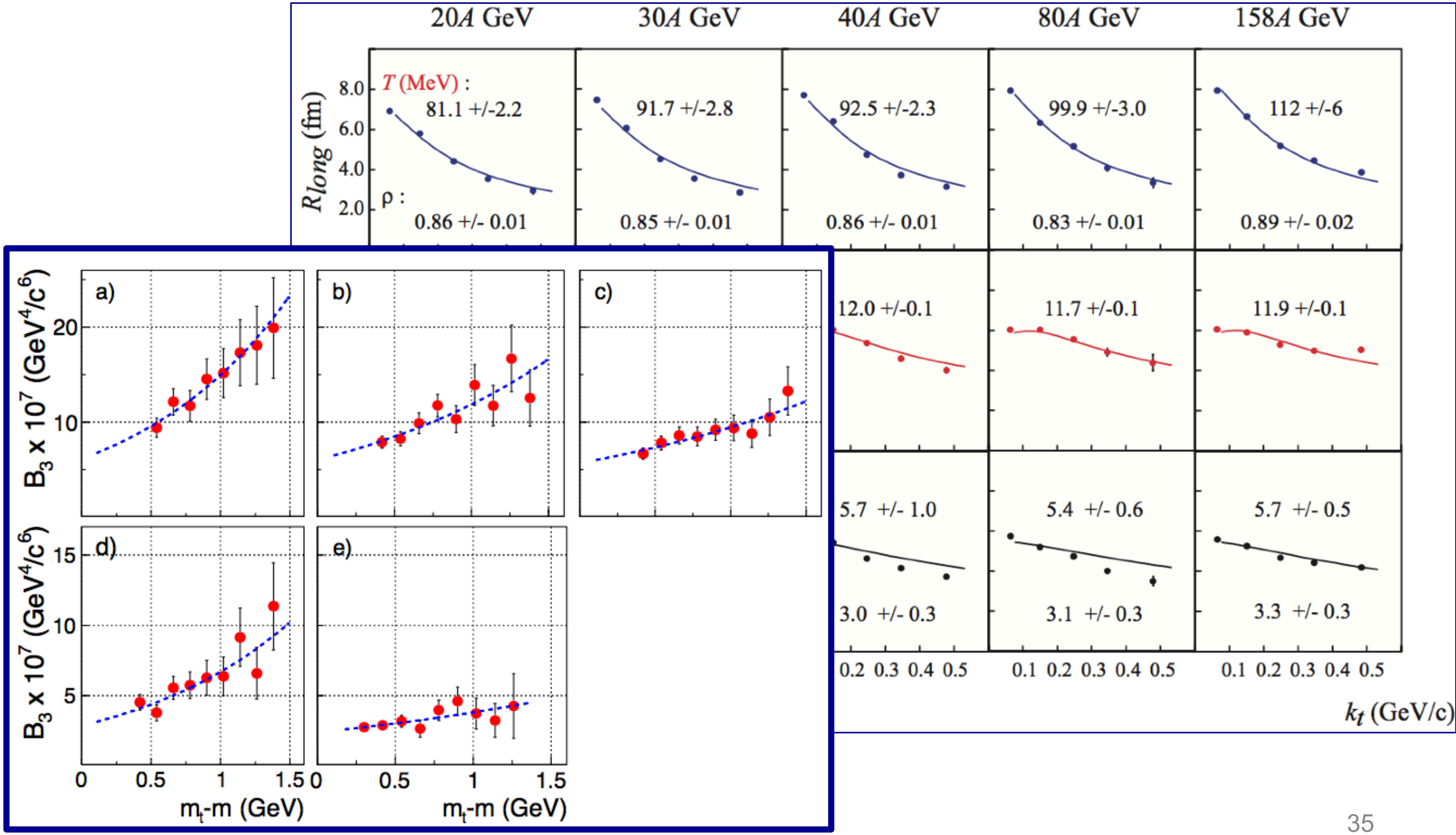
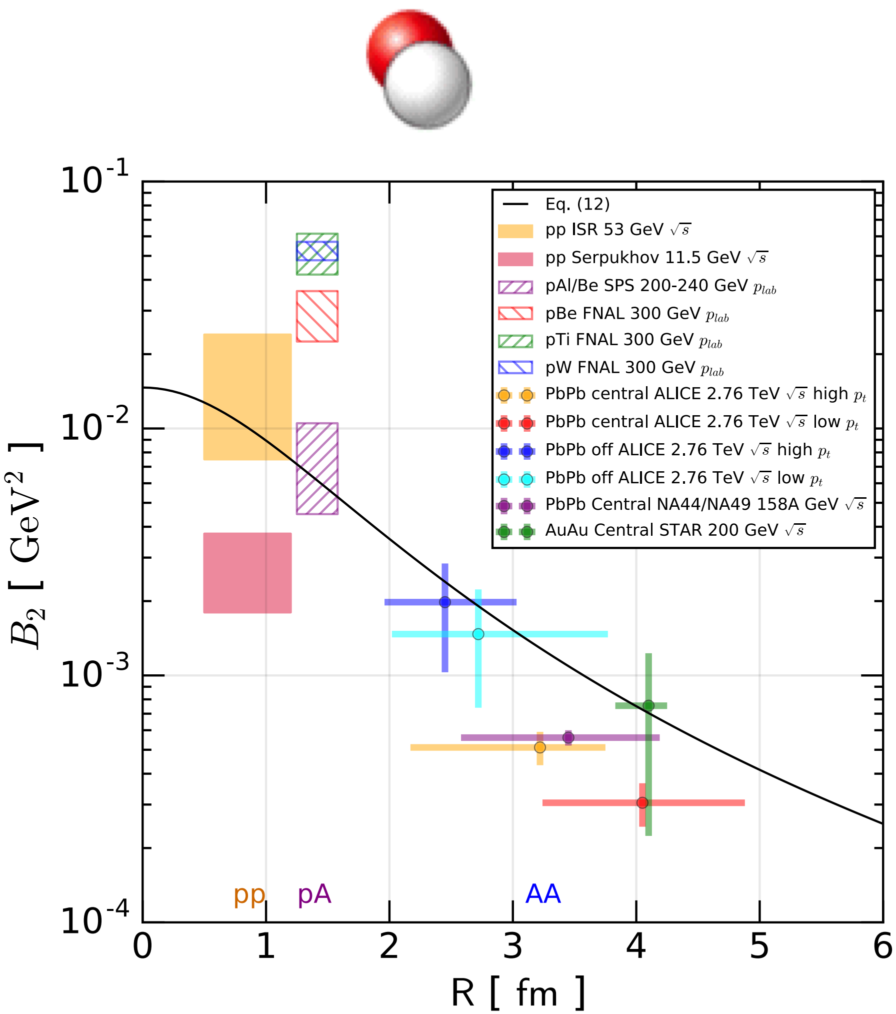
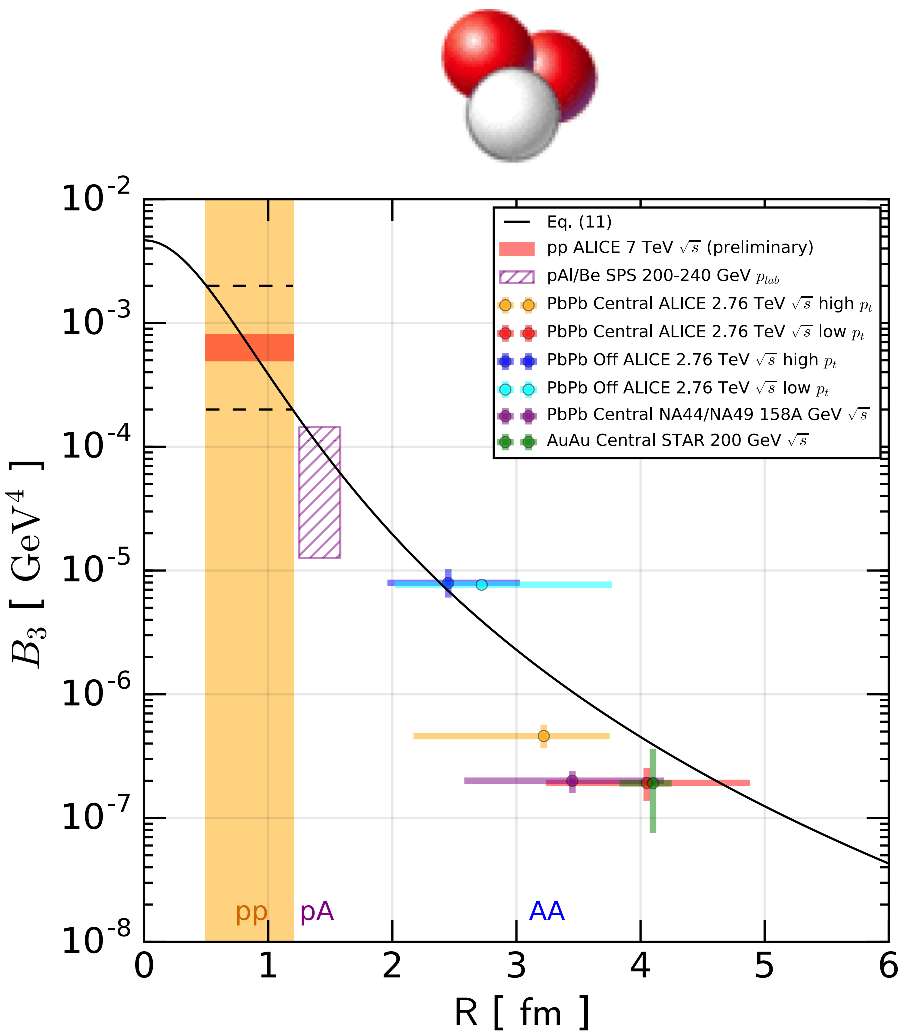


- Collected all systems for which we find nuclear yield & HBT data

Blum et al
1704.05431





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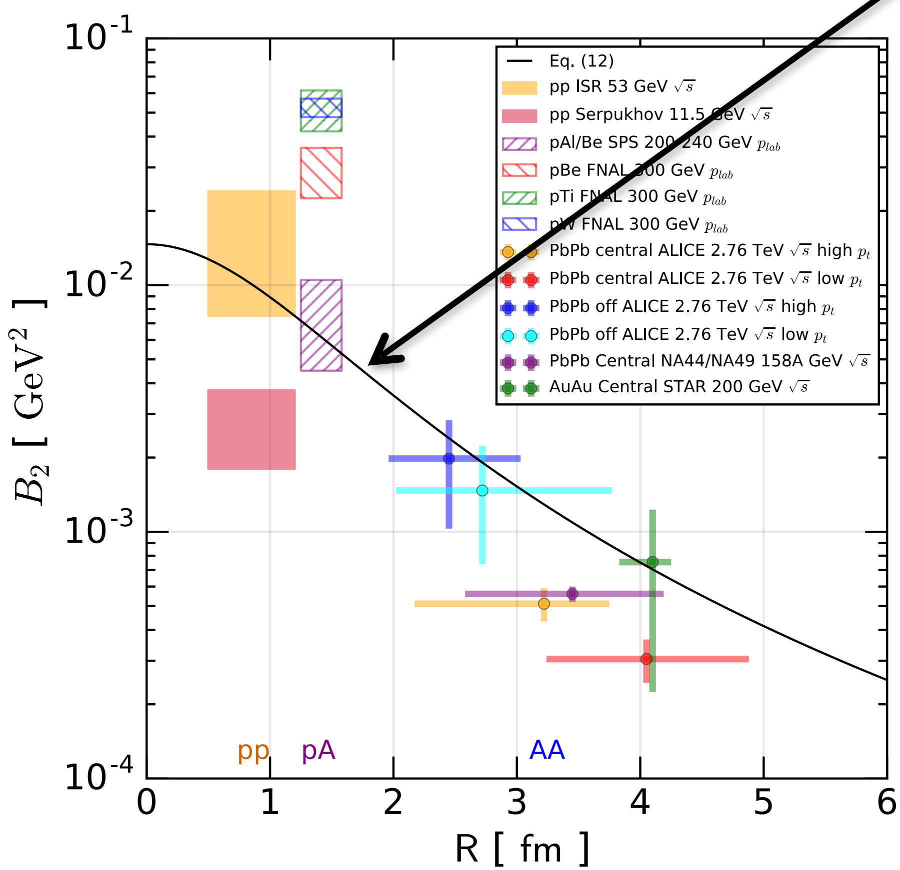

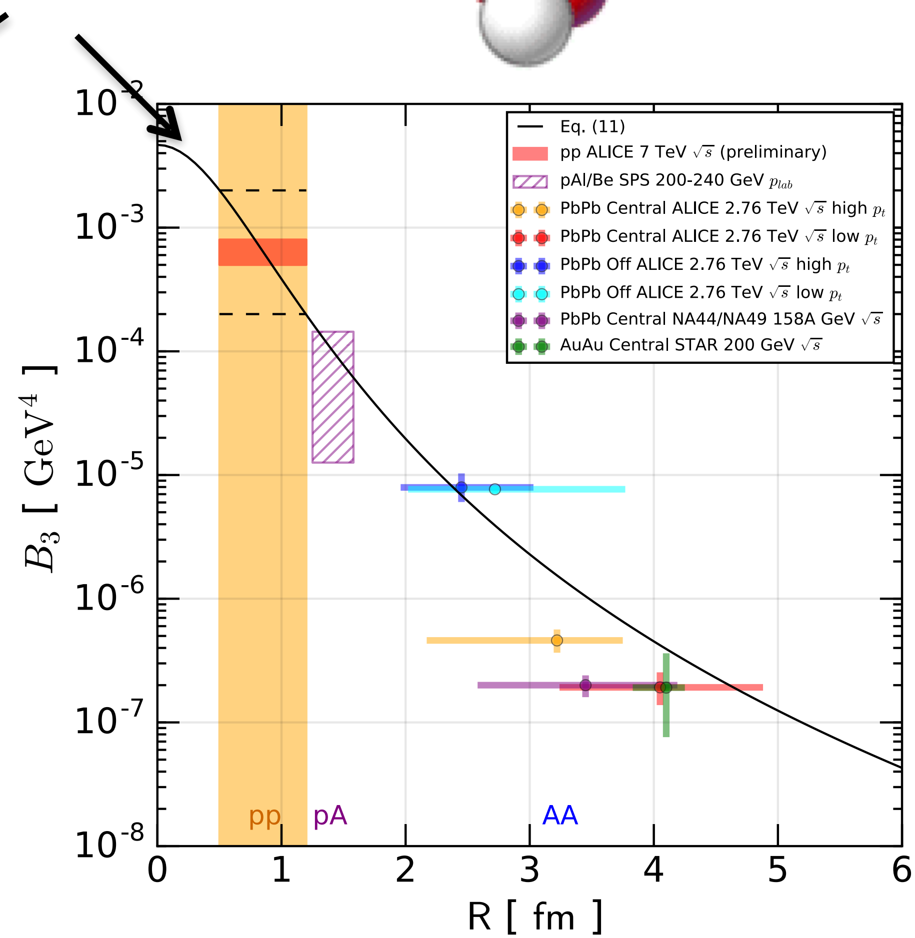

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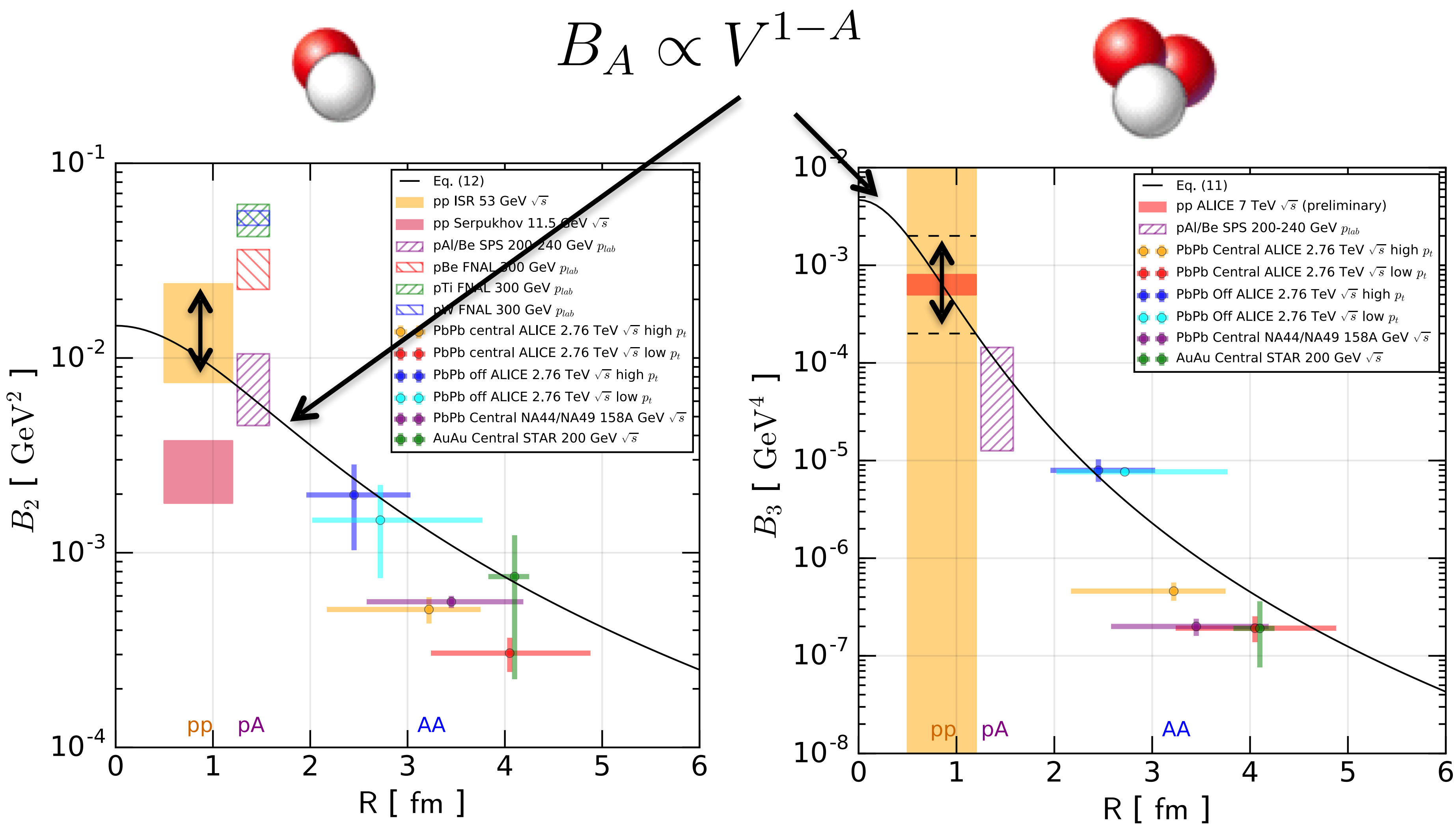
Blum et al
1704.05431



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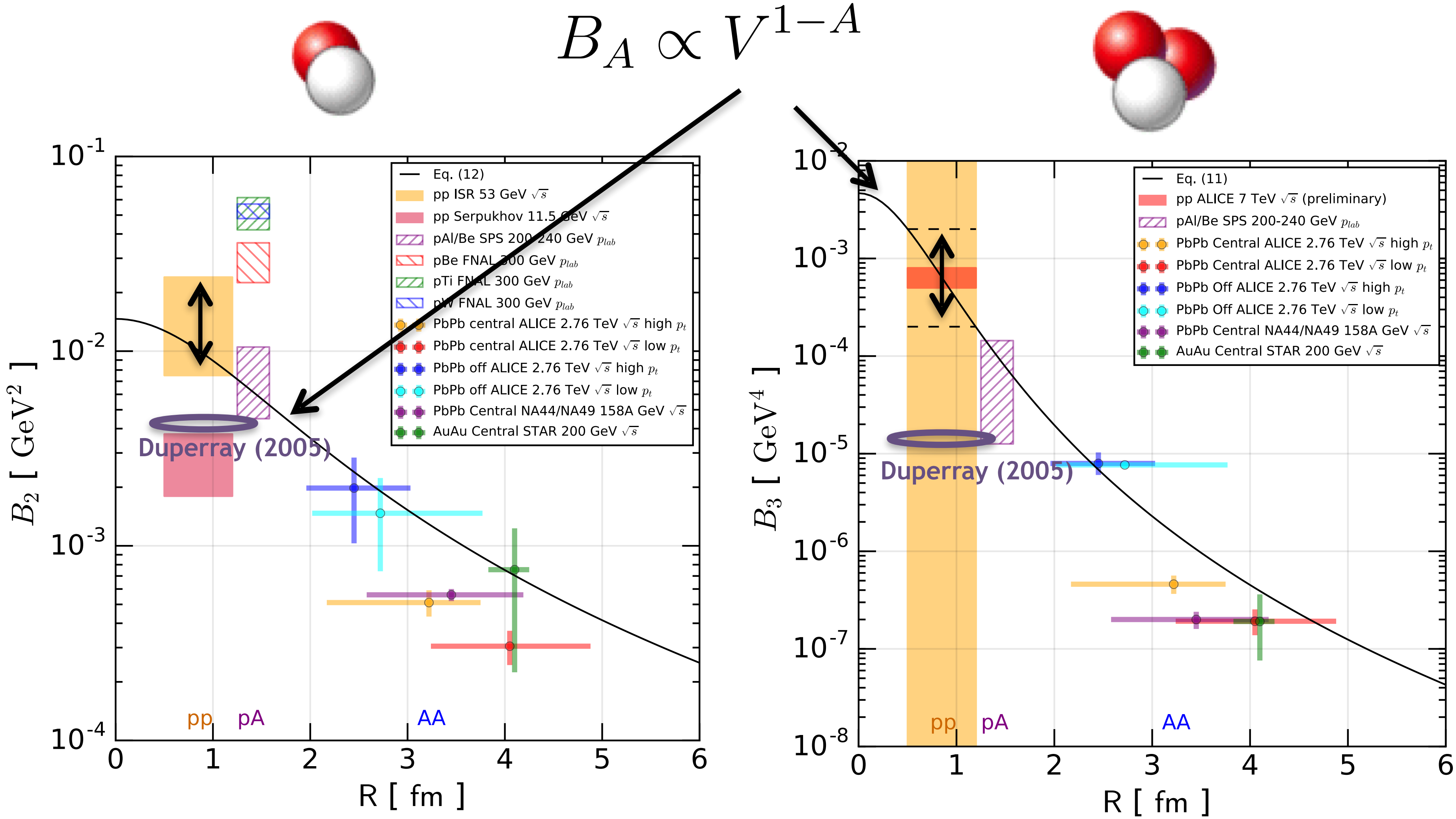

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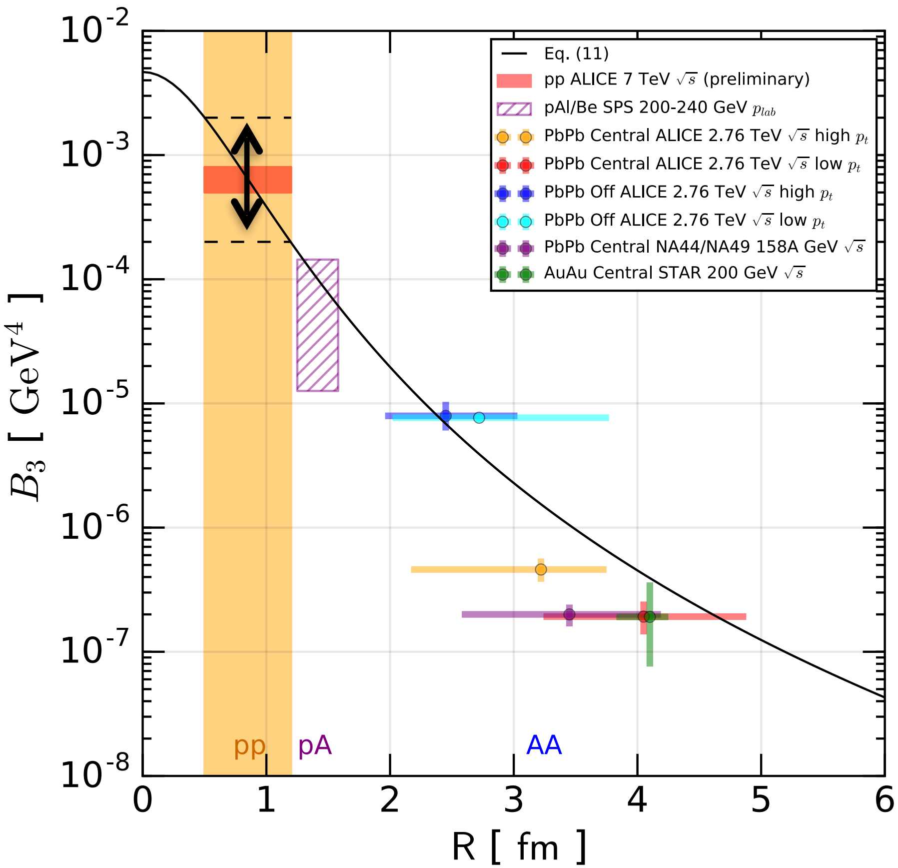

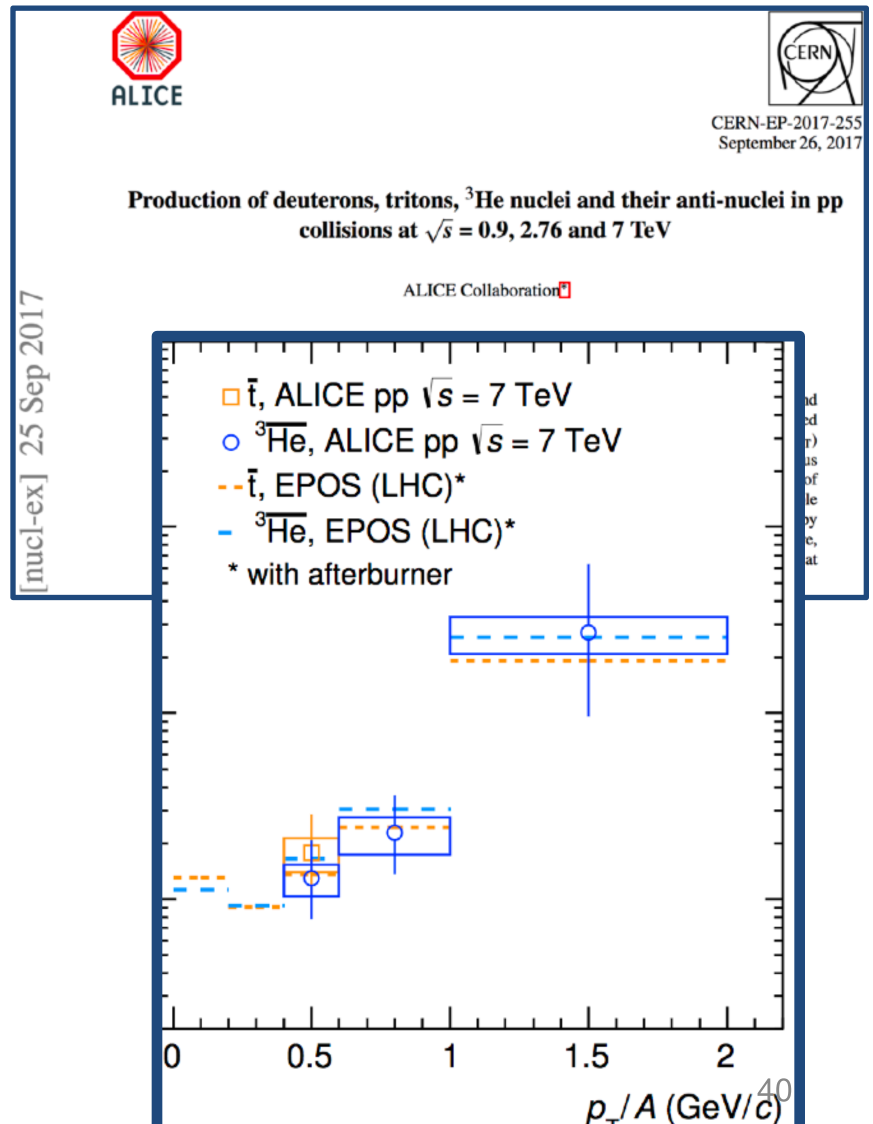

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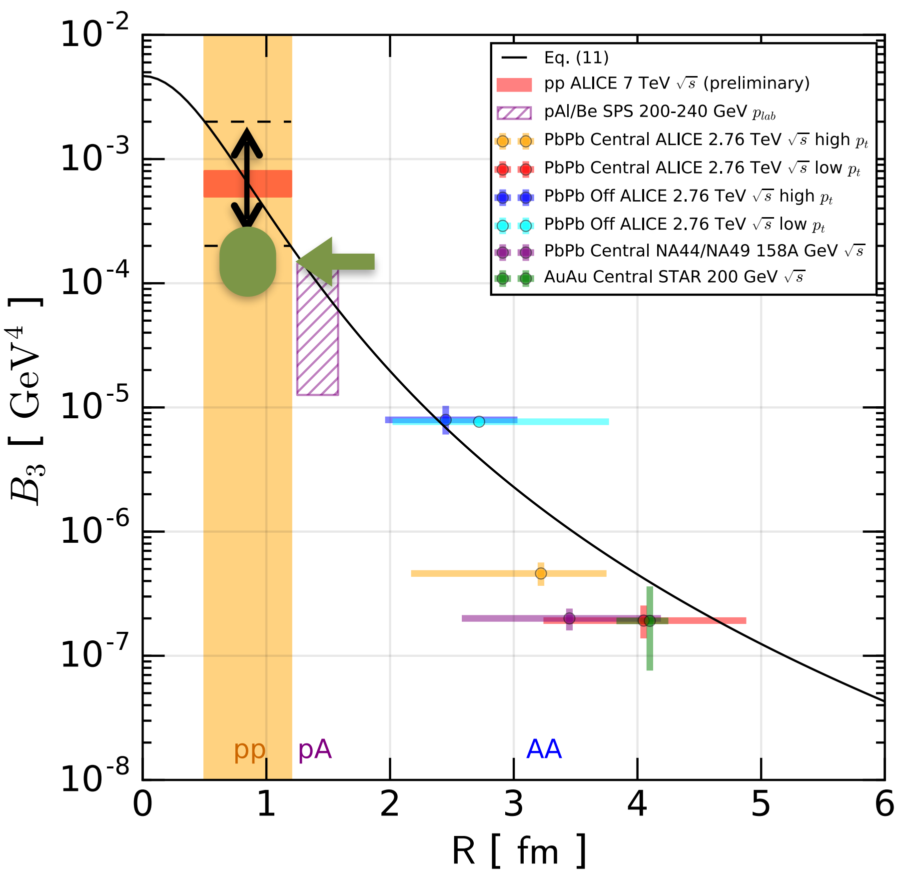

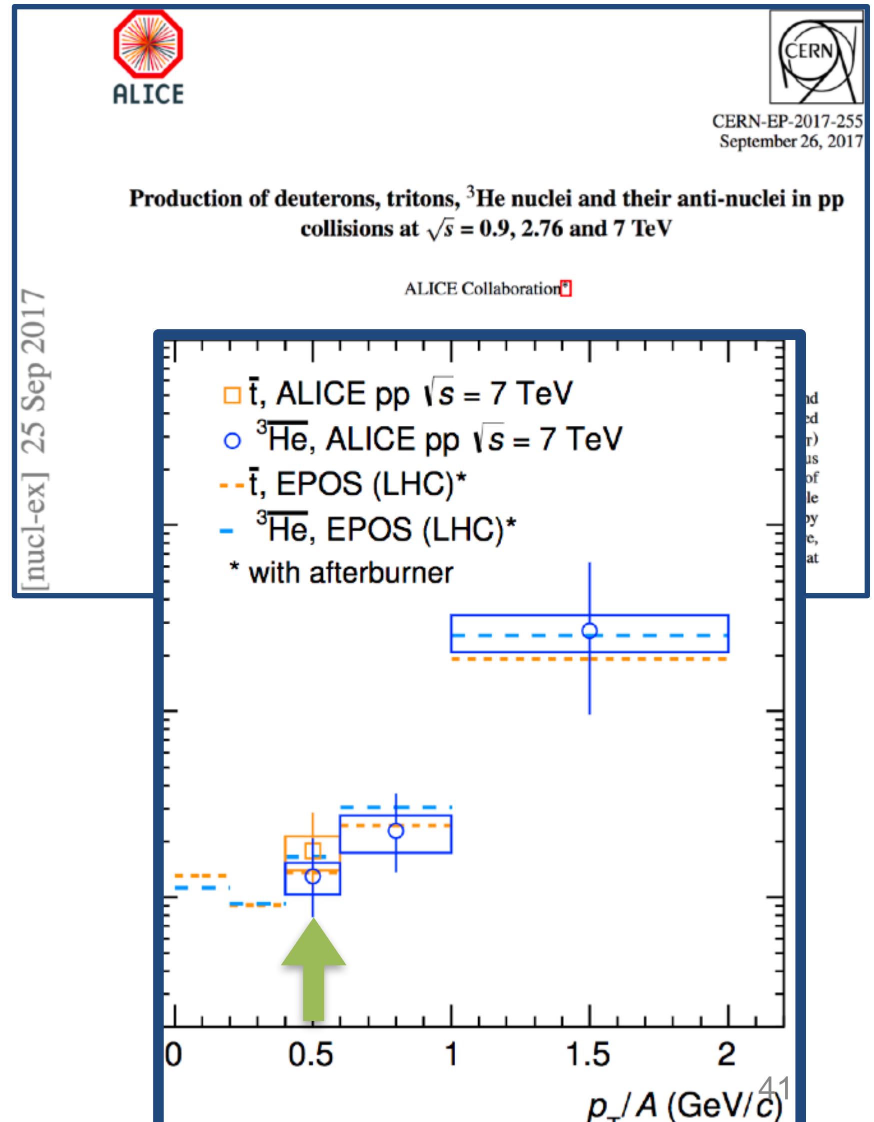

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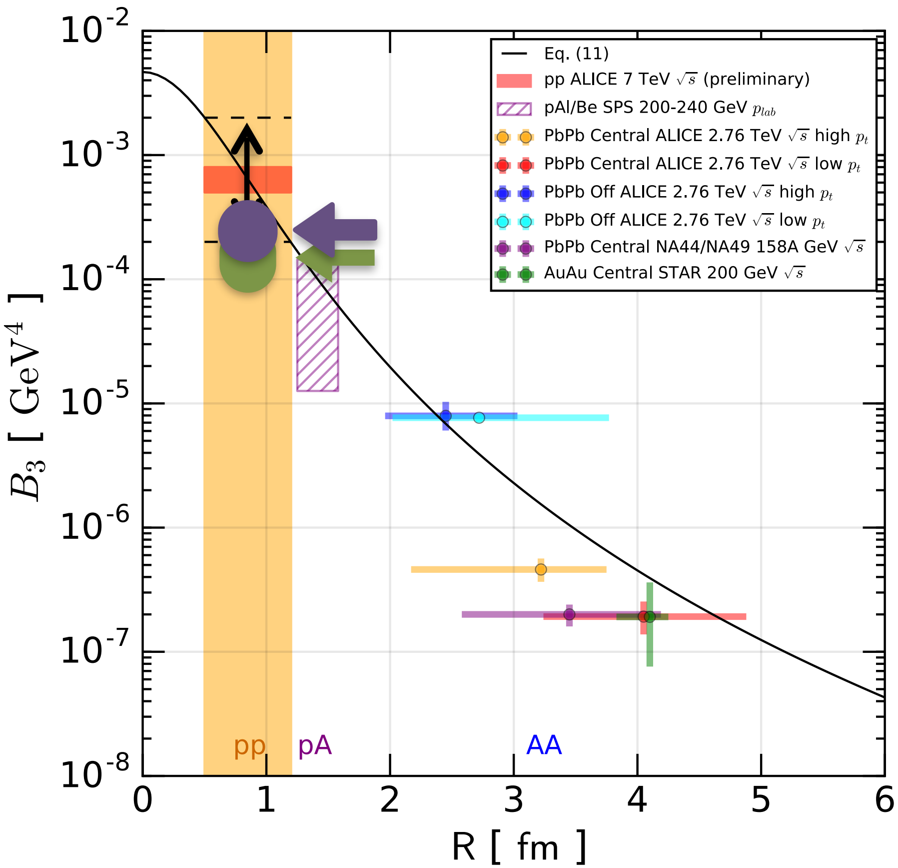

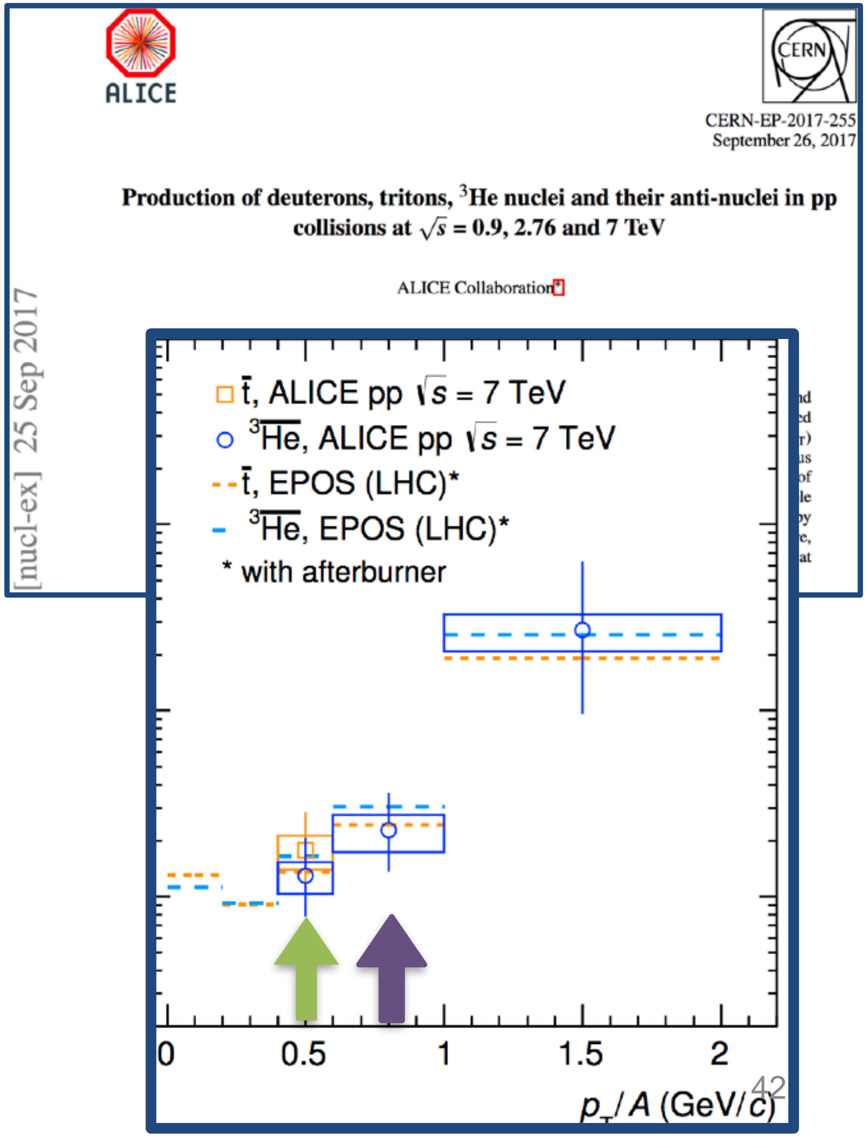

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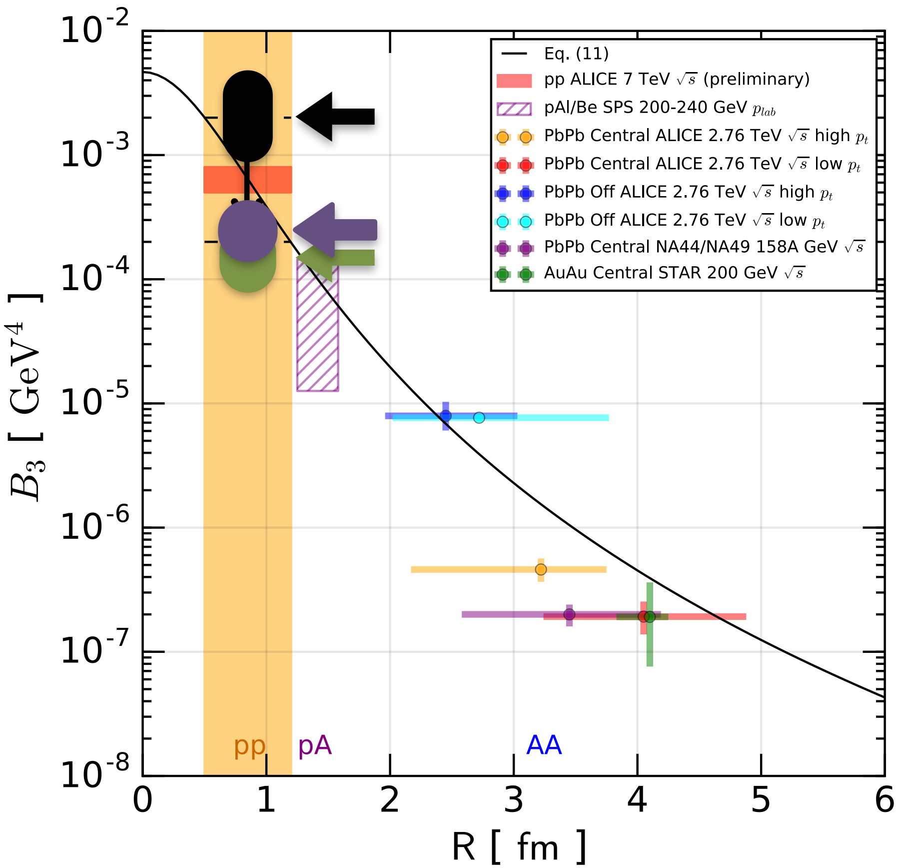
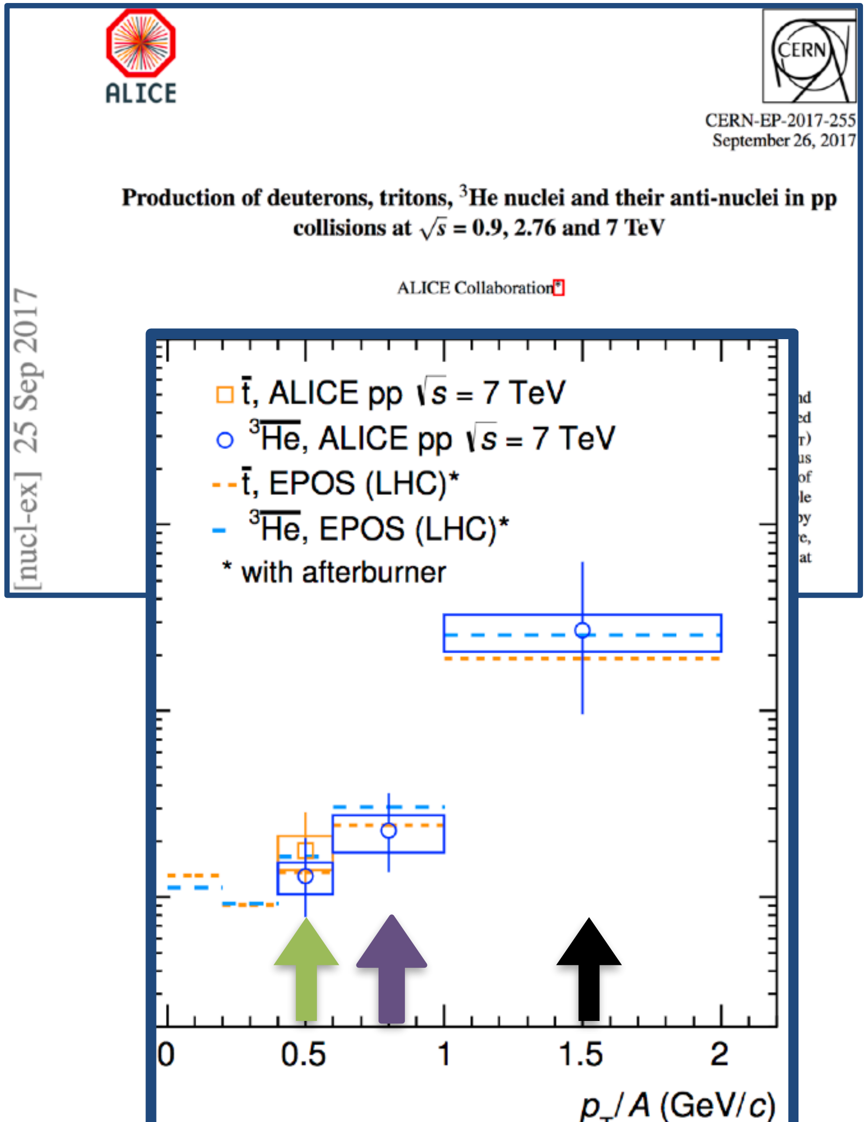
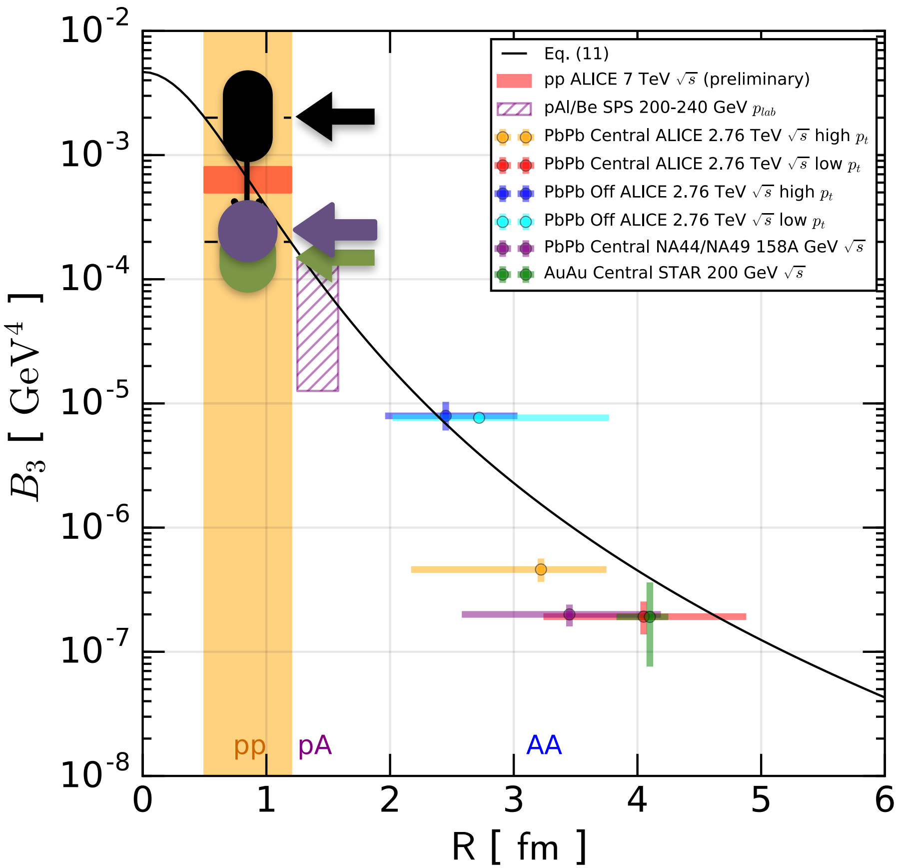


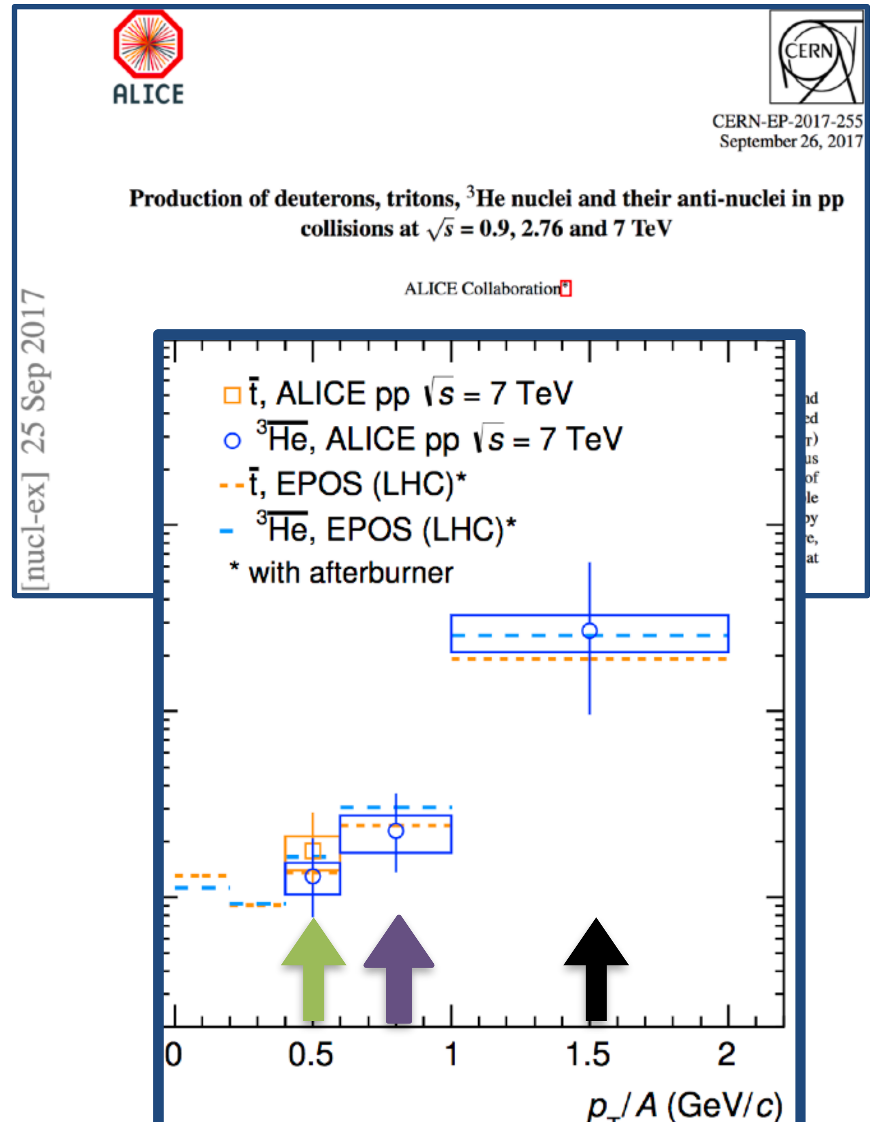


We got the basic picture more or less right.

But we have detailed data now: significant pT dependence in B3.

Most relevant for astro is pT/A < 0.5 GeV

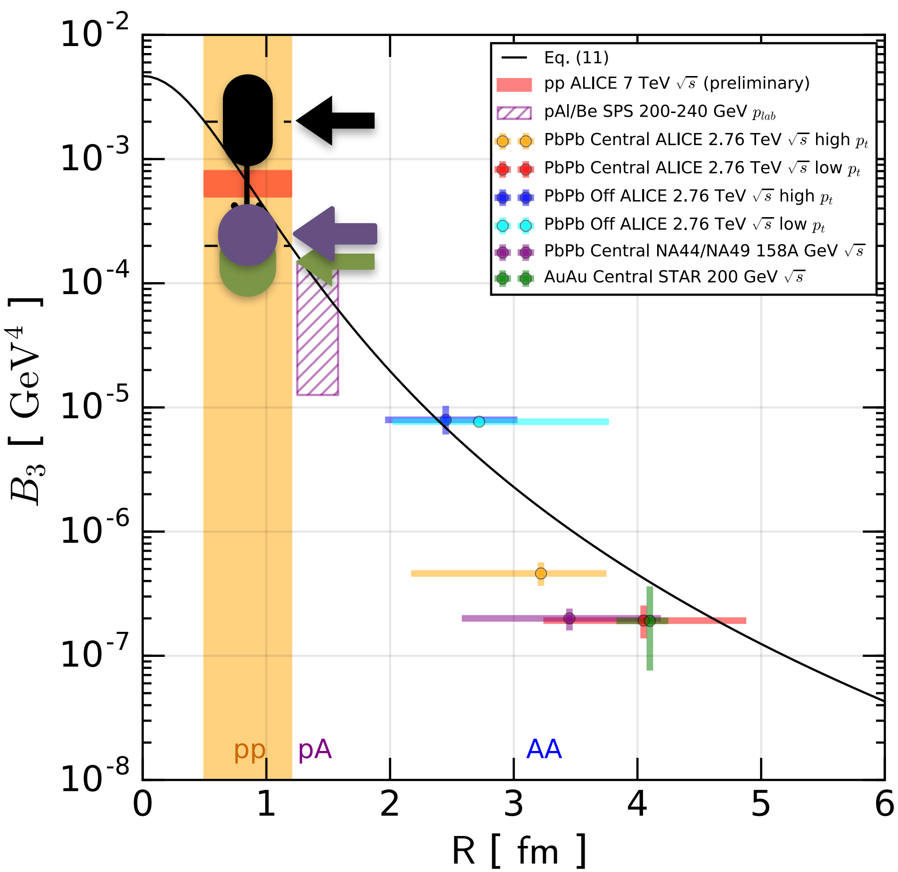


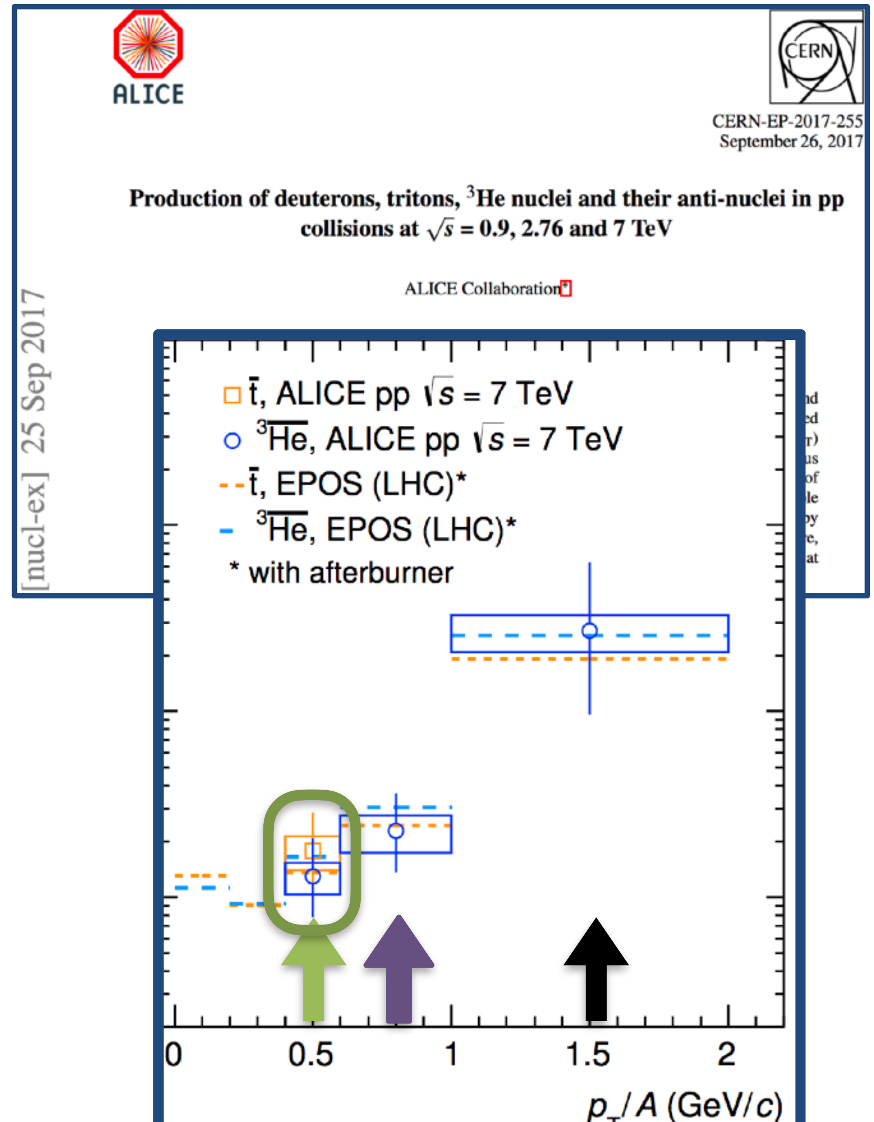


We got the basic picture more or less right.

But we have detailed data now: significant pT dependence in B3.

Most relevant for astro is pT/A < 0.5 GeV



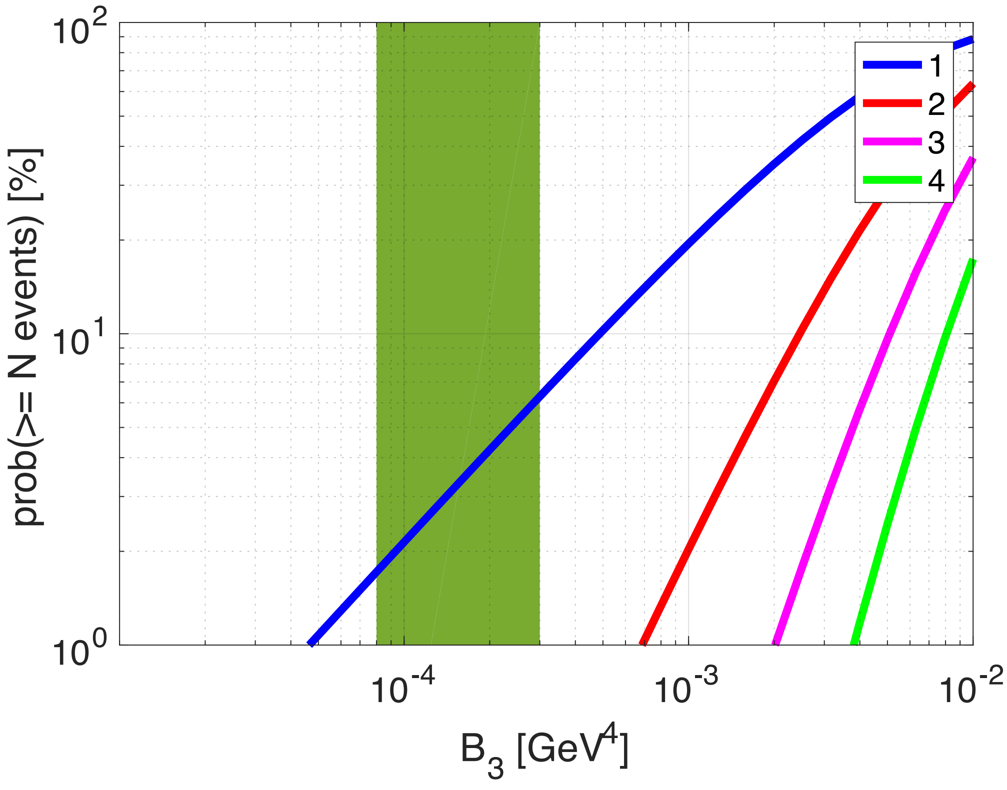


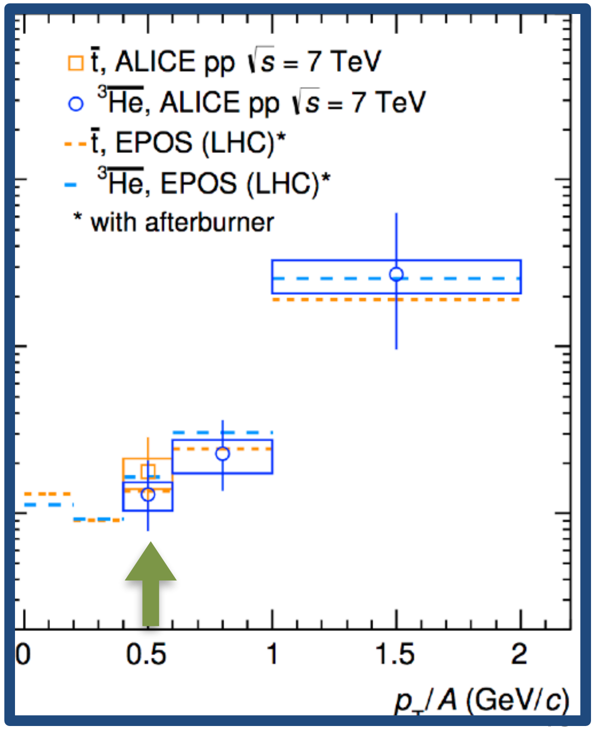
Implication of ALICE results for astrophysics.

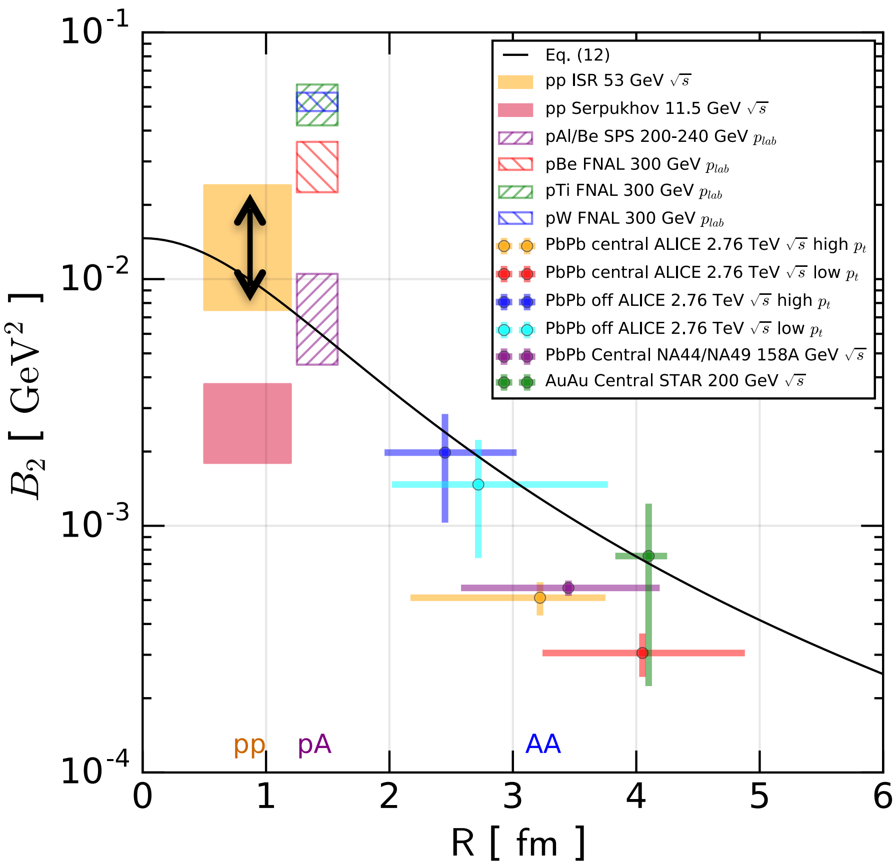
He3bar:
1 event/5yr plausible; 1 event/yr seems unlikely with current pp analysis.

Are we missing a large contribution in high-rapidity region (y >~ 1)?

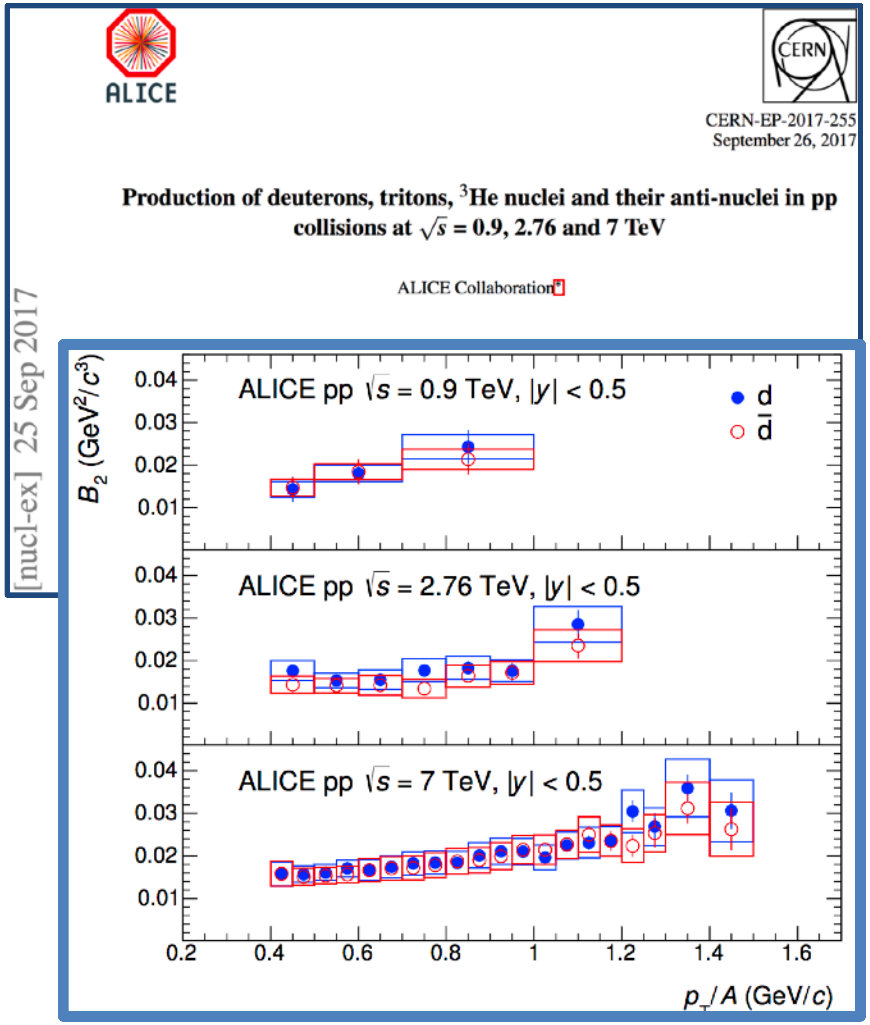
…is AMS02 seeing background?



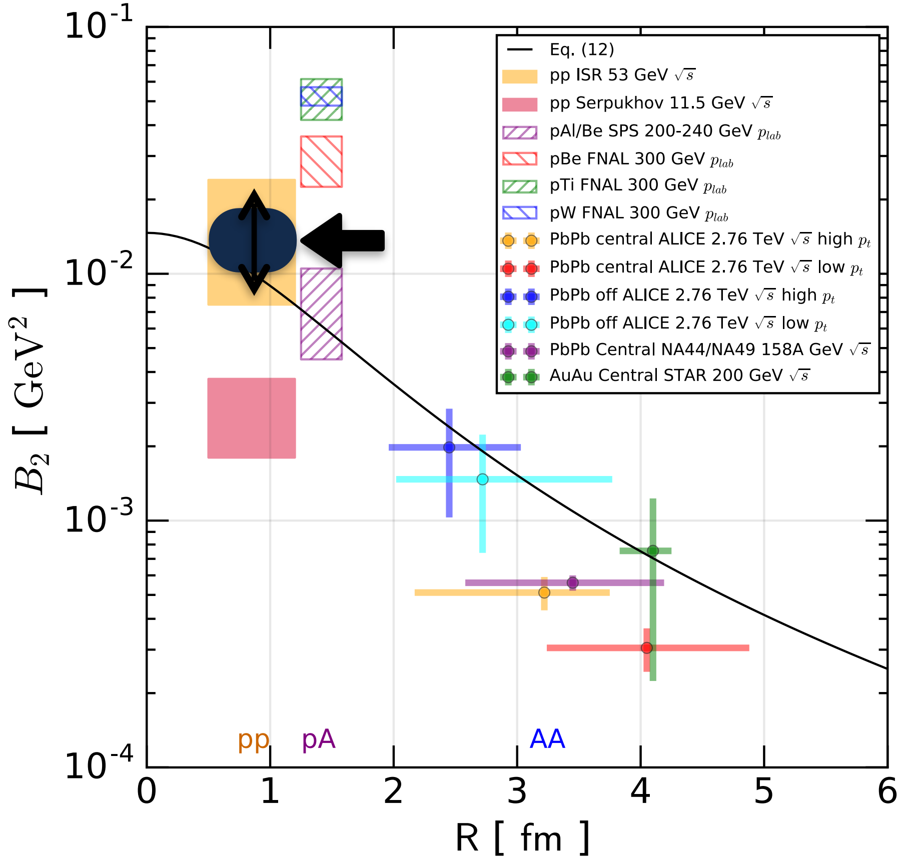




Eq. (12)
pp ISR 53 GeV $\sqrt{s}$
pp Serpukhov 11.5 GeV $\sqrt{s}$
pAl/Be SPS 200-240 GeV p_{lab}
pBe FNAL 300 GeV p_{lab}
pTi FNAL 300 GeV p_{lab}
pW FNAL 300 GeV p_{lab}
PbPb central ALICE 2.76 TeV $\sqrt{s}$ high p_t
PbPb central ALICE 2.76 TeV $\sqrt{s}$ low p_t
PbPb off ALICE 2.76 TeV $\sqrt{s}$ high p_t
PbPb off ALICE 2.76 TeV $\sqrt{s}$ low p_t
PbPb Central NA44/NA49 158A GeV $\sqrt{s}$
AuAu Central STAR 200 GeV $\sqrt{s}$
pp
pA
AA
B_2 [GeV^2]
R [fm]



ALICE
CERN
CERN-EP-2017-255
September 26, 2017
Production of deuterons, tritons, ^{3}He nuclei and their anti-nuclei in pp collisions at $\sqrt{s}$ = 0.9, 2.76 and 7 TeV
ALICE Collaboration*
[nucl-ex] 25 Sep 2017
ALICE pp $\sqrt{s}$ = 0.9 TeV, $|y|$ < 0.5
ALICE pp $\sqrt{s}$ = 2.76 TeV, $|y|$ < 0.5
ALICE pp $\sqrt{s}$ = 7 TeV, $|y|$ < 0.5
d
$\bar{d}$
B_2 (GeV^2/c^3)
p_T/A (GeV/c)



10^{-1}
10^{-2}
10^{-3}
10^{-4}
B_2 [GeV^2]
0
1
2
3
4
5
6
R [fm]
pp
pA
AA
Eq. (12)
pp ISR 53 GeV $\sqrt{s}$
pp Serpukhov 11.5 GeV $\sqrt{s}$
pAl/Be SPS 200-240 GeV p_{lab}
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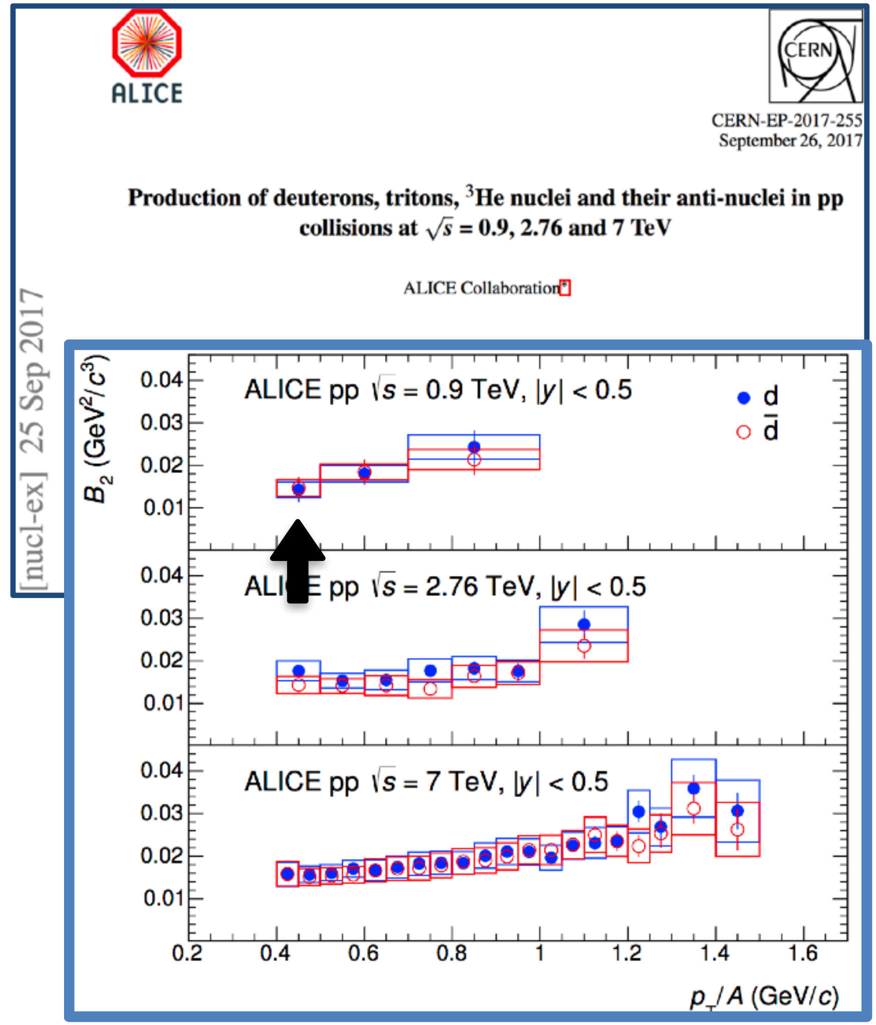

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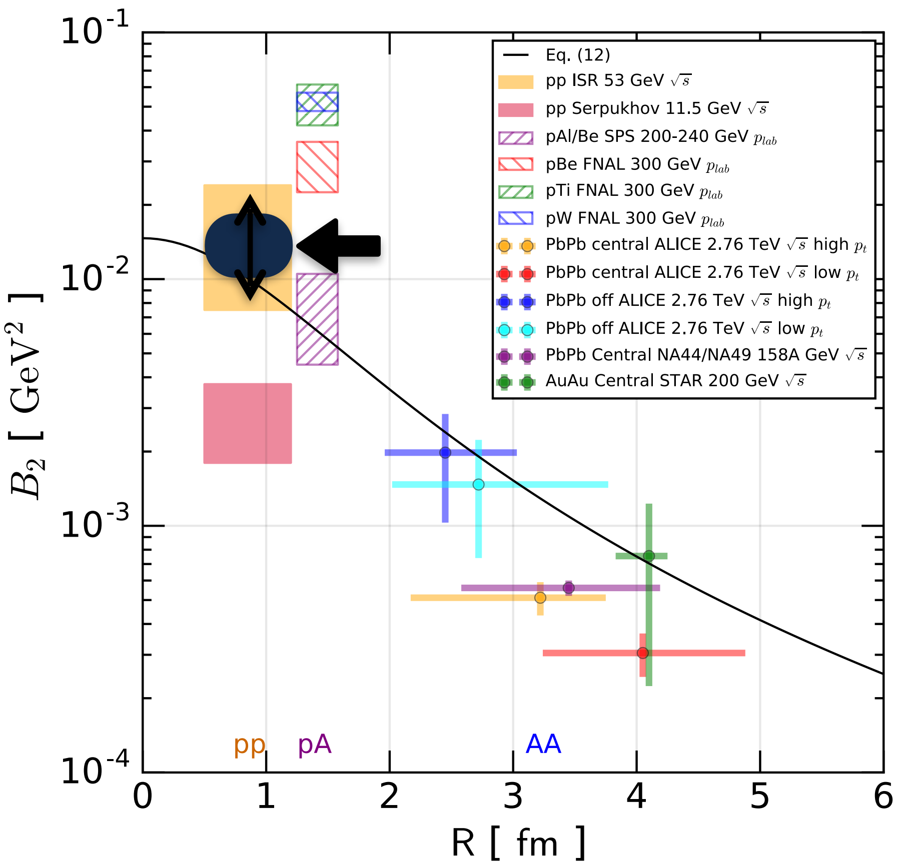
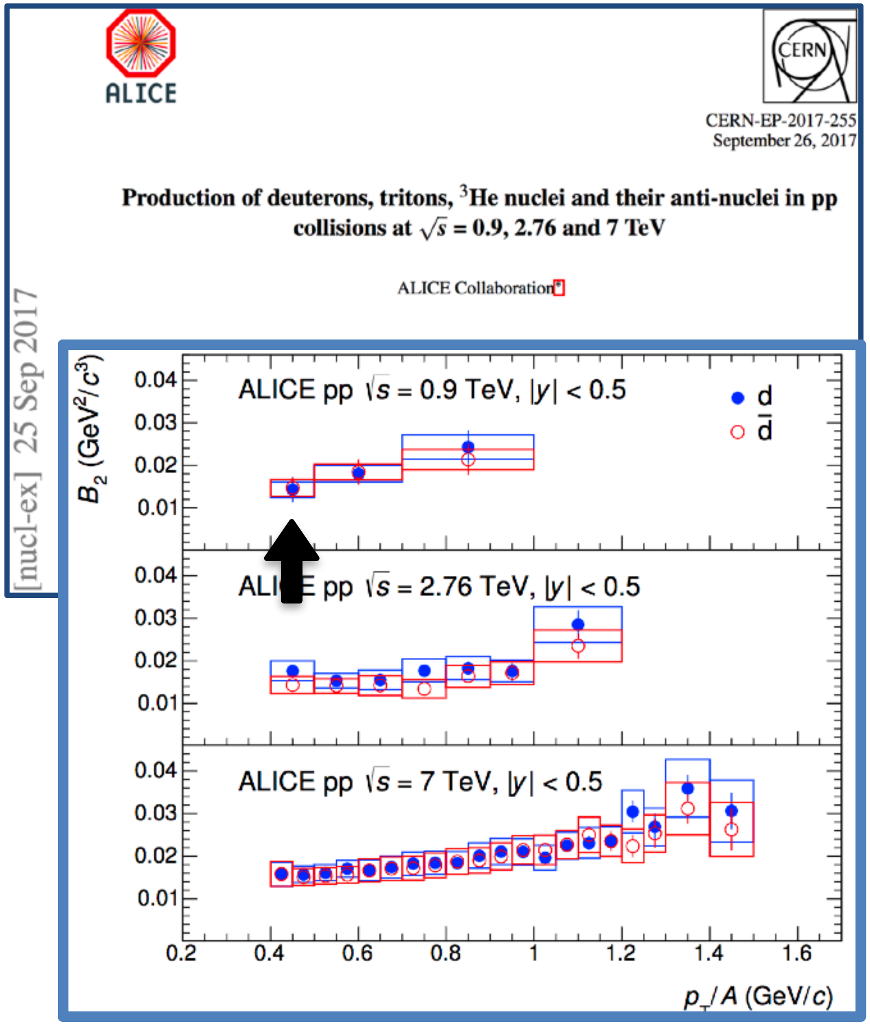
d
$\bar{d}$
ALICE pp $\sqrt{s}$ = 2.76 TeV, $|y|$ < 0.5
ALICE pp $\sqrt{s}$ = 7 TeV, $|y|$ < 0.5
0.04
0.03
0.02
0.01
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
p_T/A (GeV/c)

Implication of ALICE results for astrophysics.

dbar:
may be seen at AMS02 5yr exposure.





Summary

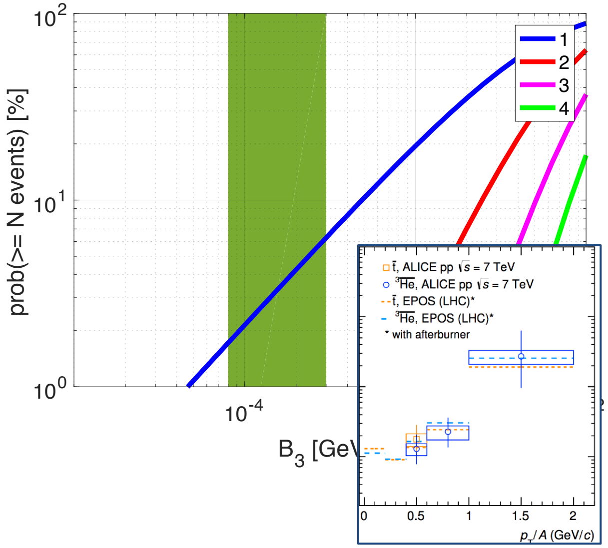
Summary

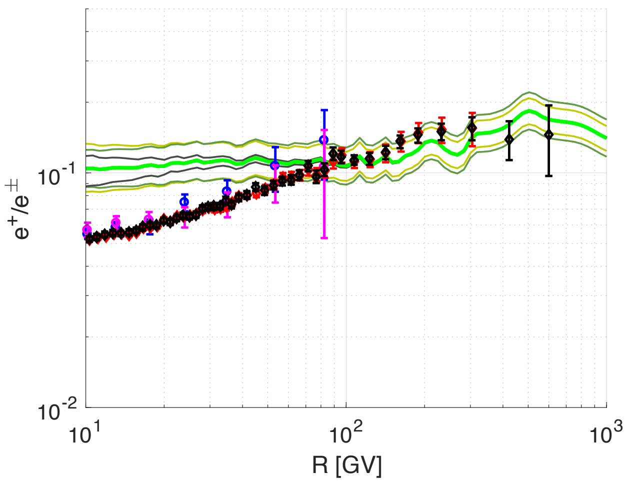
- Antiprotons are (at least dominantly) secondary.

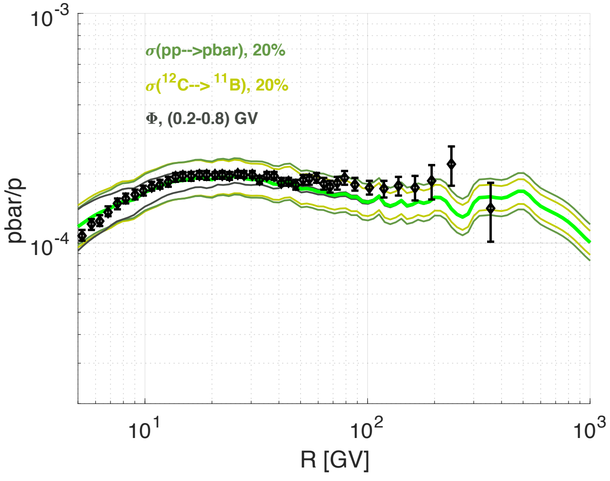
- ***Secondary*** anti-He3, anti-d events in 5-year of AMS02?

1 anti-He3 event/5yr plausible.
5 events/5yr seem unlikely from current (y~0) analysis of pp collisions,
but: are we missing key contributions at y >~ 1?

Anti-d events: possibly in reach.



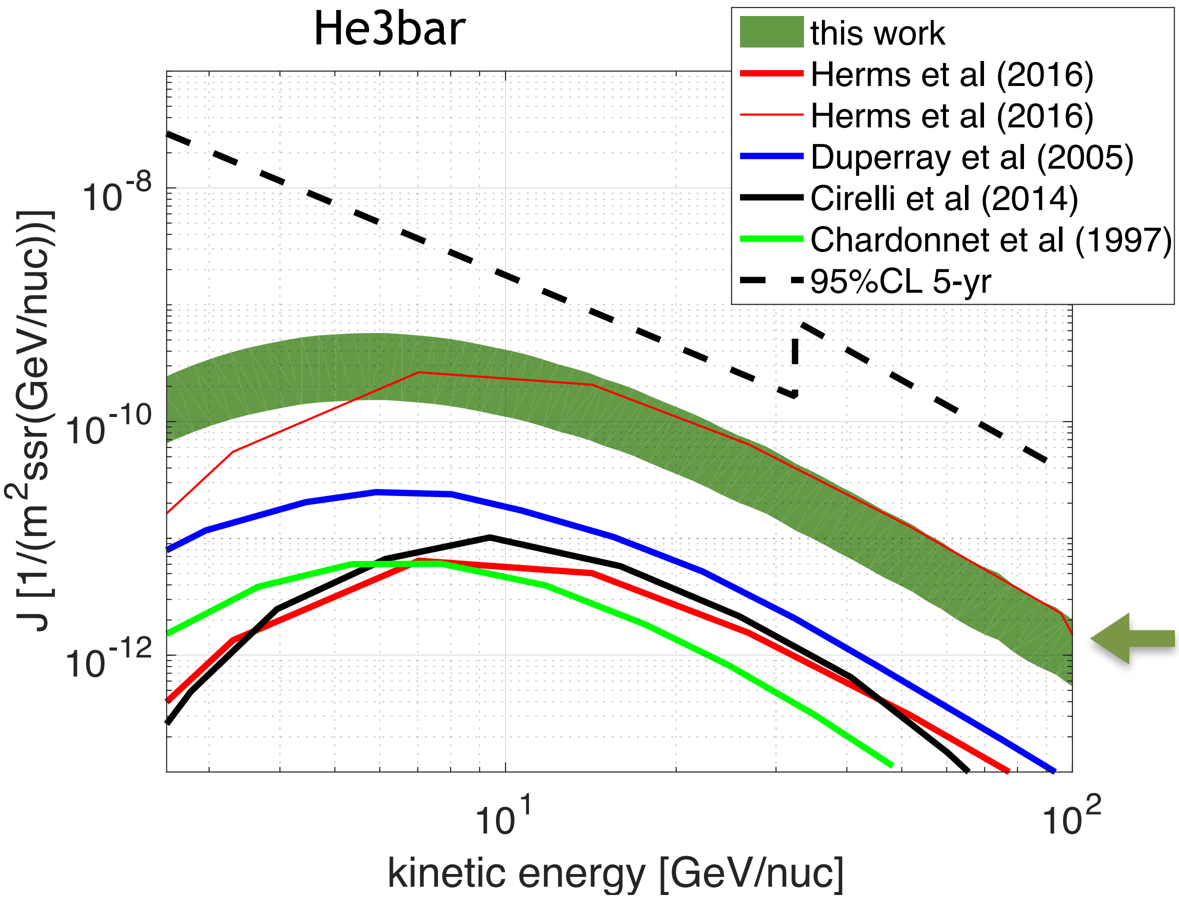


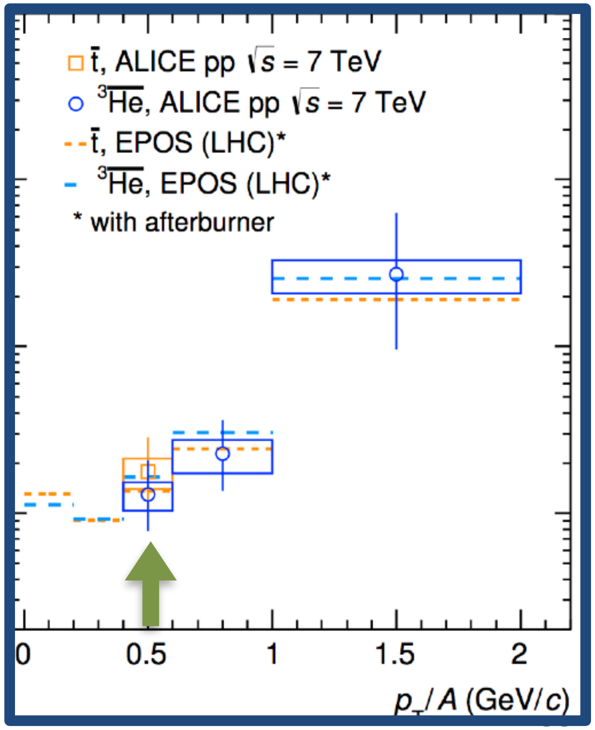


Xtra

Implication of ALICE results for astrophysics.

He3bar:
1 event/5yr at AMS02: plausible.
1 event/1yr: seems unlikely with current analysis.

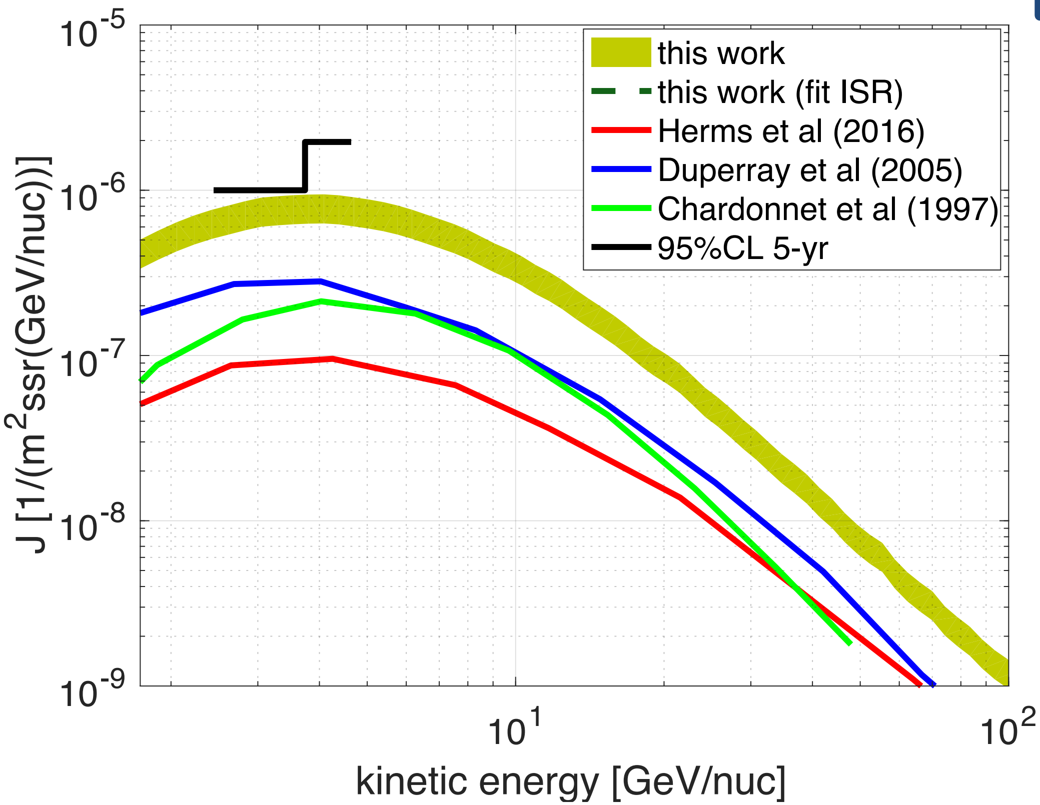


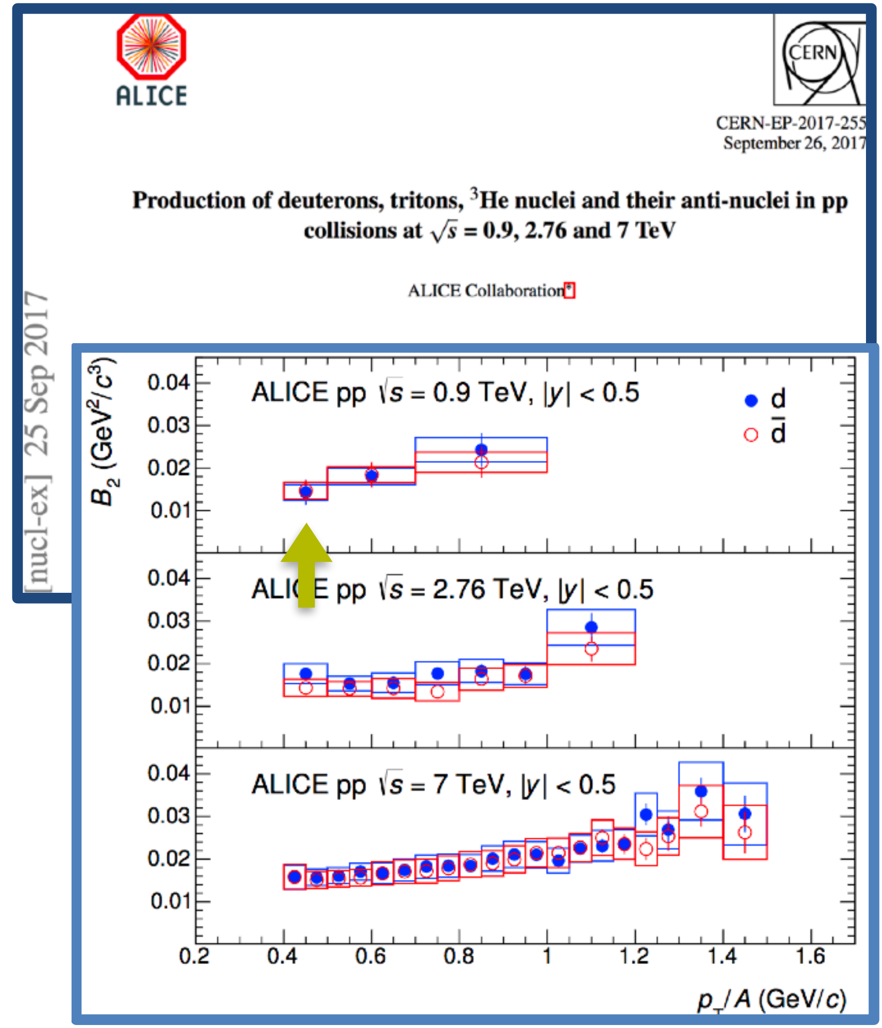


Implication of ALICE results for astrophysics.

dbar:
may be seen at AMS02 5yr exposure.

dbar




ALICE

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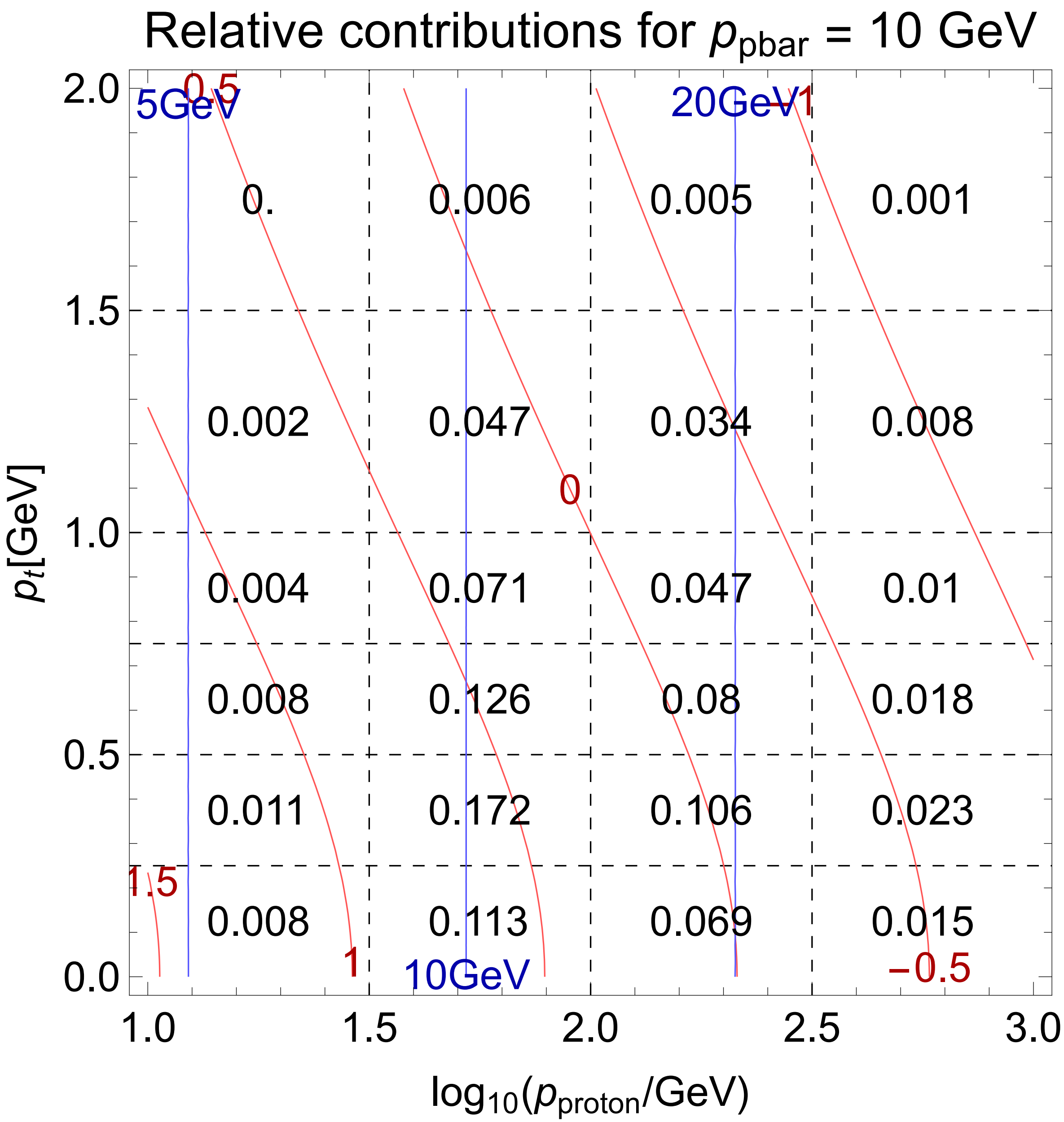
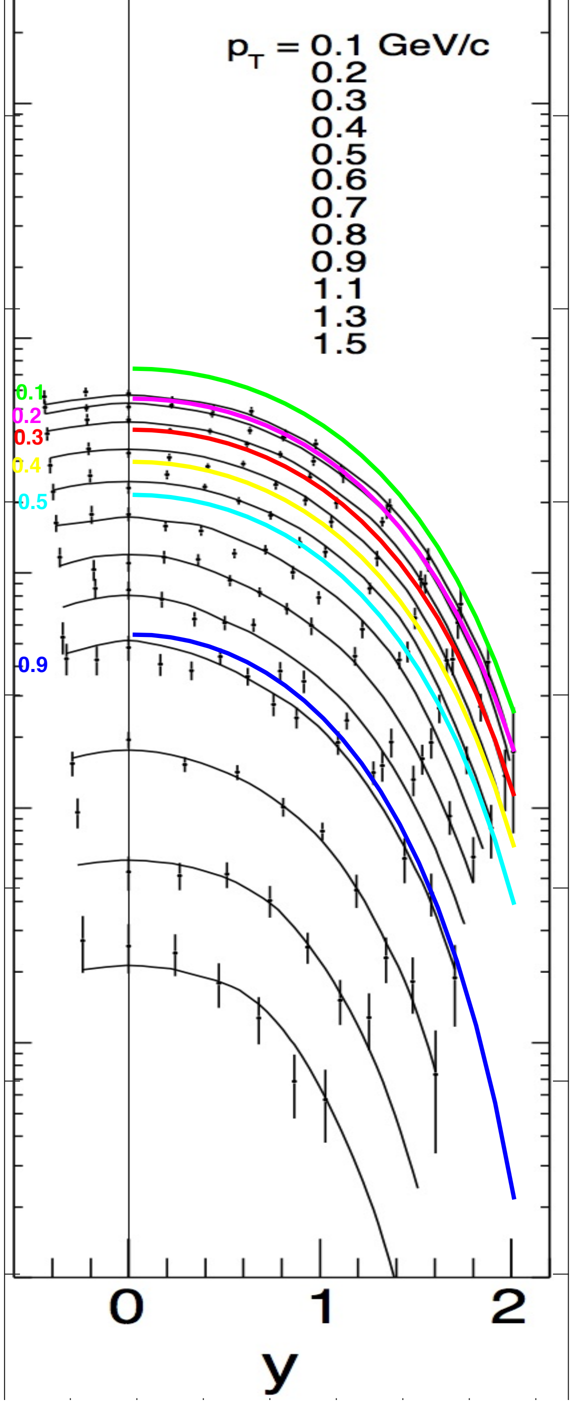
[nucl-ex] 25 Sep 2017

Y ~ 1

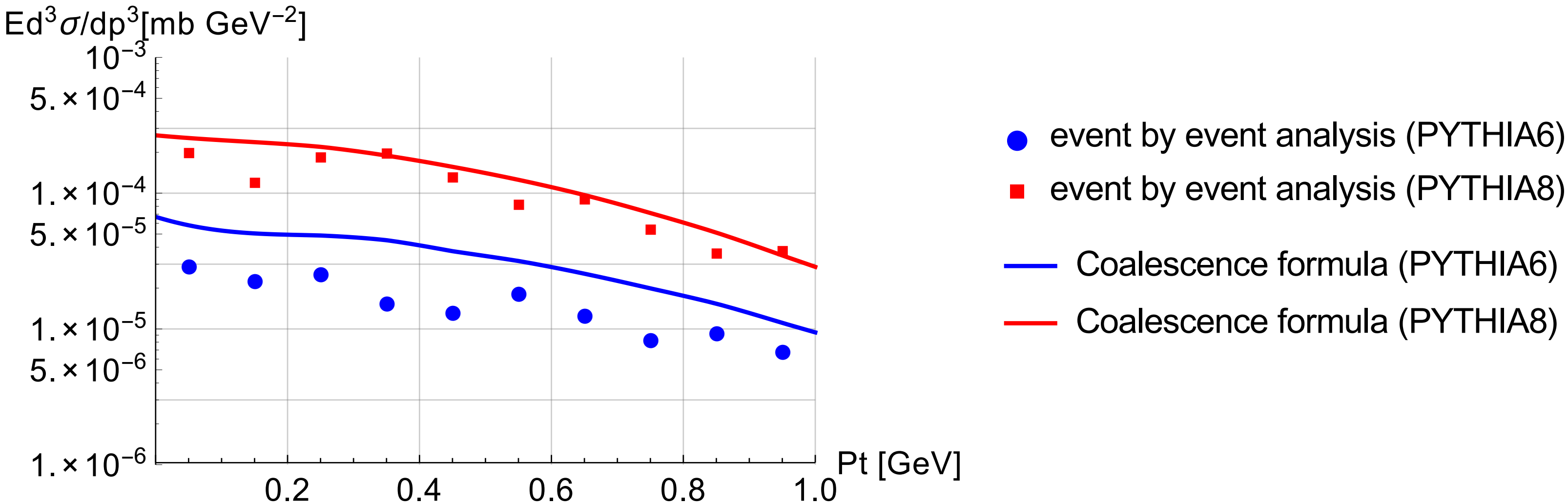


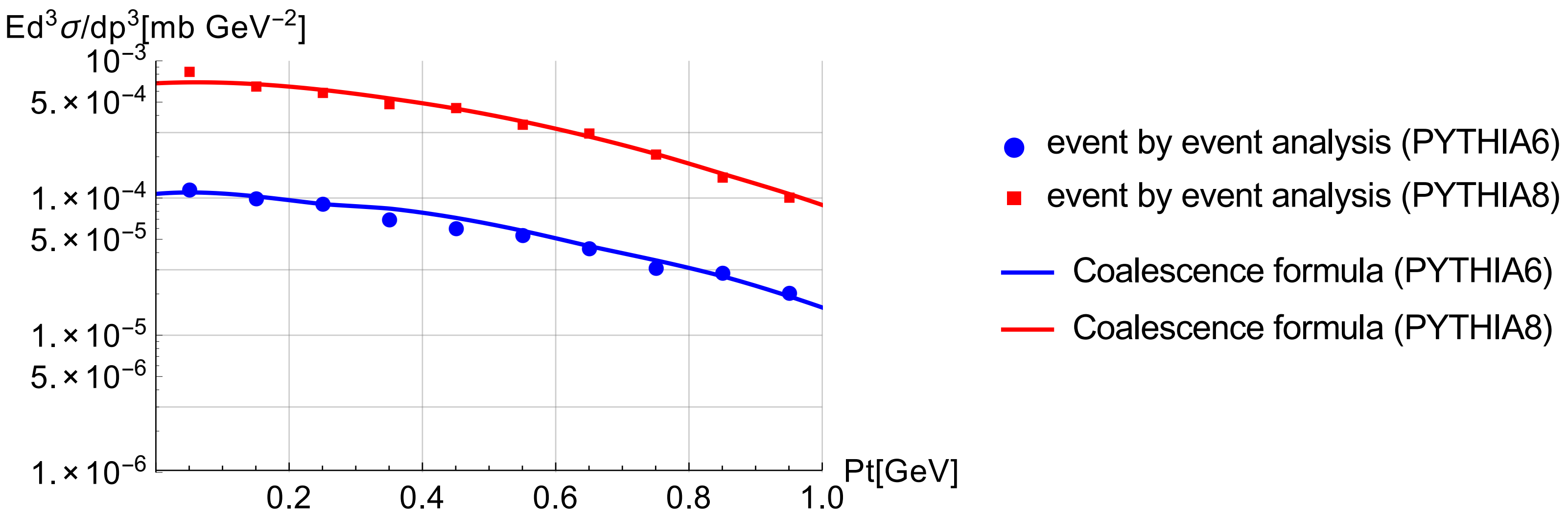
Relative contributions for p_{pbar} = 10 GeV
0.5
5GeV
20GeV
1
0.
0.006
0.005
0.001
0.002
0.047
0.034
0.008
0
0.004
0.071
0.047
0.01
0.008
0.126
0.08
0.018
0.011
0.172
0.106
0.023
1.5
0.008
0.113
0.069
0.015
1
10GeV
−0.5
2.0
1.5
1.0
0.5
0.0
1.0
1.5
2.0
2.5
3.0
p_t[GeV]
$\log_{10}(p_{proton}/GeV)$

Antiproton cross section
Vs. NA49



Coalescence: semi-analytic vs. PYTHIA



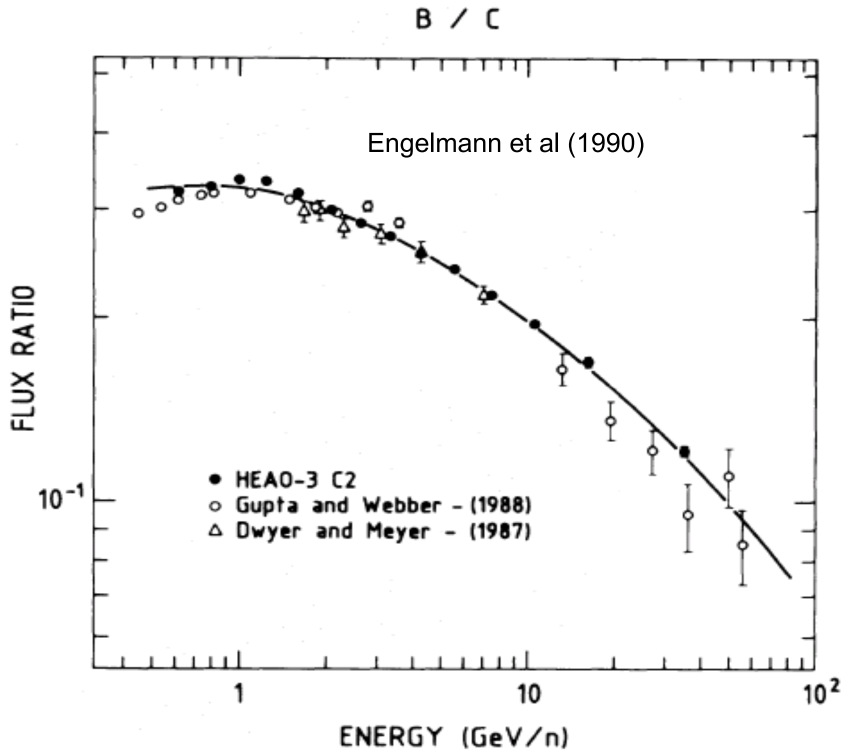


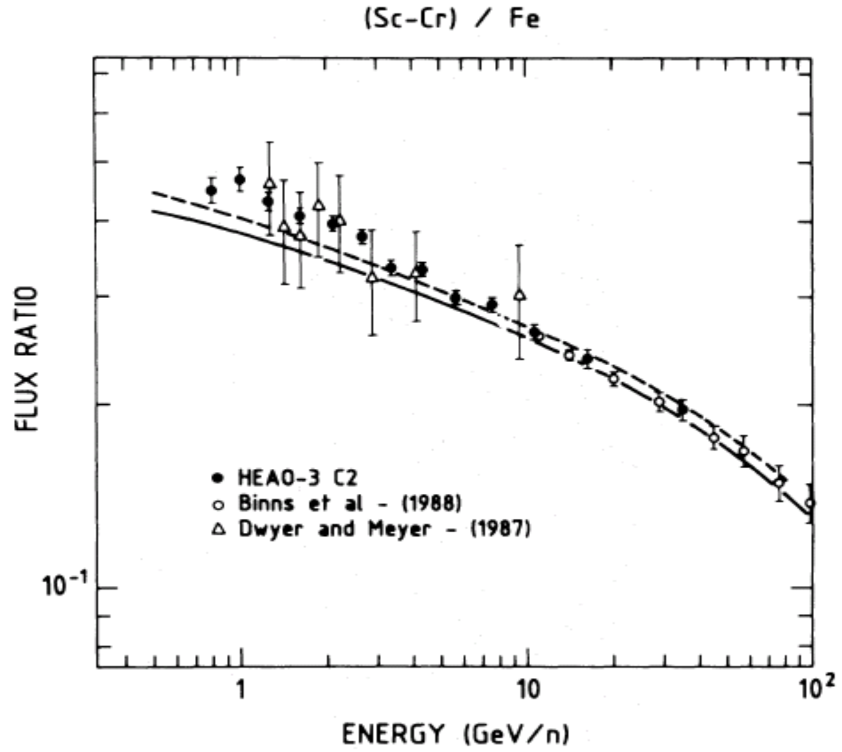
antimatter is produced in collisions of the bulk of the CRs
-- protons and He – with interstellar gas

For secondary antimatter we have a handle: particle physics branching fractions

…works for secondary nuclei B, sub-Fe (T-V-Sc-Cr)

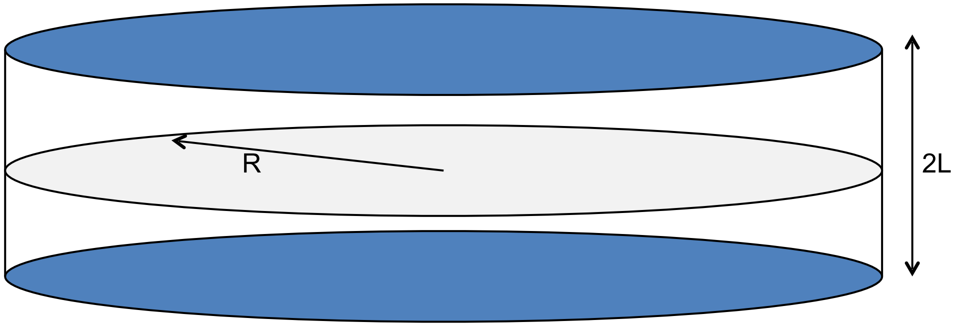
$$\frac{n_a(\mathcal{R})}{n_b(\mathcal{R})} \approx \frac{Q_a(\mathcal{R})}{Q_b(\mathcal{R})}$$



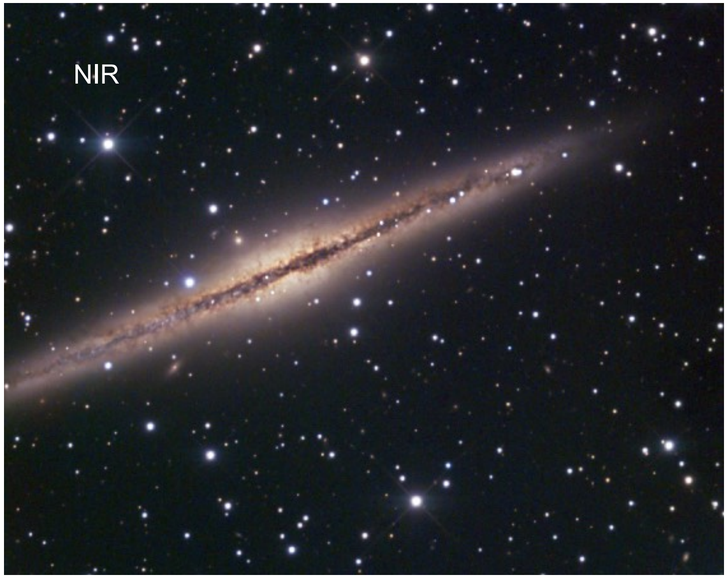


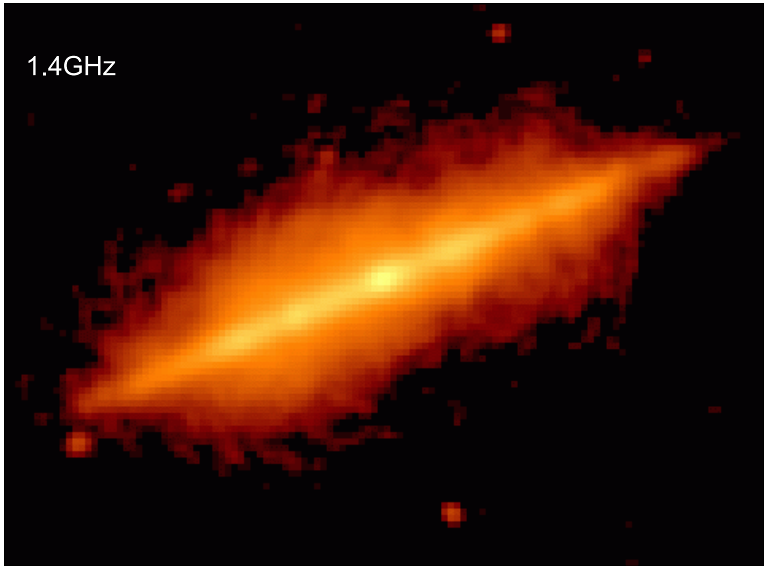
About cosmic ray propagation models

$K \sim (E/Z)^{\delta}$



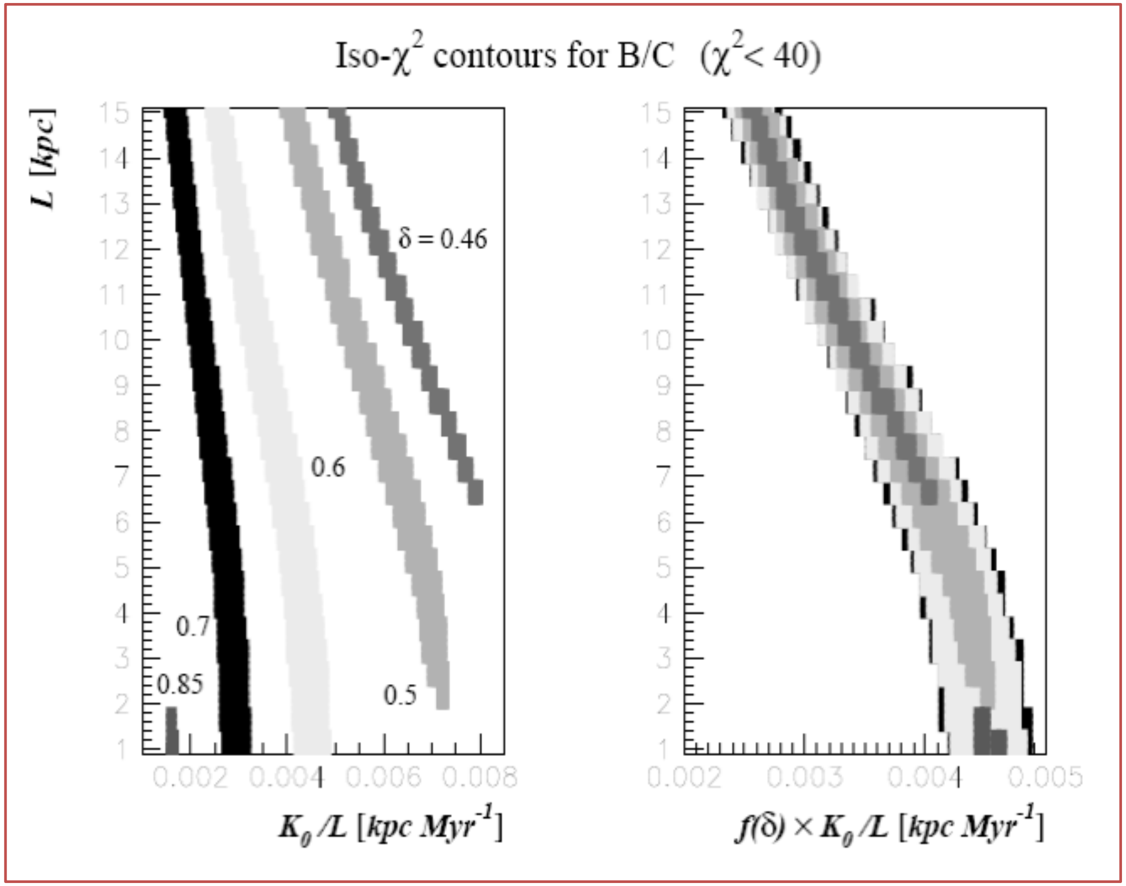
NGC 891

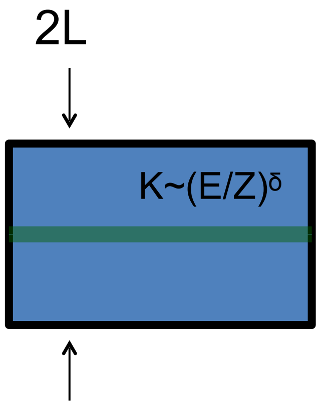




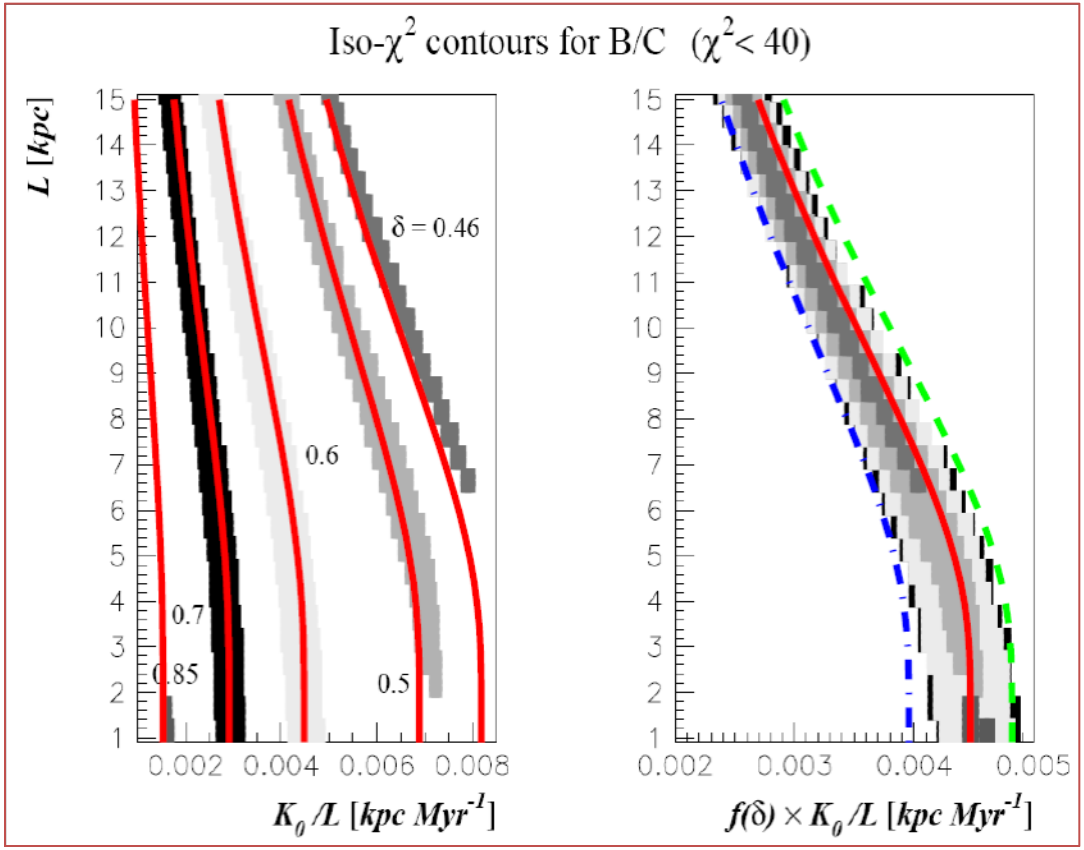
Strong, Moskalenko, Ptuskin, Ann.Rev.Nucl.Part.Sci. 57 (2007) 285-327

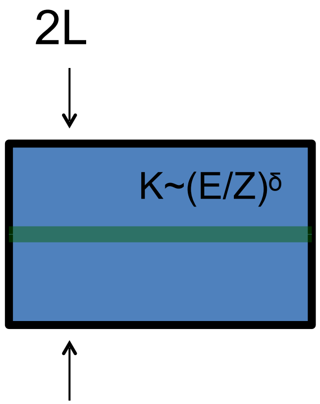
diffusion models fit X_{esc}





Maurin et al, **Astrophys.J.555:585-596,2001** diffusion models fit $X_{\rm esc}$

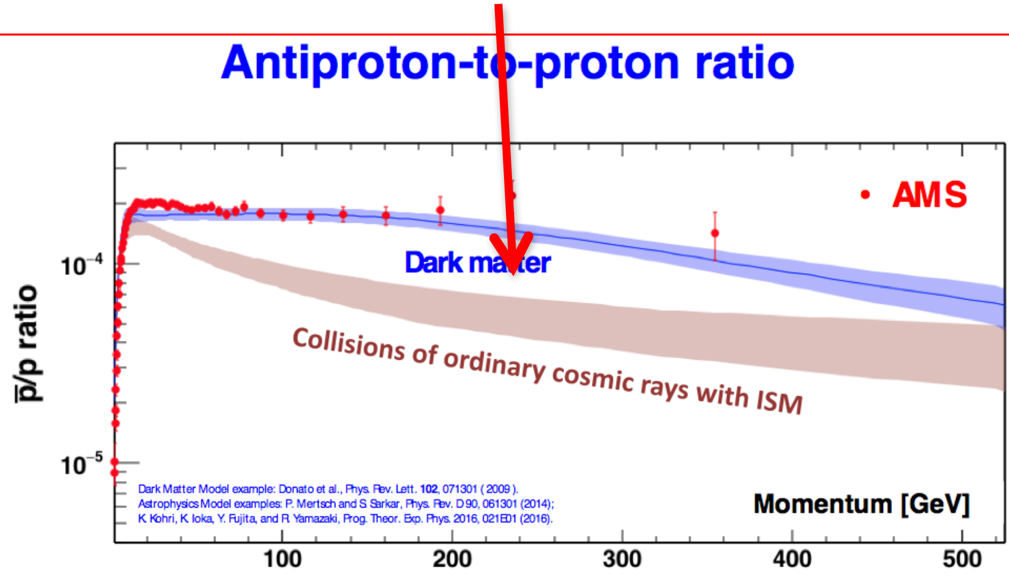




$$X_{\rm esc} = X_{\rm disc} \frac{Lc}{2D} \frac{2R}{L} \sum_{k=1}^{\infty} J_0 \left[\nu_k (r_{\rm s}/R)\right] \frac{\tanh\left[\nu_k (L/R)\right]}{\nu_k^2 J_1(\nu_k)}$$

What's going on here? (Donato et al PRL102, 071301 (2009))

Antiproton-to-proton ratio

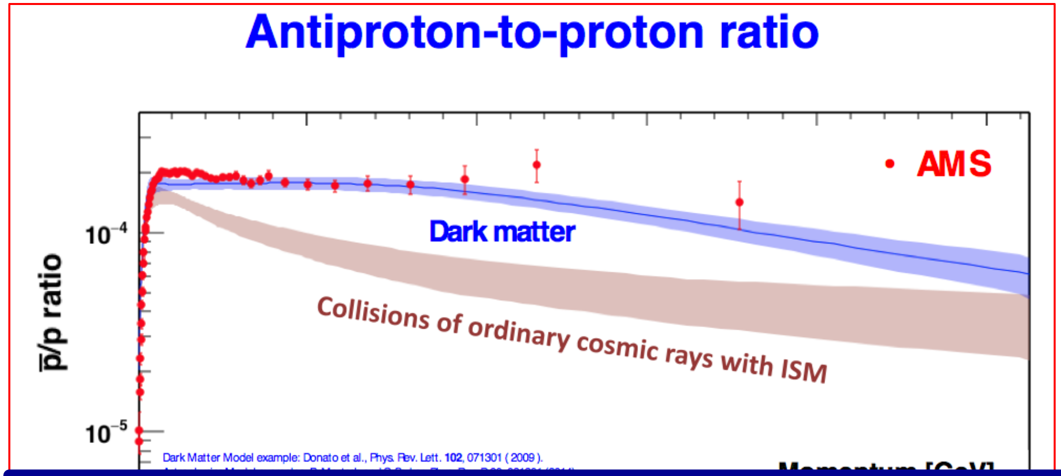


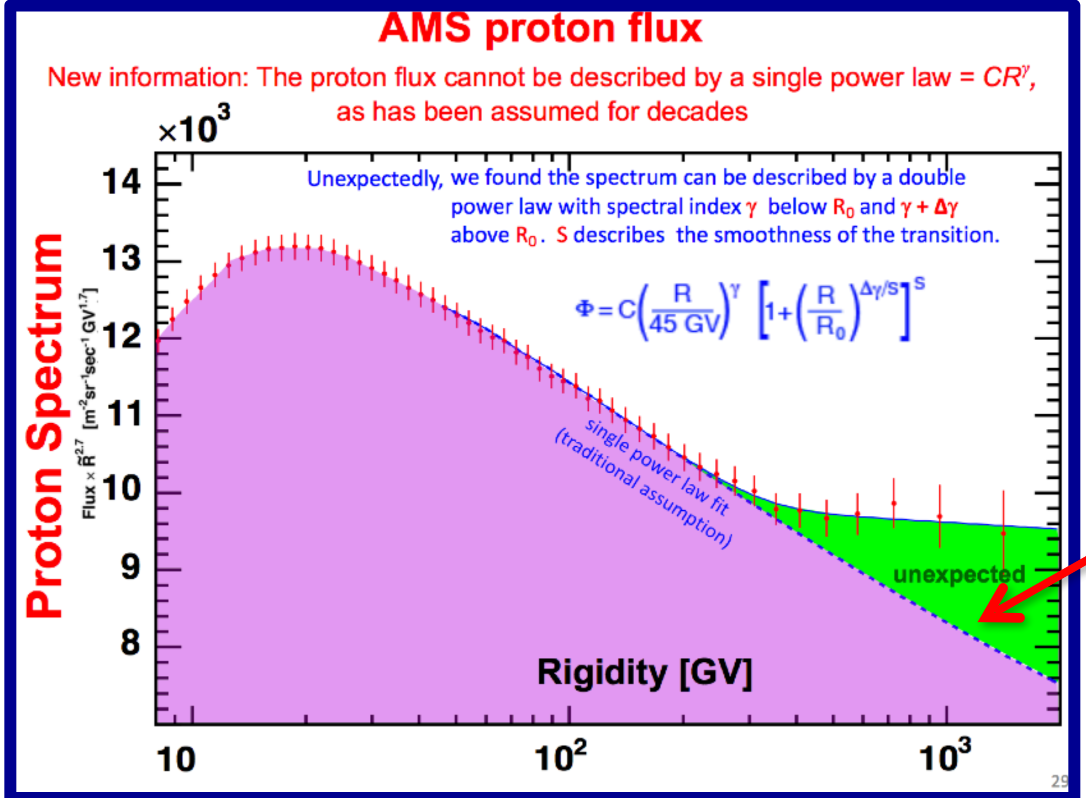
The excess of antiprotons observed by AMS cannot come from pulsars.

It can be explained by Dark Matter collisions or by new astrophysics phenomena

37

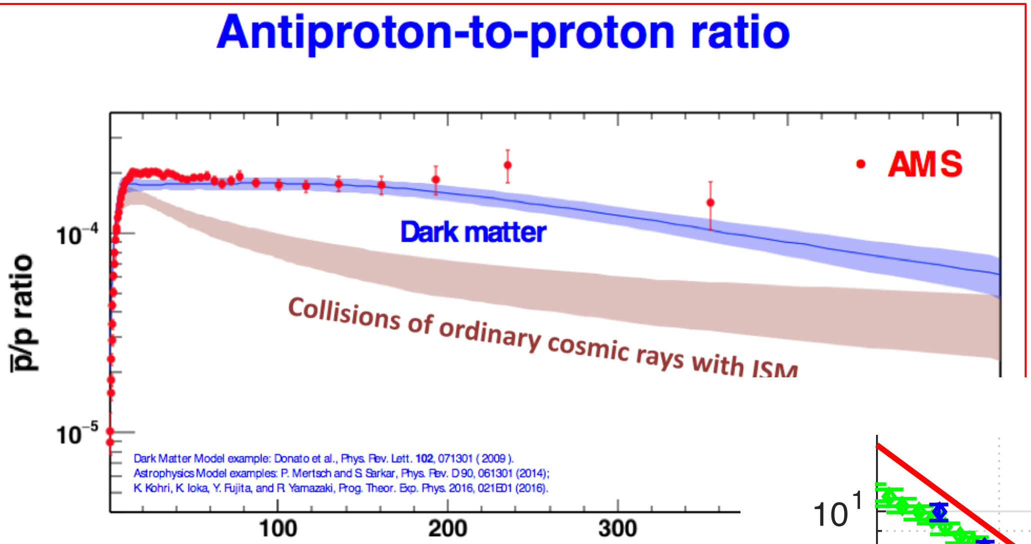
What's going on here? (Donato et al PRL102, 071301 (2009))





proton flux assumed for making the pbar/p grey line

What's going on here? (Donato et al PRL102, 071301 (2009))



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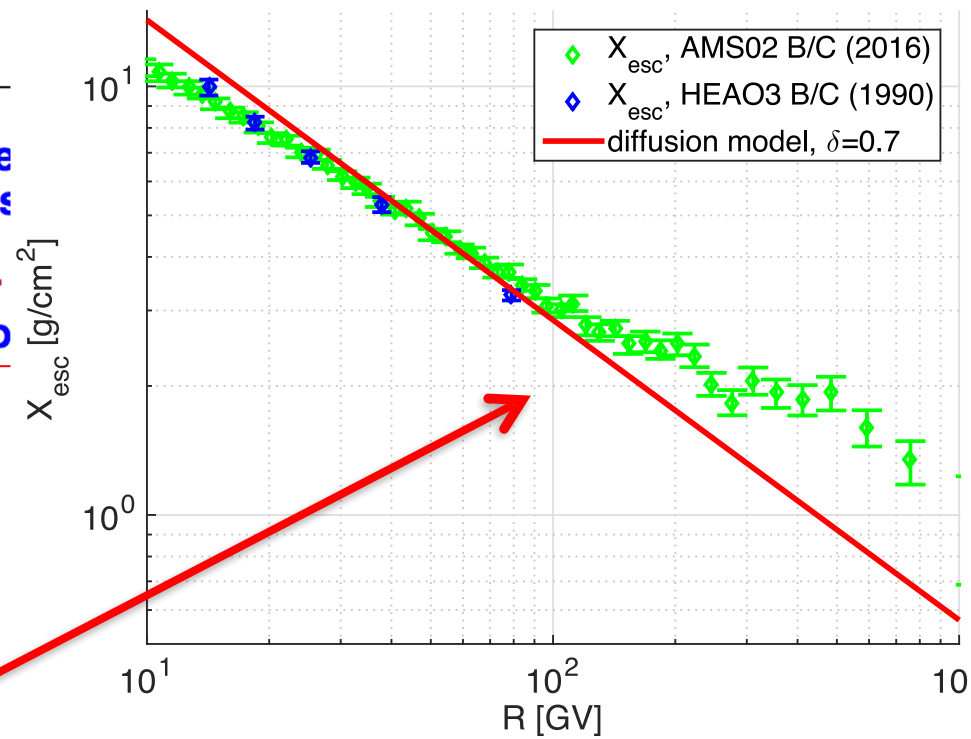
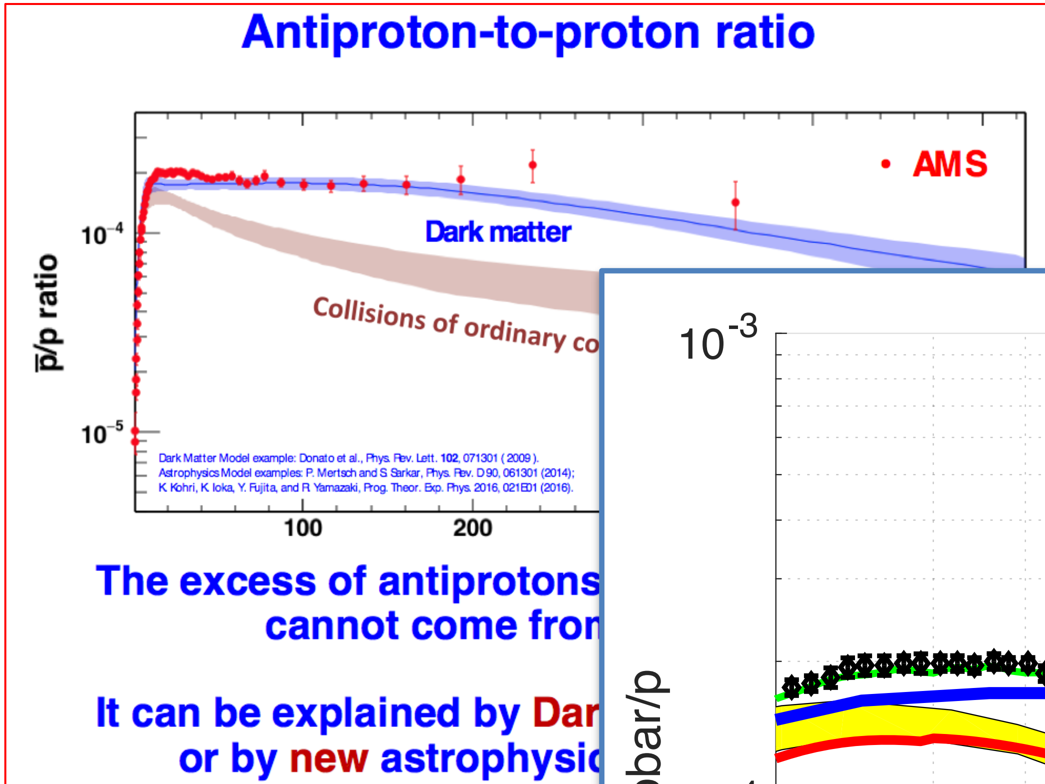
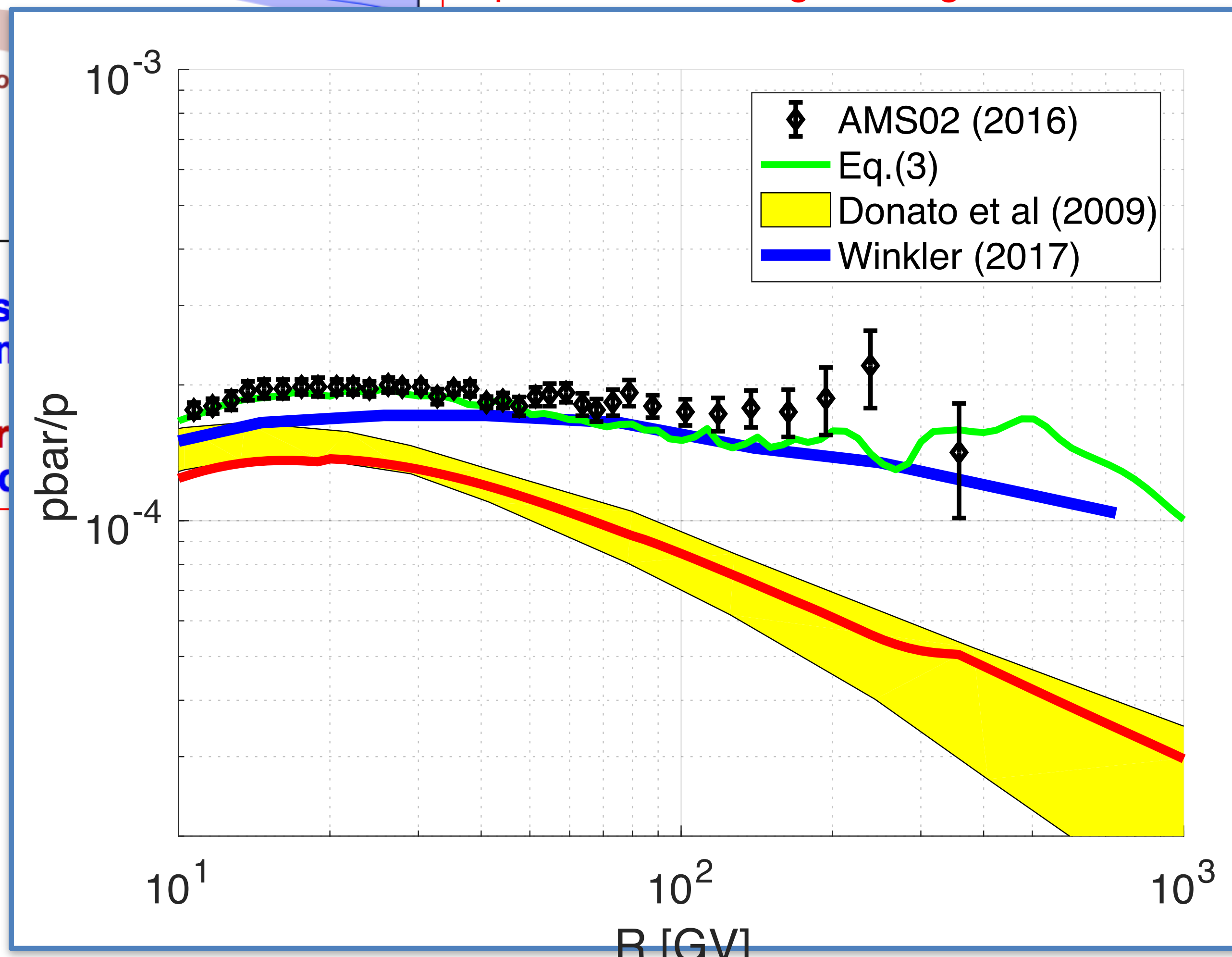


B/C grammage assumed for
making the pbar/p grey line

What's going on here? (Donato et al PRL102, 071301 (2009))



What we get if we use those old proton flux, B/C grammage



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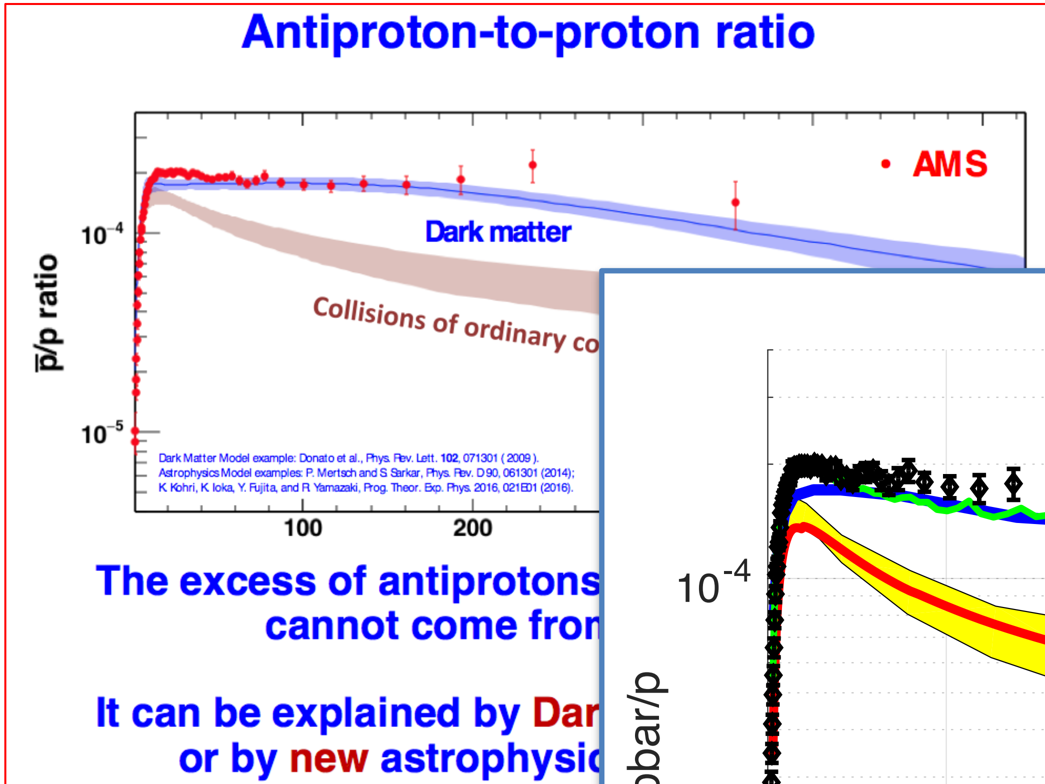

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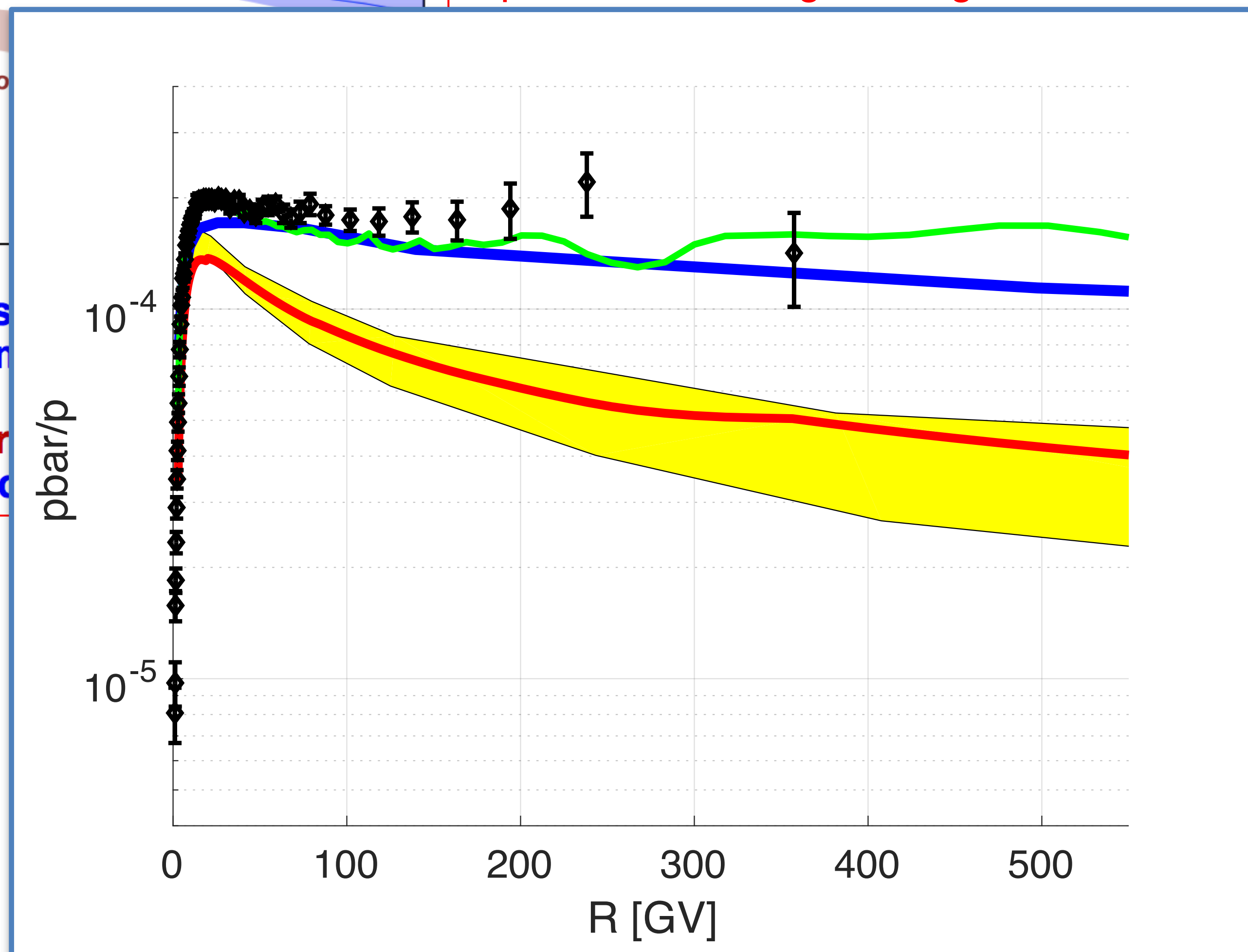
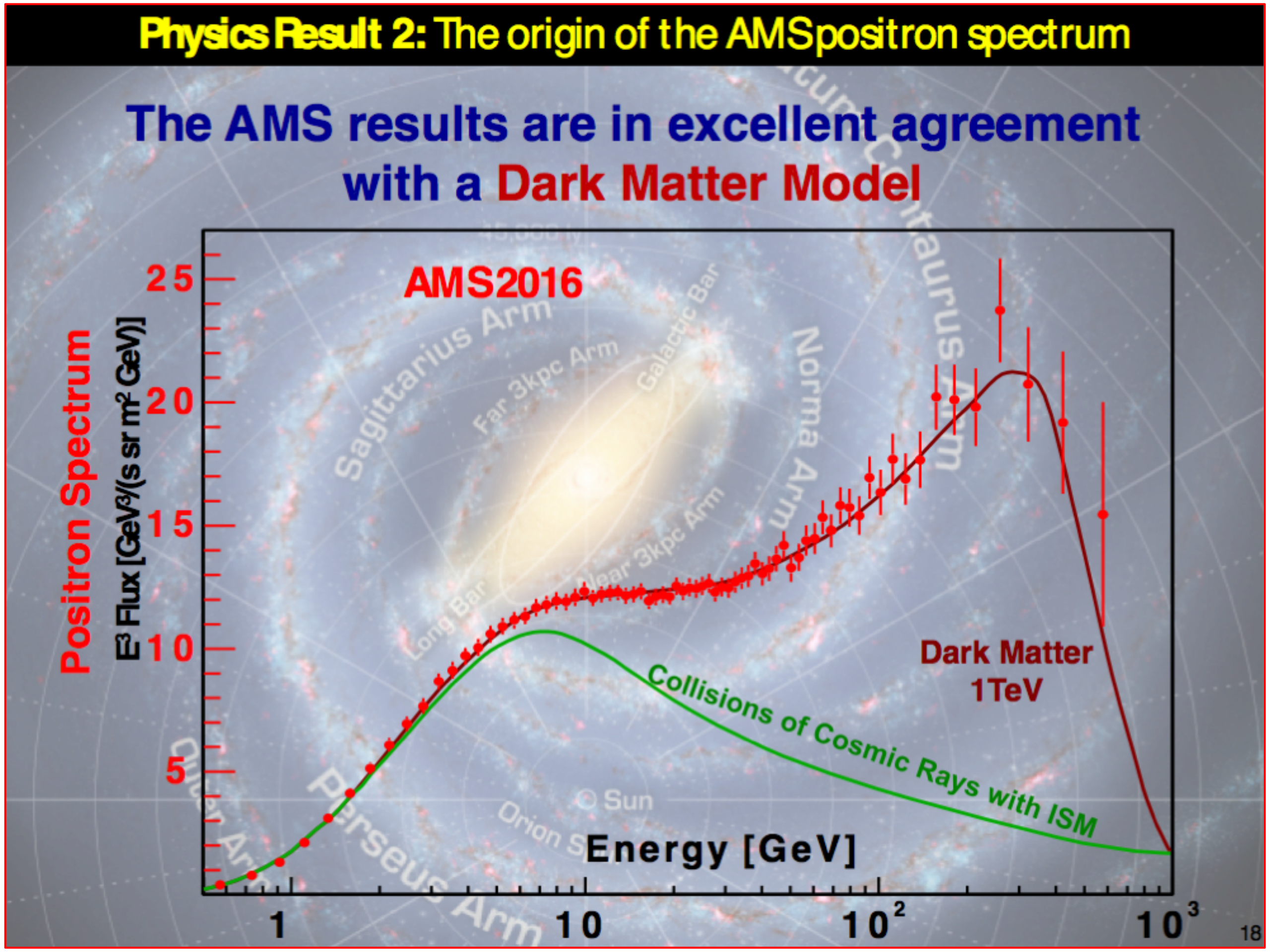


What about e+ ?

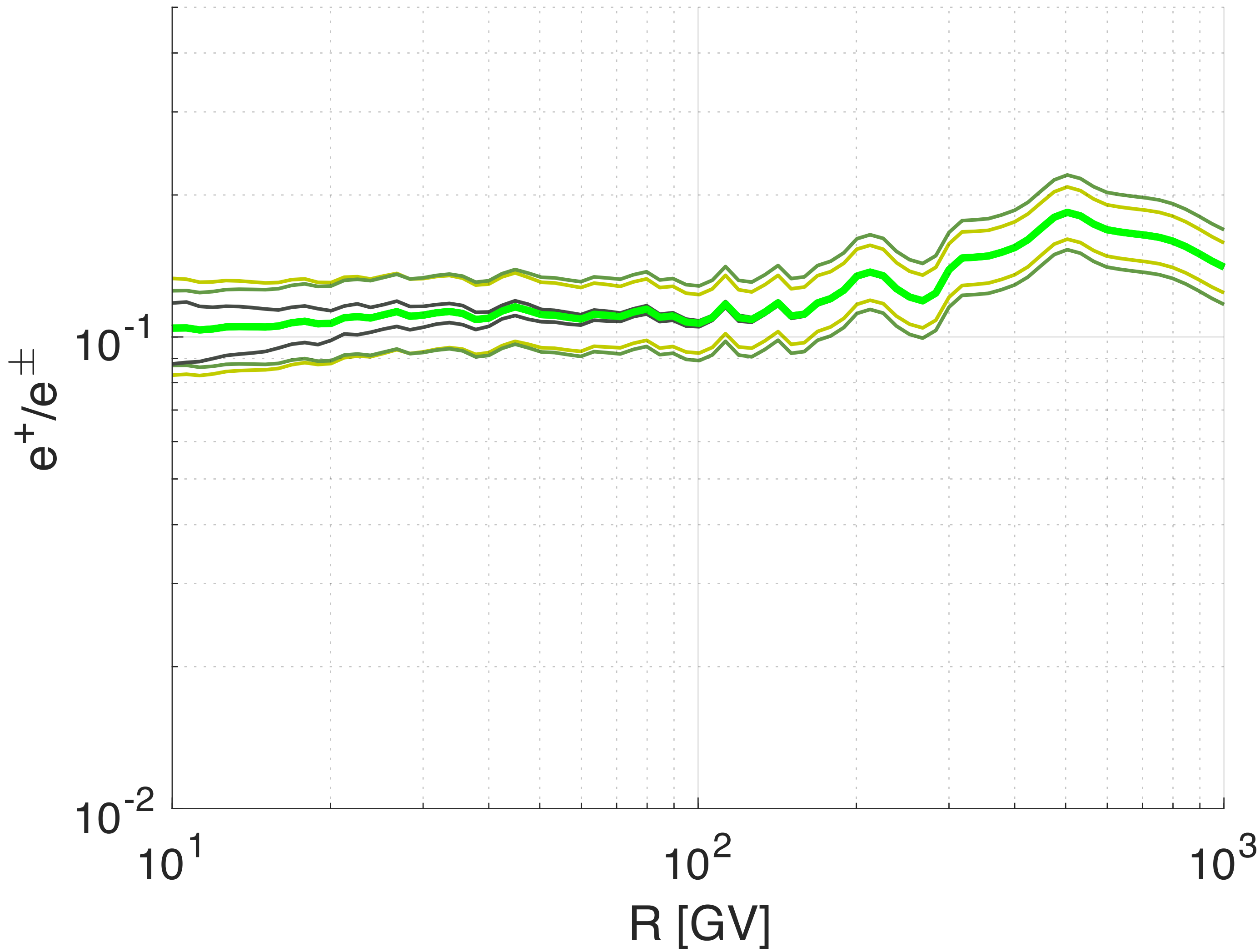
What about e+ ?

AMS02, Dec 2016



Secondary *upper bound*
(Based on B/C)

$$n_{e^+}(\mathcal{R}) \lesssim \frac{n_{\rm B}(\mathcal{R})}{Q_{\rm B}(\mathcal{R})} Q_{e^+}(\mathcal{R})$$



MNRAS 405 (2010) 1458 Katz, Blum, Morag, Waxman
1709.06507

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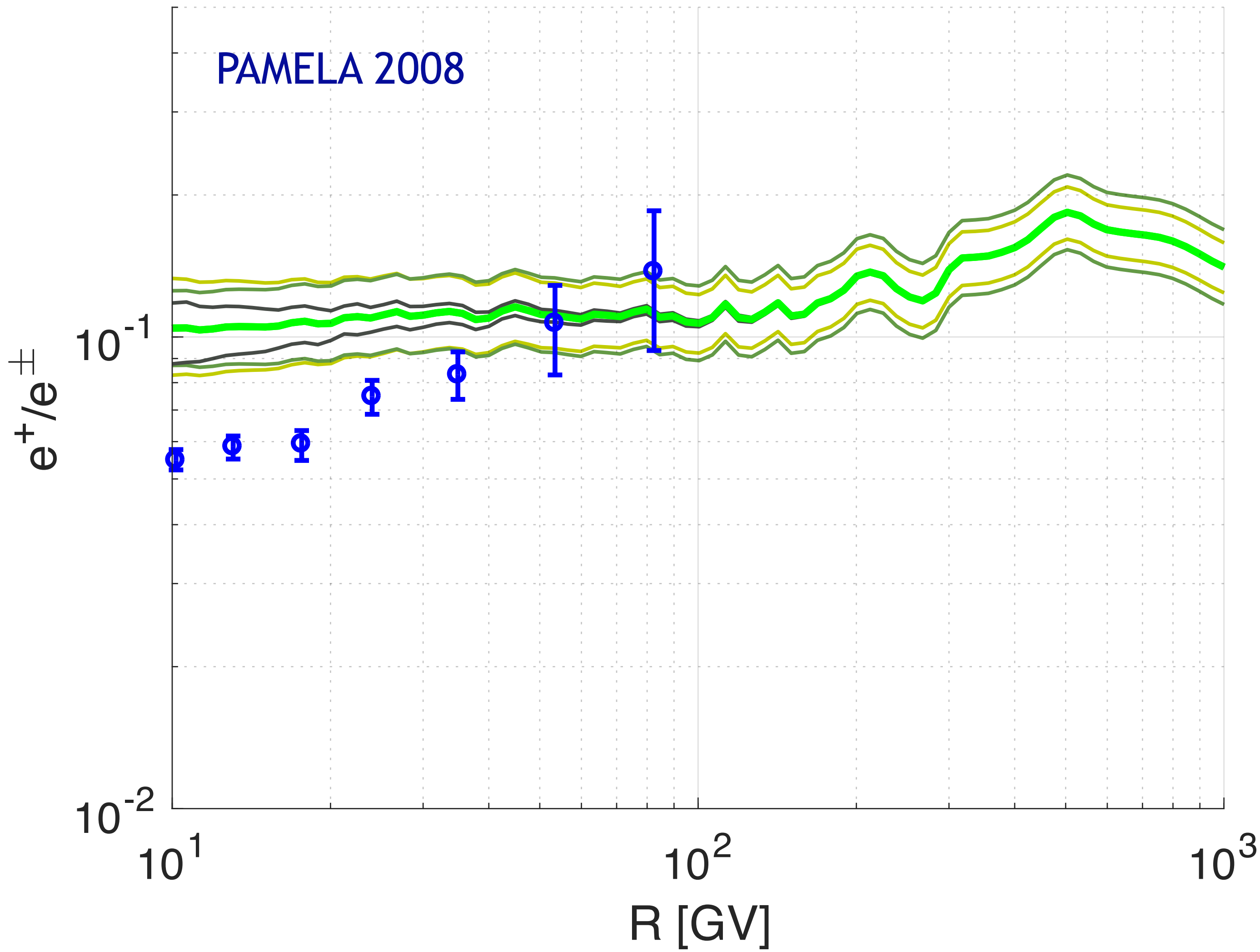

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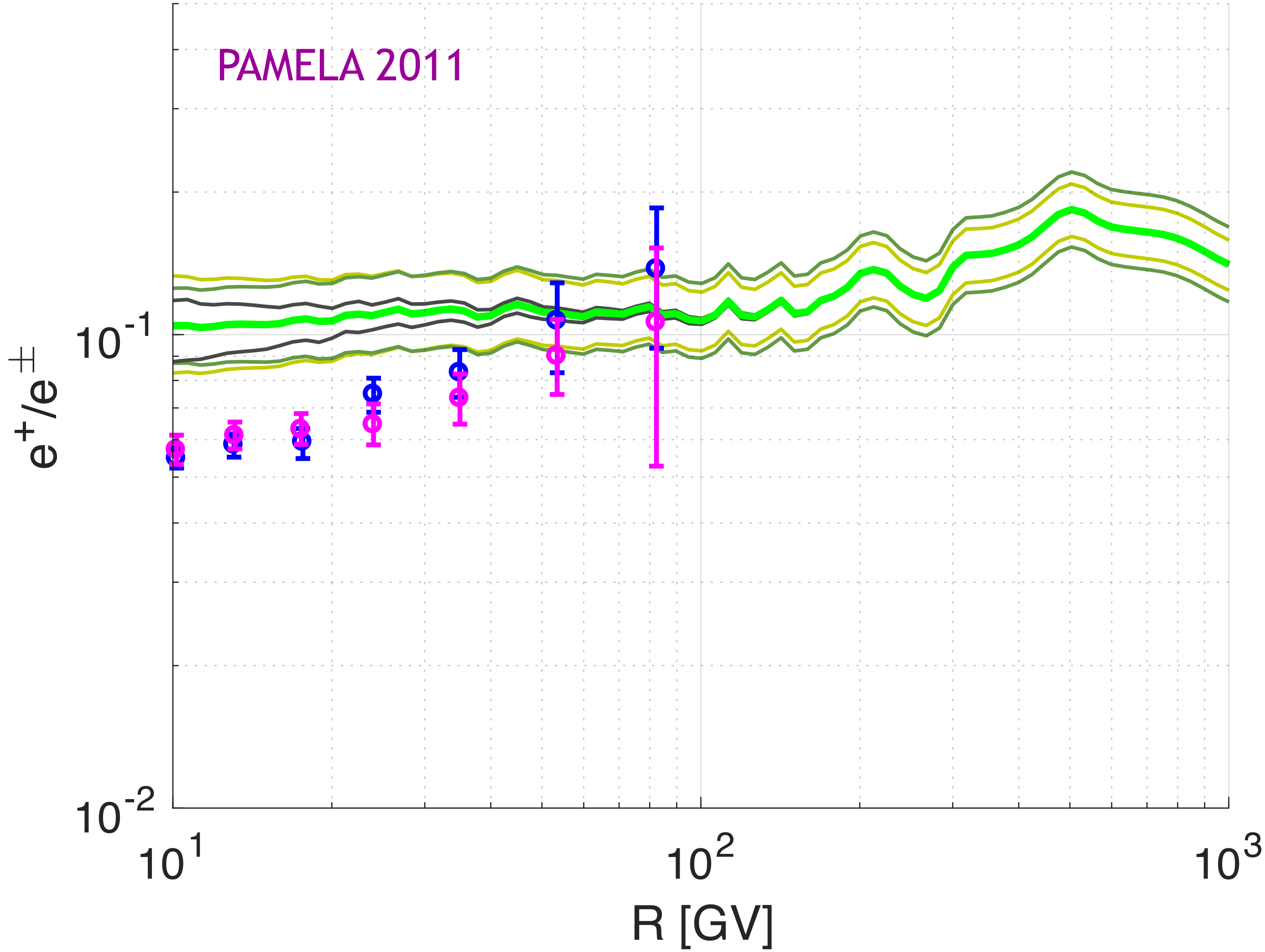

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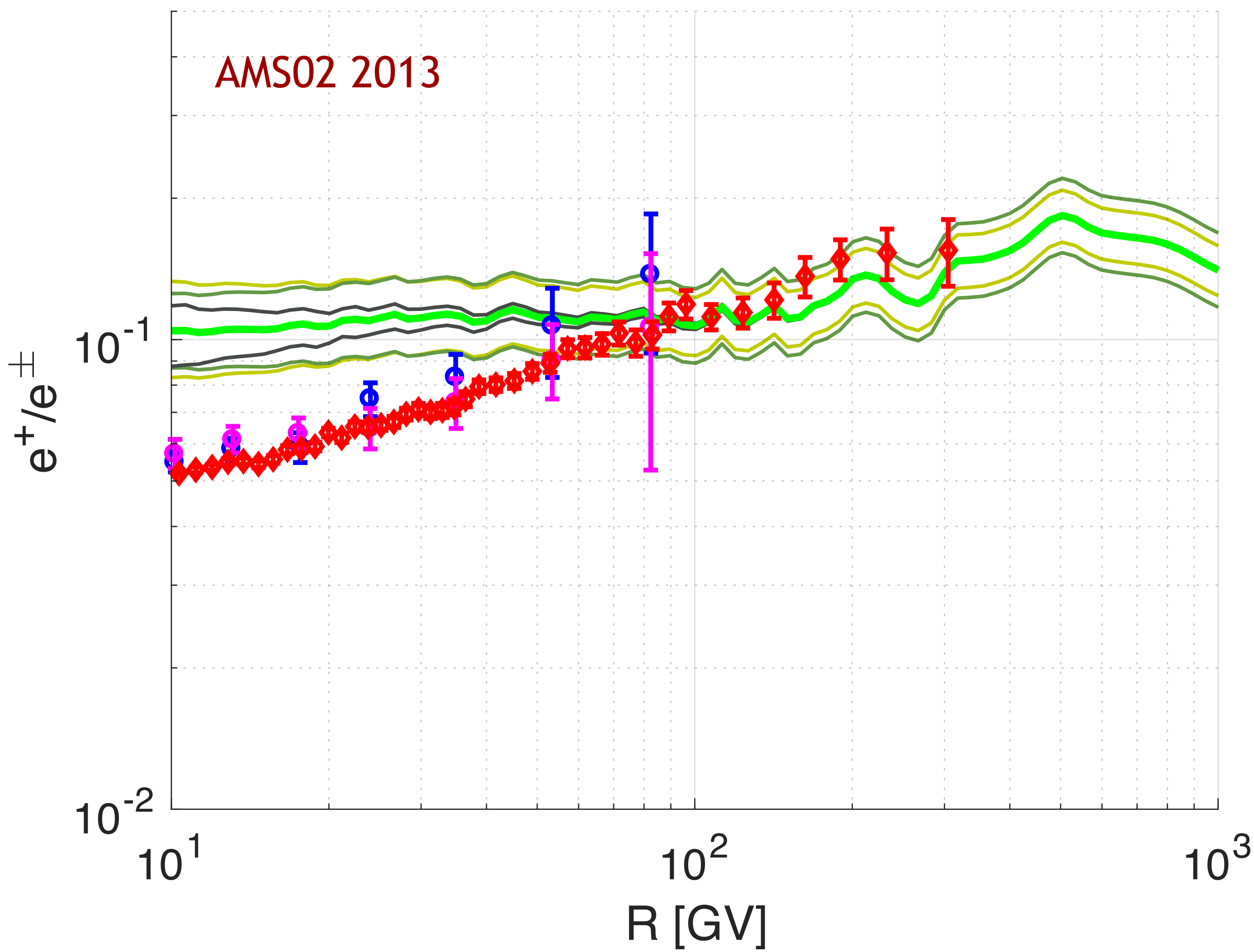

MNRAS 405 (2010) 1458 Katz, Blum, Morag, Waxman
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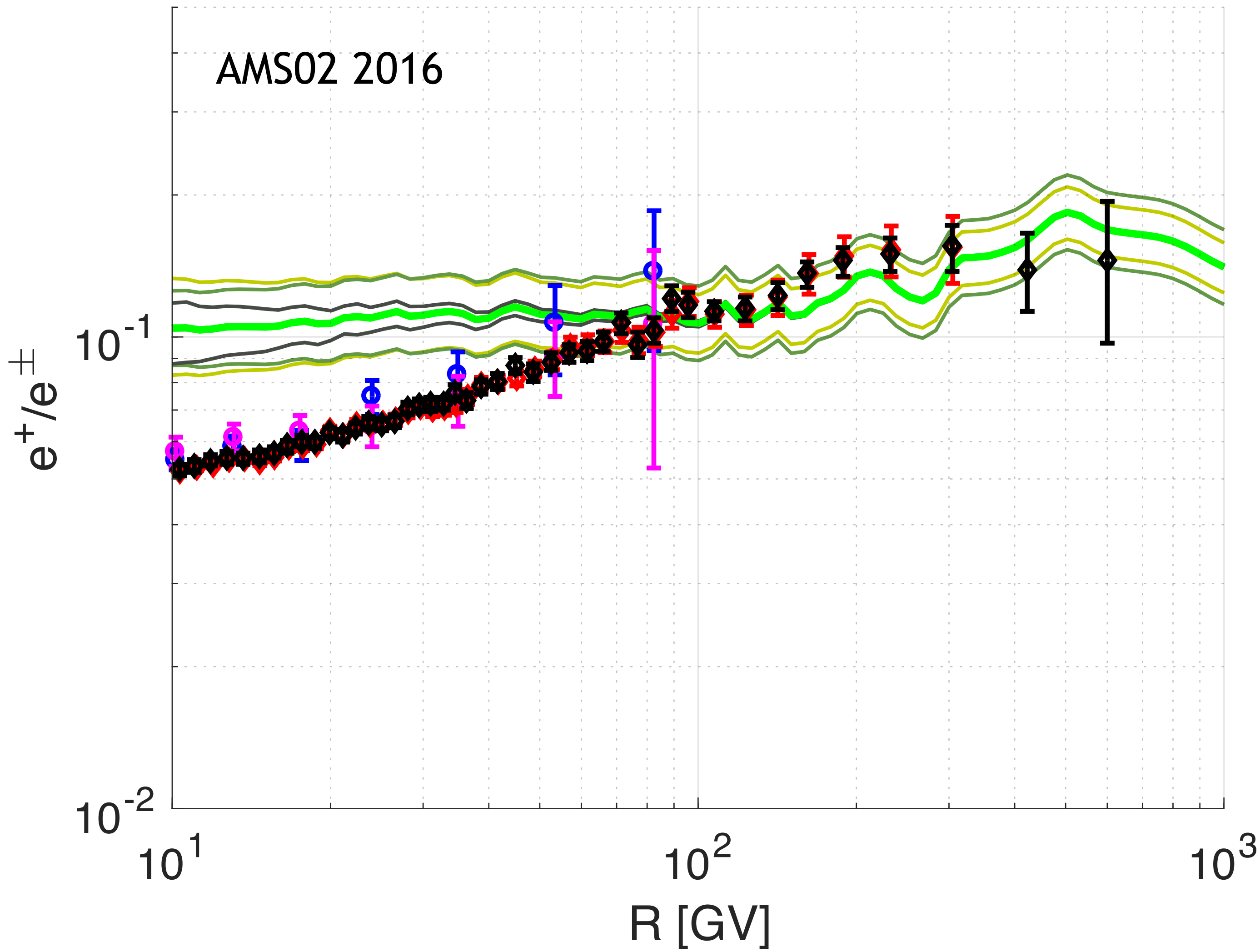
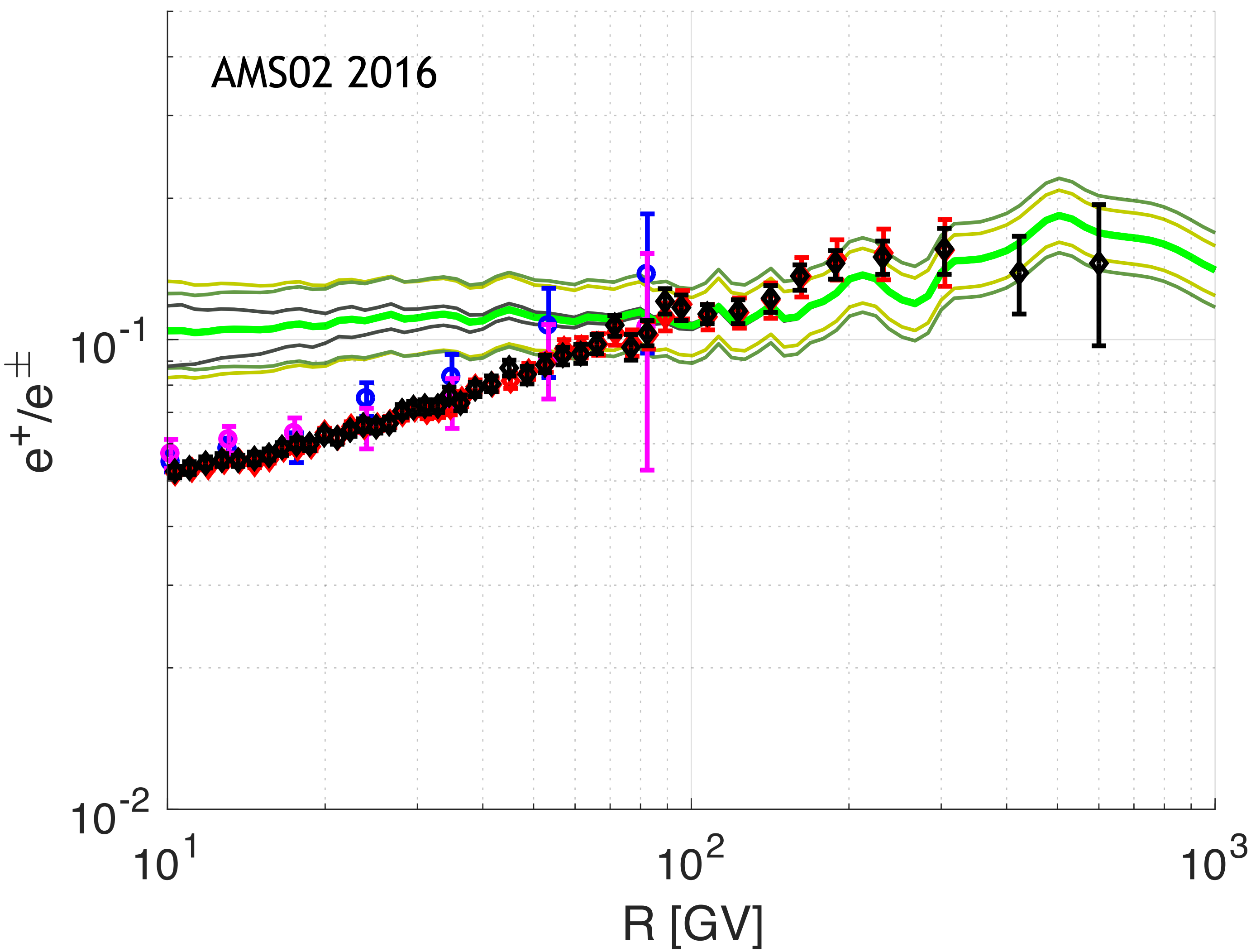


MNRAS 405 (2010) 1458 Katz, Blum, Morag, Waxman
1709.06507

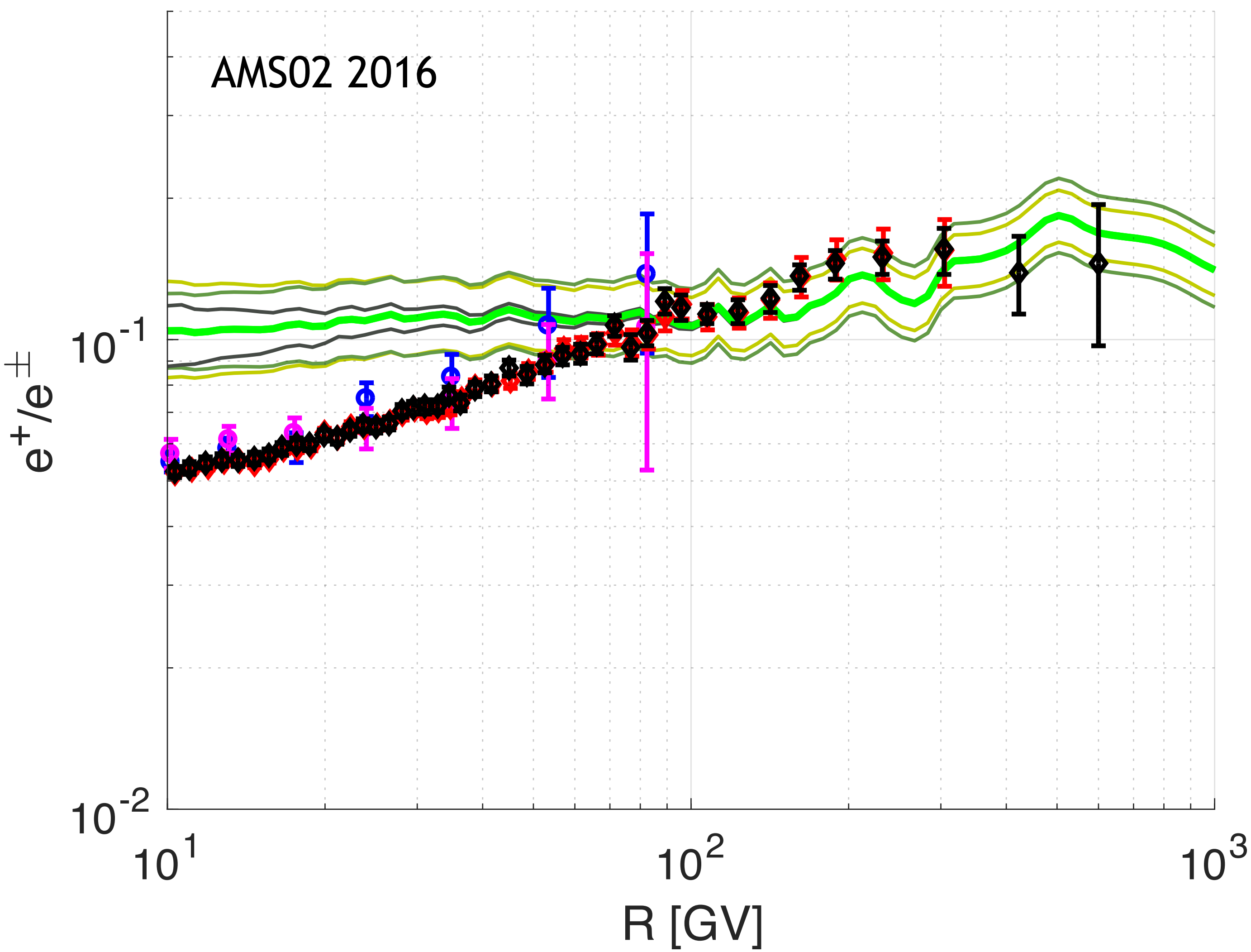
e+ are probably secondary.

$$n_{e^+}(\mathcal{R}) \lesssim \frac{n_{\mathrm{B}}(\mathcal{R})}{Q_{\mathrm{B}}(\mathcal{R})} Q_{e^+}(\mathcal{R})$$



MNRAS 405 (2010) 1458 Katz, Blum, Morag, Waxman
1709.06507

Why would dark matter or pulsars inject ***this*** e+ flux?



Blum, Katz, Waxman, Phys.Rev.Lett. 111 (2013) no.21, 211101

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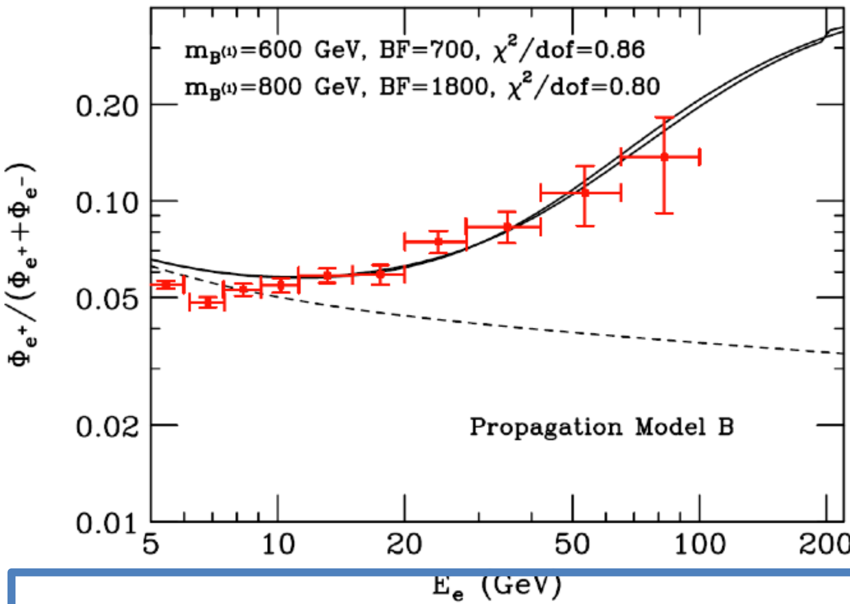
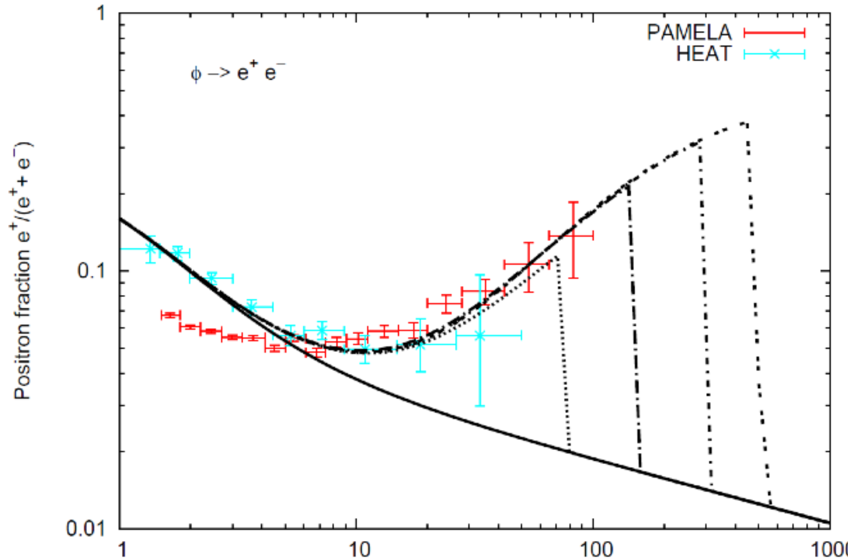
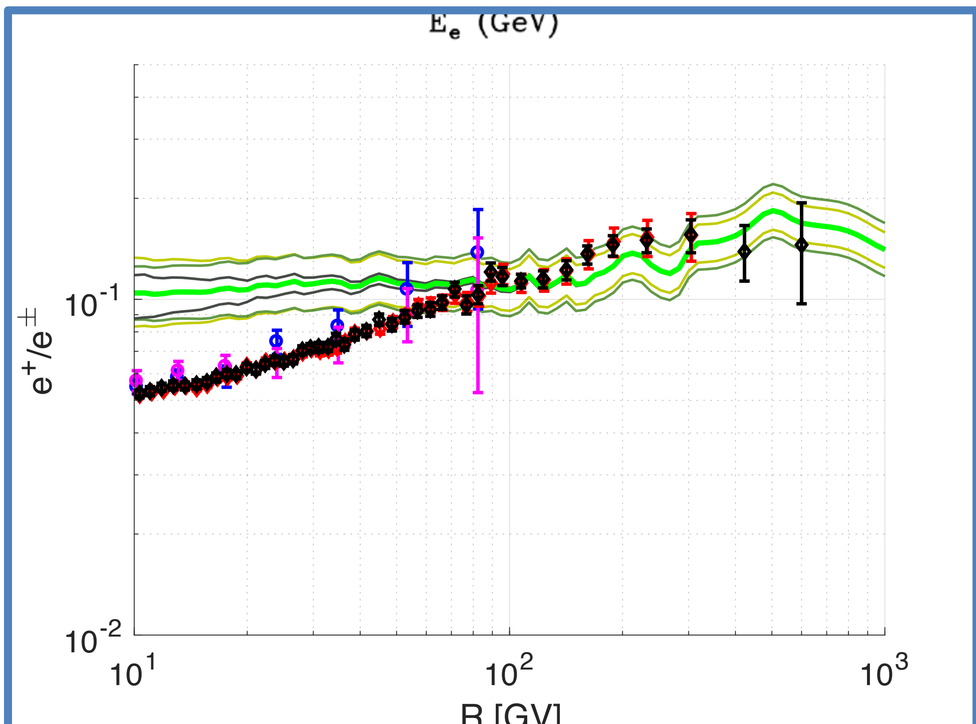
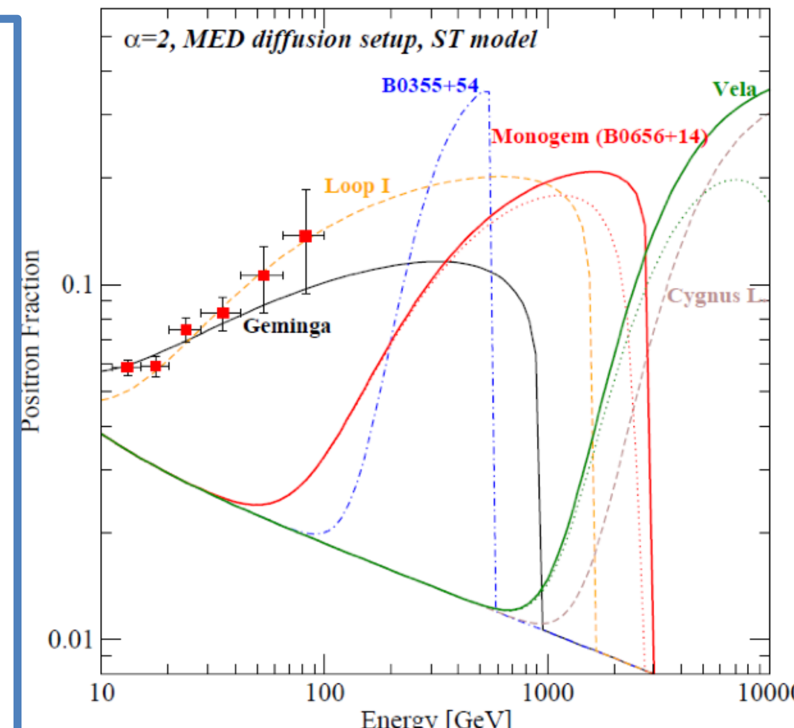
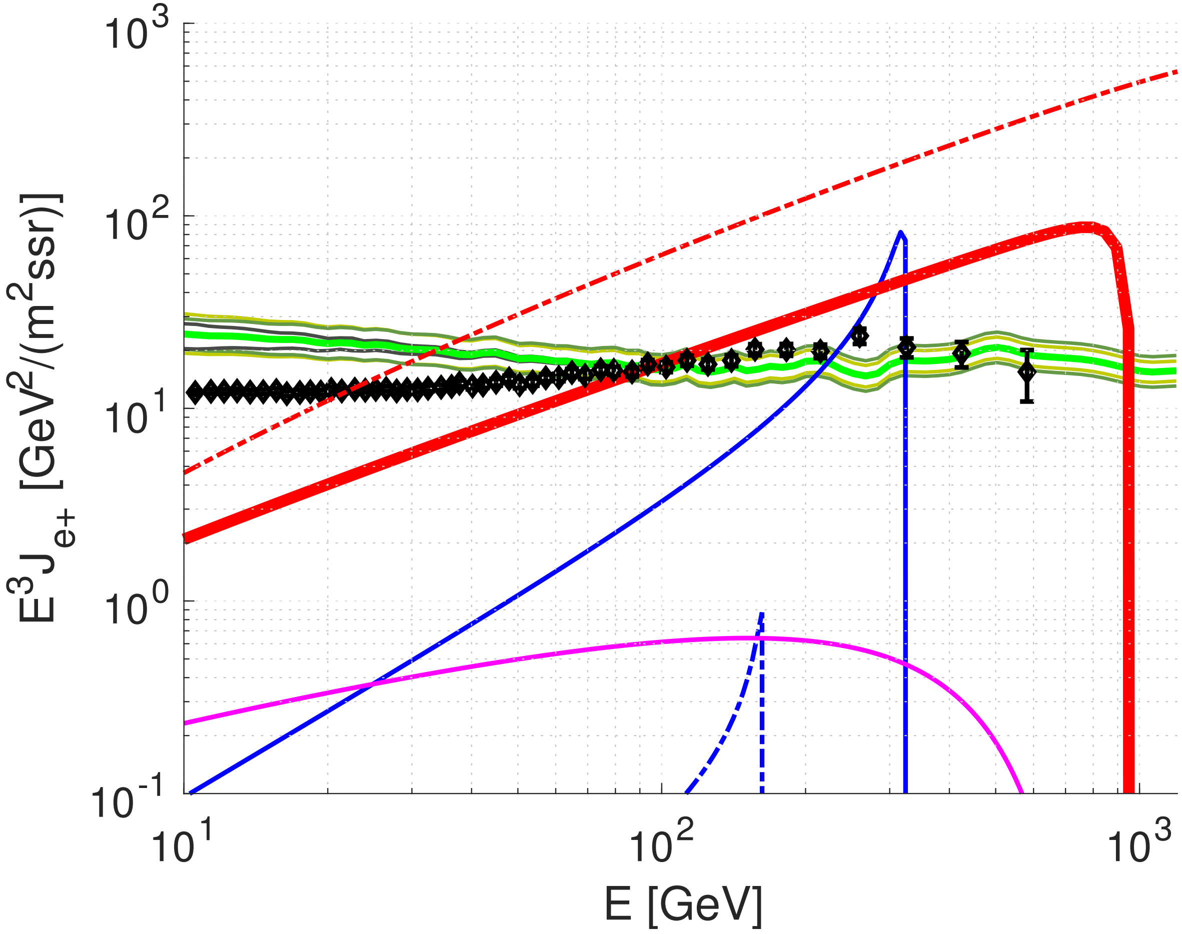








Why would dark matter or pulsars inject ***this*** e+ flux? 1709.06507



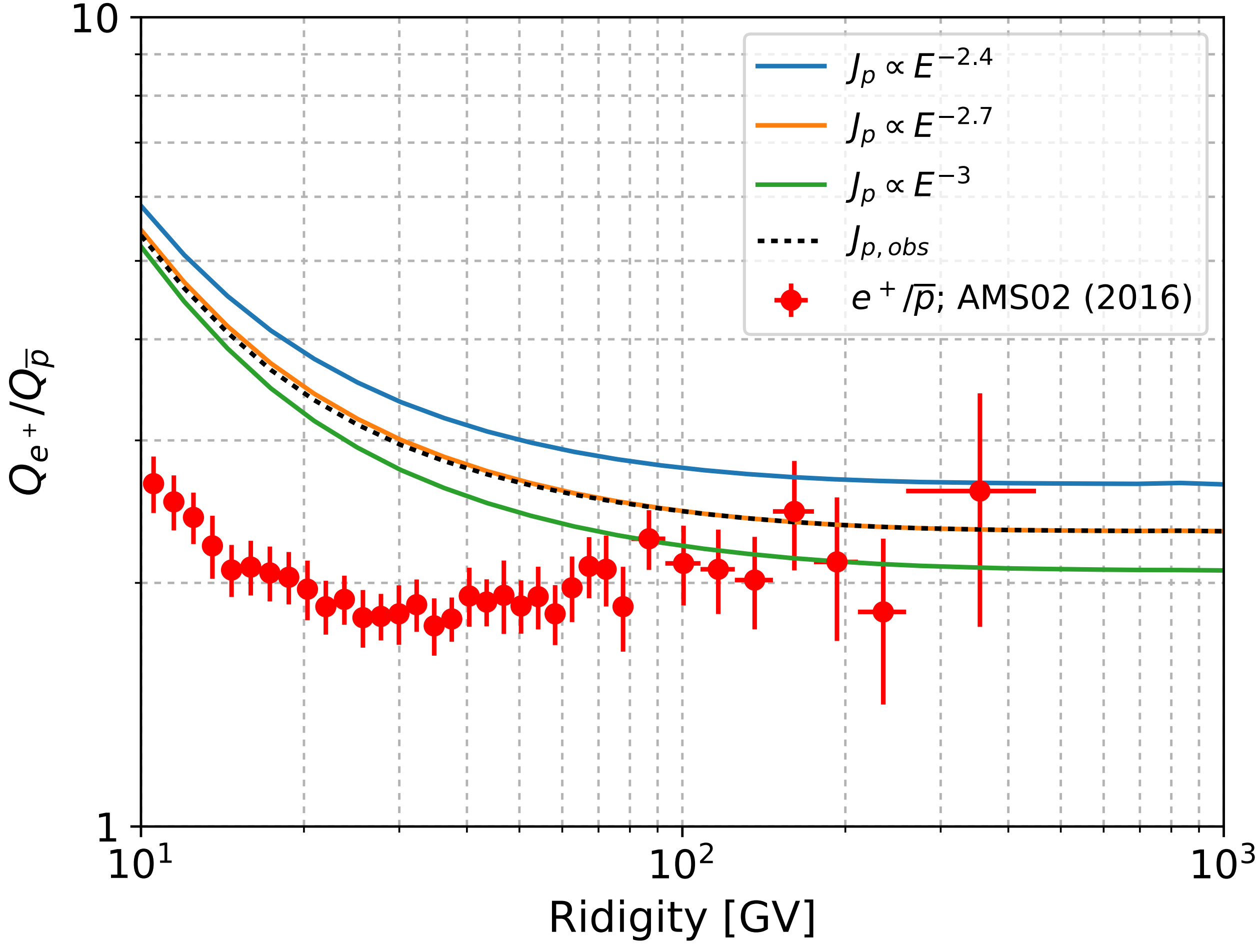
Pulsar model: D. Malyshev, I. Cholis, and J. Gelfand, Phys. Rev. **D80**, 063005 (2009)

$$\frac{n_{e^+}}{n_{\bar{p}}} = f_{e^+}(\mathcal{R})\frac{Q_{e^+}(\mathcal{R})}{Q_{\bar{p}}(\mathcal{R})}$$

Secondary upper bound

$$f_{e^+}(\mathcal{R}) \leq 1$$

More robust (no need to go via B/C):



MNRAS 405 (2010) 1458 Katz, Blum, Morag, Waxman
1709.04953, 1709.06507