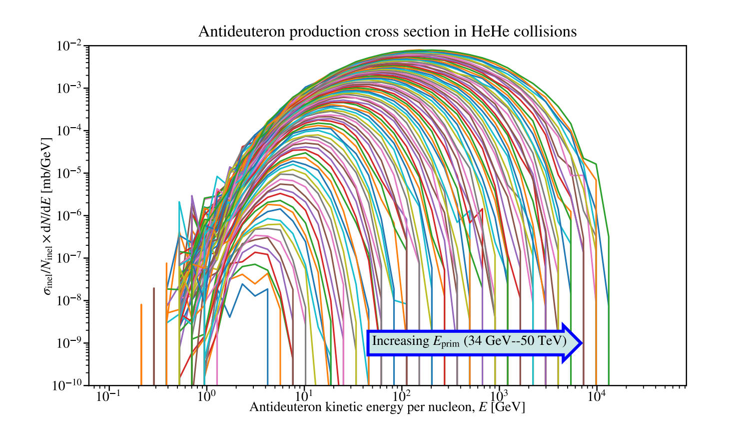
Antinuclei in the Milky Way

Michael Kachelrieß (NTNU, Trondheim)



with Jonas Tjemsland and Sergey Ostapchenko

Eur.Phys.J.A 56 (2020) 1, JCAP 08 (2020) 048, Eur.Phys.J.A 57 (2021) 5, 167, PoS TOOLS2020 (2021) 006,...

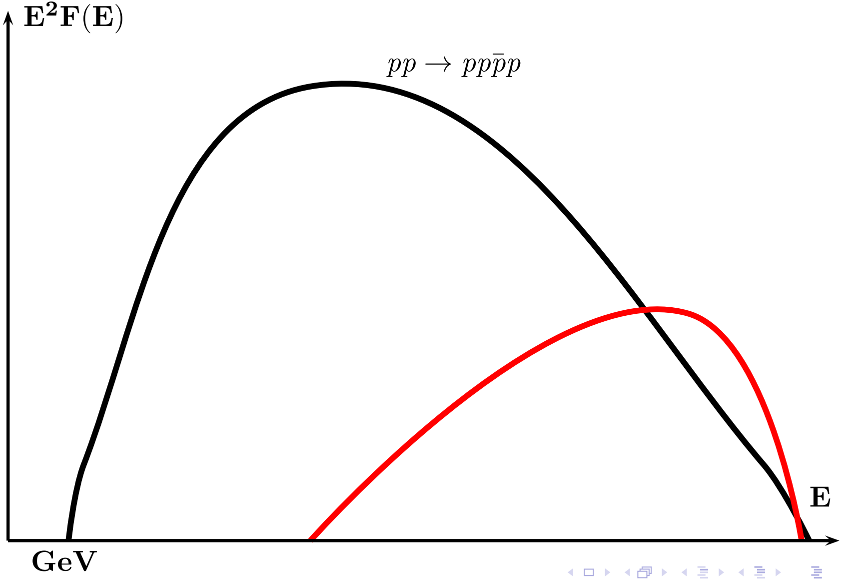
Outline of the talk

1. Introduction
   - Motivation: why antinuclei?
     - Probe of quark-gluon plasma
     - Signature of dark matter
   - Physical basis of coalescence approach
2. Coalesence models and antinuclei production
   - Coalescence in momentum space
   - Coalescence in phase space
3. Antinuclei fluxes and detection prospects
   - Boosting anti-helium fluxes?
4. Conclusions

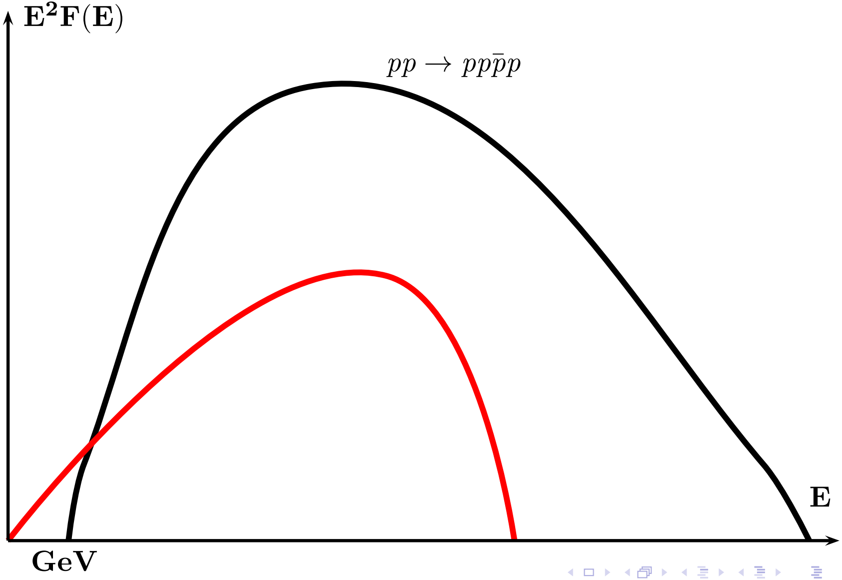
Indirect dark matter searches:

- intense search for DM since $\gtrsim 30$ years:
  - γ-ray line, γ-rays from dwarf galaxies,...
  - neutrinos from the Sun
  - excess of antimatter: positrons, antiprotons,...
- no clear evidence found yet...
- signal hidden below astrophysical backgrounds?

Antiprotons from DM: close to M_X



Antiprotons from DM: below threshold for CR secondaries



Antideuterons as signature for DM

- antiprotons: two interesting energy regions
  - high energy: increasing $\bar{p}/p$ ratio
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- up-to 10 events/yr in AMS-02
- today's expectation?

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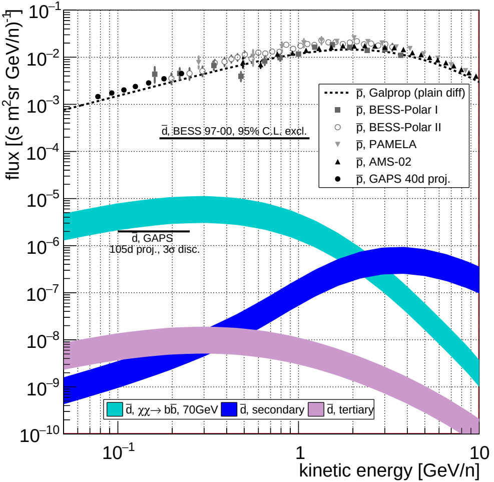
- AMS-02: six $^3\overline{\mathrm{He}}$ and two $^4\overline{\mathrm{He}}$ candidates (2019)
- GAPS: flights scheduled next antarctic summer



Formation of light nuclei

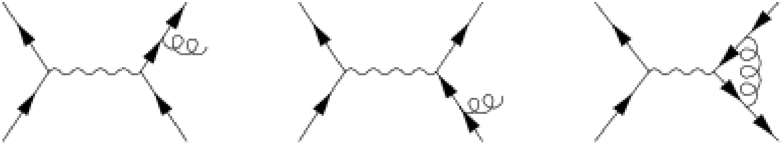
interested in various types of reactions:

- DM+DM$\to X\bar{d}$
- $e^+e^- \to X\bar{d}$
- $pp \to X\bar{d}$
- $Ap \to X\bar{d}$
- $AA \to X\bar{d}$

different physics, different communities $\Rightarrow$ different approaches

Simplest case: $e^+e^- \to$ hadrons

- hard interaction: LO or NLO matrix element



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  - ordered in virtualities and angles $s \simeq Q_1^2 > Q_2^2 > \ldots > Q_{\rm min}^2 \gg \Lambda_{\rm QCD}^2$
- hadronisation volume in cms: $\sigma_\| \sim 1/(\gamma m_p)$, $\sigma_\perp \sim 1/\Lambda_{\rm QCD}$

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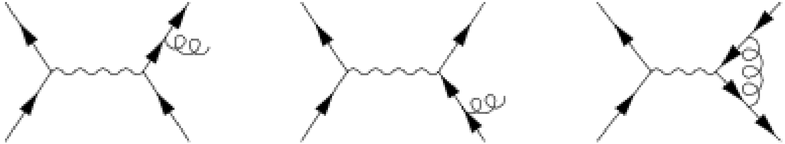

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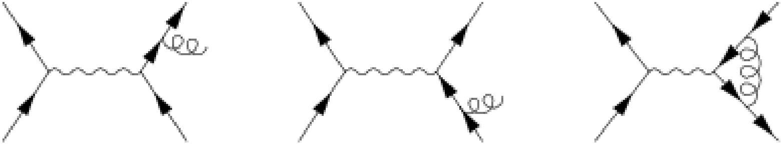

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General picture:

- separation of scales:
  - $B_d \simeq 2\,\mathrm{MeV} \ll \Lambda_{\rm QCD},\, T_{\rm QCD}$

$\Rightarrow$ coalescence happens after hadronisation

- semiclassical picture: $\bar{p}(\boldsymbol{x}, \boldsymbol{p})$ and $\bar{n}(\boldsymbol{x}', \boldsymbol{p}')$ form an antideuteron, if "close" in phase-space

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- more general: antinuclei A $\sim B_A$ antiprotons^A with

$$B_A = A \left(\frac{4\pi}{3} \frac{p_0^3}{m_N} \right)^{A-1}$$

$\Rightarrow$ strong hierarchy $\bar{p} \gg \bar{d} \gg \overline{{}^3\mathrm{He}} \gg \overline{{}^4\mathrm{He}}$

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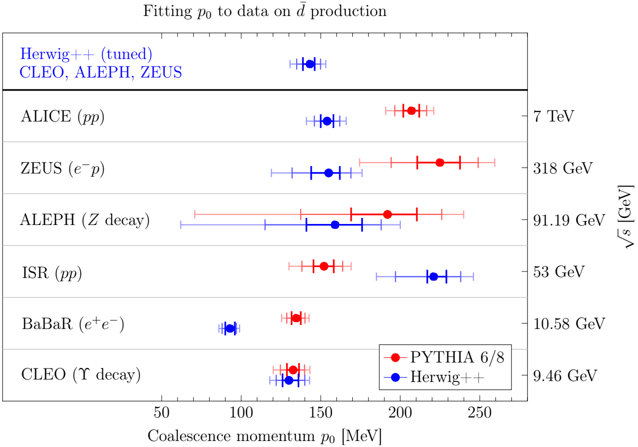
$\Rightarrow$ requires momentum correlation on event-by-event basis

Problems of this approach:

- discrepancies in p_0 between reactions & MC simulations



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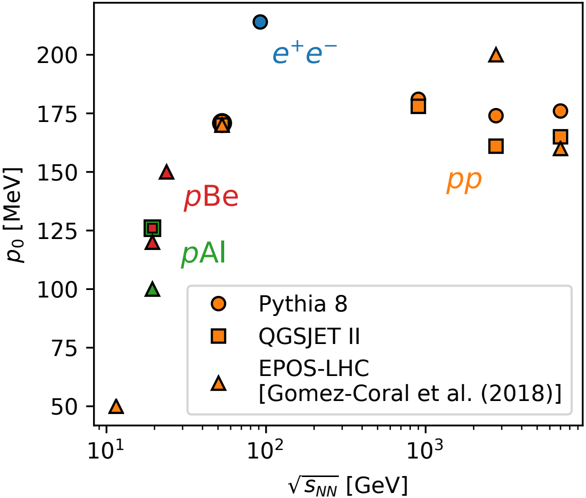

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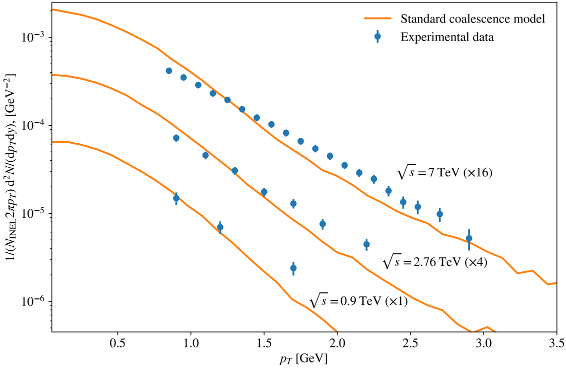
- bad fit of ALICE $p_\perp$ spectra



Solution: use Wigner functions with momentum correlation

- two-body Wigner function $W(x, p)$ contains full quantum mechanical information of a system
- probability distributions follow as

$$\int \mathrm{d}x\, W(x,p) = \phi^*(p)\,\phi(p), \qquad \int \frac{\mathrm{d}p}{2\pi}\, W(x,p) = \psi^*(x)\,\psi(x)$$

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- use momentum distribution $G_{np}(\boldsymbol{p}_n, \boldsymbol{p}_p)$ from Monte Carlo
- add Gaussian guess for spatial distribution
- use connection to density matrix

$$\left\langle \psi(\boldsymbol{x})^\dagger \psi(\boldsymbol{x}') \right\rangle = \int \frac{\mathrm{d}p}{2\pi}\, W\left(\boldsymbol{p}, \frac{\boldsymbol{x}+\boldsymbol{x}'}{2}\right) \exp[\mathrm{i}\boldsymbol{p}\cdot(\boldsymbol{x}-\boldsymbol{x}')]$$

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- standard QM using density matrices

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- two-nucleon density matrix $\rho_{\mathrm{nucl}} = |\psi_p\psi_n\rangle \langle\psi_n\psi_p|$

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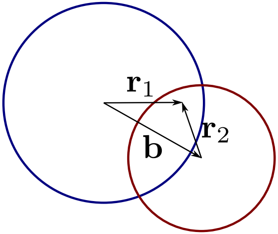
- fraction $\bar{d}/(\bar{p}+\bar{n})$ is bounded

Generalising to Ap and AA collisions



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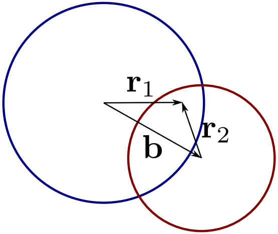

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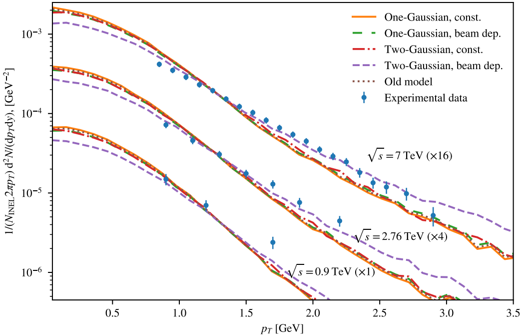
- using Gaussian profiles:
  - pp: $\sigma^{pp} = \sqrt{2}\sigma^{e^+e^-}$

Comparison with ALICE and LEP data



Best fit values for spatial extension σ: (using PYTHIA)

- $\sigma^{pp} = (7.6 \pm 0.1)/\text{GeV}$
- $\sigma^{e^+e^-} = (5.3^{+1.0}_{-0.6})/\text{GeV}$

Comparison with experimental data on pp and Ap:

- assume $R_A \simeq a_0 A^{1/3}$ with $\sigma^{pp} \simeq a_0$ as fit parameter

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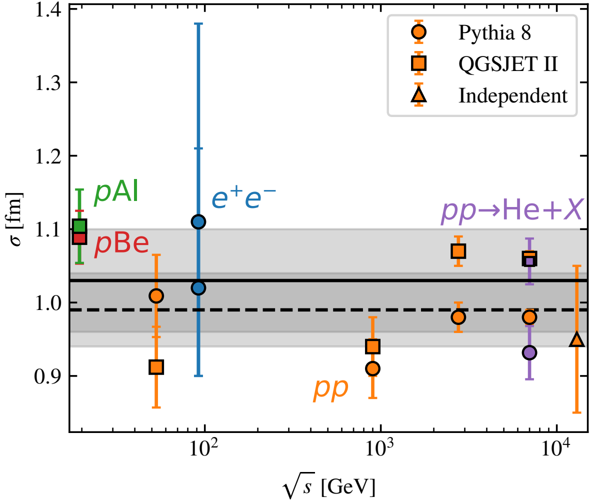

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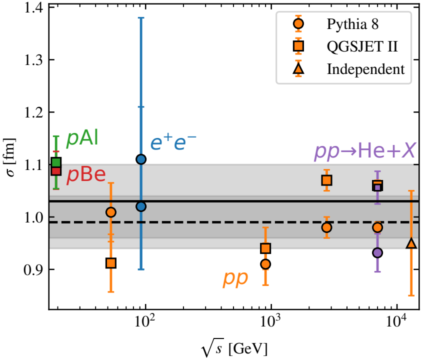
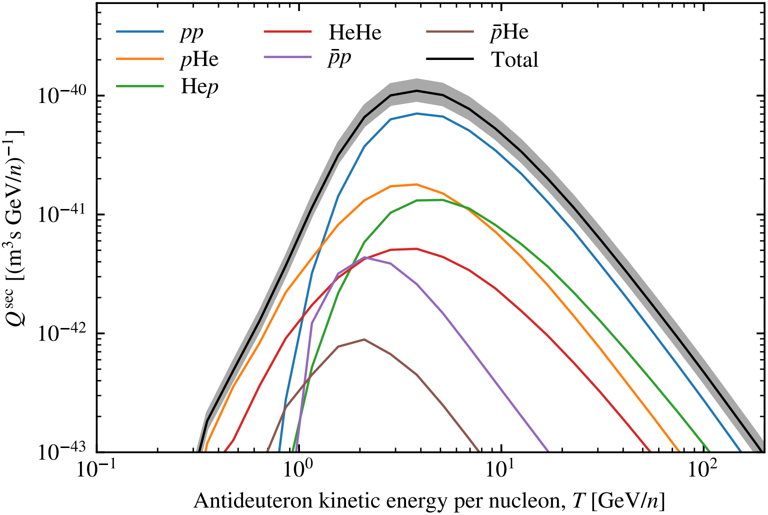


- good agreement with expectation $\sigma^{pp} \sim 1\,\text{fm}$
- independent of energy and reaction type

Source term $Q^{\rm sec}$ for secondary production of $\bar{d}$:



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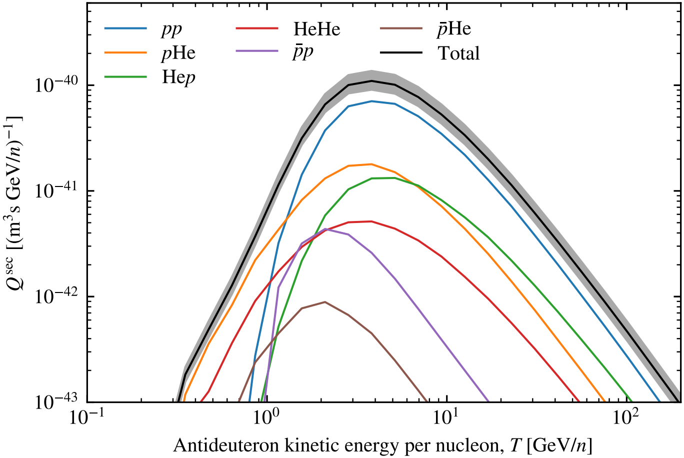
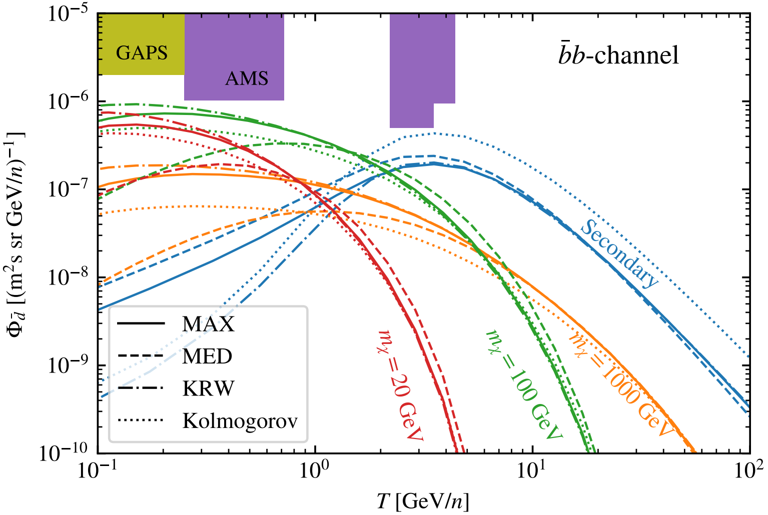


- lower threshold in pA reactions $\Rightarrow$ dominate at low T

Antideuteron flux: secondaries plus bb channel



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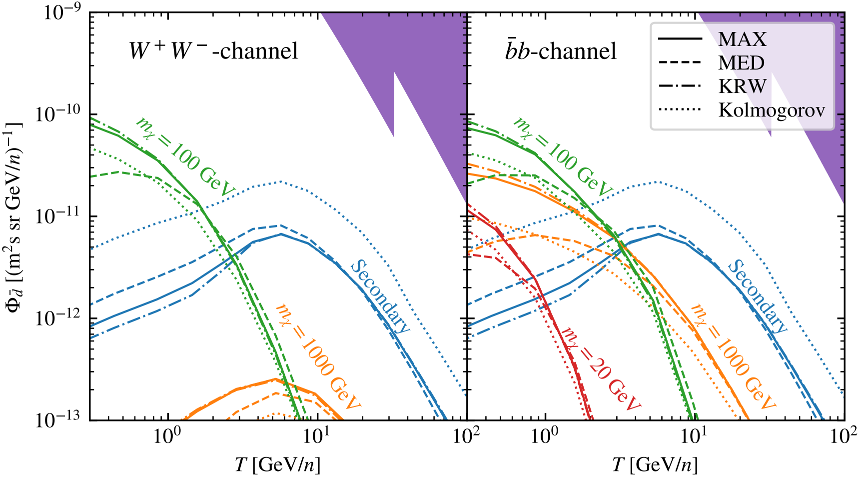
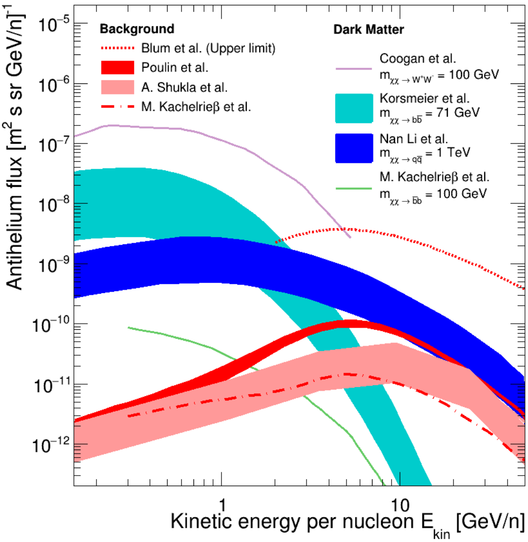
Antihelium-3 flux:



Antihelium-3: Comparison to other results



Boosting (and shifting) the He flux?

- change cosmology: inhomogenous barygenesis

  ⇒ anti-stars in Milky Way [*Dolgov, Silk '93, Poulin et al. '19*]

  - acceleration mechanism: anti-SNe, anti-SNR?

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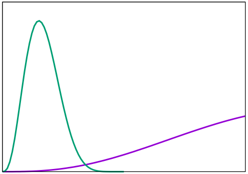
$$n_{^4\mathrm{He}}(\boldsymbol{p}) \propto n_n^4(\boldsymbol{p})$$

$\Rightarrow$ need to compress $n_n(\boldsymbol{p})$:



Boosting the He flux – particle physics

- $m_{\rm DM} = (1+\varepsilon) m_{^3\rm He}$
- involve $\bar{\Lambda}_b$ decays
- strongly coupled DM sector

Can $\bar{\Lambda}_b$ decays boost $\overline{^3\mathrm{He}}$ from DM? [Winkler, Linden '21]

- Majorana DM: $\sigma_{\mathrm{ann}} \propto m_f^2 \Rightarrow$ couples mainly to b quarks for $m_X < m_Z$

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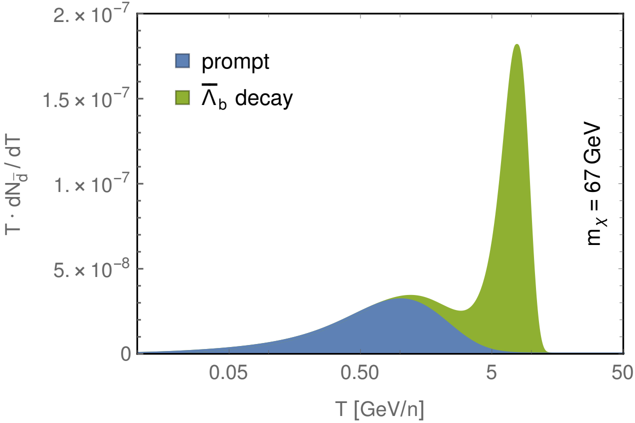

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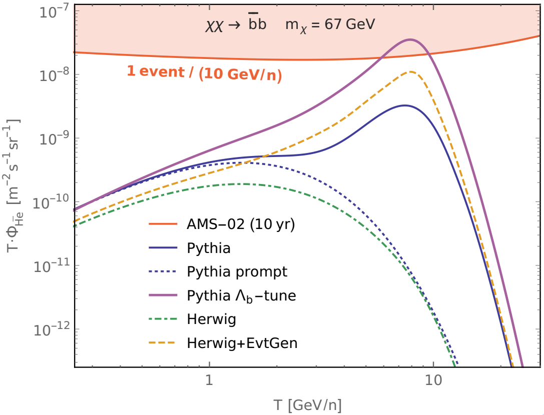

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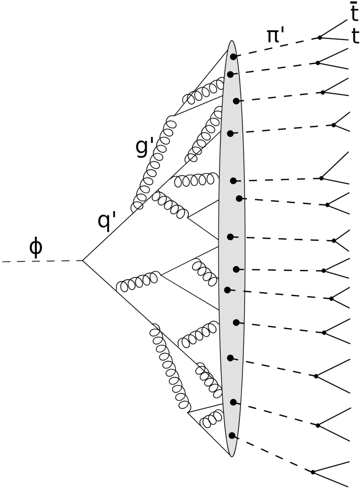
- no:
  - Λ_b tune of Pythia is excluded
  - Pythia overestimates BR($\Lambda_b \to \bar{u}du(ud_0)$)
  - \+ can be tested by LHCb

Strongly coupled DM sector

[Winkler, de la Torre, Linden '22]

- dark QCD cascade produces ~ 1000 top-quarks with $\gamma \simeq$ few



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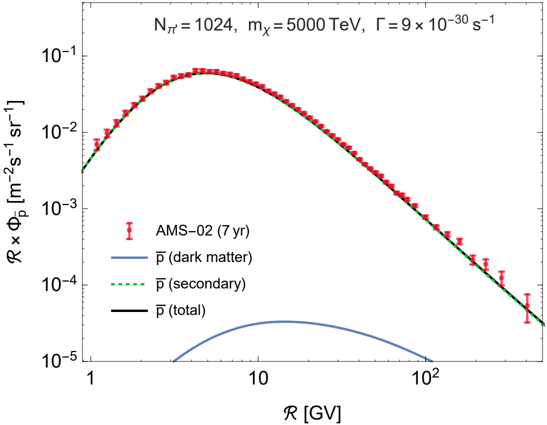

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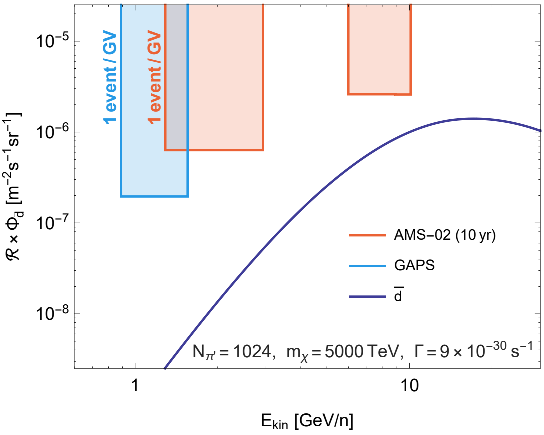

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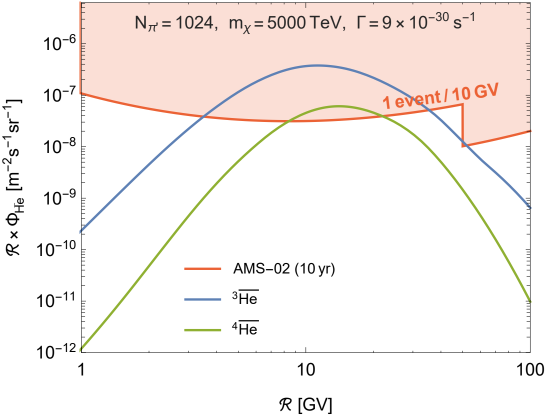

Strongly coupled DM sector

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- independent QCD cascades, all nucleons can coalesence
- problem: 1000 top within $1/\Lambda_{\rm QCD'} \simeq 1/$ TeV $\Rightarrow$ QGP

Conclusions

1. Formation of light antinuclei is interesting in itself:
   - inclusion of two-particle momentum correlations necessary
   - reaction-dependent size of source is important
   - how to deal with spatial correlations?
   - when are collective effects important?
2. Coalesence in phasespace – WiFunC model:
   - consistent description of various reactions
3. Antinuclei are a useful tool searching for new physics
   - antideuterons as signal for DM
   - strong hierarchy of fluxes as function of A
   - antihelium-3 and especially antihelium-4 challenging
4. Upgrade of AMS-02 in 2023, extension of ISS