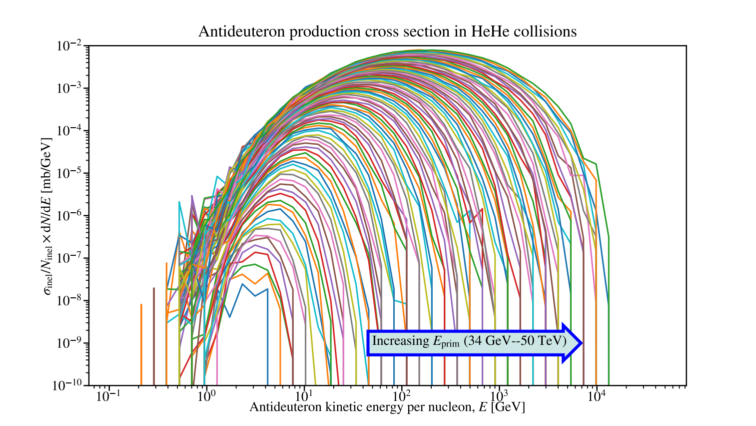
Coalescence models

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, Phys.Rev.C 108 (2023) 2,...

Outline of the talk

1. Introduction
   - Motivation: why antinuclei?
     - ★ Probe of quark-gluon plasma
     - ★ Signature of dark matter *[Salati,...]*
   - 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? *[Pöschel, Salati,...]*
4. Conclusions

Formation of light nuclei

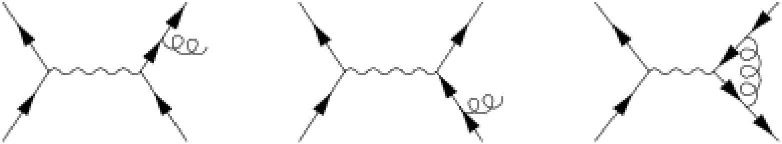
interested in various types of reactions:

• DM+DM$\to X\bar{d}$	DM
• $e^+e^- \to X\bar{d}$	LEP
• $pp \to X\bar{d}$	LHC: pQCD, CRs
• $Ap \to X\bar{d}$	$\cdots$
• $AA \to X\bar{d}$	LHC: heavy ion, CRs

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

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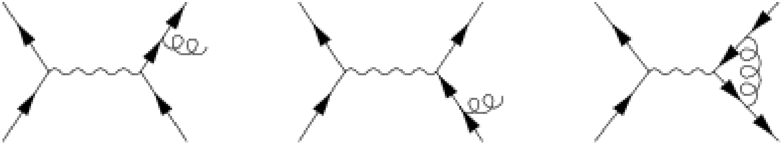

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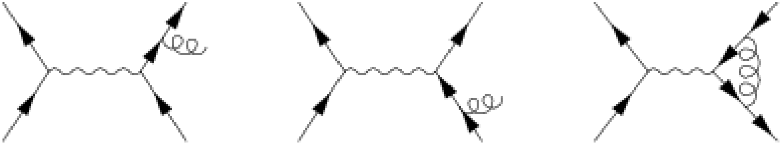

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General picture:

- separation of scales:
  - $B_d \simeq 2\,\mathrm{MeV} \ll \Lambda_{\rm QCD}, T_{\rm QCD} \sim 200$ MeV

$\Rightarrow$ 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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  - Heavy-ion: coalescence in coordinate space: $V \gg 4\pi R_d^3/3$
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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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- consider e.g. DM annihilation $XX \to W^+W^-$:

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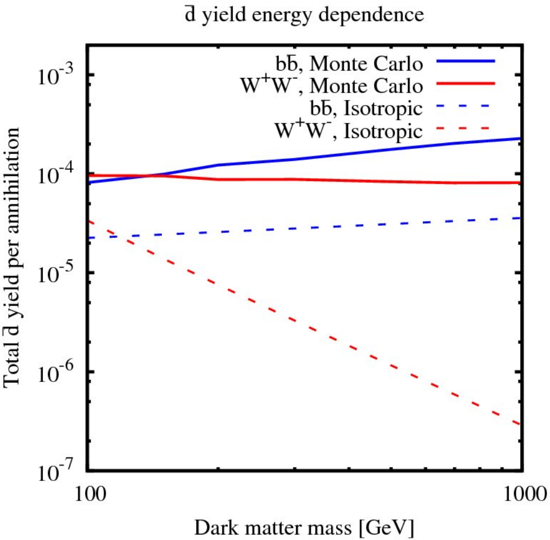
- $1/M_X^2$ suppression in contradiction to Lorentz invariance:
- decay products of W are boosted in cone with $\vartheta \sim m_W/m_X$

Deuteron yield: "Isotropic" vs. event-by-event: [Dal, MK '12]



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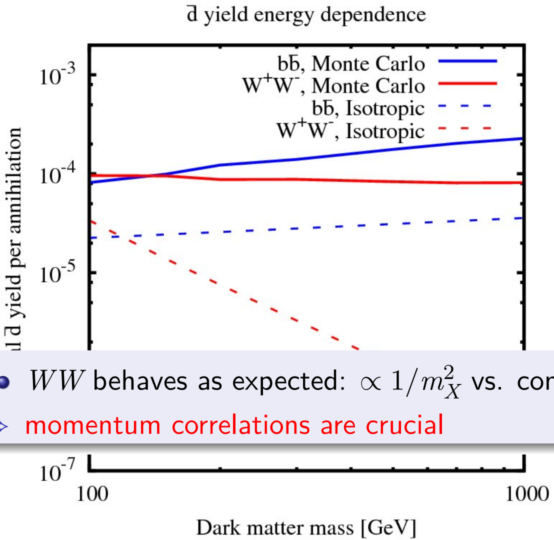
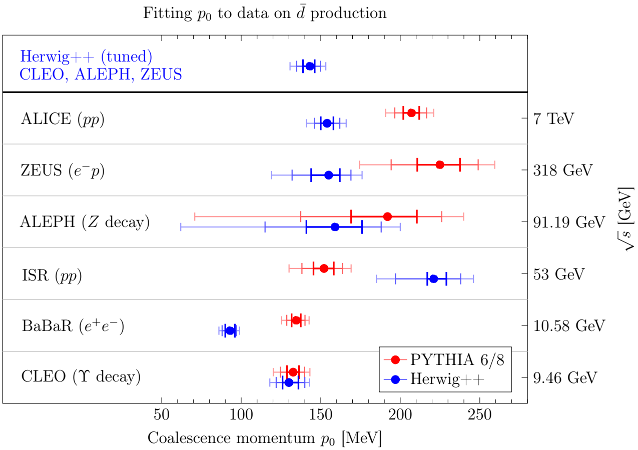


- WW behaves as expected: $\propto 1/m_X^2$ vs. const.

$\Rightarrow$ momentum correlations are crucial

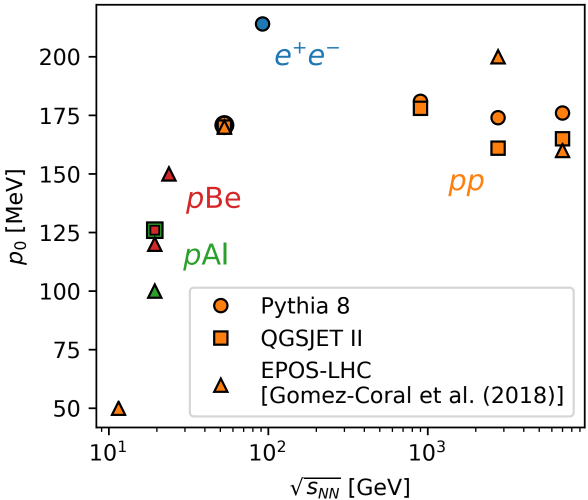
Problems of this approach:

- discrepancies in p_0 between reactions & MC simulations



Problems of this approach:

- discrepancies in p_0 between reactions & MC simulations
- energy dependence of p_0?



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

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

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

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

Evaluation using Monte Carlo correlations

- standard QM using density matrices

$$\frac{\mathrm{d}^3 N_d}{\mathrm{d}P_d^3} = \mathrm{tr}\{\rho_d\, \rho_{\mathrm{nucl}}\}$$

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with

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

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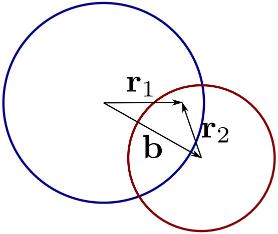
  - $\sigma \ll d \Rightarrow \zeta \to 1$
  - $\mathrm{e}^{-q^2 d^2} \to \vartheta(q - q_{\rm max})$
- fraction $\bar{d}/(\bar{p} + \bar{n})$ is bounded

Generalising to Ap and AA collisions



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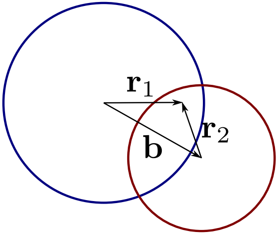

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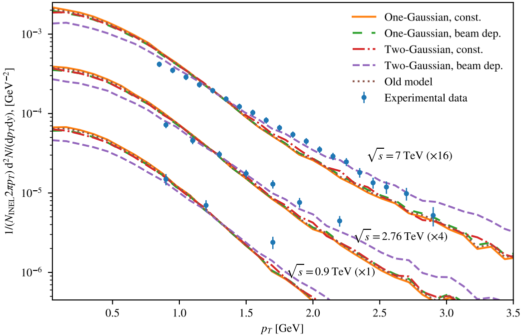
- using Gaussian profiles:
  - pp: $\sigma^{pp} = \sqrt{2}\sigma^{e^+e^-}$

Comparison with ALICE and LEP data



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

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

Comparison with experimental data on pp and Ap:

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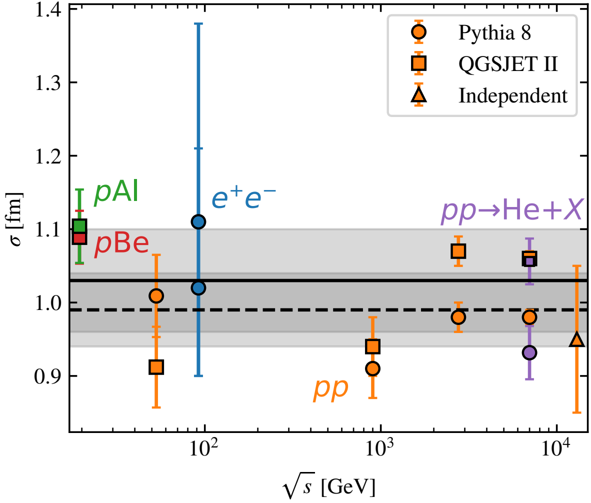

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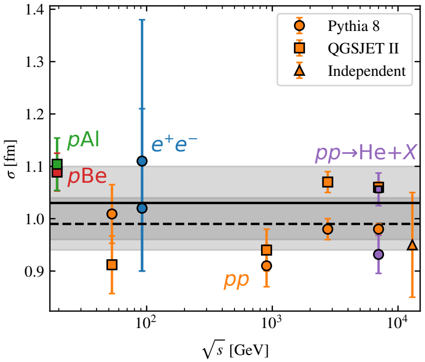

- good agreement with expectation $\sigma^{pp} \sim 1\,\text{fm}$
- independent of energy and reaction type

Determination of σ from femtoscopy:

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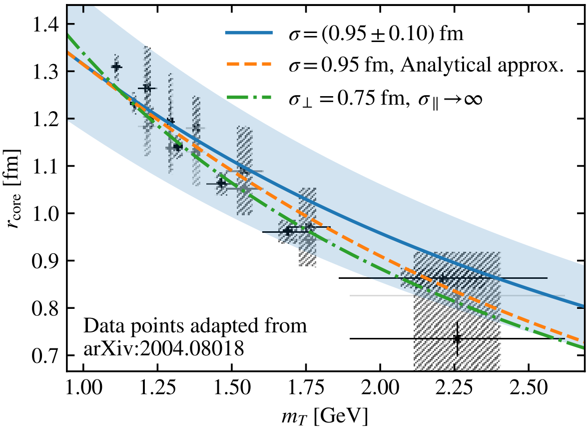

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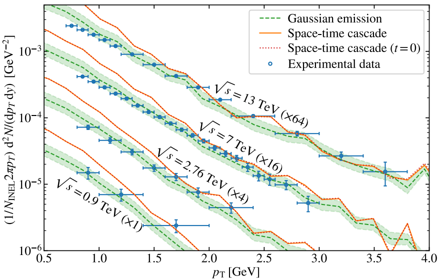
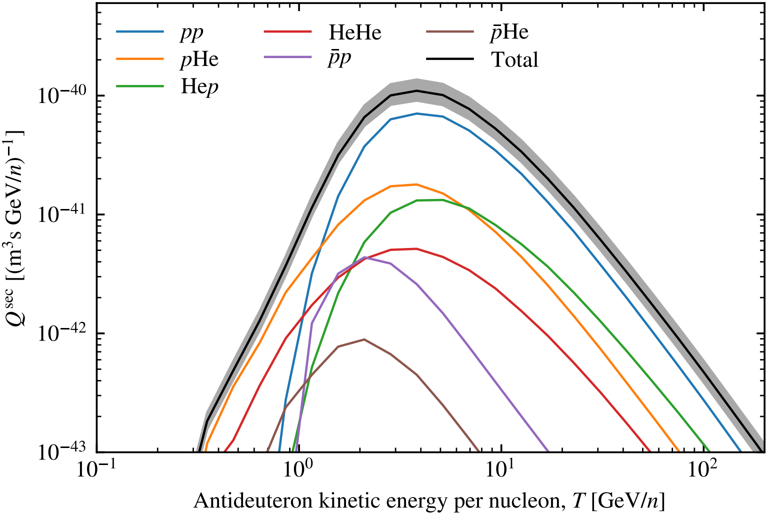


- no longitudinal spread included in Pythia
- allows to check spacetime picture

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



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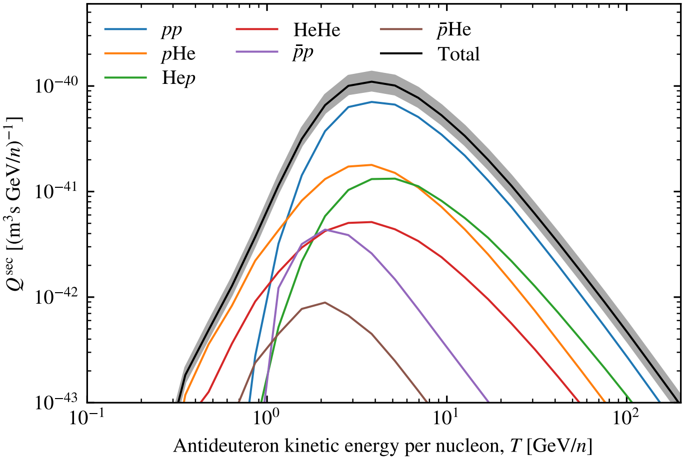

- lower threshold in pA reactions $\Rightarrow$ dominate at low T
  $\Rightarrow$ cannot be captured by constant enhancement factor

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  [Blum '18,'19,...]

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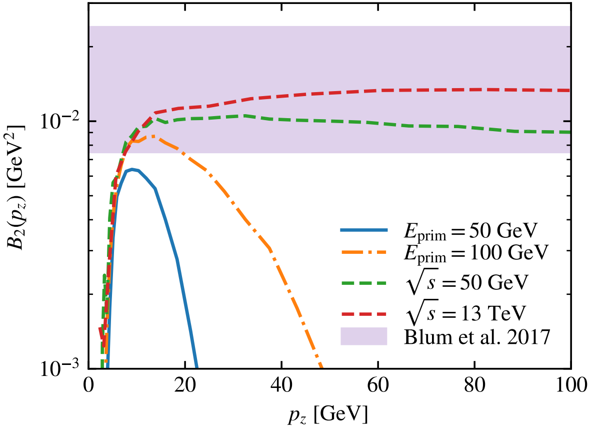
- not possible: B_2 is not a constant at CR energies



Boosting (and shifting) the He flux?

- change cosmology: inhomogenous barygenesis
  - $\Rightarrow$ anti-stars in Milky Way *[Dolgov, Silk '93, Poulin et al. '19]*
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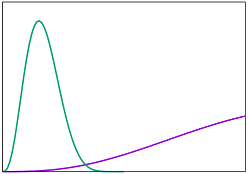
$\Rightarrow$ need to compress $n_n(\boldsymbol{p})$:



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]

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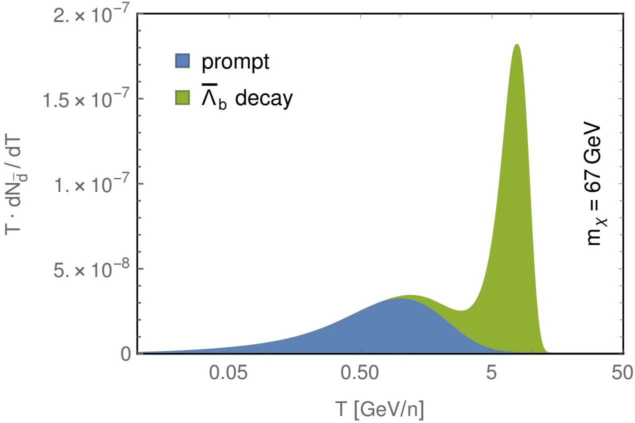

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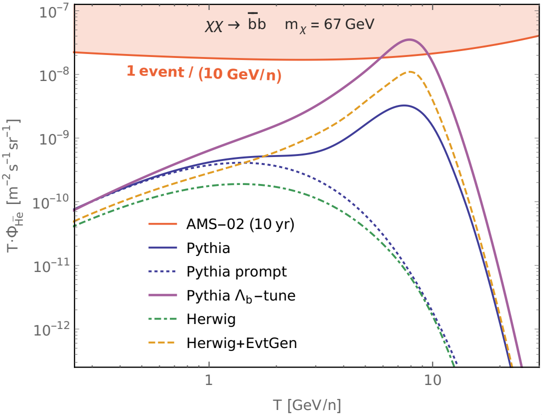

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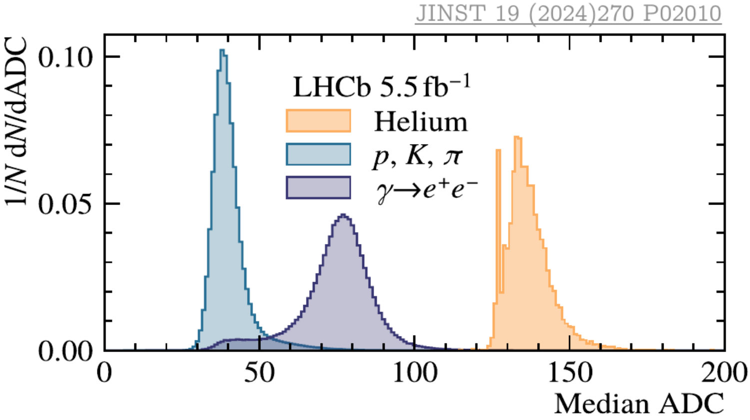
- no:
  - Λ_b tune of Pythia is excluded
  - Pythia overestimates BR($\Lambda_b \to \bar{u}du(ud_0)$)
  - \+ can be tested by LHCb

Limits on $\bar{\Lambda}_b$ from LHCb

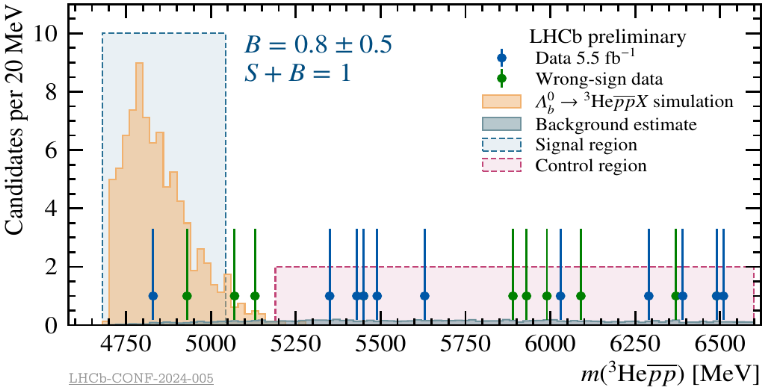
[ICHEP '24]



Limits on $\bar{\Lambda}_b$ from LHCb

[*ICHEP '24*]

$\Lambda_b^0 \to {}^3\mathrm{He}\overline{p}\overline{p}X$ data



LHCb-CONF-2024-005
(in preparation)

Limits on $\bar{\Lambda}_b$ from LHCb

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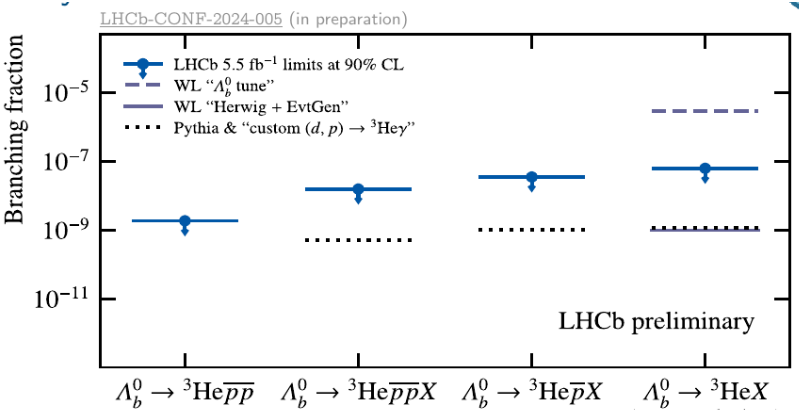

Conclusions

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 WIMPs
   - strong hierarchy of fluxes as function of A
   - antihelium-3 and especially antihelium-4 requires “super-exotic” physics
4. Upgrade of AMS-02, extension of ISS