Search for Stable Charmed Mesic Nucleus ${}^{4}_{D^-}$He in Heavy-Ion and EIC

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Possibility of Charmed Hypernuclei

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C. B. Dover and S. H. Kahana

Phys. Rev. Lett. **39**, 1506 – Published 12 December 1977

1977

Article | References | Citing Articles (38) | PDF | Export Citation

ABSTRACT

We suggest that both two-body and many-body bound states of a charmed baryon and nucleons should exist. Estimates indicate binding in the $^1S_0$ state of C_1N ($I=\frac{3}{2}$) and SN ($I=1$). We further estimate the binding energy of C_0, C_1 in various finite nuclei.

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Recent experiments[1] have established the existence of a new class of mesons and baryons possessing net charm. In particular, there is firm evidence for the charmed baryons $B_c = C_0$, C_1 (Λ_c and Σ_c) and the charmed mesons, D, D^*. It is hence of fundamental interest to establish the nature of the interactions of these charmed particles with more familiar hadrons.

In this Letter we ask whether the charmed baryons will bind to a single nucleon or to finite nuclei, producing charmed analogs of the deuteron or of hypernuclei. The estimated short lifetime of even the lowest-mass charmed baryon, $\tau(C_0) \sim 10^{-11}-10^{-14}$ sec, may make it difficult to establish the existence of such analog bound states.

Charmed Mesic Nuclei

Charmed mesic nuclei: Bound D and $\bar{D}$ states with ^{208}Pb

K. Tsushima, D. H. Lu, A. W. Thomas, K. Saito, and R. H. Landau
Phys. Rev. C **59**, 2824 – Published 1 May 1999

Garcia-Recio, et al., Phys.Rev. C85 (2012) 025203

- Due to mass difference, Coulomb force is not enough to bind the D- and light nuclei
  p-D^- ➔ n + D^0 strong decay
- There is investigation of heavy nuclei with charmed mesons more than two decays ago

  24 MeV binding Coulomb energy in ^{208}Pb and D^-
- However, it is difficult to produce and detect heavy charmed hypernuclei

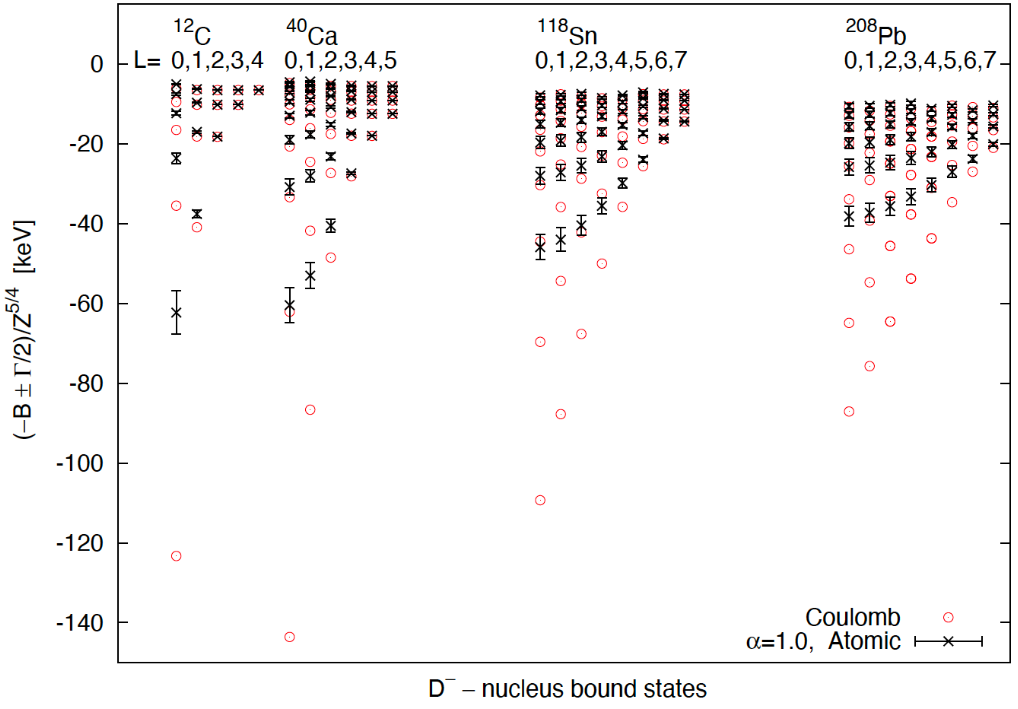


Figure 2: D^- atom levels for different nuclei and angular momenta. "⊙" points stand for pure Coulomb potential binding energies (Table 1), while "×" symbols stand for the binding energies and widths of atomic levels predicted by the SU(8) model derived in this work (see Fig. 1), with $\alpha = 1$ and gap 8 MeV (Table 2). The results are scaled down by a factor $Z^{5/4}$.

Lightest Charmed Mesic Nuclei

- D^{+-} mass: 1869.66+-0.05 MeV
- D^0 mass: 1864.84+-0.05 MeV
- Proton mass: 938.27 MeV
- Neutron mass: 939.56 MeV
- Deuteron mass: 1875.61
- Triton mass: 2808.92
- He3 mass: 2808.39
- D^-+d➔ n+n+D^0
- ^{3}He+D^-➔t+D^0

If pure Coulomb potential:

D^-+t

stable against strong decay
B~=3.5MeV

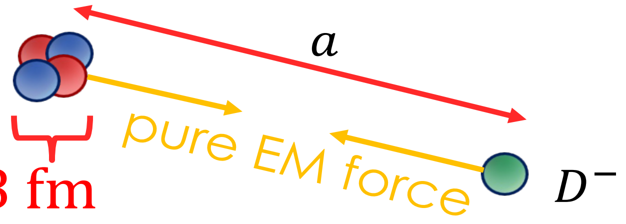
D^-+^{4}He:

stable against strong decay,
B~=16MeV

Motivations

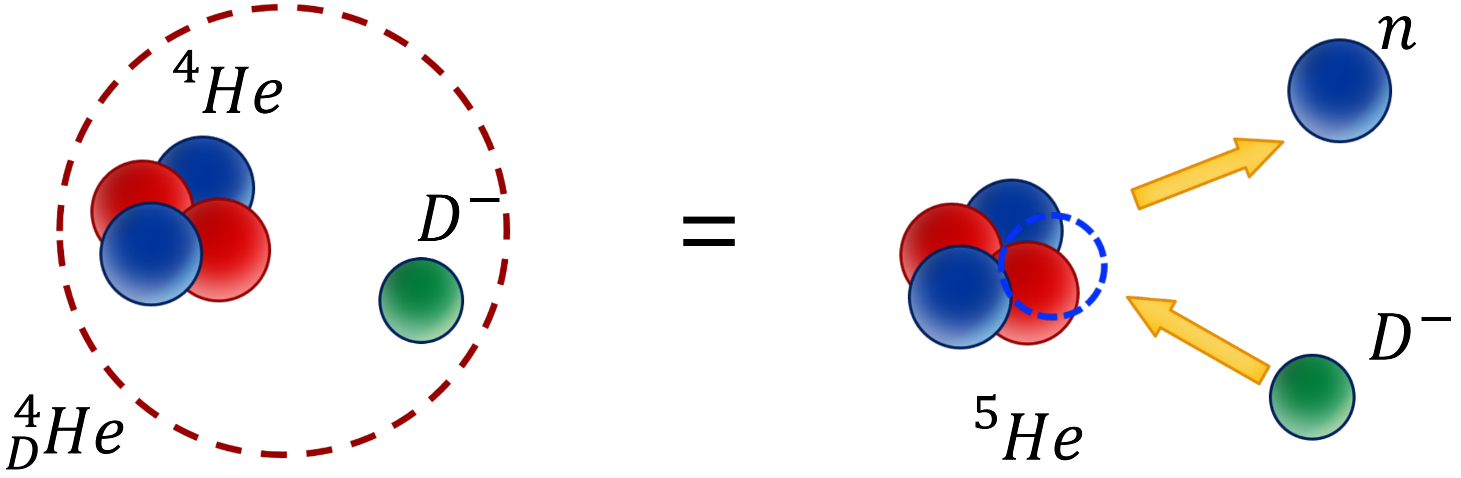
- Goal: search for the new hyper-nucleus or charmed-nucleus ($^{4}_{D}He$) in the forward region ($2.5 < \eta < 4$) (first exotic charm at RHIC)
- Studying the $^{4}_{D}He$ improves our understanding on strong interaction within the nucleus
- The forward background is less than the central region
- Newly installed STAR Forward upgrade provides us a good opportunity to search for new physics
- Using the hydrogen model to estimate the lowest limit of binding energy and radius

$$E_1 = -133\ \mathrm{keV}$$
$$a \approx 10.84\ \mathrm{fm} \gg r_\alpha = 1.678\ \mathrm{fm}$$



Rates in a data-driven coalescence model

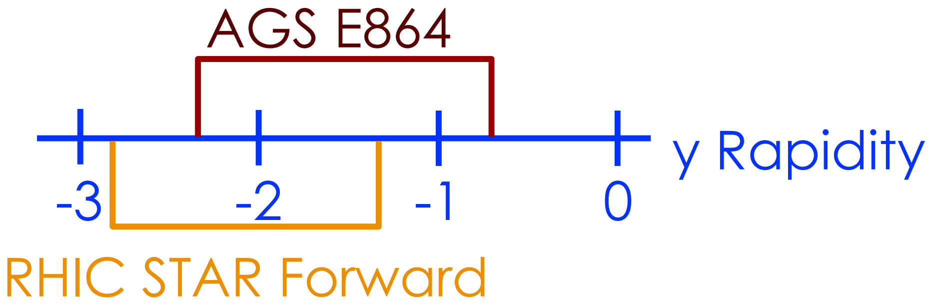
- The idea is to replace a neutron in the ^{5}He nucleus with D^{-} meson



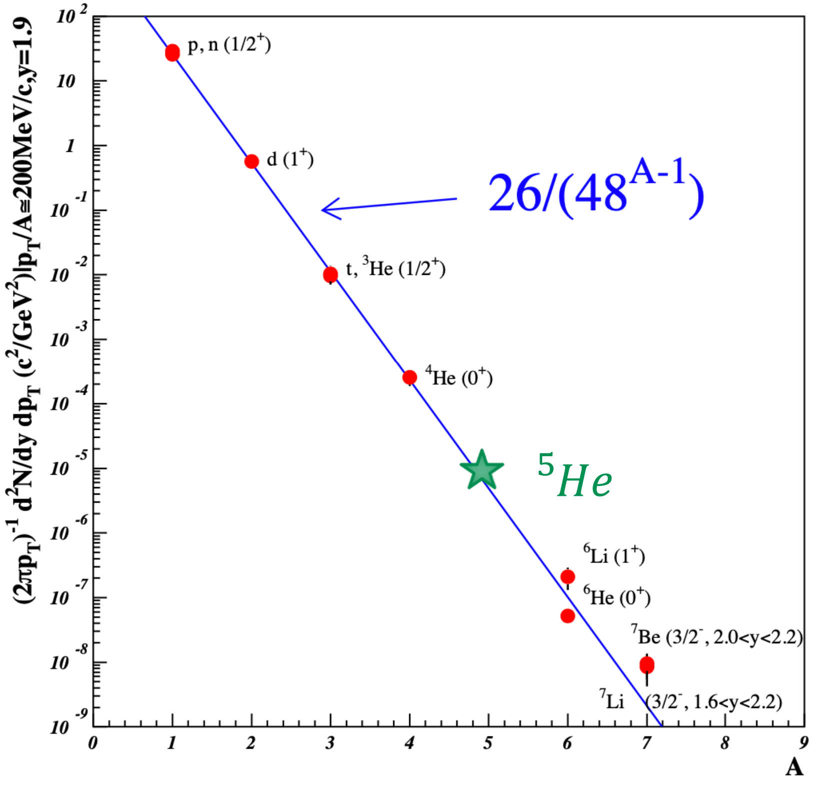
- Some benefits of this method:
  1. Don't need to calculate how alpha and D^{-} meson coalesce
  2. The invariant yield of ^{5}He can be derived directly from the experimental data

Estimate Production Rates

- Compare the rapidity range between AGS E864 and RHIC STAR Forward
  - Fixed target v.s. Collider (rapidity shift) and Energy (extended longitudinal scaling)
  - AGS: -2.44 ~ -0.84
  - RHIC: -2.86 ~ -1.36



- The relation between invariant yield and atomic number



Phys. Rev. C **61**, 064908

Event Counts

- The Invariant Yield

$$N^{\mathrm{STAR,F}}_{{}^4_{D}He} = N^{\mathrm{STAR}}_{{}^4_{D}He} \cdot A^F_\alpha \cdot A^F_D$$
$$= N^{\mathrm{AGS}}_{{}^5He} \cdot \sigma^{\mathrm{F}}_{D^-} / \sigma^{\mathrm{F}}_{n}$$
$$= 5.12\times10^{-8}$$

$$N^{\mathrm{AGS}}_{{}^5He} = 7.85\times10^{-5}$$

Pythia $\left\{ \begin{array}{l} \sigma^{\mathrm{F}}_{D^-} = 8.95\times10^{-4} \\ \sigma^{\mathrm{F}}_{n} = 1.373 \end{array} \right.$

- The expected yield of signal in STAR Forward without the detector's efficiency

collision rate (Hz) half a year (s)

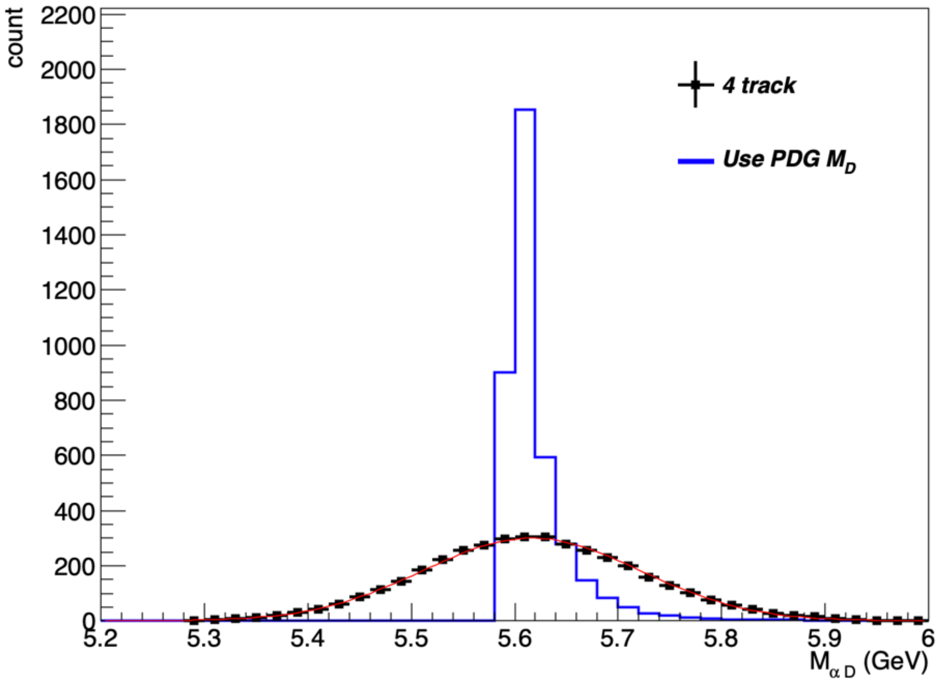
$$n = N^{\mathrm{STAR,F}}_{{}^4_{D}He} \times 10^5 \cdot 3600 \cdot 24 \cdot 365 \cdot 0.5 \sim 8\times10^4$$

- Assume a flat tracking efficiency $\varepsilon = 0.85$
  - **The K π π channel (fully reconstructed D meson)**:

    BR(D^-→Kππ) = 9.38 % and $\varepsilon^4 \sim 0.52$ ➔ **n ~ 4 x 10^3**
  - **The electron channel (α and e^- correlation)**:

    BR(D^- → e^- X) = 16.07 % and $\varepsilon^2 \sim 0.72$ ➔ **n ~ 1 x 10^4**

Detector Simulation of Signals

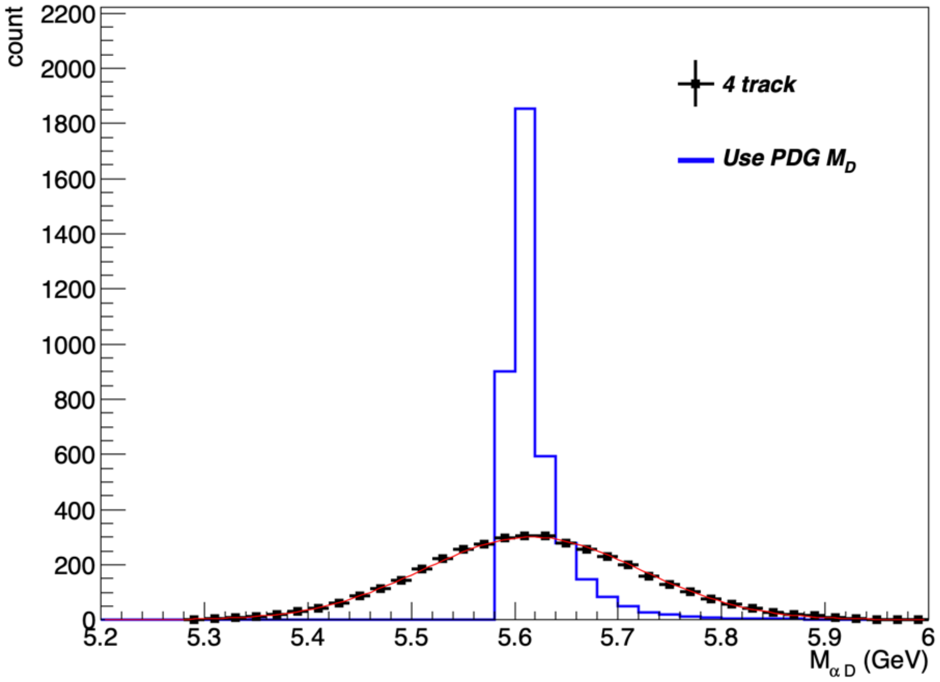


M_α = 3.73 GeV
M_{D-} = 1.86 GeV

Normalizing the yield to ~ 4000

1. $M_{\alpha+D} \sim 5.614\ \mathrm{GeV}$ (slightly larger than $M_D + M_\alpha = 5.596\ \mathrm{GeV}$)
2. From 4 tracks (α + k + π +π): $\sigma_{\alpha+D} \sim 0.108\ \mathrm{GeV}$
3. Phase space constraint (α + D_{PDG}): much narrower $\sigma_{\alpha+D}$

Detector Simulation of Signals



Difficult to detect at RHIC, likely at LHC or EIC forward: High charm rate, secondary silicon vertex

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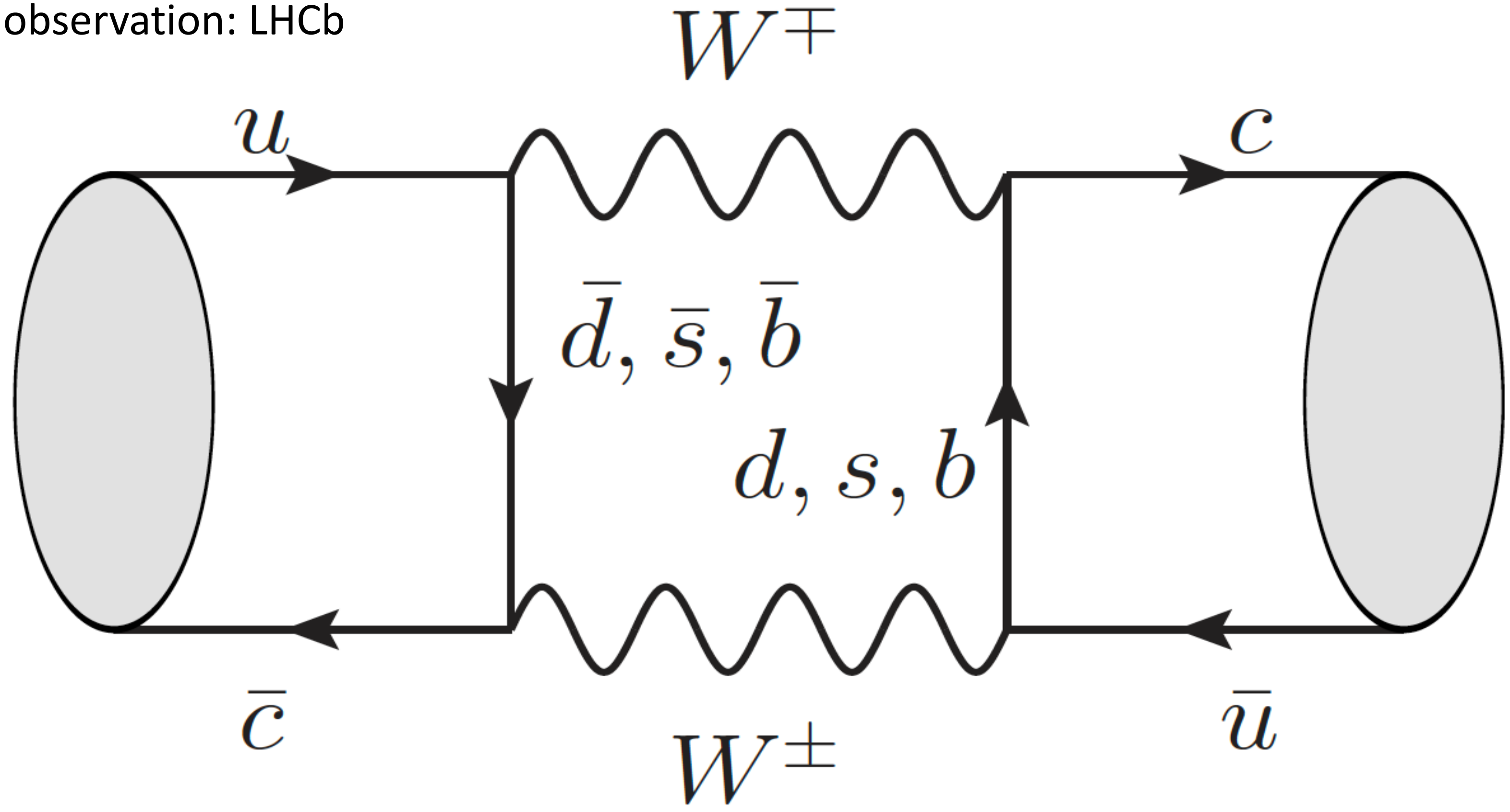
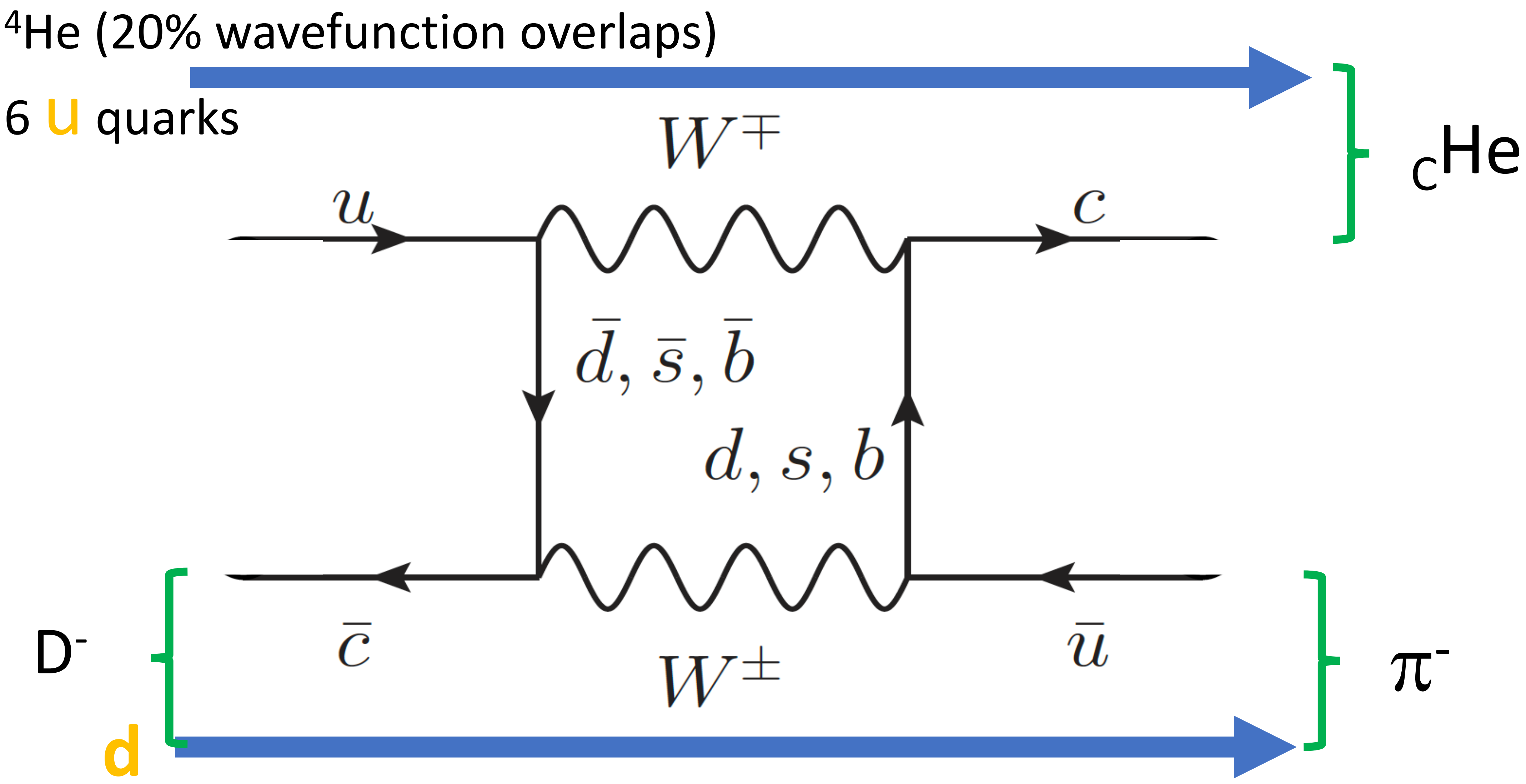
Charm Quark Oscillation with large mass difference

Box diagram of D0 and D0bar oscillation,
LQCD (C.C. Chang, 2017),
Experimental observation: LHCb

Weak interaction,
exists only in neutral mesons with small mass difference



Charm Quark Oscillation with large mass difference

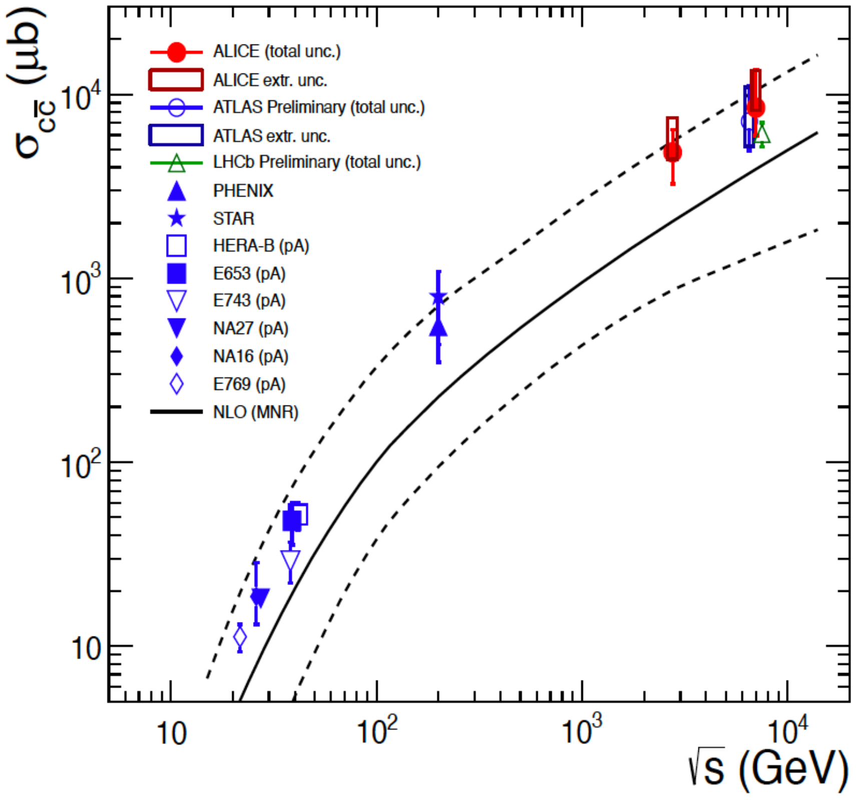


What signals are we looking for?

- Shared secondary vertex decay of He4+D^-
- Measure lifetime and maybe binding energy?
- Sequential secondary decays of ${}_{\Lambda c}$He4+π^- with mass = He4+D^-
- Measure conversion rate (CKM, in-medium charm) and binding energy

Search for Stable Charmed Mesic Nucleus $^{4}_{D^-}$He in ~~Heavy-Ion and EIC~~ CBM@FAIR

ALICE, JHEP 1207 (2012) 191



J. Steinheimer, A. Botvina, M. Bleicher, PRC 95 (2017) 014911

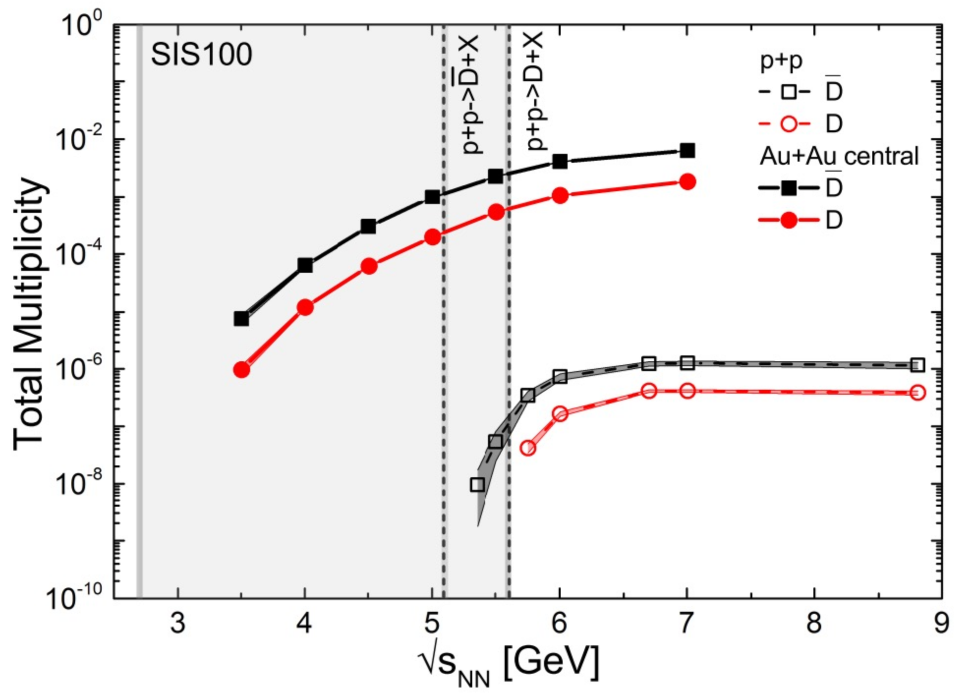


FIG. 5. [Color online] Production yields of D and $\overline{D}$ mesons in p+p and central Au+Au reactions as a function of the collision energy. The threshold energies of the corresponding channels in p+p reactions are again indicated as vertical lines. The grey area corresponds to the beam energy range expected for heavy ion collisions at the SIS100 accelerator.

FAIR vs RHIC/LHC:

He4: 10^5—10^6
Charm: 10^{-1}—10^{-2}
FXT luminosity: 10-100
Secondary Vertex and boost

Exotics and Interesting

RESEARCH ARTICLE

Observation of an Antimatter Hypernucleus

The STAR Collaboration*†
+ See all authors and affiliations

Science 04 Mar 2010:
1183980
DOI: 10.1126/science.1183980

Measurement of the mass difference and the binding energy of the hypertriton and antihypertriton

The STAR Collaboration

Nature Physics **16**, 409–412(2020) | Cite this article

Heaviest Antimatter Found; Made in U.S. Atom Smasher

Finding new particles "like stamp collecting," expert says.

3 MINUTE READ

BY **RACHEL KAUFMAN**, FOR NATIONAL GEOGRAPHIC NEWS

PUBLISHED FEBRUARY 22, 2011

A tiny "big bang" set off in Long Island recently created a new type of antimatter that's literally off the charts, scientists announced last week.

Possibility of Charmed Hypernuclei

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Received 10 August 1977

Carl Dover and I co-authored 10 E864 papers in 90s on strangelet searches

My interest:

He^4-D^- is stable against strong decay!!!
p-D^- ➔ n + D^0 strong decay

Nuclear Lab for charm in-medium effect;
Likely only can be done at CBM ~~EIC and LHC~~ with the nucleus in Lorentz Boost and very good forward detector