Exploring new physics chance with antideuteron beam at J-PARC

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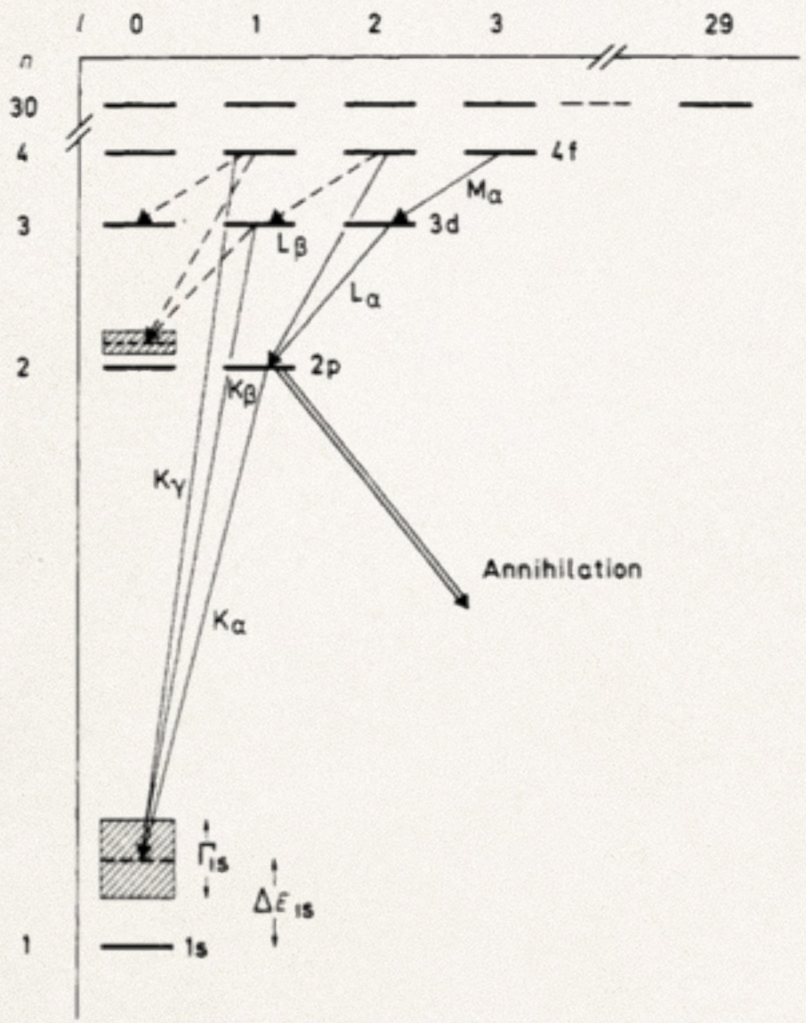
Outline

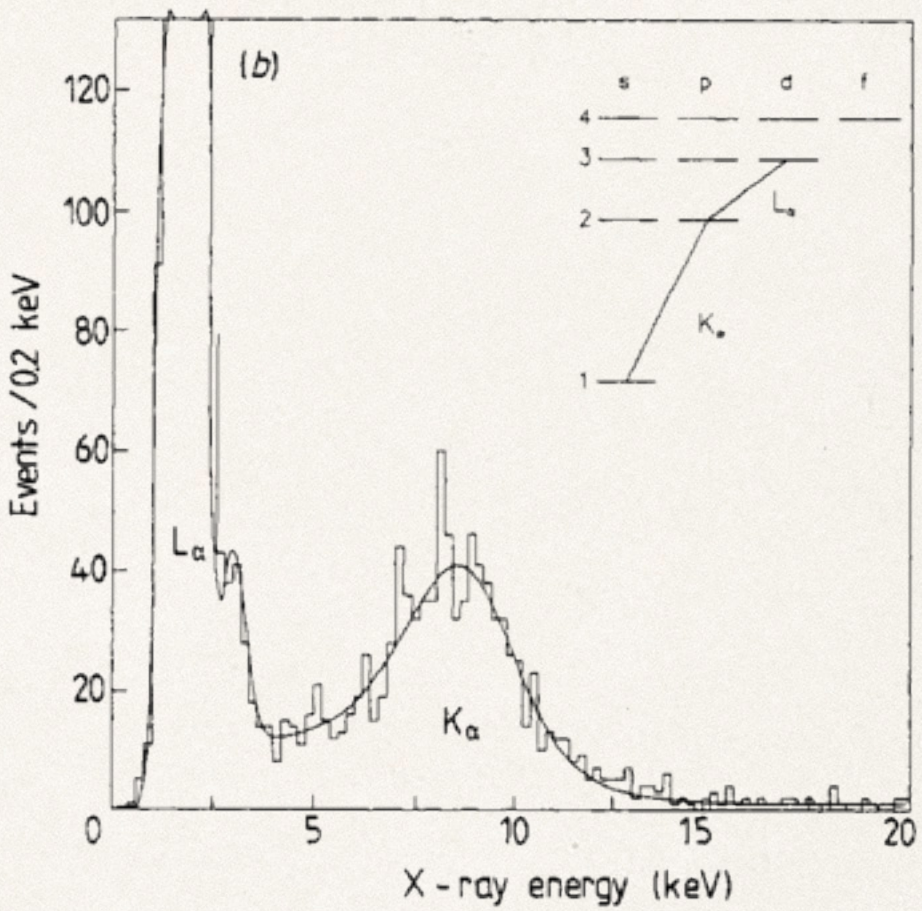
- Motivation
- Current status of $\bar{d}$ study
- Our proposal for J-PARC
  - Investigate $\bar{d} - nucleus$ potential and annihilation mechanism
  - Possible topics for the future
- Summary

Motivation

- $\bar{p} - nucleus$ interaction has inspired tremendous investigations
  - Relativistic Mean Field theory suggests an exceptionally deep potential $V_0 = -661$ MeV by flipping the $G - parity$
  - Optical potential based on experimental data:
    - $V_0 : -30 \sim -153$ MeV, $W_0 : 100 \sim 174$ MeV
- What will happen if we add one more antinucleon into the system?
  - How will the optical potential change for $\bar{d} - nucleus$?
  - How does $\bar{d}$ annihilate with nucleus? one-by-one or one-step?
  - Propose to study these topics at J-PARC K1.8 beam line

$\bar{p} - nucleus$ potential: atomic x-ray



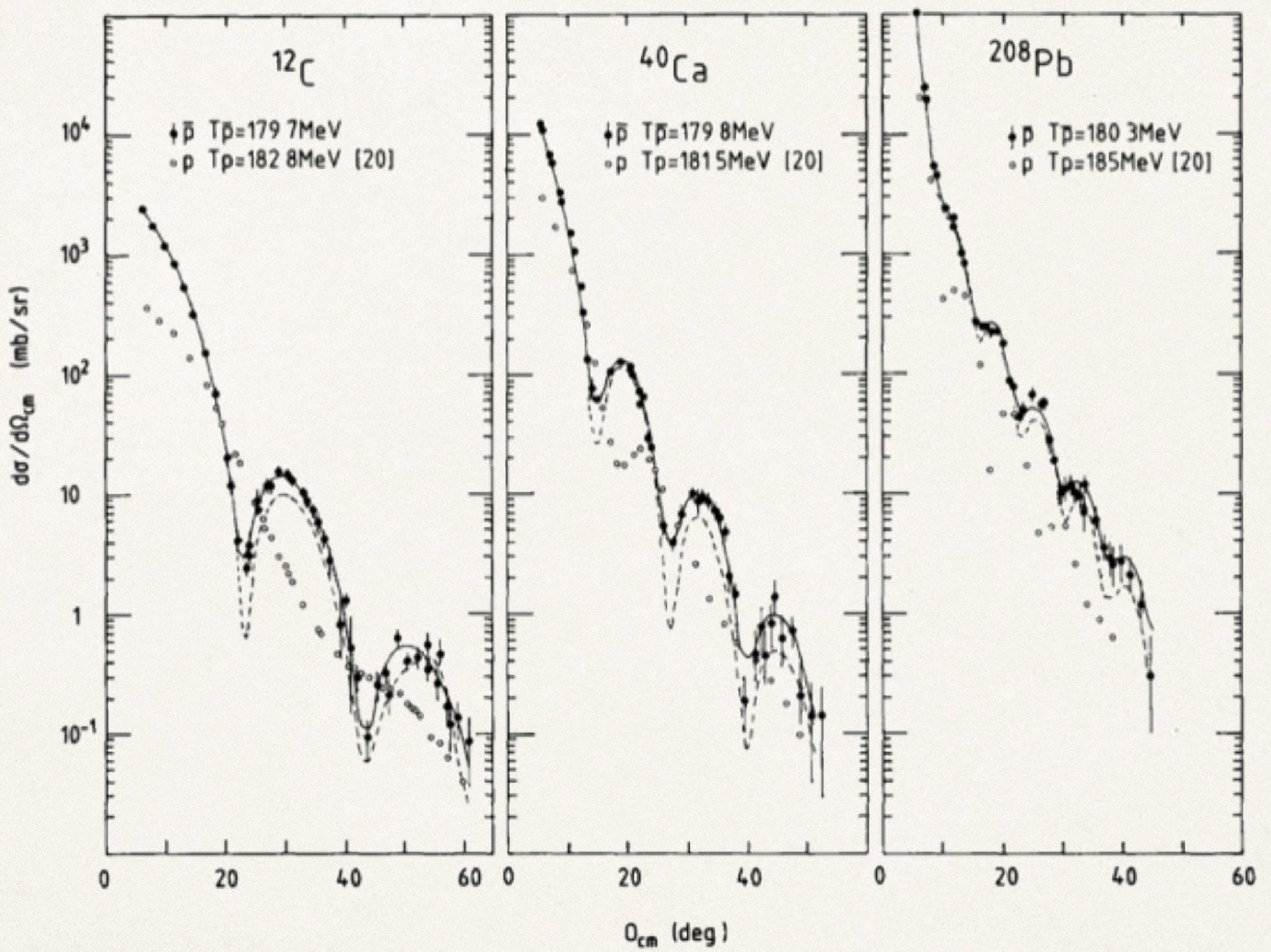


Only sensitive to peripheral region of nucleus:

$V_0 :\sim -110$ MeV, $W_0 :\sim 160$ MeV

E. Friedman et al., Nucl. Phys. A (761) p283 (2005)
C. J. Batty, Rep. Prog. Phys. (52) p.1165 (1989)

$\bar{p}$ – *nucleus* potential: elastic scattering

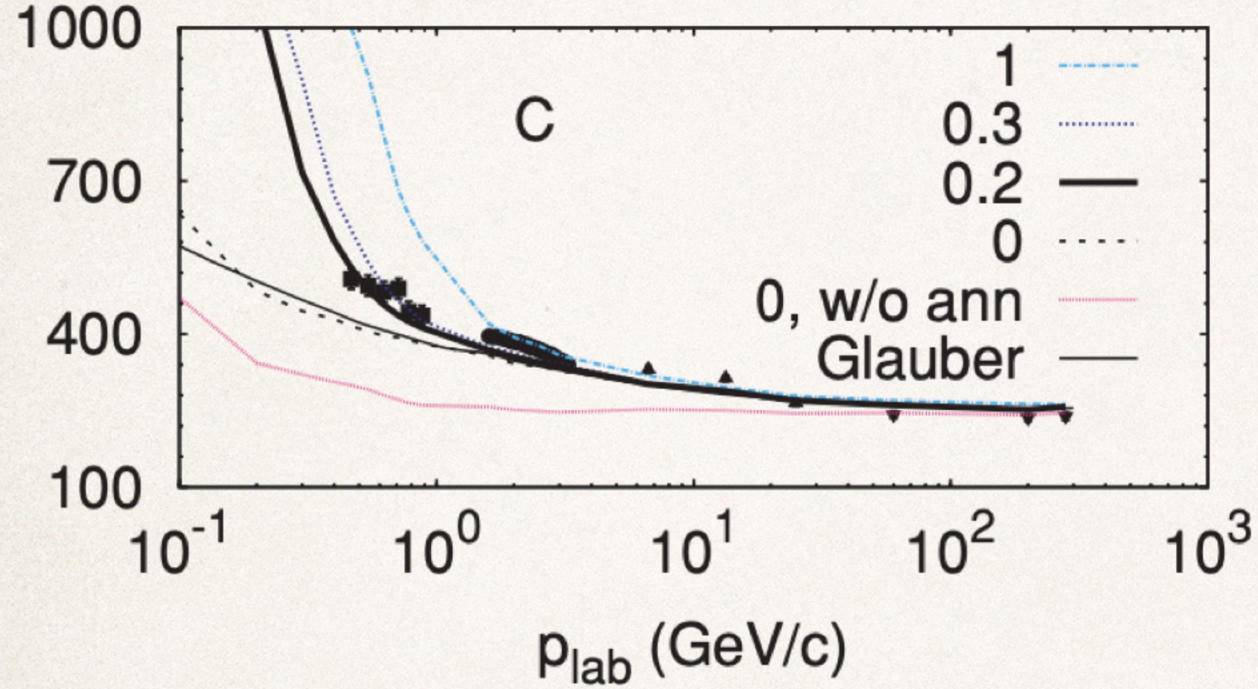


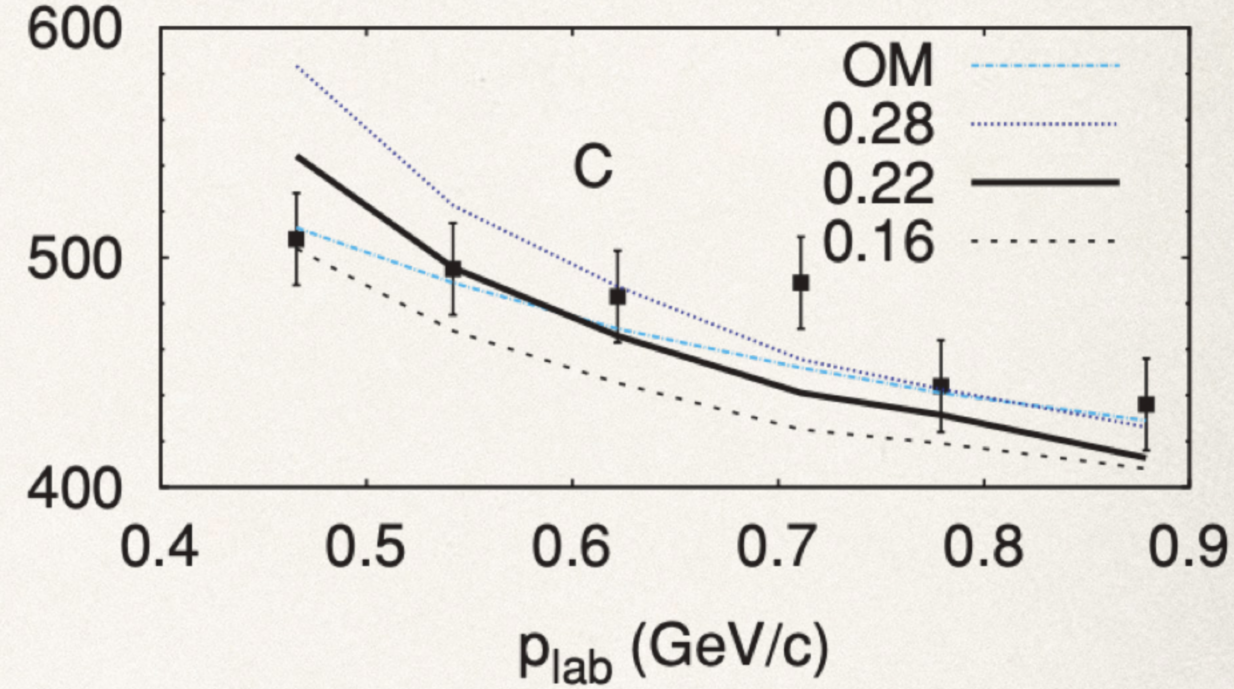
Only sensitive to peripheral region of nucleus:

$V_0 :\sim -30$ MeV, W_0 : 118 ~ 174 MeV

D. Garreta, et al., Phys. Lett. 149B, p.64, (1984)

$\bar{p} - nucleus$ potential: absorption cross section





σ_{abs} fitted with different coupling constant: $\xi = 0, V_0 = -0$; $\xi = 1, V_0 = -661$ MeV; 600 MeV/c (900 MeV/c) $\bar{p}$ annihilates at 50%(70%) of nuclear density

Sensitive to (almost) nuclear medium density

$V_0 :\sim -153$ MeV, $W_0 :\sim 110$ MeV;

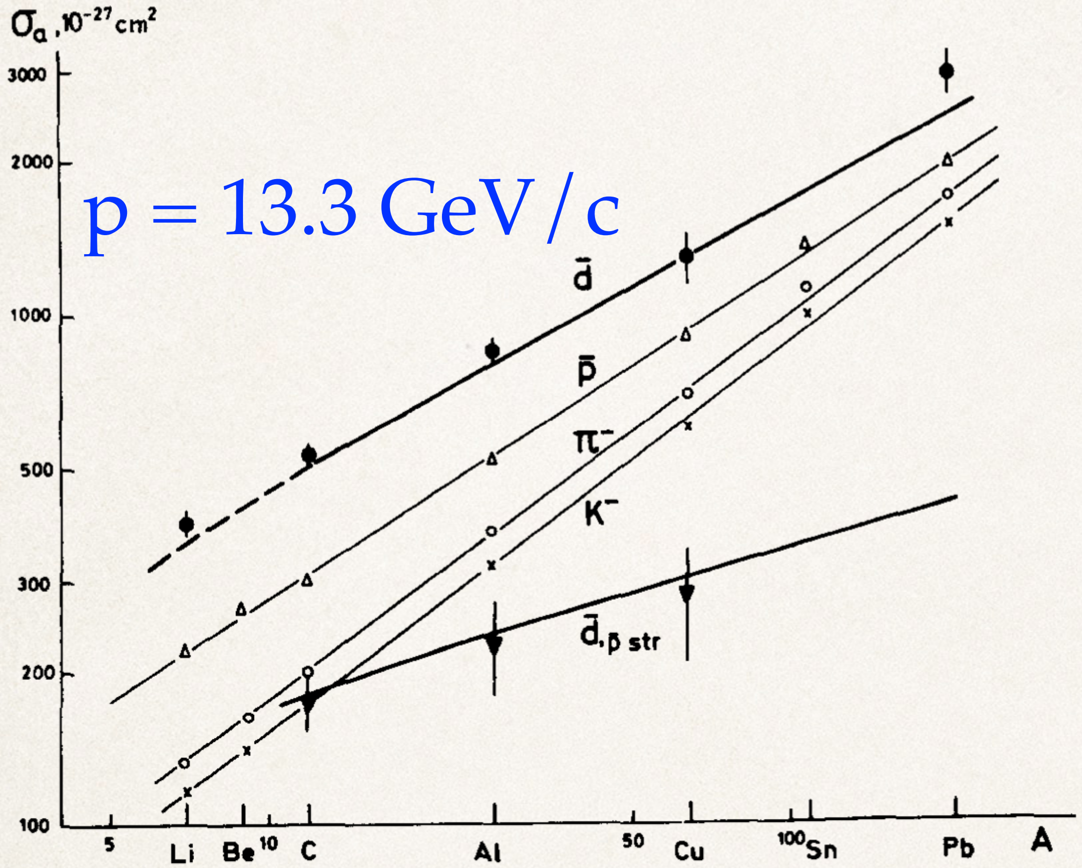
Stronger optical potential enhances $\bar{p}$ absorption

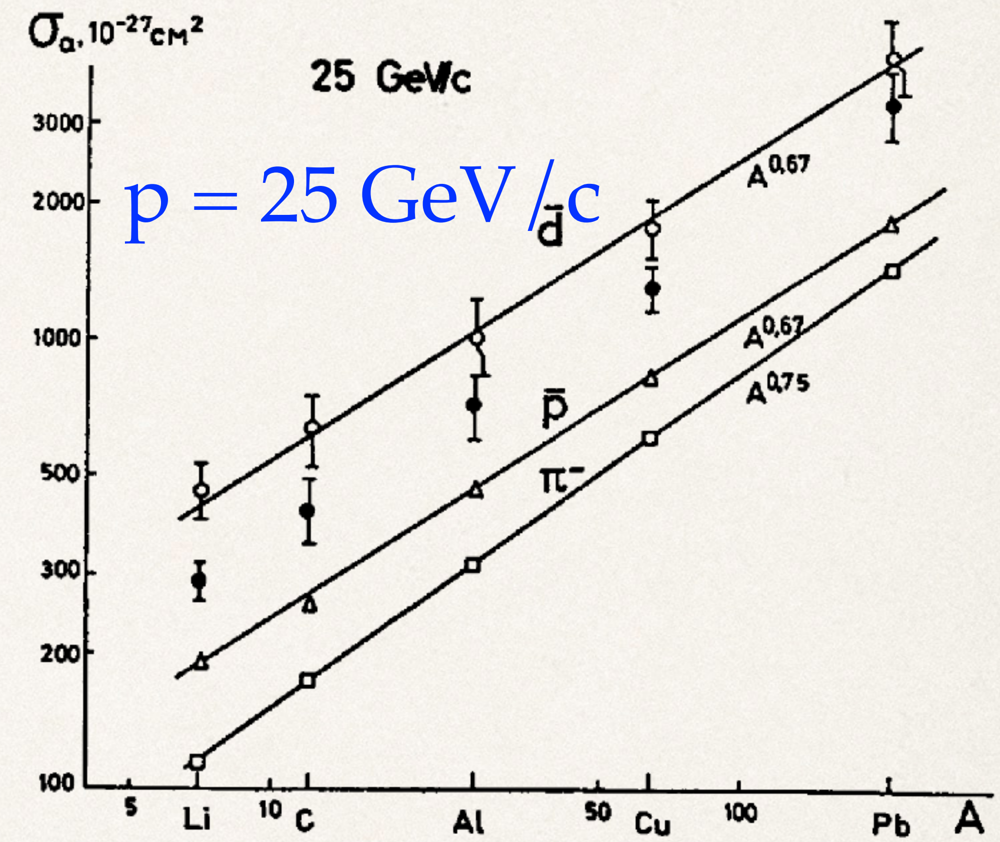
DOI:https://doi.org/10.1103/PhysRevC.80.021601

Current status of $\bar{d}$ study

- Only basic properties of $\bar{d}$ are roughly known: $E_{binding} = 2.4 \pm 0.6$ MeV with unknown size
  - d: $E_{binding} = 2.224575 \pm 0.000009$ MeV and $r = 2.1$ fm
- Available data:
  - JINR in 1970s, total absorption cross sections for $\bar{d}$ at 13.3 and 25 GeV/c momentum with various targets
  - ALICE in 2020s, total inelastic cross section for $\bar{d}$ from collider events with wide momentum range
  - Both results are insensitive to the $\bar{d} - nucleus$ potential

$\bar{d}$ absorption cross section by JINR

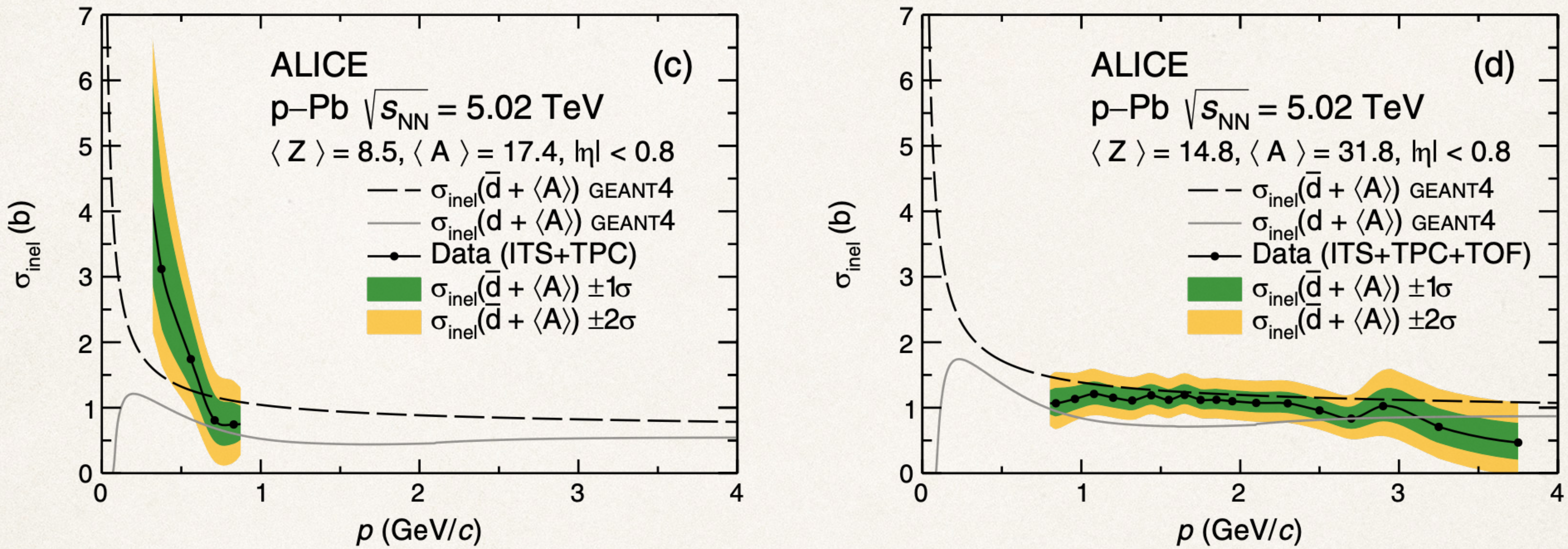




- $\bar{d}$ momentum is too high to probe the $\bar{d} - \textit{nucleus}$ potential
- Optimized $\bar{d}$ beam momentum is ~2.0 GeV/c (~1 GeV/c per nucleon) suggested by GiBUU calculation

doi: https://doi.org/10.1016/0550-3213(71)90229-X
doi: https://doi.org/10.1016/0370-2693(70)90112-7

$\bar{d}$ inelastic cross section by ALICE



Recent results from ALICE:

- Detector materials as effective targets <A> =17.4 and 31.8
- Only total inelastic cross sections are measured and different processes can not be decoupled

$$\sigma_{inelastic} = \sigma_{NonAnn} + \sigma_{ParAnn} + \sigma_{CohAnn}$$

doi: https://doi.org/10.1103/PhysRevLett.125.162001

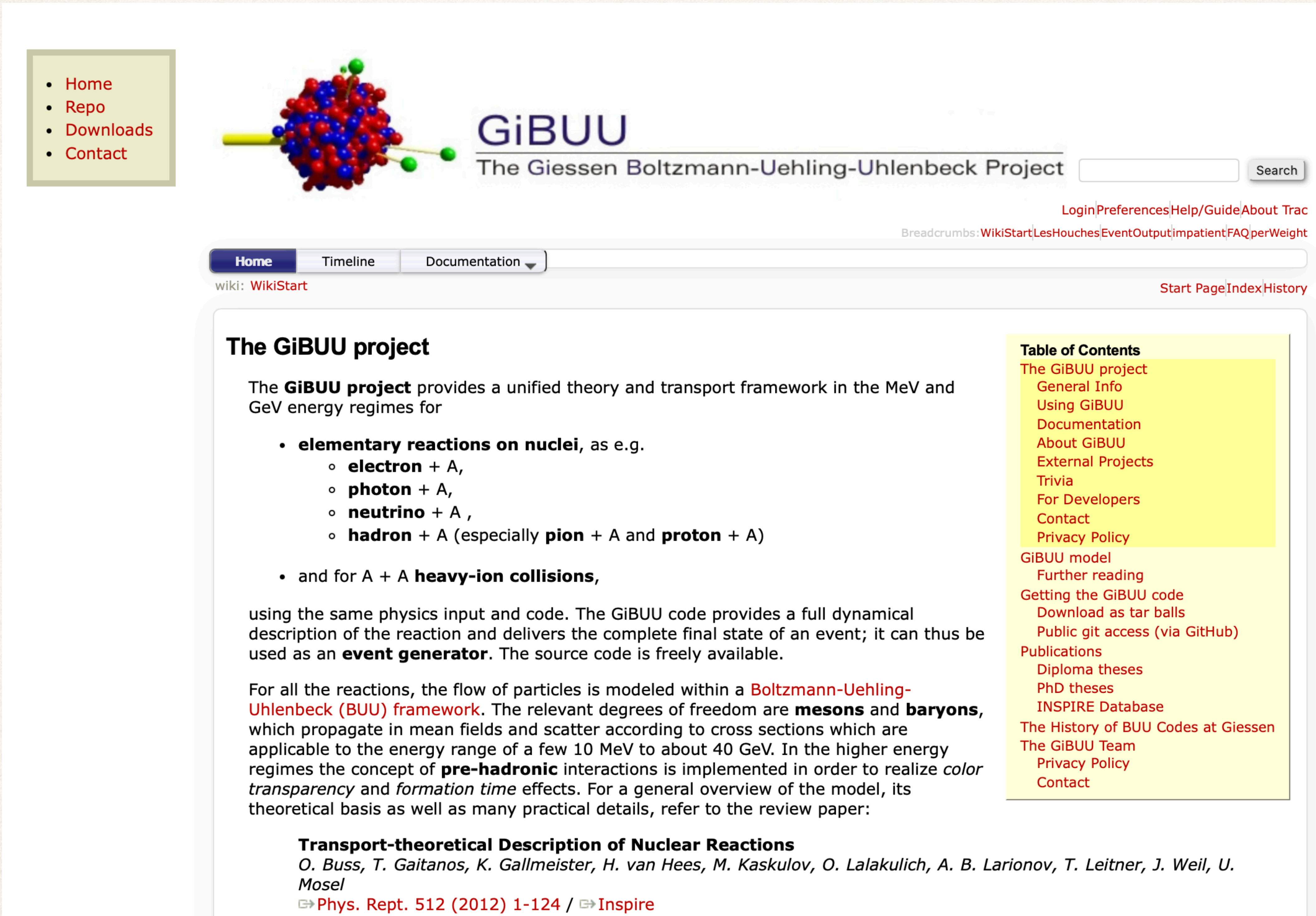
What will happen when $\bar{d}$ meets nucleus?

- How will the optical potential change for $\bar{d} - nucleus$?
  - *enhanced* due to compressed $\bar{d} - nucleus$ system?
  - *reduced* because of pion shield in $\bar{N} + N \rightarrow \pi$s?
- How does $\bar{d}$ annihilate with nucleus?
  - one-by-one or one-step?
- We want to answer these questions with our experiment at J-PARC K1.8 beam line

Our proposal for J-PARC Hadron Facility

- Definition of terminology:
  - Coherent Annihilation: $\bar{d} + A \rightarrow (A - 2) + mesons$
  - Partial Annihilation: $\bar{d} + A \rightarrow (A - 1) + \bar{N} + mesons$
- Derive $\bar{d} - nucleus$ optical potential with $\sigma_{ParAnn}/\sigma_{CohAnn}$ ratio
  - Stronger attractive potential enhances the coherent annihilation events by pulling $\bar{d}$ closer to the nucleus
- Study $\bar{d} - nucleus$ annihilation scenario by examining annihilation phase space

Our tool: GiBUU in a nutshell



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GiBUU

The Giessen Boltzmann-Uehling-Uhlenbeck Project

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The GiBUU project

The **GiBUU project** provides a unified theory and transport framework in the MeV and GeV energy regimes for

- **elementary reactions on nuclei**, as e.g.
  - **electron** + A,
  - **photon** + A,
  - **neutrino** + A ,
  - **hadron** + A (especially **pion** + A and **proton** + A)
- and for A + A **heavy-ion collisions**,

using the same physics input and code. The GiBUU code provides a full dynamical description of the reaction and delivers the complete final state of an event; it can thus be used as an **event generator**. The source code is freely available.

For all the reactions, the flow of particles is modeled within a Boltzmann-Uehling-Uhlenbeck (BUU) framework. The relevant degrees of freedom are **mesons** and **baryons**, which propagate in mean fields and scatter according to cross sections which are applicable to the energy range of a few 10 MeV to about 40 GeV. In the higher energy regimes the concept of **pre-hadronic** interactions is implemented in order to realize *color transparency* and *formation time* effects. For a general overview of the model, its theoretical basis as well as many practical details, refer to the review paper:

Transport-theoretical Description of Nuclear Reactions
O. Buss, T. Gaitanos, K. Gallmeister, H. van Hees, M. Kaskulov, O. Lalakulich, A. B. Larionov, T. Leitner, J. Weil, U. Mosel
Phys. Rept. 512 (2012) 1-124 / Inspire

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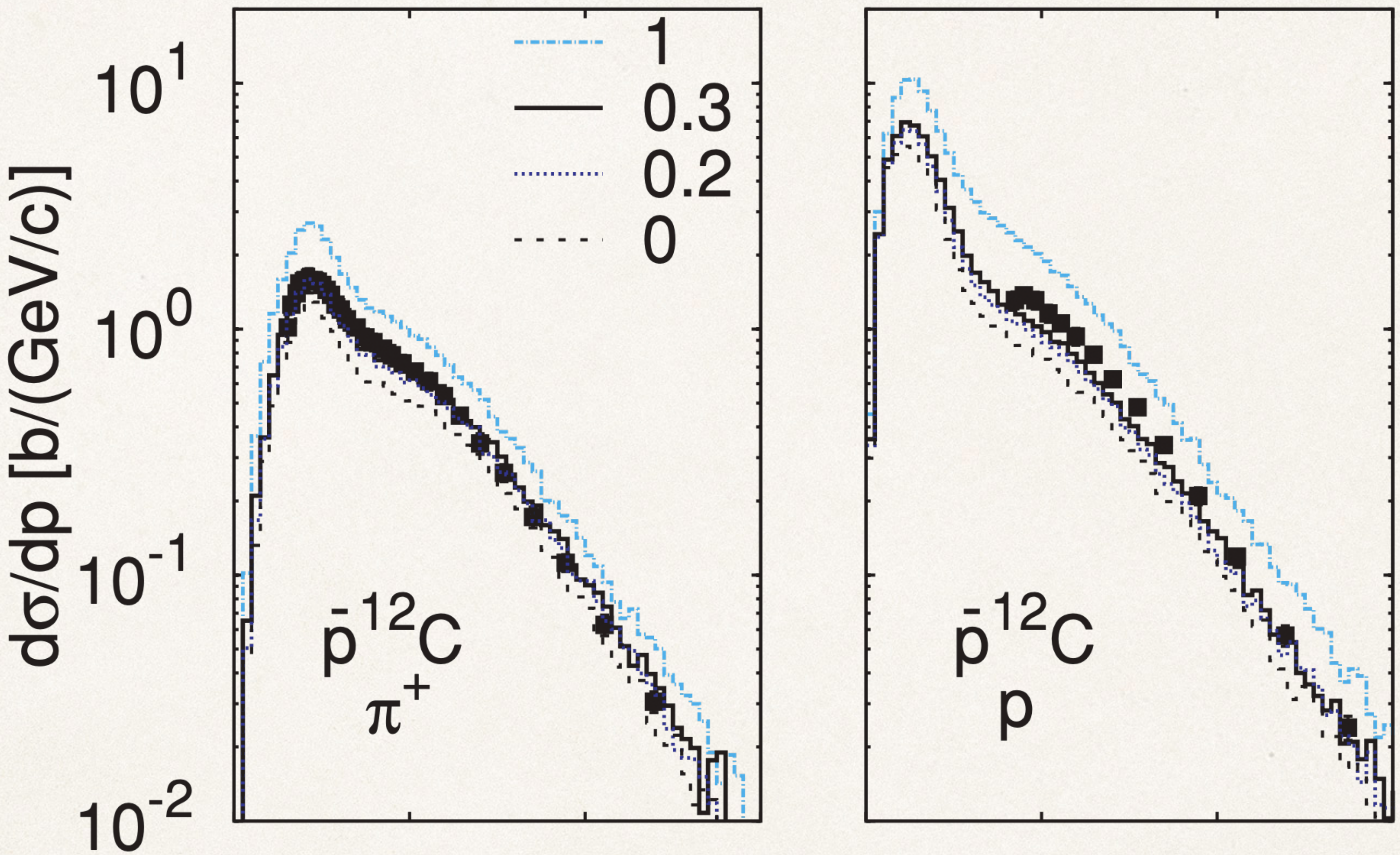
GiBUU calculation vs $\bar{p}$+^{12}C data (0.6 GeV/c)



$\bar{p}$ momentum = 0.6 GeV / c

- Very good agreement between GiBUU and data by using proper optical potential $V_0 = -153$ MeV
- Thanks to Dr. Gallmeister of Giessen University for implementing $\bar{d}$ beam into GiBUU

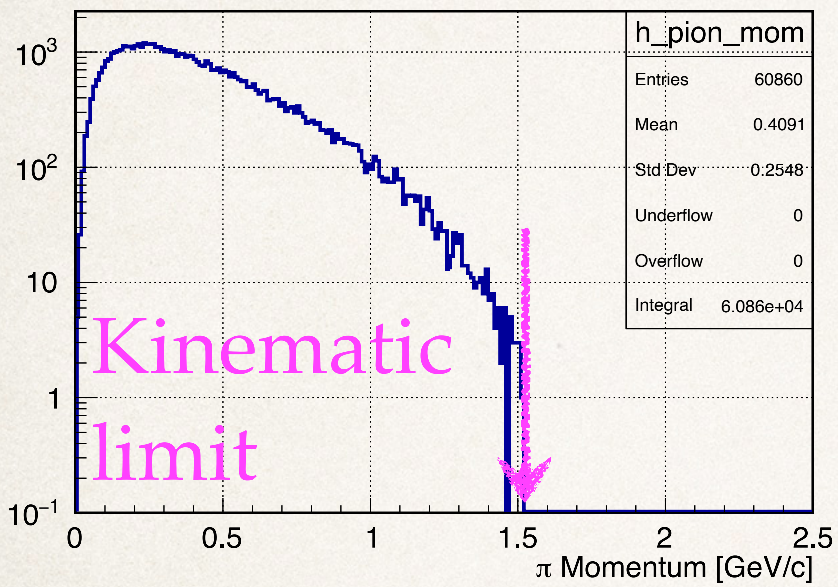
Topic I: derive $\bar{d} - nucleus$ potential

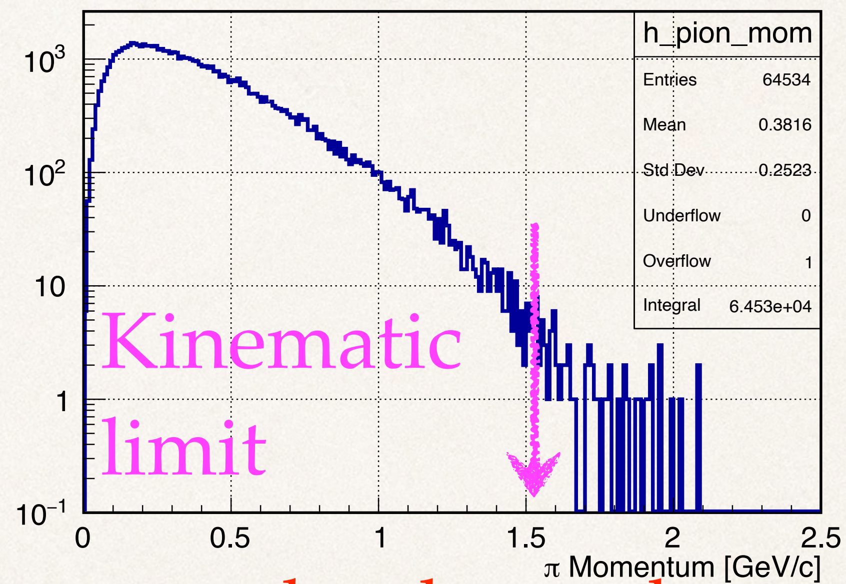
- $\sigma_{ParAnn}/\sigma_{CohAnn}$ ratio is very sensitive to optical potential because a strong attractive potential pulls antinucleon into nucleus and enhances the coherent annihilation ratio
  - $\sigma_{ParAnn}/\sigma_{CohAnn} = 61010/21911 = 2.8$ at $\xi = 0.2, V_0 = -150$ MeV
    - $\sigma_{ParAnn}/\sigma_{CohAnn} = 42631/21911 = 1.9$, $\theta_{\bar{N}} \leq 10^o$ Lab.
  - $\sigma_{ParAnn}/\sigma_{CohAnn} = 50731/31359 = 1.6$ at $\xi = 0.5, V_0 = -300$ MeV
    - $\sigma_{ParAnn}/\sigma_{CohAnn} = 26362/31359 = 0.8$, $\theta_{\bar{N}} \leq 10^o$ Lab.
- We can, therefore, derive $\bar{d} - nucleus$ optical potential by measuring $\sigma_{ParAnn}/\sigma_{CohAnn}$ ratio

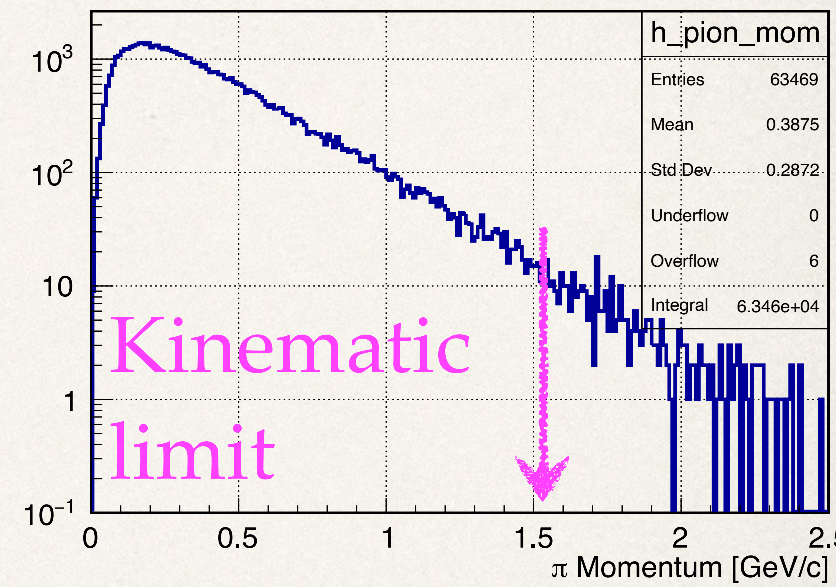
Topic II: Study $\bar{d}$ annihilation scenario

- Our question: how does matter-antimatter annihilate?
  - two-step independent annihilation: $2 \times (\bar{N} + N)$
  - correlated cascade annihilation: 1: $\bar{N} + N \rightarrow n \times \pi$, 2: $\pi + \bar{N} \rightarrow \bar{\Delta}$, 3:$\bar{\Delta} + N \rightarrow n \times \pi$
  - one-step annihilation: $\bar{d} + 2N \rightarrow n \times \pi$
- Our answer: distinguish among these annihilation scenarios by examining the phase space via pion momentum distribution

Topic II: Study $\bar{d}$ annihilation scenario







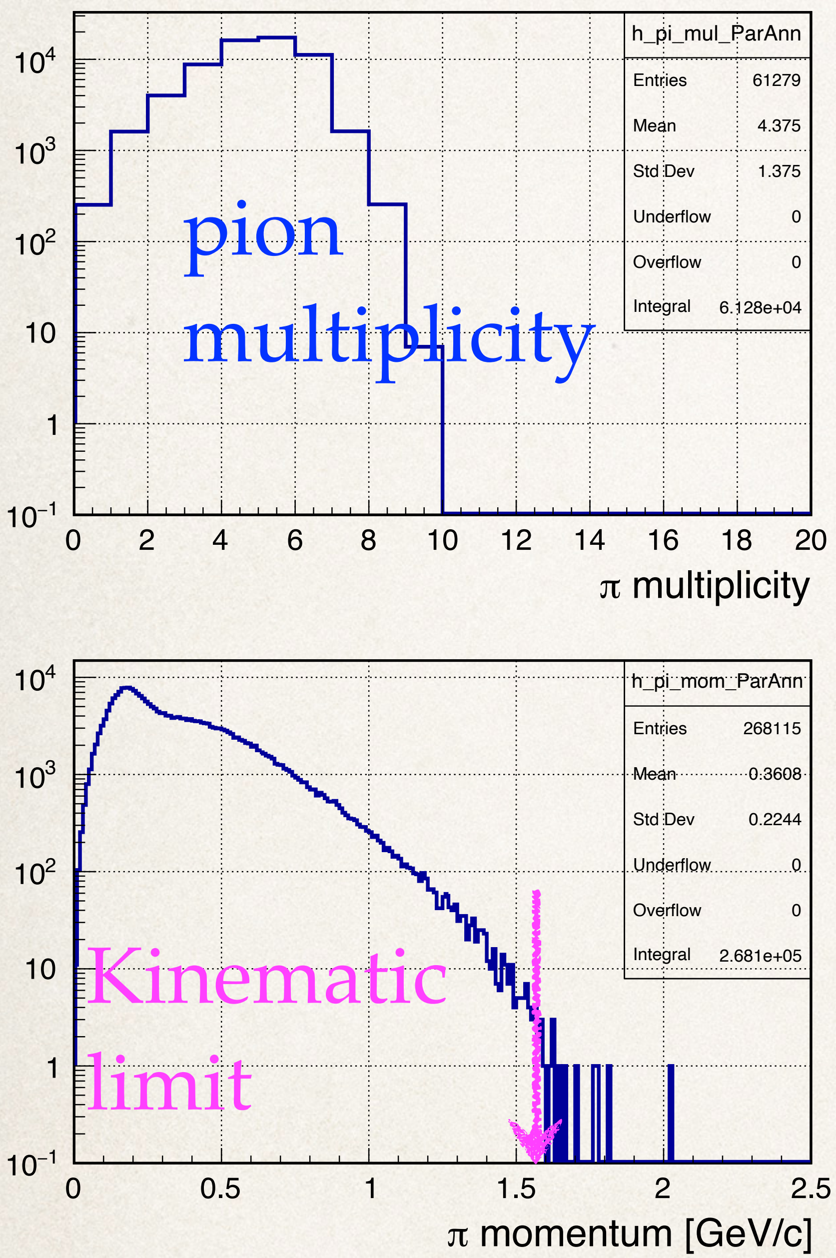
two-step independent annihilation $2 \times (\bar{p} + p)$

correlated cascade annihilation:
1: $\bar{N} + N \to n \times \pi$,
2: $\pi + \bar{N} \to \bar{\Delta}$,
3: $\bar{\Delta} + N \to n \times \pi$

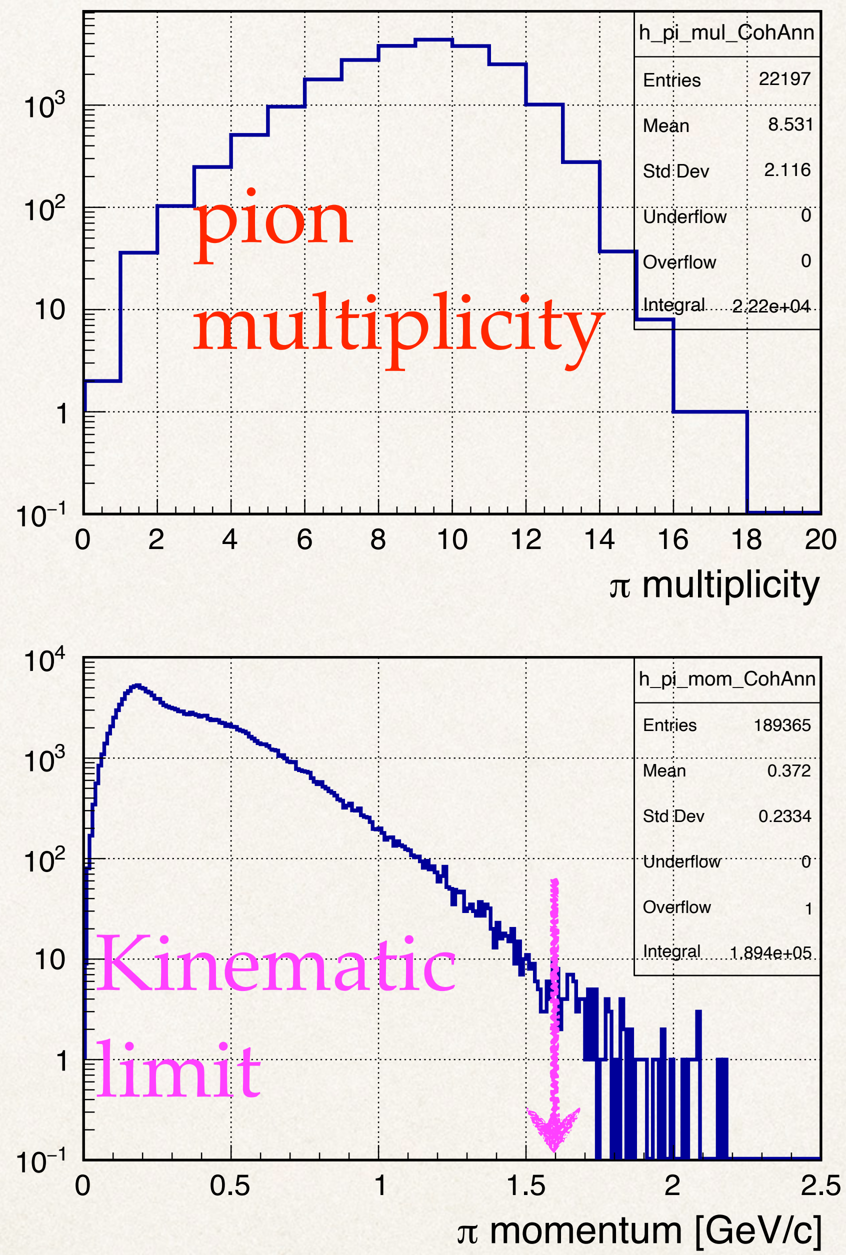
one-step annihilation:
$\bar{d} + d \to n \times \pi$,
$n = 11 \pm 2.4$
SRC or potential?

- Demonstration for difference in phase space due to different annihilation scenarios
- $n_{mean} = 5.01 \times \frac{\mathrm{IM}_{\bar{\Delta}+p}}{2 \times m_p}, n_\sigma = 1.04 \times \frac{\mathrm{IM}_{\bar{\Delta}+p}}{2 \times m_p}$

Topic II: Study $\bar{d}$ annihilation scenario



Partial annihilation with GiBUU: 24 counts due to Fermi motion



Coherent annihilation with GiBUU: 123 counts from correlated annihilation

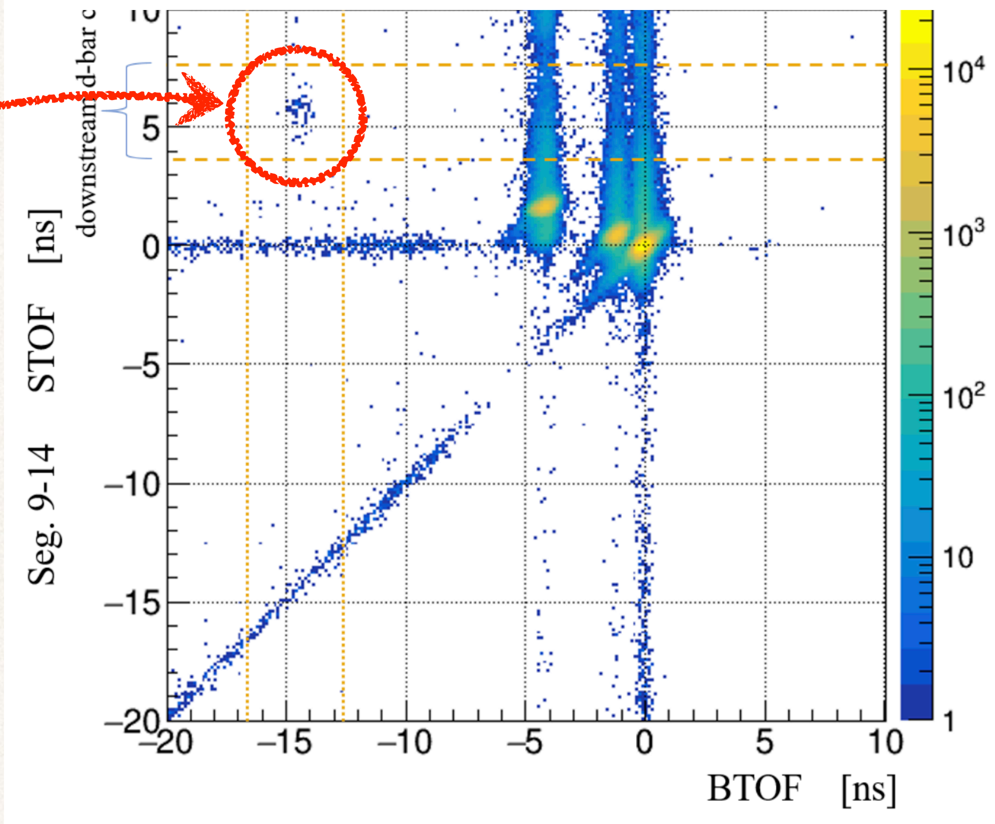
1.5×10^5 unbiased events from $\bar{d}$+^{12}C reaction by GiBUU; we can distinguish the contributions from different annihilation scenarios by examining pion events beyond $\bar{N} - N$ annihilation kinematics, i.e., phase space limit

currently, only correlated cascade annihilation included in GiBUU

Experiment concept at K1.8 beam line

$\bar{d}$ identification @ K1.8 by Ukai san

M. Ukai *et al.*, arXiv:2312.11821



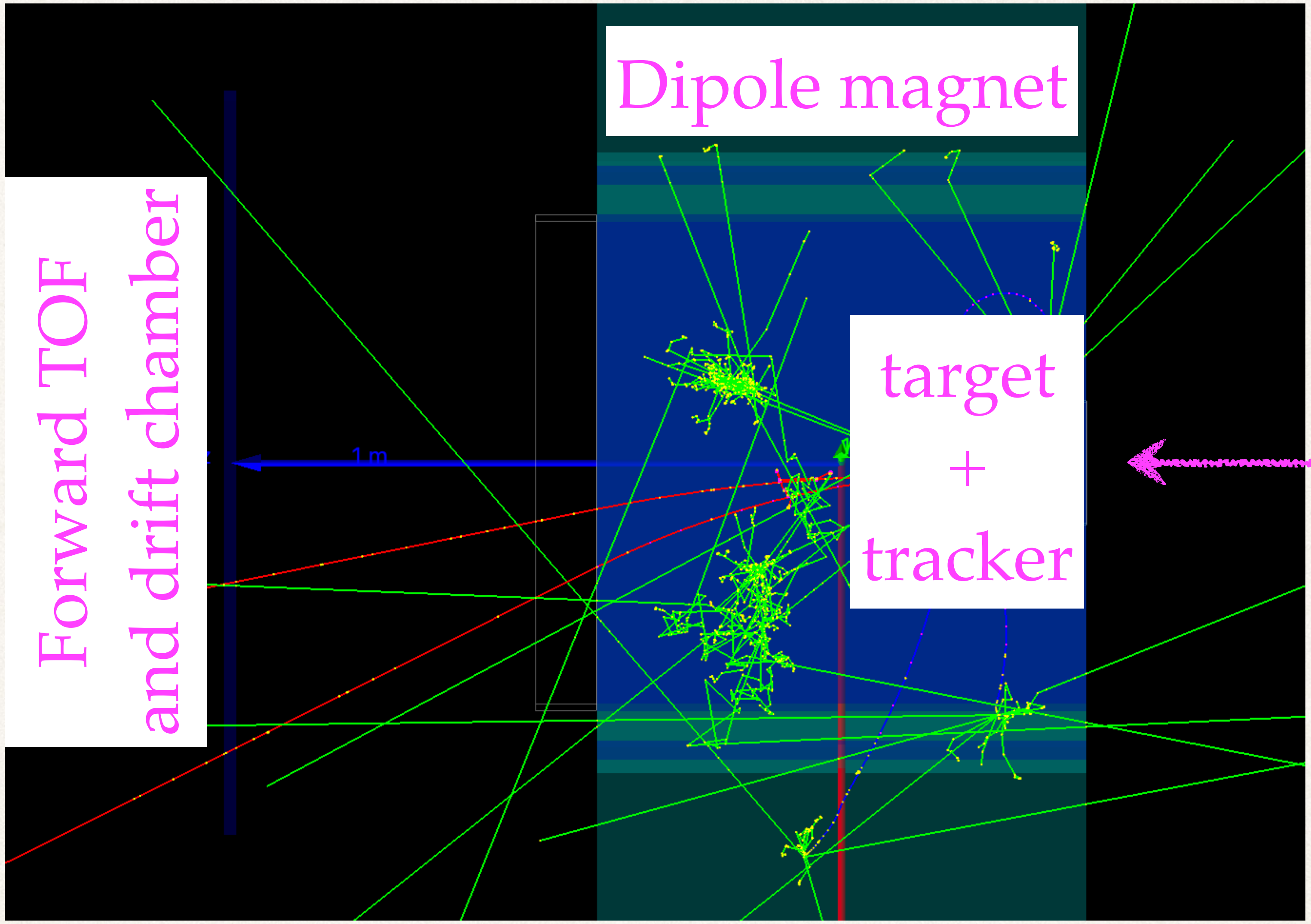
$\bar{d}$ events identified with TOF information

Existence of $\bar{d}$ was confirmed at K1.8 beam line @ 1.8 GeV/c

- Yield is estimated to be ~0.3 $\bar{d}$ /spill (~5 seconds) @ 64 kW
- 1.5×10^5 $\bar{d}$ beam particles with one month beam time

https://doi.org/10.48550/arXiv.2312.11821

Experiment concept: $\bar{d}+^{12}\mathrm{C}$

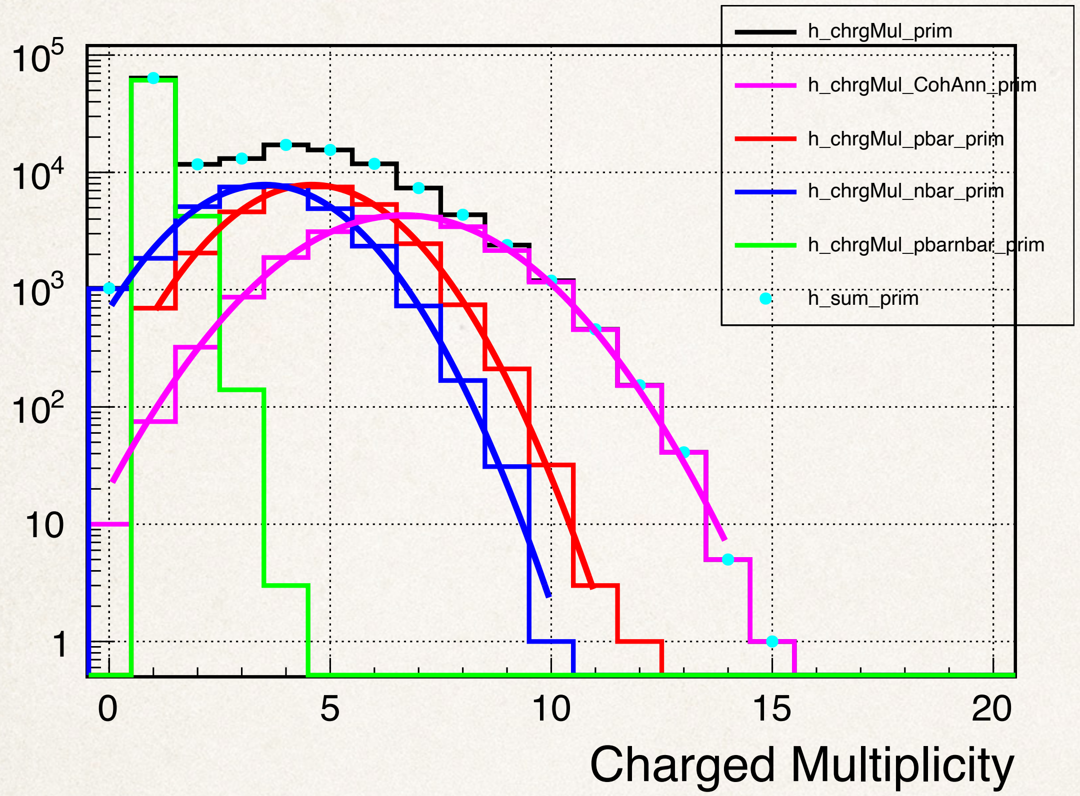


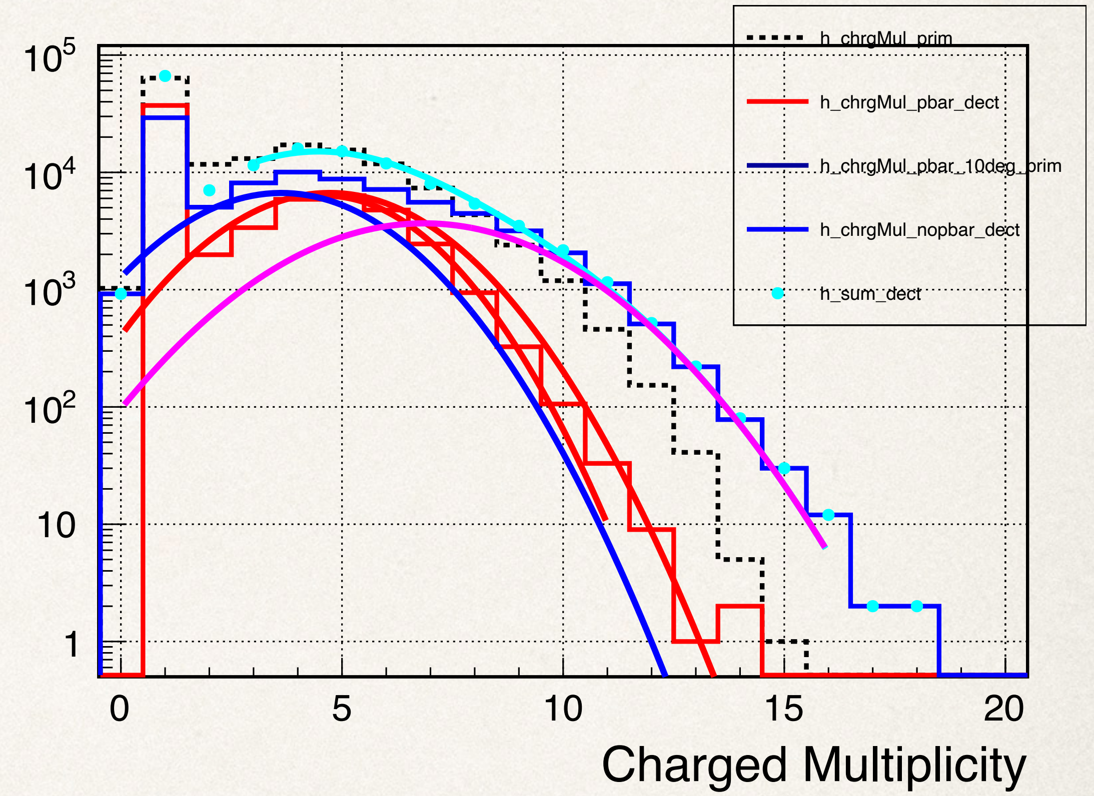
- 10 cm long graphite target in thin slice to react with $\bar{d}$ beam
- Dipole spectrometer to measure $\sigma_{ParAnn}/\sigma_{CohAnn}$ and examine annihilation phase space with $\pi^{\pm}$ momentum

Yield estimation: $\bar{d}+{}^{12}\text{C} \rightarrow \pi^{\pm,0}$

- For 1 cm of graphite with 2 g/cm^3density:
  - Reaction probability per $\bar{d}$ beam particle =
    $$1cm \times \frac{2g}{cm^3} \times \frac{6.02 \times 10^{23}}{12} \times 1.2 \times 10^{-24} cm^2 \sim 0.1$$
  - ~10 cm of graphite target will fully react with $\bar{d}$ beam
- Assuming 0.3 $\bar{d}$/spill (5 seconds) @ 64kW for one month beam time, we can expect $1.5 \times 10^5\ \bar{d} \times 14.6\,\%\ B.R. = 2.0 \times 10^4$ events for coherent annihilation and 5.6×10^4 events for partial annihilation
  - 10% precision for $\sigma_{ParAnn}/\sigma_{CohAnn}$ to derive optical potential
  - ~ 300 events $\pi^{\pm}$ events beyond $\bar{p} - p$ phase space ($\geq$ 1.6 GeV/c)

How to derive ParAnn and CohAnn





- W/O in-flight secondary annihilation background yet
- Fit $\bar{p} + \bar{n}$ParAnn for real data multiplicity including shower in between 4<=nTrack<=11 to avoid breakup events
- Obtain relative position and width between $\bar{p}/\bar{n}$ ParAnn and CohAnn from GiBUU and apply them to data fitting to decouple $\bar{p}/\bar{n}$ ParAnn and CohAnn with ~10% accuracy; reliable because of the stableness of the saturated phase space feature

Summary

- Thanks to M. Ukai *et al.*, a unique chance to investigate $\bar{d}$ related physics is now open at J-PARC Hadron Facility K1.8 beam line
- We propose to study
  - mean field perspective: derive the $\bar{d} - nucleus$ optical potential with $\sigma_{ParAnn}/\sigma_{CohAnn}$
  - microscopic picture: study $\bar{d} - nucleus$ annihilation scenario with pion yield beyond $\bar{p} - p$ annihilation phase space
  - As a by-product, we can also obtain the $\bar{d}$ radius for the first time in the world

Advertisement: J-PARC antimatter consortium

- A casual occasion to allow Physicists to exchange information and brain storming to use pbar and dbar beam at J-PARC
- Current members from Osaka University, Kyoto University and RIKEN
- If you have any interests, please feel free to contact us

Possible topics for $\bar{d}$ related physics

Topics	Method	Condition
CPT: static	$\bar{d}$ atomic x-ray	need slow $\bar{d}$
CPT: scattering	$\bar{d}$ + p vs $\bar{p}$ + d	low precision
$\bar{d}$ radius	coherent annihilation cross section	our proposal
$\bar{d}$+^{12}C potential	Partial/Coherent annihilation ratio	our proposal
$\bar{d}$ annihilation scenario	measure annihilation phase space	our proposal

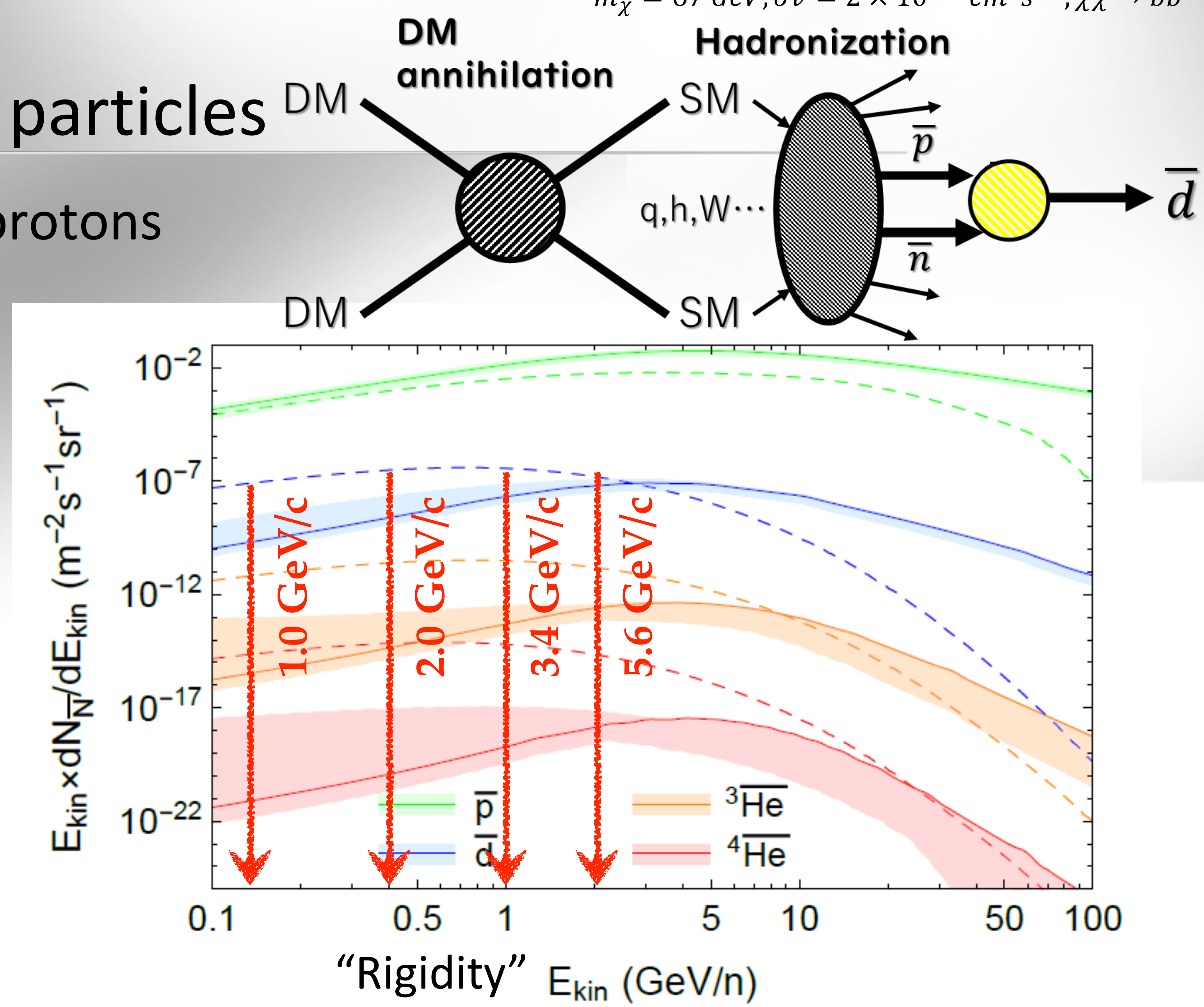
- backup

Possible topics for $\bar{d}$ related physics

Origin of the anti-matter particles

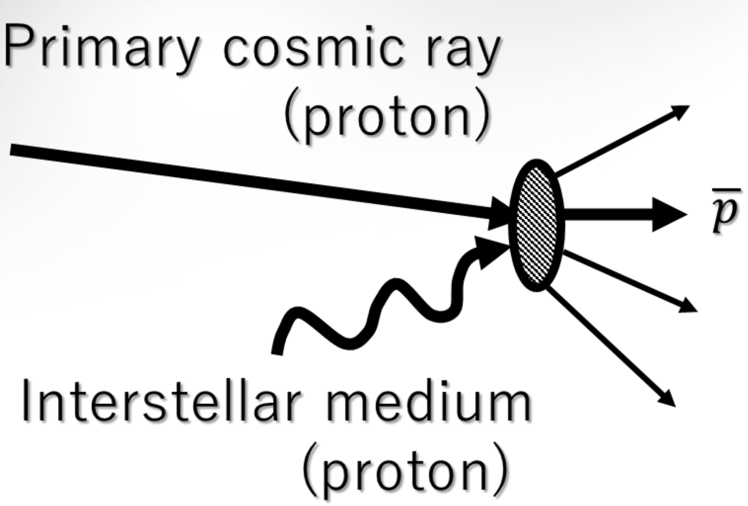
- Possible sources of the anti-protons
  - Anti-matter planets
  - Primordial Black hole
  - **Dark matter annihilation**
  - **Secondary particles**

Dashed lines $m_\chi = 67\ GeV, \sigma v = 2 \times 10^{-26} cm^3 s^{-1}, \chi\chi \to b\bar{b}$



I.Cholis, et.al, PRD 102, 103019 (2020)

Solid Line



T98@36th J-PARC PAC report by Tanaka san