Faculty of Physics
WARSAW UNIVERSITY OF TECHNOLOGY

Matter – antimatter interactions

Małgorzata Janik
Warsaw University of Technology

WPCF 6-10/11/2023

Experimental measurements

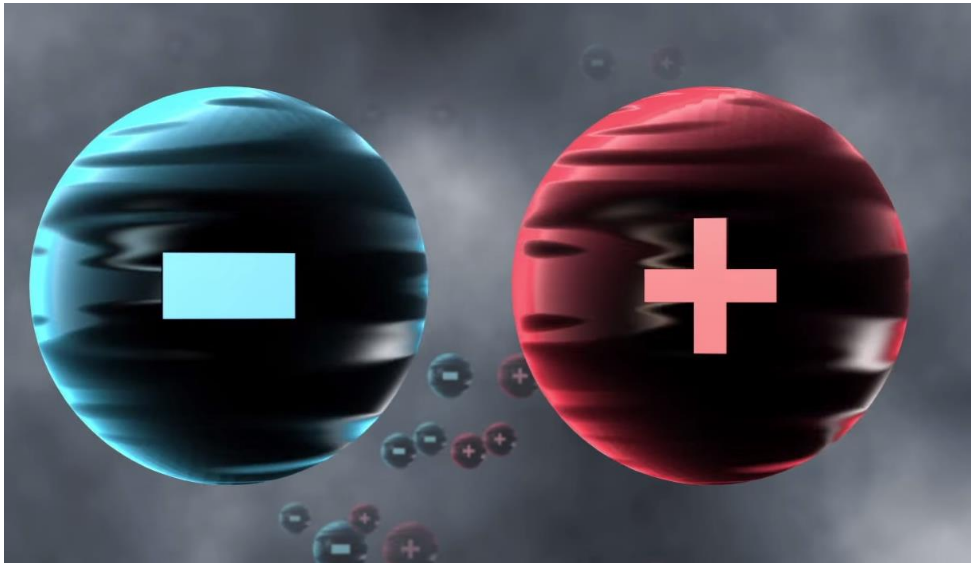
How to measure interactions with antimatter & annihilation properties?

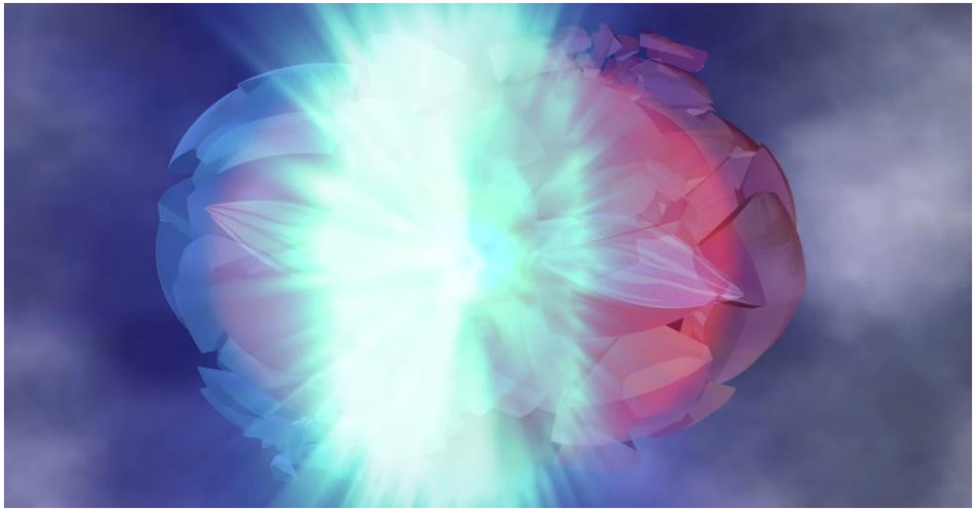
<u>Secondary antiproton beams</u>

- Scattering experiments
  Exotic atoms
  (now: AD and ELENA)

<u>Collider experiments</u>

- Collider experiments:
  e.g. LHC – (anti)matter factory
  (almost) zero baryochemical potential





Experimental measurements

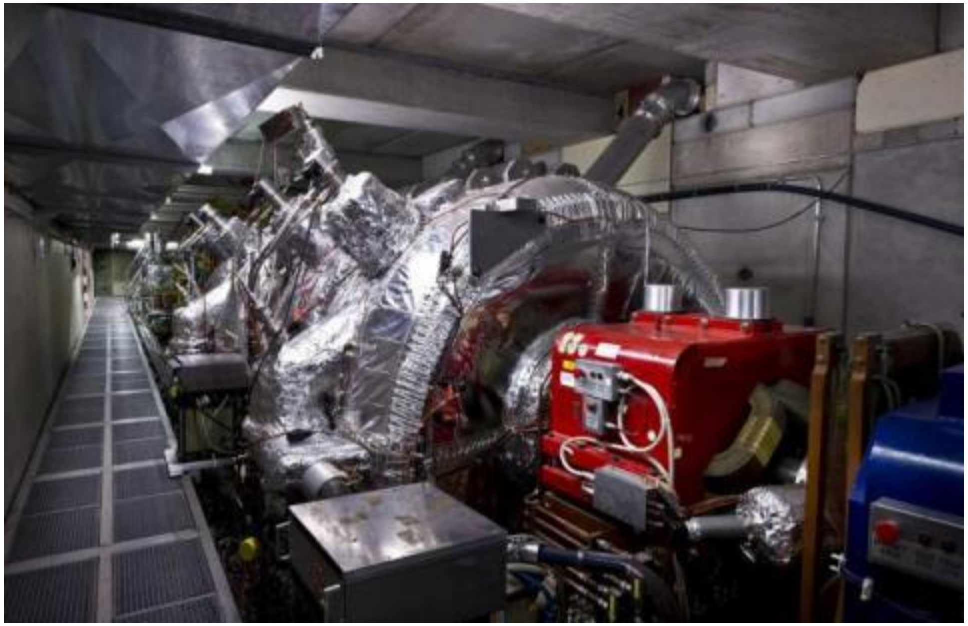
How to measure interactions with antimatter & annihilation properties?

<u>Secondary antiproton beams</u>

- Scattering experiments
  Exotic atoms
  (now: AD and ELENA)

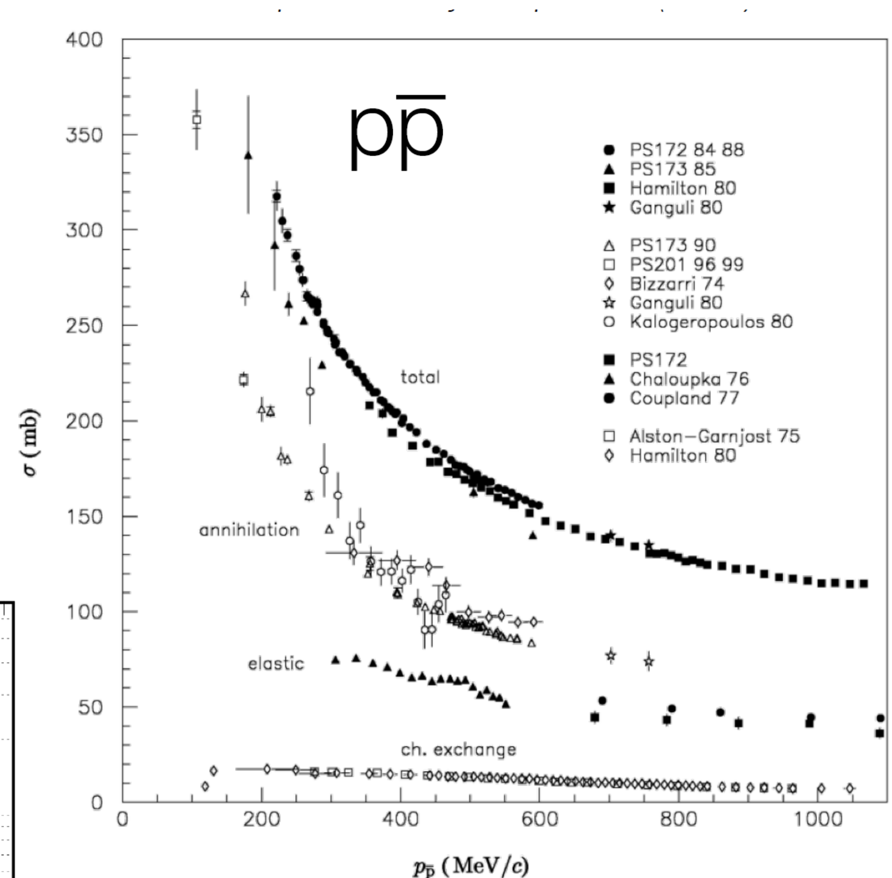
<u>Collider experiments</u>

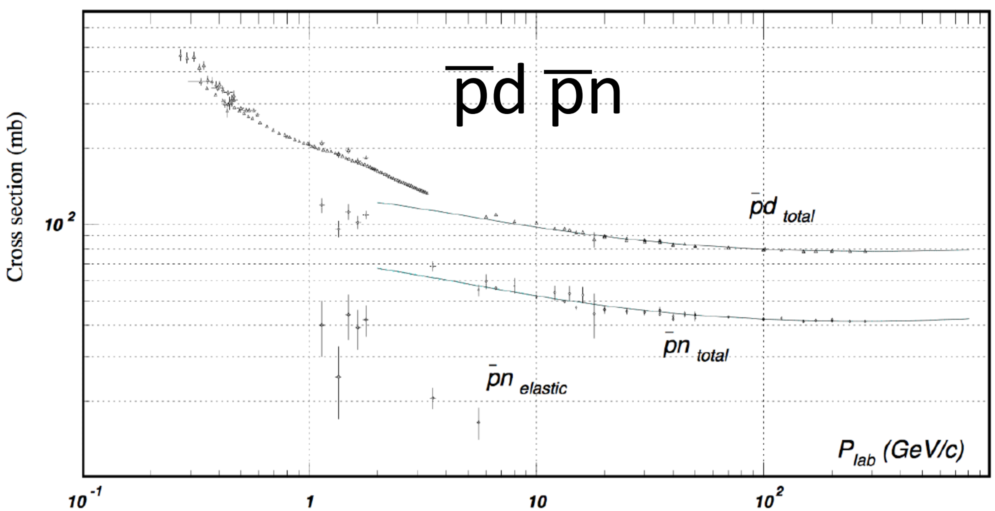
- Collider experiments:
  e.g. LHC – (anti)matter factory
  (almost) zero baryochemical potential



Scattering experiments & hadronic atoms

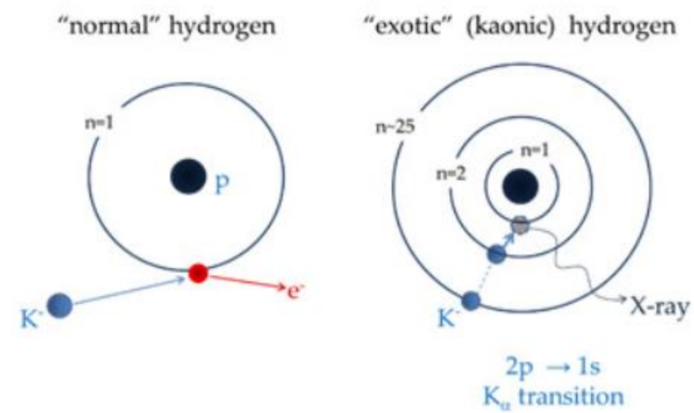
So far, the most precise data on antinucleon-nucleon interaction come from the Low Energy Antiproton Ring (LEAR) of CERN scattering experiments.



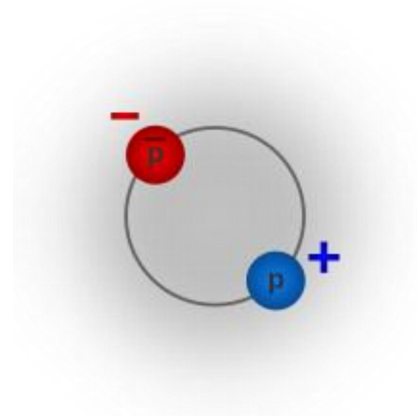


Scattering experiments & hadronic atoms

Hadronic atoms: substitute electron with a hadron in an atom and study such system.



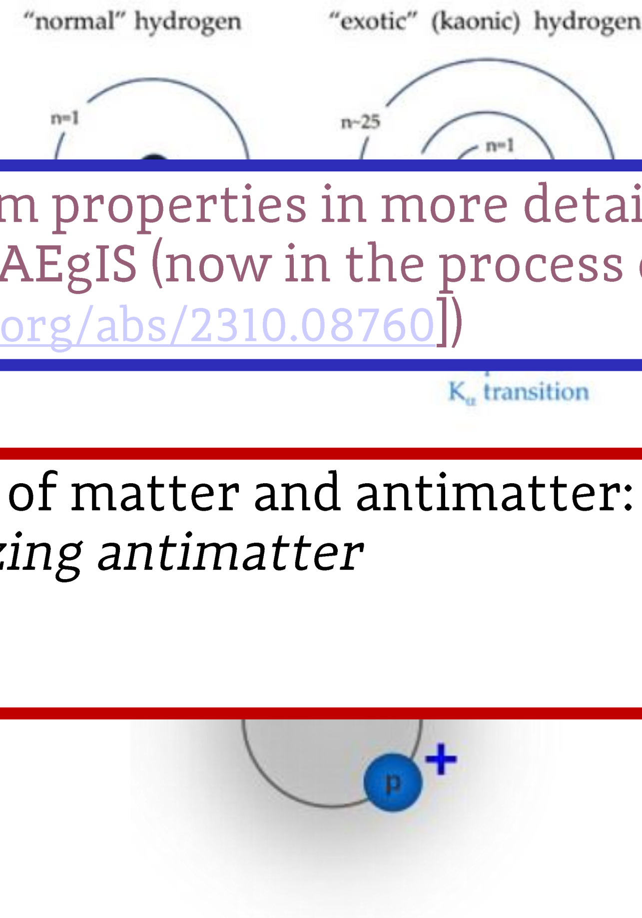
In this domain **protonium** (or antiprotonic hydrogen, denoted by the Pn symbol) is of a significant importance. It is a Coulomb bound state. One of the remaining open questions is whether protonium in the ground state can be considered a nuclear bound state?



Scattering experiments
& hadronic atoms

Hadronic atoms: substitute electron with a hadron in an atom
ar

AD experiments can measure protonium properties in more detail. Included in the measurement plans of AEgIS (now in the process of studying positronium, see [https://arxiv.org/abs/2310.08760])



In this domain **protonium** (or

For more information on bound states of matter and antimatter:
Precise physics of atomic species utilizing antimatter
Tomasz Sowiński
8 Nov 2023, 12:00

the remaining open questions is whether protonium in the ground state can be considered a nuclear bound state?

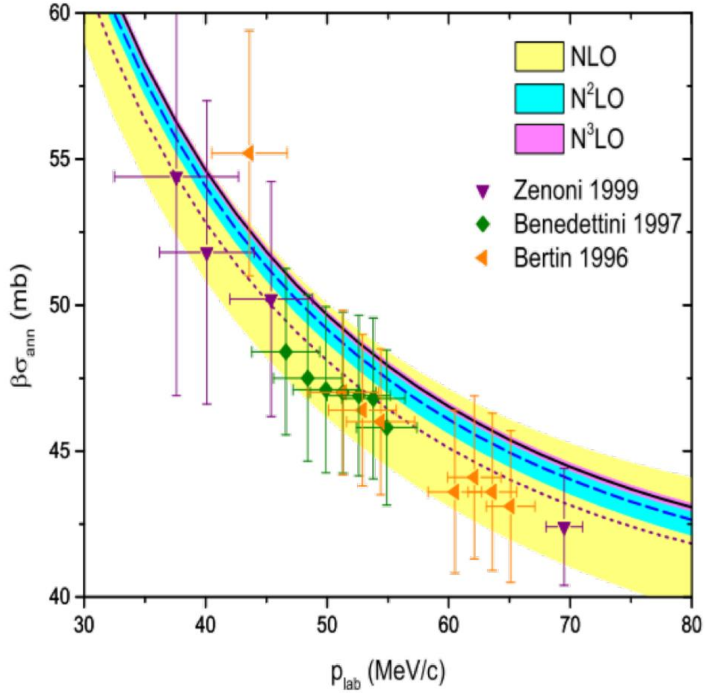
Scattering experiments & hadronic atoms

Disadvantages:

– Not accessible down to zero momenta

– Large uncertainties

– Limited to few h-h interactions



Johann Haidenbauer
EXA2017, Vienna, September 10-15, 2017

Experimental measurements

How to measure interactions with antimatter & annihilation properties?

<u>Secondary antiproton beams</u>

- Scattering experiments
  Exotic atoms
  (now: AD and ELENA)

<u>Collider experiments</u>

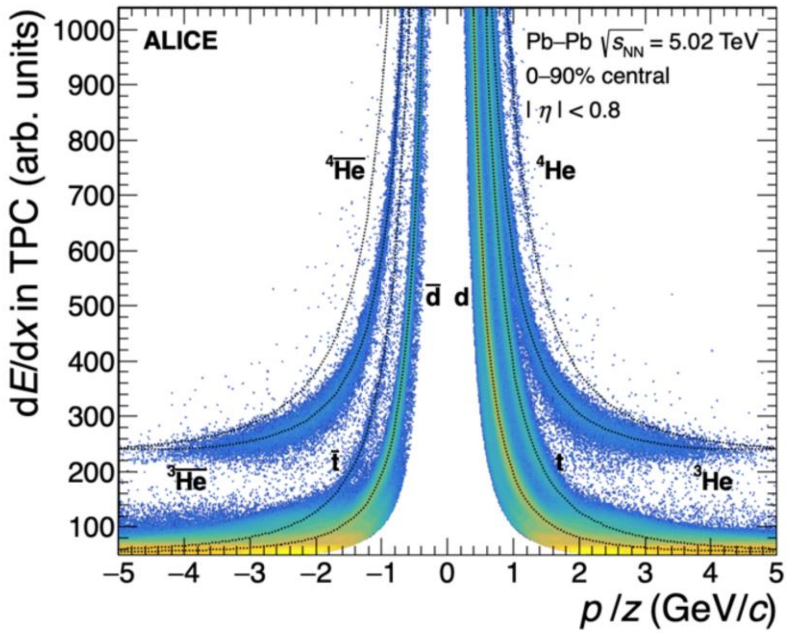
- Collider experiments:
  e.g. LHC – (anti)matter factory
  (almost) zero baryochemical potential

Light antinuclei absorption in ALICE and Galaxy

LHC – (anti)nuclei factory

Nuclei accessible in Run 2:
d, t, ${}_{\Lambda}^{3}H$, ${}^{3}He$, ${}^{4}He$

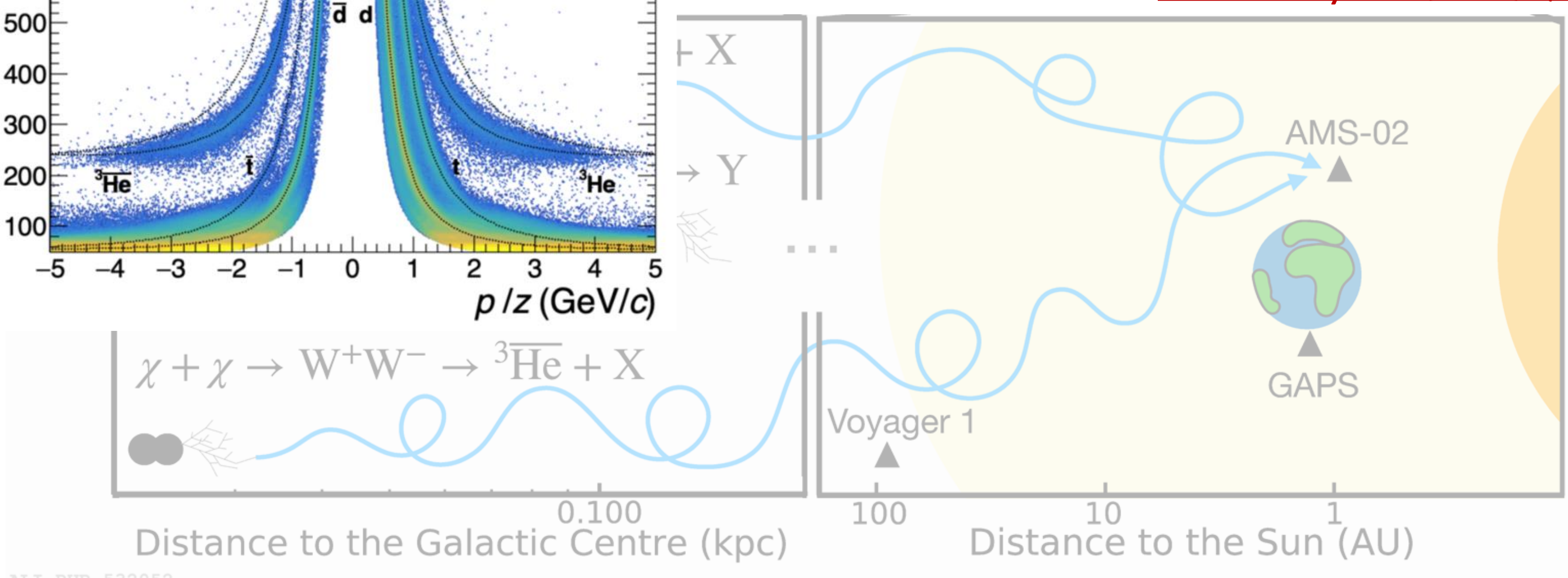
arxiv.org/2202.01549



Information about antinuclei has **strong impact on dark matter searches** in Space, e.g. $\chi_0\chi_0$ →anti-d, anti-^{3}He+X (AMS-02, GAPS, BESS)

- ${}^{3}\overline{He}$ can be produced via high-energy cosmic-ray collisions with the interstellar medium or could originate from the annihilation of dark-matter.
- **Antinuclei absorption** in space poorly known.

Nature Phys. 19 (2023) 1, 61-71



Light antinuclei absorption in ALICE and Galaxy

LHC – (anti)nuclei factory

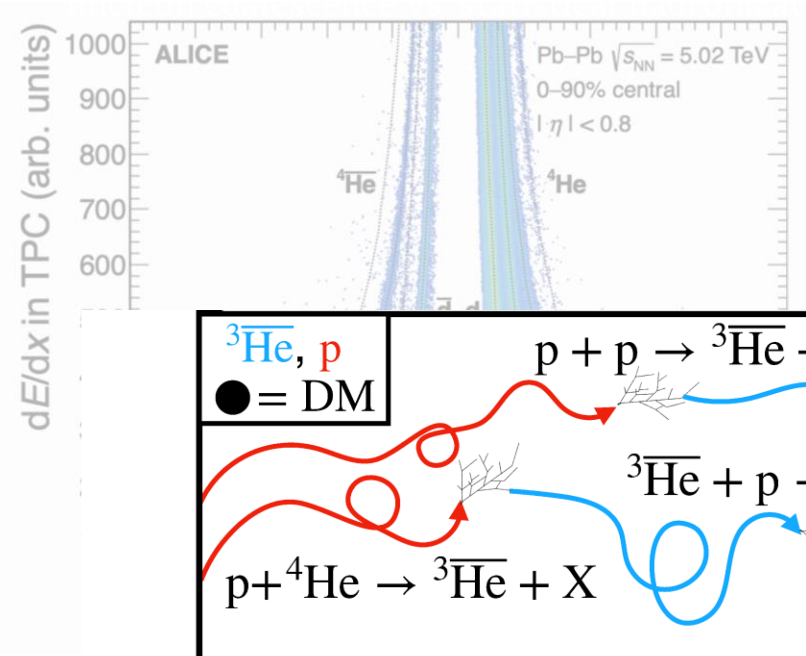
Nuclei accessible in Run 2:
d, t, ${}_{\Lambda}^{3}H$, ${}^{3}He$, ${}^{4}He$

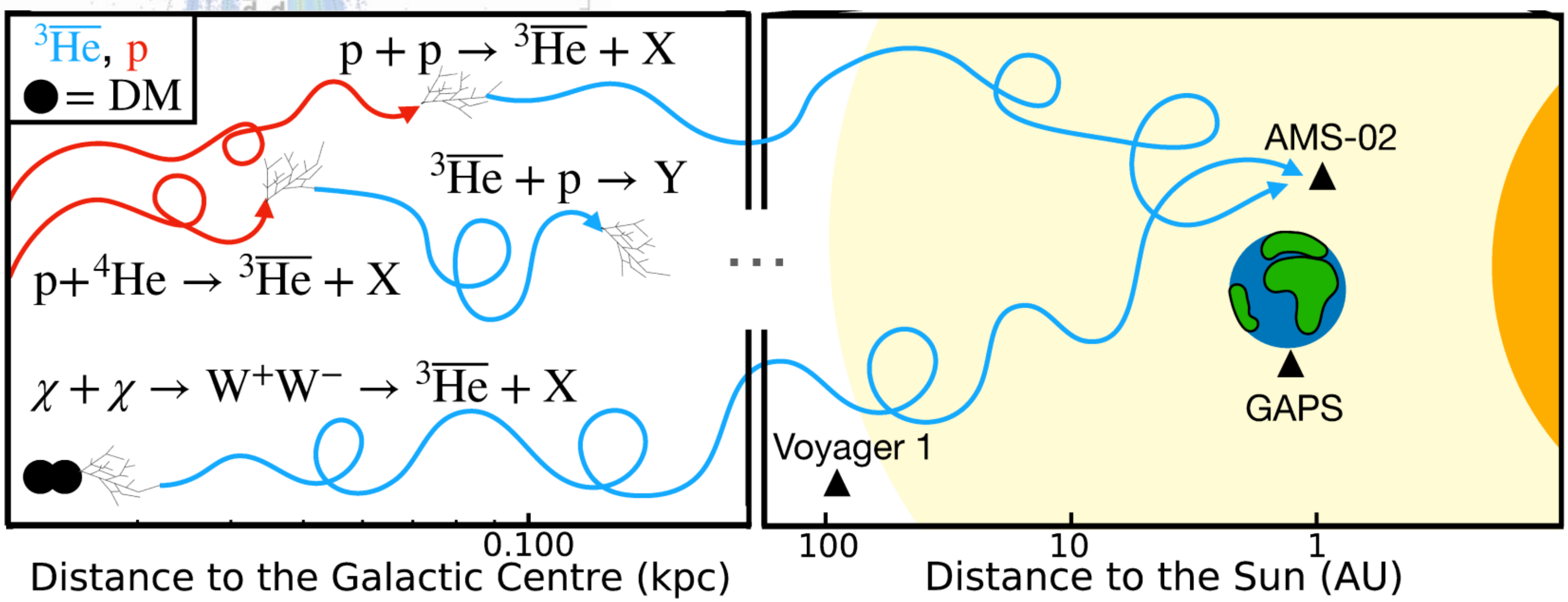
arxiv.org/2202.01549

Information about antinuclei has **strong impact on dark matter searches** in Space, e.g. $\chi_0\chi_0$ →anti-d, anti-^{3}He+X (AMS-02, GAPS, BESS)

- ${}^{3}\overline{He}$ can be produced via high-energy cosmic-ray collisions with the interstellar medium or could originate from the annihilation of dark-matter.
- **Antinuclei absorption** in space poorly known.

Nature Phys. 19 (2023) 1, 61-71

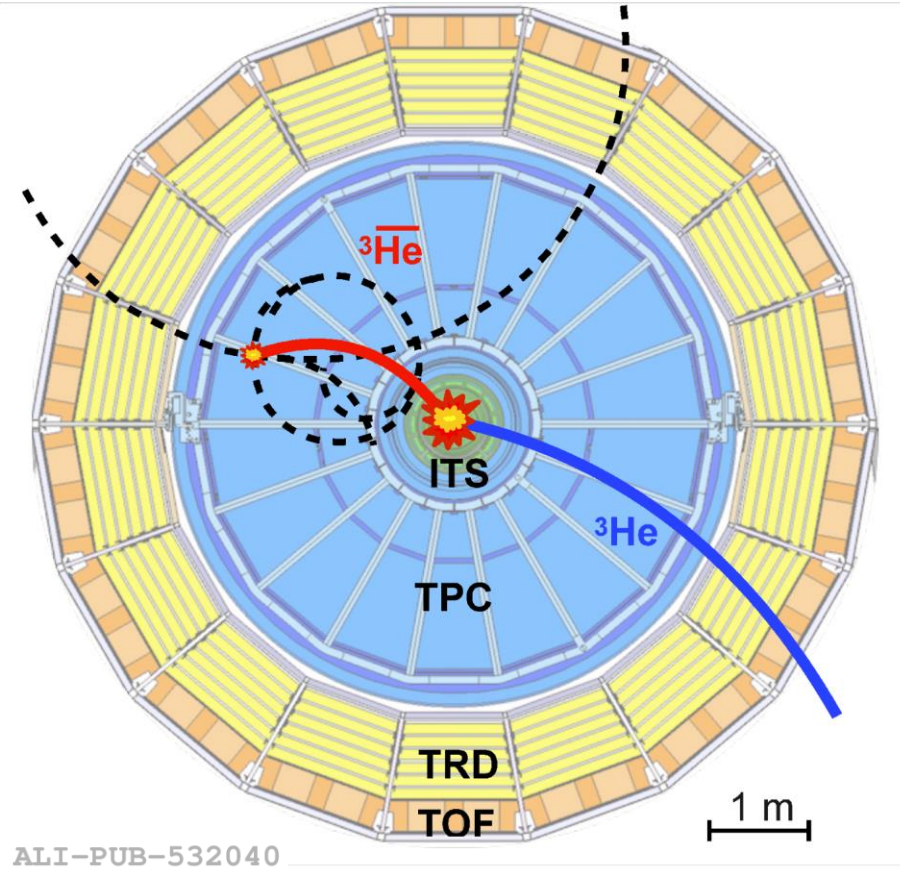




ALI-PUB-532052

Light antinuclei absorption in ALICE and Galaxy

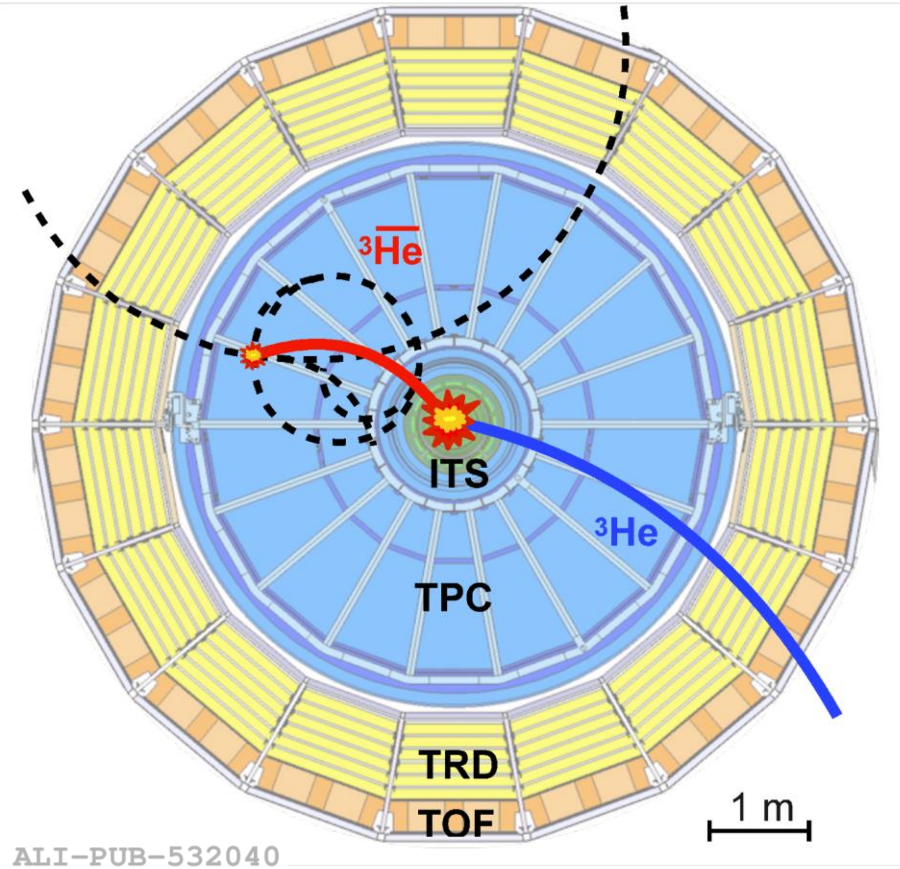
Nature Phys. 19 (2023) 1, 61-71



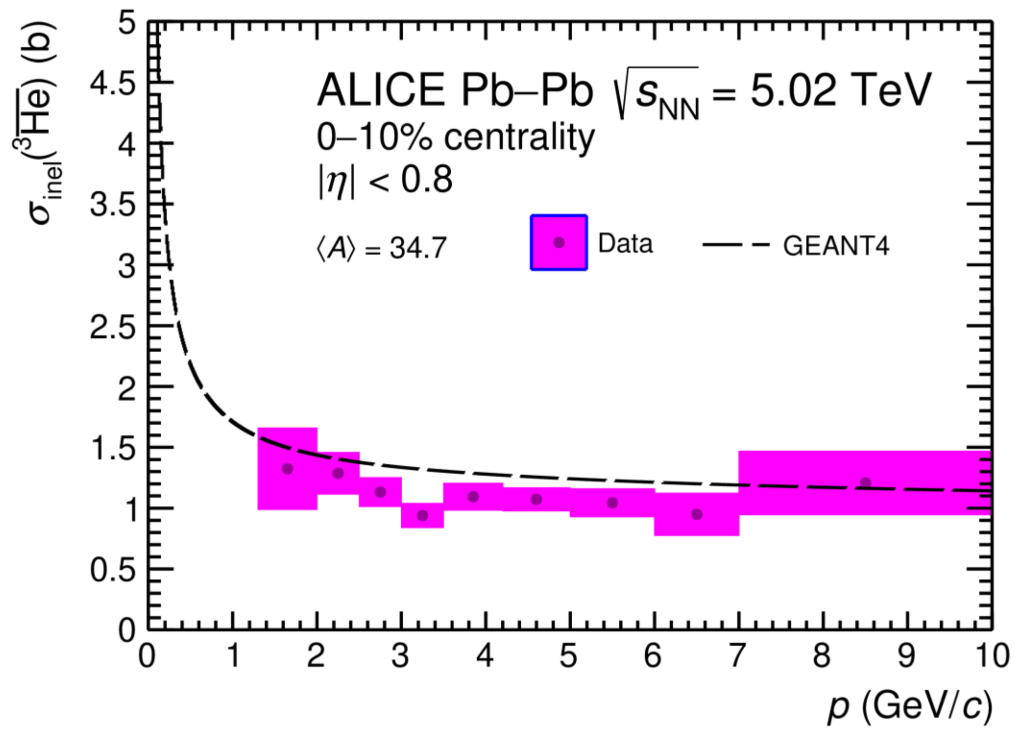
- Novel technique to use detector as an antiparticle absorber
- First experimental measurement of $\sigma_{inel}(^{3}\overline{He})$

Light antinuclei absorption in ALICE and Galaxy

Nature Phys. 19 (2023) 1, 61-71

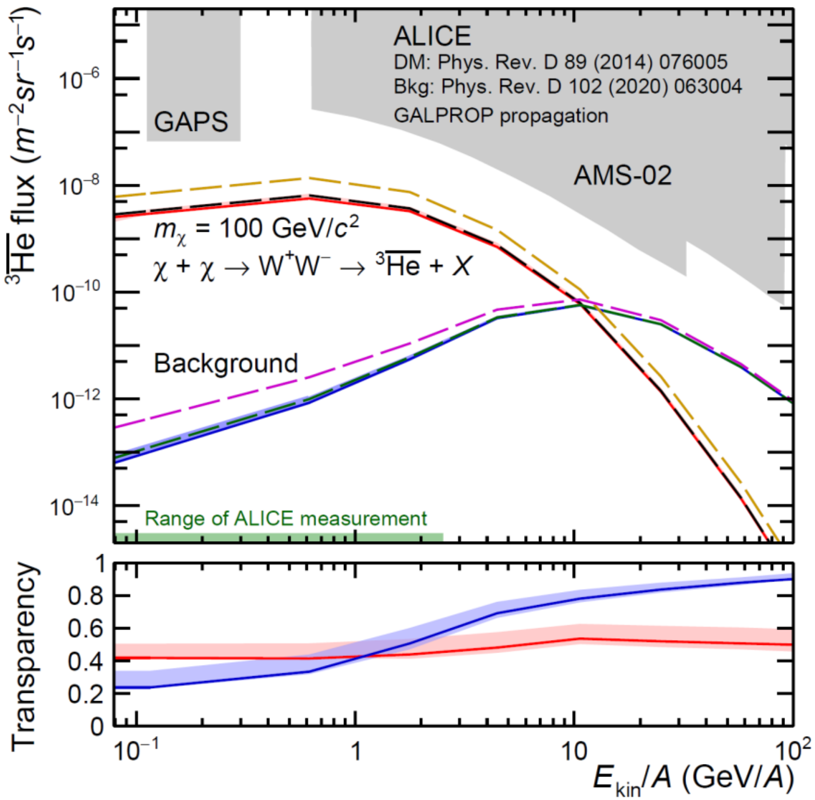


- Novel technique to use detector as an antiparticle absorber
- First experimental measurement of $\sigma_{inel}(^{3}\overline{He})$

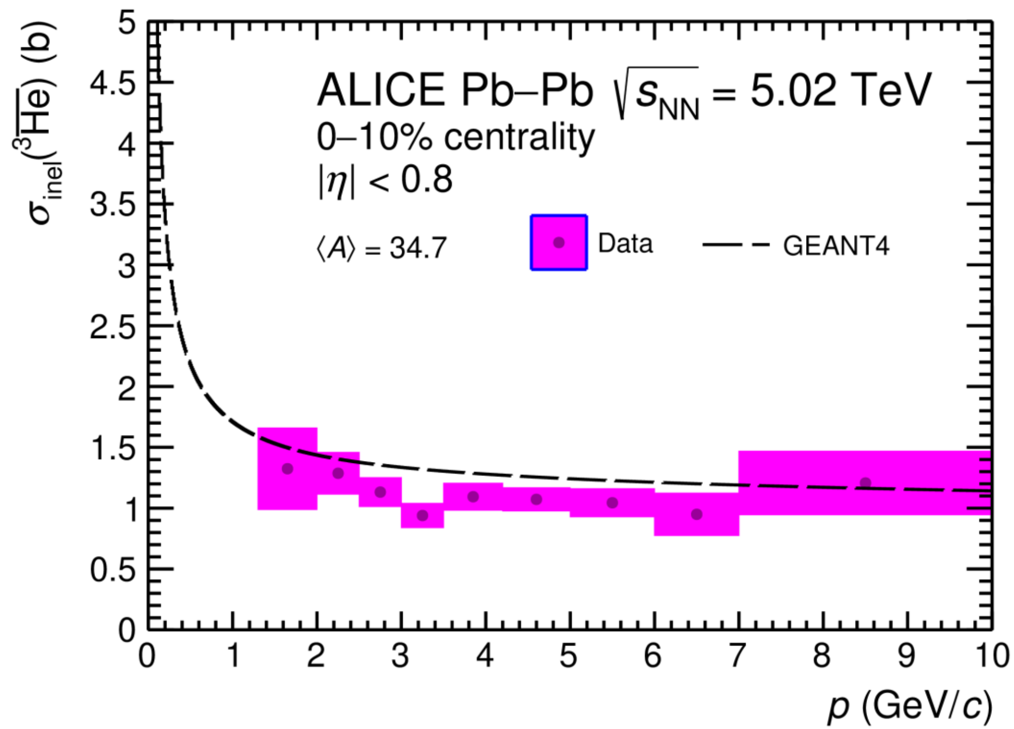


Light antinuclei absorption in ALICE and Galaxy

Nature Phys. 19 (2023) 1, 61-71



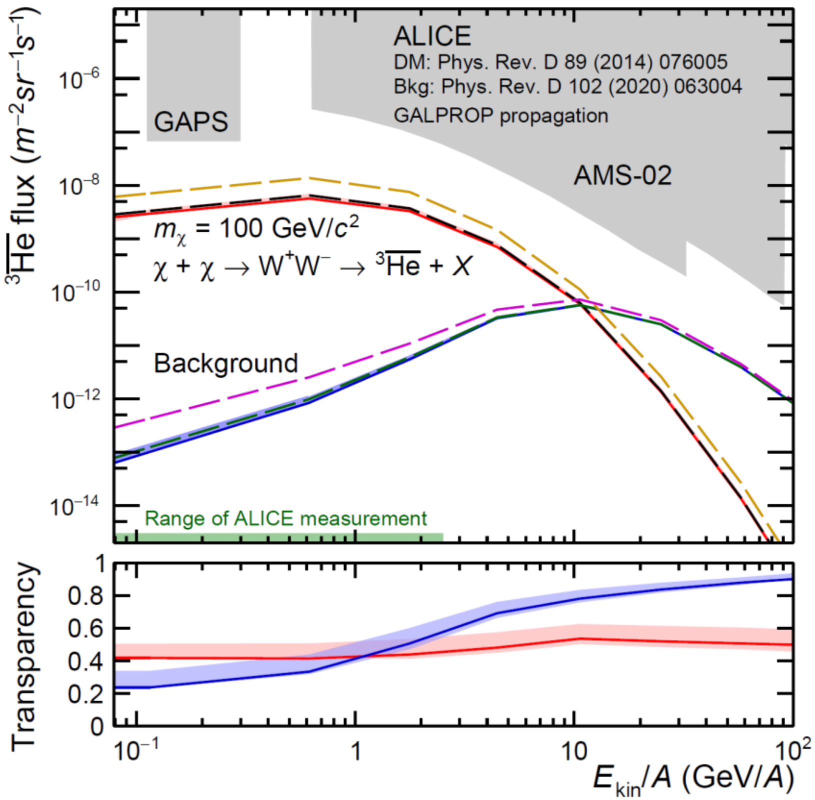
- Novel technique to use detector as an antiparticle absorber
- First experimental measurement of $\sigma_{inel}({}^3\overline{He})$



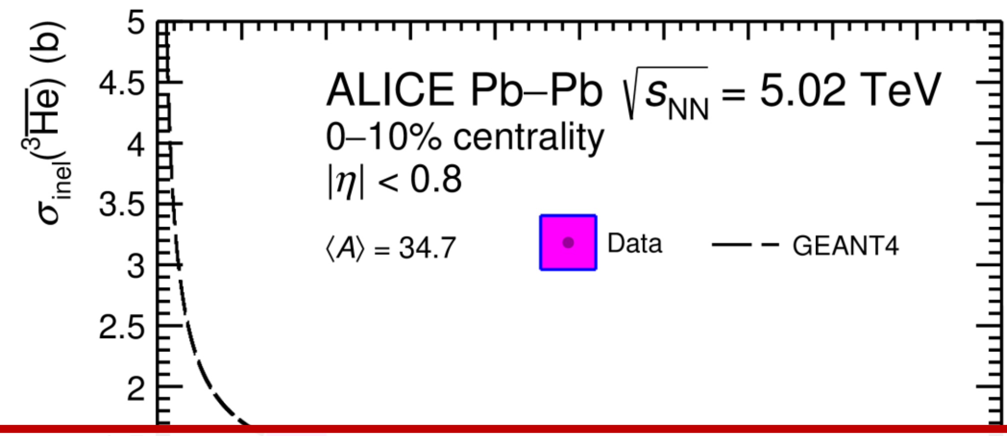
ALI-PUB-532048

Light antinuclei absorption in ALICE and Galaxy

Nature Phys. 19 (2023) 1, 61-71



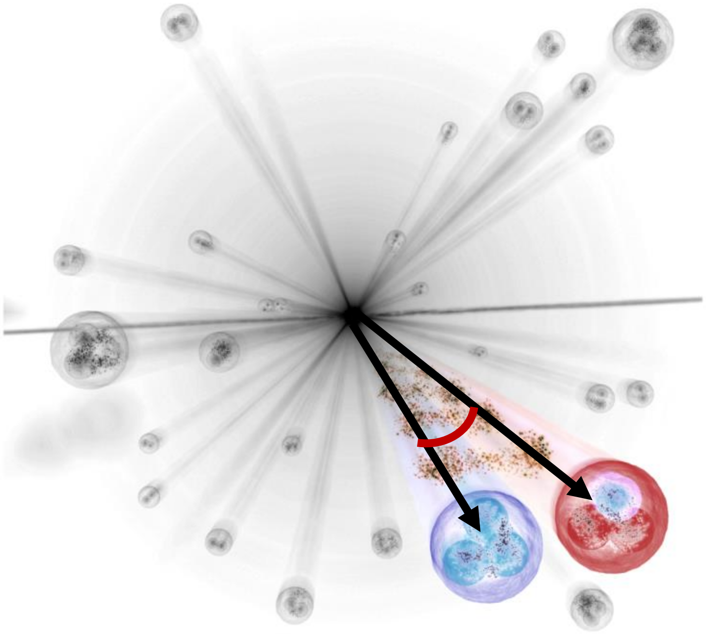
- Novel technique to use detector as an antiparticle absorber
- First experimental measurement of $\sigma_{inel}({}^3\overline{\mathrm{He}})$



→ measured $\sigma_{inel}({}^3\overline{\mathrm{He}})$ was employed to carry out the propagation of ${}^3\mathrm{He}$ using GALPROP
- can be used by for any dark-matter or cosmic-ray interaction modelling

→ ${}^3\overline{\mathrm{He}}$ nuclei can travel distances of several kpc in our galaxy without being absorbed
- excellent probe for new physics that awaits discovery

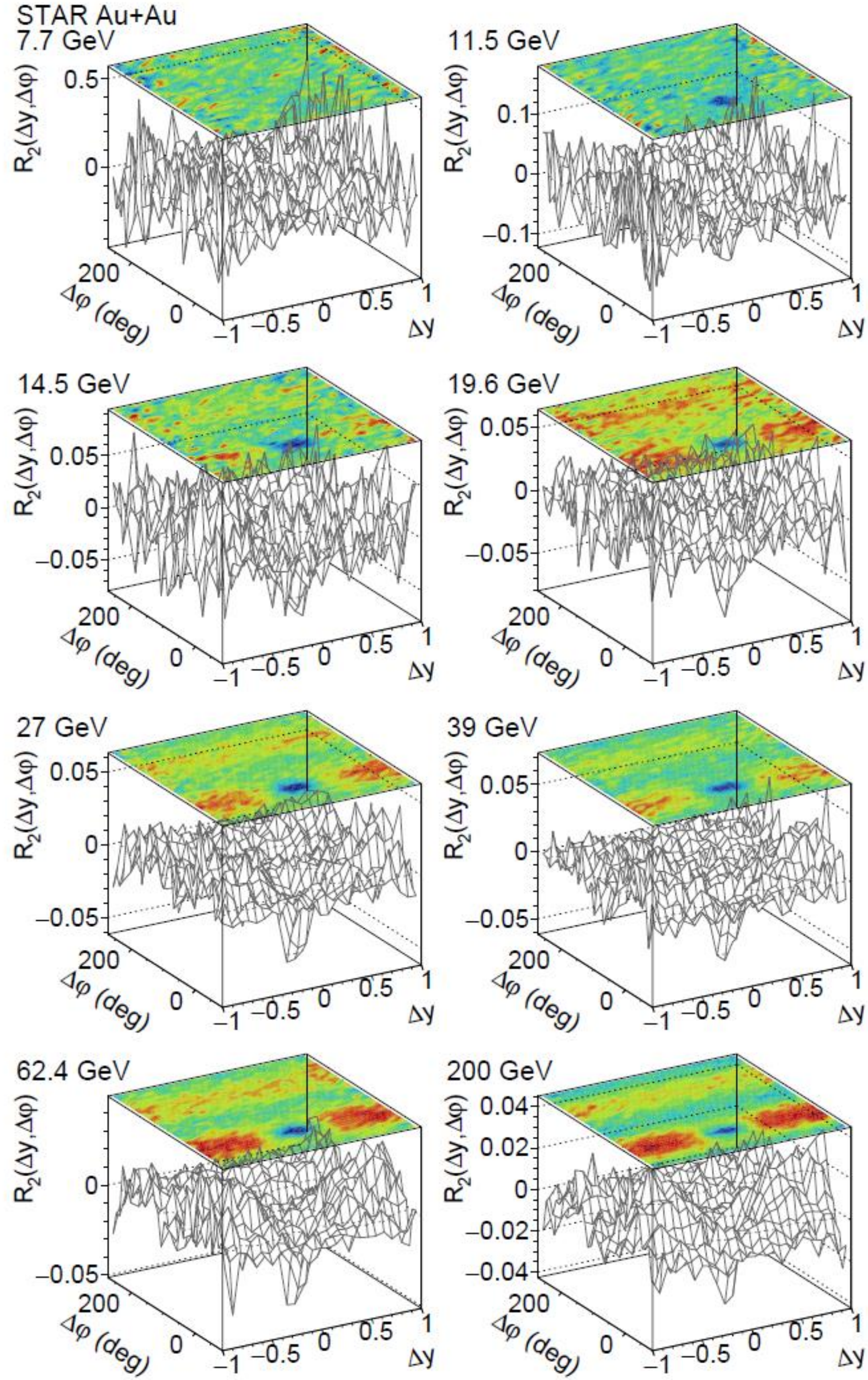
Annihilation in correlations?



Annihilation in correlations

- Angular correlations of proton-antiproton pairs in Au-Au at 7.7 – 200 GeV
- Anticorrelation (dip) in unlike-sign proton pairs on the near side in Δφ and at short range in Δy

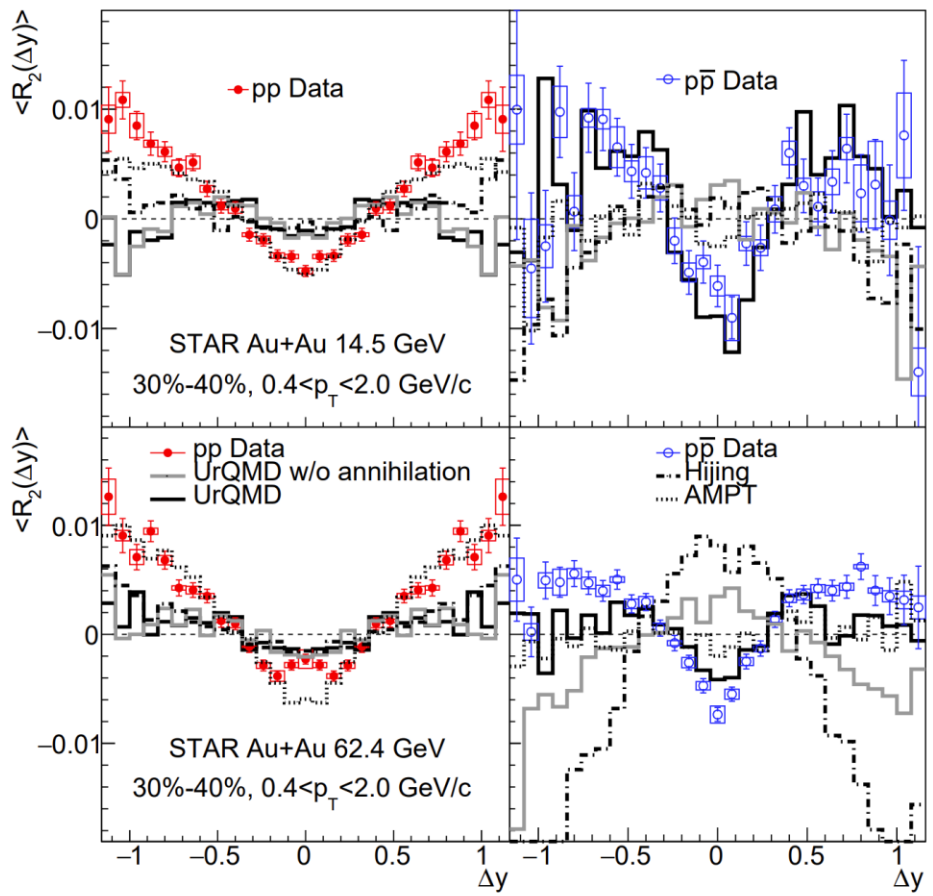
STAR, Phys. Rev. C 101, 014916 (2020)



Annihilation in correlations

STAR, Phys. Rev. C 101, 014916 (2020)

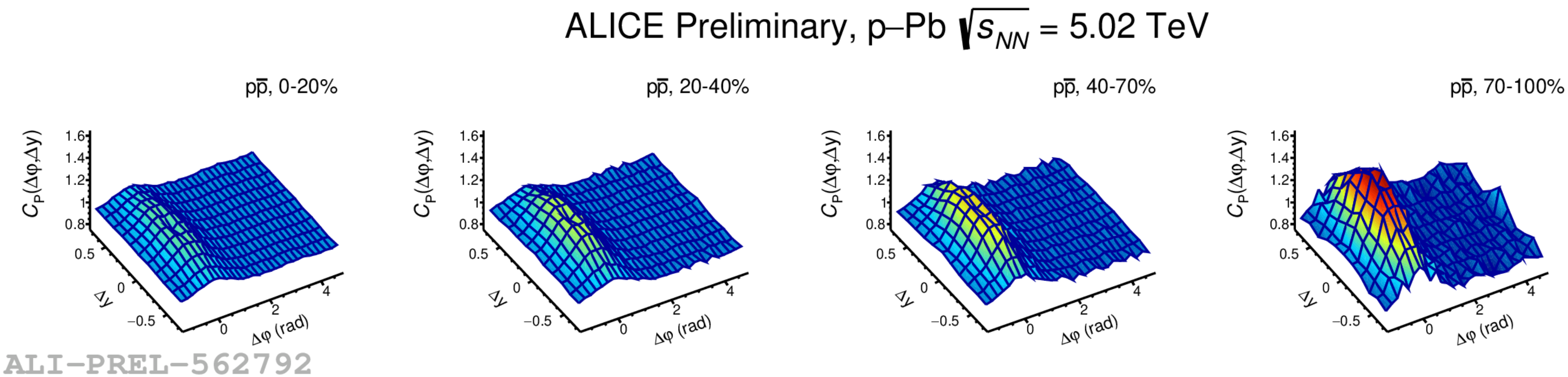
- Correlation functions were compared to several MC models, including UrQMD with and without annihilation
- The pp correlations from UrQMD with annihilation reproduce the data, while w/o it no longer reproduce the data near $\Delta y \sim 0$
- The anticorrelation in unlike-sign proton pairs on the near side in $\Delta\phi$ and at short range in Δy: annihilation effect



Not only heavy-ion effect

Baryon-antibaryon from ALICE in p-Pb

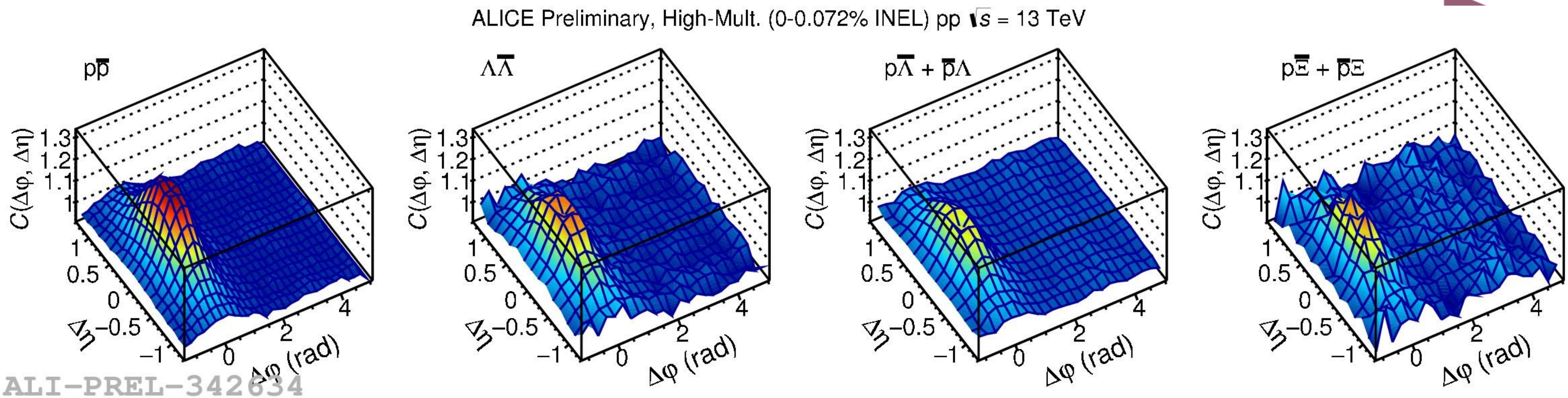
D. Ruggiano Thu 10:30



- Baryon-antibaryon correlations show dip in the (0,0) of the angular correlations distributions for all studied multiplicity classes

High-multiplicty pp

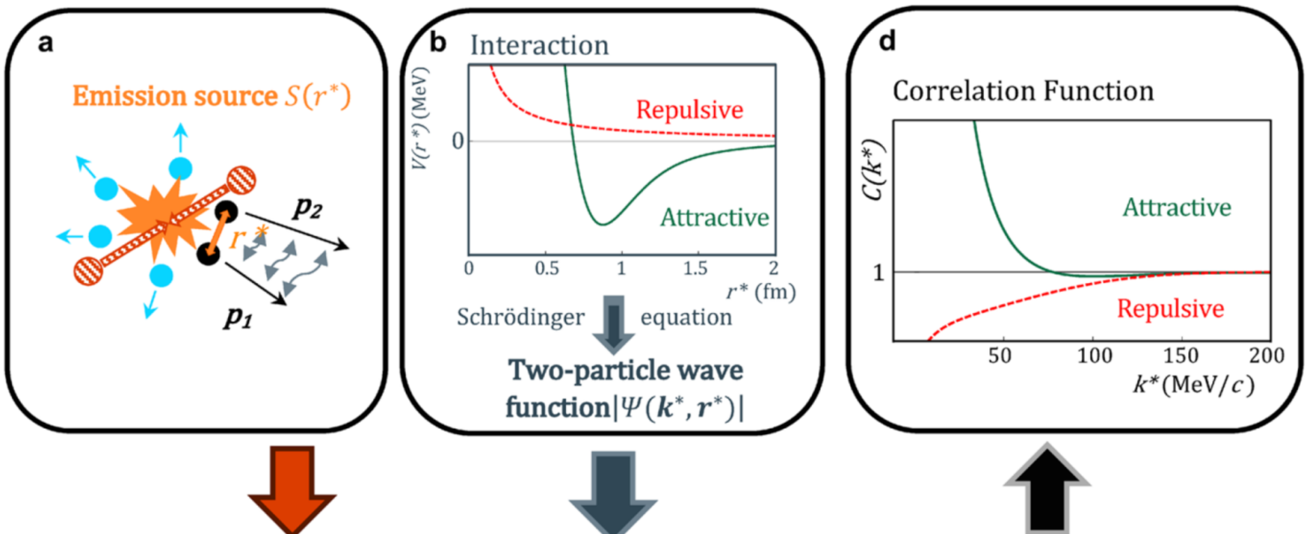
Baryon-antibaryon from ALICE

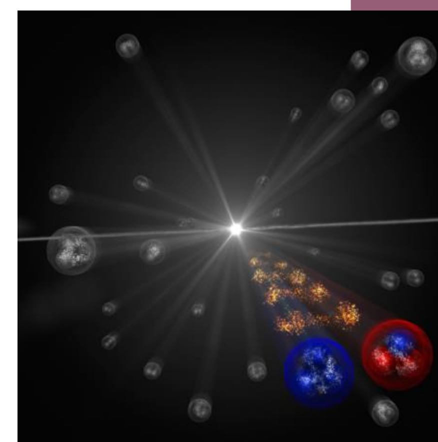


- All studied baryon-antibaryon pairs show dip in the (0,0) of the angular correlations distributions
- Annihilation of baryon-antibaryon pairs is significant for all systems (A-A, p-A, pp)

Femtoscopy measurement

Femtoscopic correlation function carry information about the particle source $S(r^*)$ from which pairs emerge, as well as the interaction potential via the two-particle wave function $\boldsymbol{\psi(k^*,r^*)}$.





c

unknown known

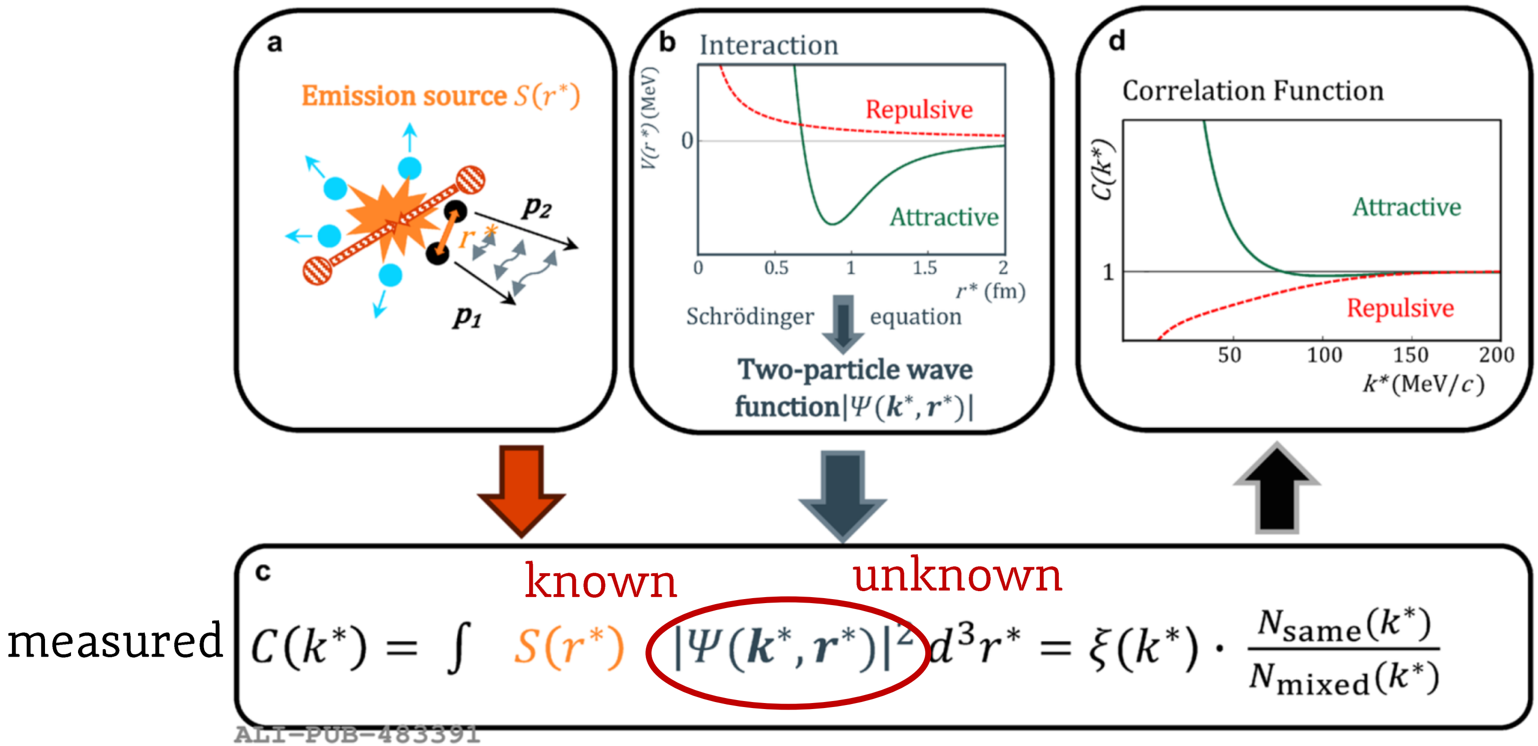
measured $$C(k^*) = \int S(r^*)\, |\Psi(\boldsymbol{k}^*,\boldsymbol{r}^*)|^2\, d^3r^* = \xi(k^*) \cdot \frac{N_{\mathrm{same}}(k^*)}{N_{\mathrm{mixed}}(k^*)}$$

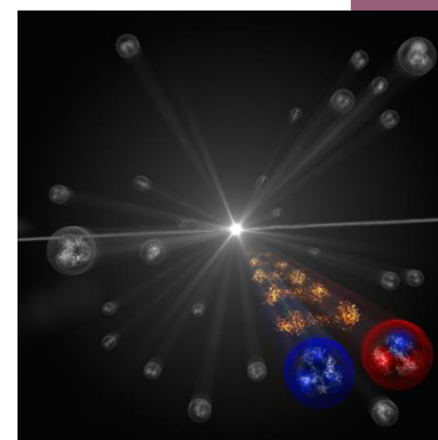
ALI-PUB-483391

If the interaction is well known we can study the source $S(r^*)$ by measuring correlation function C(k*)

Femtoscopy measurement

Femtoscopic correlation function carry information about the particle source $S(r^*)$ from which pairs emerge, as well as the interaction potential via the two-particle wave function $\boldsymbol{\psi(k^*,r^*)}$.





- We constrain the source S(r*) from pairs where interaction is known
- We can use femtoscopy to measure the interactions $\boldsymbol{\psi}$ between other particle species

Measurement of the interaction

in heavy-ion collisions

$$C(q)=\int S(r)|\Psi(q,r)|^2 d^4 r \qquad q=2\cdot k^*=p_1-p_2$$

measured correlation — emission function (source size/shape) — pair wave function (includes cross section)

pair wave function → $\Psi=\exp(-ik^*r)+f\dfrac{\exp(ik^*r)}{r}$ s-wave scattering approximation

scattering amplitude → $f^{-1}(k^*)=\dfrac{1}{f_0}+\dfrac{1}{2}d_0 k^{*2}-ik^*$ effective range approximation

- If only Strong FSI is present:

Lednicky equation

$$C(k^*)=1+\sum_S \rho_S\left[\frac{1}{2}\left|\frac{f^S(k^*)}{R}\right|^2\left(1-\frac{d_0^S}{2\sqrt{\pi}R}\right)+\frac{2\Re f^S(k^*)}{\sqrt{\pi}R}F_1(2k^*R)-\frac{\Im f^S(k^*)}{R}F_2(2k^*R)\right]$$

Sov. J. Nucl. Phys., 35, 770 (1982)

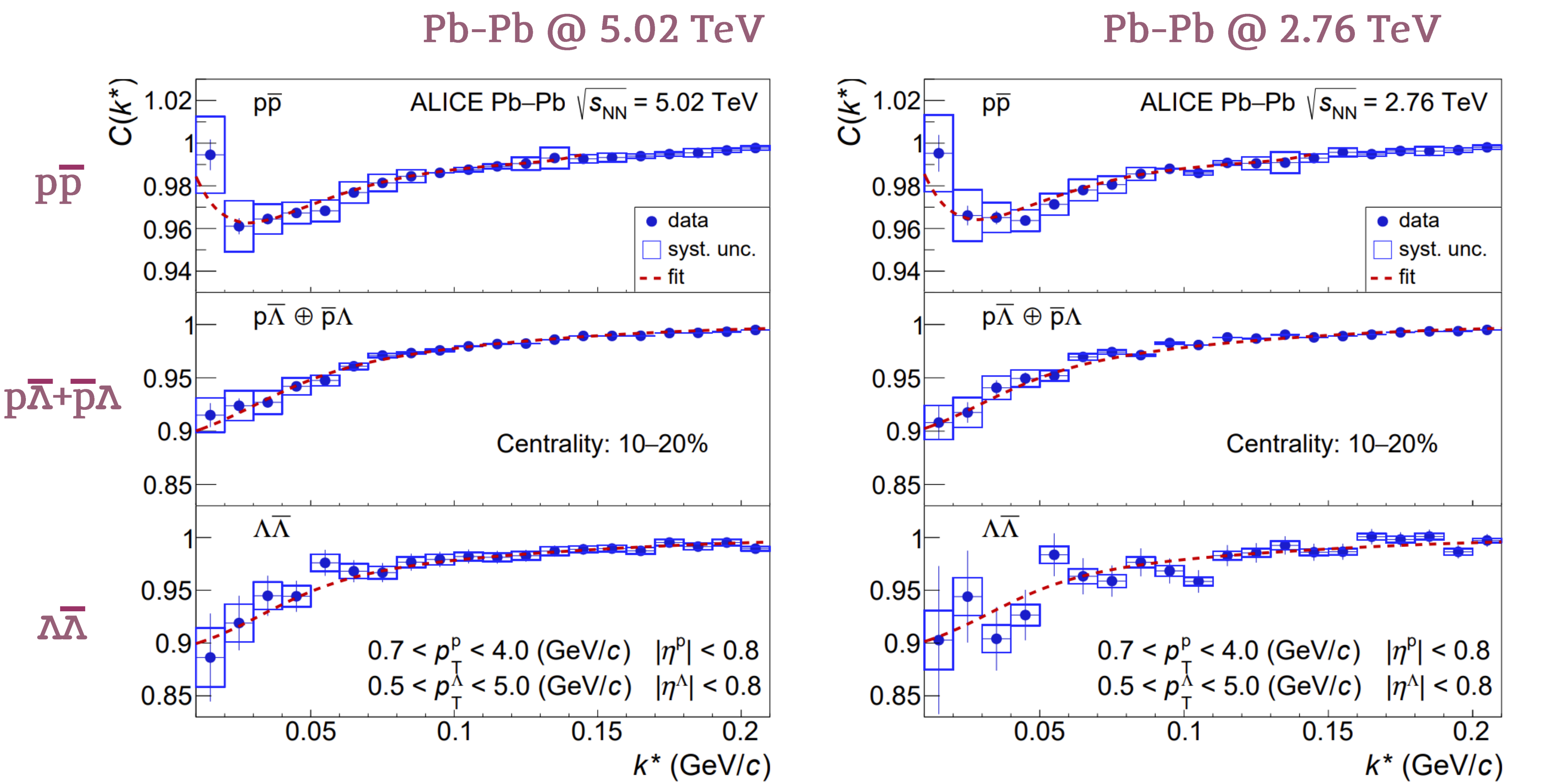
where ρ_S are the spin fractions

- The correlation function is characterized by **three parameters:**
  - **radius** R, **scattering length** f_0, and **effective radius** d_0
  - **cross section** σ **(at low** k^***)** is simply: $\sigma=4\pi|f|^2$

Baryon-antibaryon correlations

ALICE Collaboration measured baryon-antibaryon in Pb-Pb collisions

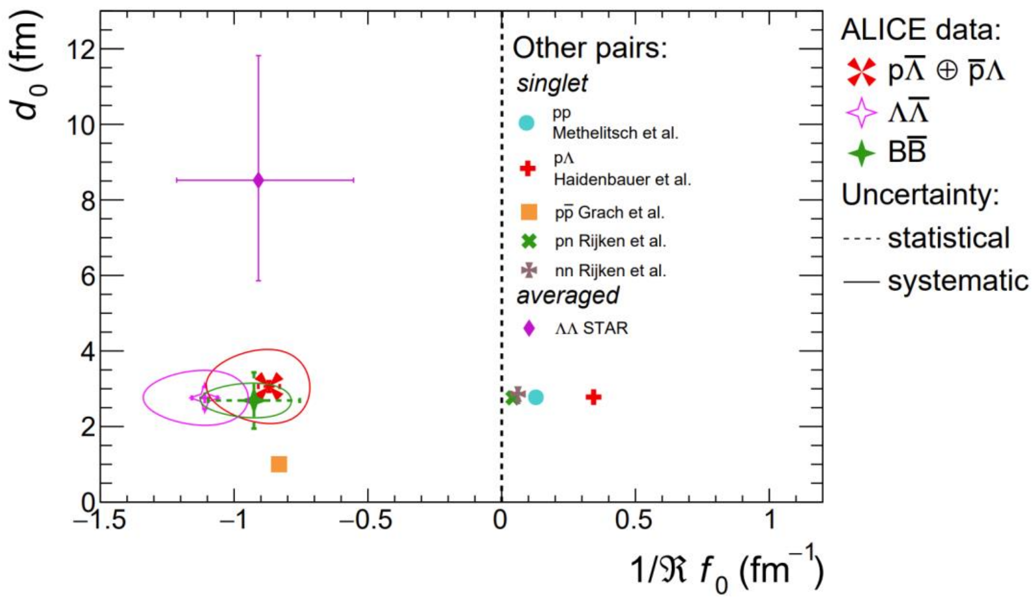
- Correlation functions measured for <u>two collision energies</u>
- $\Lambda\bar{\Lambda}$ correlations measured for the <u>first time</u> **PLB 802 (2020) 135223**
- Wide negative correlation (annihilation) seen for all pairs

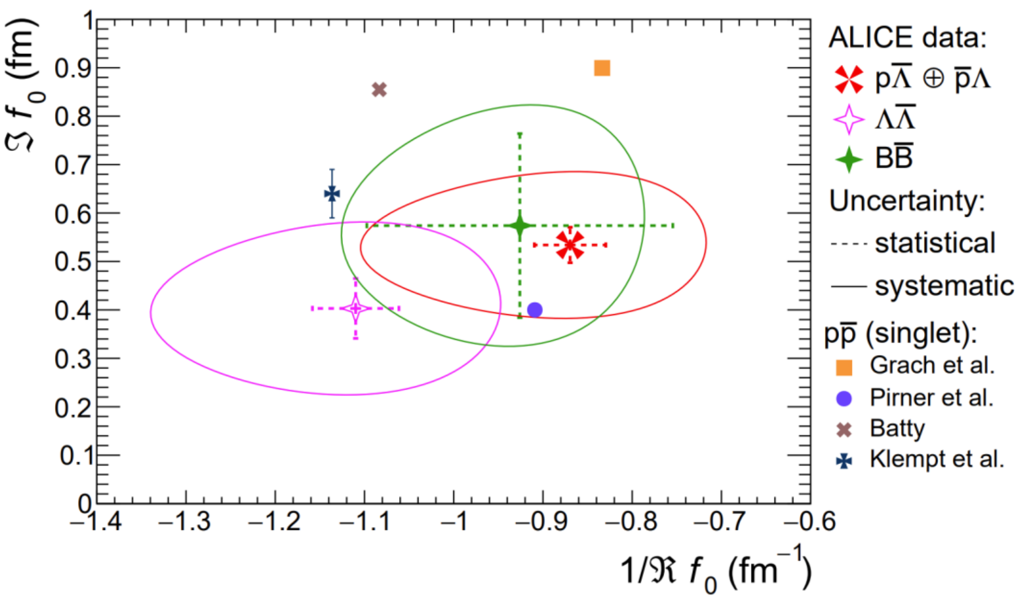


See also: STAR Collab. Phys. Rev. C, vol. 74, p. 064906, 2006.
A. Kisiel, H. Zbroszczyk, M. Szymański, Phys. Rev. C, vol. 89, p. 054916, May 2014.

Baryon-antibaryon correlations

PLB 802 (2020) 135223





Conclusions from fitting:

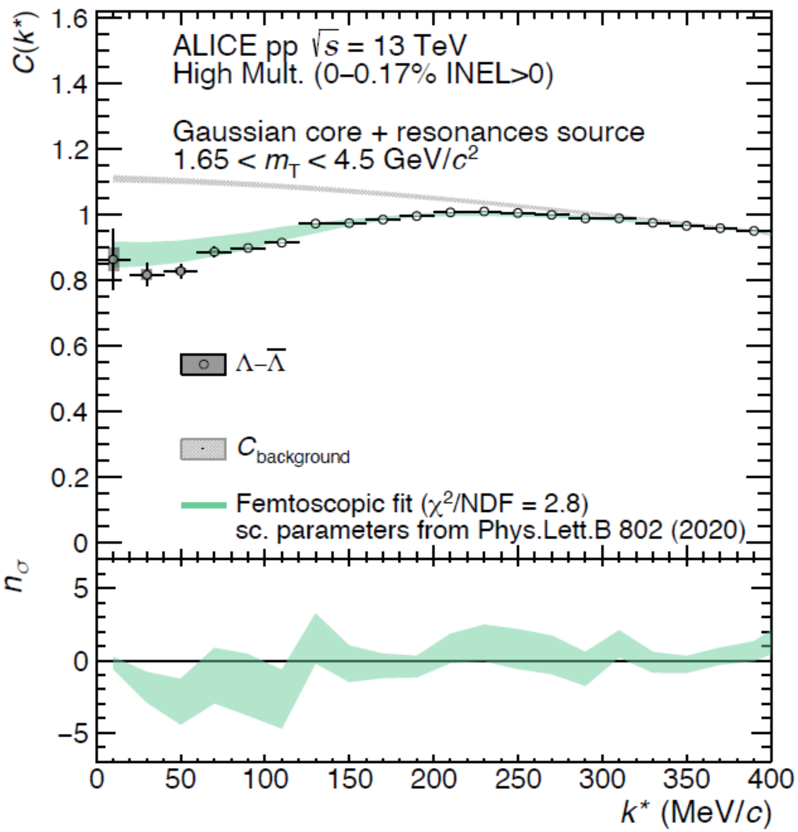
- Interaction parameters are measurable
- Scattering parameters for **all baryon-antibaryon pairs are similar to each other**
- Significant **positive imaginary part of scattering length** – presence of a non-elastic channel – annihilation
- We observe a **negative real part of scattering length** → repulsive strong interaction or creation of a bound state (existence of baryon-antibaryon bound states?)

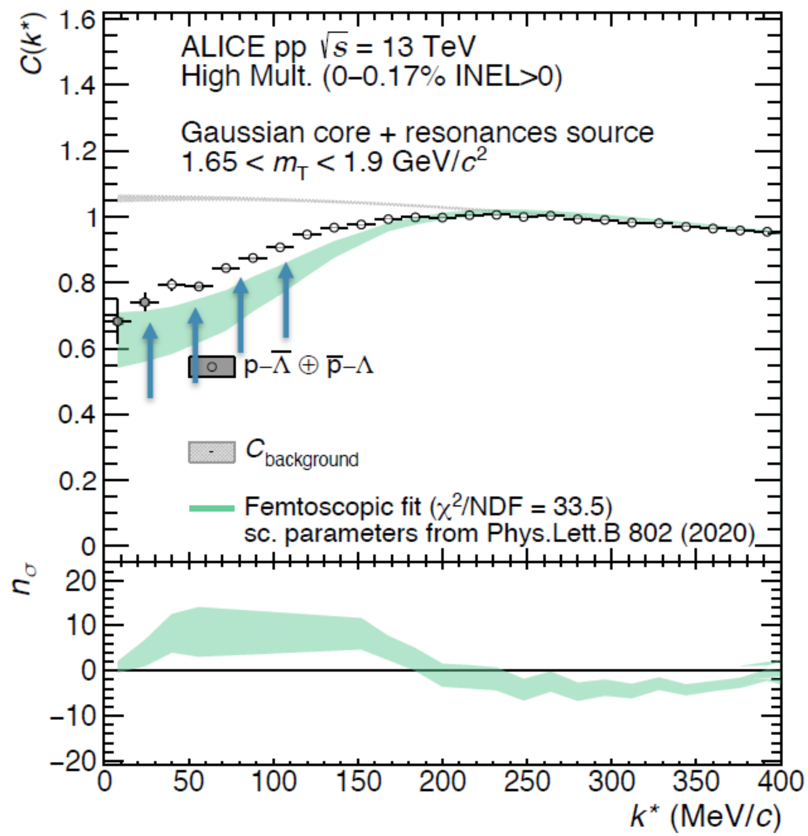
Baryon-antibaryon in pp

The analysis was repeated by ALICE in high-multiplicity pp collisions, and compared assuming the scattering parameters obtained in Pb–Pb:

- nice agreement with $\Lambda\bar{\Lambda}$ data
- underestimate of p–$\bar{\Lambda}$ data

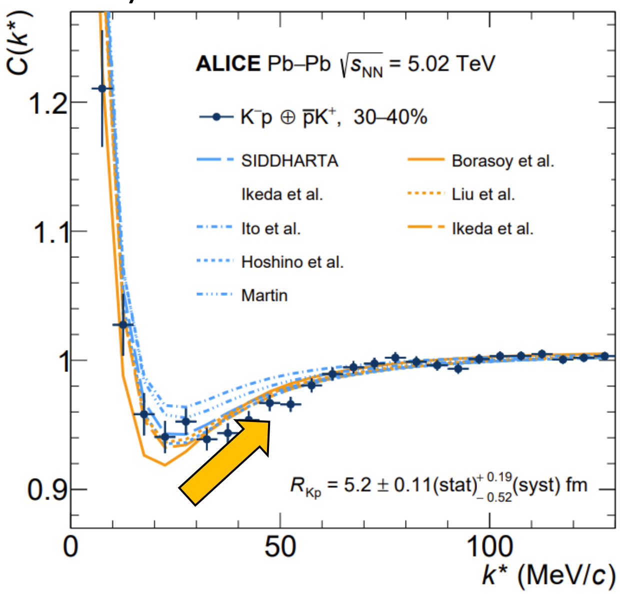
PLB 829 (2022) 137060



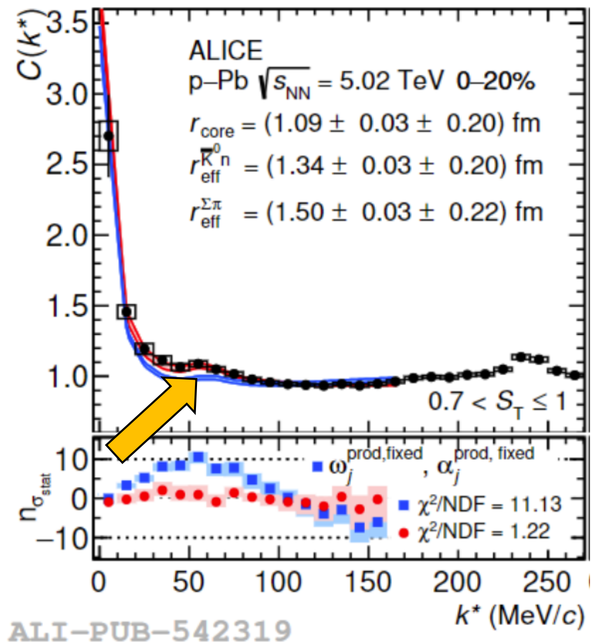


Appearance of coupled channels

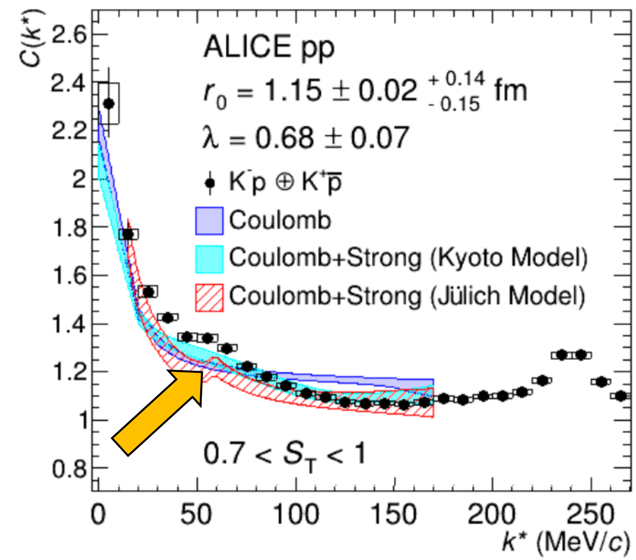
Phys. Lett. B 822 (2021) 136708

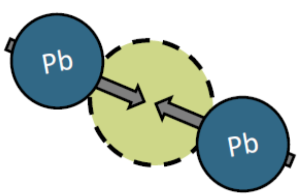


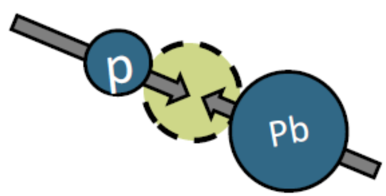
Eur. Phys. J. C 83 (2023) 340

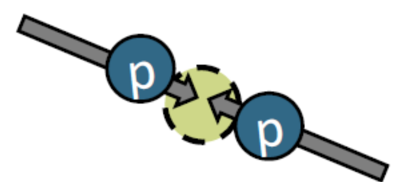


PRL 124, 092301 (2020)









- Appearance of coupled channel in K⁻p correlation function at k*~ 60 MeV/c **as the source decreases**
- Pb–Pb data well described by Lednicky single channel

Annihilation channels

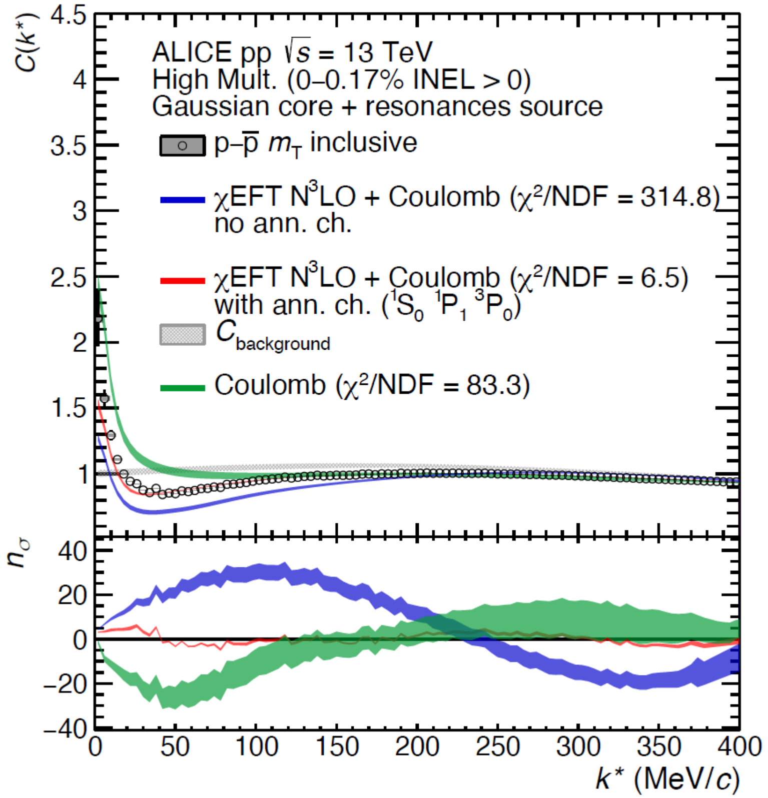
$$C_i(k^*) = \int d^3r^* S(r^*)|\psi_i(k^*,r^*)|^2 + \sum_{j\neq i}^{N} \omega_j \int d^3r^* S(r^*)|\psi_j(k^*,r^*)|^2$$

Correlation functions fitted with:
χEFT calculations with no explicit CC terms
do not reproduce the data at low k*

Approximate inclusion of annihilation channels ($X \rightarrow p\bar{p}$):

- using the Migdal-Watson approximation
- inclusion results in better agreement with the data

PLB 829 (2022) 137060



J. Haidenbauer et al. JHEP 1707 (2017)
D.Mihailov et al. Eur.Phys.J.C 78 (2018) 5, 394
Haidenbauer et al.,PRD 92 (2015) 5, 054032

Annihilation channels

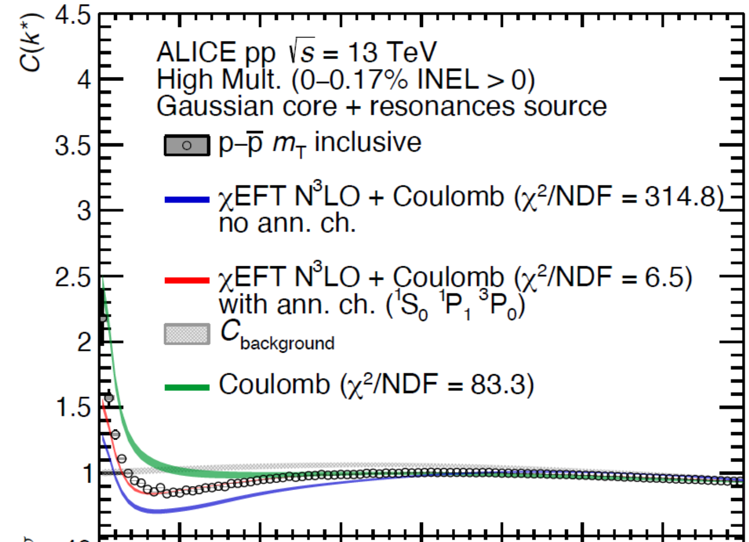
$$C_i(k^*) = \int d^3r^* S(r^*)|\psi_i(k^*,r^*)|^2 + \sum_{j\neq i}^{N} \omega_j \int d^3r^* S(r^*)|\psi_j(k^*,r^*)|^2$$

Correlation functions fitted with:
χEFT calculations with no explicit CC terms
do not reproduce the data at low k*

Approximate inclusion of annihilation channels ($X \rightarrow p\bar{p}$) :

- using the Migdal-Watson approximation
- inclusion results in better agreement with the data

PLB 829 (2022) 137060



Conclusions:

→ Large presence of annihilation channels feeding to $p\bar{p}$
→ Large contribution of these channels is observed also for $p\bar{\Lambda}$, while a negligible amount is present for $\Lambda\bar{\Lambda}$
→ The correlation function shows a large sensitivity to inelastic contributions as the source size decreases
→ Measurements of the same pair in different colliding systems can provide additional constraints on the elastic and inelastic interaction

Summary

- The nature of the strong interaction between particles is a fundamental problem in various areas of nuclear physics and astrophysics
    - detailed knowledge of the effective interaction among hadrons is still an open issue
- Tools to address:
    - Scattering experiments, hadronic atoms
    - Probing annihilation cross-sections with detector as a target
    - Annihilation in angular correlations
    - Femtoscopy as a tool to study matter-antimmater interactions

THANK YOU!

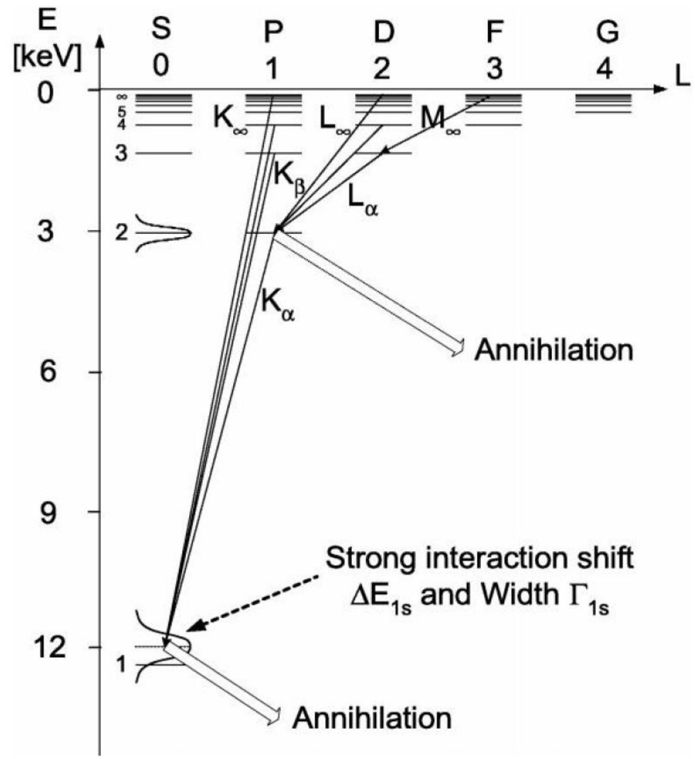
Backup

Scattering experiments & hadronic atoms

So far, the most precise data on antinucleon-nucleon interaction come from the Low Energy Antiproton Ring (LEAR) of CERN scattering experiments.

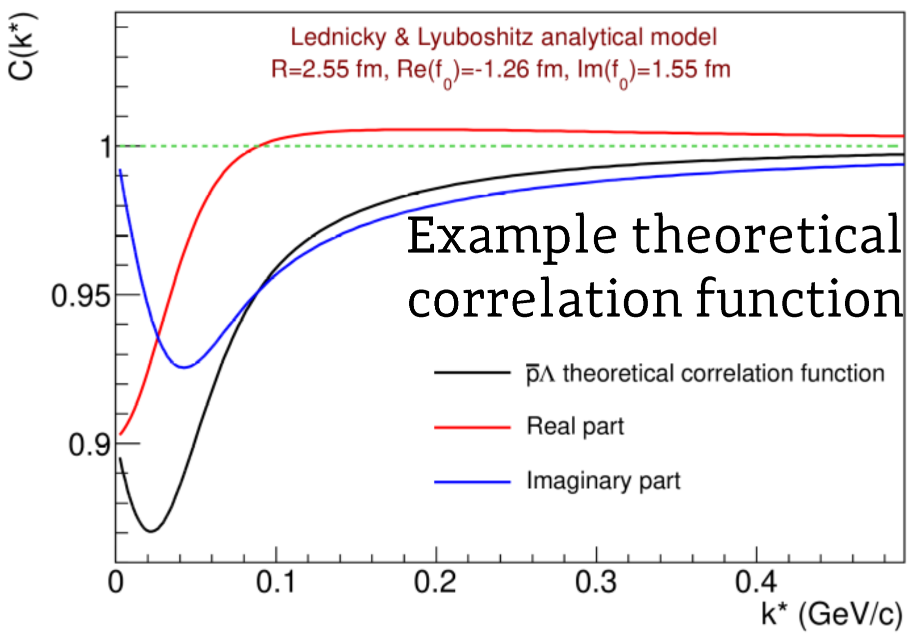
Its properties can be studied by measuring the X-ray emission spectrum from the excited states to the ground state.

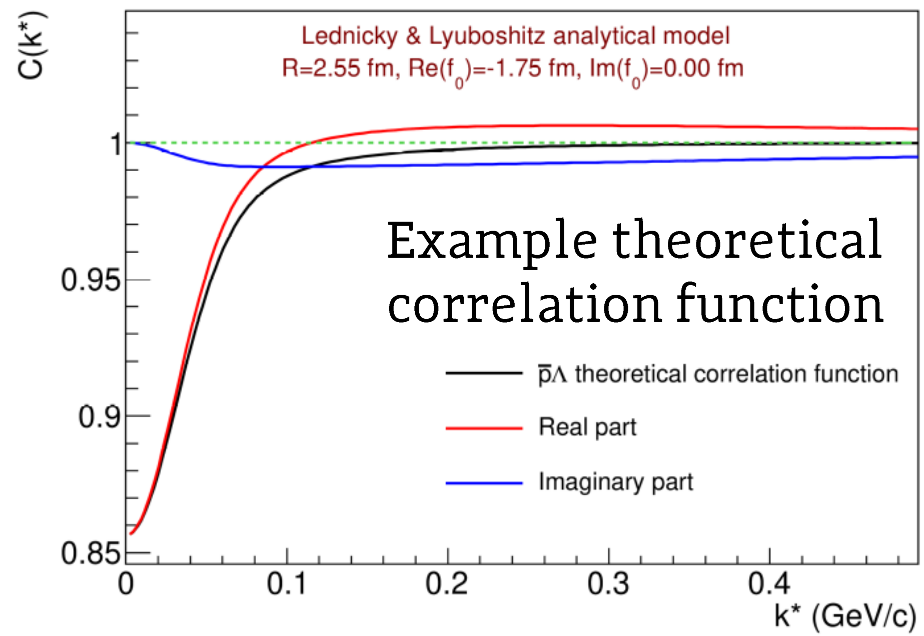
In this domain **protonium** (or antiprotonic hydrogen, denoted by the Pn symbol) is of a significant importance. It is a Coulomb bound state. One of the remaining open questions is whether protonium in the ground state can be considered



AD experiments can measure protonium properties in more detail.
Included in the measurement plans of AEgIS (now in the process of studying positronium, see [https://arxiv.org/abs/2310.08760])

Baryon-antibaryon correlations





- Real and imaginary part of scattering length have **distinctively different contributions**
- Contribution from $Re(f_0)$ is either positive or negative but **very narrow** (up to 100 MeV/c) in k^*
- The $Im(f_0)$ accounts for baryon-antibaryon annihilation and produces a **wide** (hundreds of MeV) **negative correlation**

Antimatter

- In **1928**, British **physicist Paul Dirac** wrote down an equation that combined quantum theory and special relativity to describe the behavior of an electron moving at a relativistic speed.
- **Discovery of the positron by Anderson in 1932** while studying showers of cosmic particles in a cloud chamber.
- The **Bevatron (LBNL) discovers** the **antiproton** in **1955**.
- Antiproton cross-sections measured in 1955 showed that the **annihilation part is much larger than the elastic one** for low antiproton momenta.