Overview of STAR's Results of Anti/Hyper/Exotic-matter Measurements

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U.S. DEPARTMENT OF ENERGY

Office of Science
U.S. DEPARTMENT OF ENERGY

BROOKHAVEN NATIONAL LABORATORY

STAR

Aihong Tang, CERN, July 19-23 2015

Outline

- Advantages of RHIC/STAR
- STAR's programs of anti/hyper/exotic-matter study
- Summary

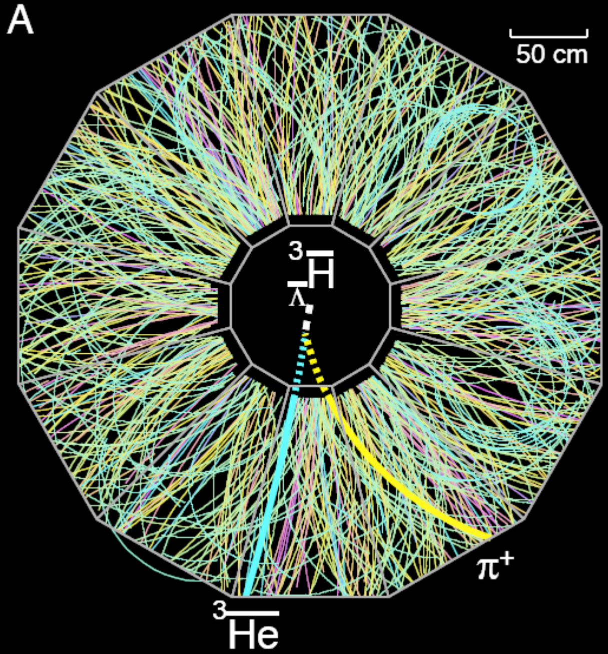
RHIC is Flexible

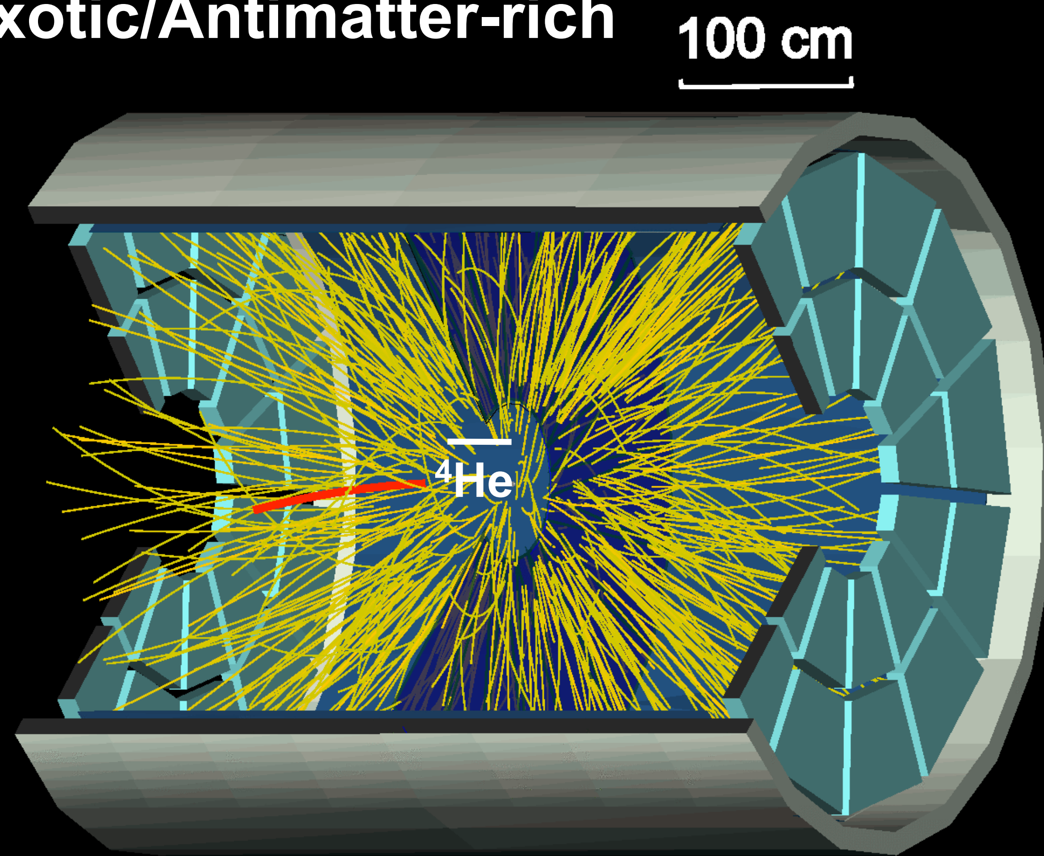
C.M. Energy per nucleon pair (GeV)	Collision Species
500/150	Polarized p+p
200	Polarized p+p, Au+Au, d+Au, Cu +Cu,Cu+Au, p+Au, He3+Au, p+Al
193	U+U
62.4	Polarized p+p, Au+Au, Cu+Cu
22.4	Cu+Cu
7.7,9.2,11.5,14.5,19.6,22.4,27, 39,130	Au + Au

RHIC is Bright

- Annual integrated luminosity p+p equivalent: ~ 0.1 fb^{-1}
- Au+Au collisions to tape in 2014 : STAR : ~ 5 billion
- Annual particles to tape: > 10^{12}

RHIC is Exotic/Antimatter-rich

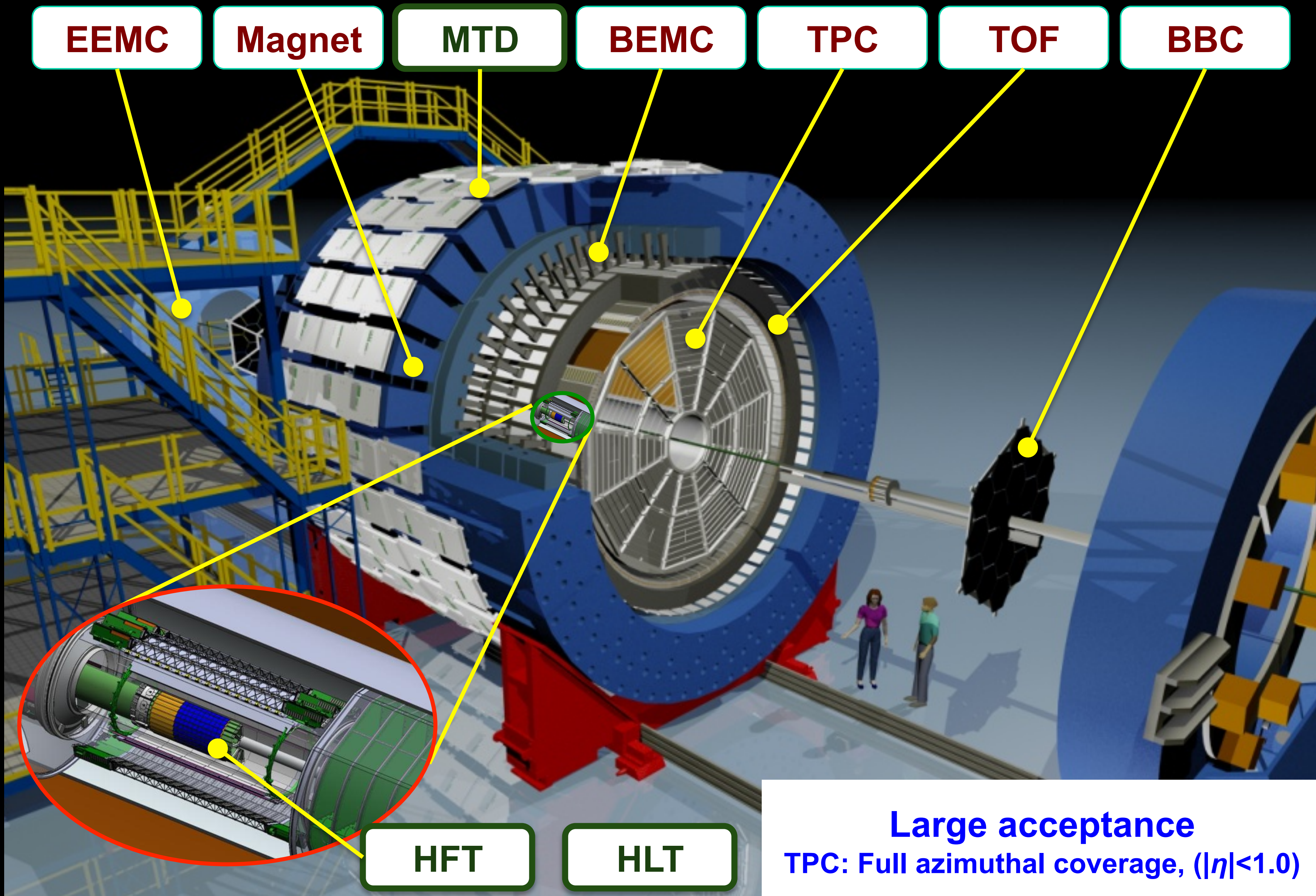




STAR, *Science* **328**, 58 (2010)

STAR, *Nature* **473**, 353 (2011)

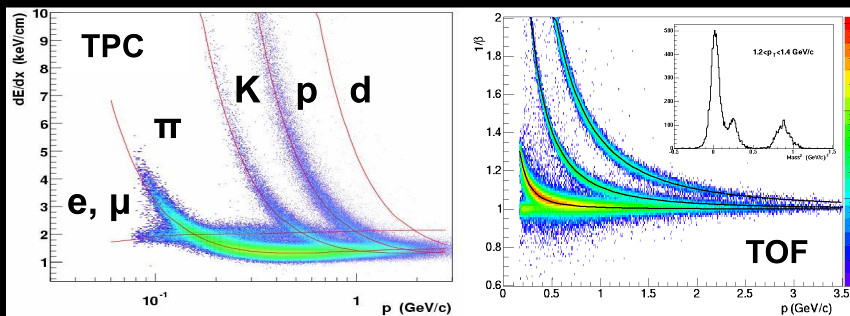
STAR : Uniform and Large Acceptance



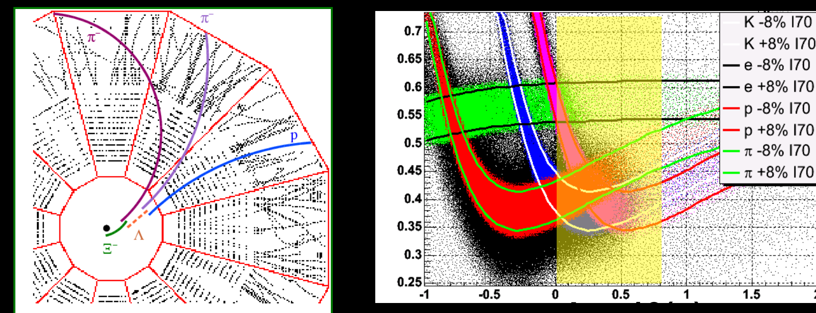
Large acceptance

TPC: Full azimuthal coverage, (|η|<1.0)

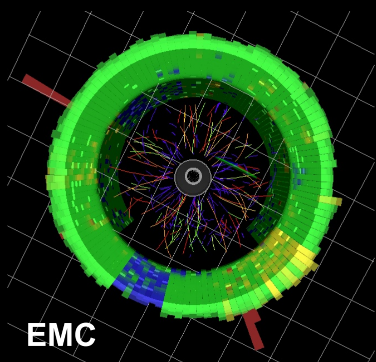
STAR : Excellent PID and Tracking



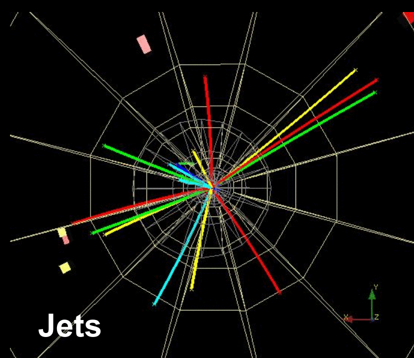
Charged hadrons



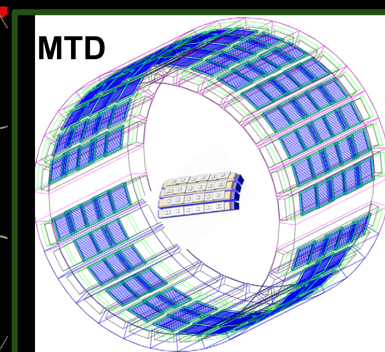
Hyperons & Hyper-nuclei



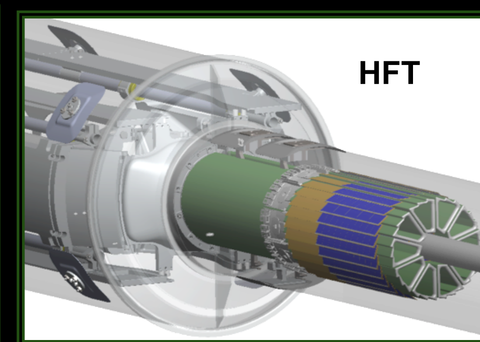
Neutral particles



Jets & Correlations



High pT muons



Heavy-flavor hadrons

Efforts at STAR

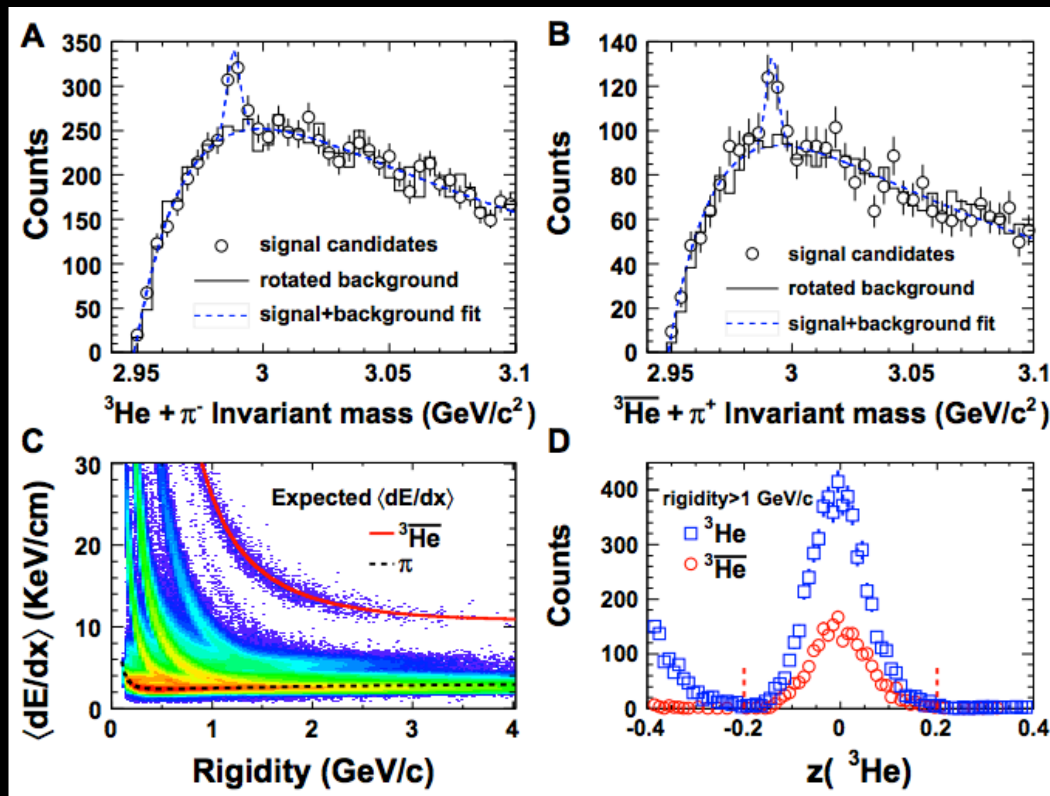
Understand the Y-N interaction
- (anti)hypertriton lifetime, 3-body decay

Push the boundary of standard model
- Strangelets and Dibaryons

Understand the fundamental force that binds antinuclei
- Measurement of interaction between antiprotons

Atom/parton chemistry
- Muonic Atoms
- Glueball

(anti)hypertriton : previous result

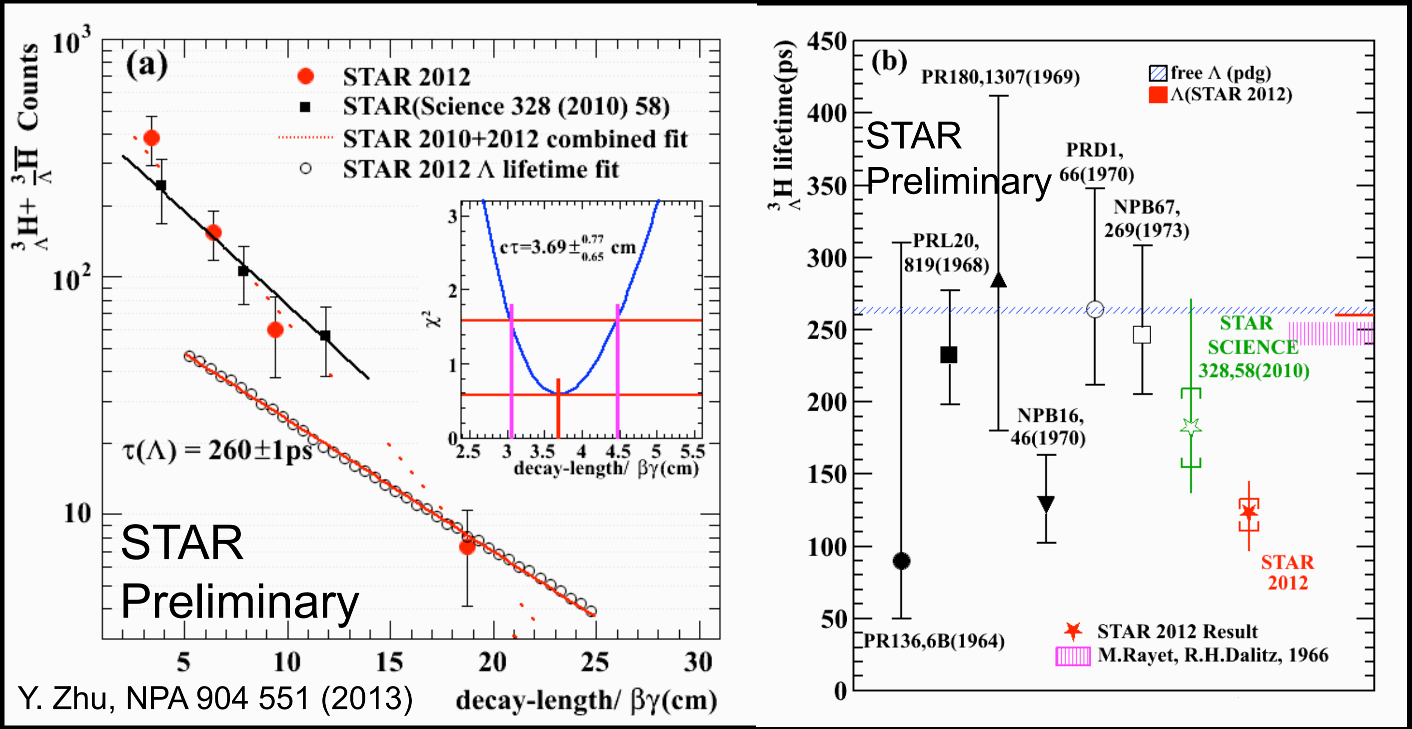


STAR, *Science* 328, 58 (2010)

$$^{3}_{\Lambda}H \rightarrow {}^{3}He + \pi^{-}$$

$$^{3}_{\overline{\Lambda}}\overline{H} \rightarrow {}^{3}\overline{He} + \pi^{+}$$

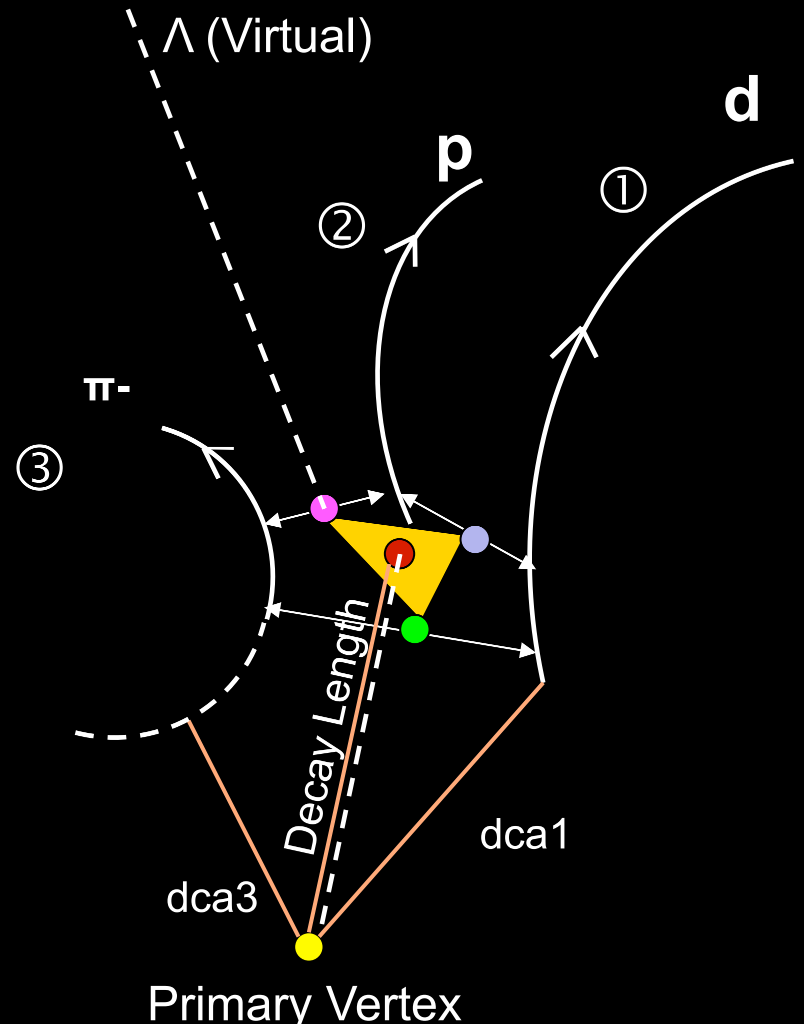
(anti)hypertriton : improved lifetime measurement with large statistics



Y. Zhu, NPA 904 551 (2013)

A precise determination of the lifetime of hypernuclei provides direct information on the YN interaction strength.

(anti)hypertriton : 3-body decay

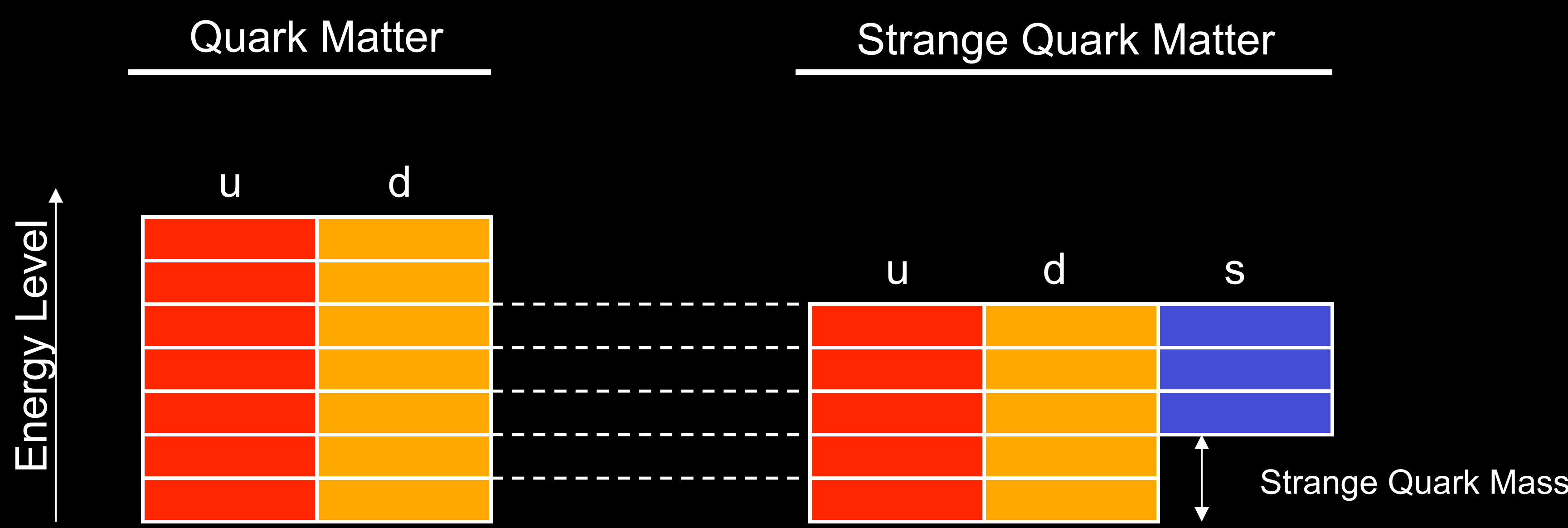


$$ {}^{3}_{\Lambda}H \rightarrow d + p + \pi^{-} $$

- v012 : Mid-point of DCA 1 to 2
- v023 : Mid-point of DCA 2 to 3
- v013 : Mid-point of DCA 1 to 3
- v0123 : Centre of gravity of the triangle

Ongoing effort of reconstructing (anti)hypertriton via 3-body decay

Strange Quark Matter



The addition of strange quarks to the system allows the quarks to be in lower energy states despite the additional mass penalty

The H^0-Dibaryon

Strangelet

6 quark-bag bound state (uuddss)

$m_{H0} < 2m_{\Lambda} = 2231$ MeV

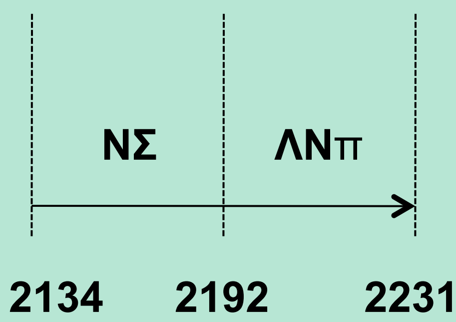
Stable against strong decay but not against weak hadronic decay

$\tau = 10^{-8}$-10^{-10} s

(R. Jaffe PRL 38 195 (1977), Donoghue'86 …)

Decay mode :

Mass threshold (MeV)



Hadronic Counterpart

$(\Lambda\Lambda)_b$

Other dibaryons might exist as bound states made by coalescence of 2 strange baryons

(Schaffner-Bielich et al PRL 84 (2000) …)

Decay length ~ 1-5cm

$(\Lambda\Lambda)_b \rightarrow \Lambda + p + \pi$ } dN/dy~10^{-2}-10^{-3}/event

$\rightarrow \Sigma^- + p$

$(\Sigma^+ p)_b \rightarrow p + p$

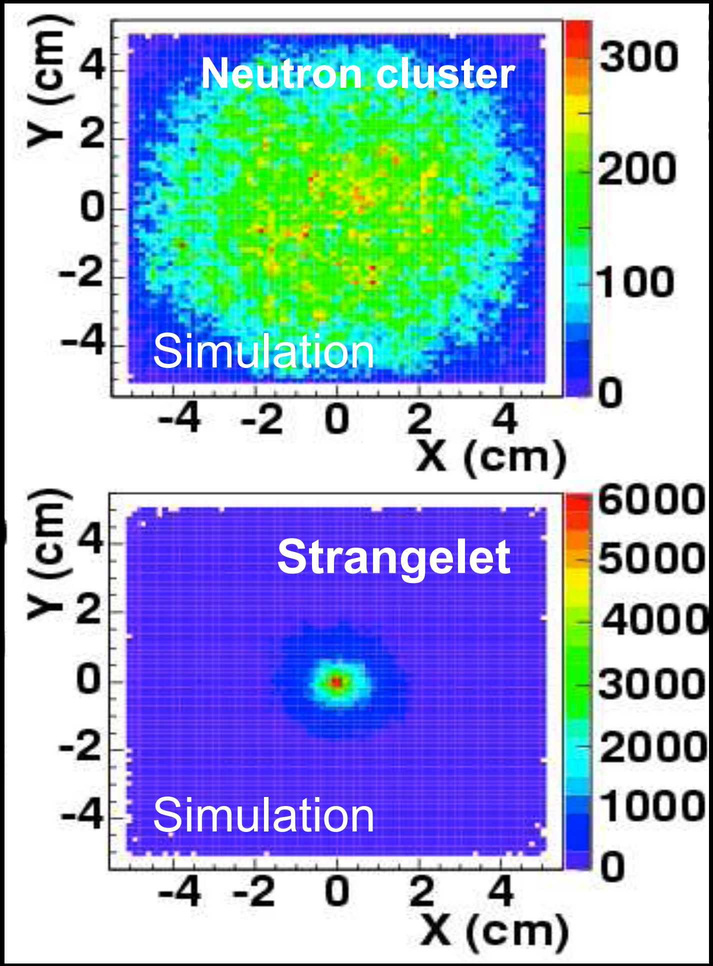
$(\Xi^0 p)_b \rightarrow \Lambda + p$

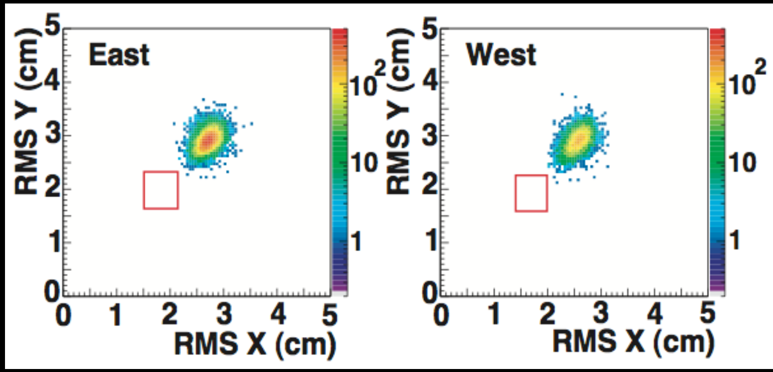
$(\Xi^0 \Lambda)_b \rightarrow \Lambda + \Lambda$

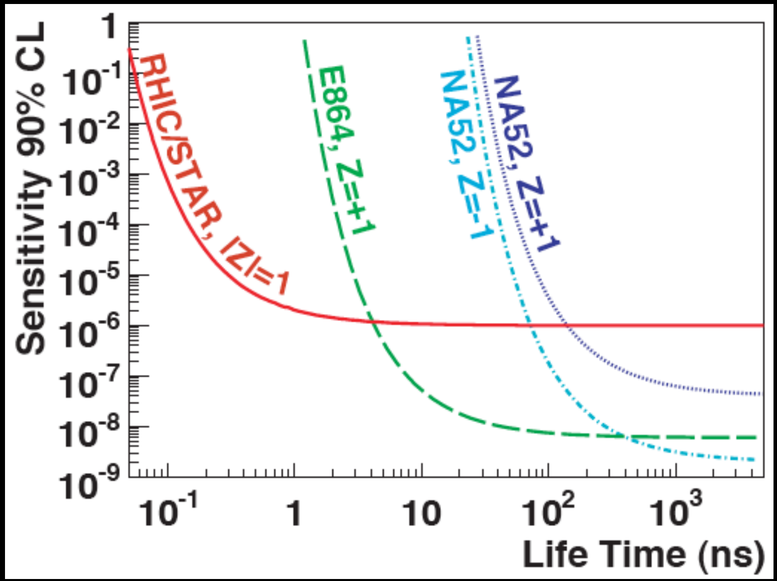
$\rightarrow \Xi^- + p$

} dN/dy~10^{-3}/event

Previous Search for Strangelet, in Forward Region

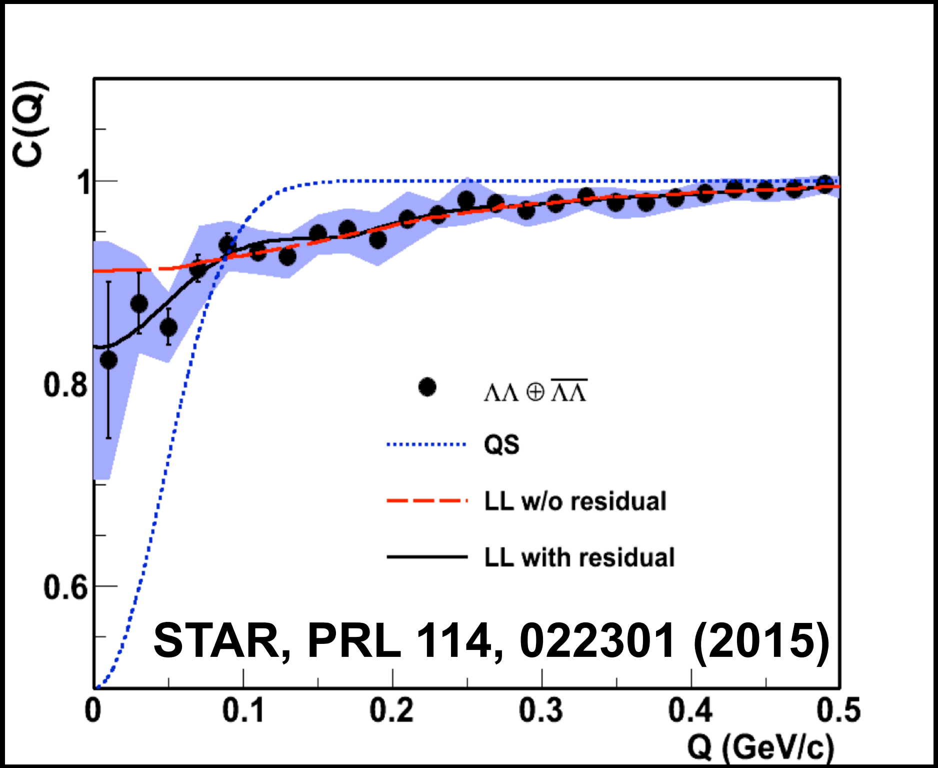






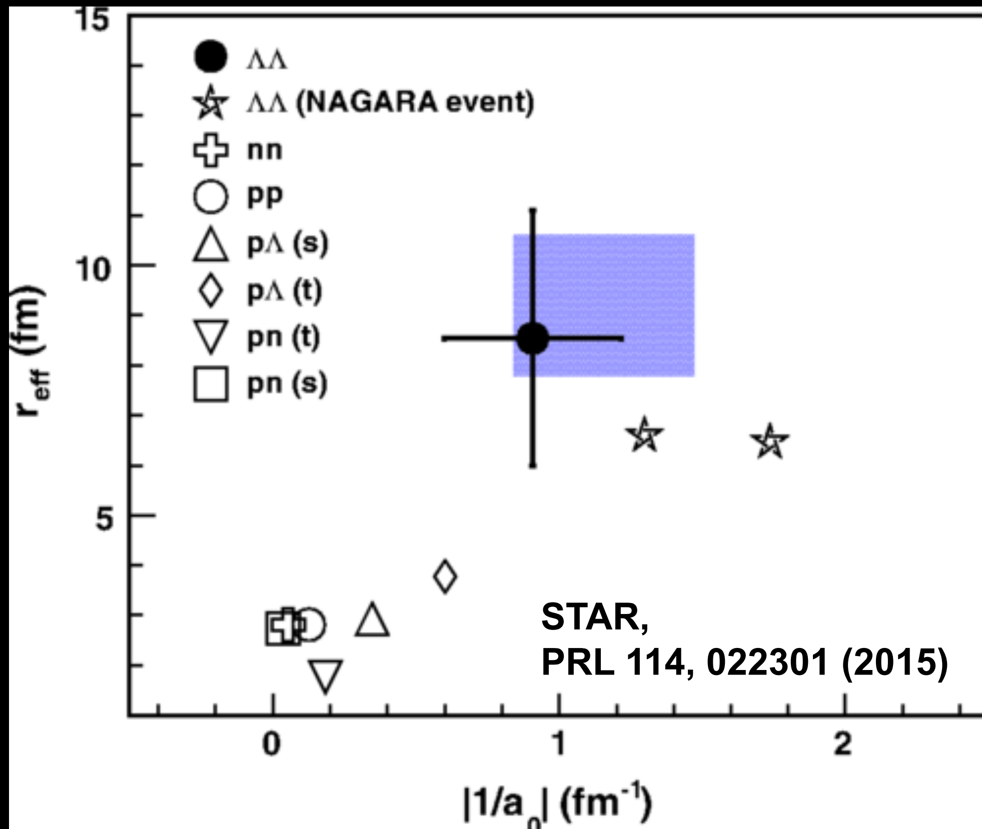
STAR, PRC 76, 011901 (2007)

Search for H^0-Dibaryon at midrapidity



Hyperon-Hyperon interaction is one of the key quantities to understand the dense matter EOS, of interest to astrophysicists

Search for H^0-Dibaryon at midrapidity



$$a_0 = -1.10 \pm 0.37^{+0.68}_{-0.08}\, fm$$
$$r_{eff} = 8.52 \pm 2.56^{+2.09}_{-0.74}\, fm$$

ΛΛ interaction parameters measured.
The sign of effective range ($d_0=r_{eff}$) and scattering length ($f_0=-a_0$) indicates no existence of a ΛΛ resonance saturating the s-wave .

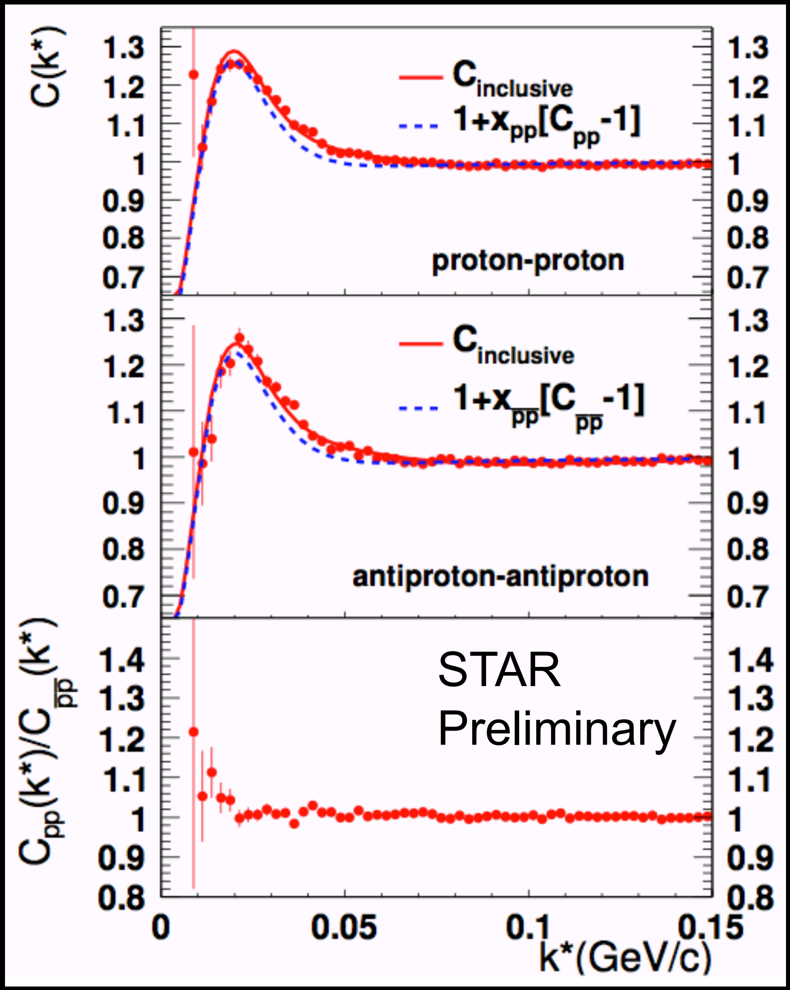
Measurement of interaction between antiprotons

• Understanding the force between nucleons is a necessary step for understanding the structure of nuclei and how nuclei interact with each other

• Not much is known about the nuclear force between antinucleons.

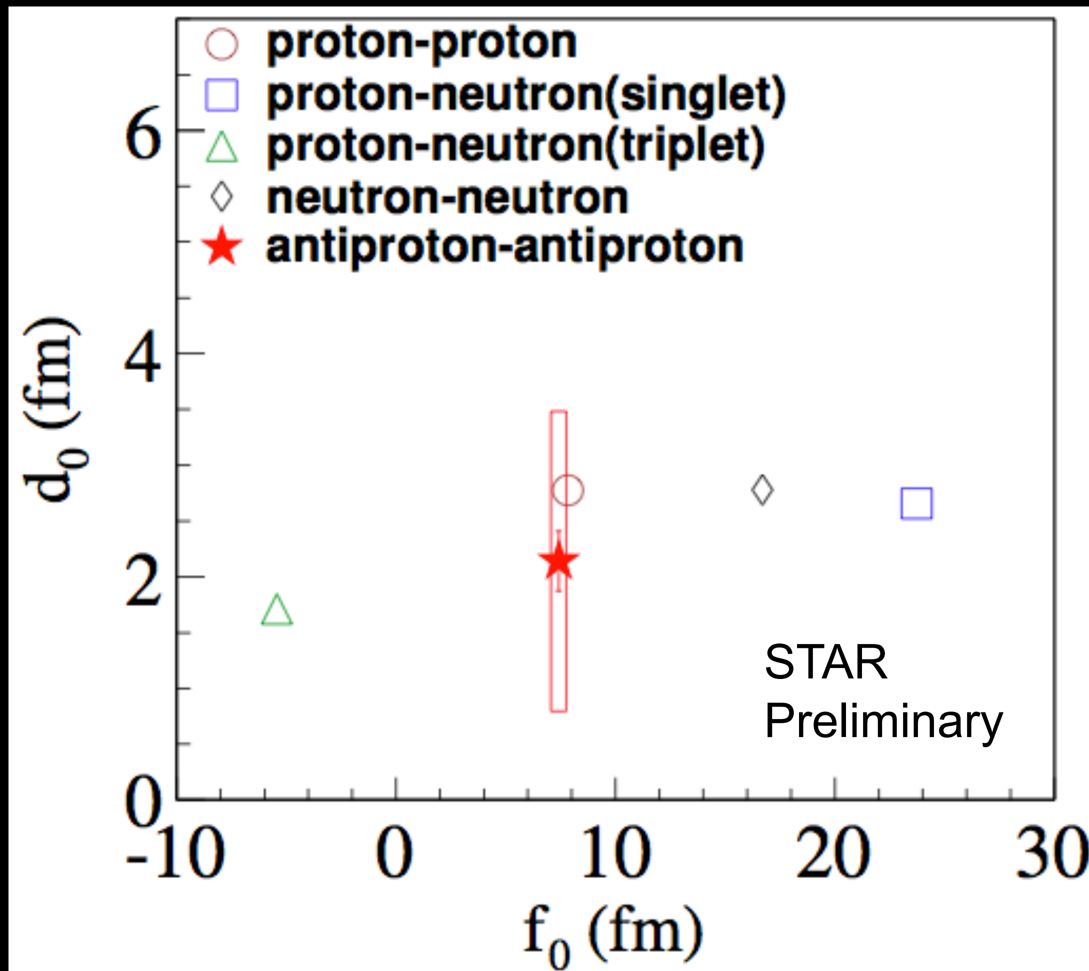
• The knowledge of interaction among two antiprotons, one of the simplest systems of antinucleons, is a fundamental ingredient for understanding the structure of more complex antinuclei and their properties.

Measurement of interaction between antiprotons



Force between two antiprotons is attractive.
Correlation Function similar to that of proton-proton.

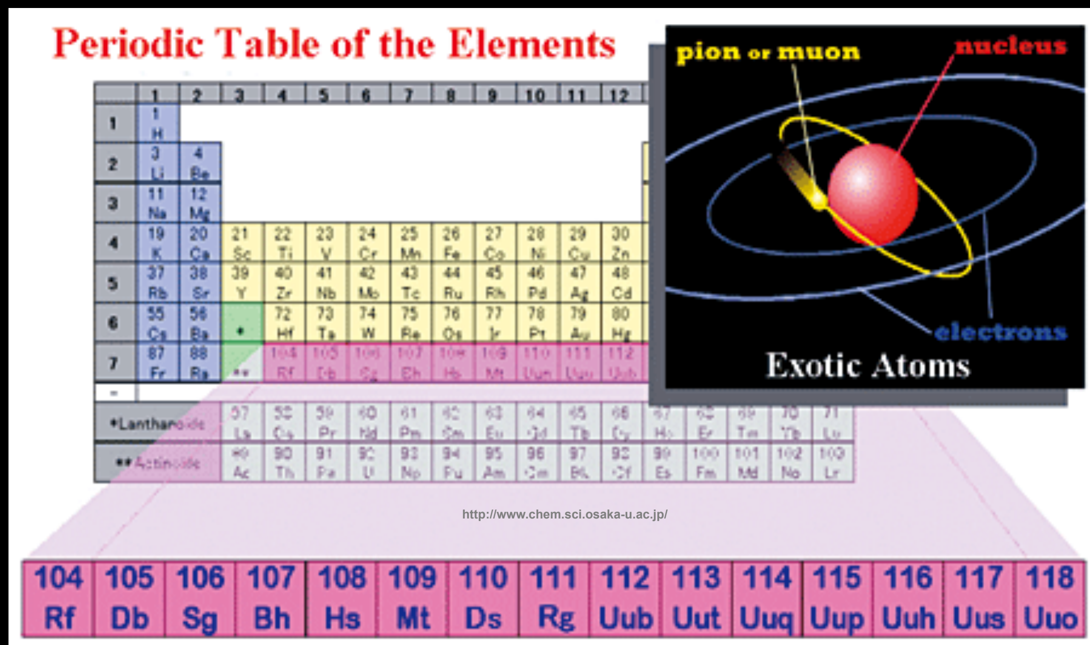
Measurement of interaction between antiprotons



f_0 and d_0 reported. They are two key parameters for characterizing the strong force between two antinucleons.

Muonic Atoms

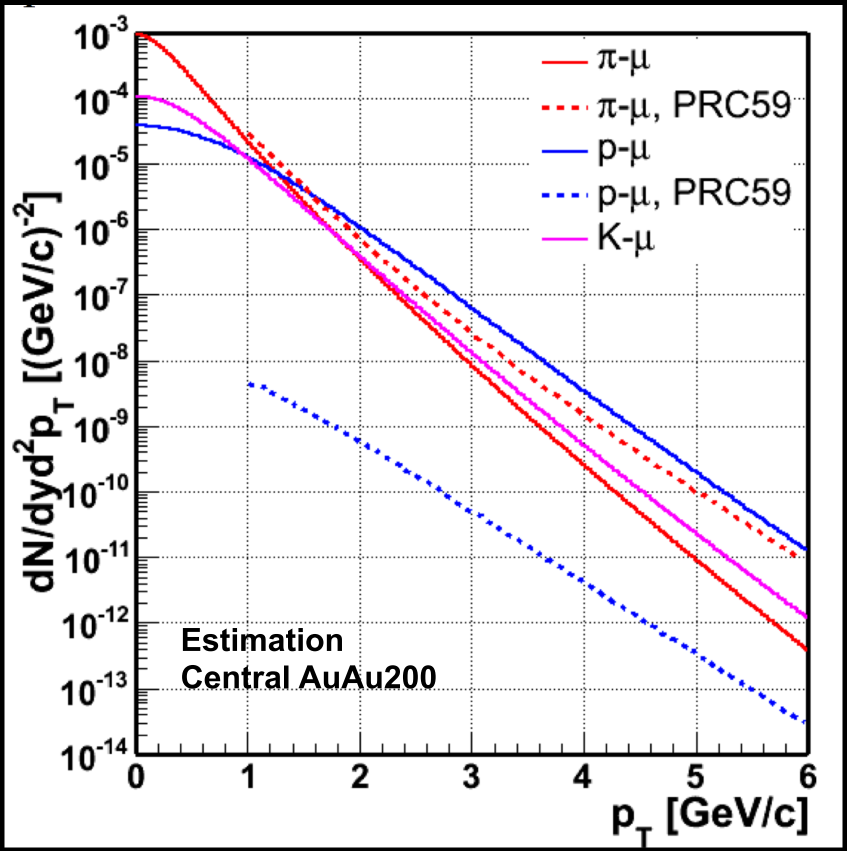
Potential discovery of new atoms



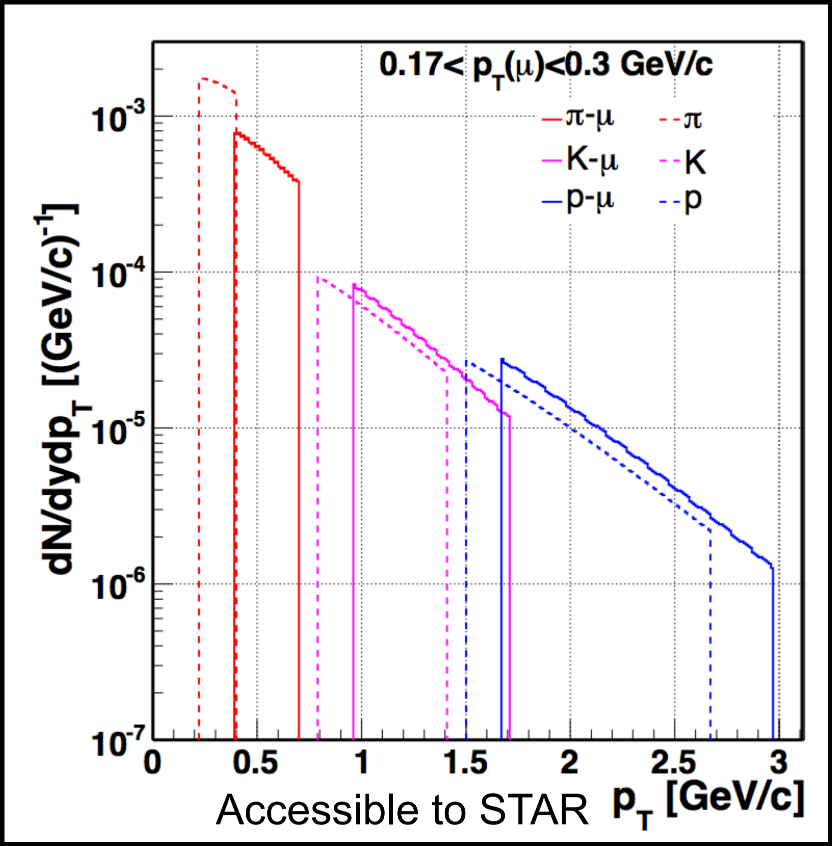
p^+-μ^- K^+-μ^- π^+-μ^-

anti-p-μ^+ K^--μ^+ π^--μ^+

Muonic Atoms : Yield estimation at STAR

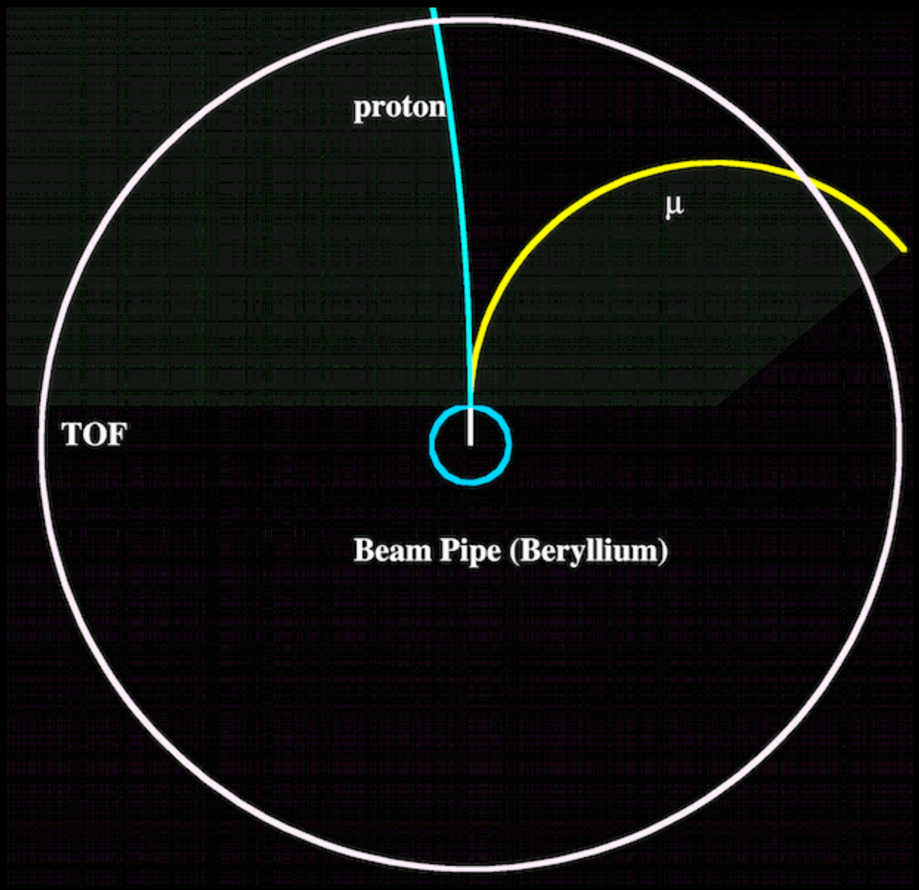


Kapusta&Mocsy PRC 59 2937



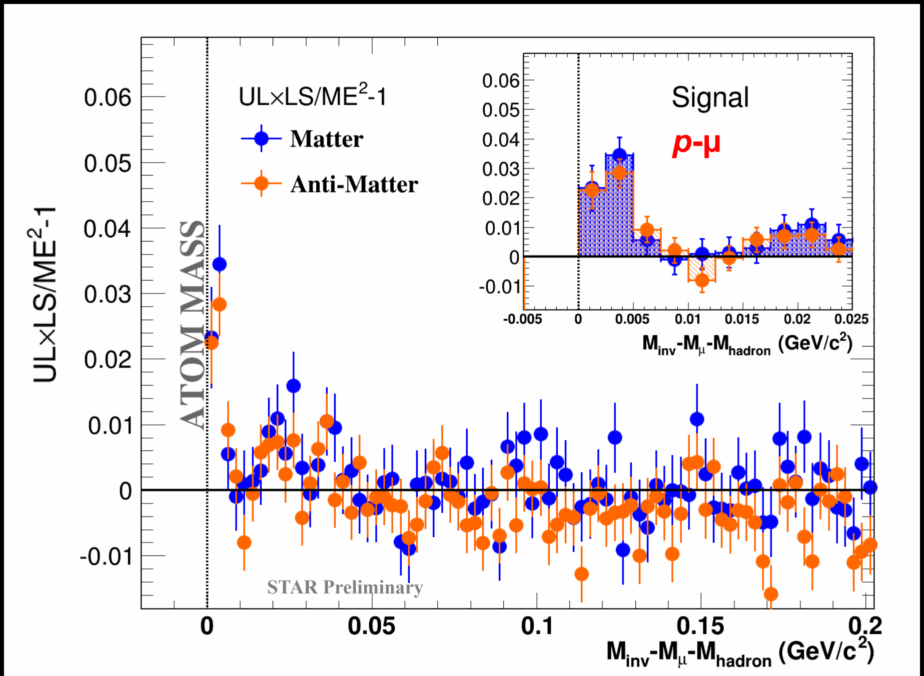
2010 STAR Decadal Plan

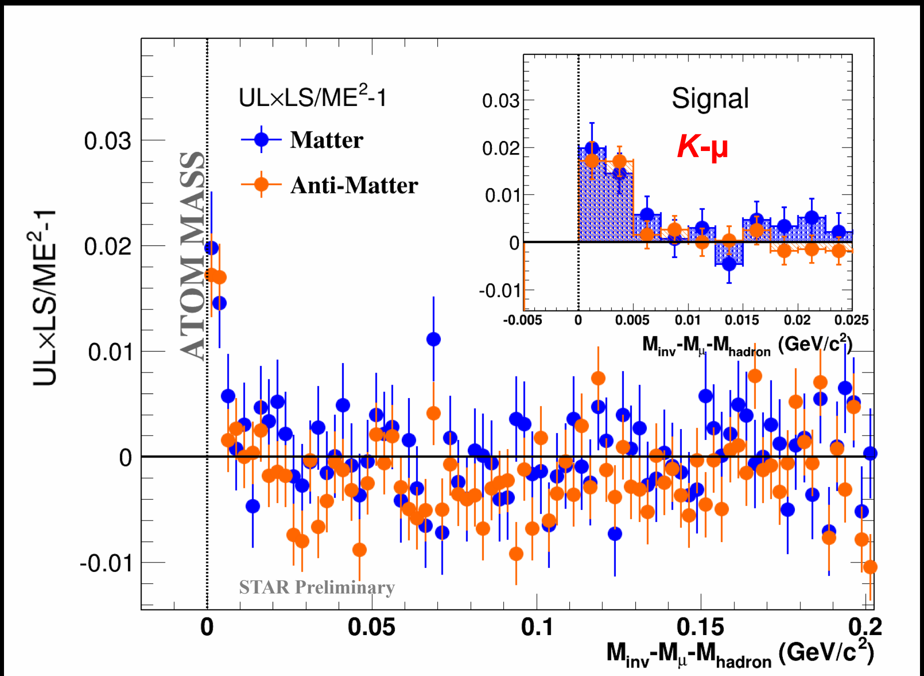
Muonic Atoms



Dissociation at the beam pipe

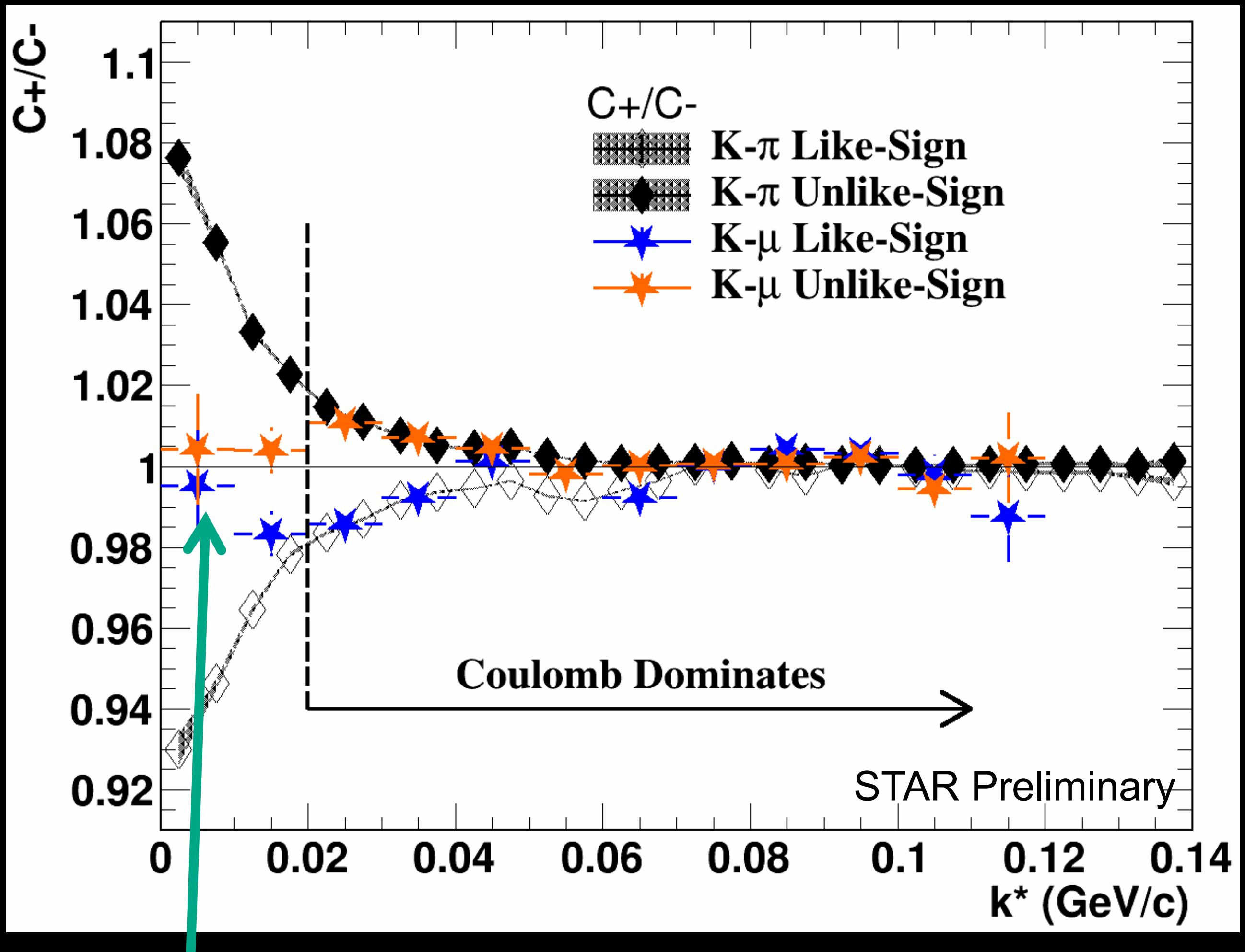
Muonic Atoms





Sharp peaks observed at the signal region.

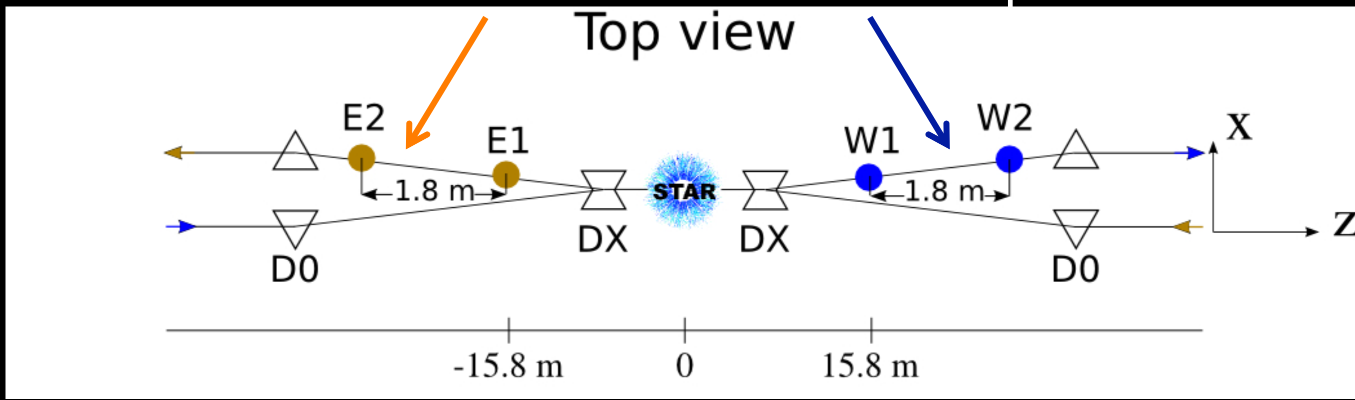
Muonic Atoms

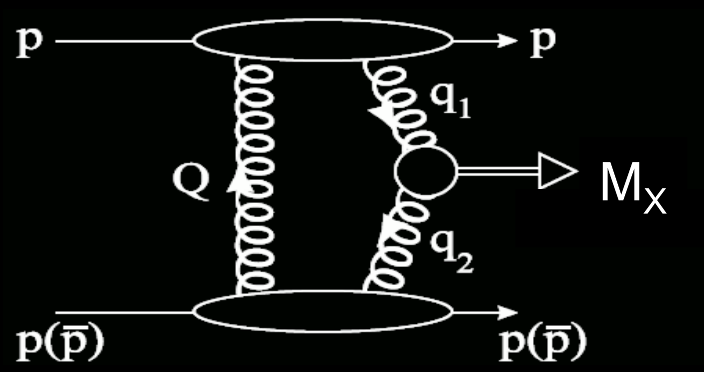


Signature of muonic atom's dissociation : two particles are emitted at the same position and time

Glueball Search with Roman Pots at STAR

Roman Pot at STAR Setup





pp ➔ pM_Xp

Roman Pots were operated in run 2015 allowing for a rich physics program with tagged forward protons in polarized p+p scattering and proton nucleus collisions at RHIC

Summary

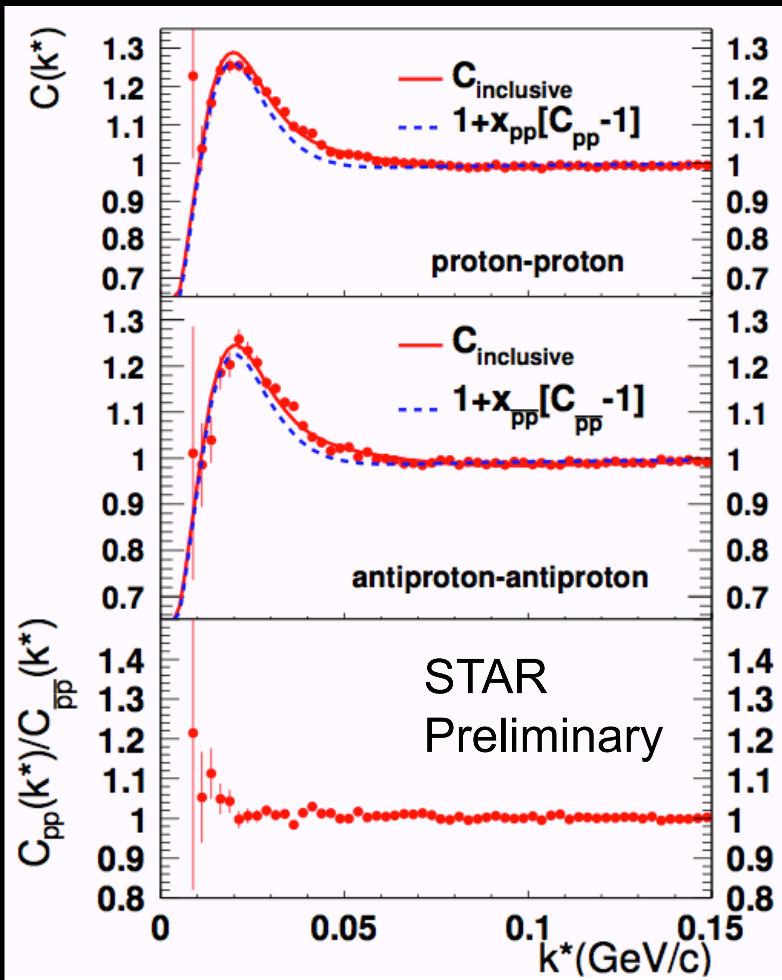
• The study of exotic, anti/hyper-matter expands RHIC's research horizon.

• RHIC (LHC too) is an ideal machine for exotic, anti/hyper-matter production.

• STAR has made important discoveries, and continues to have vigorous programs to study exotic, anti/hyper-matter.

Backup Slides

Measurement of interaction between antiprotons



$$C(\mathbf{k}^*) = \frac{\sum_{pairs} \delta(\mathbf{k}^*_{pair} - k^*) w(\mathbf{k}^*, \mathbf{r}^*)}{\sum_{pairs} \delta(\mathbf{k}^*_{pairs} - \mathbf{k}^*)},$$ where

$$w(\mathbf{k}^*, \mathbf{r}^*) = |\psi^{S(+)}_{-\mathbf{k}^*}((\mathbf{r}^*) + (-1)^S \psi^{S(+)}_{\mathbf{k}^*}(\mathbf{r}^*)|^2/2,$$ and

$$\psi^{S(+)}_{-\mathbf{k}^*}(\mathbf{r}^*) = e^{i\delta_c}\sqrt{A_c(\eta)}[e^{-i\mathbf{k}^*\mathbf{k}^*} F(-i\eta, 1, i\xi) + f_c(k^*)\frac{\widetilde{G}(\rho,\eta)}{r^*}]$$

$$f_c(k^*) = [\frac{1}{f_0} + \frac{1}{2} d_0 k^{*2} - \frac{2}{a_c} h(\eta) - i k^* A_c(\eta)]^{-1}$$ is the

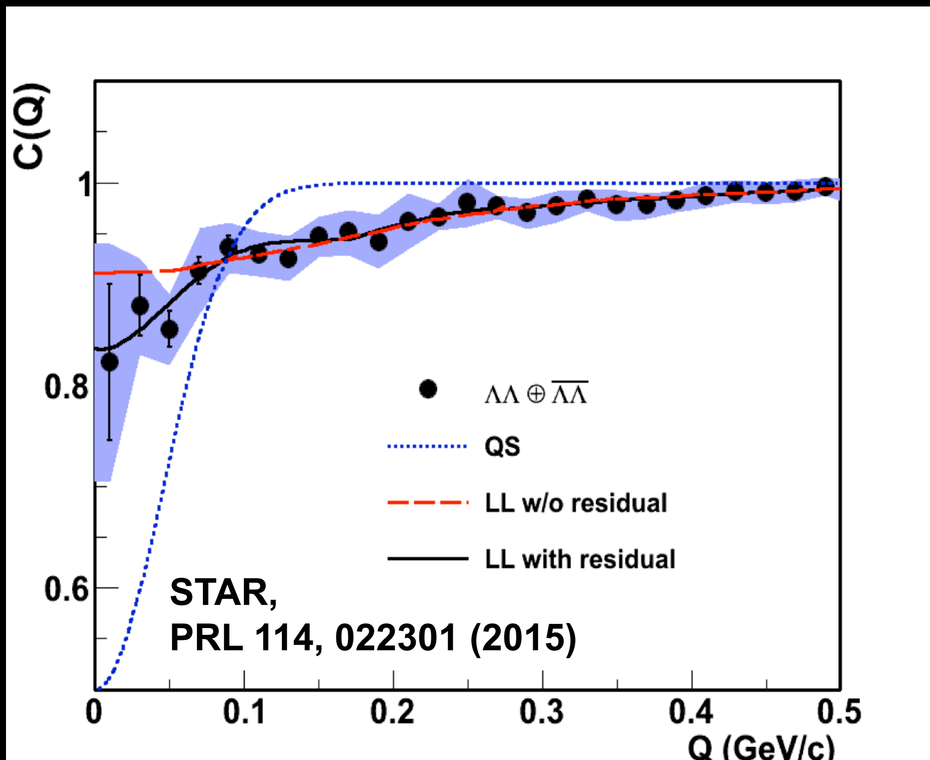
s-wave scattering amplitude renormalized by Coulomb interaction.

$$\eta = (k^* a_c)^{-1},\ a_c = (57.5\ \mathrm{fm})$$
$$\rho = k^* r^*,\ \xi = \mathbf{k}^*\mathbf{r}^* + \rho,$$
$$A_c(\eta) = 2\pi\eta[\exp(2\pi\eta) - 1]^{-1}$$

F is the confluent hypergeometric function

$\widetilde{G}(\rho,\eta) = \sqrt{A_c(\eta)}[G_0(\rho,\eta) + iF_0(\rho,\eta)]$ is a combination of the regular (F_0) and singluar (G_0) s-wave Coulomb functions. Proton pairs are from THERMINATOR2 when deriving theoretical C(k*)

Search for H^0-Dibaryon at midrapidity



$$C(Q) = N\left[1 + \lambda\left(-\frac{1}{2}\exp(-r_0^2 Q^2) + \frac{1}{4}\frac{|f(k)|^2}{r_0^2}\left(1 - \frac{1}{2\sqrt{\pi}}\frac{d_0}{r_0}\right) + \frac{\mathrm{Re} f(k)}{\sqrt{\pi} r_0} F_1(Q r_0) - \frac{\mathrm{Im} f(k)}{2 r_0} F_2(Q r_0)\right) + a_{\mathrm{res}} \exp(-r_{\mathrm{res}}^2 Q^2)\right],$$

$$k = Q/2$$

$$f(k) = \left(\frac{1}{f_0} + \frac{1}{2} d_0 k^2 - ik\right)^{-1}$$

$$F_1(z) = \int_0^1 e^{x^2 - z^2}/z\, dx$$

$$F_2(z) = (1 - e^{-z^2})/z$$

No existence of a ΛΛ resonance