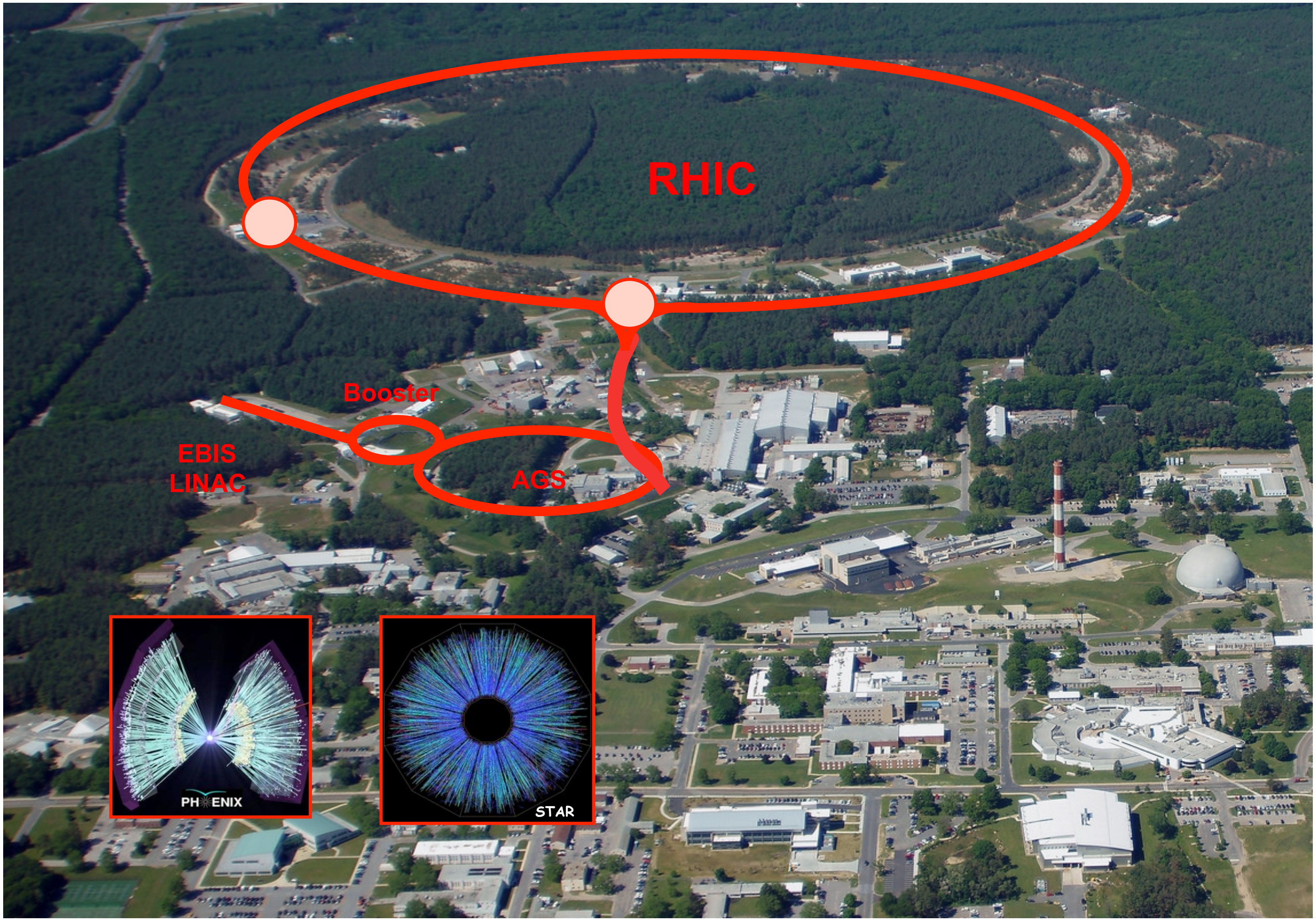
Overview of STAR's Results of Anti/Hyper/Exotic-matter Measurements

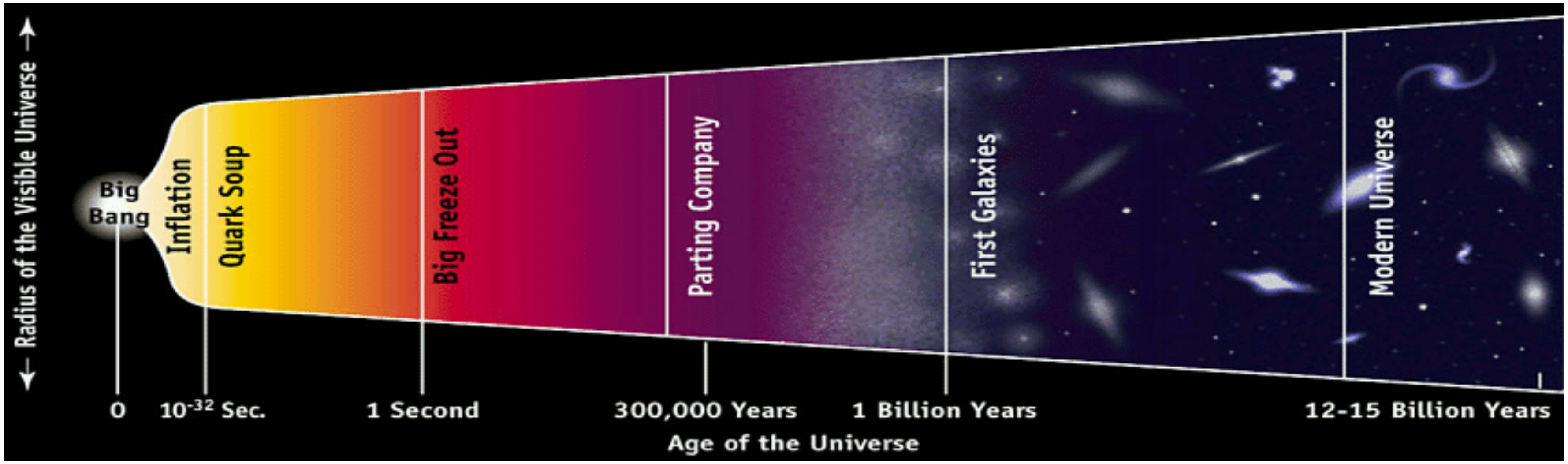
Aihong Tang for the STAR Collaboration

Relativistic Heavy Ion Collider (RHIC)



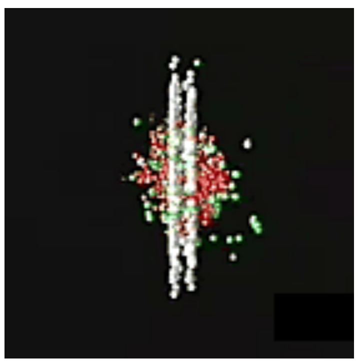
Heavy Ion Collision

Big Bang

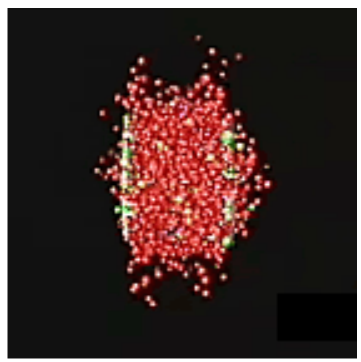


Little Bang: High Energy Heavy Ion Collision

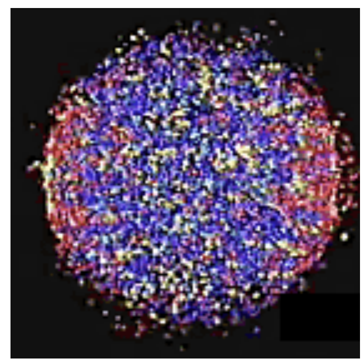
Ions about to collide



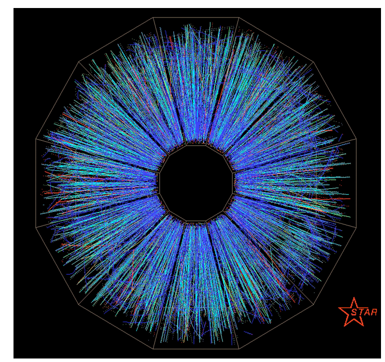
Ion collision



Plasma formation

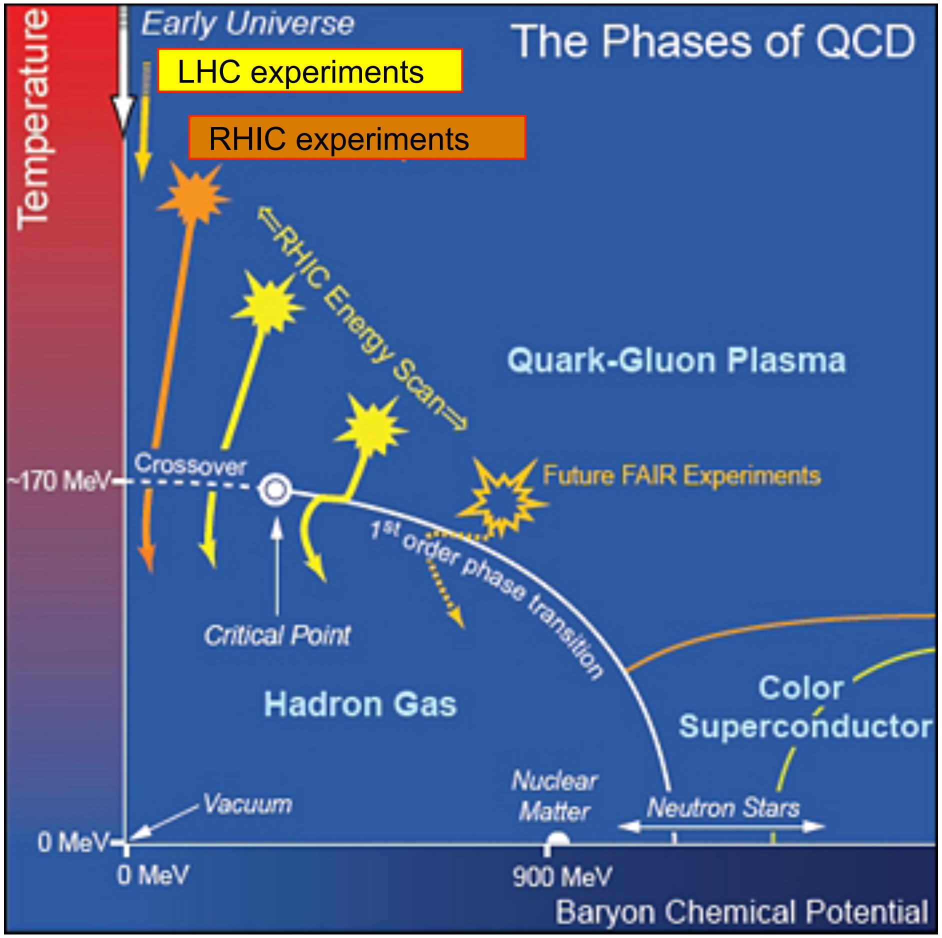


Freeze out



What we "see"

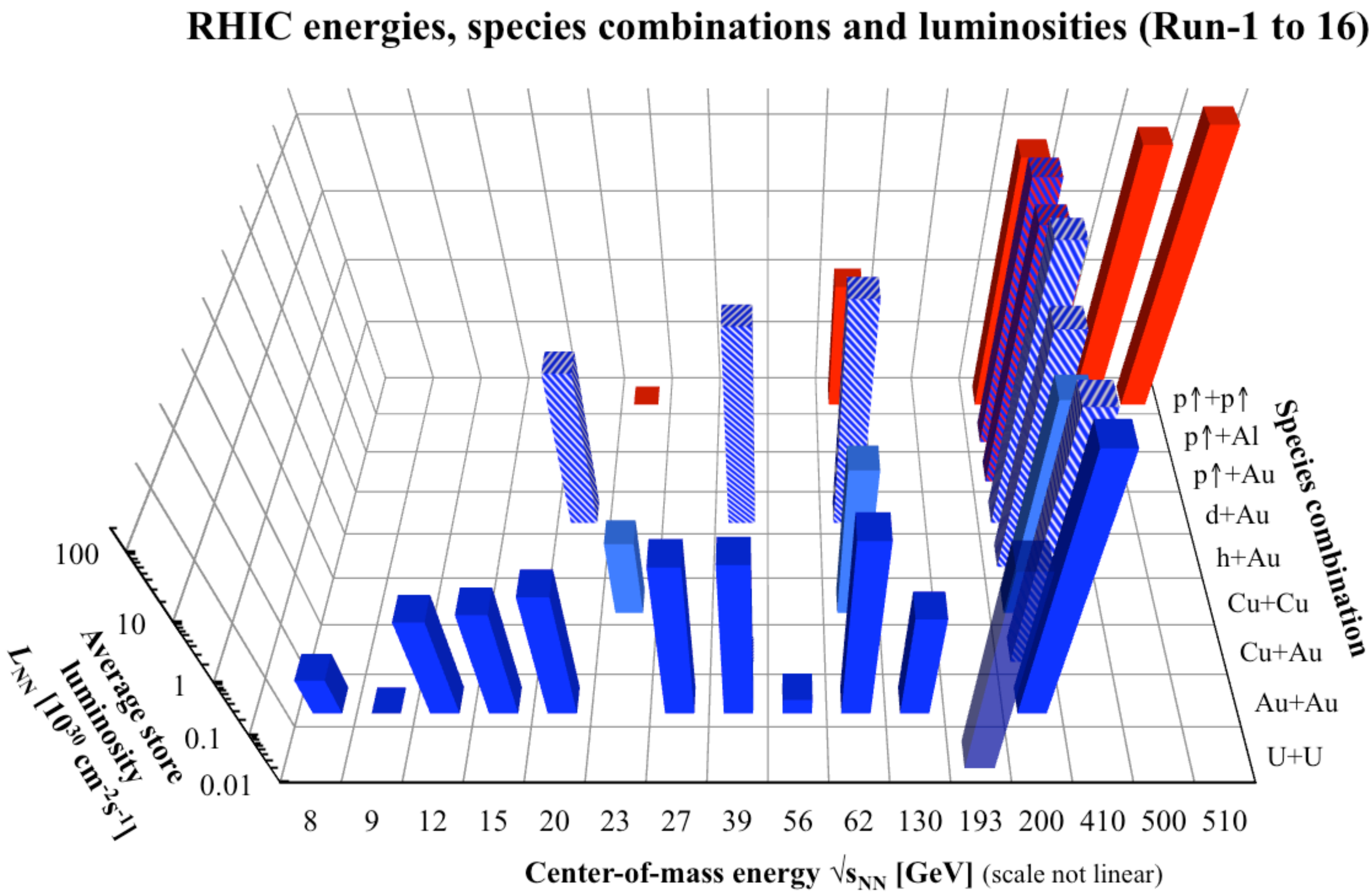
Heavy Ion Missions at RHIC



- Locate the boundary of QCD phase diagram in Beam Energy Scan.
- Study the dynamic properties of QCD matter (e.g. η/s, chiral anomaly, transport properties through jet measurements etc.)

RHIC as a QCD test ground (including exotic production)

RHIC is flexible

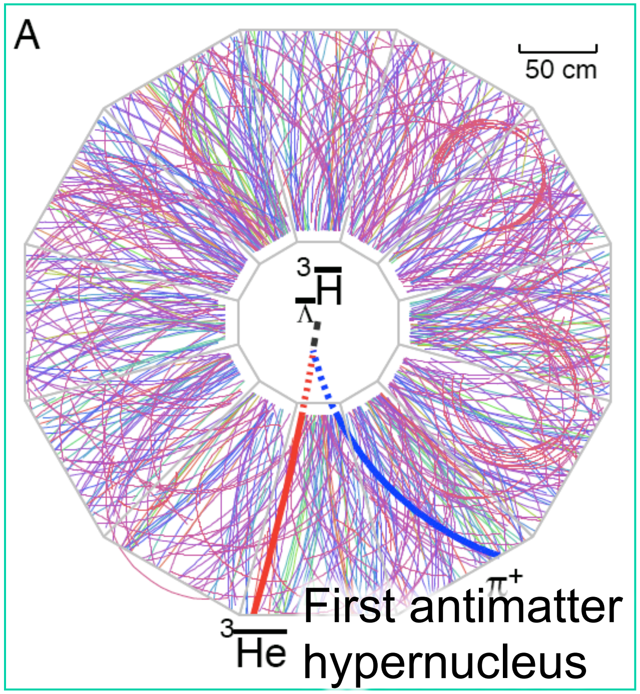


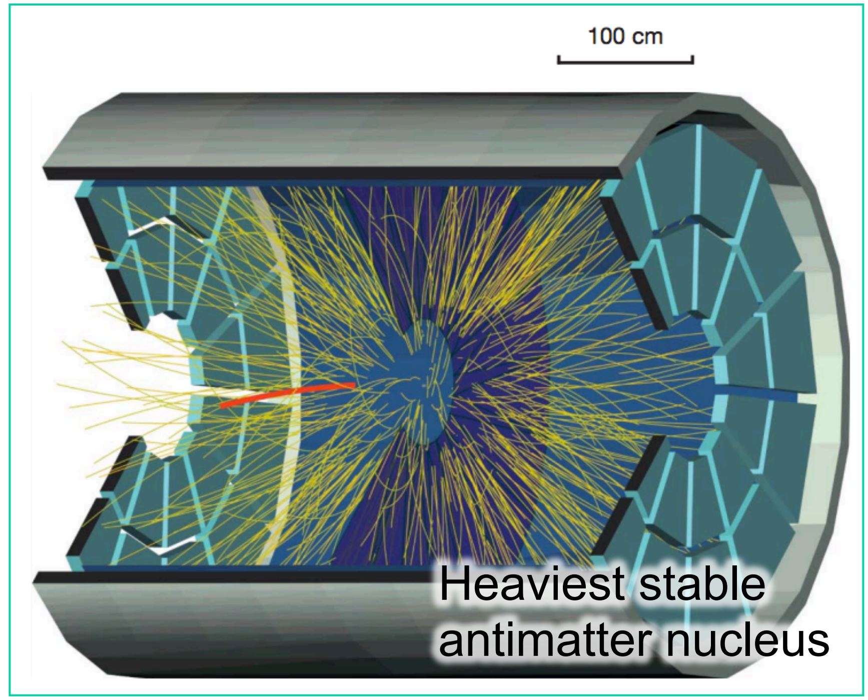
http://www.rhichome.bnl.gov/RHIC/Runs/

RHIC is Bright

- Annual integrated luminosity p+p equivalent: ~ 0.1 fb^{-1}
- Heavy ion collisions to tape @STAR : ~ 5 billion/year
- Annual particles to tape: > 10^{12}

RHIC is Exotic/Hyper/Antimatter-rich





Science

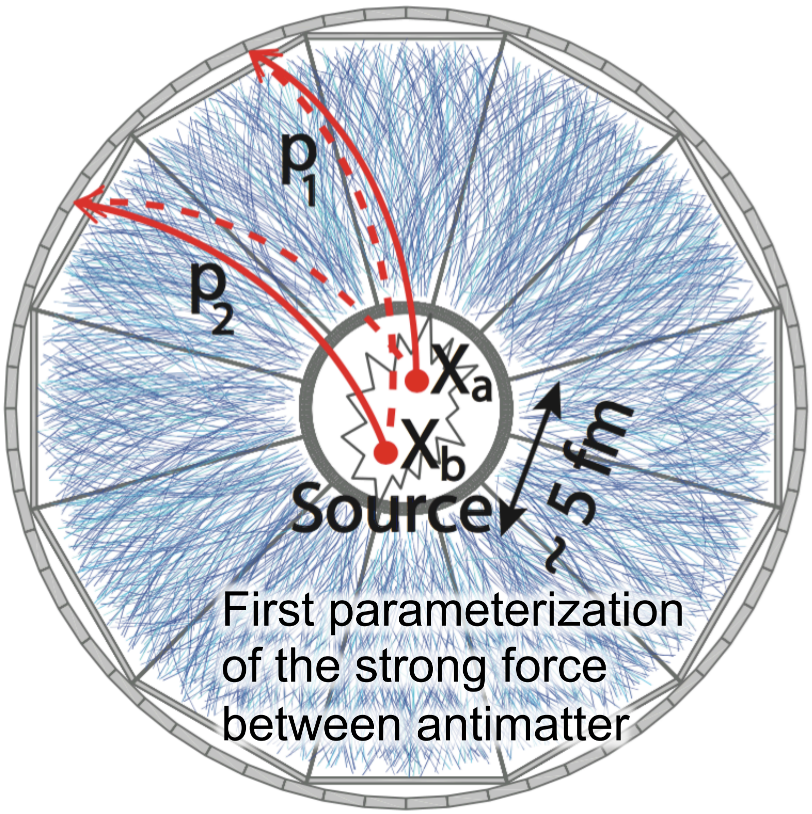
STAR ☆ ***Science* 328,** 58 (2010)

nature

STAR ☆ ***Nature* 473,** 353 (2011)

The hot and dense environment created at RHIC (and LHC too) is favorable for exotic production

RHIC is Exotic/Hyper/Antimatter-rich

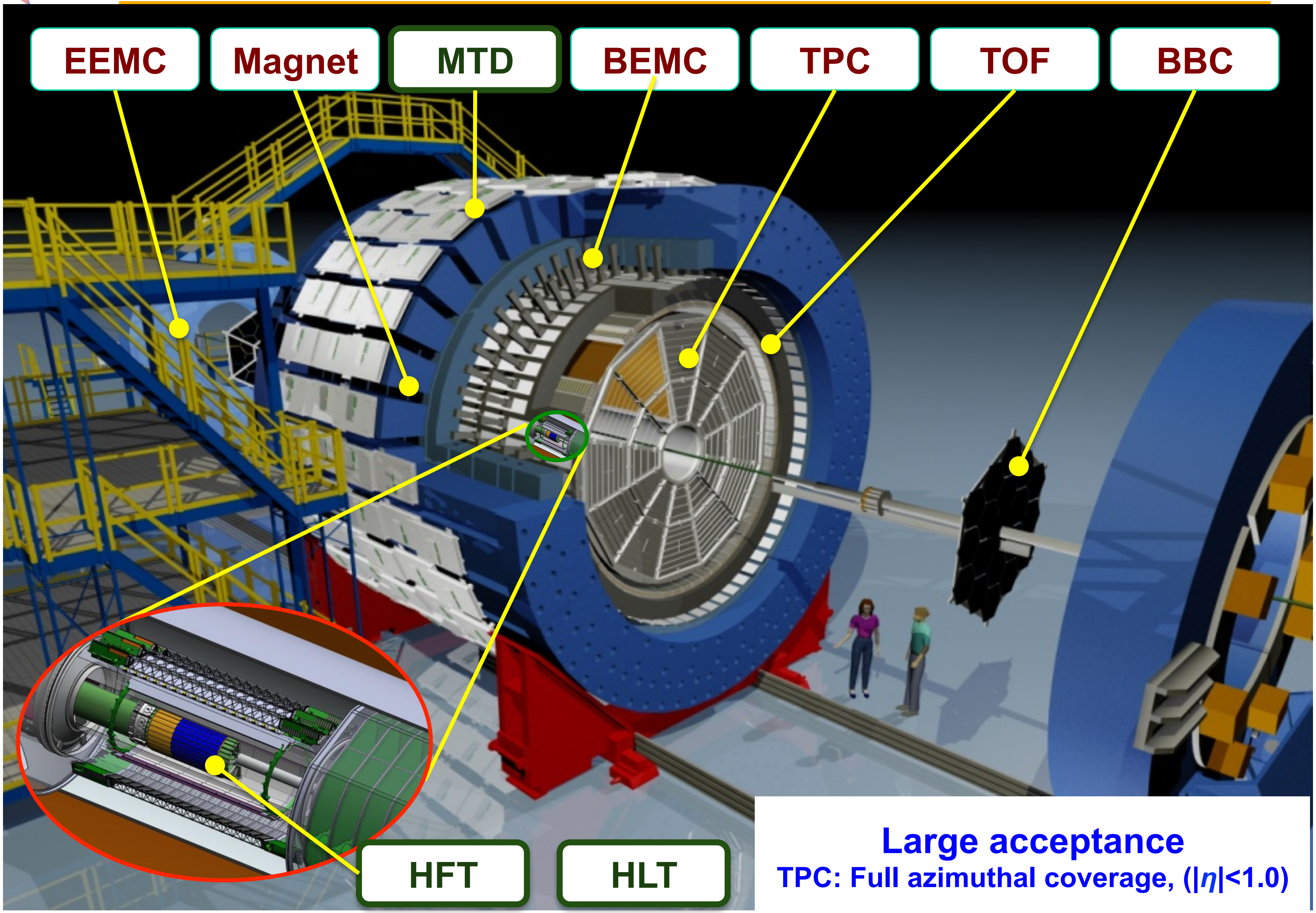


nature

A decade old experiment continues to make important, fresh contribution

STAR ☆ ***Nature* 527**, 345 (2015)

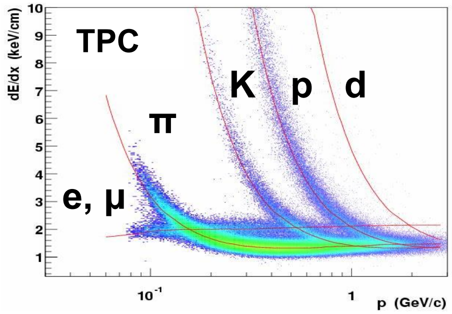
STAR : Uniform and Large Acceptance

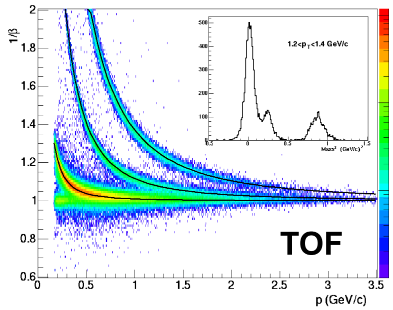


Large acceptance

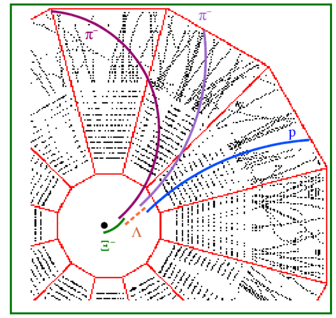
TPC: Full azimuthal coverage, ($|\eta|$<1.0)

STAR : Excellent PID and Tracking

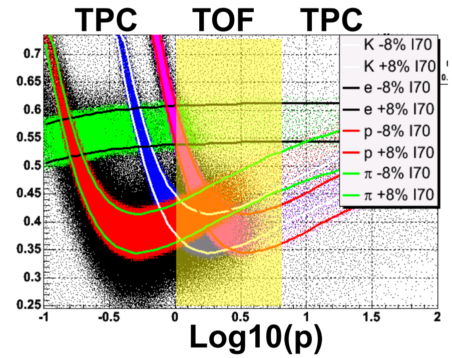


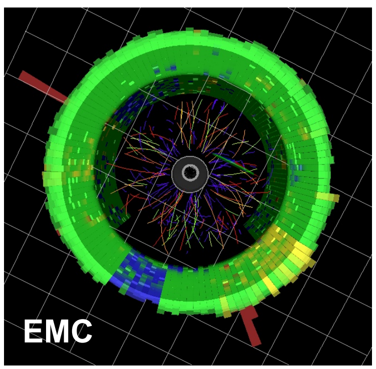


Charged hadrons

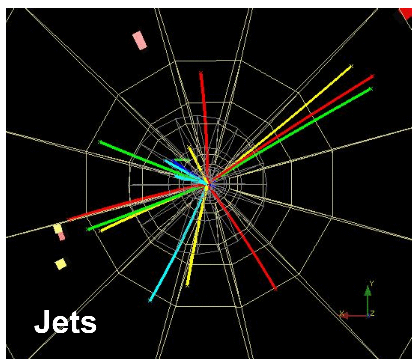


Hyperons & Hyper-nuclei

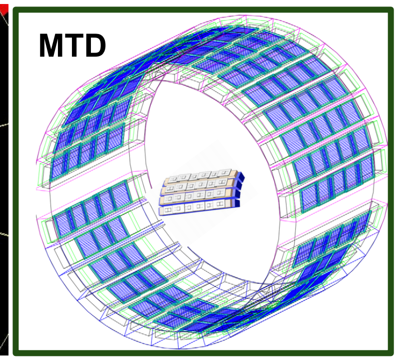




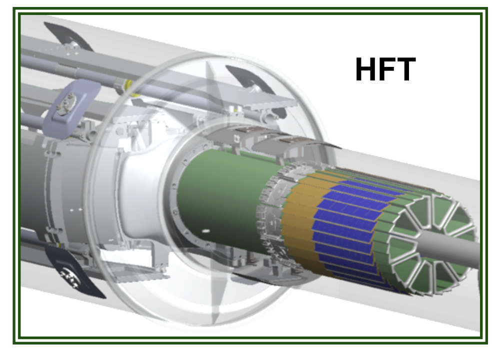
Neutral particles



Jets & Correlations



High pT muons



Heavy-flavor hadrons

Efforts at STAR

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

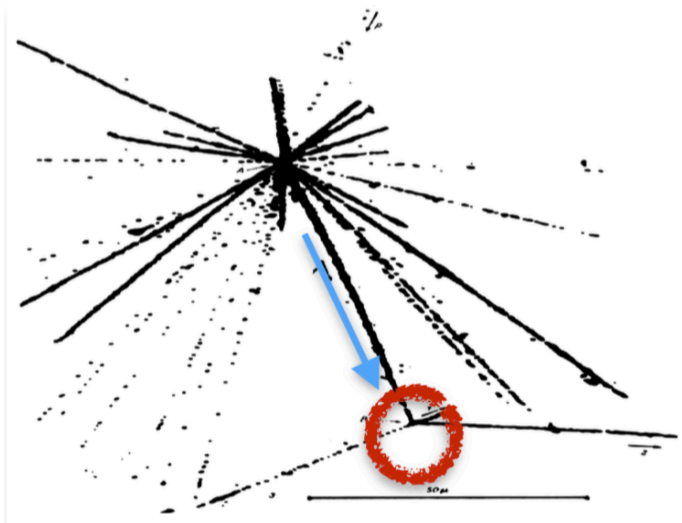
Push the boundary of standard model
- Strangelets and Dibaryons

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

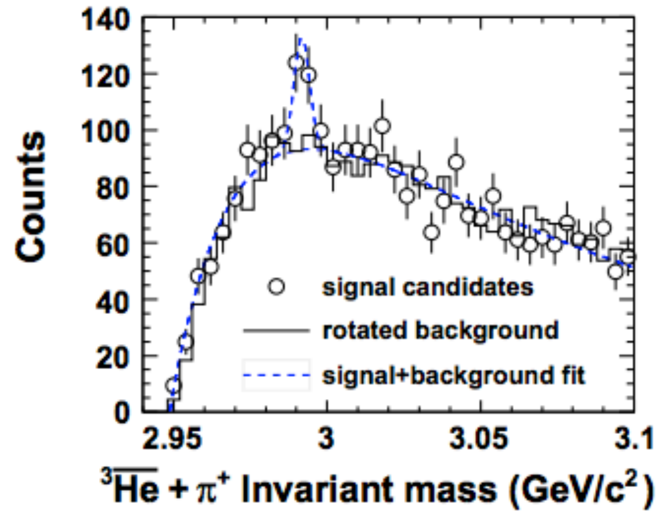
Atom/parton chemistry
- Muonic Atoms

(anti)hypertriton

Hypernucleus : Binding energy and lifetime are sensitive to YN interaction



M. Danysz and Pniewski, Phi Mag. 44 348 (1953)



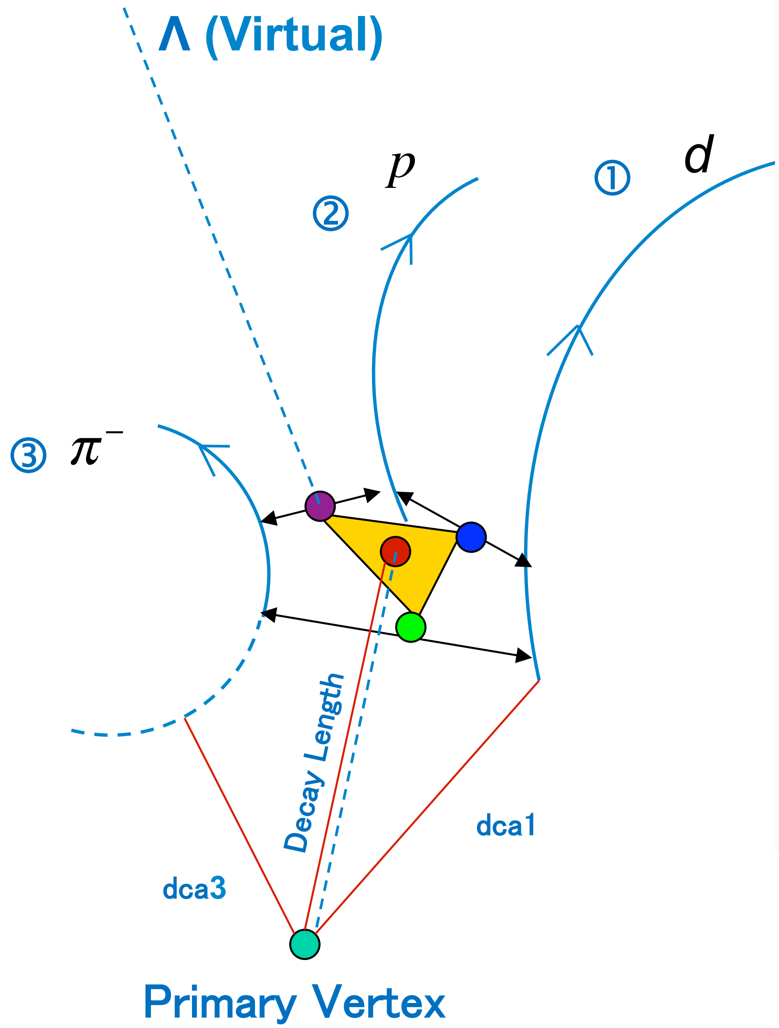
STAR ☆ ***Science* 328,** 58 (2010)

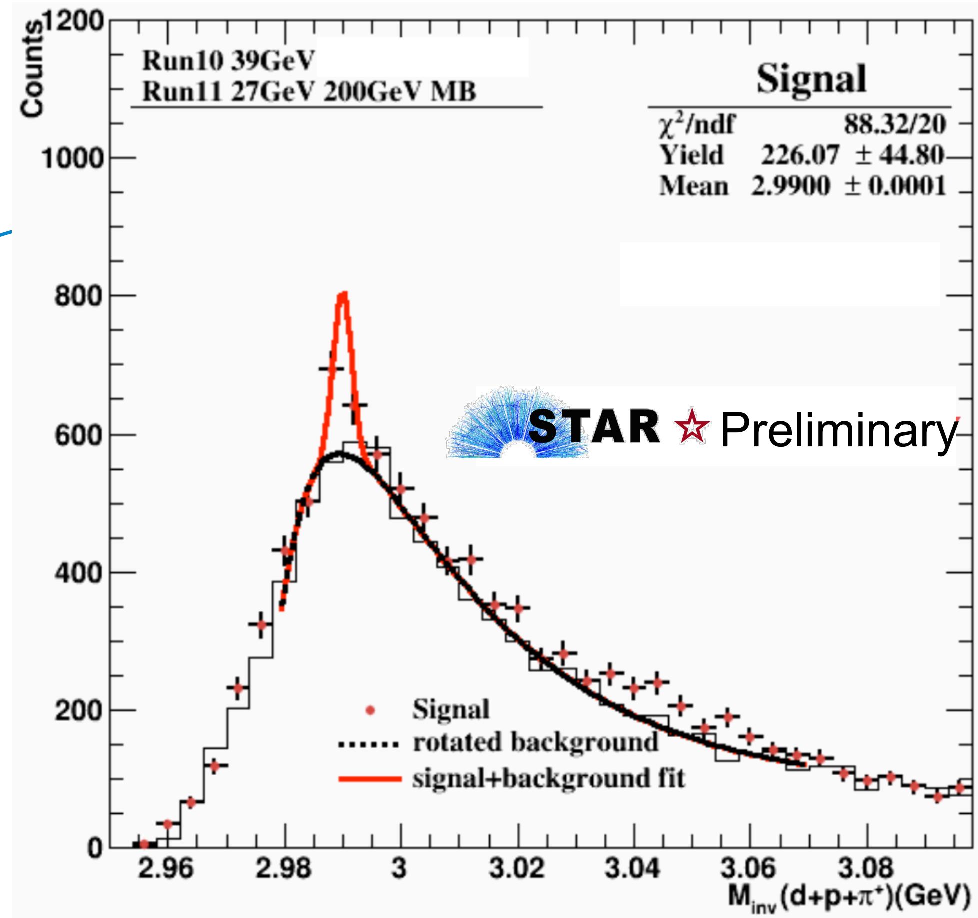
$${}^{3}_{\Lambda}H \rightarrow {}^{3}He + \pi^{-}$$

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

The first hypernucleus and the first antimatter of its kind

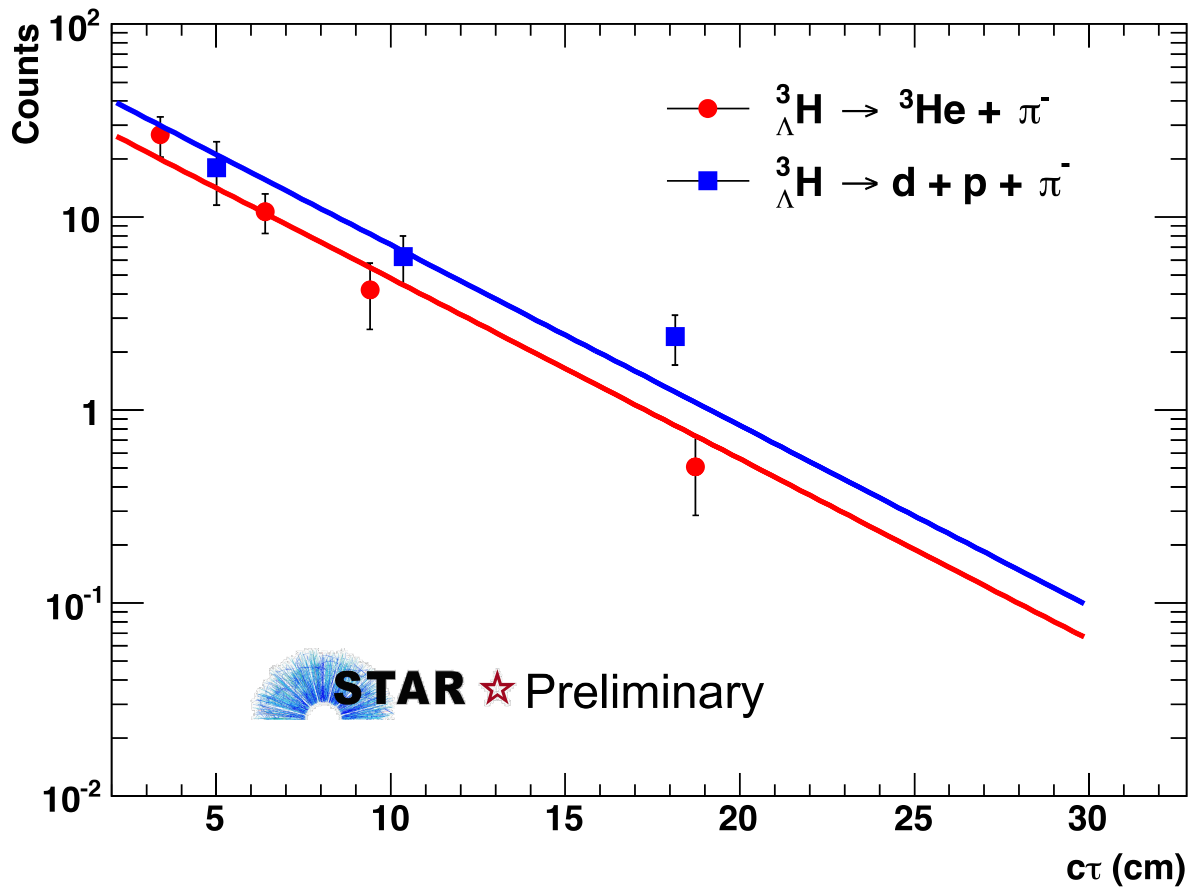
(anti)hypertriton : Three body decay





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

(anti)hypertriton : Branching Ratio

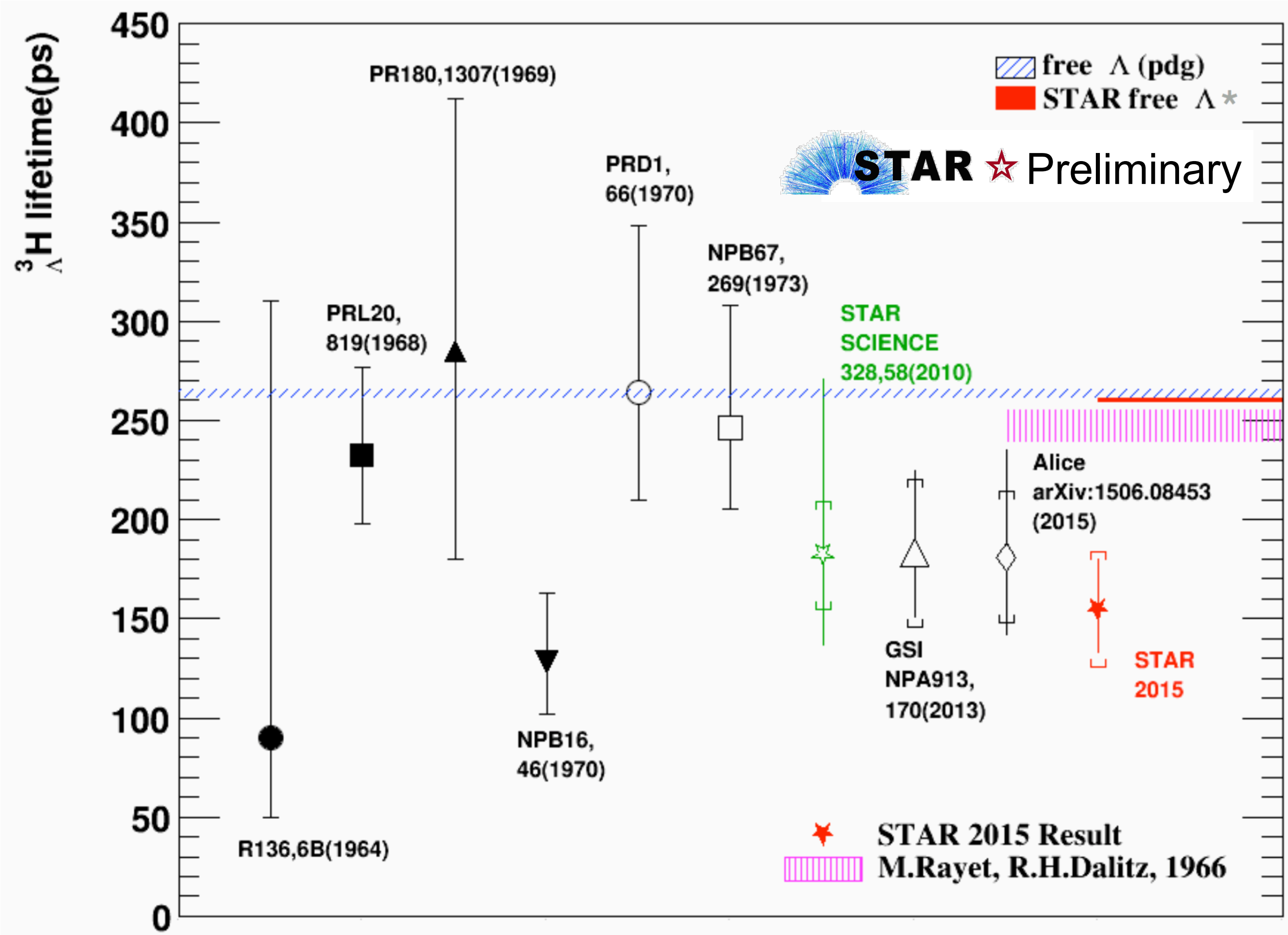


$$\frac{B.R.(d+p+\pi^-)}{B.R.(^3He+\pi^-)} = 2.41^{+0.39}_{-0.34}$$

$$Theoretical: \left(\frac{40.15}{24.88} = 1.61\right)$$

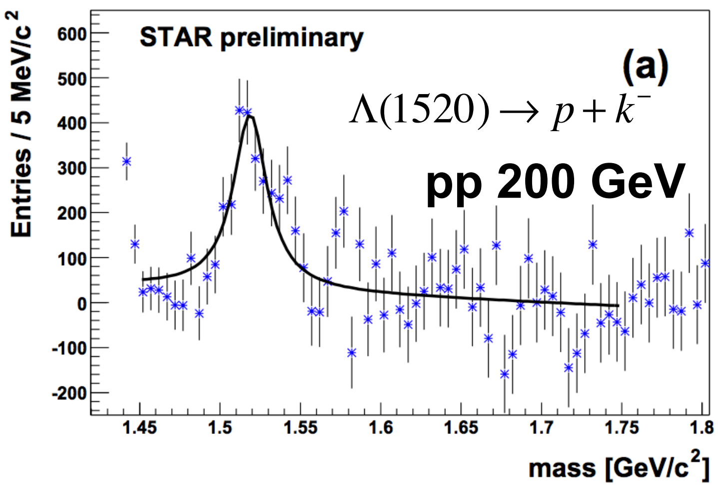
H. Kamada, J. Golak, K. Miyagawa, H. Witala and W. Glockle, Phys Rev C 57 1595 (1998)

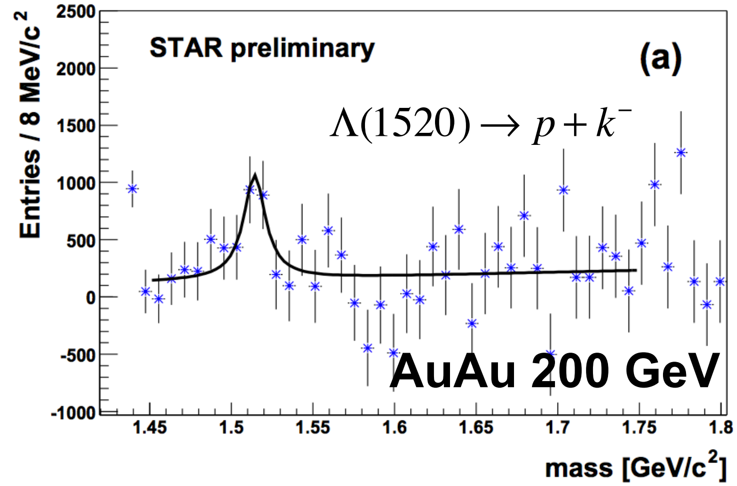
(anti)hypertriton : Lifetime

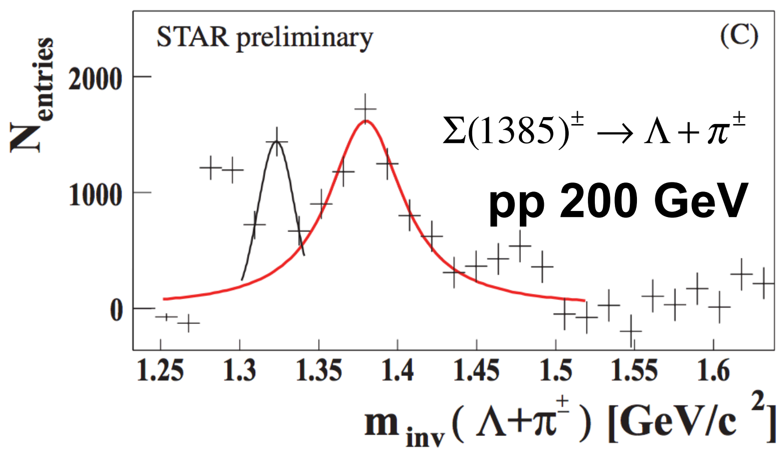


$$\tau = 155^{+25}_{-22}(stat) \pm 29(sys)\ ps$$

A side remark on the combinatorial bg at RHIC



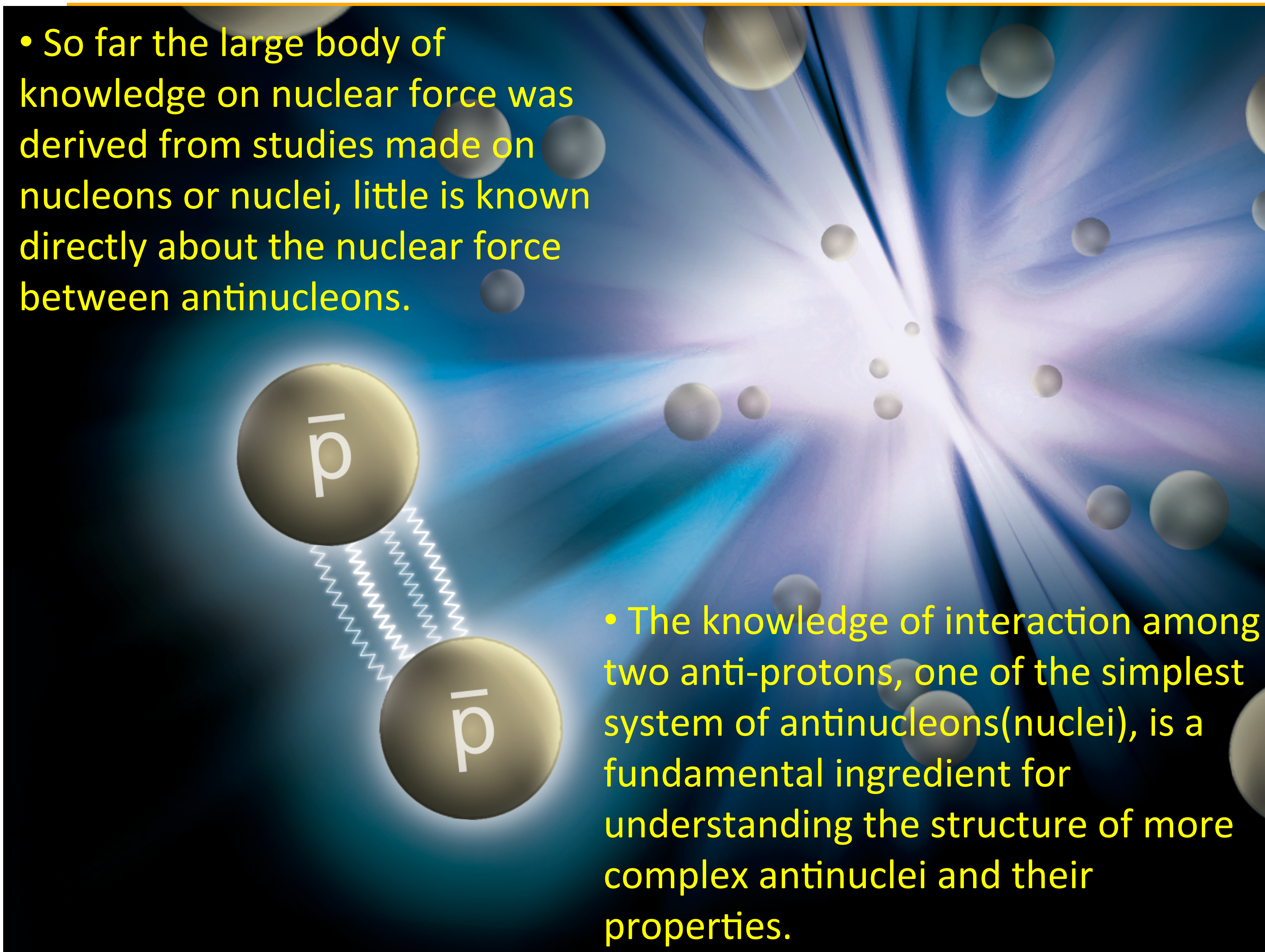




Large background in AuAu collisions
Challenging for resonance studies

Nuclear force between antimatter

- So far the large body of knowledge on nuclear force was derived from studies made on nucleons or nuclei, little is known directly about the nuclear force between antinucleons.



- The knowledge of interaction among two anti-protons, one of the simplest system of antinucleons(nuclei), is a fundamental ingredient for understanding the structure of more complex antinuclei and their properties.

Correlation analysis

Correlation Function (CF):

$$C(p_1, p_2) = \frac{P(p_1, p_2)}{P(p_1)P(p_2)}$$

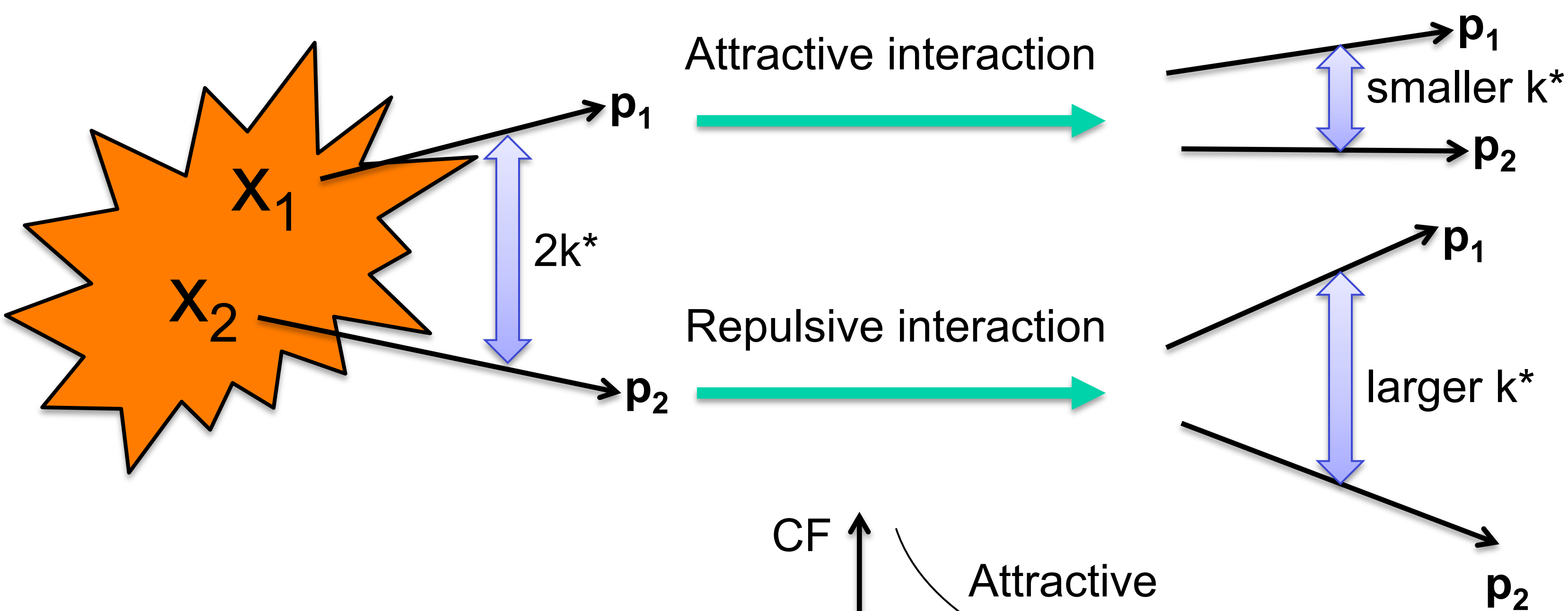
In practice,

$$C(k^*)_{measured} = \frac{\text{real pairs from same events}}{\text{pairs from mixed events}}$$

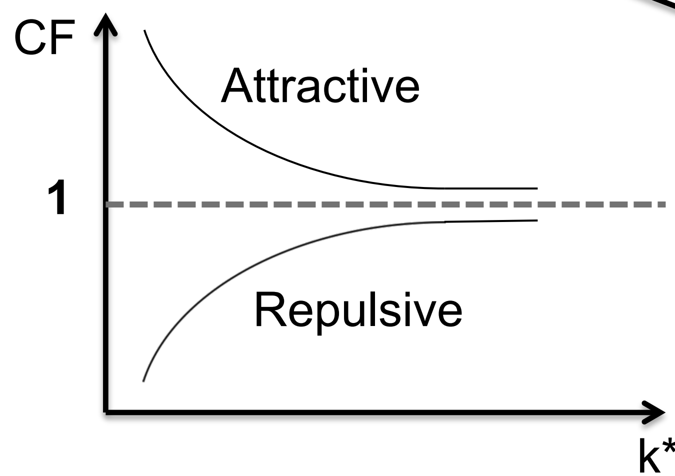
Purity correction :

$$C(k^*) = \frac{C(k^*)_{measured} - 1}{\text{PairPurity}(k^*)} + 1$$

Correlation analysis

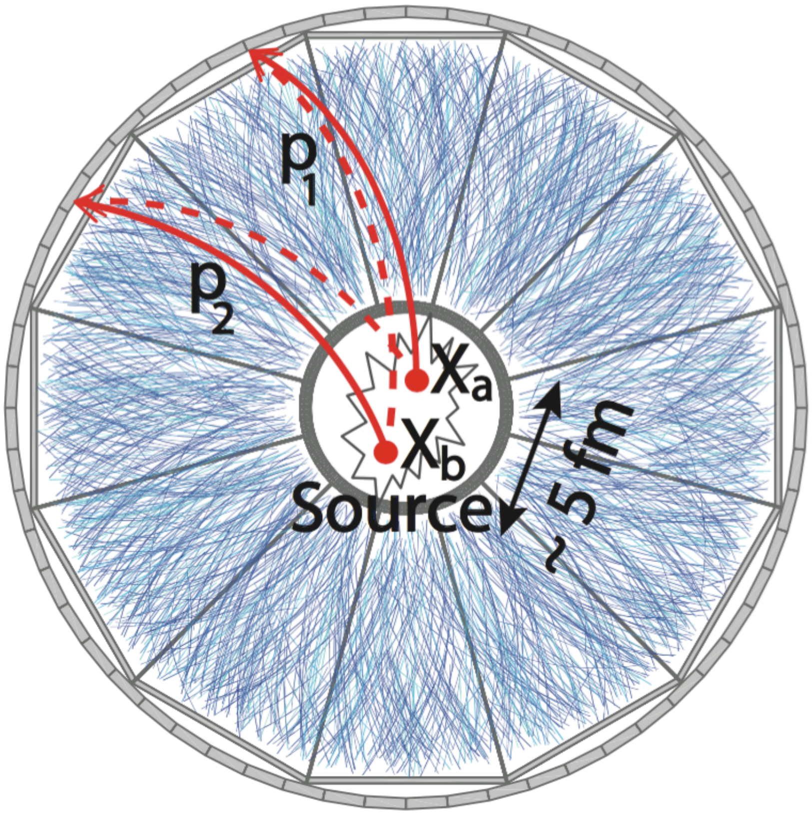


For example, if there is only Coulomb interaction between two particles



Two-particle correlation function is sensitive to the separation distribution of the source and interaction in the final state.

Final State Interactions



- Quantum Statistics Effects
- Final State Interactions
  - Formation of resonances
  - Coulomb
  - **Nuclear interaction**

Connecting f_0 & d_0 to CF

CF

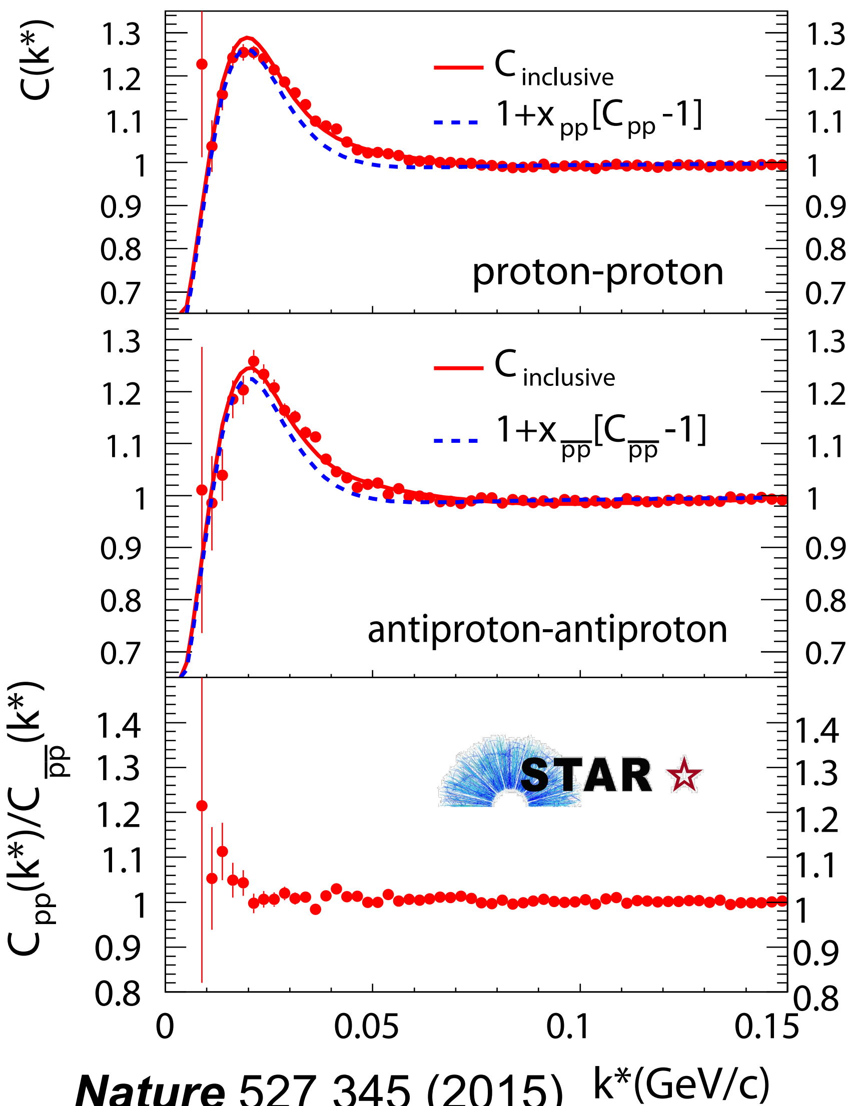
wave function

$$\psi_{-k^*}^{S(+)}(r^*) = e^{i\delta_c}\sqrt{A_c(\eta)}\left[e^{-ik^*r^*}F(-i\eta,1,i\xi) + f_c(k^*)\frac{\tilde{G}(\rho,\eta)}{r^*}\right]$$

Scattering amplitude

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

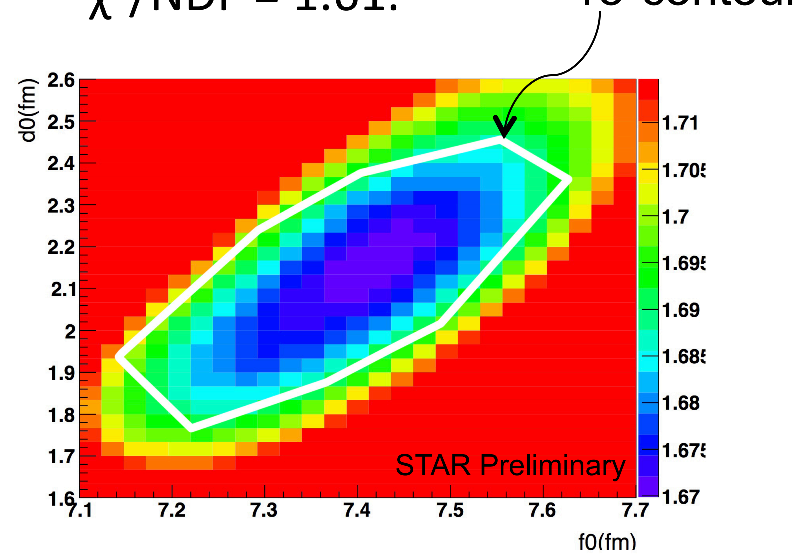
Correlation functions



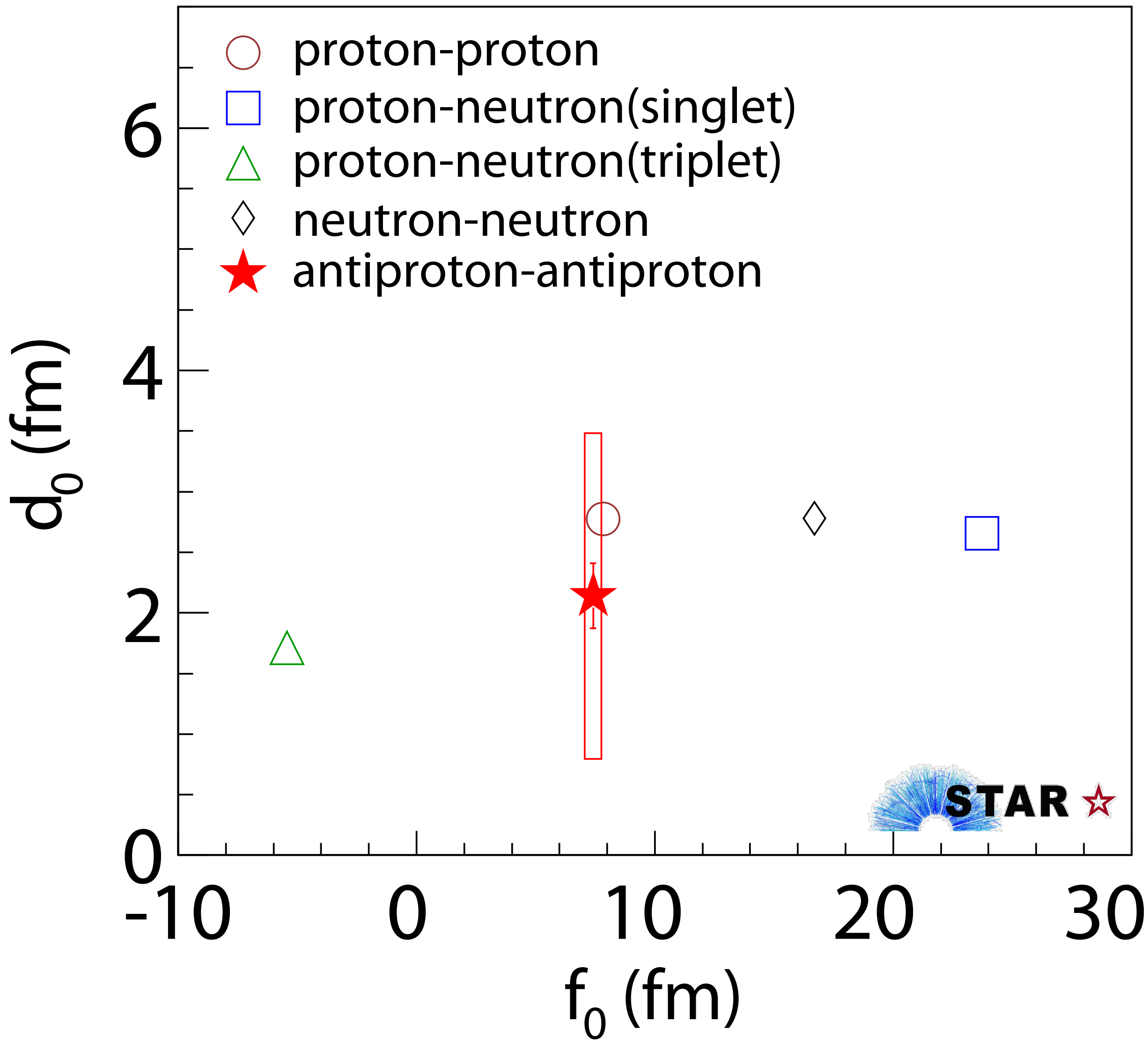
Nature 527 345 (2015)

- For proton-proton CF
  R = 2.75 ±0.01 fm;
  χ^2/NDF = 1.66.

- For antiproton-antiproton CF
  R = 2.80 ±0.02 fm;
  f_0 = 7.41 ± 0.19 fm;
  d_0 = 2.14 ± 0.27 fm;
  χ^2/NDF = 1.61.



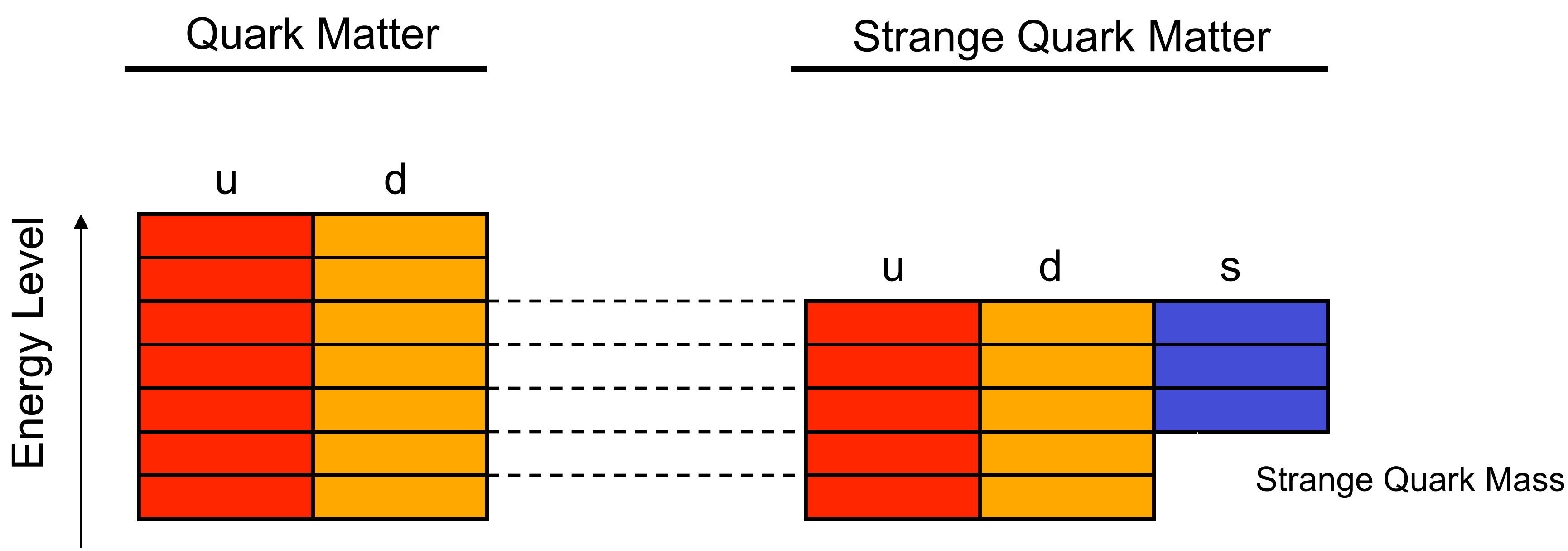
f_0 and d_0



Nature 527 345 (2015)

- The first direct measurement of interaction between two antiprotons.
- The force between two antiprotons is found to be attractive, and is as strong as that between protons.
- Besides examining CPT from a new aspect, this measurement provides a fundamental ingredient for understanding the structure of more complex anti-nuclei and their properties.

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

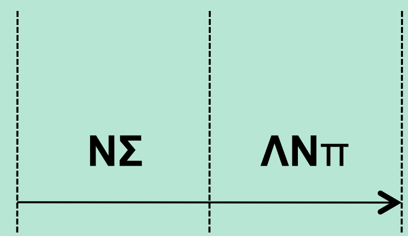
6 quark-bag bound state (uuddss)

$m_{H0} < 2m_{\Lambda} = 2231$ 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) 2134 2192 2231

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) …)

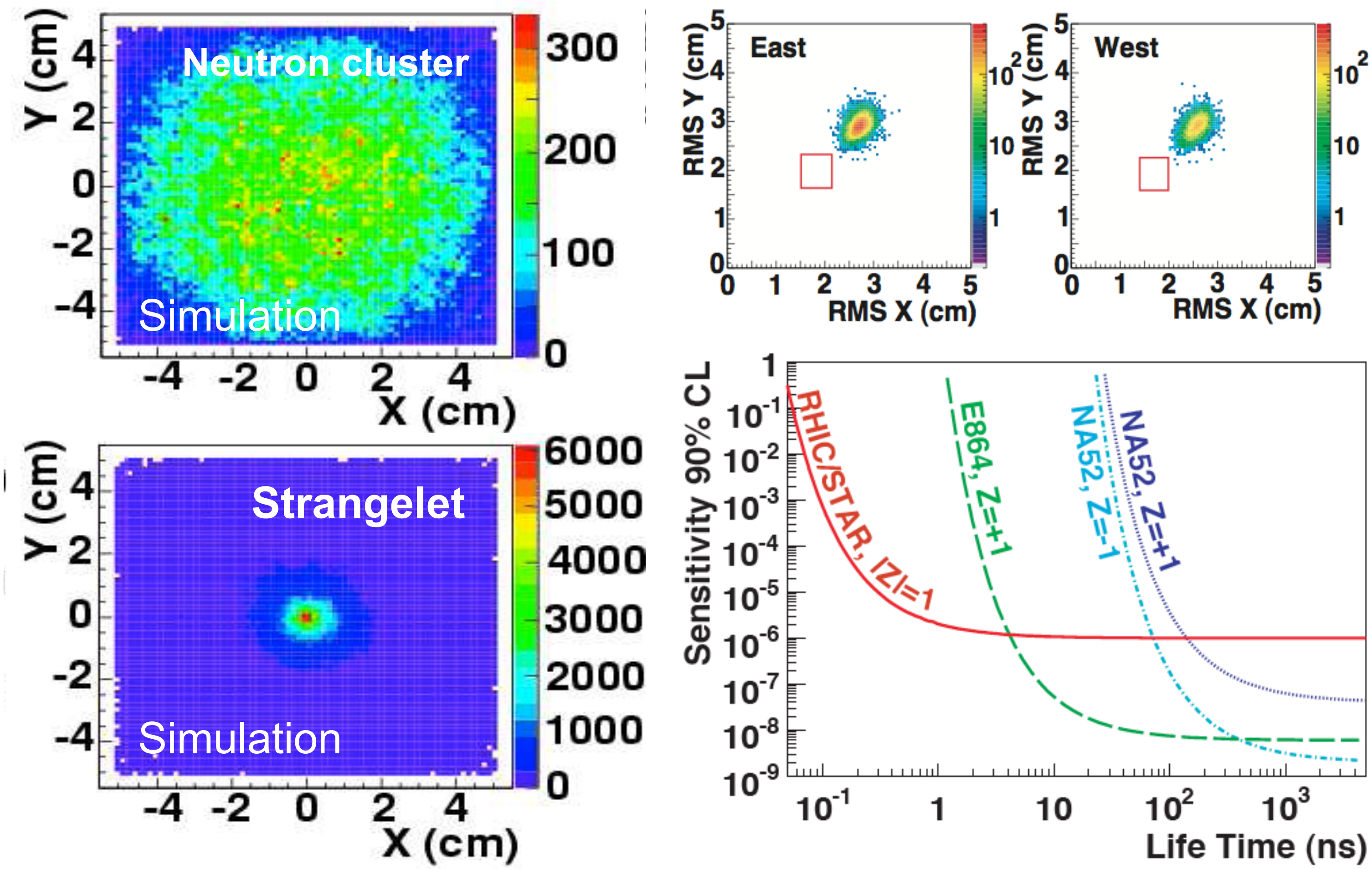
Decay length ~ 1-5cm

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

$(\Sigma^+ p)_b \rightarrow p + p$
$(\Xi^0 p)_b \rightarrow \Lambda + p$
} dN/dy~10^{-3}/event

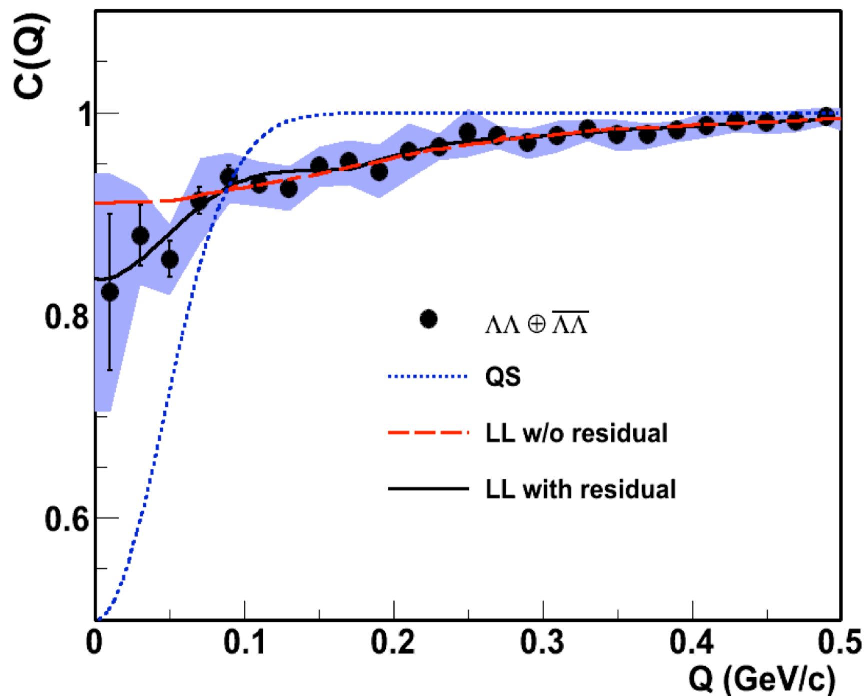
$(\Xi^0 \Lambda)_b \rightarrow \Lambda + \Lambda$
$\rightarrow \Xi^- + p$

Previous search for strangelet, in Forward Region



STAR ☆ PRC 76, 011901 (2007)

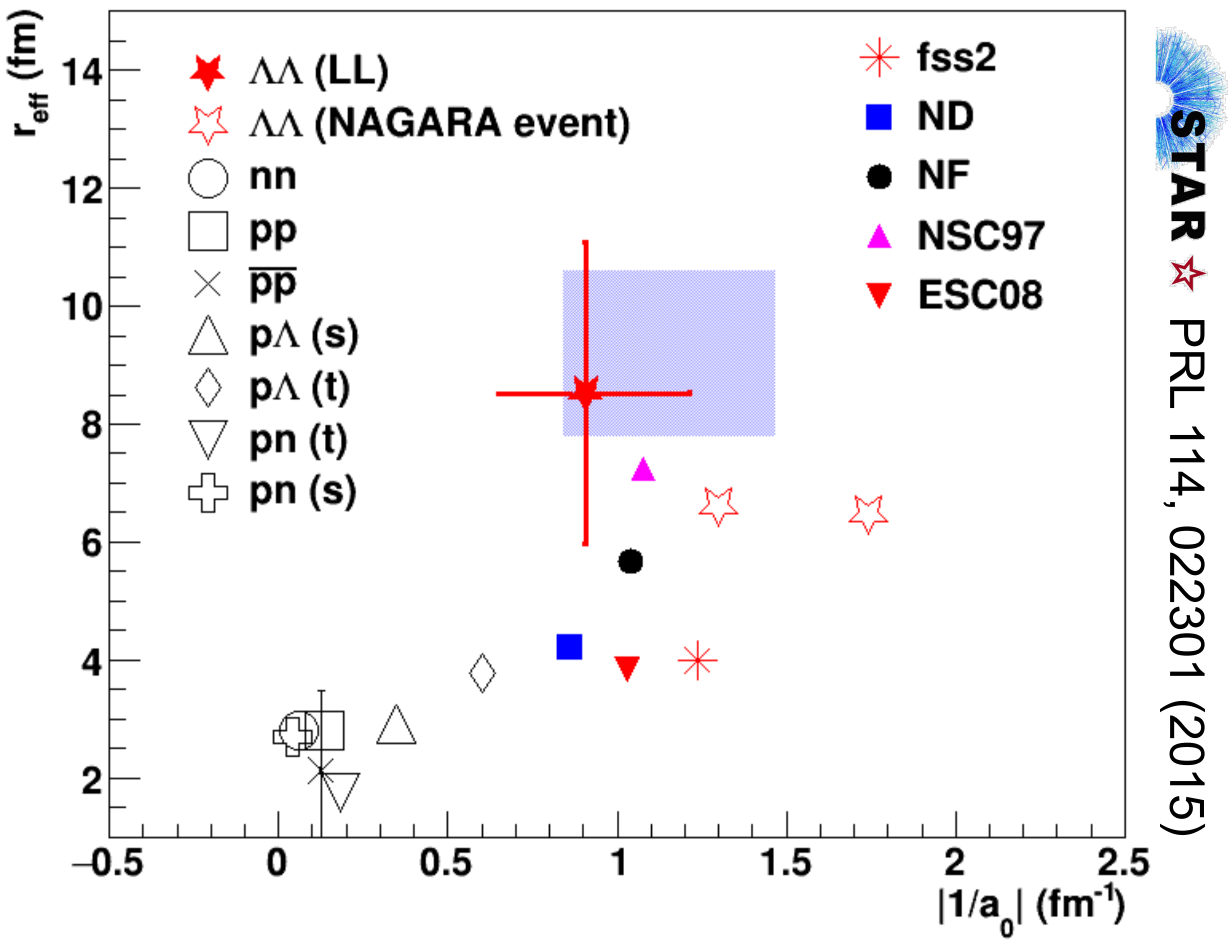
Search for H^0-Dibaryon at midrapidity



STAR ☆ PRL 114, 022301 (2015)

Hyperon-Hyperon interaction is one of the key quantities to understand the dense matter EOS, of great interest to astrophysicists.
Origin of residual (long tail) needs to be understood.

Search for H^0-Dibaryon at midrapidity



$a_0 = f_0$

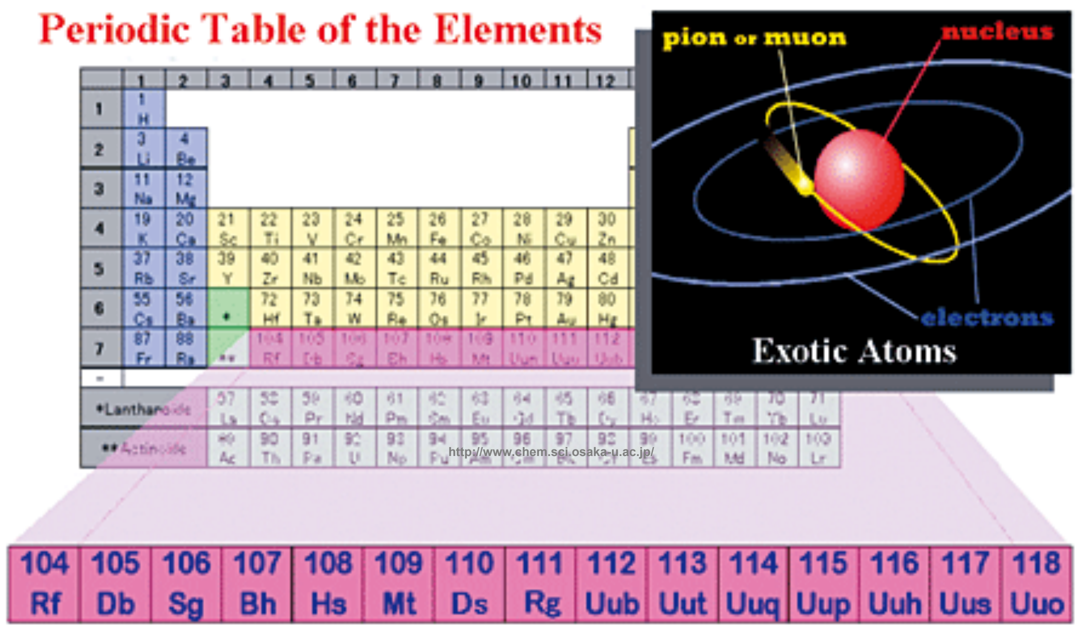
Weak interaction between ΛΛ pairs
No bound states

$$|a_{0\,\Lambda\Lambda}| < |a_{0\,p\Lambda}| < |a_{0\,NN}|$$

Muonic Atoms

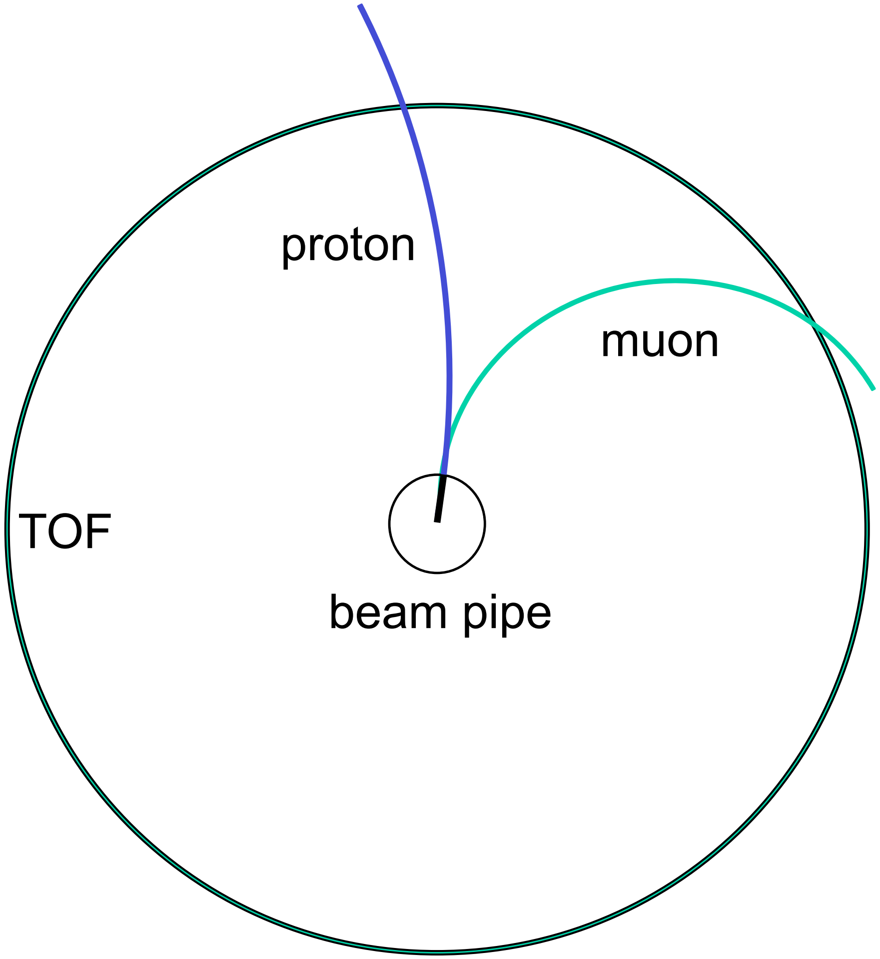
Potential discovery of new atoms

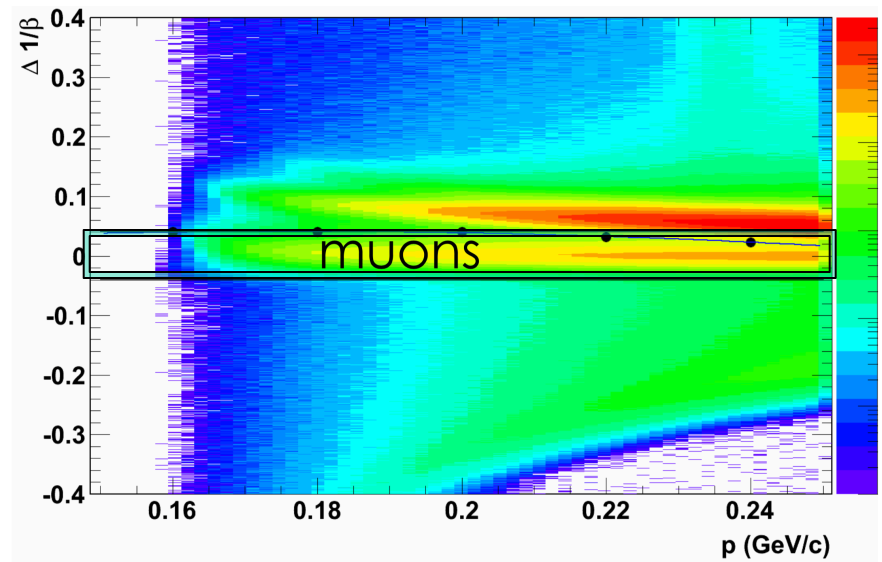
p^{+}-μ^{-}	K^{+}-μ^{-}	π^{+}-μ^{-}
anti-p-μ^{+}	K^{-}-μ^{+}	π^{-}-μ^{+}



A Side Note :
Recently π-k atoms have been observed by DIRAC Collaboration
PRL 117 112001 (2016)

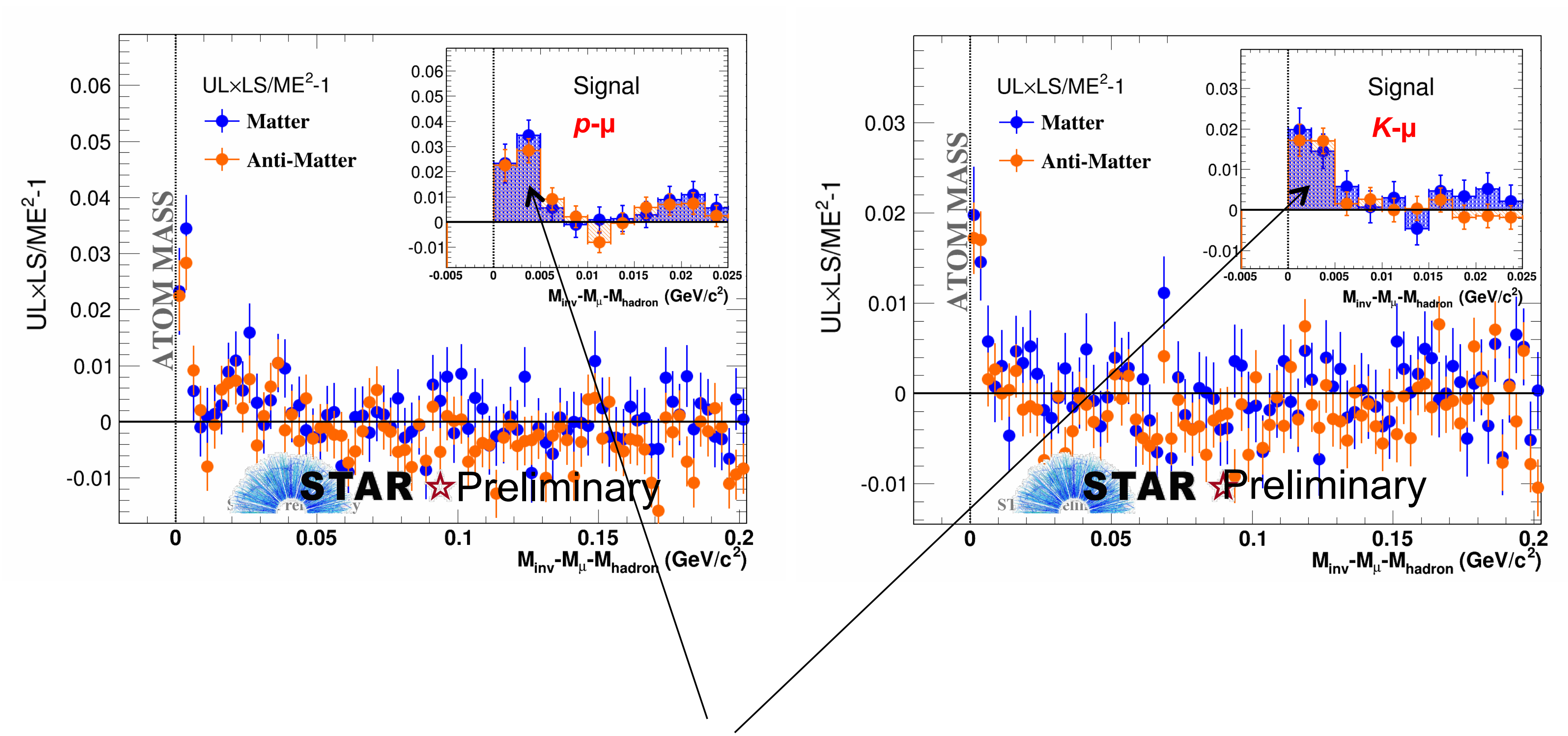
Muonic Atoms





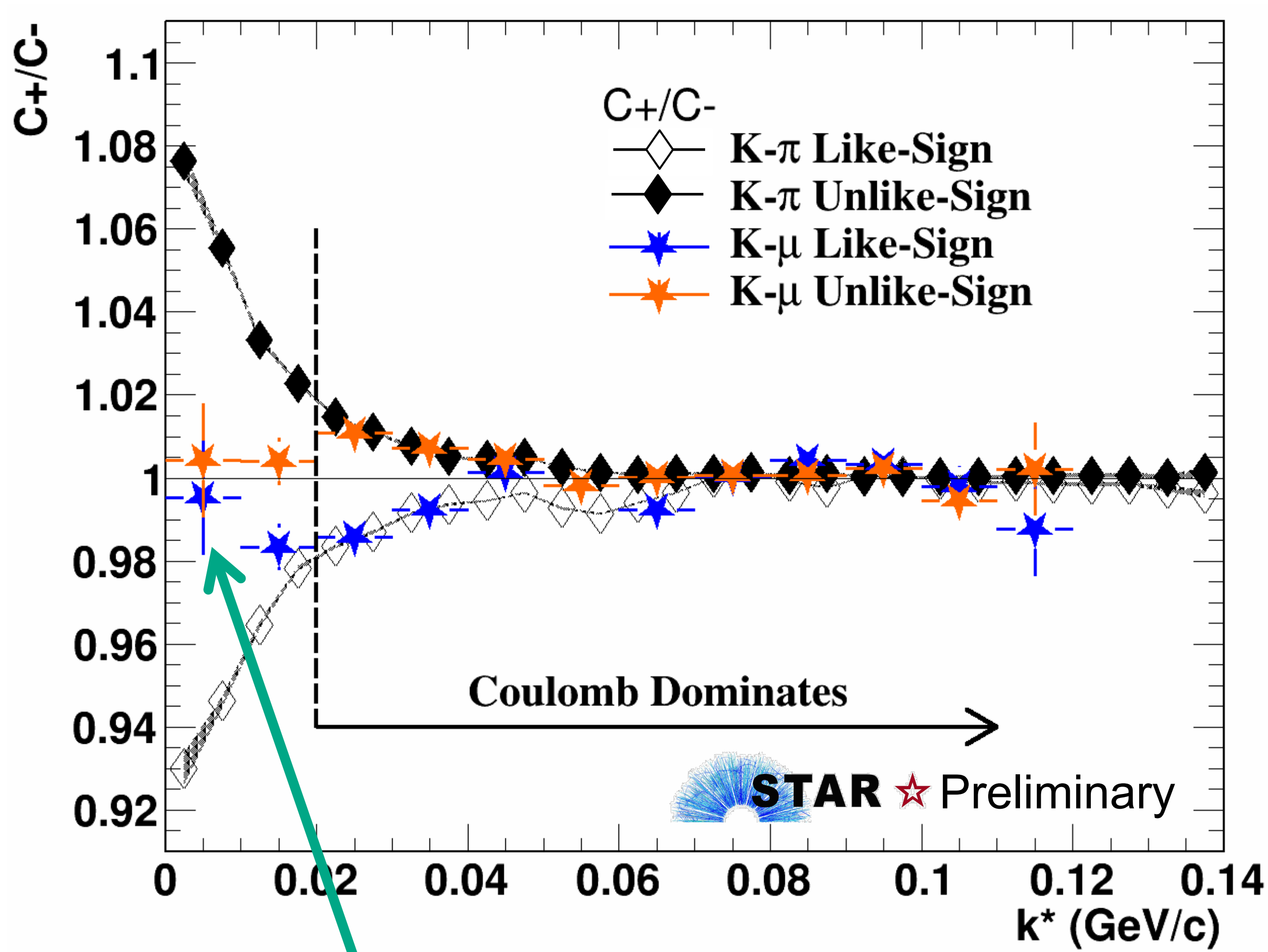
Dissociation at the beam pipe

Muonic Atoms



Sharp peaks observed in the signal region.

Muonic Atoms



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

Evidence for the existence of K-μ atoms.

Summary

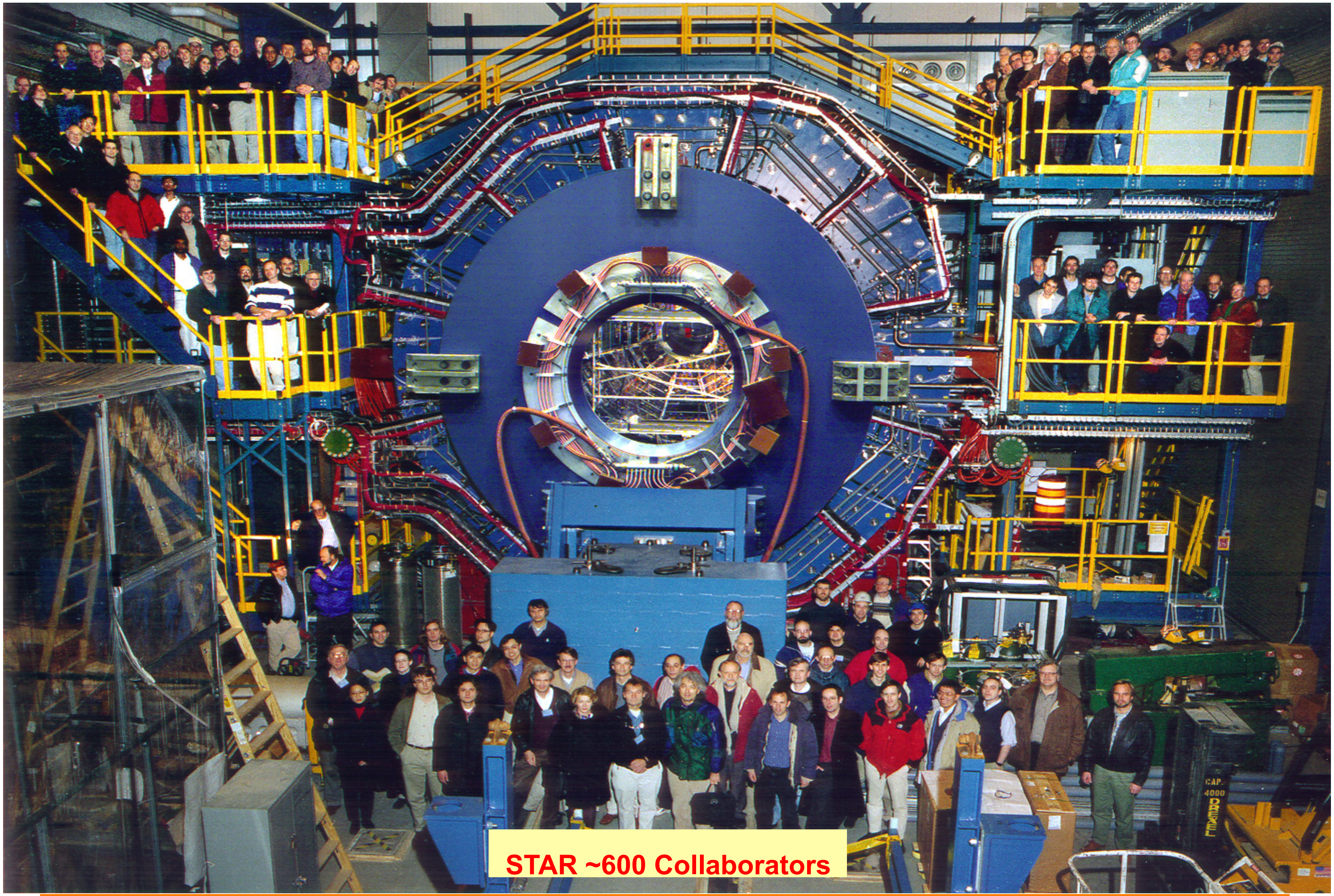
- The study of exotic, anti/hyper-matter expands RHIC's research horizon.

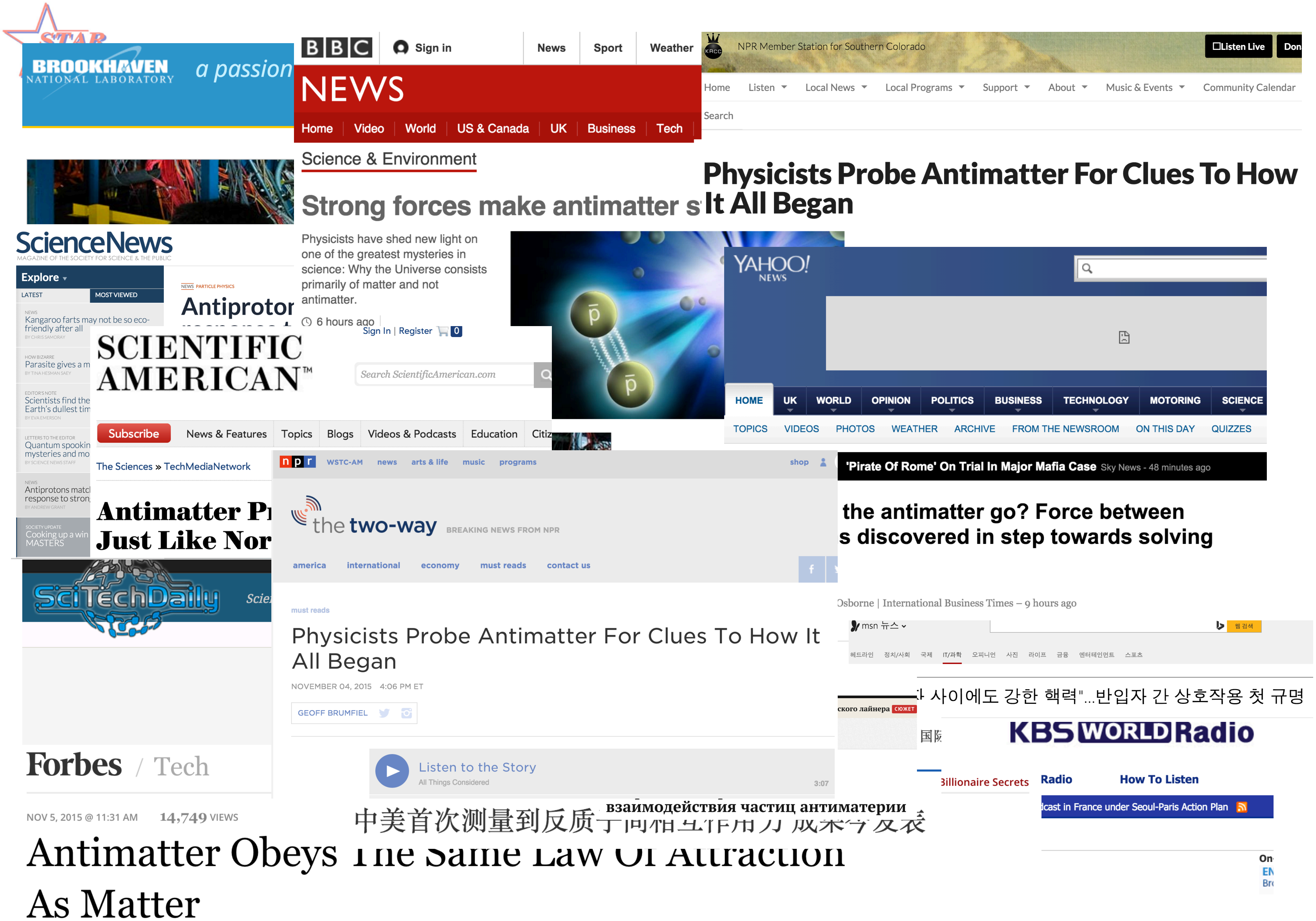
- RHIC is an ideal machine for exotic, anti/hyper-matter production.

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

Backup Slides

STAR experiment at RHIC





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Strong forces make antimatter s
Physicists have shed new light on one of the greatest mysteries in science: Why the Universe consists primarily of matter and not antimatter.
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взаимодействия частиц антиматерии
中美首次测量到反质子间相互作用力 成果今发表

STAR is a multi-purpose detector; with modern capabilities

Period	Physics	Upgrades
2008	Generic	Trigger QT
2009	Generic	TPC/DAQ1000
2010-2011	BES I, PID	TOF
2013--2015	Heavy-Flavor	HFT, MTD
2015--2016	Heavy-Flavor Diffractive, nPDF	FMS, FPS, Roman Pots, HLT
2017	Spin Sign Change Diffractive	FMS Post-shower
2018	Isobar (Zr, Ru), CME, dileptons	(EPD?)
2019--2020	BES II	iTPC, EPD, CBM endcap TOF
2022-2023	High-statistics Unbiased Jets, Open Beauty, PID FF Drell-Yan, Longitudinal correl	Forward Upgrade, HFT+?

>50M$ worth of upgrades going into 2019+

Physics Opportunities beyond BES-II

Physics Goal	Measurements	Requirements							
			Base	fCal	fTS	RP	HFT+	BSMD	Streaming
Nuclear PDFs	DY, Direct photons +J/Psi R_{pA}	★■	✓	✓	Enh				
Nuclear FF	Hadron + Jet	★■	✓						Enh
Polarized Nuclear FF	Hadron + Jet	★	✓						
Odderon & Polarized Diffraction	A_{UT} of pion + forward proton	★		✓		✓			
Low-x ΔG	Di-jets	★	Enh	✓	✓				
High-x Transversity	Hadron+jet	★■		✓	✓				
Mapping the Initial State in 3-D: QGP Transport Properties	R. Plane Rapidity de-correlations	★	Needs iTPC						
	Ridge $\|\Delta\eta\|<3$	★	Needs iTPC						
	Ridge $\|\Delta\eta\|<6$	★	Needs iTPC		✓				
	Forward Energy Flow	★	Needs iTPC	✓					
Effects of Chiral Symmetry at μ_B=0	Di-lepton spectra at μ_B=0	★■	Needs iTPC				HFT out		Enh
	Extended LPV observables	★■	Needs iTPC						Enh
Internal Structure of the QGP and Color Response	Υ(1S,2S,3S)	O	✓						
	B R_{AA}	★■	✓				✓		
	B v_2	★■	✓				✓	✓	✓
	B-tagged Jets	O	✓				✓		
	Jets	O	✓						Enh
	γ –Jets	O	✓					✓	
Phase Diagram and Freeze-out	BES-II Observables at μ_B=0	★	Needs iTPC						
	C6/C2, C4/C2	★	Needs iTPC						
The Strong Force	Exotics and Bound States (di-Baryons)	★	Needs iTPC						✓

1. **Define QCD Phase Structure**
2. **Study Chiral Properties**
3. **Map T dependence of [?]/s**
4. **Test KT factorization and Universality**

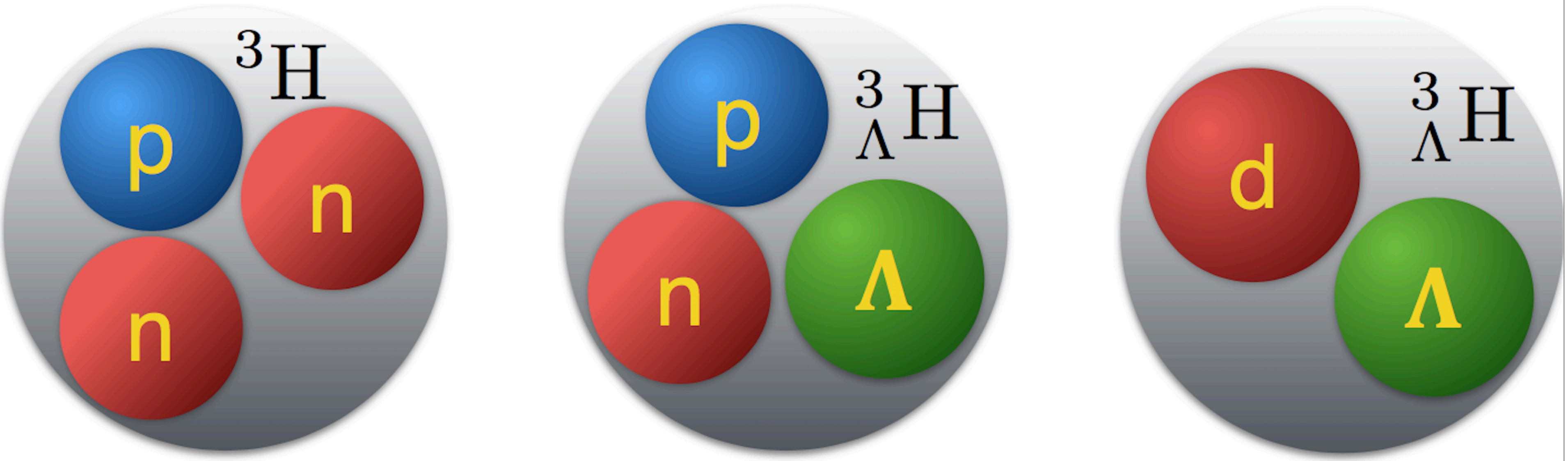
Extended coverage and targeted upgrades open up many opportunities for a diverse scientific program in 2020+

✓ Measurement needs upgrade   Enh : Enhances measurement, but is not required

★ Unique to STAR   O Complementary to sPHENIX   ■ Complemented by LHC and/or JLab

Green highlighted rows require only continued running with STAR as instrumented for the BES-II

Base : STAR as instrumented for the BES-II
iTPC : Inner sector TPC upgrade extending coverage from $|\eta|<1$ to $|\eta|<1.5$
fTS : Forward Tracking System
fCal : Forward Electromagnetic and Hadronic Calorimeters
HFT+ : An extended faster heavy flavor tracker
Streaming : An electronics and DAQ upgrade allowing significant increase in minbias data rate
BSMD : Replacing the BSMD readout
HFT out: Di-lepton spectra at μ_B=0 improved by running with less material

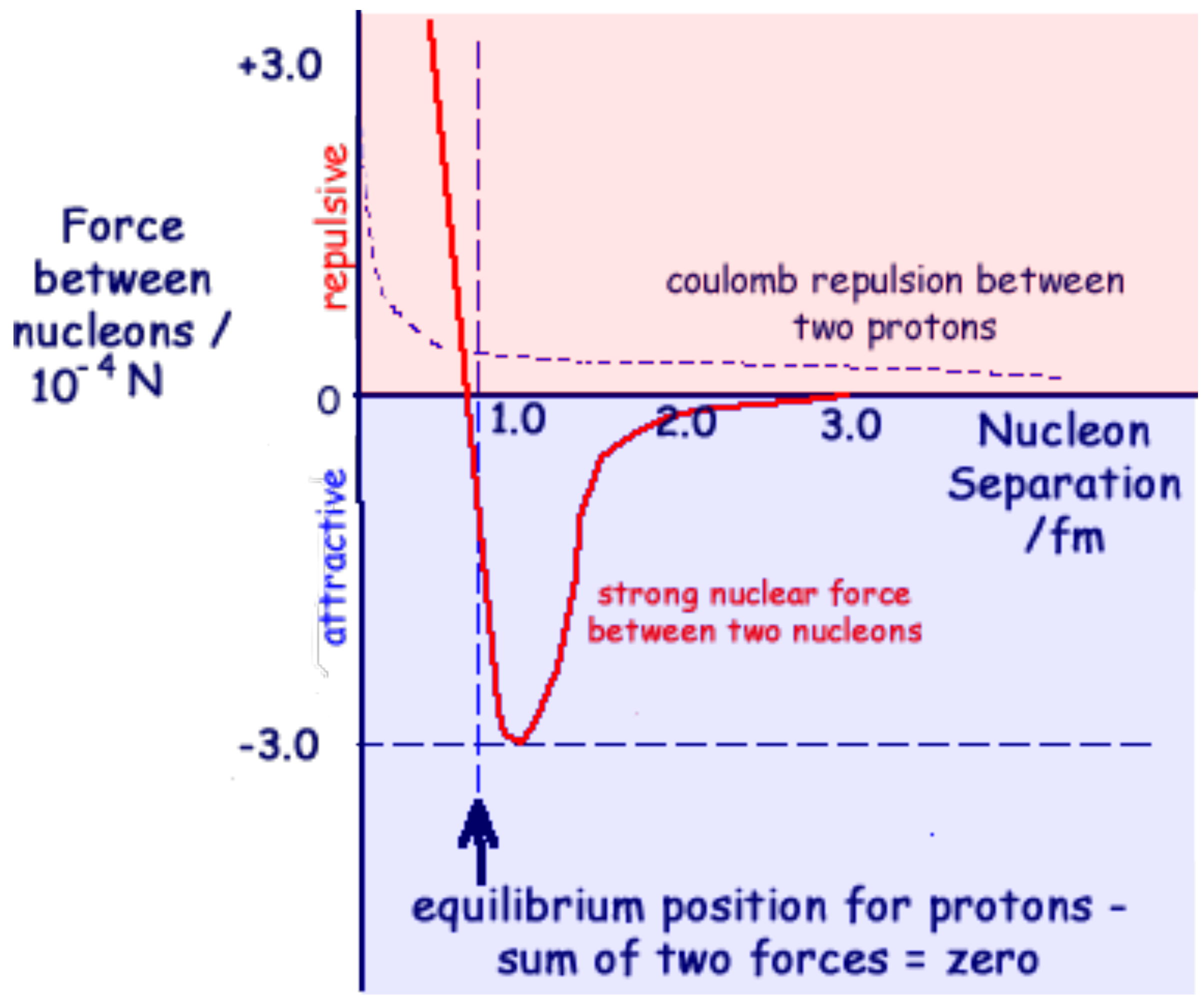


$$^{3}_{\Lambda}H \rightarrow {}^{3}He + \pi^{-}$$

small B_{Λ} → $\tau \rightarrow \tau_{\Lambda}$; 3-body decay, $R(\frac{2}{2+3})$ ↓

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

large B_{Λ} → $\tau < \tau_{\Lambda}$; 2-body decay, $R(\frac{2}{2+3})$ ↑



+3.0
repulsive
Force between nucleons / 10^{-4} N
coulomb repulsion between two protons
0
1.0
2.0
3.0
Nucleon Separation /fm
attractive
strong nuclear force between two nucleons
-3.0
equilibrium position for protons - sum of two forces = zero

Connecting *f*0 & *d*0 to CF

The theoretical correlation function can be obtained with

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

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

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

$$f_c(k^*) = \left[\frac{1}{f_0} + \frac{1}{2} d_0 k^{*2} - \frac{2}{a_c} h(\eta) - ik^* A_c(\eta) \right]^{-1}$$ is the s-wave scattering amplitude

renormalized by Coulomb interaction.

$\eta = (k^* a_c)^{-1}$, $a_c = 57.5$ fm

$\rho = k^* r^*$, $\xi = k^* r^* + \rho$

$A_c(\eta) = 2\pi\eta \left[\exp(2\pi\eta) - 1 \right]^{-1}$

F is the confluent hypergeometric function

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