BROOKHAVEN NATIONAL LABORATORY

STAR

ATHIC2014 OSAKA

Exotics Search in STAR at RHIC

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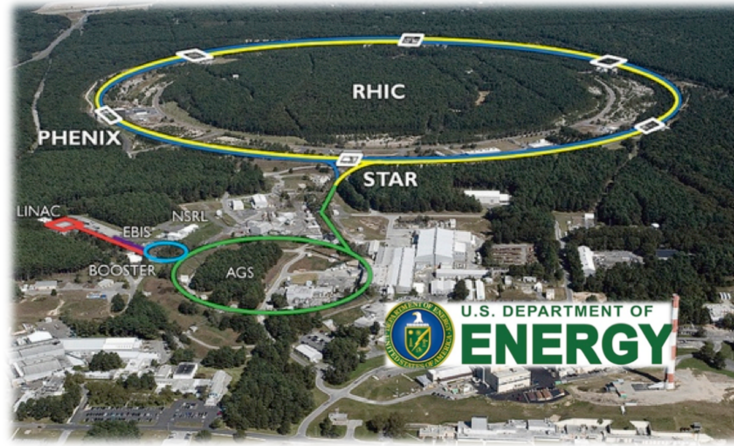
Rice University

RICE

The 5th ATHIC, Aug. 5-8, 2014, Osaka

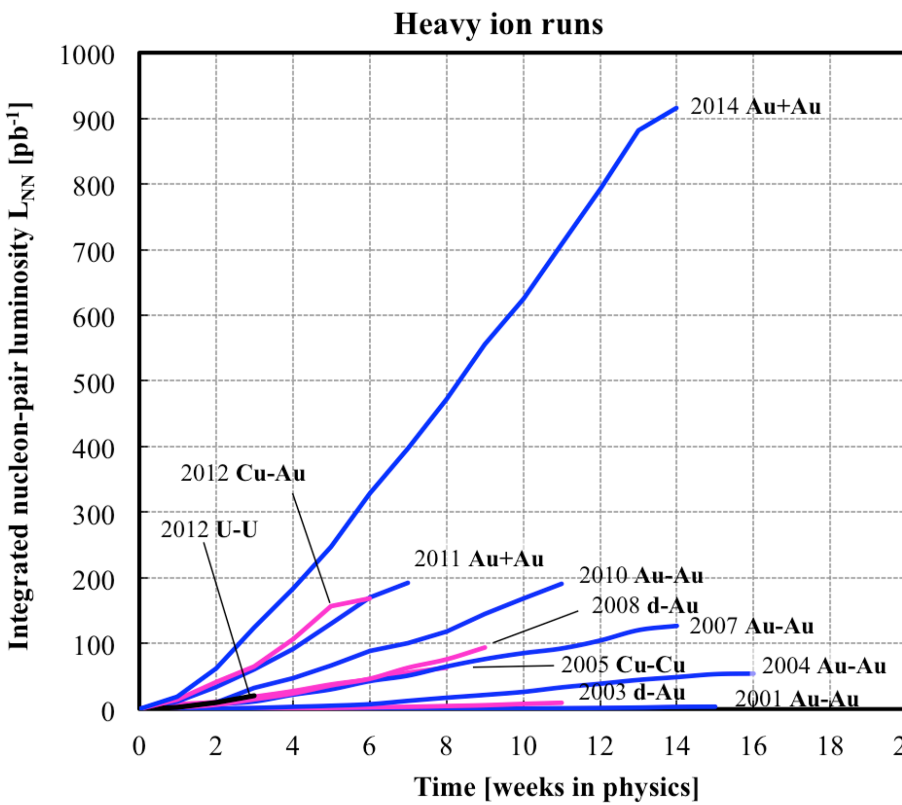
Exotics Search in STAR



- ★ RHIC/STAR experiment
  - ★ Collisions
  - ★ Detectors
- ★ STAR Search results
  - ★ **Strangelet** – a multiquark state
  - ★ **Hypertriton** – first antimatter hypernucleus
  - ★ **Anti-He^4** – heaviest antimatter
- ★ Recent Search
  - ★ **Muonic atom** – new exotic atoms
  - ★ **Hypertriton 3-body channel** – more precise measurement
  - ★ **Dibaryon** – another multiquark state

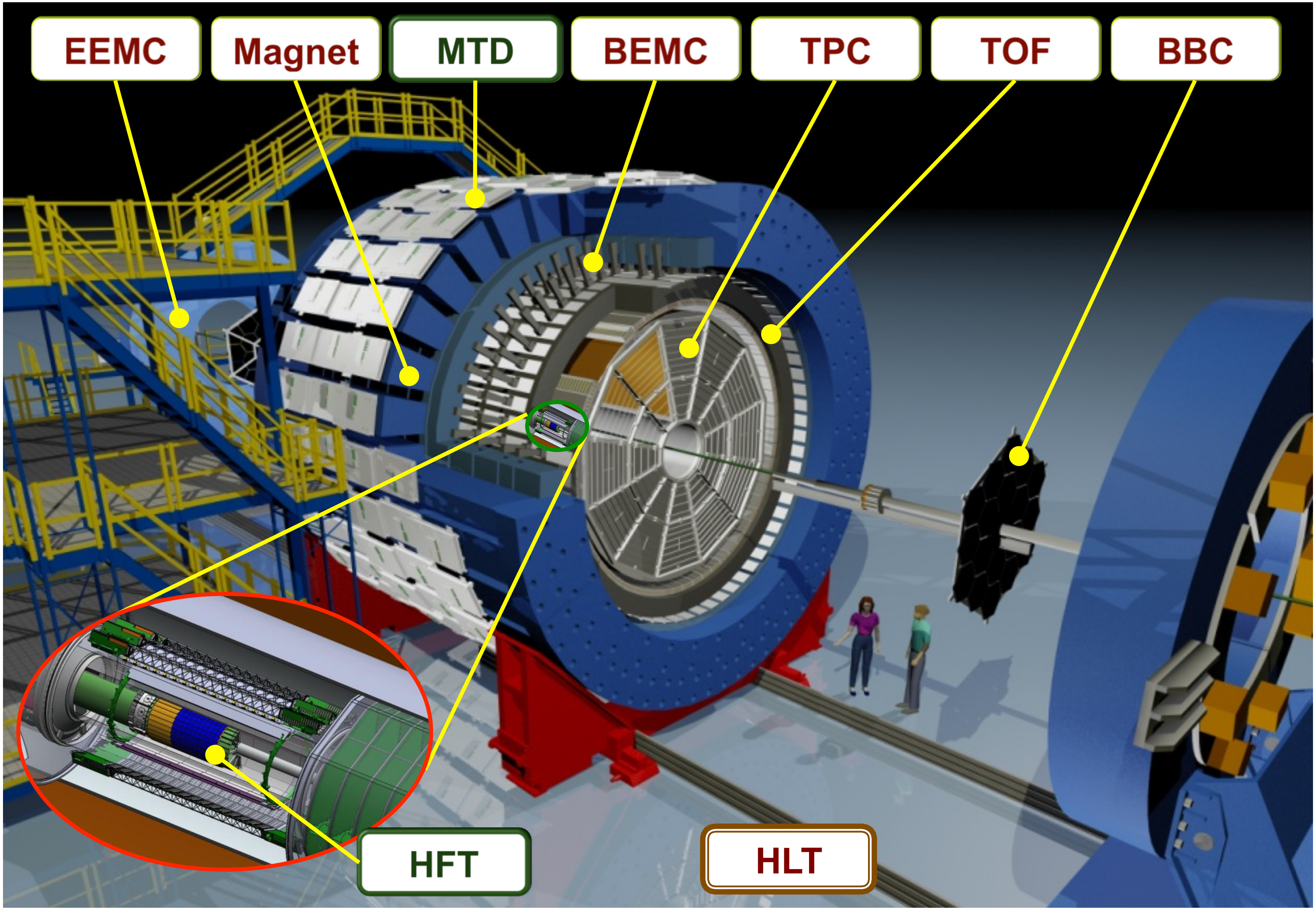
Collisions and Data Taken

Collision Species	C.M. Energy per nucleon pair (GeV)
Au+Au	200, 130, 62.4, 39, 27, 19.6, 14.5, 11.5, 7.7
U+U	193
Cu+Cu	200, 62.4, 22.4
Cu+Au	200
He^3+Au	200
d+Au	200
Polarized p+p	500/510, 200, 150, 62.4
Fixed target collisions	Lower energies

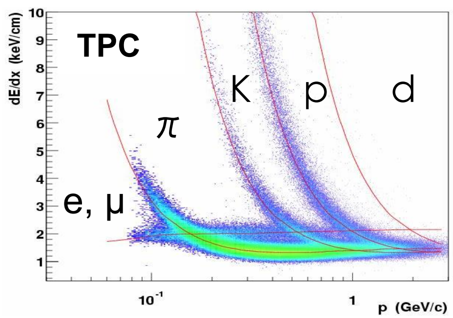


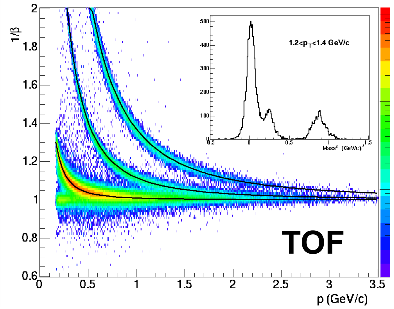
Higher Luminosity, more events – exotics!

STAR Detector System

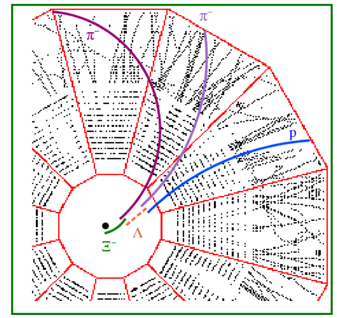


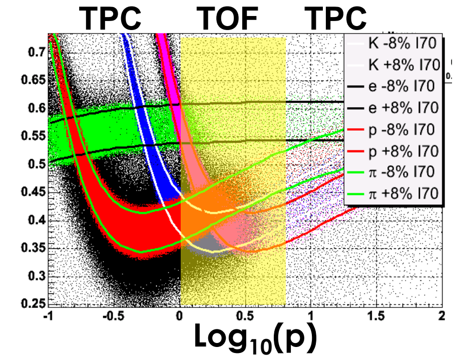
Particle Identification at STAR



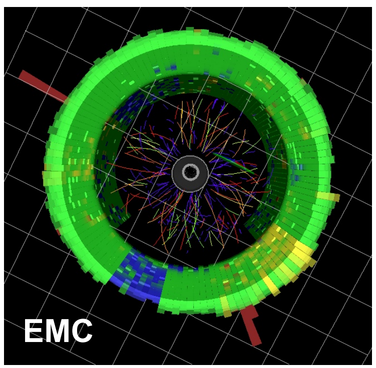


Charged hadrons

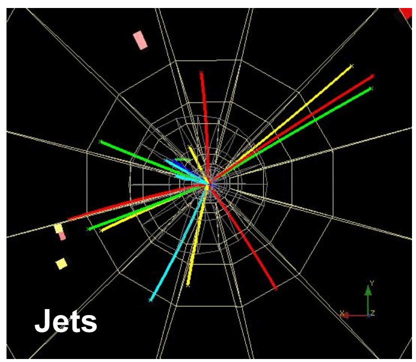




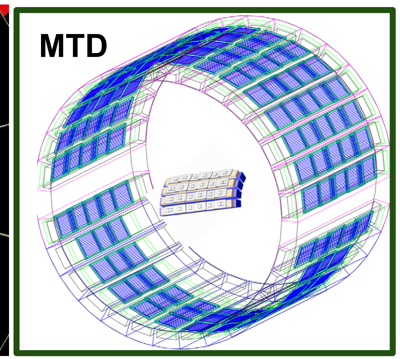
Hyperons & Hyper-nuclei



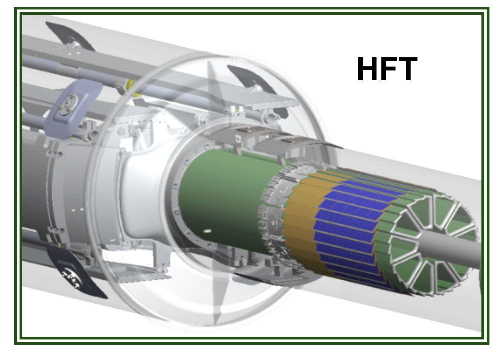
Neutral particles



Jets & Correlations



High p_T muons

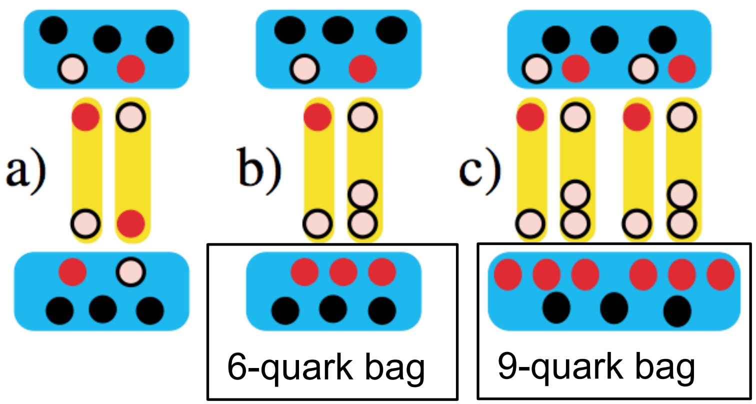


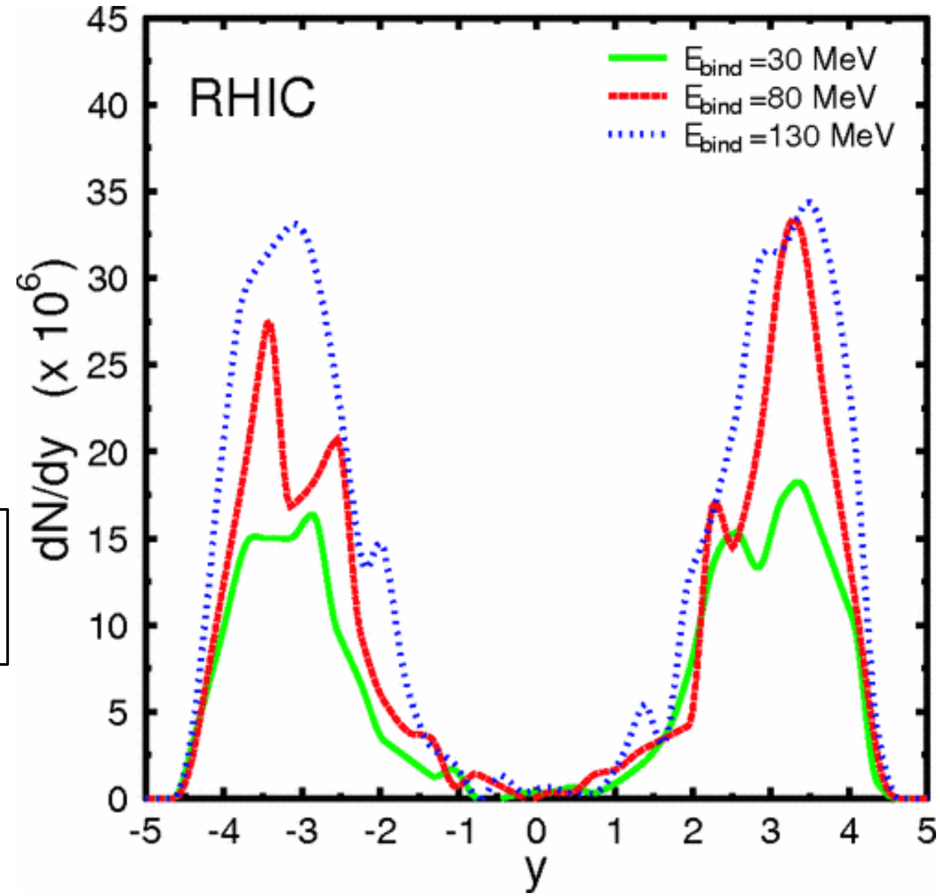
Heavy-flavor hadrons

Wide acceptance and excellent particle identification

Strangelet

A bag with 6 quarks: uuddss
Predicted mass:
~$2m_{\Lambda}$-80MeV
Stable in strong decays





Parton-Based Gribov-Regge Theory

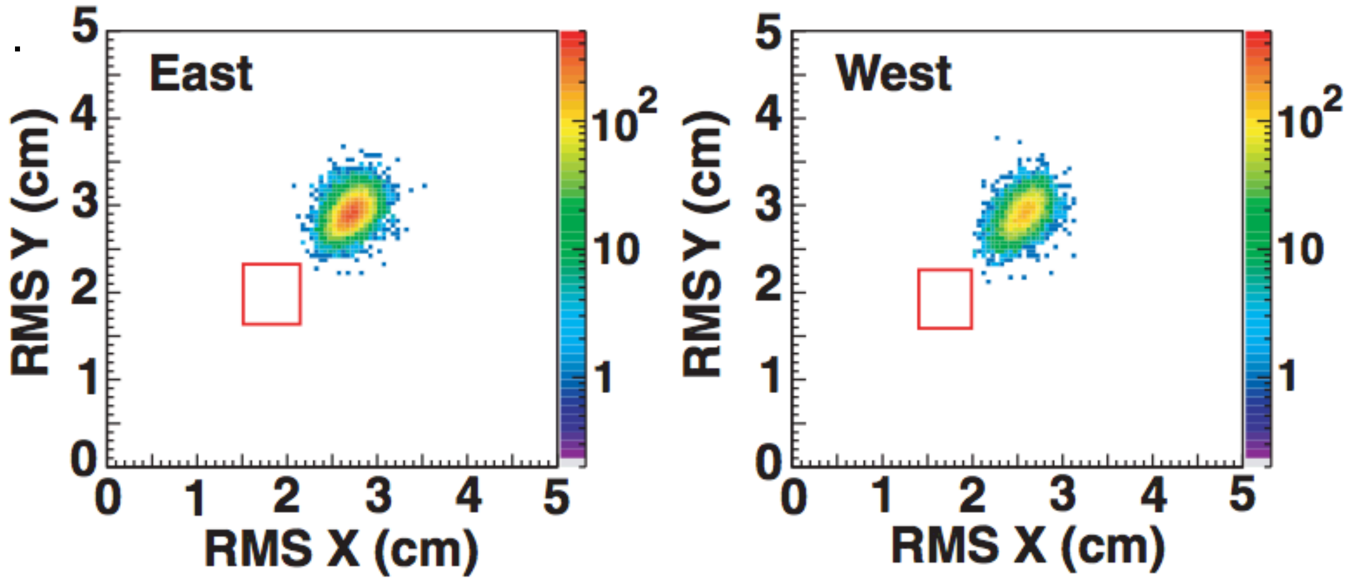
Peaks around the beam

Strangelet theorized to form in the remnants

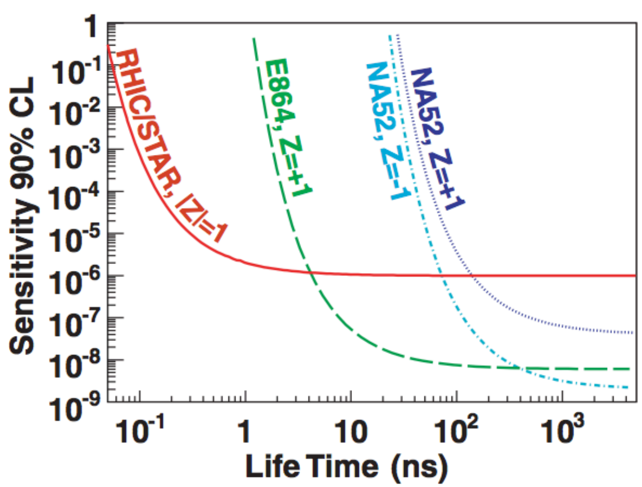
M. Bleicher PRL 92, 072301 (2004)

Strangelet

Distribution of RMS from shower maximum detector in zero degree calorimeters around the beam

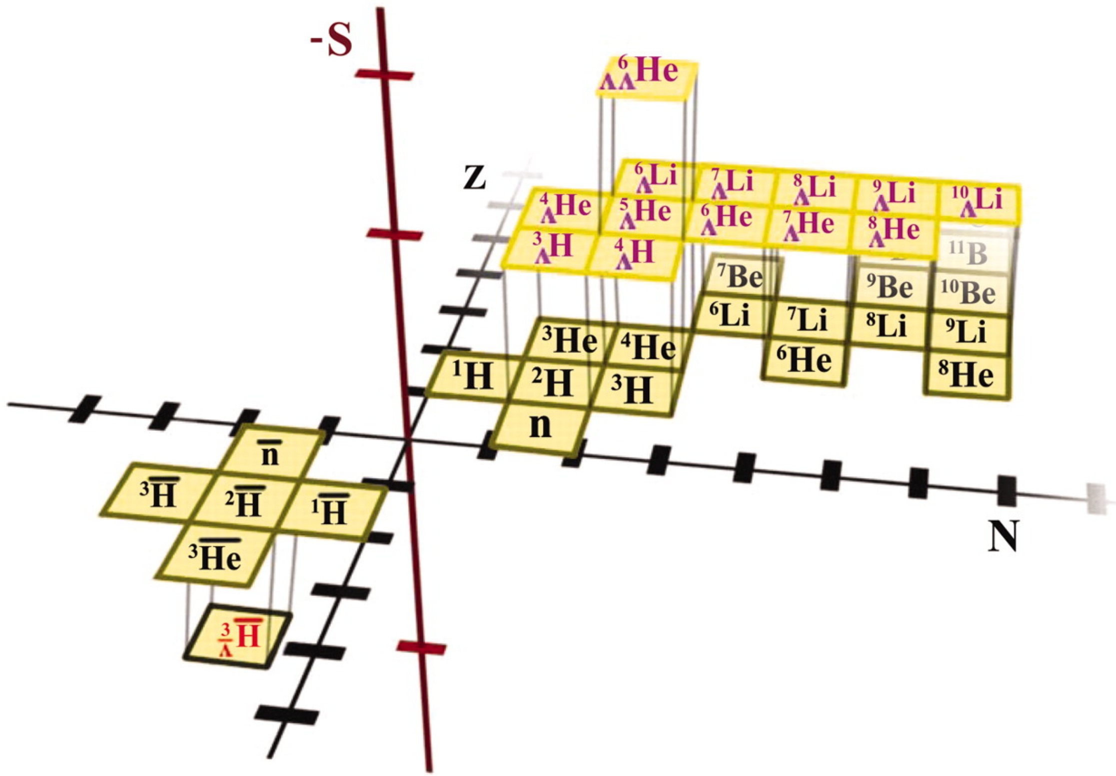


Candidates are expected to show up in the red boxes on the left.



Previous STAR search in the forward region **found no candidates**
STAR PRC**76**, 011901(2007)

(Anti-)Hypertriton

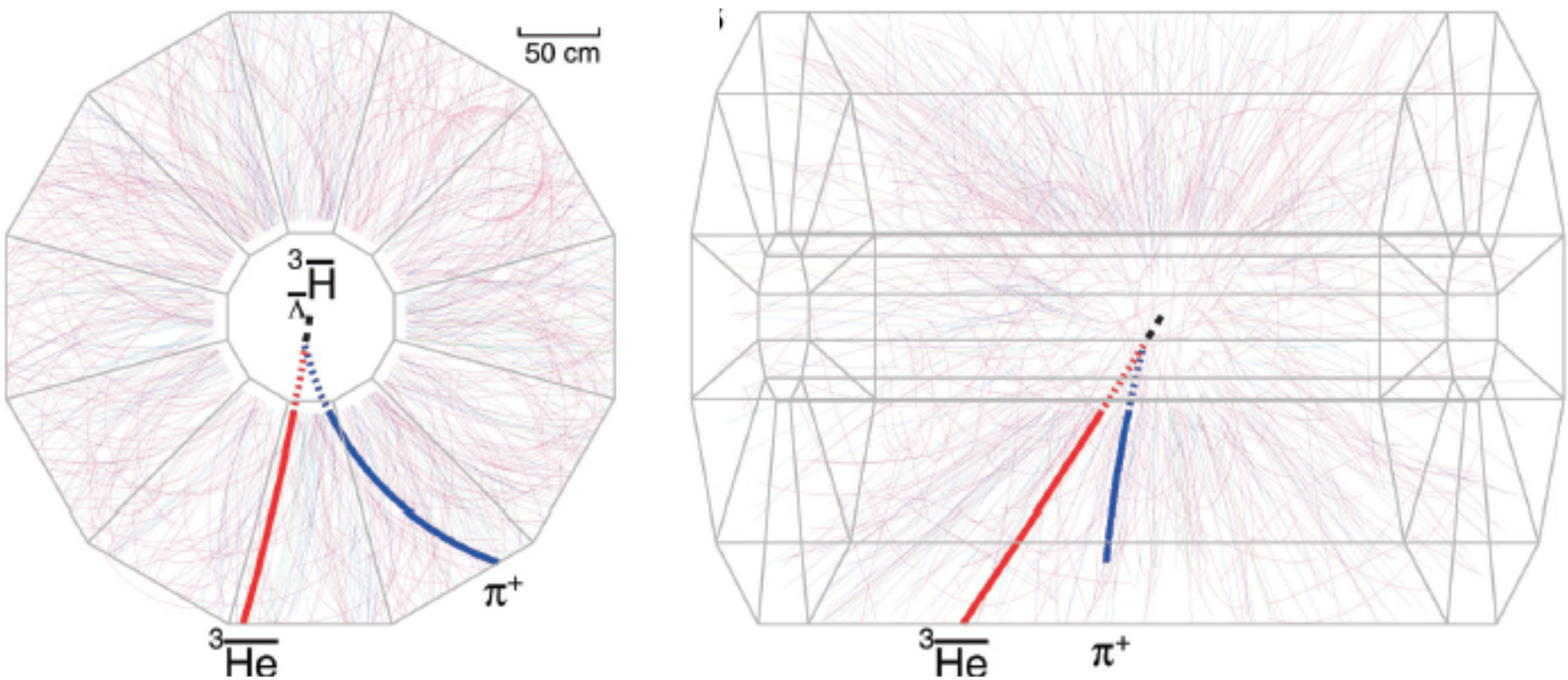


STAR has observed **the first** antimatter hypernucleus at RHIC!

Science AAAS

Observation of an Antimatter Hypernucleus
The STAR Collaboration
Science **328**, 58 (2010);
DOI: 10.1126/science.1183980

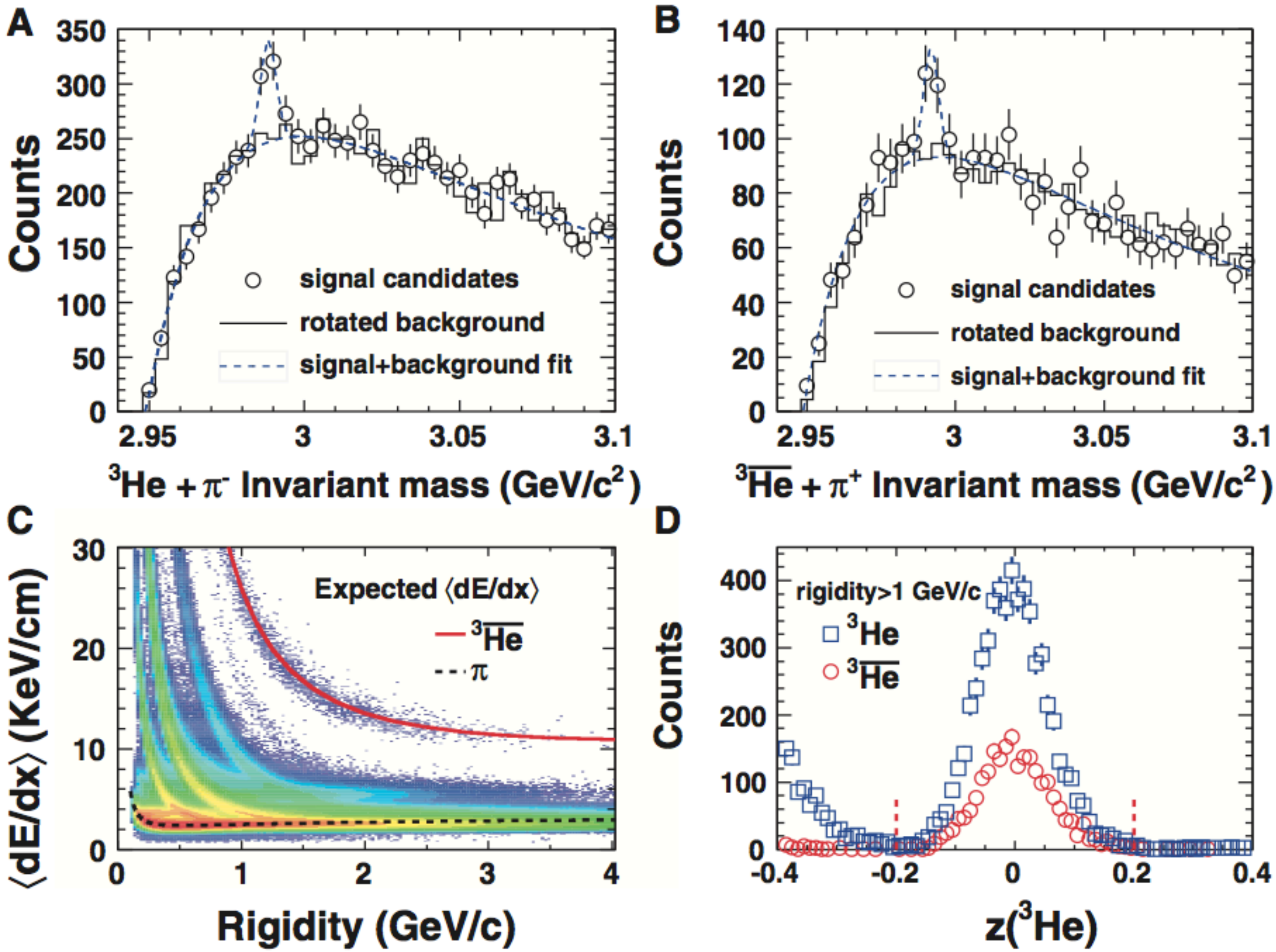
(Anti-)Hypertriton



An event display in TPC with an antimatter hypertriton

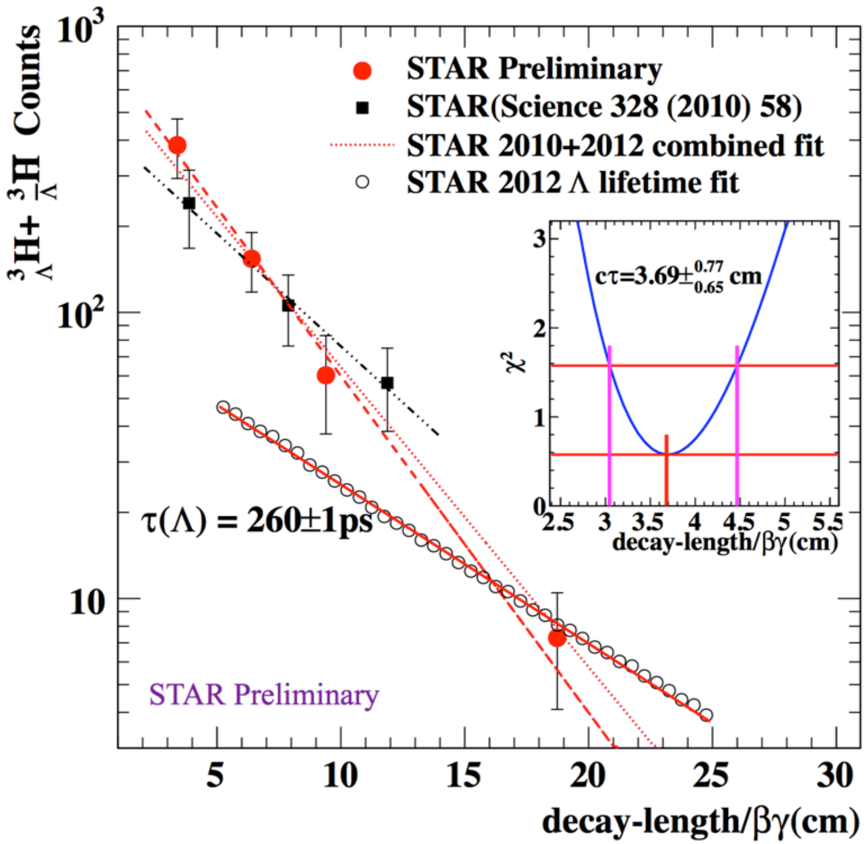
- Yield measurement
- Lifetime measurement

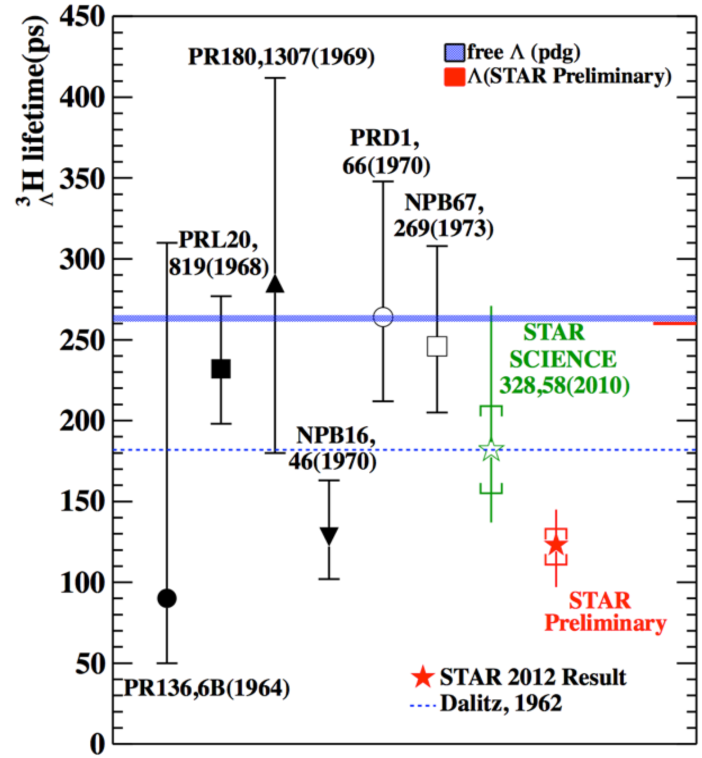
Hypertriton



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

Hypertriton

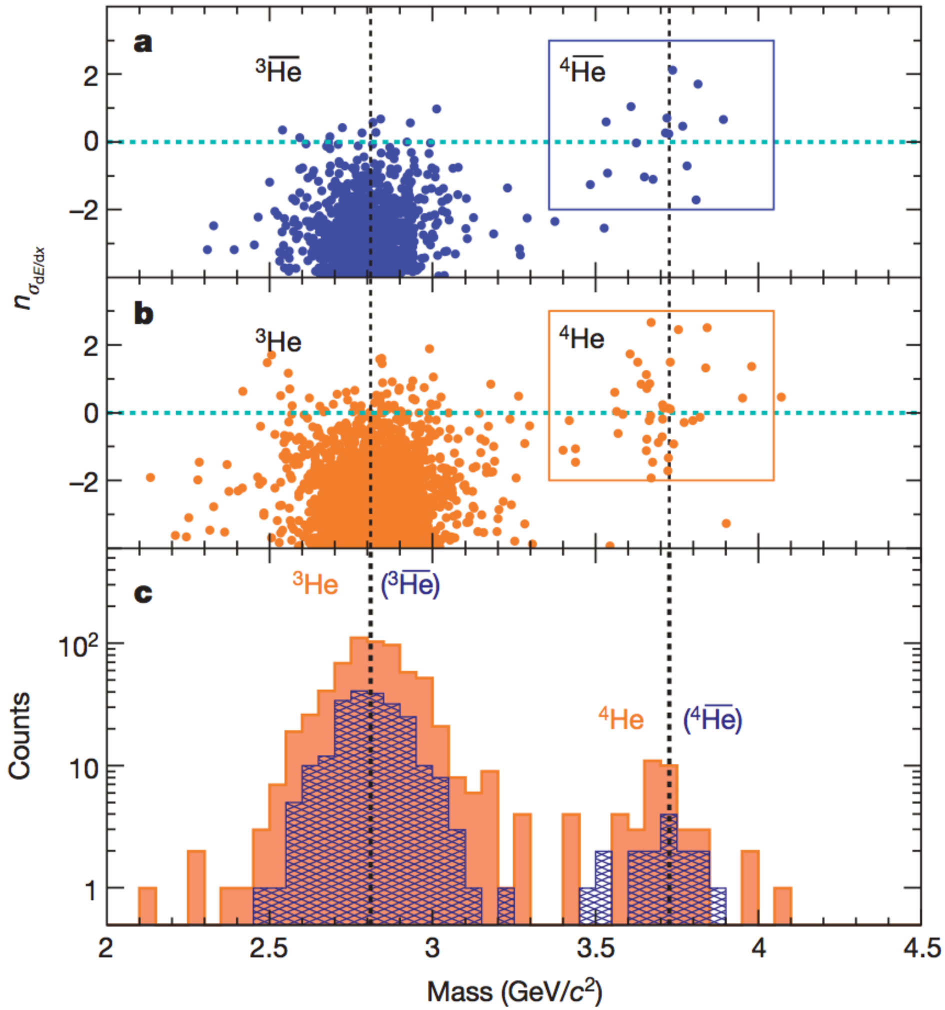


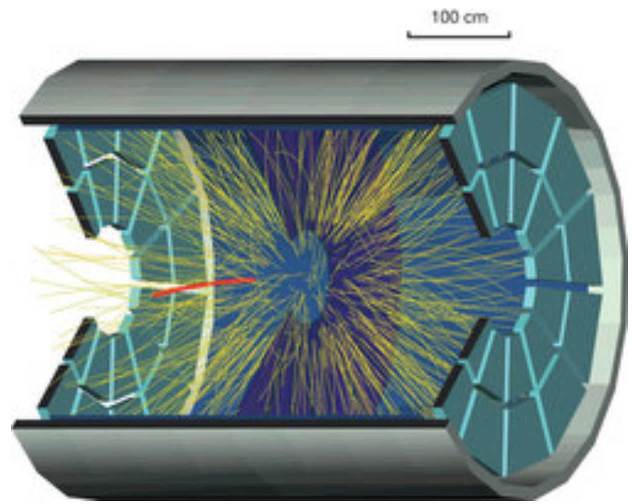


Beam Energy Scan I Combined different energies for more precise measurement

$$\sqrt{S_{NN}} = 7.7, 11.5, 19.6, 27, 39, 200$$

Anti-Alpha

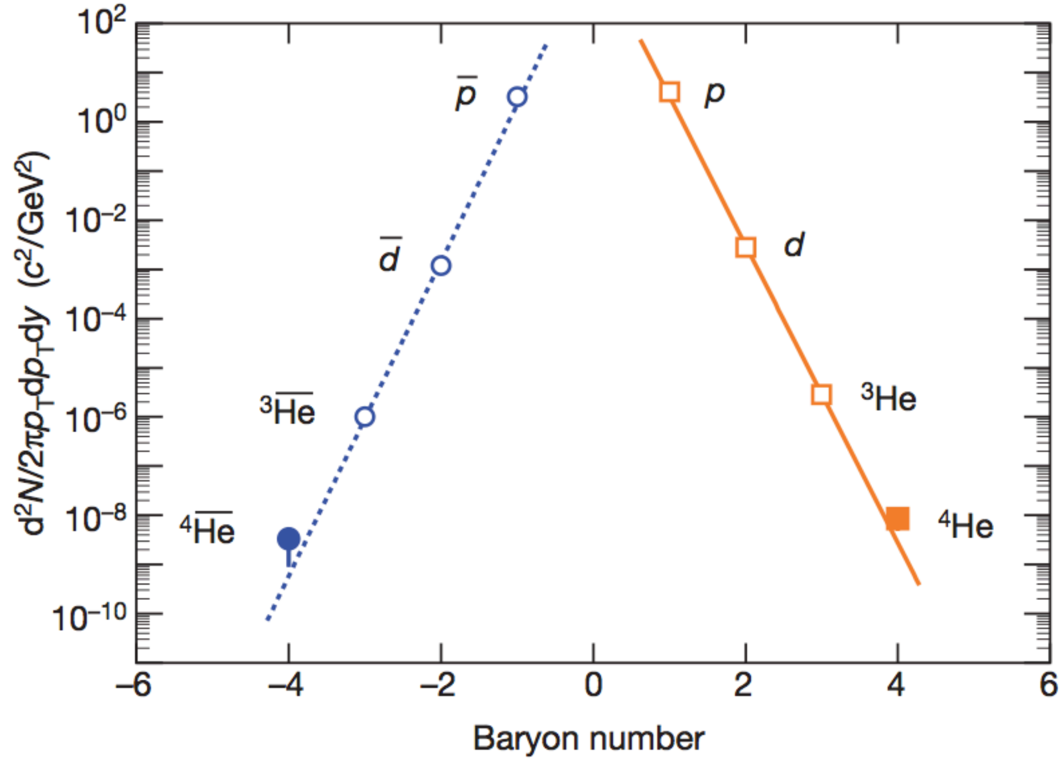




STAR *Nature* **473**, 353–356

STAR discovered the heaviest antimatter nucleus yet!

Anti-Alpha

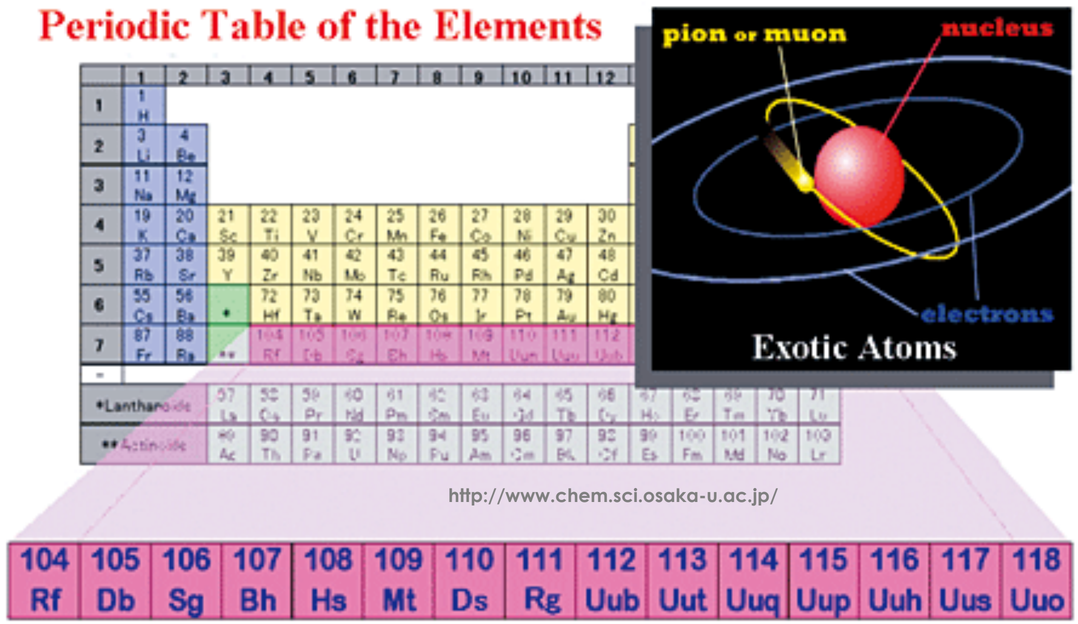


Differential invariant yields as a function of baryon number

New Searches

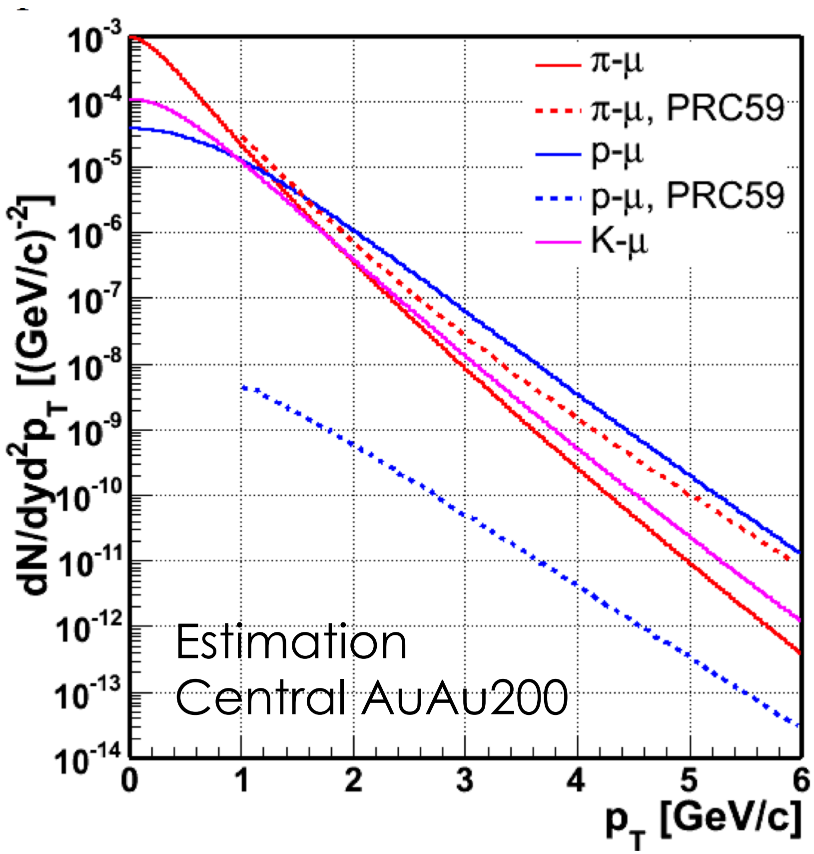
Muonic Atom

Potential discovery of new atoms



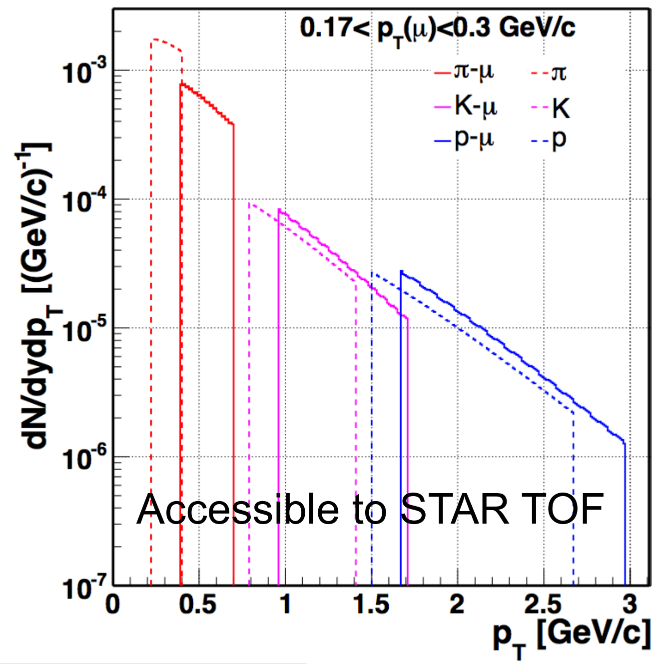
p^{+}-μ^{-}	K^{+}-μ^{-}	π^{+}-μ^{-}
anti-p-μ^{+}	K^{-}-μ^{+}	π^{-}-μ^{+}

Muonic Atom



Estimation based on: QED!!!

$$\frac{dN_{\rm atom}}{dy d^2 p_{\perp,\rm atom}} = 8\pi^2 \zeta(3) \alpha^3 m_{\rm red}^2 \frac{dN_h}{dy d^2 p_{\perp,h}} \frac{dN_l}{dy d^2 p_{\perp,l}}.$$

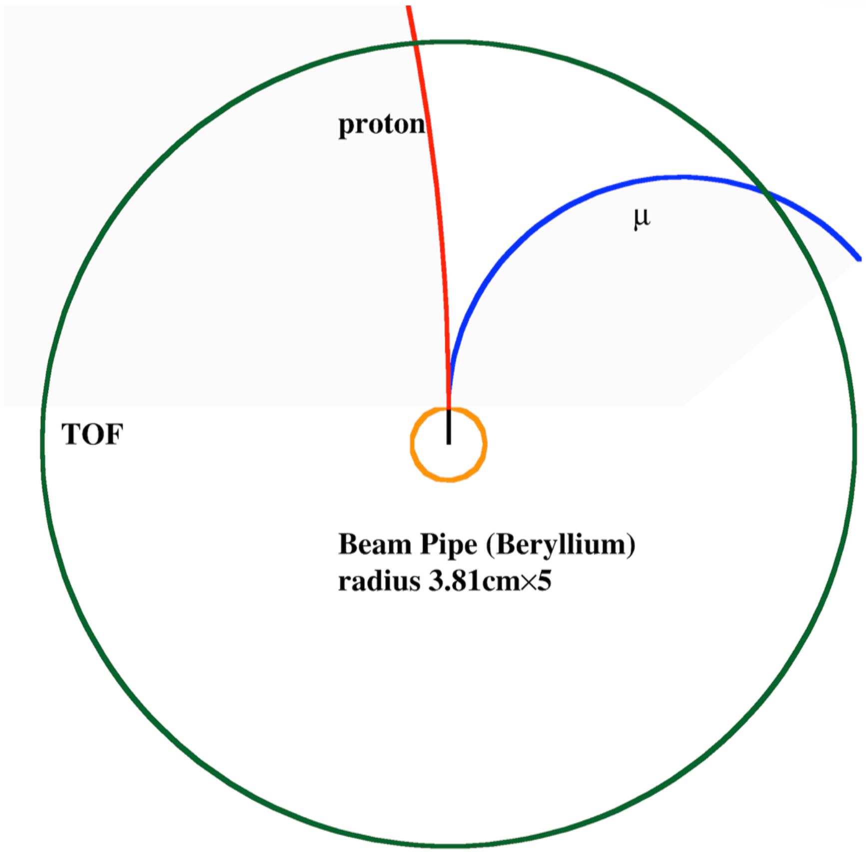


In heavy-ion physics, it provides a direct measurement of **early produced muon** emission which is sensitive to the early stage of the collisions.

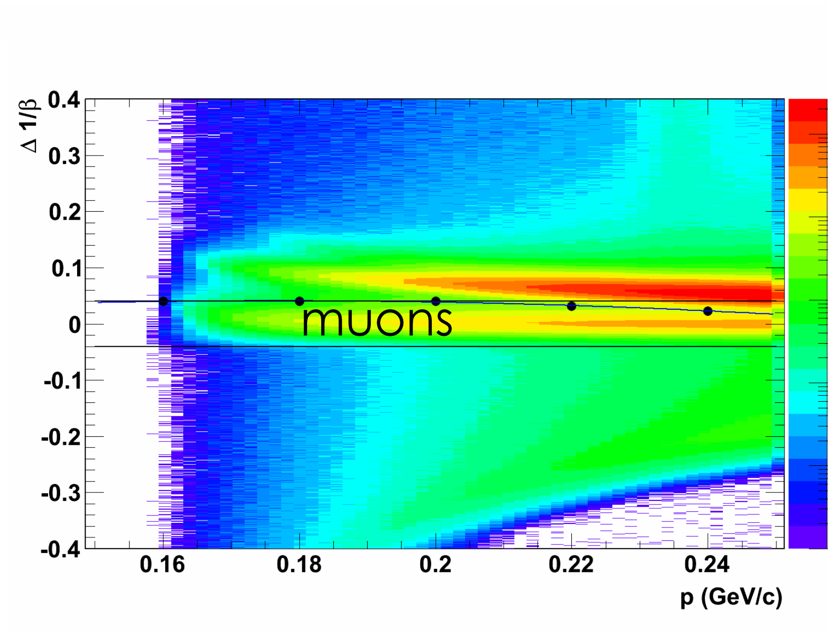
Kapusta&Mocsy PRC 59 2937
2010 STAR Decadal Plan

Muonic Atom

1> Dissociation of the atoms before the detector



2> Particle Identification



Particle Momentum (GeV/c)

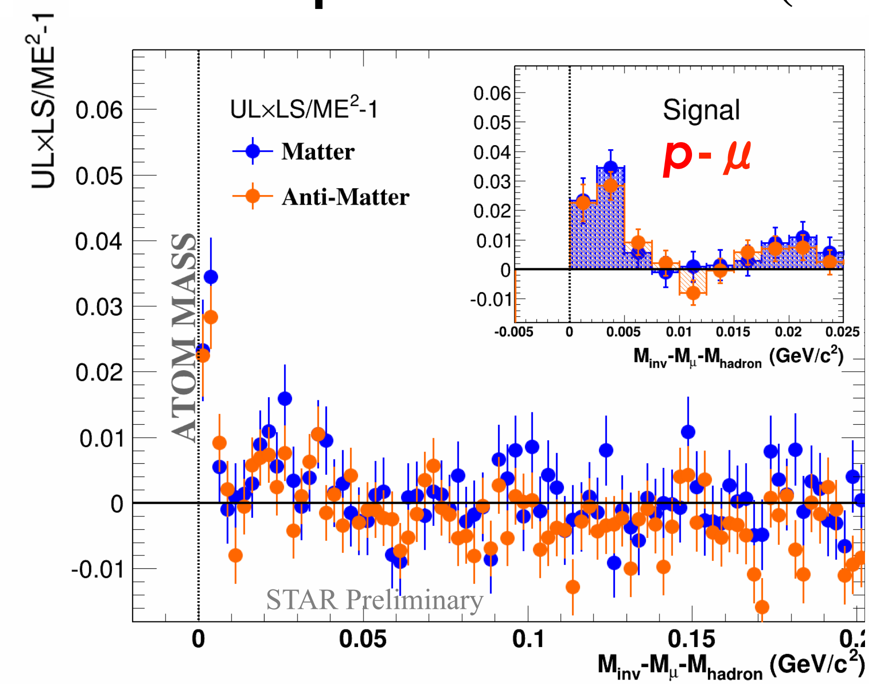
Atom	μ	Hadron
p-μ	0.15-0.25	1.3-2.2
K-μ	0.15-0.25	0.7-1.17

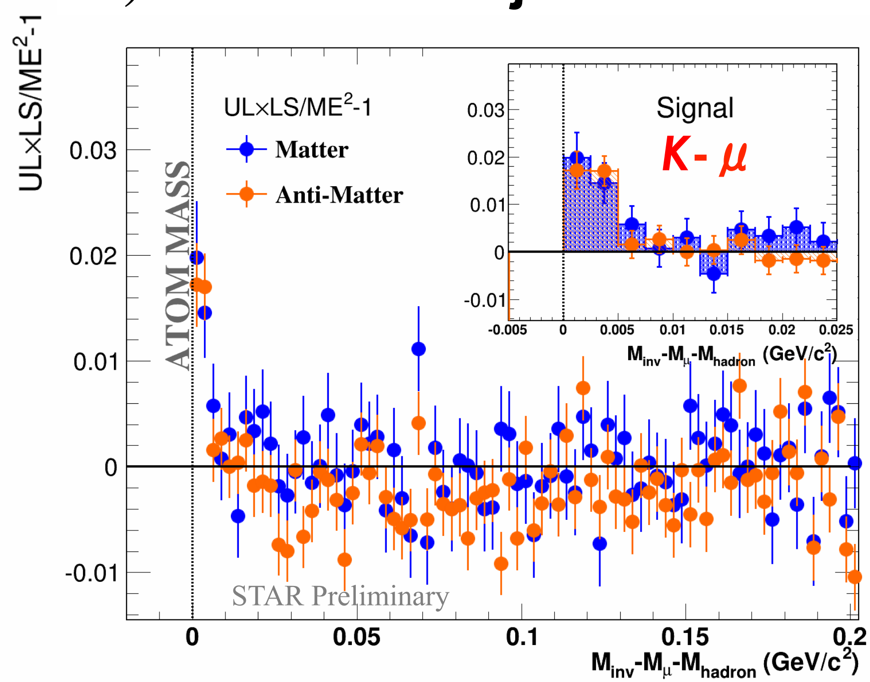
Muonic Atom

In pair invariant mass method:

- UL: UnLike-sign pairs have different charges -- attractive Coulomb
- LS: Like-Sign pairs have same charges -- repulsive Coulomb
- ME: Mixed-Event pairs – no Coulomb

We adopt the observable $(UL \times LS)/ME^2 - 1$ **to reject Coulomb**

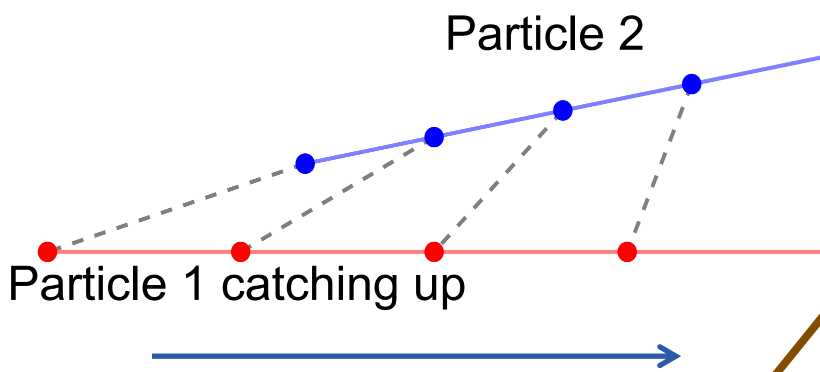




Sharp peaks observed at the signal region.

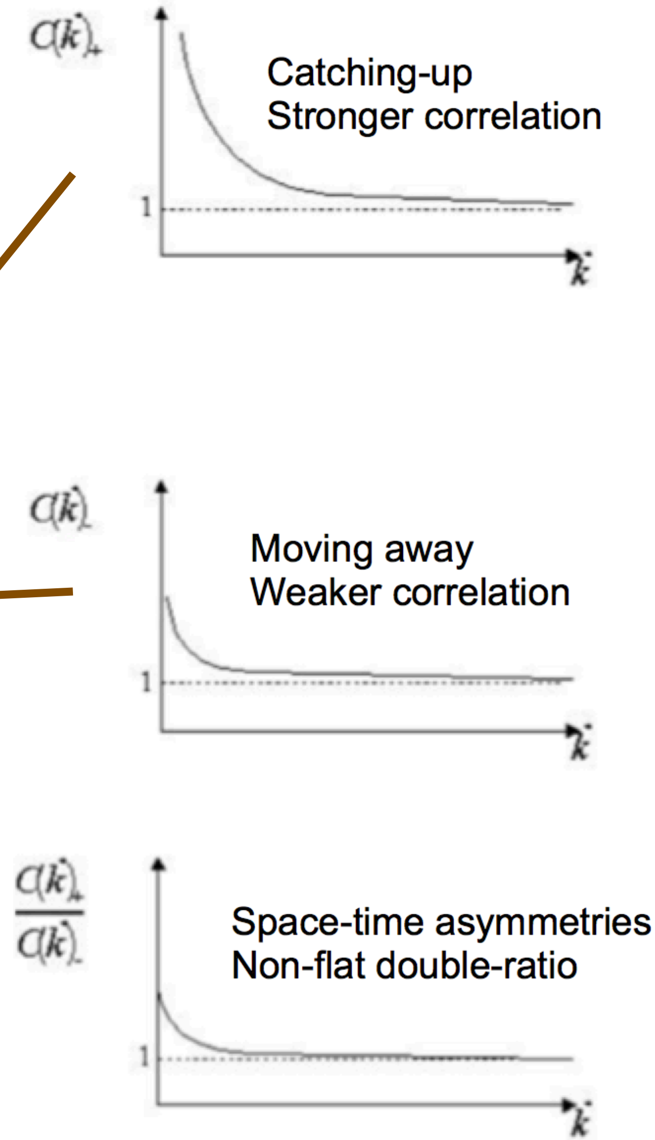
Muonic Atom

Another tool: the correlation as a function of k* -- the magnitude of momentum of either particle in pair rest frame



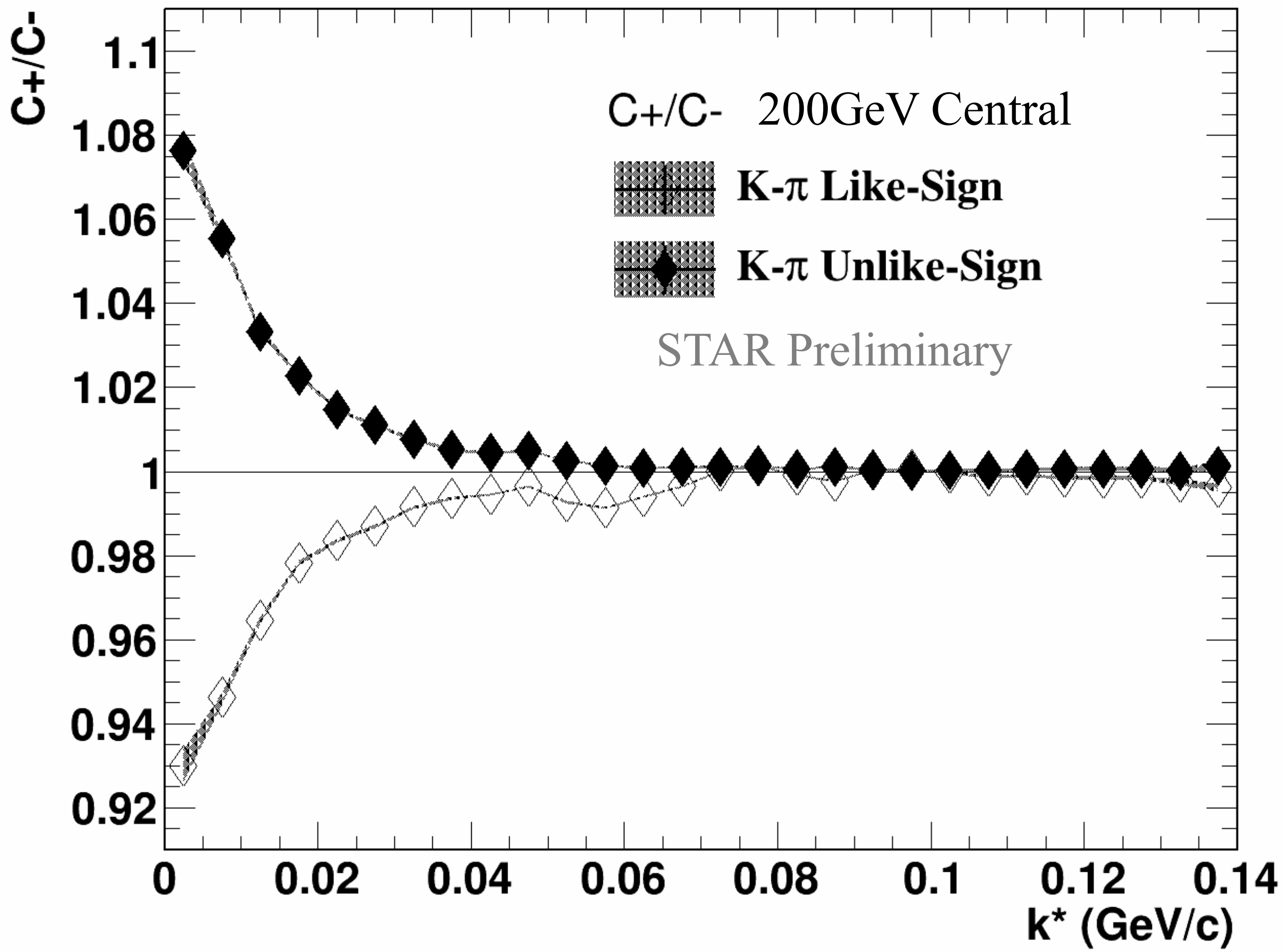
Correlation function:
Normalized relative momentum distribution of the leading particle in pair frame

Double ratio: a probe of space time asymmetries



STAR PRL 91 (2003) 262302

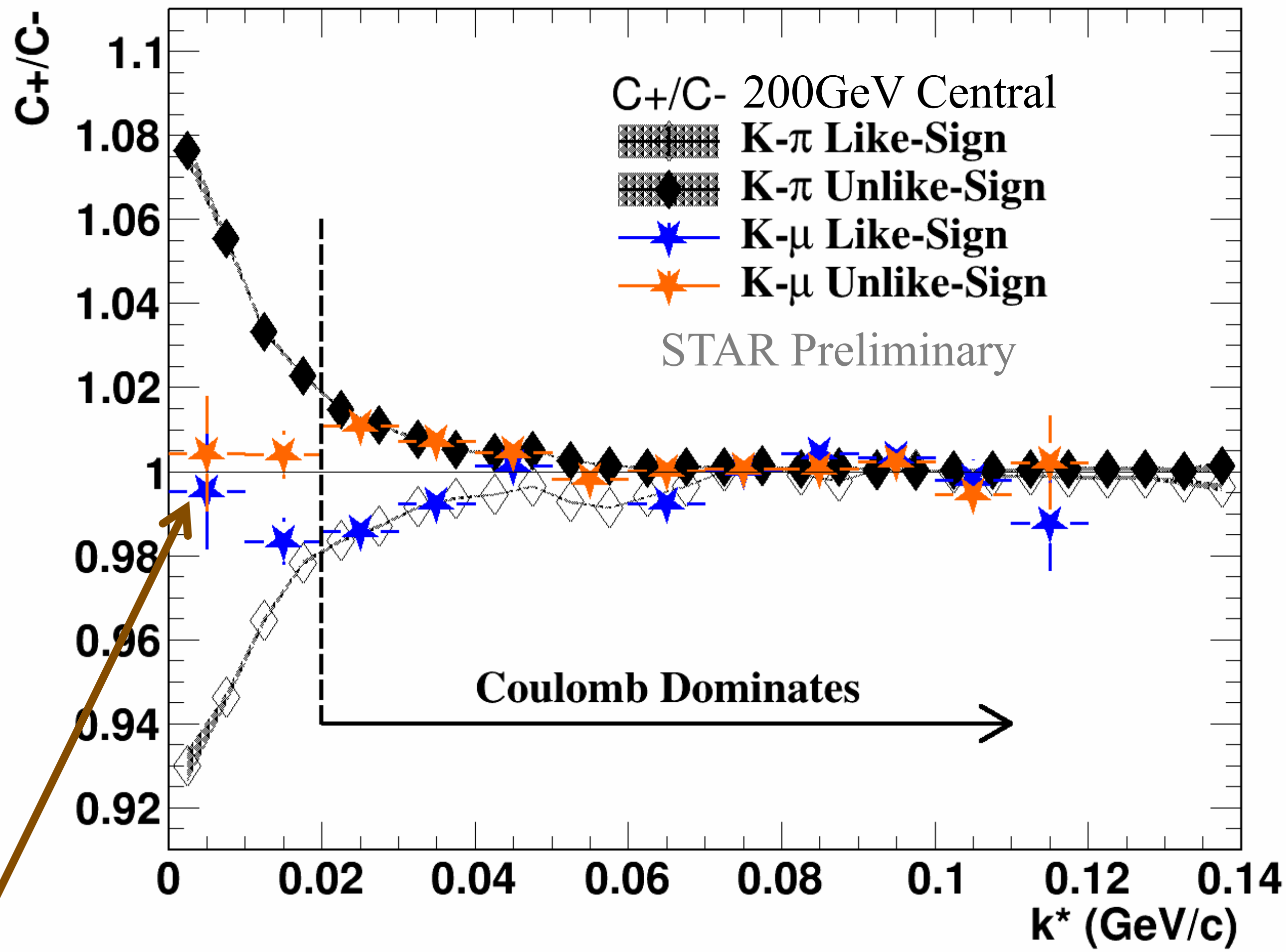
Muonic Atom



Take K-π system as a reference in which Coulomb dominates:

- Enhancement in UnLike-Sign
- Suppression in like-Sign

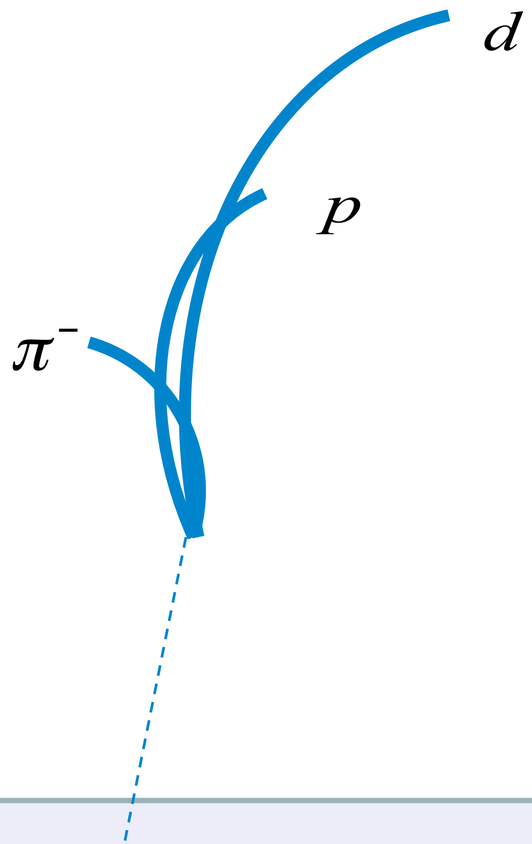
Muonic Atom



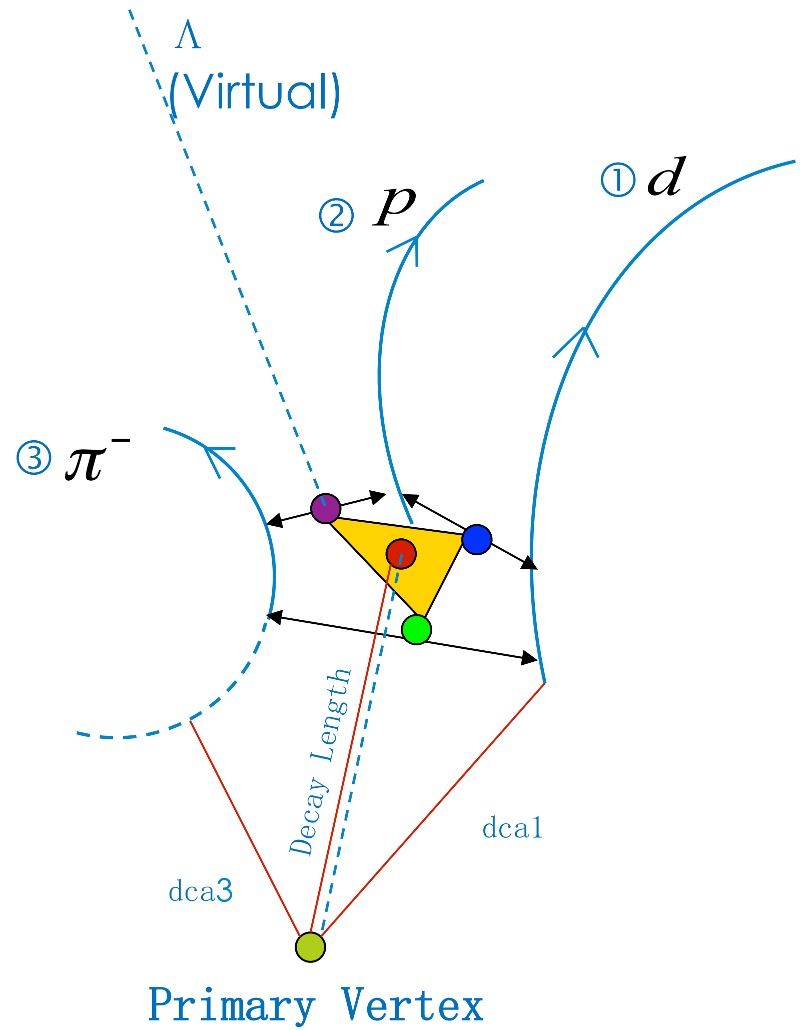
Signature of muonic atoms: two particles are **emitted at the same position and time**.

Hypertriton Three-body Channel

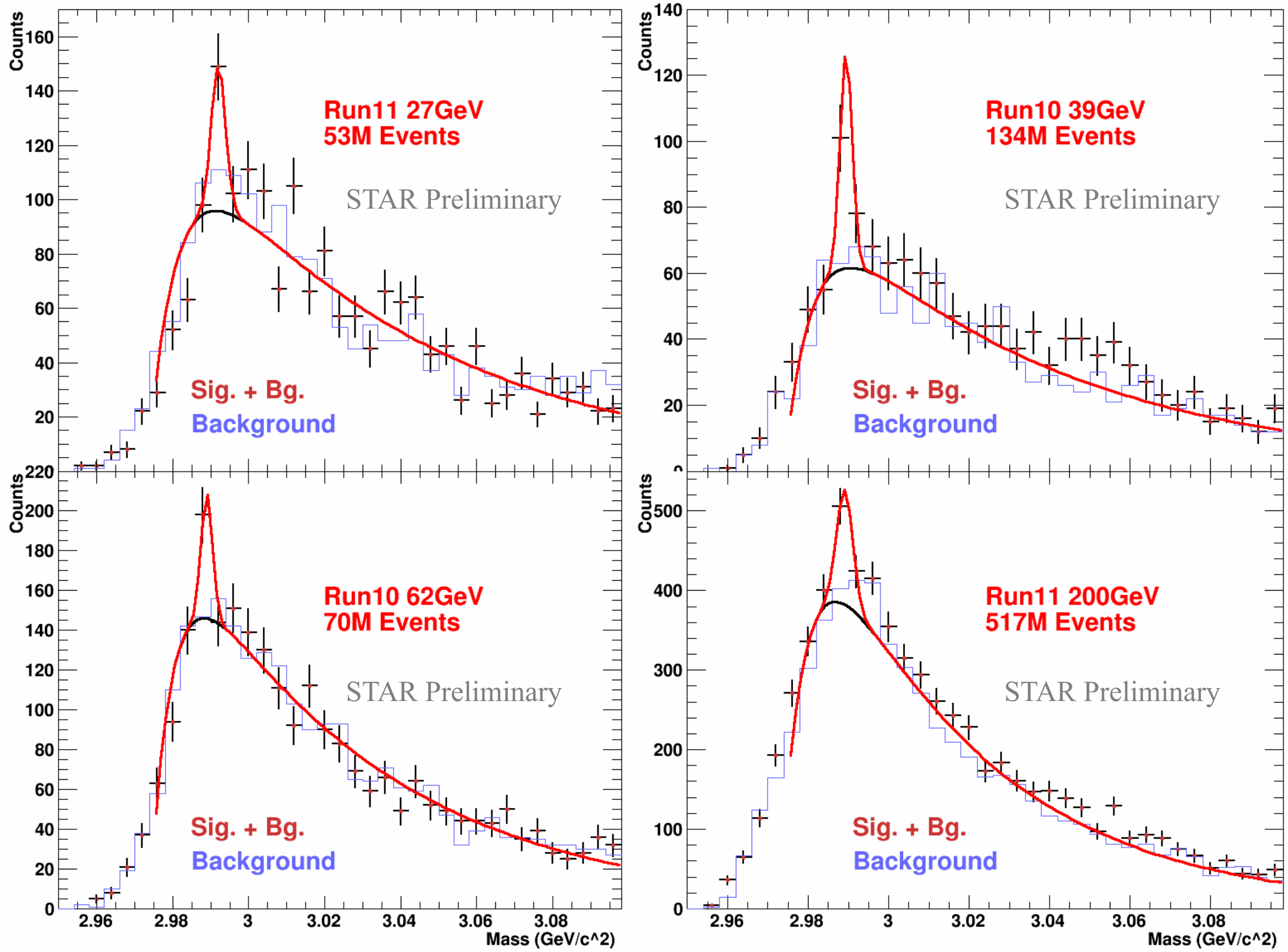
Topological Map



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



Hypertriton Three-body Channel



The invariant mass peak is observed in a range of energies from RHIC Beam Energy Scan program. Lifetime measurement is ongoing.

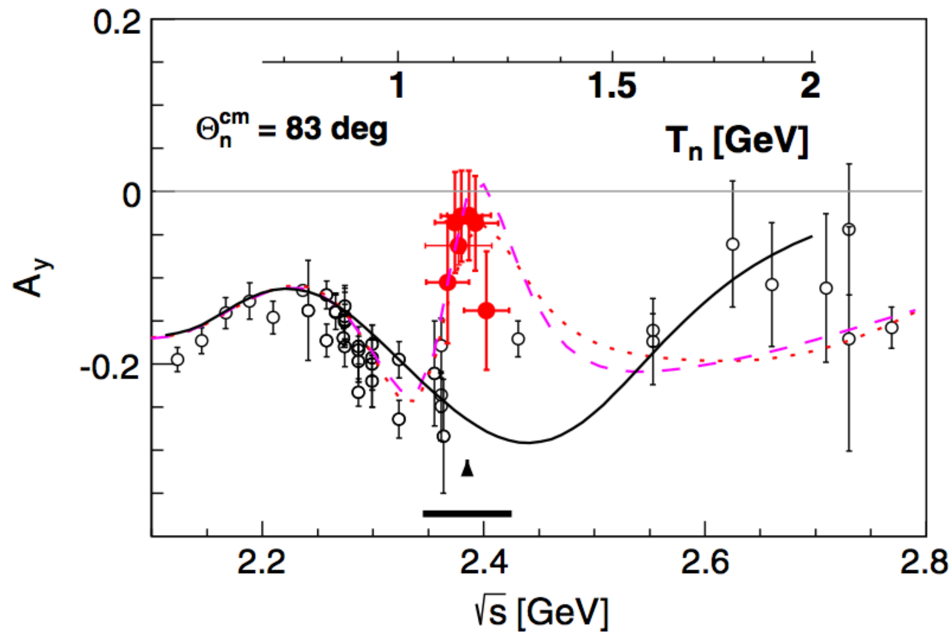
Dibaryon

Dibaryons should exist

- SU(3) and SU(6) symmetries
- Regge theory
- Phenomenological models
  - MIT bag
  - NRQM*
  - LAMP**
  - …

Evidence of unstable
“inevitable dibaryon” d*(2380)
WASA PRL 112, 202301 (2014)

WASA-at-COSY
Collaboration



Perhaps a Stable Dihyperon

Phys. Rev. Lett. **38**, 195 – Published 31 January 1977

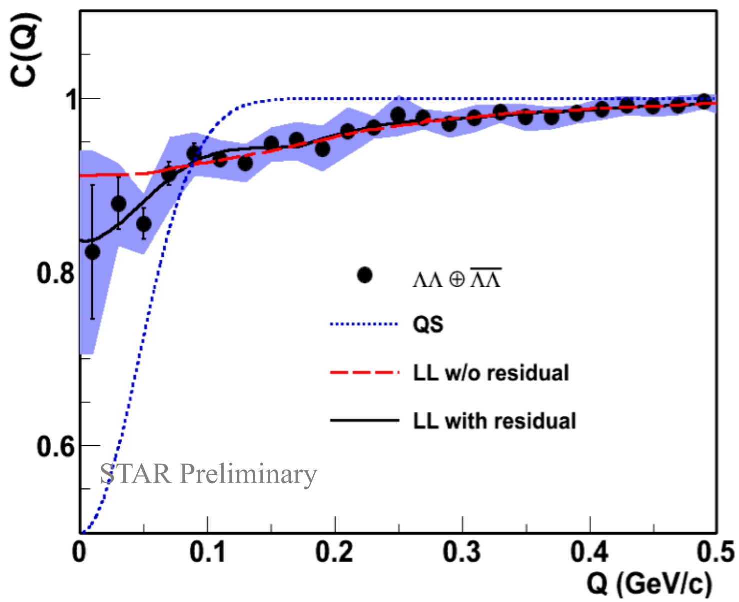
R. L. Jaffe

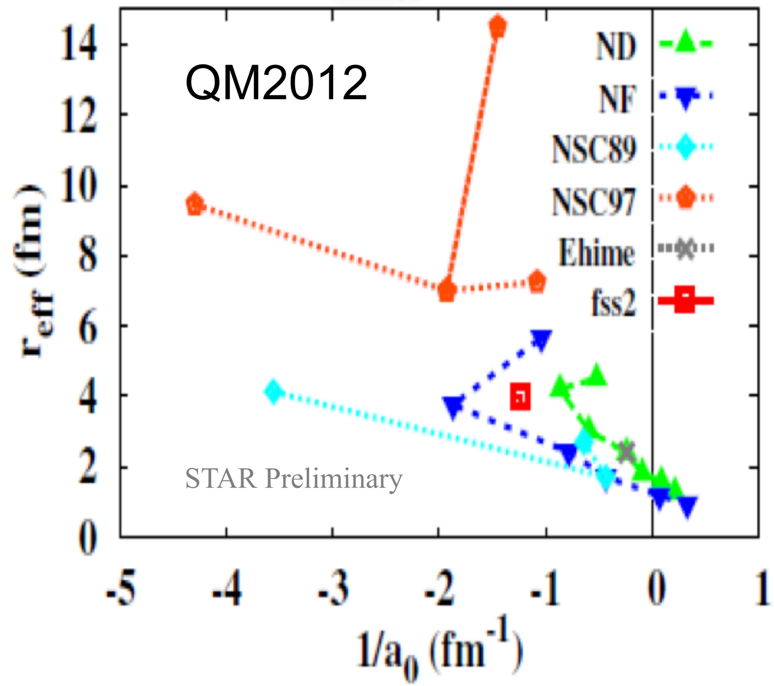
* Maltman, Nucl. Phys. A438, 669
* Oka and Yazaki, Phys. Lett. 90B, 41
** Goldman etc, Phys. Rev. Lett. 59, 627
** Goldman etc, Nucl. Phys. A481, 621

Open question:
Does the stable H^0-dibaryon exist?

Dibaryon

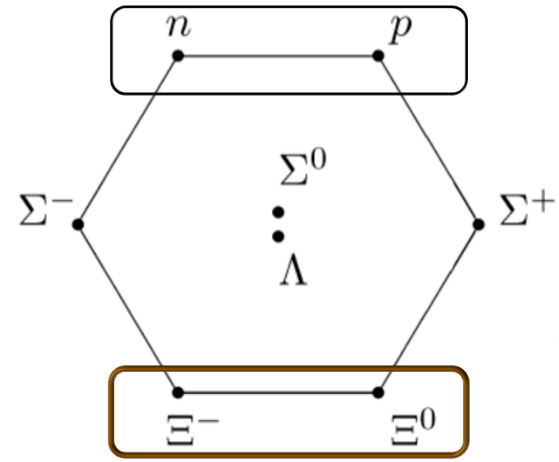
Dibaryon search at mid-rapidity at STAR



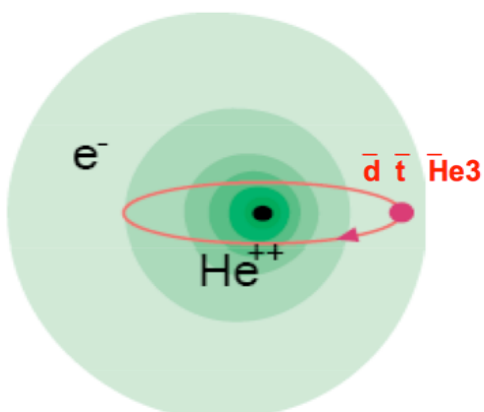


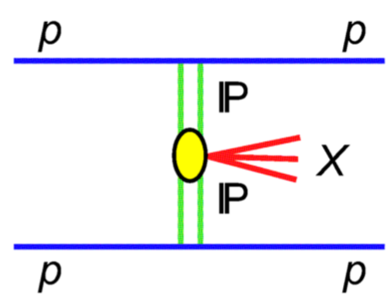
Negative scattering length
Yield upper limit requires statistics that is beyond STAR's reach for now
$dN_H/dy \sim (1.23 \pm 0.47stat \pm 0.61sys) \times 10^{-4}$

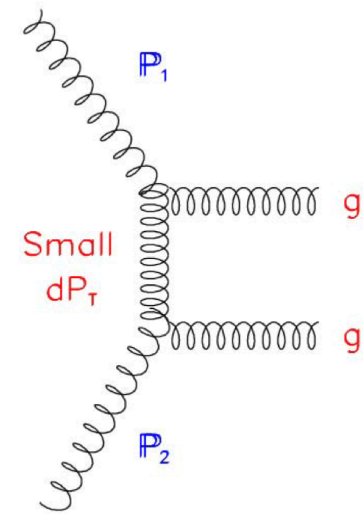
More Opportunities



- ★ Heavy flavor hypernuclear matter in EIC
- ★ Other dibaryon states, ^{4s}d etc
- ★ Glueball
- ★ Atomcules







* STAR decadal plan 2010
* T. Yamazaki etc. Nature 361 (1993) 238

Summary

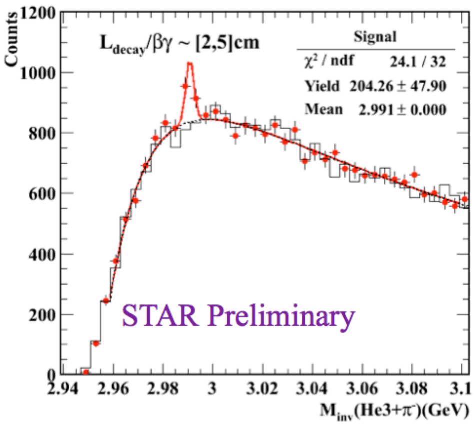
- ★ RHIC is an ideal machine for exotics production.
- ★ STAR is in excellent position for exotic search.
- ★ STAR has published important results on hypertritons, anti-alphas, strangelets.
- ★ More recent exiting studies on muonic atoms, three-body decay hypertritons, dibaryons...
- ★ With recent upgrades (HLT, HFT, MTD, DAQ10k, etc.), STAR will significantly broaden its search range for new/ exotic phenomena.

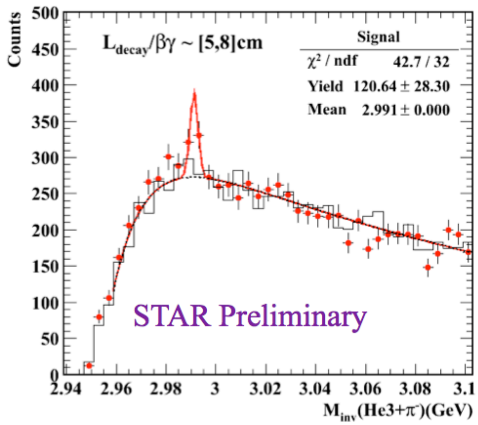
BACK UP

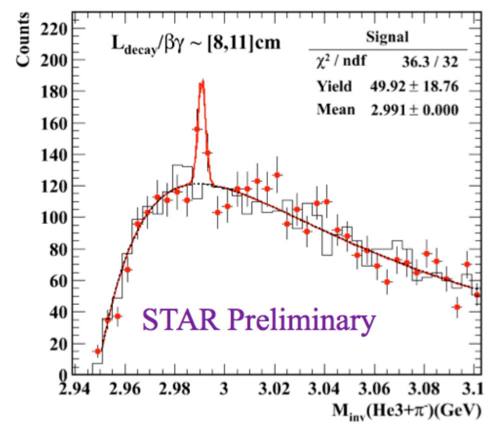
Hypertriton

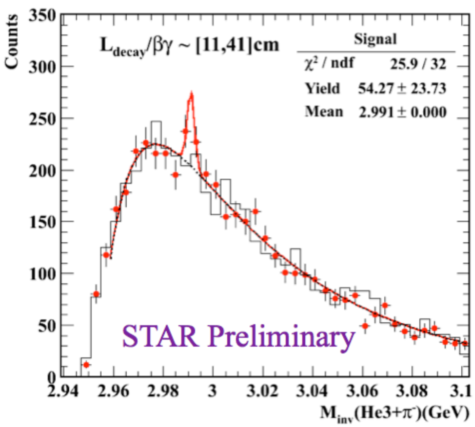
Radioactive Decay Law

$$N(t) = N(0) \times e^{-t/\tau} = N(0) \times e^{-\frac{l}{\beta\gamma}/c\tau}$$, l is the decay length









4 Bins:
[2,5]cm, [5,8]cm, [8,11]cm, [11,41]cm

Datasets:
Run10 7.7,11.5,39,200 minbias,
Run10 200 central,
Run11 19.6, 27 minbias

- Lifetime measurement

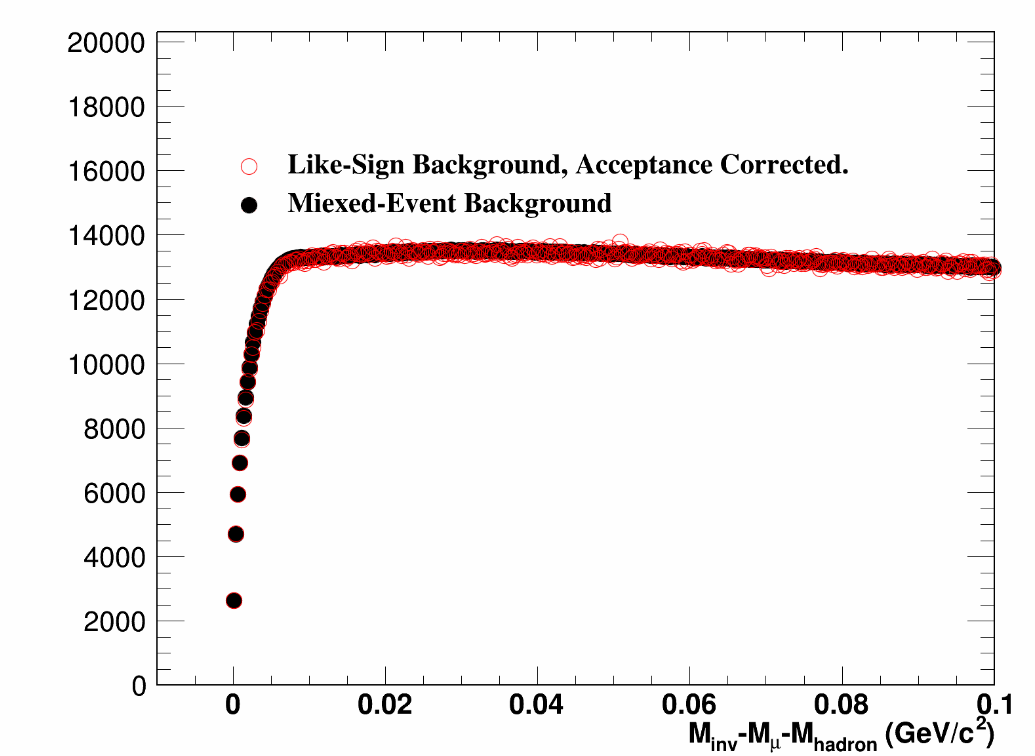
Foreground and Backgrounds

- Foreground: all unlike-sign tracks are paired in a same event
- Mixed-Event (ME) background method:

  tracks from different events are paired
- Like-Sign (LS) background method:

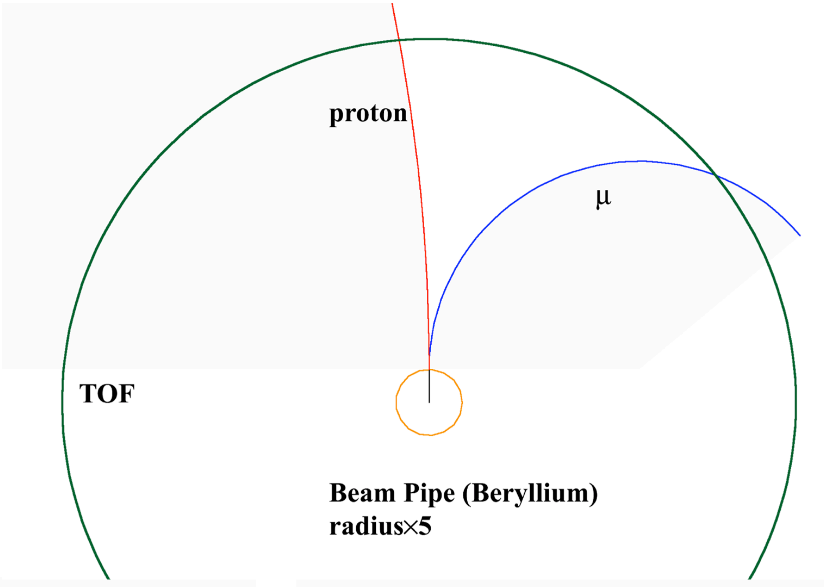
  tracks with the same charge are paired, and acceptance corrected

$$LS_{+-(corrected)} = \sqrt{LS_{++}LS_{--}}\frac{ME_{+-}}{\sqrt{ME_{++}ME_{--}}}$$



Muonic Atom Detection at STAR

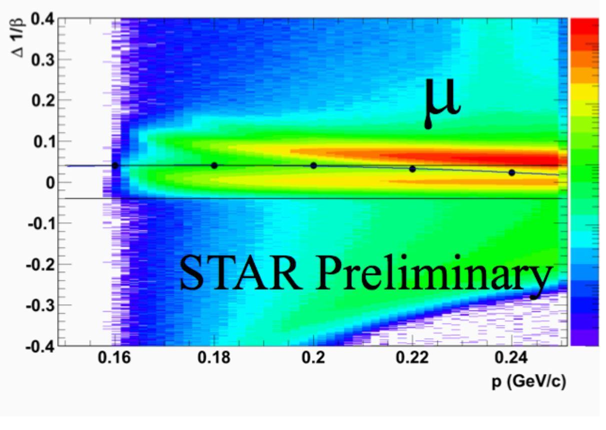
(1) Dissociation of the atoms before the detector tracking at beryllium **beam pipe**

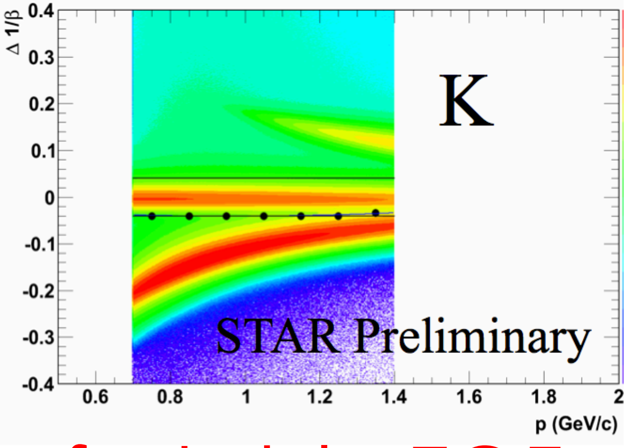


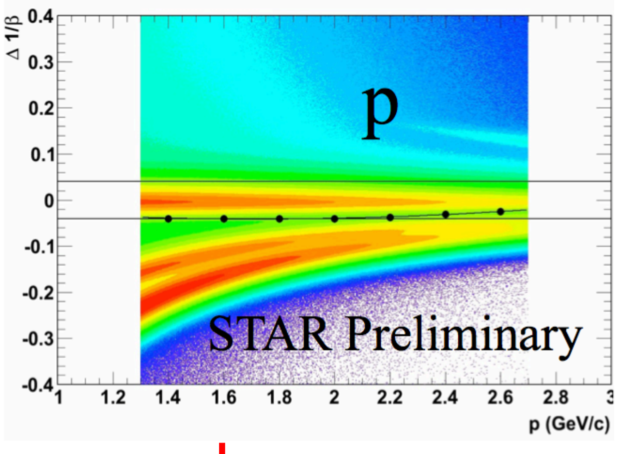
(2) Particle Identification

STAR Run10 AuAu 200GeV
231M Central Triggered Events

High purity ~99%

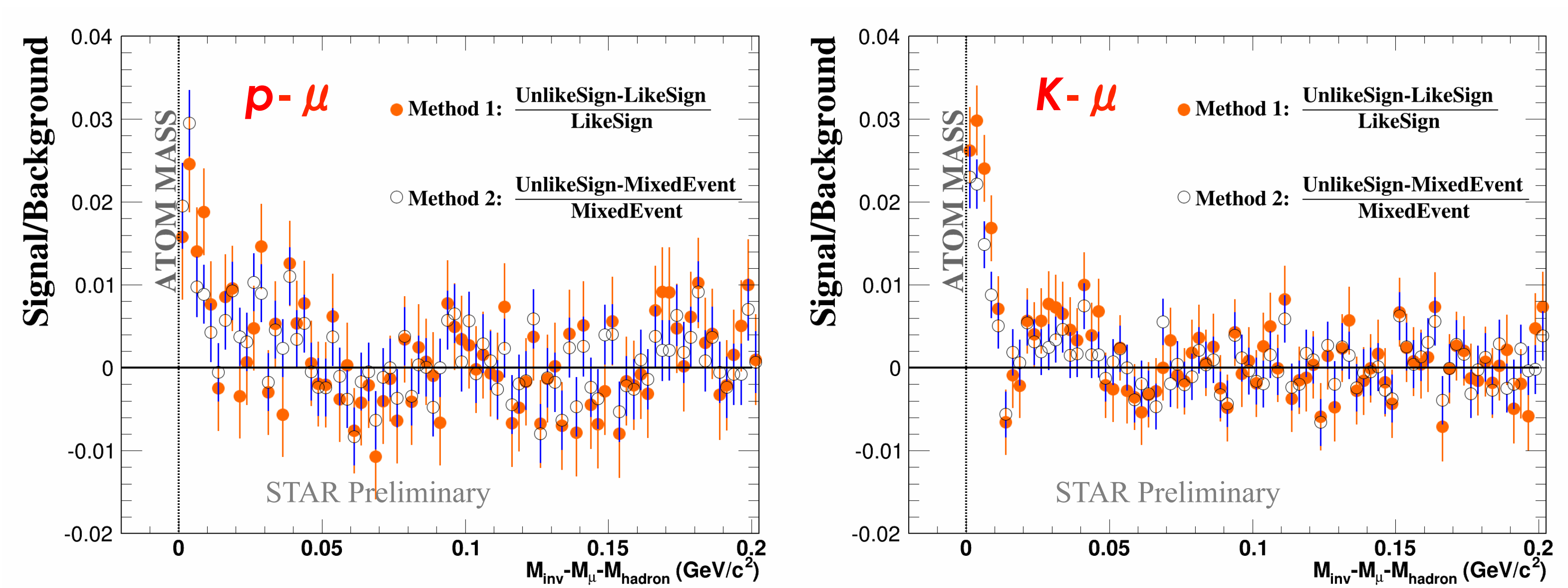






Comfortable TOF ranges!

Invariant Mass – S/B



- ✓ Observed **sharp peaks** at expect atom mass M_{inv}-M_{μ}-M_h= **0** GeV/ c^2 from both background subtraction methods
- ✓ **Good background methods** -- Flat at higher mass (0.05~0.2) GeV/c^2
- ✓ Like-Sign (LS) background has repulsive **Coulomb** contribution, and thus underestimates the background, leading to a higher "signal" than Mixed-Event (ME)

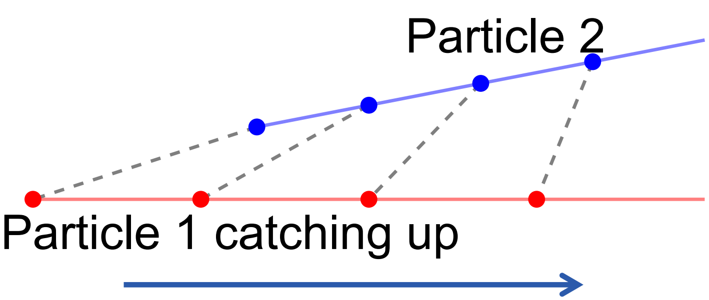
Femtoscopic Correlation

- Study small physics scale by using measured momentum from our detectors

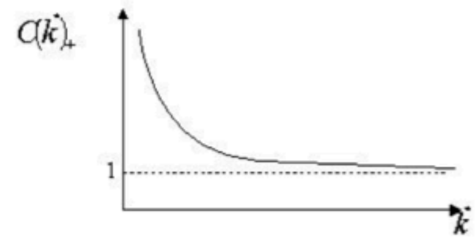
k* – the magnitude of the three-momentum of either particle in the pair rest frame.
C(k*) – the ratio of the k* distribution constructed with particles from the same event with the particles from mixed event:
C(k*)=(k* in Same Event)/(k* in Different Event) =(correlated distribution)/(uncorrelated distribution)

- For non-identical particles, correlation is used to probe **space-time asymmetries**

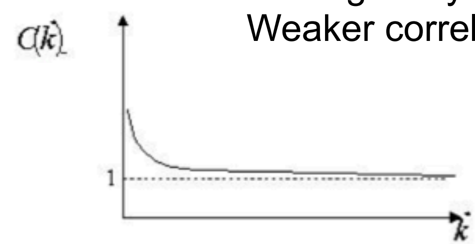
PRL 91 (2003) 262302
Pion-Kaon Correlations in Au+Au@130GeV



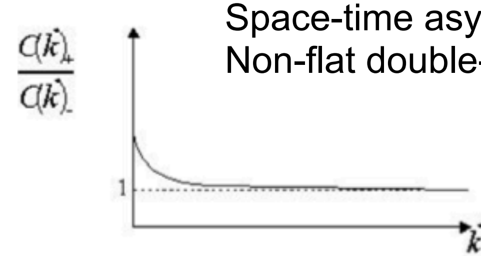
Catching-up
Stronger correlation



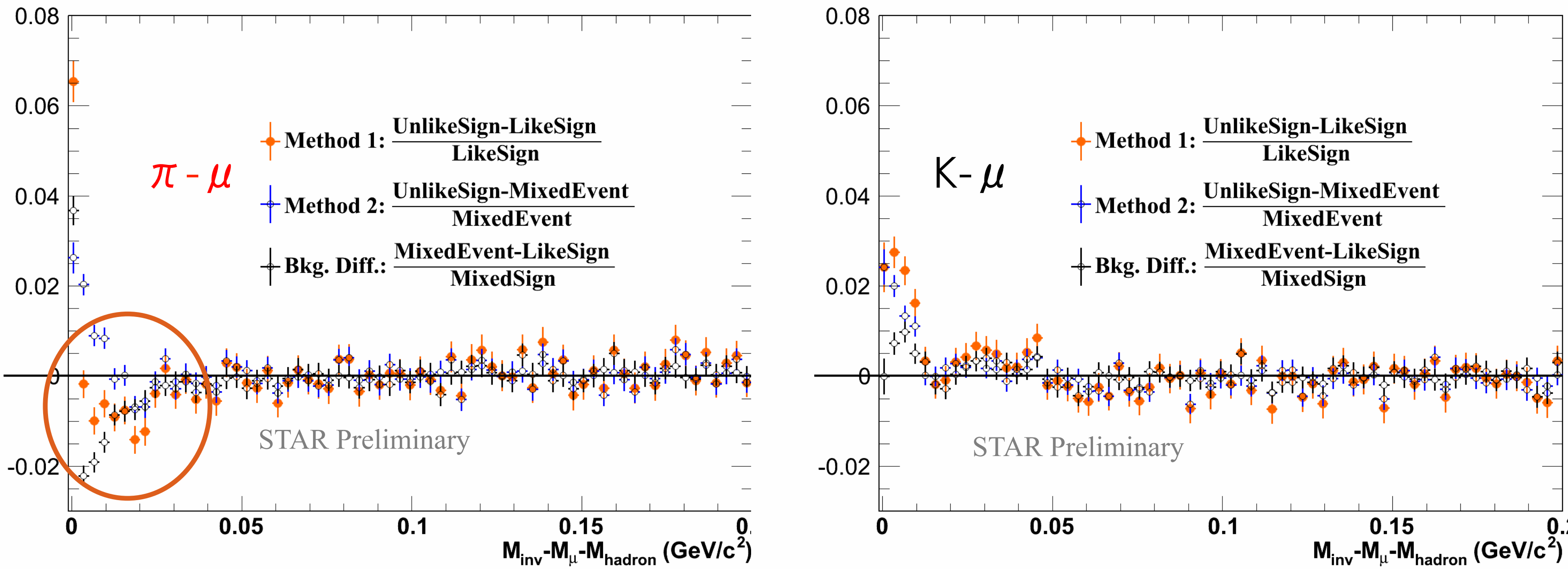
Moving away
Weaker correlation



Space-time asymmetries
Non-flat double-ratio



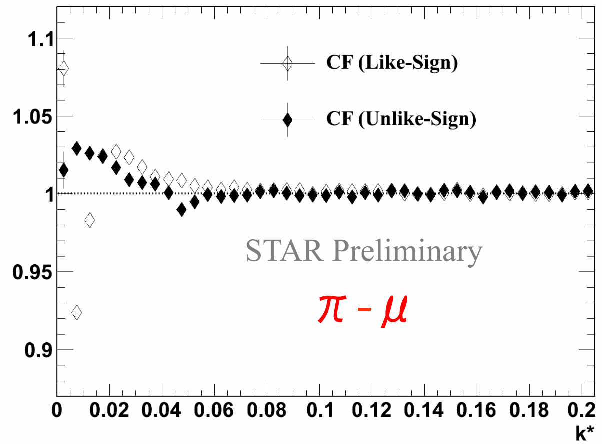
π-μ Invariant Mass Difficulty



- Like-sign background method is larger than foreground
- Leads to negative region in S/B (red in circle)
- This is not consistent with K-μ, p-μ

Identical particle quantum statistics – attractive

π-μ Correlation

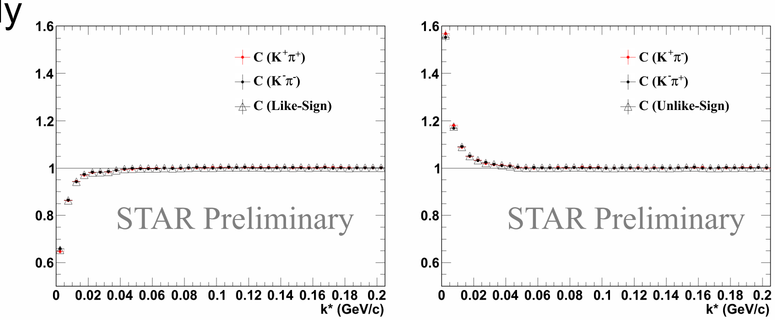


AuAu200 Run10 Central Events
$0.2<p_{\pi}<0.33$ GeV/c
$0.15<p_{\mu}<0.25$ GeV/c

- If there is only final state coulomb interactions,
  - Like-Sign CF should be <1, and decrease monotonically approaching 1
  - Unlike-Sign CF should be >1, and increase monotonically approaching 1

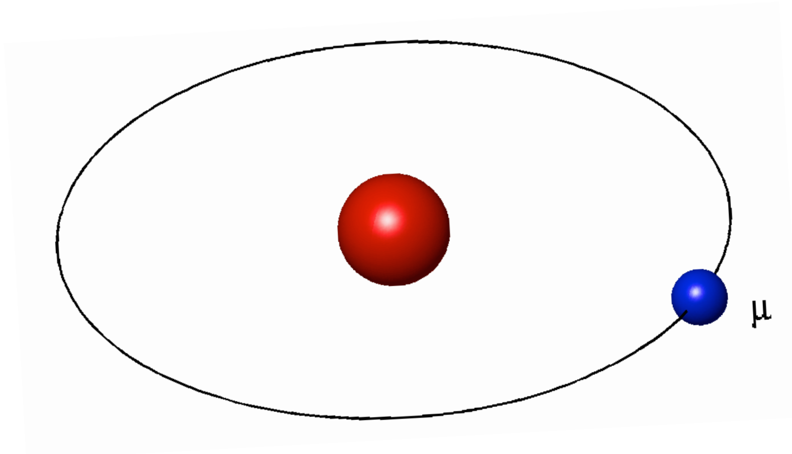
An example of Coulomb only

AuAu200 Central in Run10
with my momentum selection:
π(0.15~0.25)
K(0.53~0.88)



- The suspected source is the correlation between π and a μ from π decay

What is a muonic atom



Hadron+muon Coulomb bound state

- **Facts**
  - Small binding energy. Ionization
  - Bohr radius

  a_0*(m_e/m_red)

  =279fm (p+mu)

  =440fm (pi+mu)

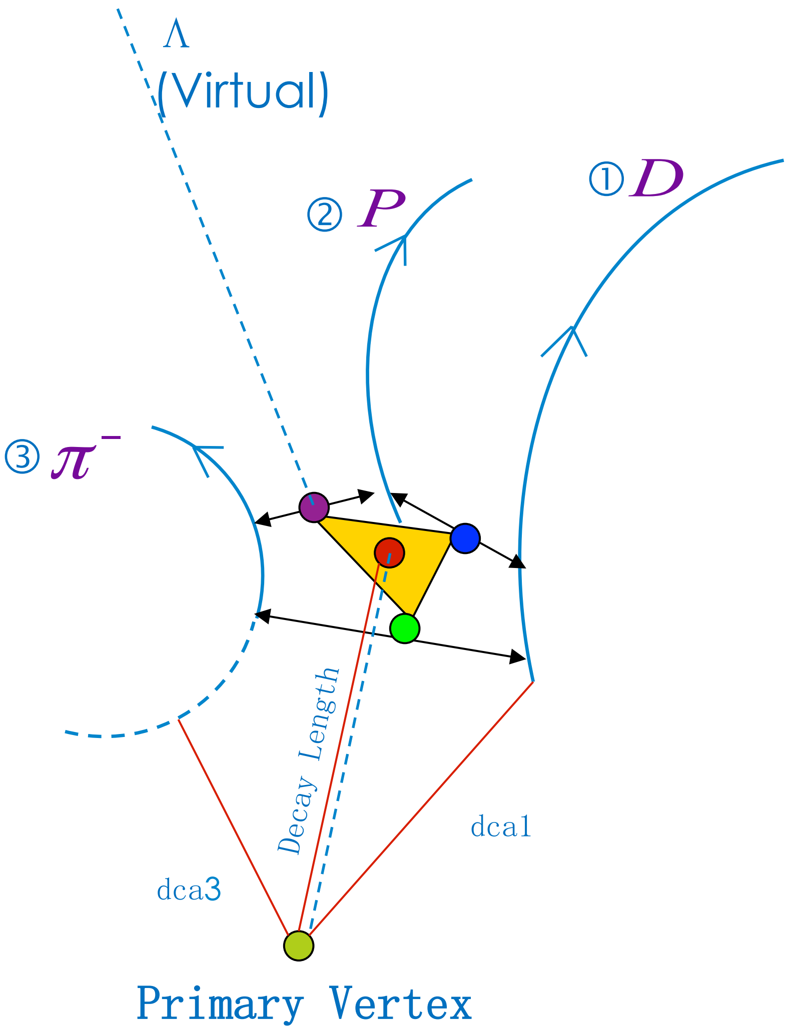
  - Bohr velocity alpha*c/n

- **What to expect**
  - Atom mass = m_p+m_mu
  - Atoms can only be at **s** state
  - Pp/mp=pmu/mmu

Hypertriton 3-body Compare

	27GeV	39GeV	62.4GeV	200GeV
Deuteron |Z|	<0.2	<0.2	<0.2	<0.1
Lambda DCA	[0, 0.9]	[0, 1.0]	[0, 0.7]	[0.6,1.6]
Lamb-Mass	<1.112	<1.110	<1.110	<1.111
LambH3 DCA	<1.0	<1.0	<1.0	<0.6
dca1-2/1-3	<1.0	<1.0	<1.0	<0.8
dca2-3	<0.8	<0.8	<1.0	<0.8
dca 1/2/3-xv0	<1.2	<1.2	<1.2	<1.0
Lambda r*p	×	×	×	<5 deg

Hypertriton Three-body Channel



Property	Value	Unit
Mass	2.991	GeV
Charge	+1(-1)	e
Lifetime	~123 *	ps

Two Bodies:

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

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

Three Bodies:

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

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