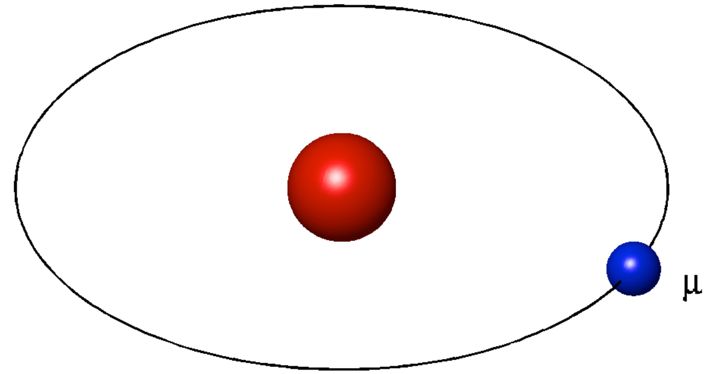


Muonic Atoms

Kefeng Xin for the STAR Collaboration

Rice University

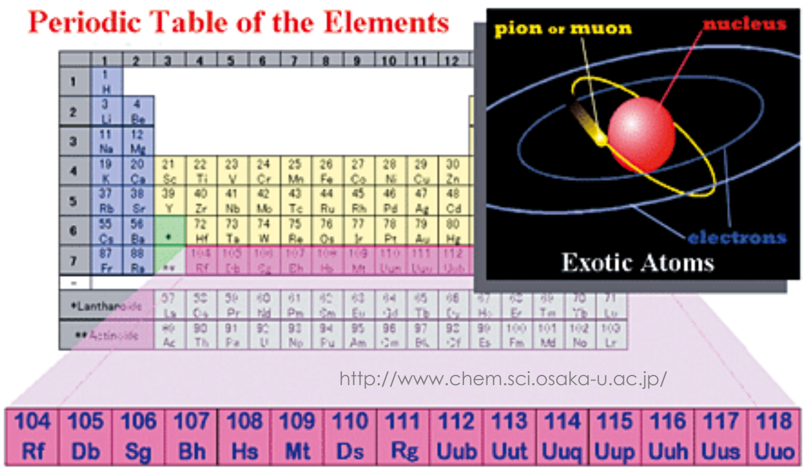
10/25/2013

- **Motivations**
- **Theory predictions**
- **Data analysis**
  - Invariant mass
  - Two particle correlations

APS Division of Nuclear Physics Meeting 2013

Motivations

- **Potential discoveries**: anti-muonic hydrogen; (anti-) K-μ atoms



$p^+ - \mu^-$	$K^+ - \mu^-$	$\pi^+ - \mu^-$
anti-p- μ^+	$K^- - \mu^+$	$\pi^- - \mu^+$

Red: not been discovered yet

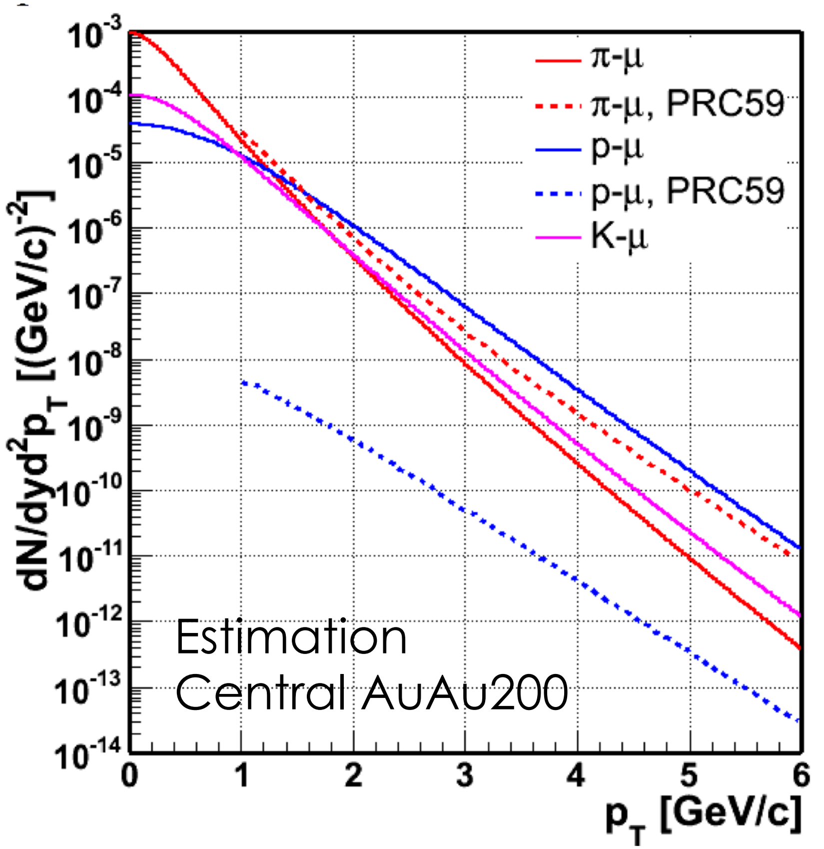
- Direct measurement of **early produced lepton** emission which is sensitive to the early stage of the collisions

  Nearly all indirectly produced leptons arise from the decay of hadrons, and these decays occur too long after the collision to allow an atom to be formed.

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

  Yield of the atoms can be estimated through a coalescence model, and is proportional to the yield of direct leptons [G. Baym et al. PRD 48 3957]

Muonic Atom Production Estimation

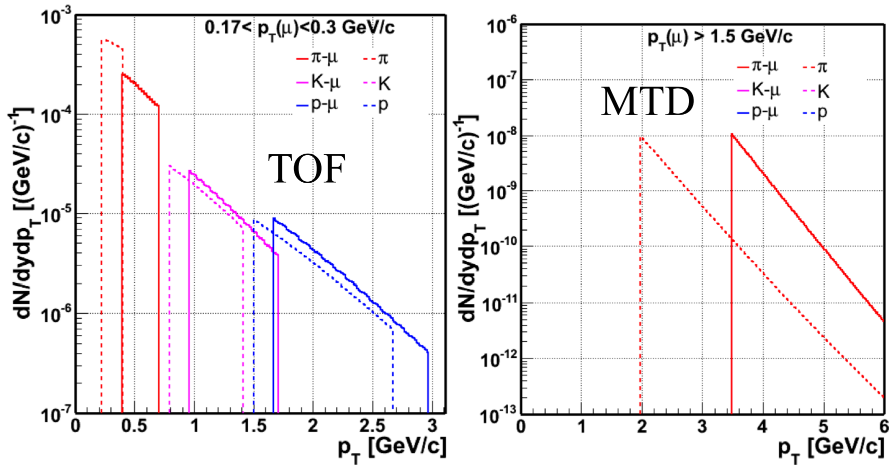


With the large amount of thermal (anti-)hadrons and muons, RHIC is expected to produce all six of the following (anti-)atoms

Dashed lines: input from thermal distributions
Solid lines: input from STAR data (except μ)
Intended to served as guidance

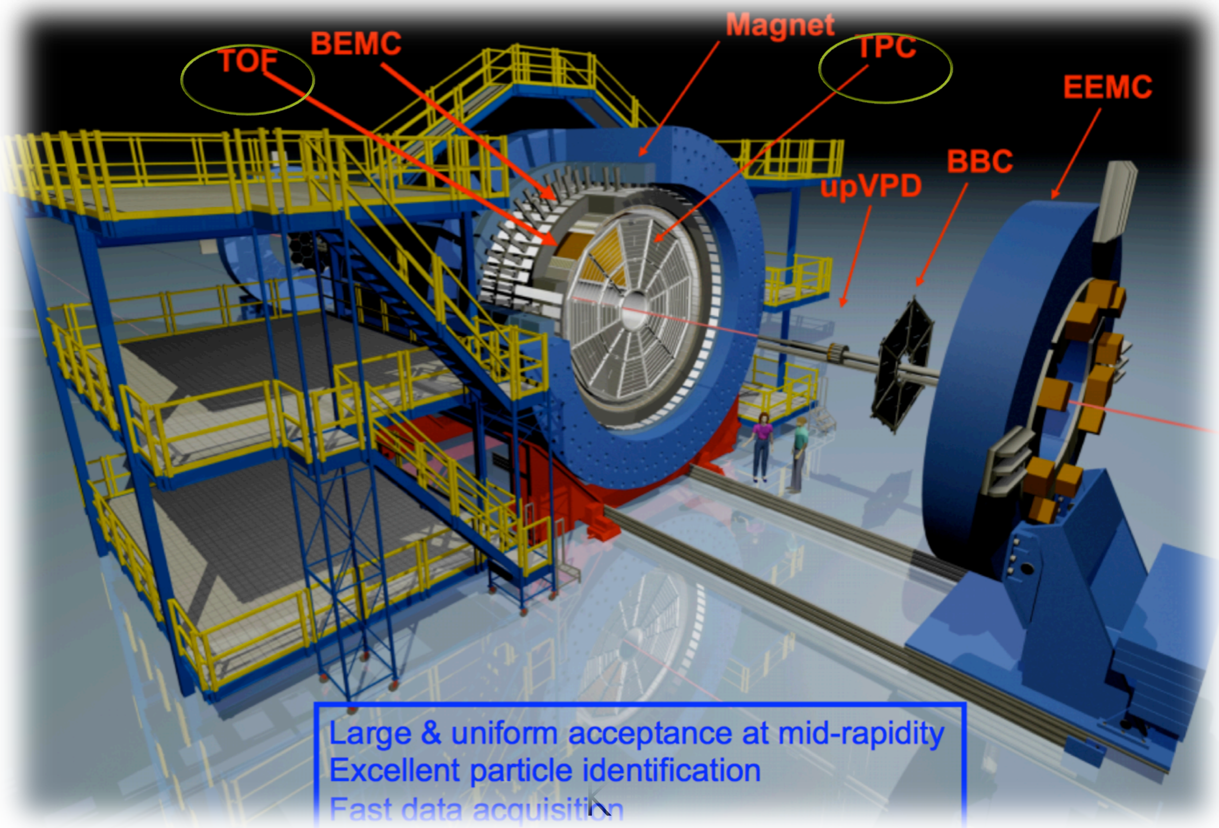
*[Kapusta and Mocsy PRC 59 2937; 2010 STAR Decadal Plan]

Accessible to STAR



>1000 anti-matter muonic hydrogens in 500M central AuAu200 events.

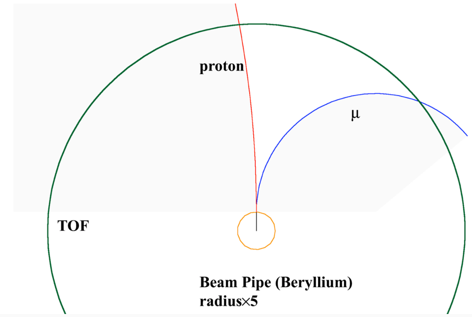
The STAR Detector



In this analysis, the two most important detectors

- Time Projection Chamber (**TPC**)
- Time of Flight (**TOF**)

Muonic Atom Detection at STAR



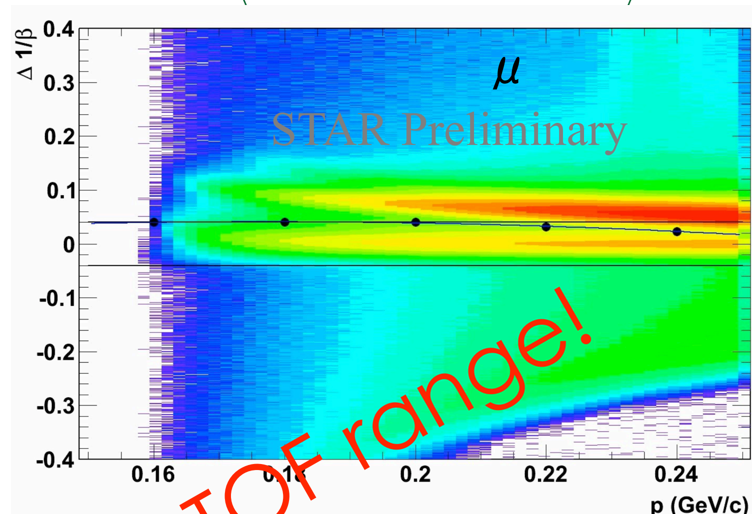
1) Dissociation of the atoms before the detector

tracking at beryllium **beam pipe**

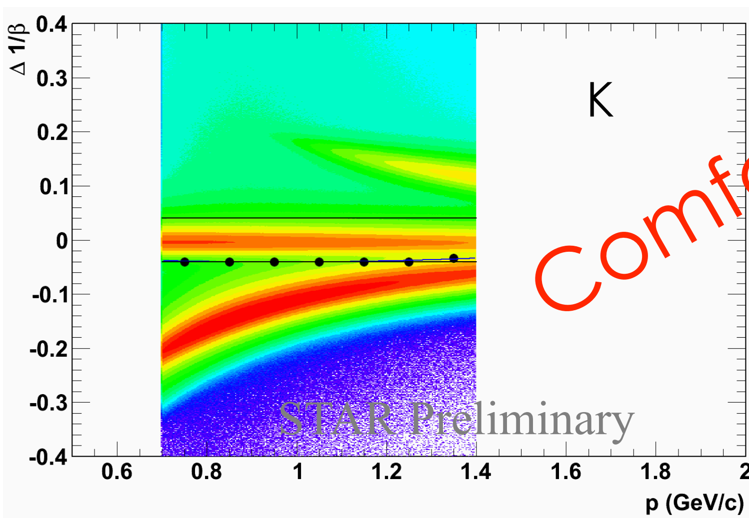
2) Particle Identification

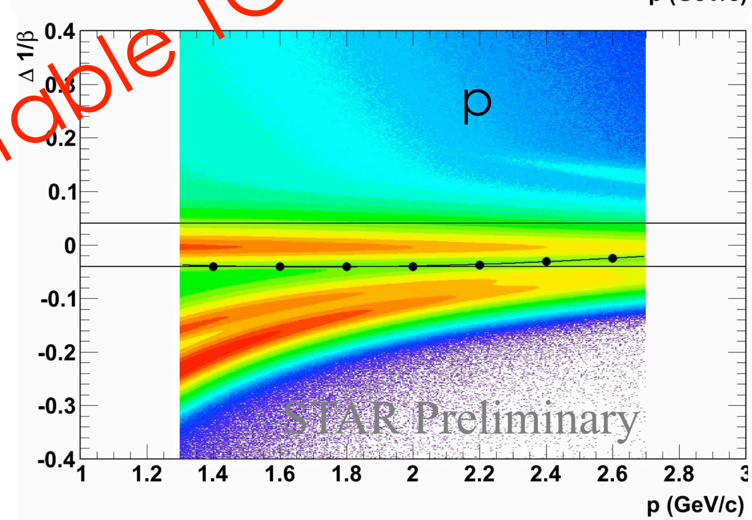
STAR Run10 AuAu 200GeV
231M Central Triggered Events

Atom	μ p(GeV/c)	Hadron p
p-μ	0.15-0.3	1.3-2.7
K-μ	0.15-0.3	0.7-1.4



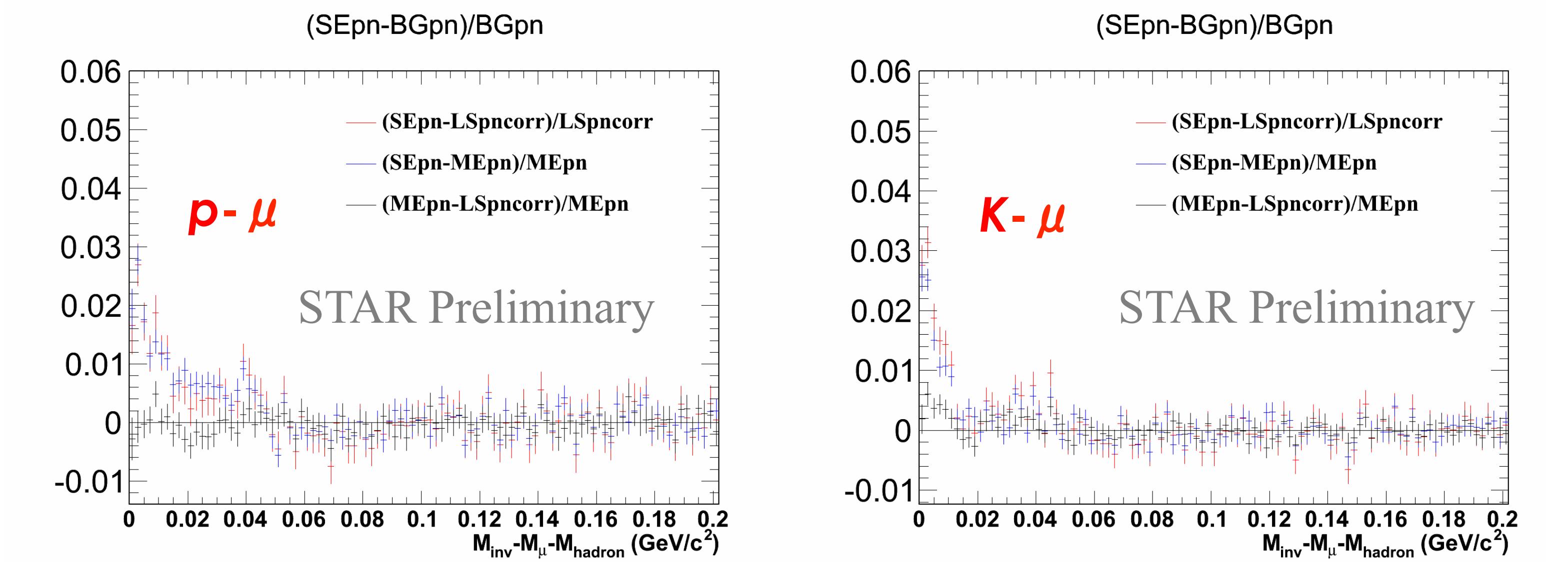
Comfortable TOF range!





Invariant Mass – S/B

Acceptance correction: $$LS_{+-(corrected)} = \sqrt{LS_{++}LS_{--}}\,\frac{ME_{+-}}{\sqrt{ME_{++}ME_{--}}}$$



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

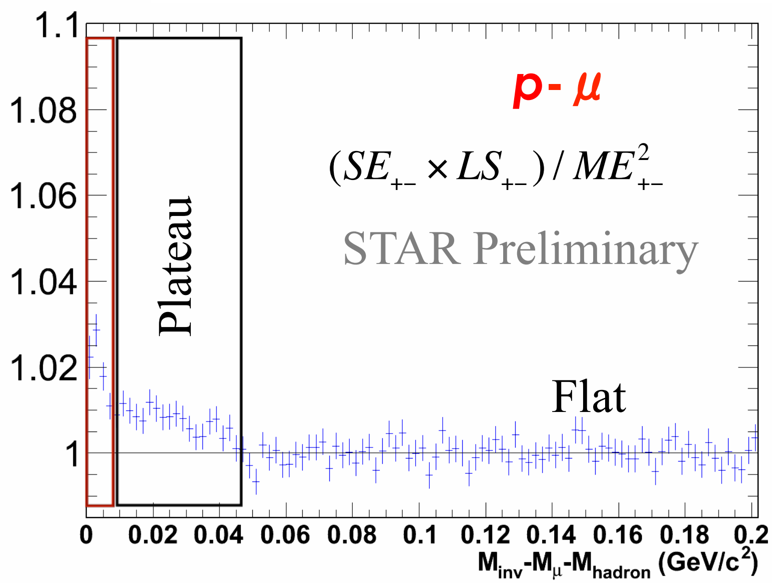
Invariant Mass – Coulomb Effect

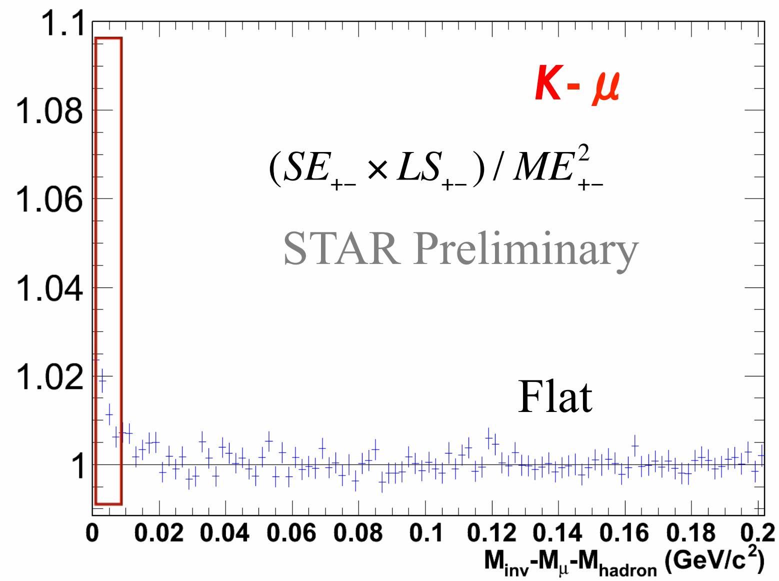
Reject coulomb effect:

Assuming coulomb effects in Like-Sign (LS) and UnLike-Sign (UL) are of the same amplitude, but have opposite signs. Then **product** of the two has no coulomb contribution

$$(SE_{+-} \times LS_{+-}) / ME_{+-}^2$$

✓ After rejecting Coulomb, the peak is preserved at net mass ~ 0GeV/c^2

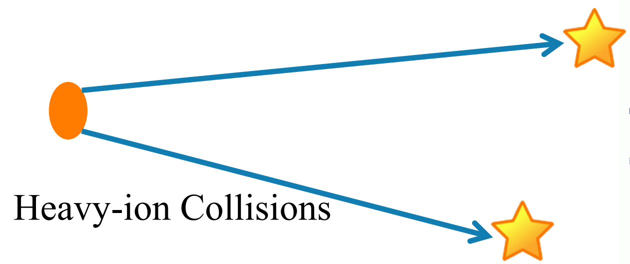


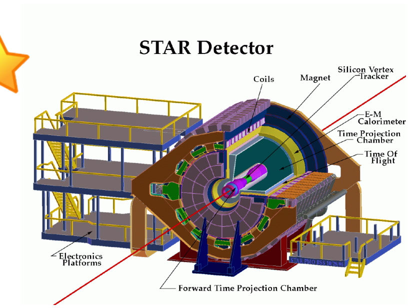


Plateau in p-μ indicates **hadron decay channels** like $\Delta \to p+\pi \to p+\mu+\nu$

Femtoscopic Correlation

- ❑ Study subatomic physics scale interactions by using measured momentum from our detectors

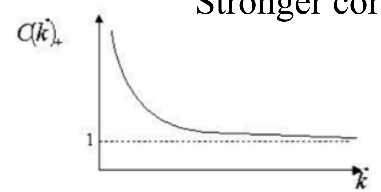




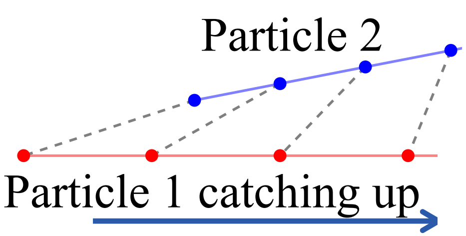
k* – the magnitude of the three-momentum of either particle in the pair rest frame.
C(k*) – the ratio of the k* distribution constructed with particles from the same event with the particles from mixed event:
C(k*)=(k* in Same Event)/(k* in Different Event)
=(correlated distribution)/(uncorrelated distribution)

Momentum difference

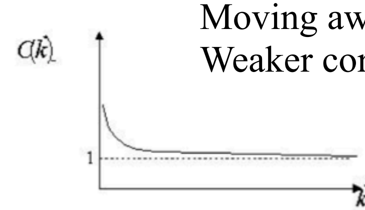
Catching-up
Stronger correlation



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



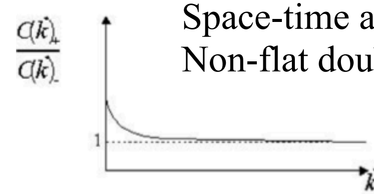
Moving away
Weaker correlation



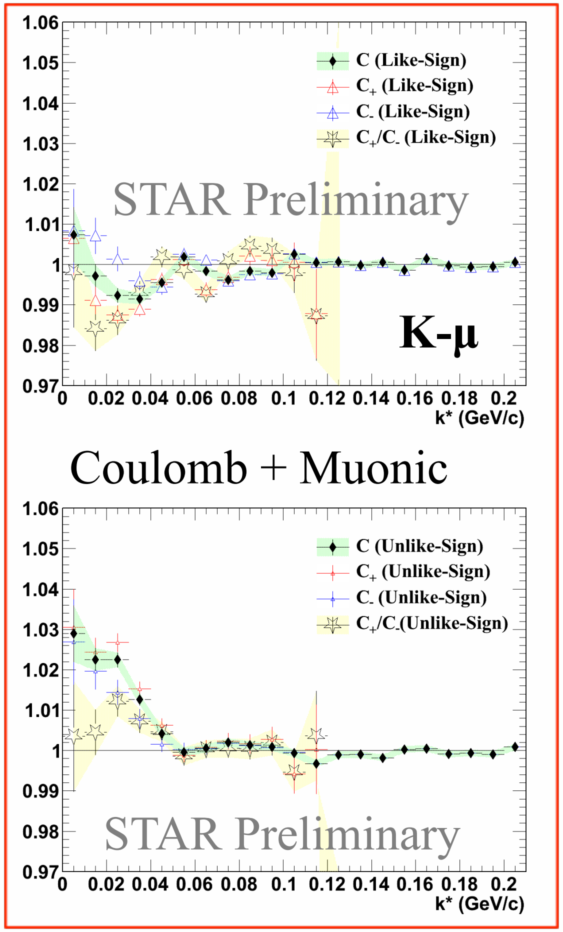
No space-time asymmetry

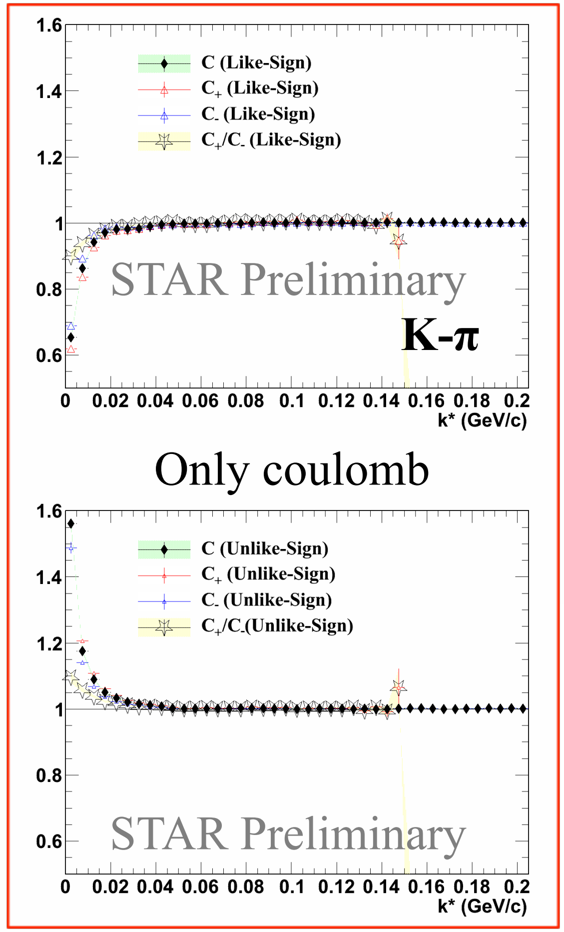
=> flat double ratio

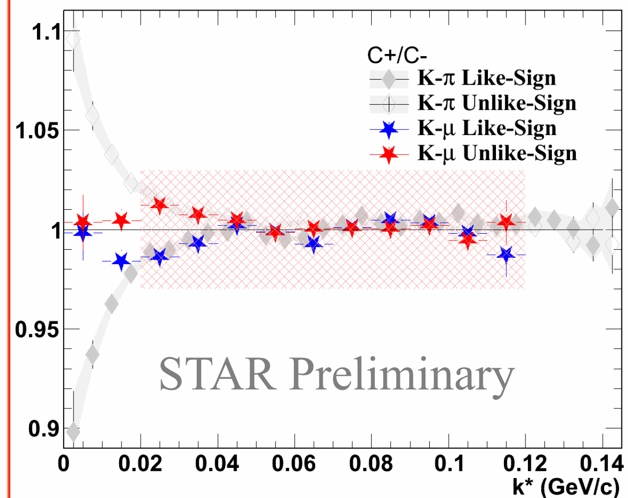
Space-time asymmetries
Non-flat double-ratio



Compare K-μ with K-π







- Double-ratios indicate Coulomb contributions are similar in LS and UL
- Correlation functions indicate additional contributions in UL between kaons and muons
- C+/C- ~ unity at k*~0 GeV/c: two particles from an atom are emitted at the same position and time, and will give C+/C-~1

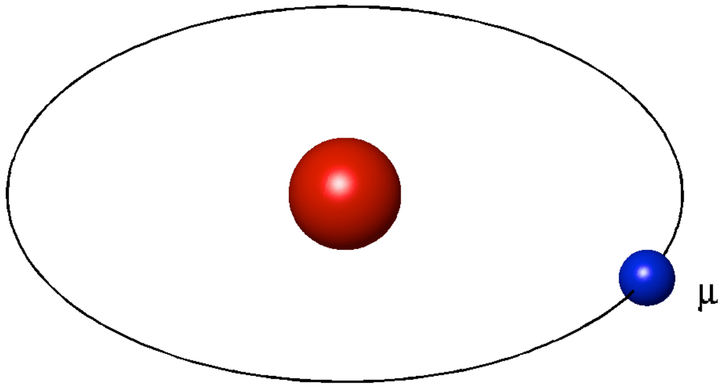
Summary

- Heavy-ion Collisions at RHIC are expected to produce significant amounts of muonic atoms
  - Combining its TPC and TOF systems, STAR is in the best position to measure such atoms
- First preliminary studies in central Au+Au at 200 GeV show indications of invariant mass enhancements at the expected atom masses
- Preliminary femtoscopic correlation studies are consistent with decay of muonic atoms

Thank you!

Backup

What is a muonic atom



Hadron+muon Coulomb bound state

- **Facts**
  - Binding energy 0 keV
  - Bohr radius

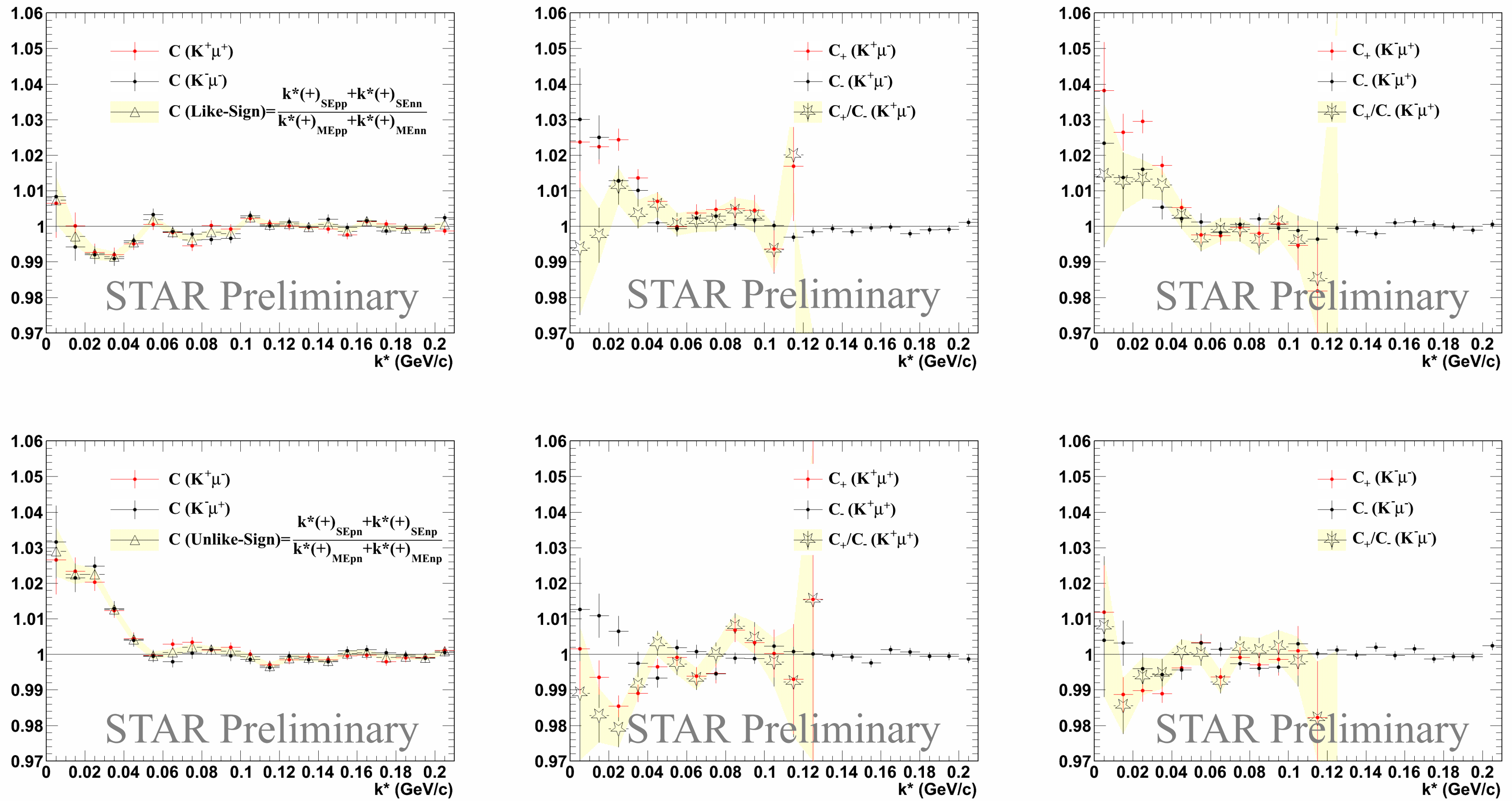
  a_0*(m_e/m_red)

  =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

Correlation Functions for K-μ



- The Coulomb contributions are weaker – washed out by long life time decays
- Differences between Like-Sign and Unlike-Sign at low k*