Search for Antimatter Muonic Hydrogen at STAR

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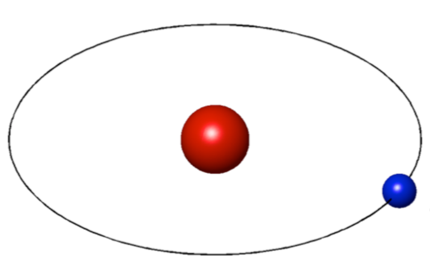
Abstract

Hydrogen-like muonic atoms are Coulomb bound states of a muon and a hadron. In ultrarelativistic heavy-ion collisions, due to the high particle multiplicities, a produced muon can be directly bound to a charged hadron, and form an atom. Among these atoms, the antimatter muonic hydrogen and the K−μ atom have been predicted but not yet been discovered. With muon identification at low transverse momentum from the Time-of-Flight detector, STAR provides a great opportunity to search for the muonic atoms with exotic cores, such as anti-matter or strange cores for the first time. This is also an ideal tool to measure the thermal emission from the Quark-Gluon Plasma via a direct measurement of the single muon spectrum. Because only thermal muons or muons from resonance decays are capable to form atoms, the background muons from weak decay are cleanly excluded.

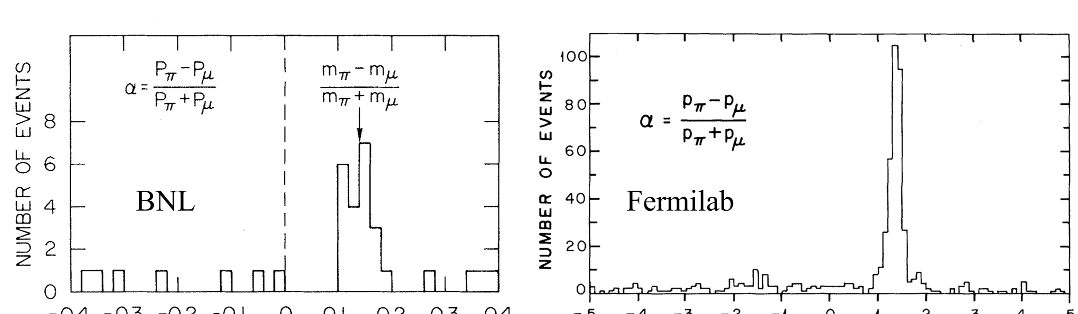


π-μ Atoms

To form atoms, two particles from the same atom must be close in phase-space, i.e. [1]

$$\alpha = \frac{|\vec{p}_\pi - \vec{p}_\mu|}{|\vec{p}_\pi + \vec{p}_\mu|} = \frac{|m_\pi \vec{v}_\pi - m_\mu \vec{v}_\mu|}{|m_\pi \vec{v}_\pi + m_\mu \vec{v}_\mu|} \approx \frac{m_\pi - m_\mu}{m_\pi + m_\mu} = 0.14$$

Pion-muon atoms have been observed in K_l^0 decay at Fermilab[2] and BNL[3]. However **antimatter/strange muonic atoms have not yet been discovered**.



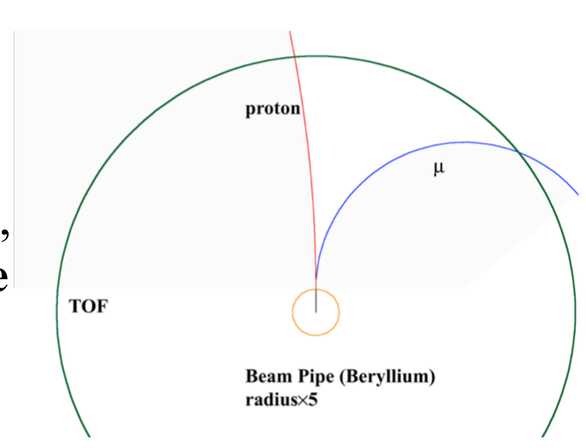
Estimations at STAR

A typical event at STAR

$p_T(\mu)$=0.2 GeV/c

$p_T(p)$=1.77 GeV/c

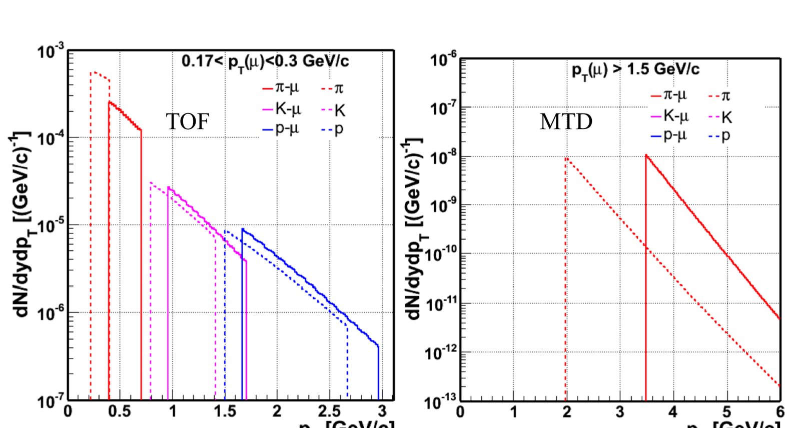
Atoms formed at the collision point, **disassociated by beam pipe** (ionization).



Atom formation occurs well after freeze-out through particle coalescence. It is only sensitive to the particle distributions at freeze-out [1]

$$\frac{dN_{\text{atom}}}{dyd^2p_{\perp,\text{atom}}} = 8\pi^2\zeta(3)\alpha^3 m_{\text{red}}^2 \frac{dN_h}{dyd^2p_{\perp,h}} \frac{dN_l}{dyd^2p_{\perp,l}}. \quad (1)$$

Muonic atom yields estimation with muon momentum accessible to STAR, calculated with STAR acceptance and the formula (1)[4][5]:



p_T ranges for muonic atoms accessible to STAR[5].

Atom	μ p_T (GeV/c)	Hadron p_T	Atom p_T	dN/dy
$\mu-\pi$	[0.17,0.3]	[0.22,0.4]	[0.39,0.7]	9×10^{-5}
$\mu-K$	[0.17,0.3]	[0.8,1.4]	[0.97,1.7]	1×10^{-5}
$\mu-\bar{p}$	[0.17,0.3]	[1.5,2.7]	[1.7,3.0]	4×10^{-6}
$\mu-\pi$	>1.5	>2	>3.5	3×10^{-9}

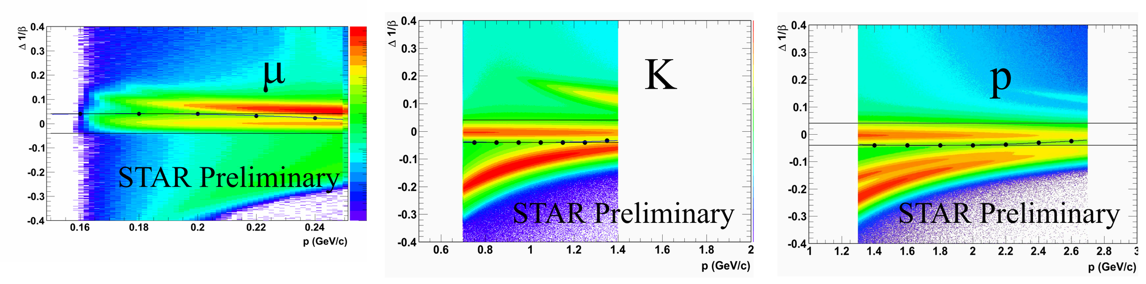
With the large amount of early produced (anti-)hadrons and muons, RHIC is able to produce all six of the above (anti-)atoms.

Particle Identification

The data set used is $\sqrt{s_{NN}}$=200GeV Au+Au central events in Run 10. A total of 230 million events have been analyzed. The two main detectors for particle identification are the Time-Projection Chamber and the Time-Of-Flight Detector.

Low transverse momentum muons are identified by first applying a tight TPC cut, $-3<n\sigma_{dE/dx(muon)}<-0.5$, and then applying the TOF cut. **The purity of the muon sample used in this analysis is 99%.**

$$\left.\frac{\Delta\beta^{-1}}{\beta^{-1}}\right|_\mu \equiv \frac{\beta_{mea}^{-1} - \beta_{\exp}^{-1}}{\beta_{mea}^{-1}} = 1 - \beta_{mea}\sqrt{m_\mu^2/p^2 + 1}$$



The corresponding kaons and protons are at TOF comfortable ranges as shown above.

Invariant Mass

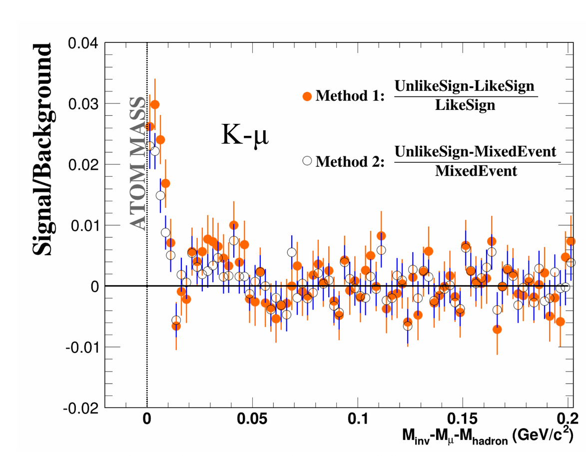
Invariant mass background is studied with two background subtraction methods.

Mixed-Event (ME) Method and **Like-Sign (LS) Method**.

The LS background is then corrected for acceptance difference between like-sign and unlike-sign pairs.

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

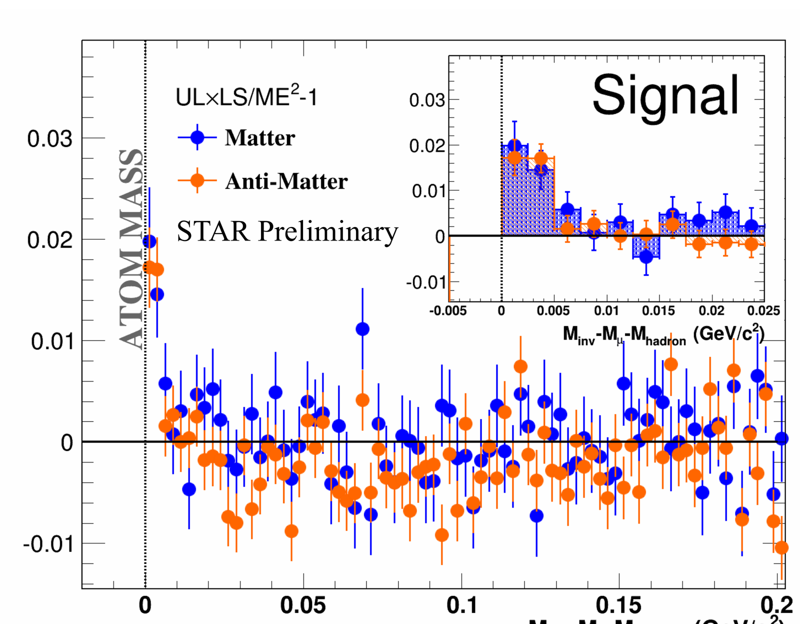
- Like-sign and Unlike-Sign have opposite Coulomb contributions, which causes the difference in LS and ME



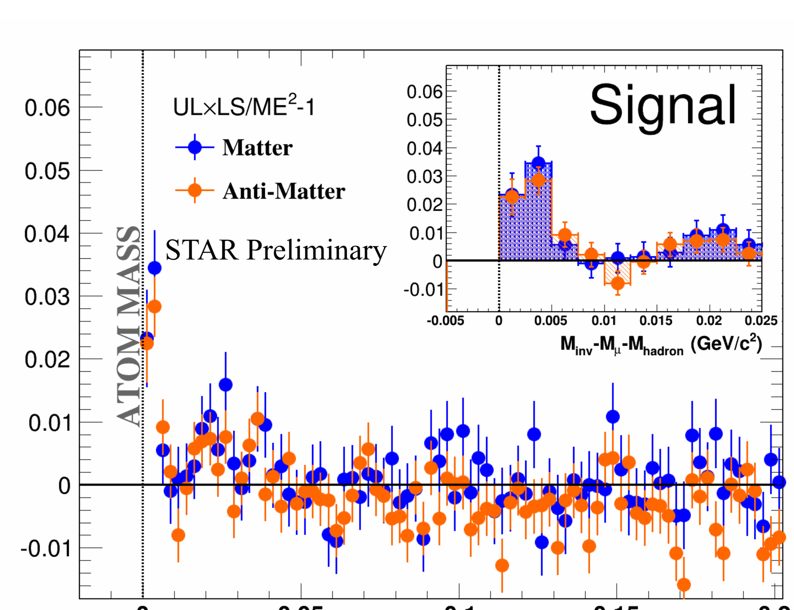
- the product cancels the major effect

$$SE_{+-} \times LS_{corrected}/ME_{+-}$$

The invariant mass distributions of **K-μ** pairs show peaks at the expected position (0 net mass).



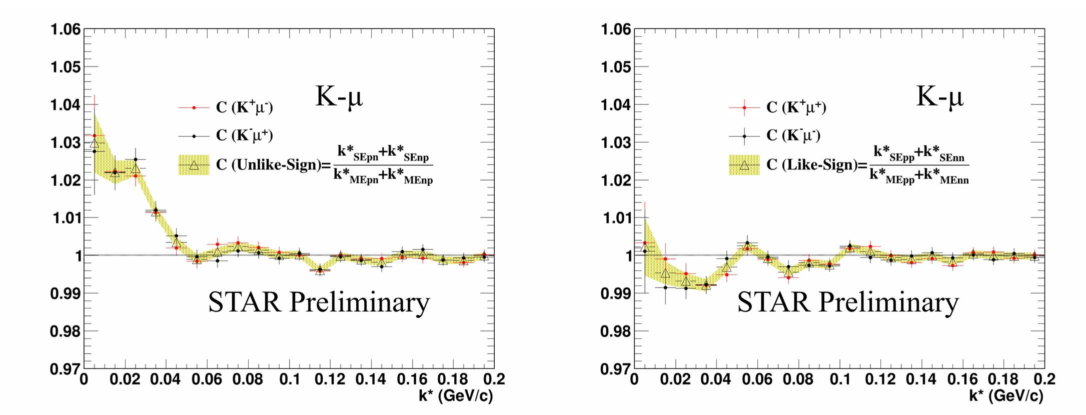
The mass distributions of **(antimatter) muonic hydrogen** also show sharp peaks at the expected position.



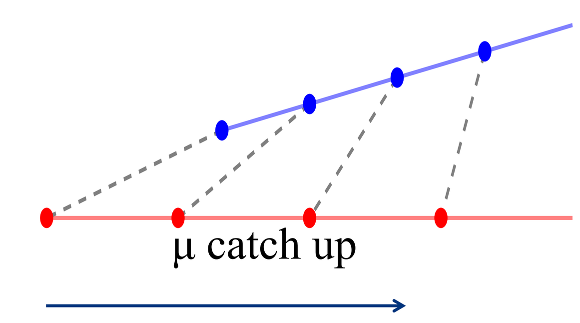
Two Particle Correlations

- **k*** – the magnitude of the three-momentum of either particle in the pair rest frame.
- **C(k*)** – the ratio of the k* distribution constructed from particles from the same events to that from particles from mixed events

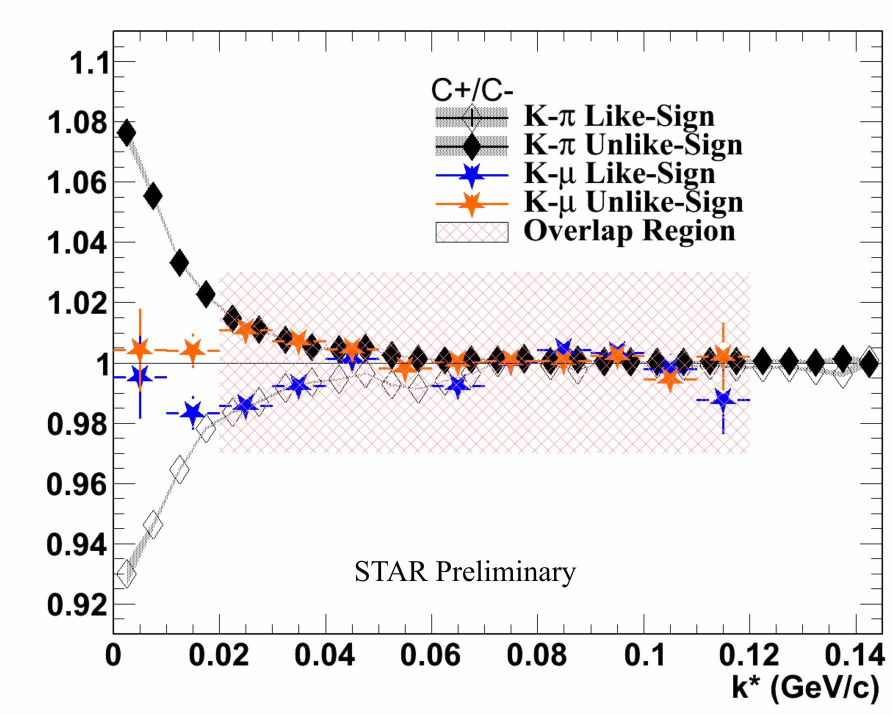
Correlation functions show the existence of Coulomb force[6] which is required by atom formation.



- **$C_+(k^*)$, $C_-(k^*)$** – the sign indices reflect the sign of $v_{pair} \bullet k^*_{\mu\_in\_pair\_rest\_frame}$



- The double ratio C_+/C_- deviating from unity is a probe of space-time asymmetry of the particle formation
- C_+/C_-(K-**π**) indicates π is emitted earlier than K[6].
- C_+/C_-(K-**μ**)~1 at low k*, meaning they are **emitted at the same time and position, suggestive of atom formation and disassociation.**



Summary

We have observed two possible signatures of the new (antimatter) atoms:

- **Invariant mass enhancement** is observed at the expected mass for both K-μ and p-μ pairs.
- Muons and kaons that are close to each other in phase space are **emitted simultaneously**, suggestive of atoms.

References

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