Searching for Muonic Atoms

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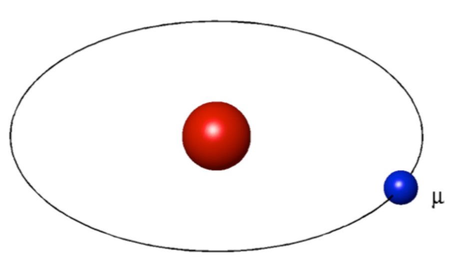
Abstract

Hydrogen-like muonic atoms are Coulomb bound states of a muon and a hadron. In ultrarelativistic heavy -ion collisions, due to the produced high particle multiplicities, a produced muon can be directly bound to a charged hadron, and form an atom. With muon identification at low transverse momentum from the Time-of-Flight (TOF) detector, STAR provides an great opportunity to search for the muonic atoms with exotic cores, such as anti-matter or strange cores. This is also an ideal tool to measure the thermal emission from the Quark-Gluon Plasma (QGP) 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.

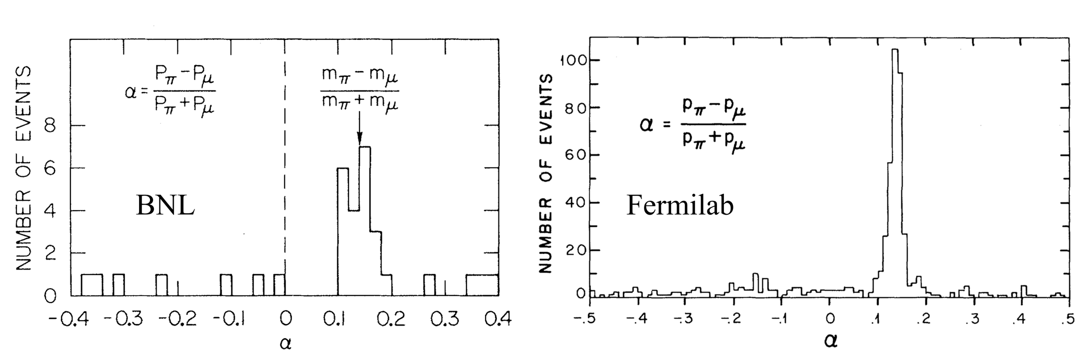


Previous Measurements

To from atoms, two particles from a same atom must be close in phase-space [1]

$$\alpha = \frac{|\vec{p}_1-\vec{p}_2|}{|\vec{p}_1+\vec{p}_2|} = \frac{|m_1\vec{v}_1-m_2\vec{v}_2|}{|m_1\vec{v}_1+m_2\vec{v}_2|} = \frac{m_1-m_2}{m_1+m_2}$$

Pion-muon atoms have been observed in K_l^0 decay at BNL and Fermilab[3][4].



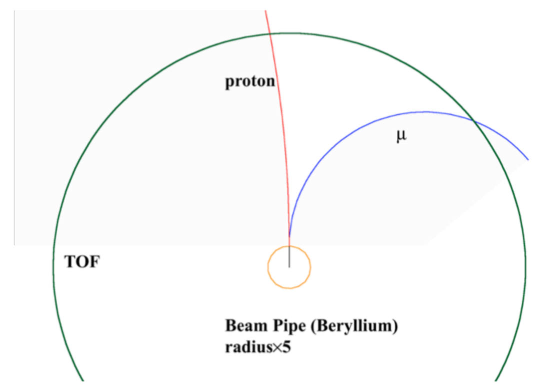
Estimations at STAR

A typical event at STAR

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

$p_T(p)$=1.77 GeV/c

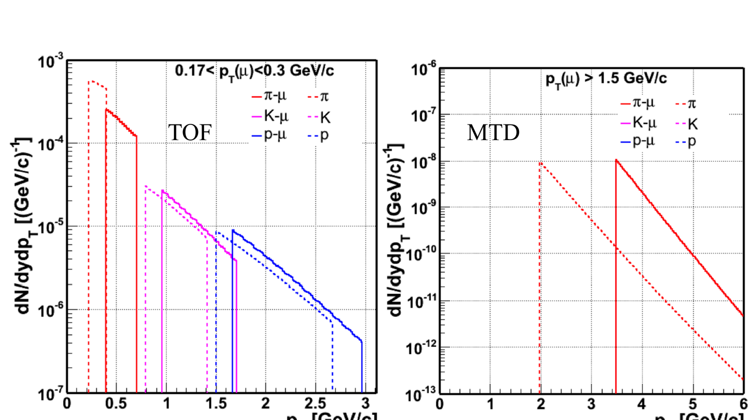
Atoms disassociated by the beam pipe



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

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

Muonic atom yields estimation with muon momentum accessible to STAR, calculated with STAR acceptance and the formula[2][3]:



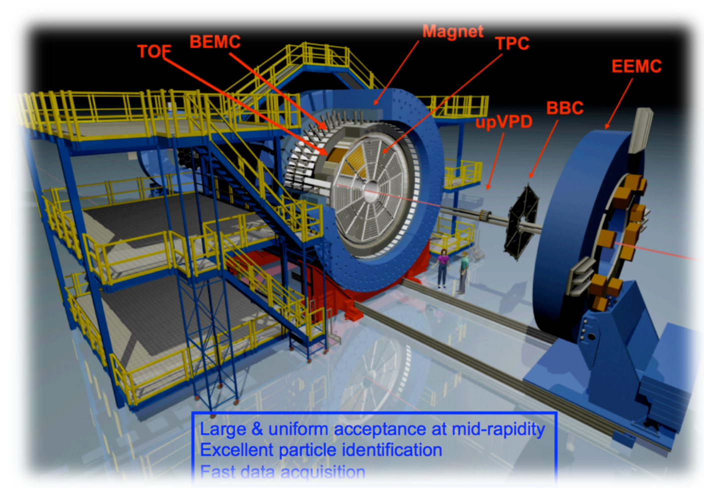
pt ranges for muonic atoms accessible to STAR[3].

Atom	$\mu\ p_T$ (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 thermal (anti-)hadrons and muons, RHIC is producing all six of the following (anti-)atoms

STAR Detector and Dataset

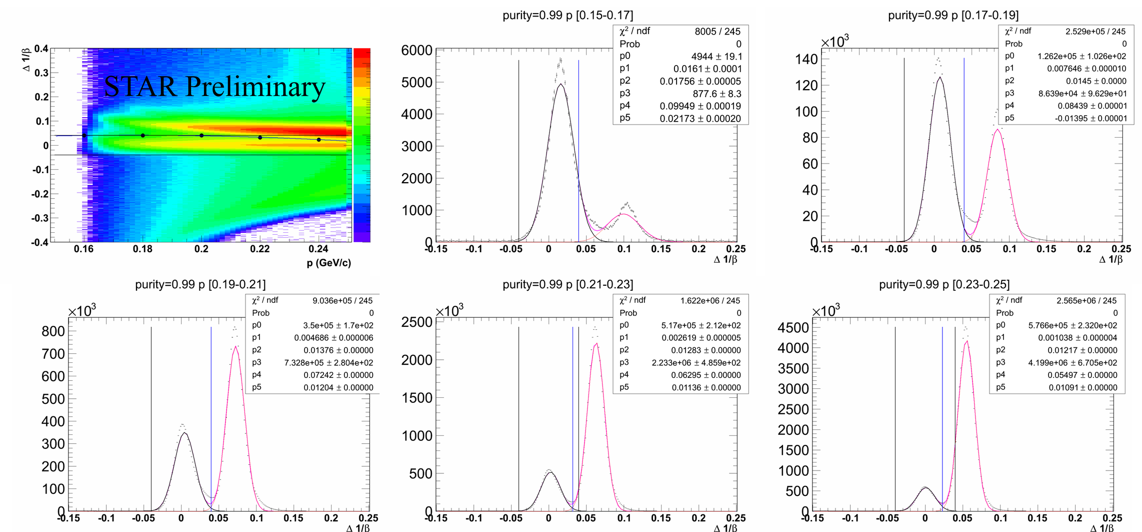
The data set used is $\sqrt{s_{NN}}$=200GeV Au+Au central events in Run 10. A total of 230 million events have been analyzed. The two main detectors for particle identification are the **Time-Projection Chamber** and the **Time-Of-Flight Detector**.



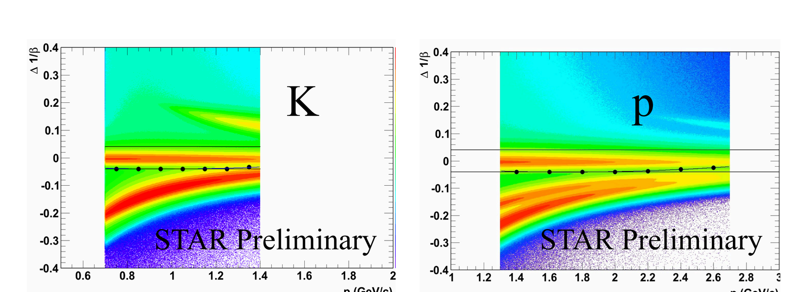
Particle Identification

Low transverse momentum muons are identified by first applying a tight TPC cut, $n\sigma_{muon}$ (-0.5,-3), and then applying the TOF cut

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



The corresponding kaons (p>0.70 GeV/c and p<1.17 GeV/c) and protons (p>1.33 GeV/c and p<2.22 GeV/c) are at TOF comfortable ranges. After $n\sigma_{kaon}$ and $n\sigma_{proton}$ (-2,2)



Invariant Mass

Invariant mass background is studied with the two background subtraction methods

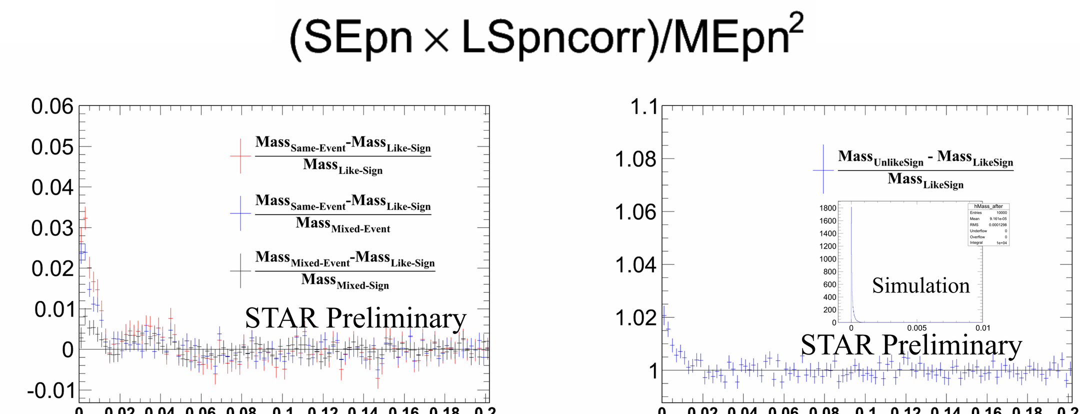
Same Event Like-Sign Method: Every muon is paired with every Kaon, if they have the same charge. The background is then corrected for acceptance difference between like-sign and unlike-sign pairs.

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

Mixed Event Unlike-Sign Method: Every muon is paired with Kaons from similar events, if they have opposite charges, to produce uncorrelated background.

- Coulomb effect exists in same event method, like-sign and unlike-sign
- Coulomb effect increase the phase space separation of like-sign pairs, and reduce the separation of unlike-sign pairs, both giving larger and wider peak.
- Like-sign and Unlike-Sign have opposite Coulomb contributions, the product can cancel the major effect

$$(SEpn \times LSpncorr)/MEpn^2$$

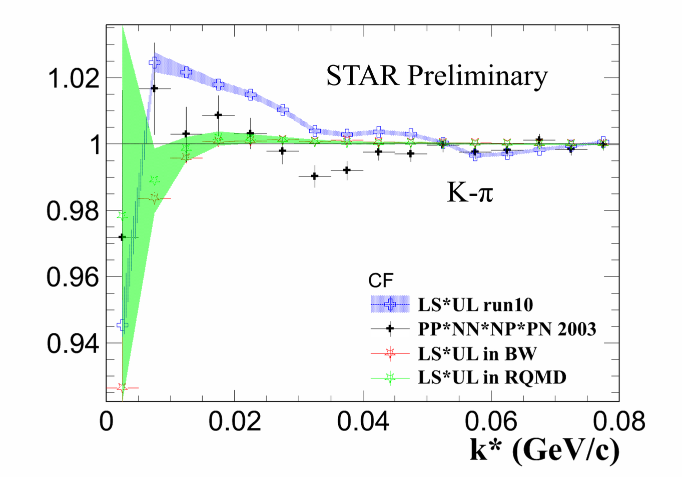


- The mass peak width is much larger than simulation

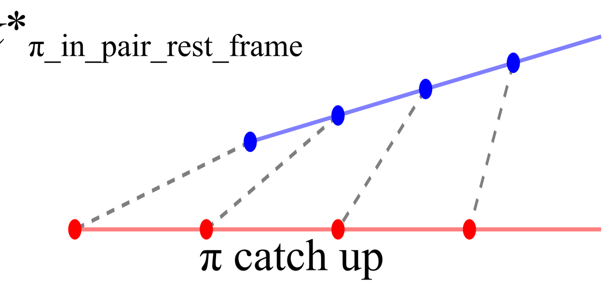
Two Particle Correlation

- **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

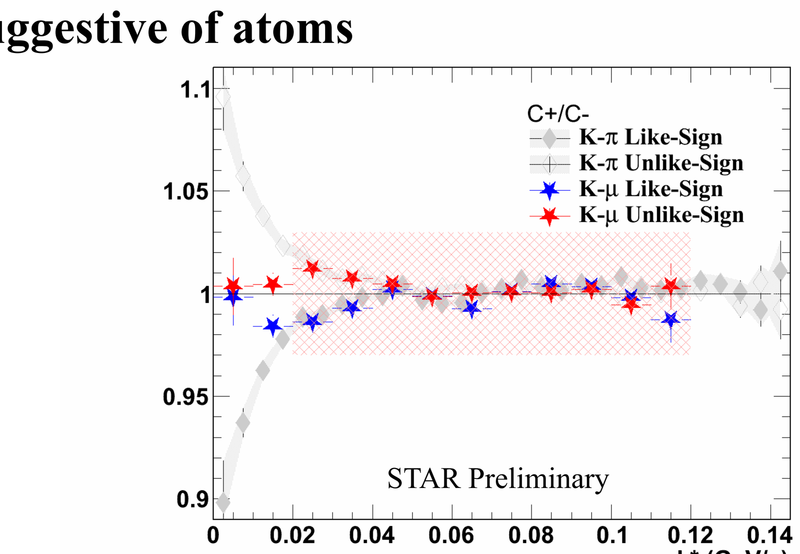
Correlation Functions (CFs) show the magnitude of Coulomb effect. The product of CFs at low k* from models (Blast-Wave and RQMD) show negative Coulomb residue (<1), while data (blue and black) show positive Coulomb residue.



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



- Pions that are emitted closer to the center of the source, pions with a larger velocity will tend to catch up with kaons. The Coulomb correlation strength will be enhanced compared to the case where pions are slower than kaons. Hence, the correlation function **C_+ will show a larger deviation from unity than C_-**[5].
- Muons and Kaons show C+/C-~1 at low k*, meaning they are **emitted at the same time and position , suggestive of atoms**



*cross-hatched band only serve as a boundary within which kaon-pion and kaon-muon agree

Summary and Outlook

- Invariant mass is studied for kaon-muon pairs.
- Kaon-pion correlation functions show coulomb residue is not completely removed.
- Muons and kaons that are close to each other in phase space are emitted at the same time, suggestive of atoms
- Run11 data will be analyzed to increase statistics
- More particle pairs will be studied. p-mu, pi-mu and their anti-matter pairs
- Alpha distributions will be studied

References

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