Search for Muonic Atoms at RHIC

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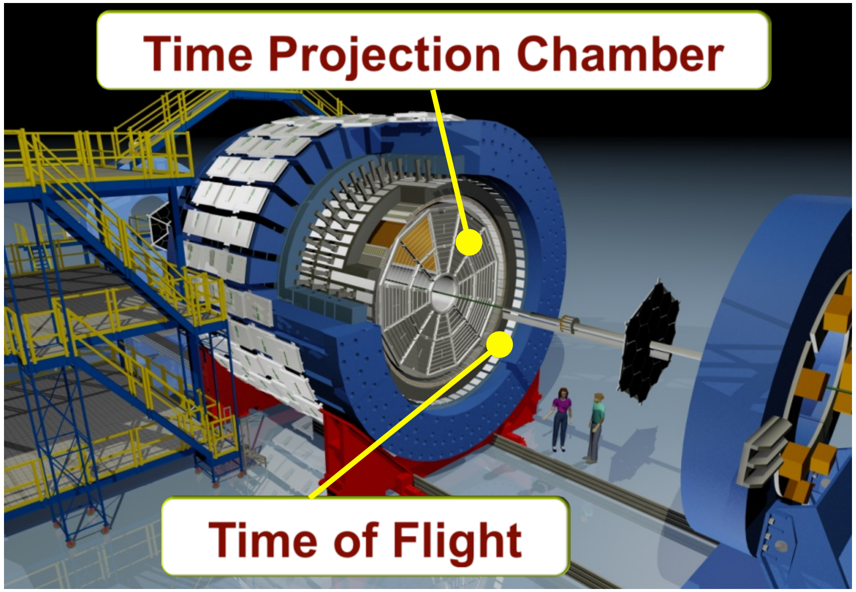
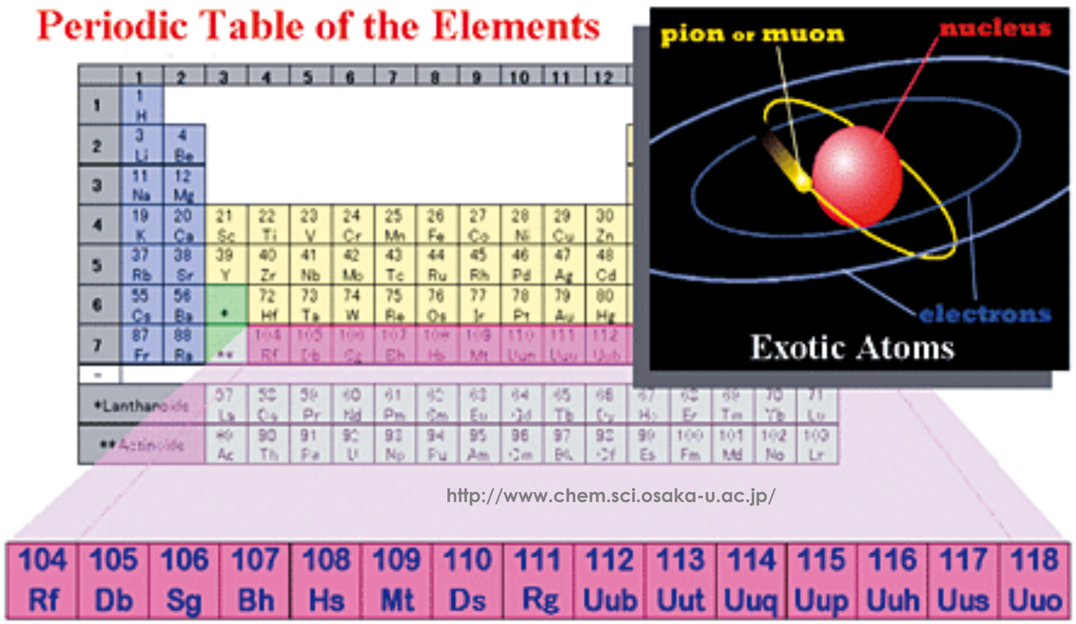
Outline

- Motivation
- Particle identification
- Invariant mass
  - Background determination
  - Coulomb rejection
  - Signal extraction
- Correlation functions
  - Coulomb revealing
  - Double ratio
- π-μ correlations



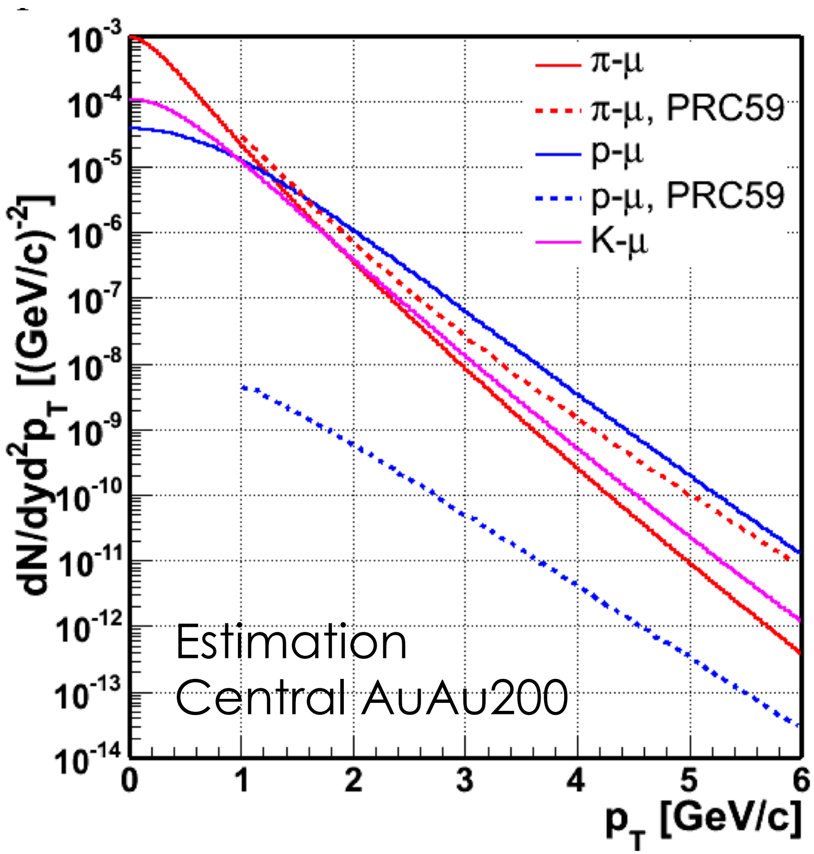
Motivation

Potential discovery of new atoms



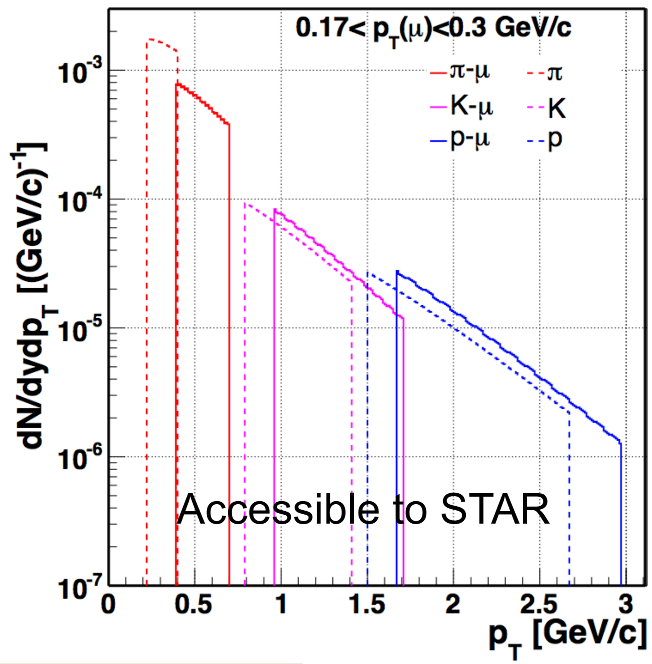
p^{+}- μ^{-}	K^{+}- μ^{-}	π^{+}- μ^{-}
anti-p- μ^{+}	K^{-}- μ^{+}	π^{-}- μ^{+}

Theory Estimations



Estimation based on: QED!!!

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



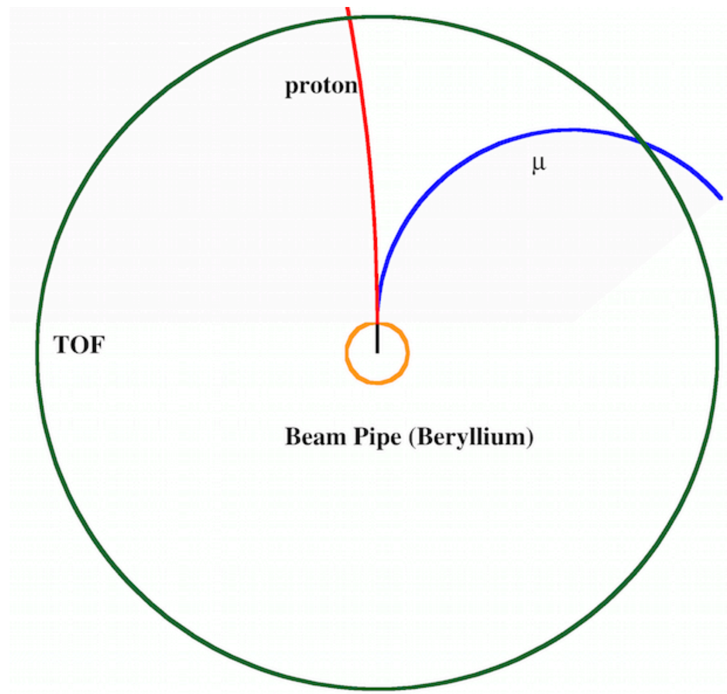
In heavy-ion physics, this study provides a direct measurement of **early produced muon** emission, which is sensitive to the early stage of the collisions.

Kapusta&Mocsy PRC 59 2937
2010 STAR Decadal Plan

Muonic Atom Detection at STAR

1) **Dissociation** of the atoms before the detector

tracking at beryllium **beam pipe**

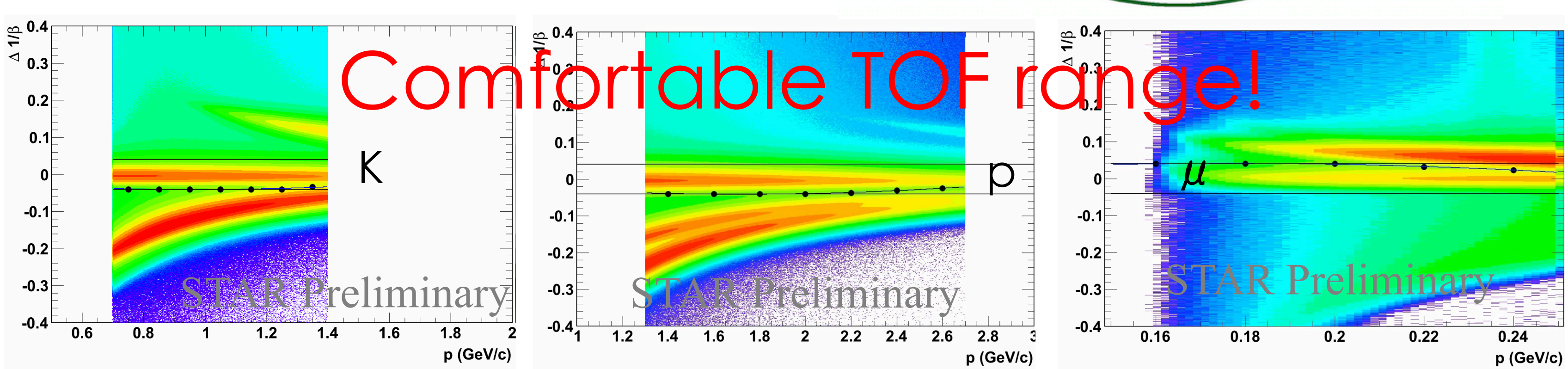


2) **Particle Identification**

STAR Run10 AuAu 200GeV
231M Central Triggered Events

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

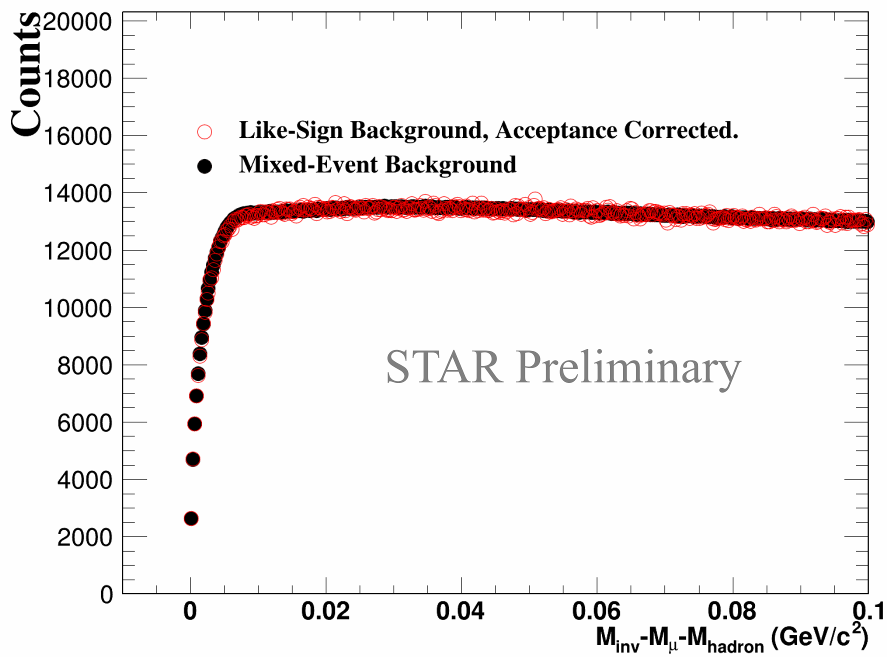
Comfortable TOF range!



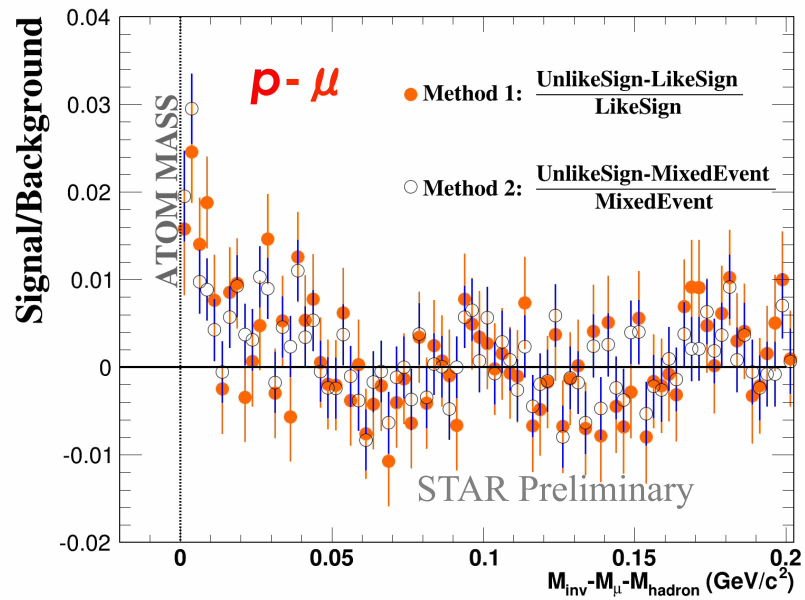
Foreground and Backgrounds

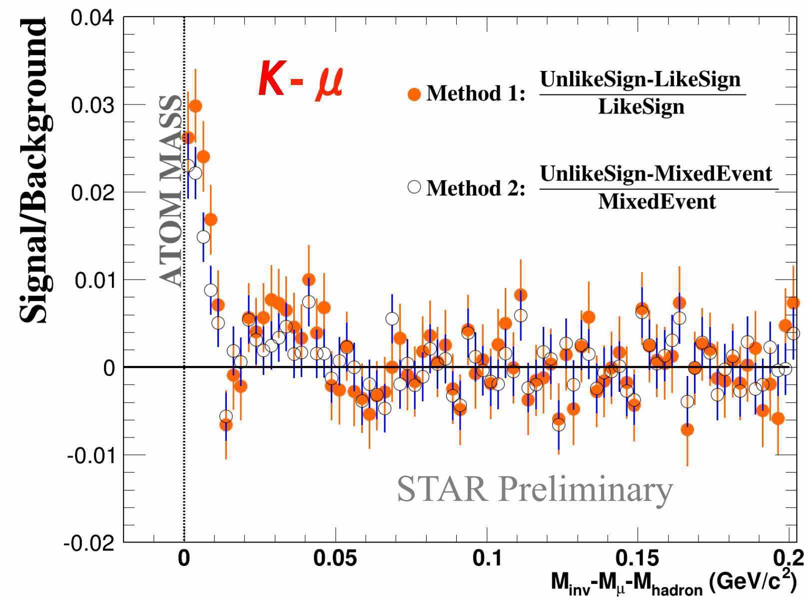
- Foreground method:
  - UnLike-sign (**UL**) foreground: tracks with the different charges are paired
- Background method:
  - Mixed-Event (**ME**): tracks from different events are paired
  - Like-Sign (**LS**): tracks with the same charge are paired

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



Invariant Mass





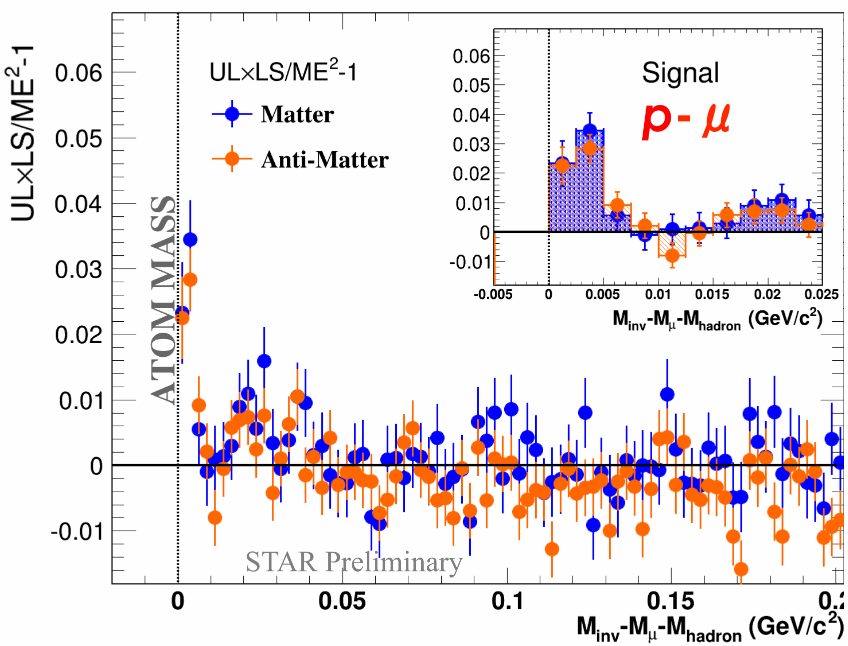
- ✓ Observed **sharp peaks** for atoms at expected mass M_{inv}-M_{μ}-M_h= **0** GeV/c^2 from both background subtraction methods
- ✓ **Good background methods** -- Flat at higher mass (0.05~0.2 GeV/c^2)
- ✓ Like-Sign (LS) background has repulsive **Coulomb** contribution, and thus underestimates the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

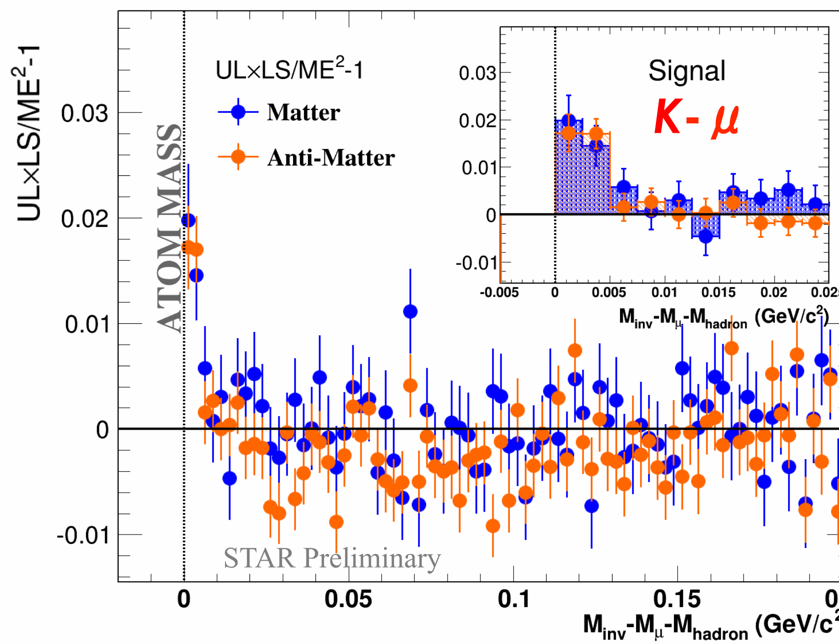
Invariant Mass

In pair invariant mass method:

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

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

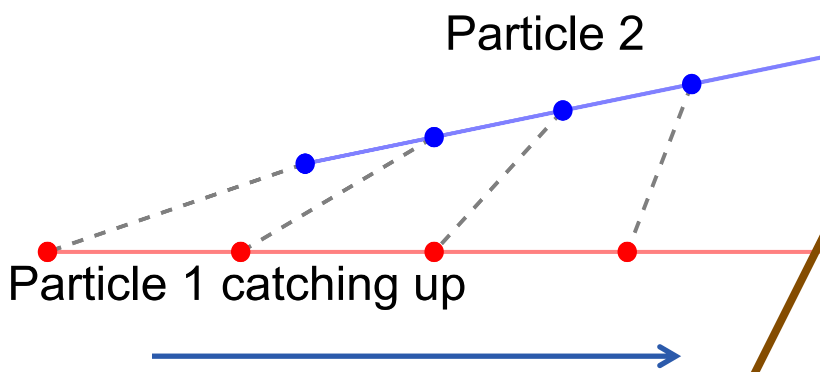




Sharp peaks observed at the signal region.

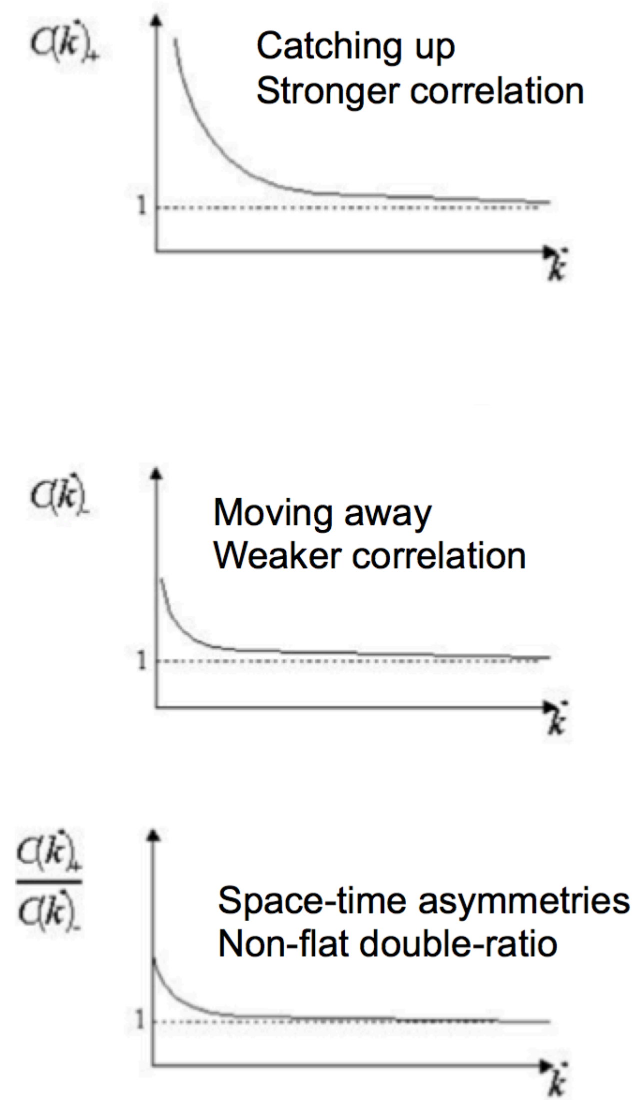
Correlation Functions

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



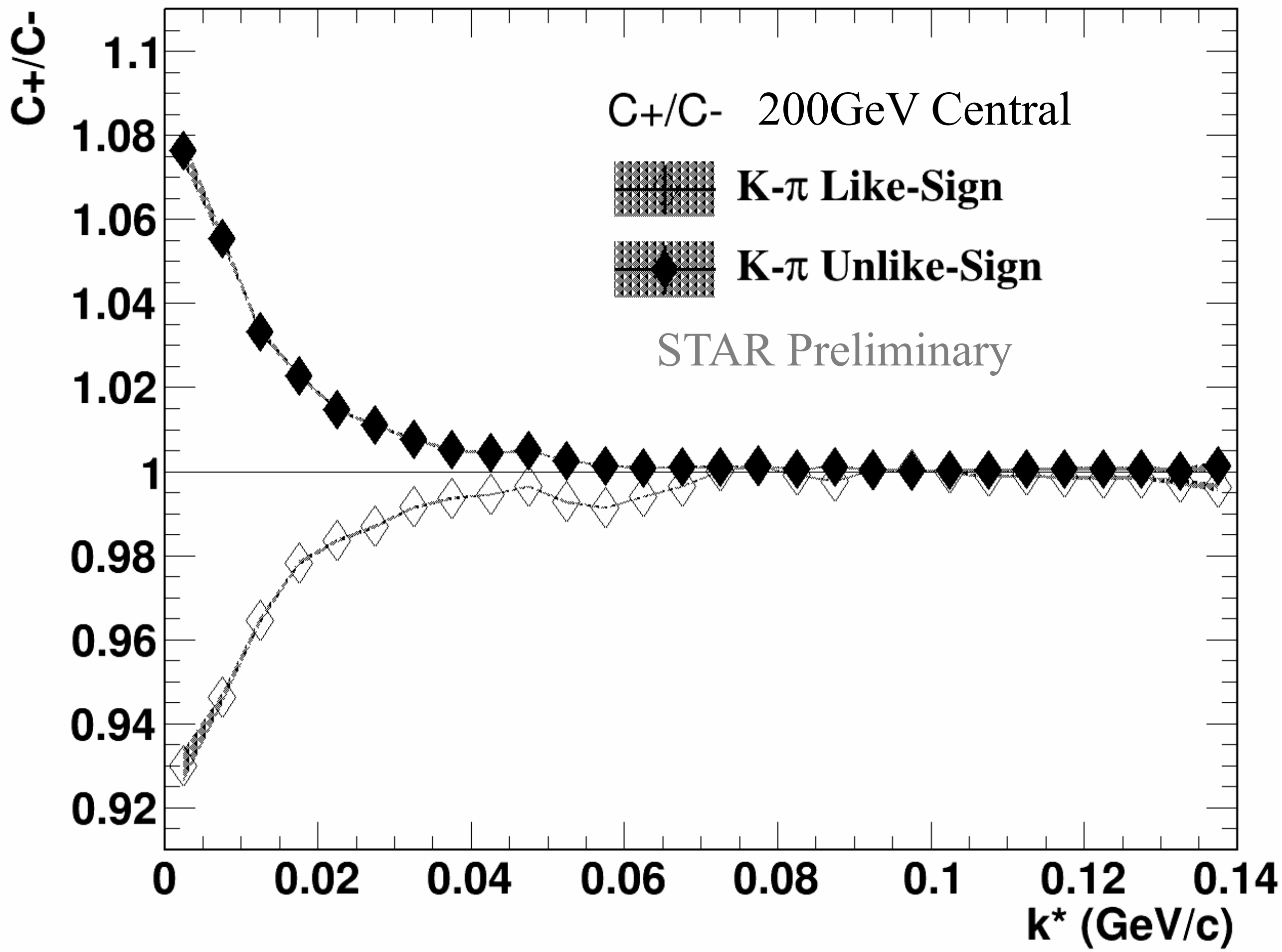
Correlation function:
Normalized relative momentum distribution of the leading particle in pair frame

Double ratio: a probe of space time asymmetries



STAR PRL 91 (2003) 262302

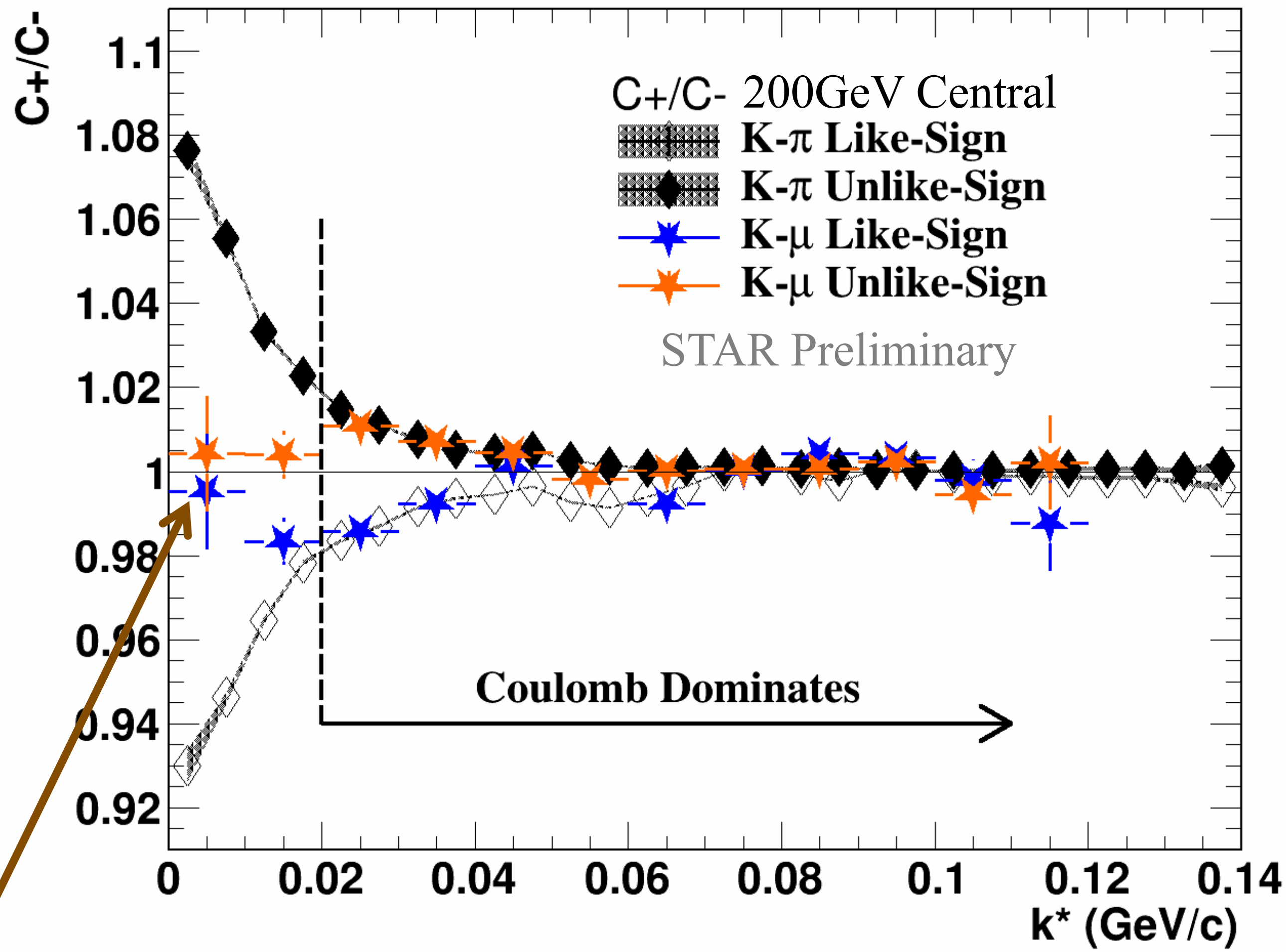
K-π Correlations



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

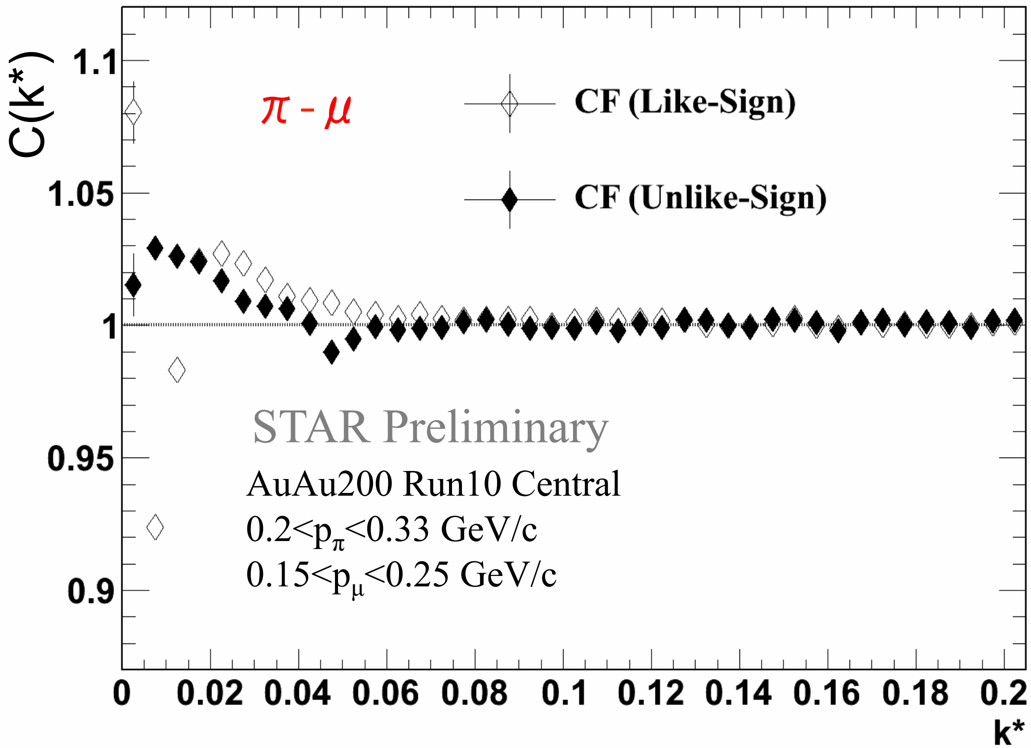
- Enhancement in Unlike-Sign
- Suppression in Like-Sign

K-μ Correlations



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

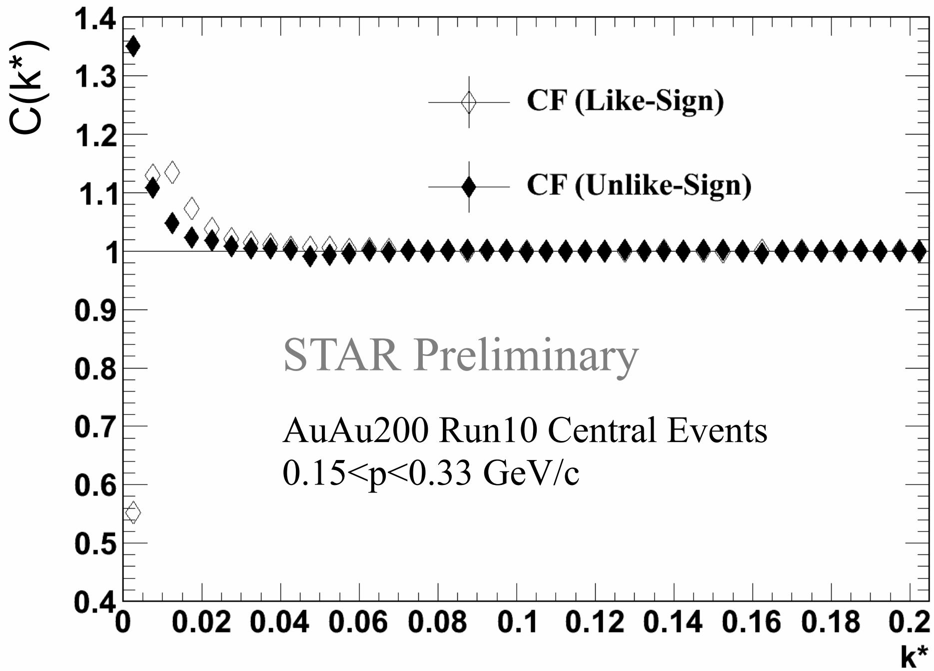
π-μ Correlations



If there are only final state coulomb interactions,

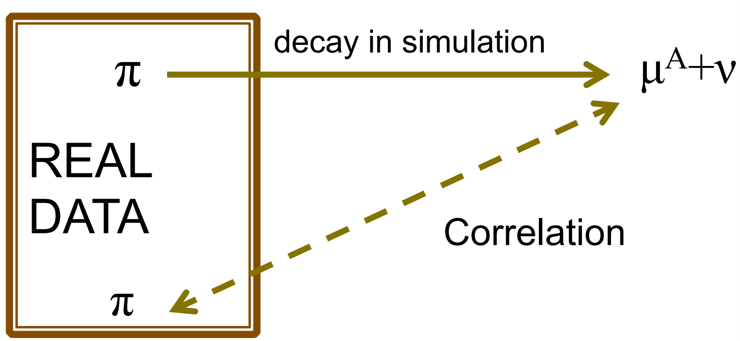
- Like-Sign CF should be <1, and increase monotonically approaching 1
- Unlike-Sign CF should be >1, and decrease monotonically approaching 1

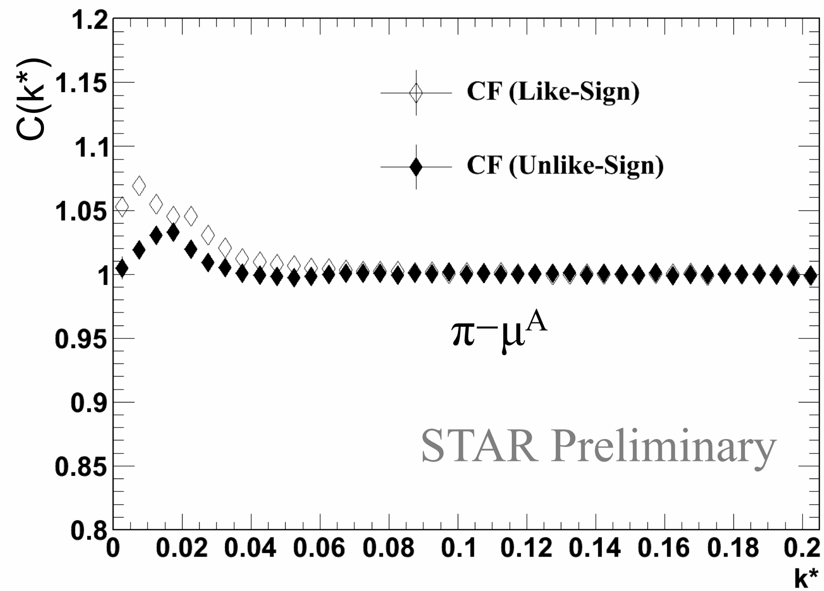
π-π Correlations



- In like-sign pairs, the correlations come from rejecting Coulomb force.
- In unlike-sign pairs, the correlations come from: [**STAR** PRC 83 064905 2011]
  - Bose-Einstein quantum statistics ↑
  - Coulomb final state interaction ↓

π-μ^A Correlations





1) Use two pions from real data

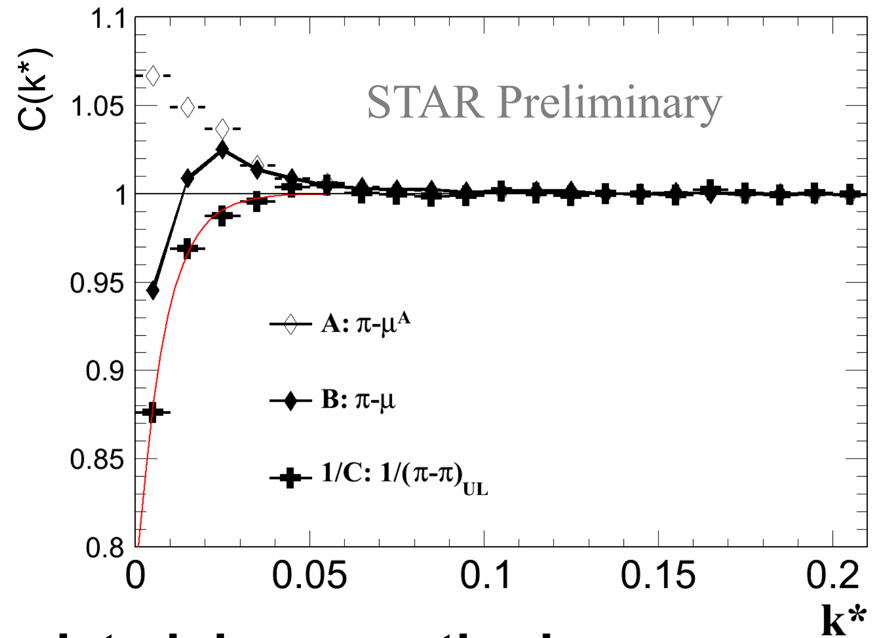
2) Let one π decay to μ+v, based on energy momentum conservation only
   1) Let decay in π center-of-mass frame
   2) boost decay products using β_π

3) Calculate the correlation between the “artificial” muon (**μ^A**) and the other π

Three Correlation Functions

- A: π-μ^A – weak-decay only
- B: π-$\mu_{measured}$ – weak-decay & primary
- C’: π-$\mu_{primary}$ -- primary only

B = α*C’ + β*A
=> B = α*1/C + β*A

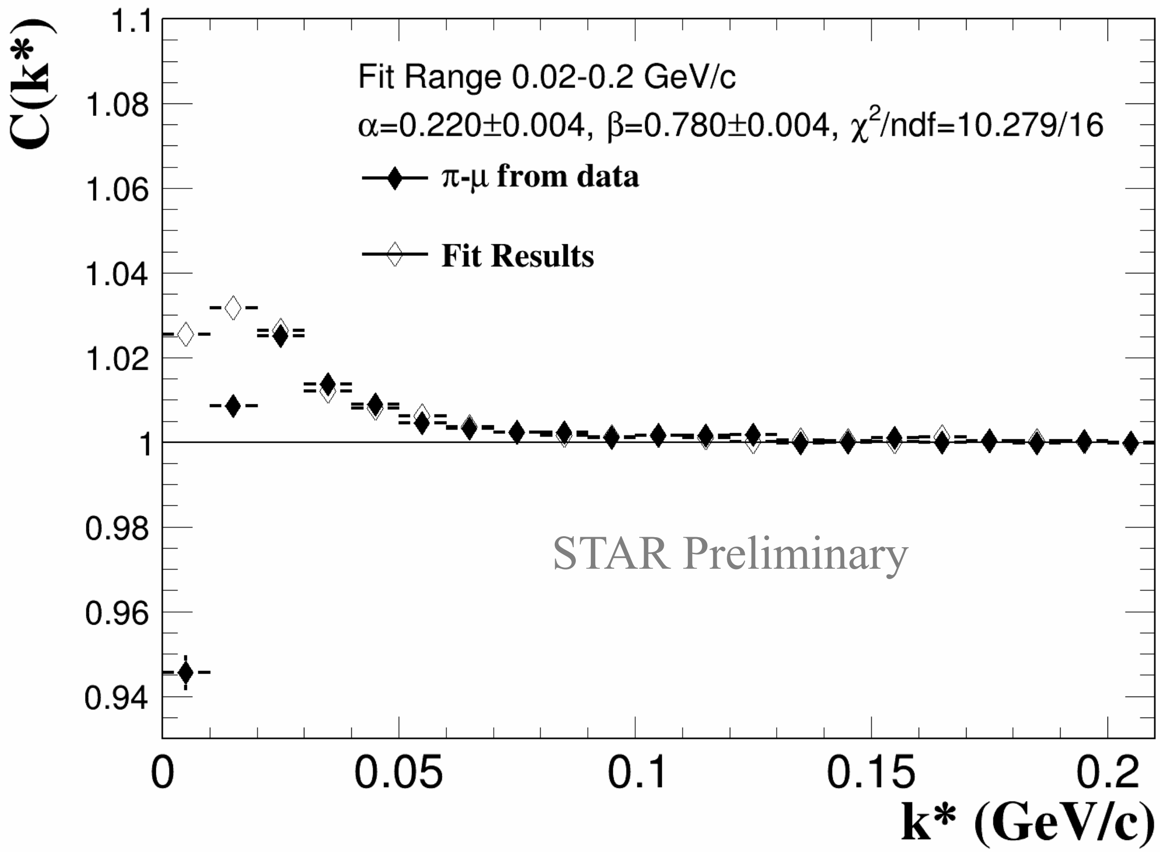


A can be determined by **the simulated decay method**

B can be measured **directly from data**

C’ ~ C(π-π) **~ 1/C(π-π)$_{UL}$** to avoid quantum statistics contribution

Fitting Results



22.0±0.4% primary muons

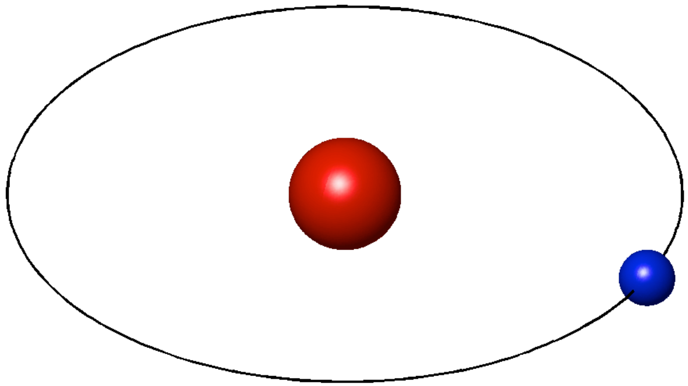
Very low k* is discarded because – when we simulate the decay π->μ^{A}+v , there are always missing pions, which can not be saved anyways due to track merging.

Summary

- **Invariant mass peaks** at the expected atom masses have been observed
  - The signal is robust after Coulomb effect is rejected
  - The singal is consistent in all (anti-matter) pairs
- Femtoscopic correlation studies are consistent with **ionization of muonic atoms**
  - Correlation shows the existence of Coulomb force
  - The double ratio indicates the daughter particles are emitted at the same space-time point – disassociated from muonic atoms
- π-μ correlations are used to extract fraction of direct muons

BACKUP

What is a muonic atom



Hadron+muon Coulomb bound state

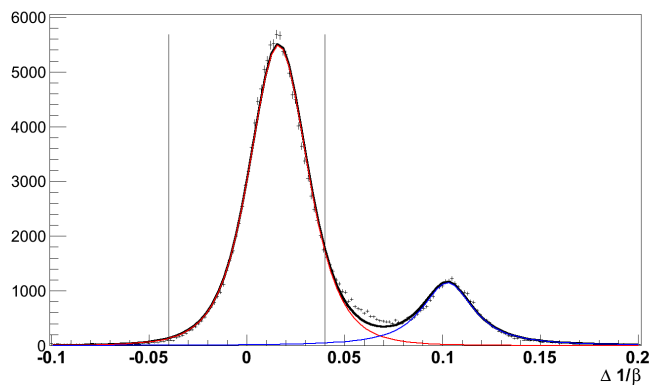
- **Facts**
  - Binding energy ~3 keV
  - Bohr radius

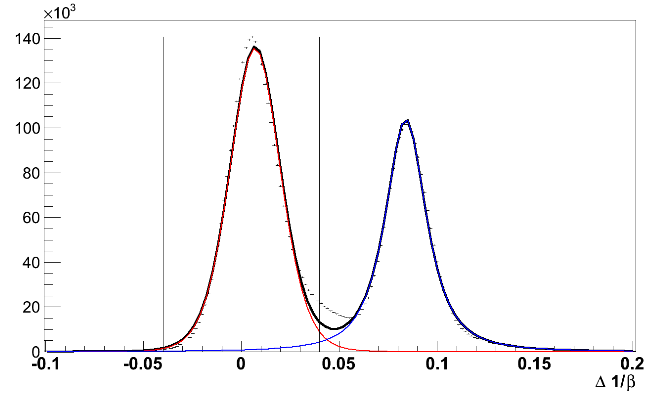
  a_0*(m_e/m_red)

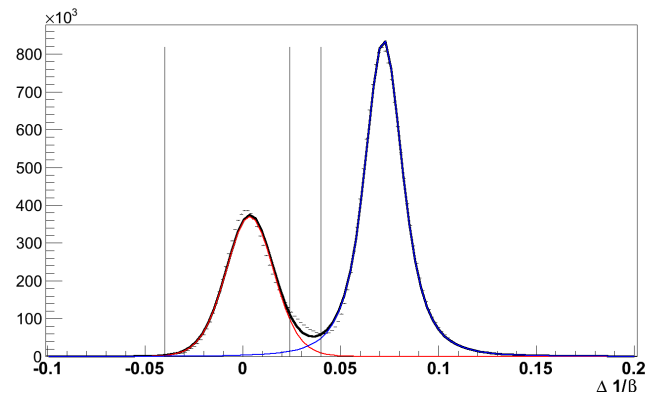
  =279fm (p+mu)

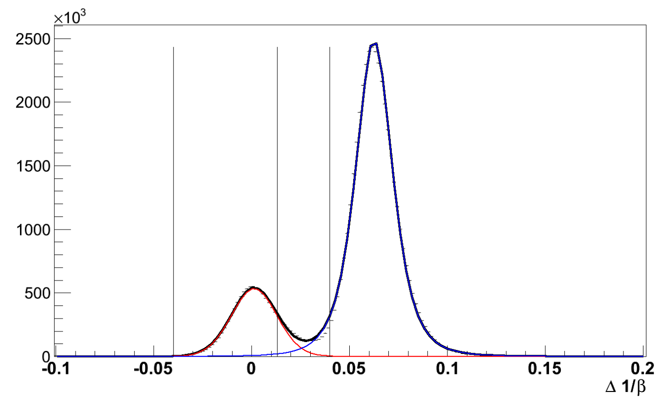
  =440fm (pi+mu)
  - Bohr velocity alpha*c/n

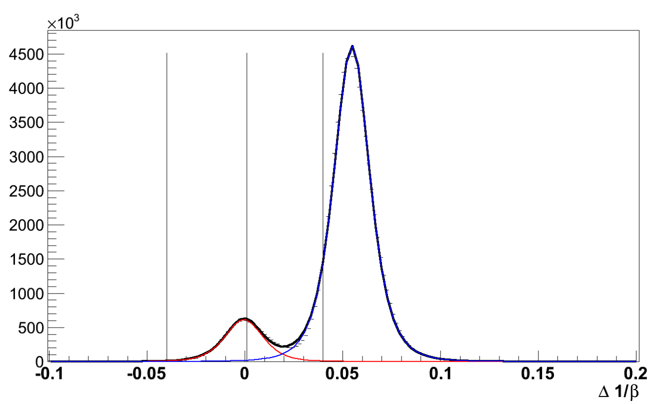
- **What to expect**
  - Atom mass = m_p+m_mu
  - Atoms can only be at **s** state
  - Pp/mp=pmu/mmu





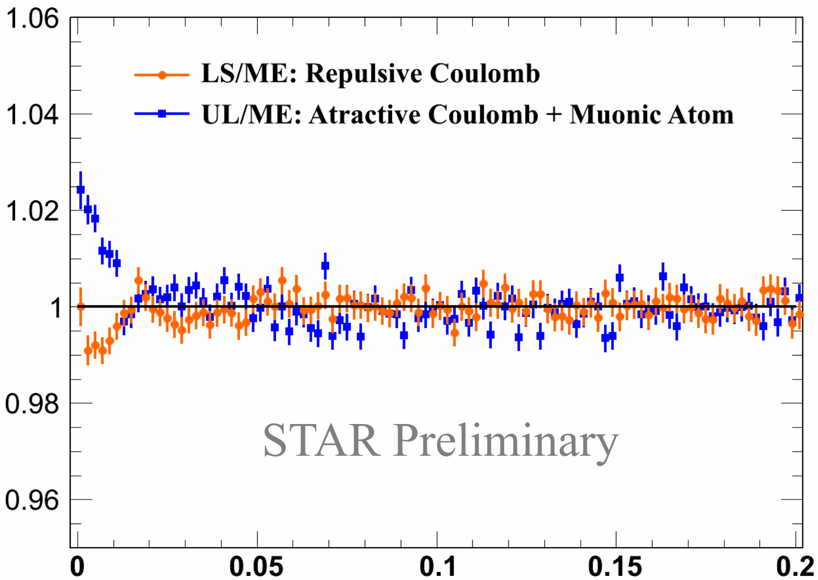






High purity muons

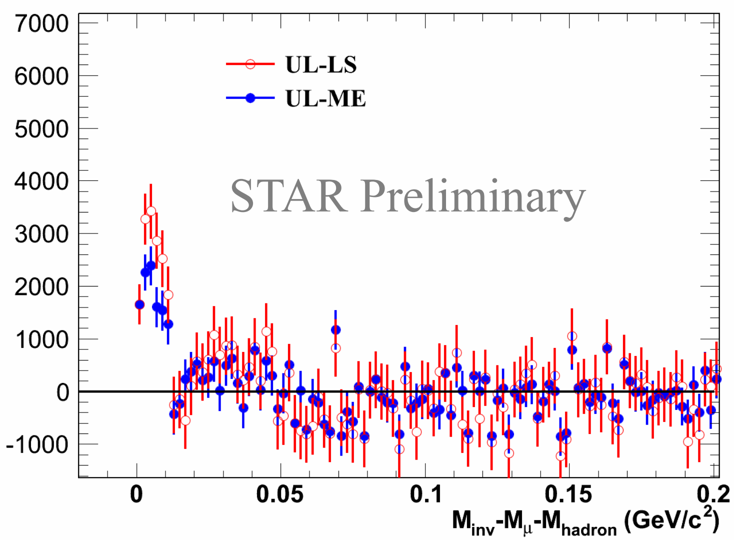
Invariant Mass -- Coulomb Effect



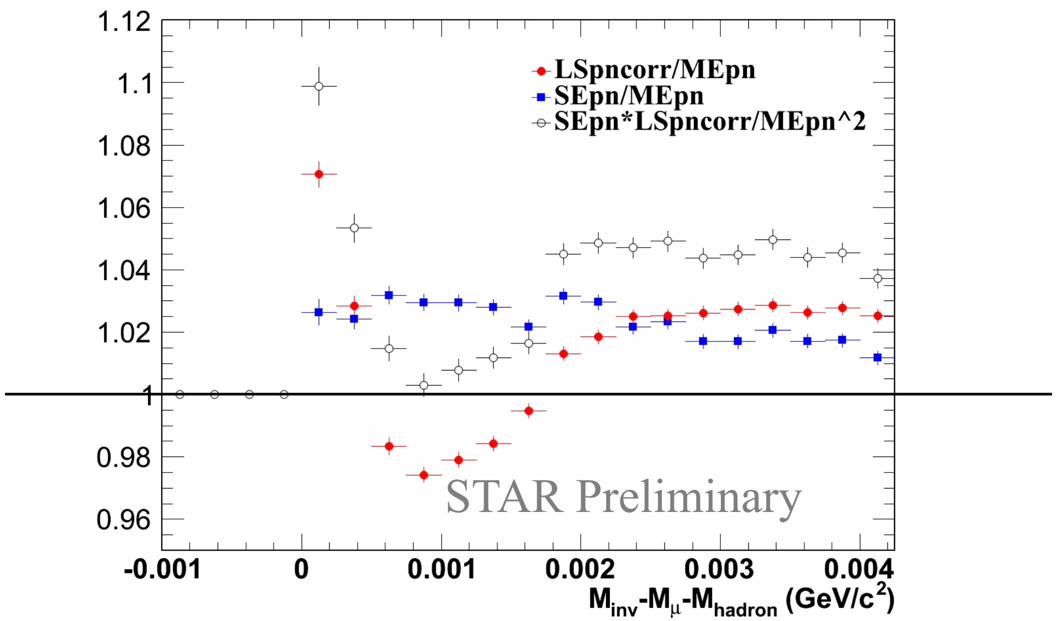
Coulomb Canceling

Like-sign background has repulsive Coulomb, which gives lower background estimation than Mixed-Event (red circles <1 at low mass).

Unlike-sign foreground has attractive Coulomb. The distribution is enhanced by both Coulomb and muonic bound states. (blue squres)

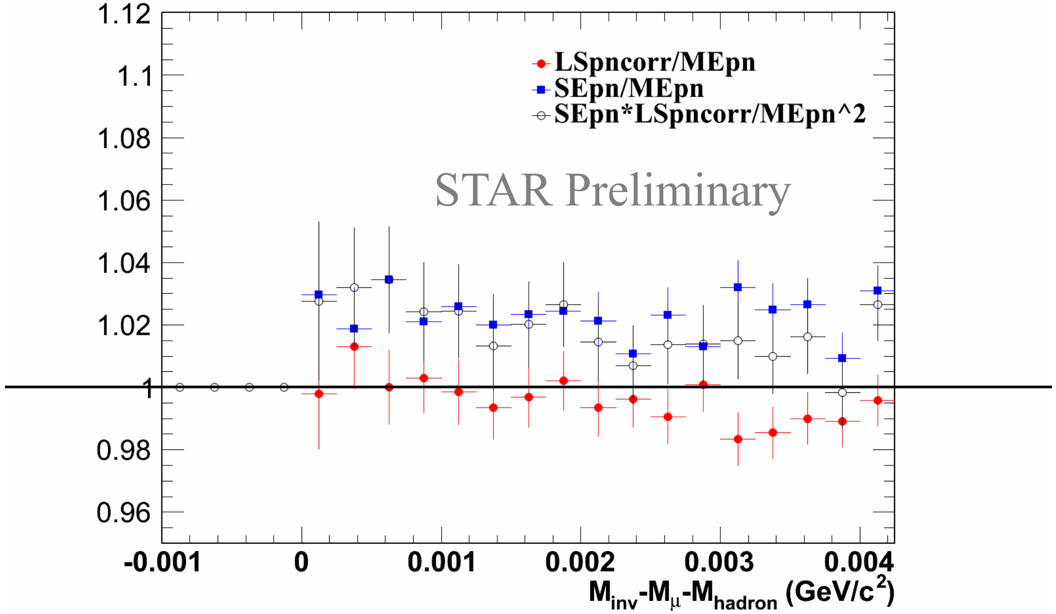


The signal extracted from Like-sign method (red) is higher than from Mixed-Event (blue), because of repulsive Coulomb in Like-Sign



A sharp peak (black empty circles ~1MeV/c^2) is observed in pi-mu pairs

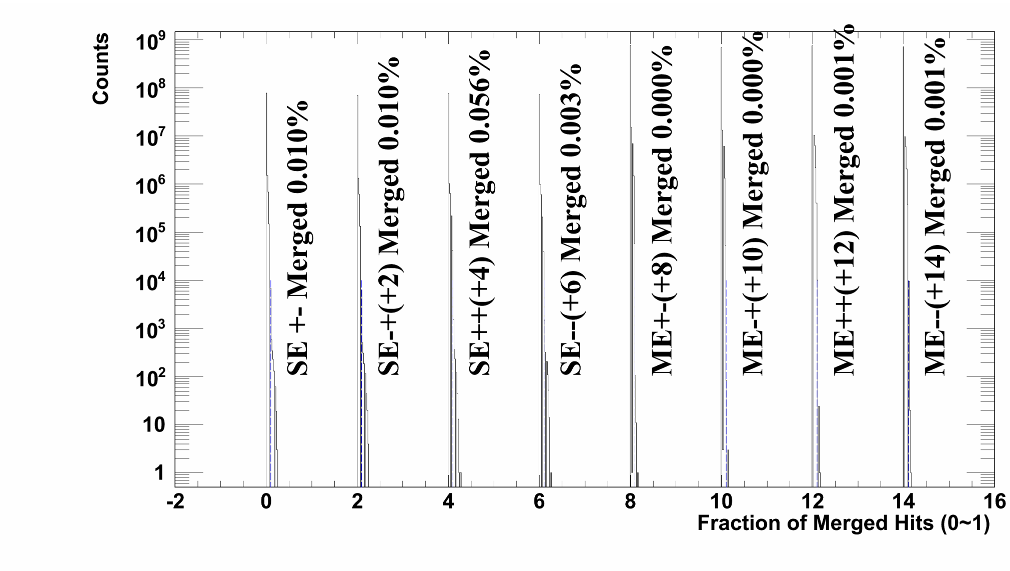
- Only in pi-mu pairs
- IF foreground had this peak, the blue (peak + attractive coulomb) would have revealed the peak
- The sharp peak is produced from backgrounds (red)



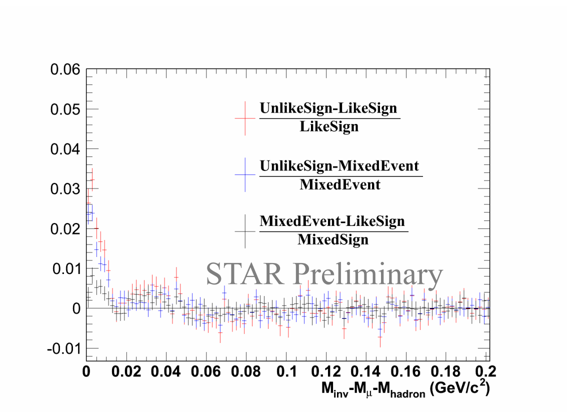
LSpncorr/MEpn
SEpn/MEpn
SEpn*LSpncorr/MEpn^2
STAR Preliminary
1.12
1.1
1.08
1.06
1.04
1.02
1
0.98
0.96
-0.001
0
0.001
0.002
0.003
0.004
M_{inv}-M_{μ}-M_{hadron} (GeV/c^2)

K-mu

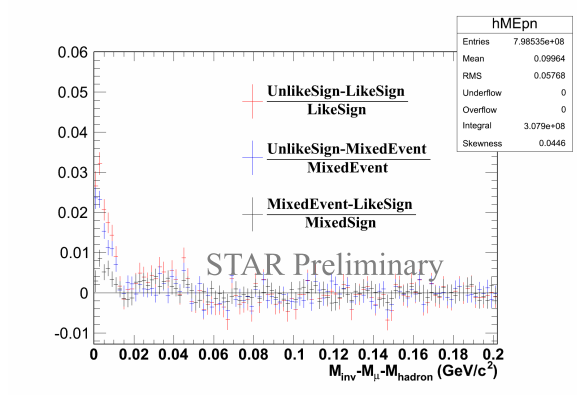
Pairs that Pass the 10% FMH cut (k-mu)



- Much fewer merged tracks

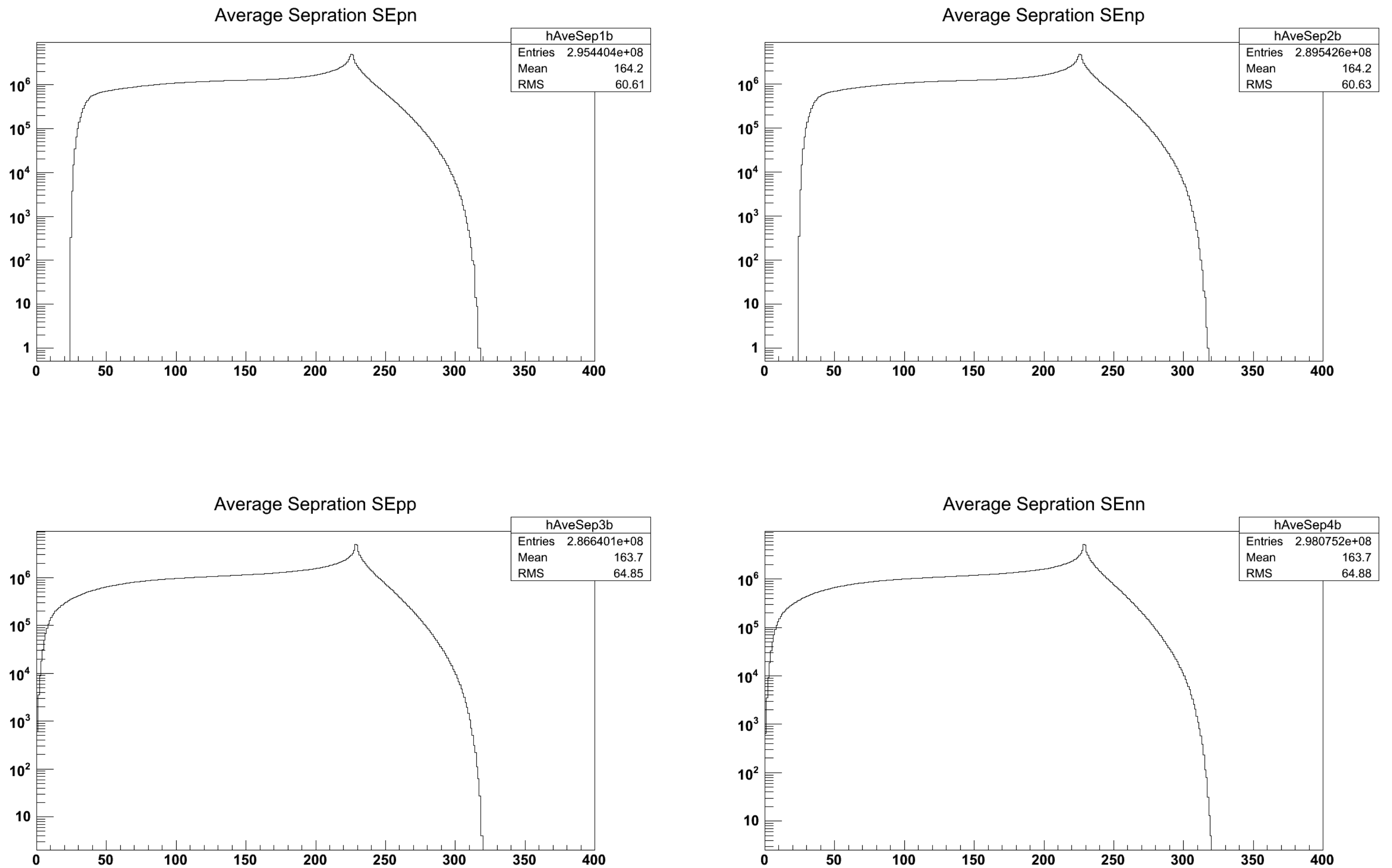


w/o FMH cut



w/ FMH cut

Average Separation – pi-mu Same-Event



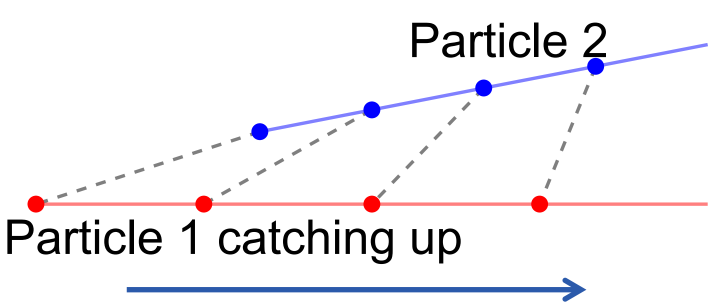
Femtoscopic Correlation

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

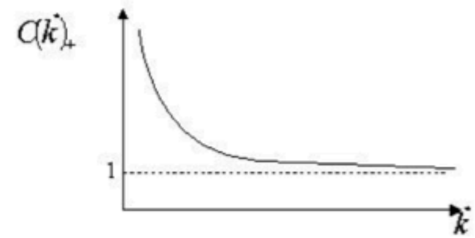
k* – the magnitude of the three-momentum of either particle in the pair rest frame.
C(k*) – the ratio of the k* distribution constructed with particles from the same event with the particles from mixed event:
C(k*)=(k* in Same Event)/(k* in Different Event)
=(correlated distribution)/(uncorrelated distribution)

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

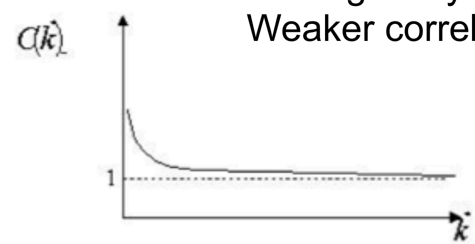
PRL 91 (2003) 262302
Pion-Kaon Correlations in Au+Au@130GeV



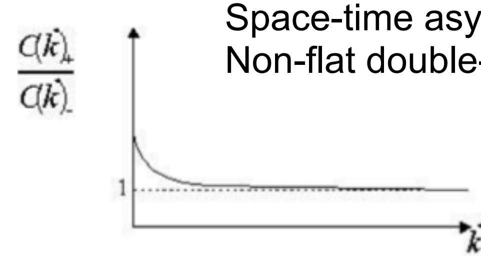
Catching-up
Stronger correlation



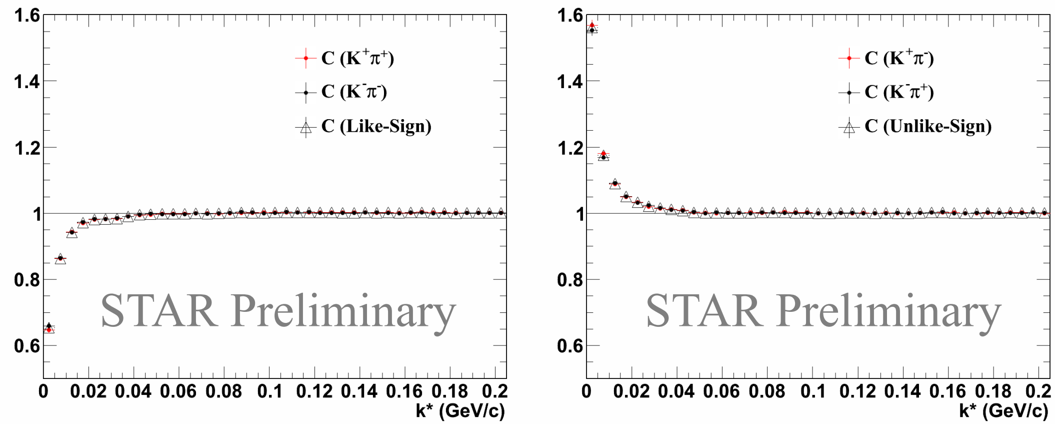
Moving away
Weaker correlation



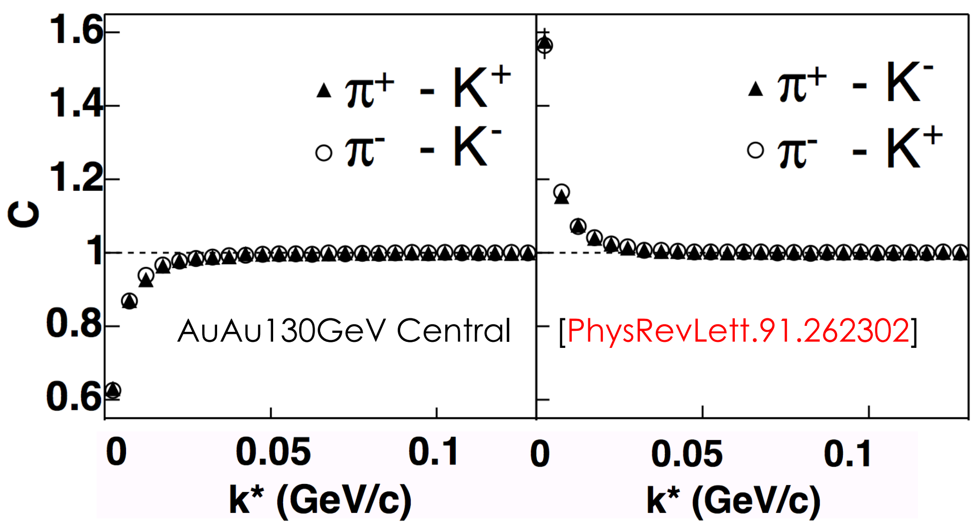
Space-time asymmetries
Non-flat double-ratio



Correlation Functions for K-π (as a reference)



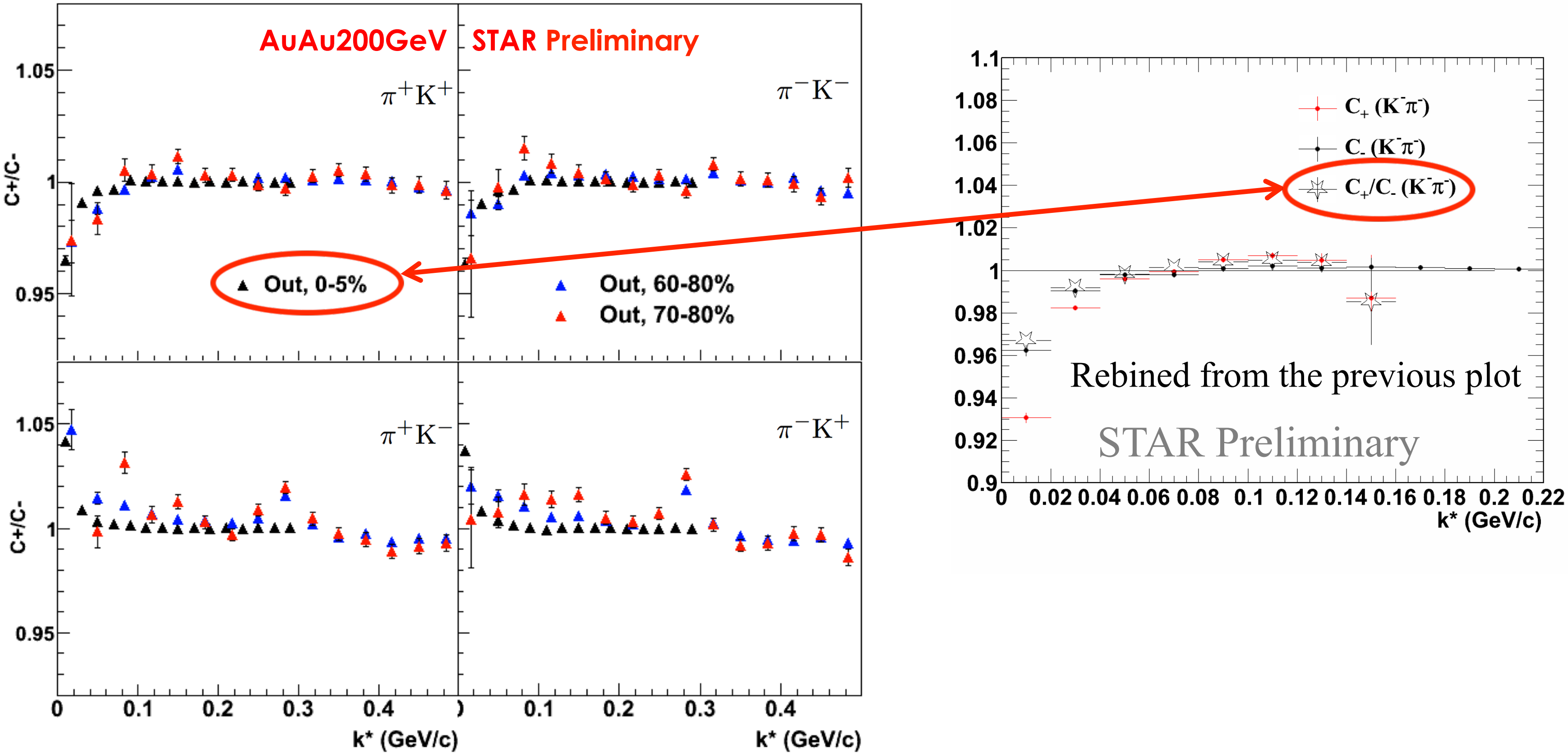
AuAu200 Central in Run10 with my momentum selection:
π(0.15~0.25)
K(0.53~0.88)



- Compare with published data
- The effective range of coulomb effect is ~50 MeV/c (also on the next slide)

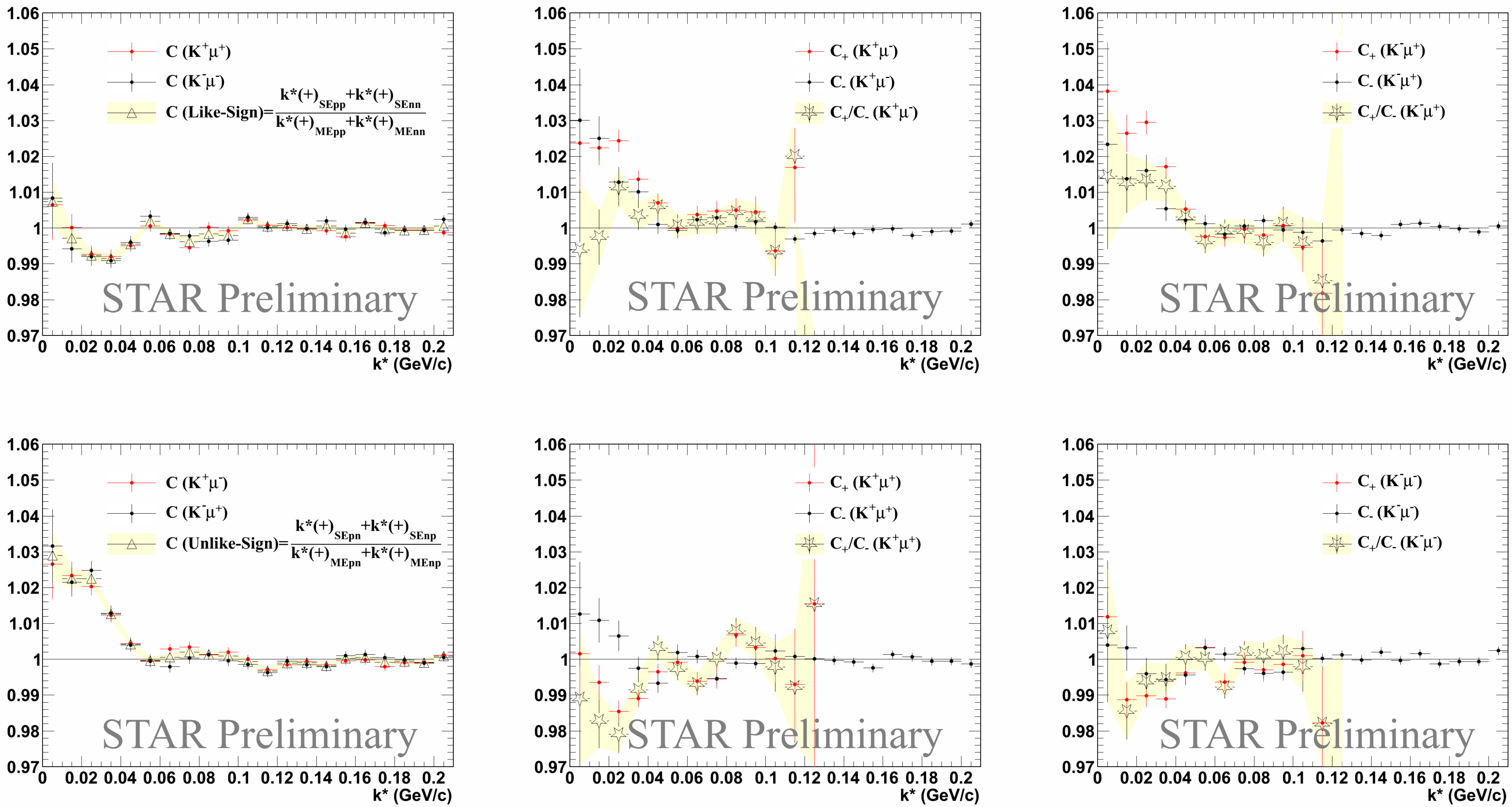
- Let's start with **K-π**, a good reference system for **K-μ**
- Not meant to be an apple to apple comparison, because we want to leave it to K-π vs K-μ

K-π Compare with STAR Preliminary Results



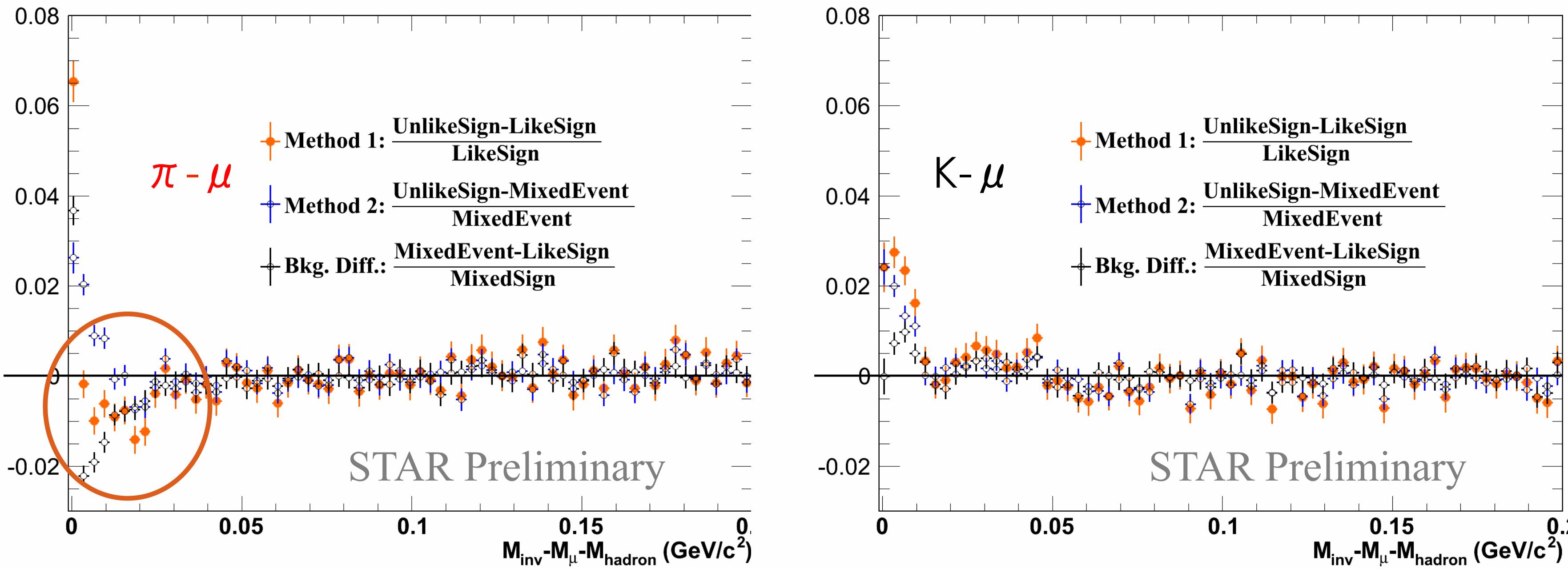
- C+/C- agree with STAR Preliminary [STAR Analysis Meeting 2012, QM2012 poster by Yan Yang]
- Projected to "Out". Note that "Side" and "Long" are both 1. Symmetry on azimuthal and mid-rapidity.

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*

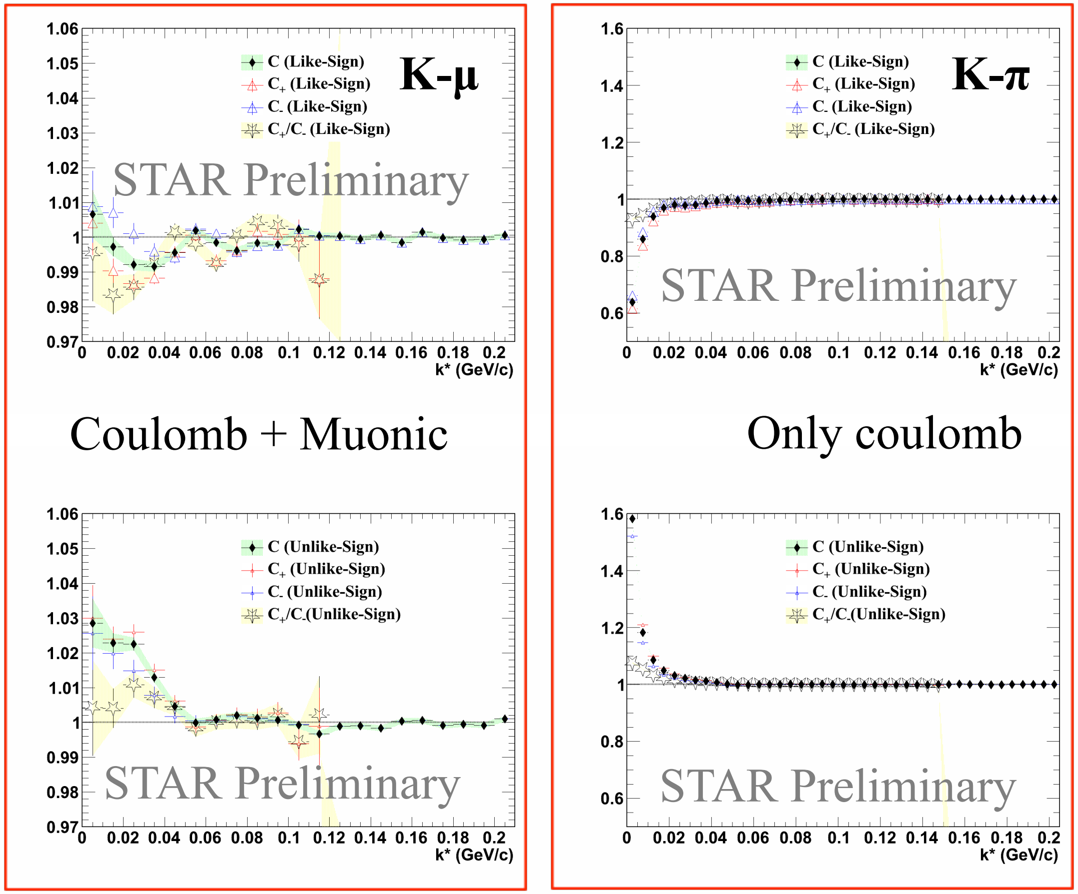
π-μ Invariant Mass



- 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

Compare K-μ with K-π



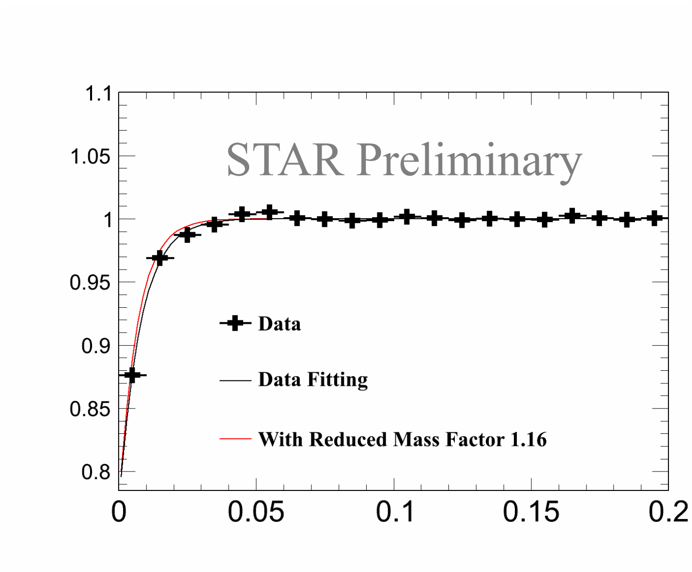
- In both K-μ with K-π, attractive **Coulomb** interaction is observed in UnLike-Sign; repulsive Coulomb is observed in Like-Sign.
- C+/C- ~ unity at k*~0 GeV/c: **no space-time asymmetry**, two particles are emitted at the same position and time. Agree with the **muonic atom ionization**

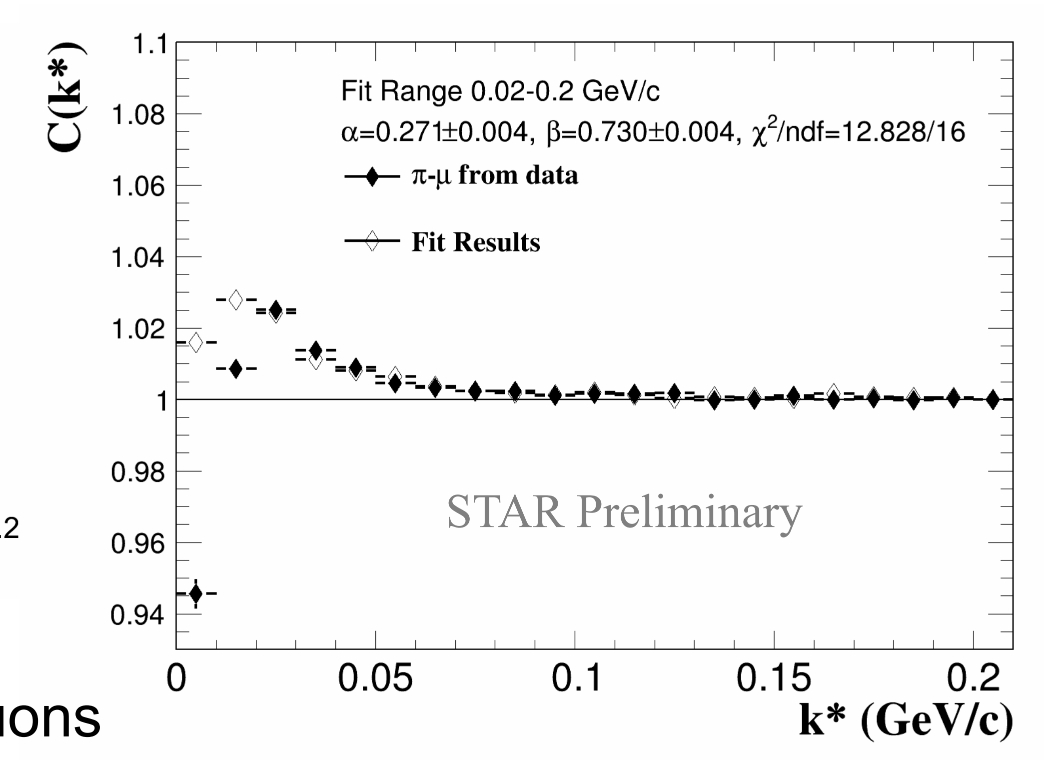
Fitting Results (Reduced Mass Factor)

The mass difference between **π** and **μ** produces different CFs.

Take into account of reduced mass factor (into k*, not CF)

$$\frac{M_{\pi\pi}^{red}}{M_{\pi\mu}^{red}} = 1.16$$





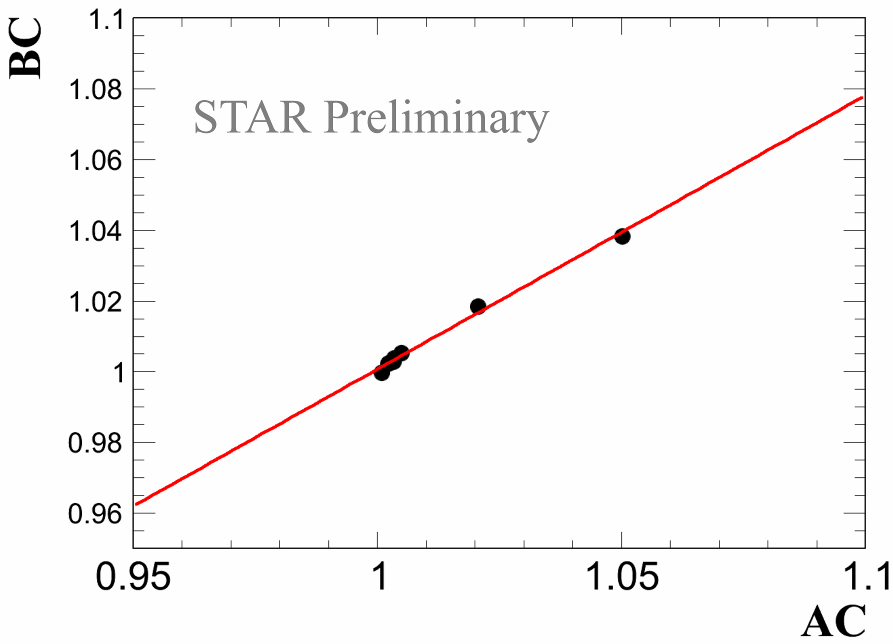
27.1±0.4% primary muons

We can check this linear relation:

$B = \alpha * 1/C + \beta * A$

=> BC = alpha+beta*AC

linear relation AC v.s. BC



Fitting Method

- **Fit function** includes parameter α, β, histogram A and 1/C

  β*A+α*1/C

- **Minimum Chi-Square Method**

$$\chi^2 = \sum_i \left[(\beta * A_i + \alpha * 1/C_i - B_i)/\sigma_i\right]^2$$

$$\Rightarrow \begin{cases} \sum_i (\beta * A_i + \alpha * 1/C_i - B_i)/\sigma_i * A_i/\sigma_i = 0 \\ \sum_i (\beta * A_i + \alpha * 1/C_i - B_i)/\sigma_i * 1/C_i/\sigma_i = 0 \end{cases}$$

$$\Rightarrow \begin{cases} \alpha = \dfrac{\left(\sum_i \frac{A_i B_i}{\sigma_i^2}\right)\left(\sum_i \frac{1}{C_i^2 \sigma_i^2}\right) - \left(\sum_i \frac{B_i}{C_i \sigma_i^2}\right)\left(\sum_i \frac{A_i}{C_i \sigma_i^2}\right)}{\left(\sum_i \frac{A_i^2}{\sigma_i^2}\right)\left(\sum_i \frac{1}{C_i^2 \sigma_i^2}\right) - \left(\sum_i \frac{A_i}{C_i \sigma_i^2}\right)^2} \\ \beta = \dfrac{\left(\sum_i \frac{A_i}{C_i \sigma_i^2}\right)\left(\sum_i \frac{A_i B_i}{\sigma_i^2}\right) - \left(\sum_i \frac{A_i^2}{\sigma_i^2}\right)\left(\sum_i \frac{B_i}{C_i \sigma_i^2}\right)}{\left(\sum_i \frac{A_i}{C_i \sigma_i^2}\right)^2 - \left(\sum_i \frac{A_i^2}{\sigma_i^2}\right)\left(\sum_i \frac{1}{C_i^2 \sigma_i^2}\right)} \end{cases}$$

Fitting Method

Fitting errors:

$$\begin{cases} \alpha = \dfrac{\left(\sum_i \dfrac{A_i B_i}{\sigma_i^2}\right)\left(\sum_i \dfrac{1}{C_i^2\sigma_i^2}\right) - \left(\sum_i \dfrac{B_i}{C_i\sigma_i^2}\right)\left(\sum_i \dfrac{A_i}{C_i\sigma_i^2}\right)}{\left(\sum_i \dfrac{A_i^2}{\sigma_i^2}\right)\left(\sum_i \dfrac{1}{C_i^2\sigma_i^2}\right) - \left(\sum_i \dfrac{A_i}{C_i\sigma_i^2}\right)^2} \\ \beta = \dfrac{\left(\sum_i \dfrac{A_i}{C_i\sigma_i^2}\right)\left(\sum_i \dfrac{A_i B_i}{\sigma_i^2}\right) - \left(\sum_i \dfrac{A_i^2}{\sigma_i^2}\right)\left(\sum_i \dfrac{B_i}{C_i\sigma_i^2}\right)}{\left(\sum_i \dfrac{A_i}{C_i\sigma_i^2}\right)^2 - \left(\sum_i \dfrac{A_i^2}{\sigma_i^2}\right)\left(\sum_i \dfrac{1}{C_i^2\sigma_i^2}\right)} \end{cases}$$

$$\delta\alpha = \sqrt{\sum_i \left(\frac{\partial\alpha}{\partial B_i}\delta B_i\right)^2 + \sum_i \left(\frac{\partial\alpha}{\partial A_i}\delta A_i\right)^2 + \sum_i \left(\frac{\partial\alpha}{\partial C_i}\delta C_i\right)^2}$$

$$\alpha = (B - \beta A)C$$

$$\frac{\partial\alpha}{\partial B_i} = C_i$$

$$\delta\beta = \sqrt{\sum_i \left(\frac{\partial\beta}{\partial B_i}\delta B_i\right)^2 + \sum_i \left(\frac{\partial\beta}{\partial A_i}\delta A_i\right)^2 + \sum_i \left(\frac{\partial\beta}{\partial C_i}\delta C_i\right)^2}$$

$$\beta = \frac{B - \alpha / c}{A}$$

$$\frac{\partial\beta}{\partial B_i} = 1 / A_i$$