The 22nd International Conference on
Strangeness in Quark Matter
22-27 March, 2026, Los Angeles, CA

Observation of a Strange Muonic Atom and Its Antimatter in Heavy-Ion Collisions

Xiaofeng Wang (Zhangbu Xu)

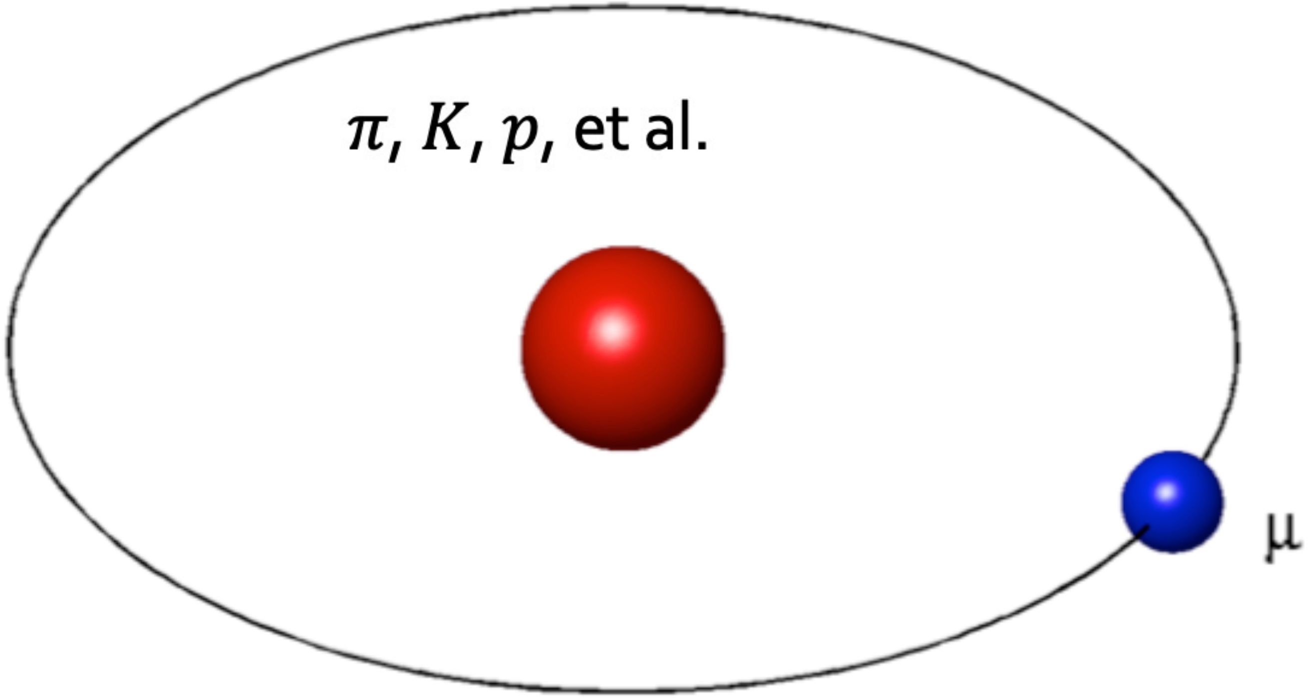
University of Science and Technology of China, Shandong University

2026.03.24

Supported in part by U.S. DEPARTMENT OF ENERGY Office of Science

National Natural Science Foundation of China

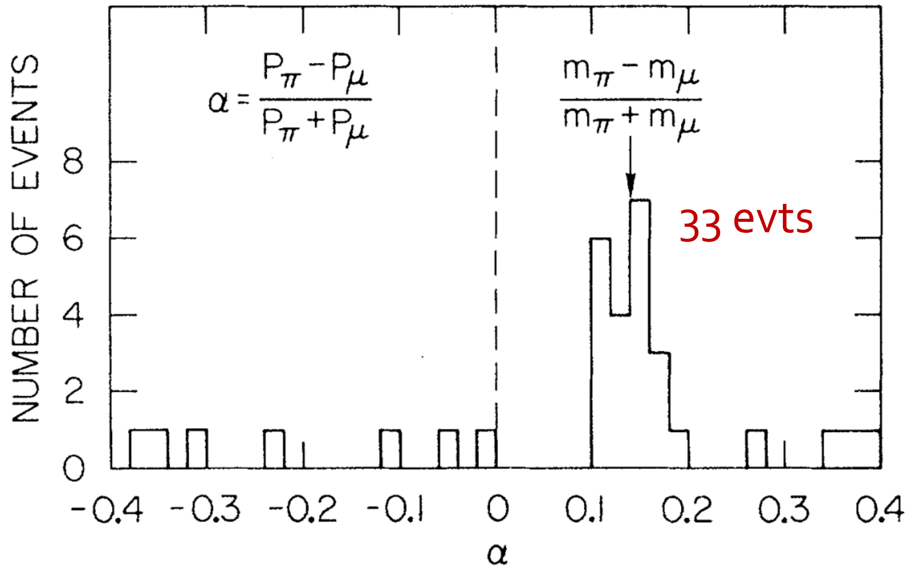
What are Muonic Atoms?



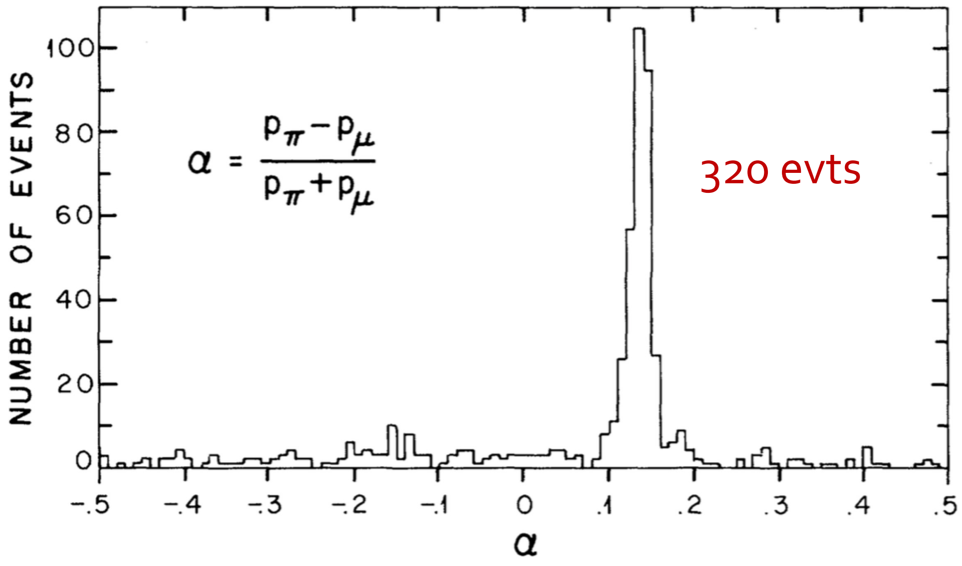
- Muonic atoms consist of a hadron (π, K, p, etc.) and a muon bound by the Coulomb force
- Like an ordinary hydrogen atom, but with a much smaller radius
- Muonic hydrogen dramatically improves proton radius measurement precision

Muonic Atom-$\pi\mu$ Observed from K_L^0 Decay

BNL, Phys.Rev.Lett. 37 (1976) 249-252



FNAL, Phys.Rev.Lett. 48 (1982) 1078-1081



- BNL/Fermilab discovered $\pi\mu$ atoms from intense K_L^0 decays
- Ionized by Al foil with π and μ same velocity
- Sharp peak at expected kinematic variable α
- $\bar{p}\mu^+$ and $K^\pm\mu^\mp$ atoms not yet discovered, need new production mechanism

Muonic Atoms in Ultrarelativistic Heavy-Ion Collisions (HICs)

- Small volume, copious hadrons and μ,
  enhance formation of hydrogen-like systems: $\pi\mu$, $K\mu$ and $p\mu$

G. Baym, et al. Phys. Rev. D 48, R3957–R3959 (1993)

- Only way to discover some of those exotic atoms
- Test QED and meson form factors
- Muonic atom yield proportional to muon and hadron yields

Xiaofeng Wang et al. Phys. Lett. B 861,139242(2025)

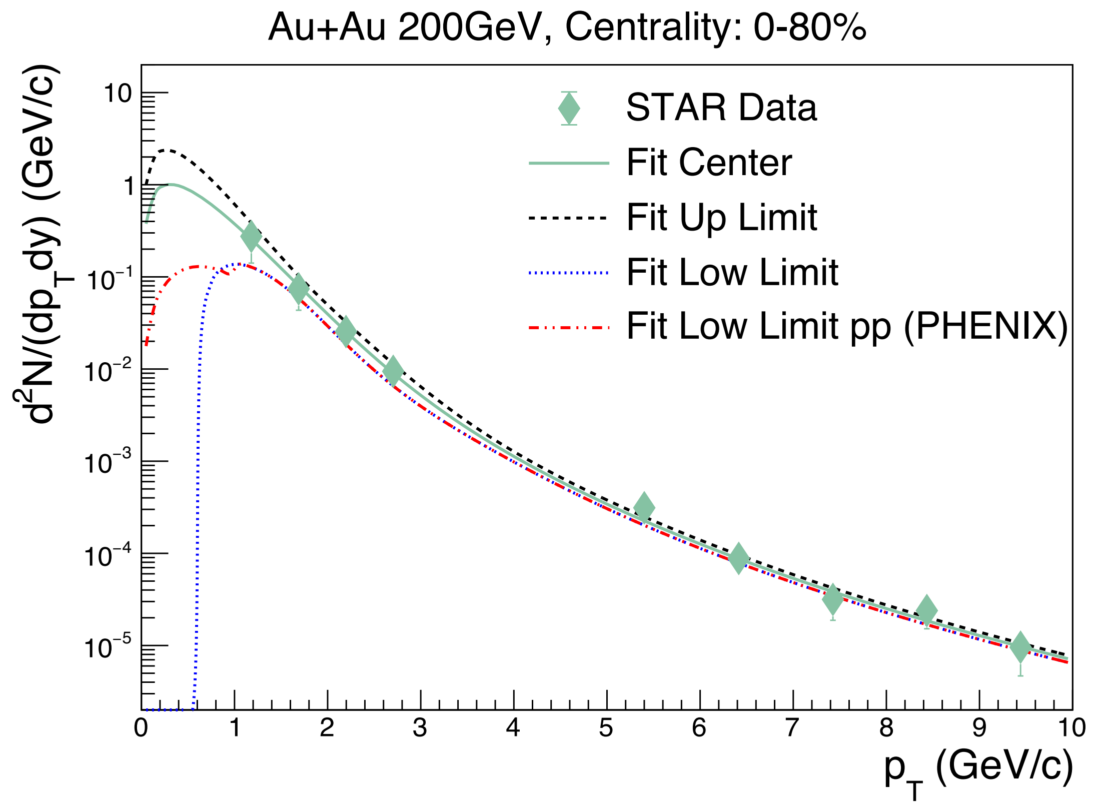
$$\frac{dN_{\mathrm{a}}}{dyd^2p_{T,\mathrm{a}}} = \frac{4\pi}{3}(2\alpha\hbar c/r_0)^{3/2} m_{\mathrm{red}}^{1/2} \frac{dN_h}{dyd^2p_{T,h}} \frac{dN_l}{dyd^2p_{T,l}}$$

- ✓ r_0: homogeneous coalescence radius
- ✓ $m_{red}^{-1} = m_h^{-1} + m_\mu^{-1}$
- ✓ All particles at same velocity

- Muonic atom yields give access to primordial muon production

Joseph Kapusta and Agnes Mocsy, Phys. Rev. C 59, 2937–2940 (1999)

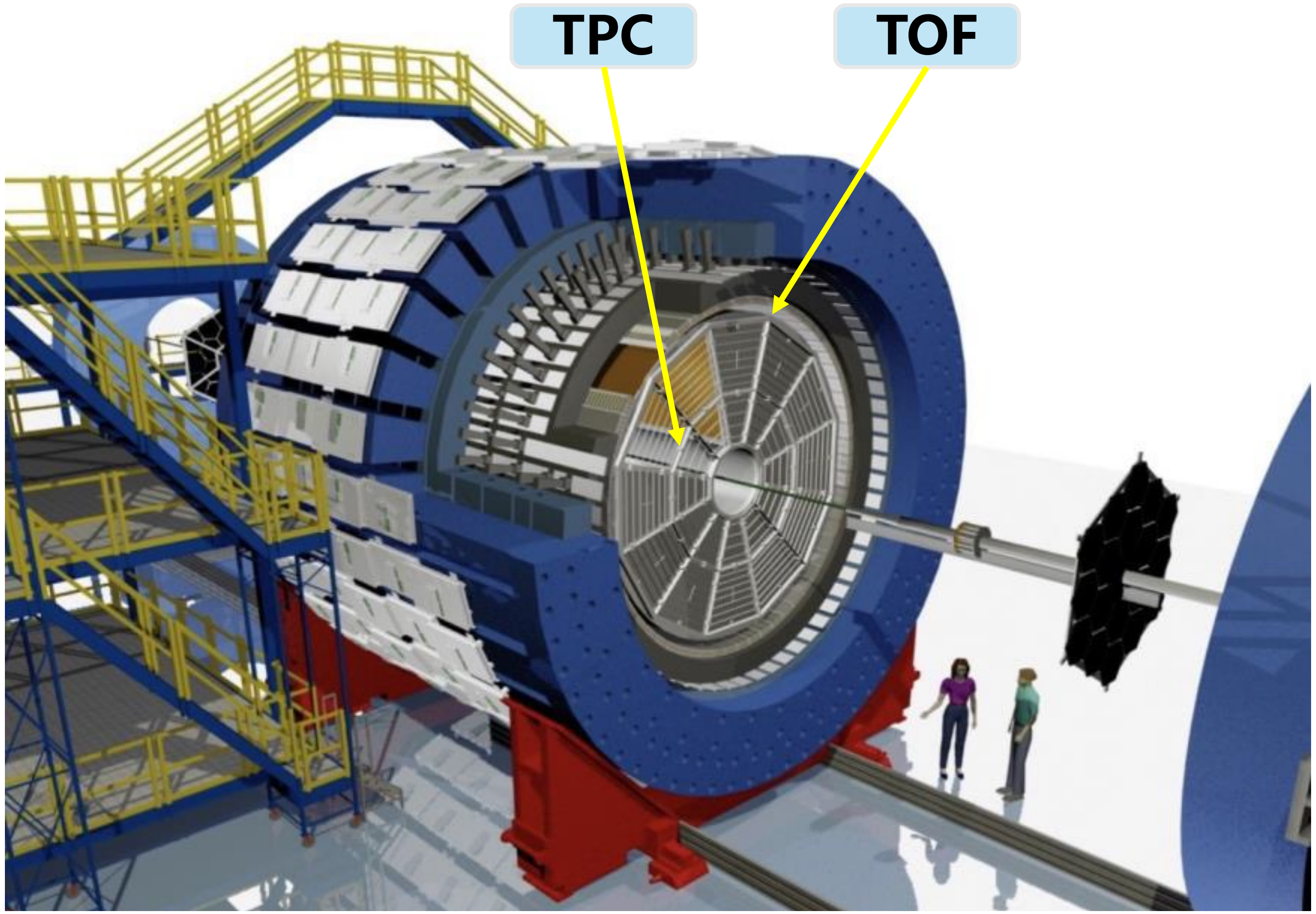
Primordial $\mu \leftrightarrow$ Direct γ

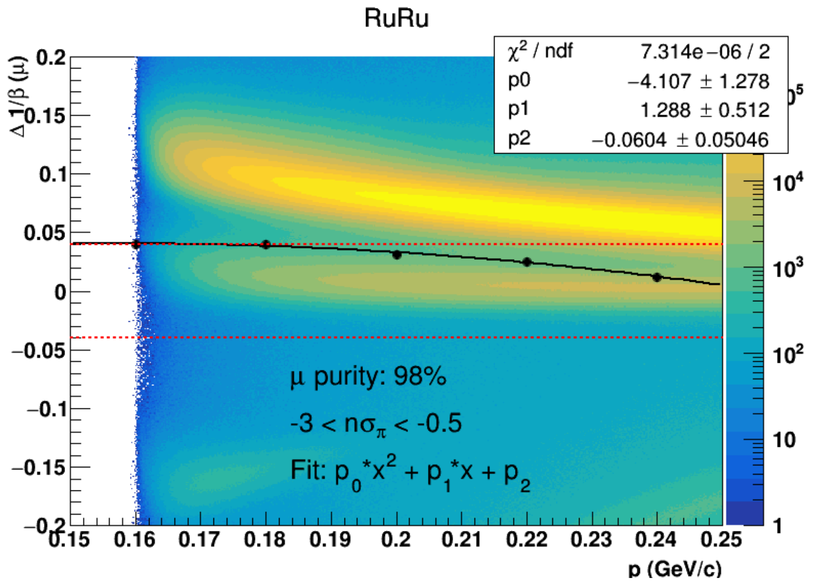


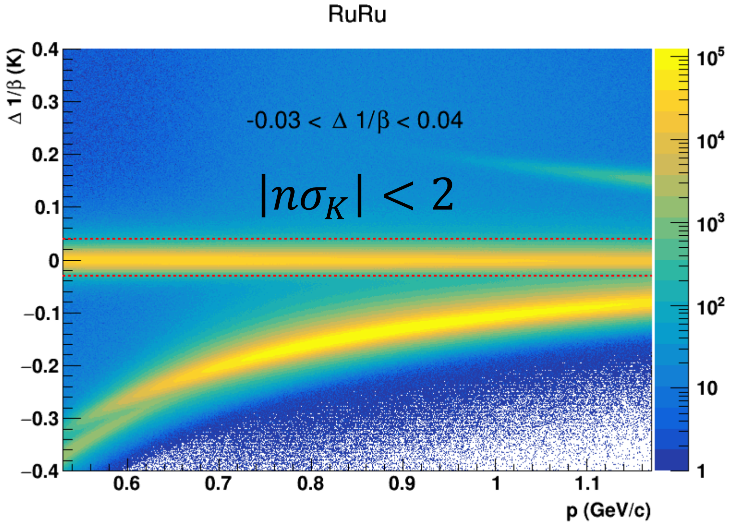
X. Wang et al., Arxiv: 2603.09327
(STAR Collaboration), Phys. Lett. B 770, 451 (2017)

- Dileptons and direct virtual photons: key probes of thermal radiation
- Low-p_T thermal region NO direct data → extrapolate from high-p_T fits → order-of-magnitude uncertainties
- Need complementary observables sensitive to primordial low-p_T muons

The Solenoid Tracker At RHIC (STAR) and PID

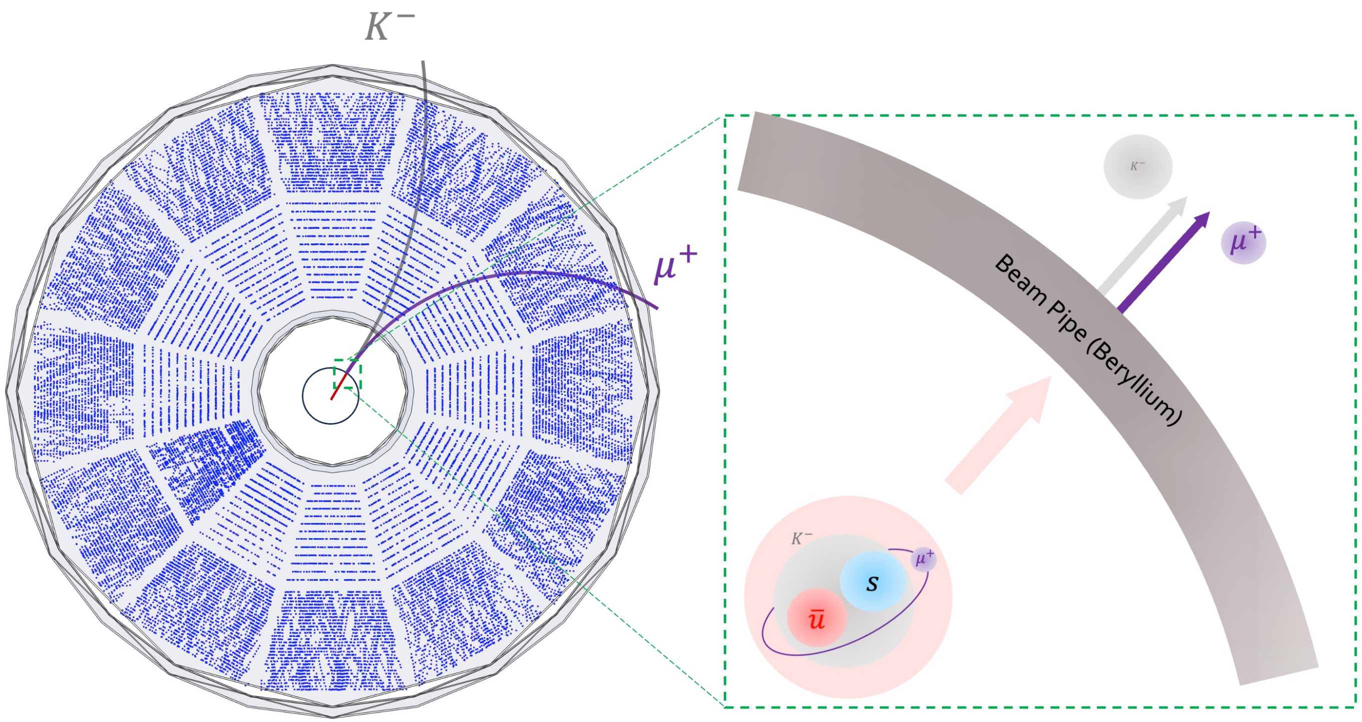




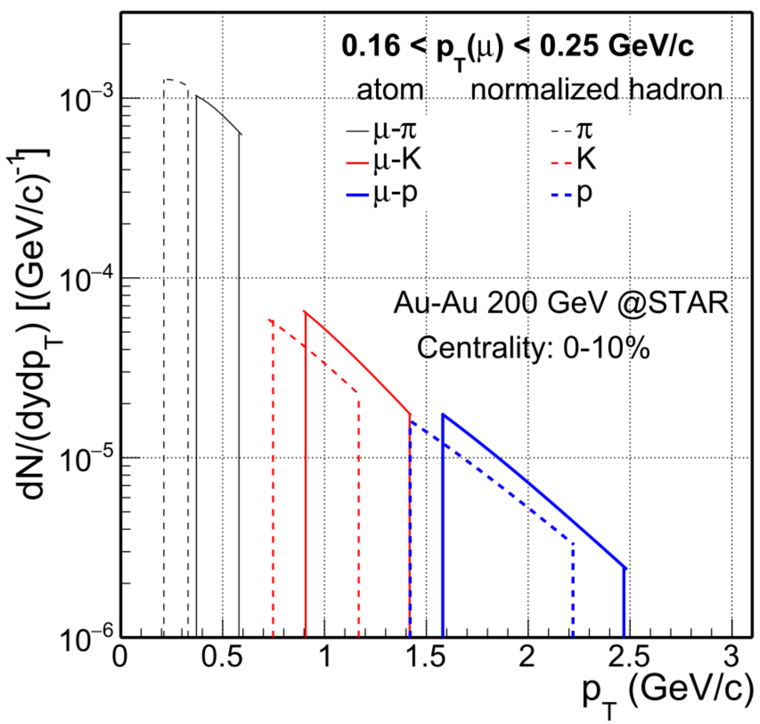


- Time Projection Chamber (**TPC**): momentum and energy loss
- Time Of Flight (**TOF**): velocity

Measurement of muonic atoms at STAR



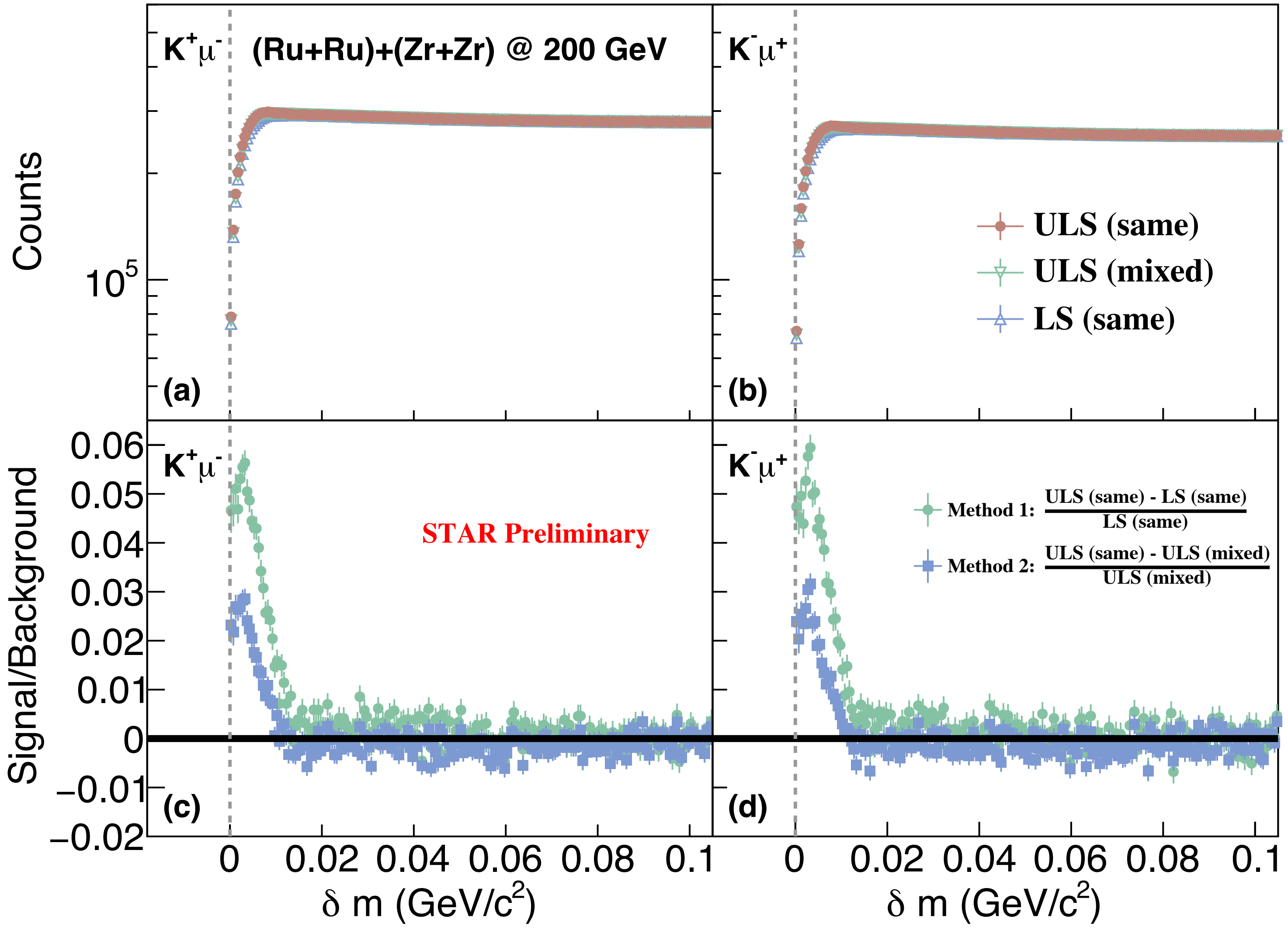
X. Wang et al. Phys. Lett. B 861,139242(2025)



- Example of a $K^-\mu^+$ event produced and detected by STAR detector
- Possible for $\pi\mu$、$K\mu$、 and $p\mu$ (anti-)atoms

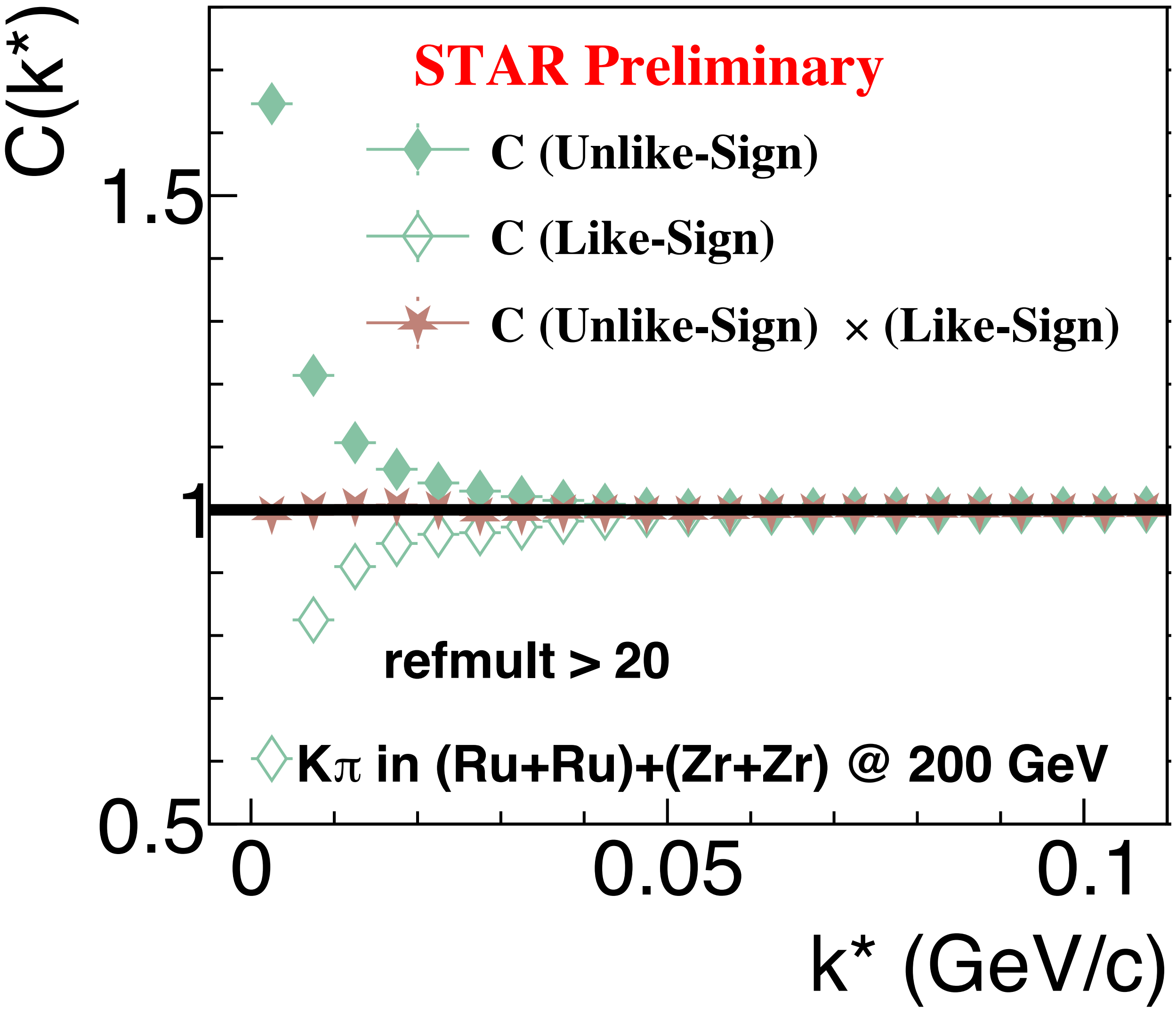
δm Distribution (primary track)

Primary tracks: tracks with DCA<3cm to the primary vertex, whose momenta are obtained from a fit assuming they originate from the primary vertex



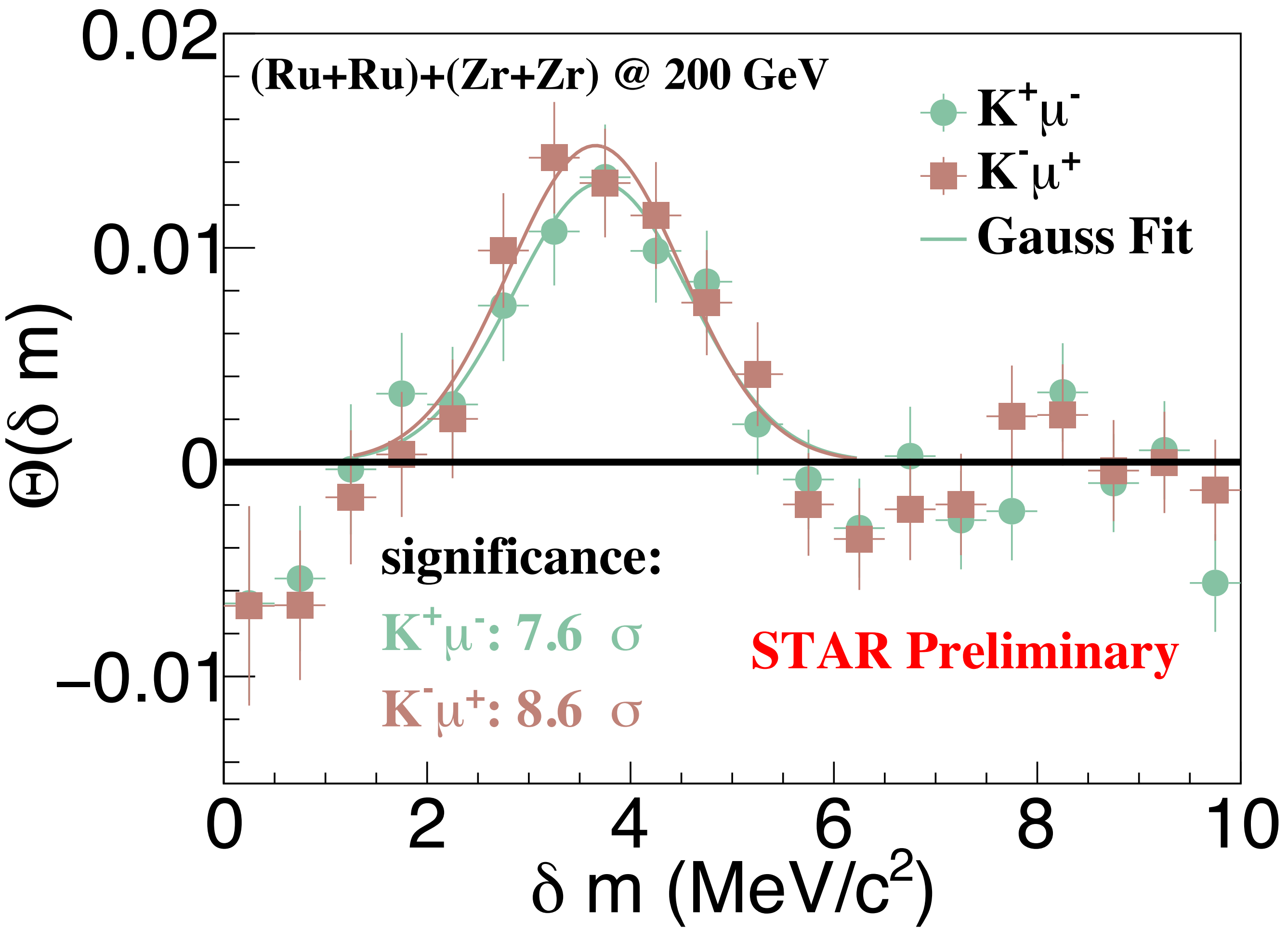
- $\delta m \equiv M_{inv} - m_{\mu} - m_{hadron}$
- A clear yield hierarchy: (same event unlike-sign) > (mixed-event unlike-sign) > (same event like-sign)
- Observed **sharp peaks** for pairs at expected $\delta m \sim 0$ from both background subtraction methods
- Flat at higher mass (0.02~0.1 GeV/c²)
- Like-Sign background has repulsive Coulomb contribution, and thus underestimates the background, leading to a higher "signal" than Mixed-Event

K- π Correlation Function (primary track)



- $C(k^*) = \frac{k^* \text{ in same event}}{k^* \text{ in mixed event}}$, k^*: relative momentum of K-π
- Unlike-sign: Coulomb attraction → enhanced correlation
- Like-sign: Coulomb repulsion → opposite correlation
- Unity product: dominant Coulomb correlation removed in this method

Signal-to-Background Ratio (Θ, primary track)



- $\Theta \equiv \frac{(\mathrm{ULS}\times\mathrm{LS})_{same\ event}}{(\mathrm{ULS}\times\mathrm{LS})_{mixed\ event}} - 1$
- Assume $K\pi$ atom does not exist
- Subtract the $K\pi$ $\Theta(\delta m)$ distribution from the $K\mu$ $\Theta(\delta m)$ distribution to account for residual Coulomb effects
- Significant $K^+\mu^-(7.6\sigma)$ and $K^-\mu^+(8.6\sigma)$ atomic peaks observed
- Using primary tracks shift the mass peak away from zero because breakup happens away from primary collision vertex

$K\mu$ Atom Dissociation Fraction

S. Mrowczynski, Phys. Rev. A 33, 1549–1555 (1986)
X. Wang et al., Arxiv: 2603.09327

STAR

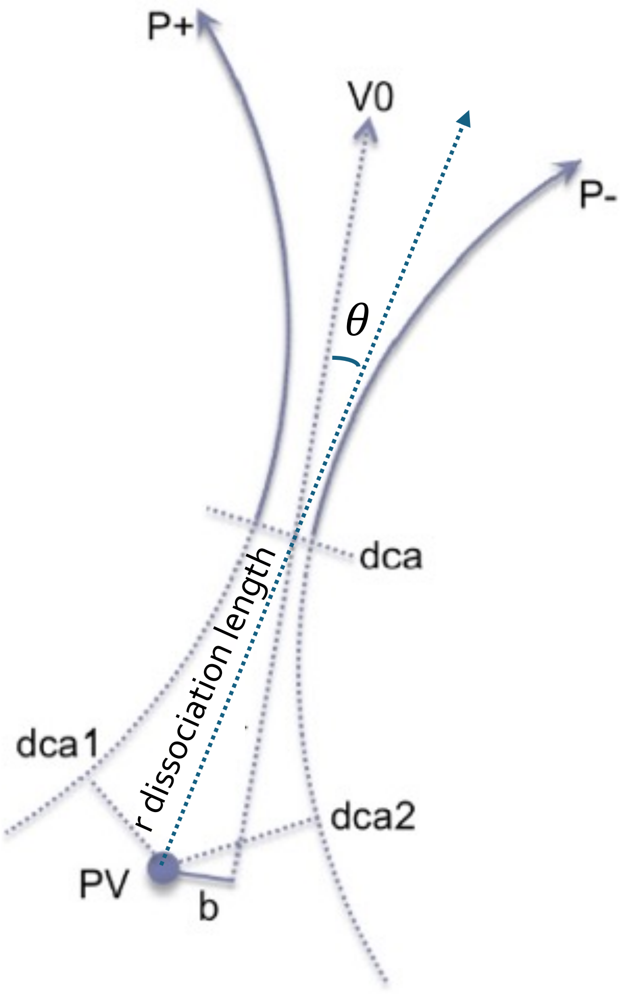
Dissociation fraction: $f = 1 - e^{-n\sigma l}$

- n: material number density,
- l: material thickness
- σ: atom–material interaction cross section
- Using $k\pi$ dissociation cross sections: $1.4\times10^{-22}\ \mathrm{cm}^2$

	RHIC-STAR
Beampipe (Z, n, l)	Be(4, 1.236×10^{23} atoms/cm^3, 0.1 cm)
Dissociation at beampipe	53.5%
Air (Z, n, l)	(7.2, 2.54×10^{19} atoms/cm^3, 46.19 cm)
Dissociation in air	$(1 - 53.5\%) \times 20.9\%$
First-layer detector (Z, n, l)	Inner field cage (Kapton, 0.6%X_0)
Total dissociation before deeper tracking	$\simeq 100\%$

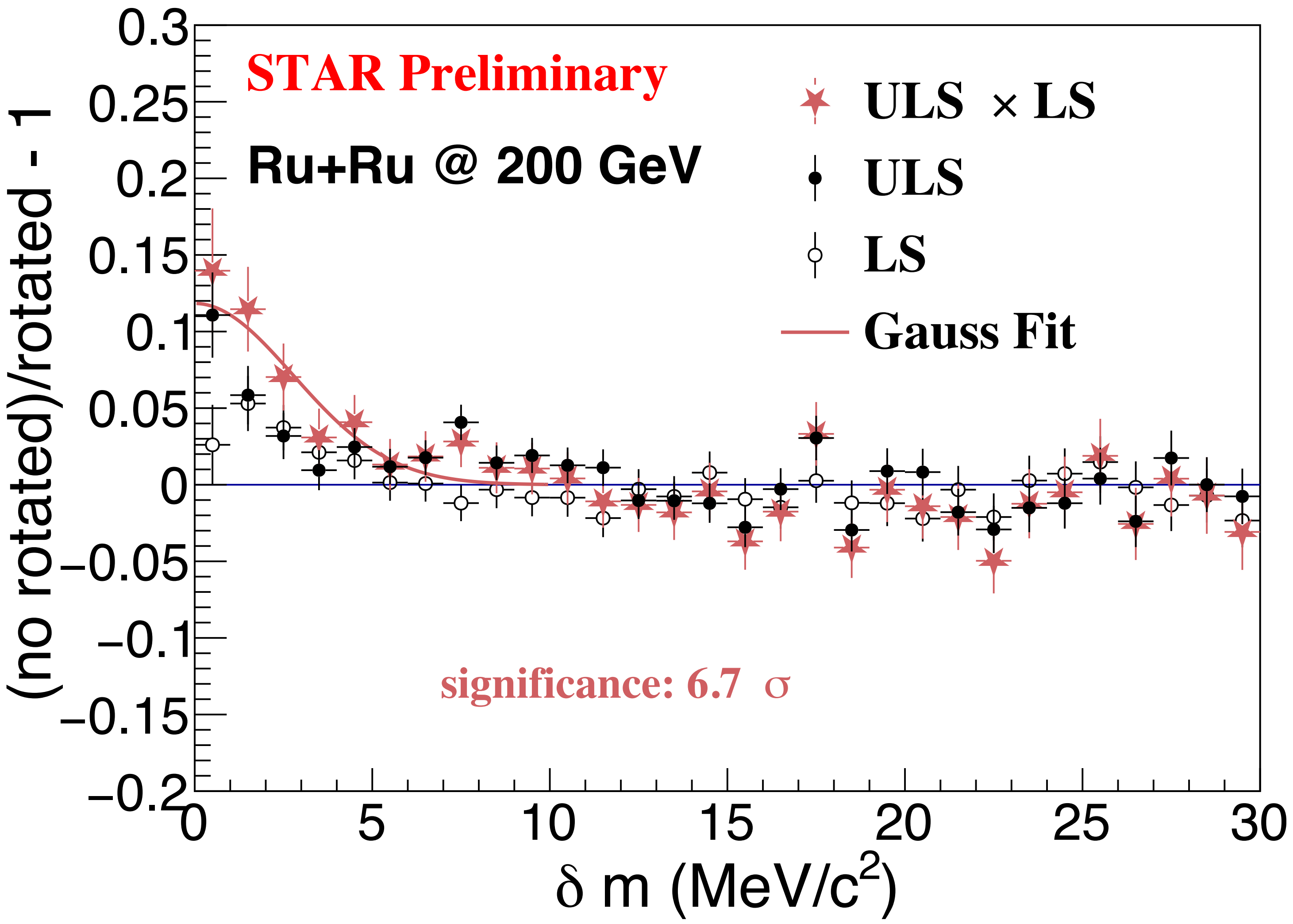
- Muonic Atom interaction with material calculated
- Breakup at several locations away from collisions
- **New signature: breakup at secondary vertex**
- Global Tracks reconstruct the breakup vertex with correct momenta

Topological Reconstruction (global track)



- Global track: tracks fitted without being constrained to the primary vertex
- Topological cuts reduce combinatorial background:
  - ✓ dca2(μ)>1.1 cm;
  - ✓ dca1(K) > 0.75 cm;
  - ✓ dca<1 cm;
  - ✓ Cos(θ)>0.99;
  - ✓ b(V0 dca) < 3cm;
  - ✓ 10 cm < r dissociation length < 50 cm

Signal-to-Background Ratio (global track)



- δm peaks at zero
- Rotated kaon track 180^0, background
- Next steps: optimize topological cuts to suppress background and improve signal extraction

Summary and Outlook

Summary

- First significant $K\mu$ atom signals observed in isobar collisions
  - ✓ Significant mass peaks shifted away from zero (primary tracks)
  - ✓ Significant mass peak at zero (global tracks and secondary vertex)

- Consistent with $K\mu$ atoms formation and breakup in detector material

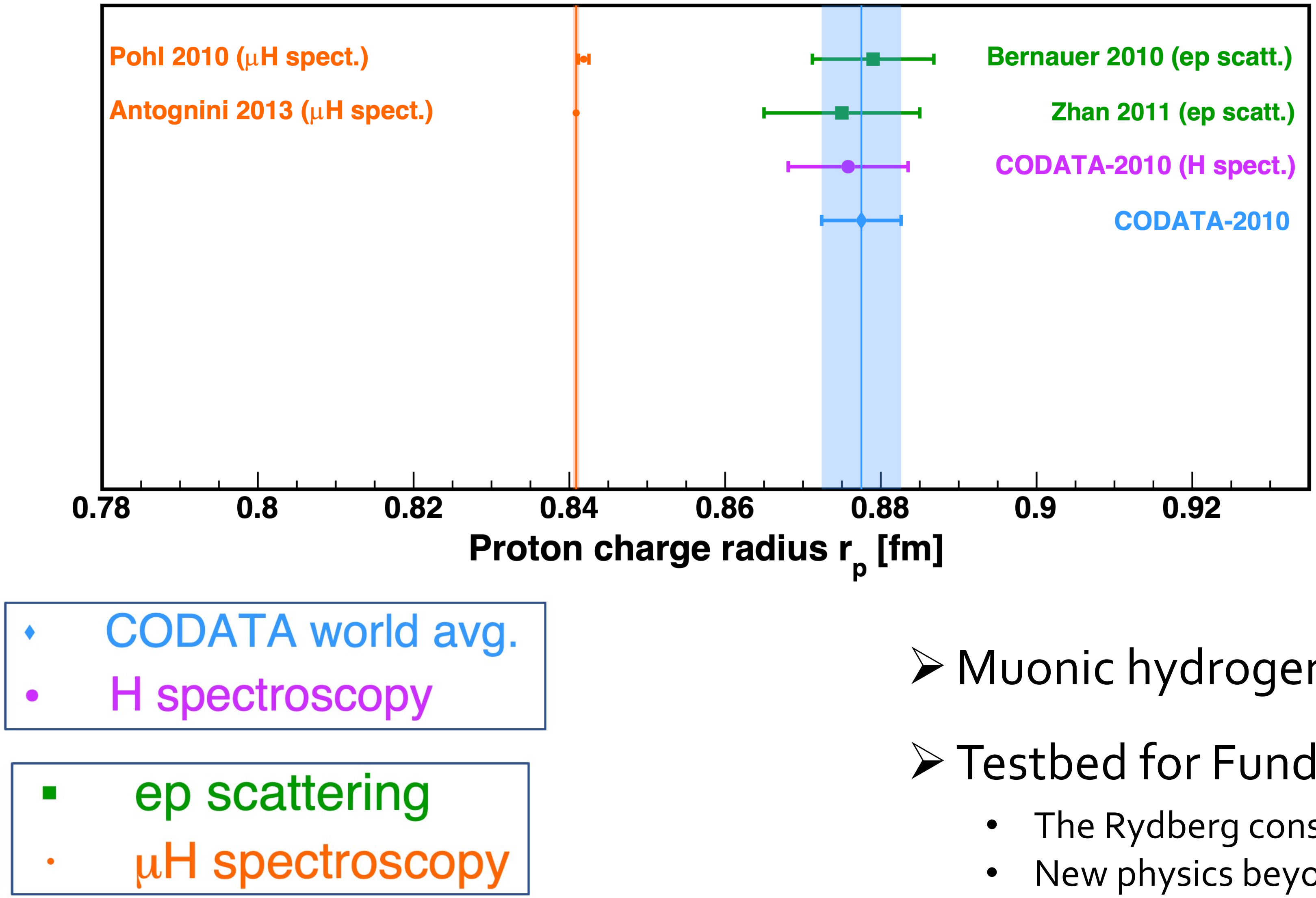
Future Perspective:

- Topological cut optimization needed to improve background suppression
- Extract muonic atom and primordial muon yields
- More detailed studies are ongoing to improve the understanding and quantification of the background

Thanks for your attention!

Backup

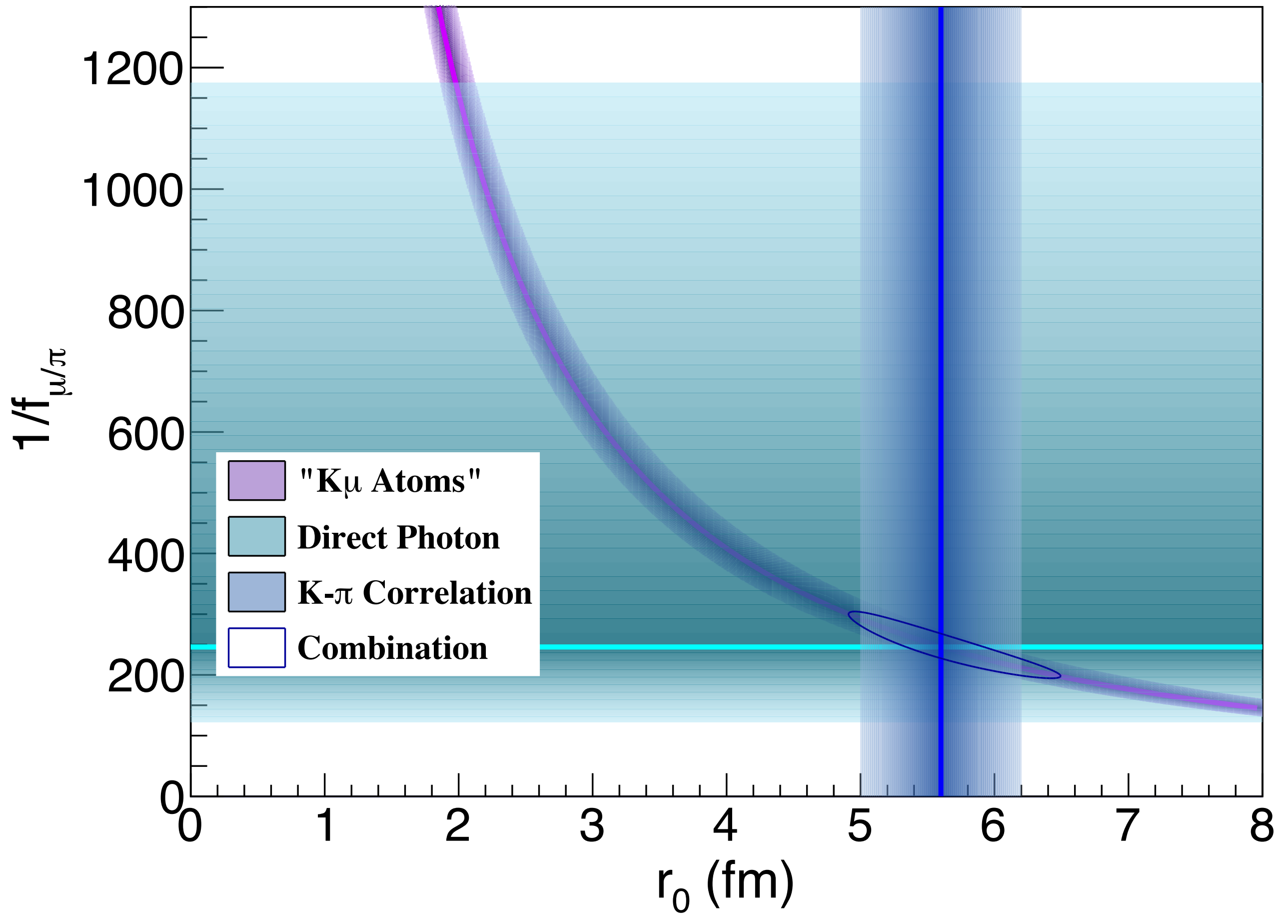
Proton charge radius puzzle



- Muonic hydrogen enhances sensitivity
- Testbed for Fundamental Physics
  - The Rydberg constant?
  - New physics beyond the standard model?

Multi-dimension Constraints on μ, Kμ and r_0

STAR



X. Wang et al., Arxiv: 2603.09327
(STAR Collaboration), Phys. Rev. Lett. 91, 262302 (2003)
(STAR Collaboration), Phys. Lett. B 770, 451 (2017)

- Direct g → $1/f_{\mu/\pi}$
- K-π Correlation → r_0
- Kμ atoms: projected measurement

A powerful probe of low-p_T thermal dilepton and direct-photon production