

Hydrogen-Like Atoms as miliAngstrom Scale Lepton Detectors



Ágnes Mócsy
Pratt Institute

Kodama'Fest
Relativistic Aspects of Nuclear Physics
Rio de Janeiro 2013 September 23-37

Hydrogenlike atoms from ultrarelativistic nuclear collisions

Joseph Kapusta* and Agnes Mocsy†

School of Physics and Astronomy, University of Minnesota, Minneapolis, Minnesota 55455

(Received 3 December 1998)

The number of hydrogenlike atoms produced when heavy nuclei collide is estimated for central collisions at the Relativistic Heavy Ion Collider using the sudden approximation of Baym *et al.* As first suggested by Schwartz, a simultaneous measurement of the hydrogen and hadron spectra will allow an inference of the electron or muon spectra at low momentum where a direct experimental measurement is not feasible. [S0556-2813(99)03605-5]

PACS number(s): 25.75.-q

The production rate of lepton pairs is a rapidly increasing function of temperature and so has long been considered a good probe of the initial high energy density phase of ultrarelativistic nuclear collisions [1]. The experimental detection of such direct leptons is a problem in the sub-GeV range of transverse momentum due to the large number of charged hadrons produced and the need to disentangle direct leptons from those arising from hadron decays. But this is just the kinematic range characterizing a quark-gluon plasma at a temperature of 200–500 MeV.

Schwartz [2] proposed to measure the distribution of atoms formed by the binding of a directly produced lepton to one of the charged hadrons emerging from the final state of the nuclear collision. A measurement of the charged hadrons and of the atoms, together with a theoretical calculation relating the distributions of the three particle species, would then imply the spectrum of leptons. The beauty of the idea lies in the fact that nearly all indirectly produced leptons

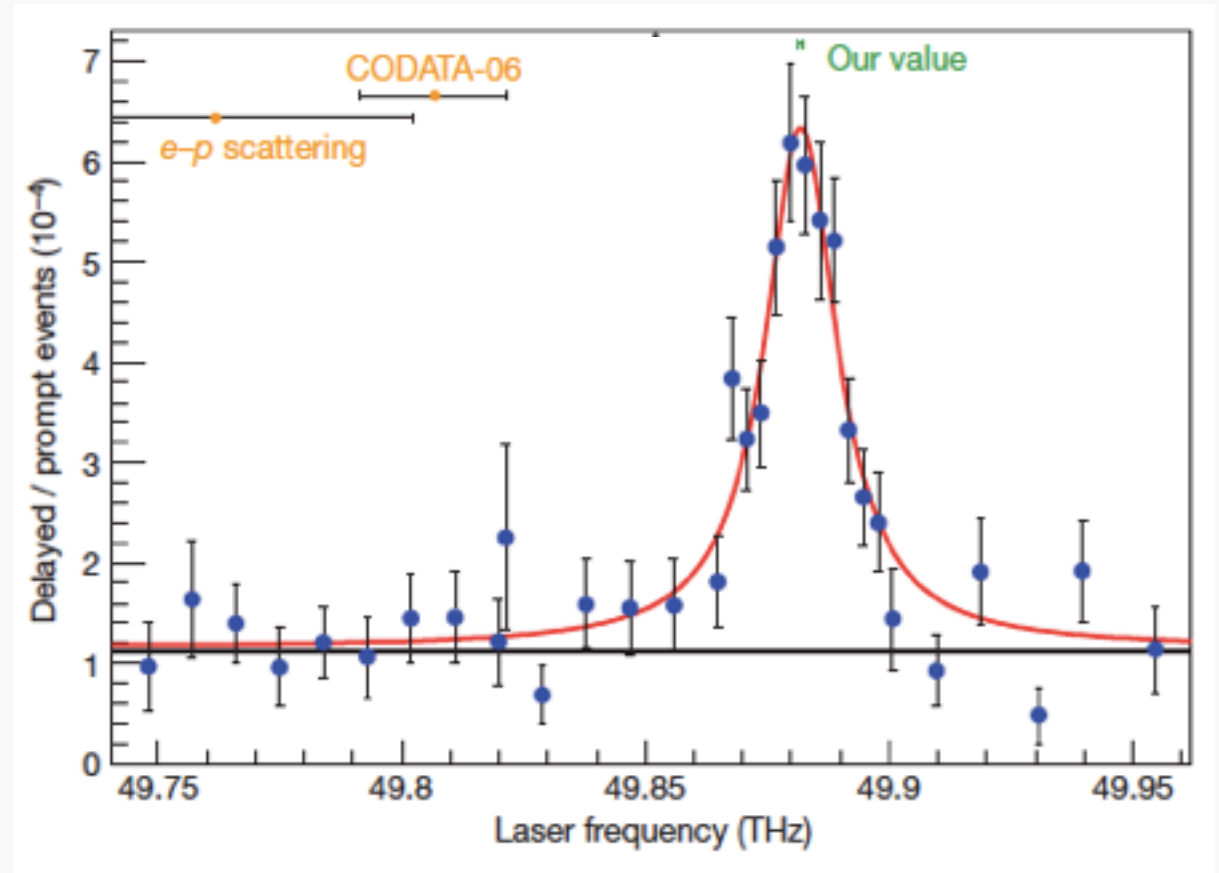
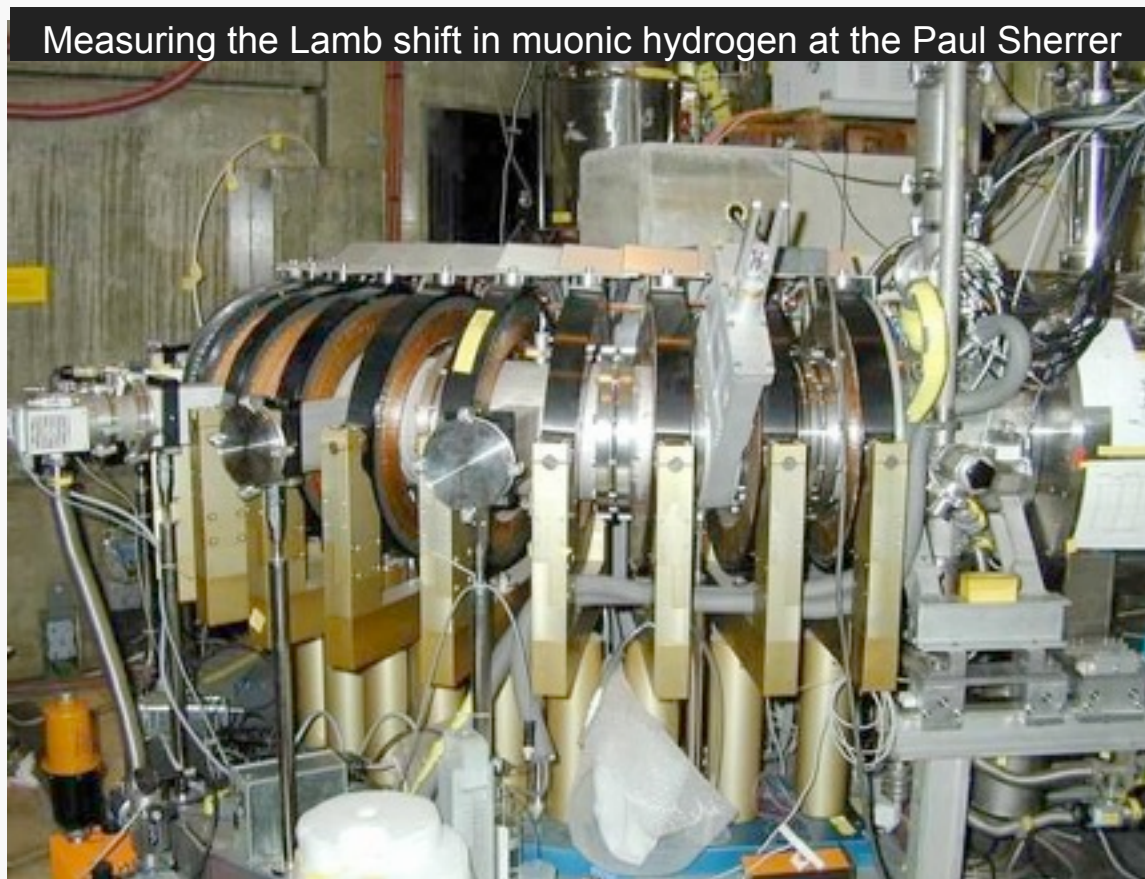
is extremely small in comparison to the Bohr period. The specific focus of Baym *et al.* was on π - μ atoms. Here we shall be interested in p - e , p - μ , π - e , and π - μ atoms. Our essential contribution is to estimate $dN/dy d^2p_\perp$ for the leptons, protons, and pions in the relevant range of transverse momentum, and from these to estimate the number of hydrogenic atoms to be formed in central Au+Au collisions at the Relativistic Heavy Ion Collider (RHIC).

First we estimate the number of leptons produced in the quark-gluon plasma phase. The reaction rate for the process $q + \bar{q} \rightarrow l^+ + l^-$ is

$$R_q = 12 \int \frac{d^3p_1}{2E_1(2\pi)^3} \frac{d^3p_2}{2E_2(2\pi)^3} \times \frac{d^3p_+}{2E_+(2\pi)^3} \frac{d^3p_-}{2E_-(2\pi)^3} f_{\text{FD}}(E_1)$$

H-like Atoms as Precision Tools

muonic hydrogen p- μ



Pohl et al. Nature 466 (8 July 2010) 09250

QED corrections to the Lamb shift due to the proton size are greater for a p- μ atom than for H

old 0.877 ± 0.007 fm
new 0.8418 ± 0.0007 fm

Proton is smaller than we thought

History of H-like Atoms

Hadronic nucleus π , K , $\bar{p}$ orbited by leptons μ (e)

We have observed atoms consisting of a pion and a muon produced in the decay $K_L^0 \rightarrow (\pi\mu)_{\text{atom}}$. This represents the first observations of an atom composed of two unstable particles and of an atomic decay of an elementary particle.

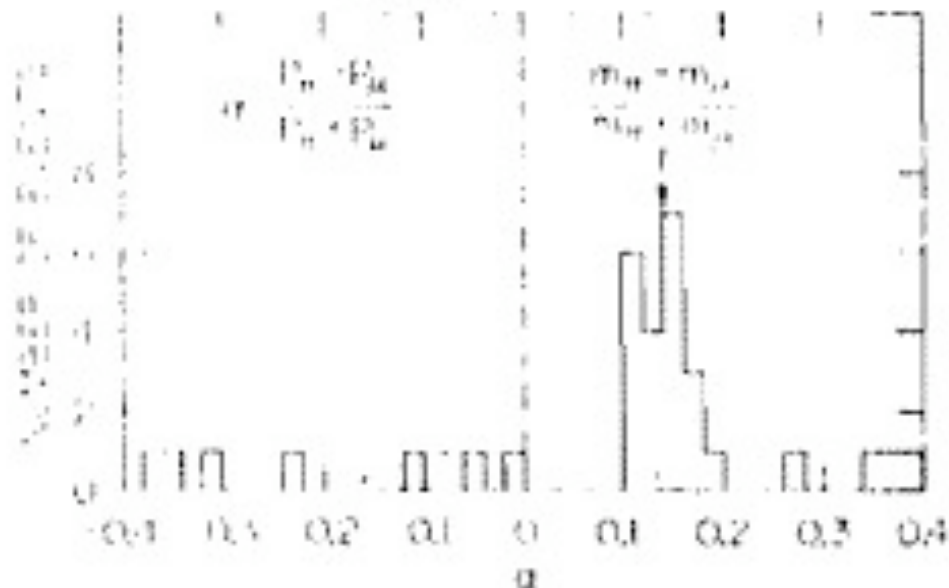


FIG. 3. A plot of the parameter α indicating the detection of π - μ atoms.

at BNL

M. Schwartz et al. PRL37(1976)249

at FermiLab

S.H. Aronson et al. PRL 48(1982)1078

H-like Atoms in HIC

Discovering Exotics: Antimatter Muonic Hydrogen ?!

H-like Atoms in HIC

Discovering Exotics: Antimatter Muonic Hydrogen ?!

LETTER

doi:10.1038/nature10079

Observation of the antimatter helium-4 nucleus

The STAR Collaboration*

High-energy nuclear collisions create an energy density similar to that of the Universe microseconds after the Big Bang¹; in both cases, matter and antimatter are formed with comparable abundance. However, the relatively short-lived expansion in nuclear collisions allows antimatter to decouple quickly from matter, and avoid annihilation. Thus, a high-energy accelerator of heavy nuclei provides an efficient means of producing and studying antimatter. The antimatter helium-4 nucleus ($^4\bar{\text{He}}$), also known as the anti- α ($\bar{\alpha}$), consists of two antiprotons and two antineutrons (baryon number $B = -4$). It has not been observed previously, although the α particle was identified a century ago by Rutherford and is present in cosmic radiation at the ten percent level². Antimatter nuclei with $B < -1$ have been observed only as rare products of interactions at particle accelerators, where the rate of antinucleus production in high-energy collisions decreases by a factor of about 1,000 with each additional antinucleon³⁻⁵. Here we report the observation of $^4\bar{\text{He}}$, the heaviest observed antinucleus to date. In total, 18 $^4\bar{\text{He}}$ counts were detected at the STAR experiment at the Relativistic Heavy Ion Collider (RHIC; ref. 6) in 10^8 recorded gold-on-gold (Au+Au) collisions at centre-of-mass energies of 200 GeV and 62 GeV per nucleon-nucleon pair. The yield is consistent with expectations from thermodynamic⁷ and coalescent nucleosynthesis⁸ models, providing an indication of the production rate of even heavier antimatter nuclei and a benchmark for possible future observations of $^4\bar{\text{He}}$ in cosmic radiation.

In 1928, the existence of negative energy states of electrons was predicted⁹ on the basis of the application of symmetry principles to quantum mechanics, but these states were only recognised to be antimatter after the discovery¹⁰ of the positron (the antielectron) in cosmic radiation four years later. The predicted antiproton¹¹ and antineutron¹² were observed in 1955, followed by antideuteron¹³ ($\bar{d}$), antitriton¹⁴ ($\bar{t}$), and antihelium-3 ($^3\bar{\text{He}}$) during the following two decades¹⁵⁻¹⁸. Recent accelerator and detector advances led to the first production of antihydrogen¹⁹ atoms in 1995 and the discovery of strange antimatter, the antihypertriton ($^3\bar{\Lambda}\bar{H}$), in 2010 at RHIC at the Brookhaven National Laboratory (ref. 18 and references therein).

Collisions of relativistic heavy nuclei create suitable conditions for producing antinuclei, because large amounts of energy are deposited into a more extended volume²⁰ than that achieved in elementary particle collisions. These nuclear interactions briefly ($\sim 10^{-23}$ s) produce hot and dense matter containing roughly equal numbers of quarks and antiquarks²¹, often interpreted as quark gluon plasma²². In contrast to the Big Bang, nuclear collisions produce negligible gravitational attraction and allow the plasma to expand rapidly. The hot and dense matter cools down and undergoes a transition into a hadron gas, producing nucleons and their antiparticles. The production of light antinuclei can be modelled successfully by macroscopic thermodynamics²³, which assumes energy equipartition, or by a microscopic coalescence process²⁴, which assumes uncorrelated probabilities for antinucleons close in position and momentum to become bound. The high temperature and high antibaryon density of relativistic heavy ion collisions provide a favourable environment for both production mechanisms.

The central detector used in our measurements of antimatter, the Time Projection Chamber (TPC)²⁵ of the STAR experiment (Solenoidal

Tracker At RHIC), is situated in a solenoidal magnetic field and is used for three-dimensional imaging of the ionization trail left along the path of charged particles (Fig. 1). In addition to the momentum provided by the track curvature in the magnetic field, the detection of $^4\bar{\text{He}}$ particles relies on two key measurements: the mean energy loss per unit track length, (dE/dx) , in the TPC gas, which helps distinguish particles with different masses or charges, and the time of flight of particles arriving at the time of flight barrel (TOF)²⁶ surrounding the TPC. In general, time of flight provides particle identification in a

higher momentum range than (dE/dx) , 7.5% and the timing resolution is 7–75 ns window.

The trigger system²⁷ of the STAR experiment is used to select events of interest. The minimum-bias trigger selects all particle-producing collisions, regardless of the extent of overlap of the incident nuclei. A central trigger (CENT) preferentially selects head-on collisions, rejecting about 90% of the events acquired using the minimum-bias trigger. The sample of 10^8 Au+Au collisions used in this search is selected on the basis of the minimum-bias trigger, on CENT, and on various specialized triggers. Preferential selection of events containing tracks with charge $Z_e = \pm 2e$ (where e is the electron charge and Z is the particle charge in units of e) was implemented using a High-Level Trigger (HLT) for data acquired in 2010. The HLT used computational resources at STAR to perform a real-time fast-track reconstruction to tag events that had at least one track with a (dE/dx) value that is larger than a threshold set to three standard deviations below the theoretically expected value²⁸ for $^4\bar{\text{He}}$ at the same magnetic rigidity. The HLT successfully identified 70% of the events where a $^4\bar{\text{He}}$ track was present while selecting only 0.4% of the events for express analyses.

Figure 2 shows (dE/dx) versus the magnitude of magnetic rigidity, $p/|Z|$, where p is momentum. A distinct band of positive particles

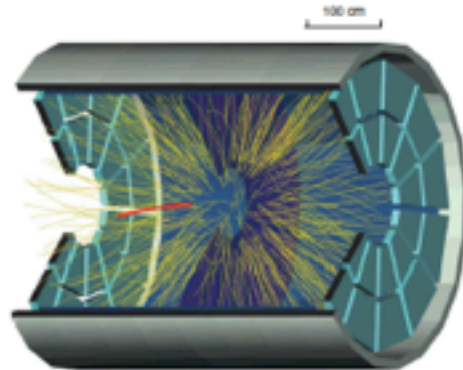


Figure 1 | A three-dimensional rendering of the STAR TPC surrounded by the TOF barrel shown as the outermost cylinder. Tracks from an event which contain a $^4\bar{\text{He}}$ are shown, with the $^4\bar{\text{He}}$ track highlighted in bold red.

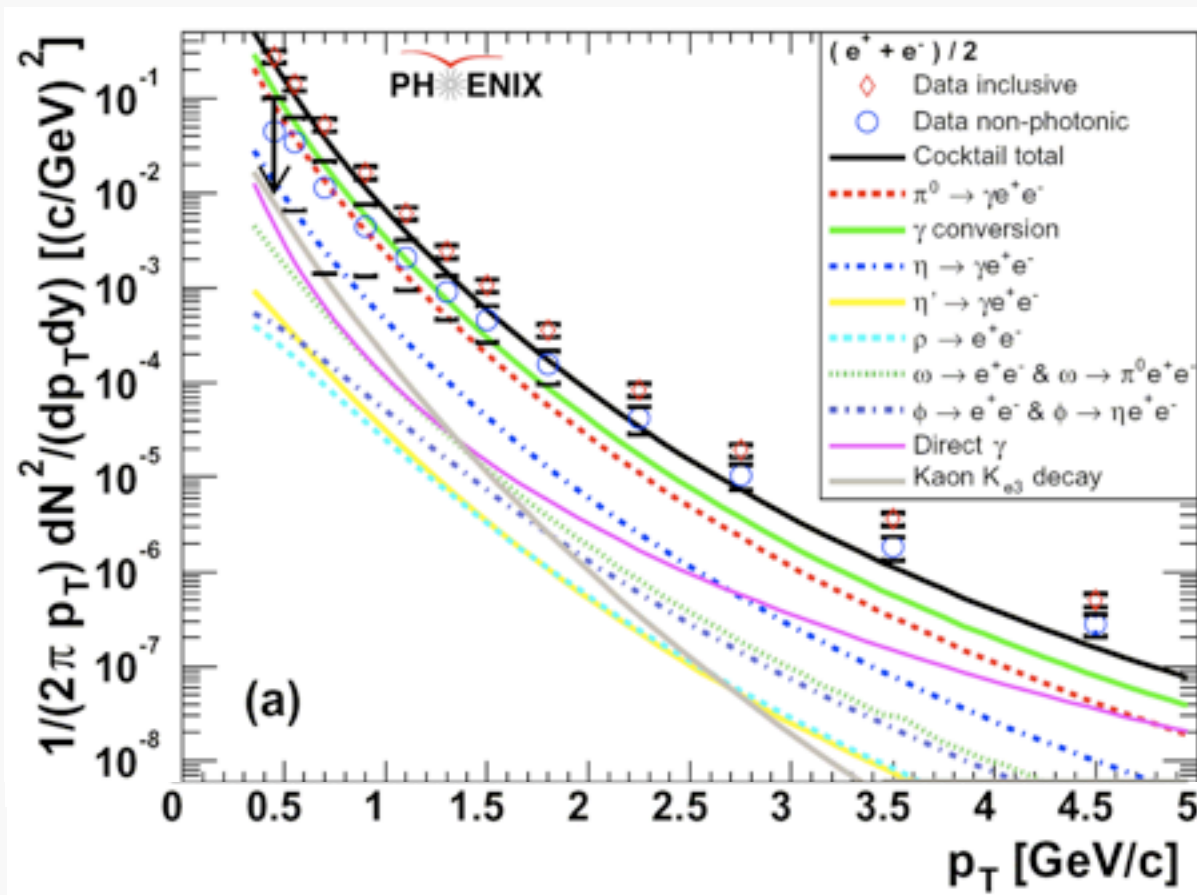
*List of participants and their affiliations appear at the end of this paper.

H-like Atoms in HIC

Direct Measurement of Single Lepton Spectrum

The shine (thermal electromagnetic emission) of the QGP is buried in the background

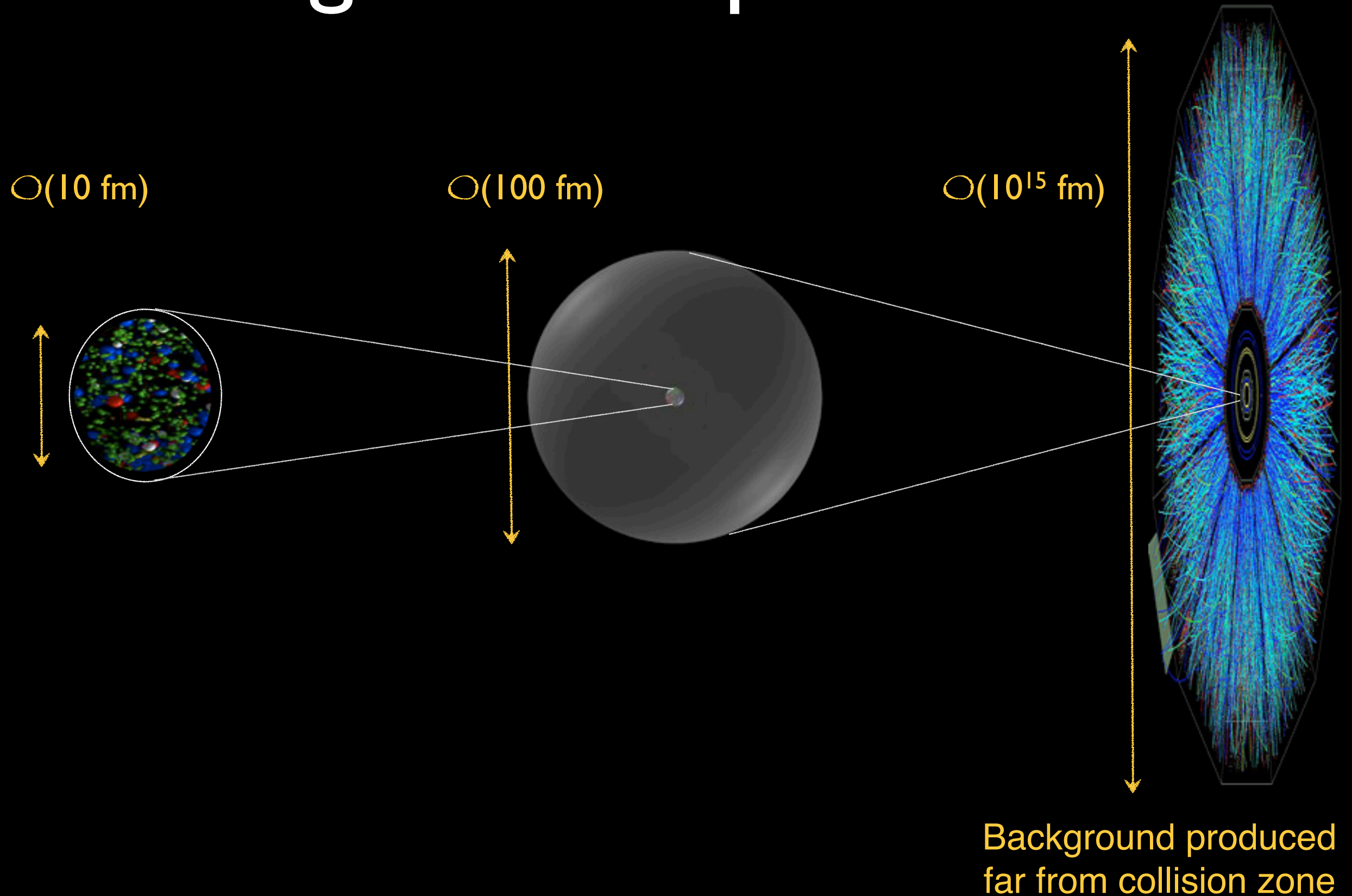
PHENIX. Phys. Rev. Lett. 96, 032301 (2006)



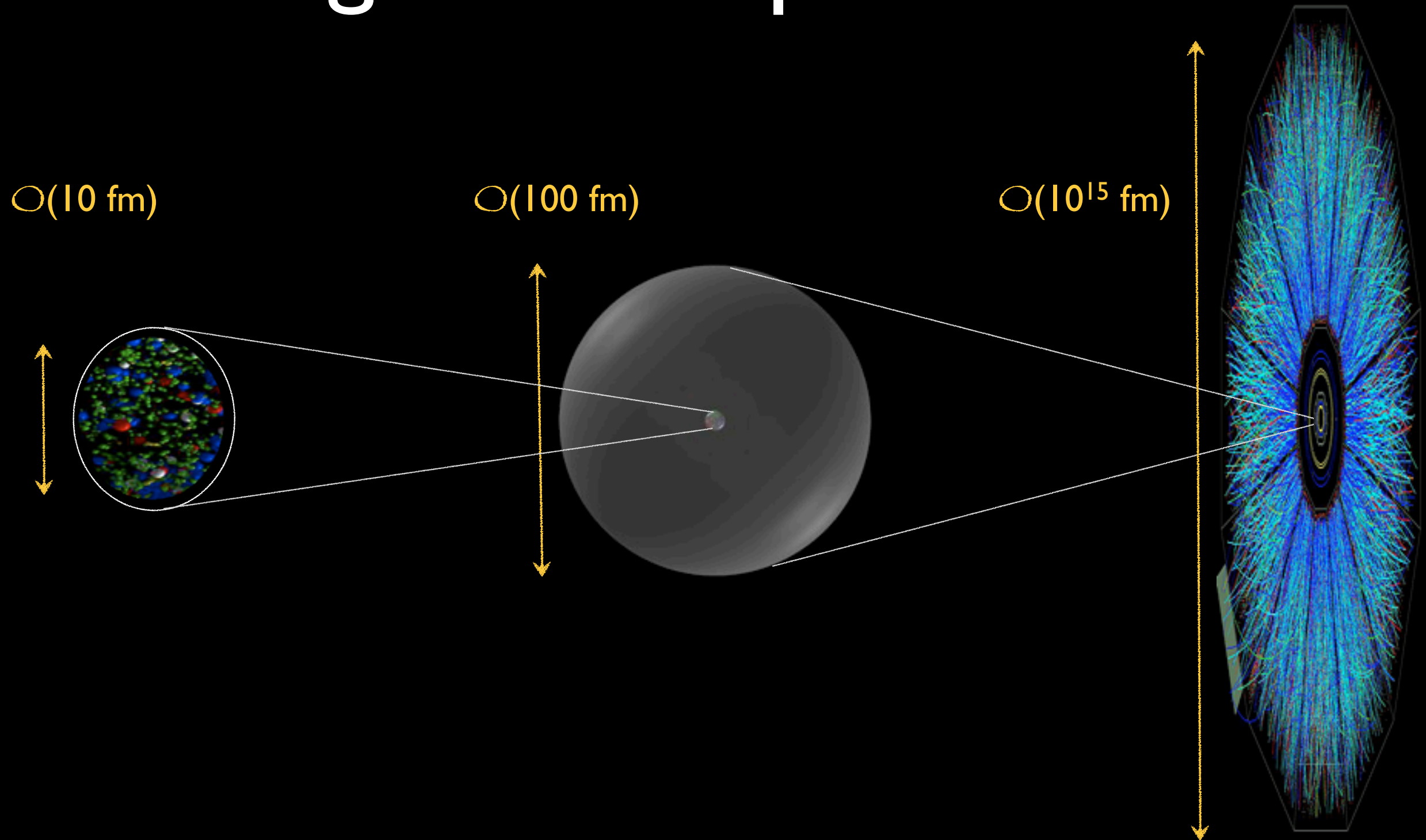
M. Schwartz (early 1990's, unpublished)

Measure the distribution of atoms formed by the binding of directly produced leptons to charged hadrons emerging from the final state of a nuclear collision

miliÅngstrom Lepton Detectors



miliÅngstrom Lepton Detectors



Atoms form after freeze-out
of particles close in phase space

Background produced
far from collision zone

Production Rate

G. Baym et al.
PRD 48 (1993) R3957

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

- Atoms form only if the lepton and hadron are close in phase-space
--> same longitudinal and transverse velocity:

$$\frac{p_t^{\text{atom}}}{m_{\text{atom}}} = \frac{p_t^{\text{lepton}}}{m_{\text{lepton}}} = \frac{p_t^{\text{hadron}}}{m_{\text{hadron}}}$$

- High momentum hadrons combine with low momentum leptons

J. Sandweiss (1998)

Suggested we investigate this problem in details

Production Rate

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

Production Rate

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



$$q + \bar{q} \rightarrow l^+ + l^-$$

$$\begin{aligned} \frac{dN}{dyd^2p_T} = & \sum_{q=u,d,s} \left(\frac{e_q}{e}\right)^2 \frac{3\alpha^2}{8\pi^3} (\tau_0 T_0^3 R_T)^2 \int_{-\infty}^{\infty} \frac{d\eta}{E} \int_{T_c}^{T_0} \frac{dT}{T^6} e^{-E/T} \int_{s_{\min}}^{\infty} ds \ln(1 + e^{-s/4ET}) \\ & \times \left[1 + 2(m_q^2 + m_l^2)/s + 4m_q^2 m_l^2/s^2\right] \sqrt{(1 - 4m_l^2/s)(1 - 4m_q^2/s)}. \end{aligned}$$

+ mixed phase $\pi^+ + \pi^- \rightarrow l^+ + l^-$

J.Kapusta, A.Mocsy PRC 59 (1998) 2937

Production Rate

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

$$\frac{dN_p}{dyd^2p_{\perp}} = \frac{Z}{2\pi y_0(m_p + T_p)T_p} \exp[(m_p - m_{\perp p})/T_p]$$

$$q + \bar{q} \rightarrow l^+ + l^-$$

$$\begin{aligned} \frac{dN}{dyd^2p_T} = & \sum_{q=u,d,s} \left(\frac{e_q}{e}\right)^2 \frac{3\alpha^2}{8\pi^3} (\tau_0 T_0^3 R_T)^2 \int_{-\infty}^{\infty} \frac{d\eta}{E} \int_{T_c}^{T_0} \frac{dT}{T^6} e^{-E/T} \int_{s_{\min}}^{\infty} ds \ln(1 + e^{-s/4ET}) \\ & \times \left[1 + 2(m_q^2 + m_l^2)/s + 4m_q^2 m_l^2/s^2\right] \sqrt{(1 - 4m_l^2/s)(1 - 4m_q^2/s)}. \end{aligned}$$

+ mixed phase $\pi^+ + \pi^- \rightarrow l^+ + l^-$

Production Rate

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

$$\frac{dN_p}{dyd^2p_{\perp}} = \frac{Z}{2\pi y_0(m_p + T_p)T_p} \exp[(m_p - m_{\perp p})/T_p]$$

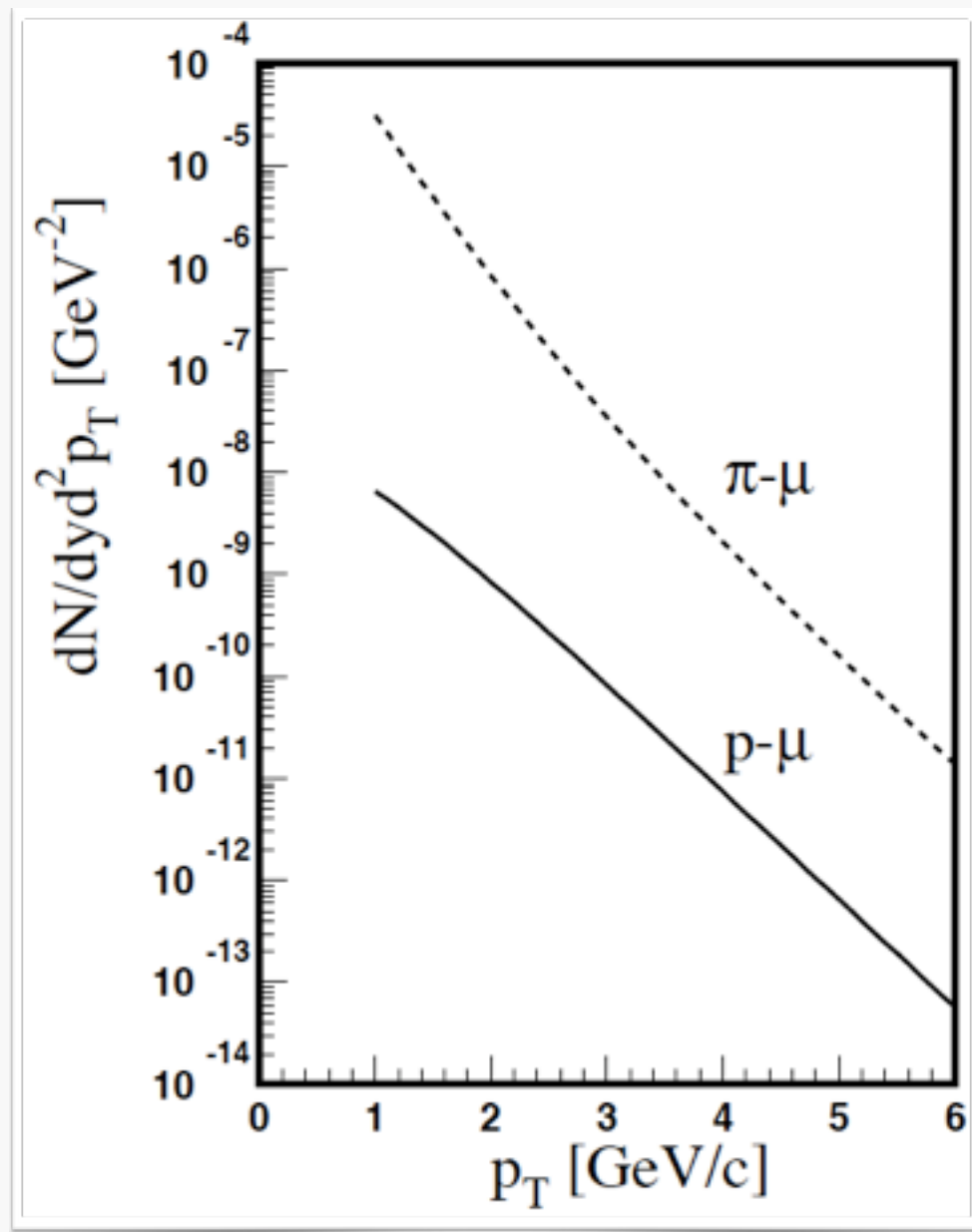
$$\frac{dN_{\pi}}{dyd^2p_{\perp}} = \frac{dN_{\pi}}{dy} \frac{1}{2\pi(m_{\pi} + T_{\pi})T_{\pi}} \exp[(m_{\pi} - m_{\perp\pi})/T_{\pi}]$$

$$q + \bar{q} \rightarrow l^+ + l^-$$

$$\begin{aligned} \frac{dN}{dyd^2p_T} = & \sum_{q=u,d,s} \left(\frac{e_q}{e}\right)^2 \frac{3\alpha^2}{8\pi^3} (\tau_0 T_0^3 R_T)^2 \int_{-\infty}^{\infty} \frac{d\eta}{E} \int_{T_c}^{T_0} \frac{dT}{T^6} e^{-E/T} \int_{s_{\min}}^{\infty} ds \ln(1 + e^{-s/4ET}) \\ & \times \left[1 + 2(m_q^2 + m_l^2)/s + 4m_q^2 m_l^2/s^2\right] \sqrt{(1 - 4m_l^2/s)(1 - 4m_q^2/s)}. \end{aligned}$$

+ mixed phase $\pi^+ + \pi^- \rightarrow l^+ + l^-$

Spectra



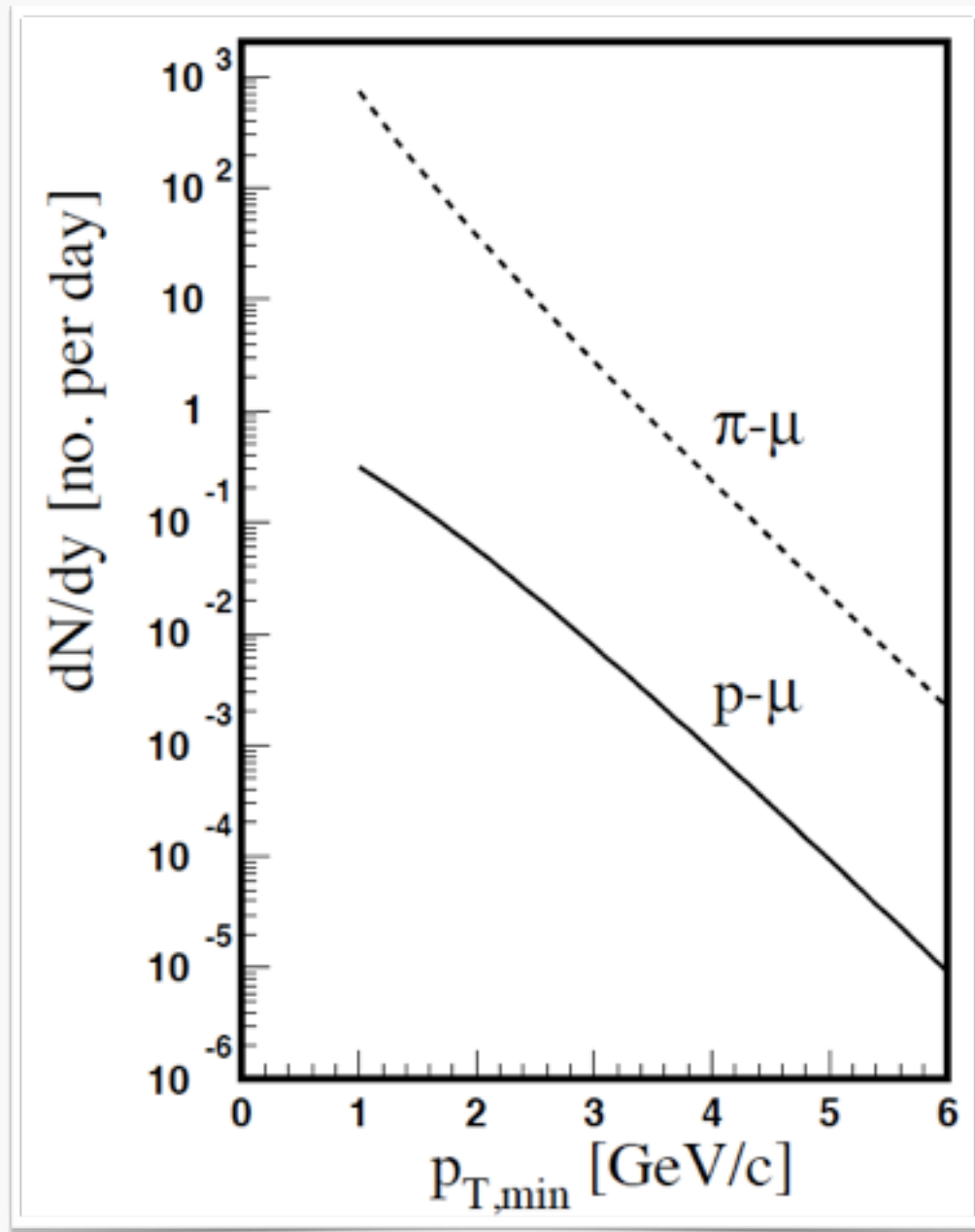
at RHIC for central AuAu

Pionic atoms dominate due to large charged pion abundance and because the π and μ masses are similar

integrated yield 10^{-5} $\pi-\mu$ atoms per unit rapidity per central AuAu collision

J.Kapusta, A.Mocsy PRC 59 (1998) 2937

Yields



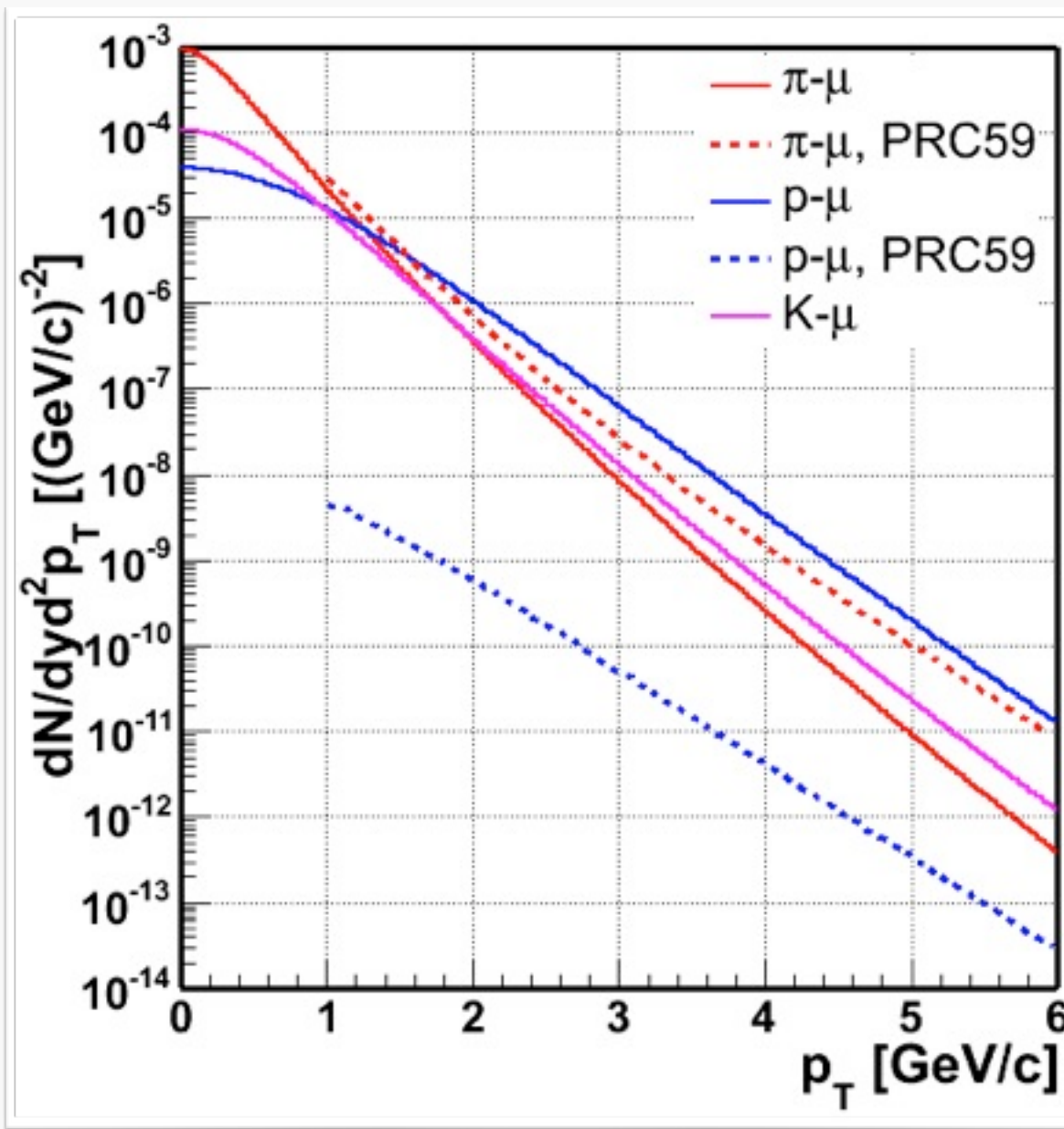
Our estimates from 1998

Based on estimated luminosity of $2 \times 10^{26} \text{ cm}^{-2} \text{ s}^{-1}$

$\sim 1000 \pi-\mu$ per unit rapidity per day with $p_T > 1 \text{ GeV}/c$

J.Kapusta, A.Mocsy PRC 59 (1998) 2937

Updates



Zhangbu Xu et al 2011/12

New estimates using

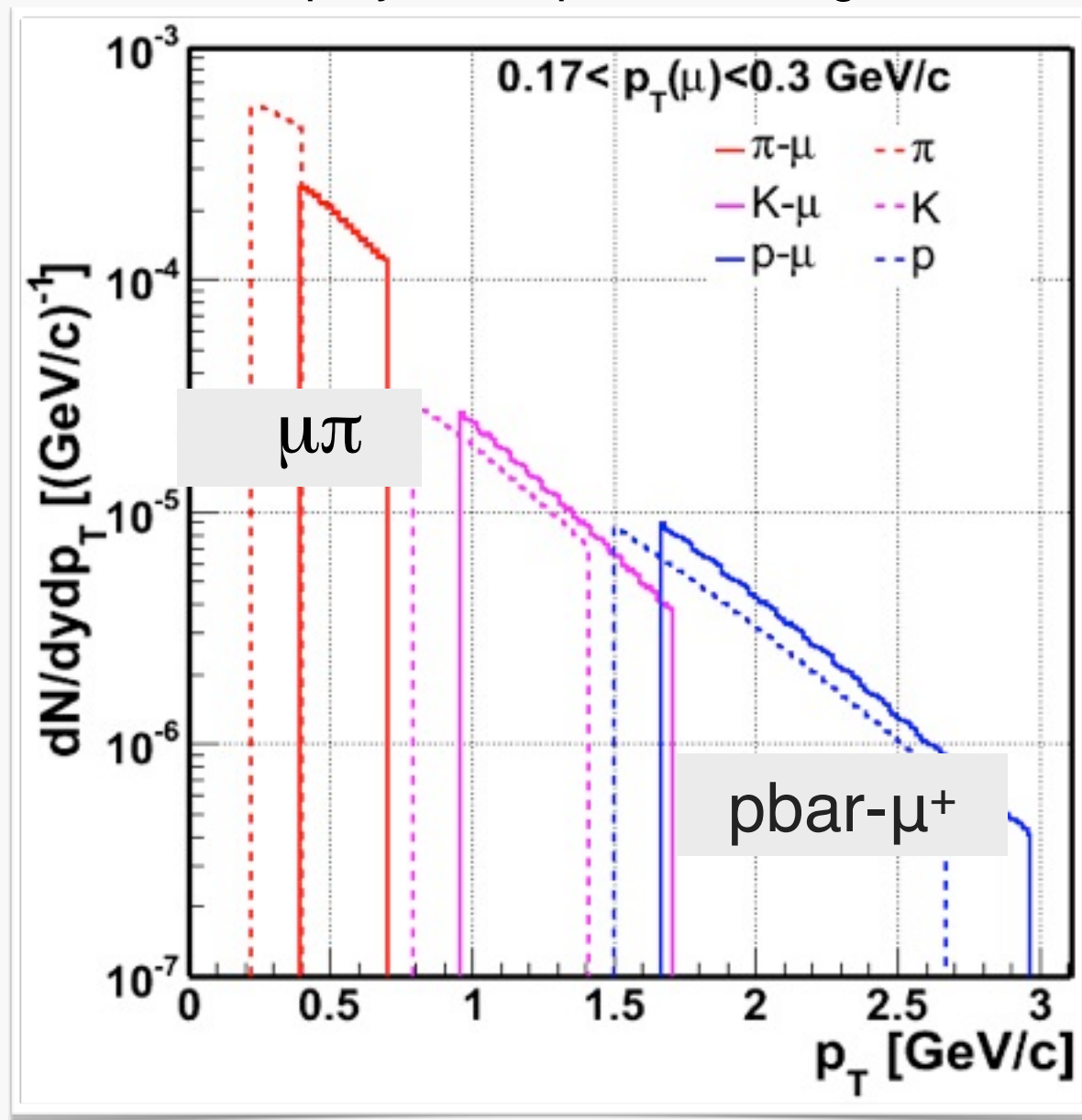
- measured hadron spectra
- μ spectra from π spectra scaled by $(\alpha/\alpha_s)^2$

π - μ shows good agreement

old estimates for p - μ are below the new ones

Feasibility in STAR

projected spectrum ranges



Zhangbu Xu et al 2011

Muons can be identified at low p_T

$$0.17 < p_T < 0.3 \text{ GeV/c}$$

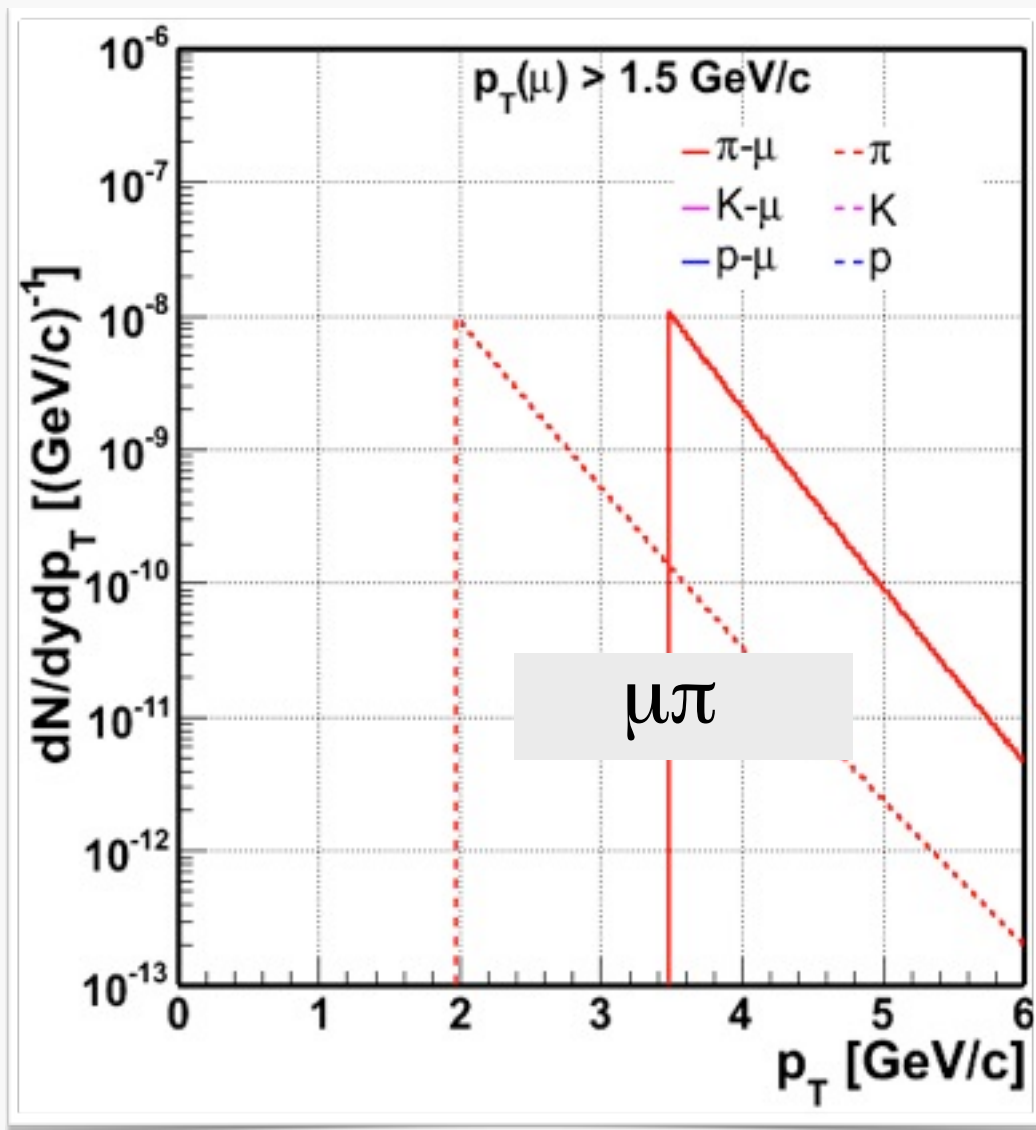
In 500M central events (one run):
500 never before observed
anti-muonic-hydrogen

22K π - μ atoms

$$\mathbf{p}_{\perp, \text{atom}} / m_{\text{atom}} = \mathbf{p}_{\perp, h} / m_h = \mathbf{p}_{\perp, l} / m_l$$

Feasibility in STAR

projected spectrum ranges



Zhangbu Xu et al 2011

Detector upgrades (*muon telescope detector*) will be used to trigger on high p_T muons

With RHICII Luminosity in a 12 week run:

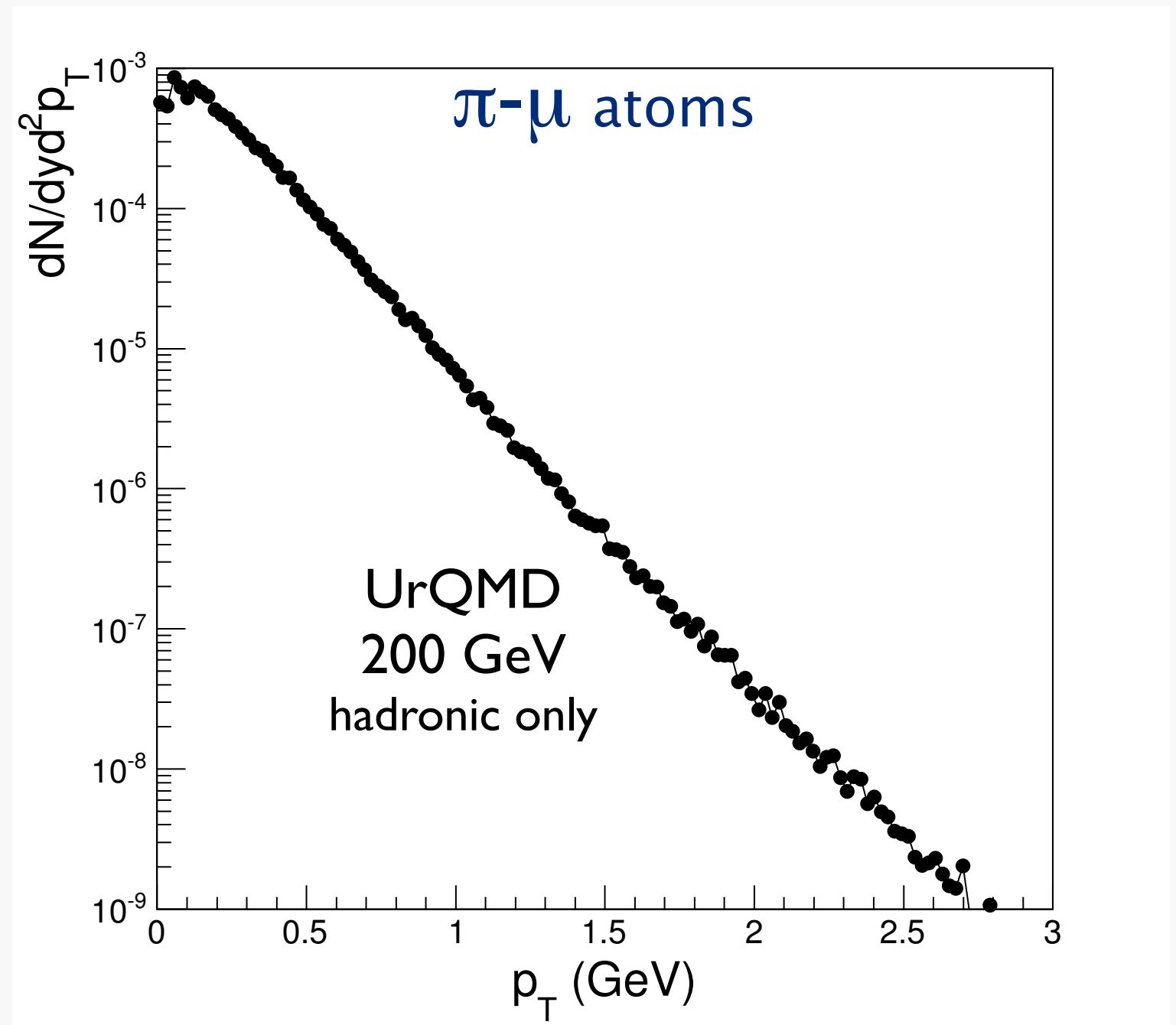
$\sim 200 \pi-\mu$ atoms $p_{T,\mu} > 1.5 \text{ GeV}$

Enough to be observed!

More complete estimates

Estimating the lepton spectra from H-like atoms allows us to disentangle many lepton sources:

We use UrQMD to estimate hadronic contributions (like ρ)



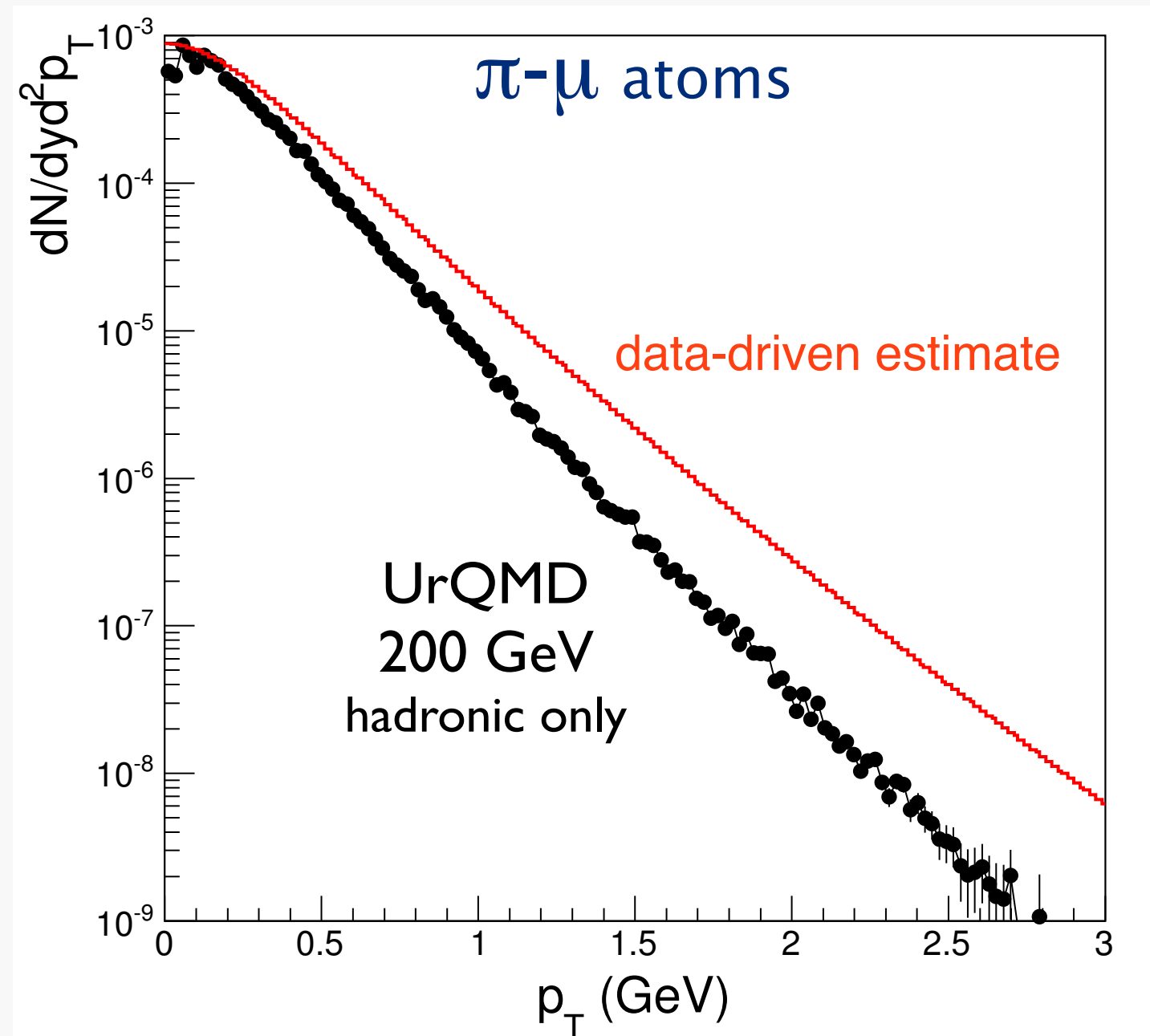
in collaboration with **Stephan Endres**, FIAS Frankfurt, 2013

More complete estimates

Estimating the lepton spectra from H-like atoms allows us to disentangle many lepton sources:

We use UrQMD to estimate hadronic contributions (like ρ)

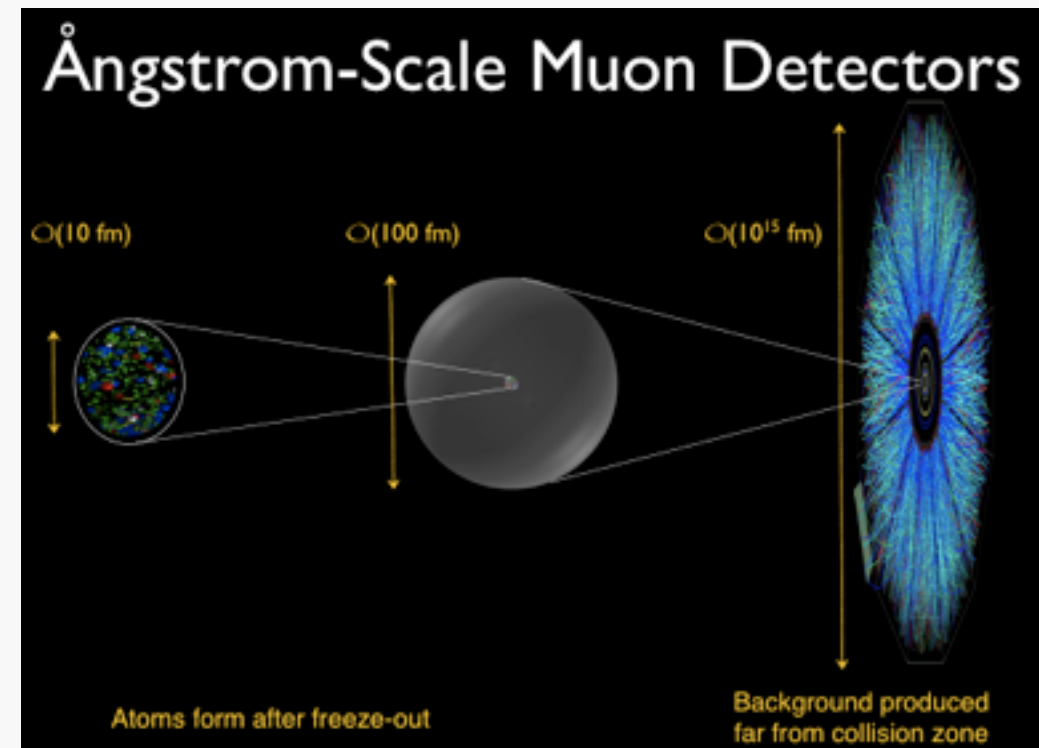
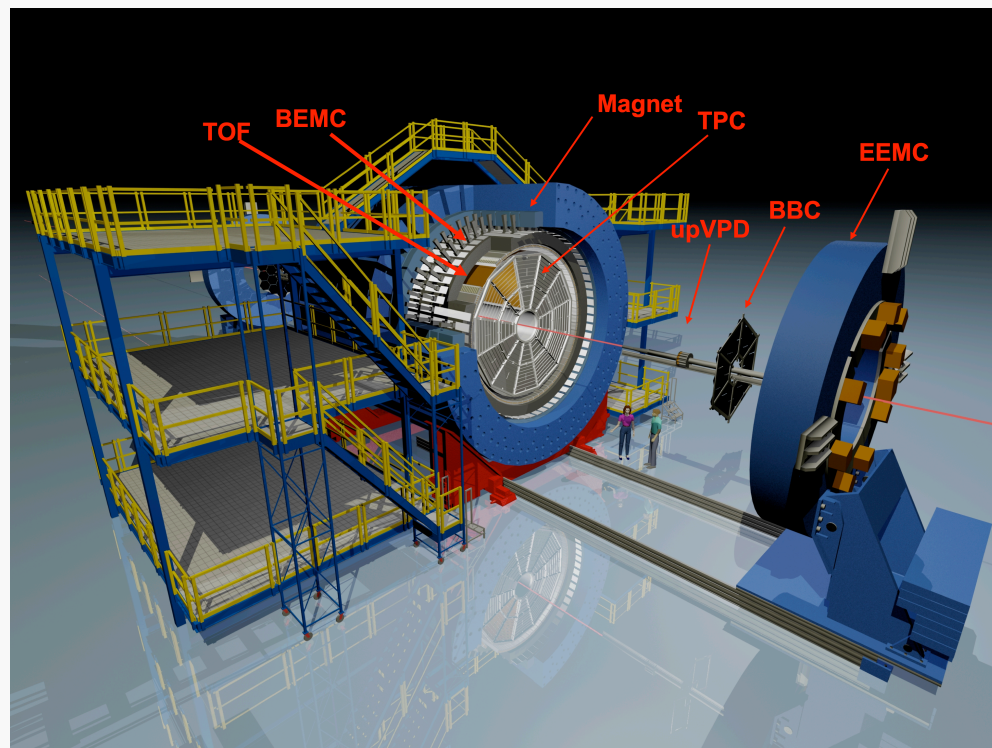
Early estimates are in the same ball-park as other estimates (work in progress)



in collaboration with **Stephan Endres**, FIAS Frankfurt, 2013

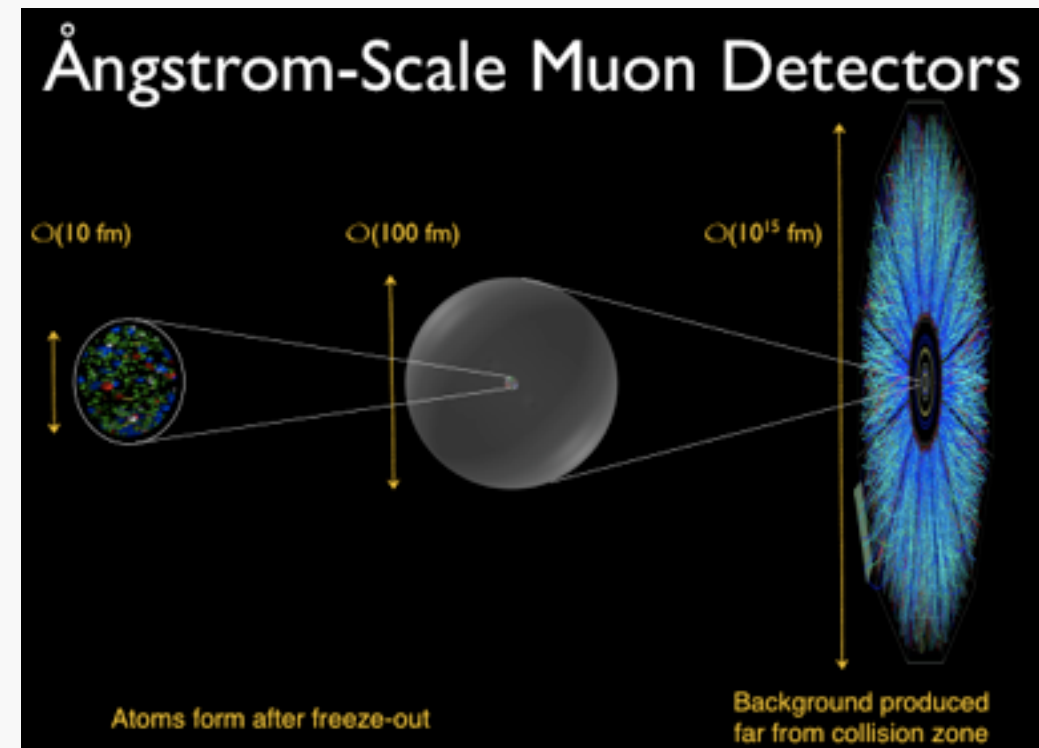
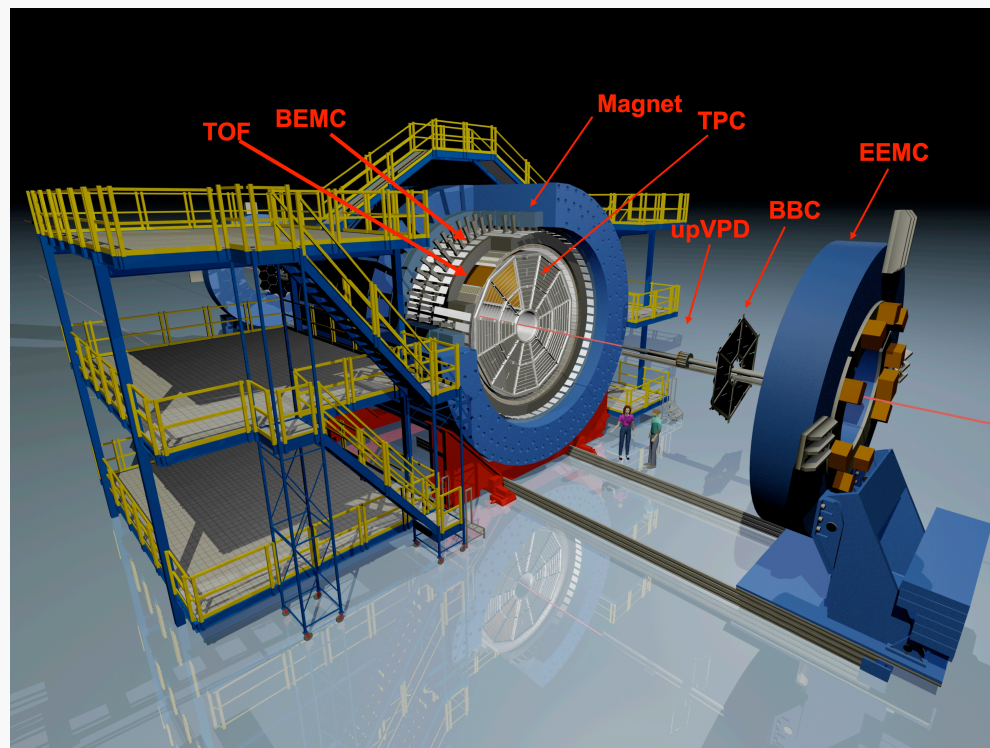
In conclusion, we have reinvestigated the rates for the production of hydrogenlike atoms at RHIC. The results are quite promising for their experimental detection. It remains to be seen whether an efficient detector can be designed to observe them.

J. Kapusta, A. Mocsy PRC 59 (1998) 2937



In conclusion, we have reinvestigated the rates for the production of hydrogenlike atoms at RHIC. The results are quite promising for their experimental detection. It remains to be seen whether an efficient detector can be designed to observe them.

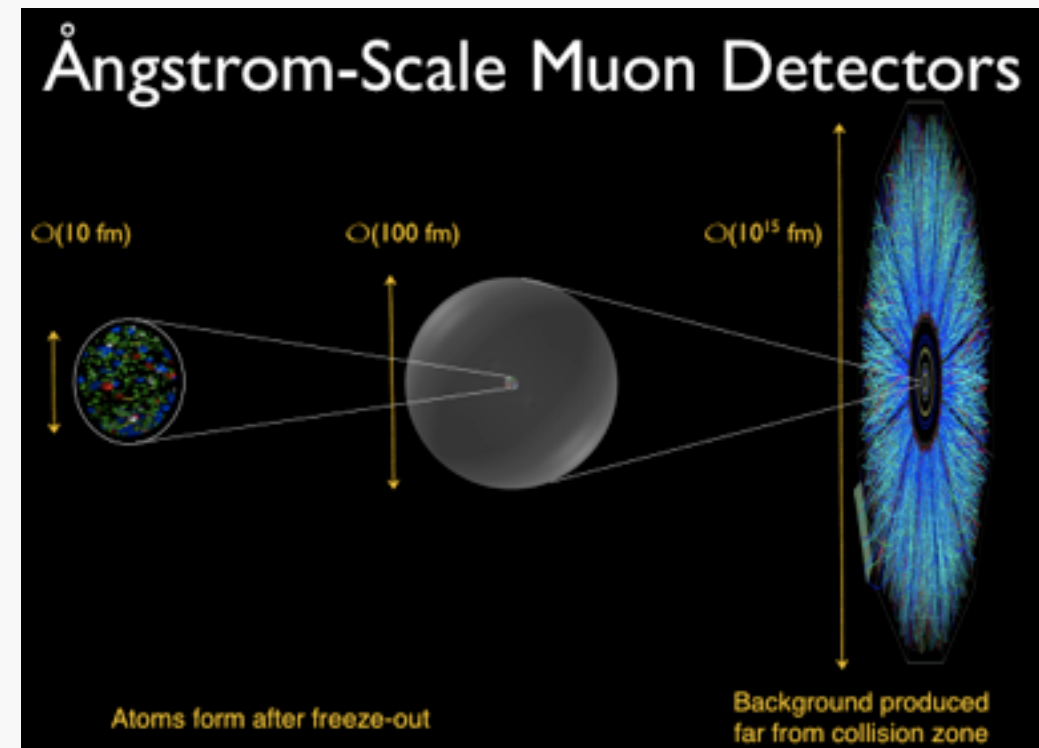
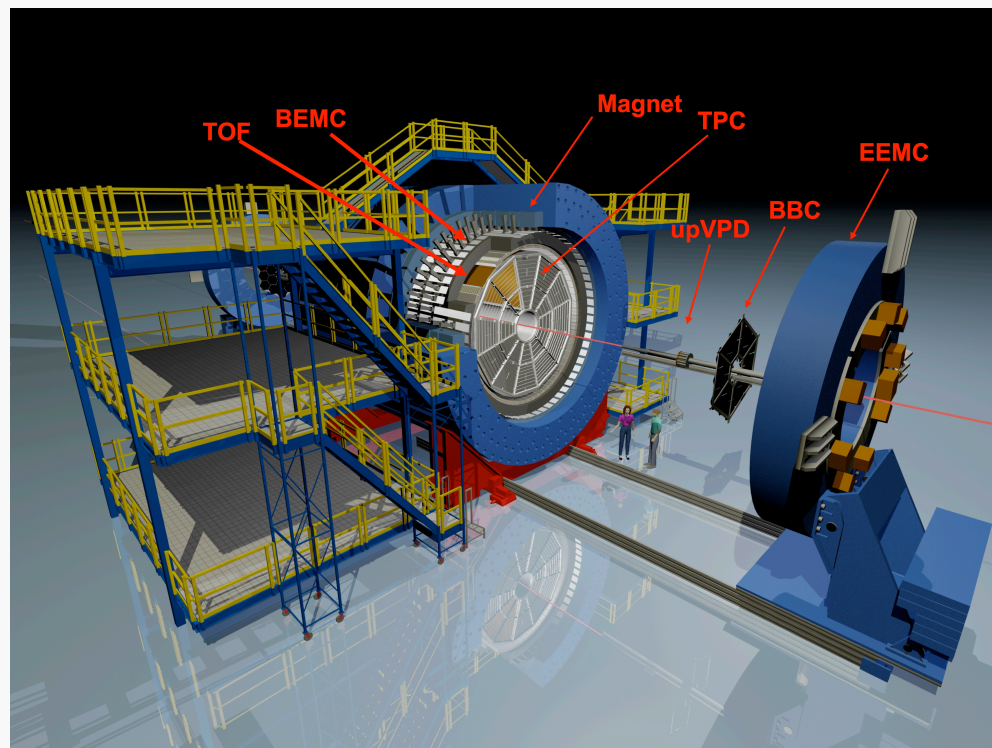
J. Kapusta, A. Mocsy PRC 59 (1998) 2937



- STAR and PHENIX believe they can be measured a unique tool for probing QGP properties
 - provides information on the direct lepton spectrum
 - possible discovery of new particle: anti-matter muonic hydrogen!
- What about at the LHC?! increased rapidity range, high multiplicity
- More complete calculations in collaboration with Stephan Endres (FIAS)

In conclusion, we have reinvestigated the rates for the production of hydrogenlike atoms at RHIC. The results are quite promising for their experimental detection. It remains to be seen whether an efficient detector can be designed to observe them.

J. Kapusta, A. Mocsy PRC 59 (1998) 2937



- STAR and PHENIX believe they can be measured a unique tool for probing QGP properties
 - provides information on the direct lepton spectrum
 - possible discovery of new particle: anti-matter muonic hydrogen!
- What about at the LHC?! increased rapidity range, high multiplicity

Thanks to Zhangbu Xu, Zebo Tang, Paul Sorensen,
Marcus Bleicher, Stephan Endres, Mauricio Martinez

Kodama-san!

the coolest gentleman - an inspiration to me

2004 Brazil



Kodama-san!

the coolest gentleman - an inspiration to me

2008 New York



Happy Birthday, Kodama-san!

2008 New York



The End