Hydrogen-Like Atoms
as
miliAngstrom Scale Lepton Detectors

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Hydrogenlike atoms from ultrarelativistic nuclear collisions

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(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 $dN/dyd^2p_\perp$ 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 $q+\bar{q}\to l^+ + l^-$ is

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

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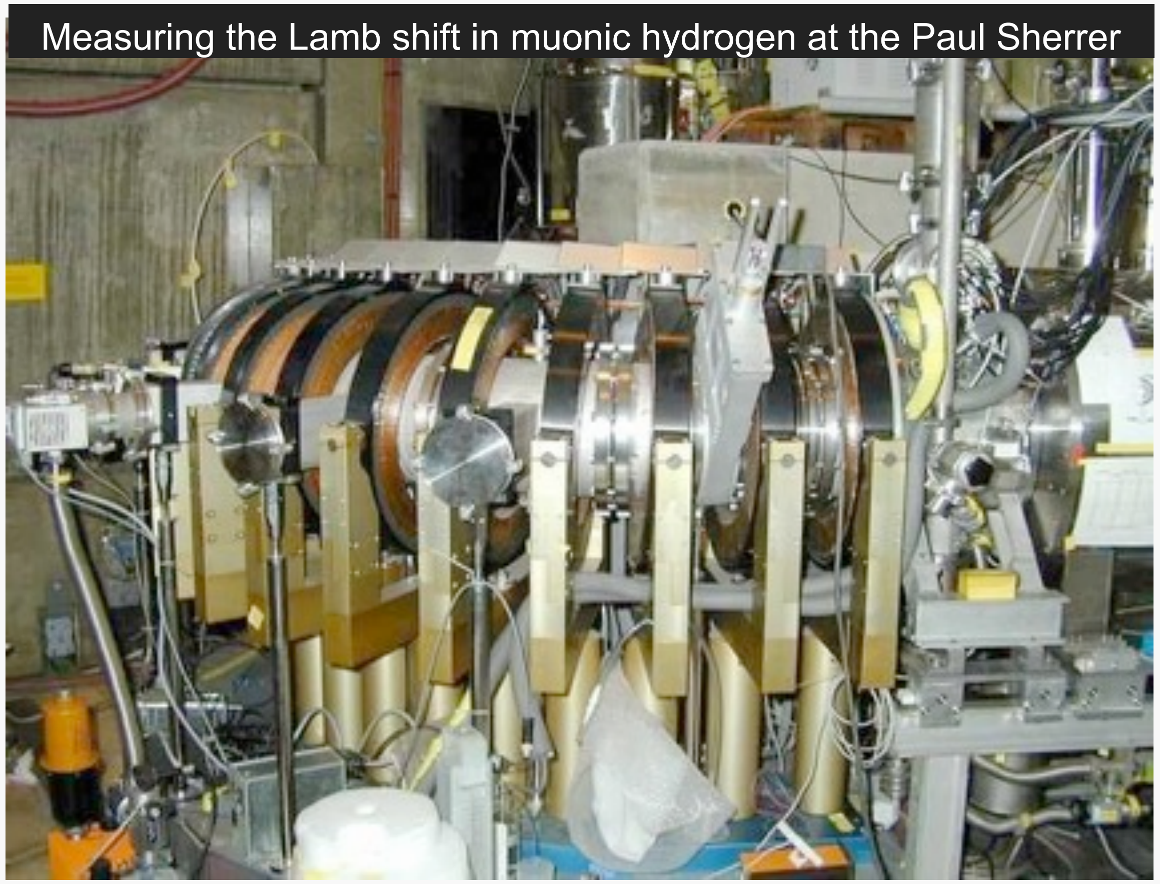
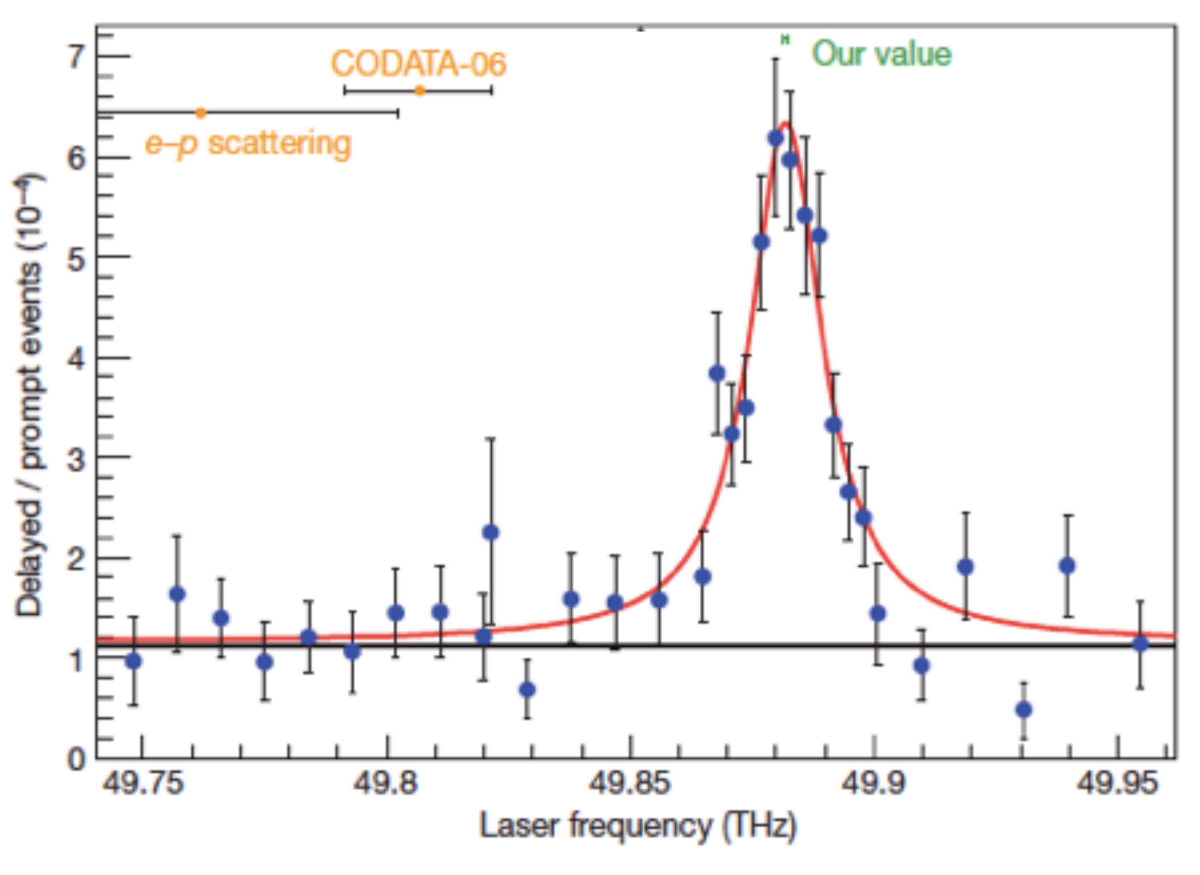
H-like Atoms as Precision Tools

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 $K_L^0 \to (\pi\mu)_{atom}\nu$. This represents the first observations of an atom composed of two unstable particles and of an atomic decay of an elementary particle.

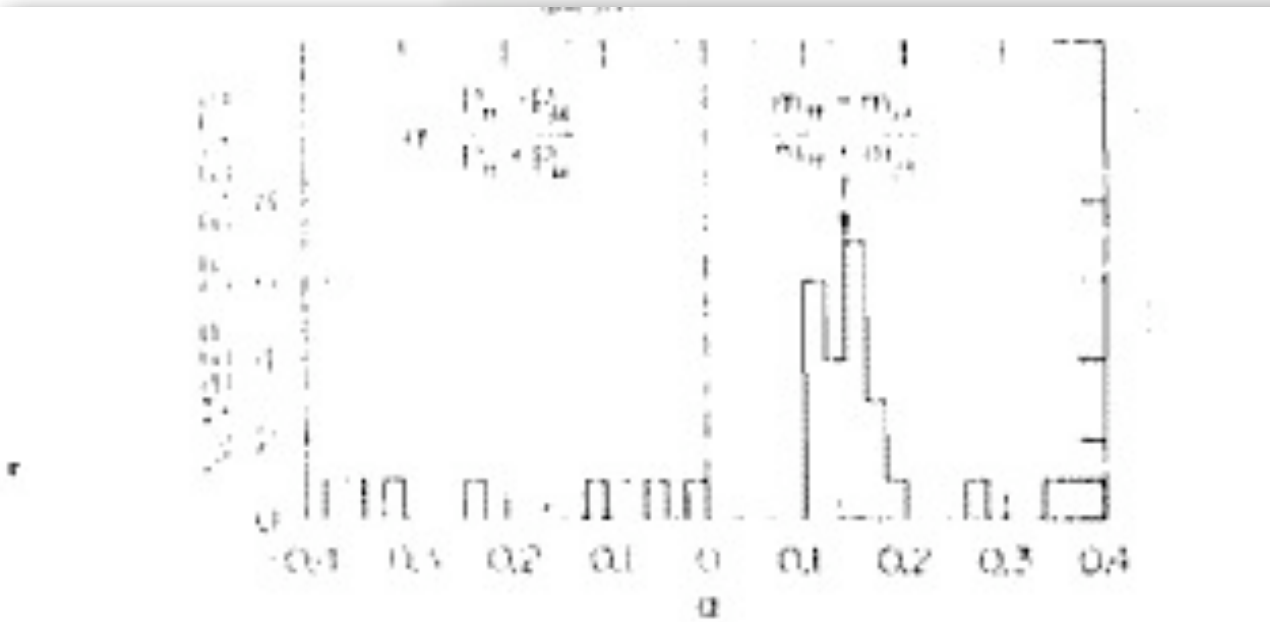


FIG. 3. A plot of the parameter α indicating the detection of π-μ atoms.

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 ?!

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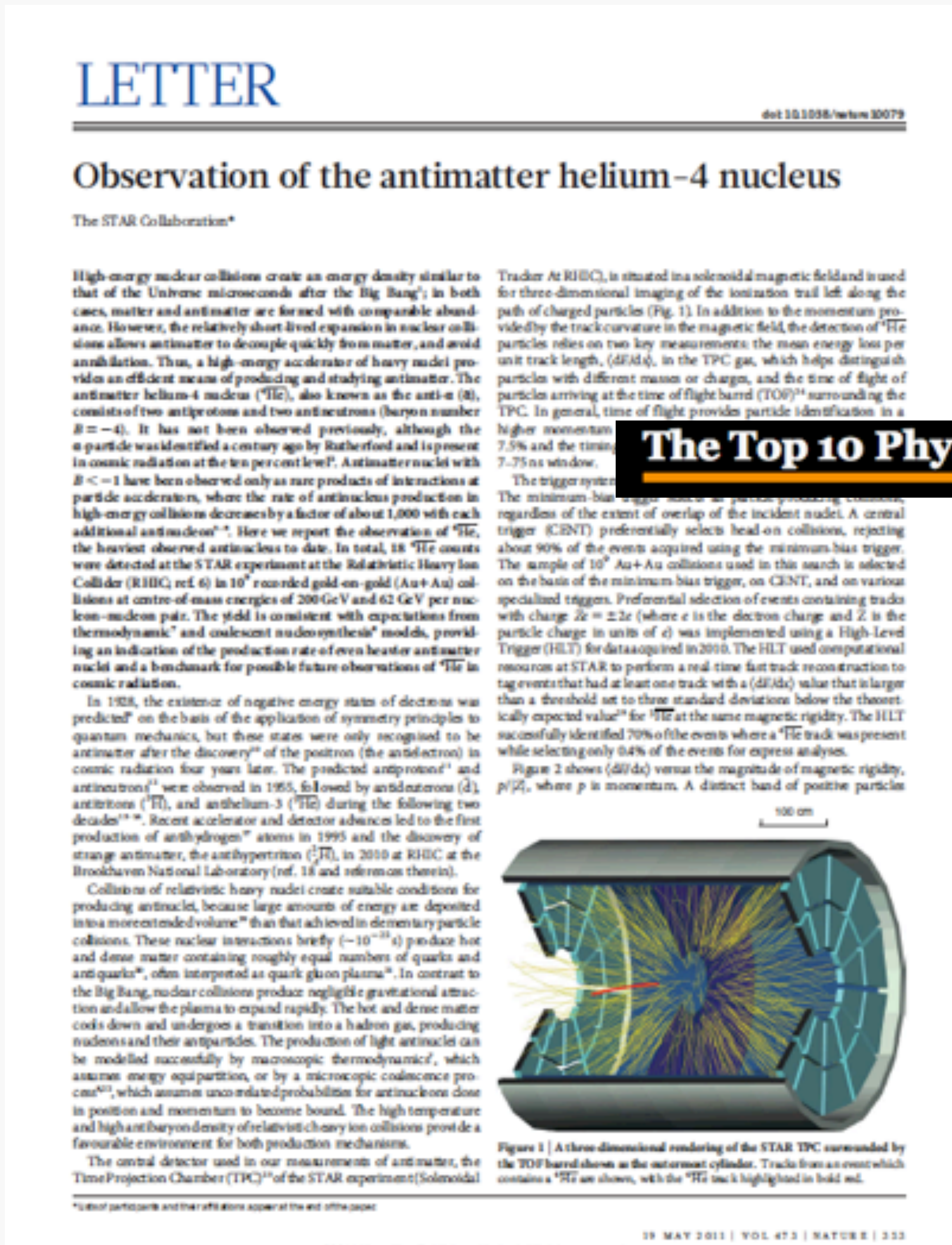

LETTER

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 Bang[1]; 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 ($^4\overline{He}$), also known as the anti-α ($\overline{\alpha}$), 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 per cent level[2]. 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 antinucleon[3-5]. Here we report the observation of $^4\overline{He}$, the heaviest observed antinucleus to date. In total, 18 $^4\overline{He}$ counts were detected at the STAR experiment at the Relativistic Heavy Ion Collider (RHIC; ref. 6) in 10^9 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 thermodynamic[7] and coalescent nucleosynthesis[8] models, providing an indication of the production rate of even heavier antimatter nuclei and a benchmark for possible future observations of $^4\overline{He}$ in cosmic radiation.

Figure 1 | A three-dimensional rendering of the STAR TPC surrounded by the TOF barrel shown as the outermost cylinder.

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The Top 10 Physics and Math Stories of 2011

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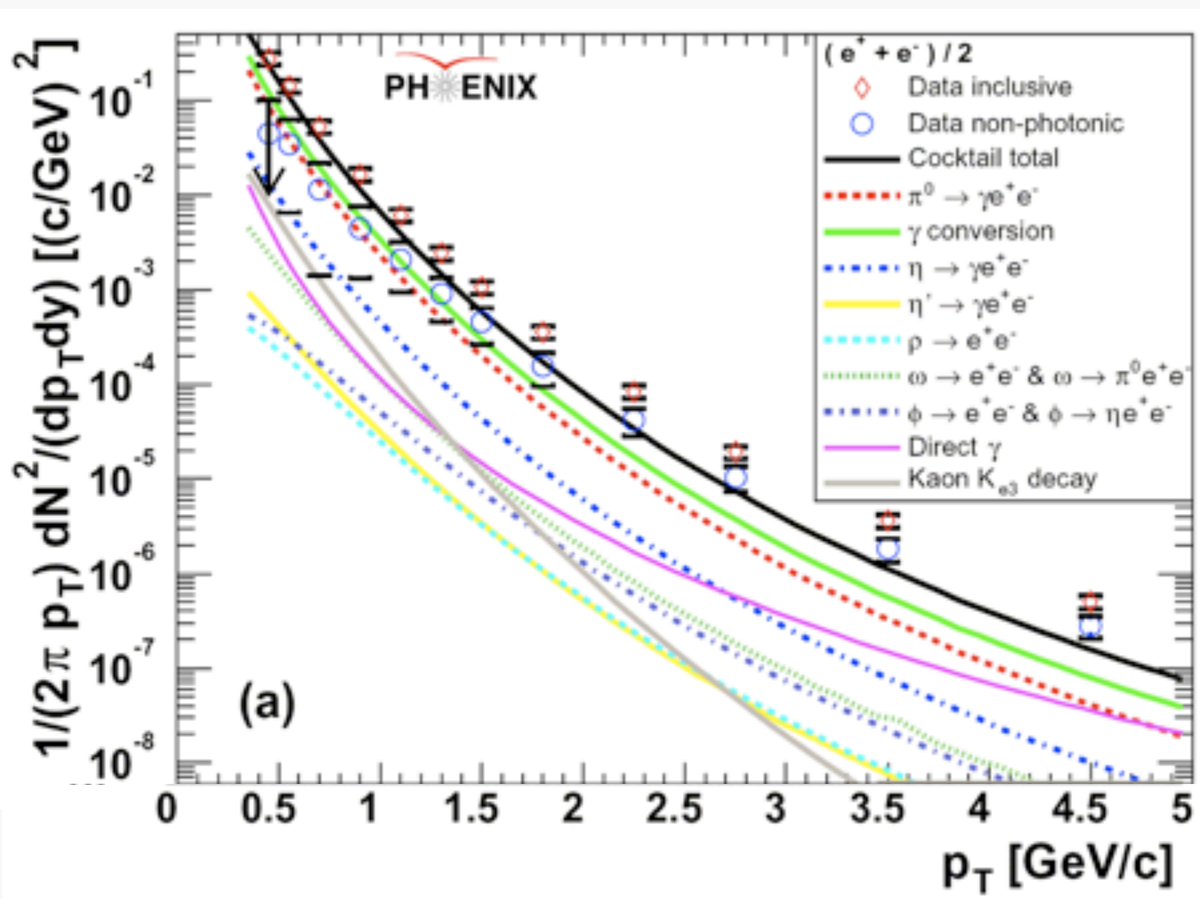
H-like Atoms in HIC

Direct Measurement of Single Lepton Spectrum

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

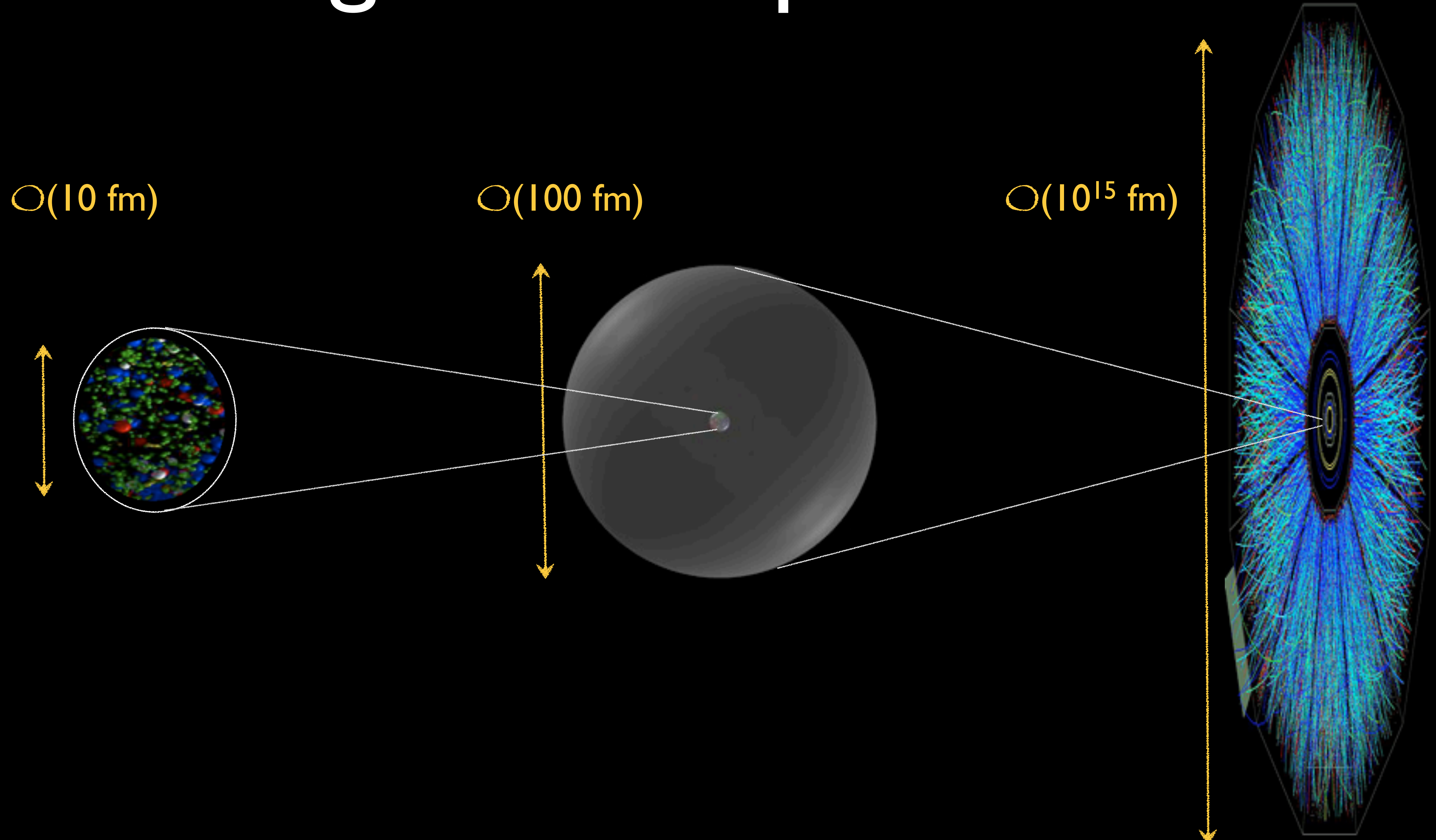
PHENIX.Phys. Rev. Lett. 96, 032301 (2006)



M. Schwartz (early 1990's, unpublished)

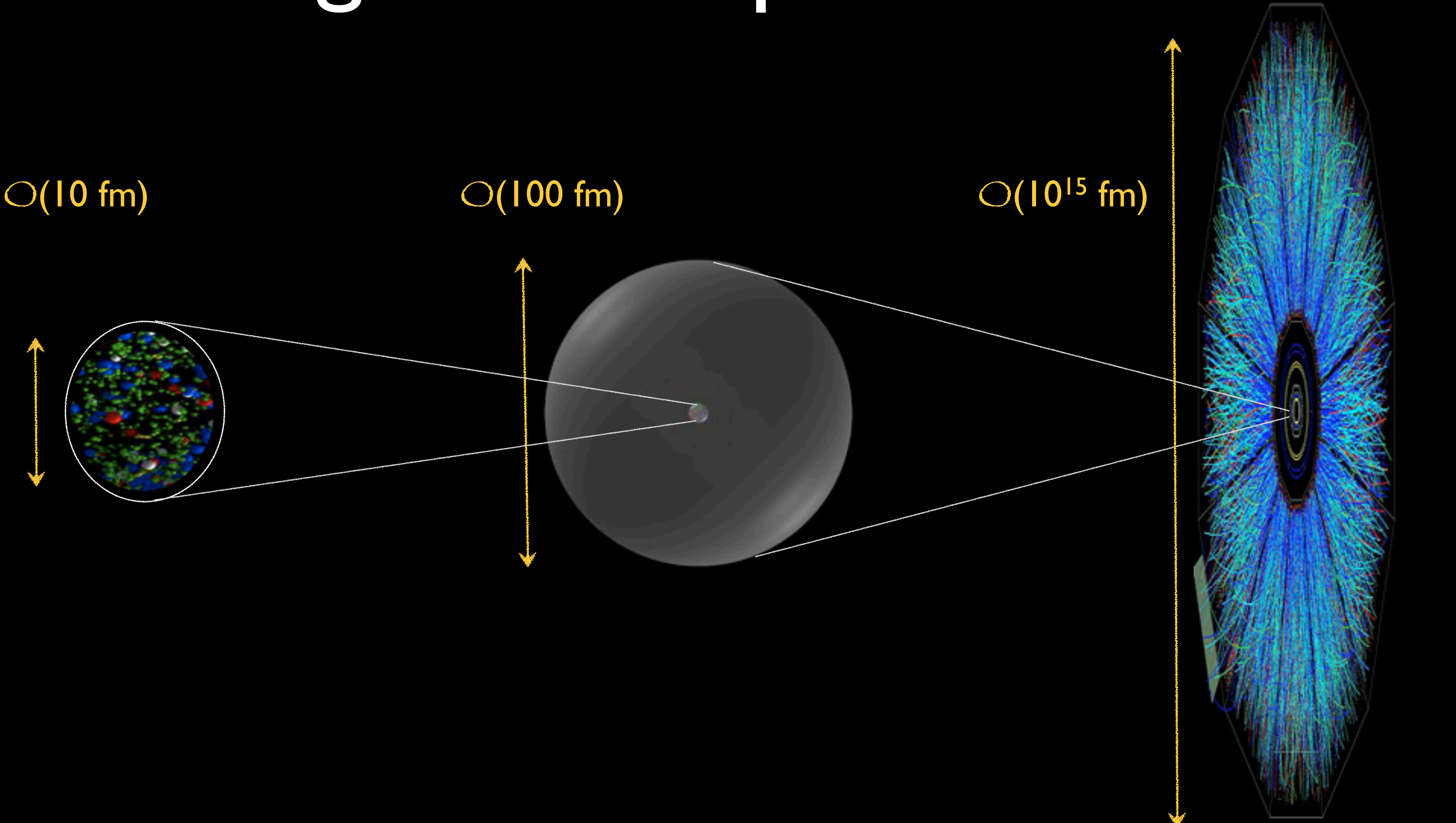
Measure the distribution of atoms formed by the binding of directly produced leptons to charged hadrons emerging from the final state of a nuclear collision

miliÅngstrom Lepton Detectors



Background produced far from collision zone

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

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

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

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

- High momentum hadrons combine with low momentum leptons

J. Sandweiss (1998) Suggested we investigate this problem in details

Production Rate

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

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

Production Rate

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

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

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

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Production Rate

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

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

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

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

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

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

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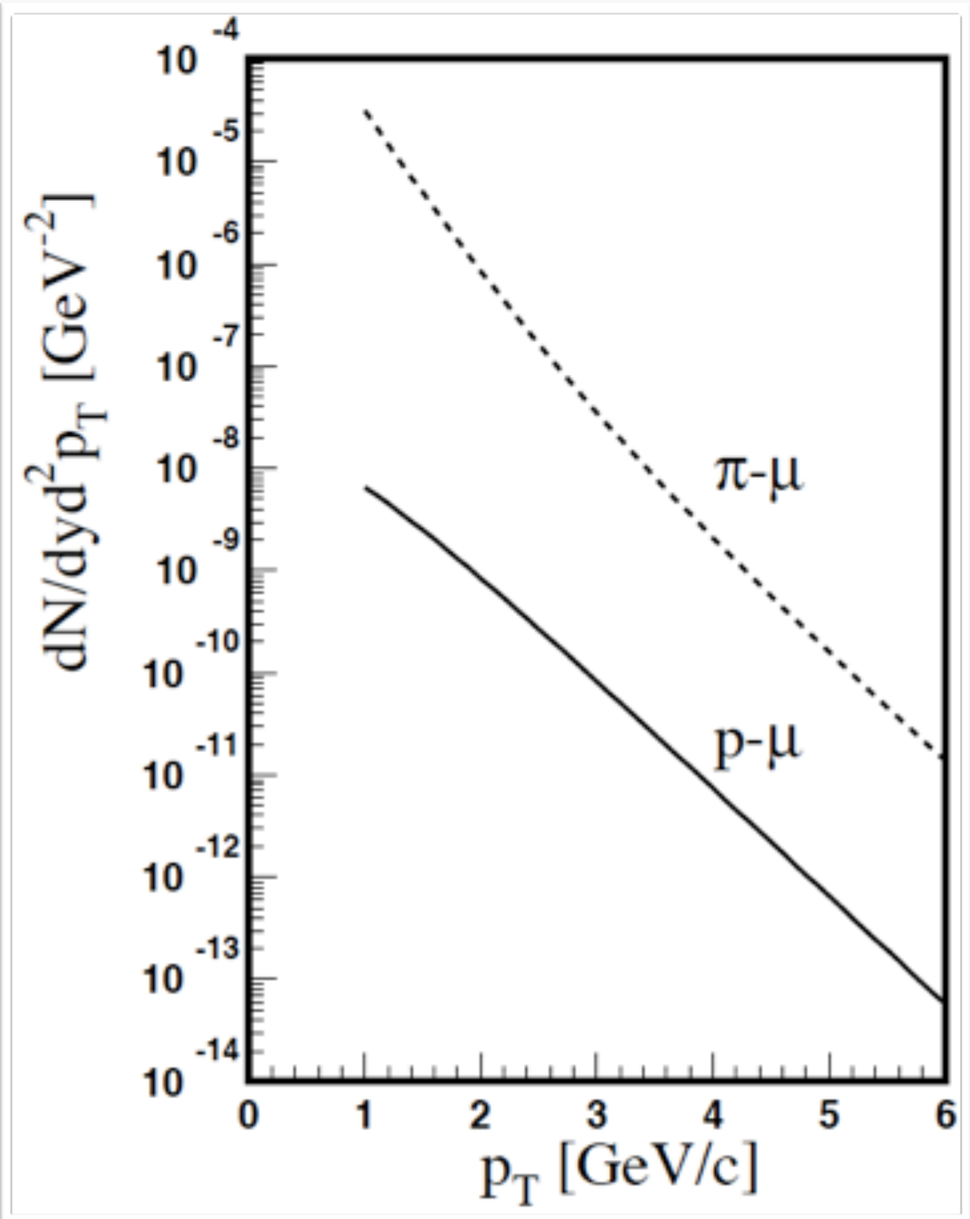
Spectra



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

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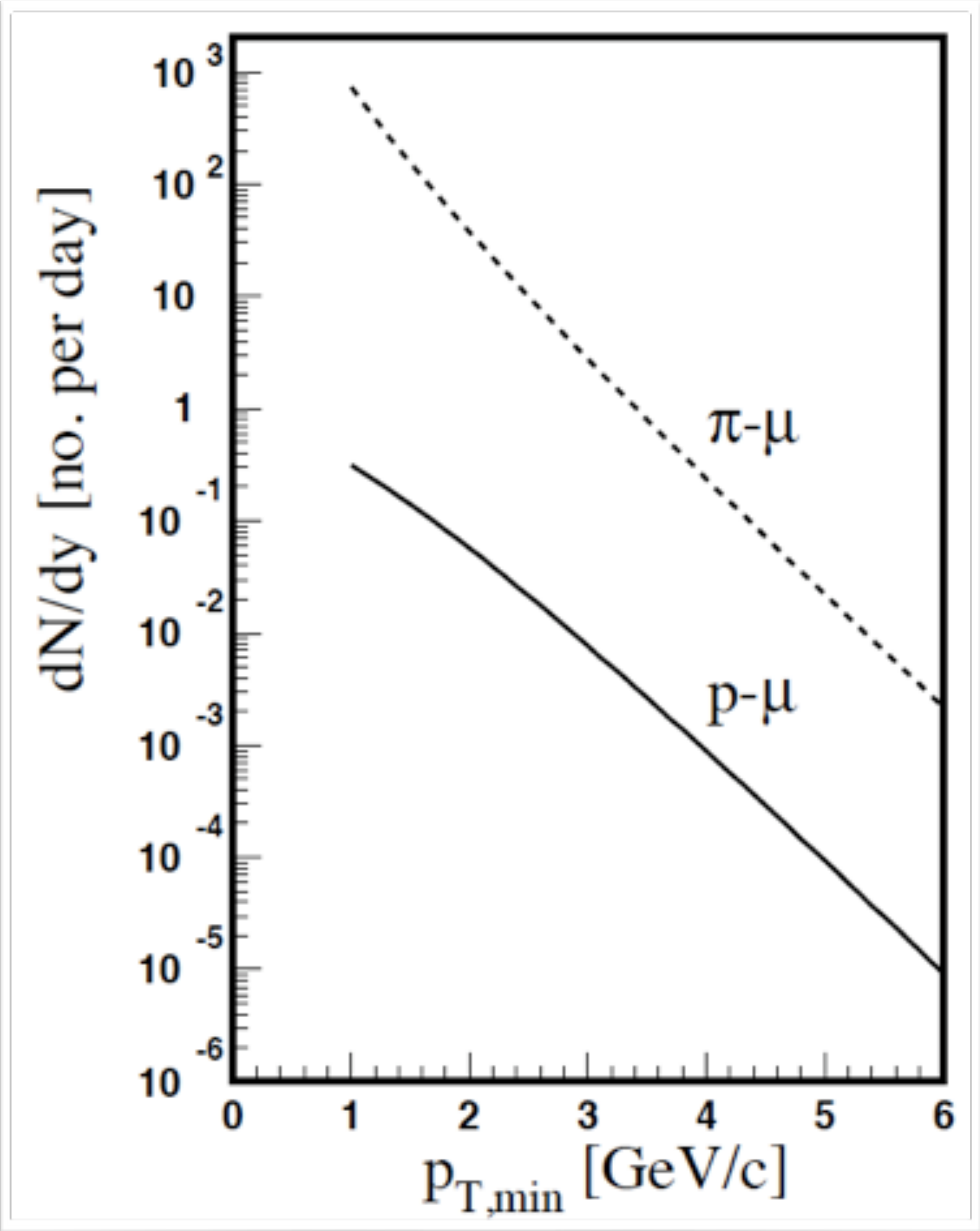
Yields



Our estimates from 1998

Based on estimated luminosity of $2x10^{26}$ $cm^{-2}s^{-1}$

~ 1000 π−μ per unit rapidity per day with p_T > 1GeV/c

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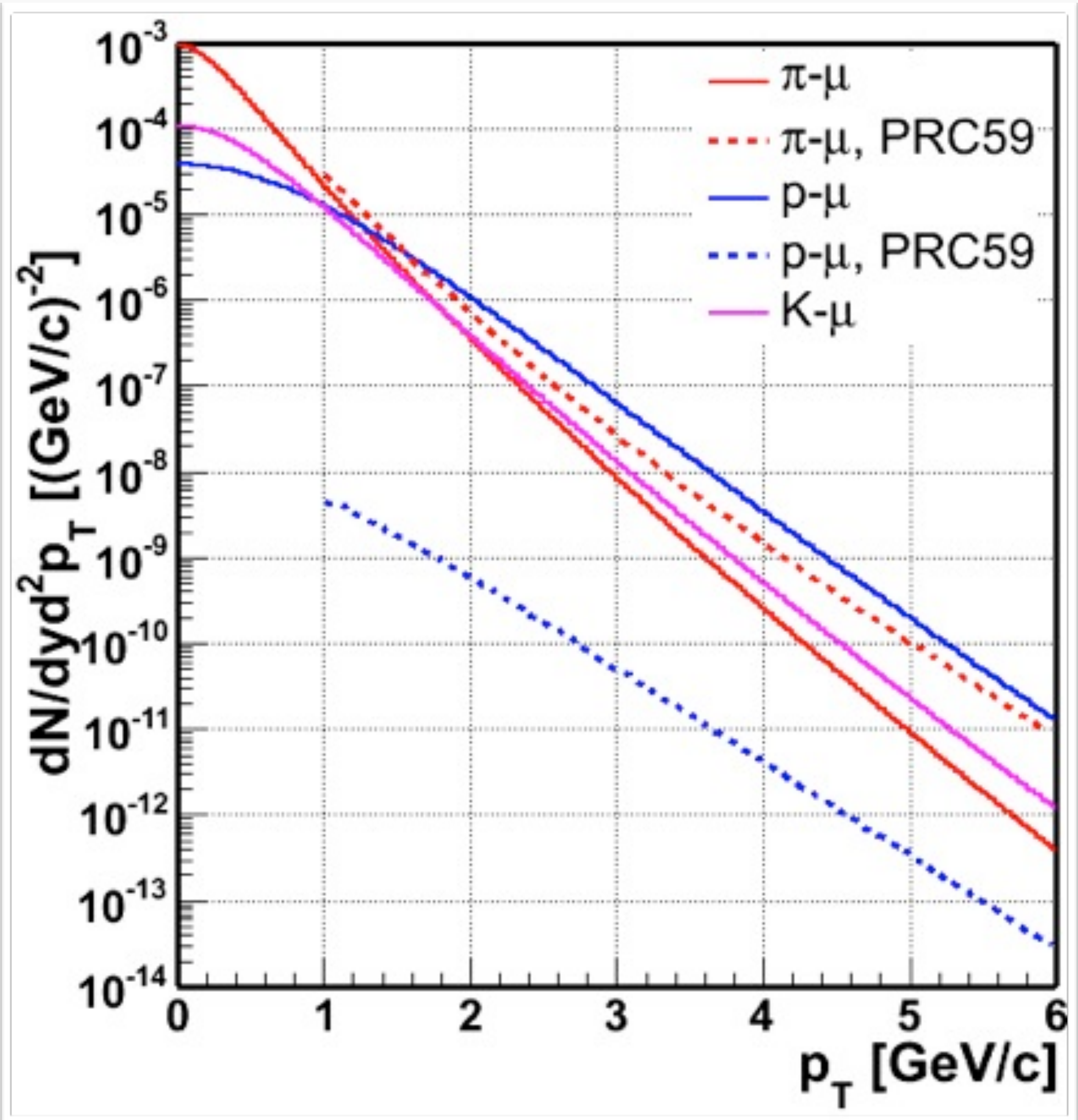
Updates



Zhangbu Xu et al 2011/12

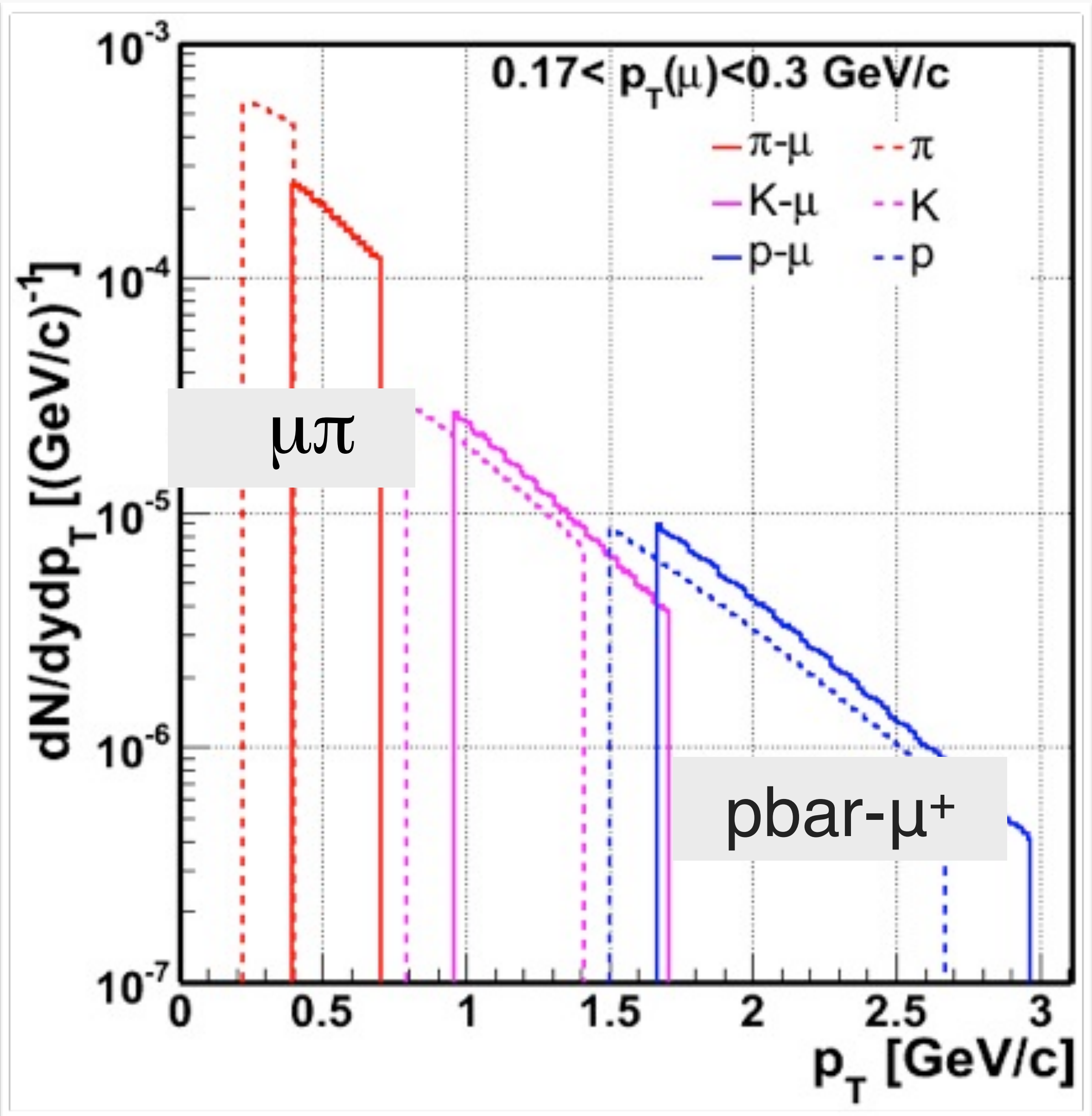
New estimates using
- measured hadron spectra
- μ spectra from π spectra scaled by $(\alpha/\alpha_s)^2$

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

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

Muons can be identified at low p_T

$0.17 < p_T < 0.3$ GeV/c

In 500M central events (one run):

500 never before observed anti-muonic-hydrogen

22K π-μ atoms

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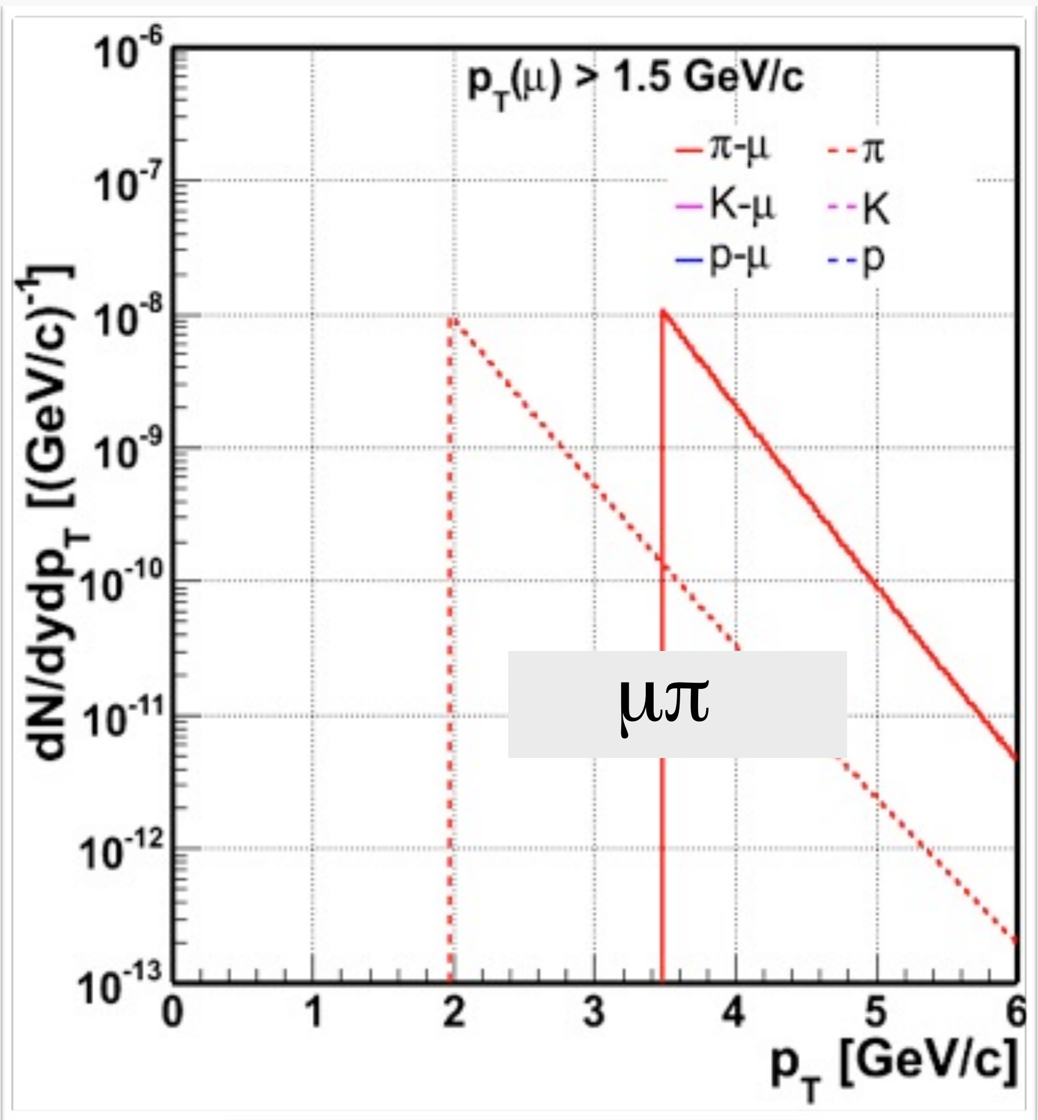
Feasibility in STAR

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:

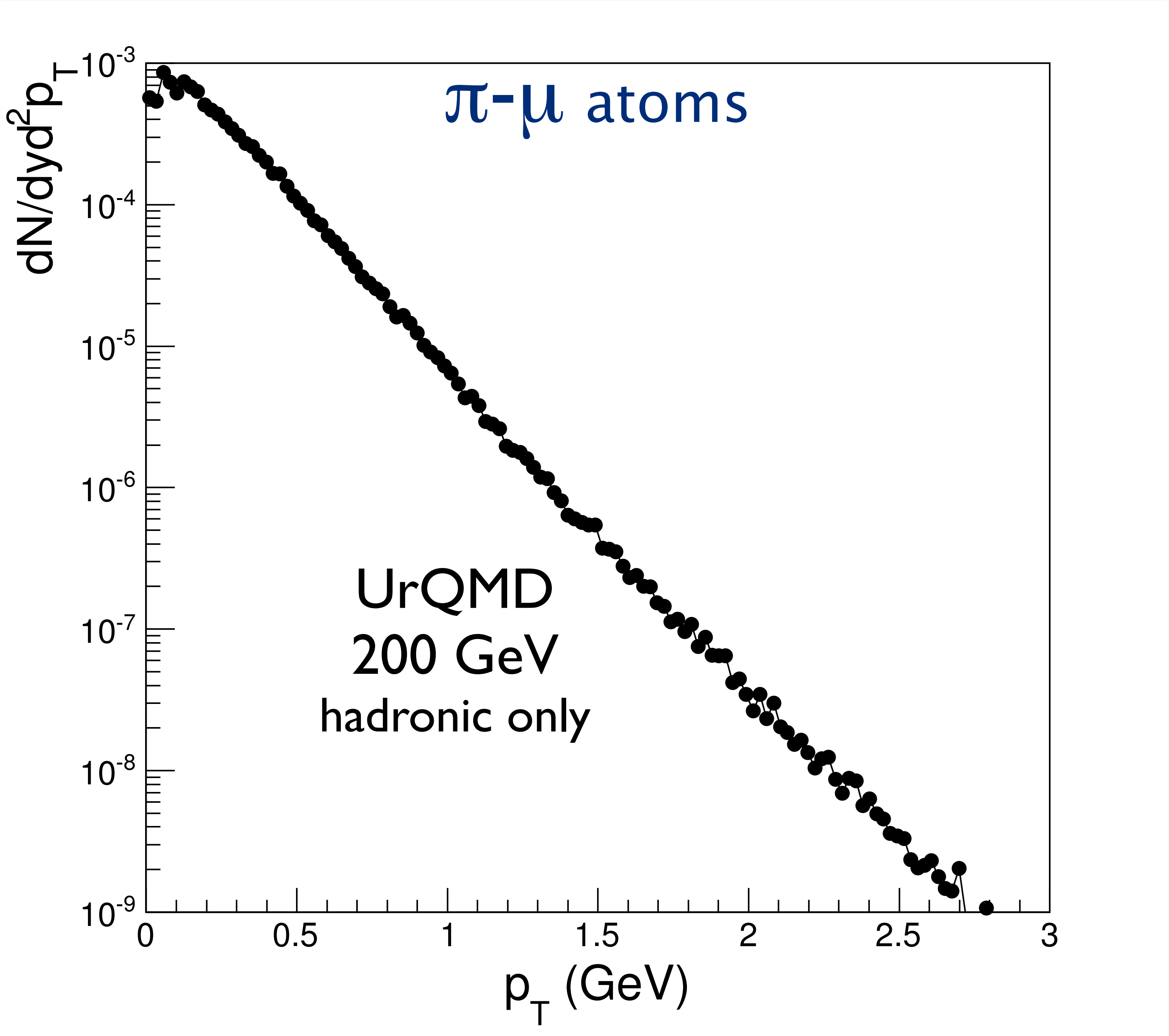
~200 π-μ atoms $p_{T,\mu} > 1.5$ GeV

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

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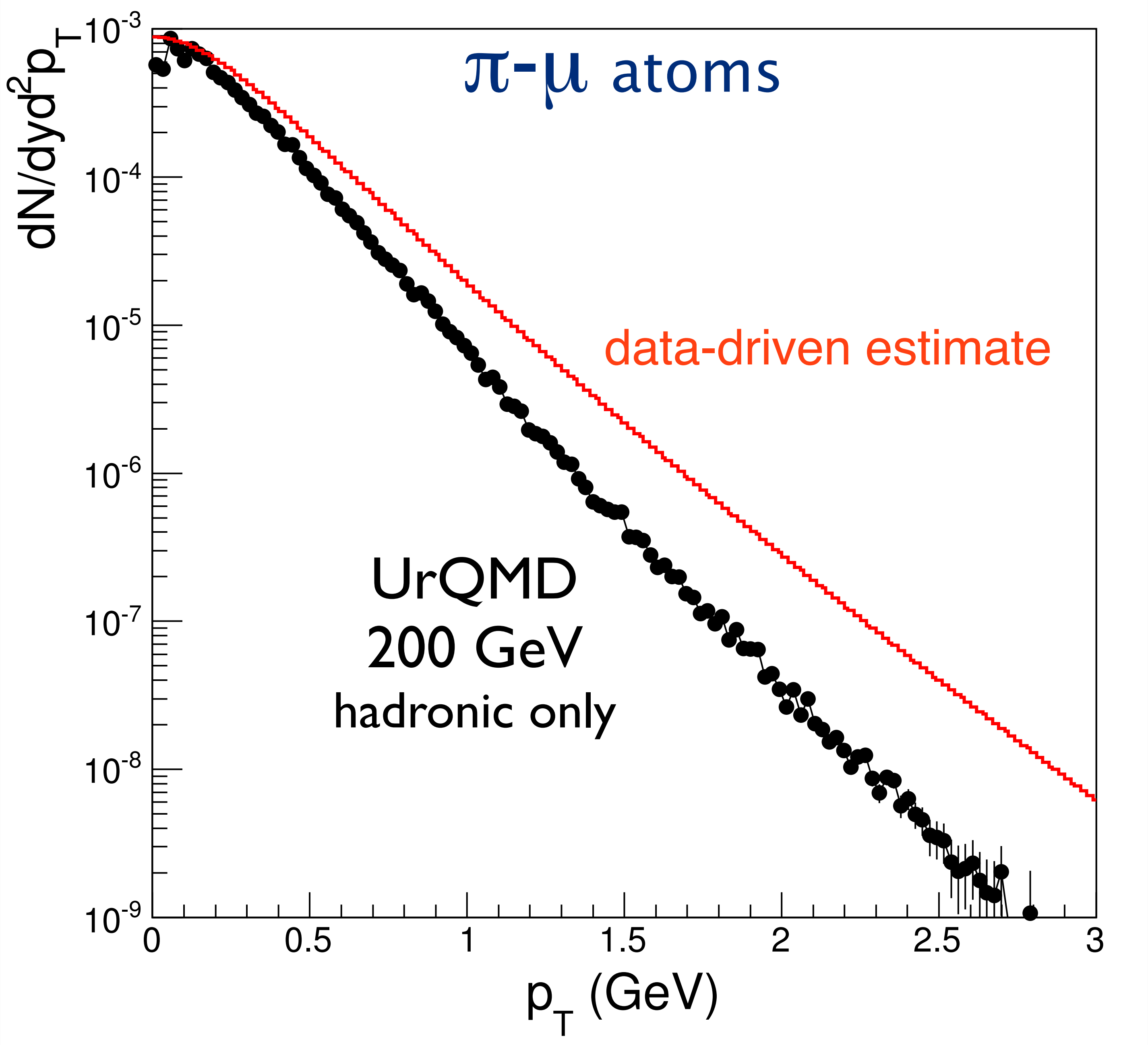
Early estimates are in the same ball-park as other estimates (work in progress)



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.

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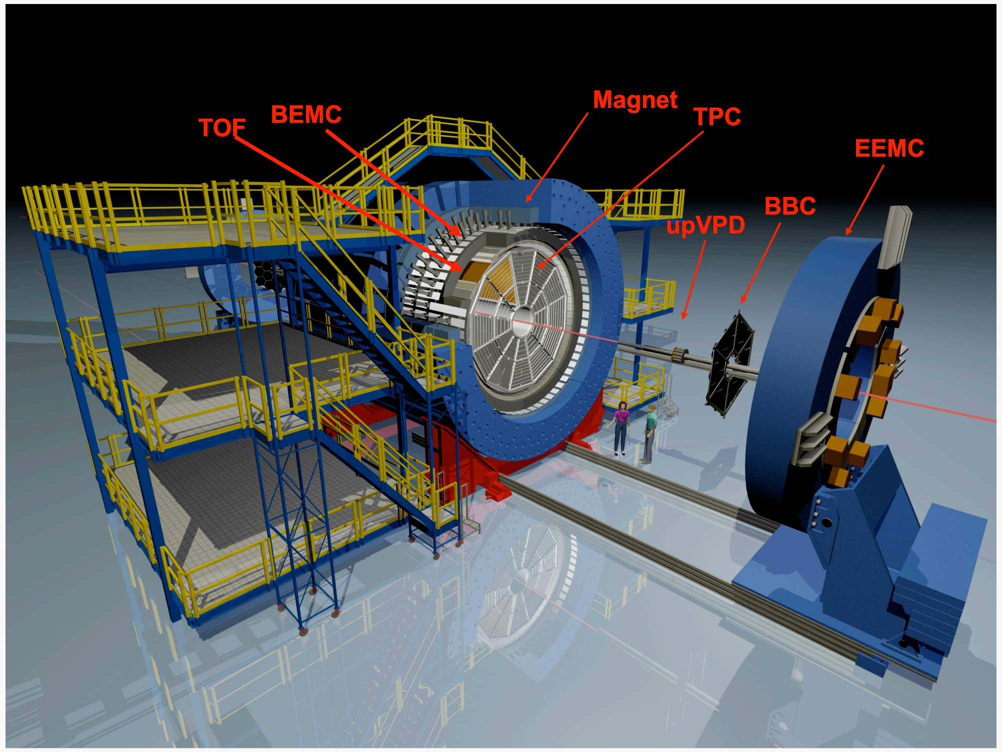

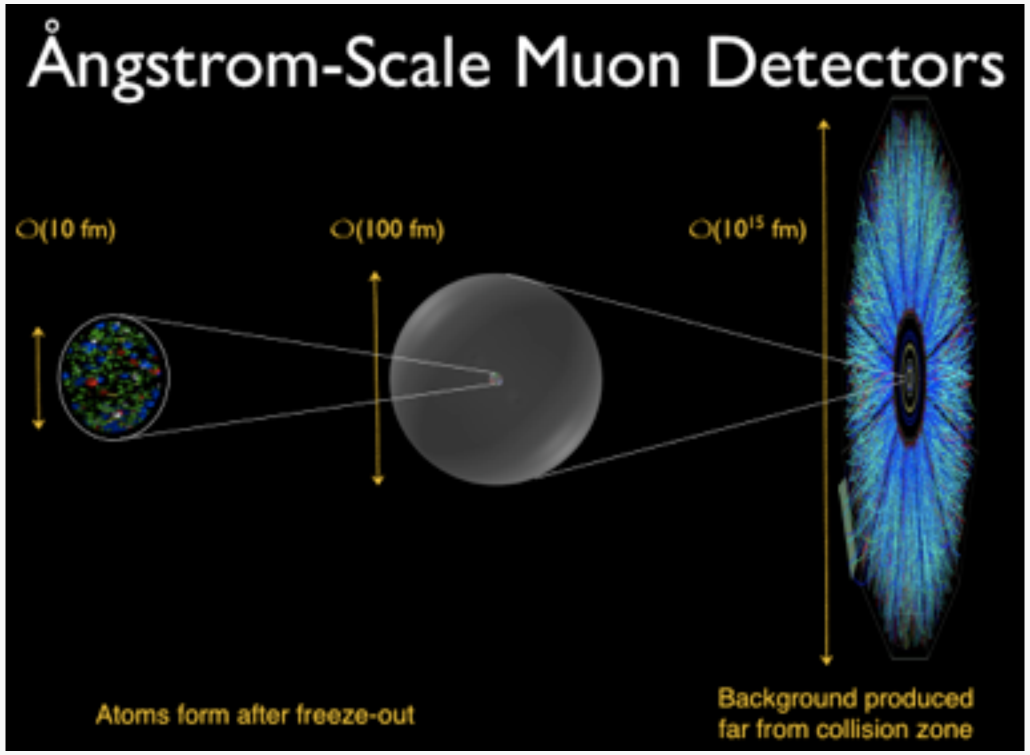

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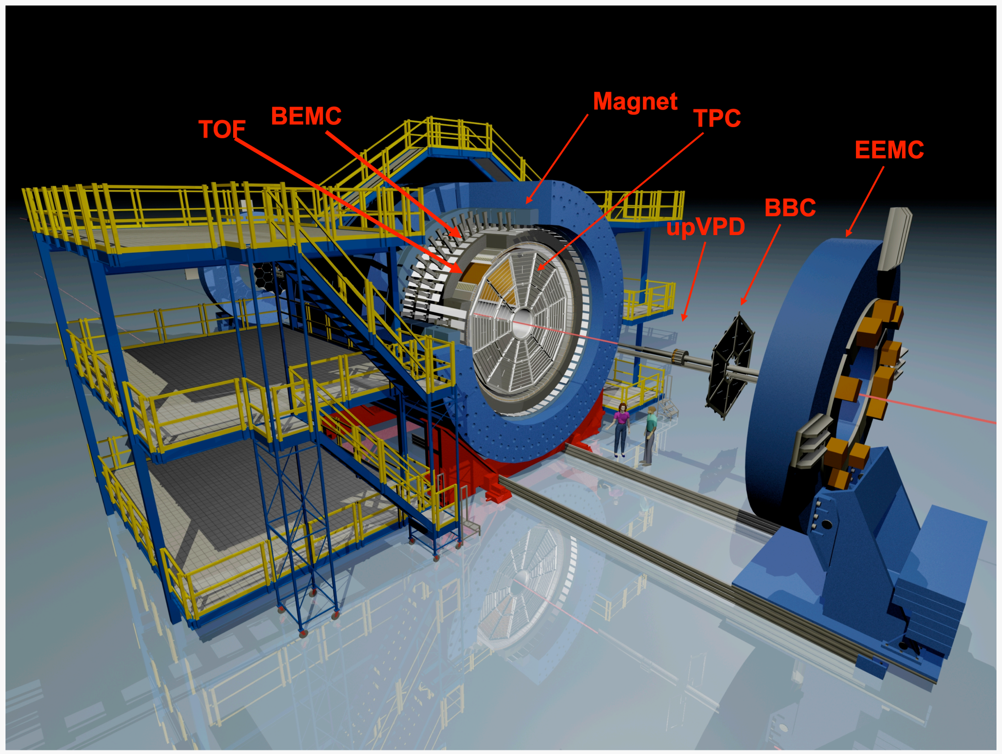

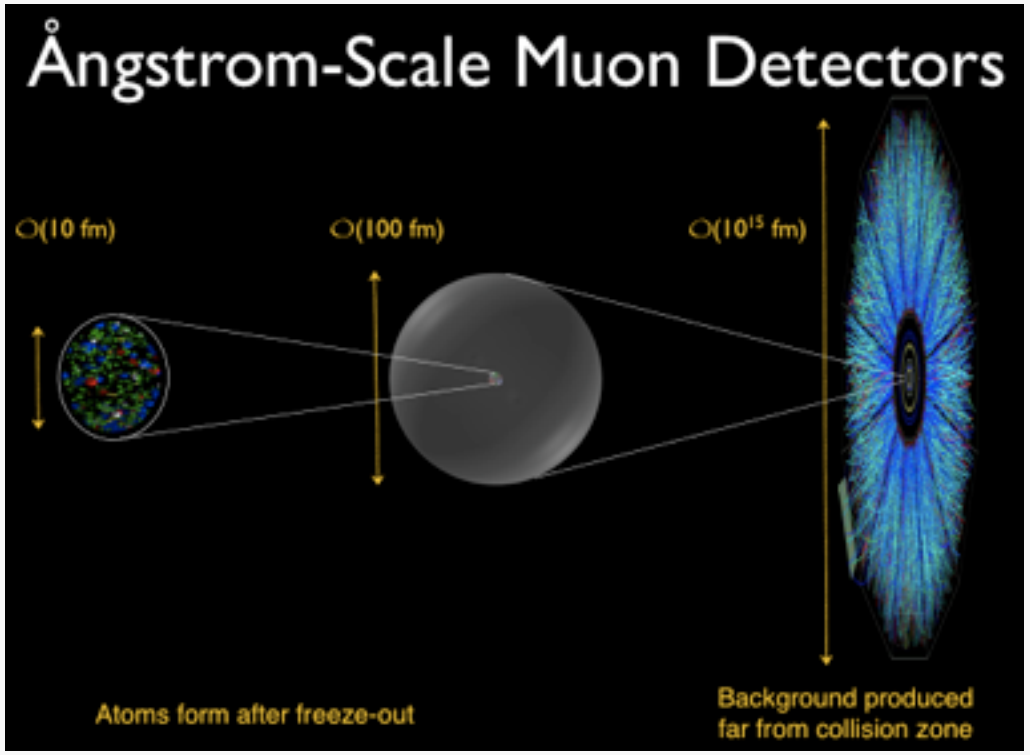

- STAR and PHENIX believe they can be measured a unique tool for probing QGP properties
  - provides information on the direct lepton spectrum
  - possible discovery of new particle: anti-matter muonic hydrogen!
- What about at the LHC?! increased rapidity range, high multiplicity
- More complete calculations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

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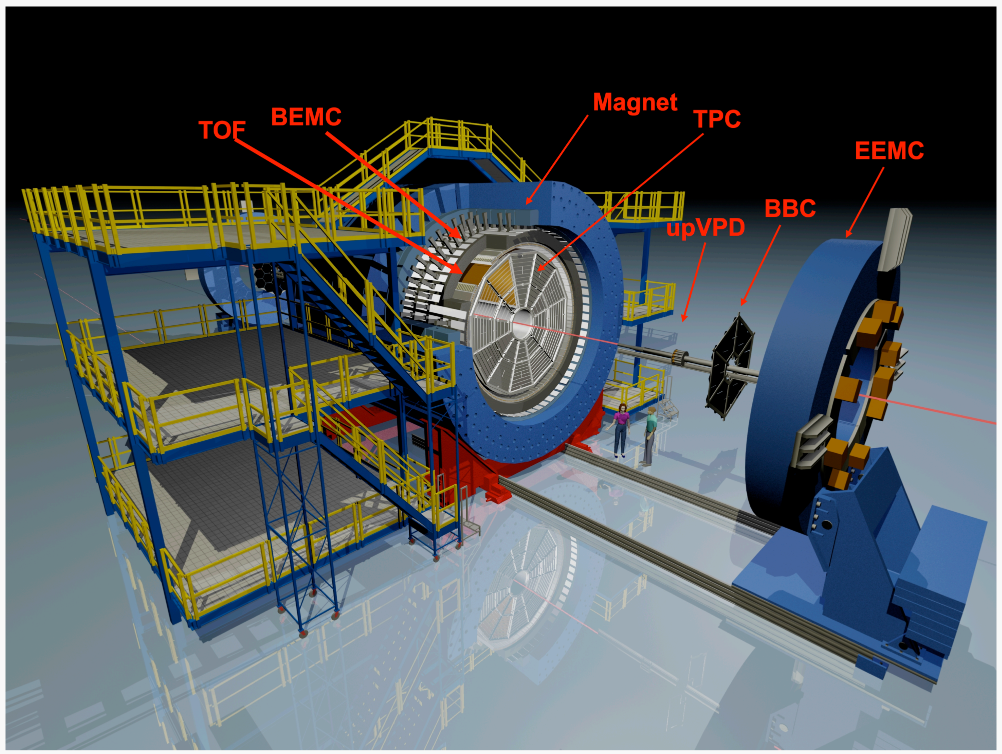

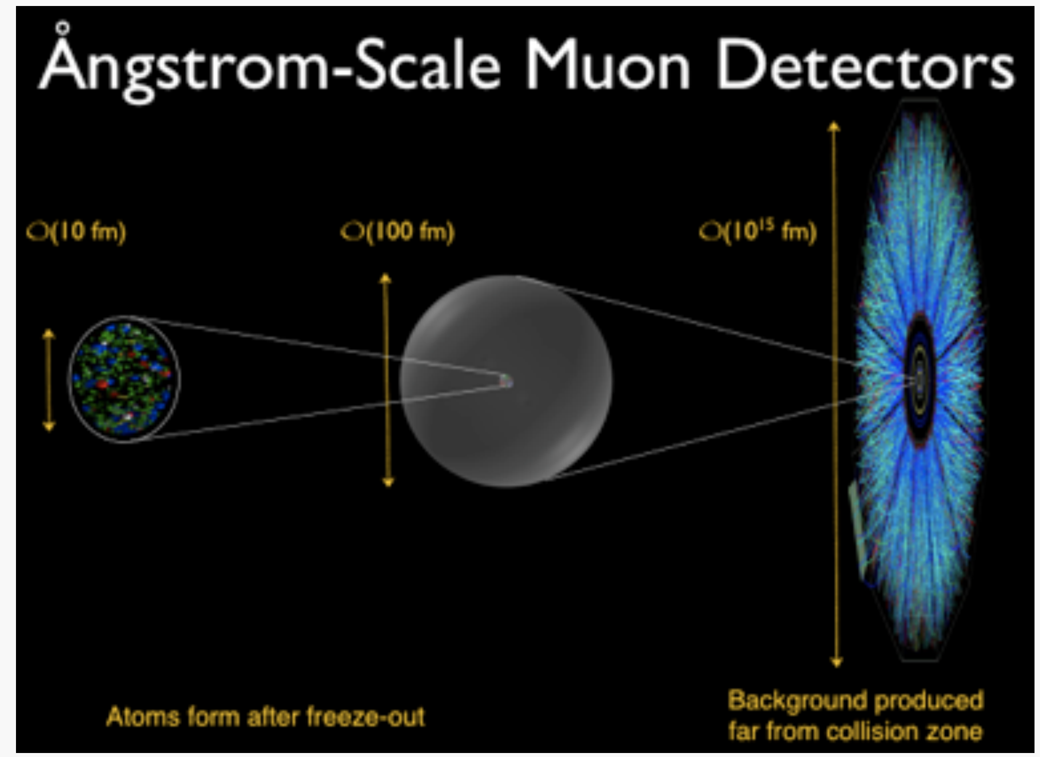

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Thanks to Zhangbu Xu, Zebo Tang, Paul Sorensen,
Marcus Bleicher, Stephan Endres, Mauricio Martinez

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Kodama-san!

the coolest gentleman - an inspiration to me

Kodama-san!

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Happy Birthday, Kodama-san!

The End