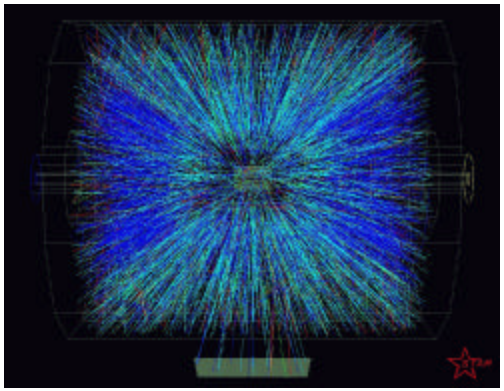


Search for New QCD Phenomena at the STAR* Experiment at RHIC

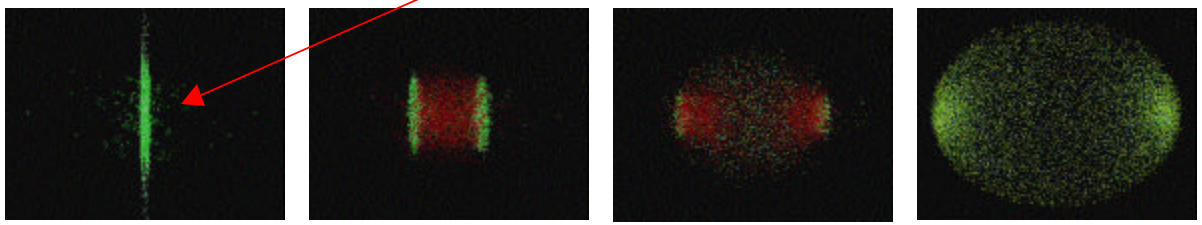
***(Solenoidal Tracker at RHIC)**

Jens Sören Lange (Frankfurt/RIKEN-BNL)
on behalf of the STAR Collaboration

4th Tropical Workshop on Particle Physics and Cosmology
Cairns, Australia, June 9, 2003

1 Au+Au Collision

QM ($\Delta x \Delta p < h$) formally induces $v > c$



t=0 1-1.5 4 10 fm/c

p freeze-out @ t~8-10 fm/c

partonic hadronic

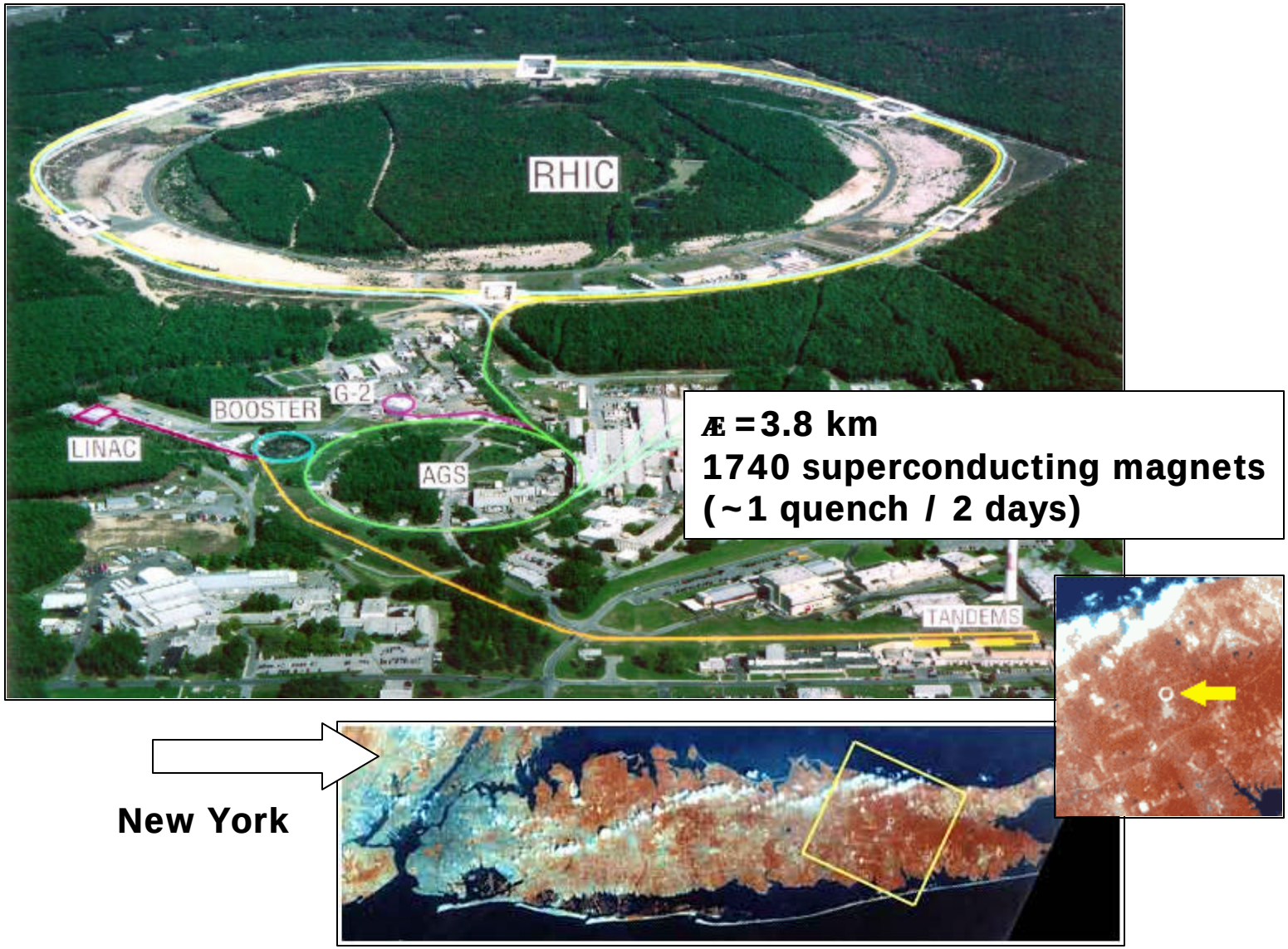
0. nuclei Lorentz contracted in lab. frame
1. hard parton scattering (qq,gg)
2. hot cylinder
3. soft partons from energy at (0,0,0)
   beam remnants peaked forward/backward
4. freezeout: all partons $\rightarrow$ particles

Au+Au	3-dim, cylinder, infinite in z (if boost-invariant)
Universe	4-dim, infinite 3-dim all directions (!)

What we want to know ?

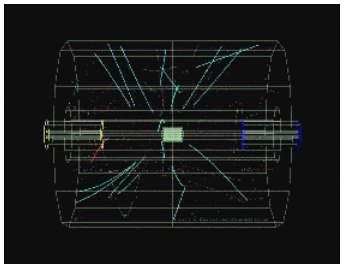
- Is there order in this mess ?
  (rules of particle production)
- Temperature ?
- Size ?
- Density ?
- How can we produce Anti-He ?
- The little and the big bang -
  are the rules the same ?

Au+Au 2000: $\sqrt{s_{NN}}$=130 GeV 2001: $\sqrt{s_{NN}}$=200 GeV

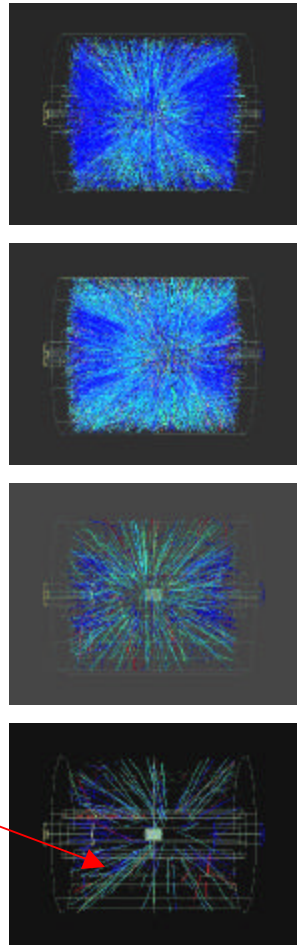


Data set.

- Au+Au 130 GeV 0.7 Mio
- Au+Au 200 GeV 3.2 Mio
- Au+Au 19.6 GeV ~20k
- d+Au 200 GeV 35 Mio.
- pp
  - un-polarized
  - vertical pol. 391/nb
  - longitudinal pol. 373/nb
    (spin flip snake)
- Level-3 trigger, rare probes
- EMC jet trigger



pile-up !

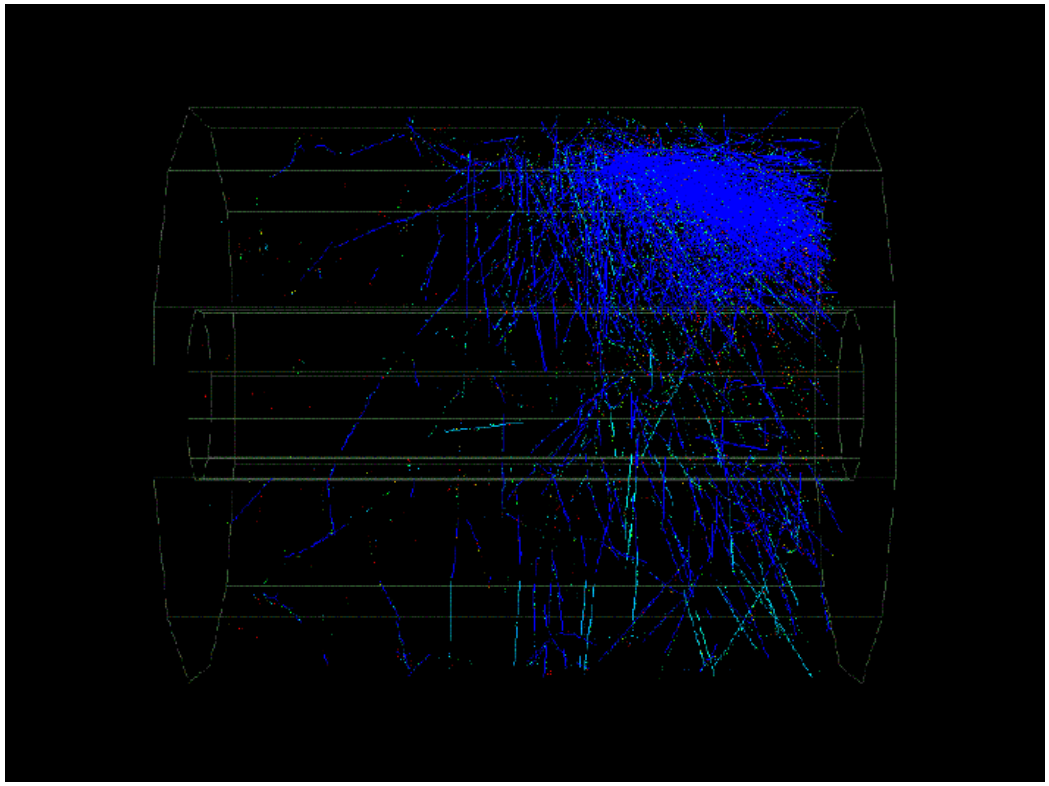


jet

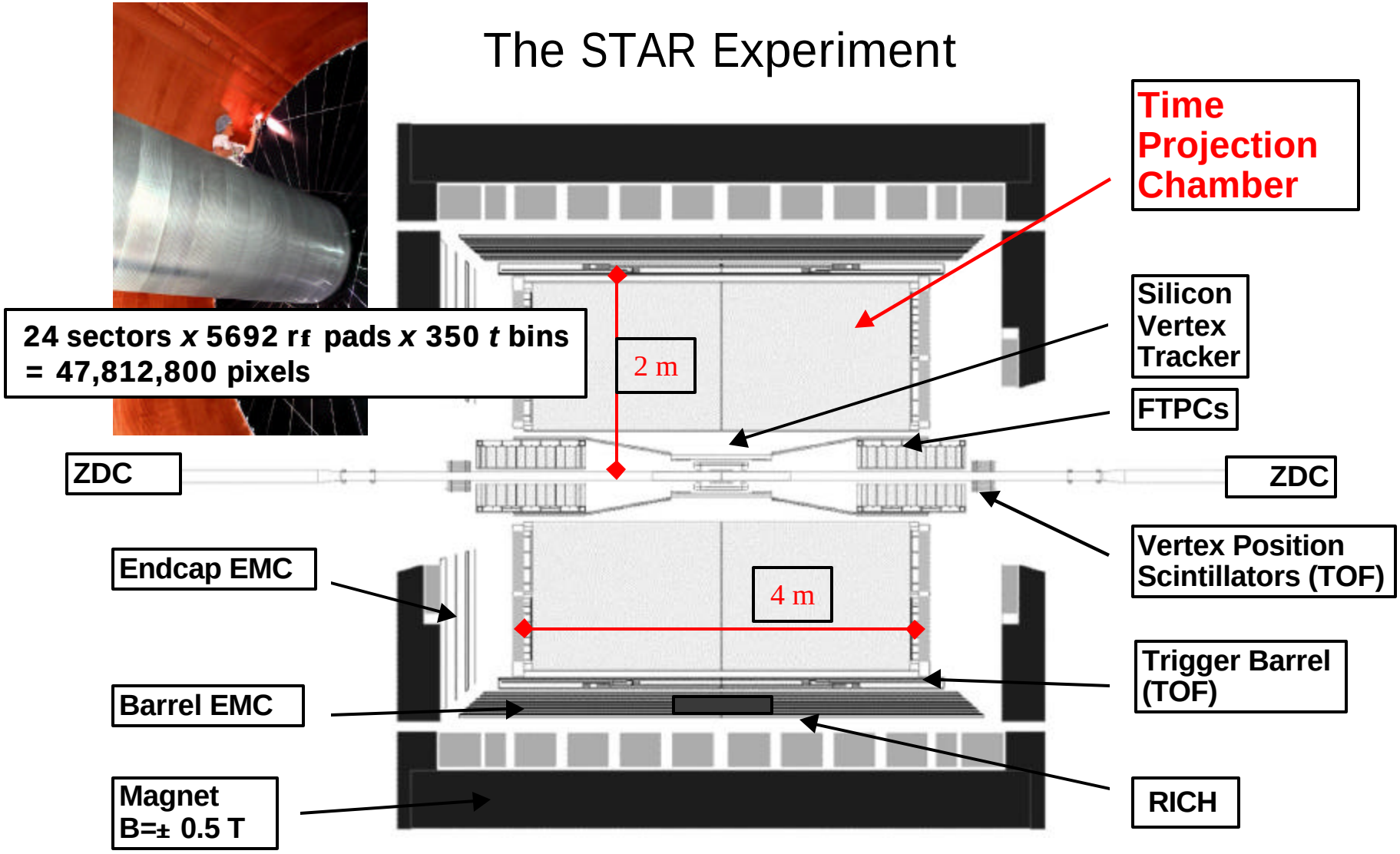
asym !

Are RHIC collisions dangerous ?

Not likely,
since the dawn of mankind we always had cosmic HI collisions.

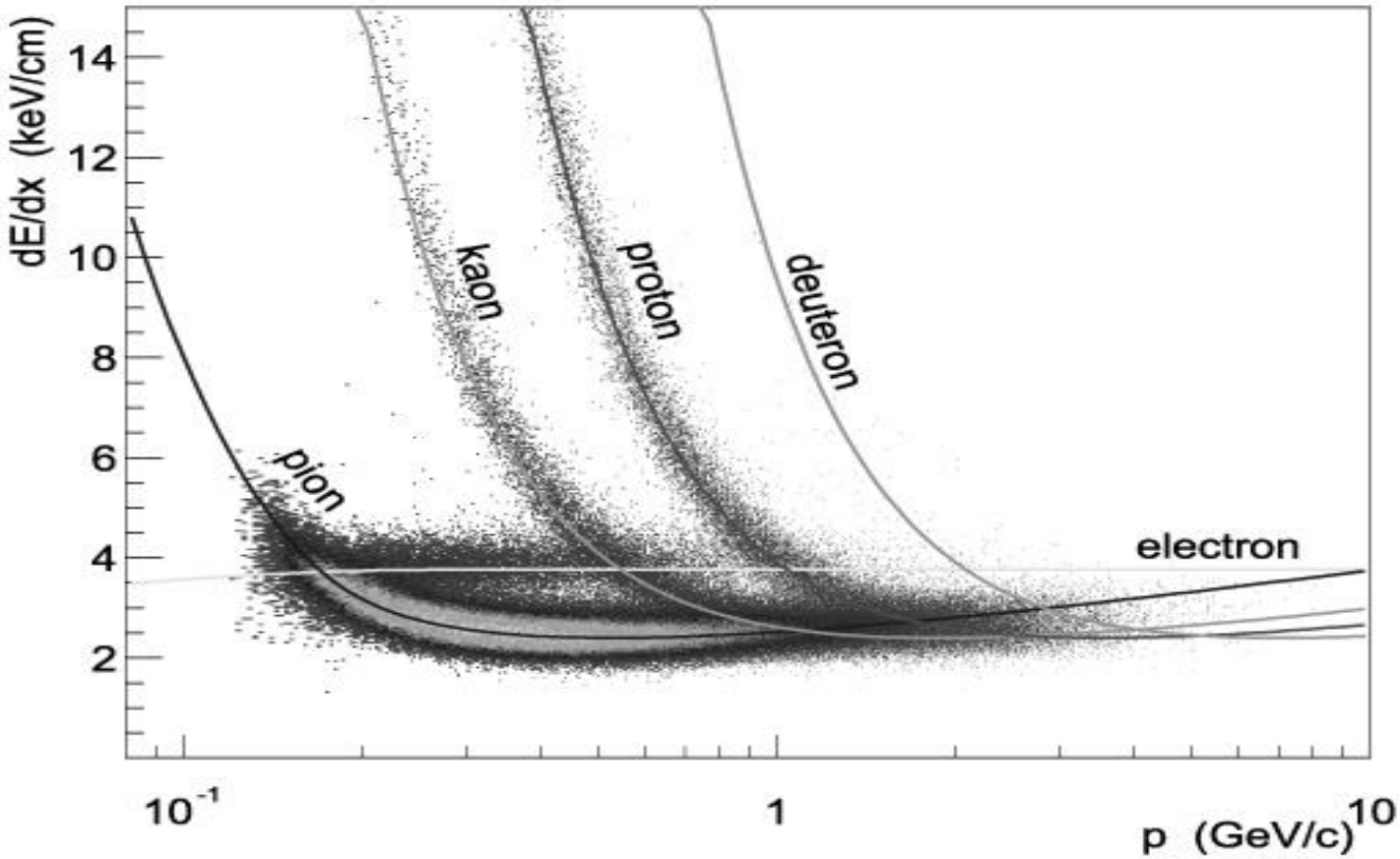


The STAR Experiment



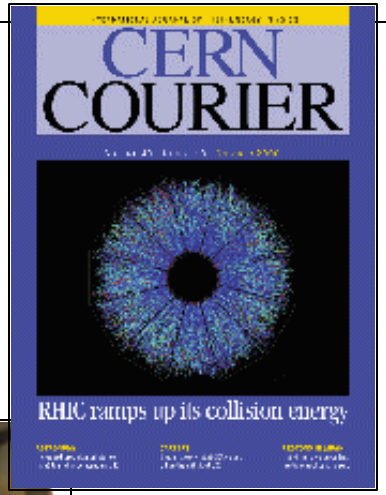
TPC dE/dx

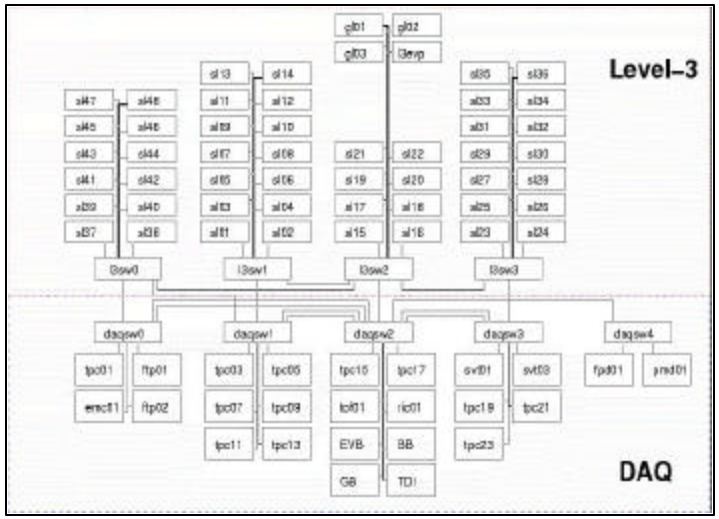
- dE/dx resolution ~11% (offline ~8%)



Level-3 Trigger System

- realtime full event reconstruction (dE/dx, invariant mass)
- $t \leq 60$ ms
  per 1 central Au+Au
  N_{Track}=4,500
  $N_{Cluster}$=130,000
- trigger rare events:
  c,b quarks
  (J/ψ, Upsilon)
  Anti-^{3}He/^{4}He





The QGP.

- deconfined (in QCD sense -> no bag anymore)
- 02/2000 CERN announced “QGP evidence”
  - strangeness enhancement (s-quark condensation in high T)
  - J/ψ suppression (gluon break-up)
- QCD phase transition

  1st order:

  mixed phase

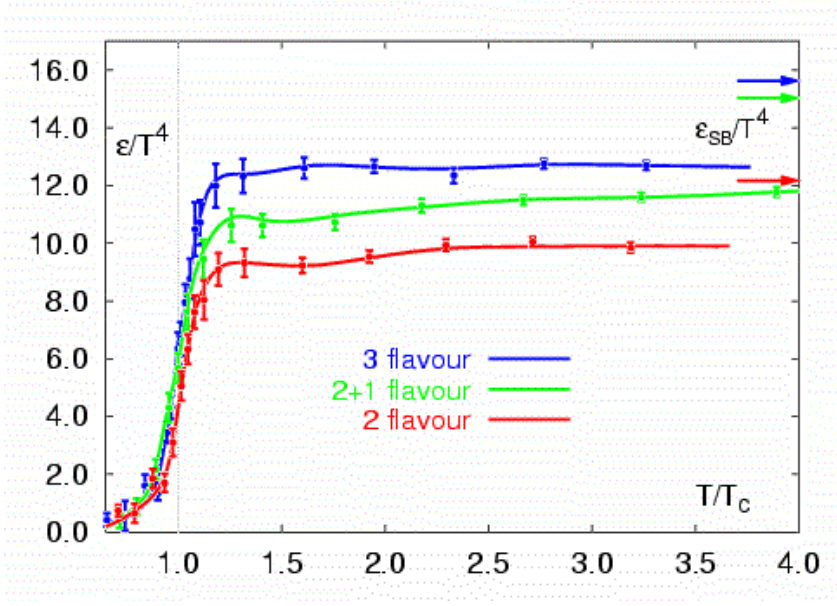
  hadrons with QGP bubbles

  2nd order:

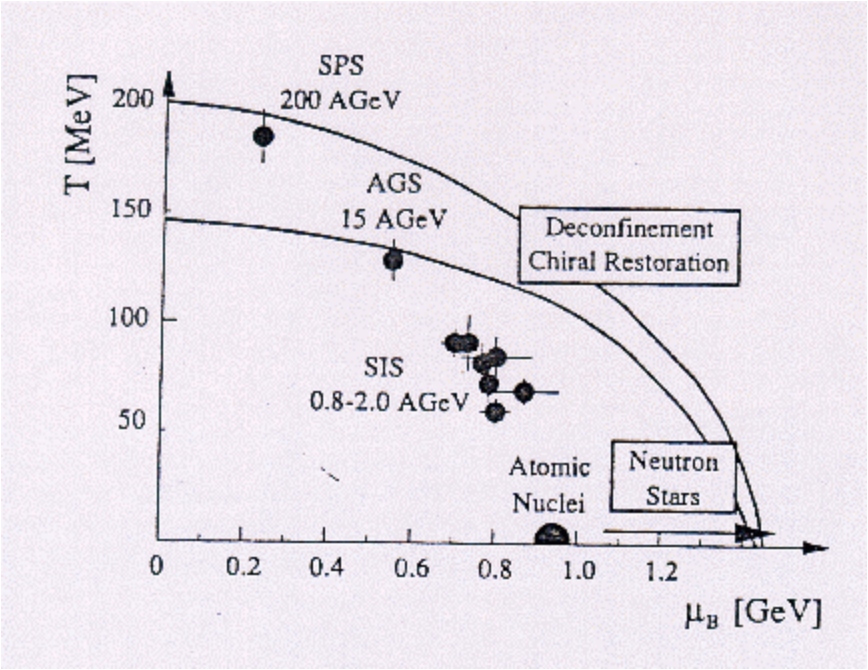
  from pure100% phase #1

  to pure 100% phase #2
- predicted by lattice QCD

  $T_c = 160 \pm 3.5$ MeV



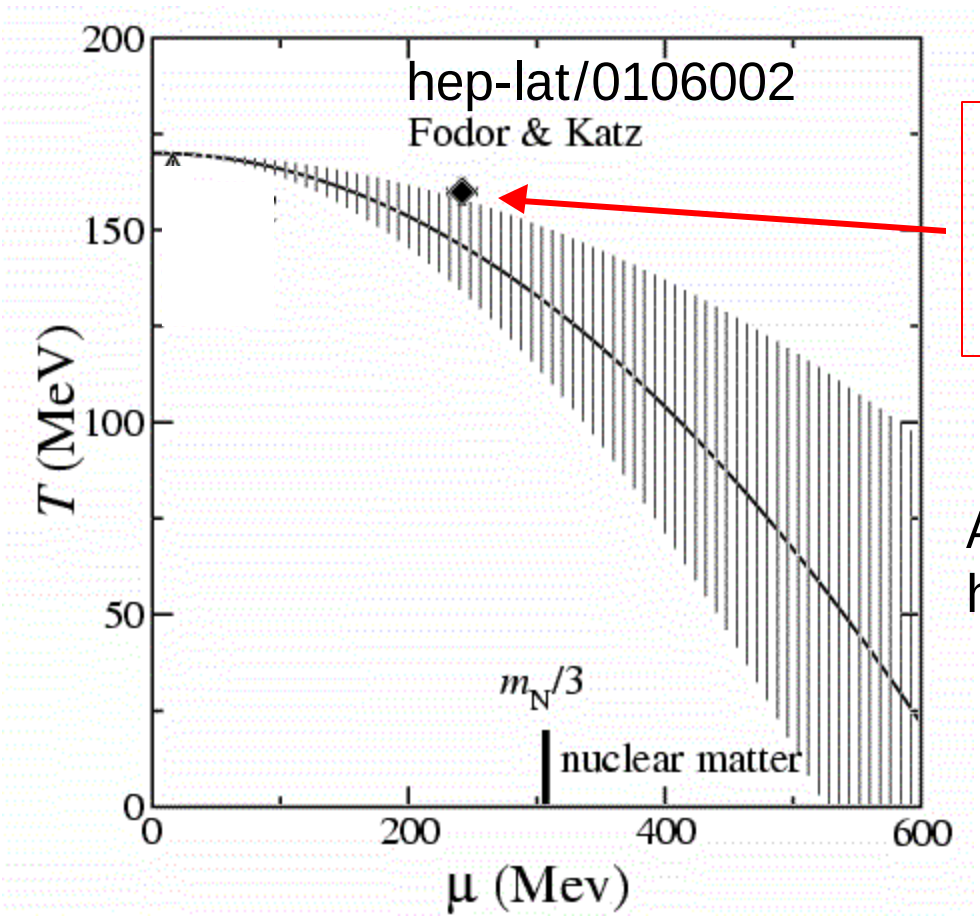
Phase Diagram before RHIC ?



$\mu_B \sim N_{Baryon} - N_{Anti\text{-}Baryon}$

$\mu_B \sim N_{sea}/N_{valence}$

Where is the critical point ?

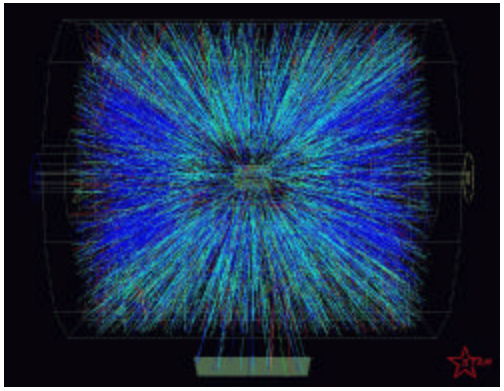


T_c=160±3.5 MeV
μ_b=725±35 MeV
ε=0.3-1.3 GeV/fm^3

Allton et al.
hep-lat/0204010

What did we learn from the number of particles ?

- ... 2-3 min after the 1st collision
- perturbative QCD expectation
  $N_{charged}(\sqrt{s}=200\ GeV)$
  = **<u>1.14</u>** x $N_{charged}(\sqrt{s}=130\ GeV)$
  fits well -> no QGP needed for interpretation



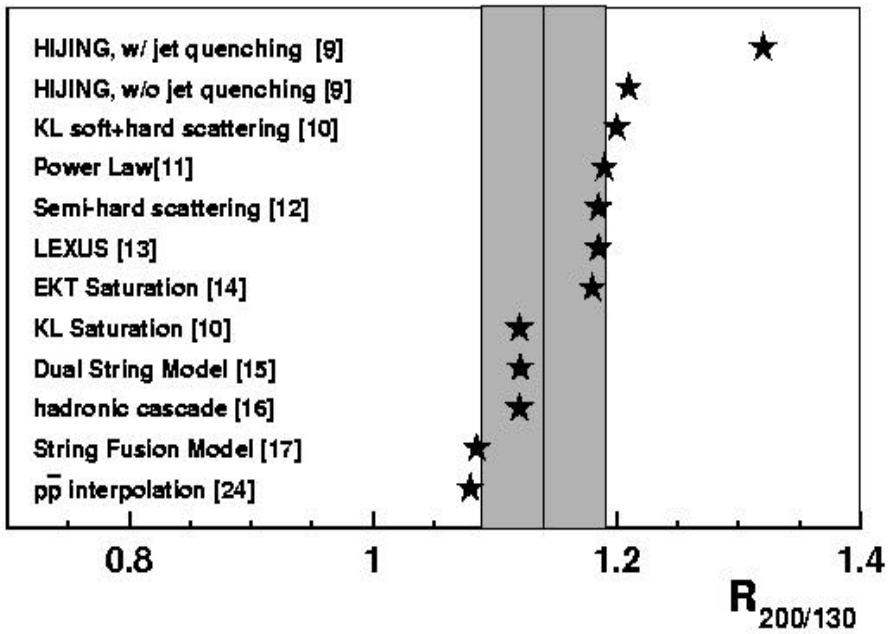
- but pQCD models need either/or
  - "high density QCD"
    α_S^{eff} changes
  - "high temperature QCD"
    α_S^{eff} changes ~ $1/(33-2N_f)\ln(T/T_{crit})$

  both cases: gluons acquire "mass" (on-shell)

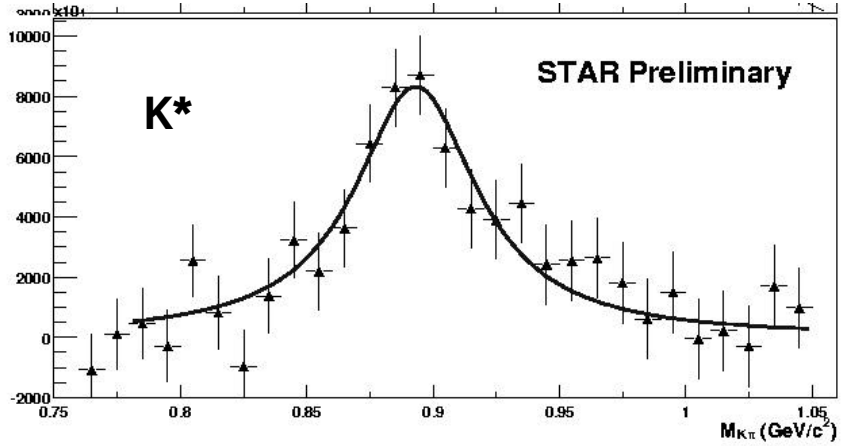
$$\frac{3\pi^2\alpha_S A}{2Q^2_{Saturation}} \times \frac{x \cdot G(x, Q^2(x))}{\pi R_A^2} = 1$$

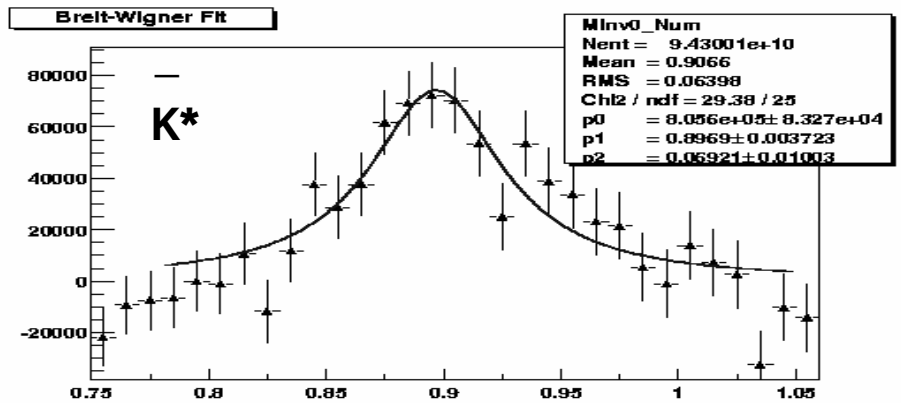
- no dramatic $N_{charged}$ event-by-event fluctuations
  → we are not near the critical point

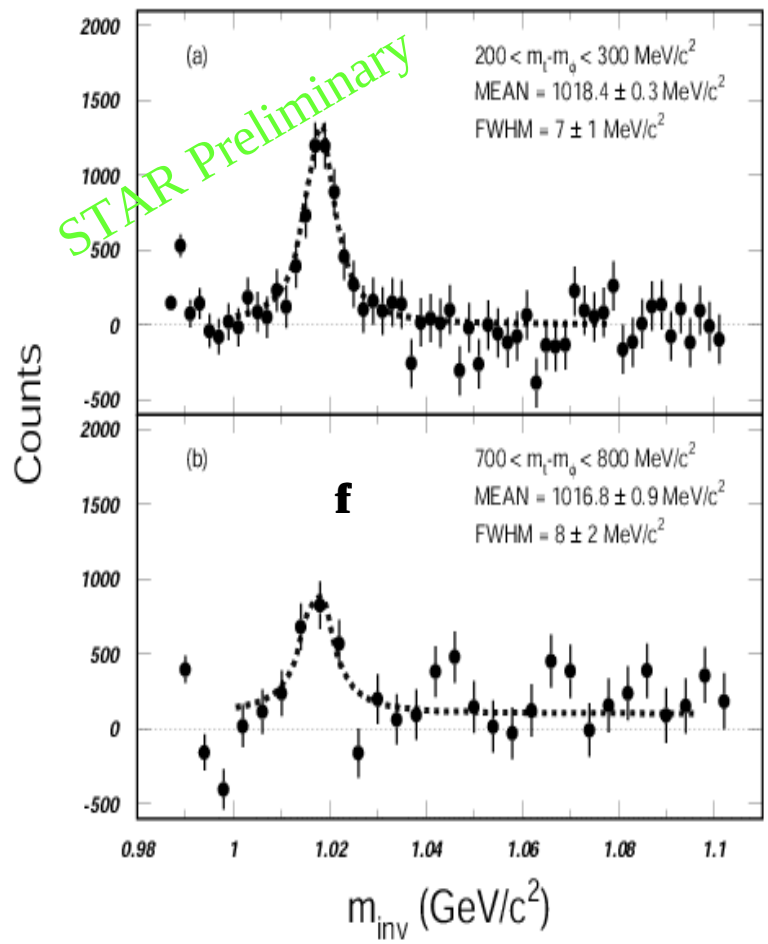
Which models fit, and which not ?



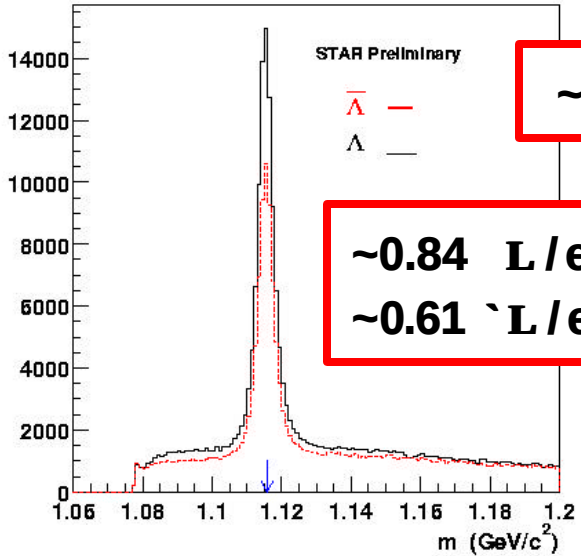
Data Quality 1: Mesons (qq)





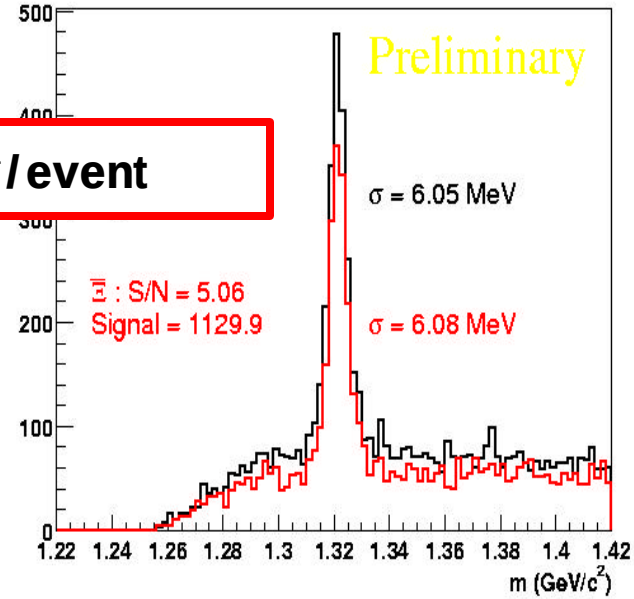


Data Quality 2: Baryons (qqq)

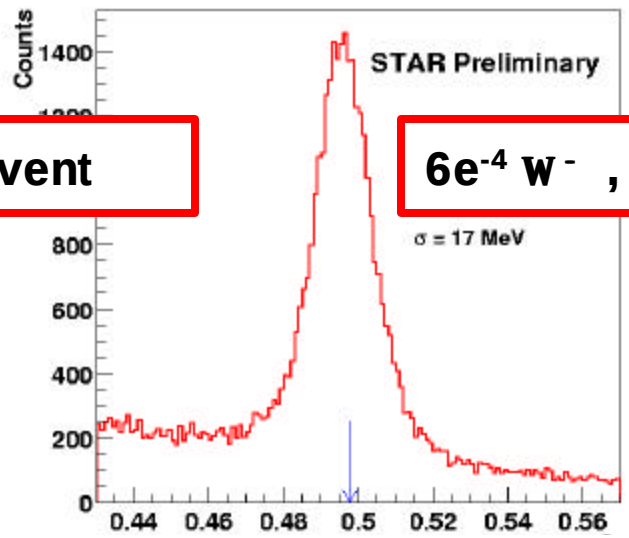


~0.84 L / event
~0.61 `L / event

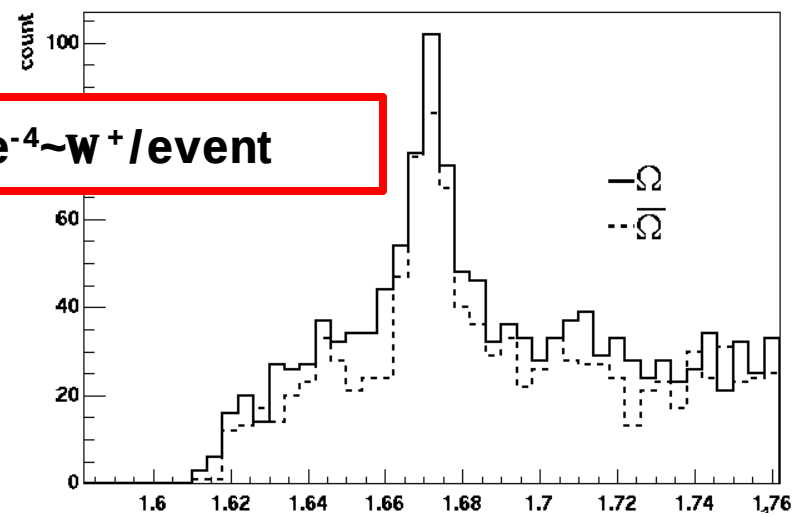
~0.006 X$^-$, ~0.005 X$^+$ / event



~1.6 K^0_s / event



6e^{-4} W$^-$, 6e^{-4}~W$^+$ / event



Thermodynamics

- T from exponential fits to m_T

$$\frac{1}{m_T}\frac{dN}{dm_T} \propto A\exp\left(-\frac{m_T}{T}\right)$$

$$m_T = \sqrt{p_T^2 + m^2}$$

- μ_B from

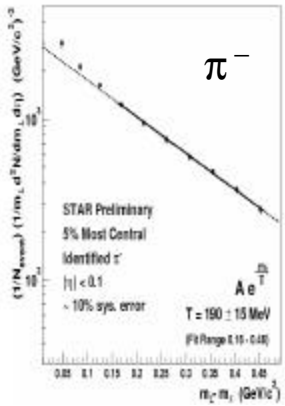
$\bar{p}$ / p ratio = 0.65±0.03(stat) ±0.03(syst) = λ_q^{-6}

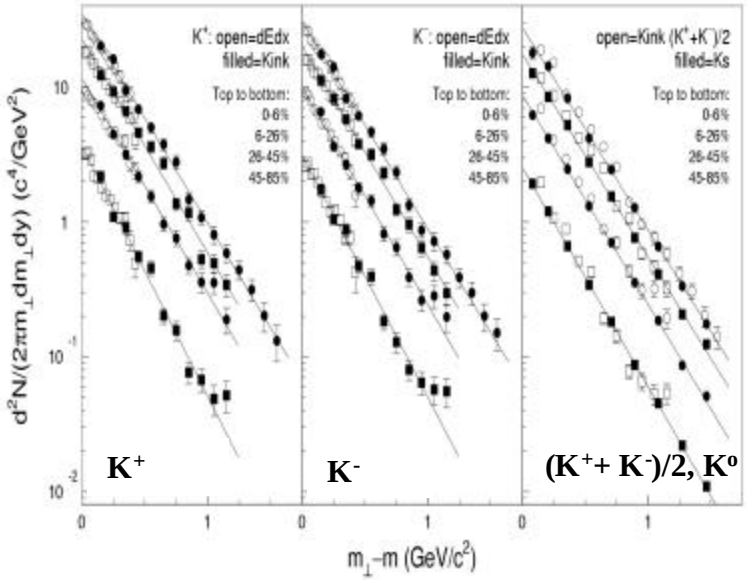
λ_q = 1.074

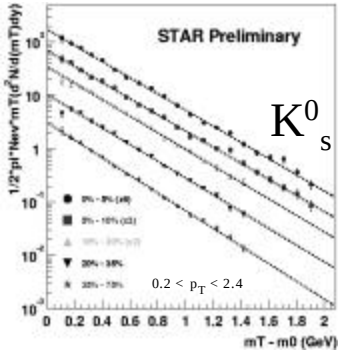
$\lambda_q = \exp(\mu_q/T)$

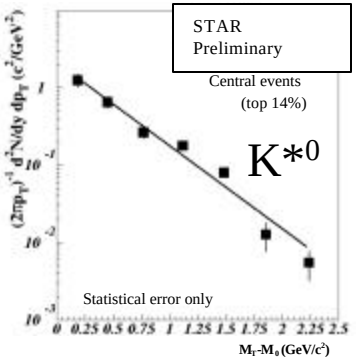
$\mu_b = \mu_u + 2\mu_d = 40.1$ MeV

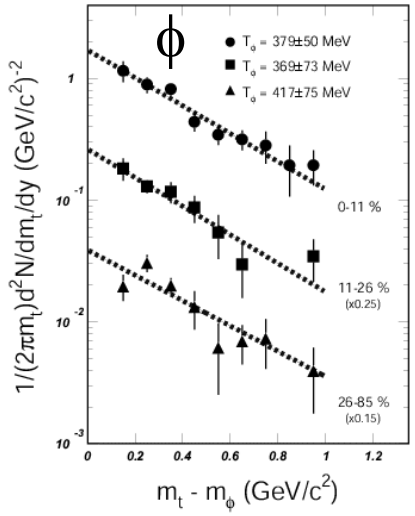
m_T Distributions

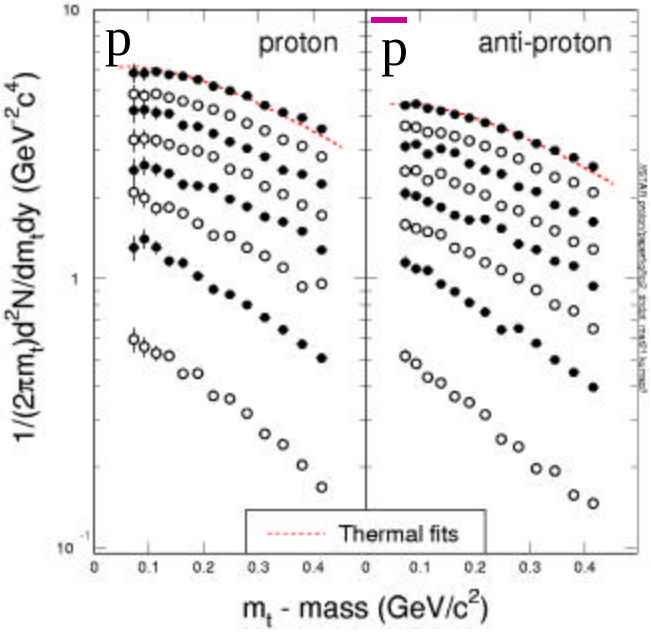


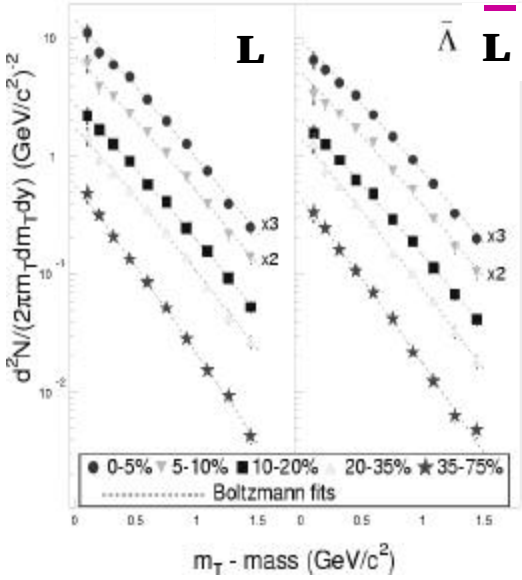


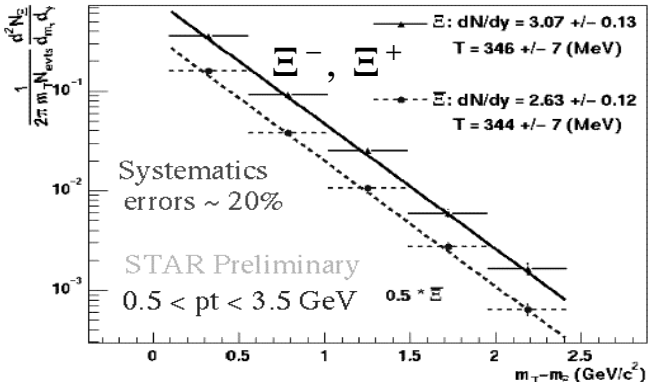










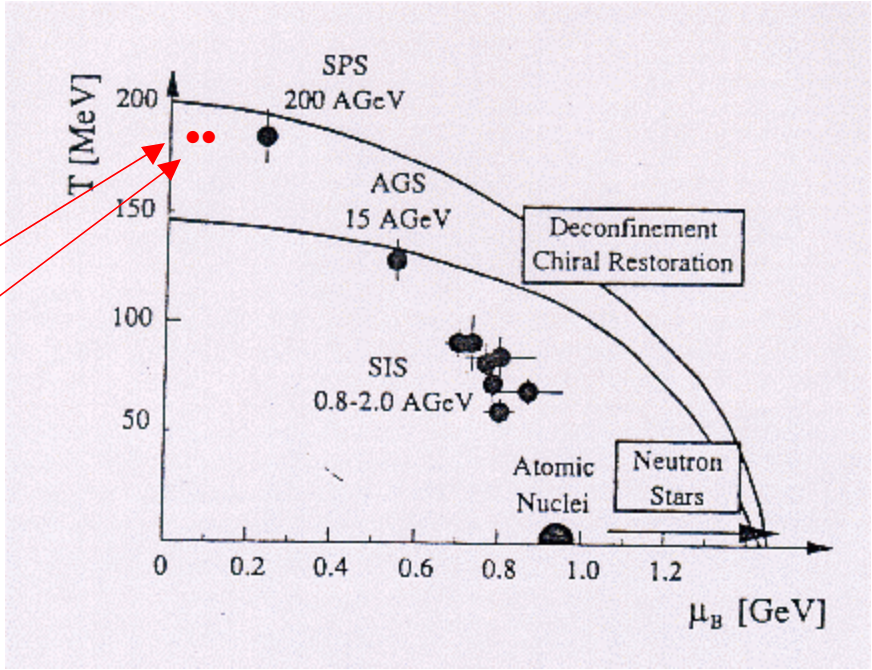


Thermal fit Result:
T=176 MeV (130 GeV), T=177 MeV (200 GeV)

μ_B=41 MeV (130 GeV)
μ_B=29 MeV (200 GeV)

T=2.1·10^{12} K

200 GeV
130 GeV



Sun
15.6·10^6 K

Supernova
~10^9 K

Plasma fusion
55·10^6 K

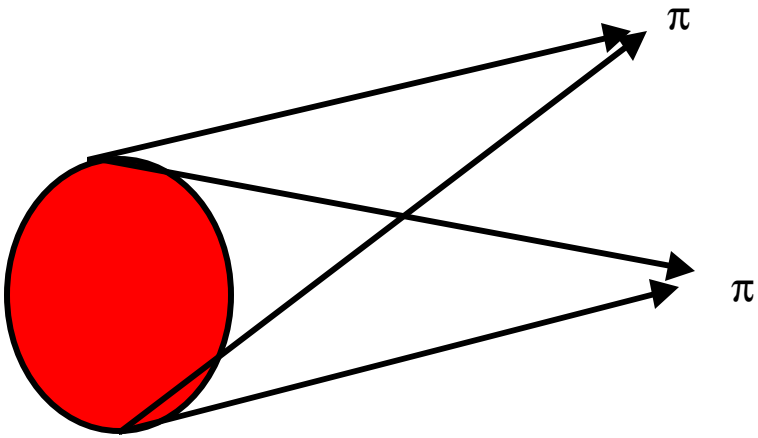
Laser fusion
4·10^6 K

Universe:
T_{Planck}=1.4·10^{34} K
but maybe Hagedorn-limited ~1/R

$\mu_B \sim N_{Baryon}-N_{Anti\text{-}Baryon}$
$\mu_B \sim N_{sea}/N_{valence}$

What is the size ?

- Hanbury-Brown-Twiss (HBT) Interferometry
  $\pi\pi$ pairs (bosons) close in Δp

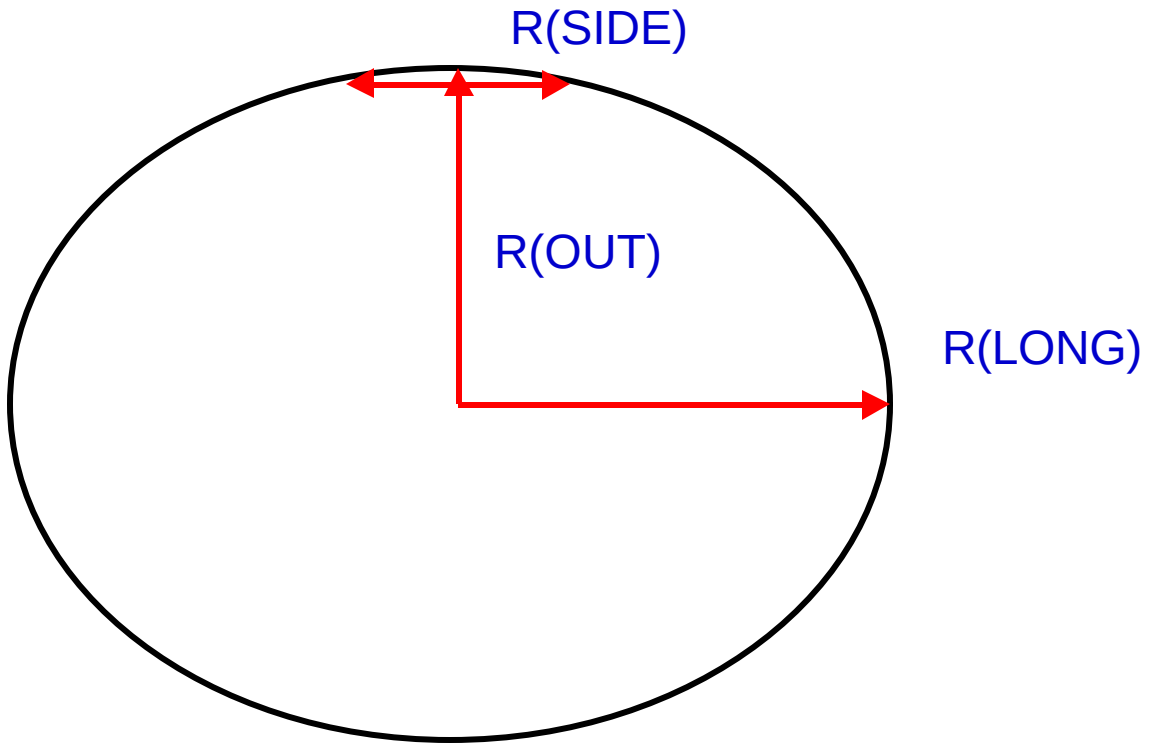


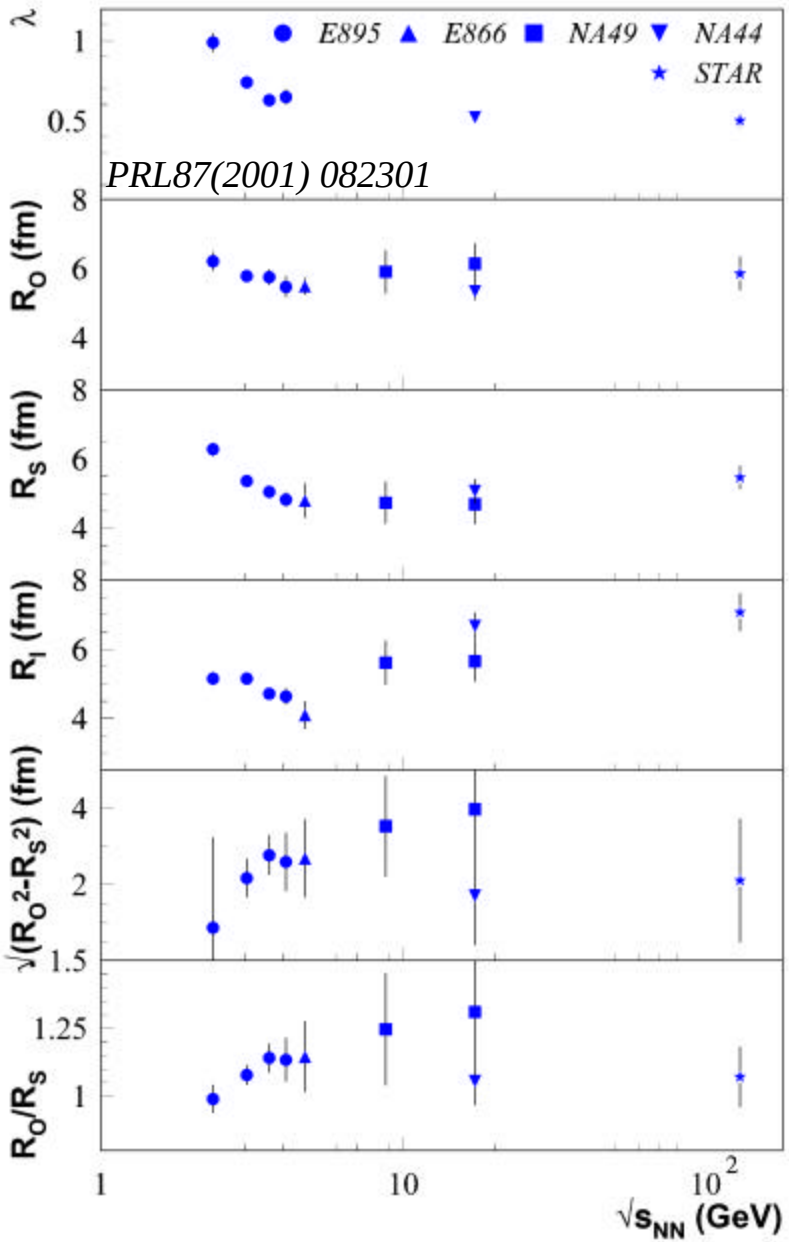
  - Universe: R(galaxy)
    difference in arrival time

  - AA collisions:
    difference in momentum Δp
    Fourier Transform $\Delta p \rightarrow \Delta x$
    Correlation Function
    $C(\Delta p)=1+\lambda \times \text{FourierTransform}[\rho(\Delta p)]=1+\lambda \exp(-\Delta p^2 \Delta R^2)$
    (λ for resonances)

- remember: expanding system R=R(t) !
- Lorentz-boost: sphere $\rightarrow$ cylinder

Expanding Volume



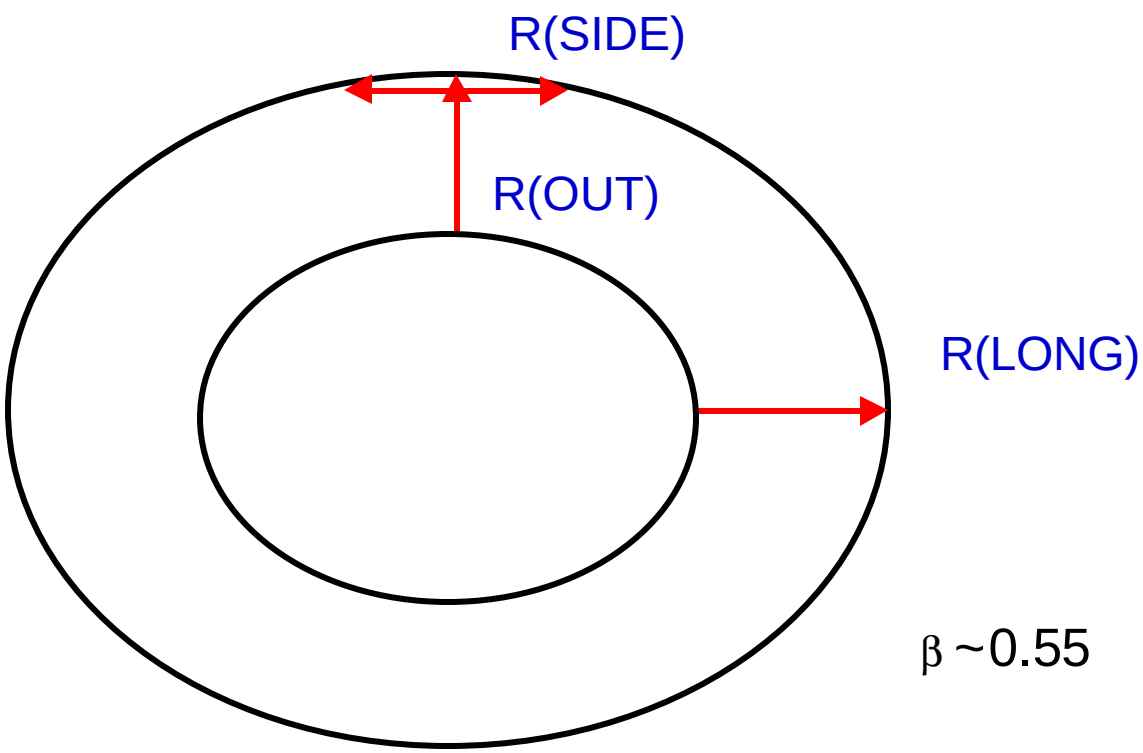


Pion HBT vs. ö s

World compilation + STAR

- Surprising: Size roughly same AGS = SPS = RHIC R<10 fm
- changes with beam energy negligible <0.5 fm
- R increase with centrality (~ overlap region) → O.K.
- Unexpected: R_{out}/R_{side} ~ 1
  - short "freeze-out"
  - explosive source

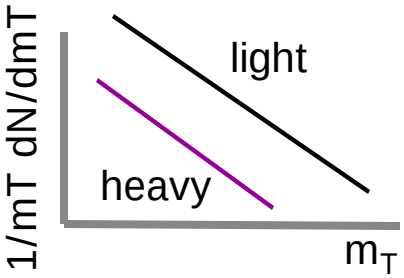
$R_{out}/R_{side} \gg 1$: Expanding Shell ("blast wave")



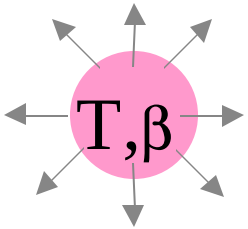
Universe:
at T~100 MeV horizon distance L~10 km !
expansion rate slower ~10^{19} (= $1/M^2_{Planck}$)

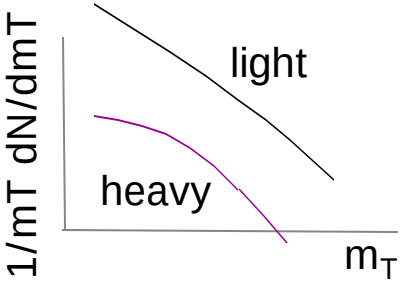
Is it an explosion ?

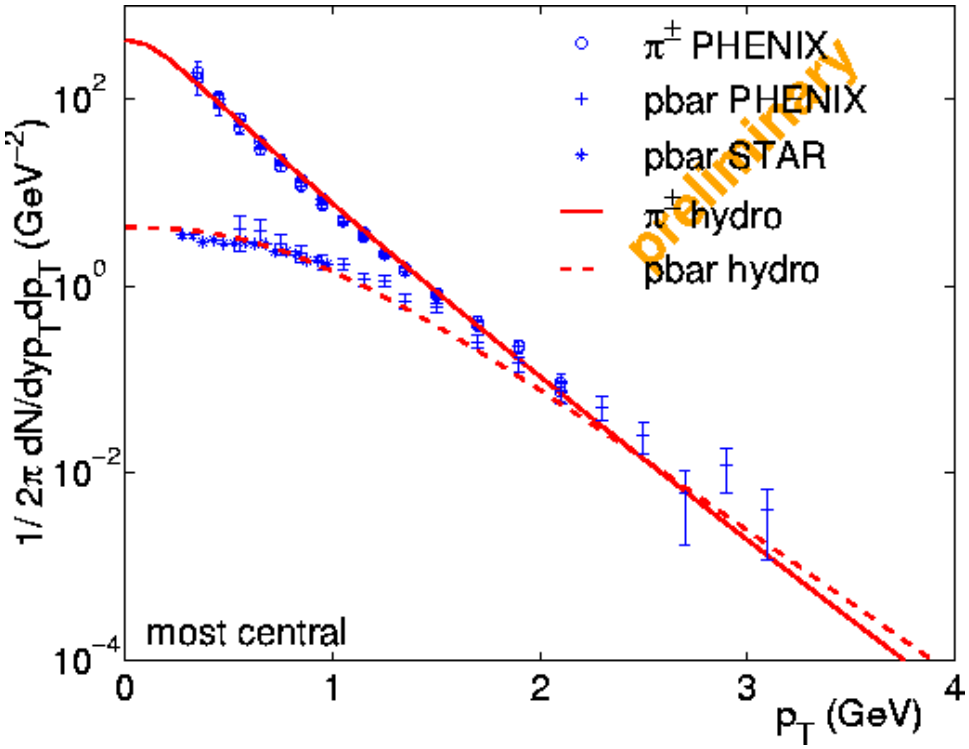
purely thermal source

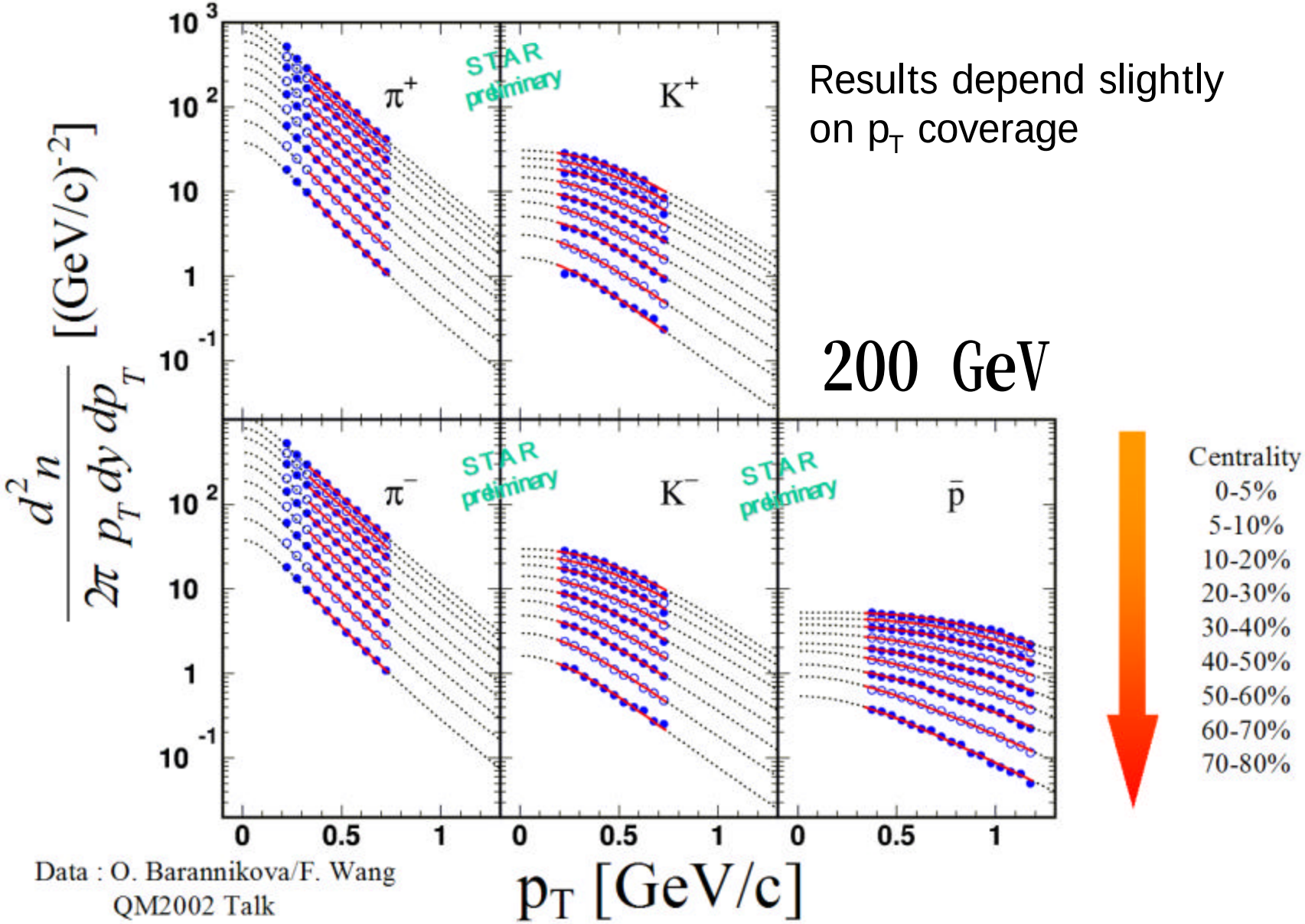


explosive source









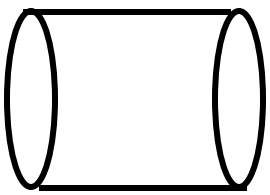
Results depend slightly on p_T coverage

200 GeV

Data : O. Barannikova/F. Wang
QM2002 Talk

What is the quark/gluon density @ t=0 ?

- we got $N_{charged}$



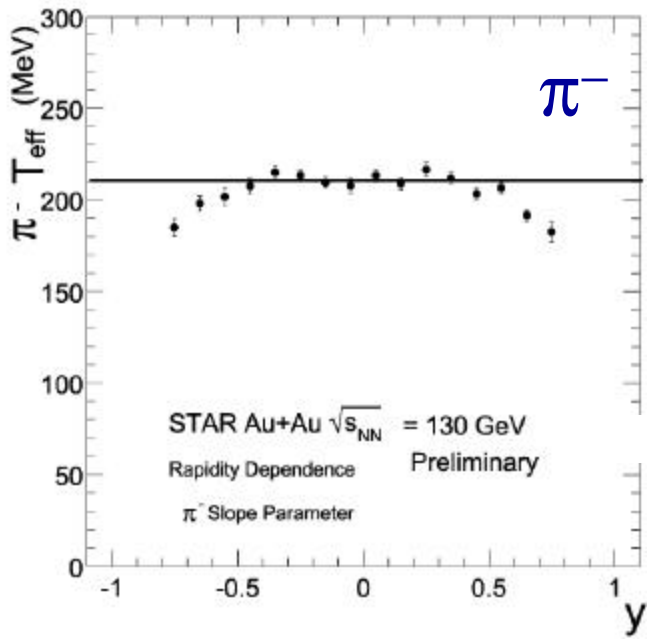
- we got R
  assume cylinder, lorentz-invariant rapidity y
  t=0 ρ=infinite, but @ t=0.2 fm/c:
  → ρ = 20/fm³ = 15 x ρ[cold Au]
  (hadrons definitely in-existent)

$$\rho \approx \frac{dN}{dy}\frac{1}{\pi R^2 t}$$

- What is the energy density ?
  we got average momentum <p>
  90% π, so assume m_π, then $E^2=m^2+p^2$
  → ε ~ 5 GeV/fm³ = 30 x ε[cold Au]

  better pQCD estimate: ε ~18 GeV/fm³ Phys. Lett. B 507(01)121
  SPS ε~3 GeV/fm³, predictions before RHIC start up to 30 GeV/fm³

Boost-Invariance ?



Boost invariance only achieved in small region |y|<0.5

- No surprise for protons:
  p/p~0.65 means 2/3 come from pair production,
  but 1/3 comes from Au nuclei (de-accelerated)
- But surprise for pions !

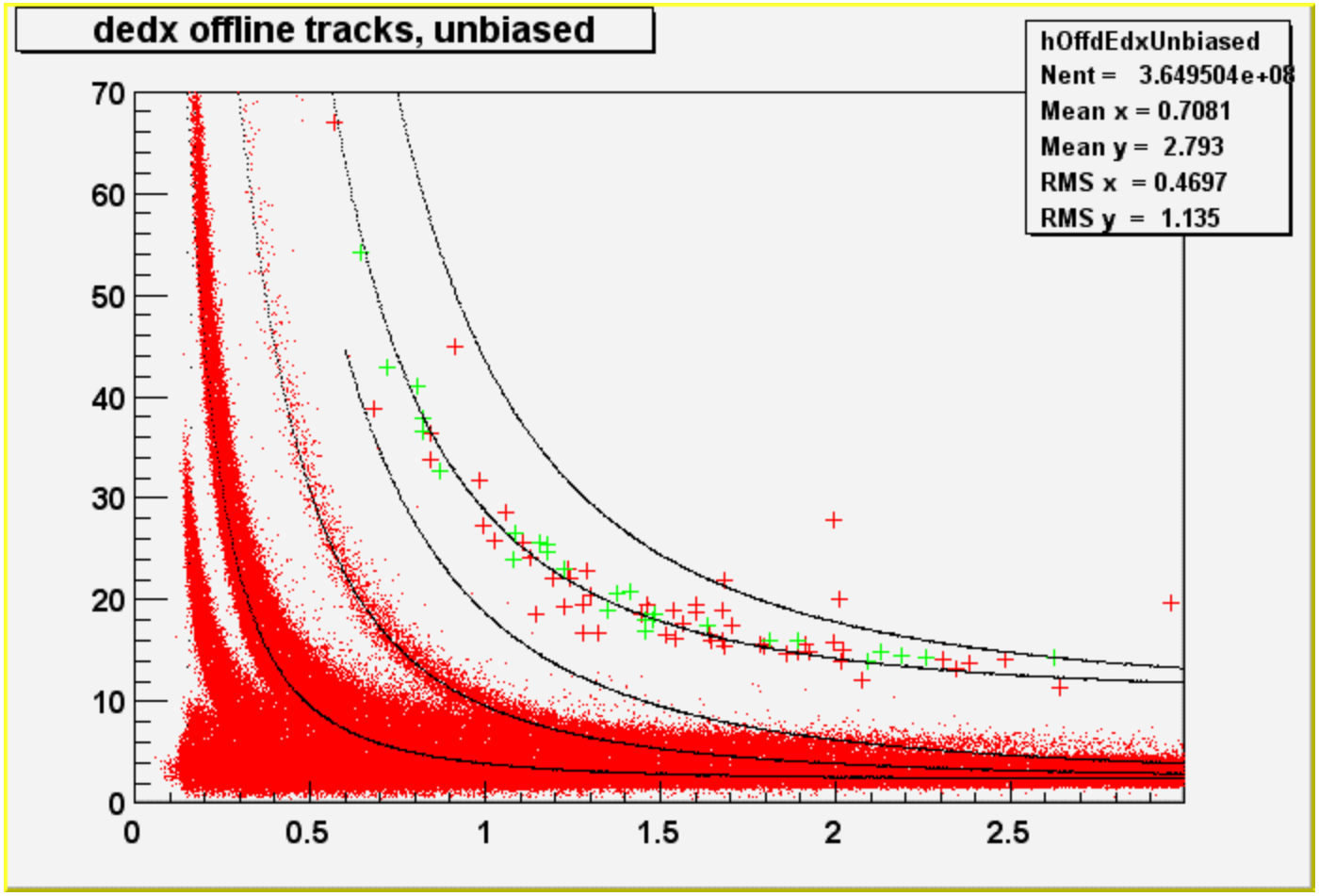
How do we create Anti-He ?

- cluster of particles can also be beam remnants,
  but cluster of anti-particles cannot
- Coalescence:
  N protons + overlapping wave functions
  (Δx and Δp small)
- Ansatz $N_{deuteron} = f \times N_{proton}$
  "penalty factor" f ~ 1/2500
- Level-3 trigger system, ~4 months:
  charge = -2
  (almost background free, but rare)
- total sample 2002

160	Anti-He^3
no	Anti-He^4 yet (would be first observation)

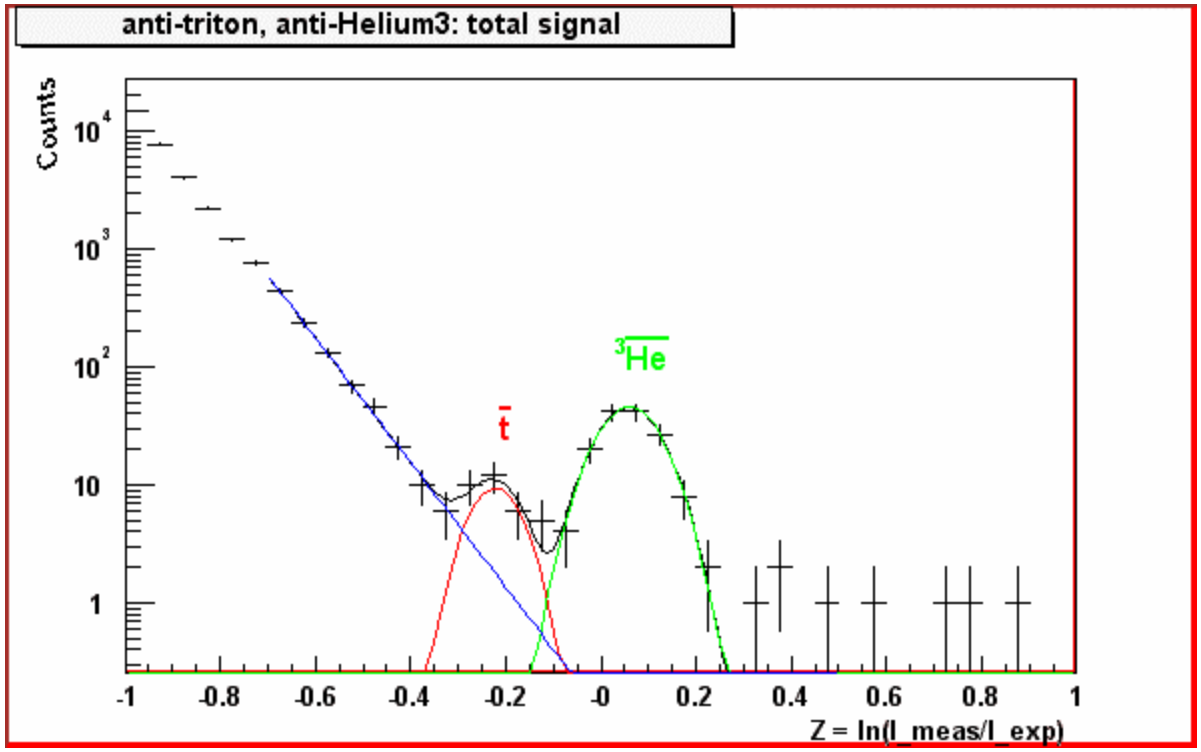
needs $15 \cdot 10^6$ events

Level-3 Q=-2 Trigger

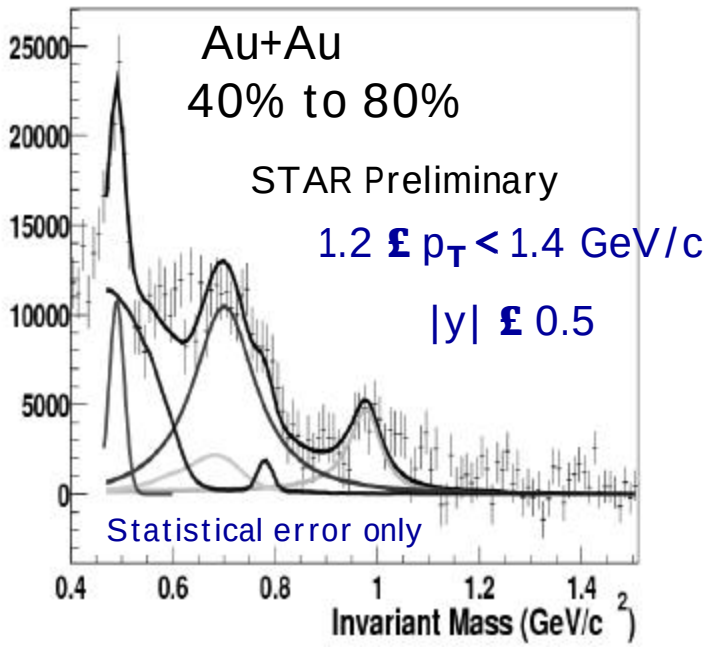


Q=-2 Candidates

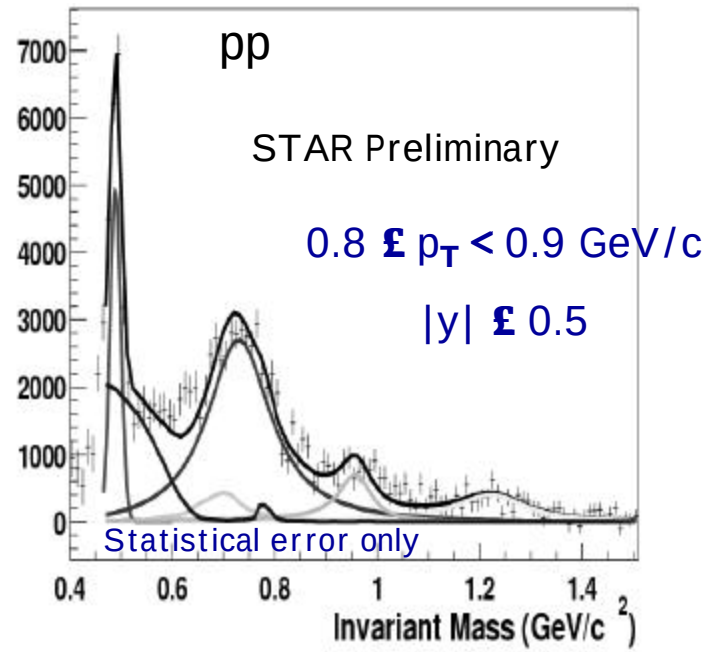
- Result: ψ overlap volume: $R^3=107\pm7$ fm^3 $\rightarrow$ R=4.8 fm
  but proton/neutron freeze-out late $t\sim$15-20 fm/c
  $\rightarrow$ <u>early</u> coalescense (parton vs. baryon coalescense ?)



Next step after T(π) and Radius(ππ) ? ππ resonances.

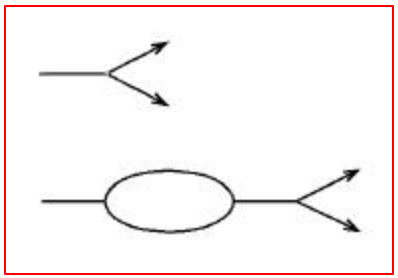


ρ^0
f_0
K^0_S
ω
K^{*0}

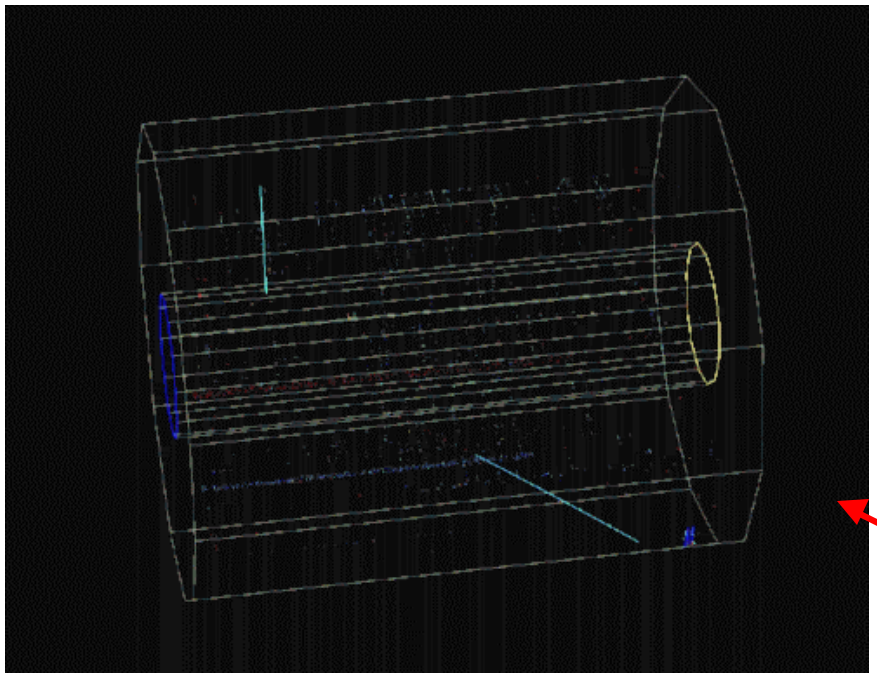


ρ^0
f_0
K^0_S
ω
K^{*0}
f_2

- ρ decay (Δt=1.3 fm)<π freeze-out (Δt~10 fm/c)<f_o decay (Δt~15 fm)
- ρ mass appears shifted 20-80 MeV = f(p_T)
- + phase-space peak shape ("re-scattering volume")
  + re-scattering (QM interference, *d*~1/3 fm)
  seems to shift mass back to PDG value



Ultra-peripheral Au+Au (nuclei don't touch)

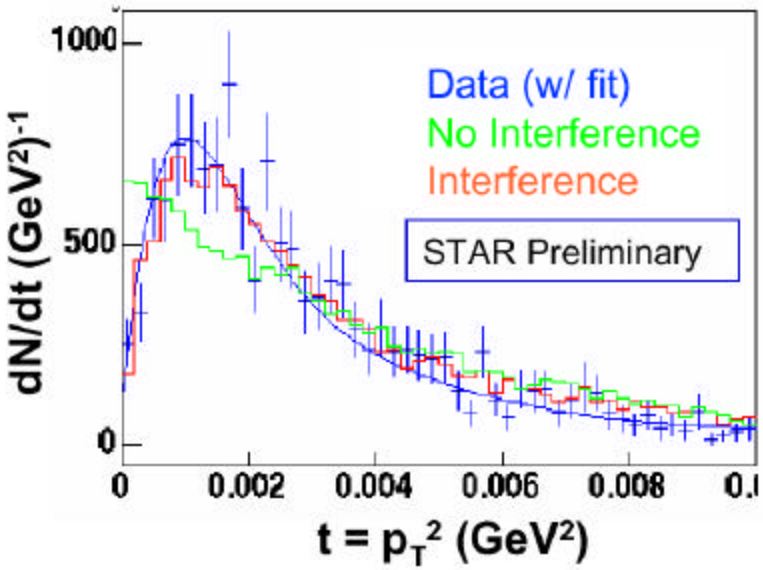


b>>R(Au)
(Weizsäcker-Williams,
vitual quanta)
Au + Au -> Au* + Au* + ρ^o

γ pomeron$\rightarrow\rho^o\rightarrow\pi^+\pi^-$
1st event 08.24.2000

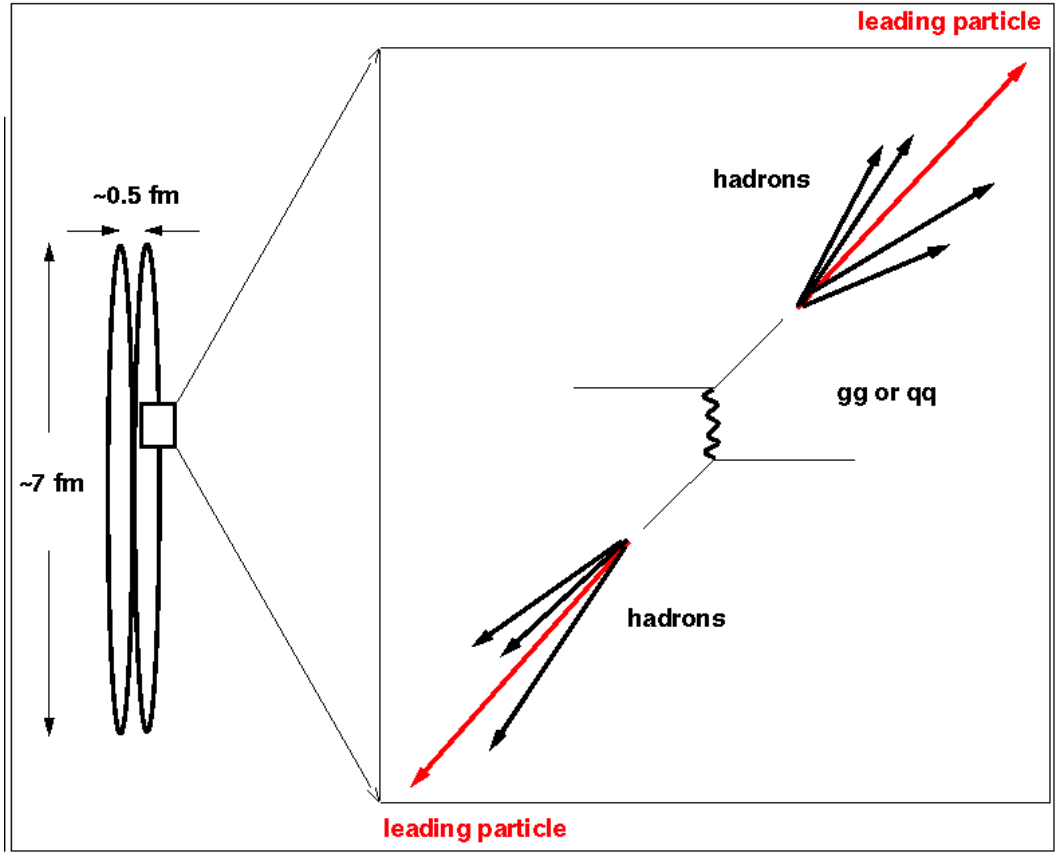
QM non-local entanglement in Au*Au*, r^o ® p^+p^-

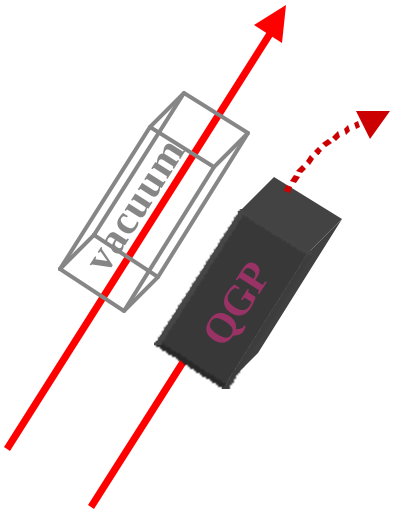
- indistuiguishable initial states (Au* Au vs. Au Au*)
  $\psi_{\pi\pi}$ contains destructive interference (parity -)
  $\sigma=\sigma_o(1-\cos(p\cdot b))$
- p_T<<1/<b> with <b>~20 fm
  $c\tau$ (ρ^o)=1.32 fm/c
  $\rightarrow$ $\pi\pi$ wave function non-local !
- coherence preserved
  even <u>after</u> the ρ decay
- clear
  "Einstein-Podolsky-Rosen"
  phenomenon



Jets in AA

- $\sqrt{s}$(RHIC) ~ 10· $\sqrt{s}$(SPS) - for the first time σ_{jet} accessible in AA collisions
- gg or qq scattering is very early t~0.1 fm/c (cylinder very short)
- pQCD $\sqrt{s}$=200 GeV: ~405 gluons, ~ 132 quarks, ~ 38 anti-quarks

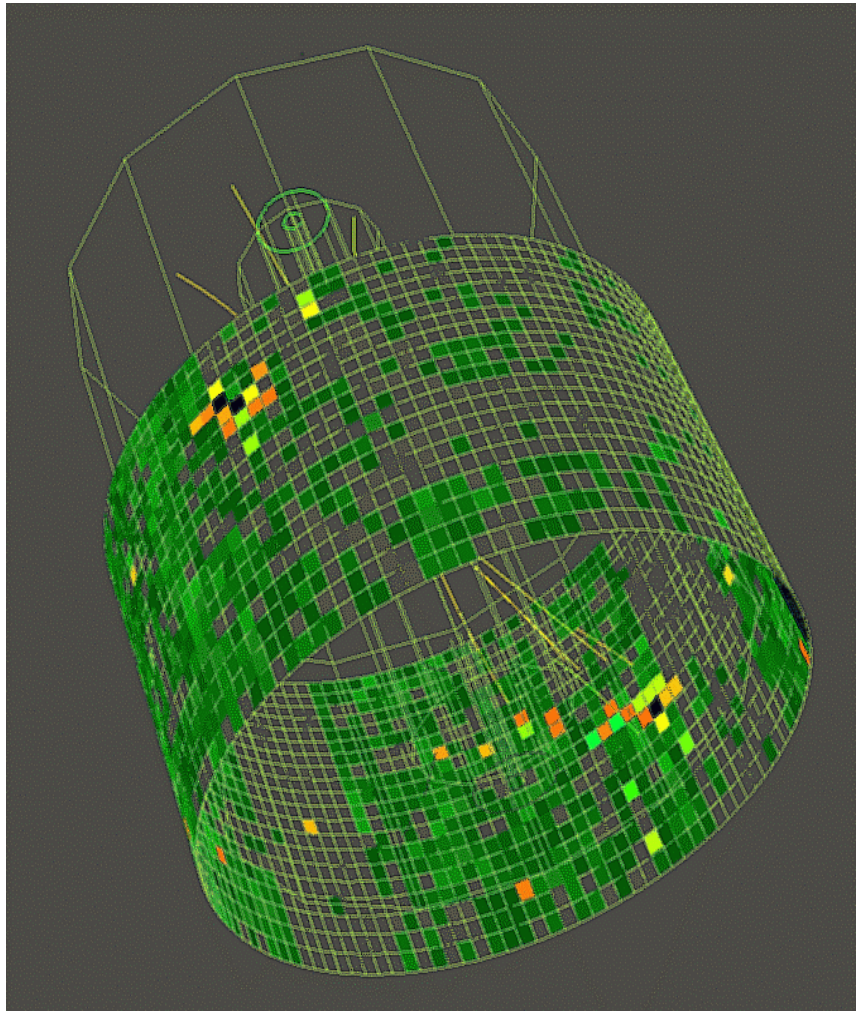




Jets at STAR (pp, Ös=200 GeV)

2 jet (gg or qq)
all tracks p_T>1 GeV/c

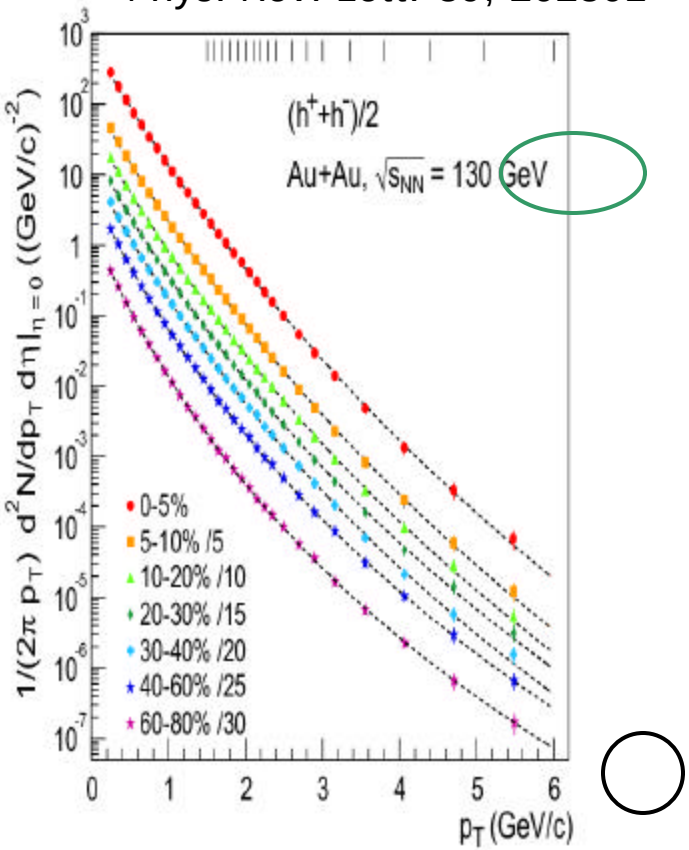
What about Au+Au ?
pQCD estimate
E_T>1 GeV
N_{Jet}~500
almost impossible
for jet finder algorithm.



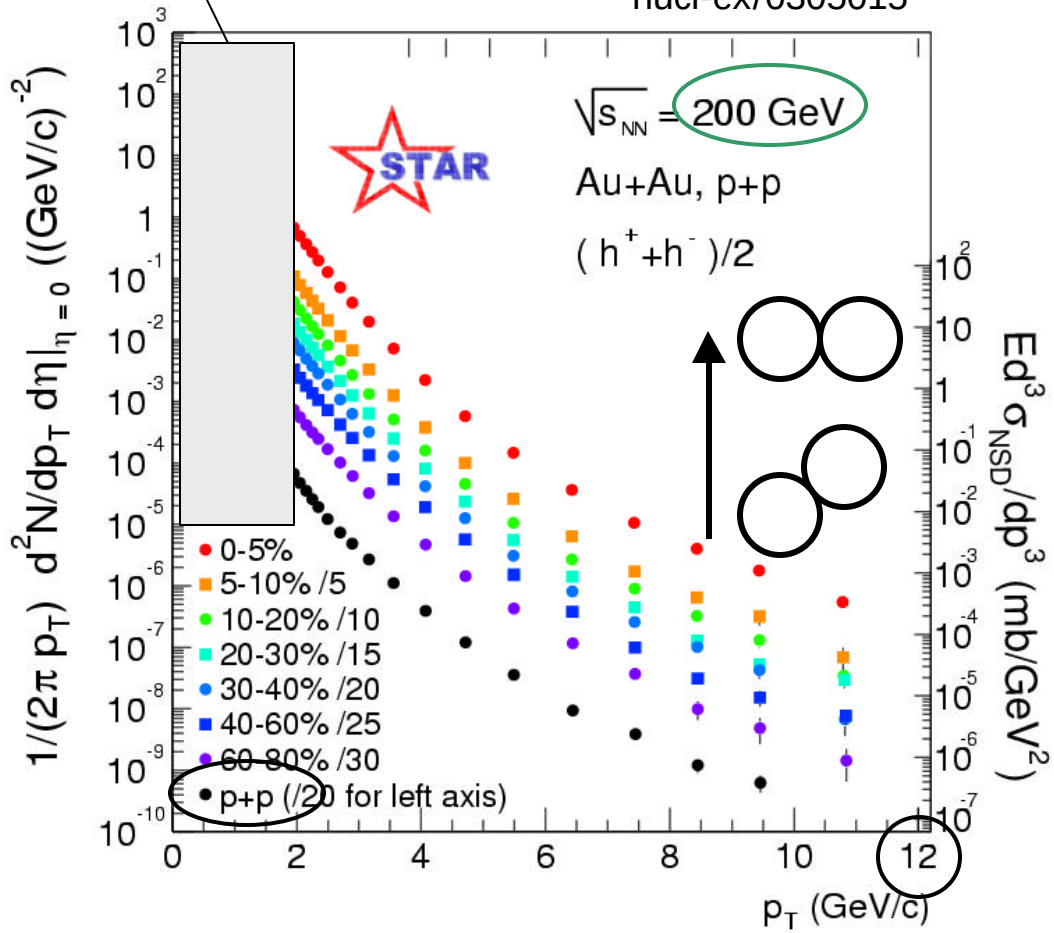
Charged high pT hadrons = <u>leading jet particles</u>

99.5%

Phys. Rev. Lett. 89, 202301



nucl-ex/0305015

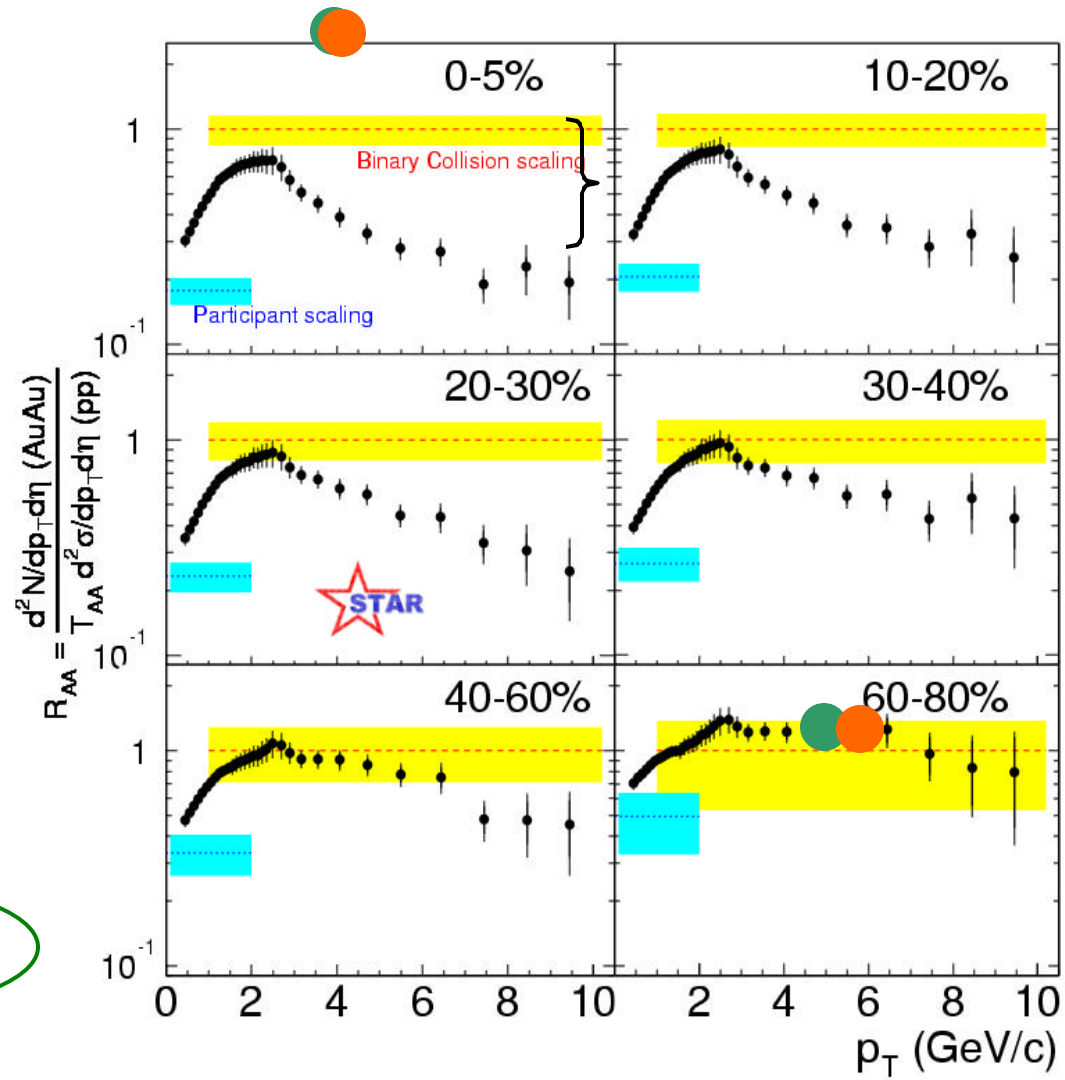


pp measured in same detector.

Au+Au relative to p+p

nucl-ex/0305015

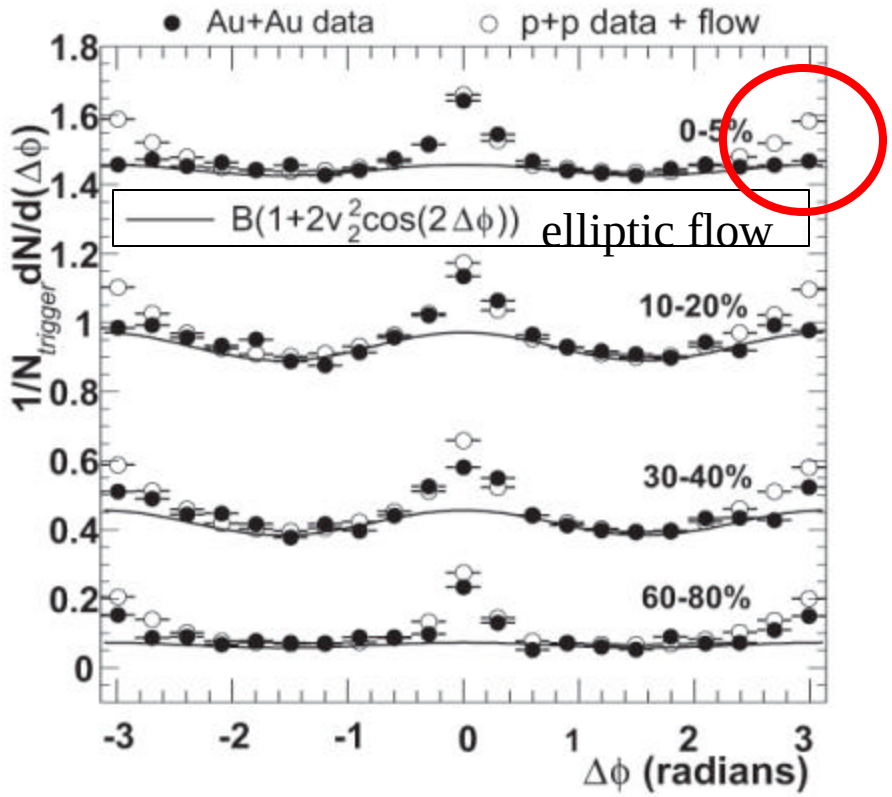
central collisions:
factor ~4-5 suppression



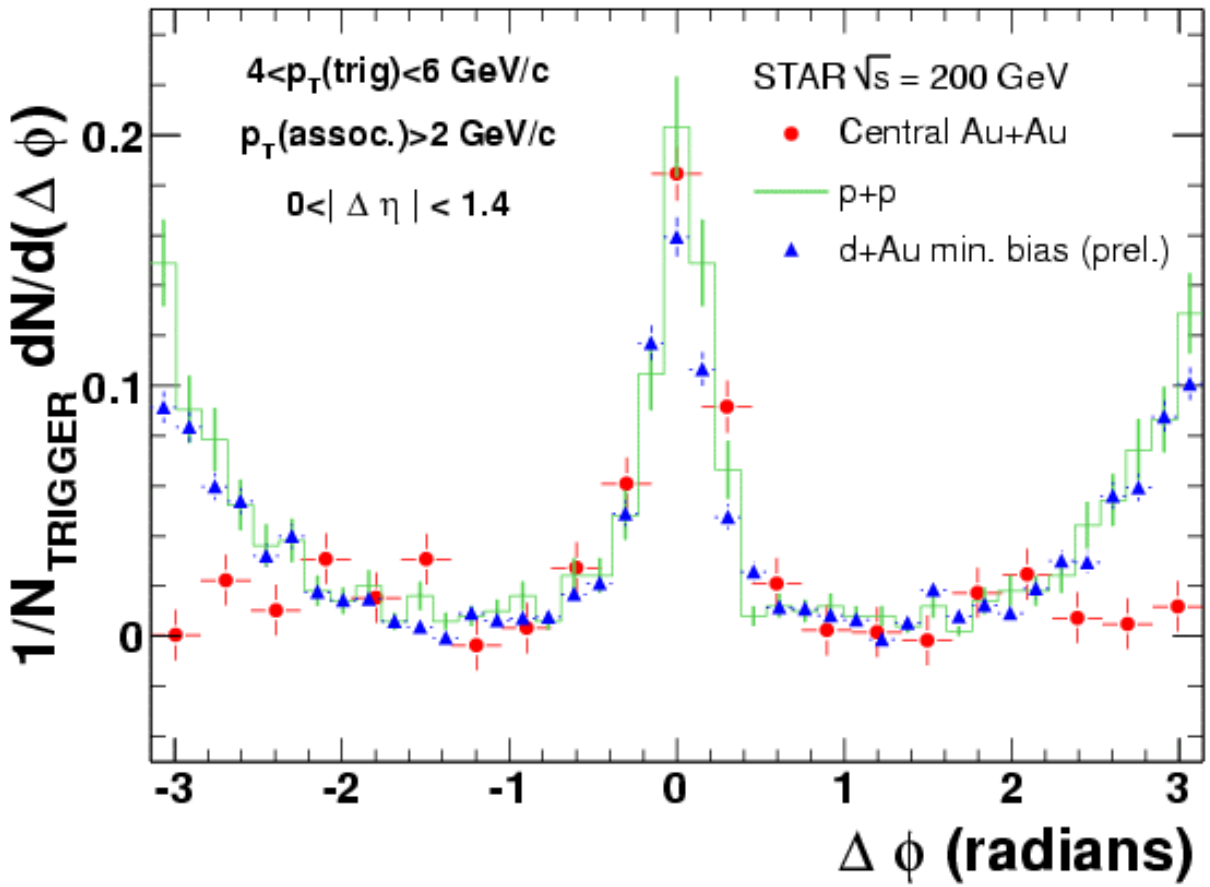
$$R_{AA}(p_T) = \frac{d^2N^{AA}/dp_T d}{T_{AA} d^2\ \ {}^{NN}/dp_T d}$$

Back-to-back leading jet particles

- Trigger particle ("same side") $p_T > 4$ GeV/c
- Away-side $2 < p_T < 4$ GeV/c
- $\Delta\phi$
- Normalize by number of trigger particles

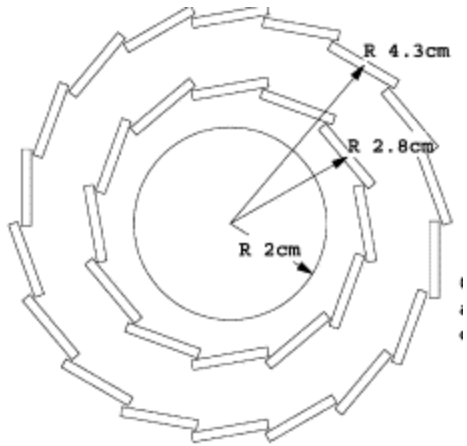


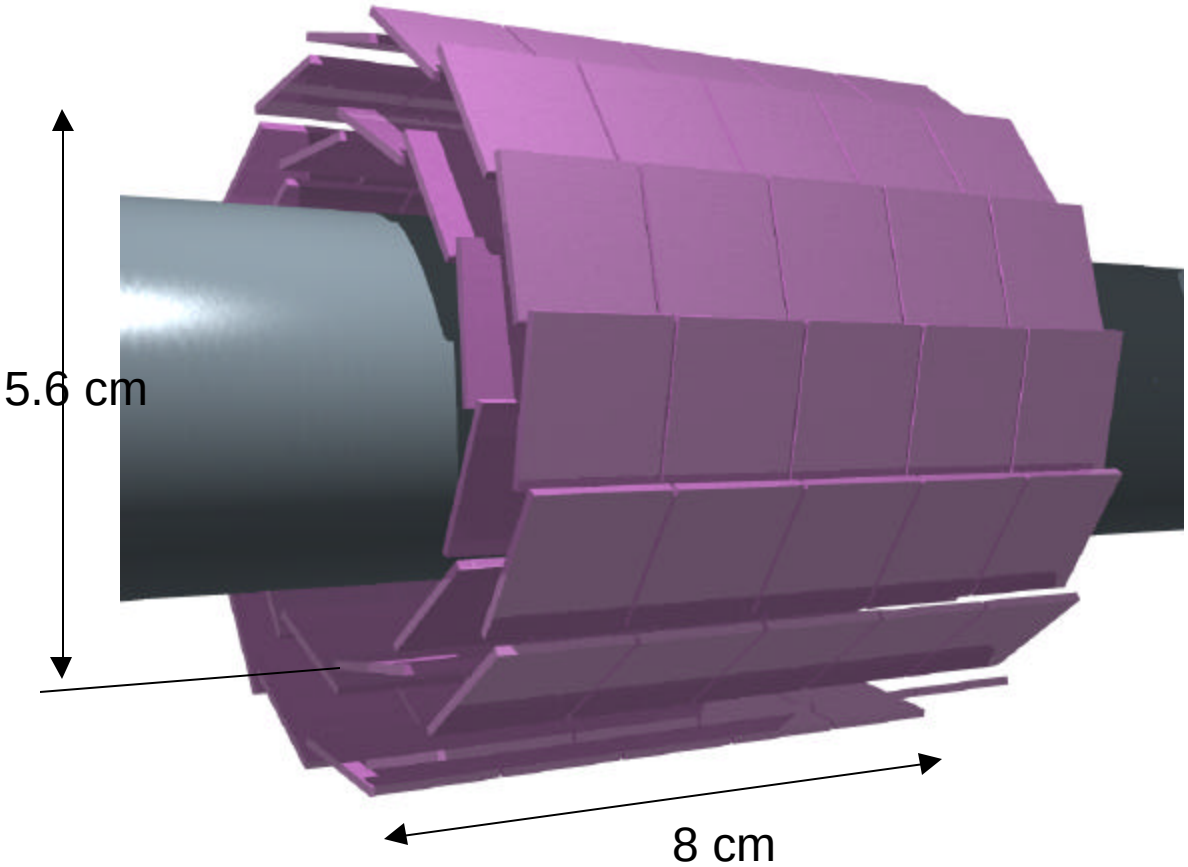
Away-Side Jets in p+p, d+Au, and Au+Au Collisions



STAR Upgrade Pixel Detector

for secondary c,b vertices





- 20 μm square pixels
- N(pixel)=90 x 10^6
- d=40 μm (monolithic)
- ADC in pixel
- SRAM in pixel

What did we learn so far ?

- t<1 fm/c temperature: beyond lattice-QCD boundary prediction.
- t<1 fm/c energy density: too high for hadron gas.
- parton-hadron transition ("freeze-out") short duration.
  $R_{out}/R_{side} \sim 1$: There is an explosion
- No indication for 1st order phase transition
  (no long-lived slowly-burning mixed quark-hadron soup).
- pQCD models need non-standard extensions,
  i.e. high density and high temperature.
- Back-to-back jets disappear.
- Nature recently exhibits surprising macroscopic phenomena
  (metallic hydrogen, left-handed materials, clockwise tornadoes).
  We will continue to search for microscopic analogons.

Motto motto,

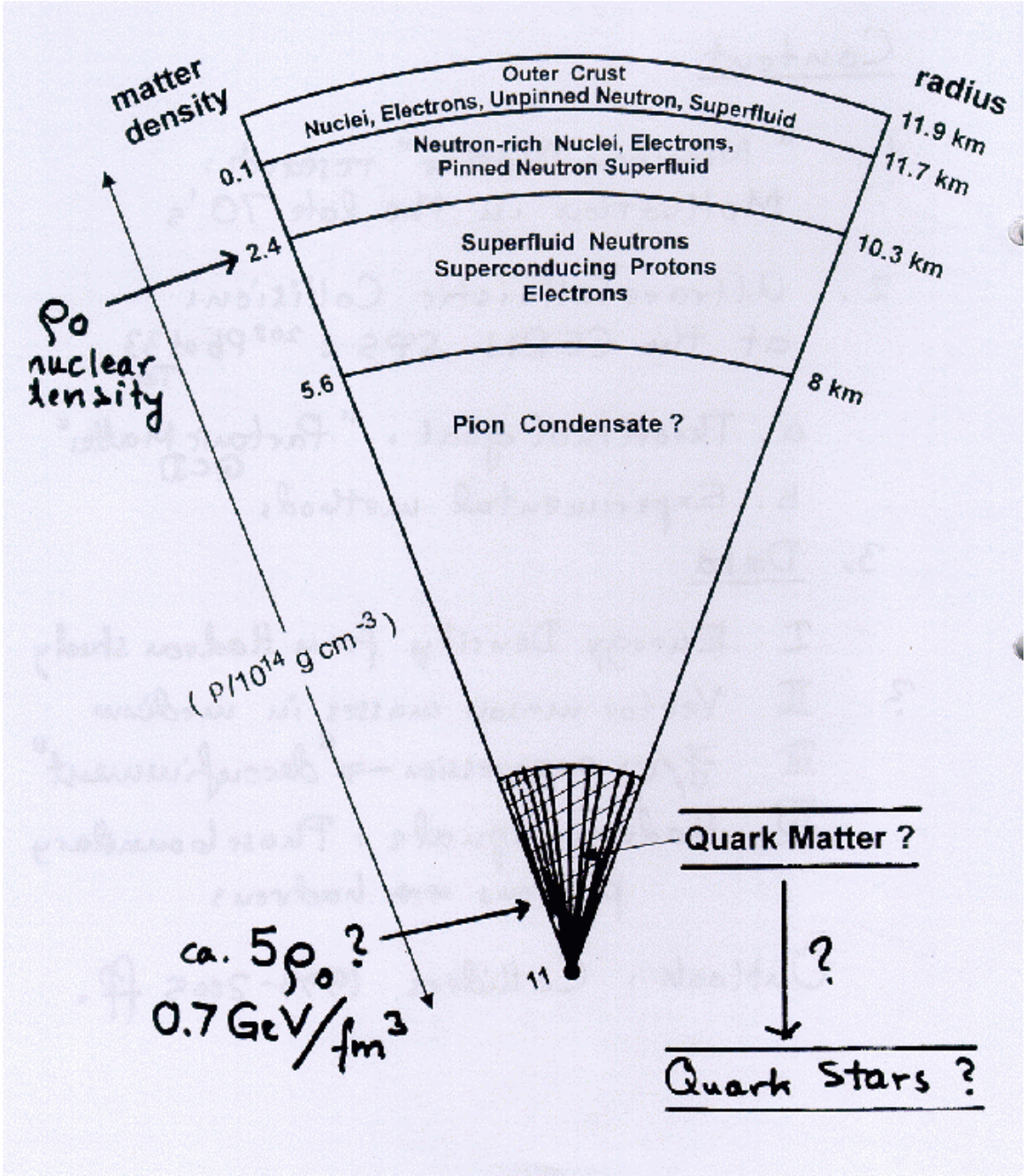
mou chotto !

What about the big bang ?

- general relativity curvature
  $ds^2 \sim dr^2/(1-k)$
  $k = 2GM/Rc^2$
  $k = 1$ black hole (escape velocity = c)
  $k \sim 10^{-22}$ @ RHIC
  $\rightarrow$ we are not bending space-time
- universe expands with v=c,
  v=0.55c @ RHIC
- big bang = thermal equilibrium
  @ RHIC: maybe, not clear yet
  but jet dE/dx could mean early equilibrium <u>before</u> suppression
- time scale 1 fm/c ~ 10^{-24} s
  in the universe: cosmic inflation 10^{-34} s
  $\rightarrow$ system already had macroscopic size

What about neutron stars ?

- for R<1 km $\rho=5\rho_0$ expected
  we have $15\rho_0$
  but energy density much smaller
  neutron star ε=0.7 GeV/fm3
- neutron star = hydrostatic equilibrium stability:
  outward <u>pressure</u> from incompressibility of nuclear matter
  incompressibility = $f(\rho)$
  (this is “equation of state”)
  @ RHIC: outward pressure generates blast wave.


matter density
radius
Outer Crust
Nuclei, Electrons, Unpinned Neutron, Superfluid
Neutron-rich Nuclei, Electrons,
Pinned Neutron Superfluid
Superfluid Neutrons
Superconducing Protons
Electrons
Pion Condensate ?
0.1
2.4
5.6
11.9 km
11.7 km
10.3 km
8 km
ρo
nuclear density
(ρ/10^14 g cm^-3)
ca. 5ρo ?
0.7 GeV/fm^3
11
Quark Matter ?
?
Quark Stars ?

Fit function

Hadron resonance ideal gas

Refs. J.Rafelski PLB(1991)333
J.Sollfrank et al. PRC59(1999)1637

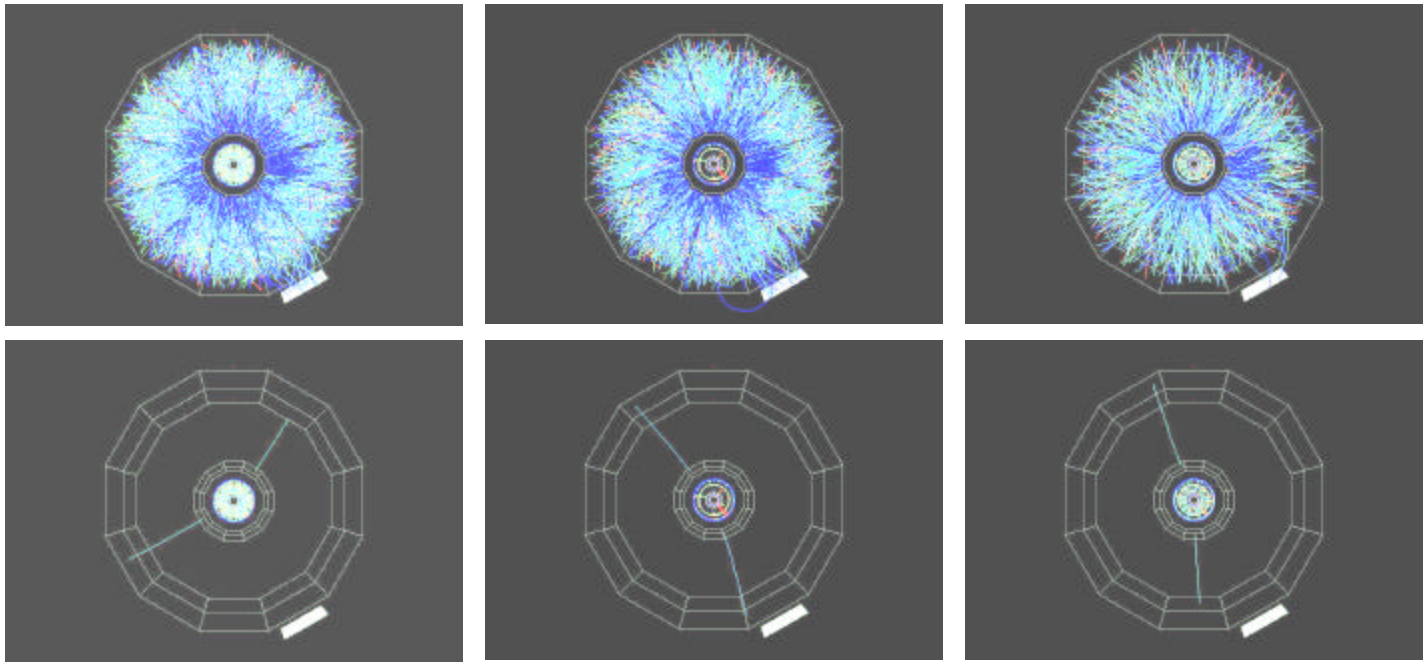
Particle density of each particle

$$\rho_i = \gamma_s^{|s_i|} \frac{g_i}{2\pi^2} T_{ch}^{\ 3} \left(\frac{m_i}{T_{ch}}\right)^2 K_2(m_i/T_{ch})\ \lambda_q^{\ Q_i}\ \lambda_s^{\ s_i}$$

$$\lambda_q = \exp(\mu_q/T_{ch}), \quad \lambda_s = \exp(\mu_s/T_{ch})$$

Q_i : 1 for u and d, -1 for $\bar{u}$ and $\bar{d}$
s_i : 1 for s, -1 for $\bar{s}$
g_i : spin-isospin freedom
m_i : particle mass

T_{ch} : Chemical freeze-out temperature
μ_q : light-quark chemical potential
μ_s : strangeness chemical potential
γ_s : strangeness saturation factor

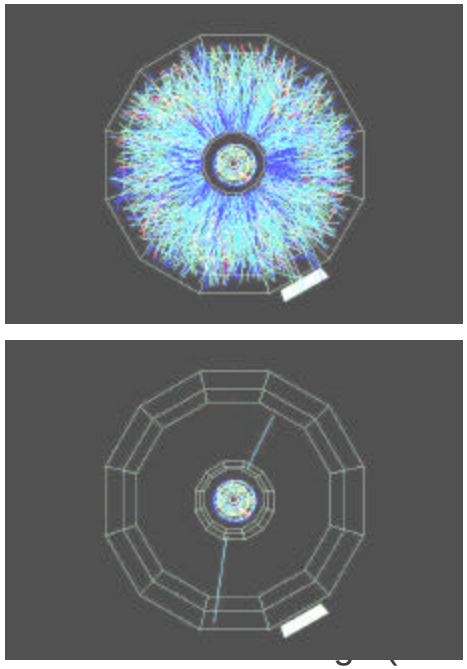


Upsilon->l+l- candidates

Run 2241022
Event #4699
m=10.21 GeV

Run 2243027
Event #1645
m=9.68 GeV

Run 2244029
Event#1570
m=9.25 GeV



p^+ p^- candidate

Run 2244032 Event #3420
m=9.38 GeV

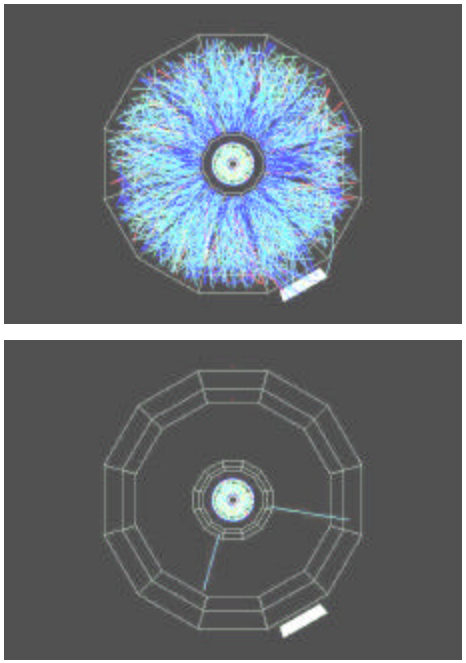
dE/dx<1.4e-5 keV/cm
P_{PID}(lepton)<3%

Drell-Yan candidate

Run 2252020 Event #8718
m=10.02 GeV

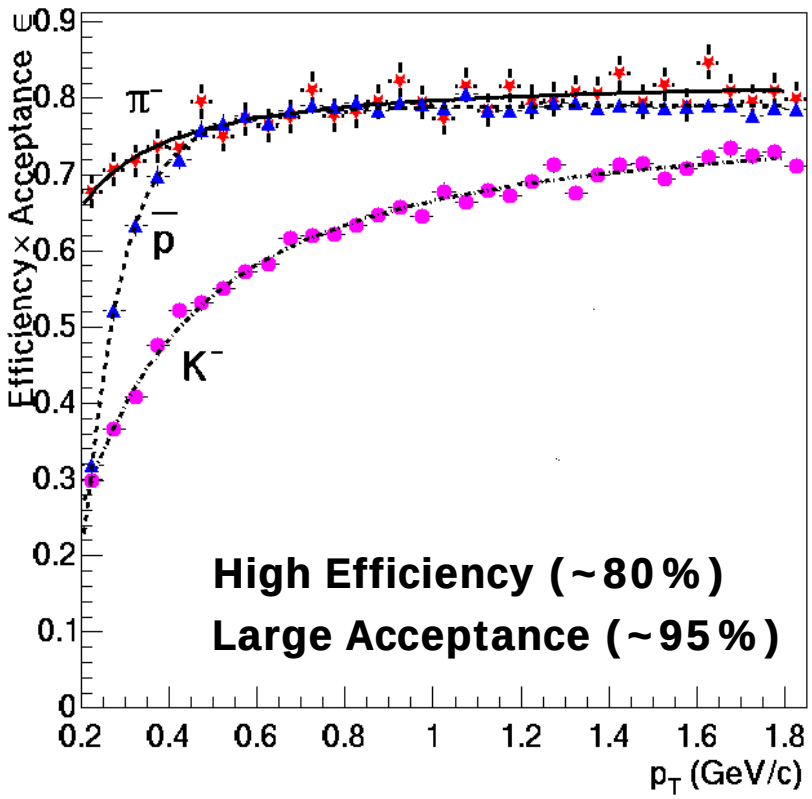
DF = 78°

Au+Au
Ös$_{NN}$=200 GeV

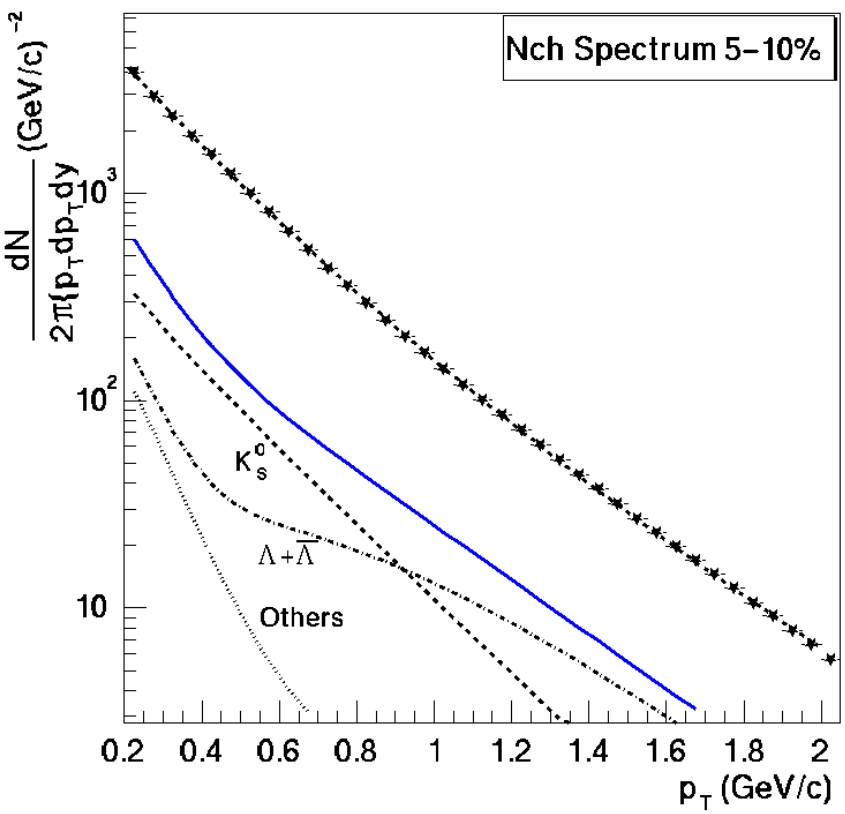


Corrections

Efficiency



Background



The STAR Collaboration

468 Collaborators
10 Countries
49 Institutions
~20 Ph.D. theses
14 PRL
3 PRC

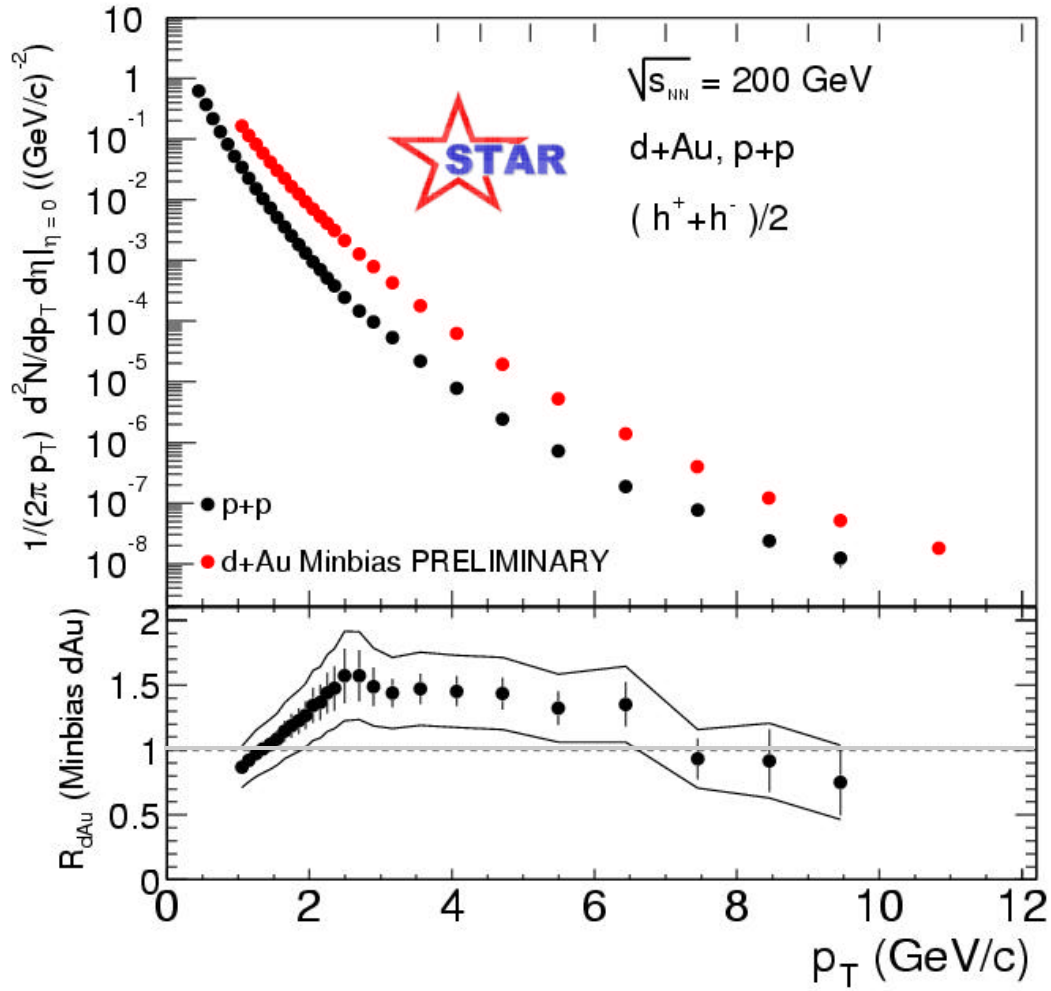
C. Adler[11], Z. Ahammed[23], C. Allgower[12], J. Amonett[14], B.D. Anderson[14], M. Anderson[5], G.S. Averichev[9], J. Balewski[12], O. Barannikova[9,23], L.S. Barnby[14], J. Baudot[13], S. Bekele[20], V.V. Belaga[9], R. Bellwied[30], J. Berger[11], H. Bichsel[29], L.C. Bland[12], C.O. Blyth[3], B.E. Bonner[24], R. Bossingham[15], A. Boucham[26], A. Brandin[18], R.V. Cadman[1], H. Caines[20], M. Calderón de la Barca Sánchez[31], A. Cardenas[23], J. Carroll[15], J. Castillo[28], M. Castro[30], D. Cebra[5], S. Chattopadhyay[30], M.L. Chen[2], Y. Chen[6], S.P. Chernenko[9], M. Cherney[8], A. Chikanian[31], B. Choi[27], W. Christie[2], J.P. Coffin[13], L. Conin[26], T.M. Cormier[30], J.G. Cramer[29], H.J. Crawford[4], M. DeMello[24], W.S. Deng[14], A.A. Derevschikov[22], L. Didenko[2], J.E. Draper[5], V.B. Dunin[9], J.C. Dunlop[31], V. Eckardt[16], L.G. Efimov[9], V. Emelianov[18], J. Engelage[4], G. Eppley[24], B. Erazmus[26], P. Fachini[25], V. Faine[2], E. Finch[31], Y. Fisyak[2], D. Flier[11], K.J. Foley[2], J. Fu[15], N. Gagunashvili[9], J. Gans[31], L. Gaudichet[26], M. Germain[13], F. Geurts[24], V. Ghazikhanian[6], J. Grabski[28], O. Grachov[30], D. Greiner[15], V. Grigoriev[18], M. Guedon[13], E. Gushin[18], T.J. Hallman[2], D. Hardtke[15], J.W. Harris[31], M. Heffner[5], S. Heppelmann[21], T. Herston[23], B. Hippolyte[13], A. Hirsch[23], E. Hjort[15], G.W. Hoffmann[27], M. Horsley[31], H.Z. Huang[6], T.J. Humanic[20], H. Hümmler[16], G. Igo[6], A. Ishihara[27], Yu.I. Ivanshin[10], P. Jacobs[15], W.W. Jacobs[12], M. Janik[28], I. Johnson[15], P.G. Jones[3], E. Judd[4], M. Kaneta[15], M. Kaplan[7], D. Keane[14], A. Kisiel[28], J. Klay[5], S.R. Klein[15], A. Klyachko[12], A.S. Konstantinov[22], L. Kotchenda[18], A.D. Kovalenko[9], M. Kramer[19], P. Kravtsov[18], K. Krueger[1], C. Kuhn[13], A.I. Kulikov[9], G.J. Kunde[31], C.L. Kunz[7], R.Kh. Kutuev[10], A.A. Kuznetsov[9], L. Lakehal-Ayat[26], J. Lamas-Valverde[24], M.A.C. Lamont[3], J.M. Landgraf[2], S. Lange[11], C.P. Lansdell[27], B. Lasiuk[31], F. Laue[2], A. Lebedev[2], T. LeCompte[1], R. Lednický[9], V.M. Leontiev[22], M.J. LeVine[2], Q. Li[30], Q. Li[15], S.J. Lindenbaum[19], M.A. Lisa[20], T. Ljubicic[2], W.J. Llope[24], G. LoCurto[16], H. Long[6], R.S. Longacre[2], M. Lopez-Noriega[20], W.A. Love[2], D. Lynn[2], R. Majka[31], S. Margetis[14], L. Martin[26], J. Marx[15], H.S. Matis[15], Yu.A. Matulenko[22], T.S. McShane[8], F. Meissner[15], Yu. Melnick[22], A. Meschanin[22], M. Messer[2], M.L. Miller[31], Z. Milosevich[7], N.G. Minaev[22], J. Mitchell[24], V.A. Moiseenko[10], D. Moltz[15], C.F. Moore[27], V. Morozov[15], M.M. de Moura[30], M.G. Munhoz[25], G.S. Mutchler[24], J.M. Nelson[3], P. Nevski[2], V.A. Nikitin[10], L.V. Nogach[22], B. Norman[14], S.B. Nurushev[22], G. Odyniec[15], A. Ogawa[21], V. Okorokov[18], M. Oldenburg[16], D. Olson[15], G. Paic[20], S.U. Pandey[30], Y. Panebratsev[9], S.Y. Panitkin[2], A.I. Pavlinov[30], T. Pawlak[28], V. Perevoztchikov[2], W. Peryt[28], V.A Petrov[10], W. Pinganaud[26], E. Platner[24], J. Pluta[28], N. Porile[23], J. Porter[2], A.M. Poskanzer[15], E. Potrebenikova[9], D. Prindle[29], C. Pruneau[30], S. Radomski[28], G. Rai[15], O. Ravel[26], R.L. Ray[27], S.V. Razin[9,12], D. Reichhold[8], J.G. Reid[29], F. Retiere[15], A. Ridiger[18], H.G. Ritter[15], J.B. Roberts[24], O.V. Rogachevski[9], J.L. Romero[5], C. Roy[26], D. Russ[7], V. Rykov[30], I. Sakrejda[15], J. Sandweiss[31], A.C. Saulys[2], I. Savin[10], J. Schambach[27], R.P. Scharenberg[23], K. Schweda[15], N. Schmitz[16], L.S. Schroeder[15], A. Schüttauf[16], J. Seger[8], D. Seliverstov[18], P. Seyboth[16], E. Shahaliev[9], K.E. Shestermanov[22], S.S. Shimanskii[9], V.S. Shvetcov[10], G. Skoro[9], N. Smirnov[31], R. Snellings[15], J. Sowinski[12], H.M. Spinka[1], B. Srivastava[23], E.J. Stephenson[12], R. Stock[11], A. Stolpovsky[30], M. Strikhanov[18], B. Stringfellow[23], H. Stroebele[11], C. Struck[11], A.A.P. Suaide[30], E. Sugarbaker[20], C. Suire[13], M. Šumbera[9], T.J.M. Symons[15], A. Szanto de Toledo[25], P. Szarwas[28], J. Takahashi[25], A.H. Tang[14], J.H. Thomas[15], V. Tikhomirov[18], T.A. Trainor[29], S. Trentalange[6], M. Tokarev[9], M.B. Tonjes[17], V. Trofimov[18], O. Tsai[6], K. Turner[2], T. Ullrich[2], D.G. Underwood[1], G. Van Buren[2], A.M. VanderMolen[17], A. Vanyashin[15], I.M. Vasilevski[10], A.N. Vasiliev[22], S.E. Vigdor[12], S.A. Voloshin[30], F. Wang[23], H. Ward[27], J.W. Watson[14], R. Wells[20], T. Wenaus[2], G.D. Westfall[17], C. Whitten Jr. [6], H. Wieman[15], R. Willson[20], S.W. Wissink[12], R. Witt[14], N. Xu[15], Z. Xu[31], A.E. Yakutin[22], E. Yamamoto[6], J. Yang[6], P. Yepes[24], A. Yokosawa[1], V.I. Yurevich[9], Y.V. Zanevski[9], I. Zborovský[9], W.M. Zhang[14], R. Zoulkarneev[10], A.N. Zubarev[9]

d+Au: minbias charged hadron yield

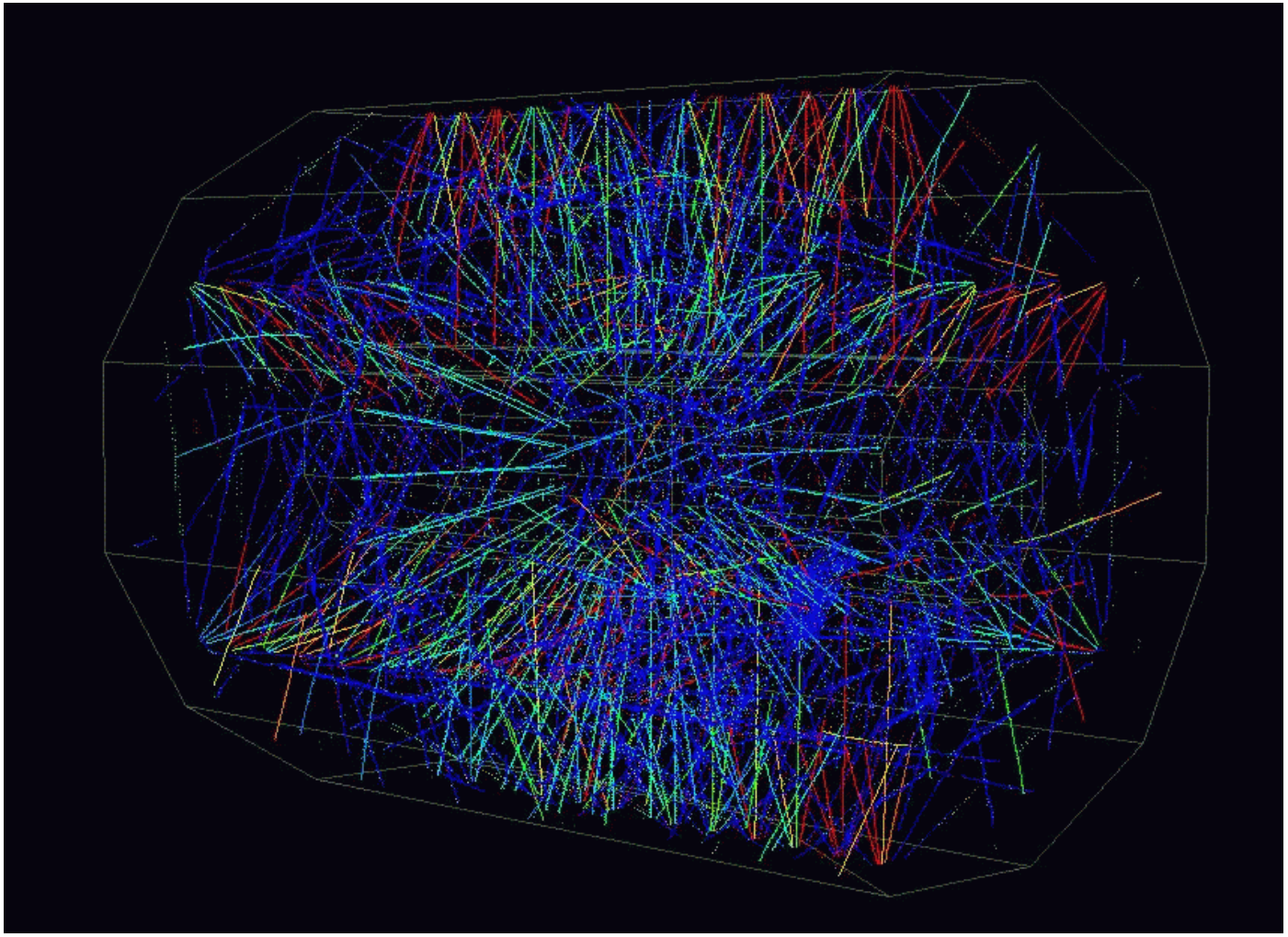
$$R_{dAu} = \frac{d^2 N^{dAu} / dp_T d}{T_{dAu} d^2 \quad {}^{pp} / dp_T d}$$

$$T_{dAu} = \frac{2 \times 197}{2.2\, b}$$

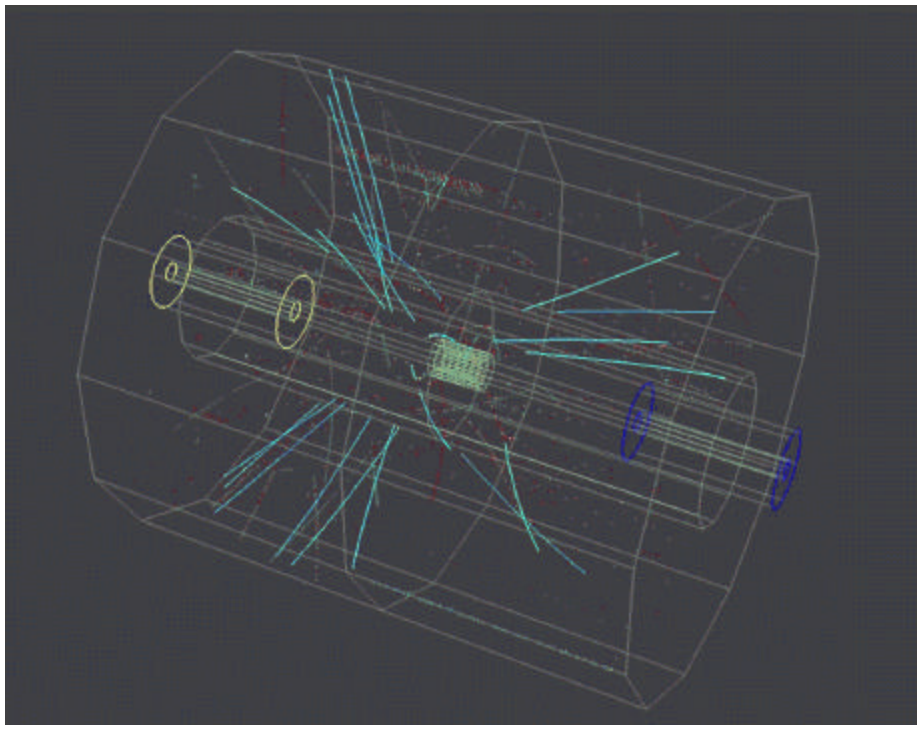
$R_{AA}>1$
charged hadron yield
<u>enhanced</u> in d+Au
Cronin effect
(expected for “cold”
nuclear matter)



Laser for TPC Calibration

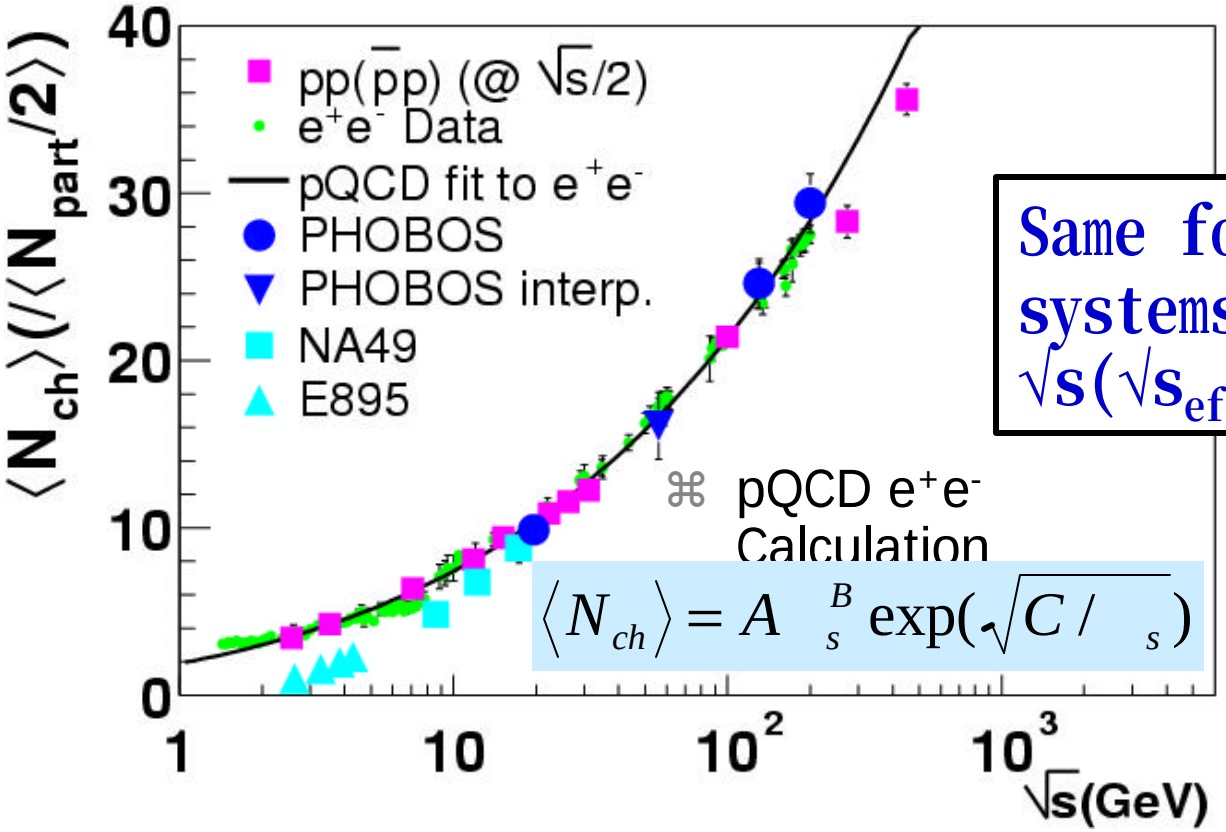


3-Jet Event (pp, Ös=200 GeV)



3 jet (ggg or qqγ or Upsilon decay)
all tracks p_T>0.5 GeV/c

$N_{charged}(\sqrt{s_{NN}})$ – Universality of Total Multiplicity?



$$\langle N_{ch} \rangle = A \; {}_s^B \exp(\sqrt{C / \; {}_s})$$

$$\sqrt{s_{eff}} = \sqrt{s} / 2$$

Same for all systems at same $\sqrt{s}$($\sqrt{s_{eff}}$ for pp)

(A. Mueller, 1983)

Total charged particle multiplicity / participant pair