Probing the QCD Phase Diagram at Collider Energies: Results from PHENIX @ RHIC

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Overview

1. Introduction:
   - Review of QCD properties (confinement, chiral symm., vacuum)
   - High-energy heavy-ion physics topics: QCD phase diagram, quark-hadron phase transition, small-x physics
2. PHENIX experiment @ RHIC:
   - Setup Run 1: Au+Au @130 GeV. Run-2: Au+Au, p+p @ 200 GeV
3. Results I: Global observables
   - Energy density, particle multiplicity, net baryon density.
4. Results II: High p_T probes
   - Suppression of high p_T hadron spectra
   - Hadron composition at high p_T
   - Azimuthal correlations: collective elliptic flow and jet-like signals
5. Results III: Heavy-flavor probes
   - Single electrons (open charm)
   - First results on J/ψ
6. Summary

“Physics Questions for the New Century” (*)

7. "Are there new states of matter at ultrahigh temperatures and densities ?"

as well as ...

5. "Where do ultra-energy particles come from ?"

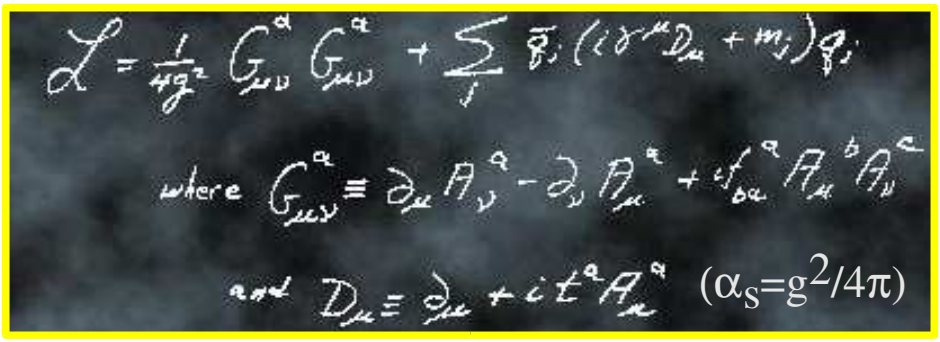
6. "Is a new theory of light and matter needed to explain what happens at very high energies and temperatures ?"

(*) National Research Council Committee on Physics of the Universe report, "*Connecting Quarks with the Cosmos: 11 Science Questions for the New Century*".

Review of QCD properties

The QCD Lagrangian:

- Degrees of freedom: quarks and gluons
- Non-abelian gauge theory
- Internal symmetry group: $SU(3)_{color}$



$\alpha_S(Q^2) \sim 1/\ln(Q^2/\Lambda^2)$, $\Lambda \sim 200$ MeV

Properties of the strong interaction:

1. Confinement: Quarks do not occur isolated in nature: only in hadronic (colorless) bound-states as mesons [$q\bar{q}$] and baryons [qqq]. $\alpha_s(Q^2)$ strong at large distances (low Q^2).

2. Asymptotic freedom: At short distances (high Q^2), $\alpha_s(Q^2)$ decreases logarithmically: quarks & gluons weakly coupled. Perturbative methods applicable (pQCD).

3. Chiral symmetry breaking:

   - Quarks acquire dynamically a mass in a confined medium:
     Current m_q (5-10 MeV) << Constituent m_q (~300 MeV)
   - Non-zero QCD ground-state (non-perturbative vacuum, "sea") filled with quark-antiquark and gluon-gluon virtual pairs :
     quark & gluon condensates: $\langle\Psi\Psi\rangle \approx -(235\ \text{MeV})^3$, $\langle\alpha_s G_{\mu\nu} G^{\mu\nu}\rangle \approx -(500\ \text{MeV})^4$

QCD at finite T and ρ

Nuclear matter at high temperatures and densities exhibits:

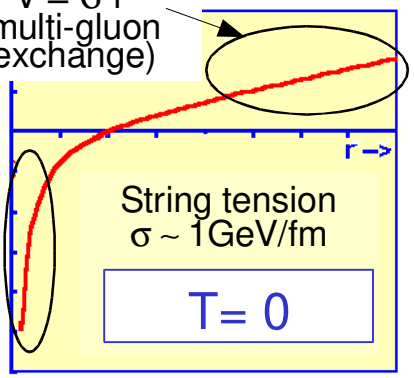
- Color deconfinement: $\alpha_{eff}(T) \sim 1/\ln(T,\rho) \rightarrow 0$
- Chiral symmetry restoration: $m_q(T,\rho) \rightarrow 0$

} New state of matter

QCD color potential:

Cornell potential: $V = \sigma r$ (multi-gluon exchange)

$V \sim -\alpha_{eff} / r$ (1-gluon exchange)

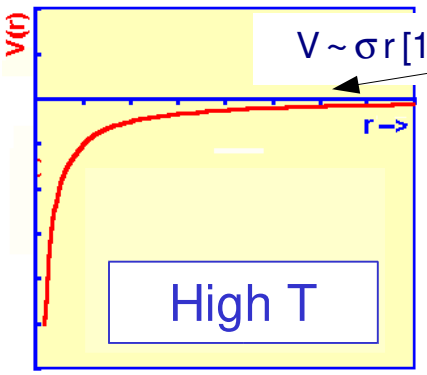


String tension $\sigma \sim 1$GeV/fm

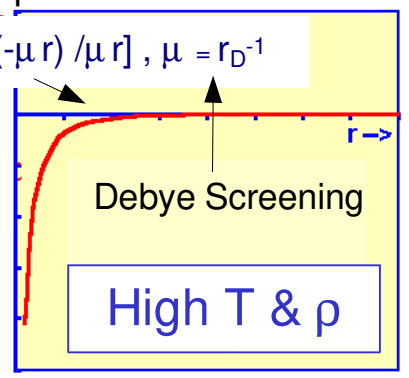
T= 0

Yukawa-like potential:

$V \sim \sigma r [1-\exp(-\mu r)/\mu r]$, $\mu = r_D^{-1}$



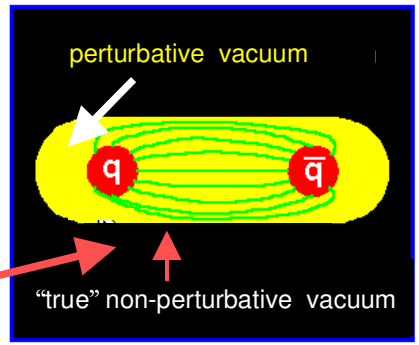
High T



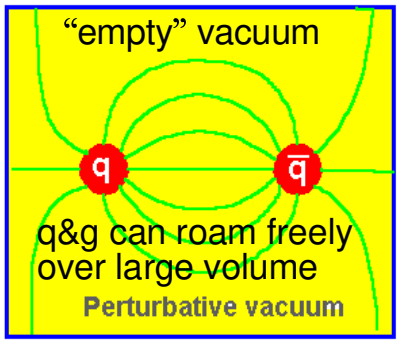
Debye Screening

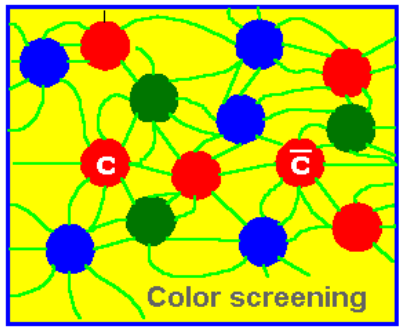
High T & ρ

QCD vacuum:



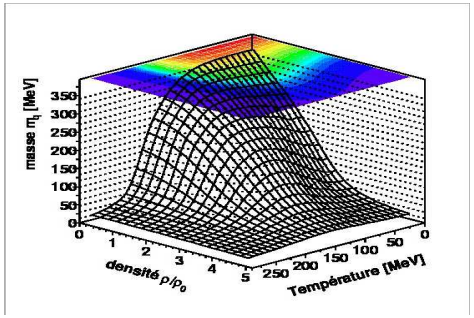
Bag pressure: $B^{1/4} \sim 0.2$ GeV



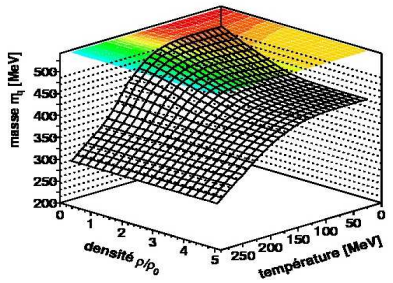


Quark masses:

u/d quarks:



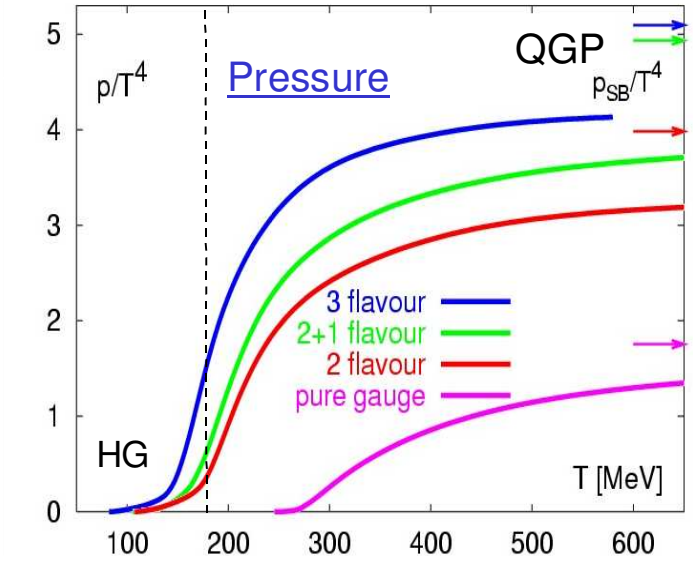
s quark :



$m_q \sim m_0 + C\langle\bar{\Psi}\Psi\rangle$ (NJL model)

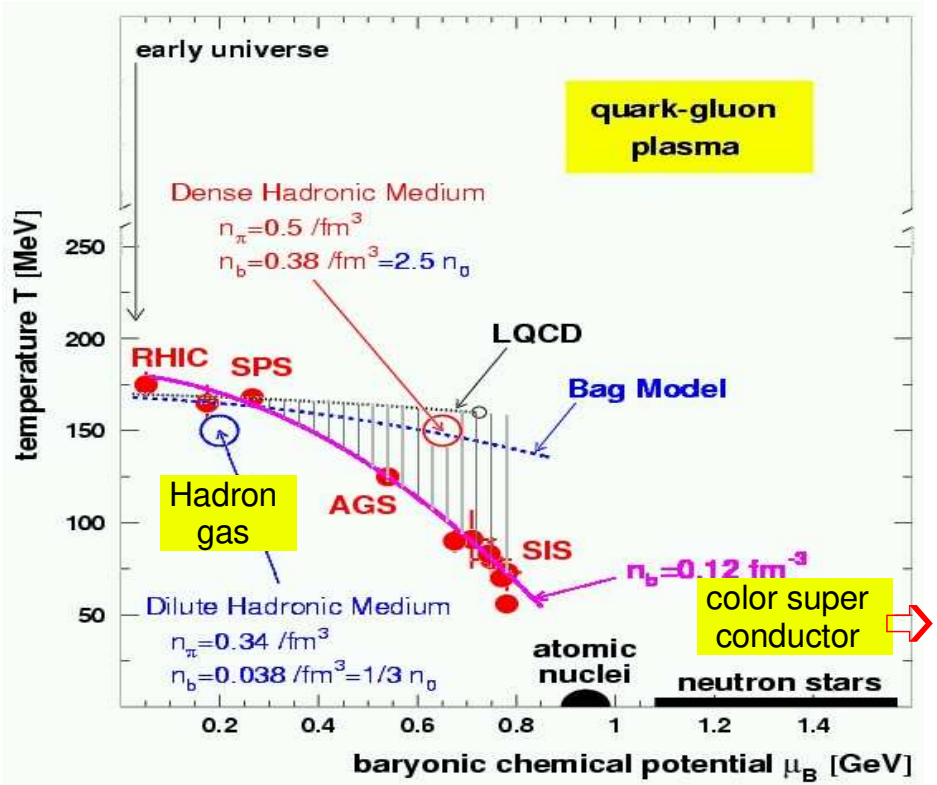
QCD thermodynamics on the lattice (*)

QCD Equation of State [F. Karsch QM2001]



(*) At zero baryon number density (μ_B=0)

Phases of strongly interacting matter



QCD critical temperature:

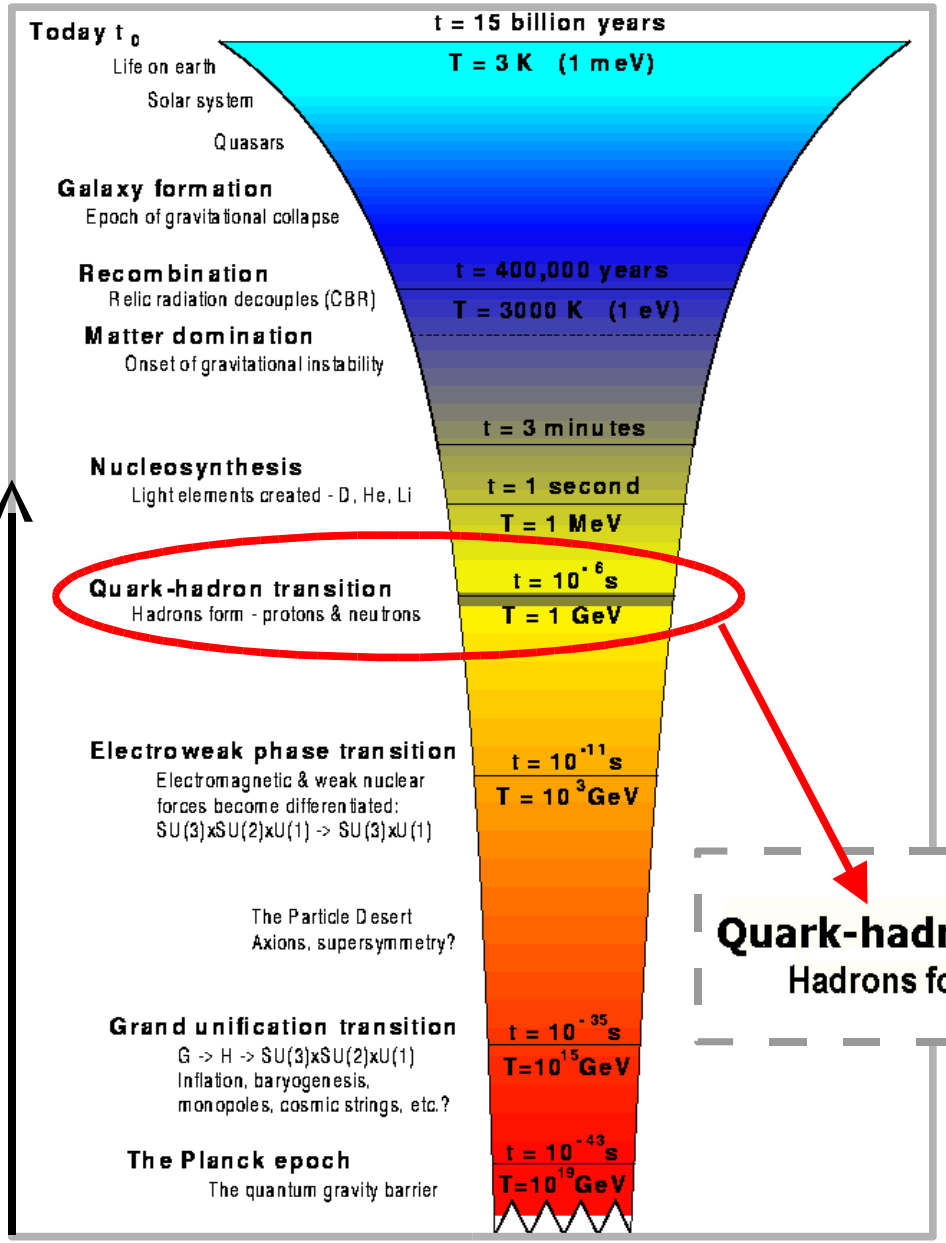
T_c = (173 ±10) MeV [n_f =2]

T_c = (154 ±10) MeV [n_f =3]

Critical energy density:

$\varepsilon_c=(6 \pm 2)T_c^4 \Rightarrow \varepsilon_c=(0.7\pm0.3)$ GeV/fm^3

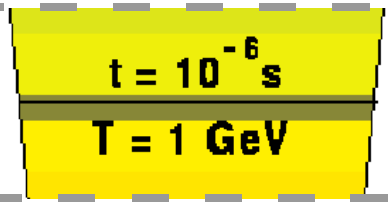
Cosmological QCD transition



The universe was in the QGP state ~10 μs after the "Big Bang"

Insights into the cosmology and phase transitions of the early universe

Quark-hadron transition
Hadrons form protons & neutrons



phase transition: *O* (μs)

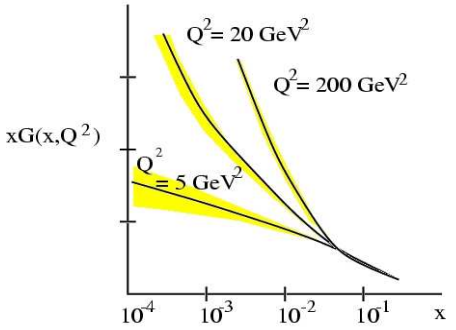
High parton density & small-x physics

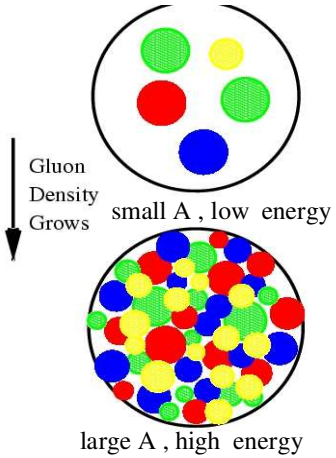
- Initial conditions at RHIC: High-Energies + Large Nuclei
  - x_{Bj}<<1: High parton (gluon) densities

$$\rho_A \simeq \frac{xG_A(x,Q^2)}{\pi R_A^2} \sim A^{1/3}$$

RHIC ~ HERA x $A^{1/3}$

High color field strengths





  - Saturation scale: *Value of the momentum transfer Q^2 at which the parton system starts looking dense to the probe*

$$Q_s^2 \sim \alpha_s \frac{xG_A(x,Q_s^2)}{\pi R_A^2}$$ ~ 1.5 GeV^2/c^2 @ RHIC

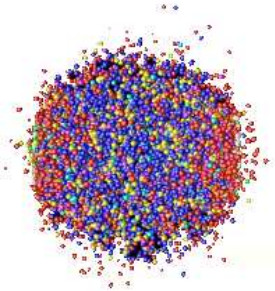
  - Theoretical interest on highly non-linear QCD regime:

    $Q^2_s >> \Lambda^2_{QCD} \Rightarrow \alpha_s << 1$ (weak coupling)

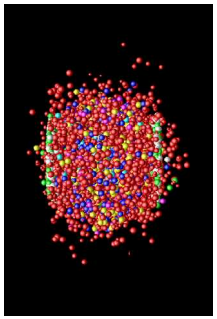
    "Classical" (Chromo-Dynamics) methods applicable:

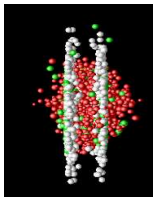
    "Color-Glass-Condensate": *Hadron wavefunction described as a state of high-density gluonic (i.e. bosonic and colored) matter, whose distribution is disordered and frozen over the relevant time scales*

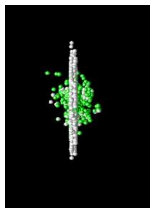
The "Little Bang" in the lab.

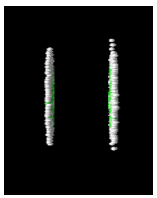


- High-energy nucleus-nucleus collisions: in fixed-target reactions ($\sqrt{s}$~17 GeV, SPS) or in colliders ($\sqrt{s}$~200 GeV, RHIC)
- QGP expected to be formed in a tiny region (~10^{-14} m) and to last very short times (~10^{-23} s).
- Collision dynamics: Diff. observables probe diff. reaction stages









Time

Free streaming

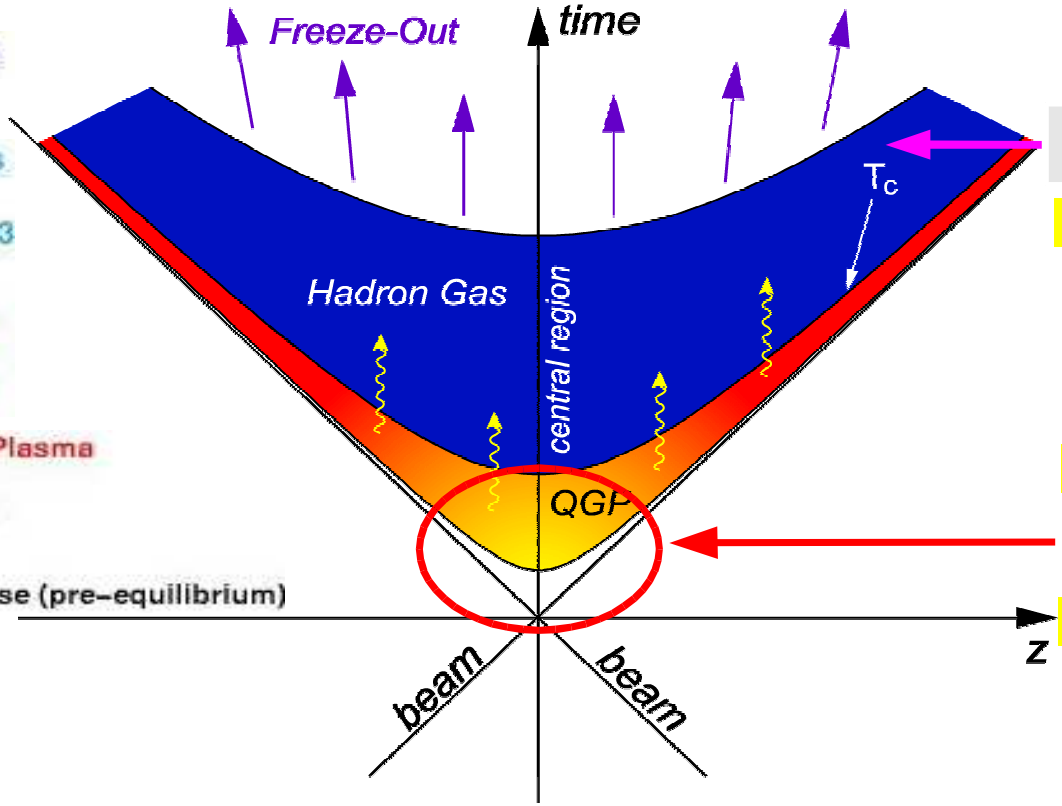
Hot Hadron gas
T~110 MeV
ε~ 0.05 GeV/fm3

Hadronization
T ~ 170 MeV
ε ~ 1 GeV/fm3

Quark–Gluon Plasma
T~300 MeV
ε ~ 5 GeV/fm3

Formation phase (pre–equilibrium)

Colliding ions
T=0 MeV
ε= 0.15 GeV/fm



Final state probes

t ~ 10^7 fm/c

t ~ 10 fm/c

Penetrating probes

t~0.1 fm/c

Relativistic Heavy-Ion Collider (RHIC) @ BNL

Specifications:

3.83 km circumference

2 independent rings:

- 120 bunches/ring
- 106 ns crossing time

Au + Au collisions @ 200*A* GeV

(~10 times CERN-SPS energy)

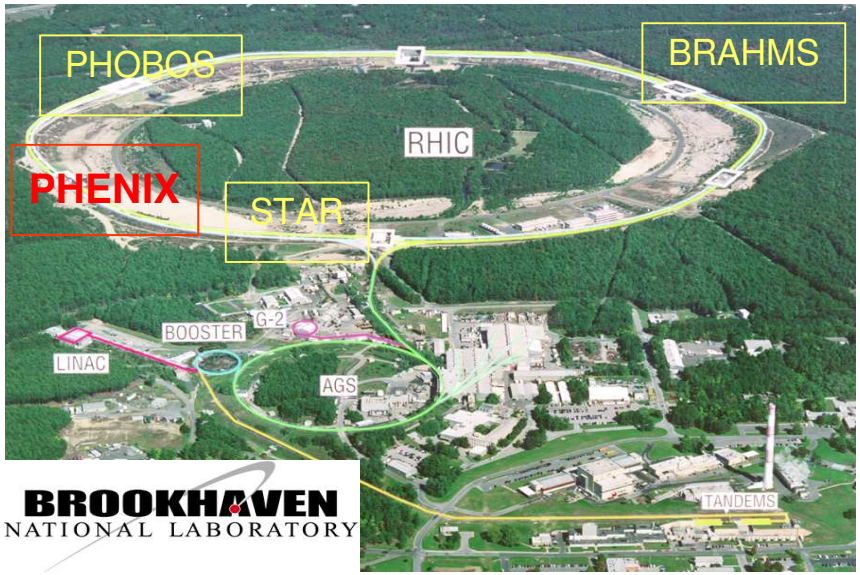
Luminosity: $2 \cdot 10^{26}$ cm^{-2} s^{-1} (~1.4 kHz)

4 experiments:

PHENIX, STAR, PHOBOS, BRAHMS

1st run: June '00 - Sept. '00
(collisions at 130*A* GeV)

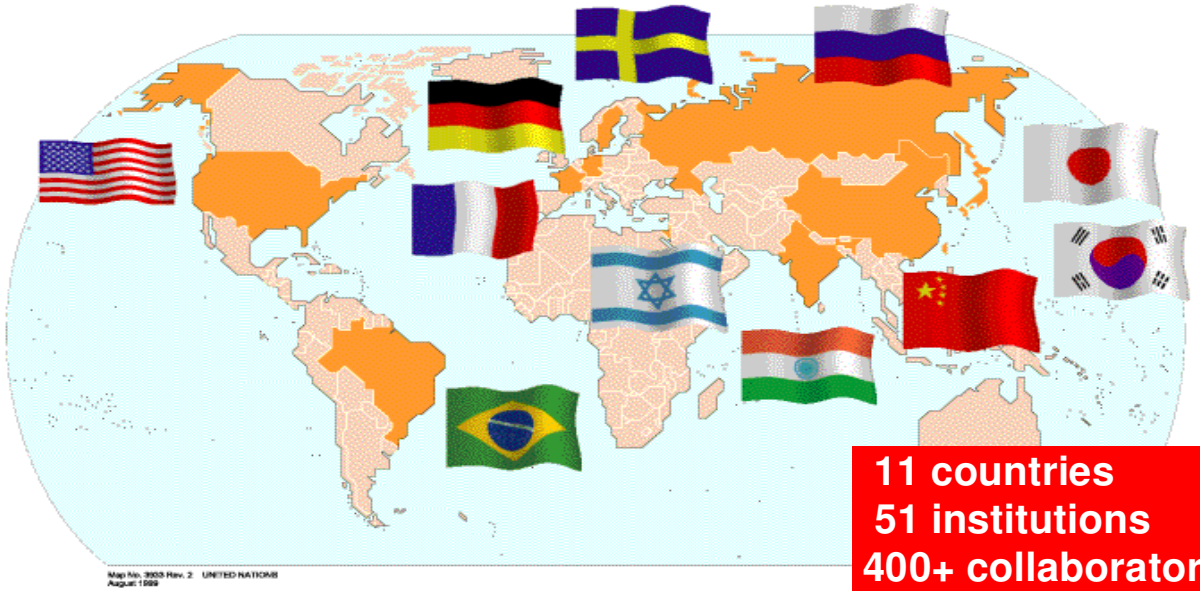
2nd run: June '01 - Jan. '02
(AuAu, *pp* collisions at 200*A* GeV)



The PHENIX collaboration

Pioneering High-Energy Ion eXperiment

PHENIX



11 countries
51 institutions
400+ collaborators

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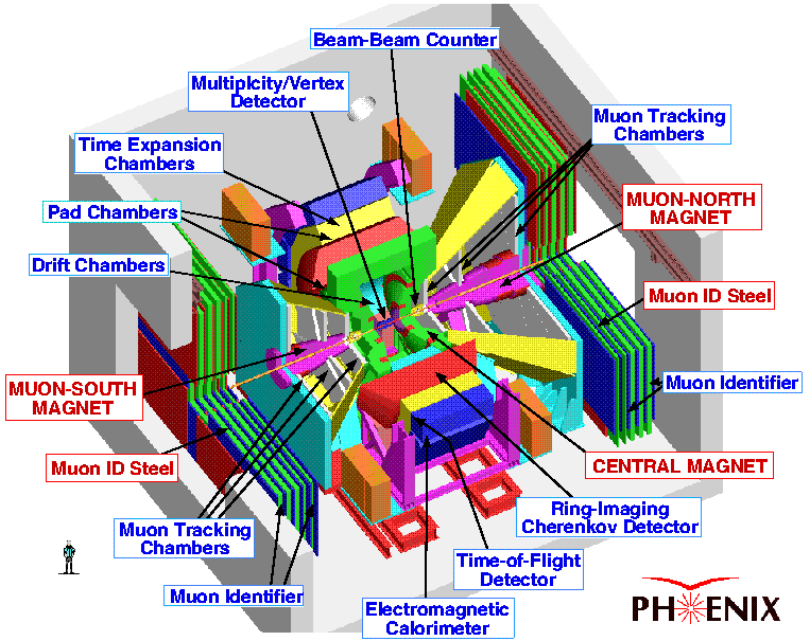
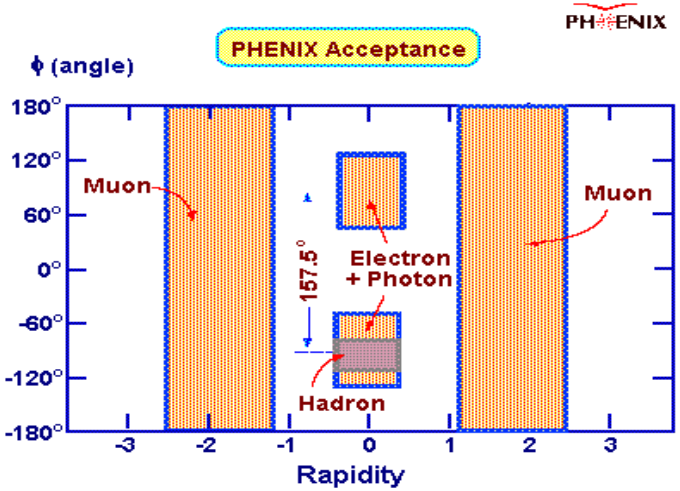
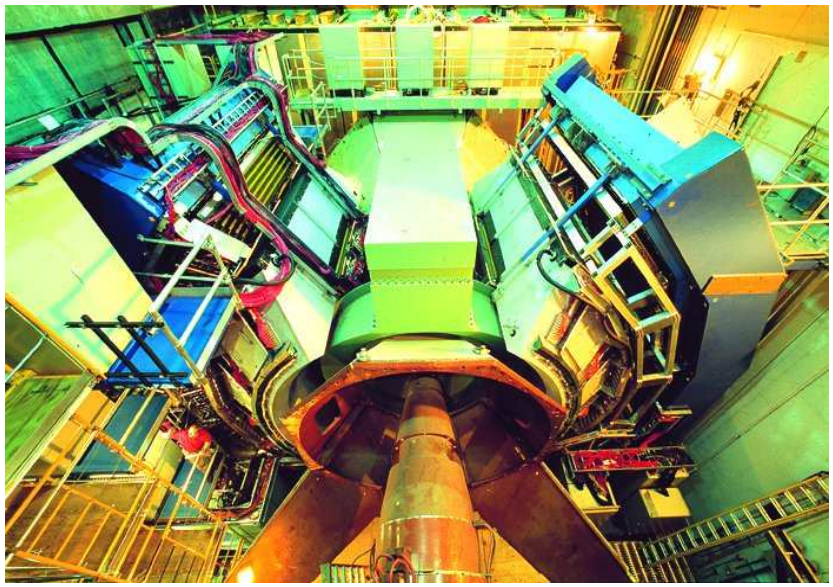
PHENIX @ RHIC

- 11 detector sub-systems
- 2 Arm central spectrometers:
  - $|\eta| < 0.35$, $\Delta\phi = \pi$ (e, γ, hadrons)
  - Open geometry axial field
- 2 forward spectrometers:
  - $1.2 < |\eta| < 2.5$, $\Delta\phi = 2\pi$ (muons)
  - Radial magnetic field
- 3 global (inner) detectors: trigger, centrality
- Designed to measure rare probes:
  - \+ high rate capability & granularity
  - \+ good mass resolution and PID
  - \- limited acceptance

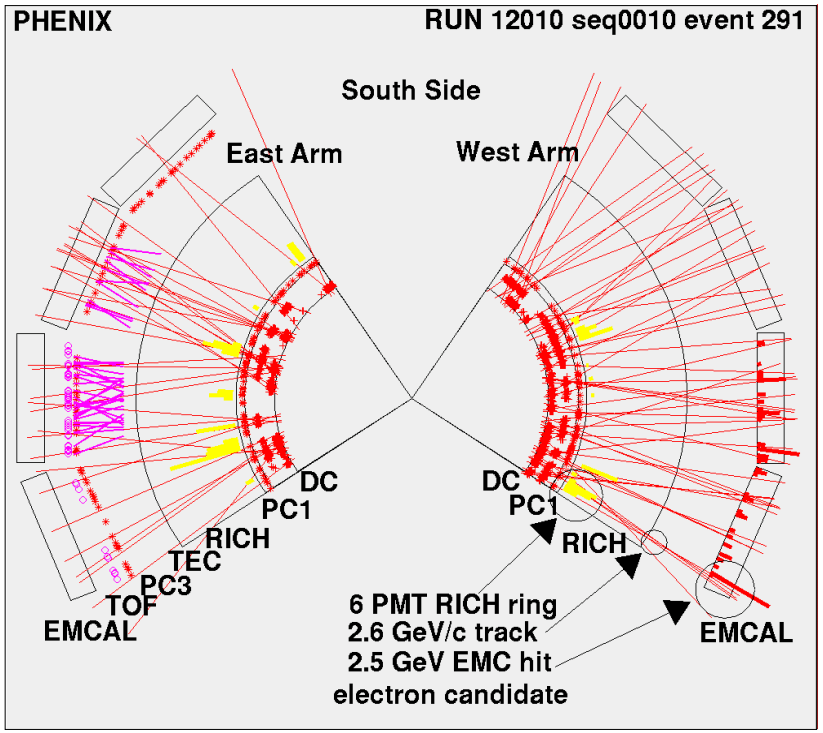


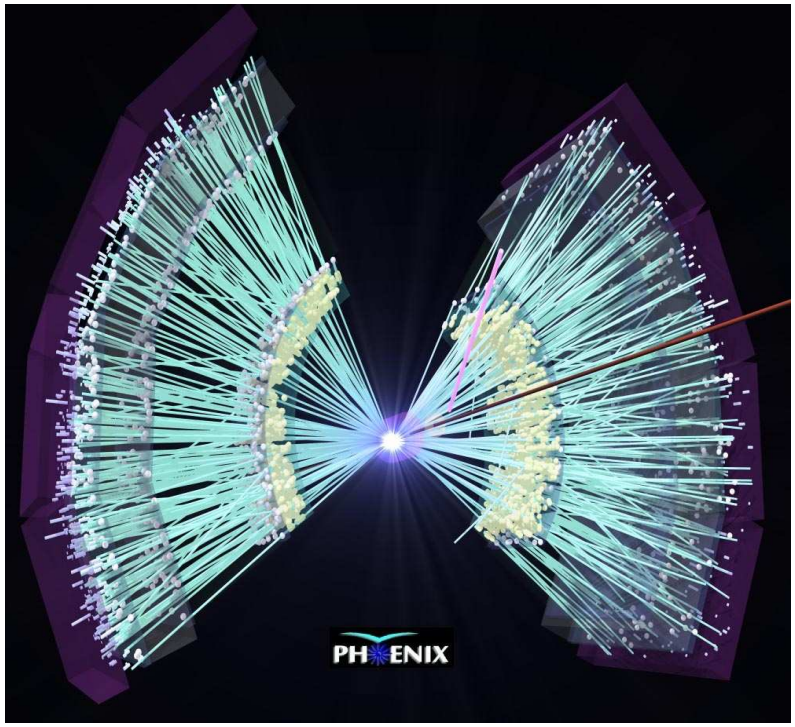




First collisions at PHENIX (Au+Au @ $\sqrt{s_{NN}}$ = 130 GeV, June 2000)

PHENIX Central Arms



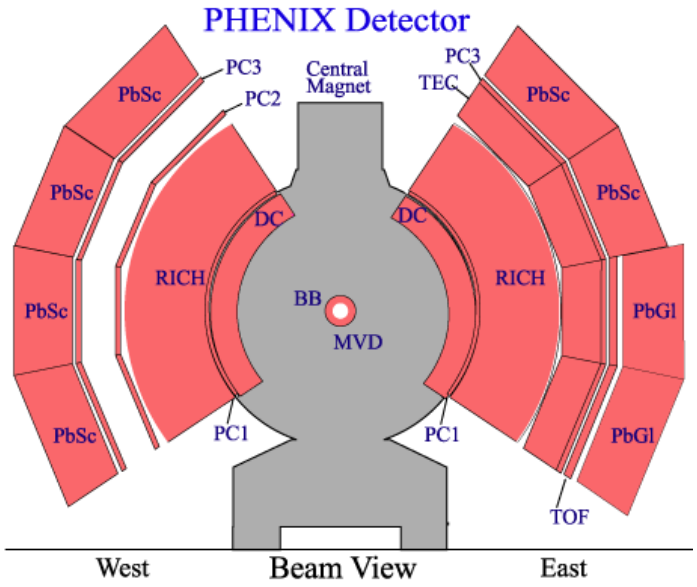


~620 ch. particles per unit rapidity !

(in top 5% most central collisions)

PHENIX Run-2 setup (2001-2002)

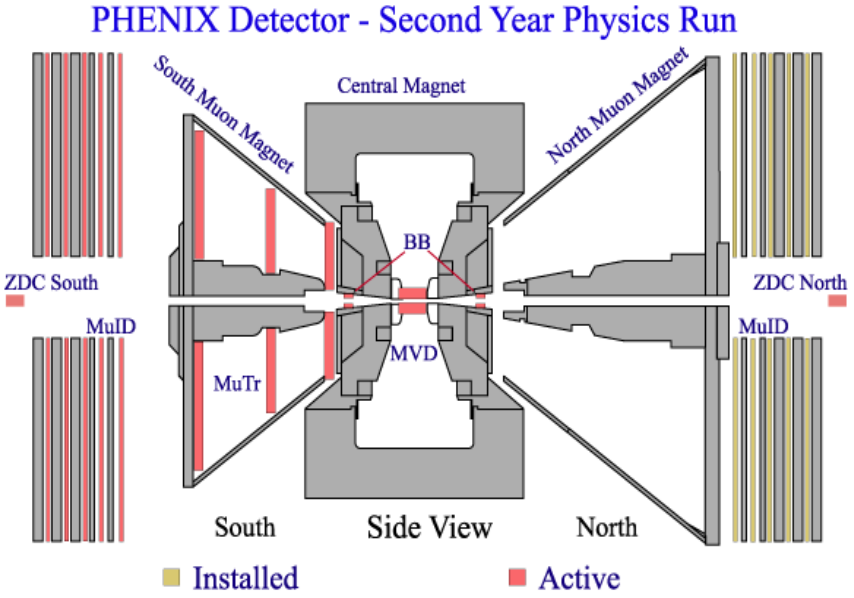
ZDC	Zero Degree Calorimeter	**Global detectors**
BB	Beam Beam Counter	
MVD	Multiplicity Vertex Detector	
DC	Drift Chamber	**Tracking**
PC	Pad Chambers	
RICH	Ring Image Cherenkov	
TEC	Time Expansion Chamber	**PID**
TOF	Time Of Flight detector	
PbSc	Lead-Scintillator Cal.	**Calorimetry**
PbGl	Lead-Glas Calorimeter	



Central magnet (~ 9m high, 500t, B = 0.78 Tm @ 90°)

MuId	(South) Muon Identifier
MuTr	(South) Muon Tracker

North/South magnet



- Au+Au, *p*+*p* collisions @ $\sqrt{s_{NN}}$ = 200 GeV

Integrated luminosity:

Au+Au: ~24 μb^{-1} recorded

p+p : ~150 nb^{-1} recorded

Stats.: ~ 200M Au+Au events "sampled" (LVL2)

~ 180M p+p events

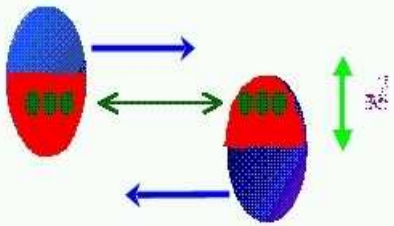
Comparing pp, pA to AA. Reaction centrality.

- Determination of the properties of the hot strongly interacting medium formed in A+A collisions requires comparing to:
  - No medium data : **p+p** collisions
  - Cold medium data: **p+A** collisions
- Particle production cross-sections in AA reactions scale according to the collision geometry (impact parameter). Reaction centrality is determined through: Glauber eikonal model + Global Detectors (ZDC, BBC) response

A+A Collision Geometry

Participant Nucleon Number

$$N_{part}(b) = 2\int d^2s\, T_A(s+\tfrac{b}{2})\left\{1-e^{-\sigma T_A(s-\frac{b}{2})}\right\} \le 2A$$



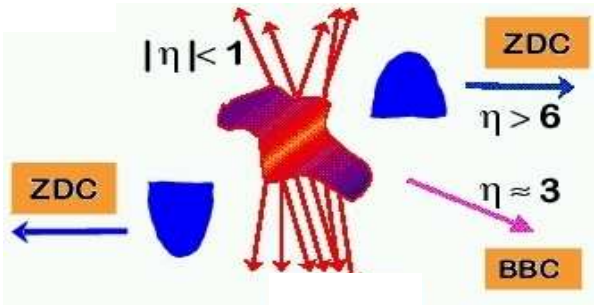
$$T_A(b) = \int dz\, \rho_A(z,b) \approx 2\rho_0\sqrt{R^2-b^2}$$

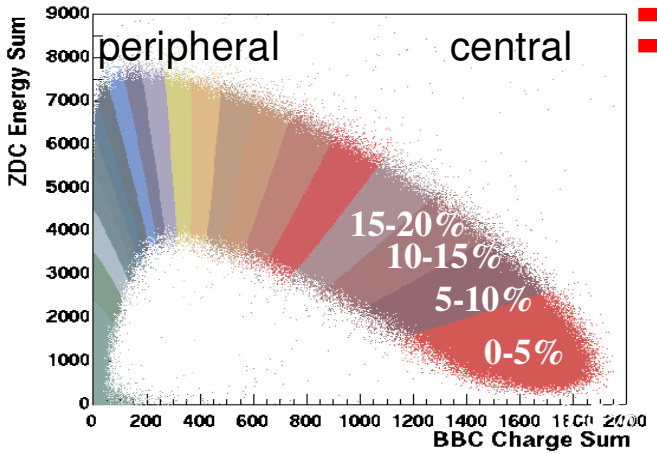
$$T_{AA}(b) = \int d^2s\, T_A(s+\tfrac{b}{2})T_A(s-\tfrac{b}{2})$$

Binary Collision Number

$$N_{coll}(b) = \sigma T_{AA}(b) \sim A^{4/3}$$

M.Gyulassy nucl-th/0106072



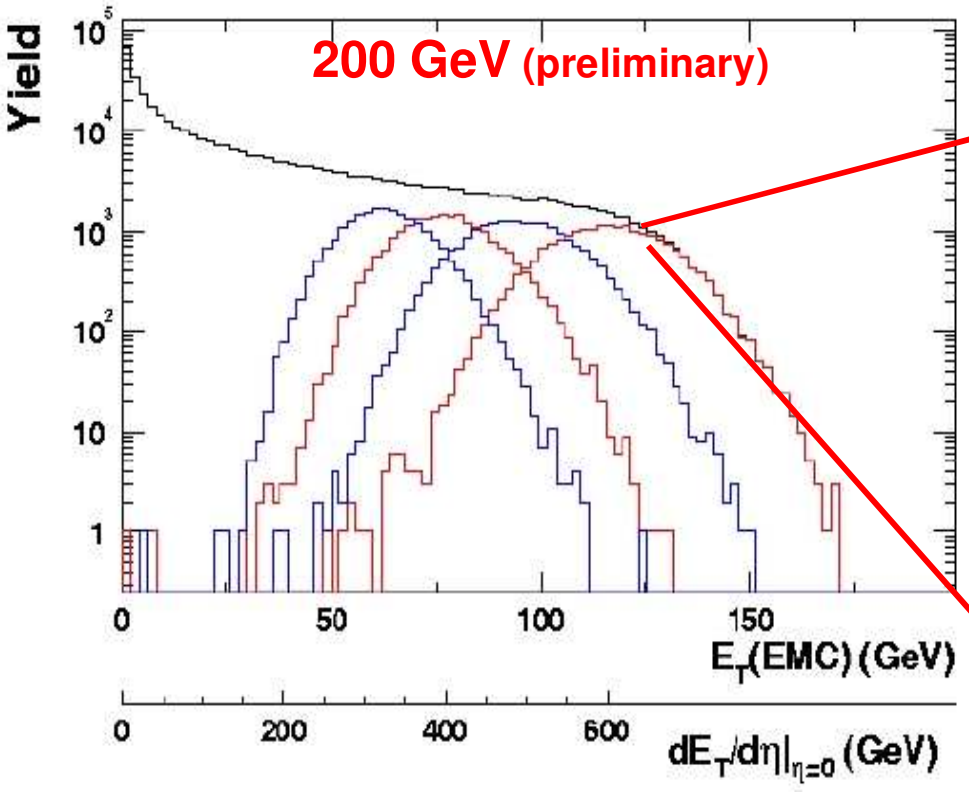


# of participant nucleons:
# of binary inelastic colls.:

cross section fraction	N_{part}	N_{binary}
0-5	348 ± 10	1009 ± 91
5-15	271 ± 9	712 ± 65
15-30	180 ± 7	406 ± 42
30-60	79 ± 5	131 ± 22
60-92	14 ± 3	14 ± 5

Global Results 1: Energy density [PRL 87, 52301 (2001) & QM2002]

E_T at mid-rapidity measured by calorimetry: PHENIX EMCal is a good *hadronic* calorimeter: $E_T^{had} = (1.17 \pm 0.05)\ E_T^{EMCal}$

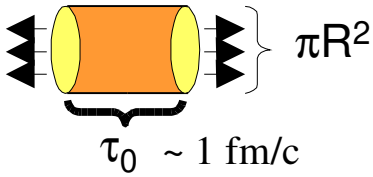


<$dE_T/d\eta$> ~ 600 GeV (top 10% central)

70% larger than at SPS energies

Bjorken's estimate of the energy density (longitudinal expansion):

$$\epsilon_{Bj} = \frac{dE_T}{dy}\frac{1}{\tau_0\,\pi R^2}$$



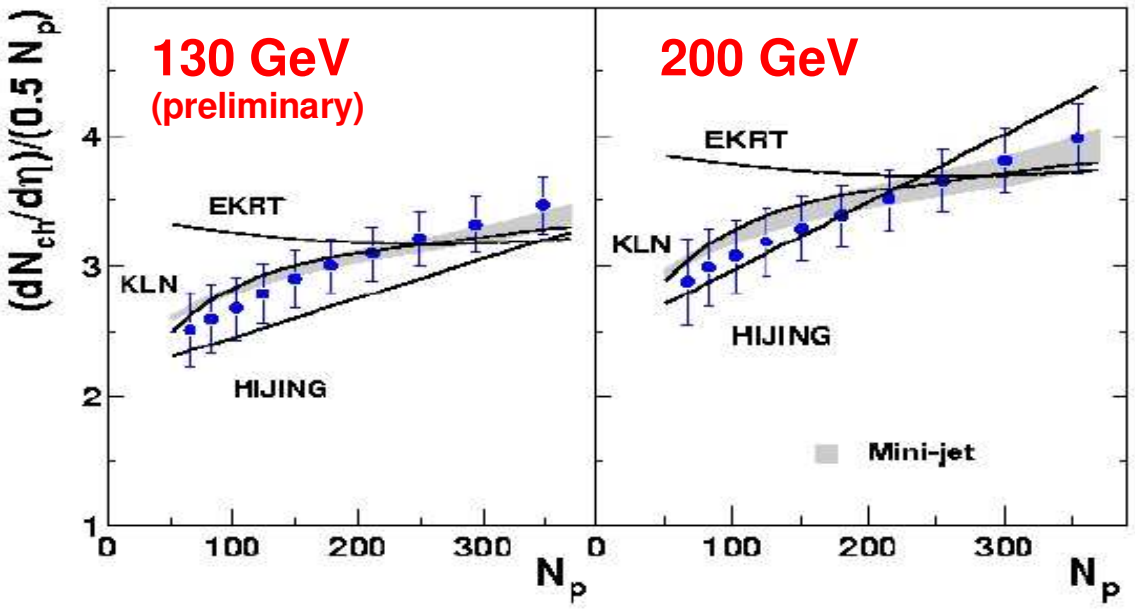
$\varepsilon_{Bjorken}$ ~5.0 GeV/fm^3

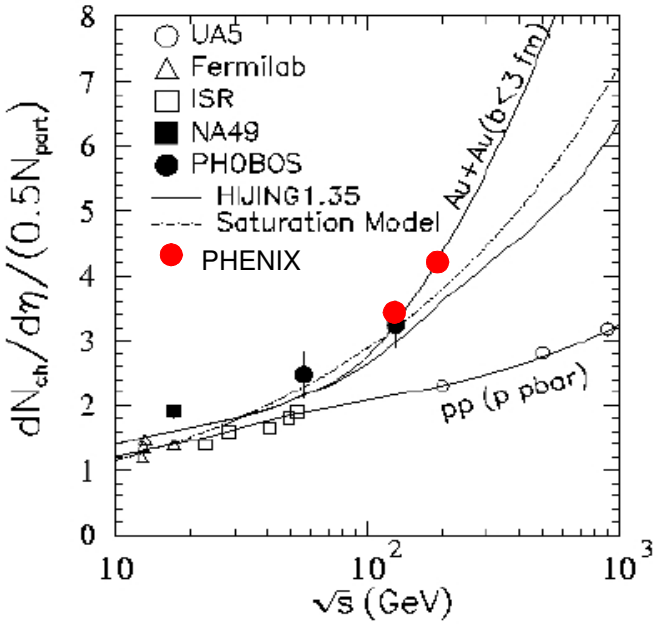
Energy density (~5 GeV/fm^3) @ RHIC > QCD critical density (~1 GeV/fm^3)

[*modulo: 1D expansion, not fully baryon-free, thermalization time estimate*]

Global Results 2: Particle Multiplicity vs. centrality

[PRL 86, 3500 (2001), and QM2002]

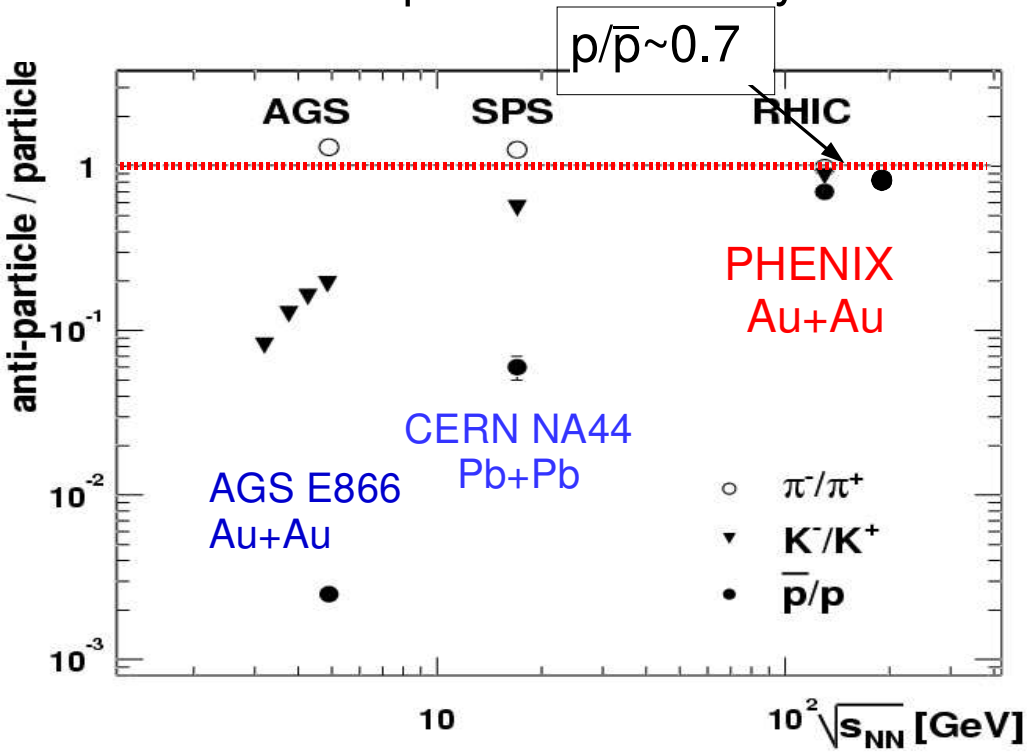




- dN_{ch}/dy constraints mechanisms of initial multi-particle production.
- dN_{ch}/dy increases faster than linearly with centrality (N_{part}):
  - ✔ "Soft + hard" (HIJING, “minijet”): increased hard contribution (prop. to N_{coll})
  - ✔ Initial-state gluon saturation (KLN): $dN_{ch}/dy \sim dN_{gluon}/dy \sim 1/\alpha_s \sim N_{part} \ln N_{part}$
  - ✖ Final-state gluon saturation (EKRT)

Global Results 3: Net baryon density at midrapidity

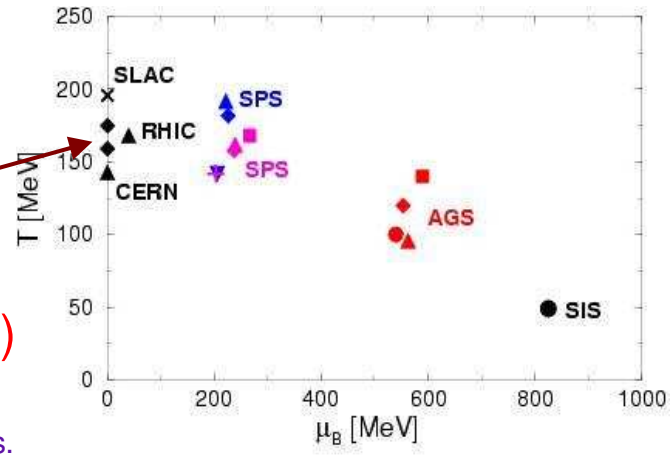
Particle to anti-particle ratios at y=0:



- 2/3 of protons at y = 0 come from pair production
- Much closer to baryon-free region than SPS
- Low baryo-chemical potential at freeze-out

(statistical model Redlich *et al*):

μ_B ~ 45 MeV ($\sqrt{s}$=130 GeV), 30 MeV ($\sqrt{s}$=200 GeV)



Hard QCD probes in HI collisions

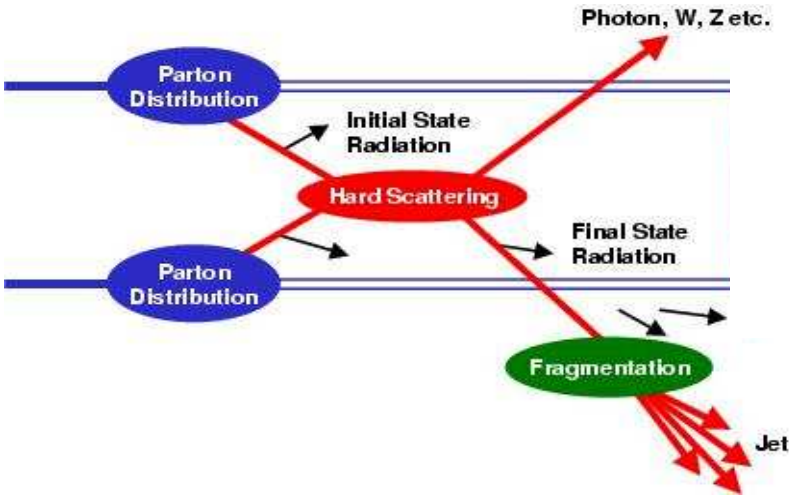
- Early production ($\tau \sim 1/p_T \sim$ 0.1 fm/c) in parton-parton scatterings with large Q^2
- Direct probes of partonic phases $\Rightarrow$ Sensitive to hot/dense medium effects: parton energy loss ("jet quenching"), color screening ("onia" suppression).
- Probes: High-p_T (jets, prompt γ), heavy-flavor (D, B, J/Ψ)
- Direct comparison to baseline "vacuum" (*pp*) data via "binary scaling":

$$\sigma_{AB\ (hard)} = \int d^2b[1-e^{-\sigma_{pp} T_{AB}(b)}] \approx AB \times \sigma_{pp\ (hard)}$$

AB = total # of binary inelastic *NN* colls.

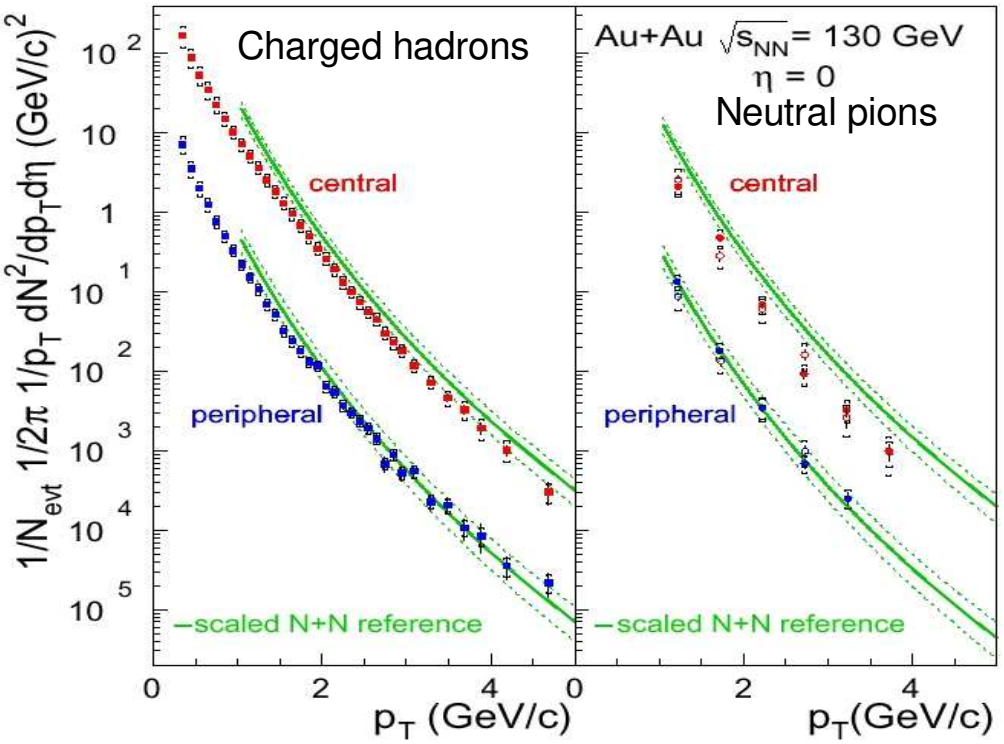
- Elementary processes calculable via pQCD (Factorization theorem):

$$\sigma_{AB \to hX} \propto f_{a/A}(x_a, Q^2_a) \otimes f_{b/B}(x_b, Q^2_b) \otimes \sigma_{a\,b \to cd} \otimes D_{h/c}(z_c, Q^2_c)$$

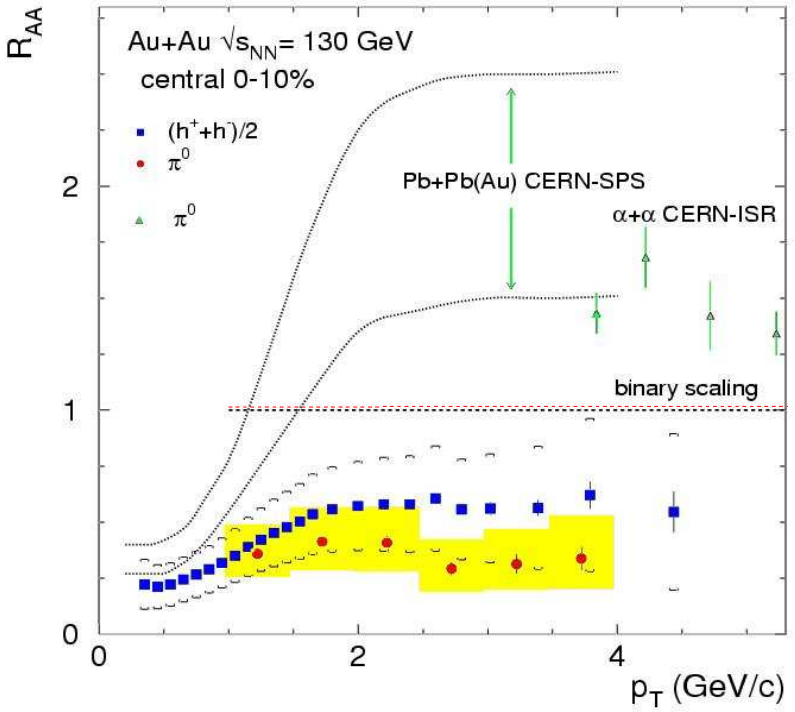


High p_T (Run-1): AuAu *vs* (scaled) *pp* [PRL88:022301 (2002)]

- Jet physics in HI collisions ≡ High-p_T hadron physics:
  - Standard jet algorithms fail in HI collisions below p_T ~ 40 GeV/c (at $\sqrt{s_{NN}}$ = 200 GeV) due to large soft background.
  - Hadrons with p_T>2 GeV/c ≡ products of parton fragmentation ("leading particle")
- Peripheral AuAu consistent with *pp* binary-scaled yields
- Central AuAu yields suppressed by a factor 2. - 4.

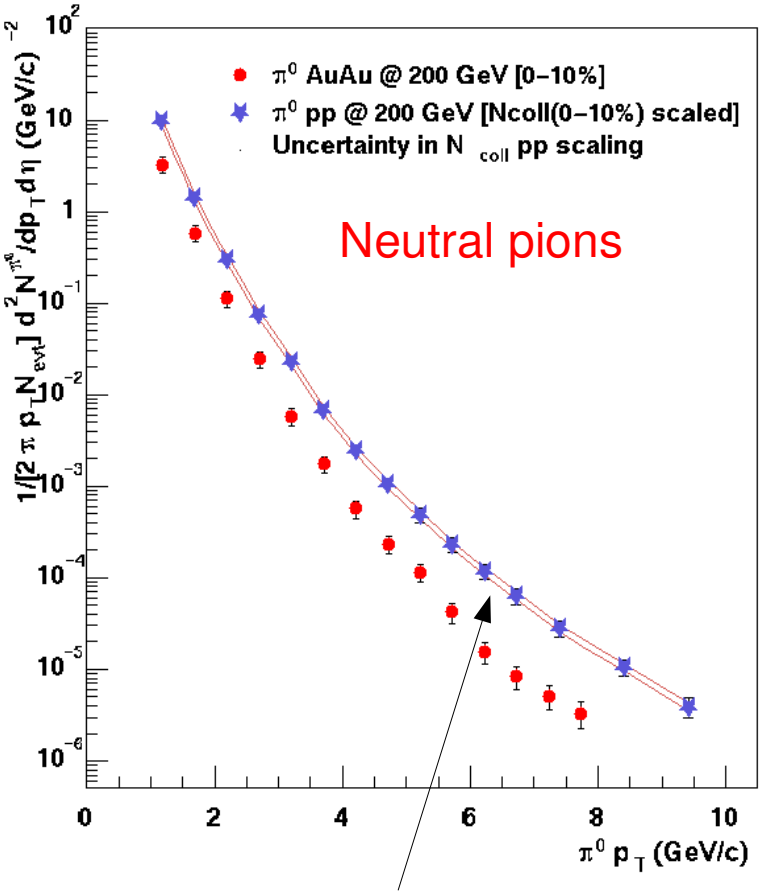


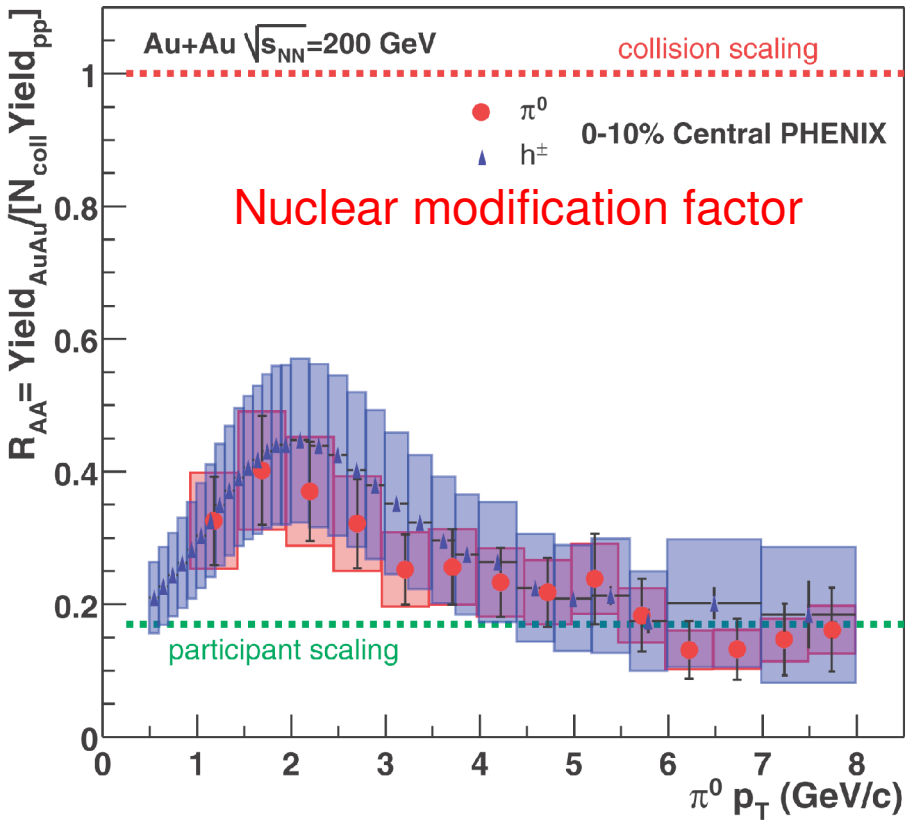
Nuclear modification factor



High p_T (Run-2): AuAu *vs* (scaled) *pp* [Quark Matter 2002]

- Peripheral AuAu consistent with *pp* data
- Central AuAu: Increasing suppression with p_T:
  - Factor ~4 (charged hadrons) and ~ 5 - 6 (π^0)



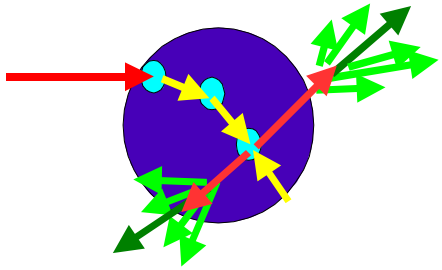


Scaled π^0 from *pp* data (measured in same run)

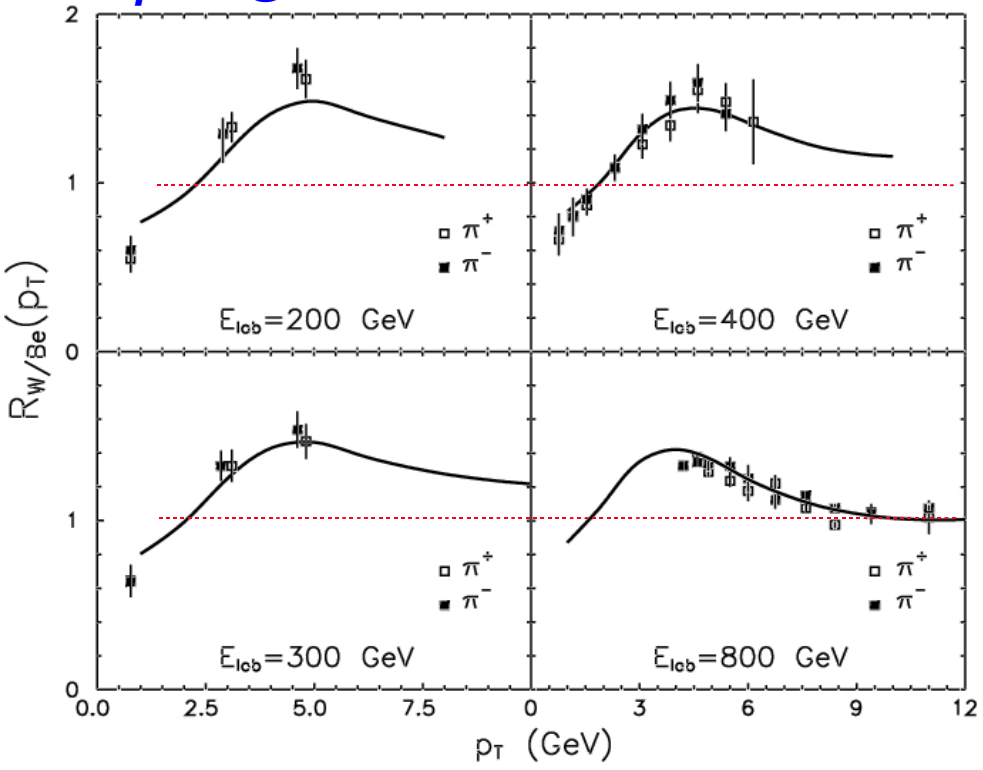
High p_T at lower energies: Cronin enhancement

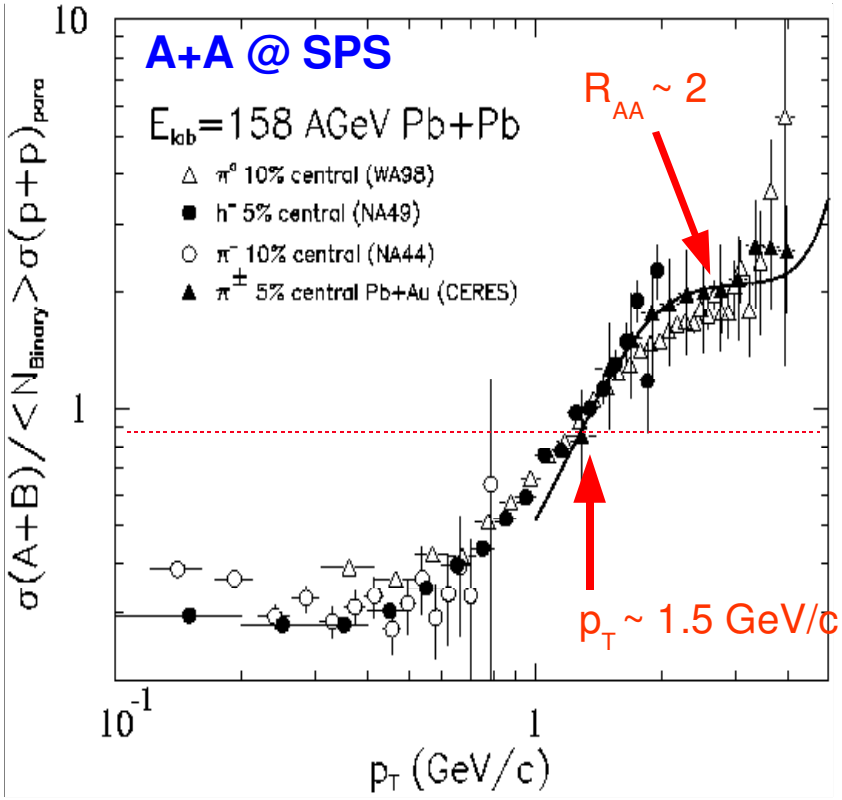
- Increased high-p_T production in *p*A, AA collisions: $R_{AB} > 1$
- Initial-state multiple (soft & semi-hard) parton interactions (before hard scattering): k_T broadening

  [*additional to intrinsic proton* $k_T^2 \sim 2.0\ GeV^2$]



***p* +A @ FNAL**





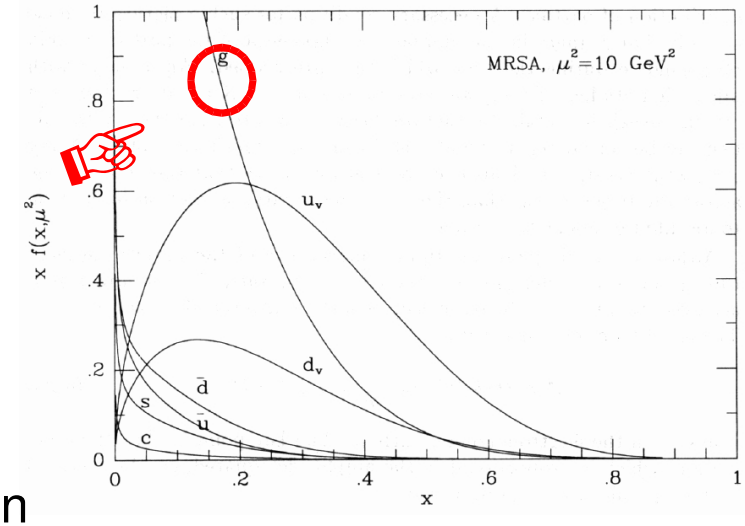
- Exactly the opposite trend is observed at RHIC !

High p_T supp. & initial-state effects: gluon shadowing (1)

- Relevant *x* region for high-p_T (2.- 10. GeV/c) @ RHIC:

  $x_T = 2p_T^{parton} / \sqrt{s} = 2\,(p_T^{hadron}/z) / \sqrt{s} \Rightarrow$

  [taking z~1, $x \sim x_T$] $\Rightarrow$ x ~ 0.02-0.2

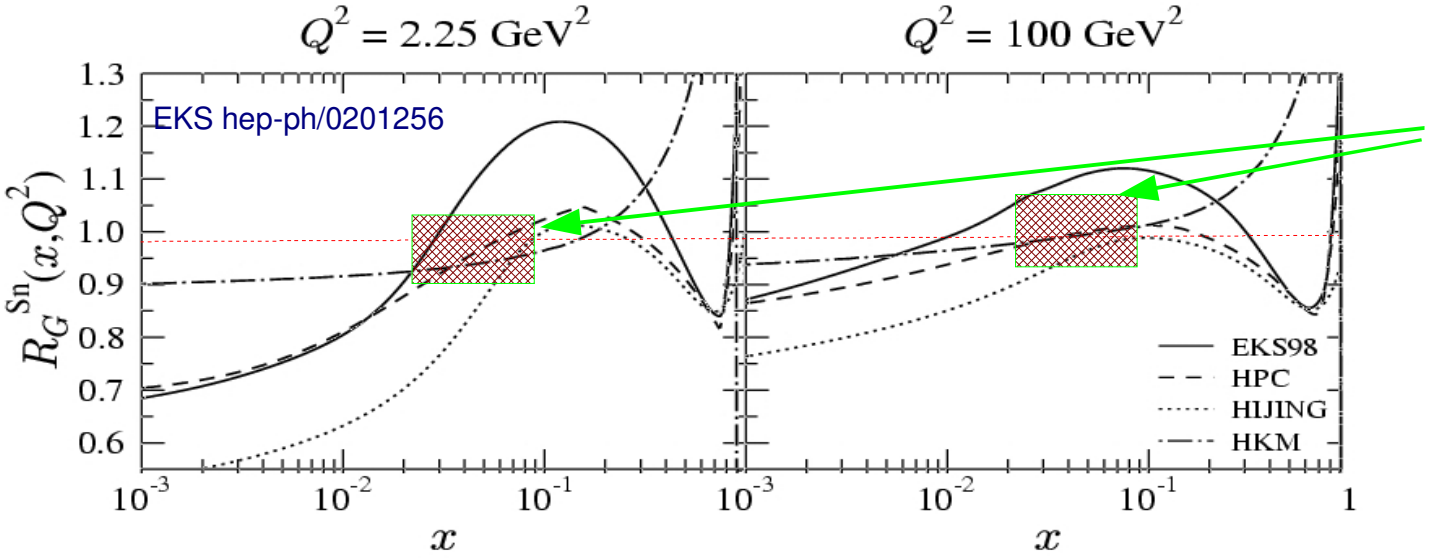


- Proton: *x* < 0.1 P(arton)DFs ≈ G(luon)DFs:
- Nuclei: Even more gluonic

$xG(x,Q^2) \sim A^{1/3}/x^{\delta}$ (with $\delta \sim 0.2$-0.3)

For x<0.1 : PDFs depleted compared to proton

$R(x,Q^2,A) \equiv f_i^A(x,Q^2) / [A\, f_i^N(x,Q^2)] < 1$ ➔ Shadowing (parton recombination, ...)



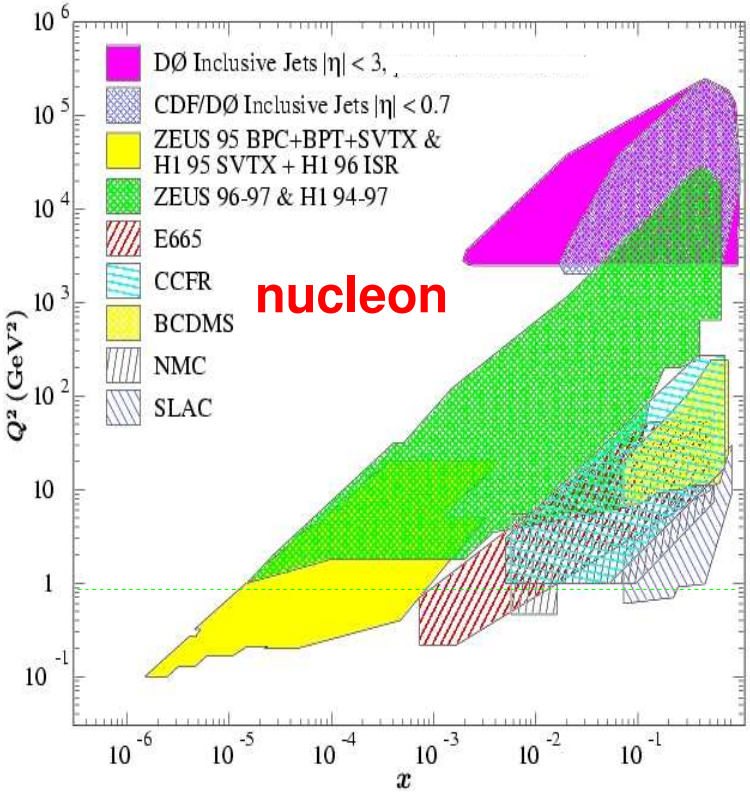
$R_G \sim 0.9$ at most for the relevant PHENIX high-p_T kinematics range

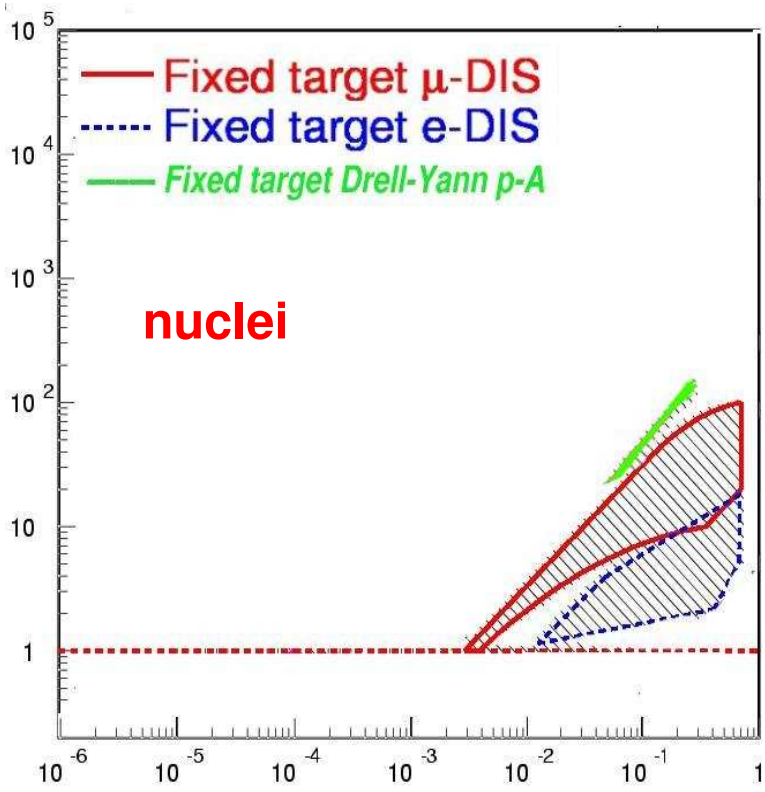
⇒ Strong shadowing is ruled out !

High p_T supp. & initial-state effects: gluon shadowing (2)

Note however ...

- (x,Q^2) scale-dependence of nuclear PDFs (specially gluons) less known than for nucleons (limited range of x, Q^2, A covered in available *lepton*- A exp.).

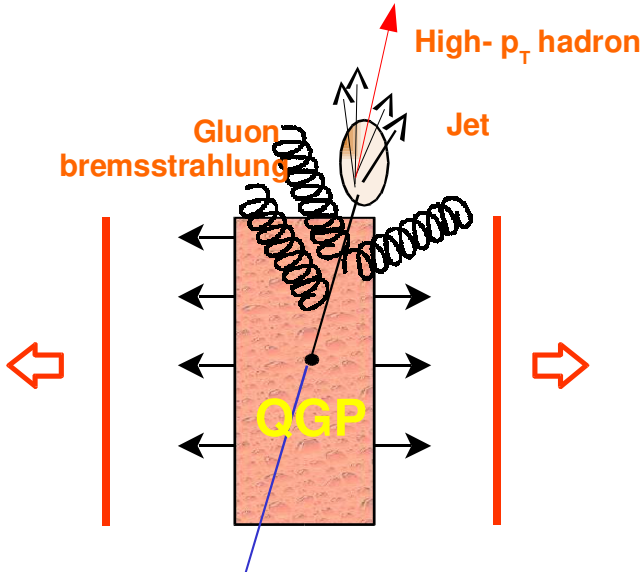


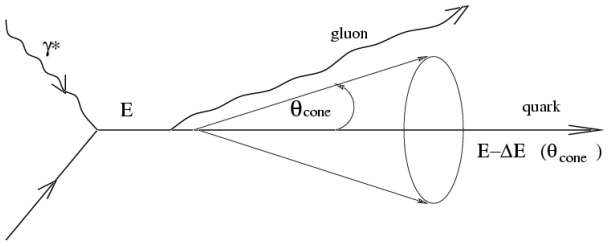


➽ *p,d*+A collisions at the same $\sqrt{s}$ needed to investigate the actual role of initial-state effects (Run-3 at RHIC !)

High p_T suppression & radiative parton energy loss

- Multiple final-state gluon radiation off the produced hard parton induced by the traversed (dense and hot) colored medium:
  - Mean parton energy loss proportional to:
    $\Delta E \sim \rho_{gluon}$ (gluon density)
    $\Delta E \sim \Delta L^{(2)}$ (medium length)
  - Energy is carried away by gluon bremsstrahung outside jet cone: $dE/dx \sim \alpha_s \langle k^2_T \rangle$
  - Expanding vs. static plasma:
    $\Delta E_{1\text{-}D} = (2\tau_0/R_A)\Delta E_{stat} \sim 15 \cdot \Delta E_{stat}$ (τ_0=0.2 fm/c, R_A=6 fm)



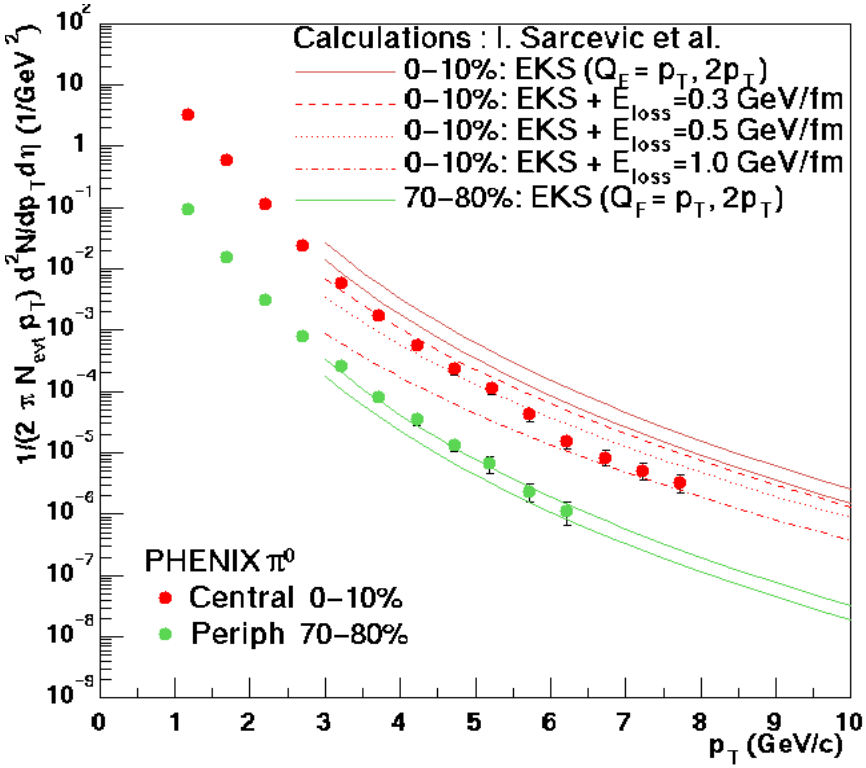


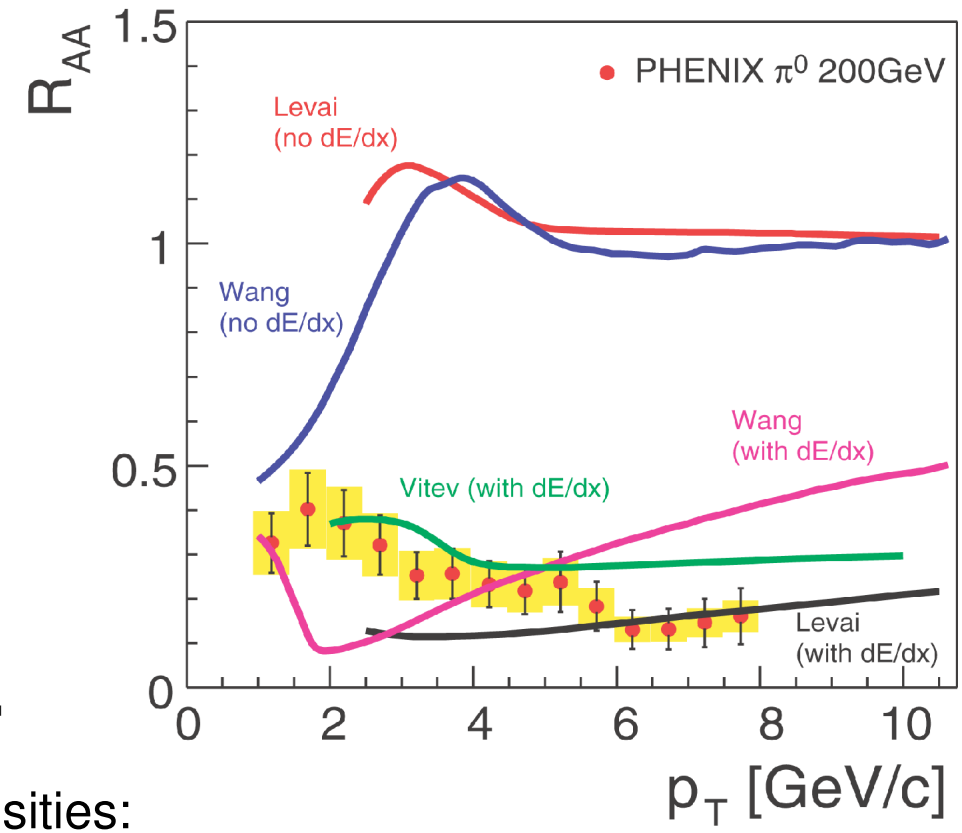
- Observables:
  i) Depletion of leading-particle inclusive high p_T spectra: "jet quenching"
  ii) Photon-tagged jets, direct γ vs fragmentation γ ...
- Well above energy loss in cold nuclear matter:

BDMPS: $\Delta E(T=250\ MeV) \sim 15 \cdot \Delta E(T=0)$, $dE/dx \sim 0.5$ GeV/fm (HERMES *eA* data), FNAL E772: $dE/dx \sim 0.2$ GeV/fm (D.Y. *pA* data)

High p_T suppression: Data vs. theory

(N)LO pQCD calculations including "conventional" nuclear effects (k_T enhanc., nuclear PDFs) + modified FFs to take into account medium-induced energy loss.





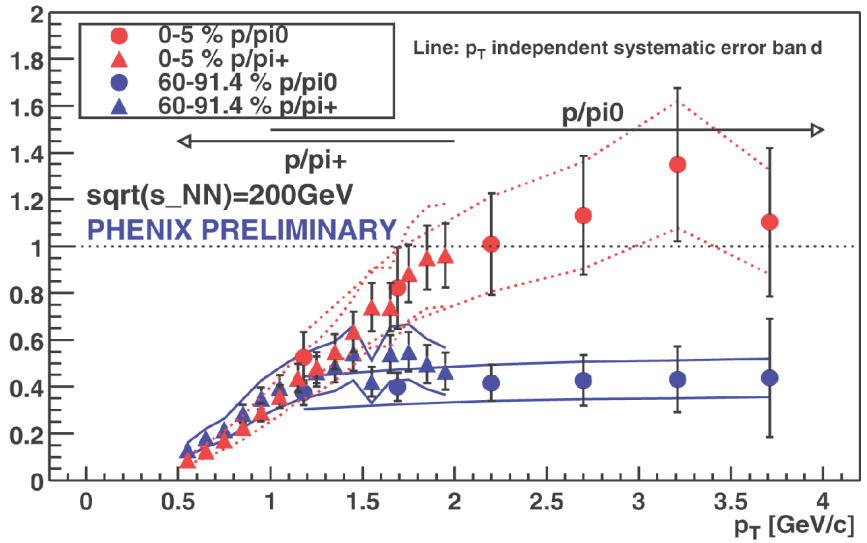
- Energy losses / opacities / gluon densities:

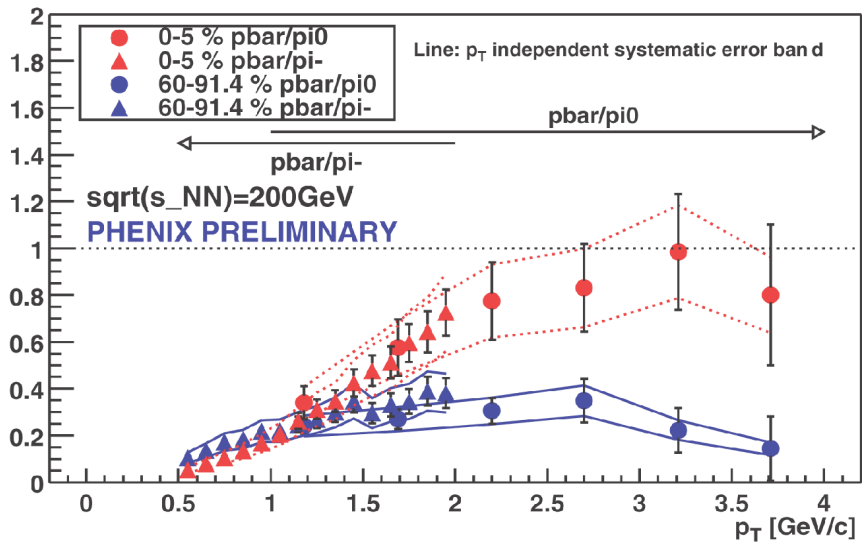
  dE/dx =0.25 GeV/fm (expanding), $L/\lambda \sim 3-4$, $dN^g/dy \sim 900$
  equivalent to $dE/dx|_{eff} \sim 7$ GeV/fm (static source)

- Yet, alternative explanations exist: Hadronic final-state energy loss, CGC, ...

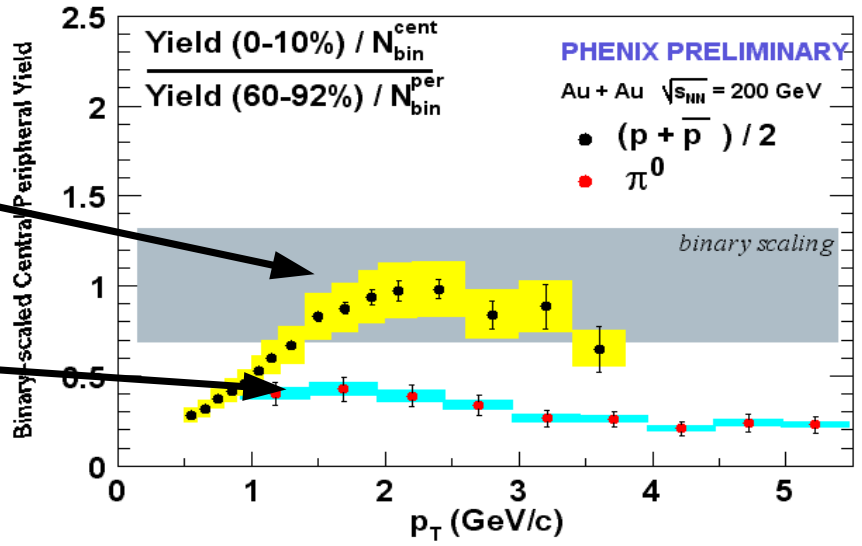
Hadron composition at high-p_T [PRL 88, 242301 (2002) & QM2002]

- Baryon yield ≈ pion yield for p_T>2 GeV/c in central colls.
- High-p_T baryon/meson ratio ~ 0.3 in p+p,pbar collisions (ISR,FNAL)





- p, pbar not suppressed !
- π^0 suppressed



High p_T azimuthal correlations: Jet signals in AA [Quark Matter 2002]

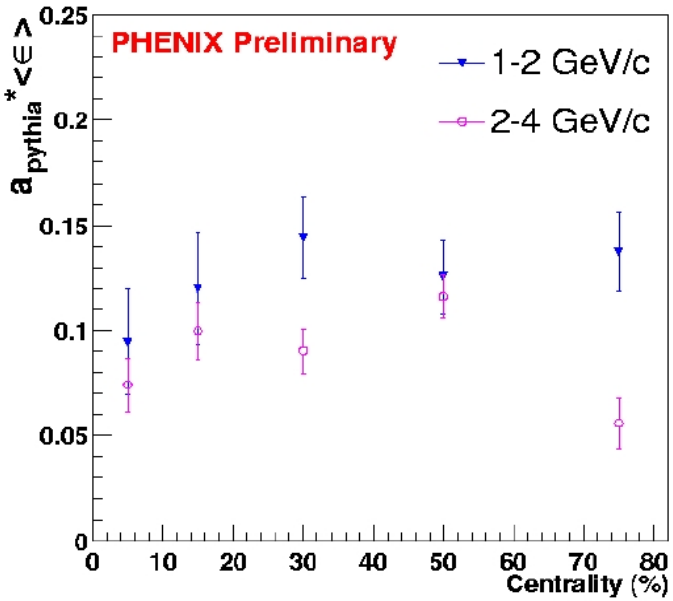
- High-p_T γ (π^0) triggered events: $dN/d\Delta\phi$ for charged-hadrons (p_T = 2- 4 GeV/c)

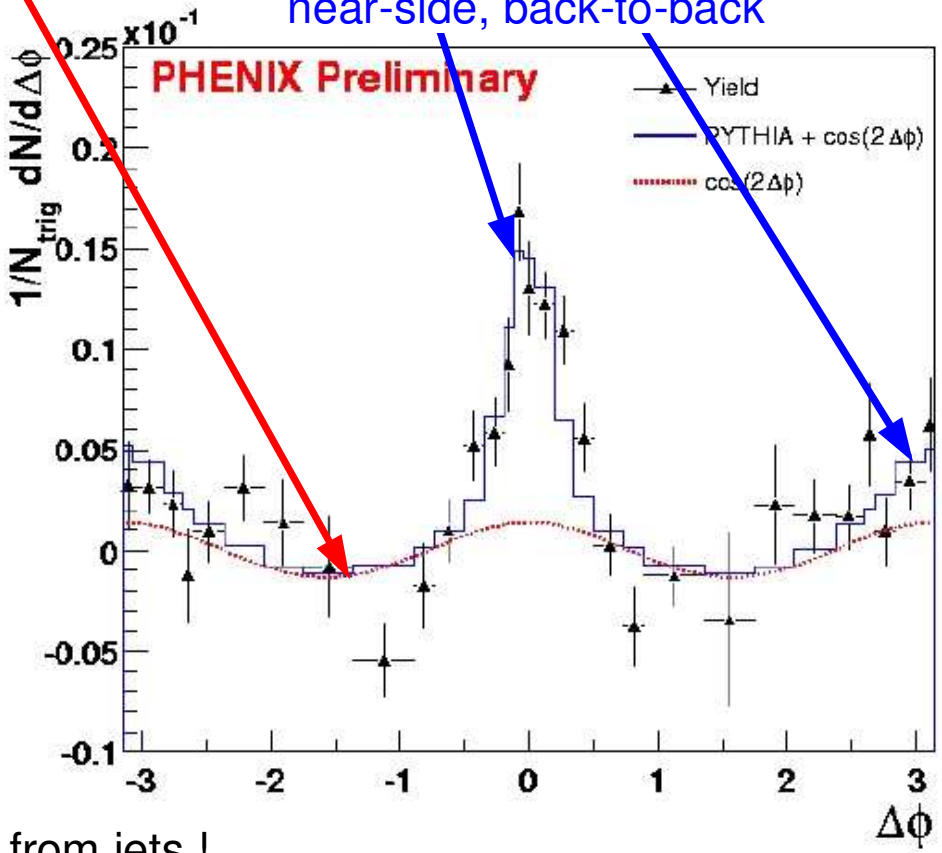
$$\frac{1}{N_{trig}}\frac{dN_{ch}}{d\Delta\phi} \sim (a_{bkg} + a_{flow}cos(2\Delta\phi) + a_{pythia}\frac{1}{N_{pythia}}\frac{dN_{ch}}{d\Delta\phi})$$

Flow contribution

Jet-like signal: near-side, back-to-back

- Near-side correlation unmodified:

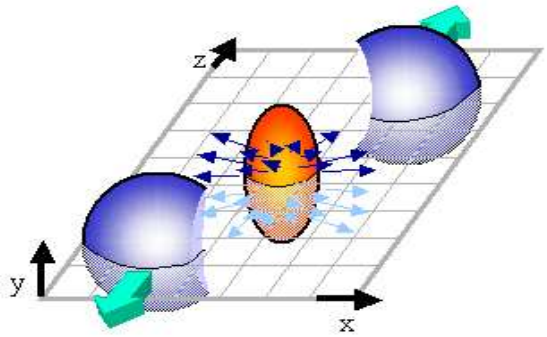




- Most trigger particles (p_T > 4GeV/c) from jets !

High p_T azimuthal correlations: Elliptic flow [PRL 89, 212301 (2002)]

- Initial anisotropy in coord. space (overlap in non-central collisions) translates into final azimuthal asymmetry in momemtum space (transverse to the reaction plane)

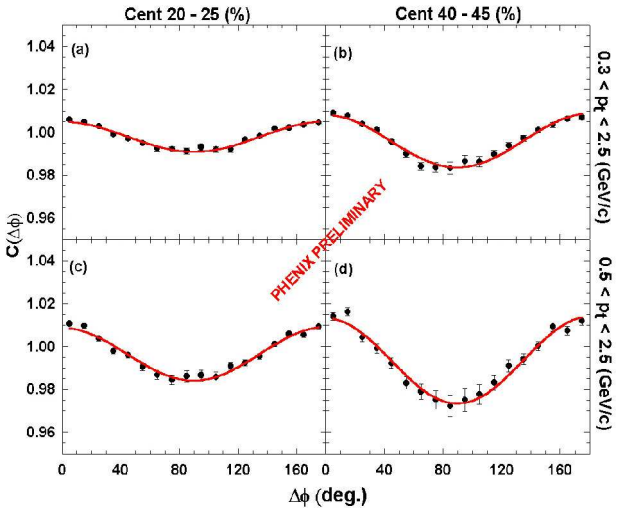


$$\frac{dN}{d^2p_\perp\, d\Phi} = \frac{dN}{d^2p_\perp}\{1 + v_2(p_\perp)\cos(2\Phi)\}\,.$$

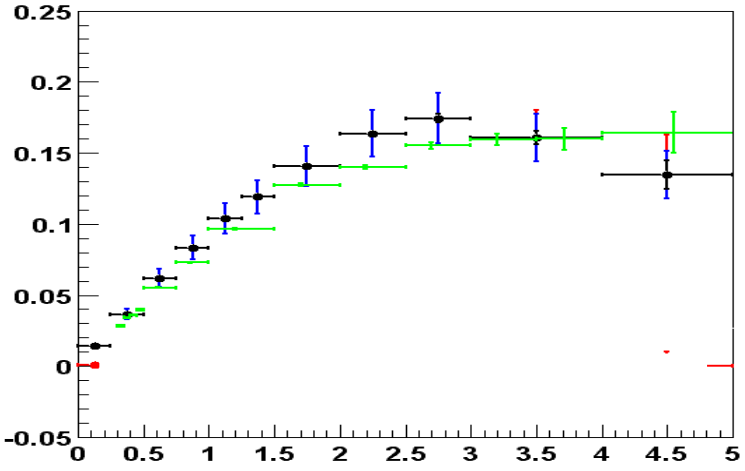
Flow = v_2 Fourier coefficient

Truly collective effect: absent in p+p colls.

- Exp. correlation functions:



- v_2 saturation at high p_T:

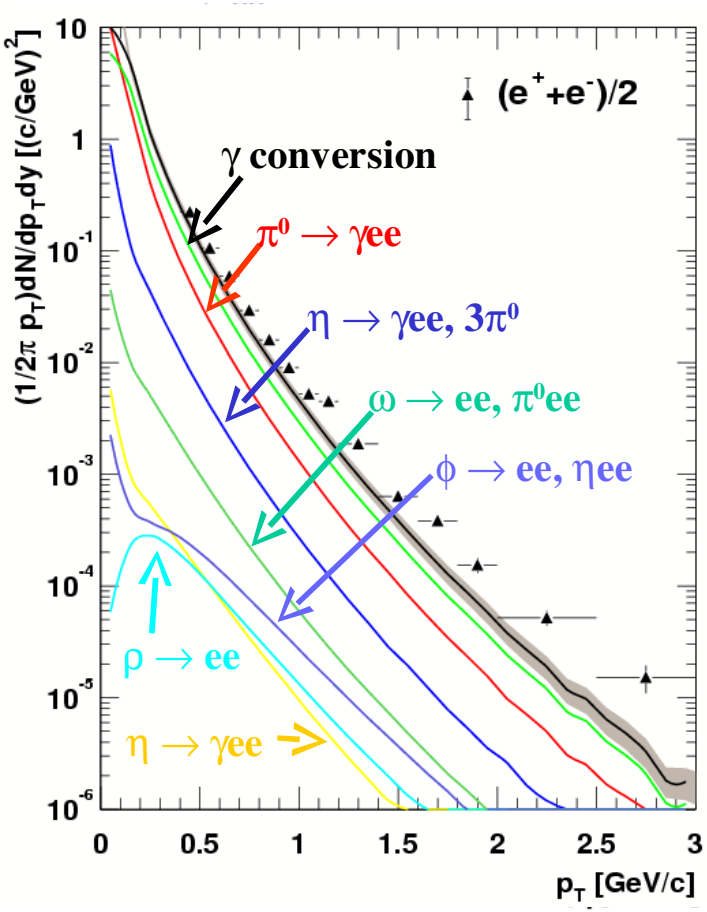


- Strong elliptic flow signal ⟹ strong (collective) pressure gradients

  ⟹ large initial state (t<1.0 fm/c) parton rescattering (early thermalization).

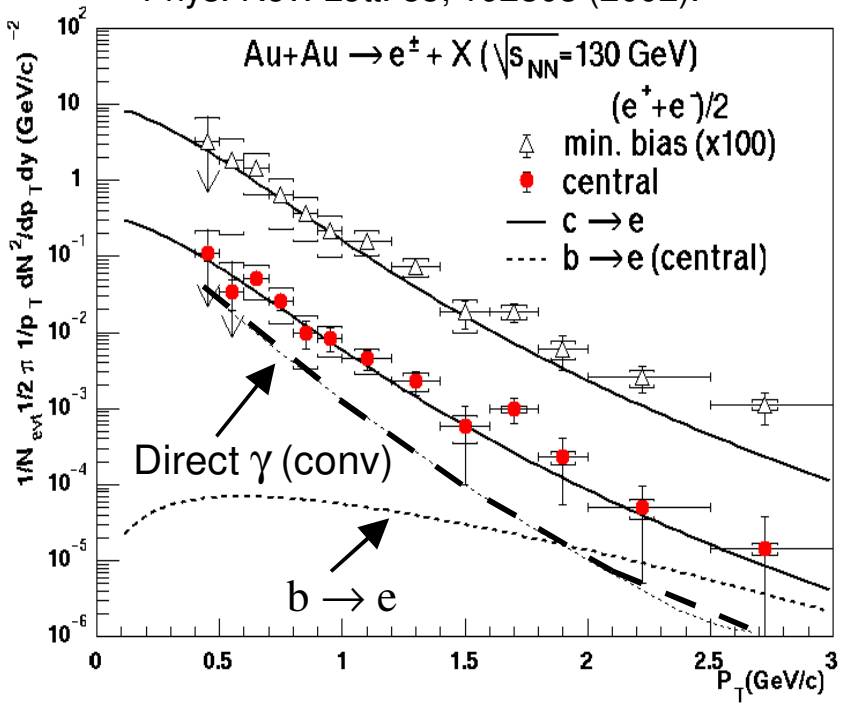
Hard probes & single electron continuum [PRL 88, 192303 (2002)]

- Hard probes signals contributing to electron spectrum:
  - Heavy quark: open charm & bottom (via semi-leptonic decays c →eX, b → eX): Initial gluon density, energy loss of heavy flavors, baseline for J/Ψ suppression ...
  - Thermal dileptons, direct photons (virtual, conversion), Drell-Yan.
- Background "cocktail":



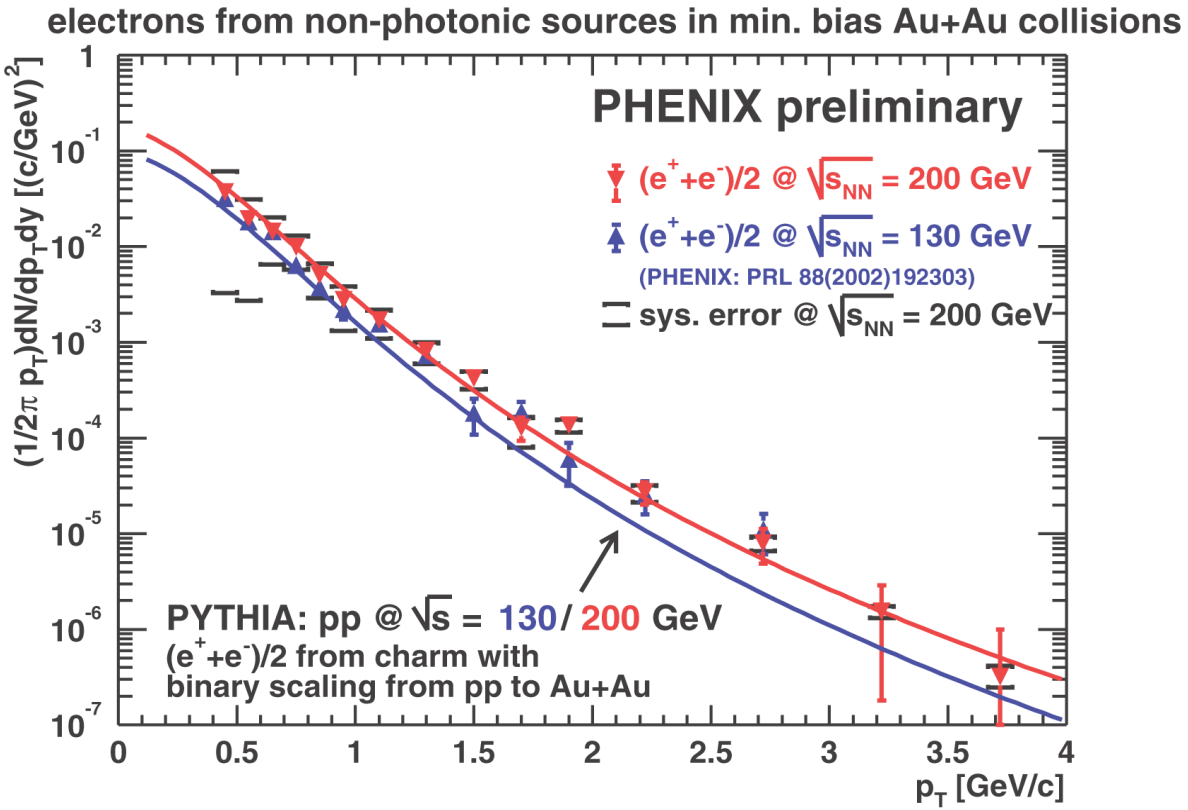
- Inclusive $(e^+ + e^-)/2$ spectrum:

Phys. Rev. Lett. 88, 192303 (2002).



Heavy-Flavor: Open charm from e- data [PRL 88, 192303 (2002), QM 2002]

- Background subtracted single electron spectra (Run-1 & Run-2):

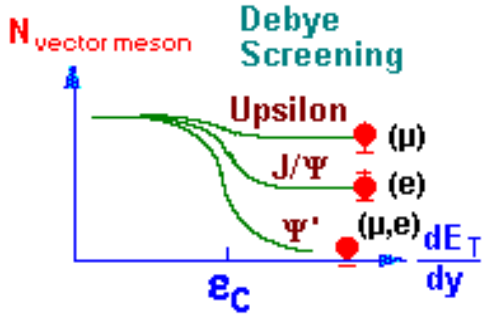


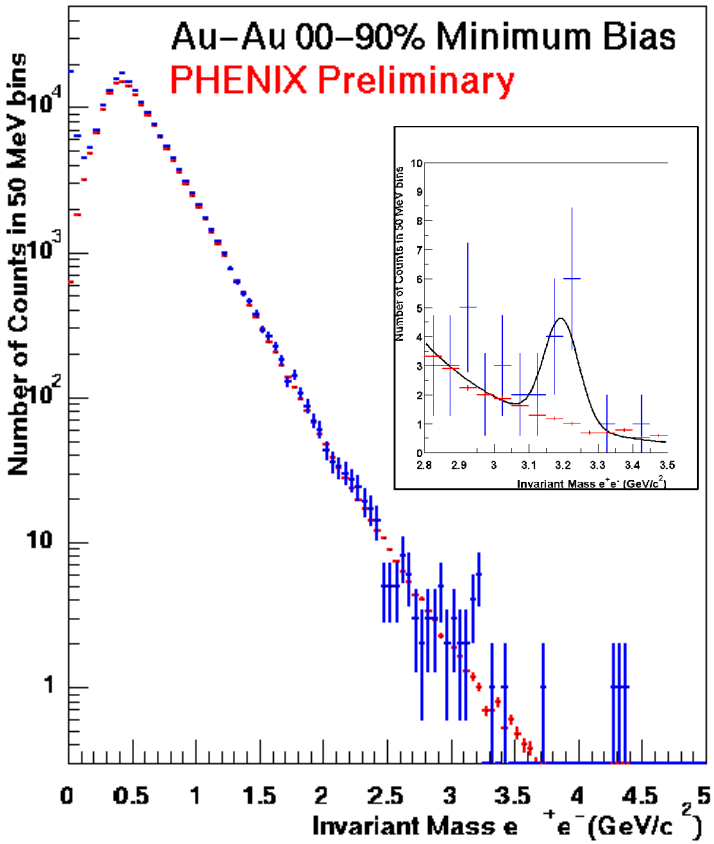
- Electron spectrum/cross-section consistent with *pp* (PYTHIA 6.152) binary-scaled charm production (i.e. no nuclear or medium effects) for all centralities.
- Factor of ~5-6 suppression in high p_T π^0 (relative to binary scaling) not observed. Less energy loss of heavy quarks in medium ("dead-cone" effect) ?

Heavy-Flavor: First look at J/ψ [Quark Matter 2002]

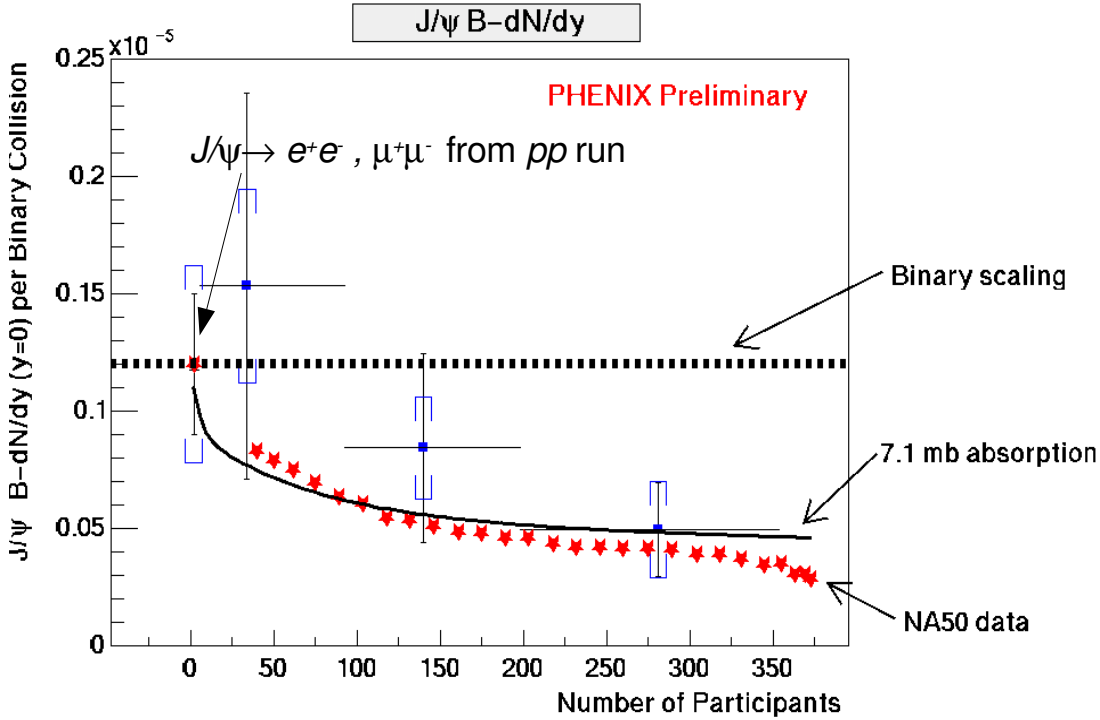
- Motivation: Suppression of heavy quarkonia states due to screening of color potential at deconfinement.
- $J/\psi \rightarrow e^+e^-$ (mid-rapidity) in AuAu:

  $N = 10.8 \pm 3.2\ (stat) \pm 3.8\ (sys)$





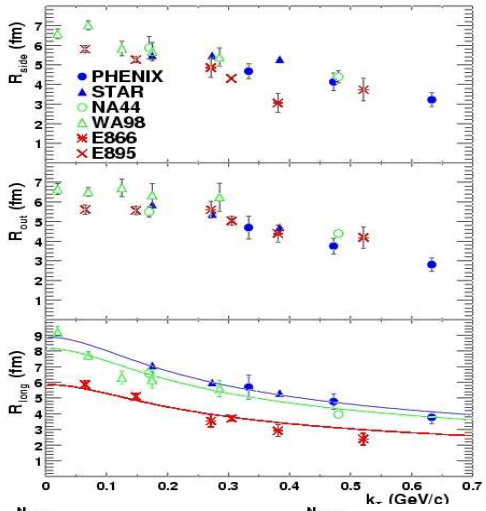
- Centrality dependence of J/ψ yield:

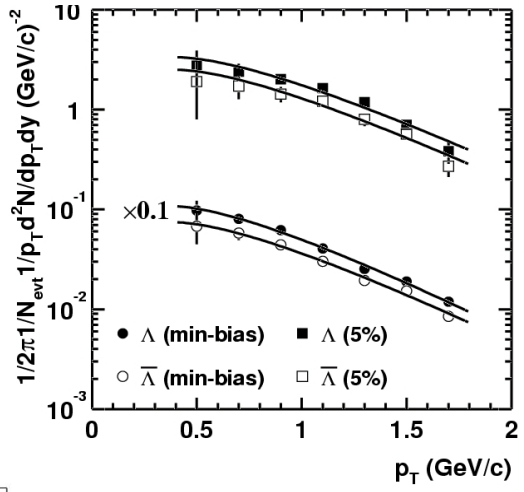


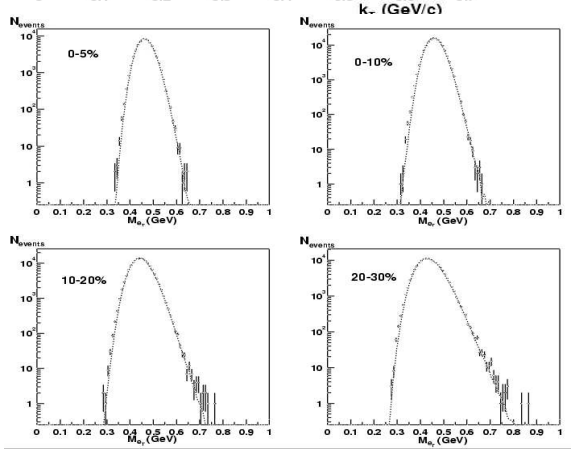
- Not firm conclusion yet. Higher luminosity running needed (also for $J/\psi \rightarrow \mu^+\mu^-$)

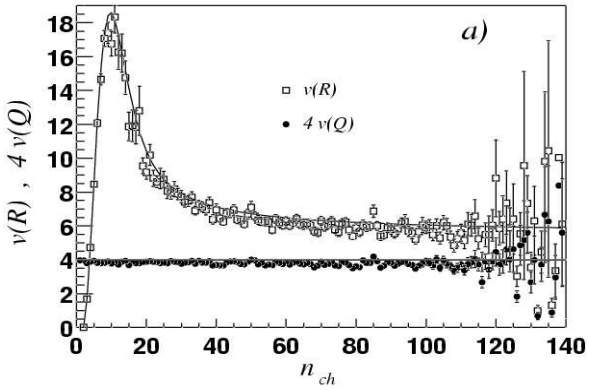
other PHENIX topics *not* covered in this talk ...

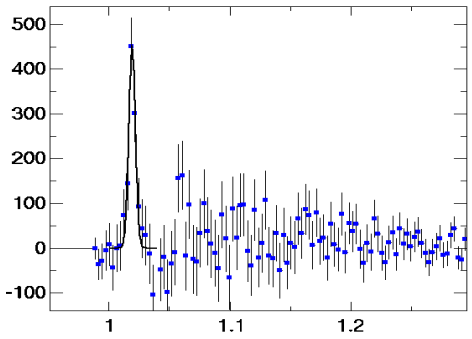
- Two-pion HBT
  PRL 88, 192302 (2002)
- Lambda baryons
  PRL 89, 092302 (2002)
- $\langle p_T \rangle$, E_T fluctuations
  PRC 66, 024901 (2002)
- Net charge fluctuations
  PRL 89, 082301 (2002)
- Vector mesons ($\phi \rightarrow e^+e^-$, K^+K^-)
  QuarkMatter 2002, nucl-ex/0209028
- Direct photons
  QuarkMatter 2002, nucl-ex/0209021

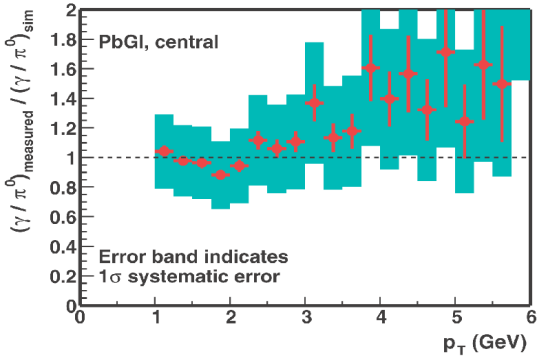












Summary (I)

- Scientific goals of high-energy heavy-ion physics:
  - Investigate the QCD phase diagram.
  - Produce/study the QGP in the laboratory: color deconfinement & chiral symmetry restoration
  - Probe the quark-hadron phase transition of the early Universe.
  - Study high gluon density & small-x physics.
- Means:
  - Producing the densest and hottest matter ever formed on Earth in high-energy ($\sqrt{s}$ ~ 200 GeV) Au-Au collisions.
  - Analyzing the experimental probes (global, hard, ...) that are sensitive to this new state of matter.
- PHENIX Run-1 data:
  - Au+Au @ $\sqrt{s_{NN}}$ = 130 GeV. 5M events, L ~ μb^{-1}
  - Inclusive charged hadrons, π^0, and $e^{\pm}$ at mid-rapidity ($|\eta|<0.35$)
- PHENIX Run-2 data:
  - Au+Au, p+p @ $\sqrt{s_{NN}}$ = 200 GeV. 200M events, L ~ 25 μb^{-1}
  - Inclusive Run-1 spectra + azimuth. corr., J/ψ, γ, + forw. rapidities

Summary (II)

- PHENIX global results :
  - Very high energy density (~70% larger than at SPS) well above the expected critical value for QGP.
  - Large particle production, rising faster than number of participant nucleons (onset of hard processes, saturation physics ?).
  - Much closer to baryon-free central region than at SPS.
- PHENIX high-p_T results :
  - High-p_T charged hadron and π^0 spectra central collisions: factor 3-- 6 suppression (qualitative agreement with energy loss in opaque medium).
  - Increased baryon over meson yield above $p_T \sim 2$ GeV/c (very different from *pp* data). p,pbar not suppressed.
  - Strong elliptic flow signal (early collective rescattering).
  - Jet-like signal in azimuthal near-side correlations.
- PHENIX heavy-flavor results :
  - Single electron spectrum/cross-section consistent with *pp* scaled open charm production (no apparent medium effect).
  - First results on charmonium.
- Run-3: d+Au collisions @ $\sqrt{s_{NN}} = 200$ GeV → "cold nuclear medium" reference: role of initial-state effects (no significant final-state effs. expected)