Selected Topics from Experimental Studies at RHIC

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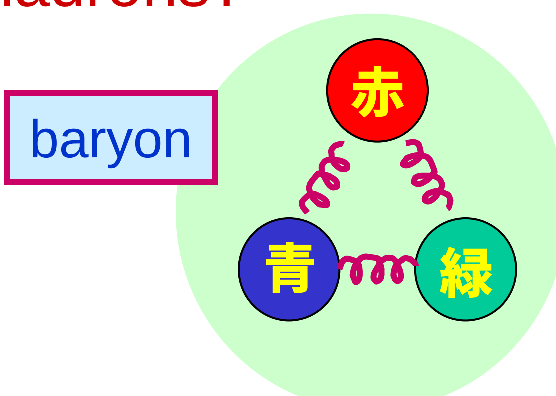
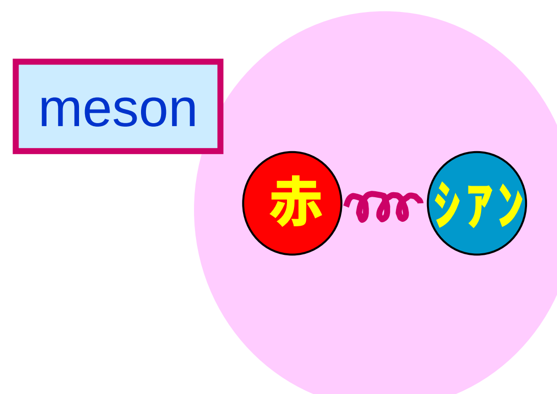
Hadrons and Quarks

Hadrons

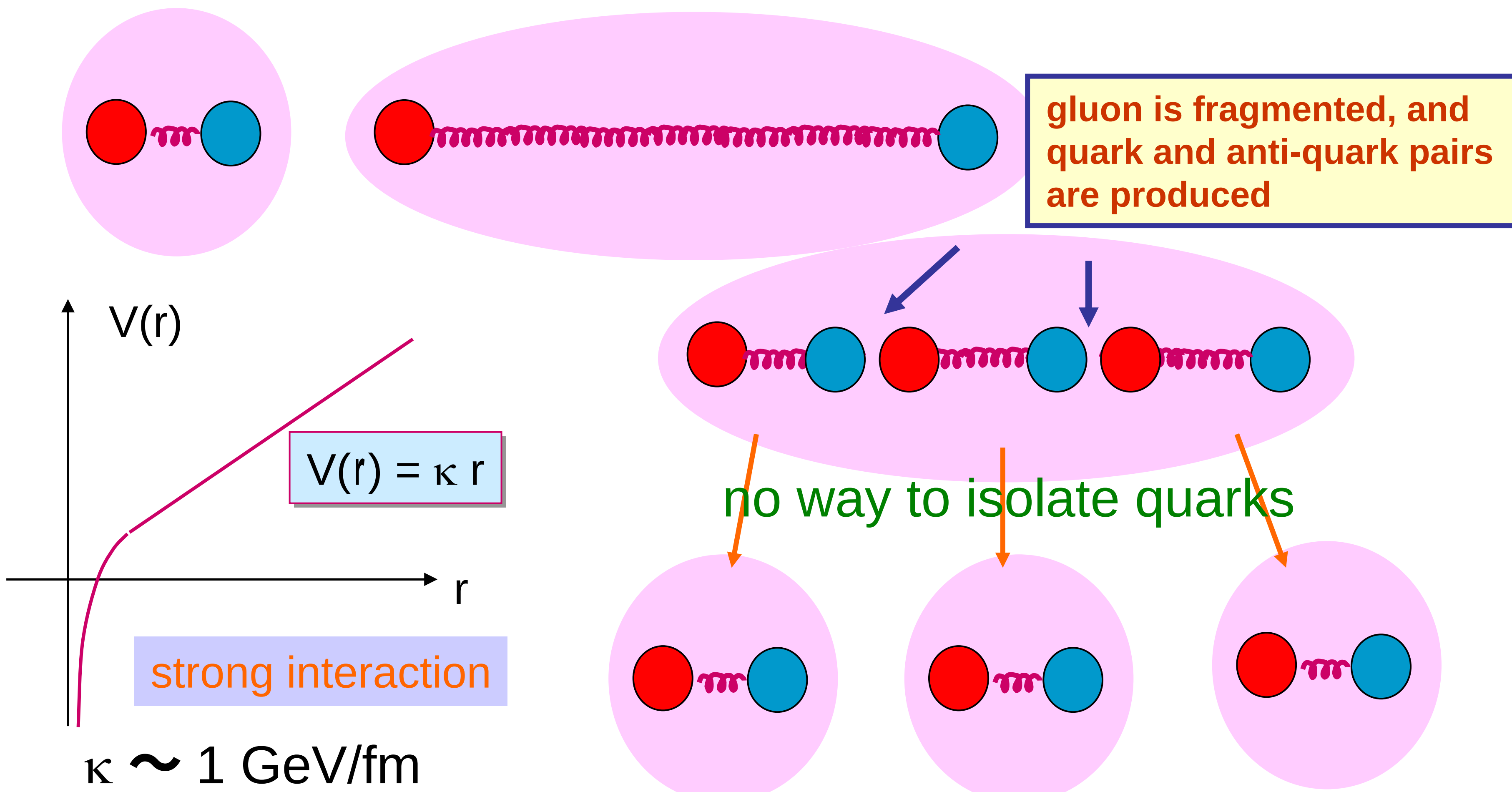
- Building blocks of matter in our universe
- Strong interaction; described by QCD
- Composite particles of quarks (anti-quarks)
  - baryon: p, n,…(three quarks)
  - meson: p, K,…(quark + anti-quark)
  - recent discovery of a new particle = penta-quark; a new class of hadrons?





Remaining Basic Problems of QCD

- confinement of quarks --- today's topic
- chiral symmetry and origin of hadron mass

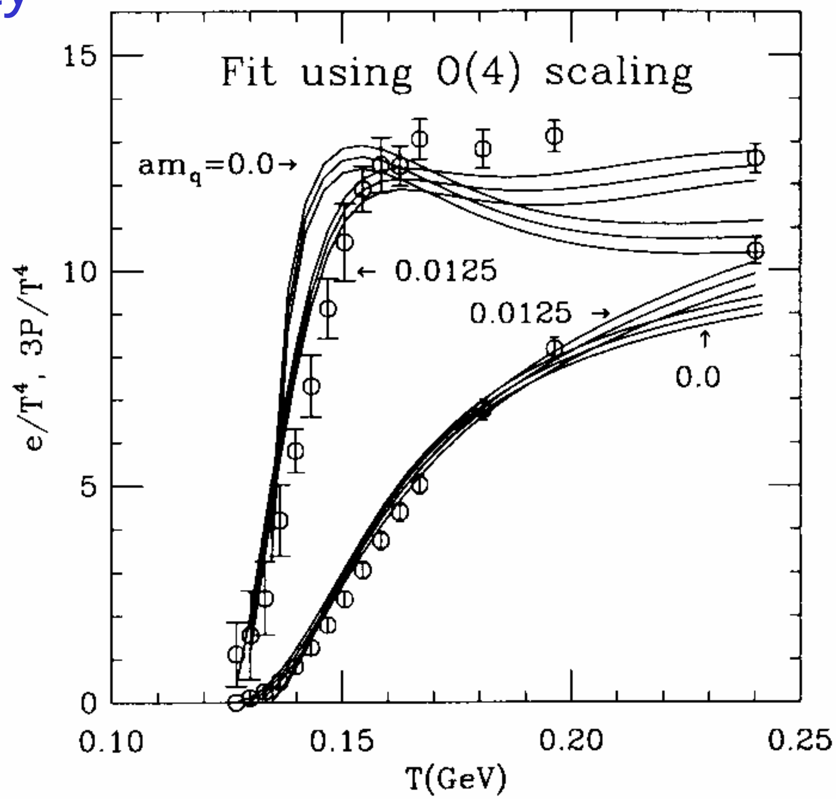


Prediction by Lattice-QCD

- Rapid increase in energy density and pressure around a certain temperature

= increase of degeneracy due to deconfinement of quarks and gluons

  - quark: 3 (flavour) x 2 (spin) x 3 (color)
  - gluon: 8 (color) x 2 (spin)
  - π mesons: 3 (isospin)



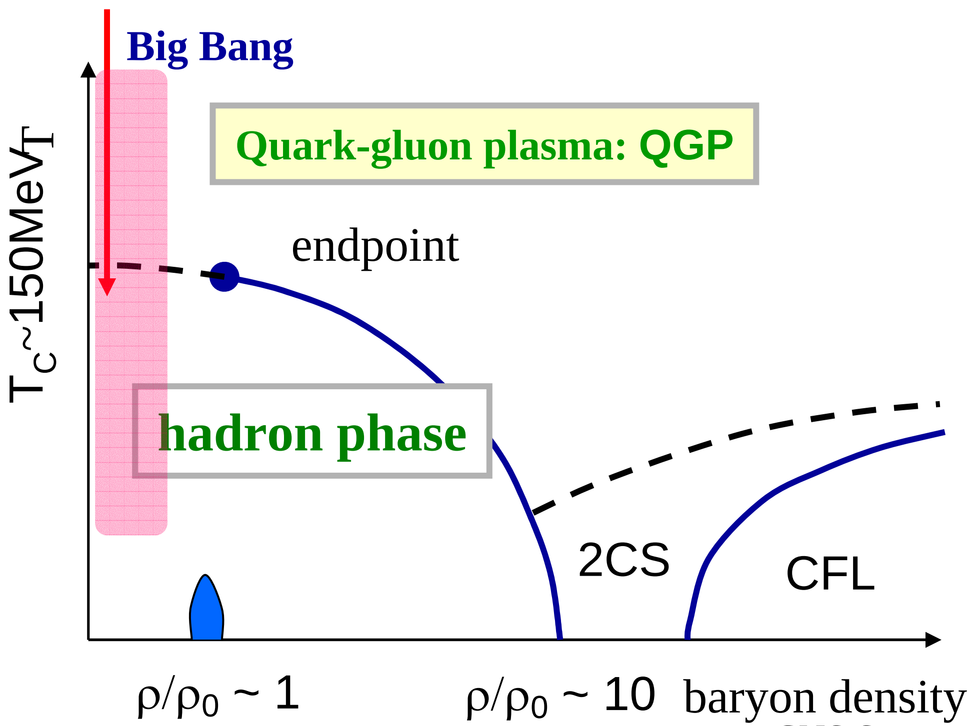
study QCD matter

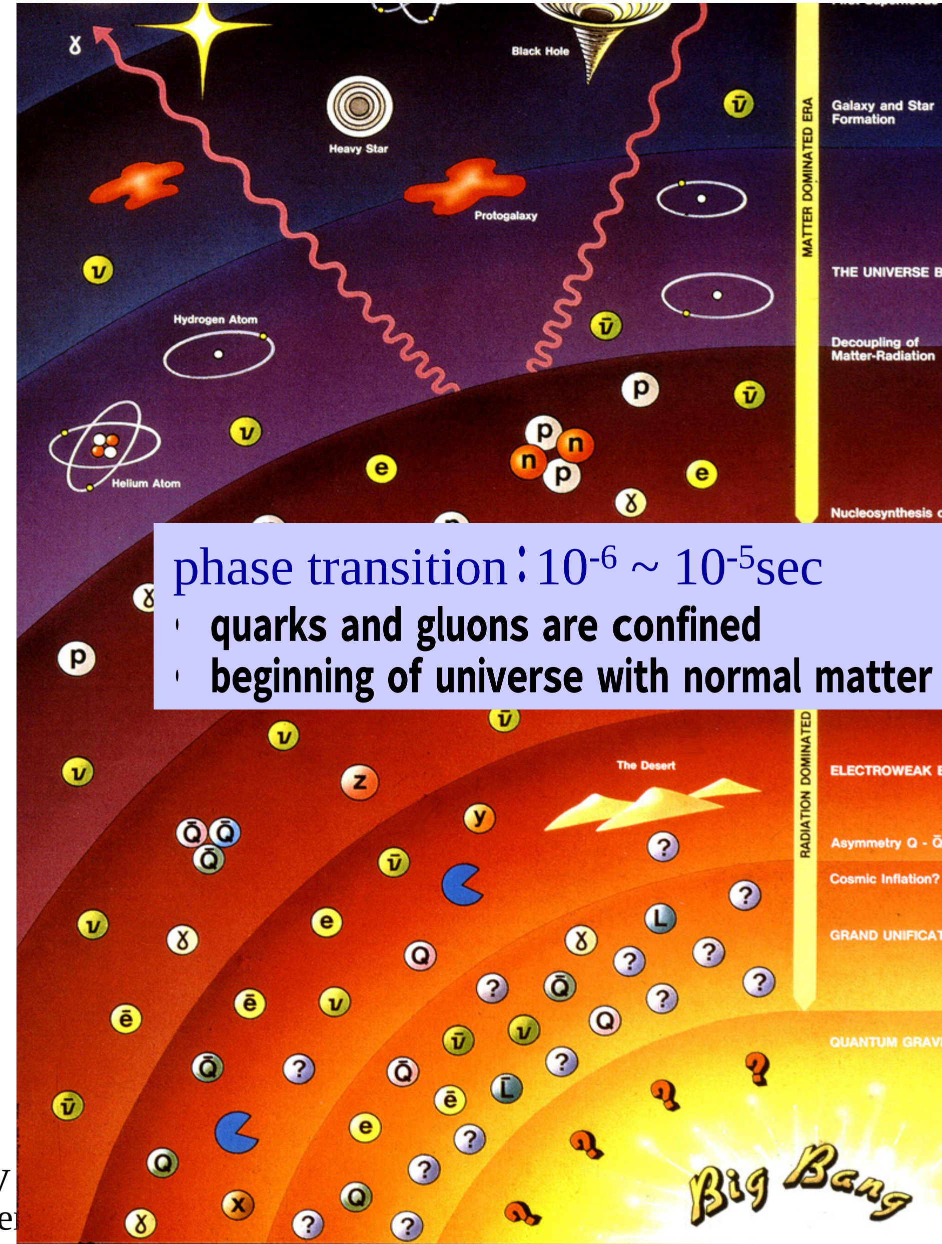
= a new approach to study basic properties of QCD such as confinement

Physics Scope of Hot QCD matter

Strong motivation
= QCD property: confinement

- Property of QCD matter
- Recreation and understanding of early universe

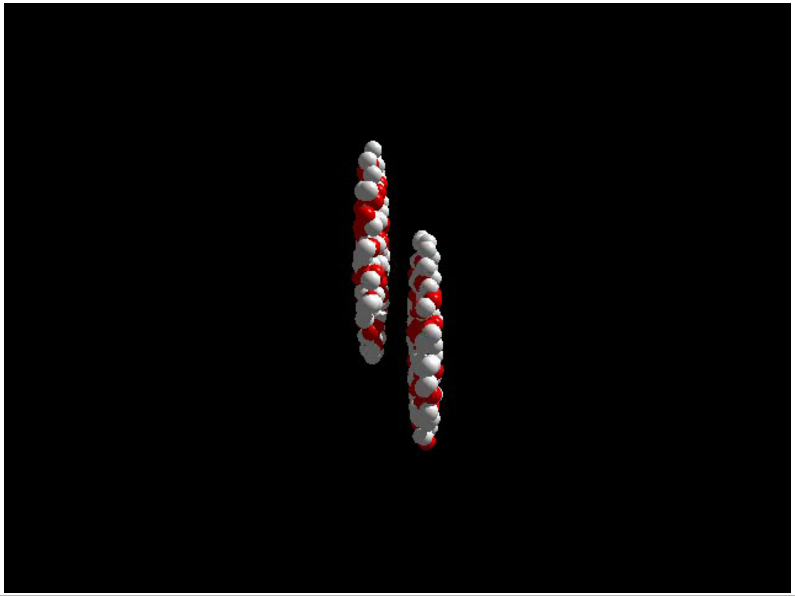




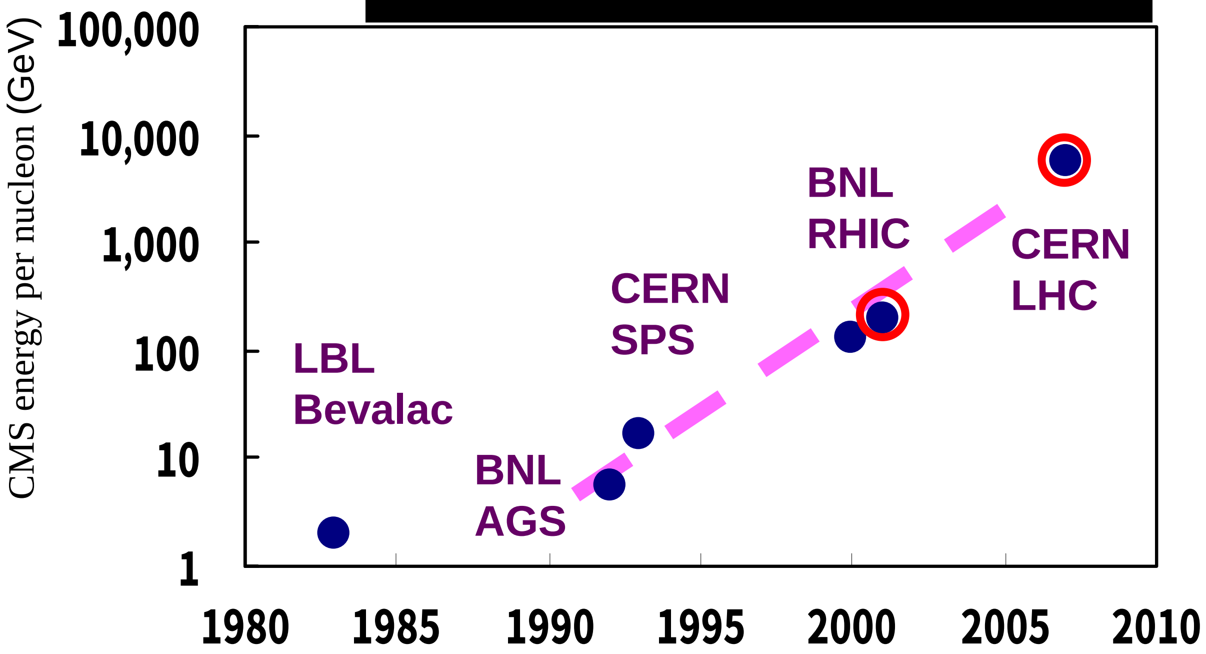
phase transition：$10^{-6} \sim 10^{-5}$sec
- quarks and gluons are confined
- beginning of universe with normal matter

Create an Early Universe in a Laboratory

High energy heavy ion collision is a unique tool to produce hot and dense QCD matter



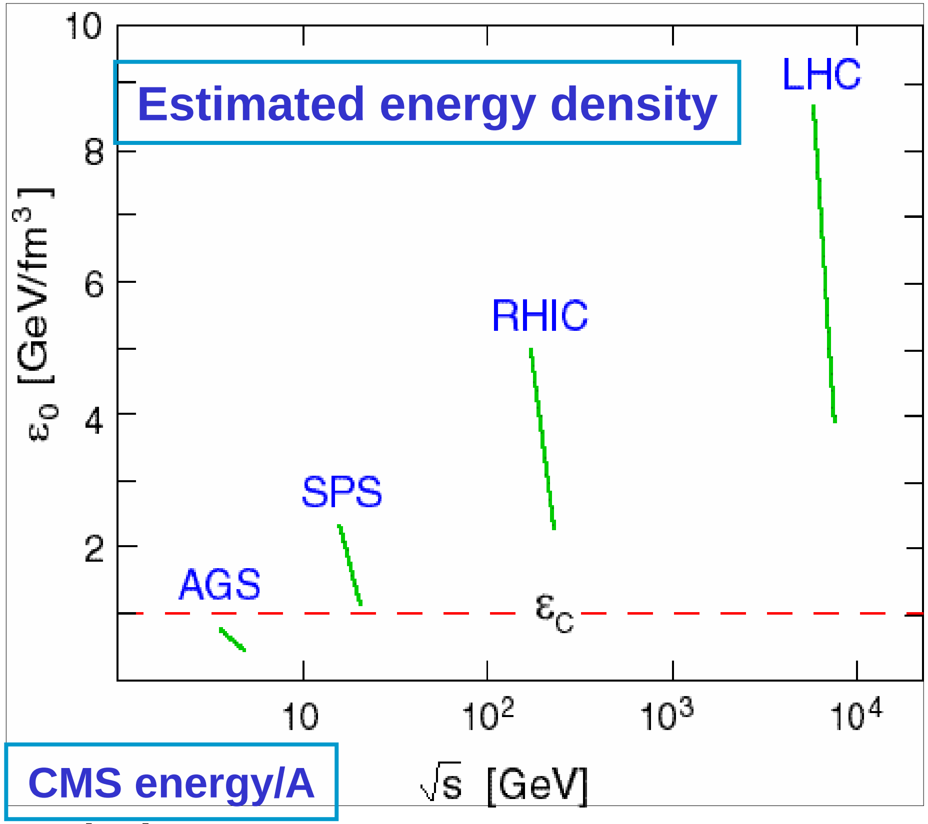
CMS energy/nucleon vs Year when collision of heavy-mass nuclei became available



Why do we need high energy?

- In general, collision process is very dynamic and complex
  - very difficult to describe the evolution of the system
- In the limit of complexity, everything gets simpler
  - hydrodynamics is applicable to describe the evolution of the colliding system

- High energy collision → a system with high complexity
- Questions is: "How high energy is really needed?"

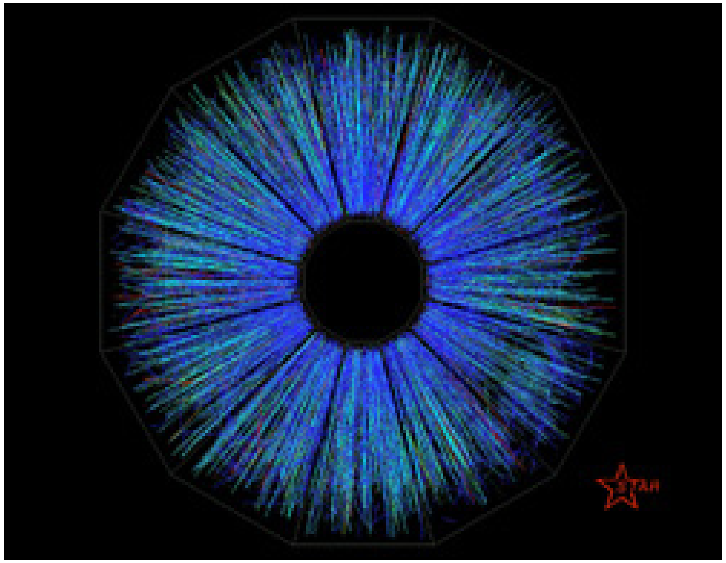


RHIC

- The first colliding-type accelerator for heavy ion study
- Brookhaven National Laboratory
  Long Island, New York, USA
- Two independent rings with superconducting magnets
  - circumference: 3.83 km
  - asymmetric-mass collisions
  - 106 ns crossing time
- Maximum energy $\sqrt{s} \approx \frac{Z}{A}(500\,\mathrm{GeV})$
  - ➔ 500 GeV for p-p
  - ➔ 200 A・GeV for Au-Au
- Luminosity (designed values)
  - Au-Au: 2 x 10^{26} cm^{-2} s^{-1}
  - p-p : 2 x 10^{32} cm^{-2} s^{-1} (polarized)

Experimental Runs at RHIC

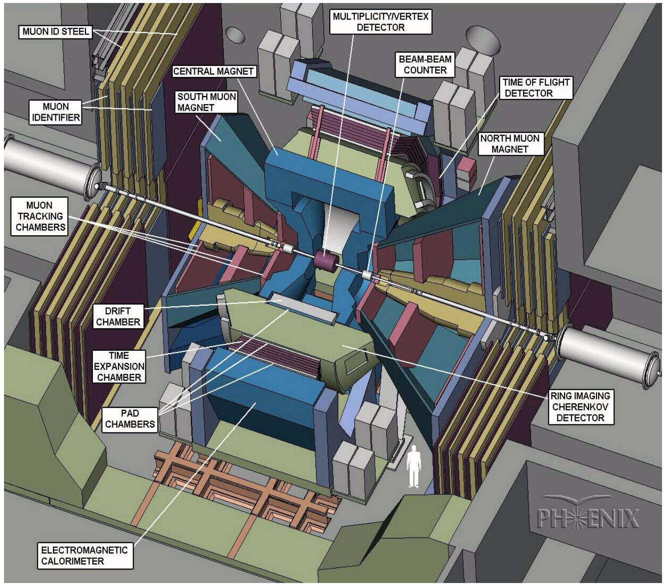
- The first encounter of Gold ions
  - June 12, 2000: Au + Au collisions at $s_{NN}^{1/2}$ = 56 GeV
- Year-1 Run
  - Au + Au at $s_{NN}^{1/2}$ = 130 GeV
  - middle of June, 2000 ~ Sep. 4, 2000
    - ~5 M minimum-bias events
- Year-2 Run
  - $s_{NN}^{1/2}$ = 200 GeV
  - Au + Au: Aug. 17, 2001 ~ Nov. 25
    - ~100 M minimum-bias events
  - p + p: end of Dec., 2001 ~ Jan. 24, 2002



- Year-3 Run
  - $s_{NN}^{1/2}$ = 200 GeV
  - d + Au: Jan. 17, 2003 ~ Mar. 23, 2003
    - The first asymmetric nuclear collisions in the colliding-type accelerators
  - pol-p + pol-p: May 2 ~ May 17, 2003

Experiments at RHIC

PHENIX



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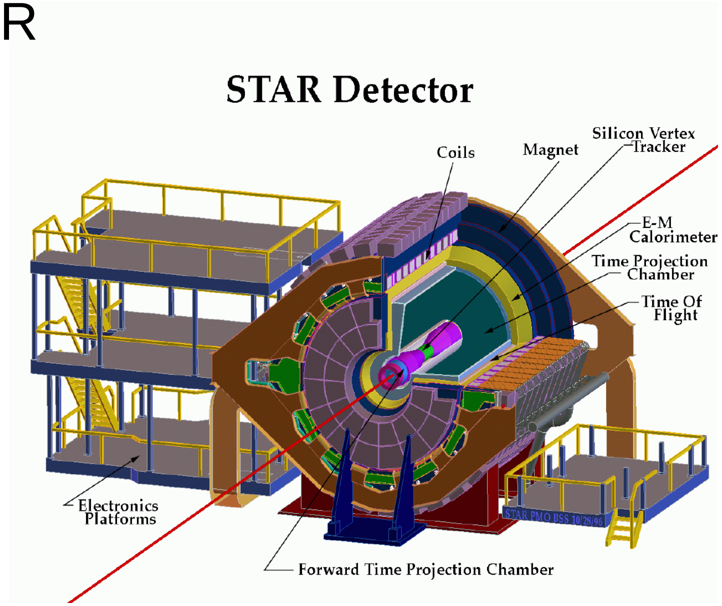
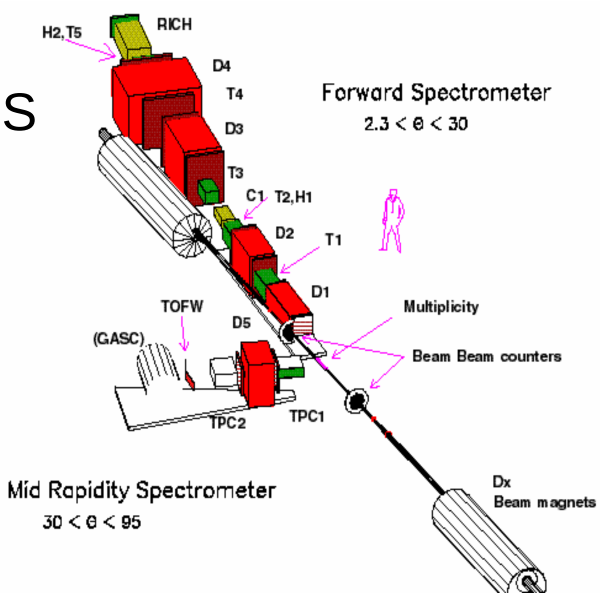
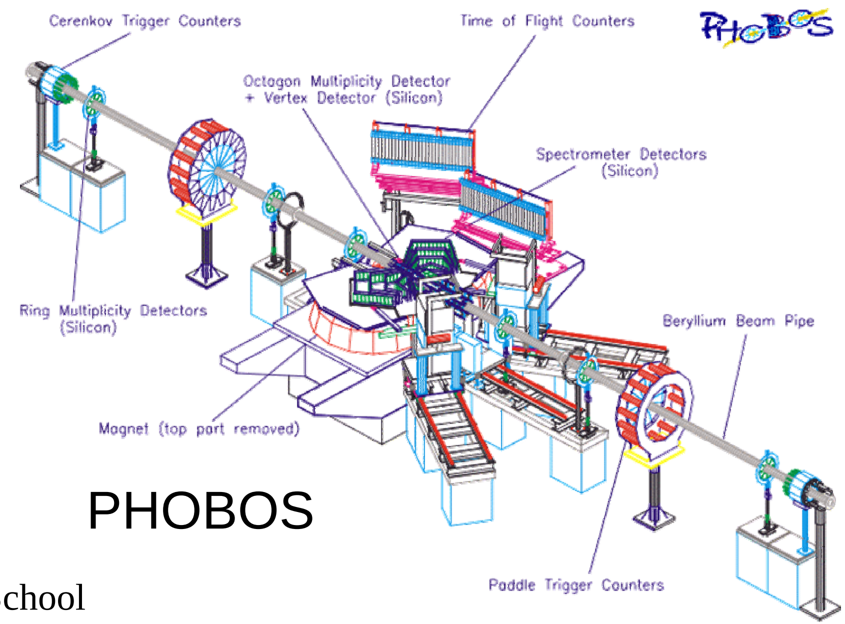


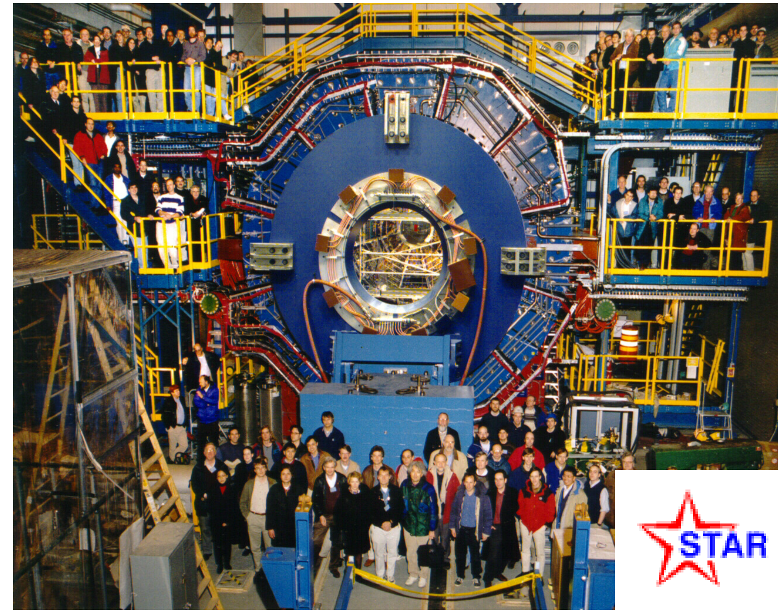
BRAHMS





PHOBOS


PHENIX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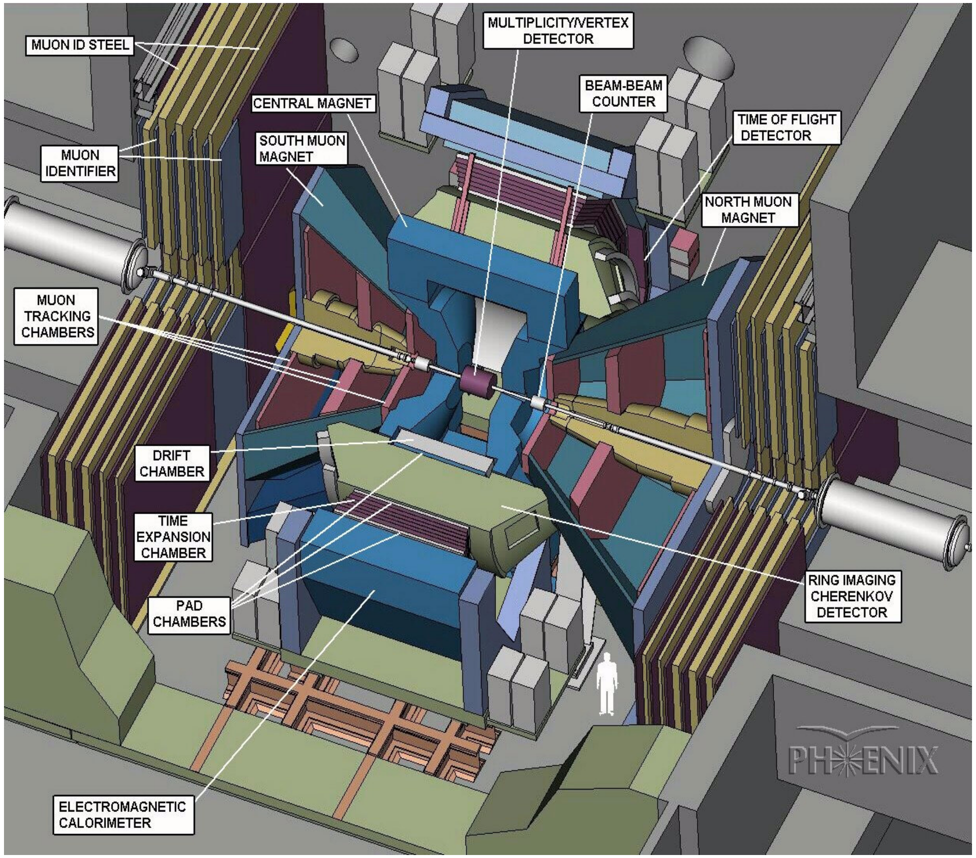
BRAHMS

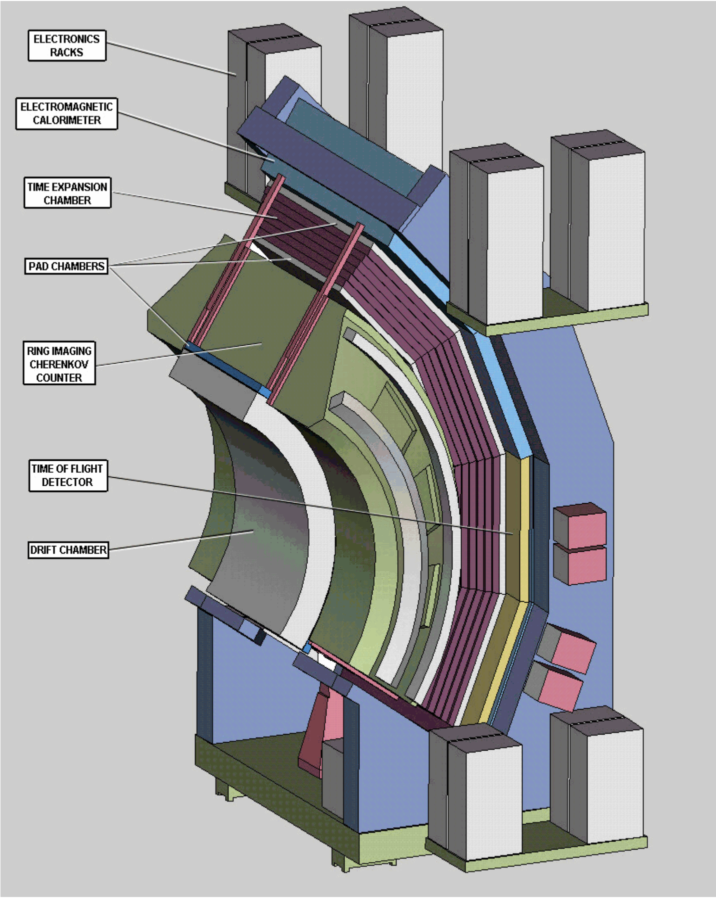

PHOBOS

PHENIX (***P***ioneering ***H***igh ***E***nergy ***I***on e***X***periment)

- ~430 from 41 institutions, 11 countries
- Measure photons, electrons, muons as well as hadrons

  = unique among the four experiments
- Cover many observables





PHENIX

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Japanese Group at PHENIX

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Primary contributions = PID

RICH: electron identification

CNS, KEK, Waseda, NIAS, BNL, FSU, KEK, SUNY/SB, ORNL

TOF：hadron identification

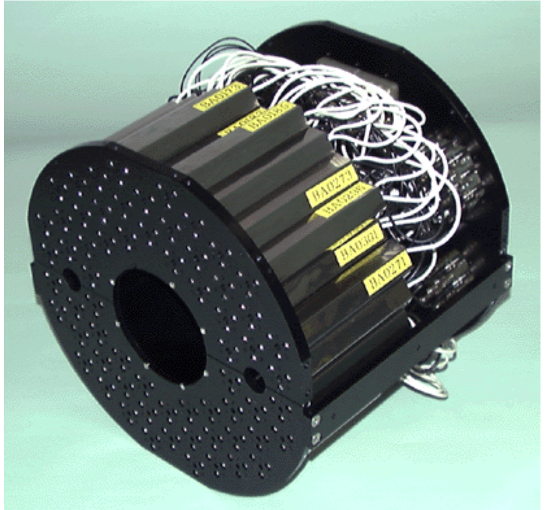
Tsukuba
Columbia

AEROGEL：

Tsukuba, CNS, BNL

BBC：TOF start, event trigger

Hiroshima, Columbia

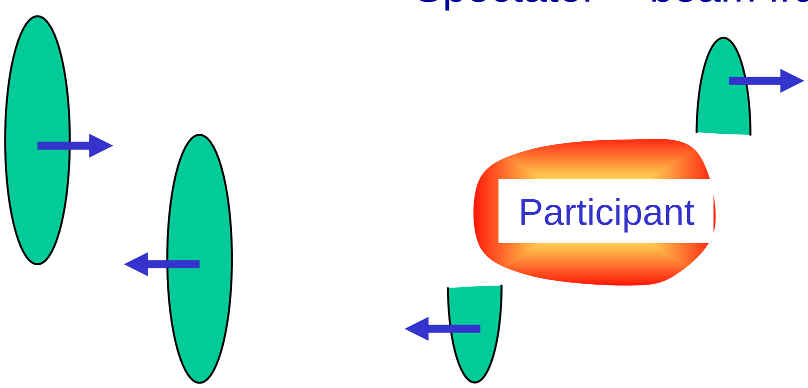


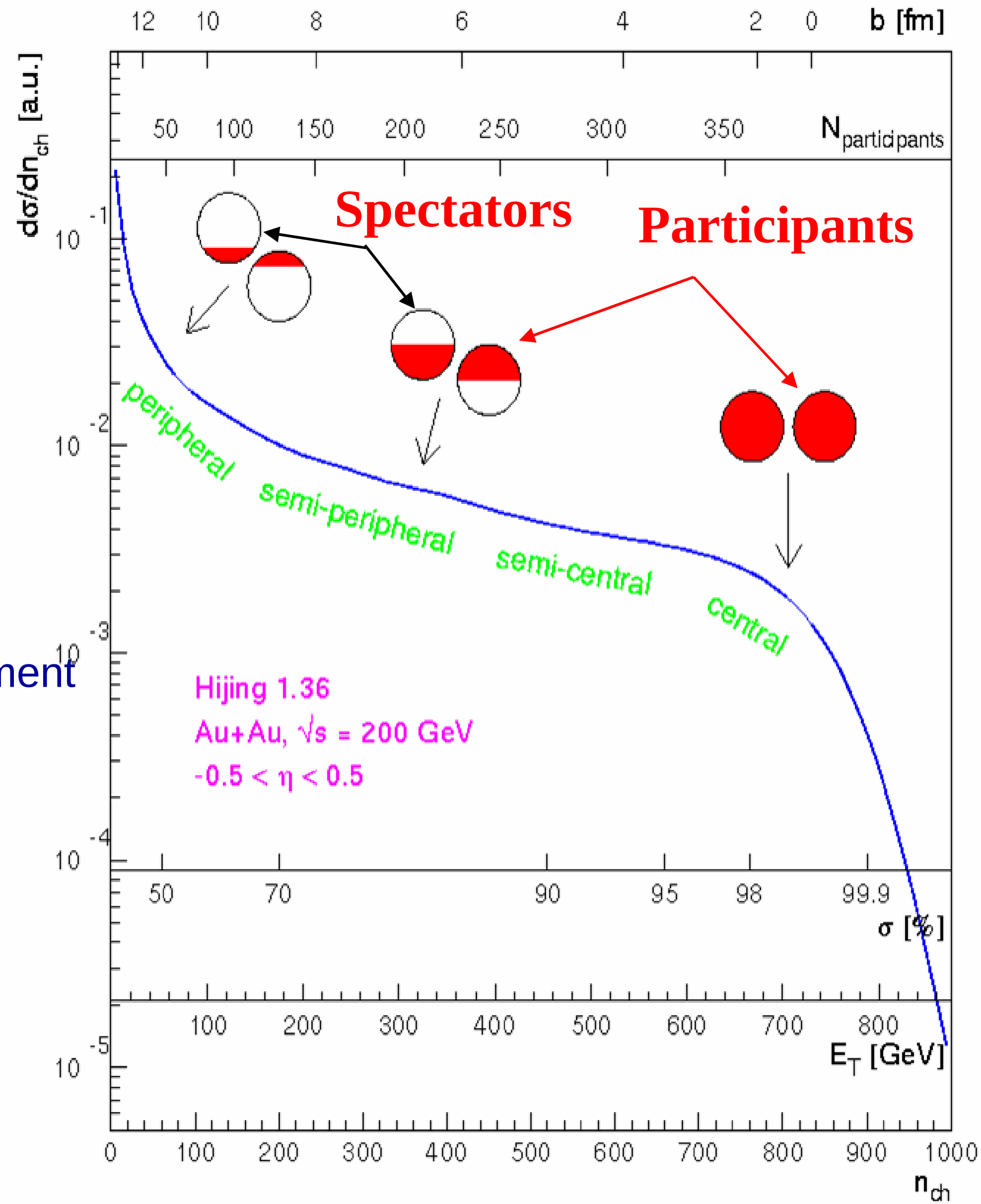
Topical Results from RHIC

- Gross feature of heavy-ion collisions
  - Participant-spectator model
- Initial conditions
  - azimuthal anisotropy and particle yield ratio
  - Basic question is: whether at RHIC thermal and chemical equilibrations are achieved?
- High p_T particle – single and correlation
  - Jet quenching; to probe hot matter with high density
- J/ψ measurement
  - THE probe of deconfinement

Participant-spectator model

- Classical description works
- Collision geometry is determined by impact parameter
- It works when collision time is short compared to a typical time scale of internal motion of nucleons inside nucleus





Topical Results from RHIC

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- Probing "initial conditions"
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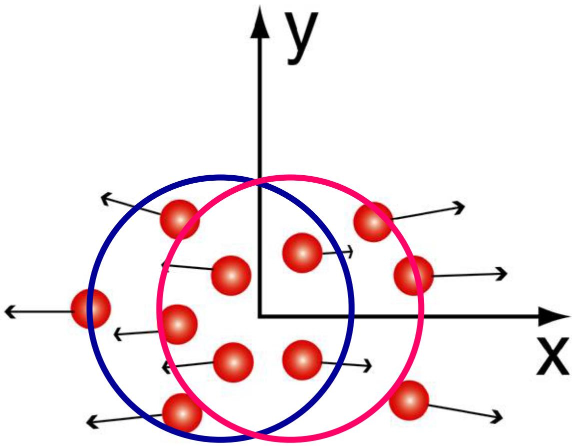
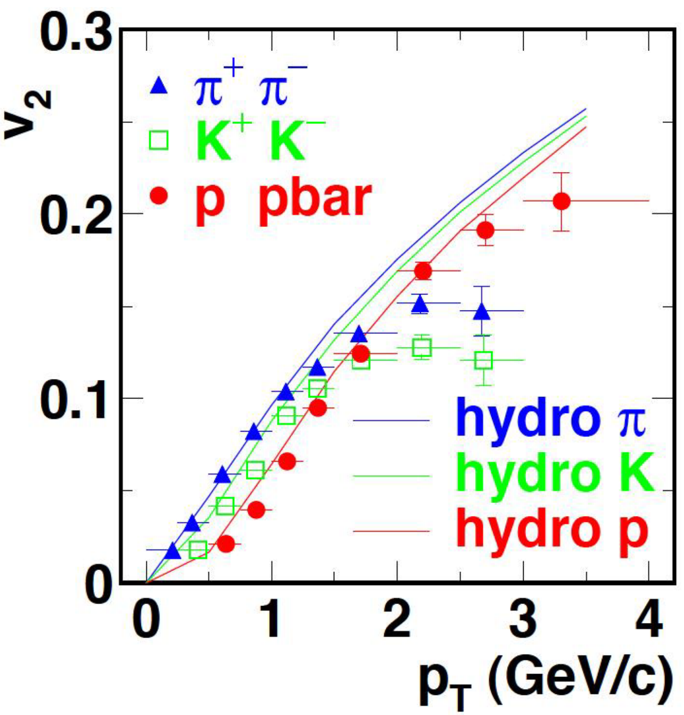
Elliptic Anisotropy in Particle Emission

$$\frac{dN}{dp_T dy d\varphi} = \frac{dN}{dp_T dy} \frac{1}{2\pi} \left(1 + 2v_1 \cos(\varphi) + 2v_2 \cos(2\varphi) + ..\right.$$

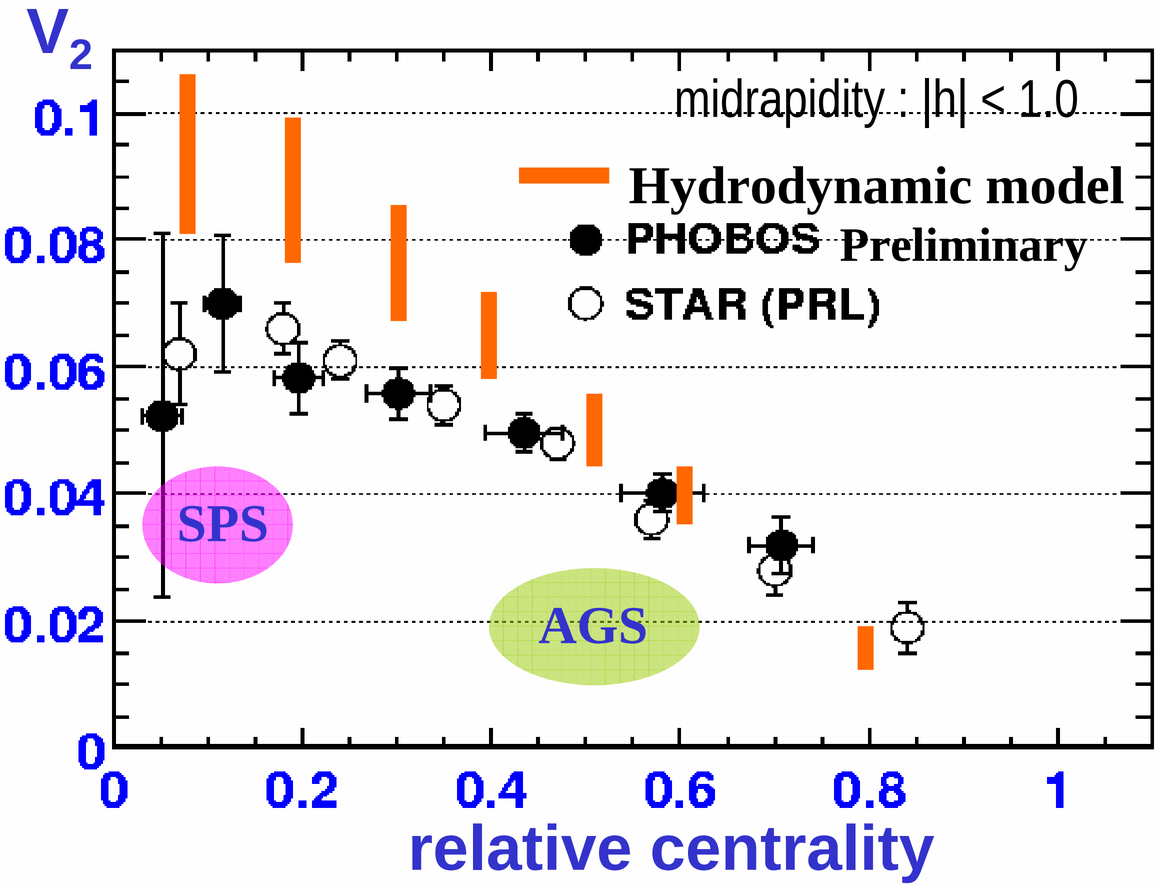


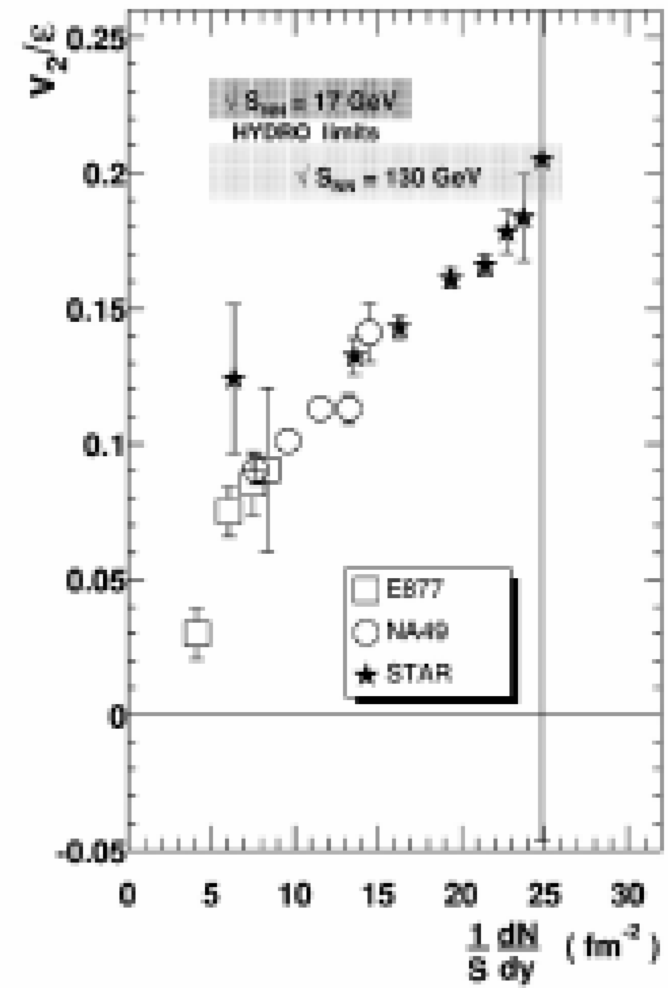
- Azimuthal anisotropy in the participant region in non-central collisions
  - if local equilibration is achieved quickly enough,
  - then anisotropy appears in the internal pressure gradient, which produces anisotropic particle flow

- Very large anisotropy at RHIC
  - comparable to the predictions from fluid dynamical calculations



Elliptic Flow → Thermal Equilibrium





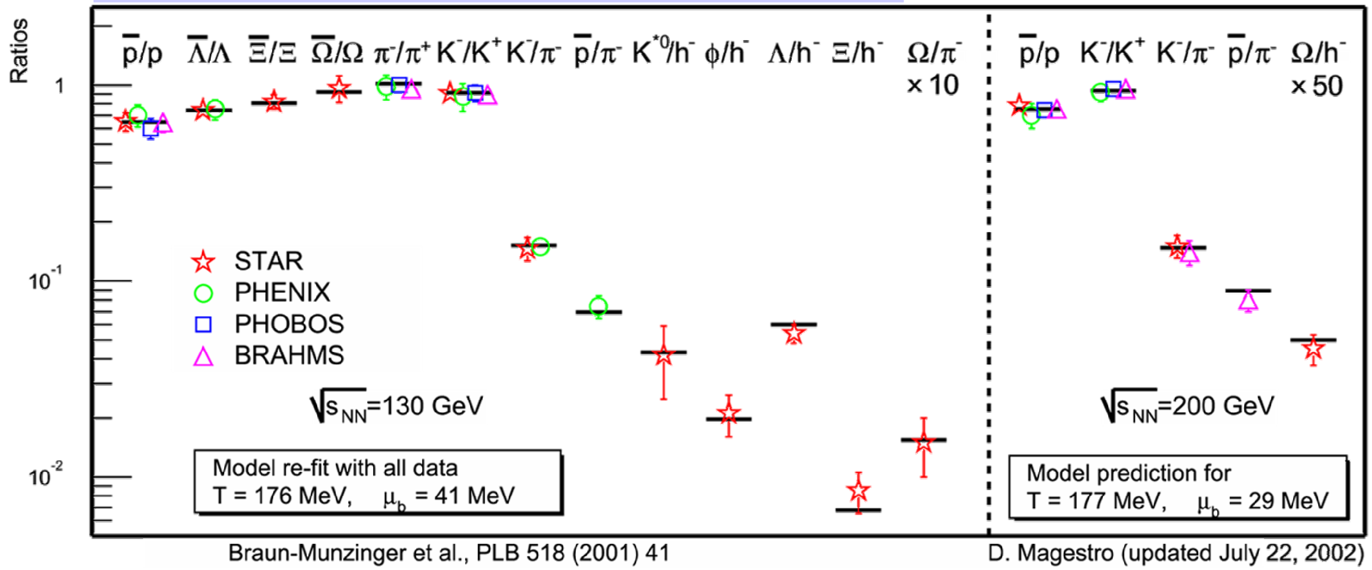
- hydro-dynamical model assumes
  - early thermalization (~0.5 fm)
  - initial state = QGP phase

Thermalization seems to be barely achieved at RHIC

Particle Yield Ratio and Chemical Equilibrium

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

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



Static thermal model reproduces the particle ratio extremely well

- To be noted: γ_s: strangeness saturation factor → ~1
  - introduced to reflect on slowness of s production in hadron interactions
  - fast strangeness production/equilibration is only possible at QGP

  → It is natural to assume that chemical equilibration is realized at QGP

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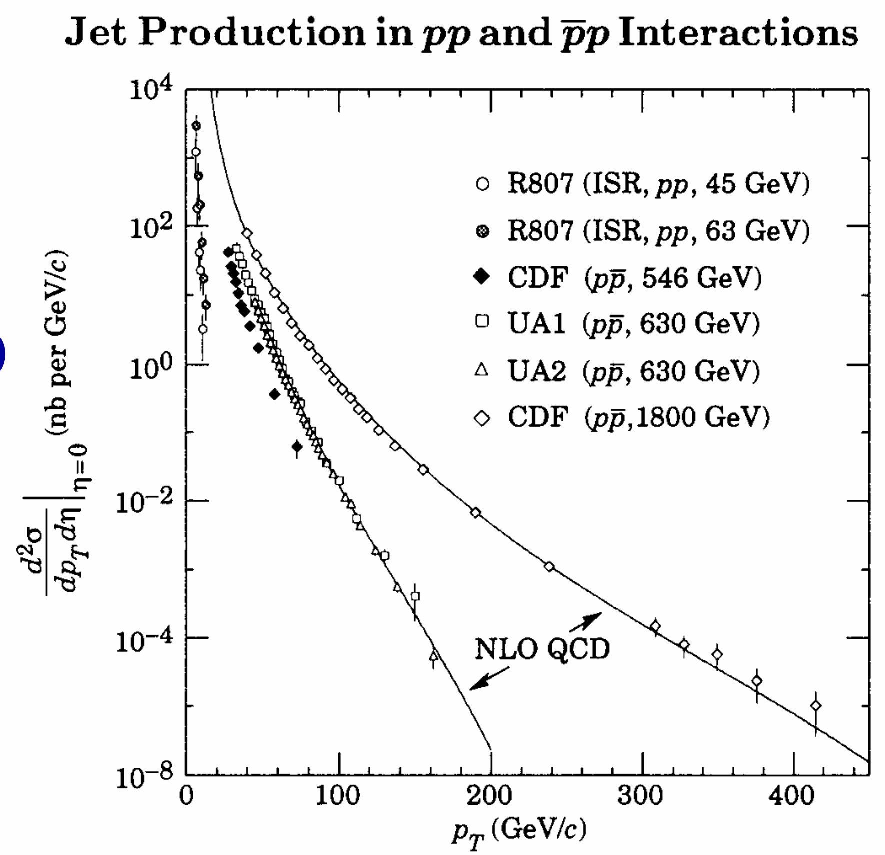
Jet

- hard scattering of partons (quarks & gluons) is frequent at high energy collisions
- calculated well with pQCD
- Rutherford scattering in high energy collisions
  - how point-like the partons are:

    p_T = 400 GeV

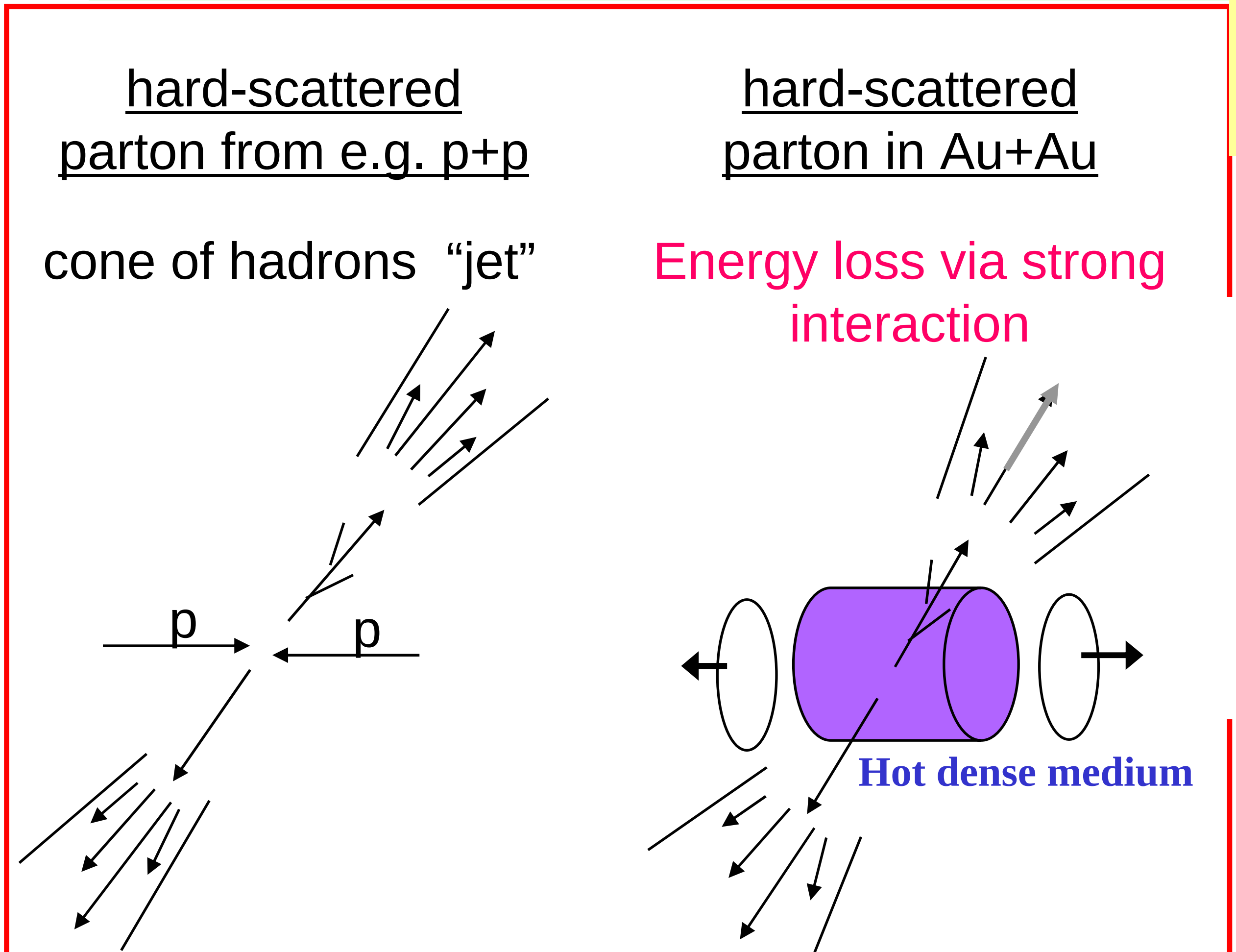
    → $\Delta x \sim 0.5 \times 10^{-3}$ fm



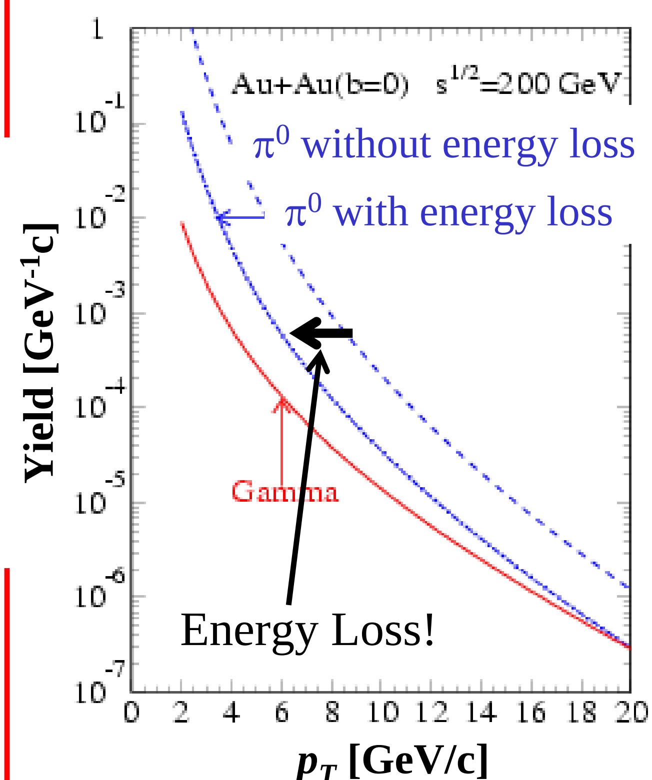
Jet quenching

Energy loss of partons (quarks and gluons inside nucleons) in media at high density

-- primarily due to gluon bremsstrahlung



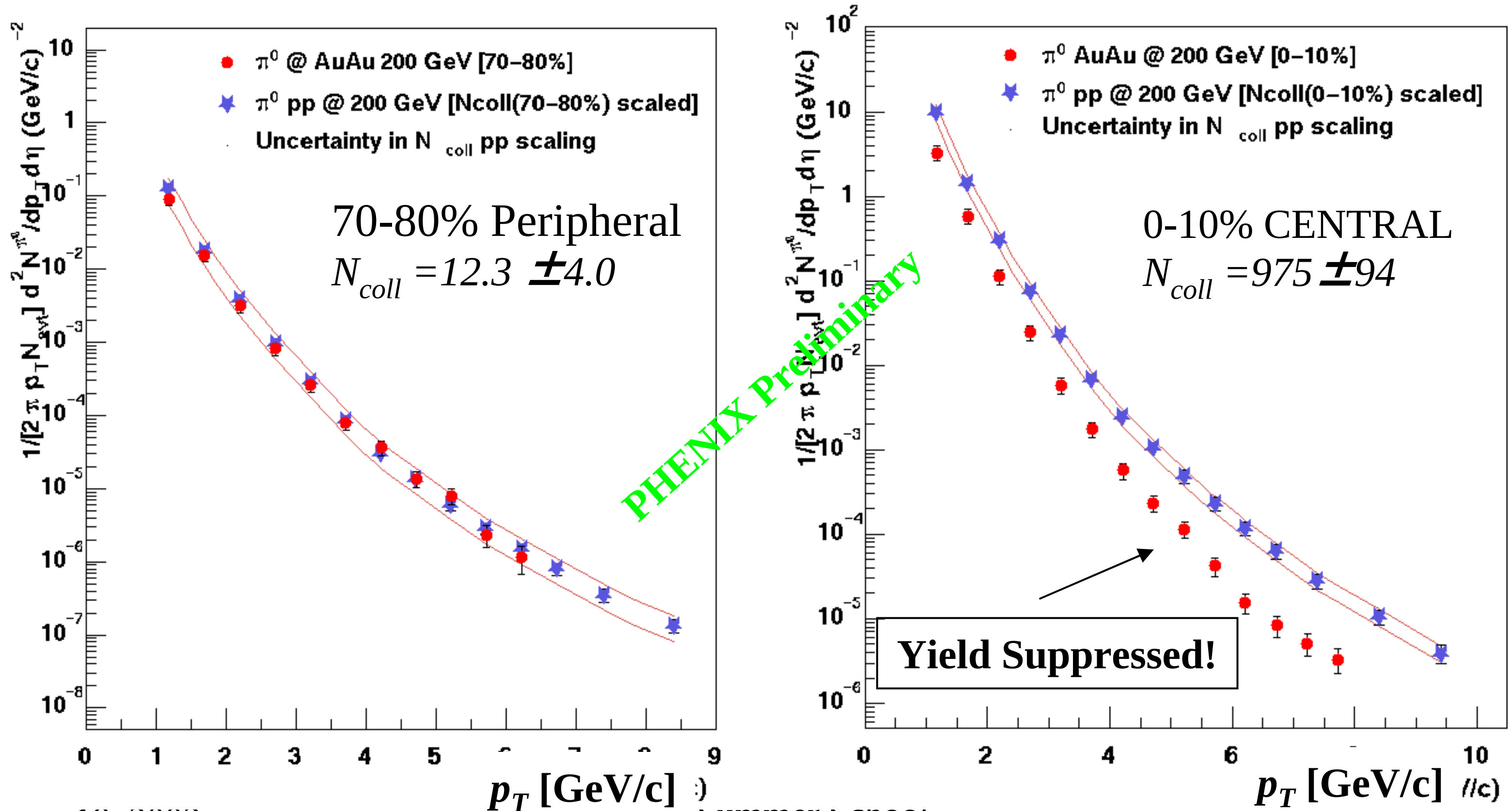
High p_T hadrons are fragments of partons



X.-N., Wang, PRC **58** (1998)2321

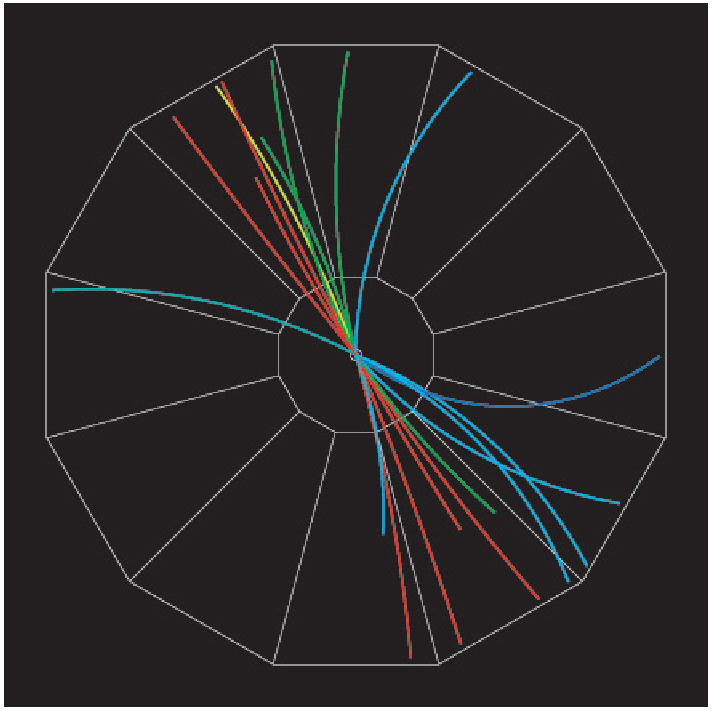
Transverse Momentum Distribution of π^0

- Compare the yield in Au+Au with that in p+p scaled with N_{coll}
  - should be scaled in hard processes, without nuclear effects
- In Au + Au collisions at CMS energy = 130 and 200GeV
  - peripheral collisions: good agreement with N_{coll} scaled p+p data
  - central collisions: significant suppression from with N_{coll} scaled p+p data



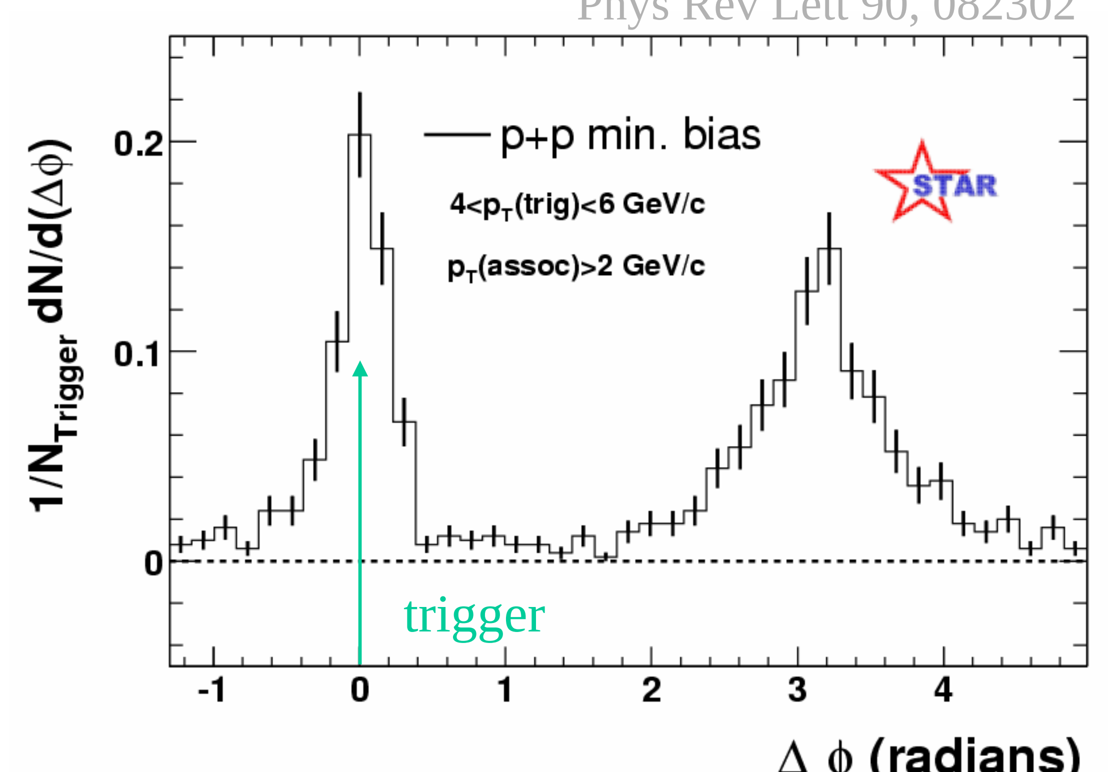
Jets and two-particle azimuthal distributions

p+p → dijet



- trigger: highest p_T track, p_T>4 GeV/c
- $\Delta\phi$ distribution: 2 GeV/c<p_T<$p_T^{trigger}$
- normalize to number of triggers

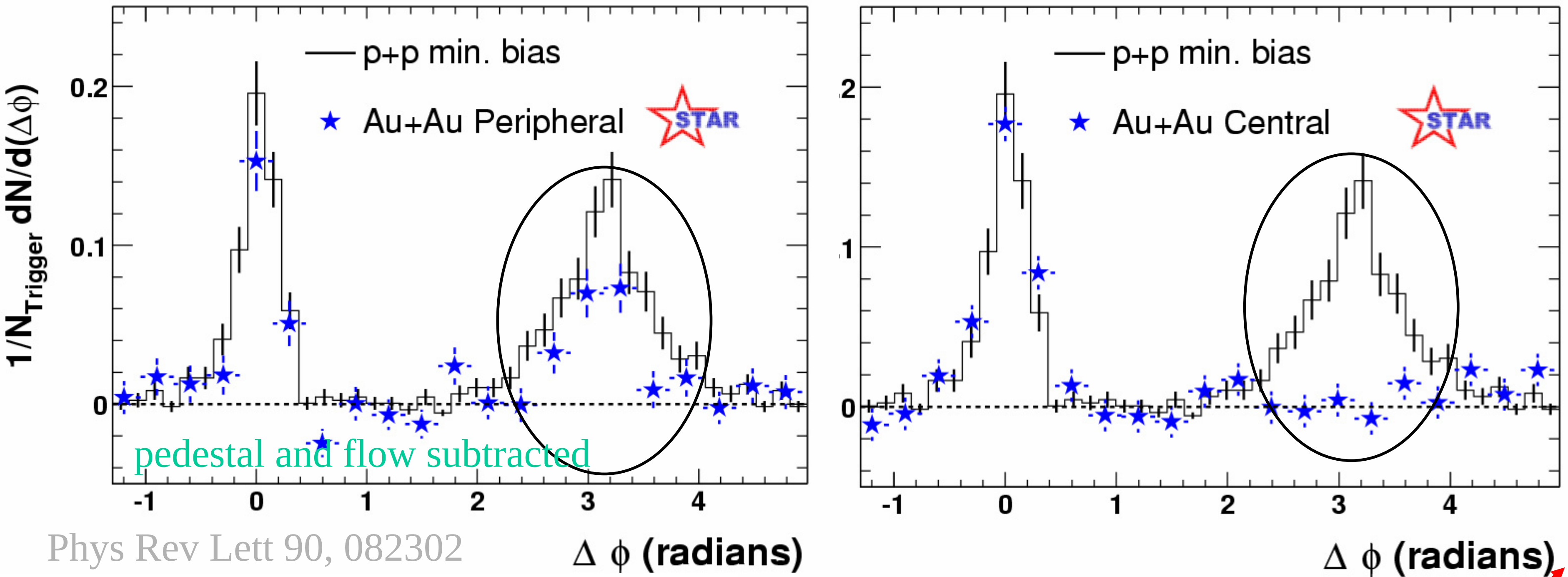
Phys Rev Lett 90, 082302



Azimuthal distributions in Au+Au

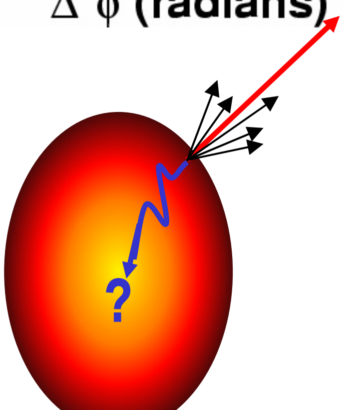
Au+Au peripheral

Au+Au central



Phys Rev Lett 90, 082302

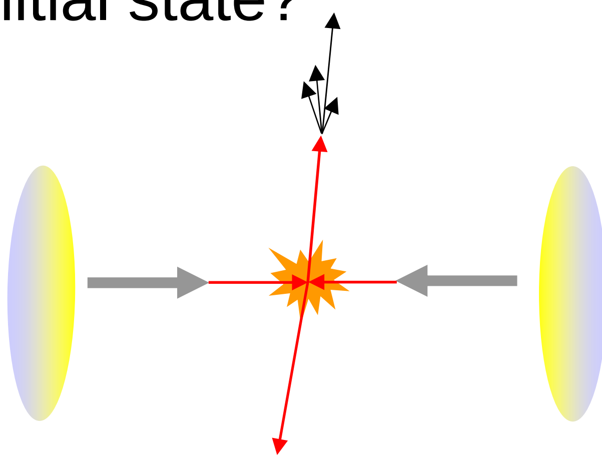
Near-side: peripheral and central Au+Au similar to p+p



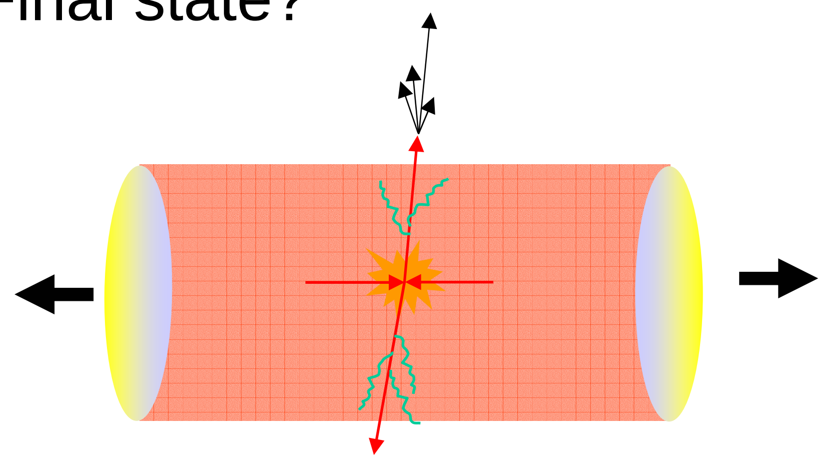
Strong suppression of back-to-back correlations in central Au+Au

Is suppression an initial or final state effect?

Initial state?



Final state?



strong modification of Au wavefunction (gluon saturation)

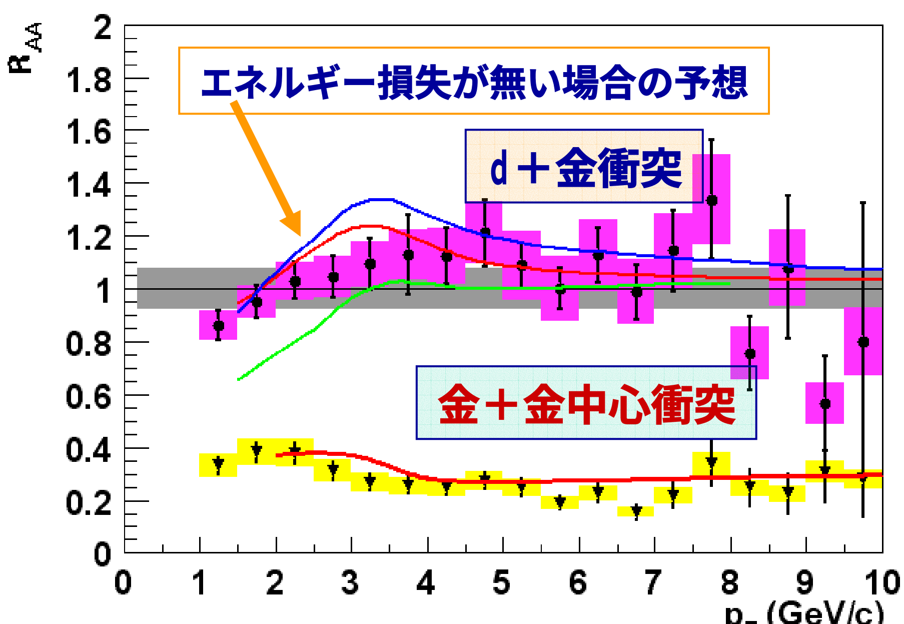
partonic energy loss in dense medium generated in collision

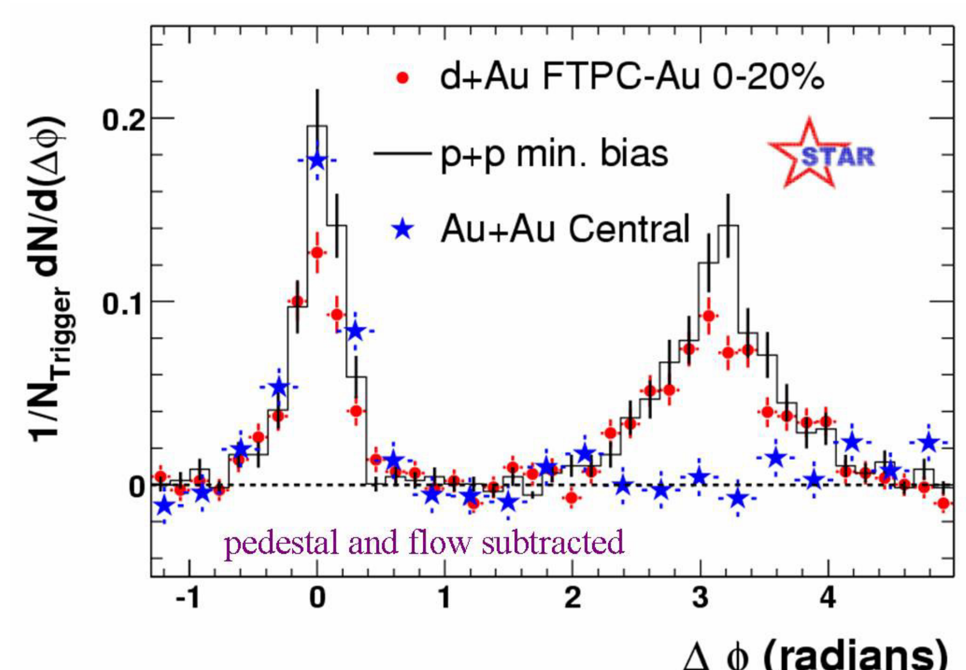
Need of results from d(p) + Au collisions

- large hot region will not be created
  → finial state effect will be smaller
- initial state effect will stay

How is it settled?

- Execution of d + Au in Year-3 RUN (2003)
- No effects seen in d + Au collisions
  - → effects are intrinsic to central Au + Au collisions
  - → final state interaction is dominant
  - → strongly suggests the creation of hot matter and significant energy-loss of partons in central Au + Au collisions

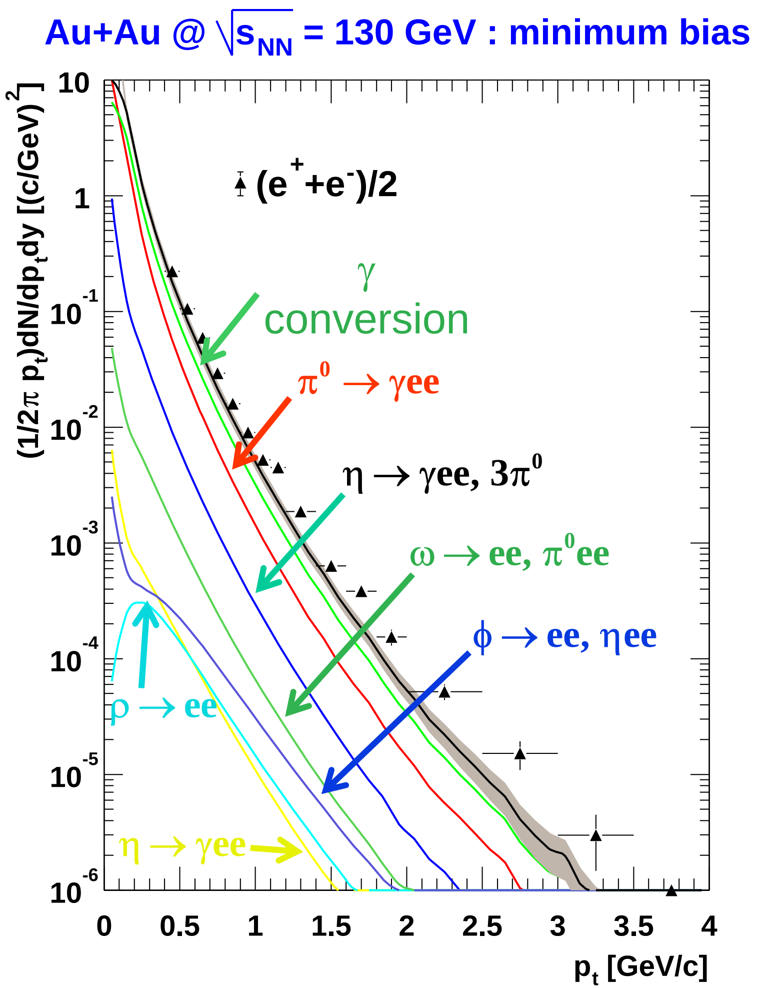




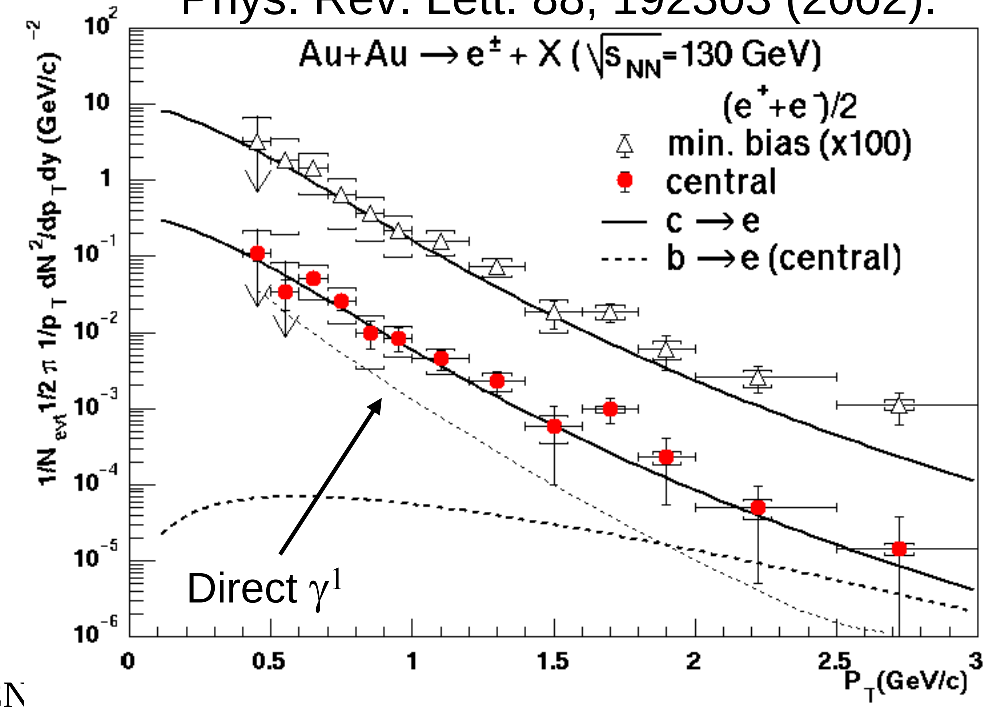
Single Electron Spectrum

Major background: π^0 Dalitz-decay and γ conversions
Careful subtraction of the backgrounds → single electron

Momentum spectra is in good agreement with the charm spectrum in p+p collisions scaled with N_{coll}
→ Is charm immune to energy loss?
→ flavor dependence is a keen subject



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



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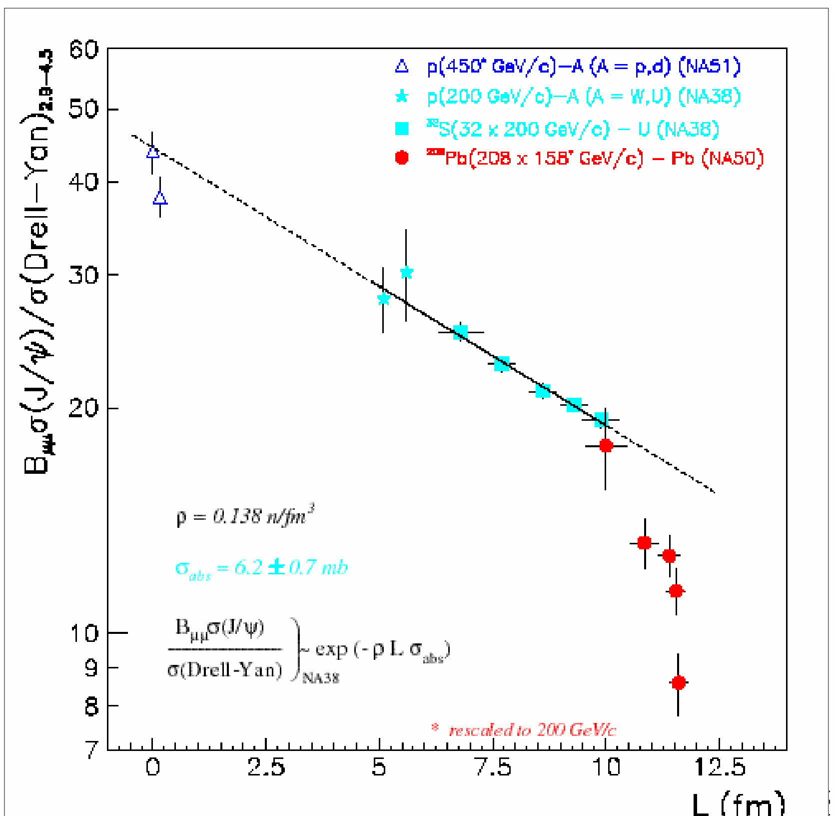
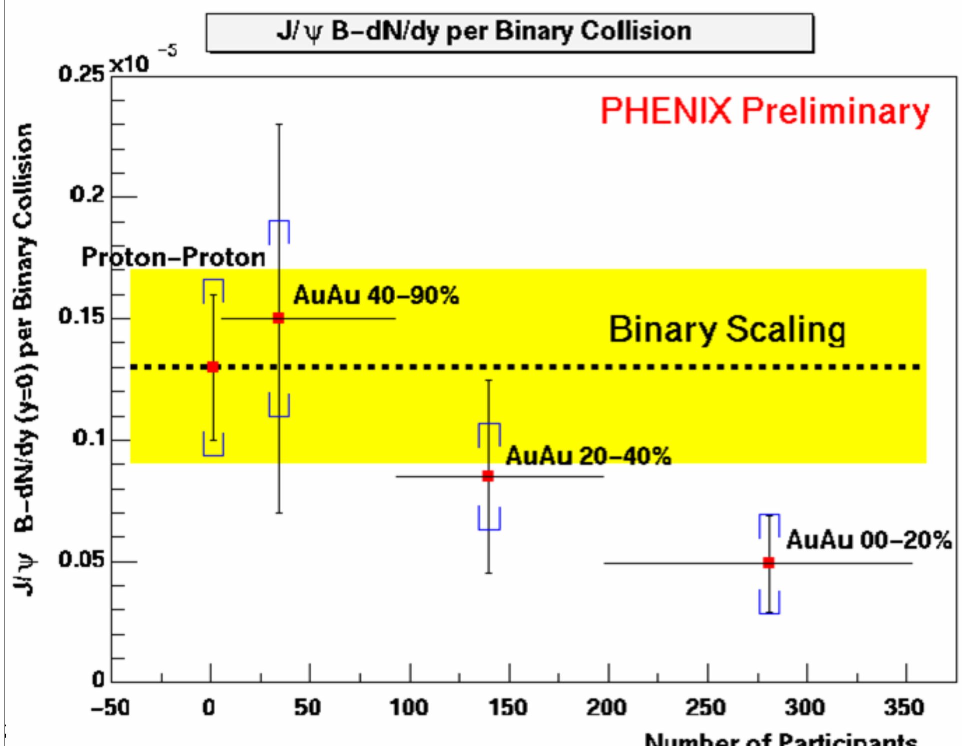
J/ψ Measurement at RHIC

- Suppression of J/ψ yields: a signature of QGP
  QGP → Debye screening → J/ψ is dissolved

In Pb+Pb at CERN-SPS, large suppression was observed in the J/ψ - Drell-Yan ratio

- At RHIC with higher T, stronger suppression may be expected
- Measurement in the Year-2 RUN
  - statistics is very poor

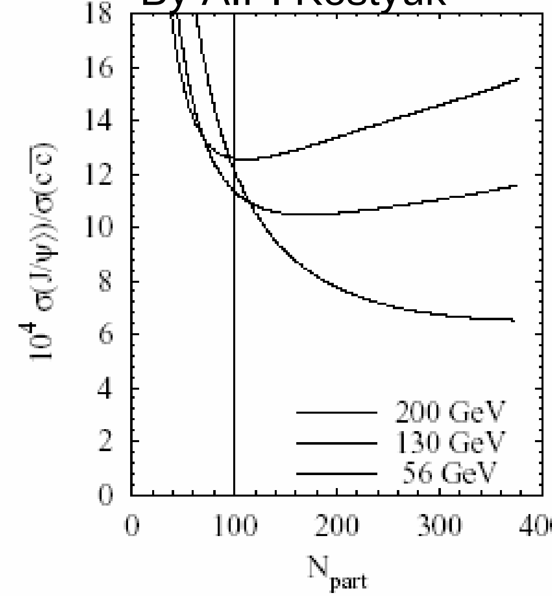


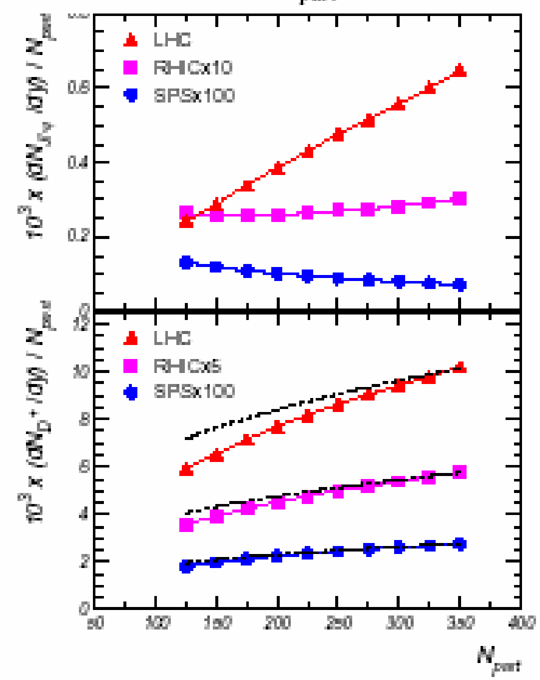


Will J/ψ be really suppressed?

- Idea of J/ψ enhancement
  - Results from RHIC suggests thermal and chemical equilibration is achieved at QGP phase
  - In the QGP at high temperature, original J/ψ will be completely dissolved, but J/ψ may be re-created via recombination process in the later (hadronization) stage
  - Probability of recombination increases quadratically with the number of c quarks
- Dedicated Au + Au in the RHIC Year-4 RUN which starts in this winter
  - total suppression or hint of enhancement
  - we will find it out soon

By A.P. Kostyuk





Summary

- Motivation and Scope
  - confinement = basic QCD property
  - hot QCD matter
  - early universe
- RHIC and PHENIX
  - RHIC started operation in 2000
  - Japanese group
- Topical results from RHIC
  - thermal and chemical equilibration
  - Jet quenching
  - J/ψ production

- Results from RHIC have been very exciting, and more will surely come. Please stay tuned.