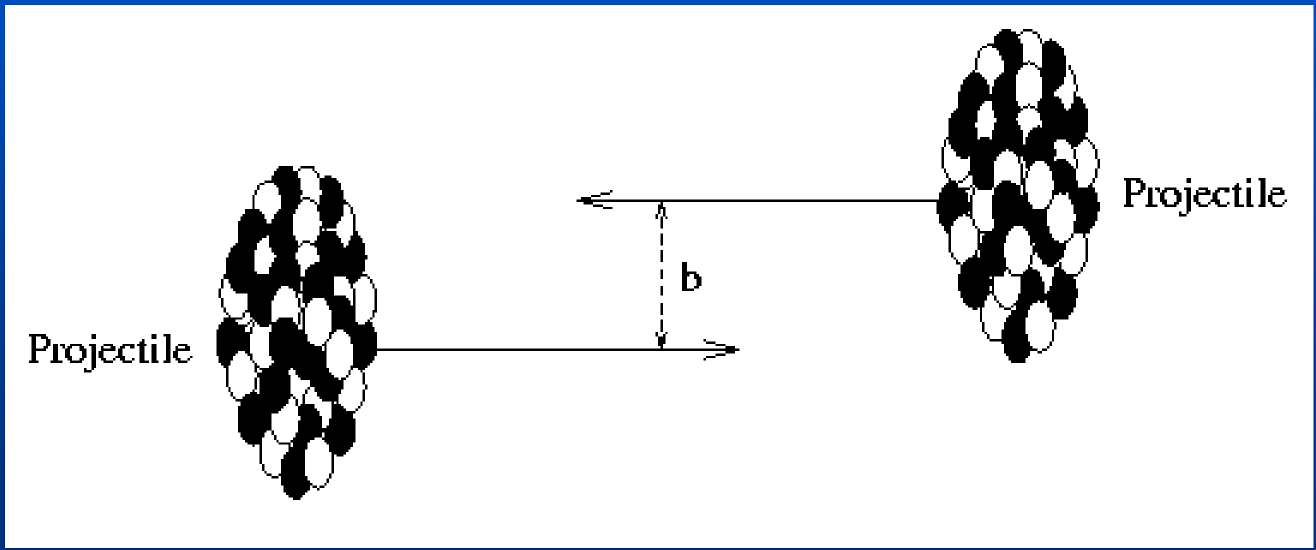
Outline

- Introduction to Relativistic Heavy Ion Collisions and Heavy Ion Colliders.
- Production of particles with high transverse momentum.
- Collective Elliptic Flow
- Global Observables
- Particle Physics with Nuclei:
  Ultra-Peripheral Collisions

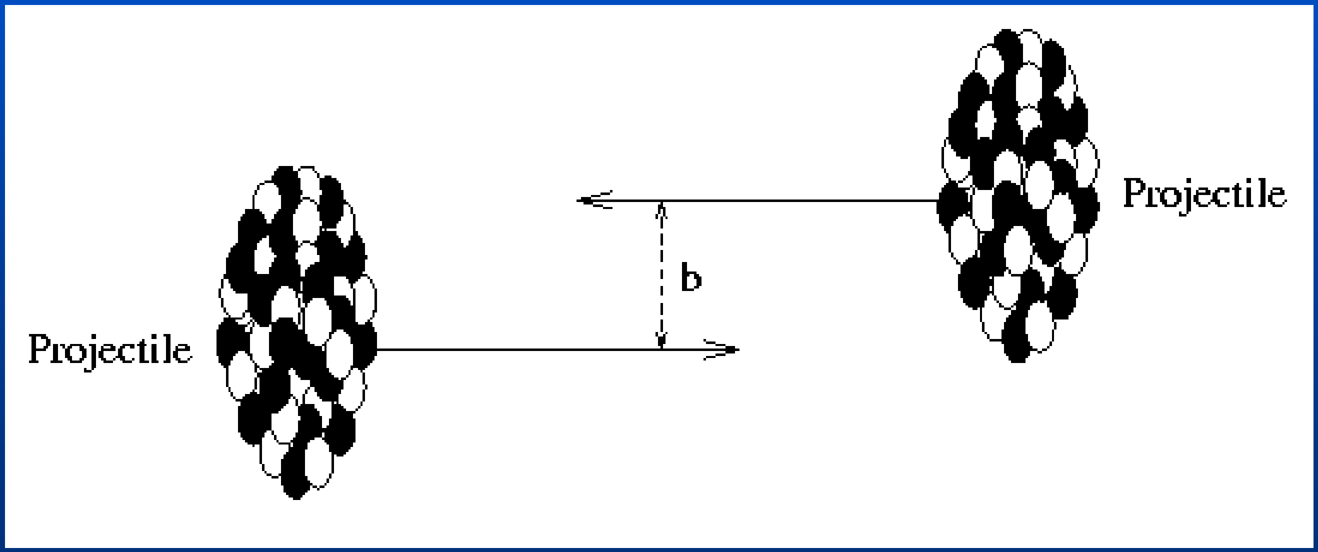
What is a ”heavy ion”?

Accelerator terminology: Any ion with A>4,
$\Rightarrow$ Anything heavier than α-particle

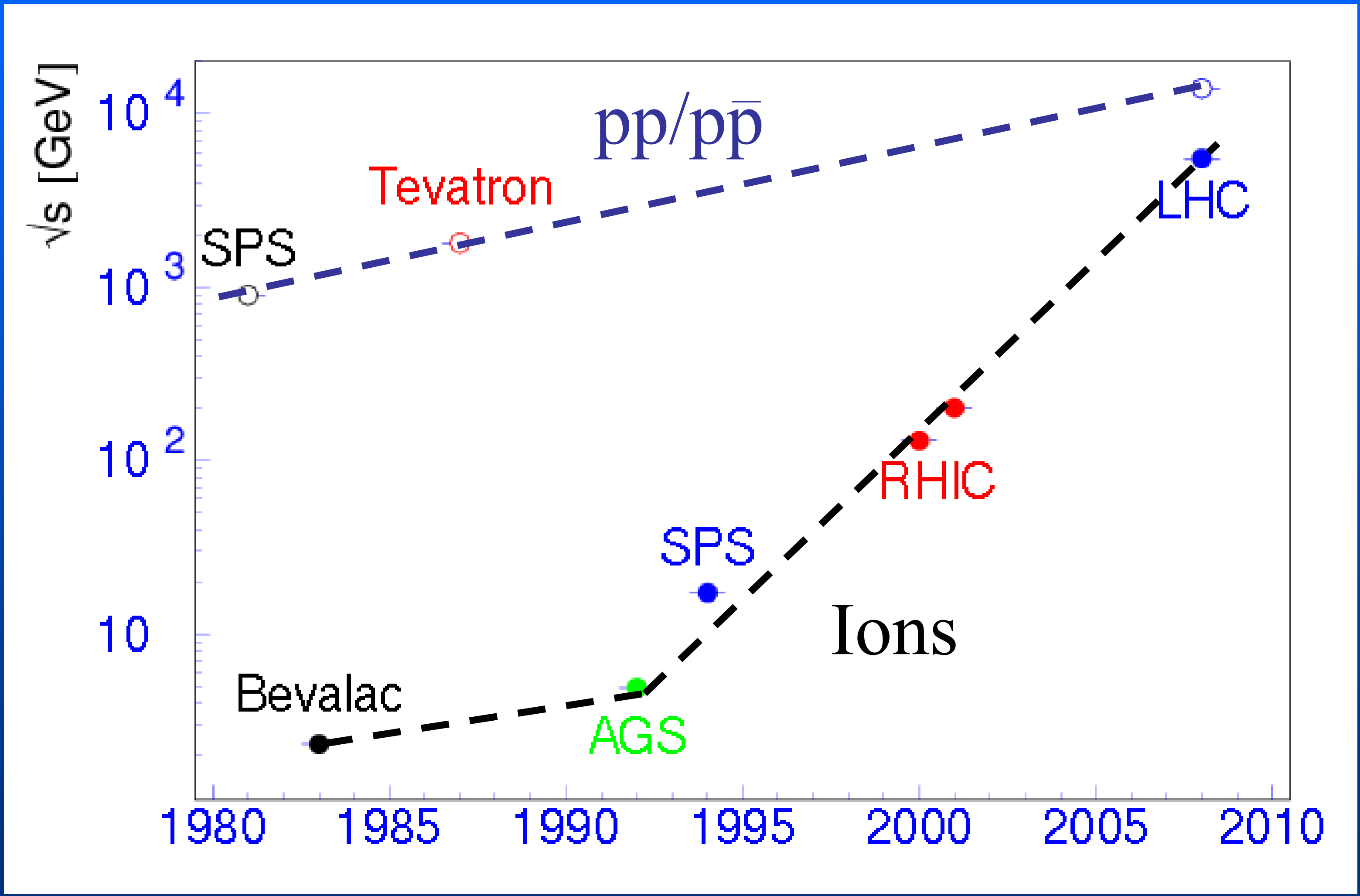
This talk: *truly heavy ions* –
ions with A≈200 (^{197}Au, ^{208}Pb)



Measure of collision energy: center-of-mass energy per nucleon-nucleon collision, $\sqrt{s_{nn}}$.



The maximum $\sqrt{s}_{nn}$ of truly heavy ions has increased dramatically during the last 25 years:



Heavy-Ion Laboratories

Two main, high-energy laboratories:

- Brookhaven (Long Island, New York)
  - ⇒ AGS, RHIC
- CERN (Geneve, Switzerland/France)
  - ⇒ SPS(fixed target), LHC

Other laboratories:

- LBL (Lawrence Berkeley Lab, California)
  - ⇒ Bevalac (Betatron)
- GSI (Darmstadt, Germany)
  - ⇒ FAIR
- JINR (Dubna, Russia)
  - ⇒Synchrophasotron

Heavy-Ion History

Birth of the field:
1986 - ^{16}O accelerated at AGS and SPS
Fixed target experiments.

1994 - ”Truly heavy ions” at AGS and SPS, Au and Pb.

SPS: NAXX or WAXX (NA49, WA98, NA57, …)
AGS: EXXX (E802, E872, …)

2000 - First collisions at RHIC (Au+Au)
First Heavy-Ion Collider

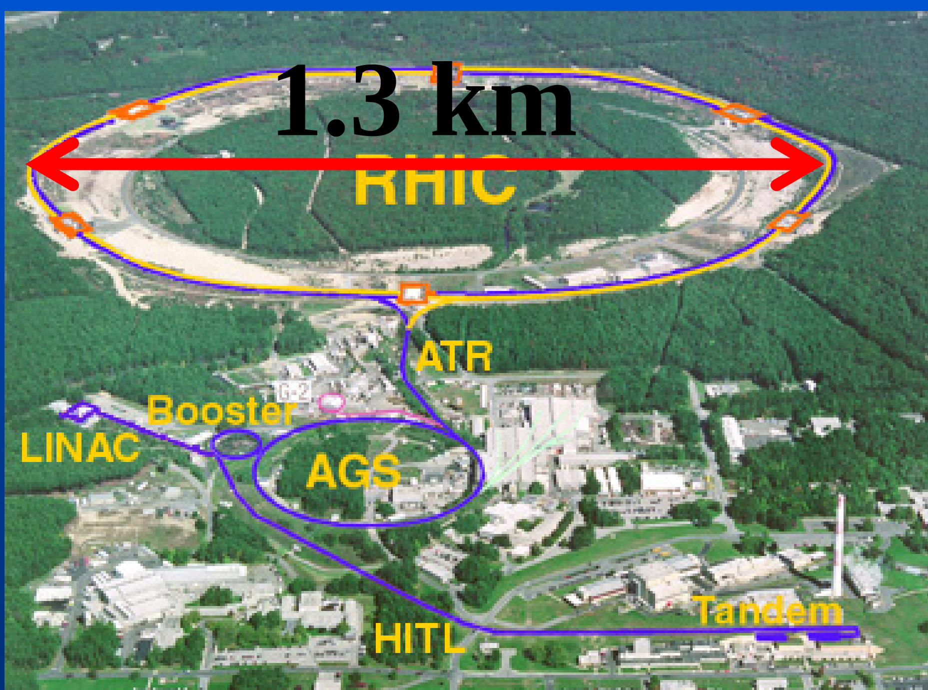
Experiments: STAR, PHENIX, PHOBOS, BRAHMS

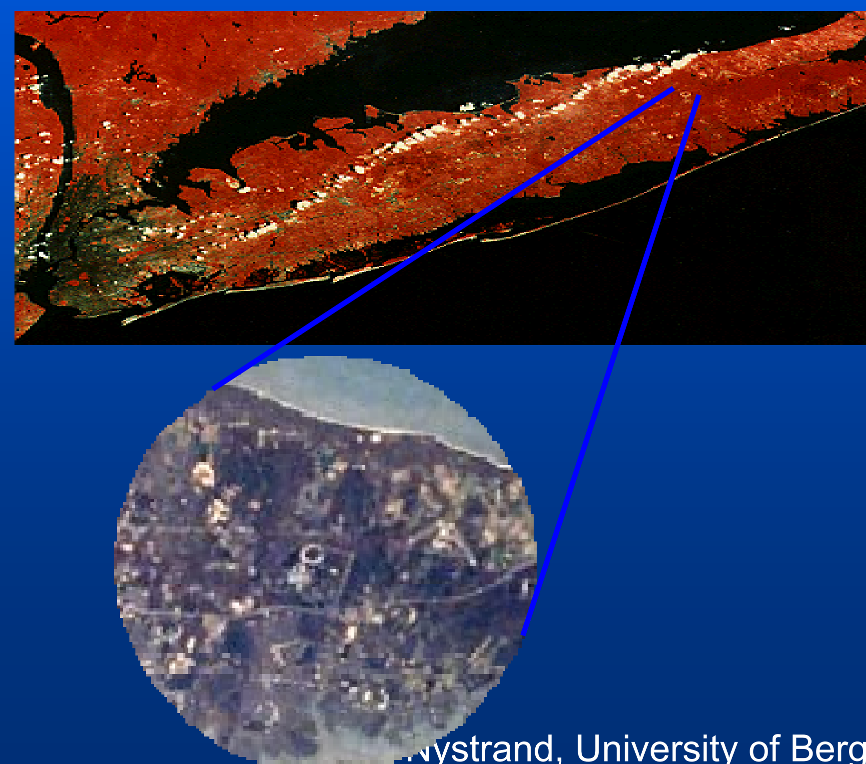
The Relativistic Heavy Ion Collider (RHIC)

Collider for heavy nuclei and (polarized) protons at Brookhaven National Laboratory.

Au+Au @ $\sqrt{s}$ = 200 A GeV

p+p @ $\sqrt{s}$ = 500 A GeV (Physics @ 200 GeV so far)

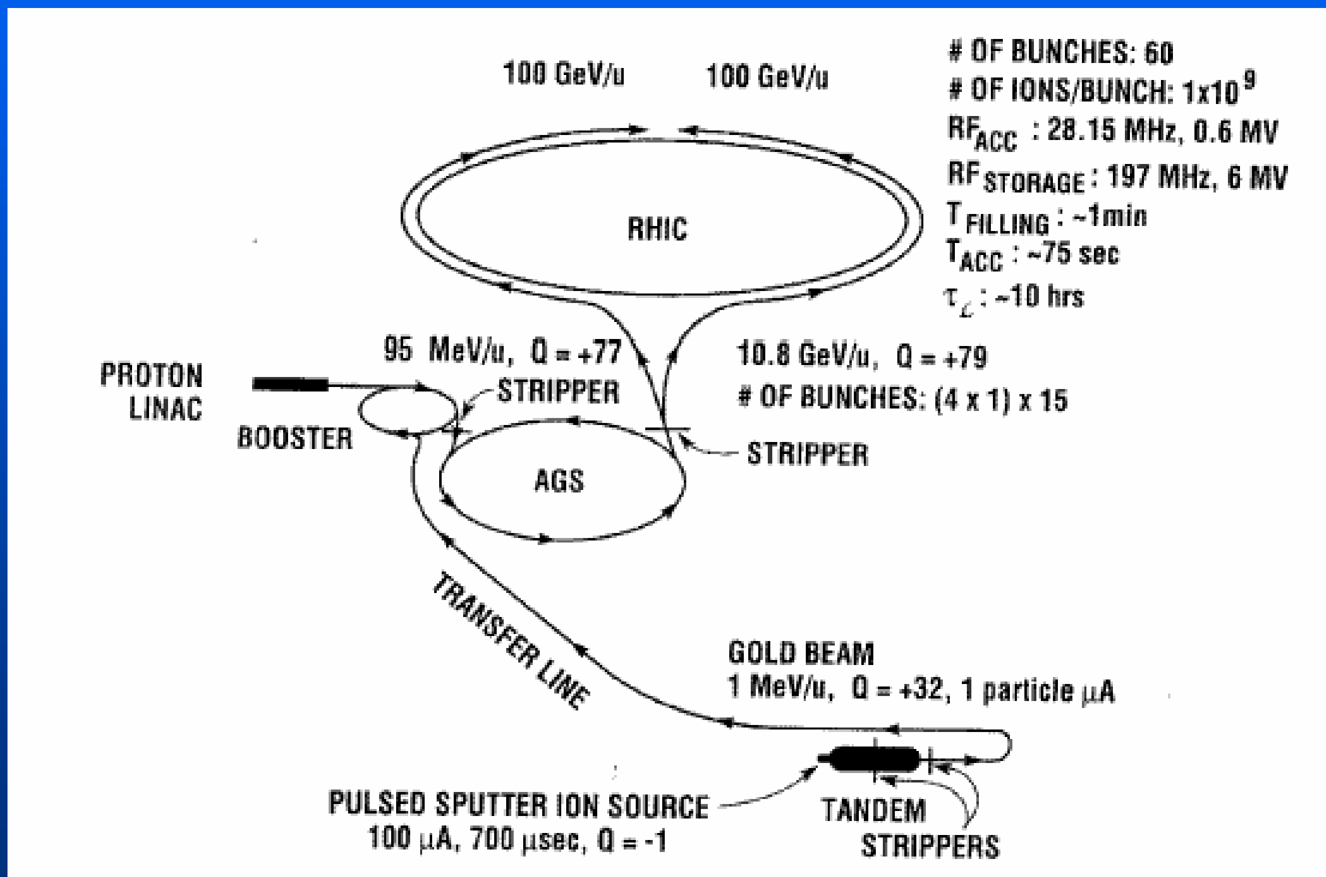




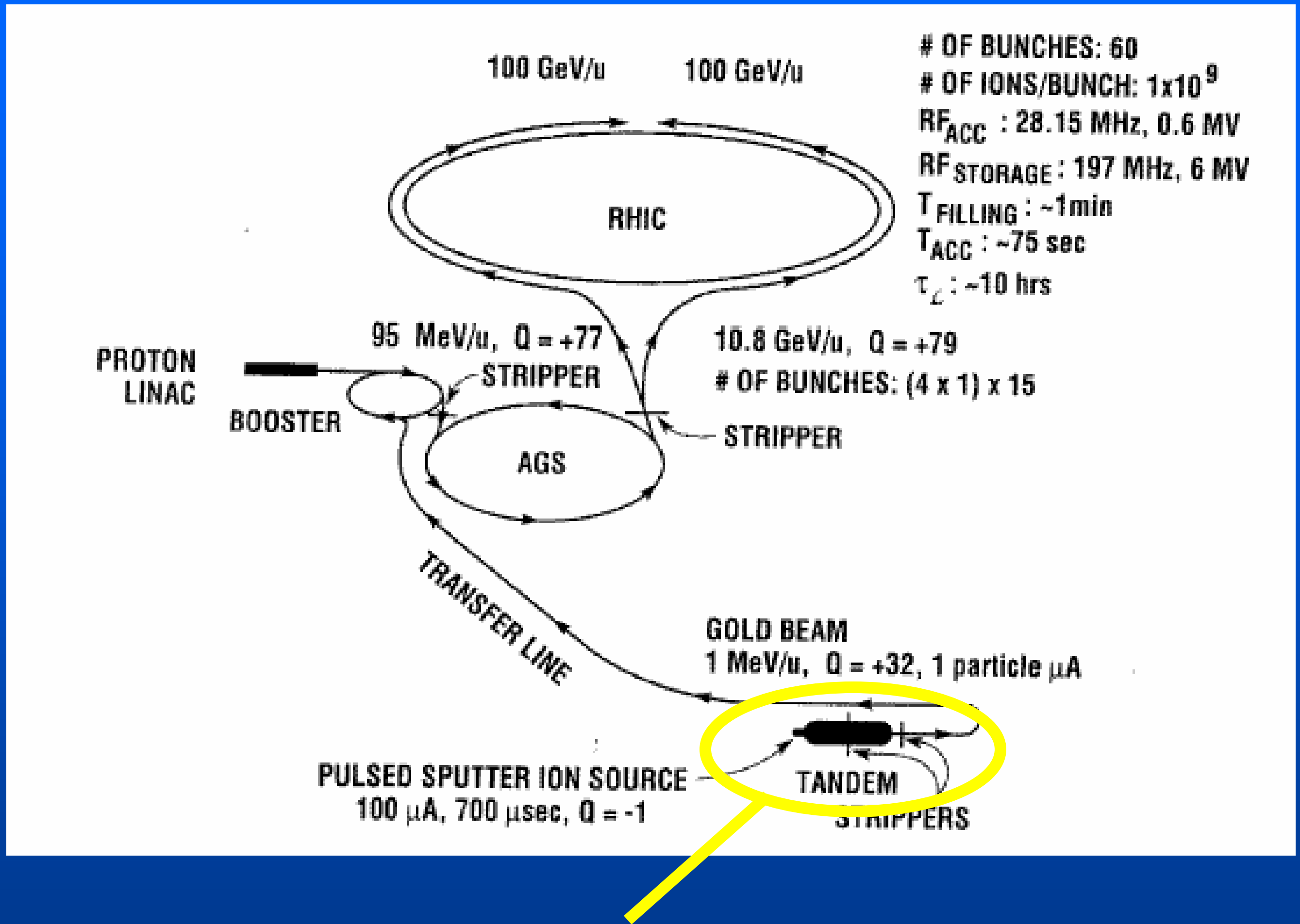
Inside the RHIC tunnel

A large system of accelerators

Relativistic Heavy-Ion Collider at Brookhaven National Laboratory



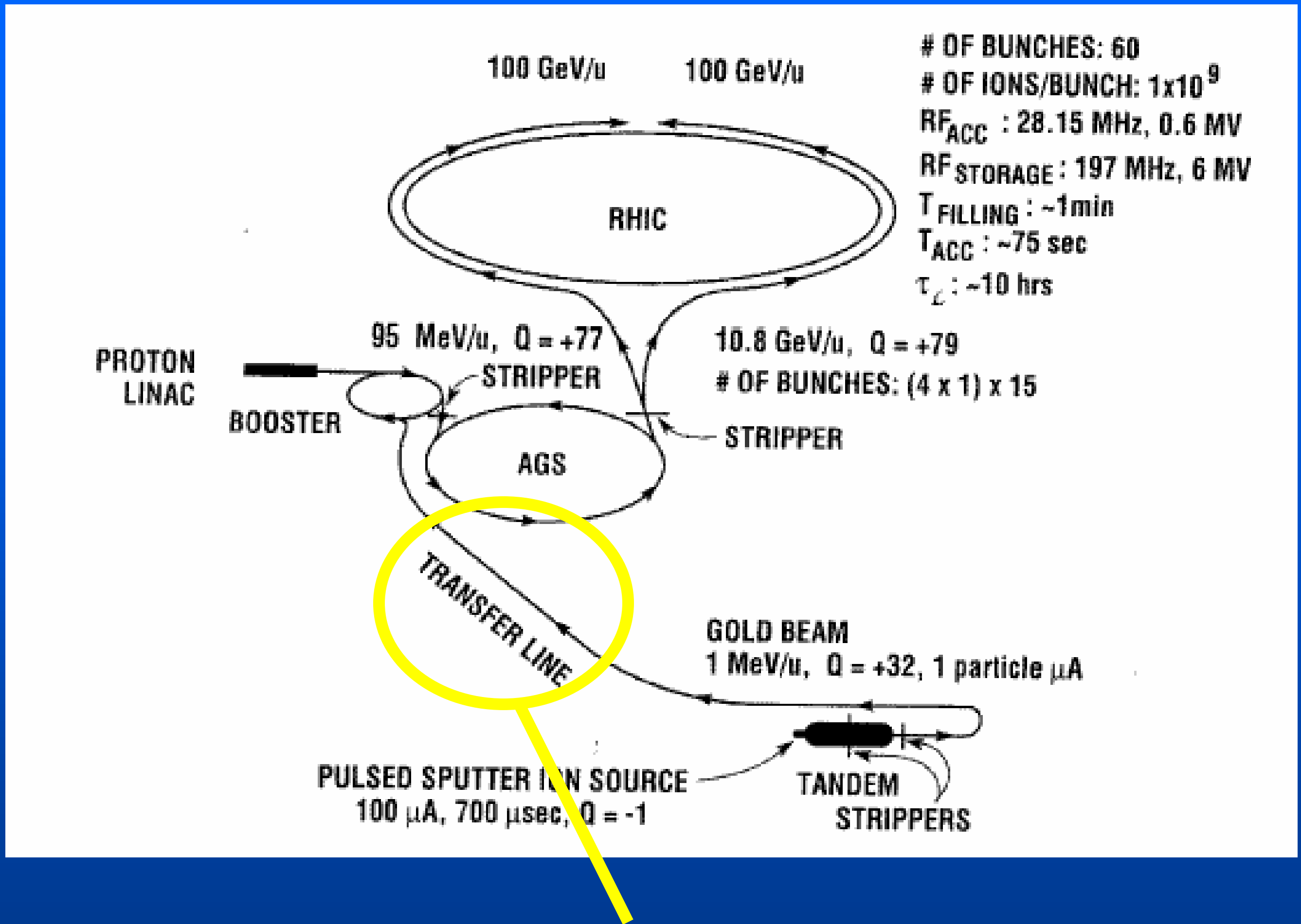
Example of a large system of accelerators



First step: Ion source + Tandem Van de Graaff

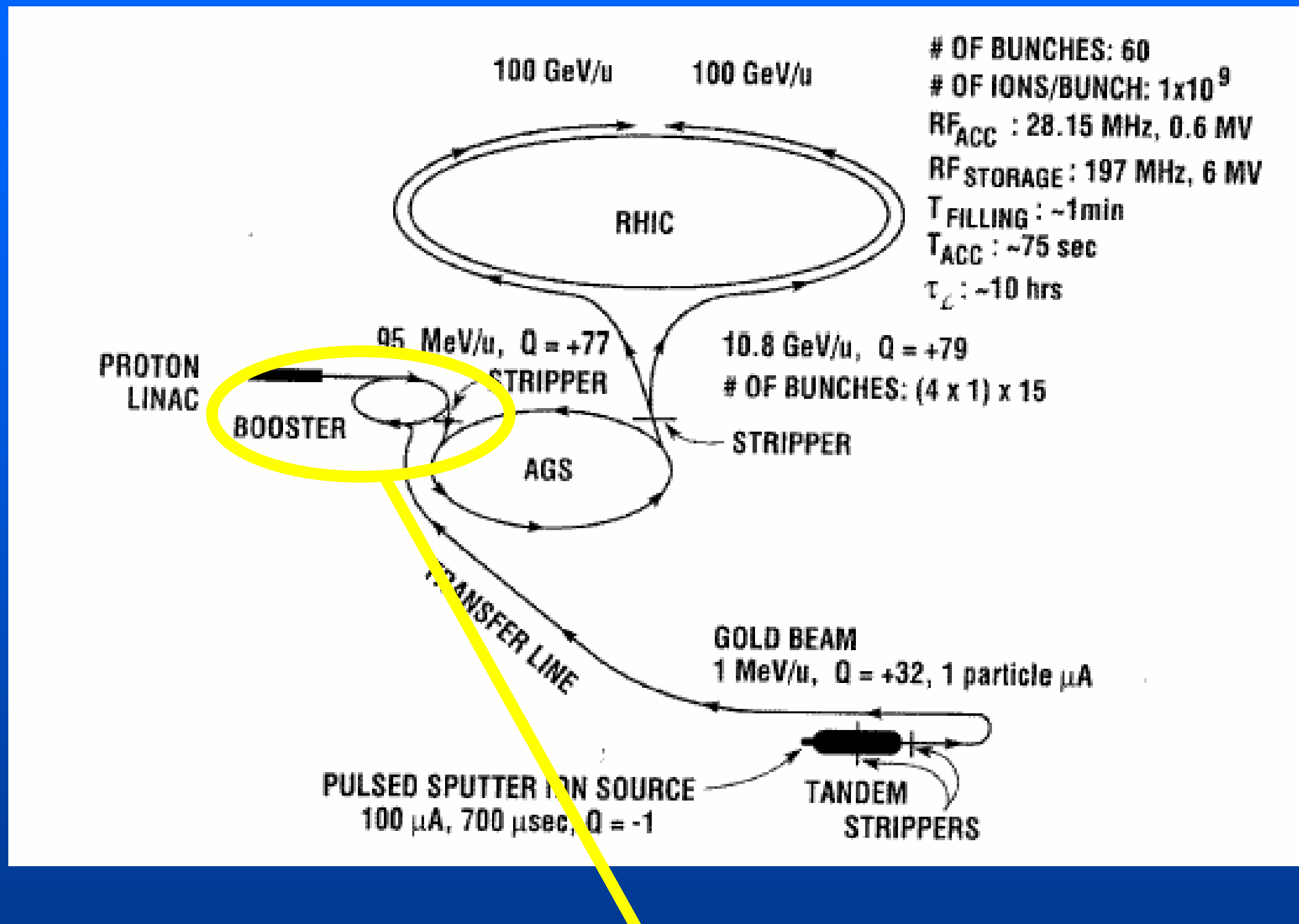
E = 1 MeV/nucleon, Q=+32e (32 of 79 Au electrons removed)

Example of a large system of accelerators



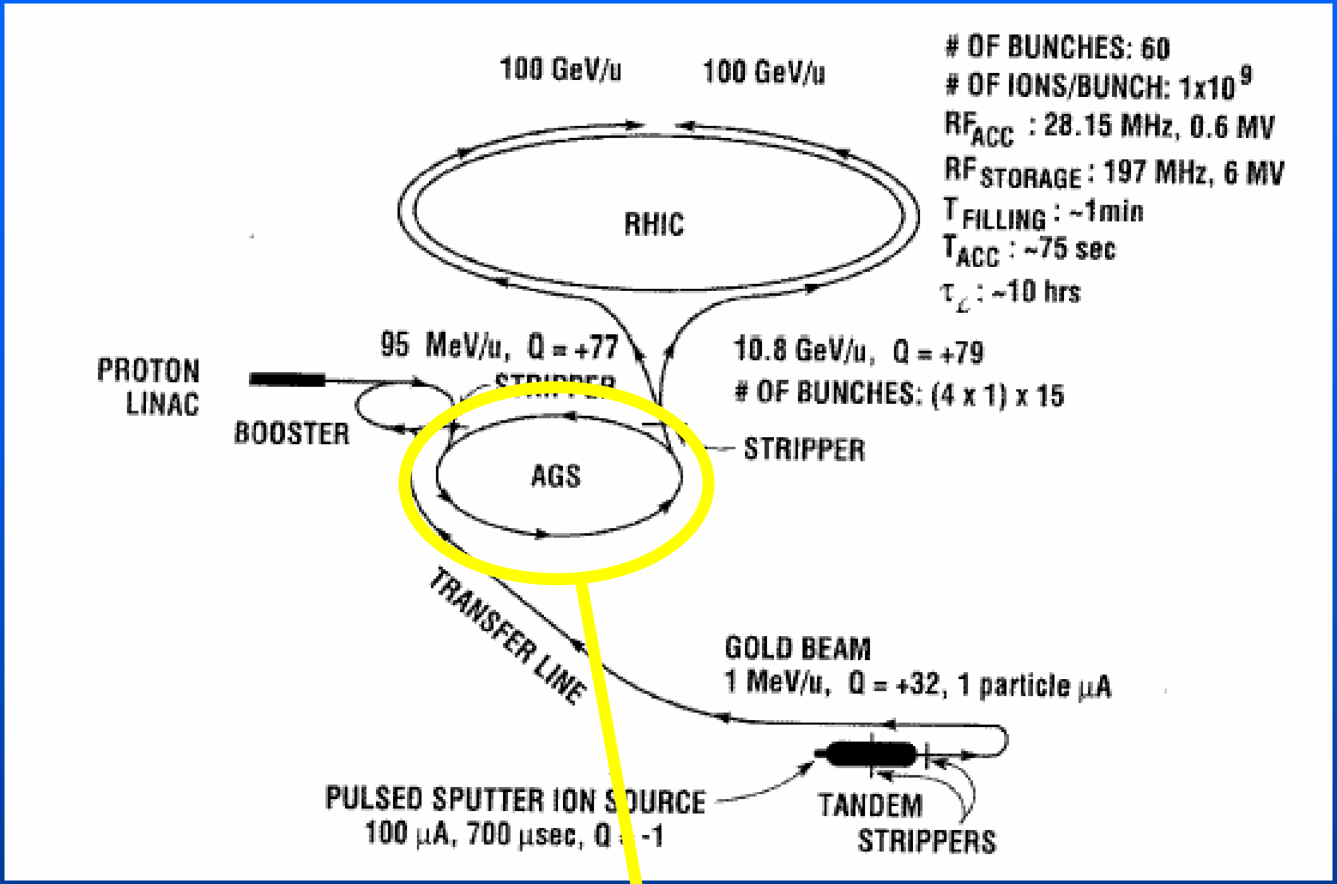
Second step: Transfer Line Tandem Van de Graaff → Booster.

Example of a large system of accelerators



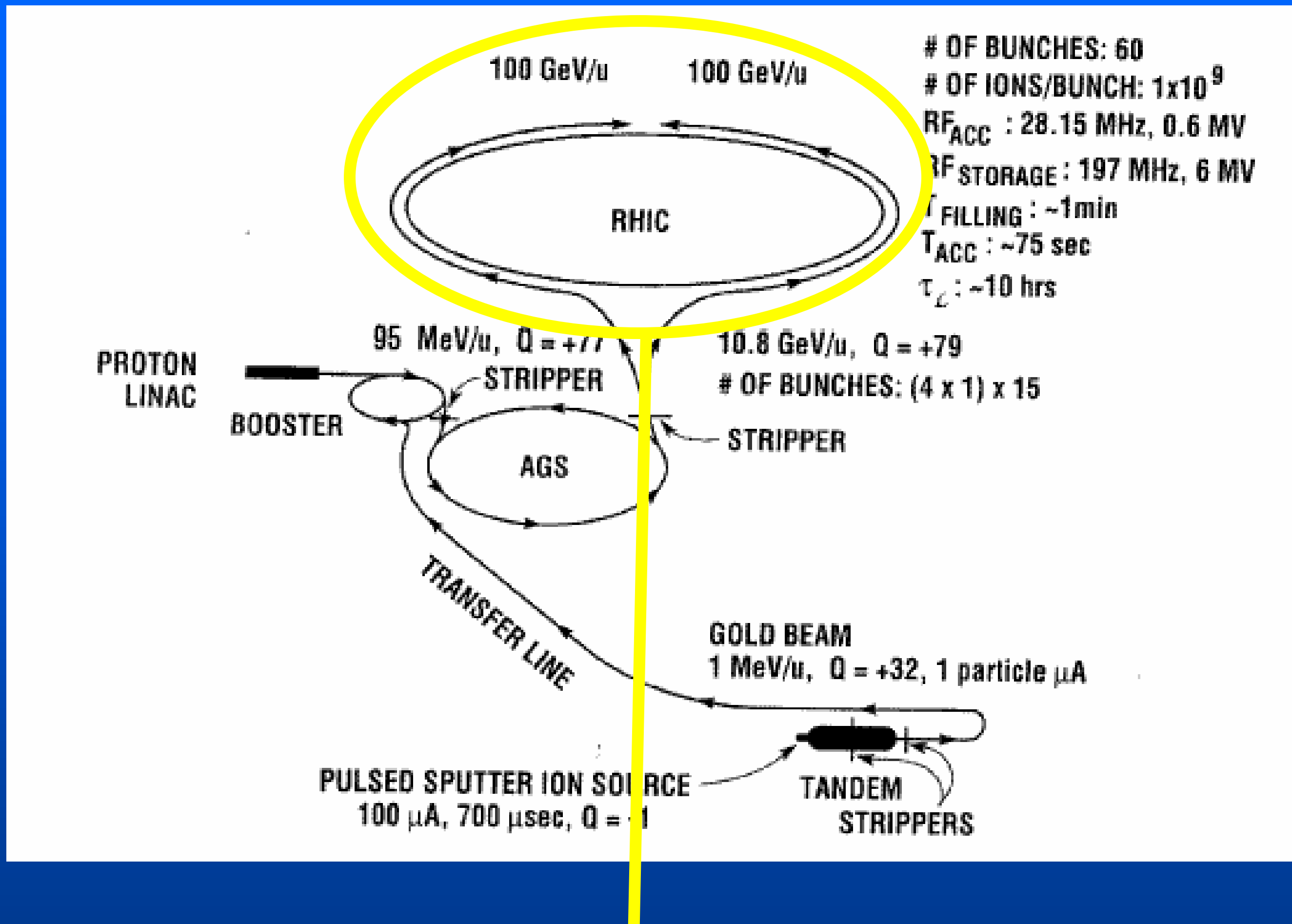
Third step: Booster, increase in E: 1 MeV/nucleon → 95 MeV/nucleon. Followed by stripping foil, removes 77 of the 79 electrons from Au atom.

Example of a large system of accelerators

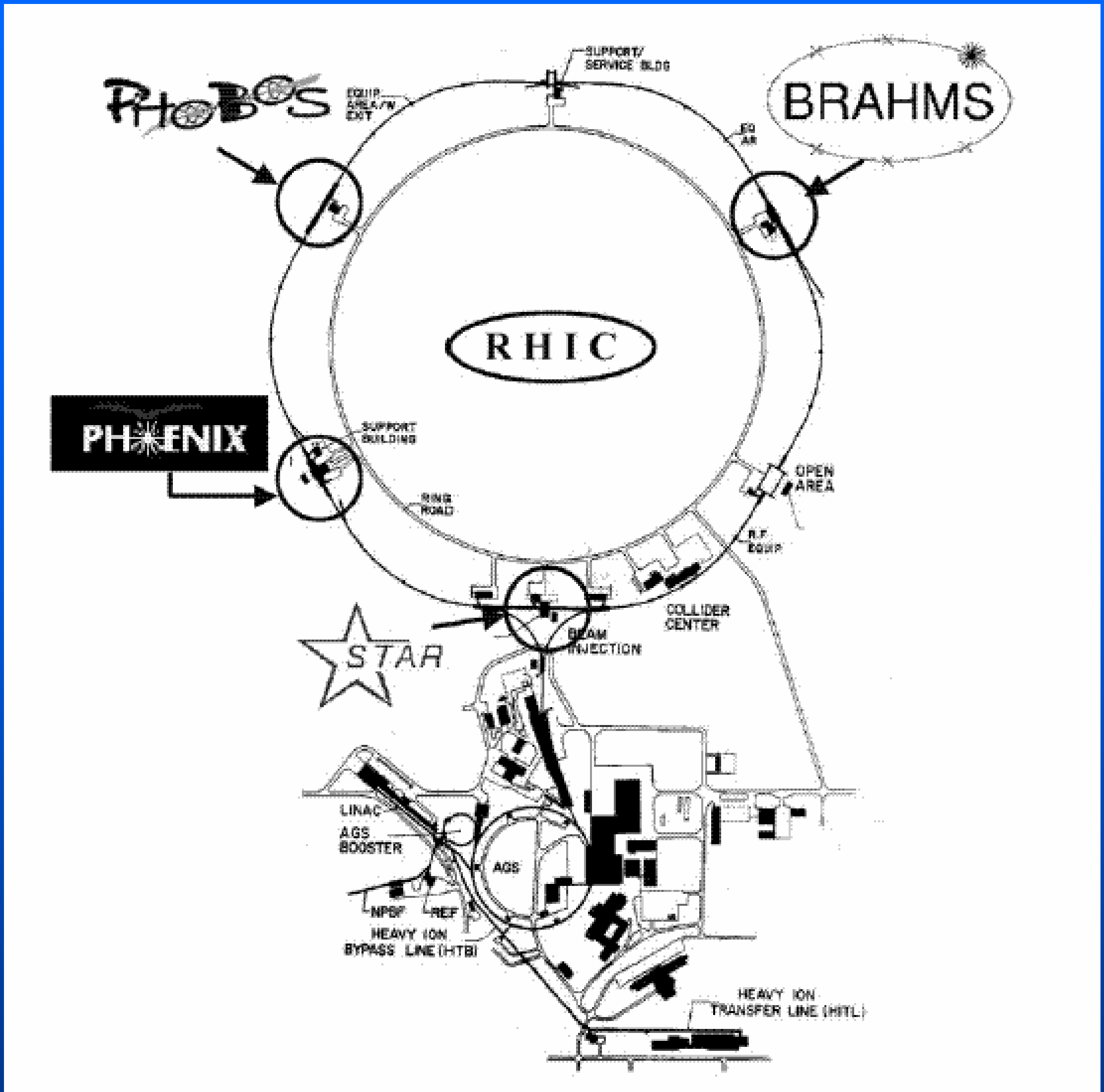


Fourth step: AGS (Alternating Gradient Synchrotron) increase in E: 95 MeV/nucleon → 10.8 GeV/nucleon. Stripping foil removes the remaining two electrons.

Example of a large system of accelerators



Final step: RHIC, increase in E: 10.8 GeV/nucleon → 100 GeV/nucleon in two beams. The beams are focussed for collisions at 4 (6) interaction points.



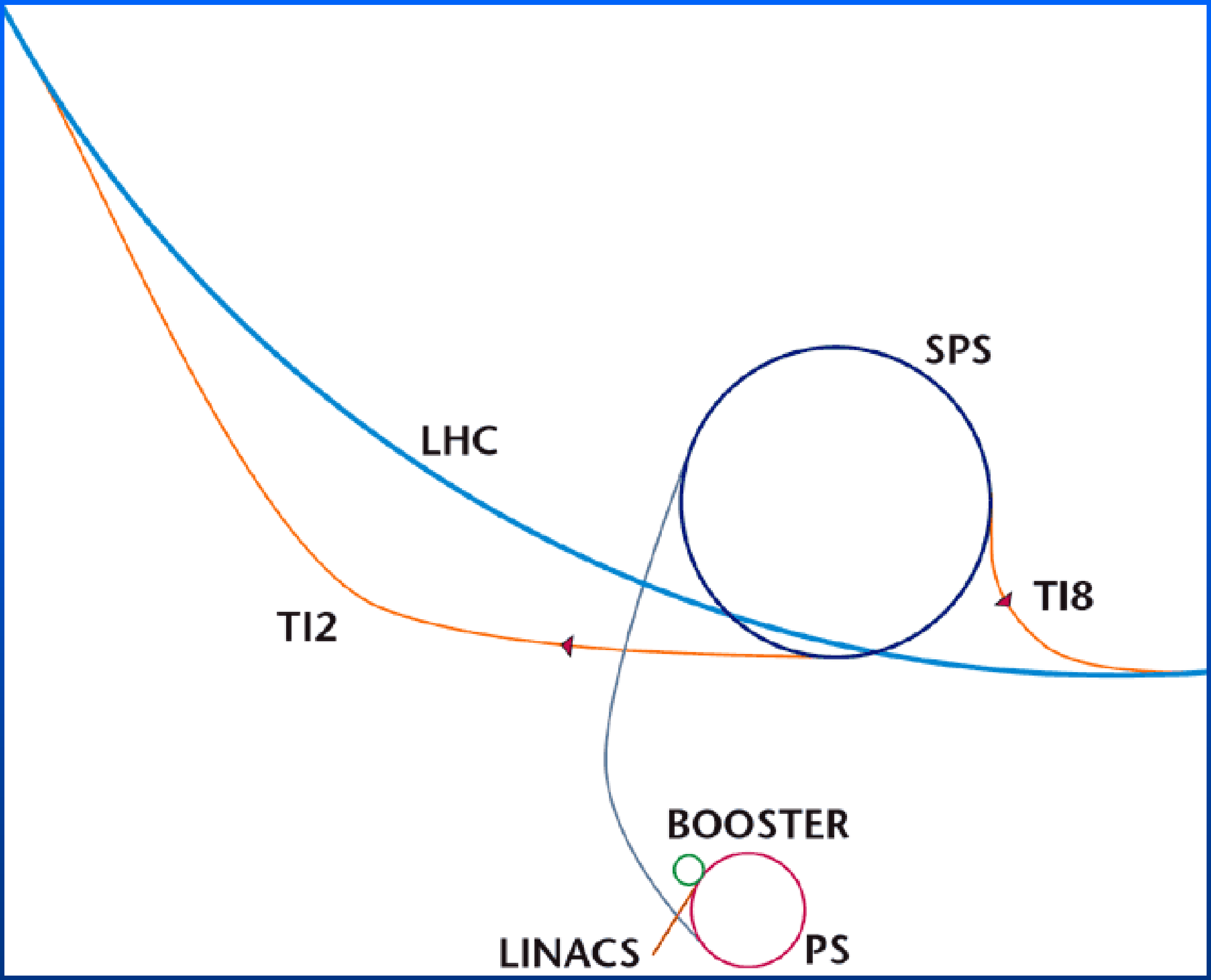
At each interaction point there is an experiment…

Some RHIC parameters

- The particles travel in bunches around the ring, 60 bunches/ring, bunch length: ~10cm
- Particles/bunch: $\sim 10^9$.
- Bunch crossing frequency 10 MHz ⇔ Time between bunch crossings 100 nsec.
- Transverse size of the beam: ~500×500 μm

	Au+Au	p+p
Luminosity:	$2 \cdot 10^{26}$ cm^{-2} s^{-1}	$1 \cdot 10^{31}$ cm^{-2} s^{-1}
Total cross section:	11 barn	42 mb
Interaction rate:	2,2 kHz	420 kHz

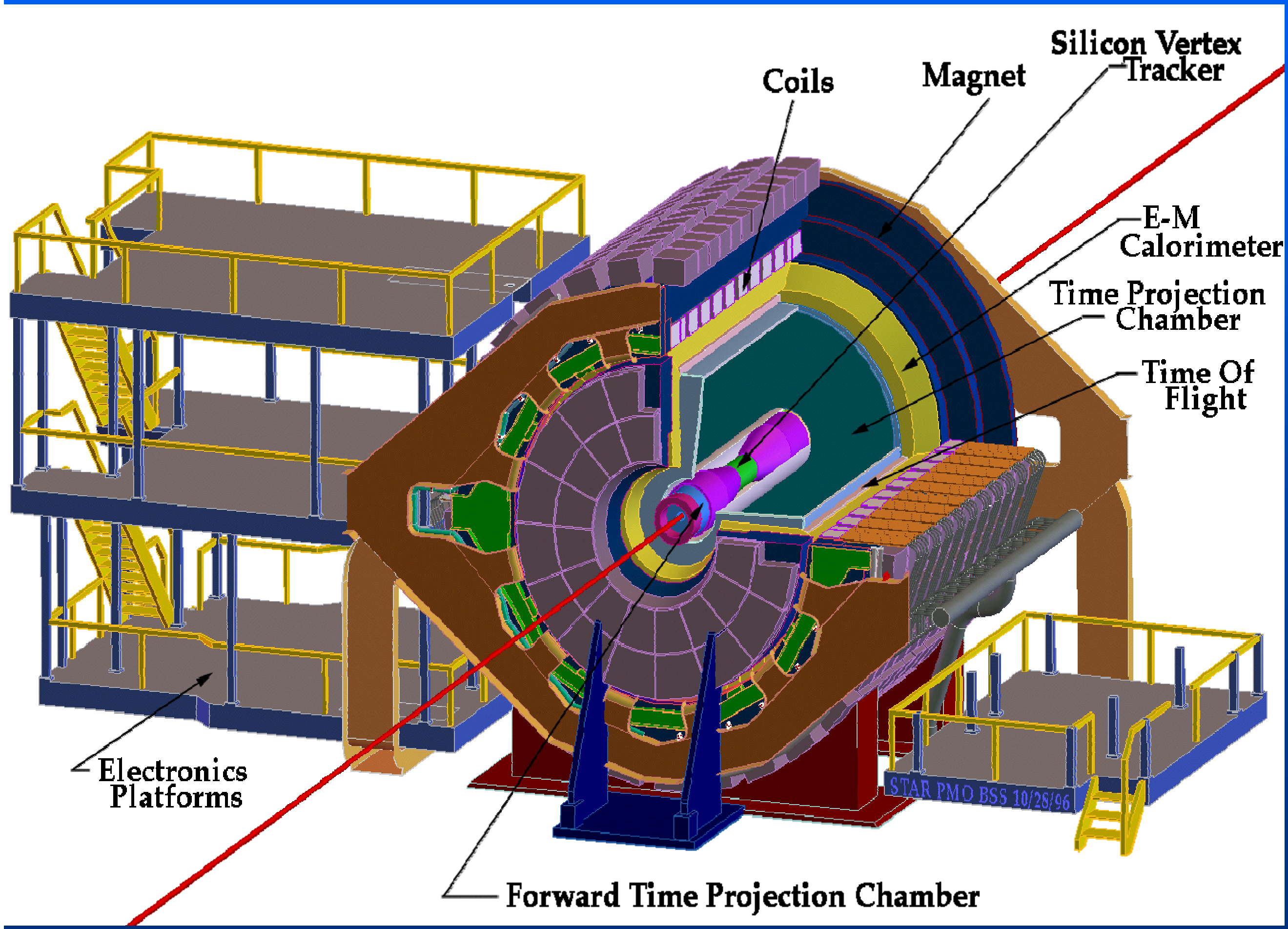
Pre-accelerators for the LHC



Experiments at RHIC

The STAR Detector

Main detector: Time Projection Chamber (TPC),
4m long, 4m diameter, $|\eta|<1.5$

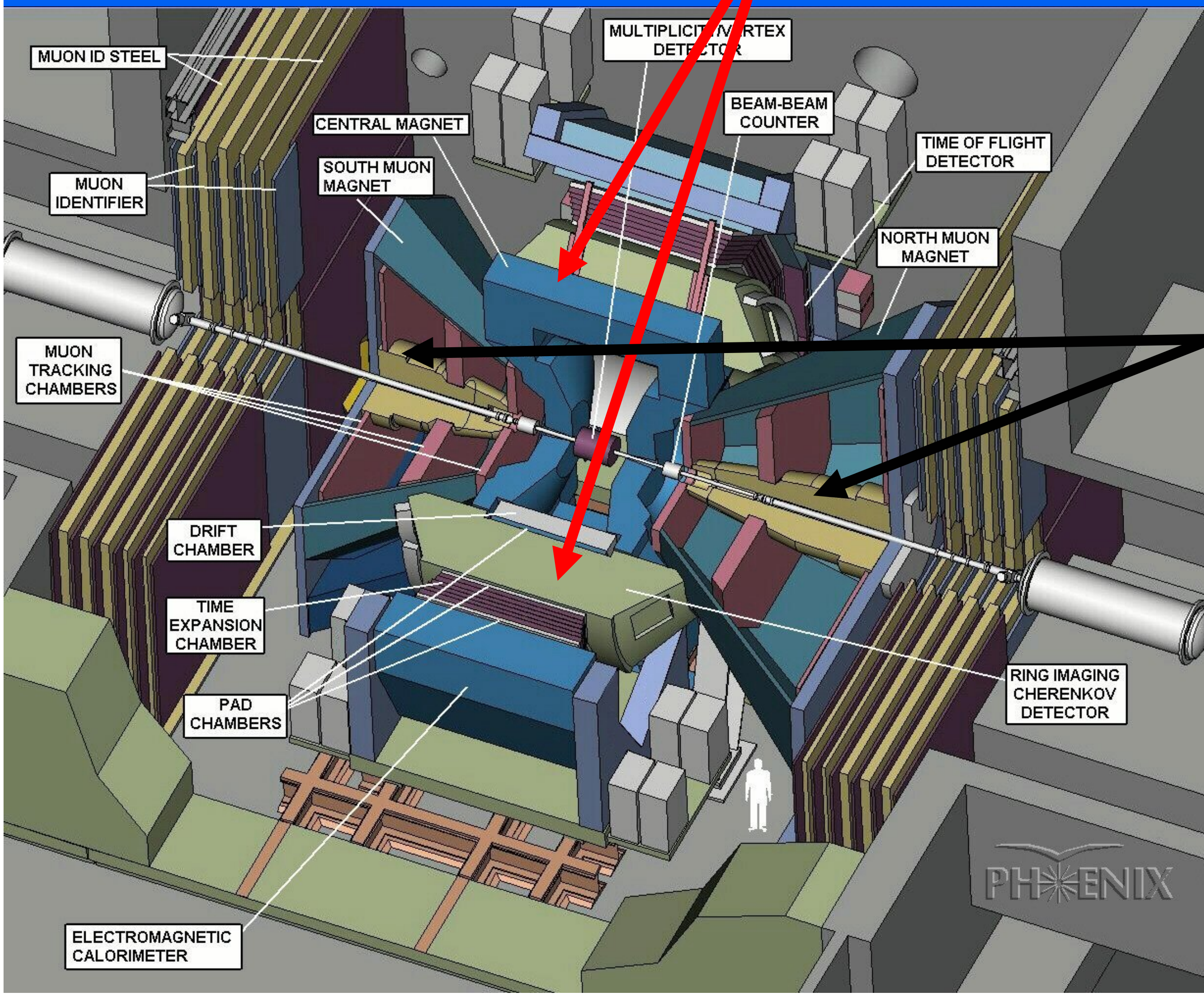


Other components:

* Forward TPCs
* Electromagnetic Calorimeter
* Silicon Vertex Tracker

The PHENIX Detector

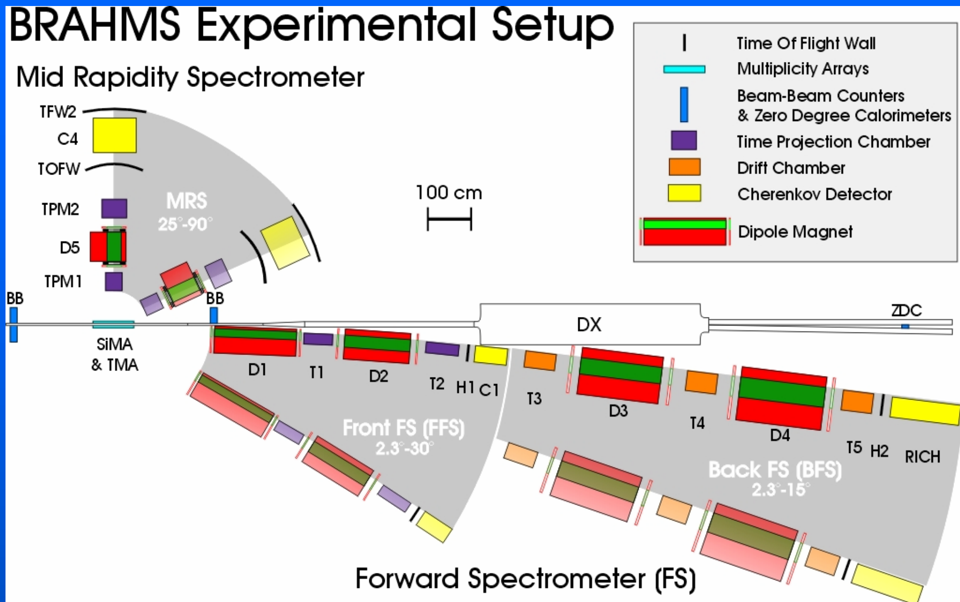
Two central tracking arms:
$|\eta|<0.35$, $2\times\Delta\varphi=90°$



Drift Chambers,
MWPCs,
RICH,
ToF, EmCal

Two muon arms:
$1.2<|\eta|<2.3$,
Tracking:
Cathode Strip Chambers,
MuId:
Streamer tubes

The BRAHMS Detector



2 Movable Spectrometer arms (TPCs for tracking). Particle Id for $|\eta|<3$.

The PHOBOS Detector

Charged Particle Tracking (Si Pad detectors) for $|\eta|<5.5$, but Particle Id only near mid-rapidity.

System and energies studied so far

- First run in June 2000:
  - Au+Au @ $\sqrt{s}$ = 130 A GeV

Quark Matter 2001

- Second run July 2001 - Jan. 2002:
  - Au+Au @ 200 A GeV
  - p+p @ 200 GeV

Quark Matter 2002

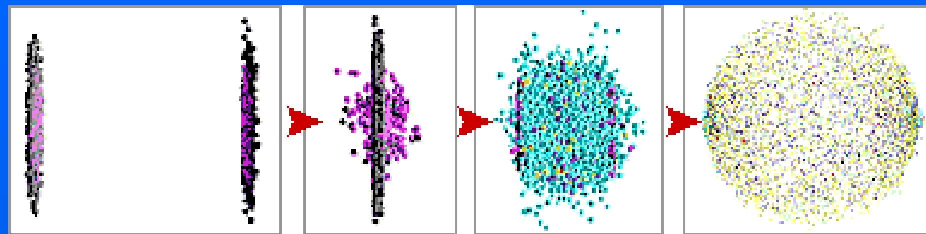
- Third Run Jan. 2003 – May 2003:
  - d+Au @ 200 A GeV
  - p+p @ 200 GeV

White Papers,
[Nucl. Phys. A Vol 757 (2005)]
Quark Matter 2004

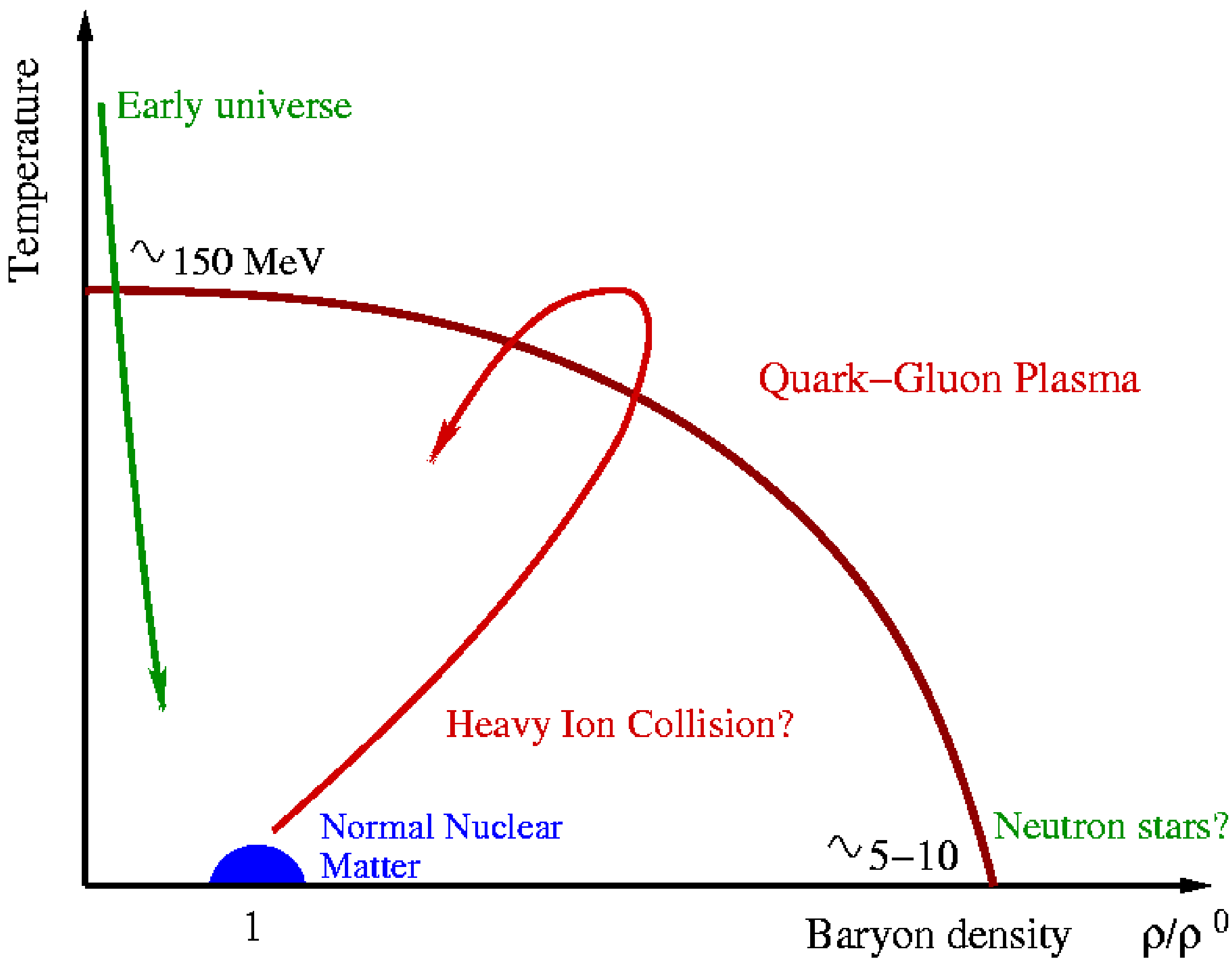
- Fourth Run Jan. 2004 – May 2004:
  - Au+Au @ 200 A GeV
  - Au+Au @ 63 A GeV (short)
  - p+p @ 200 GeV
- Fifth Run Jan. 2005 – June 2005:
  - Cu+Cu @ 200 A GeV
  - Cu+Cu @ 63 A GeV
  - p+p @ 200 GeV

Quark Matter 2005

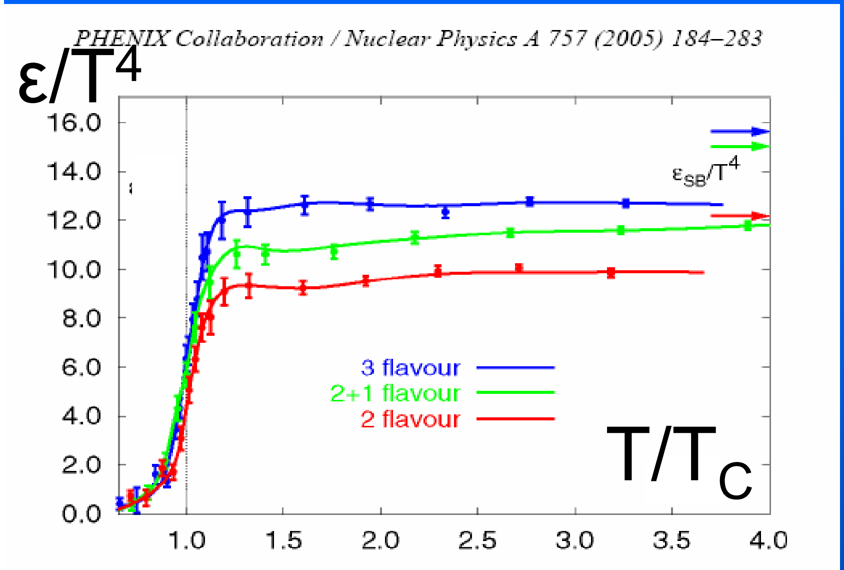
The main goal of RHIC is to study hot and dense nuclear matter



The nuclear phase diagram



THE PHASE TRANSITION



Fritiof Karsch et al.

Hagedorn 1965:

Density of hadronic resonances: $\rho(m) \propto \exp(m/T_H)$

$\Rightarrow$ Thermodynamic system of hadrons w/ $T>T_H$ impossible

$T_H \approx 160$ MeV ($\approx m_\pi \approx \Lambda_{QCD}$)

What is ε?

Average energy per unit volume:

$$\varepsilon = \frac{1}{V}\int_0^\infty E\,\frac{dn}{dE}\,dE$$

What is dn/dE ?

$\Rightarrow$ Statistical mechanics

Phase space density of particles:

$$(2\pi\hbar)^3\,\frac{1}{V}\,\frac{d^3n}{dp^3} = \frac{g}{e^{E/kT} \pm 1}$$

+ for fermions

- for bosons

g - degeneracy

$d^3n/dp^3 \rightarrow dn/dE \quad (dp^3 = 4\pi p^2 dp \approx 4\pi E^2 dE)$

$$\frac{1}{V}\frac{dn}{dE} = \frac{g}{2\pi^2}\frac{1}{(\hbar c)^3}\frac{E^2}{e^{E/kT} \pm 1}$$

For (massless) bosons ("-"):

$$\varepsilon = \frac{1}{V}\int_0^\infty E\frac{dn}{dE}dE = \int_0^\infty \frac{g}{2\pi^2}\frac{1}{(\hbar c)^3}\frac{E^3}{e^{E/kT} - 1}dE = g\frac{\pi^2}{30}\frac{(kT)^4}{(\hbar c)^3}$$

For (massless) fermions ("+"):

$$\varepsilon = \frac{1}{V}\int_0^\infty E\frac{dn}{dE}dE = \int_0^\infty \frac{g}{2\pi^2}\frac{1}{(\hbar c)^3}\frac{E^3}{e^{E/kT} + 1}dE = g\frac{7}{8}\frac{\pi^2}{30}\frac{(kT)^4}{(\hbar c)^3}$$

In natural units:

$$\varepsilon = g\frac{\pi^2}{30}\frac{(kT)^4}{(\hbar c)^3} = g\frac{\pi^2}{30}T^4$$

and

$$\frac{\varepsilon}{T^4} = (g_b + \frac{7}{8}g_f)\frac{\pi^2}{30}$$

Consider a system with kT=150 MeV
(chemical potential μ=0 ⇔ no net baryon number)

Hadrons: Pions, g_b=3 (spin=0, no color, isospin=1)

$\varepsilon/T^4 \sim 3\ (\pi^2/30) \approx 1.0$

Quarks and Gluons: u,d or u,d,s g_f = 24 or 36

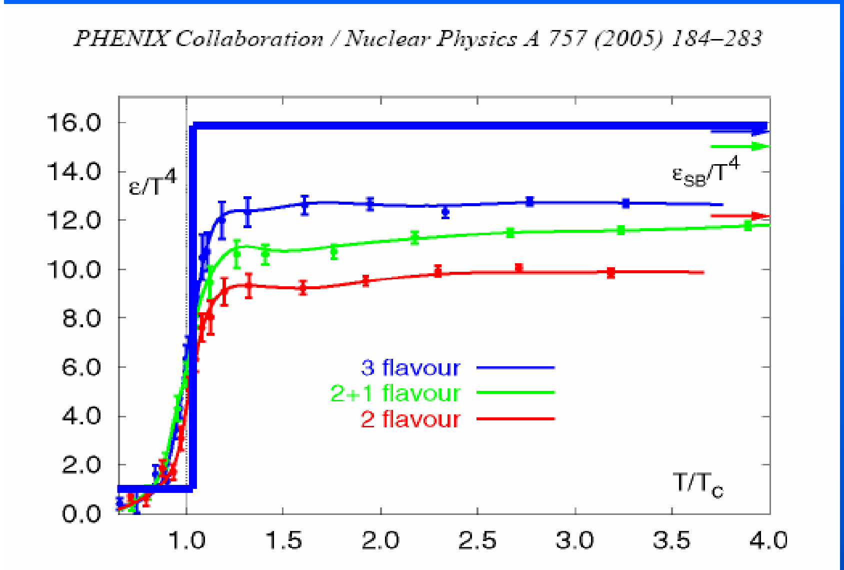
(spin=1/2, 3 colors, q and $\bar{q}$, 2 or 3 flavors)

gluons g_b=16 (8 color comb., spin=1)

$\varepsilon/T^4 \sim 37\ (\pi^2/30) \approx 12.2$ or

$47½\ (\pi^2/30) \approx 15.6$

THE PHASE TRANSITION



Fritiof Karsch et al.

For a quark-gluon plasma:

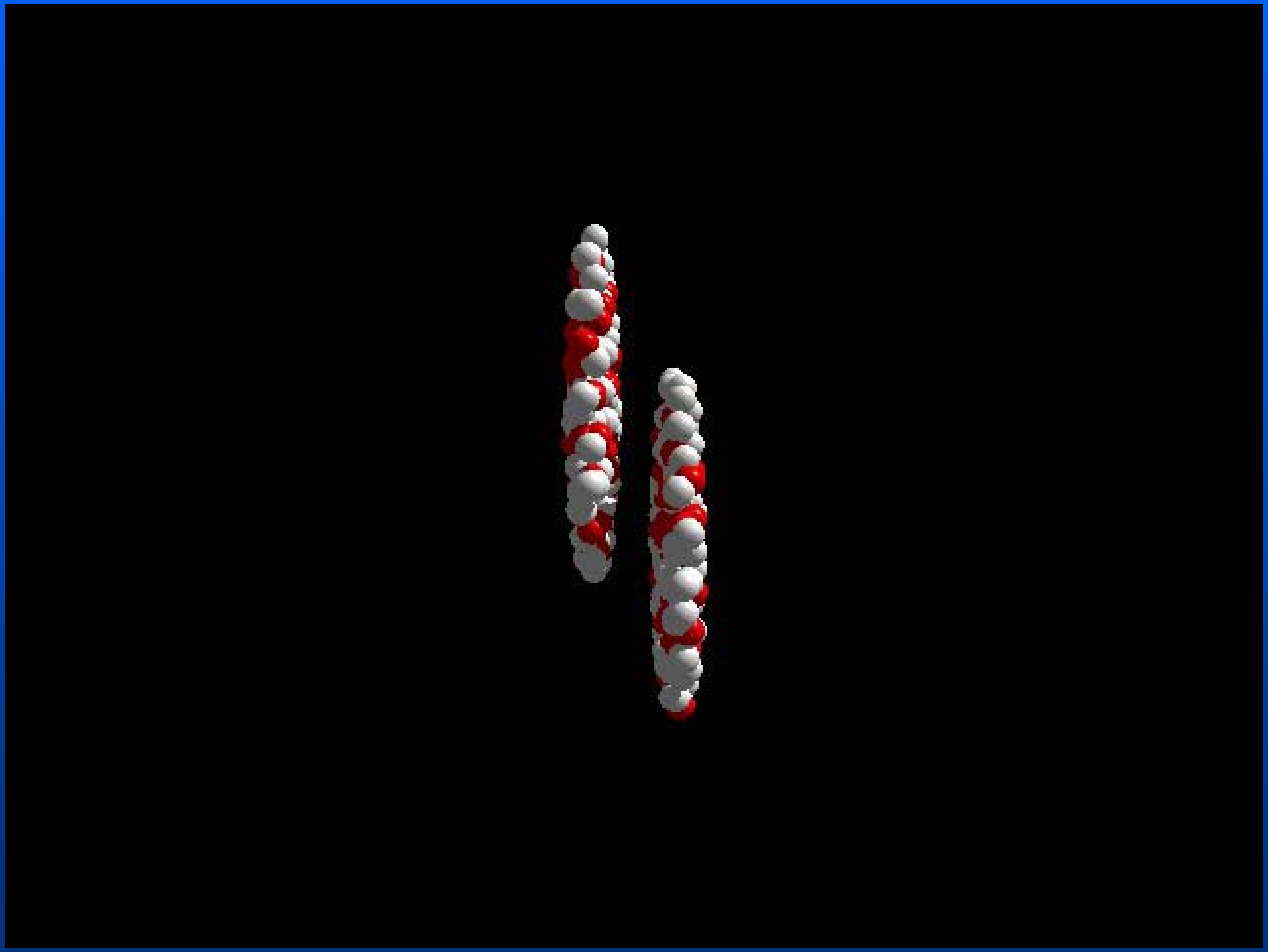
kT_C = 150 MeV $\Rightarrow$ ε > 1.0 GeV /fm^3

kT_C = 170 MeV $\Rightarrow$ ε > 1.7 GeV /fm^3

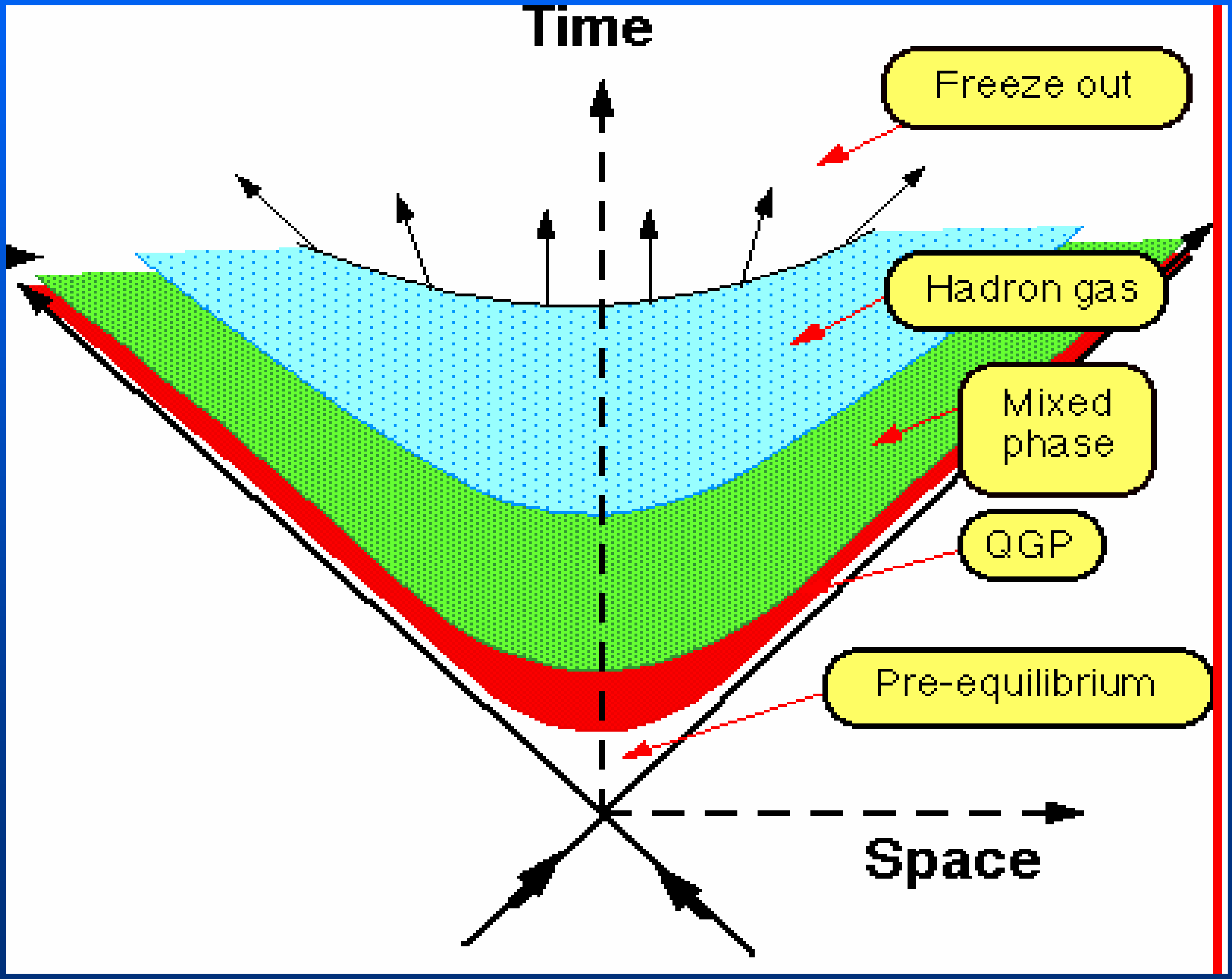
$$\varepsilon = \left(g_b + \frac{7}{8} g_f \right) \frac{\pi^2}{30} \frac{(kT)^4}{(\hbar c)^3}$$

Compare normal nuclear matter: ε ≈ 0.16 GeV/fm^3

Measuring ε and T directly is difficult



Not a static source – The system expands and cools down – Most particles emitted at the late stages of the collisions



A more general strategy to understand heavy-ion collisions:

Use heavy ions (Au+Au) to produce a new state of matter (the Quark Gluon Plasma).

Use p+p, d+Au results as benchmarks to disentangle the effects of the produced state.

The first remarkable result from RHIC:

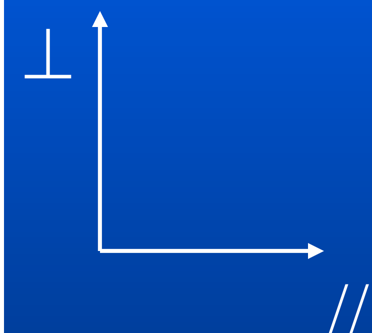
1. Suppression of particles with high-p_T , ”Jet-quenching”

Jet-quenching and high-p_T suppression

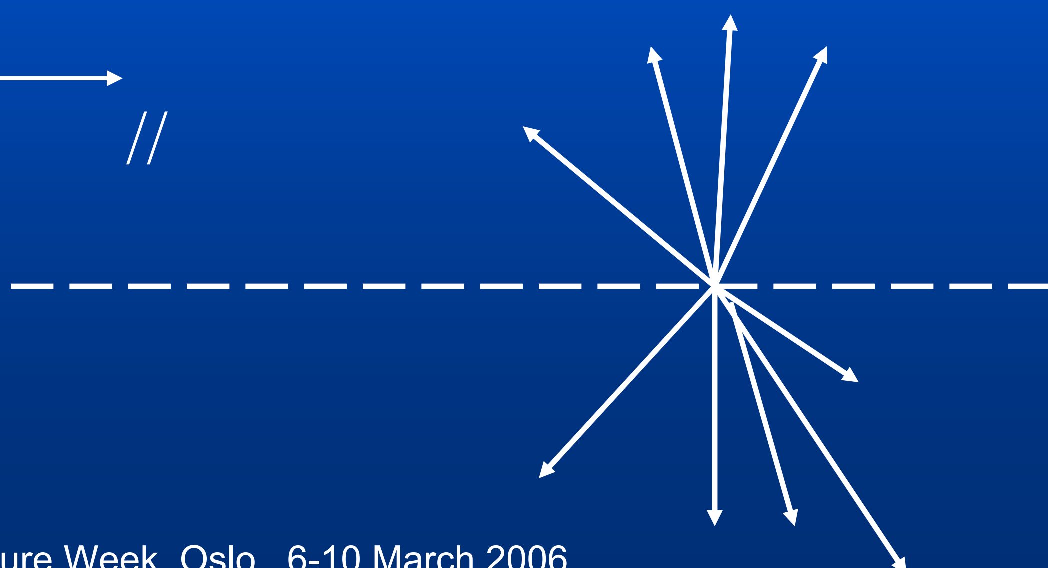
p_T or $p_\perp$: Transverse momentum

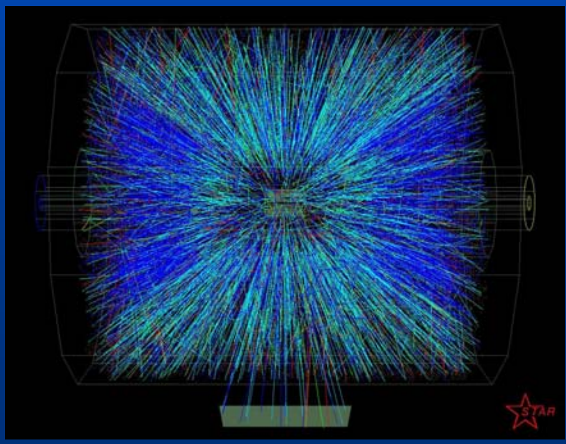
Before:

$p_{//} = +100$ GeV/c, $p_\perp = 0$ $p_{//} = -100$ GeV/c, $p_\perp = 0$



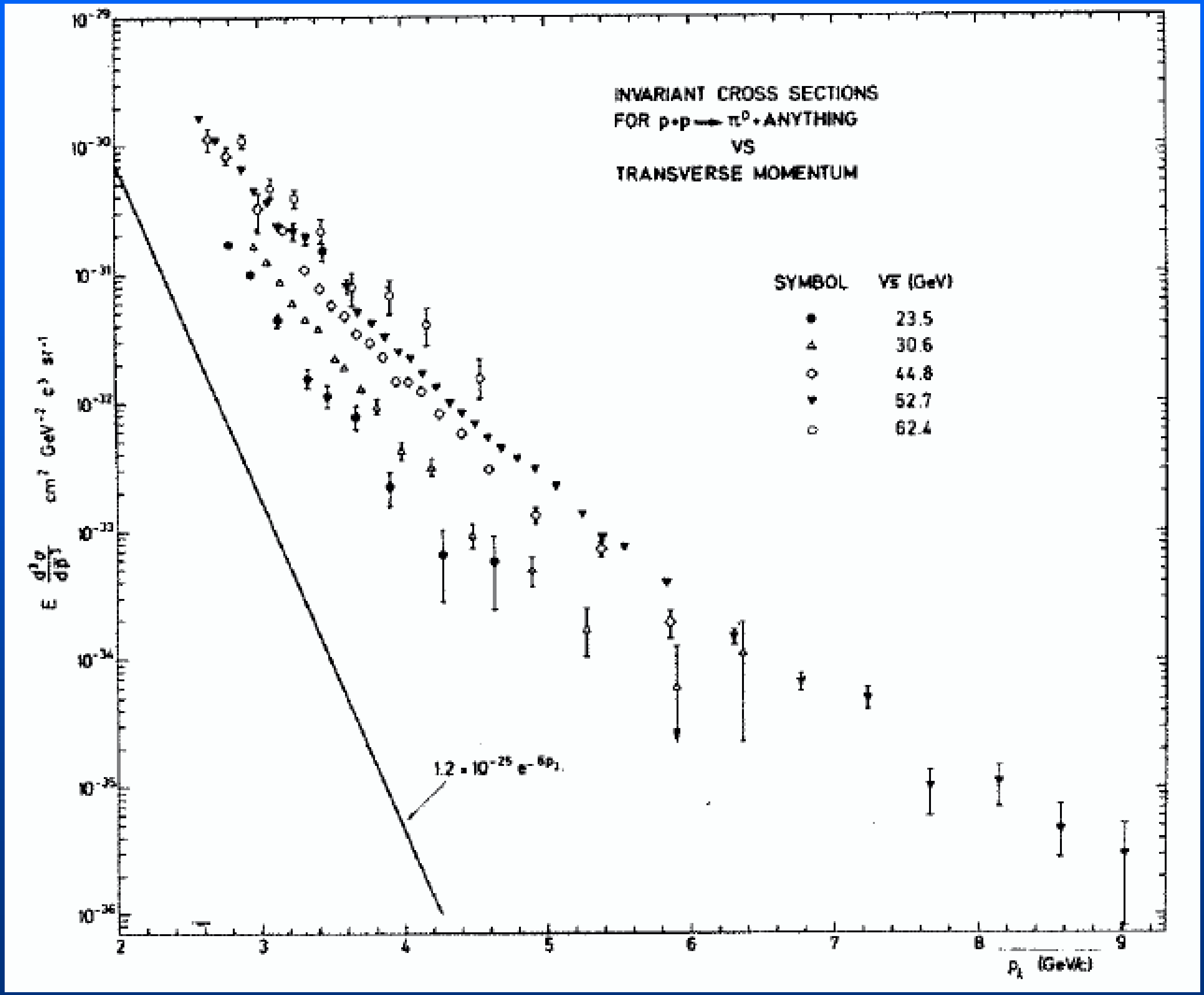
After:





p_T distribution in p+p collisions

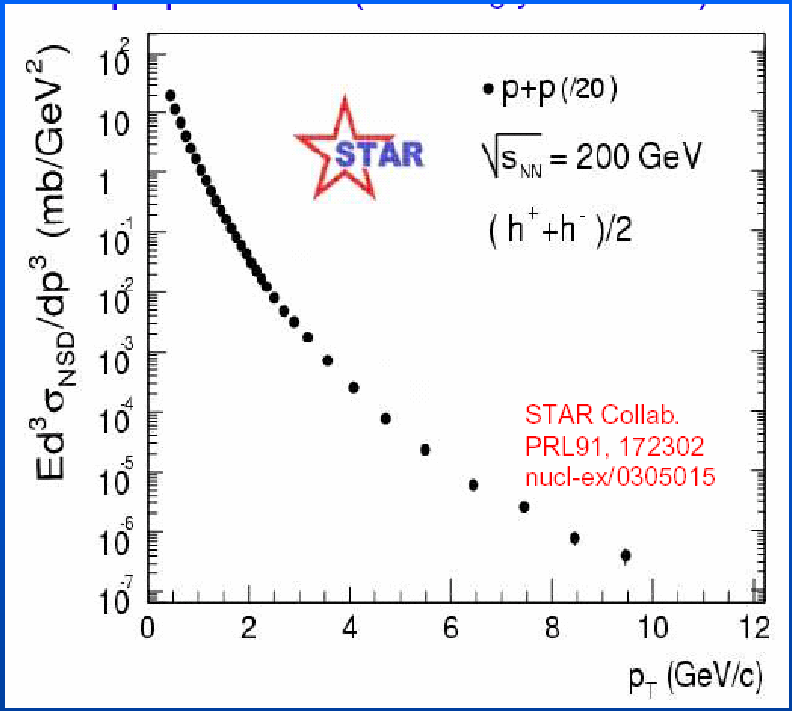
Intersecting Storage Ring (ISR), CERN ~1973, $\sqrt{s}$ = 23-62 GeV



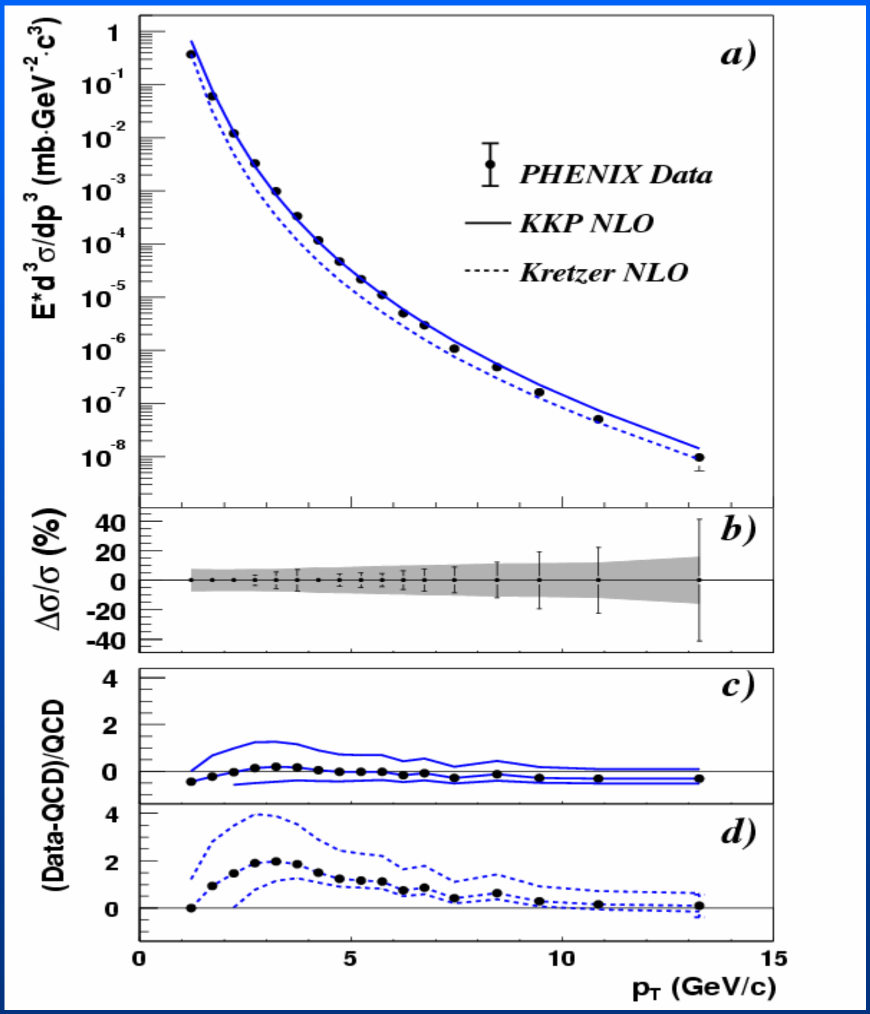
$p+p \rightarrow$
π^0 + anything

p_T distribution in p+p collisions at RHIC

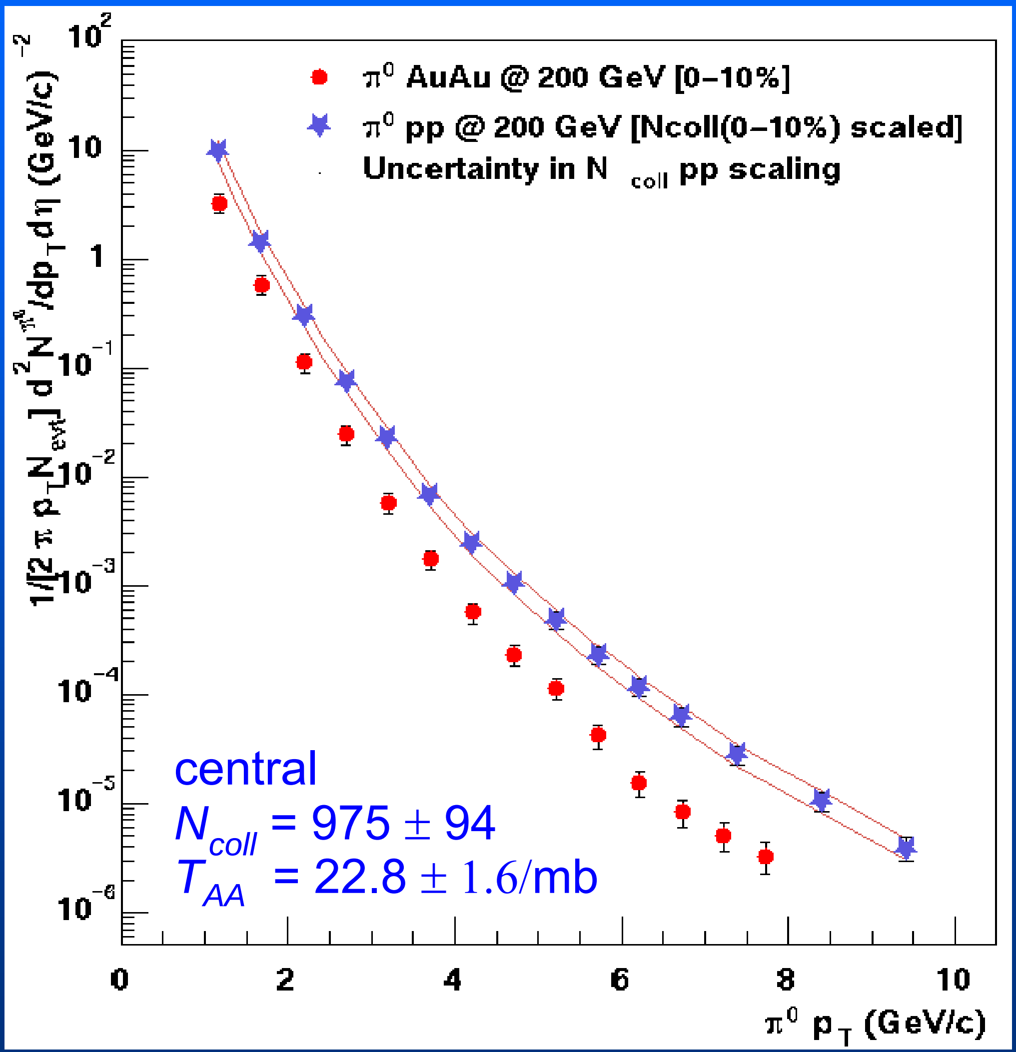
STAR p+p → $h^{+/-}$ + X



PHENIX p+p → π^0 + X



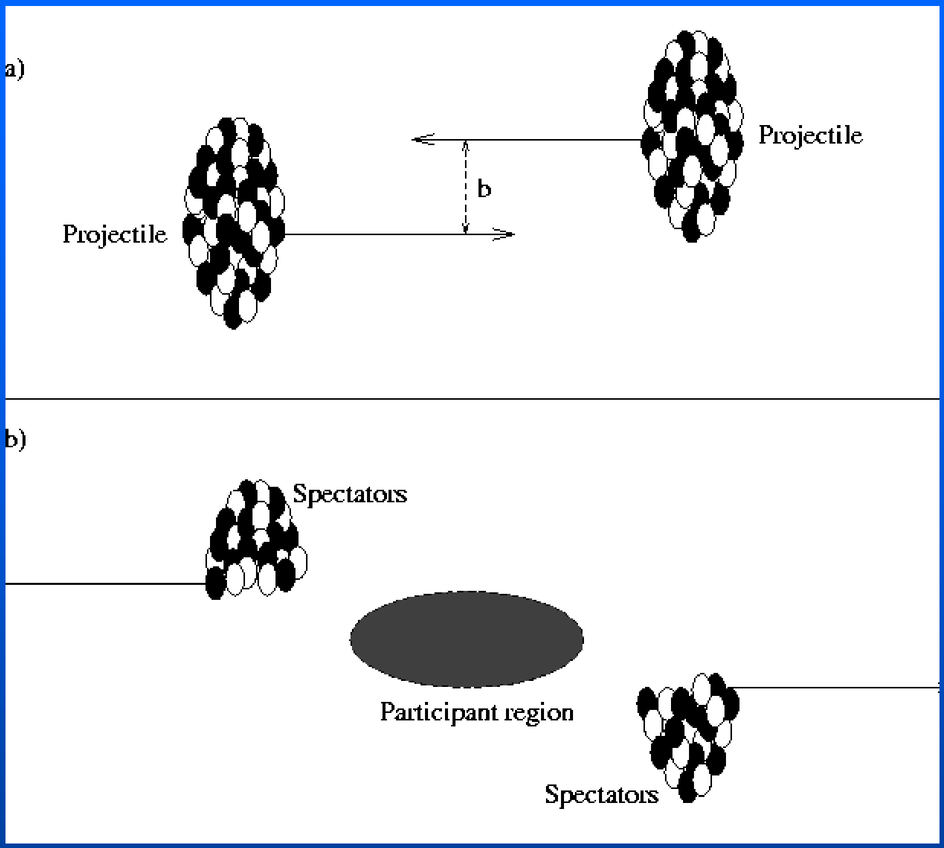
p_T distribution in Au+Au collisions at RHIC



Au+Au $\rightarrow \pi^0$ + X
compared with
scaled p+p $\rightarrow \pi^0$ + X

Scaled with N_{coll} from nuclear geometry, "Glauber Model" (in the classical limit).

The collisions are characterized by their centrality or impact parameter.



Two measures:

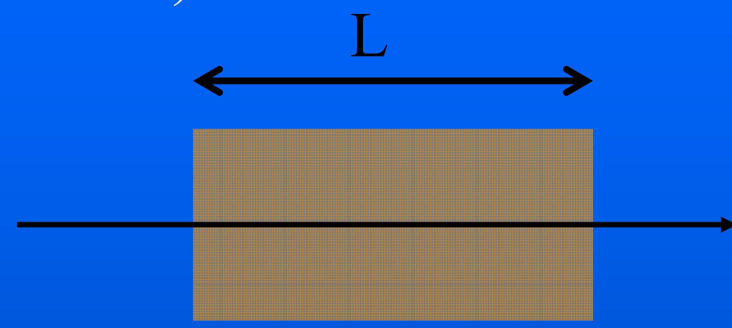
Np : Number of participating nucleons

N_{coll} : Number of binary (nucleon-nucleon) collisions

Nuclear Geometry I

For a particle going through some (uniform) material:

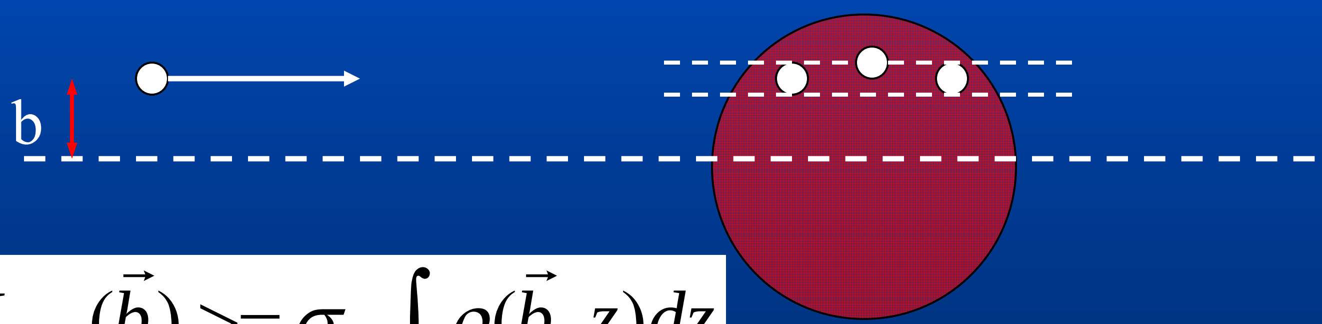
$$<N_{coll}> = \sigma \cdot n \cdot L$$



σ: cross section

n: number density of target; particles/volume

proton+nucleus collision:

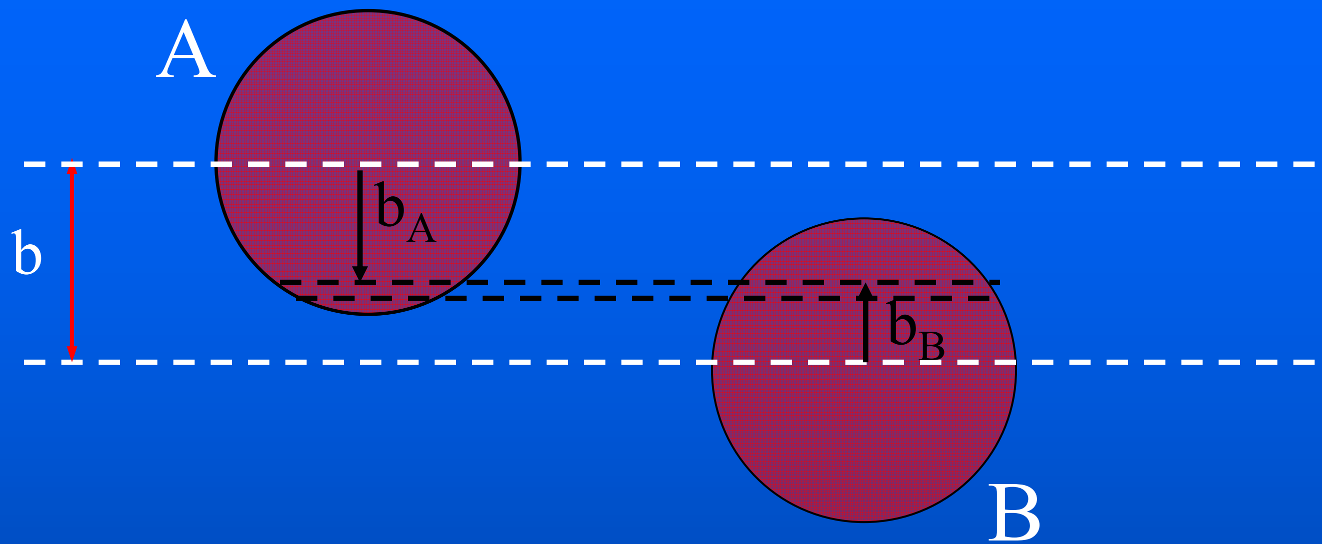


$$< N_{Coll}(\vec{b}) >= \sigma_{nn} \underbrace{\int \rho(\vec{b}, z) dz}_{T_A(\vec{b})}$$

$T_A(b)$ Nuclear Thickness Function

Nuclear Geometry II

nucleus+nucleus collision:



Consider a narrow tube with area d^2**b'** at impact parameter **b**':

Incoming particles (A):

$$N_A = \left[\int \rho(\vec{b}_A, z_A)\,dz_A\right] \cdot d^2\vec{b}'$$

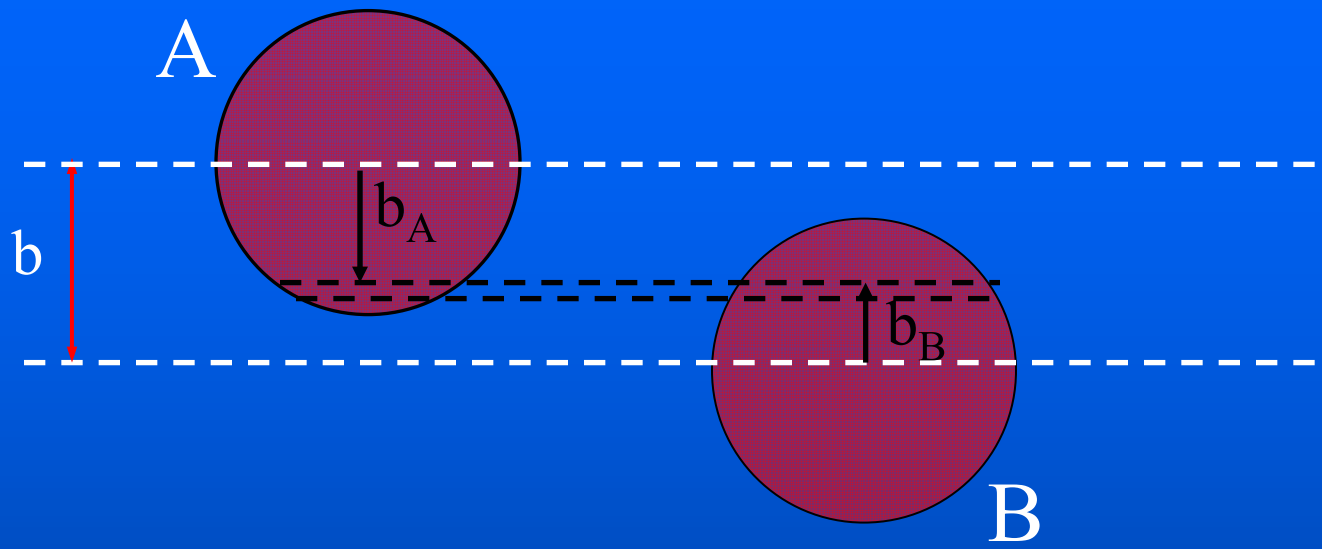
$$\vec{b}_A = \frac{\vec{b}}{2} - \vec{b}'$$

$$d(<N_{Coll}>) = \underbrace{\left[\int \rho(\vec{b}_A, z_A)\,dz_A\right]}_{T_A(\frac{\vec{b}}{2}-\vec{b}')} \cdot \sigma_{nn} \cdot \underbrace{\left[\int \rho(\vec{b}_B, z_B)\,dz_B\right]}_{T_B(\frac{\vec{b}}{2}+\vec{b}')} \cdot d^2\vec{b}'$$

$$\vec{b}_B = \frac{\vec{b}}{2} + \vec{b}'$$

Nuclear Geometry III

nucleus+nucleus collision:



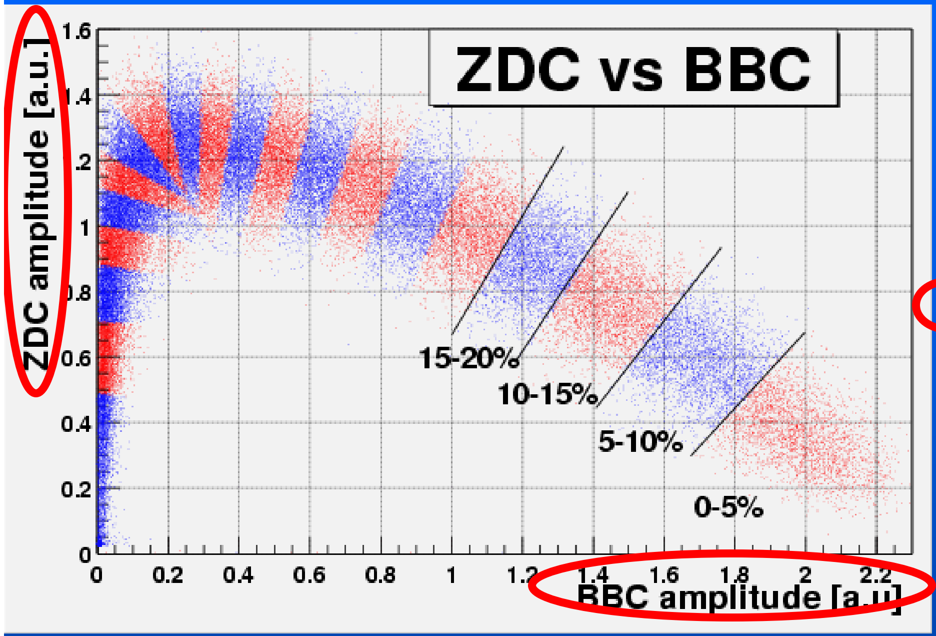
$$< N_{Coll}(\vec{b}) >= \sigma_{nn} \int T_A(\frac{\vec{b}}{2} - \vec{b}')T_B(\frac{\vec{b}}{2} + \vec{b}')d^2\vec{b}' \equiv \sigma_{nn} T_{AB}(\vec{b})$$

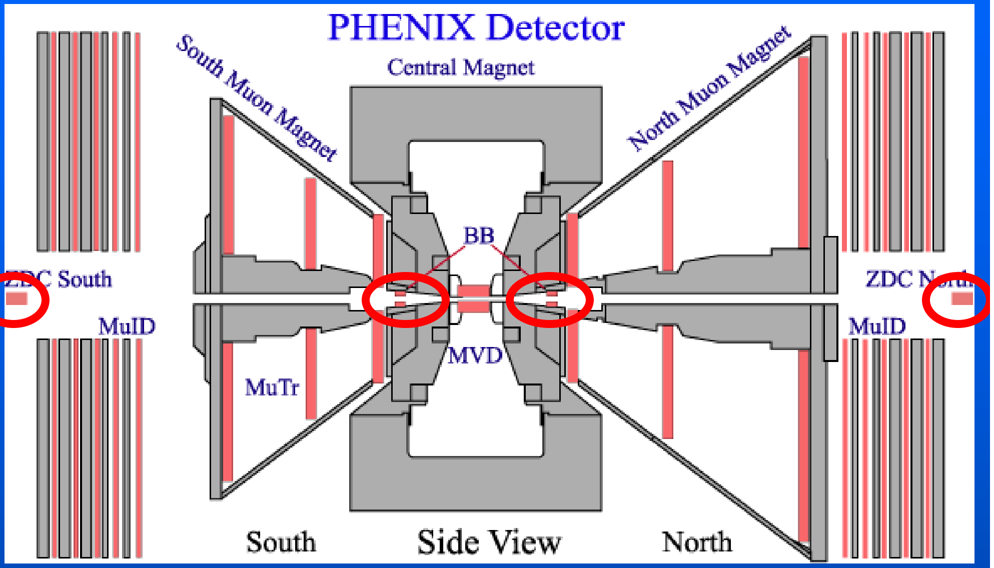
where

$$T_{AB}(\vec{b}) = \int T_A(\frac{\vec{b}}{2} - \vec{b}')T_B(\frac{\vec{b}}{2} + \vec{b}')d^2\vec{b}'$$

is the nuclear overlap function

Finally, have to relate **b** to something we can measure:

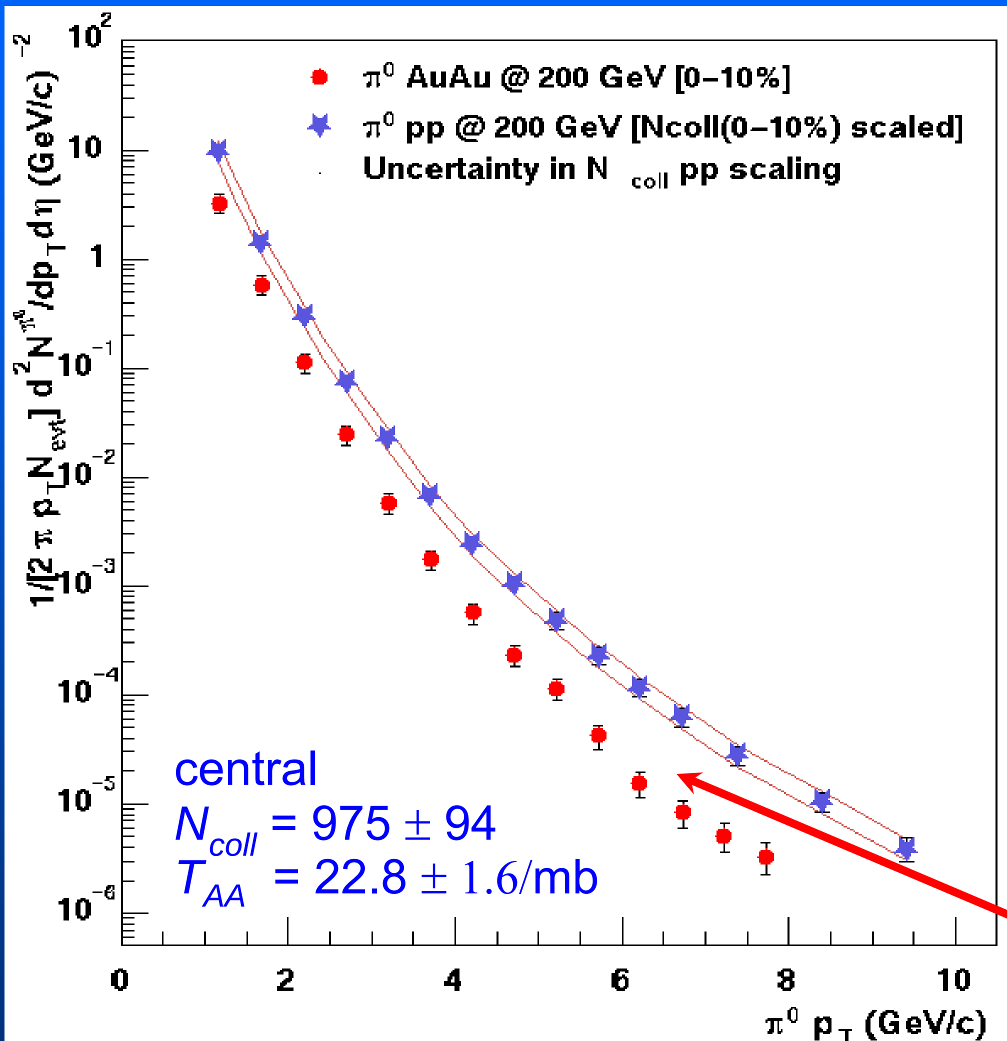




For each centrality bin, $<N_p>$ and $<N_{coll}>$ are calculated.

Centrality	$<N_{coll}>$	$<N_p>$
0 – 10%	955±94	325±3
10 – 20%	603±59	235±5
20 – 30%	374±40	167±5
•	•	•
•	•	•

p_T distribution in Au+Au collisions at RHIC



Au+Au $\rightarrow \pi^0$ + X compared with scaled p+p $\rightarrow \pi^0$ + X

Scaled with N_{coll} from nuclear geometry, "Glauber Model".

$$\frac{1}{N_{EVT}} \frac{d^2 N_{AA}^{\pi 0}}{dp_T dy} = < T_{AB}(\vec{b}) > \frac{d^2 \sigma_{pp}^{\pi 0}}{dp_T dy}$$

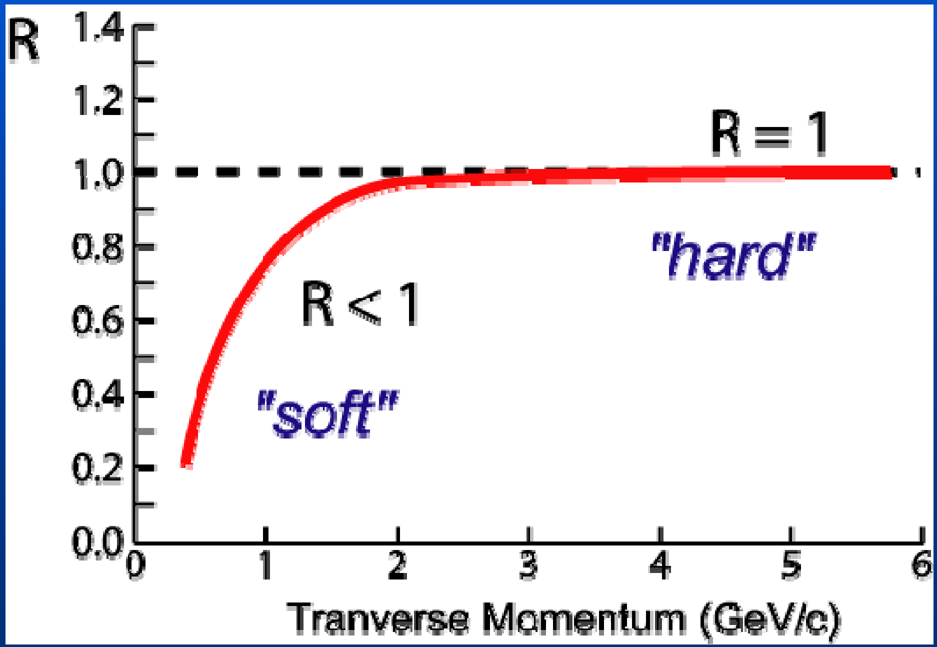
High-pT suppression

p_T distribution in Au+Au collisions at RHIC

Quantify the suppression using the R_{AA} measure:

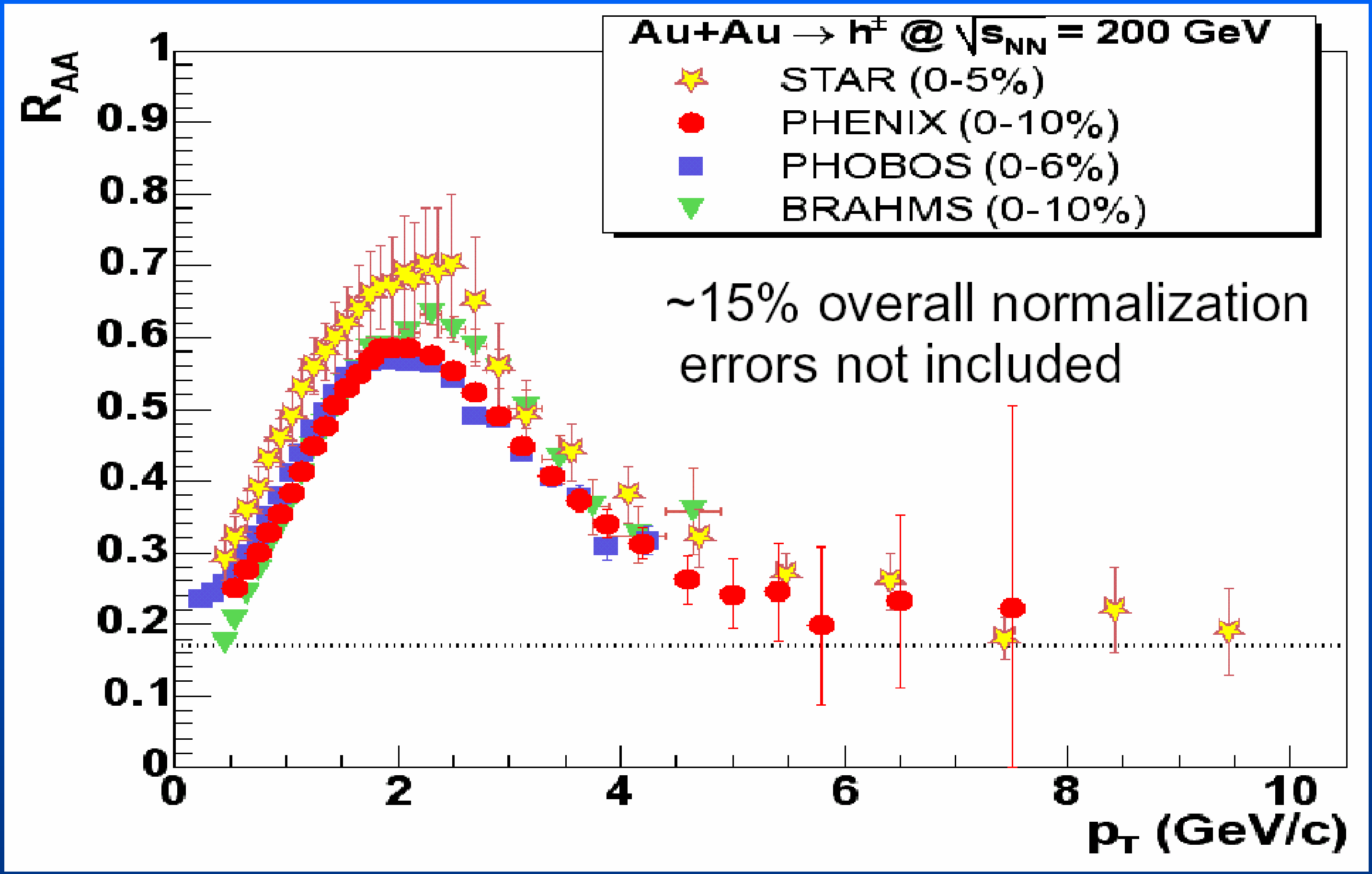
$$R_{AA}(p_T) = \frac{(1/N_{EVT})d^2N_{AA}^{\pi 0}/dp_T dy}{< T_{AB}(\vec{b}) > \times d^2\sigma_{pp}^{\pi 0}/dp_T dy}$$

Expectation in absence of medium effects



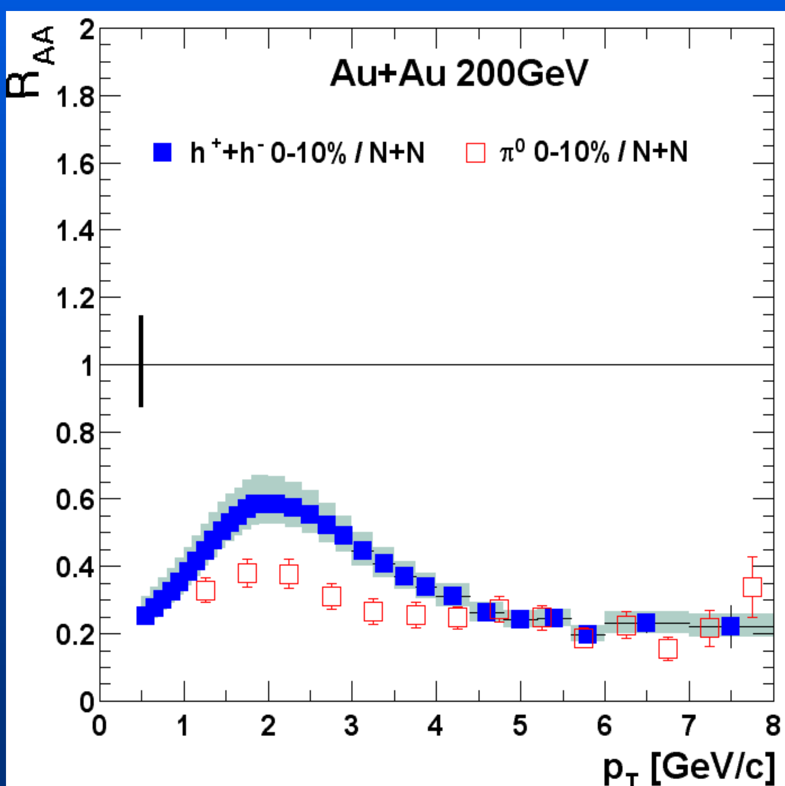
Joakim Nystrand, University of Bergen

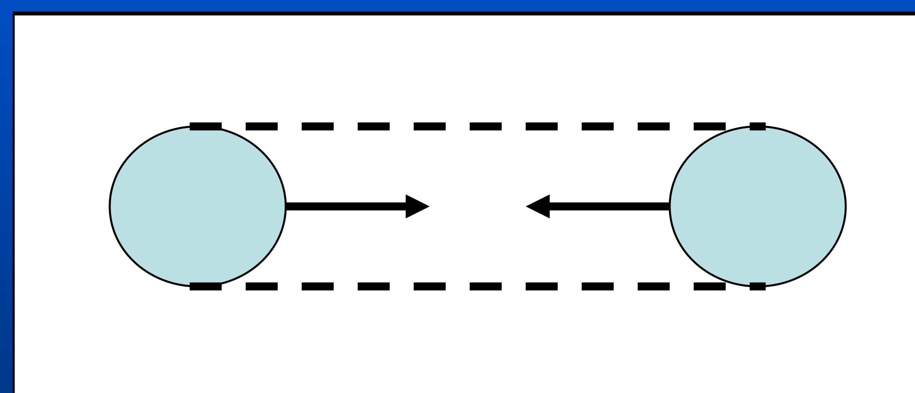
The experimental result:



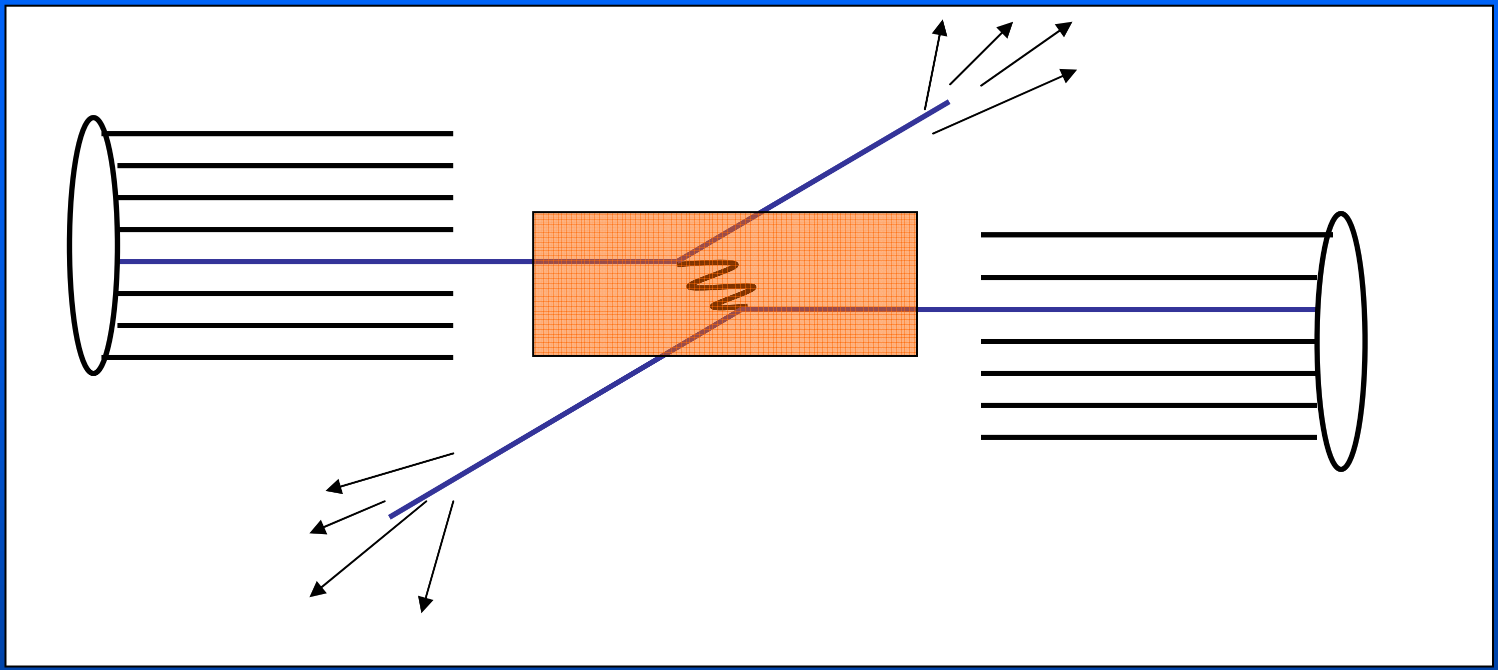
Charged hadrons (not identified)

Centrality Dependence





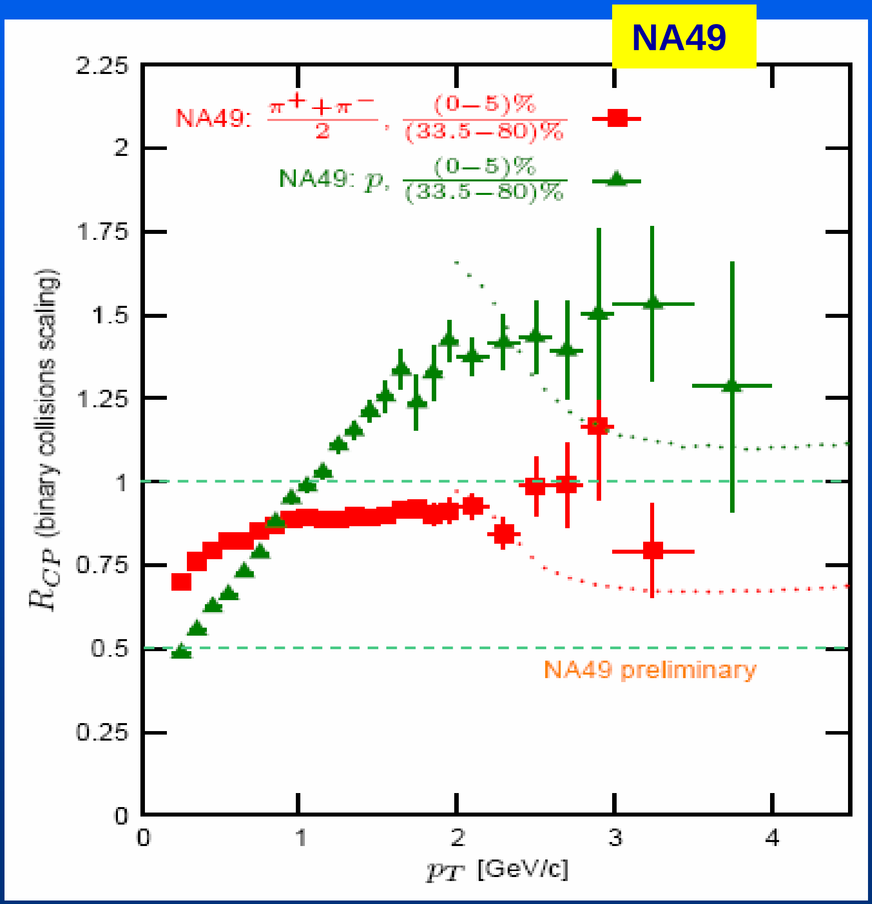
Can A+A collisions be understood from parton+parton or nucleon-nucleon interactions?

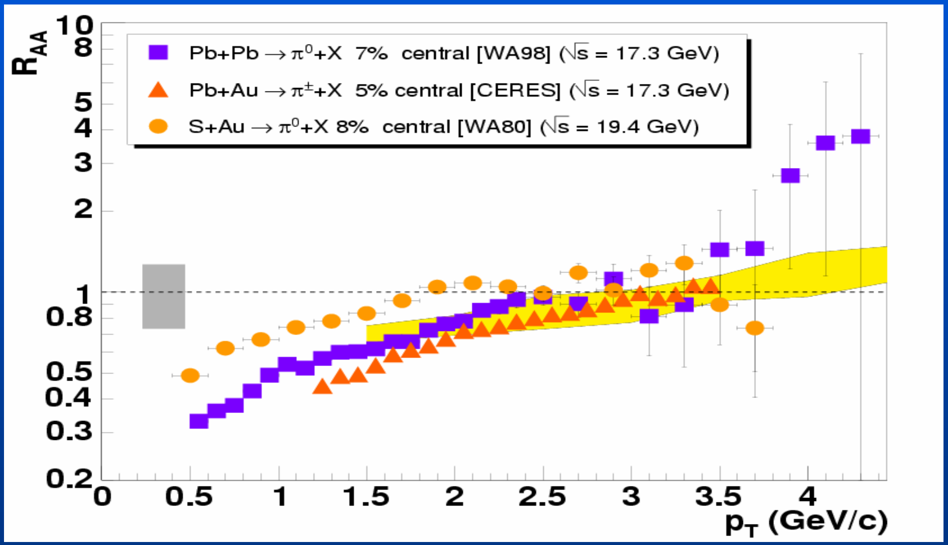


Not entirely, a dense medium is created in the collisions. The produced particle lose energy (gluon bremsstrahlung) as they traverse it.

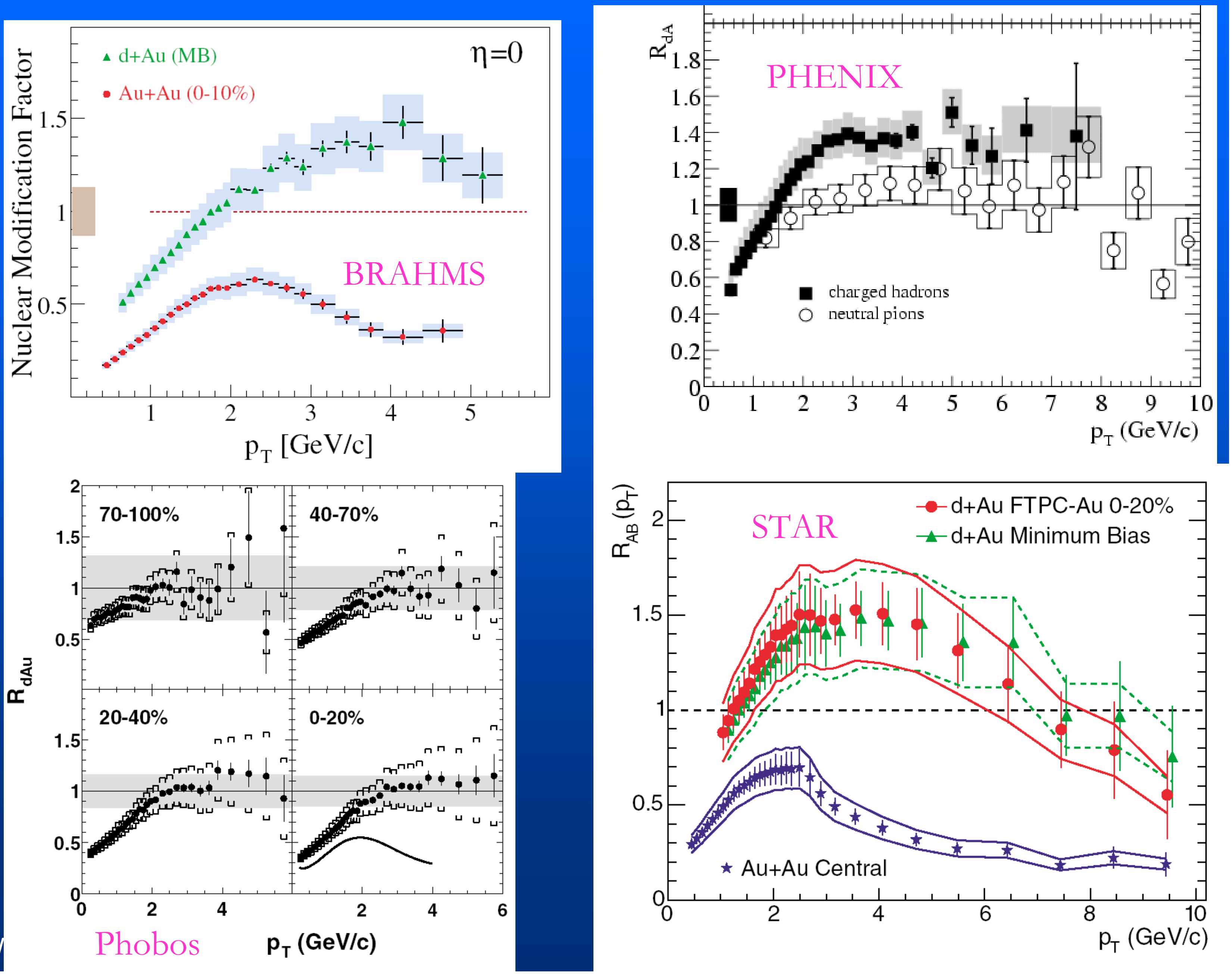
Prediction: Bjorken (1982), Gyulassy & Wang (1992), …

The high-p_T suppression is unique to RHIC– not seen at the SPS $\sqrt{s}$ = 17 GeV
(but the Croonin enhancement is absent)

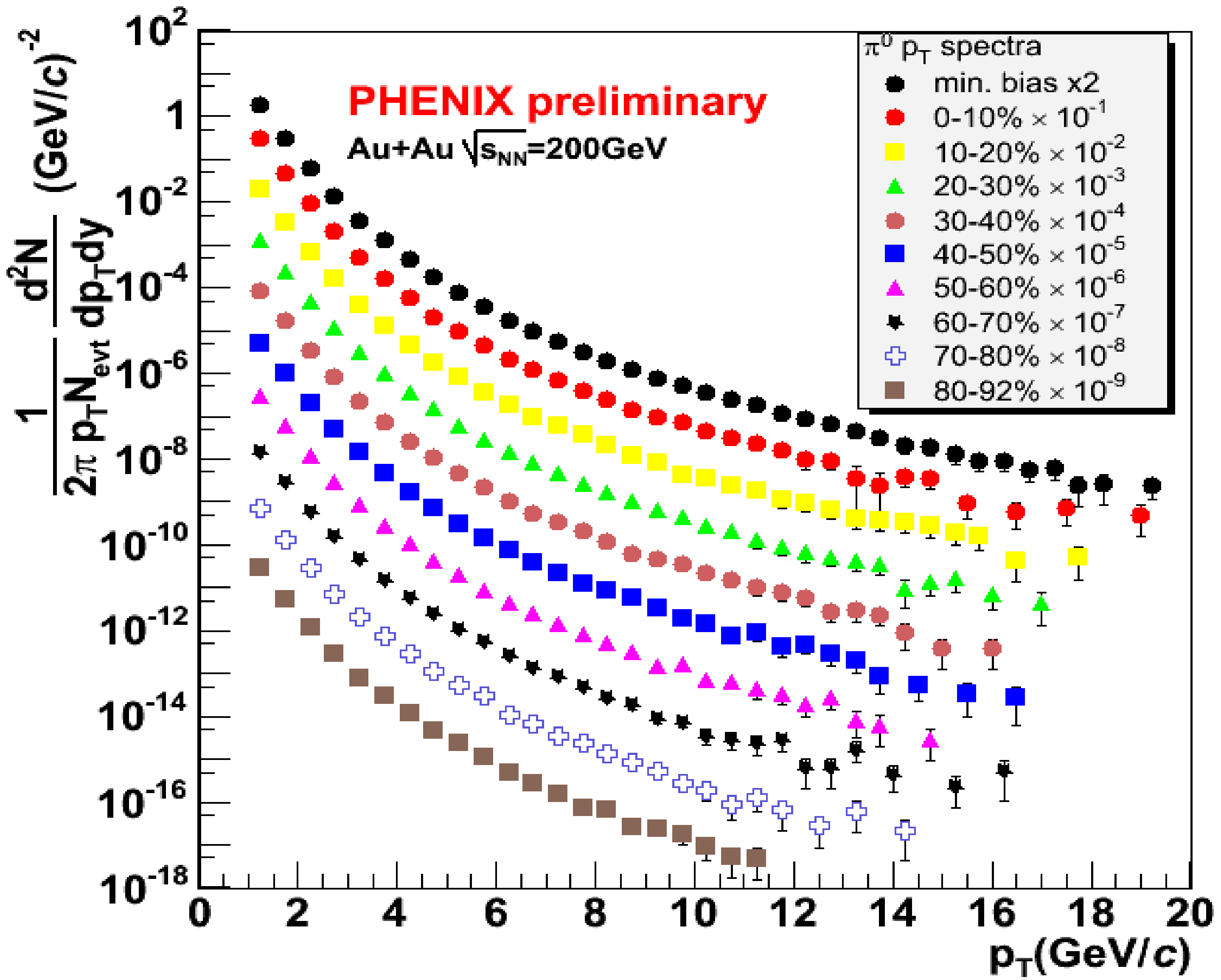




NO suppression in d+Au

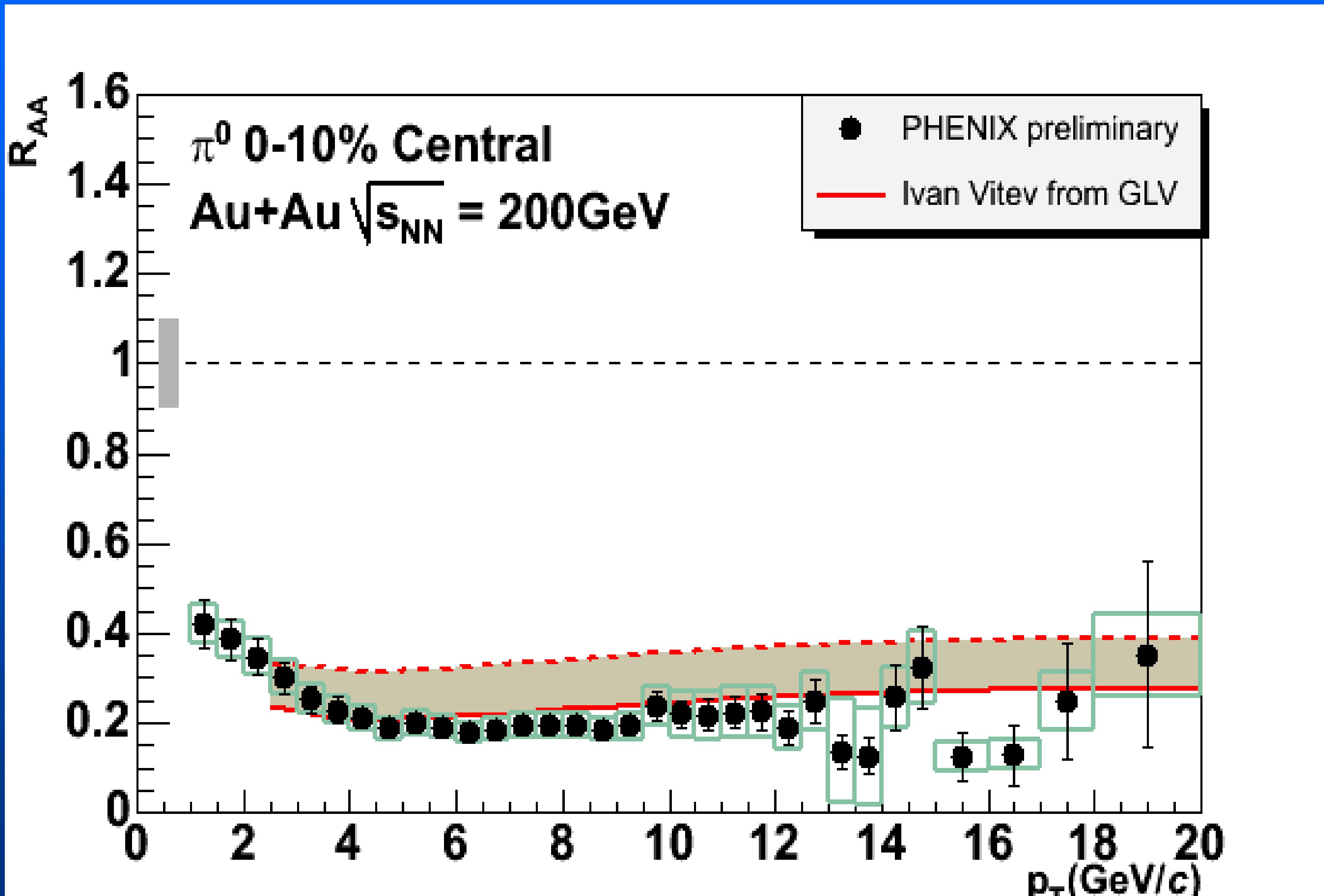


AuAu Run4

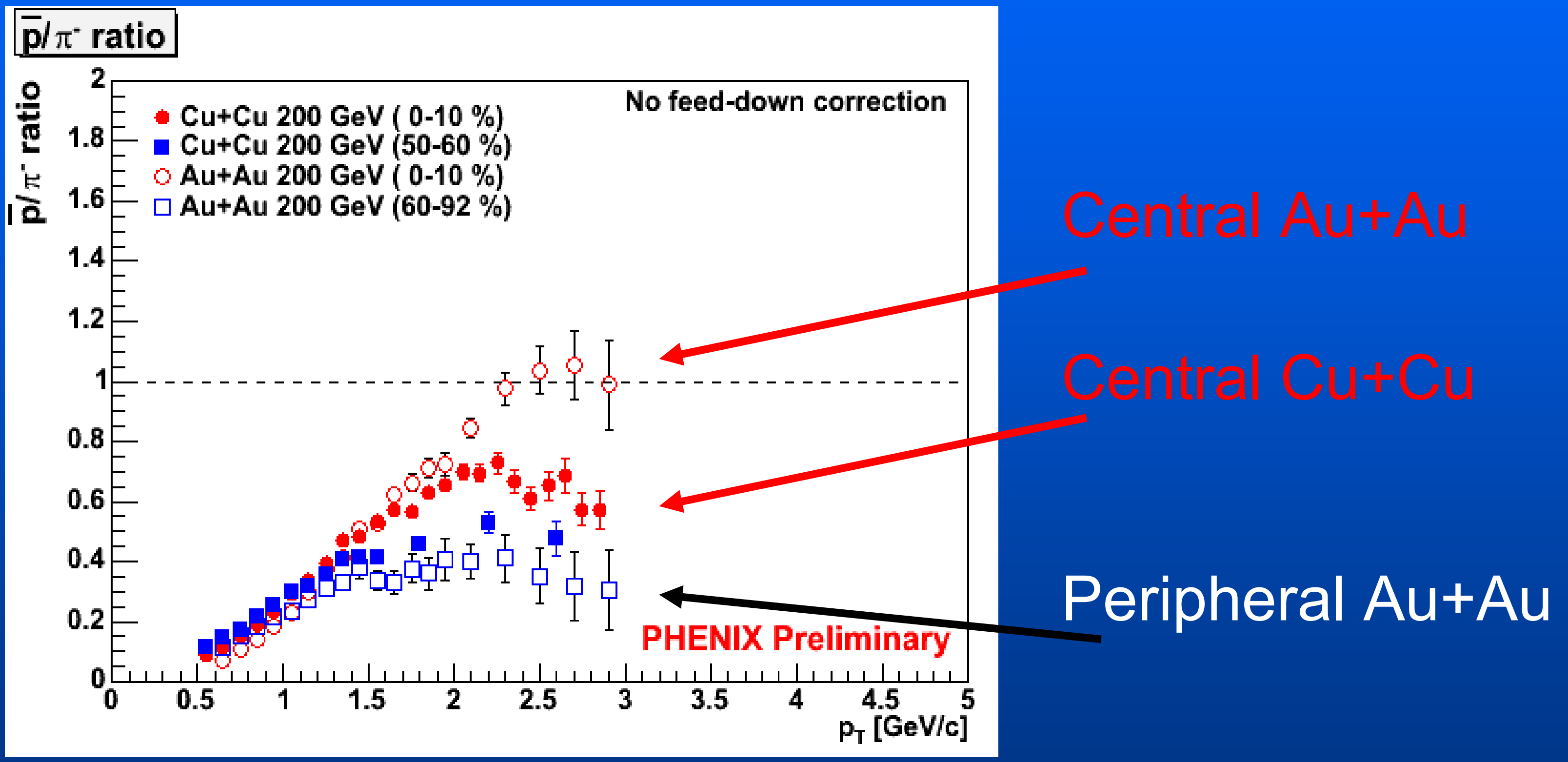


p_T reach for π^0s governed by statistics

The suppression remains also at p_T = 20 GeV



A consequence of pion suppression and transverse flow/expansion: p/π > 1!



Not consistent with only QCD+fragmentation function.