Heavy-ion perspectives RHIC - LHC
(Part 2)

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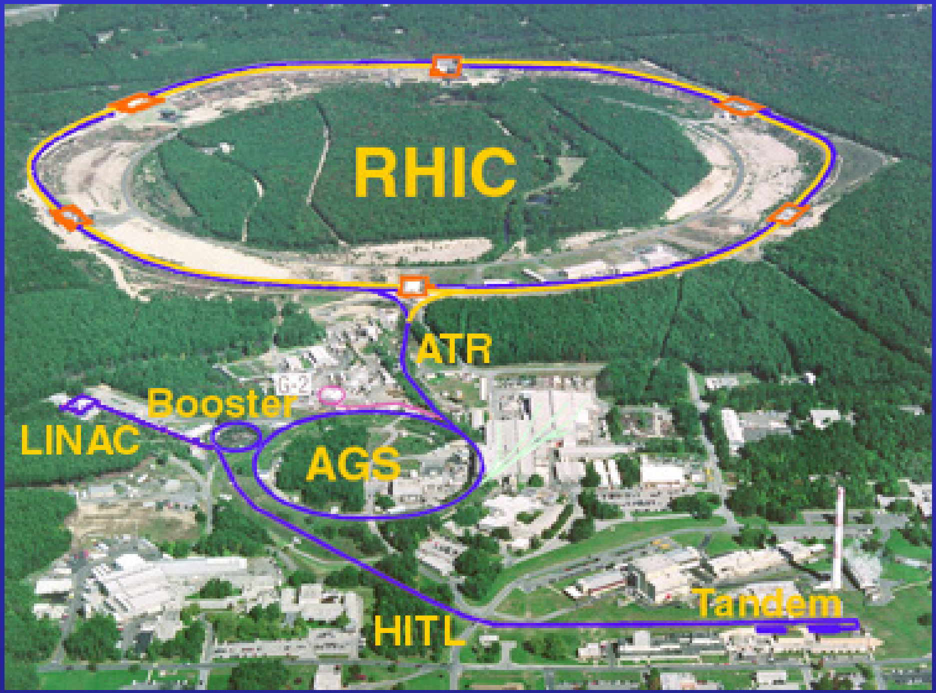
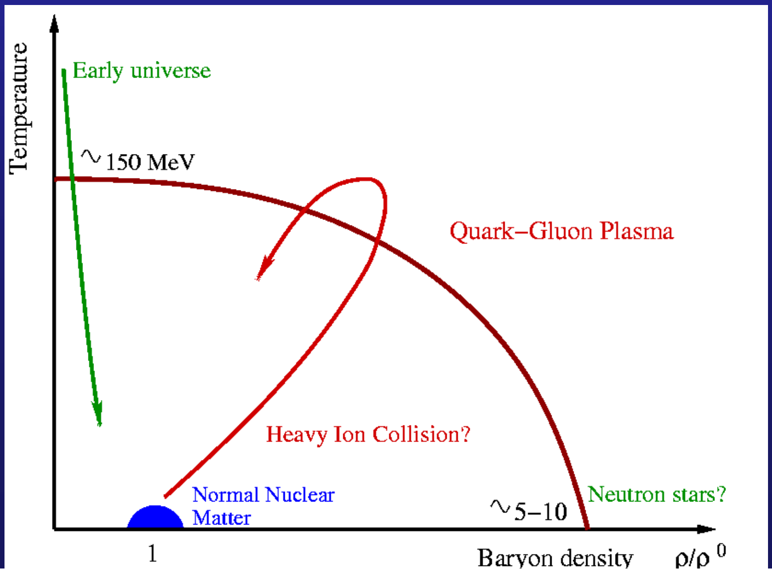
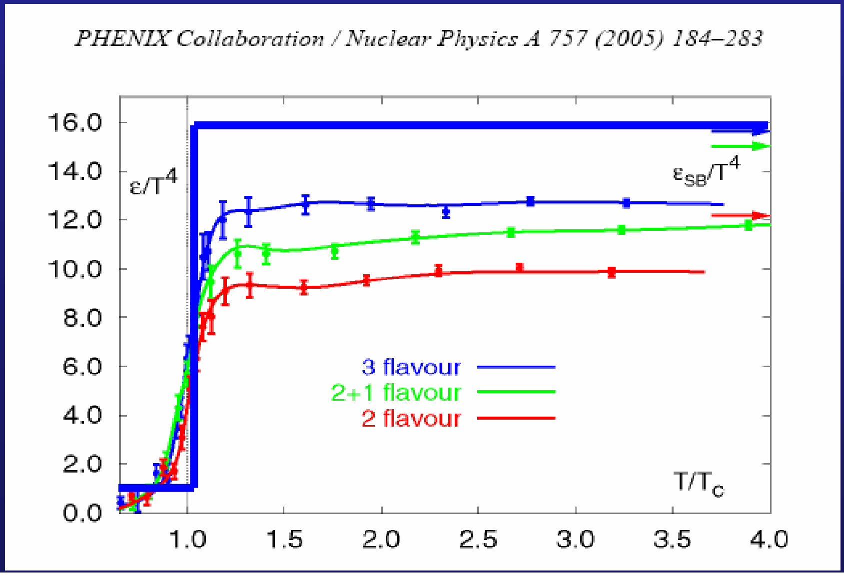
The Relativistic Heavy Ion Collider (RHIC)



Au+Au √s = 200 A GeV
p+p √s = 500 A GeV



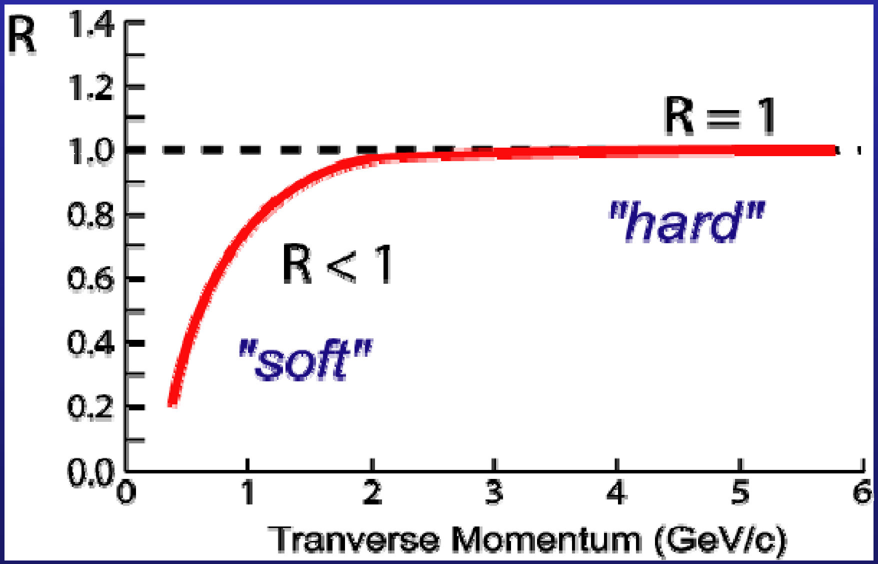


Suppression of particles with high p_T in Au+Au collisions

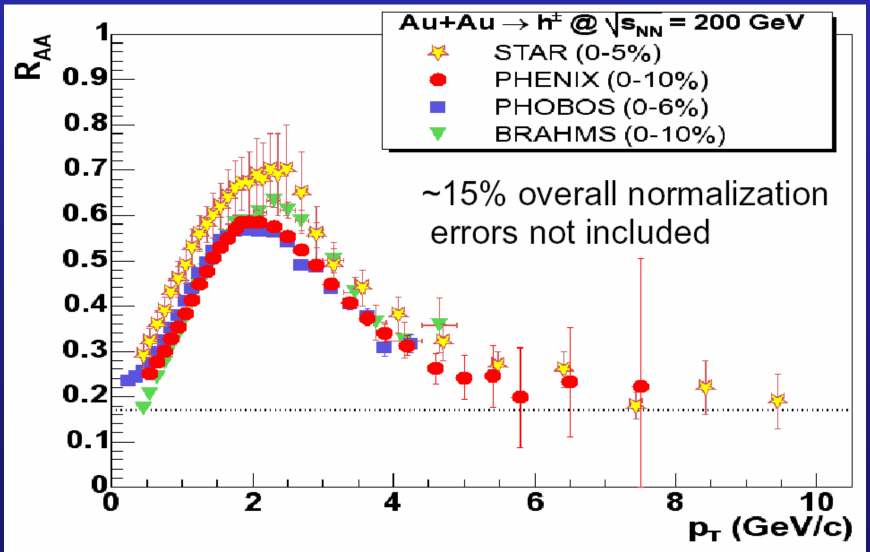
The R_{AA} measure:

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

Superposition of nn collisions

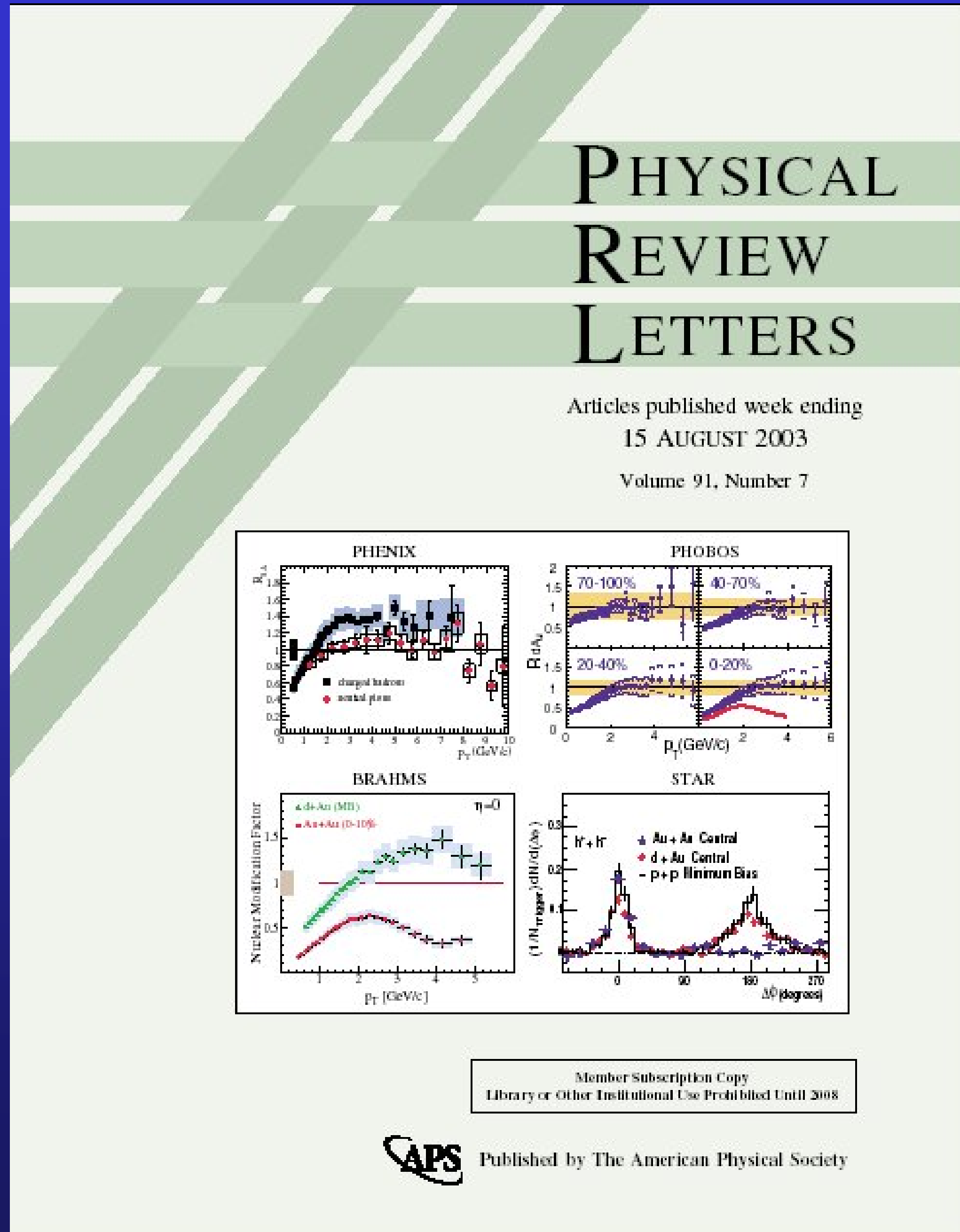


Experimental result



Suppression in Au+Au
No suppression in d+Au

⇒Final state effect produced by the medium.

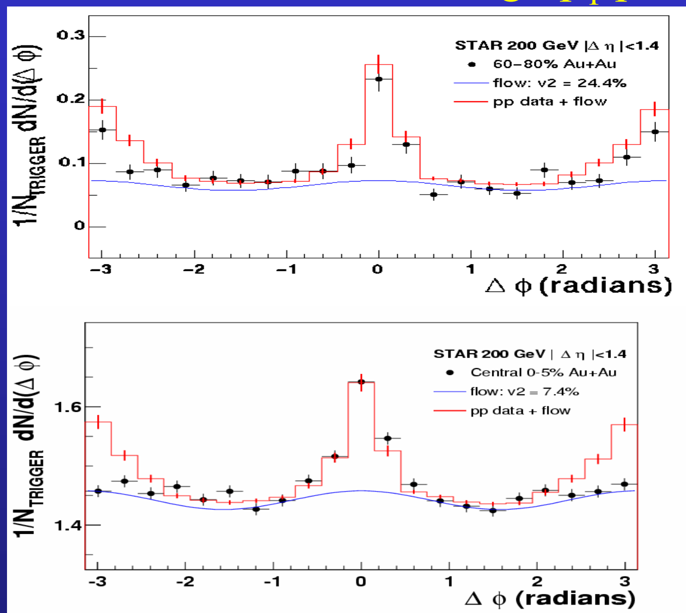


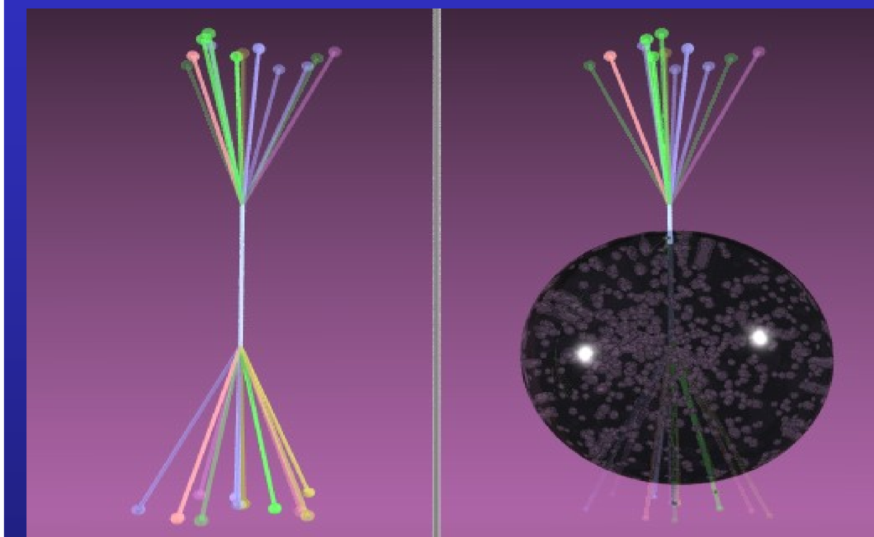
Jet-quenching and mono-jets

pp : Two jets, back-to-back

AA : Jet in only one direction in central collisions

Azimuthal distribution of high p_T particles



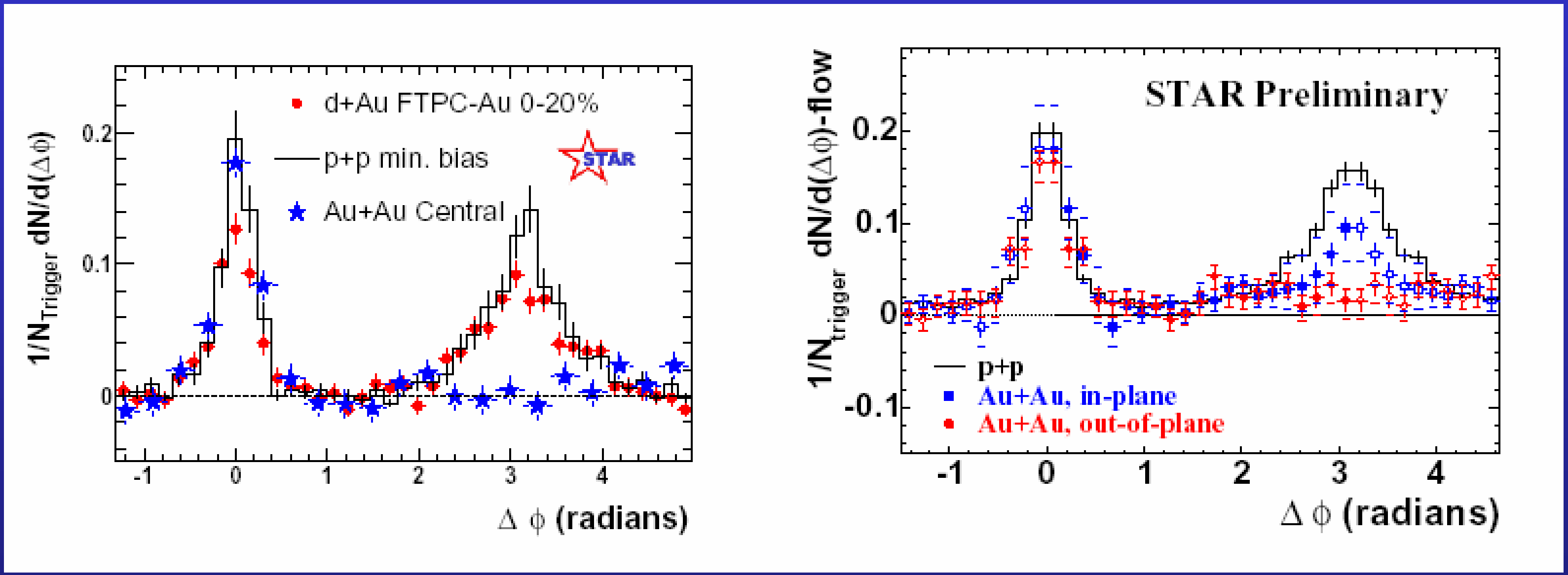


The medium is not transparent to jets

p_T (trig.) > 4 GeV/c

p_T (assoc.) > 2 GeV/c

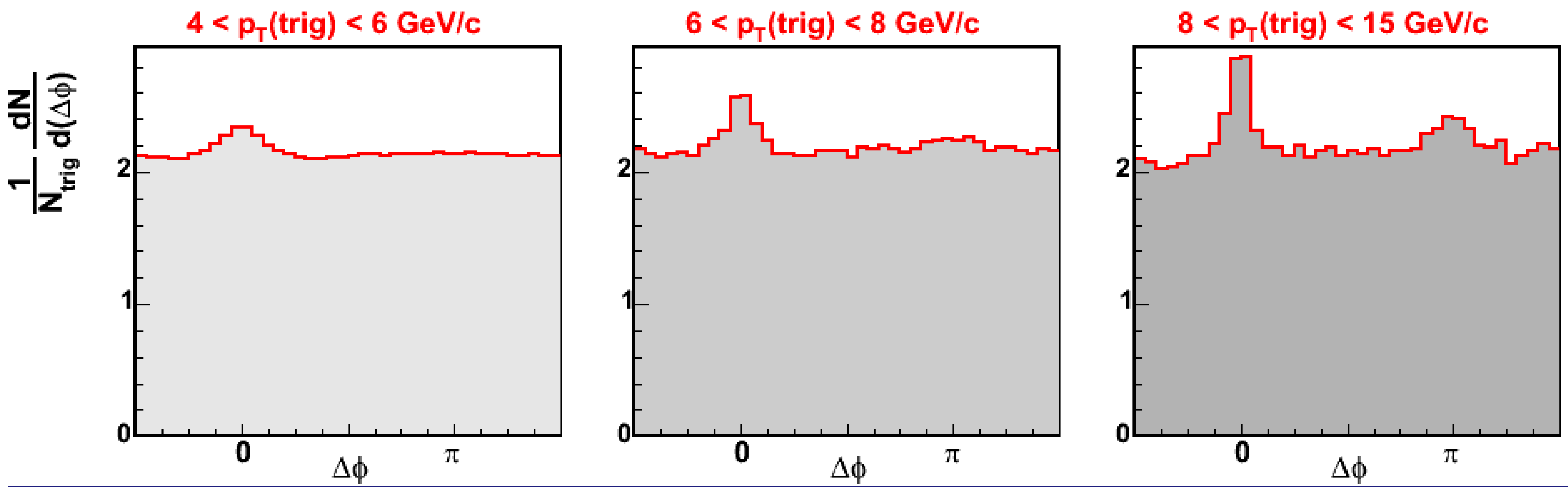
No mono-jets seen in d+Au



The suppression depends on amount of matter traversed.

Emergence of di-jets

STAR Collaboration QM05
0-5 % most central collisions

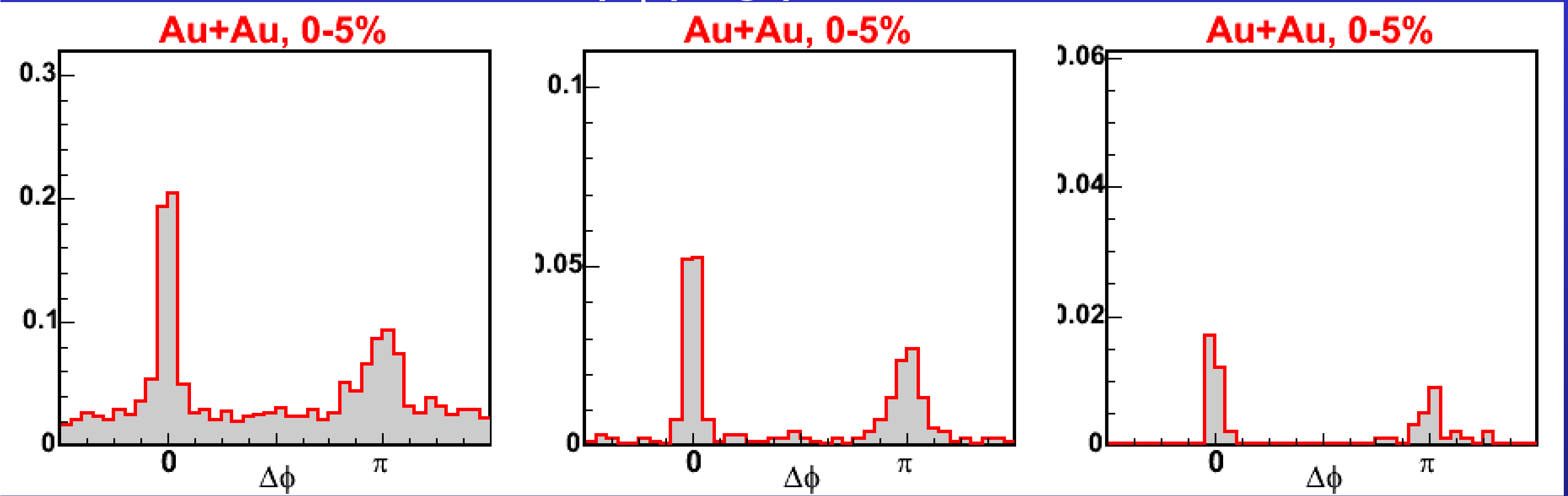


p_T(assoc.) > 2 GeV/c

Emergence of di-jets

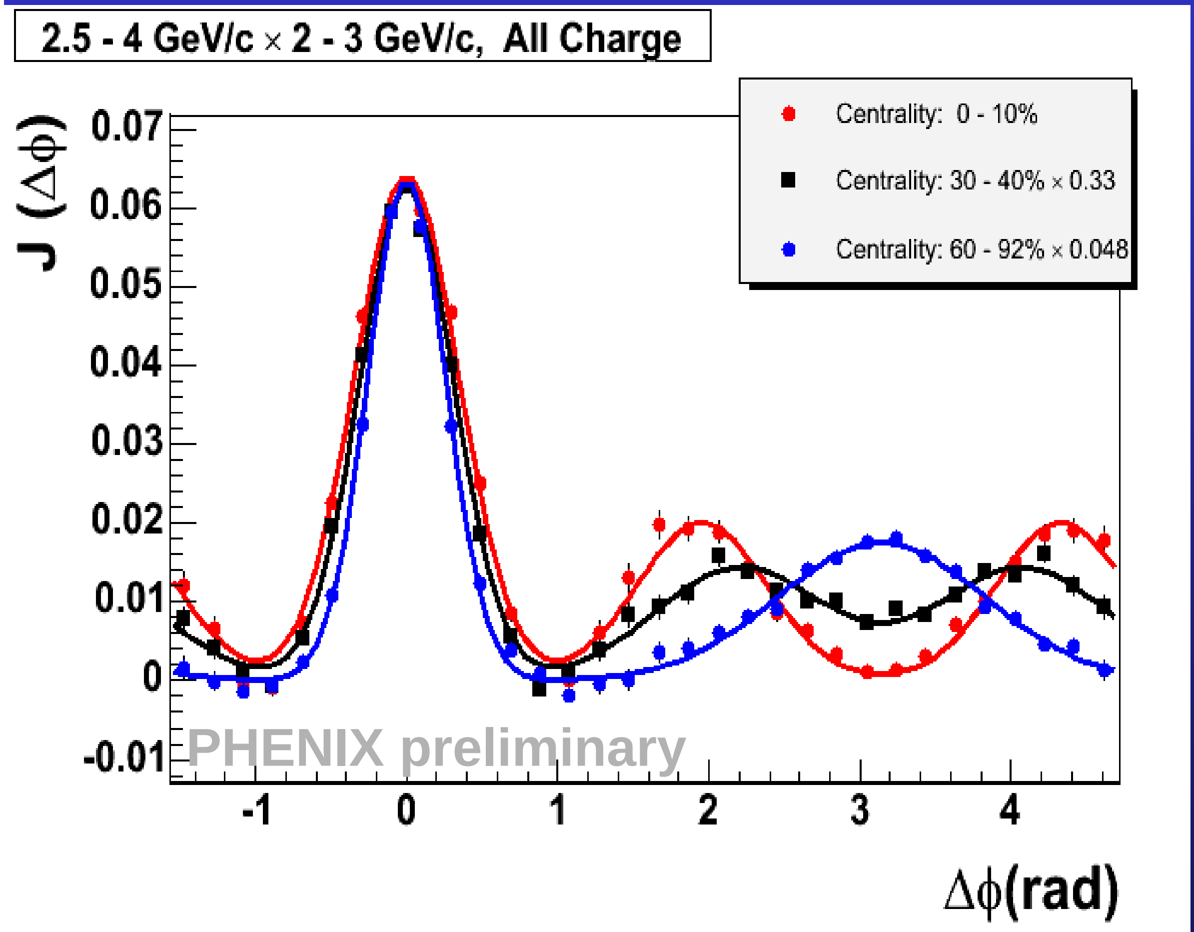
STAR Collaboration QM05

$8 < p_T(\text{trig.}) < 15$ GeV/c



$p_T(\text{assoc.}) > 4$ GeV/c $p_T(\text{assoc.}) > 6$ GeV/c $p_T(\text{assoc.}) > 8$ GeV/c

High-p_T suppression + jet modification
$\Rightarrow$ Jet Tomography, use jets to probe the (long lived) medium produced in the collision



More speculative ideas:

Mach cone?

… we conclude that there is no support in the data for *hadronic* absorption as the dominant mechanism underlying the observed suppression phenomena at high p_T and we consider *partonic* energy loss to be well established as its primary origin.

… we emphasize that while the jet quenching results seem to favor partons over hadrons *losing* energy, they do not allow any direct conclusion regarding whether the energy is lost *to* partonic or hadronic matter.

(STAR White Paper)

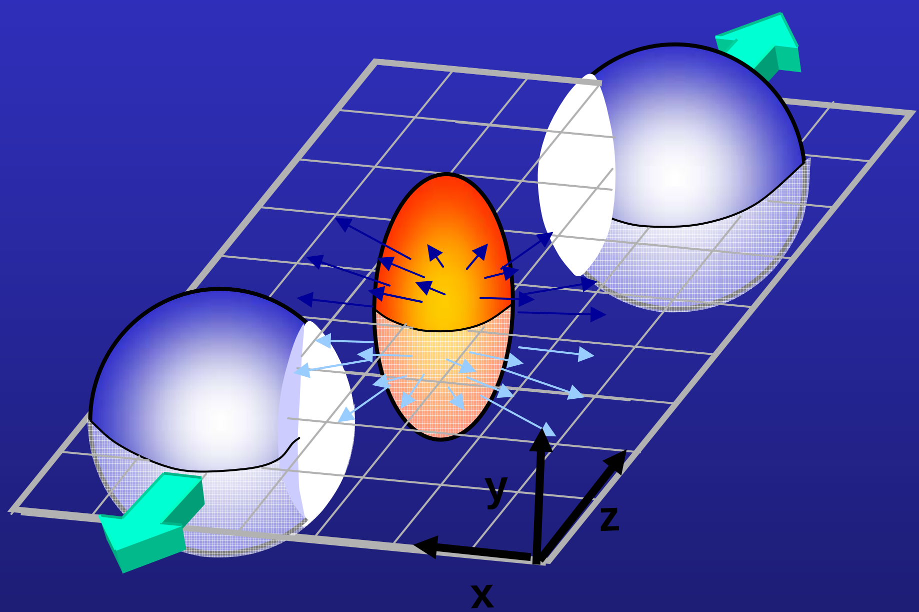
End High-p_T

Another remarkable result:

2. Collective Elliptic Flow

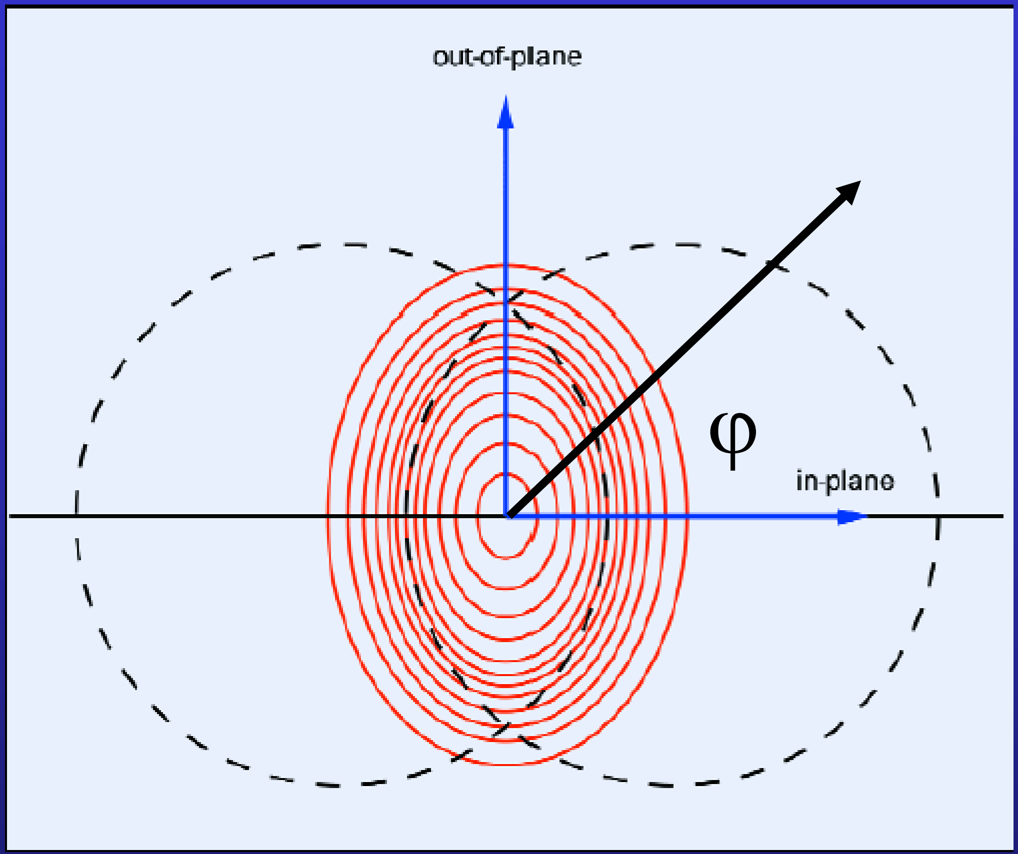
Elliptic Flow

A Nucleus-Nucleus Collision at intermediate impact parameter:



Reaction Plane:
Plane defined by beam axis and **b** (impact parameter, 2-D vector)

How are particles distributed in the transverse plane?

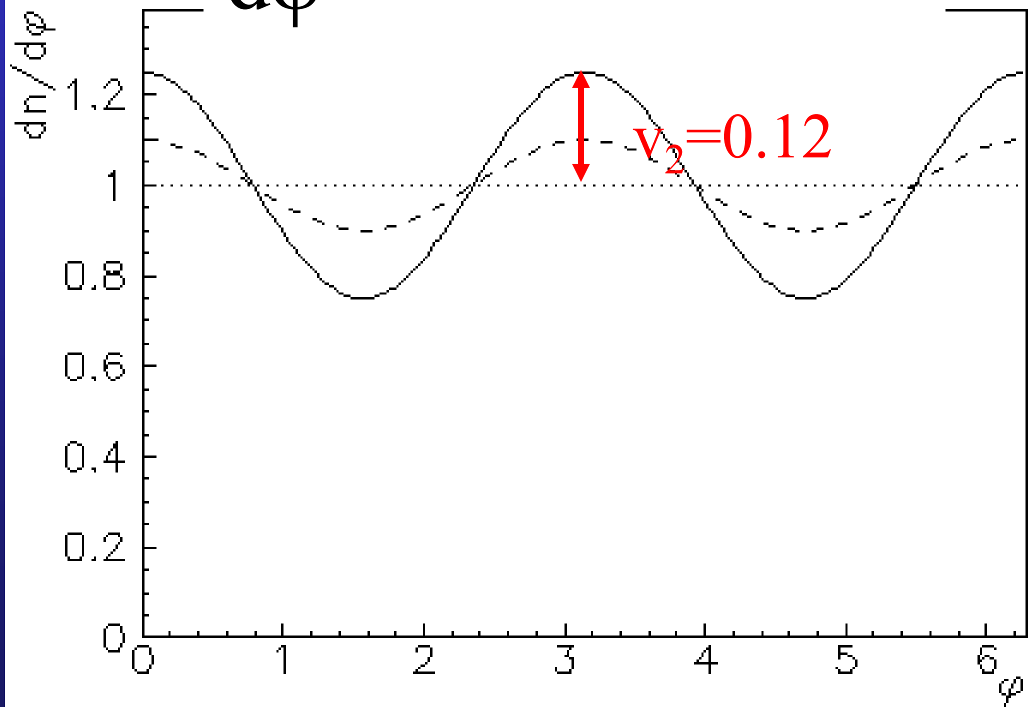


No collective effects ⇒ flat distribution in φ

Definition of v_2

For 180° symmetry

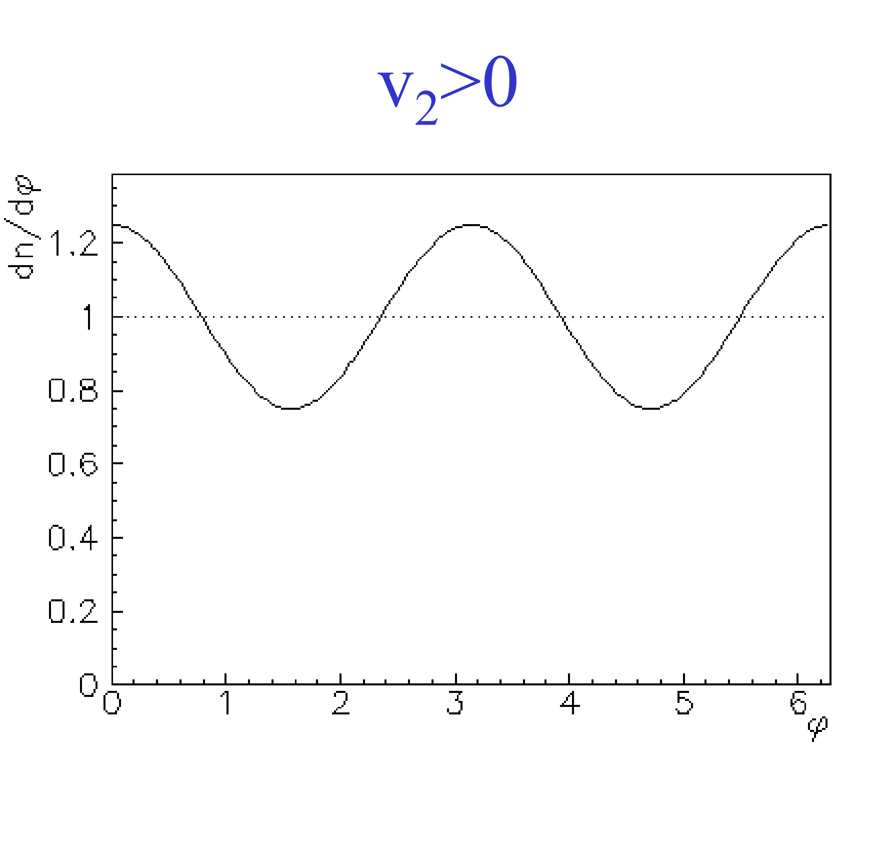
$$\frac{dN}{d\varphi} = 1 + 2v_2 \cos(2\varphi)$$

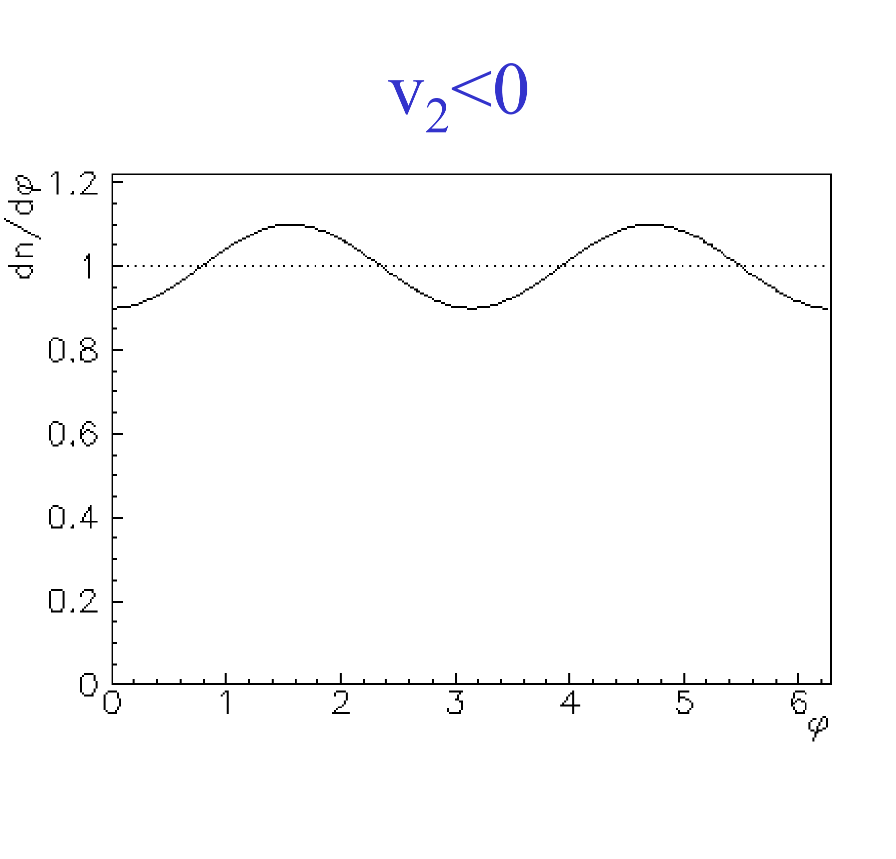


v_2 measures the strength of the flow

$v_2 > 0$: Flow in the reaction plane

$v_2 < 0$: Flow out of the reaction plane





Experimentally, v2 is calculated as the average of cos(2φ) relative to the reaction plane.

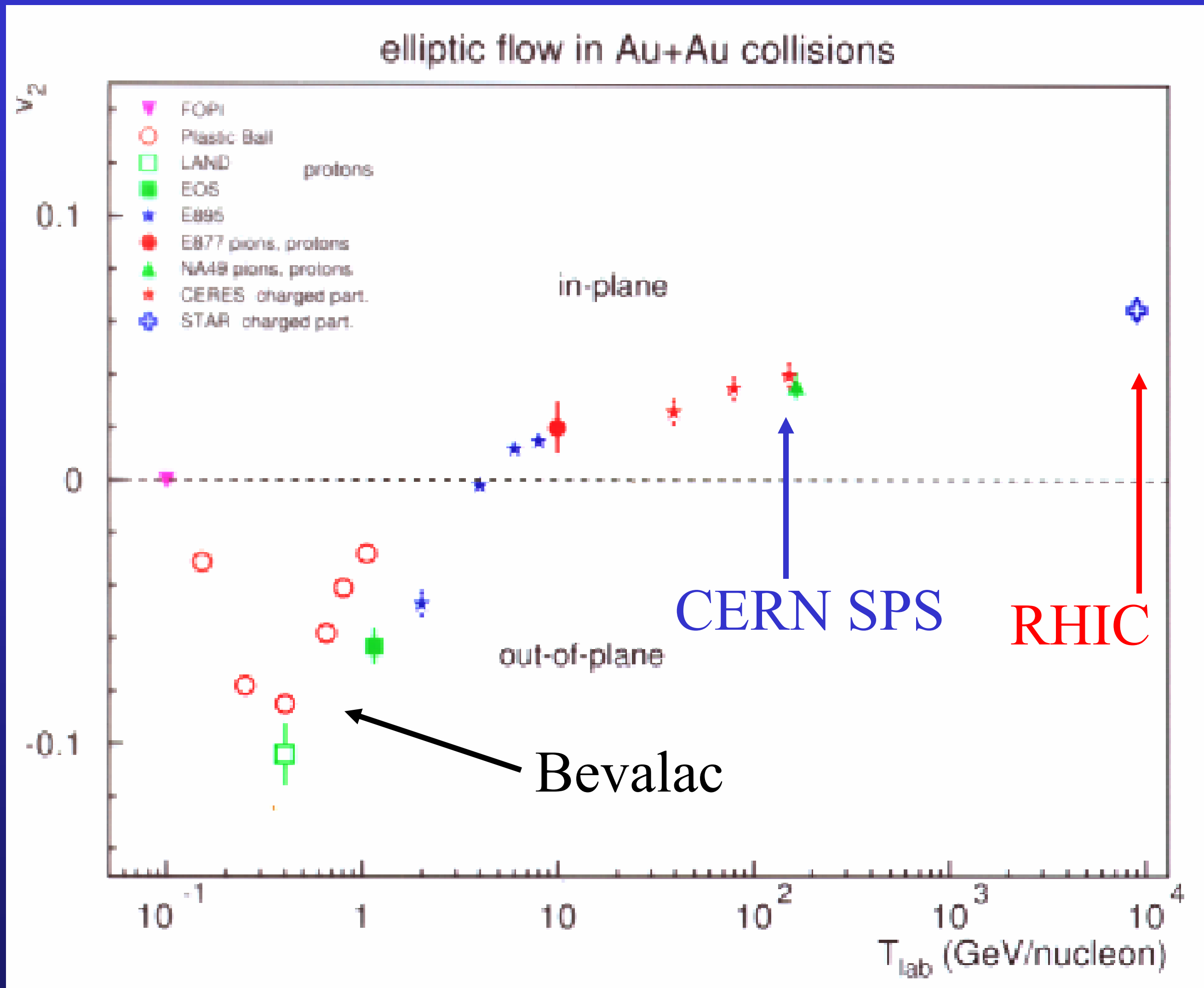
$$v_2 = < \cos(2(\varphi - \Phi)) >$$

or, in more detail,

$$v_2 = \frac{< \cos(2(\varphi - \Phi_2)) >}{< \cos(2(\Phi_2 - \Phi_{RP}) >}$$

where Φ_2 is the estimated angle of the reaction plane and $<\cos(2(\Phi_2 - \Phi_{RP})>$ accounts for the difference between the true and estimated reaction plane.

v_2 vs collision energy

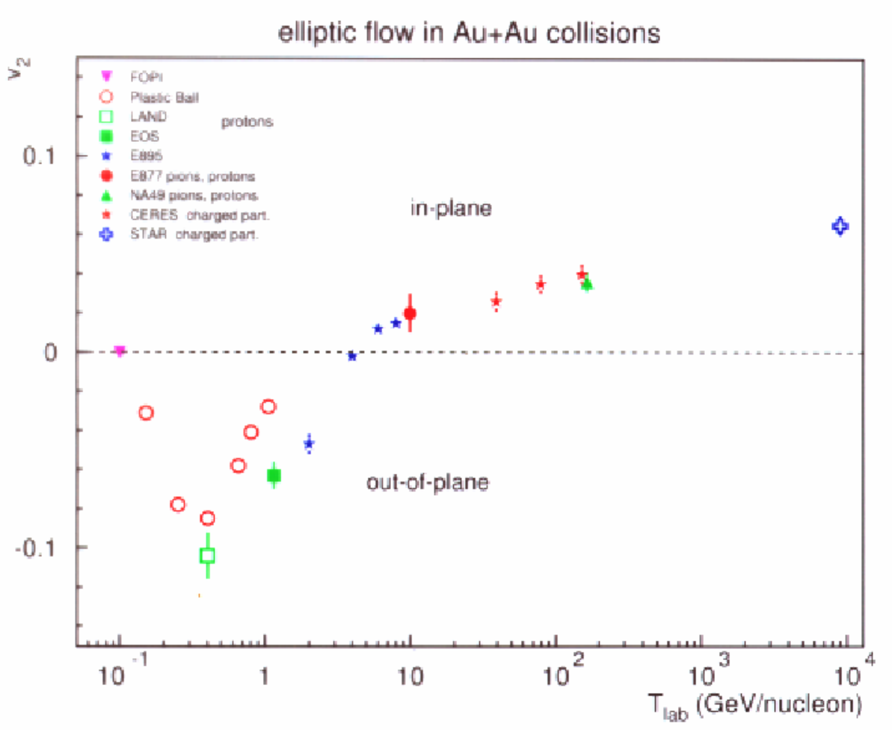


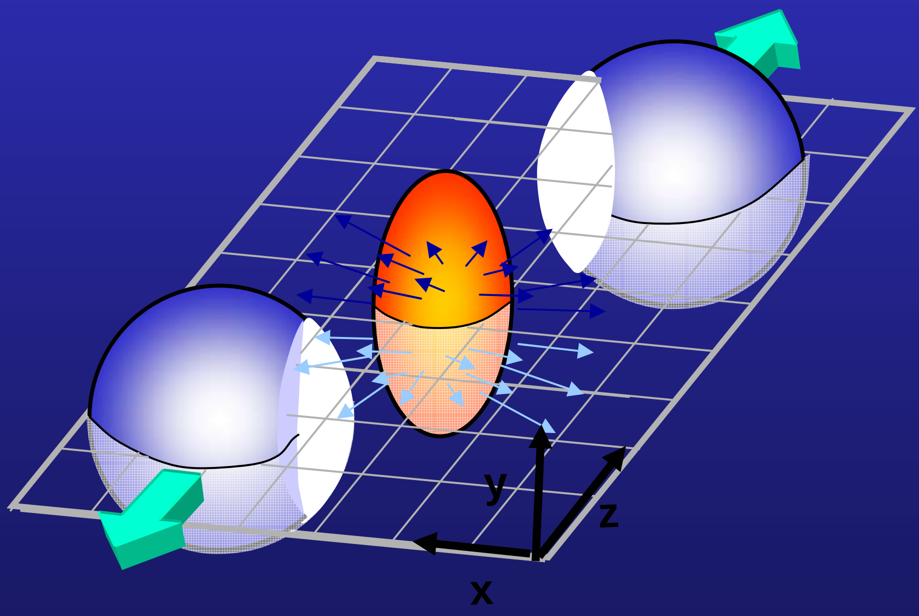
beam kinetic energy in lab frame

v_2 vs collision energy

Low Energy: The spectators block flow in reaction plane, ”squeeze-out”.

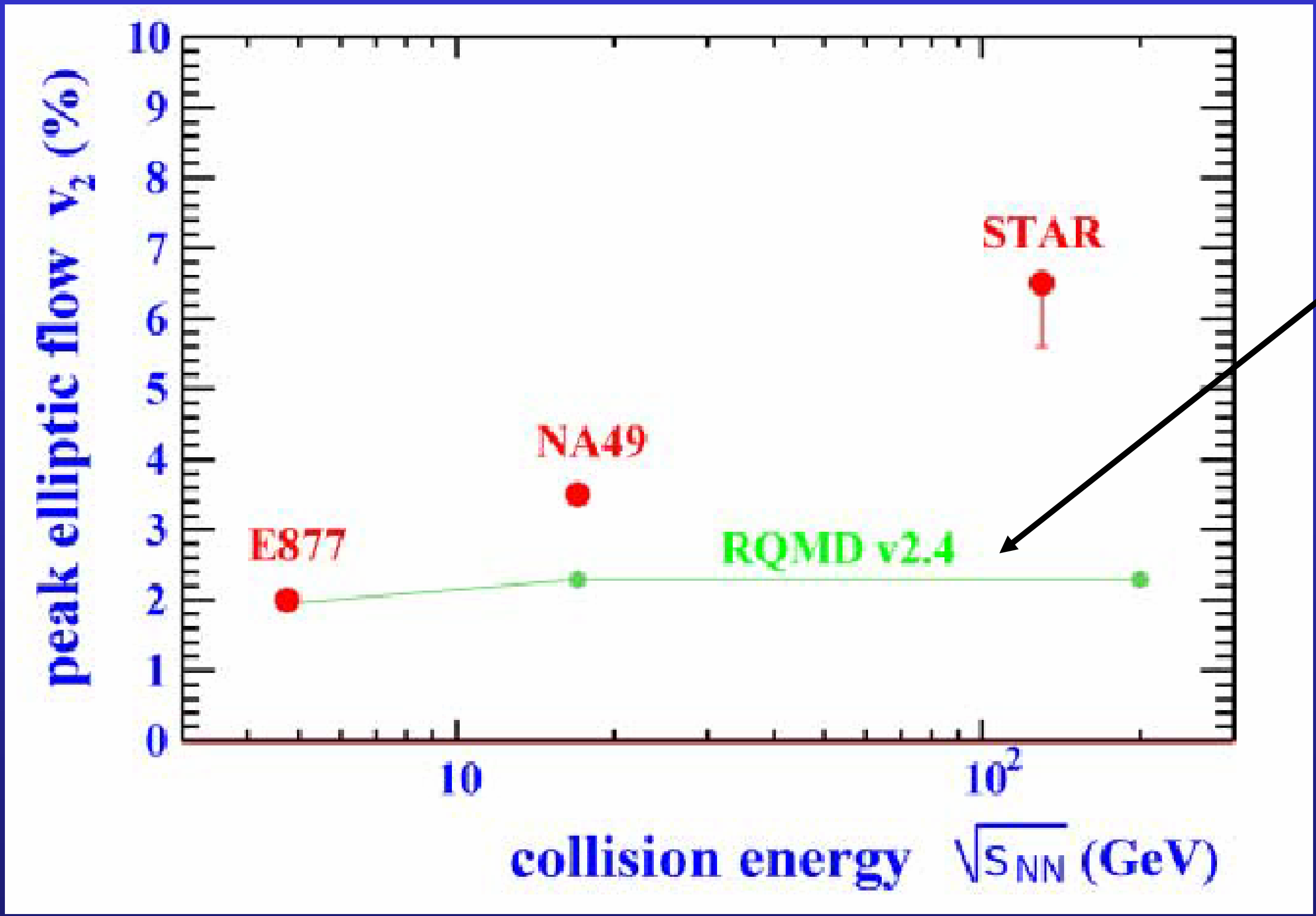
High Energy: Hydrodynamic pressure leads to flow of particles in the reaction plane.





Joakim Nystrand, University of Bergen

A few years ago…



Predictions before RHIC

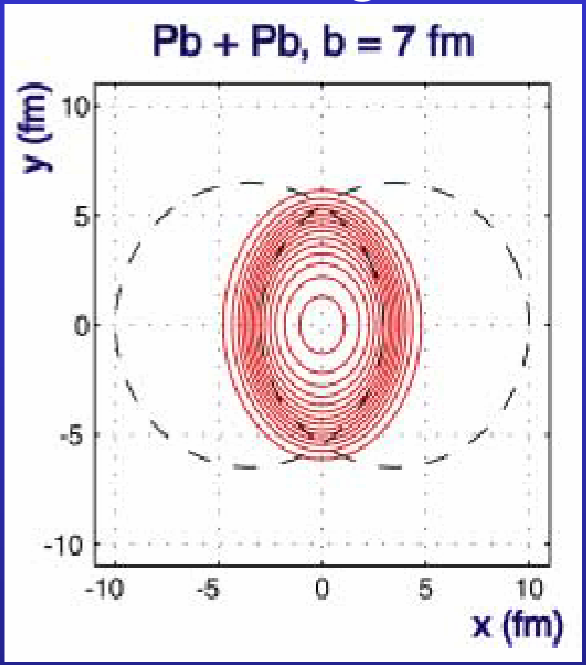
⇒The collective (elliptic) flow is much stronger at RHIC than anticipated!

An apparent paradox:

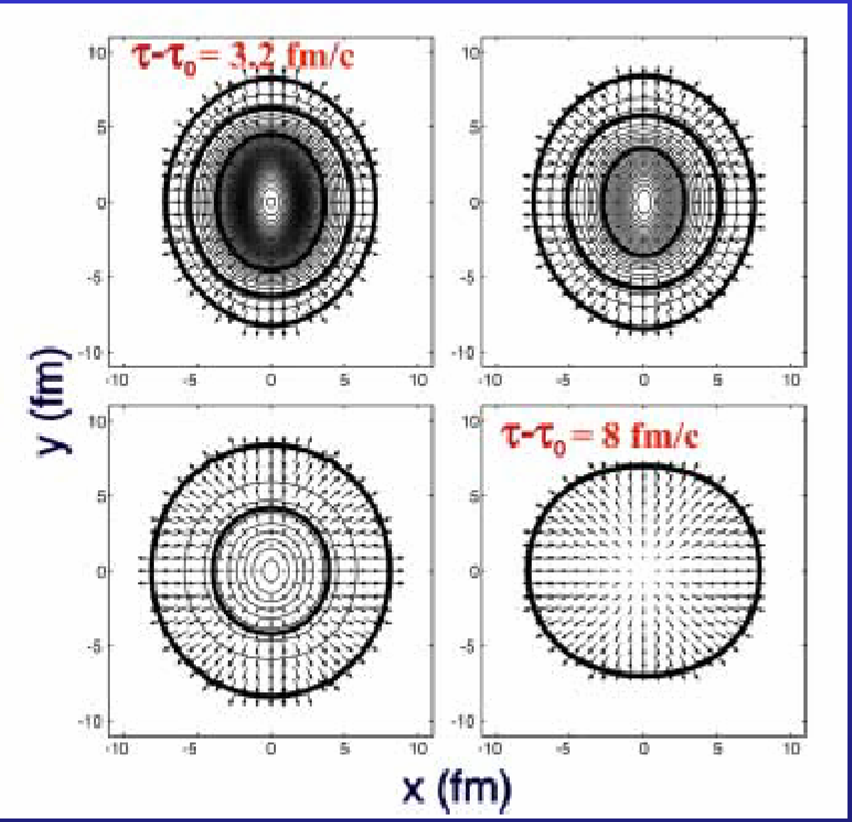
v_2 is calculated from the angular distributions of pions, kaons, protons, … emitted at the *late* stages of the collision, yet v_2 is sensitive to the equation of state *early* in the collision.

Explanation: Self-quenching

Initial Configuration

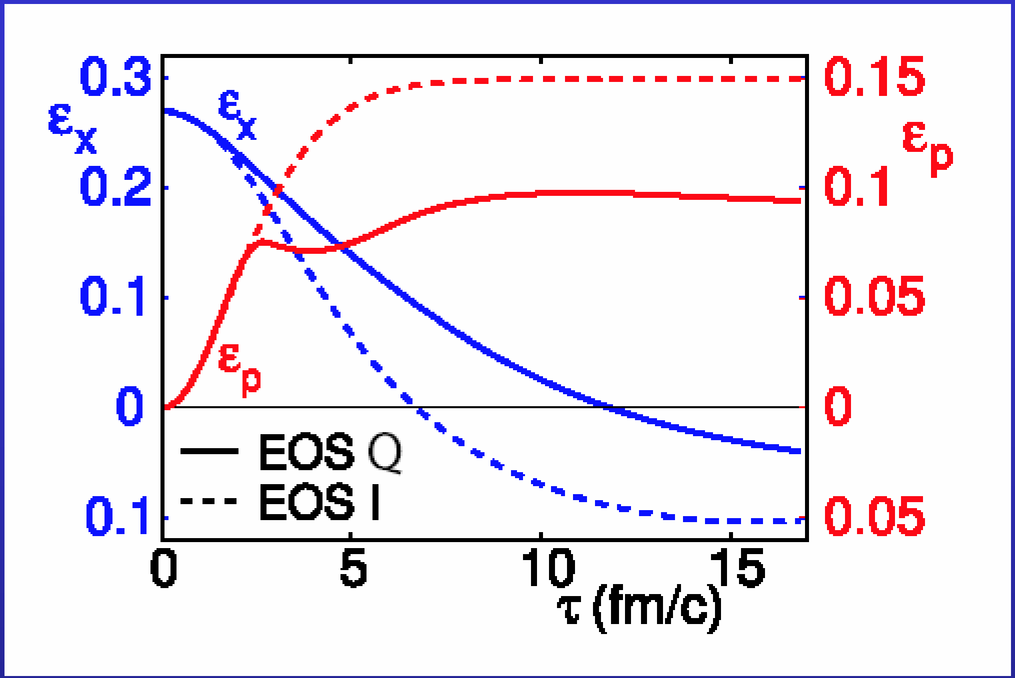


Time evolution



P. Kolb, J. Sollfrank, and U. Heinz

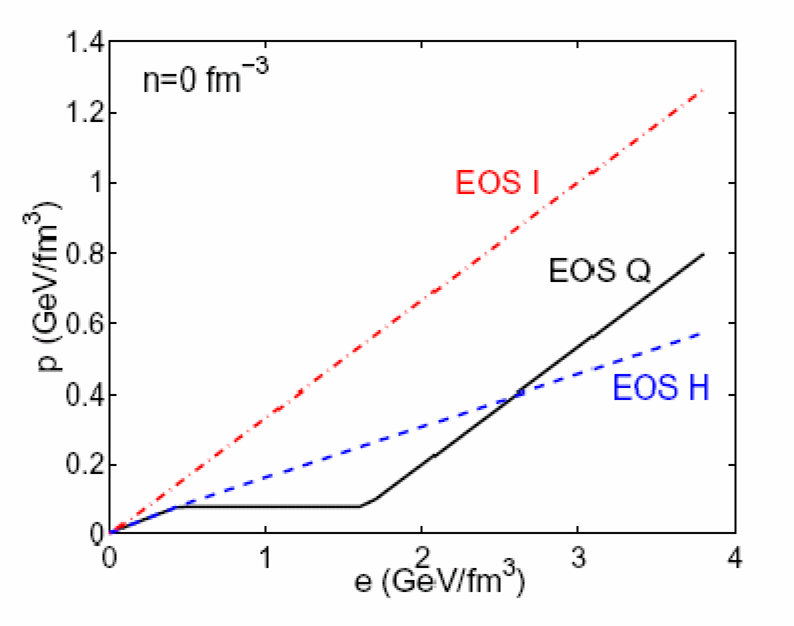
Time evolution

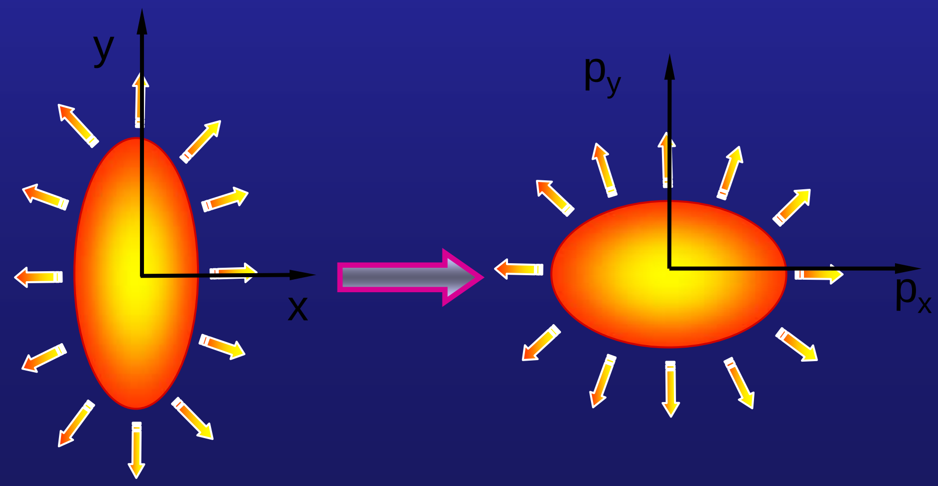


ε_x: Spatial eccentricity

ε_p: Momentum eccentricity

Kolb, Heinz 2003

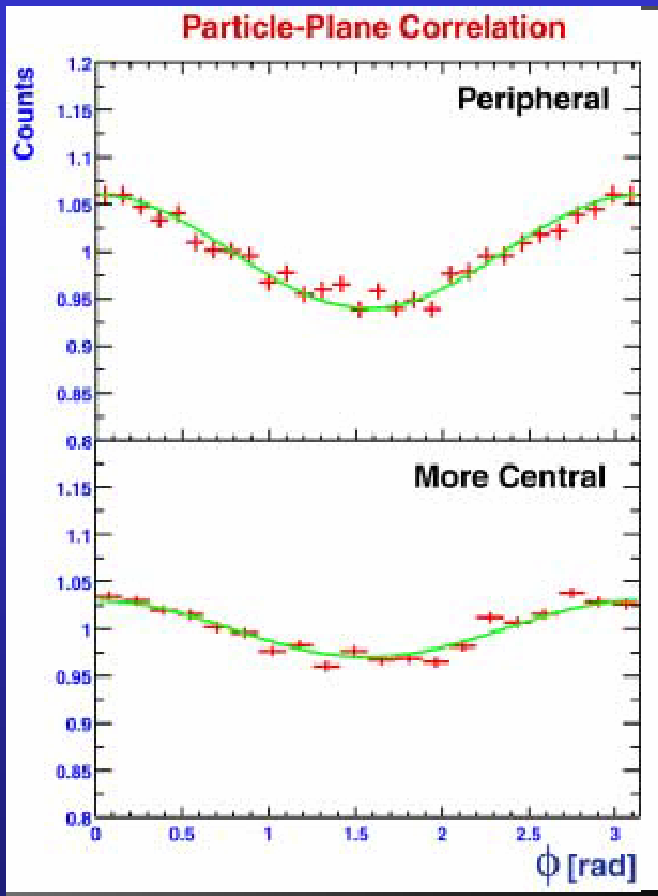




If locally equilibrated hydrodynamics is taken as the mechanism for generating elliptic flow, then the observation of any substantial amount of elliptic flow can be taken as evidence that local thermal equilibrium is achieved on a time scale before the spatial anisotropy would be completely erased.

(PHENIX White Paper)

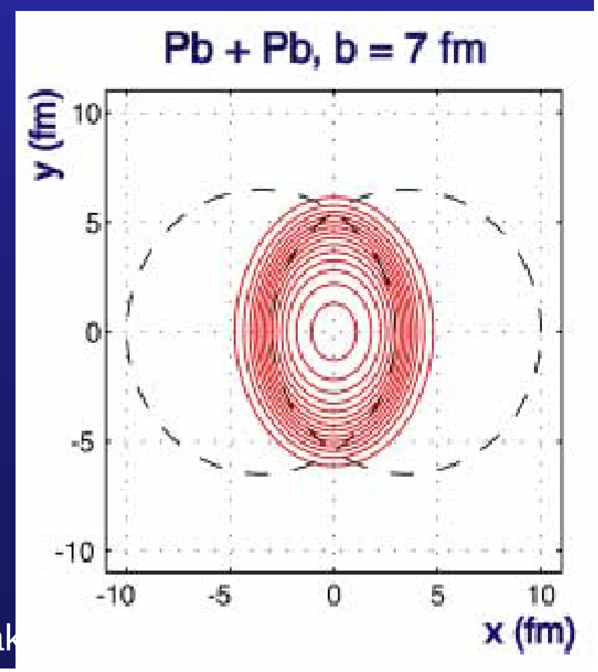
Centrality dependence of v_2



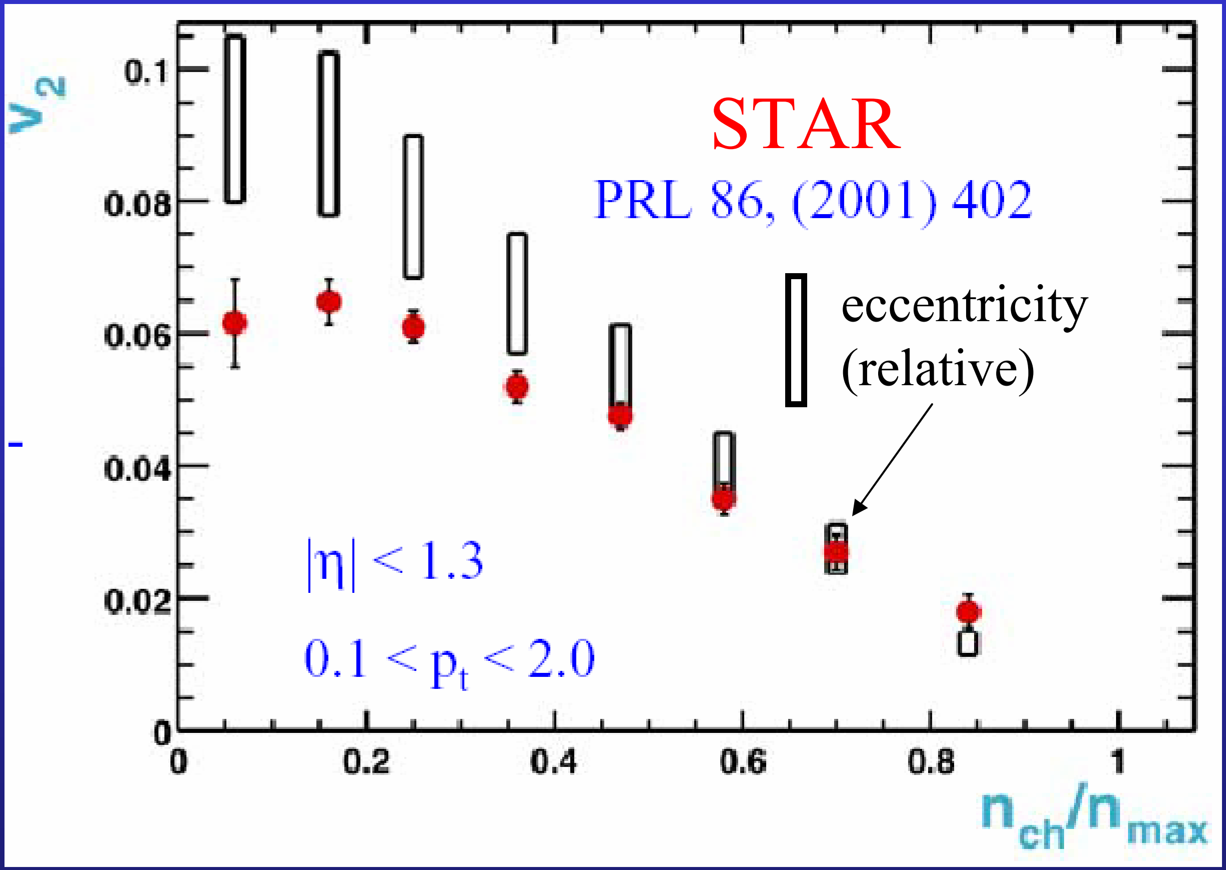
Stronger in peripheral than in central collisions.

Relate the centrality dependence to the intial eccentricity (from geometry for a given b):

$$\varepsilon = \frac{< y^2 > - < x^2 >}{< y^2 > + < x^2 >}$$



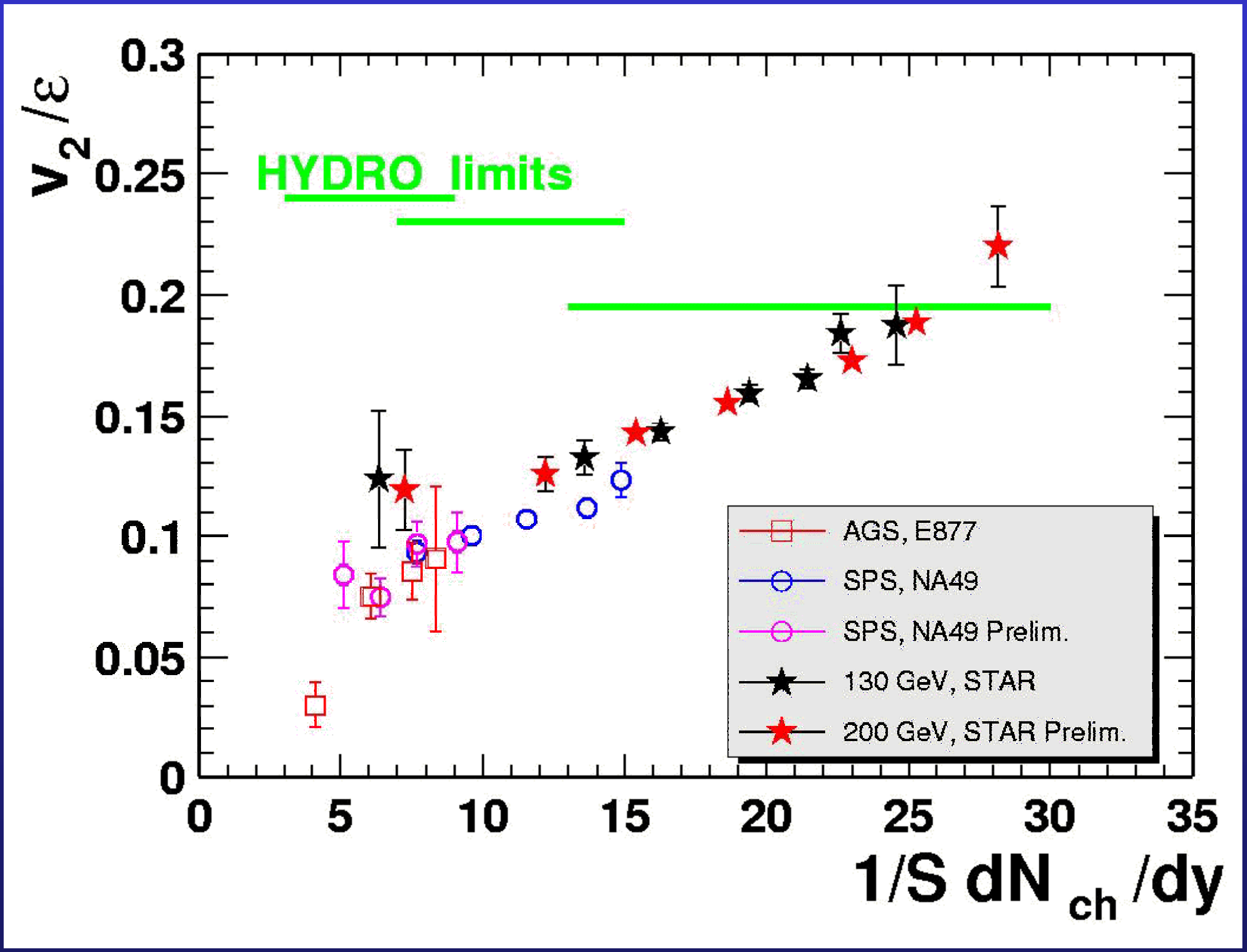
Centrality dependence of v_2



Peripheral ⟷ Central

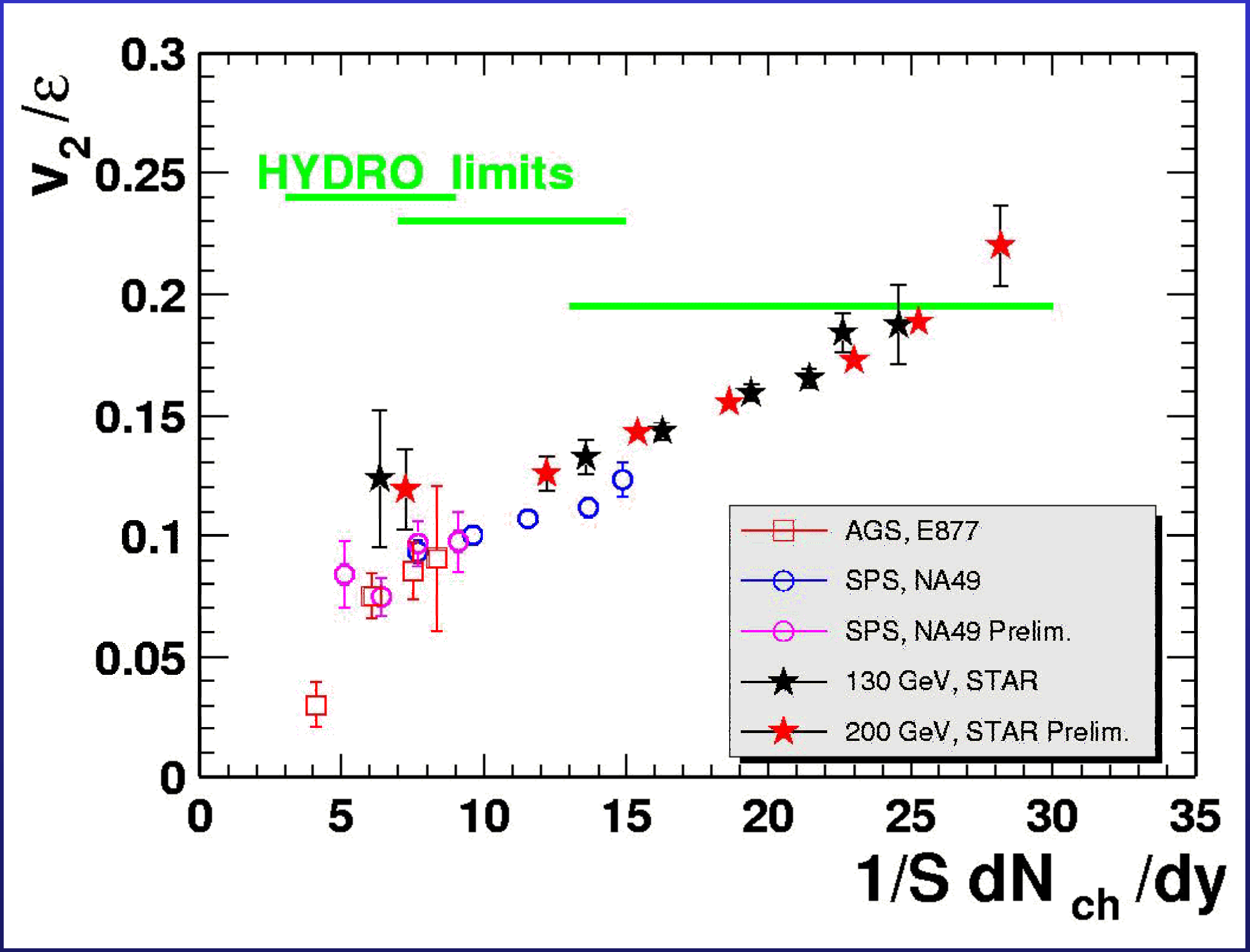
ε: Eccentricity

S: Area of overlap



Is there a "hydro limit"? Or is v_2/ε simply $\propto dn_{ch}/dy$?

One argument for accelerating ^{238}U at RHIC!



End v_2

Global Observables –
Observables that characterize the whole event

Examples:

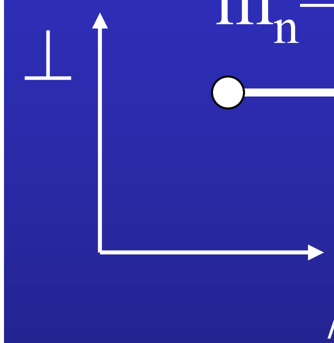
- Amount of stopping
- Total multiplicity of particles
- Size of the particle emitting source

Nuclear Stopping

Definition of rapidity, y: $$y = \frac{1}{2}\ln\left(\frac{E + p_z}{E - p_z}\right)$$

$p_{//}$ = +100 GeV/c,
m_n=0.939 GeV/c^2

$p_{//}$ = –100 GeV/c,
m_n=0.939 GeV/c^2



y_{beam} = 5.4

y_{beam} = -5.4

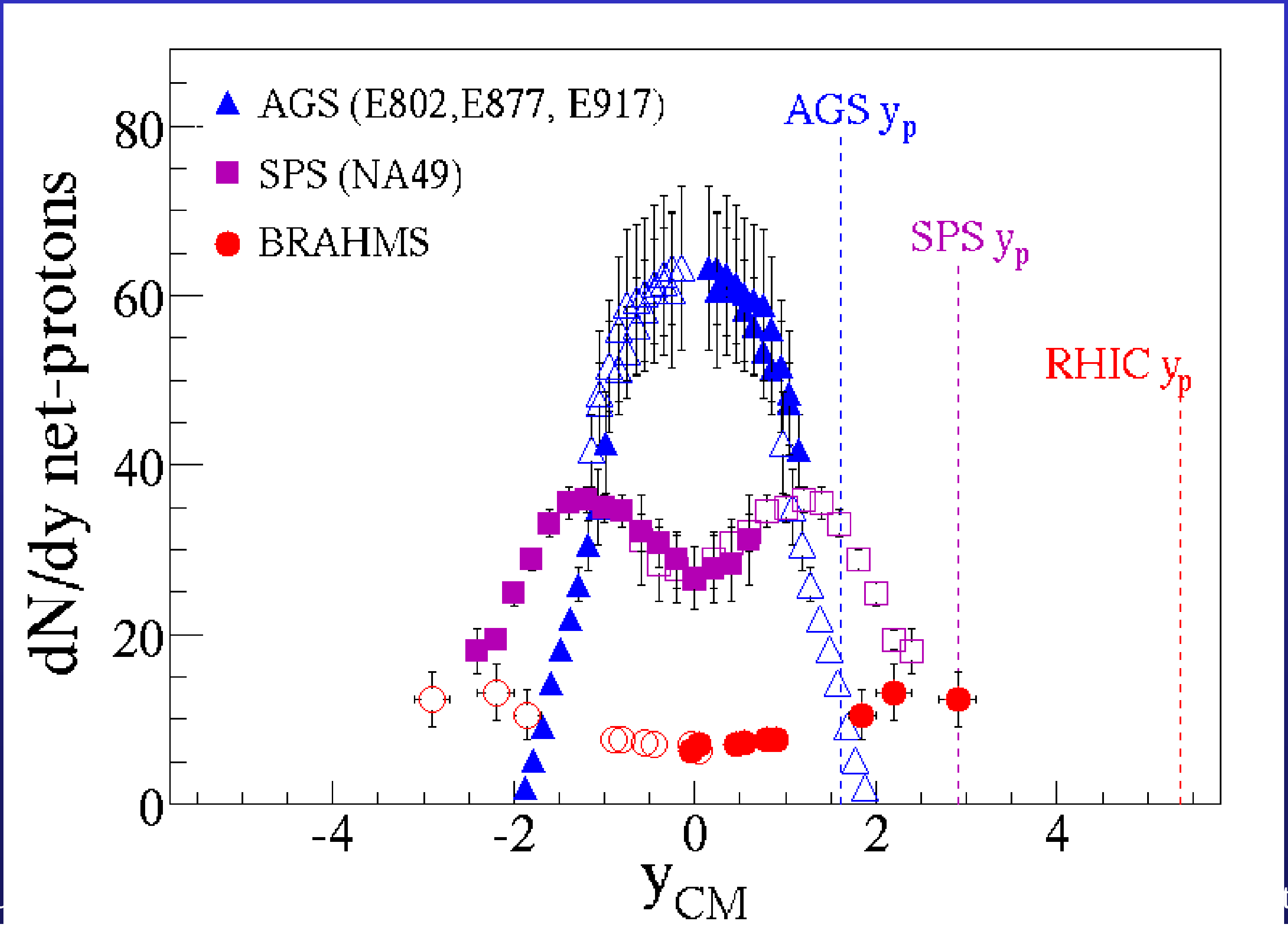
$$\frac{\sqrt{s}}{2m_n} = \cosh(y_{beam})$$

mid-rapidity ⇔ y=0 ⇔ $p_{//}$ = 0
particles emitted with θ=90°

Nuclear Stopping

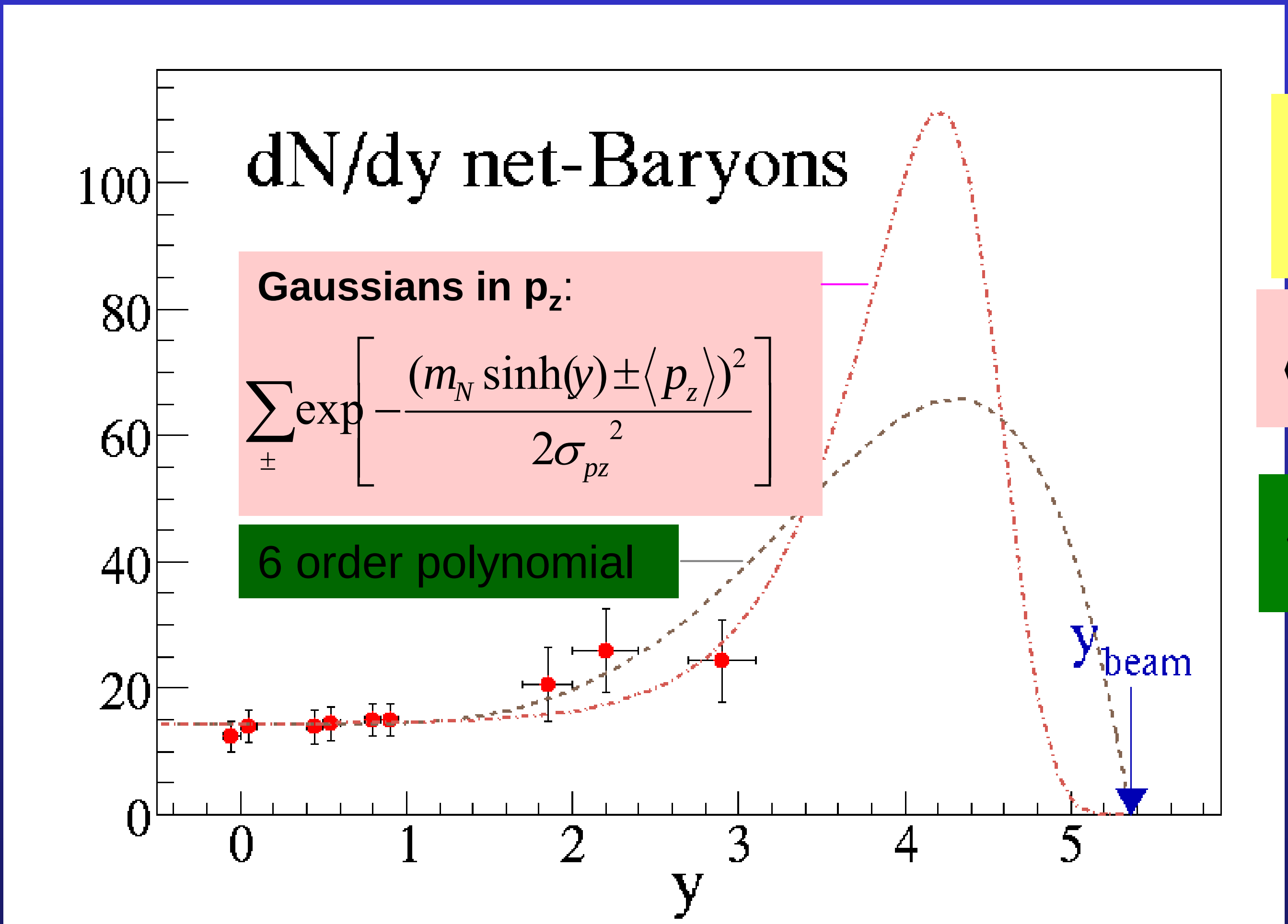
AGS: $\sqrt{s_{nn}}$ = 4.9 GeV, y_{beam} = 1.6

SPS: $\sqrt{s_{nn}}$ = 17.3 GeV, y_{beam} = 2.9



Nuclear Stopping

BRAHMS



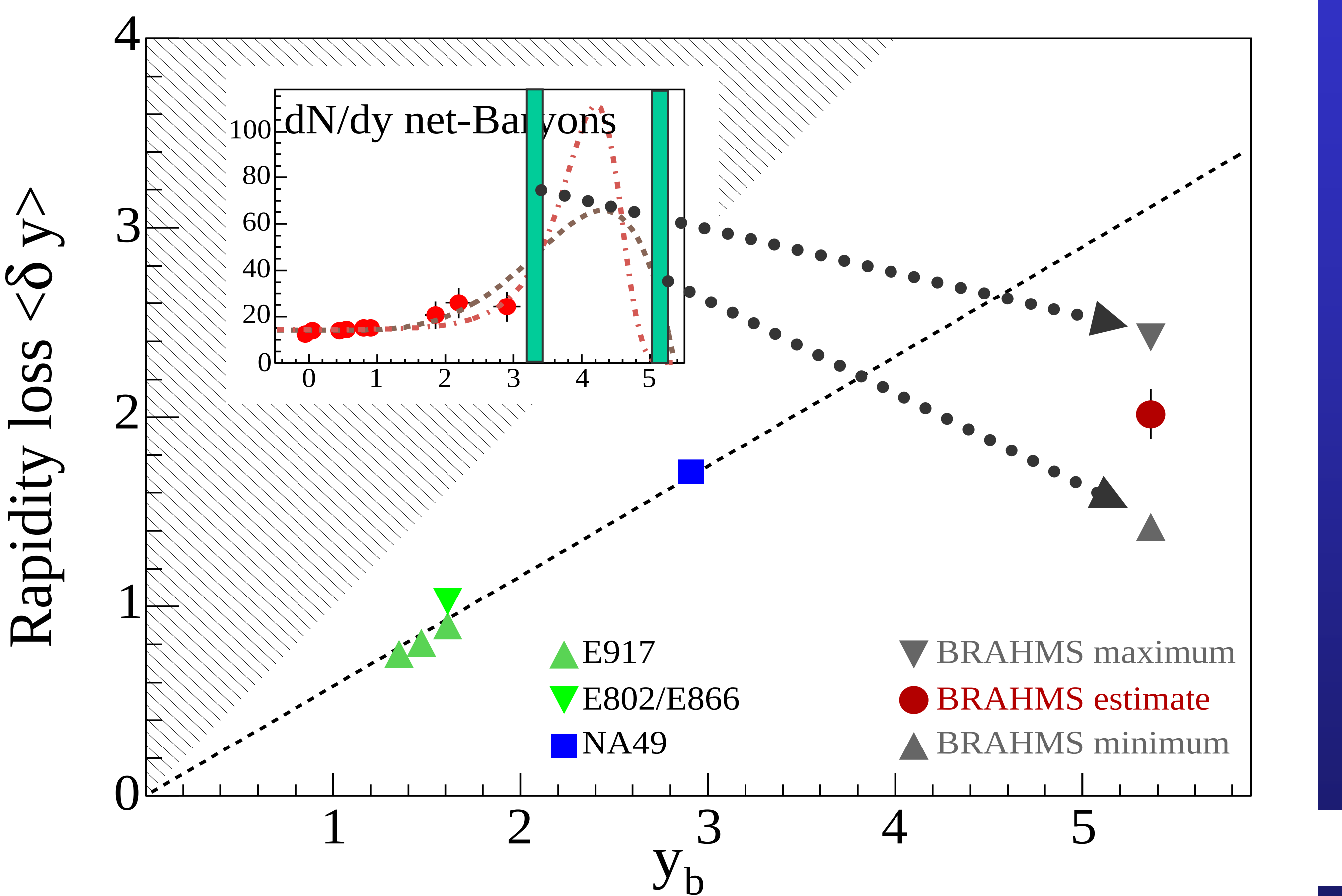
Net-baryon after feed-down & neutron corrections

$$\langle \delta y \rangle = 2.03 \pm 0.16$$

$$\langle \delta y \rangle = 2.00 \pm 0.10$$

$$\langle \delta y \rangle = y_p - \langle y \rangle = y_p - \frac{2}{N_{part}} \int_0^{y_p} y \frac{dN_{(B-\overline{B})}}{dy} dy$$

Nuclear Stopping



- Upper limit to rapidity loss?
- Energy loss:

$$\int_{-y_p}^{y_p} \langle m_T \rangle_y \frac{dN_{(B-\bar{B})}}{dy} \cosh y \, dy$$

ΔE = 25.7 ± 2.1 TeV

ΔE/nucleon = 72 ± 6 GeV

Stopping at RHIC - summary

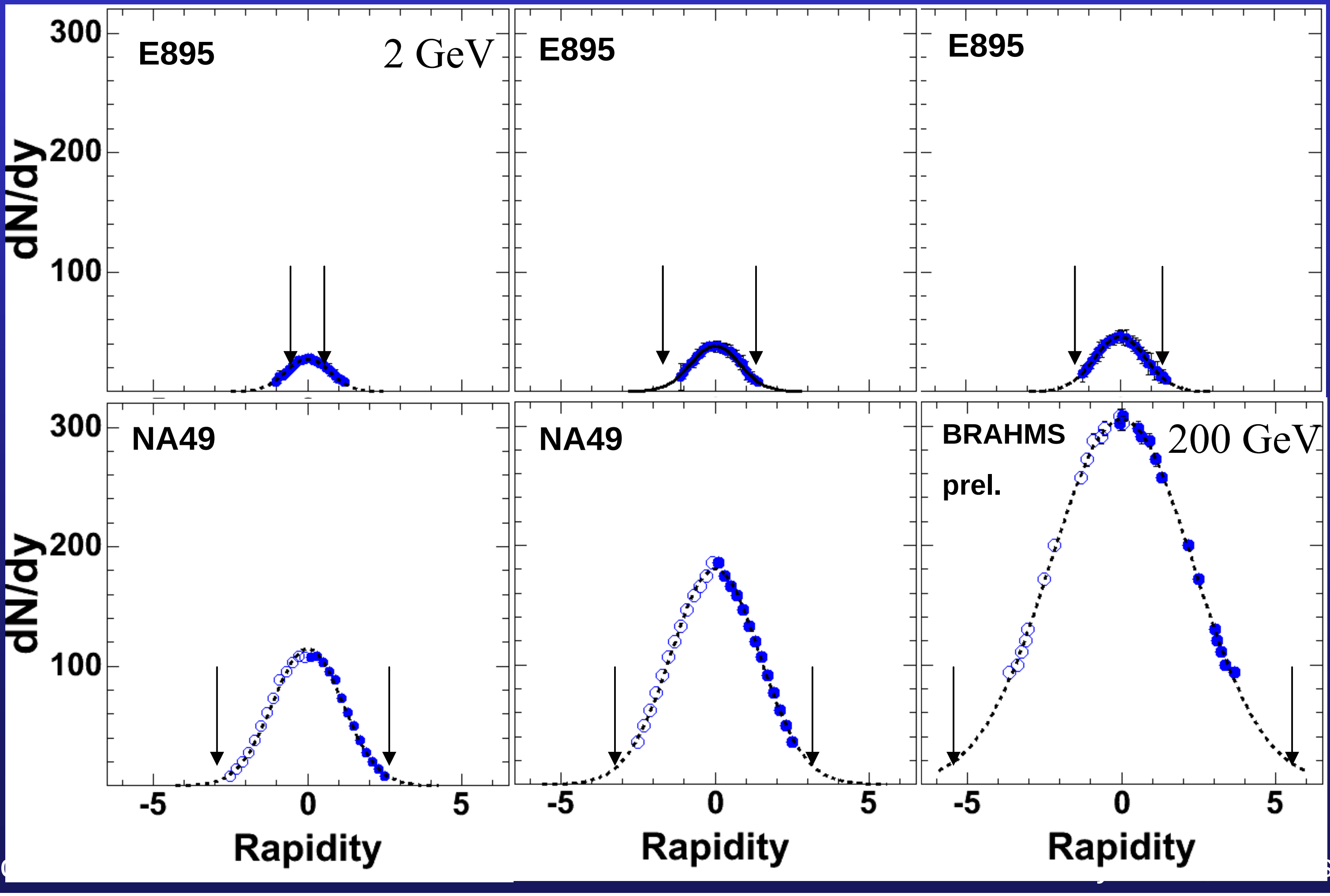
- Net-baryon poor midrapidity region
  - dN(net-protons)/dy = 7
- Total-baryon rich midrapidity region
  - dN(all baryons)/dy $\approx$ 65
- Stopping power
  - On average, the protons lose 72% of their energy in central Au+Au at RHIC

Particle Production $\sqrt{s_{nn}} = 2 – 200$ GeV

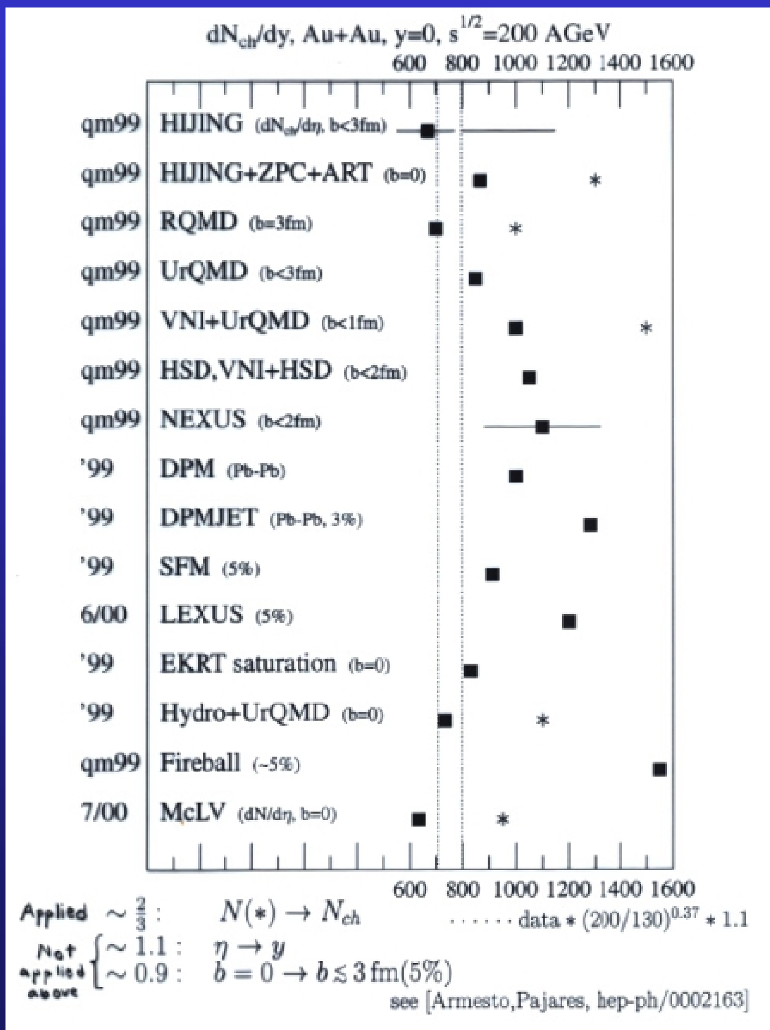
π^+ dN/dy spectra: π^+ π^0 π^- ≈ 80-90% of all produced particles

indicate y_{beam} for the various energies

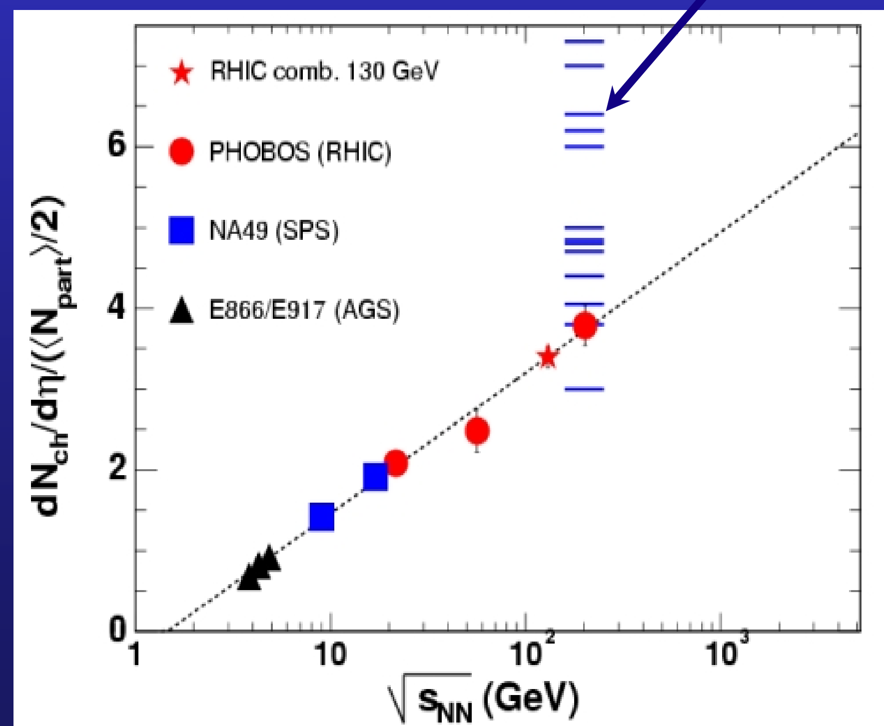
Au+Au or Pb+Pb



How many particles are produced in a central Au+Au collision at RHIC?



pre-RHIC predictions

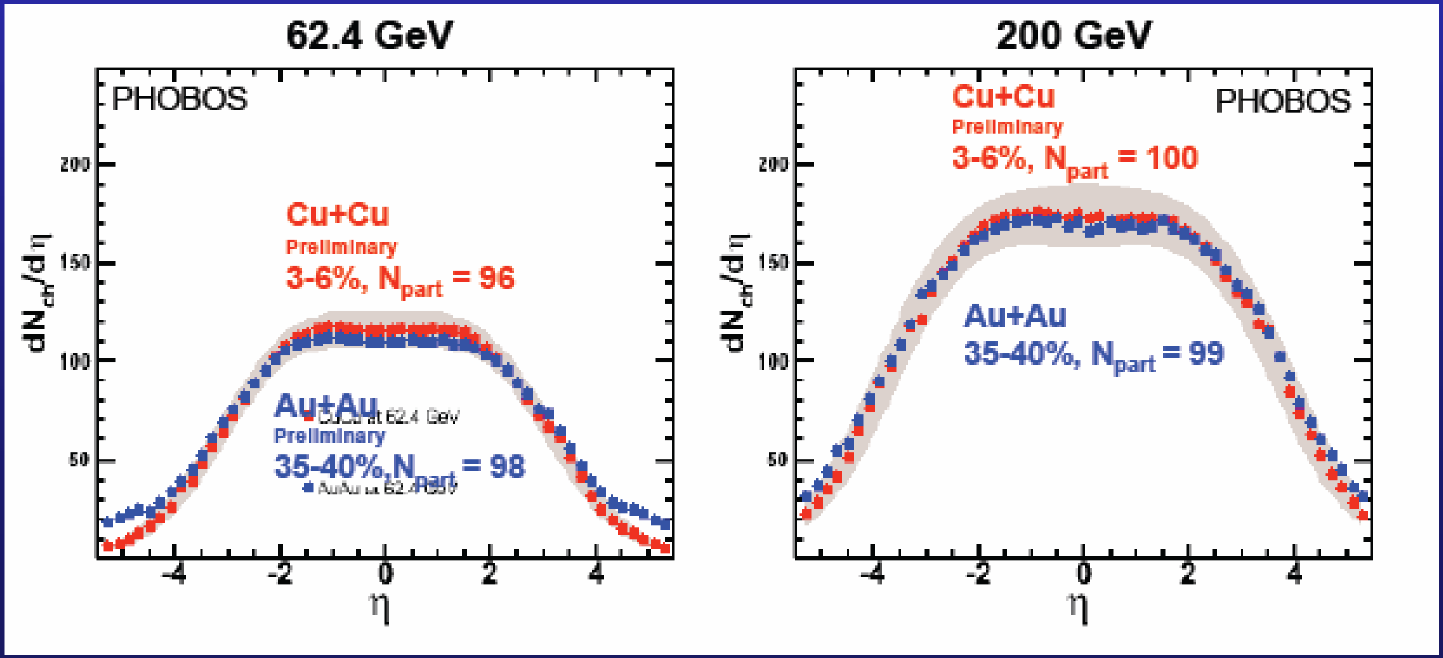


Alternative to rapidity - pseudo-rapidity

$$\eta = -\ln(\tan(\frac{\theta}{2}))$$

$\eta \approx y$ when $p_{//} \approx E \ (m \to 0)$

Scaling with number of participants nearly perfect



Multiplicity at RHIC - summary

- $dn_{ch}/d\eta$ well described by gaussian with width

$$\sigma^2 = \ln\left(\frac{\sqrt{s}}{2m_N}\right)$$

- The total multiplicity scales with the number of participating nucleons.
- The multiplicity per participant scales as $A+B\cdot\ln(\sqrt{s})$.

The Final(?) Verdict

In the words of the experiments (White Papers):

STAR:

The bottom line is that in the absence of a direct "smoking gun" signal of deconfinement revealed by experiment alone, a QGP discovery claim must rest on the comparison with a promising, but still not yet mature, theoretical framework…

The matter produced in RHIC collisions is fascinating and unique...

But we judge that a QGP discovery claim based on RHIC measurements to date would be premature.

BRAHMS:

There is no doubt that the experiments at RHIC have revealed a plethora of new phenomena that for the most part have come as a surprise. In this sense it is clear that the matter that is created at RHIC differs from anything that has been seen before. Its precise description must await our deeper understanding of this matter.

PHOBOS:

In the most central Au+Au collisions at the highest beam energy, evidence is found for the formation of a very high energy density system whose description in terms of simple hadronic degrees of freedom is inappropriate.

PHENIX:

In conclusion, there is compelling experimental evidence that heavy-ion collisions at RHIC produce a state of matter characterized by very high energy densities, …

This state of matter is not describable in terms of ordinary color-neutral hadrons, because there is no known self-consistent theory of matter composed of ordinary hadrons at the measured densities…

There is not yet irrefutable evidence that this state of matter is characterized by quark deconfinement or chiral symmetry restoration…

Finally, a different aspect of heavy-ion collisions: Ultra-peripheral collisions

(particle physics with nuclei)

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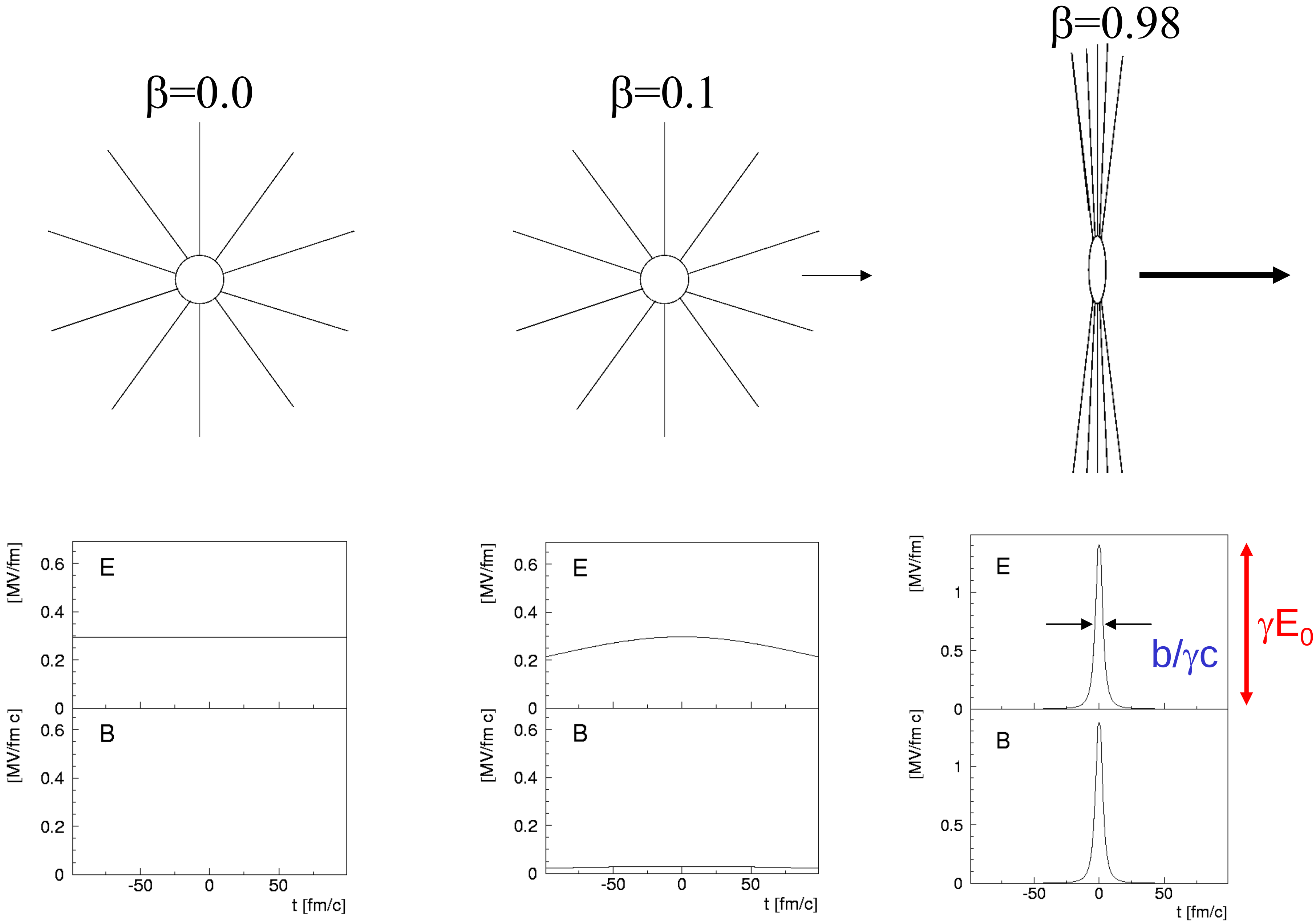
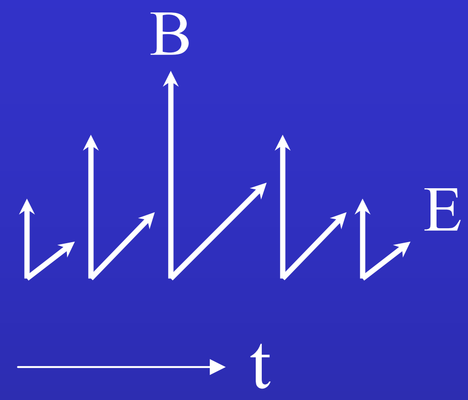
Electromagnetic fields of a moving charged particle

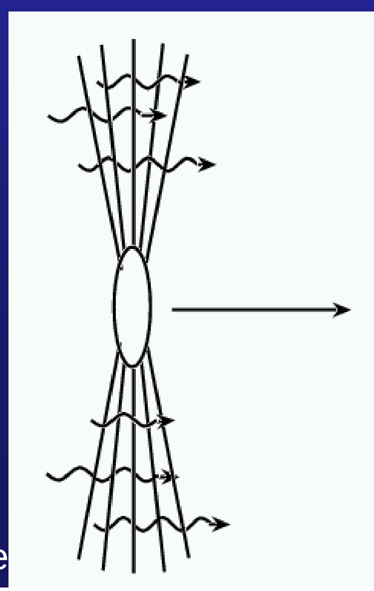


Electromagnetic fields of a moving charged particle



1) $|E| \approx |B|$ 2) $(E \perp B)$ 3) $\Delta t \sim b/\gamma c$

Fermi 1924: The effect of the fields is equivalent to a flux of of photons with a continous energy spectrum. (hep-th/0205086)

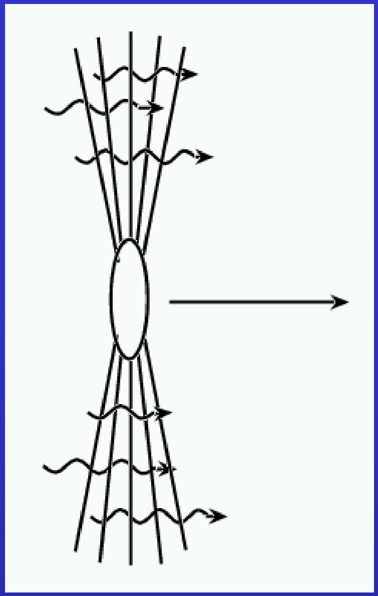


Pulse width $b/\gamma c$ $\leftrightarrow$ the spectrum contains photons w/ $\hbar\omega < \gamma\hbar c/b$

Quantum Mechanical derivation 1935 by Weizsäcker,Williams. $\Rightarrow$ *Weizsäcker-Williams method*

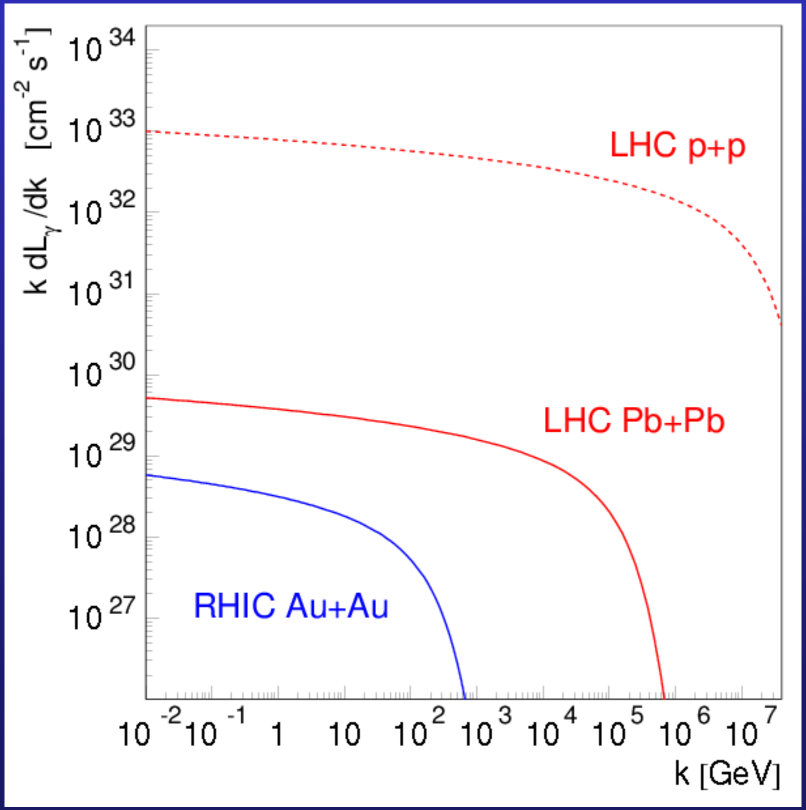
Electromagnetic field ↔ An equivalent flux of photons.

$dn/d\omega \propto Z^2$



LHC ⇒ γ-nucleus, γ-nucleon interactions at the highest energies.

Equivalent photon spectrum



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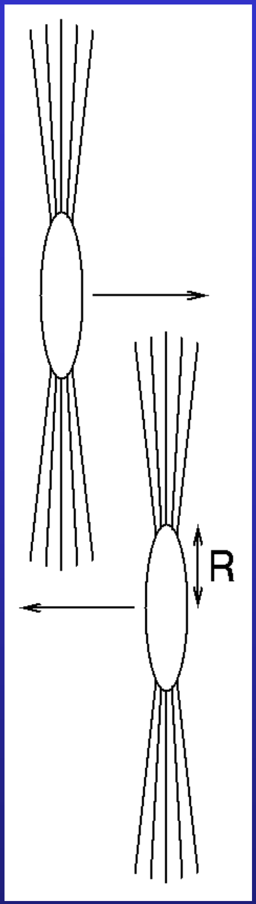


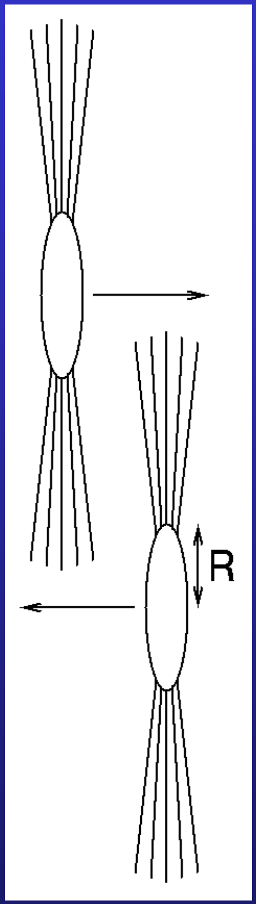
In an ultra-peripheral interaction, b > 2R, the ions can interact electromagnetically:

$\gamma\gamma \rightarrow X$

or

γ+nucleus $\rightarrow X$

The photon spectrum may be utilized in so-called Ultra-Peripheral Collisions (UPC) with b >> 2R



Two-photon interactions:

$\gamma\gamma \rightarrow e^+e^-$, $\mu^+\mu^-$ (Strong field QED, $\alpha Z \approx 82/137$ instead of $\alpha \approx 1/137$)

$\gamma\gamma \rightarrow$ mesons (meson spectroscopy)

$\gamma\gamma \rightarrow$ Higgs ($M_H > 115$ GeV $\Rightarrow$ very low rate; maybe possible in pp)

Photonuclear interactions:

Exclusive interactions, e.g. $\gamma + A \rightarrow J/\psi$ or $\Upsilon + A$.

Inclusive or "inelastic" interactions:

$Pb+Pb \rightarrow Pb+X+c\bar{c}$; $\gamma + g \rightarrow c\bar{c}$; $\sigma \approx 1$b,

$y=0 \leftrightarrow x=5\cdot 10^{-4}$, probes the nuclear parton dist.

What to watch out for in the near future (+ what was not coverd in this talk)

– J/ψ: ~ 10 years ago NA50 observed a suppression in central Pb+Pb collisions at the SPS; PHENIX data show a similar suppression at RHIC (which is somewhat surprising).

– Charm quarks: flow and high-p_T suppression, preliminary data based on spectrum of non-photonic electrons presented at QM05; better results expected with detector upgrades (Vertex detectors)

– Low mass dilepton spectrum: Very interesting new results from NA60 at SPS (In+In). Results expected from PHENIX.

– More on jet-tomography.

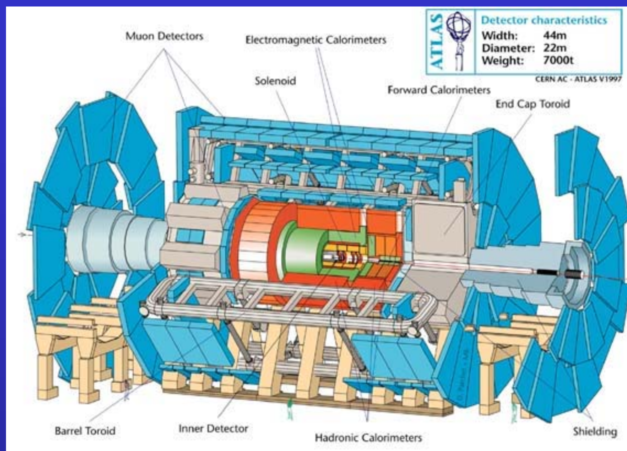
– Thermal photons.

– And …

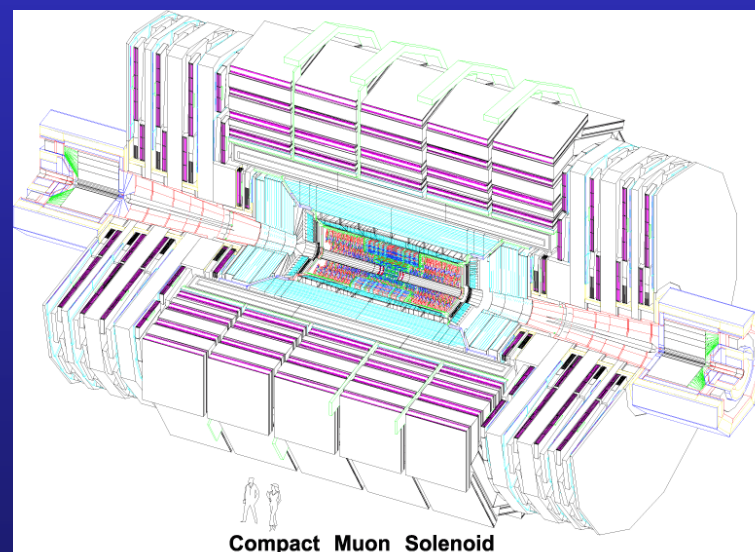
Large Hadron Collider (LHC)
First collisions 2007/2008
p+p at 14 TeV; Pb+Pb at 5.5 A TeV

Experiments at the LHC

ATLAS



CMS



ALICE

ALICE (= A Large Ion Collider Experiment)

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