Anisotropic flow and jet quenching

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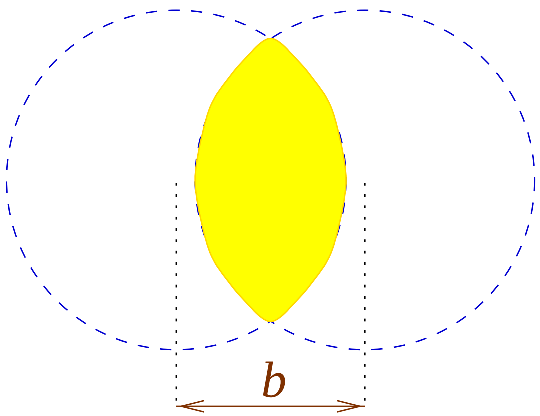
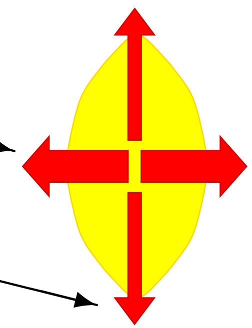
Anisotropic flow

Non-central collision:



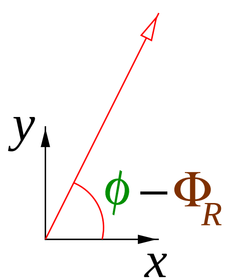
The particle source is anisotropic
(and around it there is only vacuum)

$\Rightarrow$ the pressure gradient along the impact parameter direction is stronger than the gradient perpendicular to the reaction plane



$\Rightarrow$ anisotropic particle emission: FLOW

$\underbrace{\text{anisotropic}}_{\text{in } momentum \text{ space}}$



Particles mainly emitted *in-plane* ($\phi = \Phi_R$) rather than *out-of-plane* ($\phi - \Phi_R = 90^{\rm o}$).

Anisotropic flow

- Flow is a collective effect

  ↳ affects (almost) *all* particles

  Measures bulk property of the medium: equation of state

- Anisotropy quantified by a Fourier expansion:

$$\frac{\mathrm{d}N}{\mathrm{d}\phi} \propto 1 + 2\,v_1 \cos(\phi - \Phi_R) + 2\,v_2 \cos 2(\phi - \Phi_R) + \ldots$$

  v_1: "directed flow", v_2: "elliptic flow"

- *A priori*, v_n(centrality, p_T, y, PID)

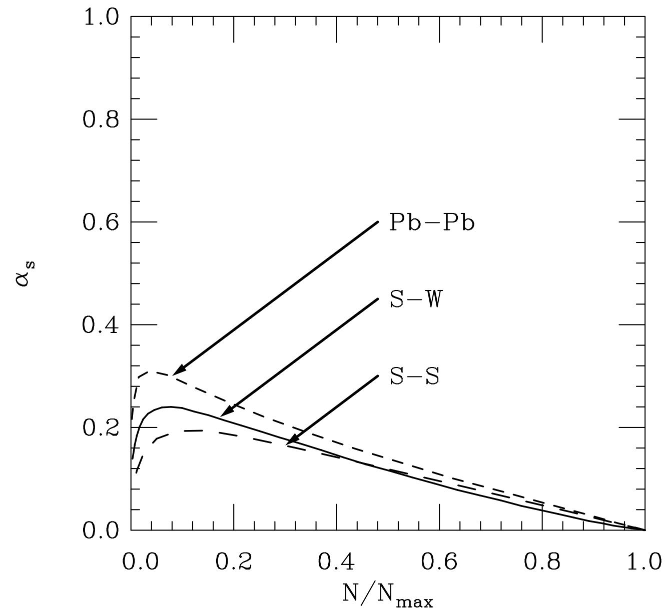
  $\Rightarrow$ differential measurements needed!

Elliptic flow v_2

$$v_2 = \langle \cos 2(\phi - \Phi_R) \rangle$$

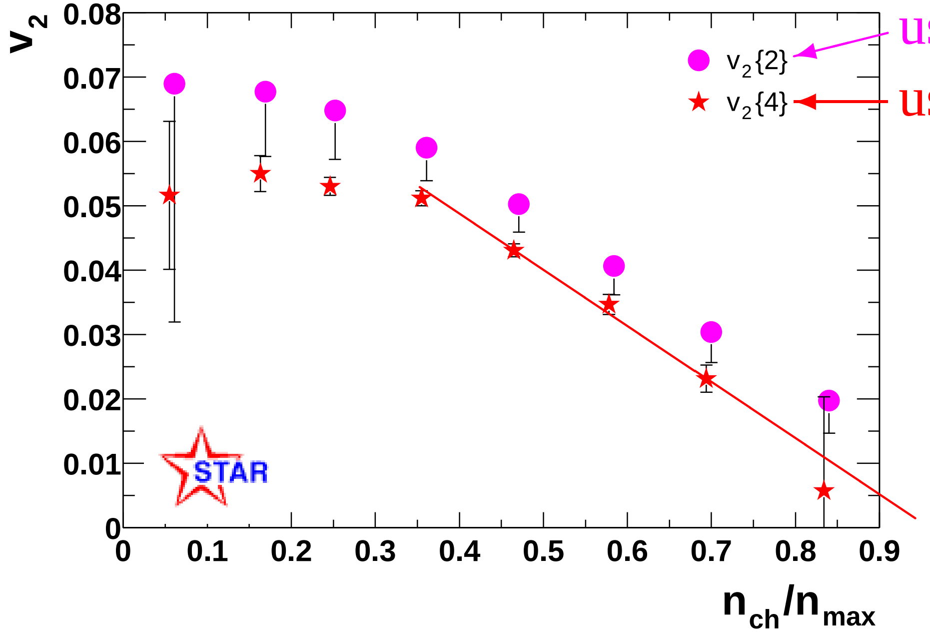
Predictions (Jean-Yves OLLITRAULT, 1992):

- At ultrarelativistic energies, particles are emitted "in-plane" ($\phi - \Phi_R = 0$ or 180°)
  $\Rightarrow$ $v_2 > 0$
- Hydrodynamical model
  (= assuming many collisions and an equation of state)
  $\Rightarrow$ v_2 linear function of centrality, up to very peripheral collisions



RHIC v_2 results [1]

♡ Centrality dependence of elliptic flow in 130 GeV collisions:



using the "standard" method

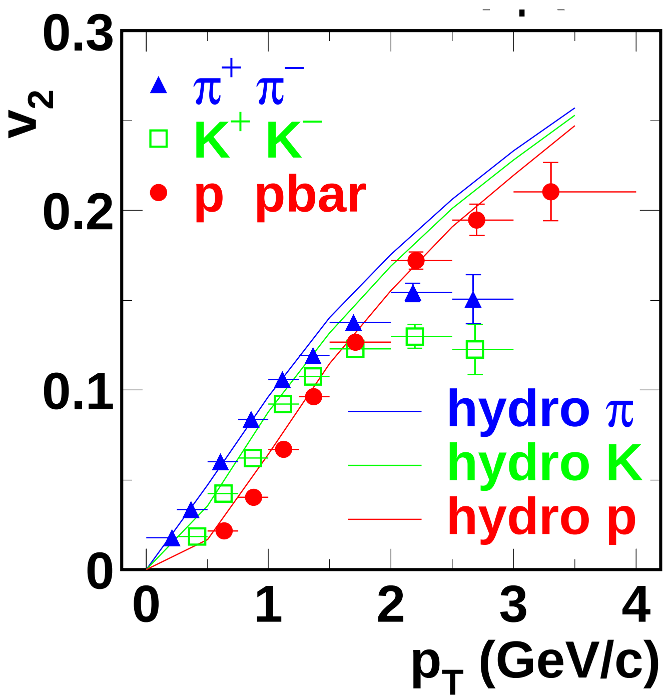
using an improved method of analysis

The difference between both measurements is due to "non-flow" effects that contaminate the standard method

♡ v_2 sign measured recently (STAR, Oct. 2003): $v_2 > 0$

RHIC v_2 results [2]

Transverse momentum & particle type dependence of elliptic flow (200 GeV collisions, PHENIX data):



Hydrodynamical model: (Huovinen *et al*)

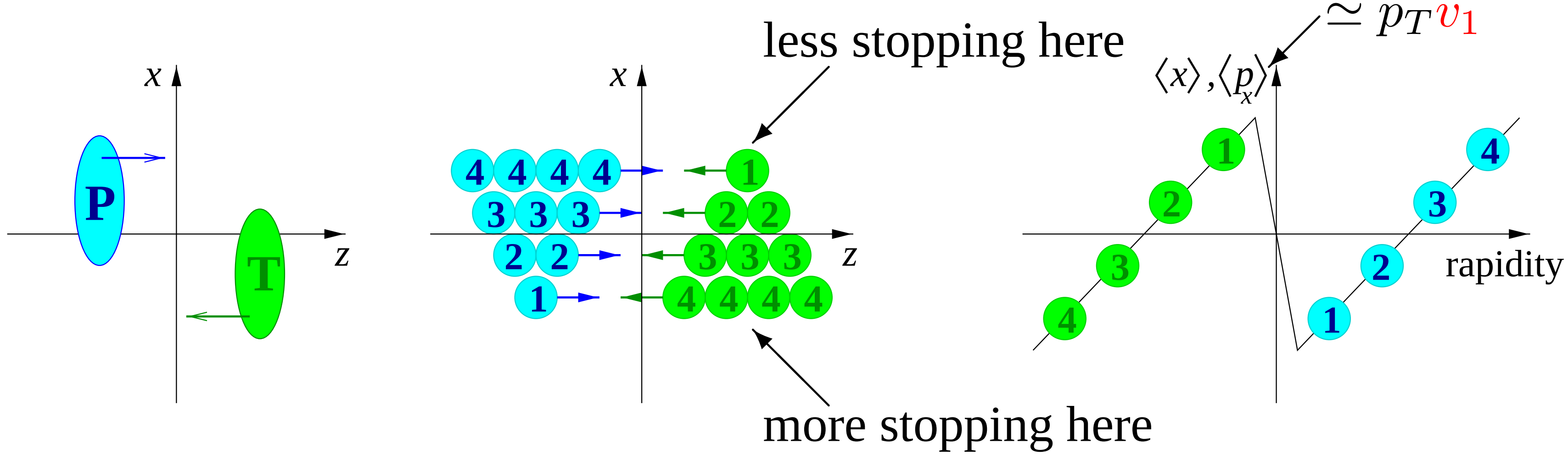
- 1st order phase transition,
- freeze-out temperature 120 MeV

$\Rightarrow$ reproduces the mass-dependent v_2 pattern, up to $\sim$ 2 GeV

For v_2 at high transverse momenta ($p_T \gtrsim 2$ GeV), see later

v_1: a simple model, "antiflow"

Assumptions: incomplete baryon stopping
position-momentum correlation



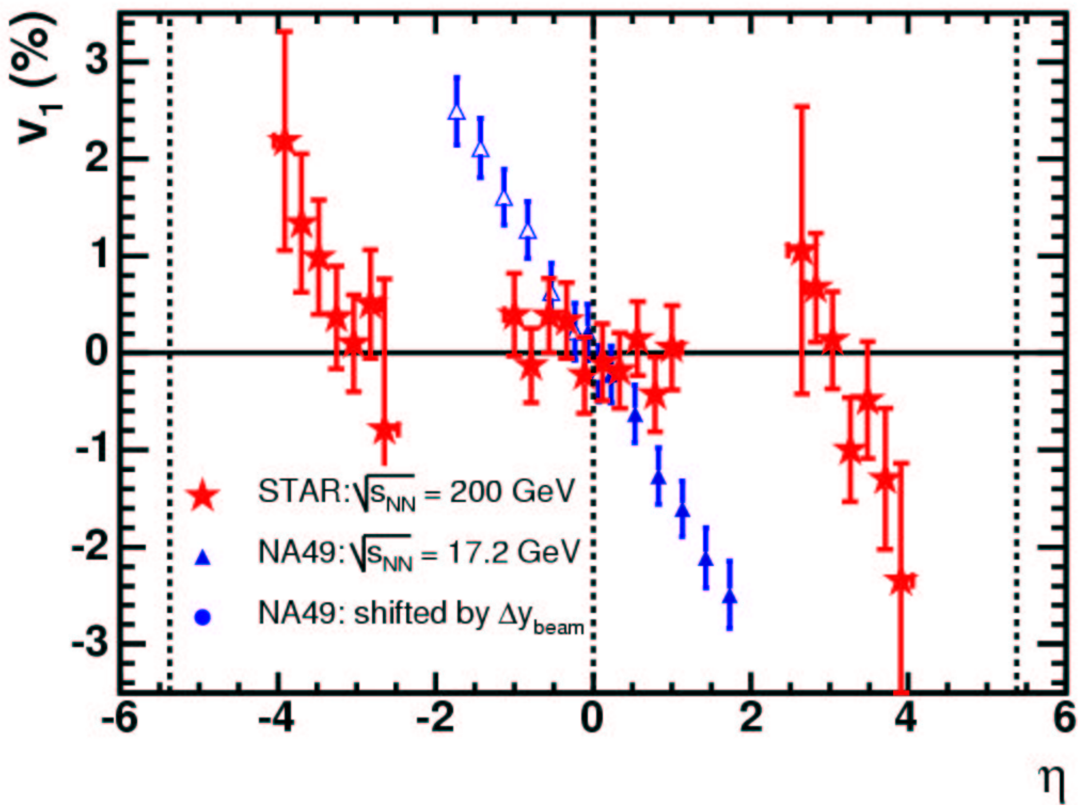
$\Rightarrow$ Proton v_1 negative just above midrapidity

R.J.M. Snellings *et al*, Phys. Rev. Lett. 84 (2000) 2803

Note: $v_1 = 0$ at midrapidity for identical nuclei (symmetry)!

v_1 at RHIC: first results

STAR Collaboration, Oct. 2003: charged particles, 10–70% centrality



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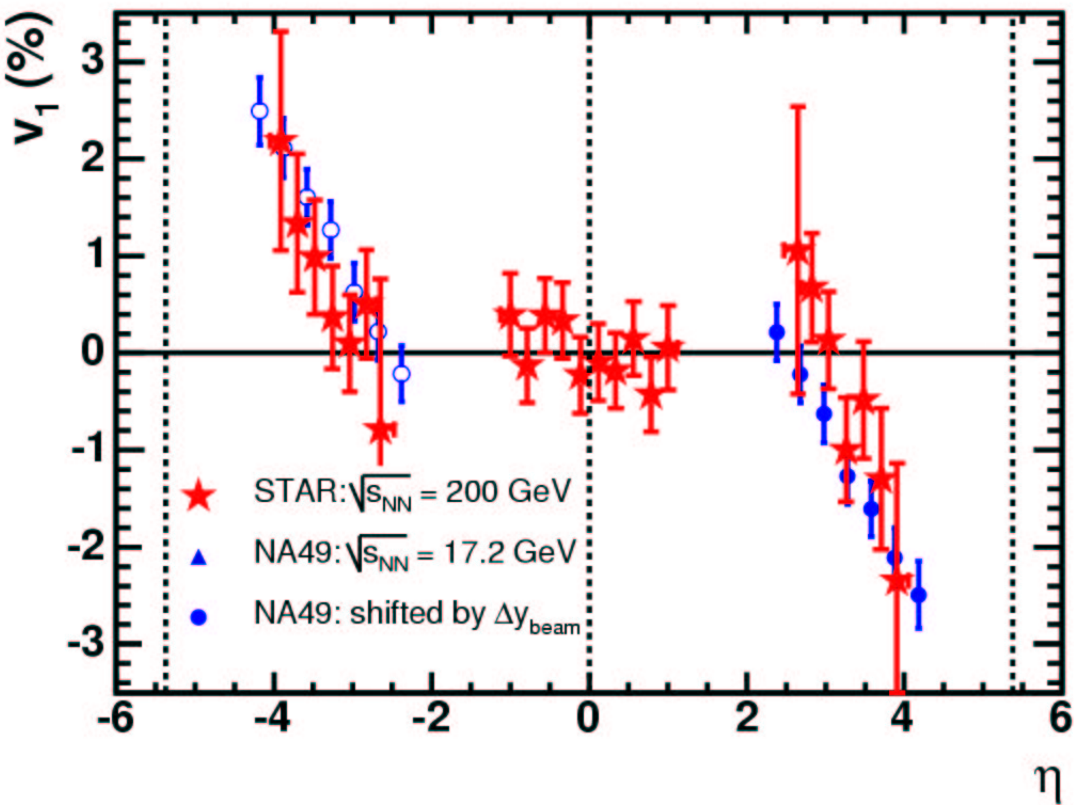
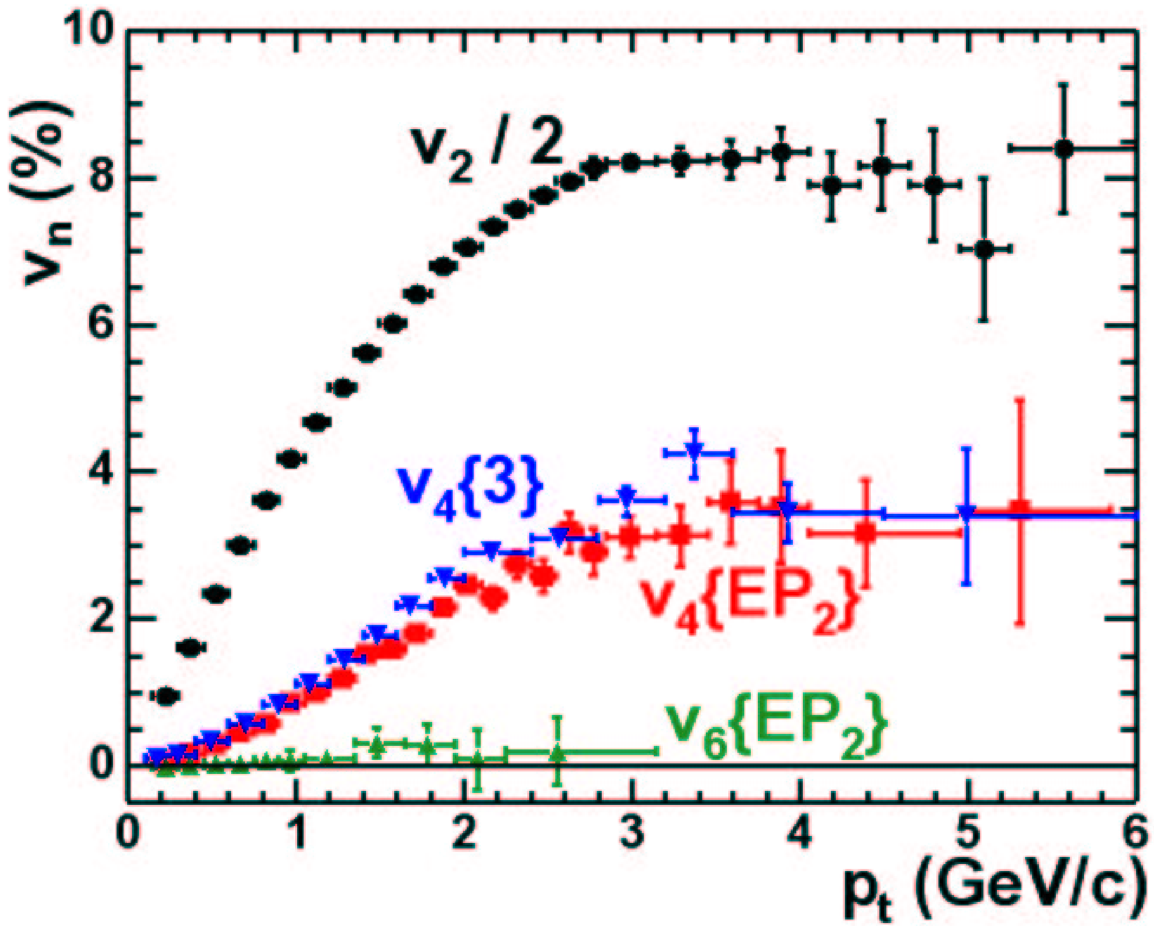


Run 4 statistics... differential measurements of v_1 (and smaller error bars)

A new observable: v_4

STAR Collaboration, charged particles, minimum bias, 200 GeV



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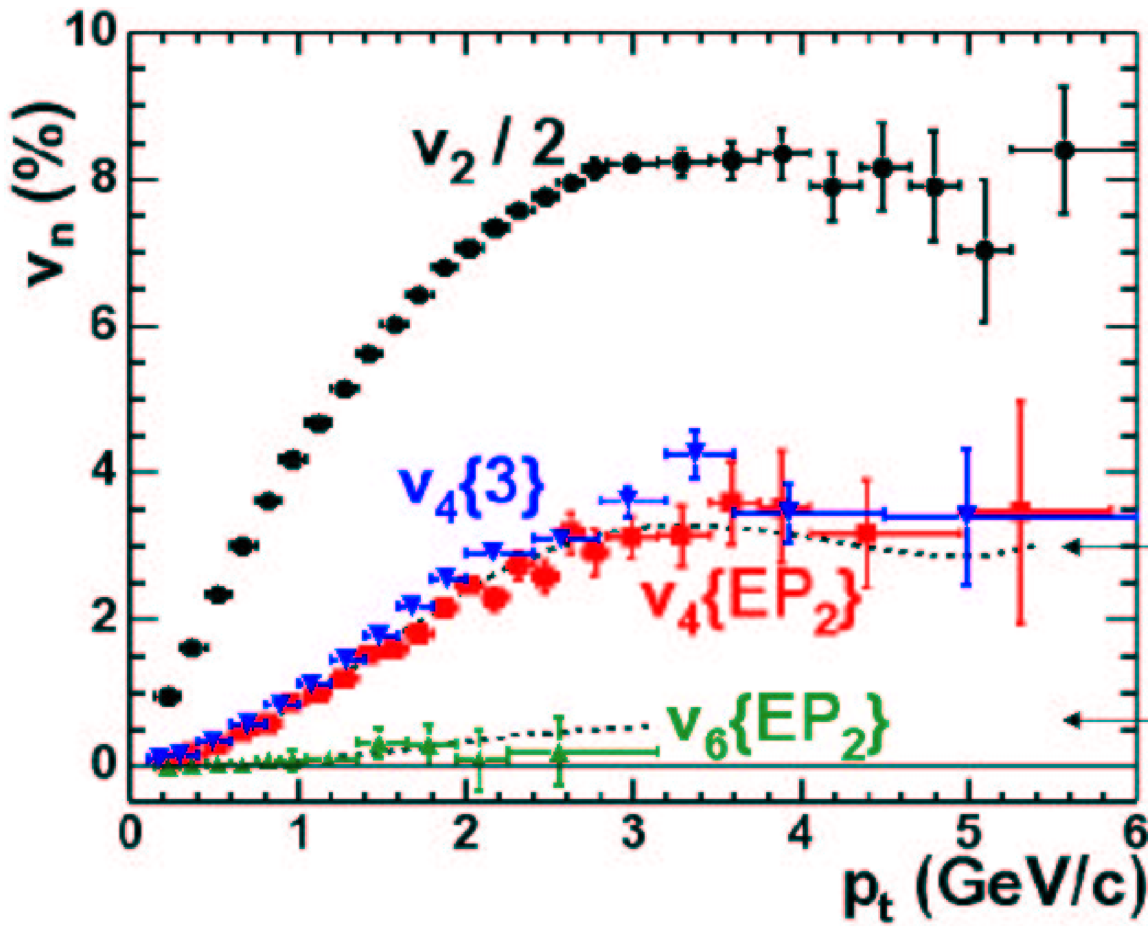


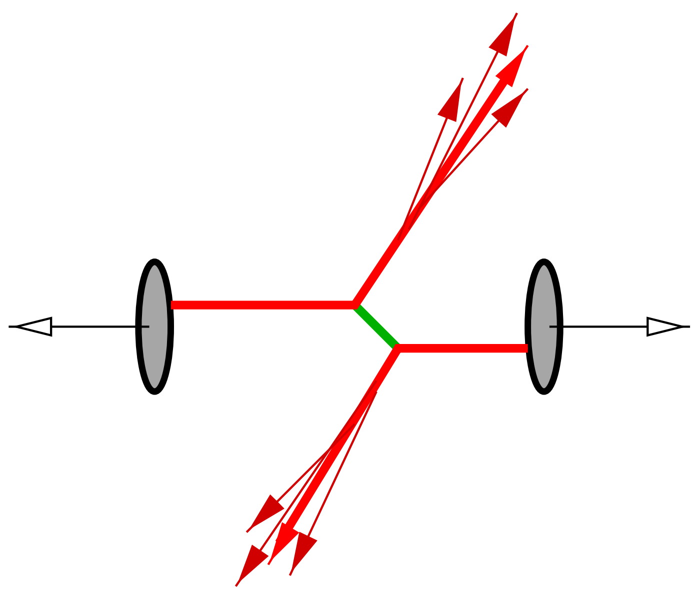
$v_n \sim v_2^{n/2}$

$1.2\ v_2^2$

$1.2\ v_2^3$

Jet quenching

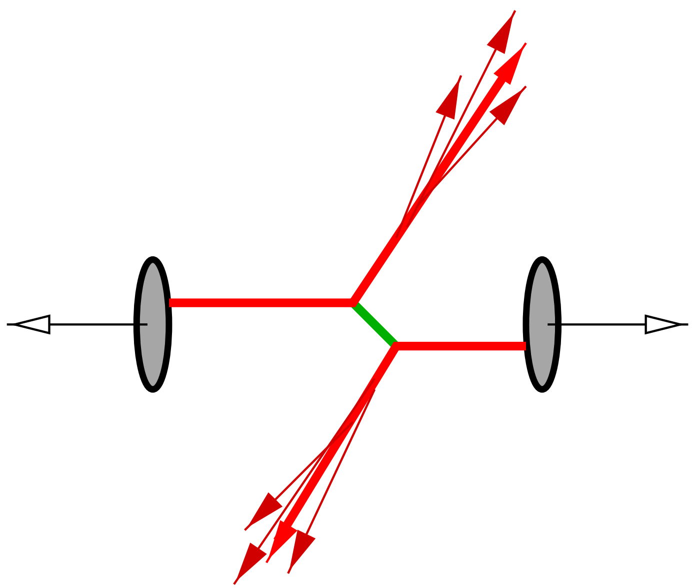
proton-proton

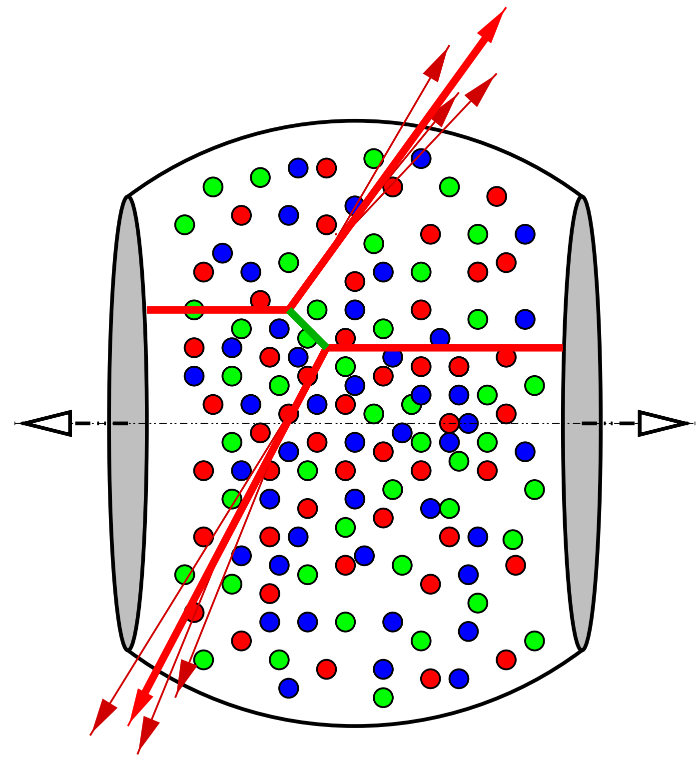


figures courtesy of F. GELIS

Jet quenching

proton-proton vs. nucleus-nucleus: medium effect?

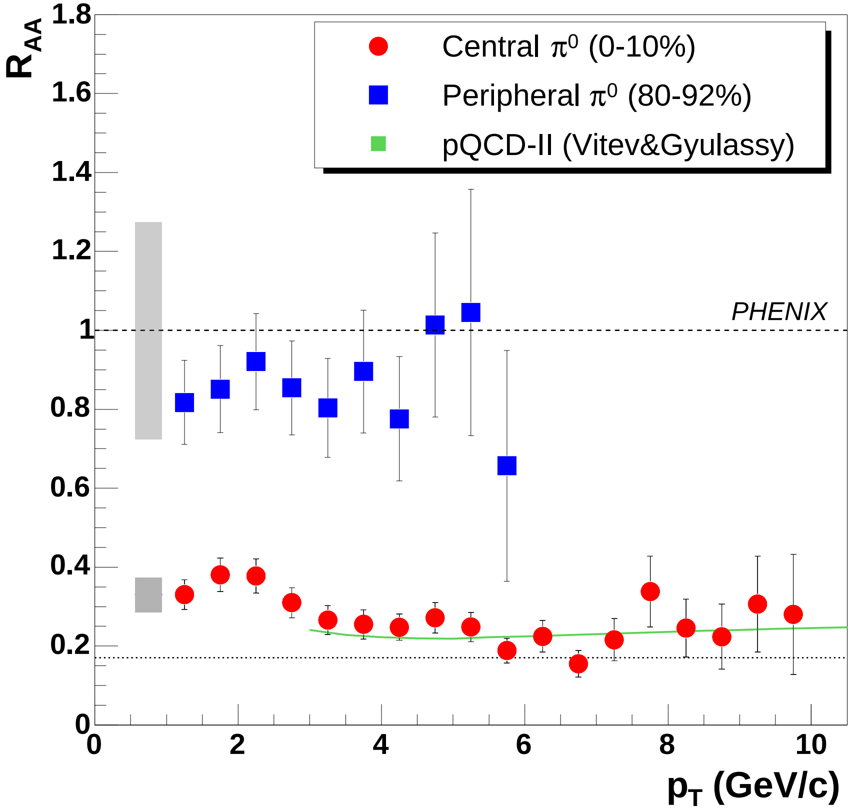


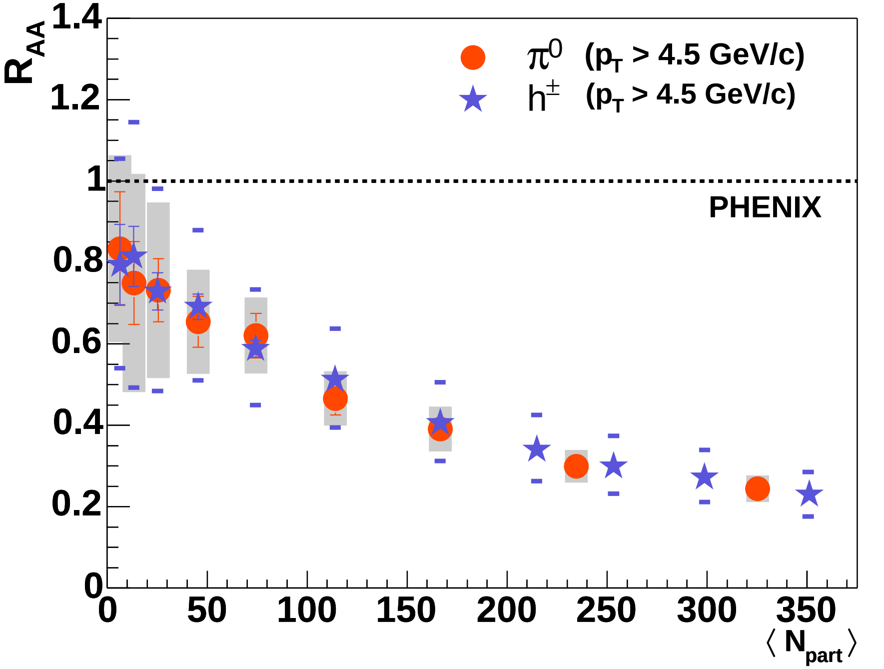


figures courtesy of F. GELIS

“Jets” in Au-Au collisions at RHIC

Nuclear modification factor $R_{AA} \equiv \dfrac{1}{N_{\rm coll}} \dfrac{\frac{{\rm d}^2 N_{AA}}{{\rm d}p_T\,{\rm d}y}}{\frac{{\rm d}^2 N_{pp}}{{\rm d}p_T\,{\rm d}y}}$

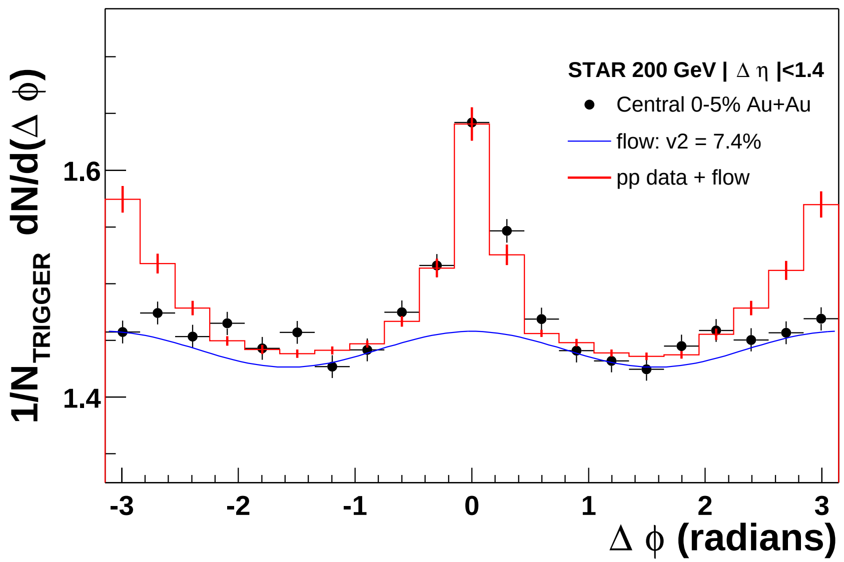


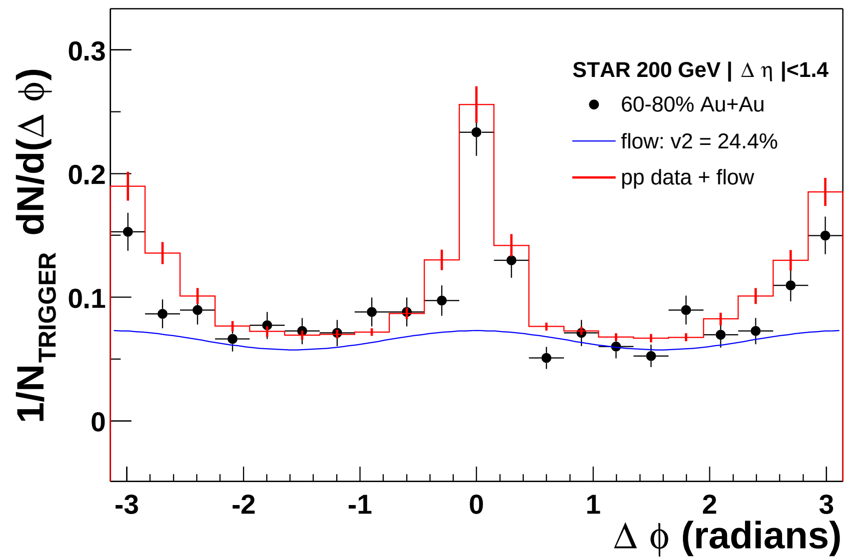


“Jets” in Au-Au collisions at RHIC

Azimuthal correlations:

1. Choose leading particle ($p_{T\max}$): origin of azimuths
2. Count associated particles ($p_{T\text{cut}} < p_T < p_{T\max}$): azimuth ϕ





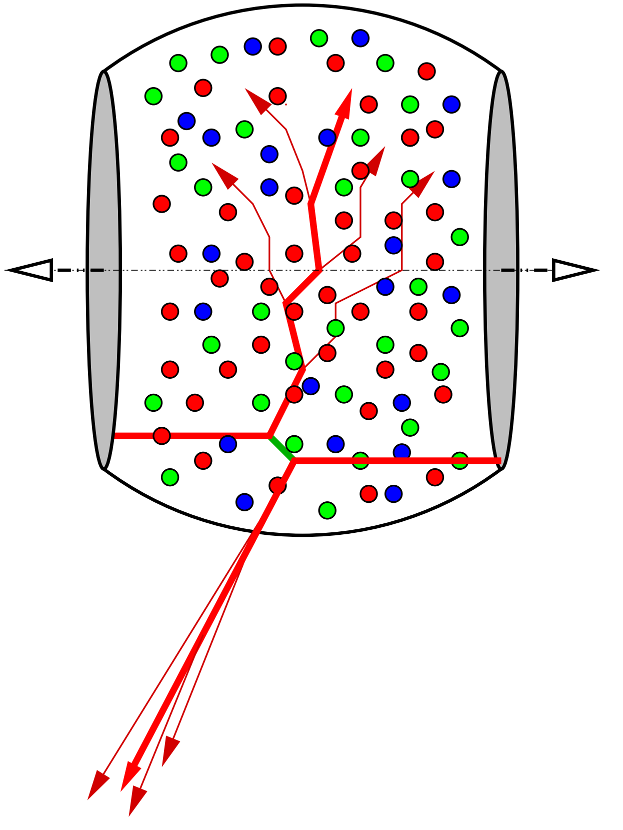
$\Rightarrow$ absence of back jet ($\Delta\phi \sim 180^{\circ}$) in central Au-Au collisions

Jet quenching

Extreme scenario:

Only the jets formed close to the edge manage to get out of the medium

Is this supported by QCD?



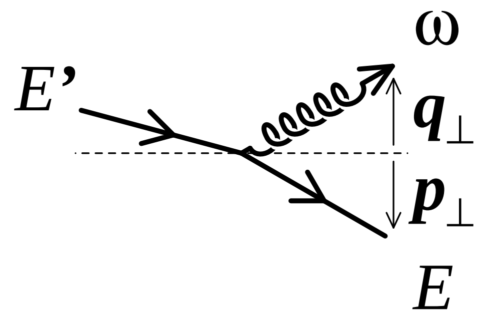
Jet quenching

Fast parton energy loss dominated by the emission of soft gluons

- Soft gluon formation time

  $t_{\rm form} \sim \dfrac{\omega}{k_\perp^2}$

- Model of the medium:
  - mean free path λ
  - screening mass μ



Multiple scatterings: $\lambda \ll t_{\rm form}$

$$\left.\begin{array}{l} N_{\rm coh} \sim t_{\rm form}/\lambda \text{ coherent scatterings} \\ \text{Accumulated } k_\perp : k_\perp^2 \sim N_{\rm coh}\,\mu^2 \end{array}\right\} N_{\rm coh} \sim \sqrt{\frac{\omega}{\lambda\mu^2}}$$

Jet quenching

Coherence length for soft gluon emission $\ell_{\text{coh}} \sim \sqrt{\frac{\lambda\omega}{\mu^2}}$

$\Rightarrow$ spectrum of energy loss, per unit length:

$$\frac{\omega\,\mathrm{d}I}{\mathrm{d}\omega\,\mathrm{d}z} \approx \frac{1}{\ell_{\text{coh}}}\alpha_S \sim \alpha_S\sqrt{\frac{\widehat{q}}{\omega}}$$

with $\widehat{q} \sim \mu^2/\lambda$

For a path length L: $\frac{\omega\,\mathrm{d}I}{\mathrm{d}\omega} \sim \alpha_S\sqrt{\frac{\widehat{q}}{\omega}}\,L$

Average medium-induced energy loss:

$$\Delta E \sim \int^{\omega_m} \frac{\omega\,\mathrm{d}I}{\mathrm{d}\omega}\,\mathrm{d}\omega \sim \alpha_S\,\widehat{q}\,L^2$$

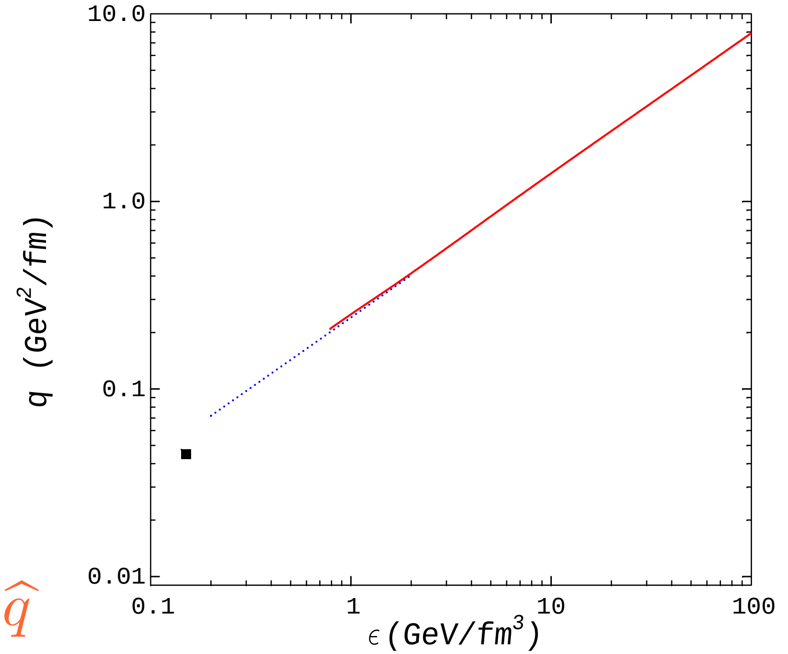
Jet quenching

$\Delta E \sim \alpha_S\,\widehat{q}\,L^2$

- ΔE goes like L^2: strong attenuation
- "Transport coefficient" $\widehat{q}$:

$$\widehat{q} = \rho \int \mathrm{d}q_\perp^2\, q_\perp^2\, \frac{\mathrm{d}\sigma}{\mathrm{d}q_\perp^2}$$

  - in cold nuclear matter: $\widehat{q}_{\rm cold} \sim 0.05\ \mathrm{GeV}^2/\mathrm{fm}$
  - in a QGP at $T = 250$ MeV: $\widehat{q}_{\rm hot} \sim 1\ \mathrm{GeV}^2/\mathrm{fm}$
  - expanding medium: effective $\widehat{q}$



Jet quenching

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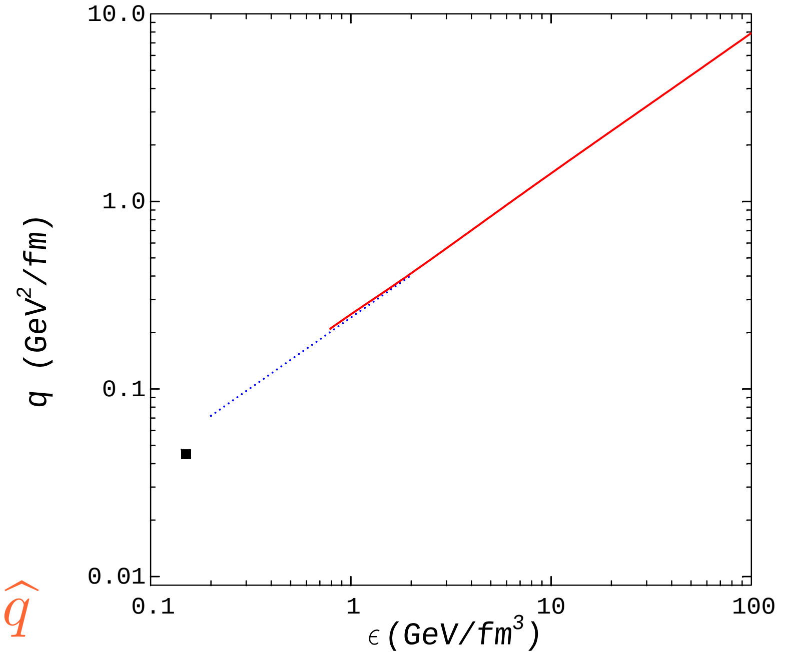
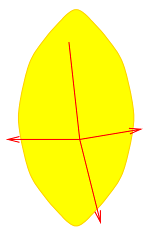


→ $L = 5$ fm, $k_\perp \lesssim 10$ GeV: 80–90% quenching: "OK"

Azimuthally dependent jet quenching

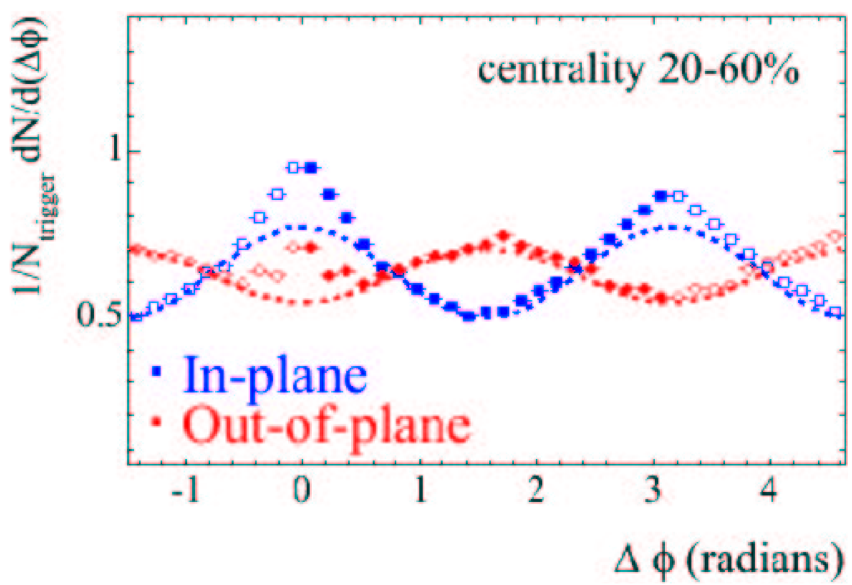
Let's come back to non-central collisions



For a given high-p_T parton, the amount of jet quenching depends on the length of the in-medium path:

$$\Delta E \sim \alpha_S \, \widehat{q} \, L^2$$

$\Rightarrow$ less jet quenching in-plane than out-of-plane



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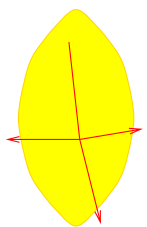

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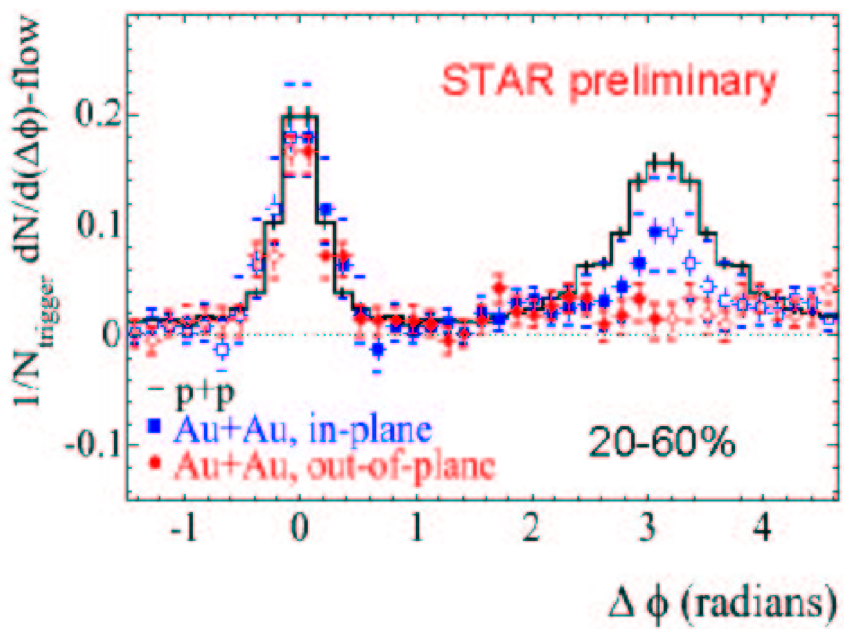
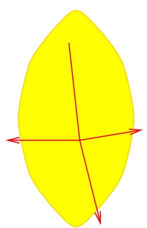


v_2 at high transverse momentum

A first idea: v_2 from jet quenching



For a given high-p_T parton, the amount of jet quenching depends on the length of the in-medium path:

$$(p_T)_{\rm measured} \approx (p_T)_{\rm emitted} - a + b\cos 2(\phi - \Phi_R)$$

$\Rightarrow$ measured momentum larger in-plane than out-of-plane

Detected distribution:

$$\frac{\mathrm{d}N}{\mathrm{d}p_T}(p_T) \approx f_0((p_T)_{\rm em.}) + f_0'((p_T)_{\rm em.})\left[-a + b\cos 2(\phi - \Phi_R)\right]$$

emitted distribution

$$\Rightarrow v_2(p_T) \propto \int \frac{\mathrm{d}N}{\mathrm{d}p_T}\cos 2(\phi - \Phi_R) \approx \frac{f_0'((p_T)_{\rm em.})}{f_0((p_T)_{\rm em.})}\, b$$

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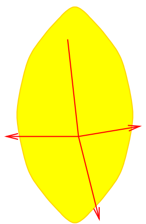

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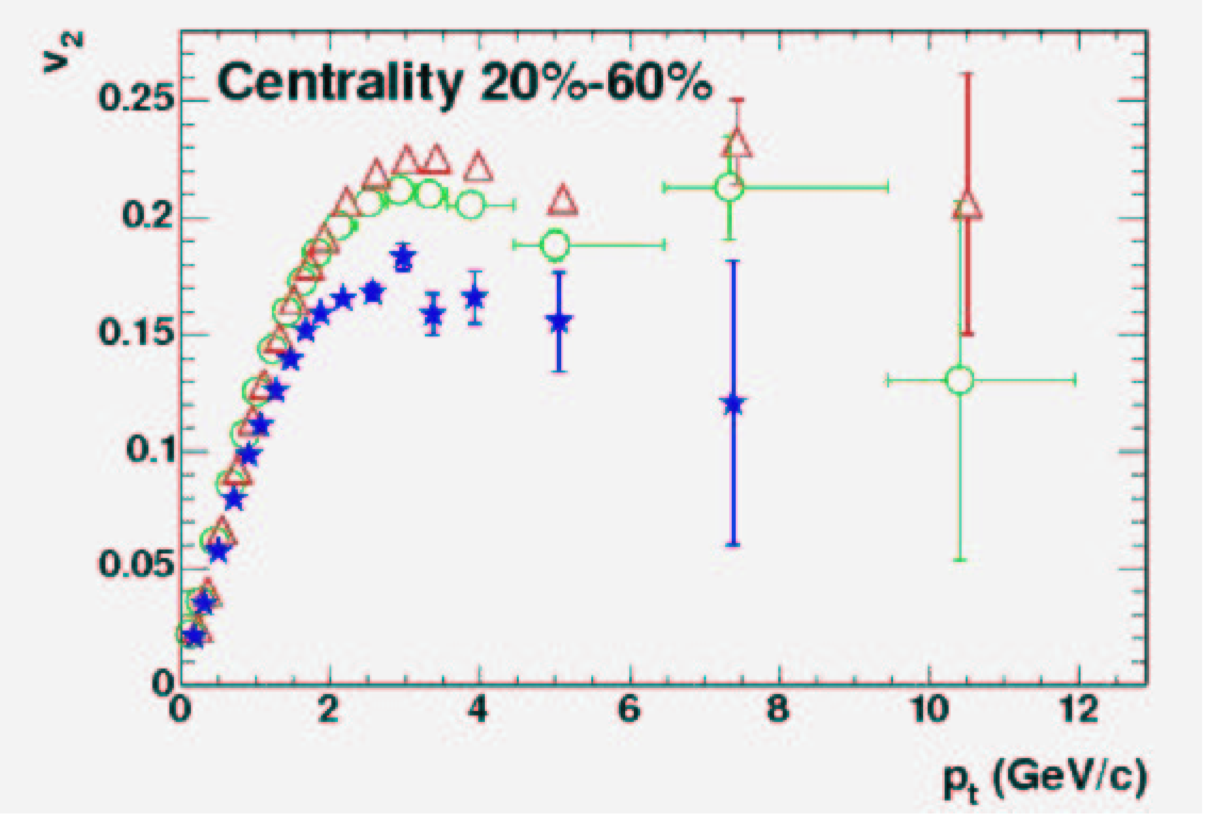
$$v_2(p_T) \approx \frac{f_0'((p_T)_{\text{em.}})}{f_0((p_T)_{\text{em.}})} b$$

- f_0 exponential $\longrightarrow$ $v_2(p_T)$ constant
- f_0 (inverse) power law $\longrightarrow$ $v_2(p_T)$ decreasing with p_T

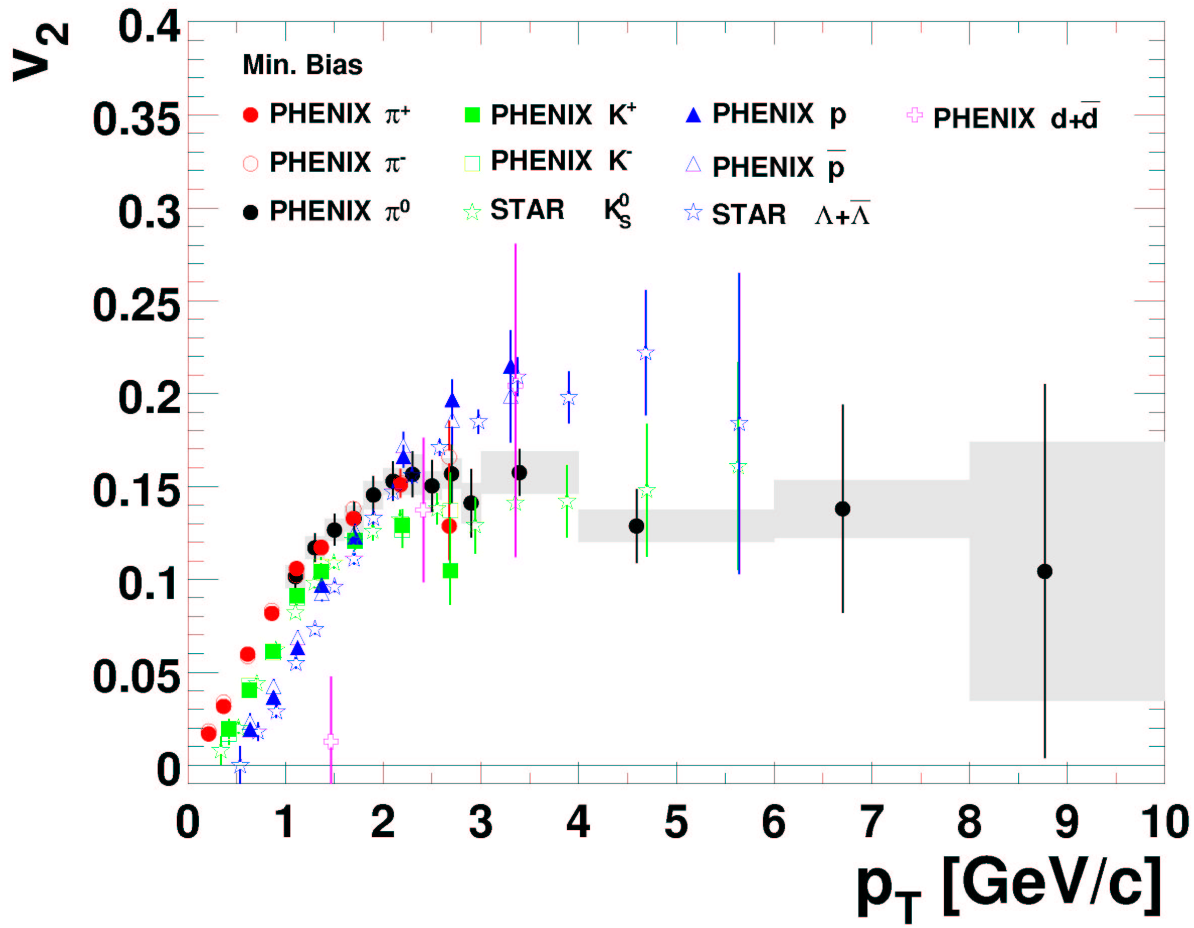
RHIC v_2 results [3]

STAR Collaboration, charged particles, 200 GeV



RHIC v_2 results [3 bis]

PHENIX Collaboration, 200 GeV



v_2 at high transverse momentum

Second idea: hadrons from parton recombination

At hadronization, two quark/antiquark (resp. three quarks) with momentum $p_T/2$ (resp. $p_T/3$) coalesce into a meson (resp. baryon) with momentum p_T

$$\Rightarrow \qquad v_2^{\rm meson}(p_T) \simeq 2\, v_2^q\left(\frac{p_T}{2}\right), \qquad v_2^{\rm baryon}(p_T) \simeq 3\, v_2^q\left(\frac{p_T}{3}\right)$$

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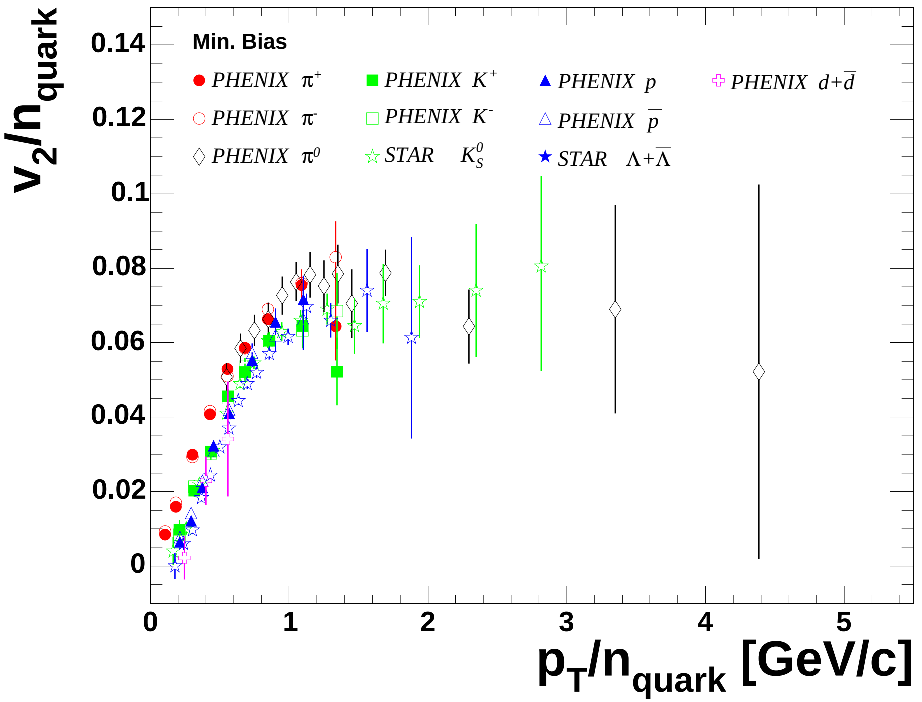

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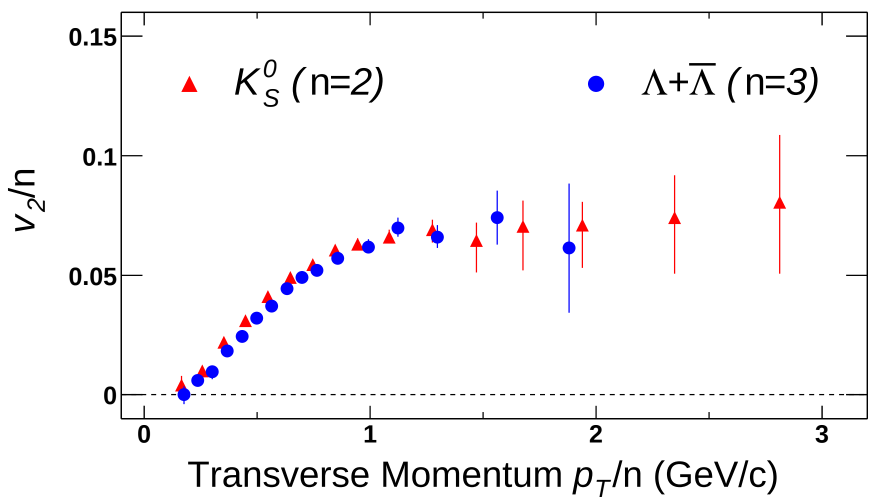

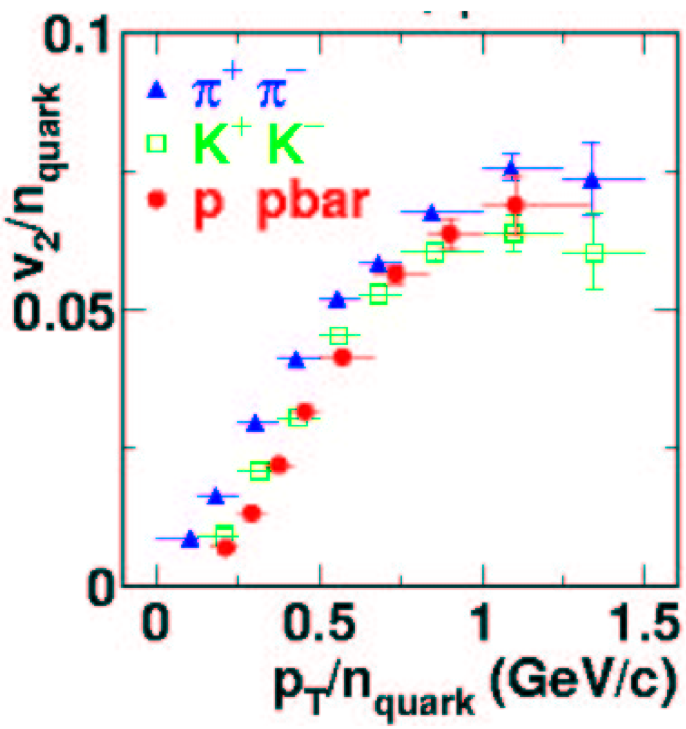

Summary

- Runs 1 & 2 (3): beautiful data
- Run 4: high statistics? Differential measurements!
  - non-ambiguous v_2, v_4(PID), v_1
    $\longrightarrow$ Jérôme, il faut qu'on cause...
  - jet quenching: azimuthal dependence, as a function of PID
- Omitted topics:
  - "dead-cone effect" for heavy quarks
  - varying the cut in jet quenching studies (especially for back jet: where has momentum gone?)
  - rapidity dependences
  - ???

Methods of flow analysis

Measuring anisotropic flow is a complicated issue:

$$\underbrace{v_n = \langle \cos n(\phi}_{} - \Phi_R) \rangle$$

lab. frame ↗ ↖ not measured!

- "standard" method: extract flow from two-particle correlations

  Idea: 2 particles are correlated together because each of them is correlated to the reaction plane by flow.

Methods of flow analysis

Measuring anisotropic flow is a complicated issue:

$$v_n = \langle \cos n(\phi - \Phi_R) \rangle$$

lab. frame   not measured!

- “standard” method: extract flow from two-particle correlations

  Problem: the measurement is contaminated by other sources of two-particle correlations: quantum (HBT) effects, minijets, etc.

  ☞ systematic uncertainty

Methods of flow analysis

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$$\underbrace{v_n = \langle \cos n(\phi}_{\text{lab. frame}} - \underbrace{\Phi_R}_{\text{not measured!}}))\rangle$$

- "standard" method: extract flow from two-particle correlations

  Problem: the measurement is contaminated by other sources of two-particle correlations: quantum (HBT) effects, minijets, etc.

  ☞ systematic uncertainty

- better methods:
  - cumulants of multiparticle correlations

    4-, 6-particle cumulants $\Rightarrow$ nonflow effects reduced
  - Lee–Yang zeroes: probe collective effects (flow!)

    $\Leftrightarrow$ "infinite-order" cumulant