Anisotropic flow: lessons from RHIC and perspectives for LHC

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Anisotropic flow at RHIC and prospects for LHC

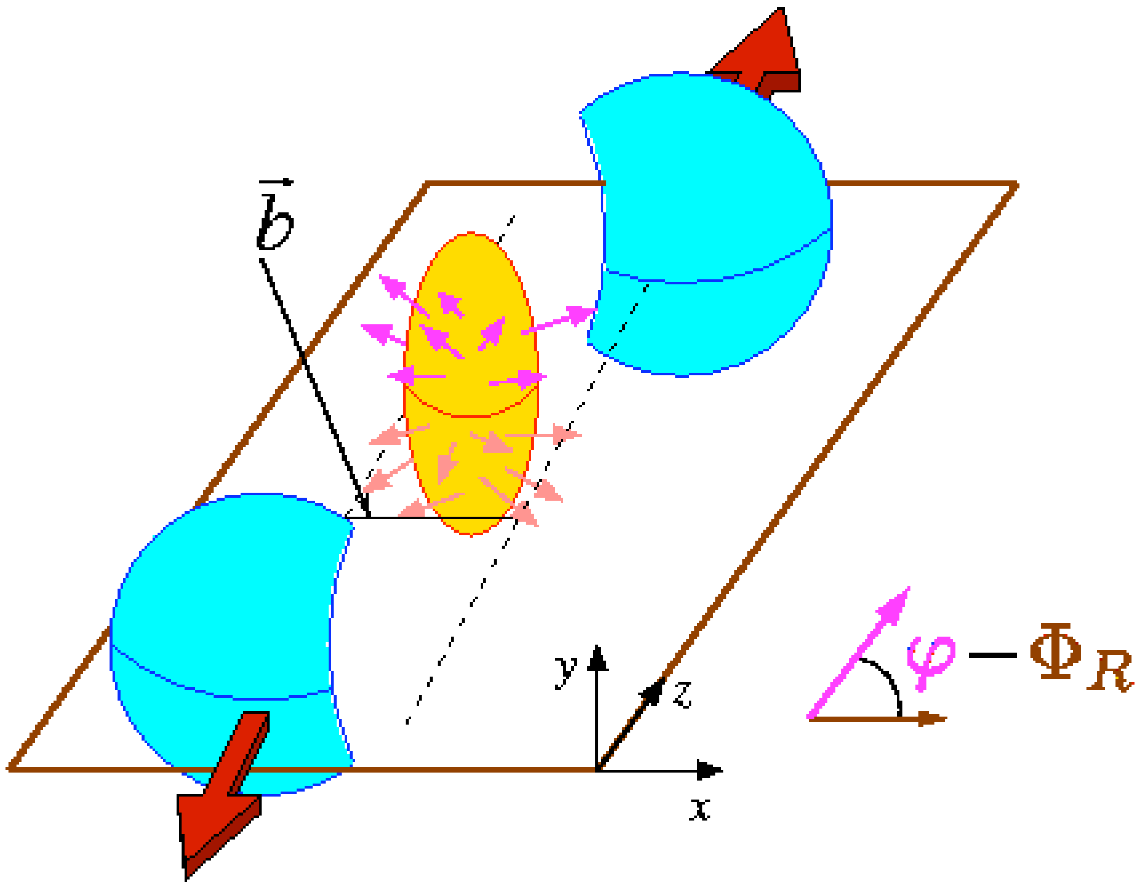
- Anisotropic flow at RHIC
  - An experimental success story
    - A wealth of data
    - As of end of November 2005, 13 PRL & 4 PRC
  - Theoretical challenges
    - Conflicting interpretations of the data:
      hydrodynamic expansion vs. out-of-equilibrium scenario
- Anisotropic flow at LHC
  - Very few theoretical predictions...
  - ... yet measuring flow with ALICE should be “easy”

Anisotropic flow at RHIC and prospects for LHC

- Anisotropic flow at RHIC
  - An experimental success story
    - A wealth of data with novel directions
    - As of February 1st, 2007 , 15 PRL & 5 PRC + 5 preprints
  - Theoretical challenges
    - Conflicting interpretations of the data: hydrodynamic expansion vs. out-of-equilibrium scenario
- Anisotropic flow at LHC
  - Very few theoretical predictions... Nihil novum sub sole
  - ... but we can build on RHIC results!

Anisotropic (collective) flow

Consider a non-central collision:



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⇒ anisotropic pressure gradients (larger along the impact parameter)

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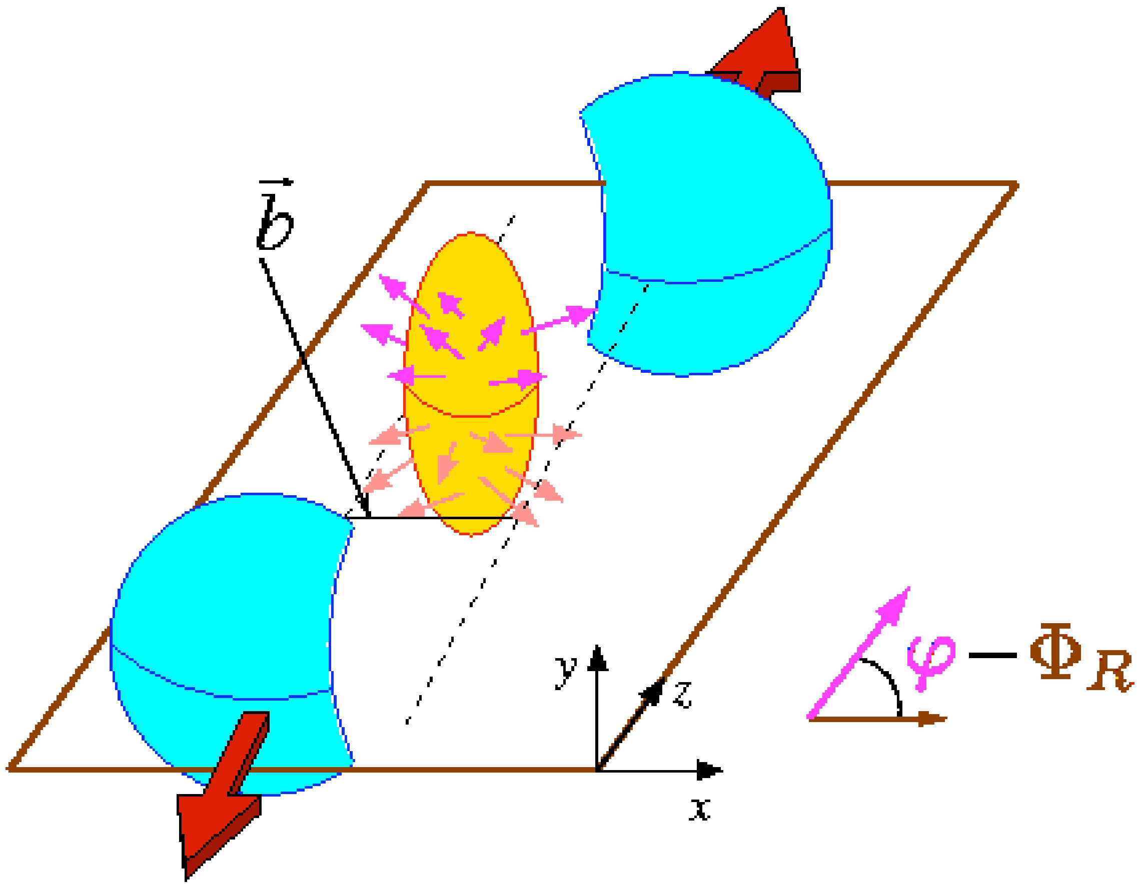

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"anisotropic collective flow"

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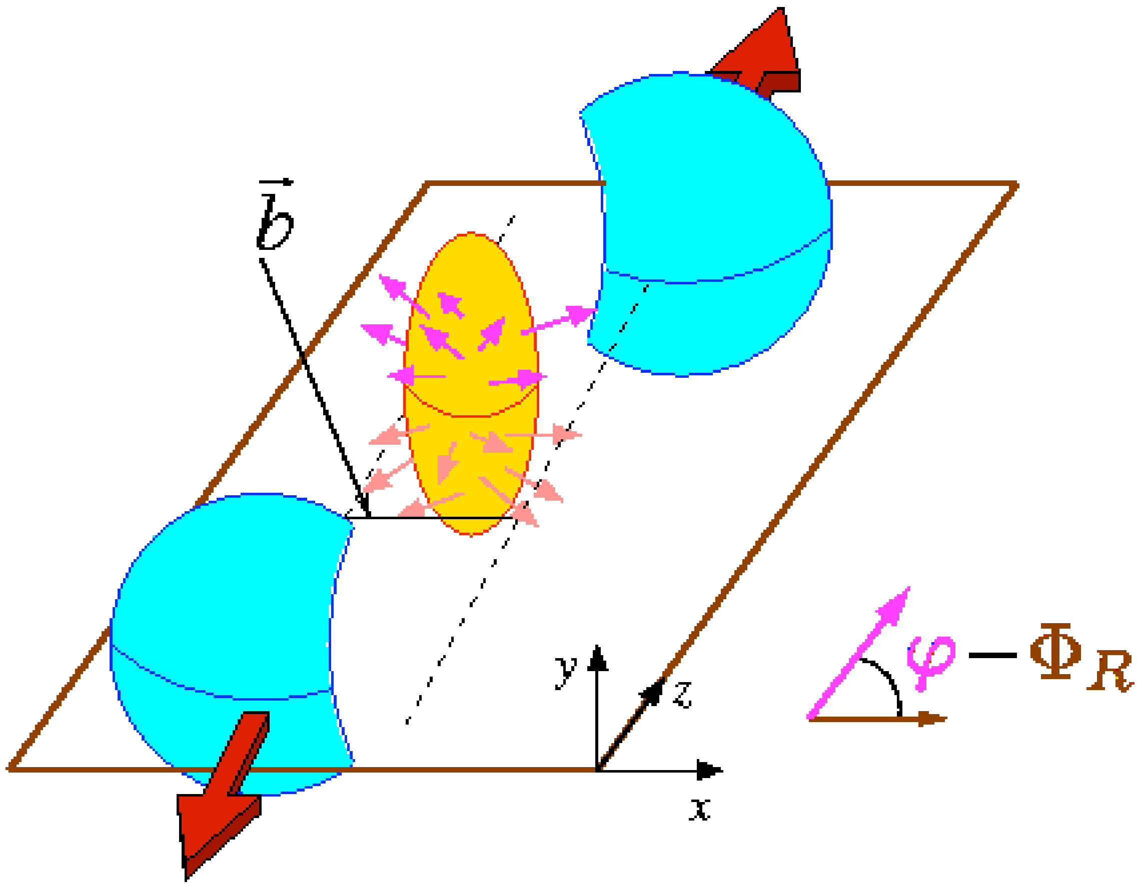

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$$E\frac{\mathrm{d}N}{\mathrm{d}^3\mathbf{p}} \propto \frac{\mathrm{d}N}{p_T\,\mathrm{d}p_T\,\mathrm{d}y}\left[1 + 2\,v_1\cos(\varphi - \Phi_R) + 2\,v_2\cos 2(\varphi - \Phi_R) + \cdots\right]$$

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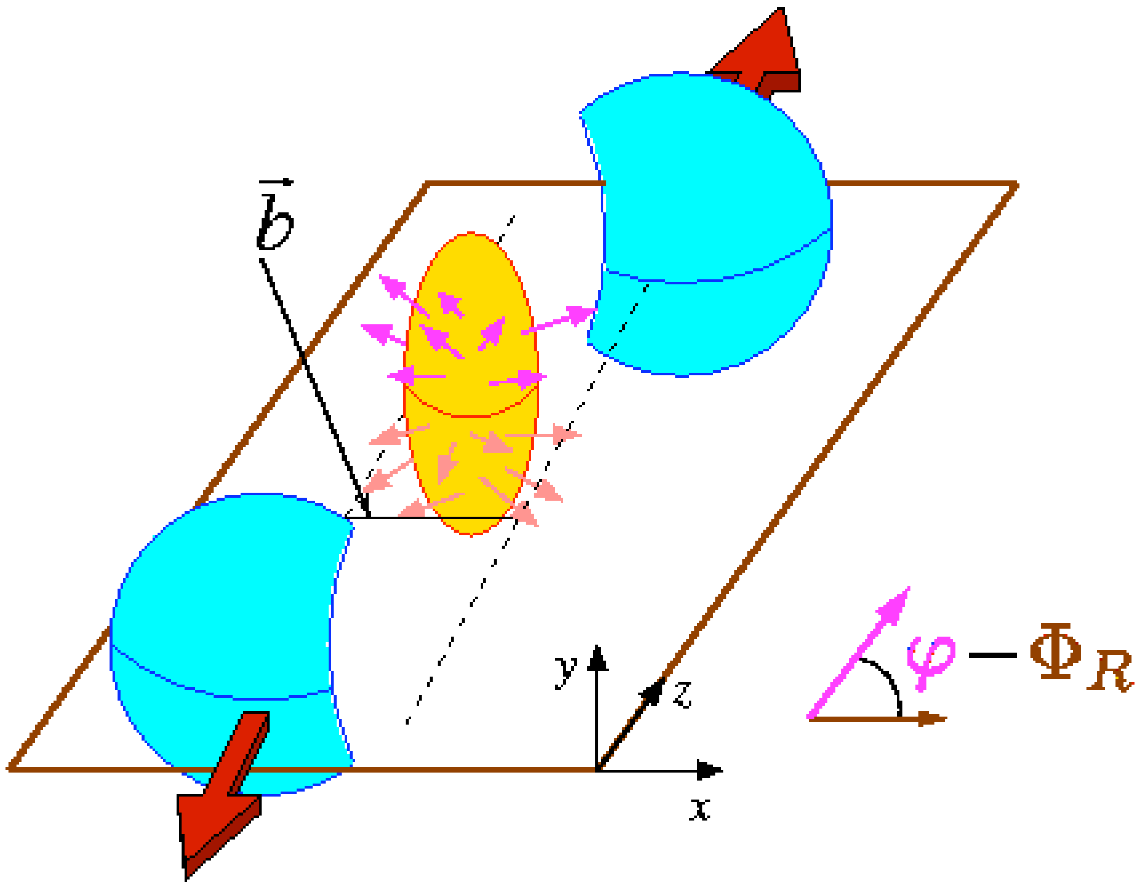

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More particles along the impact parameter ($\varphi - \Phi_R = 0$ or 180°) than perpendicular to it ☞ "elliptic flow" $v_2 \equiv \langle \cos 2(\varphi - \Phi_R)\rangle > 0$.

average over particles

Anisotropic (collective) flow

"Flow", v_n do not imply fluid dynamics...

(Transverse) anisotropy of the source in a non-central collision

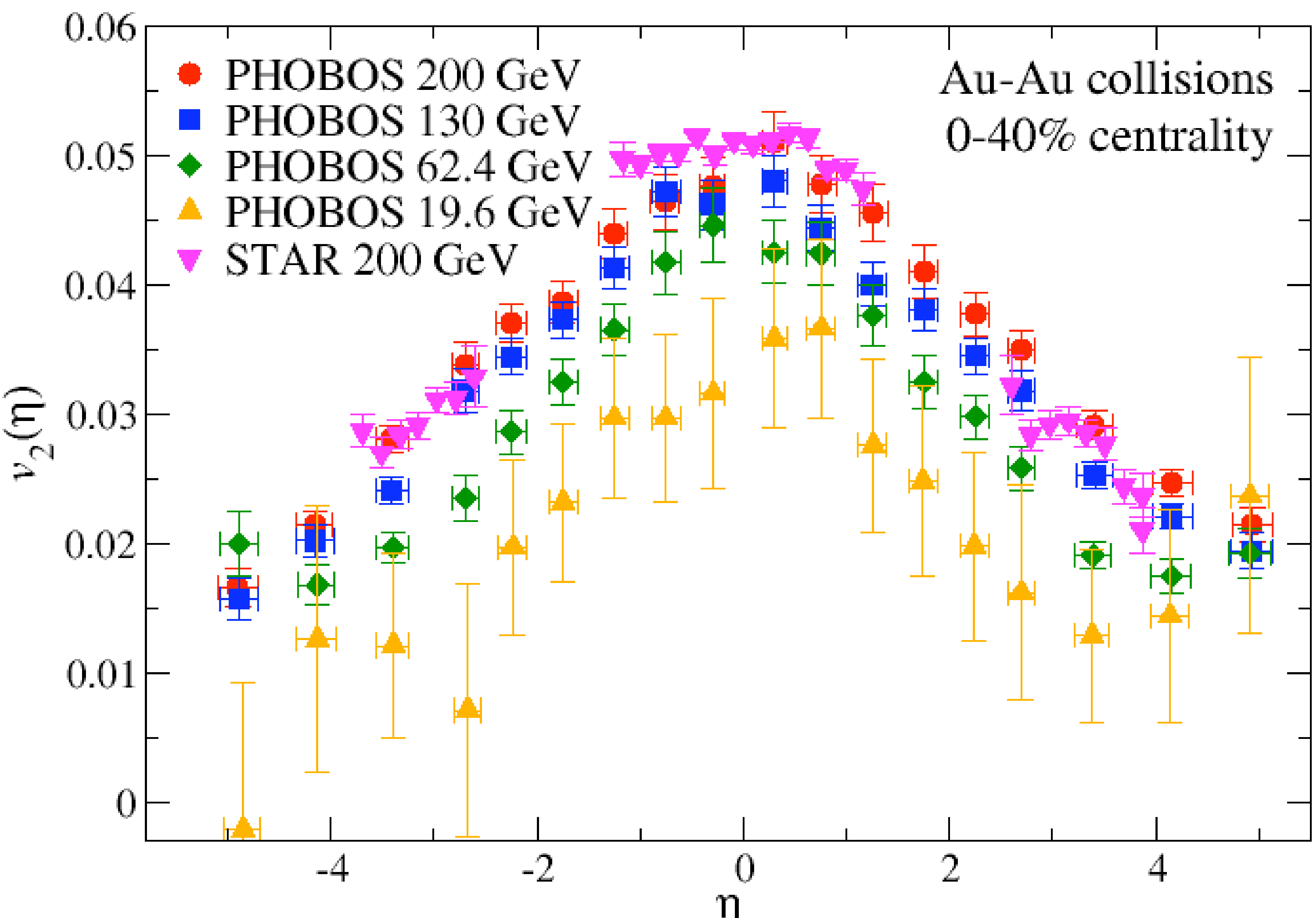
⇒ the amount of matter seen by a high-p_T particle traversing the medium is anisotropic (shorter path along the impact parameter)

⇒ anisotropic jet quenching:
anisotropic distribution of high-p_T particles

which is best characterized in terms of Fourier harmonics v_n (detector independent; more robust in Monte-Carlo computations)

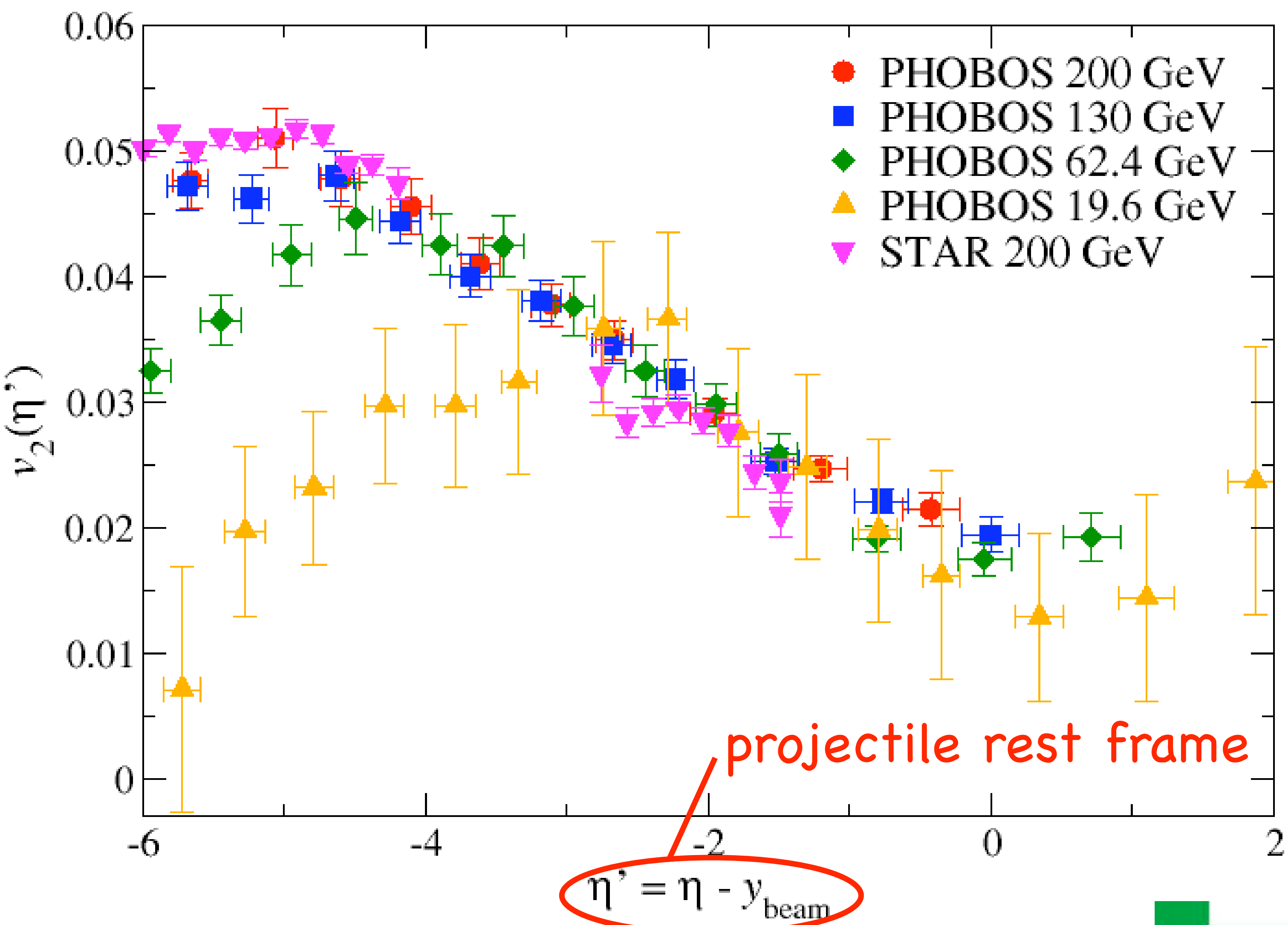
Anisotropic flow: what have we learned from RHIC?

Elliptic flow v_2 varies with (pseudo)rapidity (note: $v_2(\eta) \simeq v_2(y)$)



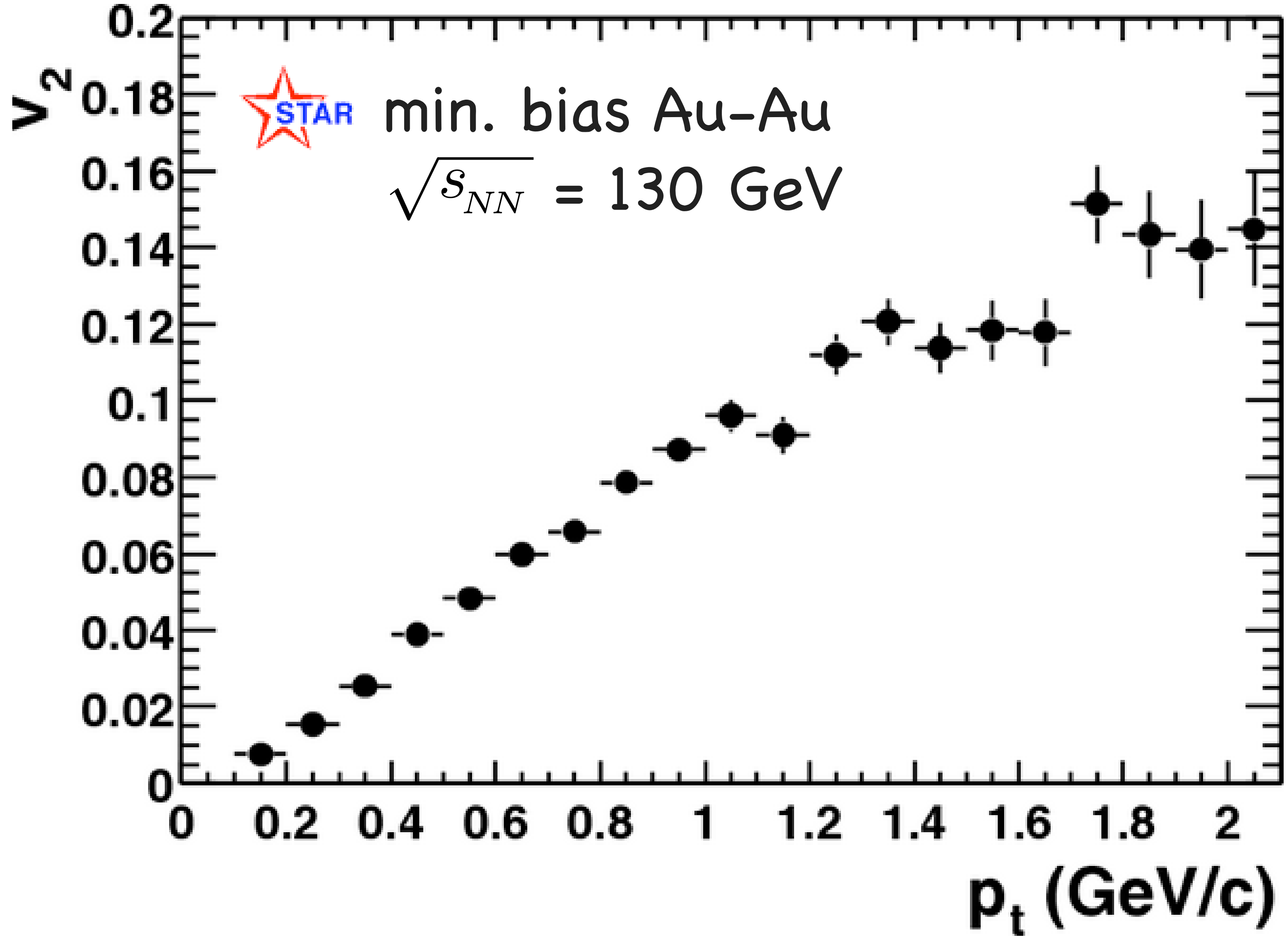
Anisotropic flow: what have we learned from RHIC?

Elliptic flow v_2 varies with (pseudo)rapidity ☞ "limiting fragmentation"



Anisotropic flow: what have we learned from RHIC?

The v_2 of charged hadrons grows linearly with transverse momentum



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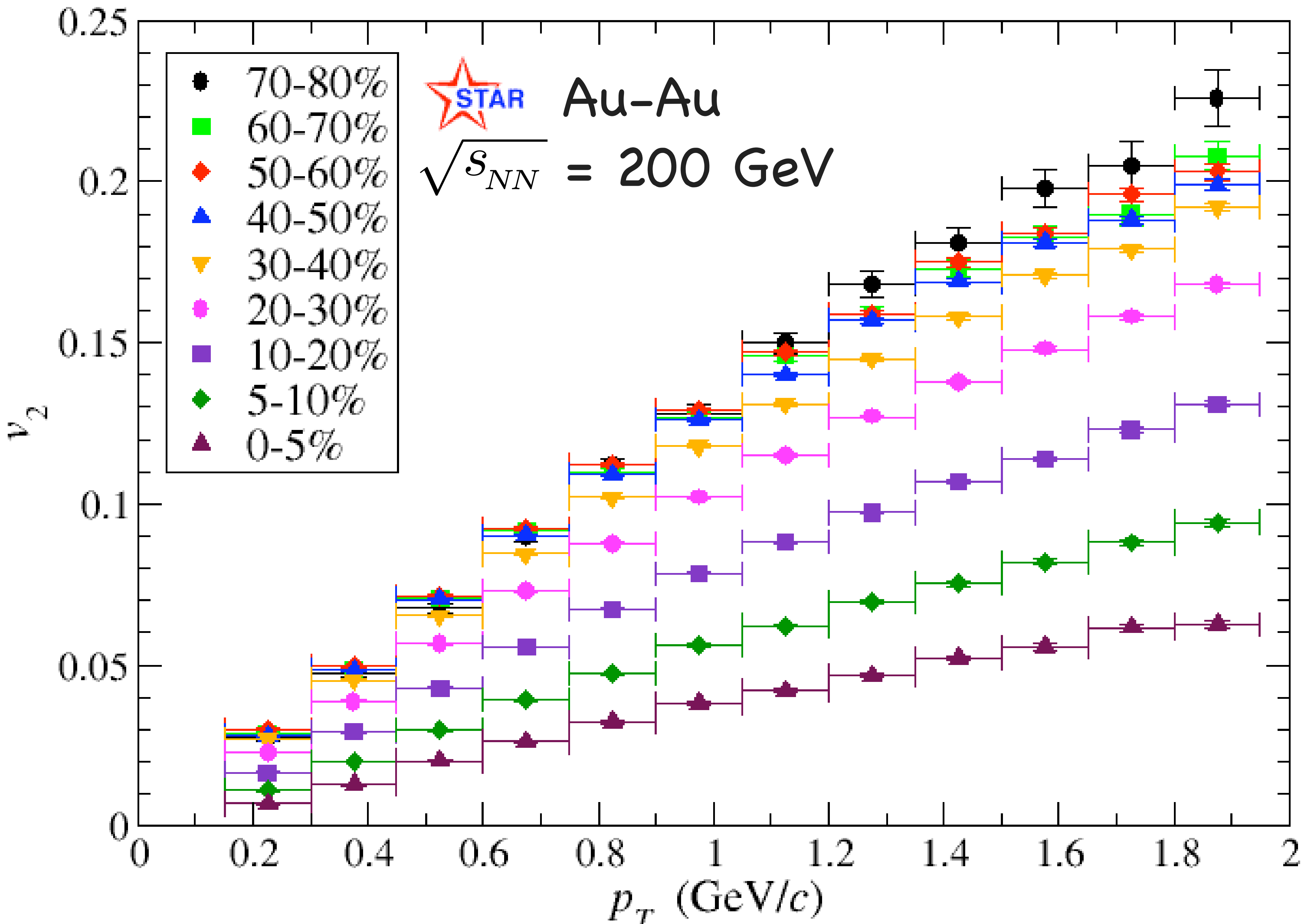
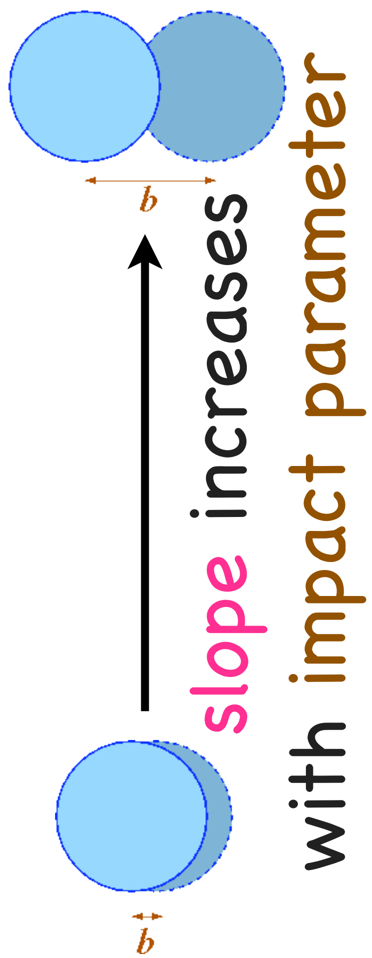
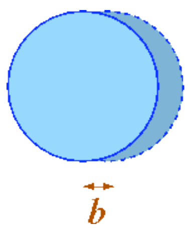
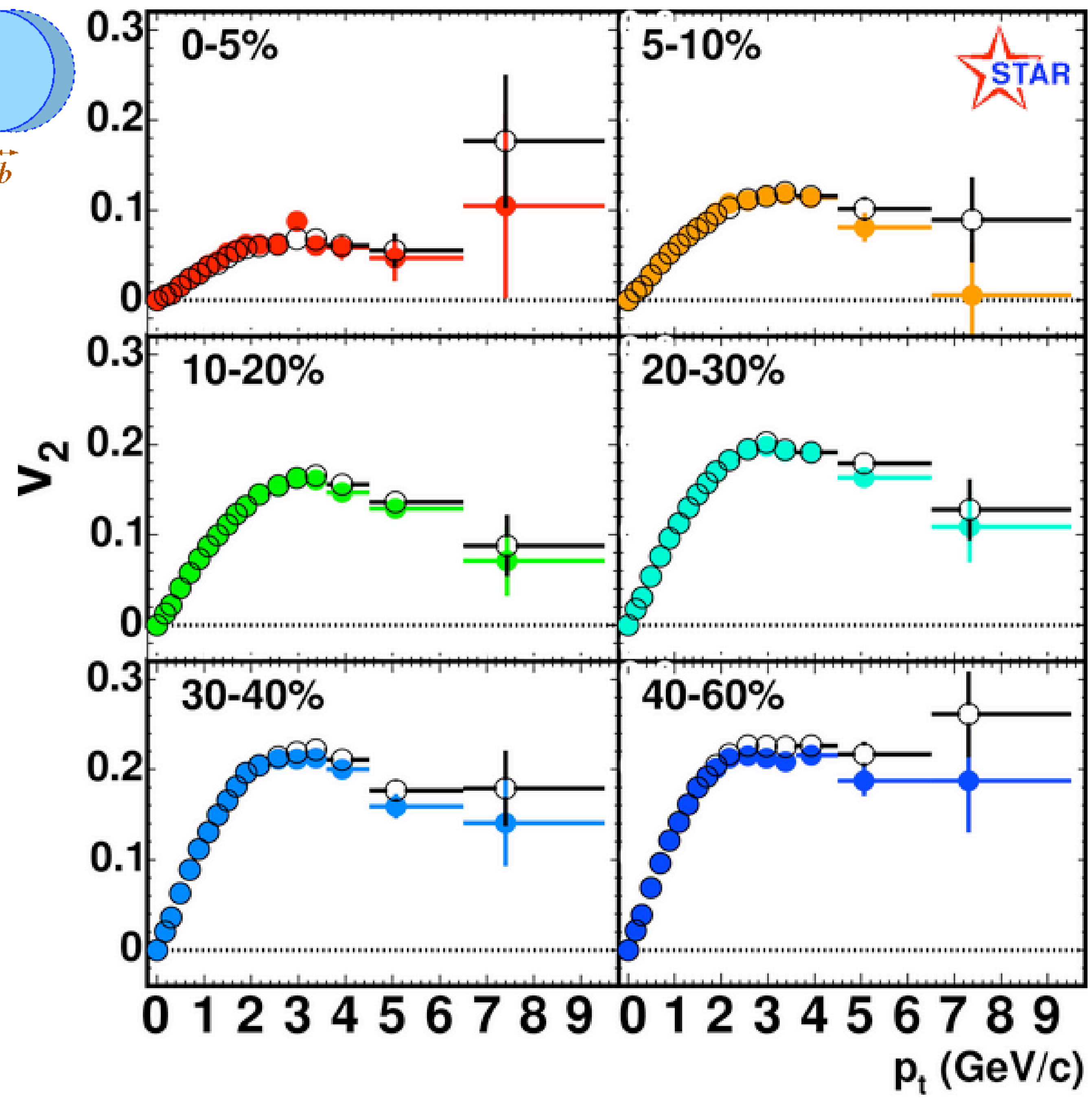




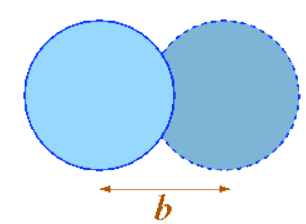
Anisotropic flow:
what have we learned from RHIC?

The v_2 of charged hadrons grows linearly with p_T, then saturates



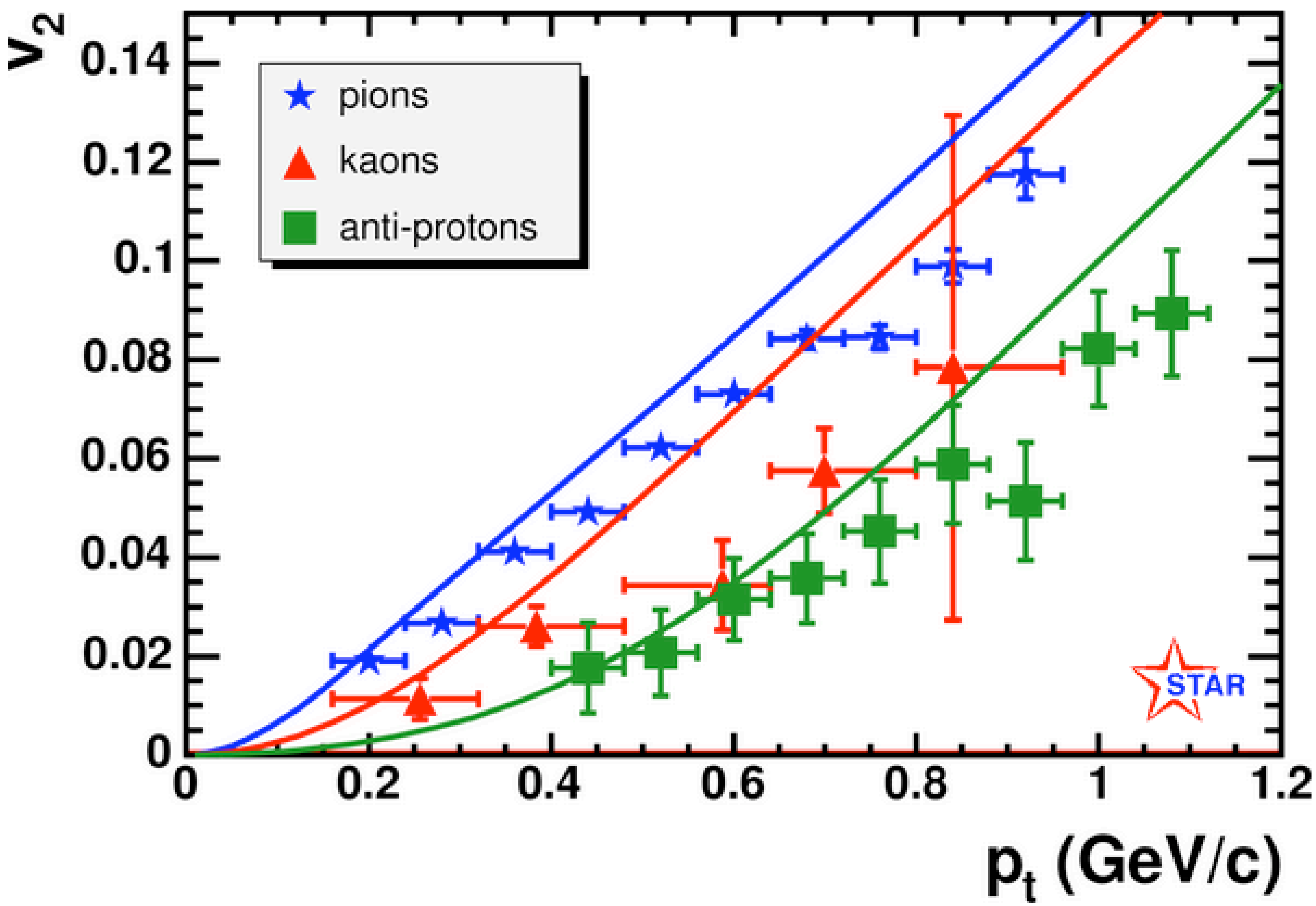


...and drops?



Anisotropic flow: what have we learned from RHIC?

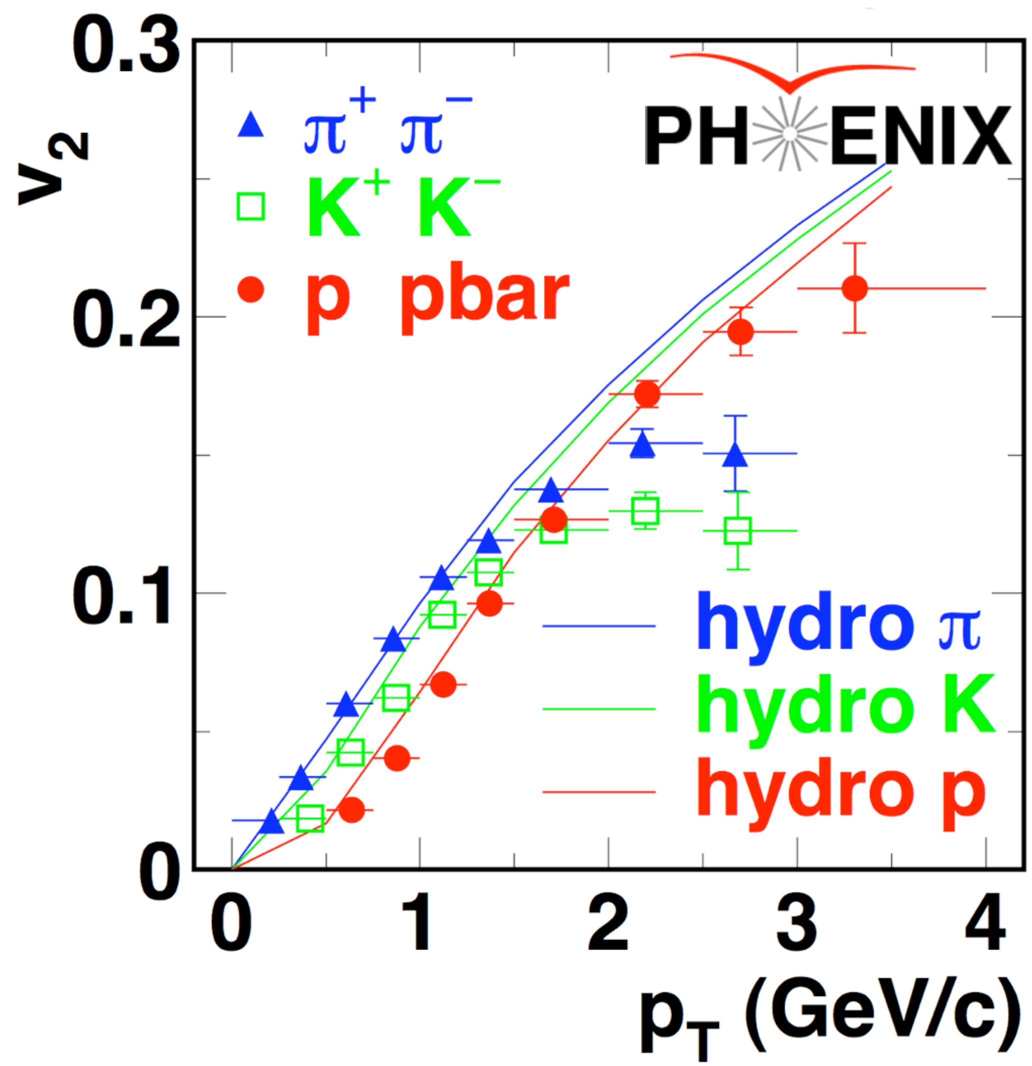
The $v_2(p_T)$ of identified hadrons show mass ordering



At a given transverse momentum, heavier hadrons have a smaller v_2

Anisotropic flow: what have we learned from RHIC?

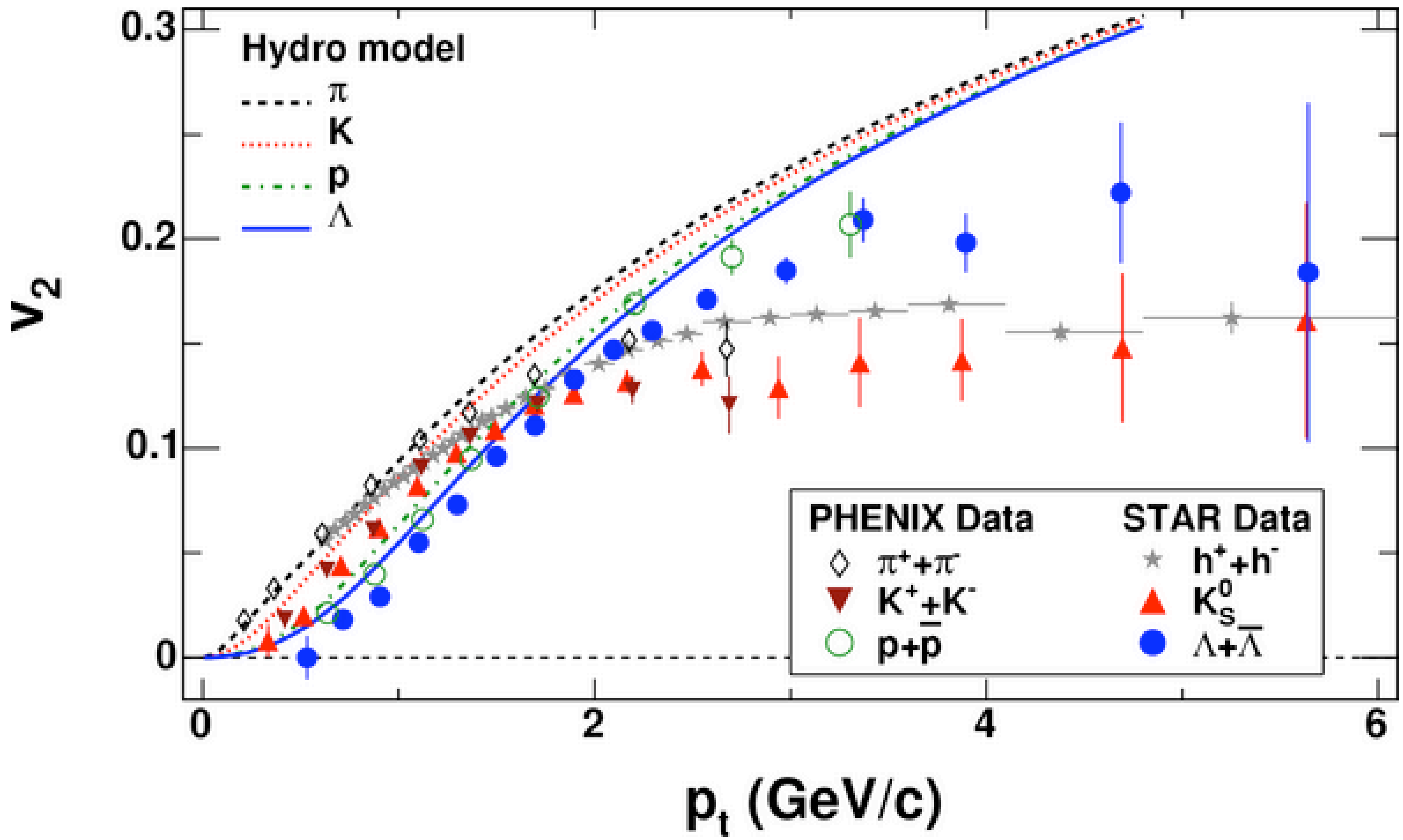
The $v_2(p_T)$ of identified hadrons show mass ordering below 1.5 GeV/c



Above, the ordering no longer holds

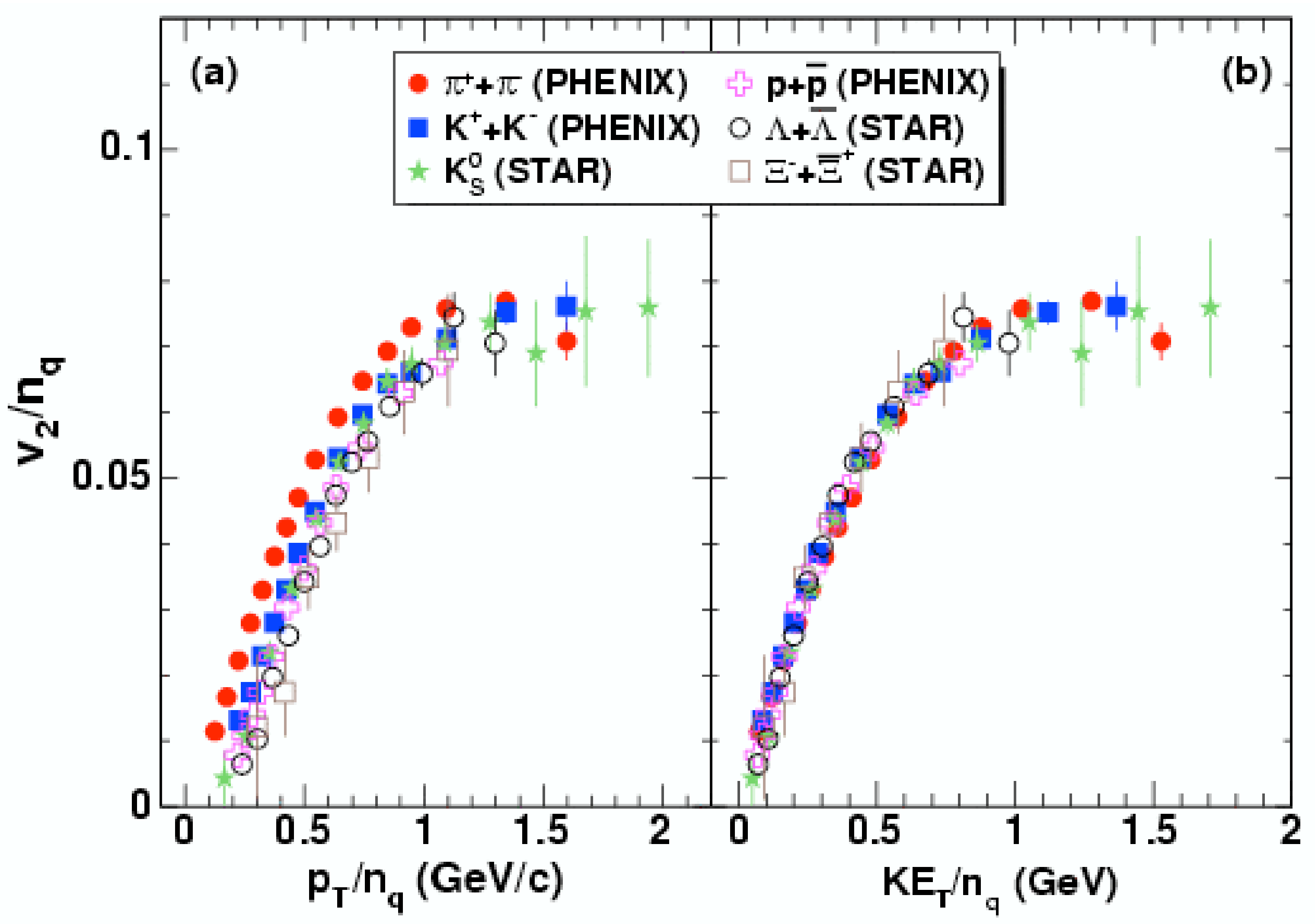
Anisotropic flow: what have we learned from RHIC?

Above 2 GeV/c there seems to be a baryon vs. meson splitting of $v_2(p_T)$



Anisotropic flow:
what have we learned from RHIC?

(Various) number-of-constituent-quark scalings can be identified



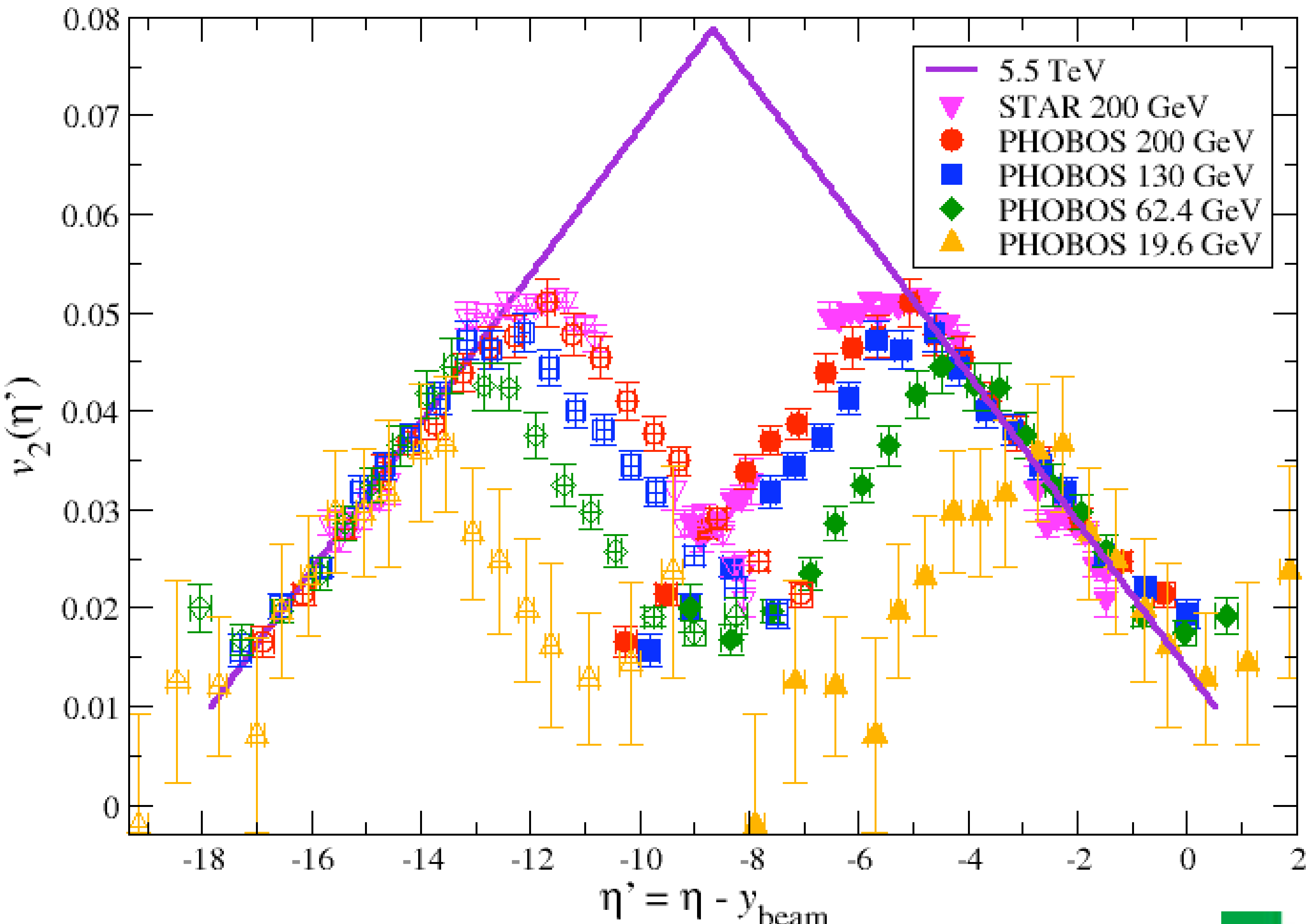
Anisotropic flow: what have we learned from RHIC?

- The p_T-integrated elliptic flow $v_2(\eta)$ shows extended longitudinal scaling ("limiting fragmentation") from $\sqrt{s_{NN}}$ = 20 to 200 GeV
- At mid-rapidity, the $v_2(p_T)$ of charged hadrons first rises linearly up to $p_T \simeq$ 2 GeV/c, then saturates
  - in the linear-rise region the slope increases with impact parameter
- The $v_2(p_T)$ of identified hadrons at mid-rapidity
  - show mass ordering for $p_T \lesssim$ 1.5 GeV/c
  - seem to scale with the number of constituent quarks above that

$$\frac{1}{n_q} v_2\left(\frac{p_T}{m}\right) \;,\; \frac{1}{n_q} v_2\left(\frac{KE_T}{m}\right) \;?$$

Anisotropic flow: what can we expect at LHC?

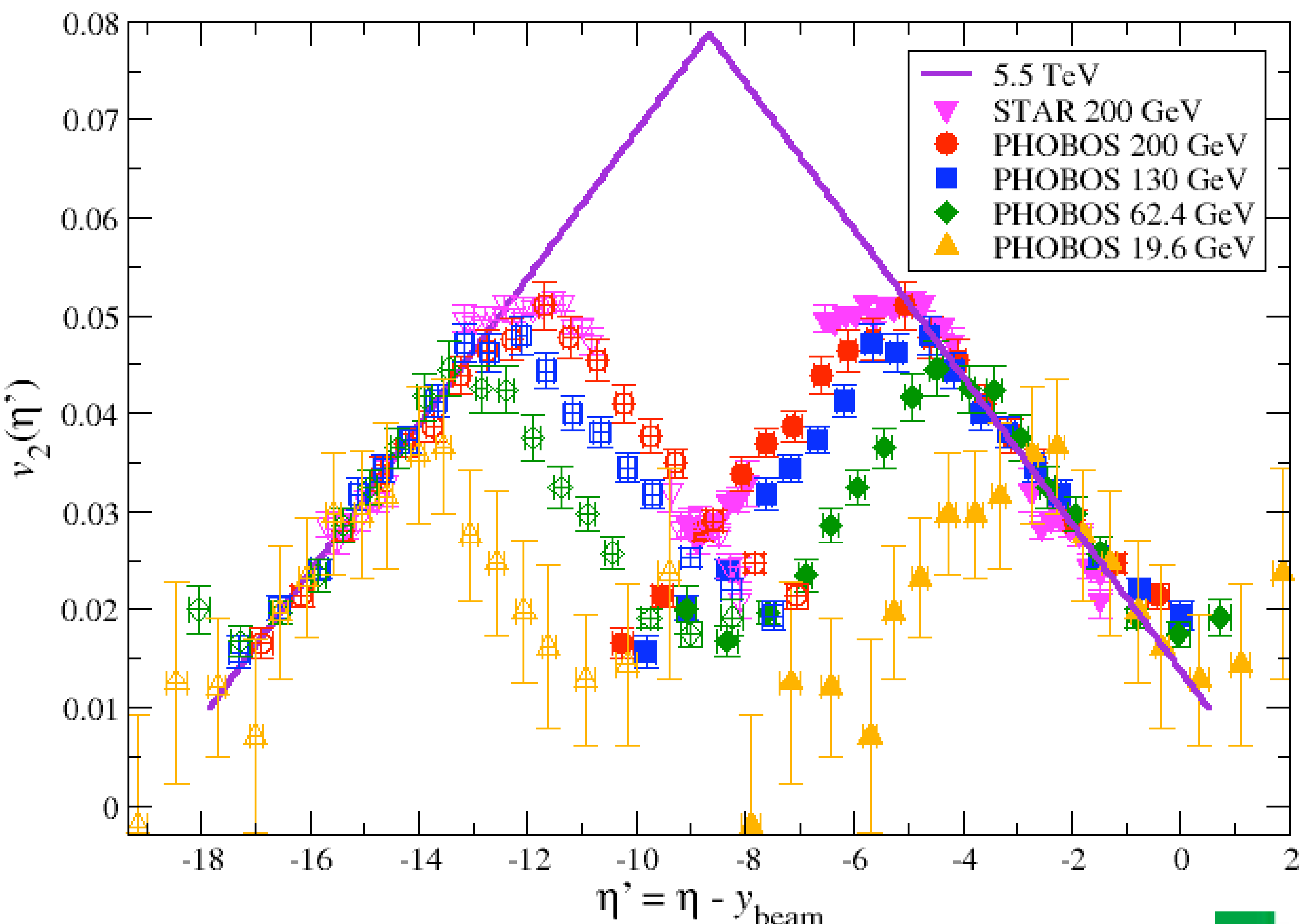
Will the extended longitudinal scaling of the p_T-integrated elliptic flow $v_2(\eta)$ persist?



Anisotropic flow: what can we expect at LHC?

Will the extended longitudinal scaling of the p_T-integrated elliptic flow $v_2(\eta)$ persist?

☞ $v_2(\eta = 0) \approx 0.08$



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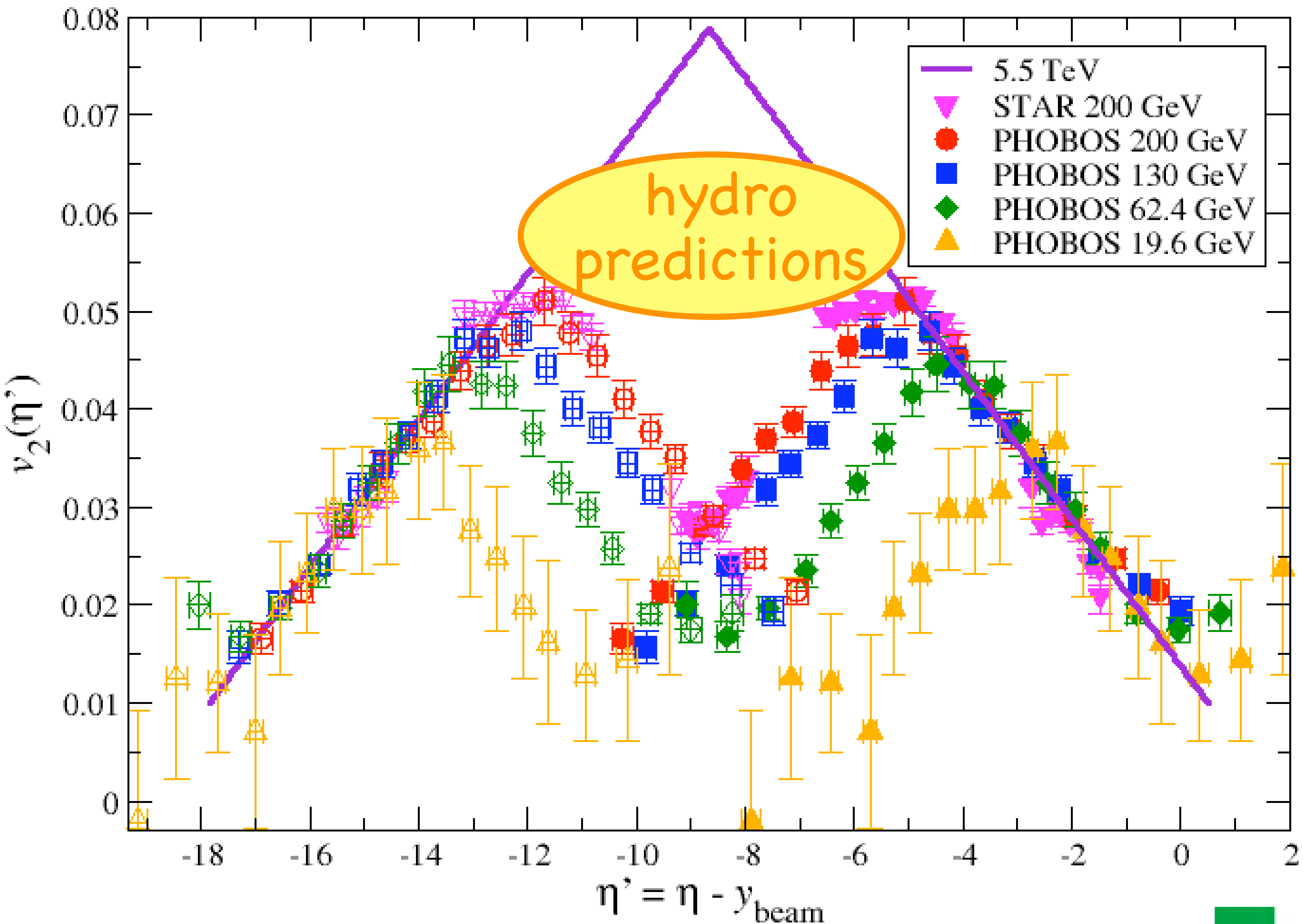
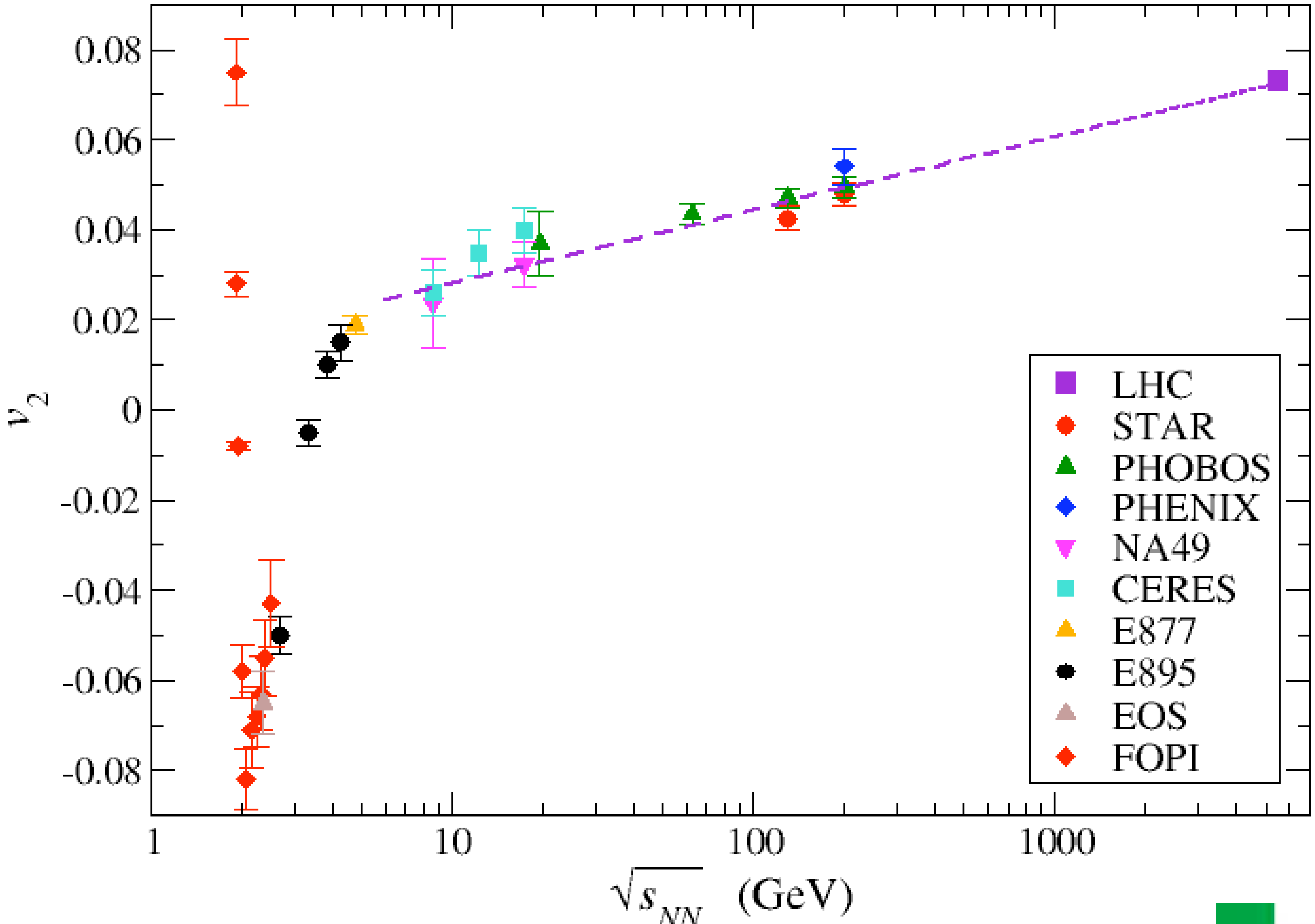


Anisotropic flow:
what can we expect at LHC?

Will the linear rise with ln $\sqrt{s_{NN}}$ of the p_T-integrated elliptic flow at midrapidity $v_2(\eta = 0)$ persist?



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Anisotropic flow:
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What if the extended longitudinal scaling of the p_T-integrated elliptic flow $v_2(\eta)$ persist?

- $v_2(\eta = 0) \approx 0.08$ ☞ present ideal-fluid dynamics approaches will need some revisiting

- the scaling will have to be taken seriously!

Anisotropic flow: what can we expect at LHC?

What if the extended longitudinal scaling of the p_T-integrated elliptic flow $v_2(\eta)$ persist?

- $v_2(\eta = 0) \approx 0.08$ ☞ present ideal-fluid dynamics approaches will need some revisiting

- the scaling will have to be taken seriously!

Up to now, only one attempt* at explaining it, as reflecting the absence of (kinetic) equilibrium of the matter created in the collision:

longitudinal scaling of $\frac{\mathrm{d}N}{\mathrm{d}y}$ $\Rightarrow$ longitudinal scaling of $v_2(y)$

* three miserable lines in Eur. Phys. J. A **29** (2006) 27

Anisotropic flow: out-of-equilibrium scenario

How does anisotropic flow depend on the number $\mathcal{N}$ of collisions undergone by particles?

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✦ In the absence of rescatterings ("gas"), no flow develops.

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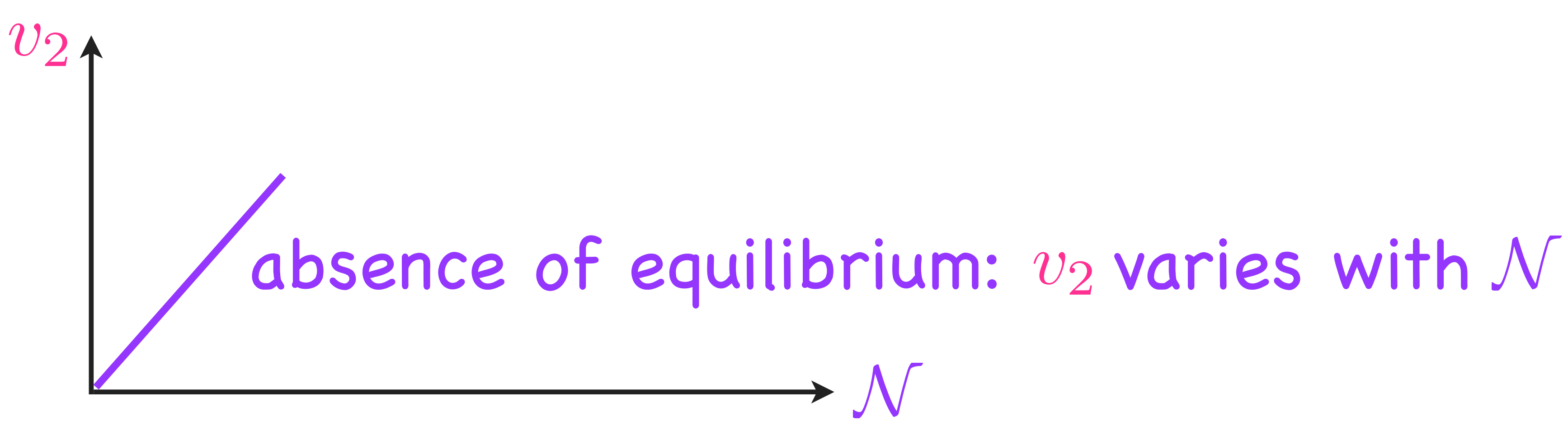
- ✦ The more collisions, the larger the flow.



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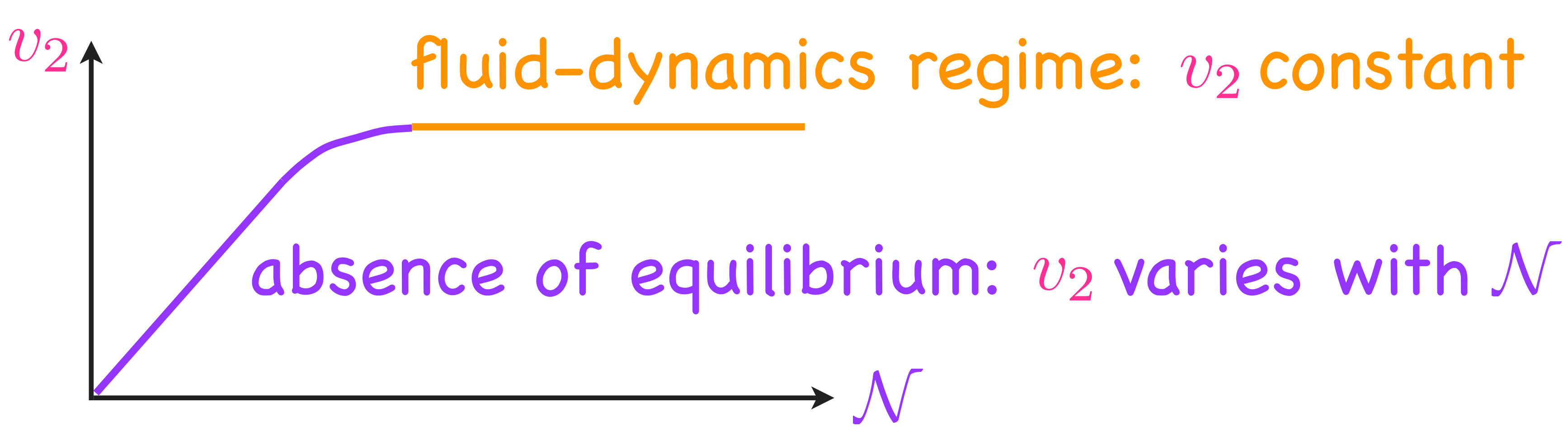
How does anisotropic flow depend on the number $\mathcal{N}$ of collisions undergone by particles?

✦ In the absence of rescatterings ("gas"), no flow develops.

✦ The more collisions, the larger the flow.

✦ For a given number of collisions, the system thermalizes: further collisions no longer increase v_2.



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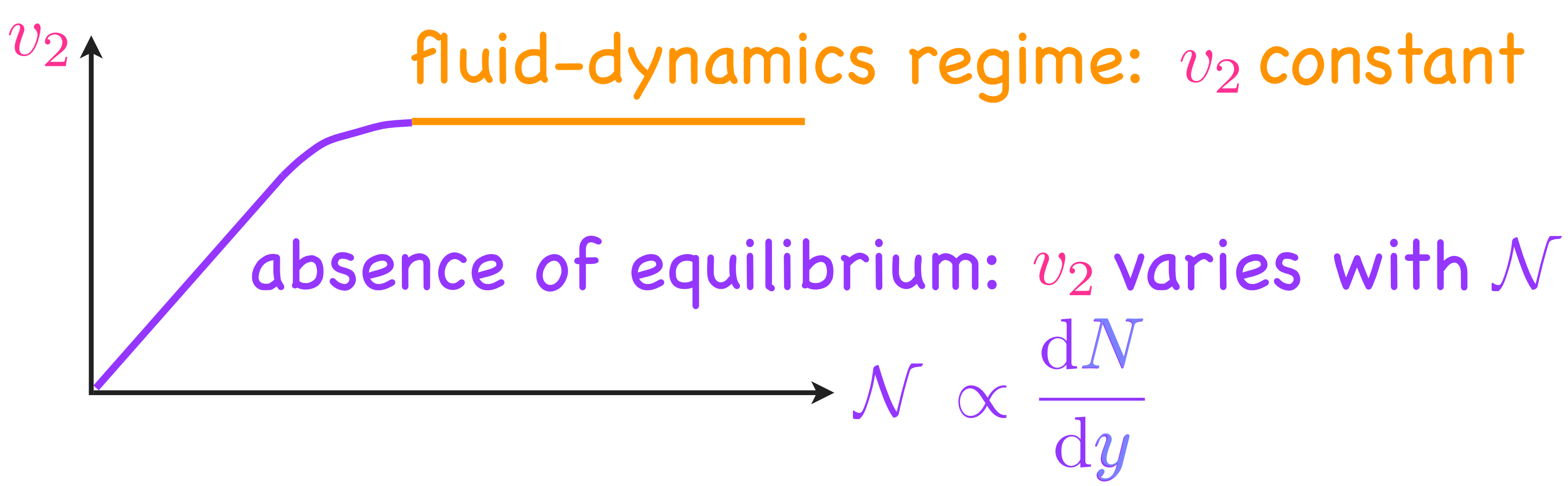
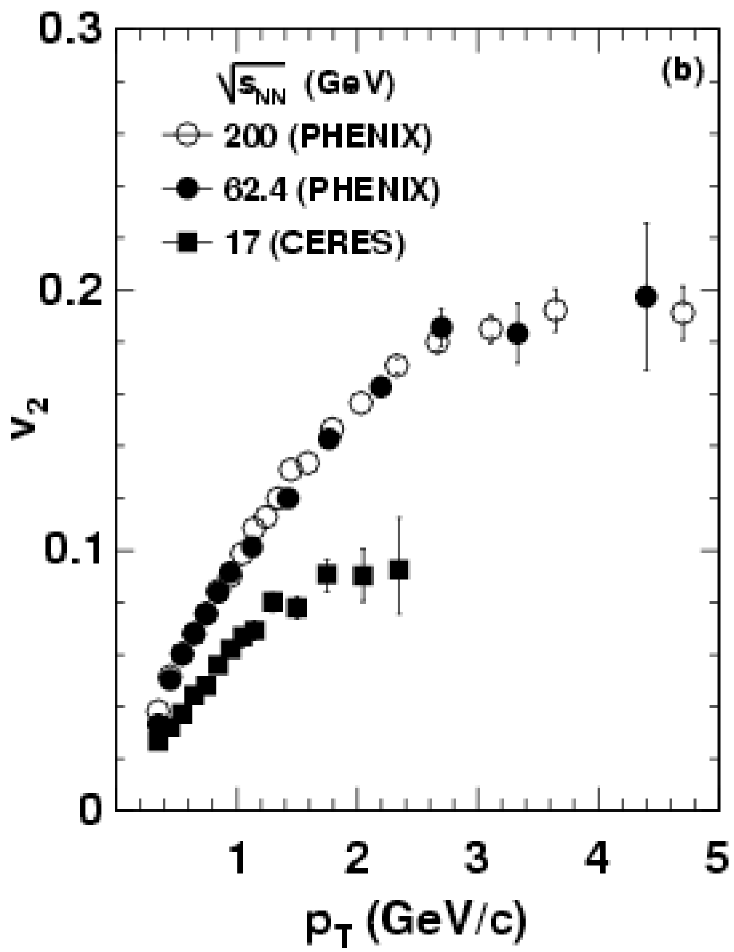


Anisotropic flow: what can we expect at LHC?

At RHIC, the $v_2(p_T)$ of charged hadrons at mid-rapidity first rises linearly up to $p_T \simeq$ 2 GeV/c

- How does the slope of $v_2(p_T)$ at a given centrality evolve with $\sqrt{s_{NN}}$?



STAR

The v_2 data for pions and kaons at 62.4 GeV tends to be about 5% smaller than the 200 GeV data (although at $p_T > 1$ GeV/c the difference is within systematic uncertainties). The anti-proton data at 62.4 and 200 GeV are consistent within errors. The data exclude a proton v_2 variation between 62.4 and 200 GeV greater than approximately 15%.

⋮

Appreciable differences are seen between the 17.3 GeV and 62.4 GeV data.

(slight disagreement)

What drives the increase of the p_T-integrated v_2? The rise in $\langle p_T \rangle$?

Anisotropic flow: what can we expect at LHC?

At RHIC, the $v_2(p_T)$ of charged hadrons at mid-rapidity first rises linearly up to $p_T \simeq 2$ GeV/c, then saturates.

- How does the slope of $v_2(p_T)$ at a given centrality evolve with $\sqrt{s_{NN}}$?

☞ What drives the increase of the p_T-integrated v_2?

- How does the position of the breaking point* in the $v_2(p_T)$ shape evolve? (with centrality, with $\sqrt{s_{NN}}$)

☞ "natural" expectation: the p_T of the breaking point should increase with centrality, with $\sqrt{s_{NN}}$, and with the size of the colliding nuclei, and decrease with rapidity

(It is far from obvious that the PHENIX data support this expectation)

* has to be defined properly...

Anisotropic flow: what can we expect at LHC?

At SPS and RHIC the $v_2(p_T)$ of identified hadrons at mid-rapidity show mass ordering for $p_T \lesssim 1.5$ GeV/c… and that should persist at LHC!

- Will the ordering be in quantitative agreement with hydro?

All slow particles (p_T/m < max fluid velocity) have the same $v_n\left(\frac{p_T}{m}, y\right)$ since they originate from the same fluid cell;

for fast particles, $v_2(p_T) \propto (p_T - m_T v_{\max})$. PLB **642** (2006) 227

Qualitative agreement is not satisfactory… If (!) hydrodynamics is the large-number-of-collisions limit of the out-of-equilibrium case, then not too far from equilibrium, the mass ordering should already be present.

see QGSM: PLB **631** (2005) 109 and RQMD/UrQMD: JPG **32** (2006) 1121

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- Till which p_T does the ordering hold? (same expectations as above: the position should increase with centrality, with $\sqrt{s_{NN}}$, and with the size of the colliding nuclei, and decrease with rapidity)

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- What happens above the mass-ordering region?

number-of-constituent-quark scaling?

cf. Peter Lévai's talk(?)

Anisotropic flow:
what have we learned from RHIC?

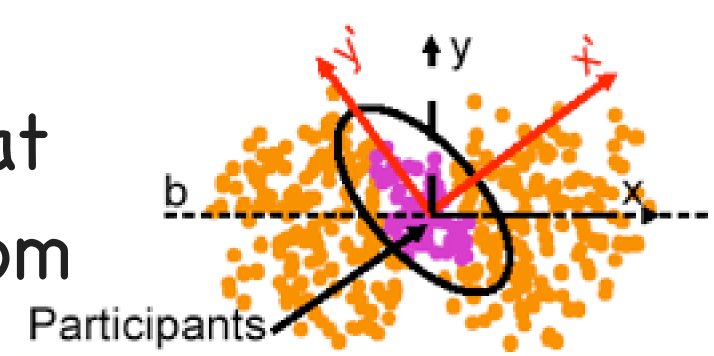
PHOBOS and STAR (+ theorists) have made huge progress in demonstrating the importance of fluctuations, in particular when comparing collisions with different centralities.

- Old vision: one should compare v_2/ϵ (which is constant in hydro)

  "geometrical" eccentricity

  (ellipsis with the shorter axis along the impact parameter)

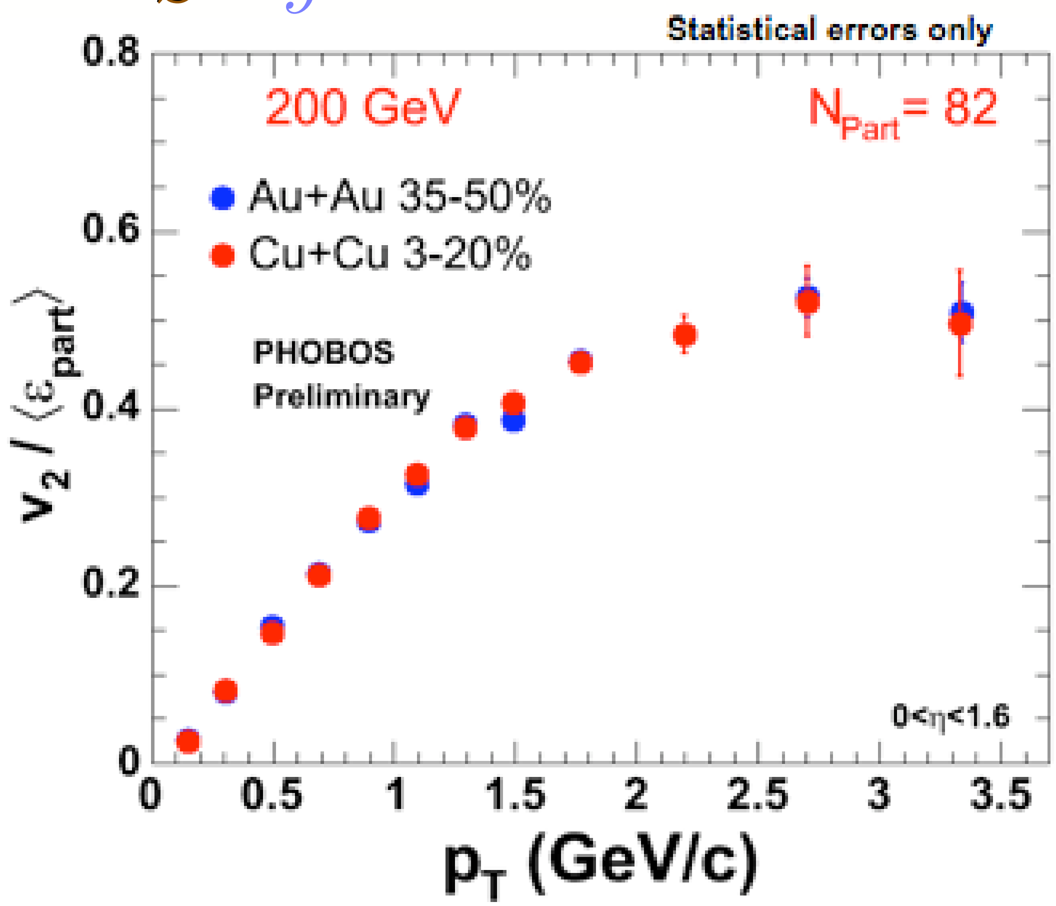
- The nuclei cross each other fast: the nucleons in the overlap region are frozen in a configuration that differs from the geometrical picture (and varies from event to event)

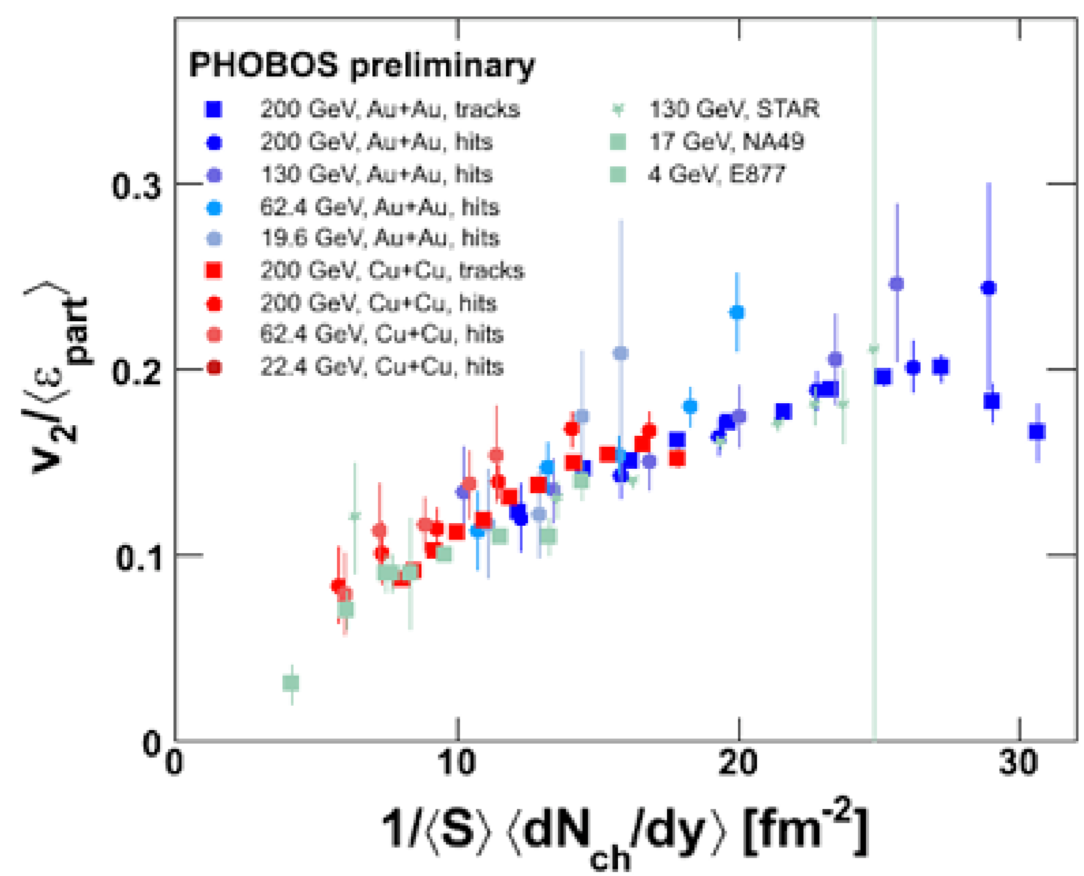


☞ the proper scaling is rather with the "participant eccentricity" $\epsilon_{\rm part}$

Anisotropic flow: what have we learned from RHIC?

Using the "participant eccentricity" $\epsilon_{\rm part}$, Cu-Cu and Au-Au data at a given $\frac{1}{S}\frac{dN}{dy}$ fall on the same curves [predicted in PLB **627** (2005) 49]





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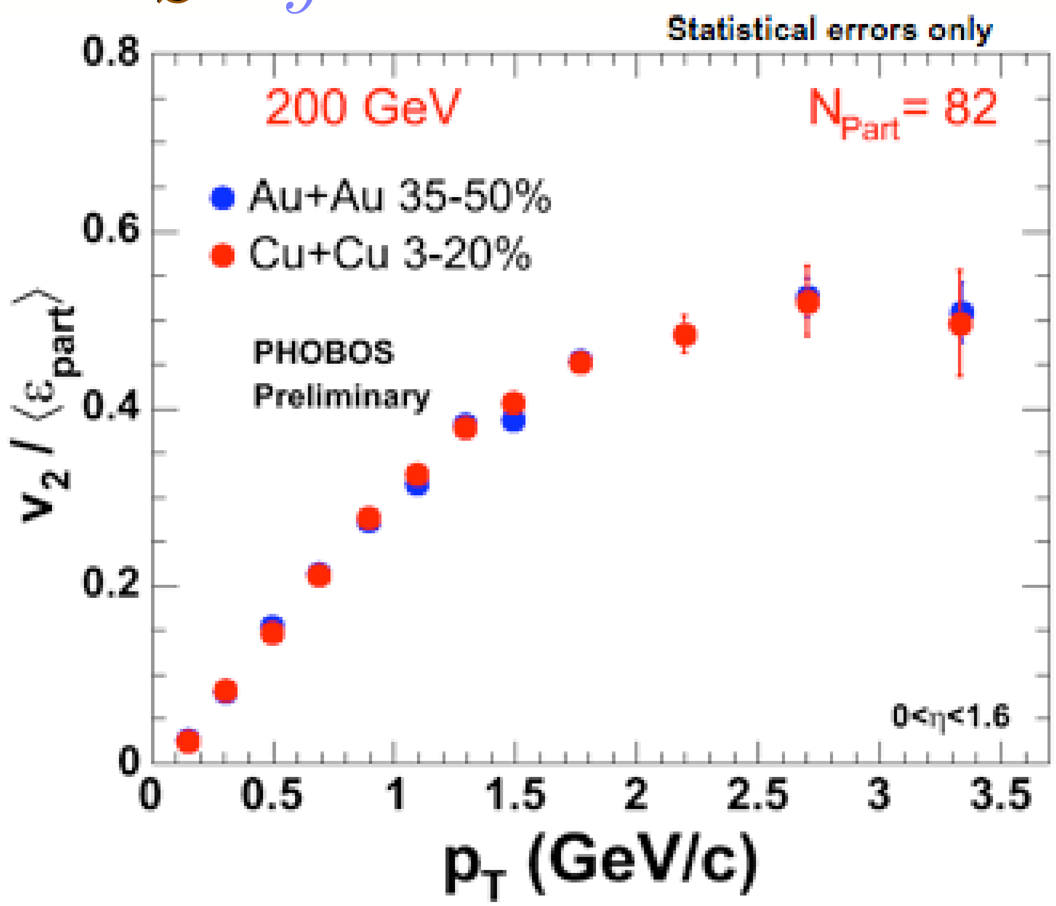
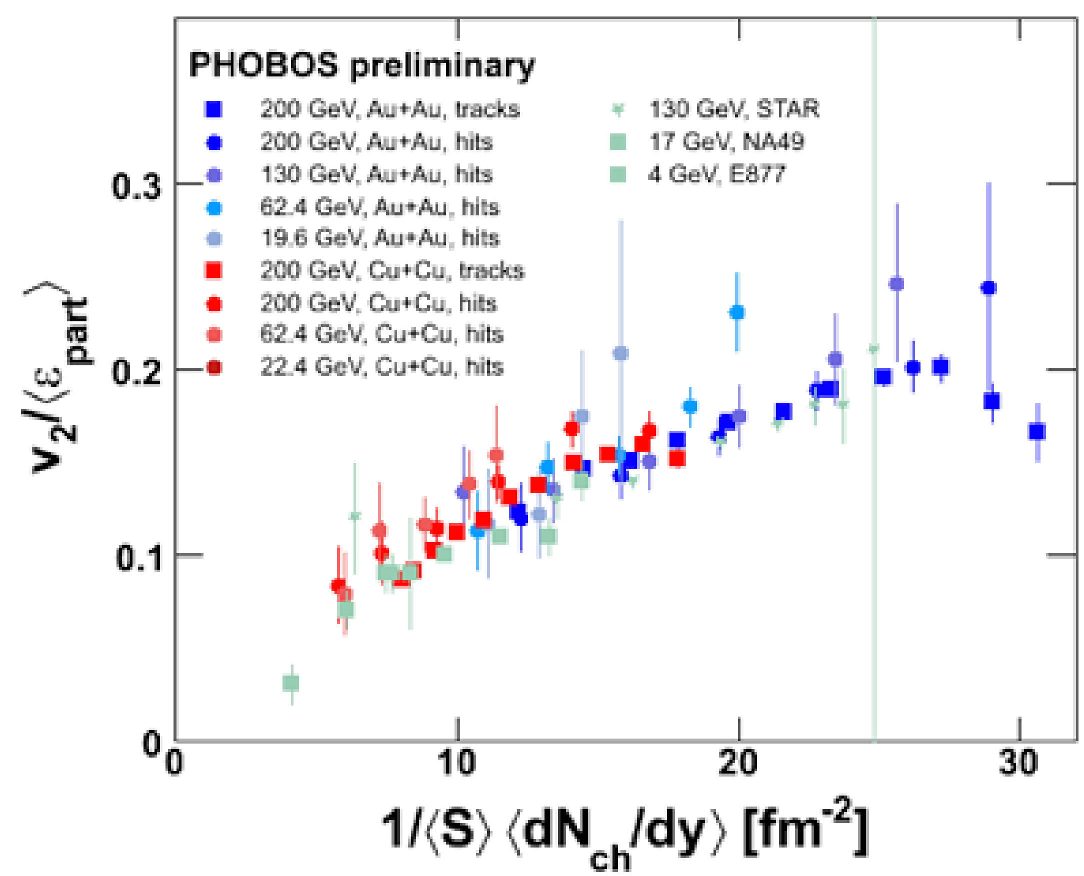


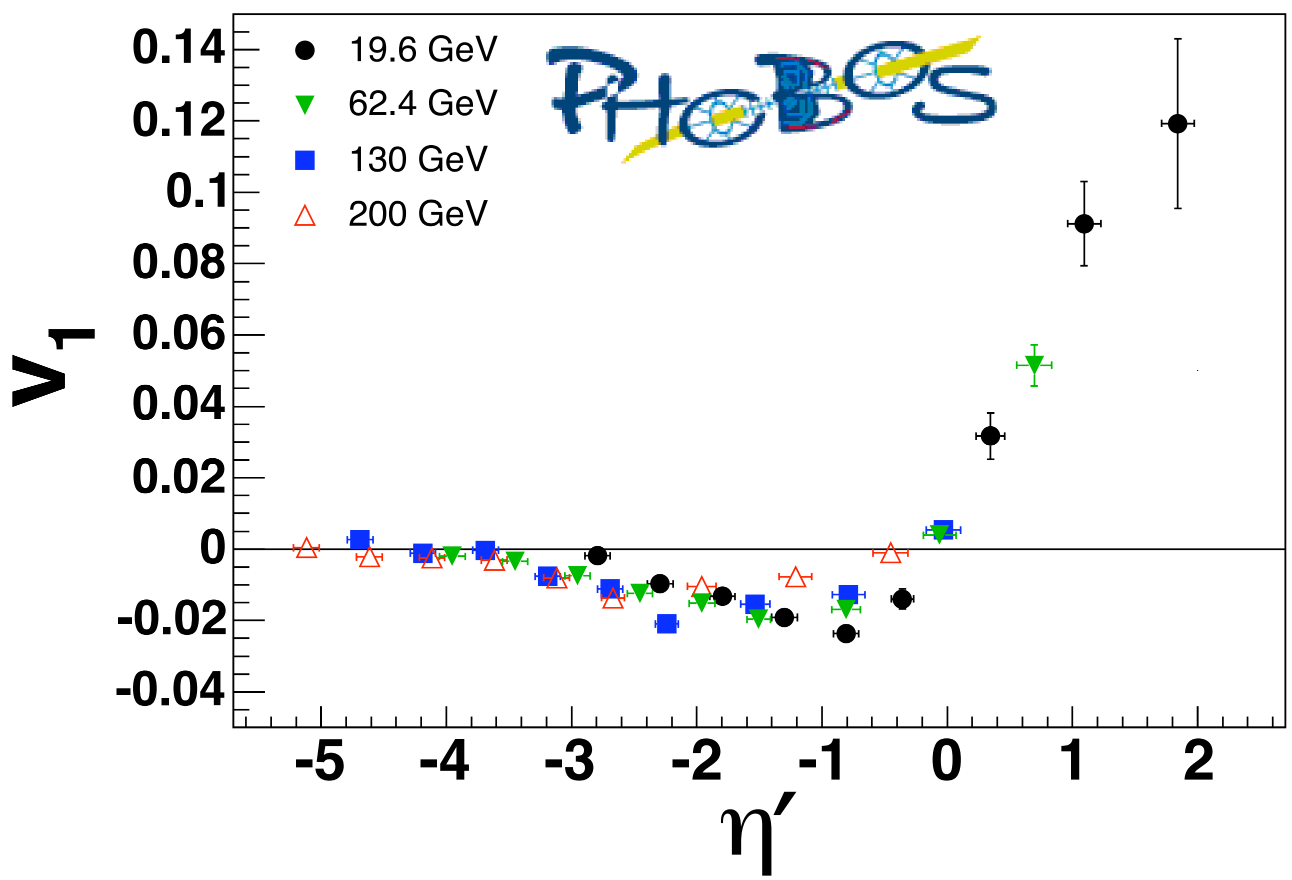


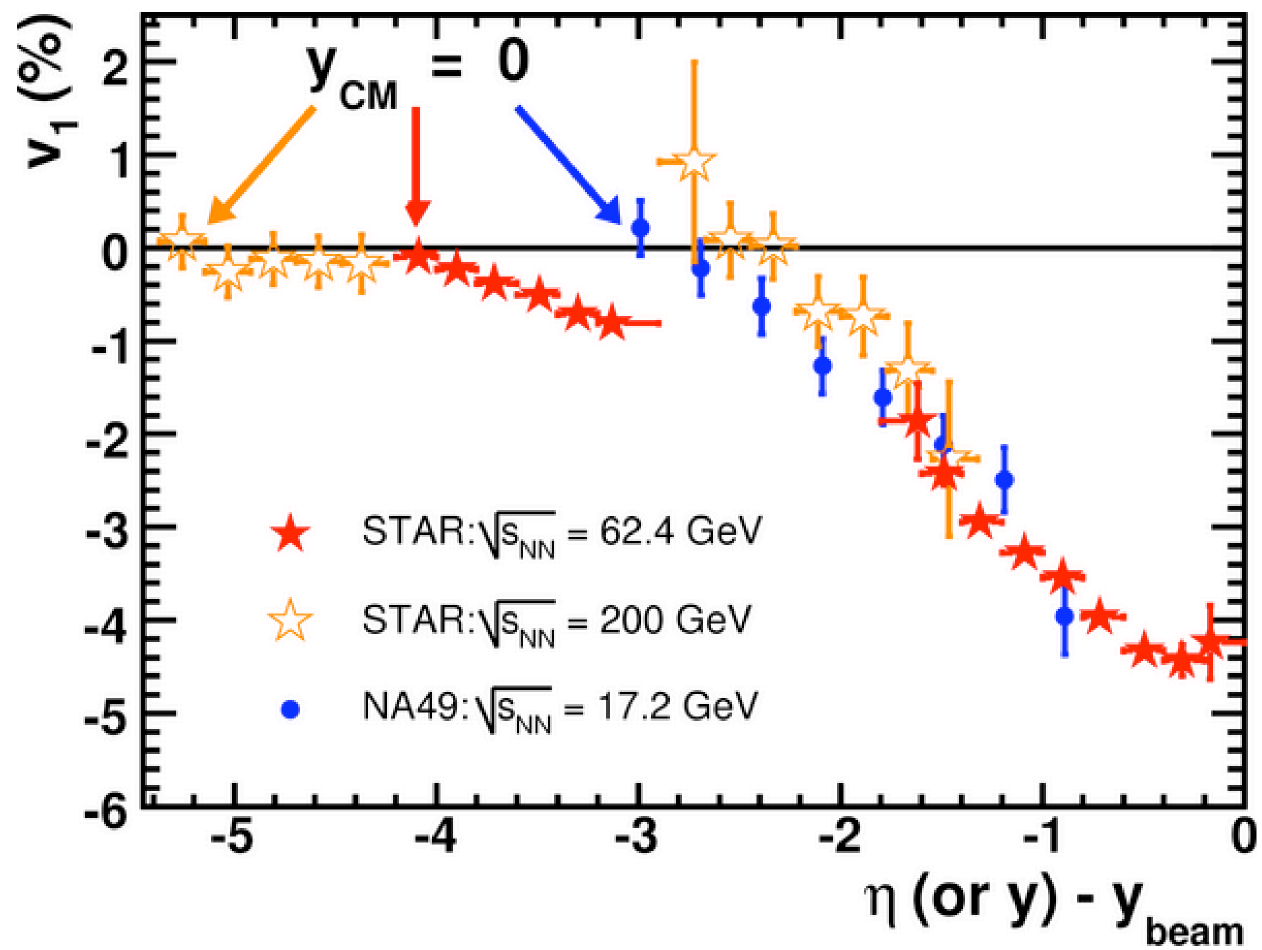
Temptation: extrapolate to LHC!

But beware, the underlying model for the eccentricity might change (here, Glauber model; CGC-inspired calculation yields larger ϵ)

Anisotropic flow: from RHIC to LHC

The p_T-integrated directed flow $v_1(\eta)$ shows extended longitudinal scaling ("limiting fragmentation") from $\sqrt{s_{NN}}$ = 20 to 200 GeV...





... but that cannot be true over the whole y range ($v_1(y=0)$ = 0),

Unless v_1 vanishes in an extended region!

Yet, expect a very small v_1 up to $y \approx 5$ at LHC.

Anisotropic flow: from RHIC to LHC

STAR has also measured the fourth anisotropic-flow harmonic v_4, as a function of p_T, y, particle type, at $\sqrt{s_{NN}}$ = 62.4 and 200 GeV

cf. Raimond Snellings in a few moments

Within ideal-fluid dynamics prediction, to leading order in the fluid-velocity anisotropies, $v_4(p_T, y) = \frac{1}{2} v_2(p_T, y)^2$ for each type of fast particle.

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Whereas in the out-of-equilibrium scenario v_2, v_4 are proportional to the number of collisions $\mathcal{N}$ $\Rightarrow \frac{v_4}{v_2^2} \propto \frac{1}{\mathcal{N}}$, minimum at equilibrium.

☞ in the non-equilibrium scenario $\frac{v_4(p_T, y)}{v_2(p_T, y)^2} > \frac{1}{2}$ (≈ 1.2 at RHIC).

Expect a smaller $\frac{v_4}{v_2^2}$ at LHC... (but v_4 will still be sizable)

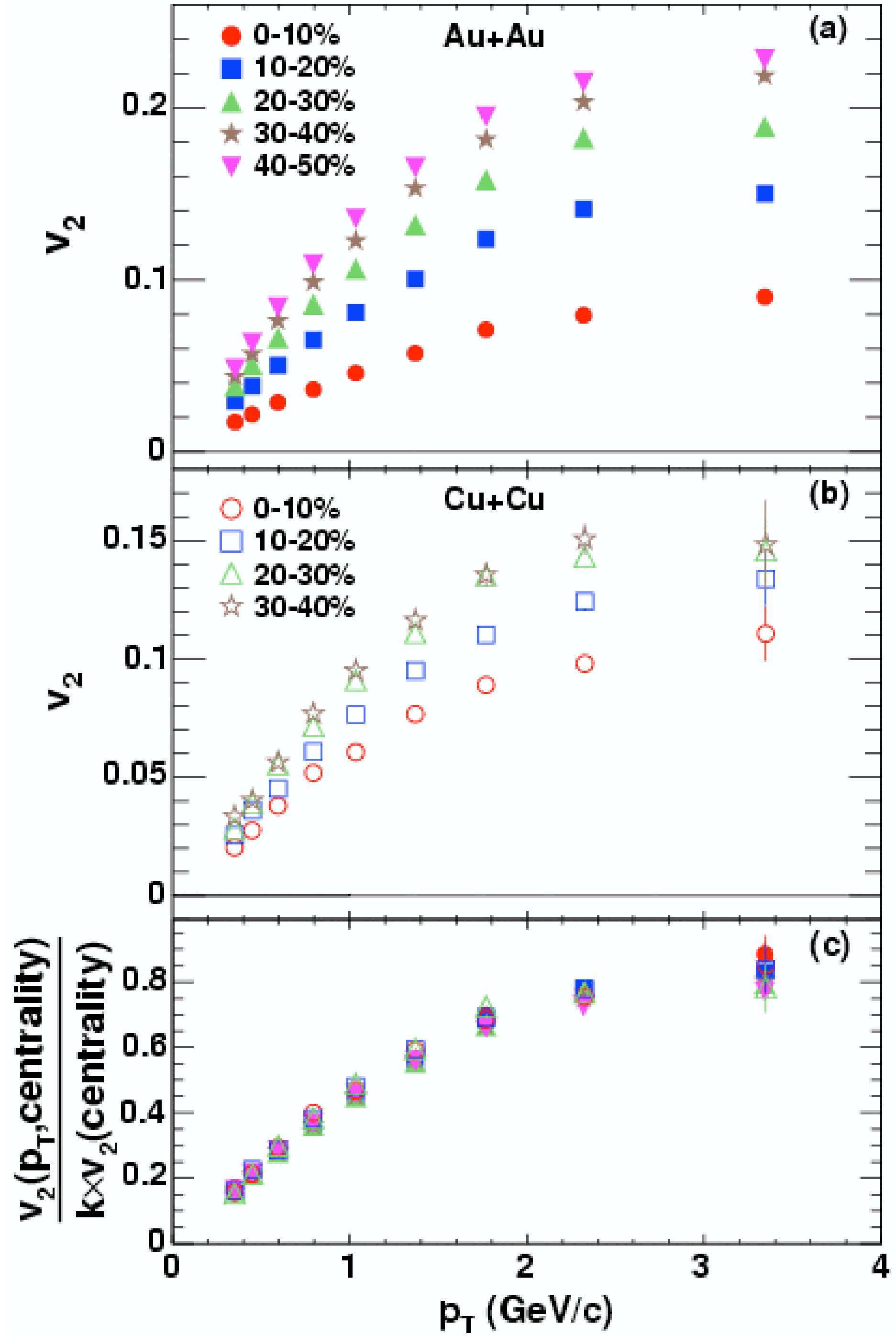
Anisotropic flow: my? questions for LHC

- Extended longitudinal scaling of the p_T-integrated elliptic flow?
- If the $v_2(p_T)$ of charged hadrons at mid-rapidity rises linearly at low transverse momentum
  - how does the slope compare to lower beam energies?
  - where does the linear rise stop? Systematics wanted.
  - does $v_2(p_T)$ goes down to 0 at some (high p_T) point?
- Regarding the $v_2(p_T)$ of identified hadrons at mid-rapidity
  - mass ordering at low p_T? (Quantitative results wanted!) Till where?
  - (not mentioned here): $v_2(p_T)$ of charm / beauty?
- v_4 will also be instructive! (at least, if theorists care...)

Extra slides

Anisotropic flow: p_T-dependence

The "natural" expectation is that the p_T of the breaking point in the $v_2(p_T)$ shape should increase with centrality, with $\sqrt{s_{NN}}$, and with the size of the colliding nuclei, and decrease with rapidity



Heavy-ion collisions: fluid-dynamics description

At freeze-out, each fluid cell emits particles according to thermal distributions (Bose-Einstein, Fermi-Dirac):

$$E\frac{\mathrm{d}N}{\mathrm{d}^3\mathbf{p}} = C\int_\Sigma \exp\left(-\frac{p^\mu u_\mu(x)}{T_{\mathrm{f.o.}}}\right) p^\mu\,\mathrm{d}\sigma_\mu$$

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fluid cell velocity

$$E\frac{\mathrm{d}N}{\mathrm{d}^3\mathbf{p}} = C\int_\Sigma \exp\left(-\frac{p^\mu u_\mu(x)}{T_{\mathrm{f.o.}}}\right) p^\mu\,\mathrm{d}\sigma_\mu$$

freeze-out hypersurface

particle momentum

Heavy-ion collisions: fluid-dynamics description

At freeze-out, each fluid cell emits particles according to thermal distributions (Bose–Einstein, Fermi–Dirac):

$$E\,\frac{\mathrm{d}N}{\mathrm{d}^3\mathbf{p}} = C\int_\Sigma \exp\left(-\frac{p^\mu u_\mu(x)}{T_{\rm f.o.}}\right)\, p^\mu\,\mathrm{d}\sigma_\mu$$

fluid cell velocity

freeze-out hypersurface

particle momentum

A consistent ideal-hydrodynamics picture requires that $T_{\rm f.o.} \ll T_{\rm in.}$

$\Leftrightarrow$

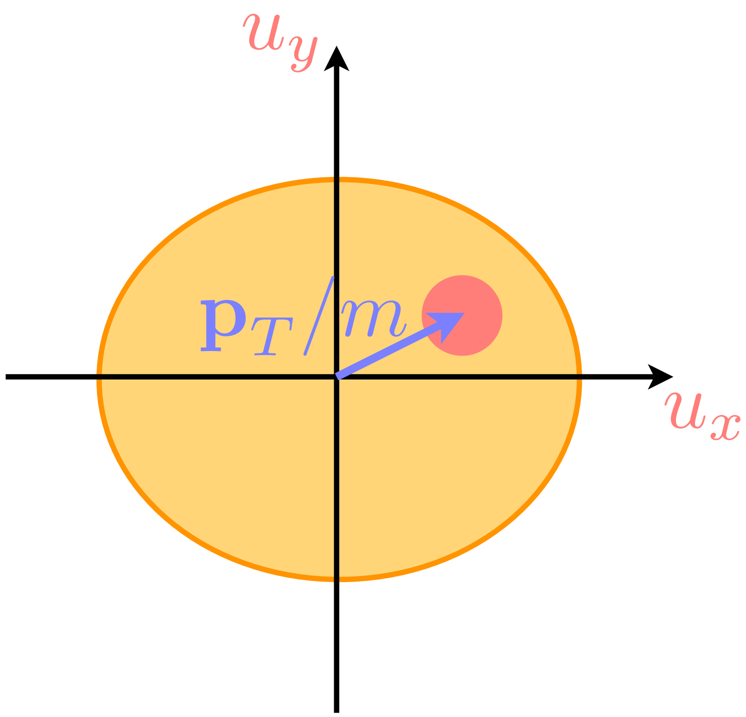
ideal-fluid limit = small-$T_{\rm f.o.}$ limit

☞ one can compute the particle distribution in a model-independent, analytic way (using a saddle-point approximation).

N.Borghini, J.-Y.Ollitrault PLB **642** (2006) 227

Ideal fluid-dynamics: analytical results

Slow particles ($p_T/m < u_{\max}\left(\frac{\pi}{2}\right)$) move together with the fluid.



There exists a fluid cell whose velocity equals the particle velocity: minimizes $p^\mu u_\mu$.

☞ Integrand in the Cooper-Frye spectrum is Gaussian, with width ∝ $1/\min(\sqrt{p^\mu u_\mu}) = 1/\sqrt{m}$.

→ saddle-point approximation!

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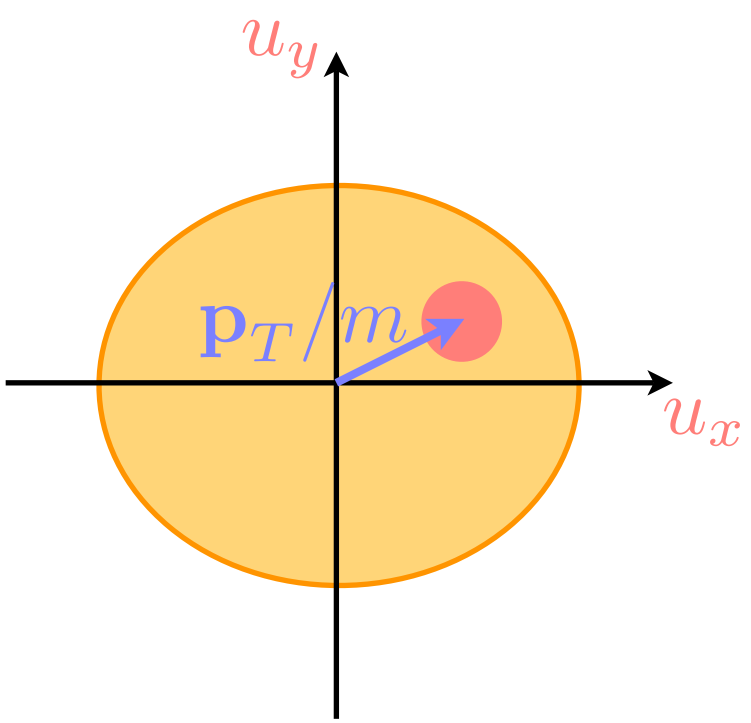

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- Similar momentum distributions for different particles

$$E\frac{\mathrm{d}N}{\mathrm{d}^3\mathbf{p}} = c^h(m) f\left(\frac{p_T}{m}, y, \varphi\right)$$

- $v_n\left(\frac{p_T}{m}, y\right)$ identical for all particles!

⇒ mass-ordering of $v_2(p_T, y)$, $\frac{v_4}{v_2^2}\left(\frac{p_T}{m}, y\right)$ universal

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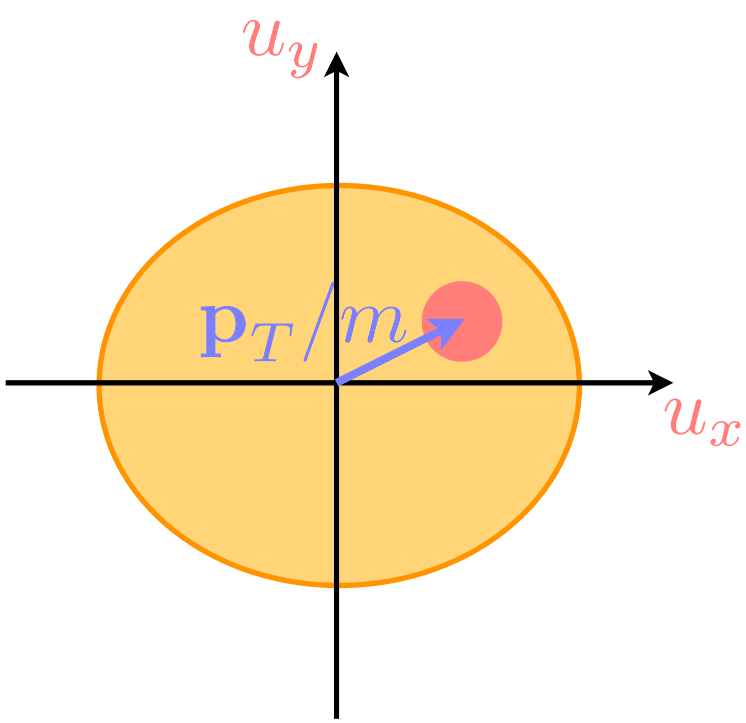

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$m \gg T_{\rm f.o.}$

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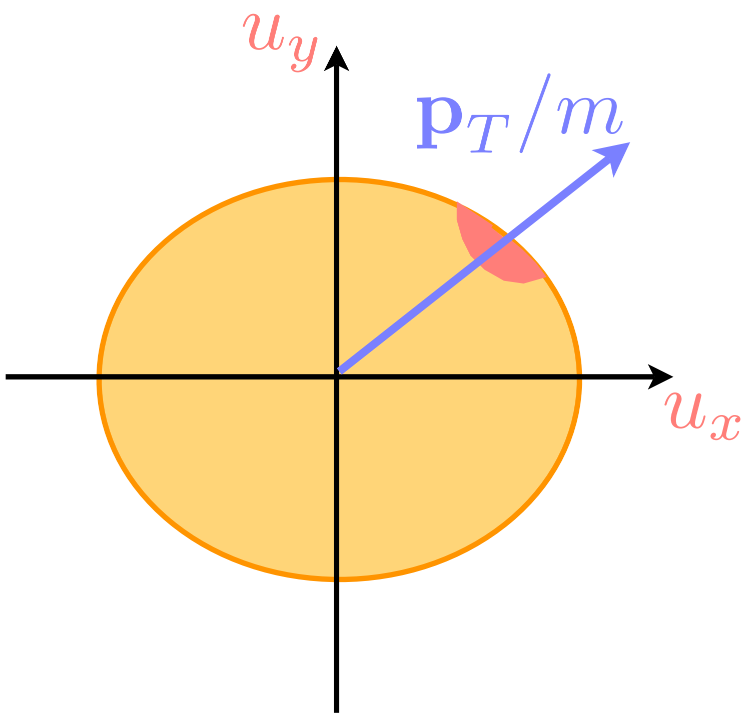
Ideal fluid-dynamics: analytical results

Fast particles ($p_T/m > u_{\max}(0)$) move faster than the fluid.



Such a particle was emitted by a cell along the direction of its velocity where the fluid is fastest (often, close to the edge of the fluid).

Saddle-point expansion of the Cooper-Frye formula around the minimum of $p^\mu u_\mu$.

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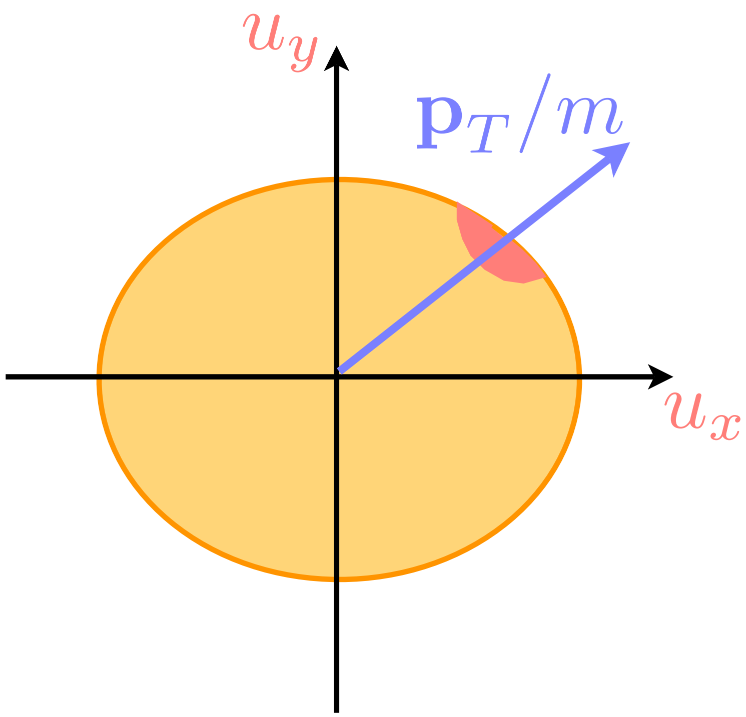

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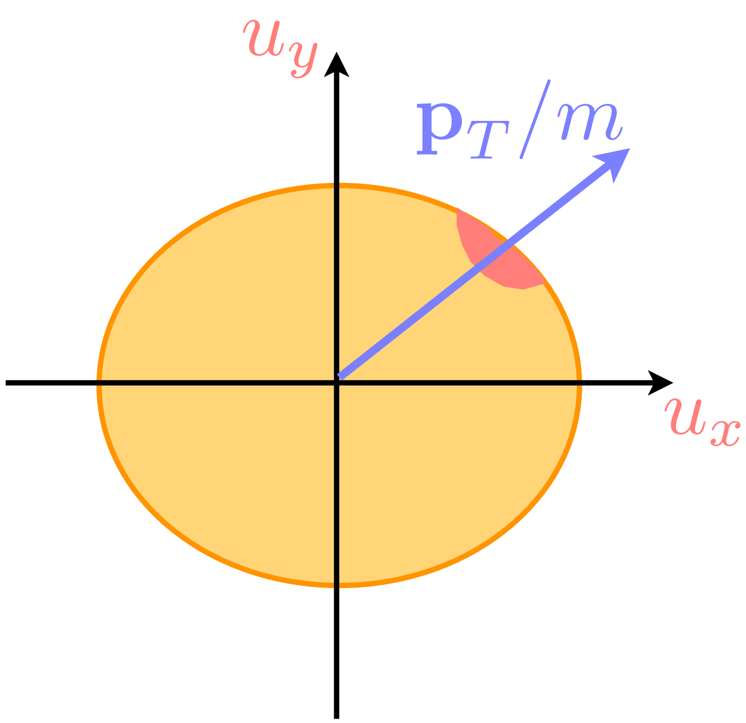

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- Momentum distribution $\propto \exp\left(\frac{p_T u_{\max} - m_T u^0_{\max}}{T_{\rm f.o.}}\right)$
- To leading order in the fluid-velocity anisotropies V_n:

  $v_2(p_T) = \frac{V_2 u_{\max}}{T_{\rm f.o.}}(p_T - m_T v_{\max})$: mass-ordering of $v_2(p_T, y)$ persists;
- Assuming additionally that $V_4 \ll V_2$, one finds for p_T large enough:

$$\frac{v_4(p_T, y)}{v_2(p_T, y)^2} = \frac{1}{2}$$