Anisotropic flow at RHIC and prospects for LHC

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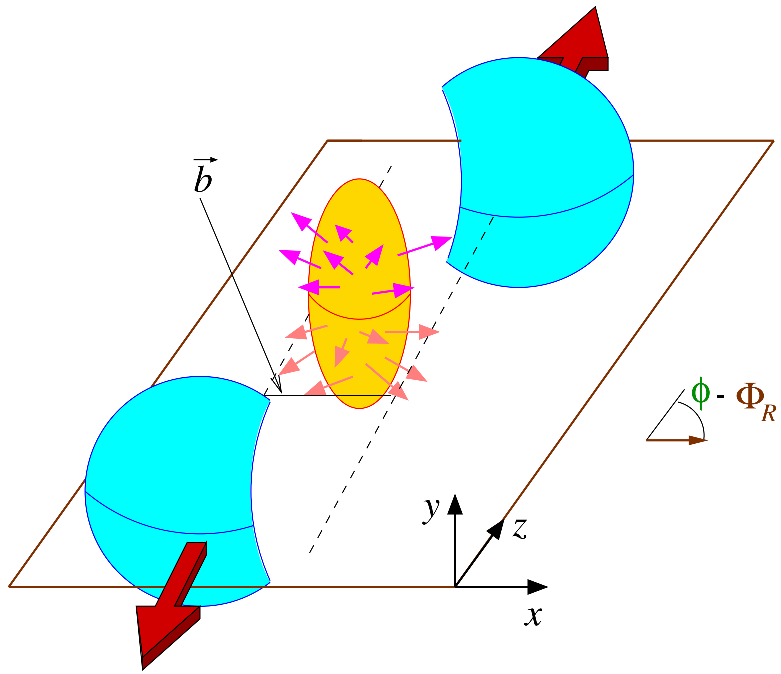
Anisotropic flow at RHIC and prospects for LHC

- 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 in heavy-ion collisions

Non-central collision:



Initial anisotropy of the source (in the transverse plane)

⇒ anisotropic pressure gradients, larger along the impact parameter $\vec{b}$

⇒ anisotropic emission of particles:

anisotropic (collective) flow

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

"directed" (v_1) "elliptic" (v_2)

"Flow": misleading terminology; does NOT imply fluid dynamics!

Anisotropic flow at RHIC: a short review [0/6]

RHIC experiments* have measured v_1, v_2, v_4, v_6

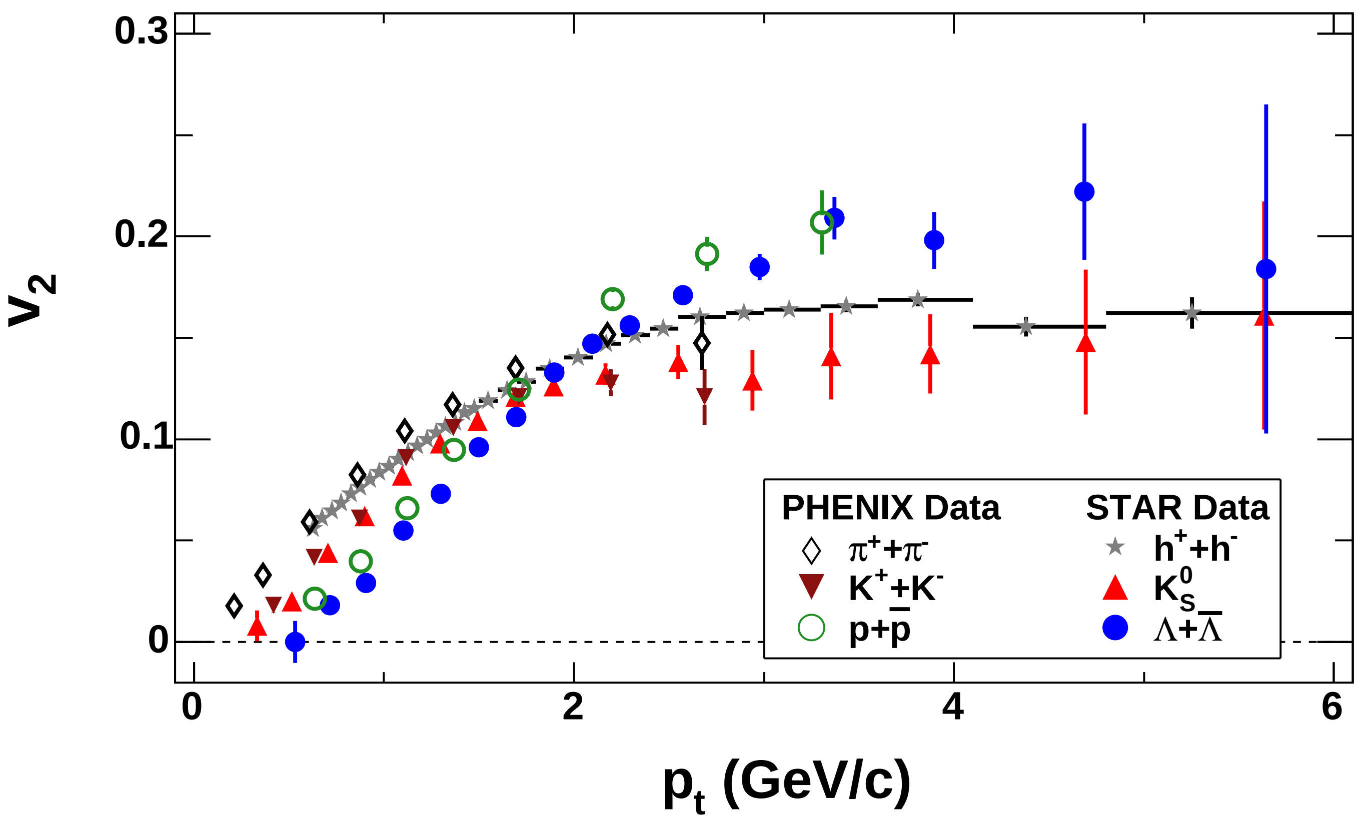
- for identified particles;
- as a function of the centrality of the collision;
- as a function of the particle transverse momentum;
- as a function of the particle (pseudo)rapidity;
- at 4 different center-of-mass energies;
- with different colliding nuclei.

and the first results came out quickly (Sep.2000).

*even those not designed to measure anisotropic flow

Anisotropic flow at RHIC: a short review [1/6]

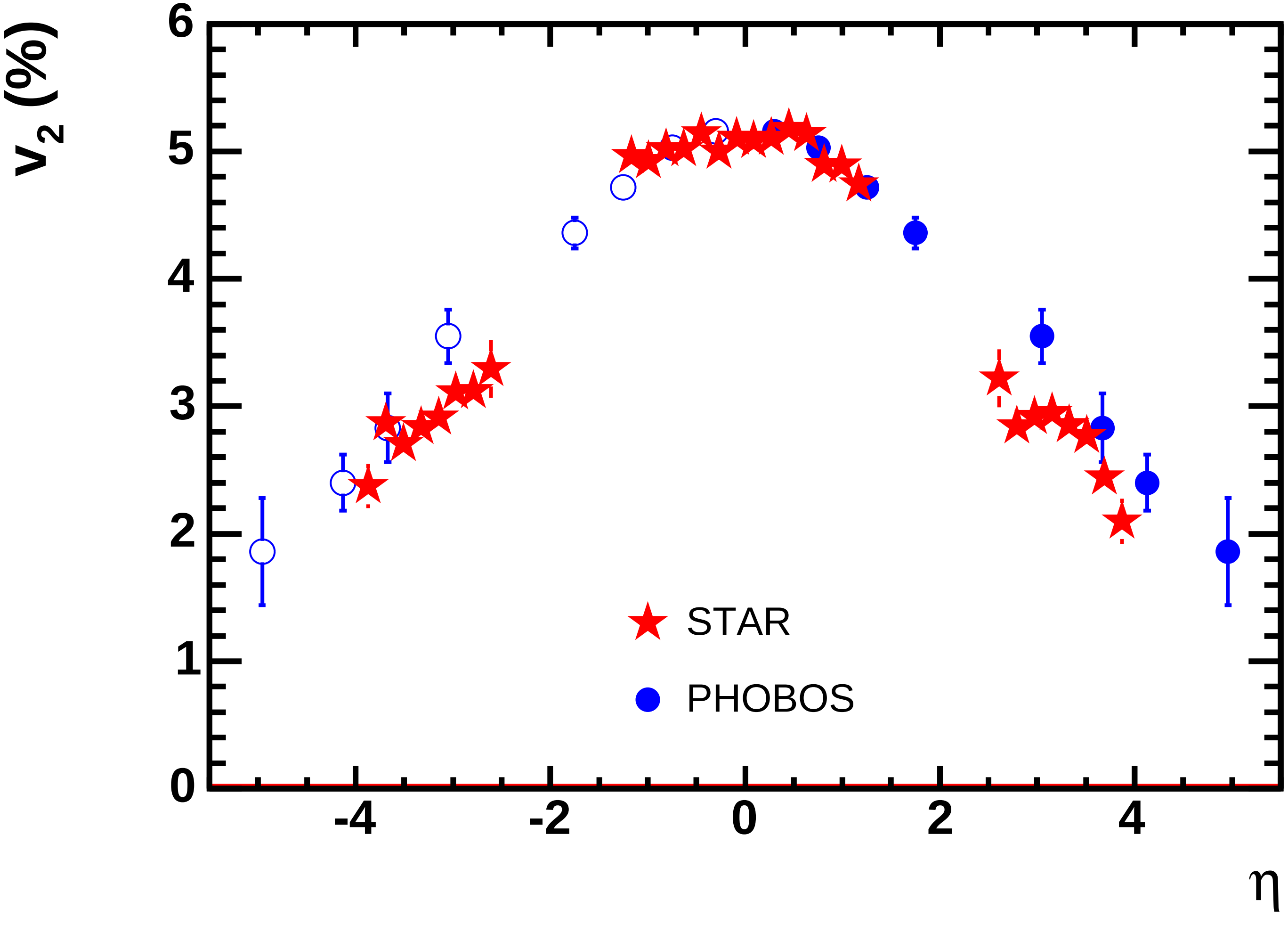
RHIC experiments have measured the elliptic flow v_2 of photons, $e^{\pm}$, $\pi^{\pm}$, π^0, $K^{\pm}$, K^0_S, p, $\bar{p}$, ϕ, $\Lambda+\bar{\Lambda}$, $\Xi^-+\bar{\Xi}^+$, $\Omega^-+\bar{\Omega}^+$ and deuterons.



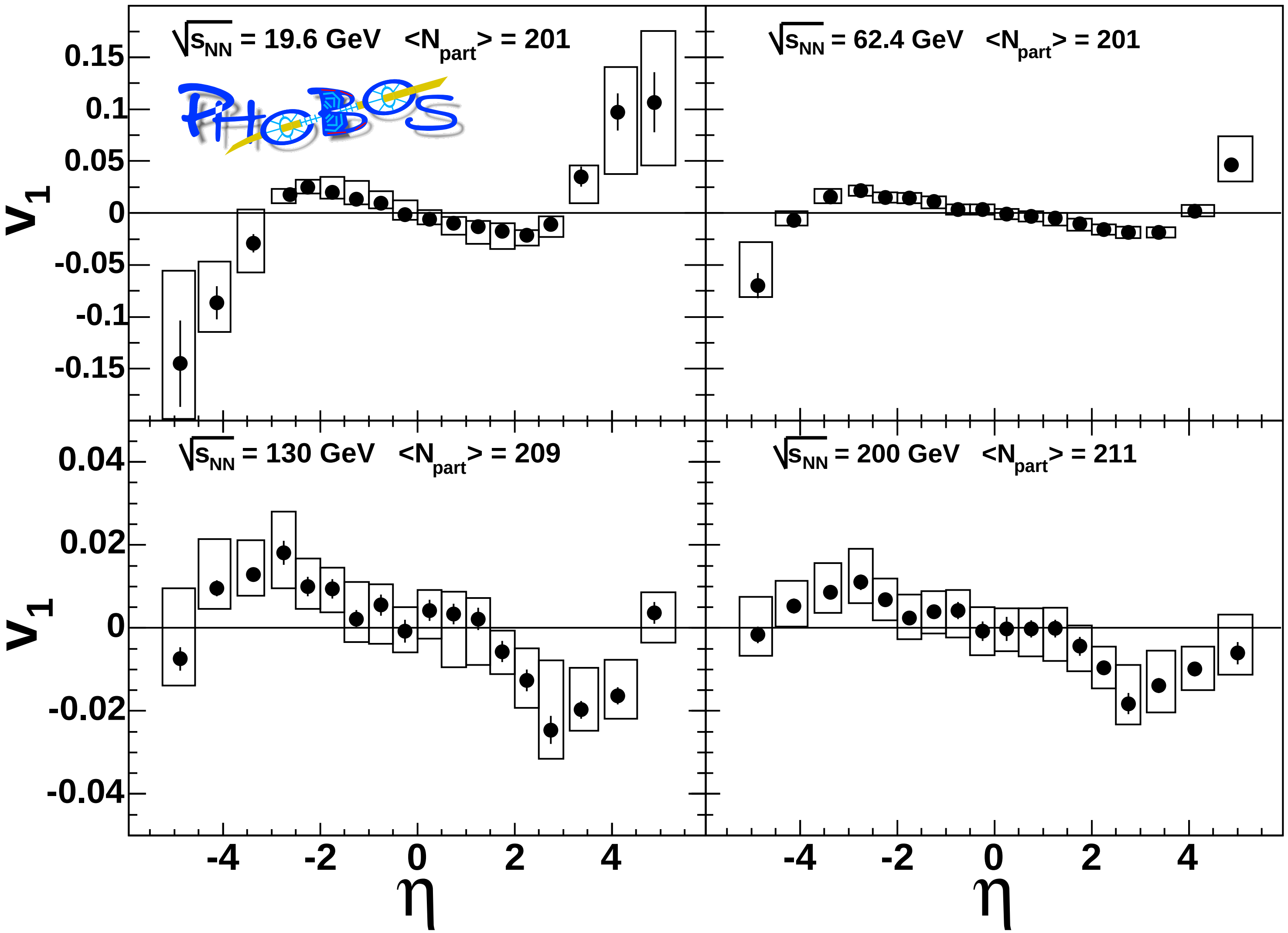
☞ "mass-ordering" of the $v_2(p_T)$

Anisotropic flow at RHIC: a short review [2/6]

Flow has been measured over a wide range in (pseudo)rapidity

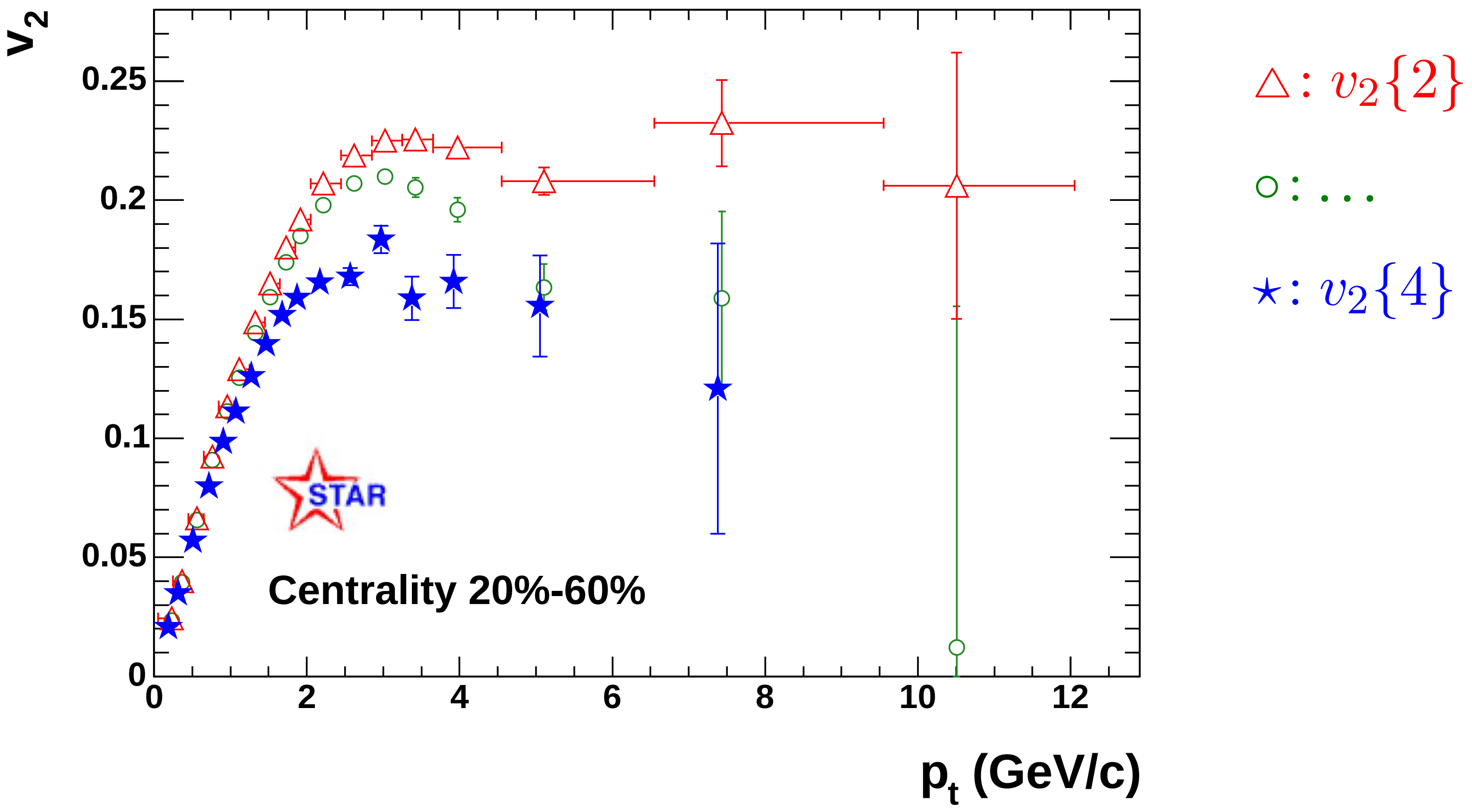


Anisotropic flow at RHIC
a short review [3/6]

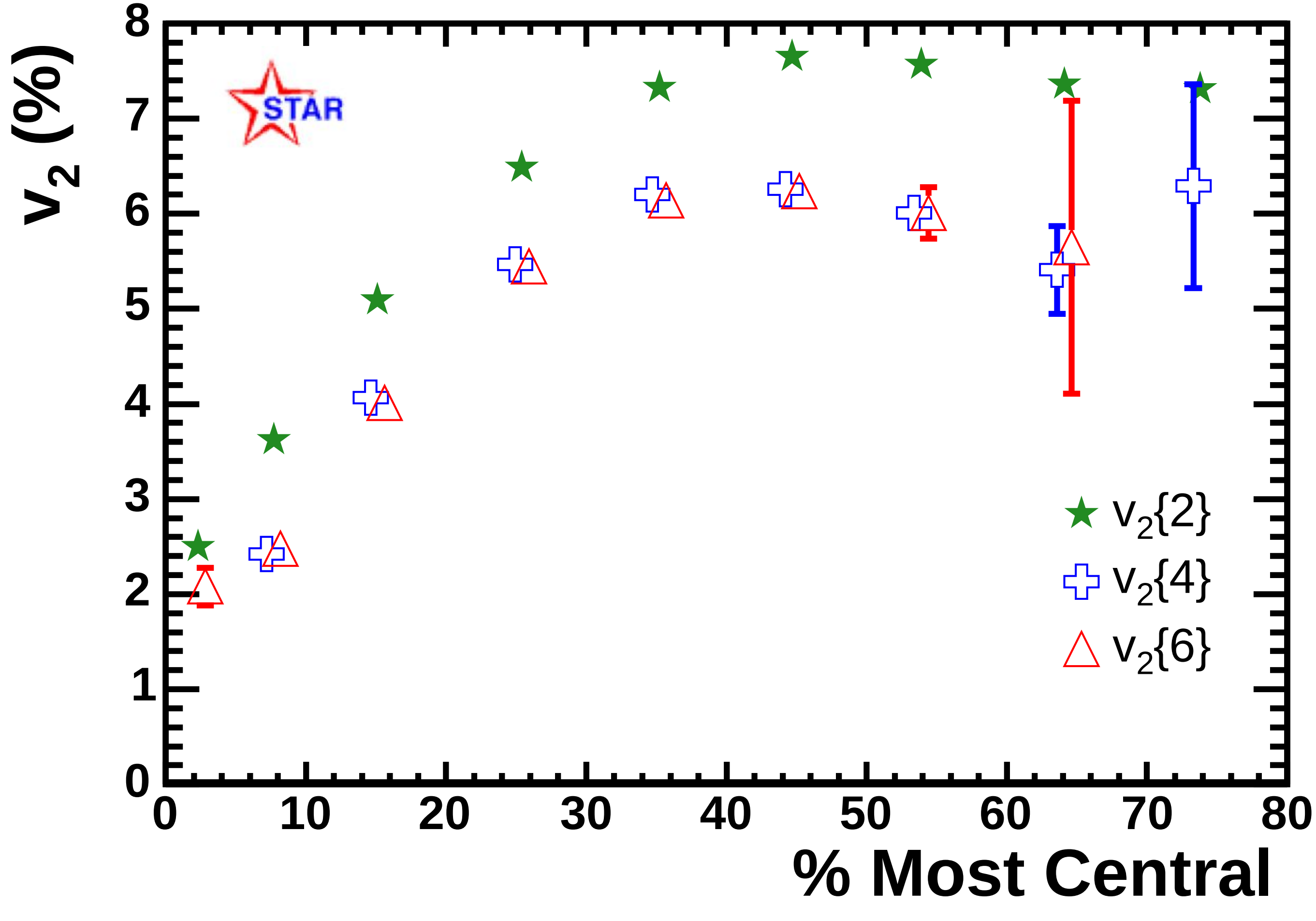


Anisotropic flow at RHIC: a short review [4/6]

The measurements extend to high values of transverse momentum, and have been performed using different methods of analysis

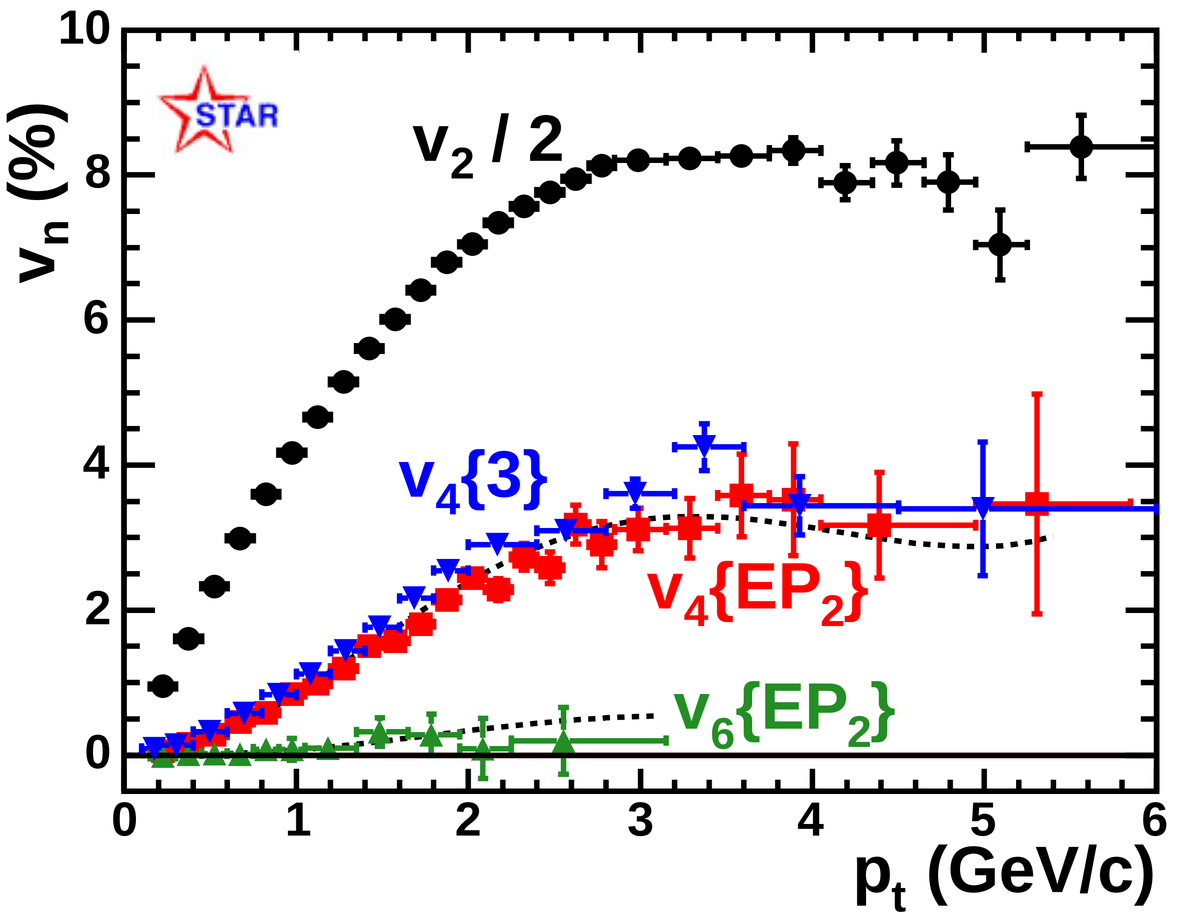


Anisotropic flow at RHIC: a short review [5/6]



Anisotropic flow at RHIC: a short review [6/6]

First measurement of v_4 + upper bounds on v_6 and v_8



Anisotropic flow at RHIC: phenomenology

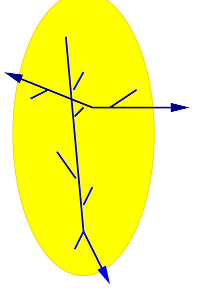
What do we learn from the measurements of anisotropic flow at RHIC?

- "Low-p_T" region: more in the next slides!
- 2 GeV$\lesssim p_T \lesssim$ 5 GeV: coalescence picture

$$v_2(p_T) \approx n_q v_2\left(\frac{p_T}{n_q}\right)$$

assuming hadrons are made of constituent quarks only.

- "High-p_T": anisotropic flow from jet-quenching



The amount of energy/momentum lost by a high-p_T parton depends on the length of its in-medium path, hence on $\phi - \Phi_R$

$\Rightarrow$ at a given momentum, less depletion in-plane than out-of-plane

$$v_2(p_T) > 0$$

(See also the "jets in the wind" of Carlos & Urs, `hep-ph/0411341`)

Anisotropic flow at RHIC: the fashionable view

BROOKHAVEN NATIONAL LABORATORY

RHIC Scientists Serve Up "Perfect" Liquid

New state of matter more remarkable than predicted -- raising many new questions

April 18, 2005

Ideal fluid dynamics reproduce both p_t spectra and elliptic flow $v_2(p_t)$ of soft ($p_t \lesssim 2$ GeV/c) identified particles for minimum bias collisions, near central rapidity.

This agreement necessitates a soft equation of state, and very short thermalization times: $\tau_{\text{thermalization}} < 0.6$ fm$/c$.

$\Rightarrow$ **strongly interacting Quark-Gluon Plasma**

Fluid dynamics: various types of flow

- **Thermodynamic equilibrium?** ☞ Knudsen number $Kn = \frac{\lambda}{L}$ (mean free path $\rightarrow \lambda$; system size $\rightarrow L$)
  - $Kn \gg 1$: Free-streaming limit
  - $Kn \ll 1$: Liquid (hydro) limit
- **Viscous or Ideal?** ☞ Reynolds number $Re = \frac{\varepsilon L v_{\rm fluid}}{\eta}$ (viscosity $\rightarrow \eta$; $\eta \sim \varepsilon \lambda c_s$)
  - $Re \gg 1$: Ideal (non-viscous) flow
  - $Re \leq 1$: Viscous flow
- **Compressible or Incompressible?** ☞ Mach number $Ma = \frac{v_{\rm fluid}}{c_s}$ (speed of sound $\rightarrow c_s$)
  - $Ma \ll 1$: Incompressible flow
  - $Ma > 1$: Compressible (supersonic) flow

Fluid dynamics: various types of flow

Three numbers:

$$Kn = \frac{\lambda}{L}, \qquad Re = \frac{\varepsilon L v_{\rm fluid}}{\eta}, \qquad Ma = \frac{v_{\rm fluid}}{c_s}$$

$\Rightarrow$ **an important relation:**

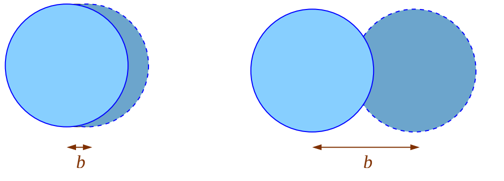
$$Kn \times Re = \frac{\varepsilon\lambda\, v_{\rm fluid}}{\eta} \sim \frac{v_{\rm fluid}}{c_s} = Ma$$

Compressible fluid: "Liquids are Ideal"

Viscosity $\equiv$ departure from equilibrium

Anisotropic flow: predictions of hydro

- Characteristic build-up time of v_2 is $\bar{R}/c_s$
  typical system size ($\bar{R}$) — speed of sound (c_s)
- v_2/ϵ constant across different centralities
  system eccentricity (ϵ)



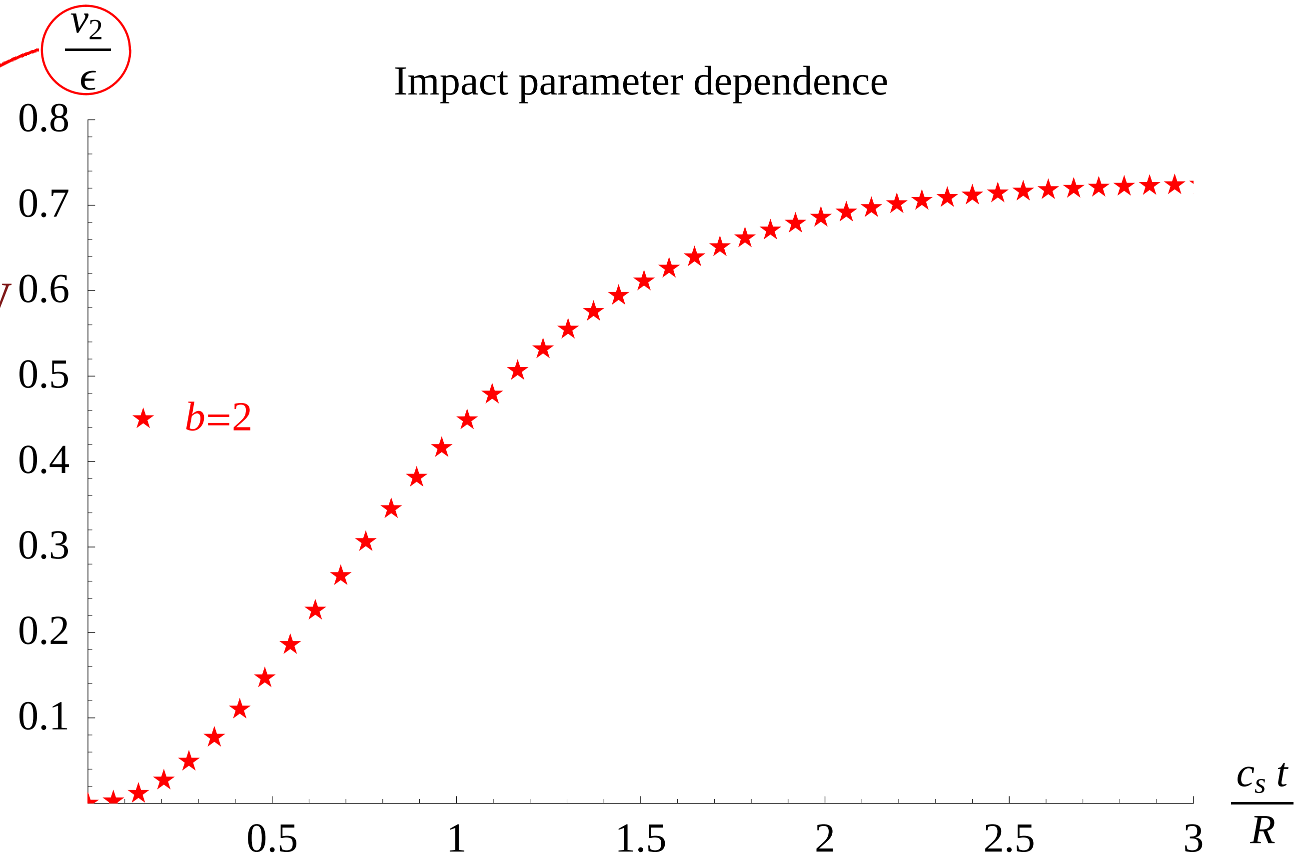
- v_2 roughly independent of the system size (Au–Au vs. Cu–Cu)
- v_2 increases with increasing speed of sound c_s
- Mass-ordering of the $v_2(p_T)$ of different particles
  (the heavier the particle, the smaller its v_2 at a given momentum)
- Relationship between different harmonics: $\dfrac{v_4}{(v_2)^2} = \dfrac{1}{2}$

Dependence of v_2 on centrality

The natural time scale for v_2 is $\bar{R}/c_s$:

massless particles $c_s^2 = \frac{1}{3}$

v_2 scaled by initial eccentricity $\frac{\langle y^2 - x^2 \rangle}{\langle x^2 + y^2 \rangle}$



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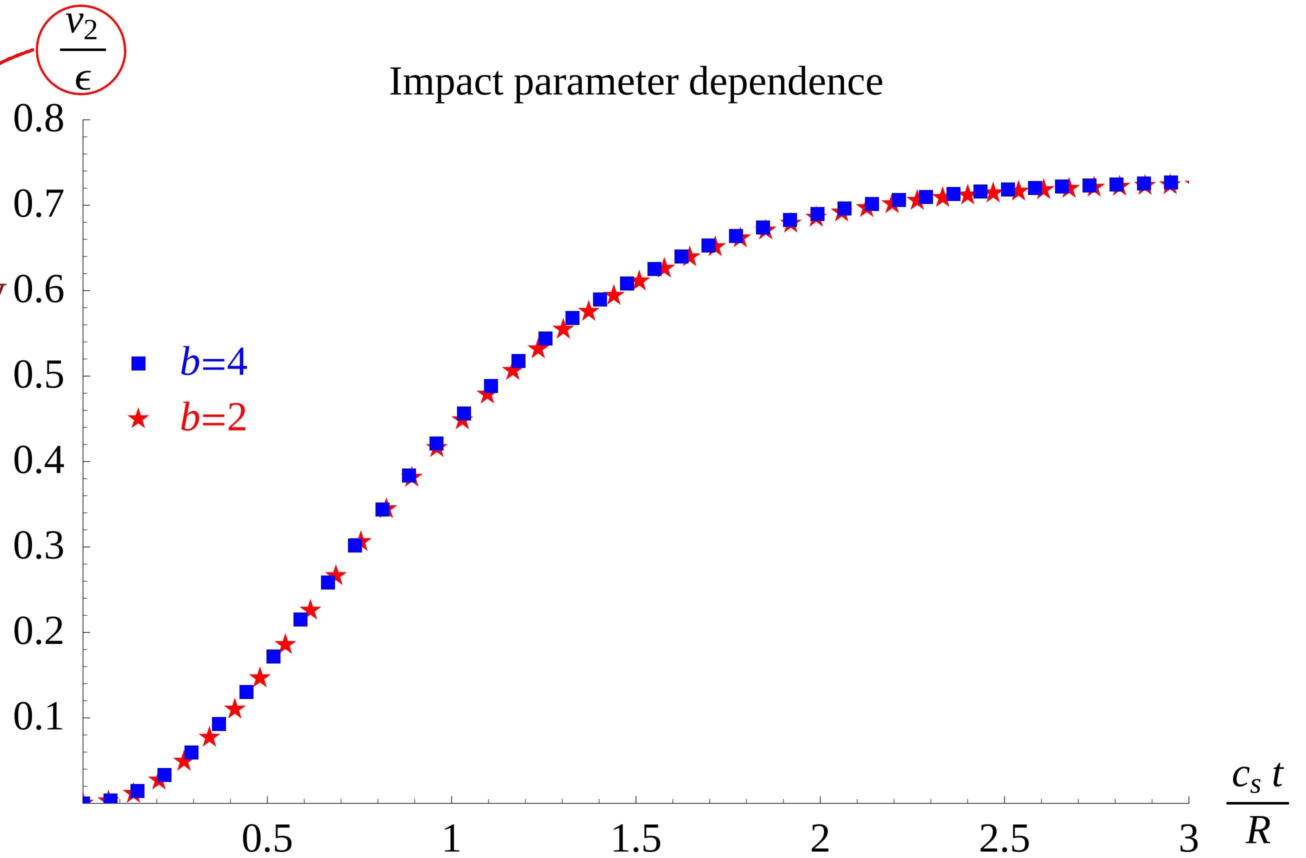

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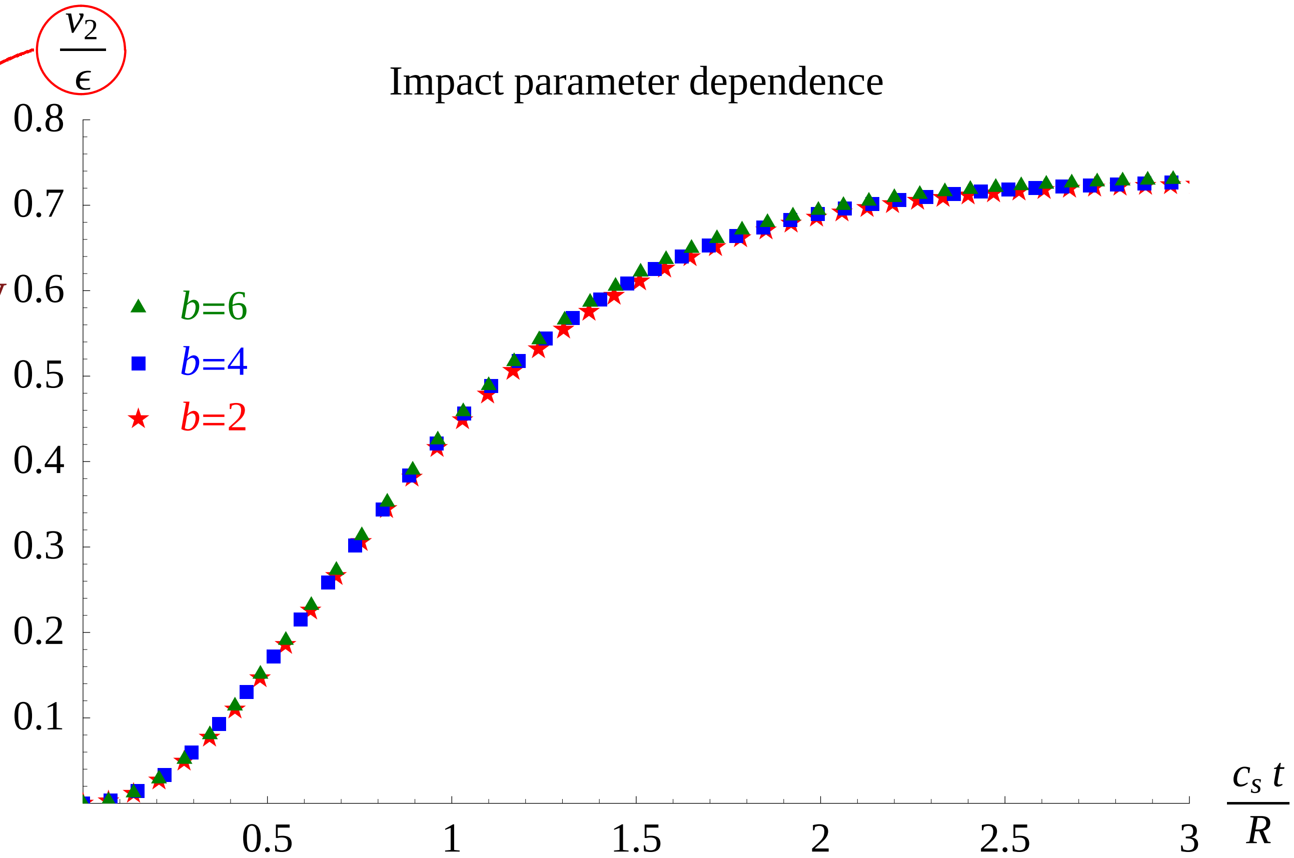

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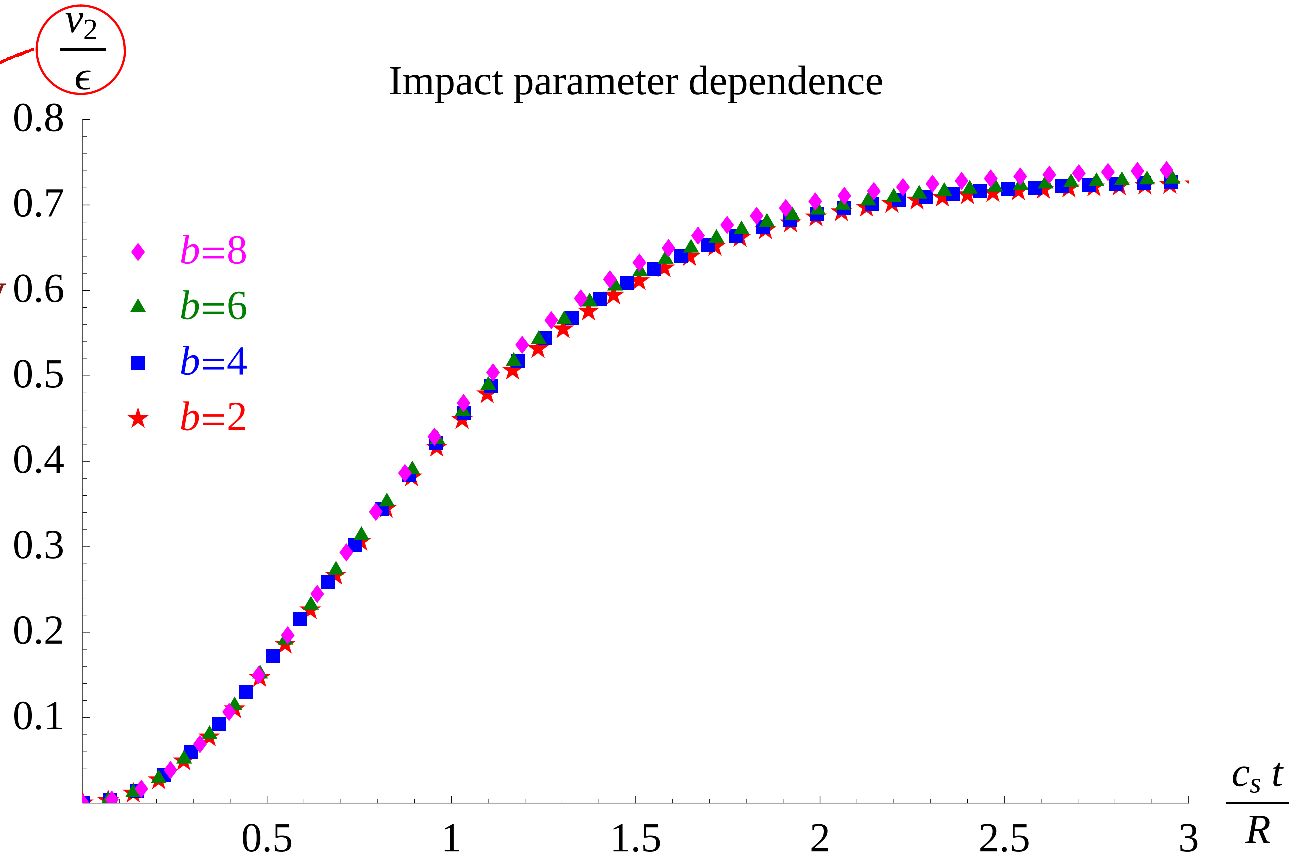

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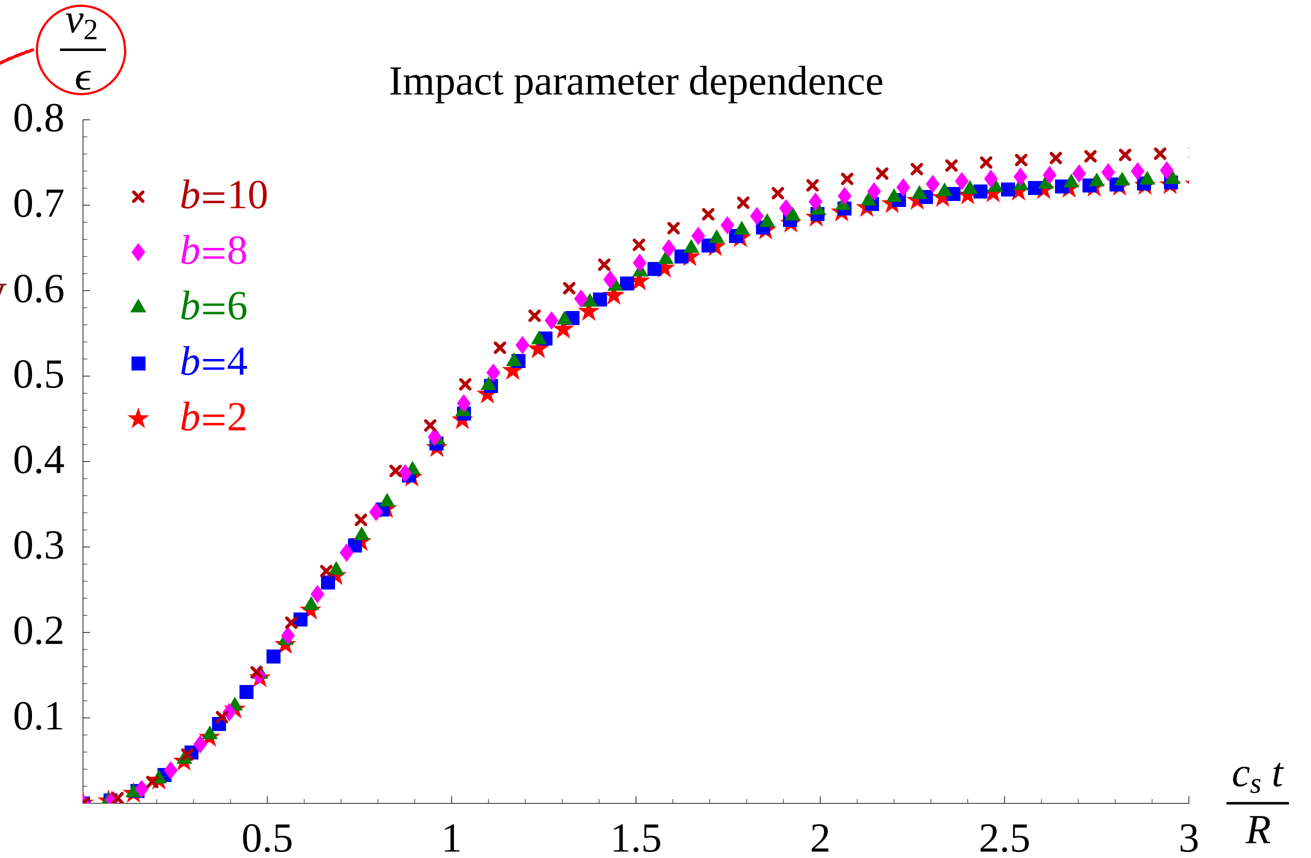

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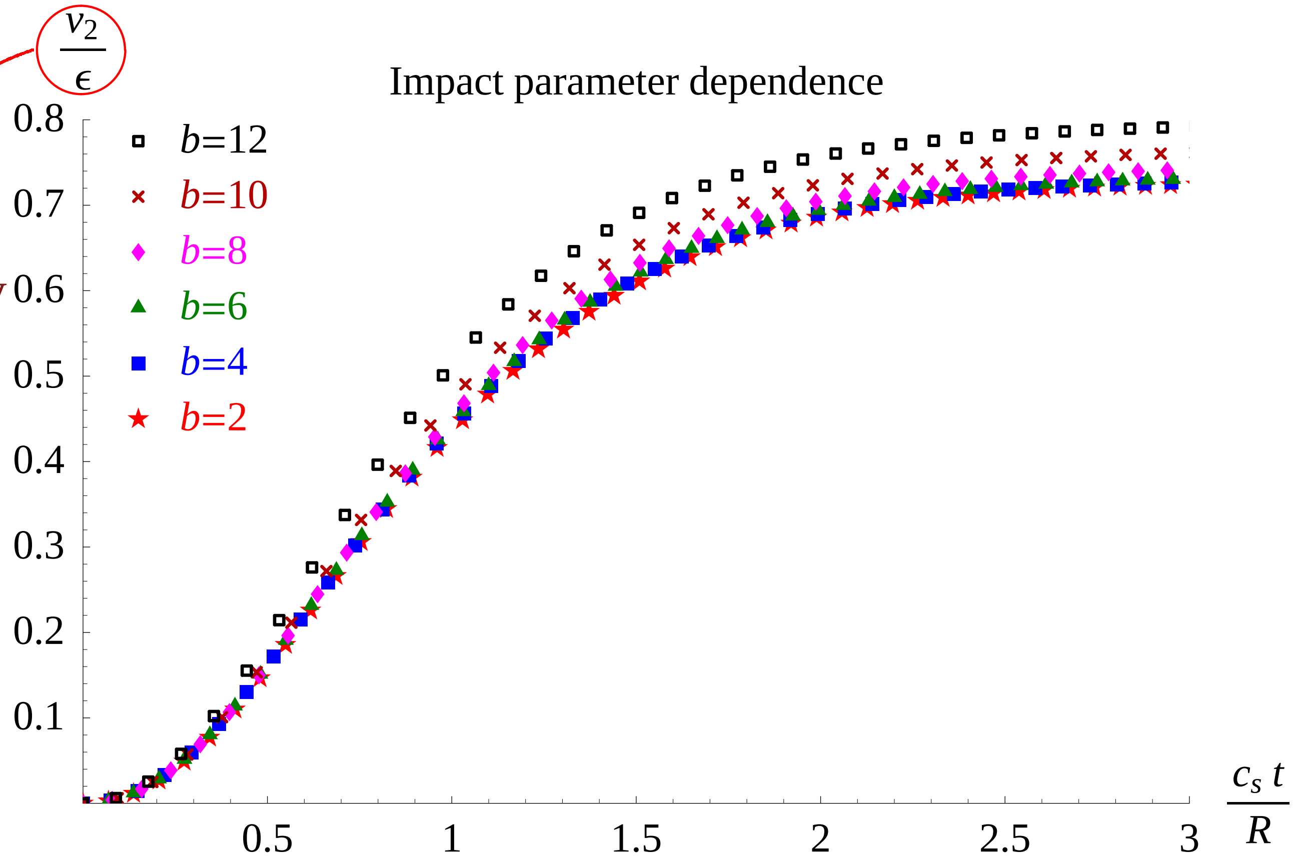
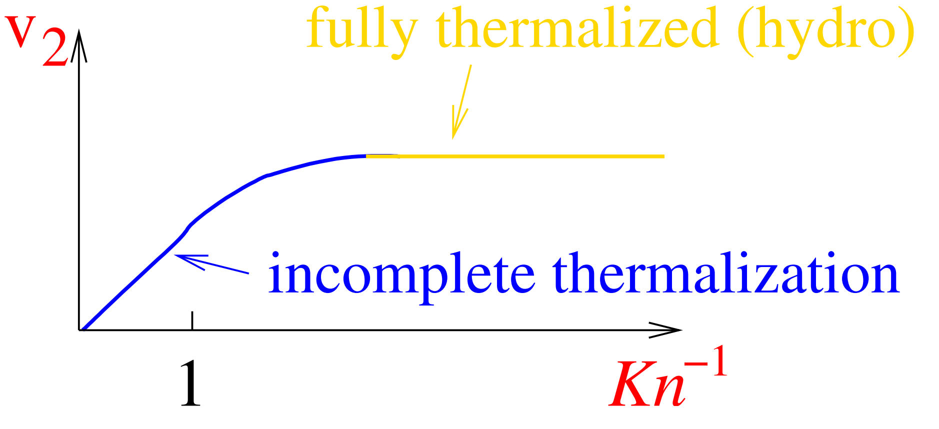


Anisotropic flow:
out-of-equilibrium scenario

An exact computation of the dependence of v_2, v_4 on the number of collisions per particle Kn requires some cascade model…

…but we can guess the general tendency!

- in the absence of reinteractions ($Kn^{-1} = 0$), no flow develops
- the more collisions, the larger the anisotropic flow
- for a given number of collisions, the system thermalizes: further collisions no longer increase v_2



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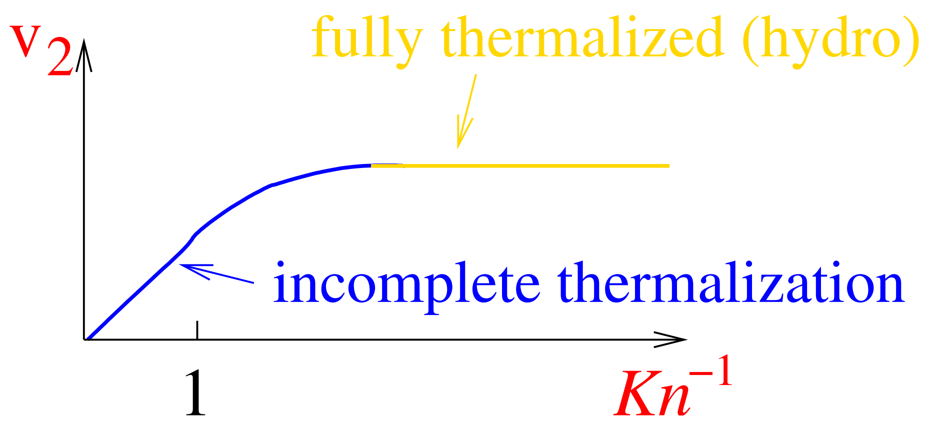
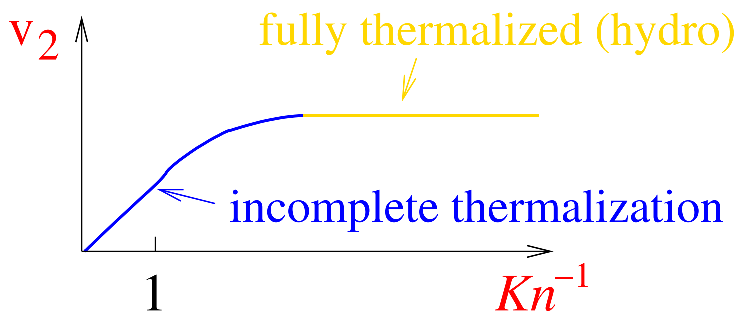
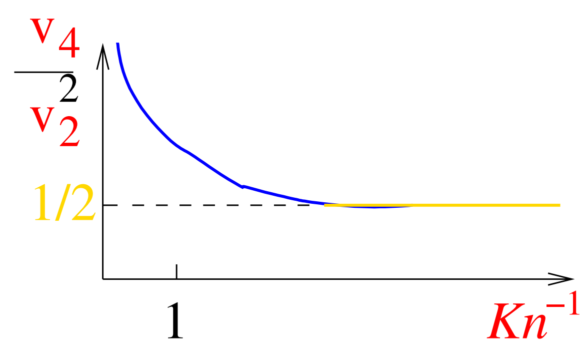
should be quantified!

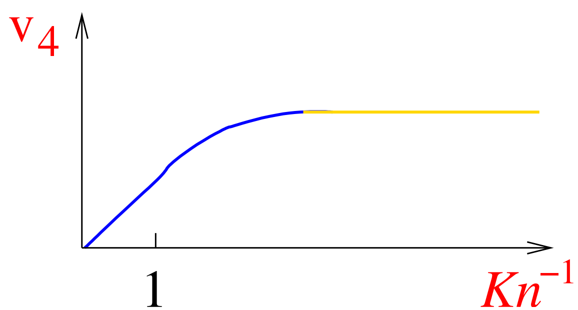


Anisotropic flow: out-of-equilibrium scenario

v_n proportional to the number of collisions Kn^{-1} $\Rightarrow$ $\dfrac{v_4}{(v_2)^2} \propto \dfrac{1}{Kn^{-1}}$







☞ in the out-of-equilibrium scenario, $\dfrac{v_4}{(v_2)^2} > \dfrac{1}{2}$

STAR (PRC **72** (2005) 014904) & PHENIX (QM'05) find $\dfrac{v_4}{(v_2)^2} \approx 1\text{–}1.5$

Out-of-equilibrium scenario: a control parameter

The natural time (resp. length) scale for v_2 is $\bar{R}/c_s$ (resp. $\bar{R}$)

$\Rightarrow$ number of collisions per particle to build up v_2:

$$Kn^{-1} \simeq \frac{\bar{R}}{\lambda} = \bar{R}\,\sigma\,n\left(\frac{\bar{R}}{c_s}\right) \simeq \frac{c_s}{c}\frac{\sigma}{S}\frac{\mathrm{d}N}{\mathrm{d}y}$$

σ interaction cross section, $n(\tau)$ particle density, S transverse surface

☞ in the out-of-equilibrium scenario, v_2 depends on

- the system size $\bar{R}$

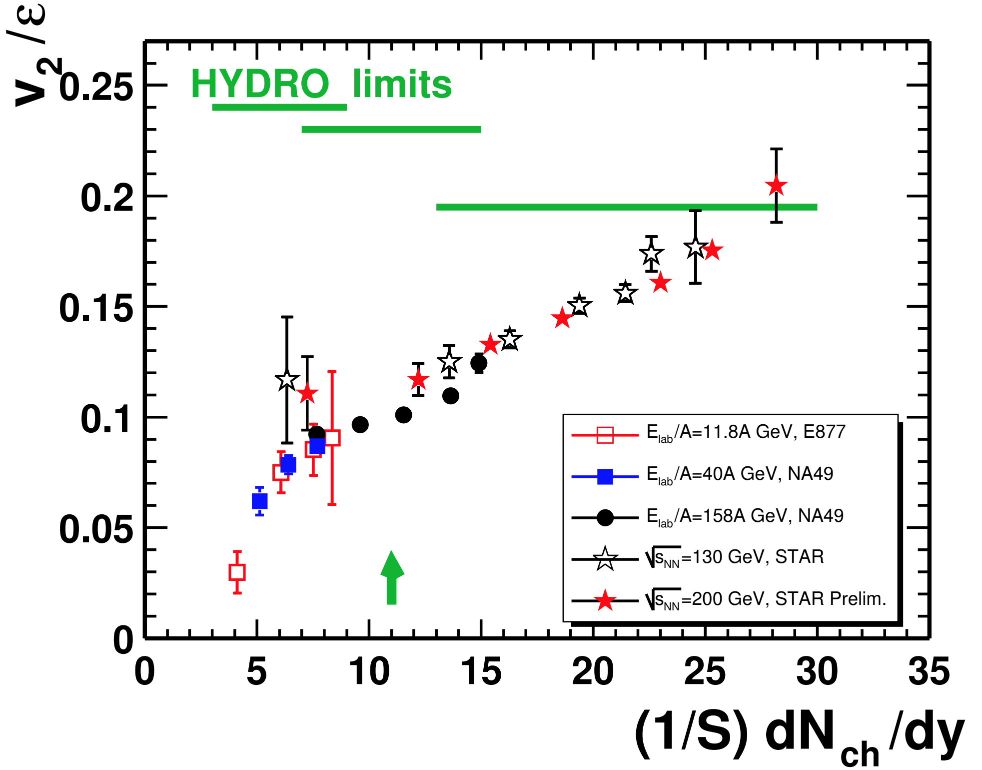
  breakdown of the scale-invariance of hydrodynamics

- the control parameter $\dfrac{1}{S}\dfrac{\mathrm{d}N}{\mathrm{d}y}$

R.S. Bhalerao, J.-P. Blaizot, N.B., J.-Y. Ollitrault, PLB **627** (2005) 49

Incomplete equilibration & RHIC data [1]

Centrality and beam-energy dependence:



NA49 Collaboration, Phys. Rev. C **68** (2003) 034903

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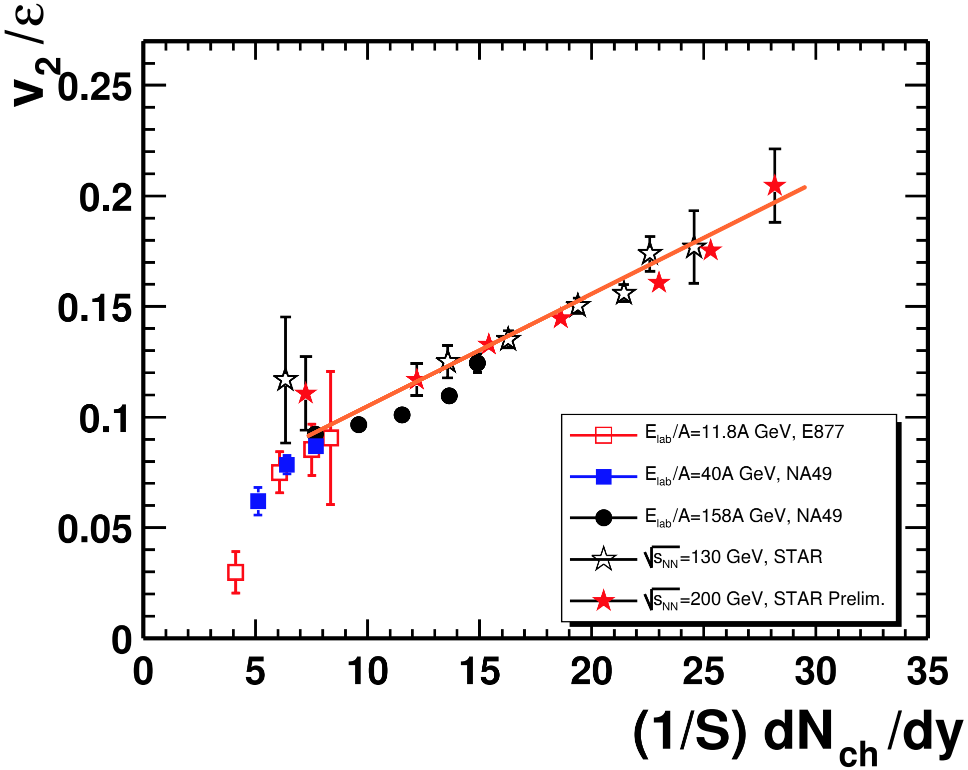


NA49 Collaboration, Phys. Rev. C **68** (2003) 034903

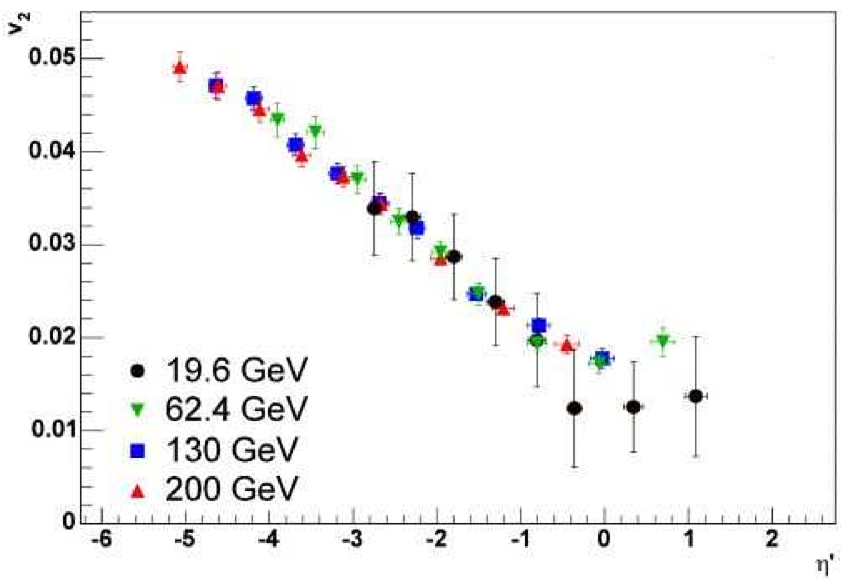
Scaling law seems to work for RHIC data (+ matching with SPS)

$v_2(Kn^{-1})$ increases steadily (no hint at hydro saturation in the data)

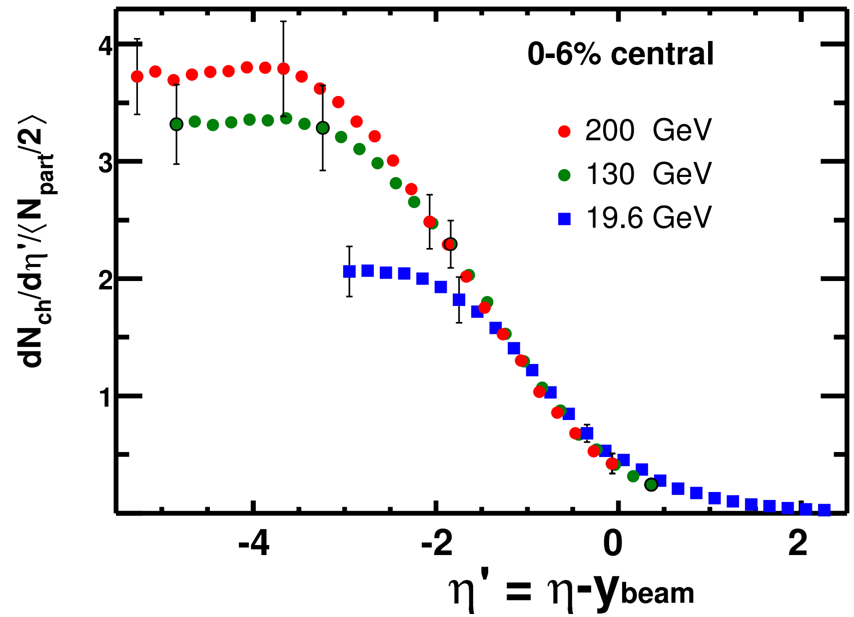
Incomplete equilibration & RHIC data [2]

(Pseudo)rapidity dependence of v_2

Steve Manly (PHOBOS Coll.)
QM'05



PHOBOS Collaboration
Phys. Rev. Lett. **91** (2003) 052303



☞ $v_2(\eta)$ and $\dfrac{\mathrm{d}N}{\mathrm{d}y}$ approximately proportional $\Leftrightarrow$ $v_2 \propto Kn^{-1}$

Hirano, Phys. Rev. C **65** (2002) 011901

Anisotropic flow at RHIC

Conflicting interpretations:

- Perfect liquid: $\lambda \ll \bar{R}$

  see e.g. T. Hirano, U. Heinz, D. Kharzeev, R. Lacey, Y. Nara, `nucl-th/0511046`

- Out-of-equilibrium scenario: $\lambda \sim \bar{R}$
  - rapidity dependence $v_2(y)$
  - dependence with the mean number of collisions $v_2(Kn^{-1})$
  - $\dfrac{v_4}{(v_2)^2} > \dfrac{1}{2}$

  advocated in R.S. Bhalerao, J.-P. Blaizot, N.B., J.-Y. Ollitrault, PLB **627** (2005) 49

Anisotropic flow at LHC: theoretical predictions

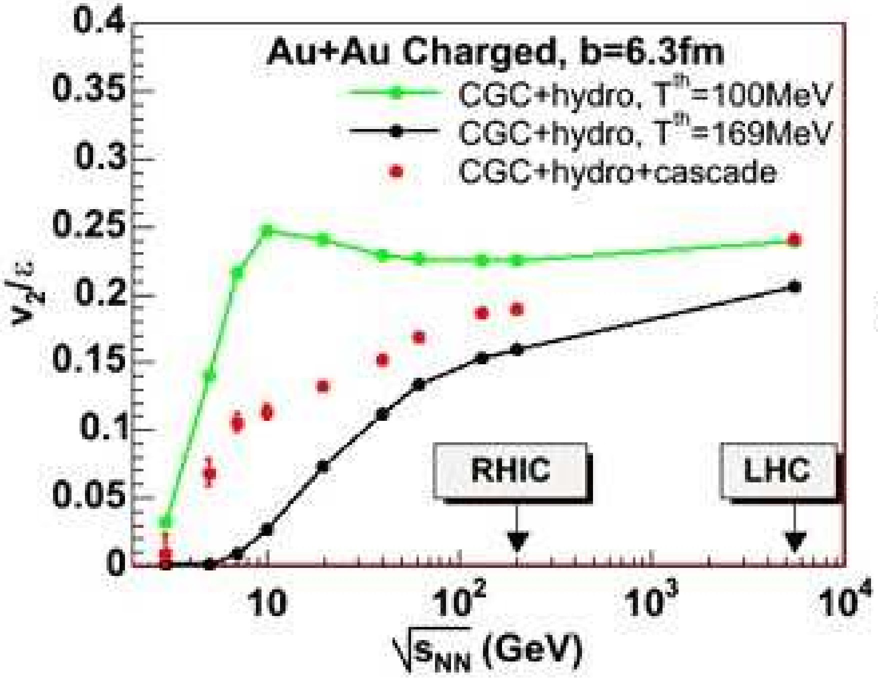
Very few predictions… 

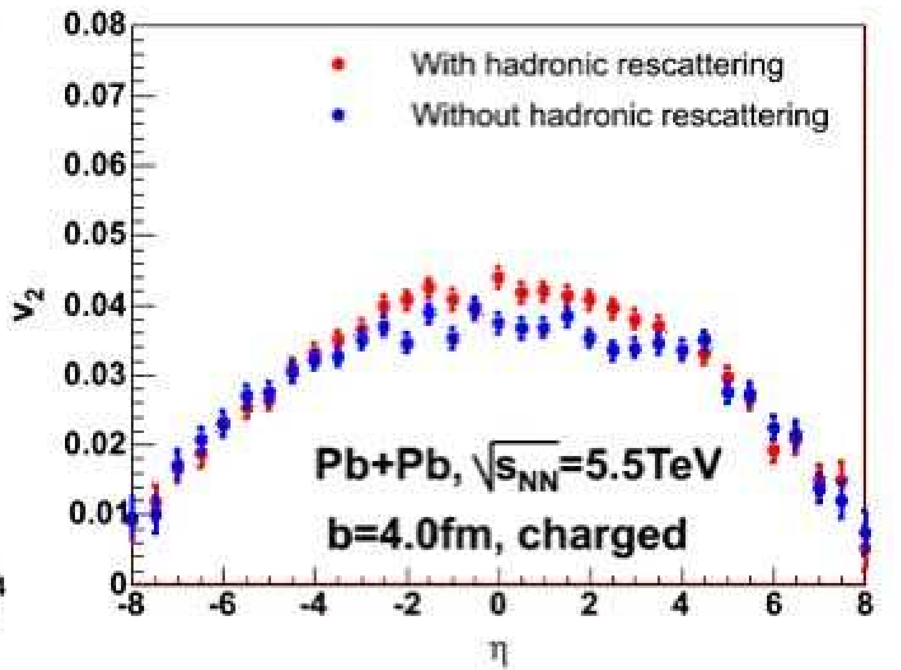
- D. Teaney, E.V. Shuryak, PRL **83** (1999) 4951:
  v_2 increases from SPS to LHC
- P.F. Kolb, J. Sollfrank, U. Heinz:
  - PLB **459** (1999) 667: v_2, v_4 constant from RHIC to LHC (v_2 smaller than at SPS);
  - PRC **62** (2000) 054909: v_2 increases from RHIC to LHC.
- R.S. Bhalerao, J.-P. Blaizot, N.B., J.-Y. Ollitrault, PLB **627** (2005) 49
  - v_2 larger than at RHIC;
  - $\dfrac{v_4}{(v_2)^2}$ smaller than at RHIC, closer to $\dfrac{1}{2}$
- T. Hirano, preliminary results presented in Vienna, August 2005

Anisotropic flow at LHC: theoretical predictions

...stolen from T. Hirano's extra slides in his Vienna talk:

CGC initial conditions + Hydro + Cascade



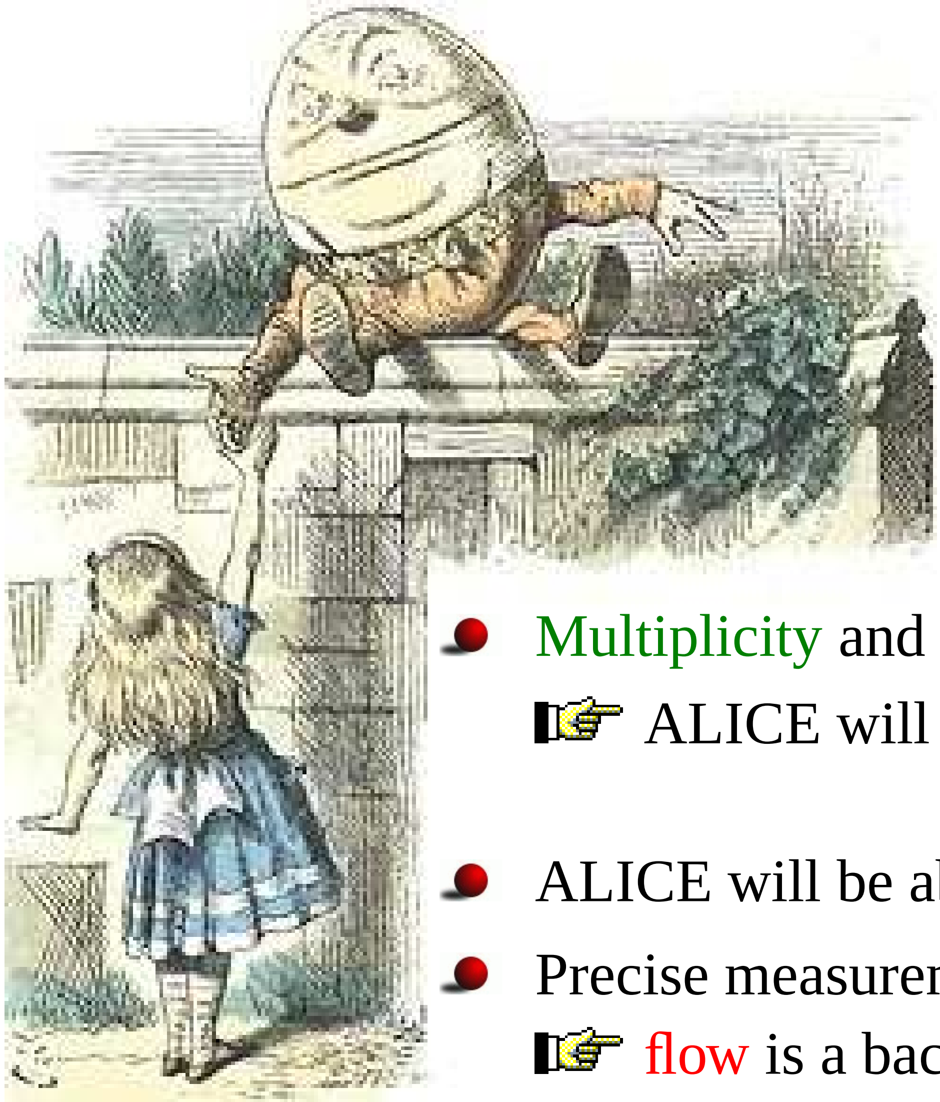


No jet component included;
systematic error from Cooper–Frye formula not estimated

Anisotropic flow at LHC: some high-odds bets

- v_2 larger than at RHIC
  - hydro satisfactory?
  - $v_2(p_T) \to 0$ at large p_T?
- v_4 sizeable $\frac{v_4(p_T)}{(v_2(p_T))^2}$?
- v_1 “smaller” than at RHIC

Anisotropic flow at LHC: some high-odds bets



- v_2 larger than at RHIC
  - hydro satisfactory?
  - $v_2(p_T) \to 0$ at large p_T?
- v_4 sizeable $\quad \dfrac{v_4(p_T)}{(v_2(p_T))^2}$?
- v_1 “smaller” than at RHIC
- Multiplicity and v_2 larger than at RHIC

☞ ALICE will measure v_2 on day 1! (or not long after) → using improved methods

- ALICE will be able to measure v_4, v_1 (and v_6, $v_8 \simeq 0$)
- Precise measurements of v_2, v_4 will be needed

☞ flow is a background for other studies (jets...)