

Elliptic flow fluctuations and non-flow correlations

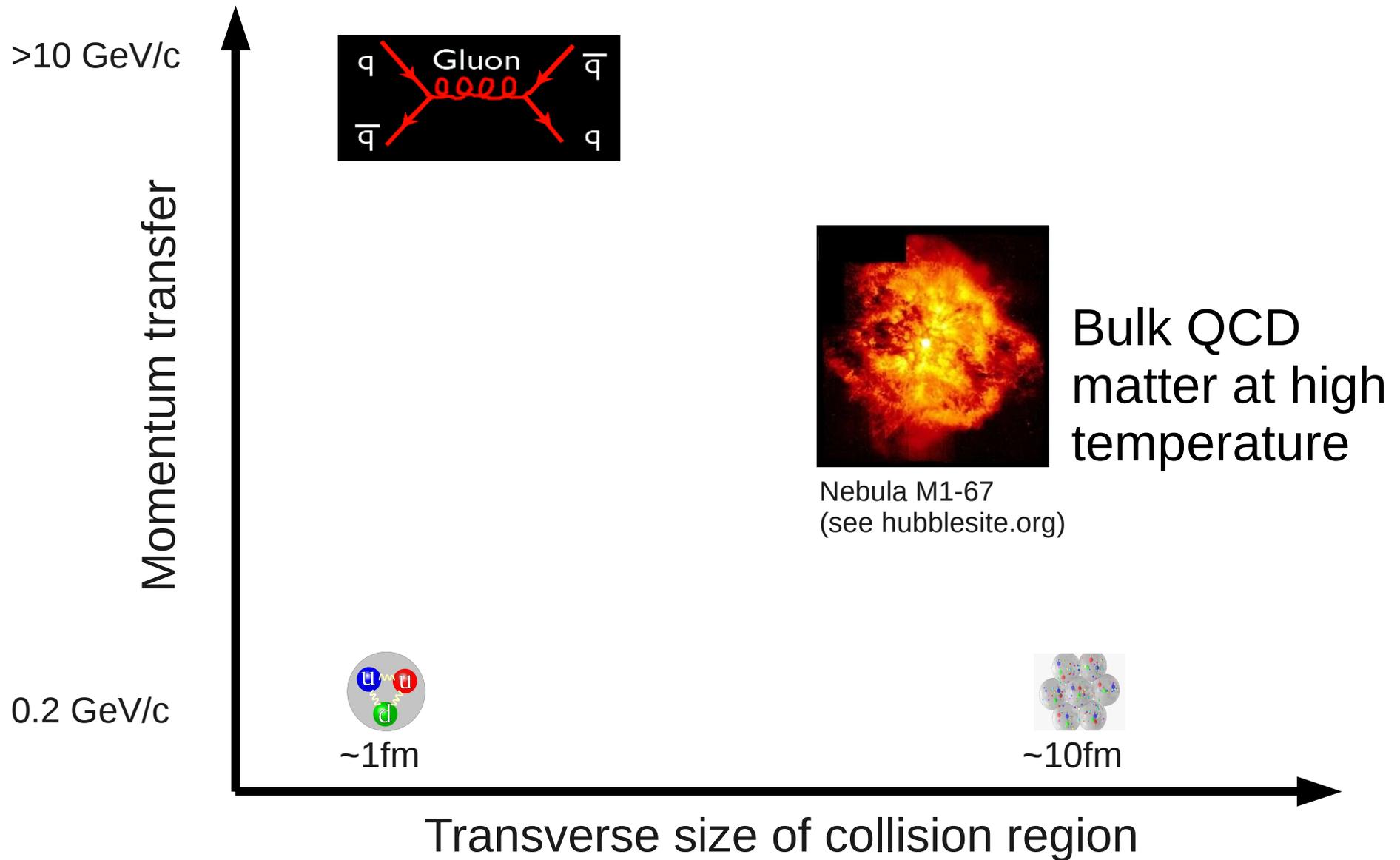
Constantin Loizides
(MIT)

V Workshop on Particle Correlations and Femtoscopy



Study of bulk QCD matter

2



The screenshot shows the AIP website interface. At the top, there is a search bar with the text "SEARCH AIP" and a "go" button. Below the search bar, the text "AMERICAN INSTITUTE OF PHYSICS" is displayed. To the right of the search bar, there are links for "home", "contact us", and "site map". The main heading is "Physics News Update" with the subtitle "The AIP Bulletin of Physics News". Below this, the article information is shown: "Number 757 #1, December 7, 2005 by Phil Schewe and Ben Stein". The article title is "The Top Physics Stories for 2005". The article text begins with "At the Relativistic Heavy Ion Collider (RHIC) on Long Island, the four large detector groups agreed, for the first time, on a consensus interpretation of several year's worth of high-energy ion collisions: the fireball made in these collisions -- a sort of stand-in for the primordial universe only a few microseconds after the big bang -- was not a gas of weakly interacting quarks and gluons as earlier expected, but something more like a liquid of strongly interacting quarks and gluons (PNU 728)."

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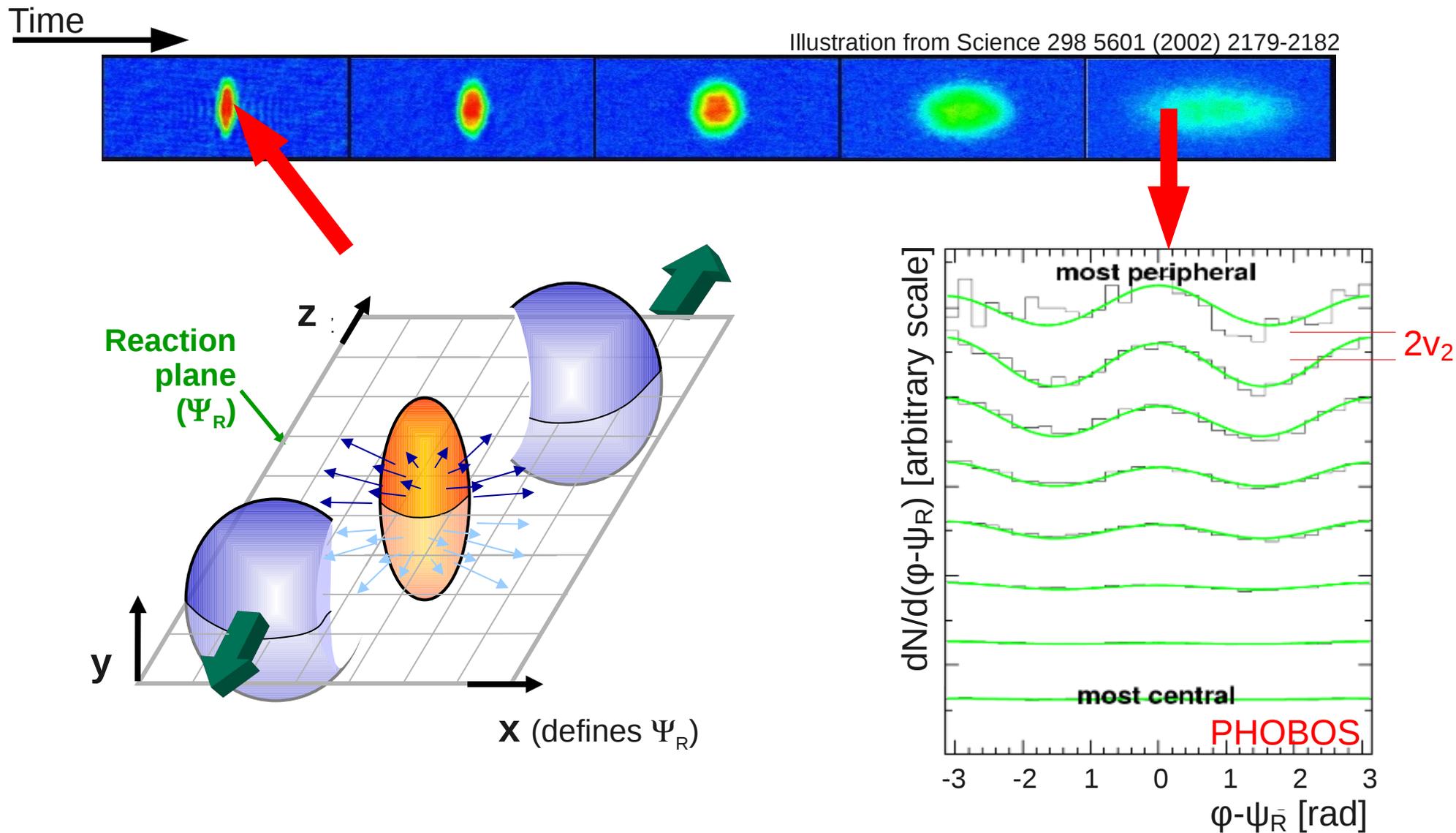
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“... the fireball made in these [heavy-ion] collisions ... was not a gas of weakly interacting quarks and gluons as earlier expected, but **something more like a liquid** of strongly interacting quarks and gluons”

Initial anisotropy and elliptic flow

4



Initial spatial anisotropy
eccentricity ϵ

Interactions
present early

Momentum space anisotropy
 $v_2 = \langle \cos(2\phi - 2\Psi_R) \rangle$

Elliptic flow and ideal hydro

5

Ideal relativistic hydrodynamics

$$T^{\mu\nu} = (e + p)u^\mu u^\nu - p g^{\mu\nu}$$

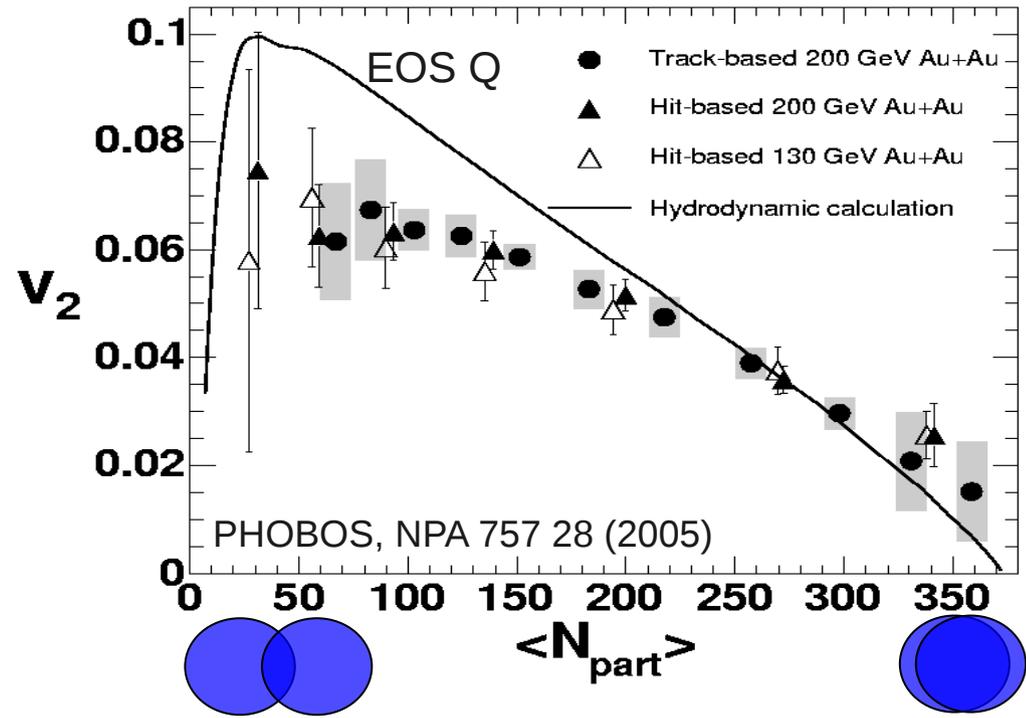
$$\delta_\mu T^{\mu\nu} = 0$$

$$\delta_\mu N_i^\mu = 0, \quad i = B, S, \dots$$

$$p = p(e, n) \quad \text{Closure with EoS}$$

Assumption:

After a short thermalization time ($\leq 1\text{fm}/c$) a system in **local equilibrium** with zero mean free path and zero viscosity is created



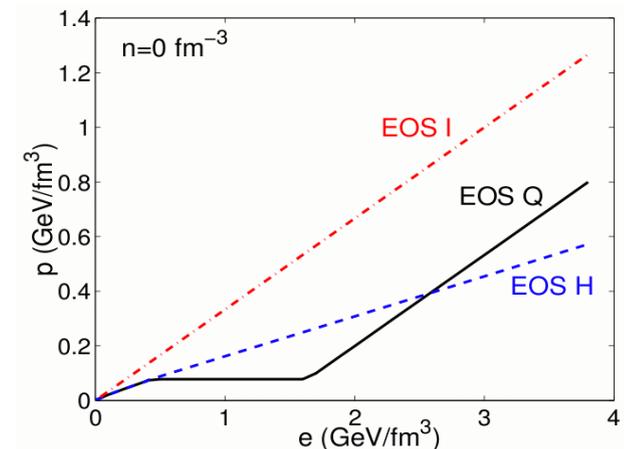
Initial conditions (IC) →

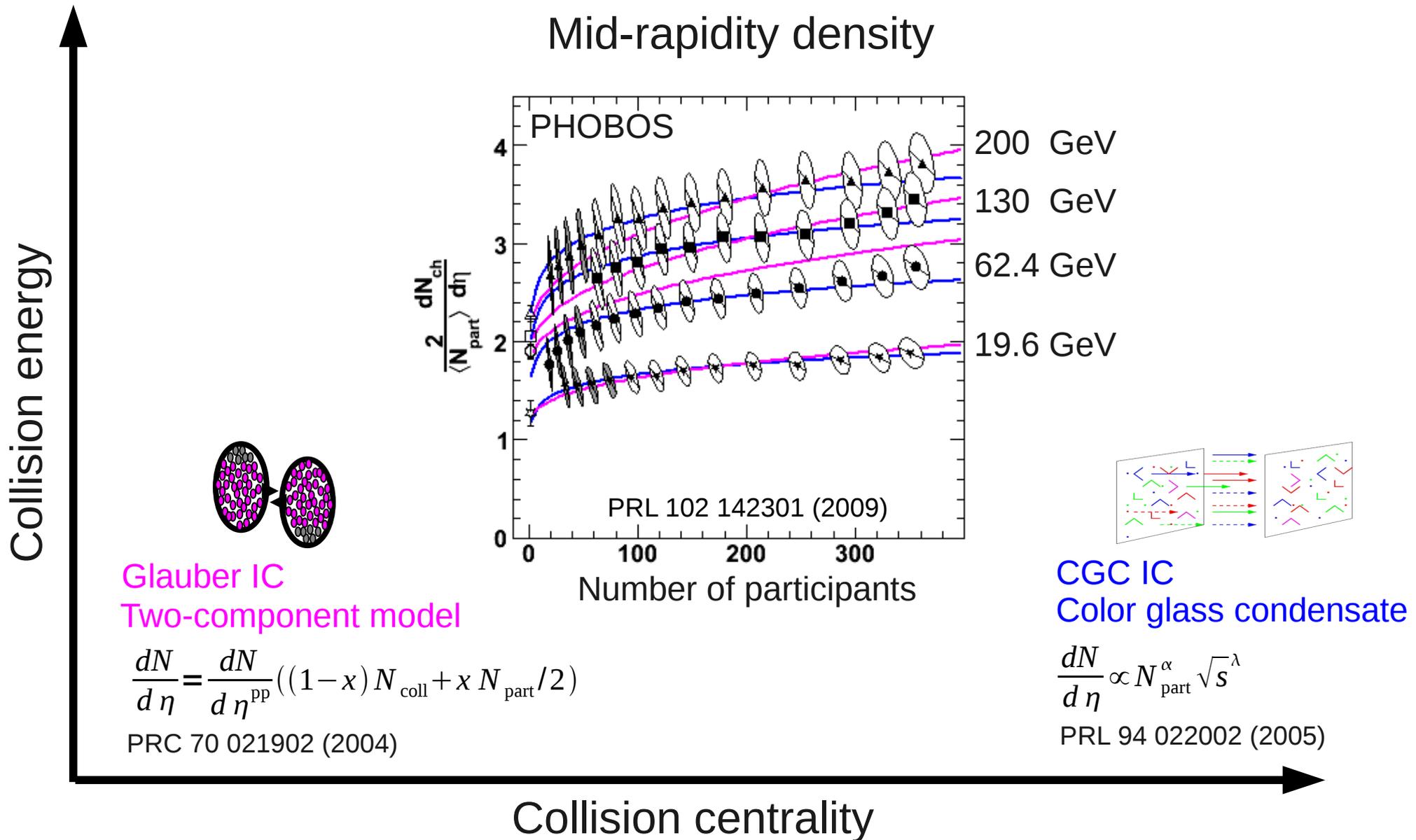
Equation of state (EOS) →

Freeze-out cond. (FO) →

Hydro

→ Observables

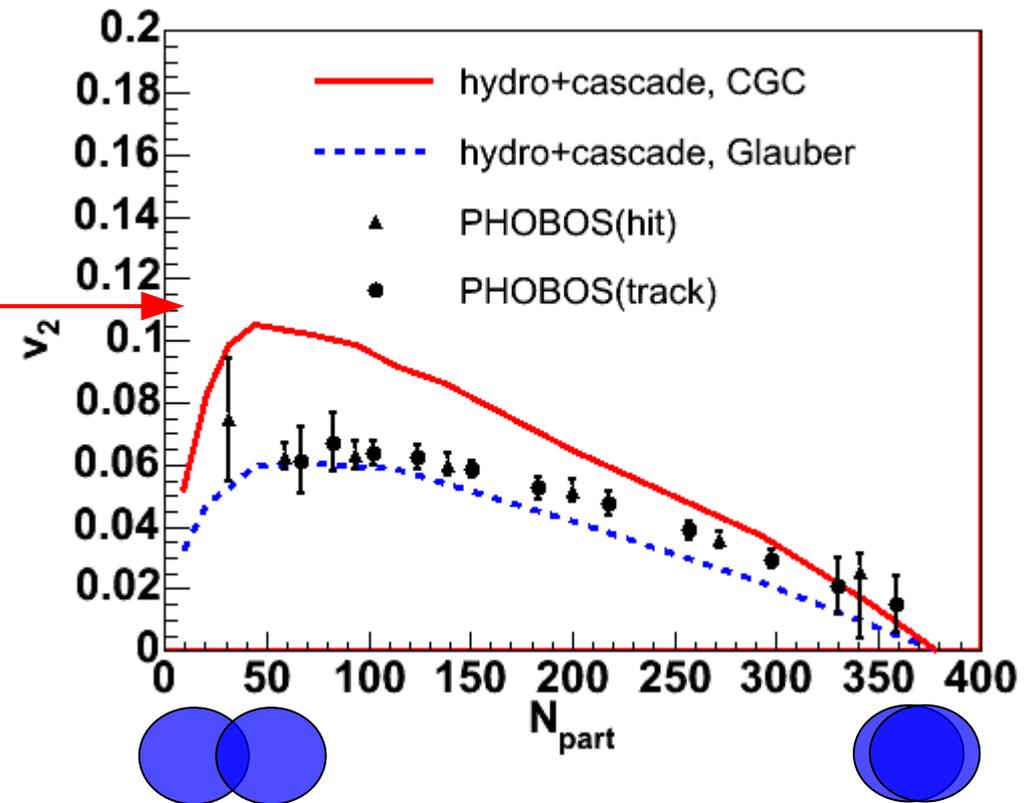
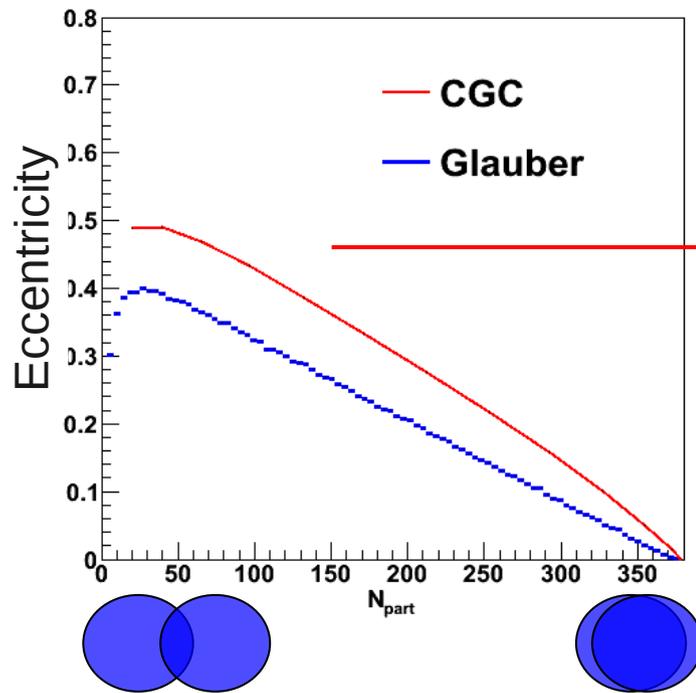




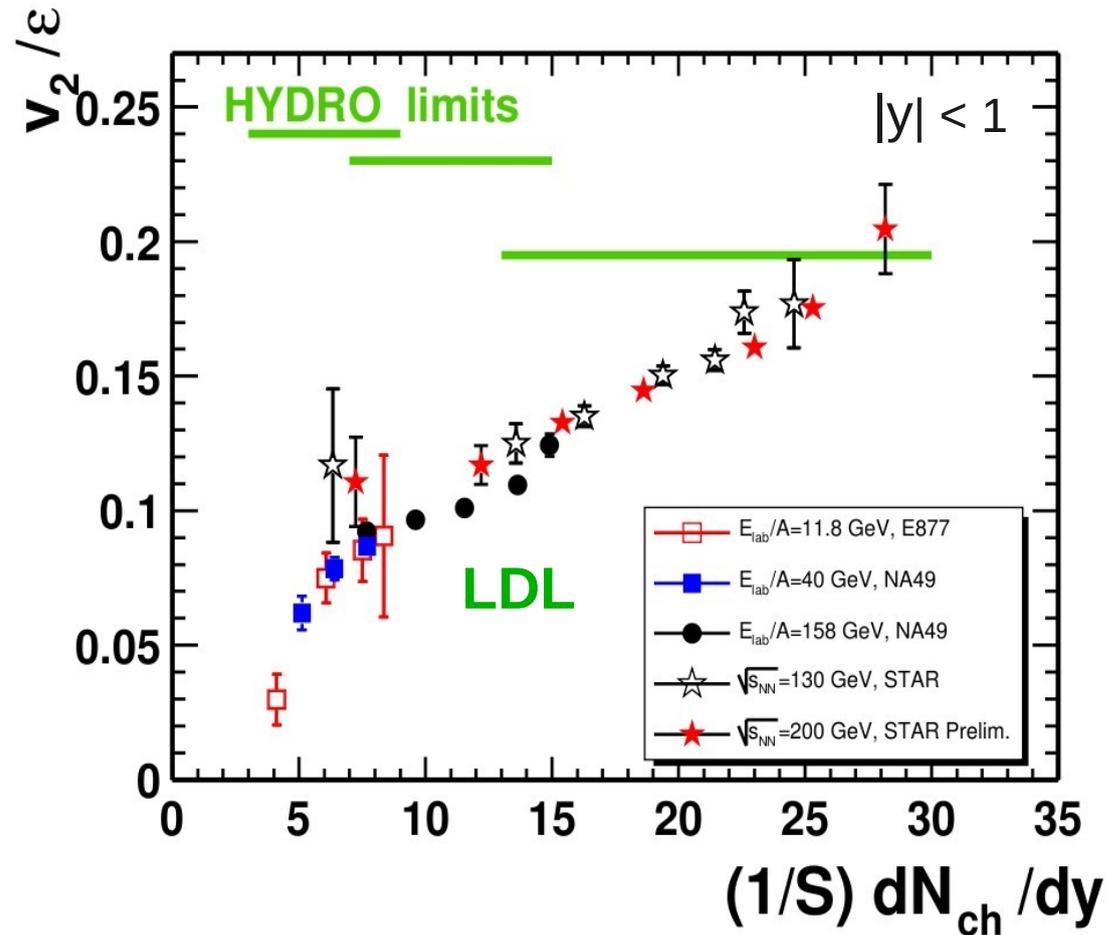
Ambiguity of conclusions

7

Higher eccentricity leads to higher flow

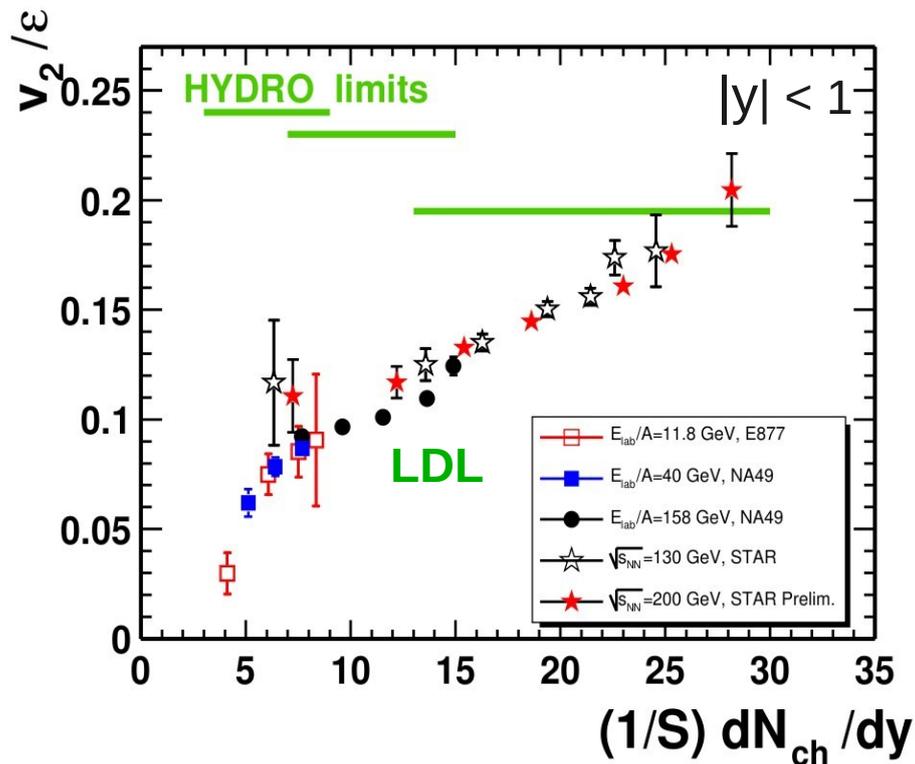


Ambiguity in description of initial state leads to ambiguity of conclusions: viscous corrections and/or soft equation of state?



Geometry should cancel out in the v_2/ϵ ratio.
 In the low density limit region, the ratio rises
 with the number of collisions per particle,
 until it is expected to saturate in the hydro limit.

There are many components in this picture: Each of them has and still is been questioned!



Note:
“Data points” in this plot depend on initial state model for ϵ and S .

- How well do we measure and understand flow
 - System/species comparison
 - Flow and non-flow fluctuations
 - Sensitivity of mean flow methods to underlying fluctuations/correlations
- How well do we model the initial conditions
 - Definition of eccentricity and eccentricity fluctuations
 - Glauber vs CGC
- What is the role of (shear) viscosity
- Does v_2 saturate at the hydrodynamical limit

(Not really covered in this talk)

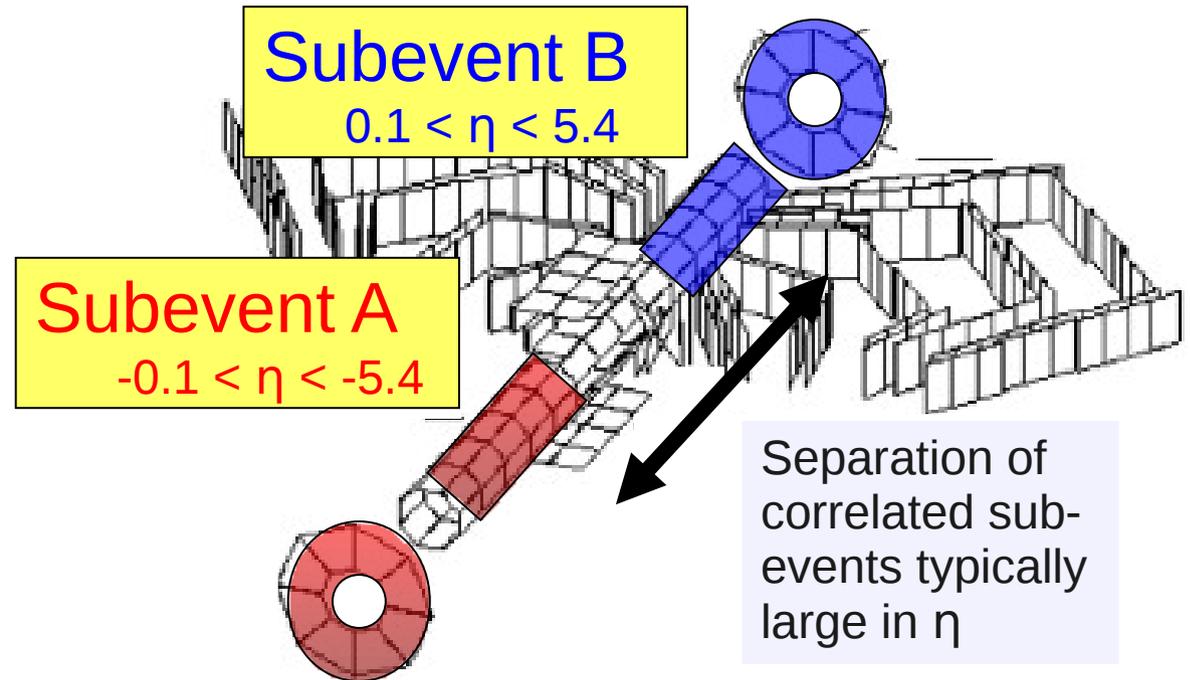
- **Reaction-plane / Sub-event technique**
 - Correlate reaction plane determined from azimuthal pattern of hits in one part of the detector with information from other parts of the detector

$$\tan(2\psi_A) = \frac{\langle \sin(2\phi) \rangle_A}{\langle \cos(2\phi) \rangle_A}$$

$$v_2^{obs} = \langle \cos(2\phi - 2\psi_A) \rangle_B$$

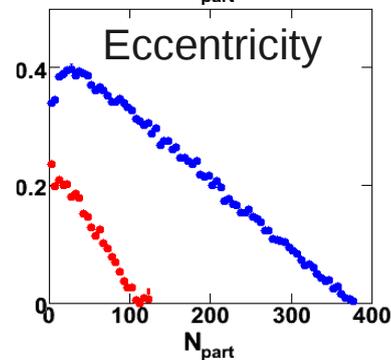
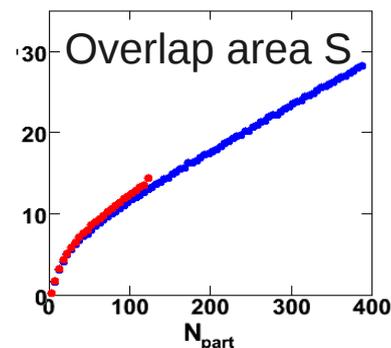
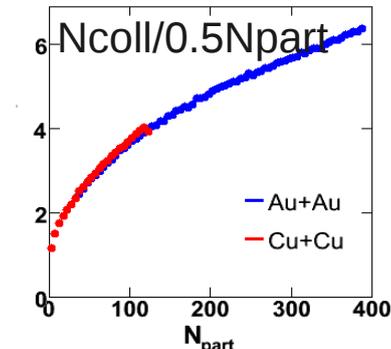
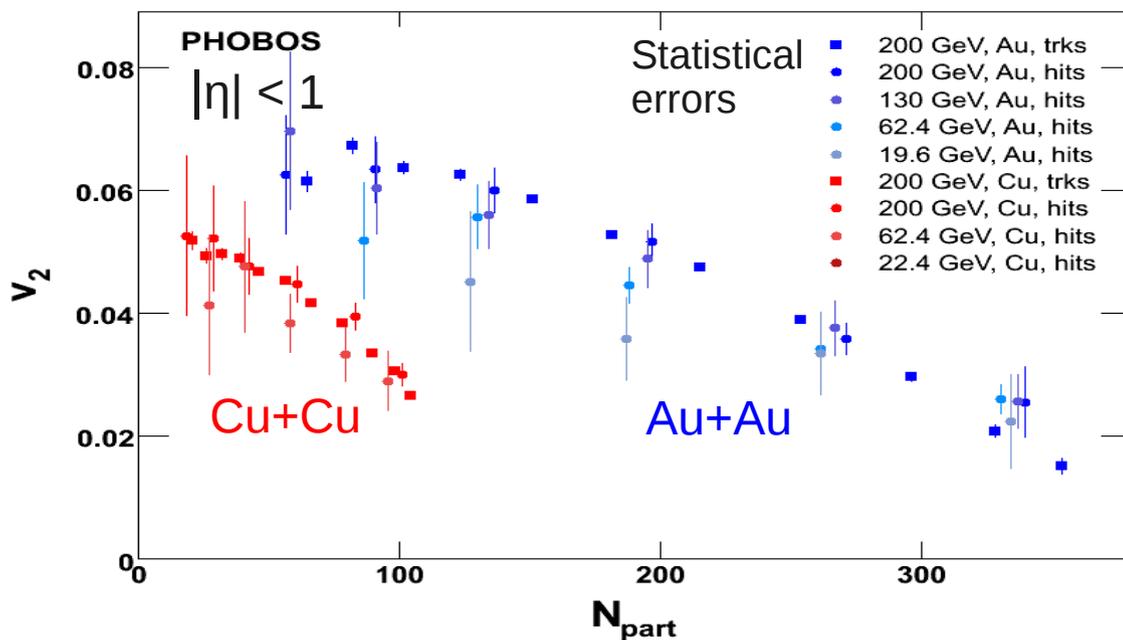
$$V_2 = \frac{\langle v_2^{obs} \rangle_{events}}{\sqrt{\langle \cos(2\psi_A - 2\psi_B) \rangle_{events}}}$$

Poskanzer, Voloshin, nucl-ex/9805001



Resolution correction

QM05



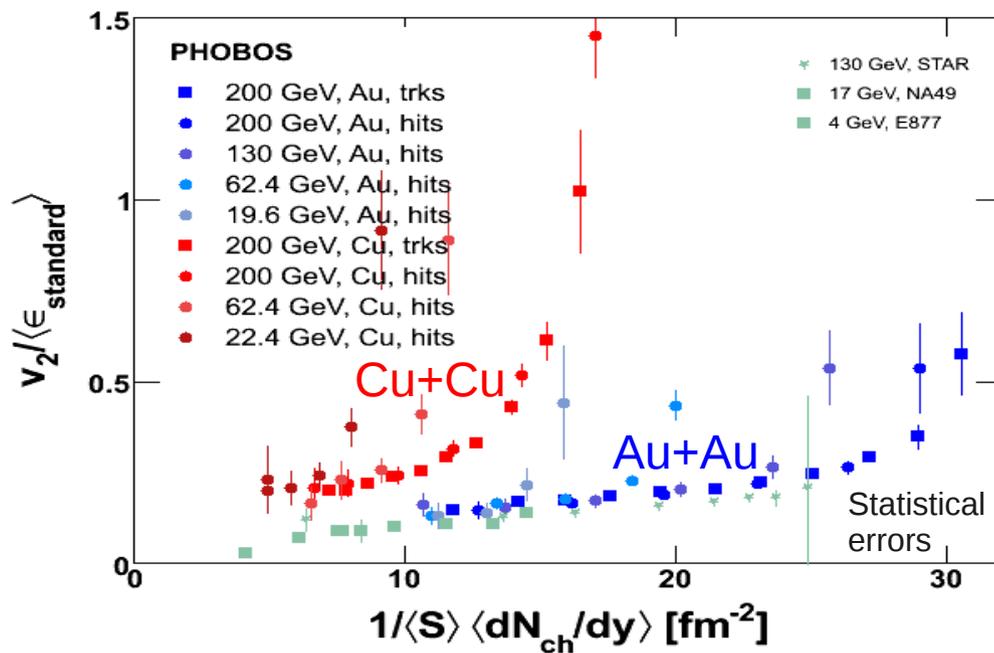
Geometry should cancel out in the v_2/ϵ ratio

PHOBOS, Au+Au, 200,130,62.4+19.6 GeV: PRL 94 122303 (2005)

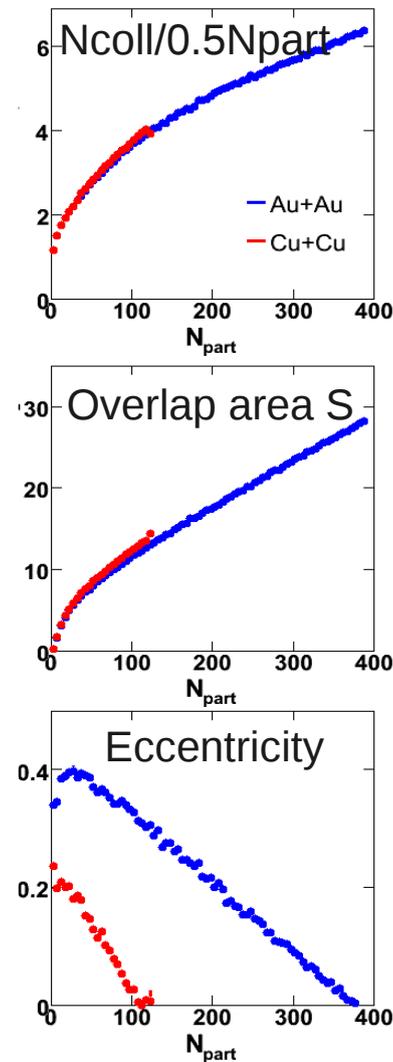
PHOBOS, Cu+Cu, 200+62.4 GeV: PRL 98 242302 (2007)

PHOBOS, Cu+Cu, 22.4 GeV: prel. QM06

QM05

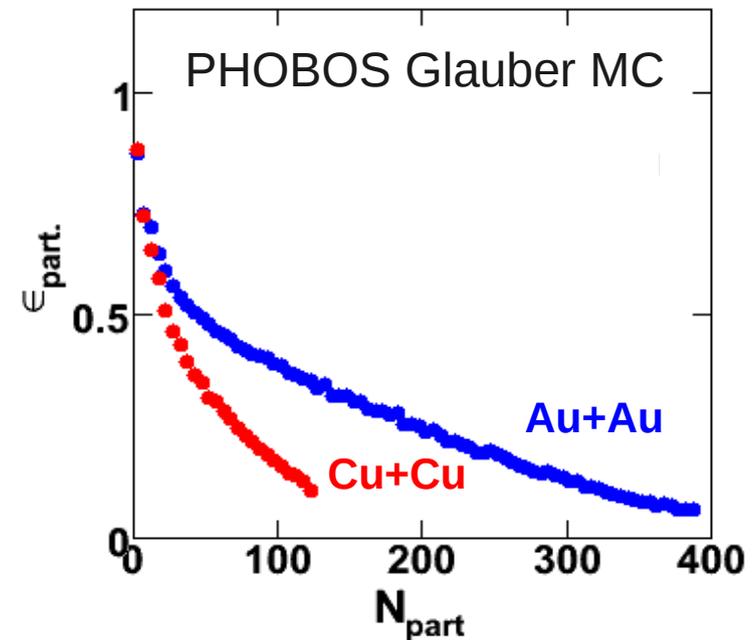
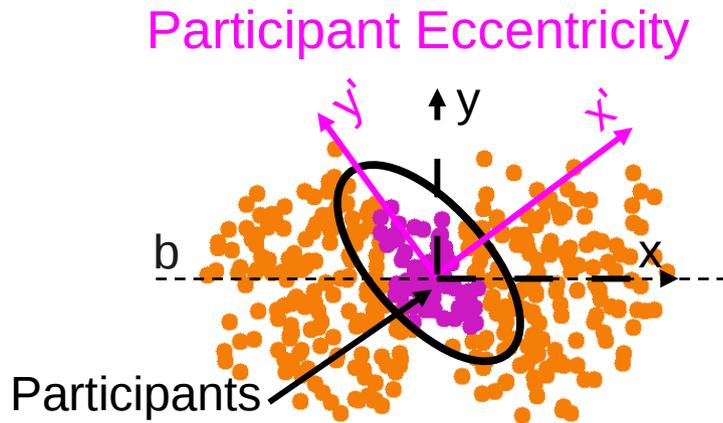


No scaling between **Cu+Cu** and **Au+Au** using the standard eccentricity definition



PHOBOS, Au+Au, 200,130,62.4+19.6 GeV: PRL 94 122303 (2005)
 PHOBOS ,Cu+Cu, 200+62.4 GeV: PRL 98 242302 (2007)
 PHOBOS, Cu+Cu, 22.4 GeV: prel. QM06
 STAR+NA49+E877, PRC 66 034904 (2002)
 (data taken with no adjustments)

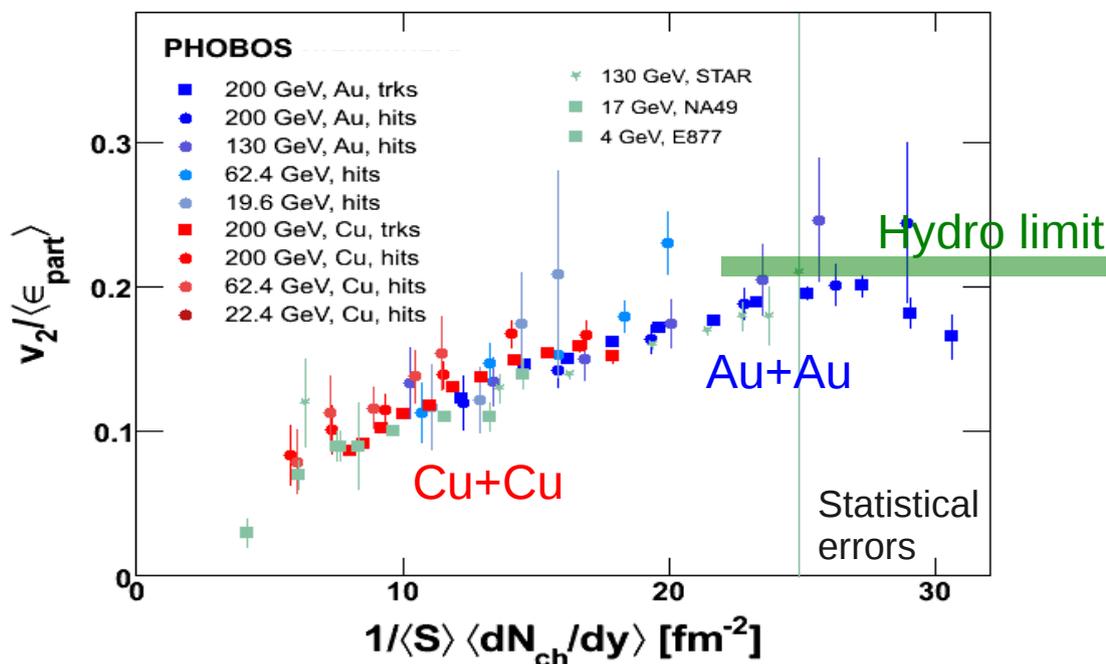
QM05



The spatial distribution of the interaction points of participating nucleons for the same b varies from event-to-event. Thus, define

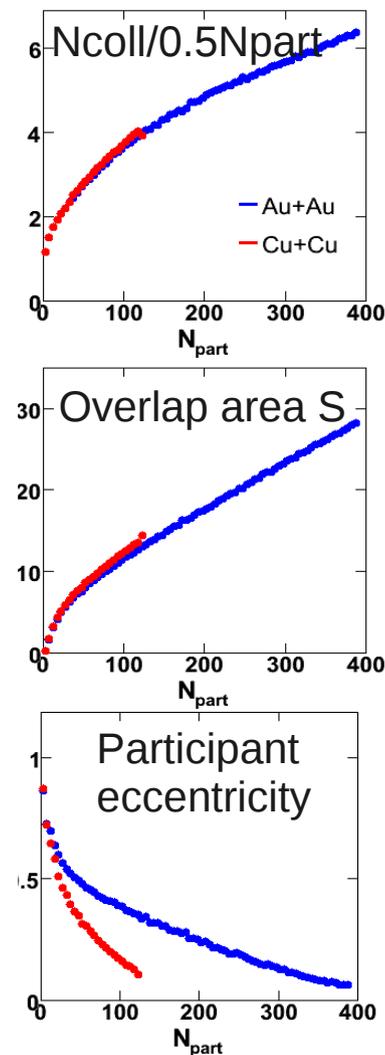
$$\epsilon_{part} = \frac{\sqrt{(\sigma_y^2 - \sigma_x^2)^2 + 4\sigma_{xy}^2}}{\sigma_y^2 + \sigma_x^2} \quad (0 < \epsilon_{part} \leq 1)$$

← Correlation term missing in standard definition

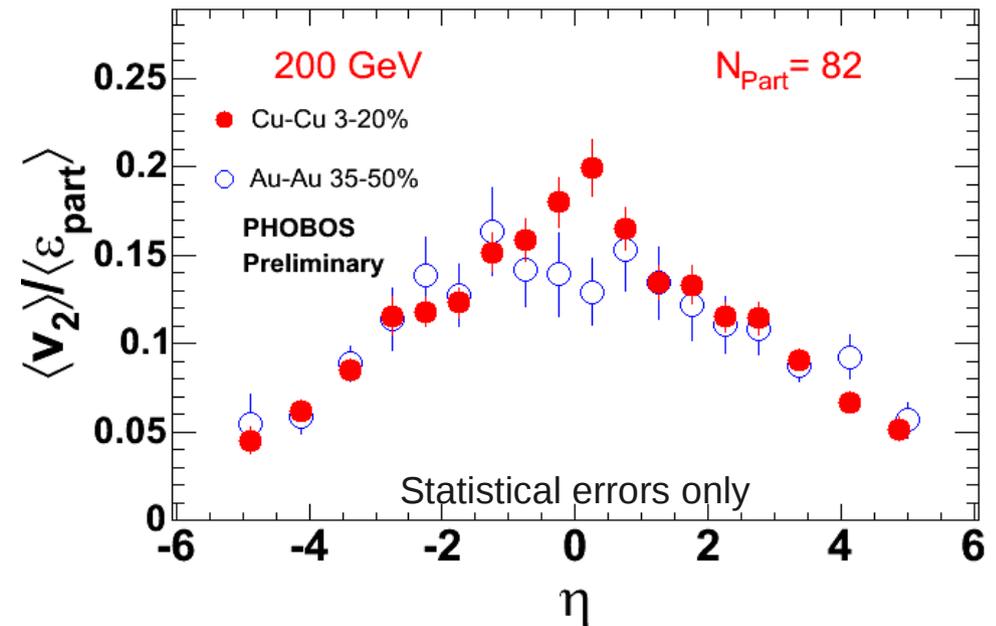
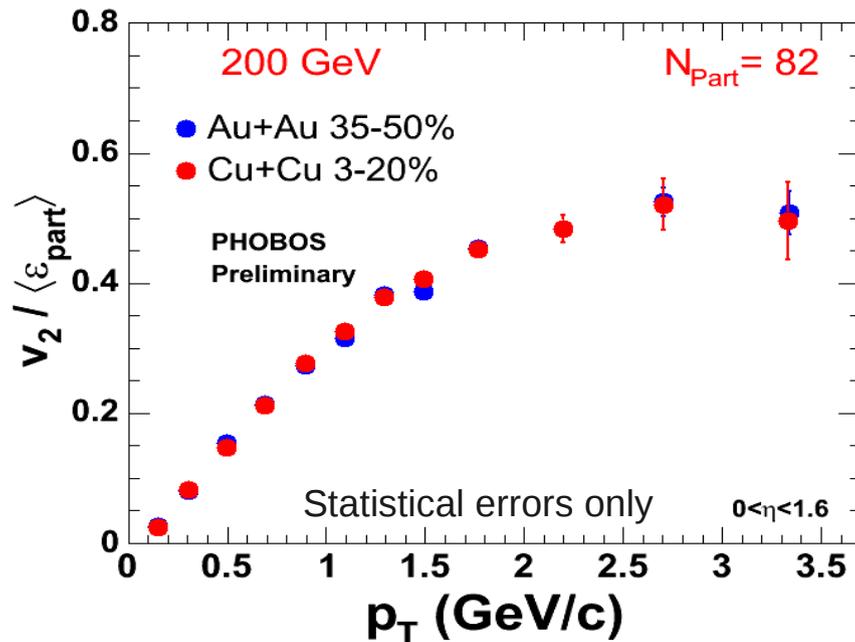


Scaling between **Cu+Cu** and **Au+Au** using participant eccentricity definition

QM05

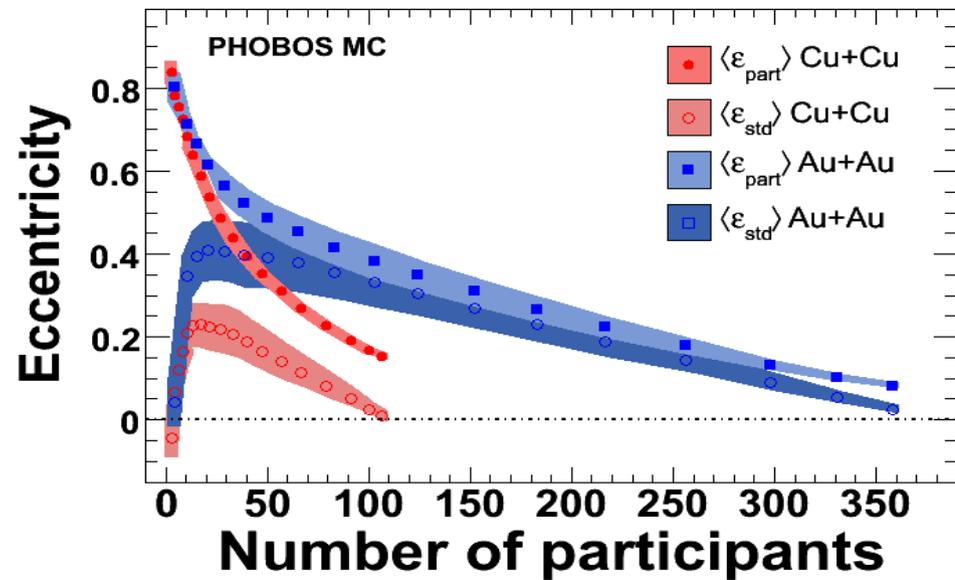
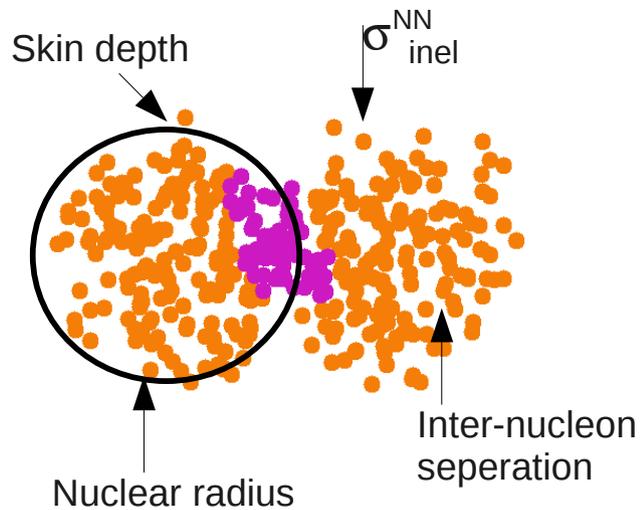


PHOBOS, Au+Au, 200,130,62.4+19.6 GeV: PRL 94 122303 (2005)
 PHOBOS ,Cu+Cu, 200+62.4 GeV: PRL 98 242302 (2007)
 PHOBOS, Cu+Cu, 22.4 GeV: prel. QM06
 STAR+NA49+E877, PRC 66 034904 (2002)
 (data taken with no adjustments)



Unity of geometry, system, energy, transverse momentum and pseudorapidity for the same N_{part} (\sim area density)

QM06



Baseline parameters:

- Nucleon-nucleon cross section: $\sigma_{\text{NN}}=42\text{mb}$
- Skin depth: $a=0.535\text{fm}$
- Wood-saxon radius: $R_A=6.38\text{fm}$
- Inter-nucleon separation distance: $d=0.4\text{fm}$

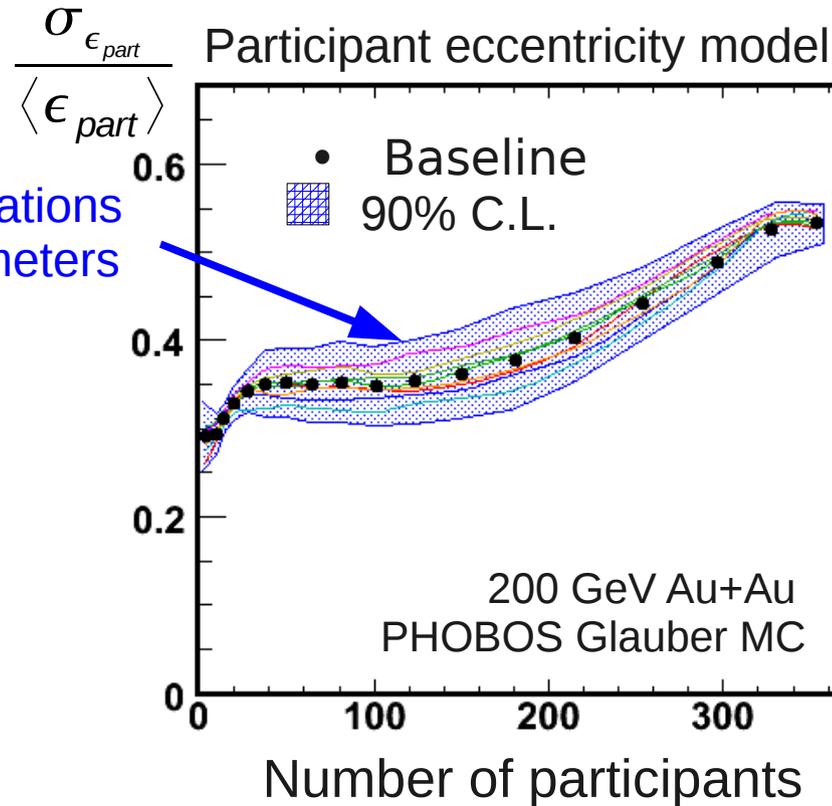
Robust definition wrt variation of Glauber parameters and to varying assumptions about matter production (not shown)

QM06

Uncertainty from variations of Glauber MC parameters

Baseline parameters:

- Nucleon-nucleon cross section: $\sigma_{NN}=42\text{mb}$
- Skin depth: $a=0.535\text{fm}$
- Wood-saxon radius: $R_A=6.38\text{fm}$
- Inter-nucleon separation distance: $d=0.4\text{fm}$



Analytic ($b=0\text{fm}$)

$$\sqrt{\frac{4}{\pi} - 1} \approx 0.52$$

Broniowski et al.,
PRC 76 054905 (2007)

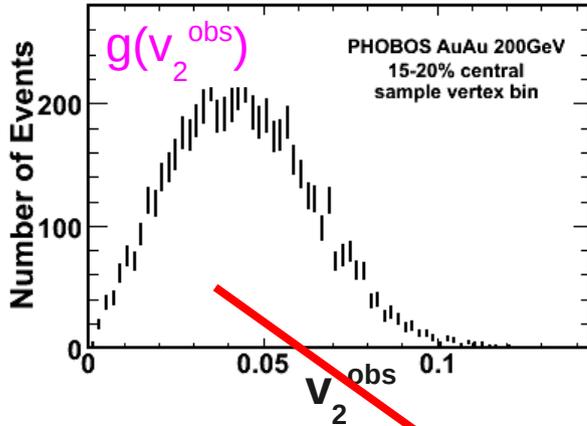
If initial state fluctuations are present, expect large relative flow fluctuations:

$$\frac{\sigma_{v_2}}{\langle v_2 \rangle} \sim \frac{\sigma_{\epsilon_{part}}}{\langle \epsilon_{part} \rangle}$$

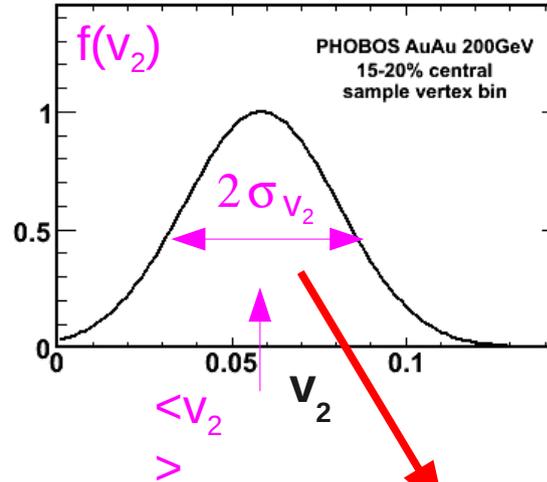
Measuring elliptic flow fluctuations

QM06

Observed v_2 distribution



Parametrized v_2 distribution



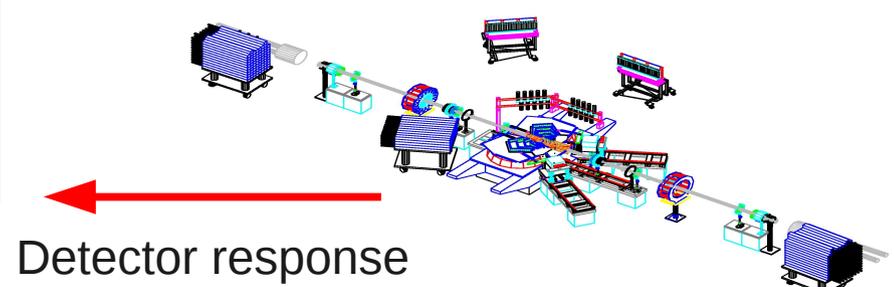
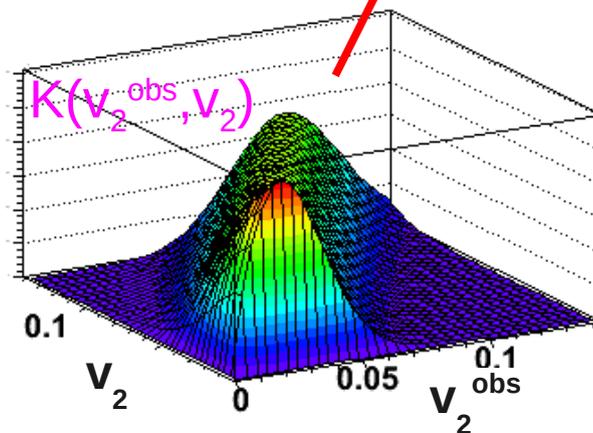
Max-Likelihood fit to determine:
 $\langle v_2 \rangle$ and σ_{v_2}

Kernel

- Detector and acceptance effects
- Finite-number fluctuations
- Multiplicity fluctuations

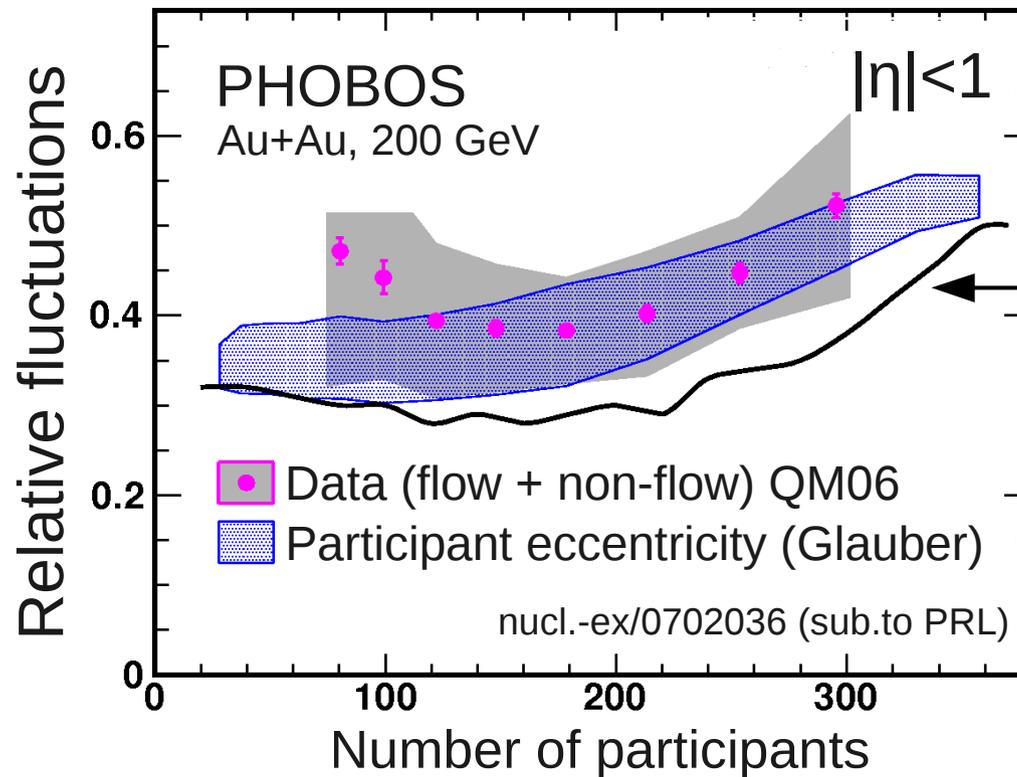
$$g(v_2^{obs}) = \int_0^1 K(v_2^{obs}, v_2) f(v_2) dv_2$$

Kernel



Detector response

QM06



Shown at QM06 as flow fluctuations, however non-flow contribution (included in sys.error) was underestimated.

Contribution from non-flow correlations 20

QM08, WORK IN PROGRESS

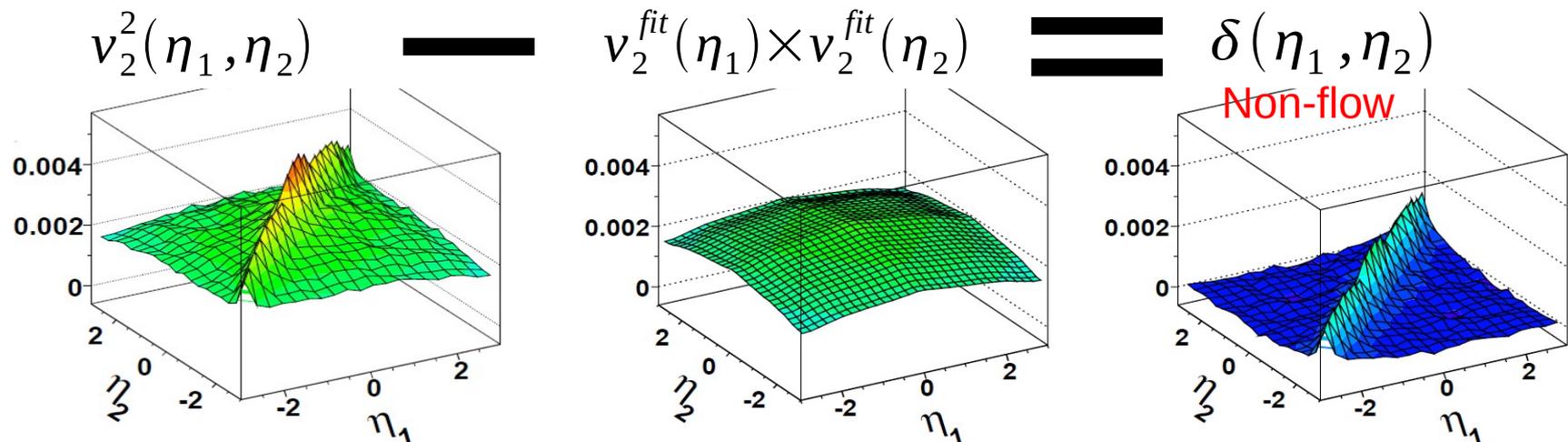
- PHOBOS has data driven analysis to measure the contribution of non-flow

- Flow is a function of η and correlates particles at all $\Delta\eta$
- Non-flow (δ) is dominated by short range correlations (small $\Delta\eta$)
- Study correlations at different $\Delta\eta$

$$v_2^2(\eta_1, \eta_2) \equiv \langle \cos(2 \Delta \phi) \rangle(\eta_1, \eta_2)$$

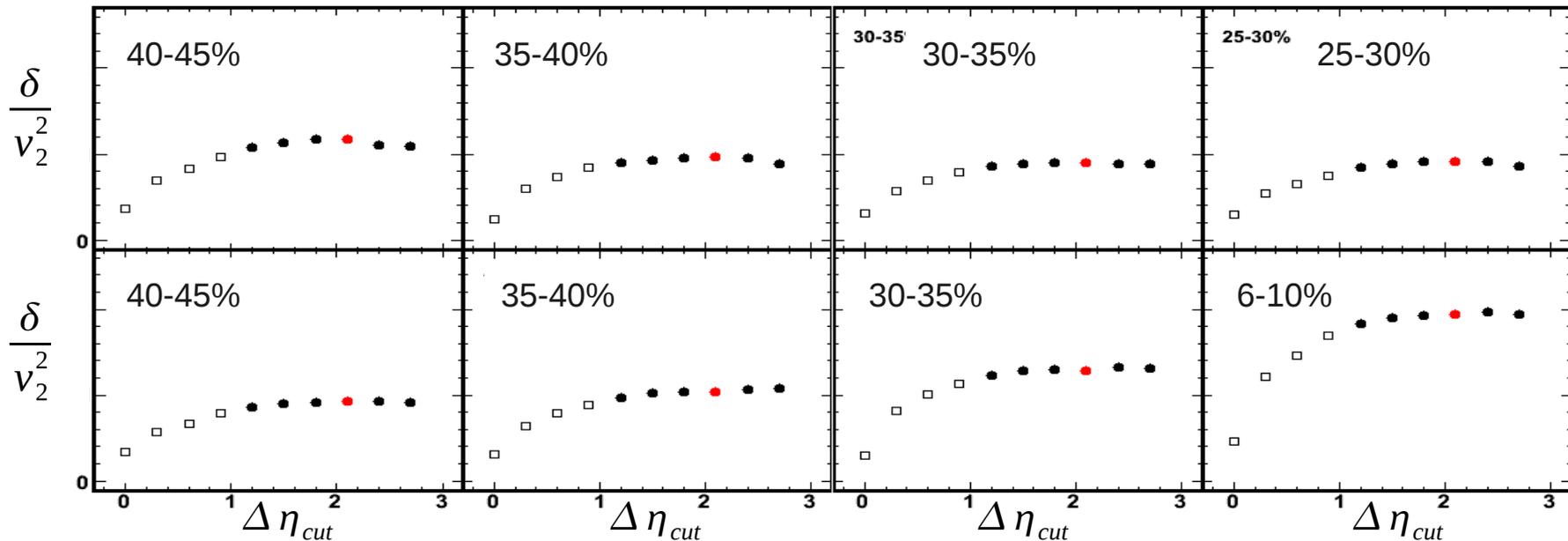
$$= v_2(\eta_1) * v_2(\eta_2) + \delta(\eta_1, \eta_2)$$

- Assume non-flow to be zero for $\Delta\eta > 2$
- Fit $v_2^2(\eta_1, \eta_2) = v_2^{fit}(\eta_1) * v_2^{fit}(\eta_2)$, $|\eta_2 - \eta_1| > 2$
- Subtract fit results at all (η_1, η_2)
- Integrate over particle pairs to obtain δ/v_2^2
- Numerically relate δ/v_2^2 , $\sigma_{tot}/\langle v_2 \rangle$ and $\sigma_{flow}/\langle v_2 \rangle$



Contribution from non-flow correlations 21

QM08, WORK IN PROGRESS

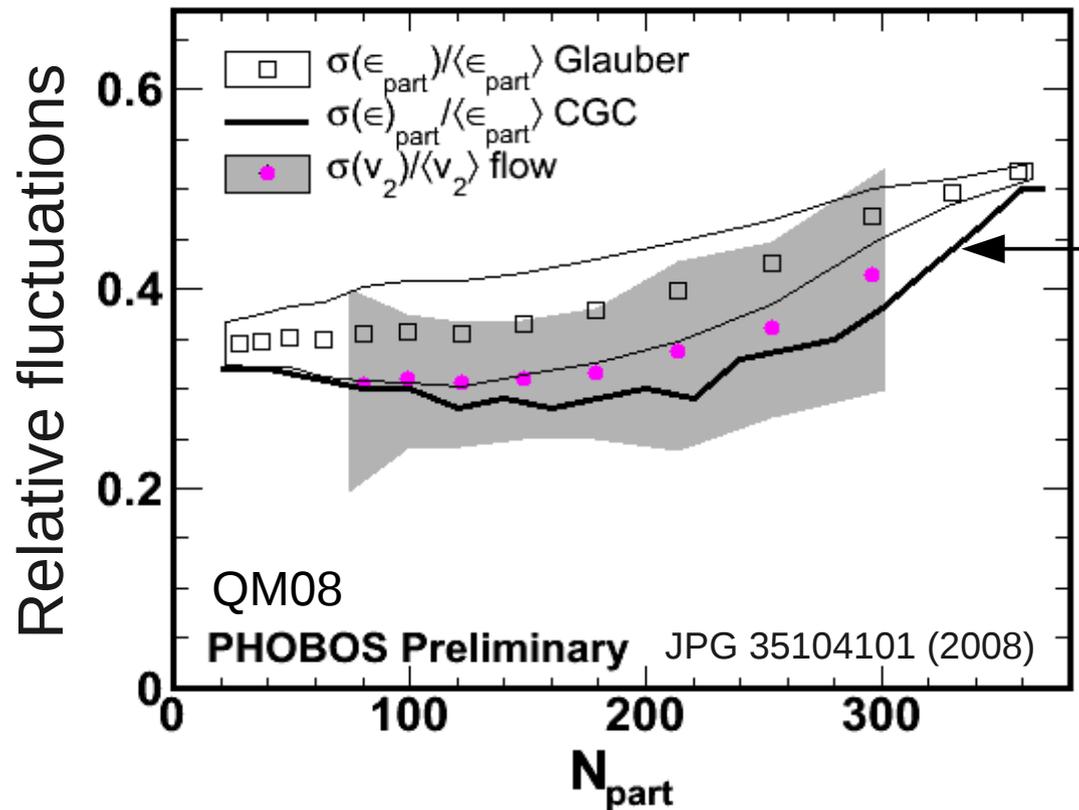


Non-flow ratio as a function of $\Delta\eta$ cut used to obtain the fit.

Saturation is very encouraging, although does not rule out contributions with very little $\Delta\eta$ dependence.

Red-point is baseline for analysis, while black points are used for systematic error

QM08, WORK IN PROGRESS



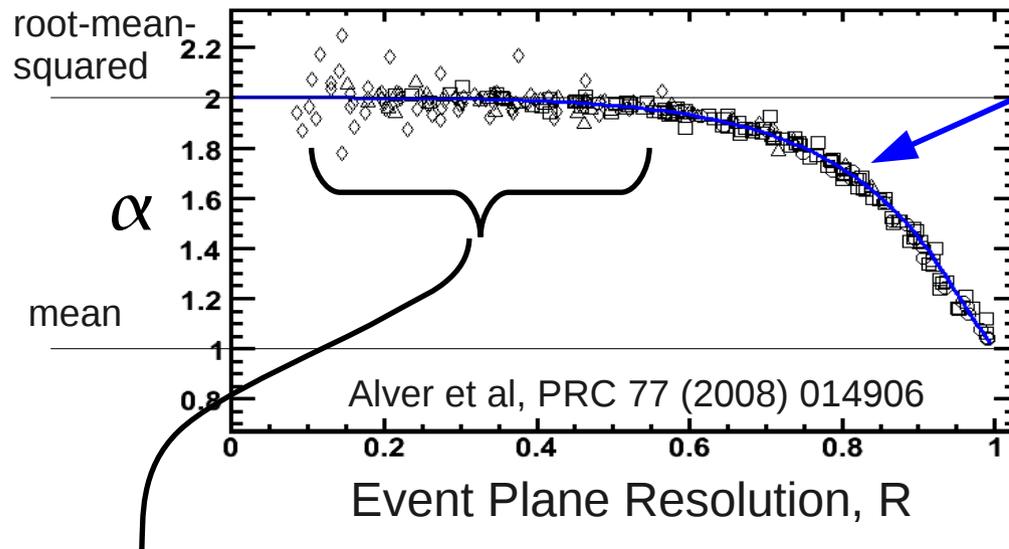
Initial state fluctuations if indeed present seem not to be significantly enhanced in later stages of the collision

Short-range non-flow contribution is taken out with method as shown at QM08

Which moment of v_2 is measured?

Define

$$v_2 \equiv \langle v_2^\alpha \rangle^{1/\alpha}$$



By now α is known:

$$\alpha = 2 - 4i_1^2 / (i_0 + i_1)^2$$

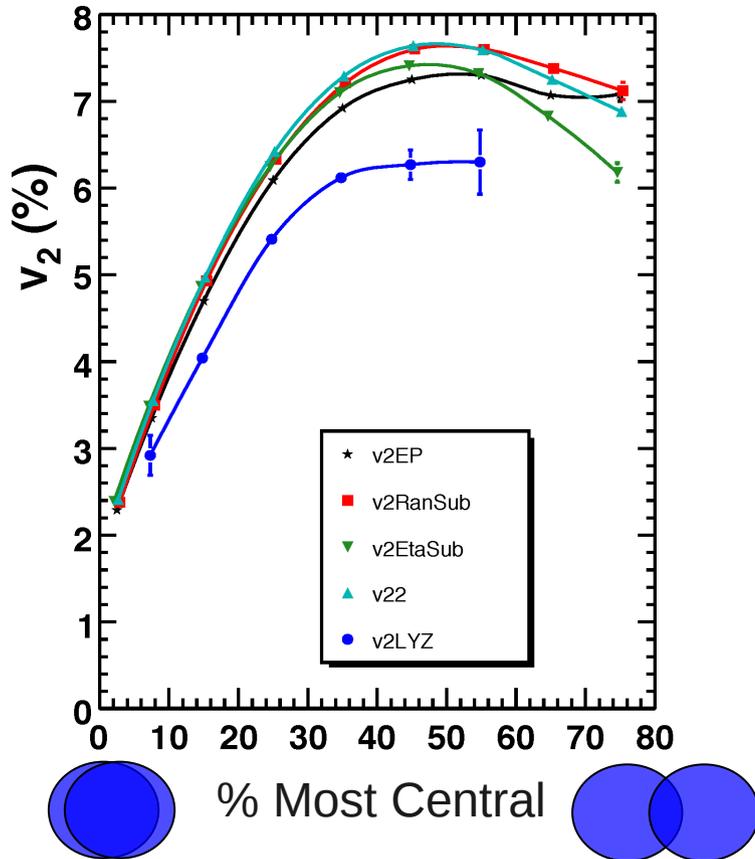
Ollitrault et. al.,
 PRC 80 80 014904 (2009)

PHOBOS R:
 0.13 – 0.55

For PHOBOS standard event-plane method $v_2 \{ EP \} = \sqrt{\langle v_2^2 \rangle}$

(For the observed fluctuations this implies about 10% difference)

Published STAR results



Derive analytic correction for non-flow and fluctuations in leading order of δ and $\sigma_{v_2}^2$

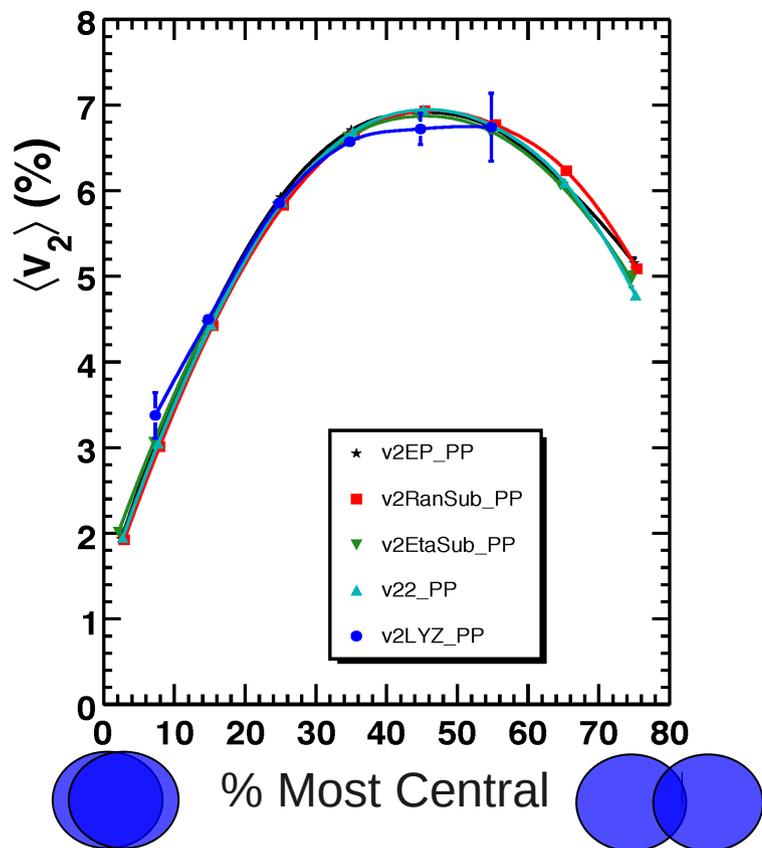
Eg, for 2-particle correlations:
 $\langle \cos(2 \Delta \phi) \rangle = \langle v_2 \rangle^2 + \sigma_{v_2}^2 + \delta$ ← Non-flow term

Differences between methods proportional to

$$\sigma_{tot} = \delta + 2 \sigma_{v_2}^2$$

Need additional assumption or information to separate between non-flow and fluctuations

Corrected mean results

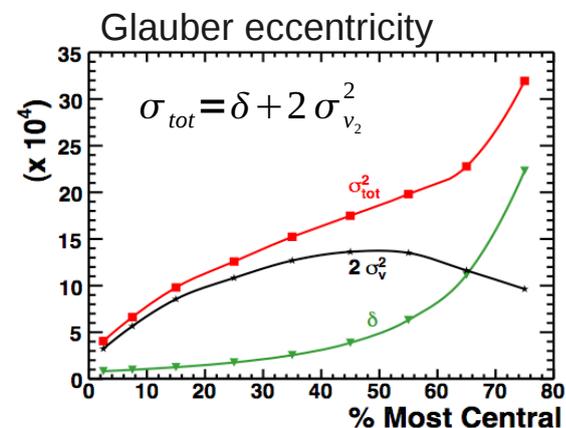


Model assuming:

$$\sigma_{v_2} = \frac{\sigma_{\epsilon_{\text{part}}}}{\langle \epsilon_{\text{part}} \rangle} \langle v_2 \rangle$$

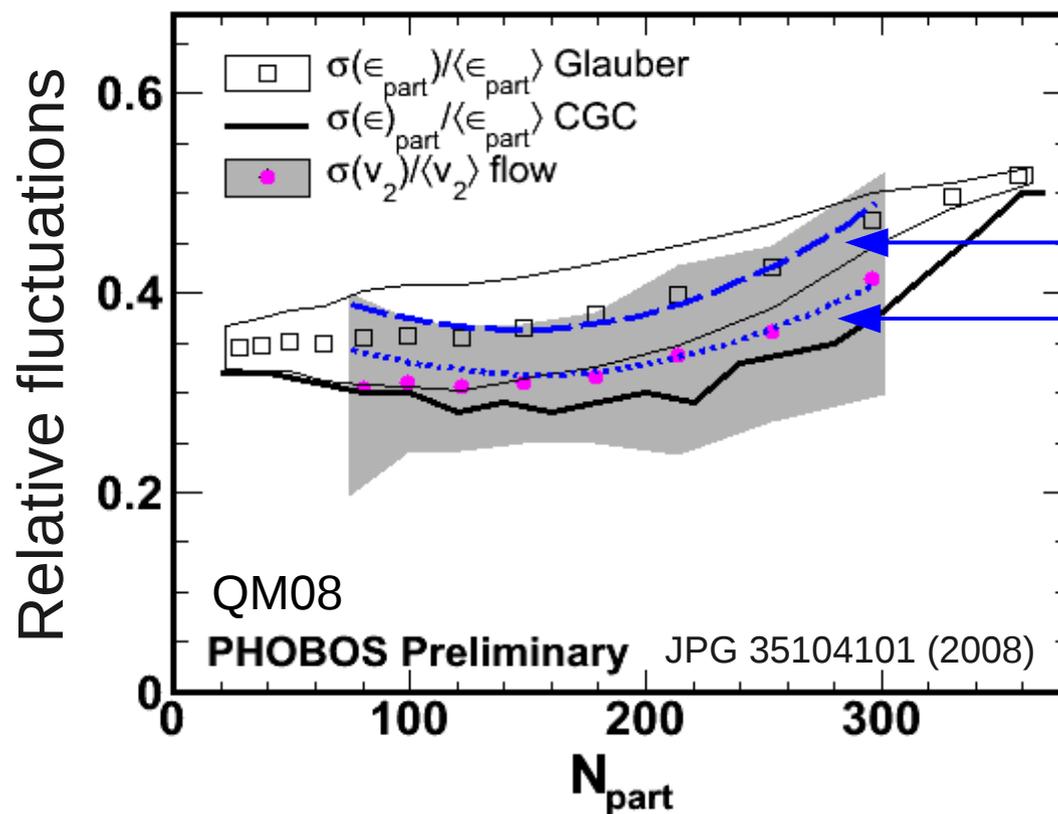
$$\delta = \frac{2}{N_{\text{part}}} \delta_{\text{pp}}$$

with $\delta_{\text{pp}} = 0.0145$



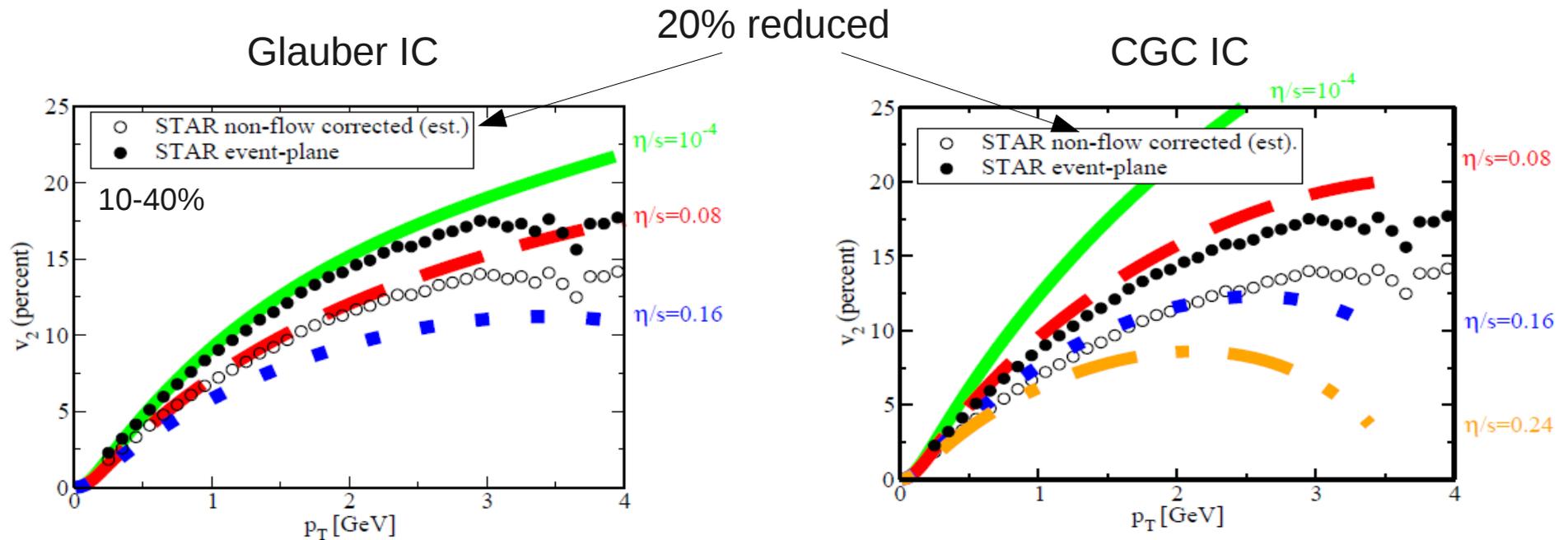
Corrected mean values agree in participant frame.
Reduces errors on v_2 measurements by about 20%.

Eccentricity values are calculated for standard Glauber and a mix of 30:70 CGC (not shown)



Analytic correction:
 Glauber
 CGC (30:70)
 Ollitrault et. al.,
 PRC 80 80 014904 (2009)

Results based on analytic model corrections are consistent with data.



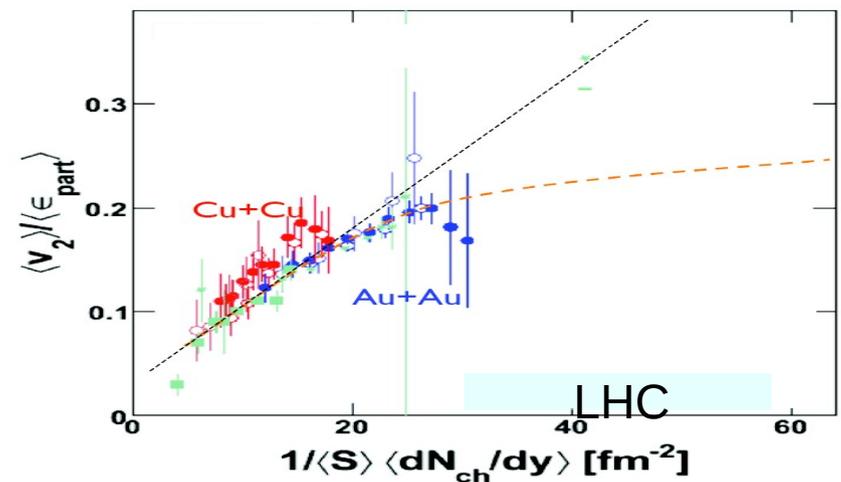
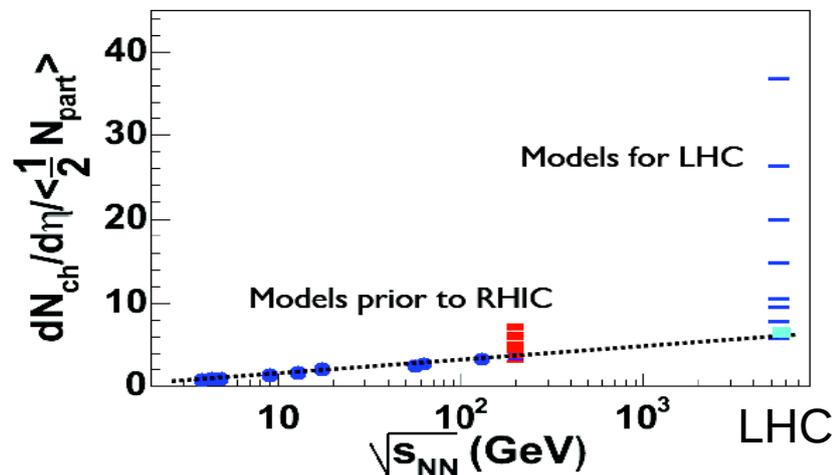
State-of-art results from second-order conformal hydrodynamics (2+1D) yield a low shear viscosity to entropy ratio.

“General consensus” (from QM09) that: $\frac{\eta}{s} < 6 \times \frac{1}{4\pi}$

Reduced errors on v_2 data allows to study 20% effects.

Luzum, Romatschke, PRC 78 034915 (2008); PRC 79 039903 (2009)

- Significant progress in understanding and quantification of "something more like a liquid"
 - Understanding of flow, non-flow correlations, flow- and eccentricity-fluctuations seems to converge
 - Remaining caveat is role of long-range non-flow contributions
 - Contribution of (short-ranged) non-flow correlations to total relative fluctuations is about 10% (absolute)
 - Initial state fluctuations if present are not significantly enhanced throughout the collision evolution
- Exiting times ahead with p+p and Pb+Pb @ LHC in 2009/10

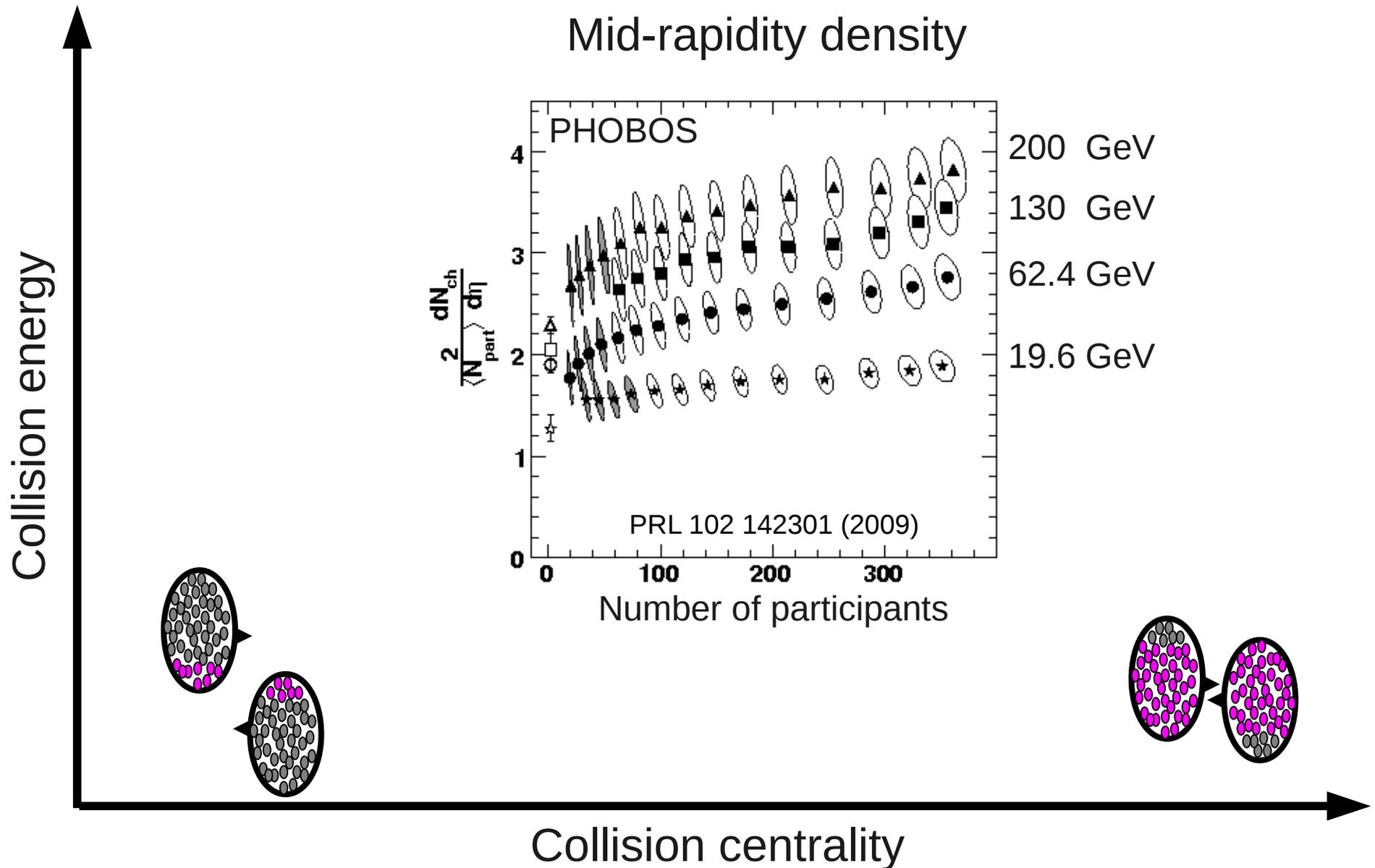


I'd like to give credit to my PHOBOS colleagues:

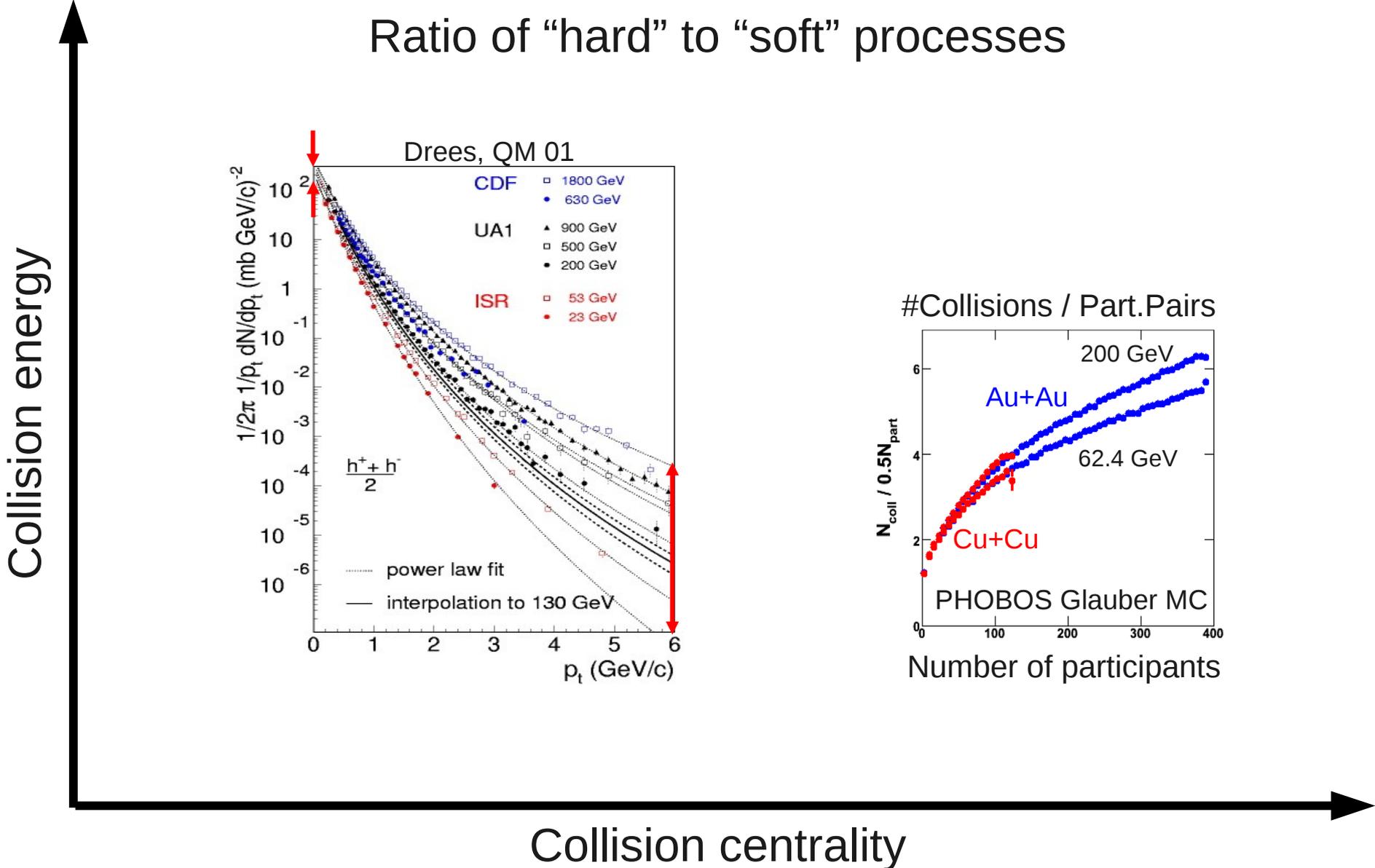
Burak Alver, Birger Back, Mark Baker, Maarten Ballintijn, Donald Barton, Russell Betts, Richard Bindel, Wit Busza (Spokesperson), Vasundhara Chetluru, Edmundo García, Tomasz Gburek, Joshua Hamblen, Conor Henderson, David Hofman, Richard Hollis, Roman Hołyński, Burt Holzman, Aneta Iordanova, Chia Ming Kuo, Wei Li, Willis Lin, Constantin Loizides, Steven Manly, Alice Mignerey, Gerrit van Nieuwenhuizen, Rachid Nouicer, Andrzej Olszewski, Robert Pak, Corey Reed, Christof Roland, Gunther Roland, Joe Sagerer, Peter Steinberg, George Stephans, Andrei Sukhanov, Marguerite Belt Tonjes, Adam Trzupek, Sergei Vaurynovich, Robin Verdier, Gábor Veres, Peter Walters, Edward Wenger, Frank Wolfs, Barbara Wosiek, Krzysztof Woźniak, Bolek Wyslouch

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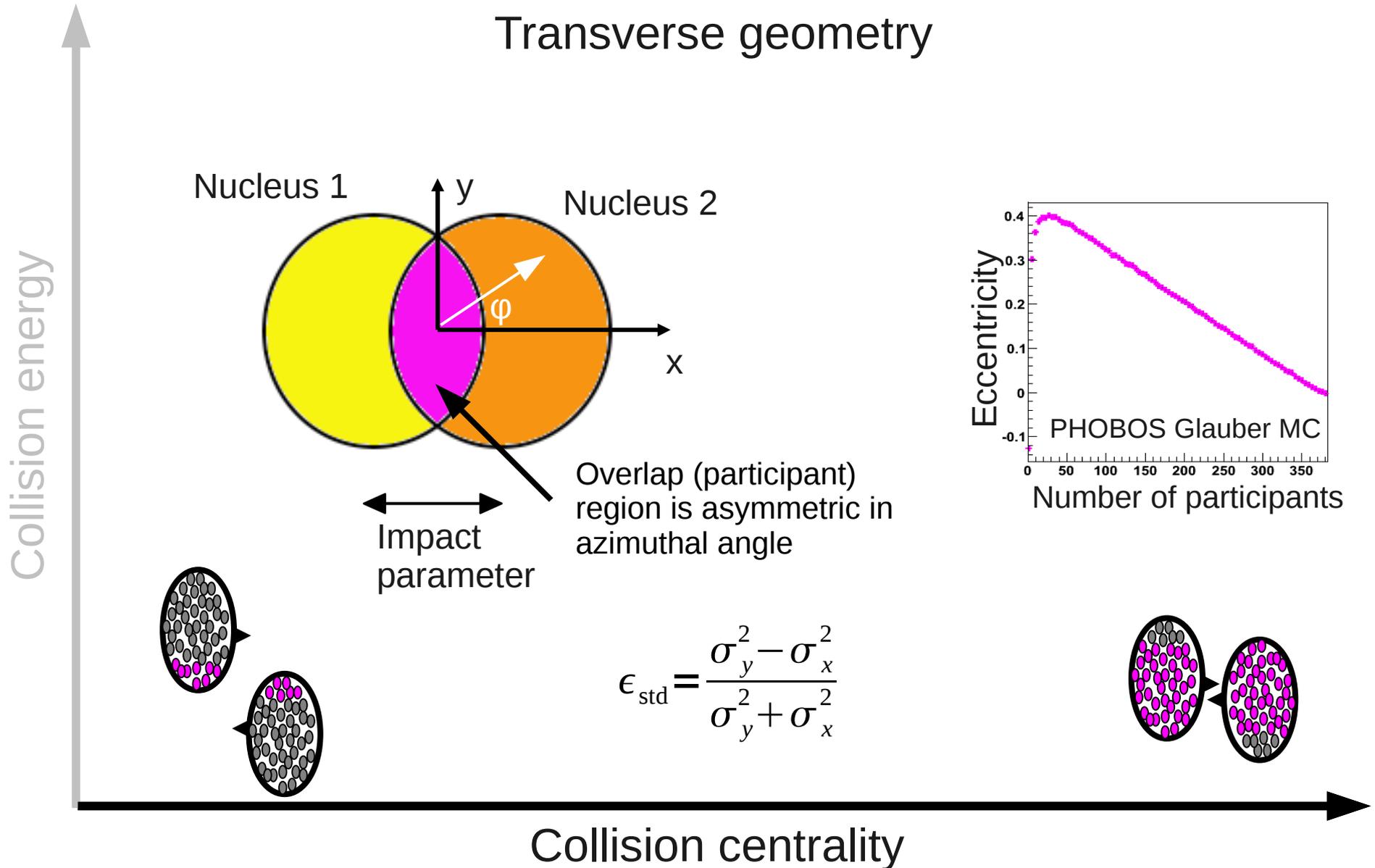
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UNIVERSITY OF ILLINOIS AT CHICAGO
UNIVERSITY OF ROCHESTER

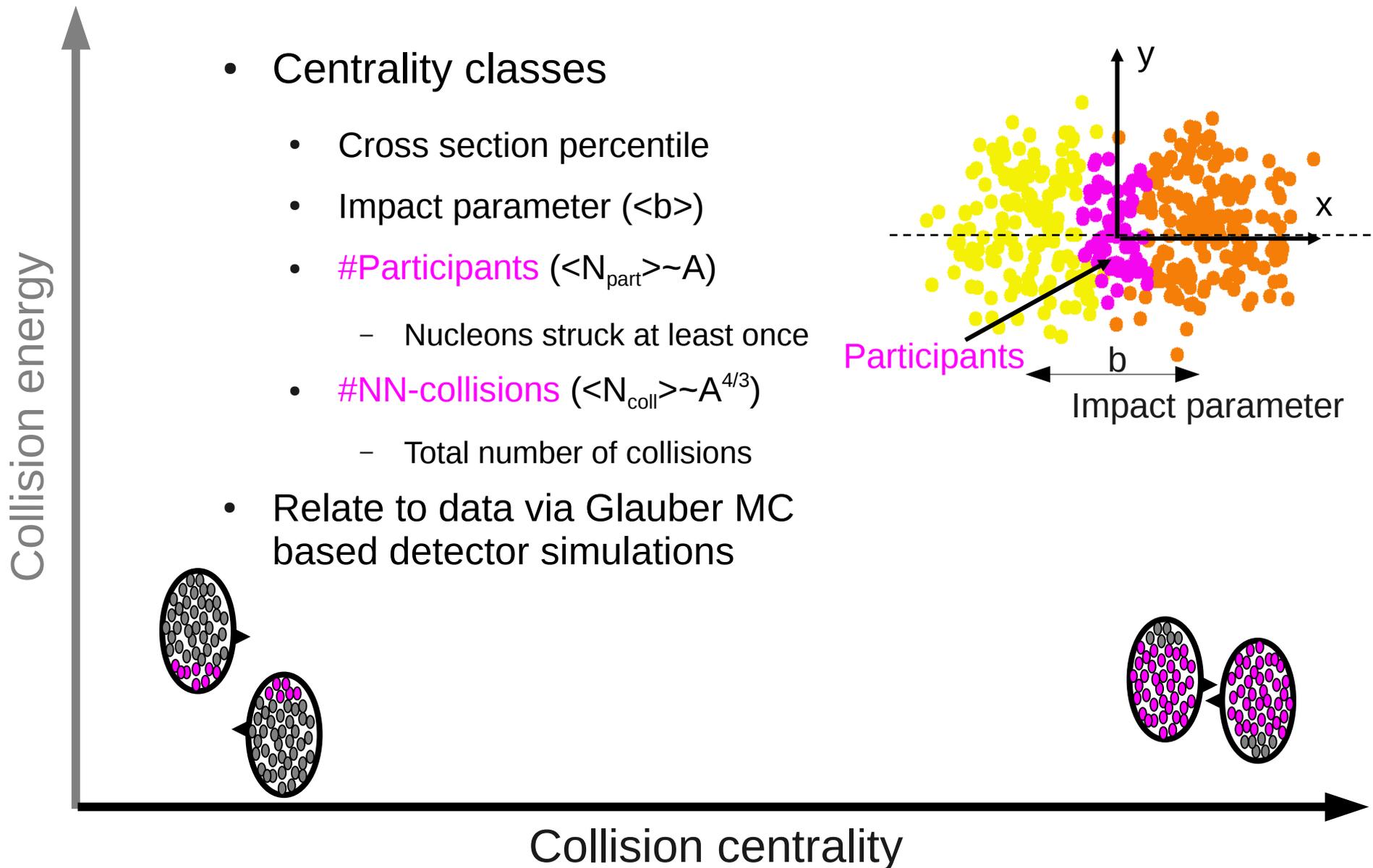


Ratio of “hard” to “soft” processes

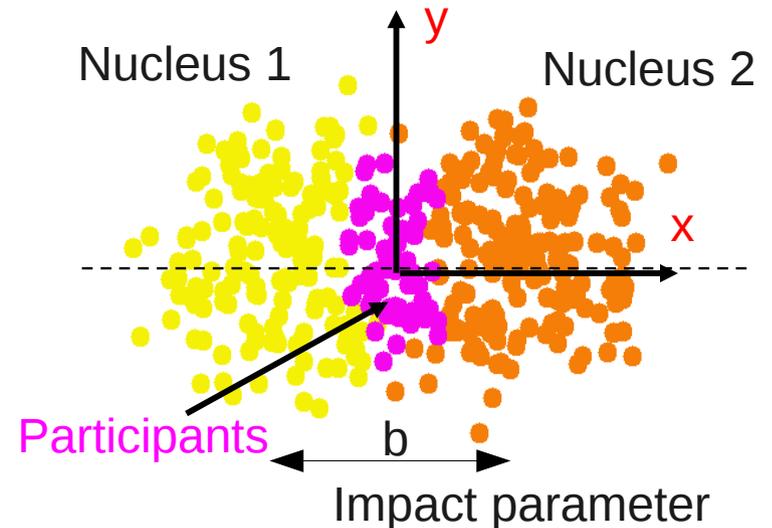
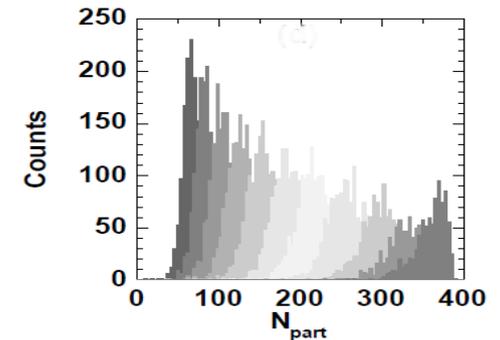
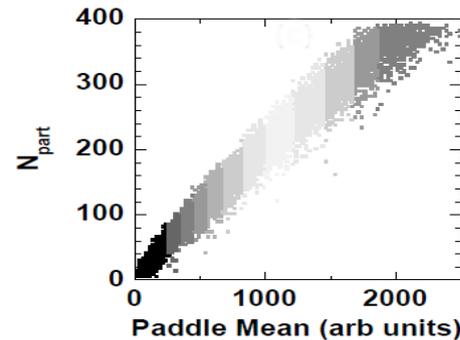
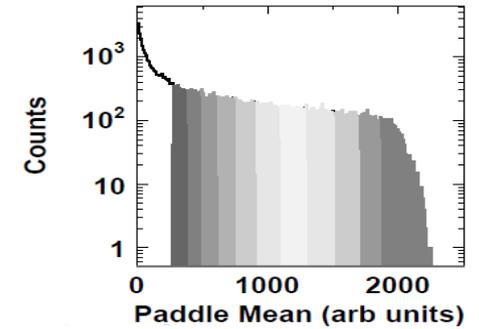
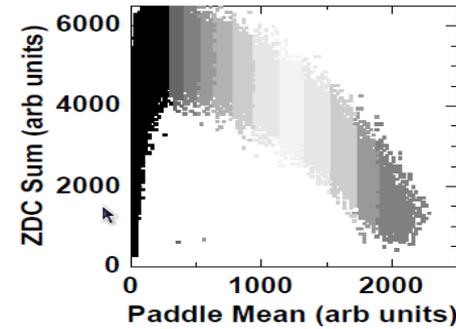


Transverse geometry



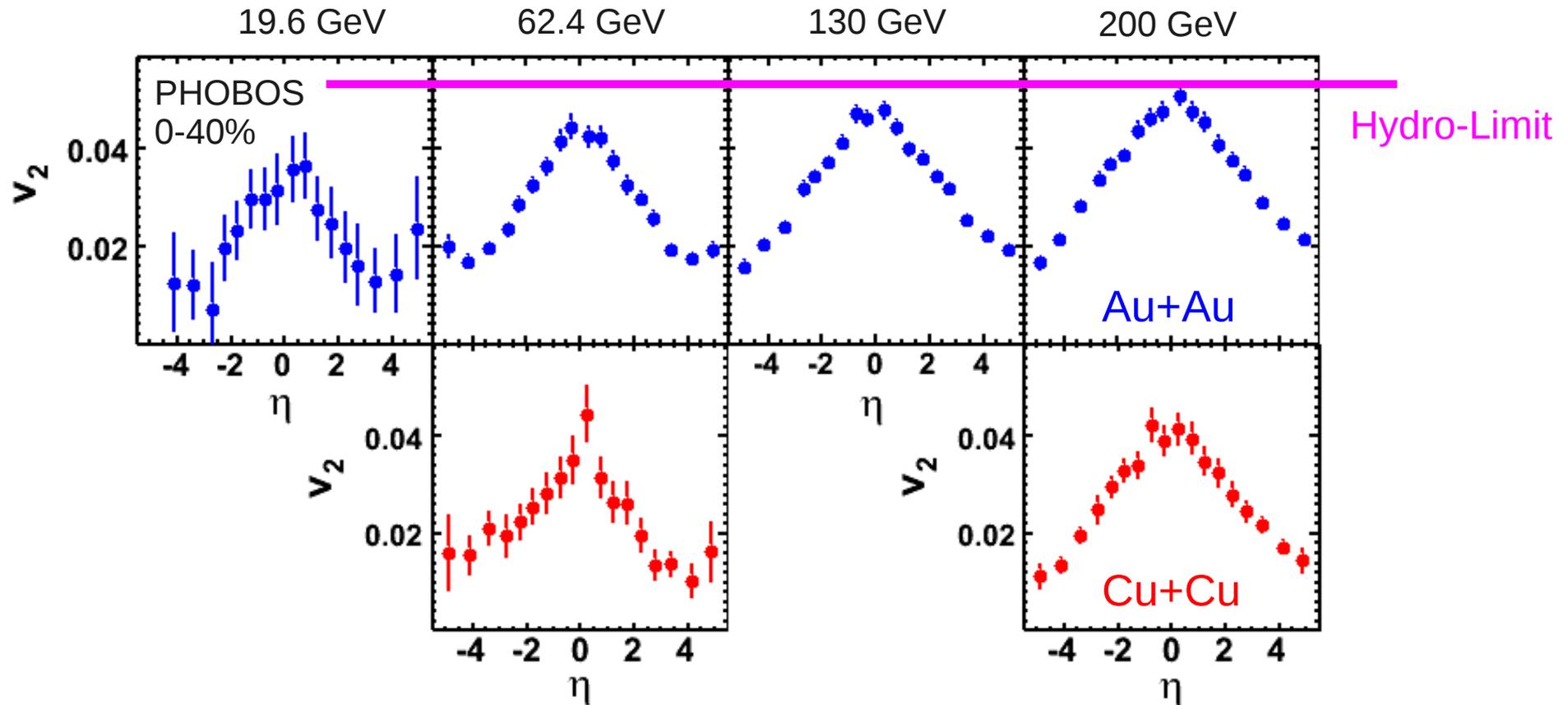


- Makeup of nuclei
 - Made up of nucleons drawn from Wood-Saxon distribution
 - Separate by b (with $dN/db \sim b$)
- Collision of nuclei
 - Assume: Nucleons travel along z on straight-line paths and interact when their centers are within $\sqrt{\sigma_{inel}^{NN}}/\pi$
 - **#Participants** is number of nucleons that interact at least once ($N_{part} \sim A$)
 - **#NN-collisions** is total number of collisions ($N_{coll} \sim A^{4/3}$)
- Relate to data via Glauber MC based detector simulations

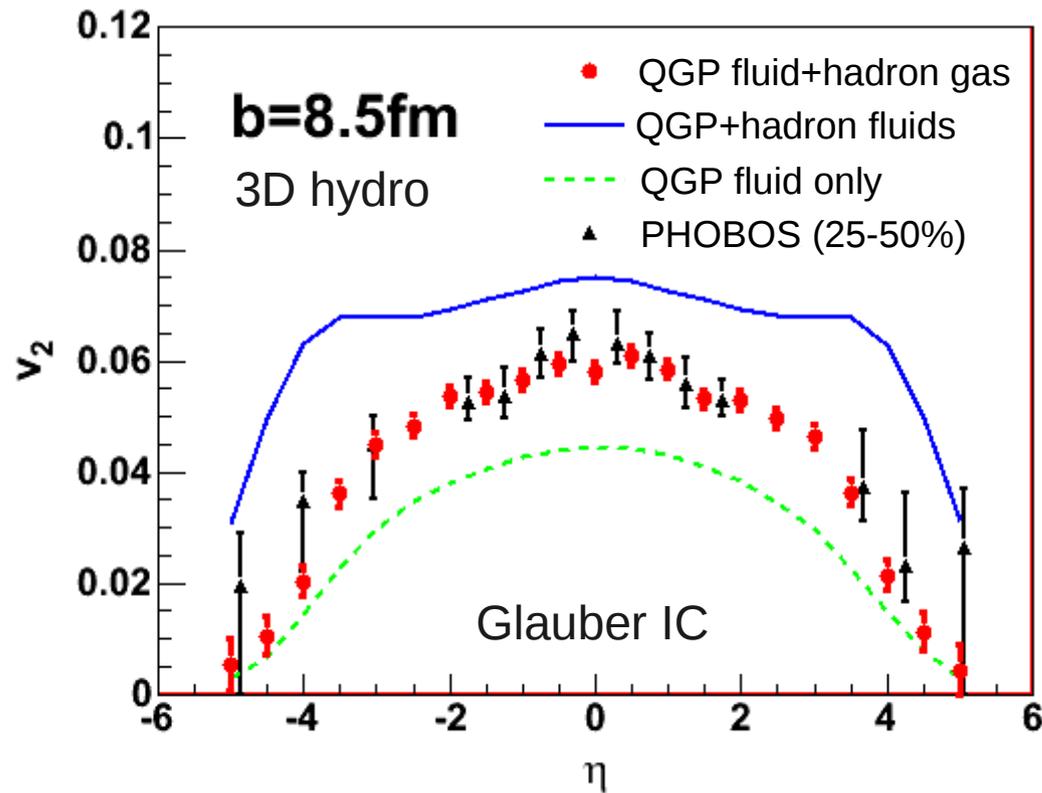


Equilibrium only at mid-rapidity?

36



Hydro-limit reached at mid-rapidity for highest energies?



Hadronic corona is important

Remark: Hydrodynamic model \neq ideal hydrodynamics (Boltzmann transport for hadrons includes effective viscosity through finite mean free path)

- Model two component scenario

- Matter production via participants and binary collisions

$$\frac{dN^{AA}}{d\eta} = \frac{dN^{pp}}{d\eta} \left(\frac{1-x}{2} N_{part} + x N_{coll} \right)$$

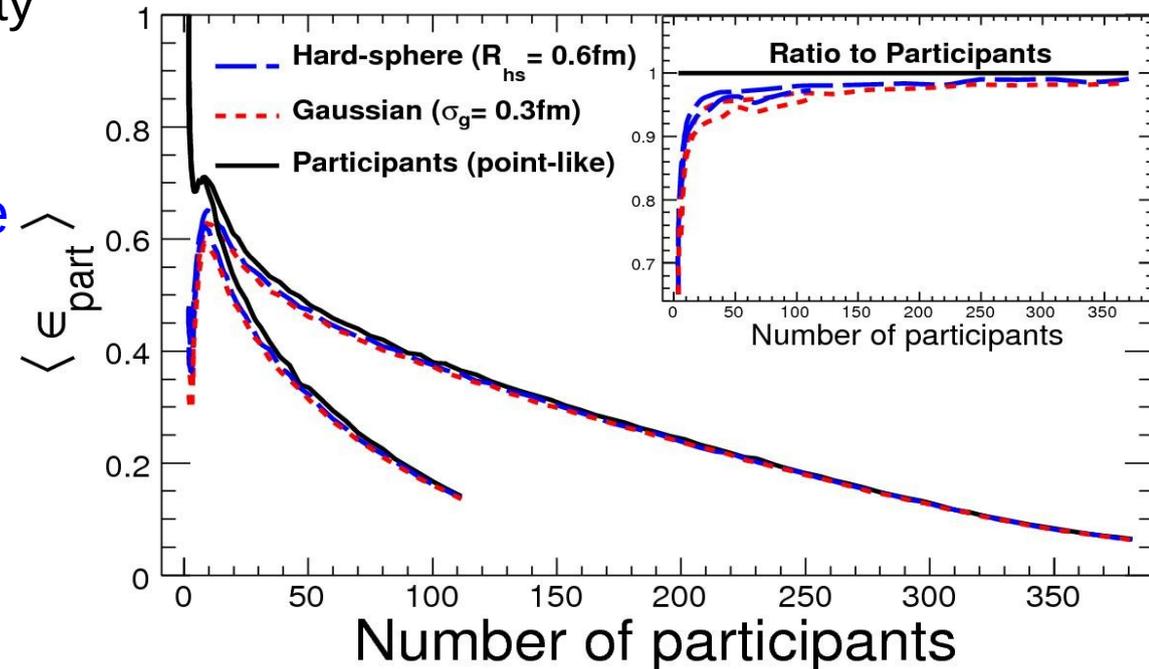
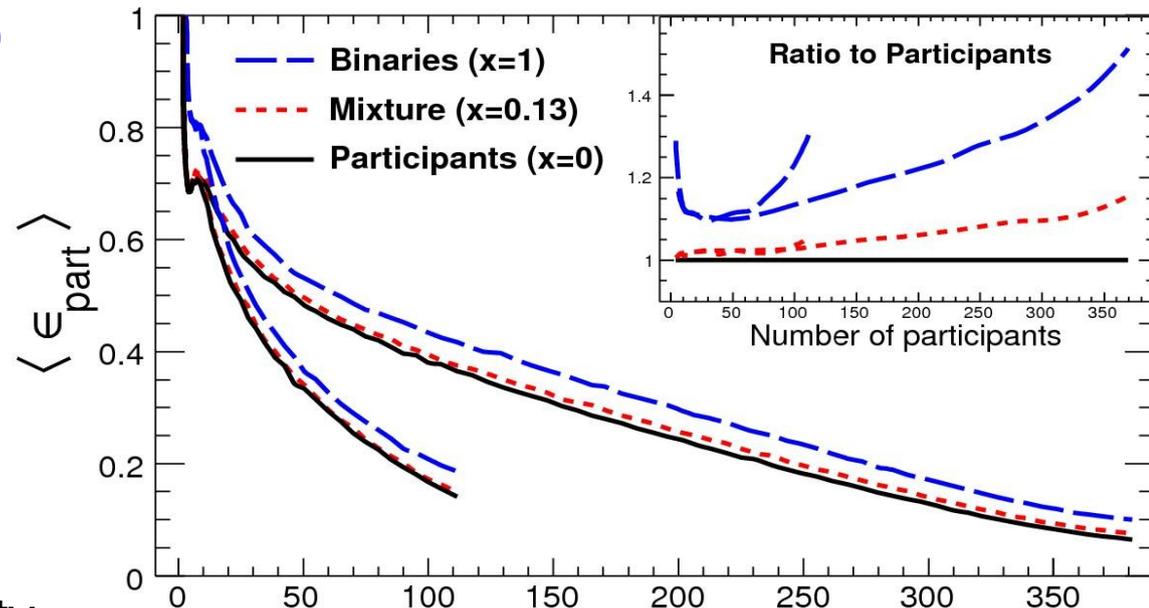
- Mixture with $x=0.13$ describes mid-rapidity $dN/d\eta$ quite well

- 10% increase in eccentricity for central Au+Au

- Include thermalization time by smearing the matter around the original production point

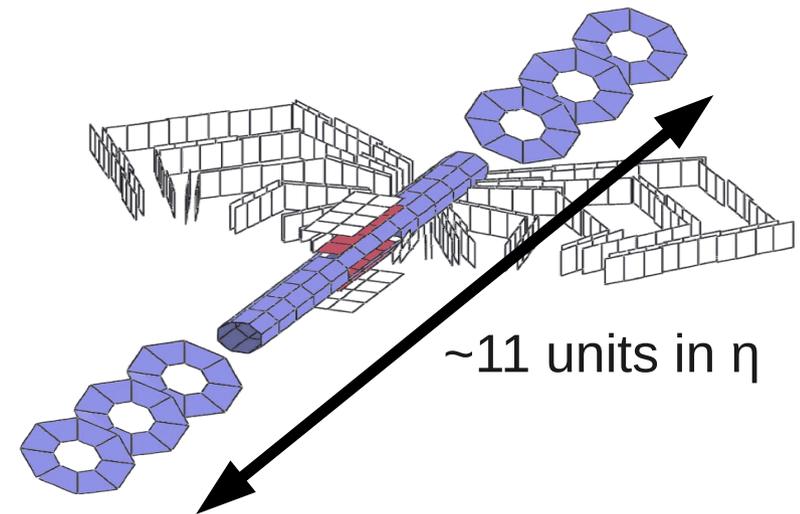
- Hard-sphere and Gaussian

- For chosen set of parameters only a very small effect

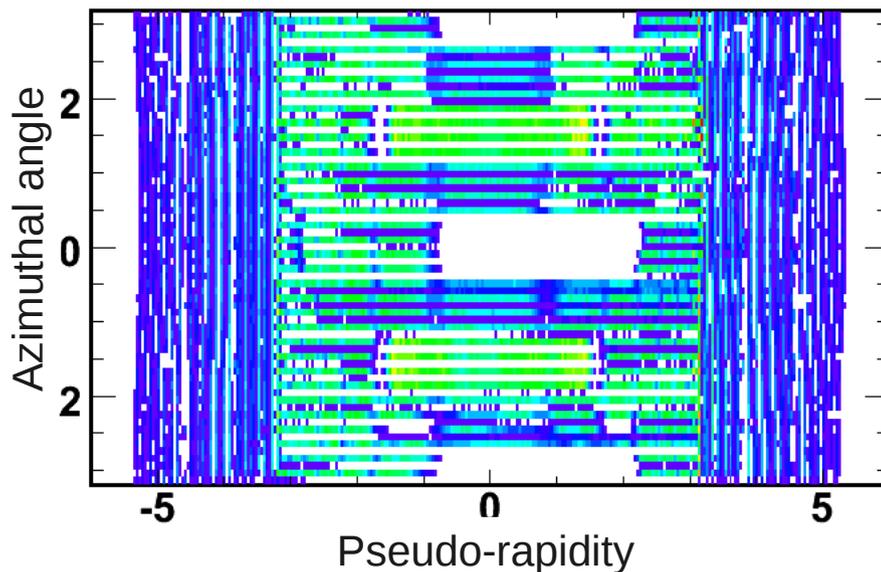


NB: More generalized studies also done, see Broniowski et al., PRC 76 (2007) 054905

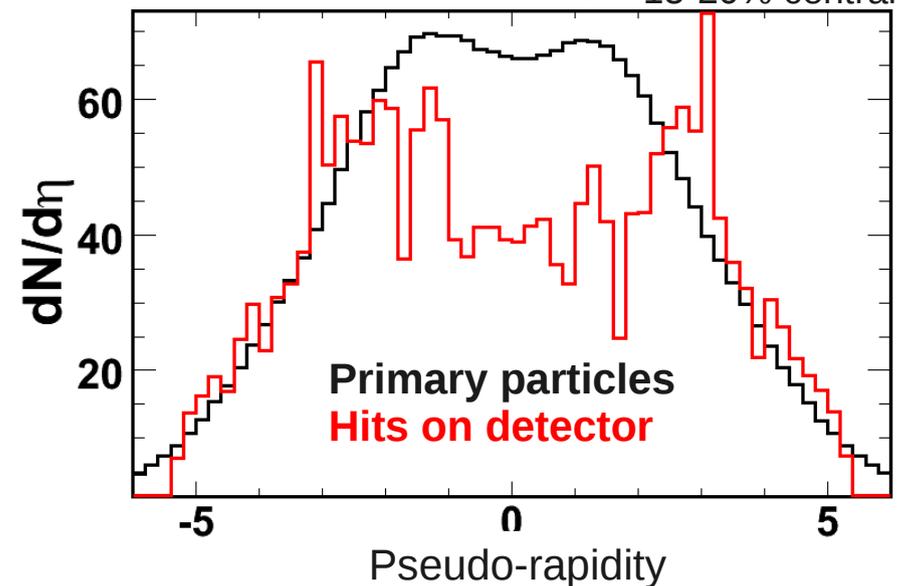
- PHOBOS Multiplicity Array
 - $-5.4 < \eta < 5.4$ coverage
 - Holes and granularity differences
- Usage of all available information in event to determine **event-by-event** a single value for v_2^{obs}



Hit Distribution

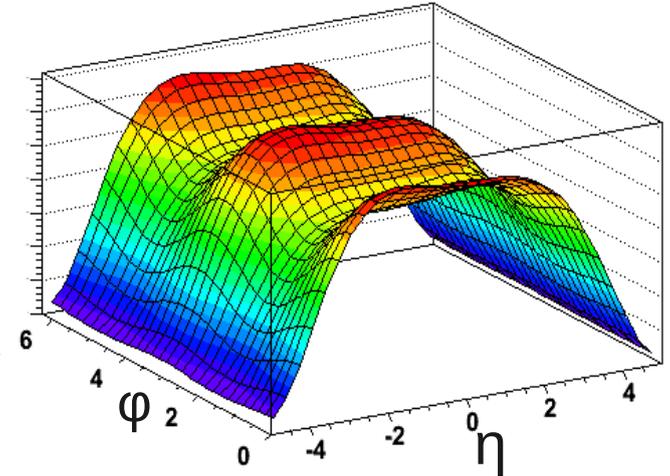


$dN/d\eta$ HIJING + Geant 15-20% central



- Event-by-event measurement of v_2^{obs}
 - Deal with acceptance effects
 - Use all available hit information
- Probability distribution function for hit positions:

Probability distribution function



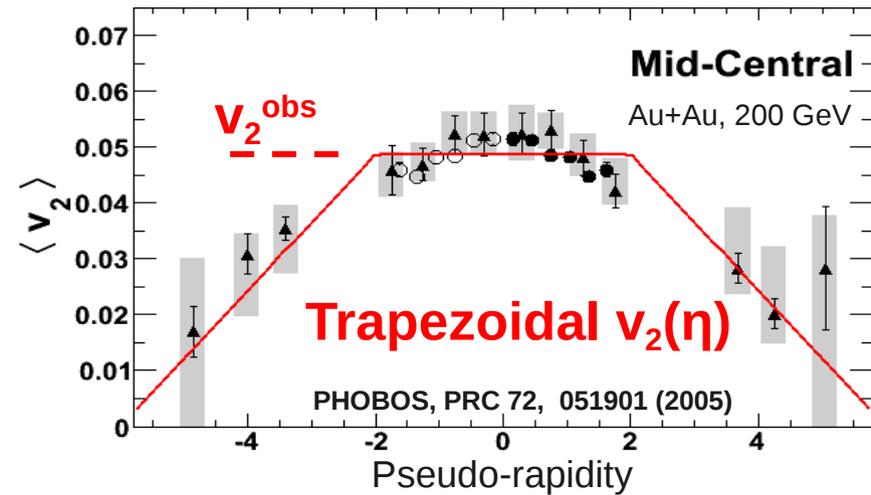
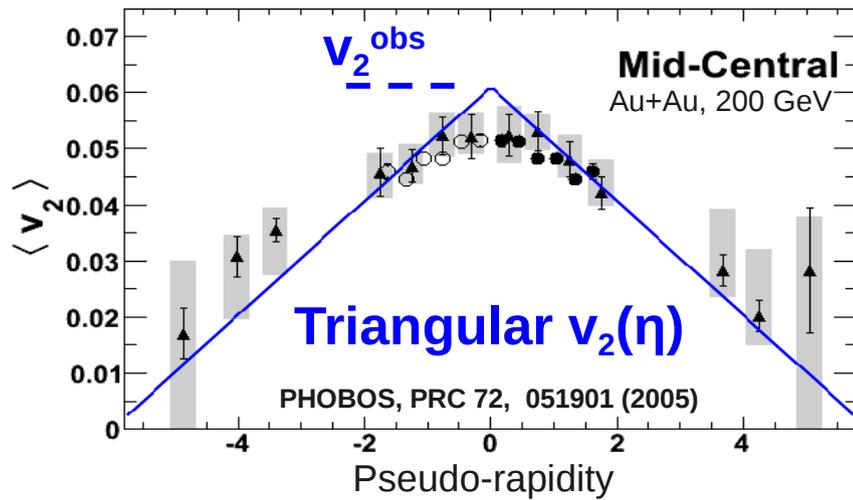
$$P(\eta, \phi; v_2^{\text{obs}}, \phi_0) = \underbrace{p(\eta)}_{\text{Normalization incl. acceptance}} \underbrace{[1 + 2v_2(\eta)\cos(2\phi - 2\phi_0)]}_{\text{Probability of hit in } (\phi, \eta)}$$

Normalization
incl. acceptance

Probability of hit in (ϕ, η)

- Maximize the likelihood function to obtain v_2^{obs} and ϕ^0 (event plane angle)

$$L(v_2^{\text{obs}}, \phi_0) = \prod_{i=1}^n P(\eta_i, \phi_i; v_2^{\text{obs}}, \phi_0)$$



$$P(\eta, \phi; v_2^{\text{obs}}, \phi_0) = p(\eta) [1 + 2 v_2(\eta) \cos(2\phi - 2\phi_0)]$$

↑
Use known, measured shape

Analysis is run on **triangular** and **trapezoidal** shape. Results are averaged at the end.

- “Measure” and record the v_2^{obs} distribution in bins of v_2 and multiplicity (n) from large MC samples

- $1.5 \cdot 10^6$ HIJING events
- Modified ϕ to include **triangular** or **trapezoidal** flow

- Fit response function (ideal case)

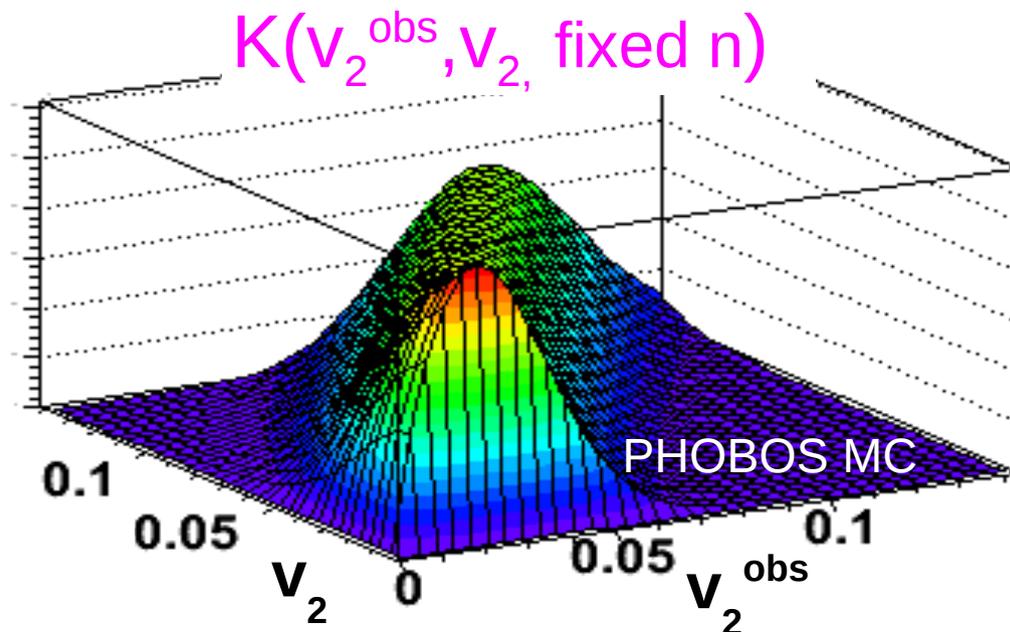
$$K(v_2^{obs}, v_2, n) = \frac{v_2^{obs}}{\sigma^2} e^{-\left(\frac{v_2^{obs} + v_2^2}{2\sigma^2}\right)} I_0\left(\frac{v_2^{obs} v_2}{\sigma^2}\right)$$

(J.-Y.Ollitrault, PRD (1992) 46, 226)

- Changed to account for detector effects

$$v_2 \rightarrow (An + B) v_2 \quad \sigma = \frac{C}{\sqrt{n}} + D$$

(suppression) (finite resolution)



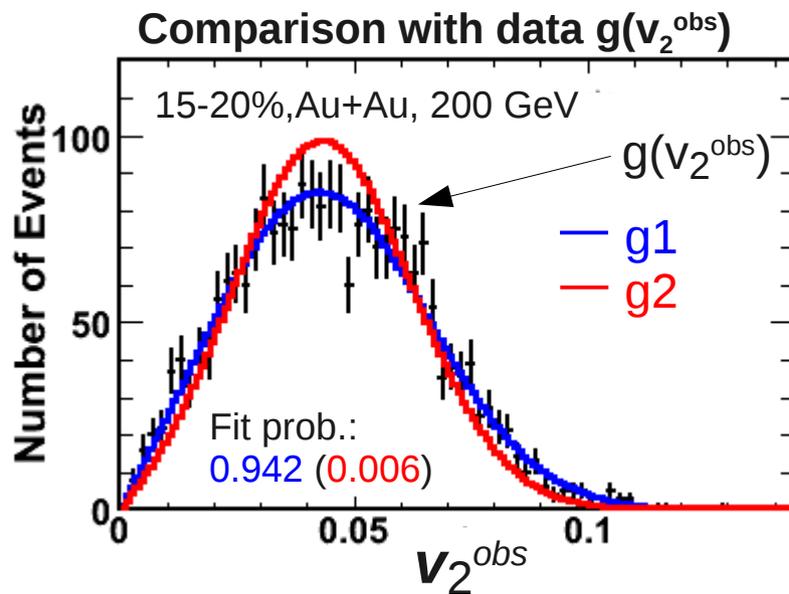
$$g(v_2^{obs}) = \int_0^1 K(v_2^{obs}, v_2) f(v_2) dv_2$$

↑
Measured

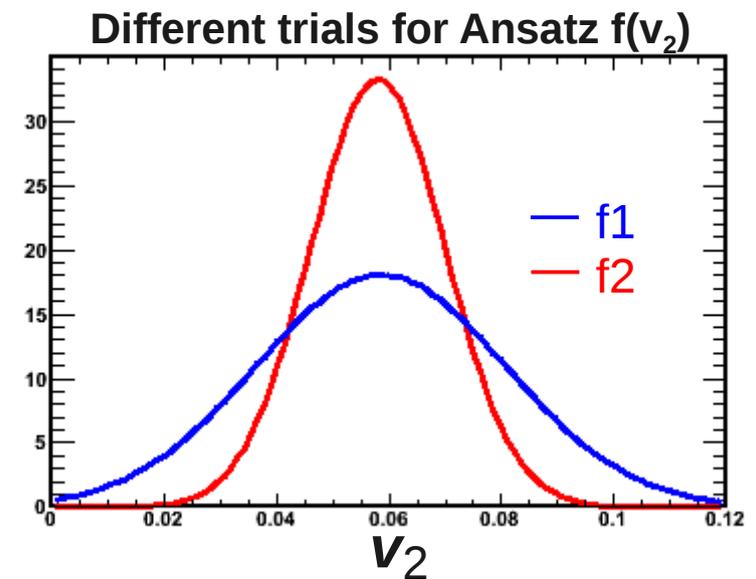
↑
Constructed
from MC

Gaussian Ansatz:

$$f(v_2) = \exp \left[\frac{-(v_2 - \langle v_2 \rangle)^2}{2\sigma_{v_2}^2} \right]$$



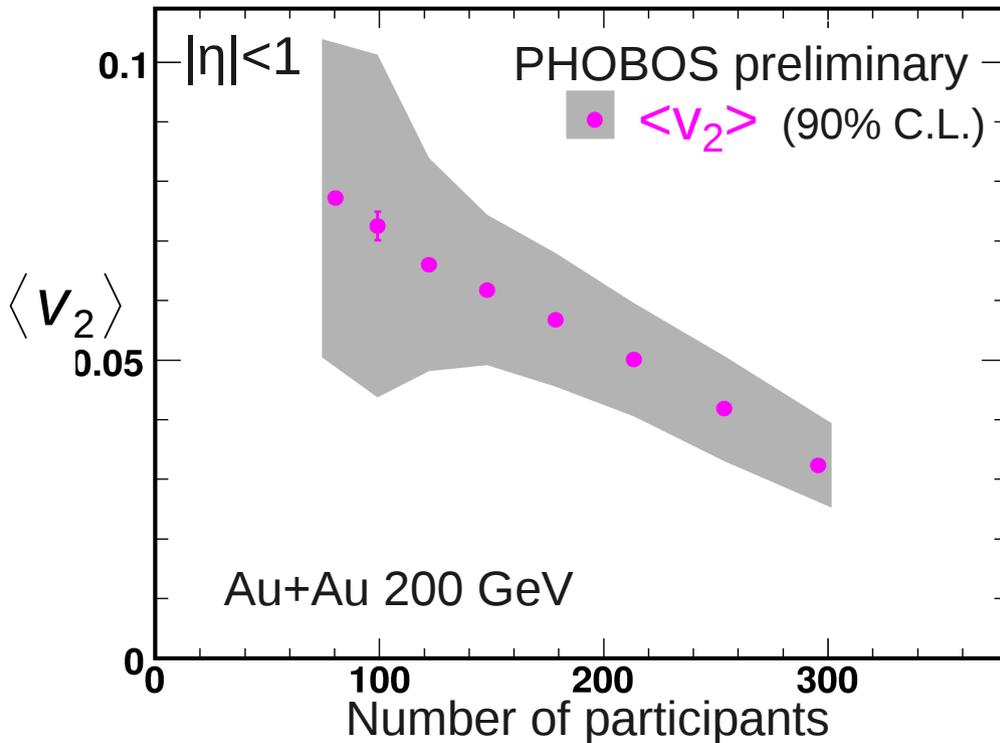
Use kernel
+ integrate



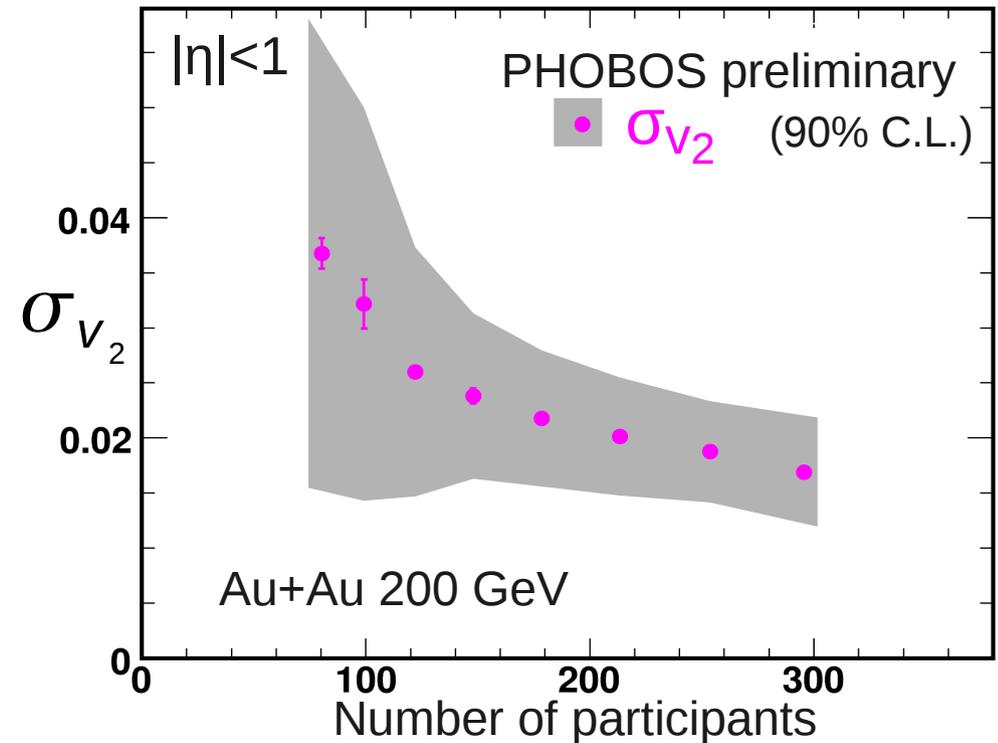
Compare expected $g(v_2^{obs})$ for trials with data:

Maximum-Likelihood fit $\rightarrow \langle v_2 \rangle$ and σ_{v_2}

Mean elliptic flow



Dynamical flow fluctuations



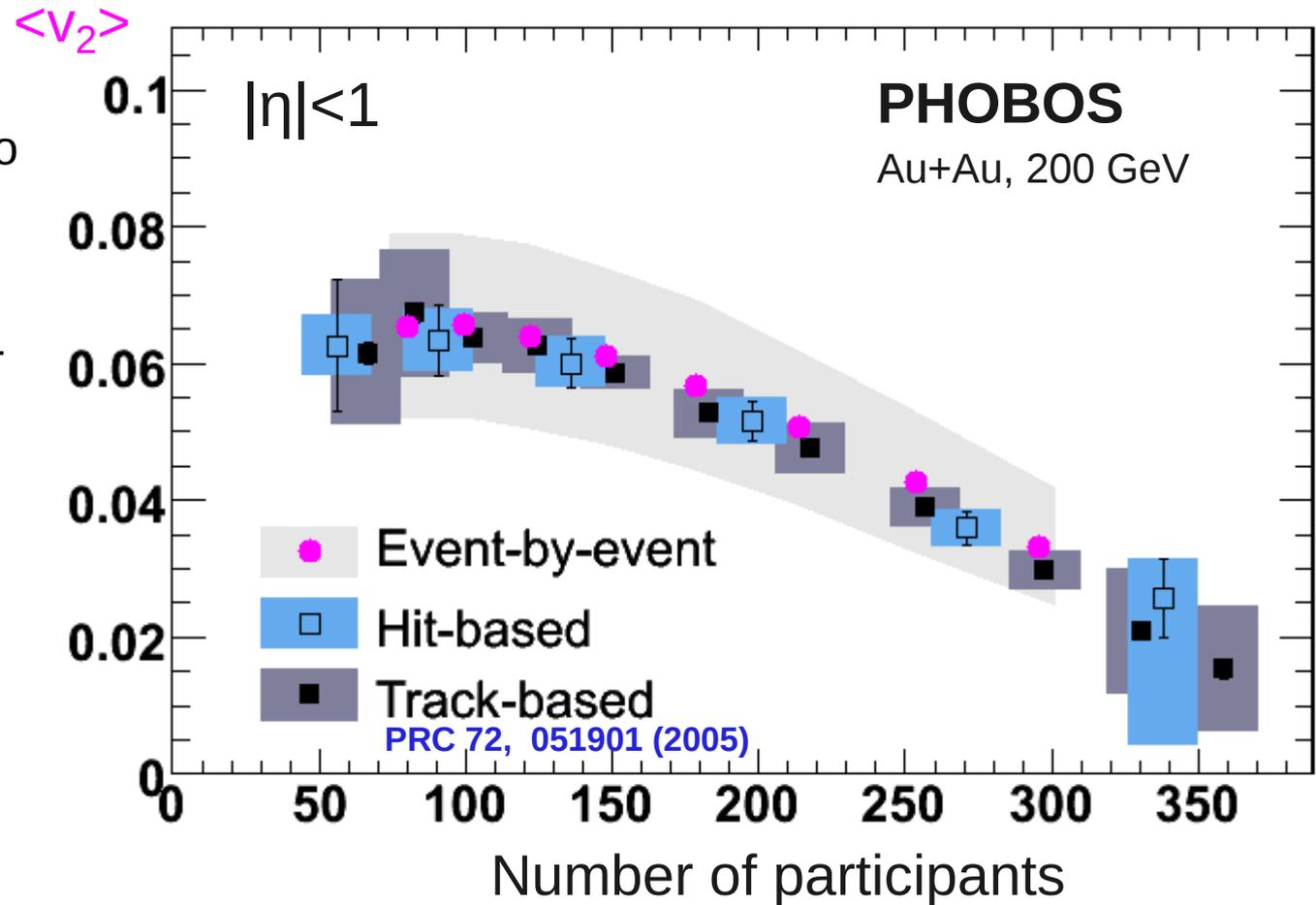
Systematic errors:

- Variation in η -shape
- Variation of $f(v_2)$
- MC response
- Vertex binning
- Φ_0 binning

“Scaling” errors cancel in the ratio:
 relative fluctuations, $\sigma_{v_2}/\langle v_2 \rangle$

- Standard methods

- Averaged over events to measure the mean
- Hit- and track-based
- Use reaction plane sub-event technique



Very good agreement of the event-by-event measured mean v_2 with the hit- and tracked-based, event averaged, published results

$$K(v_2^{obs}, v_2, n) = BG(v_2^{obs}, v_2, \sigma_n), \quad \sigma_n = 1/\sqrt{2n}$$

$$K_\delta(v_2^{obs}, v_2, n) = BG(v_2^{obs}, v_2, \sqrt{\sigma_n^2 + \sigma_\delta^2}), \quad \sigma_n = 1/\sqrt{2n}, \sigma_\delta = \sqrt{\delta/2}$$

$$g(v_2^{obs}) = \int K_\delta(v_2^{obs}, v_2, n) f_{flow}(v_2) dv_2$$

$$g(v_2^{obs}) = \int K(v_2^{obs}, v_2, n) f(v_2) dv_2$$

Generate $g(v_2^{obs})$
using this

Do a fit using this

- Keep results as lookup table
- Results slightly depend on σ_n
 - Use $\sigma_n = 0.4, 0.6$ and 0.8

