Elliptic flow fluctuations
in 200 GeV Au+Au collisions at RHIC

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for the PHOBOS collaboration

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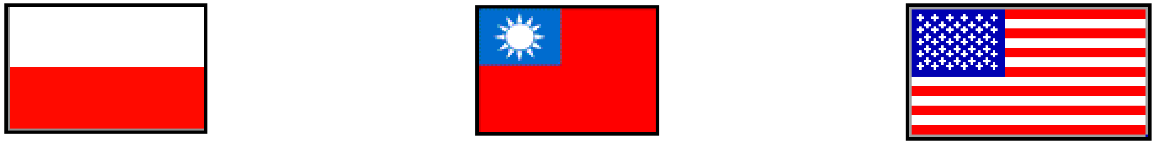
PHOBOS collaboration

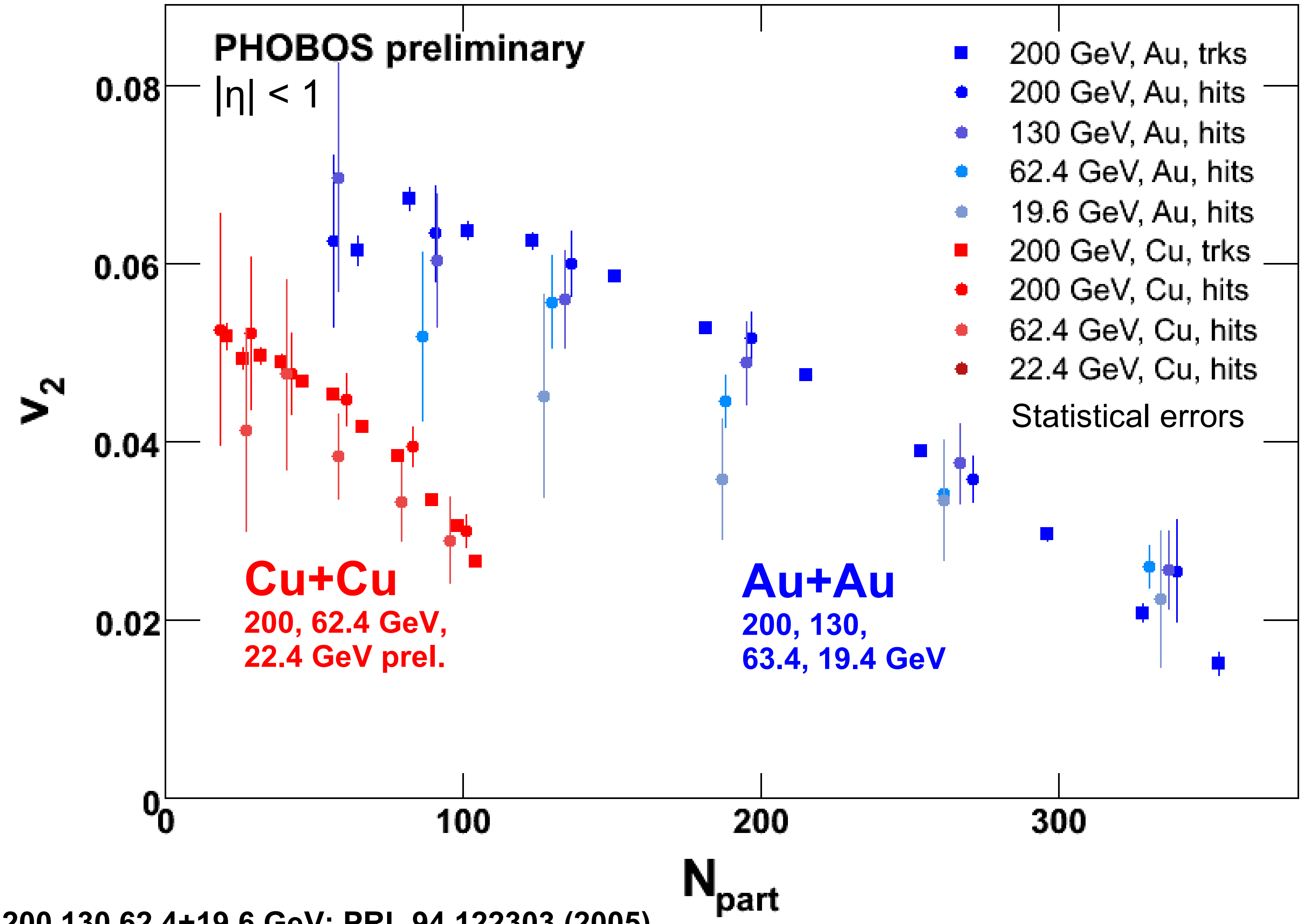


Burak Alver, Birger Back, Mark Baker, Maarten Ballintijn, Donald Barton, Russell Betts, Richard Bindel, Wit Busza (Spokesperson), Vasundhara Chetluru, Edmundo García, Tomasz Gburek, Joshua Hamblen, Conor Henderson, David Hofman, Richard Hollis, Roman Hołyński, Burt Holzman, Aneta Iordanova, Chia Ming 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 Wysłouch

46 scientists, 8 institutions, 9 PhD students

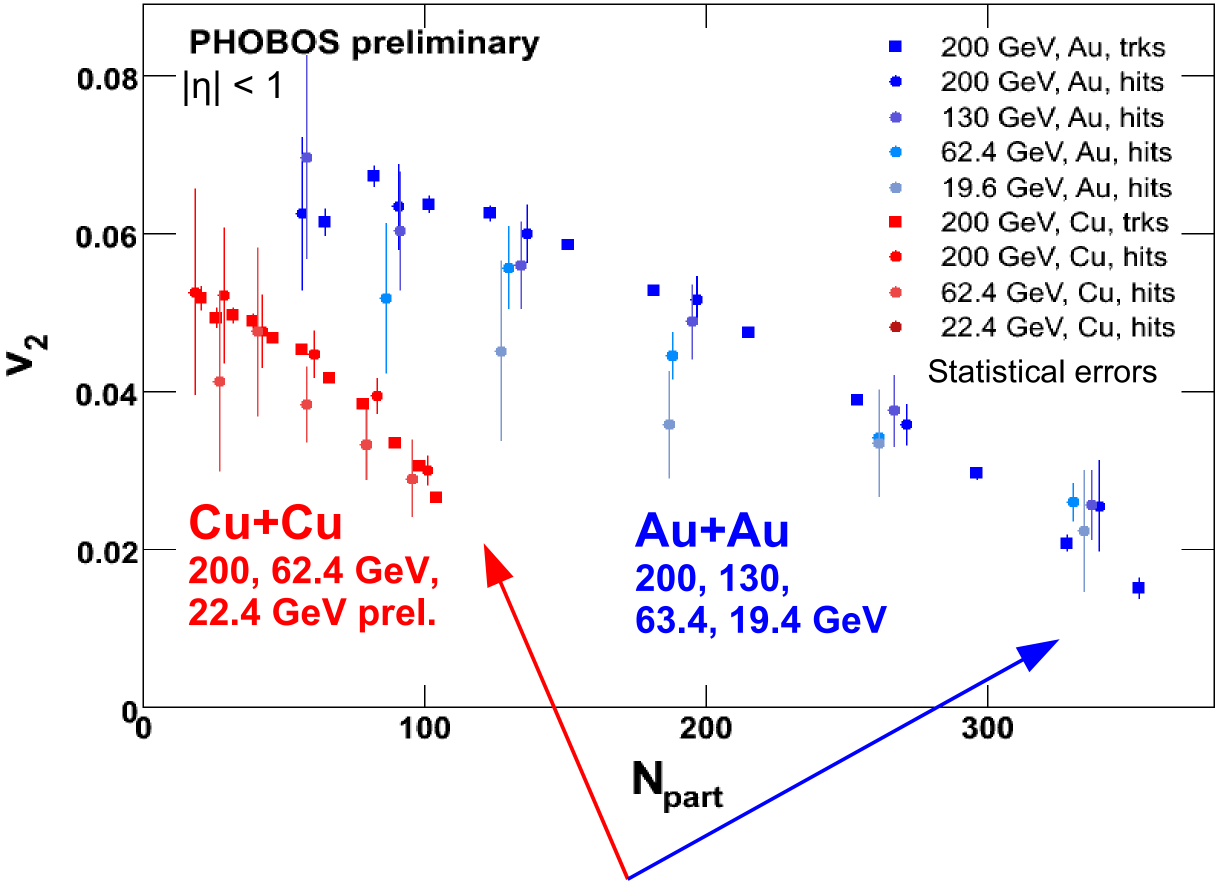
ARGONNE NATIONAL LABORATORY
INSTITUTE OF NUCLEAR PHYSICS PAN, KRAKOW
NATIONAL CENTRAL UNIVERSITY, TAIWAN
UNIVERSITY OF MARYLAND
BROOKHAVEN NATIONAL LABORATORY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
UNIVERSITY OF ILLINOIS AT CHICAGO
UNIVERSITY OF ROCHESTER

Elliptic flow for different species



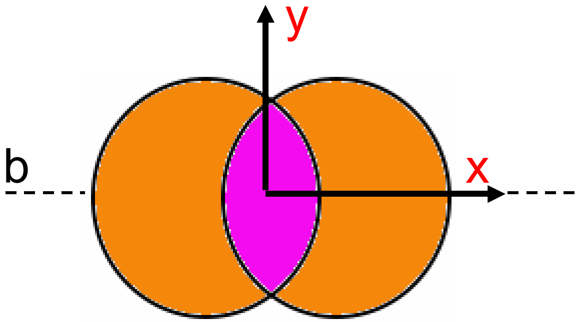
Au+Au, 200,130,62.4+19.6 GeV: PRL 94 122303 (2005)
Cu+Cu, 200+62.4 GeV: nucl-ex/0610037 (sub.to PRL)
Cu+Cu, 22.4 GeV: prel. QM06

Elliptic flow and standard eccentricity

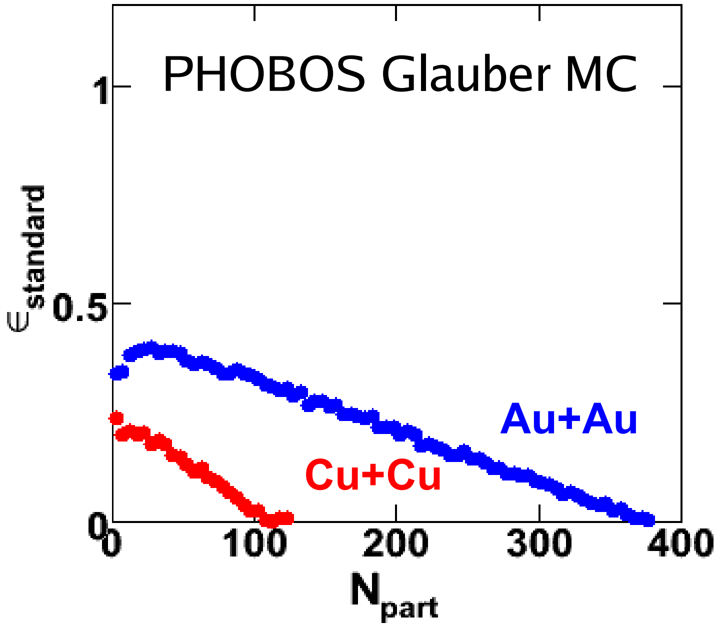


Large flow in central Cu+Cu compared to central Au+Au

Standard Eccentricity

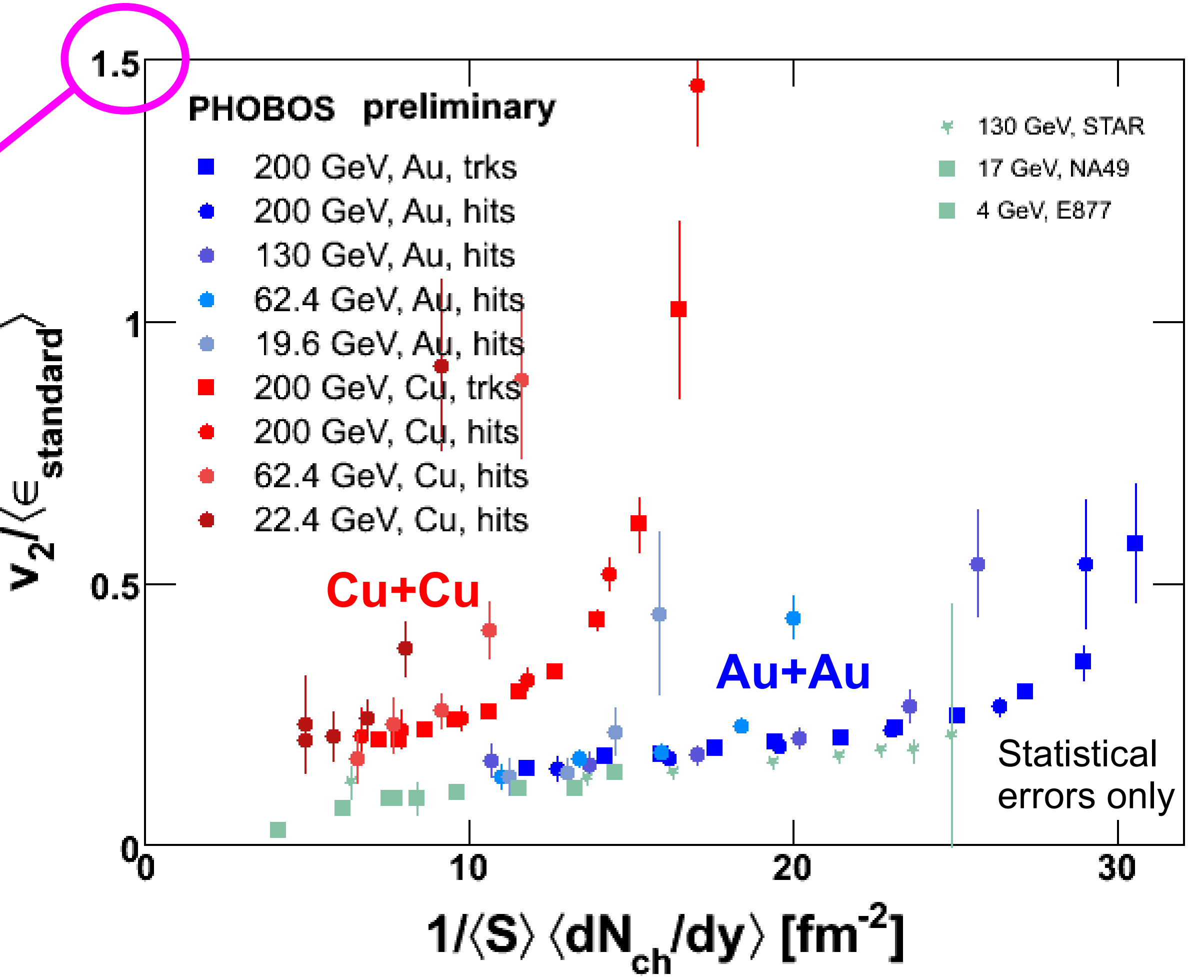


$$\epsilon_{standard} = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}$$

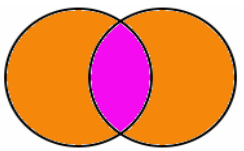


Au+Au, 200,130,62.4+19.6 GeV: PRL 94 122303 (2005)
Cu+Cu, 200+62.4 GeV: nucl-ex/0610037 (sub.to PRL)
Cu+Cu, 22.4 GeV: prel. QM06

Elliptic flow scaled with $\varepsilon_{standard}$



Notice scale



Small print:

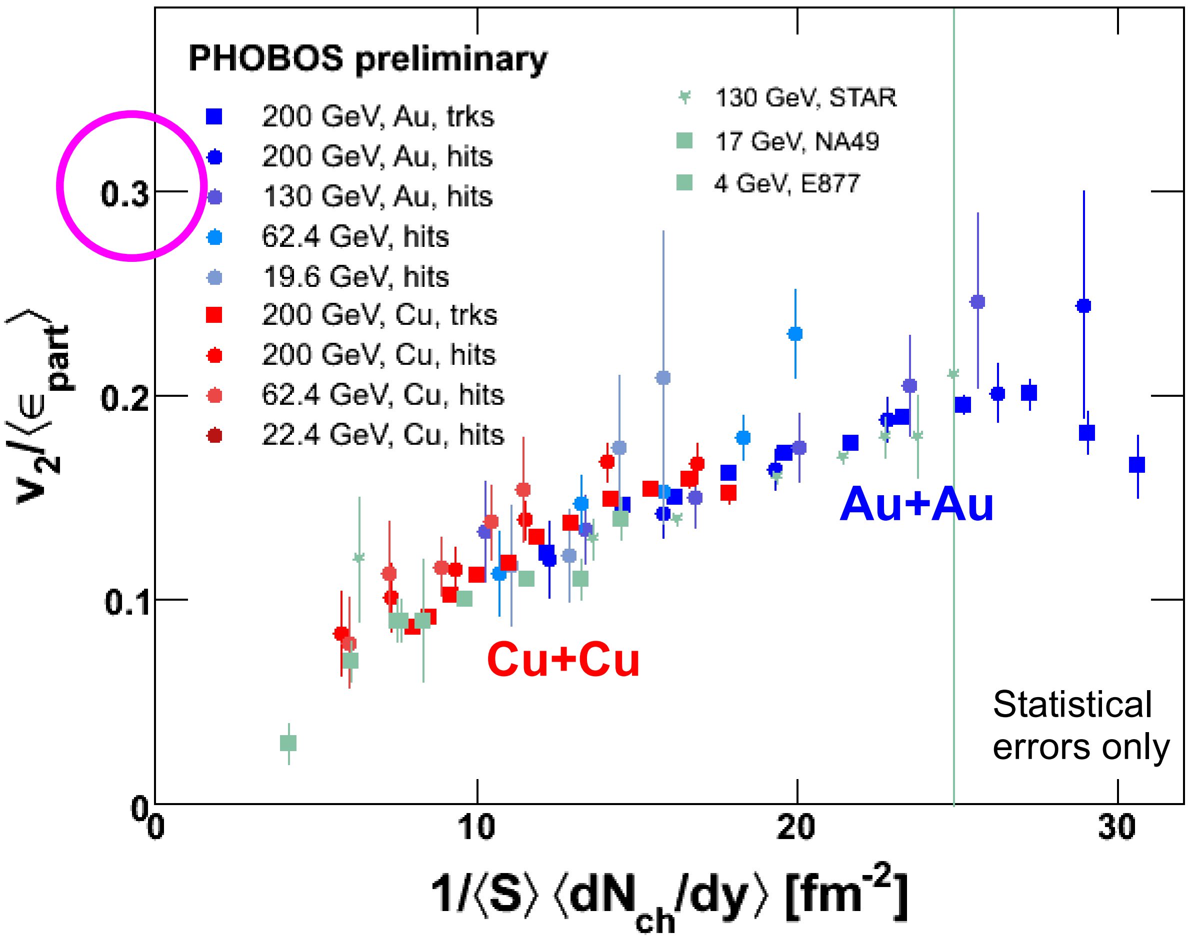
- ➢ Scale $v_2(\eta)$ to $v_2(y)$ (10% lower)
- ➢ Scale $dN/d\eta$ to dN/dy (15% higher)
- ➢ S is overlap area (MC Glauber)

No scaling between Cu+Cu and Au+Au

Au+Au, 200,130,62.4+19.6 GeV: PRL 94 122303 (2005)
Cu+Cu, 200+62.4 GeV: nucl-ex/0610037 (sub.to PRL)
Cu+Cu, 22.4 GeV: prel. QM06

Heiselberg, Levy, PRC 59 2716, (1999)
Voloshin, Poskanzer, PLB 474 27 (2000)
STAR, PRC 66 034904 (2002)

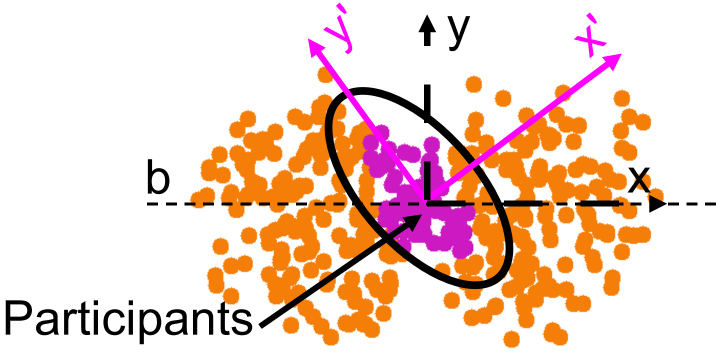
Elliptic flow and participant eccentricity



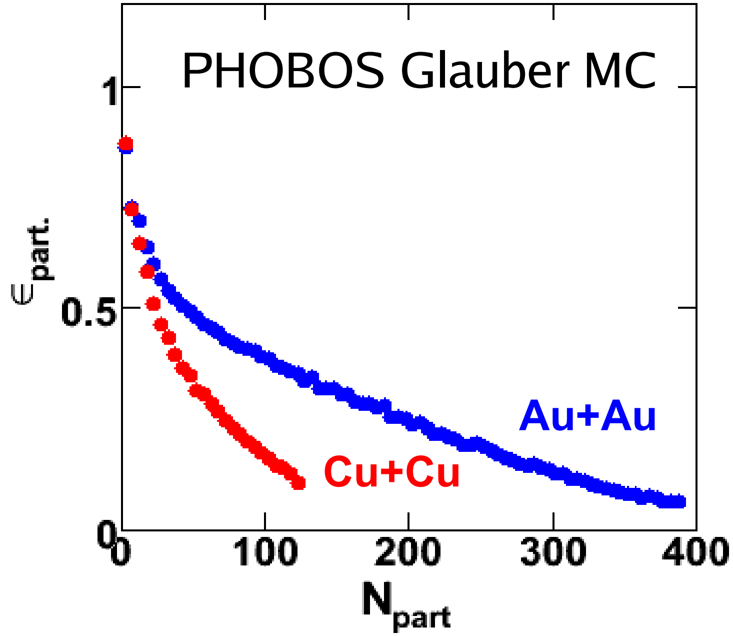
Approximate scaling between Cu+Cu and Au+Au

Au+Au, 200,130,62.4+19.6 GeV: PRL 94 122303 (2005)
Cu+Cu, 200+62.4 GeV: nucl-ex/0610037 (sub.to PRL)
Cu+Cu, 22.4 GeV: prel. QM06

Participant Eccentricity



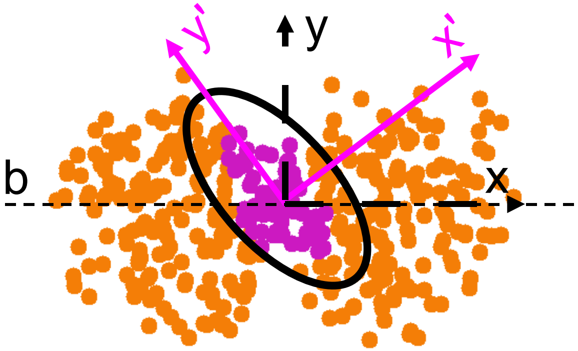
$$\epsilon_{part} = \frac{\sqrt{(\sigma_y^2-\sigma_x^2)^2+4\sigma_{xy}^2}}{\sigma_y^2+\sigma_x^2}$$



Expected elliptic flow fluctuations

Elliptic flow seems to be developed event-by-event with respect to the overlap region

$$v_2 \sim \epsilon_{part}$$

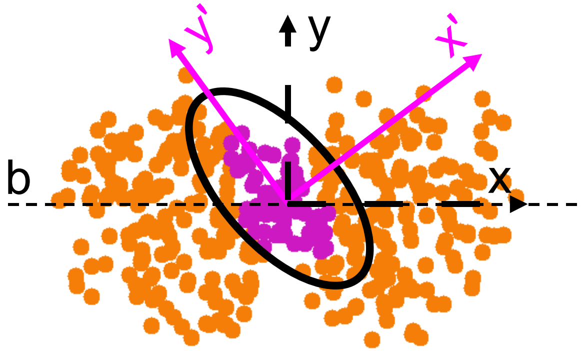


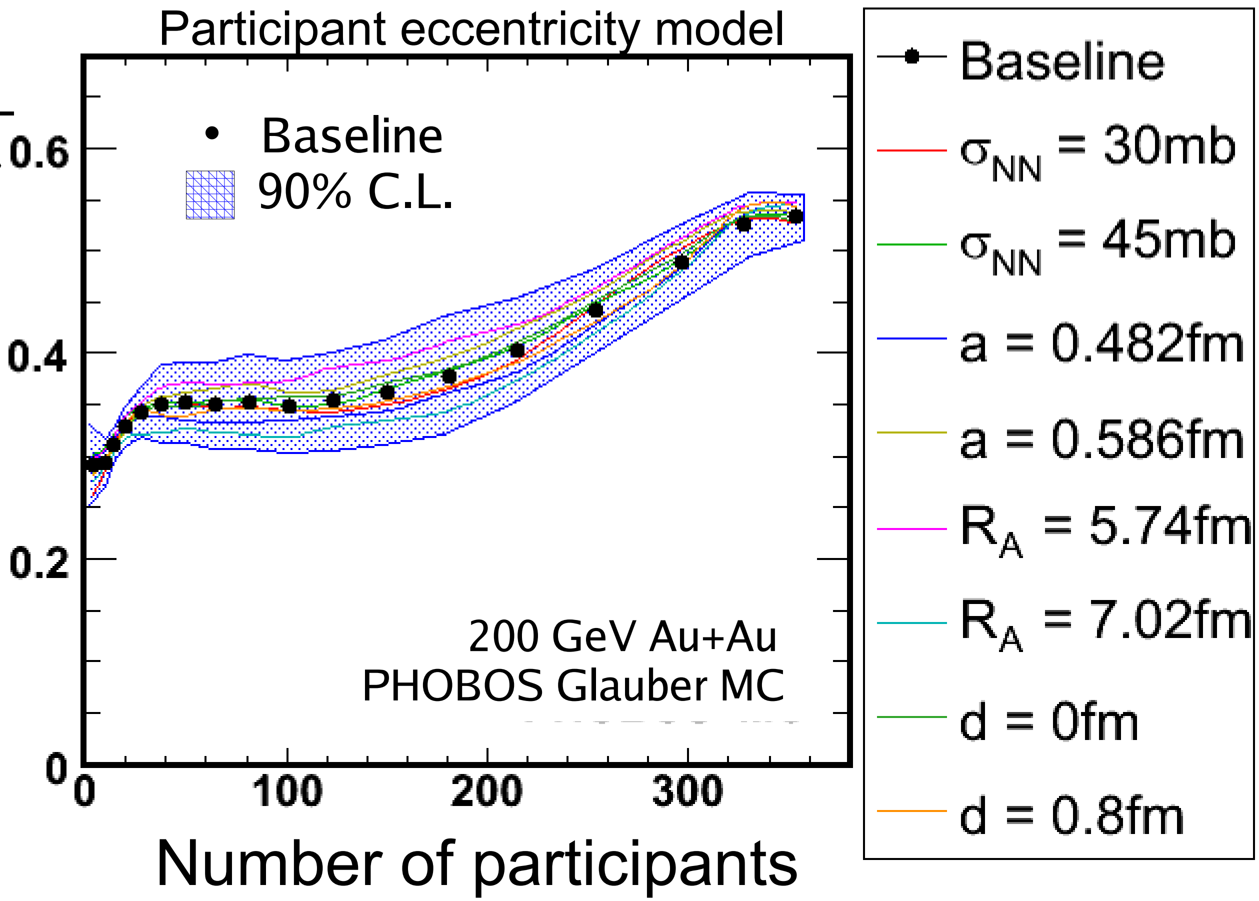
$$\frac{\sigma_{v_2}}{\langle v_2 \rangle} \sim \frac{\sigma_{\epsilon_{part}}}{\langle \epsilon_{part} \rangle}$$

Expected elliptic flow fluctuations

Elliptic flow is developed event-by-event with respect to the overlap region

$$v_2 \sim \epsilon_{part}$$



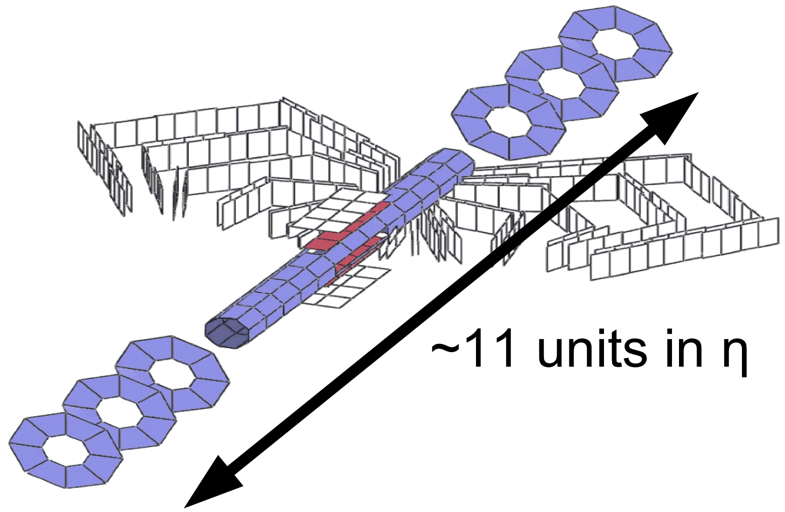


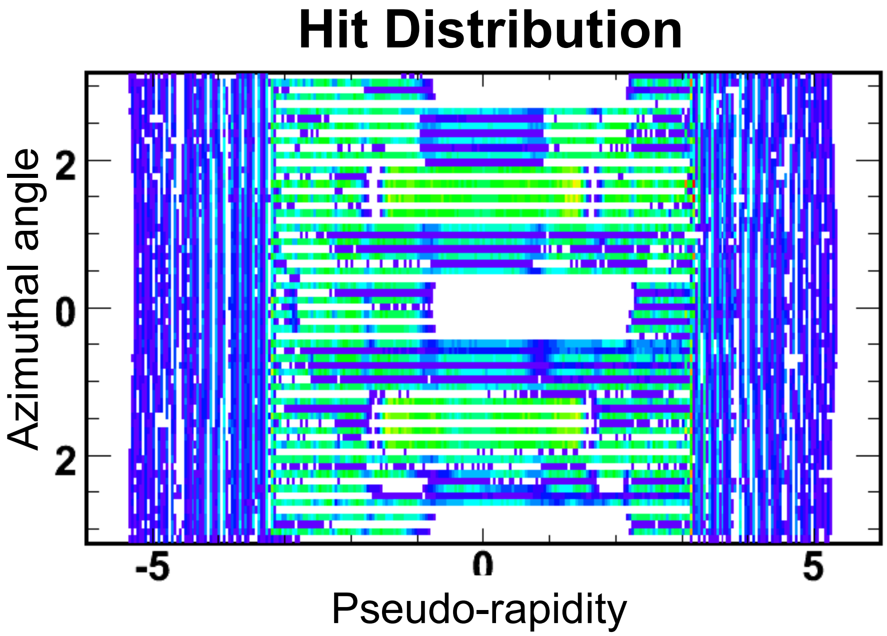
Baseline parameters:

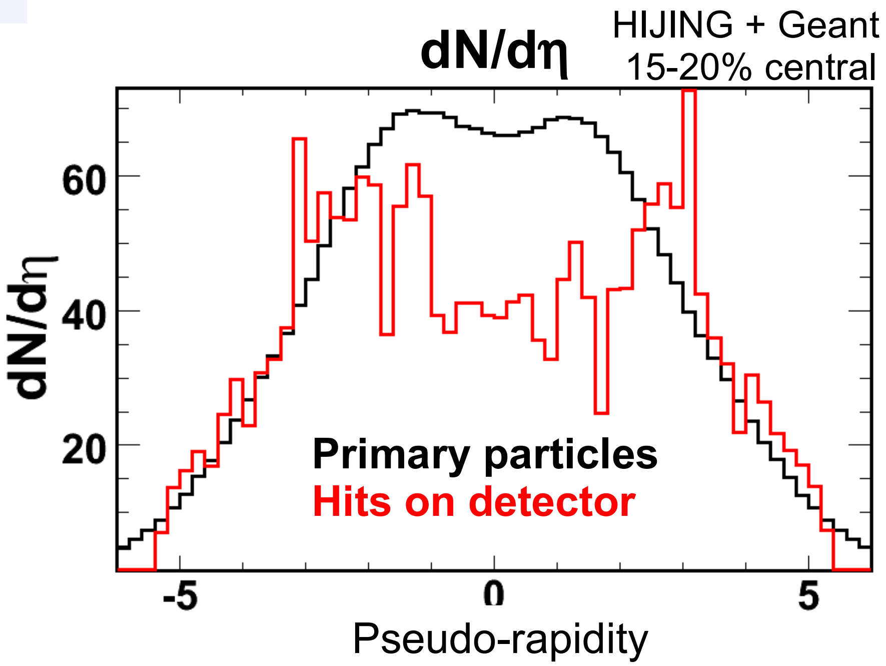
- Nucleon-nucleon cross section: σ_{NN}=42mb
- Skin depth: a=0.535fm
- Wood-saxon radius: R_A=6.38fm
- Inter-nucleon separation distance: d=0.4fm

Event-by-event measurement of v_2^{obs}

- 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}

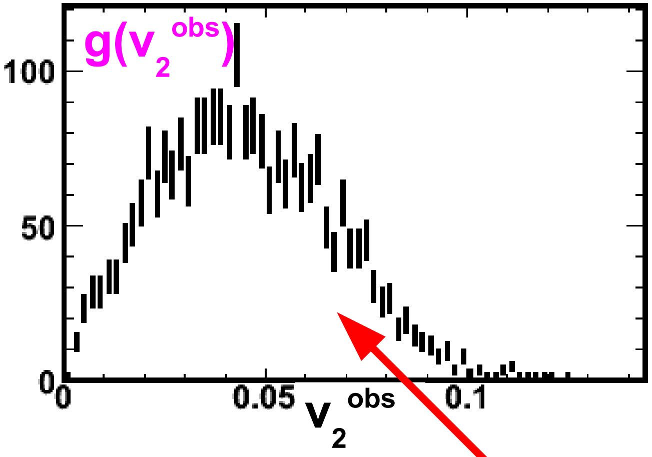




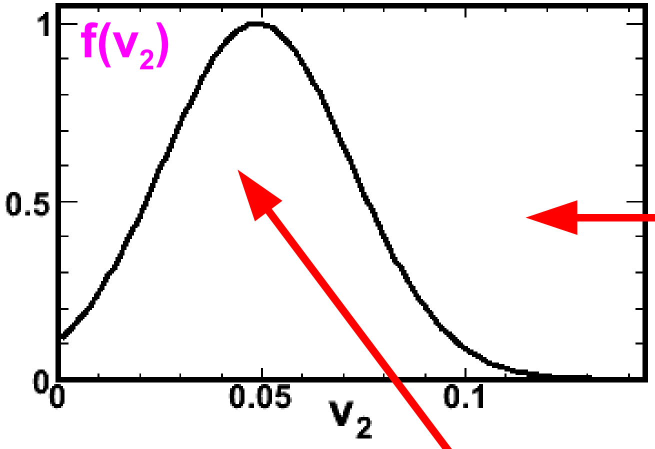


Measuring elliptic flow fluctuations

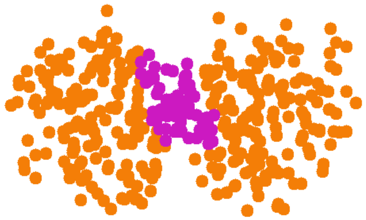
Observed v_2 distribution



True v_2 distribution



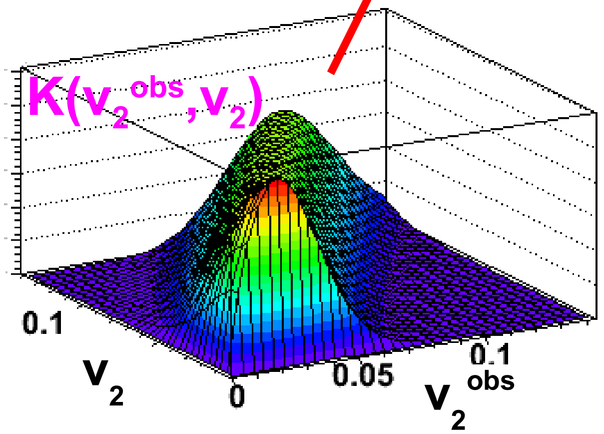
Source of v_2 fluctuation



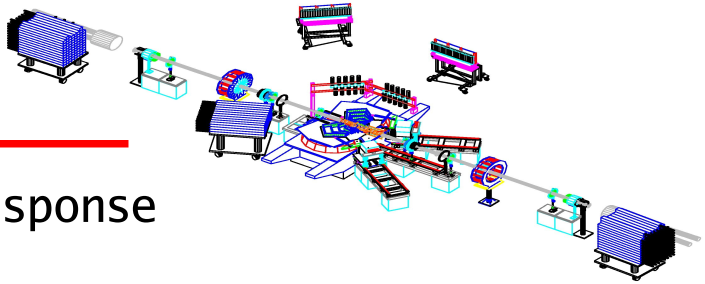
$$g(v_2^{obs}) = \int_0^1 K(v_2^{obs}, v_2)\, f(v_2)\, dv_2$$

Kernel

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



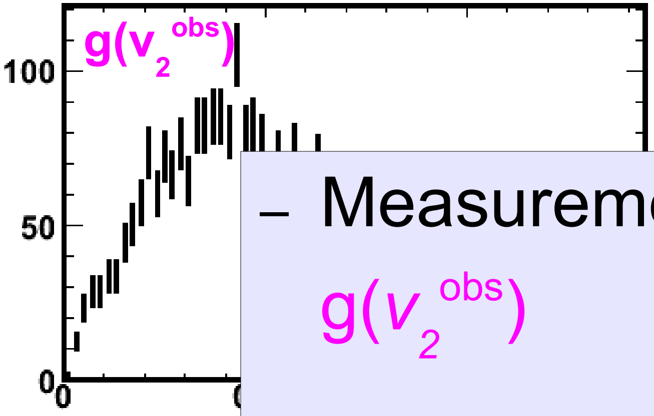
Kernel



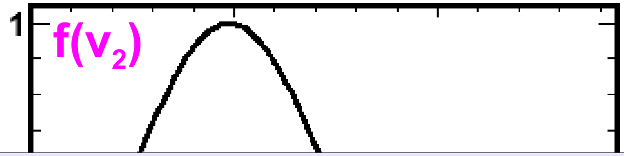
Detector response

Measuring elliptic flow fluctuations

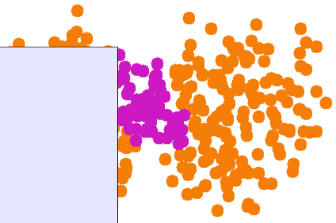
Observed v_2 distribution



True v_2 distribution



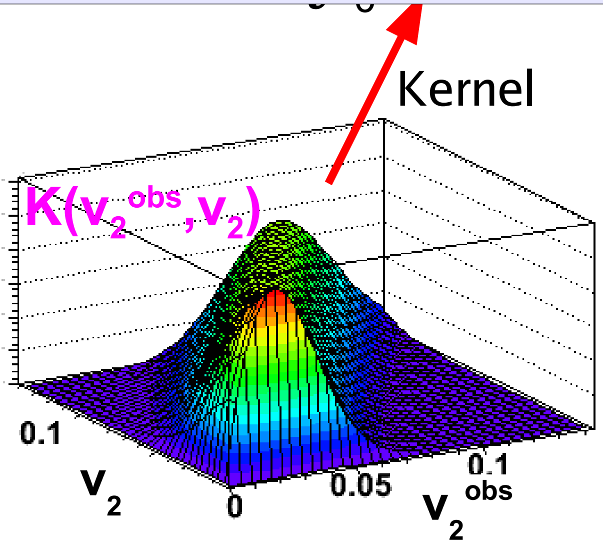
Source of v_2 fluctuation

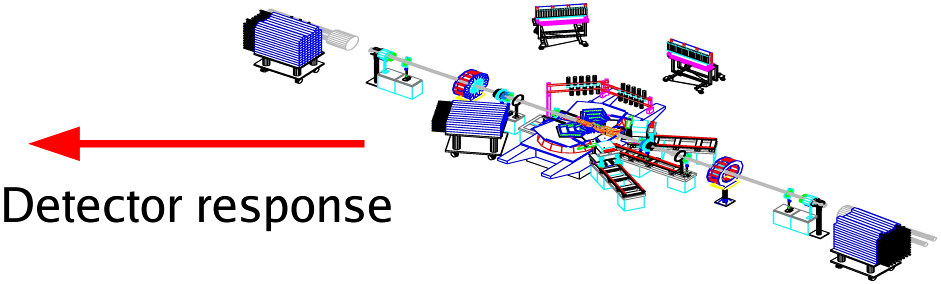


- Measurement of v_2^{obs} event-by-event: $g(v_2^{obs})$
- Construction of the kernel: $K(v_2^{obs},v_2)$
- Extraction of dynamical fluctuations: $f(v_2)$

Kernel

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

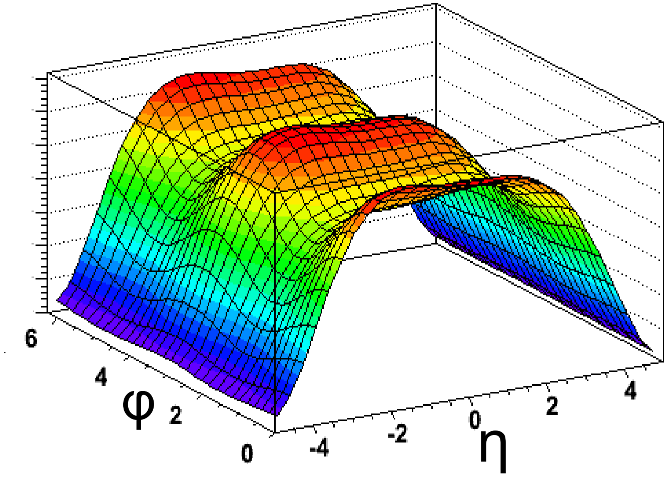




Event-by-event measurement of v_2^{obs}

- Event-by-event measurement of v_2^{obs}
  - Deal with acceptance effects
  - Use all available hit information

Probability distribution function



- Probability distribution function for hit positions:

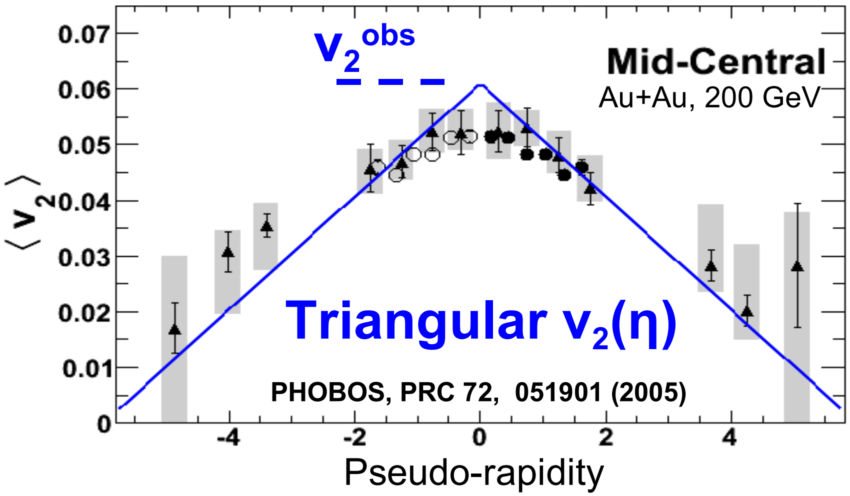
$$P(\eta,\phi;\, v_2^{obs},\phi_0)=\underbrace{p(\eta)}_{\text{Normalization incl. acceptance}}\underbrace{[1+2v_2(\eta)\cos(2\phi-2\phi_0)]}_{\text{Probability of hit in }(\phi,\eta)}$$

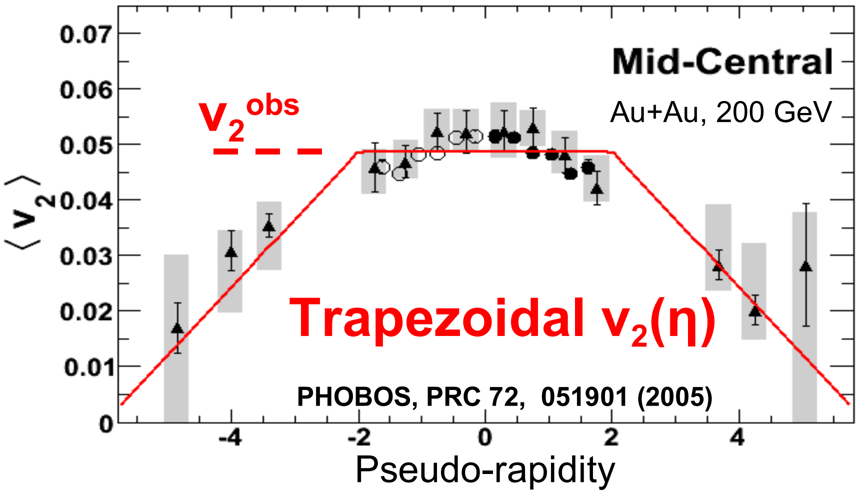
  - Maximize the likelihood function to obtain v_2^{obs} and φ^0 (event plane angle)

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

See Burak Alver's Poster 16, QM2006
B.Alver et.al. (PHOBOS), nucl-ex/0608025

Event-by-event measurement of v_2^{obs}





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

$$\uparrow$$

Use known, measured shape

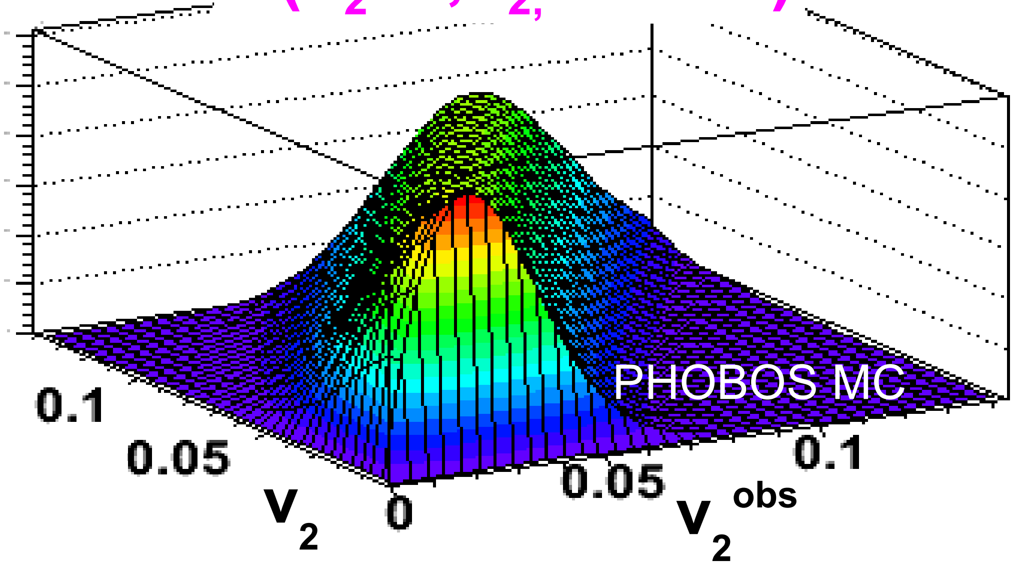
Analysis is run completely independent on triangular and trapezoidal shape. Results are averaged at the end.

See Burak Alver's Poster 16, QM2006
B.Alver et.al. (PHOBOS), nucl-ex/0608025

Determining the kernel

- "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

$K(v_2^{obs}, v_2,$ fixed n)



- Fit response function (ideal case)

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

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

- Changed to account for detector effects

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

(suppression) (finite resolution)

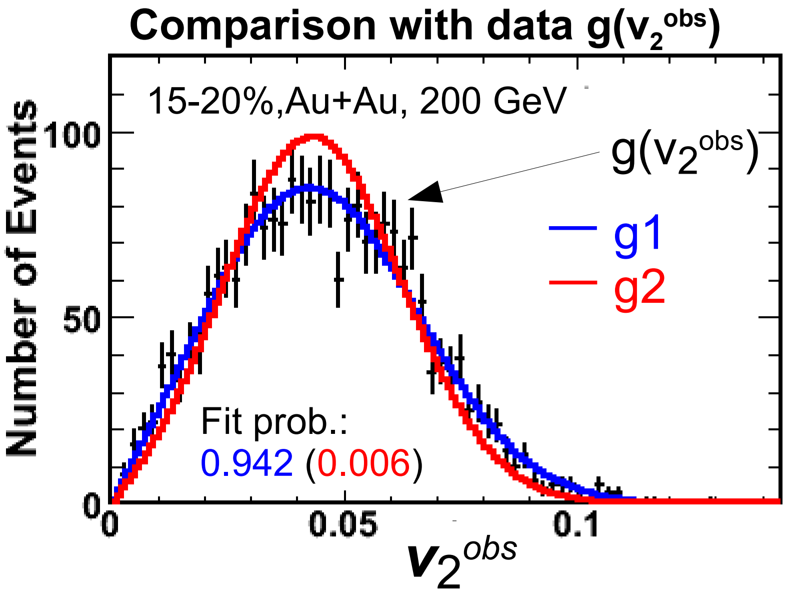
See Burak Alver's Poster 16, QM2006
B.Alver et.al. (PHOBOS), nucl-ex/0608025

Extracting dynamical fluctuations

$$\underbrace{g(v_2^{obs})}_{\text{Measured}} = \int_0^1 \underbrace{K(v_2^{obs}, v_2)}_{\text{Constructed from MC}} \underline{f(v_2)}\, dv_2$$

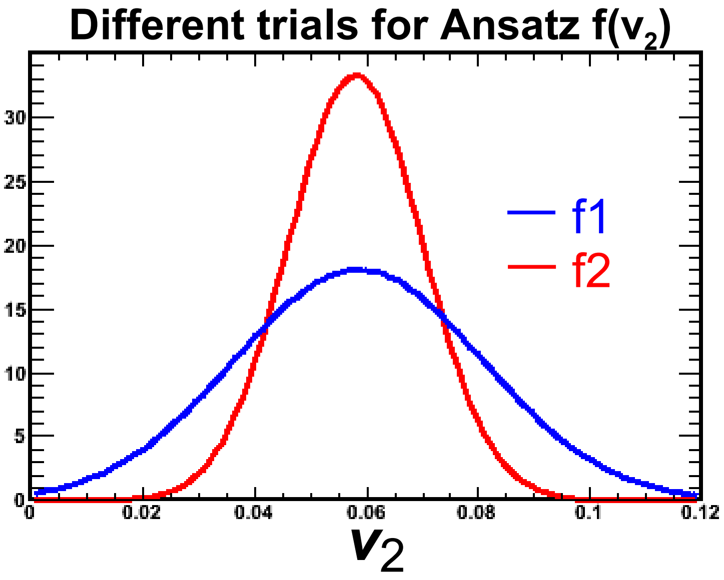
Gaussian Ansatz:

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



Comparison with data $g(v_2^{obs})$

Use kernel + integrate



Different trials for Ansatz $f(v_2)$

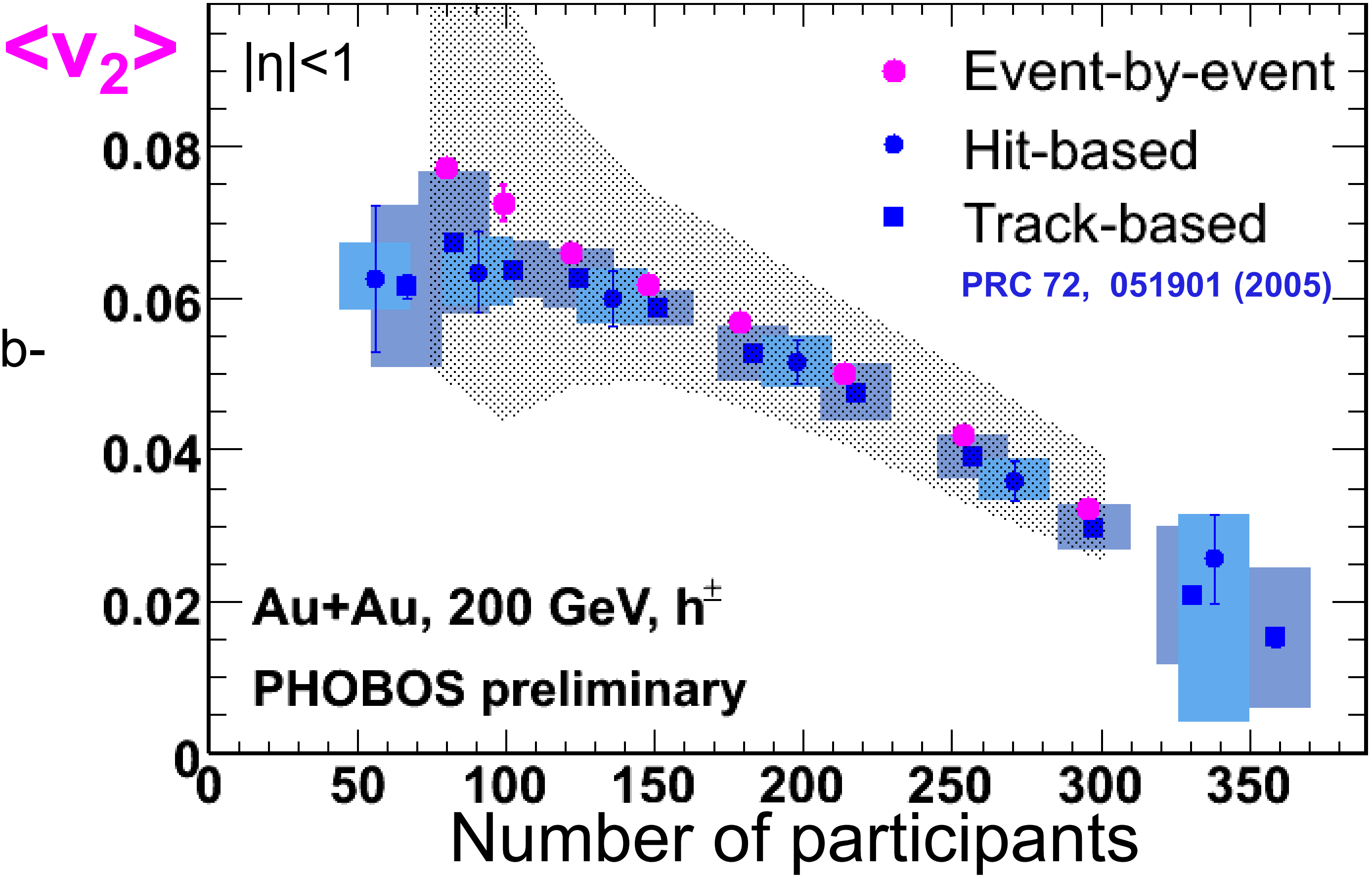
Compare expected $g(v_2^{obs})$ for trials with data:

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

See Burak Alver's Poster 16, QM2006
B.Alver et.al. (PHOBOS), nucl-ex/0608025

Event-by-event mean v_2 vs published results

- Standard methods
  - Averaged over events to measure the mean
  - Hit- and track-based
  - Use reaction plane sub-event technique
- Event-by-event:
  - PR04 Au+Au data
    - No magnetic field
    - 500.000 events
    - 10 vertex bins ($-10\text{cm}<z_{\text{vertex}}<10\text{cm}$)

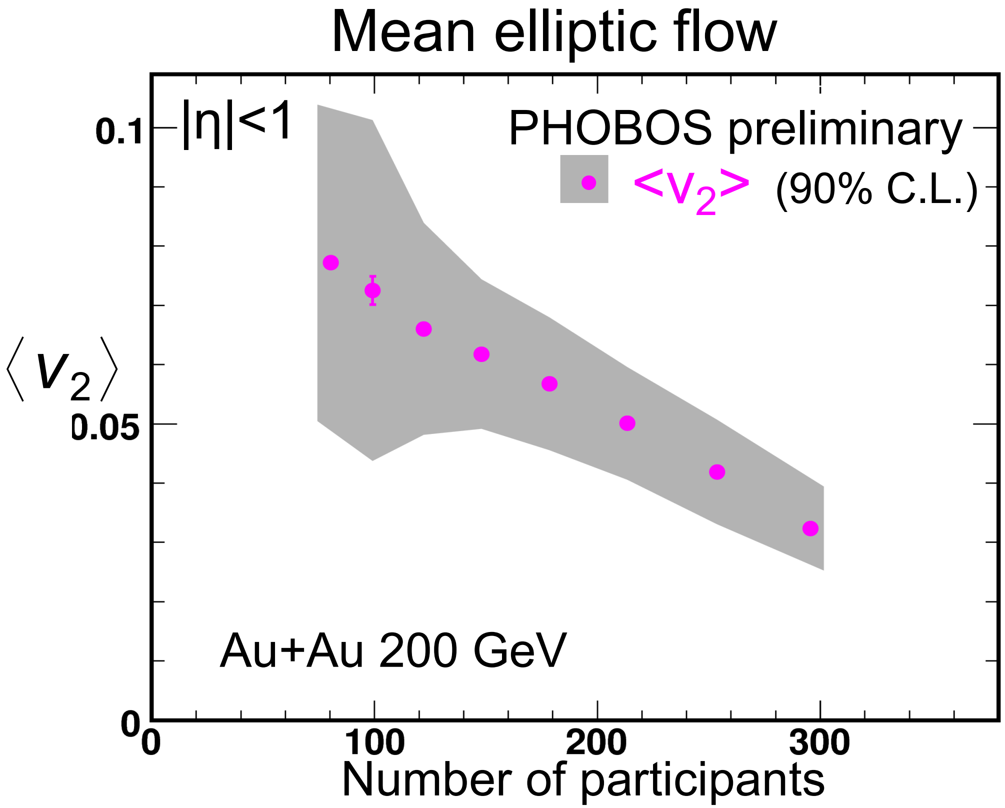


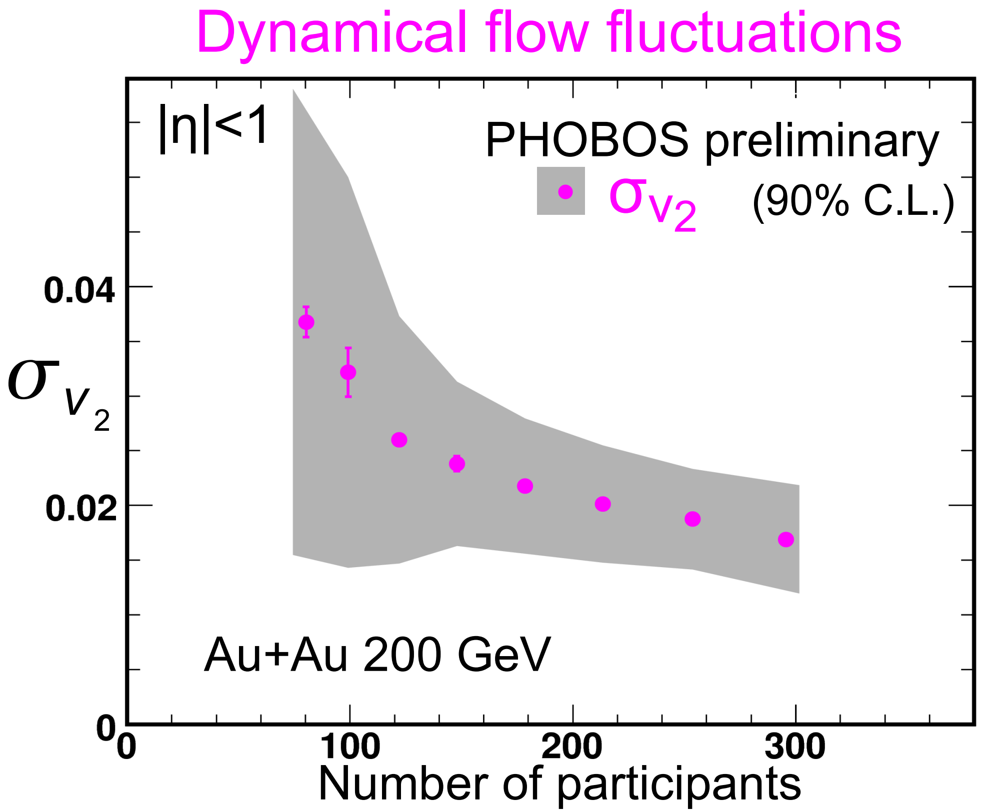
  - **Relate v_2^{obs} to $\langle v_2 \rangle$:**

$$\langle v_2 \rangle(|\eta|<1) = 0.5 \times (11/12 \langle v_2^{\text{triangular}} \rangle + \langle v_2^{\text{trapezodial}} \rangle)$$

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

Elliptic flow fluctuations: $\langle v_2 \rangle$ and σ_{v_2}


Mean elliptic flow


Dynamical flow fluctuations

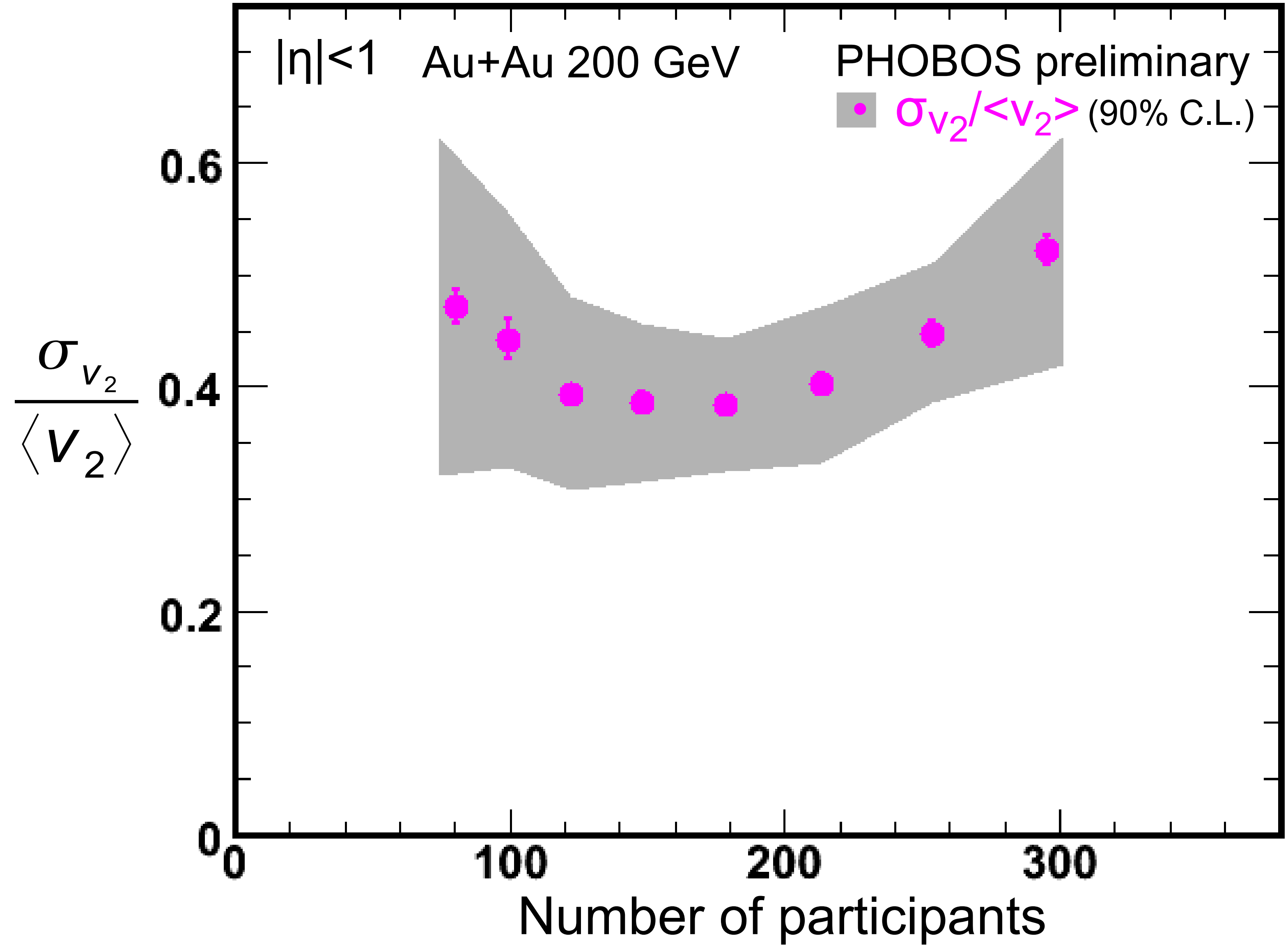
<u>Systematic errors:</u>

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

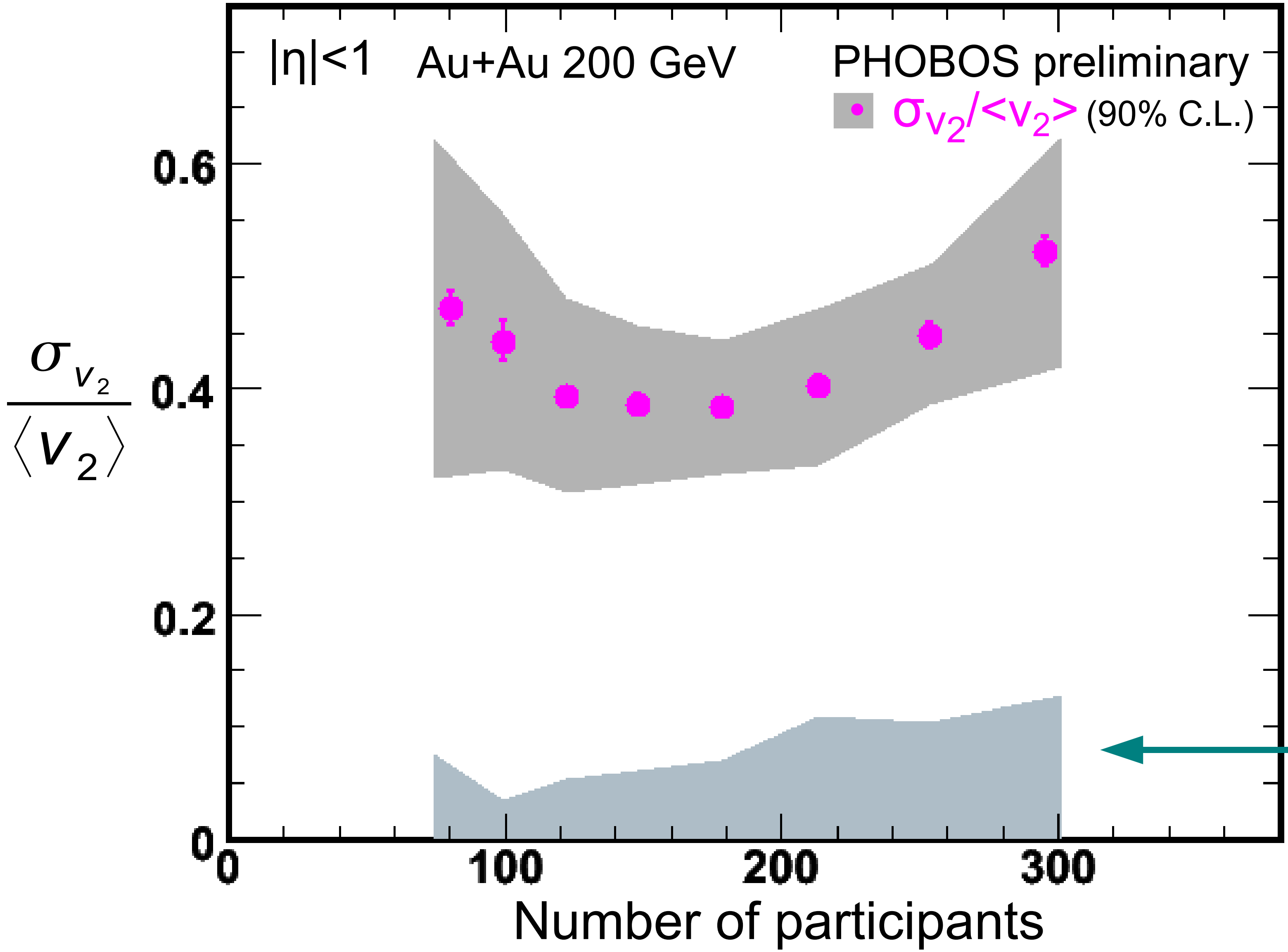
"Scaling" errors cancel in the ratio: relative fluctuations, $\sigma_{v_2}/\langle v_2 \rangle$

see next slide →

Elliptic flow fluctuations: $\sigma_{v_2}/\langle v_2 \rangle$

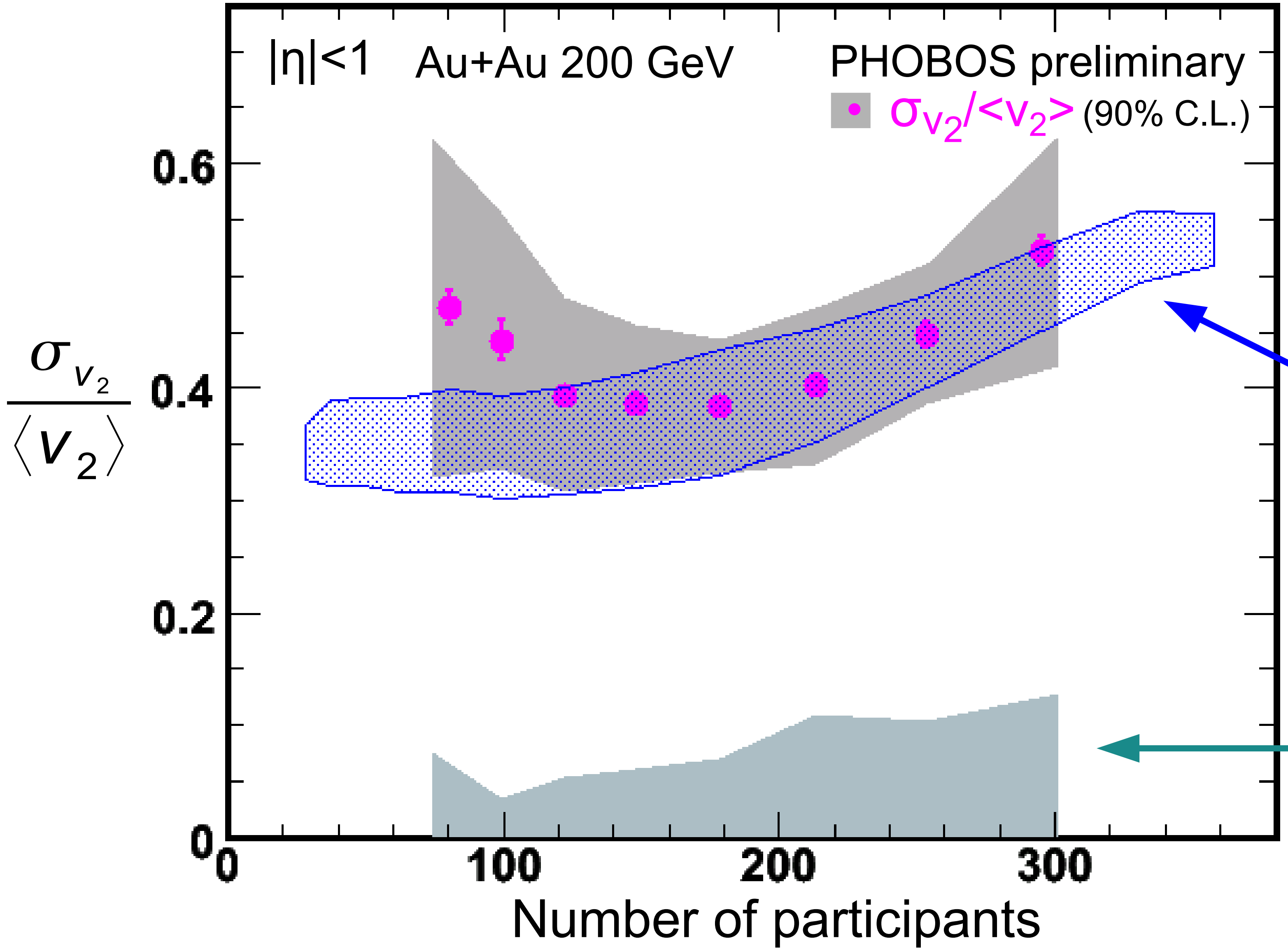


Elliptic flow fluctuations: $\sigma_{v_2}/\langle v_2\rangle$



MC with no fluctuations

Participant eccentricity compared to data



Participant eccentricity model prediction $\frac{\sigma_{\epsilon_{part}}}{\langle \epsilon_{part}\rangle}$

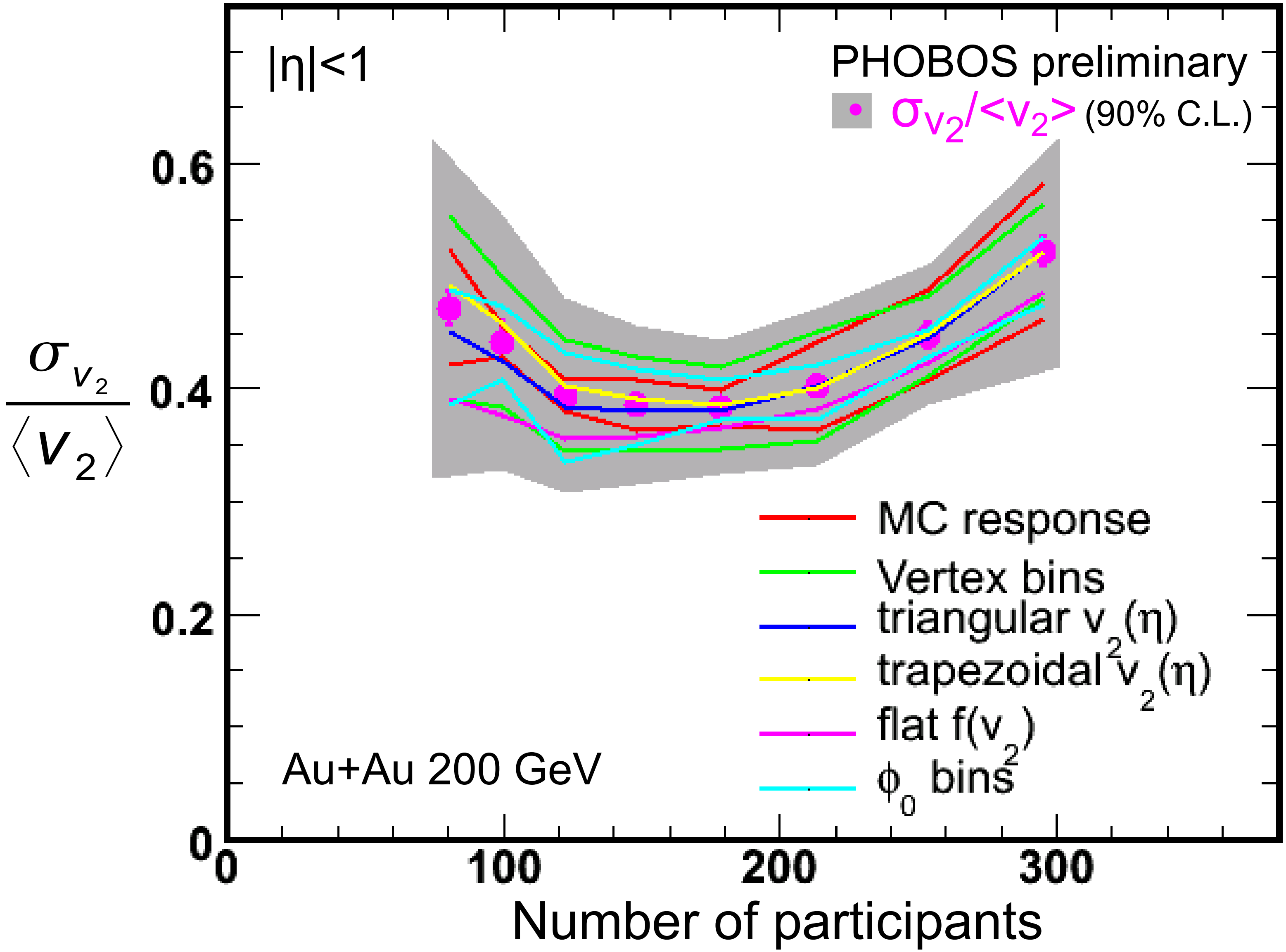
MC with no fluctuations

Summary

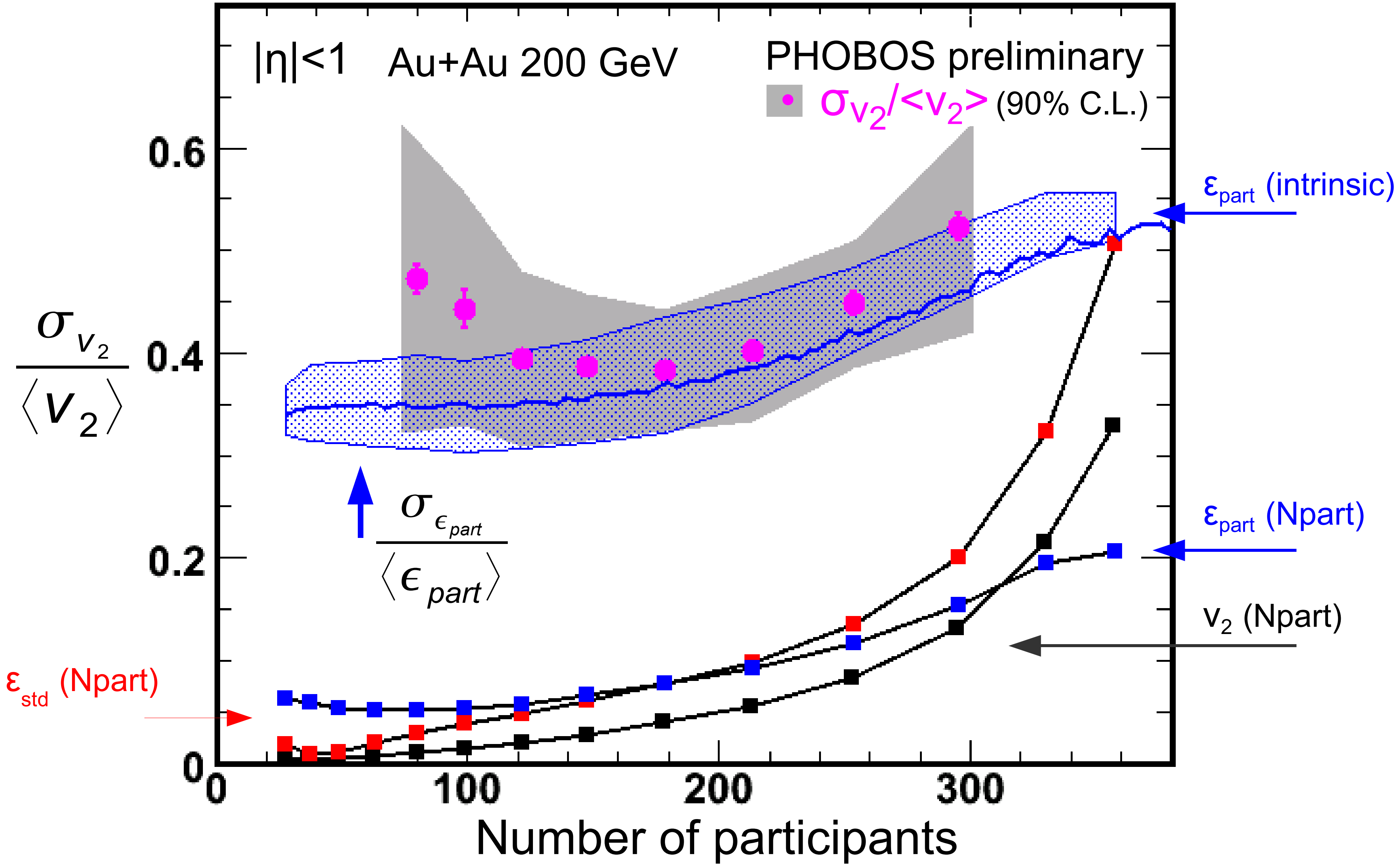
- PHOBOS has measured elliptic flow fluctuations in peripheral to semi-central Au+Au collisions at 200 GeV
  - Absolute fluctuations (σ_{v_2}) are about 0.02
  - Relative fluctuations ($\sigma_{v_2}/\langle v_2\rangle$) are about 40%
  - The participant eccentricity predictions for the magnitude of the relative fluctuations are in striking agreement with the measurement
- Modeling of interaction points with MC Glauber interpreted event-by-event, the participant eccentricity model, appears to be able to explain both
  - The magnitude of the mean elliptic flow in Cu+Cu wrt Au+Au
  - The magnitude of the elliptic flow fluctuations in Au+Au

Backup slides

Systematic error sources

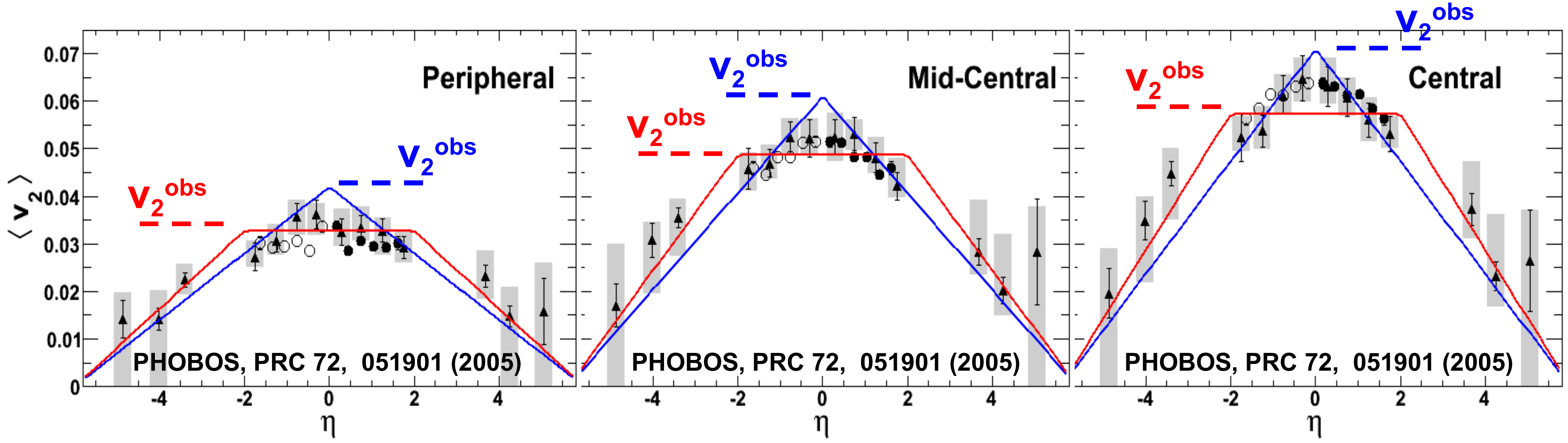


Contributions from Npart fluctuations



Fluctuations in Npart are calculated by folding f(Npart) with a Gaussian with mean and sigma as obtained from the centrality selection used in PHOBOS

Event-by-event measurement of v_2^{obs}



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

↑

Use known, measured shape

See Burak Alver's Poster 44, QM2006
B.Alver et.al. (PHOBOS), nucl-ex/0608025

Fluctuations estimates: nucl-th/0208052

- Estimation of δv_2 in e-by-e analysis using the RP method
  - Statistical noise(*) $\delta^{stat}_{v_2} = 1/\langle R\rangle / \sqrt{2\langle N\rangle} \approx 0.01 - 0.07$
  - Impact para (Npart) (**) $\delta^{b}_{v_2} = f(b)\,\delta_{Np}\ [0.024\ for\ b = 5\mathrm{fm}]$
  - Multiplicity fluctuation(*) $\delta^{N}_{v_2} = 0.4\langle v_2\rangle/\sqrt{\langle N\rangle} = 0.56\langle v_2\rangle\langle R\rangle\,\delta^{stat}_{v_2}$
  - Cluster formation $\delta^{cl}_{v_2} = 0.4\langle v_2\rangle/\sqrt{\langle N\rangle}\left(\sqrt{1-f}+\sqrt{kf}\right)\approx 2\,\delta^{N}_{v_2}$
  - Fluctuations due to filamentation instability
    - Random process occurring dominantly for b->0
    - No prediction about the distribution: $0 < v_2 < 0.46$
- Participant eccentricity $\delta^{epart}_{v_2} = 1/\langle v_2\rangle\,\delta_{\epsilon}/\langle\epsilon\rangle \approx 0.02$

(*) taken out by kernel, (**) estimated to be small

S.Mrowczynski, E.Shuryak, nucl-th/0208052

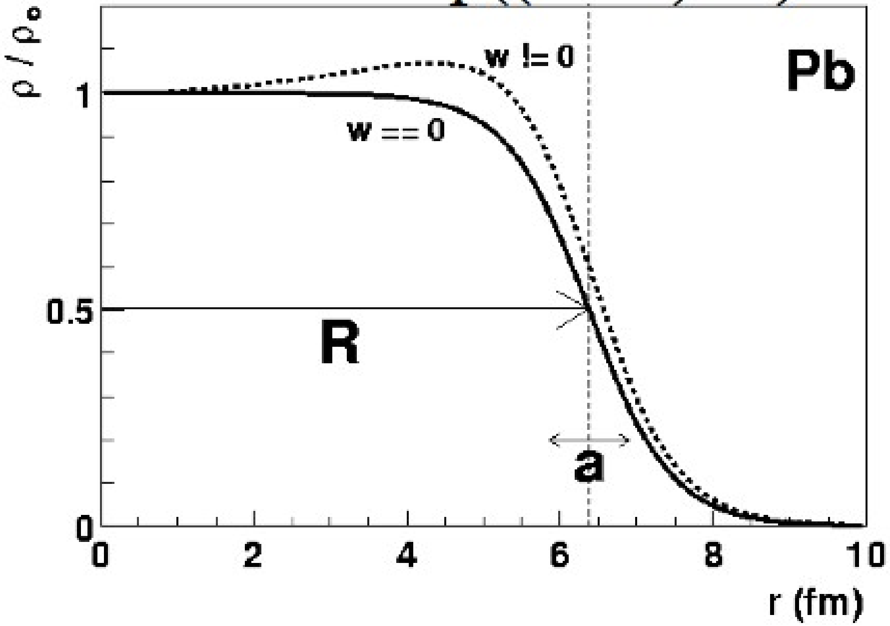
Non-flow contributions to flow fluctuations

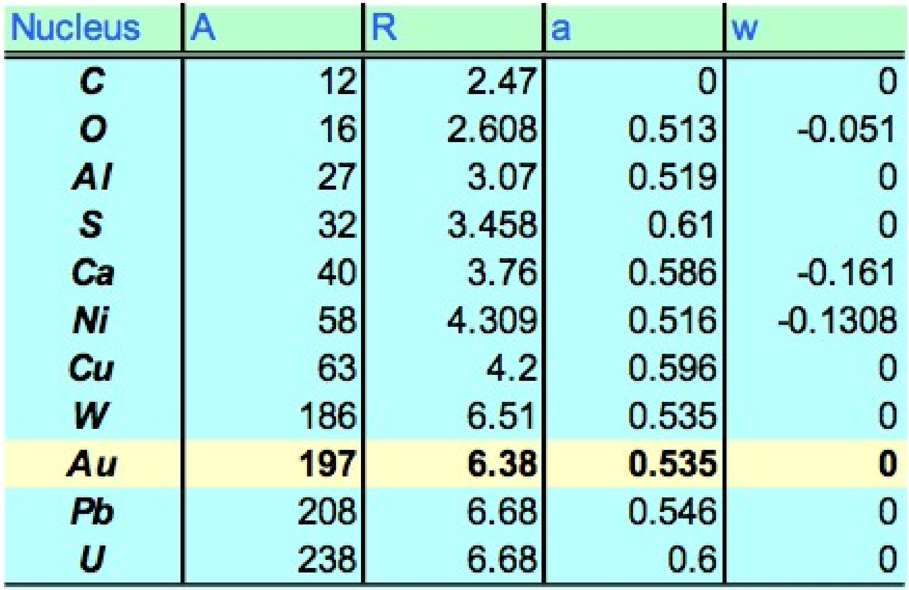
- Non-flow correlations mimic dynamical fluctuations and will contribute to the width of the v_2 distribution
  - The resolution of our method depends on the kernel
    - Modified Hijing: particle multiplicity defines the resolution
    - Data (AMPT): clusters flow and therefore the cluster multiplicity determines the resolution
  - The fluctuations we measure are real (present at particle level) but might not be the ones we are after
- Kernel could compensate for non-flow effects if they are correctly described by the MC used to construct it
  - Construct and tune MC on data
  - Two-particle correlation measurements can be used as input to disentangle the different contributions

Glauber parameters

Systematic Source	Standard	How Much We Vary
Nucleon-nucleon cross-section	42 mb (for 200GeV)	30 mb (<20GeV) 45 mb (>200GeV)
Nuclear skin depth	0.535fm(Au)0.596fm(Cu)	±10%
Nuclear radius	6.38fm (Au)4.2fm (Cu)	±10%
Minimum nucleon separation (center-to-center)	0.4fm (like HIJING)	0fm 0.8fm

$$\rho(r) = \frac{\rho_0\left(1 + wr^2/R^2\right)}{1 + \exp((r-R)/a)}$$





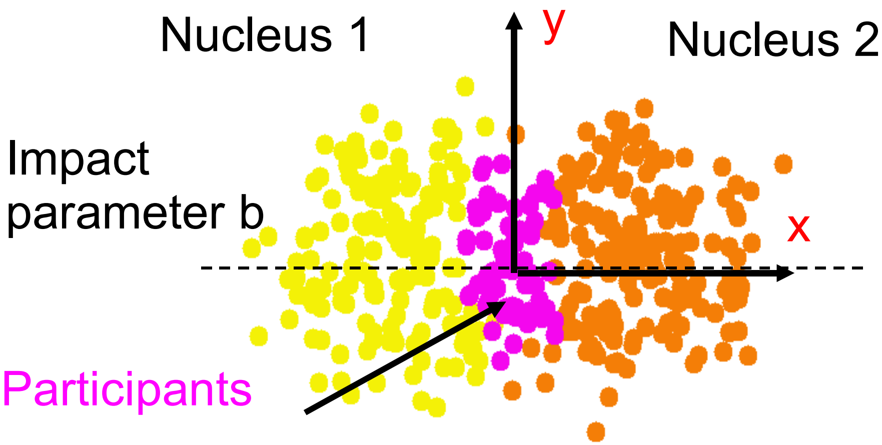
Nucleus	A	R	a	w
C	12	2.47	0	0
O	16	2.608	0.513	-0.051
Al	27	3.07	0.519	0
S	32	3.458	0.61	0
Ca	40	3.76	0.586	-0.161
Ni	58	4.309	0.516	-0.1308
Cu	63	4.2	0.596	0
W	186	6.51	0.535	0
Au	**197**	**6.38**	**0.535**	**0**
Pb	208	6.68	0.546	0
U	238	6.68	0.6	0

H. DeVries, C.W. De Jager, C. DeVries, 1987

Glauber MC

- Glauber Monte Carlo
  - Radial distribution of nucleons (in nucleus) drawn from Wood-Saxon distribution
  - Isotropic angular distribution
  - Separate by impact parameter
  - Nucleons travel on straight-line paths and interact inelastically when

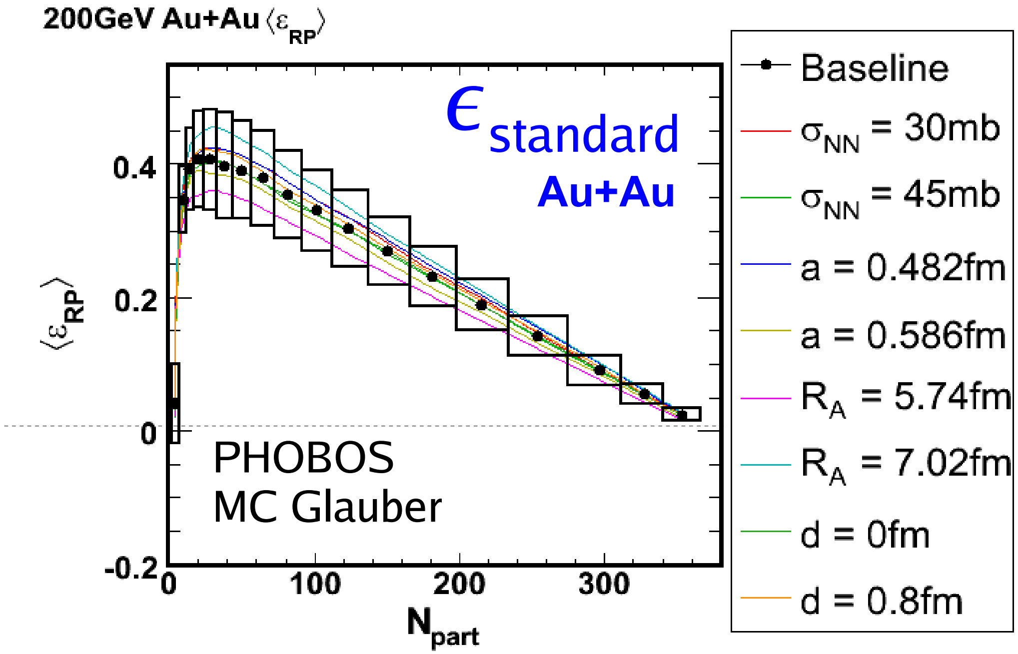
$$d=\sqrt{(x_1-x_2)^2+(y_1-y_2)^2}<\sqrt{\sigma_{NN}/\pi}$$

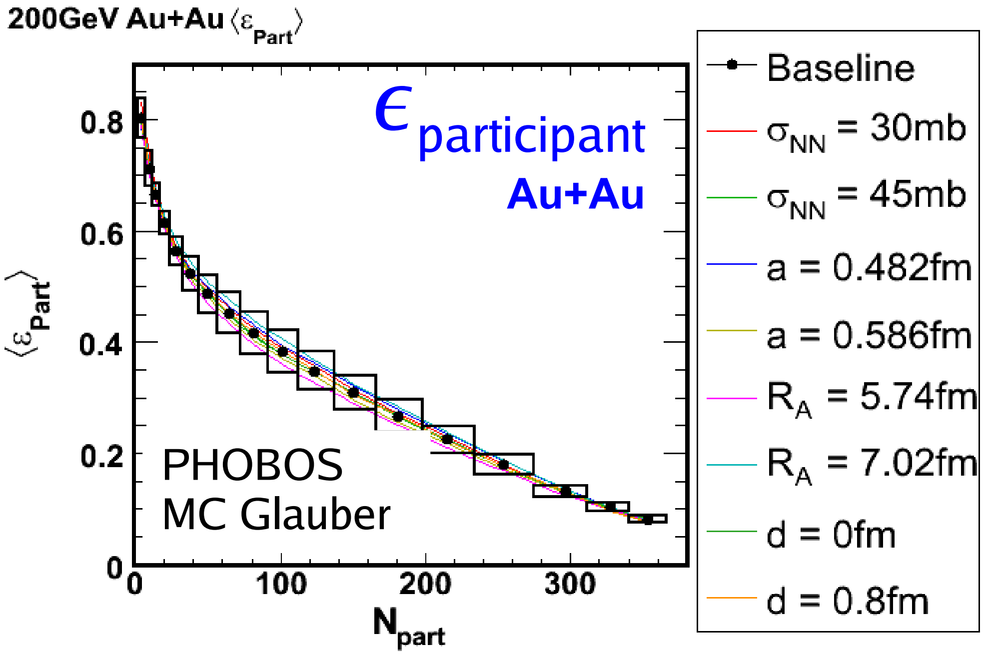


- Centrality of collision
  - #Participants
    - Nucleons that interact at least once
  - Related to cross section and impact parameter range
- Eccentricity of collision zone
  - Given by participants position distributions

Eccentricity: $\epsilon_{std}=\dfrac{\sigma_y^2-\sigma_x^2}{\sigma_y^2+\sigma_x^2}$

Robustness with geometry variables





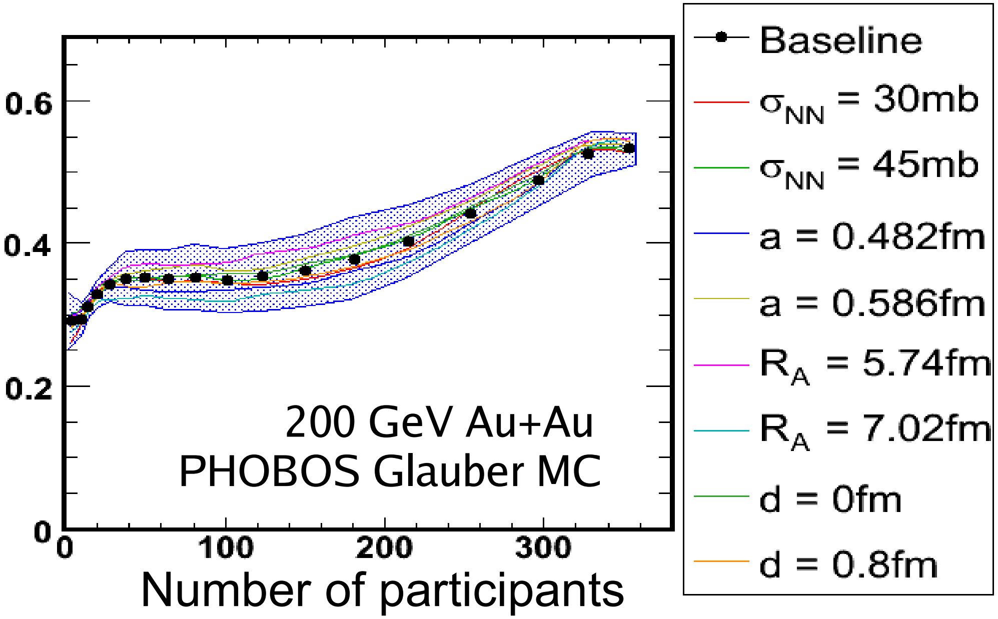
- Variation of
  - Nucleon-nucleon cross section (30-45mb)
  - Nuclear radius (±10% from the nominal value)
  - Skin depth (0.482-0.586fm)
  - Minimum separation distance between nucleons (d=0-0.8fm)

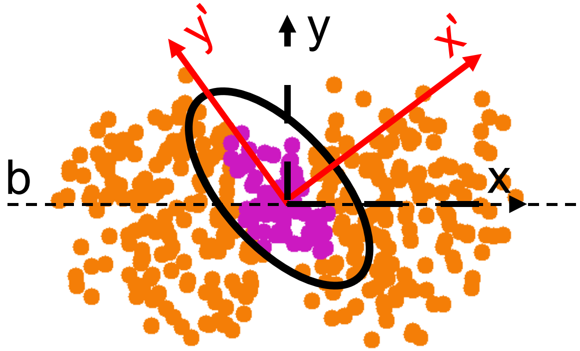
$$\rho(r)=\frac{\rho_0}{1+\exp((r-R)/a)}$$

$\epsilon_{\text{participant}}$ even slightly more robust than $\epsilon_{\text{standard}}$

Expected elliptic flow fluctuations

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





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