Fluctuation studies in Phobos

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for the PHOBOS collaboration

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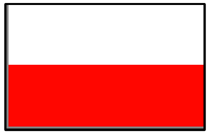
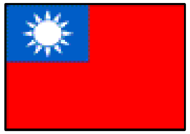
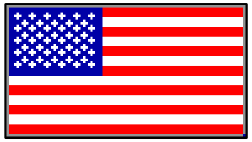
Workshop on "Correlations and fluctuations "
Florence, Italy, July 8, 2006

PHOBOS collaboration (July 2006)

Burak Alver, Birger Back, Mark Baker, Maarten Ballintijn, Donald Barton, Russell Betts, Richard Bindel, Wit Busza (Spokesperson), Zhengwei Chai, Vasundhara Chetluru, Edmundo García, Tomasz Gburek, Kristjan Gulbrandsen, Clive Halliwell, Joshua Hamblen, Ian Harnarine, Conor Henderson, David Hofman, Richard Hollis, Roman Hołyński, Burt Holzman, Aneta Iordanova, Jay Kane, Piotr Kulinich, Chia Ming Kuo, Wei Li, Willis Lin, Constantin Loizides, Steven Manly, Alice Mignerey, Gerrit van Nieuwenhuizen, Rachid Nouicer, Andrzej Olszewski, Robert Pak, Corey Reed, Eric Richardson, Christof Roland, Gunther Roland, Joe Sagerer, Iouri Sedykh, Chadd Smith, Maciej Stankiewicz, Peter Steinberg, George Stephans, Andrei Sukhanov, Artur Szostak, Marguerite Belt Tonjes, Adam Trzupek, Sergei Vaurynovich, Robin Verdier, Gábor Veres, Peter Walters, Edward Wenger, Donald Willhelm, Frank Wolfs, Barbara Wosiek, Krzysztof Woźniak, Shaun Wyngaardt, Bolek Wysłouch

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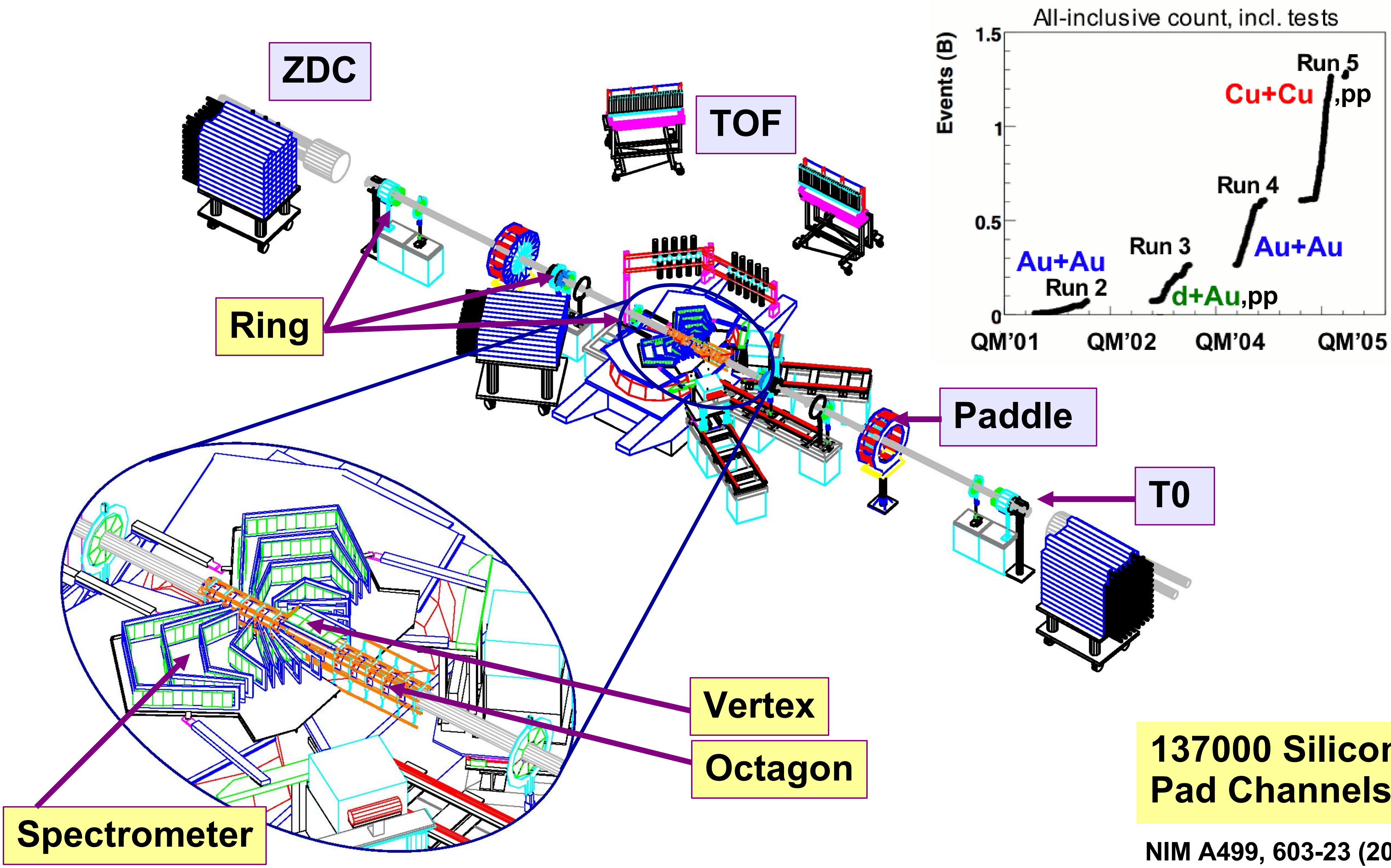
PHOBOS experiment (Run5)



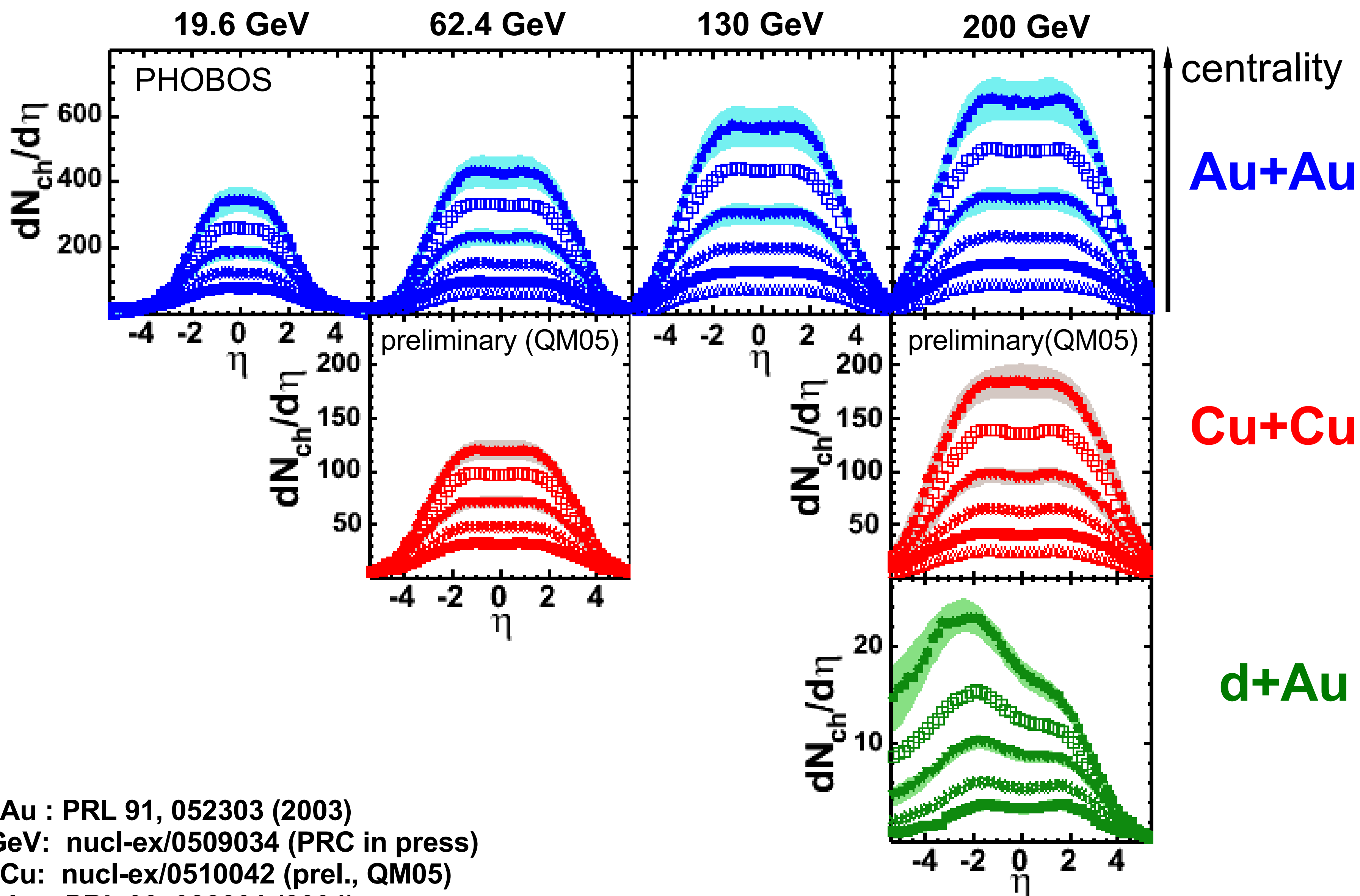
137000 Silicon Pad Channels

NIM A499, 603-23 (2003)

Outline

1) Single-particle distributions
2) Unusual event search
3) Forward/backward multiplicity correlations
4) Two-particle angular correlations
5) Eccentricity fluctuations
6) Elliptic flow fluctuations

Charged hadron dN/dη-distributions (1)



Au+Au : PRL 91, 052303 (2003)
62 GeV: nucl-ex/0509034 (PRC in press)
Cu+Cu: nucl-ex/0510042 (prel., QM05)
d+Au : PRL 93, 082301 (2004)

Charged hadron dN/dη-distributions (2)

- Rich data set of p+p, p+A and A+A
- Scaling features of charged hadron multiplicities
  - Npart scaling
  - Extended longitudinal scaling (aka Limiting Fragmentation)
  - Factorization of energy/centrality dependence
  - Universality of total multiplicity in A+A, p+p and $e^+ + e^-$
- Seen over a wide range of collision energy

Charged hadron dN/dη-distributions (2)

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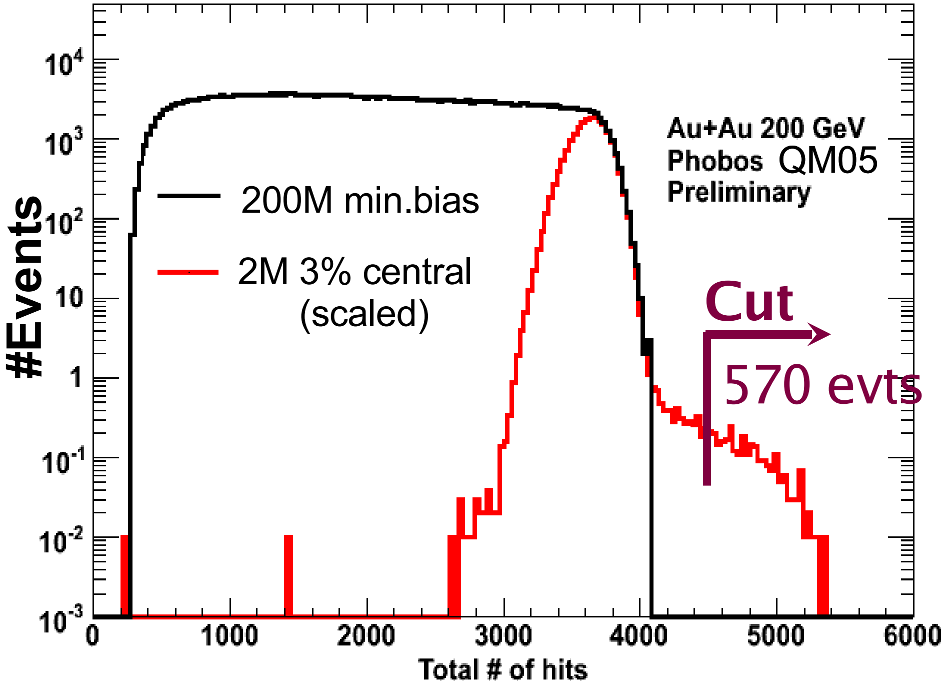
In all of the above, dN/dη is single-particle event average

2) Unusual event search

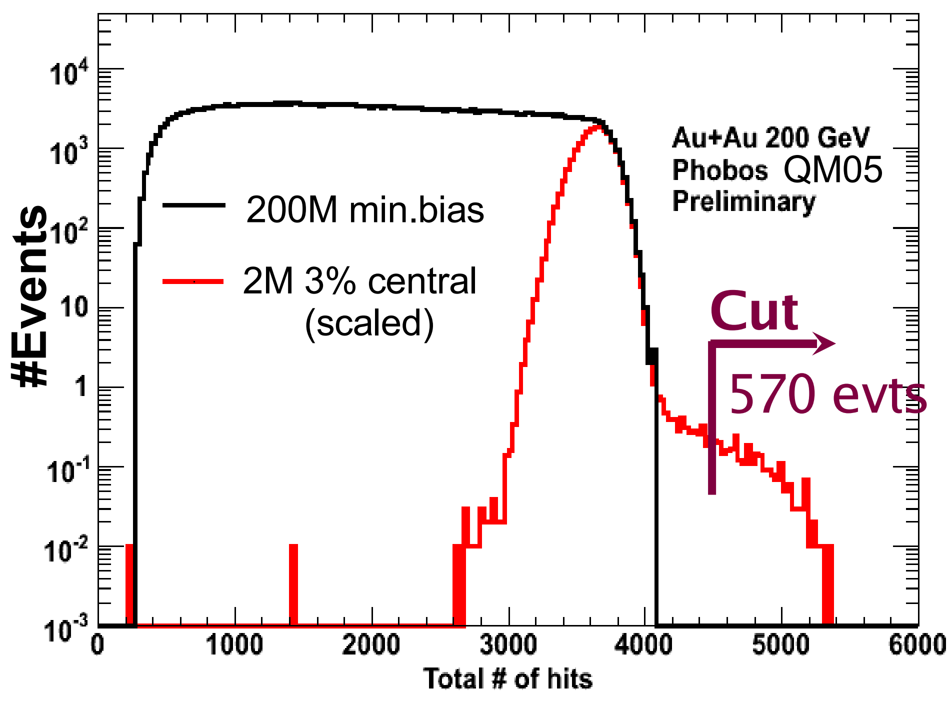
- Beyond the average dN/dη
  - Are there events with very large multiplicity?
  - Does the dN/dη shape vary from event to event?

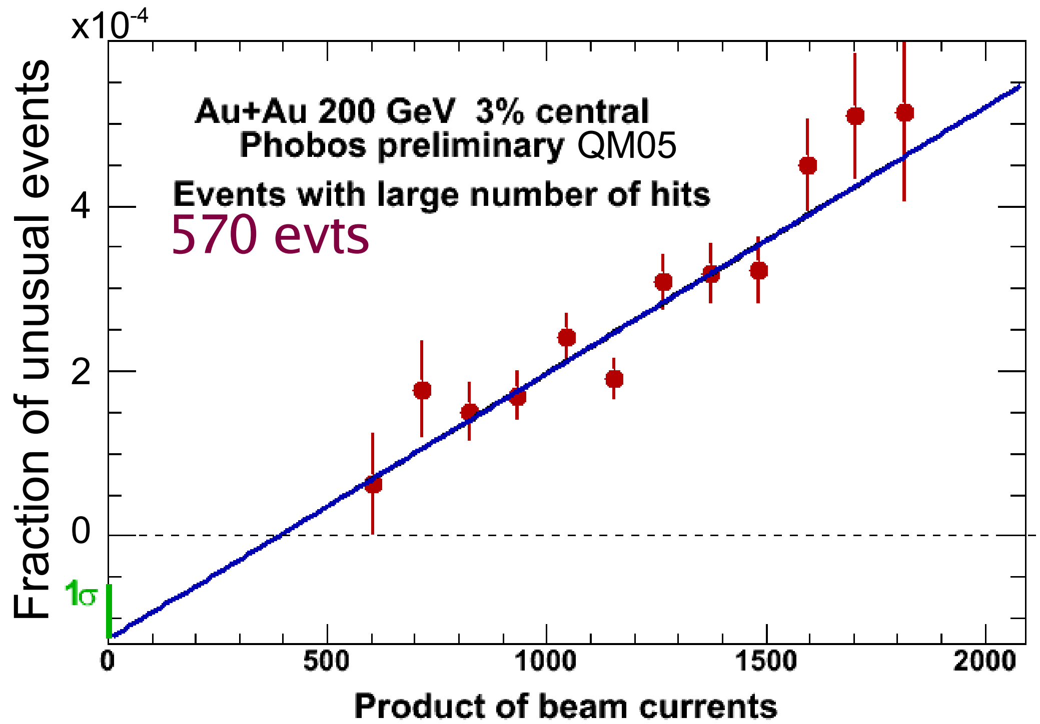
Unusual events: Large total multiplicity



- Use high-statistics Run-4 AuAu data and select 3% central data (with lose data-quality cuts)
- Look at events with a large number of hits: ~10^{-4} (570/2M) events

Unusual events: Large total multiplicity





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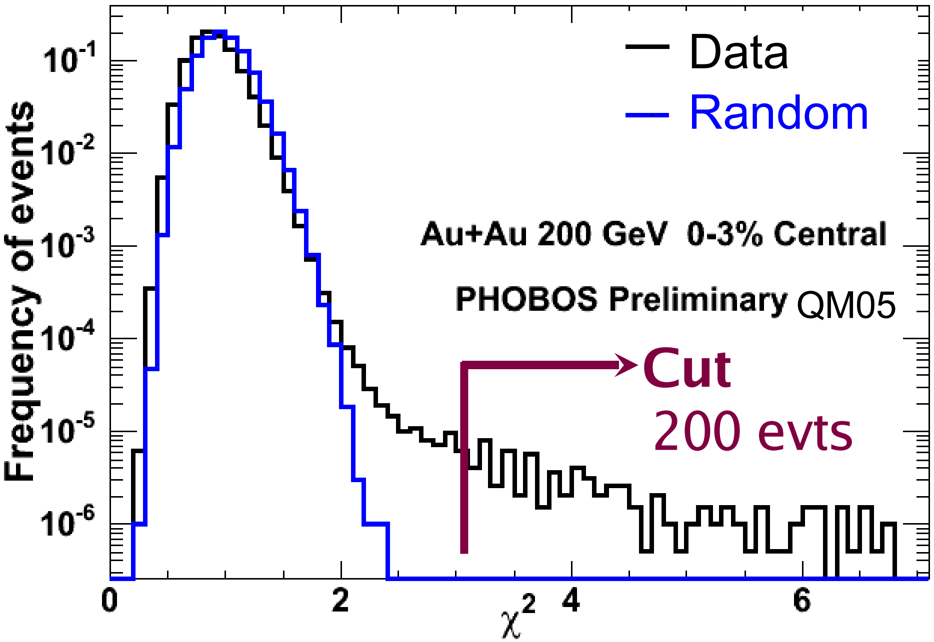
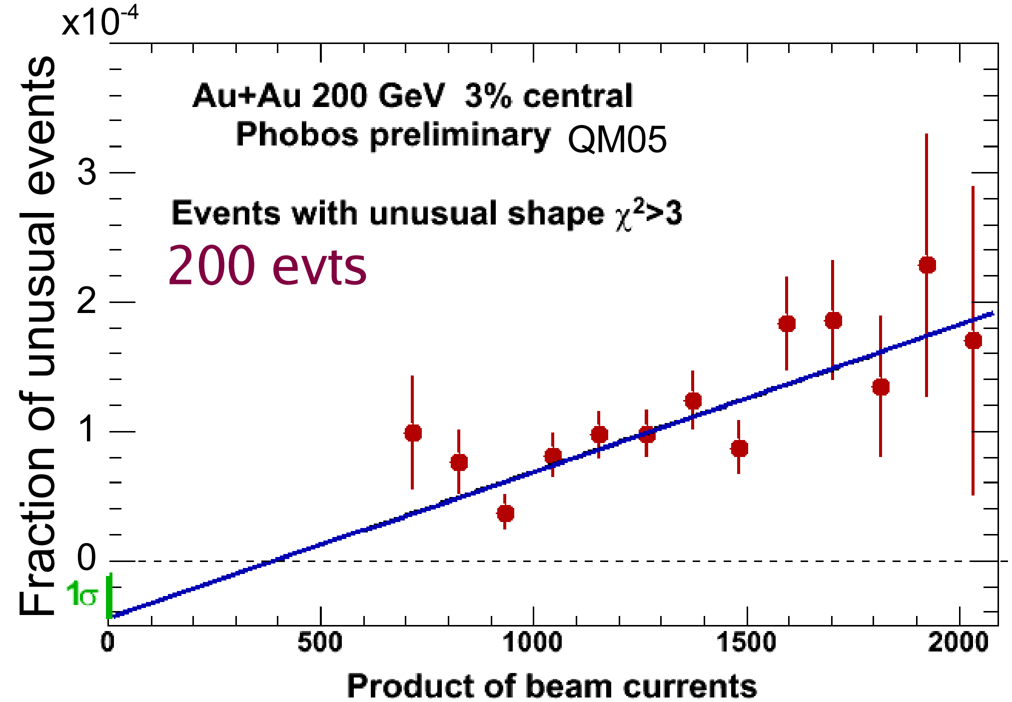
- Events with large number of hits are strongly correlated with beam rate
- Rate of "unusual" events extrapolated to low luminosity is consistent with zero

Unusual events: dN/dη-shape





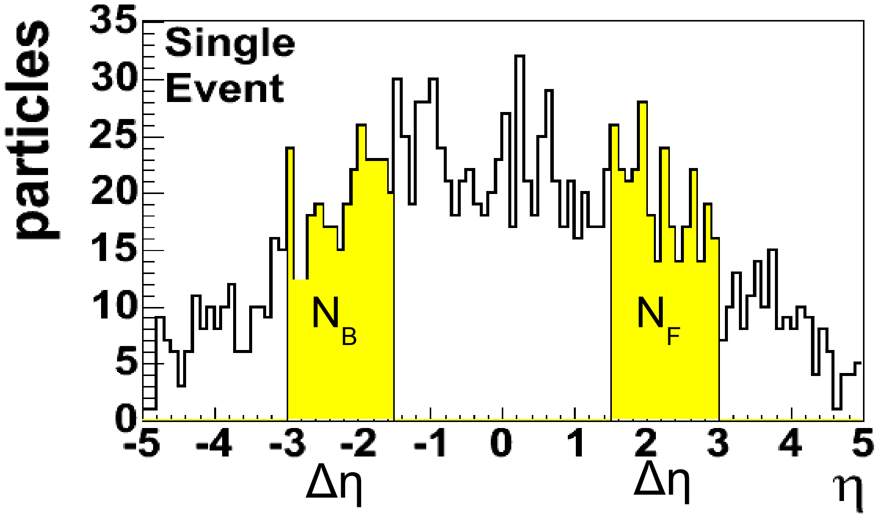
- Devide dN/dη into individual bins (η, vertex) to get the average and its variance
- Calculate χ^2 for each event
- Compare to "random" events: distinct tail ~10^{-4} (200/2M) events

- Events with large χ^2 are <u>again</u> strongly correlated with beam rate
- Rate of "unusual" events extrapolated to low luminosity is <u>again</u> consistent with zero

3) Forward/backward multiplicity fluctuations

- Beyond the average dN/dη
  - Quantify E-by-E correlations in particle-production over regions in η

Forward/backward multiplicity fluctuations



$$C(\eta, \Delta\eta) = \frac{N_F - N_B}{\sqrt{N_F + N_B}}$$

Use variance σ^2_C

- Independent particle production

  $\sigma^2_C = 1$

- Correlated particle production
  - Long range $\sigma^2_C \rightarrow 0$
  - Short range $\sigma^2_C > 1$
    - Clusters of size k within Δη

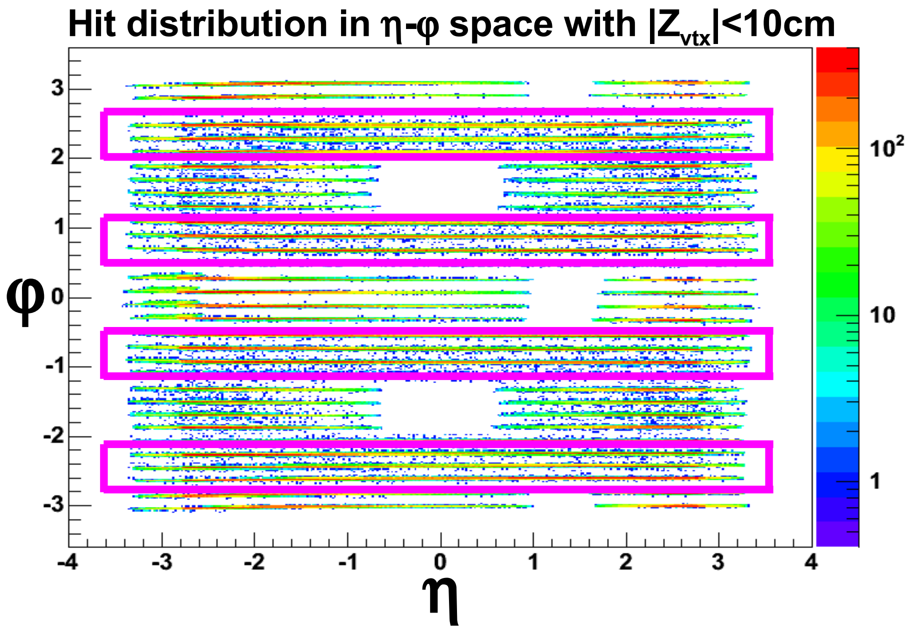
      $$C \rightarrow \sqrt{k}\, C$$
      $$\sigma^2_C \rightarrow k\, \sigma^2_C$$

    - If limited rapidity window (Δη)

      $$k \rightarrow k_{eff}$$

Extraction of σ^2_c

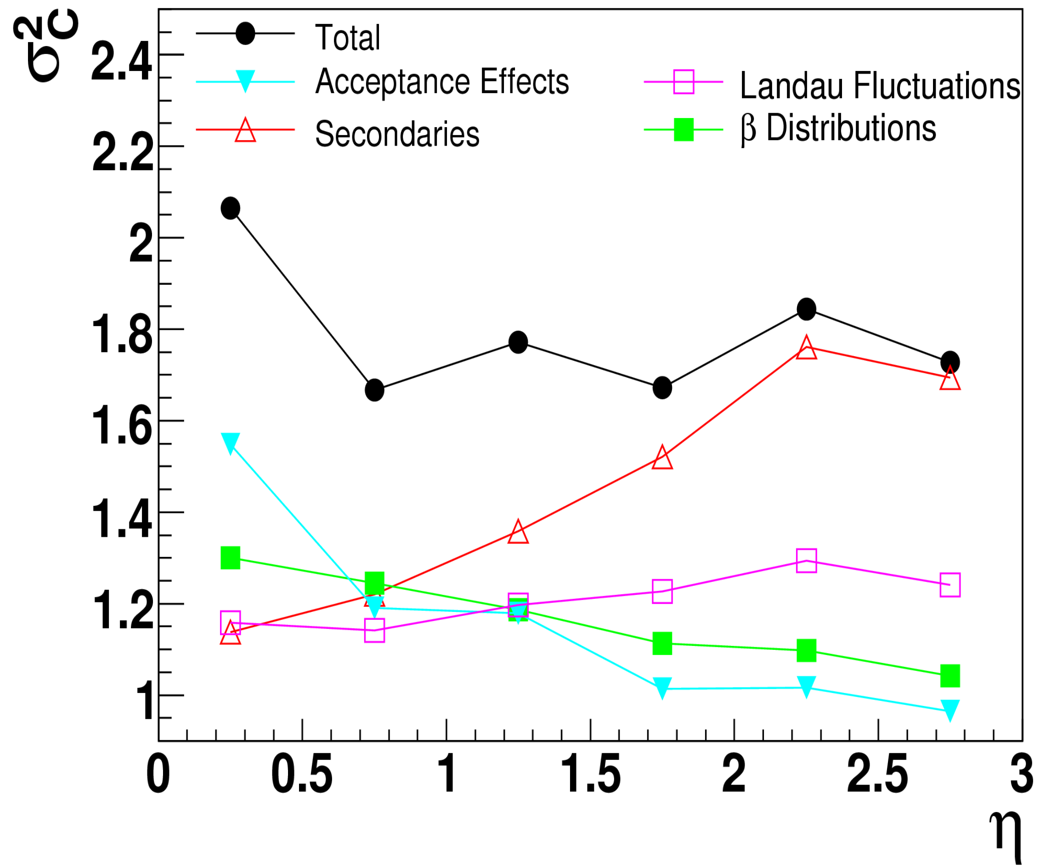
- Deal with large occupancy in the octagon
  - Use η-bin-dependent lower and upper dE/dx cuts on hits to suppress contribution from secondaries
- Deal with limited acceptance
  - Correct gap effects E-by-E with z-vertex dependent offset
  - Avoiding holes in octagon
    - Only half acceptance in φ
    - Correction ~2, found with MC



- Deal with contribution of detector effect (see next slides)

Contributing sources of detector effects

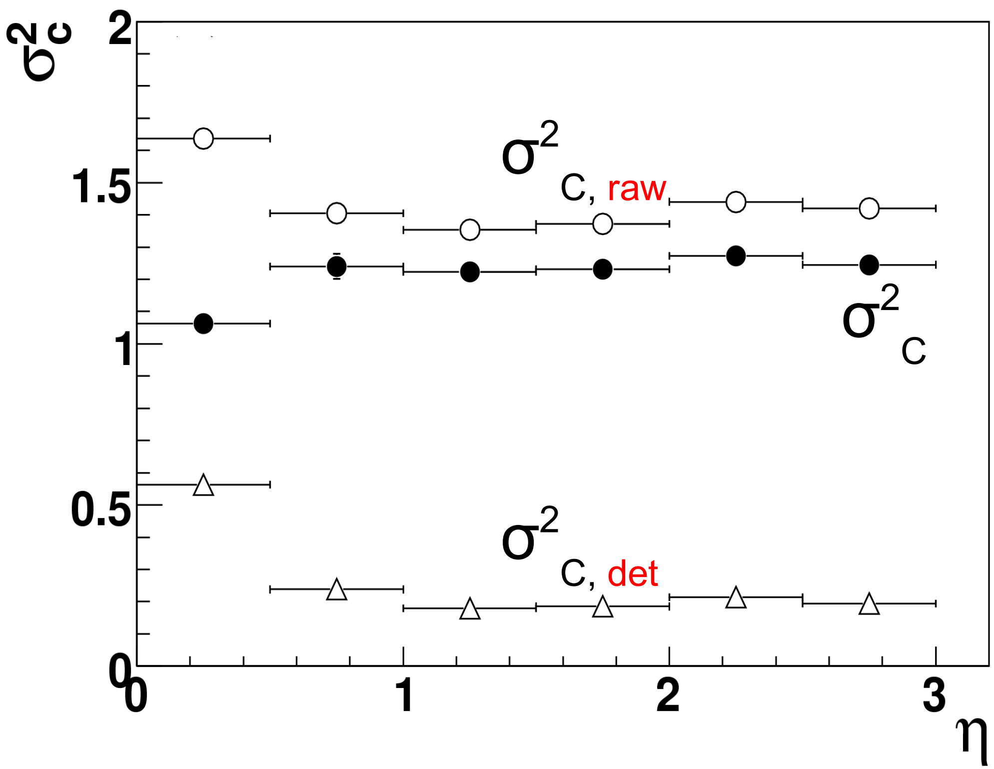
- Acceptance effects
- Secondaries
- dE/dx fluctuations
  - Landau fluctuation
  - Velocity (β) variation



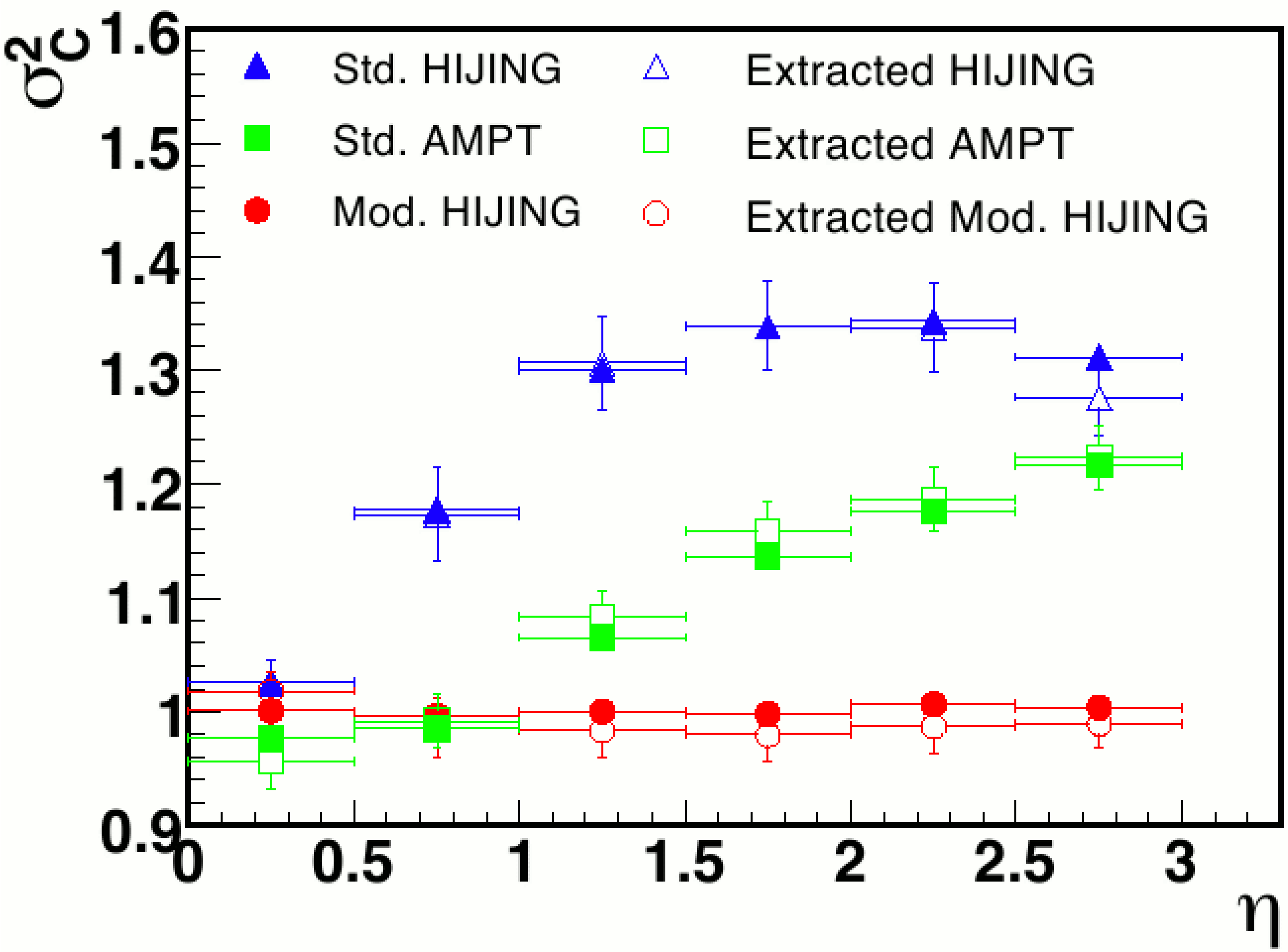
Different contributions add in quadrature
and resulting detector effects are flat in η

Removing detector effects

- Assuming $\sigma^2_{C,\,raw} = \sigma^2_C + \sigma^2_{C,\,det}$
- Modified HIJING with randomized sign of particle η to force $\sigma^2_C=1$
  - Direct access to $\sigma^2_{C,\,det}$
- Correction slightly depends on size of signal
  - Cure residual correlation $\sigma^2_{C,\,det} \rightarrow \sigma^2_{C,\,det} - \alpha\,(\sigma^2_C-1)$
    - α=constant(η, Δη, cent)
- Systematic errors estimated to $\Delta\sigma^2_C=0.1$ (averaged over η)

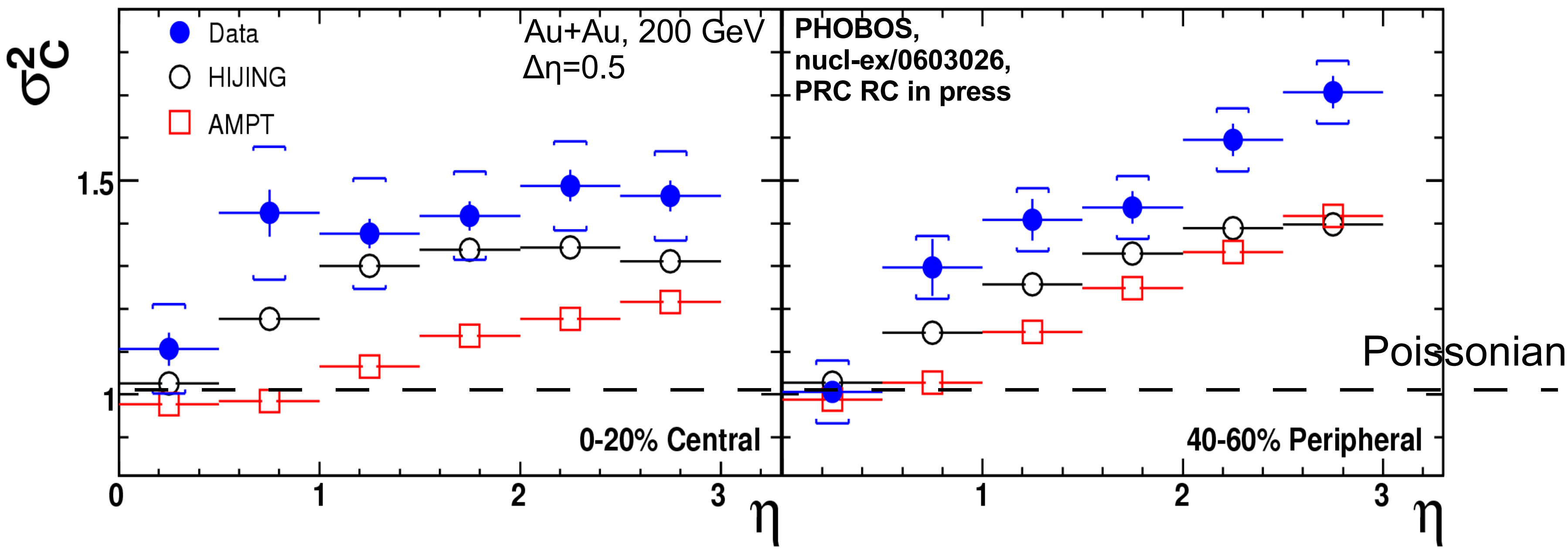


Verification with various MC

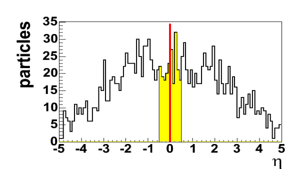
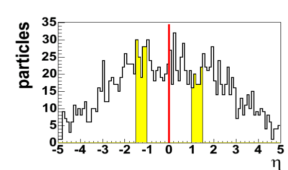
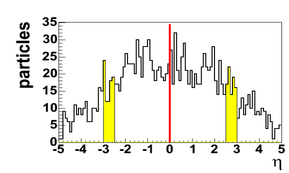


For the same tuning, the reconstructed σ^2_c agrees with raw σ^2_c within the errors in all tested models

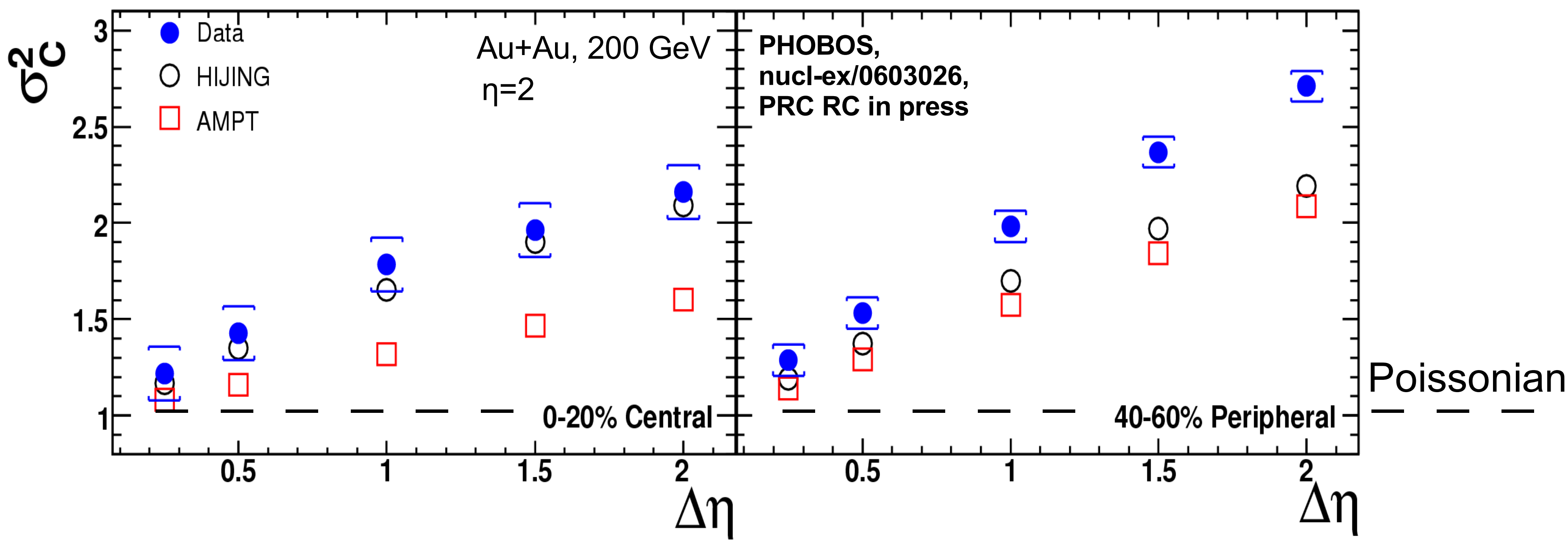
F/B results: σ^2_C vs. η for fixed $\Delta\eta$



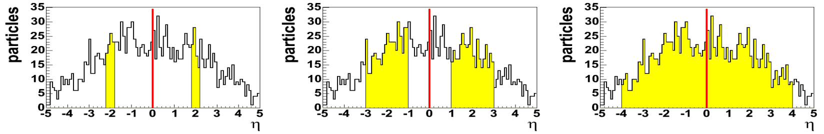
- Centrality dependence in slope observed
  - Models systematically lower (partially within errors)
- HIJING & AMPT agree in peripheral, but diverge in central events
- At $\eta=0$, models and data yield $\sigma^2_C=1$
  - Induced “intrinsic” long-range correlations?

F/B results: σ^2_C vs. $\Delta\eta$ at fixed η=2



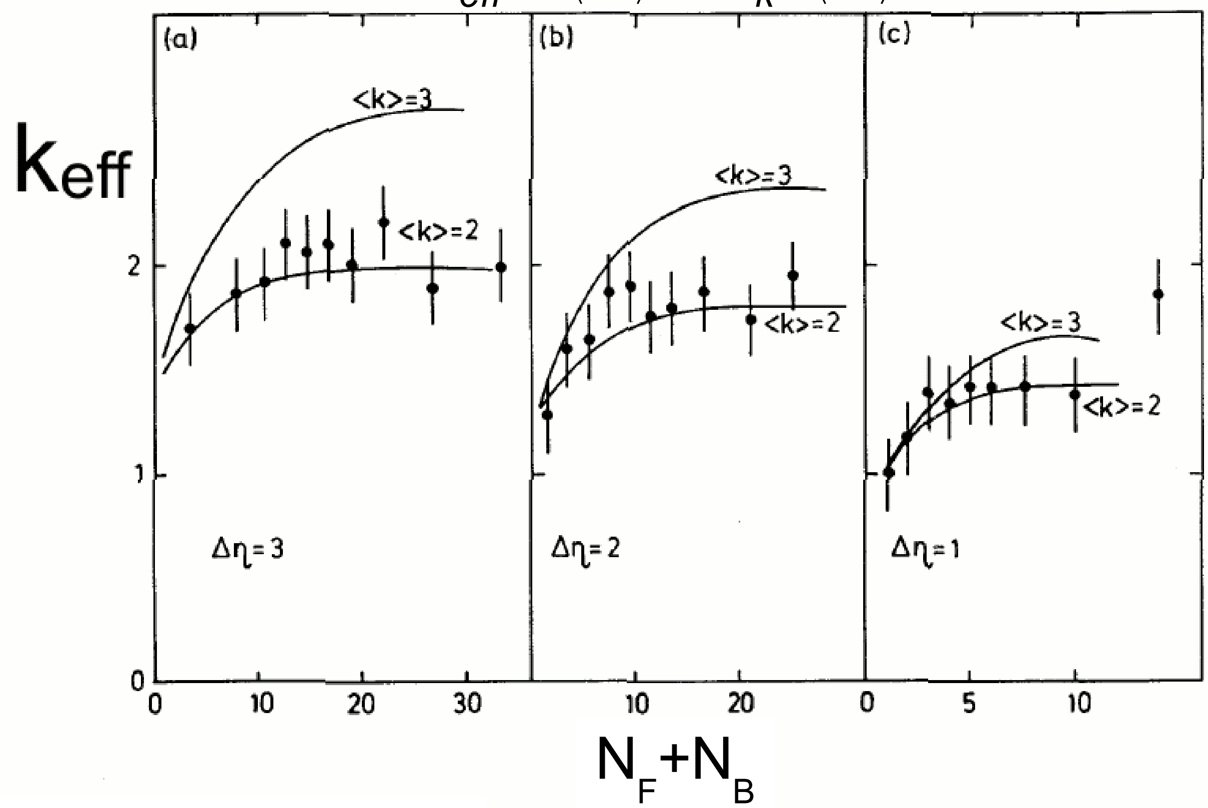
- Monotonic rise with increasing $\Delta\eta$-bin width
- Particles produced in effective cluster size
  - Central: k_{eff}=2-2.3
  - Peripheral: k_{eff}=2.6-2.8
- Models do not simultaneously describe centrality and $\Delta\eta$ dependence

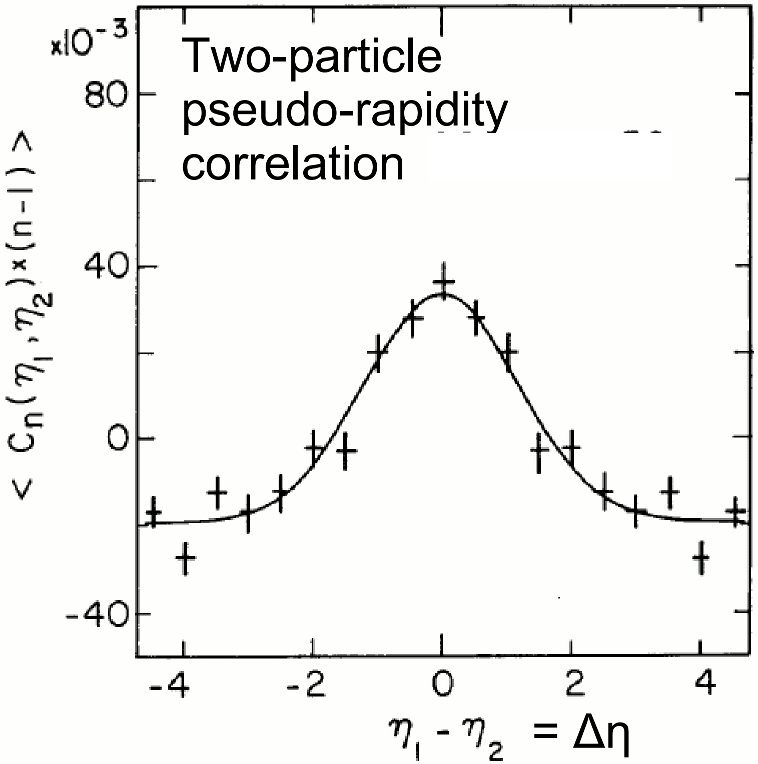


Clusters in elementary collisions

UA5: Phys.Lett.B123:361,1983

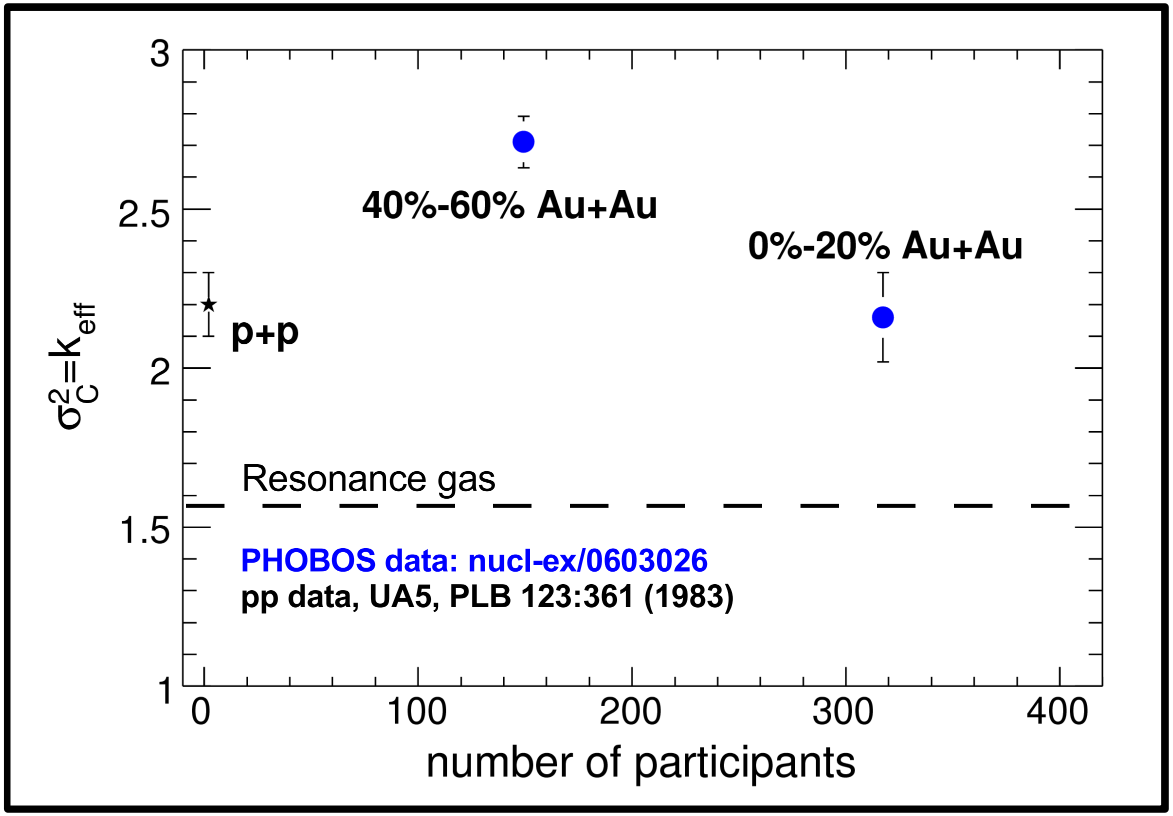
$$k_{eff} = \langle k \rangle + \sigma_k^2 / \langle k \rangle$$





Clusters in Au+Au are reminiscent
of results from p+p̄

Centrality dependence of σ^2_C



Centrality dependence of σ^2_C

- Model short and long range contribution

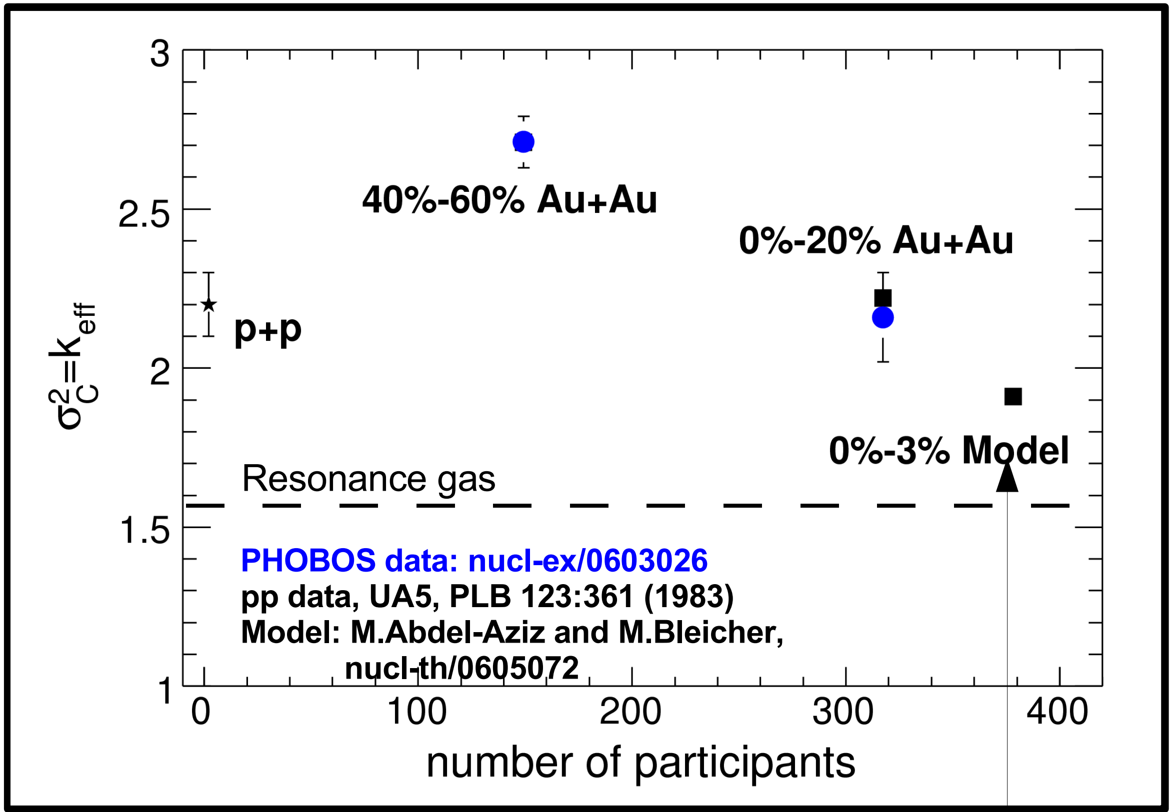
$$\sigma^2_C = f\,\sigma^2_{SR} + (1-f)\,\sigma^2_{LR}$$

where short range

$$\sigma^2_{SR} = k\left[1-\exp(-\Delta\eta/\lambda_{short})\right]$$

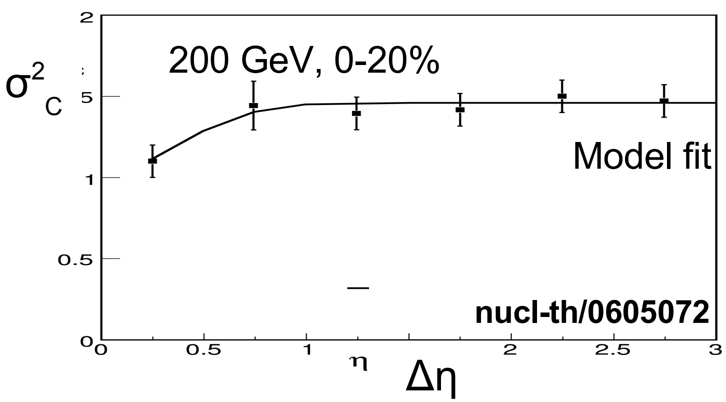
and long range

$$\sigma^2_{LR} = 1 - \frac{\xi}{f}\int d\eta_1\, d\eta_2 \exp\frac{-(\eta_1-\eta_2)^2}{2\lambda^2_{long}}$$



Cent.
Extra-
polation

- Constrain parameters



data	f	ξ	λ_{short}	λ_{long}
Au+Au 0% – 20%	0.88	1.8	0.4	0.7
Au+Au 40% – 60%	0.99	2.5	0.6	0.9

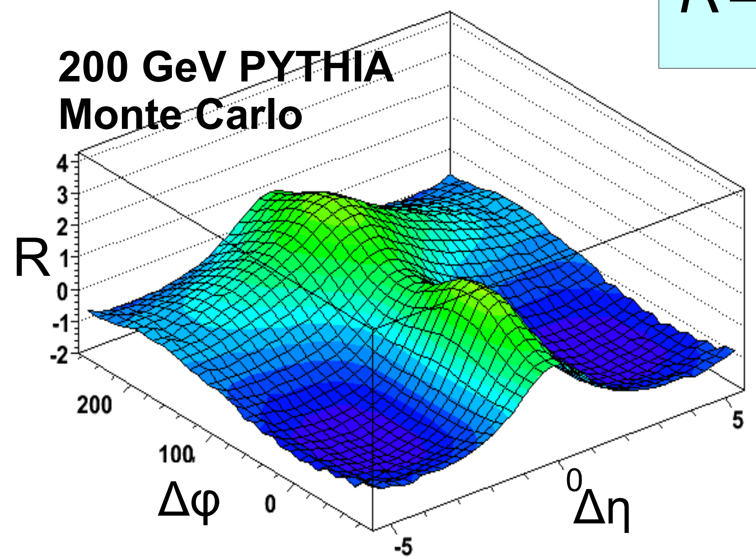
4) Two-particle angular correlations

- Extend correlations from regions in $dN/d\eta$
  - Two-particle angular correlations

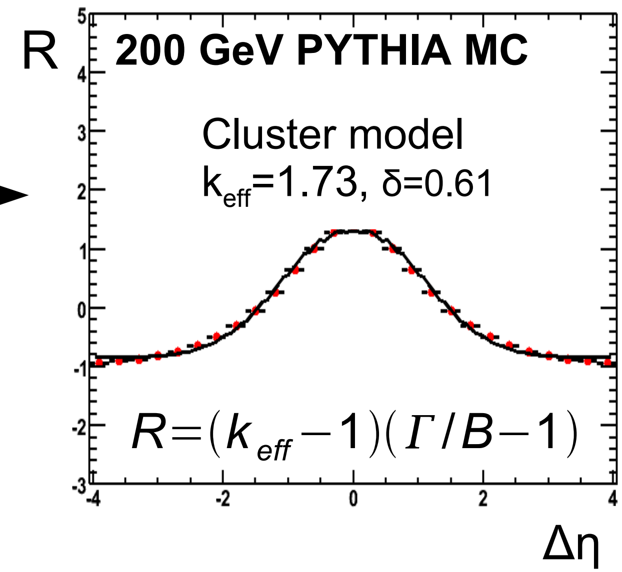
Two-particle angular correlations

See Wei Li's talk

$$R = \left\langle (n-1)\left(\frac{F}{B}-1\right)\right\rangle$$



Projection onto η
(altern. onto φ)

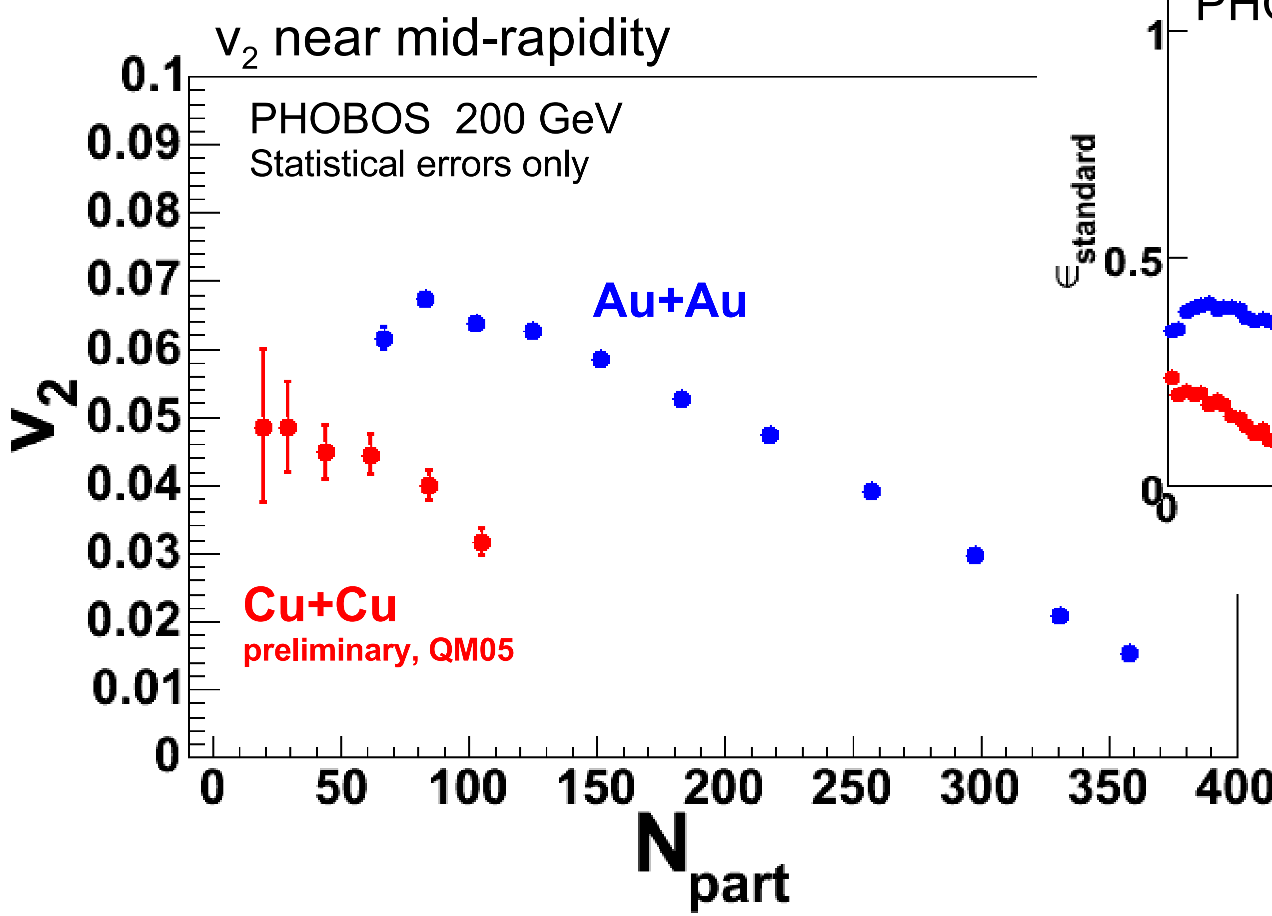


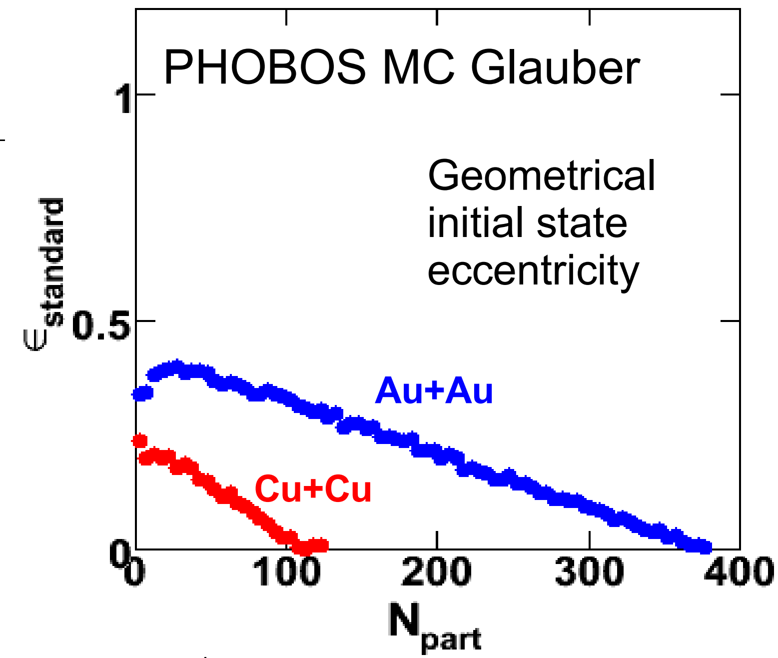
- Construction of R, event-by-event, weighted by event multiplicity
  - Full φ and large |η|≤3 coverage (|η|≤5 for future studies)
  - Single hit in silicon layer instead of particle information
    - Need special strategy for secondaries
  - No trigger particle
    - Study soft physics (fragmentation and hadronization processes)
  - Relative to trigger particle under investigation

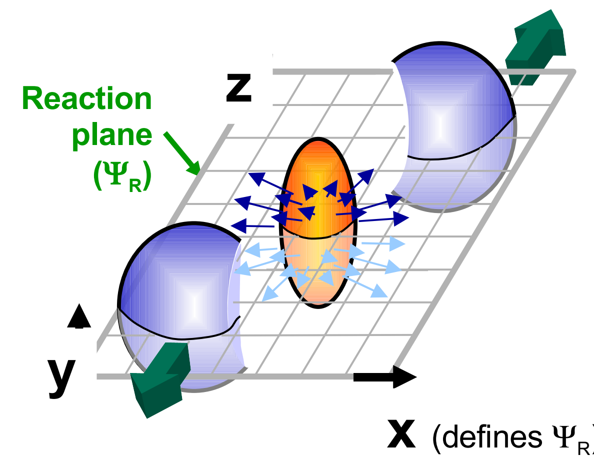
5) Eccentricity fluctuations

- From two-particle angular correlations (clusters at hadronization times)
  - To fluctuations in the initial-state geometry and its connection to elliptic flow

Elliptic flow in Cu+Cu and Au+Au



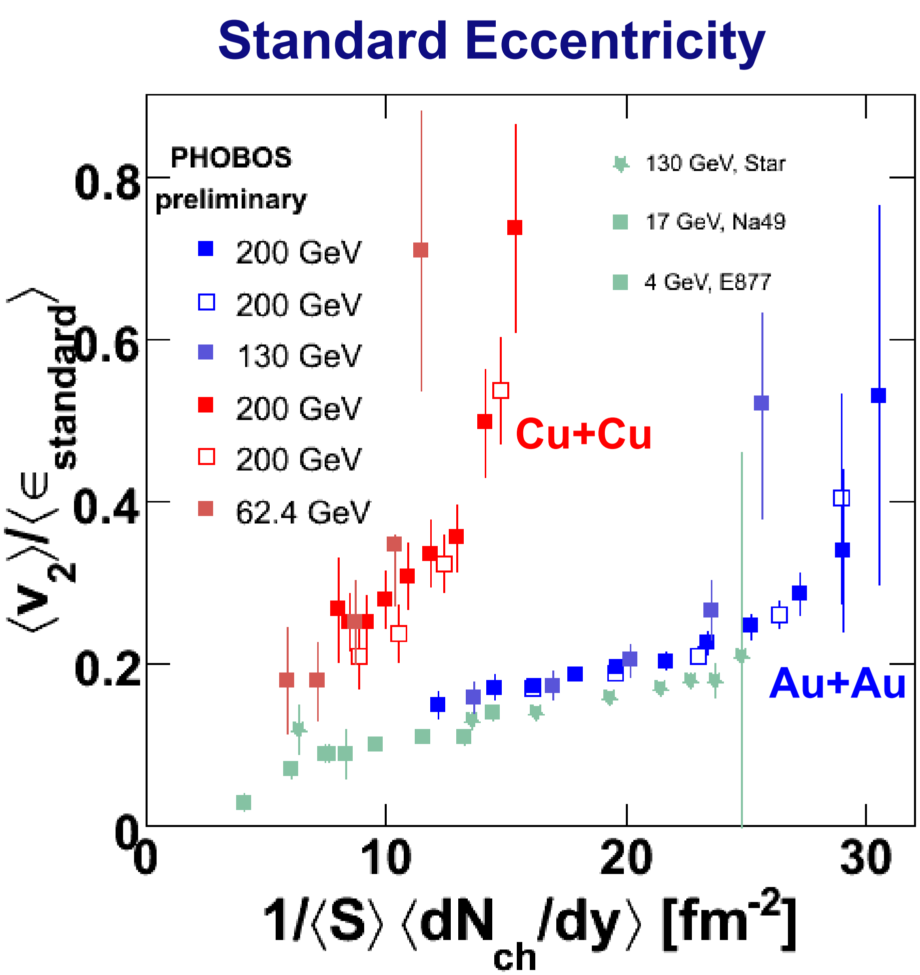




Au+Au: PRL 94, 122303 (2005)
Cu+Cu: prel. QM05, nucl-ex/0510042

$$dN/d(\phi-\Psi_R) = N[1+2v_1\cos(\phi-\Psi_R)+2v_2\cos(2\phi-2\Psi_R)+\ldots]$$

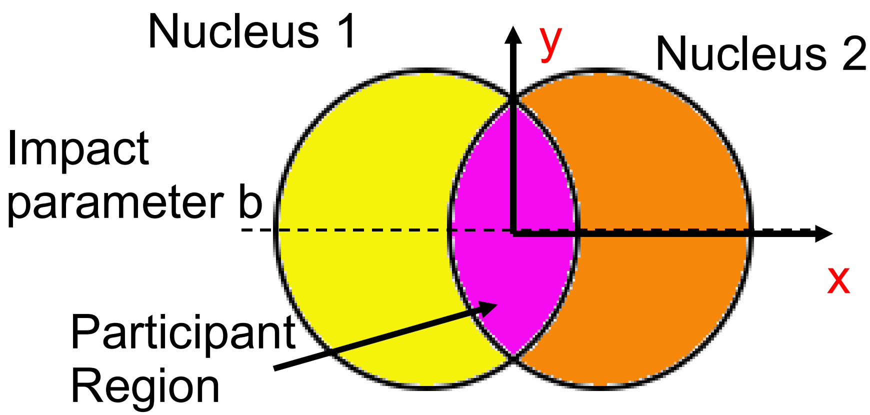
Standard eccentricity scaling



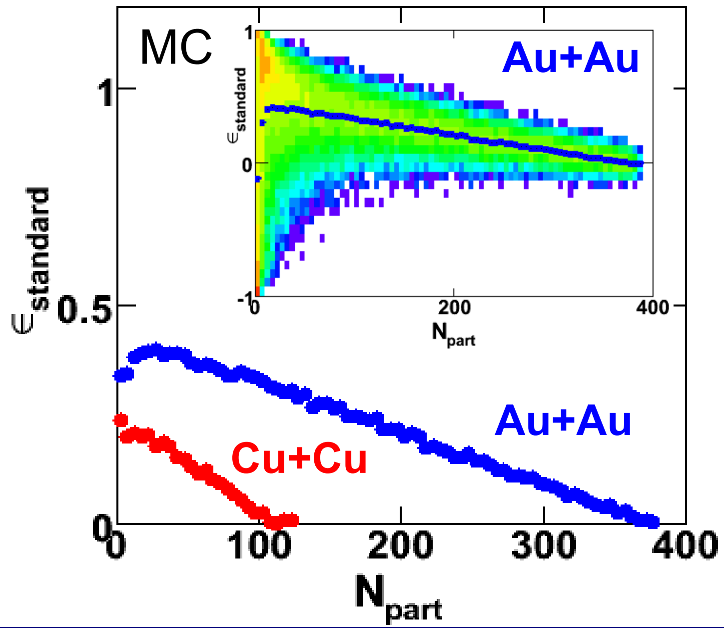
STAR, PRC 66 034904 (2002)
Voloshin, Poskanzer, PLB 474 27 (2000)
Heiselberg, Levy, PRC 59 2716, (1999)

Standard eccentricity calculation

Standard Eccentricity

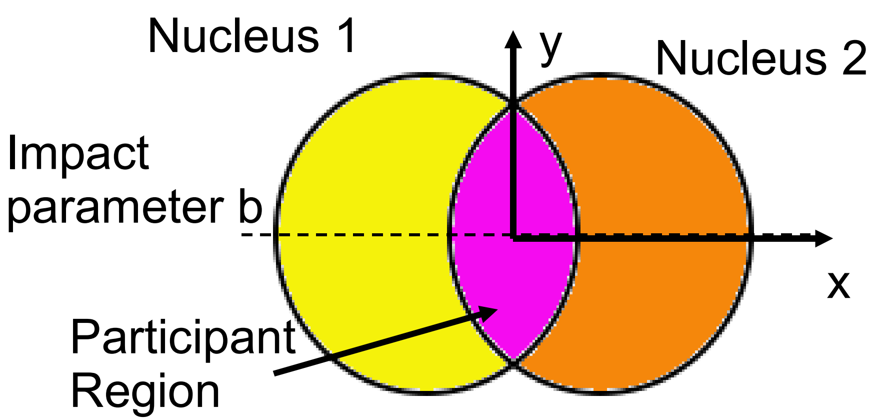


$$\epsilon_{std} = \frac{\sigma_y^2 - \sigma_x^2}{\sigma_y^2 + \sigma_x^2}$$

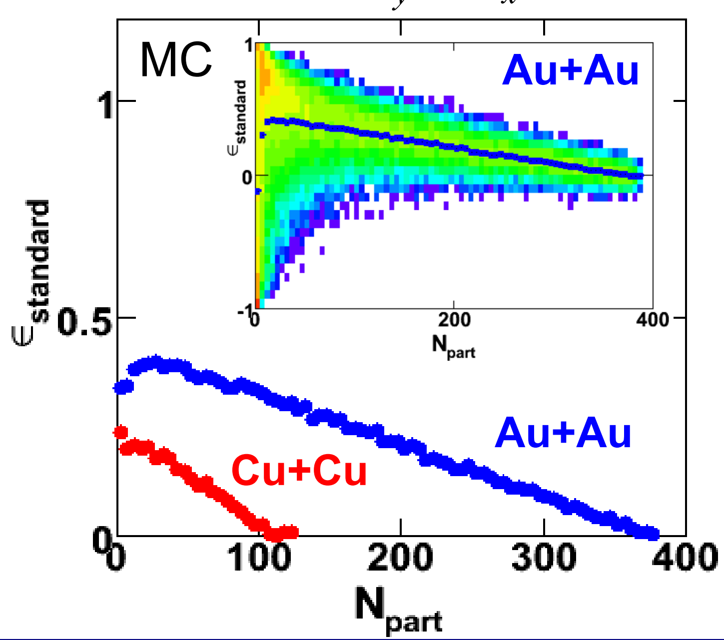


Participant eccentricity calculation

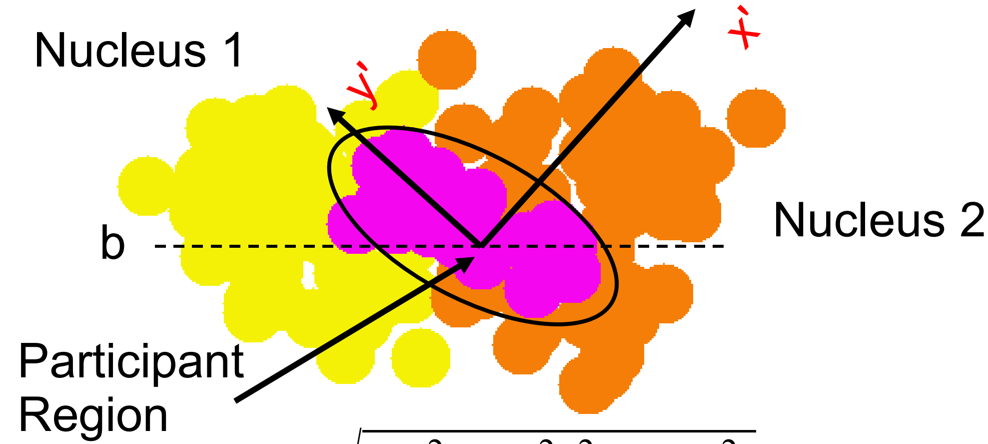
Standard Eccentricity



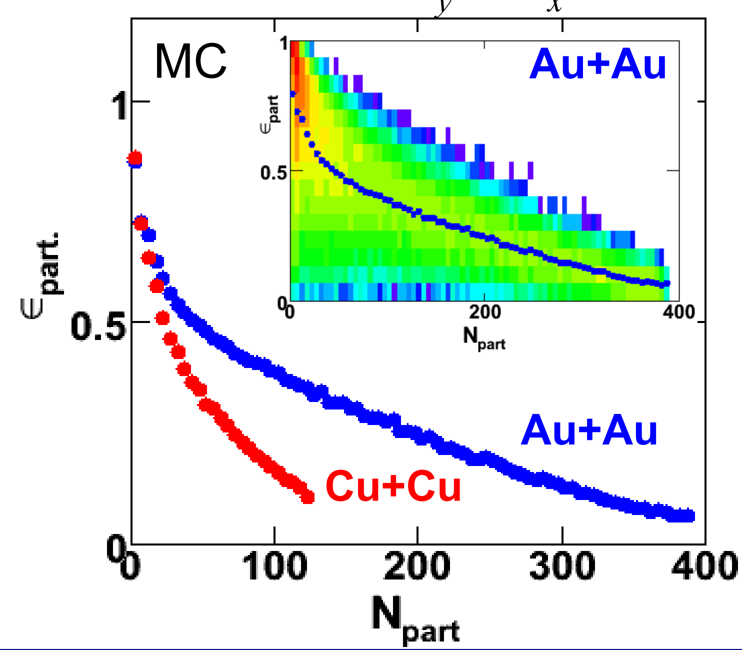
$$\epsilon_{std} = \frac{\sigma_y^2 - \sigma_x^2}{\sigma_y^2 + \sigma_x^2}$$



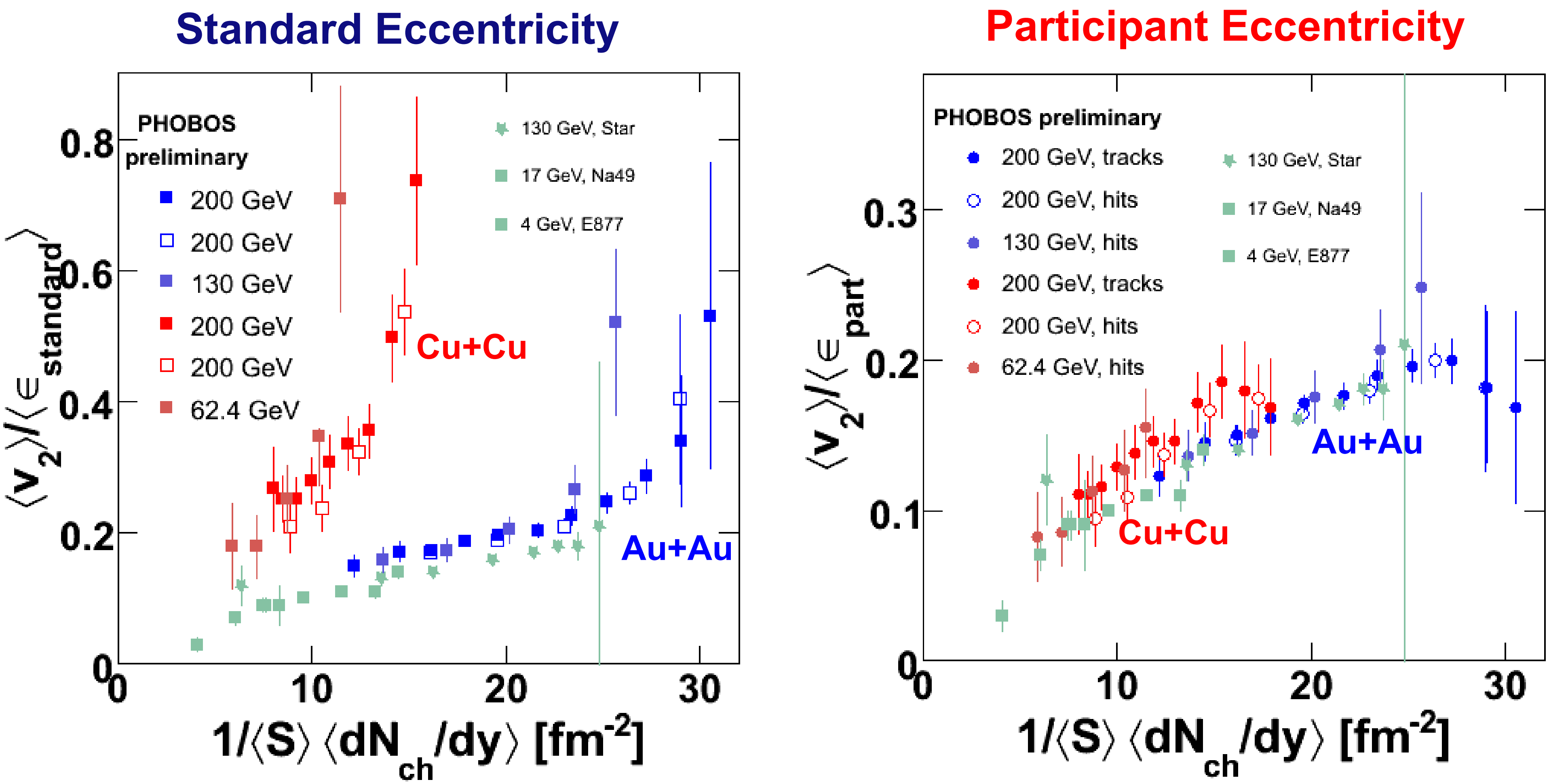
Participant Eccentricity



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



Participant eccentricity scaling



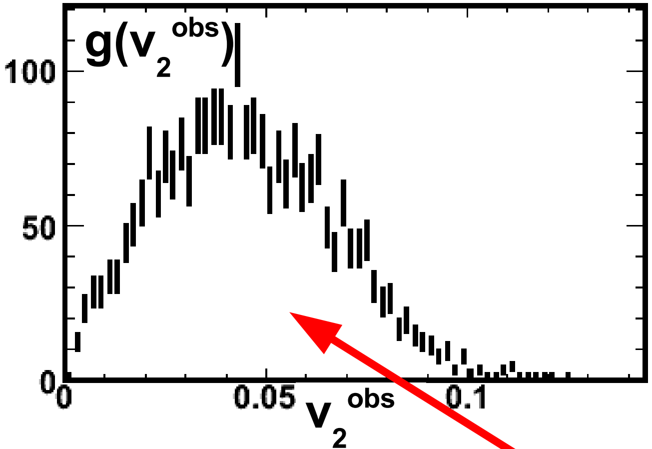
STAR, PRC 66 034904 (2002)
Voloshin, Poskanzer, PLB 474 27 (2000)
Heiselberg, Levy, PRC 59 2716, (1999)

6) Event-by-event elliptic fluctuations

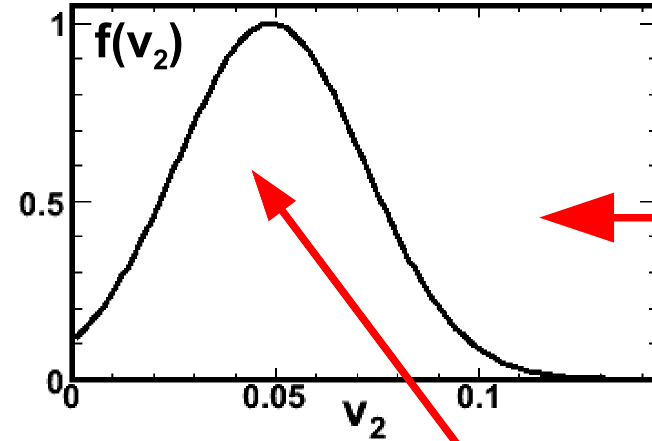
- From eccentricy fluctuations
  - To E-by-E fluctuations of the elliptic flow

Event-by-event elliptic flow fluctuations

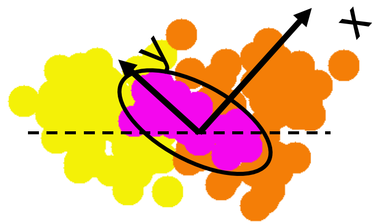
Observed v2 distribution



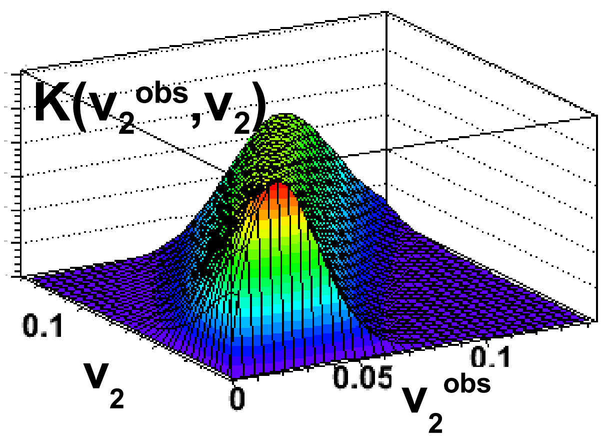
True v2 distribution

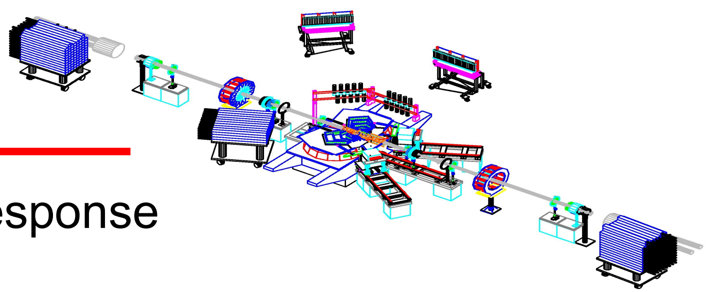


Participant eccentricity



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





Detector response

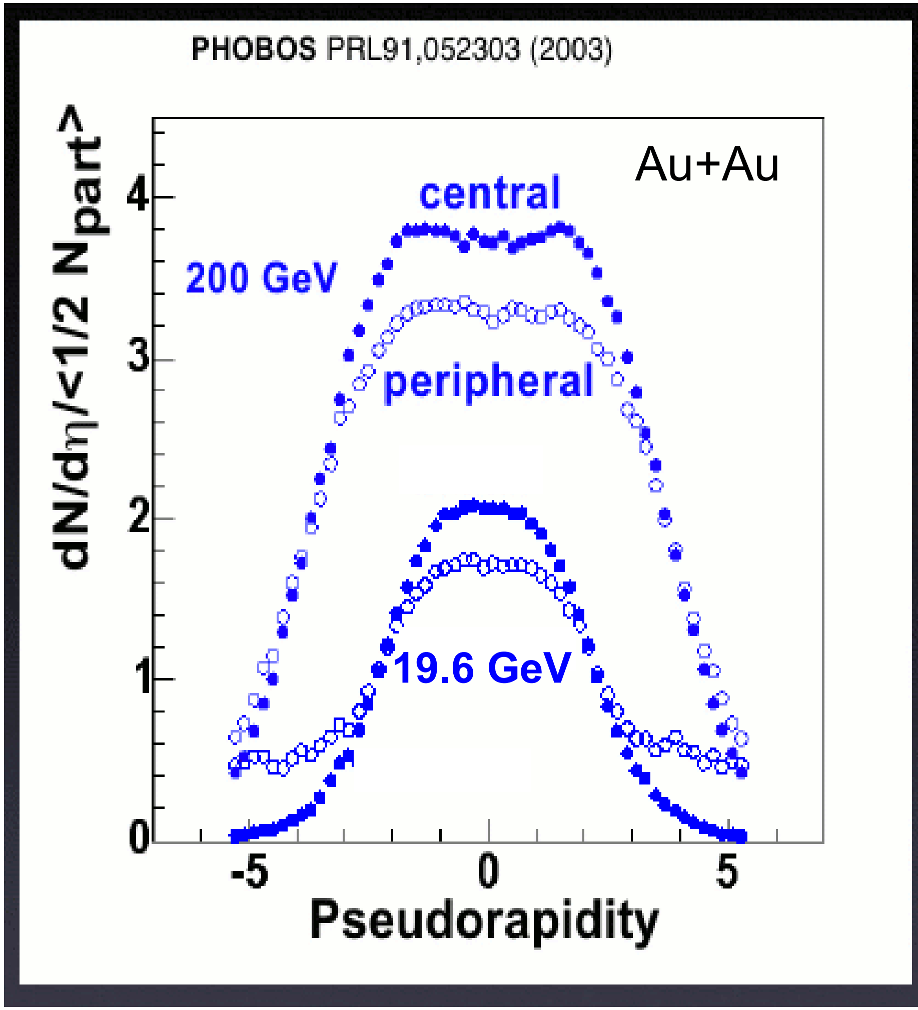
See Burak Alver's talk tomorrow

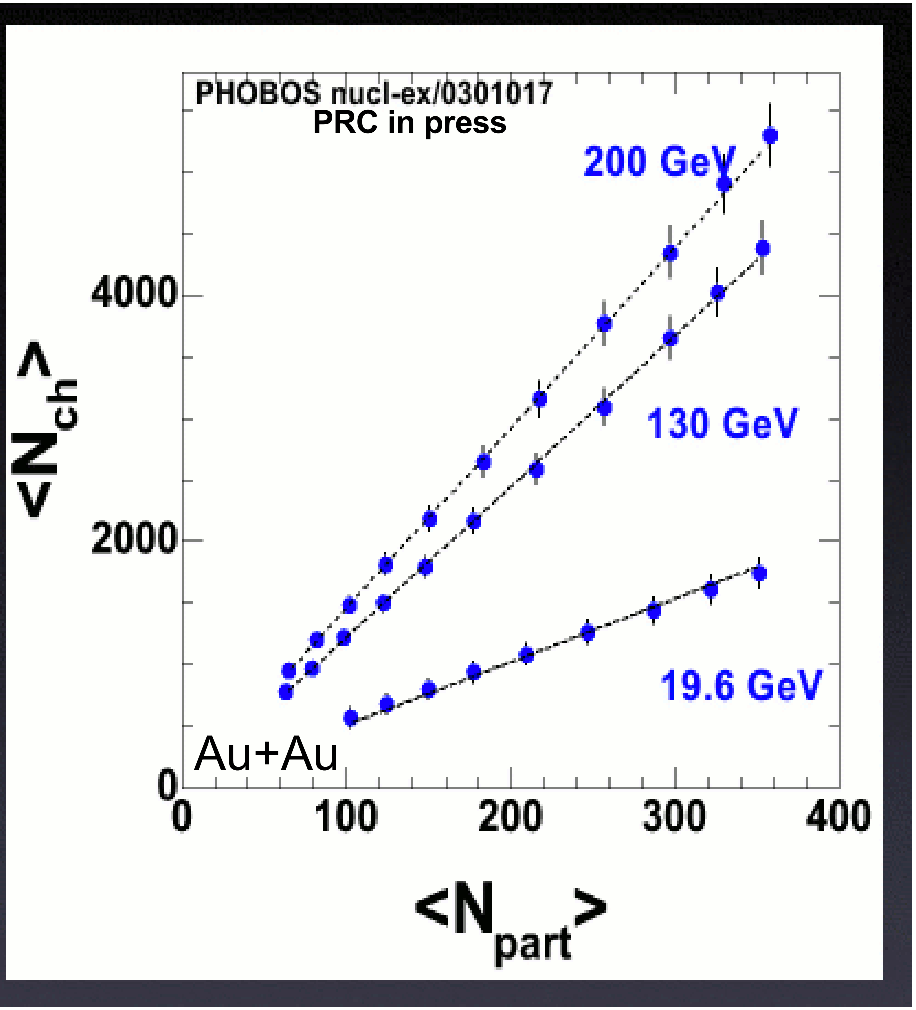
Summary and Perspectives

- Unusual event search
  - To the level of $\approx 10^{-4}$ (potentially lower) all events are “the same”
  - Refine this upper limit
- Forward-Backward multiplicity correlations
  - Connection of multiplicity fluctuations and hadron clusters
  - Interesting centrality dependence
- Two-particle angular correlation (see Wei Li's talk, 07/07/2006)
  - Comprehensive study of angular correlations in pp, dA and AA systems
- Eccentricity fluctuations
  - Participant vs standard eccentricity
  - Elliptic flow in small system connected to initial geometry fluctuations
- Elliptic flow fluctuations (see Burak Alver's talk, 07/09/2006)

Backup

Global properties of dN/dη-distributions

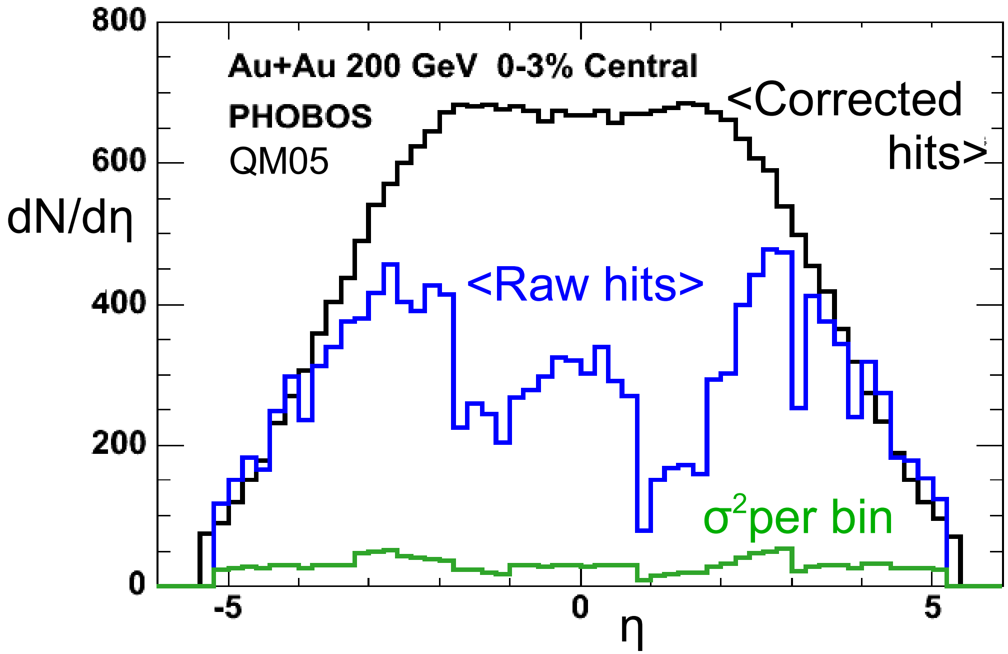




- Centrality dependence of dN/dη shape
- Npart scaling of integrated (4π) multiplicity

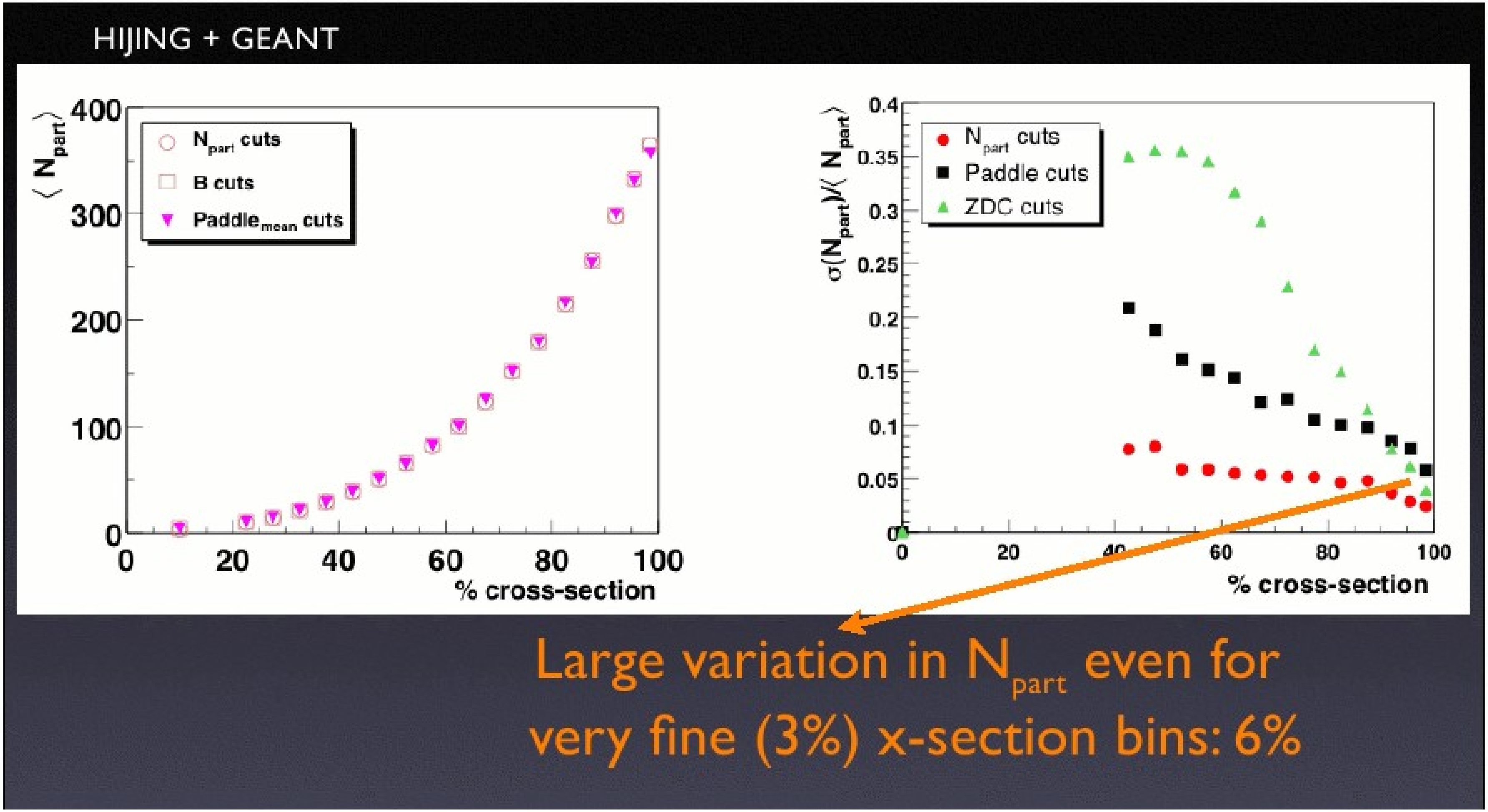
Beyond average dN/dη-distributions

- Quantify event-by-event variation of large scale structure
  - Are there events with very large multiplicity?
  - Does the dN/dη shape vary from event to event?

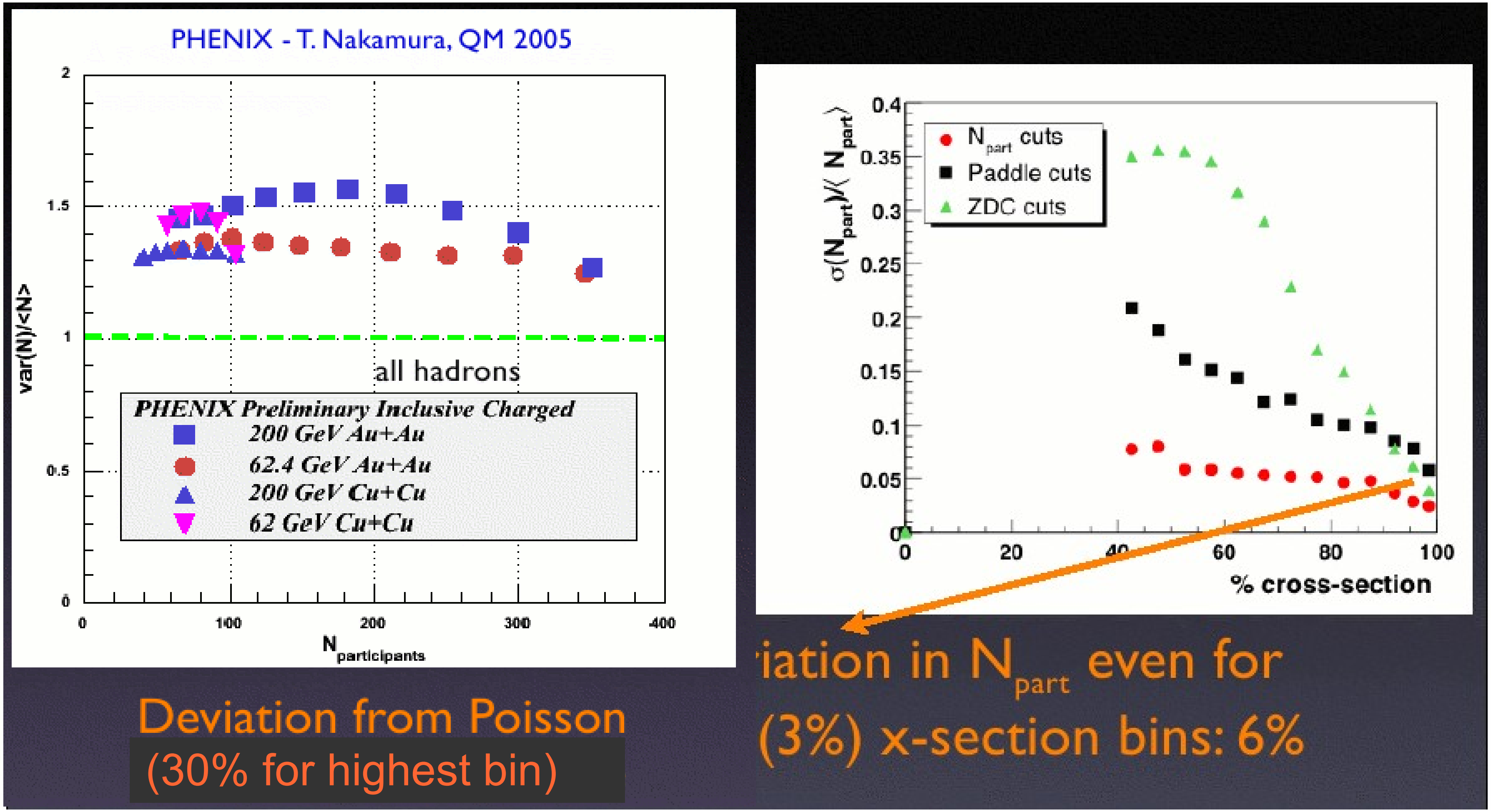


- Multiplicity fluctuations
  - Integral of raw dN/dη
- Shape fluctuations
  - χ^2 of single event vs raw (average) dN/dη

Multiplicity vs. participant fluctuations



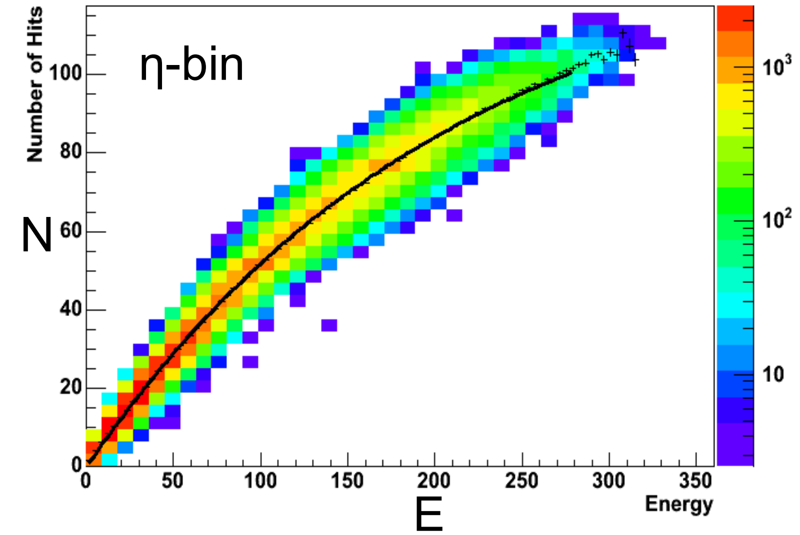
Multiplicity vs. participant fluctuations



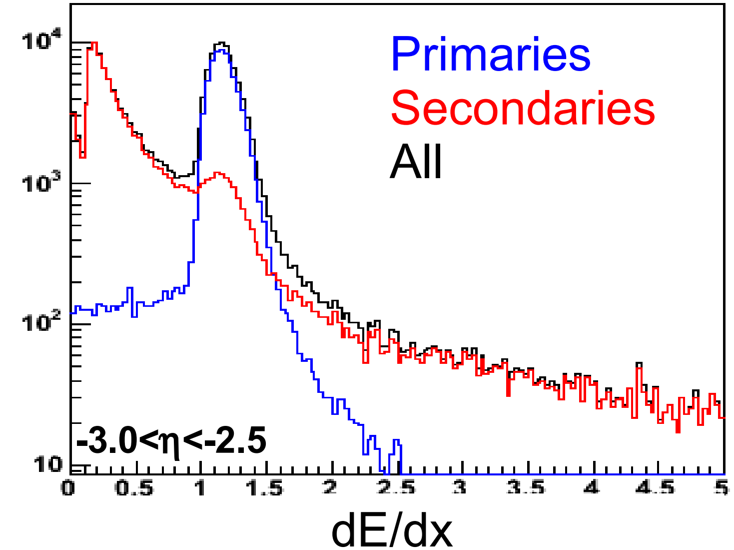
Todo: Conclusion

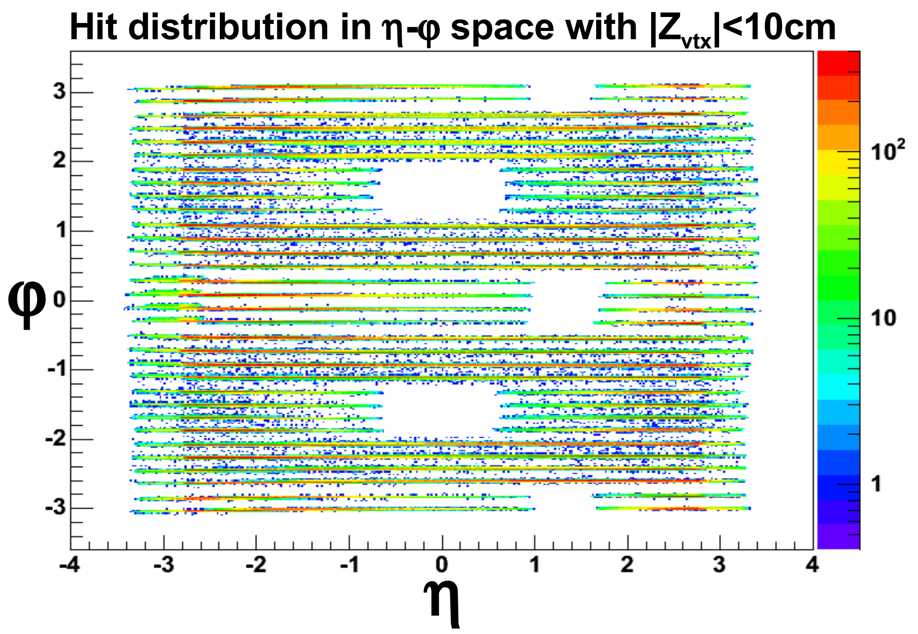
Extracting number of particles per bin

- Octagon silicon sensors
  - Number of hits, N_{hit}
  - Sum of angle-corrected dE for charged particles, $E = \Sigma dE$
- Poissonian ansatz
  - $N_{hit} = N_{max}(1-\exp(-E/E_{max}))$
- Average <dE> in η-bin given by E_{max}/N_{max}
- Estimated multiplilicty in η-bin
  $N=E/(E_{max}/N_{max})$
- Use η-bin-dependent lower and upper dE/dx cuts on hits to suppress contribution from secondaries



dE/dx distribution of MC hits

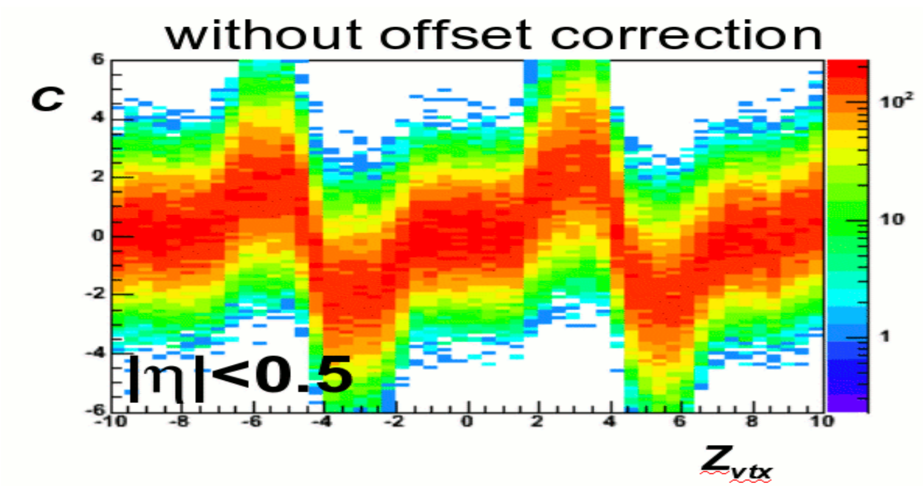


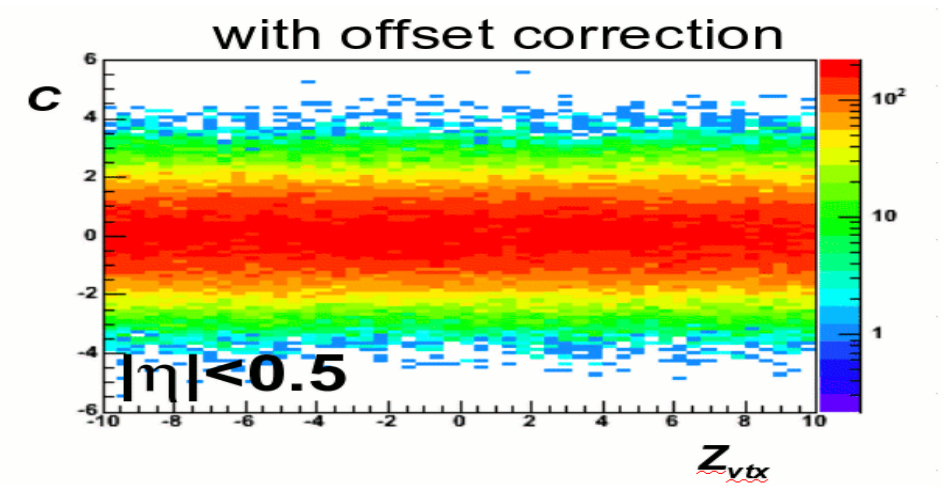


- Calculate average C per η, vertex and centrality bin

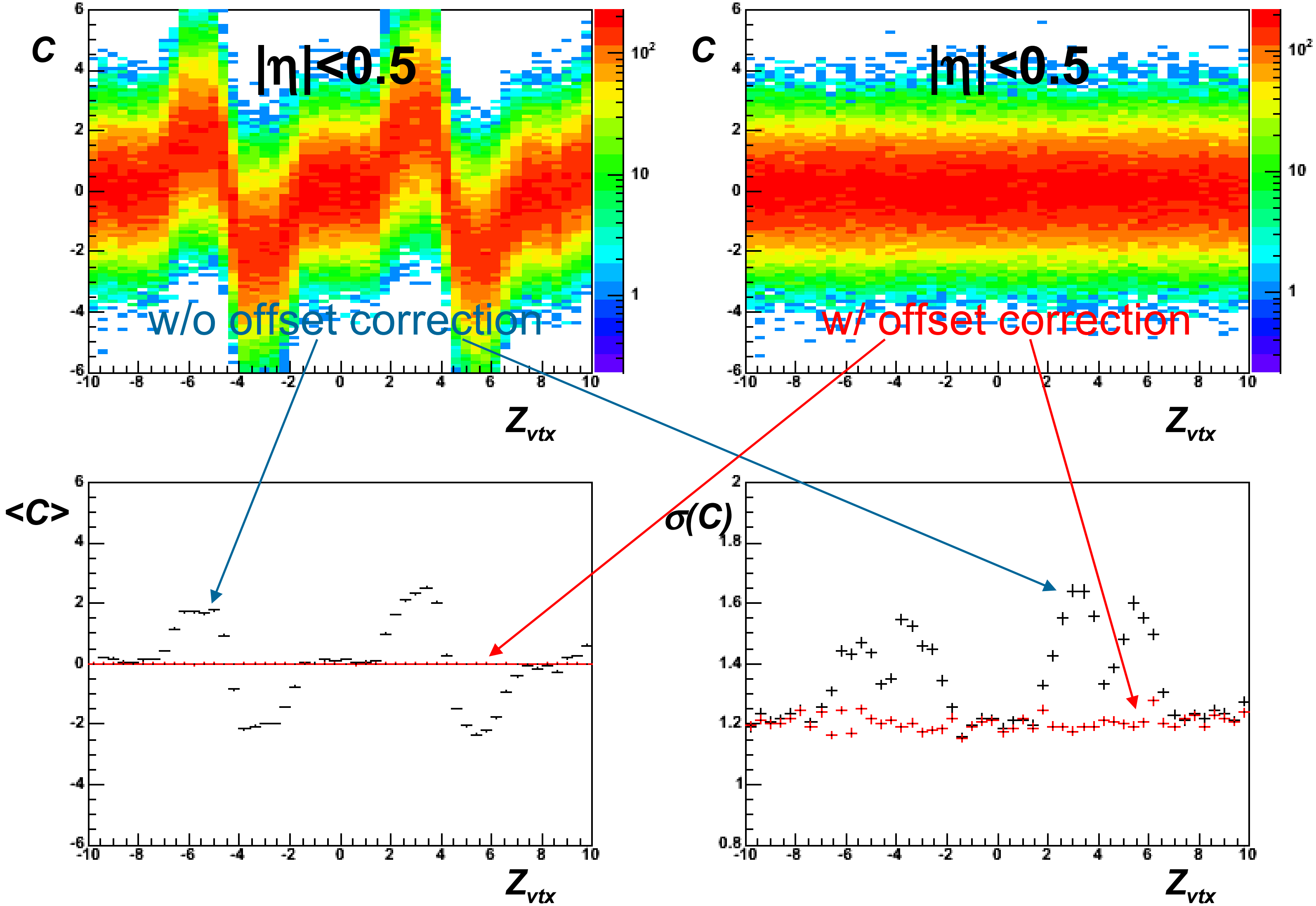
$$\Delta C = \frac{\langle N_1 - N_2 \rangle}{\sqrt{N_1 + N_2}}$$

- Substract it event-by-event from C (according to simulations this leaves fluctuations uneffected)



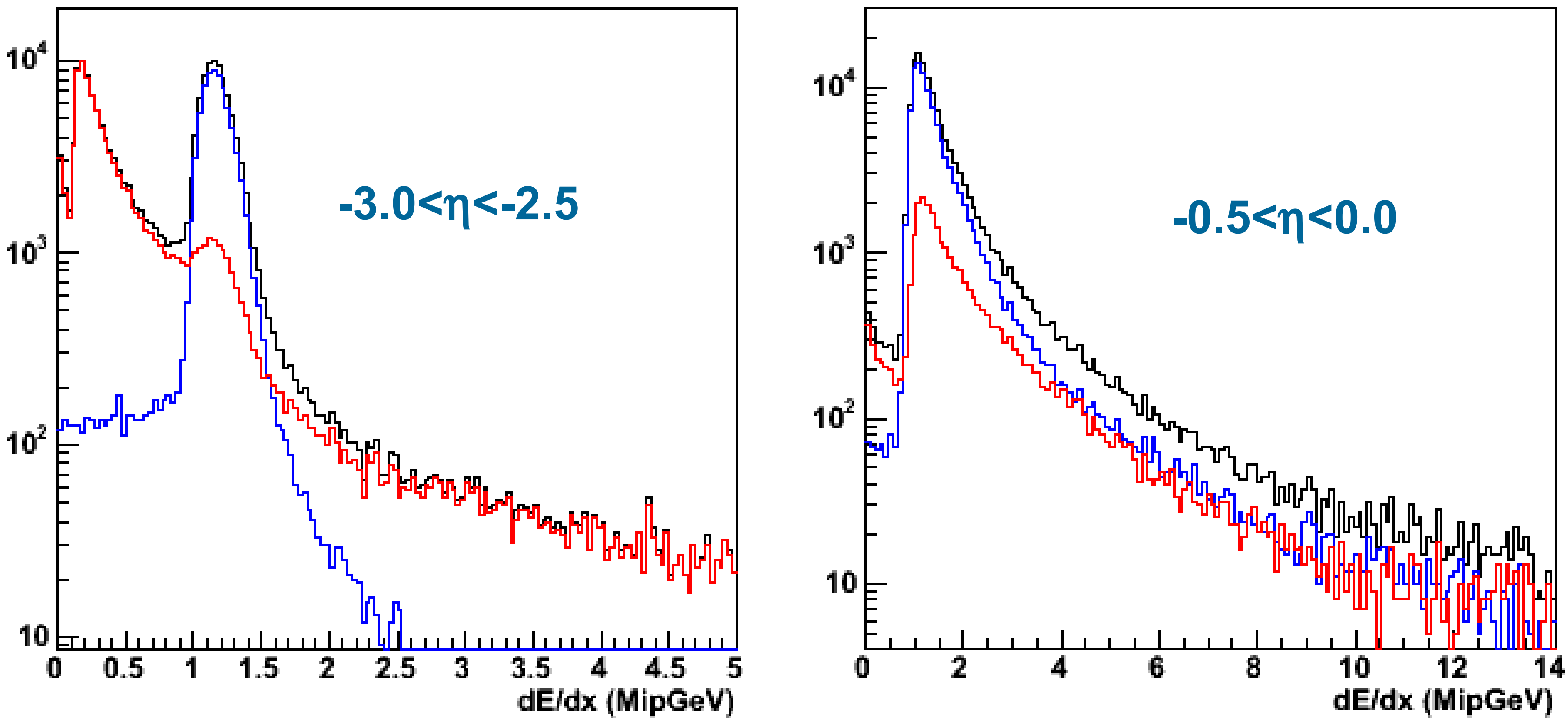


F/B: Acceptance correction

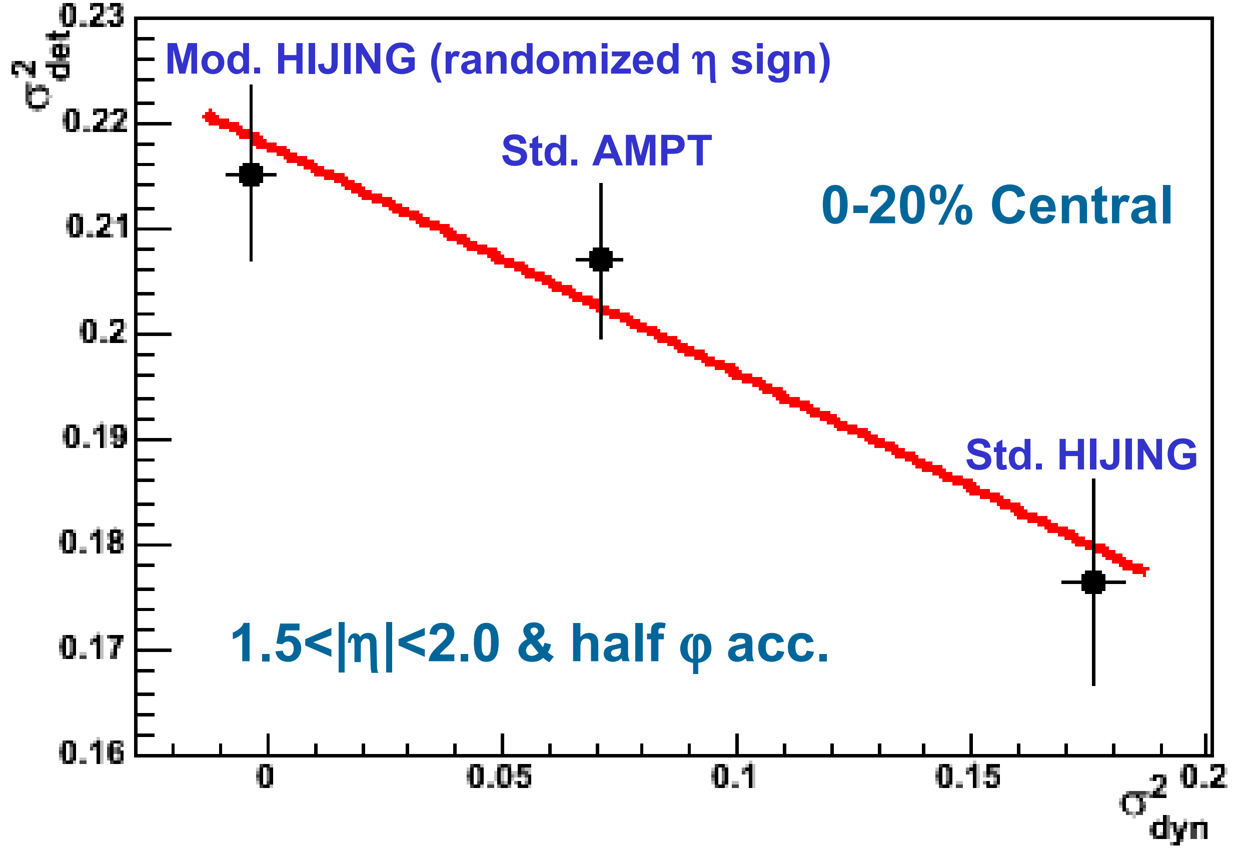


F/B: dE/dx distributions of MC hits

Black: Primaries + Secondaries, Red: Secondaries, Blue: Primaries



F/B: 1st order detector effects



Charge fluctuation

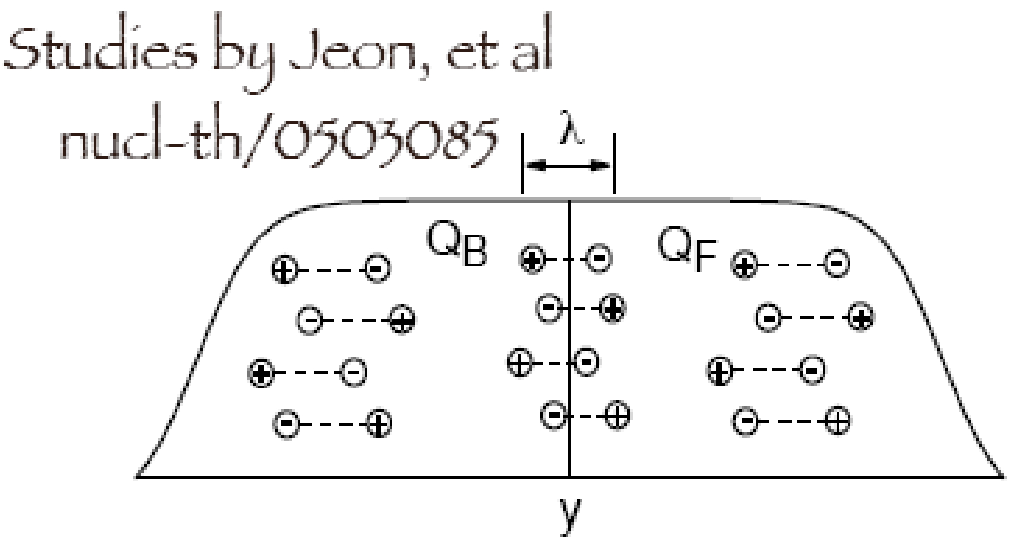
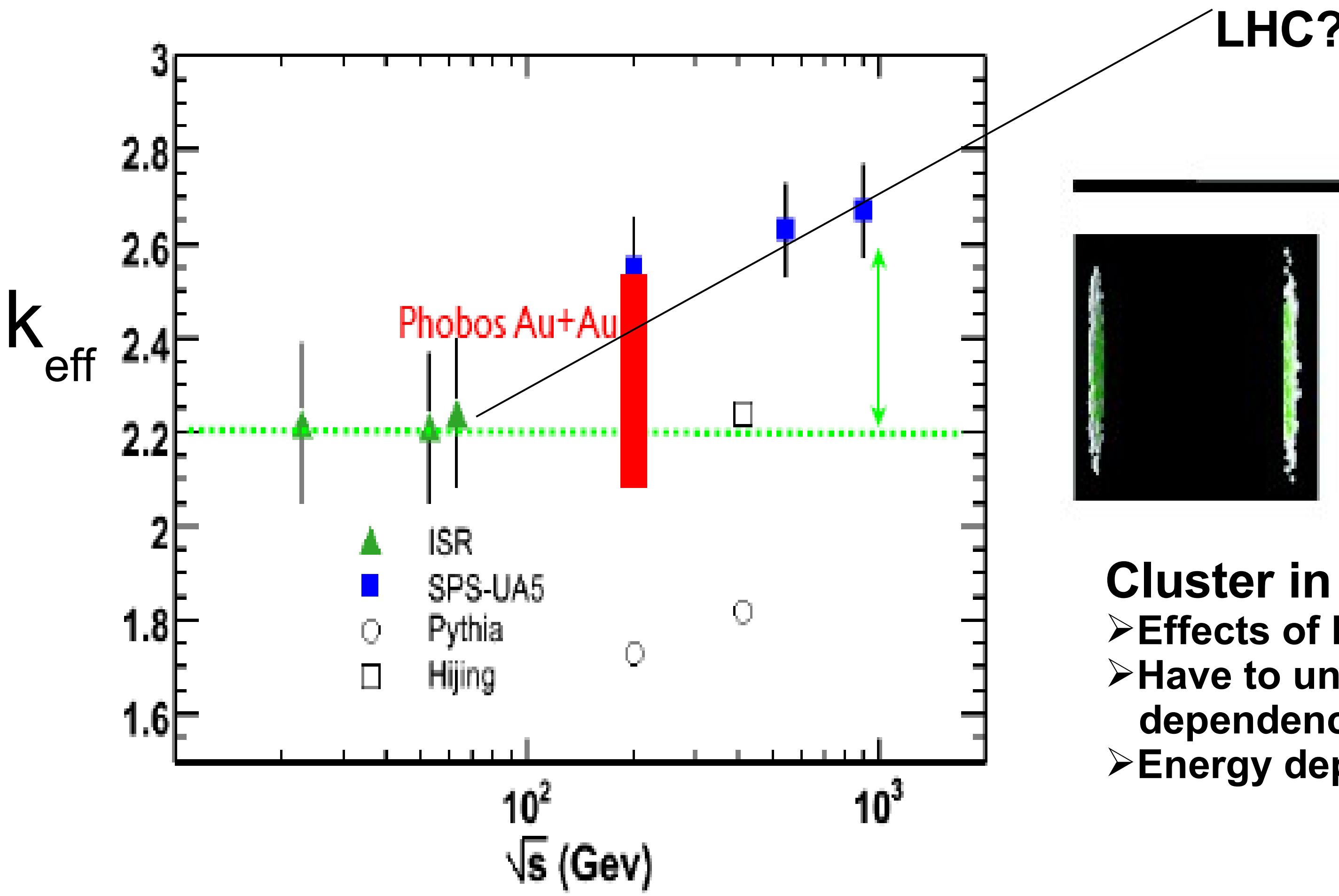
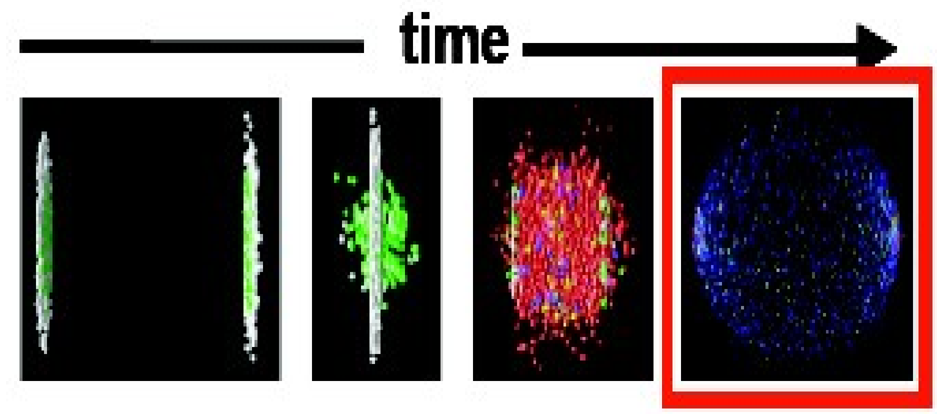


FIG. 1: A schematic illustration of the charge transfer fluctuations in the rapidity space. Only the pairs within $\lambda/2$ of y can contribute to the charge transfer fluctuation $D_u(y)$. Here λ is the rapidity correlation length, or the rapidity distance of the decay particles from a single cluster. If λ is a function of y, then $D_u(y)$ also changes with y.

- Model predicts at central region, QGP will decrease the cluster size.
- F&B method is restricted by the overlapping of F and B region near mid-rapidity.
- PHOBOS angular correlation analysis can be a useful tool to test the model.

Clusters in pp and AA





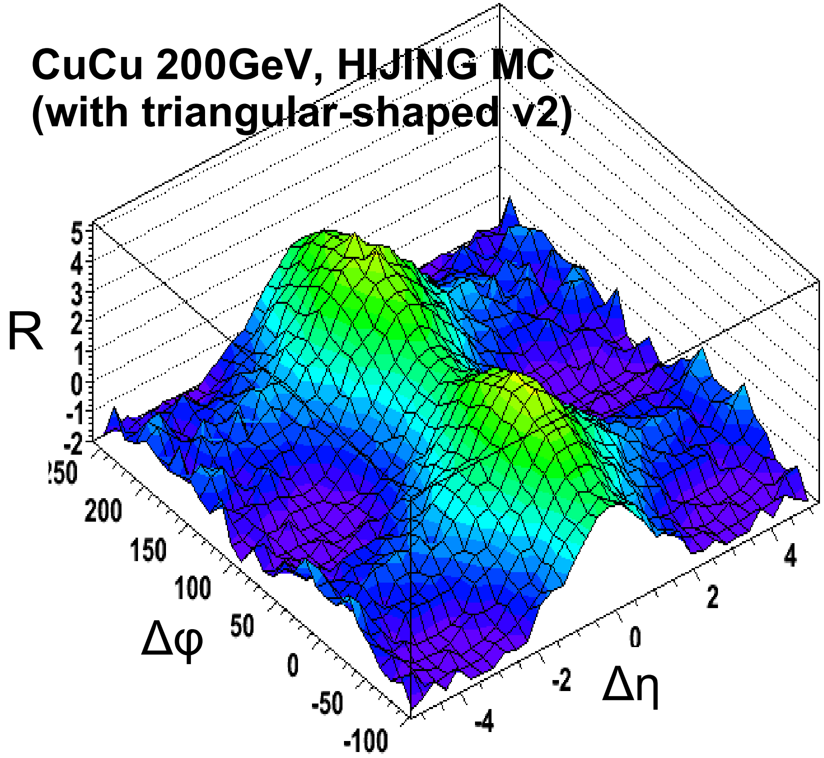
Cluster in AA is very similar to pp:

- **Effects of Hadronization?**
- **Have to understand centrality dependence in AA**
- **Energy dependence: mini-jets?**

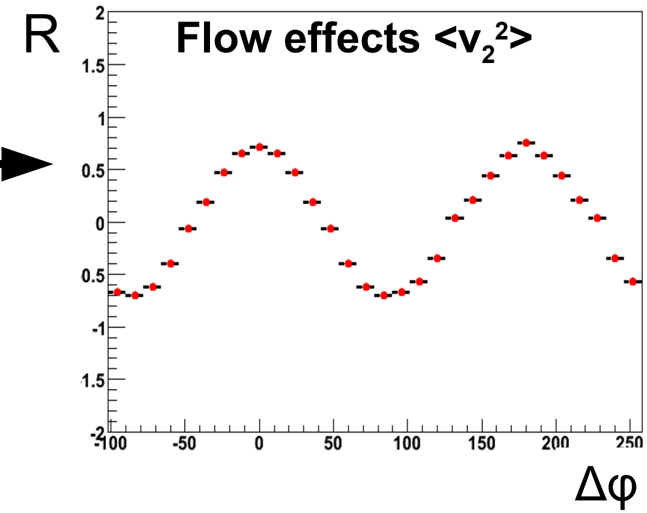
Nucl. Phys. B 86, 201 (1975)
Nucl. Phys. B 155, 269 (1979)
Z. Phys. - Particle and Fields C 37,191 (1988)

Two-particle angular correlations in A+A

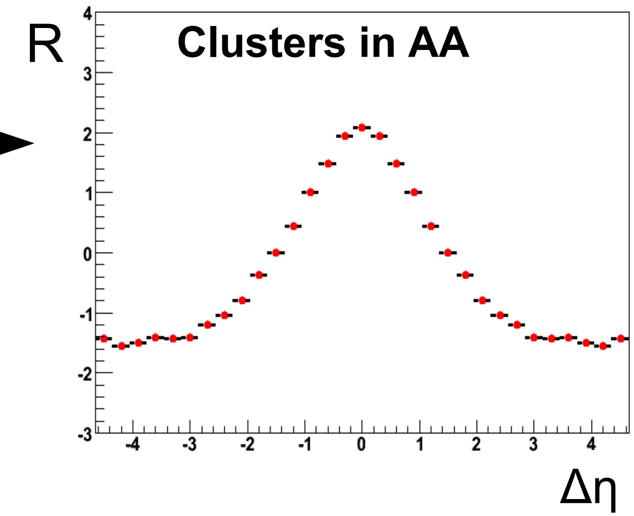
See Wei Li's talk



Projecting onto φ
from 0<|Δφ|<180

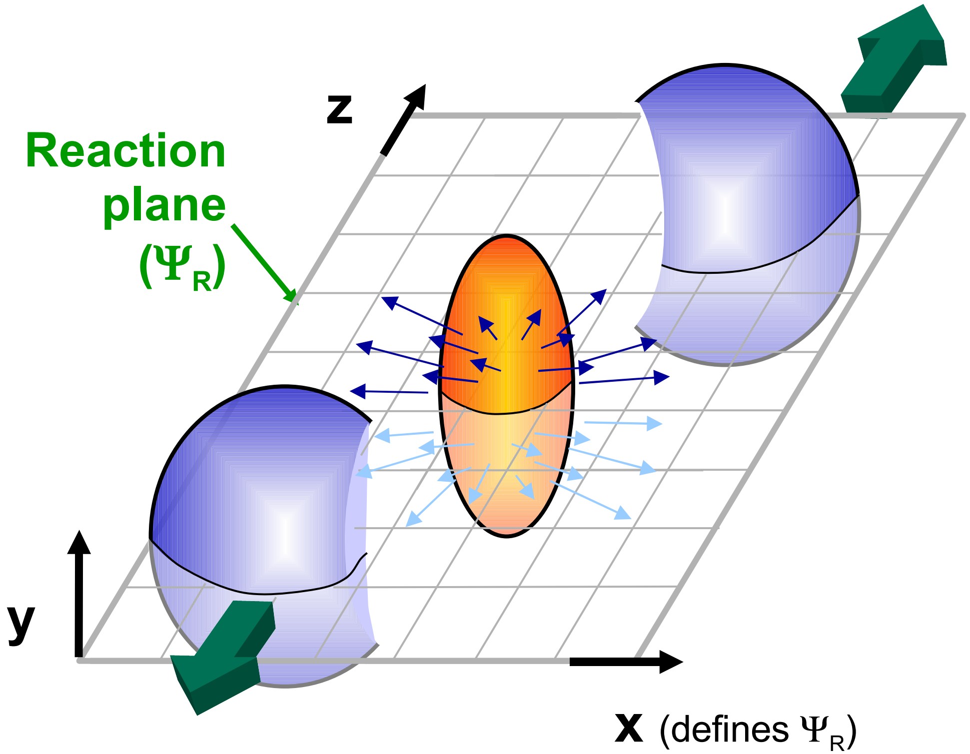


Projecting onto η
from 0<|Δη|<6

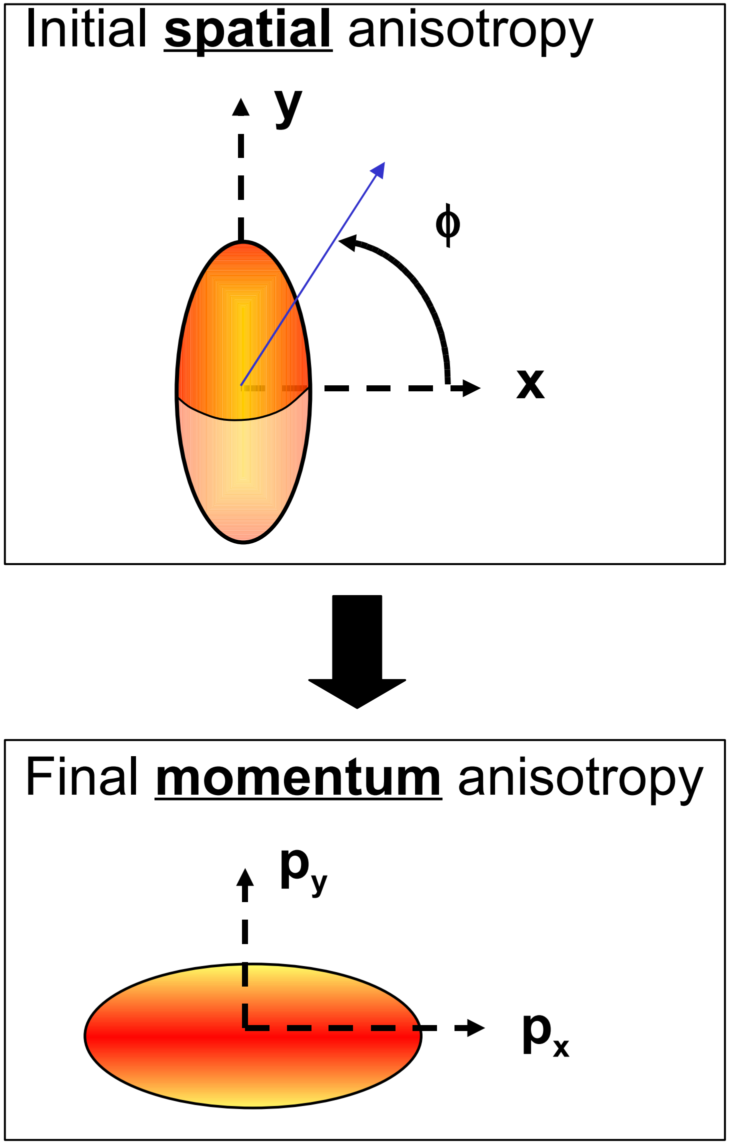


Comprehensive study of two-particle correlations in pp, dA and AA will help distangle different effects in HI systems

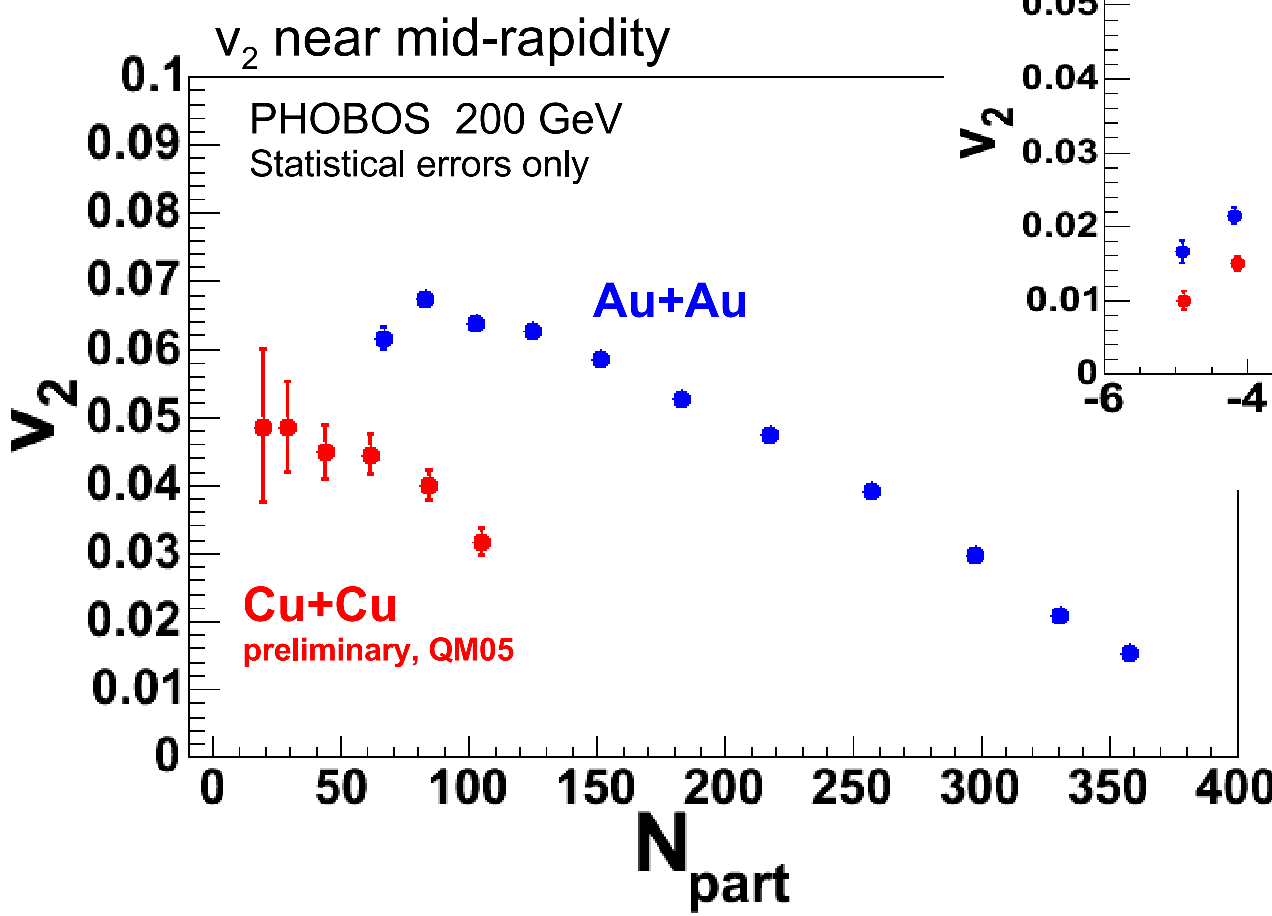
Direct (v_1) and elliptic (v_2) flow

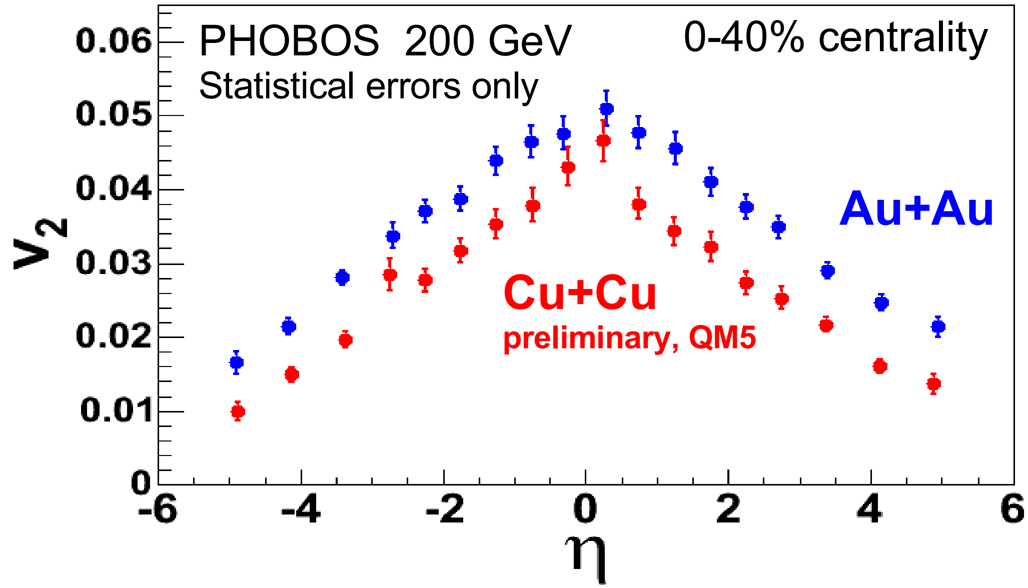


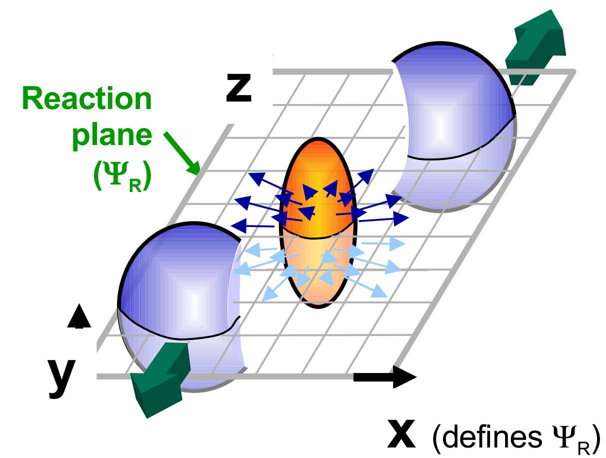
$$dN/d(\phi - \Psi_R) = N_0 (1 + 2v_1 \cos(\phi - \Psi_R) + 2v_2 \cos(2(\phi - \Psi_R)) + \dots)$$



Elliptic flow in Cu+Cu and Au+Au





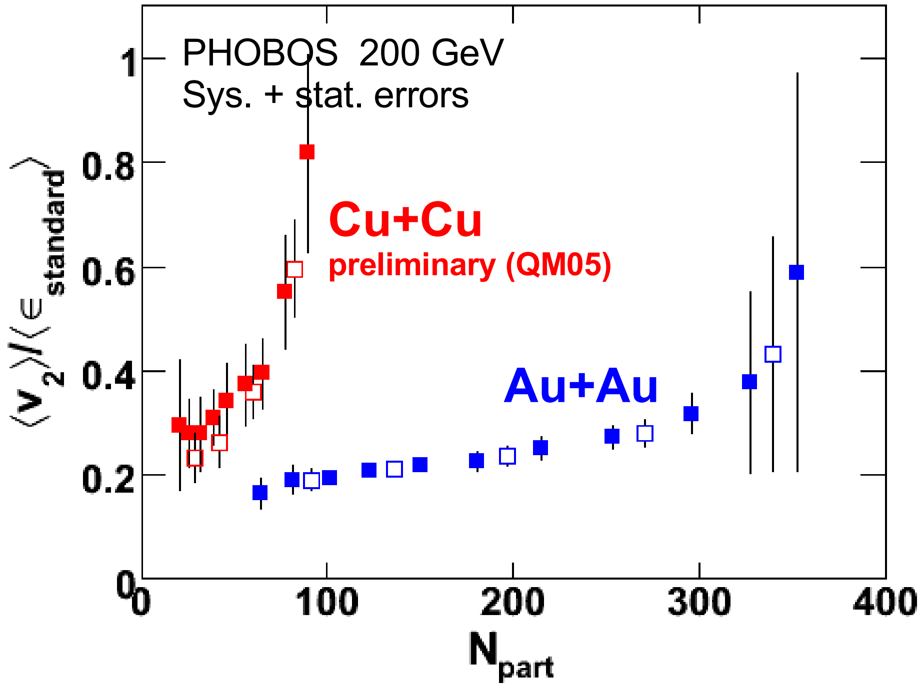


Au+Au: PRL 94, 122303 (2005)
Cu+Cu: prel. QM05, nucl-ex/0510042

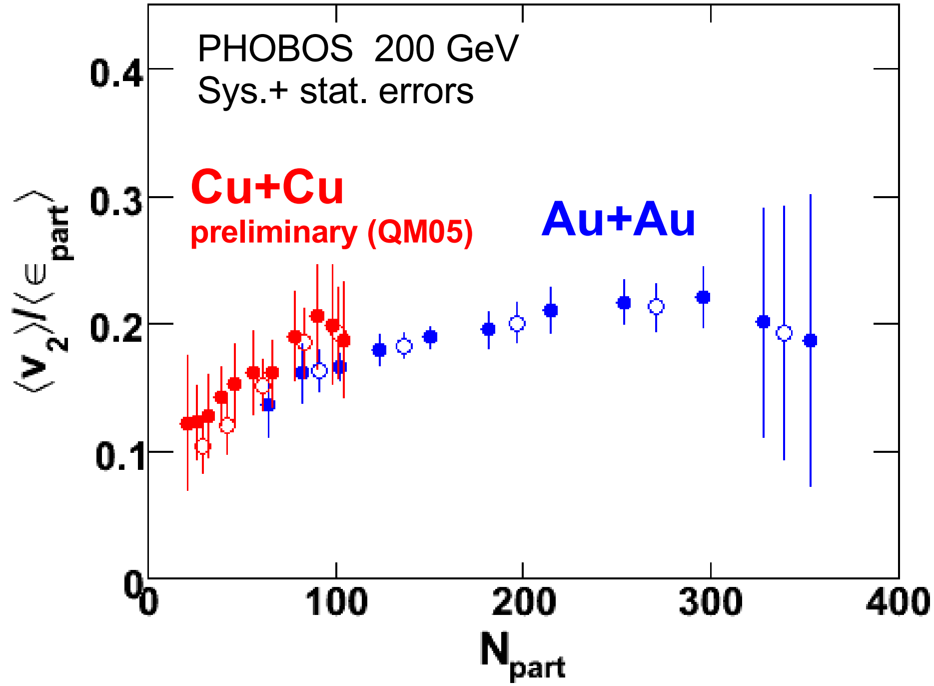
$$dN/d(\phi-\Psi_R)=N[1+2v_1\cos(\phi-\Psi_R)+2v_2\cos(2\phi-2\Psi_R)+...]$$

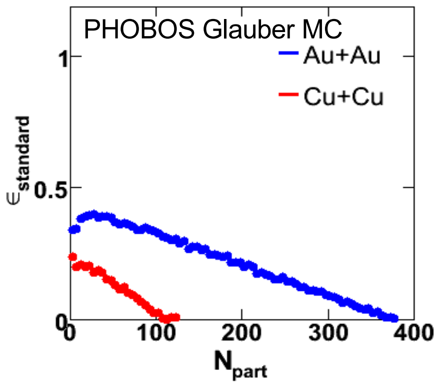
Scaled elliptic flow vs N_{part}

Standard Eccentricity

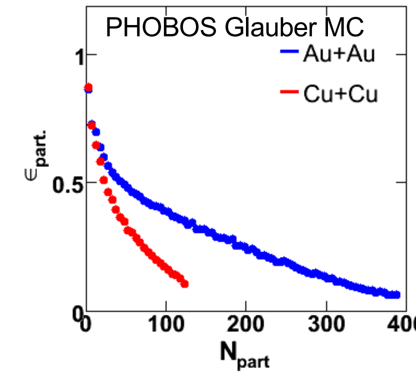


Participant Eccentricity



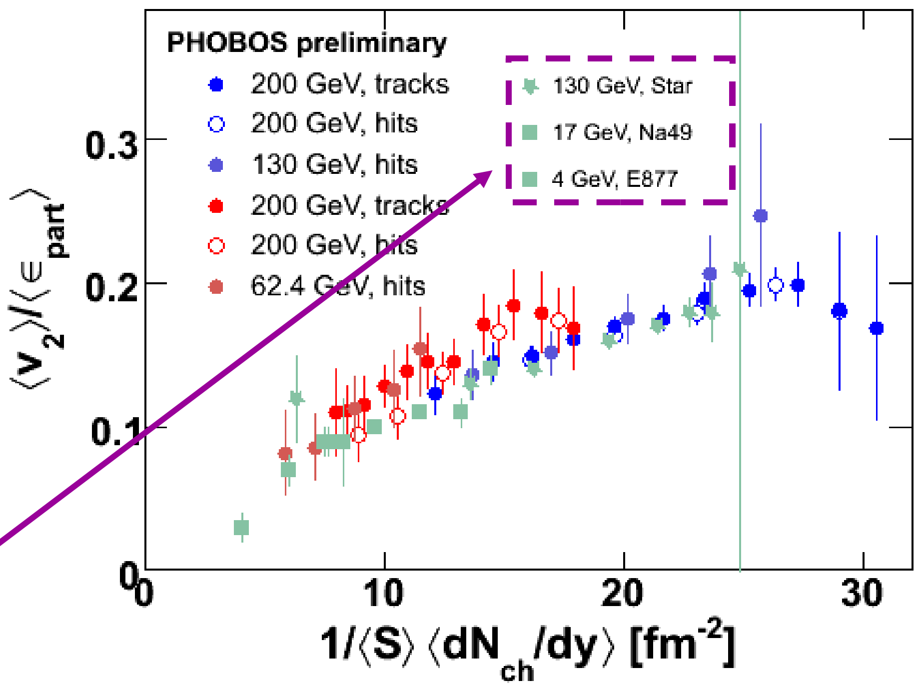


"Participant Eccentricity" allows v_2-scaling from Cu+Cu to Au+Au



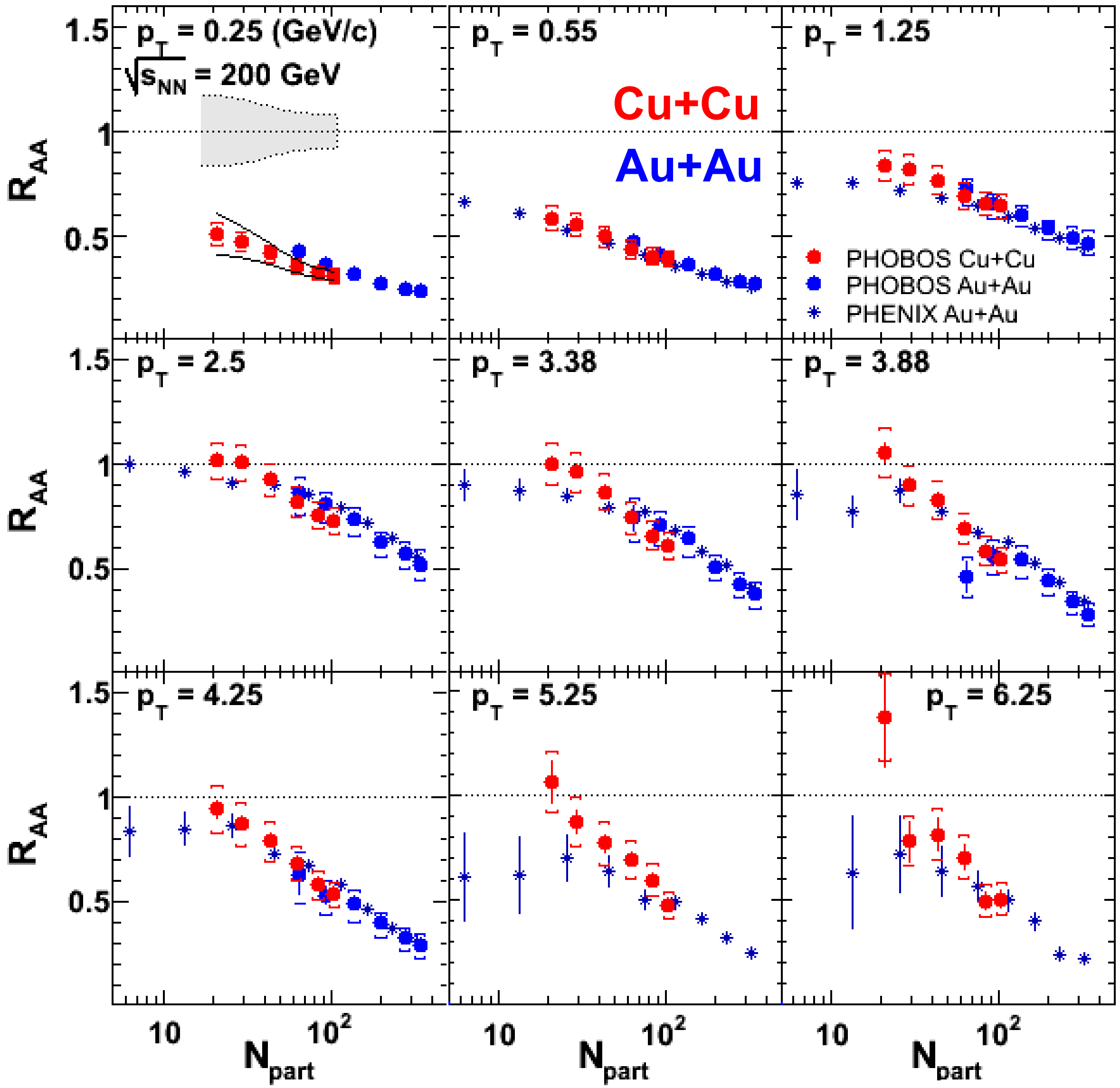
Low-density limit scaling (some details)

- **Caution: we used ε_{part} for PHOBOS data. Important for Cu-Cu, less critical for Au-Au.**
- **Scale $v_2(\eta)$ to $\sim v_2(y)$ (10% lower)**
- **Scale $dN/d\eta$ to be $\sim dN/dy$ (15% higher)**



Points for STAR, NA49 and E877 data taken from STAR Collaboration, Phys.Rev. C66 (2002) 034904 with no adjustments

Yields vs N_{part} at 200 GeV



0.2<η<1.4

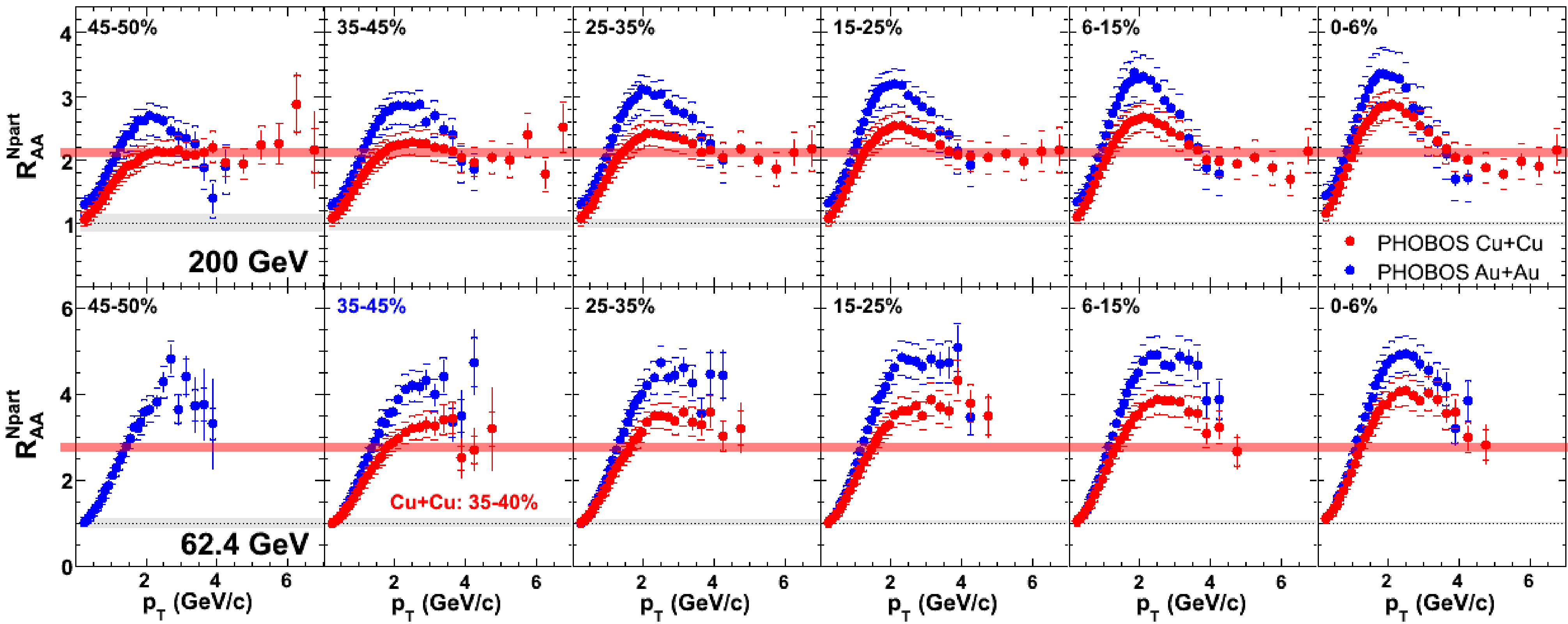
System-size scaling observed!

Au+Au: PRL 94, 082304 (2005), PLB 578, 297 (2004)
Phenix: PLB 561, 82 (2003), PRC 69, 034910 (2004)
Cu+Cu: PRL 96, 212301 (2006)
p+$\bar{p}$: UA1 -2.5<η<2.5 (acc. correction with PYTHIA)

$$R_{AA} = \frac{\sigma_{p\bar{p}}^{inel}}{\langle N_{coll}\rangle} \frac{d^2N_{AA}/dp_T d\eta}{d^2\sigma_{p\bar{p}}/dp_T d\eta}$$

R_{AA}^{Npart} in Au+Au and Cu+Cu at 200 GeV

0.2<η<1.4



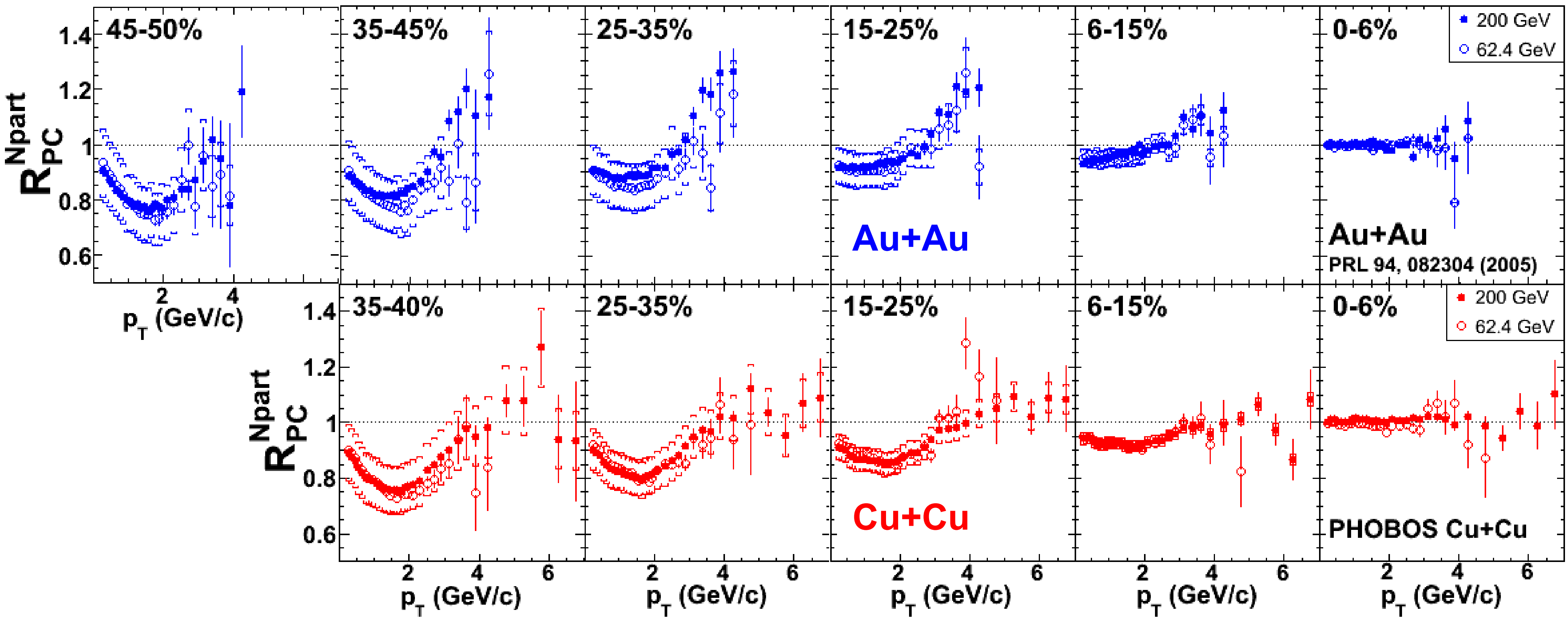
Yields normalized by N_{part} less centrality-dependent

Au+Au: PRL 94, 082304 (2005)
Cu+Cu: PRL 96, 212301 (2006)

$$R_{AA}^{N_{part}} = \frac{\sigma_{p\bar{p}}^{inel}}{\langle N_{part}/2\rangle} \frac{d^2N_{AA}/dp_T d\eta}{d^2\sigma_{p\bar{p}}/dp_T d\eta}$$

Factorization in bins of p_T

Normalized for central events



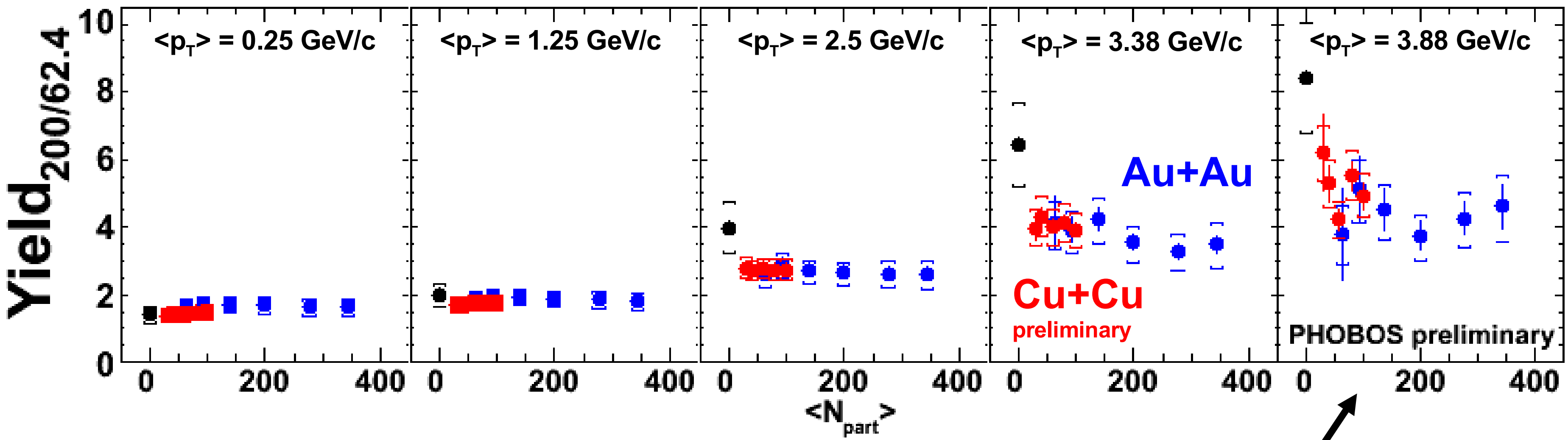
Same shape evolution from central to peripheral at 200 GeV and 62 GeV

$$R_{PC}^{N_{part}} = \frac{\langle N_{part}^{0-6\%} \rangle}{\langle N_{part} \rangle} \frac{d^2 N_{AA}/dp_T d\eta}{d^2 N_{AA}^{0-6\%}/dp_T d\eta}$$

Au+Au: PRL 94, 082304 (2005)
Cu+Cu: PRL 96, 212301 (2006)

Factorization in bins of p_T (2)

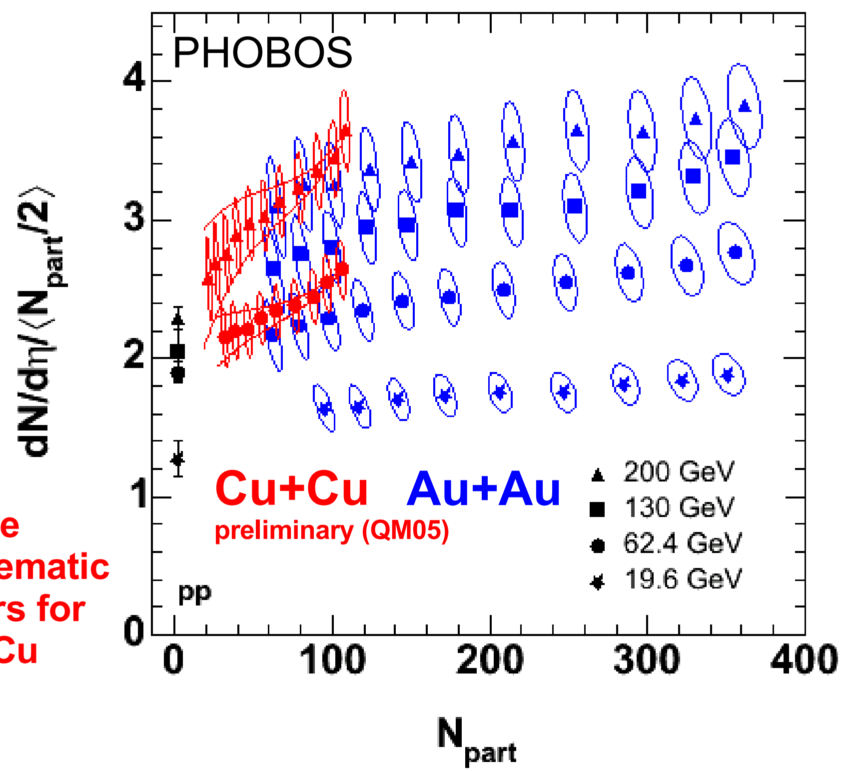
Ratio of charged hadron yields in 200 GeV to 62 GeV



Energy/centrality factorization up to $p_T \approx 4$ GeV/c for $N_{part} > 40$

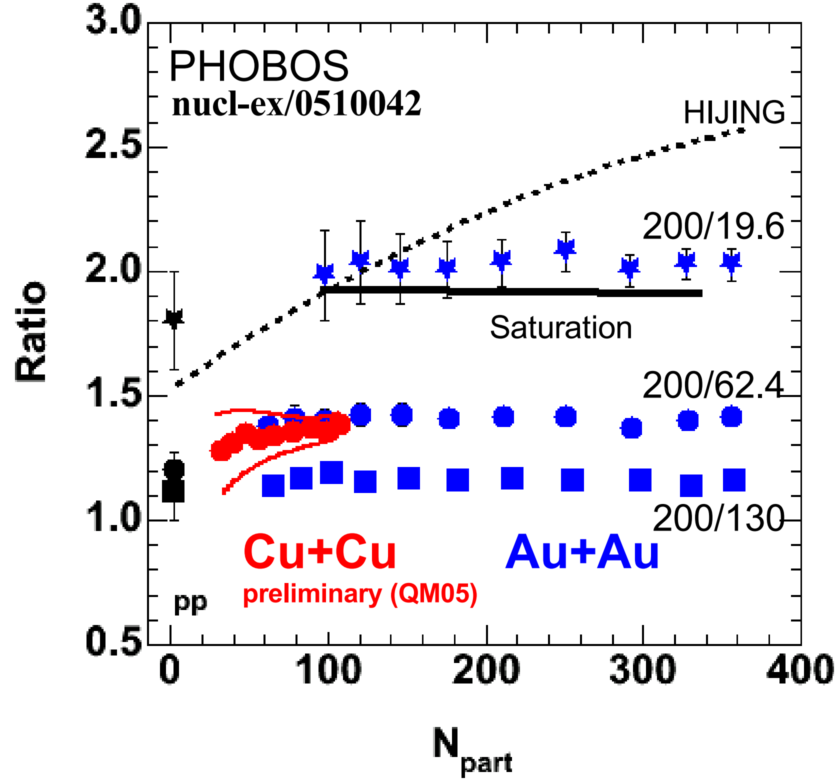
Au+Au: PRL 94, 082304 (2005)
Cu+Cu: PRL 96, 212301 (2006)

Factorization of energy and centrality



Large systematic errors for Cu+Cu

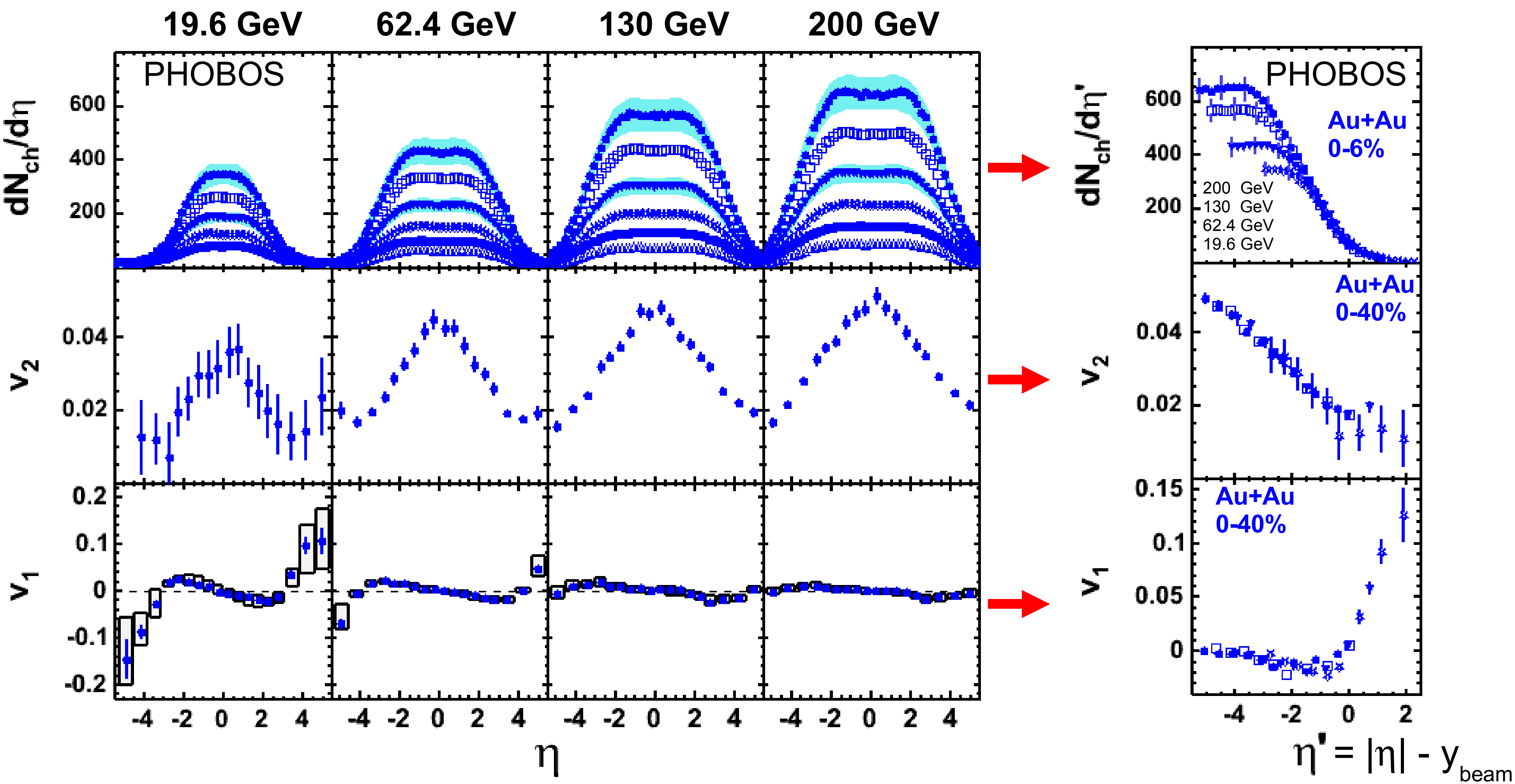
Ratio of dN/dη @ η=0 relative to 200 GeV vs centrality



Factorization of energy and centrality due to initial state effect?

Au+Au: Phys. Rev. C70, 021902(R) (2004)
62.4 GeV Au+Au: nucl-ex/0509034 (sub.to PRC)
Cu+Cu (preliminary): QM05, nucl-ex/0510042

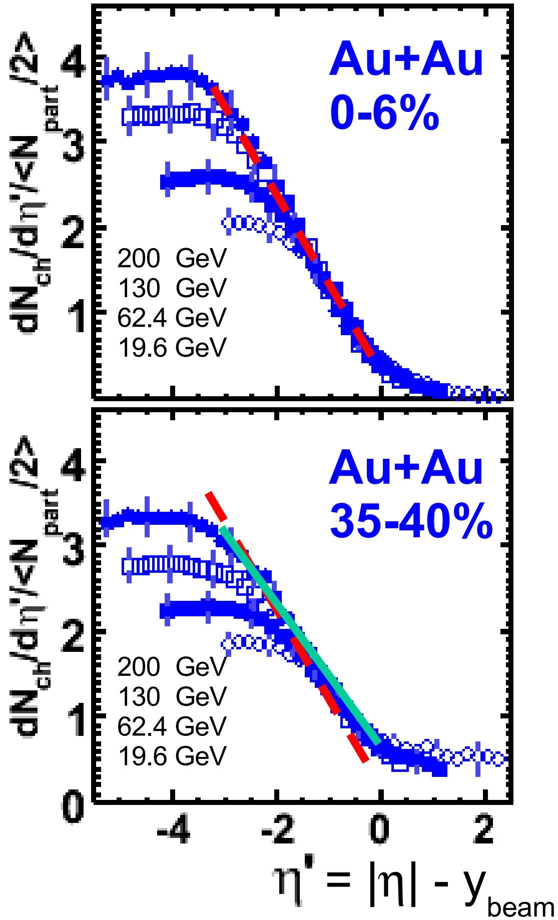
Limiting fragmentation (Au+Au)



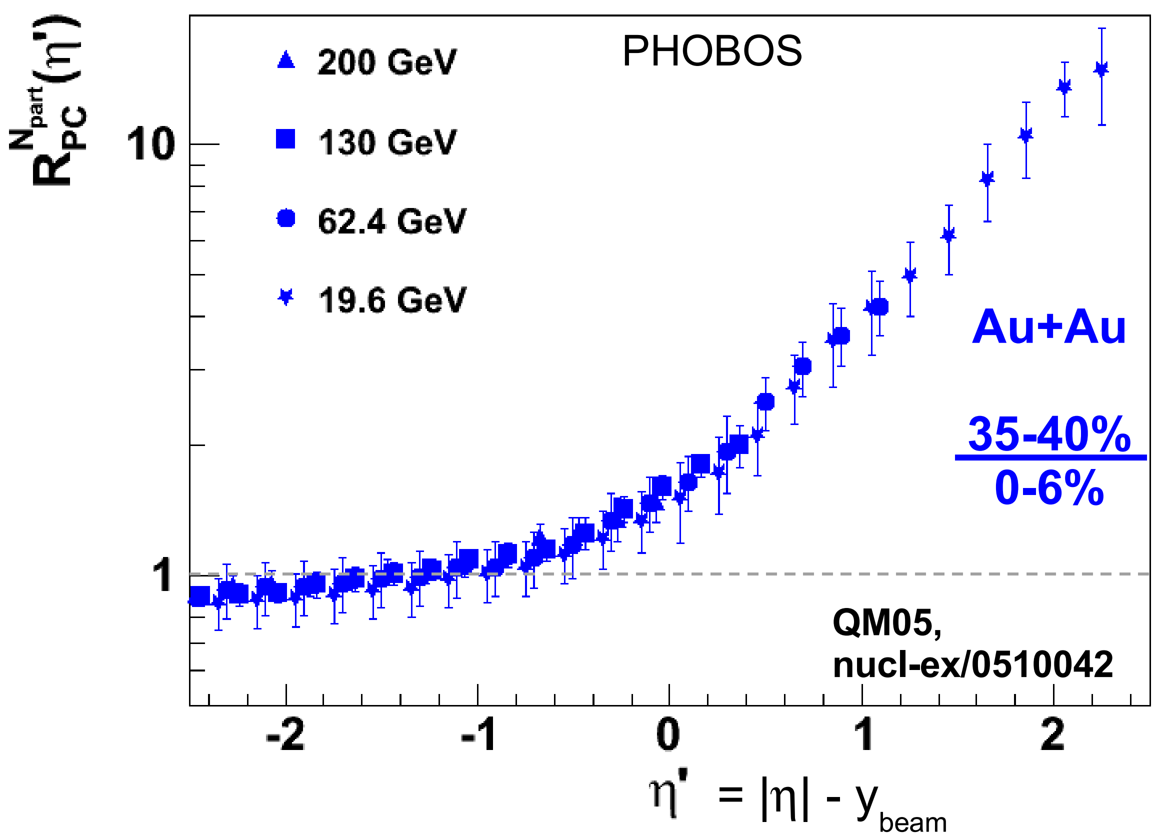
"Extended Longitudinal Scaling" of all longitudinal distributions
(same for Cu+Cu collisions)

QM05, nucl-ex/0510042

Factorization of longitudinal dynamics

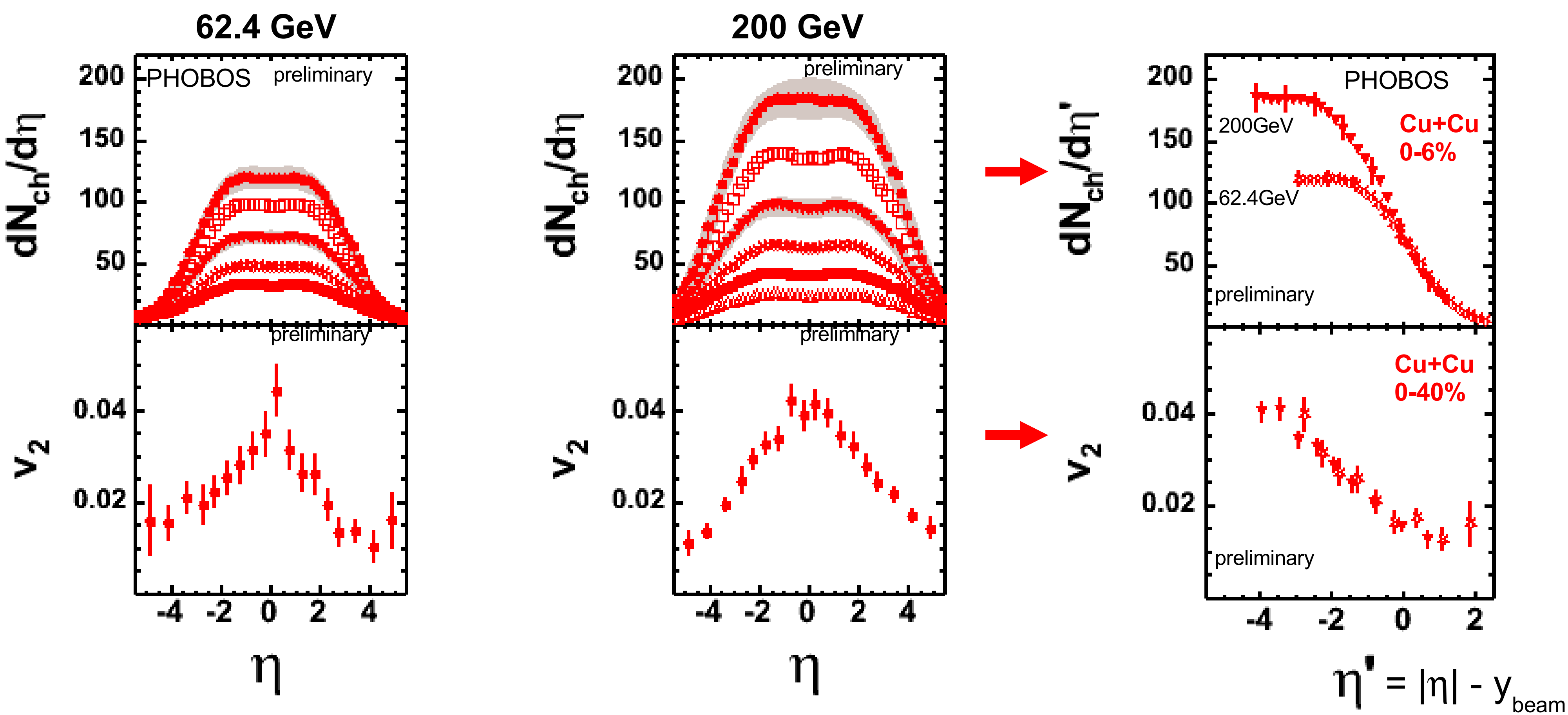


Ratio of 0-6% and 35-40% centrality bins, each normalized by N_{part}



R_{PC}^{Npart} is energy independent!

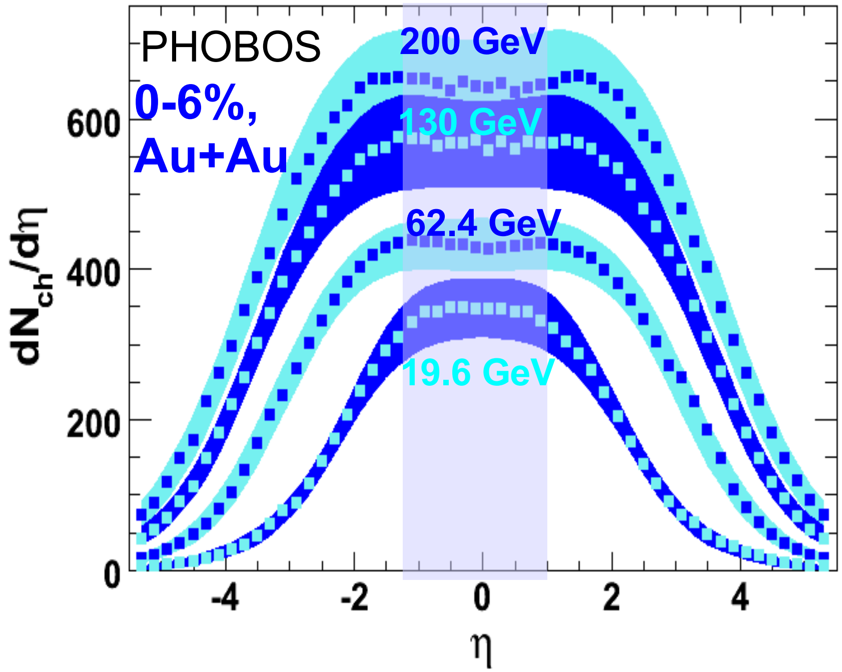
Limiting fragmentation (Cu+Cu)

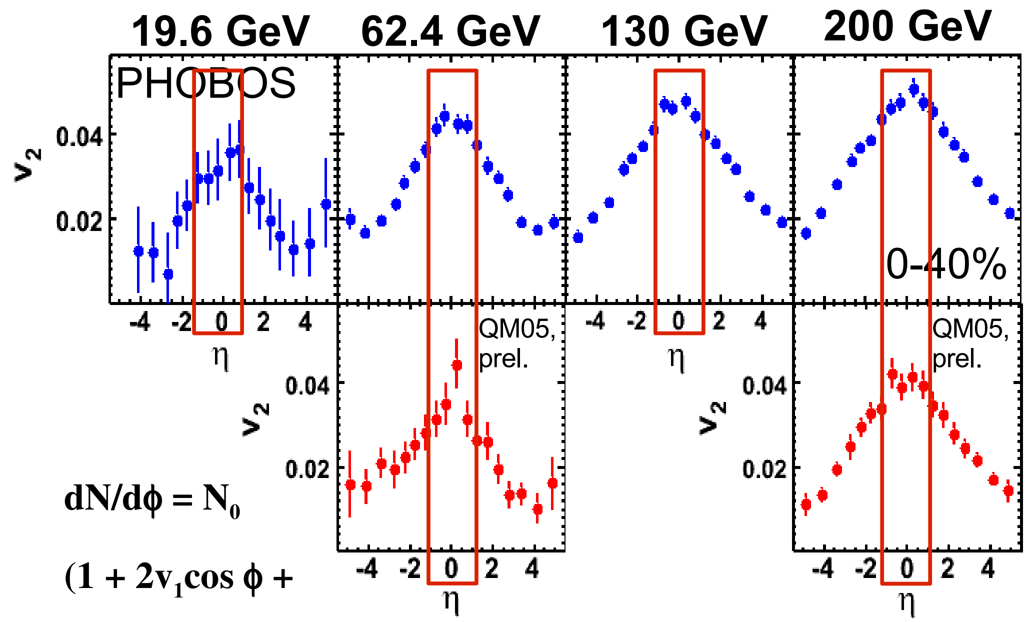


'Extended Longitudinal Scaling' also seen in Cu+Cu
Persists from p+p to Au+Au over large range in η'

QM05, nucl-ex/0510042

Properties of the medium (2)





$dN/d\phi = N_0 (1 + 2v_1\cos\phi + 2v_2\cos(2\phi) + \ldots)$

At 200 GeV:

ϵ >3 GeV/fm³

$$\epsilon = \frac{\langle E \rangle \times dN/d\eta \times corr}{\pi R^2 \times (0.1 - few)\ fm}$$

PHOBOS WhitePaper

Strongly interacting medium
with extremely high energy density

WhitePaper: NPA, 757 28 (2005)
v_2 Au+Au: PRL 94, 122303 (2005)
v_2 Cu+Cu (prel.): QM05, nucl-ex/0510042