New Results from the PHOBOS Collaboration

Structure and Fine Structure of Hadron Production at RHIC

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PHOBOS Collaboration



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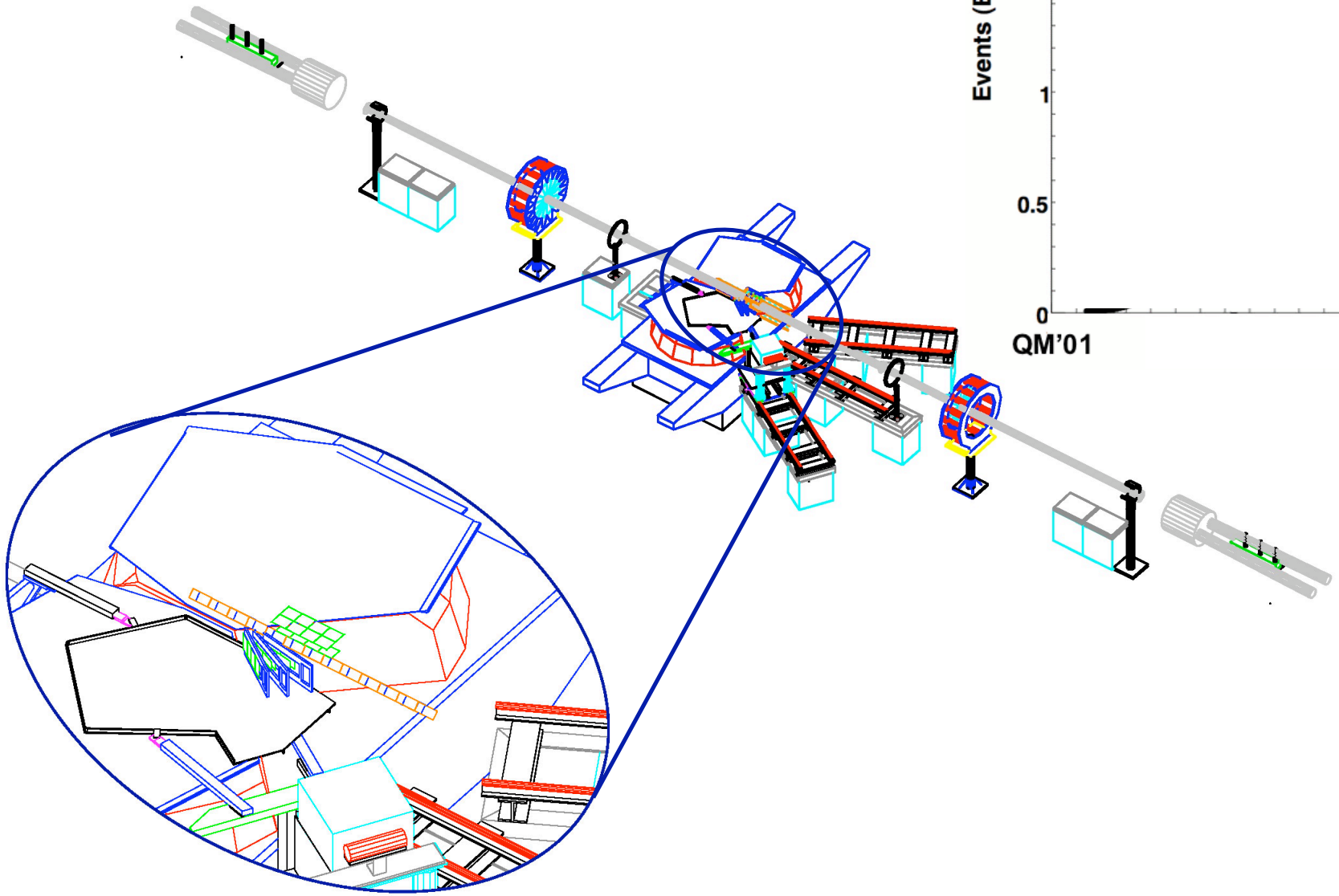
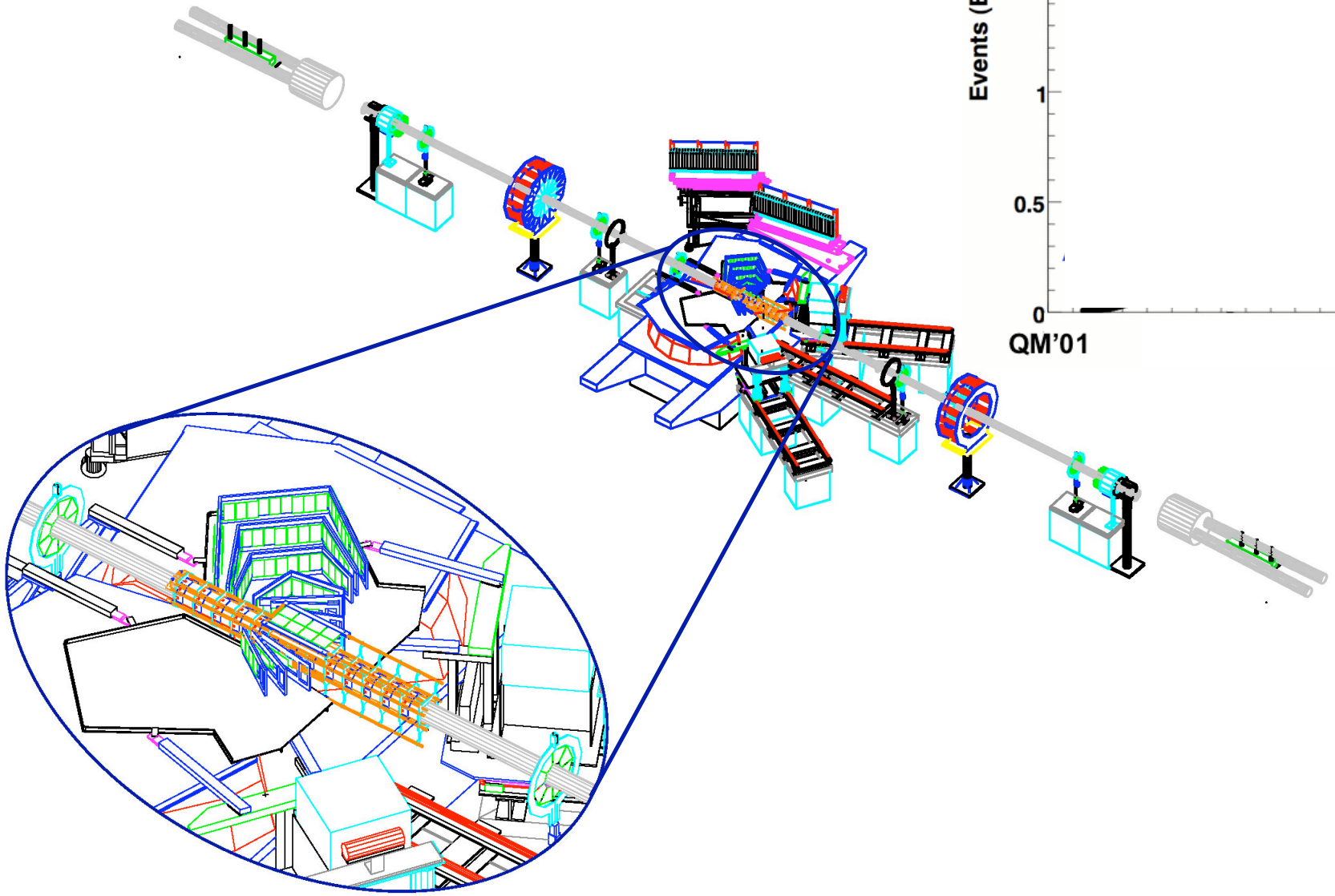
BROOKHAVEN NATIONAL LABORATORY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
UNIVERSITY OF ILLINOIS AT CHICAGO
UNIVERSITY OF ROCHESTER

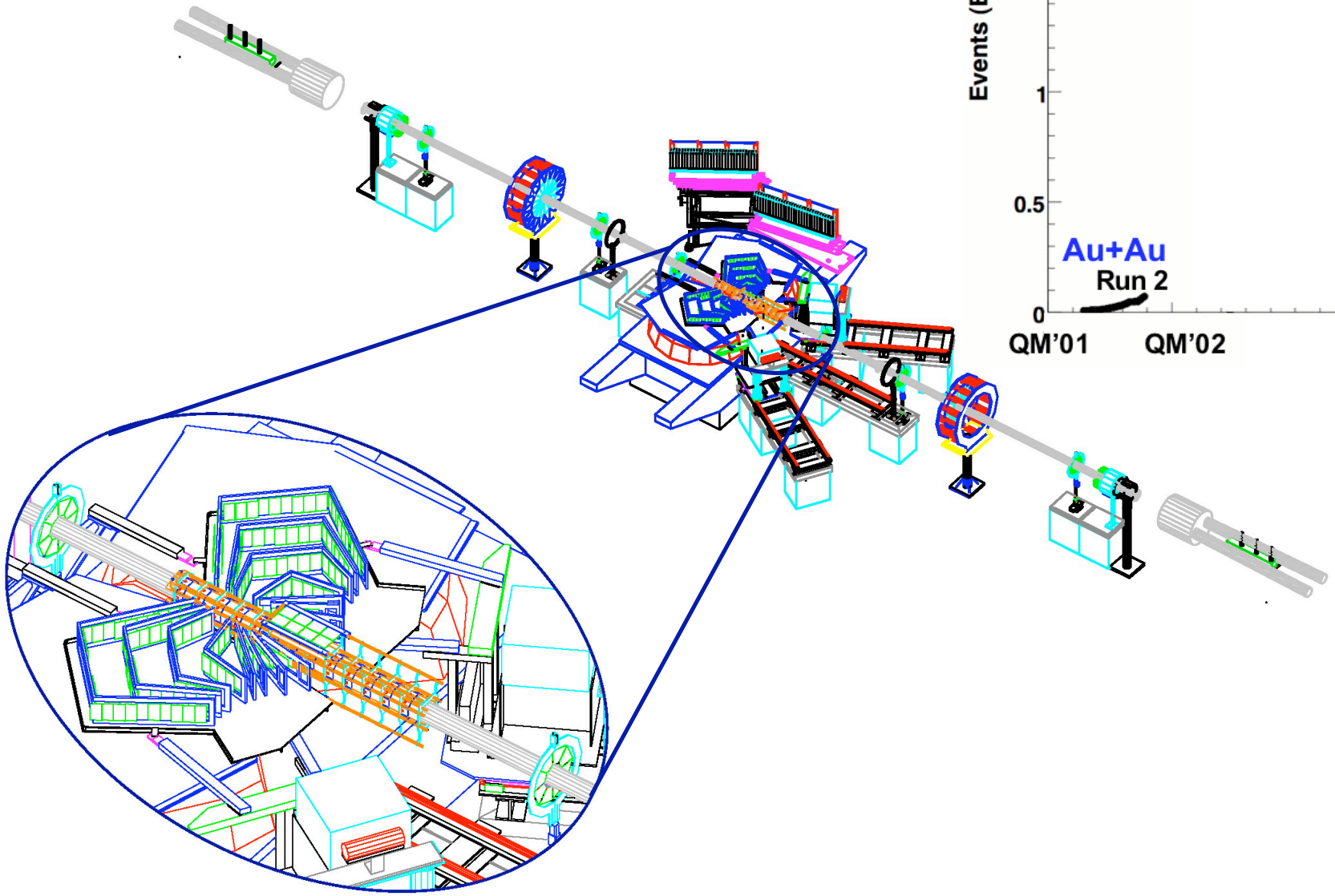
PHOBOS Experiment - Commissioning Run



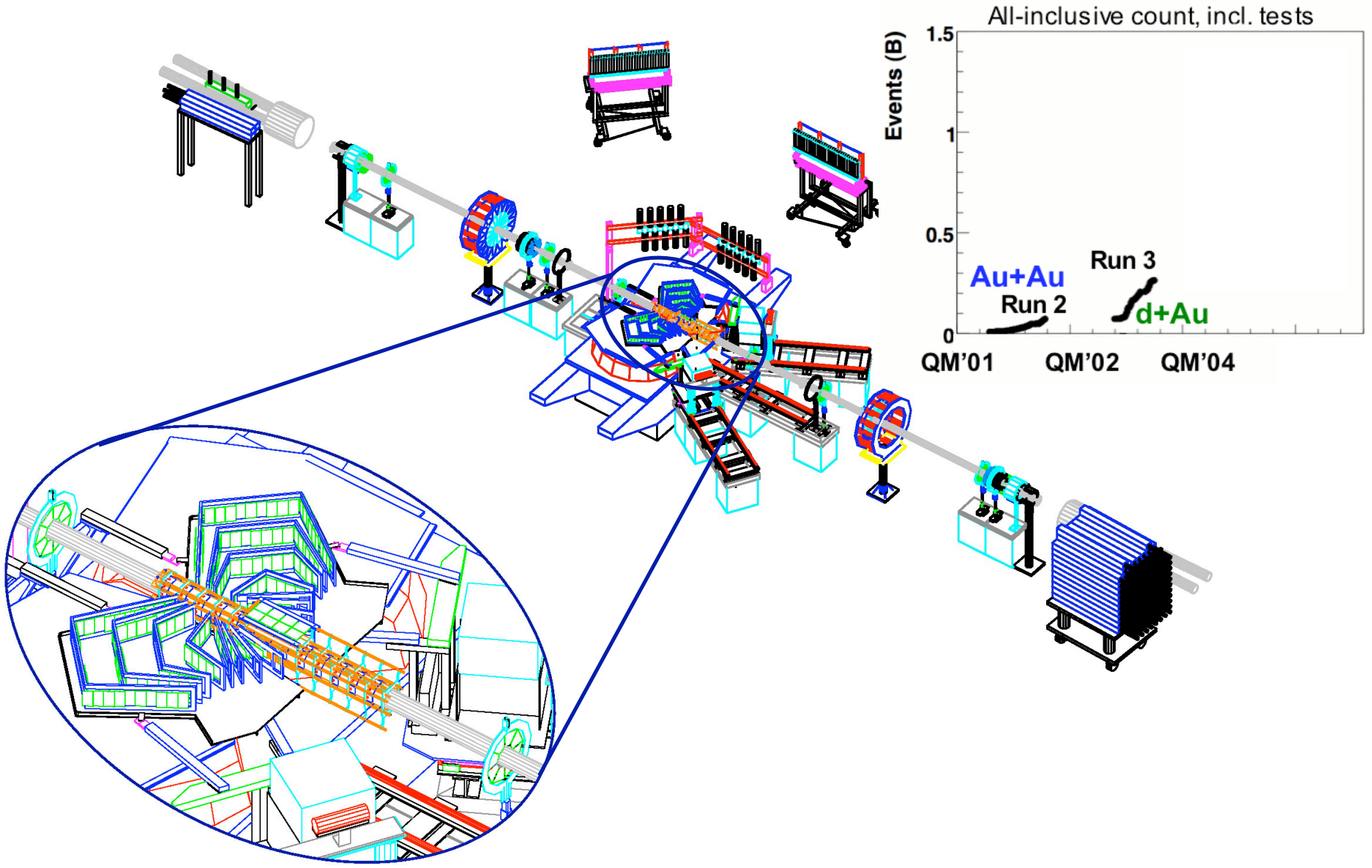
PHOBOS Experiment - Run 1



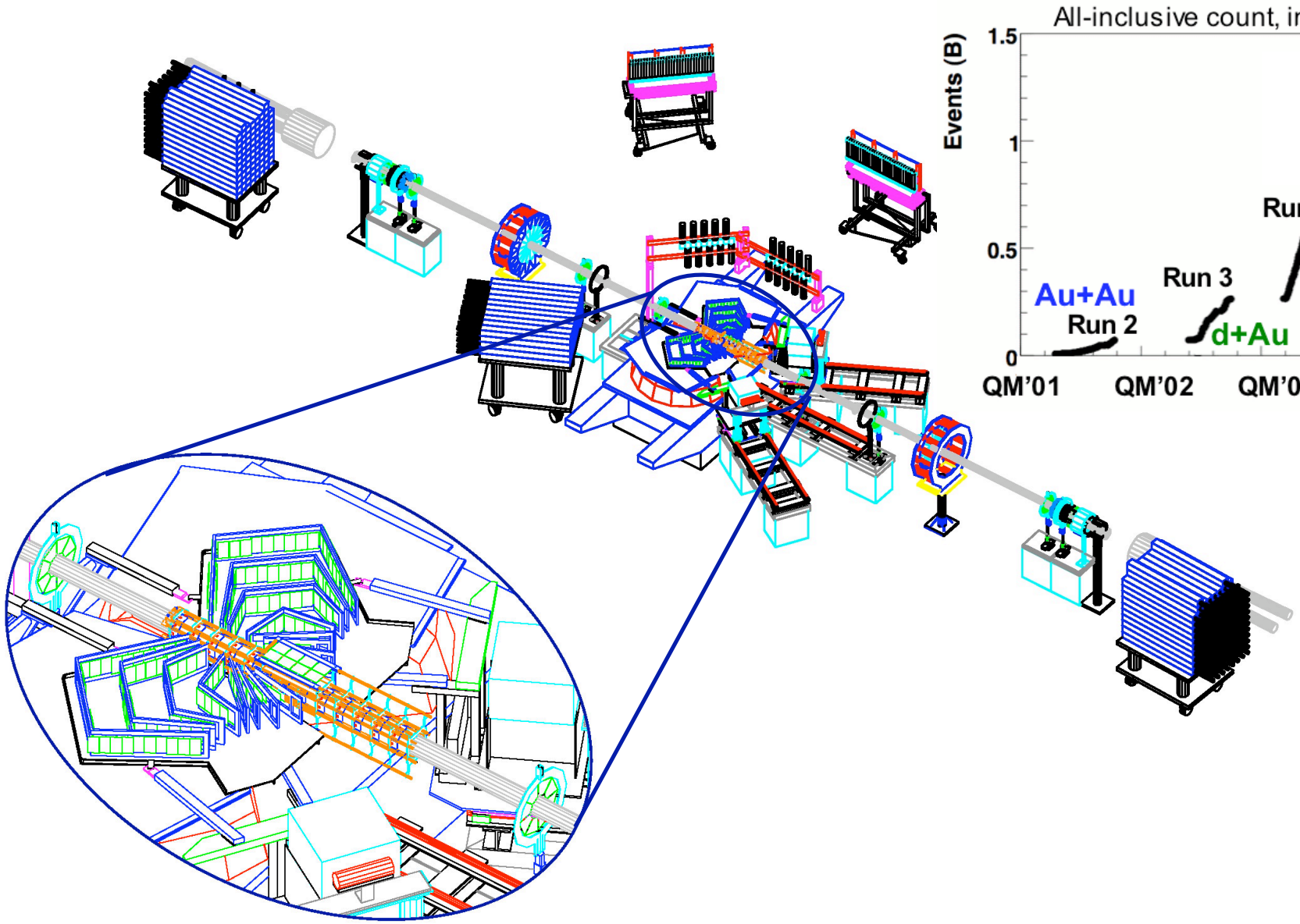
PHOBOS Experiment - Run 2



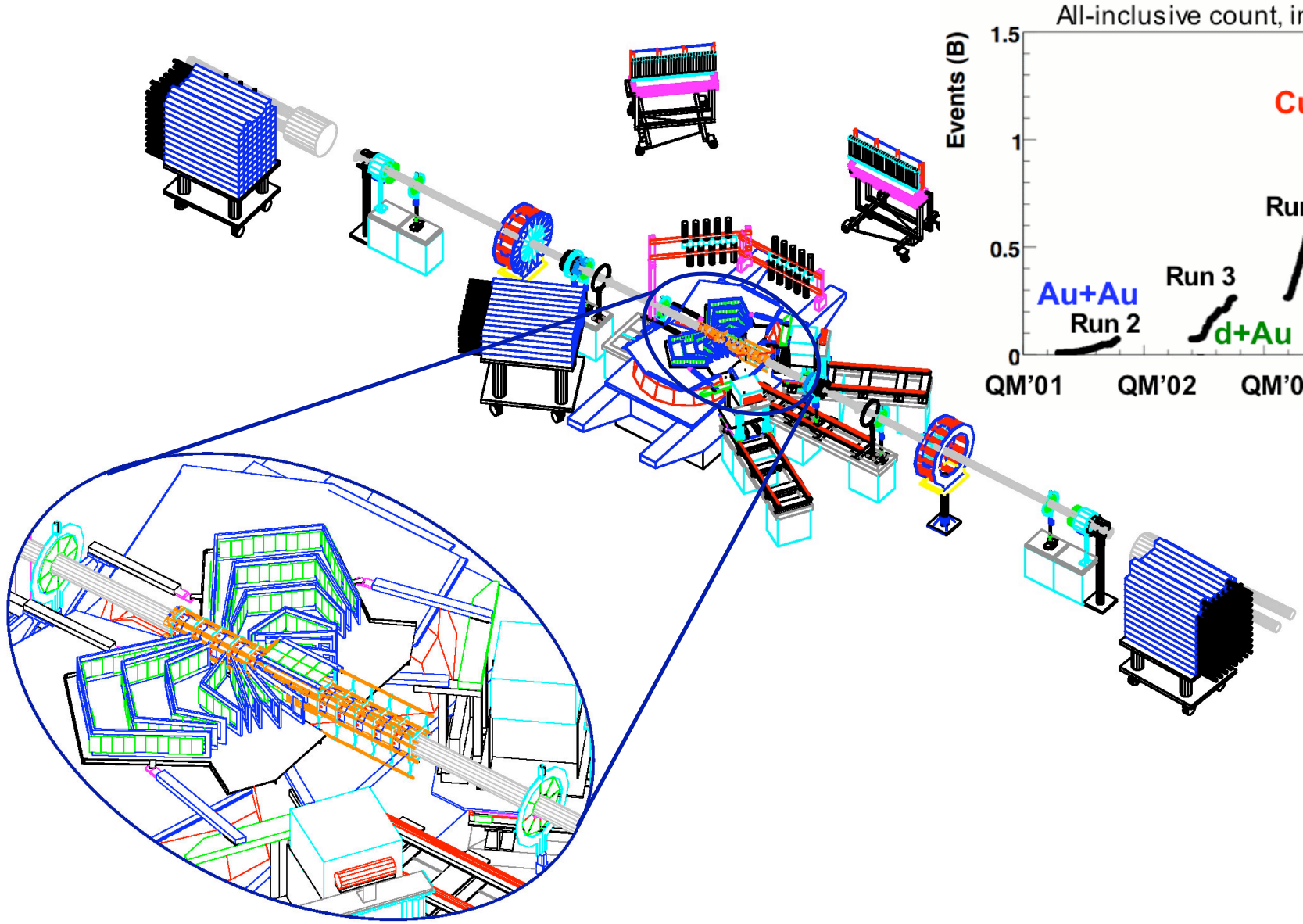
PHOBOS Experiment - Run 3



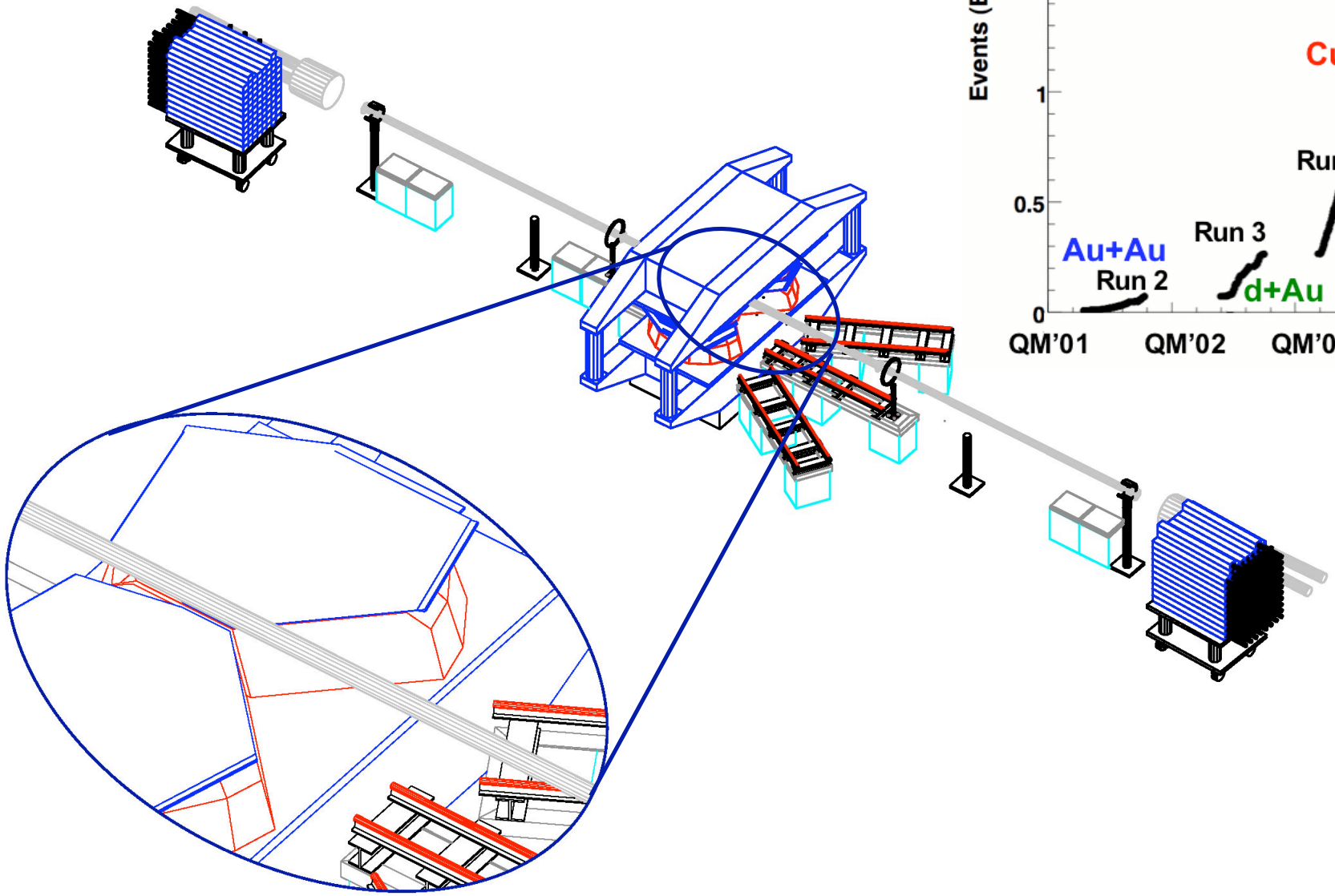
PHOBOS Experiment - Run 4



PHOBOS Experiment - Run 5



PHOBOS Experiment - Run 6



Number of Events to Tape

[in millions]

GeV \ system	p+p	d+Au	Cu+Cu	Au+Au
410	20			
200	100	150	400	250
130				4.3
62.4			110	22
55.9				1.8
22.5			20	
19.6				~1

= shown in this talk

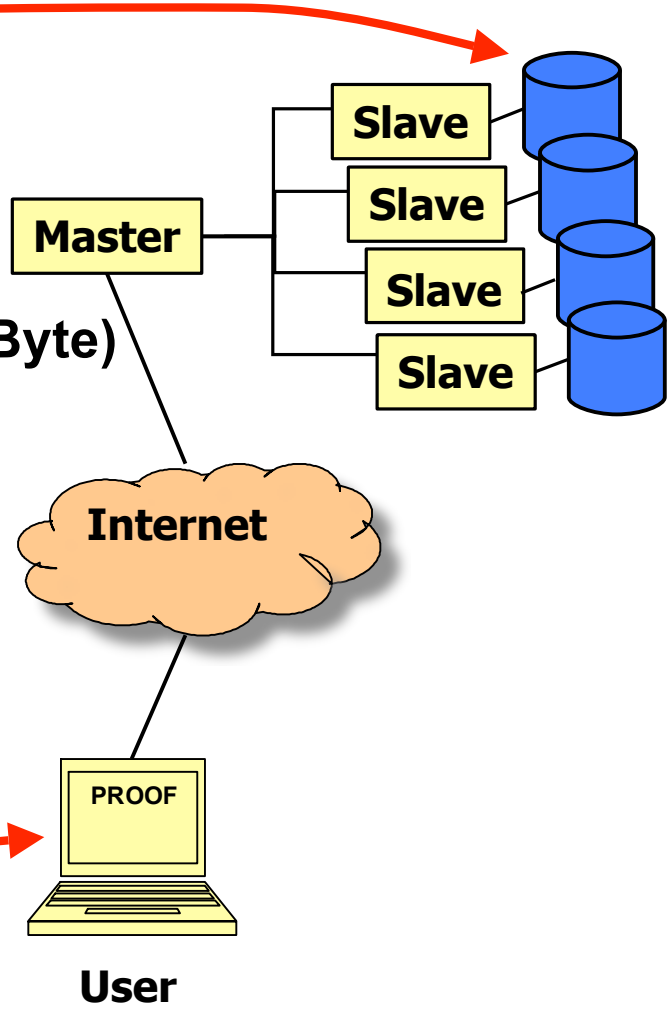
PHOBOS Computing Architecture

Distributed disks
- 100 TByte, fast access
- ALL physics data is stored on disks!

CatWeb – data management (650k files, 400 TByte)
- Easy www interface to stage HPSS→RCF
- API for access to functionality from ROOT/PhAT

AnT – Analysis Tree DST format
- ROOT Tree based, fast access to subsets of data
- Well structured, links hits to tracks etc.

PROOF – Parallel ROOT Facility
- Transparent, parallel interactive analysis,
- over x100 speed-up!
- Co-exist with regular batch usage



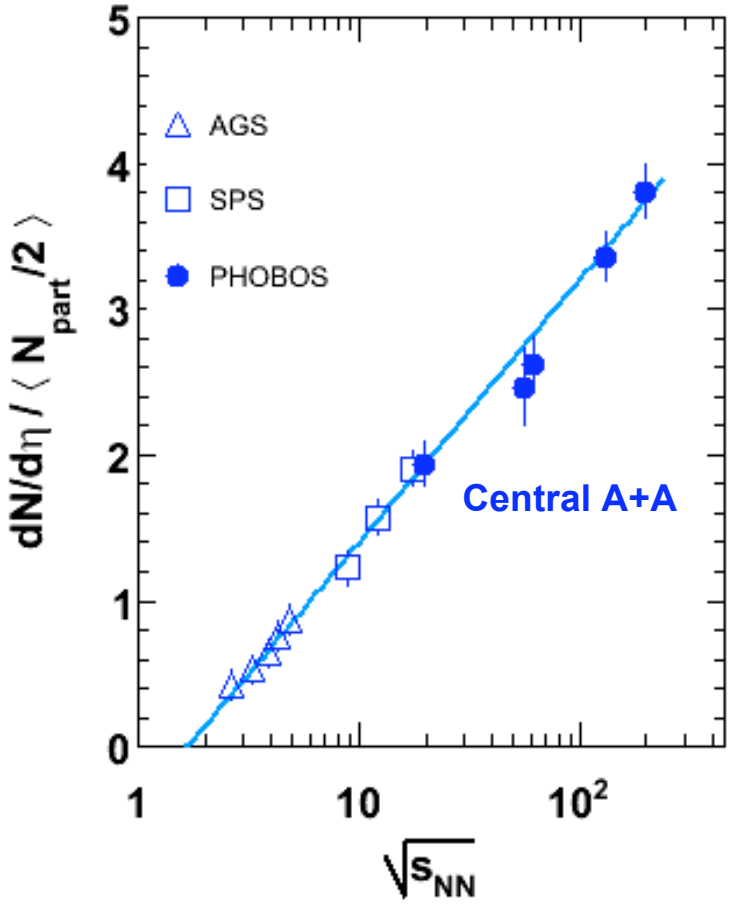
See poster by Maarten Ballintijn

Mission Statement

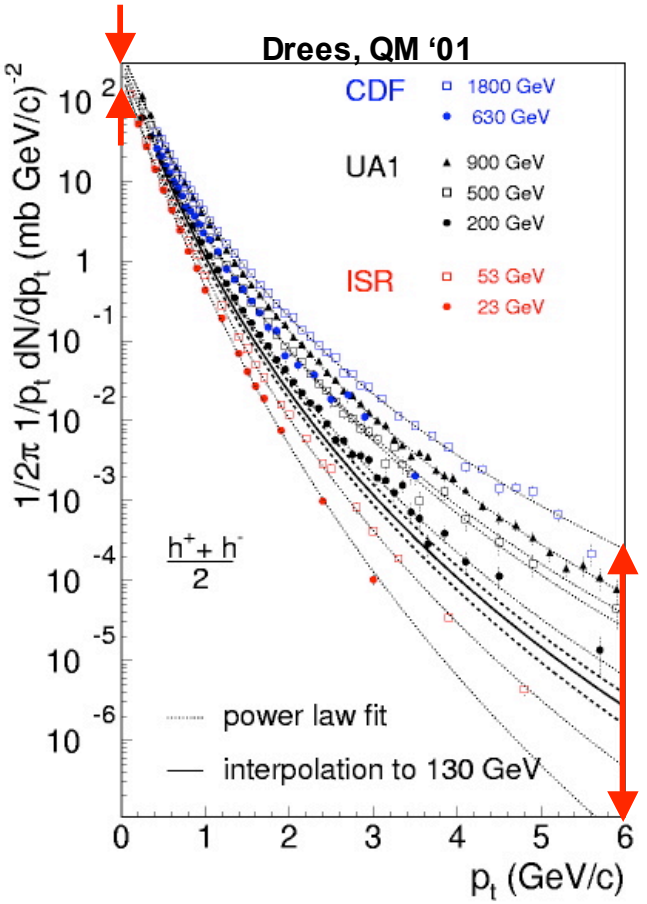
- **Systematic study of charged hadron production**
- **Search for**
  - **Organizing principles (Scaling laws, Sum rules)**
    - **Common features with elementary systems**
    - **Collective effects**

Collision Energy

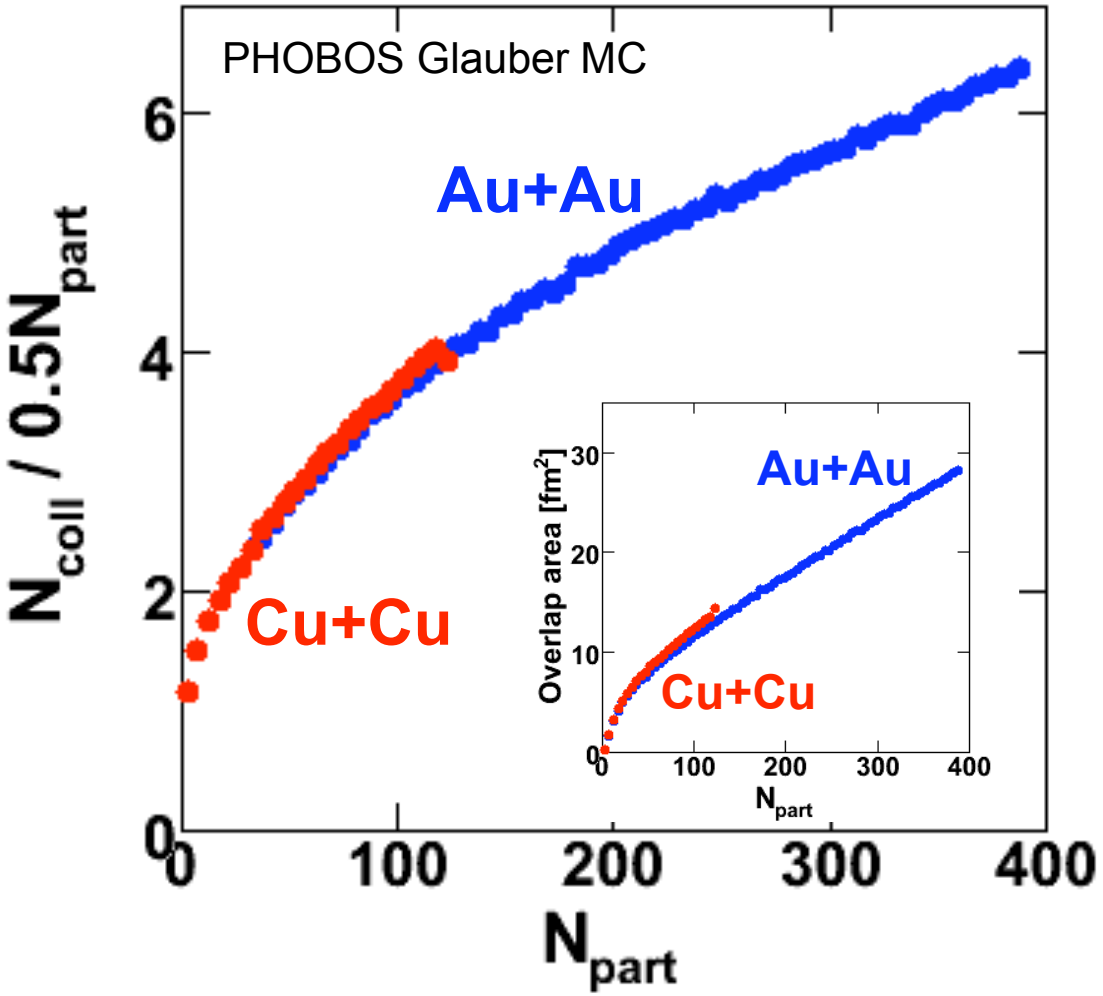
Energy Density



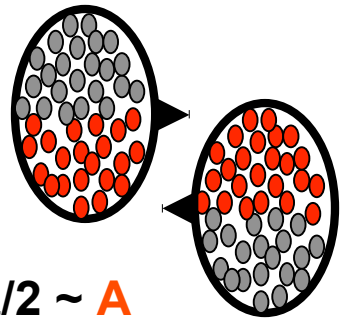
Balance of 'Hard' vs 'Soft' Particle Production



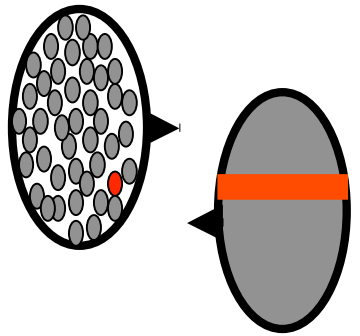
Collision Geometry



"Participants"



$N_{part}/2 \sim A$

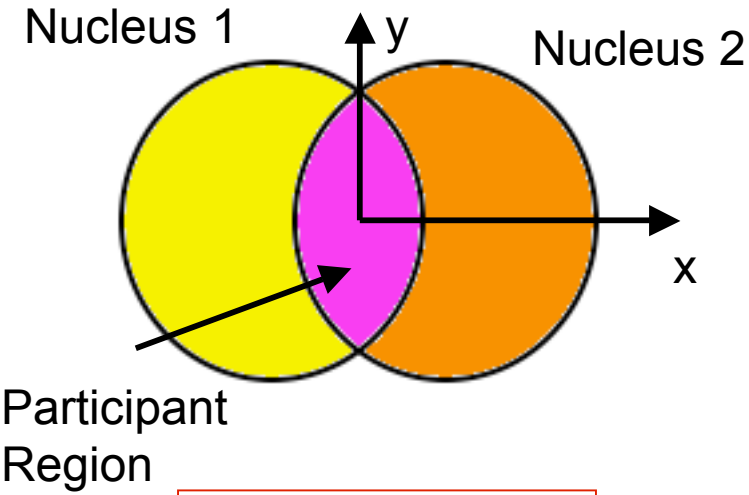


$L \sim A^{1/3}$

N_{coll} = # of NN collisions: $\sim A^{4/3}$

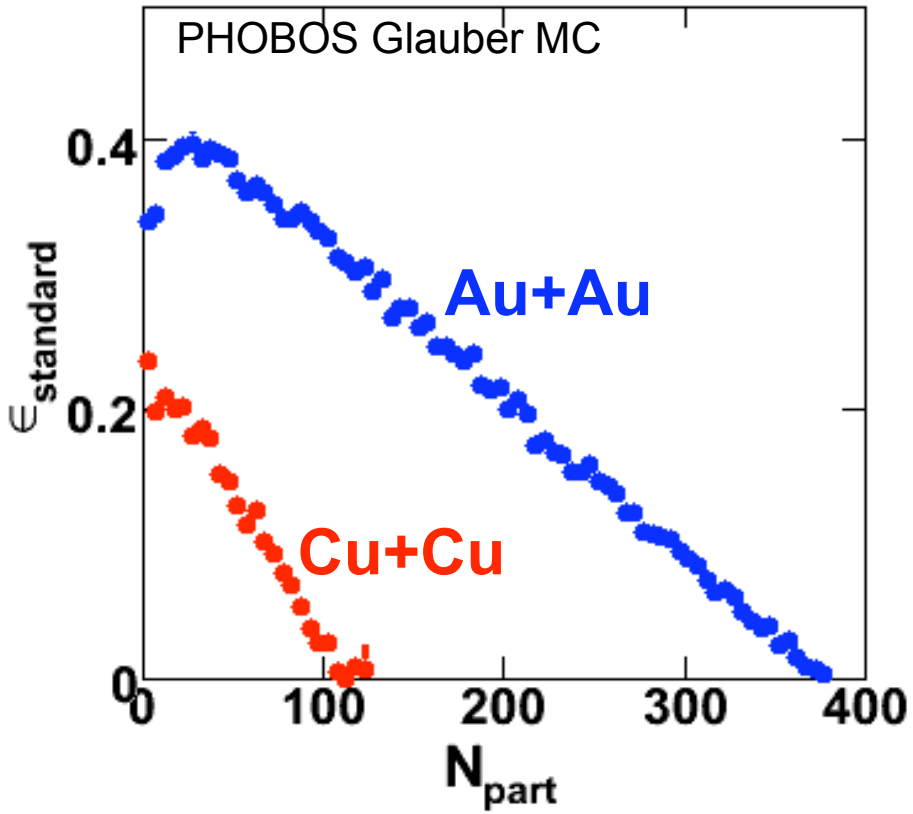
"Collisions"

Transverse Geometry



$$\varepsilon = \frac{\sigma_y^{\,2} - \sigma_x^{\,2}}{\sigma_y^{\,2} + \sigma_x^{\,2}}$$

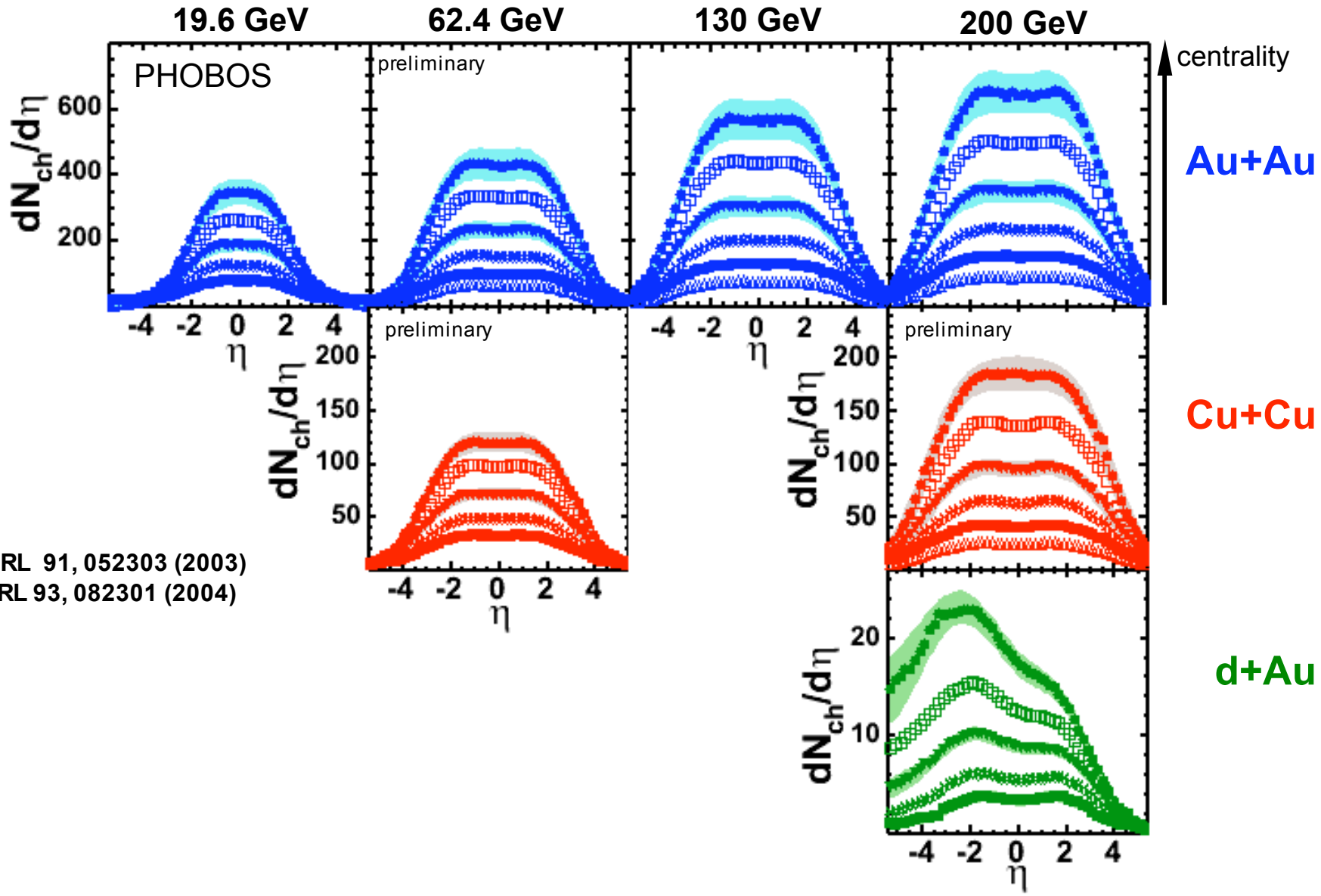
wrt reaction plane



- **Au+Au vs Cu+Cu**
  - **Interplay of initial geometry and initial density**
  - **Test ideas of early thermalization and collectivity**

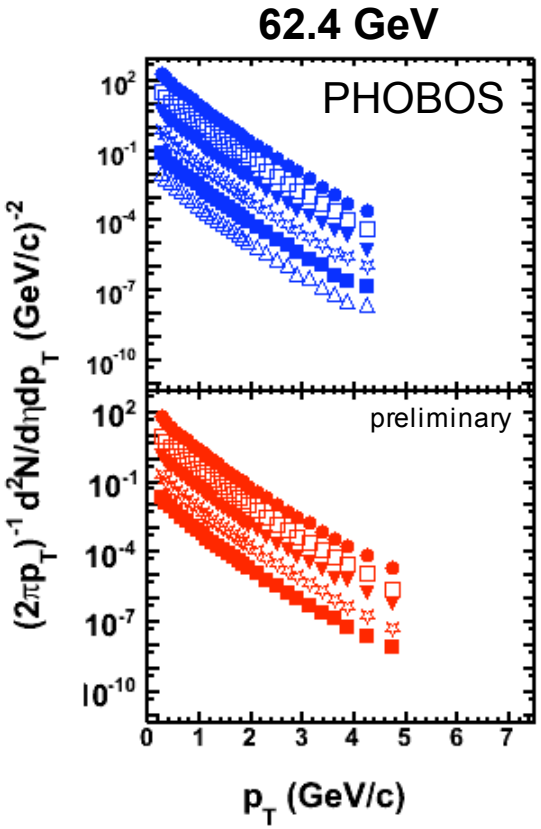
PHOBOS Data

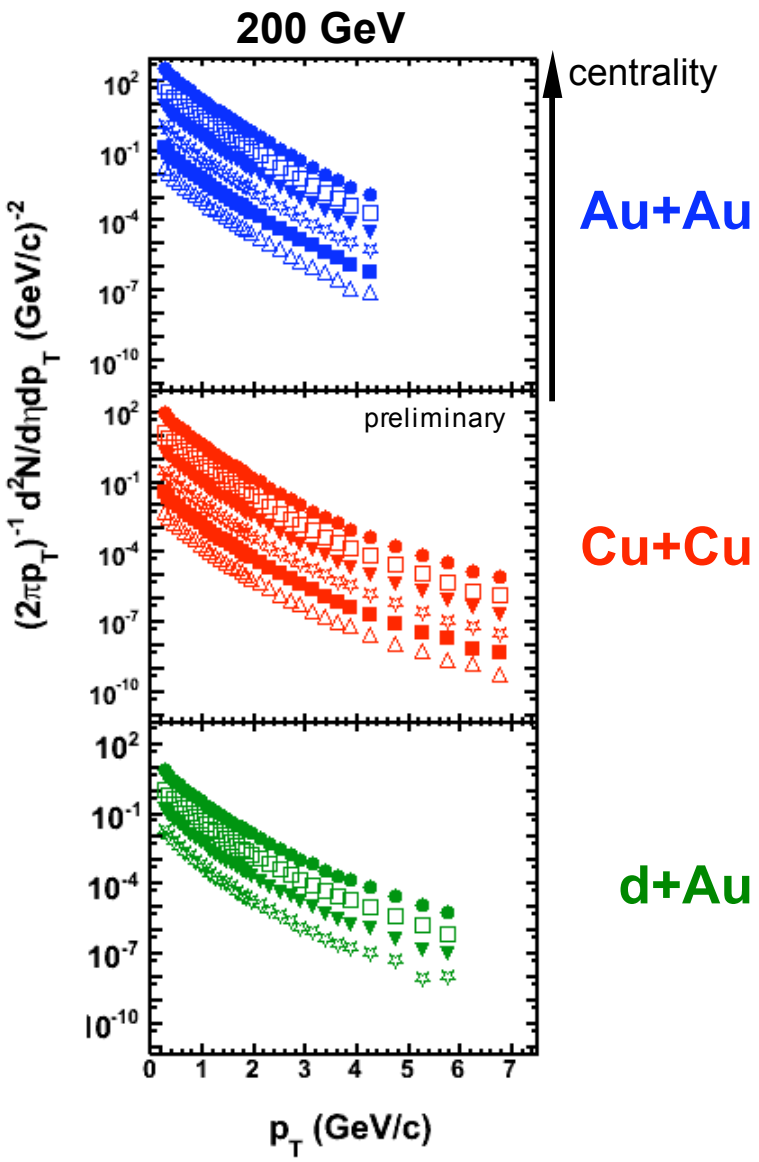
Charged Hadron dN/dη



Au+Au : PRL 91, 052303 (2003)
d+Au : PRL 93, 082301 (2004)

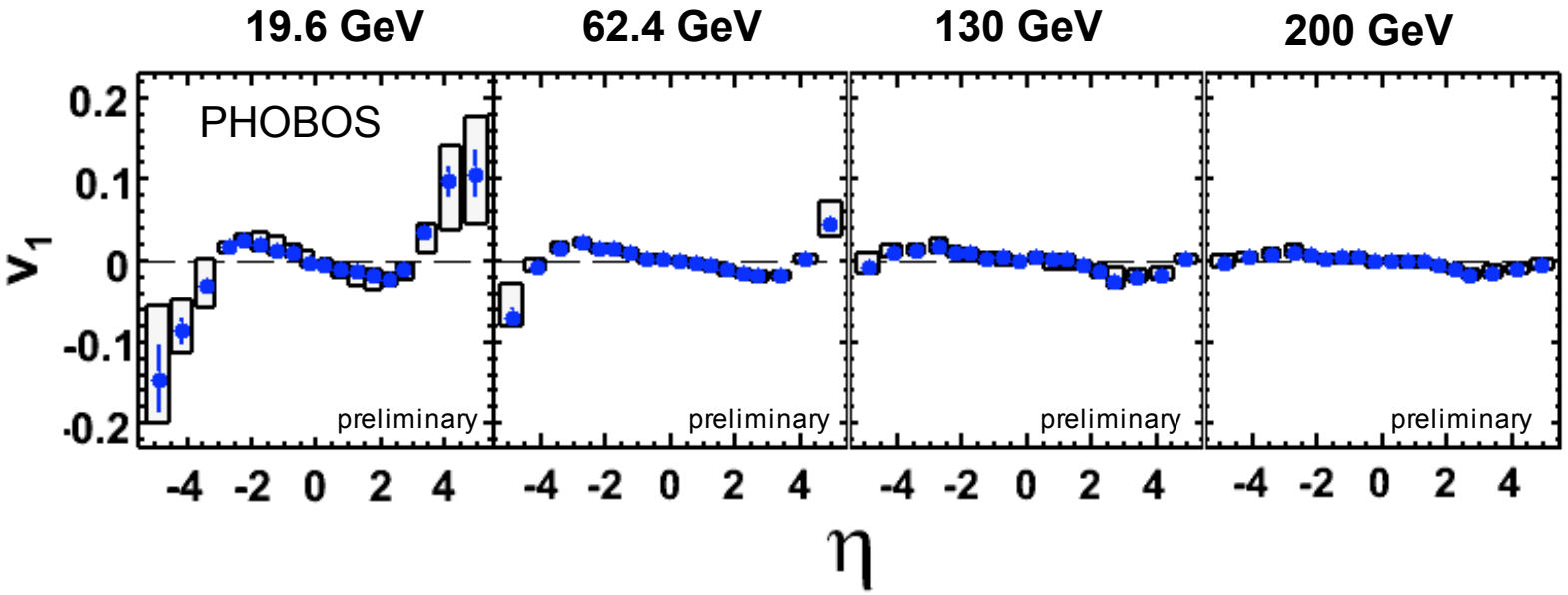
Charged Hadron p_T Spectra





Au+Au: PRL 94, 082304 (2005),
PLB 578, 297 (2004)
d+Au: Phys. Rev. Lett. 91, 072302 (2003)

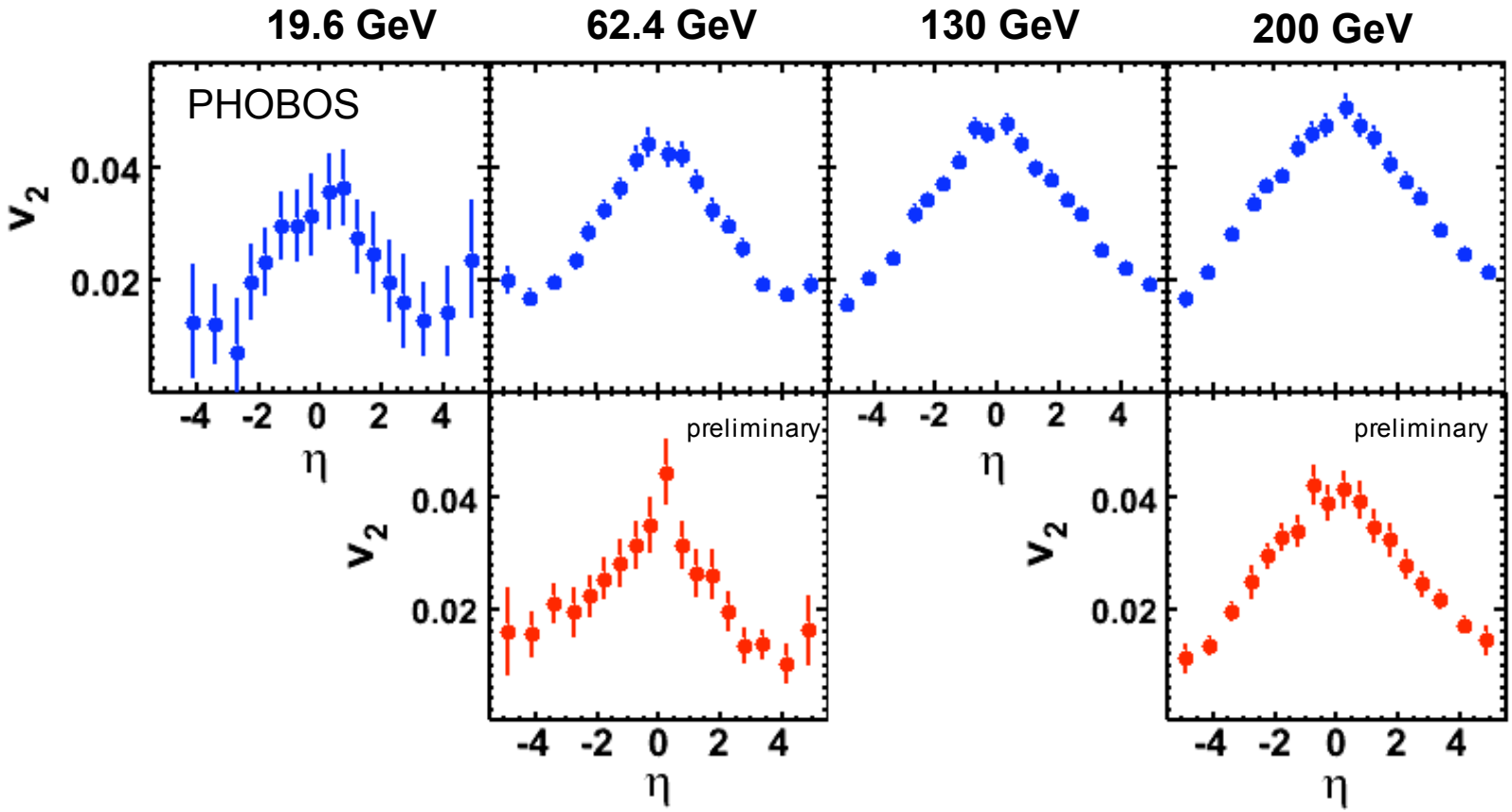
Directed Flow



Au+Au

See poster by Alice Mignerey

Elliptic Flow



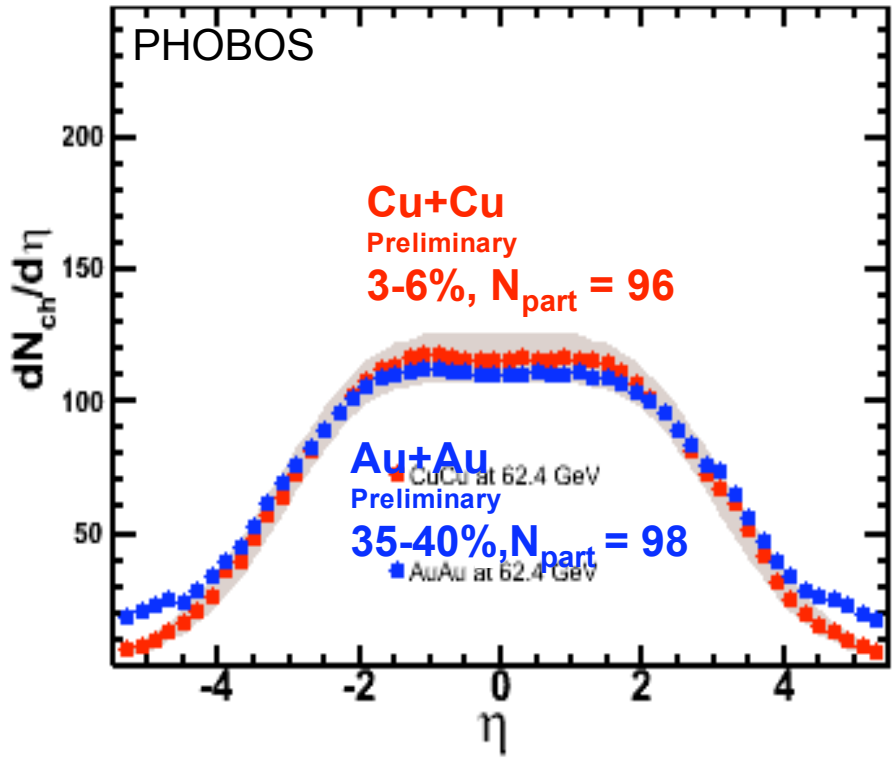
Au+Au: PRL 94 122303 (2005)

Yields in Cu+Cu vs Au+Au

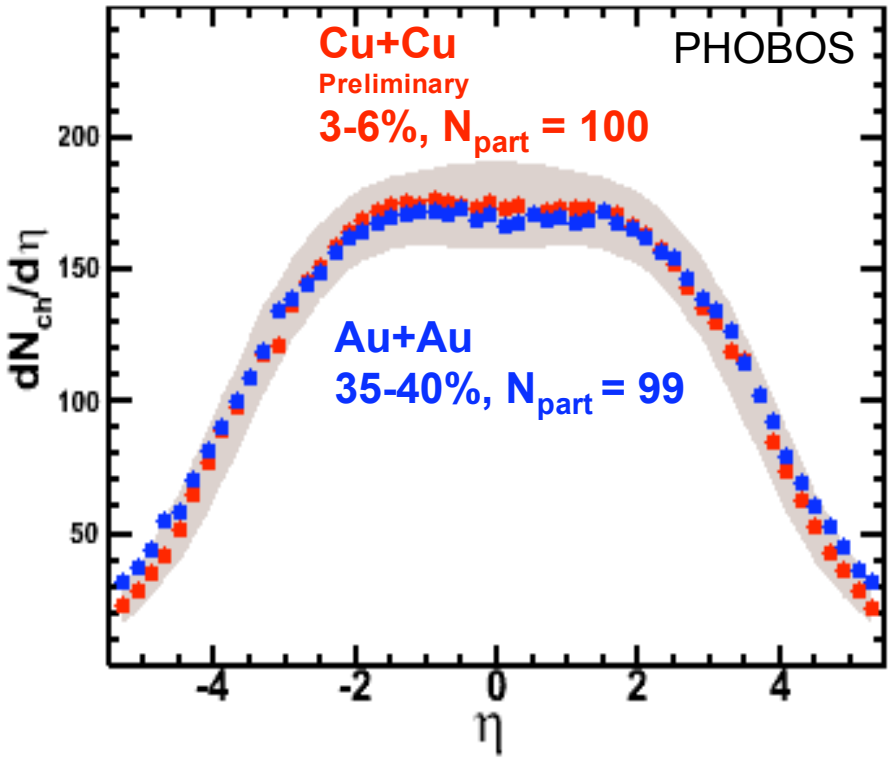
Q: How does charged hadron production in Cu+Cu compare to Au+Au?

dN/dη in Cu+Cu vs Au+Au

62.4 GeV



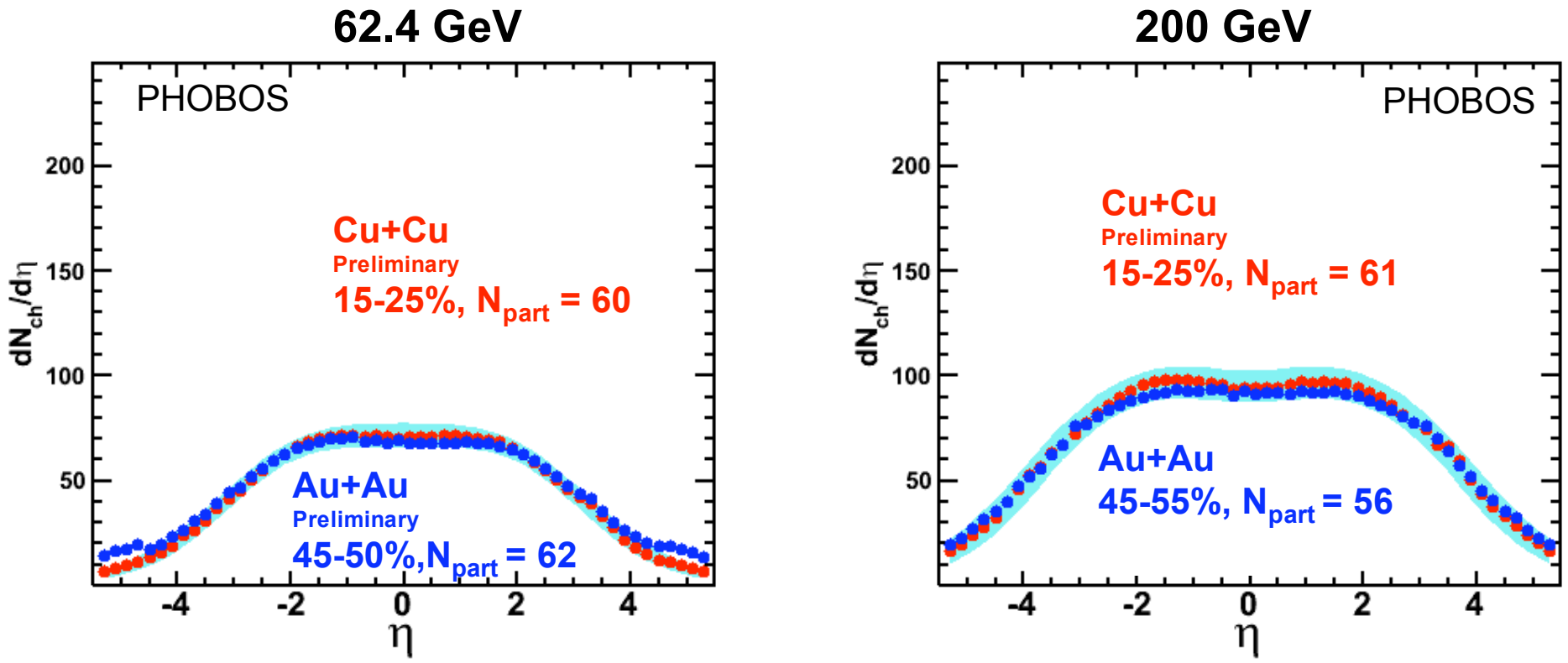
200 GeV



Unscaled dN/dη very similar for Au+Au and Cu+Cu at same N_{part}

See poster by Richard Hollis

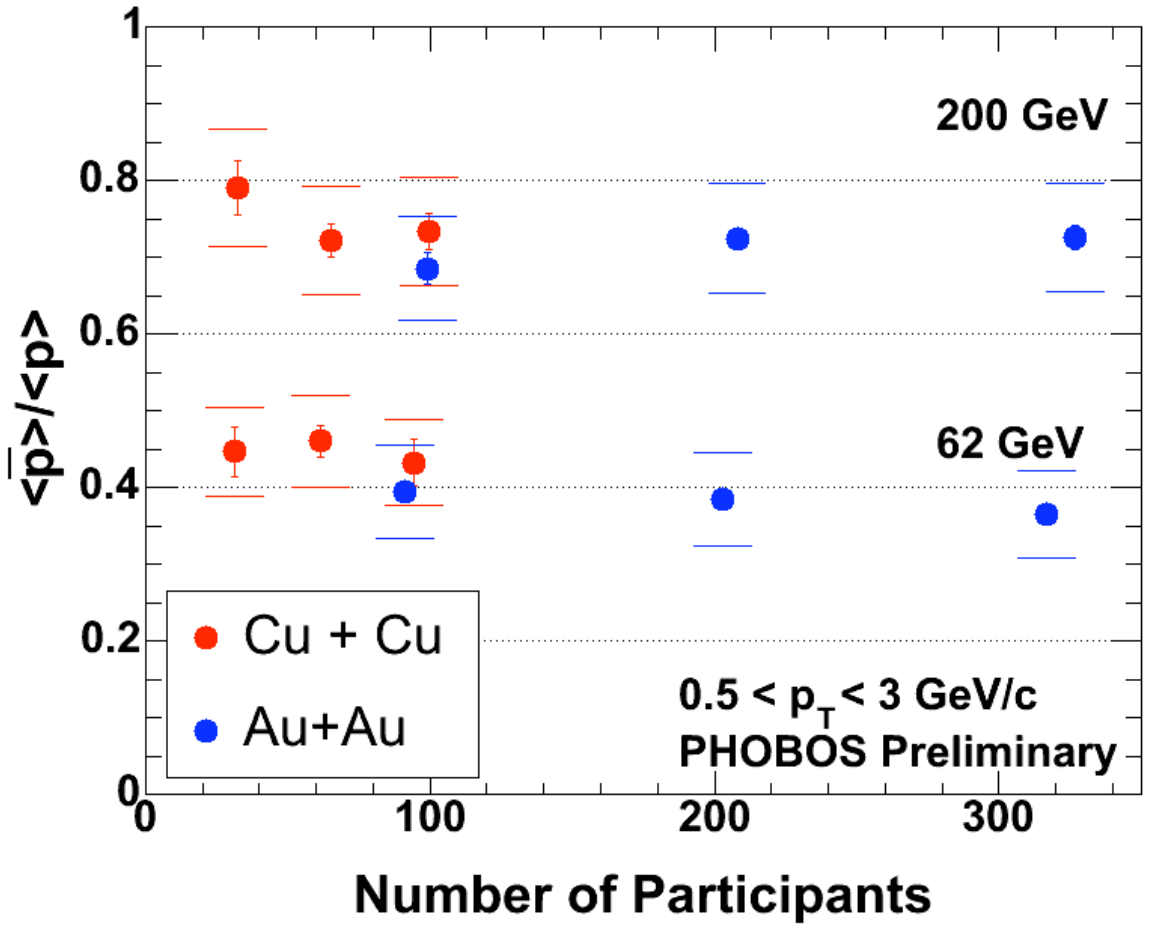
dN/dη in Cu+Cu vs Au+Au



Also true for mid-central Cu+Cu vs peripheral Au+Au

Unscaled dN/dη very similar for Au+Au and Cu+Cu at same N_{part}

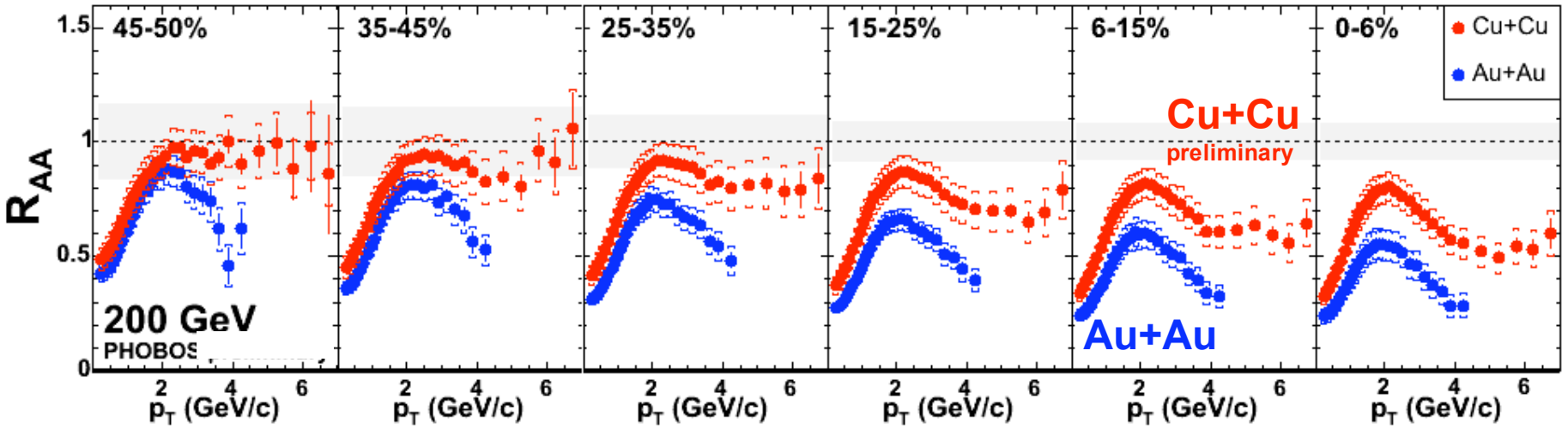
Anti-proton/proton ratio



$\bar{p}/p$ ratio very similar in Cu+Cu and Au+Au

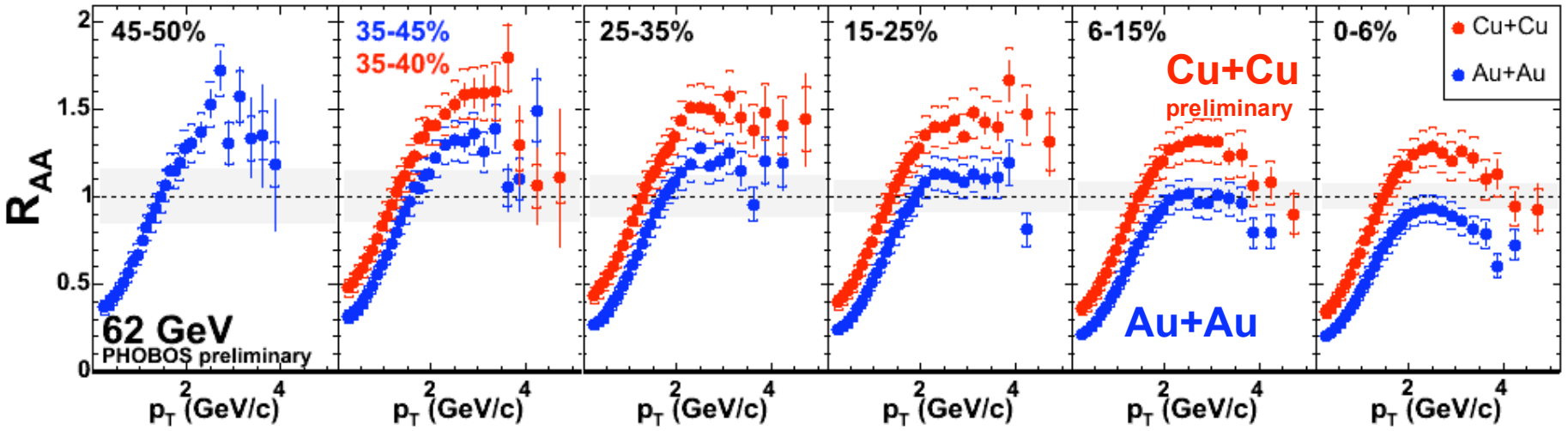
See poster by Vasu Chetluru

Particle Production vs p_T

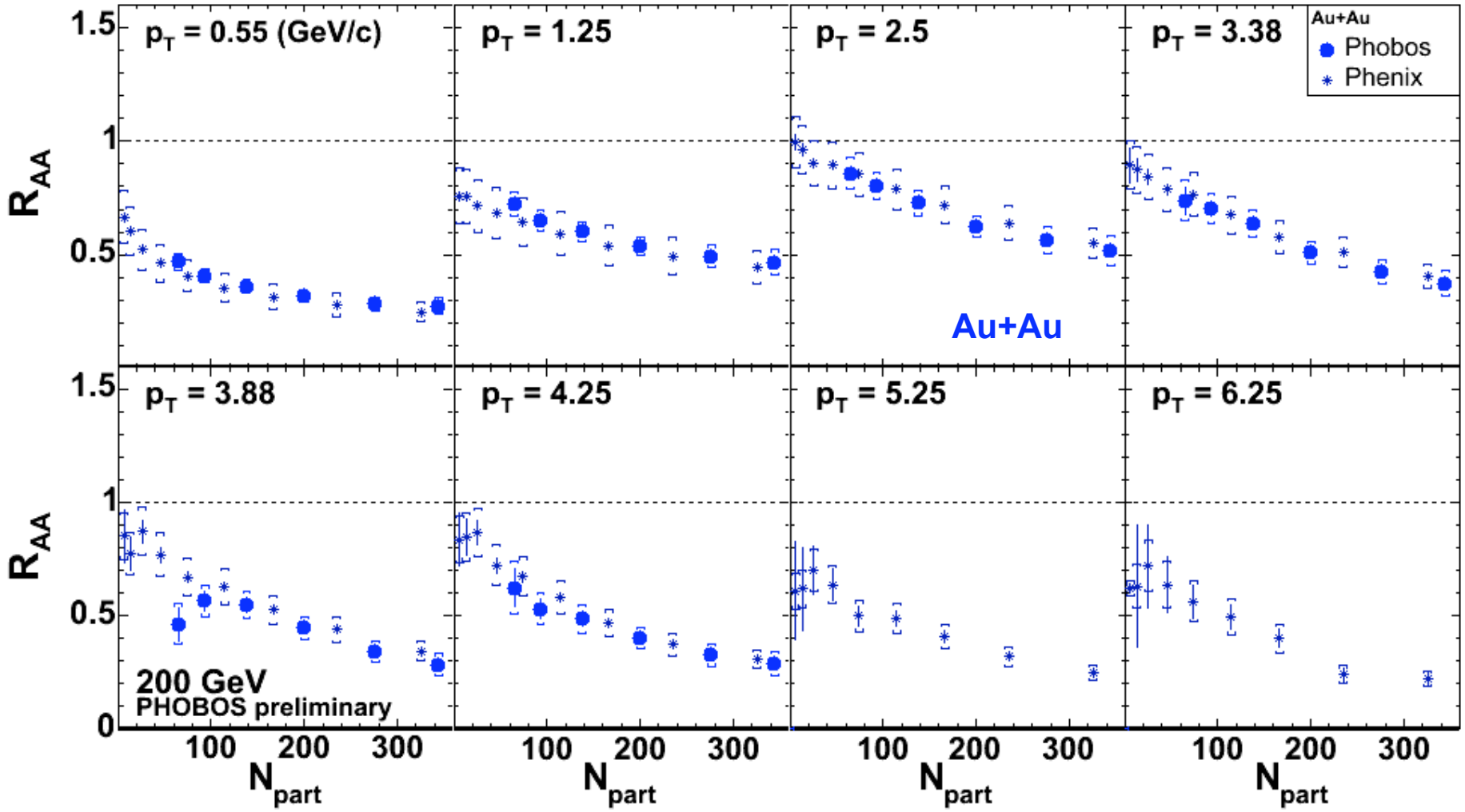


Charged hadron R_{AA} 200 GeV 63 GeV

Au+Au: PRL 94, 082304 (2005), PLB 578, 297 (2004)



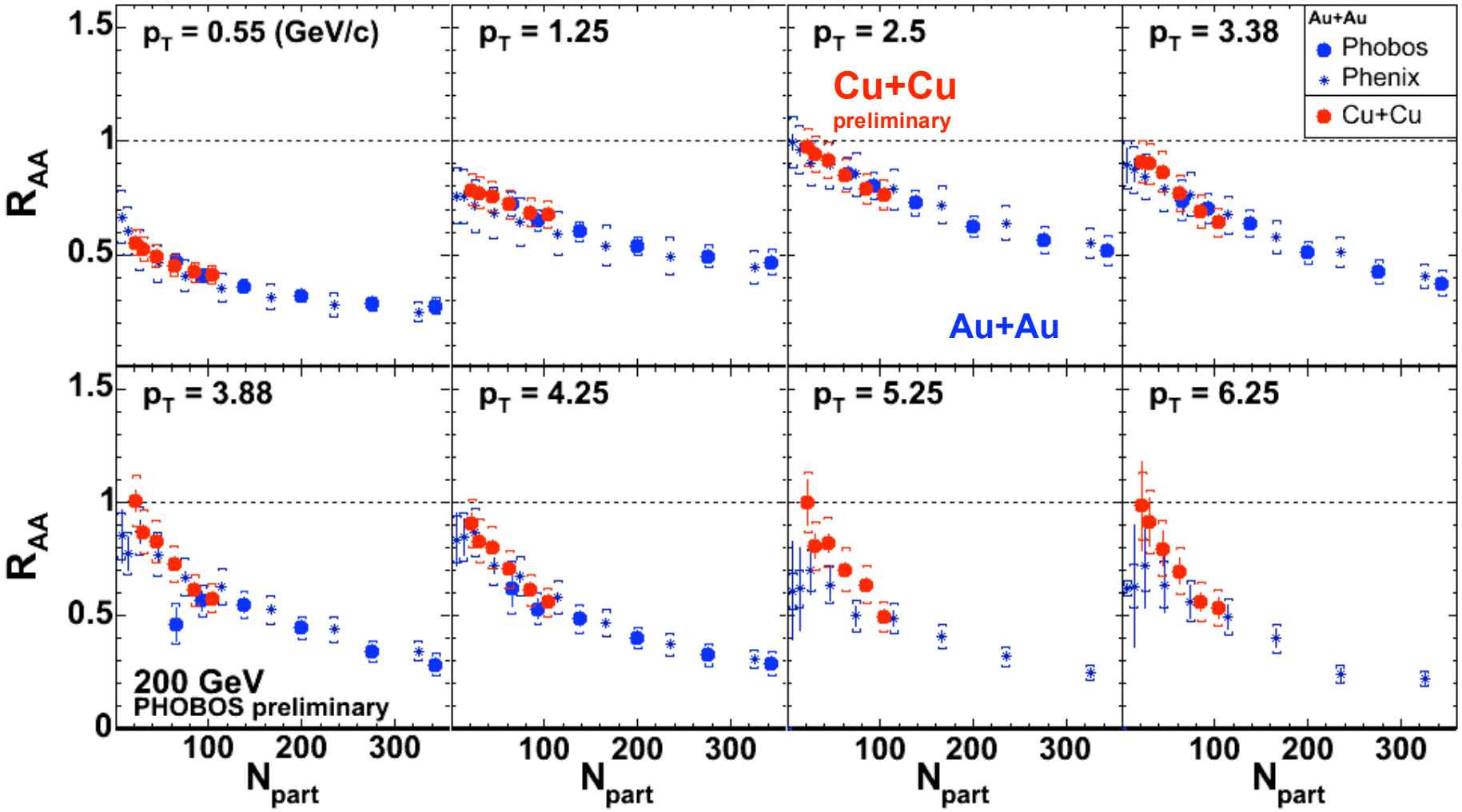
Yields vs N_{part}, 200 GeV



Au+Au: PRL 94, 082304 (2005), PLB 578, 297 (2004)

See poster by Gerrit van Nieuwenhuizen

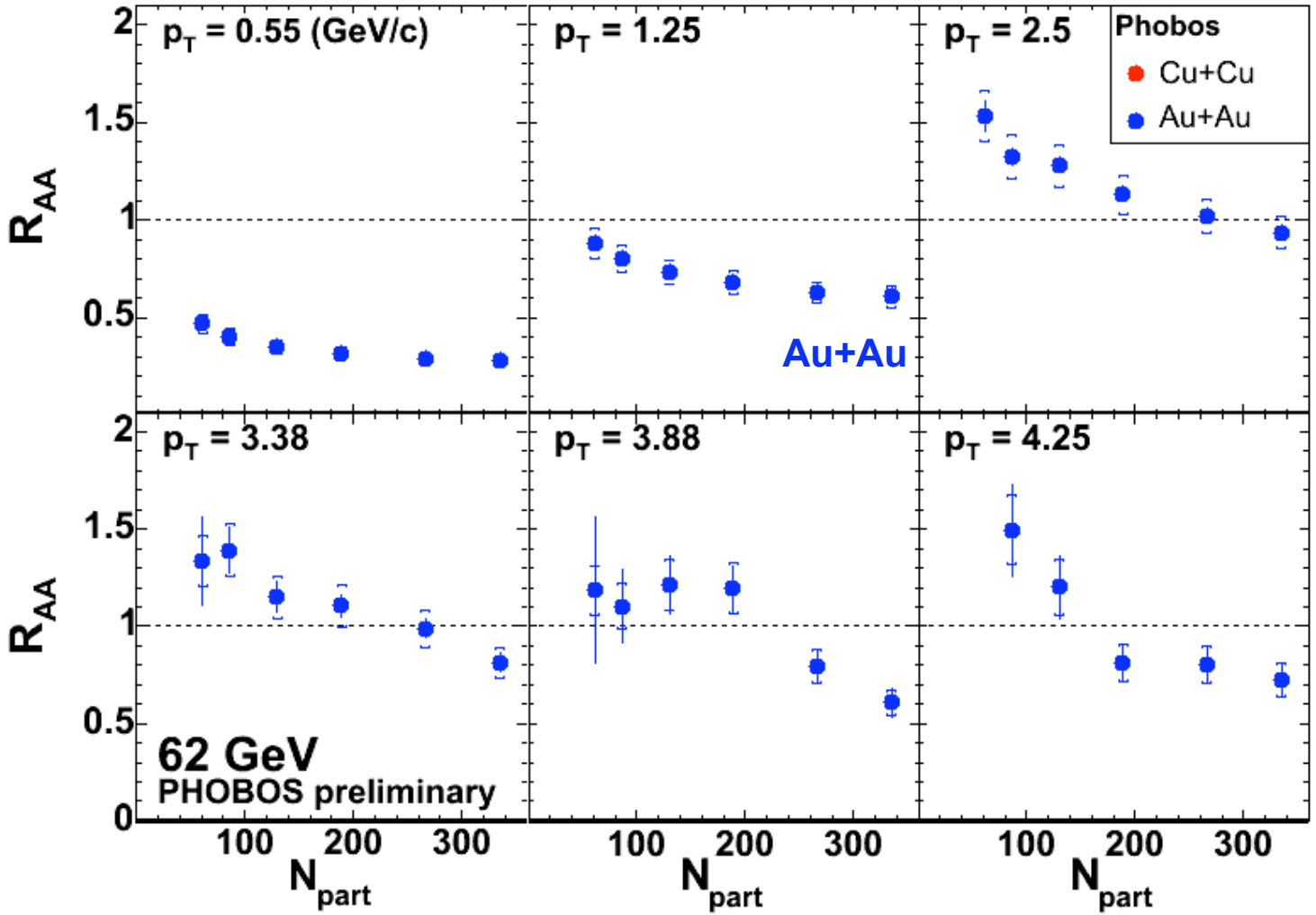
Yields vs N_{part}, 200 GeV



Au+Au: PRL 94, 082304 (2005), PLB 578, 297 (2004)

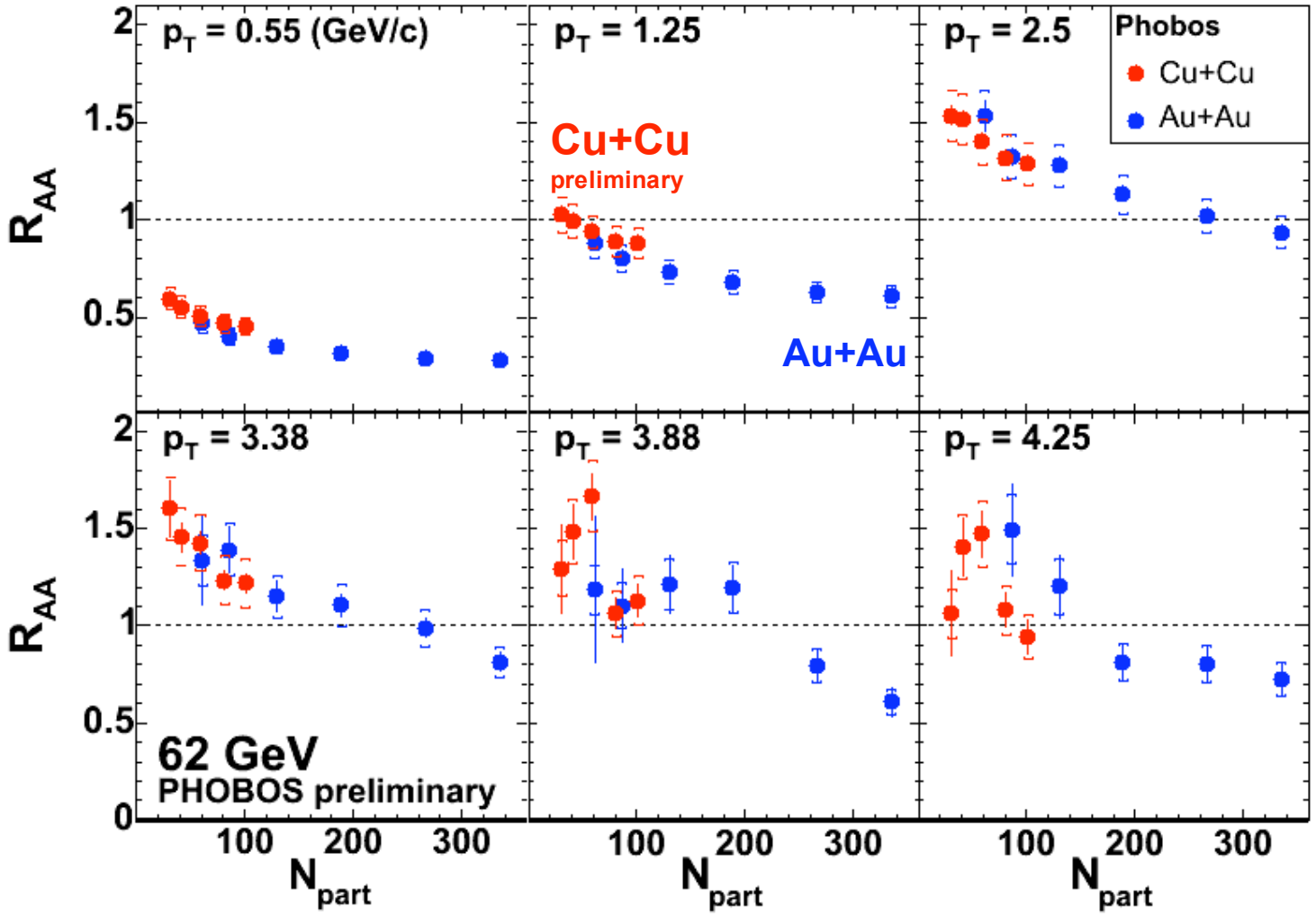
See poster by Gerrit van Nieuwenhuizen

Yields vs N_{part}, 62 GeV



Au+Au: PRL 94, 082304 (2005)

Yields vs N_{part}, 62 GeV



Au+Au: PRL 94, 082304 (2005)

Yields in Cu+Cu vs Au+Au

Q: How does charged hadron production in Cu+Cu compare to Au+Au?

A: For same system size (N_{part}, N_{coll}), Cu+Cu and Au+Au are very similar:

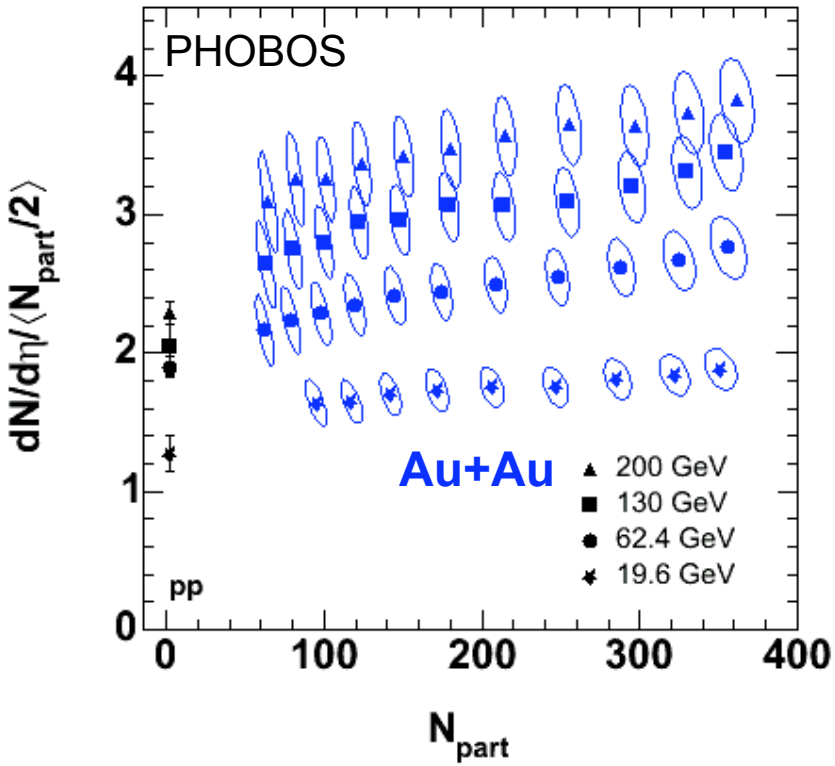
- **Total multiplicity**
- **Mid-rapidity $dN/d\eta$**
- **$\bar{p}/p$**
- **$dN/d\eta$ vs η**
- **dN/dp_T (R_{AA})**

Geometry and Energy

Q: What is the interplay between collision centrality (geometry) and collision energy?

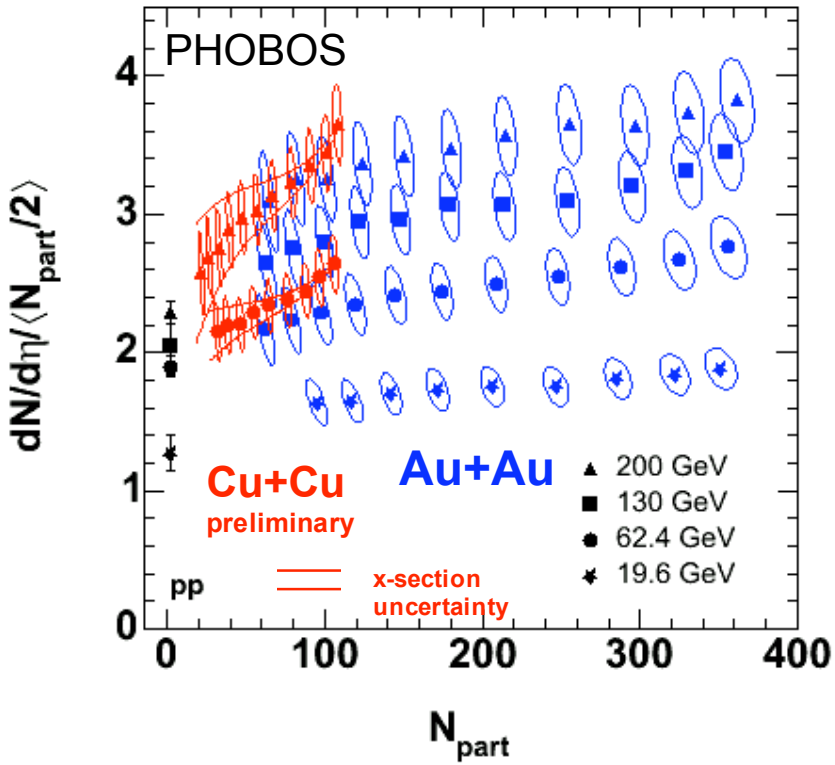
⟶ Balance of hard/soft processes

Energy/Centrality Factorization

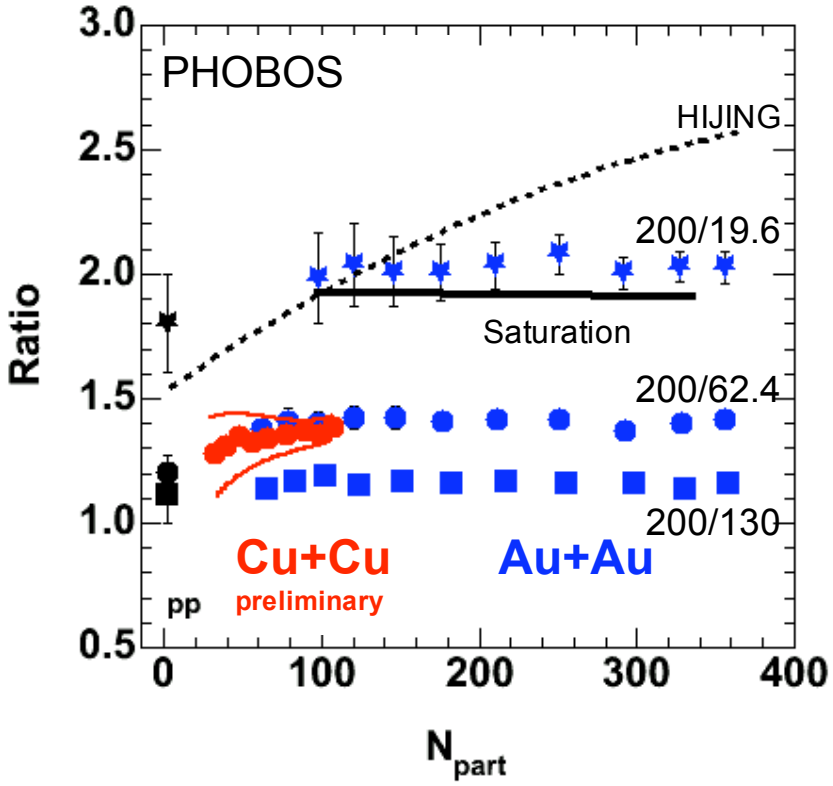


Au+Au: Phys. Rev. C70, 021902(R) (2004) + prel. 62.4 GeV

Energy/Centrality Factorization



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



Factorization of energy and centrality dependence

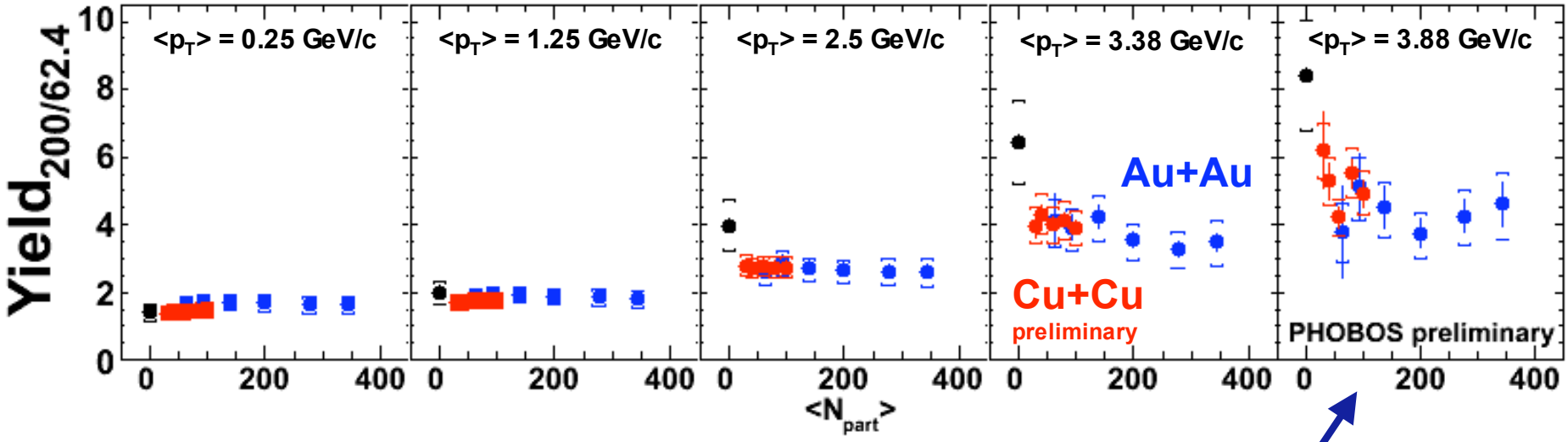
Initial state effect?

Au+Au: Phys. Rev. C70, 021902(R) (2004) + prel. 62.4 GeV

c.f. Armesto, Salgado, Wiedemann hep-ph/0407018

Factorization in p_T, I

Ratio of charged hadron yields in 200 GeV to 62 GeV

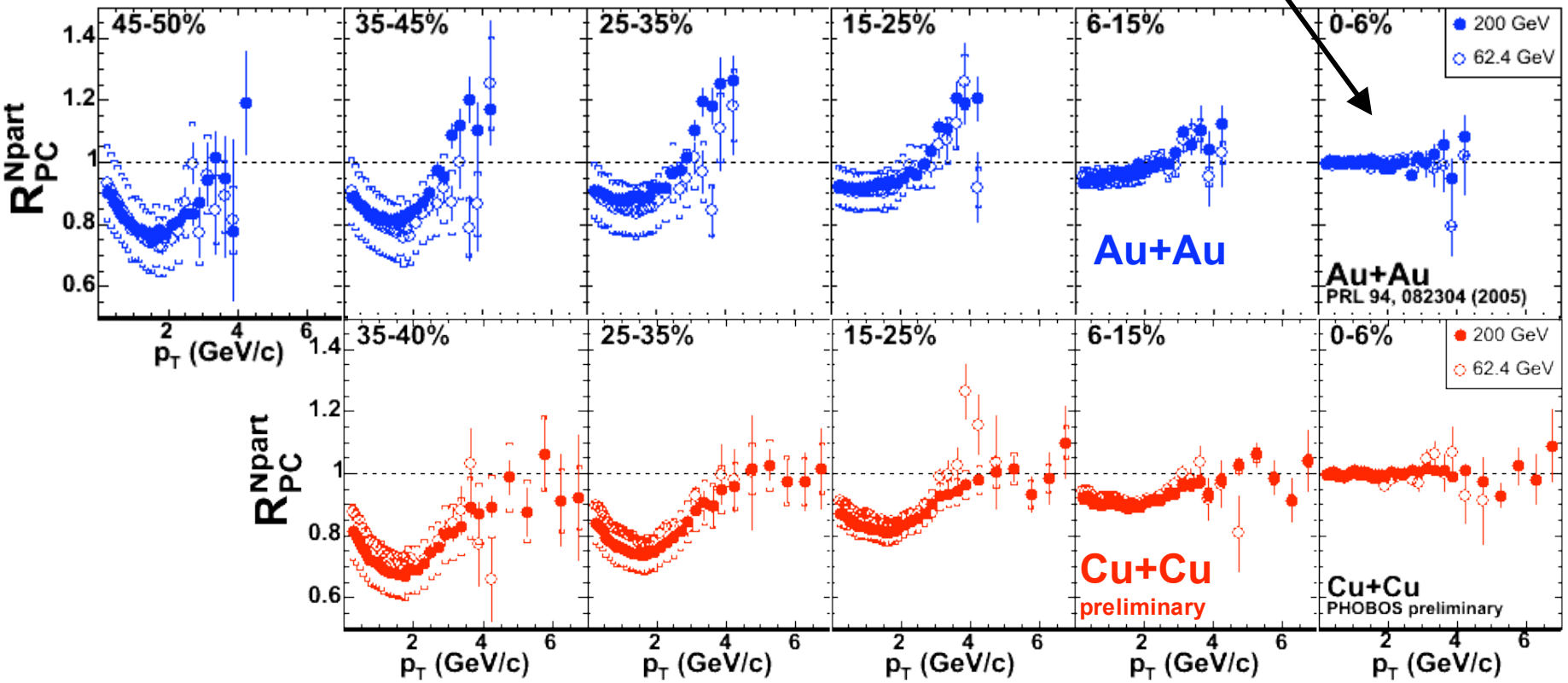


Energy/centrality factorization up to $p_T \approx 4$ GeV/c for $N_{part} > 40$

Au+Au: PRL 94, 082304 (2005)

Factorization in p_T, II

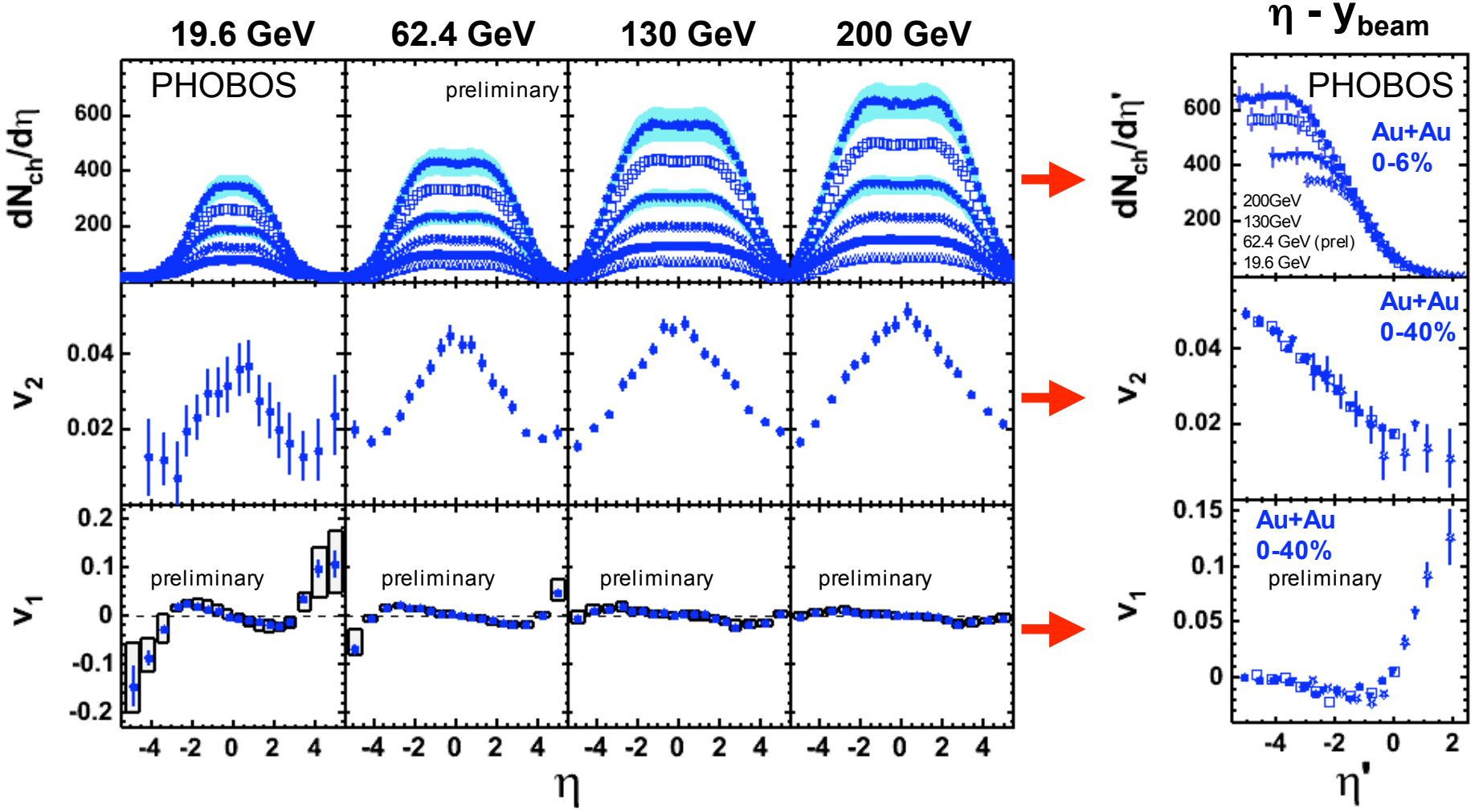
Normalized for central events



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

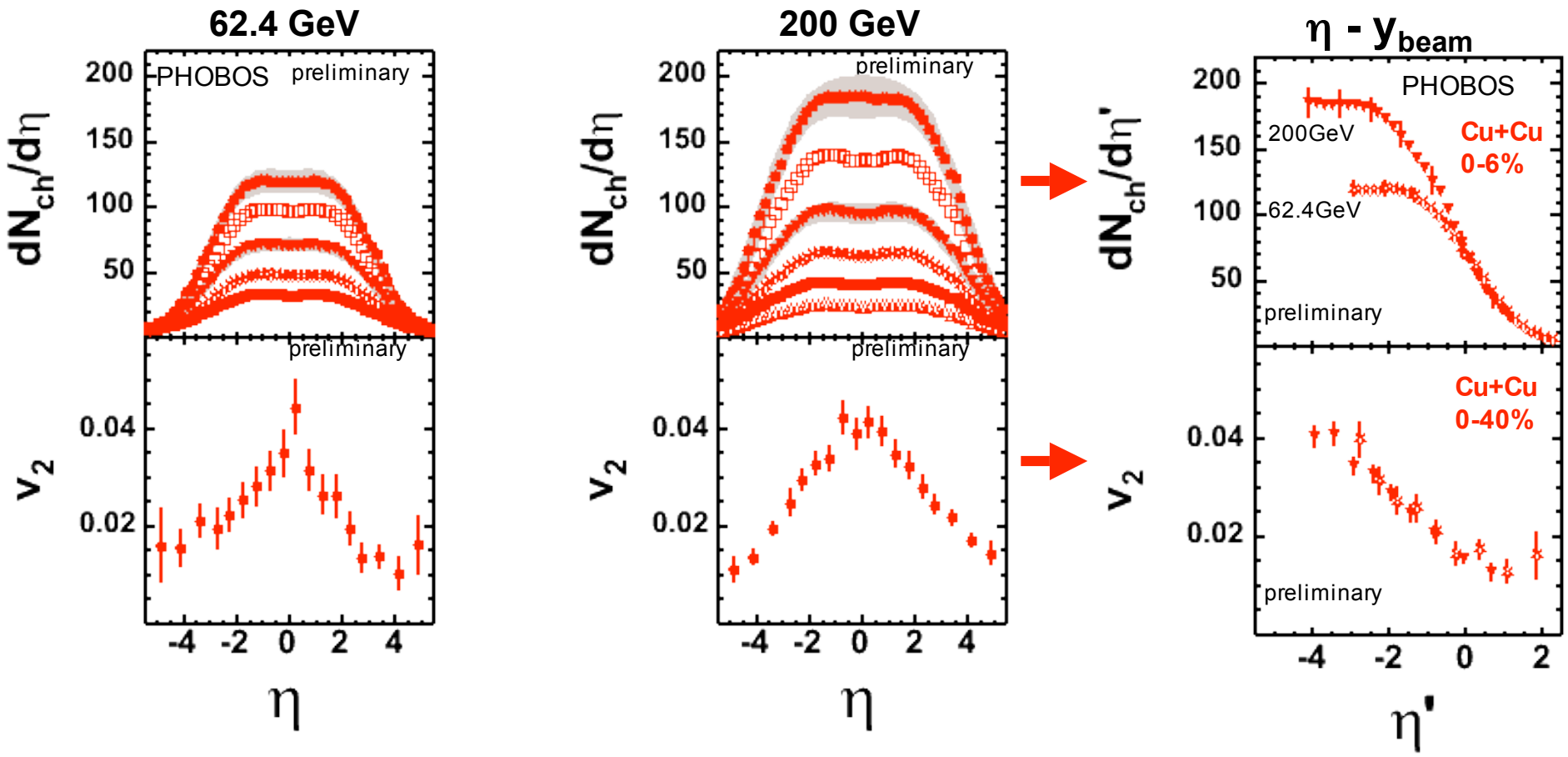
Au+Au: PRL 94, 082304 (2005)

Limiting Fragmentation (Au+Au)



"Extended Longitudinal Scaling" of all longitudinal distributions

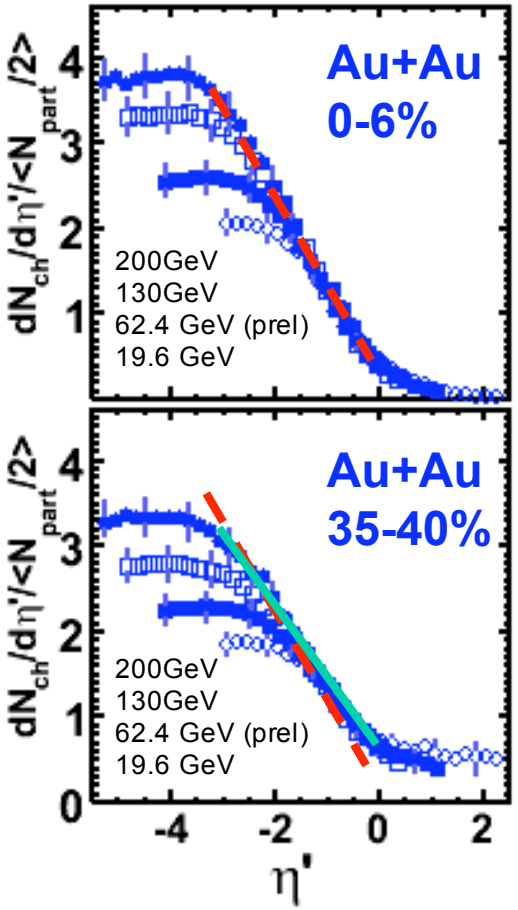
Limiting Fragmentation (Cu+Cu)

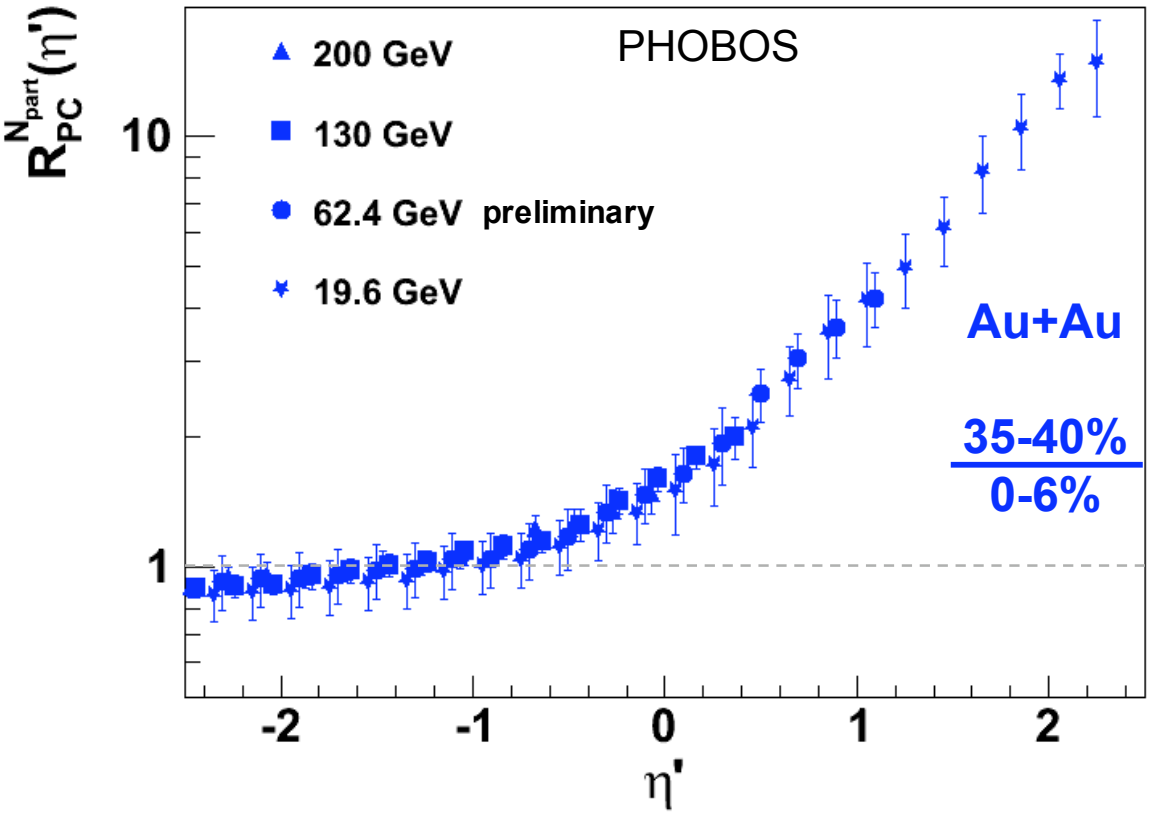


'Extended Longitudinal Scaling' also seen in Cu+Cu
Persists from p+p to Au+Au over large range in η'

$R_{PC}^{N_{part}}$ is energy independent

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





Geometry and Energy

Q: What is the interplay between collision centrality (geometry) and collision energy?

→ **Balance of hard/soft processes**

A: Factorization of geometry and energy dependence is observed:

- N_{part} scaling
- $dN/d\eta$ @ $\eta=0$
- Limiting fragmentation
- p_T spectra

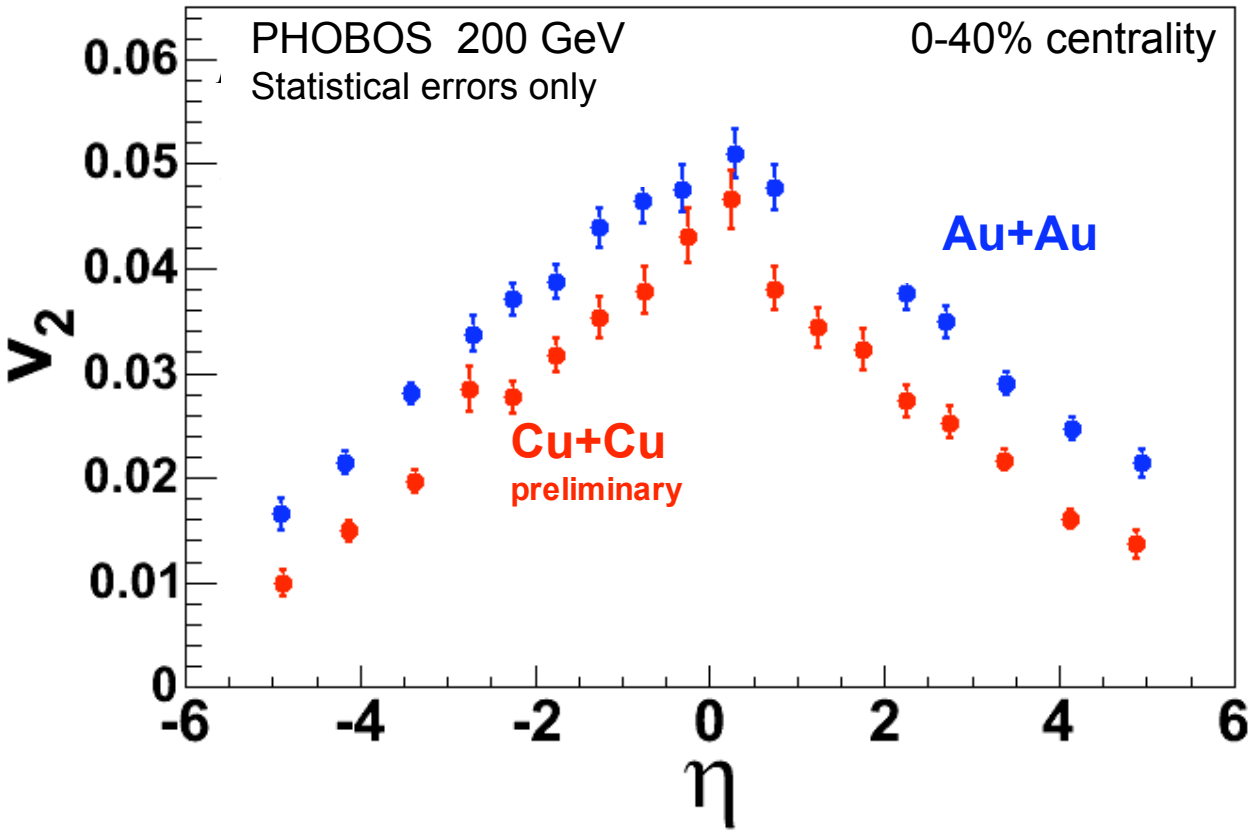
Rules out N_{part}/N_{coll} two-component picture

Dominance of geometry?

Elliptic Flow, Geometry & Density

Q: How does elliptic flow scale with geometry and density?

Elliptic Flow in Cu+Cu vs Au+Au

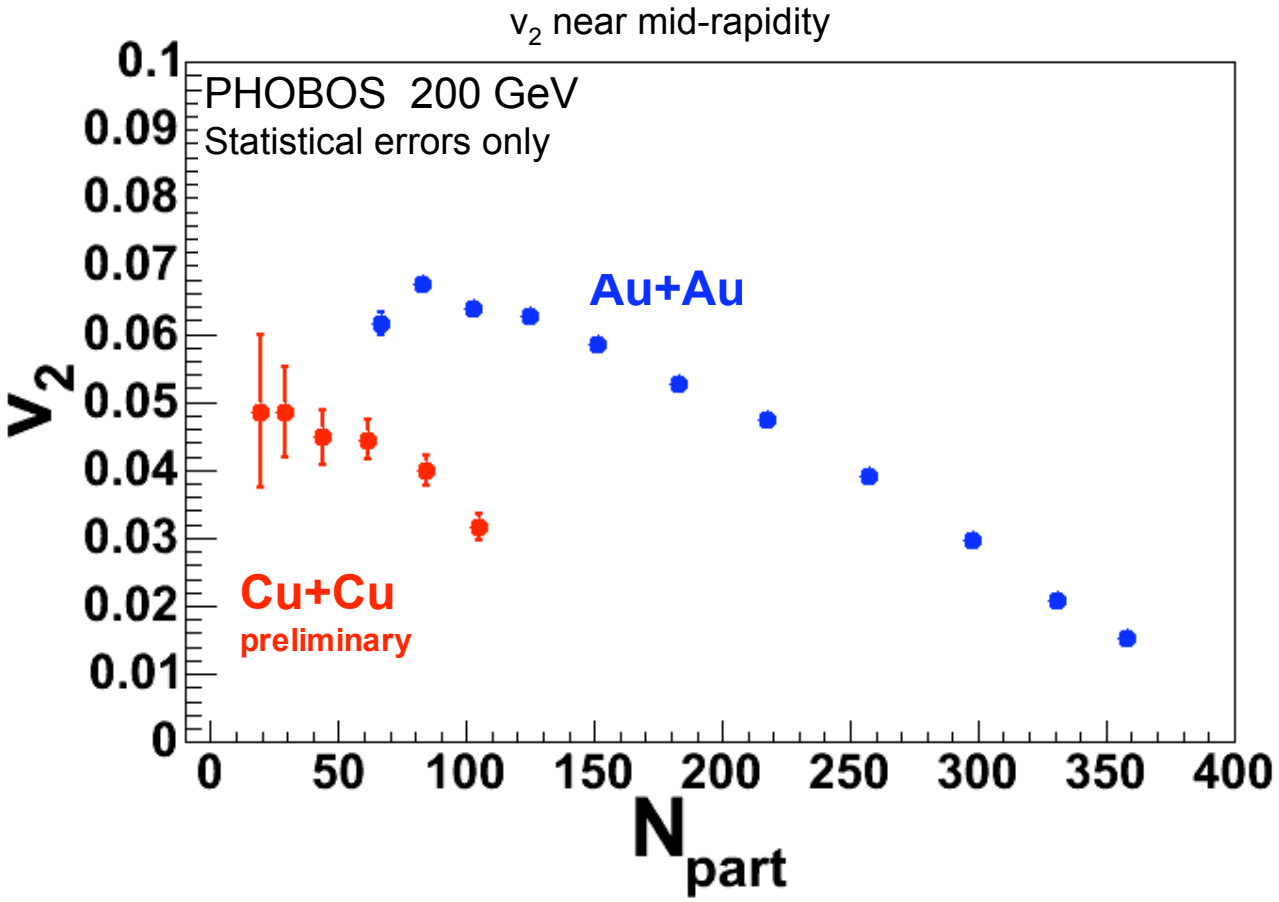


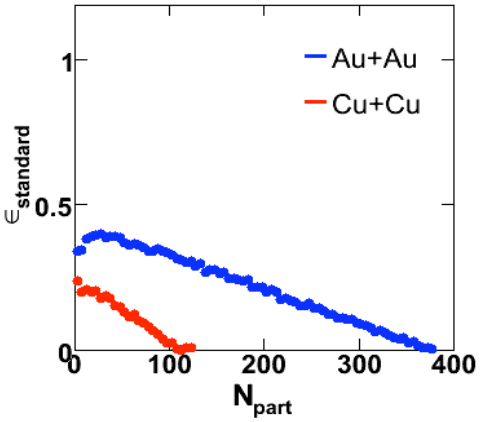
Sizable v_2 for Cu+Cu

Much larger than transport-model predictions

See talk by Steve Manly

Elliptic Flow vs N_{part}

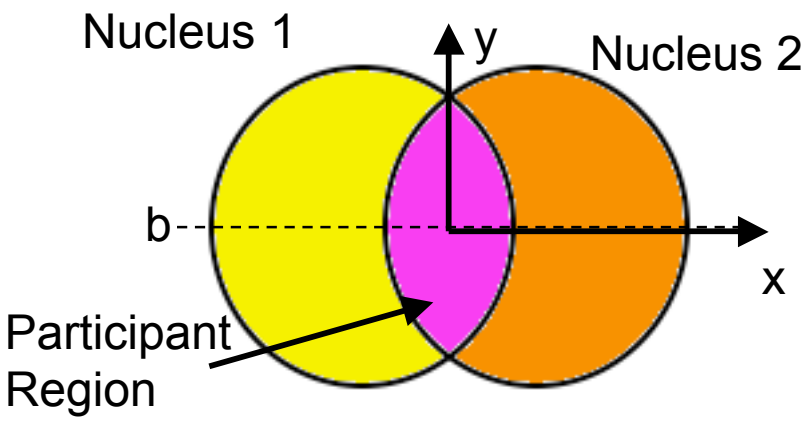




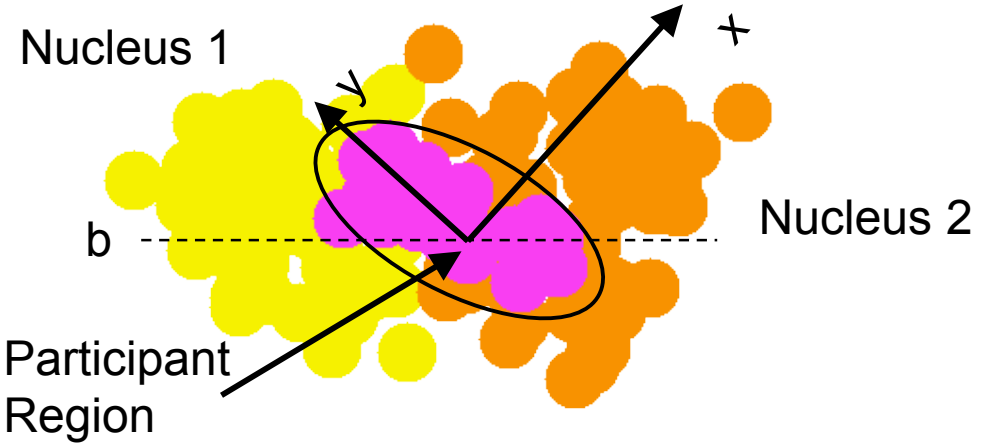
Substantial v_2 even for most central bin in Cu+Cu

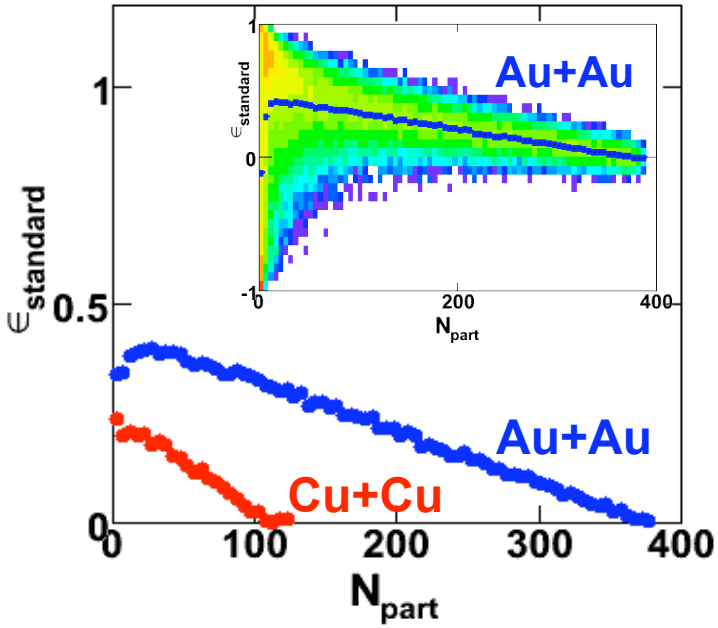
Eccentricity Calculation

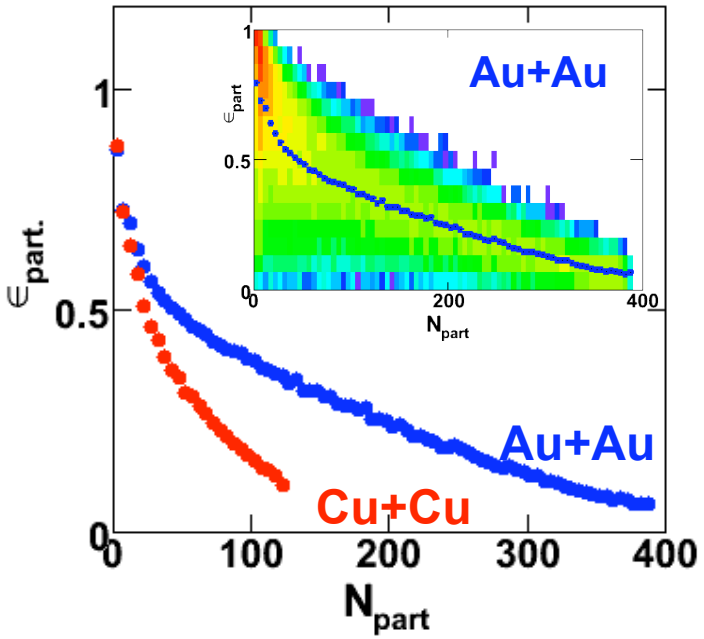
Standard Eccentricity



Participant Eccentricity

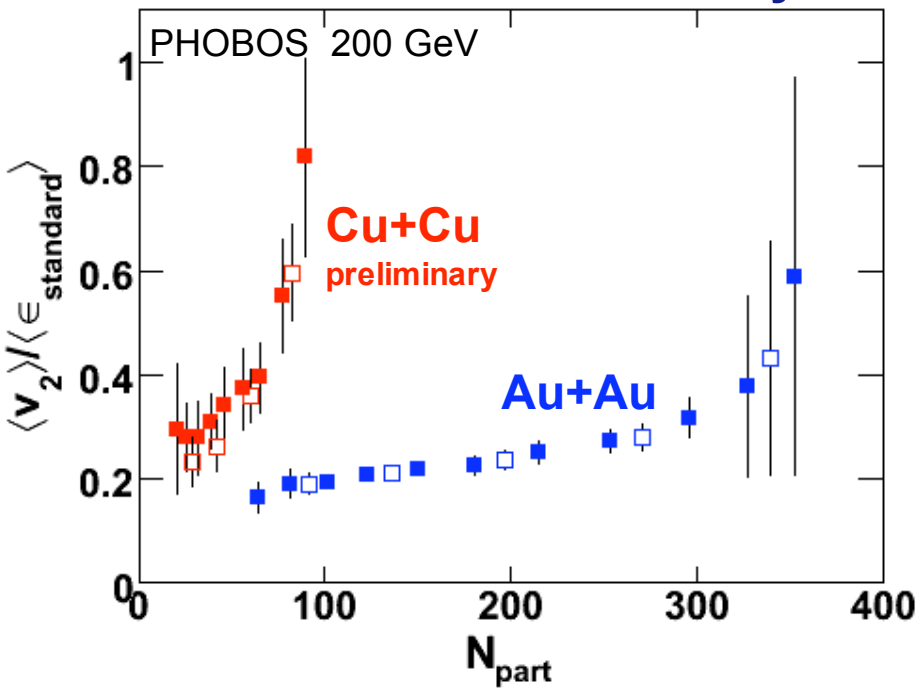




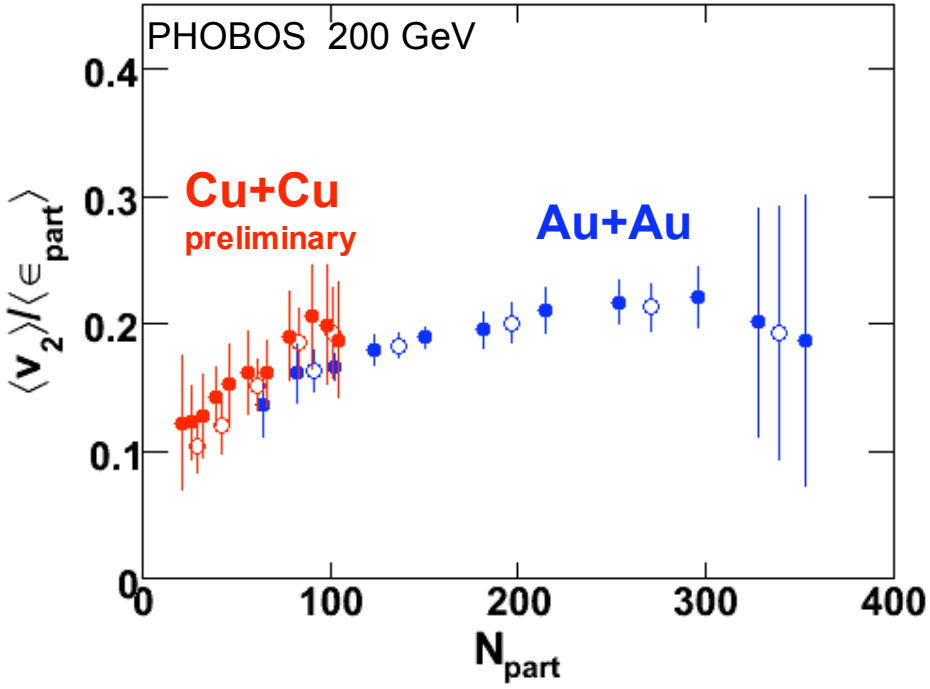


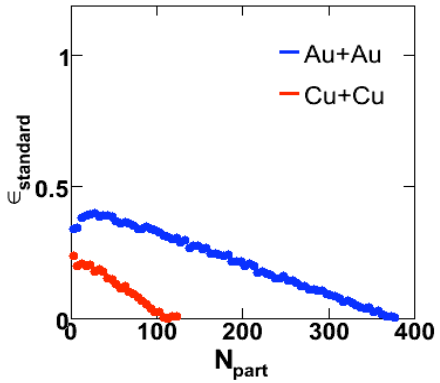
Elliptic Flow vs N_{part}, II

Standard Eccentricity

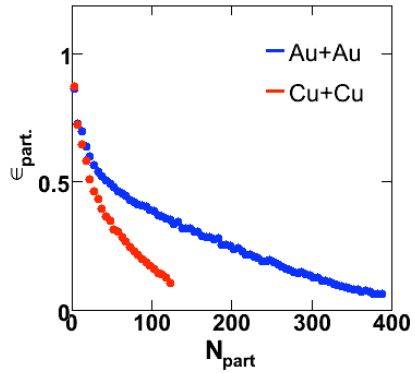


Participant Eccentricity



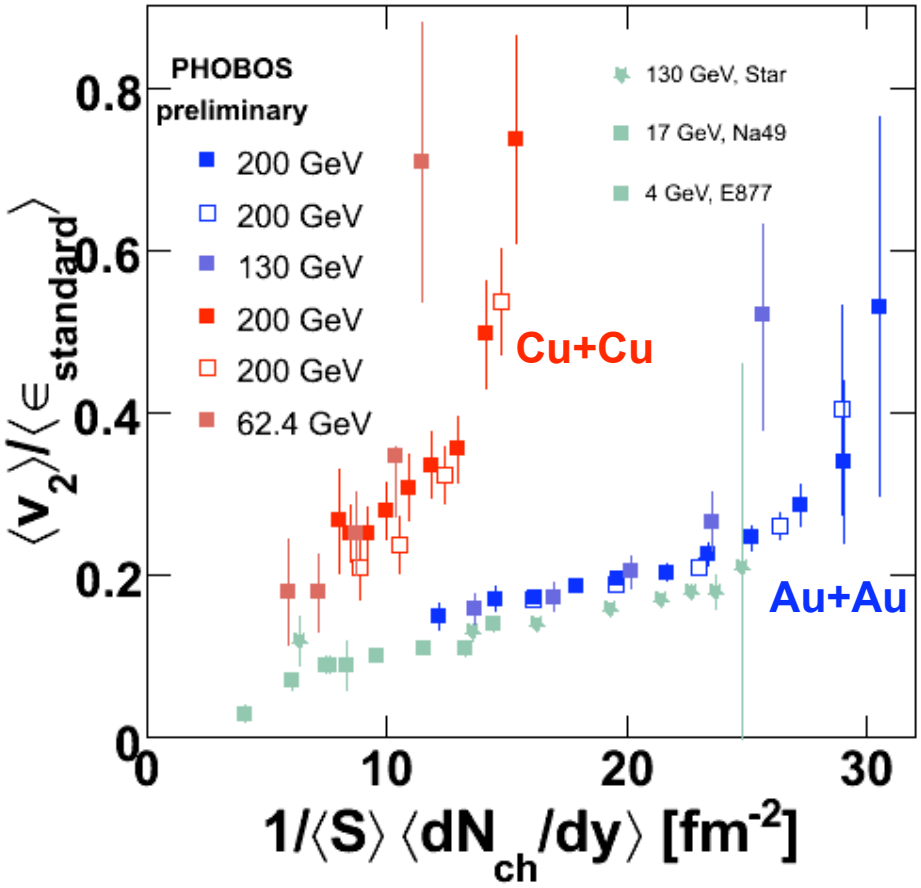


"Participant Eccentricity" allows v_2 scaling from Cu+Cu to Au+Au

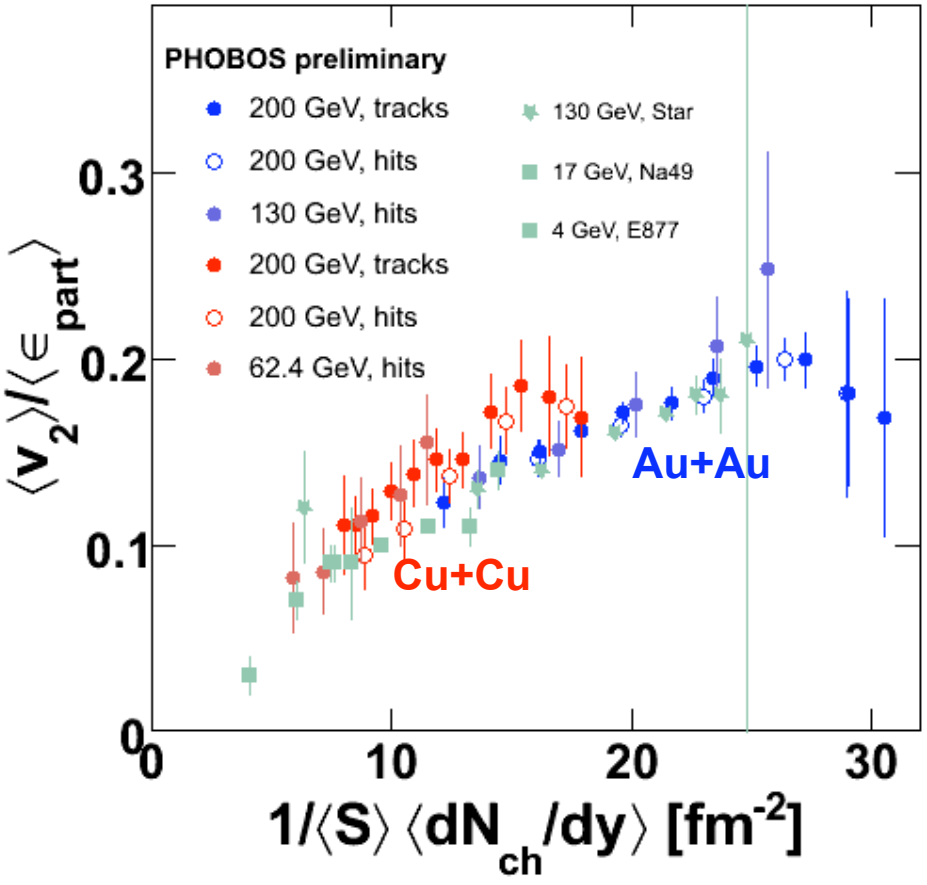


'Low Density Limit'-Scaling

Standard Eccentricity



Participant Eccentricity



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

Elliptic Flow, Geometry & Density

Q: How does elliptic flow scale with geometry and density?

A: Large elliptic flow observed in Cu+Cu

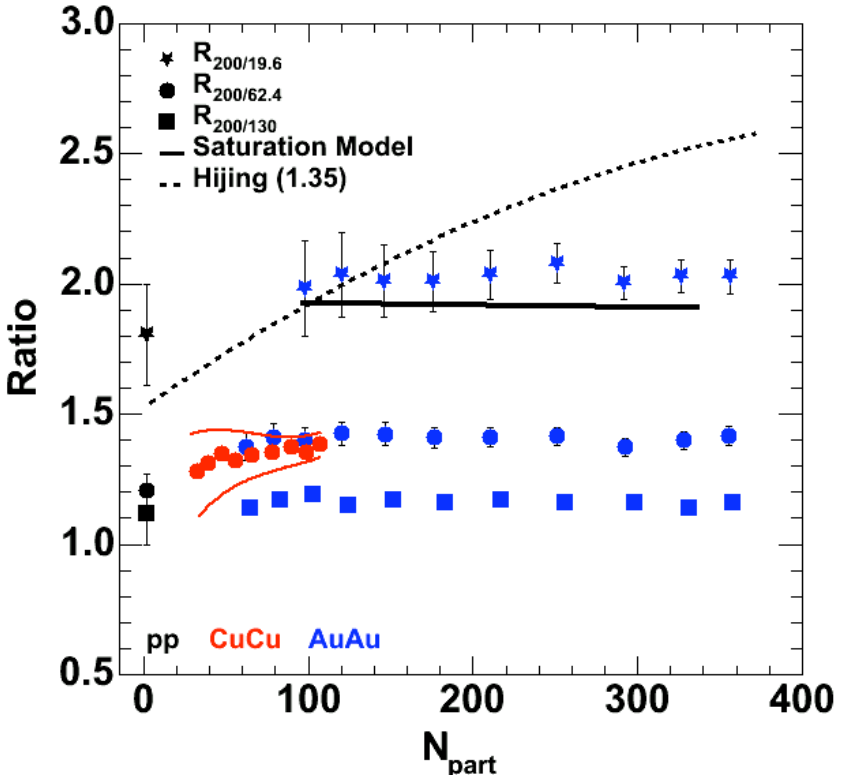
- **Non-vanishing $\langle v_2 \rangle$ for central events**
- **"Non-flow" effects?**
- **Expansion driven by participant eccentricity?**

Physics Lessons, I

Q: What Physics Lessons have we learned?

A1: Energy/Centrality factorization implies suppression/saturation of initial particle production

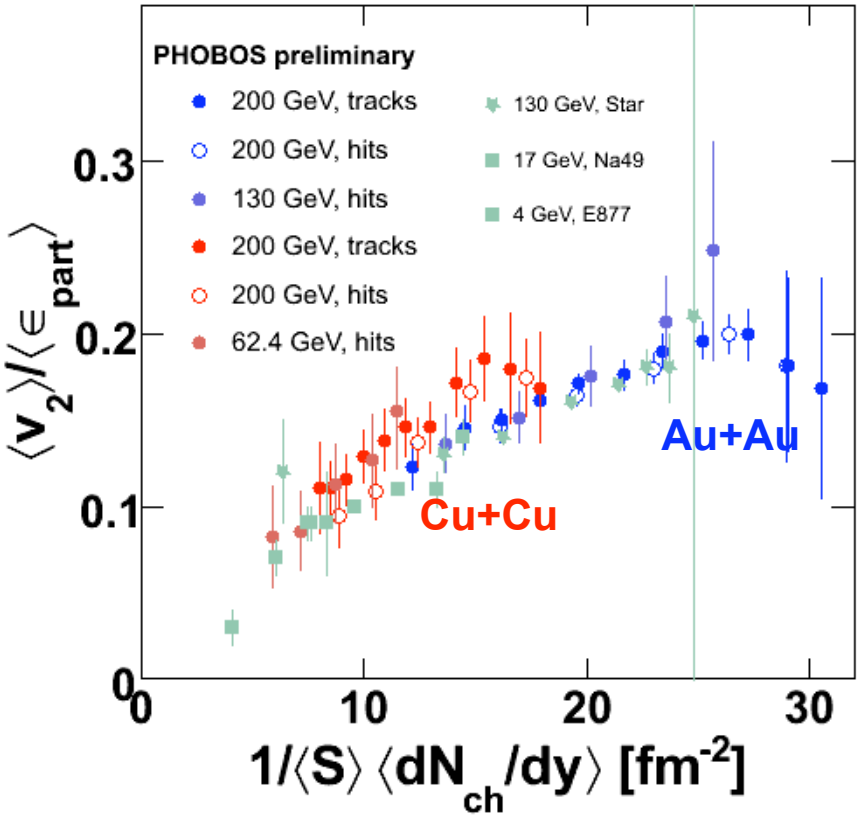
If this persists at LHC, underlying physics will dominate HIC at LHC



Physics Lessons, II

Q: What Physics Lessons have we learned?

A2: Strong collective flow observed in Cu+Cu emphasizes the need for understanding of early thermalization/pressure build up

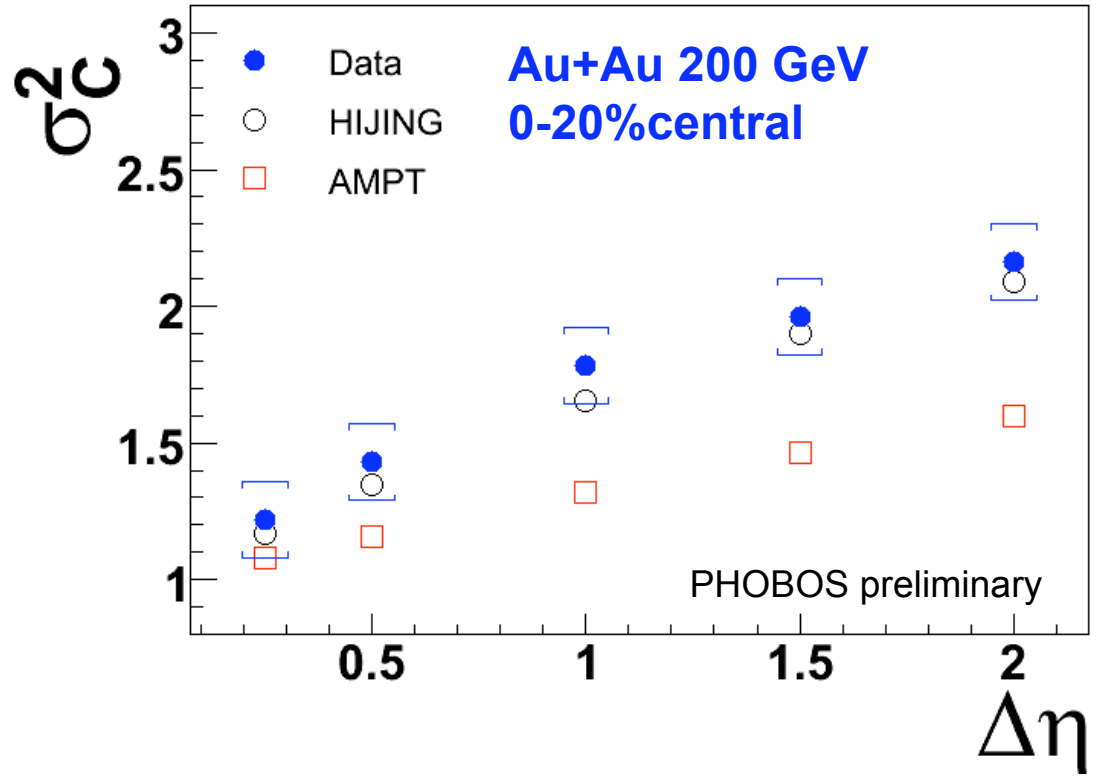


Continuing Physics Program

Q: What is the current and future physics program for PHOBOS?

Multiplicity Fluctuations

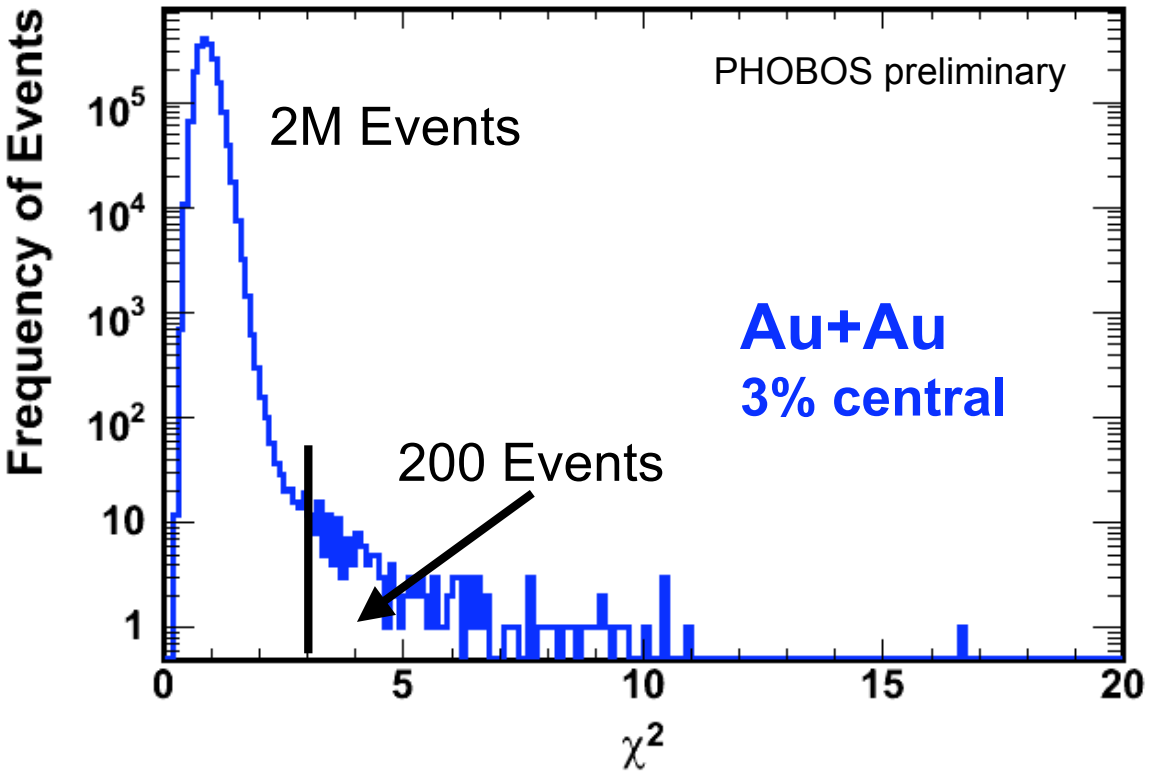
Effective cluster size



Correlated particle emission in 'clusters'

Extract cluster size from forward/backward multiplicity correlations See talk by Peter Steinberg

Search for Rare Events



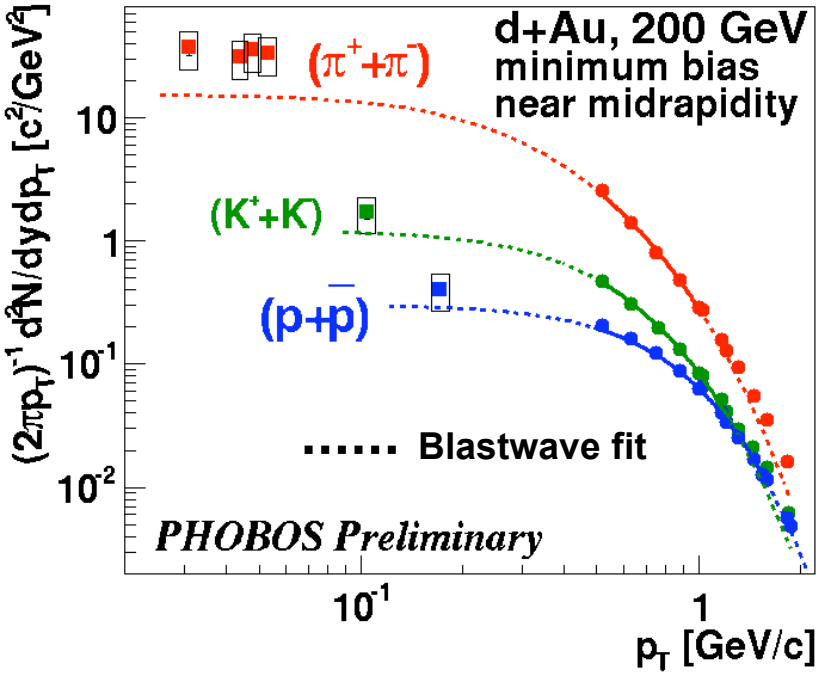
Search for 'unusual' events

Understand tails (≈10^{-4}) in terms of known backgrounds

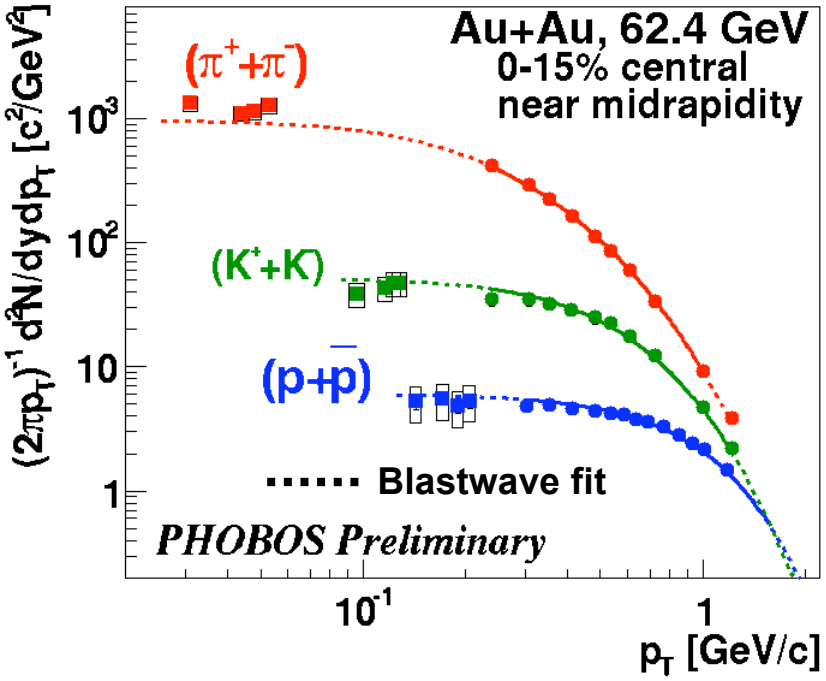
See talk by George Stephans

Particle Production at Low p_T

200 GeV d+Au (min bias)



62.4 GeV Au+Au (15% central)



Unique measurements at low p_T

See talk by Adam Trzupek (spectra) and poster by Siarhei Vaurynovich(Phi)

Continuing Physics Program

Q: What is the current and future physics program for PHOBOS?

A: We still have a long way to go

- Complete systematics of hadron production and anisotropic flow
- Comprehensive studies of correlations over full acceptance
- Comprehensive study of charged hadron and ϕ production at very low p_T

Make full use of the large Au+Au and Cu+Cu datasets

PHOBOS Talks

Adam Trzupek “Particle production at very low and intermediate transverse momenta in Au+Au and d+Au collisions” (Fri, 15:00 Rm #0.83)

Steve Manly “System-size and energy dependence of elliptic flow” (Fri, 16:20, Rm #0.81)

Peter Steinberg “Charged hadron multiplicity fluctuations in Au+Au collisions at RHIC” (Sat, 17:00, Globe Hall)

George Stephans “Two-particle angular correlations in d+Au collisions” (Mon, 16:00, Globe Hall)

PHOBOS Posters

Alice Mignerey “Systematic study of directed flow at RHIC”

Gerrit van Nieuwenhuizen “Charged Hadron spectra in Cu+Cu and Au+Au collisions at RHIC”

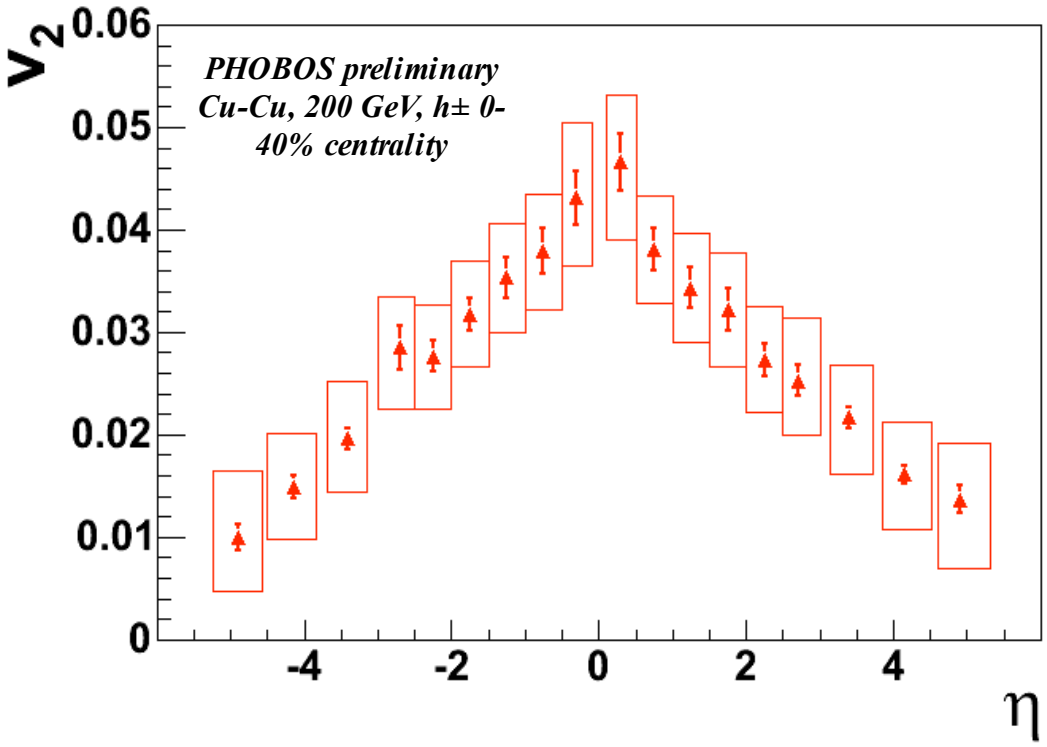
Richard Hollis “Charged particle multiplicities from Cu+Cu, Au+Au and d+Au collisions at RHIC”

Vasundhara Chetluru “Particle ratios in Cu+Cu collisions at RHIC

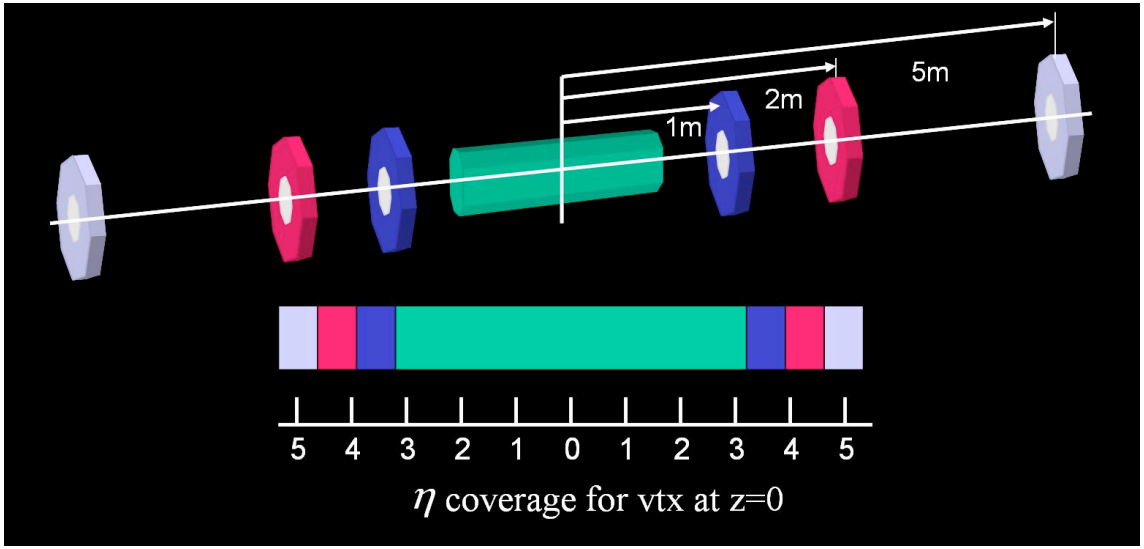
Siarhei Vaurynovich “Measurement of phi mesons with the PHOBOS detector”

Maarten Ballintijn “The PHOBOS interactive computing architecture at RHIC”

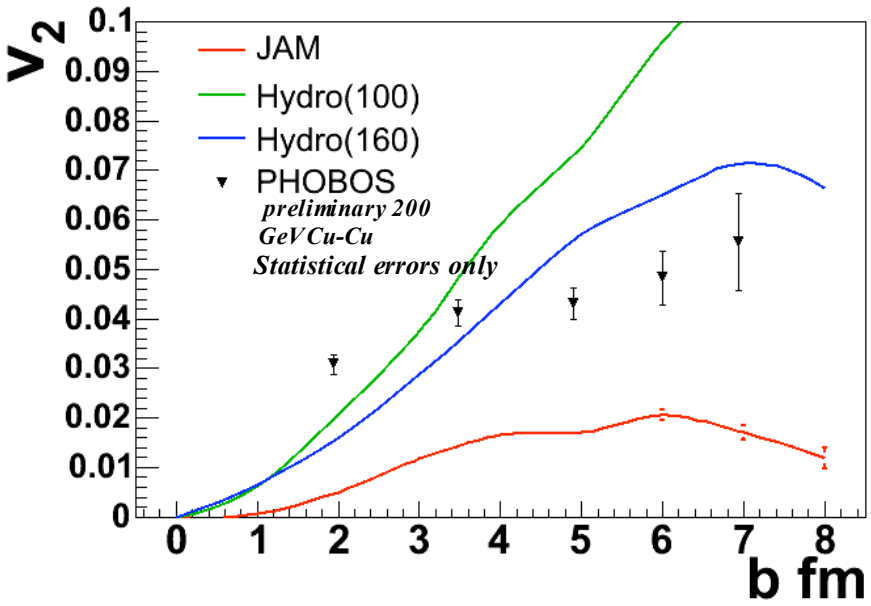
Backup


PHOBOS preliminary
Cu-Cu, 200 GeV, h± 0-40% centrality
v2
0.06
0.05
0.04
0.03
0.02
0.01
0
-4
-2
0
2
4
η

Backup



Backup

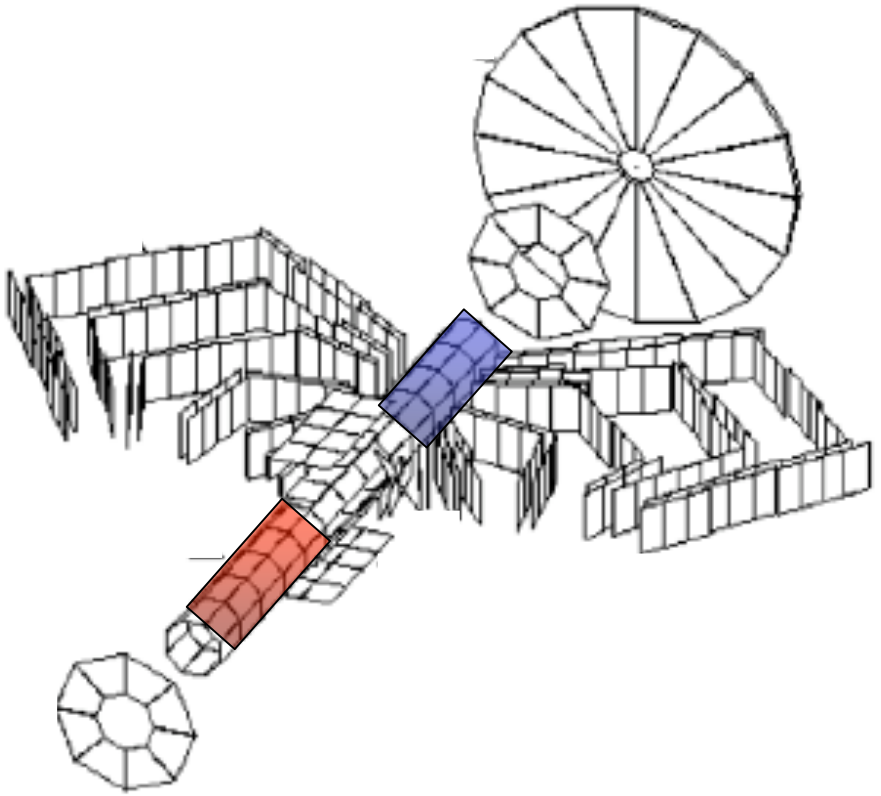

v_2
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
JAM
Hydro(100)
Hydro(160)
PHOBOS
preliminary 200 GeV Cu-Cu
Statistical errors only
0 1 2 3 4 5 6 7 8
b fm

Backup

Regions used to determine reaction plane and resolution.

Cu-Cu, 200 and 62.4 GeV and Au-Au, 19.6, 62.4, 130 and 200 GeV:
$0.1<|\eta|<3.0$

(use $0.5<|\eta|<3.0$ and $1.0<|\eta|<3.0$ for systematic studies)



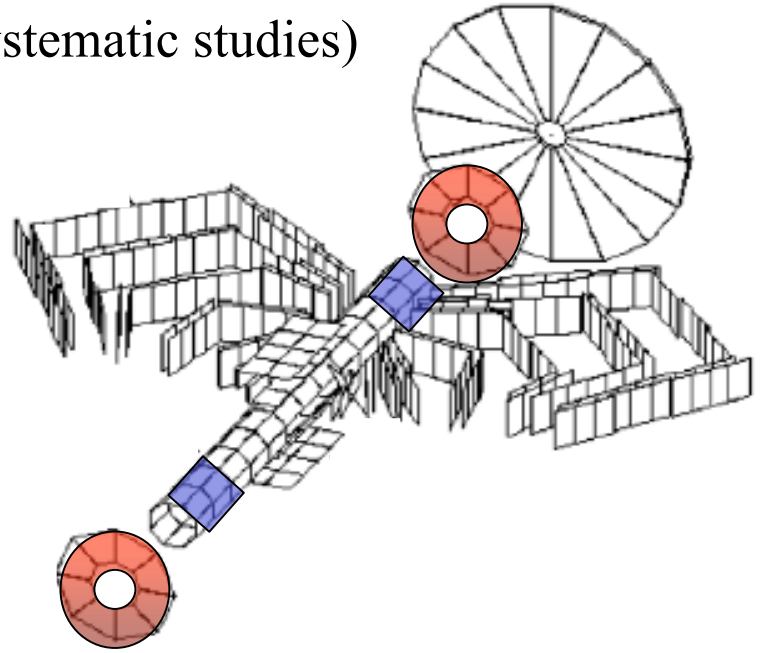
Backup

Regions used to determine reaction plane and resolution.

v_1 baseline Au-Au, 19.6, 62.4, 130 and 200 GeV: $1.5<|\eta|<3.0$ and $3.0<|\eta|<5.0$

(use $1.5<|\eta|<2.5$ and $3.5<|\eta|<5.0$ for systematic studies)

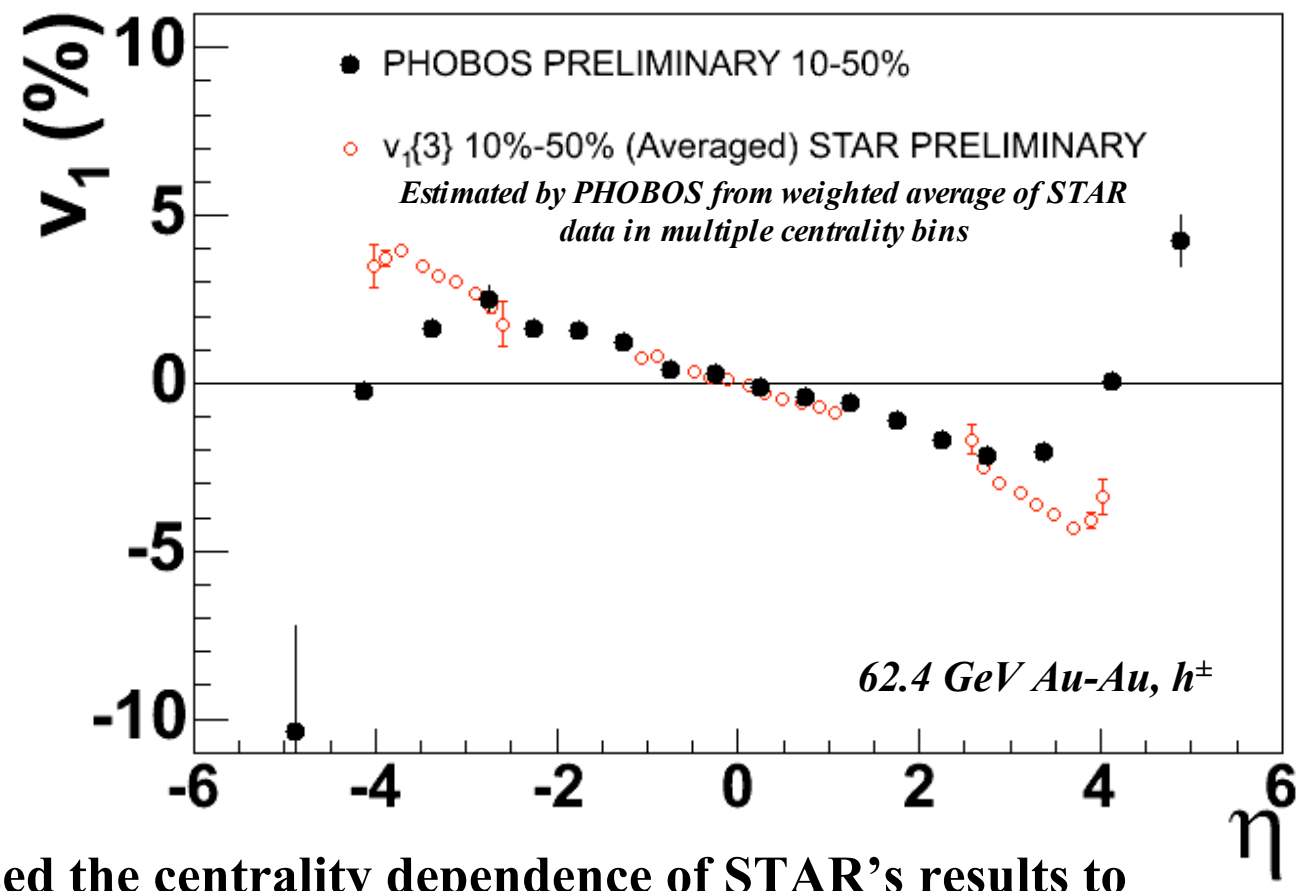
v_1 mixed harmonic Au-Au, 19.6, 62.4, 130 and 200 GeV: $1.5<|\eta|<3.0$ and $3.0<|\eta|<5.0$ for the first harmonic part and $0.1<|\eta|<3.0$ for the second harmonic part



Backup

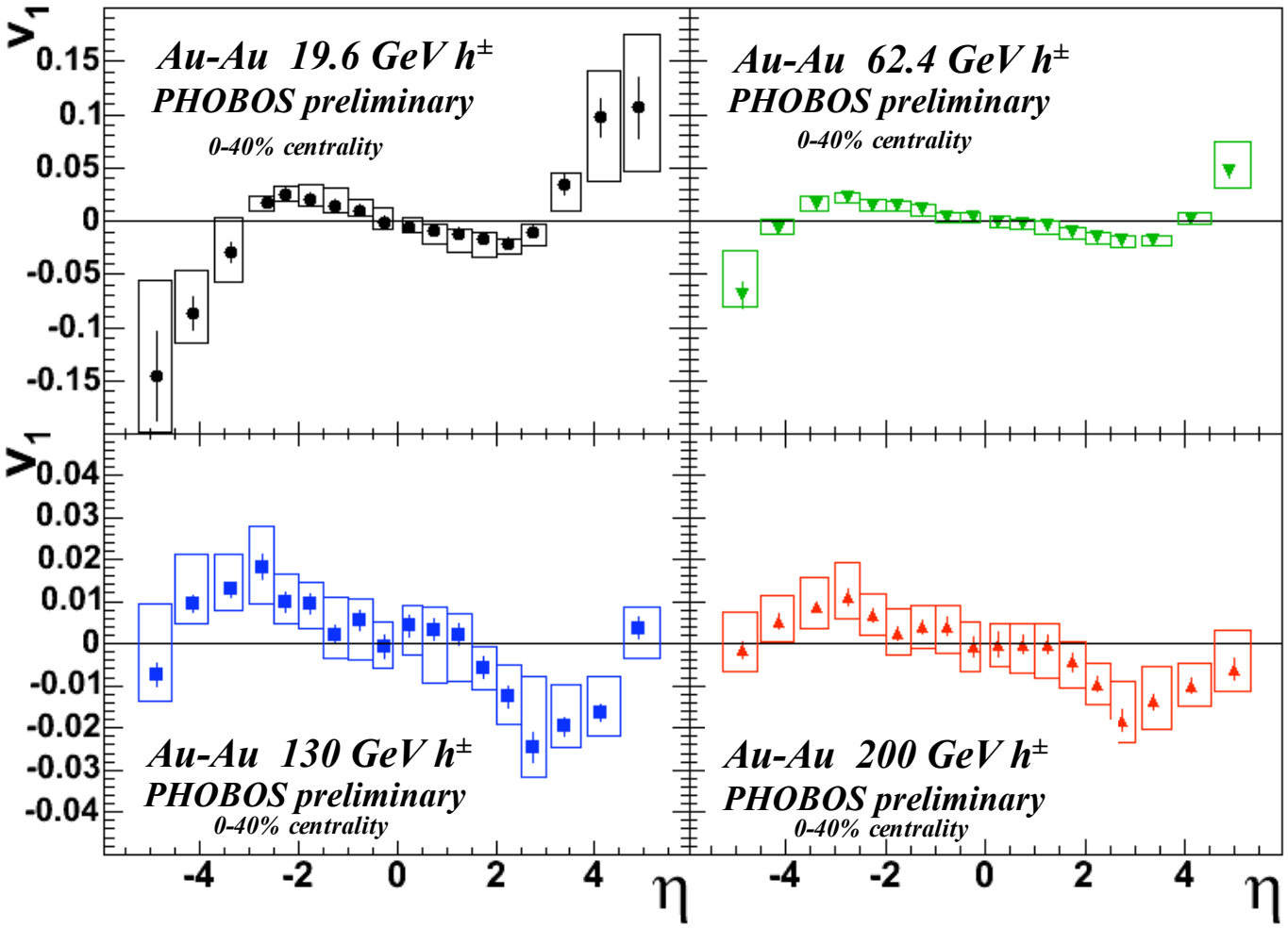
Comparison of directed flow results at 62.4 GeV

Discrepancy at high η possibly due to differences in low momentum cutoff?



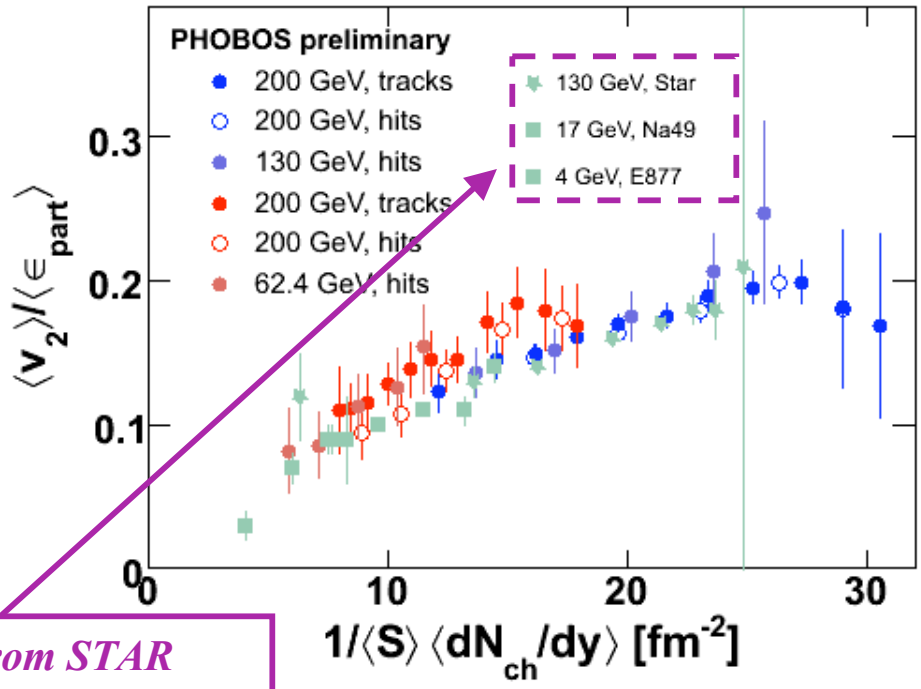
We used the centrality dependence of STAR's results to estimate the STAR results in the 10-50% centrality bin

Backup


Au-Au 19.6 GeV h±
PHOBOS preliminary
0-40% centrality
Au-Au 62.4 GeV h±
PHOBOS preliminary
0-40% centrality
Au-Au 130 GeV h±
PHOBOS preliminary
0-40% centrality
Au-Au 200 GeV h±
PHOBOS preliminary
0-40% centrality
v1
η

Backup

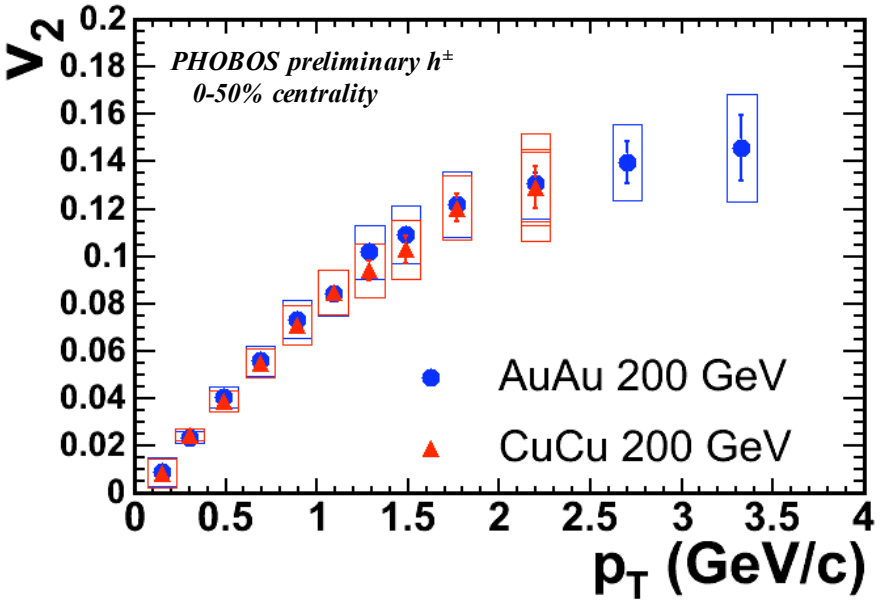
- **Caution:** we used ε_{part} for PHOBOS data. Important for Cu-Cu, less critical for Au-Au.
- Scale $v_2(\eta)$ to ~$v_2(y)$ (10% lower)
- Scale $dN/d\eta$ to be ~dN/dy (15% higher)

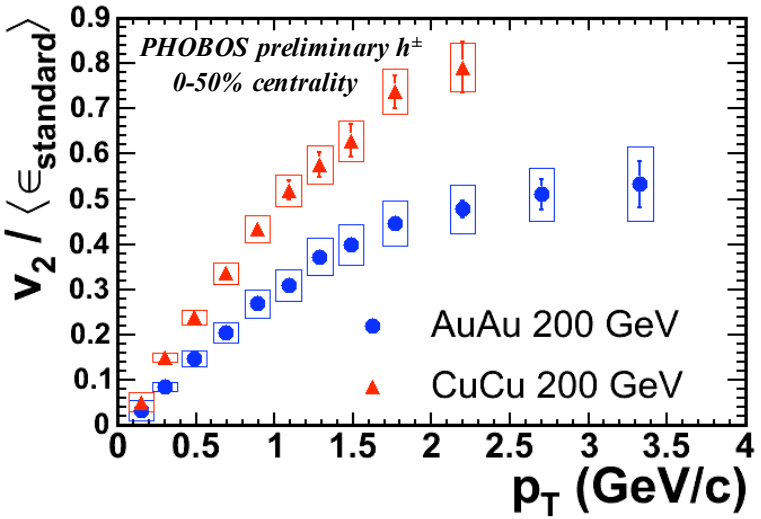


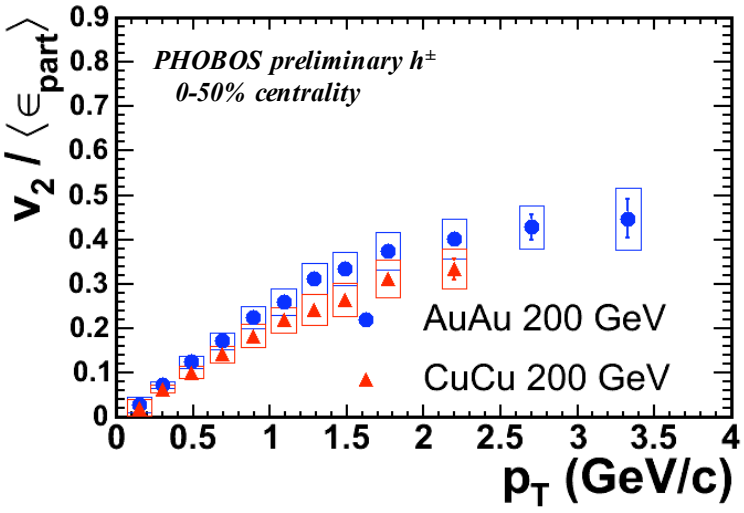
Points for STAR, NA49 and E877 data taken from STAR Collaboration, Phys.Rev. C66 (2002) 034904 with no adjustments

Approximate "LDL" scaling observed.

Backup







Eccentricity difference is important for same centrality selection.

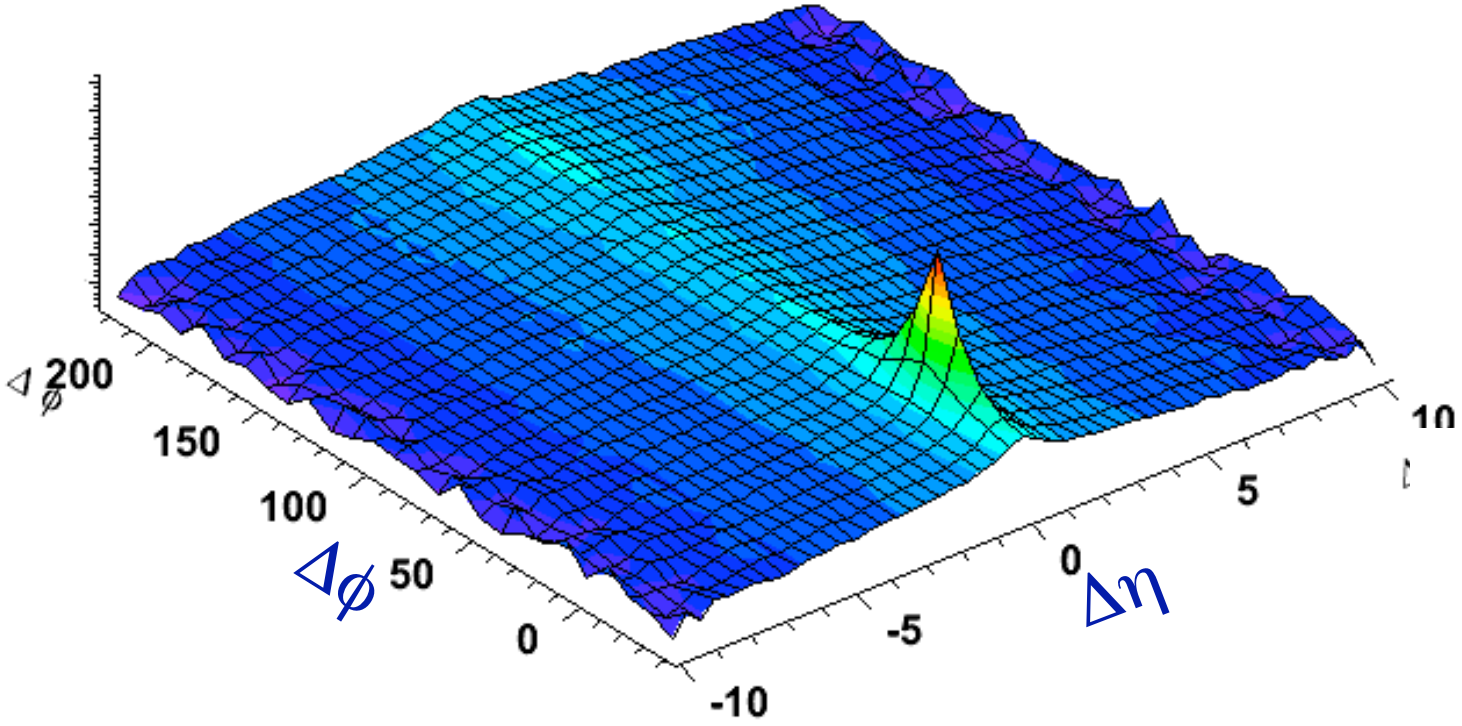
$V_2(p_T)$ for Cu-Cu is similar $v_2(p_T)$ for Au-Au when scaled by ε_{part}

Backup

Two particle correlation function of minbias dAu 200Gev

$$C(\Delta\eta, \Delta\phi) = \frac{N_{real}(\Delta\eta, \Delta\phi)}{N_{mixed}(\Delta\eta, \Delta\phi)}$$

Raw data



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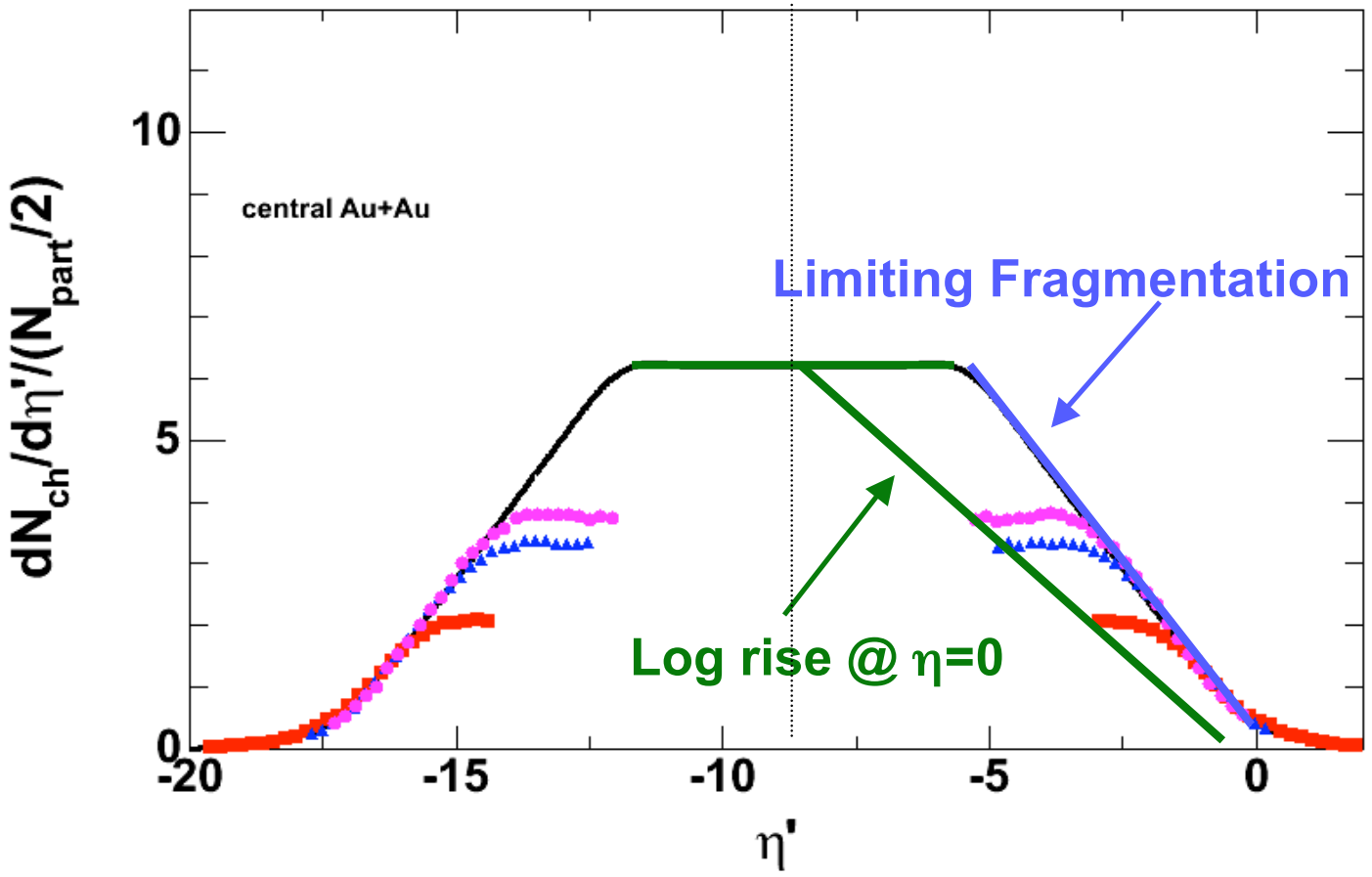
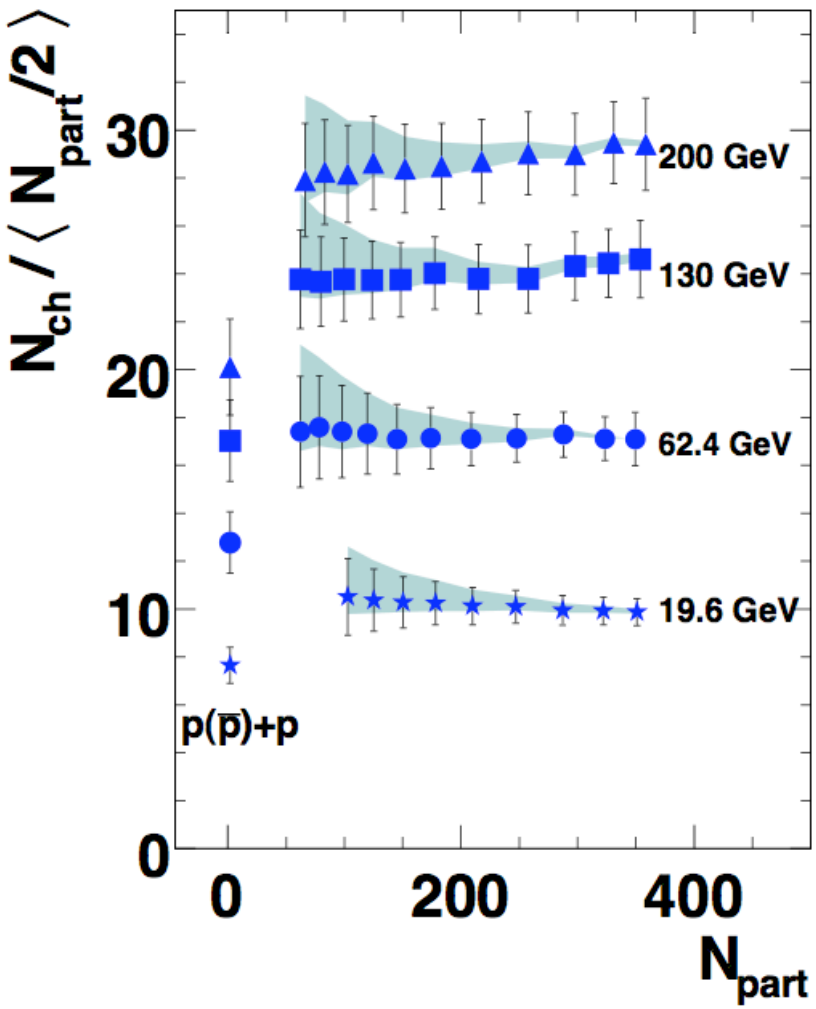

central Au+Au
Limiting Fragmentation
Log rise @ η=0
dN_ch/dη'/(N_part/2)
η'
10
5
0
-20
-15
-10
-5
0

Backup


$N_{ch} / \langle N_{part}/2 \rangle$
30
20
10
0
0
200
400
N_{part}
200 GeV
130 GeV
62.4 GeV
19.6 GeV
p(p̄)+p

Backup

Armesto, Salgado, Wiedemann hep-ph/0407018

$$\left.\frac{1}{N_{\rm part}}\frac{dN^{AA}}{d\eta}\right|_{\eta\sim 0} = N_0\sqrt{s}^{\lambda}N_{\rm part}^{\frac{1-\delta}{3\delta}}$$