Latest PHENIX observation of the large systems via hadronic and electromagnetic probes

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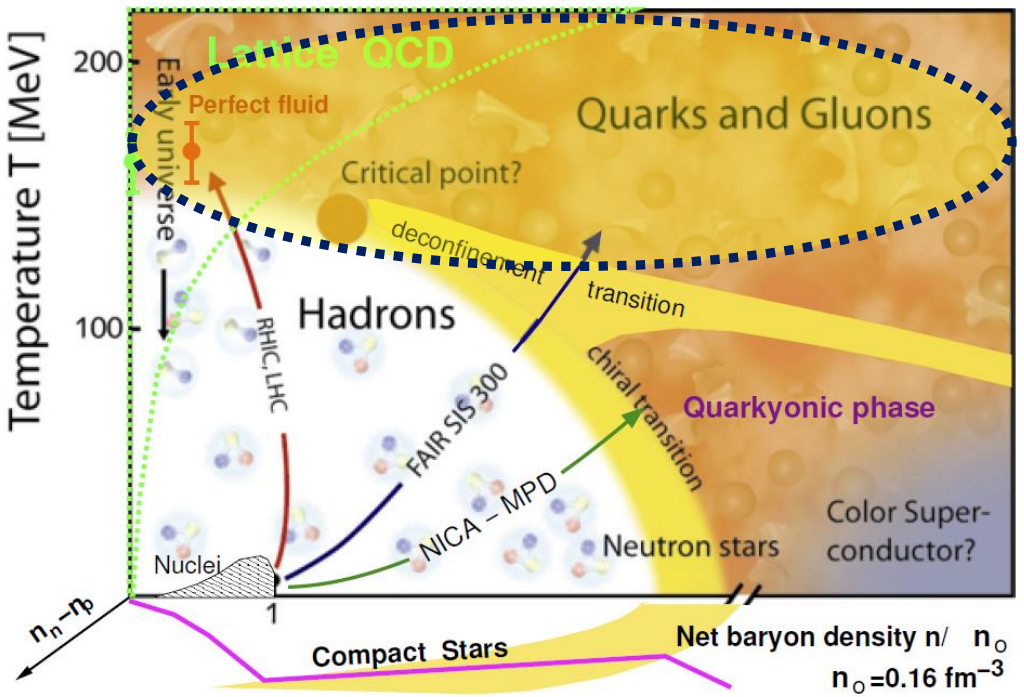
Exploring the rich QGP world

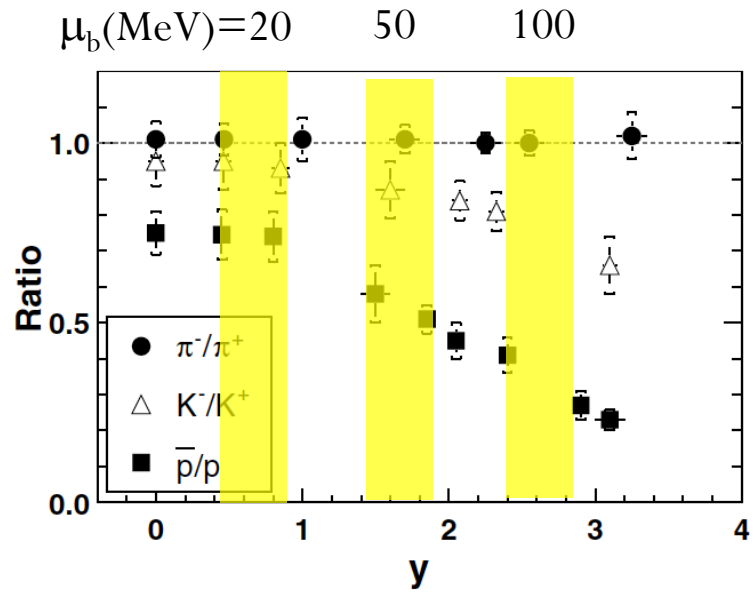
- We found QGP, but is it THE QGP?→ No! QGP world is broad.
- At LHC: hotter (and more free gas like) and smaller QGP
- At RHIC: lower energy density, and higher baryon density QGP
  - Critical point should be on one of the paths.

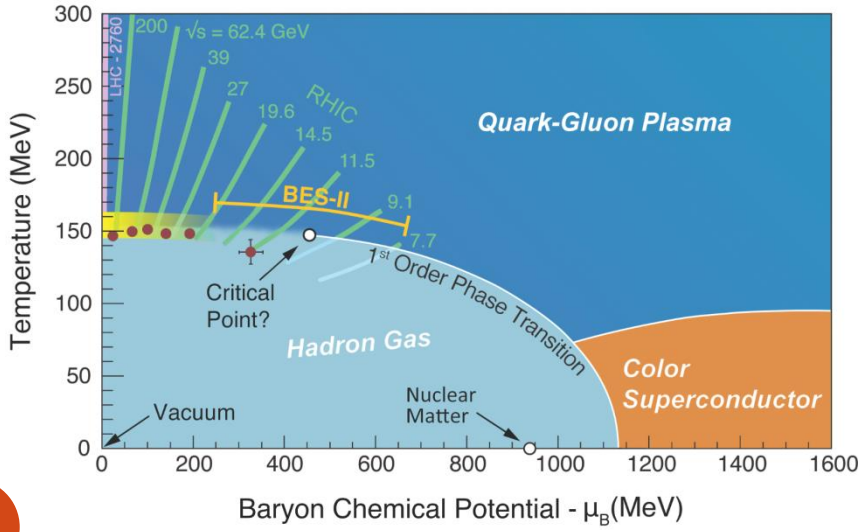


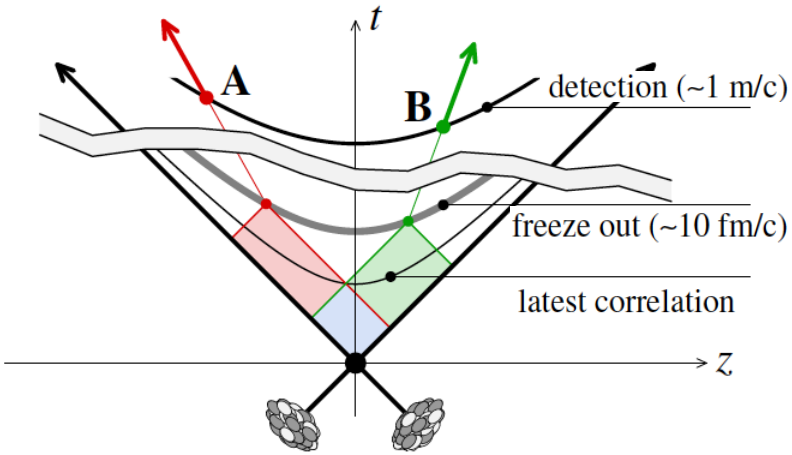
How can we explore?

- Change energy and system
  - Dialing the temperature and the baryon density of the system
- Change rapidity(-gap) of observable(s)
  - Dialing density and production time
- RHIC can widely access in baryon density and temperature, compared to LHC.

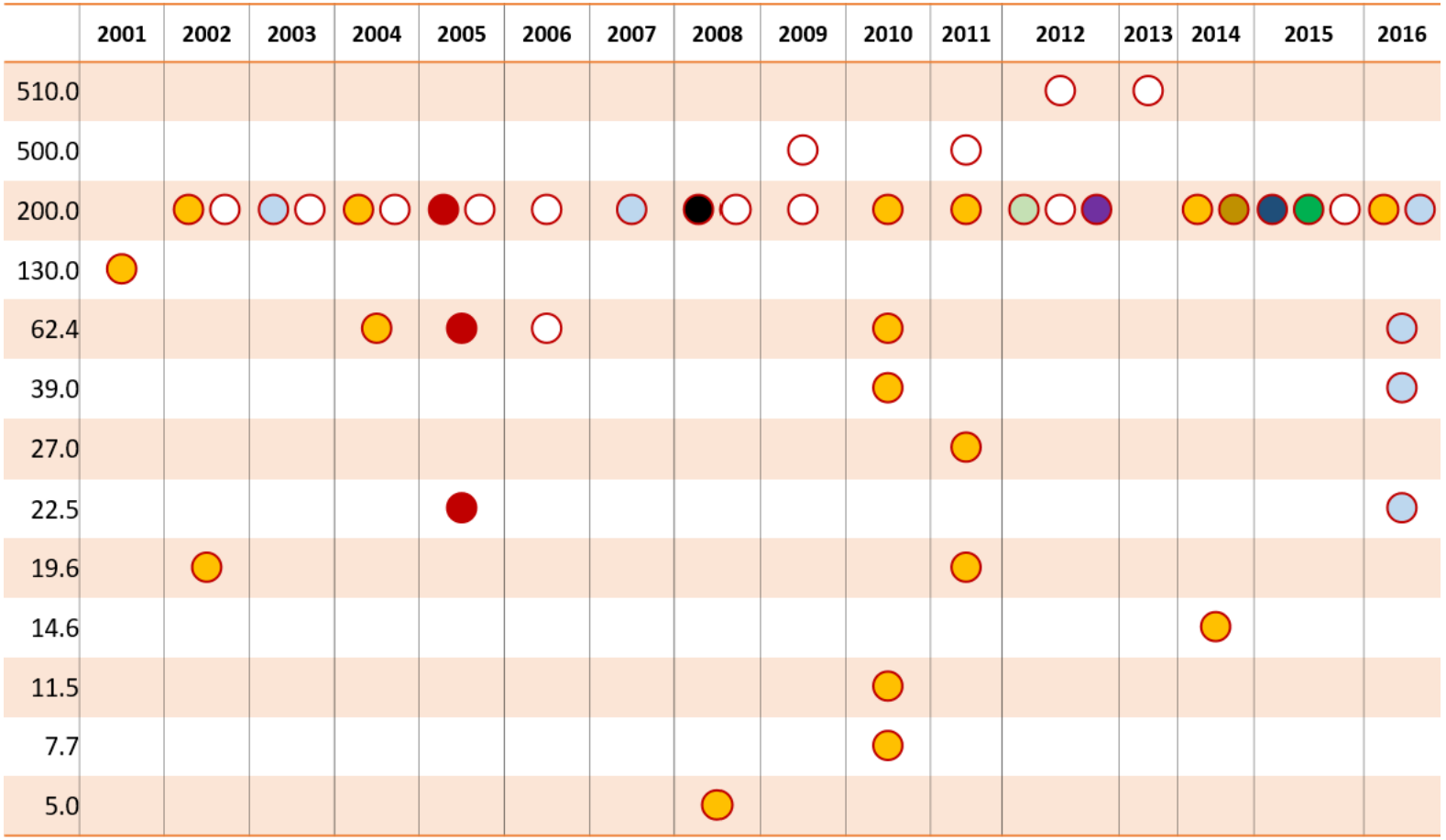
BRAHMS, PRL90, 102301 (2003)







Dataset collected by PHENIX



p+p Au+Au d+Au Cu+Cu U+U Cu+Au He+Au p+Au p+Al

See details at http://www.rhichome.bnl.gov/RHIC/Runs/

Photons in energy and system dialing

Photon spectra in 200GeV Au+Au and Cu+Cu

- Photon excess over hadron decay photons (π^0, η, etc) are observed in Au+Au and Cu+Cu collisions at 200GeV.
  - Au+Au: External conversion photons, Cu+Cu: Internal conversion photons

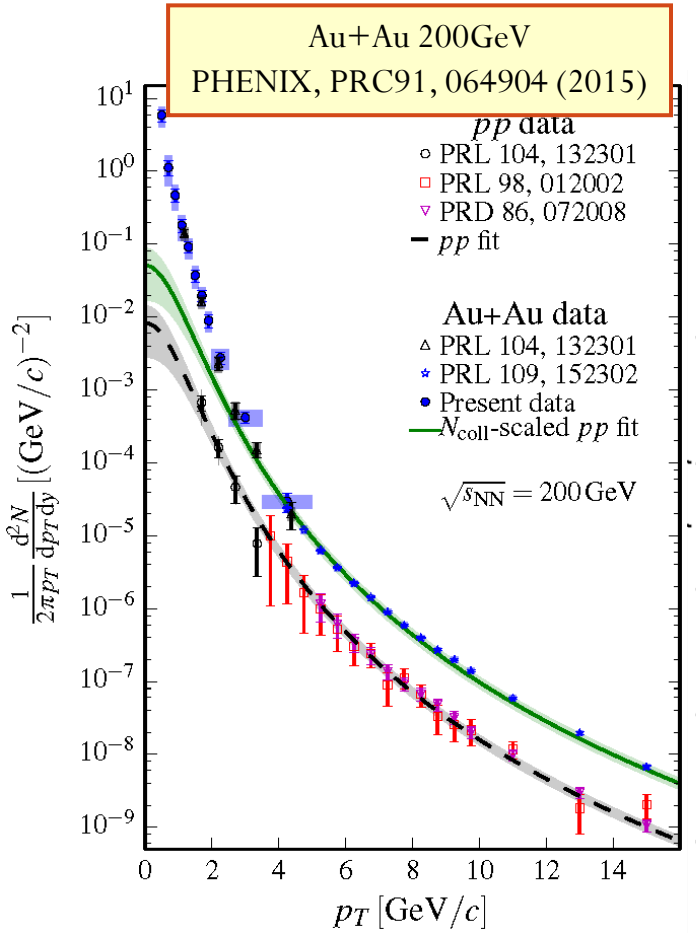
Inverse slopes:

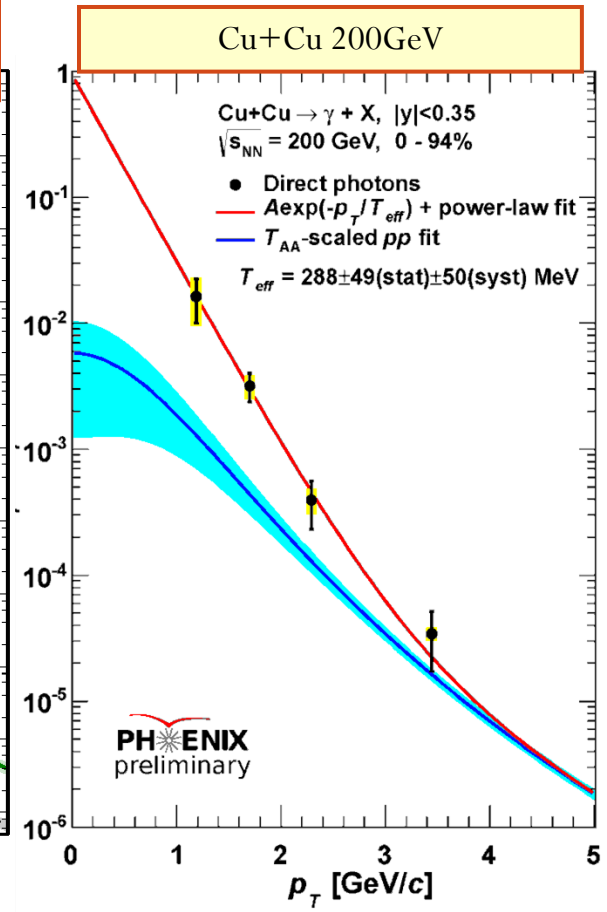
- Au+Au, min. bias

242 ± 28 (stat) ± 7 (syst) MeV

- Cu+Cu, min. bias

288 ± 49 (stat) ± 50 (syst) MeV

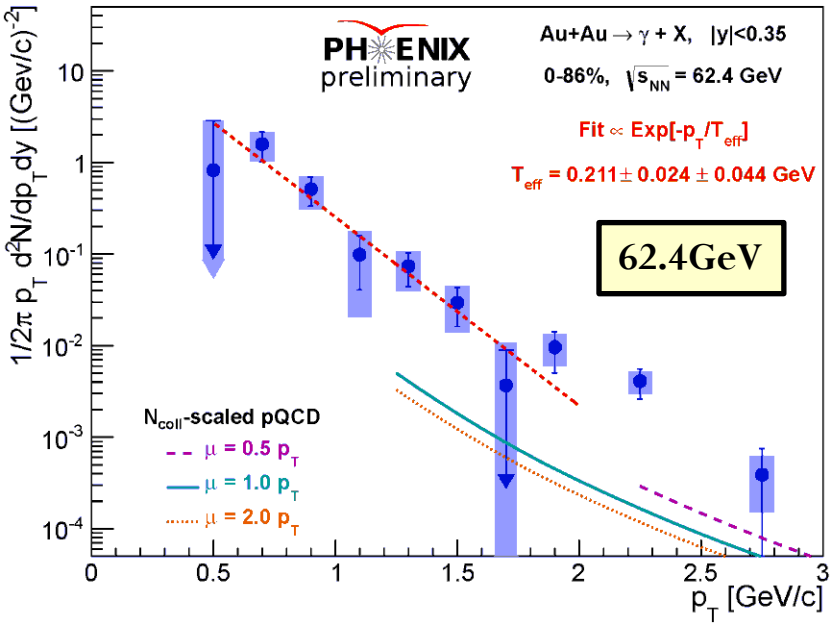


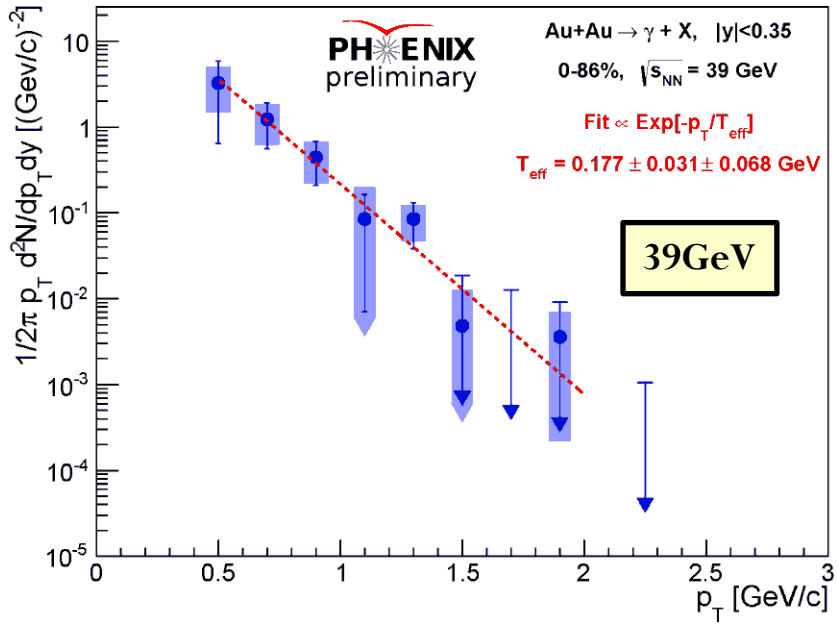


Photon spectra in 62 and 39GeV Au+Au

- Photon excesses are also observed in Au+Au at 62 and 39GeV.
  - Both are from external photon conversion.

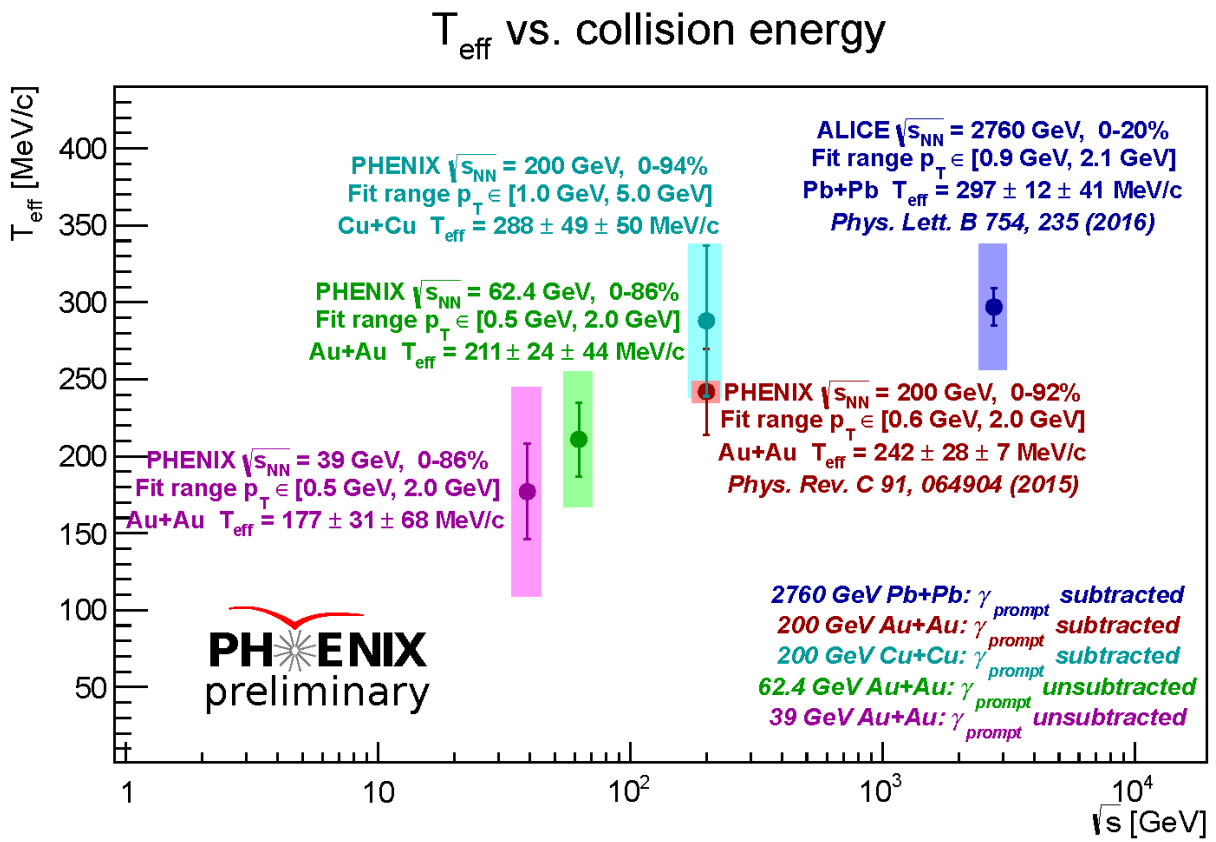
- Inverse Slopes:
  - 211 ± 24 (stat) ± 44 (syst) for 62.4GeV (min. bias)
  - 177 ± 31 (stat) ± 68 (syst) for 39GeV (min. bias)





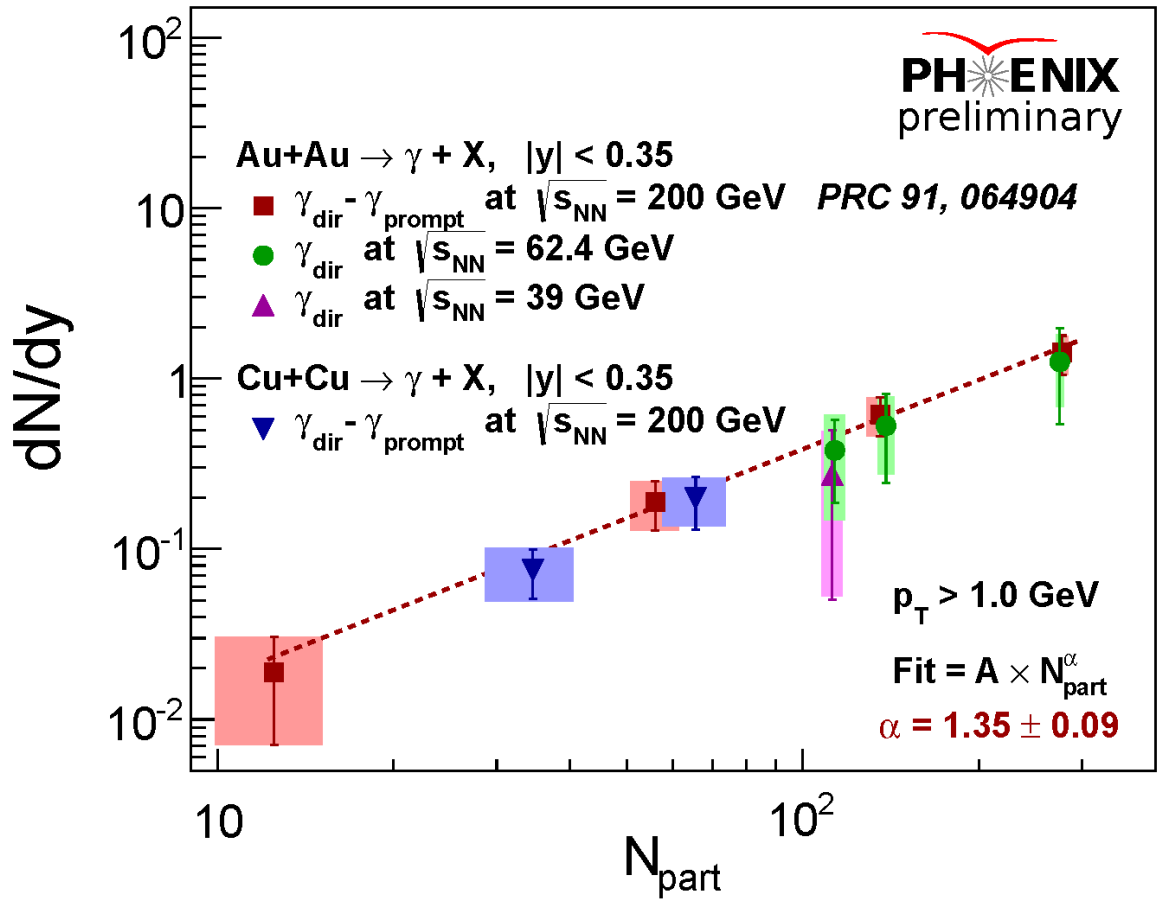
Inverse slopes from 2760 to 39GeV

- Inverse slopes as a function of collision energies
- At 200GeV, the slopes are consistent within errors for Au+Au and Cu+Cu.



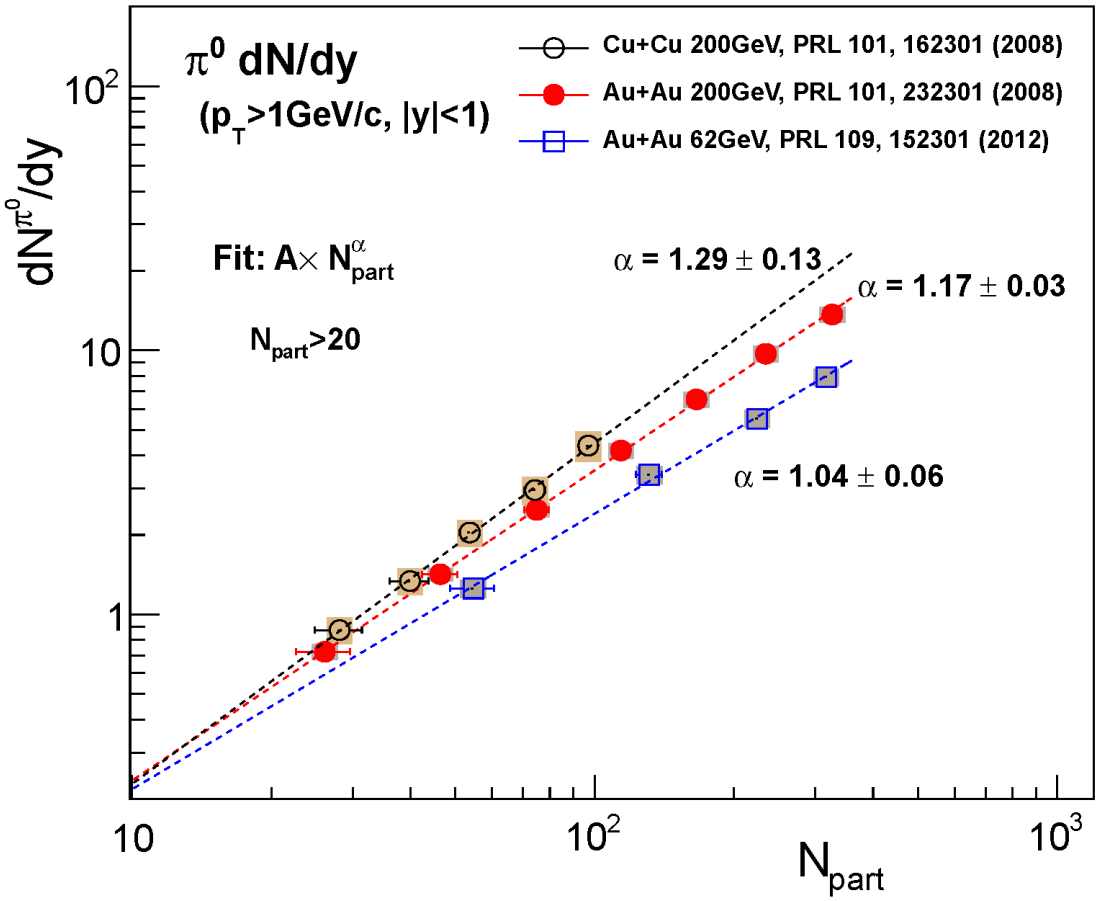
Photon dN/dy vs N_{part}

- dN/dy for direct photons for p_T>1GeV/c as a function of N_{part} are calculated for:
  - 200, 62.4 and 39GeV Au+Au
  - 200GeV Cu+Cu
- Surprisingly, they are all on the same power-law function.
  - $dN/dy = A \times N_{part}^{\alpha}$
  - **α=1.35±0.09**
- dN/dy increase faster than that of N_{part}.



cf. π^0 dN/dy vs N_{part}

- dN/dy for π^0 for p_T>1GeV/c as a function of N_{part} are calculated for:
  - 200 and 62.4GeV Au+Au
  - 200GeV Cu+Cu
- dN/dy for π^0 also increase faster than that of N_{part}.
  - **Exponent is smaller than direct photons (α=1.35).**
  - Photon excesses (γ/π^0) for Au+Au increase as $\sim N_{part}^{0.18}$ (=1.35-1.17).
- More photons from partonic phase?

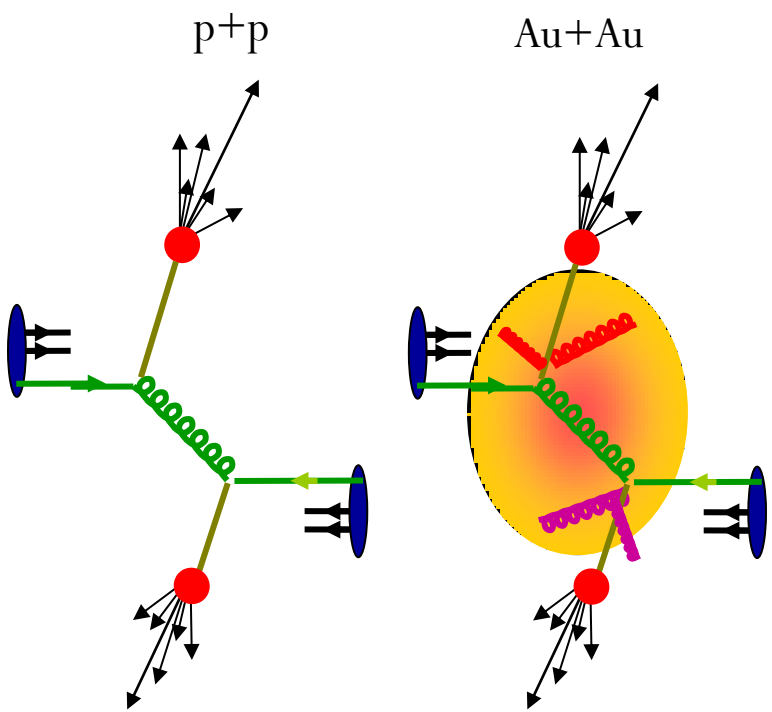


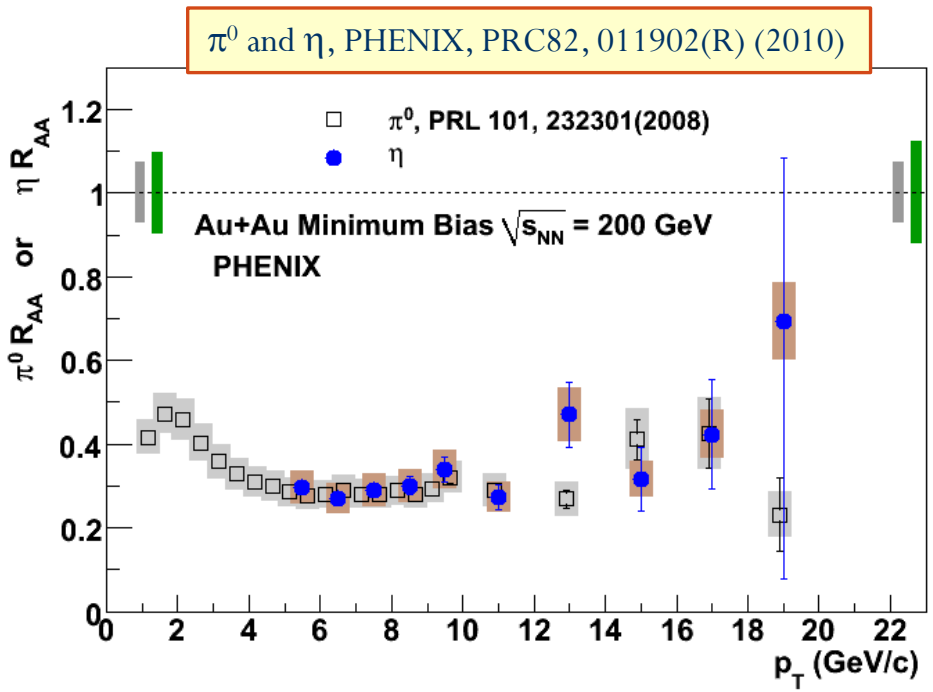
Energy (momentum) loss systematics

Yield suppression of leading particles

- Nuclear Modification Factor (R_{AA})
  - (Yield in A+A collision)/(Yield in p+p collision × N_{coll})
  - R_{AA} =1: No nuclear effect
  - R_{AA} <1: Suppression due to energy loss, etc.

$$R_{AA} = \frac{\left(\frac{d^3N}{dp^3}\right)_{AA}}{\frac{Ncoll}{\sigma_{inel}} \cdot \left(\frac{d^3\sigma}{dp^3}\right)_{pp}}$$

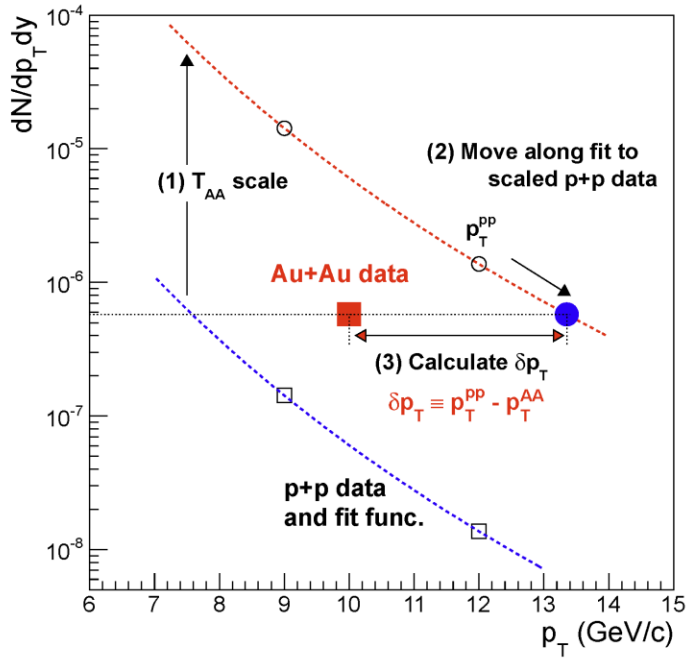


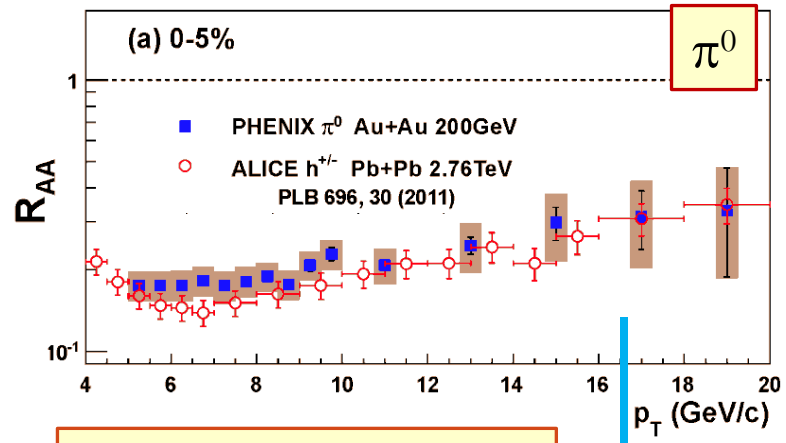


Fractional momentum loss of hadrons

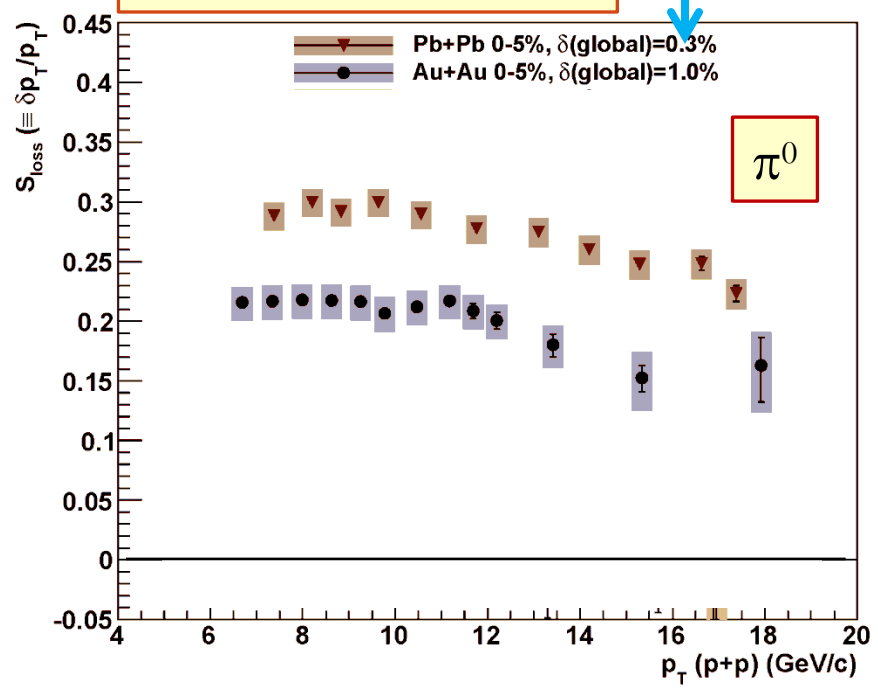
- Yield suppression is the consequence of the momentum shift of the hadrons.

- Fractional momentum loss (S_{loss}) is calculated using spectra in Au+Au and N_{coll} scaled p+p spectra.
  - $S_{loss} = (p_T^{pp} - p_T^{AA})/p_T^{pp}$





PHENIX, PRC87, 034911 (2013)

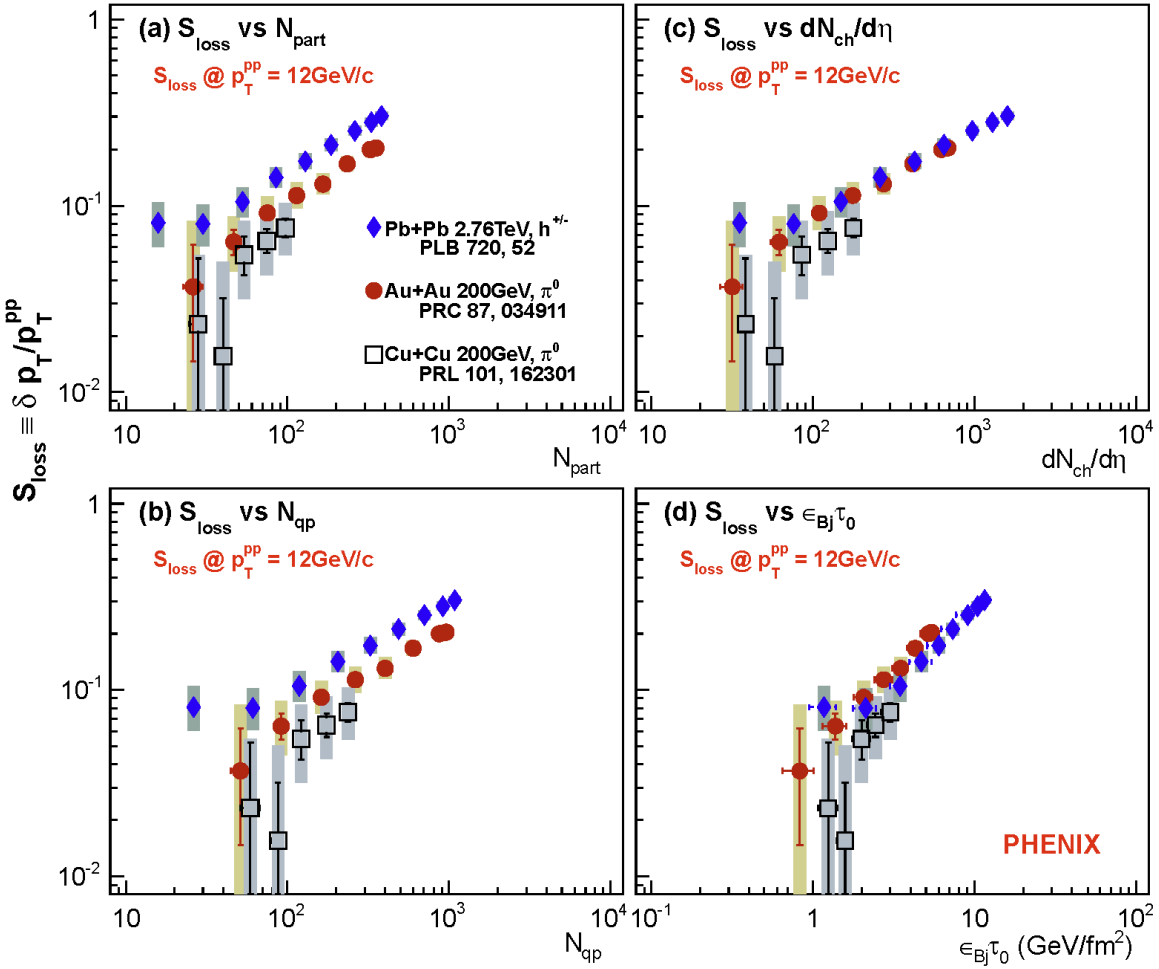


Fractional momentum loss of hadrons

- Plotted S_{loss} for various collision systems as a function of N_{part}, N_{qp} (number of quark participants), $dN_{ch}/d\eta$ and $\varepsilon_{BJ}\tau_0$.
  - Pb+Pb 2.76TeV
  - Au+Au 200 GeV
  - Cu+Cu 200 GeV
- p_T^{pp}=12GeV/c
  - Hard scattering regime
- Found the S_{loss} best scales with $dN/d\eta$.

π^0 and $h^{+/-}$

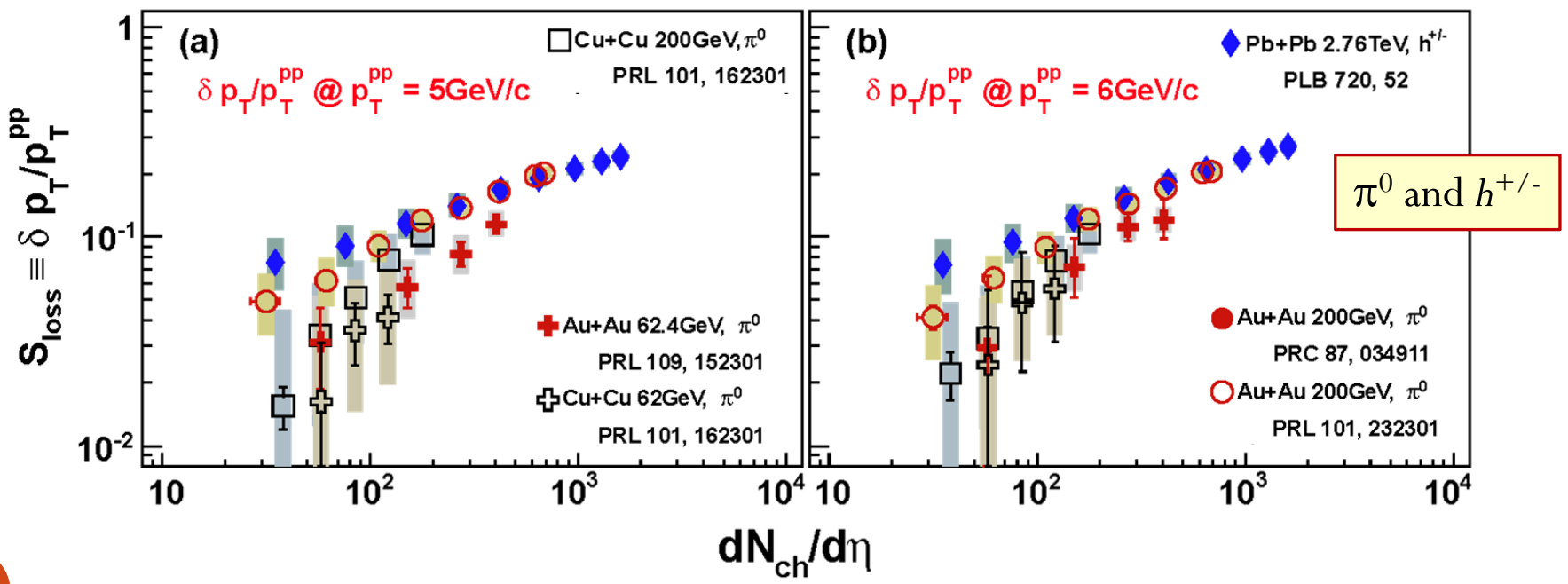
PHENIX, PRC93, 024911 (2016)



Fractional momentum loss of hadrons

- Plotted S_{loss} for 62GeV Au+Au and Cu+Cu, too.

PHENIX, PRC93, 024911 (2016)

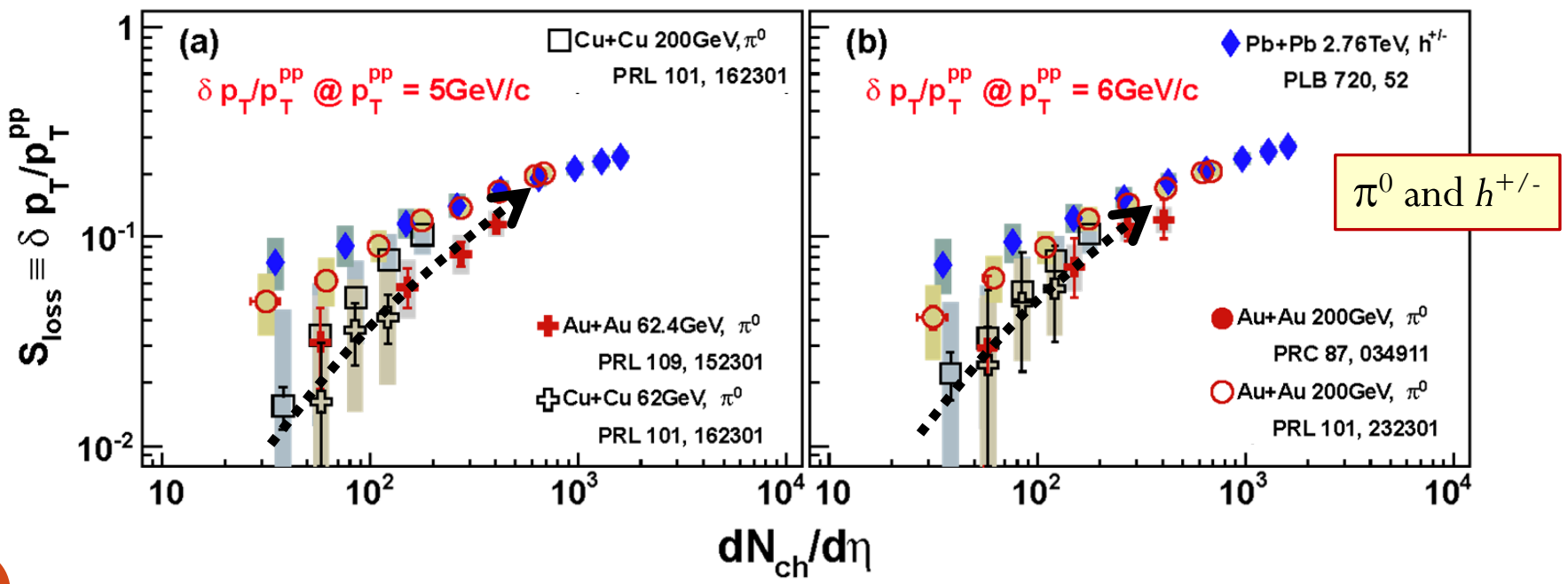


π^0 and $h^{+/-}$

Fractional momentum loss of hadrons

- Plotted S_{loss} for 62GeV Au+Au and Cu+Cu, too.
- They tend to merge into 2.76TeV and 200GeV points at highest $dN_{ch}/d\eta$.
- **If we trigger ultra-central events at 62GeV (0-1%?), the system is as hot as 2.76TeV?**

PHENIX, PRC93, 024911 (2016)



Critical Point search via HBT correlation

Levy source dist. instead of Gauss?

- Gauss function has been used to determine the source size in HBT correlation function.

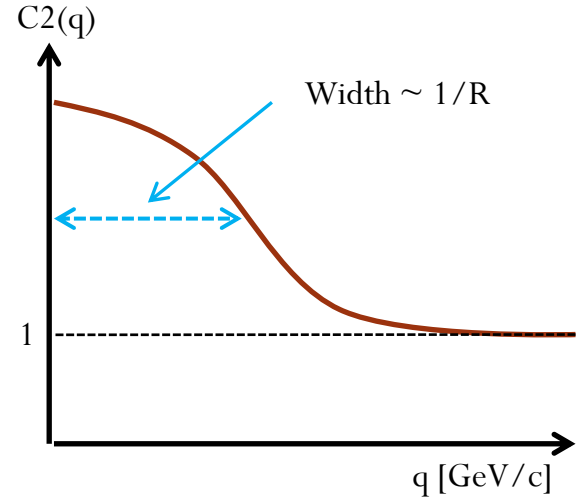
- For describing the expanding system with anomalous diffusion, Levy distribution is suggested as source function.

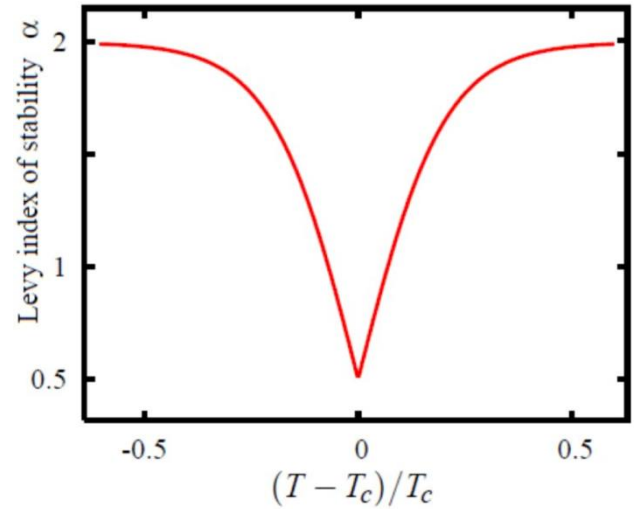
$$\mathcal{L}(\alpha, R, r) = \frac{1}{(2\pi)^3} \int d^3q e^{iqr} e^{-\frac{1}{2}|qR|^\alpha}$$

$$\rightarrow C_2(q) = 1 + \lambda \cdot e^{-(Rq)^\alpha}$$

α=2: Gaussian (hydro limit)
α=1: exponential

- Critical exponent (η) in 3D Ising model can be associated with the exponent α.
  - η~0.5 for random field 3D Ising
    - PLB52(1995)6659
  - Finite size effect is not taken into account.

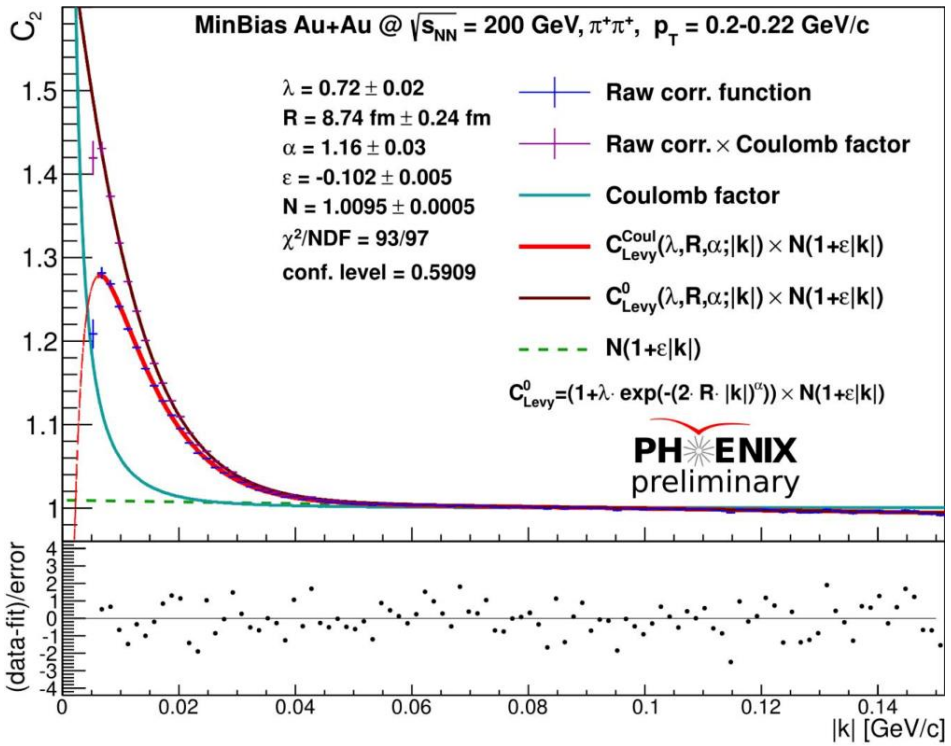


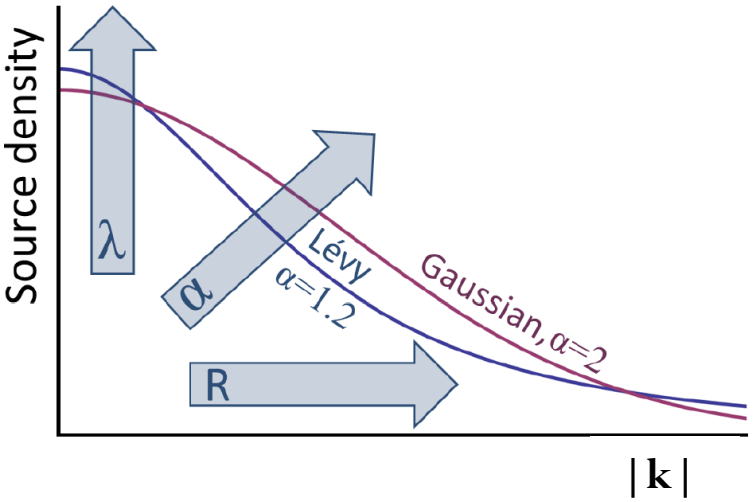


Levy-stable fit to correlation functions

- Fit to the correlation function with Levy-stable source function
  - Coulomb effect is estimated and corrected for in the fitting process.

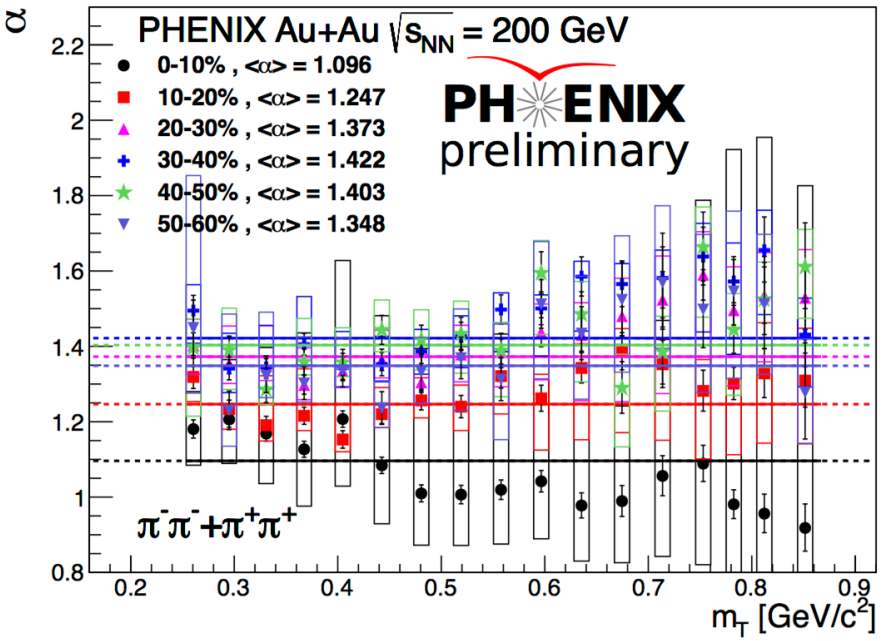
- Shape change of the correlation function depends on the λ, α and R.

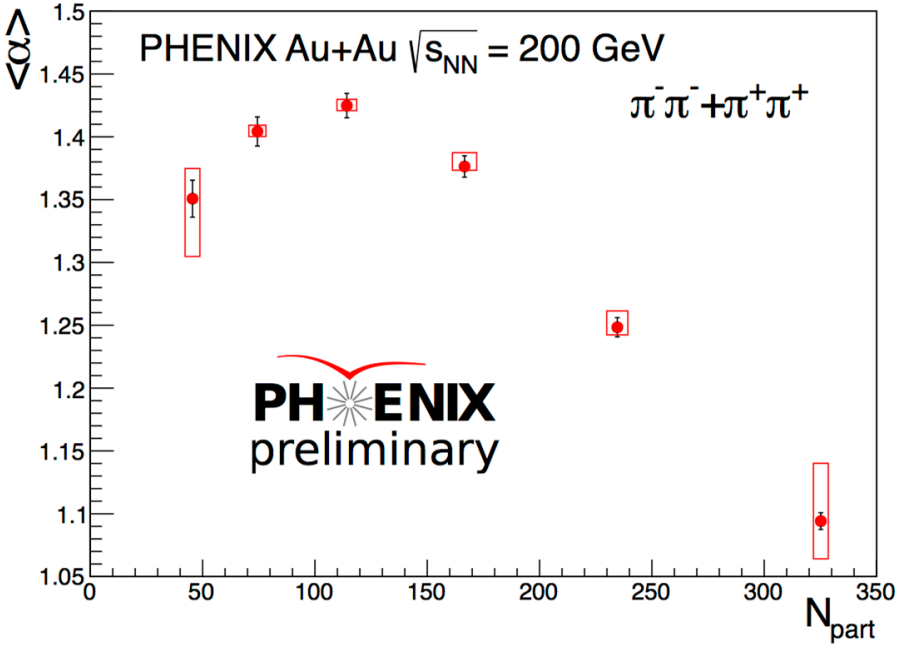




Search for Critical behavior

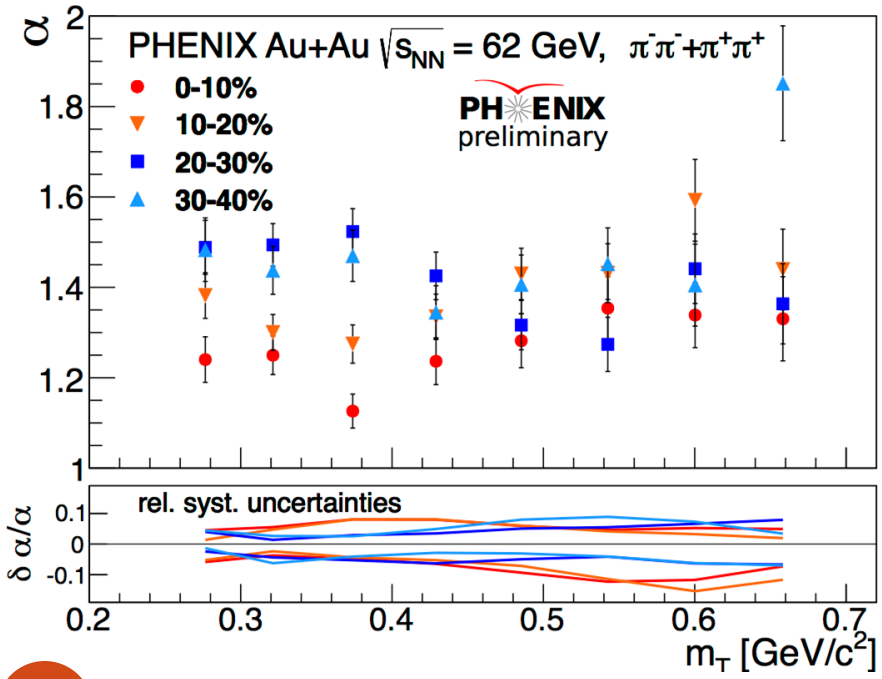
- α in Levy function fit for 200GeV as a function of m_T and centrality
  - α is averaged over the m_T ranges.
- All the α fall in between 1 and 1.5 independent of centrality.
  - $\alpha<1$ can be CP, 1.0 is exponential, and 2.0 is Gaussian (hydro limit).

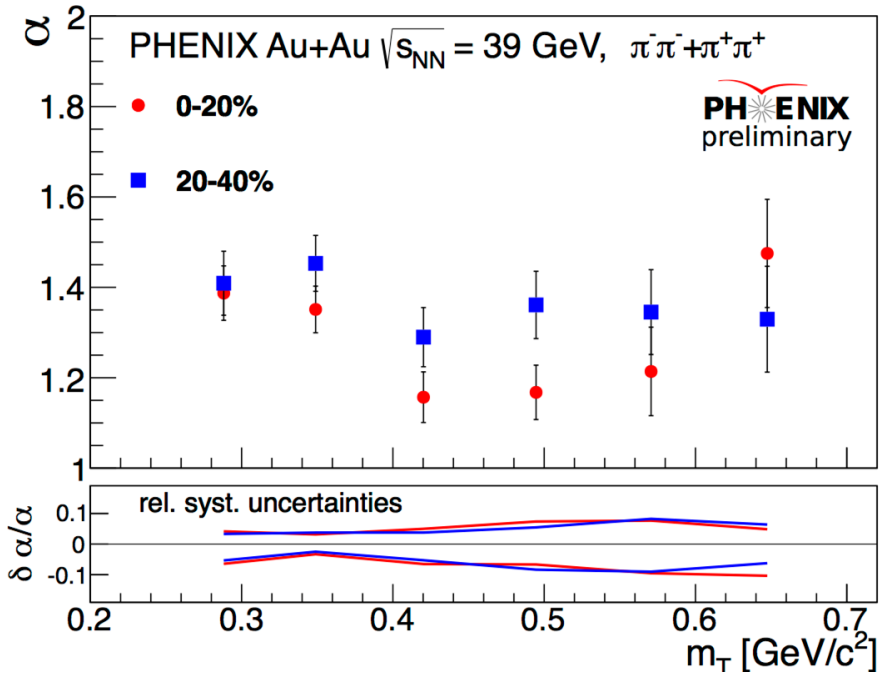




Search for Critical behavior

- α in Levy function fit for 62 and 39GeV as a function of m_T and centrality
- All the α still fall in between 1 and ~1.5.
  - **No critical behavior is seen in 200, 62 and 39GeV..**
  - Now investigating lower energy data ($\sqrt{s_{NN}}$<39GeV)





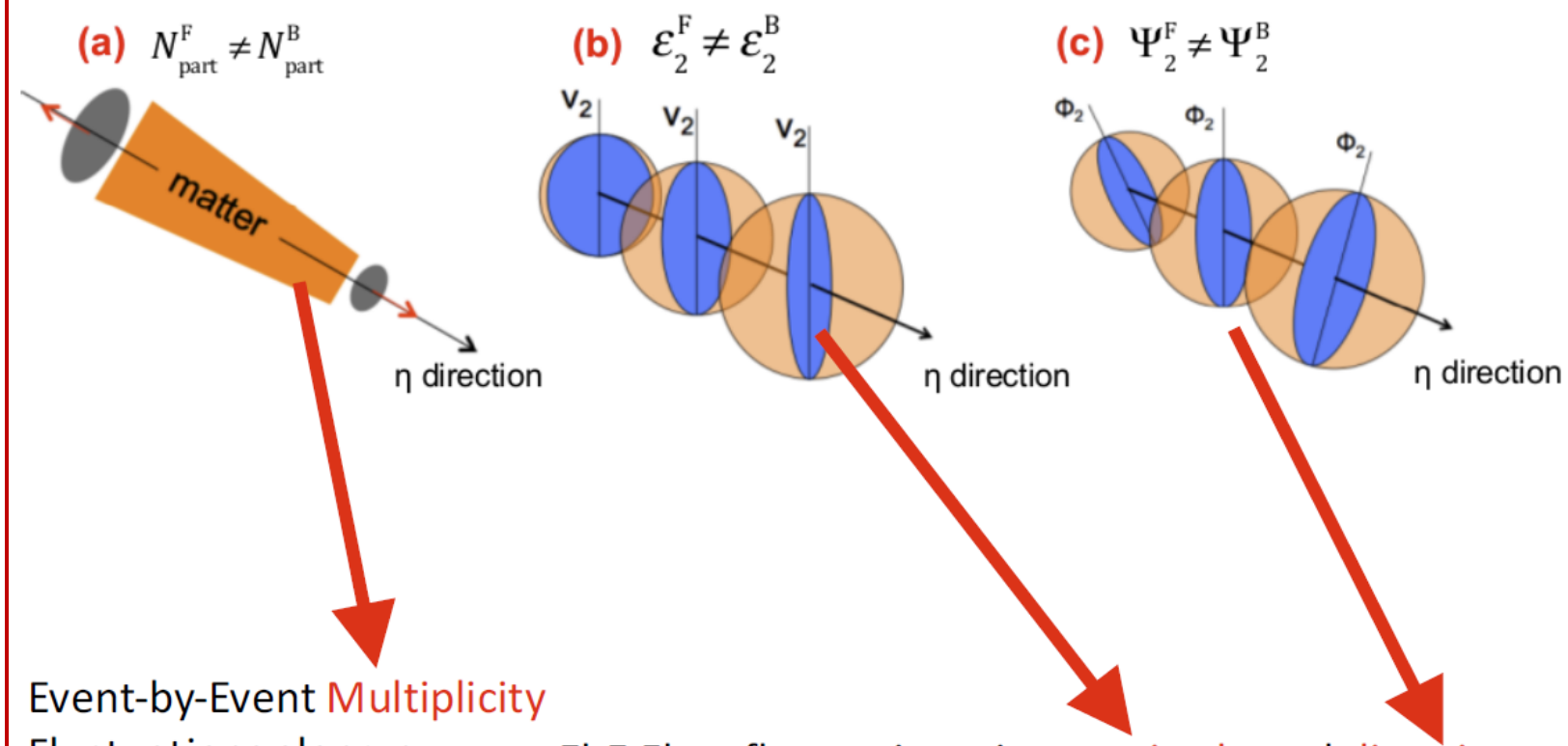
Longitudinal dynamics of the system

Longitudinal development of eventplane

Asymmetric participant:
$N_{part}(\eta) \neq N_{part}(-\eta)$

Event plane de-correlation

Event plane twist



Event-by-Event Multiplicity Fluctuations along η.

EbE Flow fluctuations, in magnitude and direction along η.

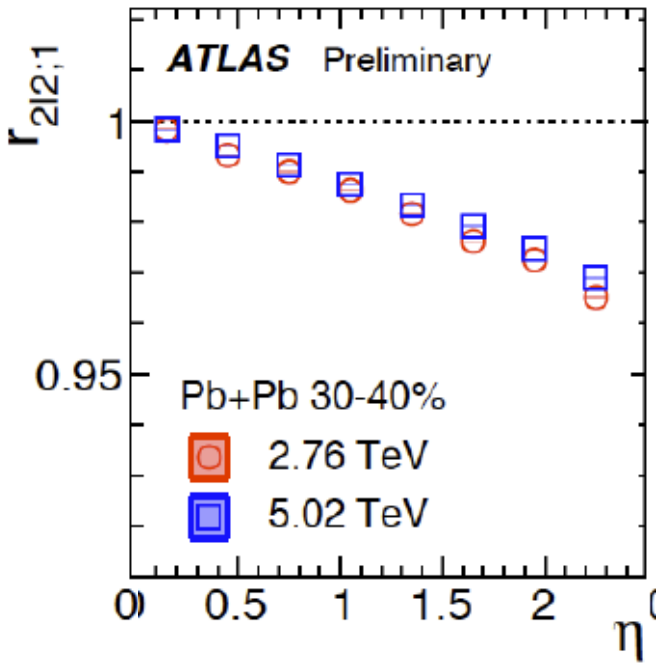
Slide from S. Mohapatra at QM17

De-correlation/twist measured by ATLAS

Plots from S. Mohapatra at QM17

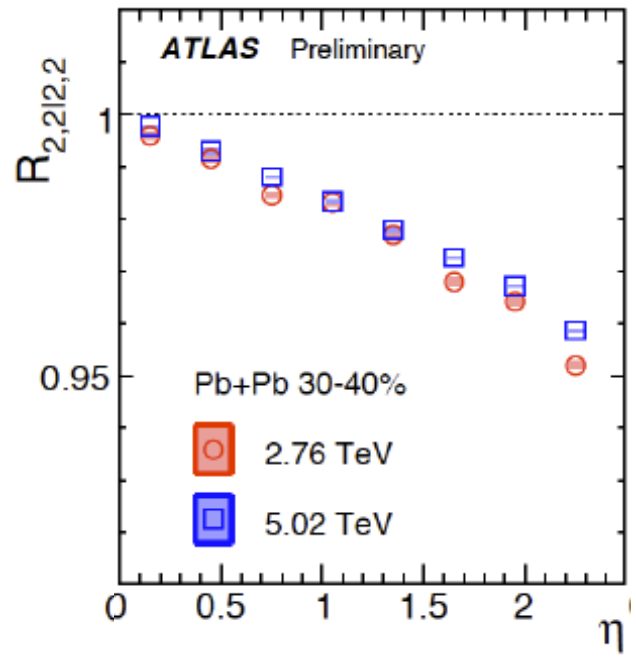
Correlator sensitive to both eventplane twist and magnitude de-correlation

$$r_{n|n;k} = \frac{\langle q_{n(-\eta)}^{k} q_{n}^{*k}(\eta_{ref})\rangle}{\langle q_{n(+\eta)}^{k} q_{n}^{*k}(\eta_{ref})\rangle}$$



Correlator sensitive only to eventplane twist

$$R_{n,n|n,n} = \frac{\langle q_n(-\eta_{ref}) q_n(-\eta) q_n^{*}(+\eta) q_n^{*}(\eta_{ref})\rangle}{\langle q_n(-\eta_{ref}) q_n(+\eta) q_n^{*}(-\eta) q_n^{*}(\eta_{ref})\rangle}$$

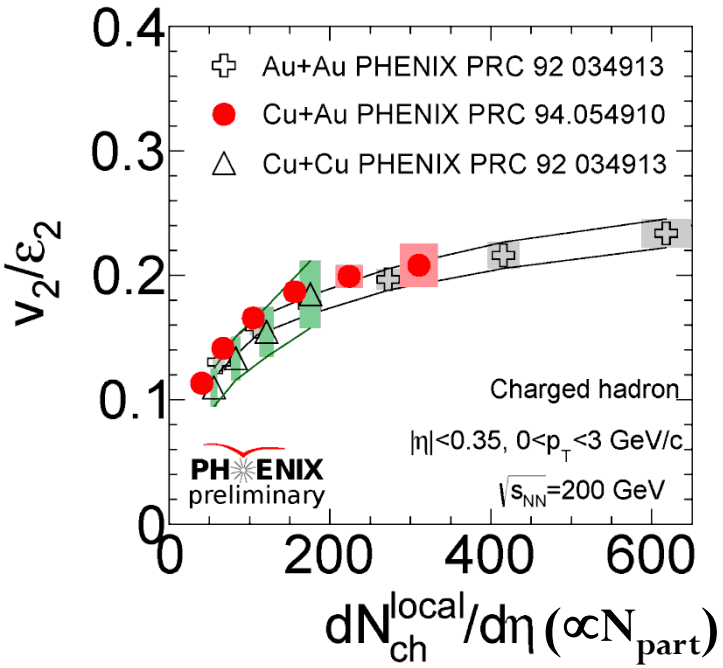


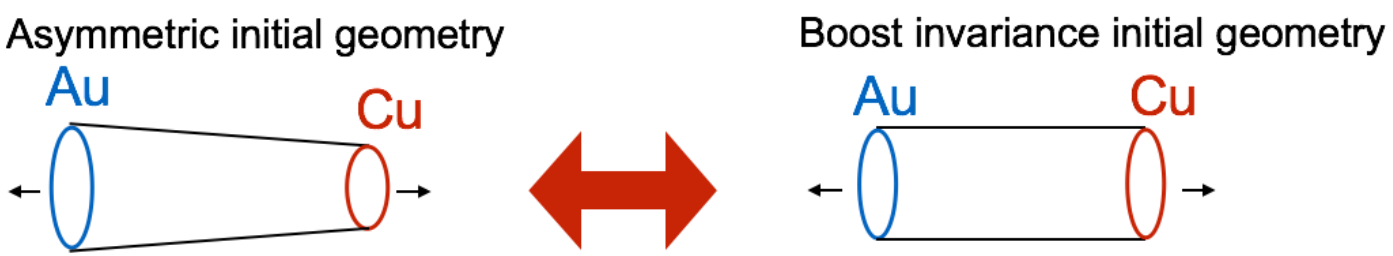
n=2 case

- More de-correlation/twist is seen in lower energy.
  - RHIC would see more drastic effect?

PHENIX observation of eccentricity vs η

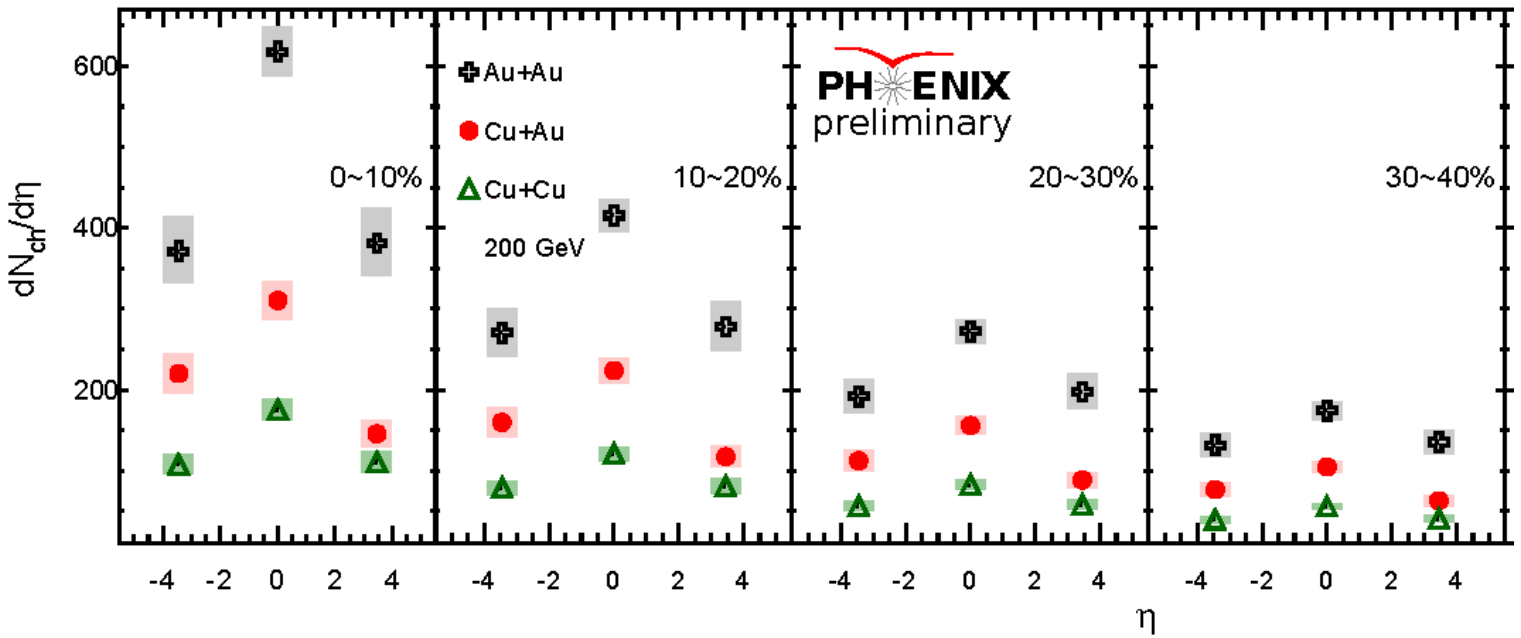
- We observed that the v_2 / ε_2 scales with $dN_{ch}/d\eta$ at mid-rapidity.
  - $dN_{ch}/d\eta$ is a measure of energy density.
- How about the flow at for(back)ward?
  - Does it scale with which $dN_{ch}/d\eta$ and which eccentricity?
- Cu+Au collisions can produce different eccentricity and energy density depending on rapidity.
  - A good lab to test





$dN_{ch}/d\eta$ vs η in Cu+Au

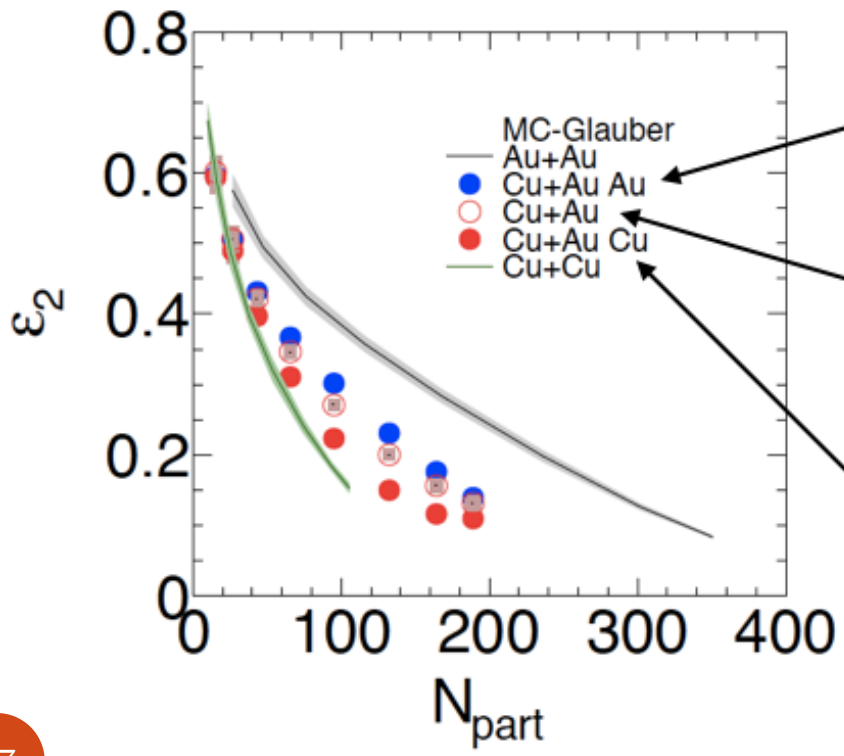
- We have measured $dN_{ch}/d\eta$ as a function of η in Au+Au, Cu+Cu and Cu+Au collisions.
  - Up to 60% centrality. Shown are up to 40%
- Cu-going direction (positive η) has lower $dN_{ch}/d\eta$ in Cu+Au collisions.

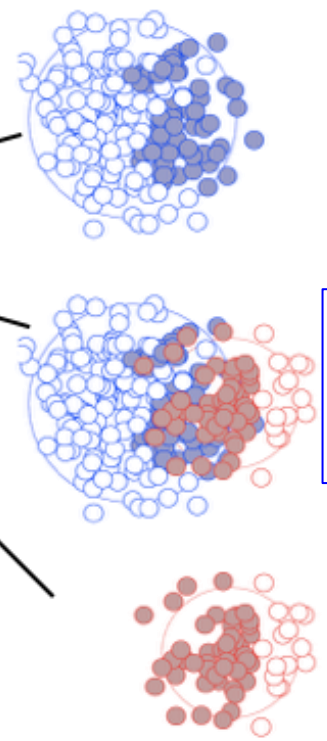


Eccentricity calculations

- For given centralities ($\propto N_{part}$), three types of eccentricities were calculated using a Glauber MC.
  - $\varepsilon_{n,\,Au}$, $\varepsilon_{n,\,Cu}$, $\varepsilon_{n,\,Cu+Au}$

$$\varepsilon_{n,\mathrm{Au(Cu)}} = \frac{\langle r^n \cos[n(\phi_{\mathrm{Au(Cu)}} - \Phi_{n,\mathrm{Cu+Au}})]\rangle}{\langle r^n \rangle}$$





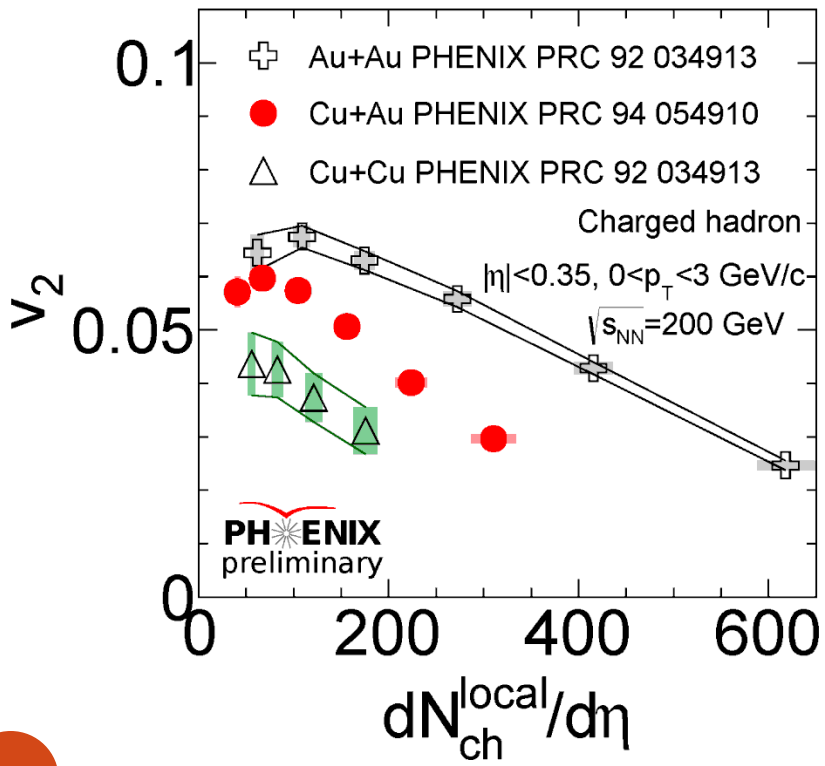
$\varepsilon_{n,Au}$: **Use only participants which belong to Au nuclei**

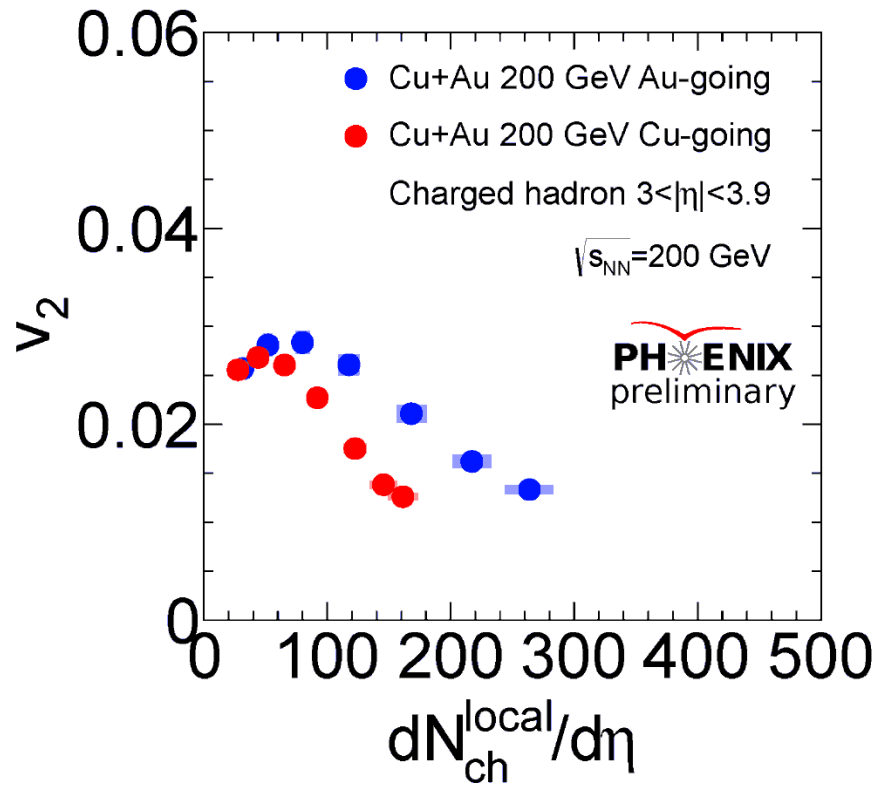
$\varepsilon_{n,CuAu}$: **Use all participants (common participant ε)**

$\varepsilon_{n,Cu}$: **Use only participants which belong to Cu nuclei**

V_2 at mid and for(back)ward rapidity

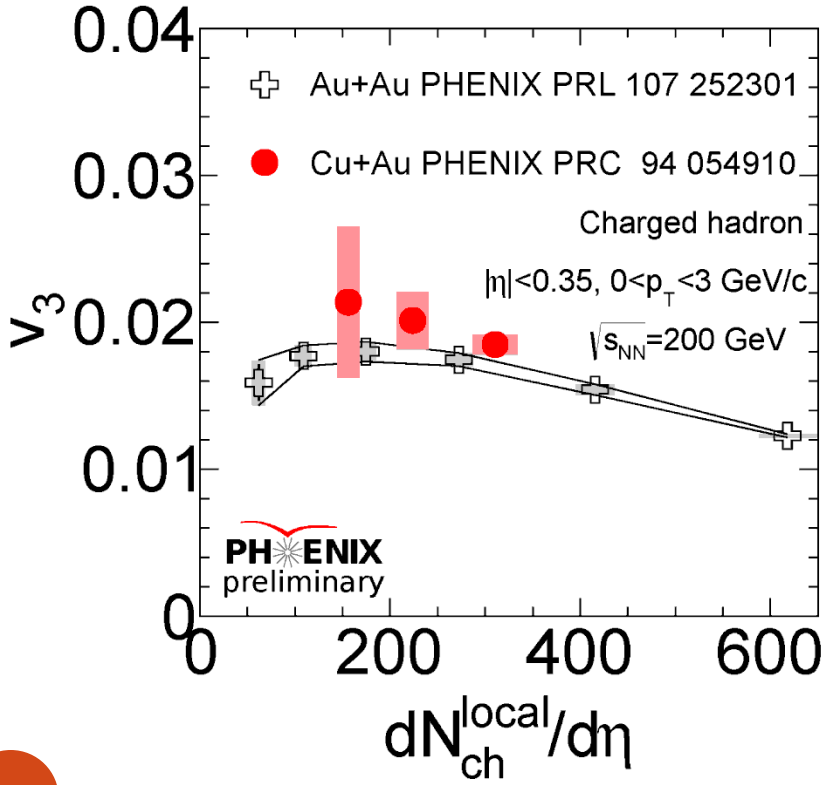
- v_2 ($dN/d\eta$) at Au-going $\neq$ v_2 ($dN/d\eta$) at Cu-going
- $dN_{ch}^{local}/d\eta$: $dN_{ch}/d\eta$ at the rapidity of measurement
  - A measure of the energy density at the given rapidity

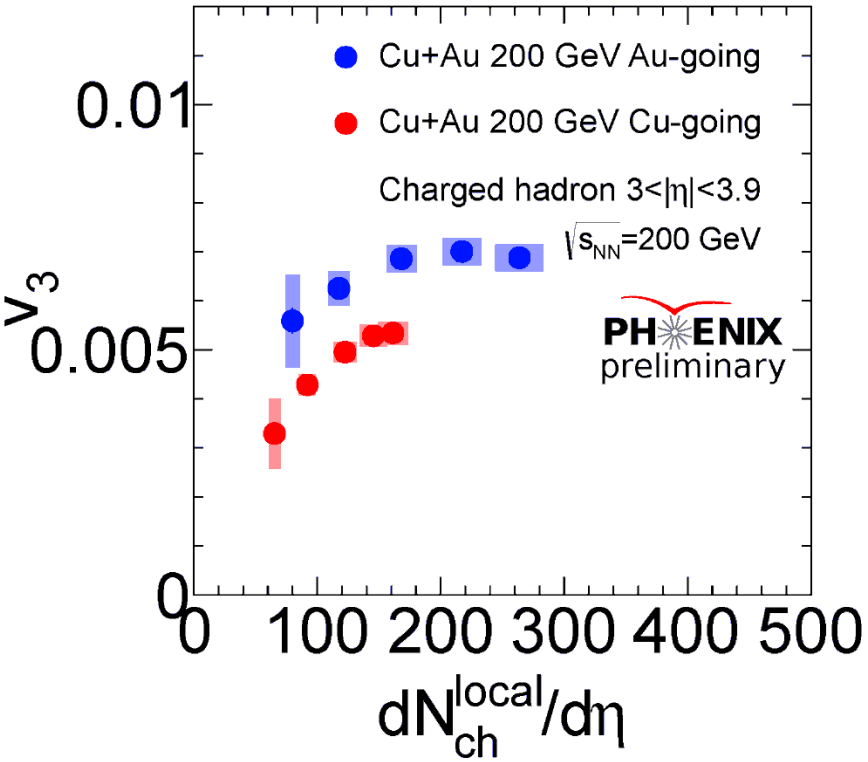




V_3 at mid and for(back)ward rapidity

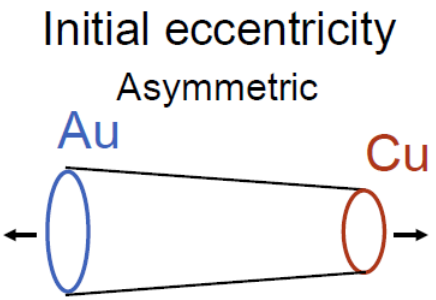
- v_3 (dN/dη) at Au-going ≠ v_3 (dN/dη) at Cu-going
- $dN_{ch}^{local}/d\eta$: $dN_{ch}/d\eta$ at the rapidity of measurement
  - A measure of the energy density at the given rapidity



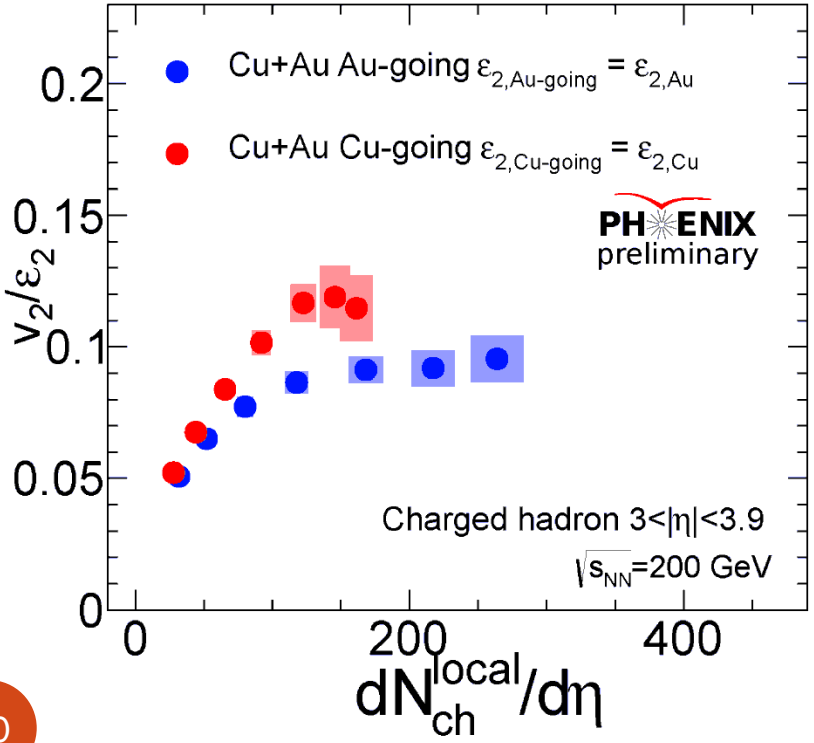


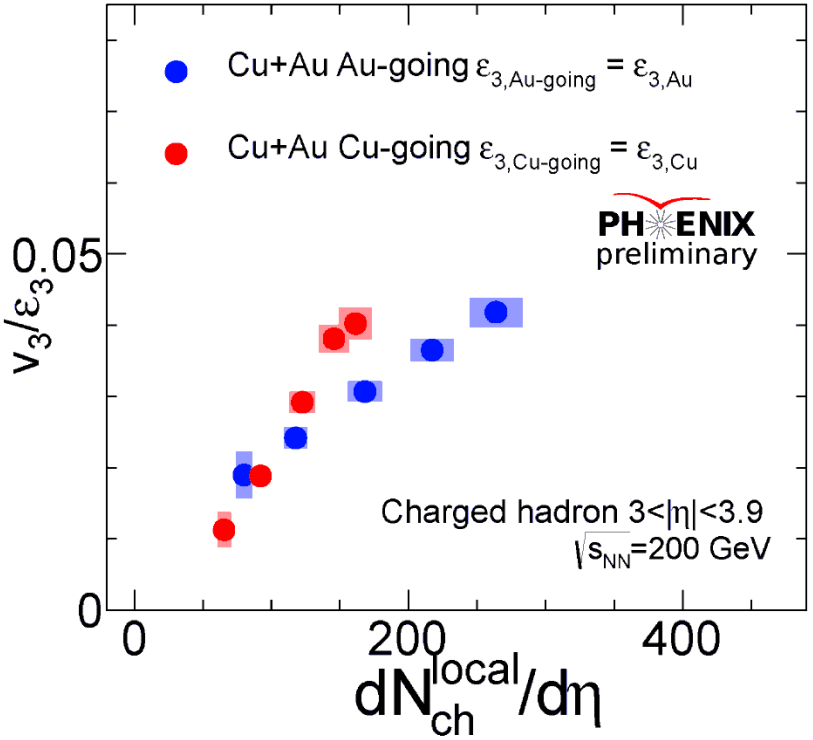
Testing eccentricity scaling (I)

- Individual eccentricity case
  - v_n/ε_n (Au-going): $v_n/\varepsilon_{n,\,Au}$
  - v_n/ε_n (Cu-going): $v_n/\varepsilon_{n,\,Cu}$



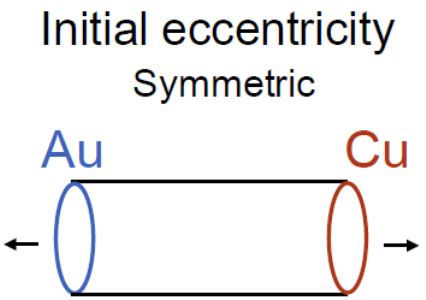
- Forward and backward v_n/ε_n don't scale with $dN_{ch}^{local}/d\eta$.



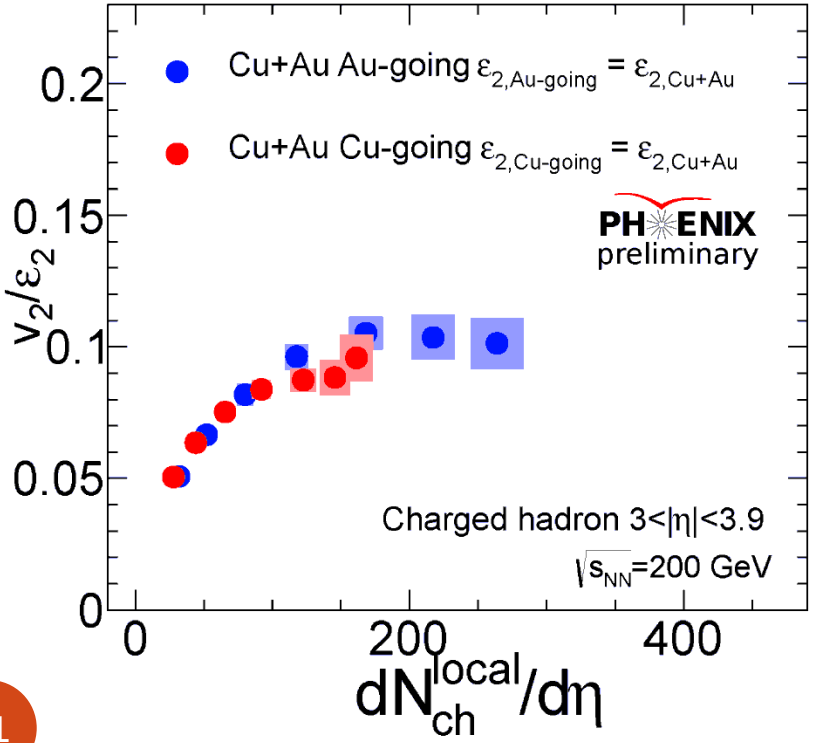


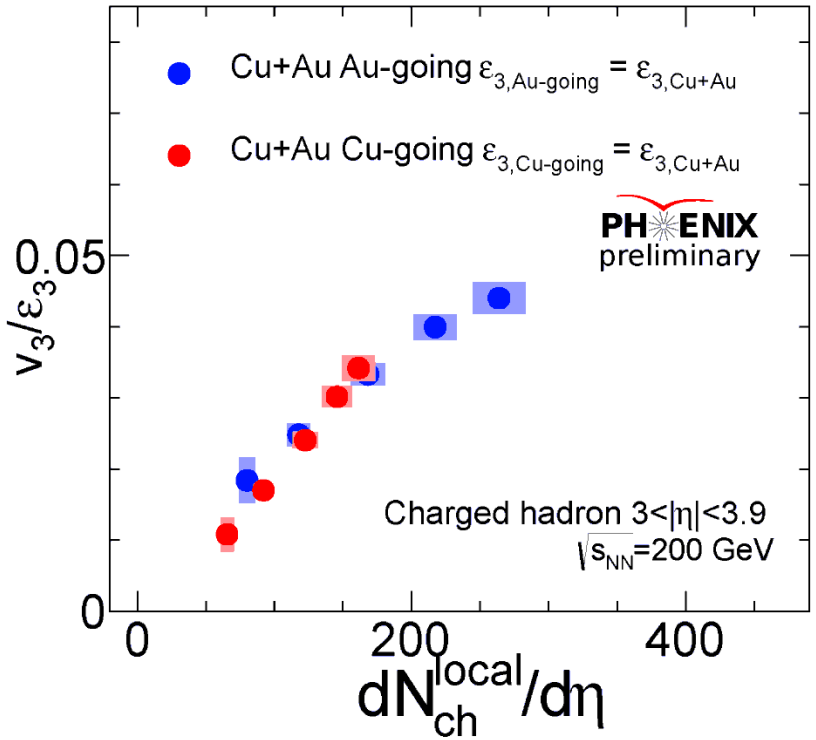
Testing eccentricity scaling (II)

- Common eccentricity case
  - v_n/ε_n (Au-going): $v_n/\varepsilon_{n,\,Cu+Au}$
  - v_n/ε_n (Cu-going): $v_n/\varepsilon_{n,\,Cu+Au}$



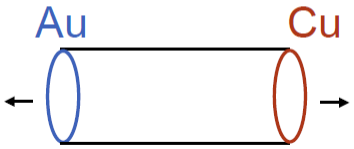
- Forward and backward v_n/ε_n scale with $dN_{ch}^{local}/d\eta$.



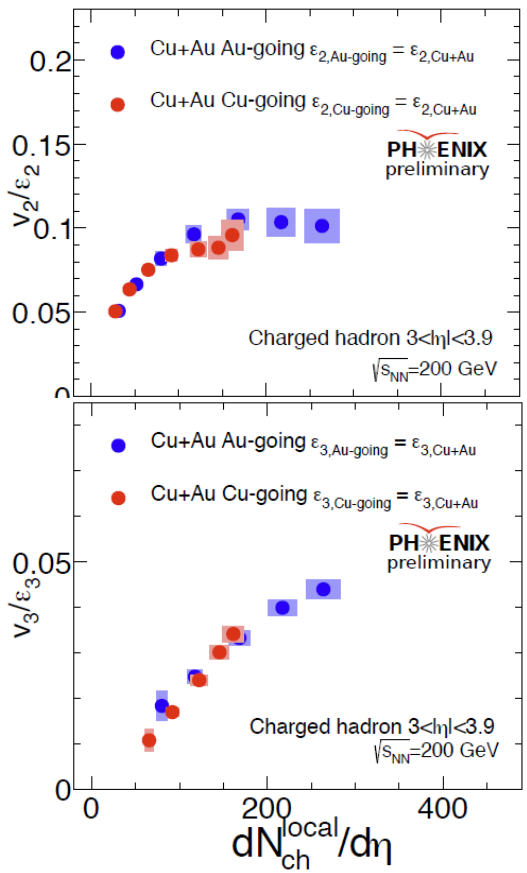


Decorrelation not seen at RHIC?

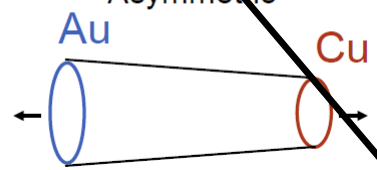
Initial eccentricity
Symmetric



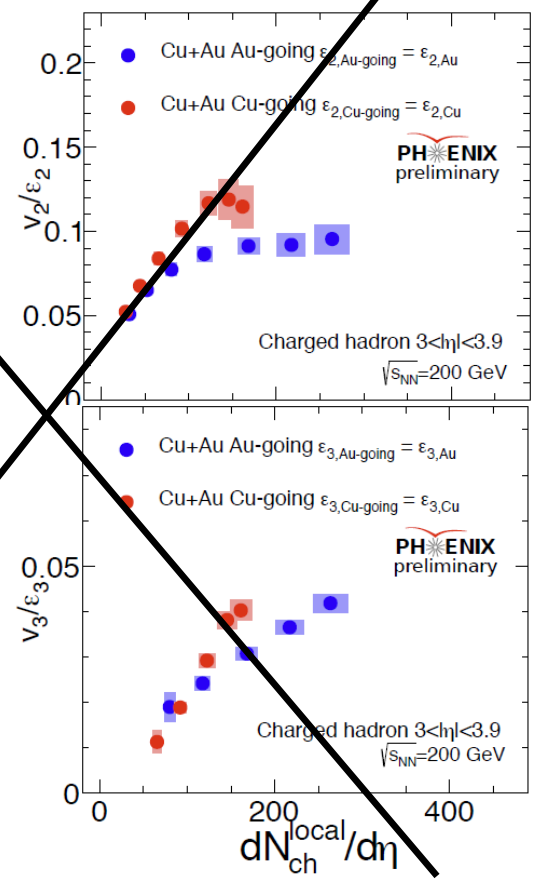
$v_{n,\text{Au-going}}/\varepsilon_{n,\text{Cu+Au}}$
=
$v_{n,\text{Cu-going}}/\varepsilon_{n,\text{Cu+Au}}$



Initial eccentricity
Asymmetric



$v_{n,\text{Au-going}}/\varepsilon_{n,\text{Au}}$
≠
$v_{n,\text{Cu-going}}/\varepsilon_{n,\text{Cu}}$



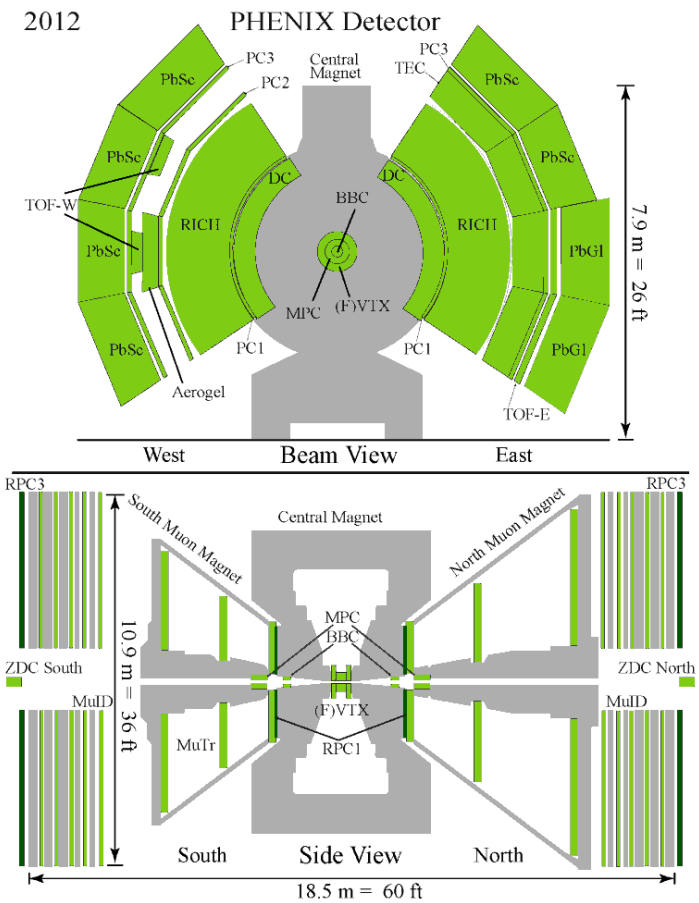
- Initial geometry is common over rapidity.
- No de-correlation of eccentricity is observed. Contradictory to LHC results?

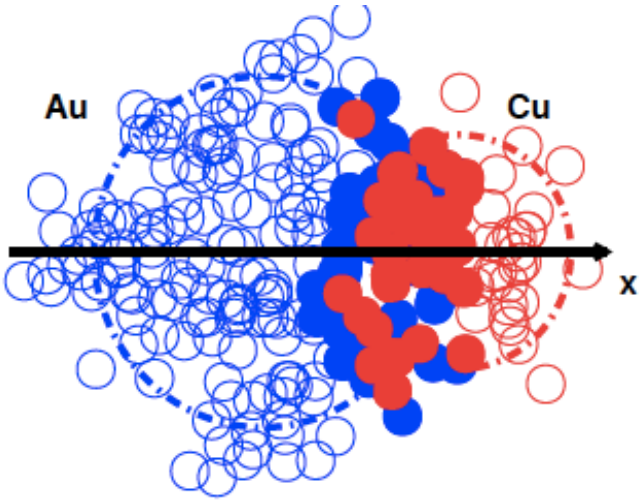
Summary

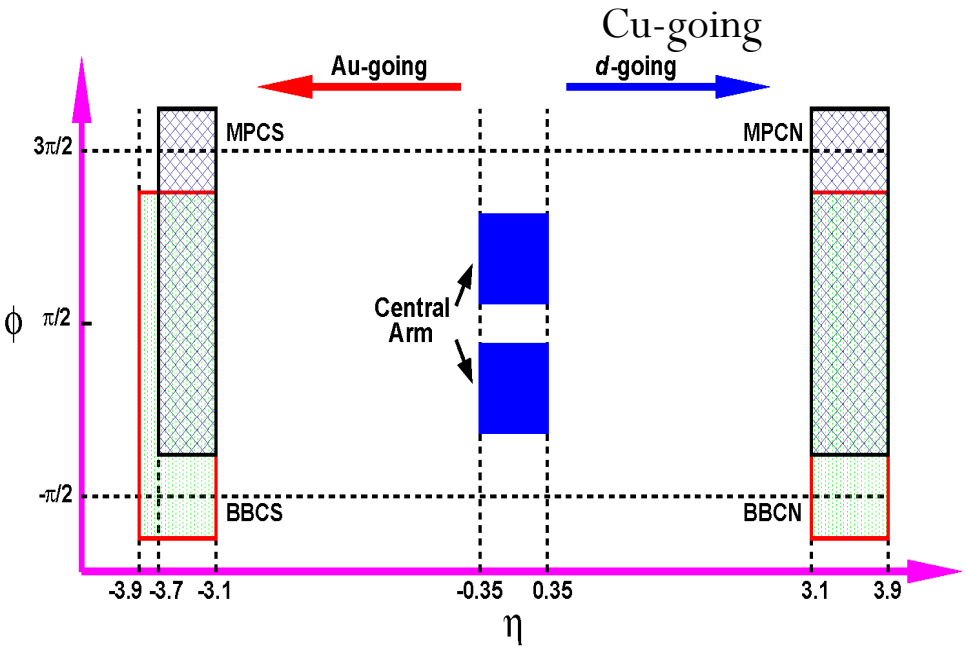
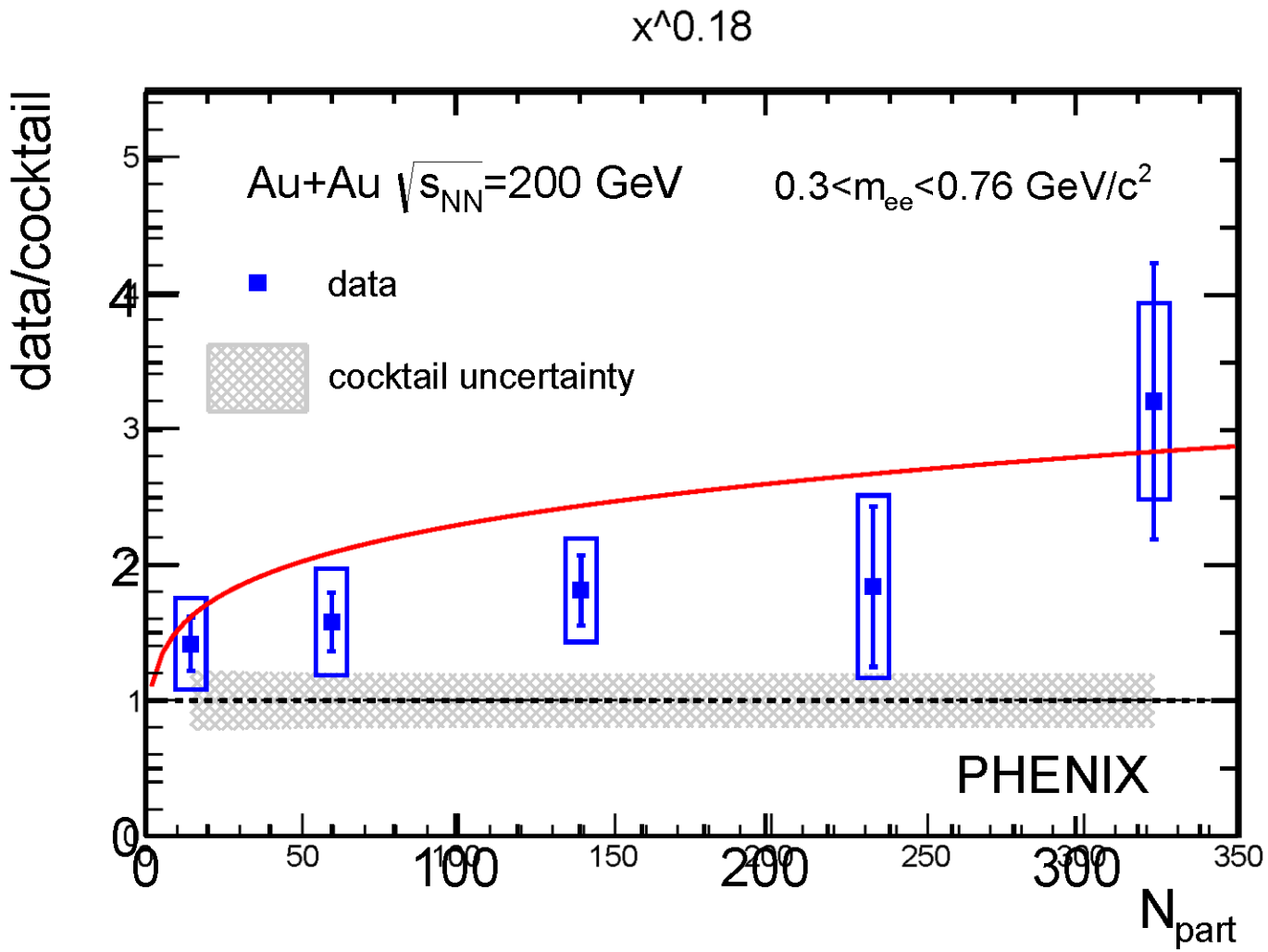
- At RHIC, we can explore lower energy, and higher baryon density QGP.
- Direct photons were measured in 200, 62.4 and 39GeV Au+Au and 200GeV Cu+Cu collisions.
  - $dN/d\eta$ for photons scales with $N_{part}^{1.35}$, while $dN/d\eta$ for π^0 is $\propto N_{part}^{1.17}$.
- Fractional momentum loss of leading hadrons scales nicely with $dN_{ch}/d\eta$ over wide range of energies.
- Levy-inspired function was applied to HBT correlations.
  - No critical behavior was found in 200, 62.4 and 39GeV Au+Au collisions.
- Flow at for(back)ward rapidity in Cu+Au collisions scales with common eccentricity and local energy density.
  - No de-correlation of eccentricity was observed.
  - Contradictory to the LHC observations?

Backup

Detector


2012
PHENIX Detector
PC3
Central Magnet
PC3
TEC
PC2
PbSc
PbSc
PbSc
PbSc
PbSc
PbSc
TOF-W
DC
DC
BBC
RICH
RICH
PbGl
PbGl
MPC
(F)VTX
PC1
PC1
Aerogel
TOF-E
7.9 m = 26 ft
West
Beam View
East
RPC3
RPC3
South Muon Magnet
North Muon Magnet
Central Magnet
MPC
BBC
ZDC South
ZDC North
MuID
MuID
(F)VTX
MuTr
RPC1
10.9 m = 36 ft
South
Side View
North
18.5 m = 60 ft


Au
Cu
x


Cu-going
Au-going
d-going
MPCS
MPCN
3π/2
π/2
-π/2
ϕ
Central Arm
BBCS
BBCN
-3.9
-3.7
-3.1
-0.35
0.35
3.1
3.9
η

Comparing with dilepton result