Detailed study of parton energy loss via measurement of fractional momentum loss of high p_T hadrons in heavy ion collisions

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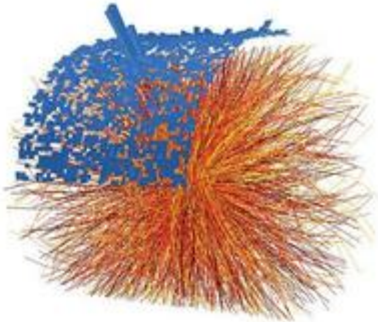


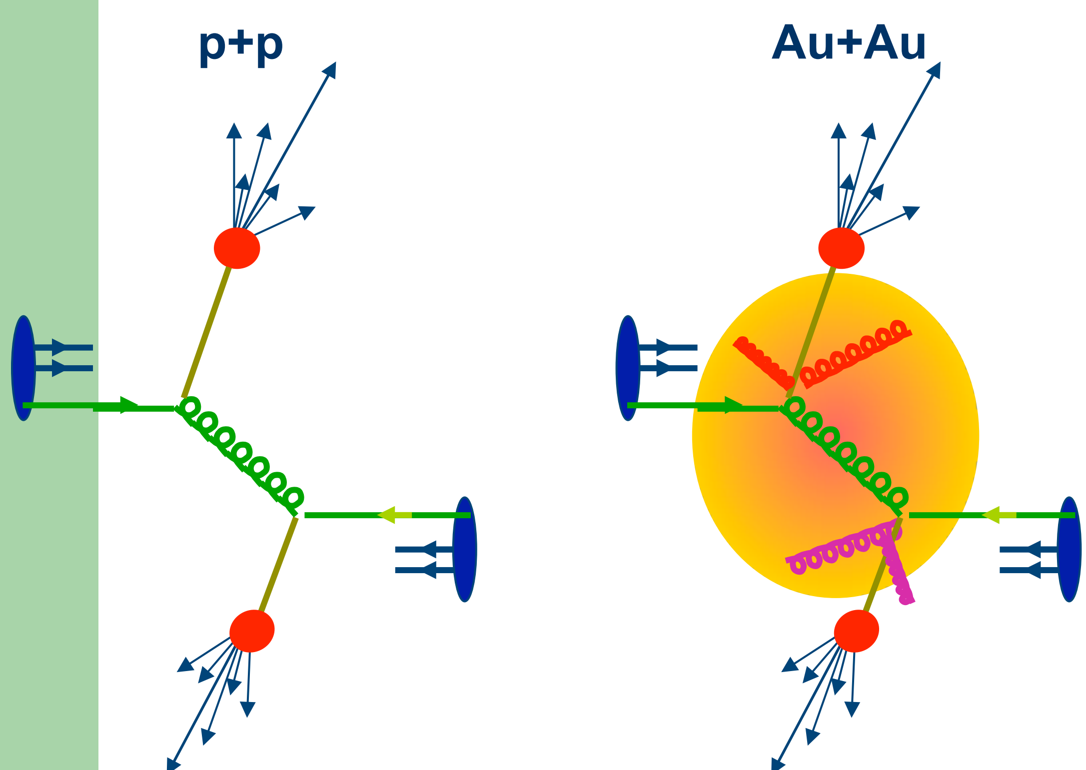
10th International Workshop on High-pT Physics in the RHIC/LHC era

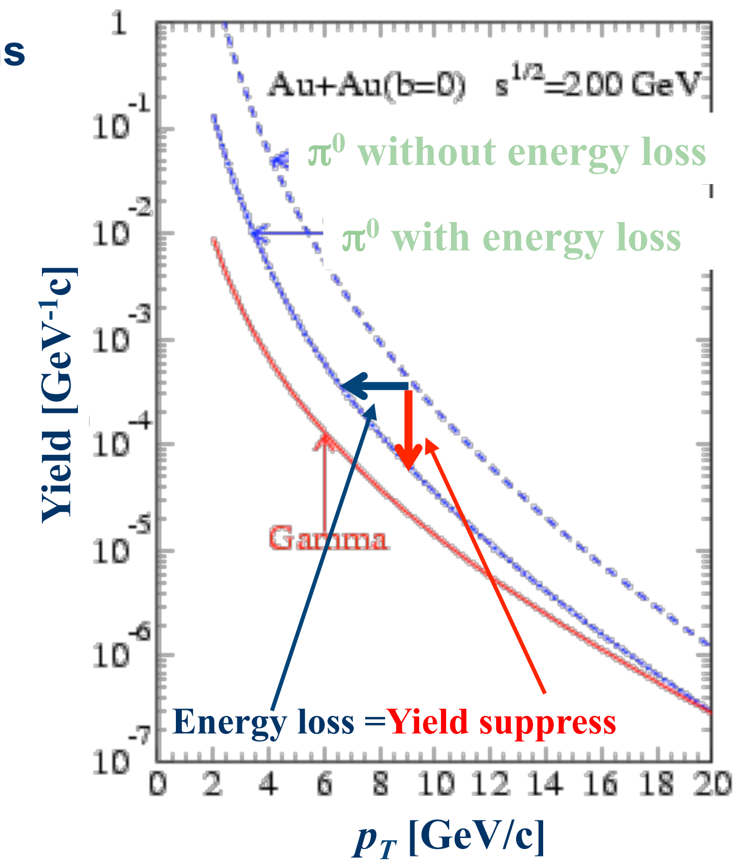
9-12 September 2014
SUBATECH Nantes
Europe/Paris timezone

Hard scattering as densimeter

- Parton may change its momentum in the medium.
  - Energy loss through Gluon radiation, etc..
- Effect is path-length and parton density dependent ~a densimeter~.
- Look at leading particles of jet as a measure of jet energy.

Cross section of A+B collisions ∝ AB × p+p collisions



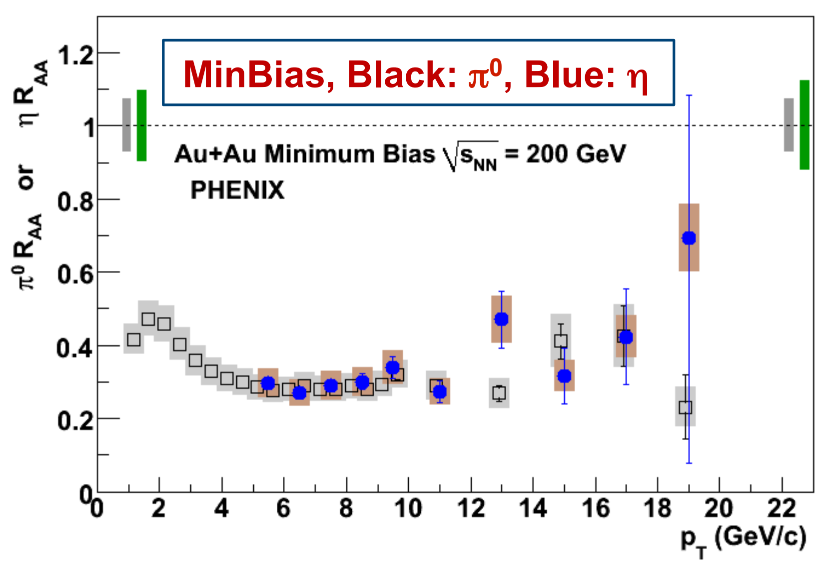


X.-N., Wang, PRC 58 (1998)2321

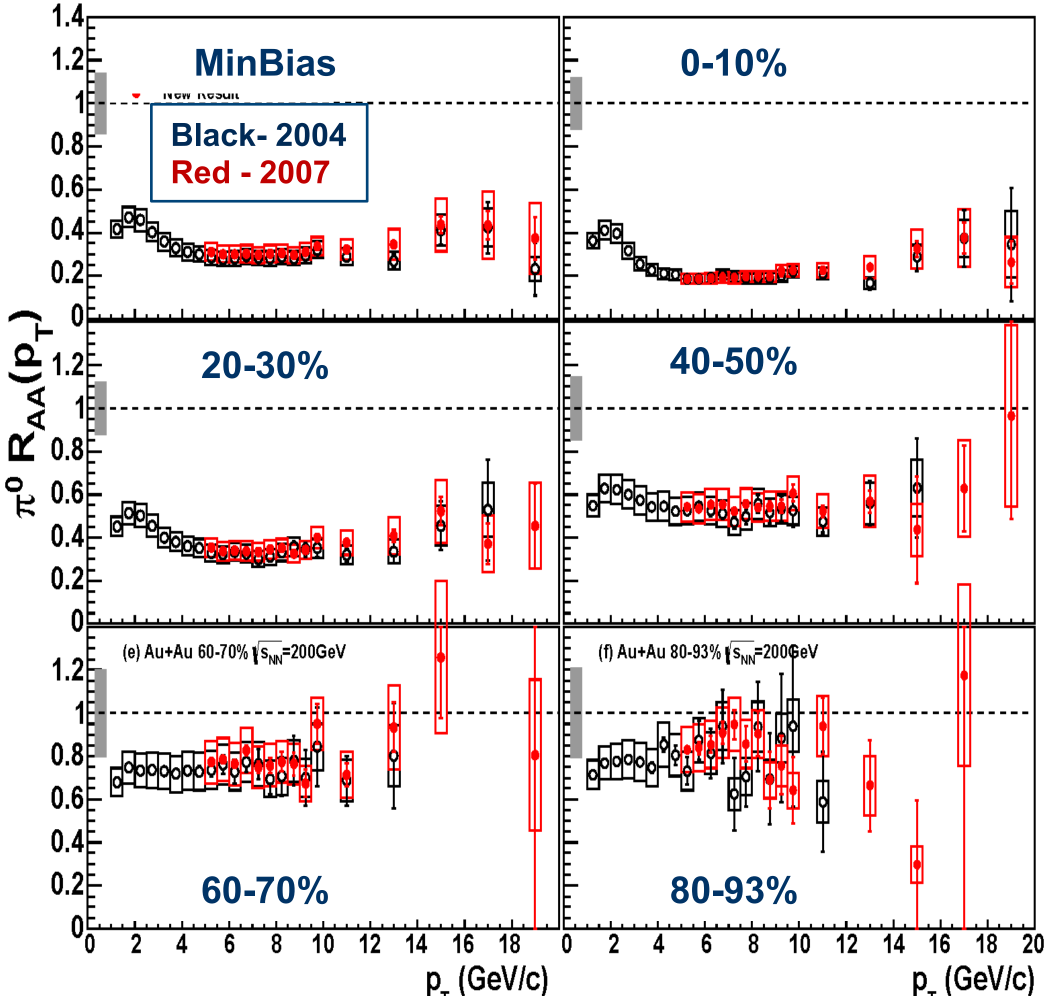
High p_T hadron R_{AA}

$$R_{AA} = \frac{(1/N_{evt}^{AA})(dN^{AA}/dp_T)}{\langle T_{AA}\rangle(d\sigma^{pp}/dp_T)}$$

- Measured in 200GeV Au+Au collisions.
- π^0 and η are very consistent.
- Results have been solid over years.



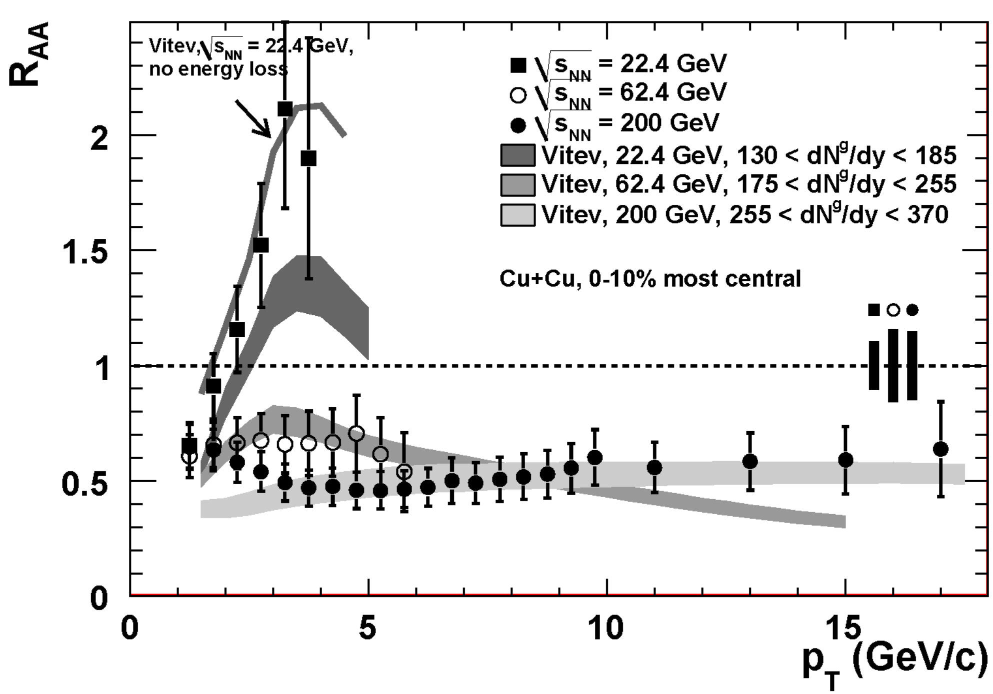
PRC82, 011902(R) (2010)



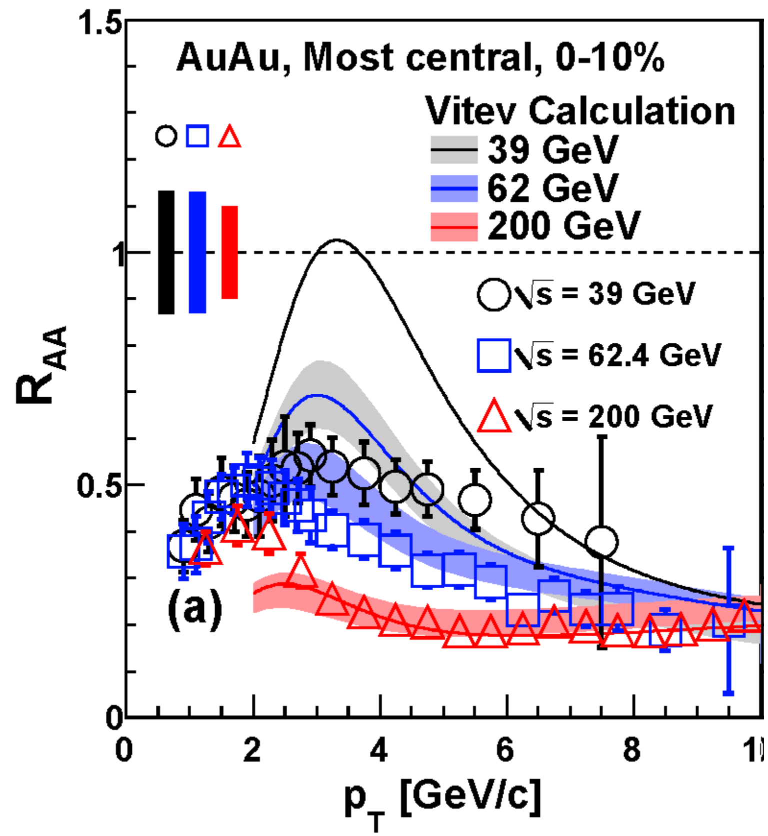
PRC87, 034911 (2013)

Collision energy dependence of R_{AA}

- π^0 in Cu+Cu @ 200, 62.4, 22.4GeV (RHIC Year-5)
  - 200GeV and 62GeV show suppression, and 22.4GeV shows enhancement (Cronin)
- π^0 in Au+Au @ 200, 62.4, 39GeV (RHIC Year-4, 7, 10)
  - Similar suppression at higher p_T



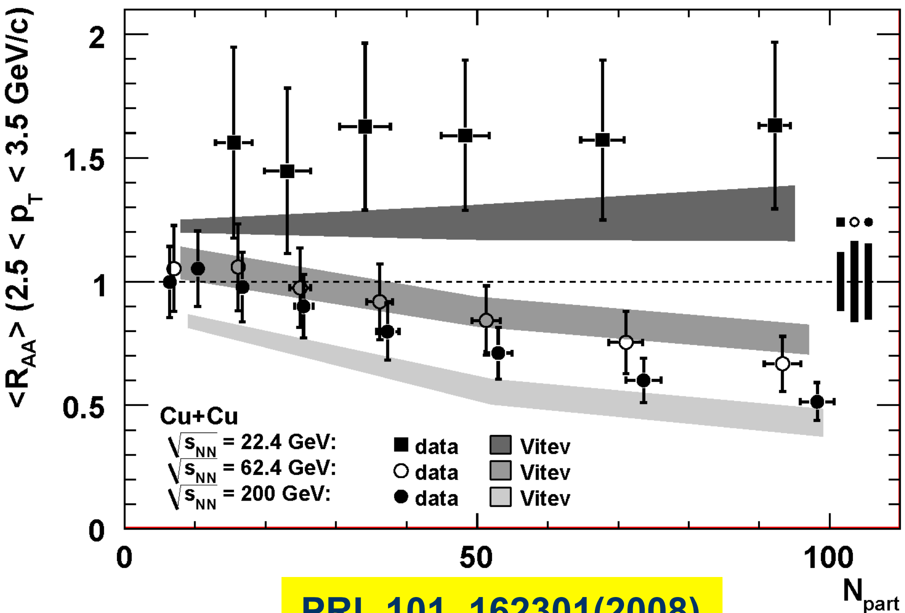
PRL 101, 162301(2008)



PRL109, 152301 (2012)

Centrality dependence of R_{AA}

- Centrality dependence of integrated π^0 R_{AA} was investigated in Cu+Cu and Au+Au collisions
  - As a function of cms energy
- Top: Cu+Cu:
  - $2.5<p_T<3.5$GeV/c
- Bottom: Au+Au
  - $p_T>6$GeV/c
- Indication of a switch of suppression and enhancement below 39GeV?



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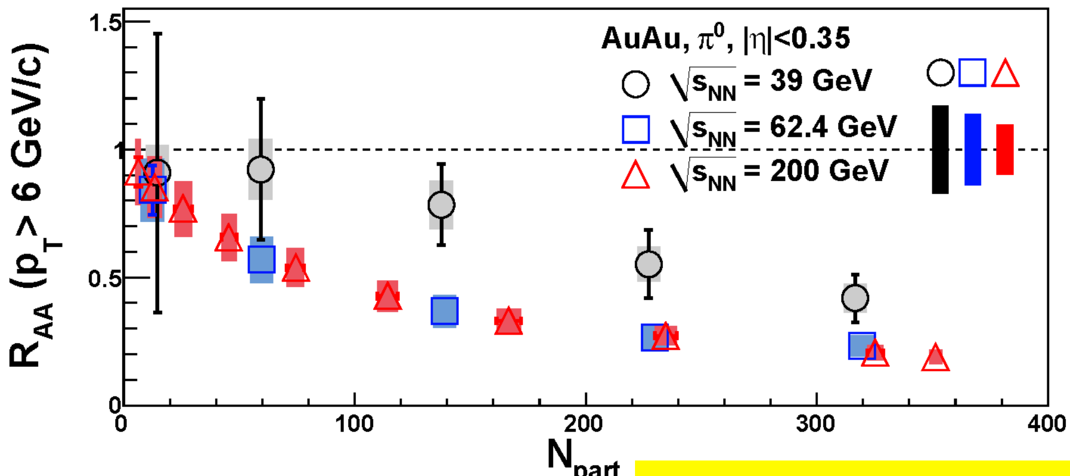
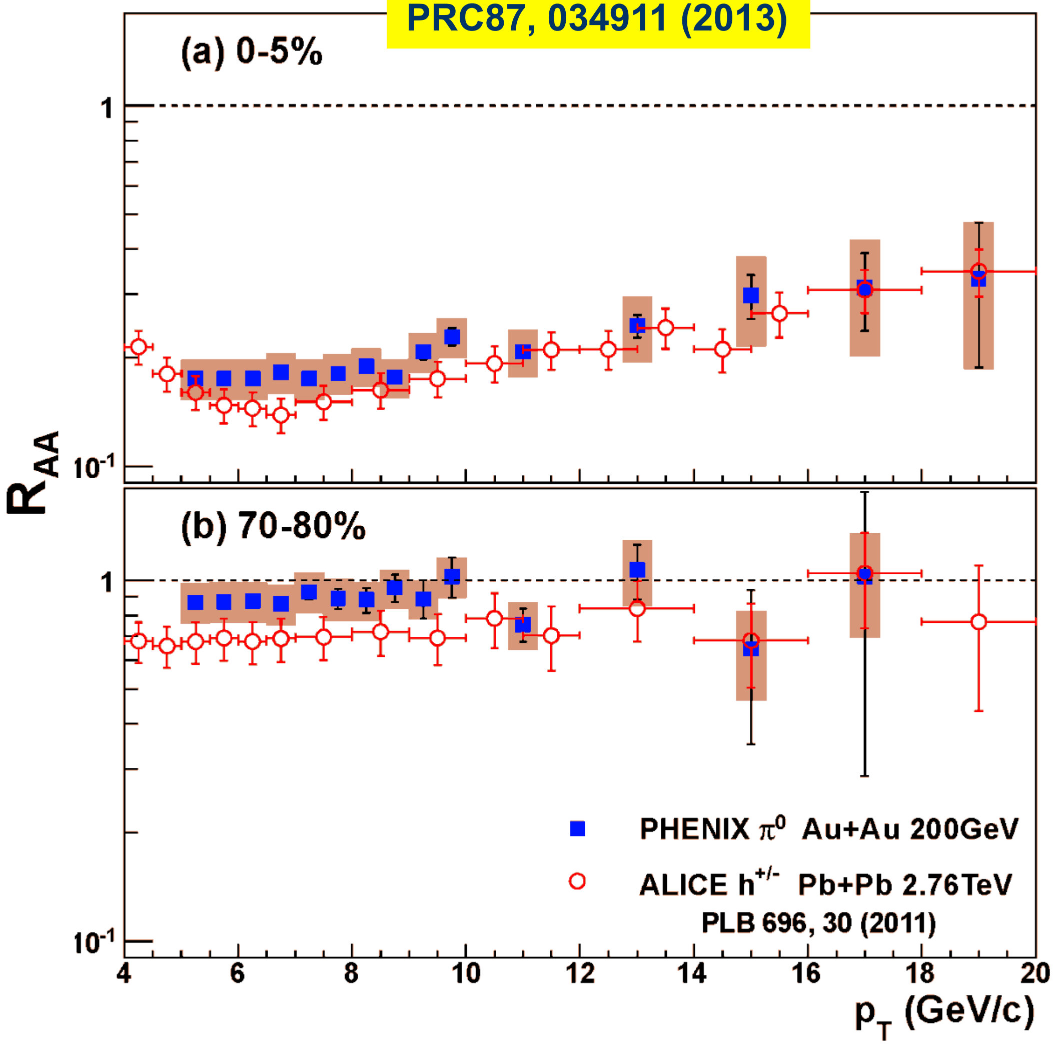


PRL109, 152301 (2012)

Similar suppression for RHIC and LHC?

- RHIC data from PHENIX publication
  - π^0 in Au+Au @ 0.2TeV
- LHC data from ALICE publication
  - Charged hadrons in Pb+Pb @ 2.76TeV
- Center-of-mass energies differ by a factor of 14!
- Similar R_{AA} doesn't mean similar energy loss
  - R_{AA} is not a good quantity?
  - Power of the spectra is different → energy loss will be different

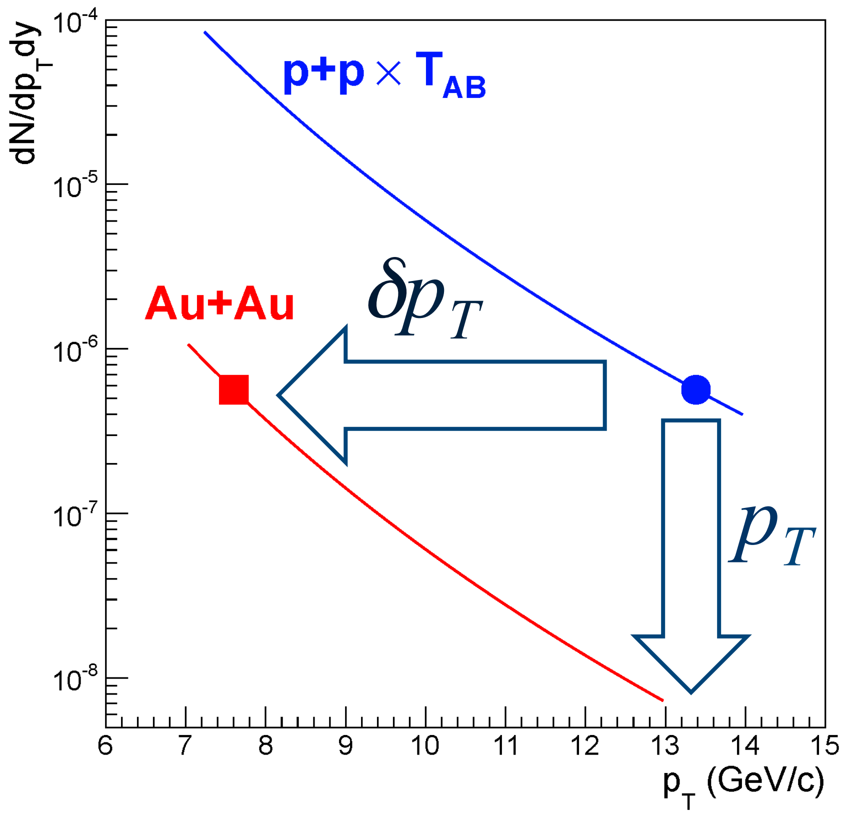
PRC87, 034911 (2013)



Looking at suppressions from a different angle

New quantity ~momentum loss~

- Coming back to the original idea: measuring energy loss of partons
- Statistically measure the fractional momentum loss ($\delta p_T/p_T$) of high p_T hadrons instead of R_{AA}.



$$p_T : p_T(p+p)$$

$$\delta p_T = p_T(p+p) - p_T(A+A)$$

(p+p) denotes p+p yield scaled by number of binary nucleon-nucleon collisions (N_{coll}).

In 2005, statistics was not enough, so..

- We assumed that the spectra at high p_T follows power-law function

$$E\frac{d^3\sigma}{dp^3} \propto {p_T}^{-n}$$

- With this assumption, we wrote a formula to obtain $\delta p_T/p_T$ from R_{AA}
  - Fractional momentum shift: $S(p_T)/p_T=S_0$

$$\frac{(1+N_{AA}^{evt})d^2N_{AA}(p_T)/dp_T dy}{\langle T_{AA}\rangle} = \frac{d^2\sigma_{pp}\left[p_T' = p_T + S(p_T)\right]}{dp_T' dy}$$
$$\times[1+dS(p_T)/dp_T]$$

$$R_{AA}(p_T) = \frac{[p_T + S(p_T)]^{-n+1}}{{p_T}^{-n+1}}[1+dS(p_T)/dp_T]$$
$$= [1+S(p_T)/p_T]^{-n+1}[1+dS(p_T)/dp_T]$$

$$R_{AA}(p_T) = (1+S_0)^{-n+2},$$
$$R_{AA}(p_T)^{1/(n-2)} = \frac{1}{1+S_0}$$

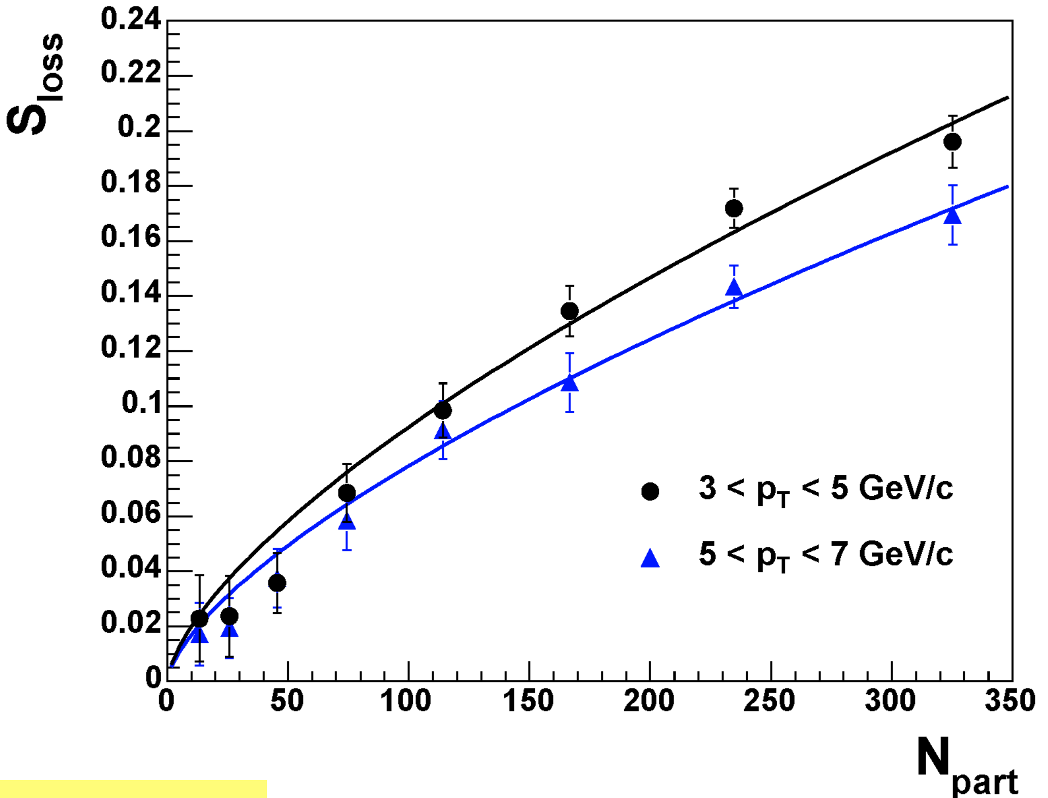
$$S_{loss} = S(p_T)/(p_T + S(p_T)) = 1 - 1/(1+S_0)$$
$$= 1 - R_{AA}(p_T)^{1/(n-2)}$$

Note p_T is p_T in Au+Au

PHENIX, PRC76, 034904 (2007)

S_{loss} in 200GeV Au+Au collisions

- S_{loss} ($\equiv\delta p_T/p_T$), where p_T is p_T at a Au+Au point
- Lines: $S_{loss} \propto N_{part}^{2/3}$
  - S_{loss} increases approximately like $N_{part}^{2/3}$
  - GLV and PQM model suggested 2/3



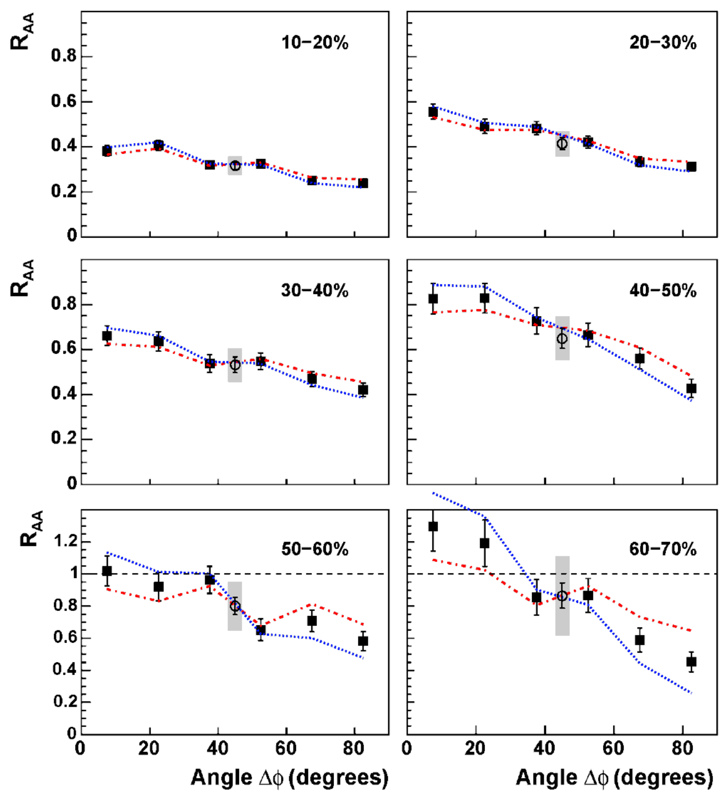
PHENIX, PRC76, 034904 (2007)

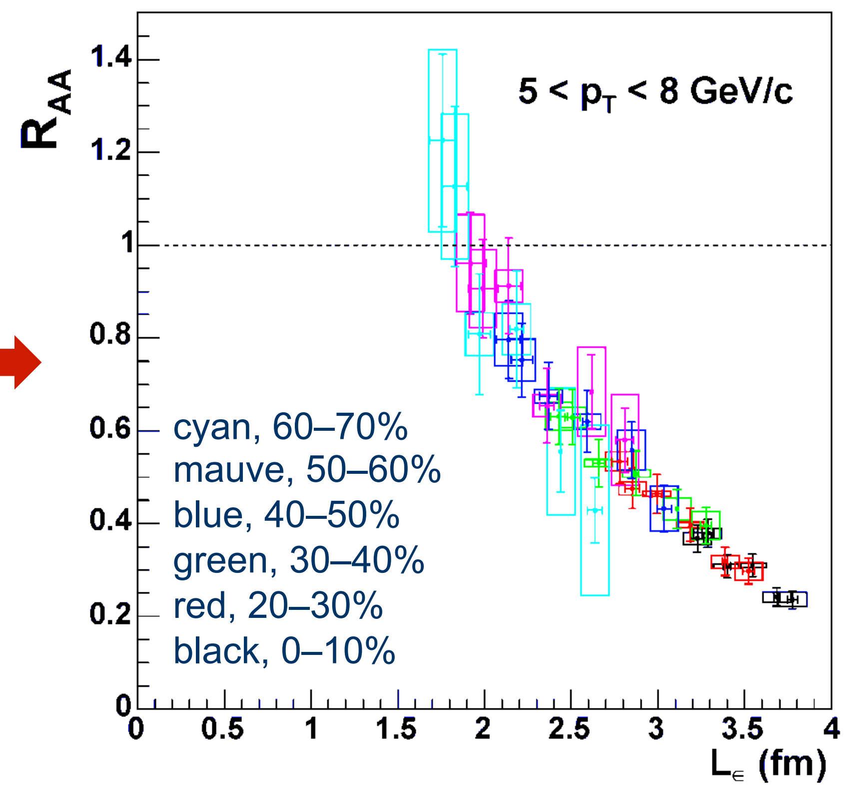
Path-length dependence of R_{AA}

- PHENIX measured the R_{AA} as a function of emission angle with respect to event planes for several centralities
  - Gives handle of path-length that partons traverse

- L_ε is path from the center of ellipse to the edge

$$L_\varepsilon = \frac{b\sqrt{1+\varepsilon}}{\sqrt{1+\varepsilon\cos(2\Delta\varphi)}}, b = \sqrt{\langle x^2 \rangle}$$

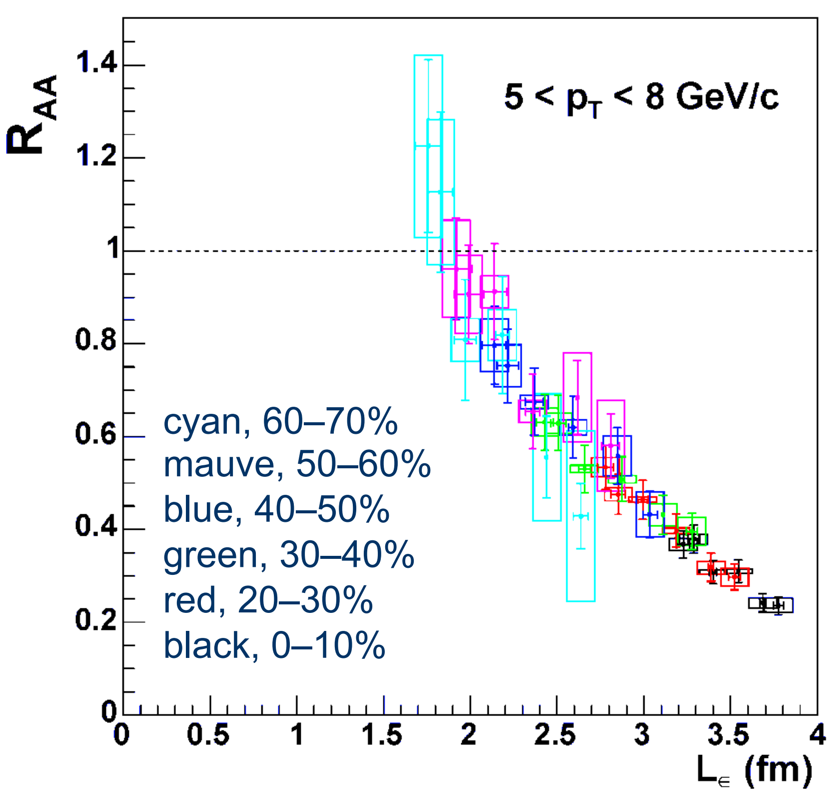


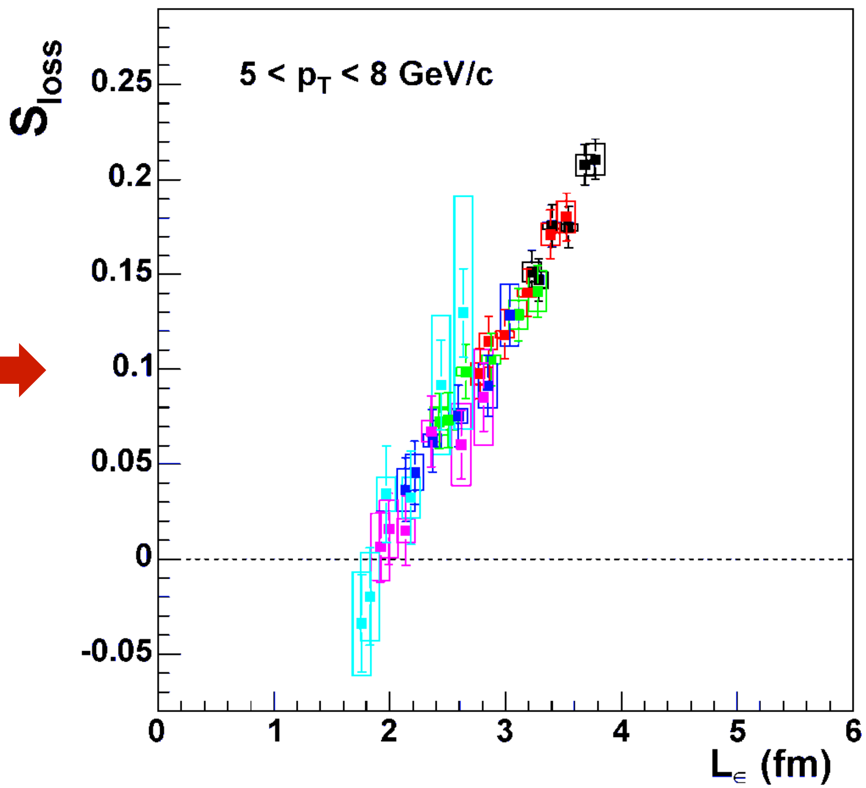


PHENIX, PRC76, 034904 (2007)

Path-length dependence of S_{loss}

- Converted R_{AA} to S_{loss} and plotted against L_ε
- Data points nicely aligned for $5<p_T<8$GeV/c

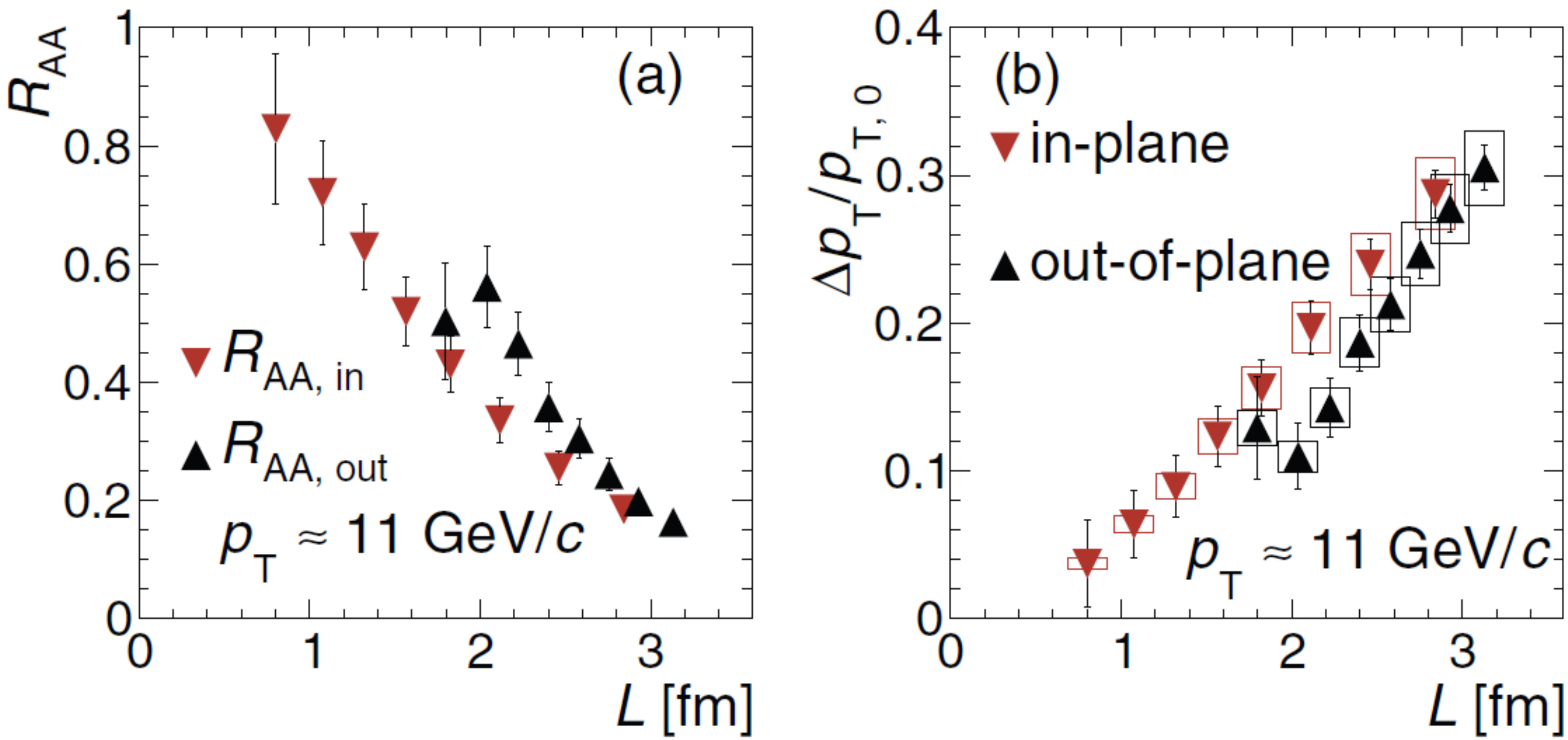




PHENIX, PRC76, 034904 (2007)

ALICE recently performed similar study

- Using Pb+Pb 2.76TeV data (ALICE). L should be equivalent to the L_ε in the previous slide
- L is not very good at higher p_T?

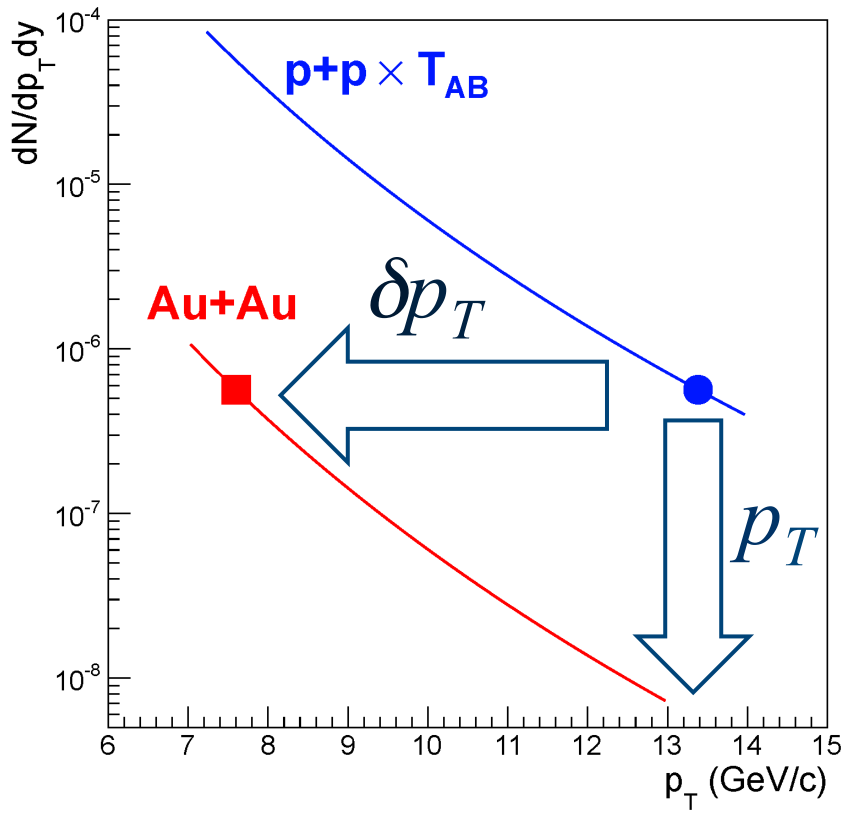


P. Christiansen, K. Tywoniuk, and V. Vislavicius, PRC 89, 034912 (2014)

With better statistics..

Direct calculation is possible

- Direct calculation of fractional momentum loss ($\delta p_T/p_T$) became possible.
- One doesn't need to assume the function form of the spectra.



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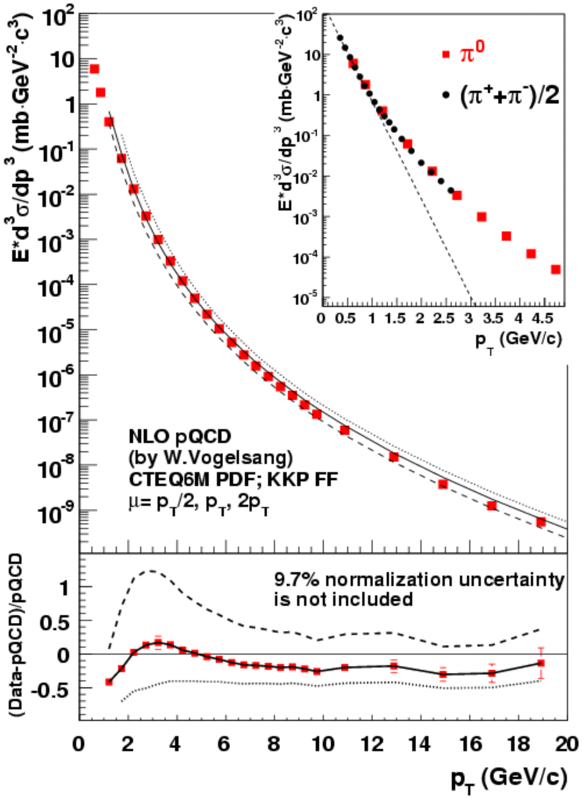
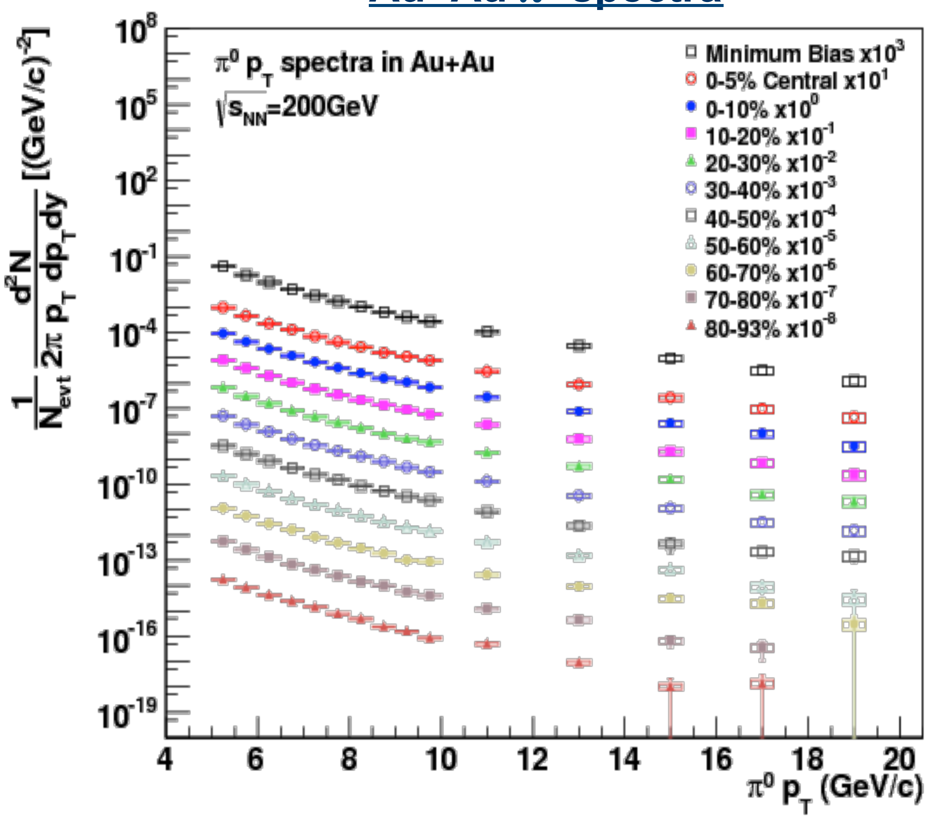
p+p π^0 spectra

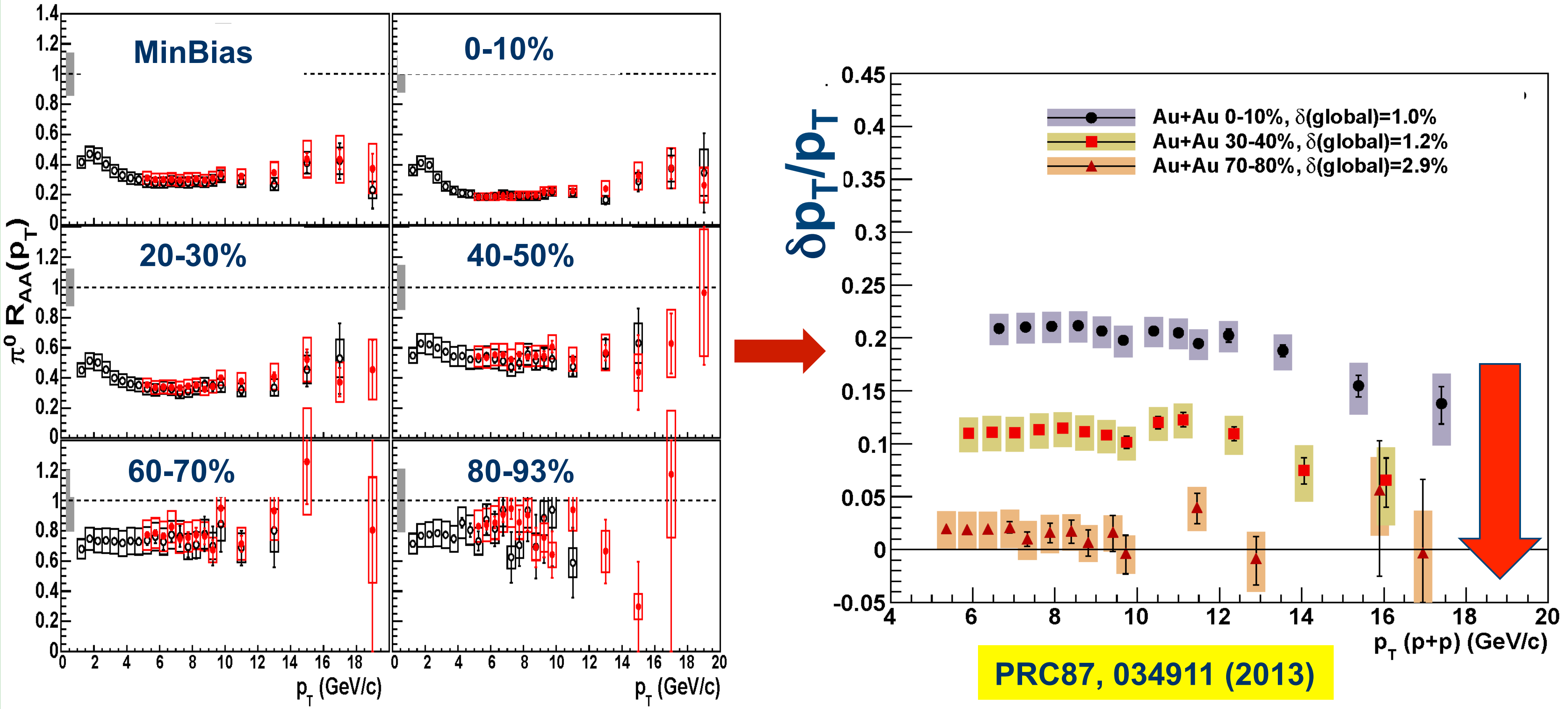


Au+Au π^0 spectra



Fractional momentum loss ($\delta p_T/p_T$) of π^0

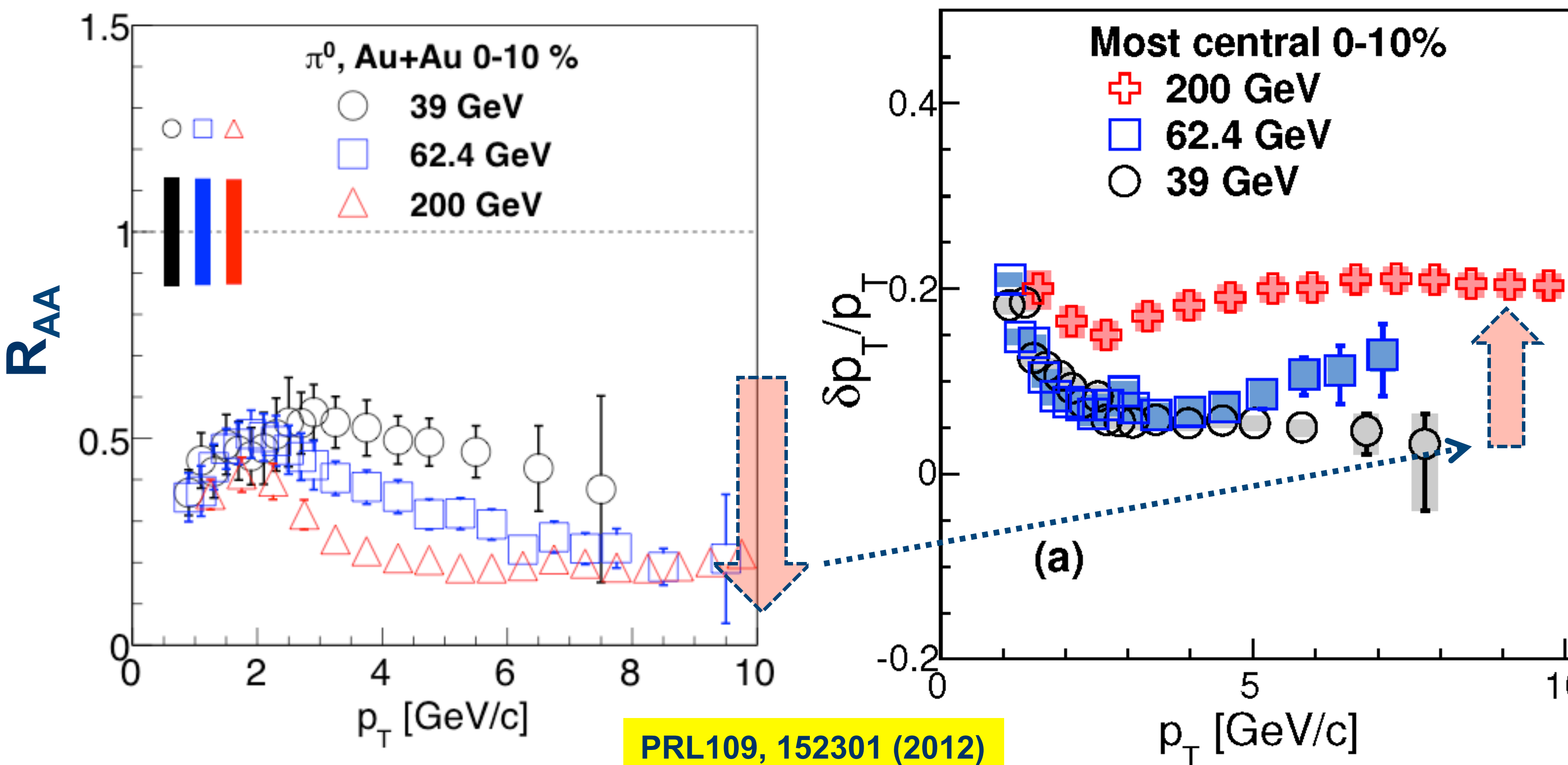
- Measured fractional momentum loss ($\delta p_T/p_T$) instead of R_{AA}
  - In Au+Au collisions
- $\delta p_T/p_T$=0.2 in 0-10% centrality, =0.02 in 70-80% centrality



PRC87, 034911 (2013)

Energy dependence of $\delta p_T/p_T$ (I)

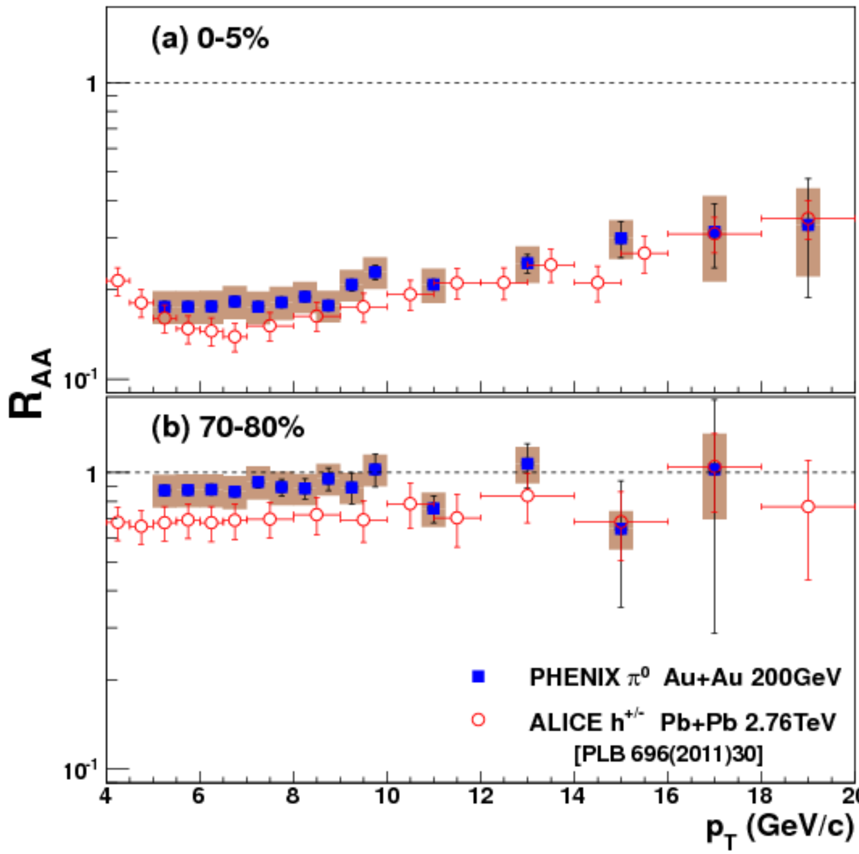
- $\delta p_T/p_T$ decreases significantly going from 200 to 62, 39GeV.
- Significantly different $\delta p_T/p_T$ while the R_{AA} is similar.

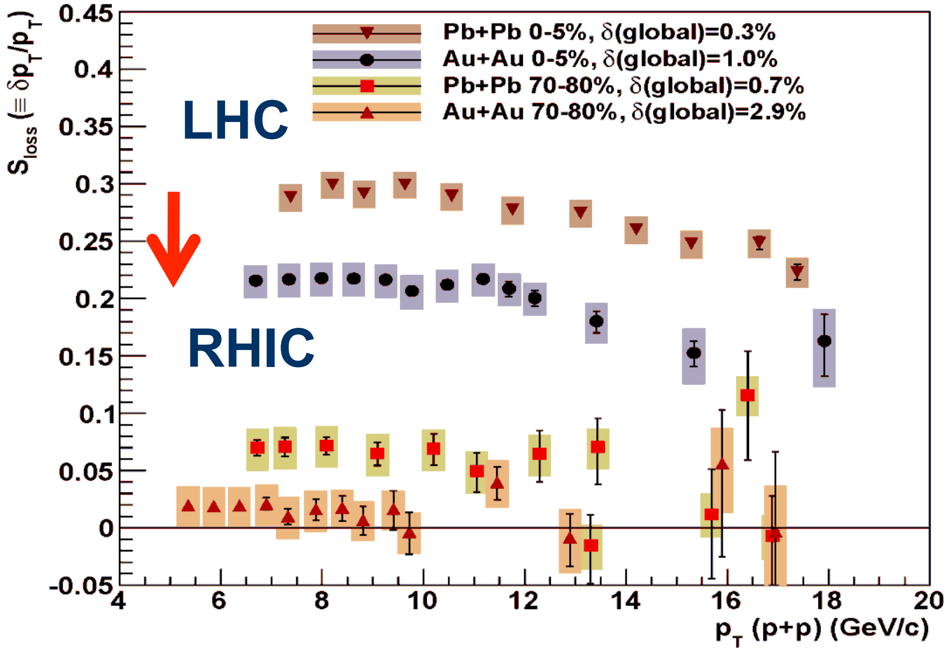


PRL109, 152301 (2012)

Energy dependence of $\delta p_T/p_T$ (II)

- $\delta p_T/p_T$ increase by a factor of 1.5 from 200GeV to 2.76TeV.
- ~0.2 for RHIC and ~0.3 for LHC

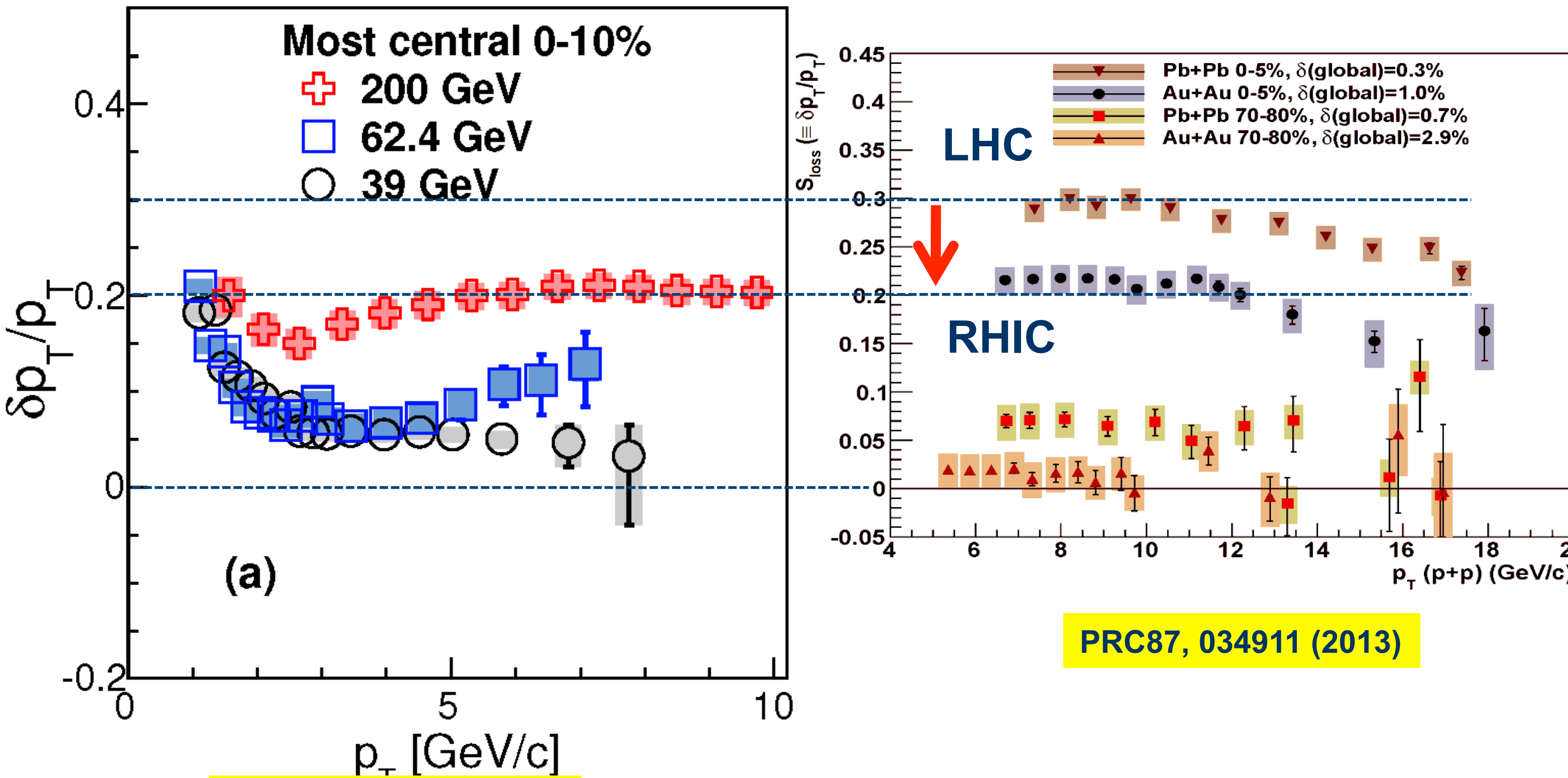




PRC87, 034911 (2013)

Energy dependence of $\delta p_T/p_T$ (III)

- $\delta p_T/p_T$ from 62GeV to 2.76TeV: by a factor of 6 change!



PRL109, 152301 (2012)

PRC87, 034911 (2013)

Systematic studies across systems

- We tried to plot $\delta p_T/p_T$ against universal variables

- Number of participant nucleons (N_{part})
- Number of quark participants (N_{qp})
- Charged multiplicity ($dN_{ch}/d\eta$), as a measure of the energy density

Number of quark participants (Nqp)?

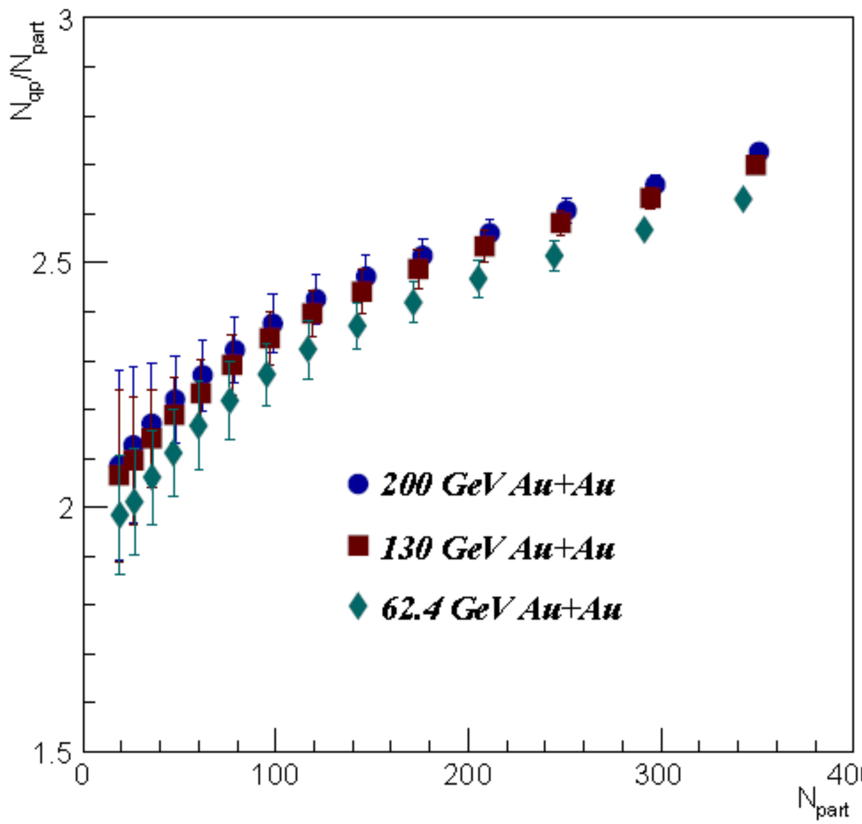
- Number of quark participants, N_{qp}, is estimated using a Glauber model.
  - Nucleons are distributed using a Woods-Saxon distribution.
  - Quarks are distributed around the nucleon centers following: $\rho(r) = \rho_0^{proton} e^{-ar}$, where a = 4.27 fm^{-1}.
- Quarks interact when their distance, d, satisfies the condition of:

$$d < \sqrt{\frac{\sigma_{qq}^{inel}}{\pi}}$$

- Quark-quark inelastic cross section (σ_{qq}^{inel}) is estimated by reproducing the n-n inelastic cross section of:

$\sqrt{s_{NN}}$[GeV]	$\sigma_{nn}^{inel.}$	$\sigma_{qq}^{inel.}$
2700	64.0	18.4
200	42.3	9.36

Ratios of N_{qp}/N_{part} as a function of N_{part} for 62, 130 and 200GeV Au+Au collisions

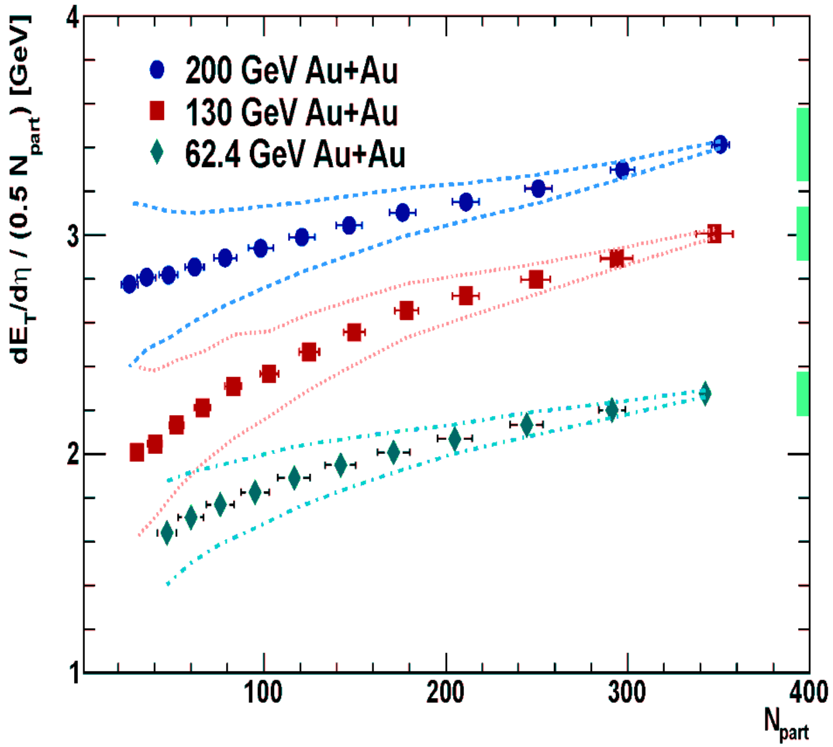


PHENIX, PRC89, 044905 (2014)

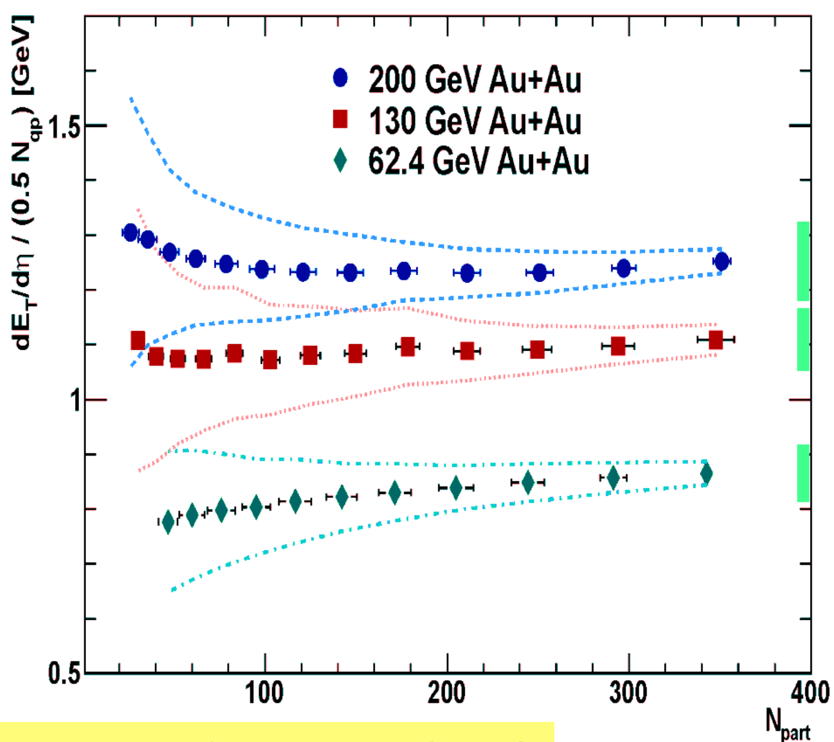
Is N_{qp} a good scaling variable?

- Recently, PHENIX found that the $dE_T/d\eta$ scales better with N_{qp} than N_{part}
- $dE_T/d\eta$ affects the energy loss of partons

$dE_T/d\eta/(0.5\ N_{part})$



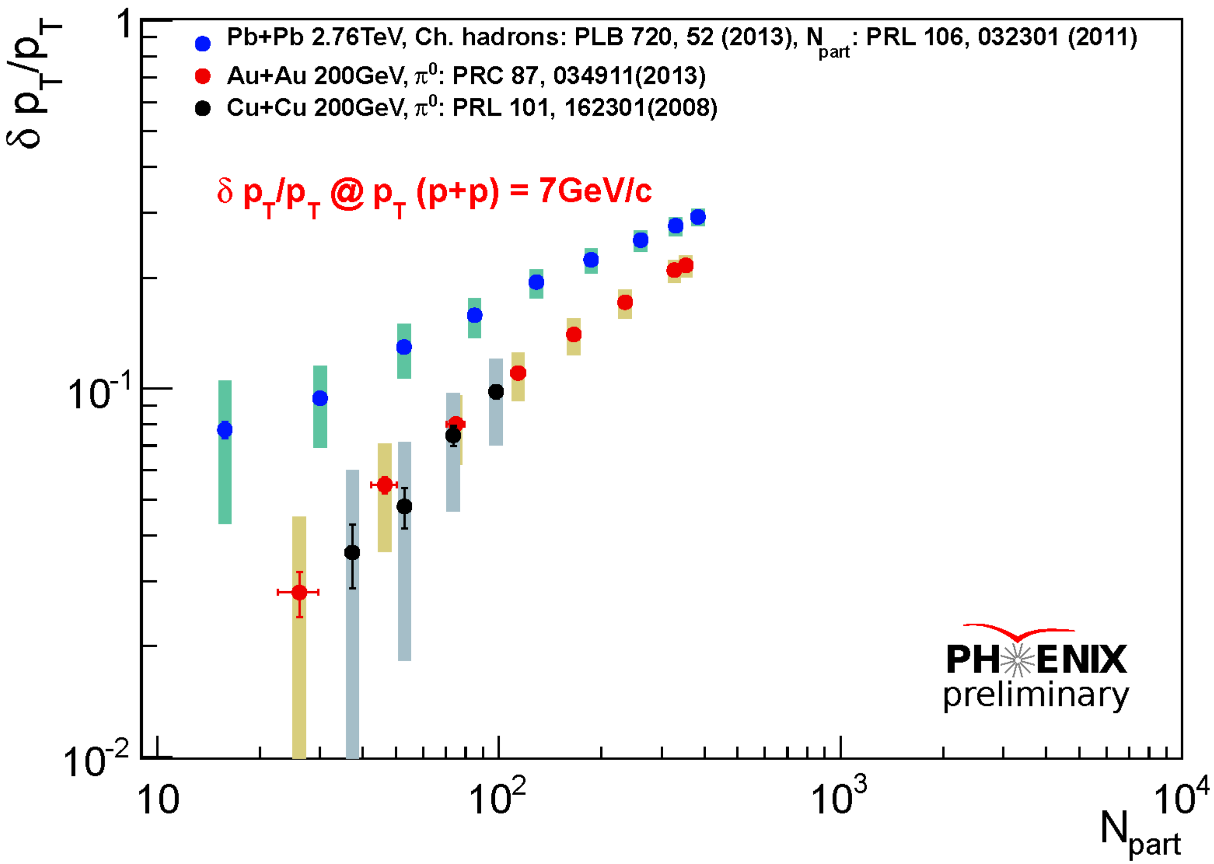
$dE_T/d\eta/(0.5\ N_{qp})$



PHENIX, PRC89, 044905 (2014)

$\delta p_T/p_T$ over collision systems (vs N_{part})

- Plotting against N_{part}
  - N_{part} are obtained in given centrality at given cms energy.
  - $\delta p_T/p_T$'s at p_T=7GeV/c of p+p are plotted.



$\delta p_T/p_T$ over collision systems (vs N_{qp})

- Plotting against N_{qp}
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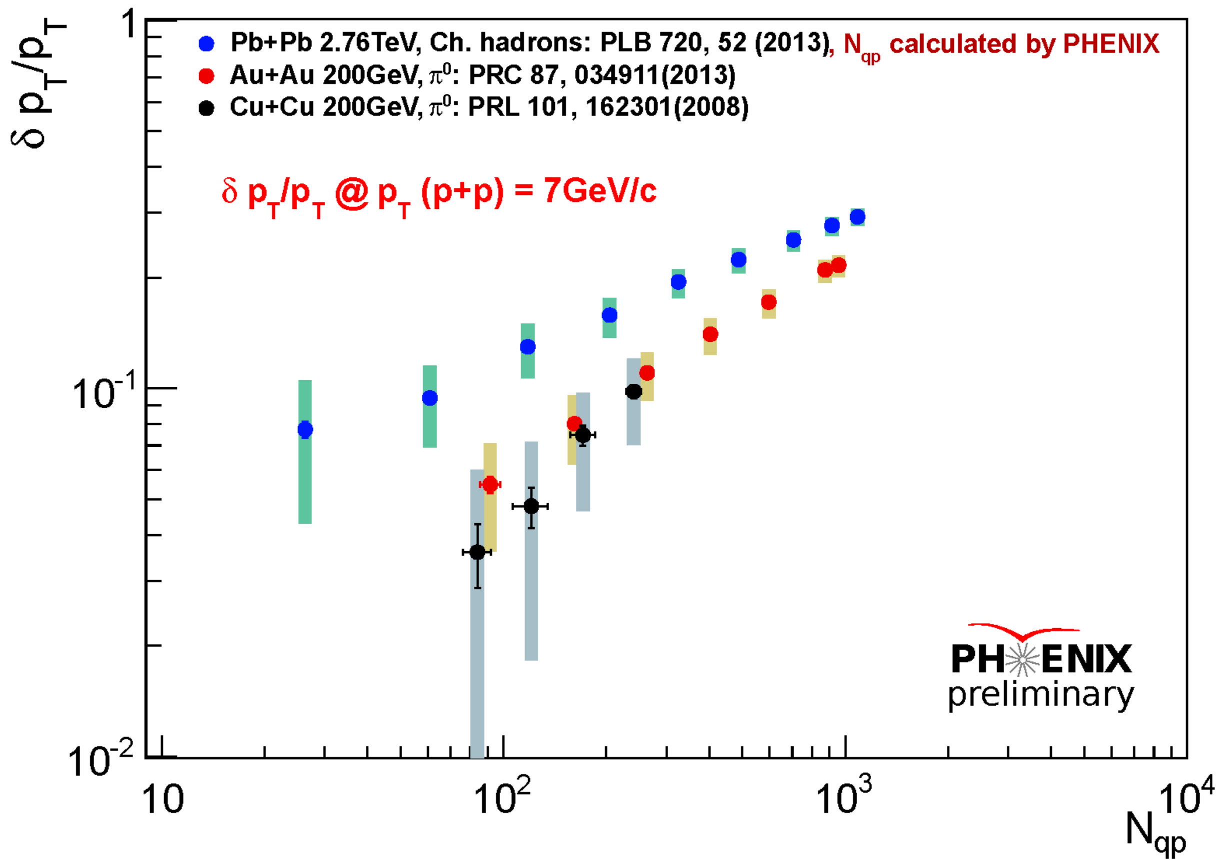
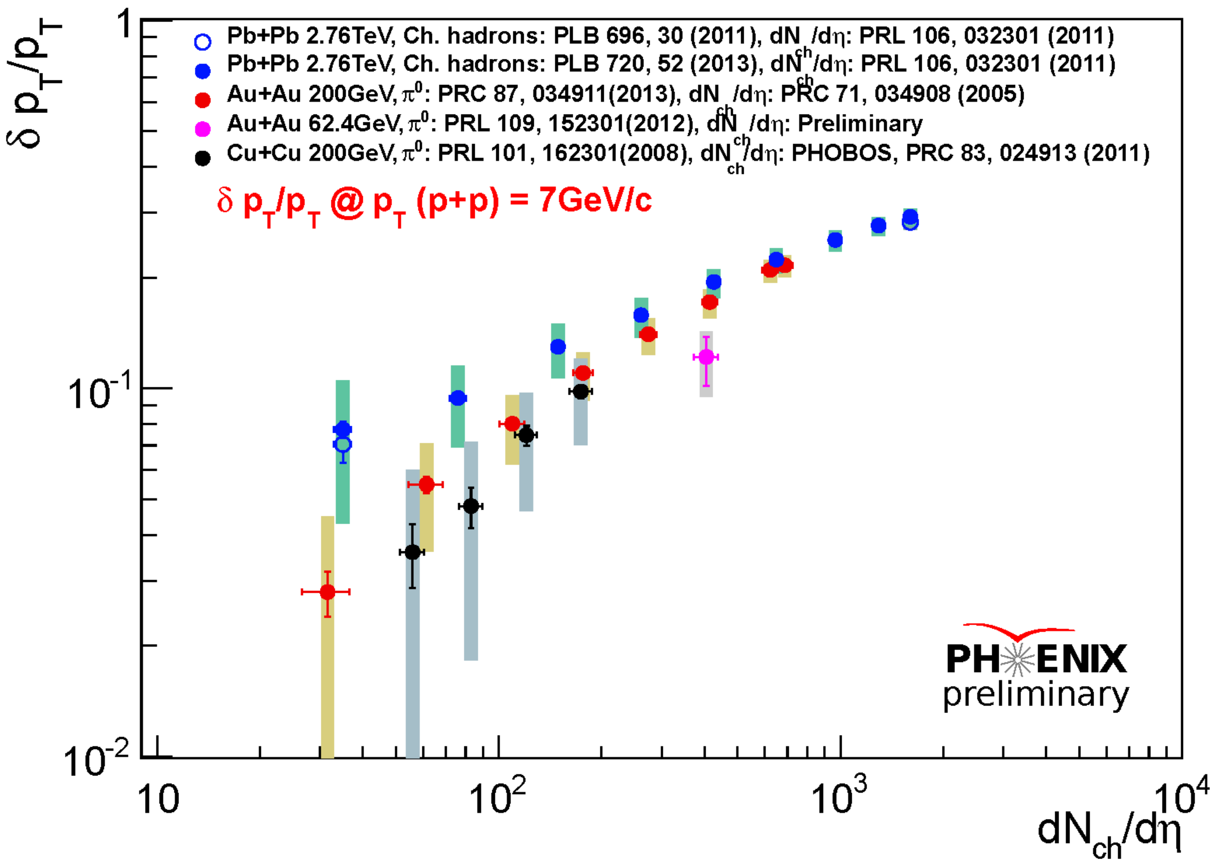


$\delta p_T/p_T$ over collision systems (vs $dN_{ch}/d\eta$)

- Plotting against $dN_{ch}/d\eta$ (as a measure of energy density)
  - $dN_{ch}/d\eta$ are obtained in given centrality at given cms energy.
  - $\delta p_T/p_T$'s at p_T=7GeV/c of p+p are plotted.



Consistency with previous studies

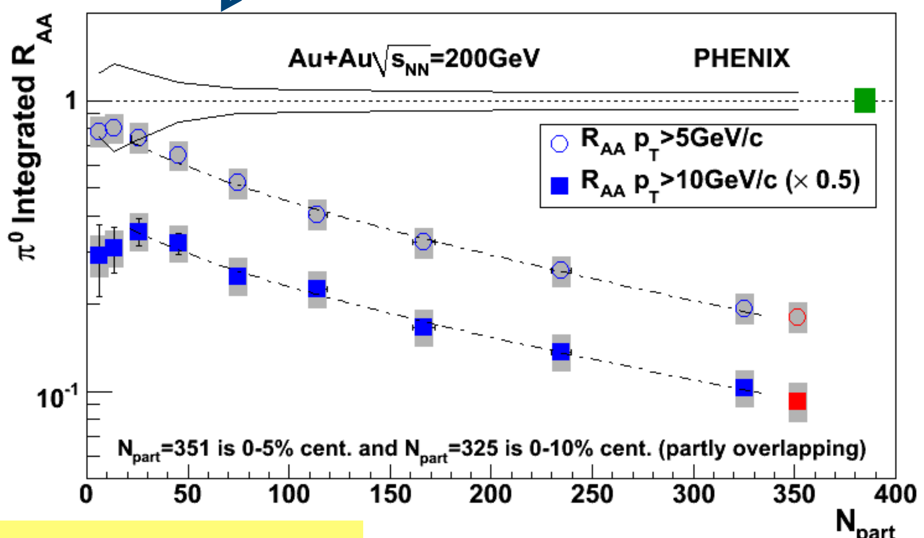
- PHENIX studied fractional momentum loss in two publications
  - PRC76, 034904 (2007), PRL101, 232301 (2008)
  - Assuming the spectra shape is power-law with the power “n”, we can write:

$$S_{loss} \equiv \delta p_T / p_T = \beta N_{part}^{\alpha}$$

$$R_{AA} = (1 - S_{loss})^{n-2} = (1 - \beta N_{part}^{\alpha})^{n-2}$$

- If we assume $dN_{ch}/d\eta \propto N_{part}^{1.16}$, found in PRC71, 034908(2005), we can write the relationship as follows:

$$\delta p_T / p_T = \beta N_{part}^{\alpha} = \beta (dN_{ch}/d\eta)^{\alpha/1.16} \equiv \beta (dN_{ch}/d\eta)^{k}$$



PRL101, 232301 (2008)

$\alpha = 0.57 \pm 0.13 @ p_T > 5GeV/c$

$k = 0.49 \pm 0.11 @ p_T > 5GeV/c$

$\delta p_T/p_T$ over collision systems (vs $dN_{ch}/d\eta$)

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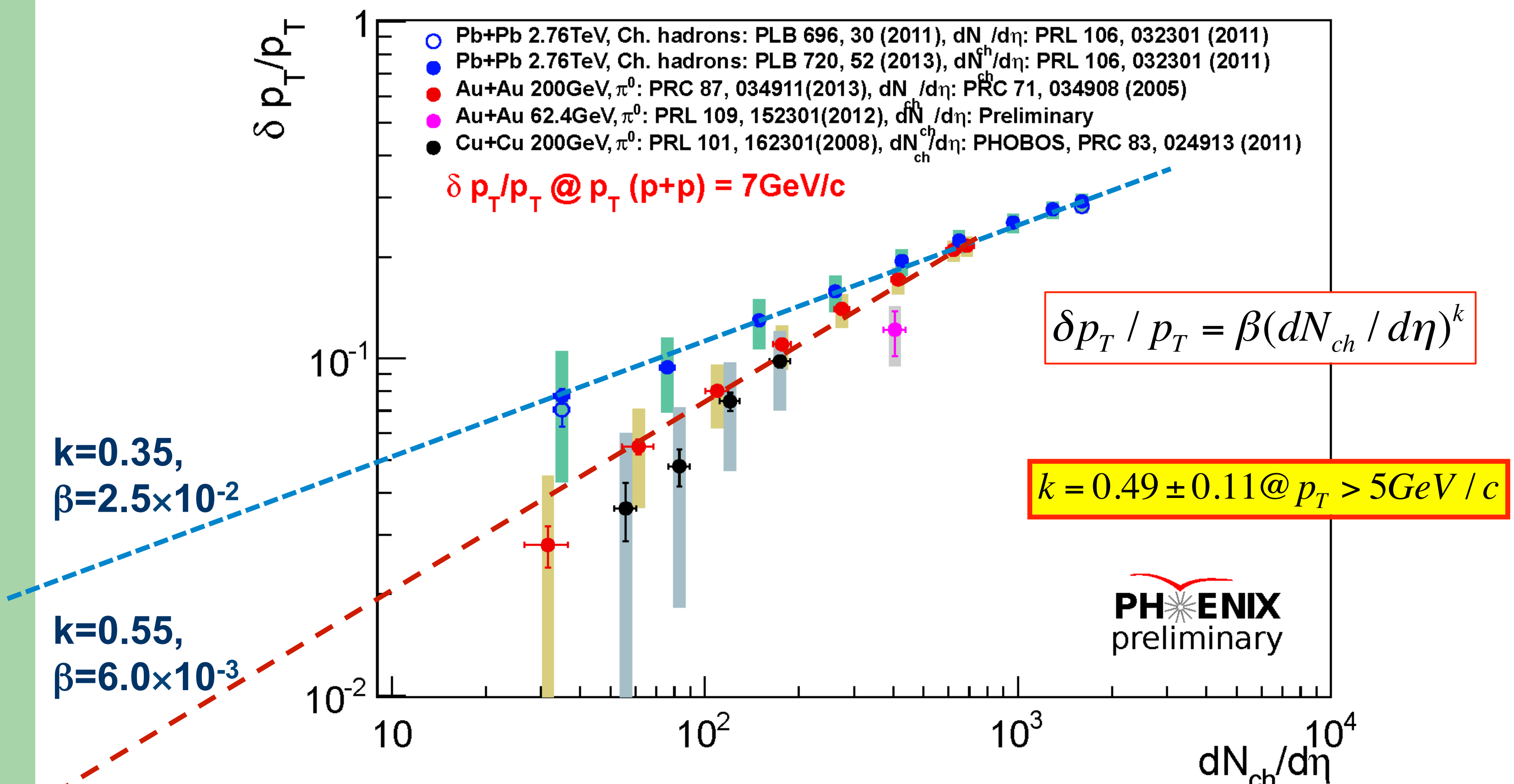
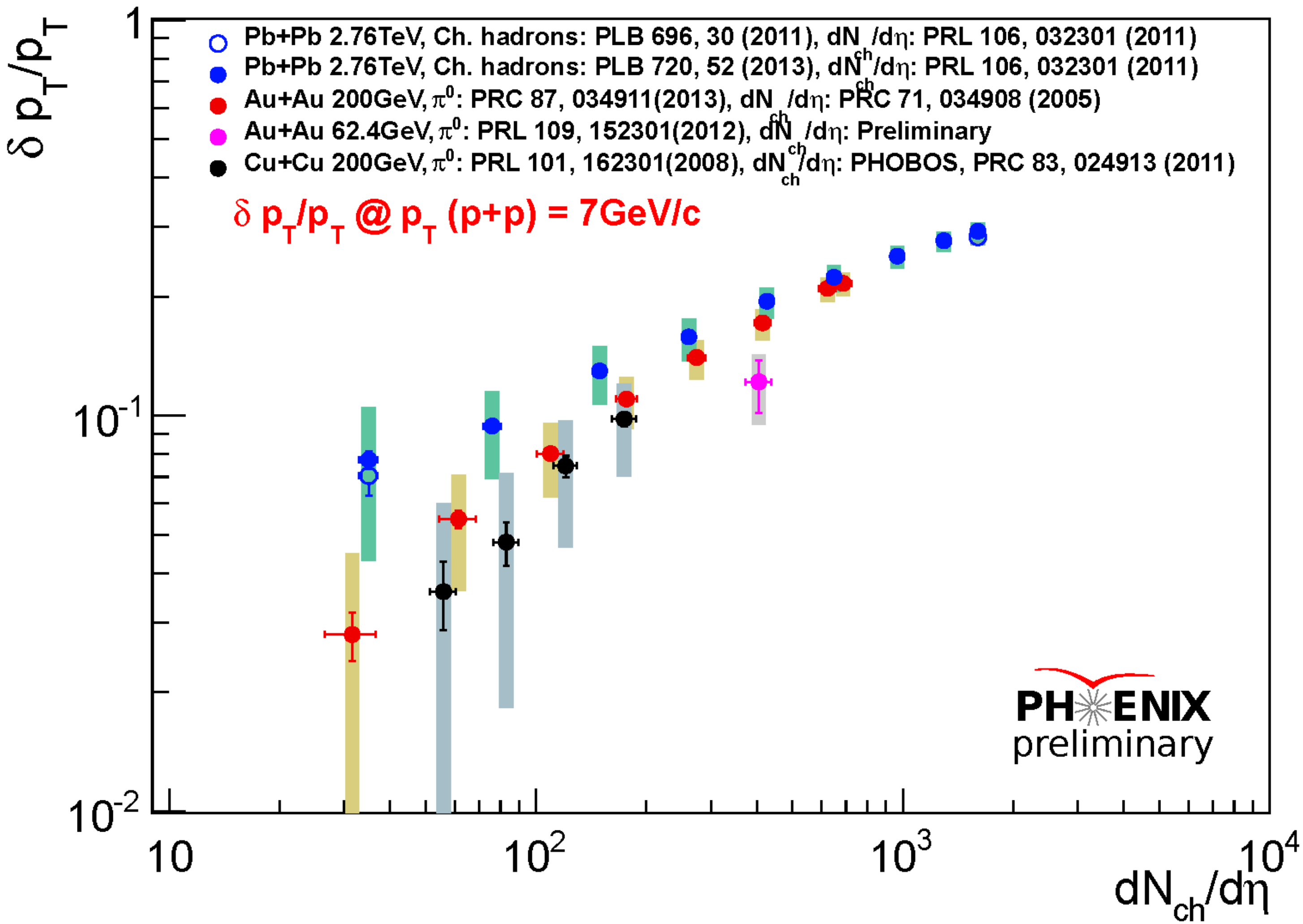


Review the money plot



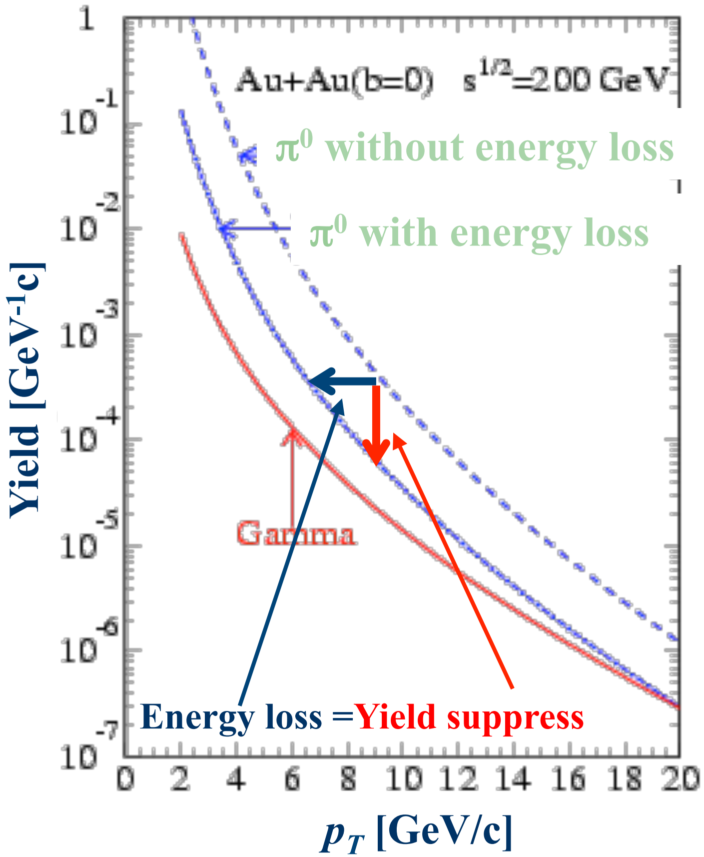
Summary

- Looking at fractional momentum loss gives more insight on actual energy loss of partons
  - Similar R_{AA} does not give similar energy loss
- Centrality, system, and energy dependence of fractional momentum loss is studied.
  - A trend is seen from 200GeV Au+Au to 2.76TeV Pb+Pb
- $\delta p_T/p_T$ vs $dN_{ch}/d\eta$ for 200GeV Au+Au and Cu+Cu collisions tend to merge into the one for 2.76TeV Pb+Pb collisions at larger $dN_{ch}/d\eta$, independent of $\sqrt{s_{NN}}$.
- Within same $\sqrt{s_{NN}}$, both N_{part} and N_{qp} scaling work very well.

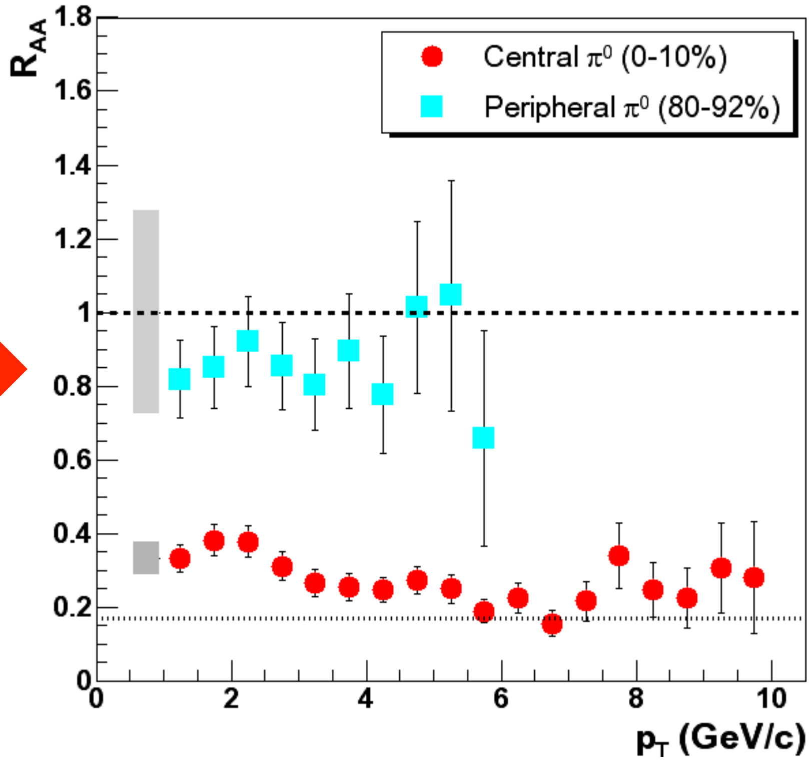
Backup

Hard scattering as densimeter

- Parton may change its momentum in the medium.
  - Energy loss through Gluon radiation, etc..
- Effect is path-length and system dependent ~a densimeter~.
- Look at leading particles of jet as a measure of jet energy.



X.-N., Wang, PRC 58 (1998)2321



PHENIX, π^0 in Au+Au, PRL. 91, 072301 (2003)

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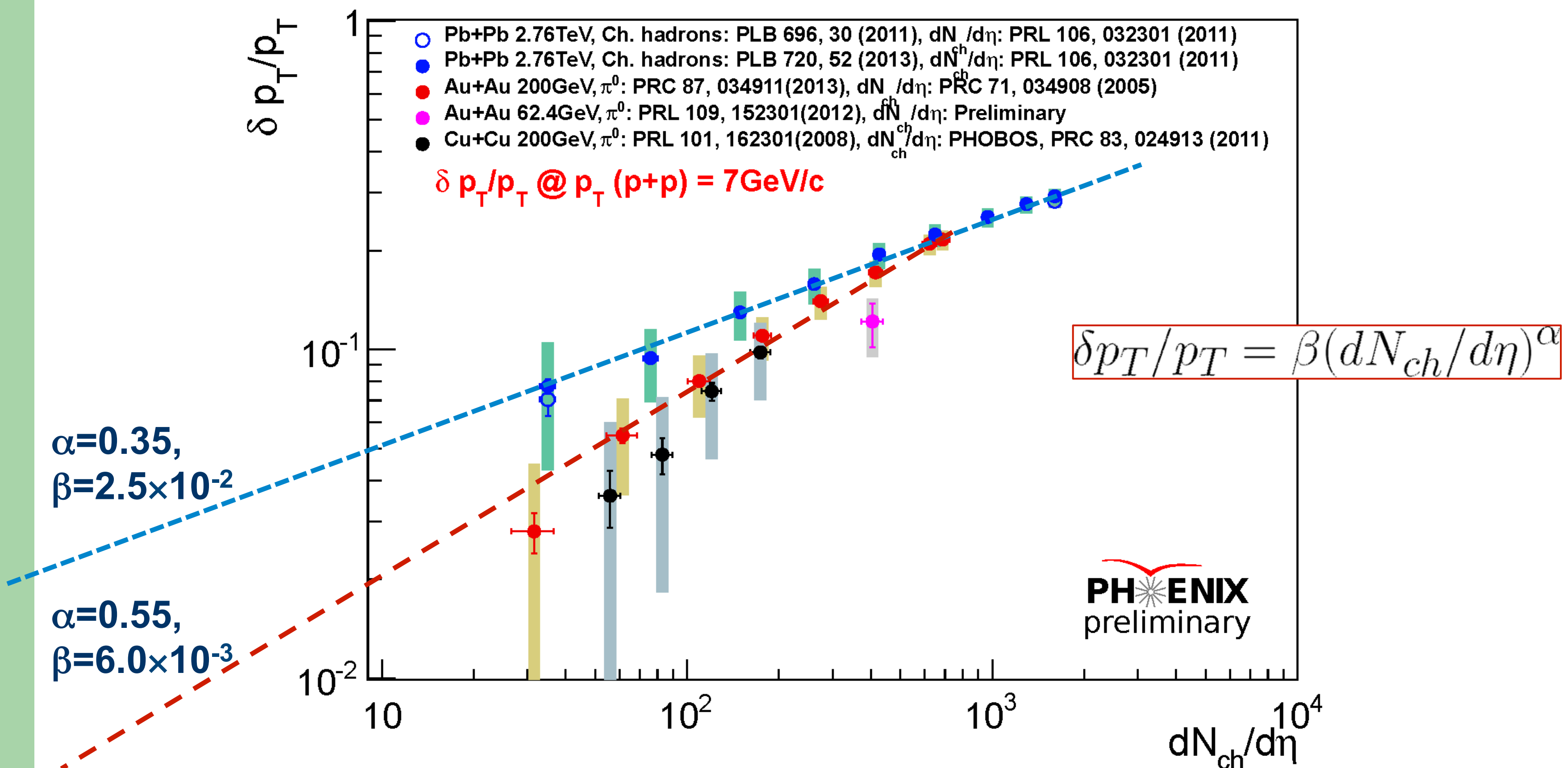

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  - Assuming the spectra shape is power-law with the power "n", we can write:

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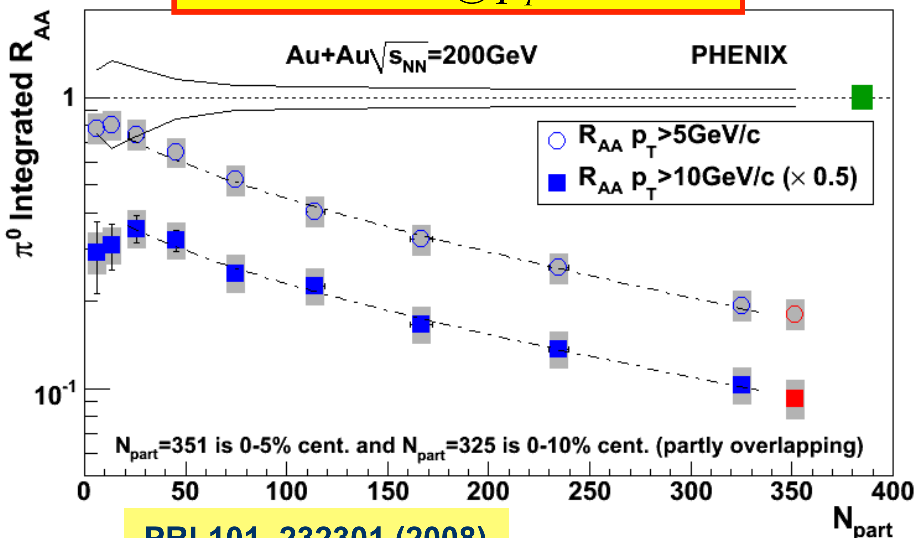
$$R_{AA} = (1 - S_{loss})^{n-2} = (1 - \beta N_{part}^{\alpha})^{n-2}$$

- In this study, if we assume $dN_{ch}/d\eta \propto N_{part}$, we can write the relationship as follows:

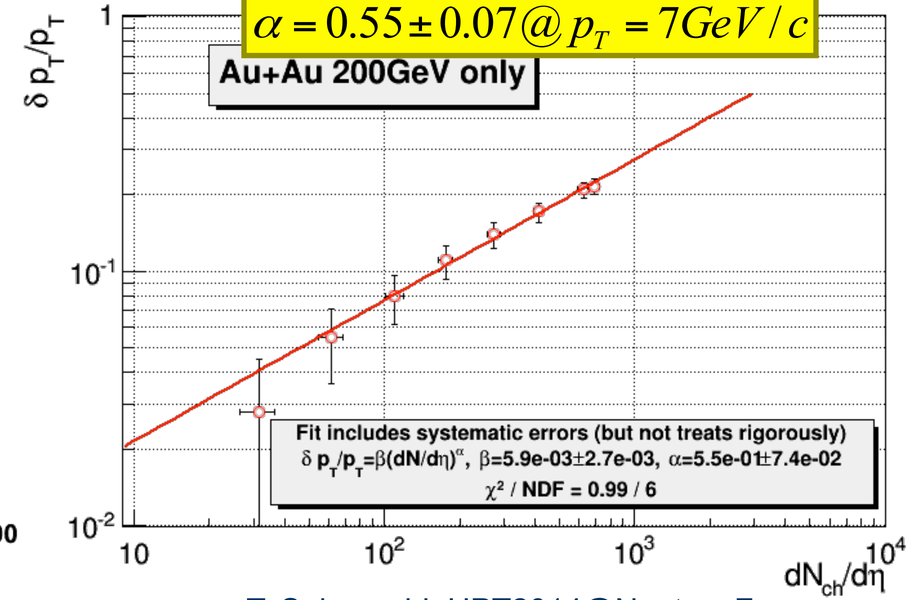
$$\delta p_T / p_T = \beta (dN_{ch}/d\eta)^{\alpha}$$

$\alpha = 0.57 \pm 0.13 @ p_T > 5GeV/c$



PRL101, 232301 (2008)

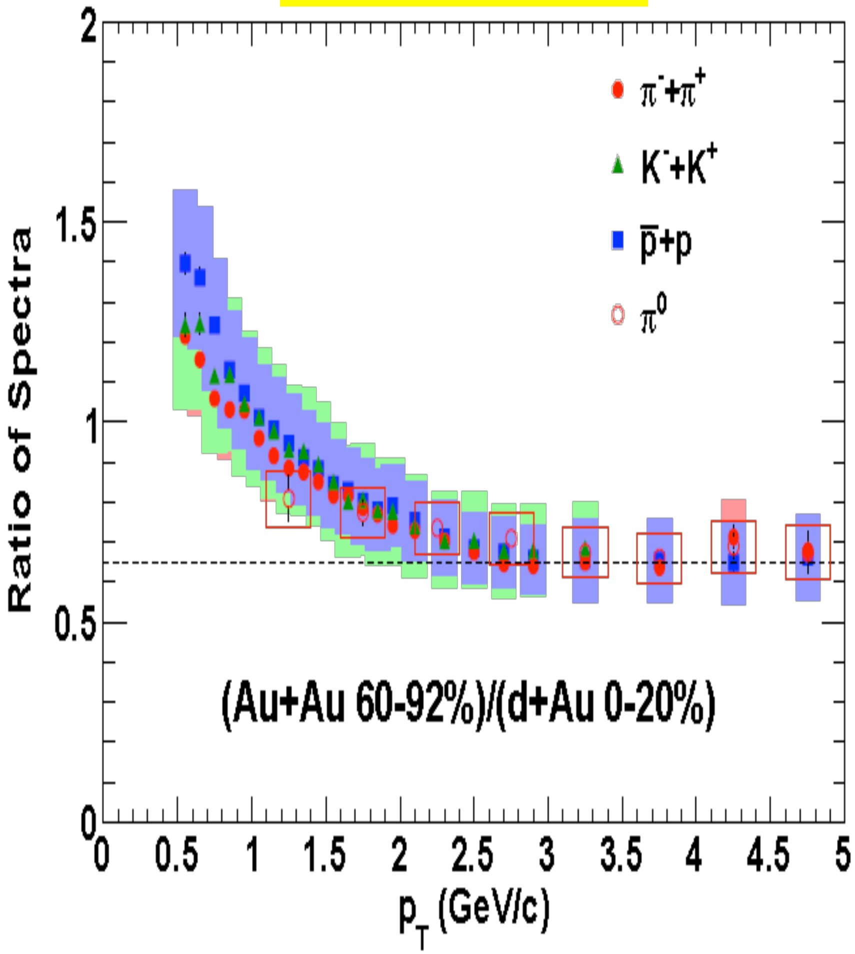
$\alpha = 0.55 \pm 0.07 @ p_T = 7GeV/c$



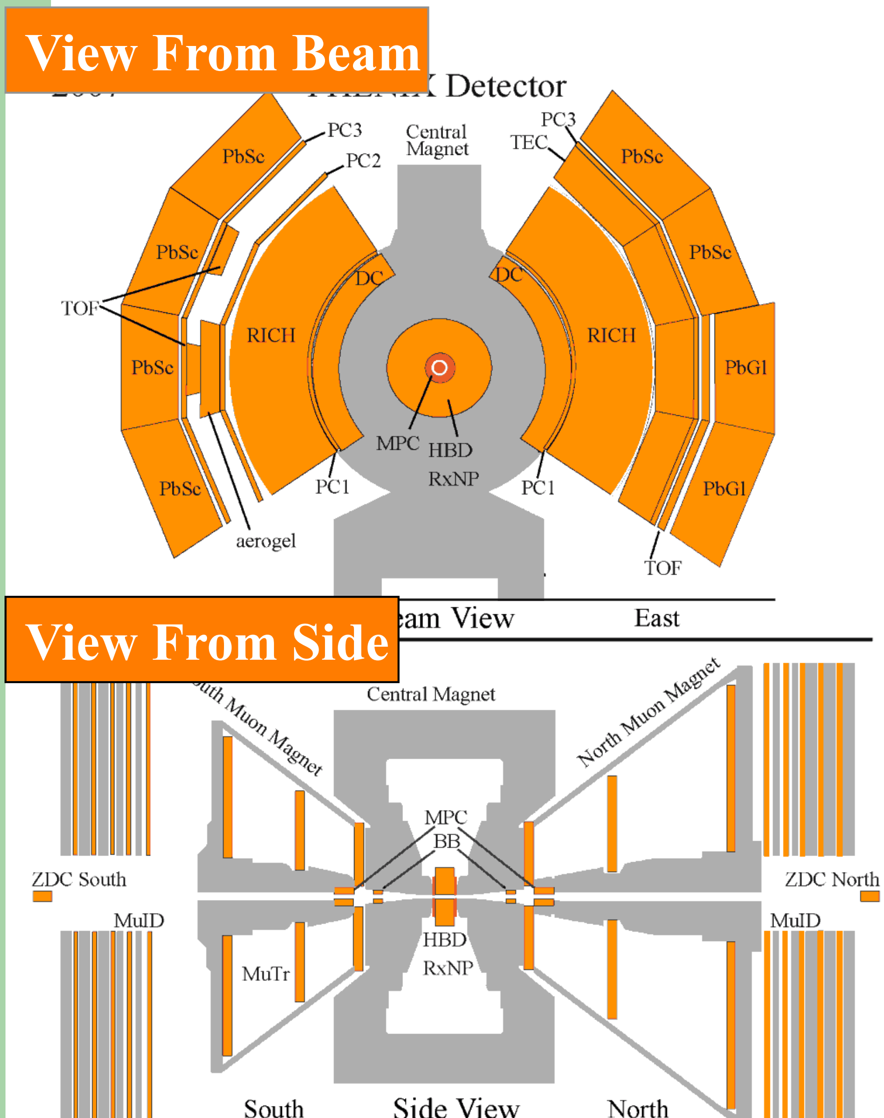
d+Au and Au+Au system similarity?

- Au+Au 60-92% and d+Au 0-20% have similar N_{part}, N_{coll}
- Ratios of all ID'ed hadron spectra are on the same curve
- Common production mechanism?
- If all CNM scales with N_{part}, ratios may mean E_{loss} in the medium in peripheral Au+Au
- Low p_T increase may rise from rapidity shift in d+Au

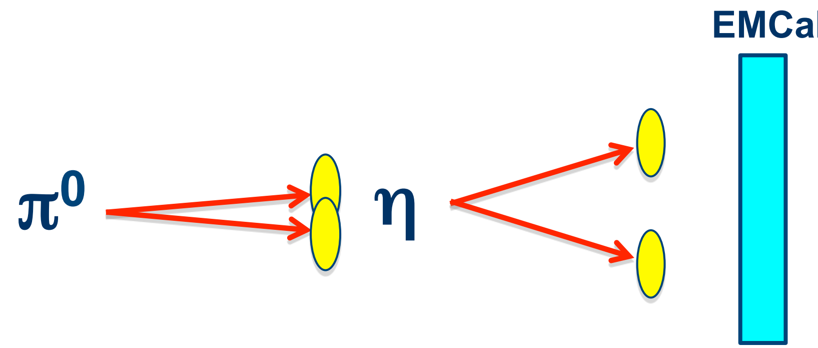
arXiv:1304.3410



Setup for measurement



- Event triggered by a coincidence of BBC South and BBC North.
  - Sitting in $3.1<|\eta|<3.9$
- π^0 and η measurement
  - EMCal(PbSc, PbGl): Energy measurement and identification of real photons.
  - Tracking(DC, PC): Veto to Charged particles.



Results presented here are obtained from 0.813 nb^{-1} Au+Au 200GeV events recorded by PHENIX in 2007.

How we measure π^0, η?

- Reconstruct hadrons via 2γ invariant mass in EMCal (example is in Au+Au)

$$M^2 = (E_1 + E_2)^2 - (\mathbf{p}_1 + \mathbf{p}_2)^2 = 2E_1E_2(1 - \cos\theta)$$

- Subtract Combinatorial background
  - Compute Mass using γs from different events. (mixed-event technique)

PRC87, 034911 (2013)

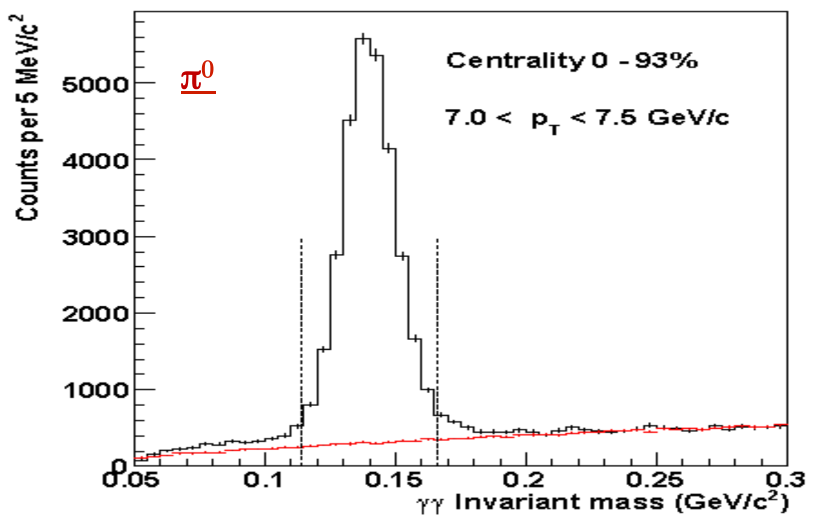
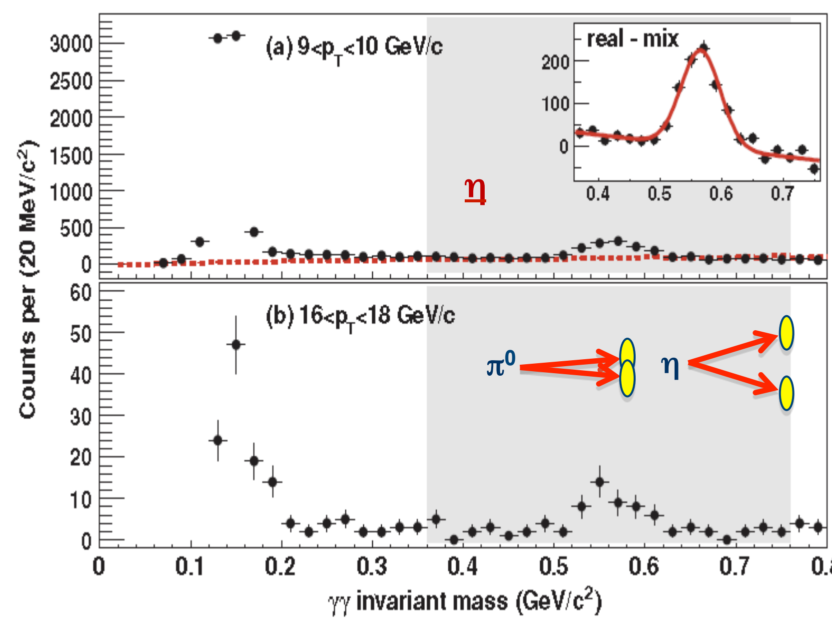


FIG. 3: (Color online) Invariant mass spectrum of two photons (black) and the corresponding mixed events (red) at $7 < p_T < 7.5$ GeV/c in minimum bias collisions. Vertical lines indicate a $\pm 2.5\ \sigma$ integration window.

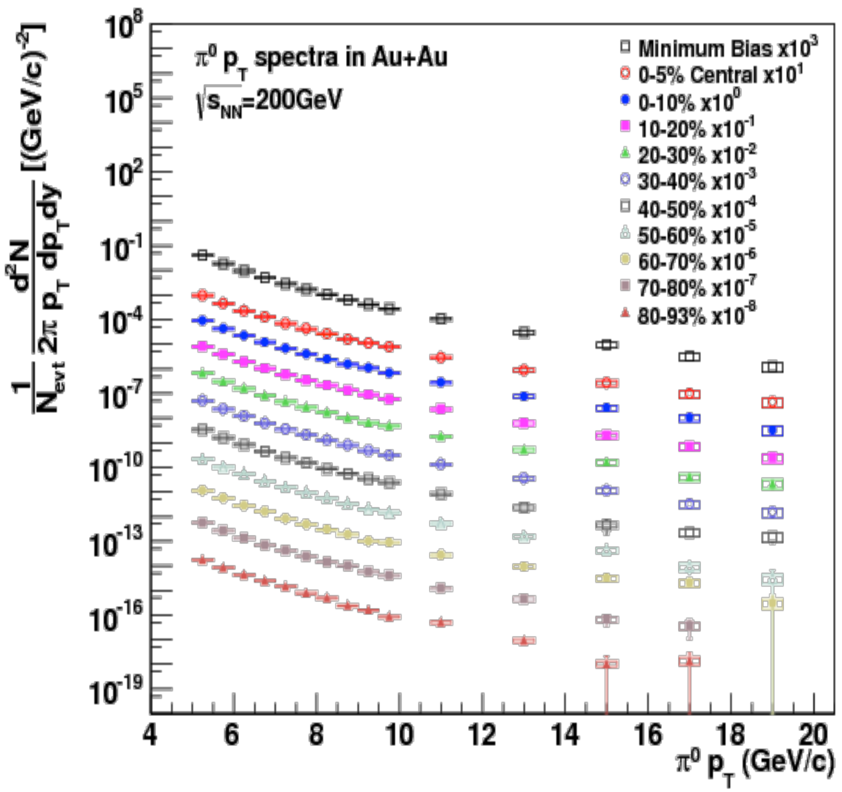
PRC82, 011902(R) (2010)



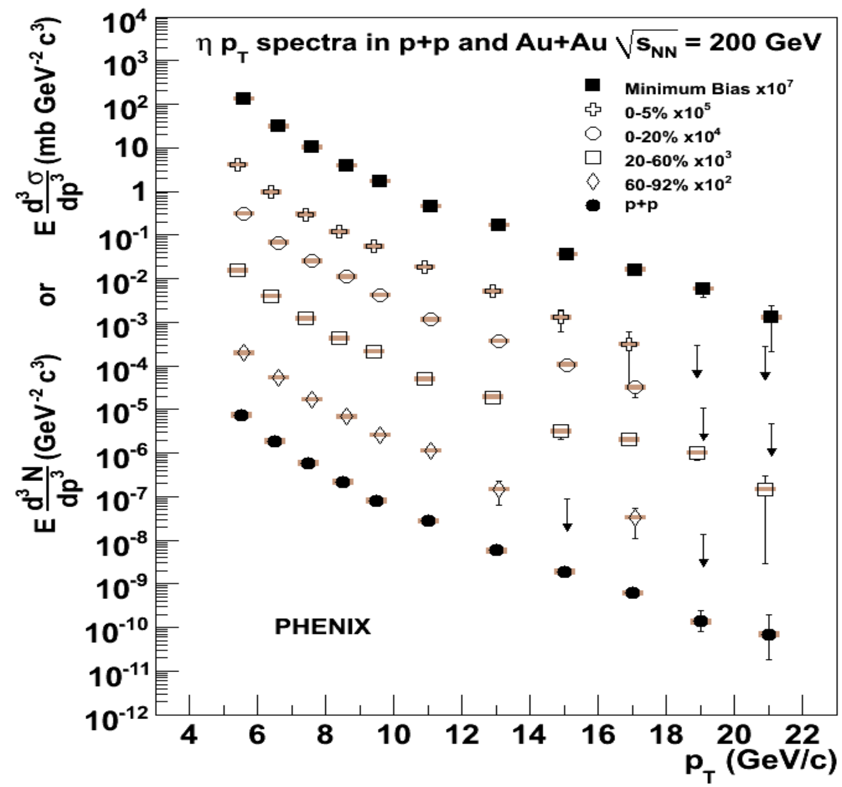
π^0, η spectra in Au+Au

- Spectra reached to ~20GeV/c for π^0 and ~22GeV/c for η

π^0



η



Systematic errors

- Type A: point-by-point fluctuating errors
- Type B: p_T-correlated errors
- Type C: overall normalization errors

π^0 systematic errors

source	type	5GeV	10GeV	15GeV	20GeV
peak extraction	B	2	2	2	2
acceptance	C	2.5	2.5	2.5	2.5
PID efficiency	B	7	8	8.5	9
energy scale	B	7.5	8	8	8
photon conversion	C	2	2	2	2
cluster merging	B	0	0	8	18
total		11	12	15	22

η systematic errors

source	type	5GeV	10GeV	15GeV
peak extraction	B	4	3.5	3
acceptance	C	2.5	2.5	2.5
PID efficiency	B	7	8	8.5
energy scale	B	11	12	12
photon conversion	C	2	2	2
total		12	15	15