High-$p_\perp$ and Jet Measurements by the PHENIX Experiment at RHIC

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For the PHENIX Collaboration

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Also subsequent PHENIX /PHENIX collaborator talks on the subject:

Henner Buesching, David d'Enterria, Barbara Jacak, Klaus Reygers,…

High-p_T Suppression →Quenching

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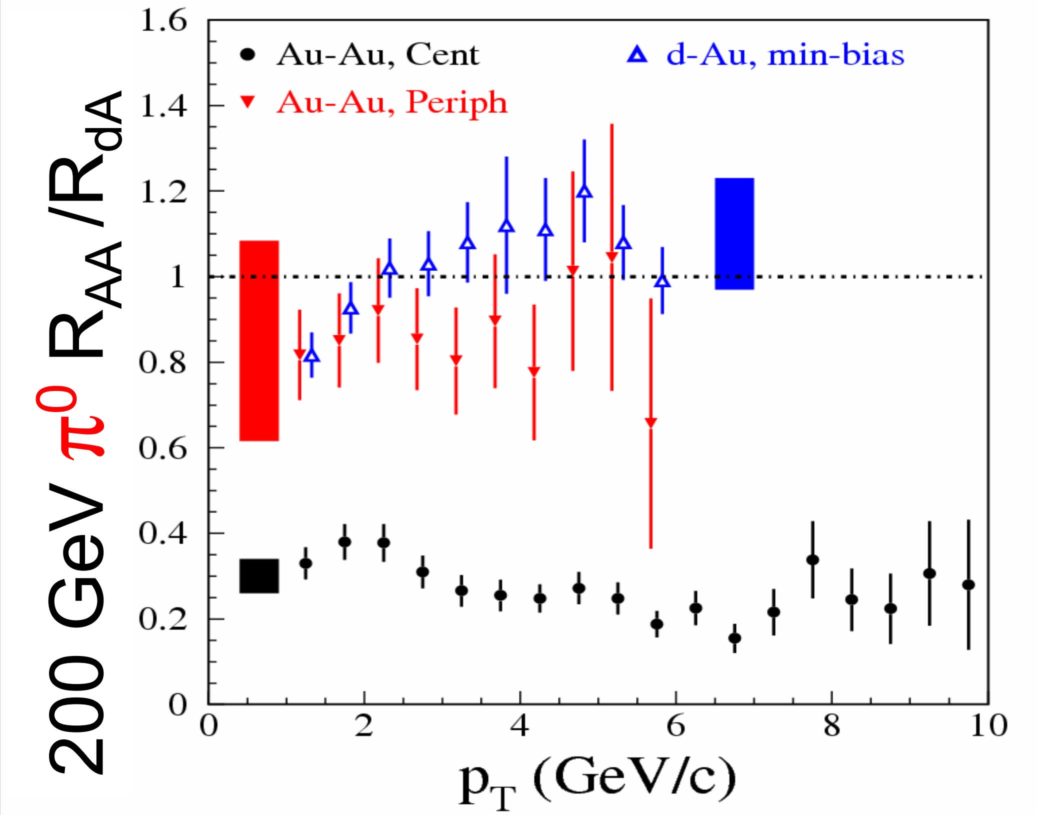
The one-plot summary:

- Factor of 4-5 suppression of π yield in central (0-10%) Au-Au
- Little/no suppression in peripheral collisions.
- No suppression in d-Au

⇒ Energy density = 15 GeV/fm³ at τ = 0.2 fm in central Au+Au

- Our job is done .. NOT!



- What have we learned about jet quenching?
- What do the results tell us about the medium?
- How well do the data constrain “models” of
- How can we better test understanding of
- Jet tomography ????

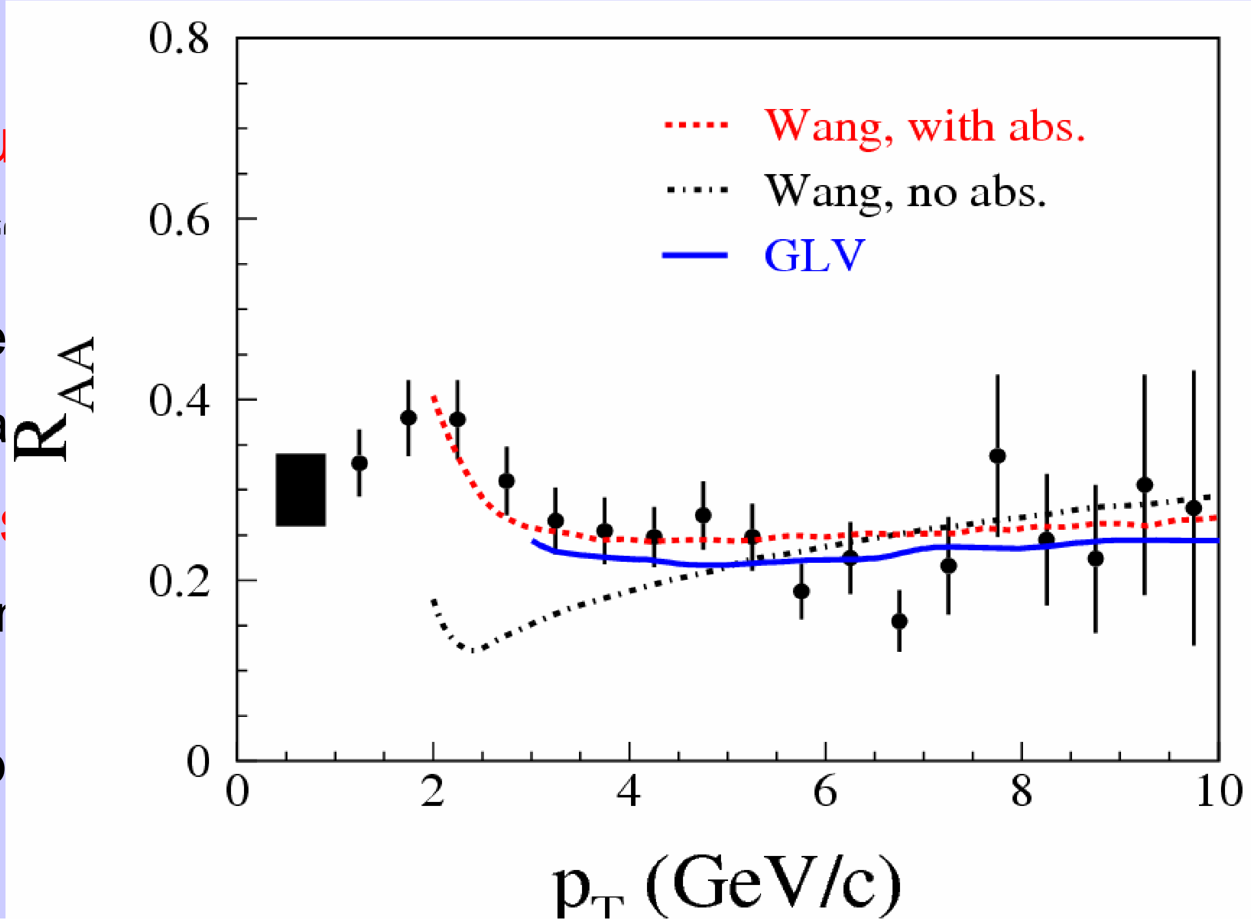
Energy Loss: Theory

- Look at 2 theoretical analyses applied to data
  - Gyulassy, Levai, Vitev formalism
  - Wang & Wang (+) analysis
    - ➢ with/without absorption of energy from medium

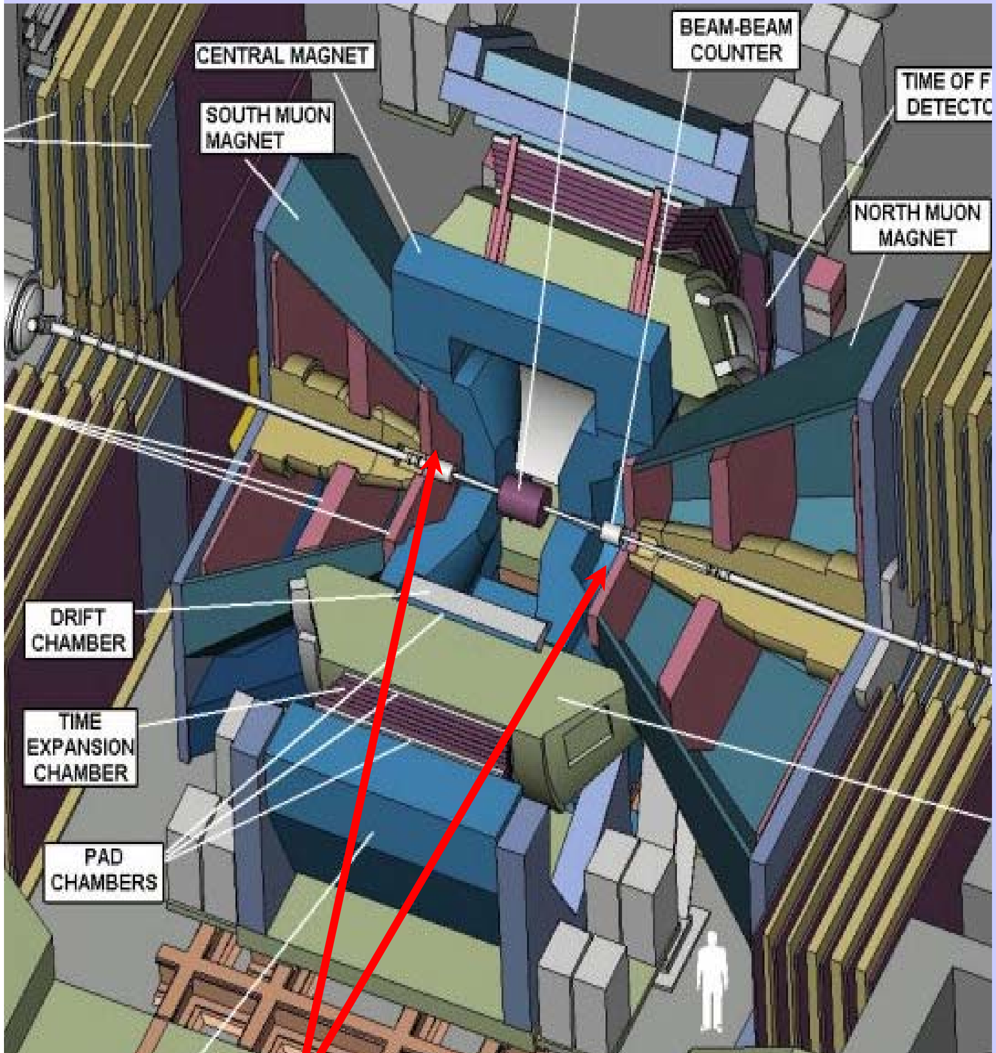
⇒ **Good description of the suppression!?**

BUT

- The magnitude of su
- The only remaining “
  - p_T dependence of the
  - In particular, ≈ consta
- However, the models
  - GLV: higher order cor shadowing, quark/glu
  - Wang & Wang: feedb
- Need more tests …

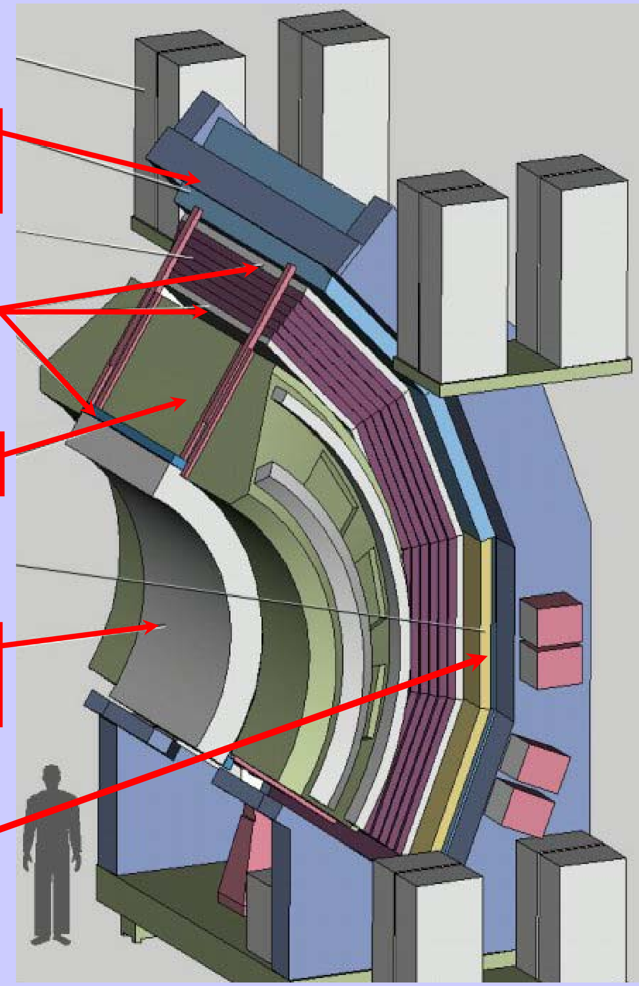


PHENIX Detector



Beam-Beam Counters

Central Arms



- Focus on high-p_T / penetrating probes
- Central arms: $\Delta\phi=1\pi$, $\Delta\eta=0.7$
- In this talk: **focus on π^0 production** for simplicity

Empirical Energy Loss Analysis

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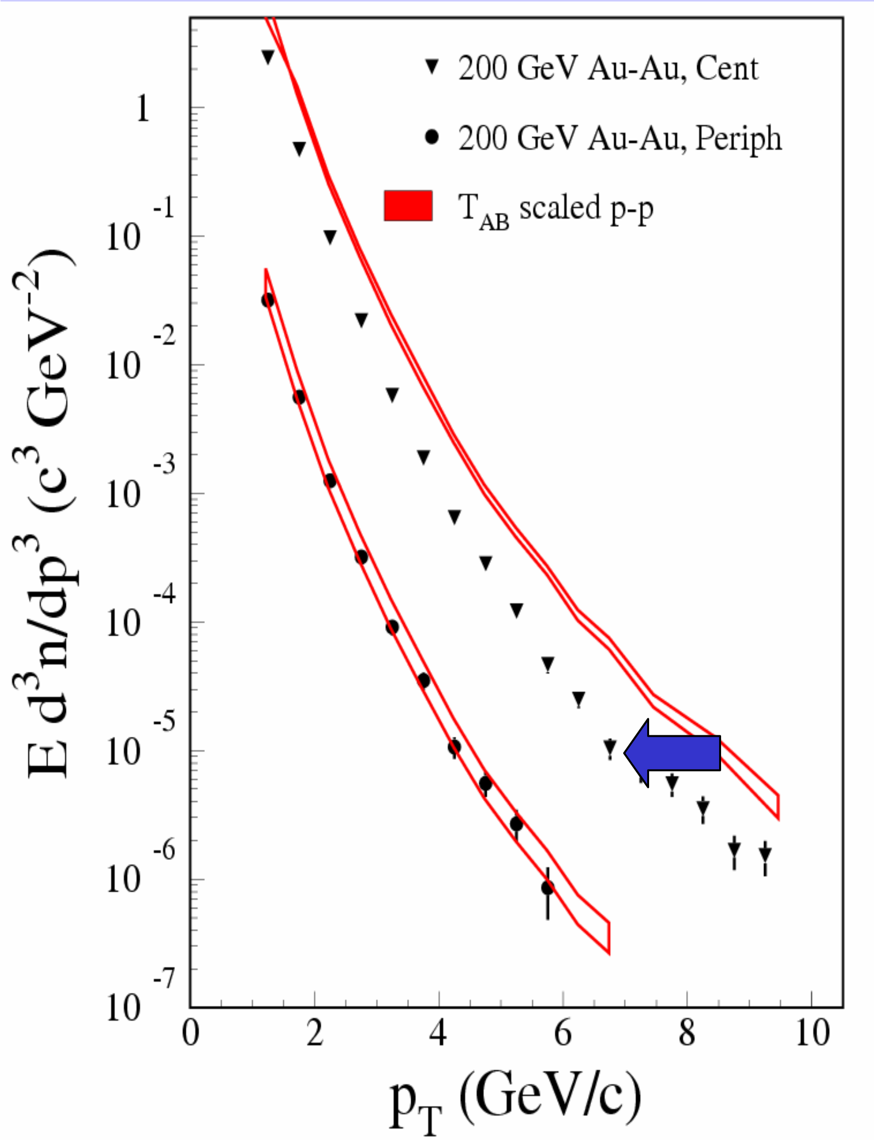


- p-p π^0 spectrum well described by power law: $\frac{dn}{dp_T^2} = \frac{A}{p_T^n}$ with $n = 8.1 \pm 0.1$
- Define p_T shift, $p_T^S = p_T^U - S(p_T^U) = (1 - S_{loss})\, p_T^U$
  - $p_T^U = p_T$ with no energy loss
  - $p_T^S = p_T$ with energy loss
  - S_{loss} is fraction of p_T lost
- Then, given S_{loss},

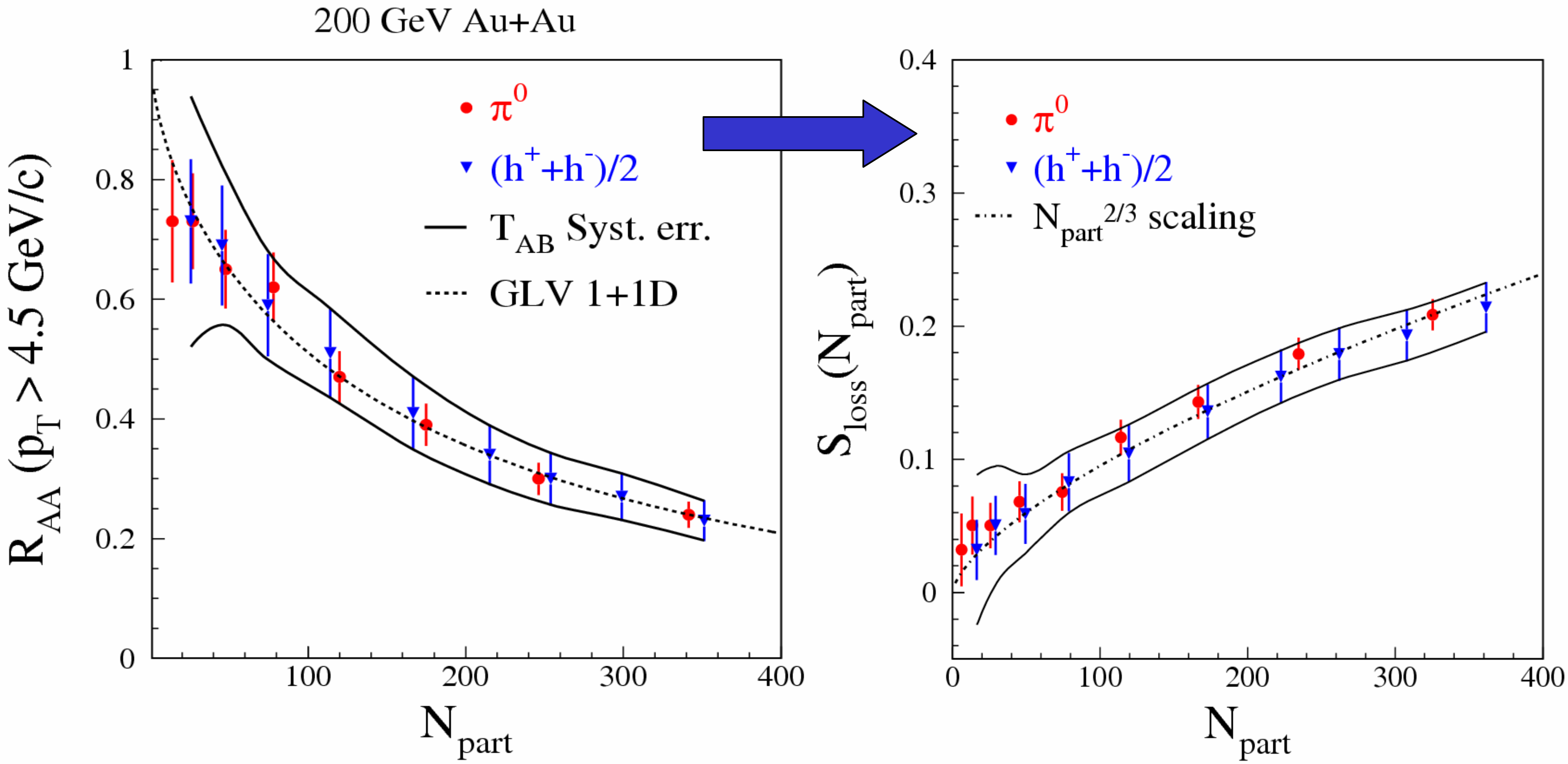
$$\frac{dn}{dp_T^S} = \frac{dn}{dp_T^U}\frac{dp_T^U}{dp_T^S} = (1 - S_{loss})^{n-2}\frac{A}{\left(p_T^S\right)^{n-1}}$$

- Now express in terms of R_{AA}:

$$R_{AA} = \frac{(1 - S_{loss})^{n-2}\ A / p_T^{n-1}}{A / p_T^{n-1}} = (1 - S_{loss})^{n-2}$$

$$S_{loss} = 1 - R_{AA}^{\ 1/(n-2)}$$

Empirical Energy Loss Applied



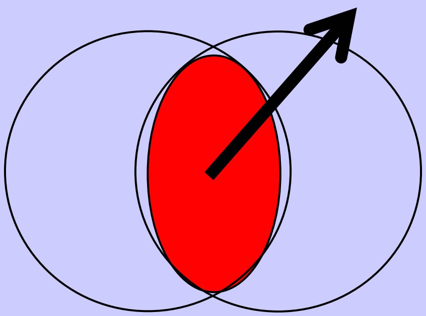
- Gyulassy, Vitev, Wang: $\Delta E \propto N_{\mathrm{part}}^{2/3}$
  - 1D expansion, simple geometric scaling

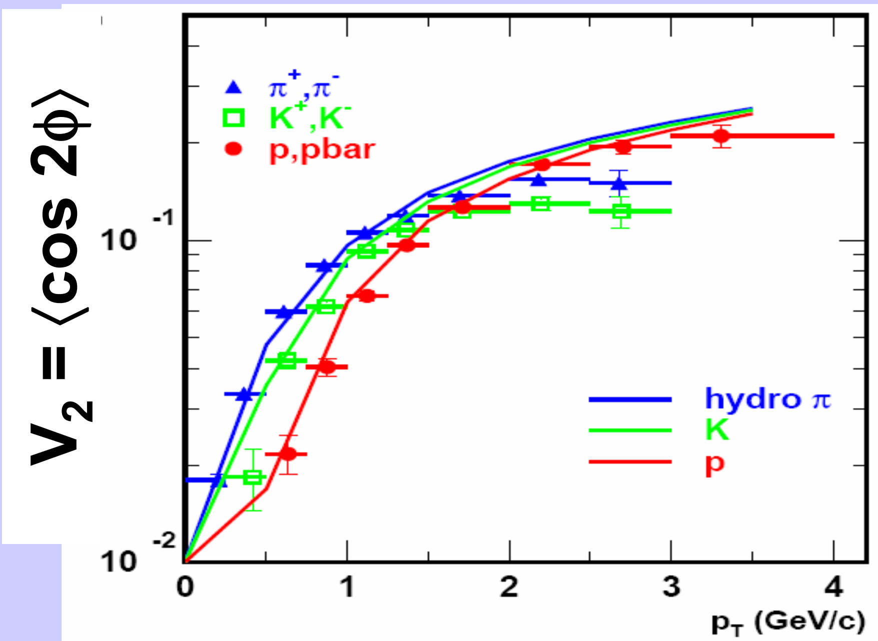
$\Rightarrow$ Well reproduced by experimental data.

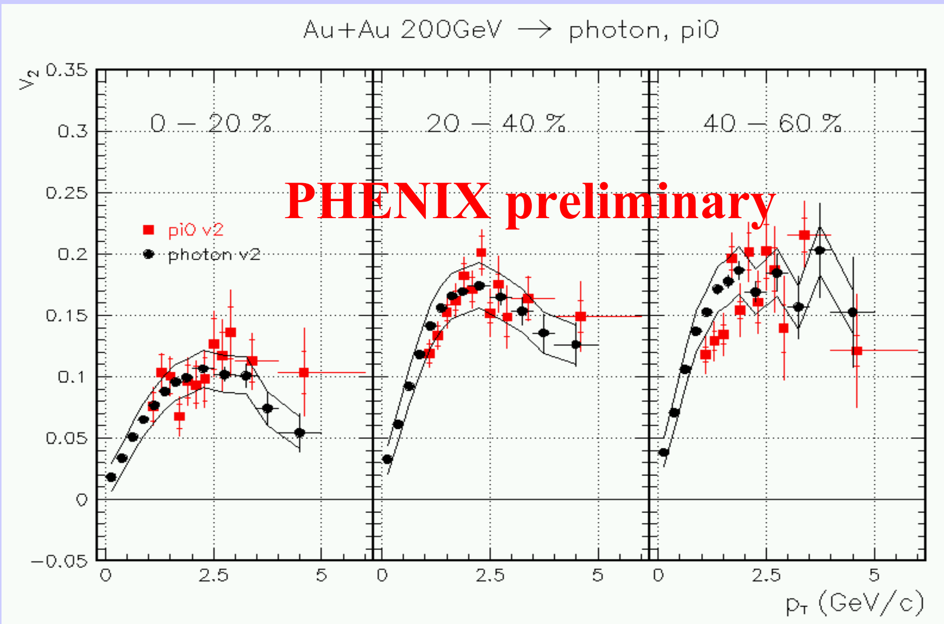
- More easily seen in $S_{loss}(N_{part})$

Angle *wrt* Reaction Plane

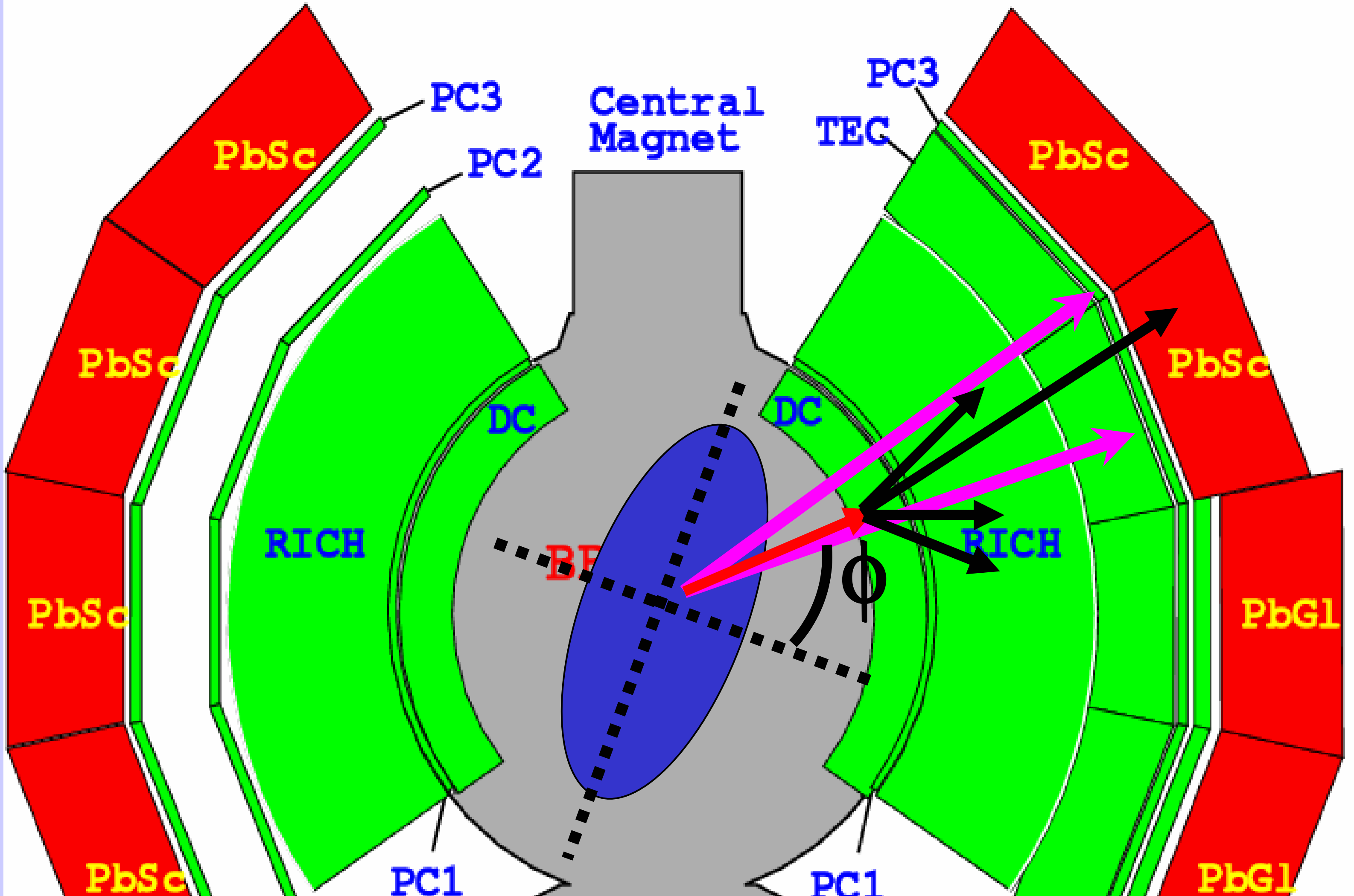
- How to further test understanding of suppression?
  - Another way to vary length of parton path in medium?!
- Change the angle of hadron(parton) relative to $\vec{b}$ in non-central collisions.
  - Spatial anisotropy $\rightarrow \Delta E(\phi)$
- Use "elliptic flow" to find $\vec{b}$ direction.
  - Study π^0 yield vs ϕ, $dn/d\phi \propto 1+2V_2 \cos(2\phi)$





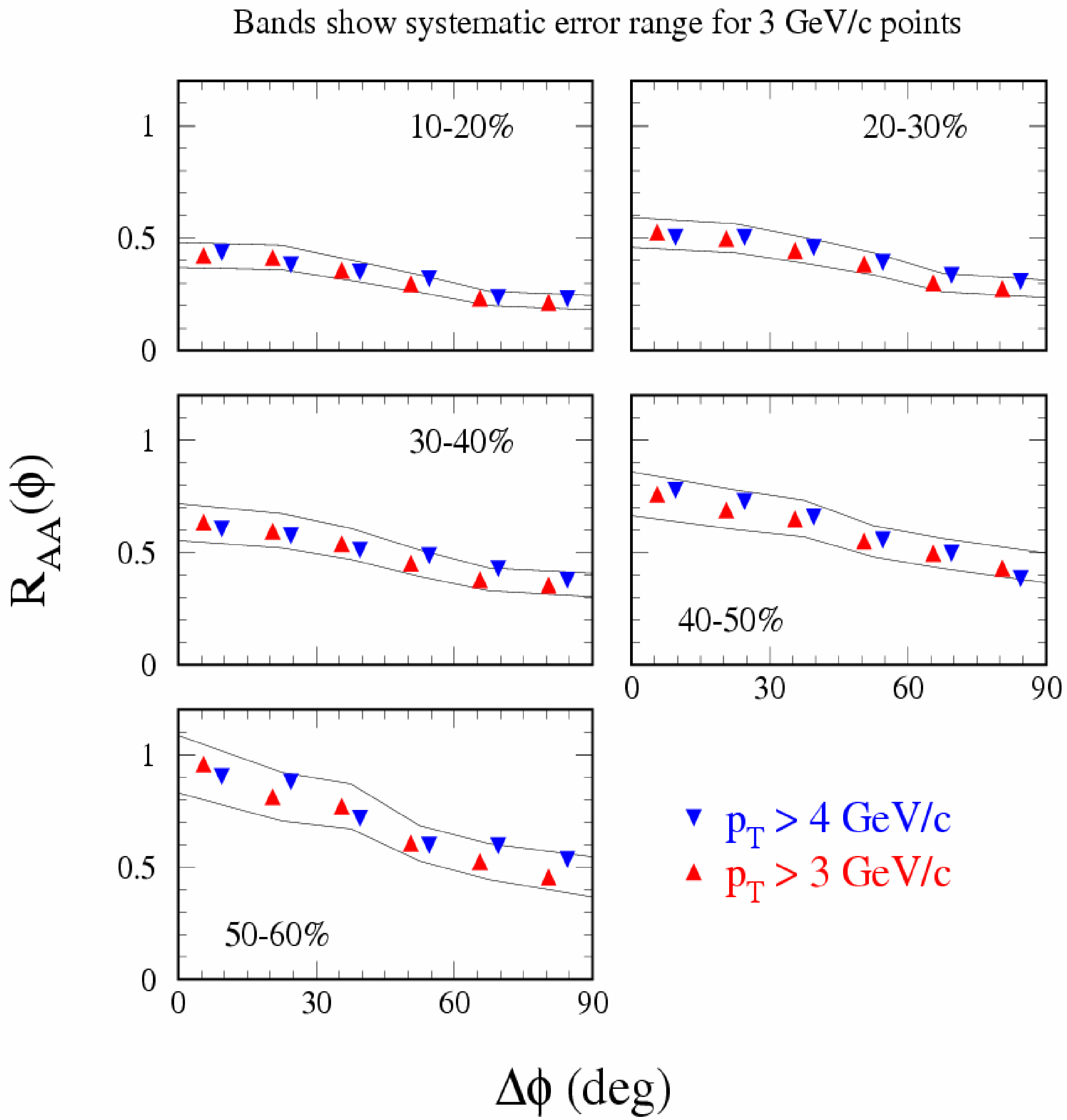


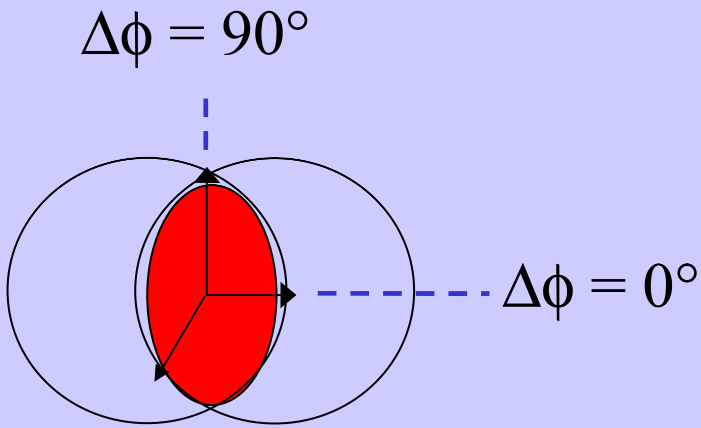
π^0 Production *wrt* Reaction Plane



- Find reaction plane with PHENIX Beam-Beam counter
- Measure π^0 yield vs angle relative to reaction plane, $\Delta\phi$
- Correct for measured reaction plane resolution.

Suppression vs Δϕ

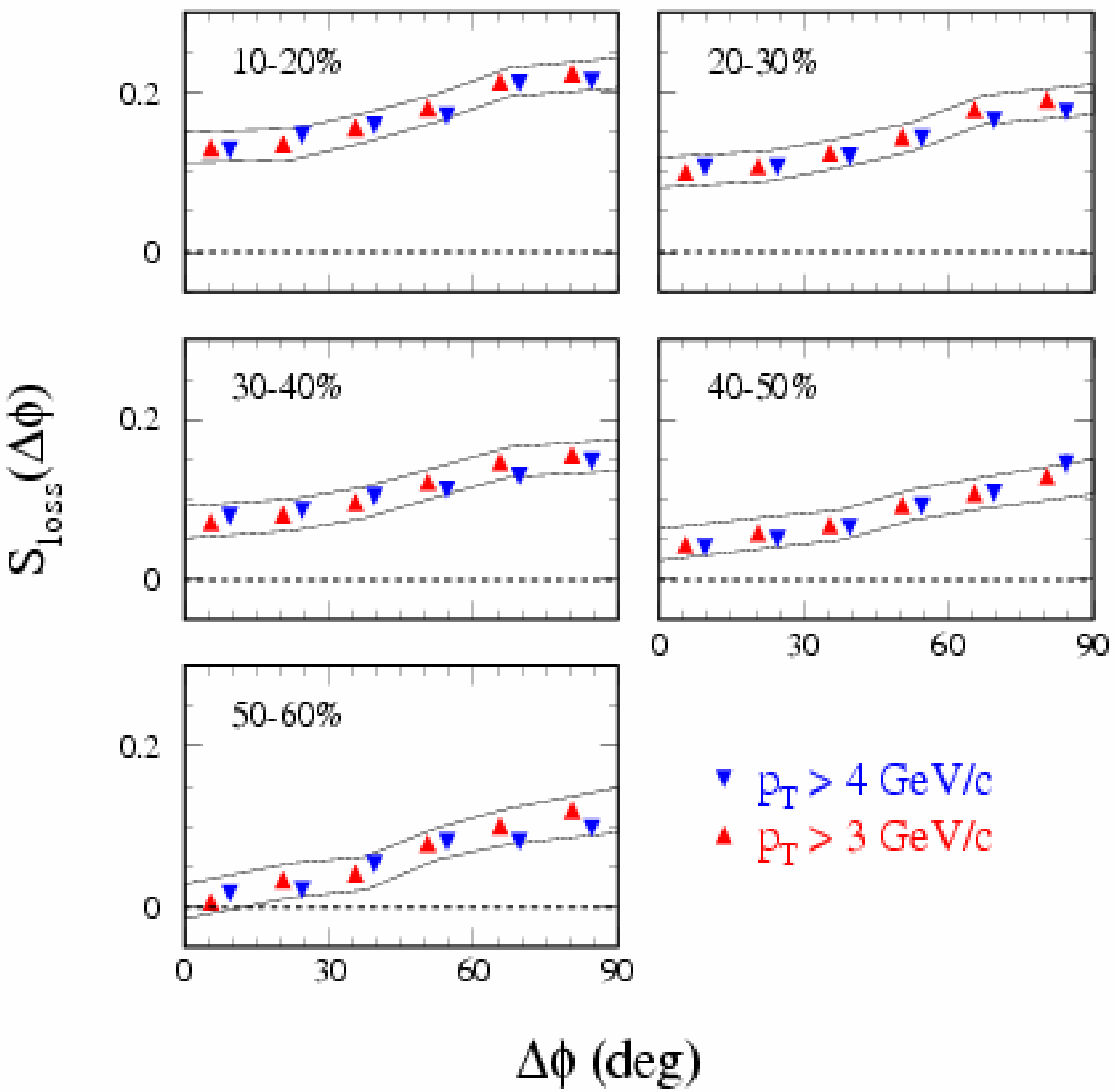


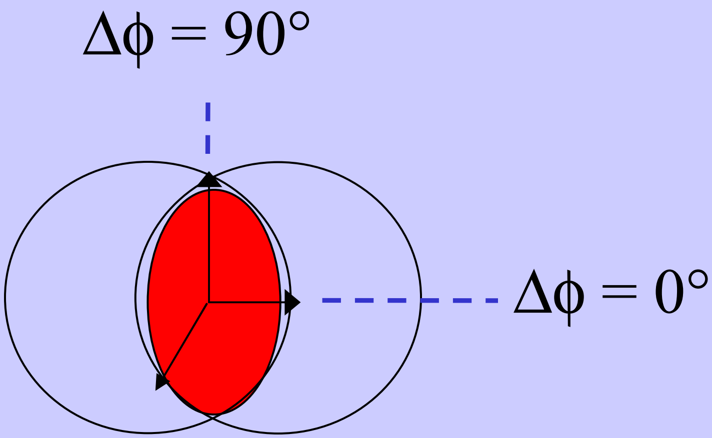


Observe:

- Less suppression in "short" direction.
- More suppression in "long" direction.
- Big variation in peripheral events.
- p_T dependence ?

Energy loss vs $\Delta\phi$





- Same conclusions as with $R_{AA}(\Delta\phi)$.

Basic Geometry Considerations

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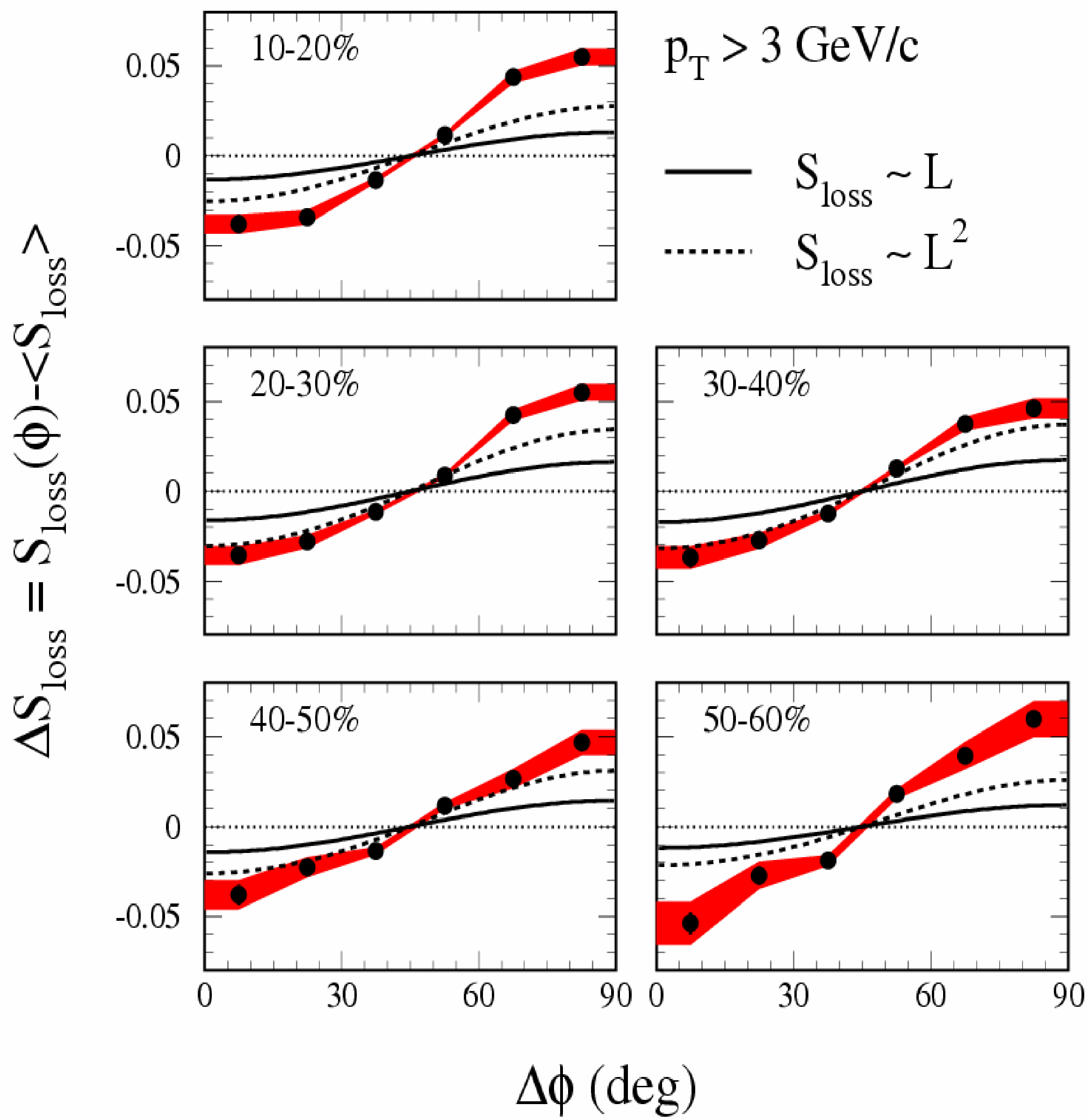
- Suppose energy loss (S_{loss}) has simple dependence on path length: $S_{loss}(L) = cL^m$
- Then, also assume: $L(\Delta\phi) = L_0 + L_2\cos(2\Delta\phi)$
- So, in this simple picture $(\gamma = L_2 / L_0)$:
  - $S_{loss}(\Delta\phi) = c[L_0 + L_2\cos(2\Delta\phi)]^m = cL_0^m[1+\gamma\cos(2\Delta\phi)]^m$
- For m =1 or γ small,
  - $S_{loss}(\Delta\phi) \approx \langle S_{loss}\rangle [1+\gamma\cos(2\Delta\phi)]^m$
- Then
- $$S_{loss}(\Delta\phi) - \langle S_{loss}\rangle \approx m\langle S_{loss}\rangle\gamma\cos(2\Delta\phi) + \frac{m(m-1)}{2}\langle S_{loss}\rangle\gamma^2\cos^2(2\Delta\phi) + \ldots$$

Energy Loss vs Path Length

PHENIX preliminary



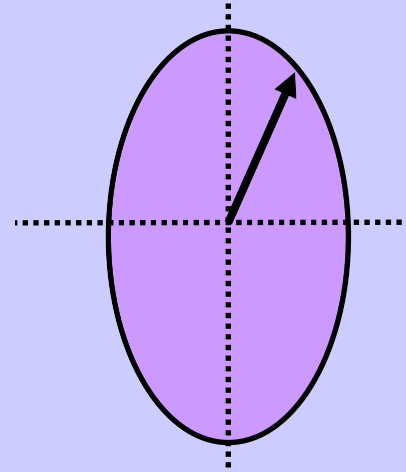
- Use Glauber to obtain (ρ_{part})

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

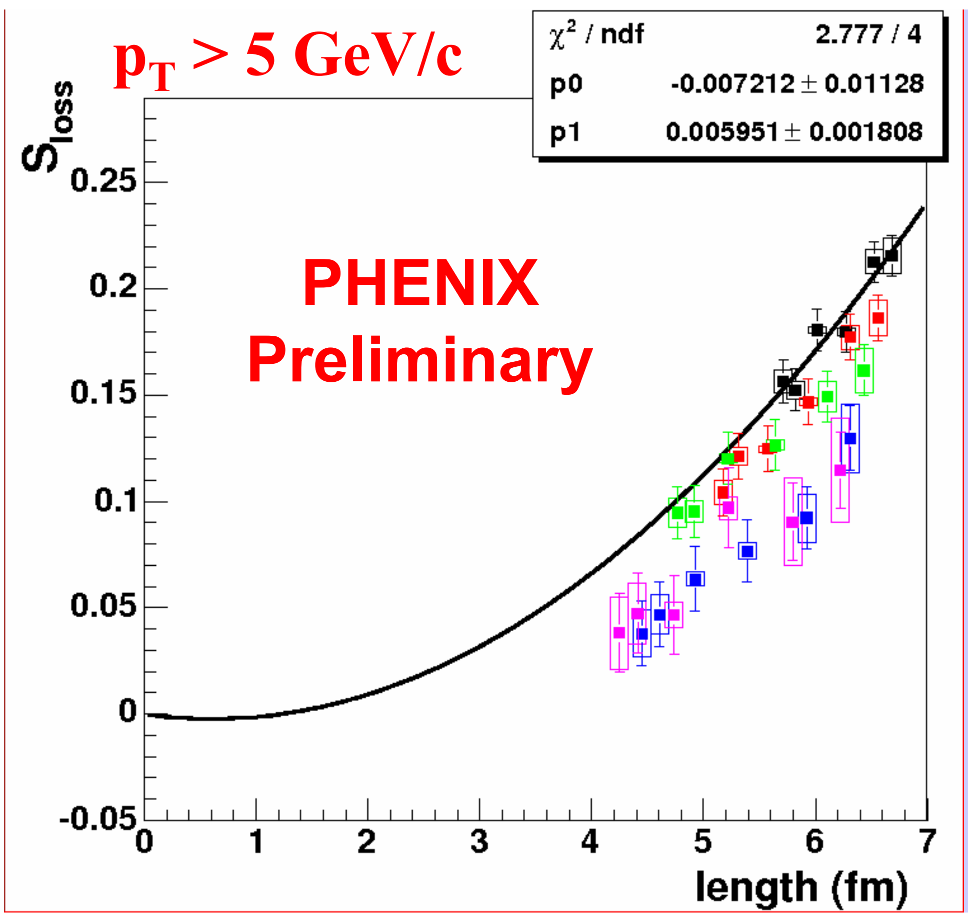
- Elliptical geom:
  - $\gamma = \varepsilon/2$.
- Test $S_{loss} \propto L, L^2$
- $S_{loss} \propto L$ badly disagrees w/ data.
- $S_{loss} \propto L^2$ somewhat better but still not good.

Centrality & $\Delta\phi$ Dependence

- Study π^0 yield vs BOTH centrality, $\Delta\phi$
- Use VERY simple geometric picture:
  - Obtain $L_{\underline{\text{too simple}}}(N_{part}, \Delta\phi)$ plot vs S_{loss}



10-20%, 20-30%, 30-40%, 40-50%, 50-60%



- ~ consistent variation with centrality, $\Delta\phi$??
- But, with unexpected dependence on L!
- $S_{loss} = -0.04L + 0.01L^2$?

  $\Rightarrow$UNPHYSICAL ??
- Or feedback from medium … Or ….

More Realistic Geometry

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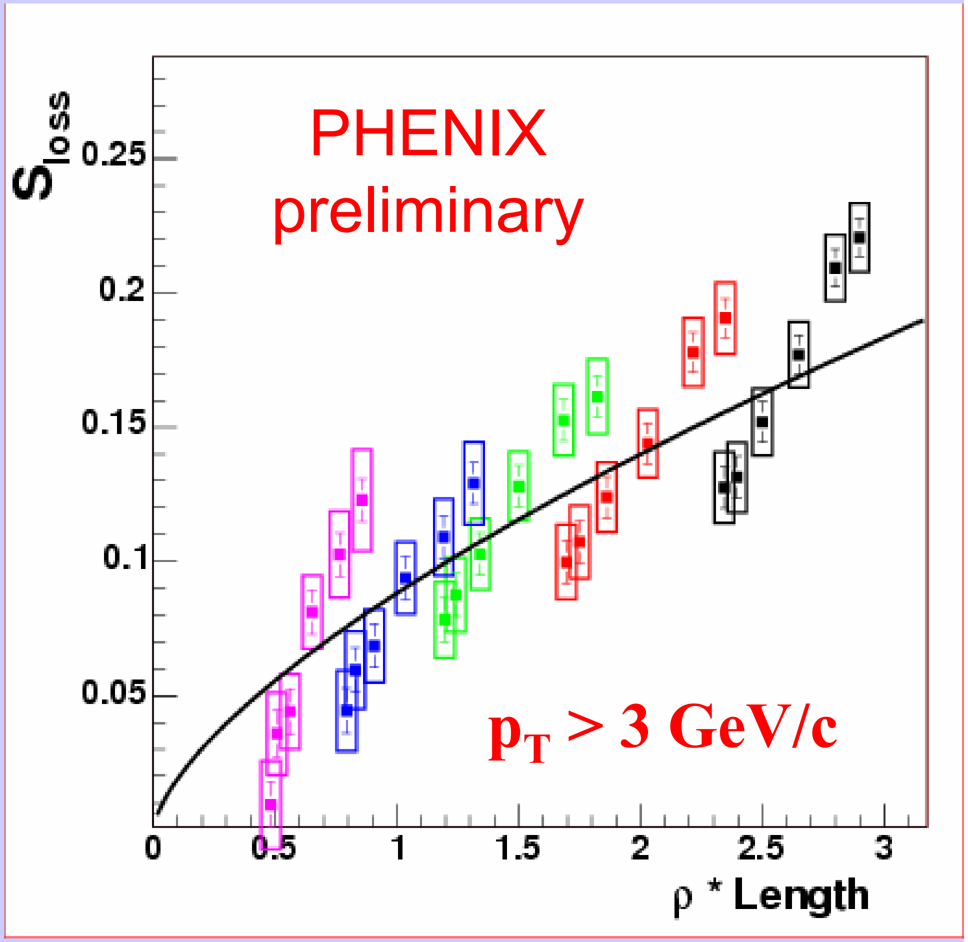
"Canonical" energy loss

- Initial parton (areal) density

$$\frac{dn_{color}}{dA} \propto \frac{dn_{part}}{dA}$$

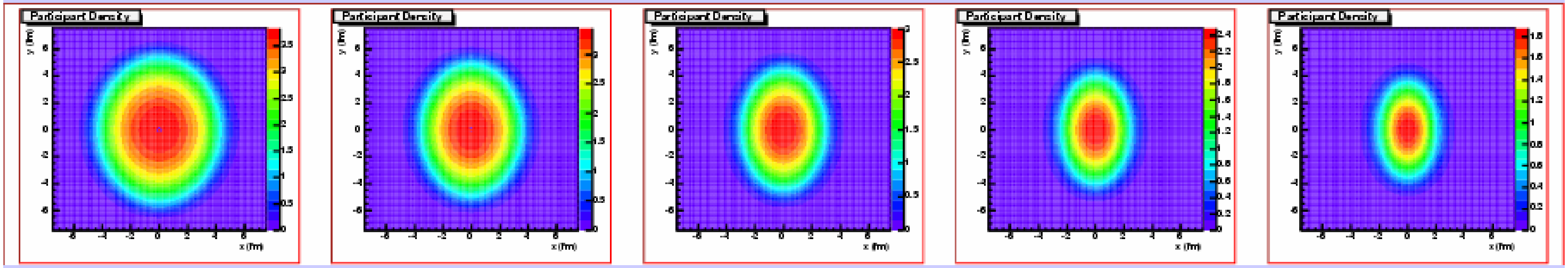
- Intrinsic: $\Delta E \propto L^2$
- Assume: $\rho_{\mathrm{color}}(\vec{x}_T) = \rho_{\mathrm{color}}^{\mathrm{init}} \frac{\tau_0}{\tau}$
- Calculate: $\int d\vec{l}\, \rho_{\mathrm{color}}^{\mathrm{init}}(\vec{l}) \frac{l\,\tau_0}{l+\tau_0}$
- For simplicity, still only evaluate path from center.
- No consistent description of centrality, $\Delta\phi$ dependence.



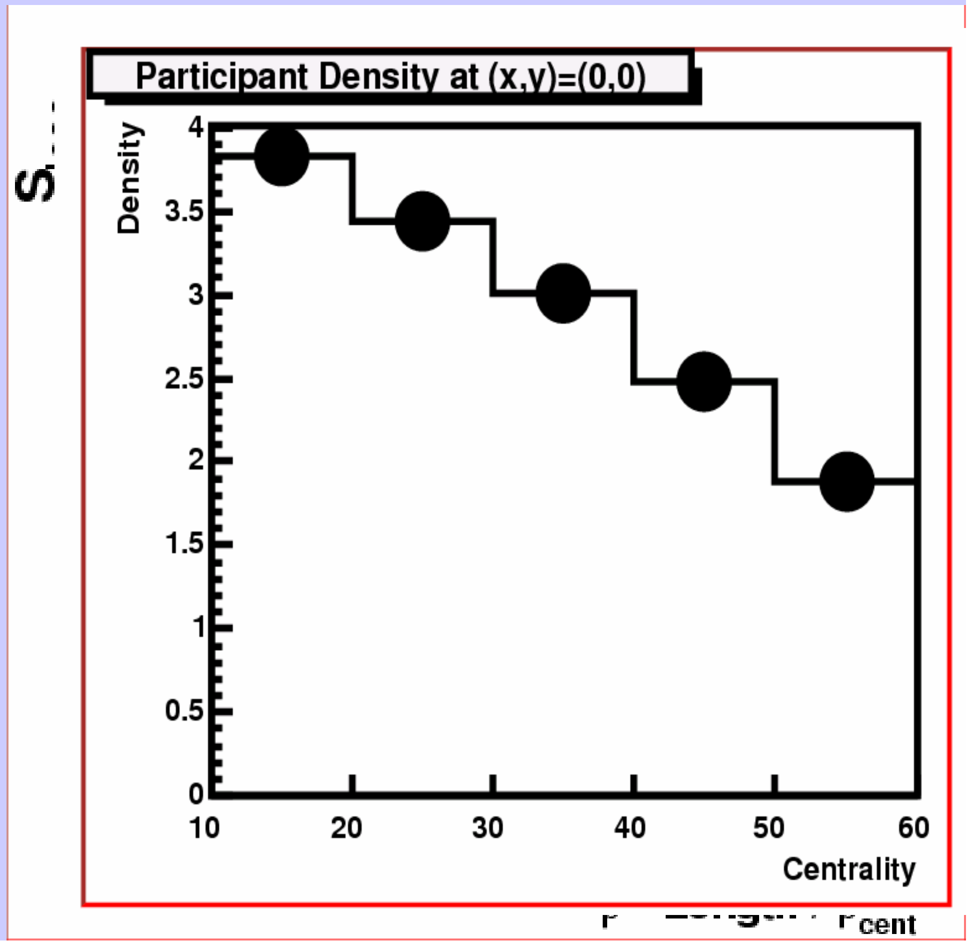
Solid line guides the eye for S_{loss} (N_{part}).

What went wrong ??

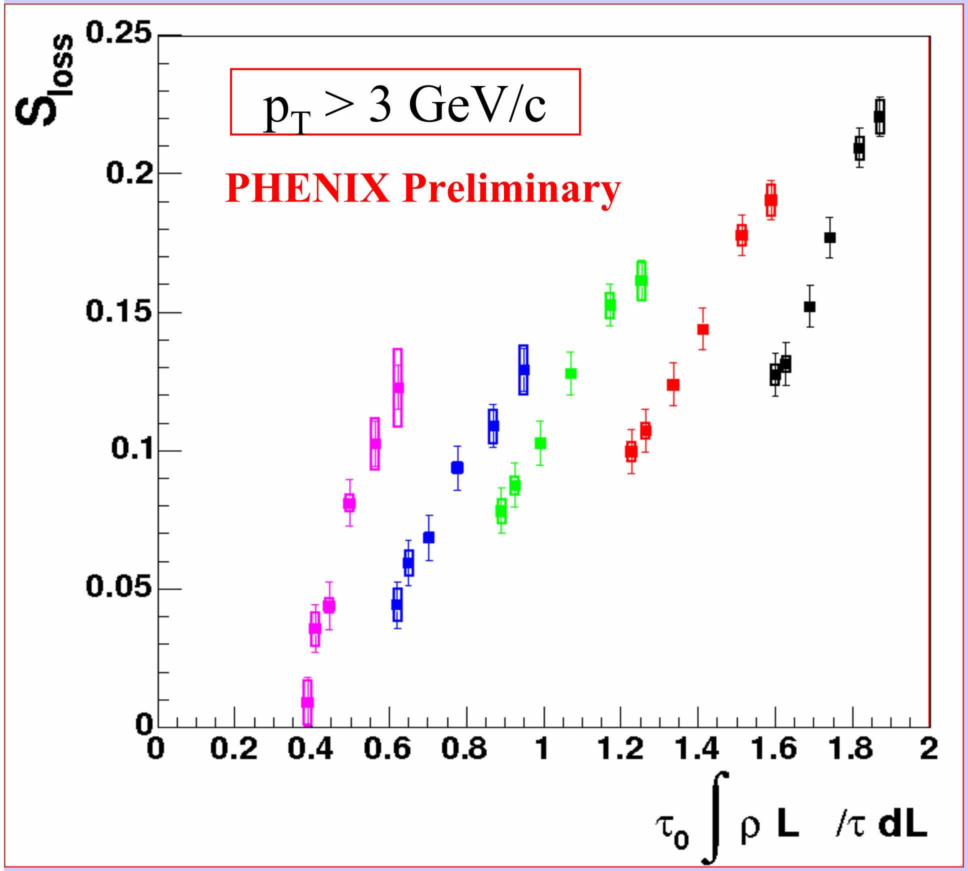
10-20% $\rho_{part}(x,y)$ vs centrality 50-60%

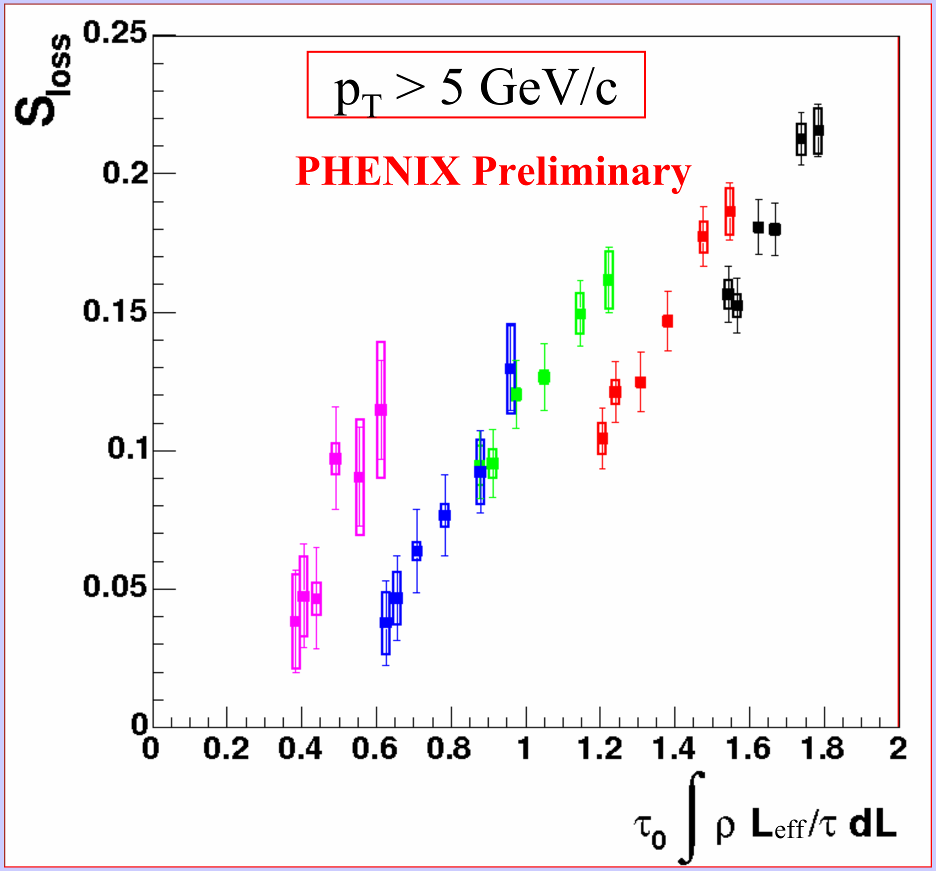


- Overlap density grows with centrality.
  - All $\Delta\phi$ in centrality bin see same overlap density.
- Centralities spread out on horizontal axis.
- Suppose we divide out central density: $\rho_{part}(x,y)$
  - Works well. Why ???

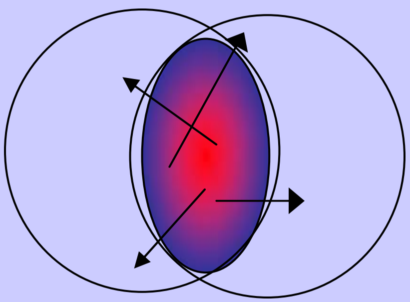


Most Realistic Geometry



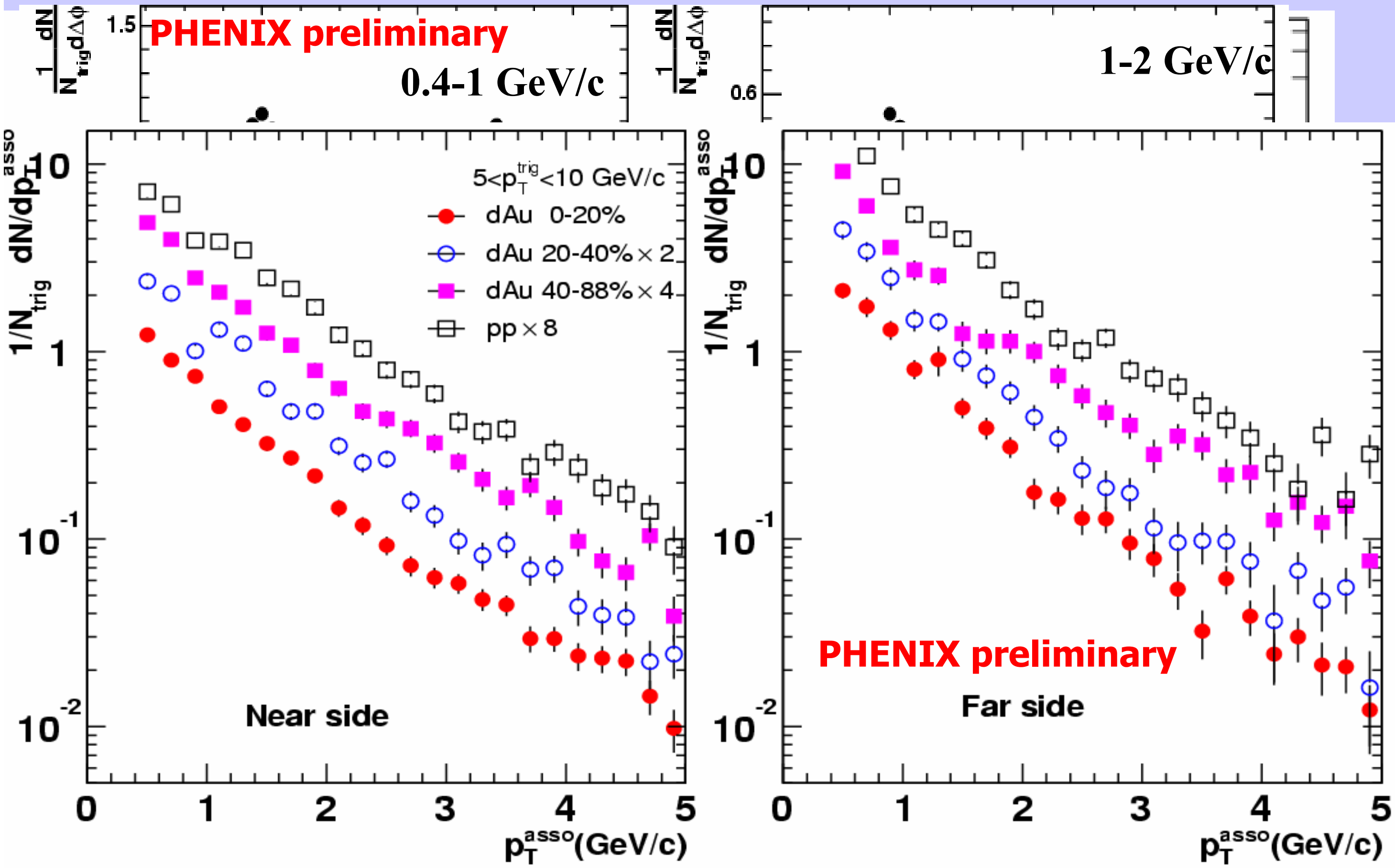


- Incorporate path length fluctuations.
  - Weight S_{loss} according to R_{AA}
- Doesn't "fix" centrality dependence.
- Even 5 GeV/c doesn't work …



PHENIX Jet Studies

- An entire > 1 hour talk by itself.
- Detailed studies of jet properties in p-p, d-Au.
  - via two-hadron correlations
  - **e.g.** $\pi^{\pm}$ (p_T > 5 GeV) – charged by J. Jia, Columbia.



Jet/di-Hadron multiplicity with Jet

Jet Correlations in Au-Au

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- PHENIX charged- charged (preliminary QM2004)
  - $2.5 < p_T^{trig} < 4$ GeV/c, $1.0 < p_T^{assoc} < 2.5$ GeV/c
  - Additional associated yield in same jet in Au+Au
  - But same angular width observed !!!

Stay tuned for final PHENIX Au+Au jet/di-jet results …

Summary, Conclusions

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- High-p_T suppression unequivocally established.
  - Centrality dependence reproduces simple 1-D expansion scaling prediction.
- But, dependence of suppression on $\Delta\phi$ does not fit "canonical" picture of suppression.
  - Requires L^2 (without $1/\tau$) dependence of energy loss?
  - Centrality, $\Delta\phi$ variation not consistent using more realistic descriptions of energy loss.

    $\Rightarrow\Delta\phi$ variation of suppression (S_{loss}) too rapid compared to centrality variation.
  - Except for (overly) simple geometry.

    $\Rightarrow$No growth of "density" with centrality ???
- Simple energy loss picture + geometry is not sufficient to describe yields(ϕ) (or v_2)

Summary/Conclusions (2)

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- Do the data provide room for/evidence of energy absorption from the medium ?
  - One can consider such an effect simply a "complication" of jet quenching
    - ⇒But observation of jets absorbing thermal energy from the medium would be pretty interesting …
- However, other effects at ~ 3 GeV/c may also affect $\Delta\phi$ dependence of hadron yields
    - ⇒Residual soft flow effects ?
    - ⇒Recombination effects ?
    - ⇒Something completely different ?
- Clearly there's something we don't understand.
  - "Higher order" effects in energy loss (opacity exp.) ?
- Important: there's still a problem above 5 GeV/c.

Summary/Conclusions(3)

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- We are not the first to point out these problems
  - Shuryak: **Phys. Rev. C: 027902,2002**.
  - **Drees, Feng, Jia: nucl-th/0310044.**
- High-p_T suppression still not yet a tool for "tomography" … as this talk demonstrates.
  - Have work to do to understand even single hadron suppression. Final version of π^0 vs $\Delta\phi$ soon…
- Jet produced hadron pair correlation results have potential to blow this field wide open …
  - **Iff** we can understand medium induced energy loss.
  - Radiation becomes a probe of the medium!
  - Already starting to see such results/ideas:
    - $\Rightarrow$STAR jet η broadening, Shuryak *et al* shock wave …

A Closer Look

- Energy loss occurs before fragmentation
  - But, energy loss analysis applied to hadron momenta?
  - In principle, not a problem because we observe a power-law spectrum!
- Given parton spectrum: d^2n/dk_T^2
- Hadron spectrum given by:

$$\frac{d^2n}{dp_T^2} = \int_0^1 \frac{dz}{z^2} D(z) \frac{d^2n}{dk_T^2}\bigg|_{k_T = \frac{p_T}{z}}$$

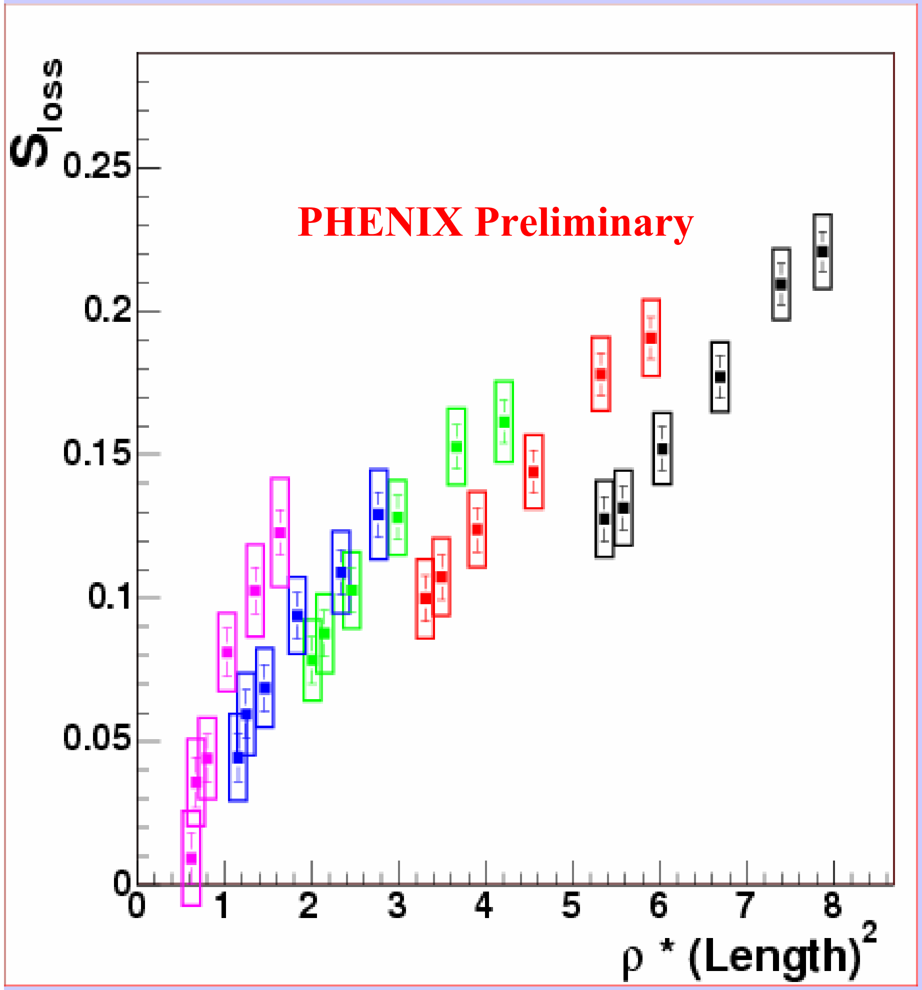
  - **But if** $d^2n/dk_T^2 = A/k_T^n$
  - **Then:** $\frac{d^2n}{dp_T^2} = \frac{A}{p_T^n} \int_0^1 \frac{dz}{z^2} D(z)\, z^n$

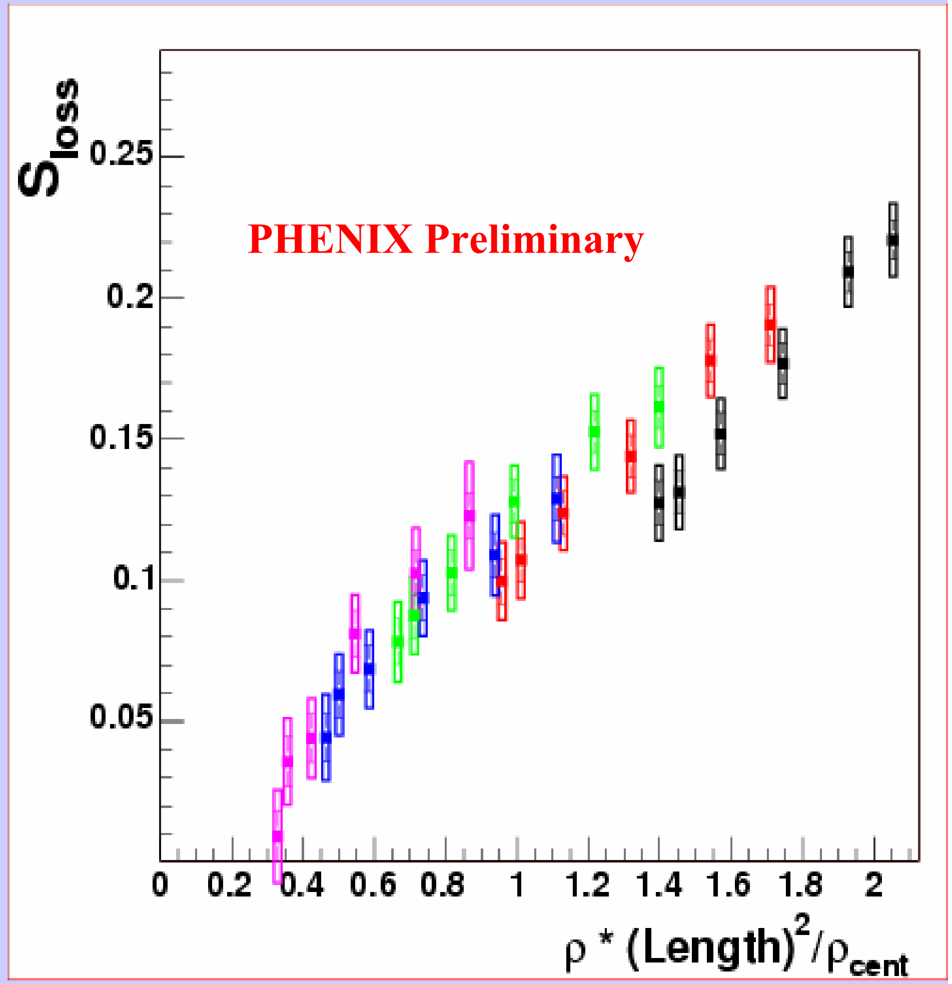
⇒Power law spectrum begets power law spectrum.

⇒Our estimated S_{loss} ≈ applies to parton momenta too.

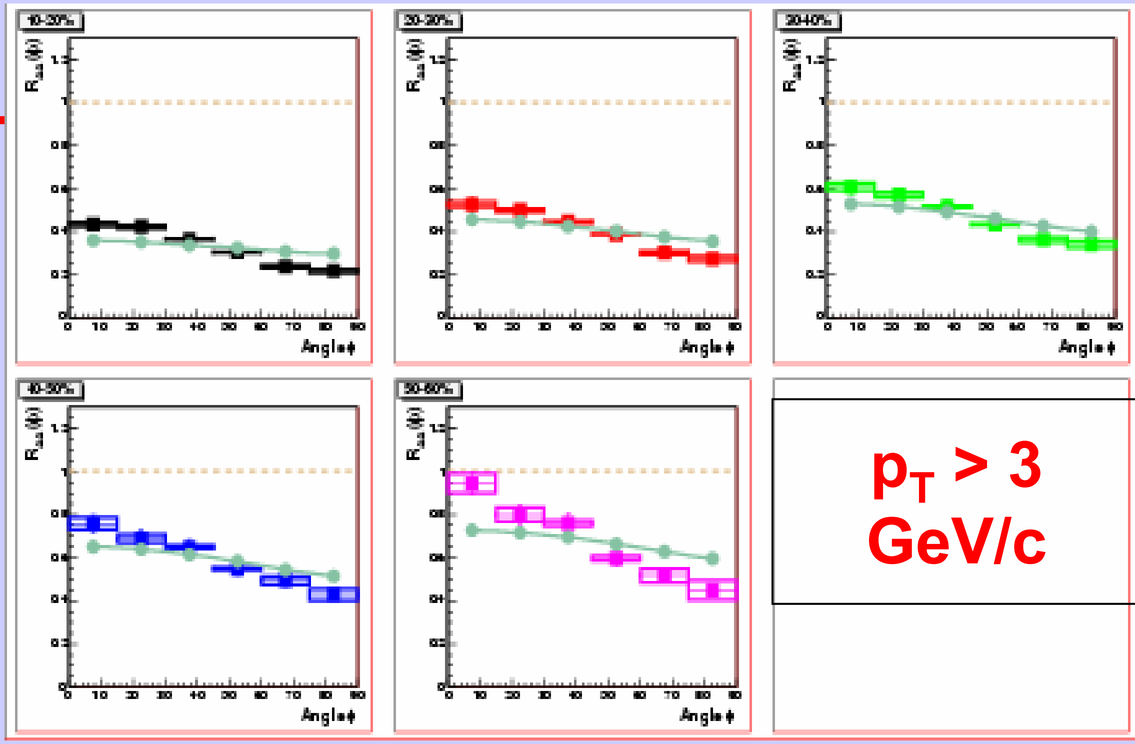
- **Beware: fluctuations reduce observed S_{loss} relative to true value by factor ~ 2 (Baier, GLV).**

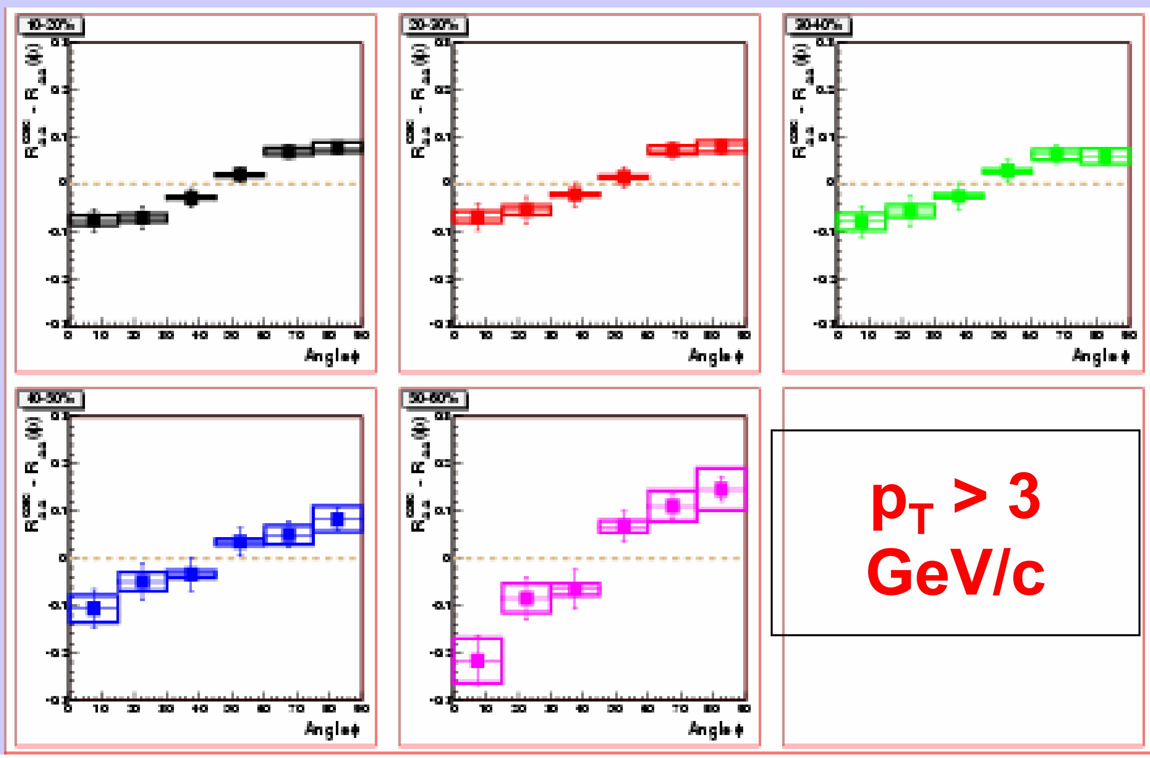
More Realistic Geometry L^2 (L^3/τ) test





- Try different L dependence: $\int d\vec{l}\ \rho_{\text{color}}^{\text{init}}(\vec{l}\,)\frac{l^{\,2}\tau_0}{l+\tau_0}$
  - Still not consistent
- Unless we again divide out $\rho_{part}(x,y)$??





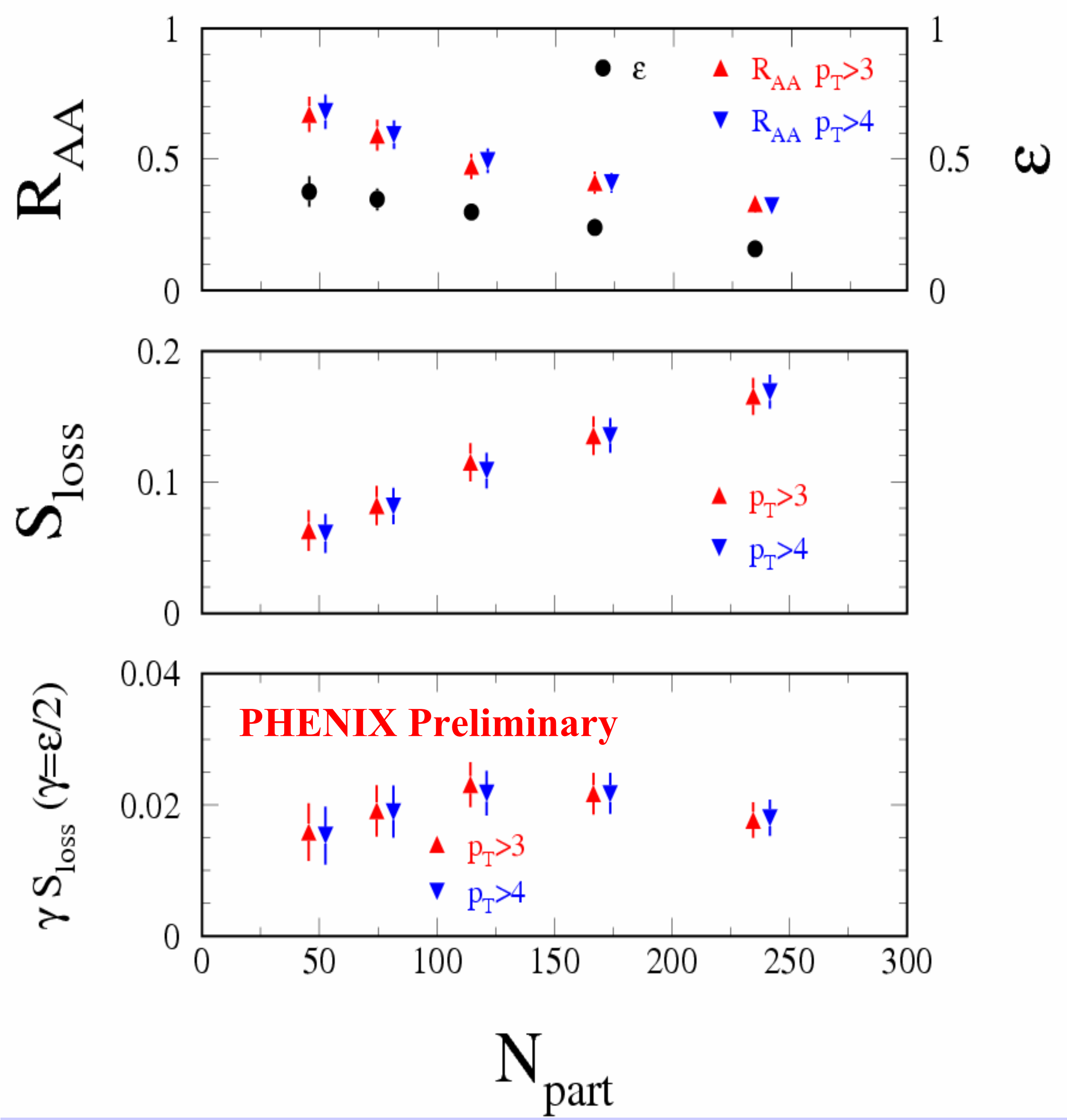
Now, Include fluctuations in length, in addition to density variations

- Lines show L-dependence of energy loss

PHENIX Preliminary

Black: 10-20%, red: 20-30%, green: 30-40%, blue: 40-50%, magenta: 50-60%

N_{part} Dependence of Key Parameters



PHENIX Centrality (Glauber) analysis:

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

For ellipse, $\varepsilon \approx 2\gamma$

Observe:

- For more peripheral collisions, $R_{AA} \downarrow$ but $\varepsilon \uparrow$
- $\gamma \langle S_{loss} \rangle \approx$ constant
- Amplitude of $S_{loss}(\Delta\phi)$ nearly constant !
- Pure accident !

A Closer Look

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- Energy loss occurs before fragmentation
- But, empirical energy loss applied to hadron momenta!?
  - Isn't this a problem? In principle, no.
    - ⇒ Because we observe a power-law spectrum.
- Given a parton spectrum, d^2n/dk_T^2
- We obtain a hadron spectrum, $\frac{d^2n}{dp_T^2} = \int_0^1 \frac{dz}{z^2} D(z) \left.\frac{d^2n}{dk_T^2}\right|_{k_T = \frac{p_T}{z}}$.
- If $\frac{d^2n}{dk_T^2} = \frac{A}{k_T^n}$, then $\frac{d^2n}{dp_T^2} = \frac{A}{p_T^n} \int_0^1 \frac{dz}{z^2} D(z)\, z^n$.
- So, if we observe a power-law spectrum,
    - ⇒ parton spectrum should also be power-law
    - ⇒ Our estimated S_{loss} applies to parton momenta too.
- What about fluctuations in ΔE, z ?
  - Reduce the apparent S_{loss} relative to the true
  - By a factor of ~ 2 (Baier, GLV).

Reaction Plane Correction

- Reaction plane resolution:

$$\sigma = \sqrt{2\cos(\Psi_{BBC_N} - \Psi_{BBC_S})}$$

- Calculate raw V_2
- Correct for resolution
- Multiply yield(ϕ) by

$$\frac{1 + v_2^{corr}\cos(2\Delta\phi)}{1 + v_2^{raw}\cos(2\Delta\phi)}$$