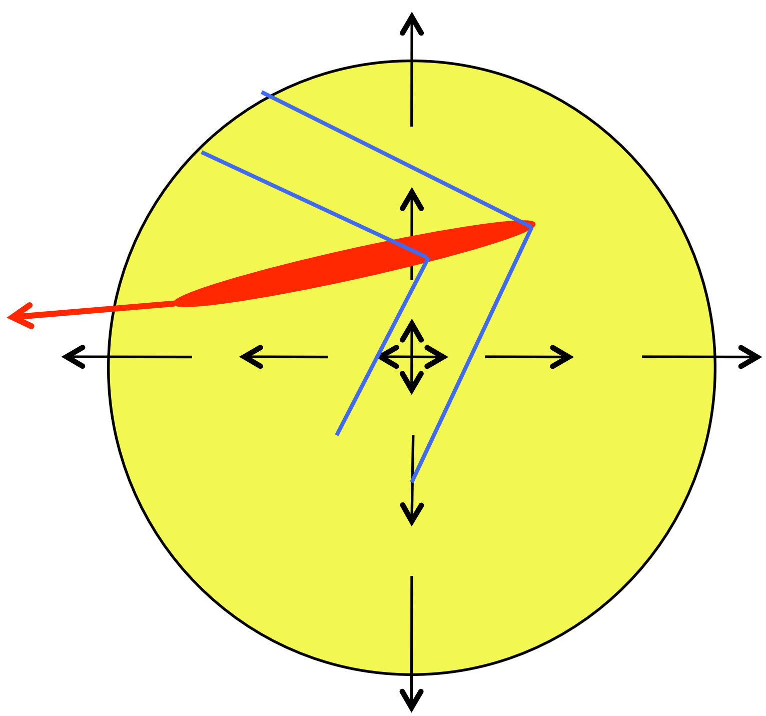
How to bridge the soft and the hard physics at RHIC ???

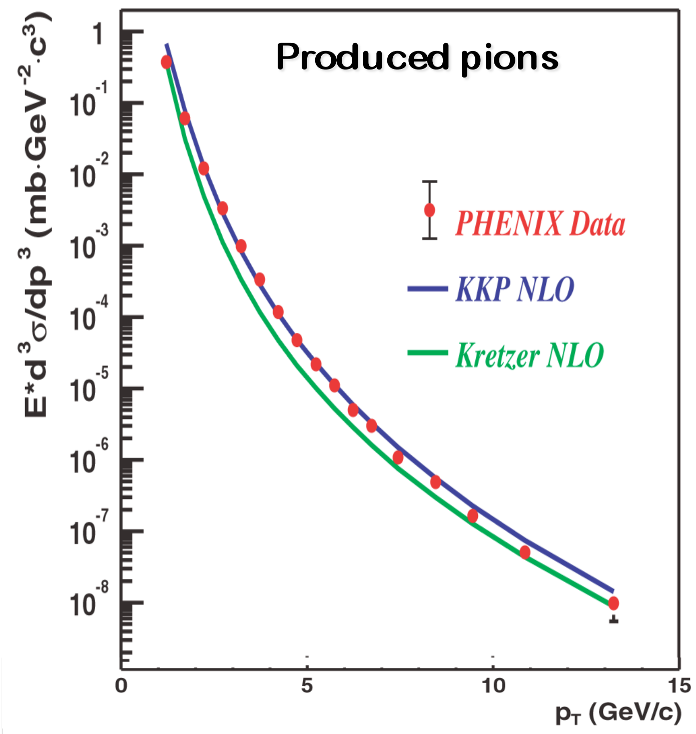
Jiangyong Jia
Stony Brook University & BNL

- Context of the discussion
- Relation between Jet quenching, medium response and flow.

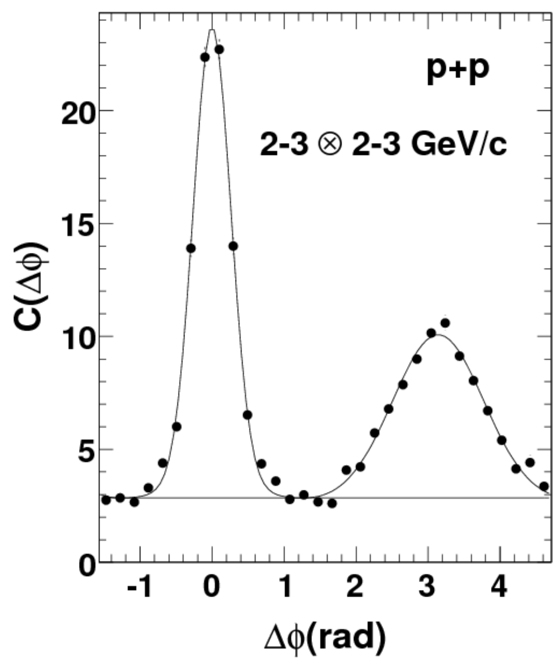


Production of hadrons in P+P

- Jet fragmentation (hard-scattering picture) describes the data down to 2 GeV
  - pQCD calculation describe hadrons spectra done to 1-2 GeV
  - Large fraction of soft pairs show jet-like correlation.

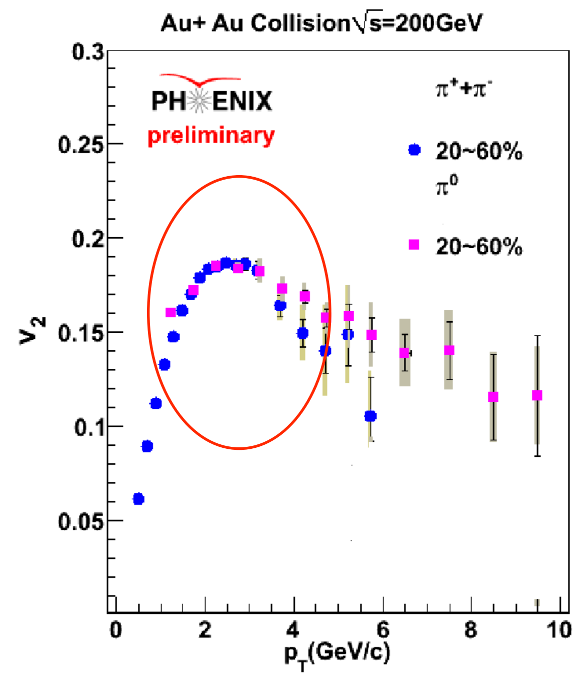


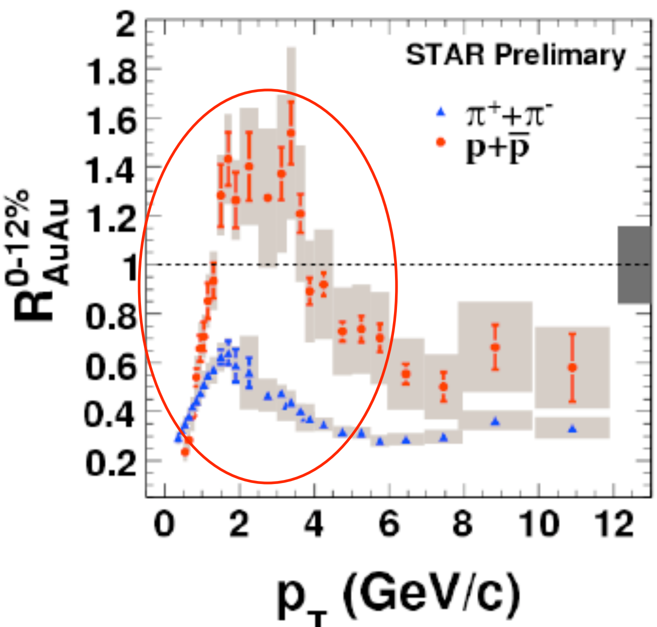
2-3 x 2-3 GeV/c

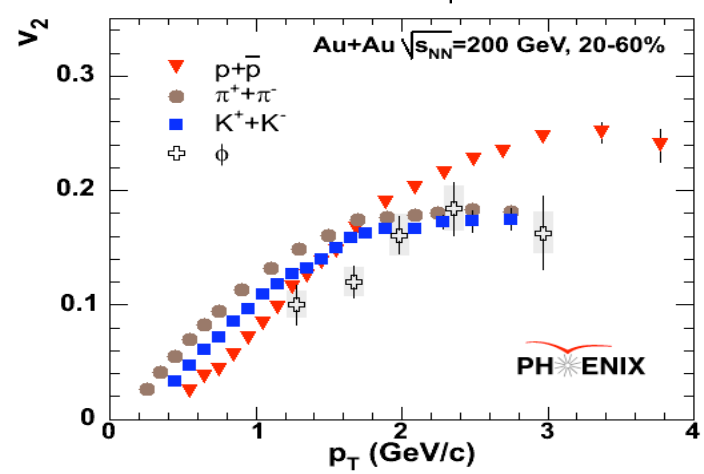


What about Au+Au?

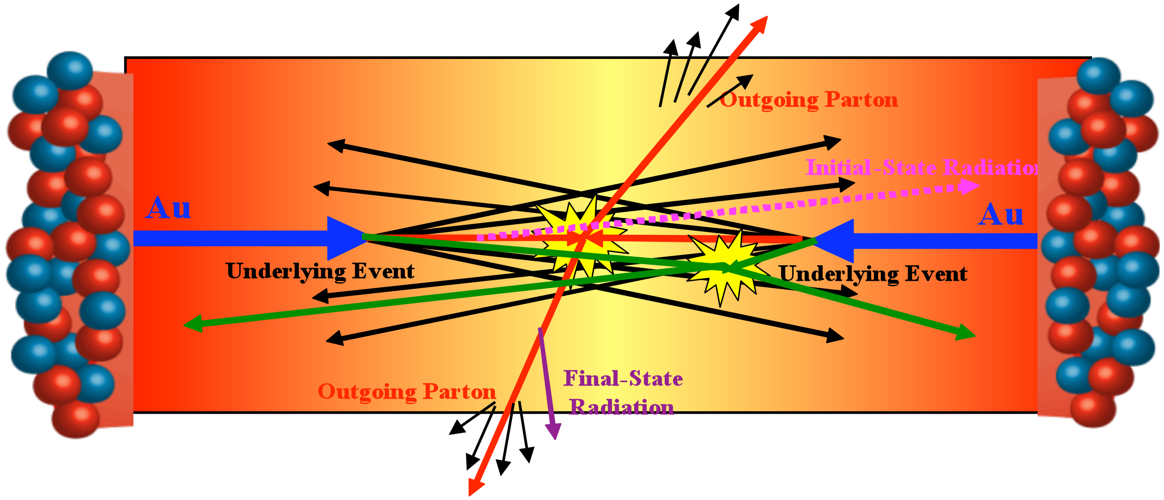
- Intermediate p_T (<5) particles are not jet-like.
  - Less suppression and large v2.
  - Strong dependence on flavor
- Hard-scattering at initial state ⊗ final state effects.
  - Flow, Jet eloss, Medium response, Parton coalesces

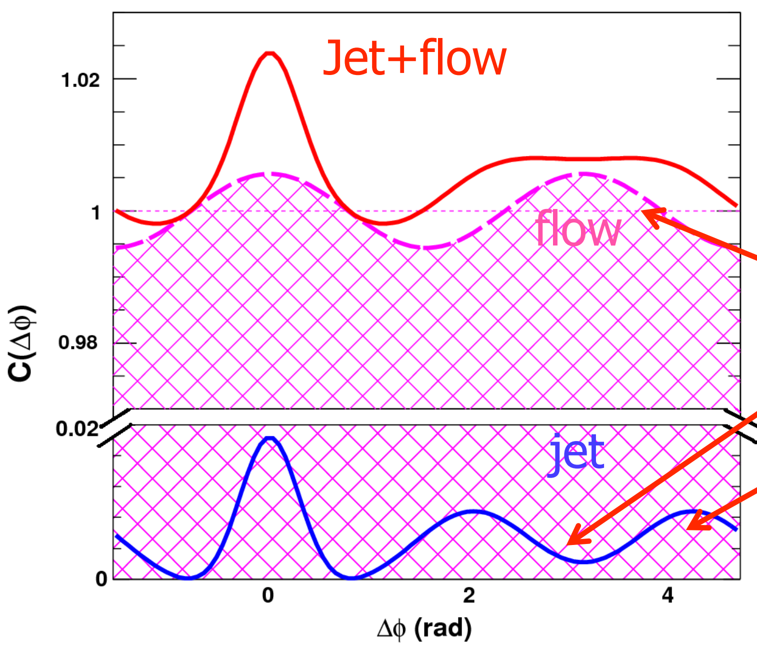






Jet and the Medium



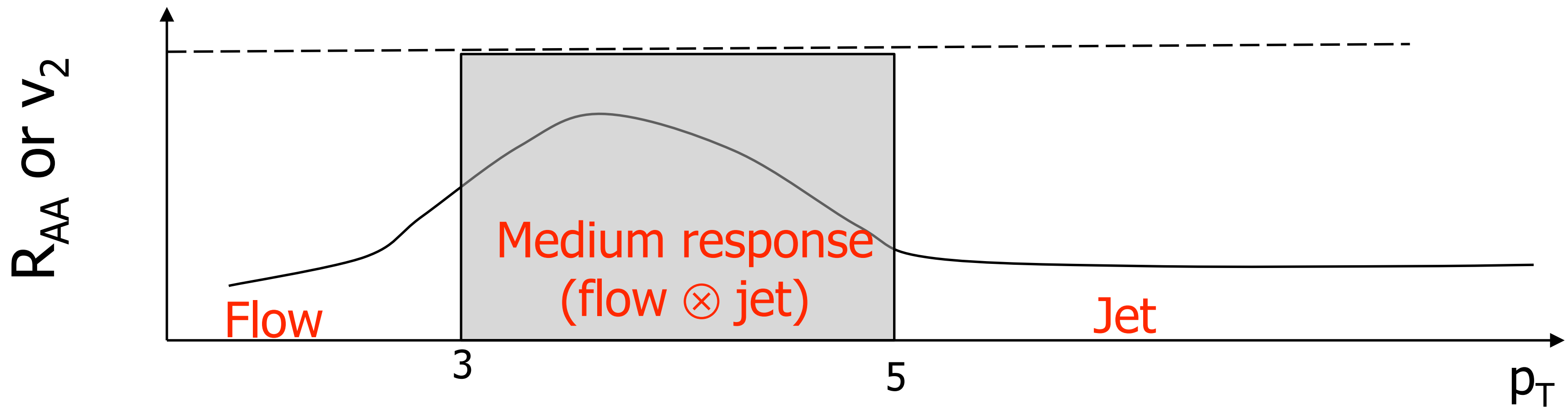


Modified jet + flowing medium

- Three inseparable aspects:
  - Jet quenching
  - medium response
  - Medium collectivity

Current model treat Jet and medium separately

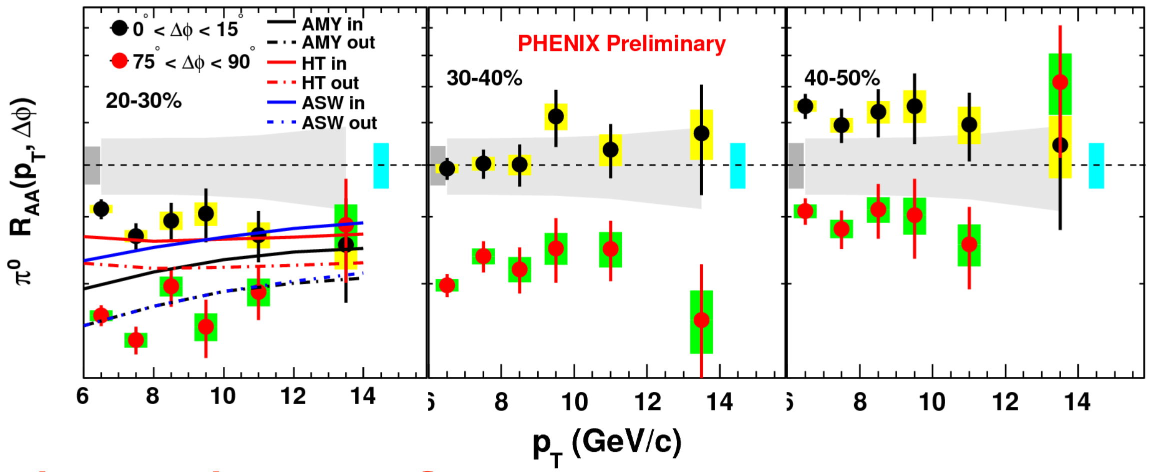
A qualitative picture: context for discussion



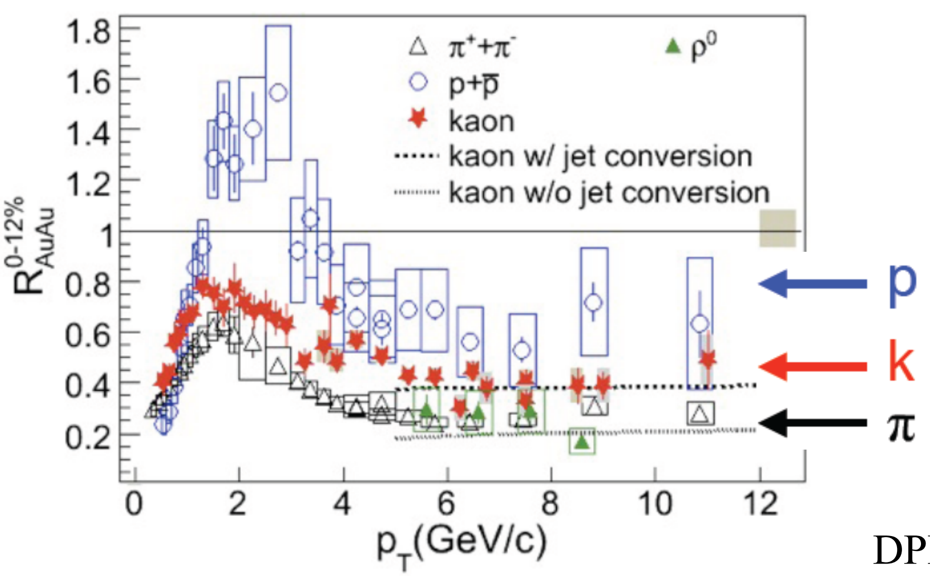
- High pT jets assumed to be described by pQCD eloss: $E>>\omega>>T$
  - Works better for leading particle and those jets that loose small energy
- If AA jet = pp hard-scattering ⊗ final state effects
  - Initial jet production should be important down to low pT, just that these semi-hard partons are strongly modified or thermalized in the medium→non perturb.?
    - Intermediate pT dominated by medium response→ partially thermalized semi-hard partons, gluon feedback from hard-partons . They have imprints of both hard-scattering and flow.
    - Low pT: Semi-hard partons that fully thermalized in the medium become part of the bulk.

Challenge for pQCD: leading particle suppression

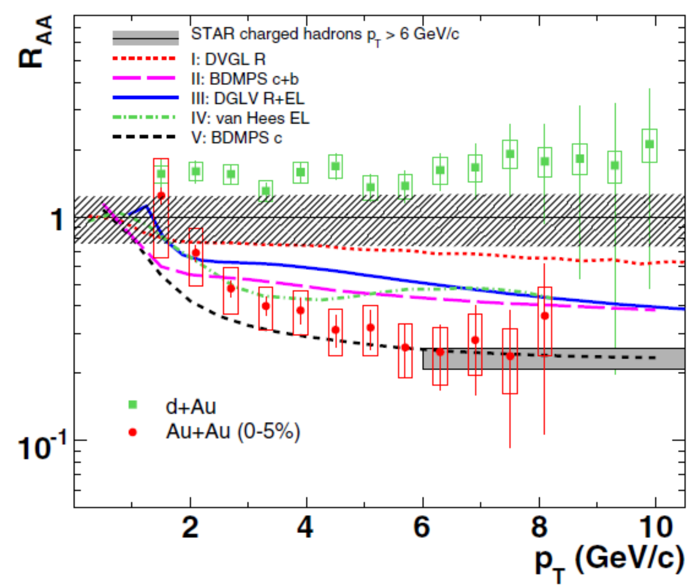
RP dependence of suppression



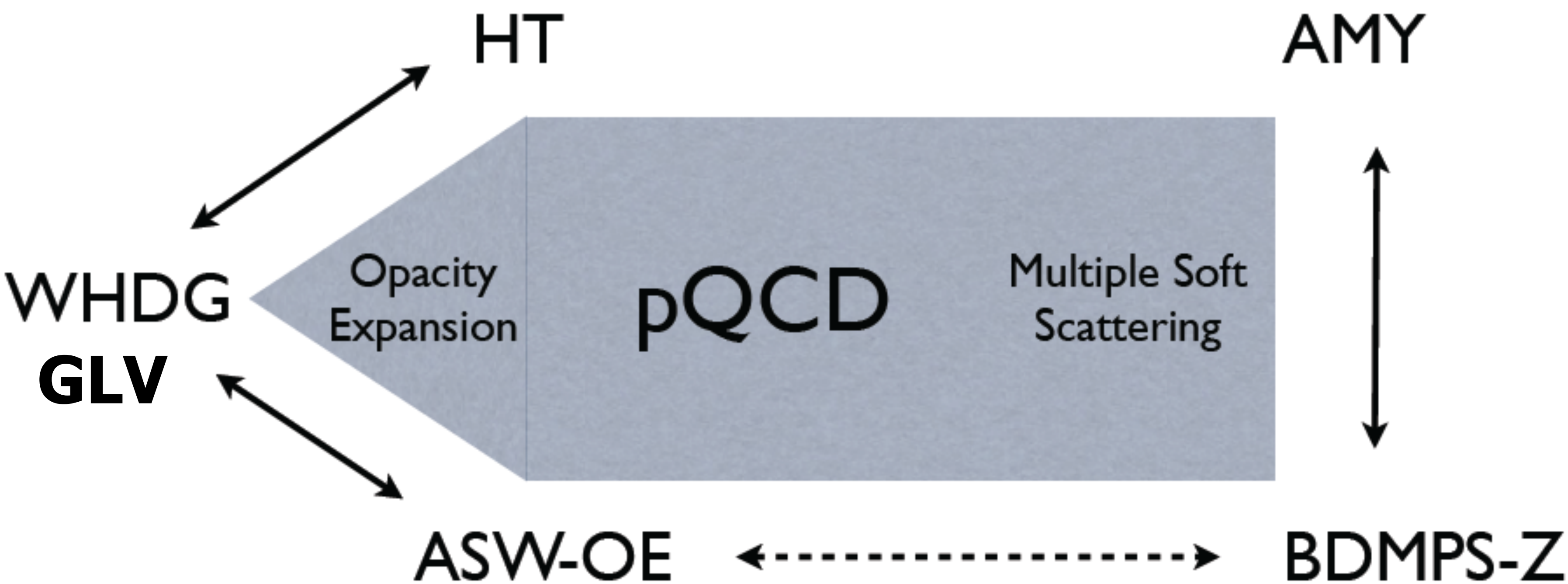
Flavor dependence of suppression



NPE suppression



Challenge for pQCD: Model Comparisons



Beyond pQCD Mechanism for leading particle suppression?

- Is pQCD treatment of eloss applicable for sQGP?

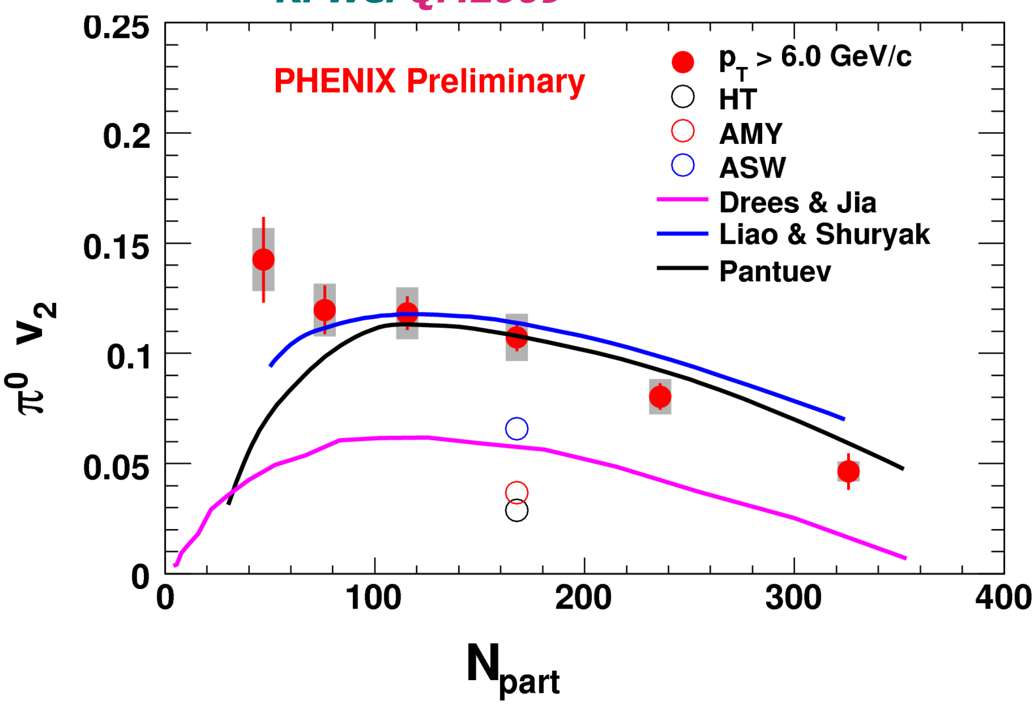
$$\hat{q} N E \alpha E_{sc}^{22}, \ ,\log \qquad \frac{dE}{dx}$$

- Non-perturbative approaches give very different density, path length dependence.

$$\hat{q} N E \alpha L \sqrt{E_{SYMc}}$$ (liu,urs 2007), (Gubsor^{32} 2008), (Khazee $\frac{dE}{dx}$ v 2008)

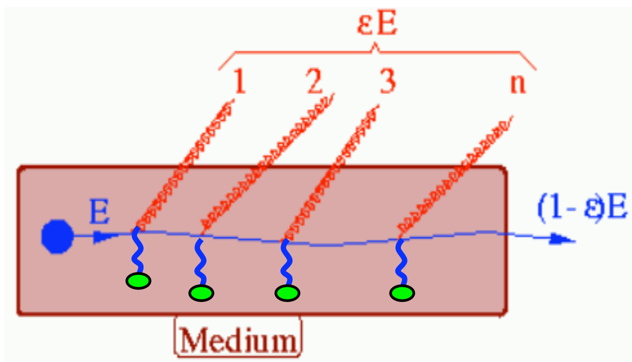
Liao, Shuryak: energy loss is strongest around T_C.

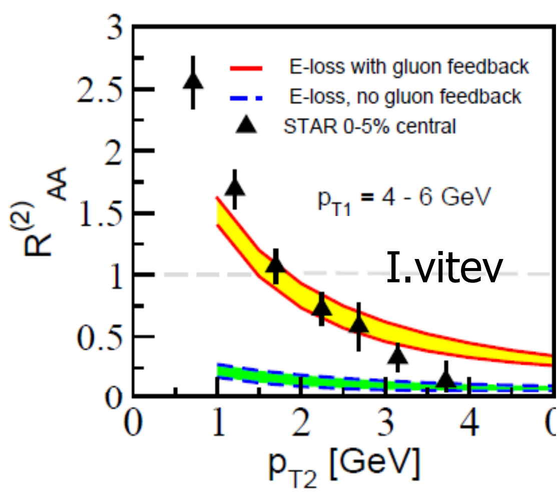
R. Wei QM2009

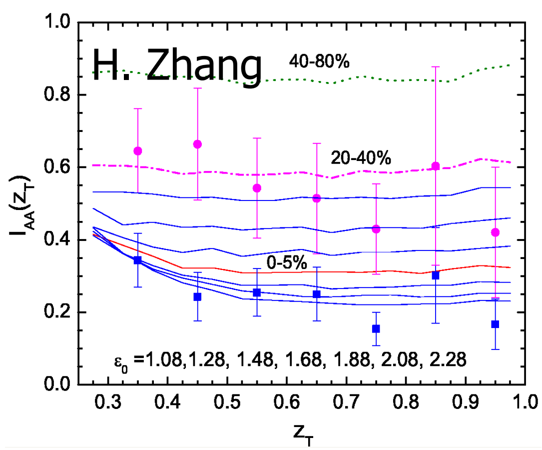


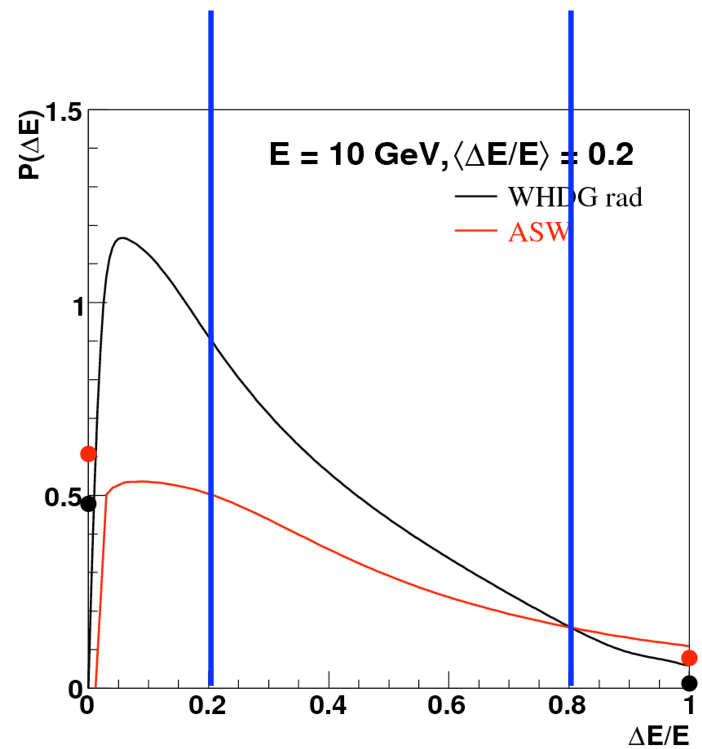
Treatments of lost energy

- pQCD: shower gluons feedback to low pT
  - Not enough yield enhancement, not enough broadening, wrong PID mix.
  - Can soft gluon radiation treated by pQCD?





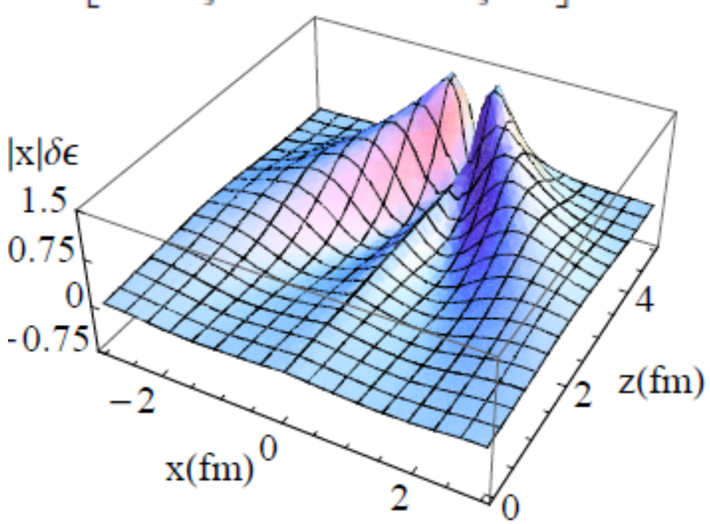




Treatment of lost energy

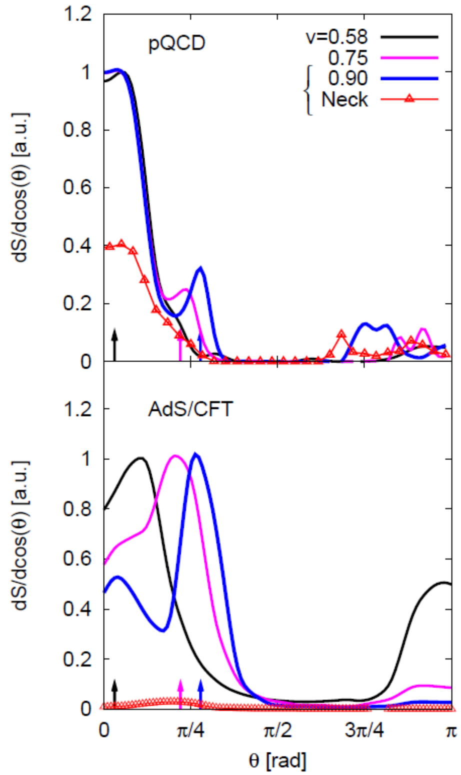
- Use shower gluons as seed for medium response.
  - Easier to generate large yield by picking from bulk.
  - Possible to generate ridge and cone.
  - Correct chemistry.
- Medium response should be sensitive to energy loss mechanism
  - Different for elastic or raidtive eloss (Majumder)
  - Significantly different from ADS/CFT prediction

$$J^\mu \equiv \left[\frac{d\Delta E(\mu,E)}{d\zeta}, 0, 0, \frac{dp_z(\mu,E)}{d\zeta}\right]\delta^2(\vec{r}_\perp)\delta(t-z).$$



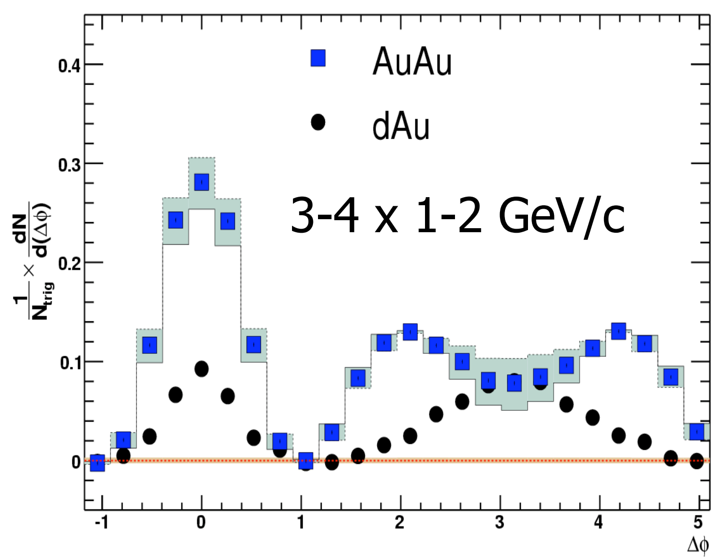
A. Majumder, B. Neufeld, B. Muller etc

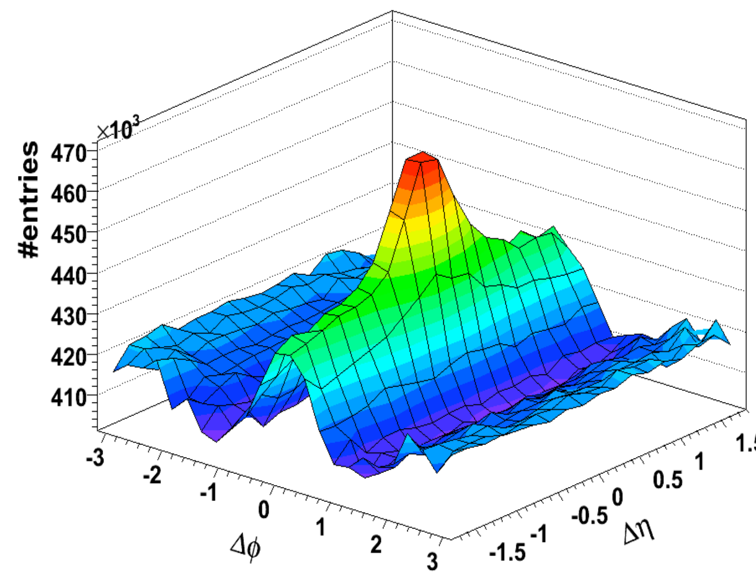
B. Betz et.al 0807.4526



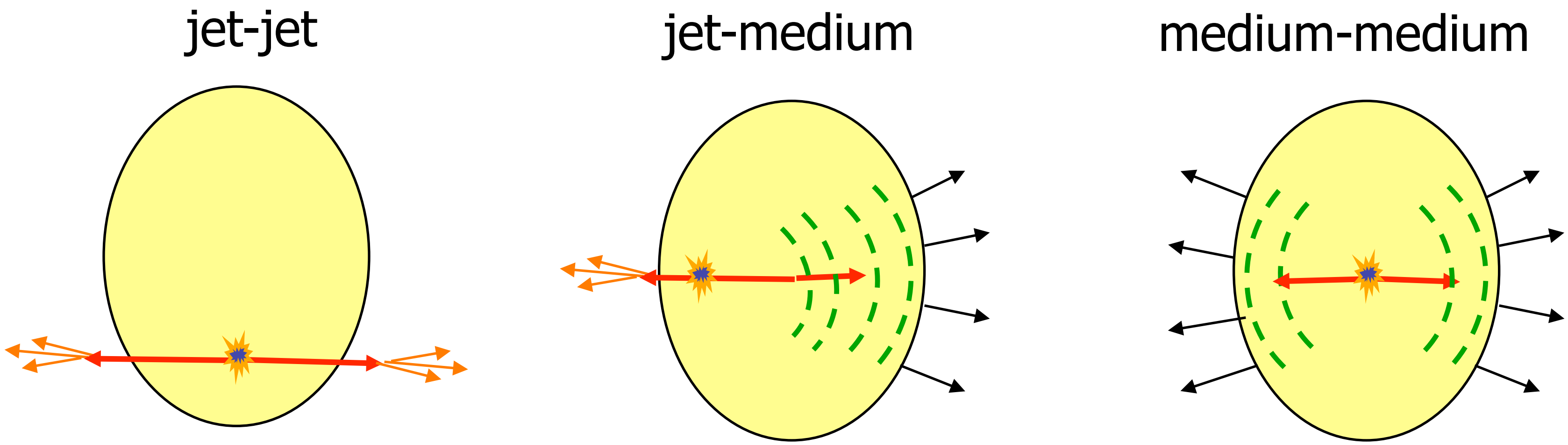
- Intermediate pT hadrons: quenched jet & medium response
  - Based on p+p: Hadrons at 2-5 GeV/c mainly from jets.
  - AA Jet correlation: Enhancement of correlated yield (larger than pp)
- Should have both hard-scattering and flow signature.
  - Implication for two source model assumption:

    $C(\Delta\phi)$ = Jet + jet-flow-cross-term + flow. ("Jet"=Jet+ cross term)





Source of pairs at intermediate p_T



$(R_{AA})^2$ $\quad$ $2R_{AA}(1 \quad)$ $\quad$ $2(1 \quad R_{AA})^2$

- Most models consider only jet-jet and jet-medium contribution.
- The medium-medium contribution (triggering on the medium) could be large, in the limit of $R_{AA} \rightarrow 0$, it dominates.

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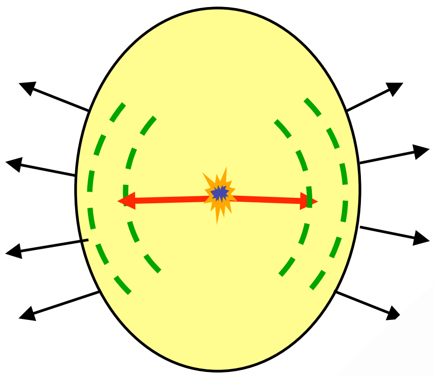
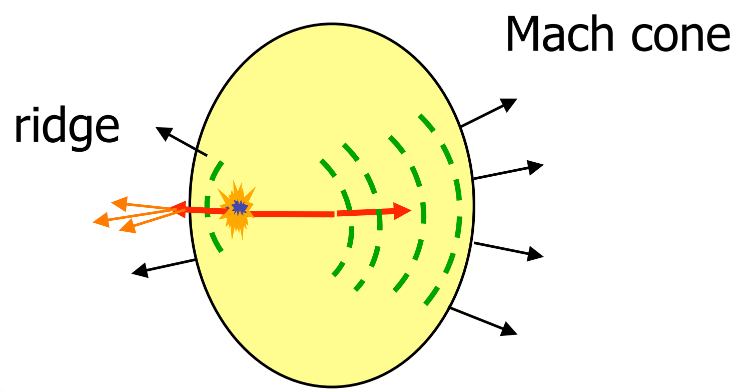
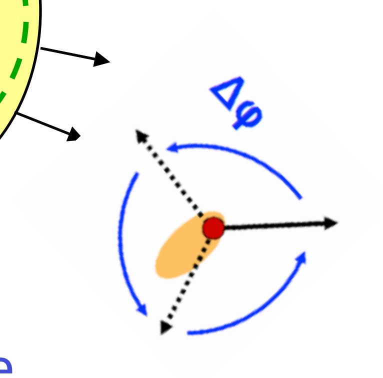
Triggering on medium response

medium-medium



jet-medium



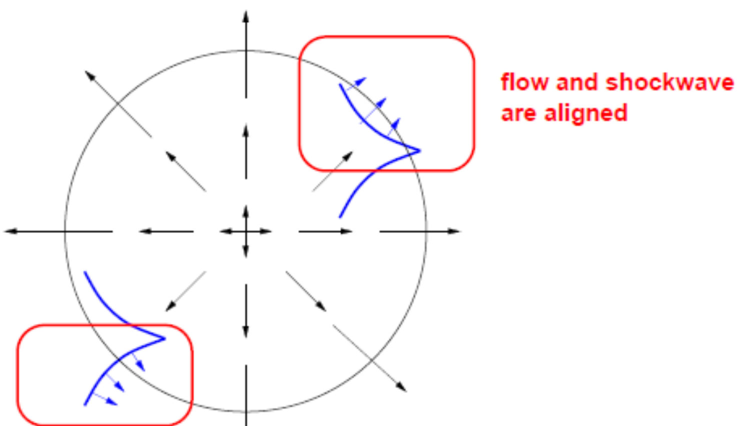


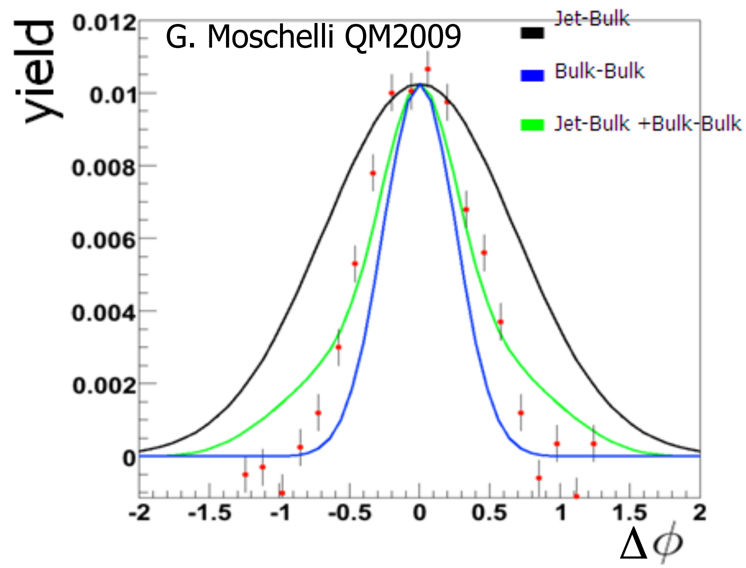
- 120º is a special case.
- Two sided mach-cone can generated peaks at $\Delta\phi$=0 and 120 degree
  - If so, may be a common origin for the ridge and the cone

I_{AA} make no sense in this region

Influence of transverse flow on medium response

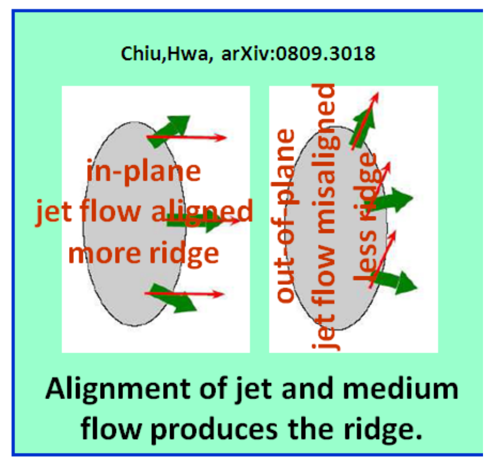
- Medium response and v_2 are entangled via radial flow





$$E\frac{d^3N}{d^3p} = \frac{g}{(2\pi)^3}\int d\sigma_\mu p^\mu \exp\left[\frac{p^\mu(u_\mu^{flow} + u_\mu^{shock}) - \mu_i}{T_f}\right]$$

T. Renk

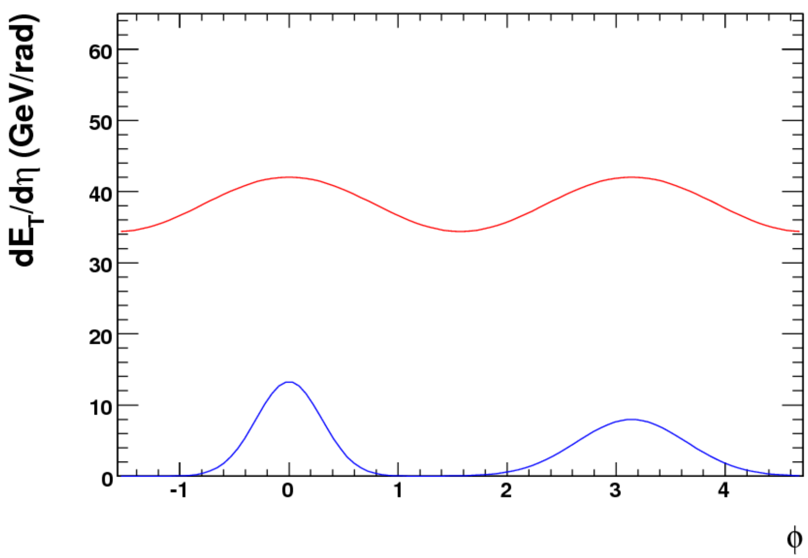


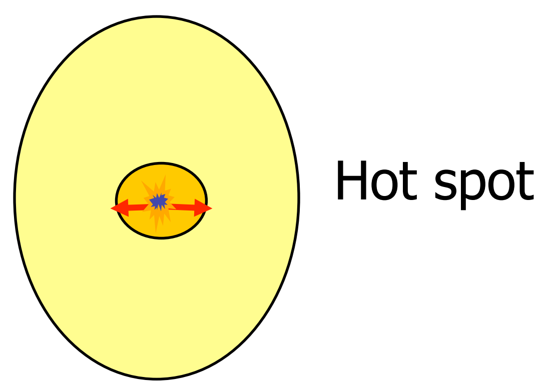
Influence of jet medium response on flow?

for 20-30% bin Au+Au, $\frac{dE_T}{d\Gamma} \approx 240\ GeV$, integral $v_2 \approx 0.05$

A 10 GeV dijet pair can single-handedly change the energy flow anisotropy

- Medium response (Quenched jet) can influence the v2

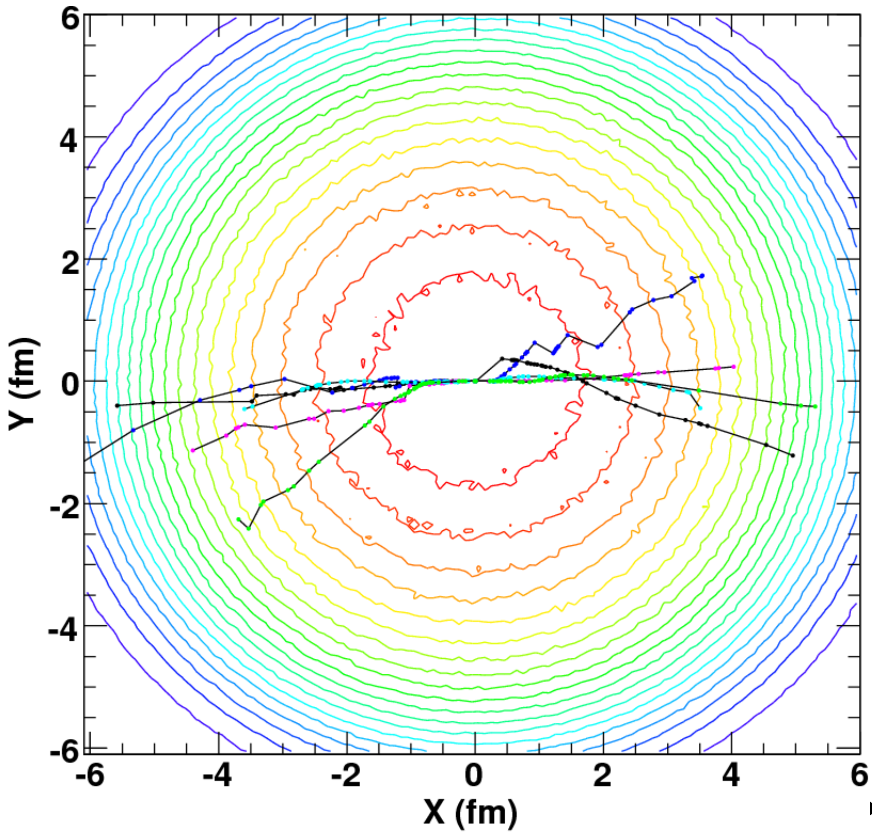


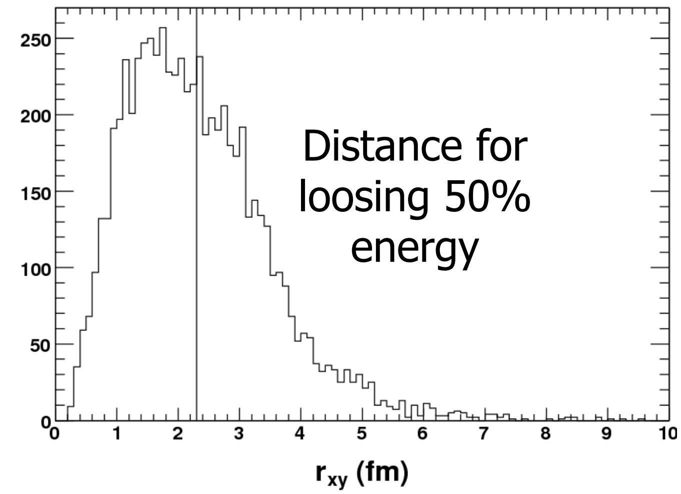


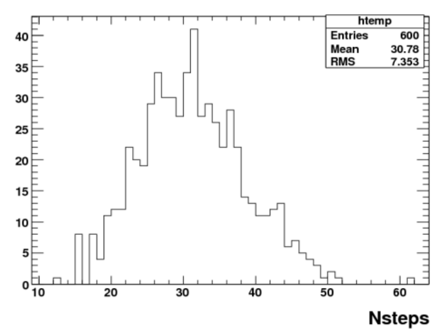
AMPT jet embedding

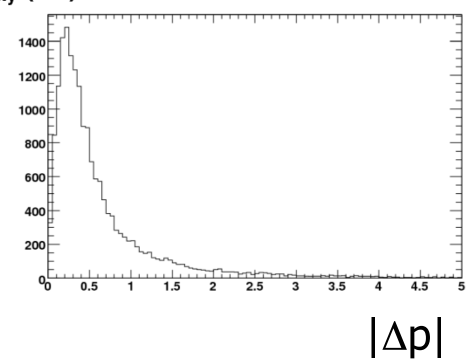
Z.W. Lin

- Embed 15 GeV dijet at b=0fm, only elastic 2 body eloss.
  - Mean scatters=30, mfp=0.16 fm, average p transfer 0.6 GeV/c
  - Most energy is deposited before freeze out.
- Energy deposited early, and shared by large number of partons.







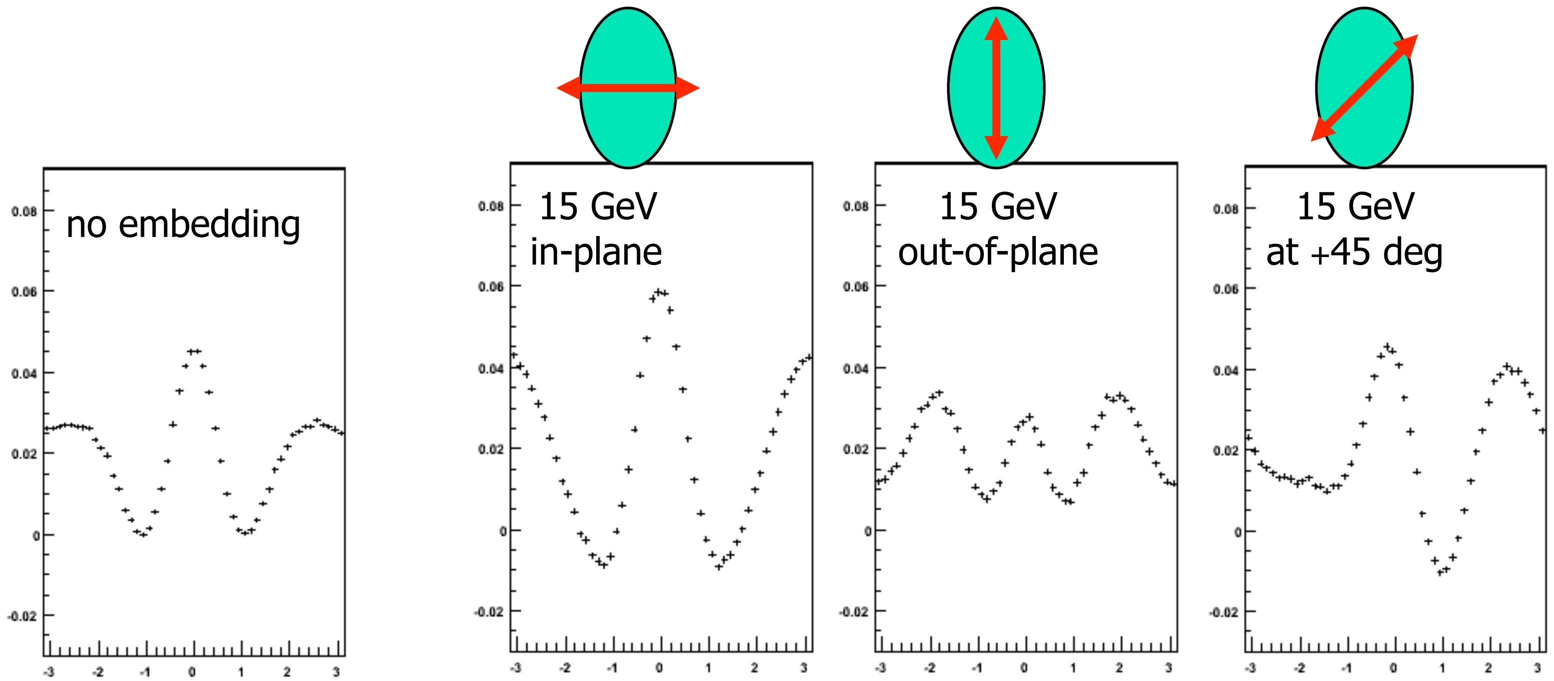


AMPT jet embedding

- Jets from center seem to enhance the in-plane flow?

By E. ShinIchi, S. Mohapatra   Very preliminary

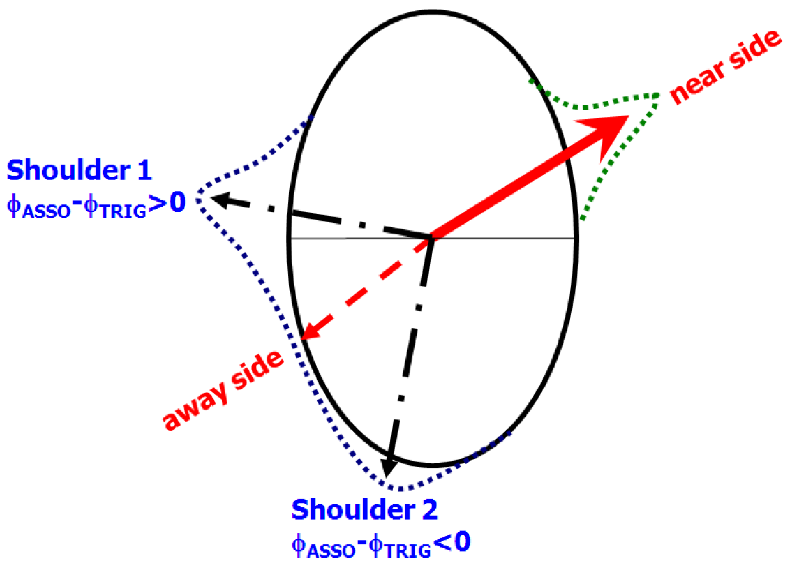
b=7fm
15 GeV dijet
2 x 1 GeV correlation

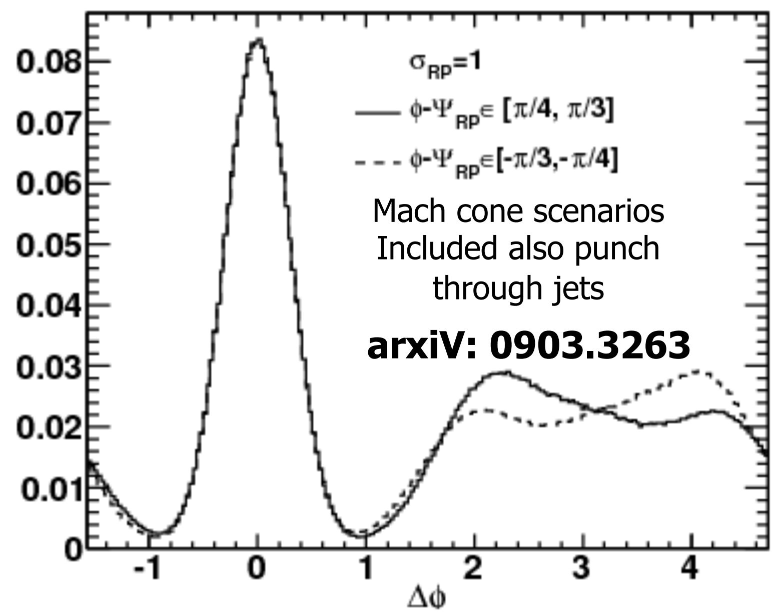


Minimum bias v2 subtracted

RP dependence of jet correlation

- The path length difference leads to a left/right asymmetry
- The pattern depends on the mechanism of jet-medium interactions
  - Mach cone: signal decreases with path length due to attenuation
  - Gluon Radiation : signal increase with path length

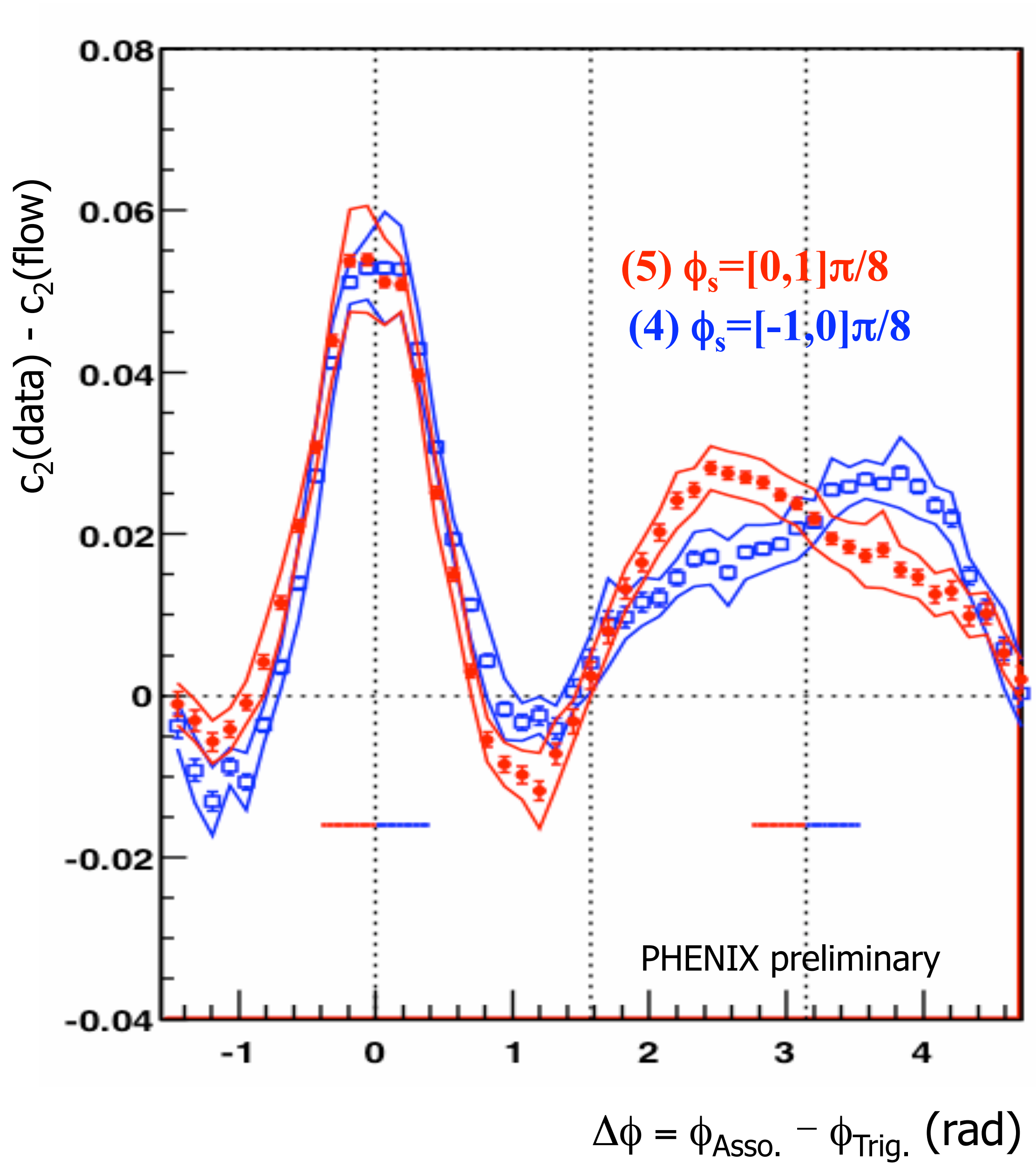


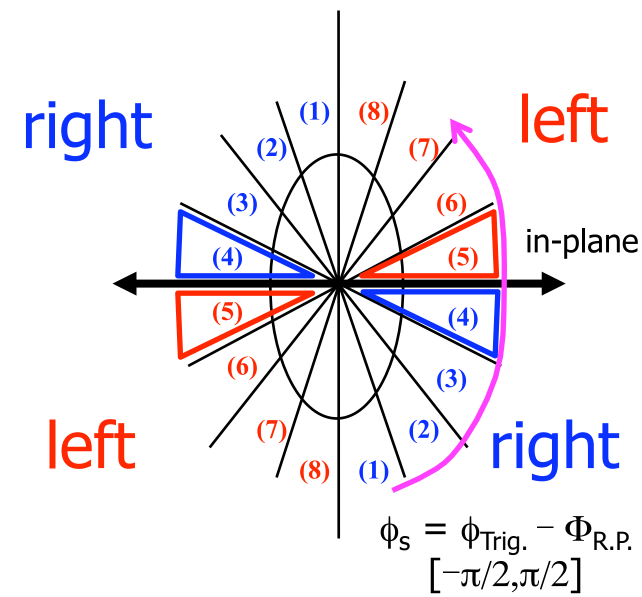


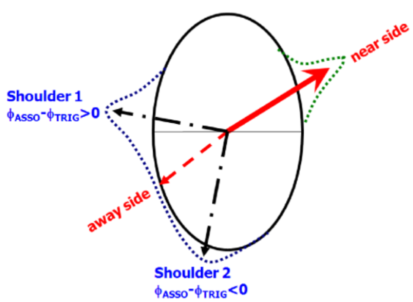
Left/Right asymmetry from Data

Esumi QM2009

200GeV Au+Au -> h-h (run7)
(p_T^{Trig}=2~4GeV/c, p_T^{Asso}=1~2GeV/c)
mid-central : 20-50%







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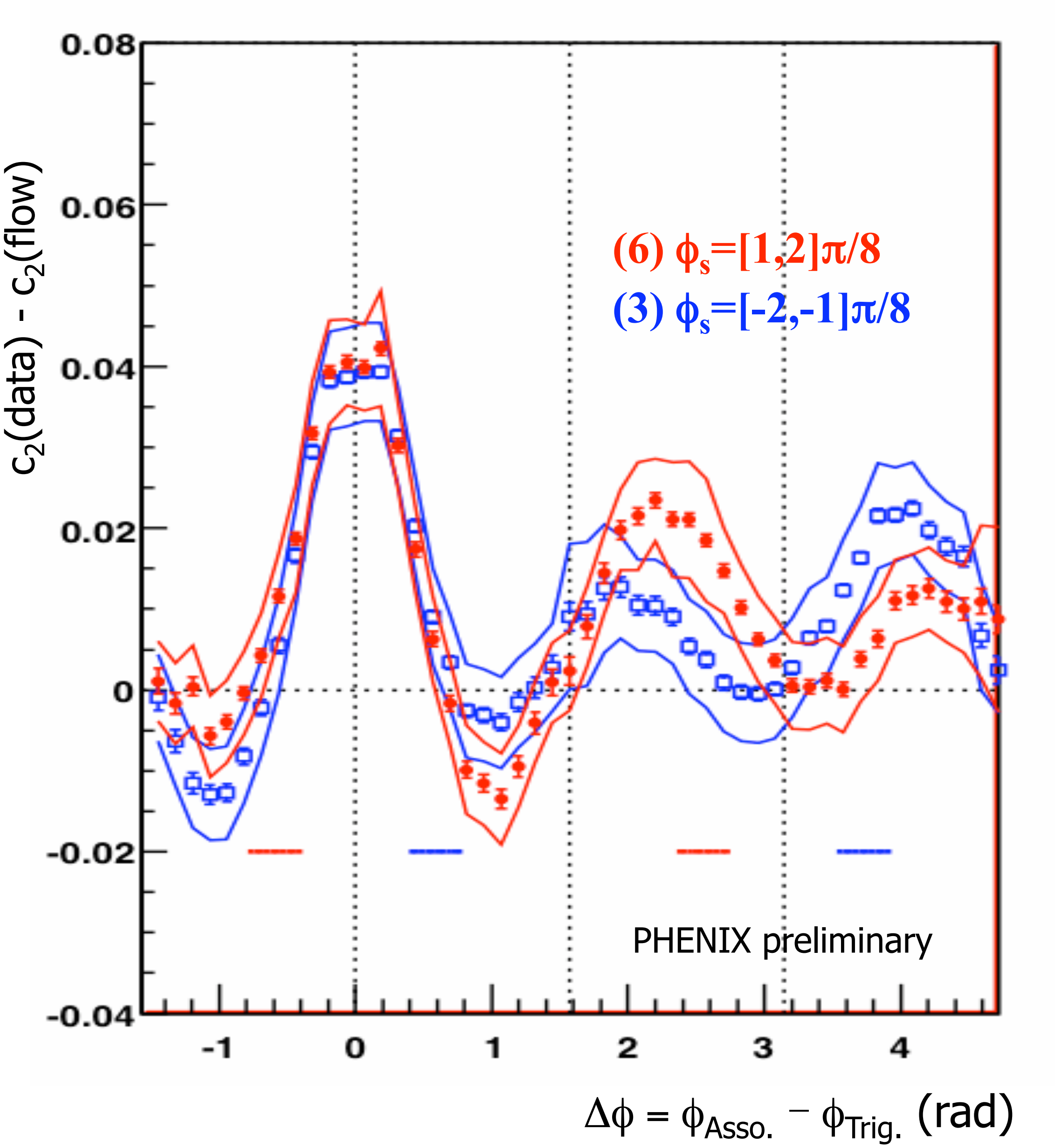

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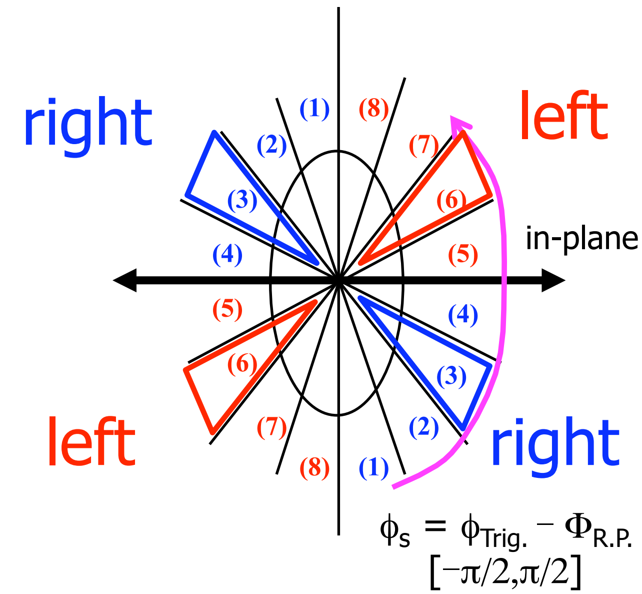

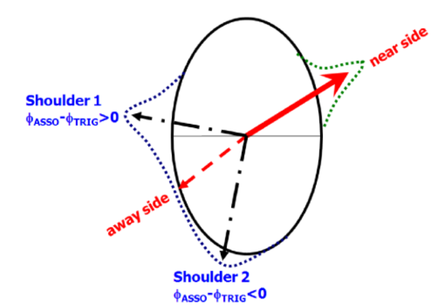

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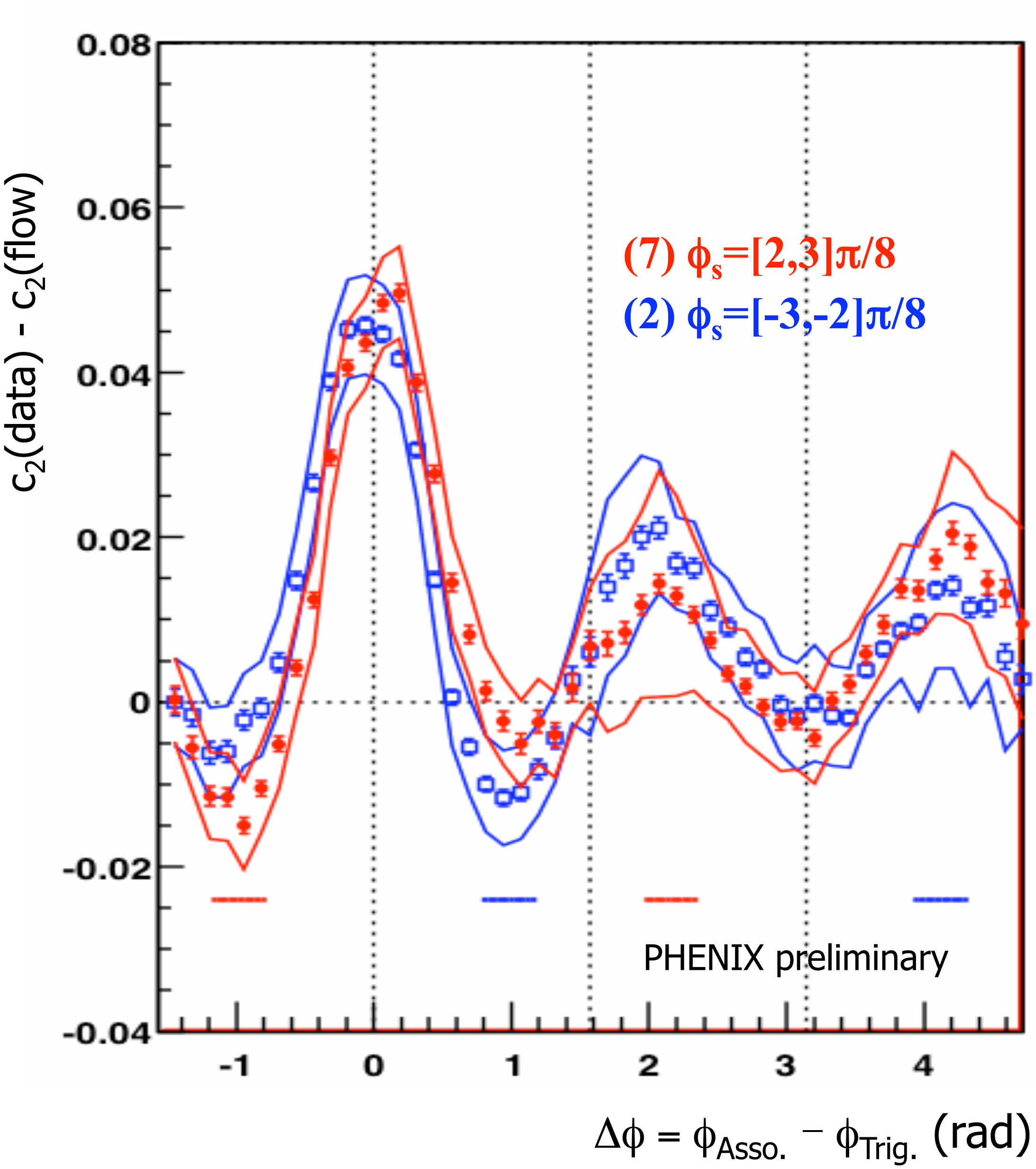

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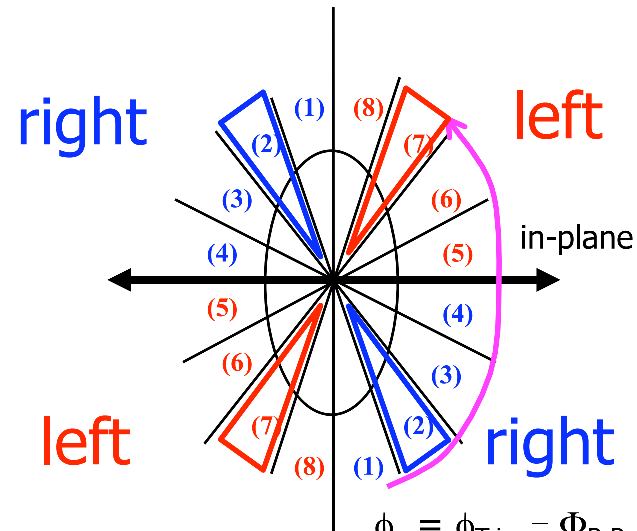
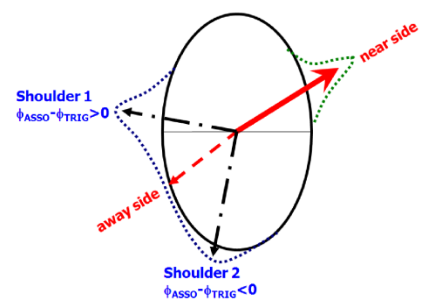


$\phi_s = \phi_{Trig.} - \Phi_{R.P.}$

$[-\pi/2, \pi/2]$



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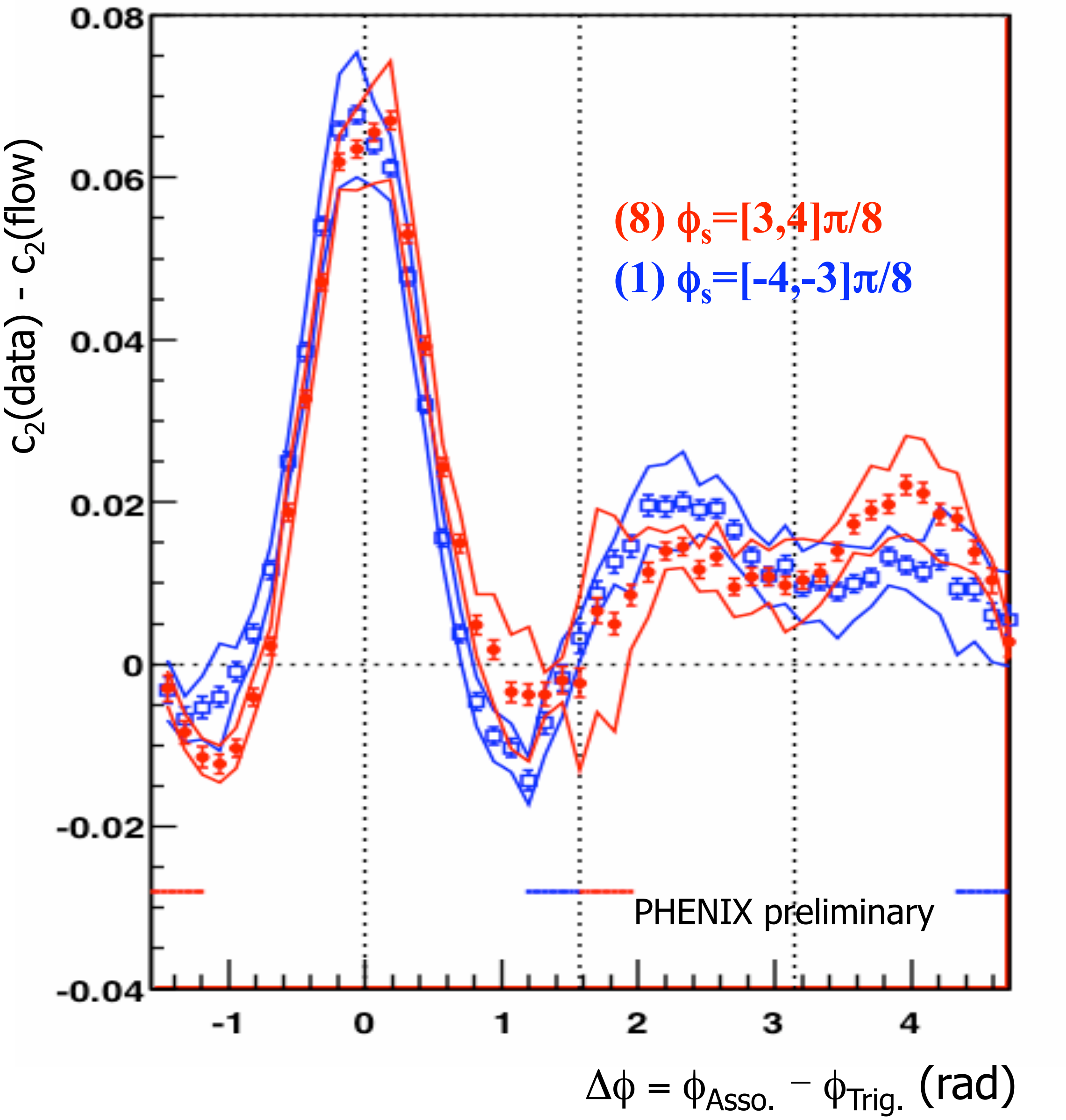

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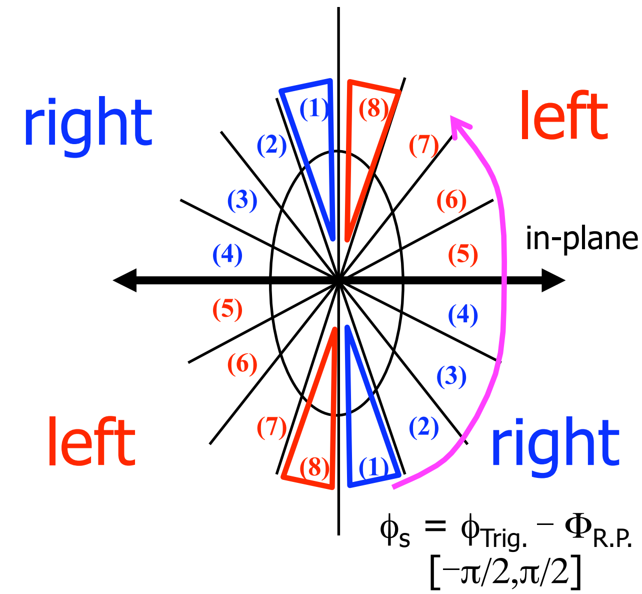
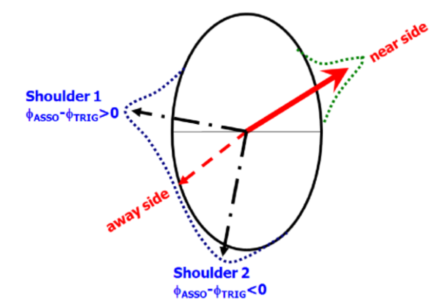
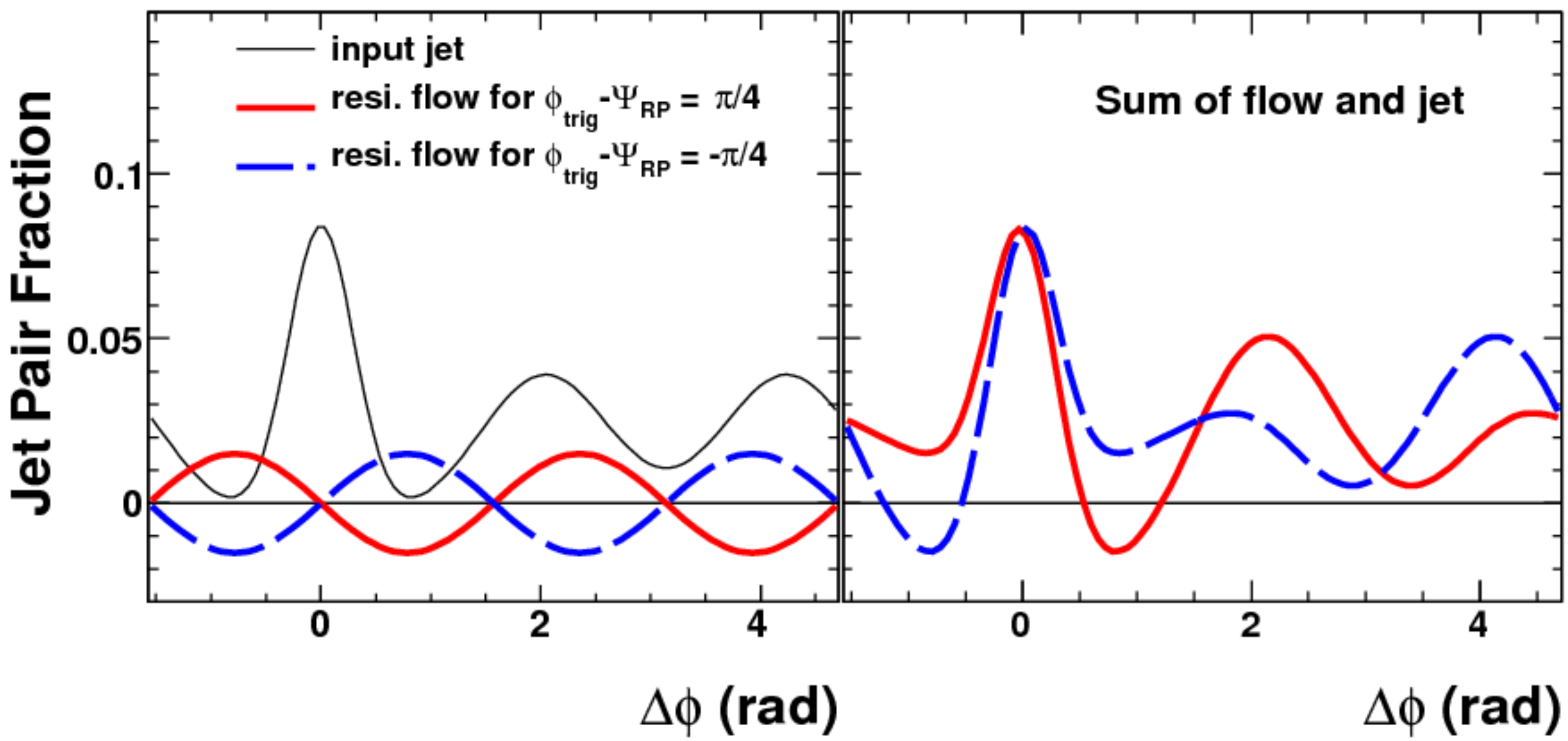




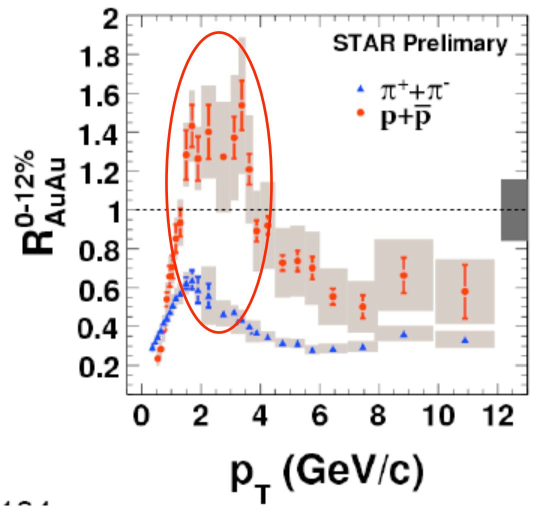
Flow bias

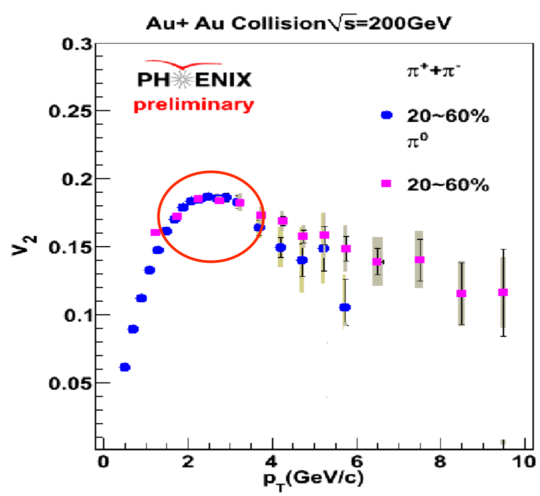
- Some of the asymmetry is caused by the residual elliptic flow.
  - But it appears also as asymmetry at the near-side.
  - A good way to check the flow background subtraction procedure
  - Or it indicates that the flow in jetty events is different from inclusive v2.



Role of hadronization

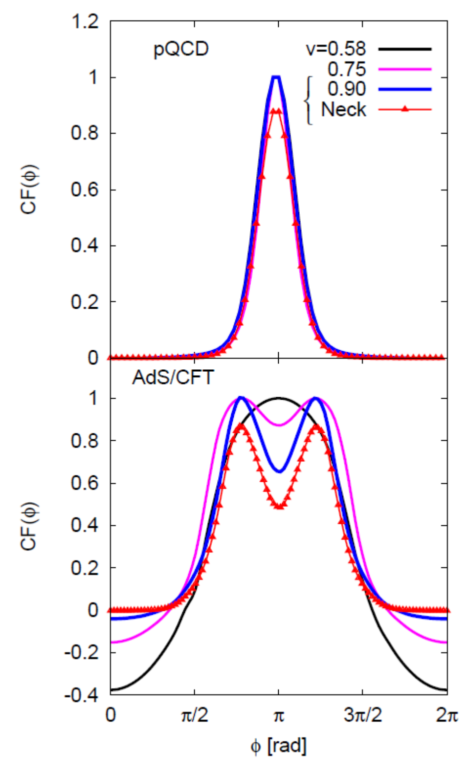
- Hadronization seems play an important role on most observables
  - Recombination peak in v2 and Raa vs pT
  - Quark number scaling of PID v2
  - Sensitivity of mach cone on the freeze out condition





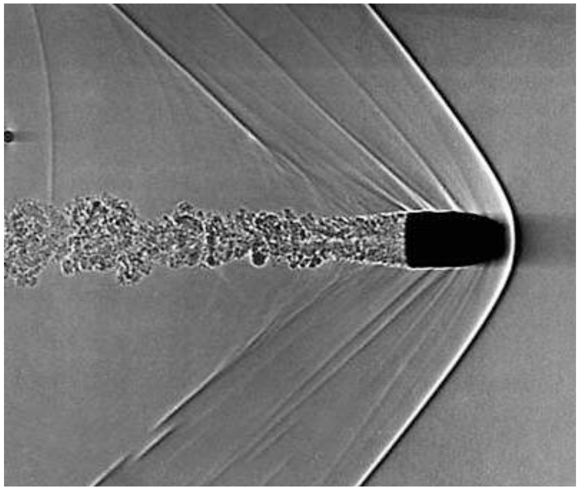
DPF 2009

B. Betz et.al 0807.4526

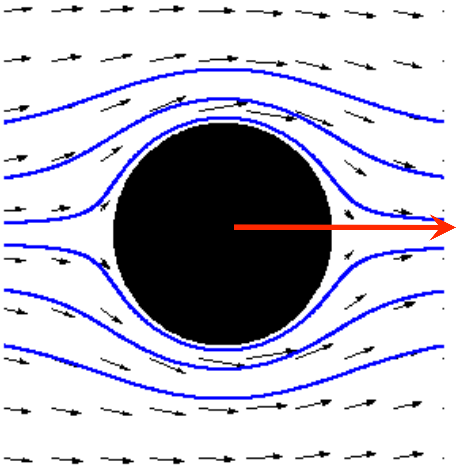


The Future

- Heavy quark is the ideal probe for jet quenching, medium response, medium collectivity.



Supersonic: probe
Energy loss/medium response



Stationary: probe
Collective flow

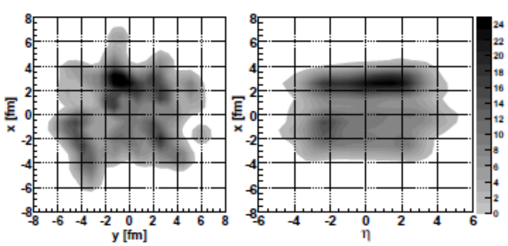
Comment on Sergey's remarks

- What one mean by two source model

  C(Δϕ) = Jet + jet-flow-cross-term + flow. ("Jet"=Jet+ cross term)

- The correlation is sensitive to localized energy deposition: could be either fluctuation or energy loss.

0902.4870

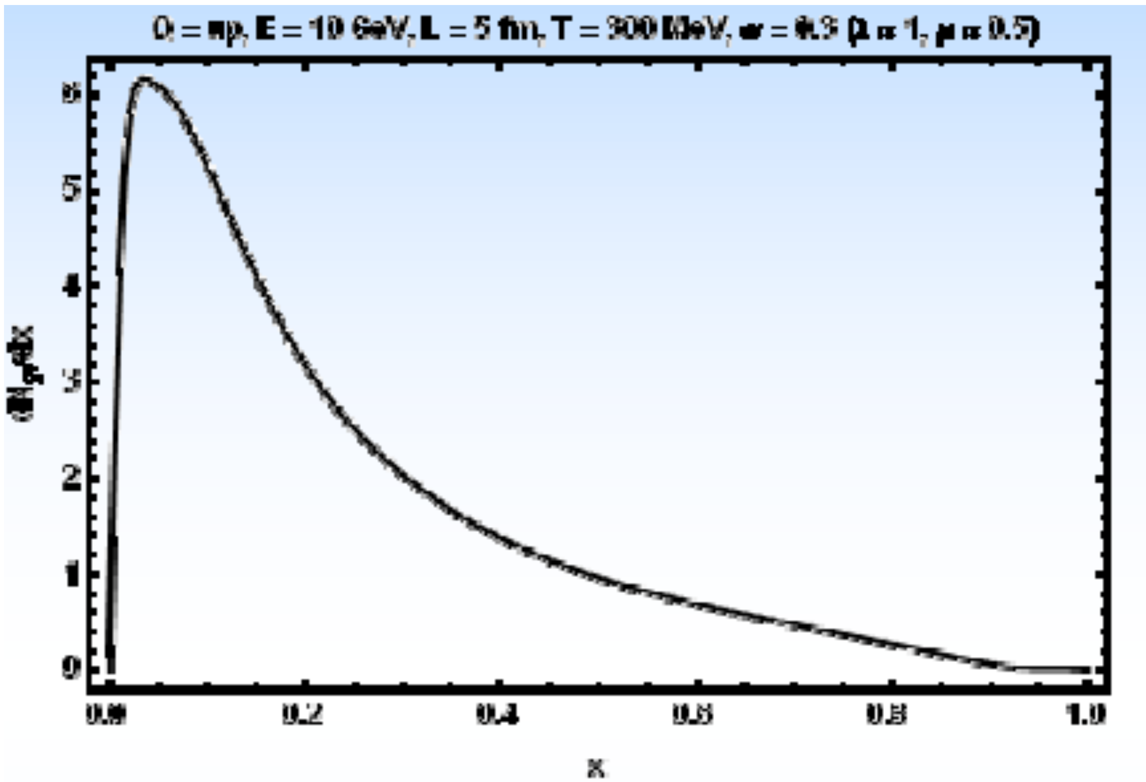


as v_2 is small, thus should not affect the main features observed here. Correlation functions from events generated using only the NEXUS code without the hydrodynamic evolution was also verified and we did not observe any type of topology structure in the correlation function, except for a narrow *Jet* like peak structure in $\Delta\eta = 0$ and $\Delta\phi = 0$. It is important to note that, when coupling the NEXUS with SPHERIO, *Jets* are averaged with softer particles and are thermalized within each hydrodynamic cell. Events generated considering just pure hydrodynamics starting with smooth initial conditions also do not generate the topology structures. Only when we couple the NEXUS outputs (the initial conditions) with the SPHERIO calculation (the hot and dense medium) *in an event-by-event fashion*, the *Ridge* structure can be observed. Thus, in conclusion, the topology structures observed in

Summary

- Jet quenching, medium response and flow are three inseparable aspects for understanding the jet-medium interaction (especially at RHIC)
  - No clear scale separation between different physics at pT<10 GeV.
- Intermediate pT particle production maybe dominated by medium response caused by lost energy of jets
  - It carries information of both initial hard-scattering and flow
- Require proper understanding the mutual influence of jet and flowing medium.
  - RP dependent correlation study may shed light on this.
  - Heavy quarks

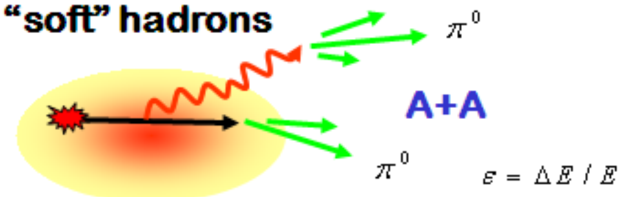
Single gluon emission spectra



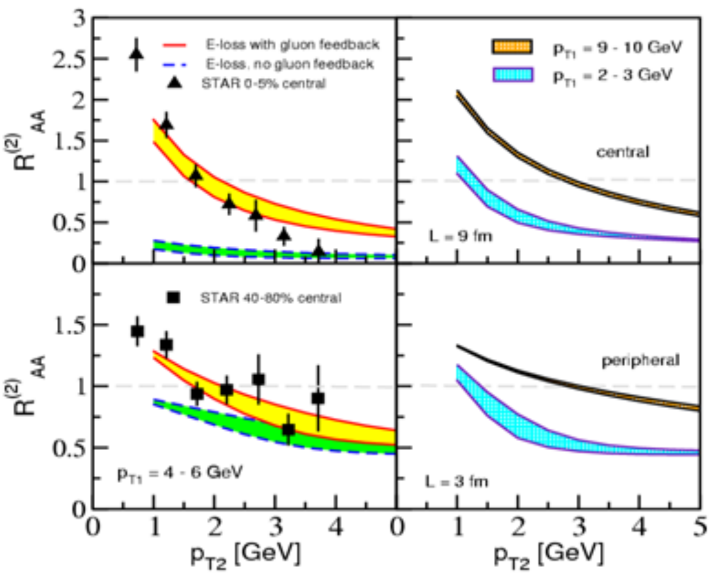
Energy Loss and Di-Jets

e) QGP effects on di-jet production

- **"Standard" quenching of leading hadrons**
- **Redistribution of the lost energy in "soft" hadrons**



Away-side yields



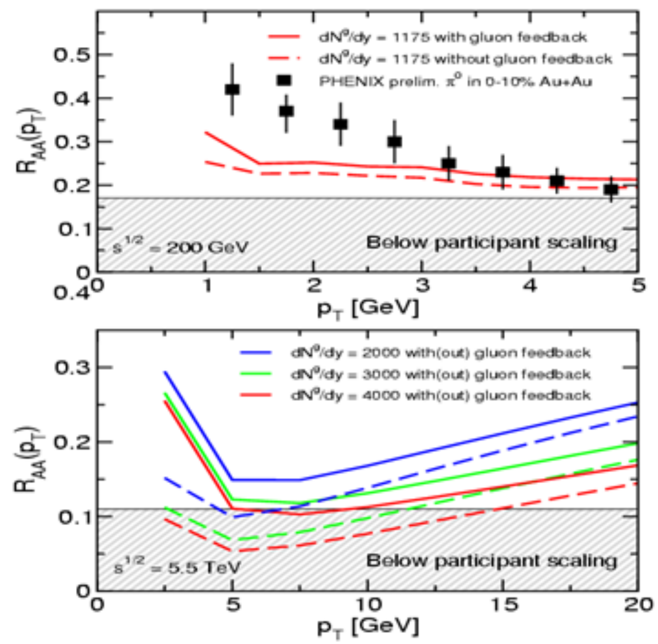
I. V., Phys.Lett.B630 (2005)

One way of incorporating energy loss:

$$D_{h/c}(z) \Rightarrow \int_0^{1-z} d\epsilon \; P(\epsilon) \frac{1}{1-\epsilon} D_{h/c}\left(\frac{z}{1-\epsilon}\right) + \int_z^1 d\epsilon \; \frac{dN^g}{d\epsilon}(\epsilon) \, \frac{1}{\epsilon} D_{h/g}\left(\frac{z}{\epsilon}\right) \; .$$

Satisfies the momentum sum rule

Single inclusive particles



RHIC

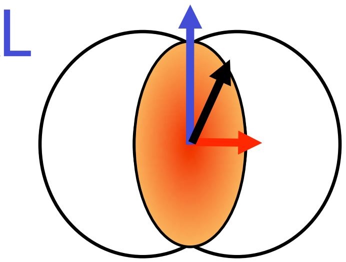
LHC

17

I.Vitev HP 2006

The Scaling Pattern of the RHIC Data

- In absorption picture: R_{AA}=exp(-kL), logR_{AA}=-kL
  - 6 centrality and 6 angular bin

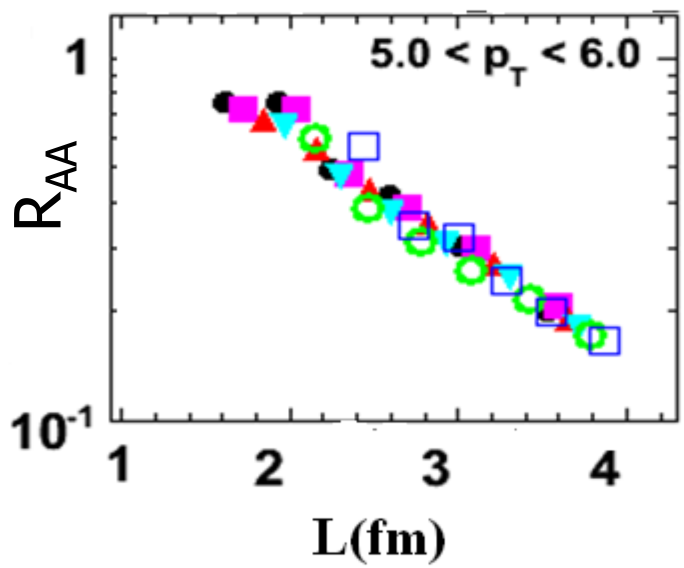


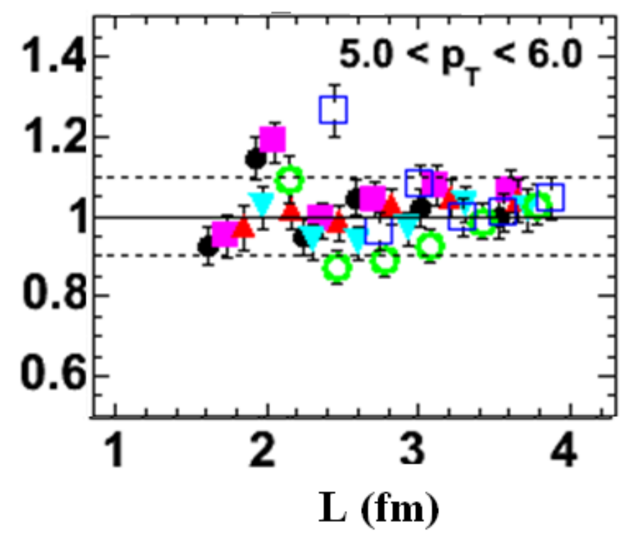
$$L_J(\infty A) \quad \frac{L_0\sqrt{1+J}}{\sqrt{1 \cos 2A}} \qquad L_0^{2} = \langle x^2 \rangle$$

- Very good scaling, but this L is different from the length implied by energy loss models

$$L N \, dr \, dl ()() \Xi_{bin} \qquad \frac{l}{\Pi I_0}$$

Data from 0903.4886 figure made by R. Wei

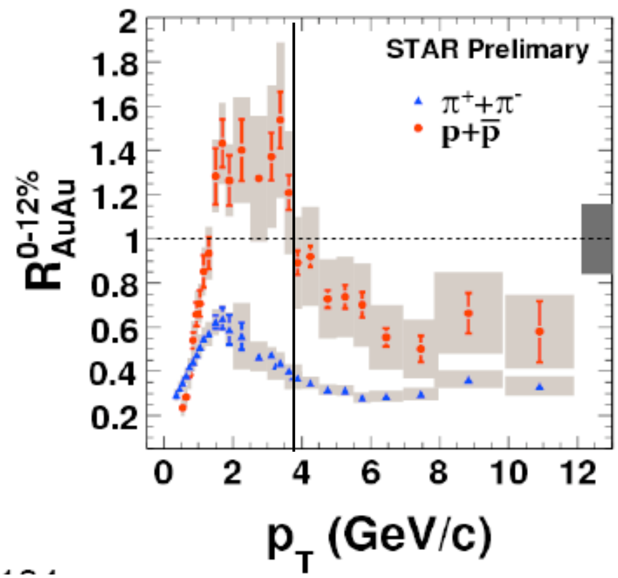


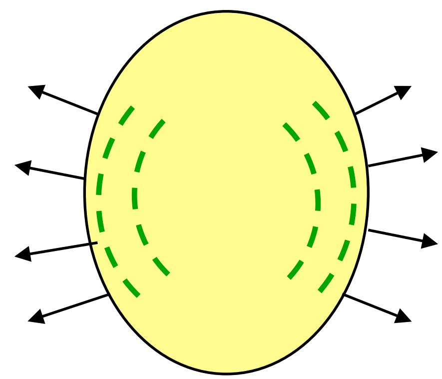


Per-trigger yield

$$\text{per-trig yield} = \frac{\text{Pair Yield}}{\text{Trig Yield}} \qquad I_{AA} = \frac{\text{per-trig yield}_{AA}}{\text{per-trig yield}_{pp}}$$

- Per-trigger yield is useful if triggers come from fragmentation.
- But origins of triggers are complicated at $p_T < 4$ GeV/c.
  - Per-trigger yield can't be compared with p+p directly.

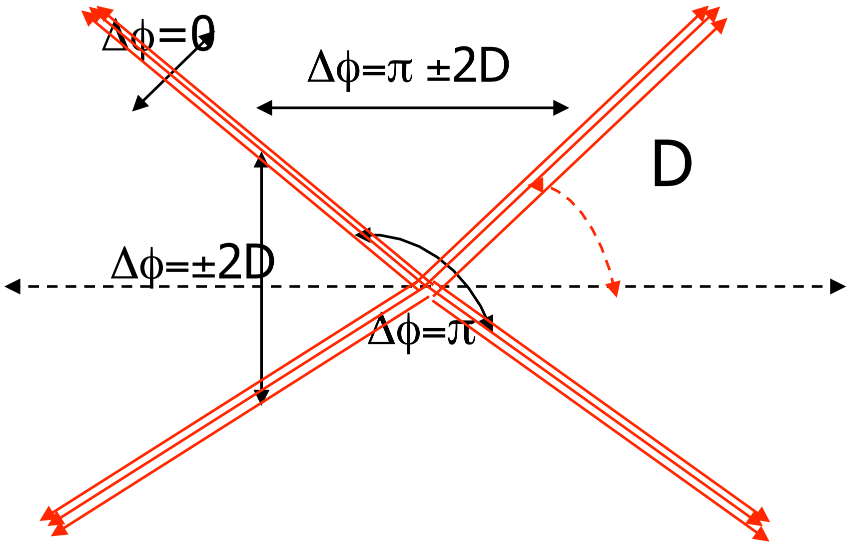


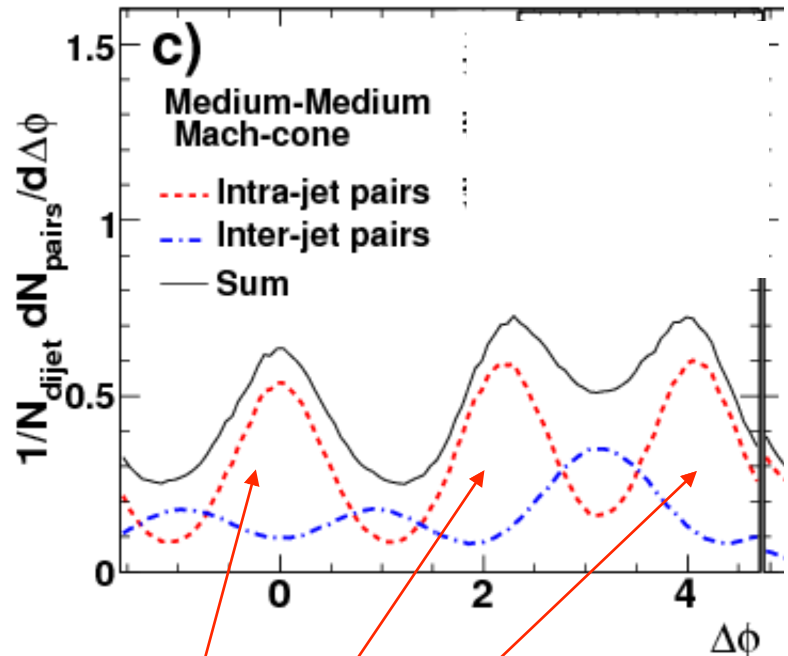


Low pT triggers may originate from the whole overlap

*

Medium-Medium term





- Both jets are converted into hadrons emitted at angle D from original jet direction. Pairs peaks at: 0, ±2D, π, π ± 2D.

- Since 2D≈ π – D, med-med pairs appear at same location as jet-medium pairs.

And they come from the Mach cone of the same jet!!!