Large Angle Hadron Correlations from Medium-Induced Gluon Radiation

Ivan Vitev

Jet Correlations at RHIC, March 10-11, 2005
Brookhaven National Laboratory, Upton, NY

Outline of the Talk

- **Radiative energy loss and jet quenching:**
  - Experimental results
  - Infrared and collinear safety property
  - Large angle emission - the death of the "dead cone"

- **Nuclear modification of di-hadrons:**
  - Modification of the yields (energy redistribution)
  - Modification of the large angle correlations
  - Sensitivity to subtraction of the elliptic flow

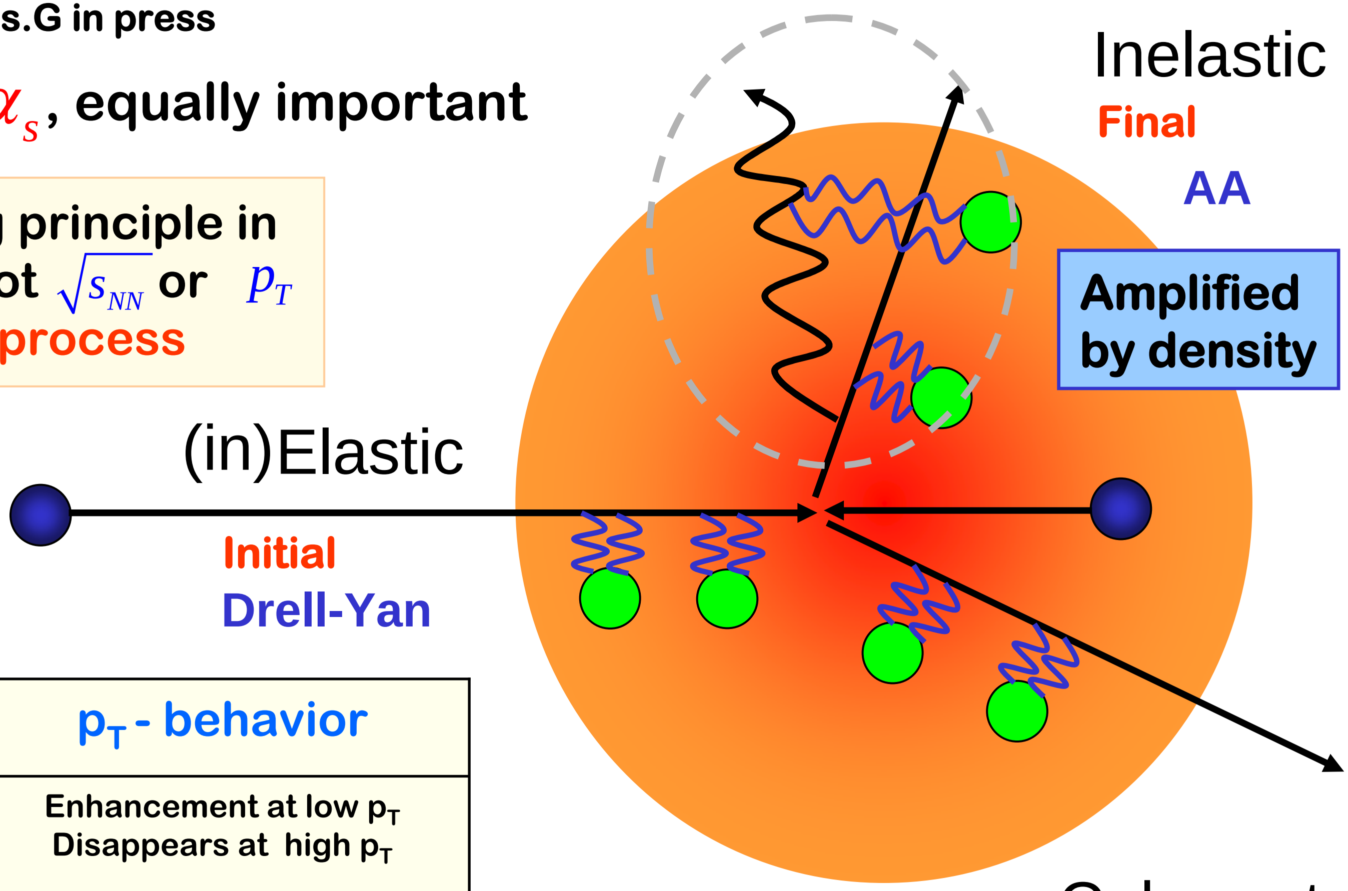
- **Conclusions:**

Specific Processes with Nuclei

I.V., J.Phys.G in press

All couplings $\sim \alpha_s$, equally important

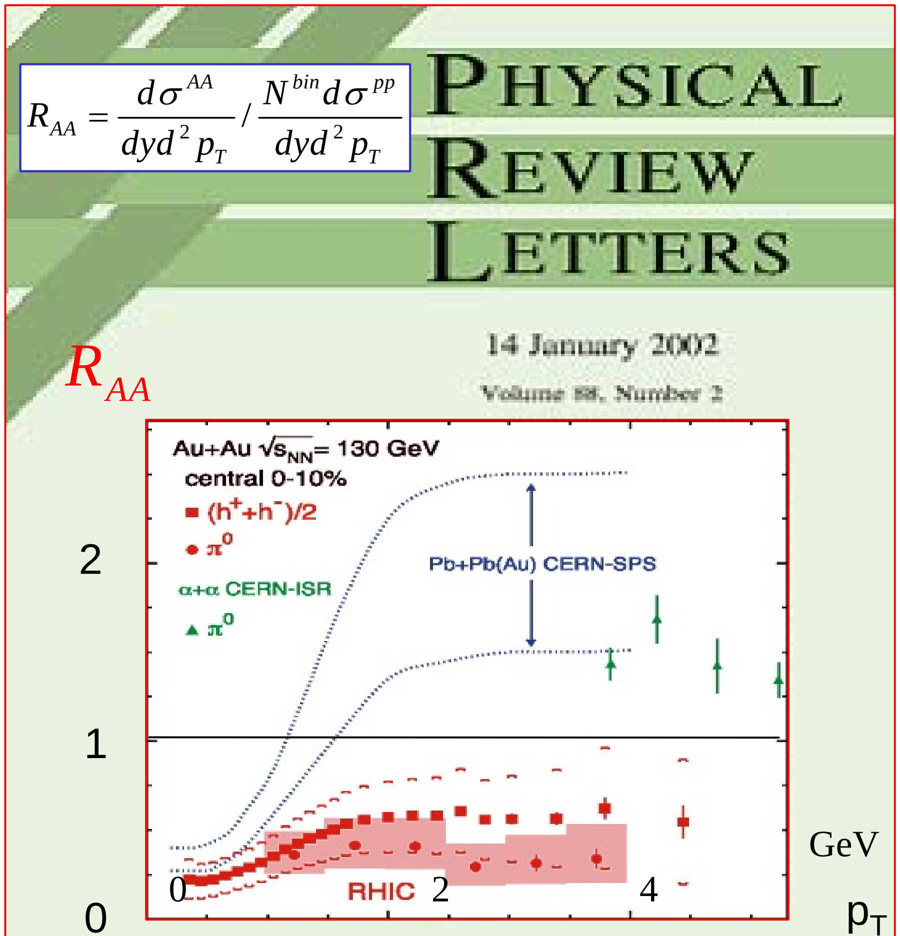
- The overarching principle in calculations is not $\sqrt{s_{NN}}$ or p_T but the physical process



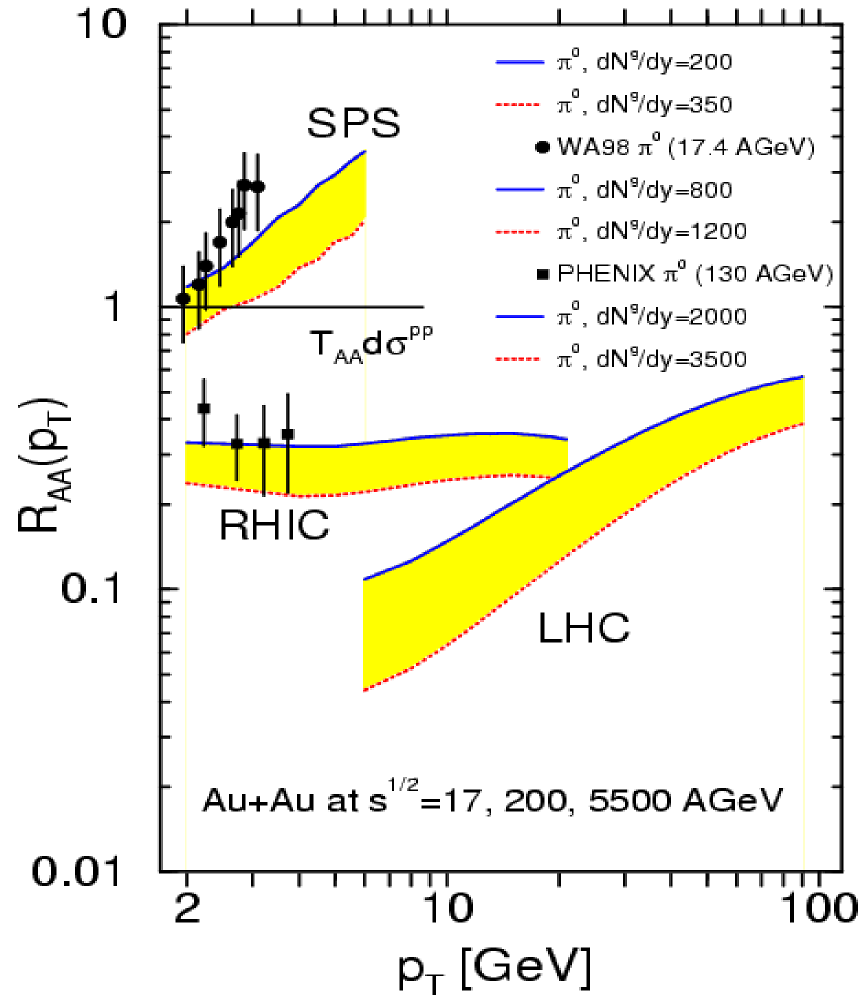
Type	Effect	p_T - behavior
Elasatic	Cronin	Enhancement at low p_T Disappears at high p_T
Inelastic	Jet quenching	Suppression at high p_T Gluons feed the low p_T
Coherent	Shadowing	Suppression at low p_T Quickly disappears at high p_T

Jet Quenching at RHIC

Depletion of high-p_T hadron multiplicities in Au+Au relative to the binary collision scaled p+p result

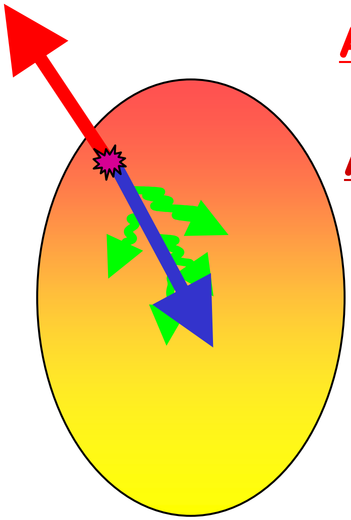


K.Adcox et al., Phys.Rev.Lett.88, (2002)



I.V., M.Gyulassy, Phys.Rev.Lett. 89 (2002)

Establishing the E-Loss Mechanism



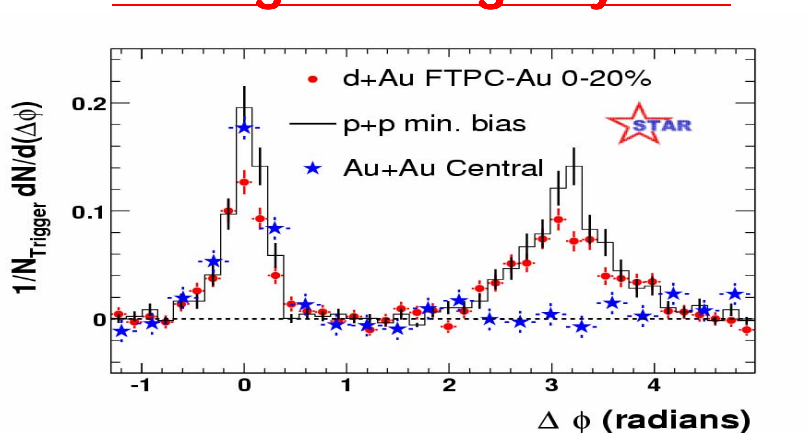
Another way to establish

d+Au ~ p+p
Au+Au is very different

Away-side jet gets "stuck" in the medium

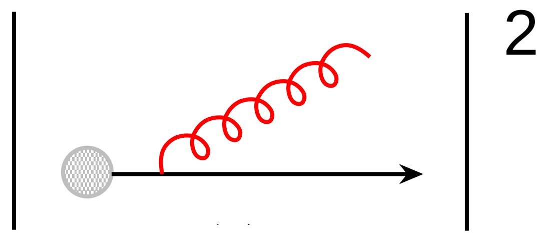
$$C_2(\Delta\phi) = \frac{1}{N_{trig}} \frac{dN^{h_1 h_2}}{d\Delta\phi}$$

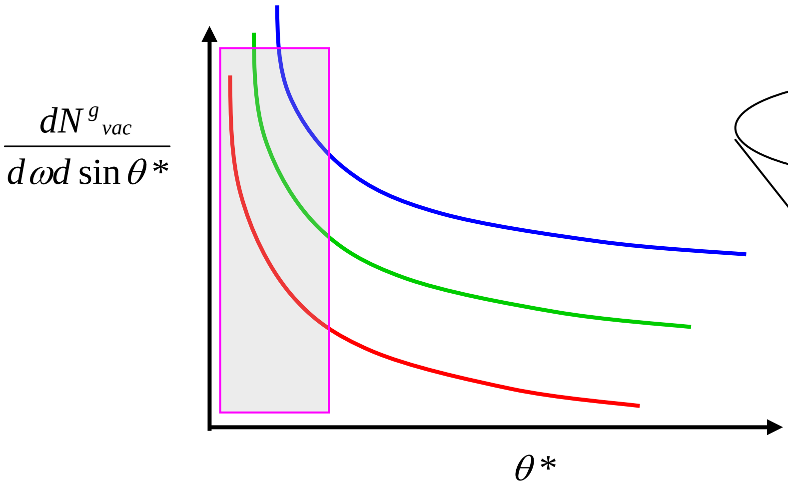
Test against a light system

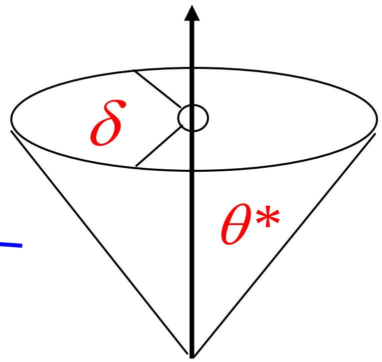


J.Adams *et al.*, Phys.Rev.Lett.91 (2003)

Vacuum Radiation







If interested in the small angle small frequency behavior

$$\frac{dN^g}{d\omega d\sin\theta^* d\delta} \propto \left| M_c \right|^2$$

$$\frac{dN^g{}_{vac}}{d\omega d\sin\theta^* d\delta} \approx \frac{C_R \alpha_s}{\pi^2} \frac{1}{\omega \sin\theta^*}$$

- Both collinear and infrared divergent
- Collinear persists. At fixed order requires subtraction in the PDFs and FFs

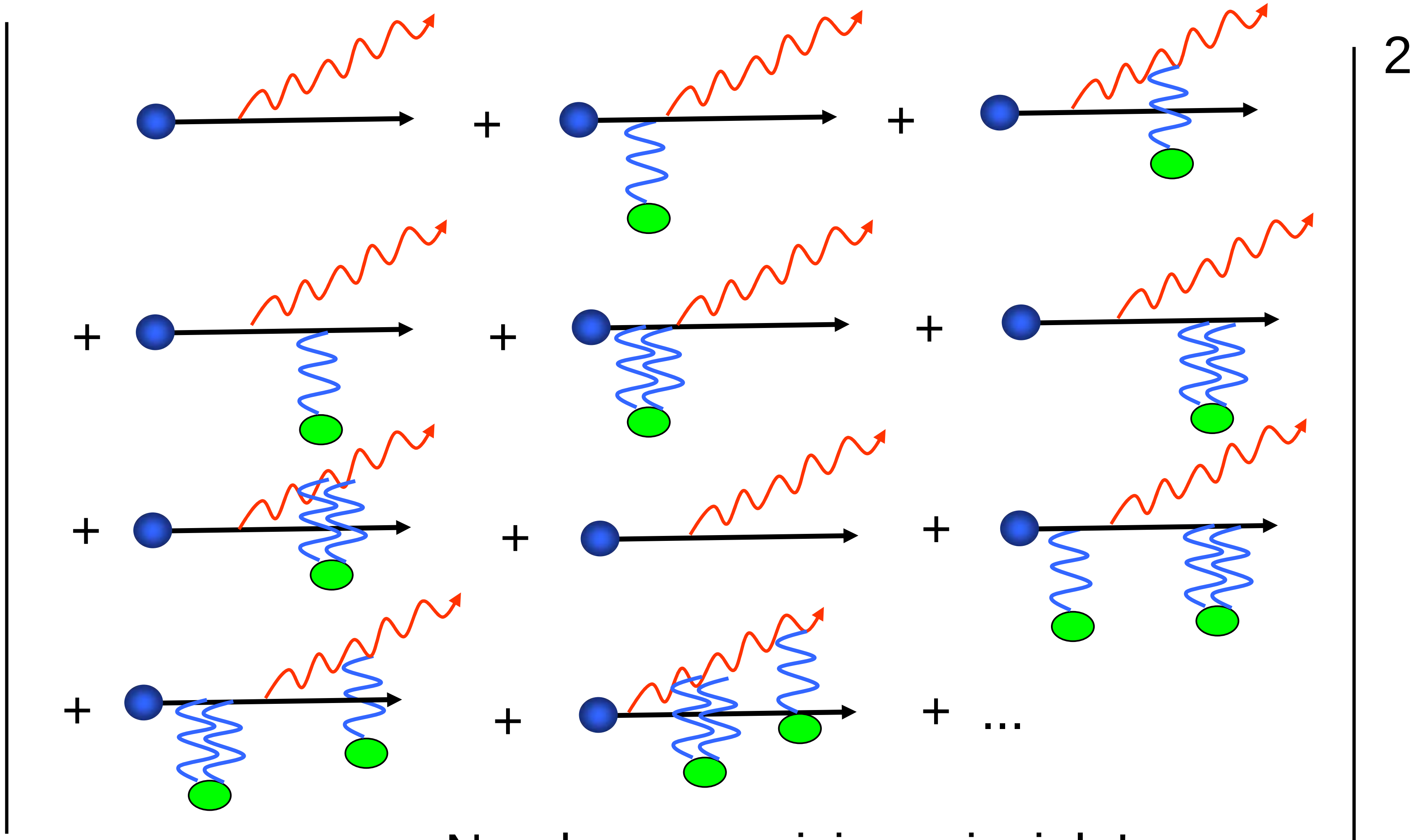
For massive quarks - "dead cone effect"

- Takes care of the collinear

$$\frac{dN^g{}_{vac}}{d\omega d\sin\theta^* d\delta} \approx \frac{C_R \alpha_s}{\pi^2} \frac{\sin\theta^*}{\omega\,(\sin^2\theta^* + M^2/E^2)}$$

Cuts part of phase space $0 \le \theta^* \le M/E$

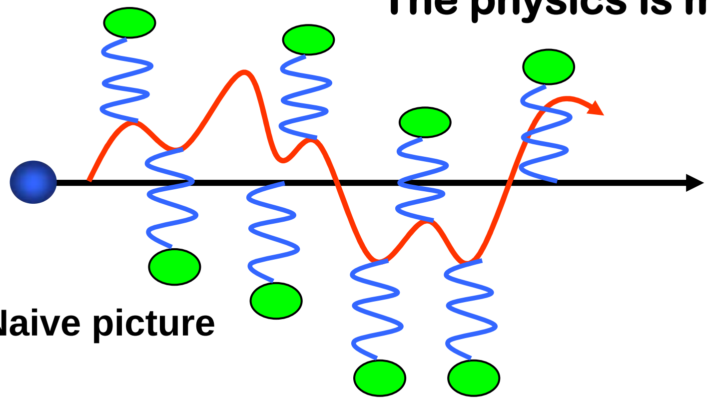
Medium-Induced Bremsstrahlung



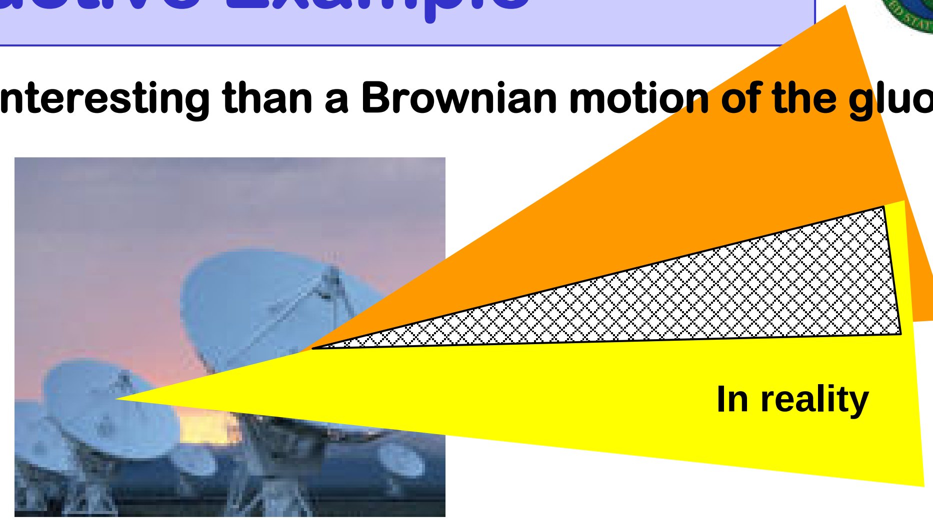
Need an organizing principle!

Instructive Example

The physics is more interesting than a Brownian motion of the gluon

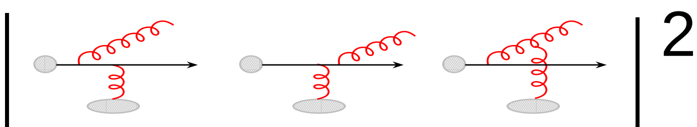


Naive picture



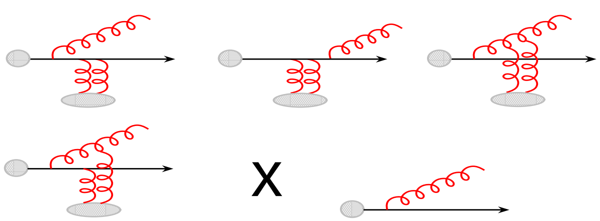
$$i(-i) = 1 \qquad i\,(i) = -1 = \cos(\pi)$$

$$\frac{dN^{g}{}_{med}}{d\omega d\sin\theta^* d\delta} \propto \left(|M_a|^2 + 2\,\mathrm{Re}\, M_b^{*} M_c \right) + \ldots$$



(a)

+2Re



(b) (c)

Solution to first order in the mean # of scatterings

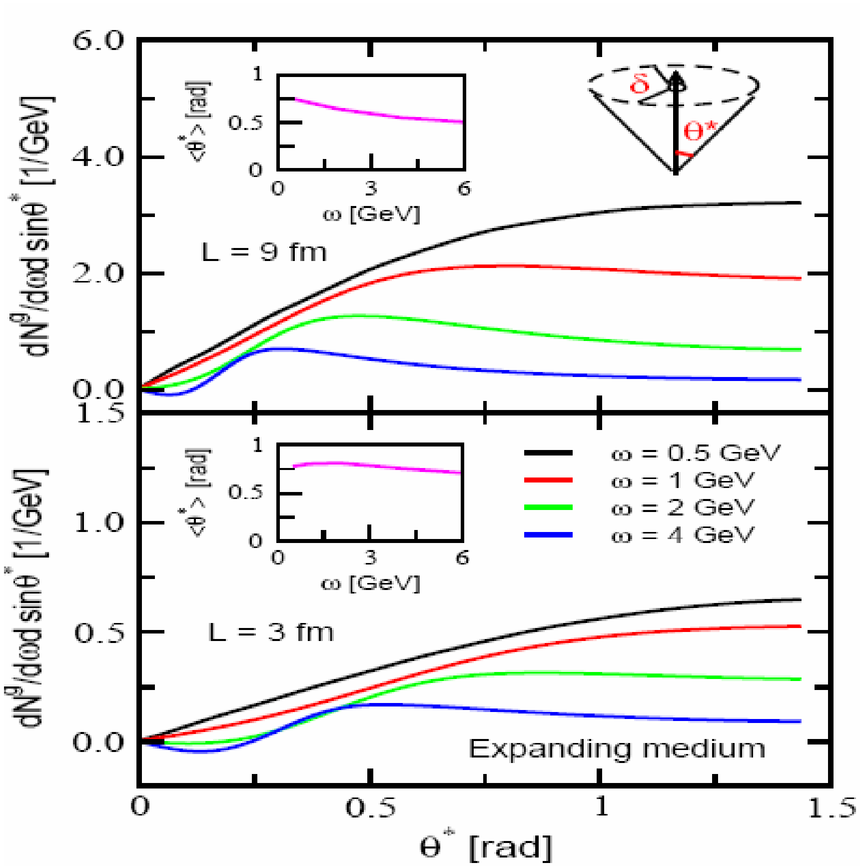
$$\frac{dN^{g}{}_{med}}{d\omega d\sin\theta^* d\delta} \approx \frac{2C_R\alpha_s}{\pi^2} \int_{z_0}^{L} \frac{d\Delta z}{\lambda_g(z)} \int_0^{\infty} dq_\perp q_\perp{}^2 \frac{1}{\sigma_{el}} \frac{d\sigma_{el}}{d^2 q_\perp}$$

$$\times \int_0^{2\pi} d\alpha \frac{\cos\alpha}{(\omega^2 \sin^2\theta^* - 2q_\perp \omega \sin\theta^* \cos\alpha + q_\perp^2)}$$

$$\times \left[1 - \cos \frac{(\omega^2 \sin^2\theta^* - 2q_\perp \omega \sin\theta^* \cos\alpha + q_\perp^2)\Delta z}{2\omega} \right]$$

I.V., hep-ph/0501255

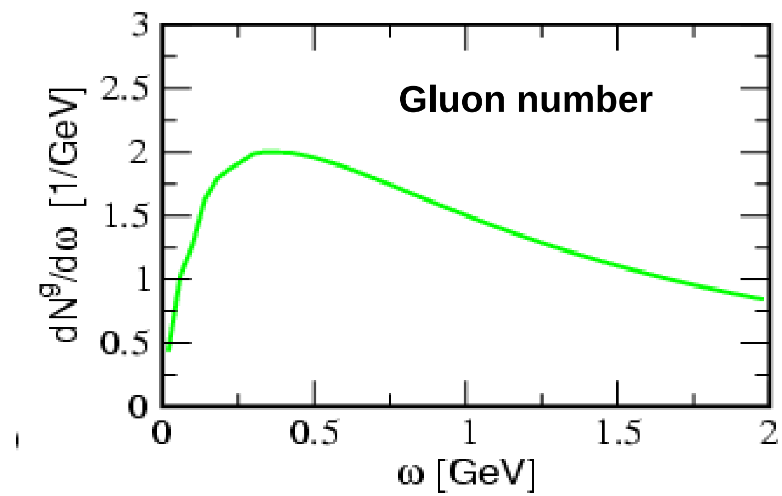
Angular and Frequency Behavior



I.V., hep-ph/0501255

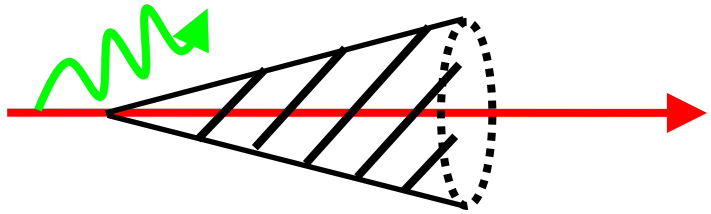
- **Radiation is moderately large angle (cancellation near the jet axis)**
- **Finite gluon number**

$$l_f = \frac{2\omega}{(\omega^2 \sin^2\theta^* - 2q_\perp \omega \sin\theta^* \cos\alpha + q_\perp^2)} \sim \Delta z \sim L/2$$



- The small angle $\theta^* \to 0$ and small frequency $\omega \to 0$ behavior of the radiative spectrum is under perturbative control

The Death of the "Dead Cone"



Y.Dokshitzer, D.Kharzeev, Phys.Lett.B519 (2001)

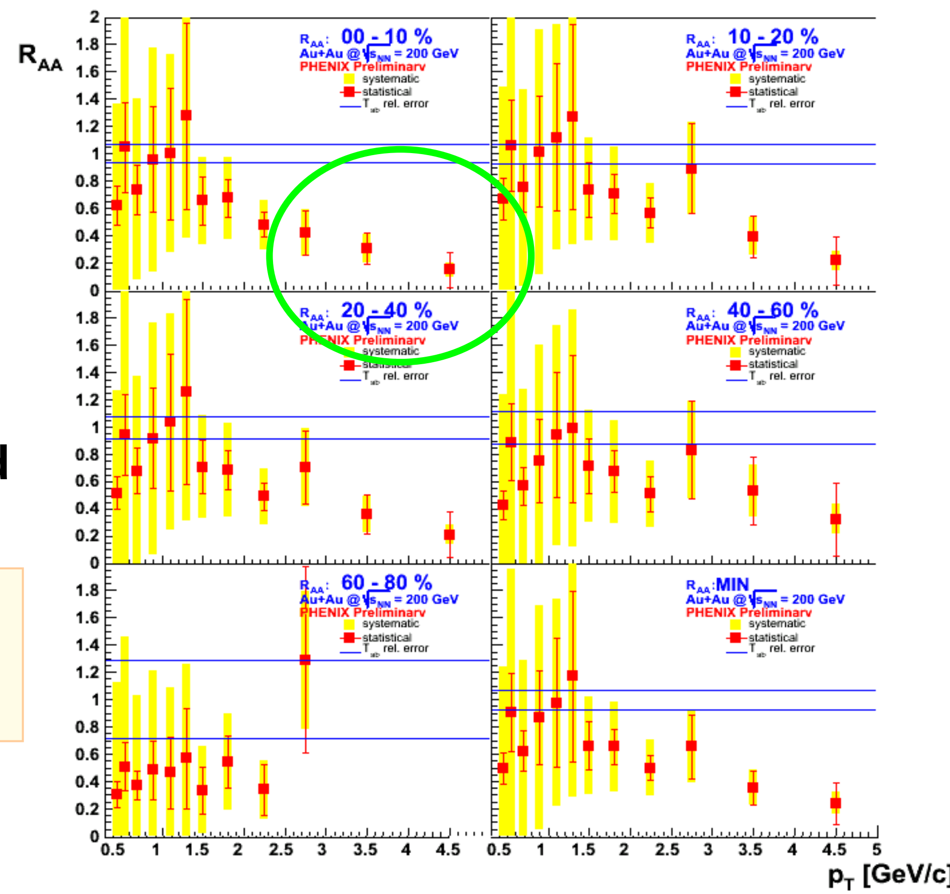
- Of course the "dead cone" will be important **if** the medium induced radiation is still dominated by forward emission

Key point: It is difficult to suppress what is not there in the first place

Not the whole story! (In preparation)

Stay tuned!

Preliminary PHENIX non-photonic electrons



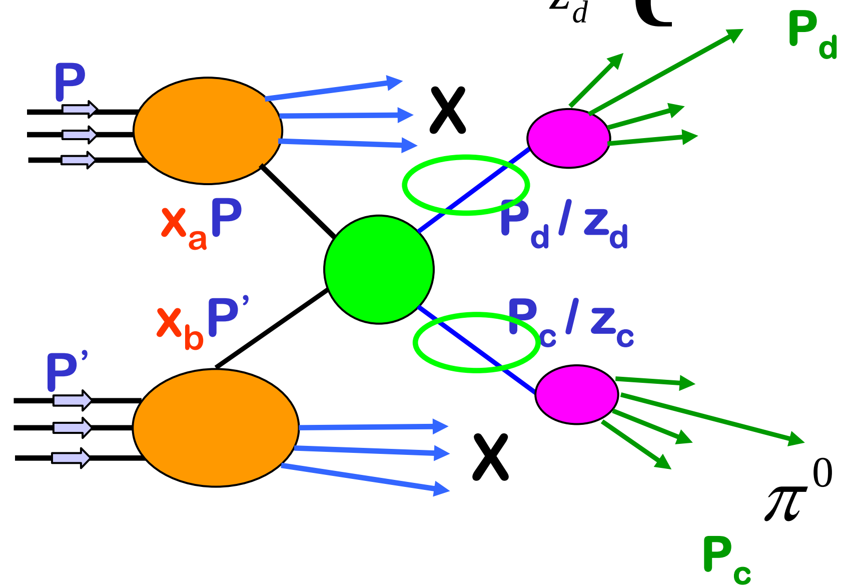
- Quenching of heavy q ~ light q

The pQCD Formalism

- Reliable formalism with predictive power

J.Collins, D.Soper, G.Sterman, Adv.Ser.Dir. 5 (1988)

$$\int d\frac{p_d}{z_d}\Big\{ \pi^0$$



QCD factorization

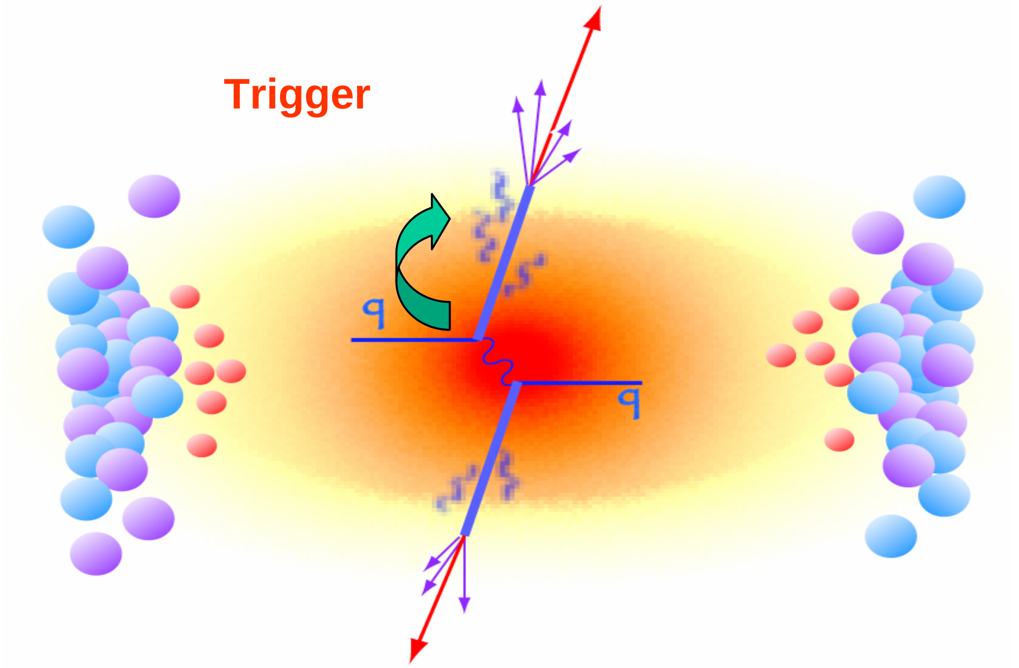
- To LO (2 to 2 scattering) - single and double inclusive hadron production

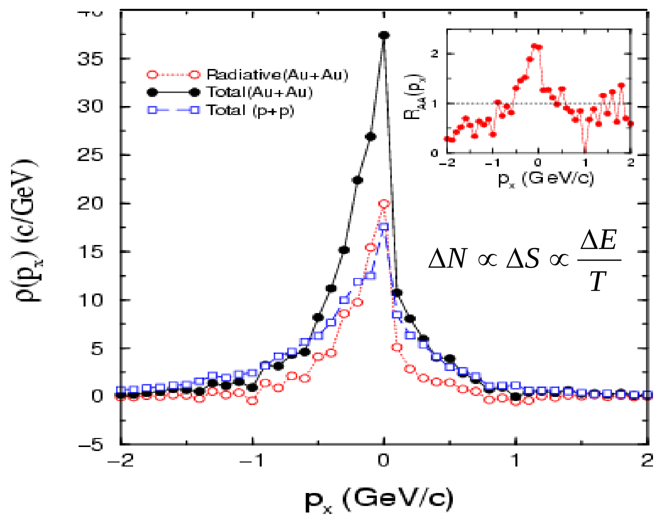
Can also incorporate Cronin effect: $\int d^2k_T\, f_{med}(k_T)$

$$\frac{d\sigma^{h_1}_{NN}}{dy_1\, d^2p_{T1}} = \sum_{abcd}\int_{x_a\,\min}^{1} dx_a \int_{x_b\,\min}^{1} dx_b\, \phi(x_a)\phi(x_b)\frac{\alpha_s^2}{(x_a x_b S)^2}\left|\overline{M}\right|^2_{ab\to cd}\frac{D_{h_1/c}(z_1)}{z_1}$$

$$\frac{d\sigma^{h_1h_2}_{NN}}{dy_1\,dy_2\,d^2p_{T1}\,d^2p_{T2}} = \frac{\delta(\Delta\varphi-\pi)}{p_{T1}\,p_{T2}}\sum_{abcd}\int_{z_1\,\min}^{1} dz_1\, \frac{D_{h_1/c}(z_1)}{z_1}D_{h_2/d}(z_2)\,\frac{\phi(\bar{x}_a)\phi(\bar{x}_b)}{\bar{x}_a\bar{x}_b}\,\frac{\alpha_s^2}{S^2}\left|\overline{M}\right|^2_{ab\to cd}$$

Di-Hadrons and Feedback Energy





S.Pal, S.Pratt, Phys.Lett.B574 (2003)

- **In the context of a transport model**

But the formation length is ~ L/2. May fragment outside the medium

$$D_{h_1/d}(z_2)\delta(\Delta\varphi-\pi) \rightarrow \frac{1}{1-\varepsilon} D_{h_1/d}\left(\frac{z_2}{1-\varepsilon}\right) f_{med}(\Delta\varphi)$$

Quenched parent parton

Feedback gluons (not DGLAP)

$$+\frac{p_{T_1}}{z_1}\int_0^1 \frac{dz_g}{z_g} D_{h_1/d}(z_g)\int_{-\pi/2}^{\pi/2} d\phi \, \frac{dN^g(\phi)}{d\omega d\phi} f_{vac}(\Delta\varphi-\phi)$$

- **Use energy conservation to verify the fragmentation sum rule**

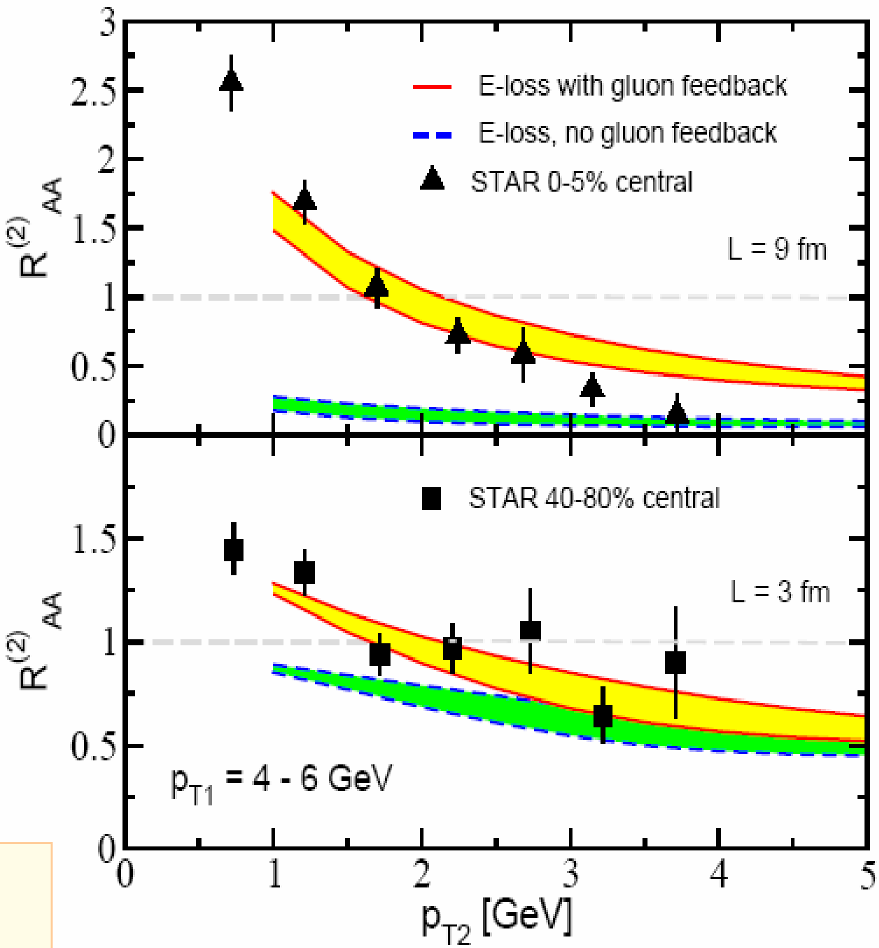
Numerical Results

Define a measure for nuclear modifications to di-hadron correlations:

$$R_{AA}^{(2)} = \frac{d\sigma_{AA}^{h_1 h_2} / dy_1 dy_2 dp_{T1} dp_{T2}}{\langle N_{bin} \rangle d\sigma_{pp}^{h_1 h_2} / dy_1 dy_2 dp_{T1} dp_{T2}}$$

P_{T1} trigger:

- **Fix the energy**
- **Ensure high Q^2,**
- **Minimize the effect on the near side**
- **Maximize the effect on the away side**



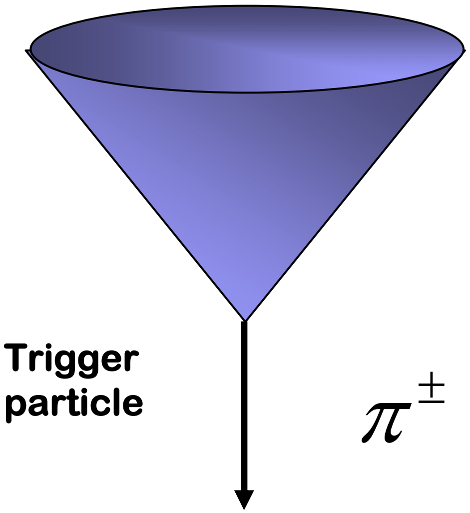
I.V., hep-ph/0501255

- **The redistribution of the energy is a parameter free prediction**
- **For large energy loss - the radiative gluons dominate to unexpectedly high $p_{T2} \sim 10\ GeV$**

Data is from:

J.Adams *et al.*, nucl-ex/0501016

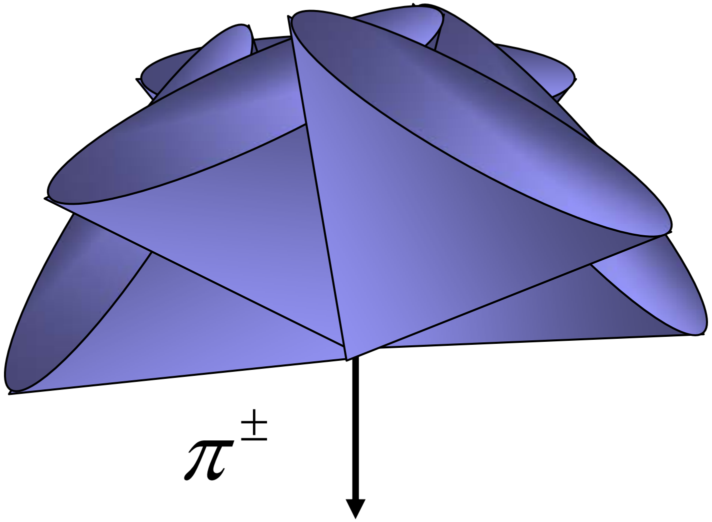
Superposition of Jet Cones



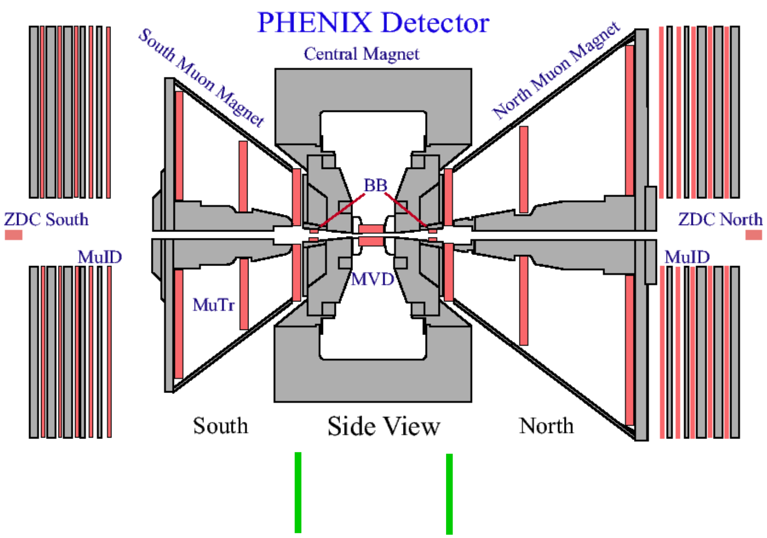
<u>Some</u> mechanism of jet cone production

Trigger particle

$\pi^{\pm}$



$\pi^{\pm}$



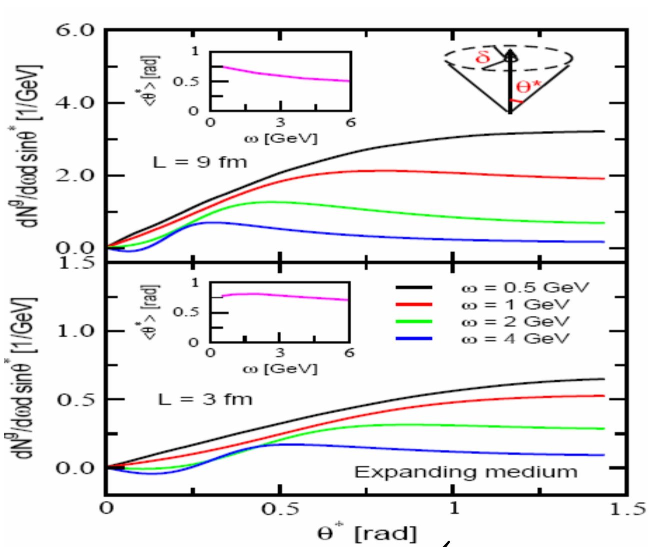
$\Delta\eta = \pm 0.35$

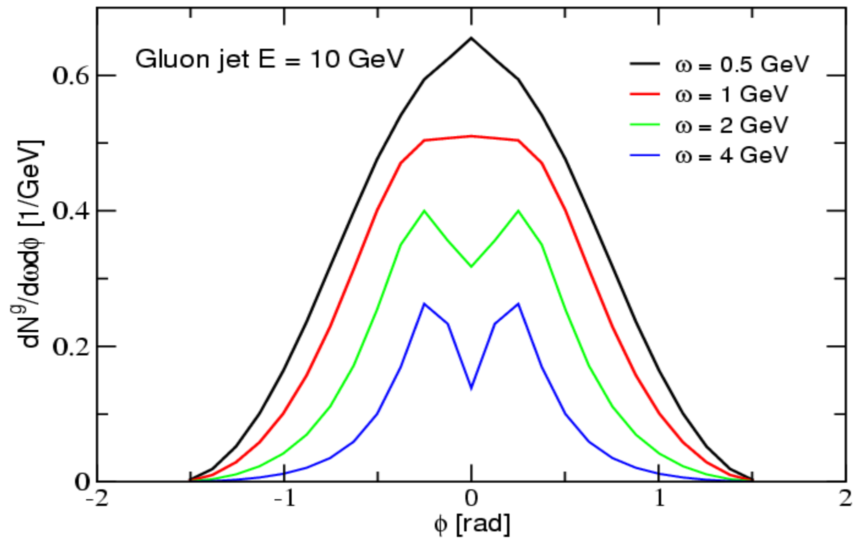
Experiments measure in the plane ϕ
(to make the life of theorists difficult)

- **Surprisingly flat dijets in a wide rapidity range** $\Delta y \simeq 2-3$
- **One has to filter through the di-jet rapidity distribution**

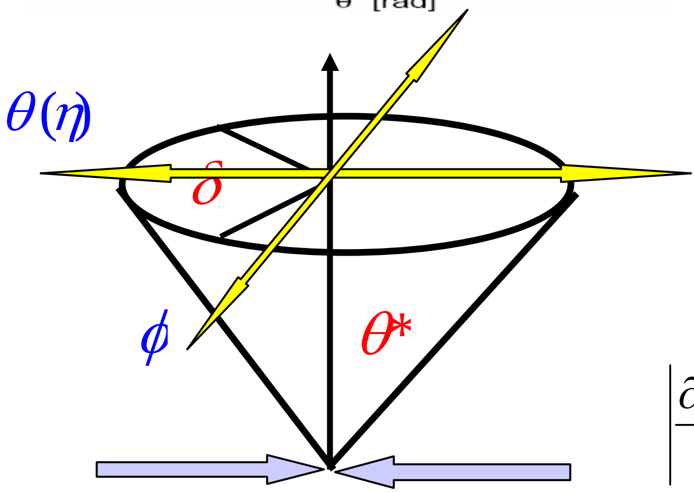
Projected Medium-Induced Radiation

From this | **to that**





The double hump structure is gone



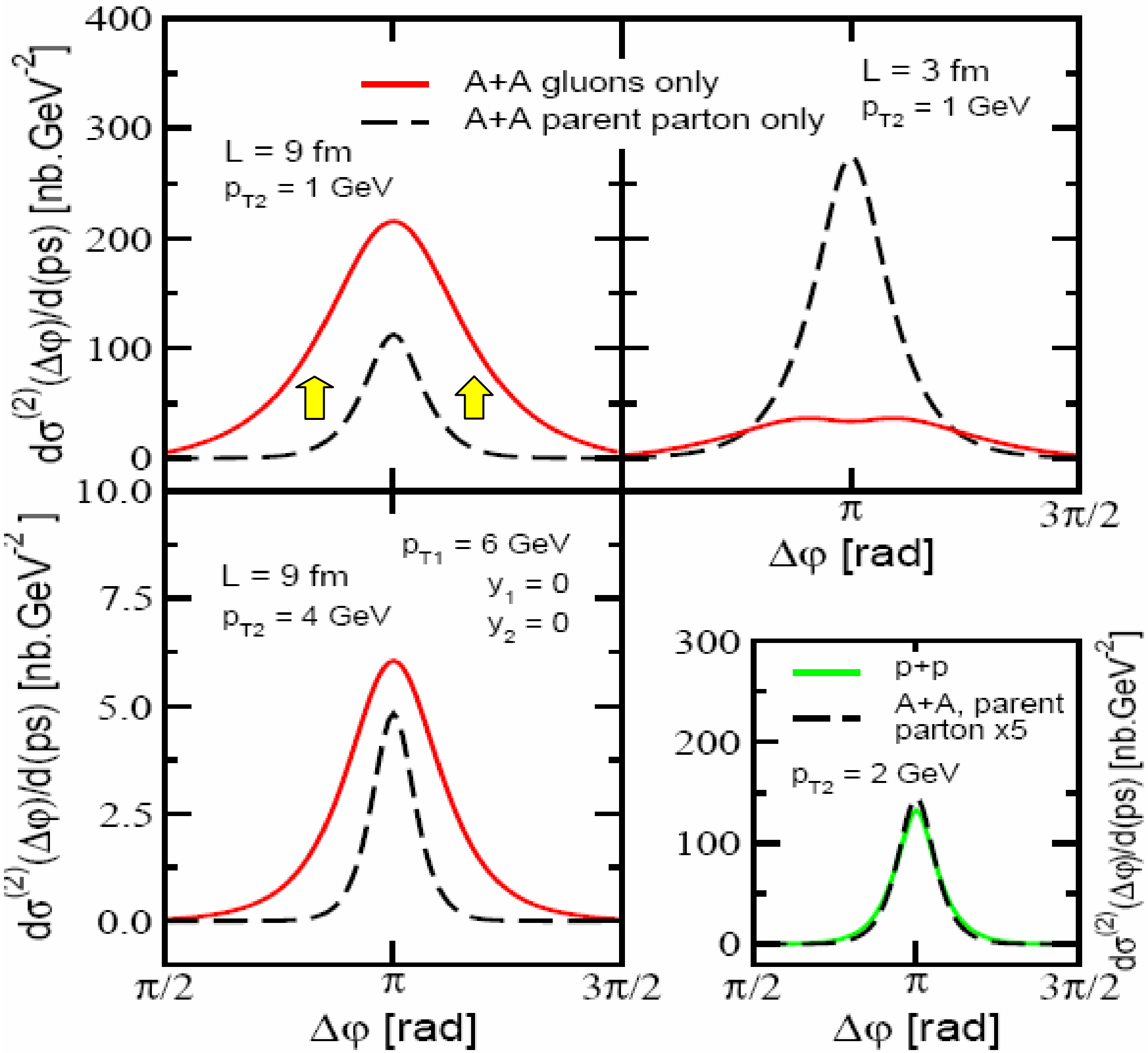
$$y \approx \eta = -\ln tg(\theta/2)$$

$$tg^2\theta^* = ctg^2\theta + tg^2\phi$$

$$tg\delta = -\frac{ctg\theta}{tg\phi}$$

$$\left|\frac{\partial(\sin\theta^*,\delta)}{\partial(\theta,\phi)}\right| = \frac{1}{\sin^2\theta\cos^2\phi}\,\frac{(ctg^2\theta+tg^2\phi)^{-1/2}}{(1+ctg^2\theta+tg^2\phi)^{3/2}}$$

Angular Di-Hadron Distribution



I.V., hep-ph/0501255

$$\sigma_{Far}(AA) > \sigma_{Far}(pp)$$

- The width $|\Delta\varphi - \pi|$ of the large-angle correlations is dominated by medium induced gluon radiation

- Reassessment of the origin of small and moderate p_T away triggered hadrons

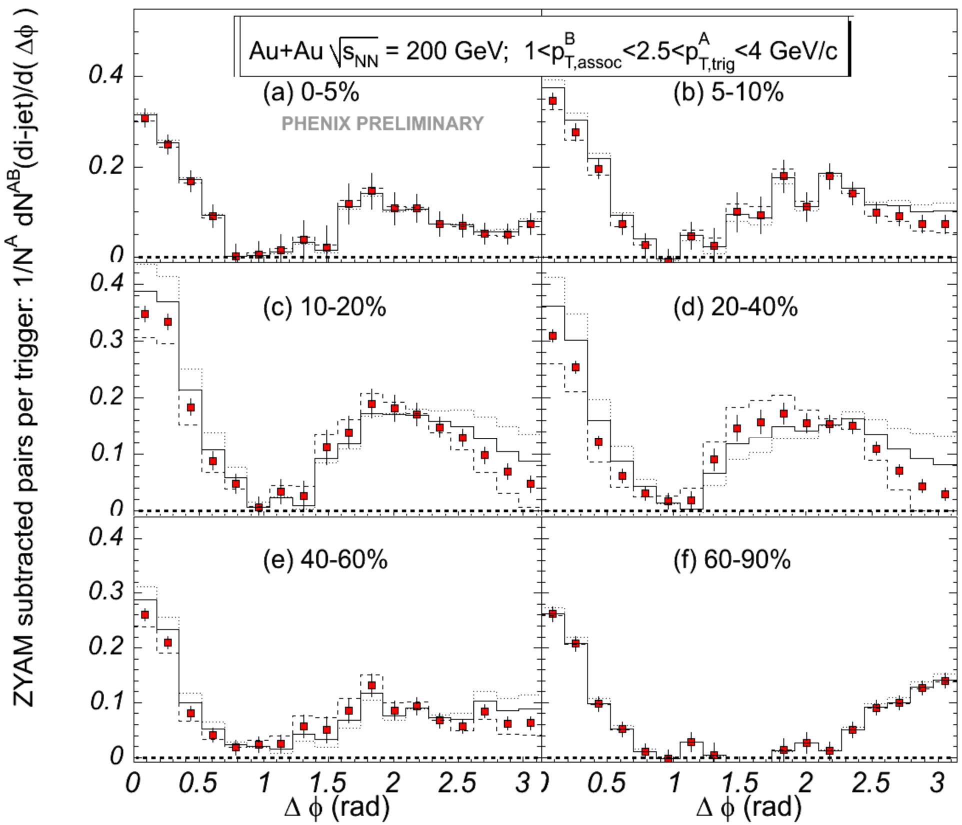
The quenched parton is not wider

Because:

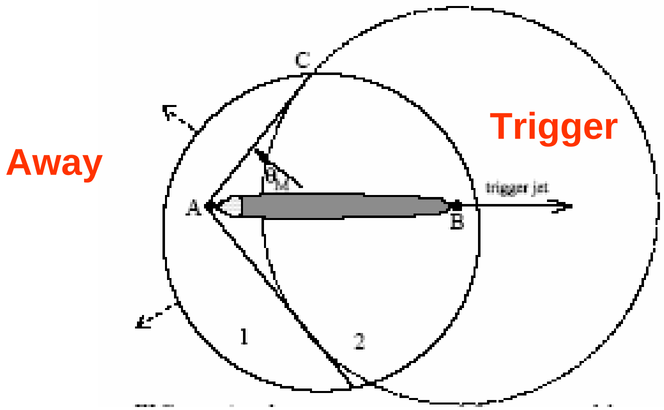
$$\sigma_{Far} \approx \frac{\sqrt{\langle k_T^2 \rangle_{vac}}}{p_{Tc}} \rightarrow \frac{\sqrt{\langle k_T^2 \rangle_{tot}}}{[p_{Tc}/(1-\varepsilon)]}$$

Results in Au+Au

PHENIX **preliminary**:



- What's going on with this hole in the middle?



Solana,Shuryak,Teaney, hep-ph/0411315

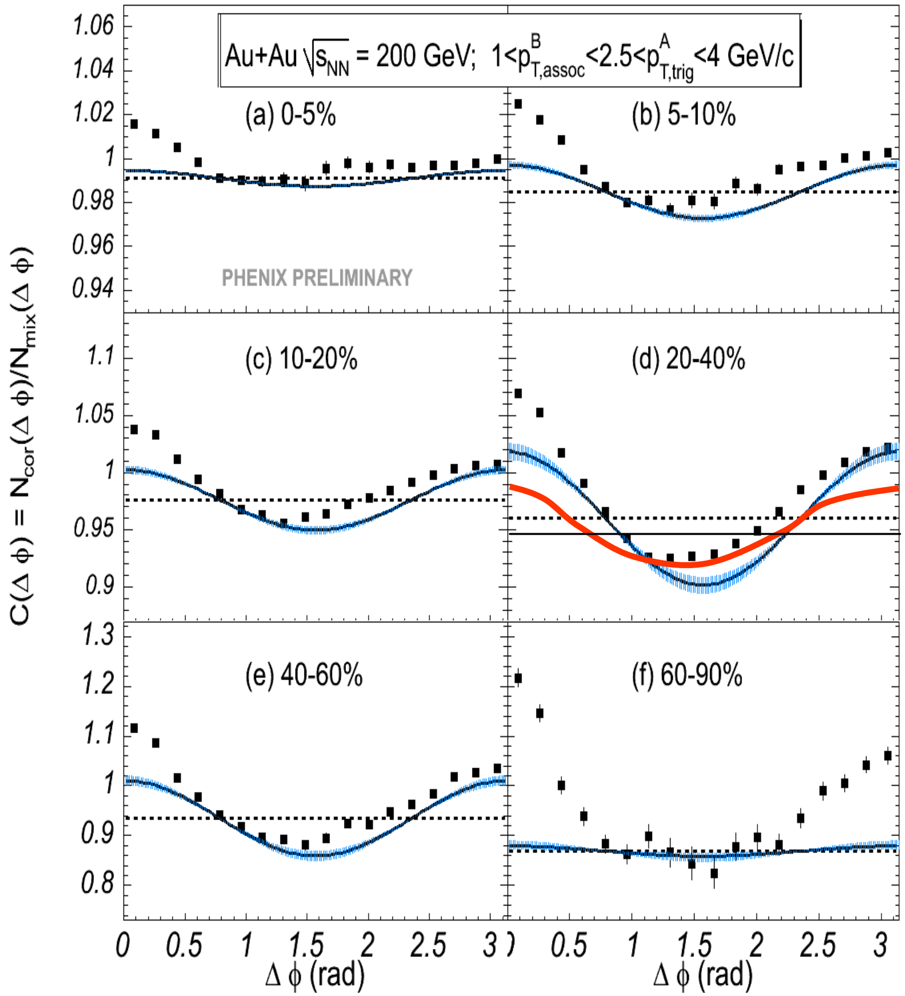
Did not do the averaging over the away-side di-jet distribution

- Figure taken from B. Jacak, ICPAQGP 2005

$$\sigma_{Far}(AA) > \sigma_{Far}(pp)$$

- **Confirmation** of a very broad distributions of away-side triggered hadrons

The Experimental Technique



Two source model gives :

Correlation		*Flow*		*Jet*

$$C(\Delta\phi) = a_0\left[H(\Delta\phi) + J(\Delta\phi) \right]$$

- **Assumption, which I think is incorrect**
- **There is no constraint on now big of a harmonic is subtracted in this method**

The v_2 used by PHENIX seems to differ from STAR

There may be in uncertainty associated with the amplitude of flow and jets ZYAM

- **Figure taken from N.N.Ajitanand ICPAQGP 2005**

- **PHENIX says: Both (di-) jet correlations and flow are evident**

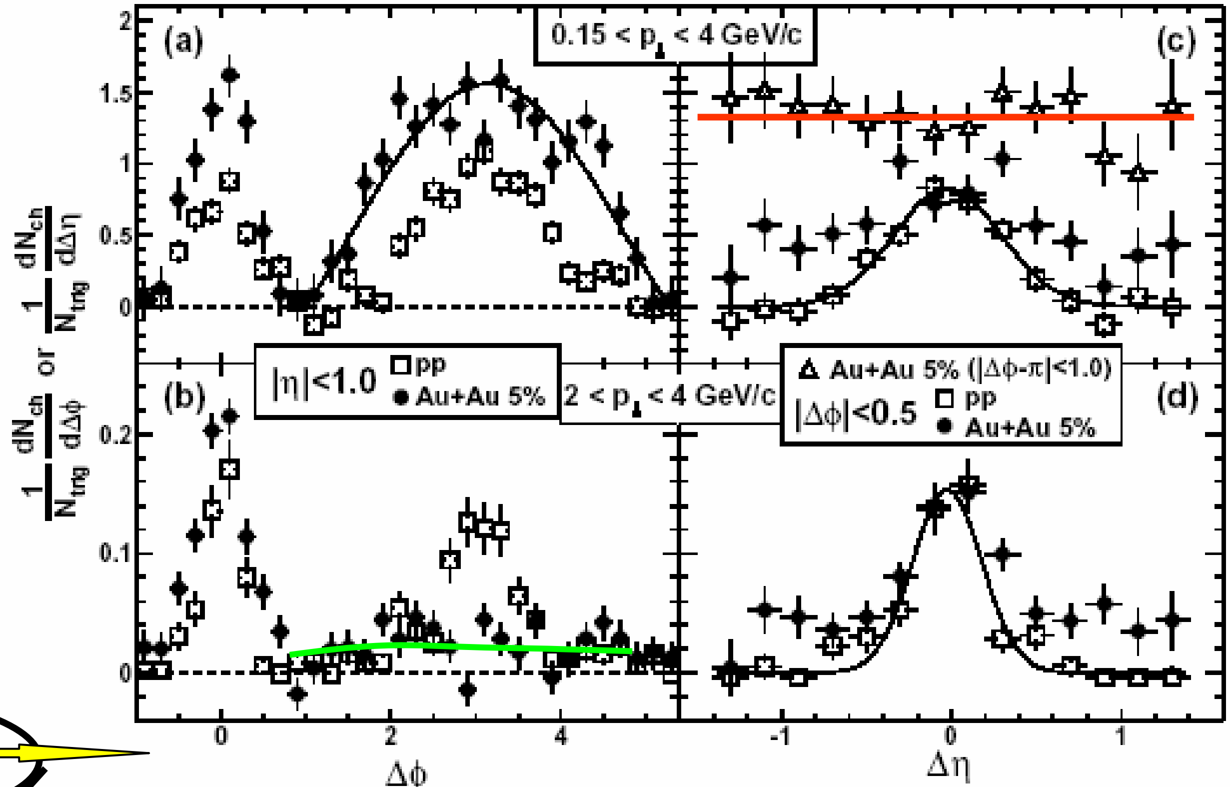
The Rapidity Story is Known

Rapidity coverage $\eta = \pm 1.4$

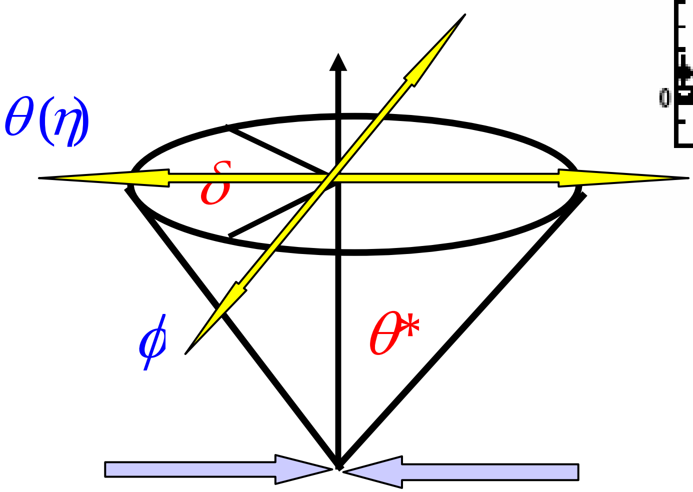
$$y \approx \eta = -\ln tg(\theta / 2)$$

$$\theta \in (28^\circ, 152^\circ)$$

No (curious) structure in rapidity or azimuth



J.Adams *et al.*, nucl-ex/0501016, submitted to Phys.Rev.Lett.



- **Slicing in ϕ and slicing in $\theta(\eta)$ is the same**

Conclusions

- New jet quenching studies demonstrated the large angle hadron production from and the possible disappearance of the dead cone effect. Possible evidence from single electrons (not the full story!)

- A parameter free description of the redistribution of the lost energy for tagged jets can be obtained in the peturbative approach. The medium parameters only specify -dE

- Significant broadening of the away side correlations confirmed by PHENIX. The extra structure is possibly from over subtraction of v_2. Checked against STAR results and rapidity