Parton Energy Loss and its Application to Hadronic Reactions

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ECT* Seminar, Trento, Italy

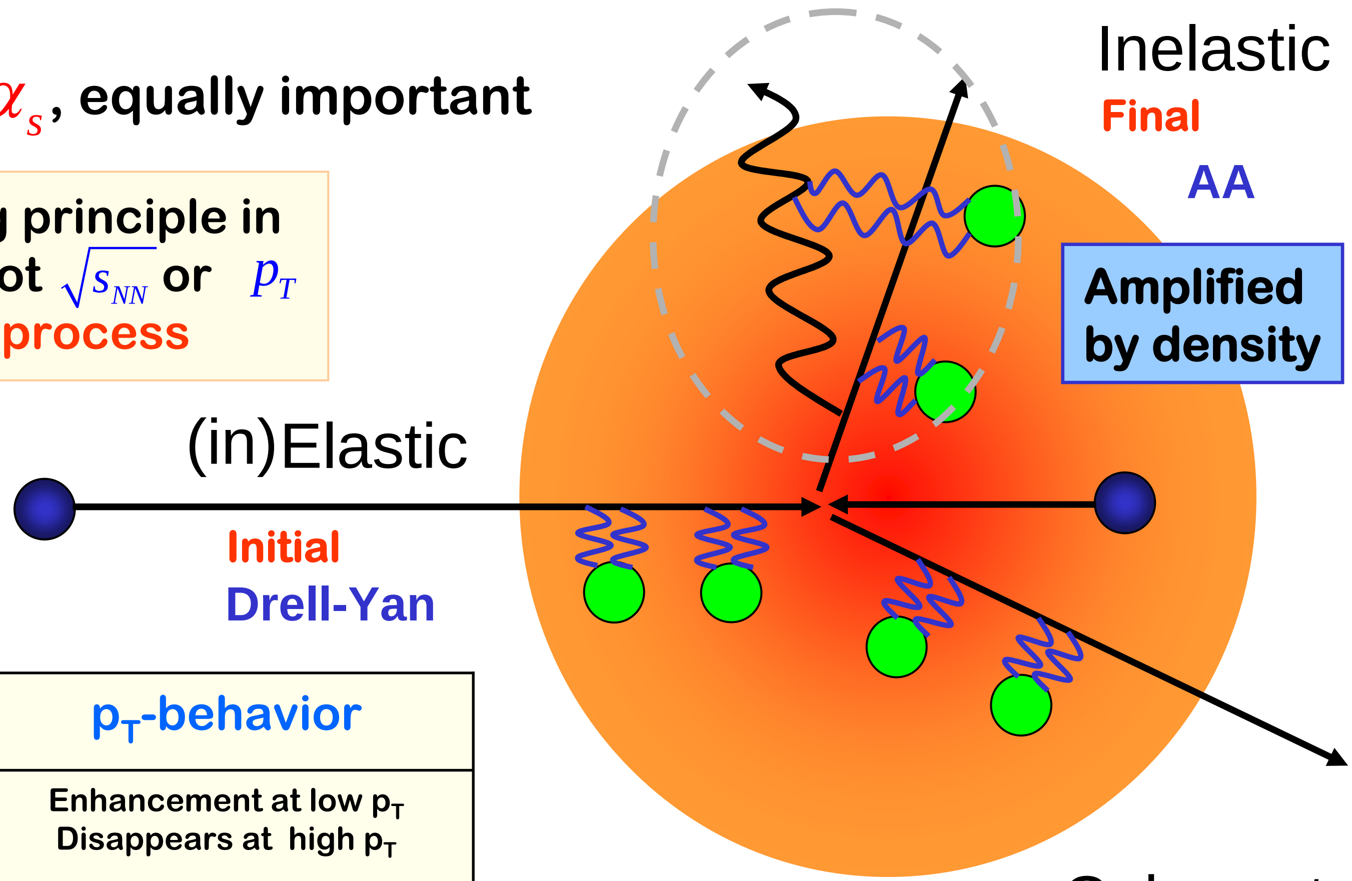
Outline of the Talk

- **Radiative energy loss and jet quenching:**
  - Theoretical derivation to first order in opacity
  - Large angle emission - the death of the "dead cone"
  - Derivation to all orders in opacity (reaction operator)
  - Implementation in the perturbative QCD formalism
- **Nuclear modification of (di-)hadrons:**
  - Energy dependence of the inclusive quenching
  - Modification of the yields (energy redistribution)
  - Modification of the large angle correlations
  - Dijet attenuation
- **Conclusions:**

Specific Processes with Nuclei

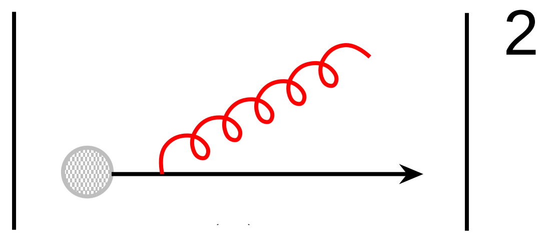
All couplings $\sim \alpha_s$, equally important

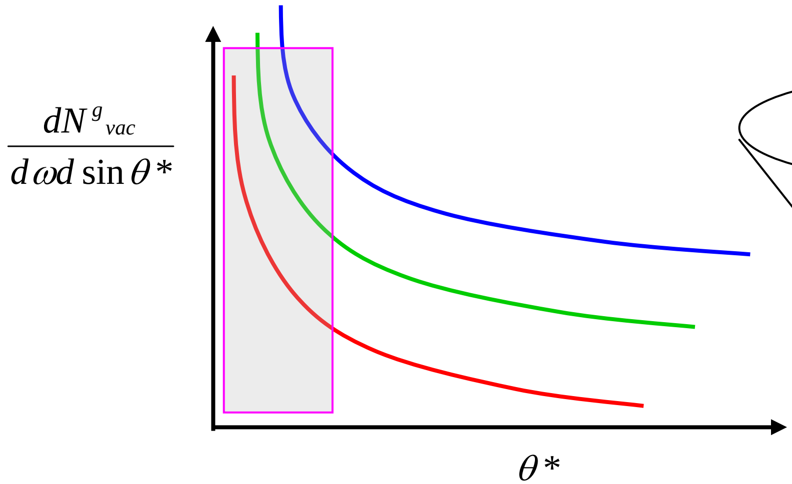
- The overarching principle in calculations is not $\sqrt{s_{NN}}$ or p_T but the physical process

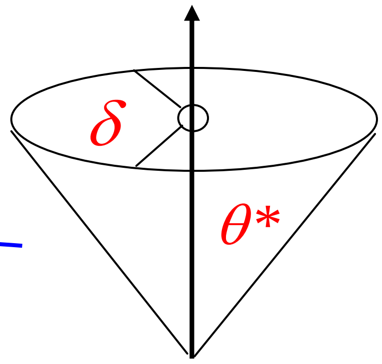


Type	Effect	p_T-behavior
Elasatic	Cronin	Enhancement at low p_T Disappears at high p_T
Inelastic	Jet quenching	Suppression at high p_T Gluons feed the low p_T
Coherent	Shadowing	Suppression at low p_T Quickly disappears at high p_T

Vacuum Radiation







If interested in the small angle small frequency behavior

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

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

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

For massive quarks - "dead cone effect"

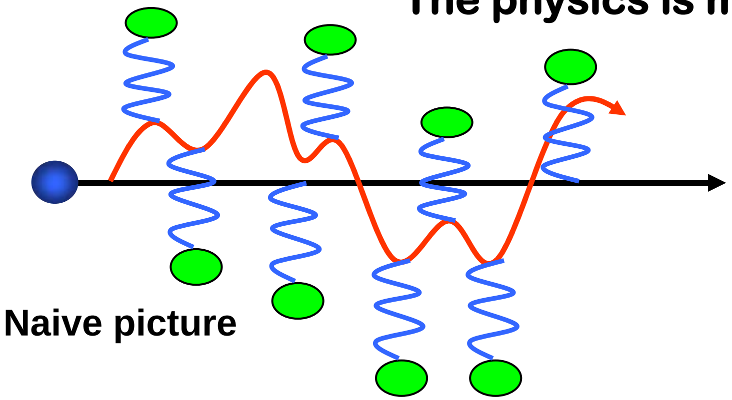
- Takes care of the collinear

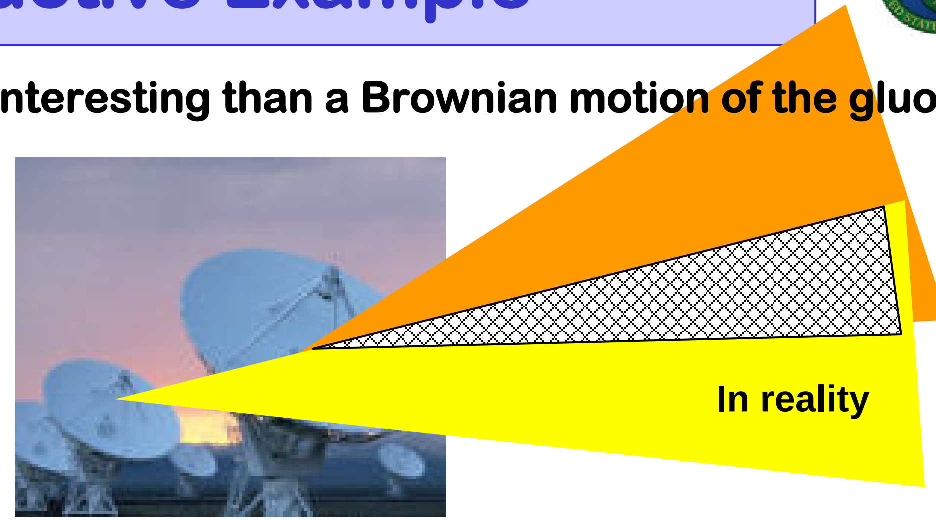
$$\frac{dN^g{}_{vac}}{d\omega d\sin\theta^* d\delta} \approx \frac{C_R\alpha_s}{\pi^2}\frac{\sin\theta^*}{\omega\,(\sin^2\theta^* + M^2/E^2)}$$

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

Instructive Example

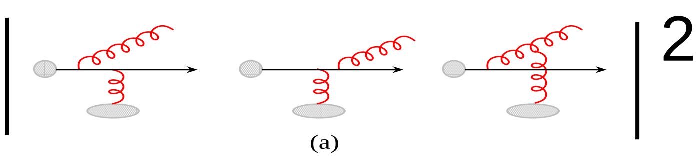
The physics is more interesting than a Brownian motion of the gluon



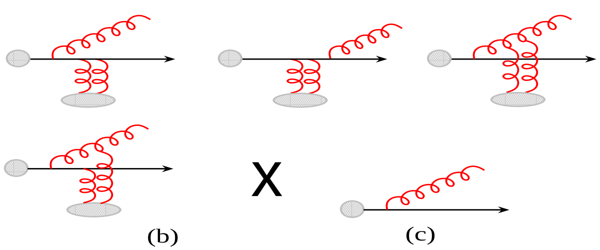


$i(-i)=1 \qquad i\,(i) = -1 = \cos(\pi)$

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



+2Re



Solution to first order in the mean # of scatterings

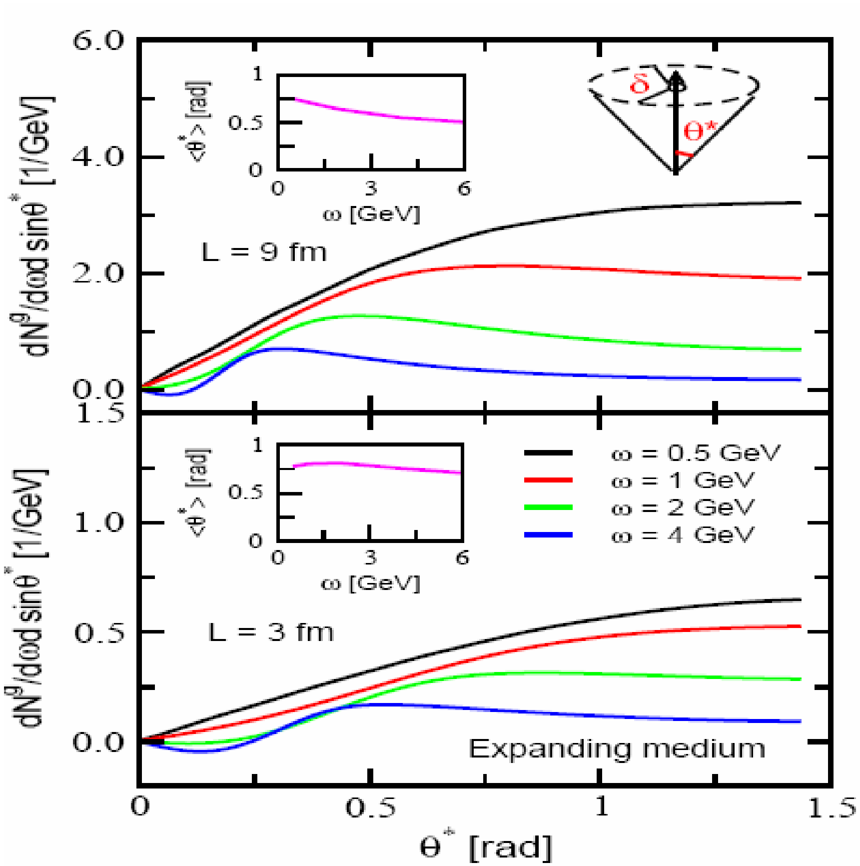
$$\frac{dN^g{}_{med}}{d\omega d\sin\theta^* d\delta} \approx \frac{2C_R\alpha_s}{\pi^2} \int_{z_0}^{L} \frac{d\Delta z}{\lambda_g(z)} \int_0^{\infty} dq_\perp q_\perp^{\;2} \frac{1}{\sigma_{el}} \frac{d\sigma_{el}}{d^2 q_\perp}$$

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

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

I.V., hep-ph/0501255

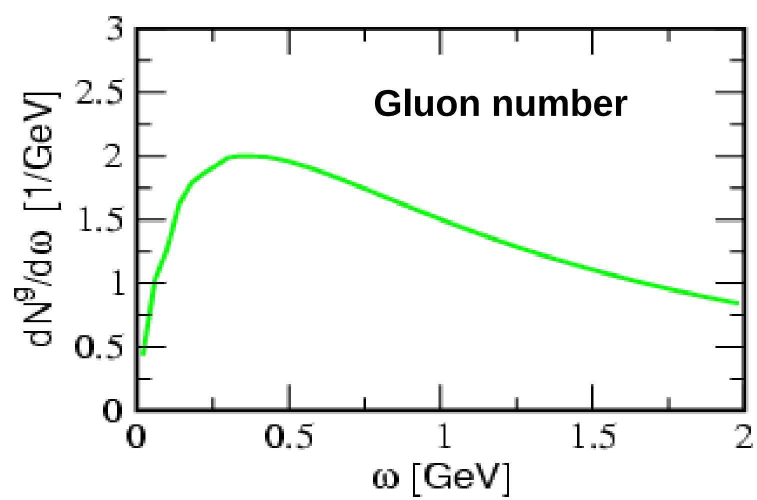
Angular and Frequency Behavior



I.V., hep-ph/0501255

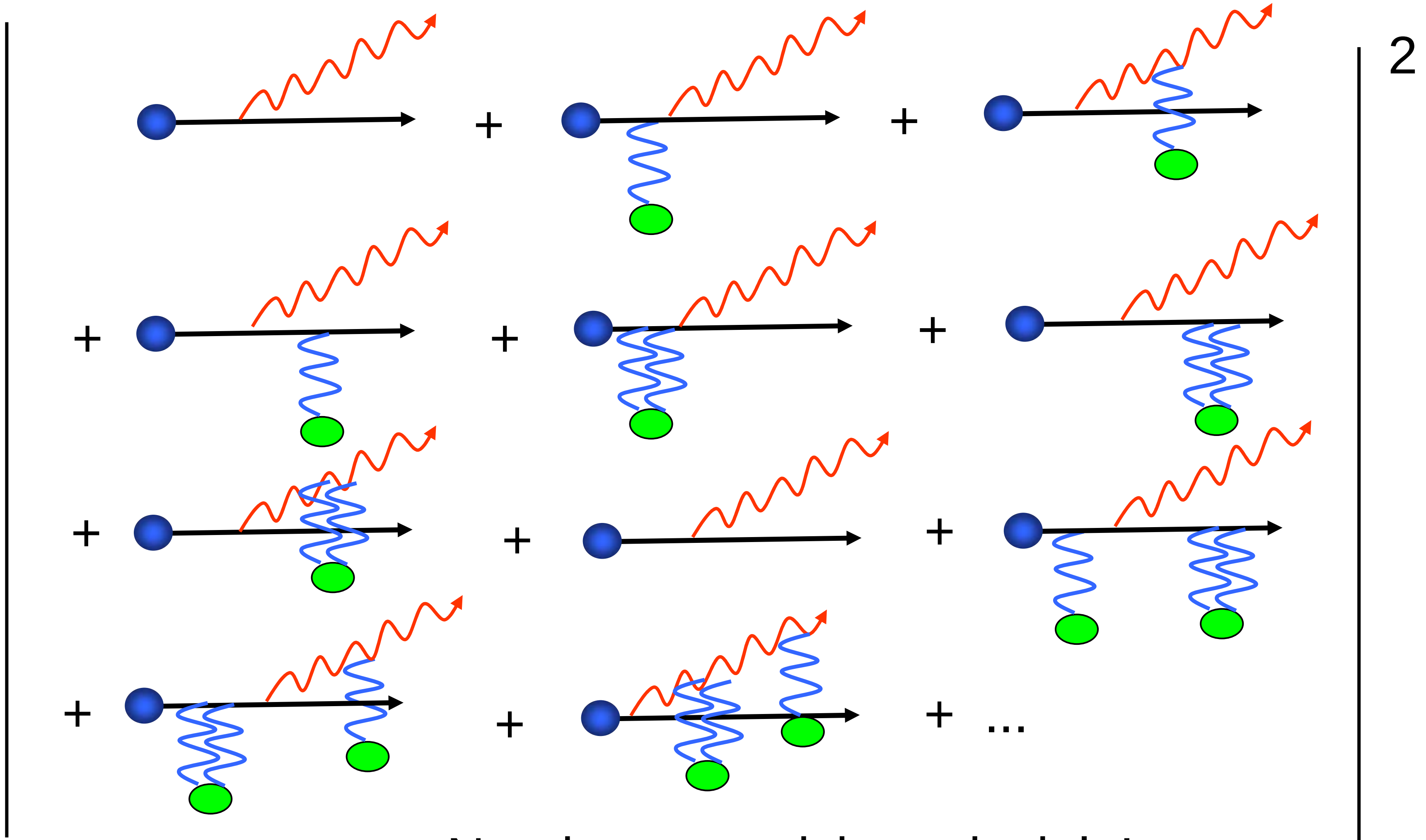
- **Radiation is moderately large angle (cancellation near the jet axis)**
- **Finite gluon number**

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



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

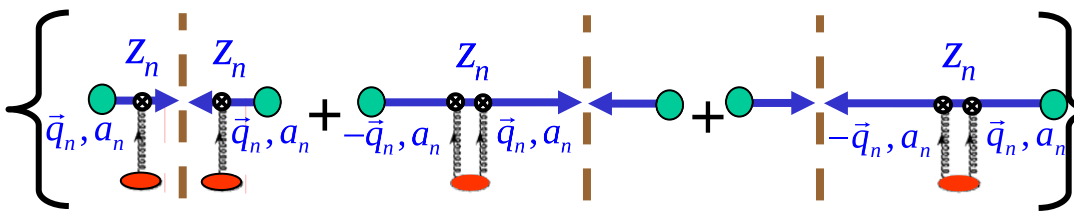
Medium-Induced Bremsstrahlung



Need an organizing principle!

Recall the Elastic Case

- The calculation of the elastic case (**transverse momentum diffusion**) was easy since we organized the opacity series as a solution to the **Reaction Operator** (Although some limiting cases may have been guessed)

R = 

$$= \hat{D}_n^{\dagger}\hat{D}_n + \hat{V}_n + \hat{V}_n^{\dagger}$$

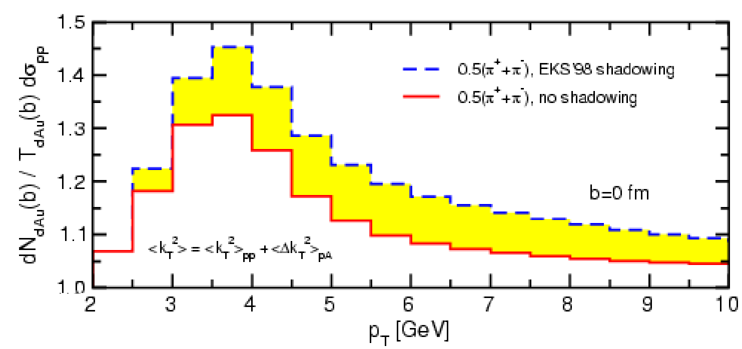
Acquire broadening: $dN^i(k_\perp) = \delta^2(k_\perp)$

$$\frac{d\sigma_{el}(b)}{d^2q} = \frac{\mu b}{4\pi^2} K_1(\mu b) \approx \frac{1}{4\pi^2}\left(1 - \frac{\mu^2 b^2}{2}\xi + O(b^3)\right)$$

$$dN^f(k_\perp) = \frac{1}{2\pi}\frac{e^{-\frac{k_\perp^2}{\chi\mu^2\xi}}}{\chi\mu^2\xi}, \quad \left\langle \Delta k_\perp^2 \right\rangle = 2\chi\mu^2\xi$$

Were $\xi = \log 2/(1.08\mu b)$

- Obviously the Cronin Effect



- For our current purpose - **elastic unitarity**

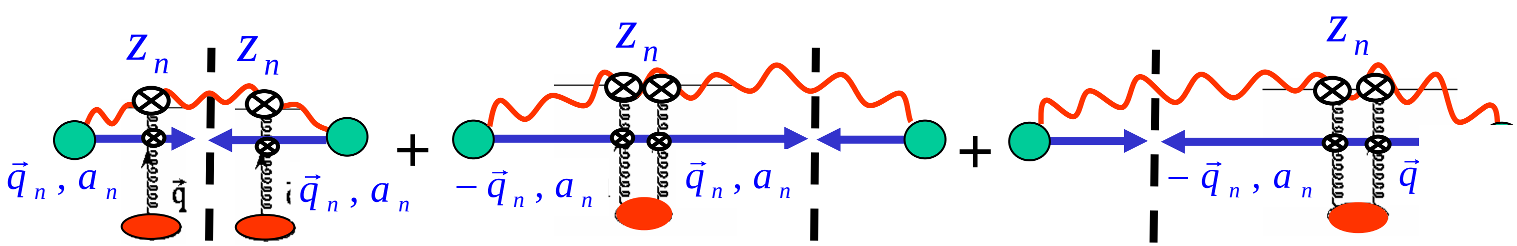
Medium Induced Non-Abelian Radiative Spectrum

The goal:

- Landau-Pomeranchuk-Migdal destructive interference effect in QCD
- Incorporates finite kinematics and small number of scatterings
- Applicable for realistic systems

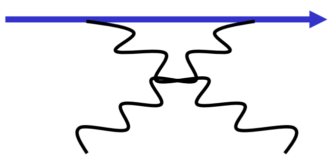
The idea:

$\hat{R} =$



Iterative solution M.Gyulassy, P.Levai, I.V., Nucl.Phys.B594 (2001); Phys.Rev.Lett.85 (2000)

The constraint:



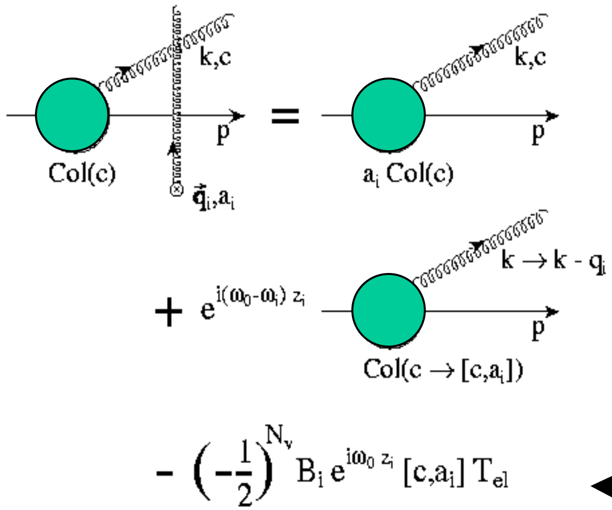
$\sim \quad e^{-\lambda\mu}$

Inconsistent with large number of scatterings approximation

Direct Insertion Operator

$$\omega_0 = \frac{\mathbf{k}^2}{2\omega}\ , \ \omega_i = \frac{(\mathbf{k}-\mathbf{q}_i)^2}{2\omega}\ , \ \omega_{(ij)} = \frac{(\mathbf{k}-\mathbf{q}_i-\mathbf{q}_j)^2}{2\omega}\ , \ \omega_{(i\cdots j)} = \frac{(\mathbf{k}-\sum_{m=i}^{j}\mathbf{q}_m)^2}{2\omega}$$

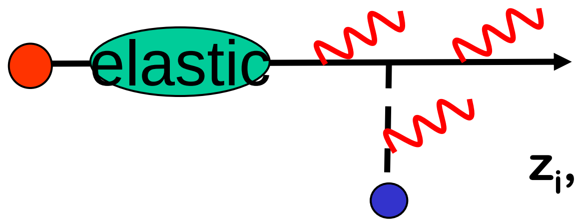
$$E^+ \gg k^+ \gg \omega_{(i\cdots j)} \gg \frac{(\mathbf{p}+\mathbf{k})^2}{E^+}$$



$$\mathbf{H} = \frac{\mathbf{k}}{\mathbf{k}^2}\ , \qquad \mathbf{C}_{(i_1 i_2\cdots i_m)} = \frac{(\mathbf{k}-\mathbf{q}_{i_1}-\mathbf{q}_{i_2}-\cdots-\mathbf{q}_{i_m})}{(\mathbf{k}-\mathbf{q}_{i_1}-\mathbf{q}_{i_2}-\cdots-\mathbf{q}_{i_m})^2}\ ,$$

$$\mathbf{B}_i = \mathbf{H} - \mathbf{C}_i\ , \qquad \mathbf{B}_{(i_1 i_2\cdots i_m)(j_1 j_2\cdots i_n)} = \mathbf{C}_{(i_1 i_2\cdots j_m)} - \mathbf{C}_{(j_1 j_2\cdots j_n)}\ .$$

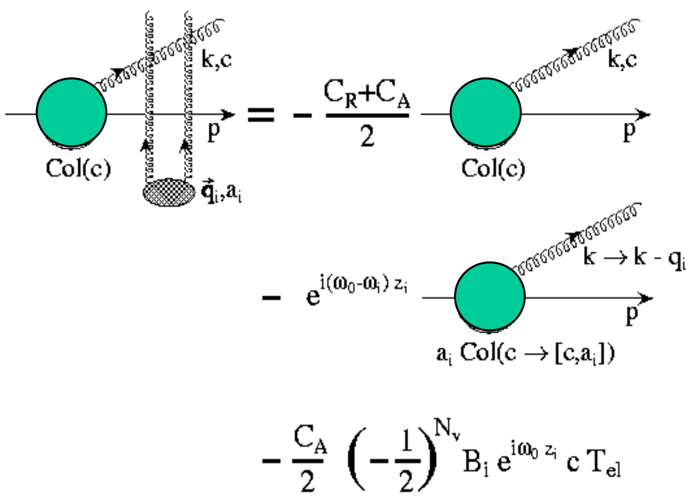
Gunion-Bertsch $\mathbf{B}_i = \frac{\mathbf{k}_\perp}{\mathbf{k}_\perp^{\,2}} - \frac{\mathbf{k}_\perp - \mathbf{q}_{i\perp}}{(\mathbf{k}_\perp - \mathbf{q}_{i\perp})^2}$



$$\hat{D}_n A_{i_1\cdots i_{n-1}}(x,\mathbf{k},c) \equiv (a_n + \hat{S}_n + \hat{B}_n) A_{i_1\cdots i_{n-1}}(x,\mathbf{k},c)$$
$$= a_n A_{i_1\cdots i_{n-1}}(x,\mathbf{k},c) +$$
$$e^{i(\omega_0-\omega_n)z_n} A_{i_1\cdots i_{n-1}}(x,\mathbf{k}-\mathbf{q}_n,[c,a_n]) -$$
$$\left(-\frac{1}{2}\right)^{N_v(A_{i_1\cdots i_{n-1}})} \mathbf{B}_n\, e^{i\omega_0 z_n}[c,a_n] T_{el}(A_{i_1\cdots i_{n-1}})$$

A unity + shift + BG

Virtual Insertion Operator



$$\hat{V}_n A_{i_1\cdots i_{n-1}}(x,\mathbf{k},c) = -\frac{C_R+C_A}{2} A_{i_1\cdots i_{n-1}}(x,\mathbf{k},c)$$

$$- e^{i(\omega_0-\omega_n)z_n} a_n A_{i_1\cdots i_{n-1}}(x,\mathbf{k}-\mathbf{q}_n,[c,a_n])$$

$$-\left(-\frac{1}{2}\right)^{N_v}\frac{C_A}{2}\,\mathrm{B}_n\, e^{i\omega_0 z_n} c a_{n-1}^{i_{n-1}}\cdots a_1^{i_1}$$

$$\hat{V}_n = -\frac{1}{2}(C_A + C_R) - a_n(\hat{S}_n + \hat{B}_n) = -a_n \hat{D}_n - \frac{1}{2}(C_A - C_R)$$

$\hat{V}_n \sim \hat{D}_n$ **suggests huge cancellations at the probability level**

Key Identity for Calculating Induced Gluon Radiation

Example: $\hat{R} = D^\dagger D + V^\dagger + V = D^\dagger D - aD^\dagger - aD - (C_A - C_R) = \left(D^\dagger - a\right)\left(D - a\right) - C_A$

Medium Induced Non-Abelian Radiative Spectrum

$$\sum_{n=1,2,\ldots} x\frac{dN^g}{dx\,d^2\mathbf{k}} = \frac{C_R\alpha_s}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{n!}\prod_{i=1}^{n}\left(\int_{z_{i-1}}^{\infty} dz_i \int d^2\mathbf{q}_i \left[\frac{d^2\sigma_g(z_i)}{d^2\mathbf{q}_i} - \sigma_g(z_i)\delta^2(\mathbf{q}_i)\right]\right)$$

$$\times\, \rho_n(z_1,\cdots,z_n)\left(-2\,\mathbf{C}_{(1,\cdots,n)}\cdot\sum_{m=1}^{n}\mathbf{B}_{(m+1,\cdots,n)(m,\cdots,n)}\right.$$

$$\left.\times\left[\cos\left(\sum_{k=2}^{m}\omega_{(k,\cdots,n)}\Delta z_k\right) - \cos\left(\sum_{k=1}^{m}\omega_{(k,\cdots,n)}\Delta z_k\right)\right]\right),$$

$$\rho_n(z_1,\cdots,z_n) = n!\,\rho_0^n\;\theta(L-z_n)\theta(z_n-z_{n-1})\cdots\theta(z_2-z_1)$$

$$\rho_0 = N_s/LA_\perp$$

where

$$\omega_{(j,\cdots,n)} = \frac{(\mathbf{k}-\mathbf{q_j}-\cdots-\mathbf{q_n})^2}{2xE}$$

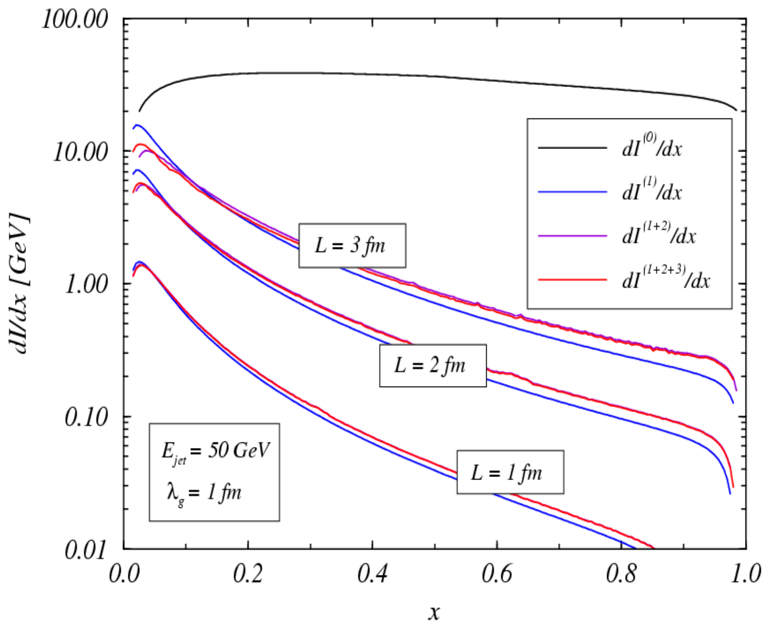
Inverse formation times

$$\mathbf{C}_{(j,\cdots,n)} = \frac{\mathbf{k}-\mathbf{q_j}-\cdots-\mathbf{q_n}}{(\mathbf{k}-\mathbf{q_j}-\cdots-\mathbf{q_n})^2}$$

$$\mathbf{B}_{(j+1,\cdots,n)(j,\cdots,n)} = \mathbf{C}_{(j+1,\cdots,n)} - \mathbf{C}_{(j,\cdots,n)}$$

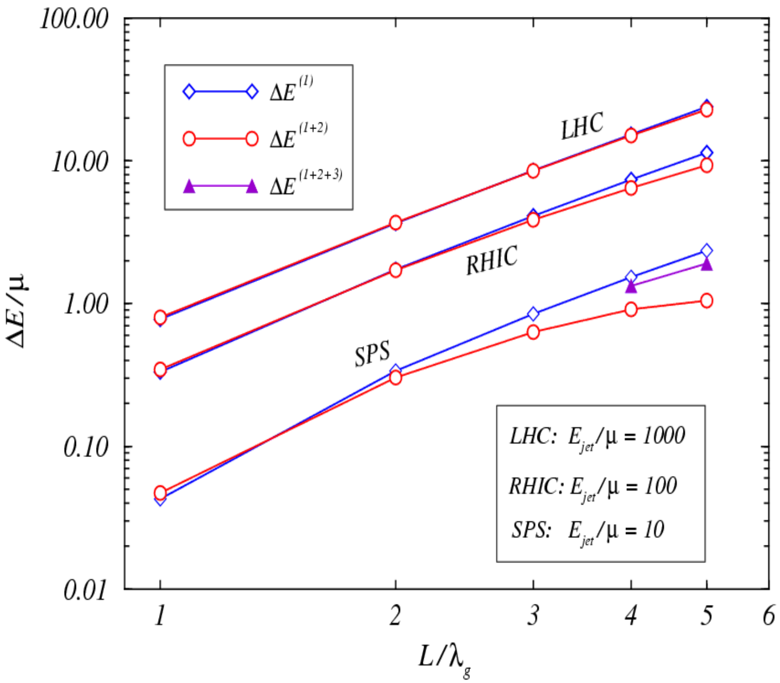
Color current propagators

Numerical Results



- We look at the radiative spectrum and the mean energy loss from a different perspective – **what are the higher order corrections?**

GLV, Nucl.Phys.B 594 (2001)



- It Is the interference between the hard vacuum radiation and one scattering that sets the overall scale for the intensity spectrum and the mean energy loss.
- Higher order corrections provide an oscillating and relatively quickly converg-ing series

Radiative Energy Loss

The energy loss measures the line weighted integral through the expanding gluon density

$$\langle \Delta E \rangle \propto I_1 = \int_{t_0}^{\infty} dt \; t \rho(t, \vec{x}_0 + \hat{v}(t - t_0))$$

In contrast, k_T-broadening measures the zeroth order moment

$$\langle \Delta k_T^2 \rangle \propto I_0 = \int_{t_0}^{\infty} dt \; \rho(t, \vec{x}_0 + \hat{v}(t - t_0))$$

M.Gyulassy, I.V., X.N.Wang , Phys.Rev.Lett.86 (2001)

$$\Delta E^{(1)} \approx \frac{C_R \alpha_s}{4} \frac{\mu^2 L^2}{\lambda_g} \mathrm{Log} \frac{2E}{\mu^2(L) L} + \ldots ,$$

– Static medium

$$\Delta E^{(1)} \approx \frac{9\pi C_R \alpha_s^3}{4} L \frac{1}{A_\perp} \frac{dN^g}{dy} \mathrm{Log} \frac{2E}{\mu^2(L) L} + \ldots ,$$

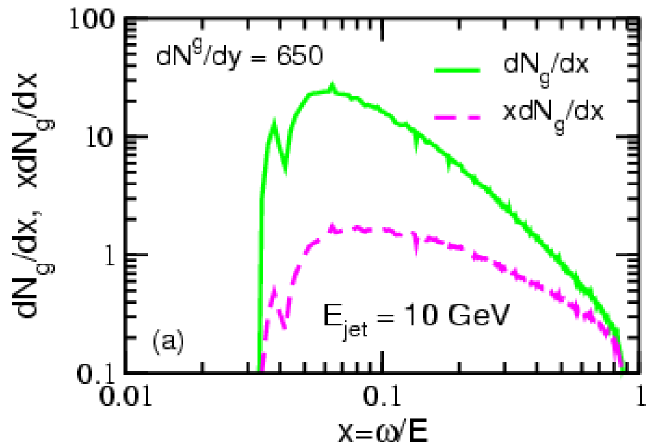
– 1+1D Bjorken

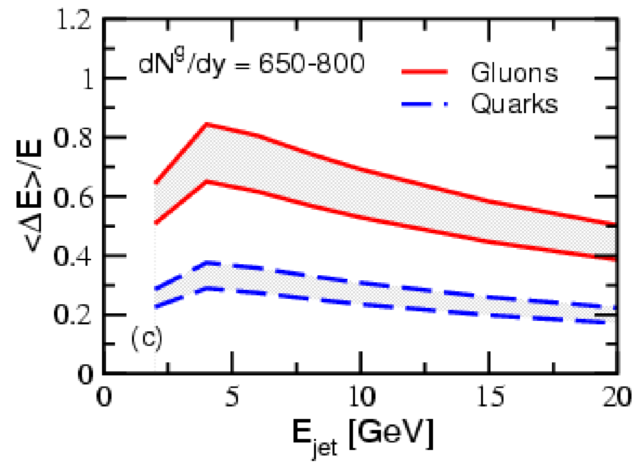
μ^2 / λ - transport coefficient

dN^g / dy - effective gluon rapidity density

Linear Regime : "Thin Plasma"

$$Z(x,z) \ll 1 \;\Rightarrow\; x_c \equiv \frac{\mu^2(z)}{2E}(z - z_0) \ll x \leq 1$$





Numerically slow $\Delta E / E$ dependence

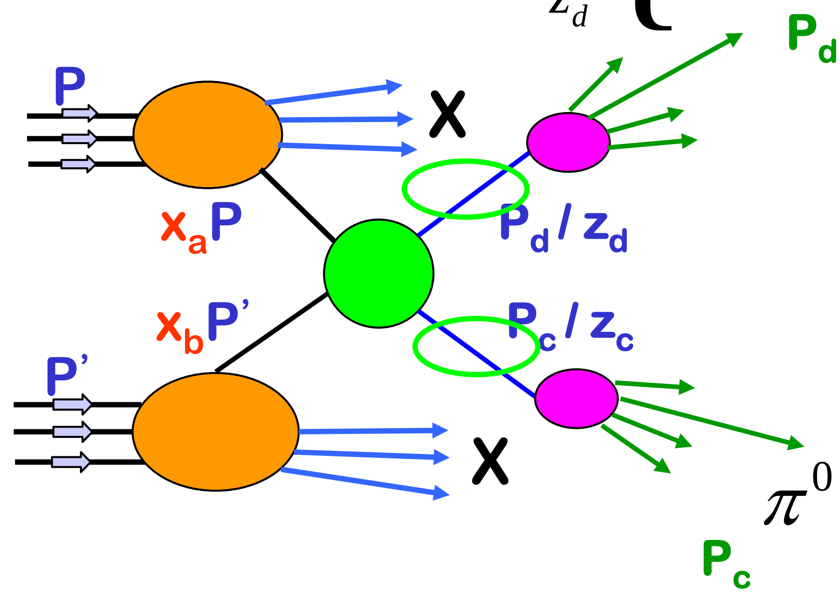
The pQCD Formalism

- **Reliable formalism with predictive power**

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

$$\int d\,\frac{p_d}{z_d}\left\{\ \pi^0\right.$$

QCD factorization



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

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

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

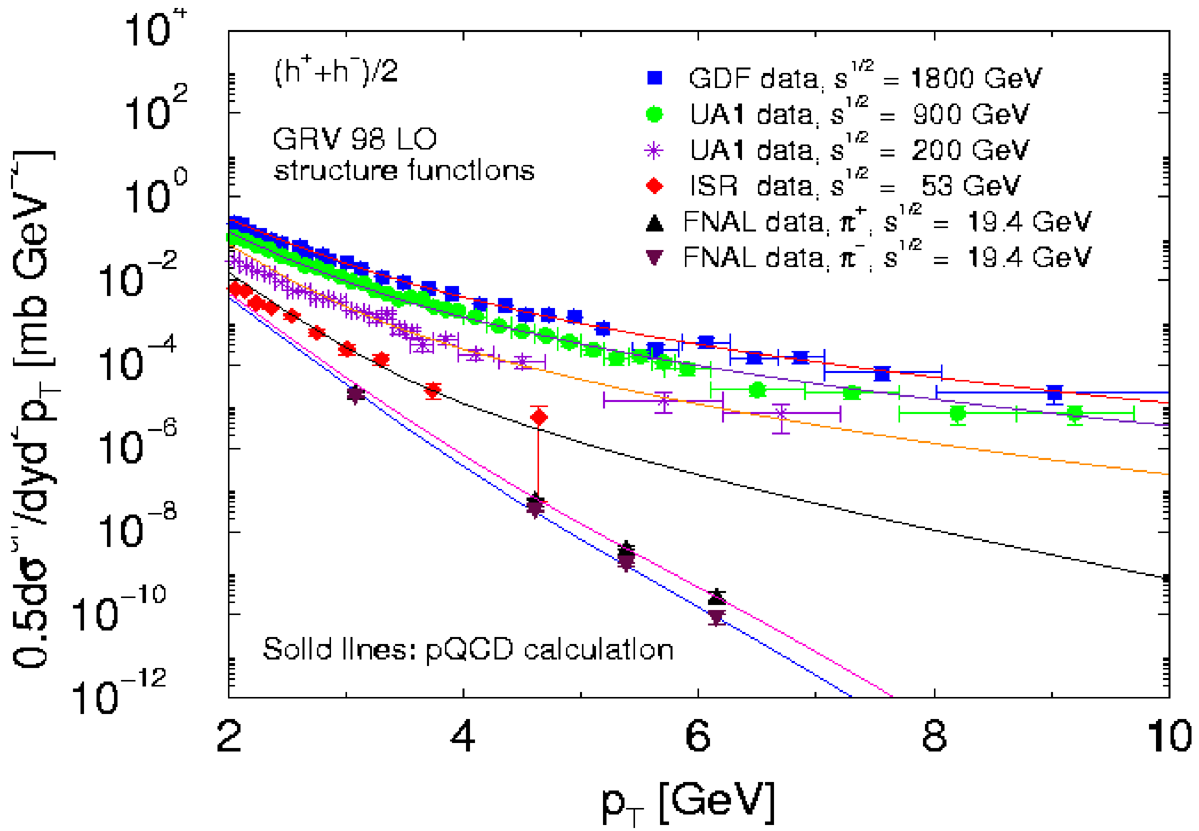
$$\frac{d\sigma^{h_1h_2}_{NN}}{dy_1 dy_2 d^2p_{T1} d^2p_{T2}} = \frac{\delta(\Delta\varphi-\pi)}{p_{T1}p_{T2}}\sum_{abcd}\int_{z_1\,\min}^{1} dz_1 \frac{D_{h_1/c}(z_1)}{z_1} D_{h_2/d}(z_2)\frac{\phi(\overline{x}_a)\phi(\overline{x}_b)}{\overline{x}_a\overline{x}_b}\frac{\alpha_s^2}{S^2}\left|\overline{M}\right|^2_{ab\to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

Calibrated Probes

- **Inclusive hadron distributions**

Leading order pQCD phenomenology

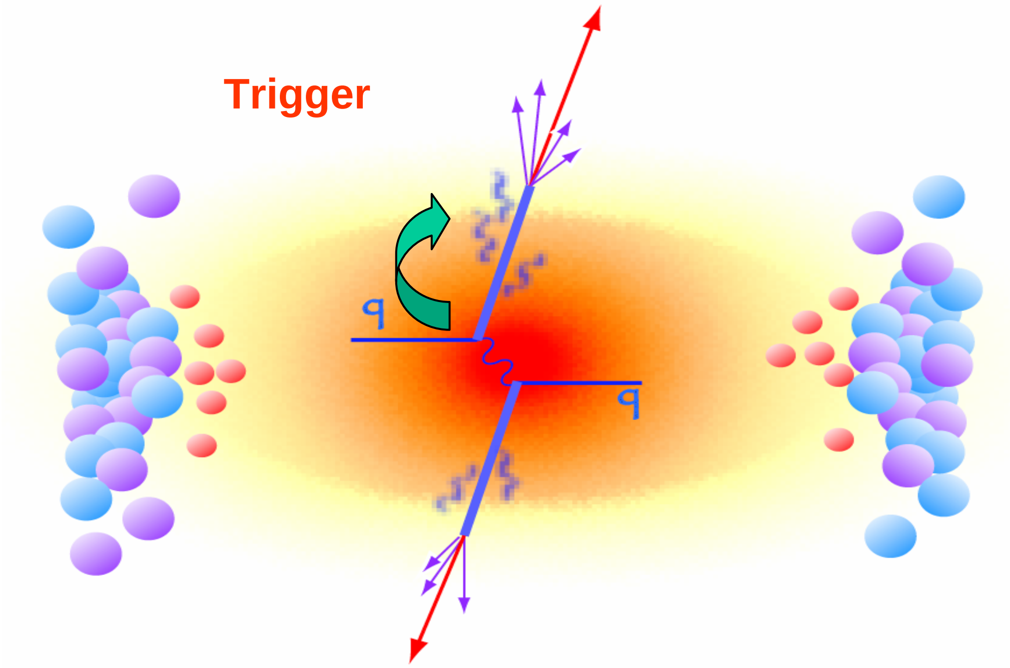
I.V., hep-ph/0212109

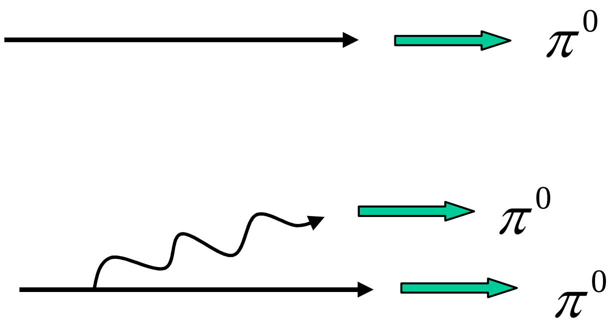


$$E_h \frac{d\sigma}{d^3p} \propto f_{a/A}(x_a, Q^2) \otimes f_{b/B}(x_b, Q^2) \otimes \frac{d\sigma^{ab\to cd}}{dt} \otimes D_{h/c}(z_c^*, Q^2)$$

Parton distribution functions **Perturbative cross sections** **Fragmentation functions**

Di-Hadrons and Feedback Energy





$$p_c \to p_c(1-\varepsilon), \quad z_c \to \frac{z_c}{(1-\varepsilon)}$$

$$p_c \to (\varepsilon)\, p_c, \quad z_g \to \frac{z_c}{(\varepsilon)}$$

$$D_{h_1/d}(z_1) \to \frac{1}{1-\varepsilon} D_{h_1/d}\left(\frac{z_1}{1-\varepsilon}\right)$$

Quenched parent parton

$$+ \frac{p_{T_1}}{z_1} \int_0^1 \frac{dz_g}{z_g} D_{h_1/d}(z_g) \frac{dN^g}{d\omega}$$

Feedback gluons

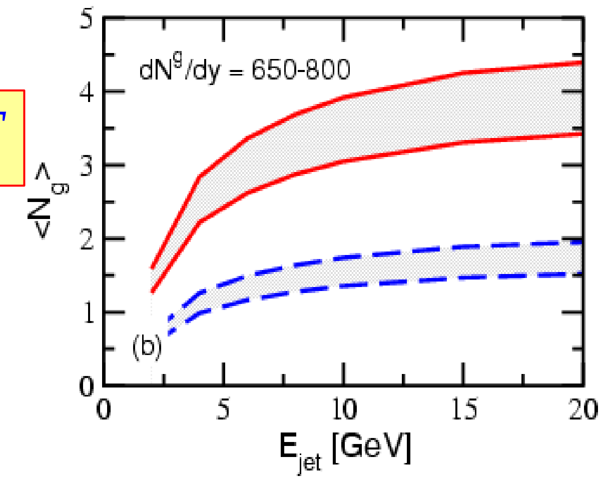
- Use energy conservation to verify the fragmentation sum rule

Probabilistic Interpretation

- **We calculated the single inclusive spectrum**

Several extra gluons. The plasmon frequency forces the radiation in fewer higher-frequency gluons

$$\omega_{pl} \sim \mu \sim gT$$



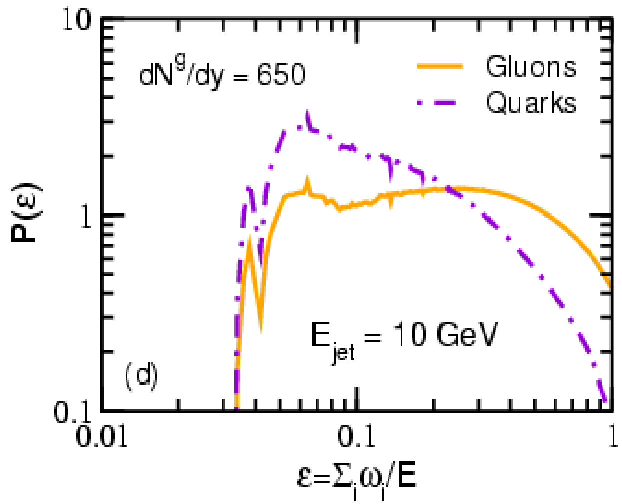
$$P(\varepsilon,E) = \sum_{n=0}^{\infty} P_n(\varepsilon,E) \qquad \frac{\Delta E}{E} = \int_0^{\infty} d\varepsilon\, \varepsilon P(\varepsilon,E)$$

$$P_{n+1}(\varepsilon,E) = \frac{1}{n+1}\int_{x_0}^{1-x_0} dx_n\, \rho(x_n,E) P_n(\varepsilon - x_n, E)$$

$$P_1(\varepsilon,E) = e^{-\langle N_g \rangle}\rho(\varepsilon,E)$$

The probability can be constructed iteratively from the calculated gluon spectra

$$\int_0^1 P(\varepsilon) d\varepsilon = 1, \qquad \int_0^1 P(\varepsilon)\varepsilon\, d\varepsilon = \frac{\Delta E}{E}$$

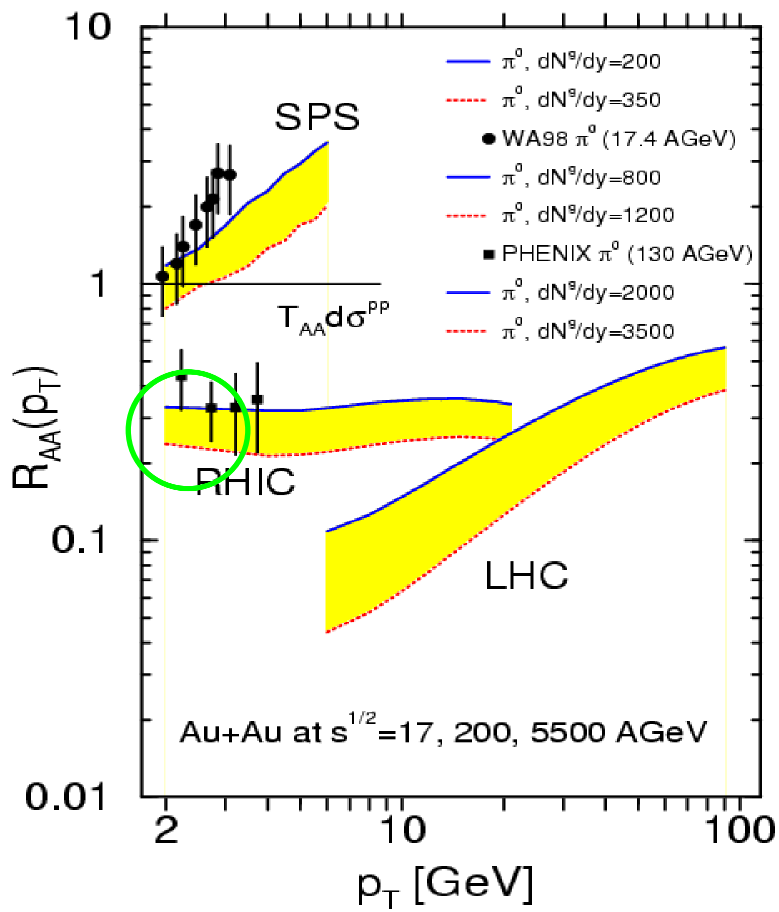


The normalization of $\int_0^1 P(\varepsilon) d\varepsilon = 1$ **in the interval** $\varepsilon \in [0,1]$ **ensures** $\Delta E < E$

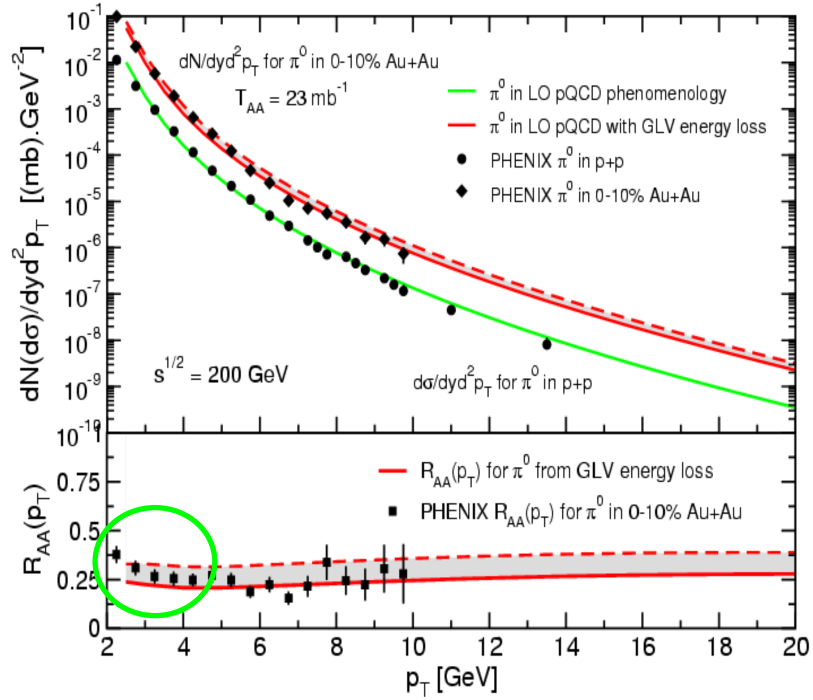
- **So far exclusive gluon distributions have not been calculated.**

M.Gyulassy,P.Levai,I.V., Phys.Lett.B 538 (2002)

Single Inclusive Quenching



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



$$\rho = \frac{1}{\pi R^2}\frac{1}{\tau_0}\frac{dN^g}{dy}$$

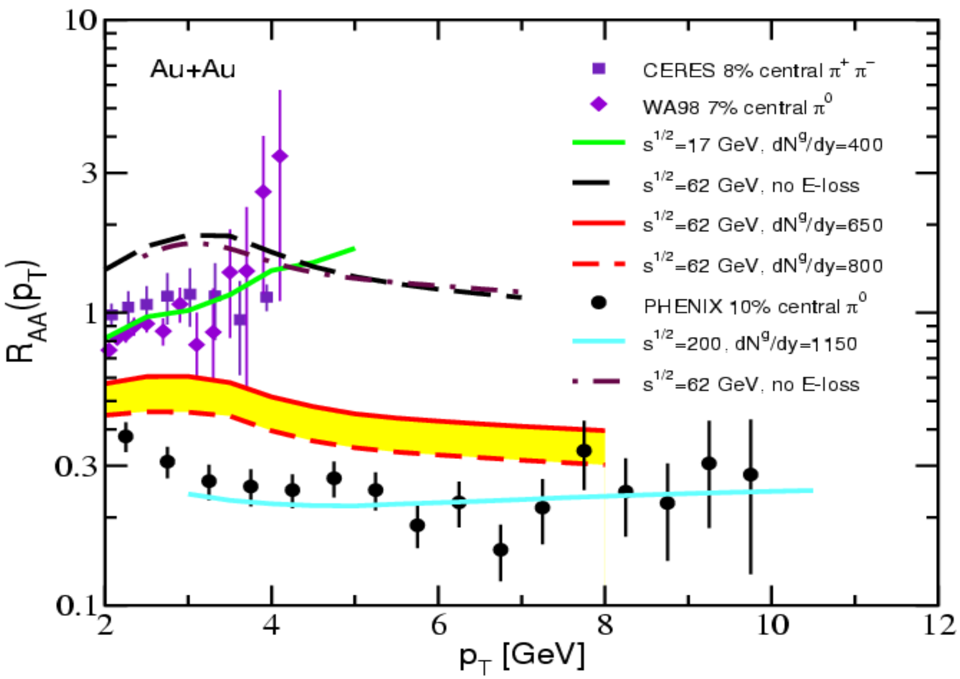
$$\pi R^2 = 120 \ \ fm^2, \ \ \tau_0 = 0.5 \ \ fm$$

- Room for improvement at small and moderate p_T

20 times the critical energy density for deconfinement

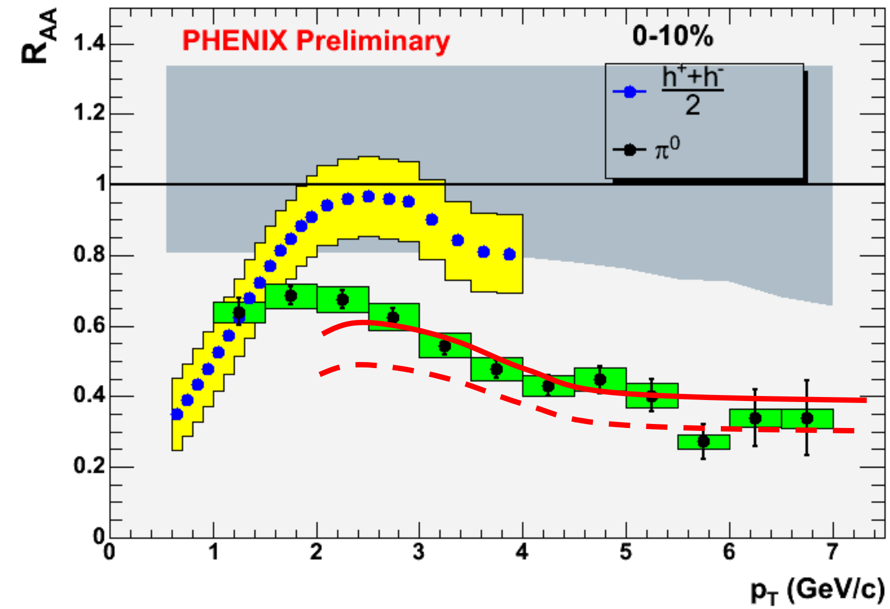
Energy Dependence - 62 GeV

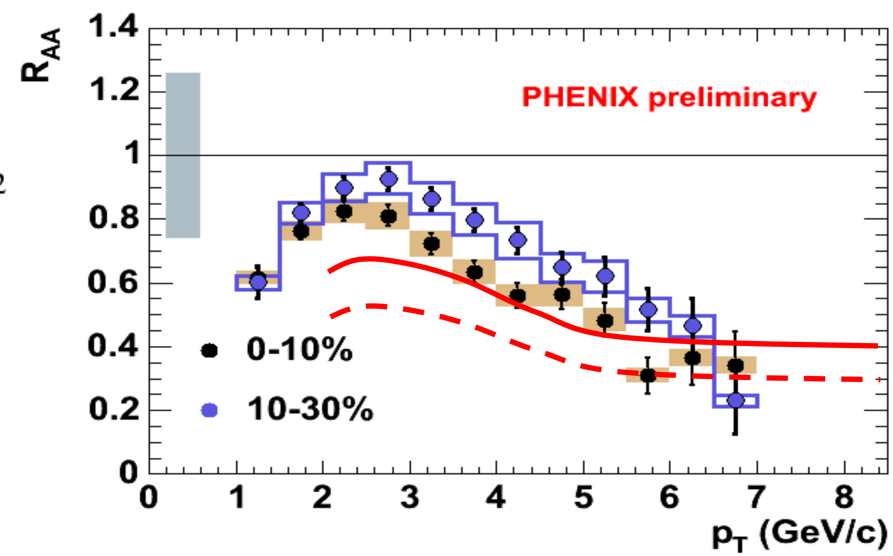
Change only the gluon rapidity density



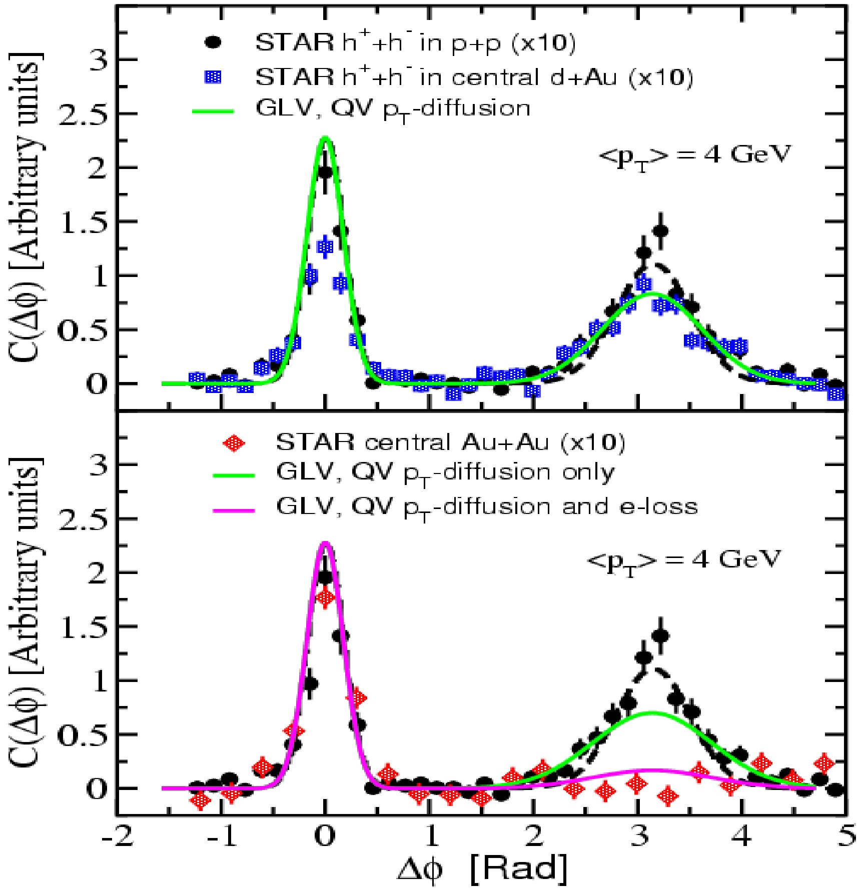
I.V., Phys.Lett.B nucl-th/0404052

- **Qualitative** and somewhat quantitative agreement





Modification of the Jet-like Correlations



$$R_{AA}^{\;h_1h_2}(p_T) = \frac{d^2\sigma^{AA} / dp_{T1}dp_{T2}d\eta_1 d\eta_2}{\langle N_{bin}\rangle d^2\sigma^{NN} / dp_{T1}dp_{T2}d\eta_1 d\eta_2}$$

$$C_2(\Delta\phi) = \frac{1}{N_{trig}} \frac{dN^{h_1h_2}{}_{dijet}(|y_1 - y_2|)}{d\Delta\phi}$$

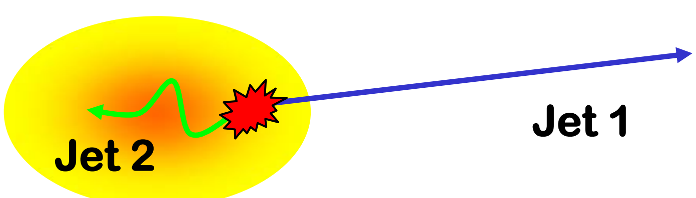
$$\approx \frac{A_{Near}(|y_1 - y_2|)}{\sqrt{2\pi}\sigma_{Near}} e^{-\Delta\phi^2/2\sigma^2_{Near}} + \frac{A_{Far}}{\sqrt{2\pi}\sigma_{Far}} e^{-(\Delta\phi-\pi)^2/2\sigma^2_{Far}}$$

In triggering on the near side all effects are taken by the away side correlation function

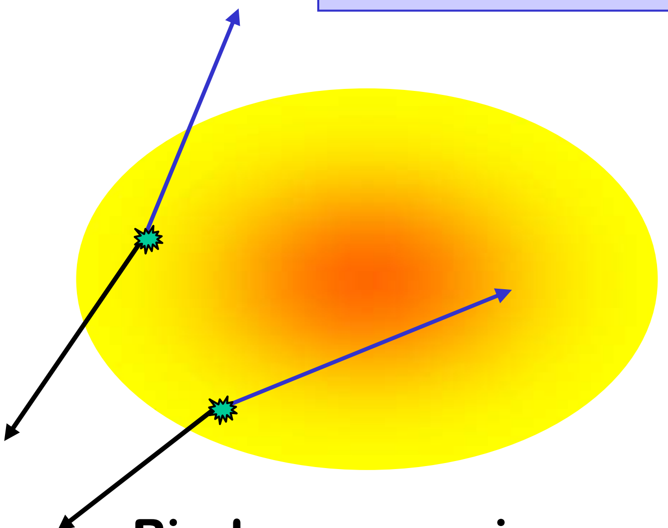
$$R^{h_1h_2} / R^{h_1} \sim 1.5$$

- **The attenuation of the double inclusive hadron production is between the two naïve limits** $R^{h_1h_2} / R^{h_1} \sim 1$, $R^{h_1h_2} / R^{h_1} \sim 2$

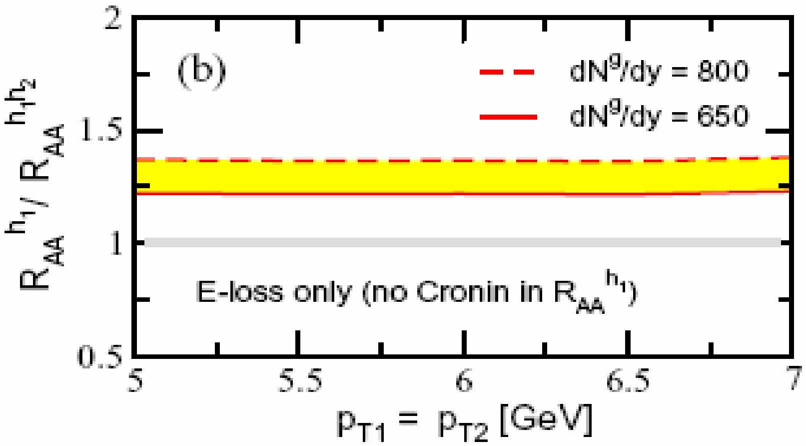
- **Attenuation (disappearance) of the away-side correlation function**
- **Dependence relative to the reaction plane**

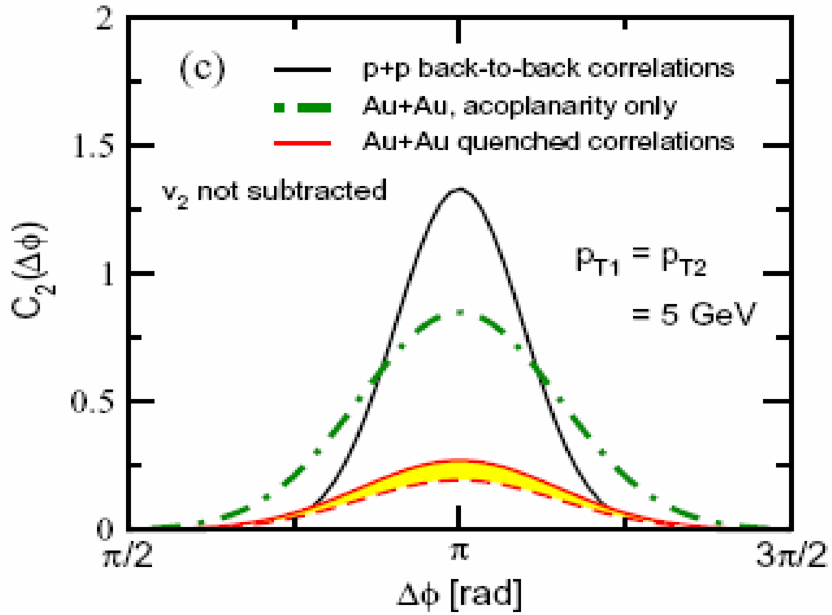


Numerical Results for 62 GeV Correlations



Bjorken expansion



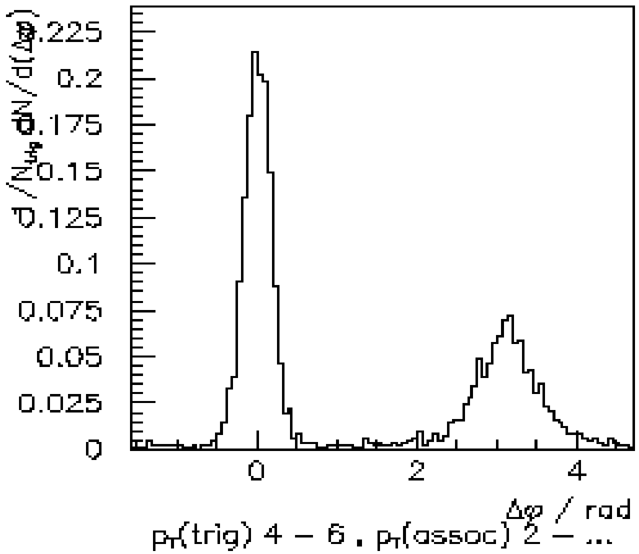


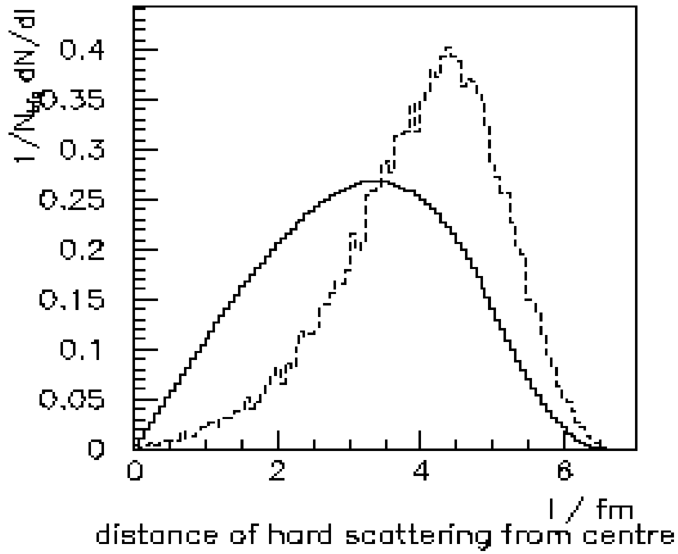
- Even passage through the center is not effective any more

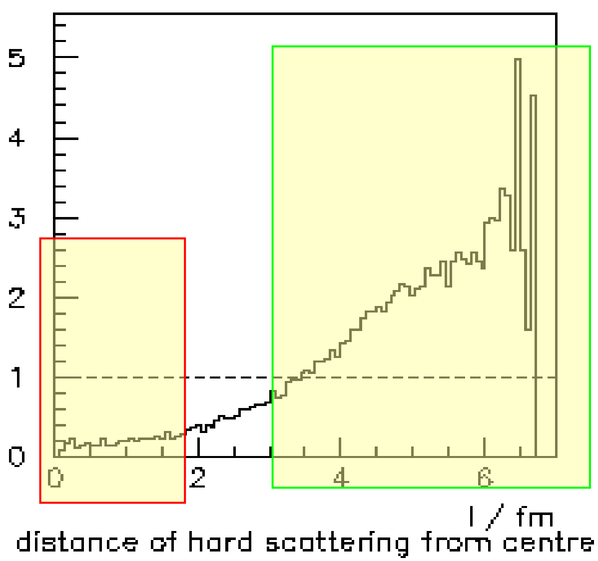
- Only 25 - 50 % more suppression for dihadrons

I.V., Phys.Lett.B nucl-th/0404052

Dijets from K. Zapp



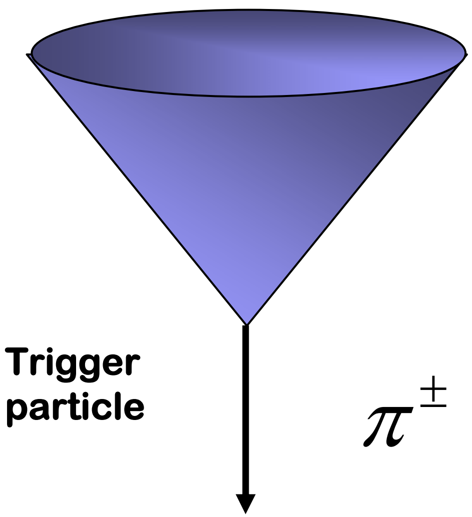




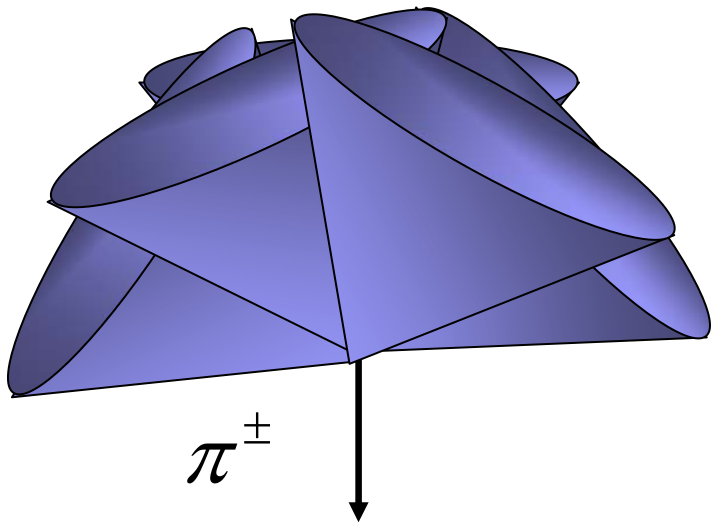
Thanks to K. Zapp

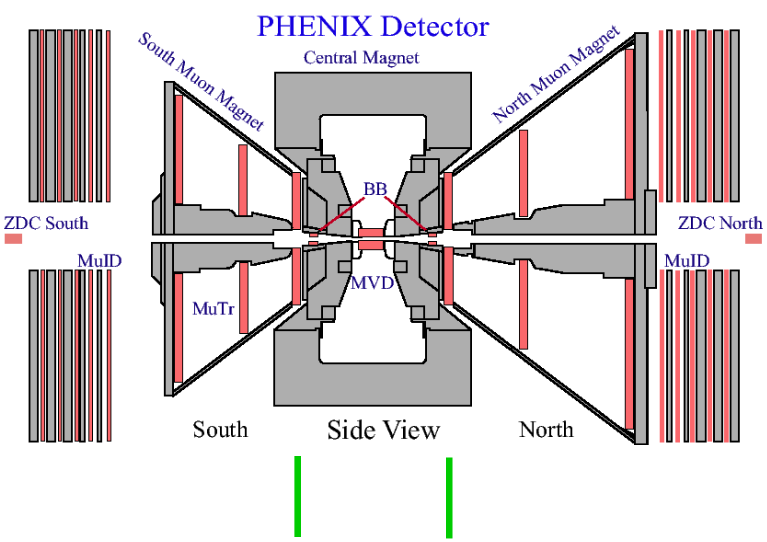
- Certainly not surface
- Certainly gradual dependence on r

More Realistic Simulations



Some mechanism of jet cone production



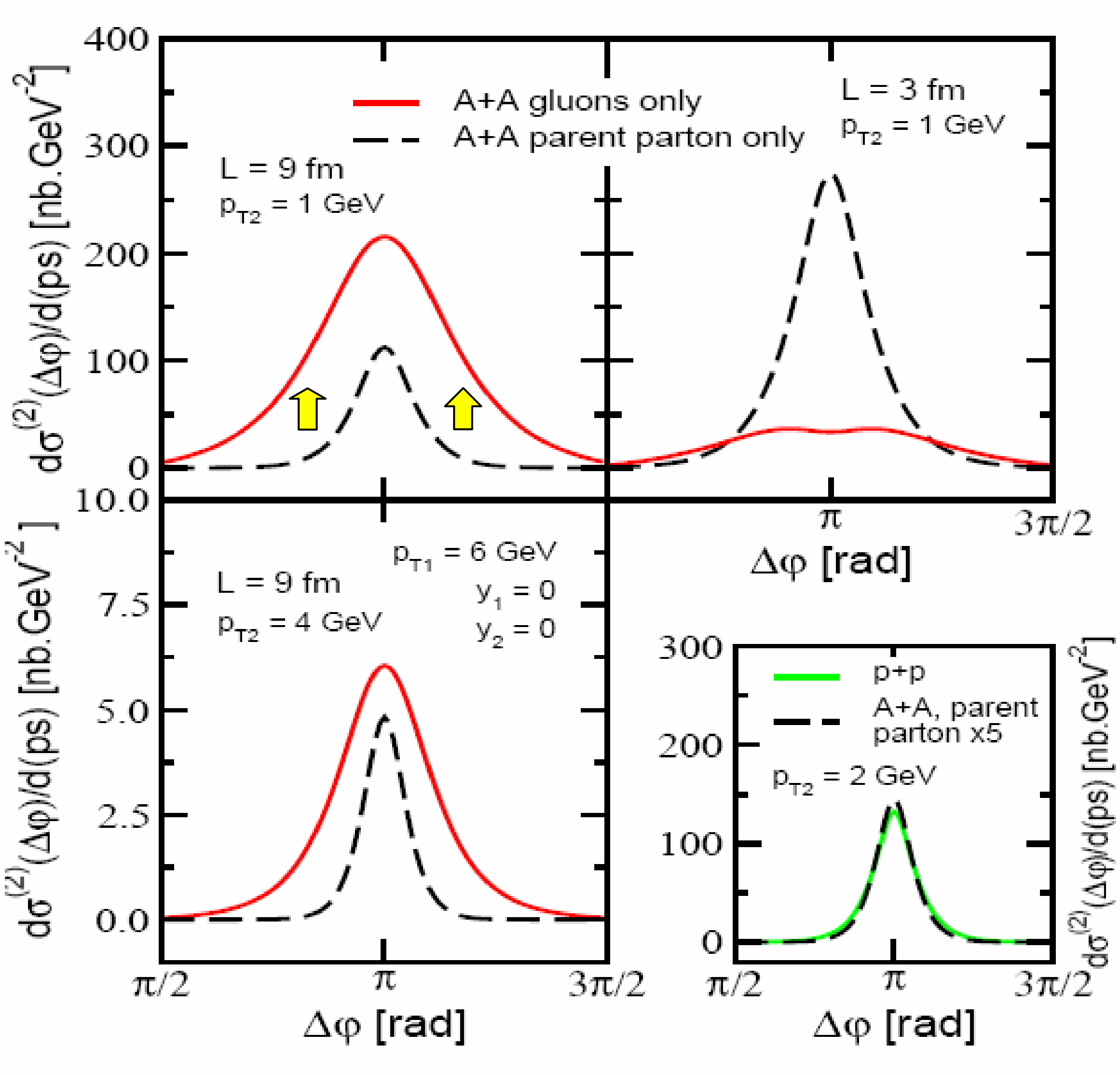


$\Delta\eta = \pm 0.35$

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**

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**

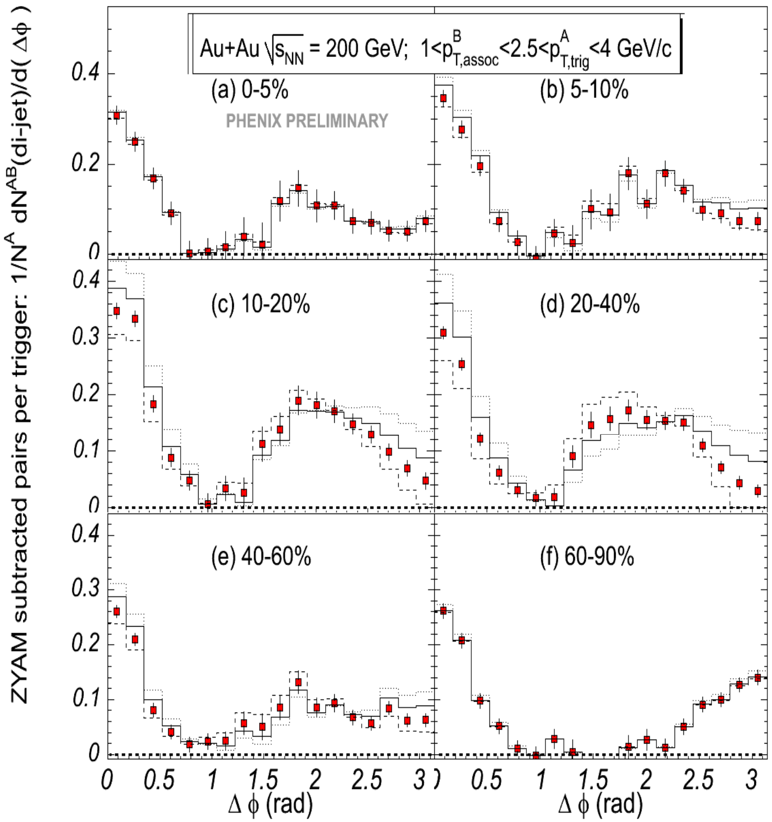
The quenched parton is not wider

Because:

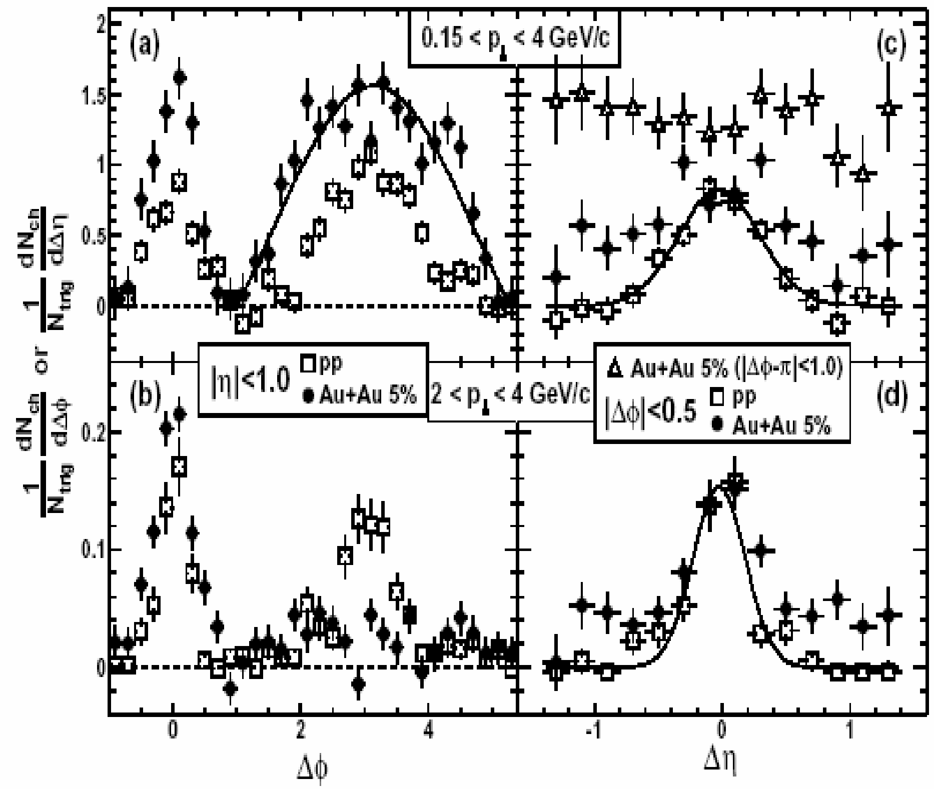
$$\sigma_{Far} \approx \frac{\sqrt{\langle k_T^2 \rangle_{vac}}}{p_{Tc}} \rightarrow \frac{\sqrt{\langle k_T^2 \rangle_{tot}}}{[p_{Tc}/(1-\varepsilon)]}$$

Results in Au+Au

PHENIX data



STAR data



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

Analytic Model

- **Hadron production cross section**

$$\frac{d\sigma^h}{dyd^2p_T} = \sum_c \int_{z_{\min}}^1 dz \, \frac{d\sigma^c(p_c = p_T/z)}{dyd^2p_{T_c}} \frac{1}{z^2} D_{h/c}(z)$$
$$\approx \sum_c \frac{d\sigma^c(p_T/\langle z\rangle)}{dyd^2p_{T_c}} \frac{1}{\langle z\rangle^2} D_{h/c}(\langle z\rangle)$$
$$\approx \sum_c \frac{A}{p_{T_c}^n} \langle z\rangle^{(n-2)} D_{h/c}(z)$$

- **Energy loss**

$$dN^g/dy \propto dN^h/dy \propto A \propto N_{part} \, ,$$
$$L \propto A^{1/3} \propto N_{part}^{1/3} \, ,$$
$$A_\perp \propto A^{2/3} \propto N_{part}^{2/3} \, .$$

Combine them to find:

Nuclear modification

$$R_{AB} = \frac{1}{N_{AB\ col}} \frac{d\sigma^h_{AB}/dyd^2p_T}{d\sigma^h/dyd^2p_T}$$
$$= (1-\epsilon)^{n-2} = \left(1 - \frac{k}{n-2} N_{part}^{2/3}\right)^{n-2}$$

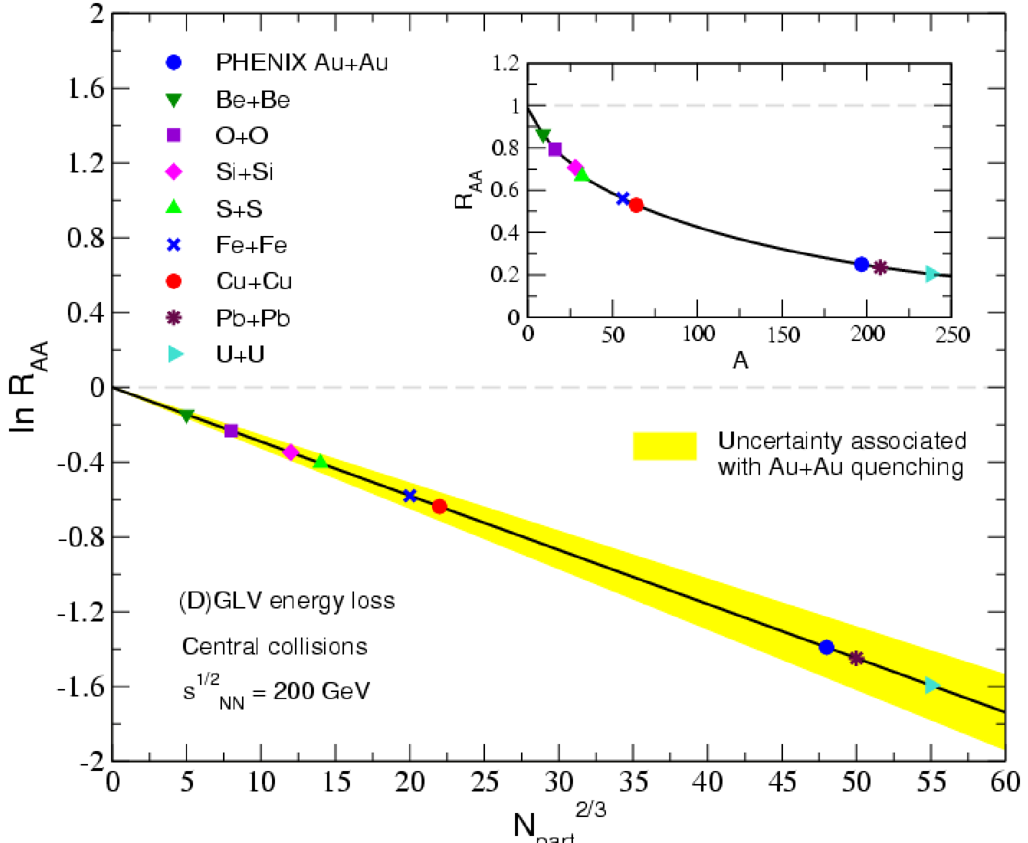
Natural variables

$$\ln R_{AA} = -k N_{part}^{2/3}$$

Results from the Analytic Model

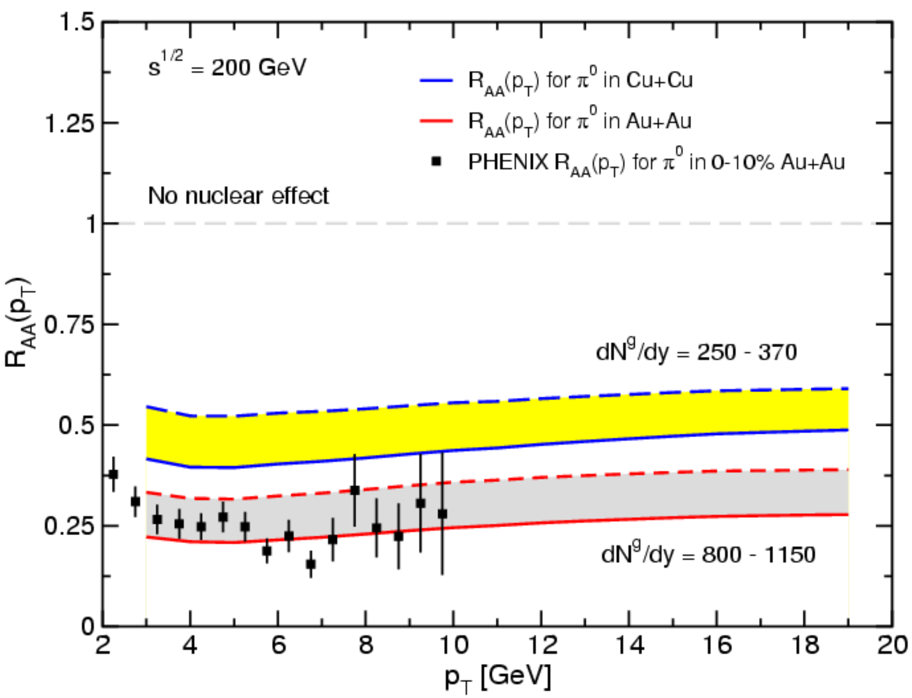
$Species$	^{9}Be	^{16}O	^{28}Si	^{32}S	^{56}Fe	^{64}Cu	^{197}Au	^{208}Pb	^{238}U
$b\,[fm]$	1	1	1.5	1.5	2	2	3	3	3
$N_{part}^{2/3}$	5	8	12	14	20	22	48	50	55

- **Peripheral reactions are normalized to R_{AA} = 1**
- **Good for qualitative and even quantitative description of the quenching**
- **For central Cu+Cu R_{AA} = 0.5**
- **Will do a better job if fixed to the central bin**

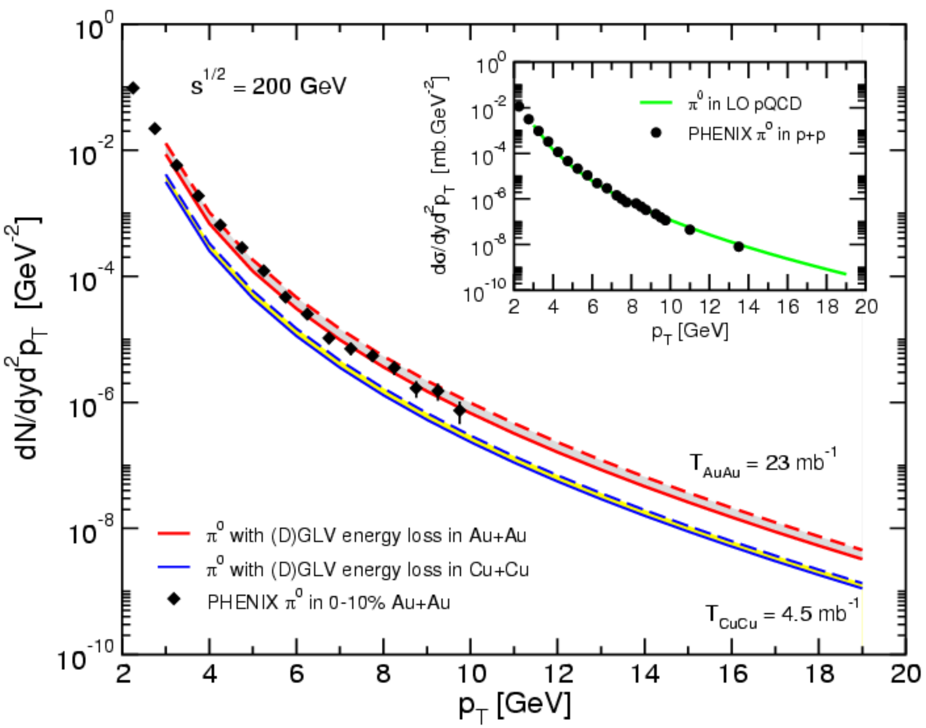


Medium-Induced Bremsstrahlung

- **Absolte scale comparison for Au+Au and Cu+Cu**
- **R_{AA} = 0.4-0.5**
- **Within 20 % of an analytic guess**



- **Absolte scale comparison for Au+Au and Cu+Cu**



Energy Redistribution

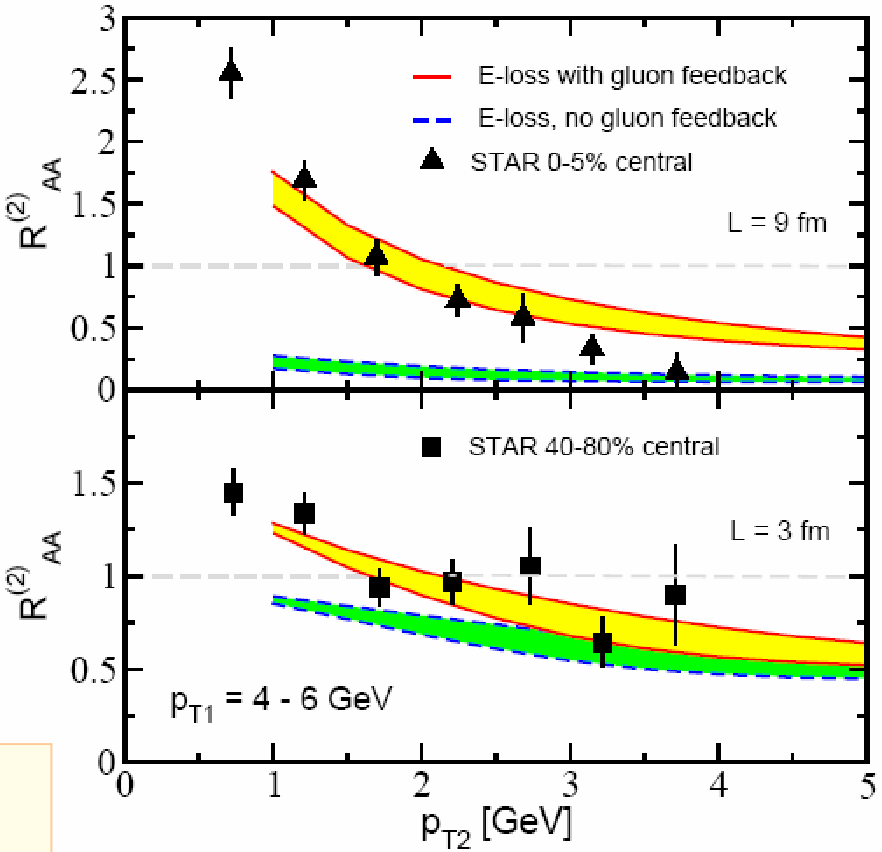
The slide I forgot to put but is critical to see how E is redistributed

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

$$R_{AA}^{(2)} = \frac{d\sigma_{AA}^{h_1h_2} / dy_1dy_2dp_{T1}dp_{T2}}{\langle N_{bin} \rangle d\sigma_{pp}^{h_1h_2} / dy_1dy_2dp_{T1}dp_{T2}}$$

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

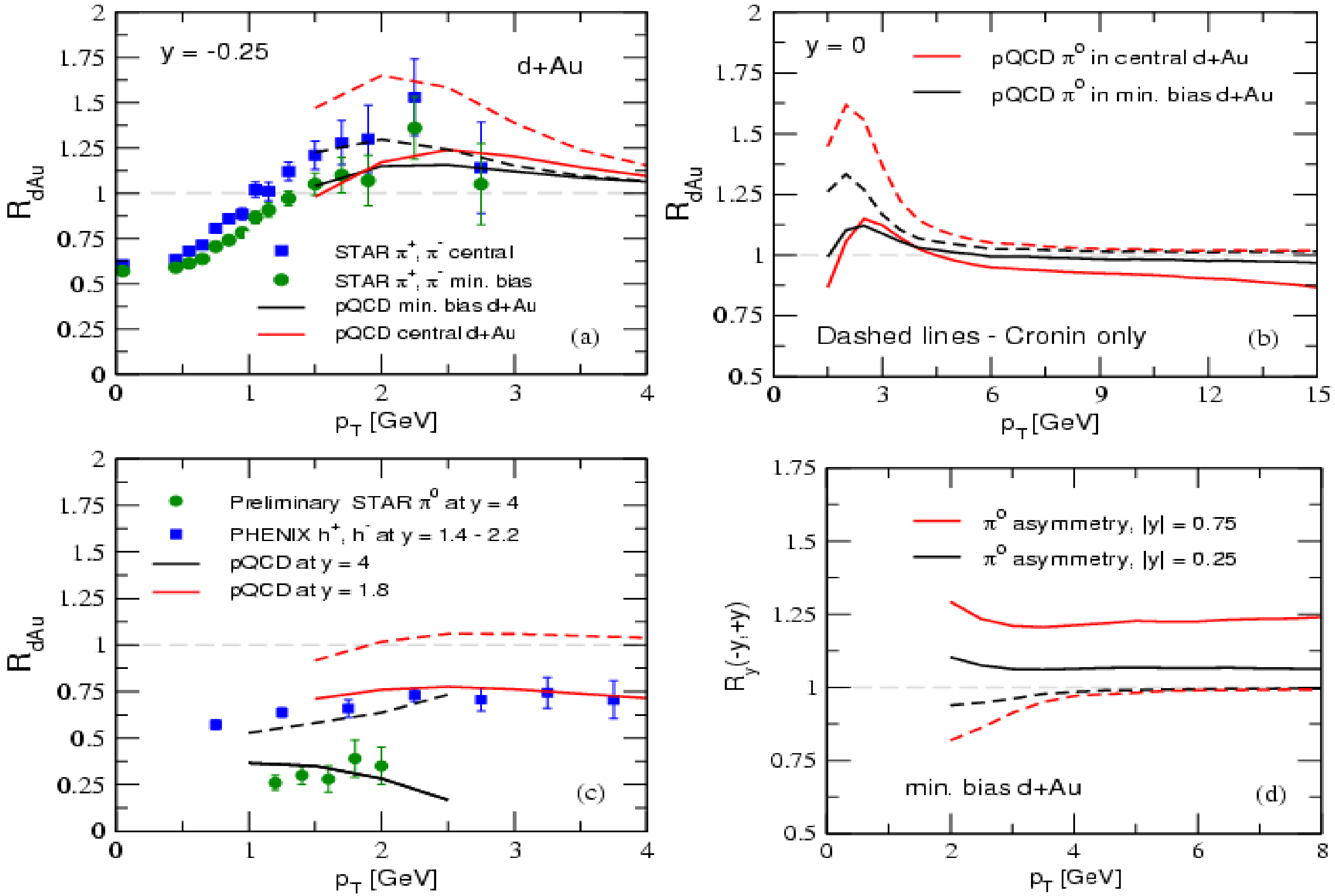
- **The redistribution of the energy is a parameter free prediction**
- **For large energy loss - the radiative gluons dominate to unexpectedly high** $p_{T2} \sim 10\ GeV$

Data is from:

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

Medium-Induced Bremsstrahlung

Now replaced by the 4 figures I sent and pQCD II added



Conclusions

- **Energy loss formulation** to all orders on the mean number of scatterings. Studied the convergence of the series. Found that numerical calculations of energy loss provide large corrections to the analytic formulas. and verified, it can be used to extract information about the density in the early stages of HIC (jet tomography)
- Jet quenching simulations have successfully predicted the difference in the nuclear modification at SPS and RHIC (LHC t be tested). The extracted e = 15 GeV/fm^3 is well into the deconfinement phase transition
- Showed the first study of large angle gluon emission and large angle hadron production. Implications about the dead cone effect.
- 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 (to be improved). Predictions versus p_T trigger
- Significant broadening of the away side correlations confirmed by PHENIX. Extra theoretical work needed - none of the other models has included any away side distribution of jets. This calculation - approximate way.
- In a realistic calculation $I_{AA} \sim R_{AA.}$ Has been predicted at least at 2 energies.