Parton Equilibration, Energy Loss and Brute Force Quenching

1. Intro: a) Glue thermal or chem equilib is not assured at RHIC

   b) Need $p_\perp \gtrsim 3\,GeV$ data to probe QCD energy loss mech

2. Why Few $N_{scatt} = 1,2,3$ collision energy loss is important

   a) color coherence hides collinear glue

   b) Nuclear corona hides $N_{scatt} \gg 1$

   c) N=0 Self Quench is huge

   d) Hadronization reduces sensitivity

3. Brute Force pQCD $N_{scatt} = 1,2,3$

   P. Levai, I. Vitev, M.G. (work in progress)

M. Gyulassy
LBL Winter Workshop 1/8/99

Part 1:

Status of Parton (Non) Equilibration

1) ZPC B. Zhang
2) DMPC D. Molnar
3) Hydro Dumitru
4) HIJING quenching X. Wang, M.

Parton Cascade Event Generators and the Story of ET

Miklos GYULASSY, Yang PANG and Bin ZHANG

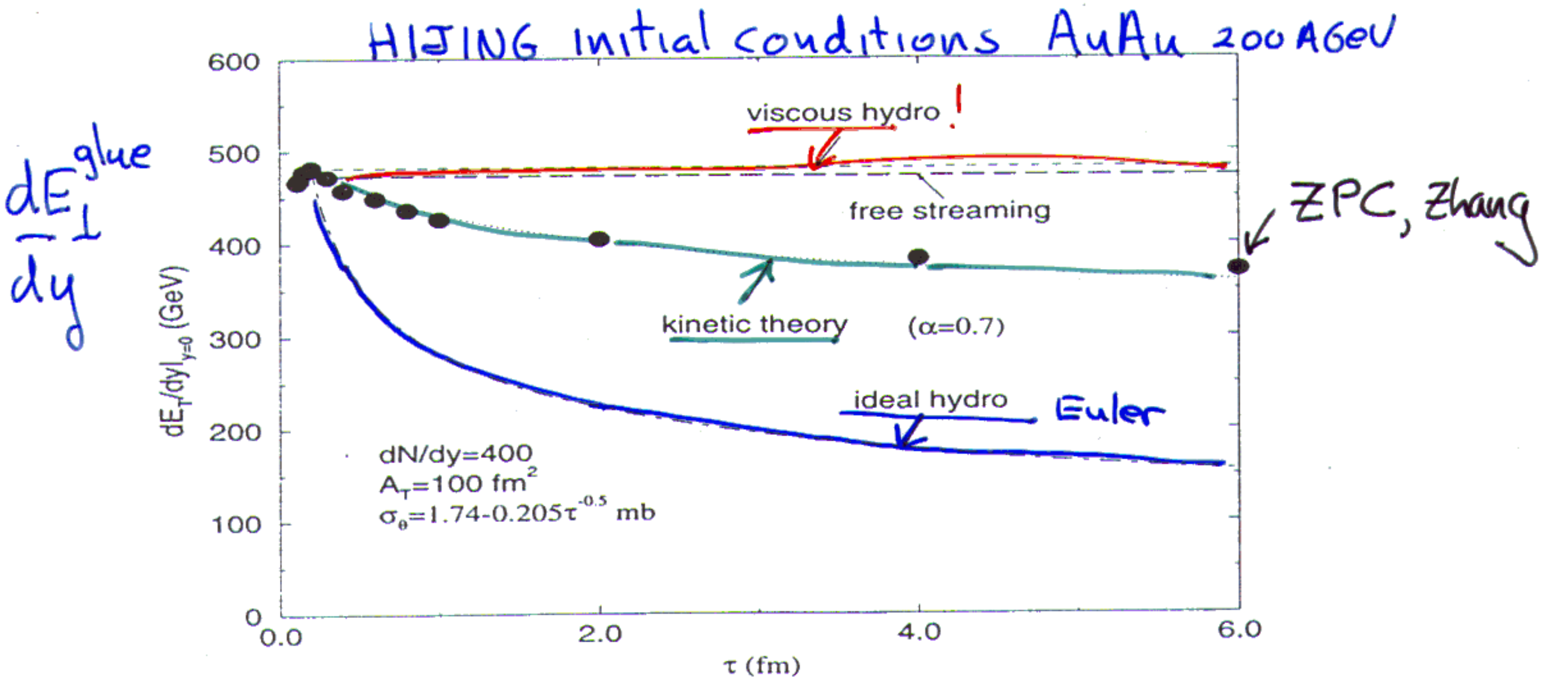


Fig. 2. Comparison of analytic kinetic theory results to numerical ZPC code[20] results obtained by averaging 20 events. A periodic transverse grid of dimensions 10 fm was used. Initially (at $\tau = 0.1$ fm), $T_0 = 500$ MeV, in an interval $-5 < \eta <, 5$, with $\frac{dN}{d\eta} = 400$. The screening mass was $\mu = 3\ \mathrm{fm}^{-1}$ and the initial mean free path was ≈ 0.3 fm. Note agreement of ZPC and analytic results in this case where Navier Stokes fails.

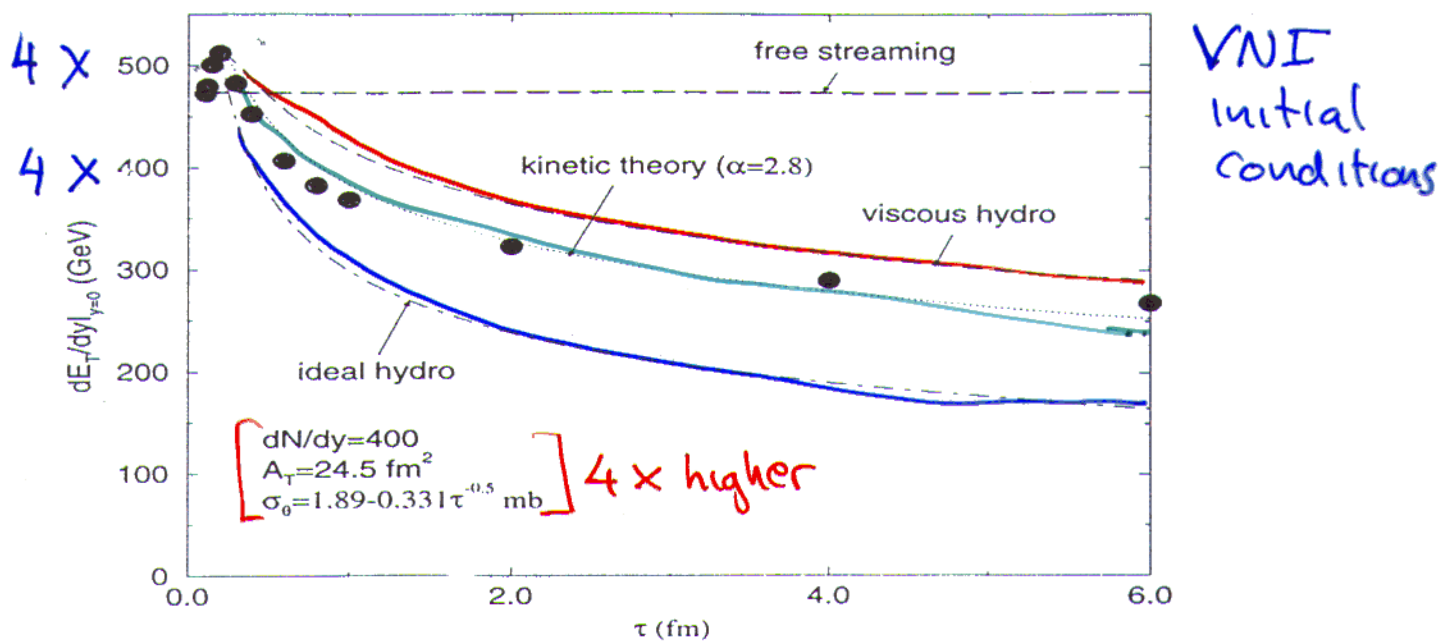
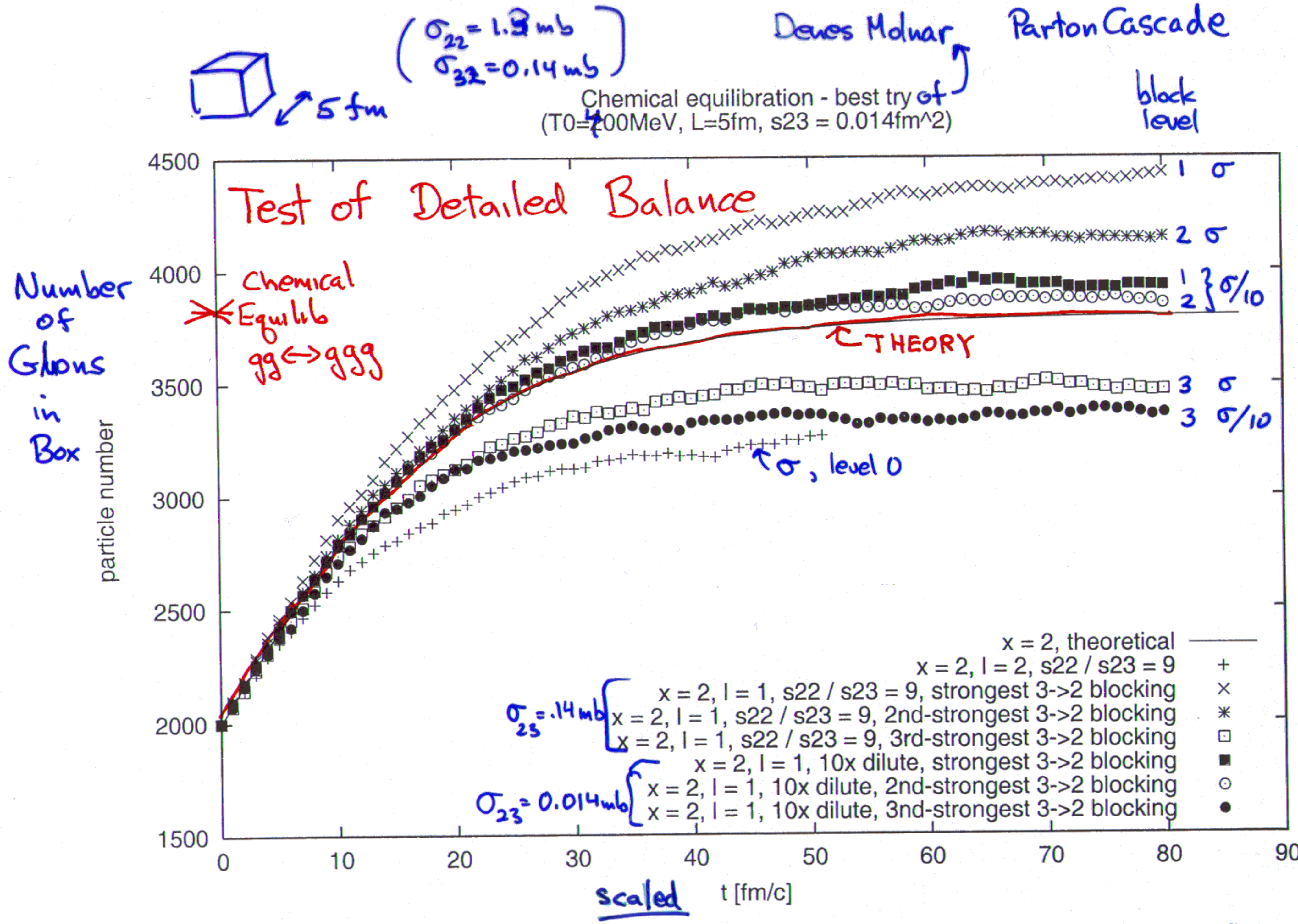


Fig. 3. Comparison of ZPC results with analytic kinetic theory and scaling Navier-Stokes for initial conditions with the parameter $\alpha = 2.8$. This demonstrates the ability of the ZPC cascade model to approach the Navier-Stokes dissipative hydrodynamic domain under extreme initial conditions corresponding to four times the default HIJING parton density.

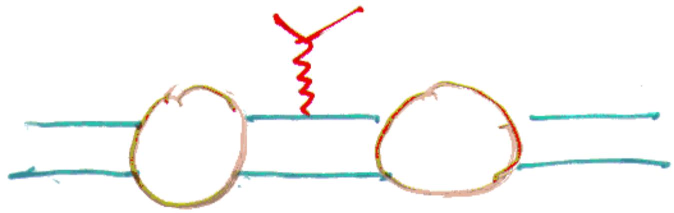


Chemical equilibration - best try of Denes Molnar Parton Cascade
(T0=400MeV, L=5fm, s23 = 0.014fm^2)
5 fm
σ22 = 1.3 mb
σ32 = 0.14 mb
Test of Detailed Balance
Chemical Equilib gg<->ggg
THEORY
σ, level 0
block level
1 σ
2 σ
1 } σ/10
2 } σ/10
3 σ
3 σ/10
Number of Gluons in Box
particle number
scaled t [fm/c]
x = 2, theoretical
x = 2, l = 2, s22 / s23 = 9
σ23 = .14 mb
x = 2, l = 1, s22 / s23 = 9, strongest 3->2 blocking
x = 2, l = 1, s22 / s23 = 9, 2nd-strongest 3->2 blocking
x = 2, l = 1, s22 / s23 = 9, 3rd-strongest 3->2 blocking
σ23 = 0.014 mb
x = 2, l = 1, 10x dilute, strongest 3->2 blocking
x = 2, l = 1, 10x dilute, 2nd-strongest 3->2 blocking
x = 2, l = 1, 10x dilute, 3nd-strongest 3->2 blocking

Blocking Assumptions

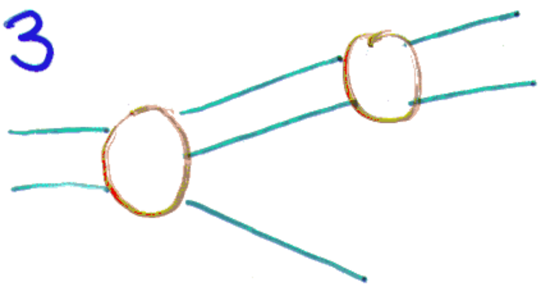
2 ↔ 2

no block level 0

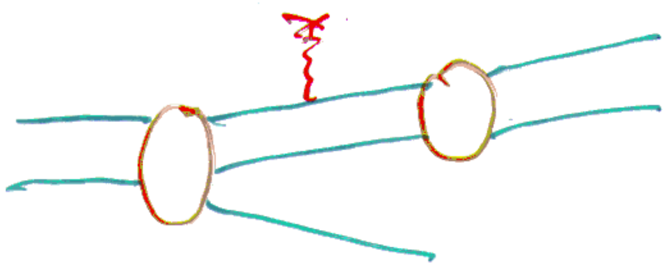


require at least on extra scatt
level 1

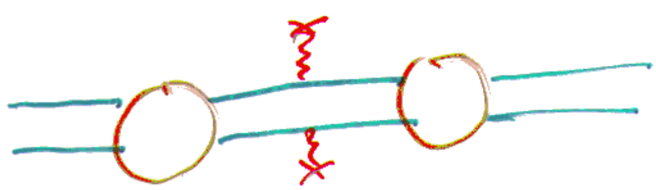
2 → 3



no block
allows 2 of 3 to rescatt again

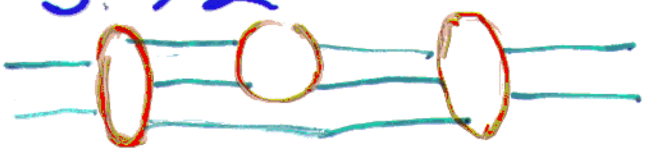


level 1 block



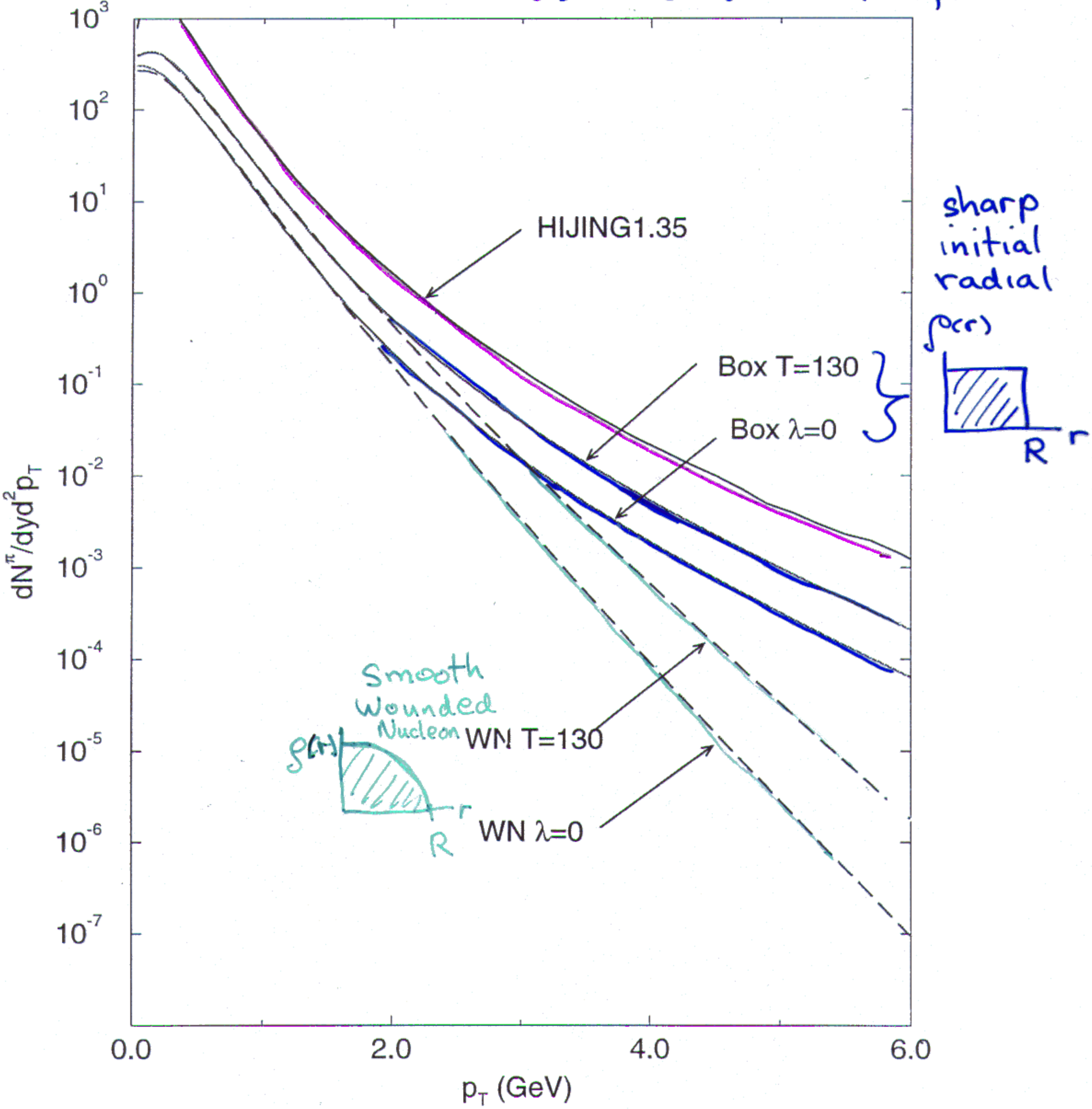
level 2 block

3 → 2



no block
levels 1 ....

Au+Au RHIC 2+1 Hydro Dumitru, Rischke
vs HIJING M.G., P. Levai



How to separate soft (phenomenology) and hard (pQCD calculable) probes?

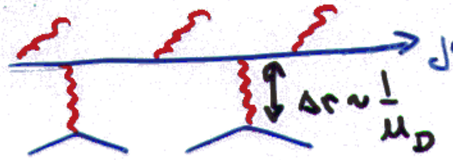
$\frac{dN}{dp_\perp}$ is hard probe at $p_\perp >$??

Proposed Answer

Compare pQCD to Hydro
(quantum non-eq) vs (local equilibrium)

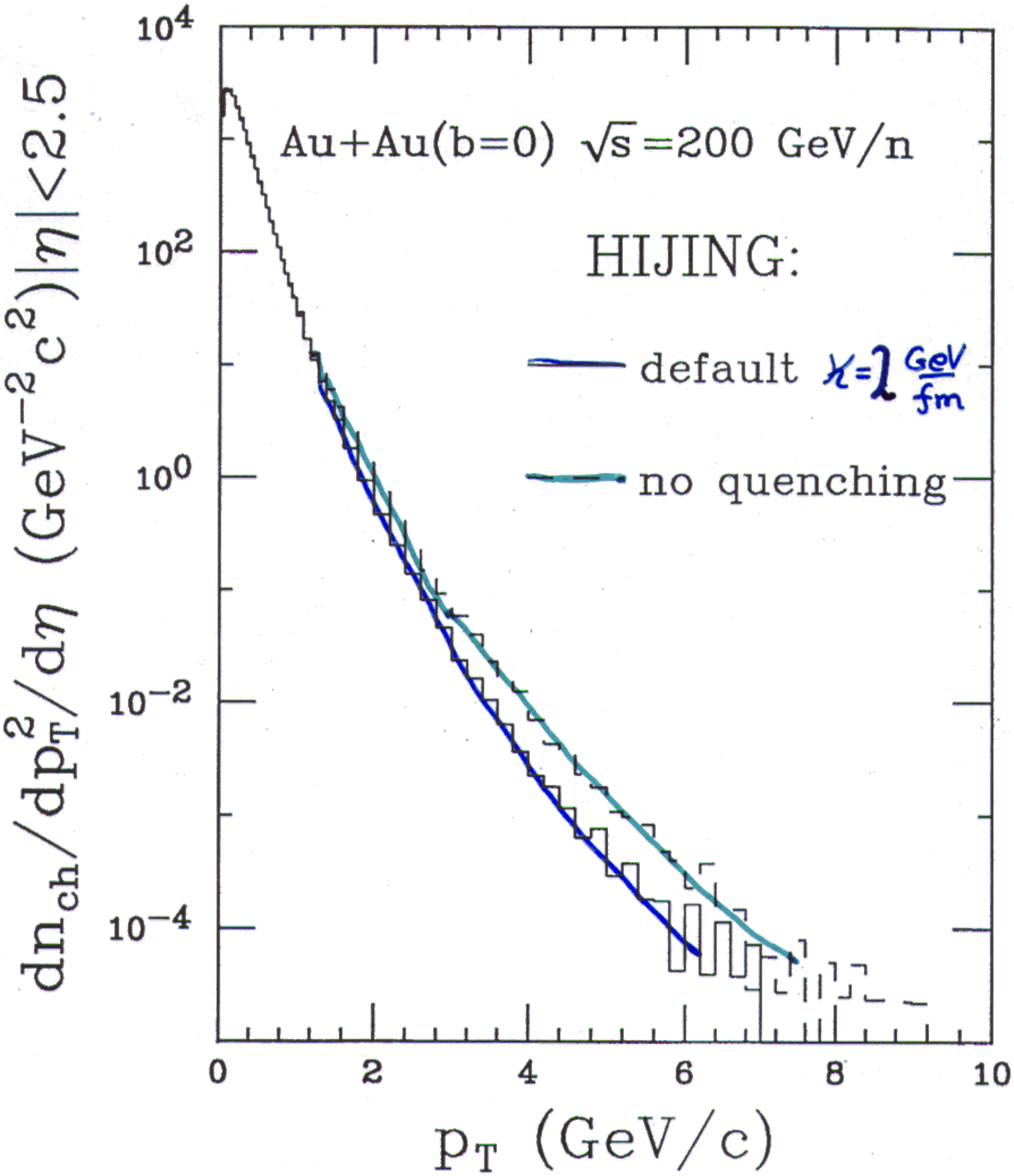
At SPS $p_\perp$ spectra have no break

At RHIC there is good news
pQCD >> Hydro
$p_\perp \gtrsim 3$ GeV



$$\frac{dE}{dx} \approx \alpha_s \mu_D^2 \log^2 s/4\mu_D^2 \quad \text{energy loss}$$
$$\sim 1-2 \text{ GeV/fm}$$

Effects of Energy Loss

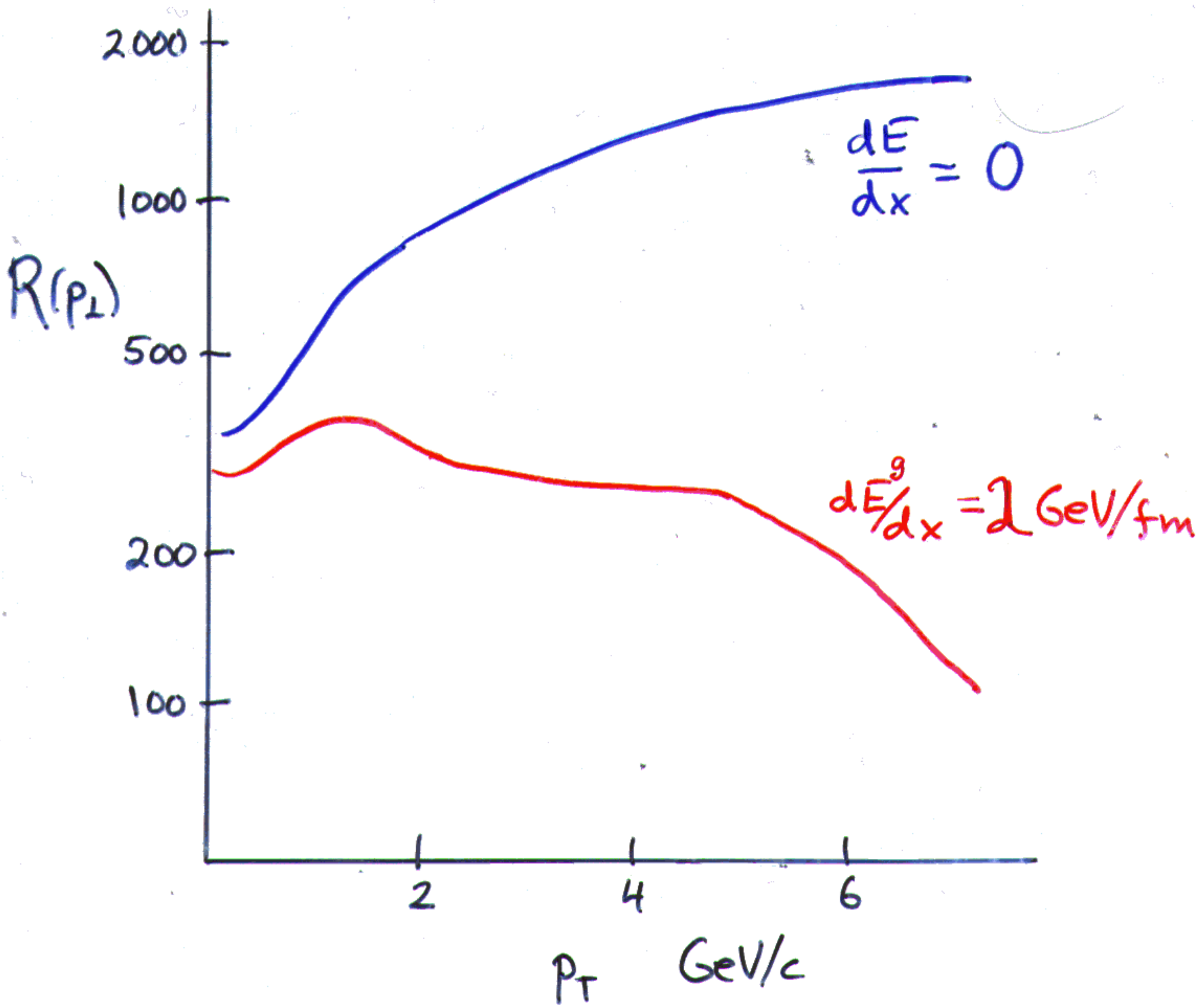


Jet quenching provides info on non abelian energy loss

* Wang, MG, PRD 44 (91) 3501

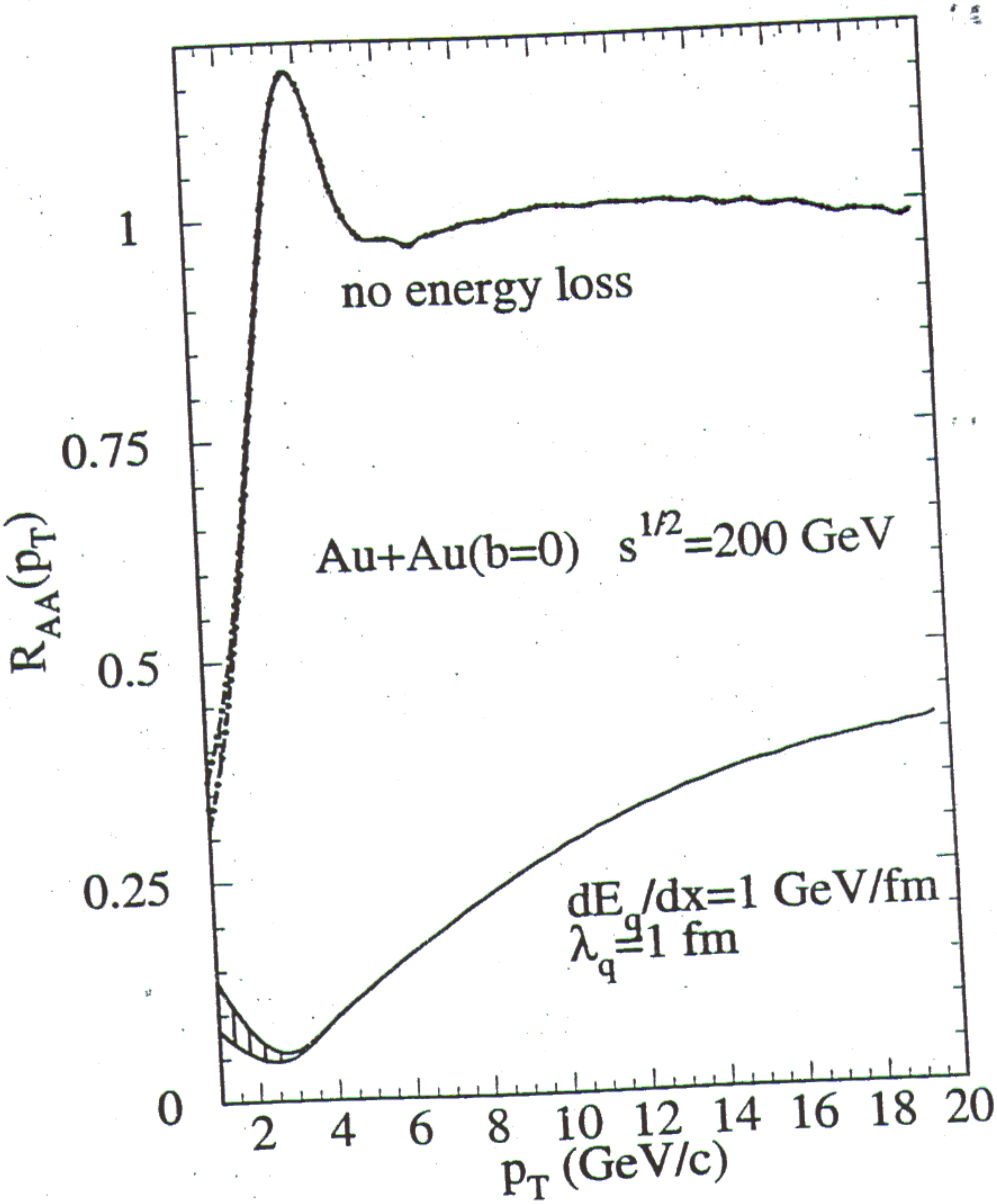
$$R = \frac{dN_{AA}/dp_\perp}{dN_{pp}/dp_\perp}$$

Au+Au (RHIC)

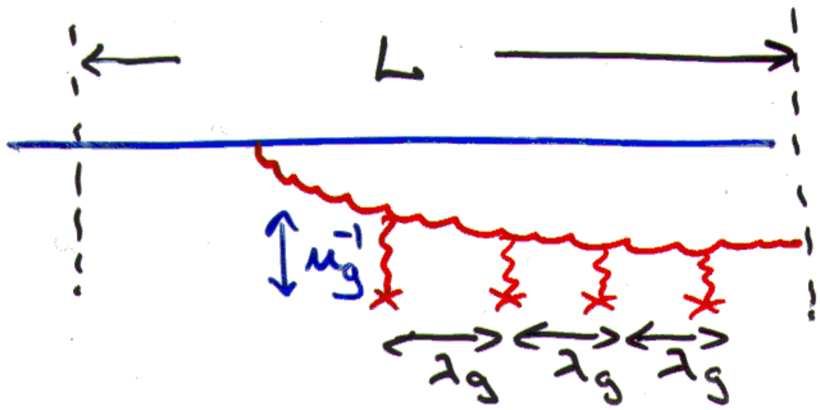


X.N. Wang 98

Cronin + Quench



Random Walk in $\vec{p}_\perp$ shortens formation time



$$\langle k_\perp^2 \rangle_L \approx \frac{L}{\lambda_g} \mu_g^2$$

$$\frac{dE}{dx} \lesssim \bar{\rho}\, L \left(\frac{\mu^2}{\lambda}\right)_g$$

Non linear $\Delta E(L)$!

Mueller, BDPS (96)

$$\bar{\rho} = \frac{2}{3}\frac{\alpha N_c}{8} \log\frac{L}{\lambda} \sim 1/3 \left(\frac{2}{3}\right)$$

In QGP $\mu = \mu_{Debye} \approx gT \approx 2T \sim 0.6\,\text{GeV}$

$$\lambda_g^{-1} = \sigma_g \rho_T \approx \frac{4\pi\alpha^2}{\mu^2}(2T^3)$$

$$\boxed{\left(\frac{\mu^2}{\lambda}\right)_{QGP} \approx 4\pi\alpha^2 \rho_T} \approx 3T^3 \sim 2\,\frac{\text{GeV}}{\text{fm}^2}$$

$T = 300$ MeV

In cold nuclei use $p + A \to J/\psi + X$

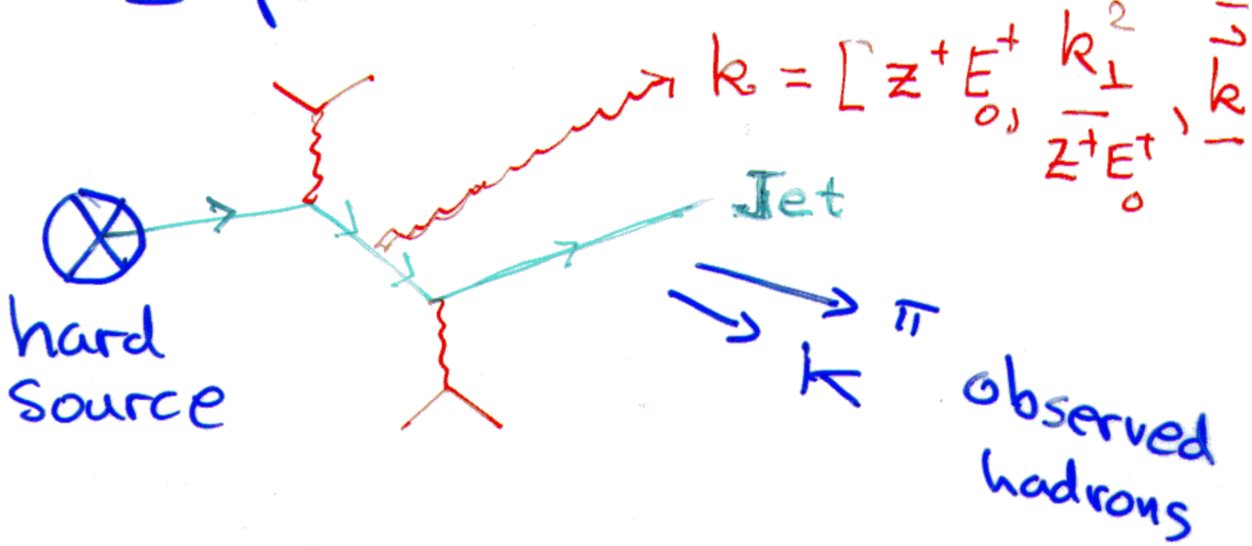
$$\langle p_\perp^2 \rangle_A = p_0^2 + \nu_A \lambda_N (\mu_g^2/\lambda_g)_{T=0} \qquad \nu_A \lambda_N \approx 1.8 A^{1/3}\,\text{fm}$$

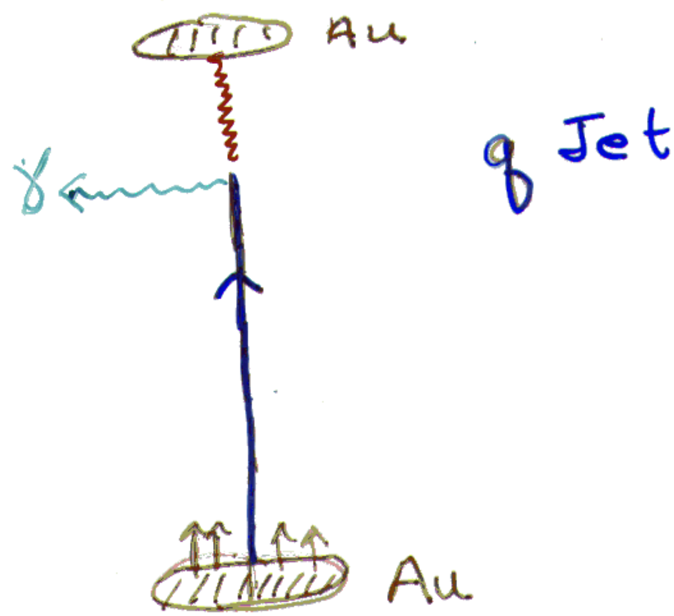
Badier et al $\langle p_\perp^2 \rangle_{Pt} - \langle p_\perp^2 \rangle_p \approx 0.36\,\text{GeV}^2$

$$\left(\frac{\mu_g^2}{\lambda_g}\right)_{T=0} \approx 0.05\,\text{GeV}^2/\text{fm} \approx \Lambda_{QCD}^3 \approx \frac{1}{10}\left(\frac{\mu_g^2}{\lambda_g}\right)_{QGP}$$

Part II :

Why Few Collision Processes are Important





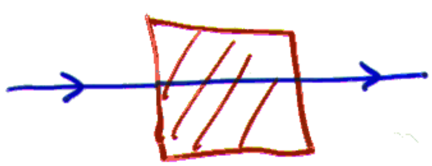
Au
γ
q Jet
Au

At RHIC $AA \to \pi + X$

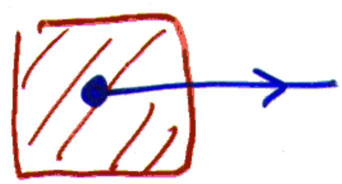
In order to test non-linear $\frac{dE}{dx}$(QCD) at observable hadronic distrib level we need

1) $N_{scatt} < \infty$, $N_c < \infty$, angular info $\frac{dN_g}{dy\, d^2k_\perp}$

2) Must consider $|\text{Hard} + \text{Soft}|^2$ destructive interference



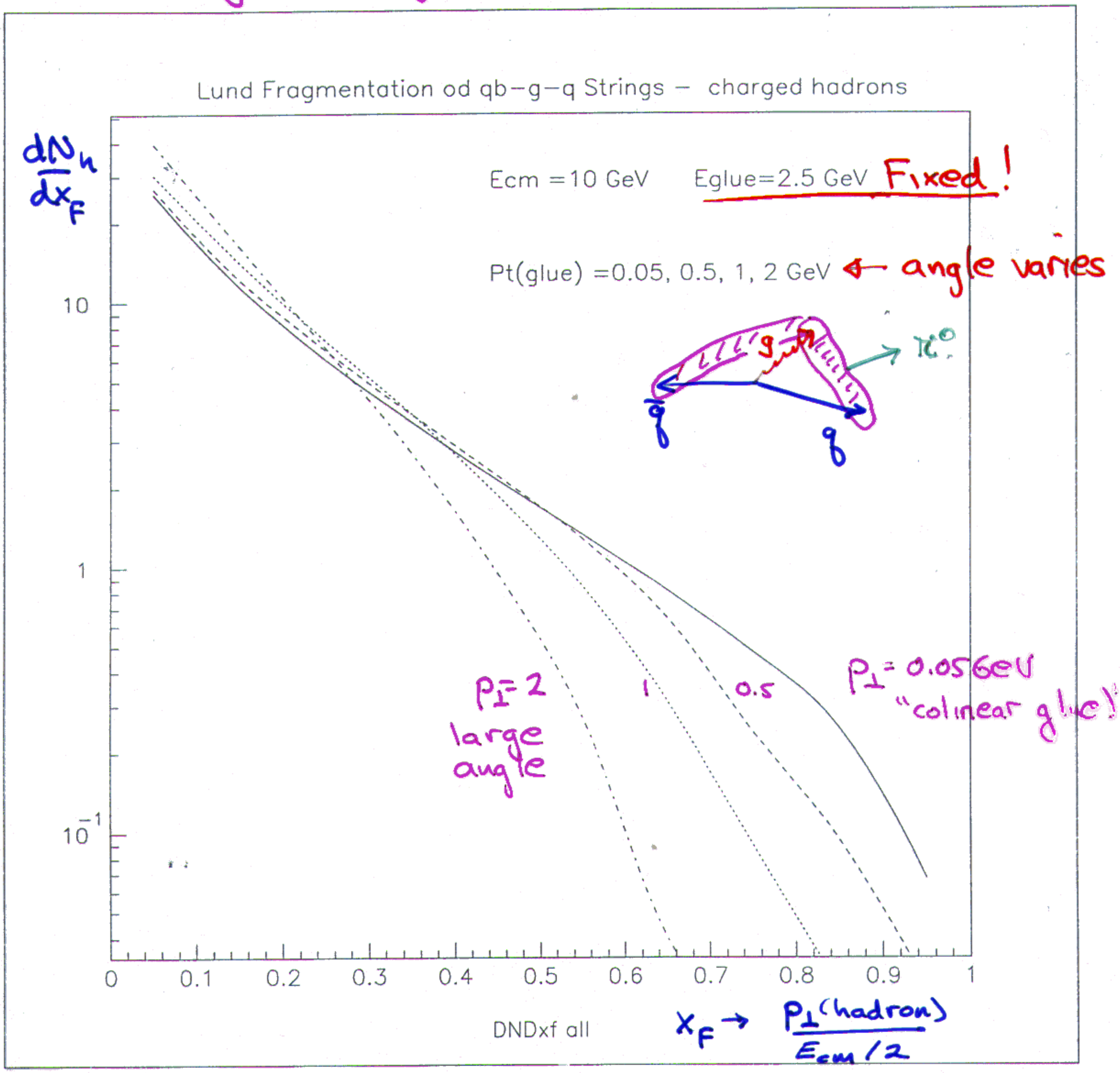
"Jackson Problem"



Our nuclear problem
Jets are born naked
and take time to dress

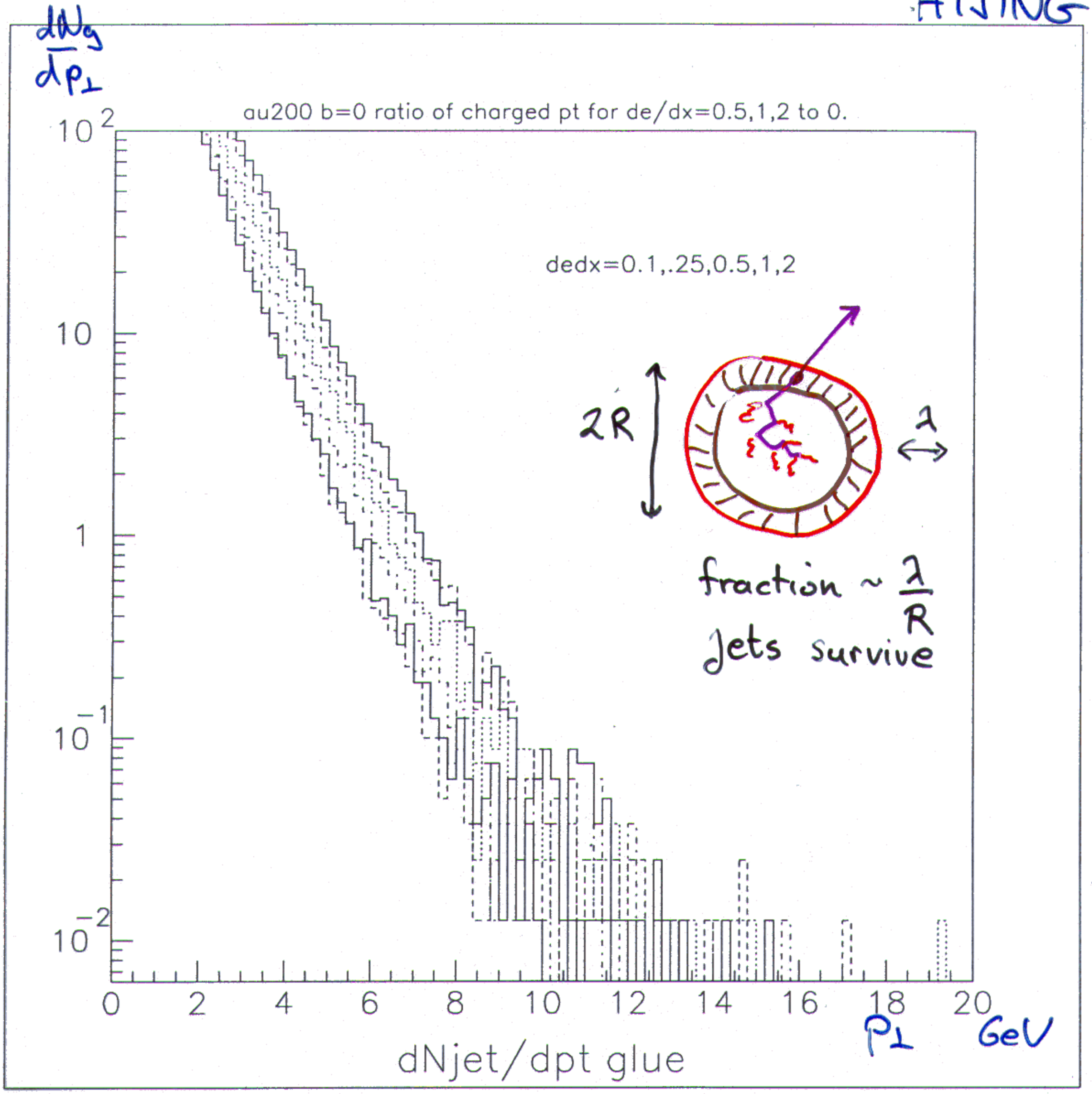
3) Need Hadronization Model

Dependence of hadron quenching on gluon angular distribution



Saturation of Jet Quench

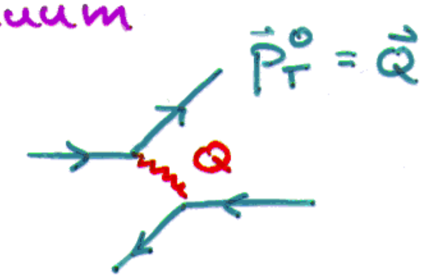
HIJING



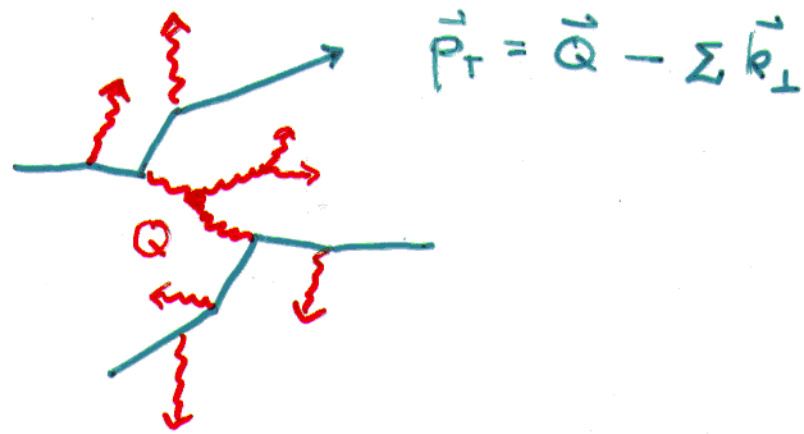
Result sensitive to finite N_{scat} = 1, 2, 3

"Self Quenching" of Hard Processes in Vacuum

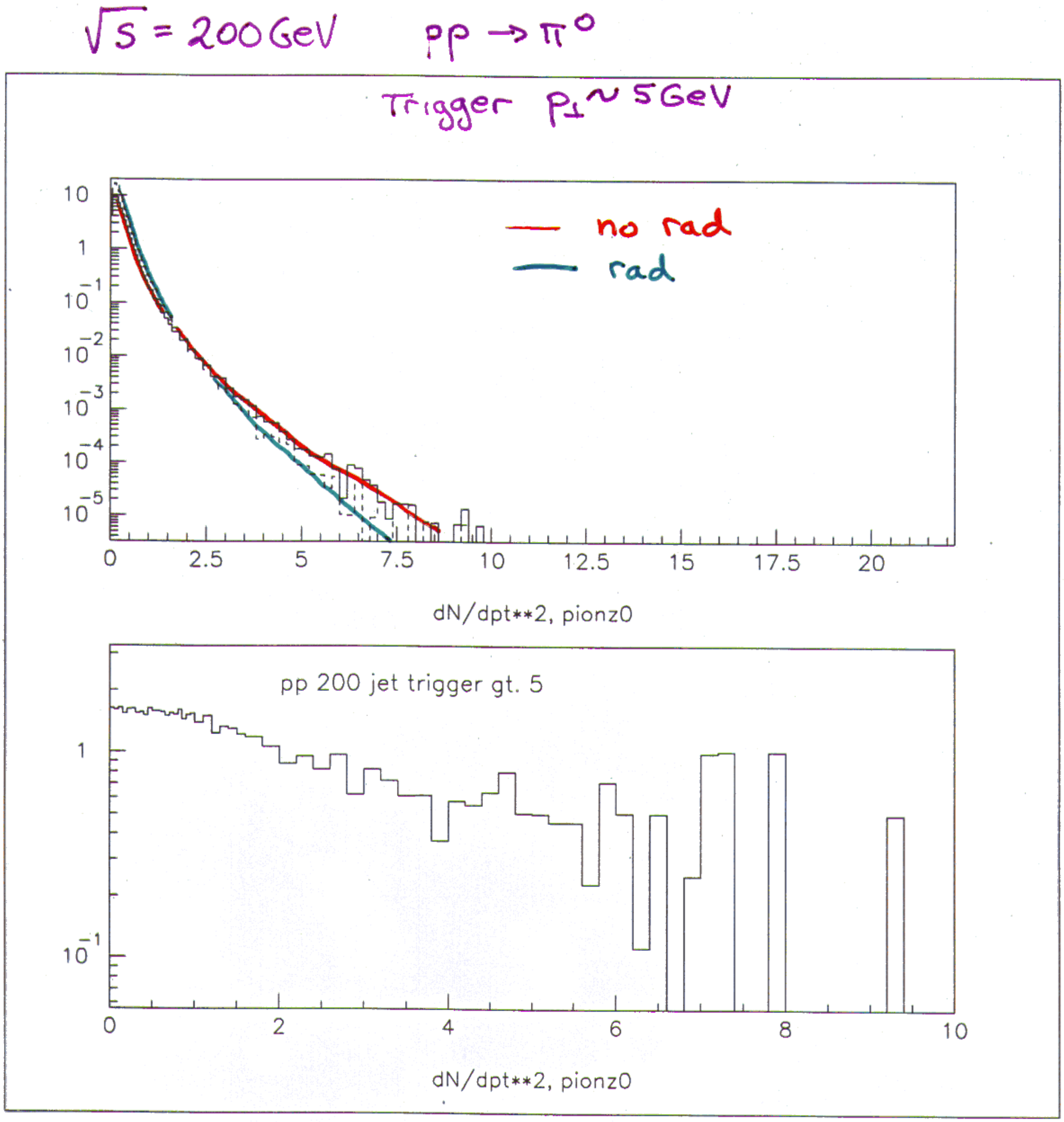
Bare Born



Radiative Hair



Fragmentation of $q \to \pi$ softens at high Q

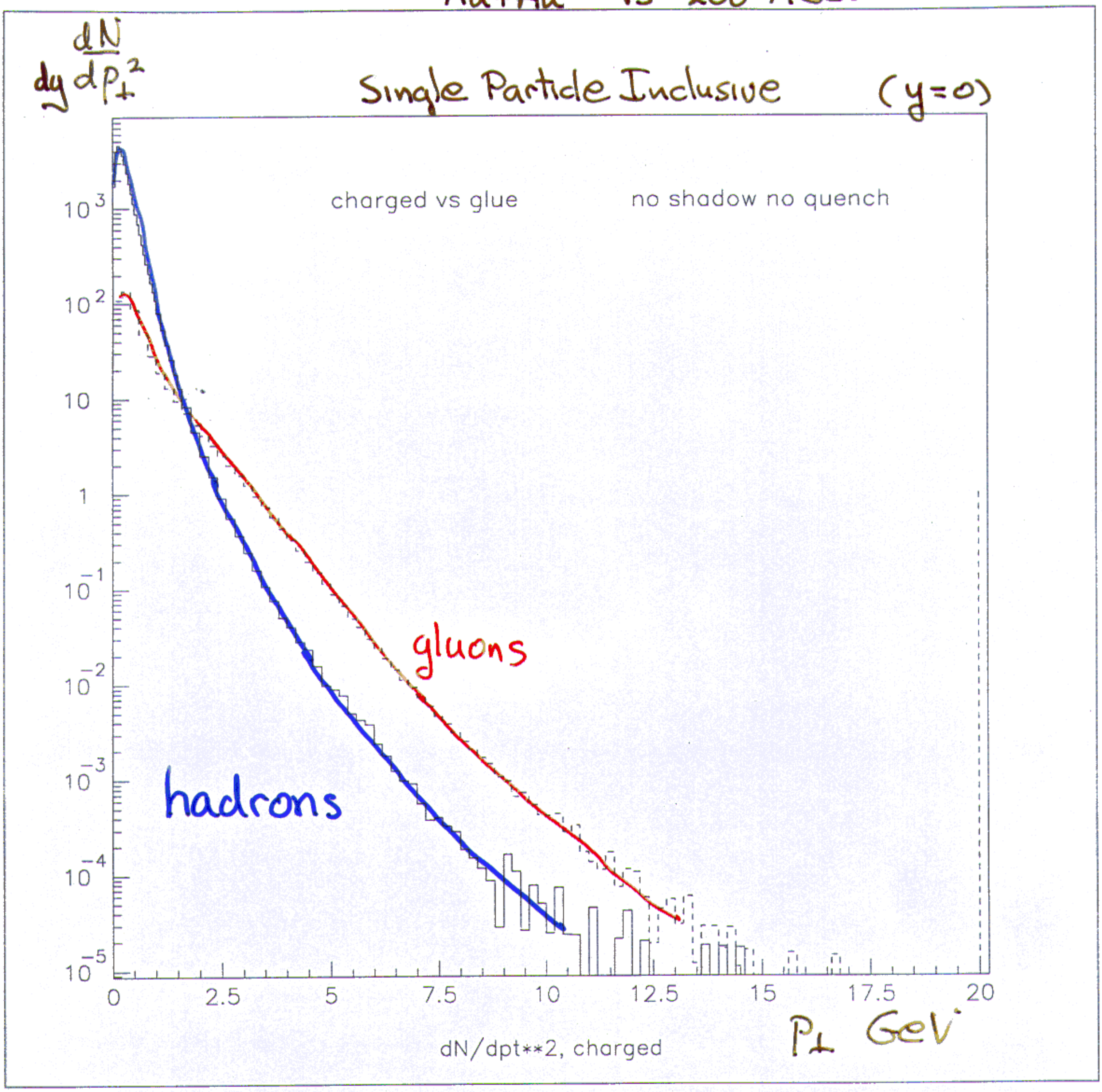


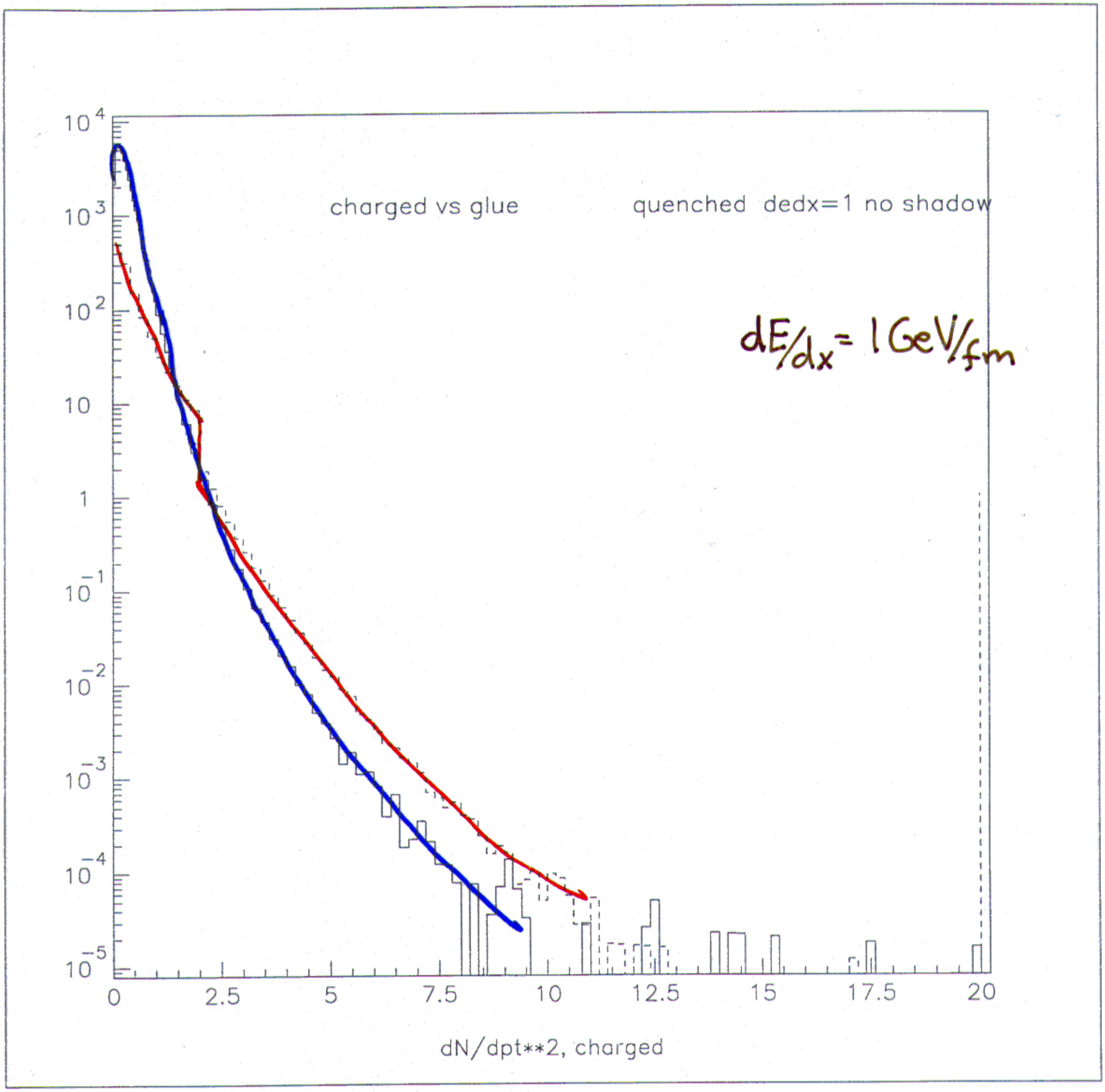
√s = 200 GeV   pp → π⁰
Trigger p⊥ ~ 5GeV
no rad
rad
10
1
10⁻¹
10⁻²
10⁻³
10⁻⁴
10⁻⁵
0
2.5
5
7.5
10
12.5
15
17.5
20
dN/dpt**2, pionz0
pp 200 jet trigger gt. 5
1
10⁻¹
0
2
4
6
8
10
dN/dpt**2, pionz0

Jet Quench via HIJING

X.N.Wang, M.G

Au+Au $\sqrt{s} = 200$ AGeV




charged vs glue
quenched dedx=1 no shadow
dE/dx = 1 GeV/fm
10^4
10^3
10^2
10
1
10^-1
10^-2
10^-3
10^-4
10^-5
0
2.5
5
7.5
10
12.5
15
17.5
20
dN/dpt**2, charged

Part 3:

Brutus Forcus pQCD

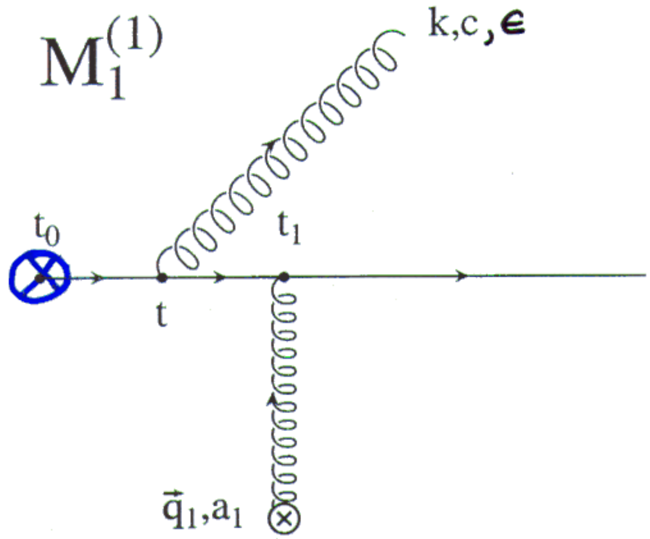
Peter Levai   Ivan Vitev   MG

progress report

Hard Jet Source at t_0 + $N_{sc}=1$ Rescattering at t_1

use O.F.P.T. à la BDMPS

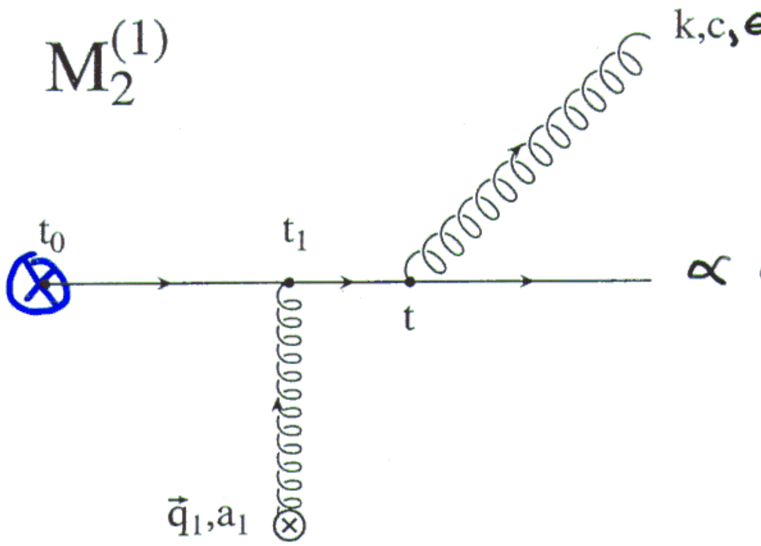
$M_1^{(1)}$



$$\propto g\vec{\epsilon}_\perp \cdot \vec{H}\,(1-e^{i\phi_1})\,T_a T_c$$

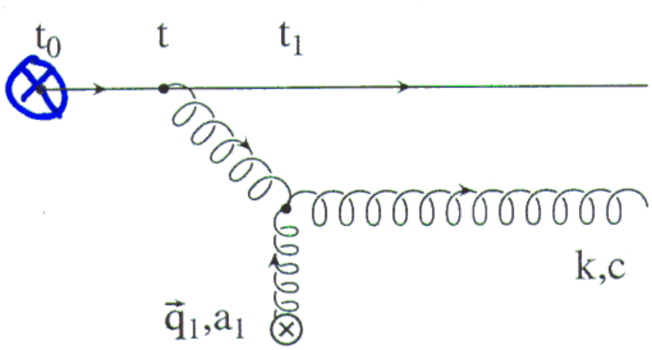
$$\begin{cases} \vec{H} \equiv \vec{k}_\perp / k_\perp^2 \\ \phi_1 \equiv (t_1 - t_0)\,\dfrac{k_\perp^2}{2\omega} \end{cases}$$

$M_2^{(1)}$



$$\propto g\vec{\epsilon}_\perp \cdot \vec{H}\, e^{i\phi_1}\; T_c T_a$$

$M_3^{(1)}$

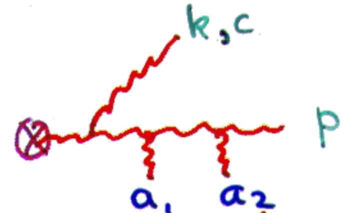


$$\propto g\vec{\epsilon}_\perp \cdot \vec{C}_1\,(e^{i\phi_2} - e^{i\phi_1})\;[T_c, T_a]$$

$$\begin{cases} \vec{C}_1 \equiv \dfrac{\vec{k}_\perp - \vec{q}_{\perp 1}}{(\vec{k}_\perp - \vec{q}_{\perp 1})^2} \\ \phi_2 = \phi_1 - \Delta t\,\dfrac{(k_\perp - q_\perp)^2}{2\omega} \end{cases}$$

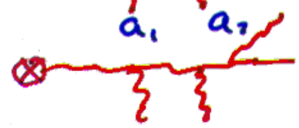
Gluon Radiation with Two Scattering Centers
BDPMS, NPB484 (97) 291

$$\mathcal{M}_1 = 2ig_s \frac{\vec{\epsilon}_\perp \cdot \vec{k}_\perp}{k_\perp^2}\left(e^{it_1\frac{k_\perp^2}{2\omega}} - e^{it_0\frac{k_\perp^2}{2\omega}}\right) a_2 a_1 c,$$



$$\mathcal{M}_2 = 2ig_s \frac{\vec{\epsilon}_\perp \cdot \vec{k}_\perp}{k_\perp^2}\left(e^{it_2\frac{k_\perp^2}{2\omega}} - e^{it_1\frac{k_\perp^2}{2\omega}}\right) a_2 c a_1,$$

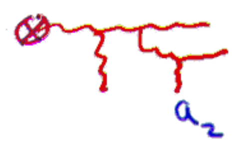
$$\mathcal{M}_3 = 2ig_s \frac{\vec{\epsilon}_\perp \cdot \vec{k}_\perp}{k_\perp^2}\left(-e^{it_2\frac{k_\perp^2}{2\omega}}\right) c a_2 a_1,$$



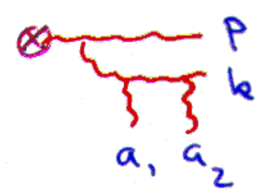
$$\mathcal{M}_4 = 2ig_s \frac{\vec{\epsilon}_\perp \cdot (\vec{k} - \vec{q}_1)_\perp}{(k-q_1)_\perp^2} e^{it_1\frac{k_\perp^2 - (k-q_1)_\perp^2}{2\omega}} \times$$
$$\times\left(e^{it_1\frac{(k-q_1)_\perp^2}{2\omega}} - e^{it_0\frac{(k-q_1)_\perp^2}{2\omega}}\right) a_2 \left[c, a_1\right],$$

$$\mathcal{M}_5 = 2ig_s \frac{\vec{\epsilon}_\perp \cdot (\vec{k} - \vec{q}_2)_\perp}{(k-q_2)_\perp^2} e^{it_2\frac{k_\perp^2 - (k-q_2)_\perp^2}{2\omega}} \times$$
$$\times\left(e^{it_1\frac{(k-q_2)_\perp^2}{2\omega}} - e^{it_0\frac{(k-q_2)_\perp^2}{2\omega}}\right) a_1 \left[c, a_2\right],$$

$$\mathcal{M}_6 = 2ig_s \frac{\vec{\epsilon}_\perp \cdot (\vec{k} - \vec{q}_2)_\perp}{(k-q_2)_\perp^2} e^{it_2\frac{k_\perp^2 - (k-q_2)_\perp^2}{2\omega}} \times$$
$$\times\left(e^{it_2\frac{(k-q_2)_\perp^2}{2\omega}} - e^{it_1\frac{(k-q_2)_\perp^2}{2\omega}}\right) \left[c, a_2\right] a_1,$$



$$\mathcal{M}_7 = 2ig_s \frac{\vec{\epsilon}_\perp \cdot (\vec{k} - \vec{q}_1\vec{q}_2)_\perp}{(k-q_1-q_2)_\perp^2} \left[\left[c, a_2\right], a_1\right]$$
$$e^{it_2\frac{k_\perp^2 - (k-q_2)_\perp^2}{2\omega}} e^{it_1\frac{(k-q_2)_\perp^2 - (k-q_1-q_2)_\perp^2}{2\omega}}$$
$$\times\left(e^{it_1\frac{(k-q_1-q_2)_\perp^2}{2\omega}} - e^{it_0\frac{(k-q_1-q_2)_\perp^2}{2\omega}}\right).$$



$$\mathcal{M} = \mathcal{M}_1 + \mathcal{M}_2 + \mathcal{M}_3$$

$$= e^{i\phi_0}\, \vec{\epsilon}_\perp \cdot \left\{ \vec{H}\, T^a T^c + \left(\vec{B}\, e^{i\phi_1} + \vec{C}\, e^{i\phi_2} \right) [T^c, T^a] \right\}$$

$\phi_0 = t_0 \frac{k_\perp^2}{2\omega}$

$\vec{H}\,T^aT^c$: initial hard; $\vec{B}\,e^{i\phi_1}$: Bertsh-Gunion; $\vec{C}\,e^{i\phi_2}$: gluon rescattering

$$\vec{H} = \frac{\vec{k}_\perp}{k_\perp^2}, \qquad \vec{C} = \frac{\vec{k}_\perp - \vec{q}_\perp}{(\vec{k}_\perp - \vec{q}_\perp)^2}$$

$$\phi_1 = (t_1 - t_0)\frac{k_\perp^2}{2\omega}$$

$$\phi_2 = \phi_1 - \frac{(t_1 - t_0)(\vec{k}_\perp - \vec{q}_\perp)^2}{2\omega}$$

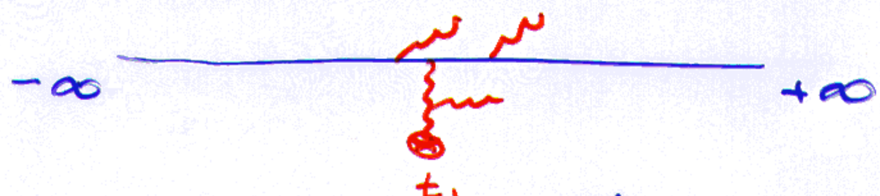
$$\vec{B} = \vec{H} - \vec{C} = \frac{\vec{k}_\perp}{k_\perp^2} - \frac{\vec{k}_\perp - \vec{q}_\perp}{(\vec{k}_\perp - \vec{q}_\perp)^2}$$

Limits:

1) $t_0 \to -\infty$ $\quad e^{i\phi_0}$ and $e^{i\phi_0 + \phi_2} \to 0$

But $e^{i\phi_0 + \phi_1} \to e^{i t_1 k_\perp^2/2\omega}$ finite

$$\mathcal{M} \to \mathcal{M}_{BG} \propto \vec{\epsilon}_\perp \cdot \vec{B}\; [T^c, T^a]$$



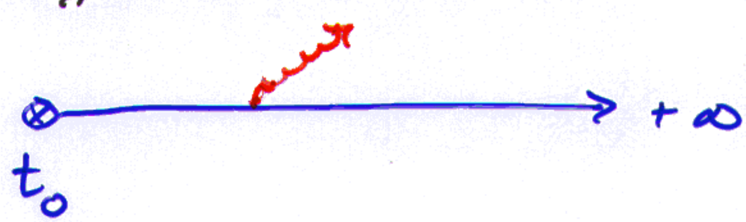
isolated Bertsch Gunion

2) $t_1 \to +\infty$ $\quad e^{i\phi_1}$ and $e^{i\phi_2} \to 0$

t_0 fixed

But $e^{i\phi_0} = e^{i t_0 k_\perp^2/2\omega}$ finite

$$\mathcal{M} \to \mathcal{M}_H \propto \vec{\epsilon}_\perp \cdot \vec{H}\; T^a T^c$$

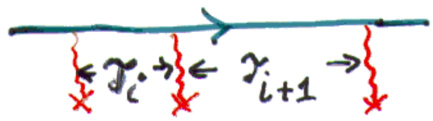


pure Hard process

Multiple Collision Ensemble Average:

M.G., X. Wang

① over collision times $\tau_i = t_i - t_{i-1}$



$$\langle dN \rangle_\lambda = \int \prod_i \frac{d\tau_i}{\lambda_i} e^{-\tau_i/\lambda_i} \, dN$$

$$\langle \cos \tau_1 \omega_1 \rangle = \frac{1}{1+\lambda_1^2 \omega_1^2}$$

$$\langle \cos(\tau_1 \omega_1 + \tau_2 \omega_2) \rangle = \frac{1 - \lambda_1 \lambda_2 \omega_1 \omega_2}{(1+\lambda_1^2 \omega_1^2)(1+\lambda_2^2 \omega_2^2)}$$

(Converts oscillating terms to rational fncs)

② Over $\vec{q}_{\perp i}$ via Yukawa cross sec

$$u_i \equiv \frac{\mu^2}{q_{\perp i}^2 + \mu^2}$$

μ = screening scale

$$\langle dN \rangle_u = \int_{u_0}^{1} \prod_i \frac{du_i}{1-u_0} \, dN$$

$$u_0 \equiv \frac{\mu^2}{Q^2 + \mu^2}$$ where $Q^2 = 6 E_{jet} T$

requires numerical evaluation

N=0 Distribution

$$dN^0 \propto \frac{dz^+}{z^+}\frac{dk_\perp^2}{k_\perp^2} = d\log z^+ \; d\log k_\perp^2$$

$$\frac{\mu}{E_0^+} < z^+ = (\omega + k_z)/E_0^+ < 1 \quad , \quad 0 < k_\perp < \omega (\frac{E}{2}$$

$$k_z > 0 \quad \Rightarrow \quad z^+ > \frac{k_\perp}{2E_0^+}$$

N=1 Distribution (ave over $t_1 - t_0$)

$$\langle dN^1 \rangle_\lambda = dN^0 \left(1 + \mathcal{F}_1\left(\xi = \frac{\mu^2\lambda}{2\omega}, \vec{k}_\perp, \vec{q}_\perp\right)\right)$$

$$\mathcal{F}_1 = \frac{C_A}{C_R}\xi^2 \left\{ \frac{k_\perp^4}{\mu^4 + \xi^2 k_\perp^4} - \frac{\vec{k}_\perp\cdot(\vec{k}_\perp - \vec{q}_\perp)(2k_\perp^2 - \vec{k}_\perp\cdot\vec{q}_\perp)}{(\mu^4 + \xi^2 k_\perp^4)(\mu^4 + \xi^2(q_\perp^2 + 4(\vec{k}\vec{q})(\vec{k}\vec{q} - q^2)))} + \frac{2(\vec{k}\vec{q})(\vec{k}_\perp - \vec{q}_\perp)^2}{\mu^4 + \xi^2(\vec{k}_\perp - \vec{q}_\perp)^4} \right\}$$

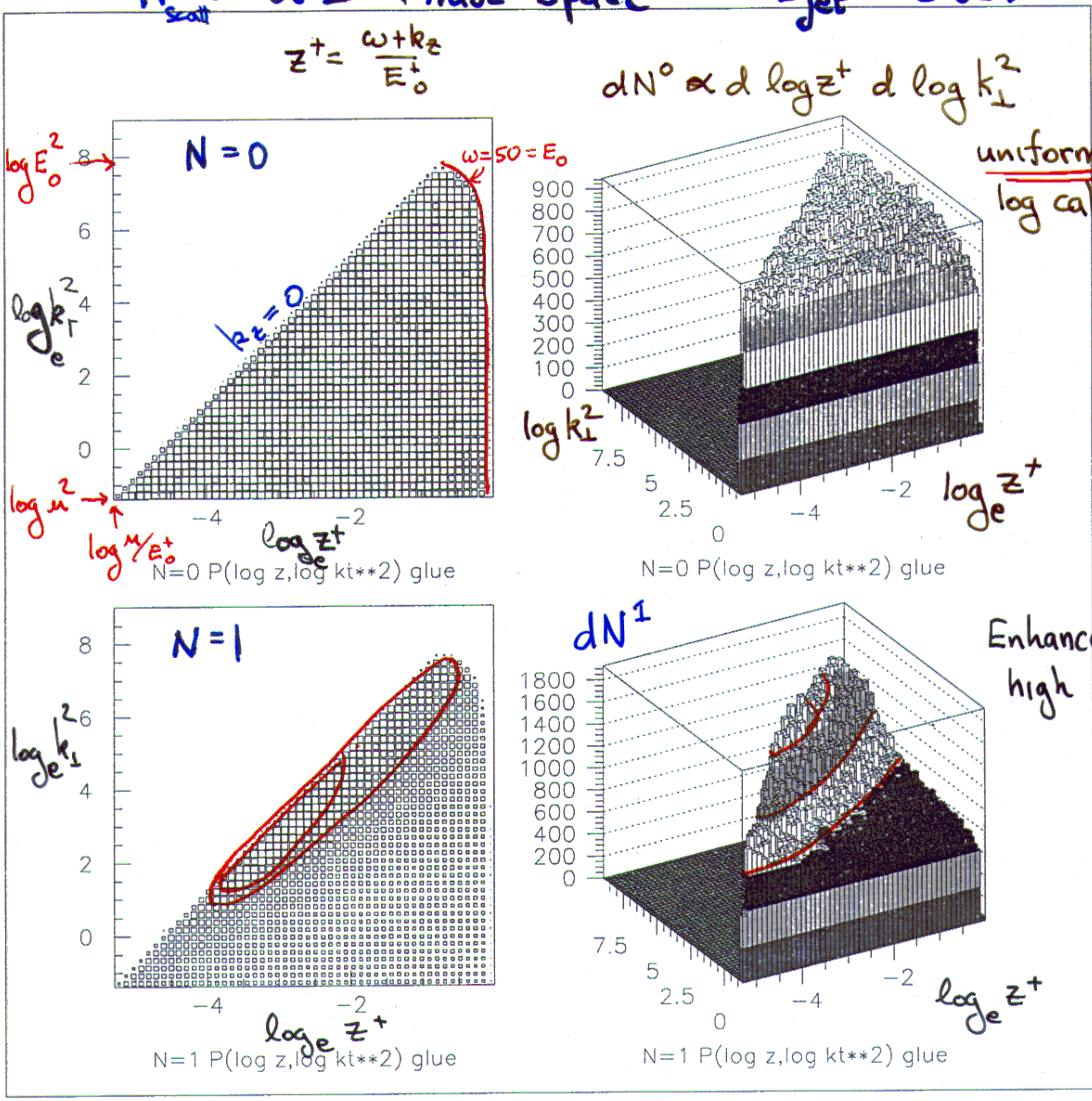
Finite Singularity free due to time ave

$\mathcal{F}_1 \to 0$ fixed $k_\perp$ large $\omega \Rightarrow$ small ξ

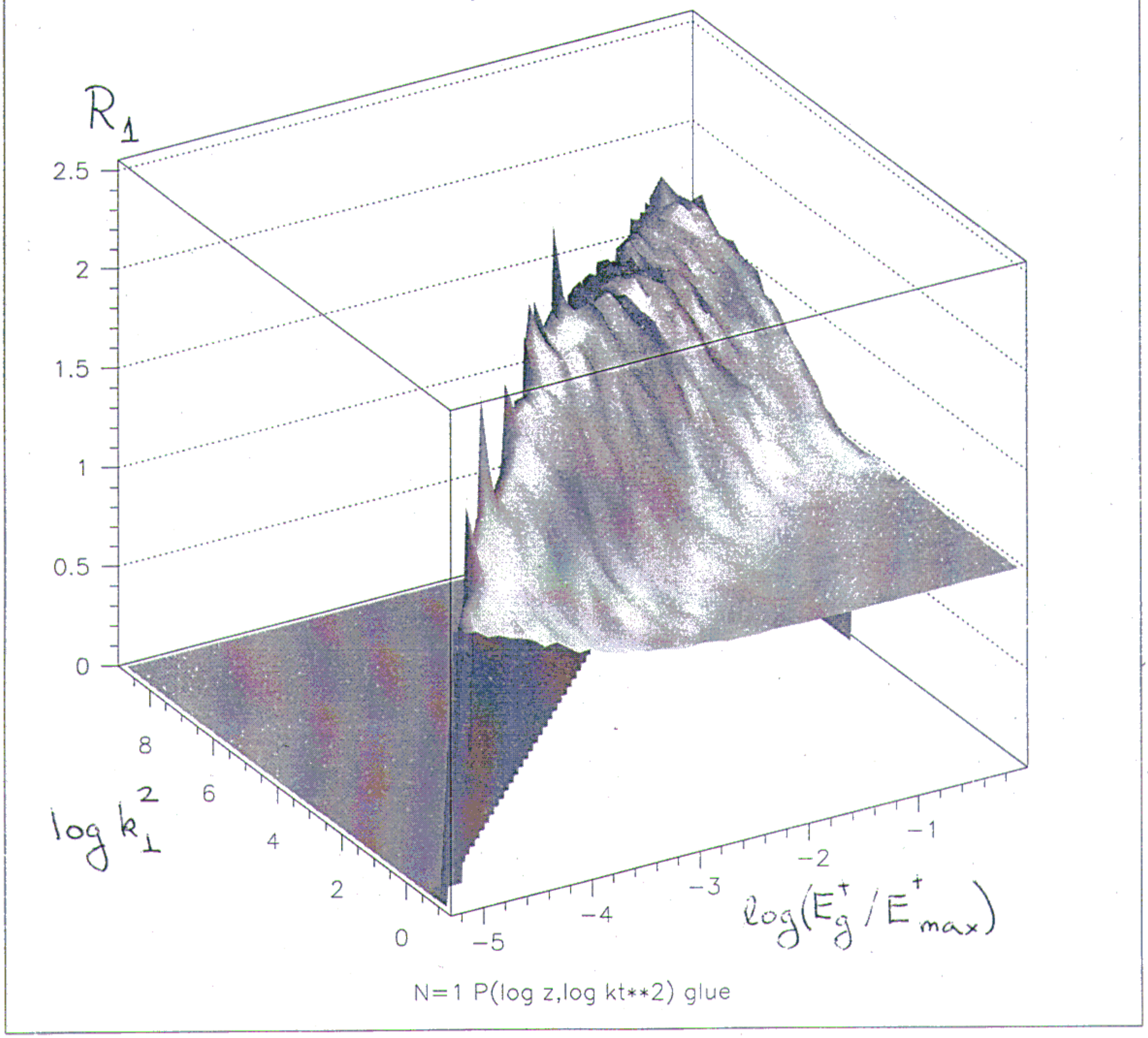
$\to 0$ fixed ω small $k_\perp$

$$\langle dN^1 \rangle_{\lambda,\mu} = dN^0 \left(1 + f_1(\xi, k_\perp)\right)$$

$N_{scatt}=0$ vs 1 Phase space $E_{jet} = 50$ GeV



$$dN_g^1 = dN_g^0 \; R_1(k_\perp, z)$$



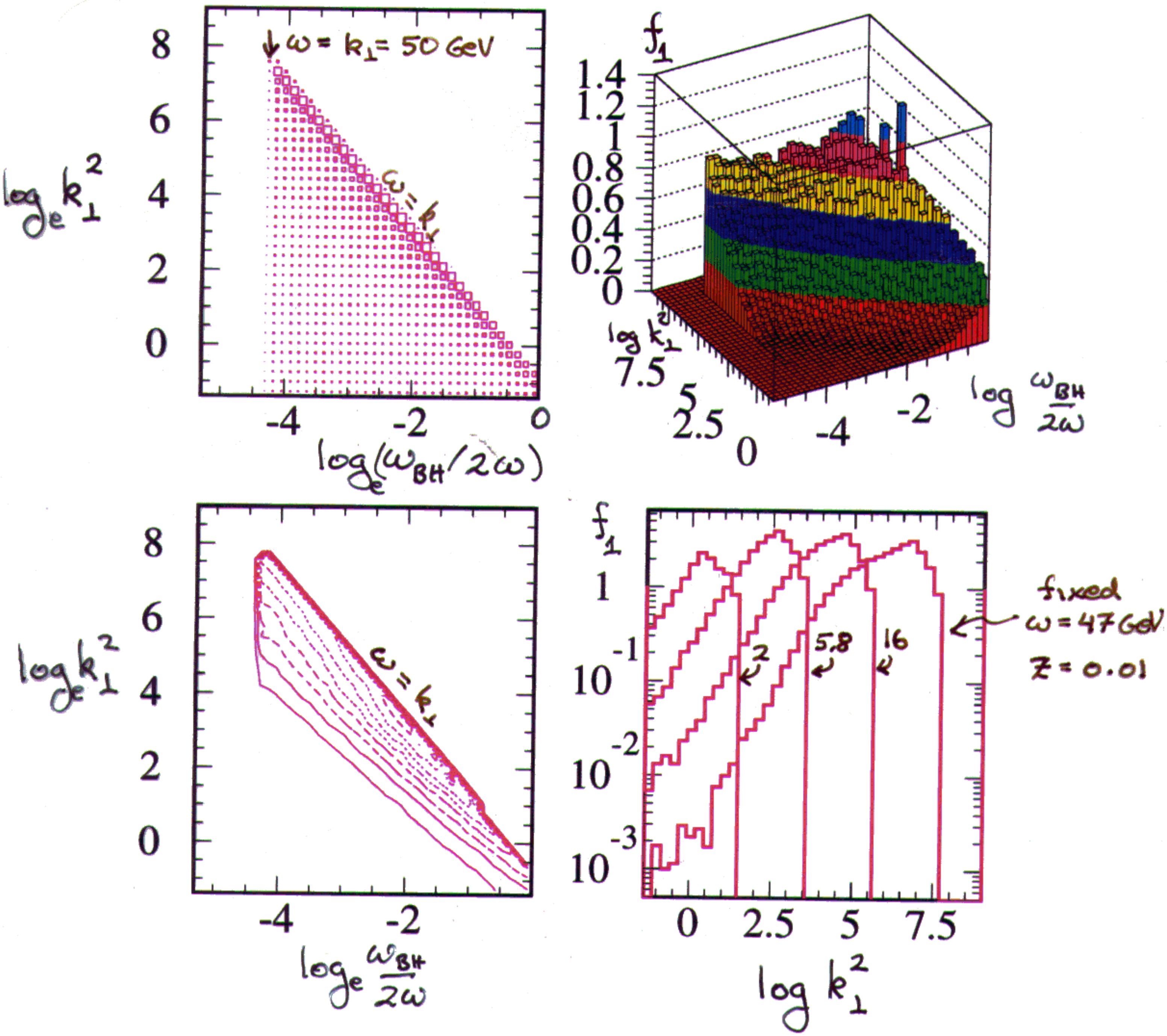
Radiation Phase Space

$E_q = 50\,\text{GeV}$

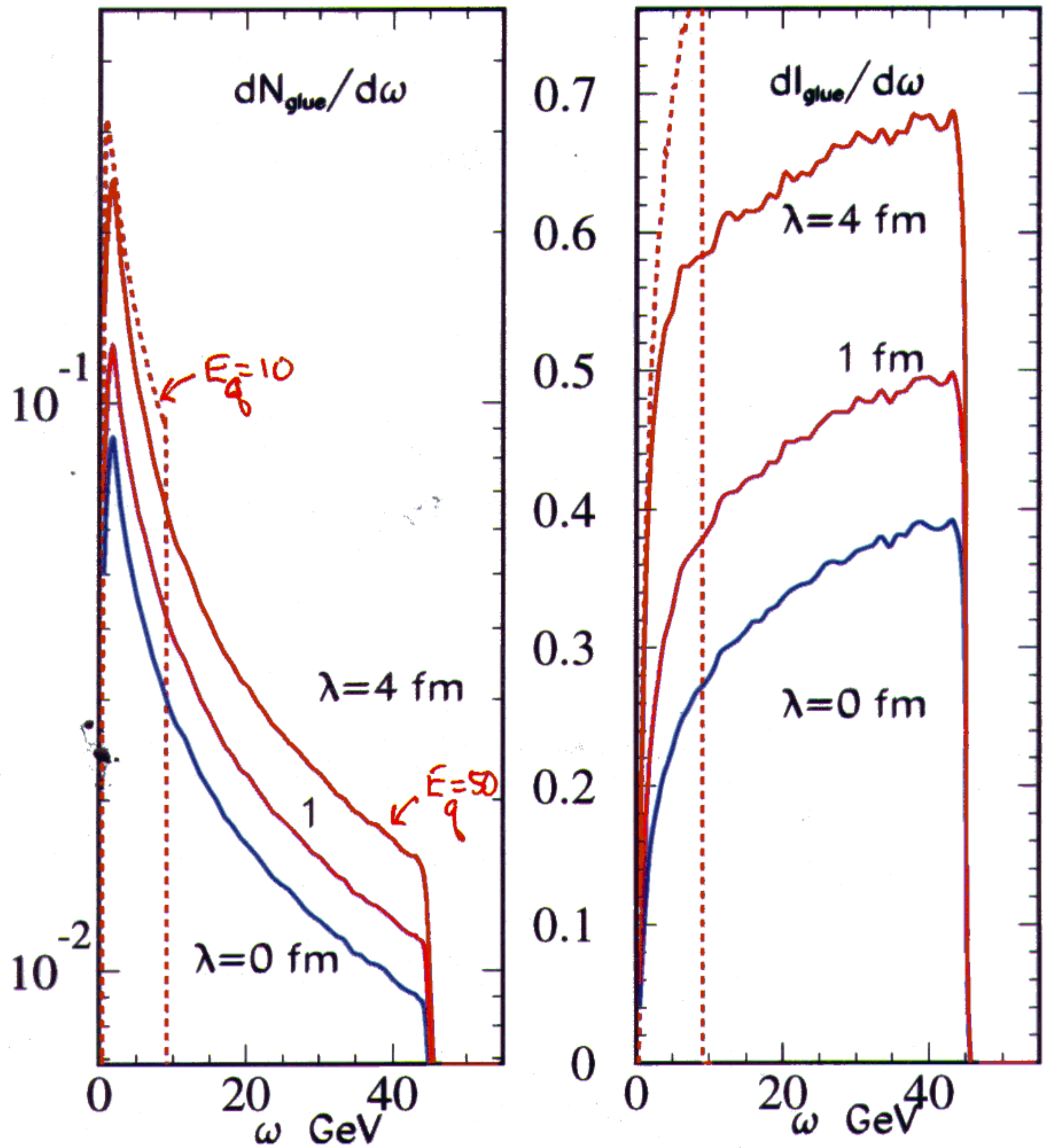
$$dN_1 = dN_0\,(1 + f_1(z, k_\perp))$$

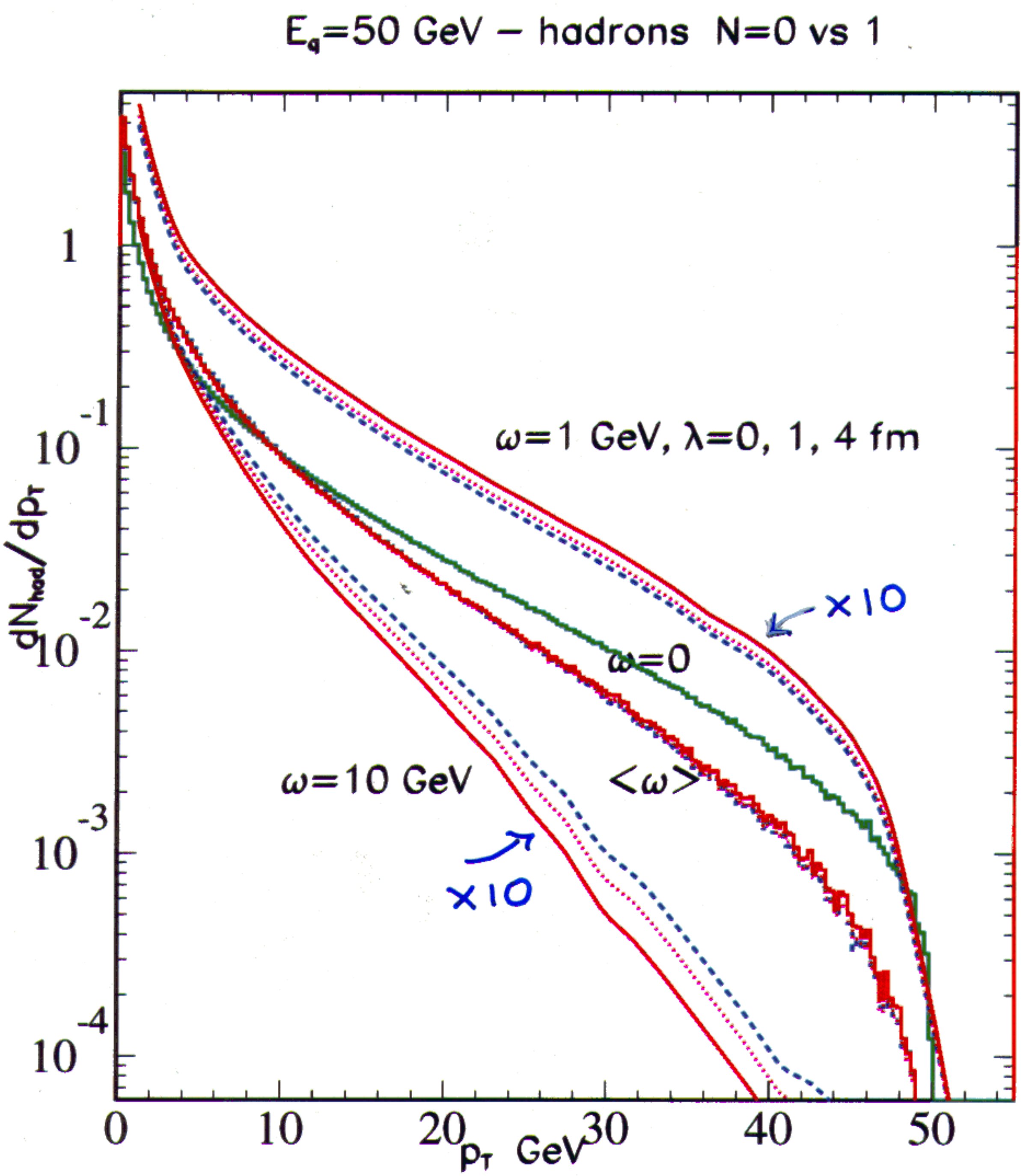
$\omega_{BH} = 1.3\,\text{GeV}$

$\mu = 0.5\,\text{GeV}$



Hard + N_{sc}=1 Gluon Spectrum, E_q=10,50 GeV





E_q=50 GeV – hadrons N=0 vs 1
ω=1 GeV, λ=0, 1, 4 fm
×10
ω=0
<ω>
ω=10 GeV
×10
dN_had/dp_T
p_T GeV
1
10^-1
10^-2
10^-3
10^-4
0
10
20
30
40
50

Summary (Part 3)

1) $\omega \frac{dN_g}{d\omega\, d\vec{k}_\perp}$ computed for $N = 0, 1, 2, 3$

2) Interference Hard + B.G. + Cascade limits enhancement to large $\vec{k}_\perp$

$$\sqrt{\omega/\lambda} < k_\perp < \omega$$

($k_\perp \ll \omega$) approximations used are poor and need improvement !

Bertsch-Gunion induced radiation terms are greatly suppressed

Cascade terms dominate

3) Lund Hadronization of $N=1$ $\frac{dN_1}{dy\, d\vec{k}_\perp}$ is totally insensitive to modifications at high $k_\perp$

4) But $\frac{dI}{d\omega}$ is $\approx$ uniformly enhanced
$\Rightarrow$ need to go to multiple glue showers
(via modified Alterelli Parisi evolution)

5) Small N_{scat} Fluctuations (very skewed distrib important. Ave $\langle \frac{dE}{dx} \rangle$ is not enough