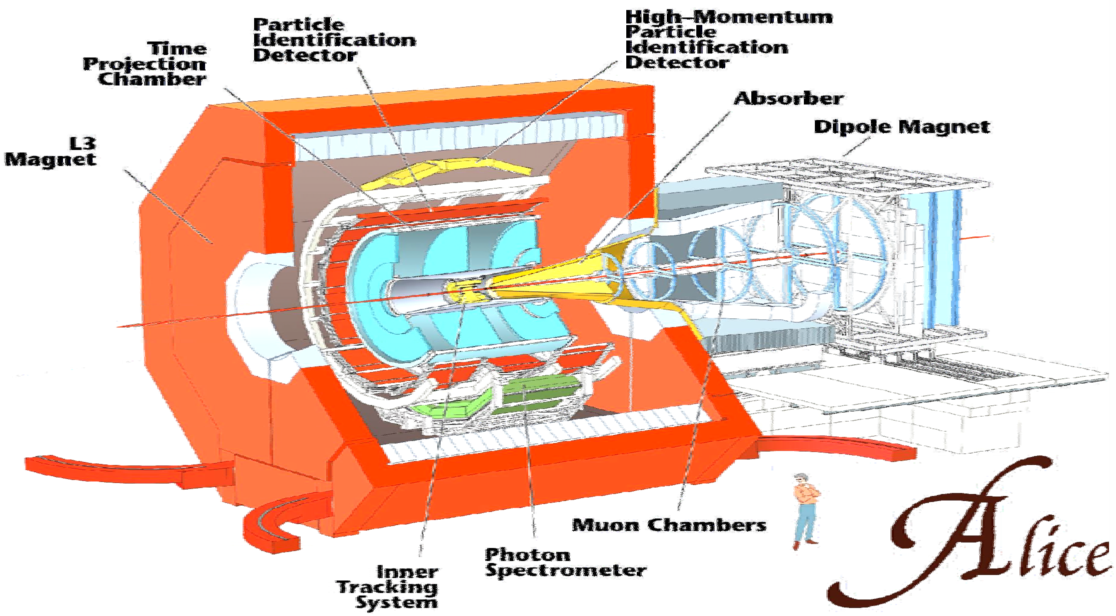
Jet Quenching

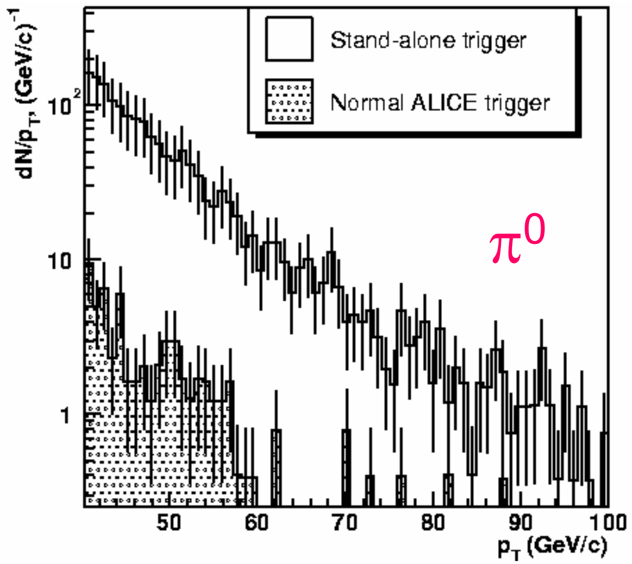
Ivan Vitev

Heavy Ion Physics at the LHC, PANIC 2005
Santa Fe, NM

ALICE at High p_T

A.Dainese, ALICE talk

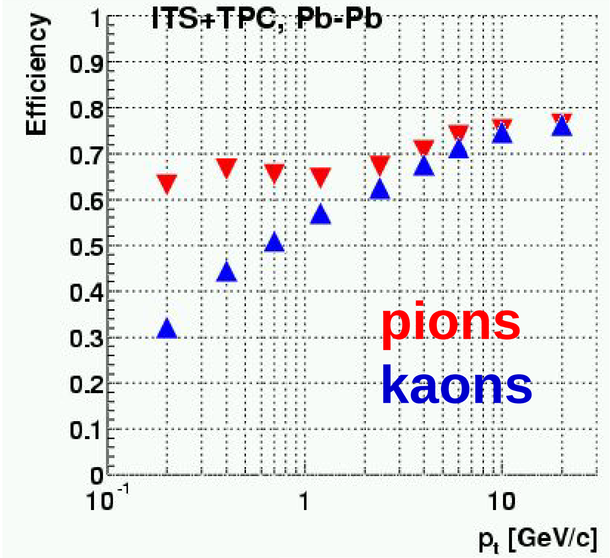




1 year ALICE: ~10^3 p_t > 50 GeV

Identified particles: D^0 to 15 GeV

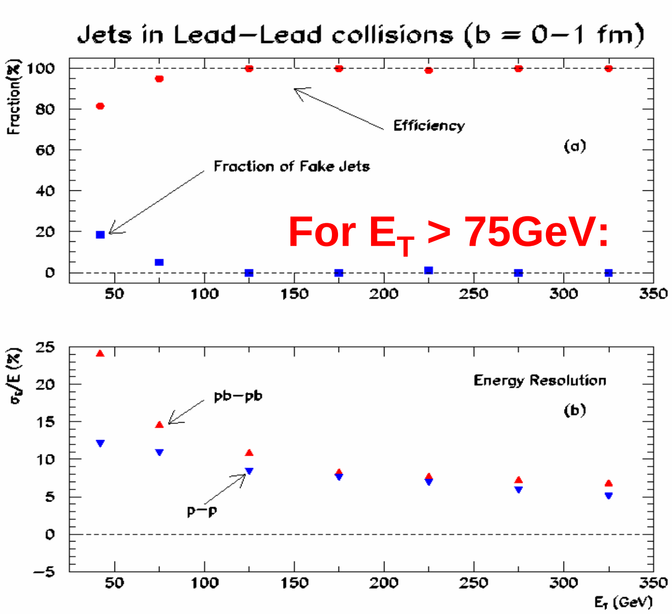
Λ to 12 GeV, γ/π^0 to 100 GeV



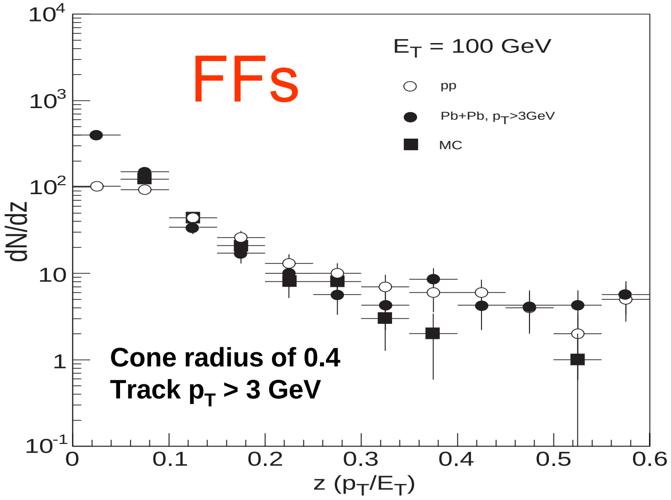
Tracking capabilities
for low p_T < 1 GeV

Particle ID

ATLAS for Heavy Ions



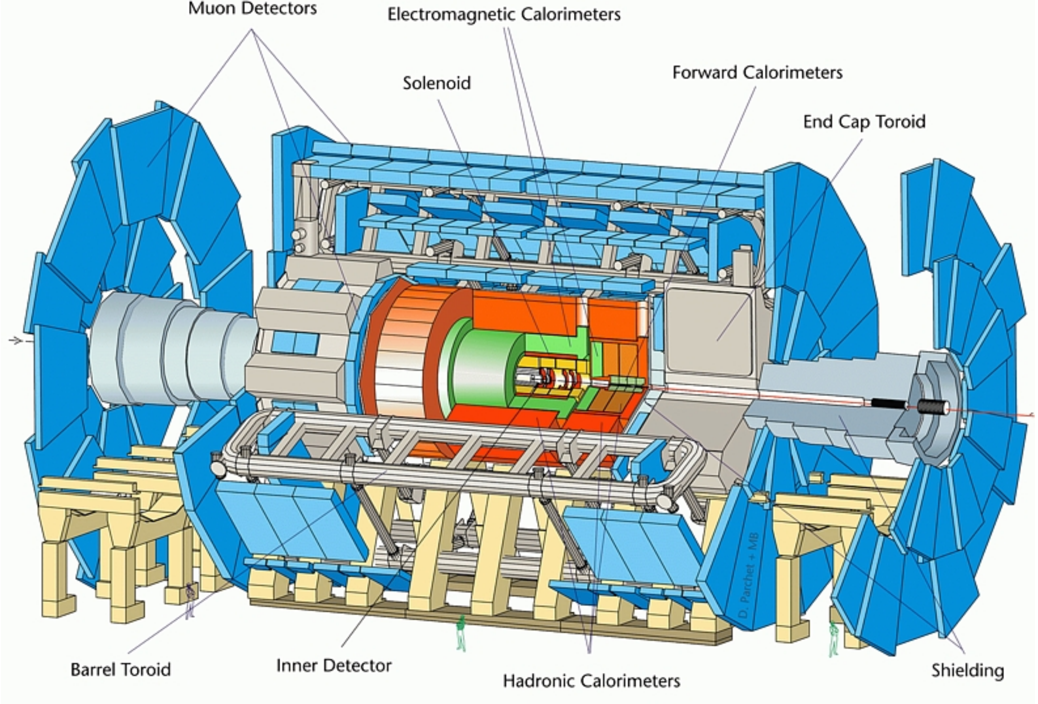
For E_T > 75GeV:



FFs

Cone radius of 0.4
Track p_T > 3 GeV

L.Rosselet, ATLAS talk



Hermetic calorimeter $|\eta|<4.9$

$\Delta\eta\Delta\Phi=0.025\times0.025$ (e.g.) EM; 0.1x0.1 Hadronic

Large acceptance μ-spectrometer $|\eta|<2.7$

Silicon Tracker $|\eta|<2.5$

Finely segmented pixel and strip detector (SCT)

Good resolution $p_T \geq 0.5$ GeV

CMS for Heavy Ions

Silicon Tracker

Excellent momentum resolution Δp/p~1%

Fine Grained High Resolution Calorimeter (E-cal+H-cal)

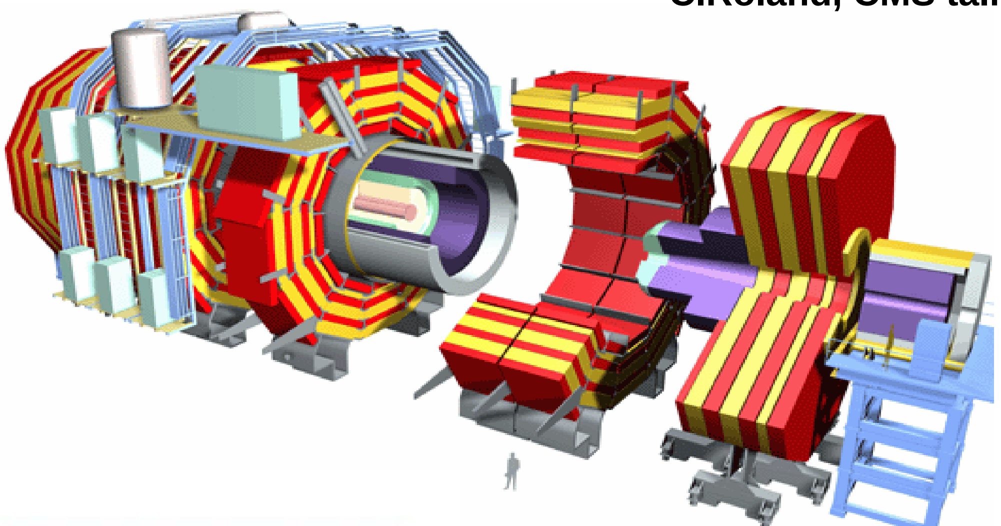
Hermetic coverage up to |η|<5

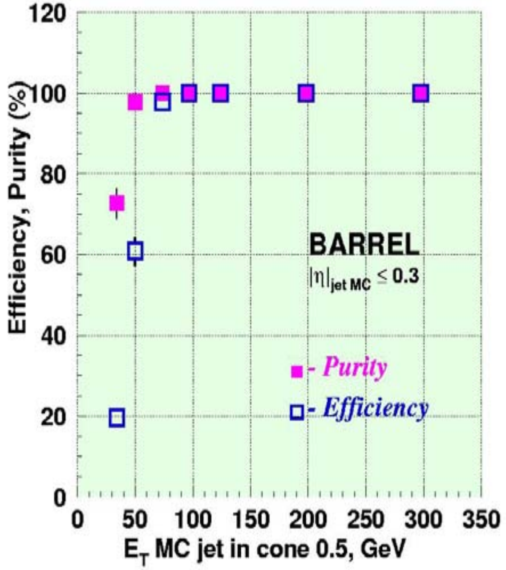
Muon Reconstruction

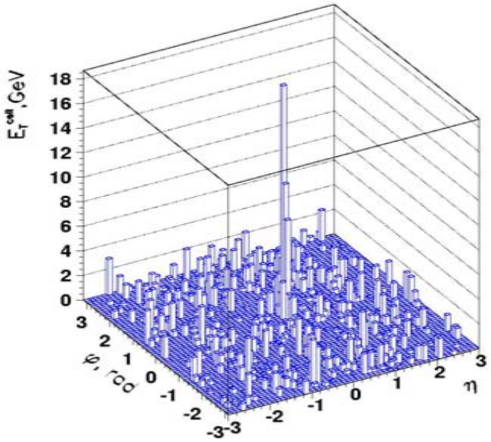
Tracking μ from Z^0, J/ψ, ϒ

Wide rapidity range |η|<2.5

C.Roland, CMS talk

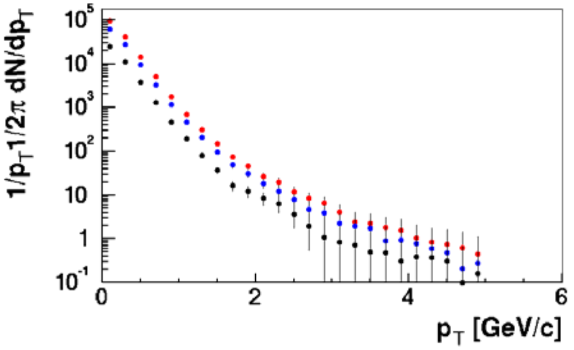






100GeV Jet in a Pb+Pb event (after background subtraction)

1000 Pb Pb Events @ LHC:



Theoretical Input (Outline)

- **Single inclusive particle quenching at high p_T:**

⇨ Careful implementation of valid e-loss approaches. Centrality and particle species dependence. Heavy flavor energy loss

Light mesons π^0 to 100 GeV (ALICE), Baryons to 10 – 15 GeV? (ALICE)
Heavy flavor D-mesons to 15 GeV (ALICE)

- **Tagged $\gamma,\ Z^0$ inclusive (multi) hadrons:**

⇨ Realistic differential calculations of double differential gluon distribution. Integration in jet shape formalisms. Redistribution of the energy.

Above few GeV (“FFs”) (ATLAS) Particle distributions in the jets
k_T > 1 GeV (CMS)

- **High E_T jets at $Y = 0$ and $Y \neq 0$, jet correlations:**

⇨ High E_T TeV jets, algorithm dependence, energy loss as a function of Y, jet correlations with large rapidity gaps

Millions of > 200 GeV Jets (ATLAS, CMS). Large |y|<5 coverage (ATLAS, CMS)

LHC Cross Sections

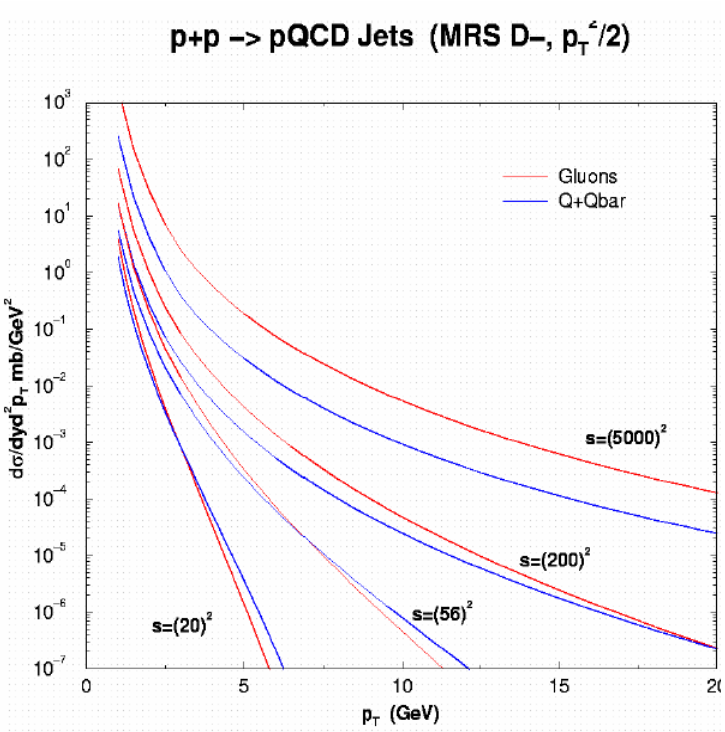
Unprecedented new capabilities for high p_T and jet physics

p+p @ $\sqrt{s} = 14\ TeV$

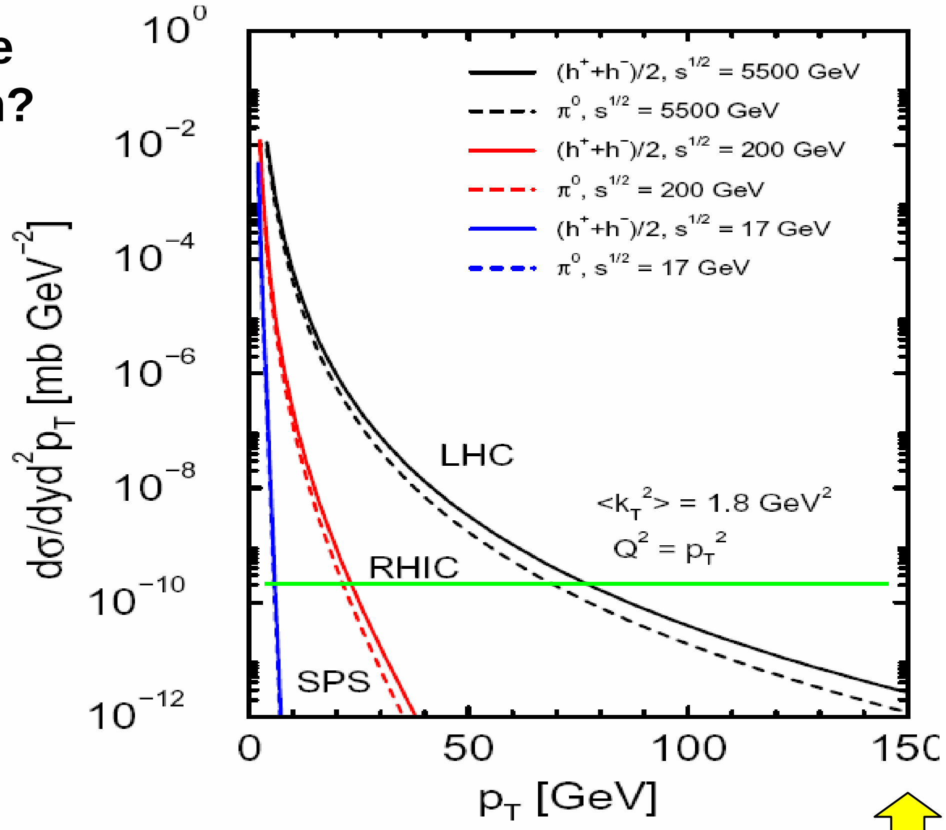
p+A @ $\sqrt{s} = 8.8\ TeV$

A+A @ $\sqrt{s} = 5.5\ TeV$

Baseline problem?



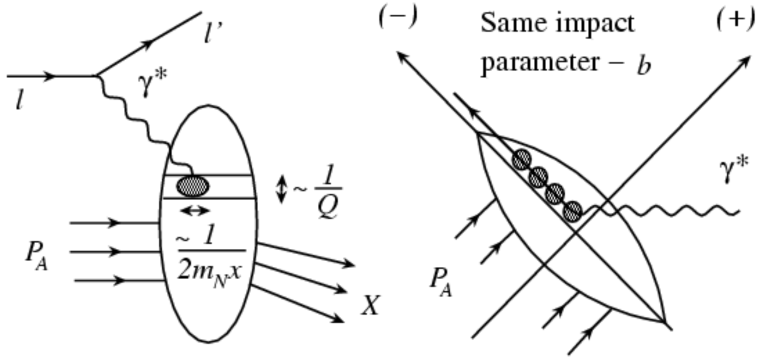
A.Adil, M.Gyulassy



I.V., CERN Yellow Report

Orders in magnitude gain in both jet and inclusive particle cross sections

Low x and High p_T



Longitudinal size: $\sim 1/2m_N x$

If $x < 0.1$ then $\Delta z > r_0$

Transverse size: $\sim 1/Q$

If $Q < m_N$ then exceed the parton size

- **Interactions will happen coherently but this does not mean that they don't have substructure – at high p_T single hard scattering dominates**

Condition: $p_T^{\ 2} > \mu^2 L/\lambda,\ \xi^2 A^{1/3},\ Q_s^2$

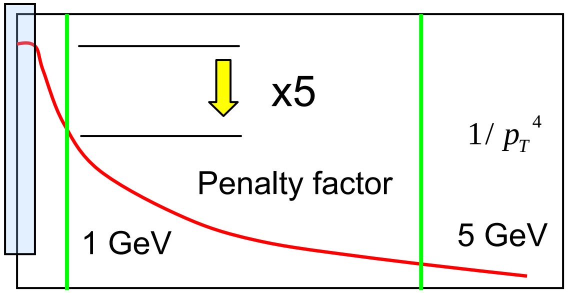
$$\frac{dW_h}{d^2p_t}(x,b,\beta) = \Gamma_h(x,b-\beta)\sum_{\nu=1}^{\infty}\frac{1}{\nu!}\int \Gamma_A(x'_1,b)\dots\Gamma_A(x'_\nu,b)\, e^{-\int dx'\Gamma_A(x',b)\sigma(xx')}$$

$$\times \frac{d\sigma}{d^2k_1}\dots\frac{d\sigma}{d^2k_\nu}\,\delta^{(2)}(\mathbf{k}_1+\dots+\mathbf{k}_\nu-\mathbf{p}_t)\ d^2k_1\dots d^2k_\nu\ dx'_1\dots dx'_\nu$$

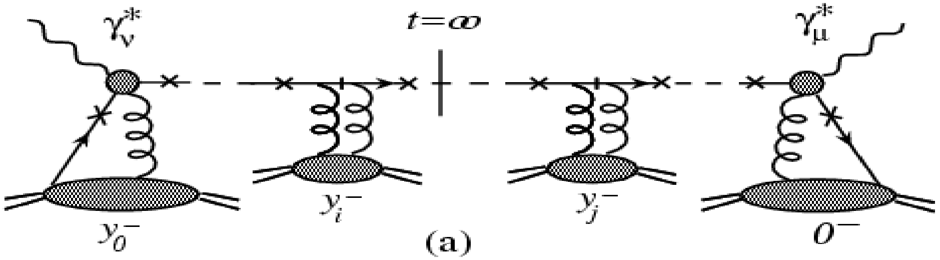
$$\langle p_t^2(x,b)\rangle_A \sim \begin{cases} \langle p_t^2(x,b)\rangle_1 & \text{as } p_0\to\infty \\ \langle p_t^2(x,b)\rangle_1\langle n_A(x,b)\rangle & \text{as } p_0\to 0\ . \end{cases}$$

A.Accardi and D.Treleani, Phys.Rev.D 64 (2001)

$\xi^2 = 0.1 - 0.2\ GeV^2$



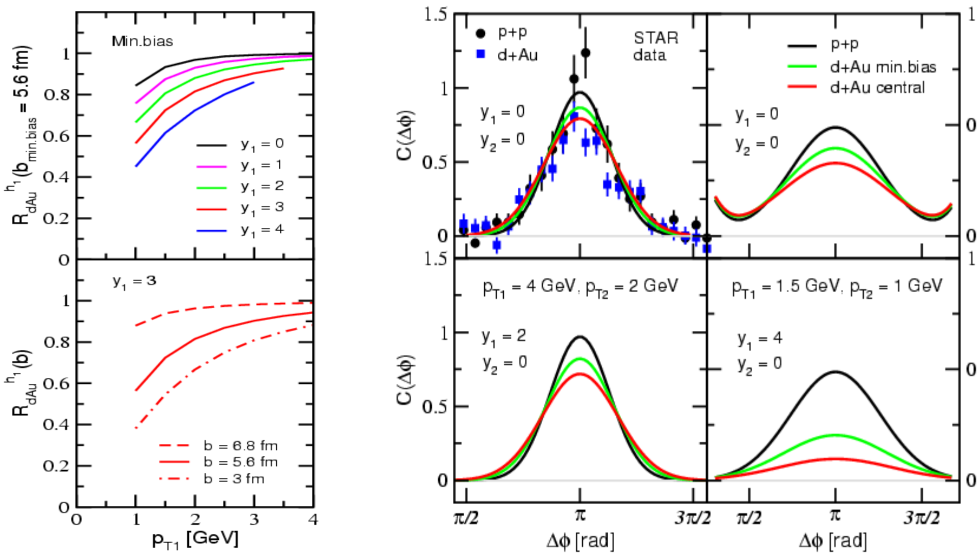
Coherent Power Corrections



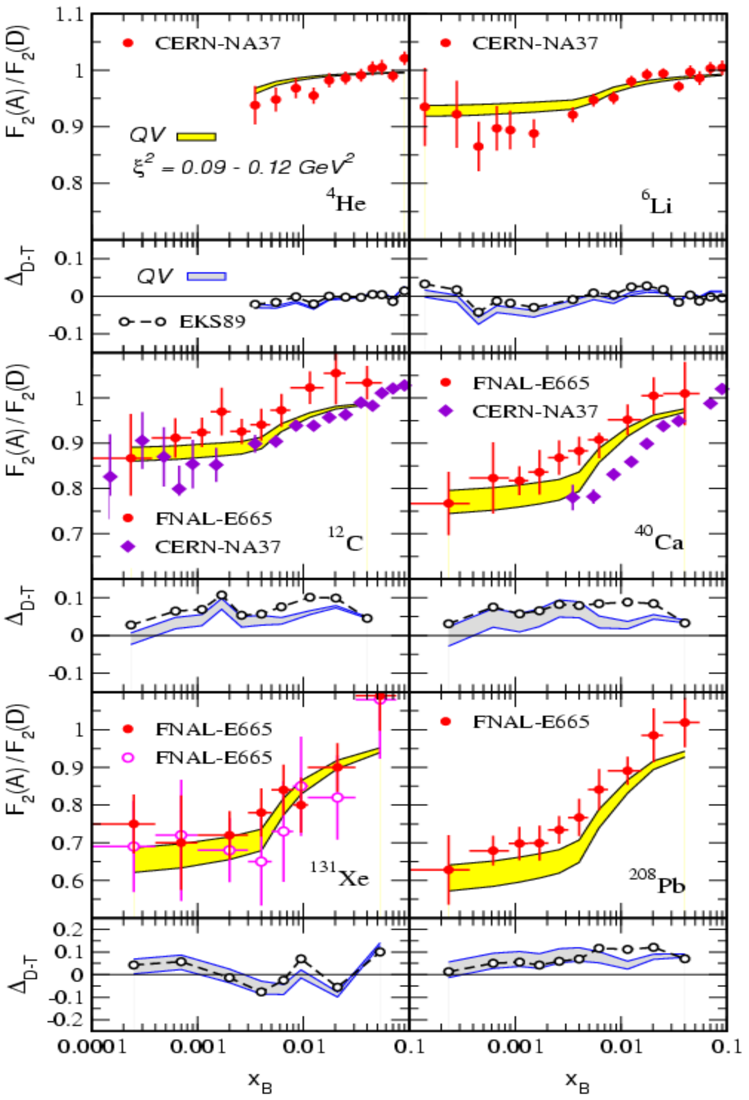
Purely quantum effect

$$F_T^A(x,Q^2) \approx A\, F_T^{(LT)}\left(x + \frac{x\xi^2 (A^{1/3}-1)}{Q^2}, Q^2 \right)$$

The scale of higher twist per nucleon is small $\xi^2 \simeq 0.1\ GeV^2$

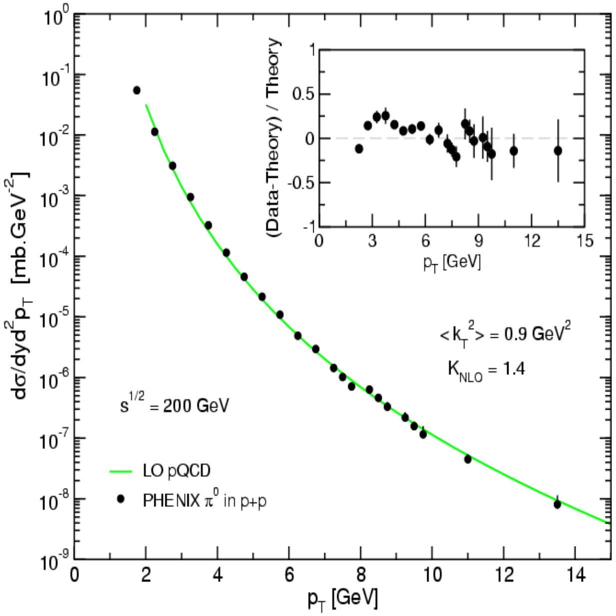


J.W.Qiu, I.V., hep-ph/0405068



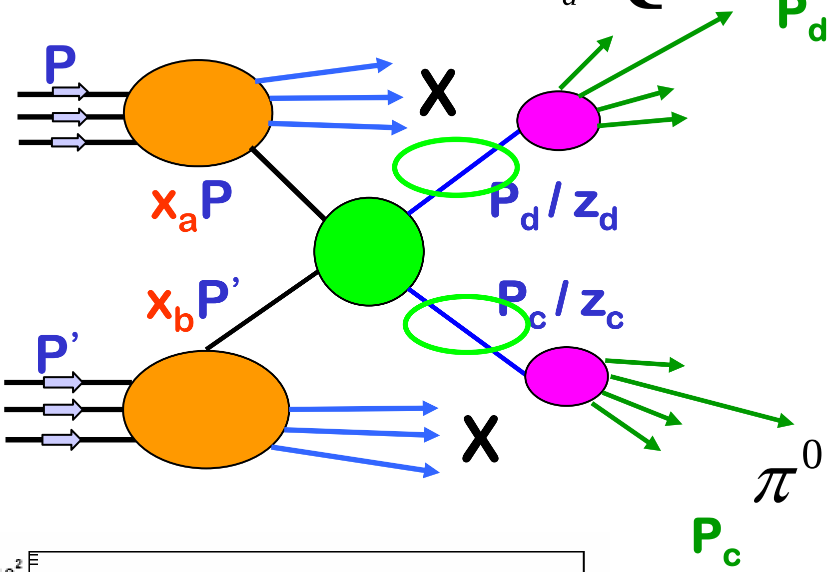
J.W.Qiu, I.V., Phys.Rev.Lett. 93 (2004)

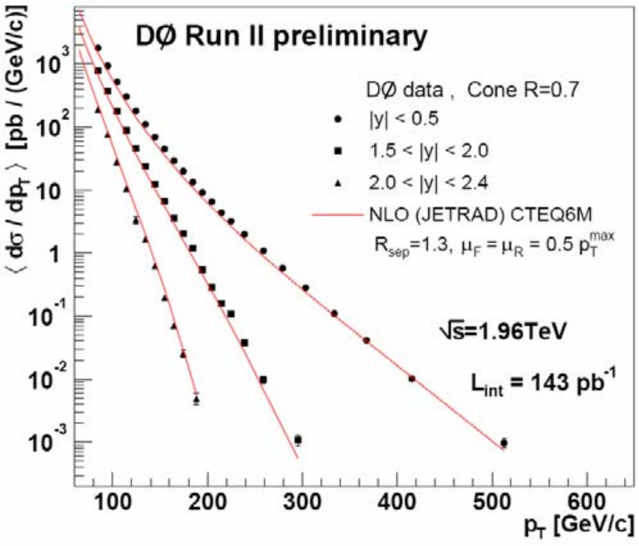
pQCD Jets and Hadrons

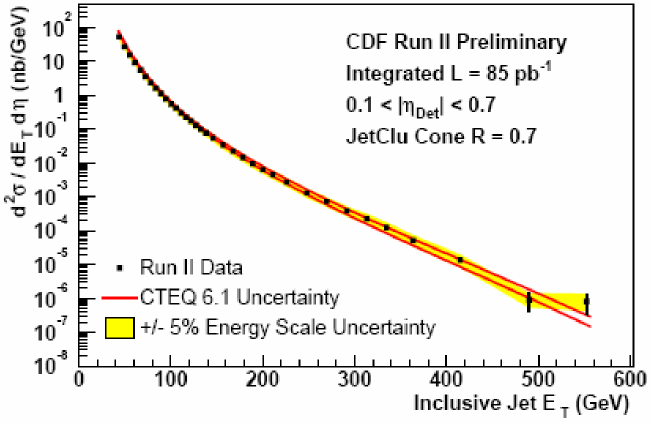


Factorization approach

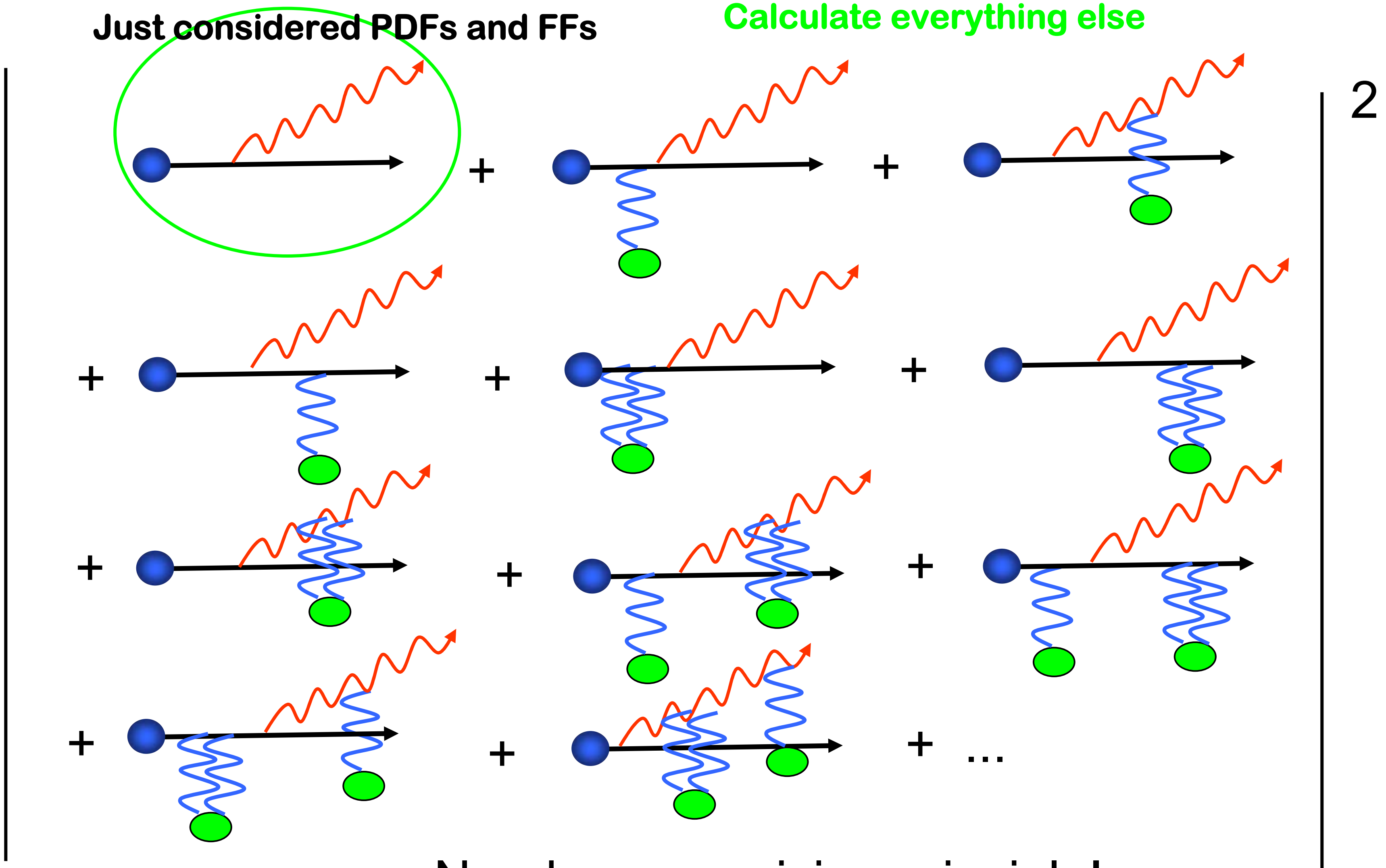
$$\int d\,\frac{p_d}{z_d}\left\{\pi^0\right.$$







Medium-Induced Bremsstrahlung



Just considered PDFs and FFs

Calculate everything else

Need an organizing principle!

E-Loss Calculations

3 Theoretical approaches

GLV

(Gyulassy-Levai-Vitev)

Momentum space T-matrix expansion approach

No Gaussian approximation

Expansion in the # scattering correlations

↓ (D)GLV

(Djordjevic - GLV)

Heavy quarks

↘ WW

(Wang-Wang)

Twist expansion

BDMPS

(Baier-Dokshitzer-Muller Peigne-Schiff)

2D Schrödinger equation approach

Gaussian approximation

Evaluated at the mean

Z

(Zakharov)

Light cone path Integral approach

Gaussian approximation

Evaluated at the mean

↓ W

(Wiedemann)

Beware of "improvements"

Summary articles

M.Gyulassy, I.V.,X-N.Wang, 'Quark-gluon plasma III, nucl-th/0302077

A.Kovner, U.Wiedemann, 'Quark-gluon plasma III, nucl-th/0304151

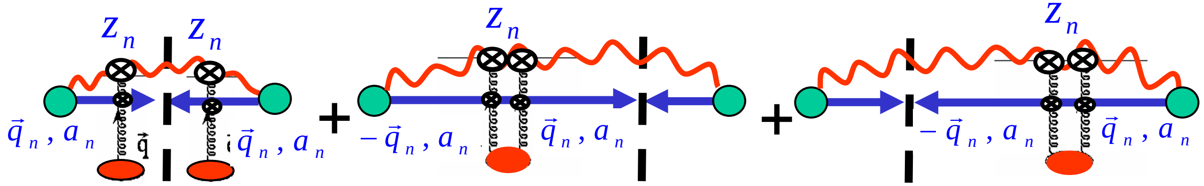
R.Baier et al., Ann.Rev.Nucl.Part.Sci.50 (2000)

Papers

- G. Bertsch, F. Gunion, Phys. Rev. **D25** 746 (1982)
- M. Gyulassy, X.-N. Wang, Nucl. Phys. **B420** 583-614 (1994); Phys. Rev. **D51** 3436-3446 (1995)
- R. Baier, Yu. Dokshitzer, A. Mueller, S. Peigne, D. Schiff, Nucl. Phys. **B483** 291-320 (1997); Phys. Rev. **C58** 1706-1713 (1998)
- B. Zakharov, JETP Lett. **65** 615-620 1997, JETP Lett. **73** 49-52 (2001)
- M. Gyulassy, P. Levai, I.V., Nucl. Phys. **B594** 371-419 (2001); Phys. Rev. Lett. **85** 5535-5538 (2000)
- U. Wiedemann, Nucl. Phys. **B588** 303-344 (2000), Nucl. Phys. **B582** 409-450 (2000)

Medium Induced Radiation

$\hat{R} =$



Applicable for realistic systems

Study the convergence of the series: 2, 3, 4, …n, … body correlations

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

– **Static medium**

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

– **1+1D Bjorken**

		Static	RHIC, LHC
Transport coefficient	$\hat{q} = \frac{\mu^2}{\lambda}$	OK	Bad
Parton rapidity density		-	OK

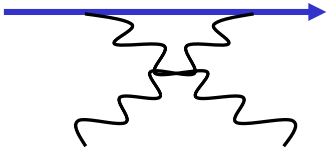
$\mu(RHIC) = gT \sim 1\ GeV$ $\quad \hat{q} = 4 - 14\ GeV^2/fm$ $\quad \lambda = 0.25 - 0.07\ fm$

$\mu(LHC) = gT \sim 2\ GeV$ $\quad \hat{q} = 30 - 100\ GeV^2/fm$ $\quad \lambda = 0.125 - 0.04\ fm$

$$\Delta E^{(1)} \propto \frac{C_R \alpha_s}{2} \left(\frac{\mu^2}{\lambda} \right)_0 \tau_0 L \dots$$

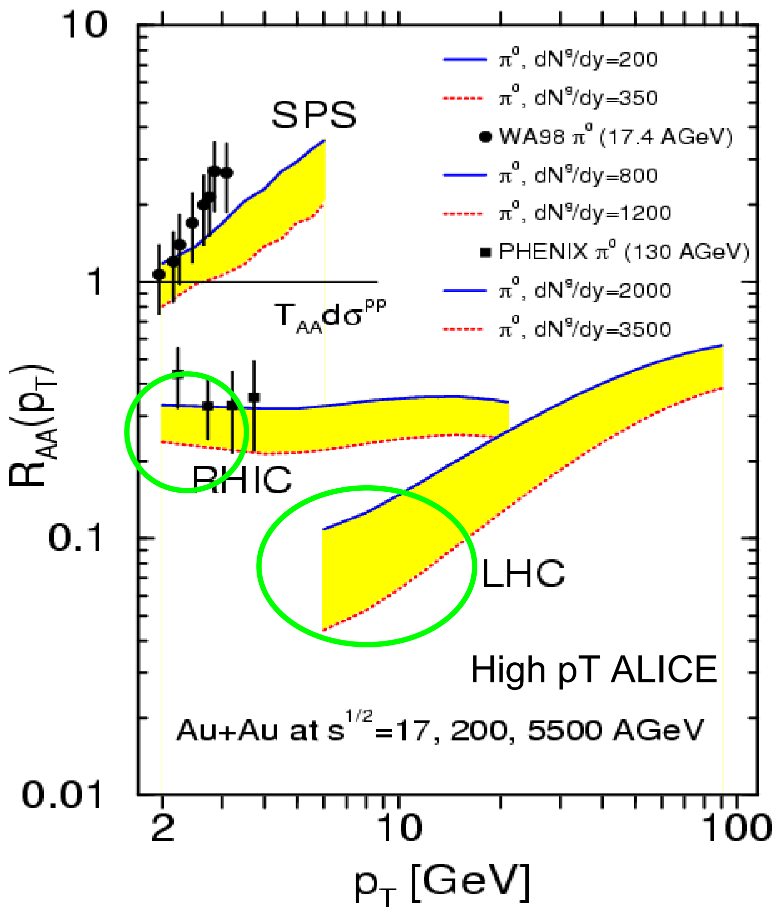
The constraint (all approaches):

Inconsistent with large number of scatterings approximation



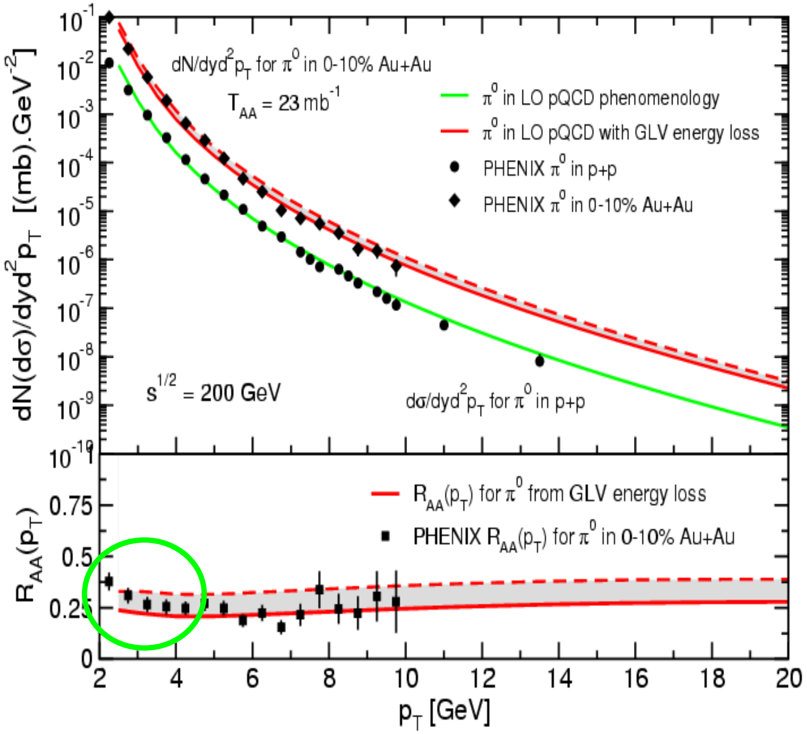
$\sim \quad e^{-\lambda\mu}$

Single Inclusive Quenching



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

- **Room for improvement at small and moderate p_T**



$$\rho = \frac{1}{\pi R^2}\frac{1}{\tau_0}\frac{dN^g}{dy}, \quad \pi R^2 = 120 \ \ fm^2, \ \ \tau_0 = 0.5 \ \ fm$$

RHIC **20 times e=E/V for deconfinement**

LHC **200 times e=E/V for deconfinement**

See also Wang et al., Paic et al., Eskola et al., Gale et al. ...

Coexistence RHIC II and LHC

Very important to be tested – establish the role of kinematics versus dynamics

- **The density dN^g/dy at the LHC is assumed 2-3 times larger**

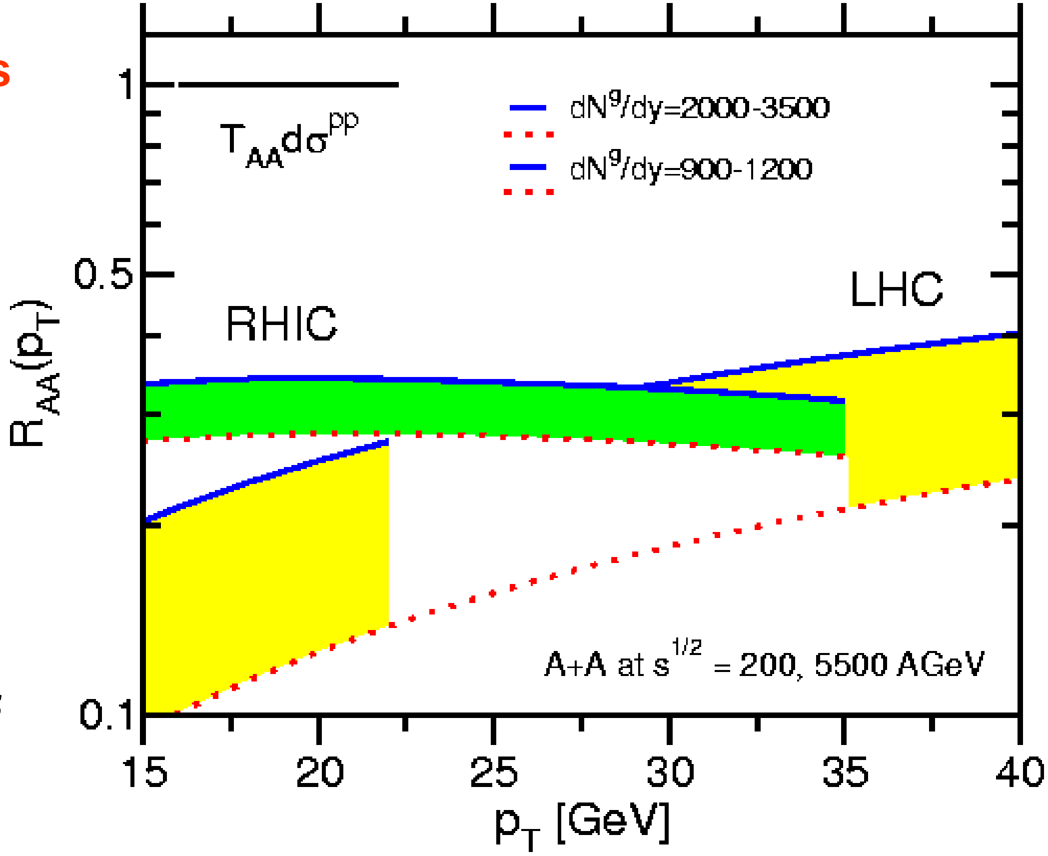
$$\Delta E \propto dN^g / dy \;\; Bjorken$$

- **This p_T range is dominated by gluons, not quarks, at the LHC**

$$\Delta E \propto C_A = 3 \;\; gluons, \;\; C_F = 4/3 \;\; quarks$$

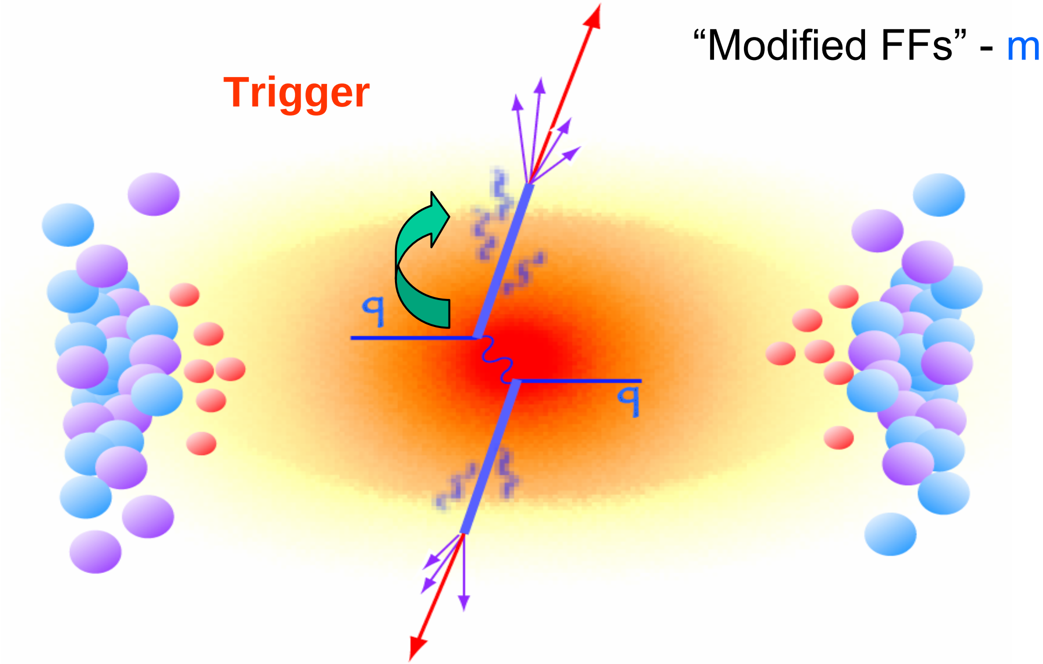
(analog to el. charge squared)

In spite of these factors in the 30-40 GeV range the suppression at RHIC increases - comparable or larger than at the LHC



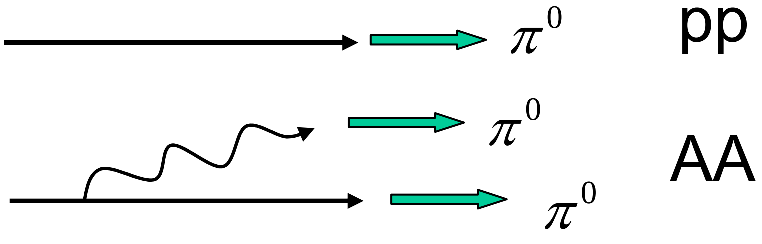
Can be only achieved only through comparison of similar quenching under different physics conditions

(Di)Hadrons and Feedback Energy



"Modified FFs" - misconception

- Not universal
- Kinematic redistribution of E



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

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

Known

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

Quenched parent parton

Feedback gluons

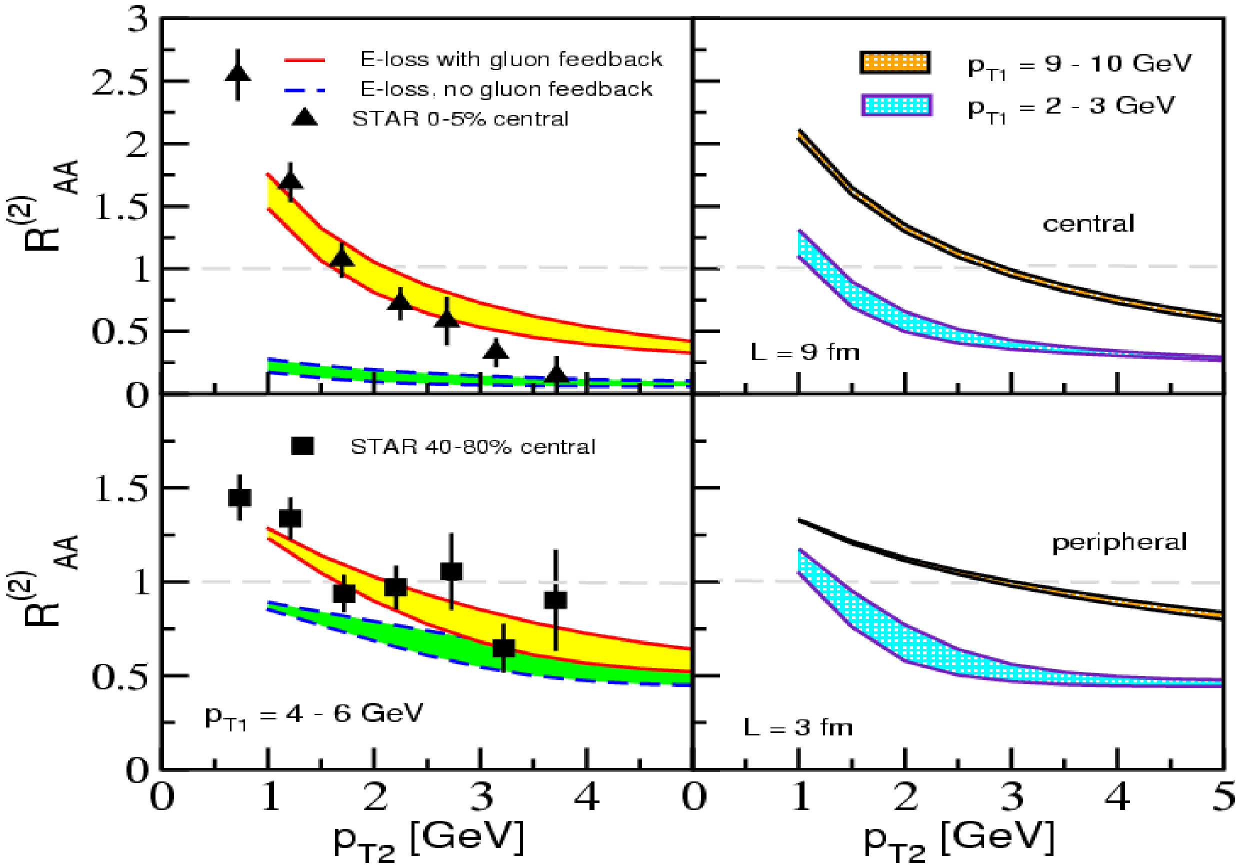
New

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

- Use energy conservation to verify the fragmentation sum rule

I.V., Phys.Lett.B in press, hep-ph/0501255

Example of E-Redistribution



Data is from:

J.Adams *et al.*, Phys.Rev.Lett. in press, nucl-ex/0501016

Very interesting as a function of trigger

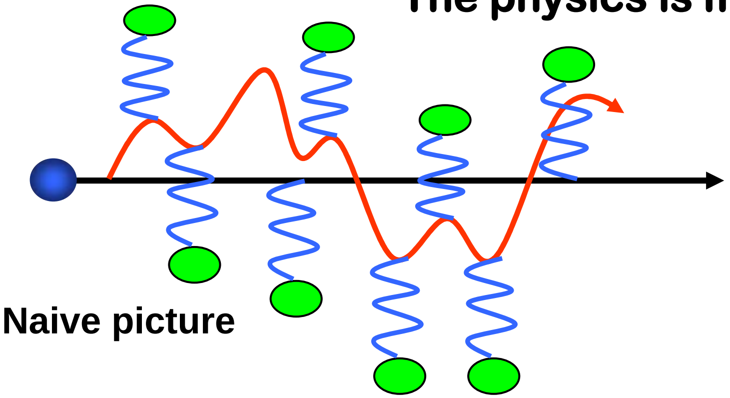
Even more important at the LHC

ALICE, ATLAS, CMS

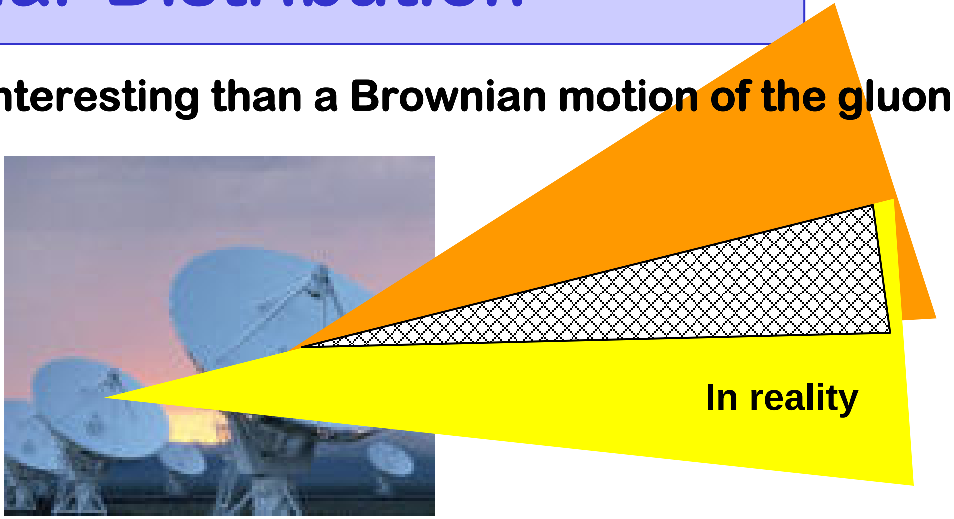
- **To be implemented in the single inclusives (extend to lower p_T at the LHC)**
- **For tagged jets - radiative gluons to unexpectedly high p_T ("FFs")**
- **The angular distribution?**

Angular Distribution

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

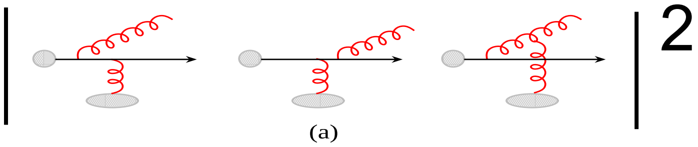


Naive picture

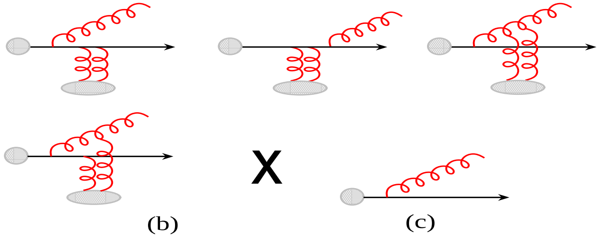


$i(-i)=1 \qquad i\,(i)=-1=\cos(\pi)$

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



+2Re



Solution to first order in the mean # of scatterings

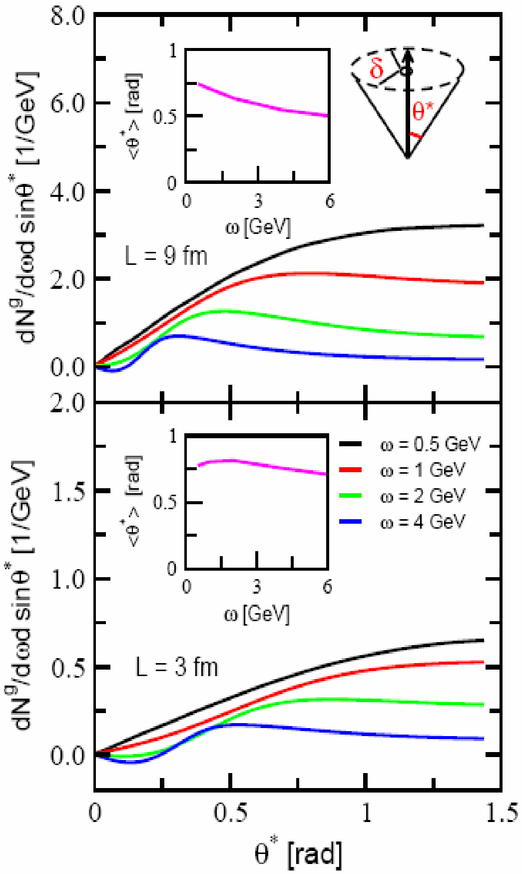
$$\frac{dN^g{}_{med}}{d\omega\, d\sin\theta^*\, d\delta} \approx \frac{2C_R\alpha_s}{\pi^2}\int_{z_0}^{L}\frac{d\Delta z}{\lambda_g(z)}\int_0^\infty dq_\perp q_\perp{}^2\,\frac{1}{\sigma_{el}}\frac{d\sigma_{el}}{d^2 q_\perp}$$

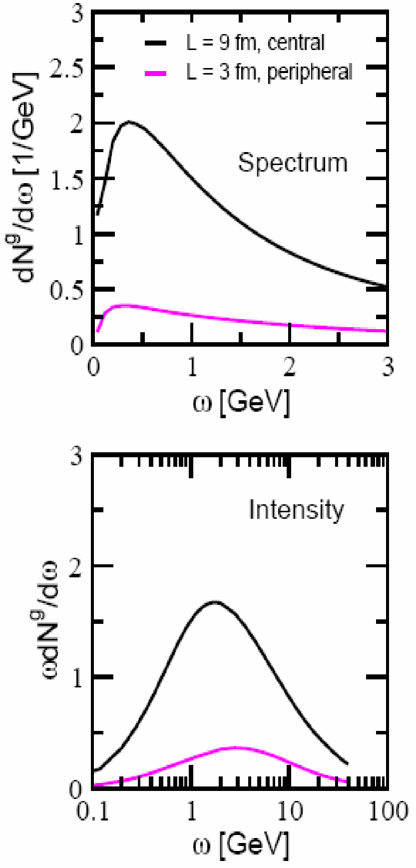
$$\times\int_0^{2\pi} d\alpha\,\frac{\cos\alpha}{(\omega^2\sin^2\theta^* - 2q_\perp\omega\sin\theta^*\cos\alpha + q_\perp^2)}$$

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

I.V., Phys.Lett.B in press, hep-ph/0501255

Angular Distribution (Jet Cone)



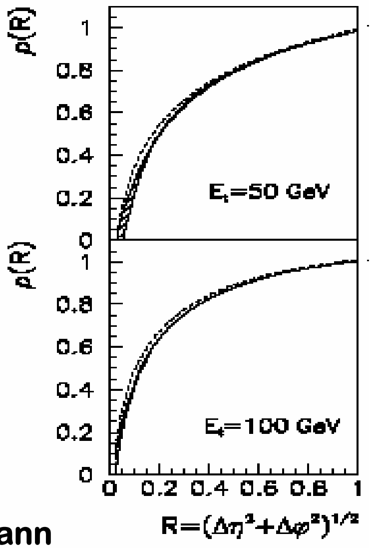


- **Radiation is** **moderately large angle** **(cancellation near the jet axis)**
- **Finite** **gluon number. E carried be few 0.5 – 5 GeV gluons 0.25 – 0.75 rad**

Choices for opening angles $(\theta *)$

$$R = \sqrt{\Delta\eta^2 + \Delta\phi^2} \quad = \ 0.4, 0.7, 1$$

- **Promising**
- **To be done for LHC kinematics**



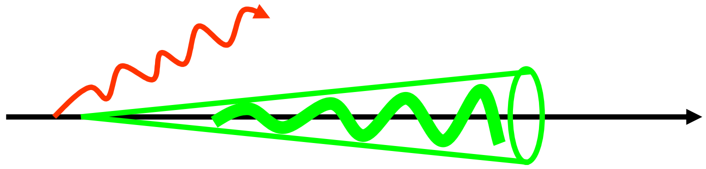
Previous study found less than 10% effect

C.A.Salgado, U.Wiedemann Phys.Rev.Lett. (93) 2004

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

Mass Effects on E-Loss

Cutting out part of the available phase space



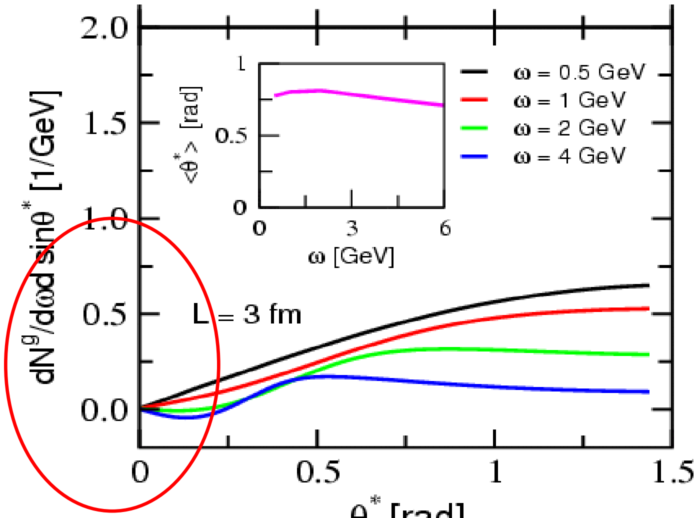
$$\left[\omega_{(1\ldots n)}\right]^{-1} \rightarrow \left[\omega_{(1\ldots n)} + \frac{m_g^2 + x^2 M^2}{2xE}\right]^{-1}$$

$$\frac{\vec{k}_\perp}{\vec{k}_\perp^{\,2}} \rightarrow \frac{\vec{k}_\perp}{\vec{k}_\perp^{\,2} + m_g^2 + x^2 M^2}, \quad x = \frac{k^+}{p^+} \approx \frac{\omega}{E}$$

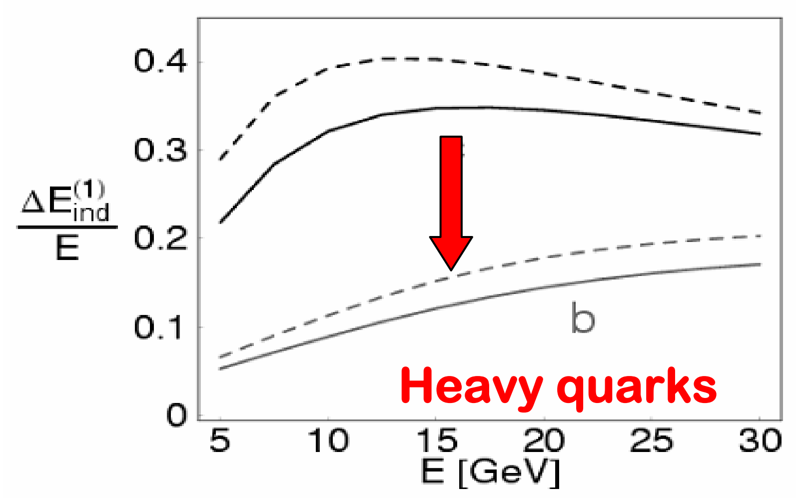
"Dead cone"

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

Note that the characteristic features of E-loss are related to the interference phases (QM versus PS)



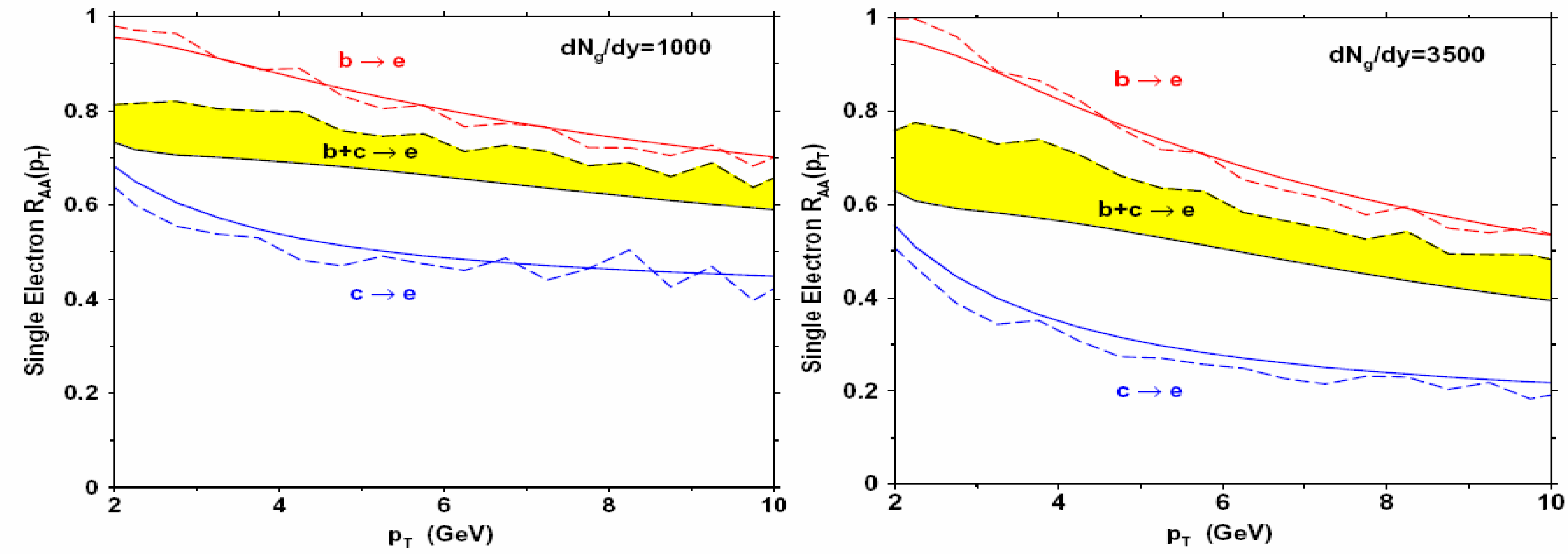
Not a large contribution



Reduction of E-loss

M.Djordjevic, M.Gyulassy, Nucl.Phys.A (2004)

Heavy Quarks R_{AA}



M.Djordjevic, M.Gyulassy, R.Vogt, nucl-th/0507019 See also Armesto, et al.

The R_{AA} for charm can be reach values of 1/4 but bottom is limited to 1/2
One should be careful about the physical meaning of the parameters!

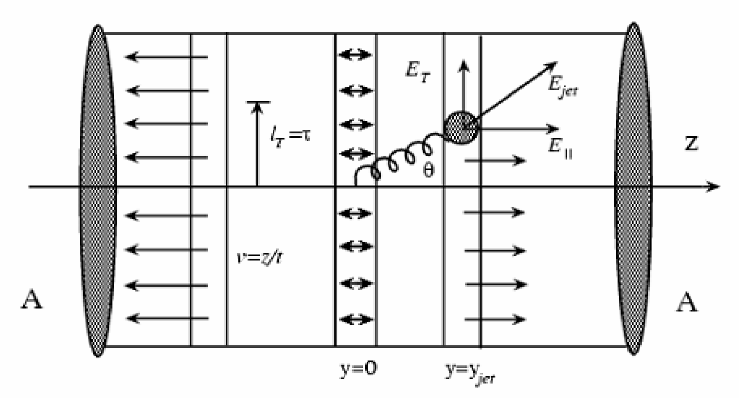
$dN^g/dy = 3500$ $\hat{q} = 15\ GeV^2/fm$ Where does one get such parameters from?

Are these leptons from heavy mesons? (Coctail methods…) FVTX

What are the different attenuation mechanisms for heavy mesons?

Forward Y (Di)Jet Quenching

Very relevant to ATLAS and CMS

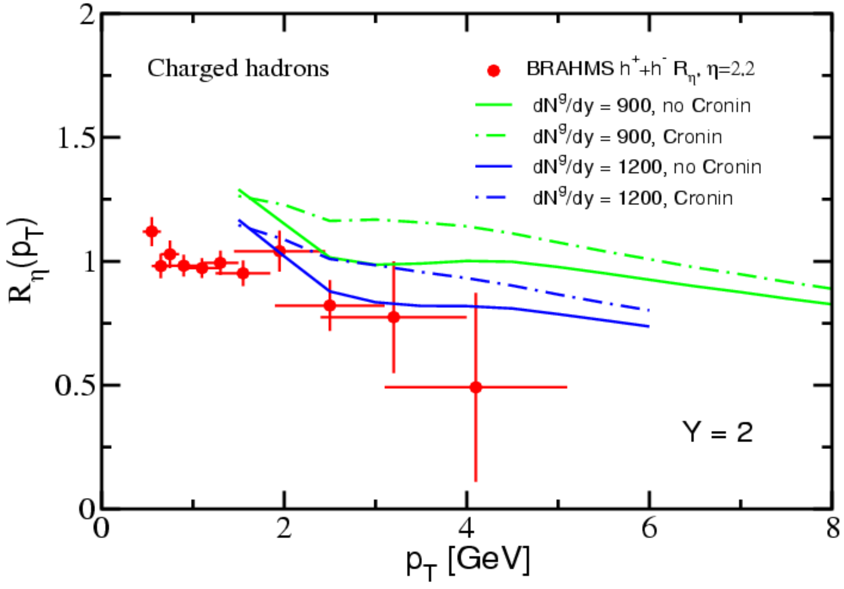


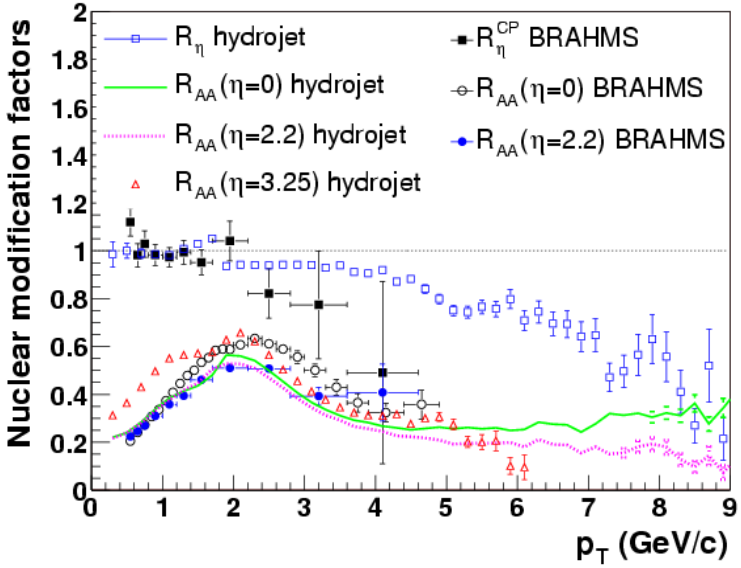
Baseline: $$\frac{d\sigma}{dy\,d^2p_T} = \frac{a}{(p_0+p_T)^n} \approx \frac{a}{p_T{}^n}$$

$$\frac{\Delta E}{E} \propto \frac{L}{A_\perp}\frac{dN^g}{dy} \propto A^{2/3} \propto N_{part}^{2/3}$$

Start from: $p_T + \Delta p_T$

$$R_{AA} = \frac{1}{\left(1+\dfrac{\Delta p_T}{p_T}\right)^{n-2}} = \frac{1}{\left(1+\kappa' N_{part}^{2/3}\right)^{n-2}}$$



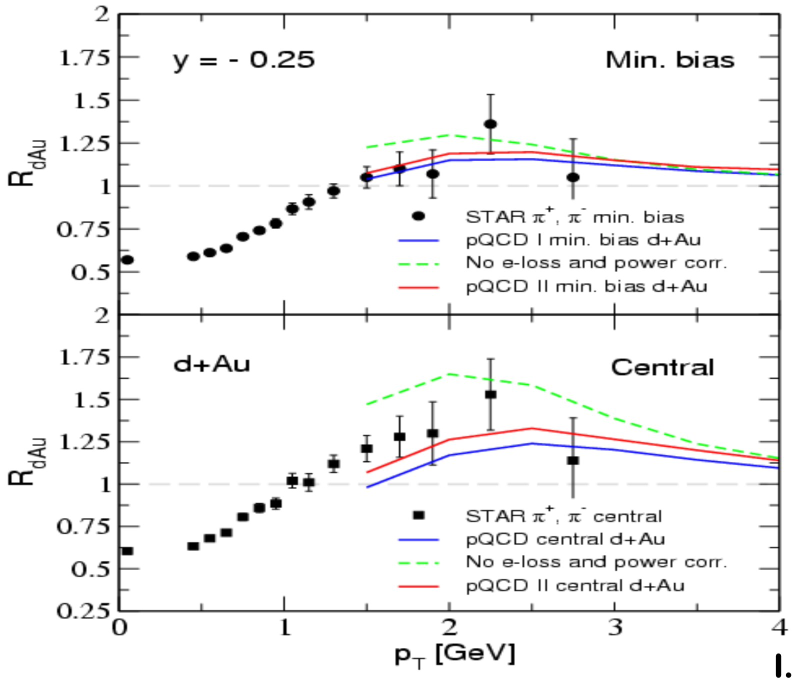


A.Adil, M.Gyulassy, I.V. in preparation

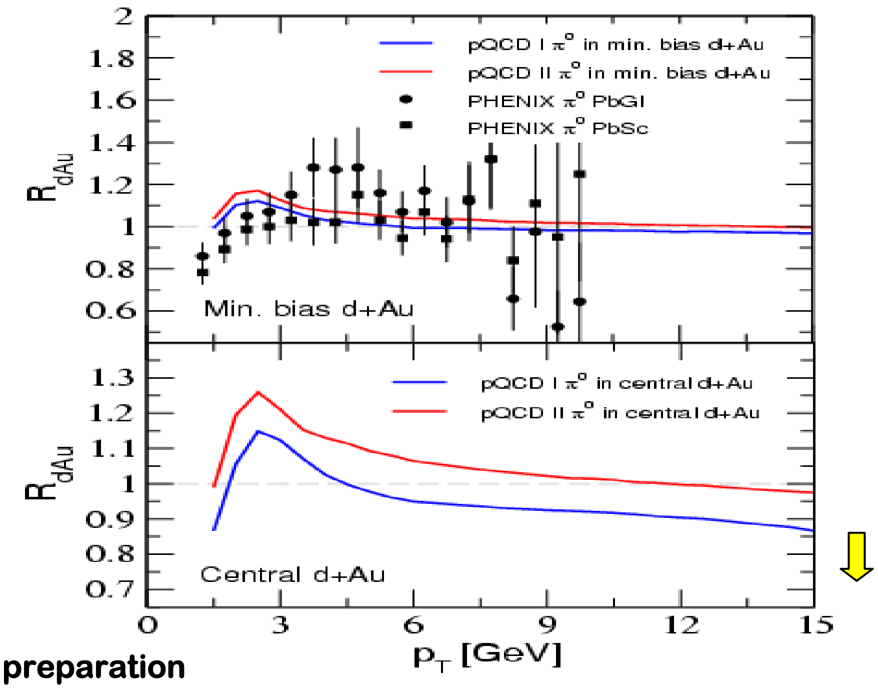
T.Hirano, Y.Nara, Phys.Rev.C68 (2003)

E-Loss in Cold Nuclear Matter

A number of nuclear effects: Cronin, power corrections, energy loss



I.V. in preparation



$$\frac{\omega dN^{g}{}_{med}}{d\omega d^2k_\perp} \approx \frac{C_A\alpha_s}{\pi^2}\left(\frac{L}{\lambda}\right)\left\langle \frac{q_\perp{}^2}{k_\perp{}^2(k_\perp - q_\perp)^2}\right\rangle_{q\perp} \to \frac{C_A\alpha_s}{\pi^2}\left(\frac{L}{\lambda}\right)\frac{\mu^2}{k_\perp{}^2(k_\perp{}^2+q_\perp{}^2)}$$

Parton splitting, not parton fusion

$$\frac{\Delta E}{E} \propto \frac{C_A\alpha_s}{\pi}\left(\frac{L}{\lambda}\right)\ln\frac{\mu^2}{\Lambda^2}$$

Substantial: ? not "Are they sufficient"
"Why are they so small"

B.Z. Kopeliovich, J. Nemchik, I.K. Potashnikova, M.B. Johnson, I. Schmidt, hep-ph/0501260

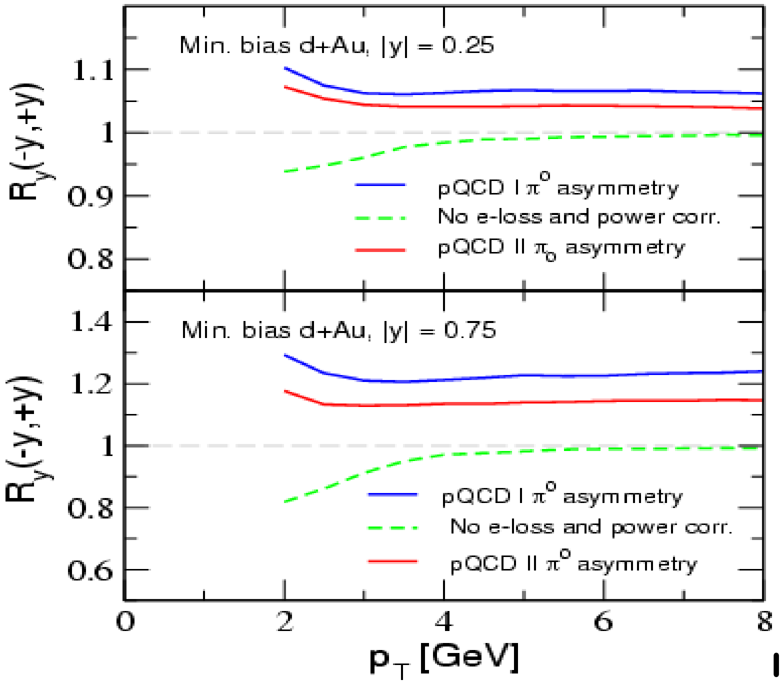
On the example of Drell-Yan or di-jets (effective rapidity shift)

$$\Delta y(mid\ \ rap.) = 0.25 - 0.35 \qquad \Delta y(\,forward\,) = 0.08 - 0.12$$

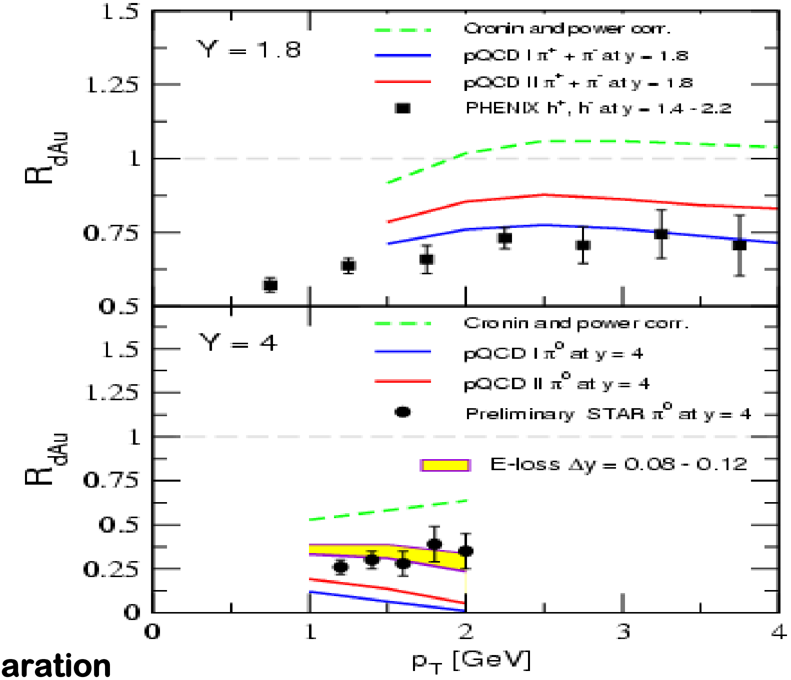
K.Werner, F.Liu, T.Pierog, hep-ph/0506232

Forward Observables

Rapidity asymmetry



Forward Y suppression



I.V. in preparation

- Reduces the centrality dependence of the Cronin effect around Y=0
- Generates rapidity asymmetry (from backward enhancement to forward supression)
- Consistent with suppression at smaller C.M. energies (NA35 at 17 GeV)
- Indicative of Y and p_T dependence of the cold nuclear matter quenching – to be studied in detail for LHC applications

T.Goldman, M.Johnson,J.Qiu,I.V. in preparation (similar results for heavy quarks)

Conclusions

- Energy loss formulations to all orders on the mean number of scatterings exist. Should be formulated in terms of transparent physical quantities. Correctly incorporated in the pQCD calculations.
- Inclusive particle quenching is the first handle on the densities achieved in heavy ion collisions. At RHIC extracted $e = 15$ GeV/fm^3 At the LHC anticipated $e > 200$ GeV/fm3
- Redistribution of the energy. For tagged to p_T=4 GeV at RHIC and much higher at the LHC. In terms of angular re-distribution of the energy - large and measurable according to the calculated distributions.
- "Heavy quarks" don't seem to be consistent with normal densities. Are these heavy quarks? Is this the correct e-loss mechanism?
- Forward rapidity particle production is indicative of power corrections and energy loss. Cold nuclear matter energy loss should be studied great detail for applications at the LHC.