Z^0 Tagged Jets as a Probe of the QGP

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In collaboration with

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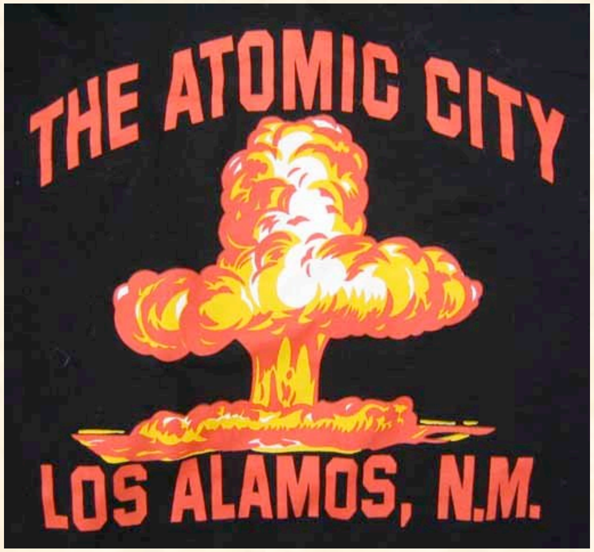
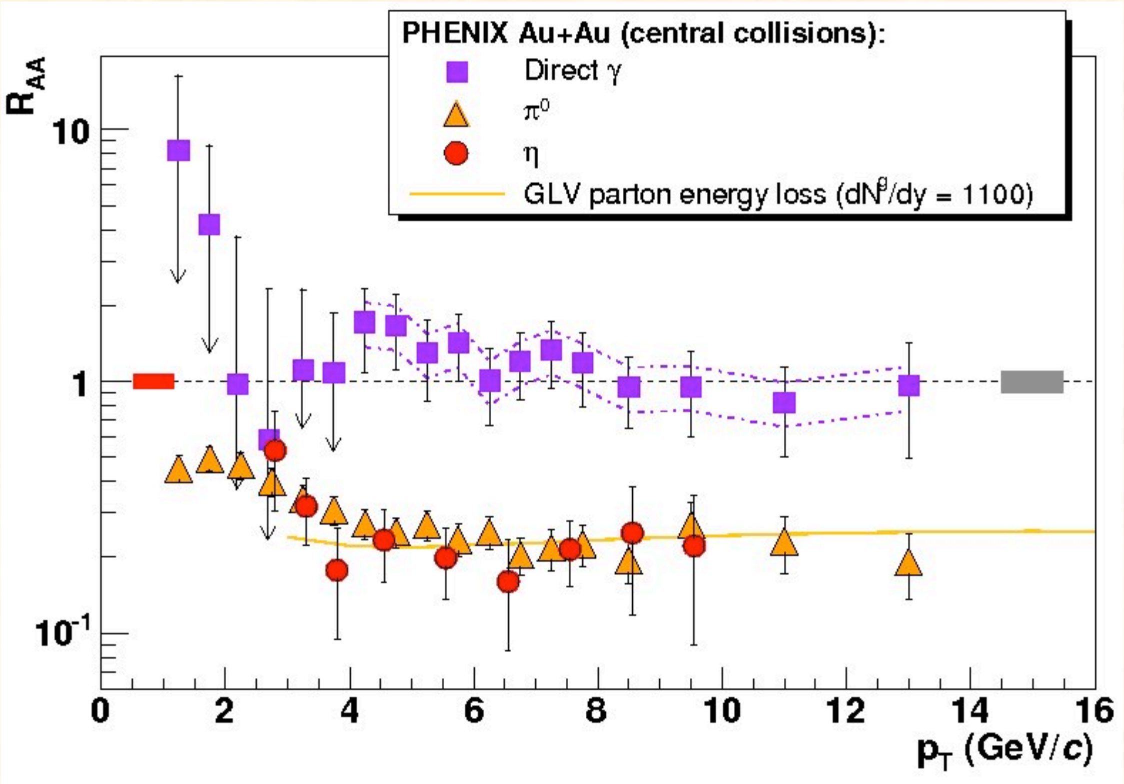


Presentation of work done at
Los Alamos National Lab

Introduction

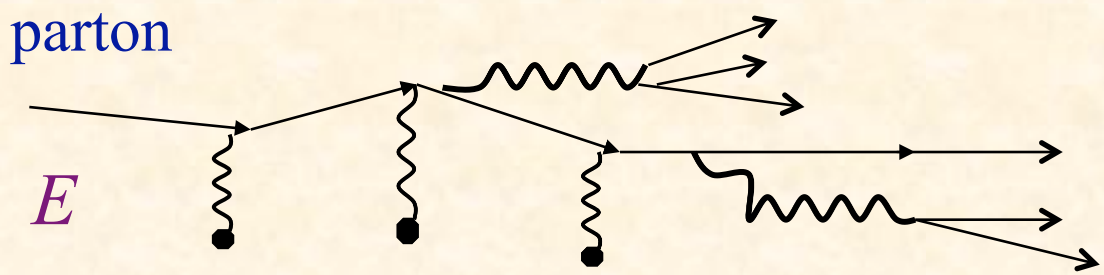
Jet Quenching at RHIC – experimentally well established



$$R_{AA}(p_T,\eta) = \frac{1}{< N_{coll} >} \cdot \frac{d^2\sigma^{AA} / d\eta dp_T}{d^2\sigma^{NN} / d\eta dp_T}$$

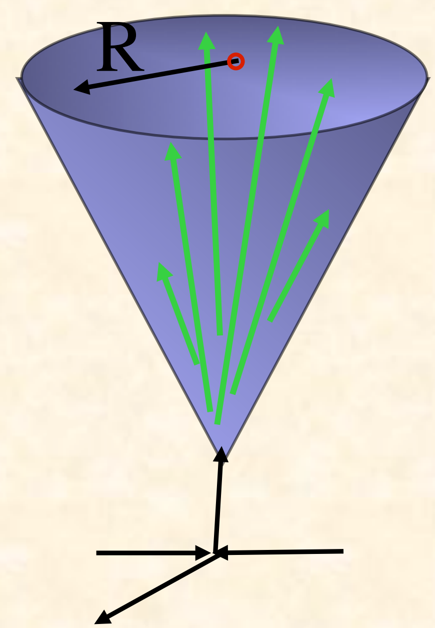
Jet quenching as a probe of QGP

- Large leading particle suppression strong evidence for formation of QGP in HIC
- Parton energy loss sensitive probe of medium density, Debye scale, strong coupling, transport coefficients



Limitations of leading particle suppression

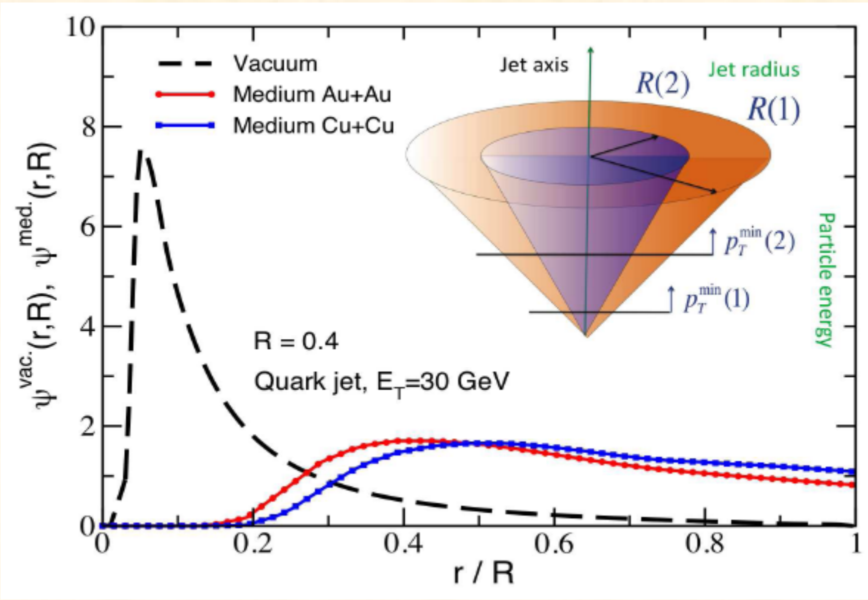
- R_{AA} for single particle or I_{AA} for two particle correlations only measure the leading fragments of a jet.
- Jets: a spray of final-state particles moving roughly in the same direction.
- LP R_{AA} can be fit by formalisms with very different assumptions



$$R_{ij} = \sqrt{(y_i - y_j)^2 + (\phi_i - \phi_j)^2}$$

The future of jet quenching physics- Jet shapes and jet cross sections

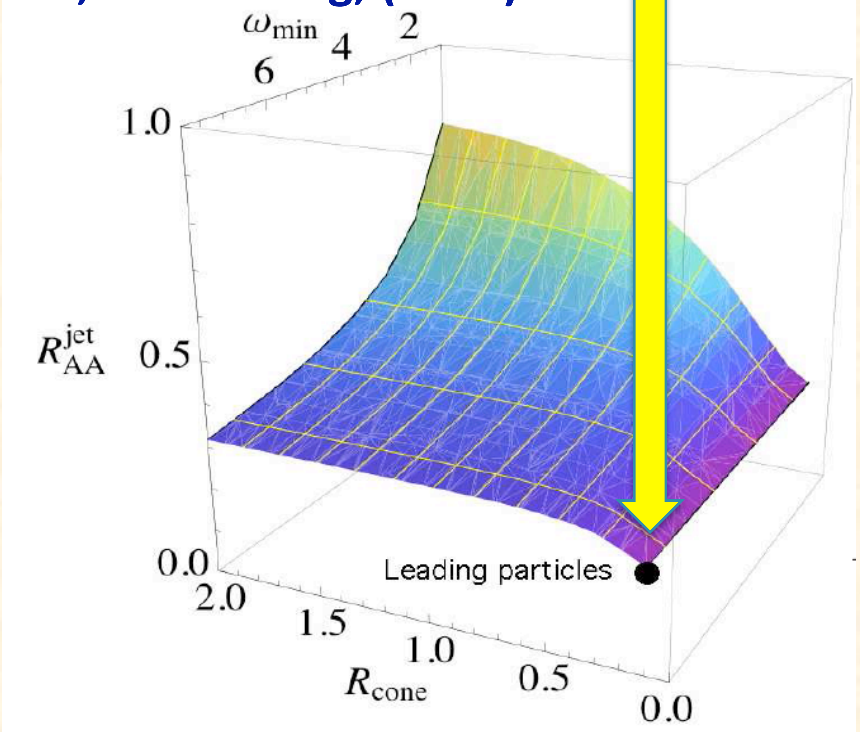
Explore the fraction of energy lost and variation of R_{AA} with changing cone radius/p_{Tmin}



$$\Psi_{\rm int}(r;R) = \frac{\sum_i (E_T)_i \Theta(r-(R_{\rm jet})_i)}{\sum_i (E_T)_i \Theta(R-(R_{\rm jet})_i)},$$

$$\psi(r;R) = \frac{d\Psi_{\rm int}(r;R)}{dr}.$$

IV, B.-W Zhang, (2008)



A theory of jet shapes and cross sections: from hadrons to nuclei,

I Vitev, S Wicks, BWZ, JHEP 0811,093 (2008)

Investigated for inclusive jets using GLV energy loss formalism

Number of scatterings — Momentum transfers

$$k^+ \frac{dN_g}{dk^+ d^2 k_\perp} = \sum_{n=1}^{\infty} k^+ \frac{dN^n{}_g}{dk^+ d^2 k_\perp} = \sum_{n=1}^{\infty} \frac{C_R \alpha_s}{\pi^2} \left[\prod_{i=1}^{n} \int_0^{L - \sum_{j=i+1}^{n} \Delta z_j} \frac{d\Delta z_i}{\lambda_g(z_i)} \int d^2 q_i \left(\frac{1}{\sigma_{el}} \frac{d\sigma_{el}}{d^2 q_i} - \delta^2(q_i) \right) \right]$$

$$\times \left[-2 C_{(1\ldots n)} \cdot \sum_{m=1}^{n} B_{(m+1\ldots n)(m\ldots n)} \left(\cos\left(\sum_{k=2}^{m} \omega_{(k\ldots n)} \Delta z_k \right) - \cos\left(\sum_{k=1}^{m} \omega_{(k\ldots n)} \Delta z_k \right) \right) \right]$$

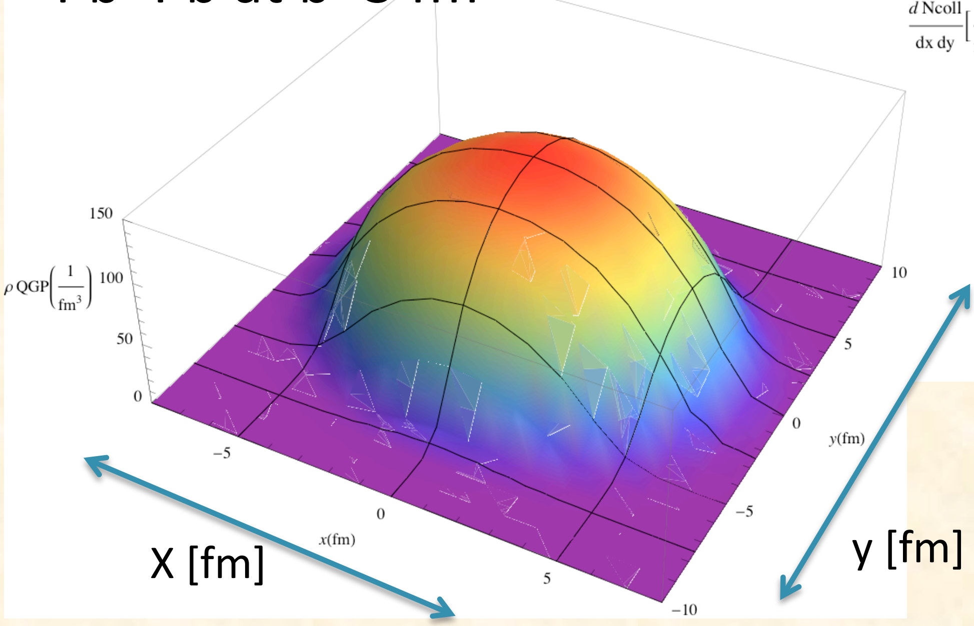
Color current propagators — Coherence phases (LPM effect)

Initial Geometry

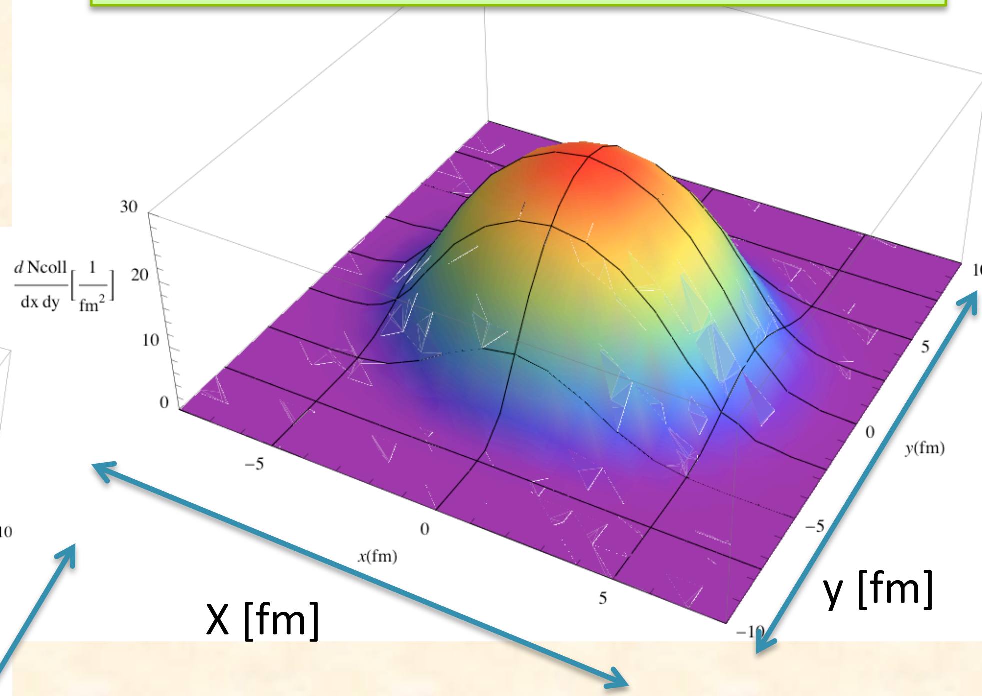
$S^{1/2}_{NN}$ = 5.5 TeV, σ_{in} = 65 mb
Optical Glauber

QGP density (3D) ~ participant density (2D)

Pb+Pb at b=3 fm



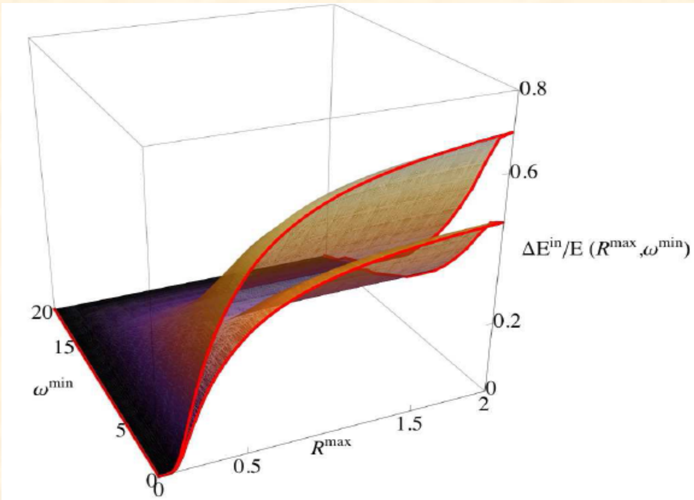
Binary collision density (2D) – corresponds to jet production

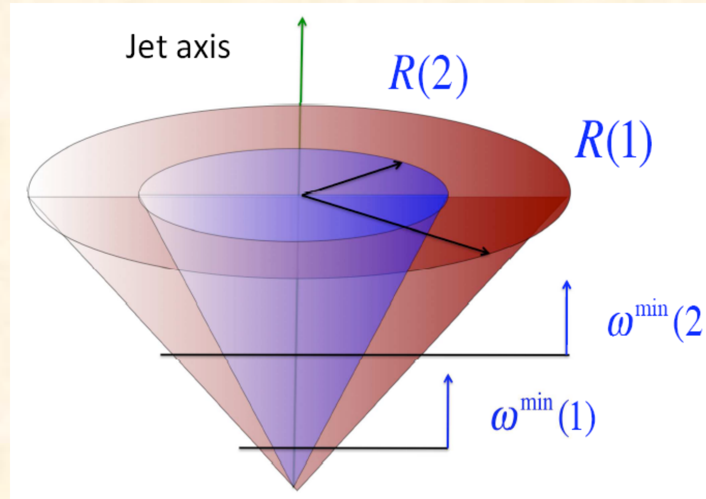


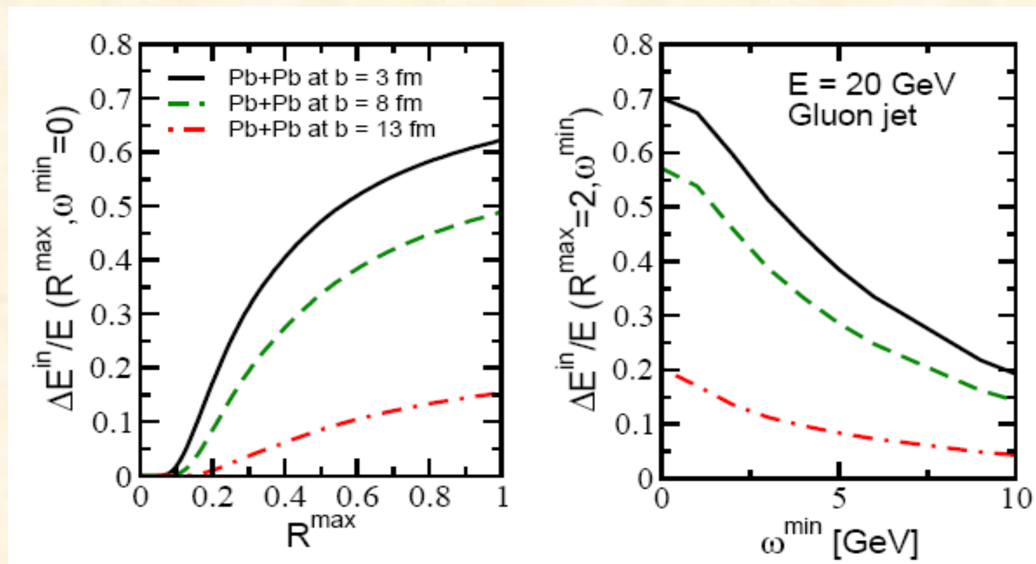
- Note the difference in the distributions

Energy loss distribution

$$\frac{\Delta E^{in}}{E}(R^{\max},\omega^{\min}) = \frac{1}{E}\int_{\omega^{\min}}^{E} d\omega \int_{0}^{R^{\max}} dr \frac{dI^{g}}{d\omega dr}(\omega, r)$$







- **Energy ratio goes down with larger b.**
- **Energy ratio becomes smaller with smaller R and larger $\omega^{\min}$**

Inclusive Jet cross section @HIC and R_{AA}

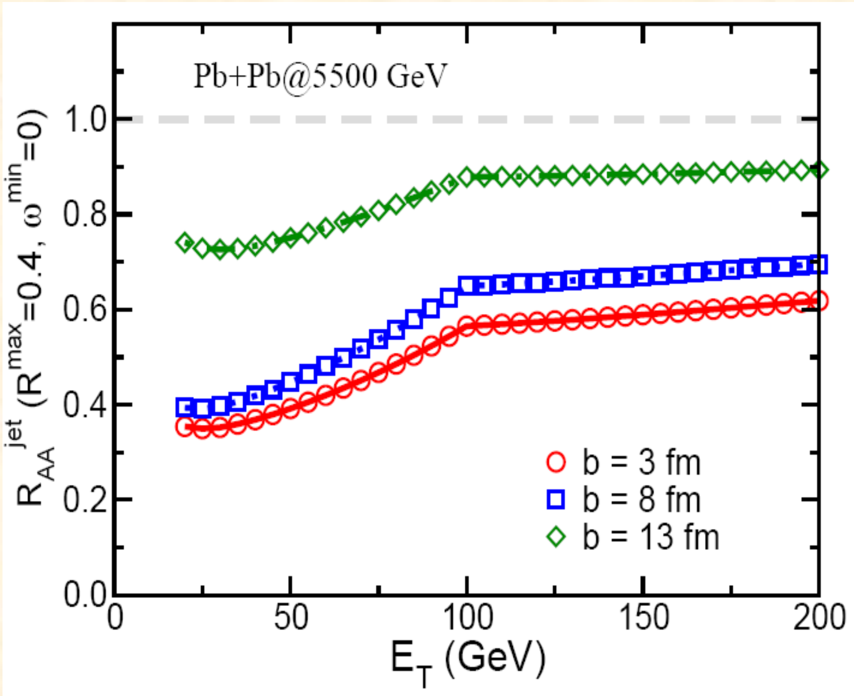
$$\frac{\sigma^{AA}(R,\omega^{\min})}{d^2E_T dy} = \int_{\epsilon=0}^{1} d\epsilon \sum_{q,g} P_{q,g}(\epsilon) \frac{1}{(1-(1-f_{q,g})\cdot\epsilon)^2} \frac{\sigma^{NN}_{q,g}(R,\omega^{\min})}{d^2E'_T dy}$$

$$E'_T = E_T/(1-(1-f_{q,g})\cdot\epsilon)$$

$$f = \frac{\Delta E_{\rm rad}\{(0,R);(\omega^{\min},E)\}}{\Delta E_{\rm rad}\{(0,R^{\infty});(0,E)\}}$$

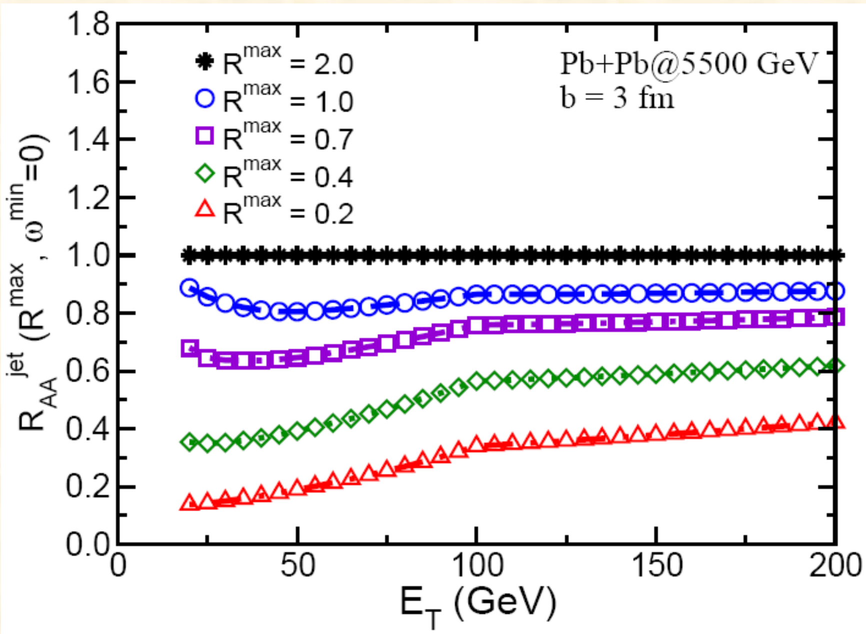
Define nuclear modification factor for jet cross section:

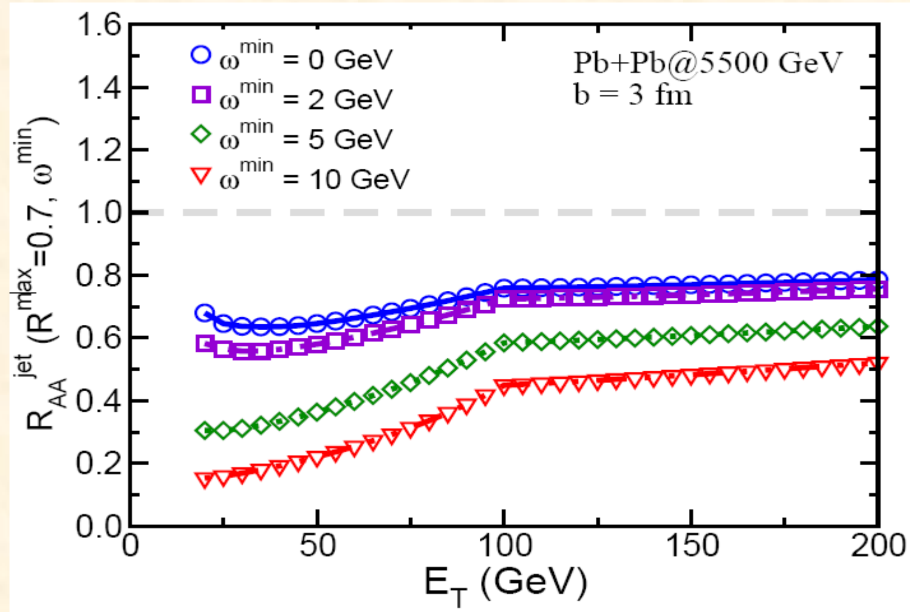
$$R^{\rm jet}_{AA}(E_T;R^{\max},\omega^{\min}) = \frac{\frac{d\sigma^{AA}(E_T;R^{\max},\omega^{\min})}{dyd^2E_T}}{\langle N_{\rm bin}\rangle \frac{d\sigma^{pp}(E_T;R^{\max},\omega^{\min})}{dyd^2E_T}}$$



Centrality dependence of R_{AA} for jet cross section is similar to that for single hadron production

R_{AA} vs R^{max} and ω^{min}





- R_{AA} for jet cross section evolves continuously by varying cone size and acceptance cut.
- Contrast: single result for leading particle
- Limits: R_{AA} approaches to single hadron suppression with R^{max} and large ω^{min}

Tagging with Z^0 boson

Tagged Jets

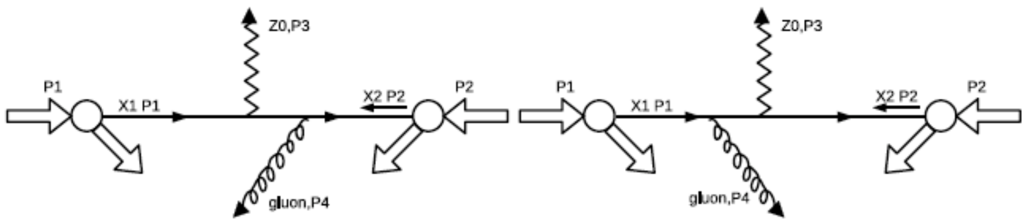


Figure 1: Diagrams contributing to Z^0 + gluon jet production.

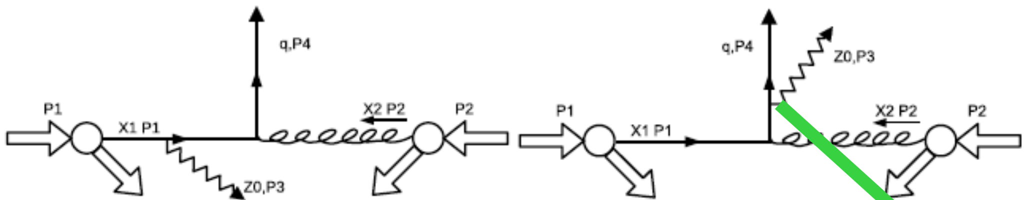


Figure 2: Diagrams contributing to Z^0 + (anti)quark jet production.

$$R_q^2 + L_q^2 = \tau_q^2 - 4\, e_q\, \tau_q\, \sin^2\theta_w + 8\, e_q^2\, \sin^4\theta_w \, .$$

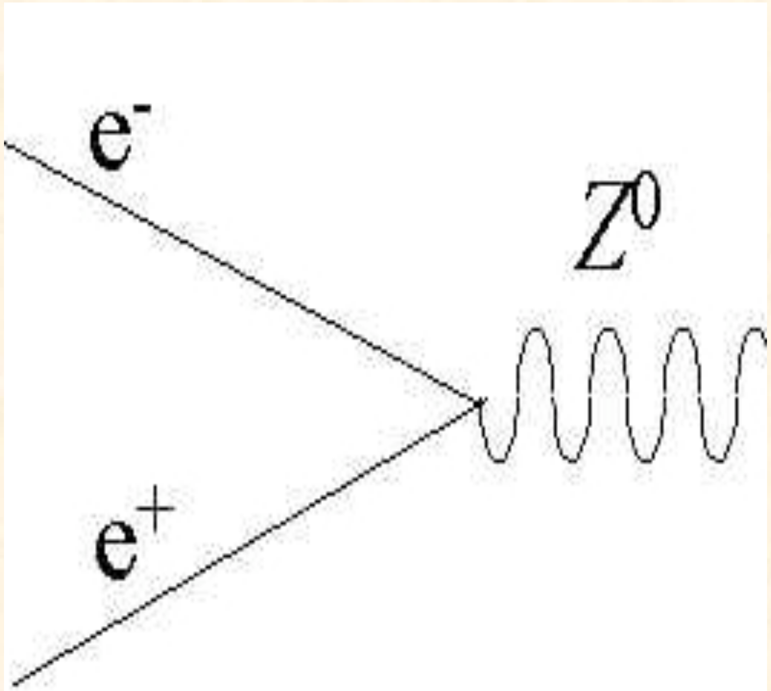
$$\frac{d\sigma}{dy_3\, dy_4\, d^2 p_T} = \frac{|M|^2\, \delta(x_1 - \bar{x}_1)\delta(x_2 - \bar{x}_2)}{(2\pi)^2\, 4\, x_1\, x_2\, S^2}$$

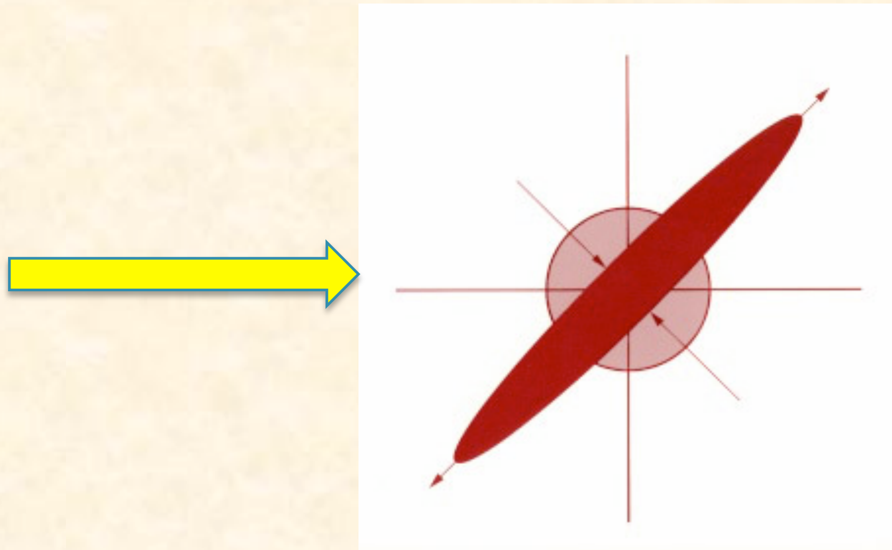
$$|M_T|^2 = \frac{32\,\pi}{9\sqrt{2}}\, \alpha_s\, G_F\, m_z^2\, Q_{EW} \left(\frac{\hat{t}^2 + \hat{u}^2 + 2\,\hat{s}\, m_z^2}{\hat{t}\hat{u}} \right)$$

$$+(\hat{u} \to -\hat{s},\ \hat{s} \to \hat{u})$$

- **Consider both Z^0+jet and γ*+jet (small correction)**
- **Z^0+jet has small yield, but is excellent handle for jet energy loss**

From Z^0 to dileptons

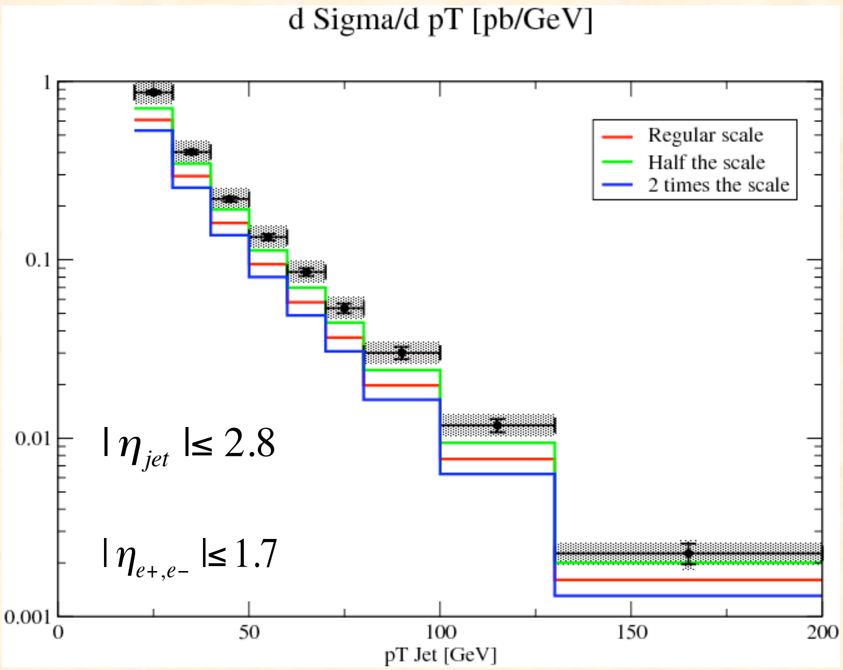


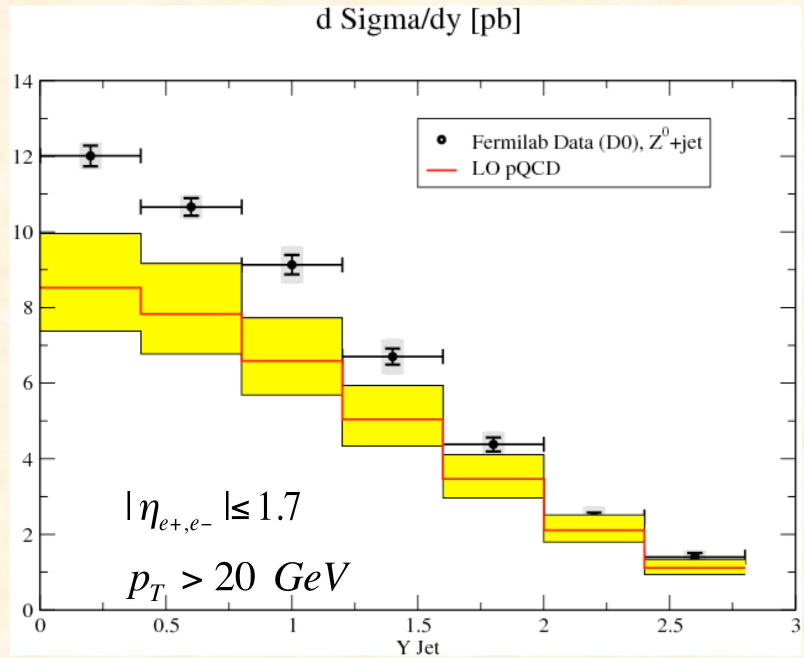


- **Experimentally, dileptons are observed. We perform the decay by a Lorentz boost weighted with branching ratio.**

Comparison to Data

- Z^0+jet measurements recently became available





- As expected within 30% - 50% of the data. Shape is reasonably well described, NLO in progress

At LO, quenched cross section takes simple form, probes P(ε), f

$$\frac{d\sigma}{dy_3\, dy_4\, dp_T^3\, dp_{TQ}^4} = P\Big(\frac{1-\frac{p_{TQ}^4}{p_T^3}}{1-f}\Big)_{q,g} \frac{|M|^2\,\delta(x_1-\bar{x}_1)\delta(x_2-\bar{x}_2)}{(2\pi)^2\, 4\, x_1\, x_2\, S^2\,(1-f)}$$

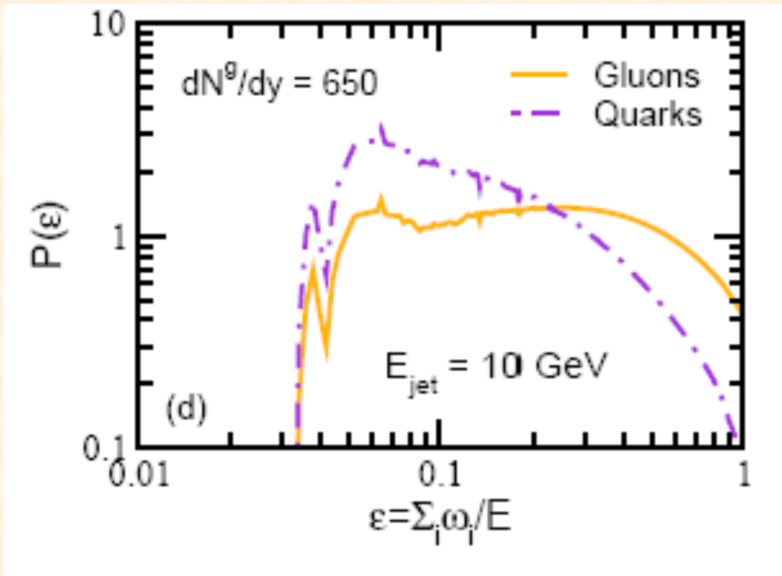
$$\varepsilon = \sum_{i=1}^{n} \frac{\omega_i}{E}, \quad P(\varepsilon) = \sum_{0}^{\infty} P_n(\varepsilon) \quad P_0(\varepsilon) = e^{-\langle N_g \rangle}\delta(\varepsilon)$$

$$P_1(\varepsilon) = \frac{dN}{d\varepsilon}(\varepsilon), \; P_n(\varepsilon) = \frac{1}{n}\int_0^{\varepsilon} d\varepsilon'\; P_{n-1}(\varepsilon-\varepsilon')\frac{dN}{d\varepsilon}(\varepsilon')$$

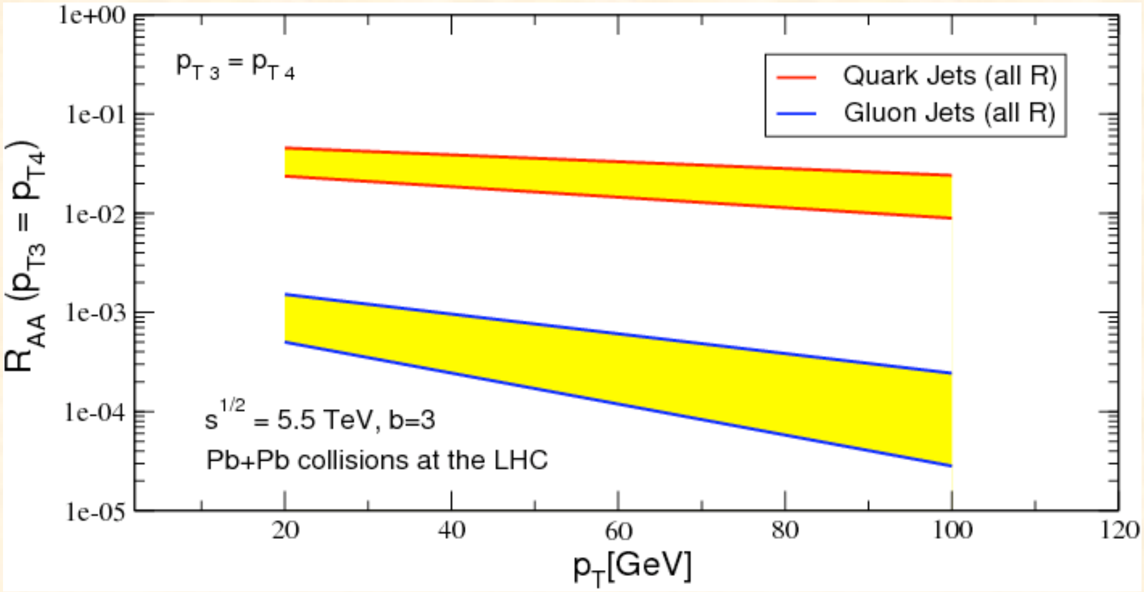
$$\int_0^1 d\varepsilon'\; P(\varepsilon') = 1, \qquad \int_0^1 d\varepsilon'\; \varepsilon' P(\varepsilon') = \left\langle \frac{\Delta E}{E} \right\rangle$$

GLV, BDMPS (ASW)

Example of probability density



Obtaining the number of radiated gluons



Constrain $p_{T3} = p_{T4}$

$$\langle N^g \rangle = -\ln (R_{AA})$$

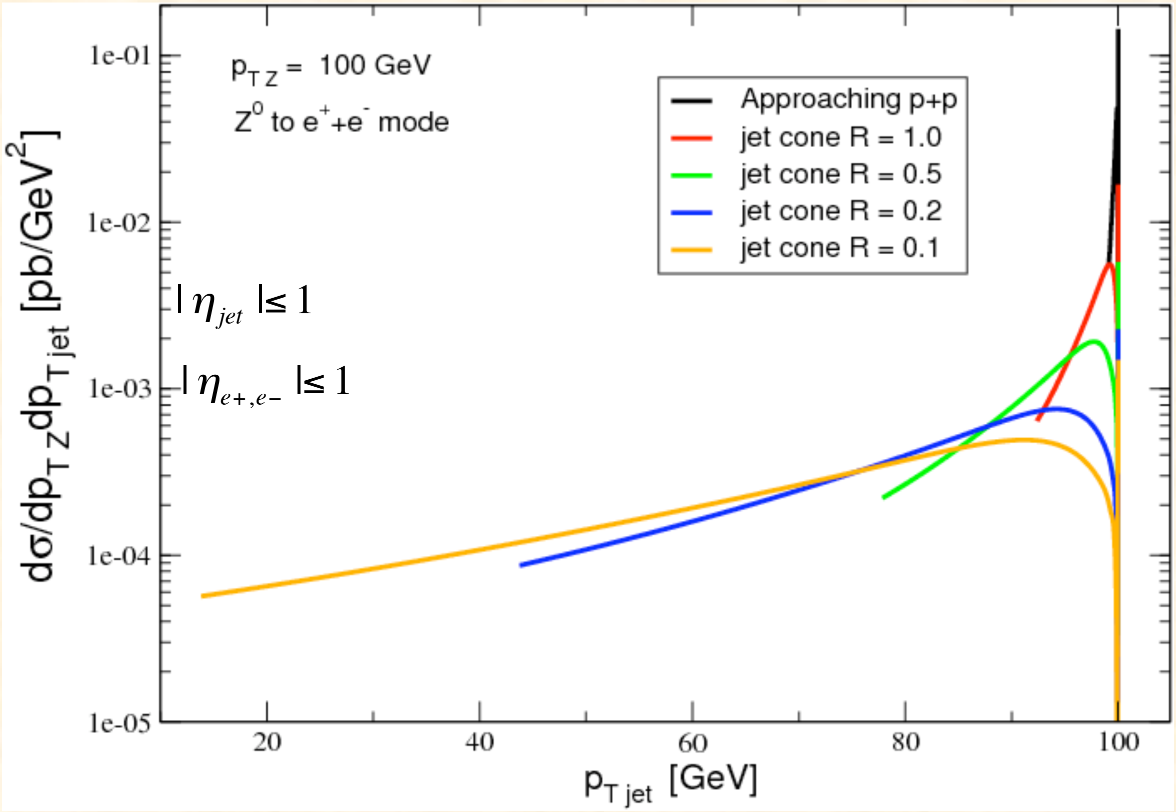
The form of the quenched cross section

Consider $p_{T\,jet} < p_{T\,Z}$

$$\frac{d\sigma^{Quench}}{dy_Z dy_{jet} dp_{T\ Z} dp_{T\ jet}} =$$

$$\sum_{q,g} \frac{d\sigma^{pp}}{dy_Z dy_{jet} dp_{T\ Z}} \times \frac{1}{p_{T\ Z}(1-f_{q,g})}$$

$$\times P\left(\frac{1 - p_{T\ jet}/p_{Z\ jet}}{1-f_{q,g}}\right)$$

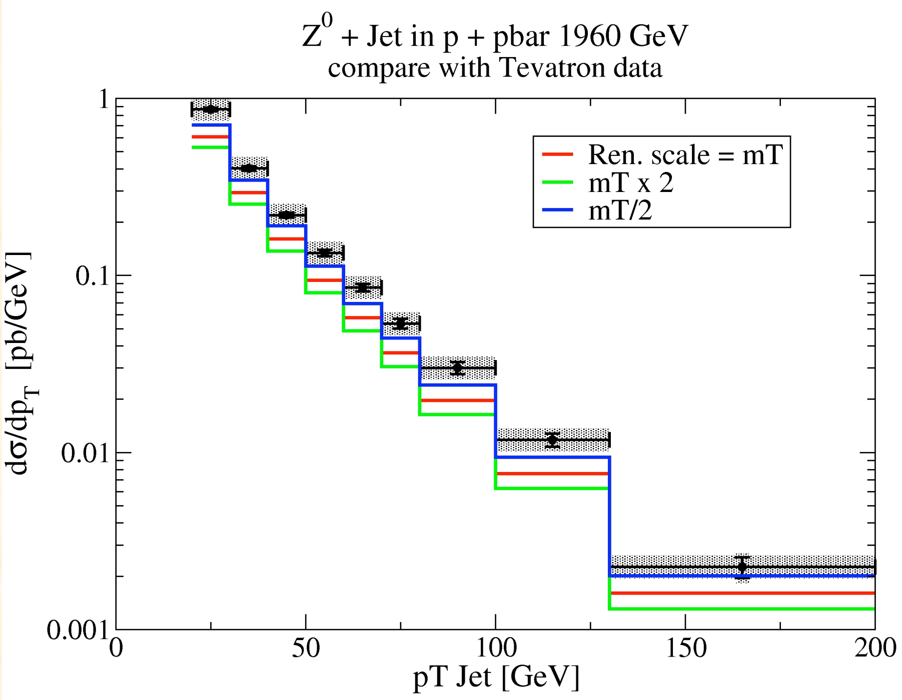


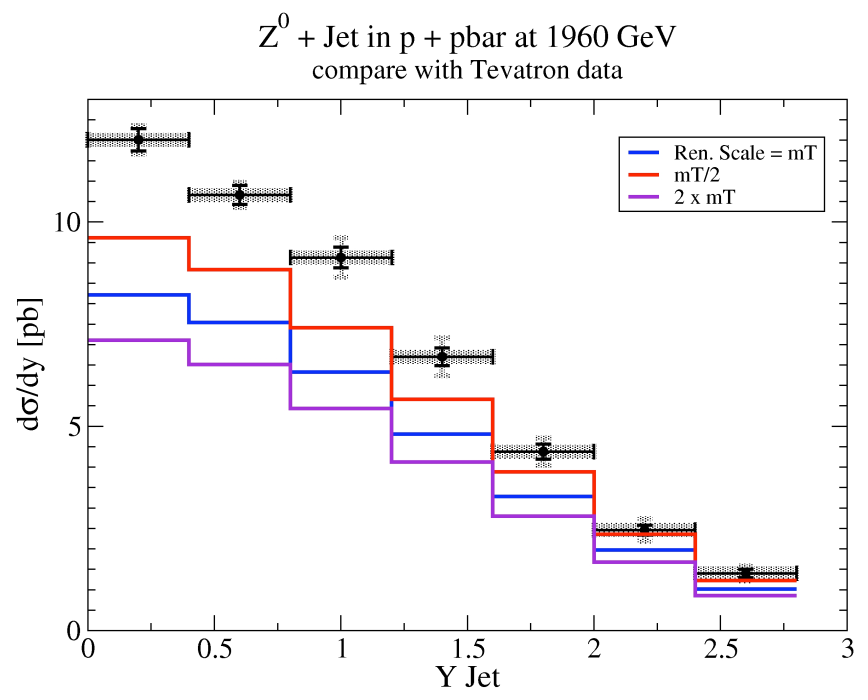
Neufeld, IV, Zhang (2010)

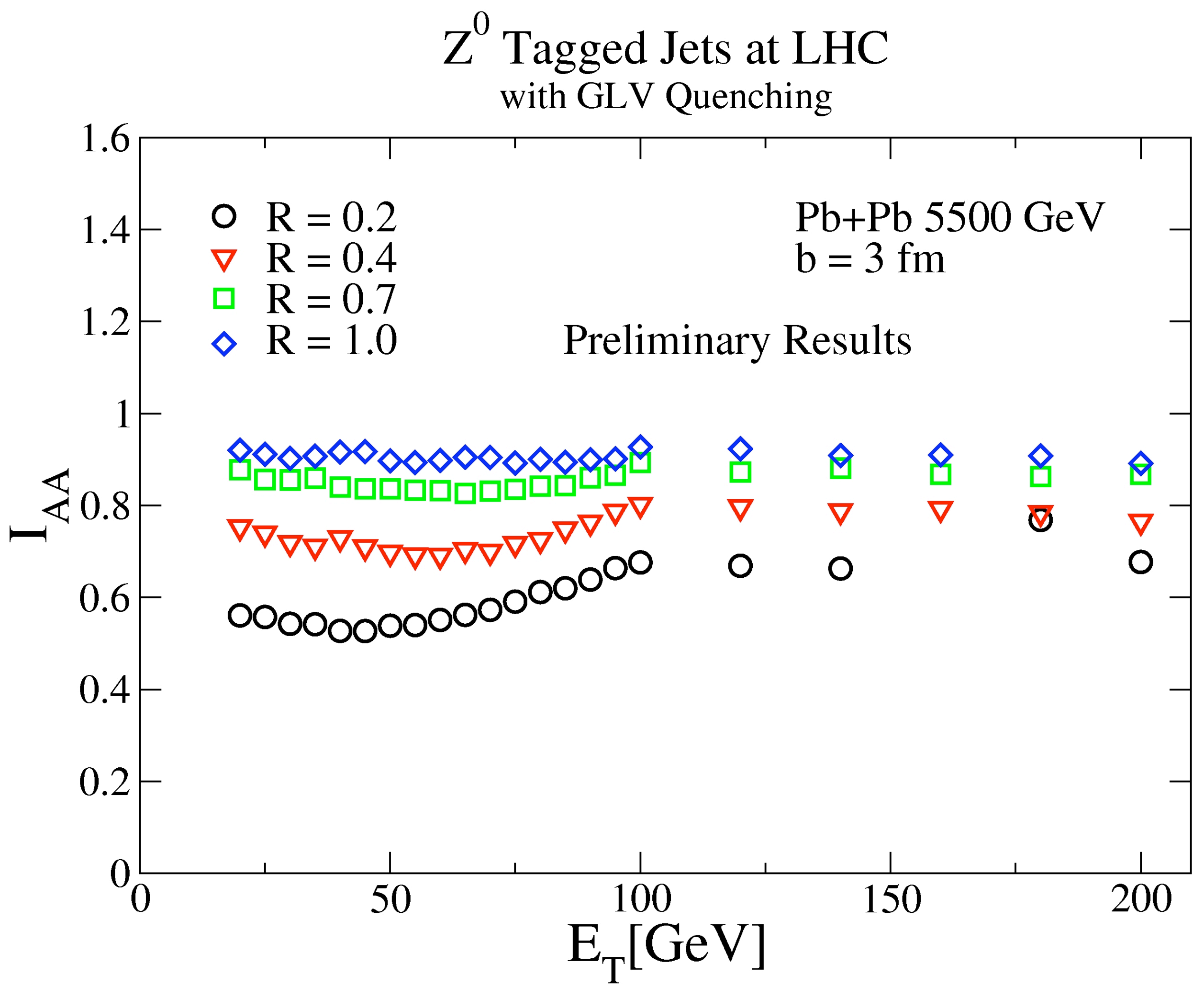
Summary

- Jet quenching is well established experimentally, however, leading particle suppression by itself provides incomplete information
- Jet shapes and jet cross sections may be able to distinguish between energy loss formalisms, determine fundamental properties of QGP
- The theory of jet shapes and jet cross sections in nuclear collisions has been developed by VWZ, and applied to inclusive jets at LHC
- Work now shifting to tagged jets, here presented preliminary results on Z^0 tagged jets at LHC energies

Backup


Z0 + Jet in p + pbar 1960 GeV
compare with Tevatron data
Ren. scale = mT
mT x 2
mT/2
dσ/dpT [pb/GeV]
1
0.1
0.01
0.001
0
50
100
150
200
pT Jet [GeV]


Z0 + Jet in p + pbar at 1960 GeV
compare with Tevatron data
Ren. Scale = mT
mT/2
2 x mT
dσ/dy [pb]
10
5
0
0
0.5
1
1.5
2
2.5
3
Y Jet



Z^0 Tagged Jets at LHC
with GLV Quenching
R = 0.2
R = 0.4
R = 0.7
R = 1.0
Pb+Pb 5500 GeV
b = 3 fm
Preliminary Results
I_{AA}
E_T[GeV]
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
0
50
100
150
200

What to use for the source term?

A common choice: $$J^{\nu}(x) = \frac{dE}{dt}\,(1,\vec{u})\,\delta(\vec{x}-\vec{u}t)\ ?$$

- Conserves energy and momentum globally (simply integrate the equation of motion over all space)
- Neglects local excitations, terms which integrate to zero globally

The linearized hydro equations couple to the source term, in turn yielding the particle emission spectrum

$$\delta\epsilon(\vec{k},\omega) = \frac{ikJ_L(\vec{k},\omega) + J^0(\vec{k},\omega)(i\omega - \Gamma_s k^2)}{\omega^2 - c_s^2 k^2 + i\Gamma_s \omega k^2}$$

$$\vec{g}_L(\vec{k},\omega) = \frac{i\omega\hat{\mathrm{k}}J_L(\vec{k},\omega) + ic_s^2\vec{k}J^0(\vec{k},\omega)}{\omega^2 - c_s^2 k^2 + i\Gamma_s \omega k^2}$$

$$\vec{g}_T(\vec{k},\omega) = \frac{i\vec{J}_T(\vec{k},\omega)}{\omega + \frac{3}{4}i\Gamma_s k^2}$$

↓

$$\frac{dN}{dy\,d\phi}(y=0) = \int_{p_T^i}^{p_T^f} dp_T\, p_T \int d\Sigma_\mu P^\mu (f(p) - f_{eq}(p))$$