A Theory of Jet Shapes and Cross Sections in Hadronic and Nuclear Collisions

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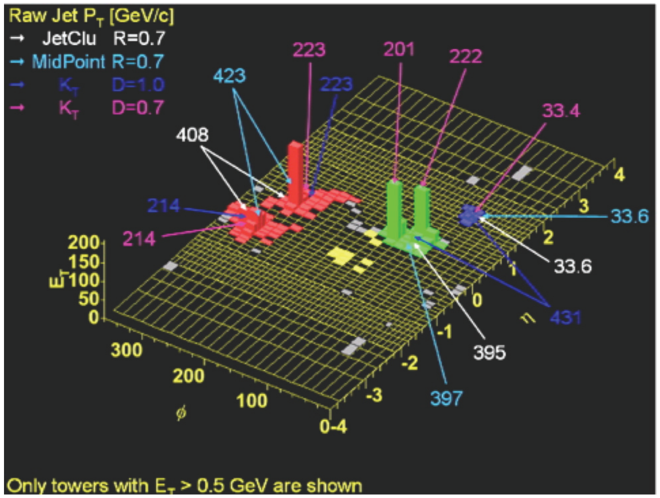
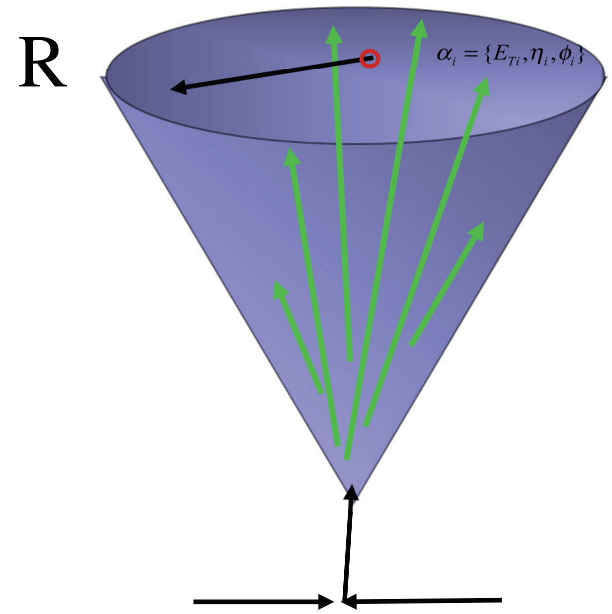


- JHEP 0811, 093 (2008), IV, Simon Wicks, Ben-Wei Zhang
- Eur. Phys. J. C 62, 139 (2009), IV, Ben-Wei Zhang, S. Wicks
- IV, Ben-Wei Zhang, in progress

DPF 2009 Meeting, Wayne State University, Detroit MI, July 2009

Jets: New Opportunity at RHIC, LHC

- R_{AA} for single hadron production only measures the leading fragments of a jet.
- LHC will open an entirely new frontier: the study of the internal structure of the entire jet.
- Jet shapes and jet cross sections have not been discussed so far in HIC – first work.
- It will take a few years (if measured and confirmed) before it suffers R_{AA} fate.



$$E_T = \sum_{i \in jet} E_{T,\ i}$$

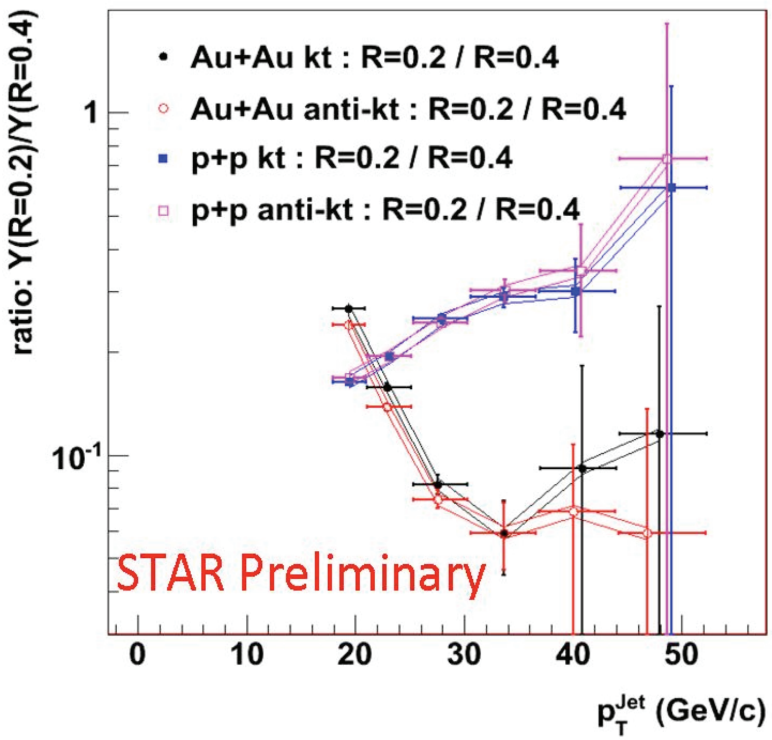
$$\eta = \sum_{i \in jet} \eta_i E_{T,\ i} / E_T$$

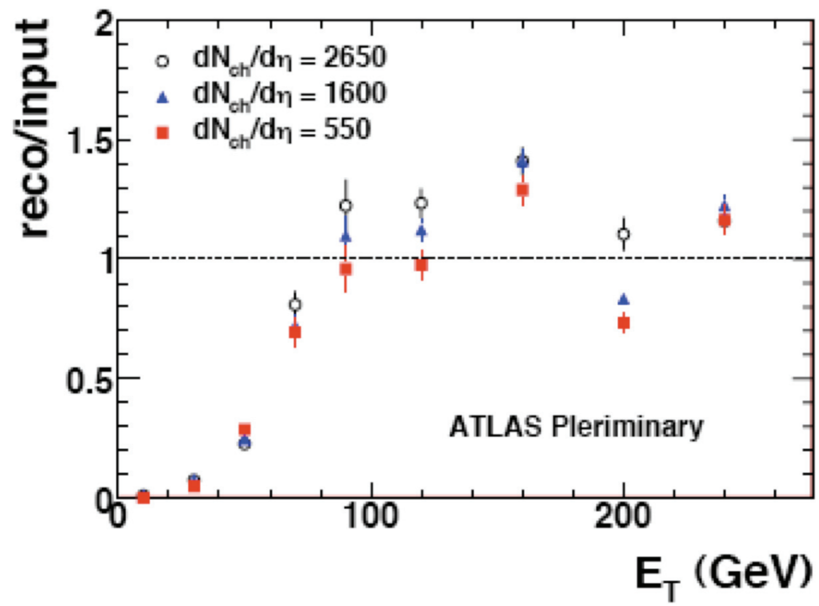
$$\phi = \sum_{i \in jet} \phi_i E_{T,\ i} / E_T$$

$$R = \sqrt{(\eta - \eta_{jet})^2 + (\phi - \phi_{jet})^2}$$

Measurements Become Feasible

- Seen at RHIC, developed by ATLAS





- The effect is observed

- The sensitivity to measure it at the LHC is there

Salur, S. (2008)

Poloszkon, M. (2009)

Grau, N. (2008, 2009)

Theory of NLO Jet Cross Sections

- NLO jet code by Ellis, Soper and Kuntz

The cross section

$$\frac{d\sigma_{jet}}{dp_J dy_J} = \frac{1}{2!}\int dy_1 dp_2 dy_2 d\phi_2 \frac{d\sigma[2\to 2]}{dy_1 dp_2 dy_2 d\phi_2} S_2 + \frac{1}{3!}\int dy_1 dp_2 dy_2 d\phi_2 dp_3 dy_3 d\phi_3 \times \frac{d\sigma[2\to 3]}{dy_1 dp_2 dy_2 d\phi_2 dp_3 dy_3 d\phi_3} S_3 \, .$$

Lowest Order (+ VC)

$$S_2 = \sum_{i=1}^{2} \delta(p_i - p_J)\delta(y_i - y_J)$$

Next-to-Leading Order

$$S_3 = \sum_i \delta(p_i - p_J)\delta(y_i - y_J) \prod_{j(j\neq i)} \theta\left([(y_i - y_j)^2 + (\phi_i - \phi_j)^2]^{1/2} > \frac{p_i + p_j}{\max(p_i, p_j)} R\right) + \sum_{i,j(i<j)} \delta(p_i + p_j - p_J)\delta(\frac{p_i y_i + p_j y_j}{p_i + p_j} - y_J)\theta\left([(y_i - y_j)^2 + (\phi_i - \phi_j)^2]^{1/2} < R_{com}\right)$$

- Theoretical subtleties – the meaning of NLO for jets is *K=NLO/LO can be < 1*

Ellis, Soper, Kuntz (1996)

Analytic "Jet Finders"

- Jet finders: for proper collinear and infrared safe identification of jets

• Cone algorithms: not infrared and collinear safe

$$R_{ij} = \sqrt{(\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2}.$$

• Midpoint cone algorithms

• K_T algorithm: preferred, collinear and infrared safe to all orders in PQCD

$$d_{ij} = \min(E_{Ti}, E_{Tj})^2 R_{ij}^2 \left(\approx \min(E_i, E_j)^2 \theta_{ij}^2 \approx k_\perp^2\right)$$

$$d_{ib} = E_{Ti}^2 R^2. \ \min\{d_{ij}\} < \min\{d_{ib}\}, \ merge$$

Ellis, S.D. et al. (1993)

• "Seedless" cone algorithm: practically infrared safe

• Anti-K_T algorithm: "round" jets

Salam, G. et al. (2007,2008)

Parton merging parameter

$$R_{com} = \min(R_{sep}R, \frac{p_i+p_j}{\max(p_i,p_j)}R)$$

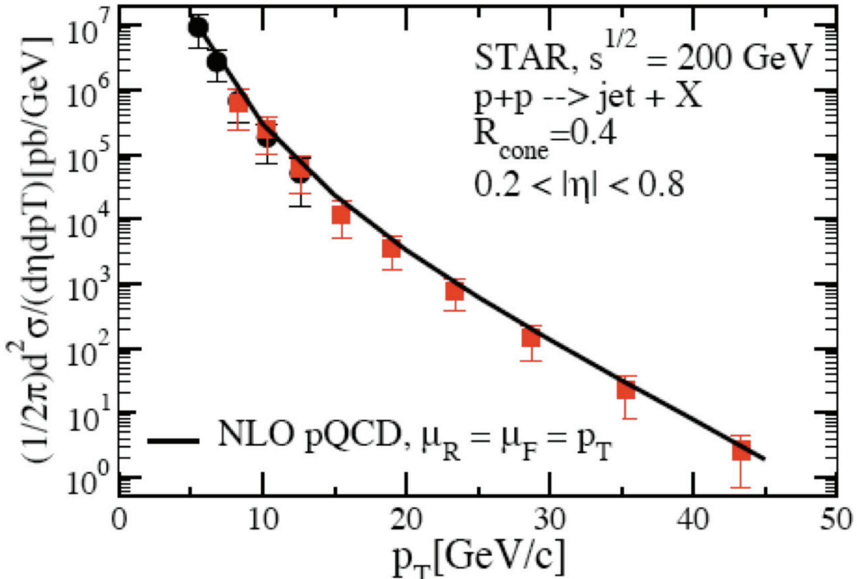
• Midpoint cone $R_{sep} = 2$

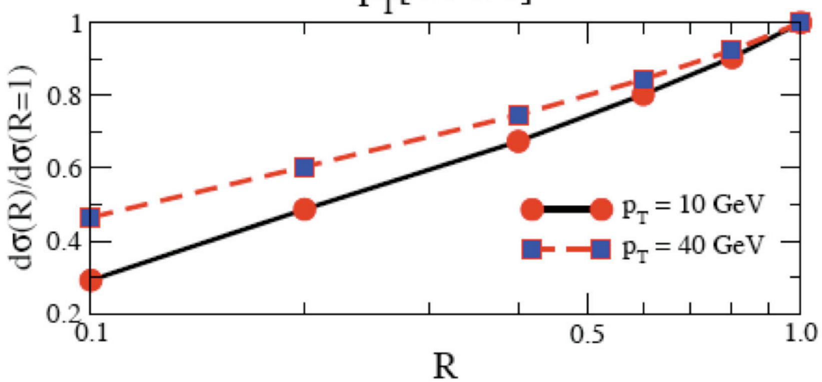
• Cone $1 < R_{sep} < 2$

• K_T $D = R, \ R_{sep} = 1$

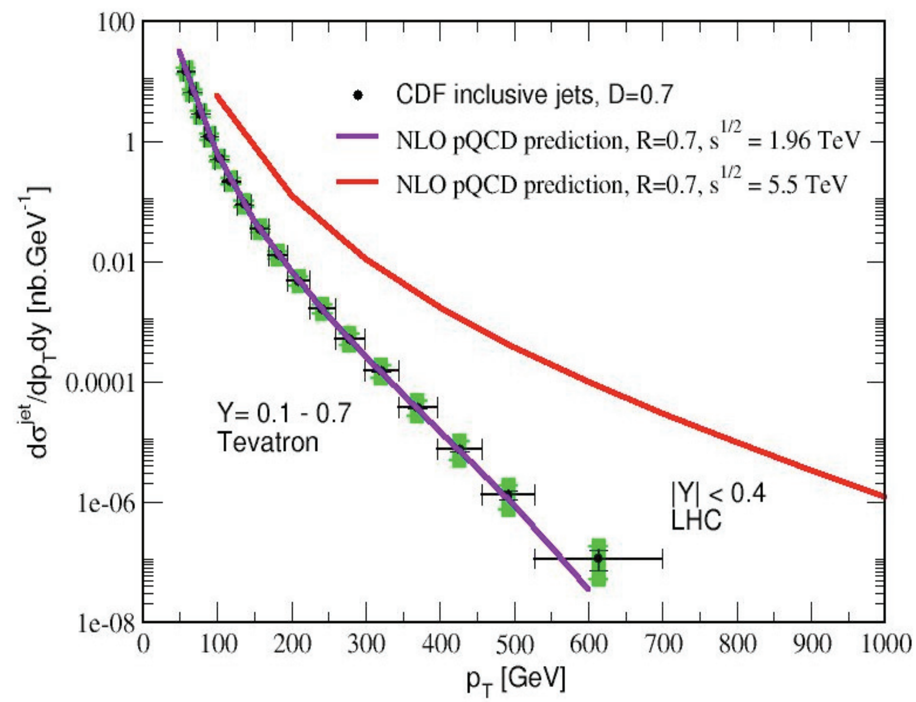
Soper, D. et al. (1996)

Comparison to Data





IV, Zhang (2008,2009)



Excellent perturbative QCD description of the experimental data

Intra-Jet Energy Flow

- More detailed calculation related to vacuum and medium-induced parton splitting

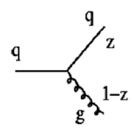
QCD splitting kernel

Seymour, M.H. (1997)

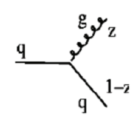
$$\Psi_{\text{int}}(r;R) = \frac{\sum_i (E_T)_i \Theta(r - (R_{\text{jet}})_i)}{\sum_i (E_T)_i \Theta(R - (R_{\text{jet}})_i)},$$

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

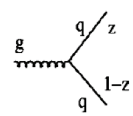
$$dP_a = \frac{\alpha_s}{2\pi}\frac{d\rho^2}{\rho^2}\frac{d\phi}{2\pi} dz P_{a\to bc}(z)$$



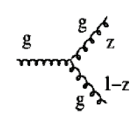
$$P_{qq}^{(1)}(x) = C_2(F)\left[(1+x^2)\left(\frac{1}{1-x}\right)_+ + \frac{3}{2}\delta(1-x)\right]$$



$$P_{gq}^{(1)}(x) = C_2(F)\frac{(1-x)^2+1}{x}$$



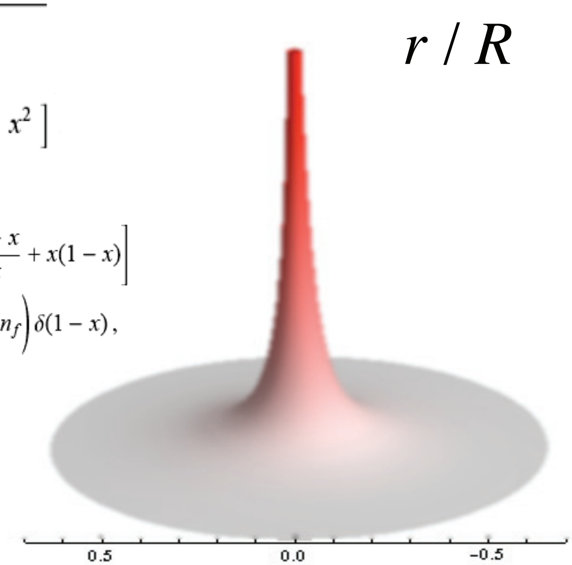
$$P_{qg}^{(1)}(x) = T(F)\left[(1-x)^2 + x^2\right]$$



$$P_{gg}^{(1)}(x) = 2C_2(A)\left[\frac{x}{(1-x)_+} + \frac{1-x}{x} + x(1-x)\right] + \left(\frac{11}{6}C_2(A) - \frac{2}{3}T(F)n_f\right)\delta(1-x),$$

Jet shapes at LO with the acceptance cuts

$$\psi_a(r;R) = \sum_b \frac{\alpha_s}{2\pi}\frac{2}{r}\int_{z_{min}}^{1-Z} dz\, z P_{a\to bc}(z).$$



Elements of the Jet Shape

- Jet shapes induced by a quark and a gluon are:

$$\psi_q(r) = \frac{C_F\alpha_s}{2\pi}\frac{2}{r}\left(2\log\frac{1-z_{min}}{Z} - \frac{3}{2}\left[(1-Z)^2 - z_{min}^2\right]\right),$$

$$\psi_g(r) = \frac{C_A\alpha_s}{2\pi}\frac{2}{r}\left(2\log\frac{1-z_{min}}{Z} - \left(\frac{11}{6} - \frac{Z}{3} + \frac{Z^2}{2}\right)(1-Z)^2 + \left(2z_{min}^2 - \frac{2}{3}z_{min}^3 + \frac{1}{2}z_{min}^4\right)\right) + \frac{T_R N_f \alpha_s}{2\pi}\frac{2}{r}\left(\left(\frac{2}{3} - \frac{2Z}{3} + Z^2\right)(1-Z)^2 - \left(z_{min}^2 - \frac{4}{3}z_{min}^3 + z_{min}^4\right)\right)$$

Jet cross sections are sensitive to the leading 1/r - logarithmic

- The collinear divergence requires Sudakov resummation

First take the small r/R limit

$$P(<r) = \exp(-P_1(>r)) = \exp\left(-\int_r^R dr'\,\psi_{\rm coll}(r')\right)$$

Power Correction and IS Radiation

- Power correction: include running coupling inside the z integration and integrate over the Landau pole.

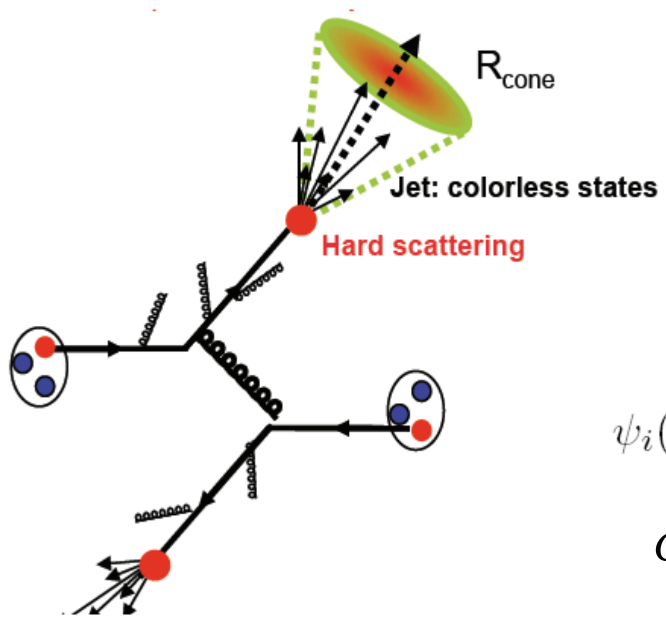
$$\psi_{PC}(r) = \frac{2C_R}{2\pi}\frac{2}{r}\frac{Q_0}{rE_T}\left(\bar{\alpha_0}'(Q_0,k_{min}) - \alpha_s(\mu) - 2\beta_0\alpha_s(\mu)^2\left(1+\log\frac{\mu}{Q_0}\right)\right) + \frac{2C_R}{2\pi}\frac{2}{r}\frac{k_{min}}{rE_T}\left(\alpha_s(\mu) + 2\beta_0\alpha_s(\mu)^2\left(1+\log\frac{\mu}{k_{min}}\right)\right),$$

$$\bar{\alpha_0}'(Q_0,k_{min}) = \frac{1}{Q_0}\int_{k_{min}}^{Q_0} dk\,\alpha_s(k)$$

$$\bar{\alpha_0}'(2\,\mathrm{GeV},0) = 0.52\ ,\quad \bar{\alpha_0}'(3\,\mathrm{GeV},0) = 0.42$$

Webber, B. et al. (1998)

non-perturbative scale Q_0.



- Initial-state radiation should be included. The leading order result is:

$$\psi_i(r) = \frac{C\alpha_s}{2\pi}2r\left(\frac{1}{Z^2} - \frac{1}{(1-z_{min})^2}\right)$$

$$C = \frac{C_A}{2} \approx C_F$$

Theory vs Tevatron Data

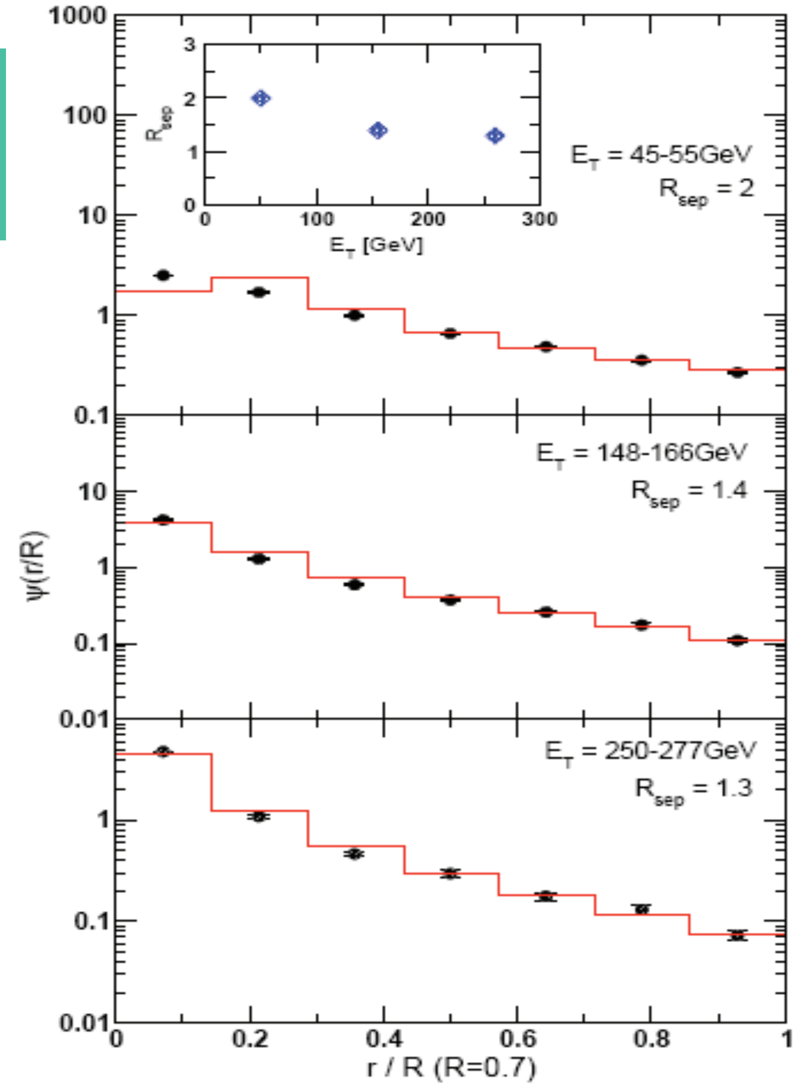
- Total contribution to the jet shape in the vacuum:

$$\sqrt{s} = 1960\ \mathrm{GeV}$$

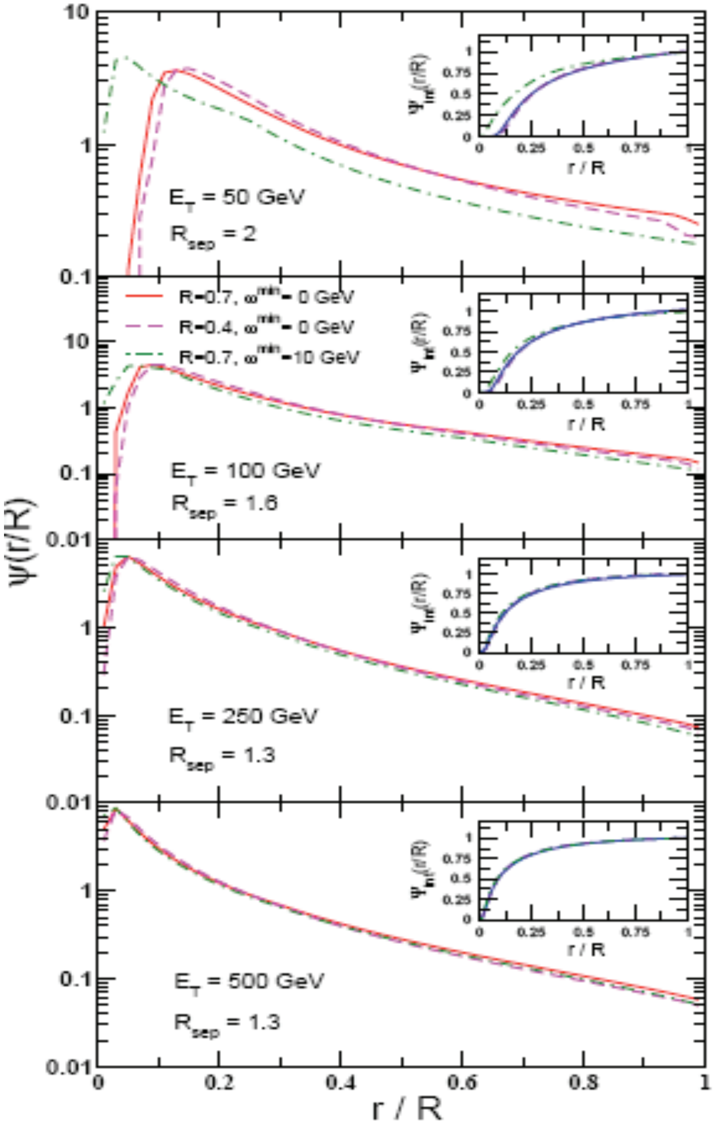
$$\psi(r) = \psi_{\mathrm{coll}}(r)\left(P(r)-1\right) + \psi_{\mathrm{LO}}(r) + \psi_{i,\mathrm{LO}}(r) + \psi_{\mathrm{PC}}(r) + \psi_{i,\mathrm{PC}}(r)\ ,$$

This theoretical model describes CDF II data fairly well after including all relevant contributions

IV, Wicks, Zhang (2008)

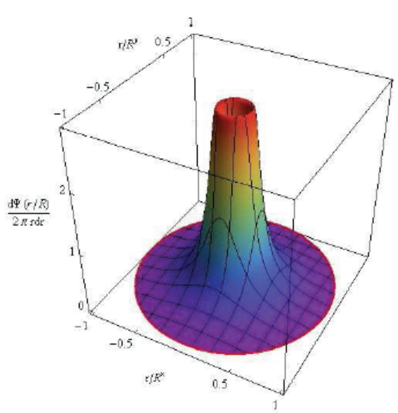


Predictions for the Shape at LHC

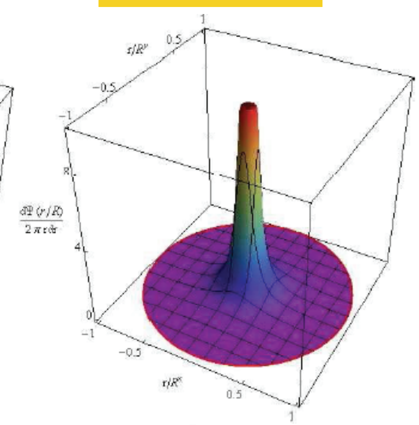


- Jet shapes at the LHC are very similar to those at the Tevatron:
- As a function of the jet opening angle jet shapes are self-similar.
- First study of finite detector acceptance effect is carried out: the effect is observable with 10-20% energy cut.
- Jet shapes change dramatically with E_T

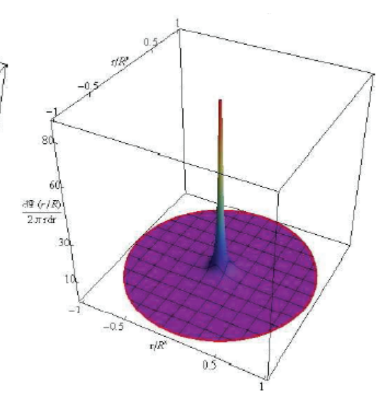
20GeV



100GeV



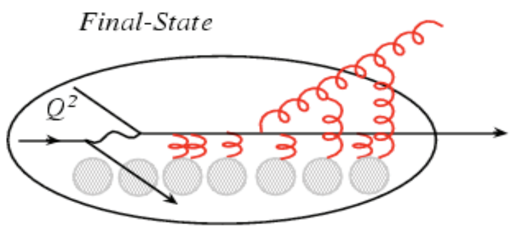
500GeV

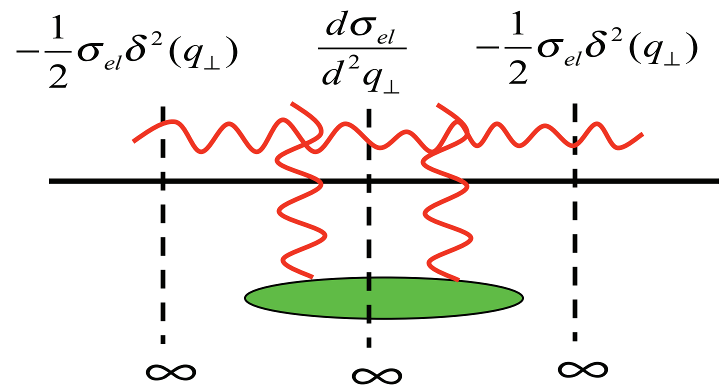


Medium-Induced Radiation: Theory

- Includes interference with the radiation from hard scattering

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





Number of scatterings **Momentum transfers**

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

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

Color current propagators

Coherence phases (LPM effect)

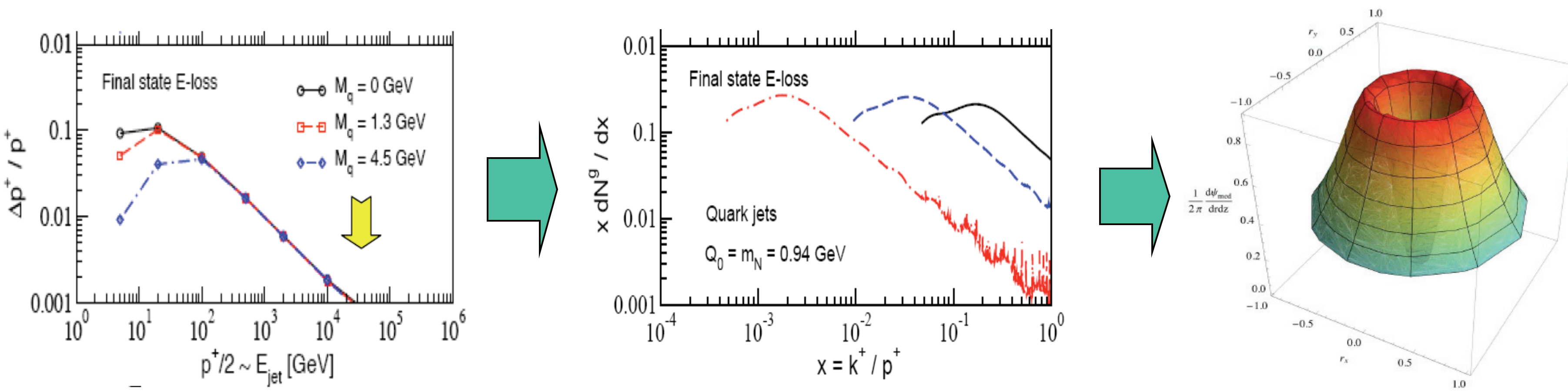
LPM Effect and the Medium-Induced Jet Shape

- An intuitive approach to medium-induced jet shapes

$$\Delta E^{rad}_{\text{LPM suppressed}} \Rightarrow \frac{dI^g}{d\omega}(\omega \sim E)_{\text{LPM suppressed}}$$

$$\Rightarrow \frac{dI^g}{d\omega d^2 k_T}(k_T \ll \omega)_{\text{LPM suppressed}} \sim \frac{dI^g}{d\omega dr}(r \ll R)_{\text{suppressed}}$$

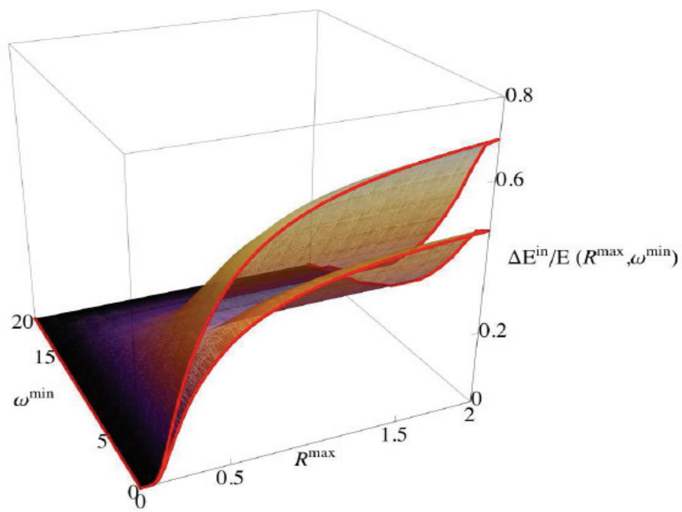
IV, (2005)

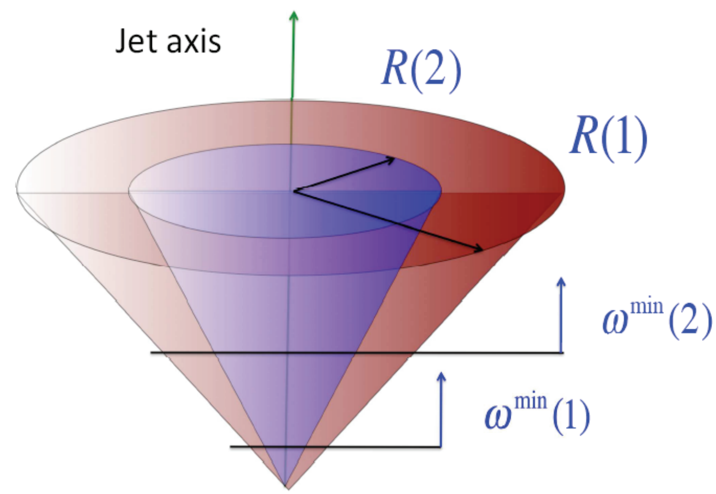


- Coherence and interference effects guarantee broad angular spectrum

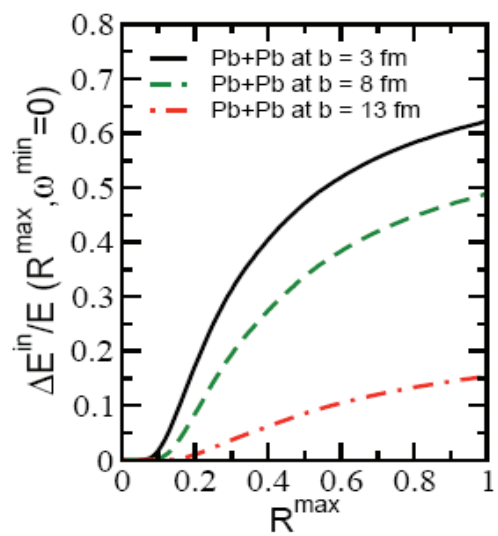
Energy Loss Distribution

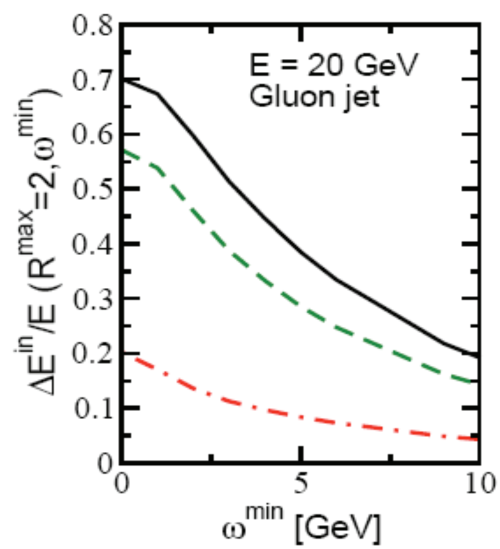
$$\frac{\Delta E^{in}}{E}(R^{\max},\omega^{\min}) = \frac{1}{E}\int_{\omega^{\min}}^{E} d\omega \int_0^{R^{\max}} dr \frac{dI^g}{d\omega dr}(\omega, r)$$





- Energy loss ratio goes down with larger b.
- Energy loss ratio becomes smaller with smaller R and larger ω^{min}.





Jet Cross sections in HIC

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

- Only a fraction f of the lost energy falls inside the cone and above the acceptance cut:

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

- Higher energy needed due to energy loss E':

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

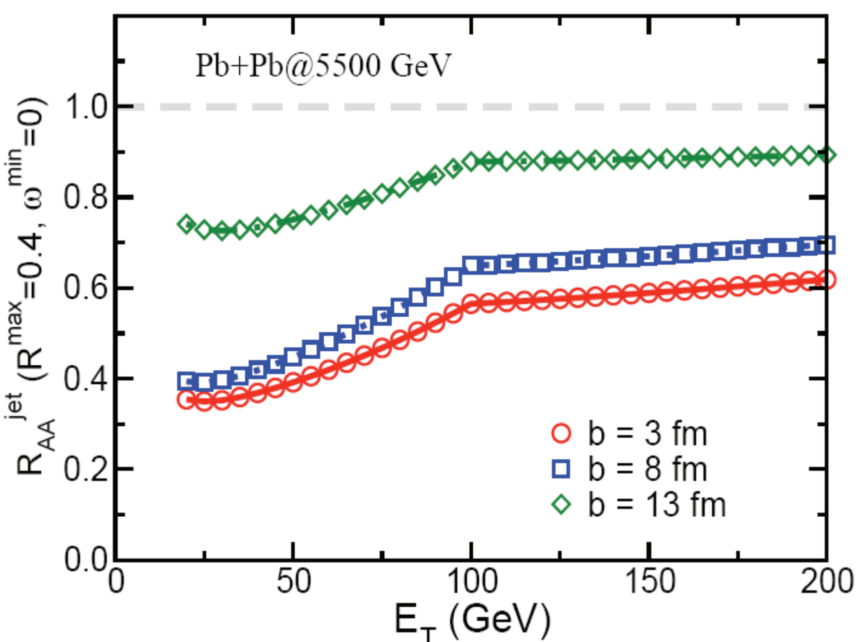
- Define nuclear modification factor for jet cross section:

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

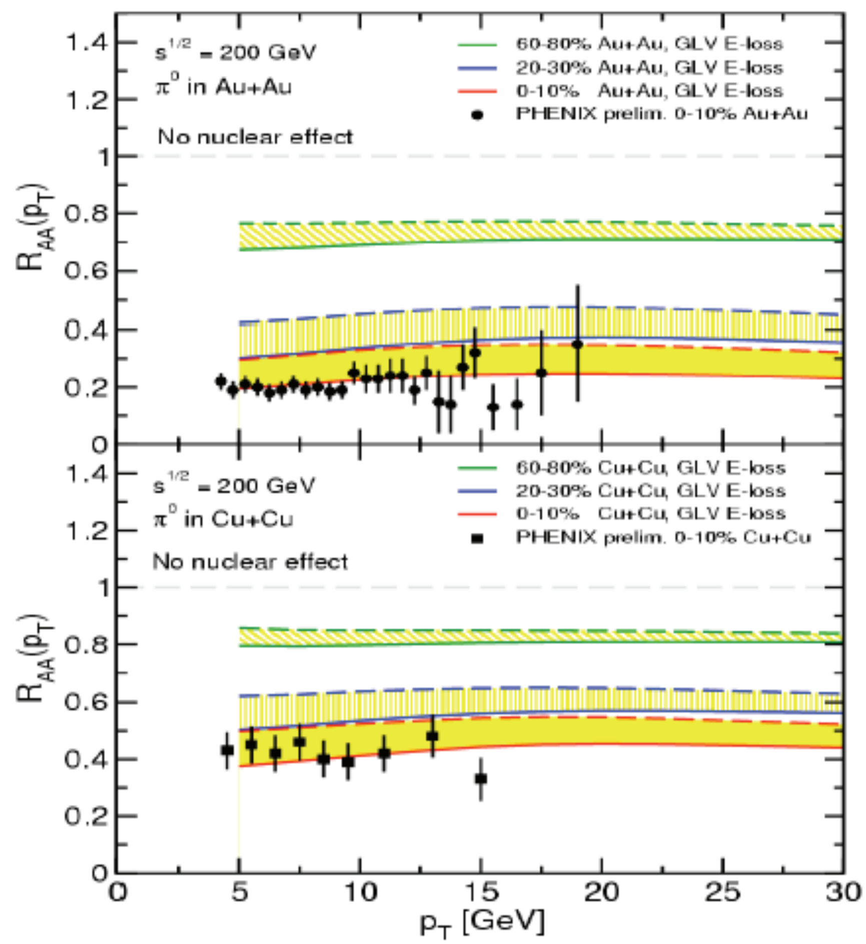
IV, Wicks, Zhang (2008, 2009)

R_{AA} vs Centrality

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



Jets

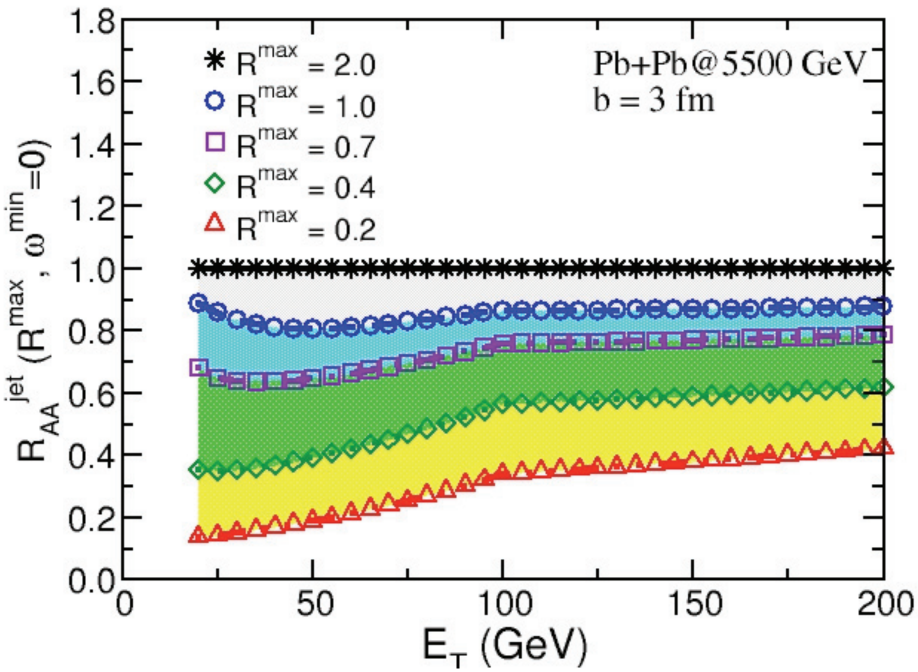


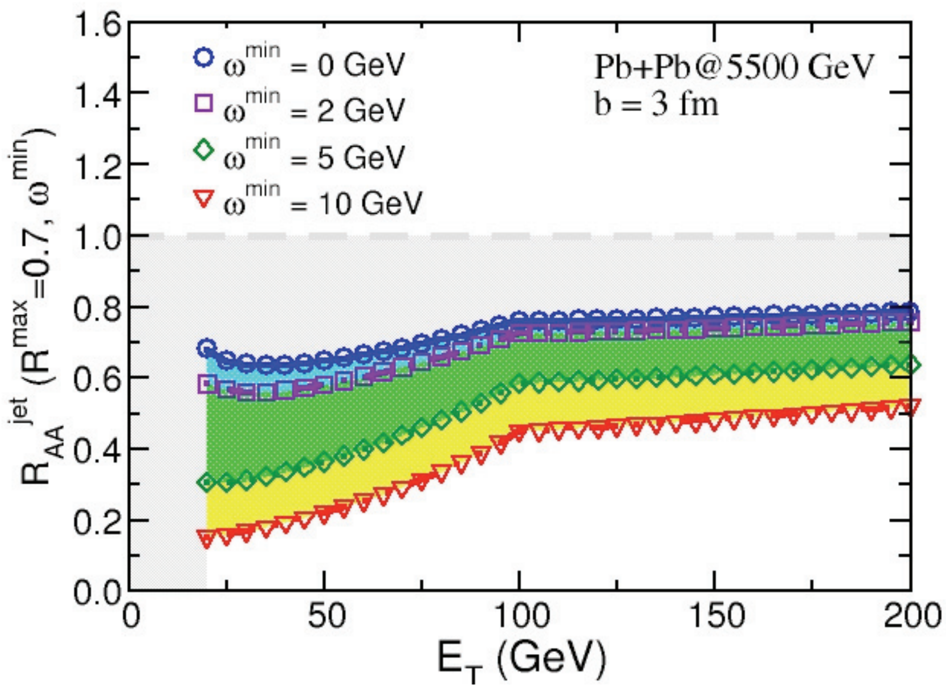
IV (2006)

Leading particles

R_{AA}^{jet} vs R^{max} and ω^{min}

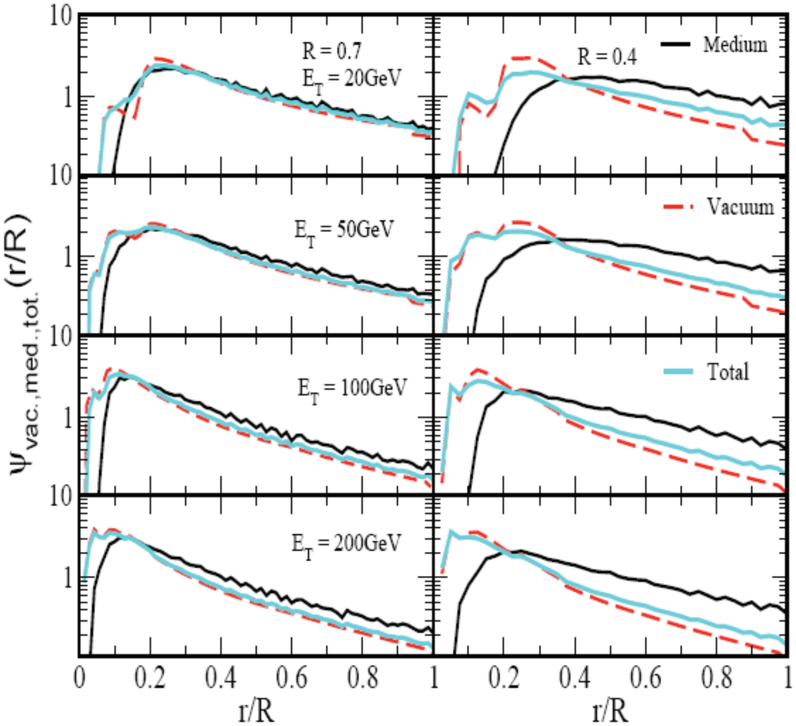
IV, Wicks, Zhang (2008)





- R_{AA} for the jet cross section evolves continuously with the cone size R^{max} and the acceptance cut ω^{min}.
- Contrast: single result for leading particles.
- Limits: small R^{max} and large ω^{min} approximate single particle suppression.

The Full Jet Shape in the QGP (I)



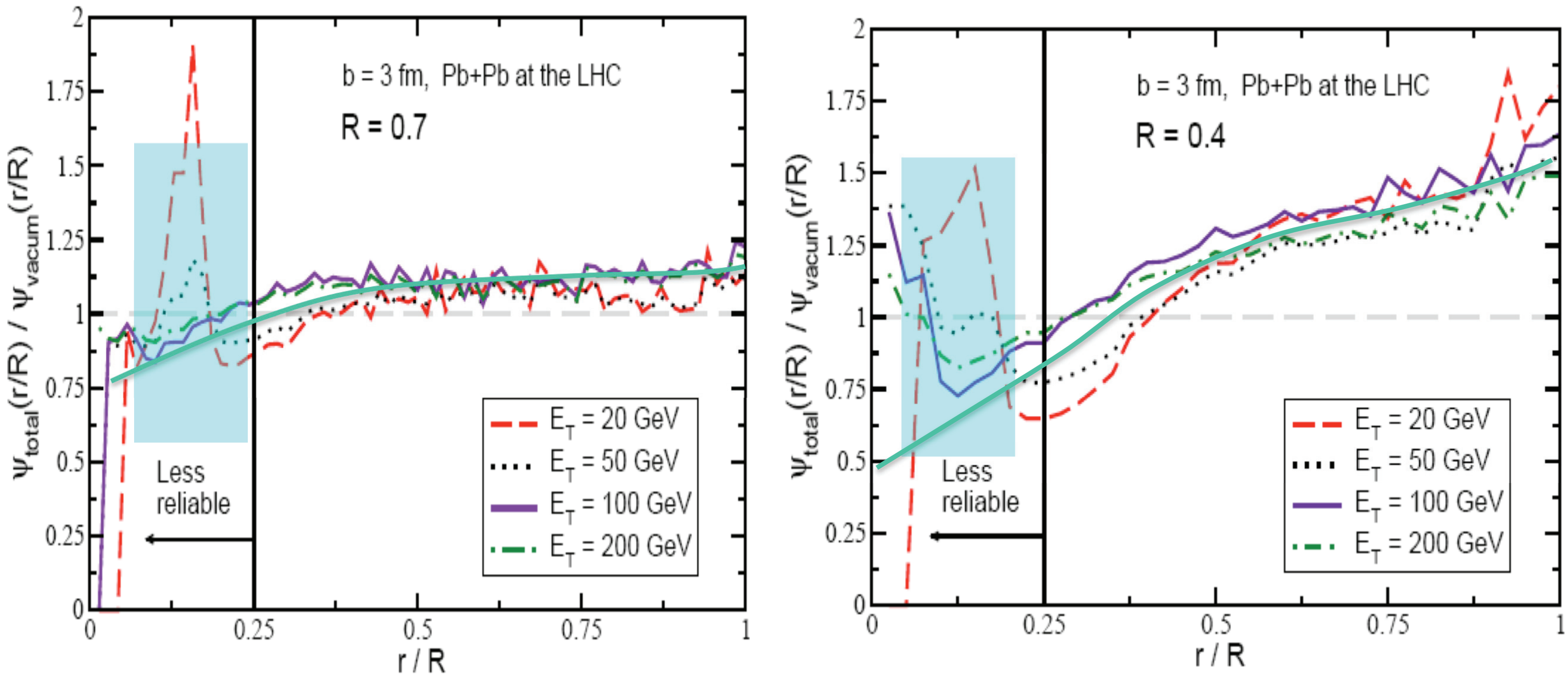
R=0.4	Vacuum	Complete E-loss	Realistic Case
<r/R>,E_T=20GeV	0.41	0.57	0.45
<r/R>,E_T=50GeV	0.35	0.53	0.38
<r/R>,E_T=100GeV	0.28	0.42	0.32
<r/R>,E_T=200GeV	0.25	0.42	0.28

R=0.7	Vacuum	Complete E-loss	Realistic case
<r/R>,E_T=20GeV	0.41	0.45	0.42
<r/R>,E_T=50GeV	0.33	0.41	0.37
<r/R>,E_T=100GeV	0.27	0.34	0.29
<r/R>,E_T=200GeV	0.24	0.32	0.26

- Surprisingly, there is no big difference between the jet shape in vacuum and the total jet shape in the medium. The broadening effect is offset by the steeper jet shape in vacuum due to energy loss.
- The medium is "gray" instead of "black": only a fraction of energy of leading parton lost in the QGP.

The Full Jet Shape in the QGP(II)

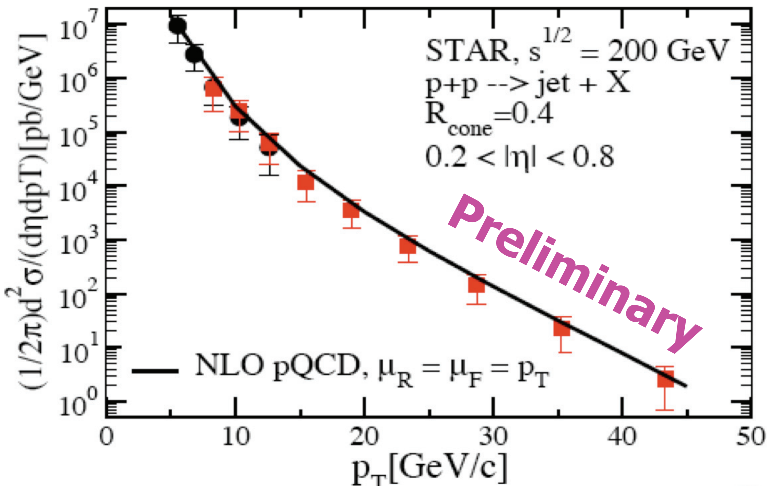
- The ratio of the total in-medium jet shape to the vacuum jet shape is smaller than 1 at 0<r/R<0.4, and larger than 1 when r/R>0.4.
- Big differences are manifest at the periphery of the cone, and for smaller cone radii: the ratio is ~ 1.7 when r/R~1 and R=0.4.

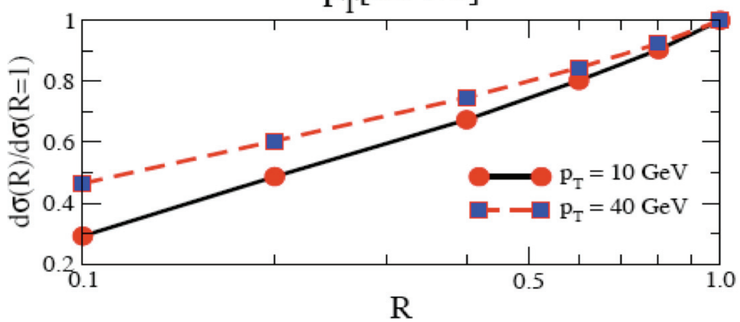


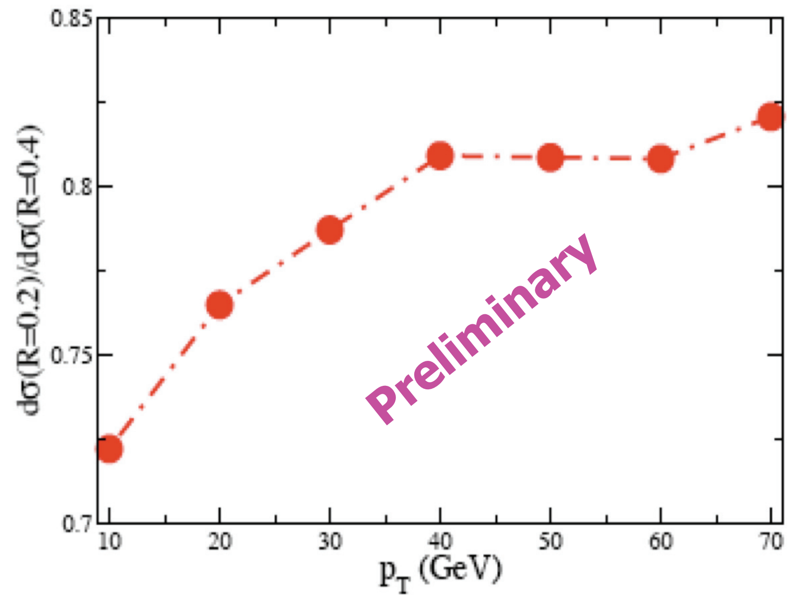
New Results for RHIC

- In p+p collisions

B. Zhang, IV (2009)







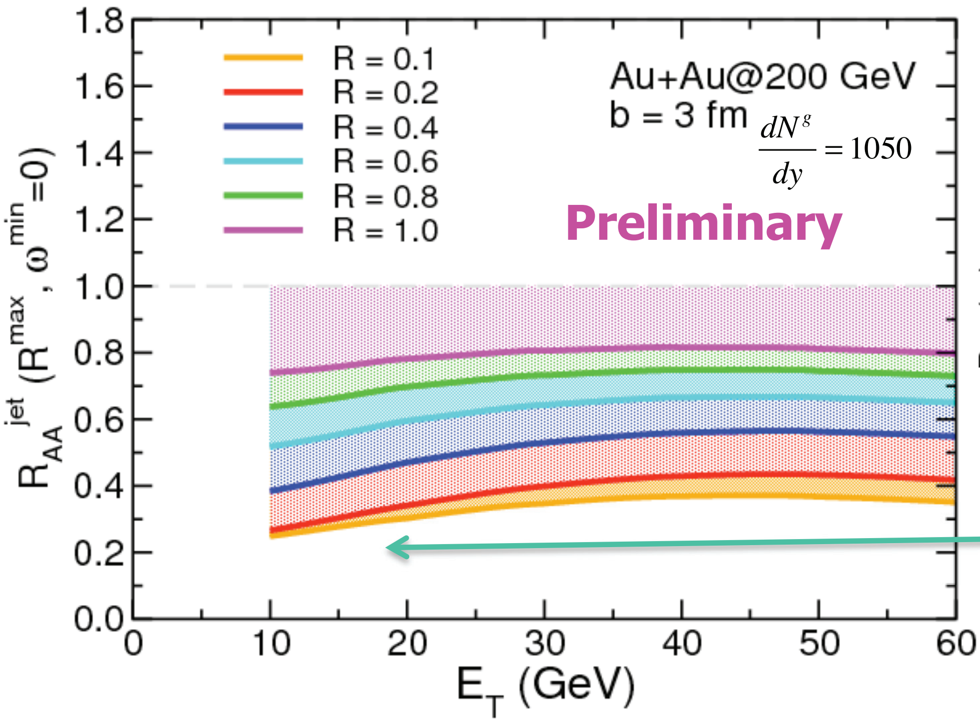
- Studied, factorization/renormalization, and R_{sep} dependence - small

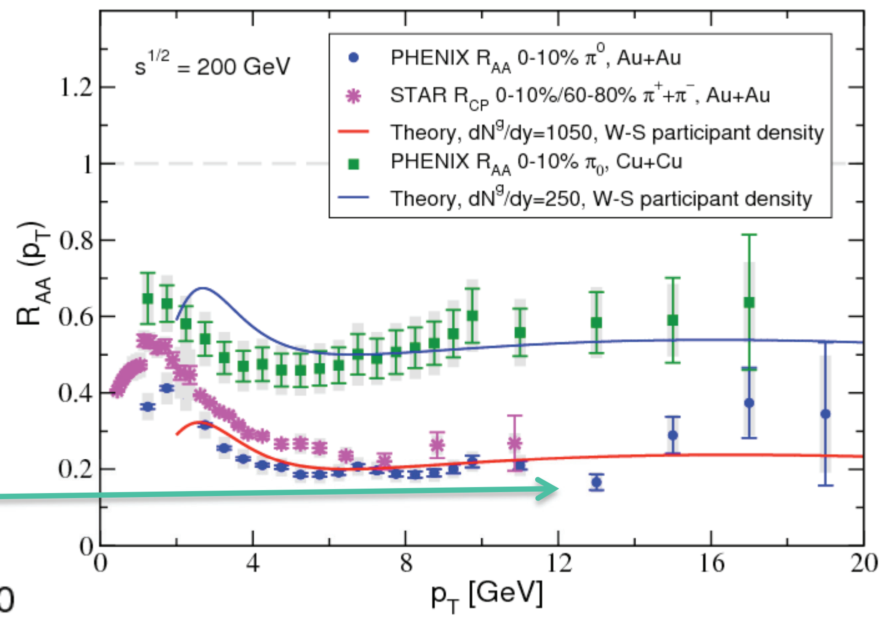
- More significant dependence on R, small dependence on on p_T in cross section ratios. Qualitatively compatible with STAR measurements but much smaller magnitude.

Jets in Au+Au Collisions

Eliminates p+p jet effects. Includes initial state effects

- Reference calculation of leading particle quenching



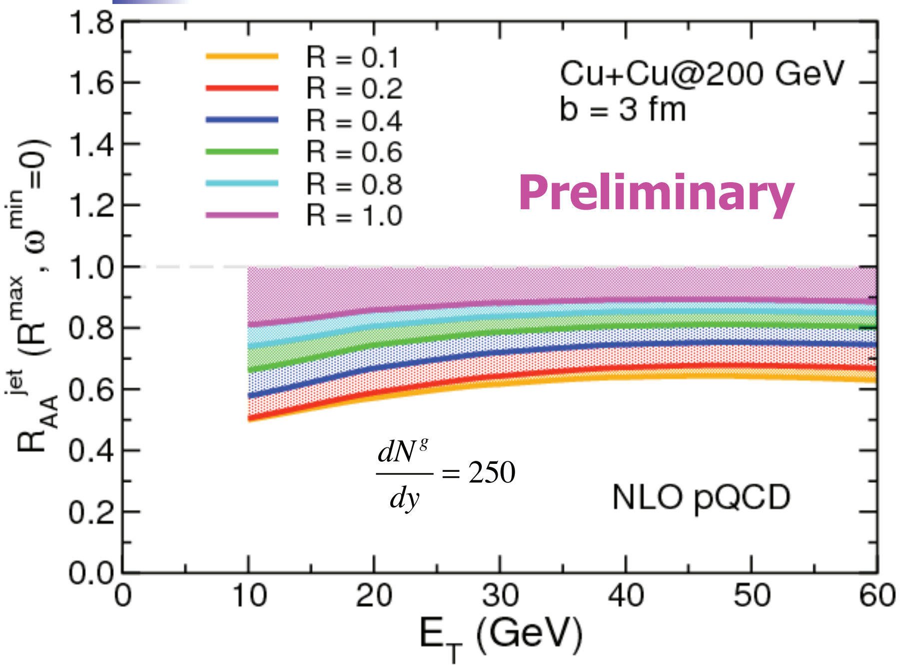


- NLO calculation

R. Sharma et al. (2009)

- Jet suppression is bound by the suppression of leading particles. Cold nuclear matter effects are not included (initial-state energy loss)

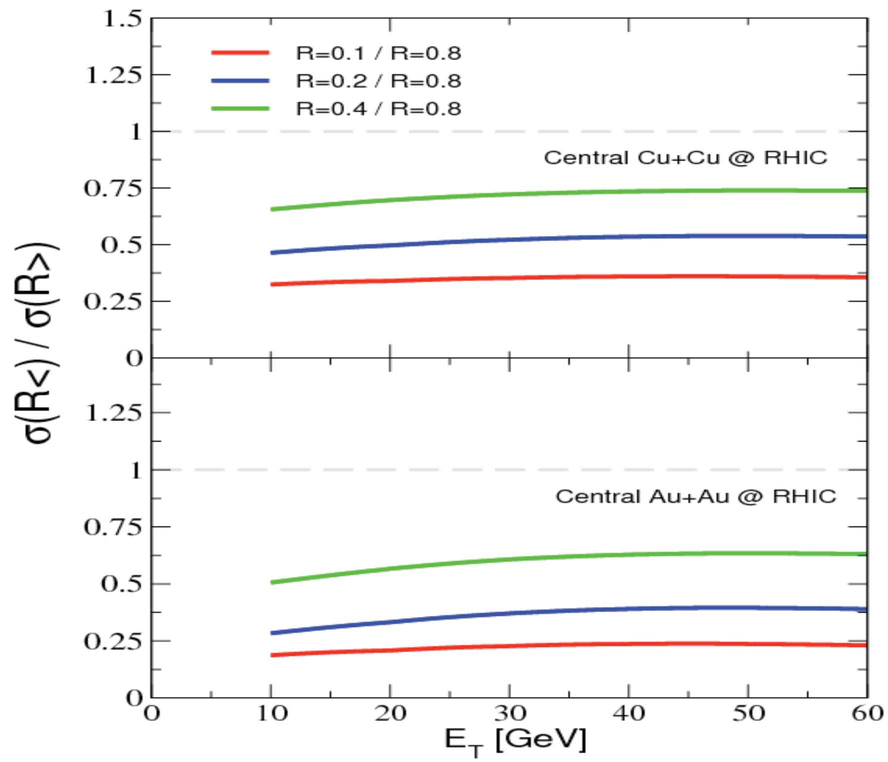
Cu+Cu Collisions at RHIC



- Again, qualitatively the trend is observed by STAR. The magnitude, however is much smaller

- Alternative measures

B. Zhang, IV (2009)



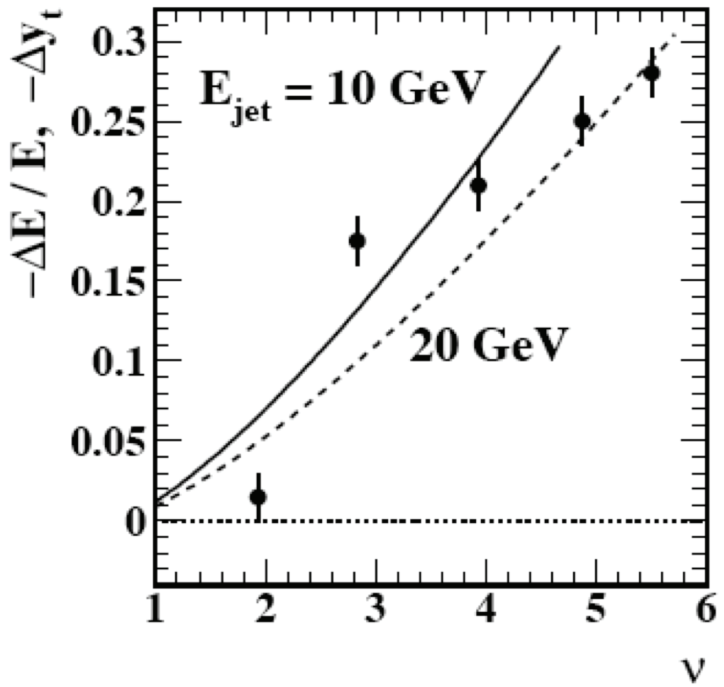
- Eliminates CNM effects, includes p+p jet effects

Conclusions

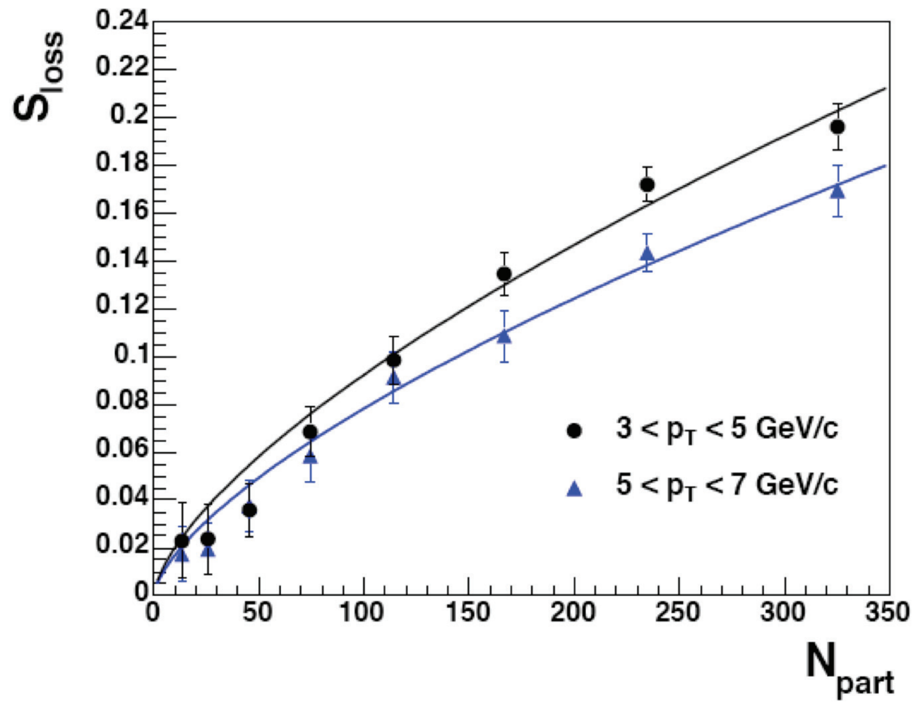
- Jet cross sections are calculated in NLO PQCD for different jet definitions.
- The theory of jet shapes in the vacuum was generalized to include finite detector acceptance effect.
- The QGP-induced jet component was computed in the non-Abelian theory of radiative energy loss. It was shown to be significantly different from the vacuum jet shape.
- A variable quenching R_{AA} for jet cross sections at LHC was derived (R^{max}, ω^{min}), contrary to single R_{AA} for leading particles.
- Prospects or independent experimental determination of the differential energy loss pattern were discussed.
- Full jet shapes in Pb+Pb collisions at LHC: small broadening at mean relative jet radii; up to 70% deviation from the vacuum jet shape was found in the "tails" $r/R>0.5$.
- New calculations have been carried out at NLO for emerging jet measurements in p+p and A+A collisions at RHIC.

Experimental Extraction

T. Trainor et al. (2007)



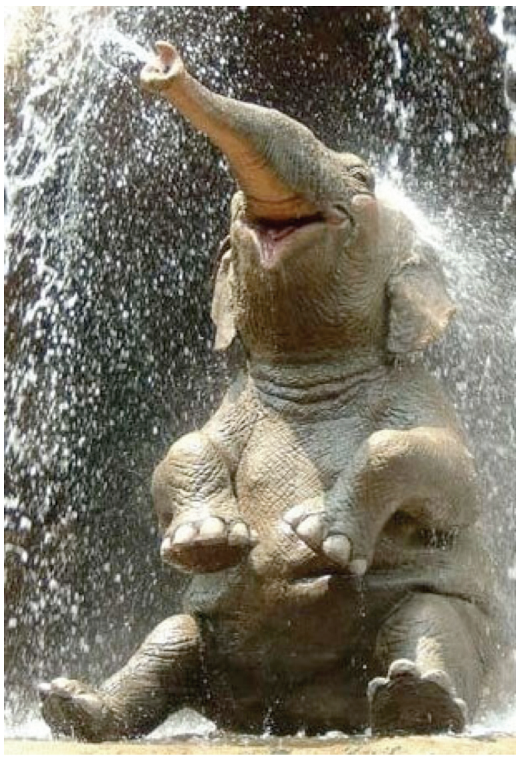
S. Adler et al. (2006)



- In spite of claims to the opposite, experiments are actually able to extract the fractional energy loss
- When done vs R^{max}, ω^{min} it will allow independent determination of the bremsstrahlung spectrum

What Do I Think About …

T. Sjostrand, Creator of PYTHYA



Final Words of Warning

[. . .] The Monte Carlo simulation has become the major means of visualization of not only detector performance but also of physics phenomena. So far so good. But it often happens that the physics simulations provided by the Monte Carlo generators carry the authority of data itself. They look like data and feel like data, and if one is not careful they are accepted as if they were data.

[. . .] I am prepared to believe that the computer-literate generation (of which I am a little too old to be a member) is in principle no less competent and in fact benefits relative to us in the older generation by having these marvelous tools. They do allow one to look at, indeed visualize, the problems in new ways. But I also fear a kind of "terminal illness", perhaps traceable to the influence of television at an early age. There the way one learns is simply to passively stare into a screen and wait for the truth to be delivered. A number of physicists nowadays seem to do just this.

J.D. Bjorken

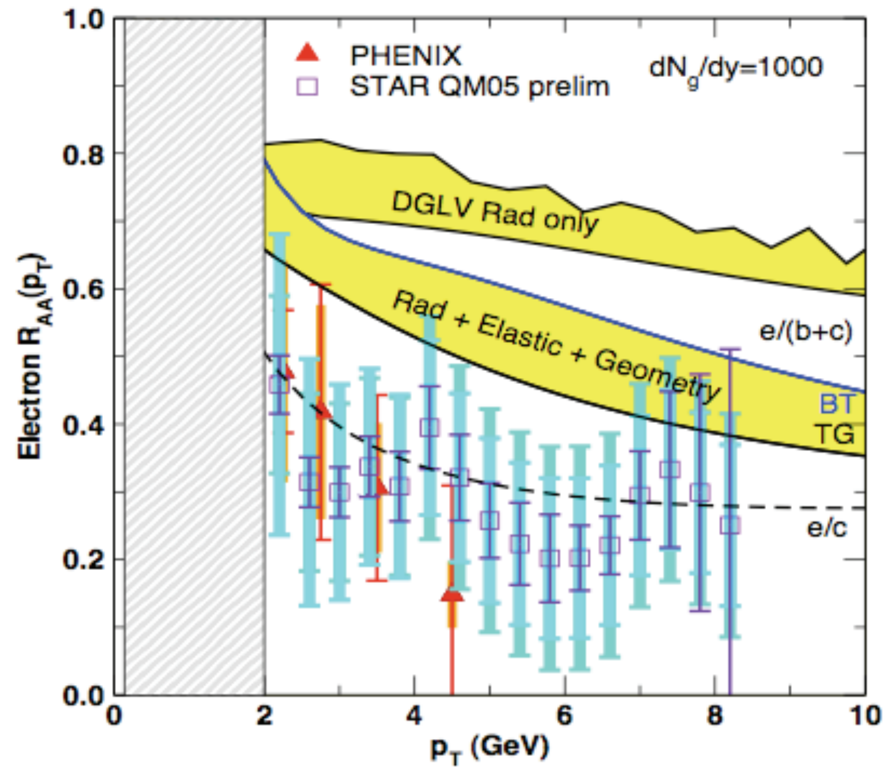
from a talk given at the 75th anniversary celebration of the Max-Planck Institute of Physics, Munich, Germany, December 10th, 1992. As quoted in: Beam Line, Winter 1992, Vol. 22, No. 4

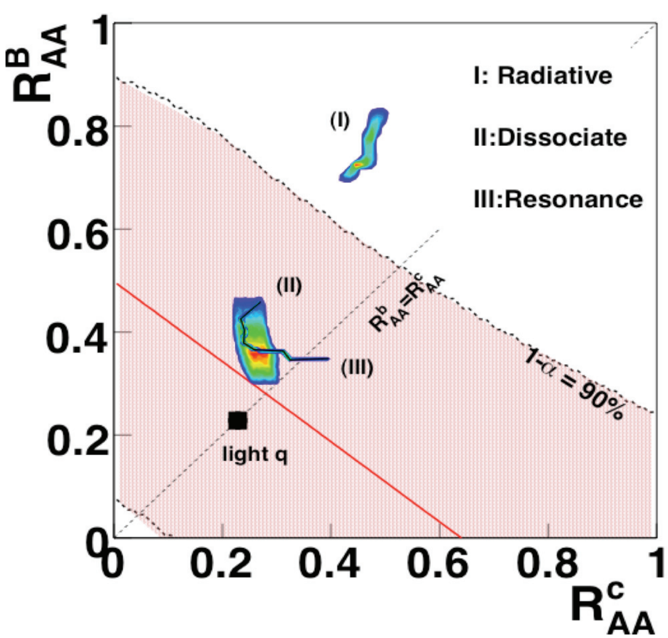
With four parameters I can fit an elephant, and with five I can make him wiggle his trunk

J. von Neumann

Heavy Flavor

- Inclusive heavy flavor suppression
- Heavy flavor jets
- Heavy flavor *tagged* jets
- Heavy flavor correlations

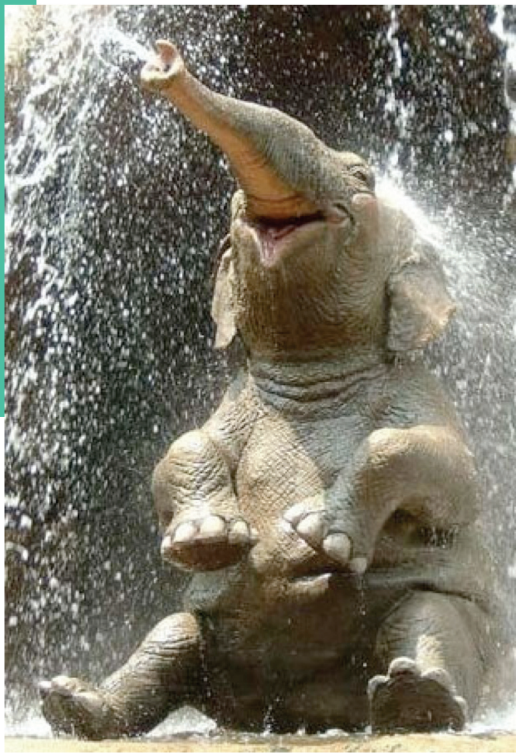




But it doesn't work. Data favors B meson Suppression comparable to that of D mesons

Outline of this Talk

- A theory of jet shapes and cross sections in nuclear collisions
- Predictions for the LHC, ongoing work at RHIC
- Heavy mesons near the phase transition
- Heavy flavor dynamics at RHIC and the LHC, example of inclusive particles



With four parameters I can fit an elephant, and with five I can make him wiggle his trunk

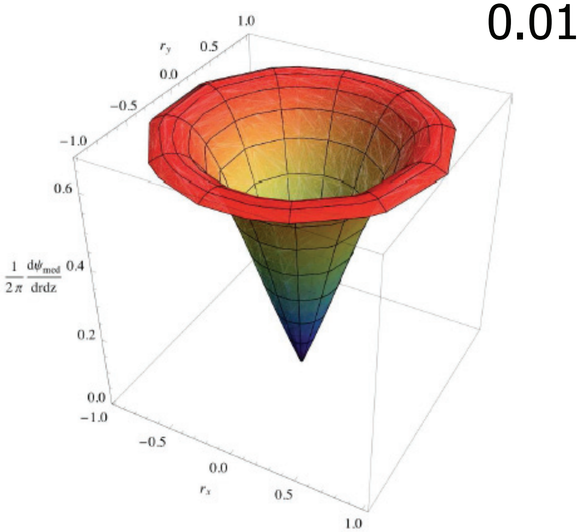
J. von Neumann

Double Differential Jet Shape

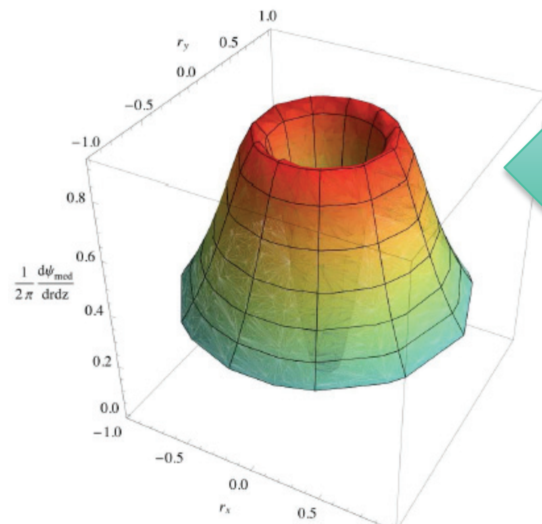
We study double differential jet shape:

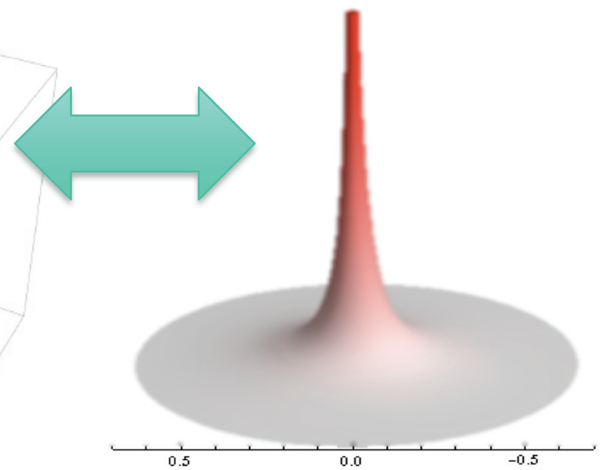
$$\frac{d^2\Psi_{\text{med.}}(r,R)}{dr\,dz} = \frac{1}{\Delta E^{in}(R,0)}\frac{dI^g(\omega = zE_{jet}, r)}{d\omega\,dr}$$

0.01



0.03

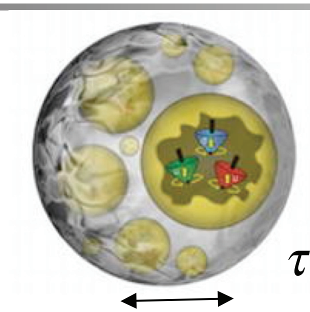




- The medium alters the energy flow associated with propagating fast partons
- Clear strategy is to use tools (like radius R and minimum particle energy $p_{T\,min}$)

The Space-Time Picture of Hadronization

- Inside-outside cascade
- Outside-inside cascade



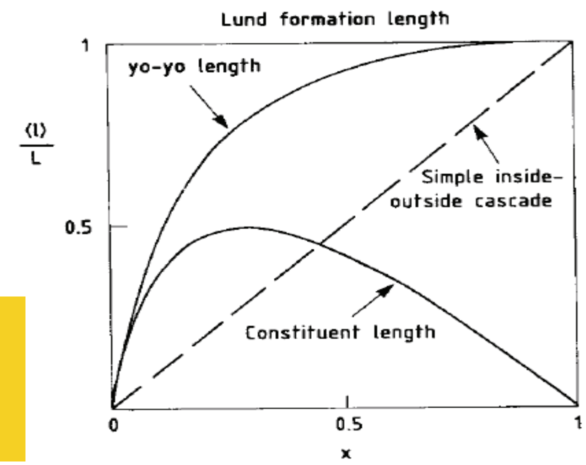
$\tau_0 \sim 1\ \text{fm}$

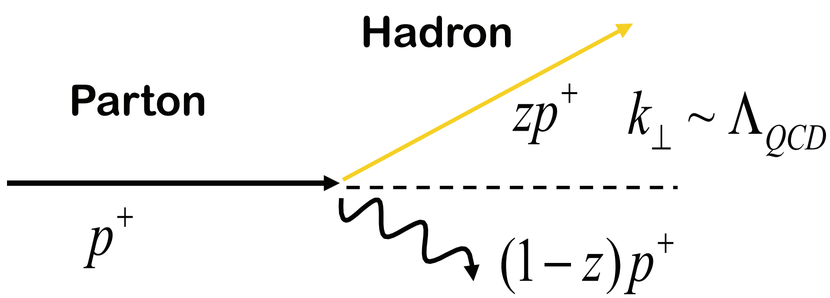
$$\tau_{\text{form}} = \tau_0 \frac{E}{m} = \tau_0 \gamma$$

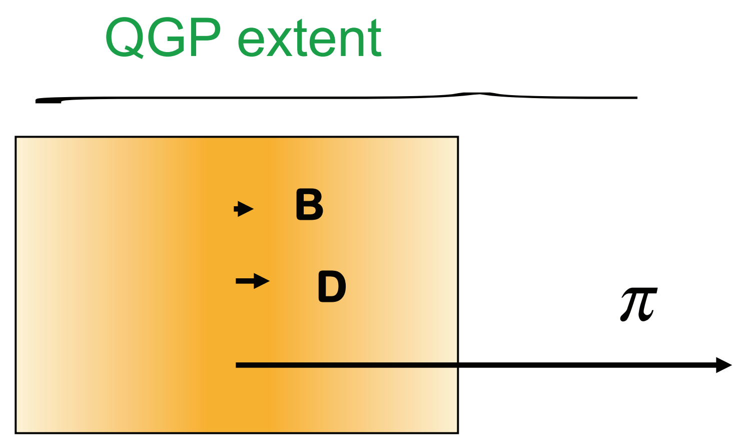
String models

Bjorken (1984)

Bialas, Gyulassy (1987)







$$\Delta y^+ = \frac{1}{\Delta p^-} = \frac{(0.2\ GeV.fm)\ 2z(1-z)p^+}{k_\perp^{\,2} + (1-z)m_h^{\,2} - z(1-z)M_q^{\,2}}$$

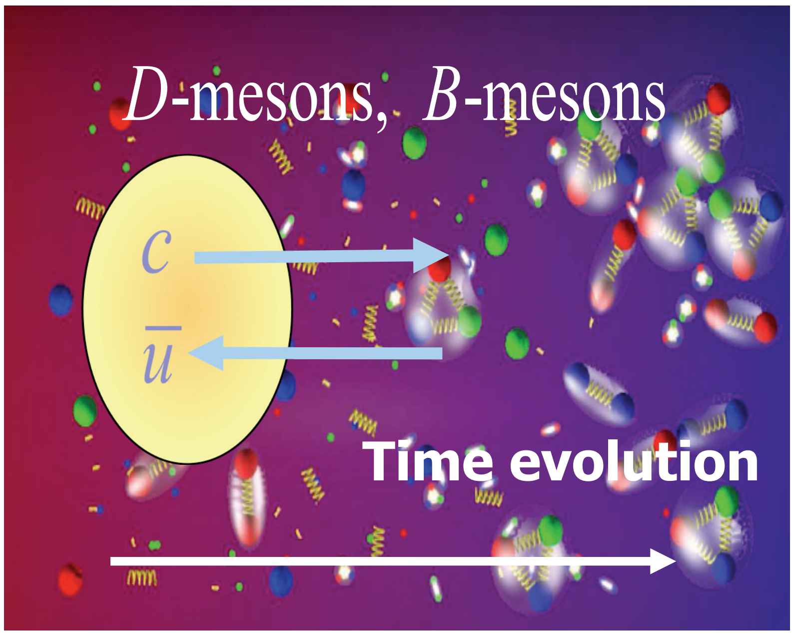
$$\tau_{\text{form}} = \Delta y^+ / (1+\beta_Q)$$

Perturbative QCD

$\tau_{\text{form}}(p_T = 10\ GeV)$	π	D	B
	20 fm	**1.5 fm**	**0.4 fm**

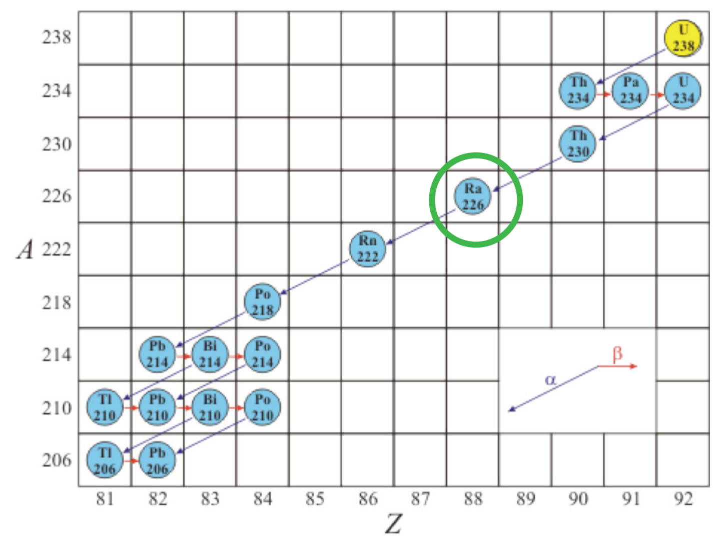
Collisional Dissociation of D / B Mesons

- An alternative



Simultaneous fragmentation and dissociation call for solving a system of coupled equations

- Example: radioactive decay chain



$$\frac{dN_i}{dt} = \lambda_{i-1} N_{i-1} - \lambda_i N_i$$

- Both emulate energy loss and lead to suppression of the final observable spectra

Adil, IV (2007)

But How is This Possible …?

… I "know" that nothing can survive the QGP, it is liquid, it is perfect!

- Non-relativistic – Schroedinger
- Relativistic - Dirac

Avila (1994)

Coulomb

$$V = -\xi \frac{1}{r}, \quad \xi = \frac{4}{3}\alpha_s$$

Linear

$$S = br$$

$$\begin{bmatrix} \frac{dG}{dr} = -(\varepsilon - V' + S' + m)F - \left(\frac{k+1}{r} - \frac{b}{2M}\right)G \\ \frac{dF}{dr} = \left(\frac{k-1}{r} - \frac{b}{2M}\right)F + (\varepsilon - V' - S' - m)G \end{bmatrix}$$

$$V(r) = \begin{cases} -\frac{\alpha}{r} + \sigma r & r < r_{med}(T) \\ -\frac{\alpha_1(T)\exp(-\mu(T)r)}{r} + \sigma r_{med}(T) & r > r_{med}(T) \end{cases}$$

- $\sigma = 0.22$ GeV^2, $\alpha = 0.45$, $r_{med} = 0.4 T_c/T$ fm.

Mocsy, Petreczky (2007)

T	T(GeV)	E_b(GeV)	$\sqrt{\langle r^2 \rangle}(GeV)^{-1}$
0	0	0.730	2.374
$0.2T_c$	0.038	0.733	2.361
$0.4T_c$	0.077	0.611	2.351
$0.6T_c$	0.115	0.256	2.540
$0.8T_c$	0.154	0.098	3.202
$1.0T_c$	0.211	0.043	3.980
$1.2T_c$	0.230	0.031	4.917
$1.4T_c$	0.269	0.017	6.402

- J/ψ can survive to ~ 2 T_c

- B, D can survive to ~ 1.5 – 2 T_c

PDFs and FFs at T ≠ 0

- Light cone gauge $A^+=0$, $0<x<1$

Adil, IV (2007)

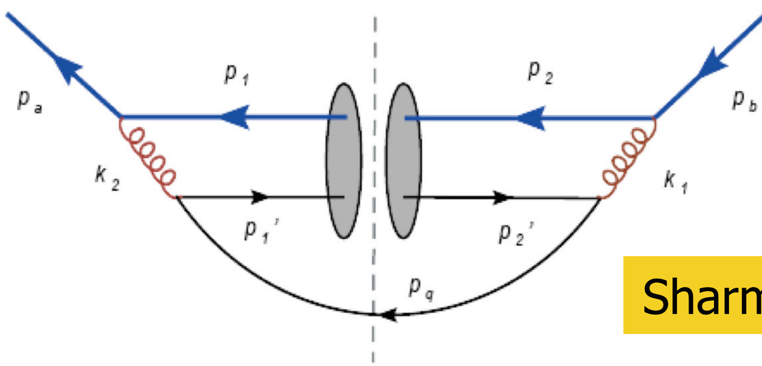
Distribution function

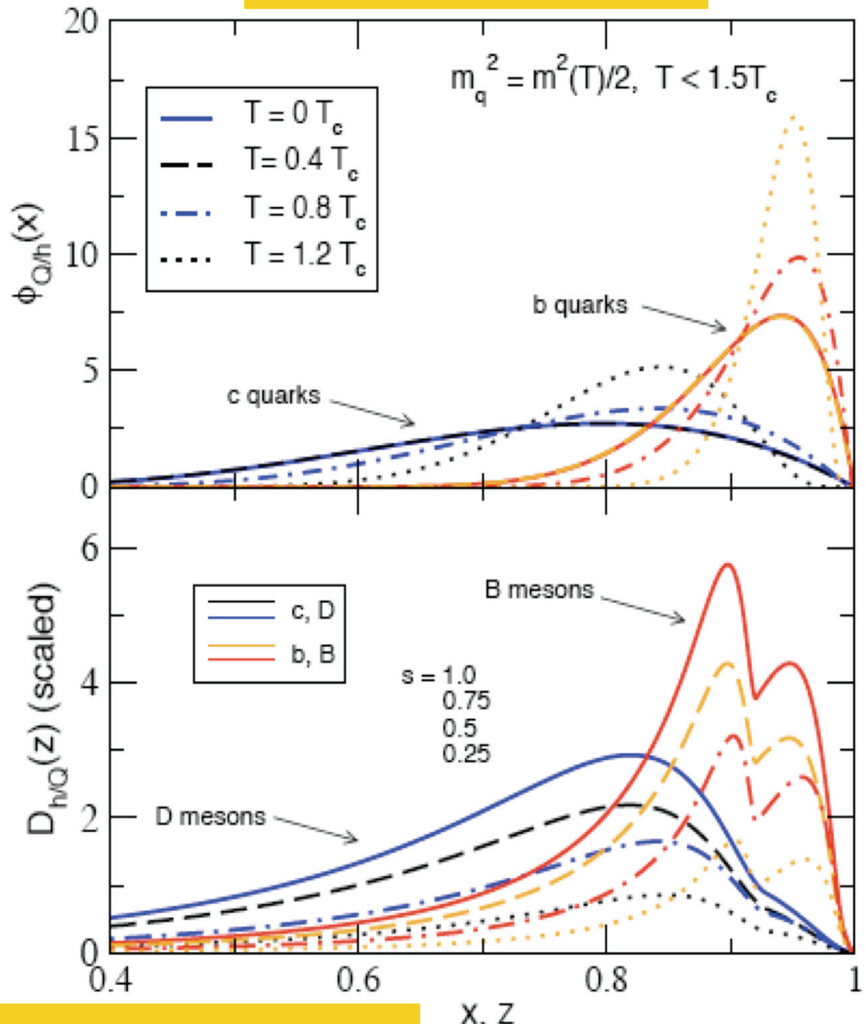
$$\phi_{q/P}(x) = \int \frac{dy^-}{2\pi} e^{-ixP^+y^-} \left\langle P \left| \bar{\psi}^a(y^-,0) \frac{\gamma^+}{2} \psi^a(0,0) \right| P \right\rangle$$

Fragmentation function

$$D_{H/q}(z) = z \int \frac{dy^-}{2\pi} e^{iP^+/z\, y^-} \frac{1}{3} Tr_{color} \frac{1}{2} Tr_{Dirac}$$

$$\times \frac{\gamma^+}{2} \left\langle 0 \left| \psi^a(y^-,0) a_H^\dagger(P^+) a_H(P^+) \bar{\psi}^a(0,0) \right| 0 \right\rangle$$

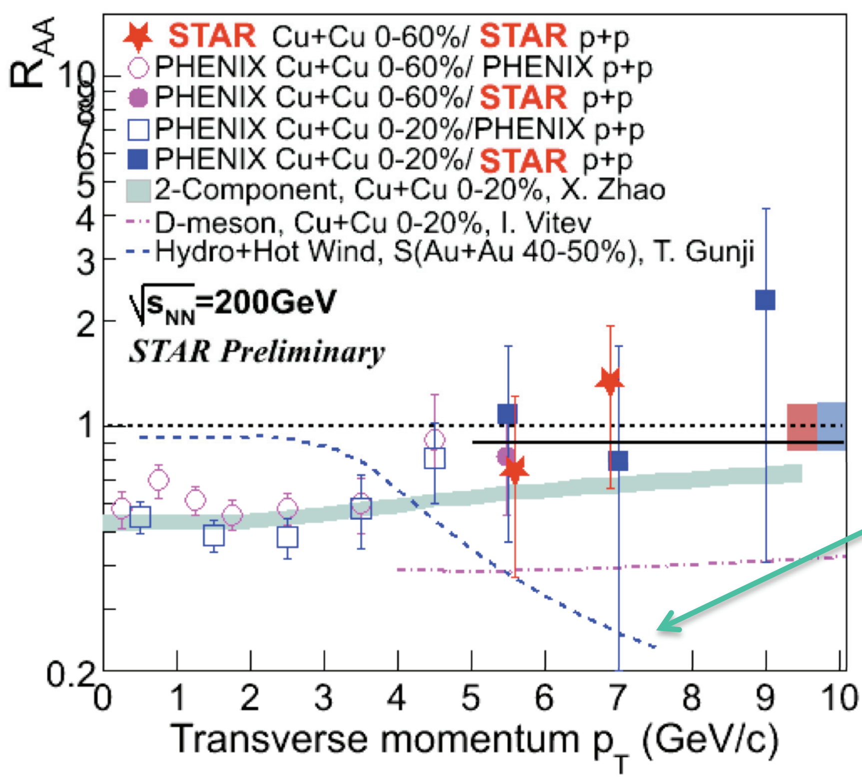


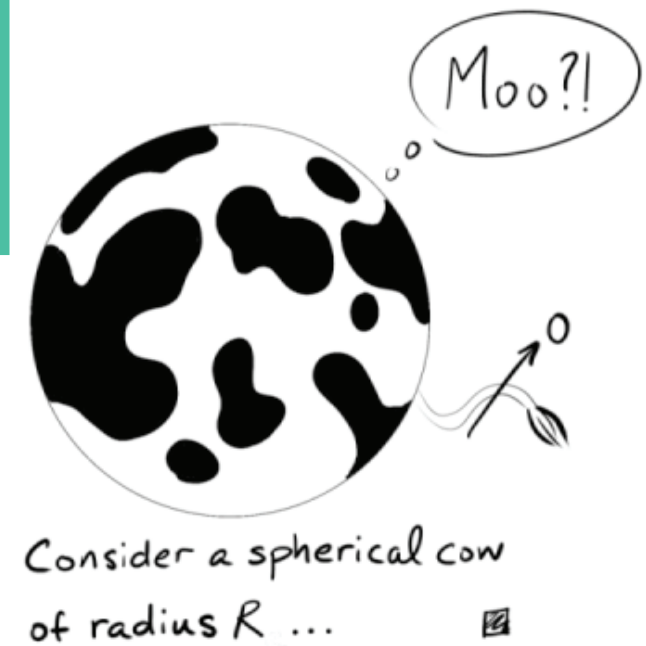


Sharma, IV, Zhang (2009)

Assumptions, Assumptions …

- It is not the screening, but the subsequent dissociation that reduce the rates of open heavy flavor and quarkonia

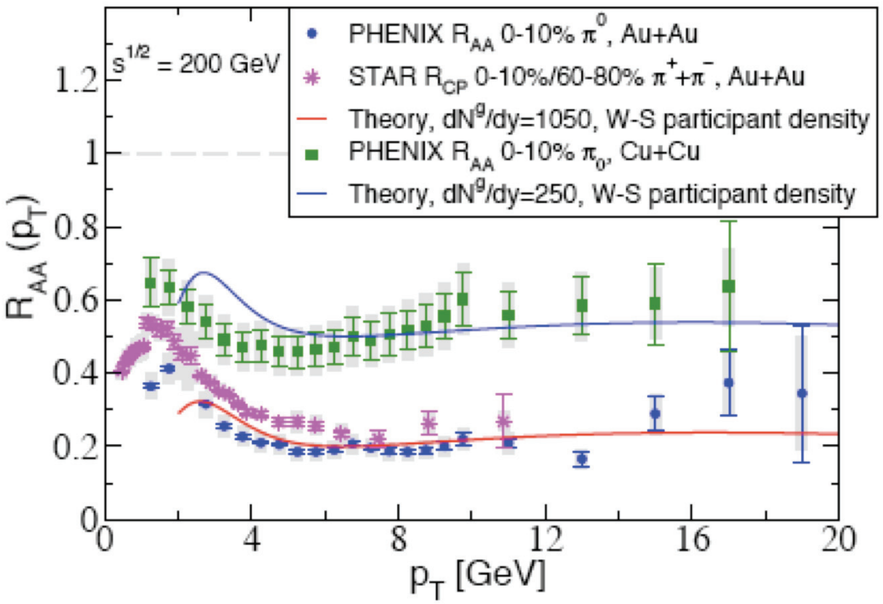




- Incompatible with equilibrium + boost assumption

Theoretically $\gamma r_{med} \gg t_{form}$

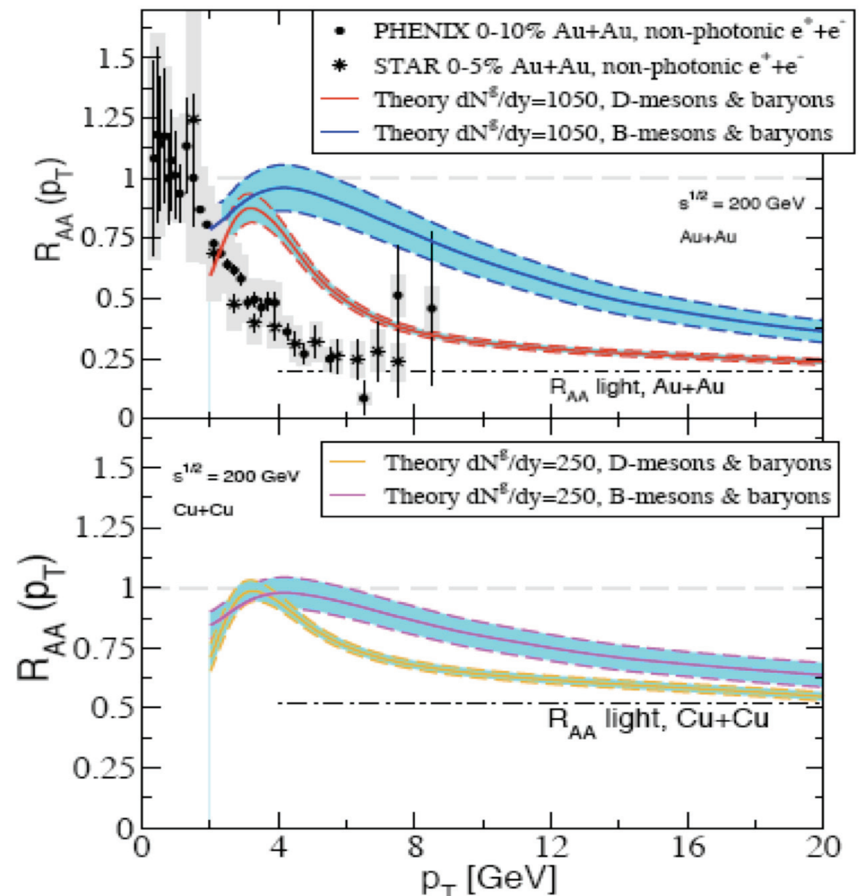
"Instant" Approximation



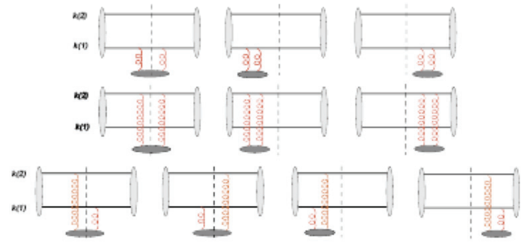
- $\frac{dN^g}{dy} = 1050$ for Au and $\frac{dN^g}{dy} = 250$ for Cu.

- Compatible with measured multiplicities

- Full treatment of cold nuclear matter effects



Solving the problem



- Dissociation probability
  $P_{\text{diss}}(t) =$
  $1 - |\langle \psi_t^*(\Delta k, x) | \psi_i(\Delta k, x) \rangle|^2$
- $\tau_{\text{diss}} = \frac{1}{P_{\text{diss}}(t)} \frac{dP_{\text{diss}}(t)}{dt}.$

$$\partial_t f^Q(p_T,t) = -\frac{1}{\langle \tau_{form}(p_T,t) \rangle} f^Q(p_T,t) + \frac{1}{\langle \tau_{diss}(p_T/\bar{x},t) \rangle} \int_0^1 dx \, \frac{1}{x^2} \phi_{Q/H}(x) f^H(p_T/x,t)$$

$$\partial_t f^H(p_T,t) = -\frac{1}{\langle \tau_{diss}(p_T,t) \rangle} f^H(p_T,t) + \frac{1}{\langle \tau_{form}(p_T/\bar{z},t) \rangle} \int_0^1 dz \, \frac{1}{z^2} D_{H/Q}(z) f^Q(p_T/z,t)$$

- The subtlety is how to include partonic energy loss
- It cannot be incorporated as drag/diffusion

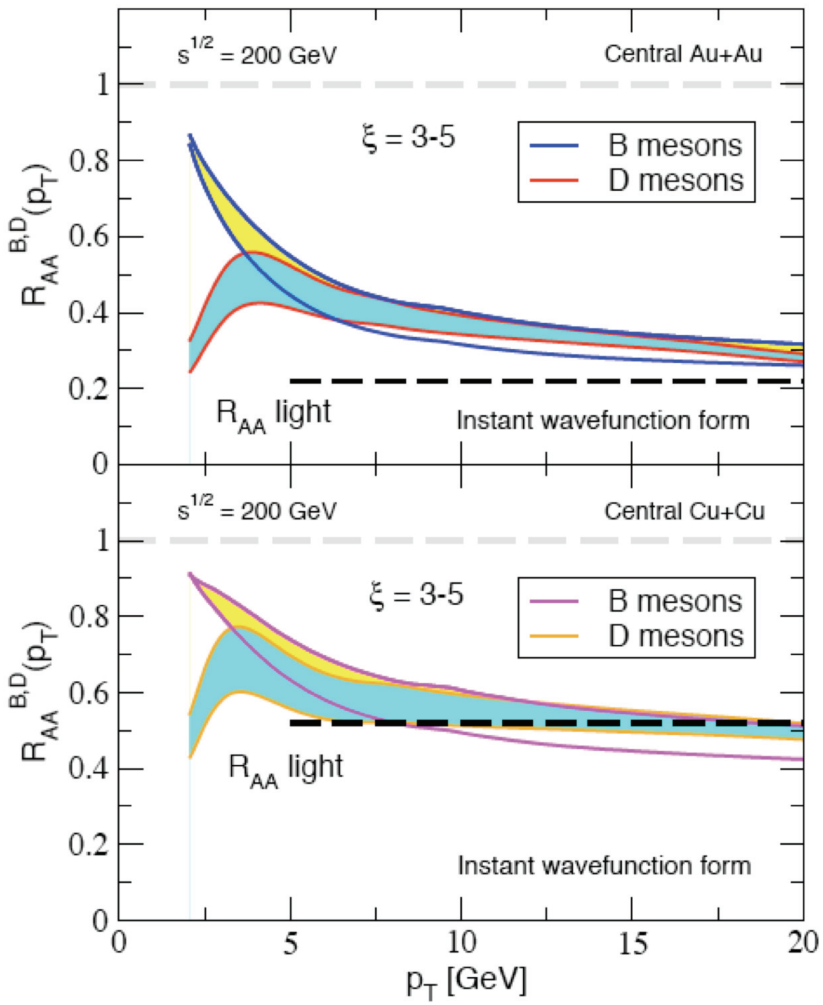
- We include it approximately as MODIFIED INITIAL CONDITION

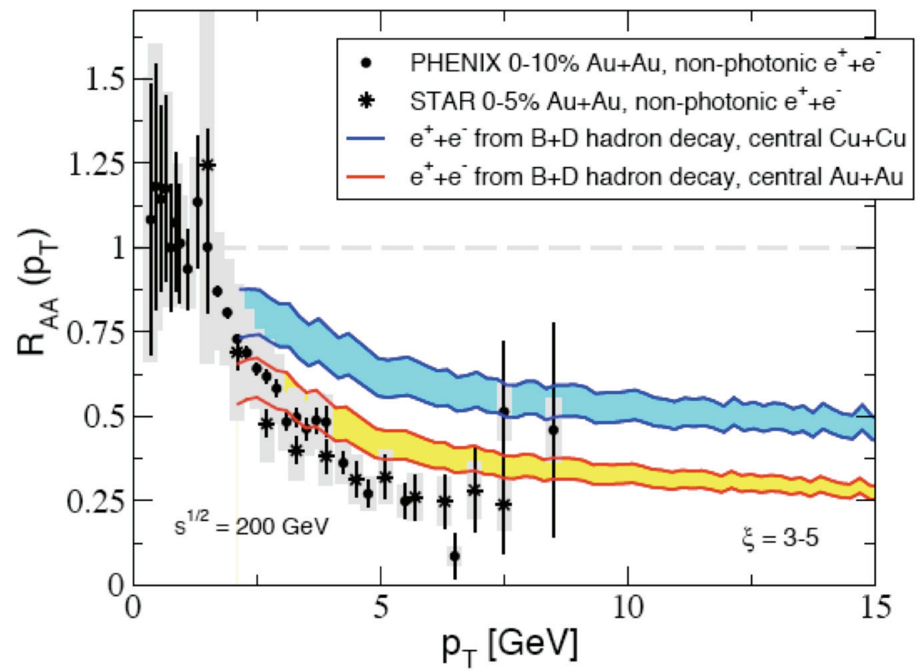
$$f^Q(p_T, t=0) = \frac{d\sigma}{dy d^2 p_T} f^Q(p_T, QUENCHED)$$

$$f^H(p_T, t=0) = 0$$

Numerical Results

- D/B mesons and non-photonic electrons :Au+Au, Cu+Cu at RHIC

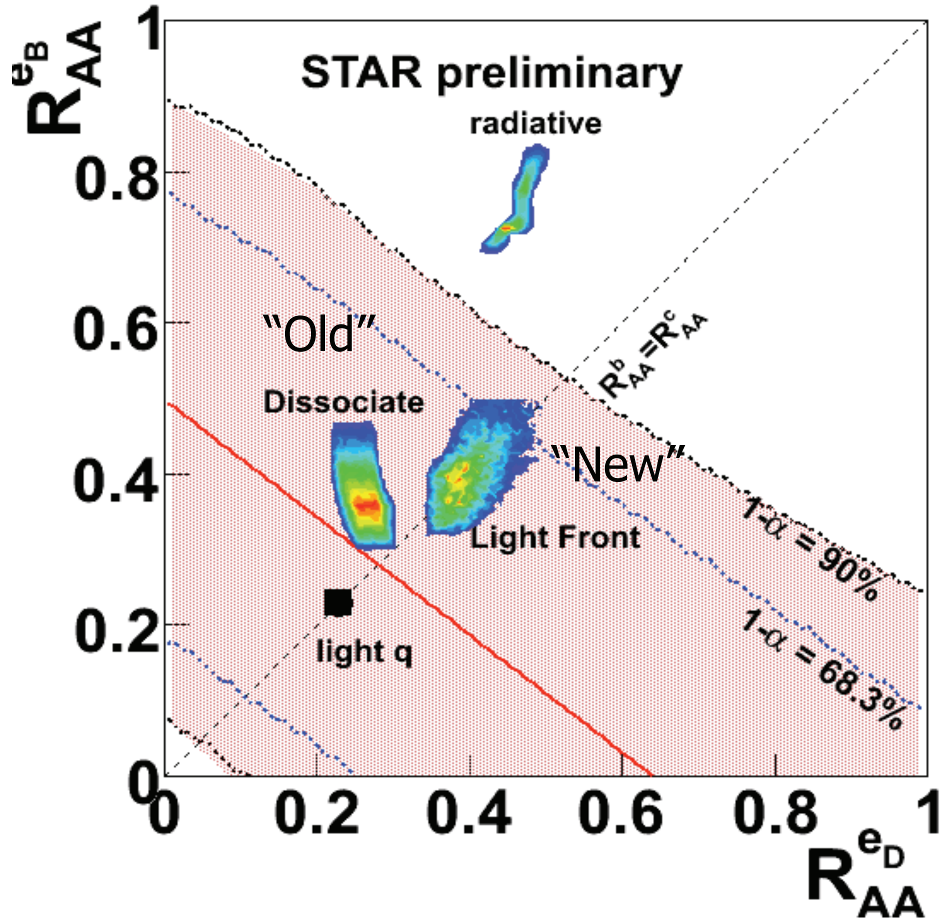




- Cronin effect is very important.
- Reduces the suppression at intermediate p_T

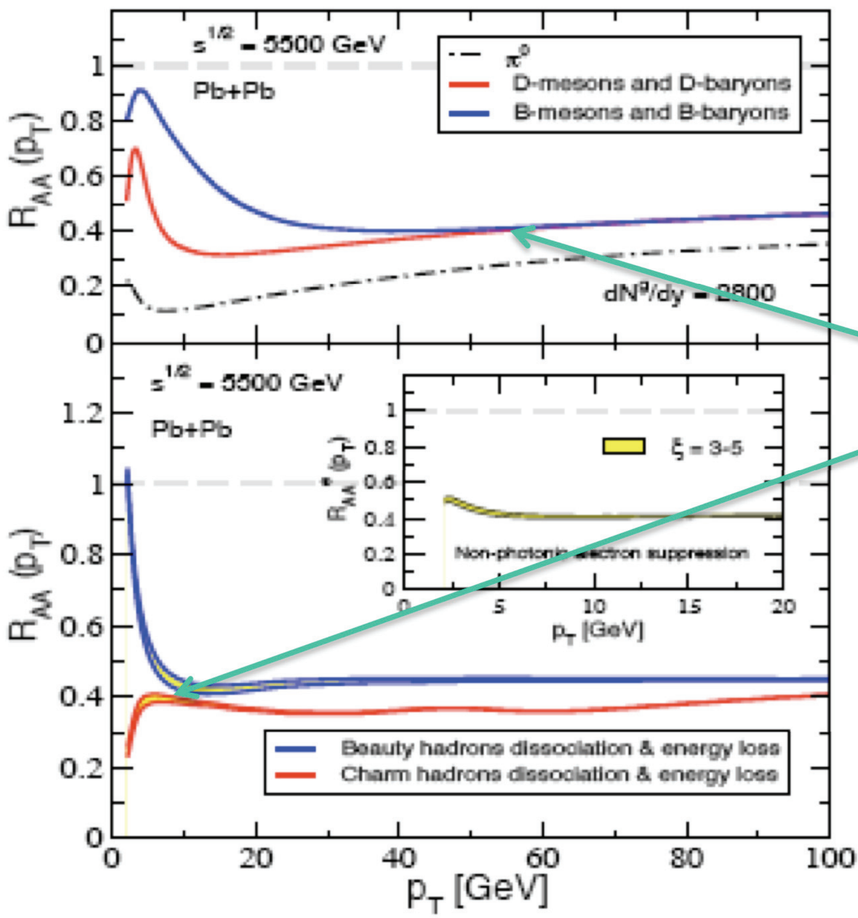
Discussion of Results

- Theoretically a more complete and consistent calculation
- Reduces slightly the overall suppression magnitude at intermediate p_T
- D and B meson suppression are practically the same for all p_T > 5 GeV



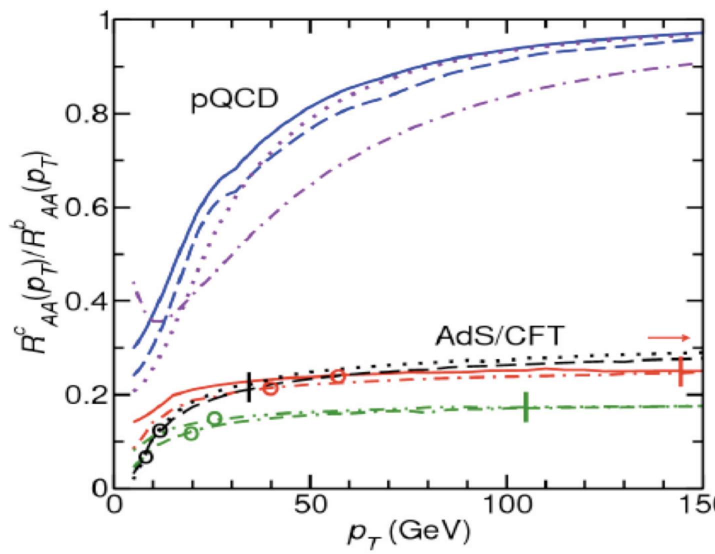
The best way to measure the suppression of B and D mesons for now

The Role of LHC



LHC is critical to cover the pT range needed for b-quark, B-meson dynamics

$$R^B_{AA}(p_T) = R^D_{AA}(p_T) \quad \infty$$



Forget AdS/CFT - this is the incoherent limit of radiative energy loss”

Conclusions

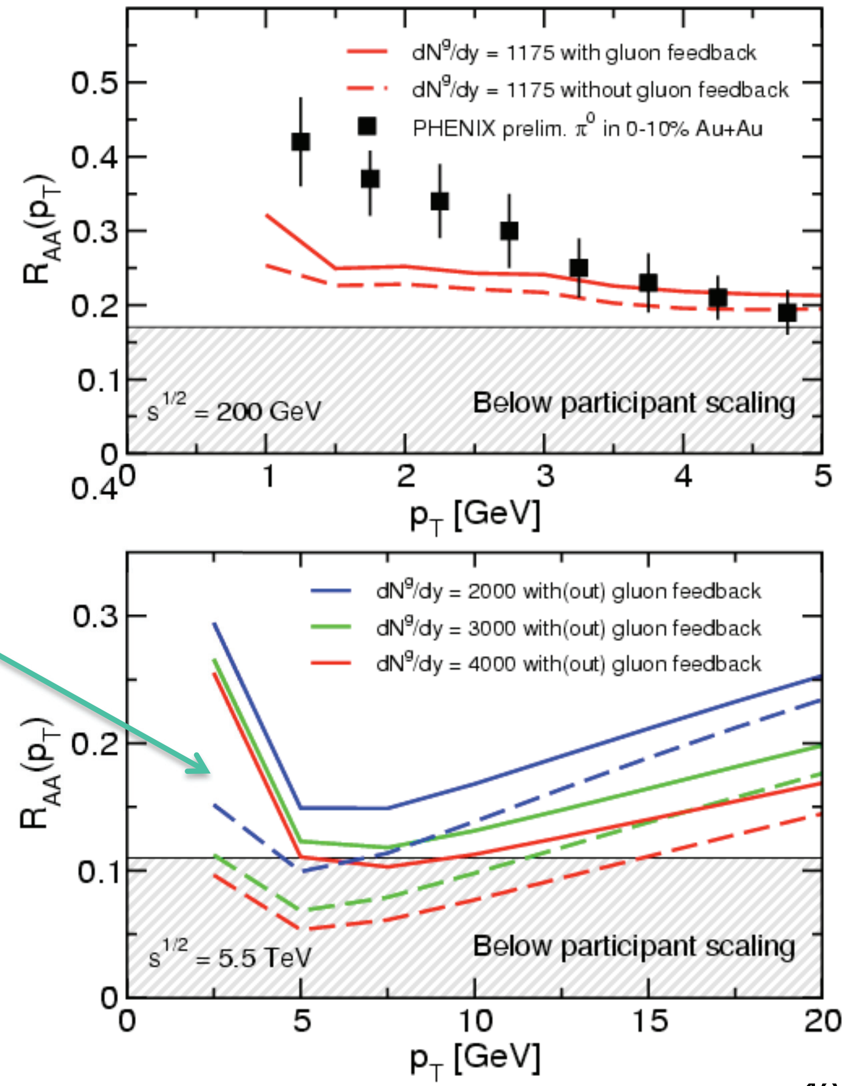
- We have developed the theory of jet shapes and jet cross sections in nuclear collisions
- Experimental measurements at RHIC indicate the feasibility of these studies. These ramp up as a major direction at the LHC
- First calculations of heavy meson survival in the vicinity of T_c are done. Partonic energy loss and meson dissociation are combined
- Predictions for LHC are given and work soon start on other heavy flavor observables

Gluon Feedback to Single Inclusives

- Note that $N_{bin} / (N_{part}/2) = 0.11$

- The redistribution of the lost energy is very important at the LHC. 100% correction and p_T<15 GeV affected

- Can quickly eliminate some models or indicate very interesting new possibilities for modeling



Outline of the Talk

Jet tomography of the QGP

- Jet quenching for light hadrons, QGP tomography
- The heavy quark puzzle at RHIC. A space-time picture of hadronization

Collisional dissociation of hadrons in dense QCD matter

- Dissociation: new approach to D- and B-mesons suppression in the QGP
- Light-front quantization and light-front wave-functions
- Possibilities to calculate parton distribution functions and fragmentation functions
- Evaluating the medium modification of heavy quark fragmentation

Phenomenological results

- Heavy hadron cross sections and correlations
- Solving the rate equations and relative meson suppression in Cu+Cu
- Results for decay electrons and caveats

Summary and outlook

Talk based upon: R.Sharma, I.Vitev, in preparation
A.Adil, I.Vitev, Phys. Lett. B649 (2007)

Calculating the Meson Wave Function

- Relativistic Dirac equation

$$S' = S - \frac{3}{2}\frac{VS}{M_Q} - \frac{m}{M_Q}V \qquad \kappa = \begin{cases} -l+1, & j = l+1/2 \\ l, & j = l-1/2 \end{cases}$$

$$V' = S - \frac{1}{2}\frac{S^2}{M_Q} - \frac{m}{M_Q}S$$

Coulomb

$$V = -\xi\frac{1}{r},\ \xi = \frac{4}{3}\alpha_s$$

Linear

$$S = br$$

Reduces to:

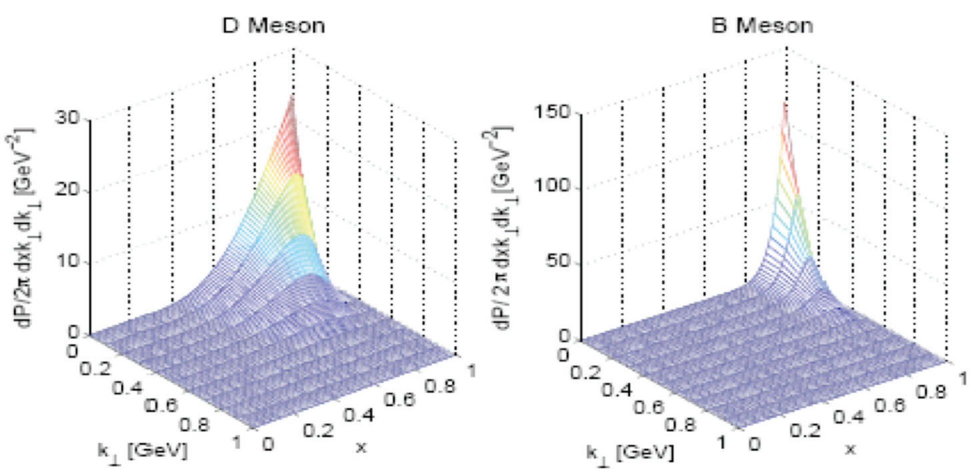
$$\begin{bmatrix} \dfrac{dG}{dr} = -(\varepsilon - V' + S' + m)F - \left(\dfrac{k+1}{r} - \dfrac{b}{2M}\right)G \\ \dfrac{dF}{dr} = \left(\dfrac{k-1}{r} - \dfrac{b}{2M}\right)F + (\varepsilon - V' - S' - m)G \end{bmatrix}$$

Reduces to:

- Radial density: $\rho(r) \sim (F^2 + G^2)$

$^1S_0 \quad ^3S_1$

$D^0, \bar{D}^0, D^- D^+, D_s \ldots\ The^*,\ \ldots\ Same\ for\ B$



Boost with large P+ - end up at the same longitudinal rapidity

$$|\ \psi\ (\Delta k_\perp, x)\ |^2 \sim Exp\left[-\frac{\Delta k_\perp^2 + 4m_Q^2(1-x) + 4m_q^2(x)}{4\Lambda^2 x(1-x)}\right]$$

M. Avila, Phys. Rev. D49 (1994)

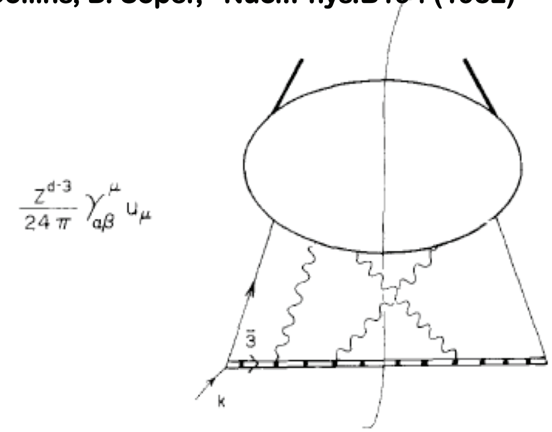
Fragmentation Functions

- Light cone gauge $A^{+}=0$, $0<z<1$

J. Collins, D. Soper, Nucl.Phys.B194 (1982)

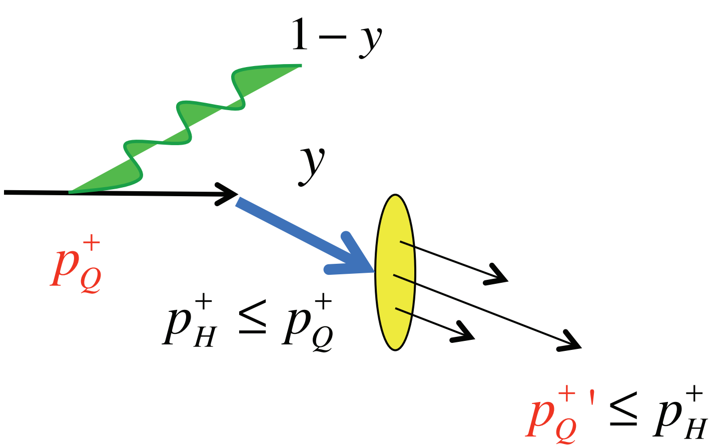
$$D_{H/q}(z)=z\int\frac{dy^{-}}{2\pi}e^{iP^{+}/z\,y^{-}}\frac{1}{3}Tr_{color}\frac{1}{2}Tr_{Dirac}\frac{\gamma^{+}}{2}\left\langle 0\left|\psi^{a}(y^{-},0)a_{H}^{\dagger}(P^{+})a_{H}(P^{+})\bar{\psi}^{a}(0,0)\right|0\right\rangle$$

$$D_{H/\bar{q}}(z)=z\int\frac{dy^{-}}{2\pi}e^{iP^{+}/z\,y^{-}}\frac{1}{3}Tr_{color}\frac{1}{2}Tr_{Dirac}\left\langle 0\left|\bar{\psi}^{a}(y^{-},0)\frac{\gamma^{+}}{2}a_{H}^{\dagger}(P^{+})a_{H}(P^{+})\psi^{a}(0,0)\right|0\right\rangle$$



- Kinematically FFs at tree level do not exist except for exclusive processes

Factorization



$$D_{H/q}(z)\propto\frac{1}{2\pi\beta_0}\ln\frac{\ln Q^2/\Lambda^2}{\ln m_Q/^2\ \Lambda^2}\frac{1}{2(2\pi)^3}\int_0^1 dyP_{qq}(y)\sum_{n=2,3}^{\infty}\int\prod_{i=1}^{n}\frac{dx_i}{2x_i}\frac{d^2k_{\perp i}}{(2\pi)^3}$$
$$\left|\psi_n\left(\{x\}_i,\{k_{\perp i}\},\{\lambda_i\}\{a_i\}\right)\right|^2\delta\left(\sum_{i=1}^{n}x_i-1\right)\delta\left(\sum_{i=1}^{n}k_{\perp i}\right)\times\sum_{\alpha}\ \delta\left(x_q^{\alpha}-y/z\right)$$

$$D_{H/\bar{q}}(z)\propto\frac{1}{2\pi\beta_0}\ln\frac{\ln Q^2/\Lambda^2}{\ln m_Q/^2\ \Lambda^2}\frac{1}{2(2\pi)^3}\int_0^1 dyP_{qq}(y)\sum_{n=2,3}^{\infty}\int\prod_{i=1}^{n}\frac{dx_i}{2x_i}\frac{d^2k_{\perp i}}{(2\pi)^3}$$
$$\left|\psi_n\left(\{x\}_i,\{k_{\perp i}\},\{\lambda_i\}\{a_i\}\right)\right|^2\delta\left(\sum_{i=1}^{n}x_i-1\right)\delta\left(\sum_{i=1}^{n}k_{\perp i}\right)\times\sum_{\alpha}\ \delta\left(x_{\bar{q}}^{\alpha}-y/z\right)$$

Remarkable connection between PDFs and FFs

Modification Fragmentation Functions

Start from the definition

$$D_{H/q}(z) = z\int \frac{dy^-}{2\pi} e^{iP^+/z\, y^-} \frac{1}{3} Tr_{color} \frac{1}{2} Tr_{Dirac} \frac{\gamma^+}{2} \langle 0 | \psi^a(y^-,0) a_H^\dagger(P^+) a_H(P^+) \bar{\psi}^a(0,0) | 0 \rangle$$

phase space density

1. Fragmentation of the partons, just from the QGP

G.Nayak (2008)

$$D_{H/q}(z) = z\int \frac{dy^-}{2\pi} e^{iP^+/z\, y^-} \frac{1}{3} Tr_{color} \frac{1}{2} Tr_{Dirac} \frac{\gamma^+}{2} \langle 0 | \psi^a(y^-,0) a_H^\dagger(P^+) a_H(P^+) \bar{\psi}^a(0,0) | 0 \rangle$$

2. Thermal modification

New solution for the wave function. As a function of time

3. Pure coalescence from the QGP

Need to work out the Fiertz decomposition factors

4. Corrections to the hard fragmentation

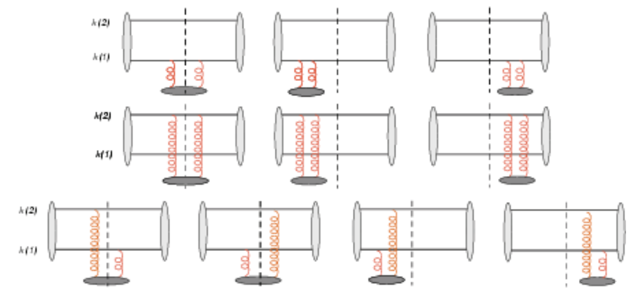
Need to work also the pQCD vs thermal rates

Medium Dissociation of Heavy Mesons

Initial distribution:

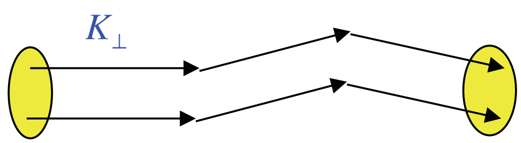
$$|\psi_i(\Delta k_\perp,x)|^2 = \left[\delta^2(K_\perp)\right] \times \left[\text{Norm}^2 e^{-\frac{\Delta k_\perp^2}{4x(1-x)\Lambda^2}} e^{-\frac{m_1^2(1-x)+m_2^2 x}{x(1-x)\Lambda^2}} \right]$$

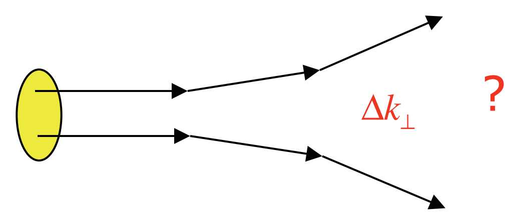
Resum using GLV the multiple scattering in impact parameter (B,b) space



$$|\psi_f(\Delta k_\perp,x)|^2 = \left[\frac{e^{-\frac{K_\perp^2}{4\chi\mu^2\xi}}}{4\chi\mu^2\xi} \right] \times \left[\text{Norm}^2 \frac{x(1-x)\Lambda^2}{\chi\mu^2\xi + x(1-x)\Lambda^2} e^{-\frac{\Delta k_\perp^2}{4(\chi\mu^2\xi + x(1-x)\Lambda^2)}} e^{-\frac{m_1^2(1-x)+m_2^2 x}{x(1-x)\Lambda^2}} \right]$$

- Heavy meson acoplanarity: $\langle K_\perp^2 \rangle = 2\left(2\mu^2 \frac{L}{\lambda_q}\xi\right)$ $\quad 2\left(2\mu^2 \frac{L}{\lambda_q}\xi\right) \equiv \int_0^L 2\left(2\mu^2(l)\frac{1}{\lambda_q(l)}\xi\right) dl$

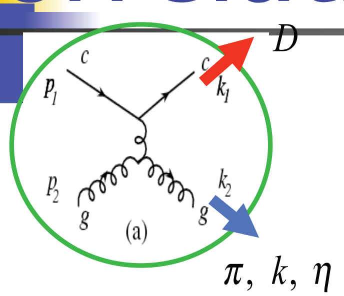


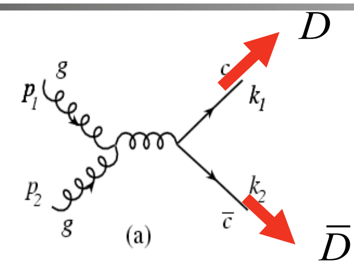


- Broadening (separation) the q q-bar pair:

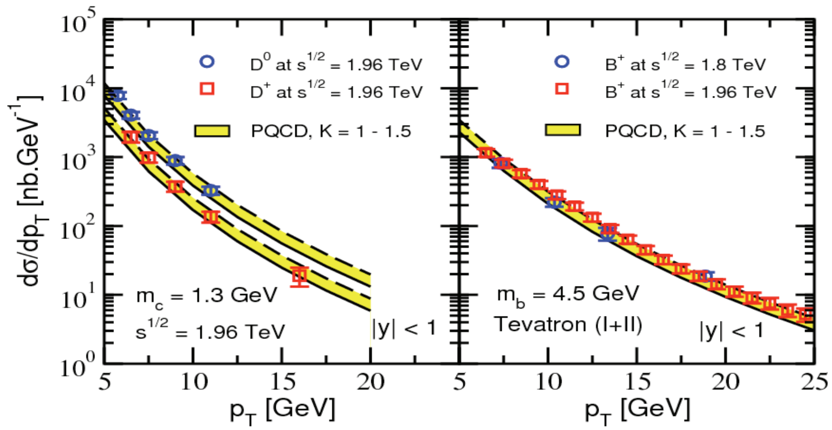
$$\psi_f(\Delta k_\perp,x) = a\psi_M(\Delta k_\perp,x) + (1-a)\psi_{q\bar{q}\ \text{dissociated}}(\Delta k_\perp,x)$$

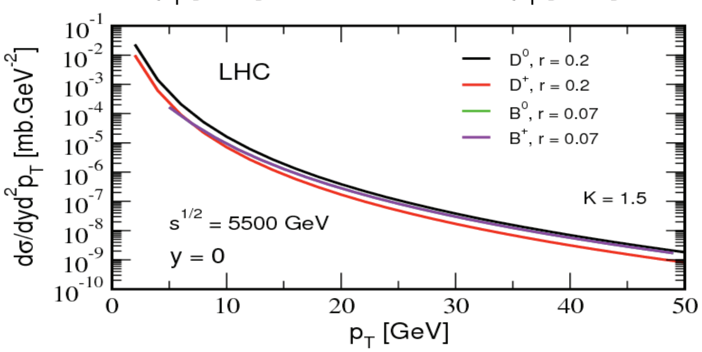
Heavy Quark Production and Correlations

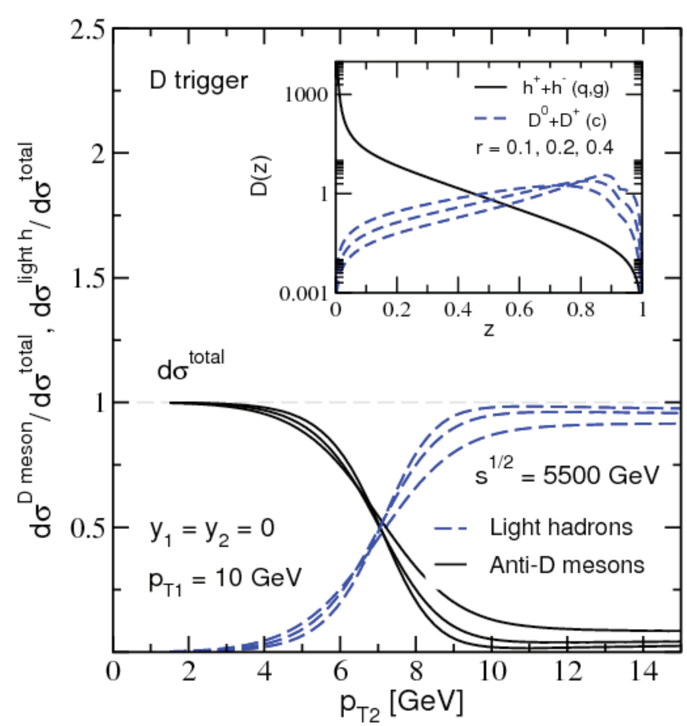




- Fast convergence of the perturbative series
- Possibility for novel studies of heavy quark-triggered (D and B) jets: hadron composition of associated yields







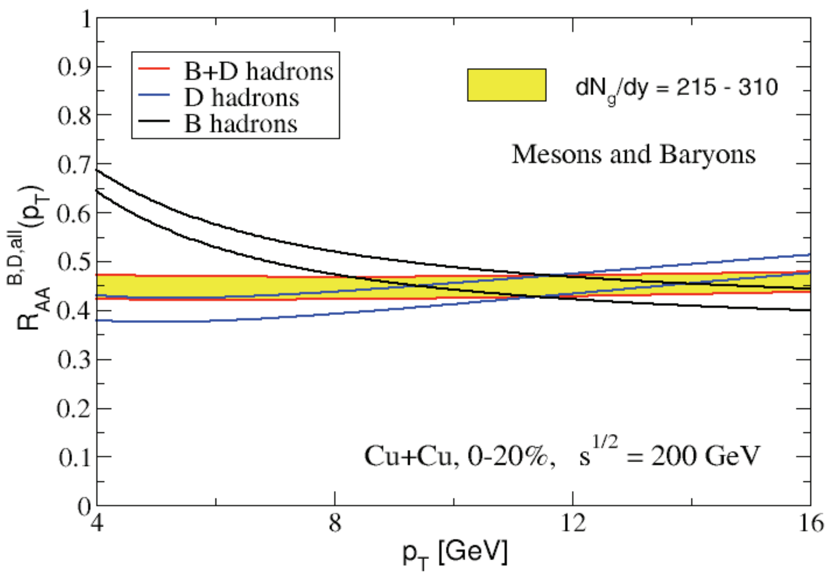
Heavy Meson Dissociation at RHIC and LHC

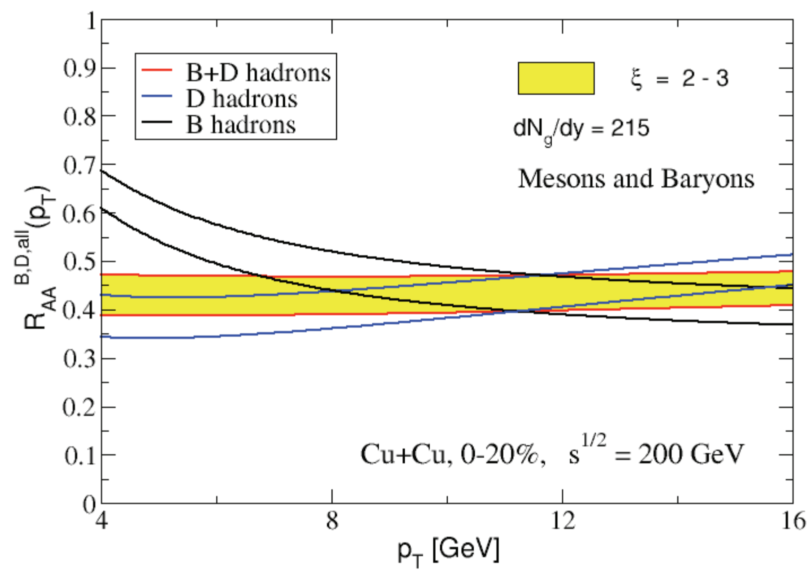
Coupled rate equations

$$\partial_t f^Q(p_T,t) = -\frac{1}{\langle \tau_{form}(p_T,t)\rangle} f^Q(p_T,t) + \frac{1}{\langle \tau_{diss}(p_T/\bar{x},t)\rangle}\int_0^1 dx \, \frac{1}{x^2}\phi_{Q/H}(x) f^H(p_T/x,t)$$

$$\partial_t f^H(p_T,t) = -\frac{1}{\langle \tau_{diss}(p_T,t)\rangle} f^H(p_T,t) + \frac{1}{\langle \tau_{form}(p_T/\bar{z},t)\rangle}\int_0^1 dz \, \frac{1}{z^2} D_{H/Q}(z) f^Q(p_T/z,t)$$

- The asymptotic solution in the QGP - sensitive to t_0~0.6 fm and expansion dynamics
- Features of energy loss $(\bar{x} < 1, \ \bar{z} < 1)$
- B-mesons as suppressed as D-mesons at p_T~ 10 GeV at the LHC





Quenching of Non-Photonic Electrons

- Full semi-leptonic decays of C- and B-mesons and baryons included. PDG branching fractions and kinematics. PYTHIA event generator

$$R_{AA}^{e^\pm}(p_T) = \frac{d\sigma_{AA}^{e^\pm}/dyd^2p_T}{\langle N_{\rm coll}\rangle d\sigma_{pp}^{e^\pm}/dyd^2p_T}$$

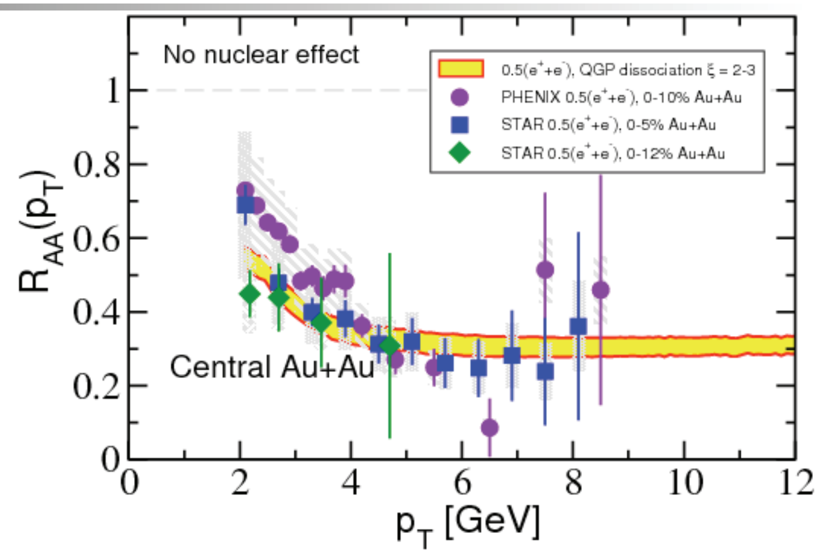
- Similar to light π^0, however, different physics mechanism

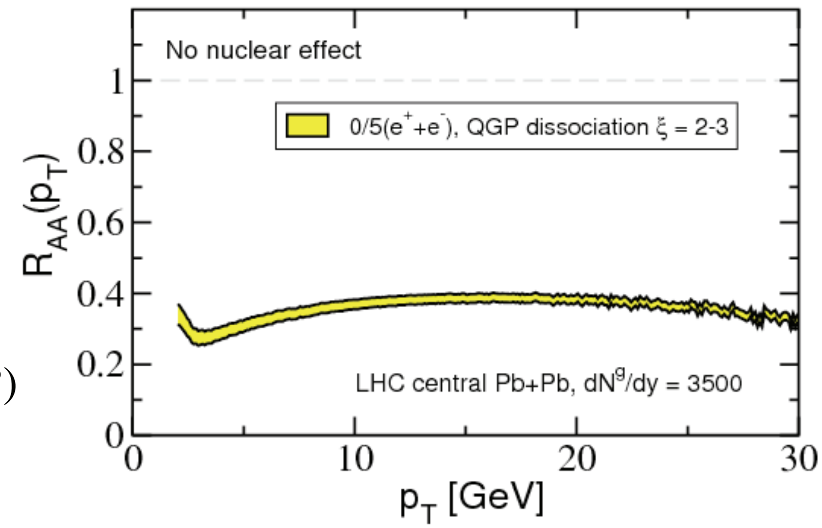
- B-mesons are included. They give a major contribution to $(e^+ + e^-)$

Note on applicability

D-, B-mesons to $R_{AA}(D) = R_{AA}(B)$

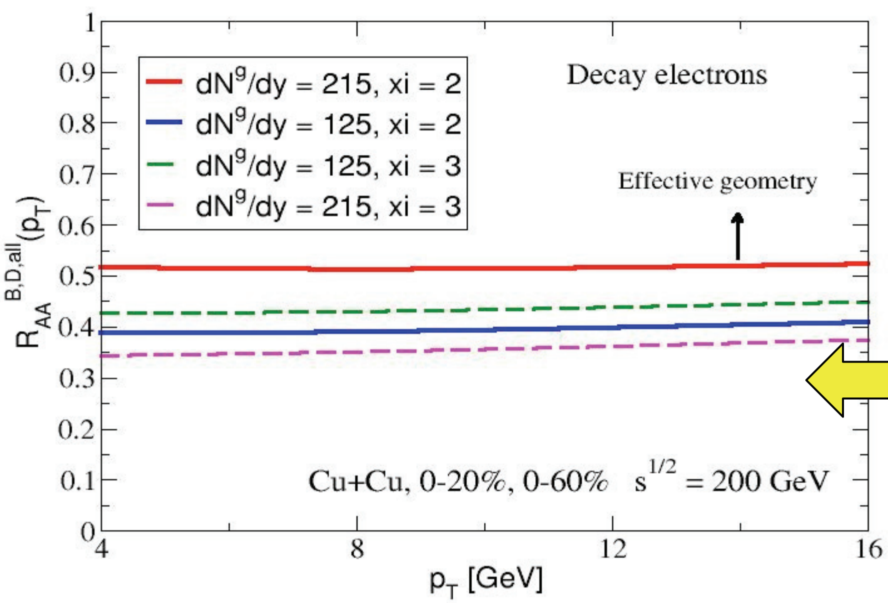
$(e^+ + e^-)$ to 25 GeV

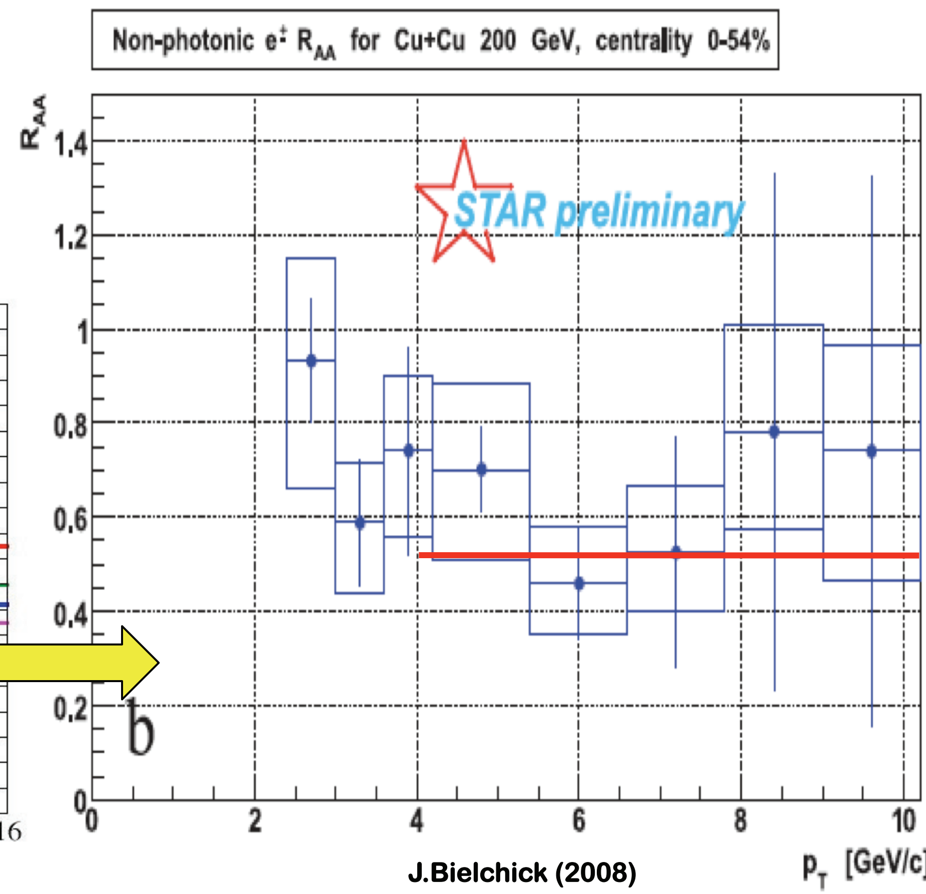




Electron Suppression in Cu +Cu

- Of more recent relevance are the results in Cu+Cu. Calculated for several centralities, both mesons and electrons





- Main caveat: cylindrical geometry. While this is not very important for radiative e-loss it is more important for dissociation (short distance). Expect stronger centrality dependence.

Conclusions

Heavy Quarks / Hadrons

- Time dependence of fragmentation/hadronization in the spotlight
- The heavy quark puzzle at RHIC may require different solution than the interaction strength

Collisional dissociation of hadrons in dense QCD matter

- Begin to understand from QCD the FFs and PDFs beyond global analysis. Shifts the problem to the wave-function. HQ tractable
- Derived the theoretical results. Identified the sources of medium modification of FFs

Phenomenological results

- Gave results in Cu+Cu directly comparable to previous Au+Au calculations. Both mesons and electrons
- Found comparable suppression of light and heavy

To do list

- Carry the numerical implementation of the modification of the FFs
- Update calculations in Cu+Cu, estimate geometry effects
- Compare fragmentation/coalescence contributions calculated in this approach

Effects of Partial Chiral Symmetry Restoration

$$\mathcal{L} = i\bar{\psi}_N \not{D} \psi_N + 0\bar{\psi}_N \bar{\psi}_N + \mathcal{L}_g$$

$$SU(N)_L \times SU(N)_R \to SU(N)_{L+R}$$

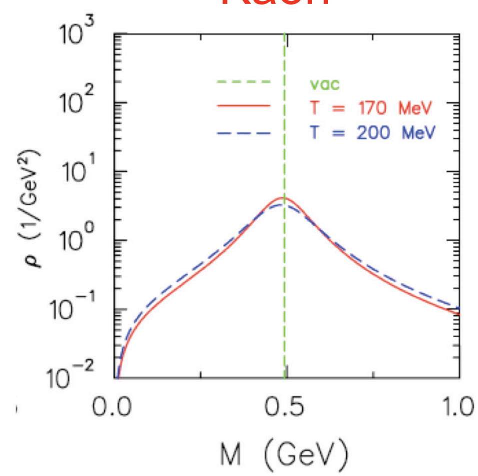
- Scale of chiral symmetry restoration
  - Includes approximately strange quarks $\quad m_\rho \le \Lambda_\chi \le 4\pi f_\pi$

Mass shifts

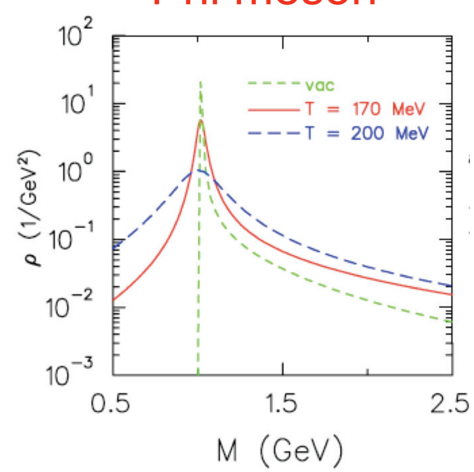
Width broadening

Manifestation for baryons

Kaon



Phi meson

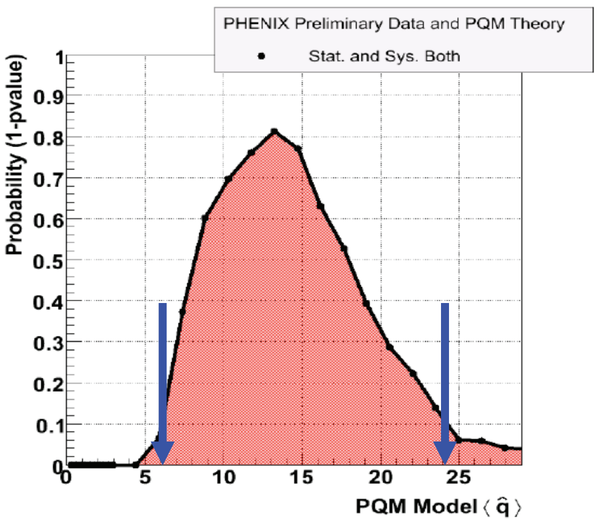


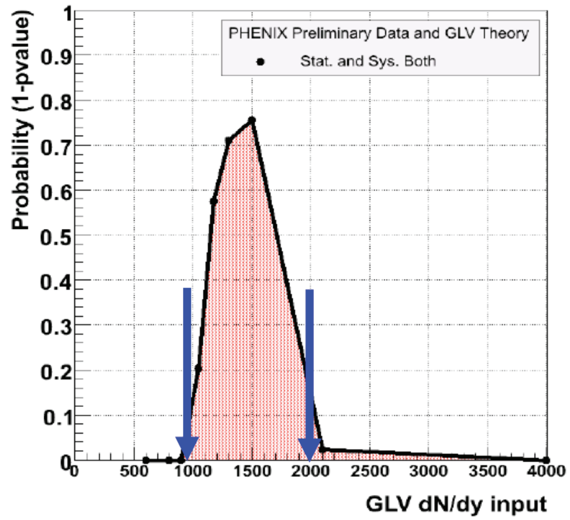
L. Holt, K.Haglin, J. Phys. G31, S245 (2005)

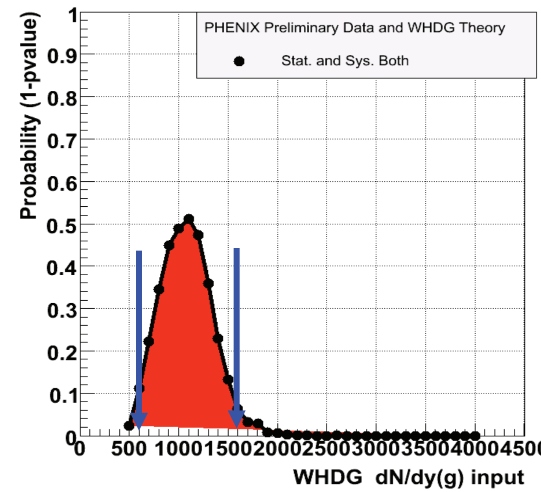
Backup

Backup

Comparing R_{AA} to Theory







$6 \leq \langle \hat{q} \rangle \leq 24 \ \text{GeV}^2/\text{fm}$

(Probability $> 10\%$)

$1000 \leq {dN_g}/{dy} \leq 2000$

(Probability $> 10\%$)

$600 \leq {dN_g}/{dy} \leq 1600$

(Probability $> 10\%$)

Add stat and uncorr point-to-point syst err in quadrature – χ^2 minimization fit to obtain the probability of a given parameter

Then offset the data points by +/- 1 RMS of the correlated syst errors and do the same

Sum up 1 & 2 to obtain the curves above

Little sensitivity to model parameters

“Disadvantages” of R_{AA}

Gyulassy-Levai-Vitev(GLV) formalism

Gyulassy, Levai, Vitev, NPB 594(2001)371

$$\epsilon \approx \frac{p_0}{\tau_0 \pi R^2} \frac{dN_g}{dy} \approx 15 - 20 \frac{\text{GeV}}{\text{fm}^3}, \qquad \epsilon_A \simeq 0.16 \frac{\text{GeV}}{\text{fm}^3}.$$

- Advantage of R_{AA} : providing useful information of the hot/dense medium, with a simple physics picture.
- Disadvantage of R_{AA}: unable to resolve the order of magnitude systematic discrepancy in the extracted medium properties.

Medium transport coefficient: $\hat{q}$

1-2.5GeV^2/fm (GLV, HT), 4-5GeV^2/fm(AMY), 10-15 GeV^2/fm(ASW)

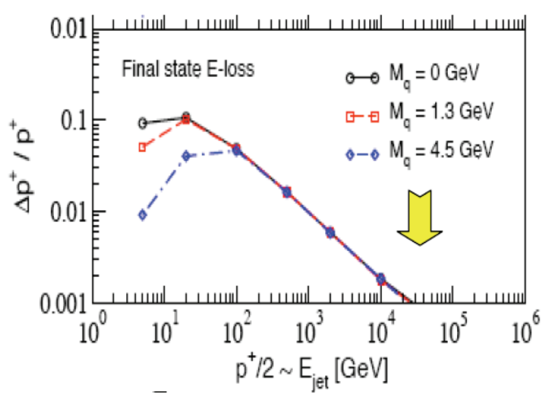
LPM Effect and the Medium-Induced Jet Shape

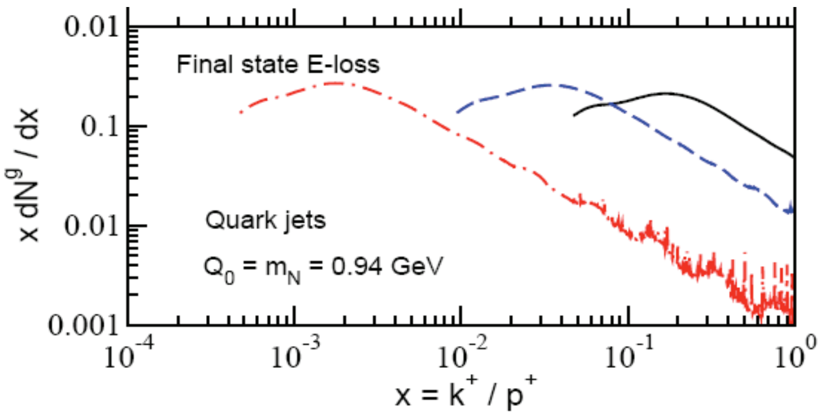
- An intuitive approach to medium-induced jet shapes

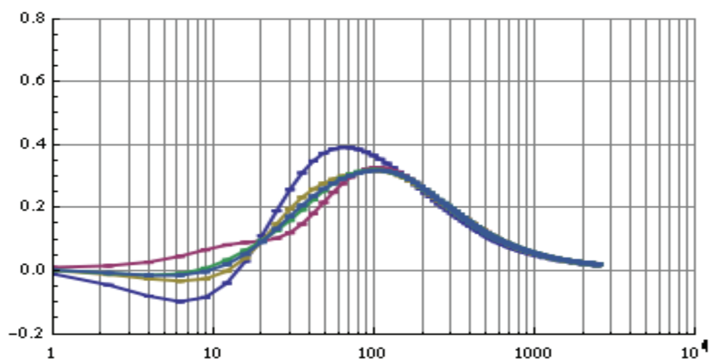
$$\Delta E^{rad}_{\rm LPM\ suppressed} \Rightarrow \frac{dI^g}{d\omega}(\omega \sim E)_{\rm LPM\ suppressed}$$

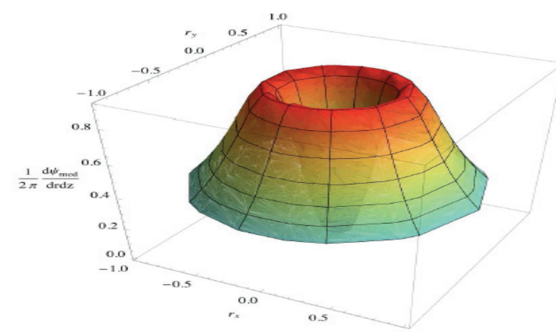
Gyulass-Levai-Vitev

$$\Rightarrow \frac{dI^g}{d\omega d^2k_T}(k_T \ll \omega)_{\rm LPM\ suppressed} \sim \frac{dI^g}{d\omega dr}(r \ll R)_{\rm suppressed}$$







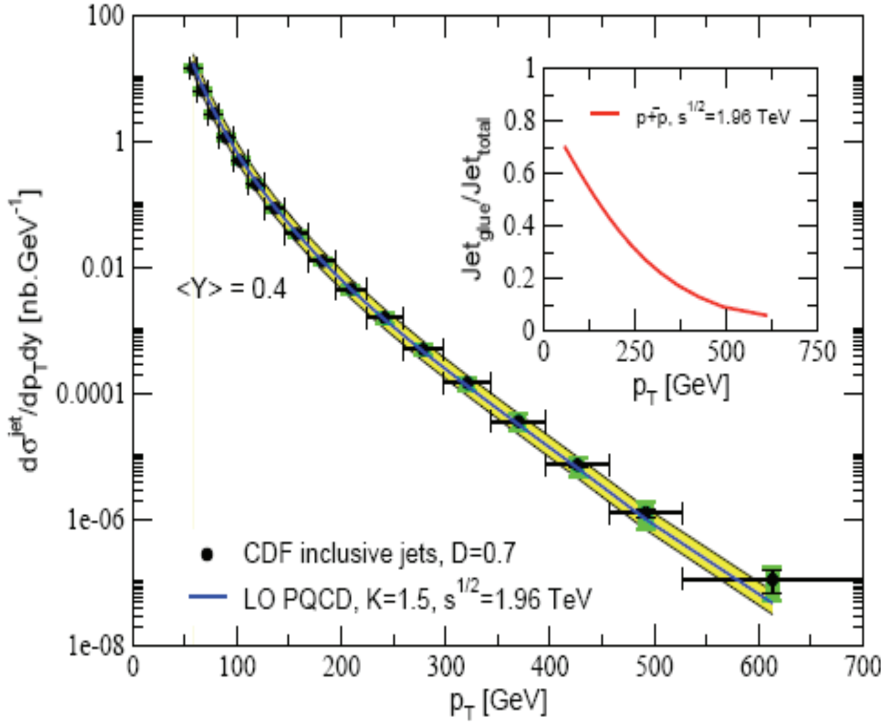


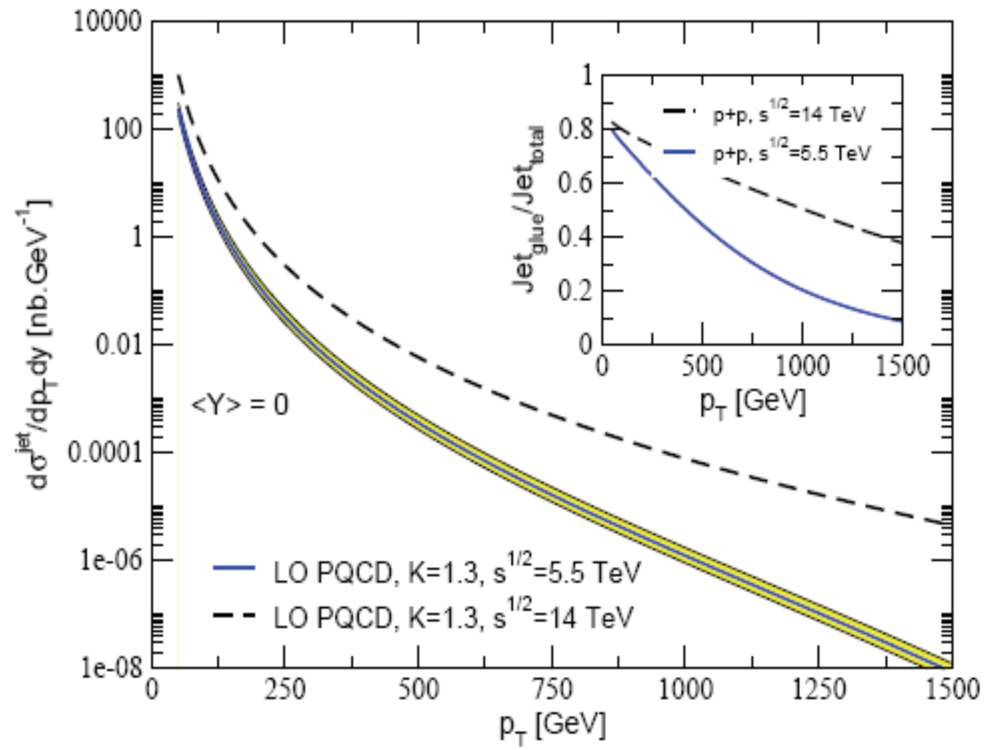
Signatures: Hard Probes

- We need signatures to tell whether a new kind of matter is produced in heavy-ion collision: dilepton production, J/psi suppress, HBT effect, strangeness enhancement, collective flow…
- From SPS to RHIC, and to LHC, the colliding energy is larger and larger, hard probes will become more and more important.
- Applications of hard probes are more reliable with large momentum transfer: the asymptotic freedom

$$\alpha_s(Q) \propto \frac{1}{\ln(\frac{Q^2}{\Lambda_c^2})}$$

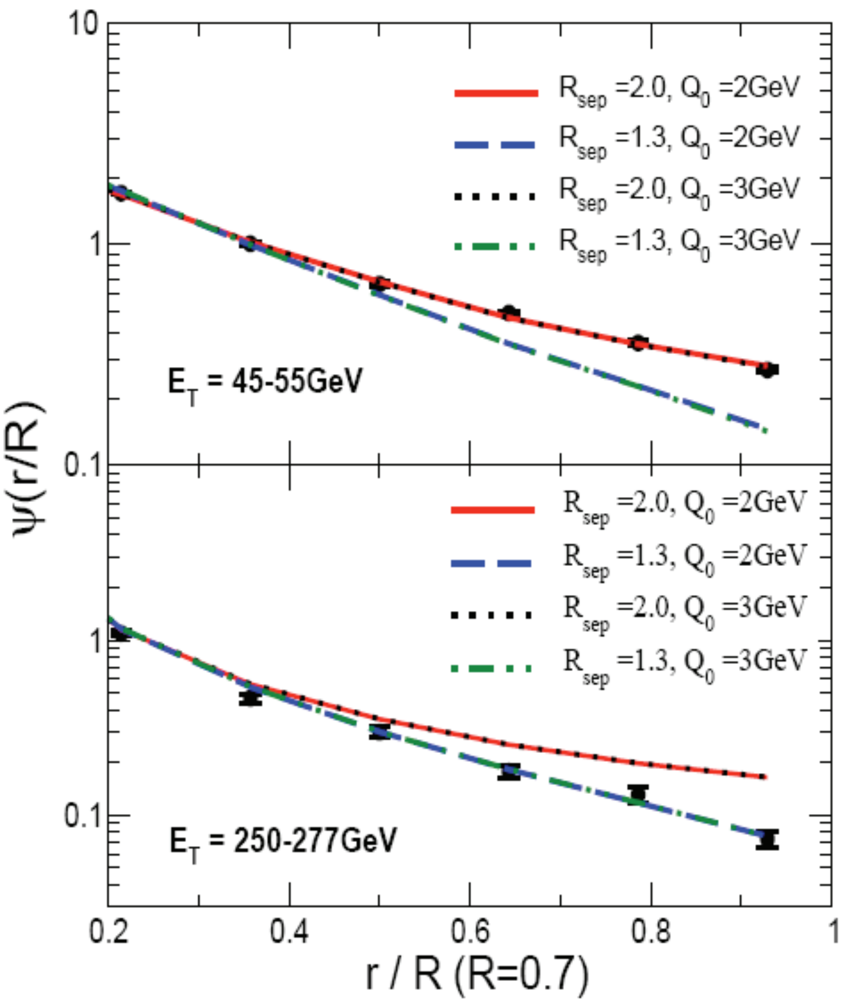
Jets Cross Section in p+p





- 10% statistical @ 160GeV inclusive jets
- 5%-30% statistical @ 100GeV jet shapes

Jet shapes vs R_{sep} and Q_0



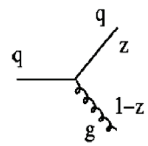
Leading Order (I)

An analytic approach to the energy distribution in a jet

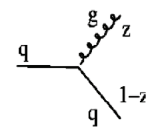
Seymour, M. (1998)

QCD splitting kernel

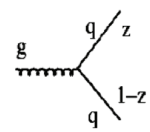
$$dP_a = \frac{\alpha_s}{2\pi}\frac{d\rho^2}{\rho^2}\frac{d\phi}{2\pi}dzP_{a\to bc}(z)$$



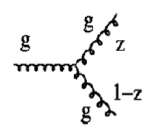
$$P^{(1)}_{qq}(x) = C_2(F)\left[(1+x^2)\left(\frac{1}{1-x}\right)_+ + \frac{3}{2}\delta(1-x)\right]$$



$$P^{(1)}_{gq}(x) = C_2(F)\frac{(1-x)^2+1}{x}$$



$$P^{(1)}_{qg}(x) = T(F)\left[(1-x)^2 + x^2\right]$$



$$P^{(1)}_{gg}(x) = 2C_2(A)\left[\frac{x}{(1-x)_+} + \frac{1-x}{x} + x(1-x)\right] + \left(\frac{11}{6}C_2(A) - \frac{2}{3}T(F)n_f\right)\delta(1-x),$$

Jet shapes at LO with the acceptance cuts

$$z_{min} = p_{T\ \min}/E_T$$

$$Z = \max\left\{z_{min}, \frac{r}{r+R}\right\} \quad \text{if } r < (R_{sep}-1)R\,,$$
$$Z = \max\left\{z_{min}, \frac{r}{R_{sep}R}\right\} \quad \text{if } r > (R_{sep}-1)R\,.$$

$$\psi_a(r;R) = \sum_b \frac{\alpha_s}{2\pi}\frac{2}{r}\int_{z_{min}}^{1-Z} dz\, zP_{a\to bc}(z).$$

Sudakov Resummation

- Sudakov form factors are given by:

$$P_q(r > z_{min}R) = \exp\left(2C_F \log\frac{R}{r} f_1\left(2\beta_0\alpha_s \log\frac{R}{r}\right) - \left[\frac{3}{2}C_F - CR^2 - c_q^>(z_{min})\right] \times f_2\left(2\beta_0\alpha_s \log\frac{R}{r}\right)\right) ,$$

$$P_g(r > z_{min}R) = \exp\left(2C_A \log\frac{R}{r} f_1\left(2\beta_0\alpha_s \log\frac{R}{r}\right) - \left[\frac{1}{2}b_0 - CR^2 - c_g^>(z_{min})\right] \times f_2\left(2\beta_0\alpha_s \log\frac{R}{r}\right)\right) .$$

$$P_q(r < z_{min}R) = P_q(r > z_{min}R; r = z_{min}R) \times \exp\left(-\left[\frac{3}{2}C_F - c_q^<(z_{min})\right] \times f_2\left(2\beta_0\tilde{\alpha}_s \log\frac{z_{min}R}{r}\right)\right) ,$$

$$P_g(r < z_{min}R) = P_g(r > z_{min}R; r = z_{min}R) \times \exp\left(-\left[\frac{1}{2}b_0 - c_g^>(z_{min})\right] \times f_2\left(2\beta_0\tilde{\alpha}_s \log\frac{z_{min}R}{r}\right)\right) .$$

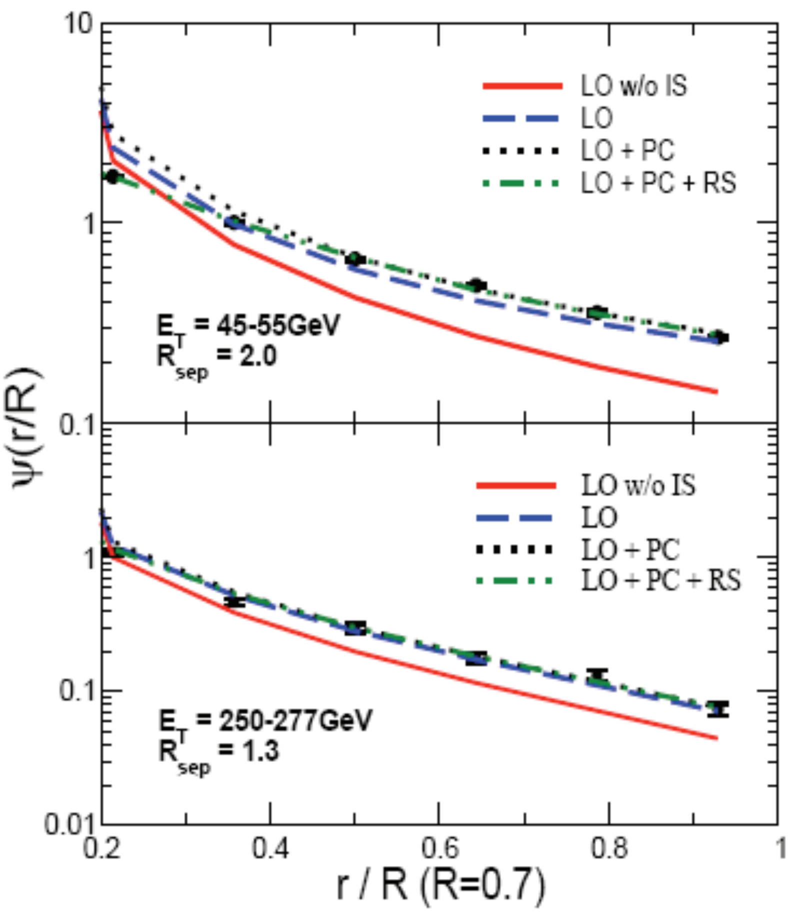
- Jet shape from resummation

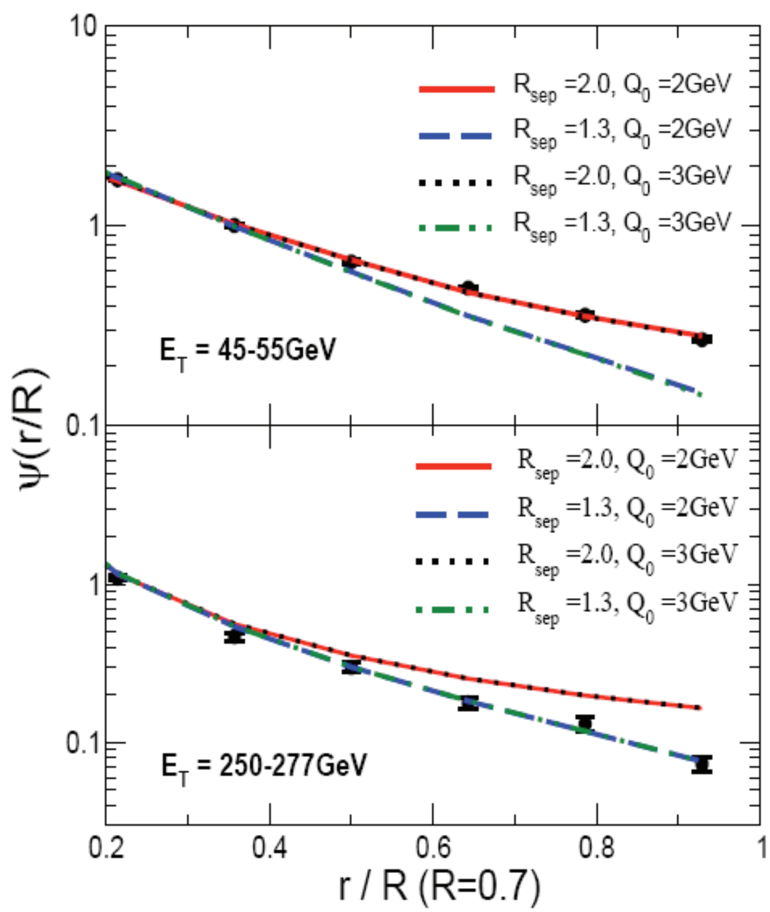
$$\psi_{\mathrm{RS}}(r) = \frac{dP(r)}{dr}$$

Jet shapes vs R_{sep} and Q_0

- Relative importance

- Insensitivity to Q_0
- Sensitivity to R_{sep}

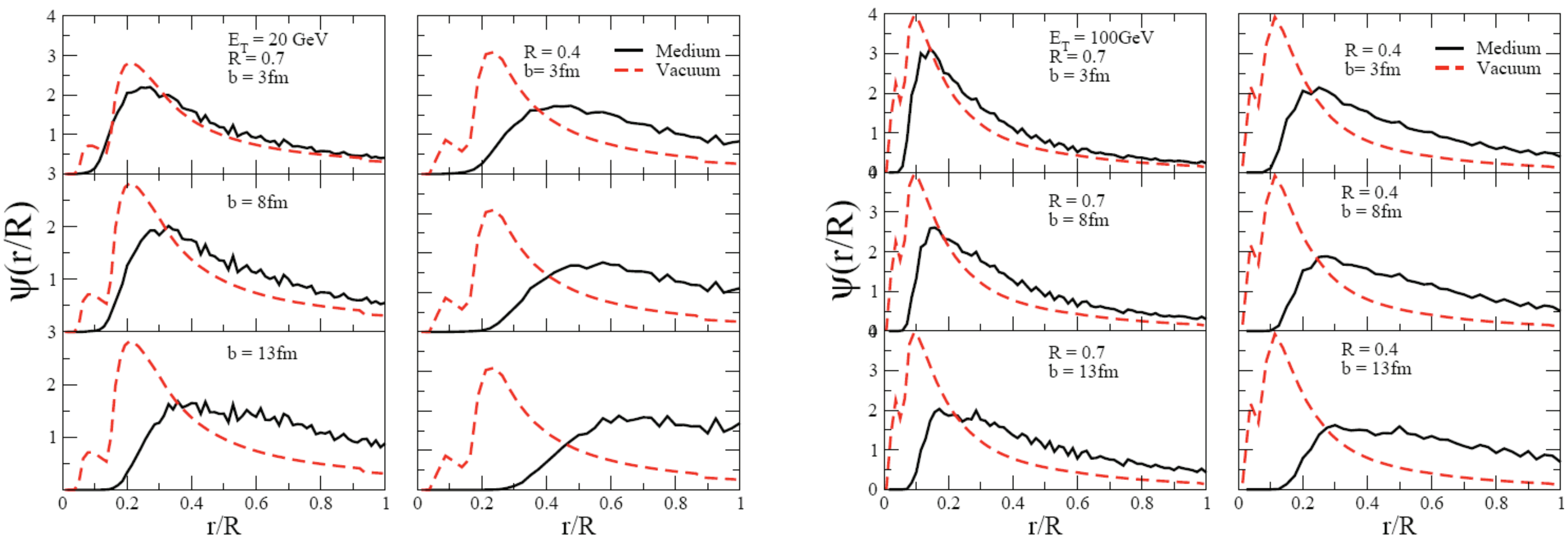




Jet Shapes vs Centrality & Energy

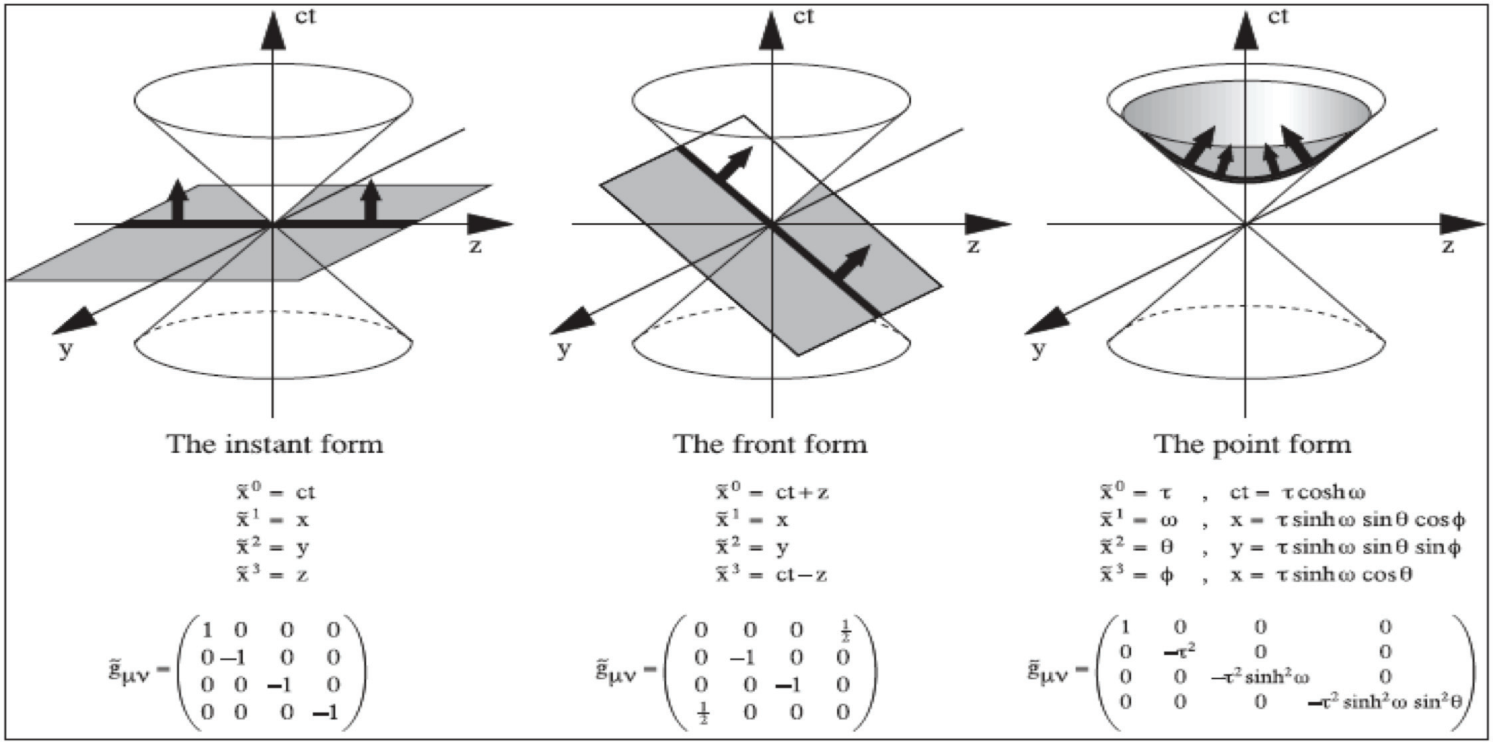
$$\psi_{\text{tot.}}(r/R) = \frac{1}{\text{Norm}} \int_{\epsilon=0}^{1} d\epsilon \sum_{q,g} P_{q,g}(\epsilon) \frac{1}{(1-(1-f_{q,g})\cdot\epsilon)^3}$$

$$\times \frac{\sigma_{q,g}^{NN}(R,\omega^{\min})}{d^2 E_T' dy} \left[(1-\epsilon)\, \psi_{\text{vac.}}^{q,g}(r/R) + f_{q,g}\cdot\epsilon\, \psi_{\text{med.}}^{q,g}(r/R) \right]$$



- Big difference between the medium-induced jet shape and the vacuum jet shape, especially for smaller cone radius.
- The medium-induced jet shape becomes flatter at peripheral collisions.
- Jet shapes in the medium and in vacuum are narrower at higher energy.

Light Front Quantization



- Advantages of light front quantization: simple vacuum, the only state with $p^+=0$
- Full set of operators, commuting: $M^2 = 2p^+p^- - p_\perp^2,\ p^+,\ p_\perp$

  $S^2,\ S_z$

S.Brodsky, H.C.Pauli, S.Pinsky, Phys. Rep. (1998)

QCD on the Light Front

The free theory

- Quarks
- Anti-quarks
- Gluons

$$\psi^a(\vec{x}^-) = \int \frac{dp^+}{2p^+}\frac{d^2p_\perp}{(2\pi)^3}\sum_\lambda \left(a^a_\lambda(\vec{p}^+)u_\lambda(p)e^{-ip\cdot x} + b^{\dagger a}_\lambda(\vec{p}^+)v_\lambda(p)e^{+ip\cdot x}\right)_{|x^+=0}$$

$$\bar{\psi}^a(\vec{x}^-) = \int \frac{dp^+}{2p^+}\frac{d^2p_\perp}{(2\pi)^3}\sum_\lambda \left(b^a_\lambda(\vec{p}^+)\bar{v}_\lambda(p)e^{-ip\cdot x} + a^{\dagger a}_\lambda(\vec{p}^+)\bar{u}_\lambda(p)e^{+ip\cdot x}\right)_{|x^+=0}$$

$$A^a(\vec{x}^-) = \int \frac{dp^+}{2p^+}\frac{d^2p_\perp}{(2\pi)^3}\sum_\lambda \left(d^a_\lambda(\vec{p}^+)\varepsilon_\lambda(p)e^{-ip\cdot x} + d^{\dagger a}_\lambda(\vec{p}^+)\varepsilon^*_\lambda(p)e^{+ip\cdot x}\right)_{|x^+=0}$$

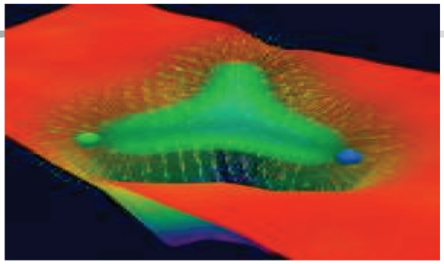
Commutation relations and normalization of states

$$\left\{a^{a'}_{\lambda'}(\vec{p}^{+'}), a^{\dagger a}_\lambda(\vec{p}^+)\right\} = 2p^+(2\pi)^3\delta^3\left(\vec{p}^+ - \vec{p}^{+'}\right)\delta^{aa'}\delta^{\lambda\lambda'} \qquad \left\{b^{a'}_{\lambda'}(\vec{p}^{+'}), b^{\dagger a}_\lambda(\vec{p}^+)\right\} = 2p^+(2\pi)^3\delta^3\left(\vec{p}^+ - \vec{p}^{+'}\right)\delta^{aa'}\delta^{\lambda\lambda'}$$

$$\left[b^{a'}_{\lambda'}(\vec{p}^{+'}), b^{\dagger a}_\lambda(\vec{p}^+)\right] = 2p^+(2\pi)^3\delta^3\left(\vec{p}^+ - \vec{p}^{+'}\right)\delta^{aa'}\delta^{\lambda\lambda'}$$

- States: $\left|n, \{\vec{p}^+_n\}, \{\lambda_n\}\{a_n\}\right\rangle = \prod_{i,j,k\to n} \ldots\ a^{\dagger a}_{\lambda,i}(\vec{p}^+_i)\ldots b^{\dagger a}_{\lambda,j}(\vec{p}^+_j)\ldots d^{\dagger a}_{\lambda,k}(\vec{p}^+_k)|0\rangle$
  - Implicit: quark flavor, (anti)symmetrization
  - Normalization trivially obtained from above

Light Front Wave Functions



Baryon

- Expansion in Fock components

$$\left|P^+,P_\perp,S^2,S_z\right\rangle=\sum_{n=2,3}^{\infty}\int\prod_{i=1}^{n}\frac{dx_i}{2x_i}\frac{d^2k_{\perp i}}{(2\pi)^3}\psi_n\left(\{x\}_i,\{k_{\perp i}\},\{\lambda_i\}\{a_i\}\right)\,\delta\left(\sum_{i=1}^{n}x_i-1\right)\delta\left(\sum_{i=1}^{n}k_{\perp i}\right)$$
$$\times\prod_{i,j,k\to n}\ldots a^{\dagger a}_{\lambda i}(x_i\vec{P}^+ + k_{\perp i})..b^{\dagger a}_{\lambda j}(x_j\vec{P}^+ + k_{\perp j})\ldots\, d^{\dagger a}_{\lambda k}(x_k\vec{P}^+ + k_{\perp k})\ldots\left|0\right\rangle$$

Composite hadron creation operator: $a_H^{\dagger s_z}(\vec{P}^+)$

$$\left\langle P^{+'},P_\perp',S^{2'},S_z'\right\|\left|P^+,P_\perp,S^2,S_z\right\rangle=2P^+(2\pi)^3\delta^3\left(\vec{P}^+-\vec{P}^{+'}\right)\delta^{s_z s_z'}$$

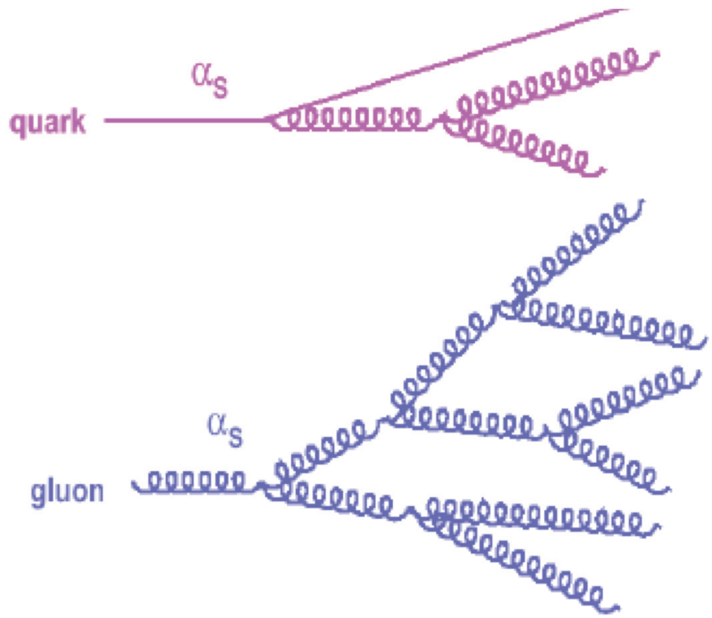
The normalization then becomes

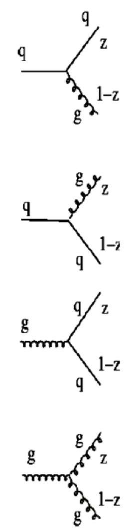
$$1=\frac{1}{2(2\pi)^3}\sum_{n=2,3}^{\infty}\int\prod_{i=1}^{n}\frac{dx_i}{2x_i}\frac{d^2k_{\perp i}}{(2\pi)^3}\left|\psi_n\left(\{x\}_i,\{k_{\perp i}\},\{\lambda_i\}\{a_i\}\right)\right|^2\delta\left(\sum_{i=1}^{n}x_i-1\right)\delta\left(\sum_{i=1}^{n}k_{\perp i}\right)$$

From Low to High Fock Components

- Perturbative generation of the higher Fock states

$$dP_a = \frac{\alpha_s}{2\pi}\frac{d\rho^2}{\rho^2}\frac{d\phi}{2\pi}dzP_{a\to bc}(z)$$





$$P_{qq}^{(1)}(x) = C_2(F)\left[(1+x^2)\left(\frac{1}{1-x}\right)_+ + \frac{3}{2}\delta(1-x)\right]$$

$$P_{gq}^{(1)}(x) = C_2(F)\,\frac{(1-x)^2+1}{x}$$

$$P_{qg}^{(1)}(x) = T(F)\left[(1-x)^2 + x^2\right]$$

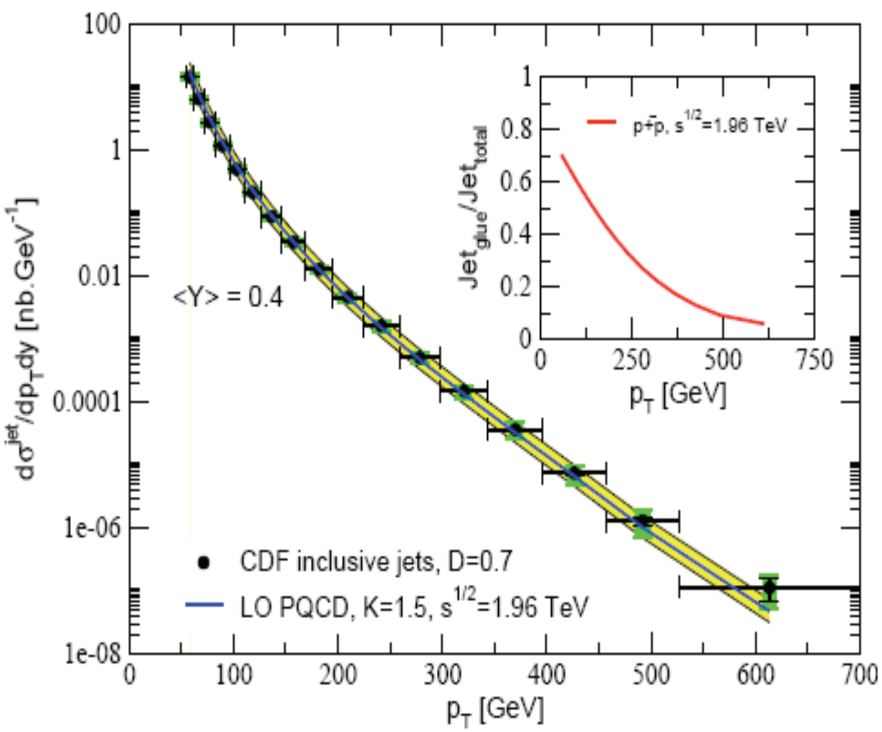
$$P_{gg}^{(1)}(x) = 2C_2(A)\left[\frac{x}{(1-x)_+} + \frac{1-x}{x} + x(1-x)\right] + \left(\frac{11}{6}C_2(A) - \frac{2}{3}T(F)n_f\right)\delta(1-x),$$

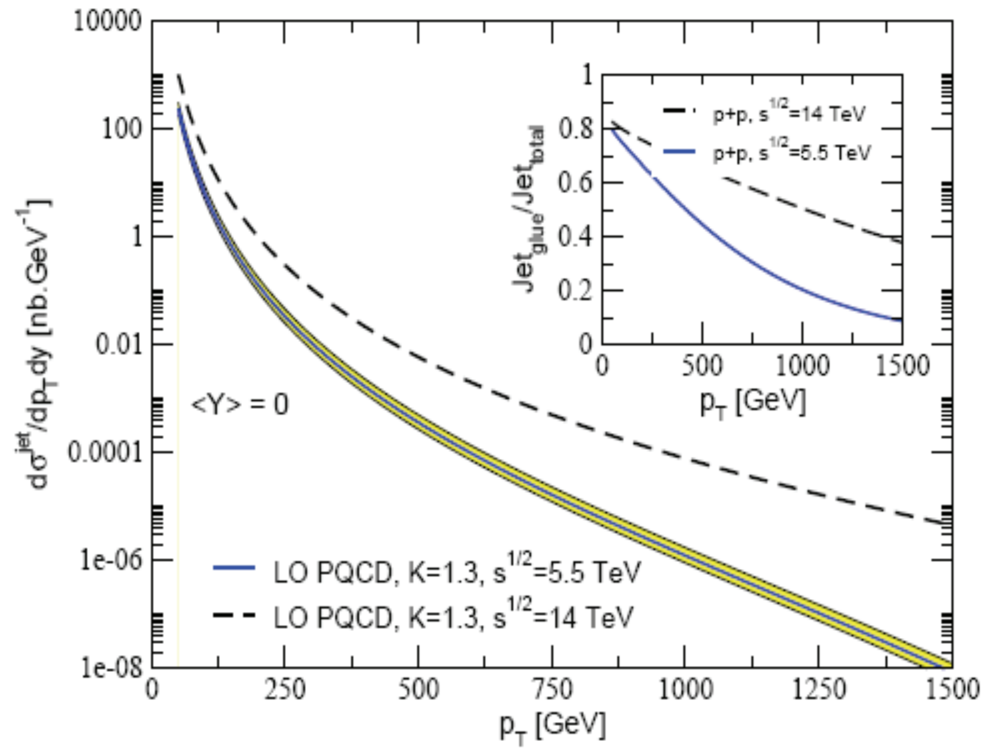
At the QCD vertexes: conserve color, momentum, flavor, …

- The lowest lying Fock state (non-perturbative) – the most important

Correct quantum #s carry over to higher states

Jets Cross Section in p+p





- 10% statistical @ 160GeV inclusive jets (p+p)
- 5%-30% statistical @ 100GeV jet shapes (p+p)

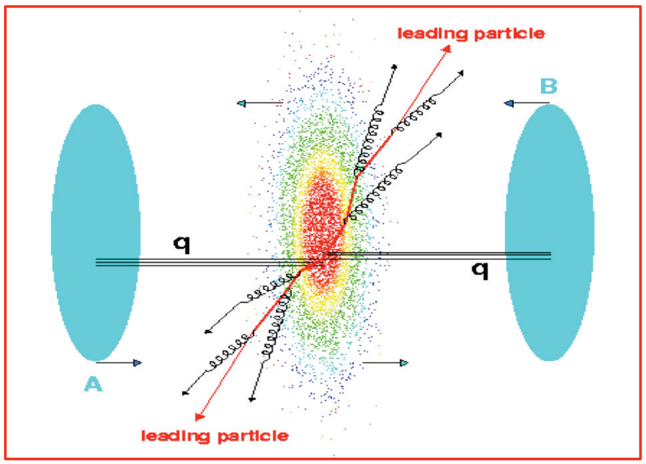
p+p $\int L\,dt = 10^{-fb}$

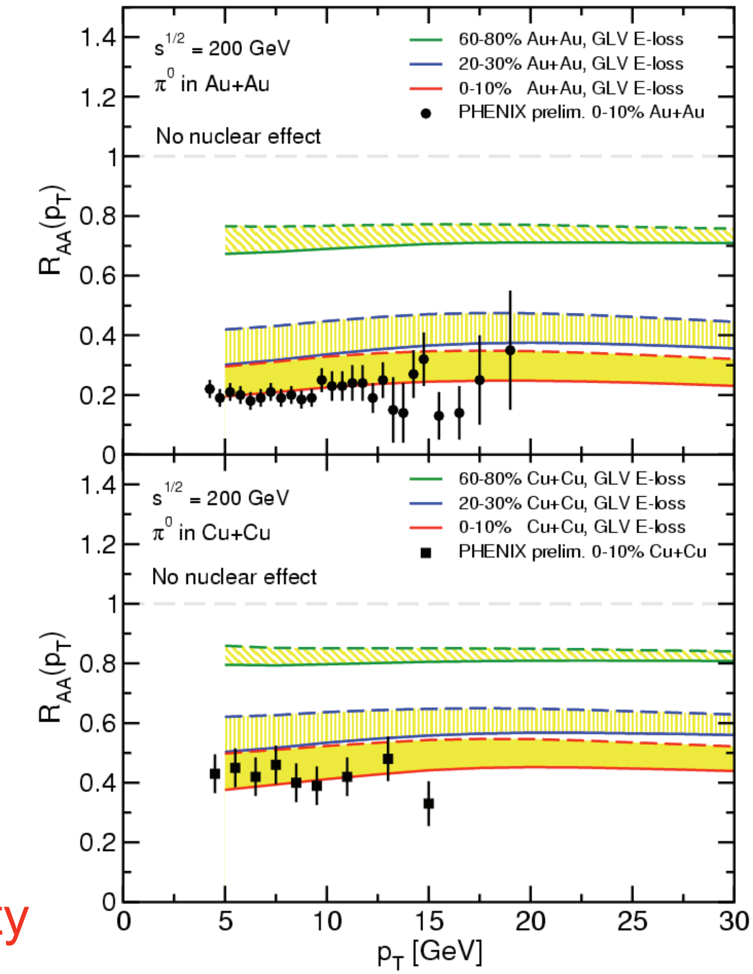
Pb+Pb $\int L\,dt = 1^{-nb}$

Light Hadron vs Heavy Meson Quenching

- Nuclear modification factor

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





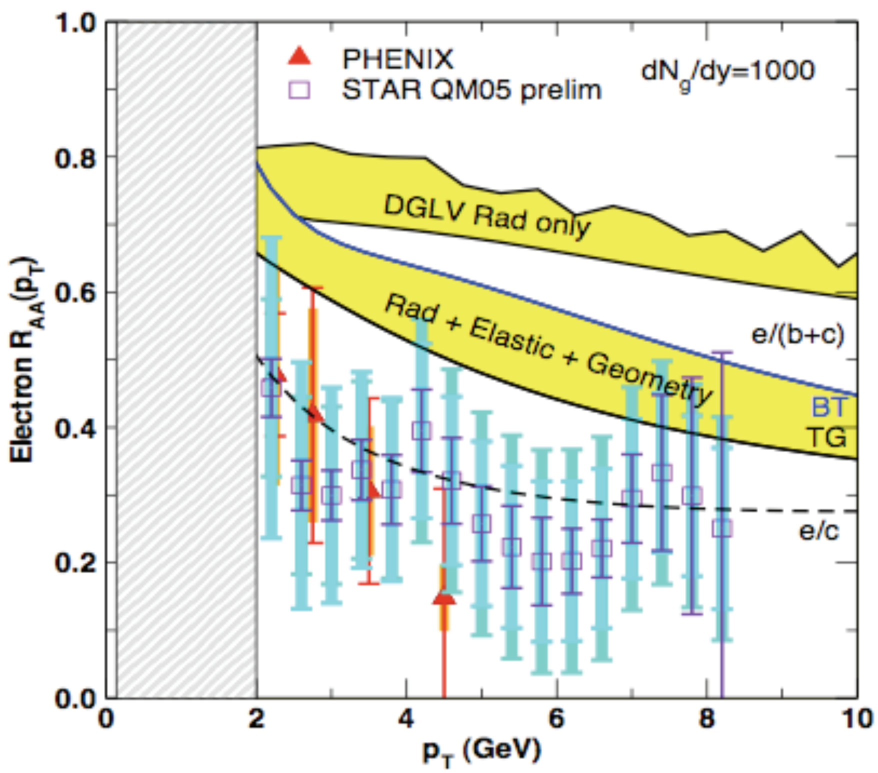
- Predictions of this formalism tested vs particle momentum, C.M. energy, centrality

I.V., Phys.Lett.B 639 (2006)

Non-Photonic Electron / Heavy Flavor Quenching

Proceed to A+A collisions

- Single electron measurements (presumably from heavy quarks) may be problematic



S. Wicks et al., Nucl.Phys.A (2007)

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

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

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

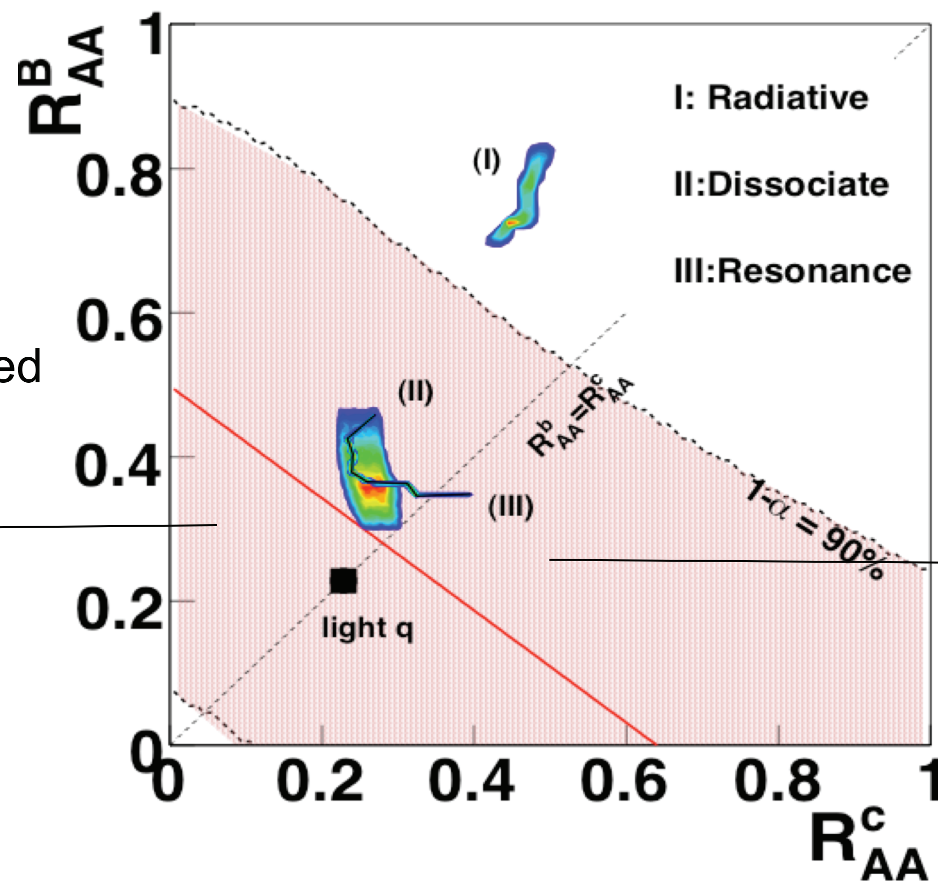
- Radiative Energy Loss using (D)GLV (both c + b)
- Radiative + Collisional + Geometry (both c + b) (overestimated)
- Deviation by a factor of two
- Is it accidental or is it symptomatic?

Non-Photonic Electron / Heavy Flavor Quenching

Another way to look at the same problem

STAR Collab., preliminary (2009)

“Problem” is that
D is more suppressed
than Light



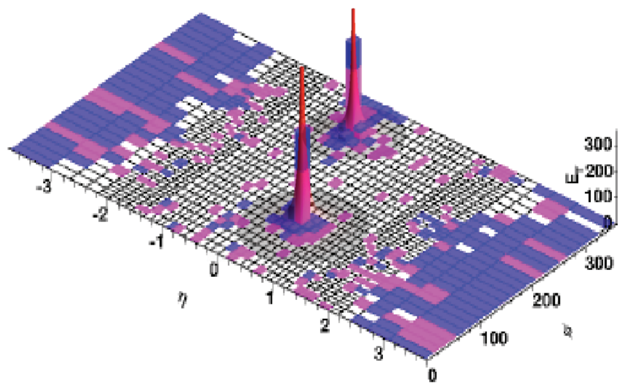
“Problem” is that
B is more suppressed
than D

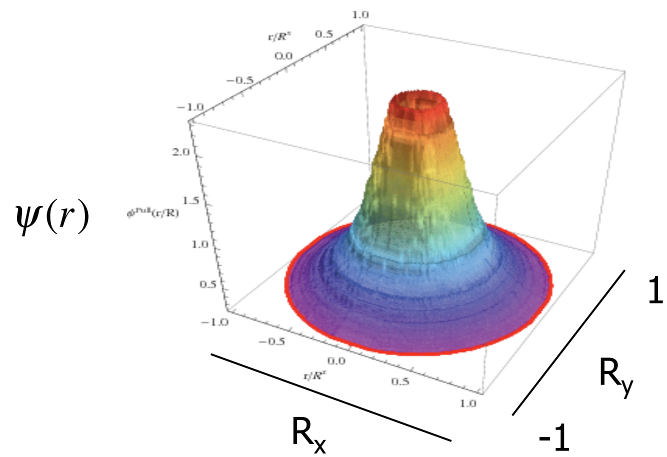
- Is there a mechanism where D suppression = B suppression arises naturally?

Will naturally focus on hard probes

Inclusive particles, jets, photons, and heavy quarks

Largely based upon:





- JHEP 0811, 093 (2008), IV, Simon Wicks, Ben-Wei Zhang
- Phys. Lett. B 649, 139 (2007), Azfar Adil, IV
- arXiv 0904.0032, Rishi Sharma, IV, Ben-Wei Zhang

Few Basic Assumptions

- **Local parton-hadron duality**
- **Local thermal equilibrium**

- **Local thermal equilibrium**
- **Local parton-hadron duality**
- **Gluon-dominated soft sector**
- **Bjorken expansion / approximate boost invariance**

- Experimental:

$$\frac{dN^g}{dy} = 1200$$

$$\rho_{\exp}(\tau) = \frac{1}{A_\perp \tau}\frac{dN^g}{dy}, \qquad A_\perp = 120\ \ fm^2$$

$$\tau_0 = 0.6\ \ fm$$

$$\Rightarrow \ \rho_{\exp}(\tau_0) = 17\ \ fm^{-3}$$

na

$\rho_{theory}(T) = \# DoF \int_0 \ldots \frac{\ldots}{e^{p/T} - 1} \ldots \frac{\ldots}{(2\pi)^3} \ldots \frac{\ldots}{\pi^2} \varsigma[3] \times T^3$

where $\# DoF = 2(polarization) \times 8(color), \ \varsigma[3] = 1.2$

$$T = 400\ \ MeV$$

- Energy density

$$\varepsilon_{theory}(T) = \frac{\pi^4}{30\varsigma[3]} \times \rho_{theory}(T) \times T$$

$$\varepsilon_{\exp}(\tau_0) = 18\ \ GeV.fm^{-3} \geq 100 \times 0.14\ \ \ GeV.fm^{-3}$$

Derivative Quantities in a Thermalized QGP

- Transport coefficients (not a good measure for expanding medium)

$$\mu_D \approx gT,\ \ g = 2-2.5\ \ (\alpha_s = \frac{g^2}{4\pi} = 0.3-0.5)$$

$$\sigma^{gg} = \frac{9\pi\alpha_s^2}{2\mu_D^2},\quad \lambda_g = \frac{1}{\sigma^{gg}\rho}$$

$$\mu_D = 0.8-1\ GeV$$
$$\lambda_g = 0.75-0.42\ fm$$

$$\hat{q} = \frac{\mu_D^2}{\lambda_g} = \frac{9\pi\alpha_s^2}{2}\rho$$

$$\hat{q} = 1-2.5\ GeV^2.fm^{-1}$$

- Define the average for Bjorken $\langle\langle \hat{q} \rangle\rangle = \frac{2}{(L-z_0)^2}\int_{z_0}^{L} \hat{q}(z) z dz$

$$\langle\langle \hat{q} \rangle\rangle = 0.35-0.85\ GeV^2.fm^{-1}$$

The role of theory and experiment is to identify approximations that are compatible with the bulk properties

LHC

$$\frac{dN^g}{dy} = 2800 \Rightarrow$$

$$\tau_0 = 0.25\ fm$$

$$\Rightarrow\ \rho_{exp}(\tau_0) = 95\ fm^{-3}$$

$$T = 720\ MeV$$

$$\mu_D = 1.44-1.8\ GeV$$

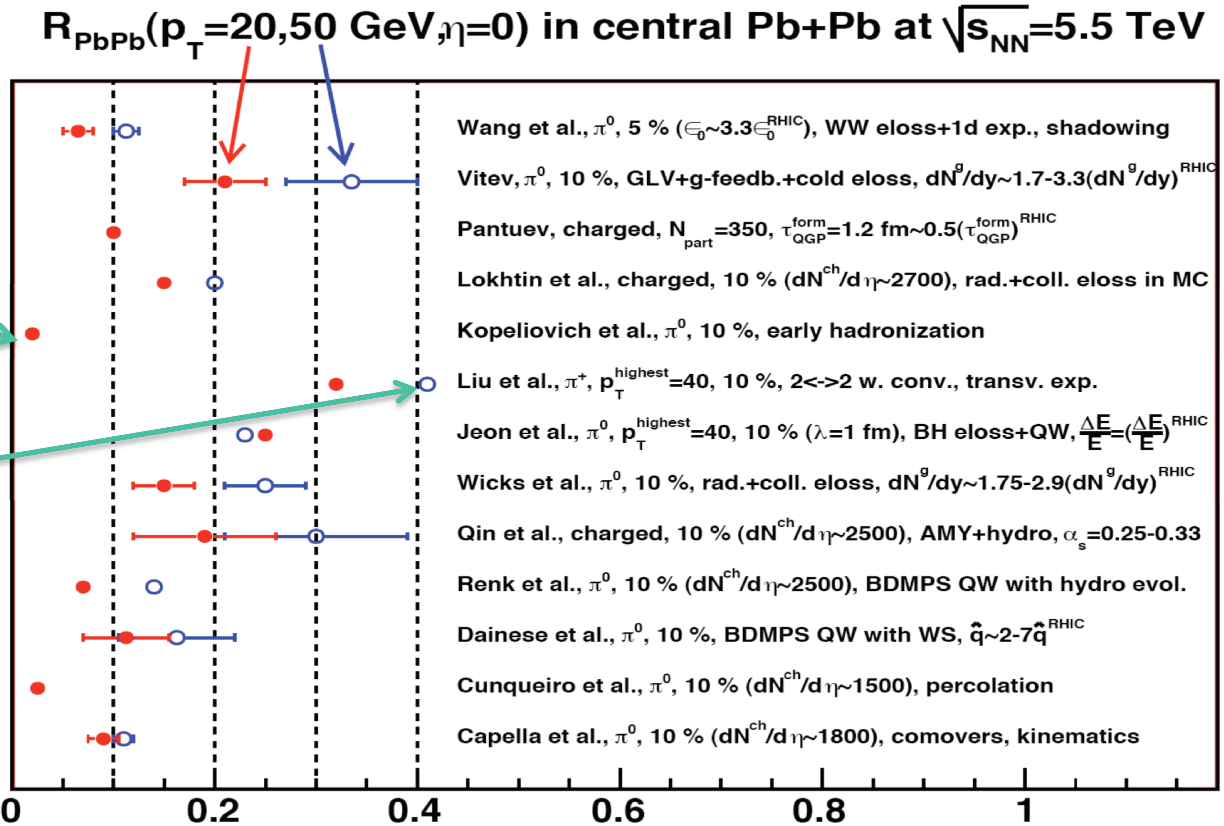
$$\lambda_g = 0.39-0.25\ fm$$

$$\hat{q} = 5-13\ GeV^2.fm^{-1}$$

$$\langle\langle \hat{q} \rangle\rangle = 0.40-0.99\ GeV^2.fm^{-1}$$

II. Inclusive Particle Suppression

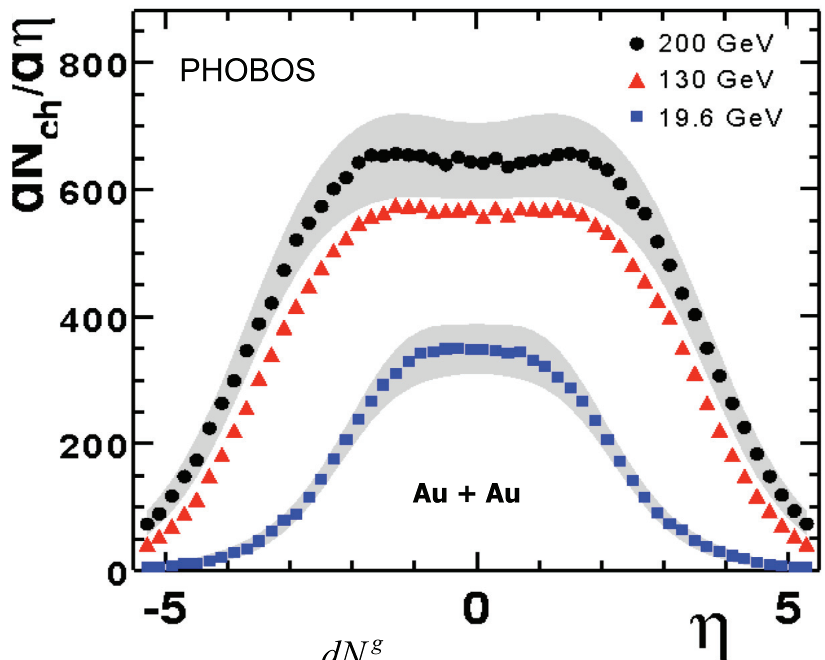
Pion absorption



Collisional energy loss

- Certain trends are visible: collisional vs radiative vs collisional +radiative
- These results are not directly comparable - different dN/dy or not at all connected to the medium properties

The Soft Medium



- **Local thermal equilibrium**
- **Local parton-hadron duality**
- **Gluon-dominated soft sector**
- **Bjorken expansion / approximate boost invariance**

$$\rho_{\exp}(\tau) = \frac{1}{A_\perp \tau}\frac{dN^g}{dy},\qquad \frac{dN^g}{dy} = 1200,\quad A_\perp = 120\ fm^2,\quad \tau_0 = 0.6\ fm$$

$$\Rightarrow\ \rho_{\exp}(\tau_0) = 17\ fm^{-3}$$

$$\mu_D \approx gT,\ \ g = 2-2.5\ \left(\alpha_s = \frac{g^2}{4\pi} = 0.3-0.5\right)$$

$$\sigma^{gg} = \frac{9\pi\alpha_s^2}{2\mu_D^2},\quad \lambda_g = \frac{1}{\sigma^{gg}\rho}$$

$$\rho_{theory}(T) = \#DoF\int_0^\infty \frac{1}{e^{p/T}-1}\frac{4\pi p^2 dp}{(2\pi)^3} = \frac{\#DoF}{\pi^2}\varsigma[3]\times T^3$$

where $\#DoF = 2(polarization)\times 8(color),\ \varsigma[3] = 1.2$

	RHIC	LHC
T [MeV]	370	720
μ_D [GeV]	.75-1.	1.4-1.8
λ_g [fm]	.75-.42	.39-.25

High p_T (E_T) Observables

Power laws: $n = n(\sqrt{s}, p_T, system)$

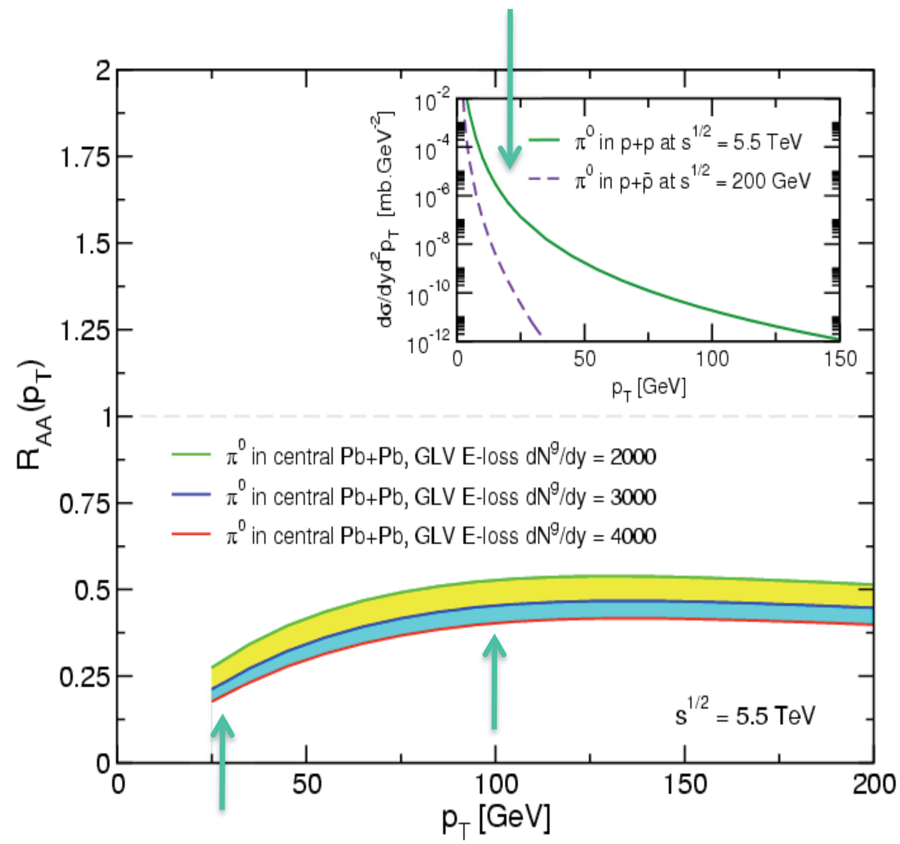
$$\frac{d\sigma}{d^2 p_T} = \frac{A}{(p_T + p_0)^n} \approx \frac{A}{(p_T)^n}$$

$$\text{m-Particle Observable} \sim \frac{1}{E_T^n}$$

$$R_{AA}^{Observable} \approx \left(1 - \frac{\Delta E_T}{E_T}\right)^{n-(2m')}$$

- Most models' R_{AA} varies with the underlying power law spectrum
- High p_T suppression at the LHC can be comparable and smaller than at RHIC
- Complete absorption models produce a constant R_{AA}

Quenching factor correlated to spectra



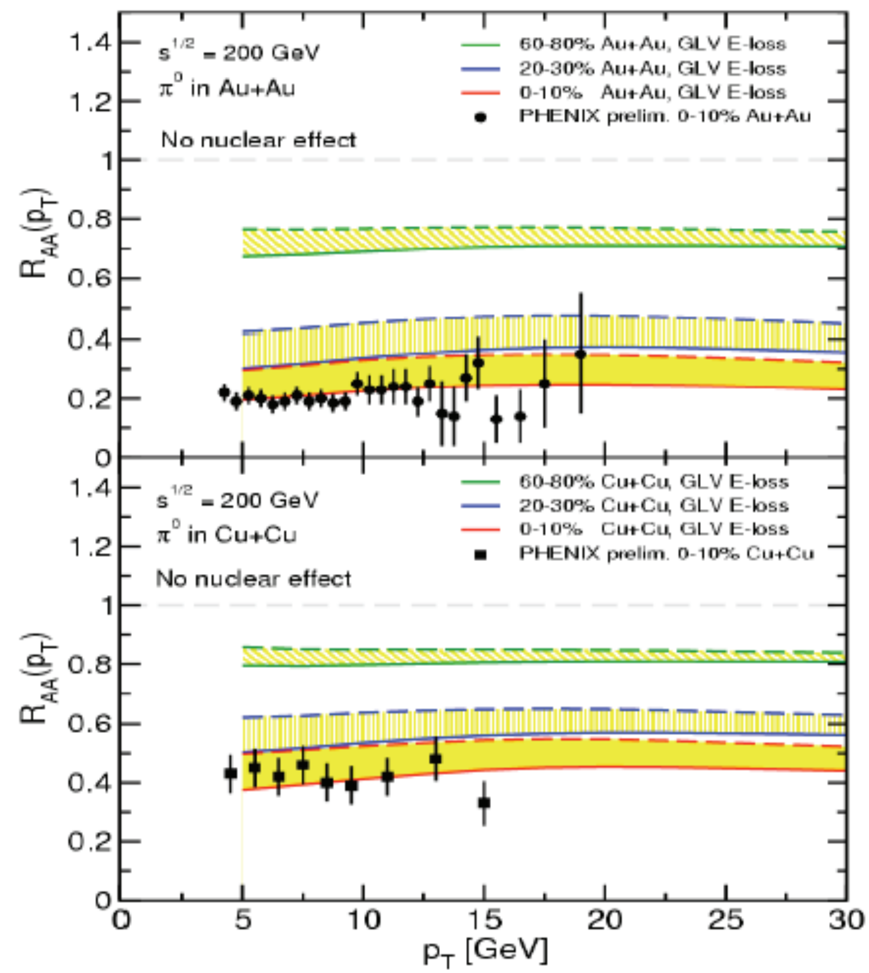
Light Particle Quenching

- So far has worked very well versus p_T, root(s), centrality, …

- Advantage of R_{AA} : providing useful information of the hot / dense medium, with a simple physics picture.

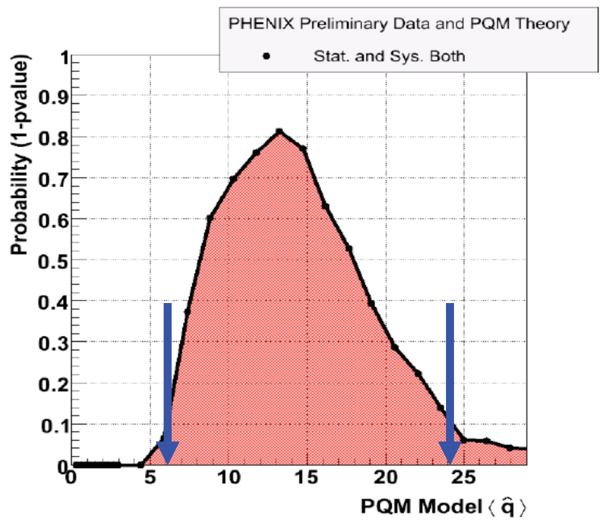
Gyulassy-Levai-Vitev(GLV) formalism

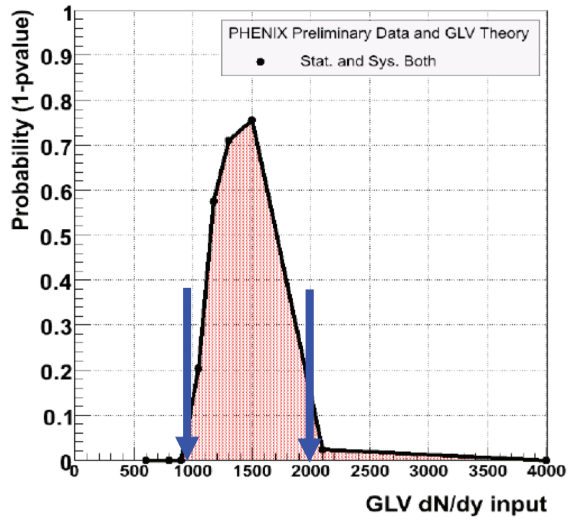
Gyulassy, Levai, IV, NPB 594(2001)371

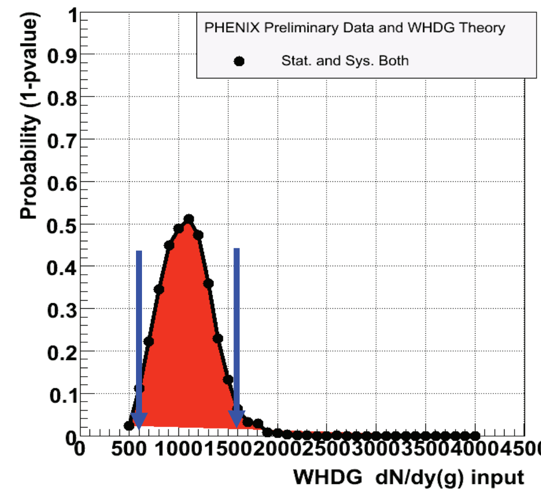


Leading particles

Fits - the Good and the Bad







$6 \leq \langle \hat{q} \rangle \leq 24$ GeV^2/fm
(Probability > 10%)

$1000 \leq {}^{dN_g}\!/_{dy} \leq 2000$
(Probability > 10%)

$600 \leq {}^{dN_g}\!/_{dy} \leq 1600$
(Probability > 10%)

- Disadvantage of R_{AA}: unable to resolve the order of magnitude systematic discrepancy in the extracted medium properties.

Medium transport coefficient:

1-2.5GeV^2/fm (GLV, HT), 4-5GeV^2/fm(AMY), 10-15 (~60) GeV^2/fm(ASW)