Studies on full jet in high energy nuclear collisions

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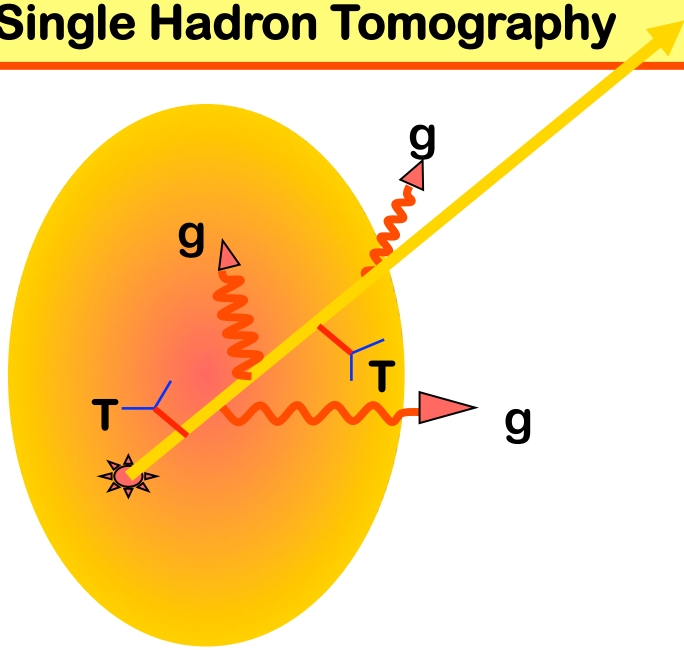
Introduction

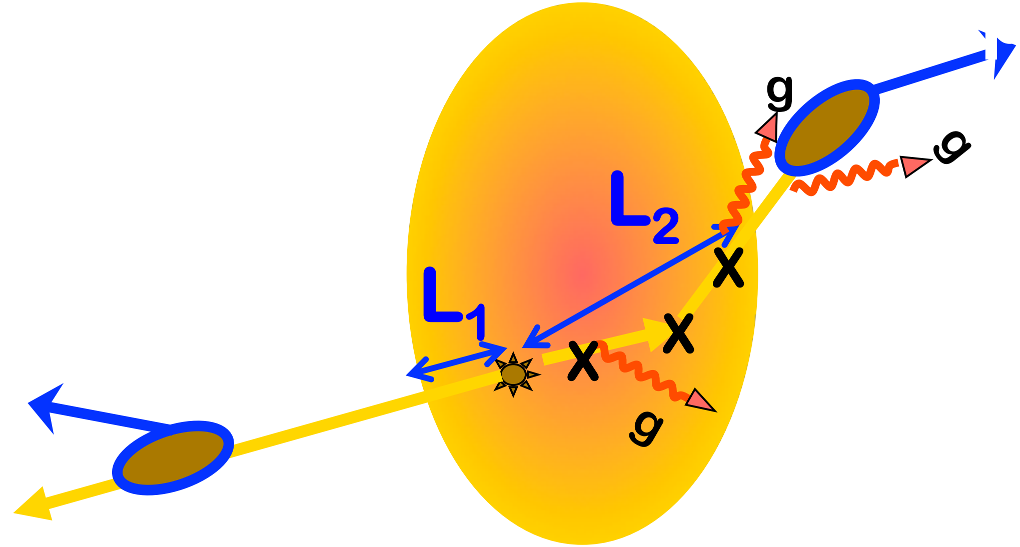
Jet quenching as a hard probe

Jet quenching has been proposed as an excellent probe of the hot/dense matter created at HIC.

Single Hadron Tomography



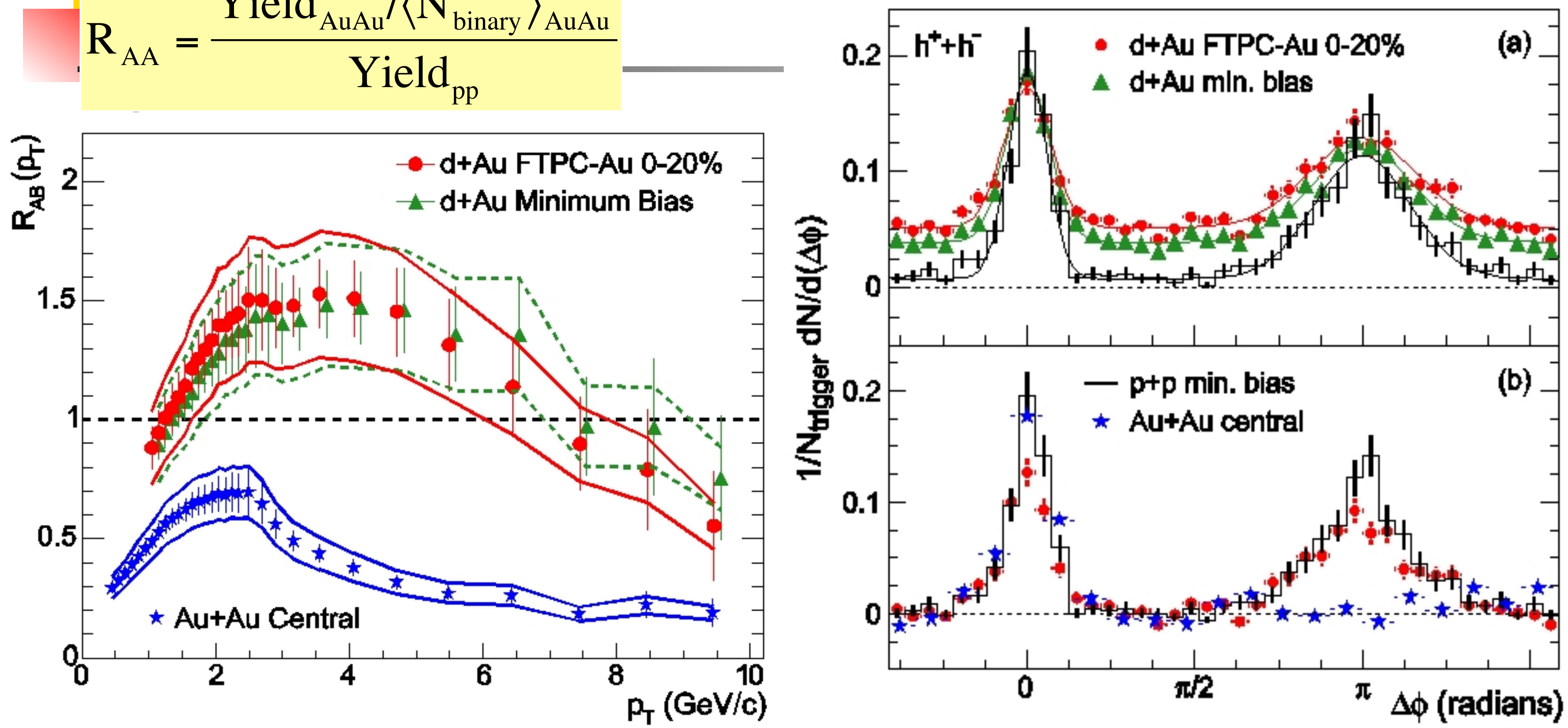
Di-Hadron Tomography



Xin-Nian Wang, M. Gyulassy, PRL68(1992)1480

Jet quenching at RHIC

$$R_{AA} = \frac{\text{Yield}_{AuAu} / \langle N_{binary} \rangle_{AuAu}}{\text{Yield}_{pp}}$$

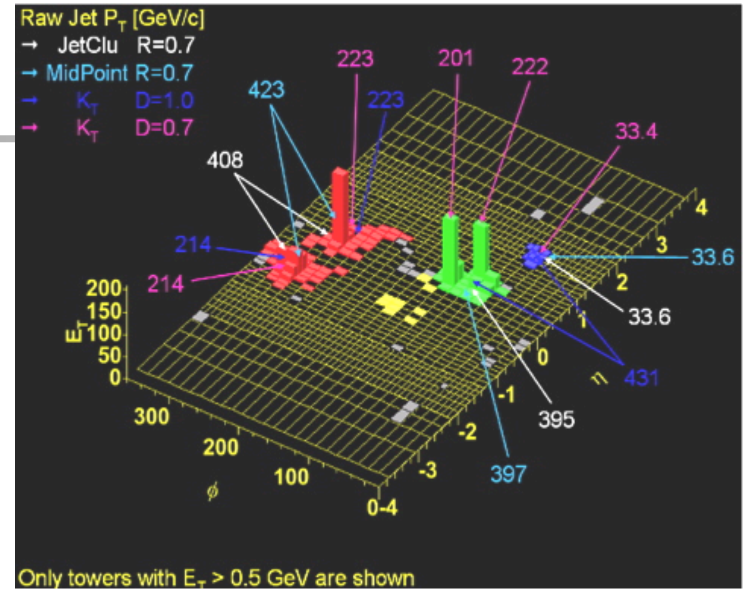


Finding of the jet quenching effect in A+A collisions has been regarded as one of the most important discoveries made at RHIC.

Gyulassy, Vitev, X.N.Wang, BWZ, 《QGP3》 p123-191 (2004);nucl-th/0302077.

Jets: new opportunity at HIC

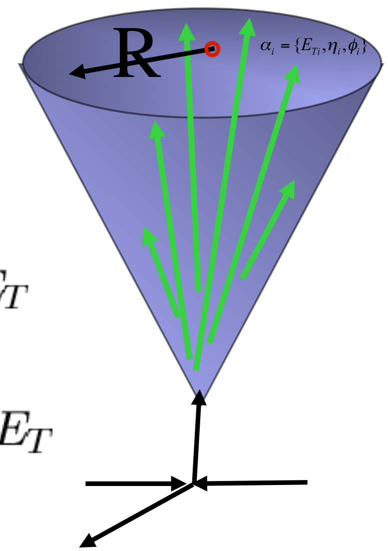
- R_{AA} for single particle or I_{AA} for two particle correlations only measure the leading fragments of a jet.
- Jets: a spray of final-state particles moving roughly in the same direction.
- Jet observables: more differential, less non-perturbative input, precise pQCD calculations.



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

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

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

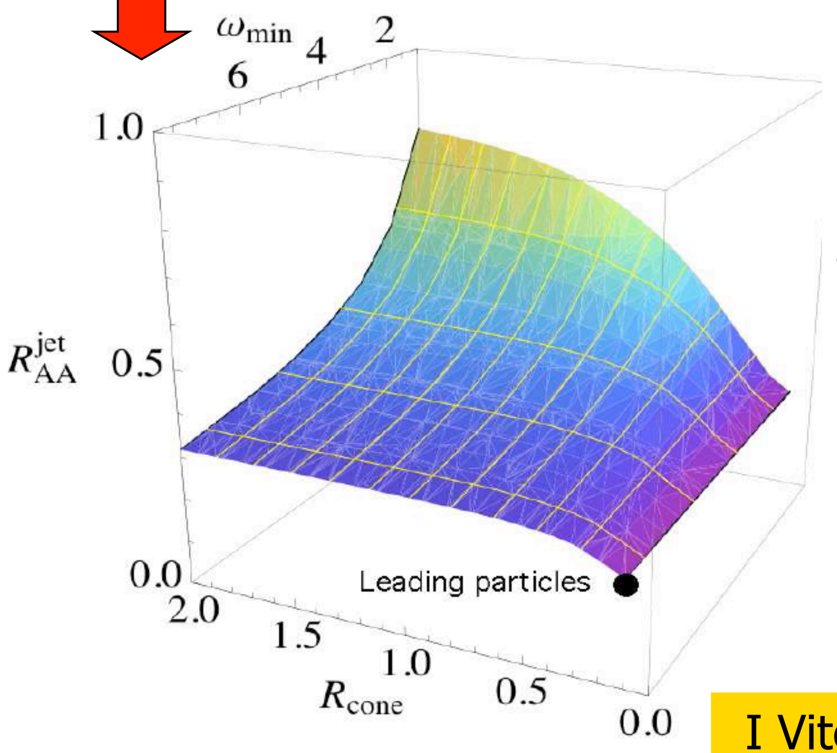


$$R_{ij} = \sqrt{(y_i - y_j)^2 + (\phi_i - \phi_j)^2}$$

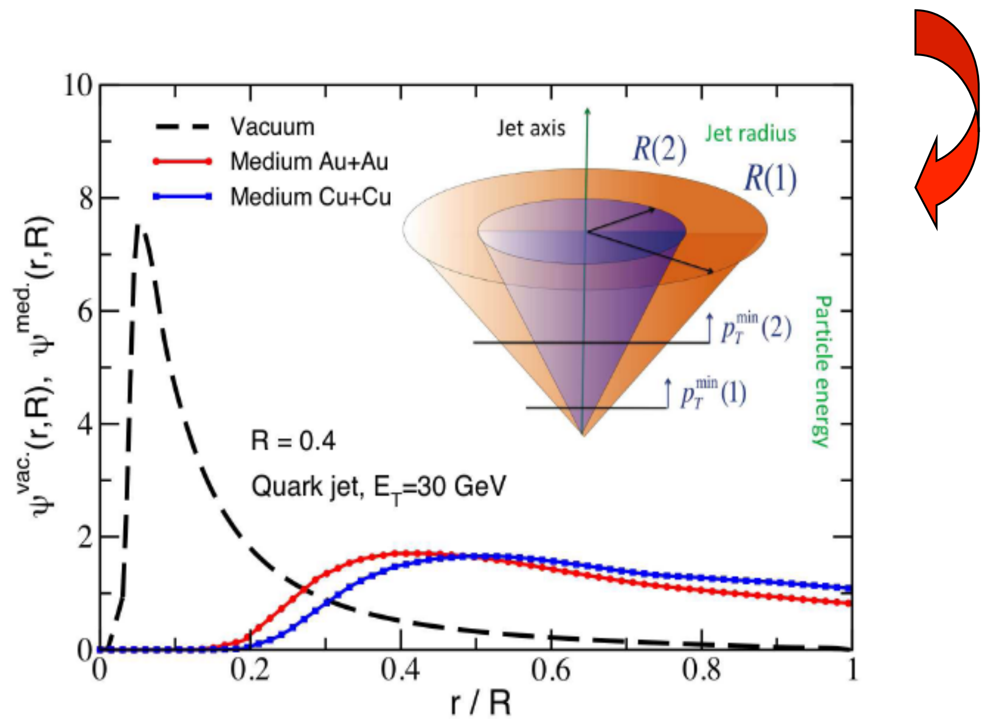
Full jet tomography in HIC

- An entirely new frontier of HIC: full jet observables.

Jet cross section



jet shapes: intra-jet energy flow



I Vitev, BWZ, (2008)

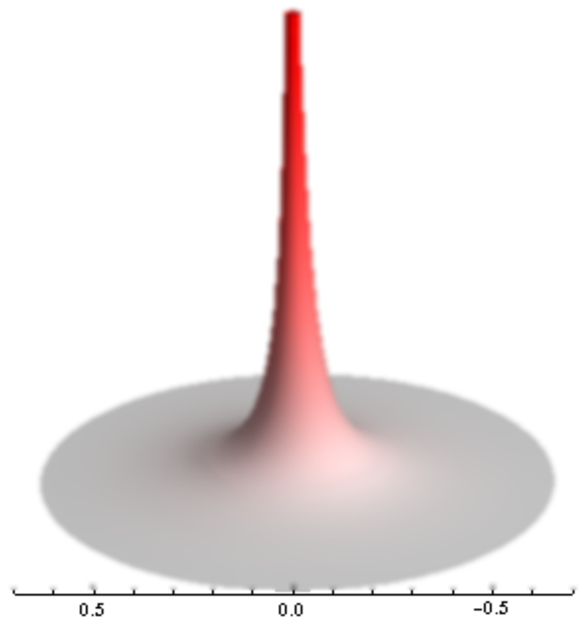
Jet shapes in vacuum: the p+p baseline

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

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

I Vitev, S Wicks, BWZ,

JHEP 0811,093 (2008)



Theory VS Tevatron Data

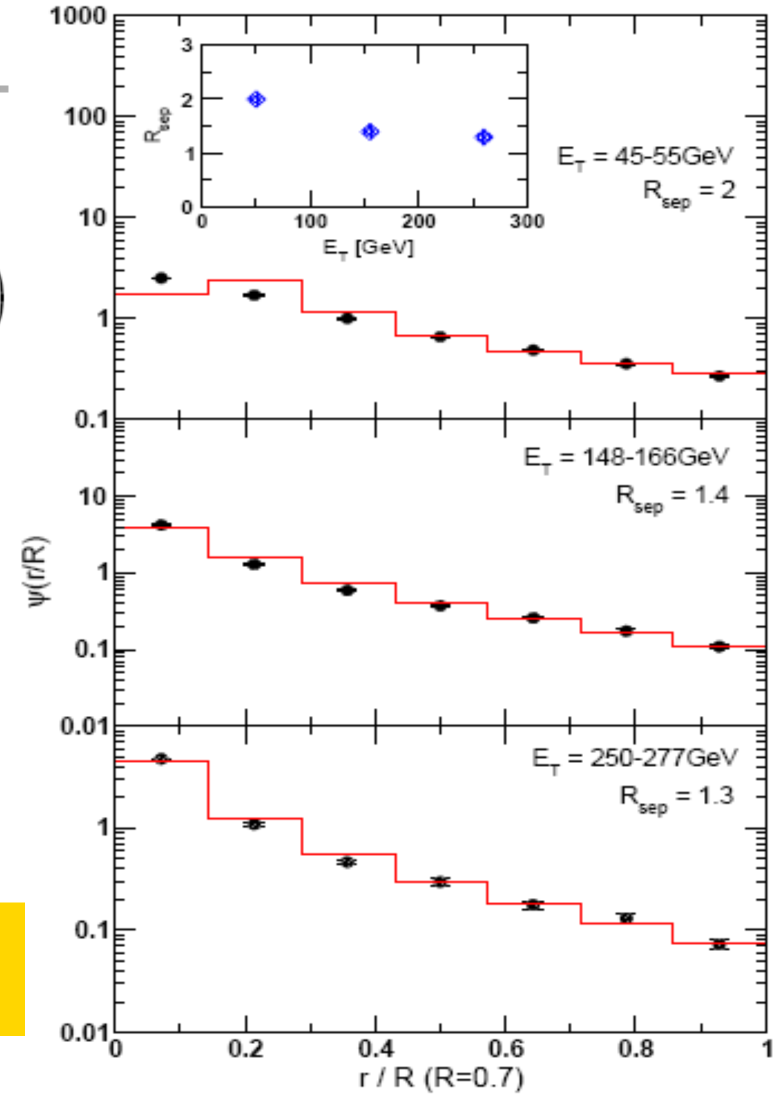
- Total contribution to jet shape in vacuum:

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

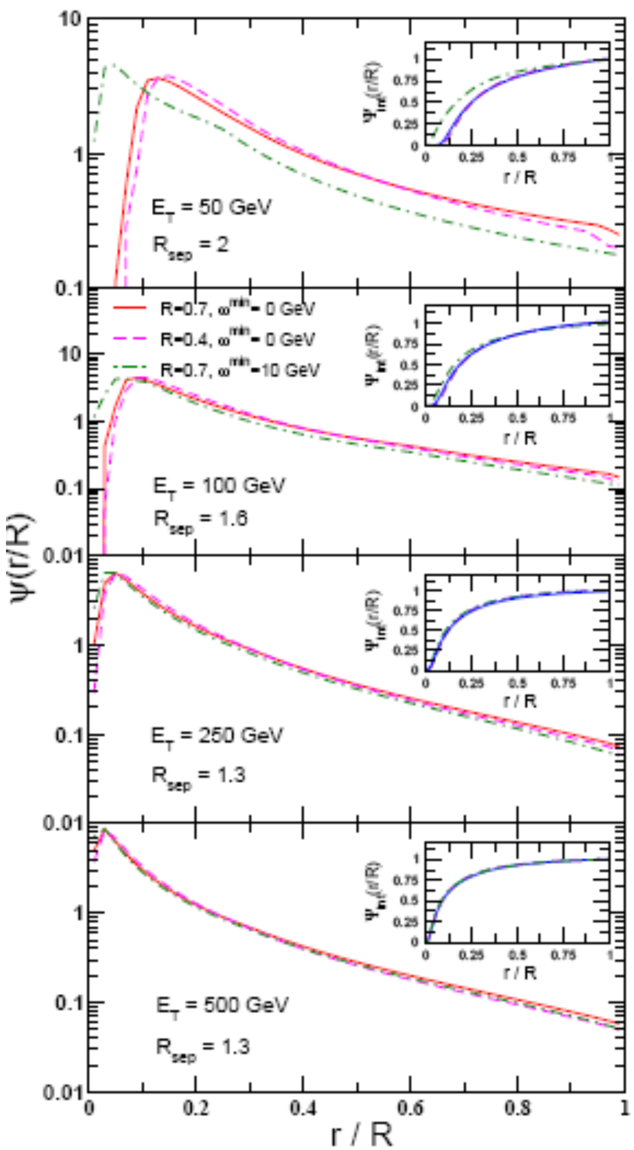
Theoretical model describes CDF II data fairly well after including all kinds of contributions

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

CDF collaboration
Acosta et al (2005)



Predictions for Jet shape at LHC



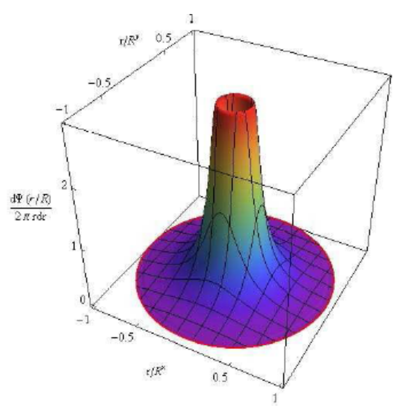
- Jet shapes at LHC are very similar to those at Tevatron:

- As a function of the jet opening angle jet shapes are self-similar.

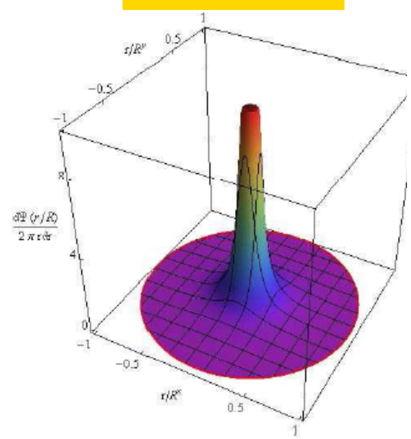
- First study of finite detector acceptance effect is carried out: the effect is observable with 10-20% energy cut.

- Jet shapes change dramatically with E_T

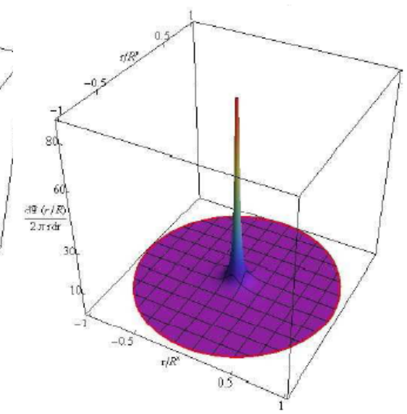
20GeV



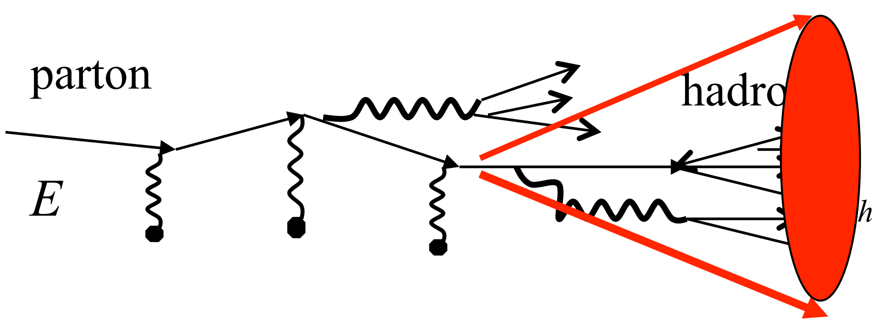
100GeV

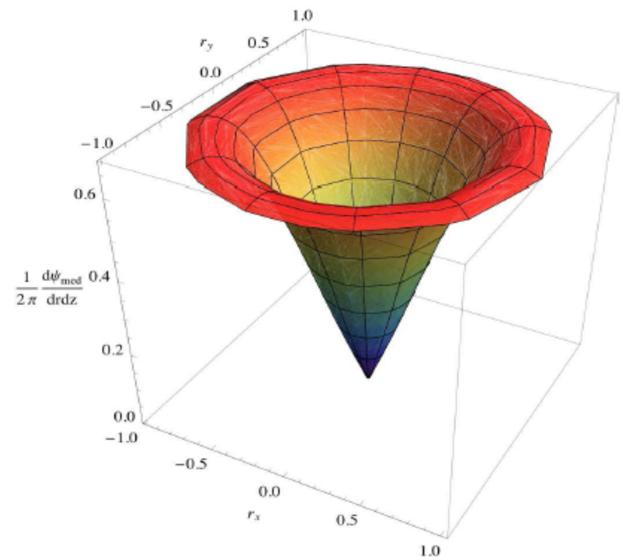


500GeV

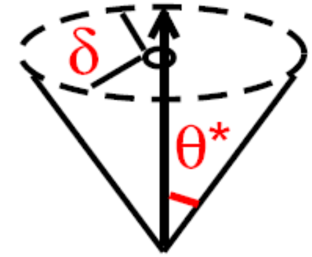


Medium-induced jet shape





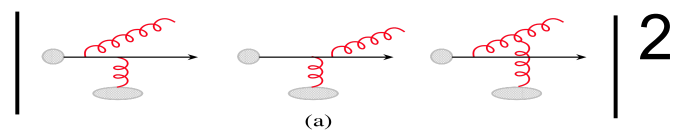
I Vitev, S Wicks, BWZ, JHEP 0811,093 (2008)



An analytic approach

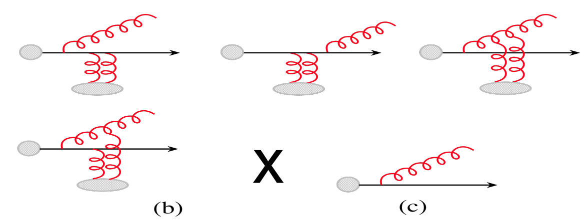
- GLV formalism provides an analytic approach

Gyulass-Levai-Vitev



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

+2Re



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

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

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

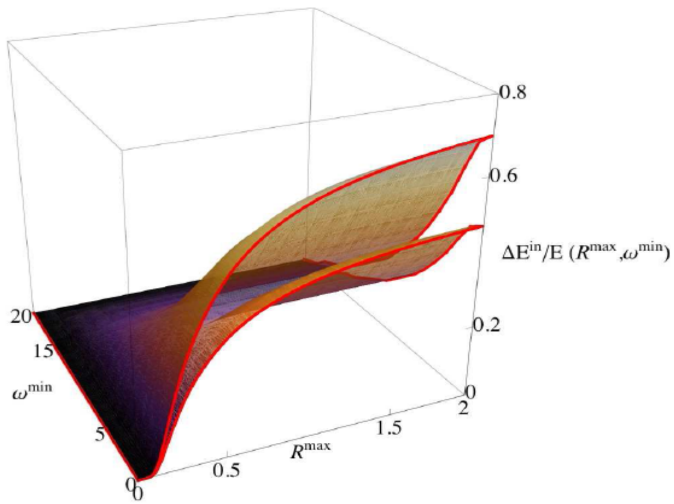
$$\lim_{r\to 0}\frac{\omega dN^g_{\mathrm{med}}}{d\omega\, d\phi\, dr} = 0$$

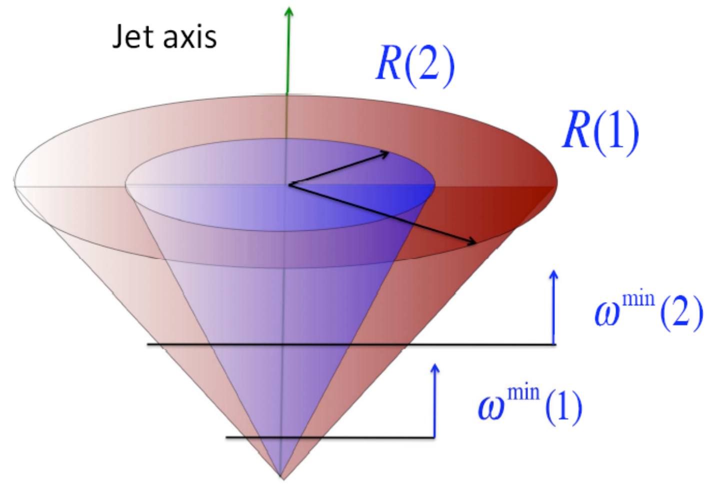
I. Vitev (2005)

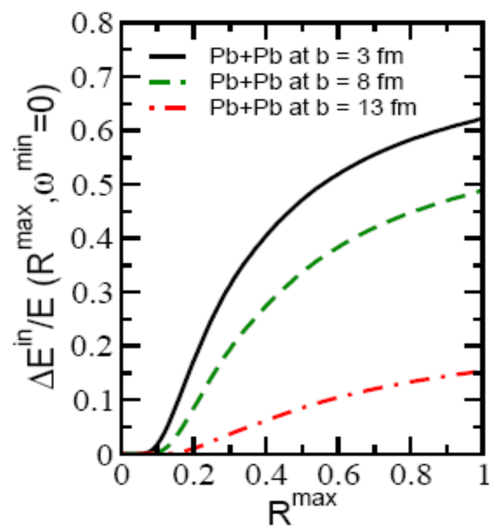
- It is proved to all order in opacity expansion.

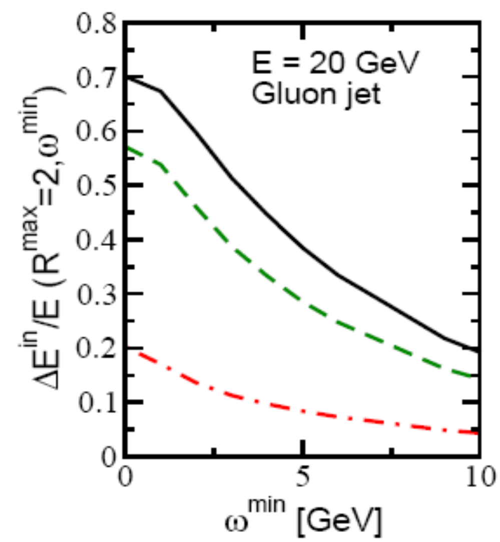
Energy loss distribution

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



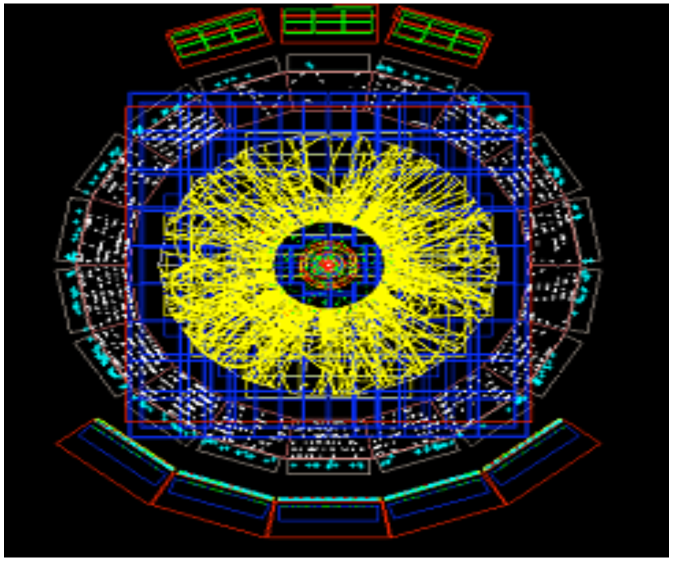






- Energy ratio goes down with larger b.
- Energy ratio becomes smaller with smaller R and larger $\omega^{\min}$.

Tomography of jets in heavy-ion collisions

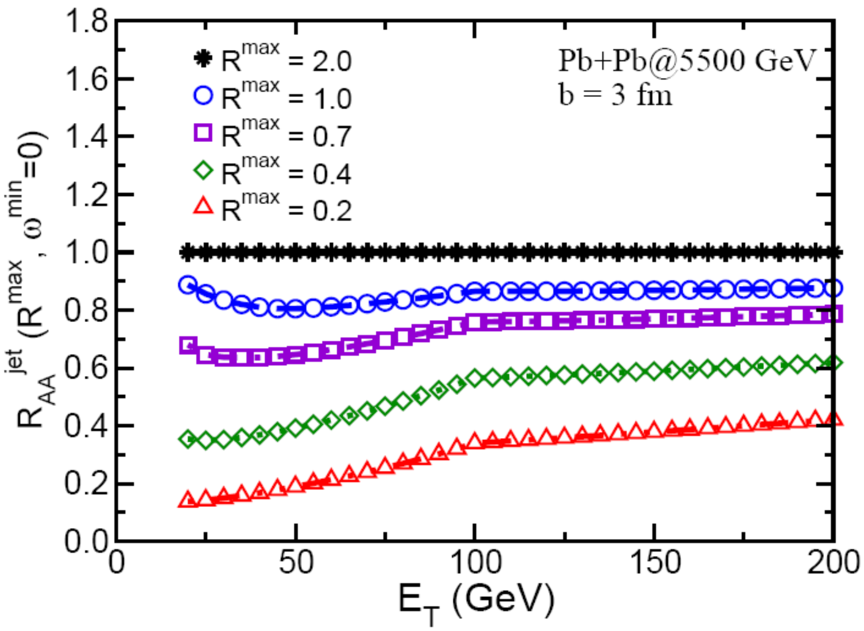


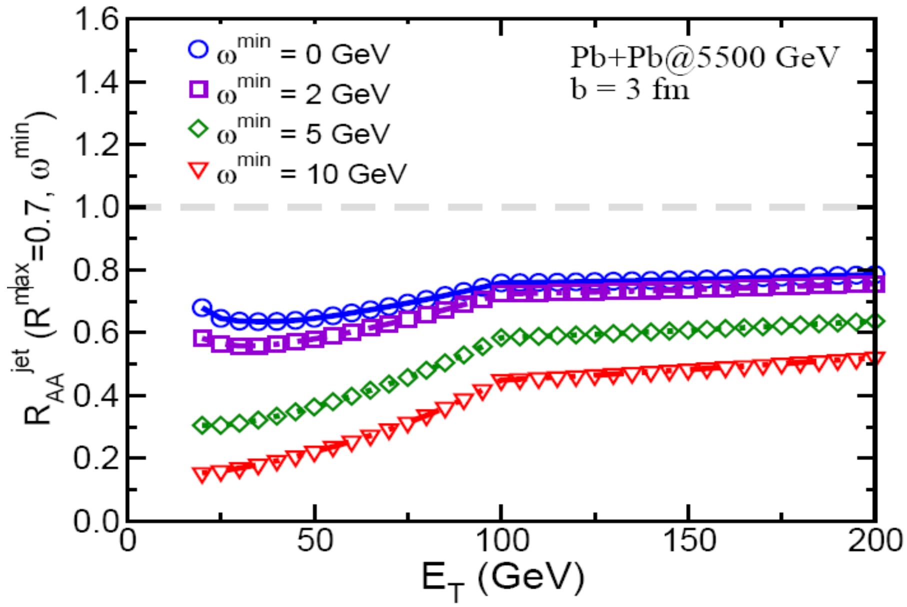
I Vitev, S Wicks, BWZ,

JHEP 0811,093 (2008); EPJC 62, 139 (2009).

R_{AA} vs R^{max} and ω^{min}

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

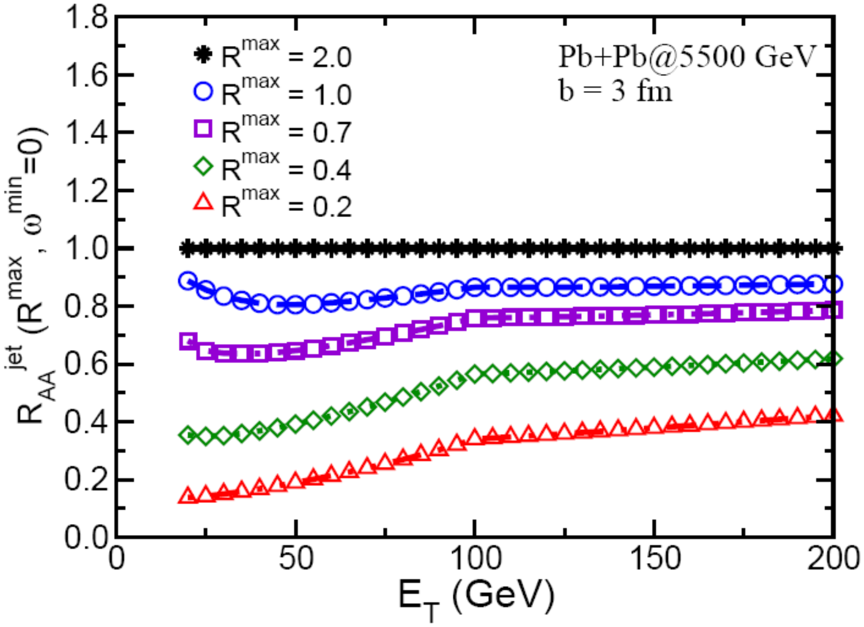


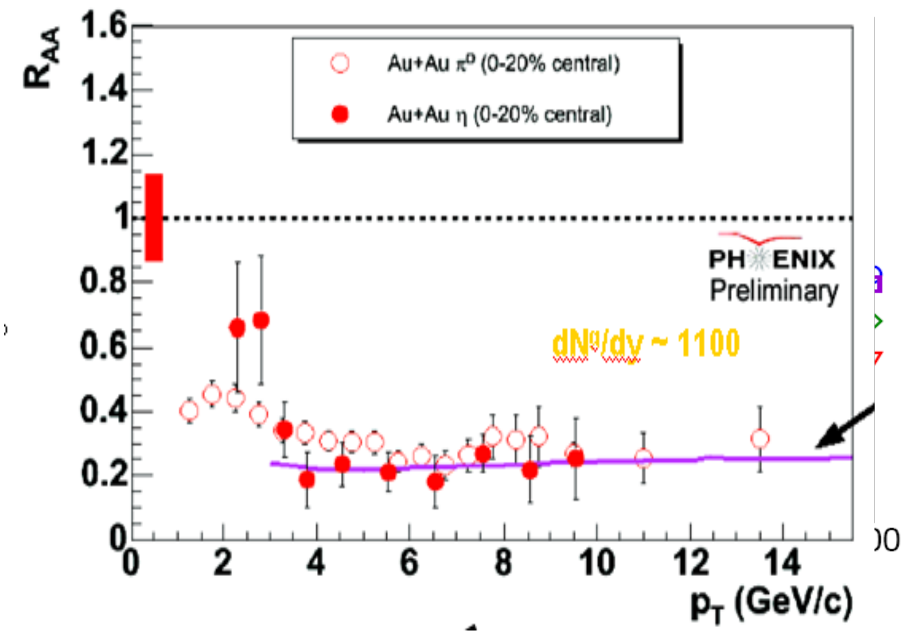


- R_{AA} for jet cross section evolves continuously by varying cone size and acceptance cut.
- Contrast: single result for leading particle.

R_{AA} vs R^{max} and ω^{min}

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



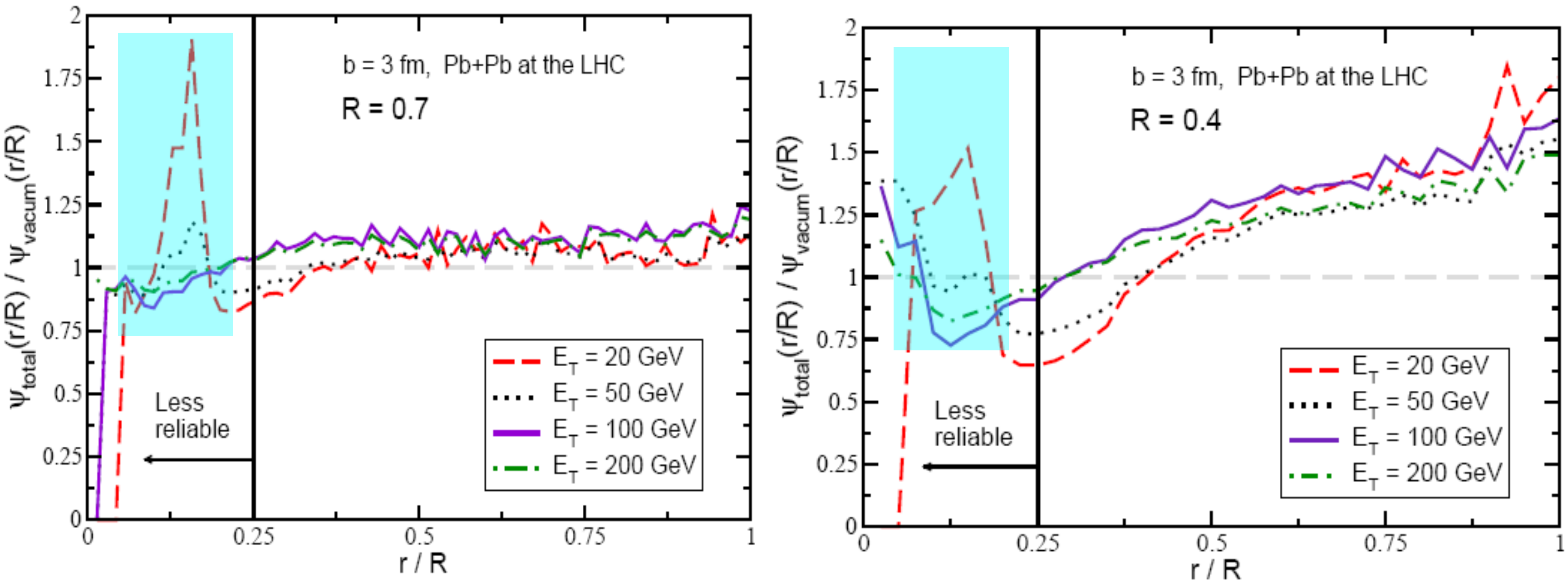


- R_{AA} for jet cross section evolves continuously by varying cone size and acceptance cut.
- Contrast: single result for leading particle.

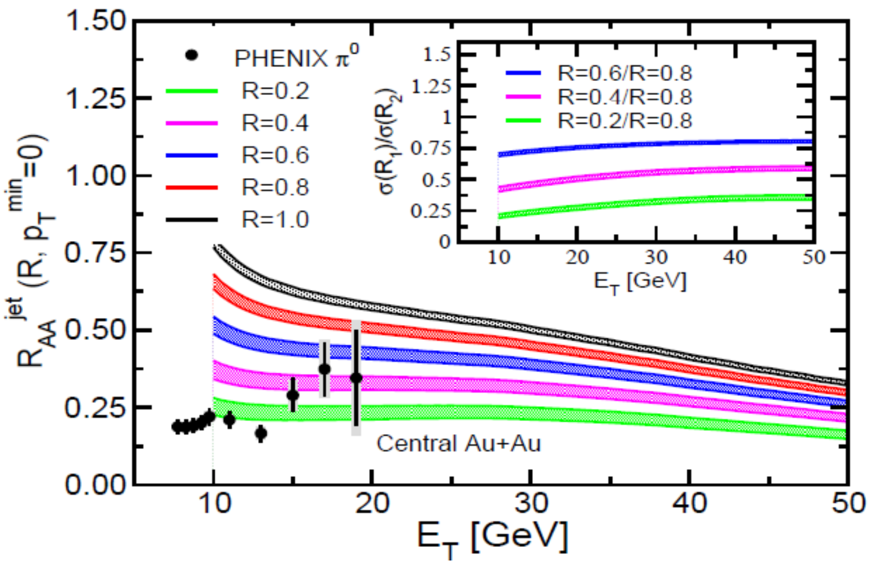
Total jet shape in medium

$$\psi_{\rm tot.}(r/R) = \frac{1}{\rm Norm}\int_{\epsilon=0}^{1} d\epsilon \sum_{q,g} P_{q,g}(\epsilon)\frac{1}{(1-(1-f_{q,g})\cdot\epsilon)^3} \times \frac{\sigma_{q,g}^{NN}(R,\omega^{\rm min})}{d^2E'_T dy}\Big[(1-\epsilon)\,\psi_{\rm vac.}^{q,g}(r/R) + f_{q,g}\cdot\epsilon\,\psi_{\rm med.}^{q,g}(r/R)\Big]$$

- The ratio of total jet shape in medium to jet shape in vacuum is smaller than 1 at 0.25<r/R<0.5, and larger than 1 when r/R>0.5.



Jet observables at next-to-leading order



I Vitev, BWZ, Phys. Rev. Lett. 104,132001 (2010)

Jet cross section at NLO in p+p

- Jet cross sections at NLO in p+p :

$$\frac{d\sigma^{\rm jet}}{dE_T dy} = \frac{1}{2!}\int d\{E_T,y,\phi\}_2 \frac{d\sigma[2\to 2]}{d\{E_T,y,\phi\}_2} S_2(\{E_T,y,\phi\}_2) + \frac{1}{3!}\int d\{E_T,y,\phi\}_3 \frac{d\sigma[2\to 3]}{d\{E_T,y,\phi\}_3} S_3(\{E_T,y,\phi\}_3)$$

- Function S_2 and S_3 contain jet find algorithm:

Lowest order

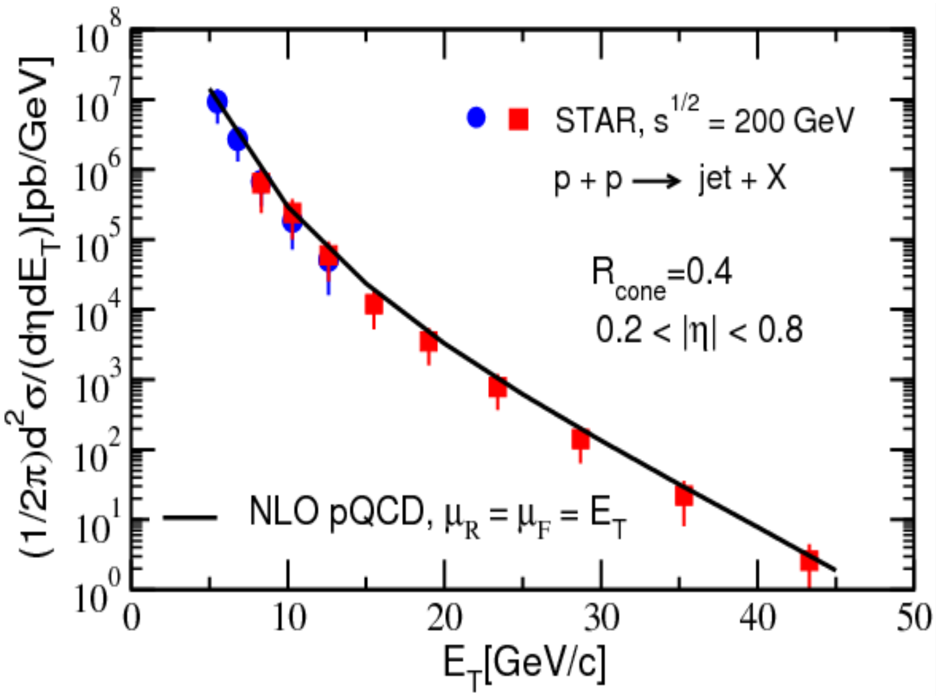
$$S_2 = \sum_{i=1}^{2} S(i) = \sum_{i=1}^{2} \delta(E_{T_i} - E_T)\delta(y_i - y)$$

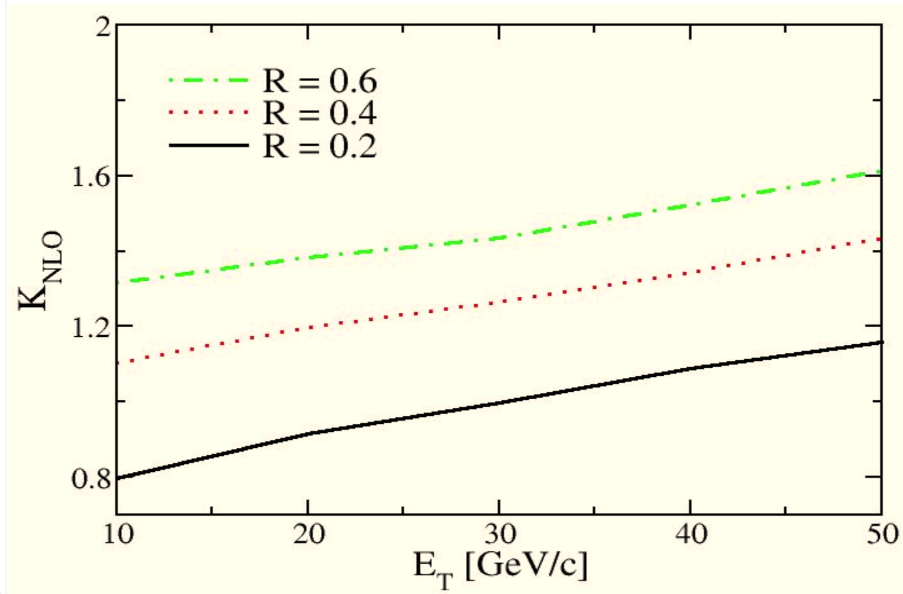
higher order

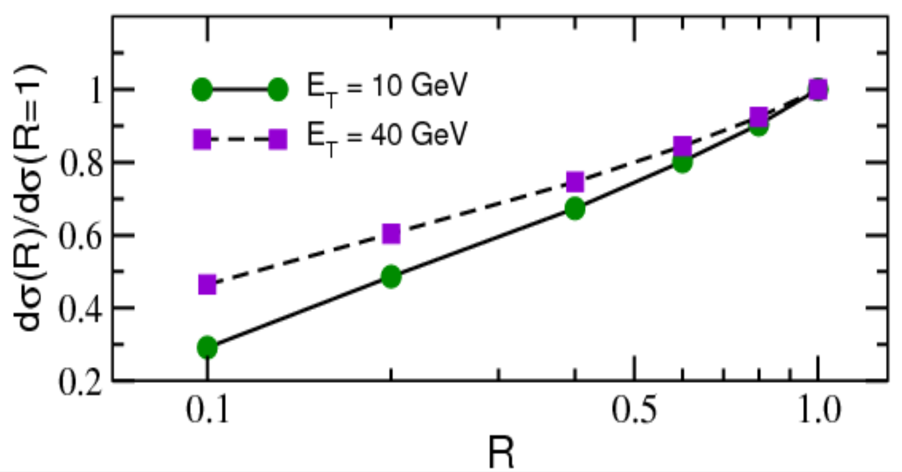
$$S_3 = \sum_i \delta(p_i - p_J)\delta(y_i - y_J) \prod_{j(j\neq i)} \theta\left(R_{ij} > \frac{p_i + p_j}{\max(p_i, p_j)} R\right) + \sum_{i,j(i<j)} \delta(p_i + p_j - p_J)\delta\left(\frac{p_i y_i + p_j y_j}{p_i + p_j} - y_J\right)\theta\left(R_{ij} < R_{\rm rc}\right)$$

Ellis, Kunszt, Soper, PRL 64:2121(1990); PRL 69:1496(1992)

Jets in p+p at RHIC







- Very good agreement between data and theory is achieved;
- K_{NLO}=NLO/LO can be smaller than 1 at small cone radius.

Cold nuclear matter effects

- Initial-state parton energy loss:

I. Vitev, PRC 75(2007)064906

- Shadowing effect: is calculated from the coherent higher-twist parton interactions.

Qiu, Vitev, PRL 93(2004)262301.

- EMC effect: using parametrization of EKS

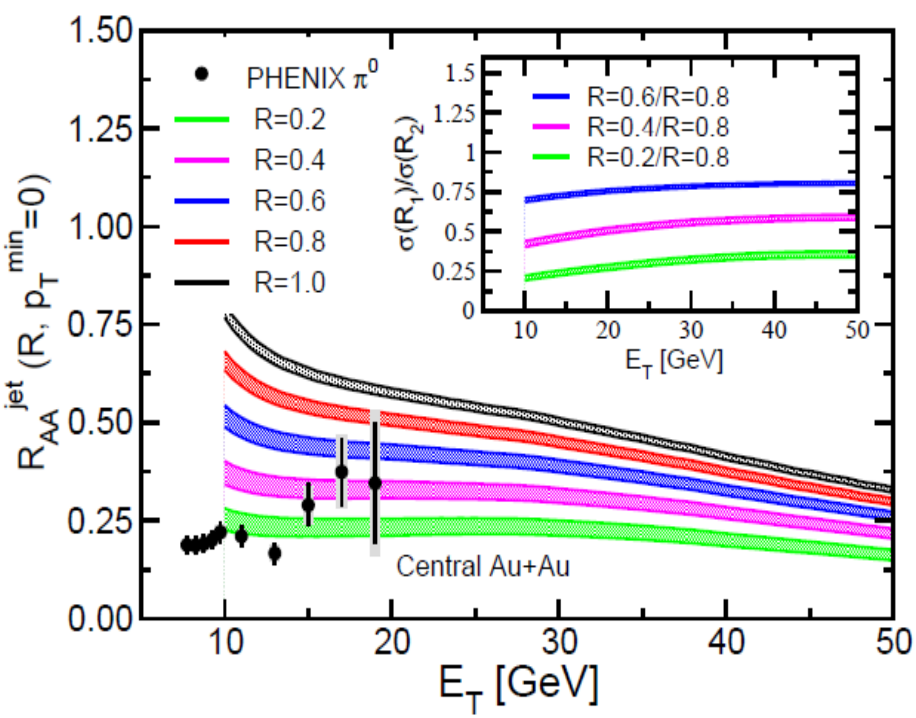
Eskola, Kolhinen, Salgado, EPJC 9(1999)61.

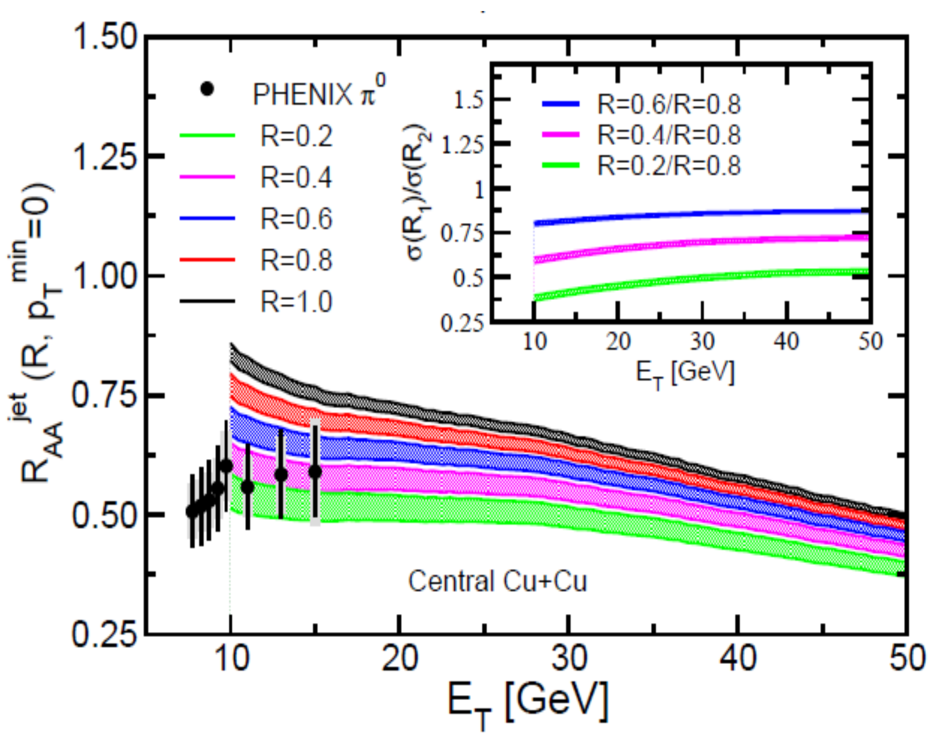
- Cronin Effect: kt broadning of the IS partons

I Vitev, BWZ, PLB 669(2008)337.

Jets in A+A at RHIC (I)

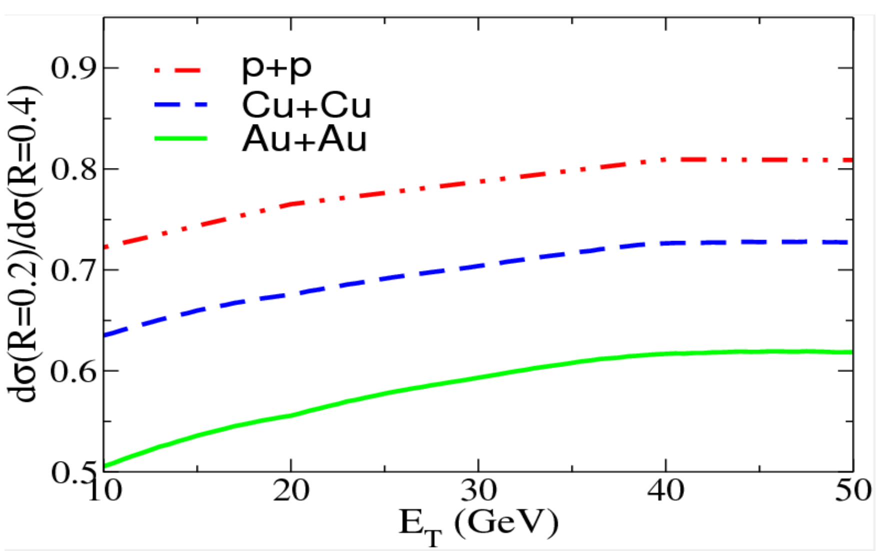
- R_{AA} for jet cross sections with CNM and final-state parton energy loss effect are calculated with different R;
- CNM effect will contribute close to ½ at the high E_T.

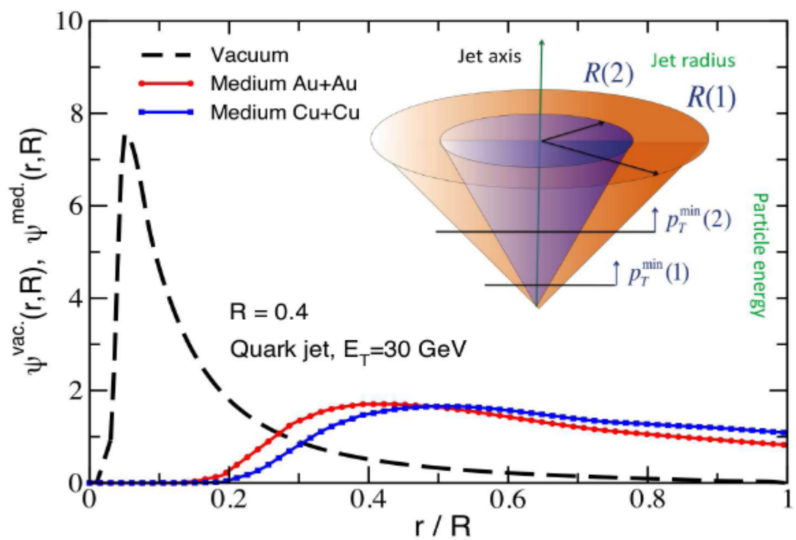




Jets in A+A at RHIC (II)

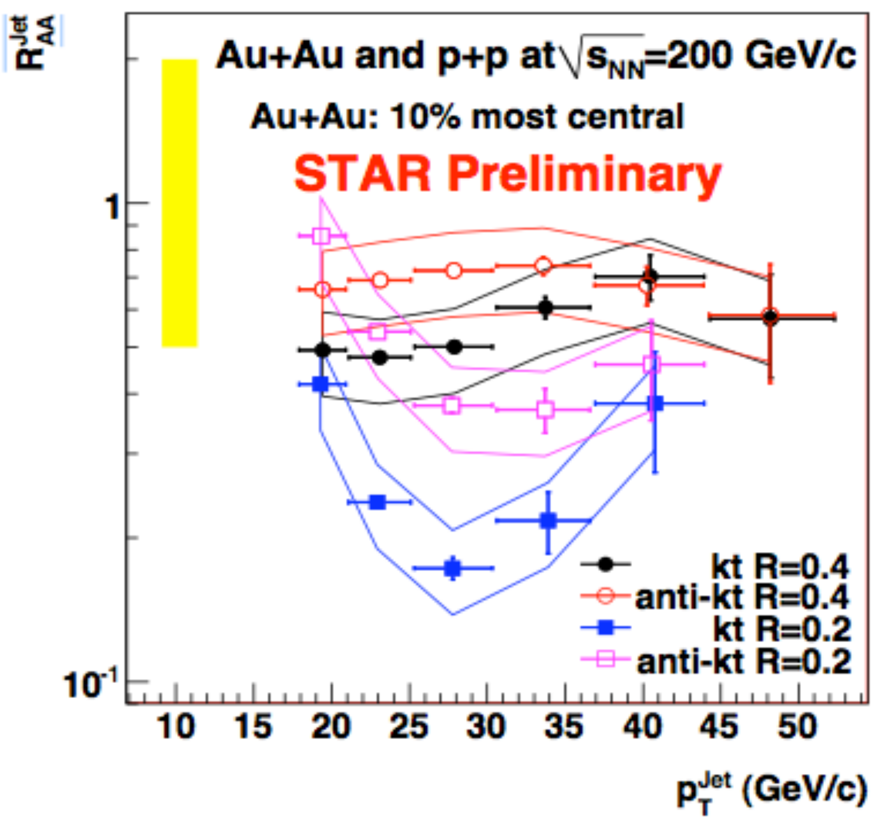
- Ratios of jet cross sections at different R in p+p, Cu+Cu and Au+Au have a similar trend with different magnitudes.
- Increasing of mean relative radii in medium is small.

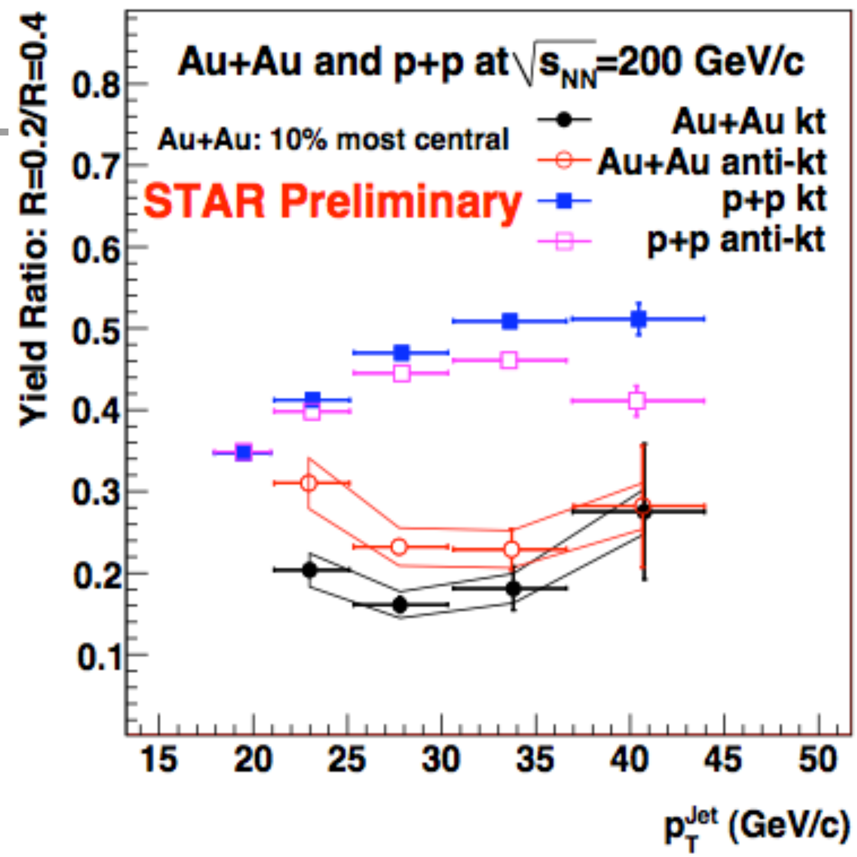




$\langle r/R \rangle$	Vacuum	Medium	Total	Δ
Au+Au	0.271	0.601	0.283	4%
Cu+Cu	0.271	0.640	0.272	0.4%

Jet measuring at RHIC





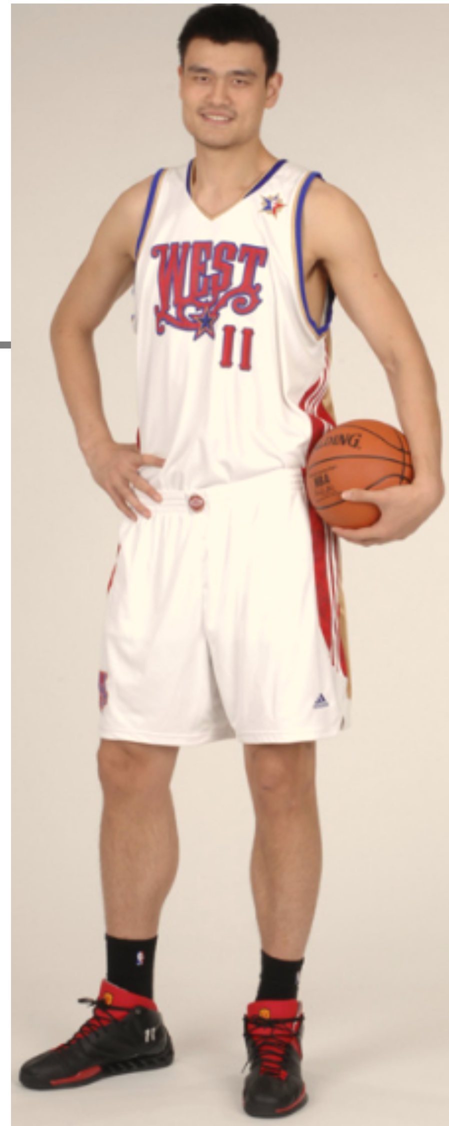
- Jets in Au+Au by STAR

M. Poloszkon et al, (2009)

S. Salur et al, (2009)

Summary

- Theory and phenomenology of full jet tomography in relativistic heavy-ion collisions are developed.
- A variable quenching of R_{AA} for jet cross section in A +A collisions is demonstrated, which is contrary to single result of R_{AA} for leading particle.
- Total jet shapes in A+A reactions are given: small broadening at mean relative jet radii; large deviation are shown at the periphery r-> R.
- First results of NLO calculations for jet productions are discussed.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谢谢！

Backup

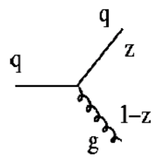
Leading order

An analytic approach to the energy distribution of jet

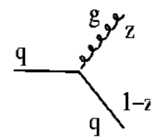
Seymour, M. (1998)

QCD splitting kernel

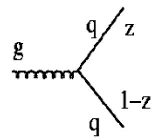
$$dP_a = \frac{\alpha_s}{2\pi}\frac{d\rho^2}{\rho^2}\frac{d\phi}{2\pi}dzP_{a\to bc}(z)$$



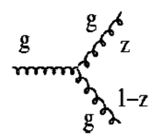
$$P_{qq}^{(1)}(x) = C_2(F)\left[(1+x^2)\left(\frac{1}{1-x}\right)_+ + \frac{3}{2}\delta(1-x)\right]$$



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



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



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

Jet shape at LO with the acceptance cut

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

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

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

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

Resummation & NP Corr.

Jet shapes for a quark and a gluon are:

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

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

Collinear divergence
Requires Sudakov resummation

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

- Sudakov form factors:

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

- Power correction: include running coupling inside the z integration.
- Initial-state radiation should be included

Power corr. & IS radia.

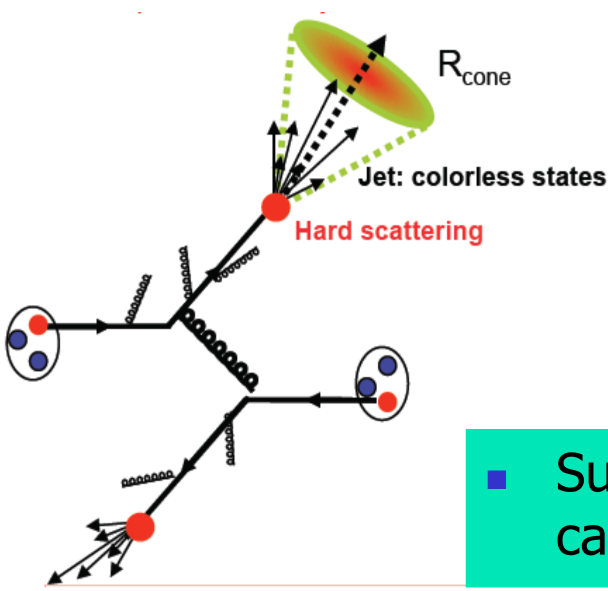
- Power correction: include running coupling inside the z integration and integrate over the Landau pole.

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

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

non-perturbative scale Q_0.

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

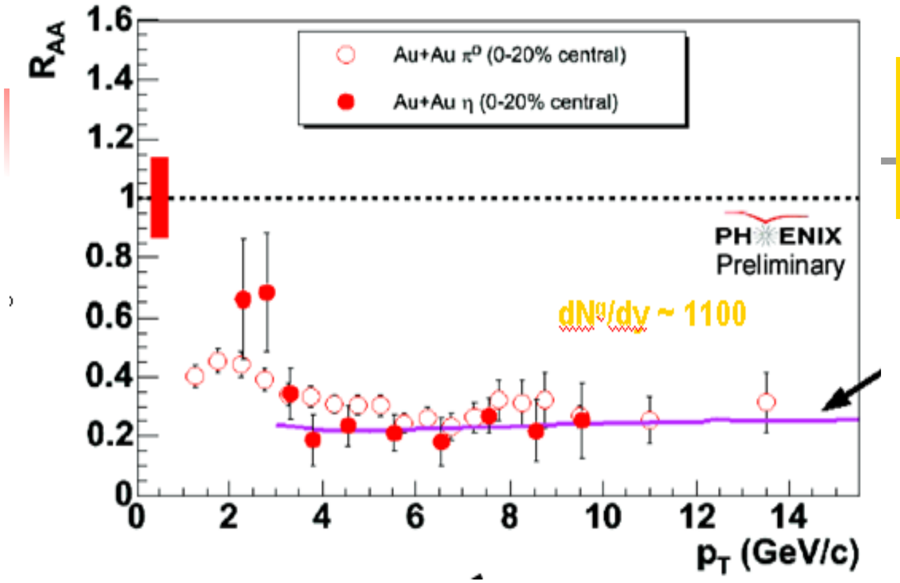


- Initial-state radiation should be included, which gives:

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

- Sudokov resummation & power correction for ISR can be given in same way as those for FSR.

Jet quenching with R_{AA}



Gyulassy-Levai-Vitev(GLV) formalism

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

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

- 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)

Jet cross section@HIC and R_{AA}

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

Higher energy needed due to energy loss

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

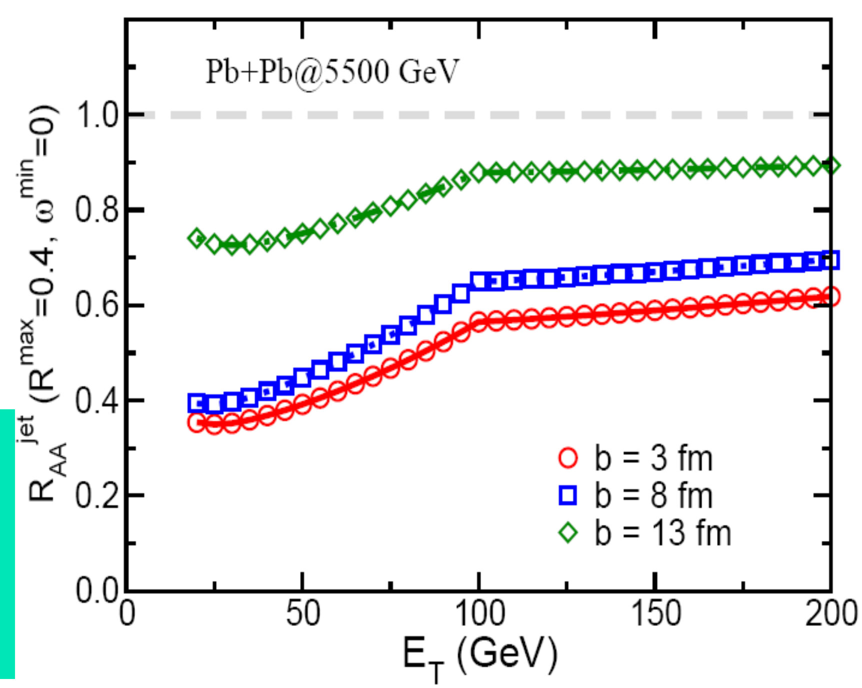
Only a fraction of lost energy falls inside the cone and above the acceptance cut.

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

Define nuclear modification factor for jet cross section:

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

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



Jet finding algorithms

- Cone algorithm
- Midpoint cone algorithm
- k_T algorithm

$$k^2_{T,i} = p^2_{T,i}$$

$$k^2_{T,(i,j)} = \min(p^2_{T,i}, p^2_{T,j}) \frac{R^2_{i,j}}{D^2}$$

$$\text{if } k^2_{T,(i,j)} < k^2_{T,i}, \text{ merge}$$

- Anti-k_T algorithm
- Seedless algorithm

Parton merge parameter

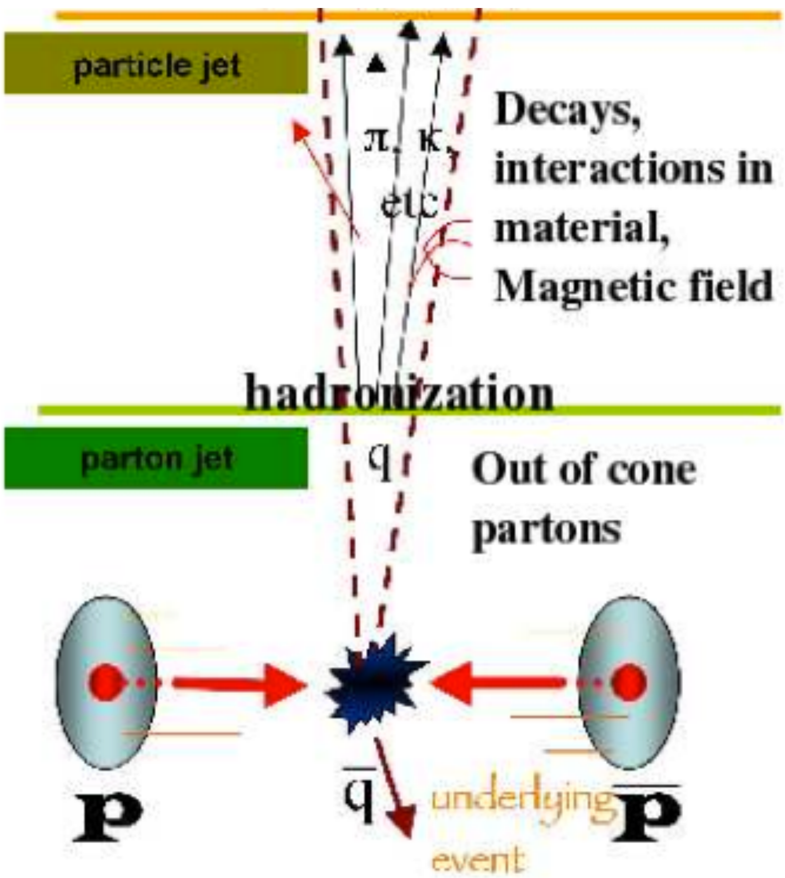
NLO

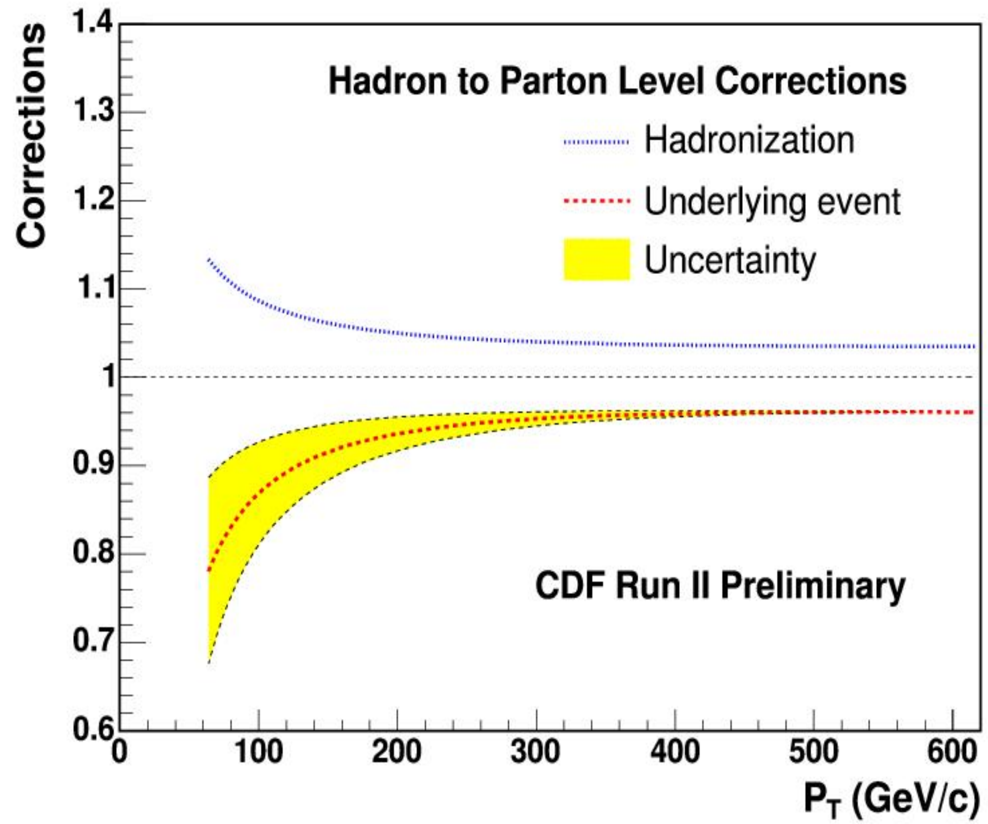
$$R_{\rm rc} = \min\left(R_{sep}R, \frac{E_{T_i} + E_{T_j}}{\max(E_{T_i}, E_{T_j})} R\right)$$

- Midpoint cone $R_{sep} = 2$
- Cone $1 < R_{sep} < 2$
- K_T $D = R,\ R_{sep} = 1$

Non-perturbative effects

- Non-perturbative effects: hadronization & underlying event.
- Two effects will go in opposite direction: partial cancellation between "splash-out" effect and "splash-in" effect.





Tagged jet production in HIC

photon + jet

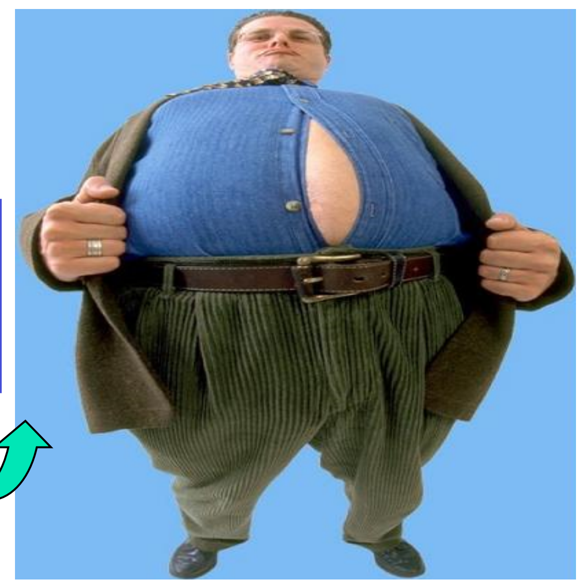
- Advantage: large yield
- Disadvantage: final-state effects

Z^0 + jet

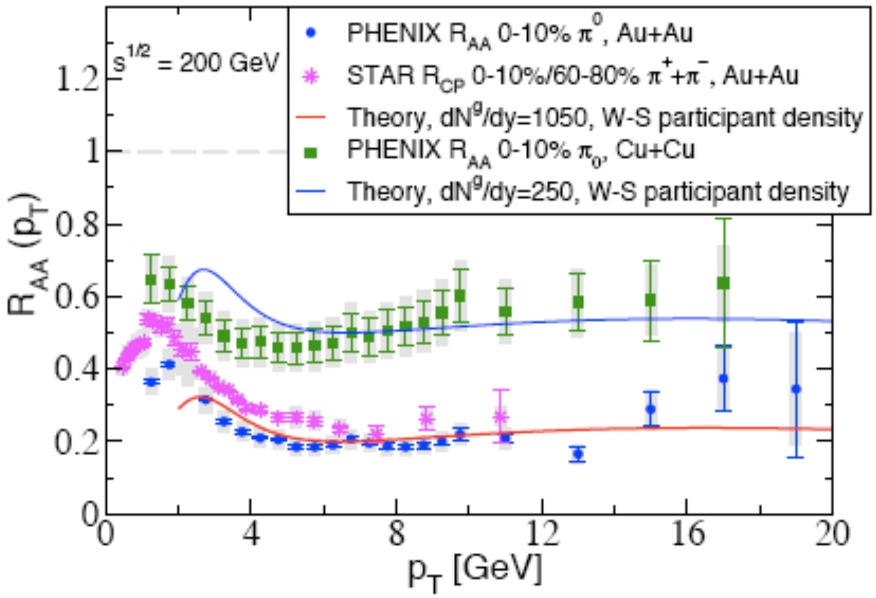
- Disadvantage: small cross section
- Advantage: no final-state effects

Neufeld, Vitev, BWZ, in progress

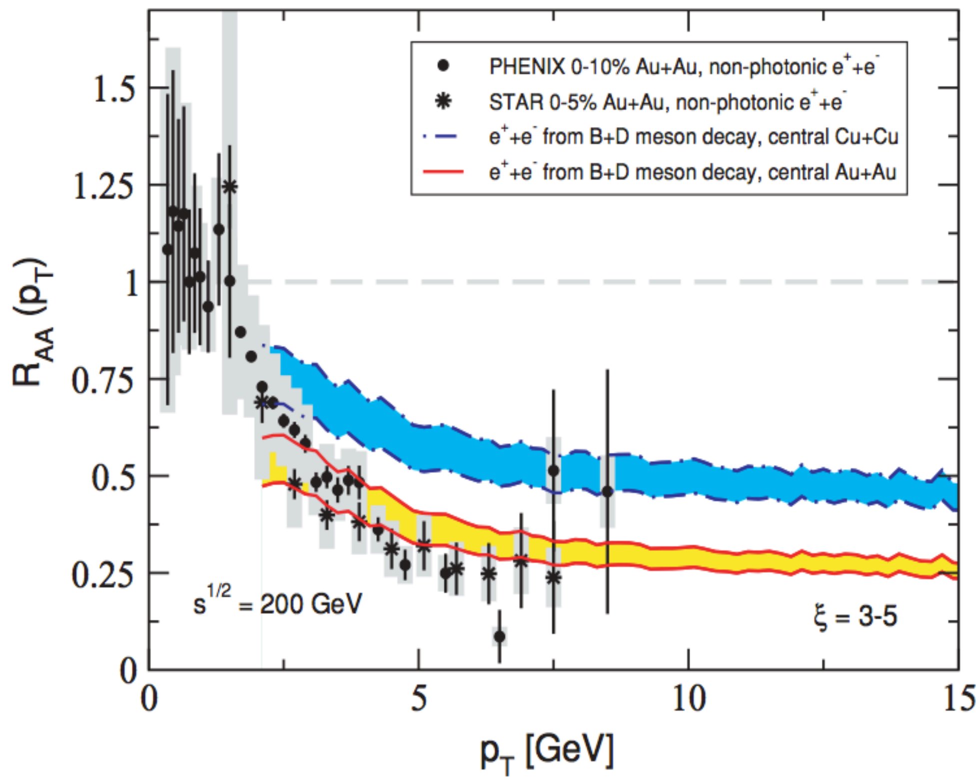
You are so light, I am too heavy.



Leading particle production



- Full treatment of cold nuclear matter effects



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

- Compatible with measured multiplicities

I Vitev, BWZ, PLB 669,337 (2008)

Sharma, Vitev, BWZ, PRC 80:054902 (2009)