Theoretical Developments in Light and Heavy Flavour Energy Loss

'Science is the organized skepticism in the reliability of expert opinion.' - R. P. Feynman

Ivan Vitev, Nuclear Theory, T-16 , LANL

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Quark Matter 2008, February 4-10, Jaipur, India

Outline of the Talk

Theoretical developments in light and heavy quark energy loss

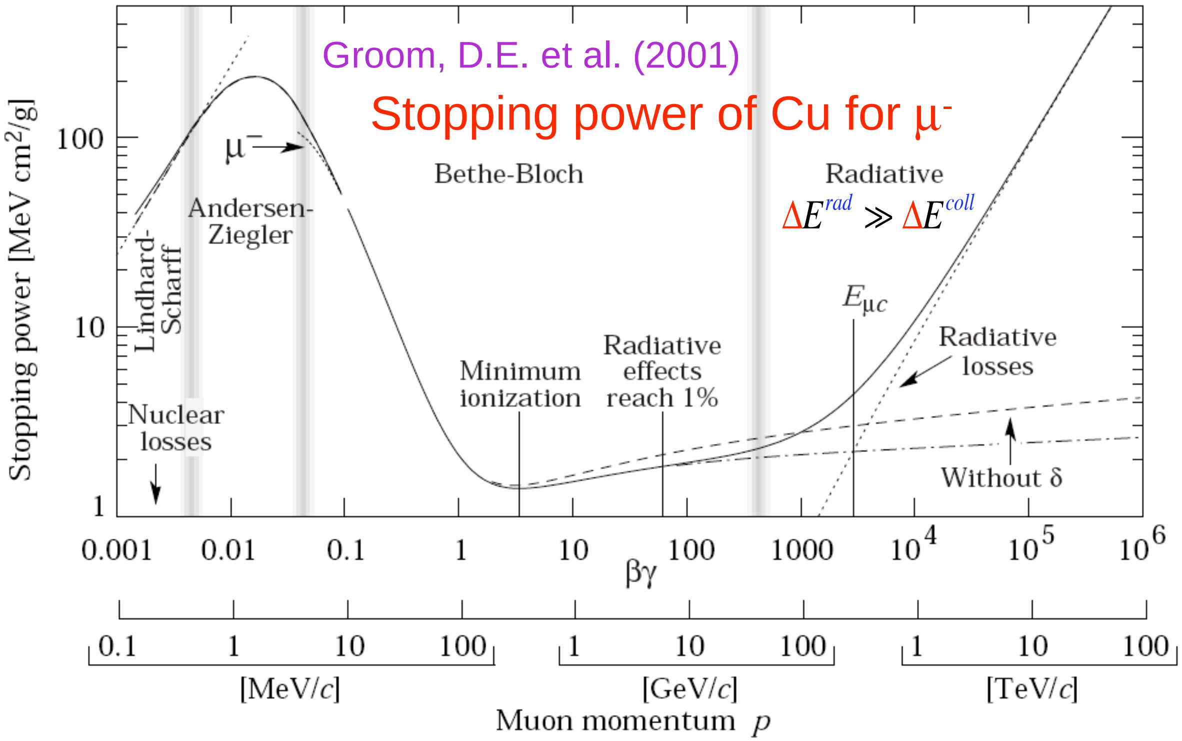
- Radiative and collisional energy loss of fast quarks and gluons - toward a consistent picture
- Models of heavy flavor suppression - from the perturbative to the non-perturbative - and back
- Recent insights in the stopping power of cold nuclear matter

New theoretical and experimental opportunities for jet quenching physics at the LHC

- Jet finding algorithms and jet shapes in elementary N-N collisions
- Medium-induced jet shapes in QGP - a theoretical approach
- Toward a 2D tomography *of* jets - a differential test of parton interactions in the QGP

Outlook and Conclusions

The Stopping Power of Matter



- Collisional energy loss
  - medium excitation

$$\frac{d\Delta E^{coll}}{dz} \approx 4\pi\alpha_{em}^2 z^2 Z \rho_{num} \frac{1}{\beta^2 m} \ln B_q$$

Bethe, H.A. (1930,1932)

- Radiative energy loss
  - bremsstrahlung

$$\frac{d\Delta E^{rad}}{dz} \approx \frac{16}{3} \alpha_{em}^3 z^4 Z^2 \rho_{num} \frac{1}{M^2} E \ln(\lambda\gamma)$$

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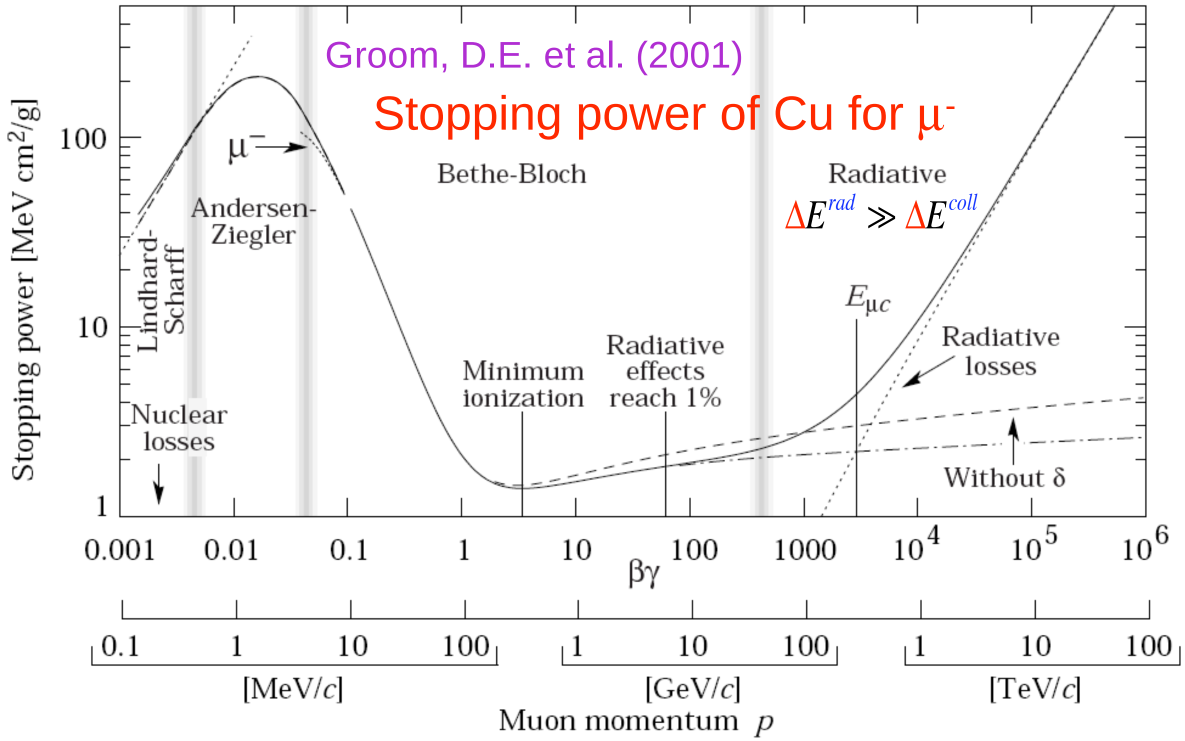

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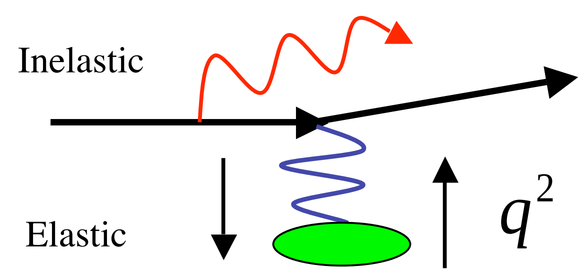
- The same qualitative behavior in QCD:

$\Delta E^{coll} = c_1 L$ Braaten, E. et al. (1991)

$\Delta E^{rad} = c_2 E L$ Bertsch, G et al. (1982)



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Toward Proper Comparison of $\Delta E^{rad} / \Delta E^{coll}$

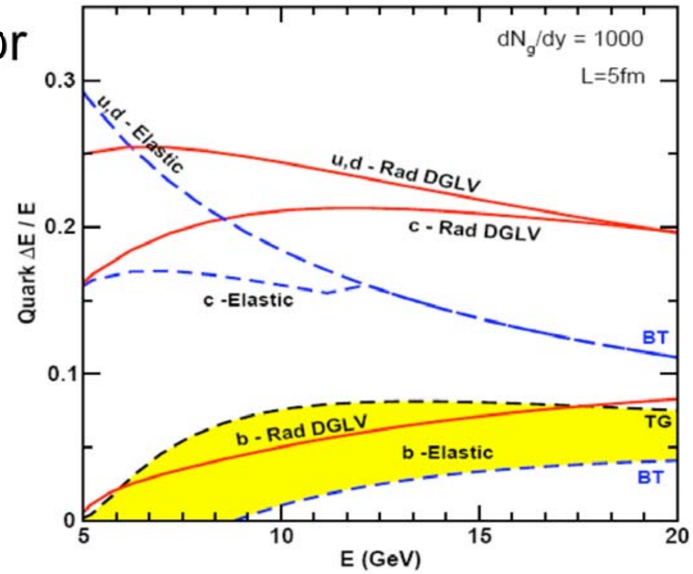
- LPM - new path length and energy behavior

Majumder, A. (2007)

Radiative E-loss: $$\frac{d\Delta E^{rad}}{dL} = \frac{2\alpha_s}{3}\frac{\mu^2 L}{\lambda_g}\log\left(\frac{2E}{\mu^2 L}\right)$$

Collisional E-loss: $$\frac{d\Delta E^{coll}}{dL} = \frac{2\alpha_s}{3}\mu^2\frac{1}{2}\log\left(\kappa\frac{TE}{\mu^2}\right)$$

Mustafa, M et al. (2005) Wicks et al. (2006)



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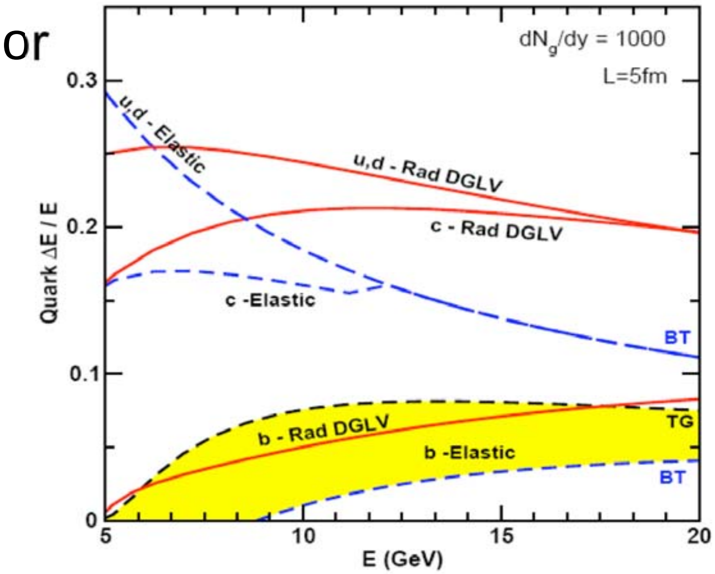
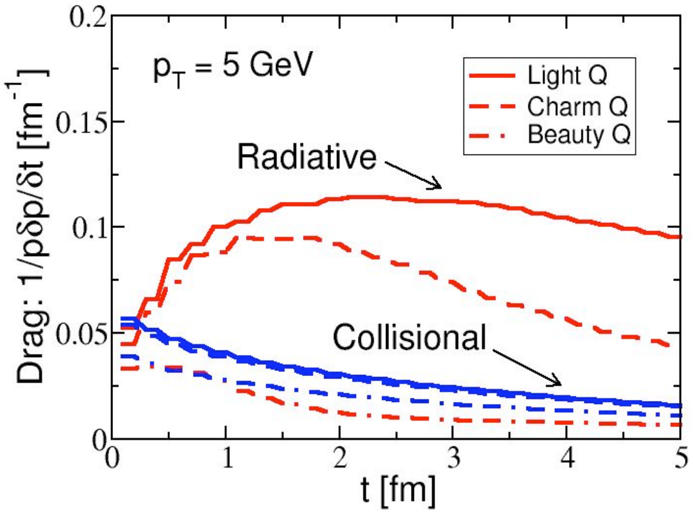


- Comparison in the the same model of the medium / momentum exchanges

V., I. (2006) Wang (2006)

$$\frac{1}{\sigma}\frac{d\sigma}{d^2q} = \frac{\mu^2}{\pi\left(q^2+\mu^2\right)^2}$$



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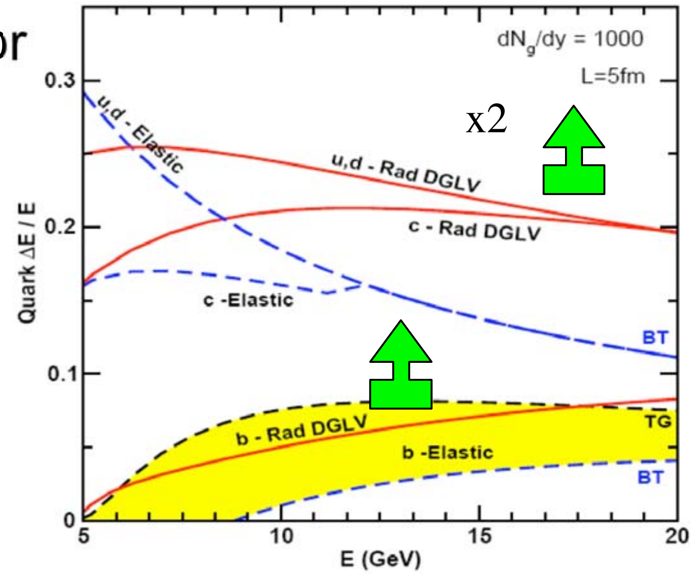

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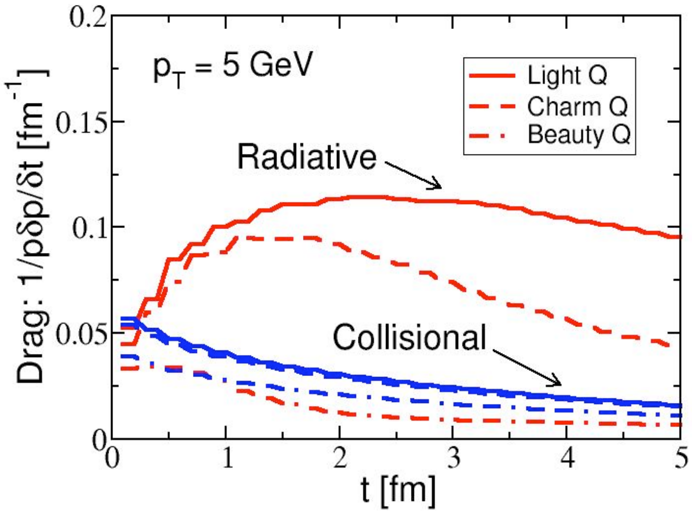
$$\frac{\mu^2}{\pi\left(q^2+\mu^2\right)^2} \to \frac{\mu^2}{\pi q^2\left(q^2+\mu^2\right)}$$

Djordjevic, M et al. (2007) Wang, X.-N. (2000)



- Inelastic E-loss dominates $\gamma = \frac{E}{m} \geq few$

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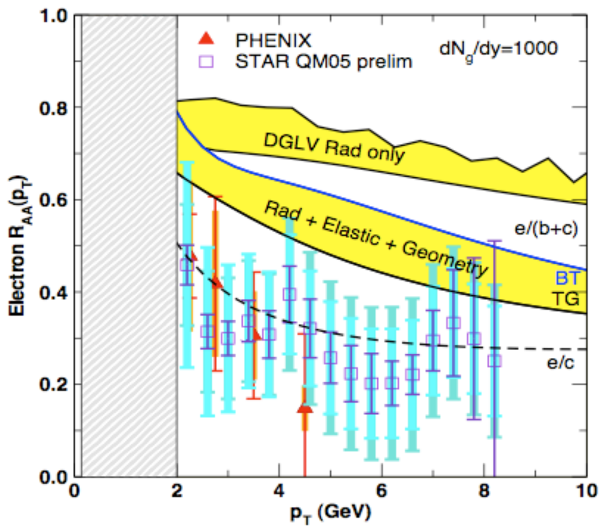
Heavy Flavor: Perturbative Quenching or Not?



- Smaller contribution of the elastic compared to radiative energy loss, fluctuations
- One can recast the under-quenching of $e^{\pm}$ into over-quenching of π^0 but not resolve both
- LO HTL may lead to 30% correction in the QGP density estimates

Wicks, S. et al. (2007) Wicks, S. et al. (2008)

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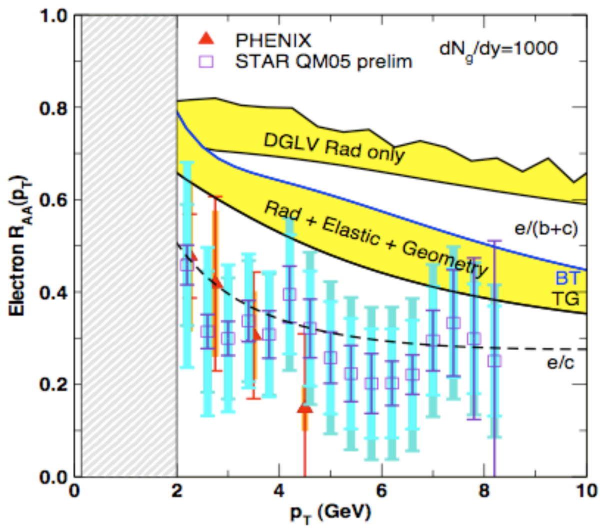

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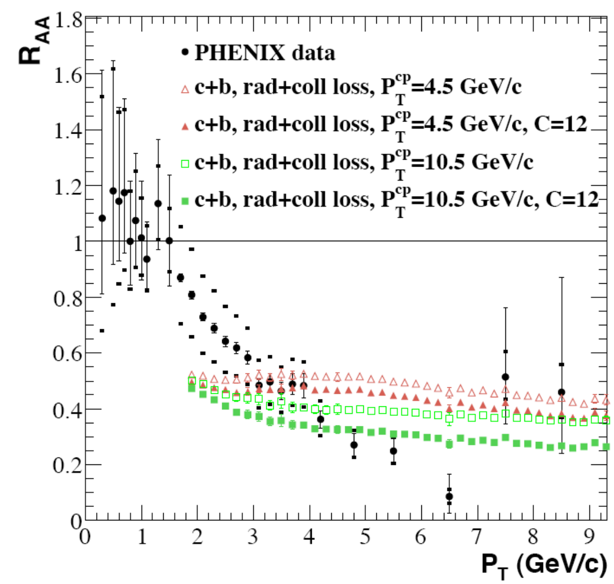
Charm baryon enhancement

$$N_{\Lambda_c} / N_D \sim 0.08 \text{ in p+p}, \quad N_{\Lambda_c} / N_D \sim 1 \text{ in Au+Au}$$

- Smaller branching fraction of Λ_c to electrons
- About 25% suppression effect for $C_{enhancement}$ = 12

$$R^e_{AA} = \frac{1+\left(N_{\Lambda_c}/N_D\right)_{pp}}{1+C\left(N_{\Lambda_c}/N_D\right)_{pp}} \times \frac{1+C\left(N_{\Lambda_c\to e}/N_{D\to e}\right)_{pp}}{1+\left(N_{\Lambda_c\to e}/N_{D\to e}\right)_{pp}}$$

Martinez-Garcia, G. et al. (2007)



Heavy Meson Dissociation at RHIC and LHC

Formation times of mesons/baryons

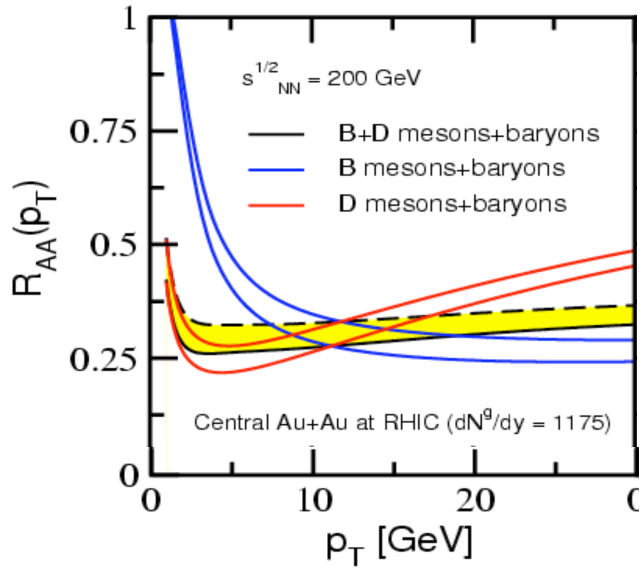
$$\Delta y^+ = \frac{1}{\Delta p^-} = \frac{(0.2\ GeV.fm)\ 2z(1-z)p^+}{k_\perp{}^2 + (1-z)m_h{}^2 - z(1-z)M_q{}^2} \quad \tau_{\rm form} = \frac{\Delta y^+}{1+\beta_Q}$$

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

Adil, A. et al. (2007)

- Application to heavy resonances

Markert, K. et al. (2008)



Ivan Vitev

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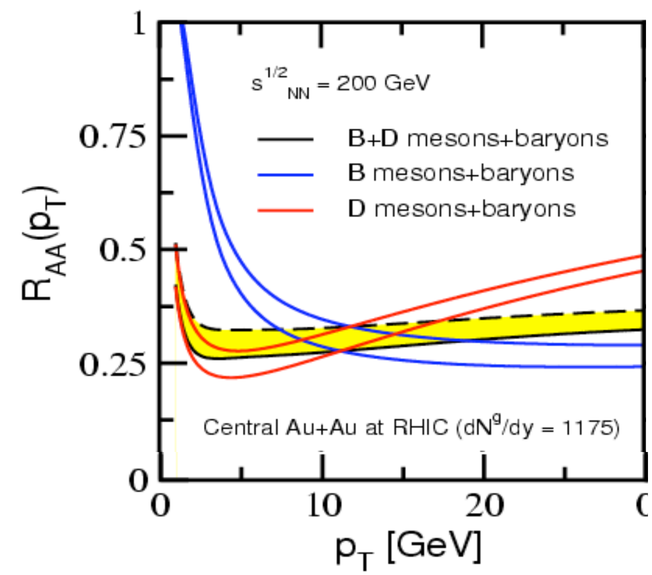
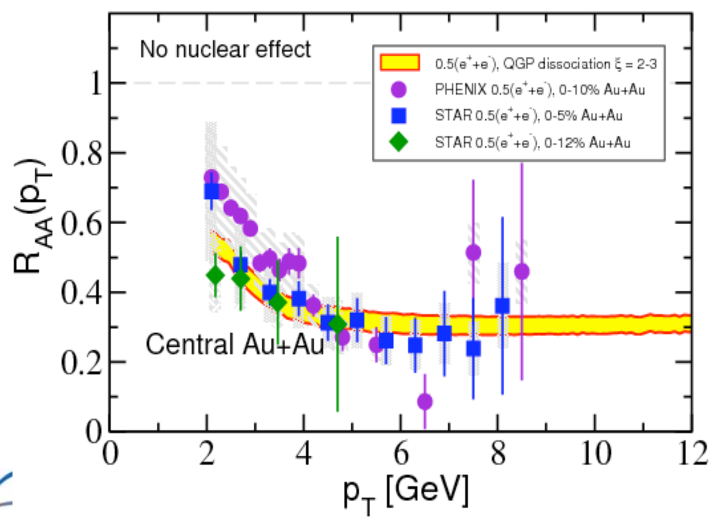




- Direct and separate measurements of D- and B-meson R_{AA}

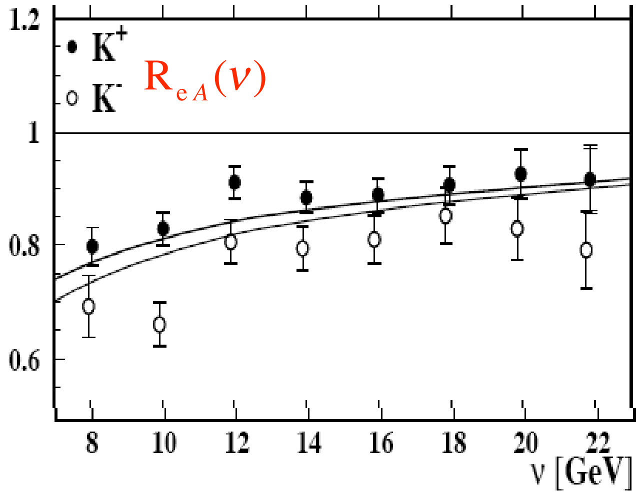
Model	Partonic Energy Loss	Heavy Meson Dissociation	Heavy Baryon Enhancement
Characteristic Feature	$R^{B}_{AA} \gg R^{D}_{AA}$ $R^{e^{\pm}}_{AA} > R^{\pi,h}_{AA}$	$R^{B}_{AA} \simeq R^{D}_{AA}$ $R^{e^{\pm}}_{AA} \simeq R^{\pi,h}_{AA}$	$R^{B}_{AA} \gg R^{D}_{AA}$ $R^{e^{\pm}}_{AA} \simeq R^{\pi,h}_{AA}$

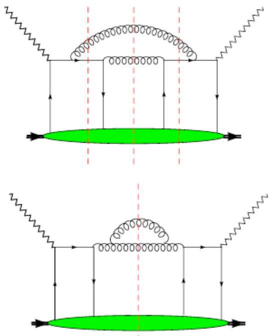
- Via experimental upgrades at RHIC, LHC

Coupling the Quark and Gluon Energy Loss

Jet quenching in SDIS - cold nuclei

- Can quarks and gluons become indistinguishable?
- Leading antiquark fragmentation is more suppressed than leading quark fragmentation





$\phi_q(x) > (\gg) \phi_{\bar{q}}(x)$

Zhang, B.W. et al. (2007)

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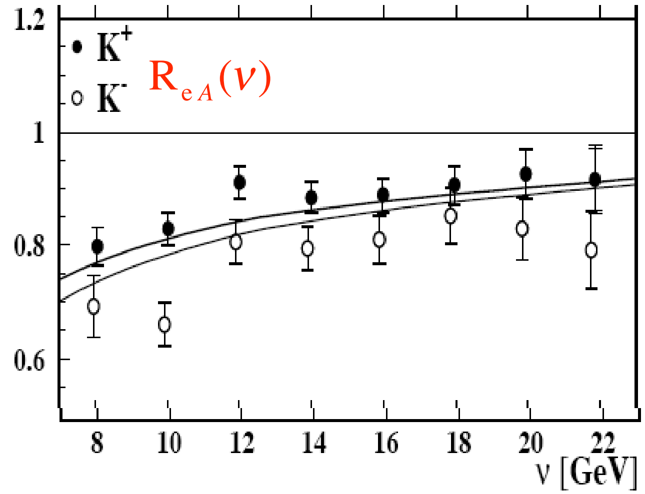
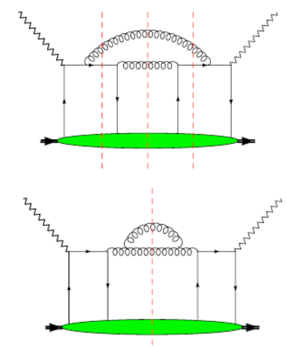




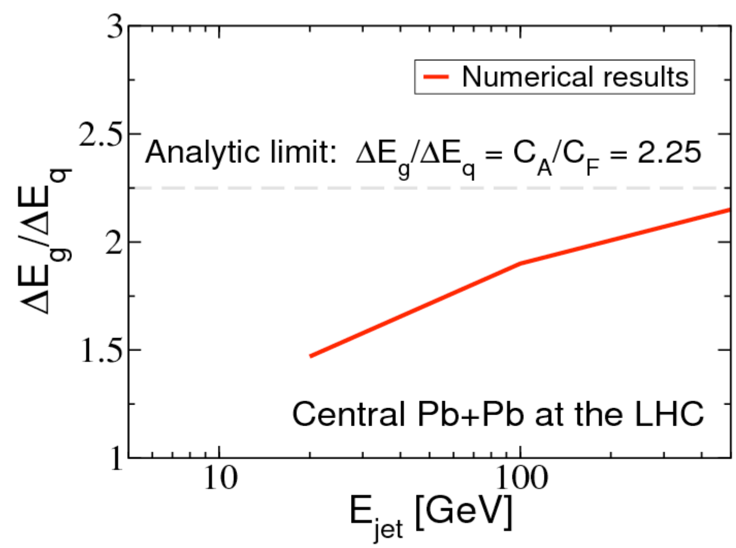
$\phi_q(x) > (\gg) \phi_{\bar{q}}(x)$

Zhang, B.W. et al. (2007)

QGP application of jet conversion

- Indirect indication that $\Delta E^g \neq 2.25 \Delta E^q$
- Non-asymptotic limits bring the q, g losses closer together
- Jet conversion may play a role but significant rate enhancement is needed

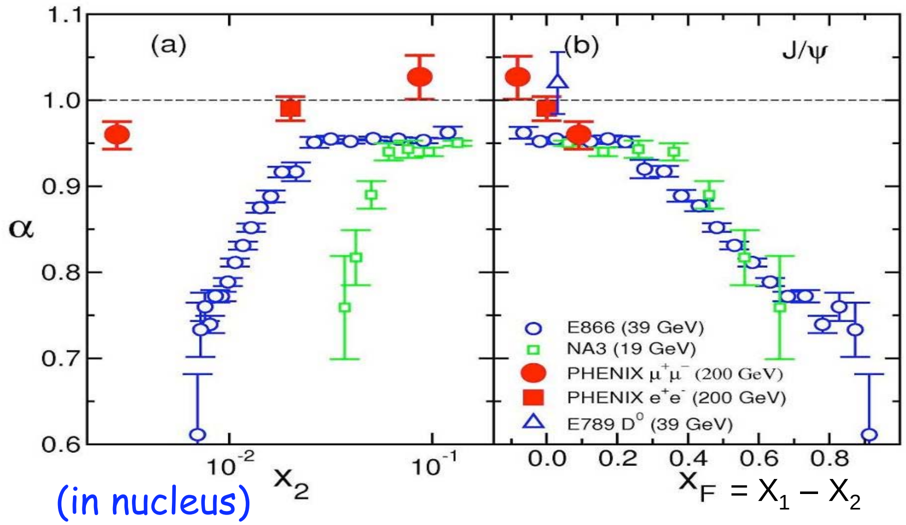
Liu, W. et al. (2007)



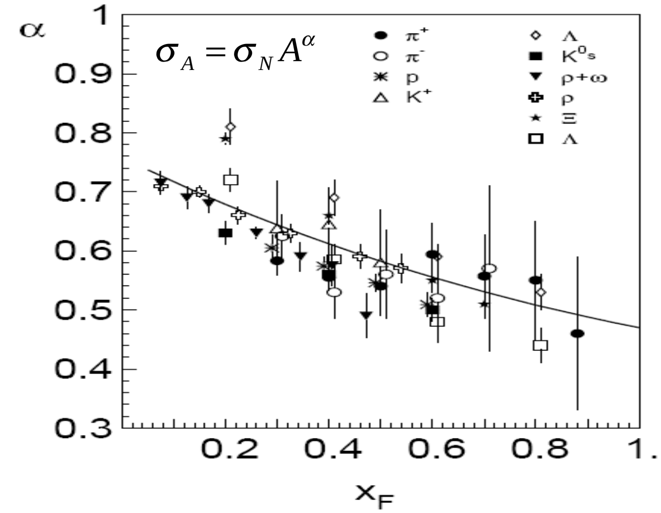
Gyulassy, M. et al. (2002)

Theory of Cold Nuclear Matter Energy Loss

Scaling with x_F (x_1), not x_2, indicates initial state energy loss



Gavin, S. et al. (1992)



Kopeliovich, B. et al. (2005)

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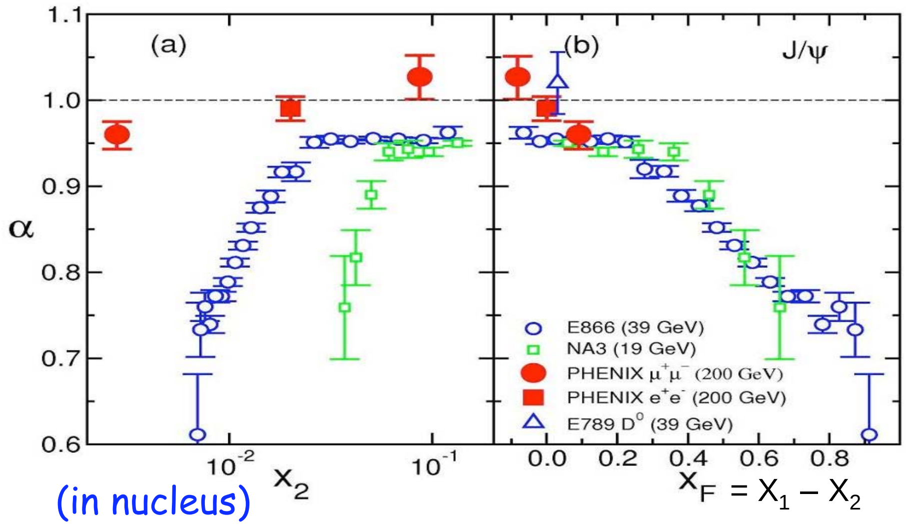

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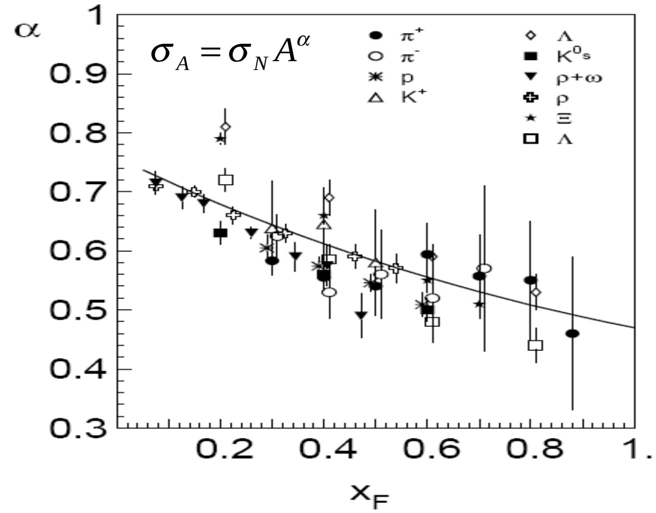
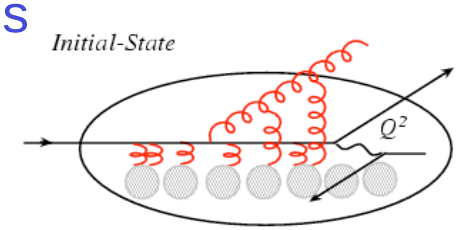


Kopeliovich, B. et al. (2005)

Advances in understanding the energy loss regimes



- Derivation of the Initial State energy loss

$$\frac{\Delta E^{IS}}{E} = \left(\kappa_{LPM} \sim \frac{1}{5}\right)\frac{\Delta E^{BH}}{E} \propto \alpha_s \frac{L}{\lambda_g} \qquad \frac{\Delta E^{IS}{}_{quark}(Pb, Au)}{E} \approx 5\%$$

- Toward consistent phenomenology at forward rapidity / large X_F V., I. (2007)
  - Can be tested in DY at Fermilab's E906 and J-PARC

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A Note on Phenomenology

Particle correlations, combining quenching and hydro models, looking at the medium response

Developments Theory and Phenomenology

Wicks, S.	Jet energy loss in rarer harder collisions
Roy, P.	Quenching of light hadrons in the collisional energy loss scenario
Bass, S. A.	Comparison of energy loss schemes in 3D hydro
Cassaldery-Solana, J.	Energy dependence of the jet quenching parameter
Barnafoldi, G.G.	Where does the energy loss lose strength
B. Betz,	Mach cones in 3+1D ideal hydro
B. Mueller	Mach cones in pQGP
W. Horowitz	Falsifying AdS/CFT or pQCD
R. Mizukawa	Jet quenching and the soft ridge

See also posters

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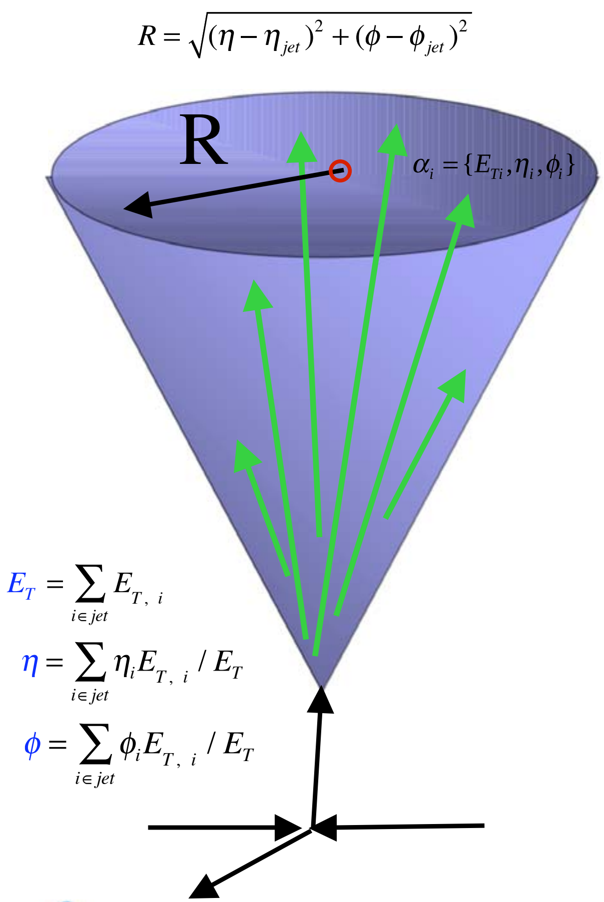
See also posters

- From very complex systems simplicity can emerge again
- For hard probes: transition 1, 2, …n particles $\longrightarrow$ jets

Jets: New Opportunities at the LHC

• Jets are collimated showers of energetic particles that carry a large fraction of the energy available in the collisions



Sterman, G. et al. (1977)

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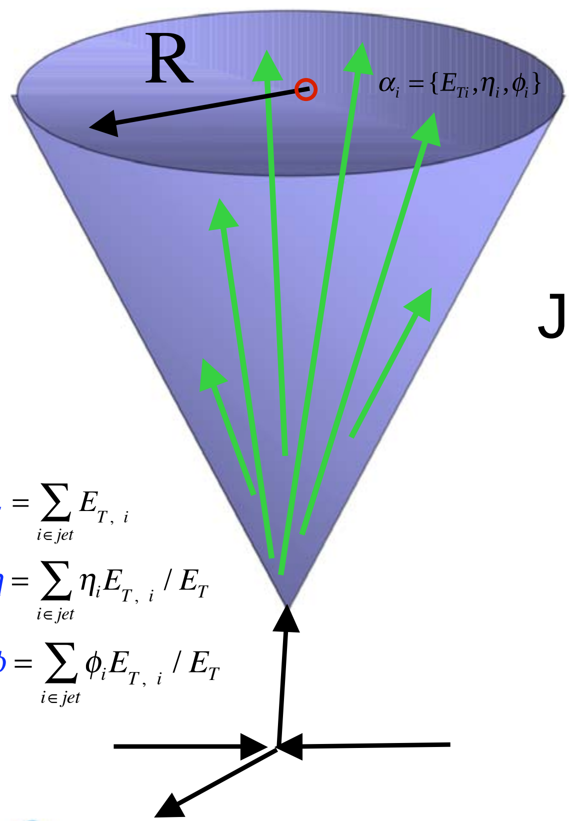
$$R=\sqrt{(\eta-\eta_{jet})^2+(\phi-\phi_{jet})^2}$$



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

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

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

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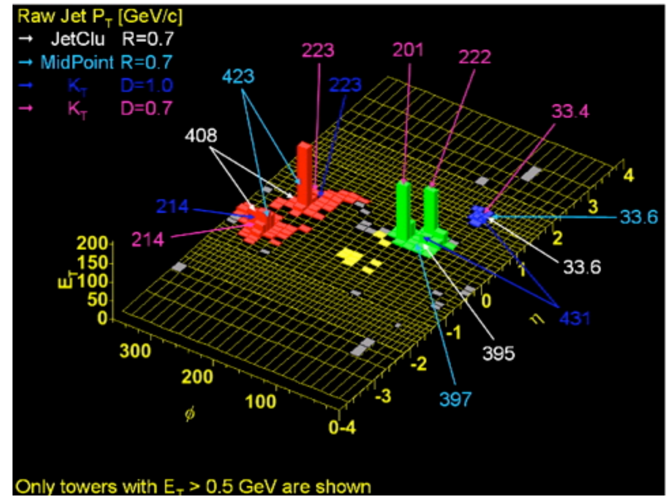

Jet algorithms:

- K_T algorithm: preferred, collinear and infrared safe to all orders in PQCD
- "Seedless" cone algorithm: practically infrared safe

Ellis, S.D. et al. (1993) Salam, G. et al. (2007)

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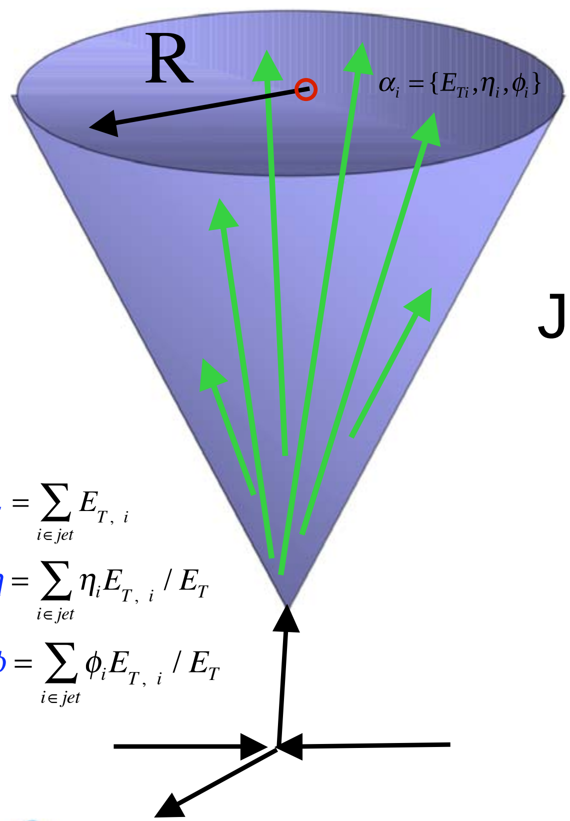


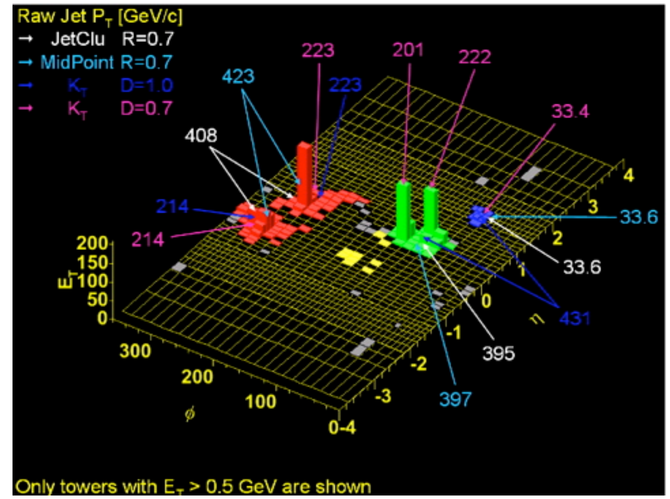
$\alpha_i = \{E_{Ti}, \eta_i, \phi_i\}$

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

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

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

Sterman, G. et al. (1977)



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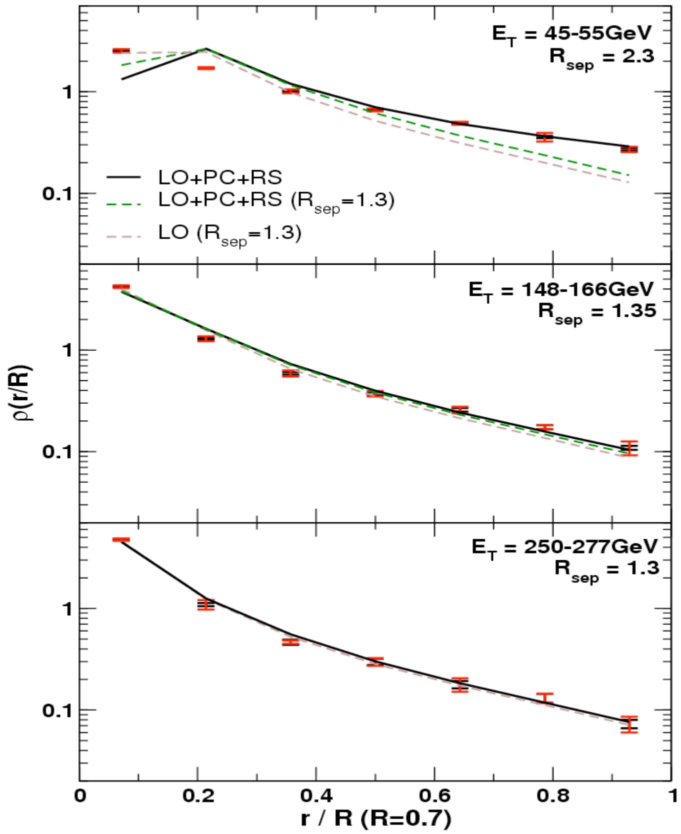
Ellis, S.D. et al. (1993)   Salam, G. et al. (2007)

- Opportunity exists to discover and characterize jets in heavy ion collisions

In p+p - STAR   Abelev, B. I. et al. (2006)

Energy Flow in Jets from PQCD: the Baseline

- Energy distribution $\Psi(r,R) = \frac{\sum_i E_{Ti}\Theta(r - R_{ijet})}{\sum_i E_{Ti}\Theta(R - R_{ijet})}$
- Shape function $\psi(r,R) = \frac{d\Psi(r,R)}{dr}$



An analytic approach to shape functions

$$dP_a = \frac{\alpha_s}{2\pi}\frac{d\rho^2}{\rho^2}\frac{d\phi}{2\pi}dzP_{a\to bc}(z)$$ Seymour, M. (1998)

MLLA, initial state contribution, power corrections, `R_{sep}' algorithm adjustment factor

V., I et al. (2008)

Perez-Ramos, R et al. (2007)

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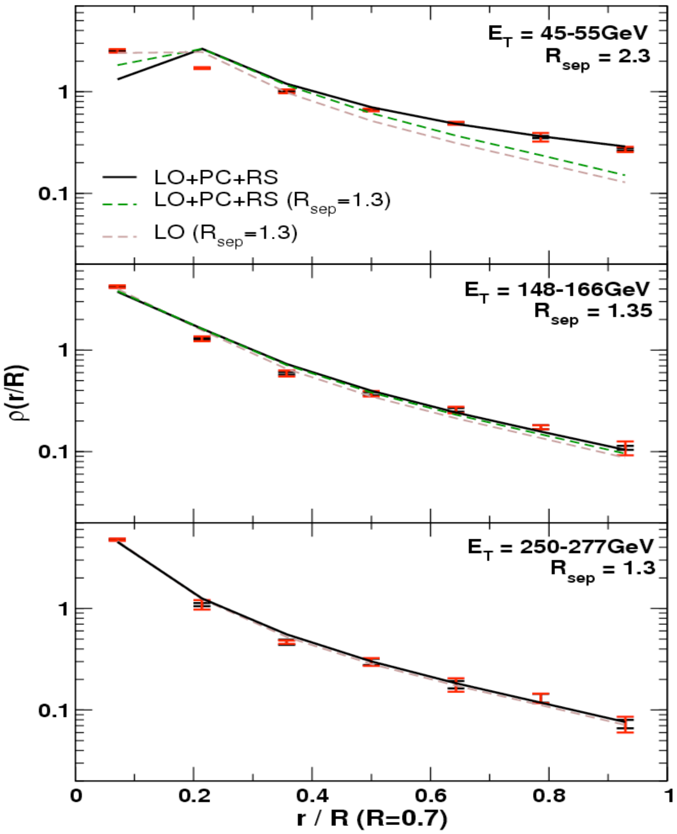

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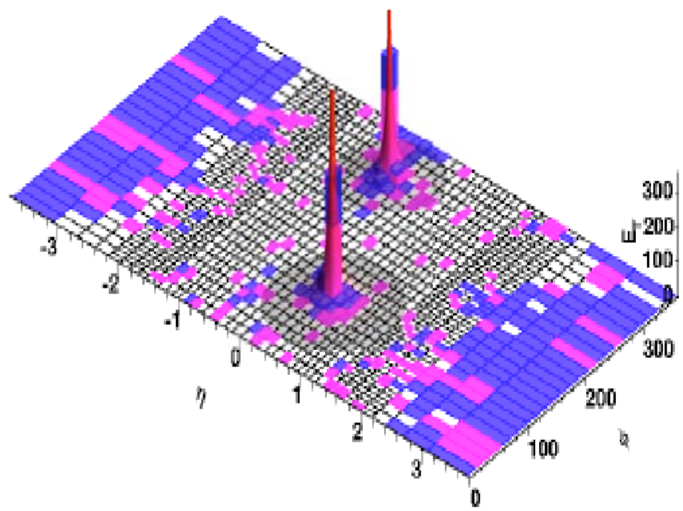
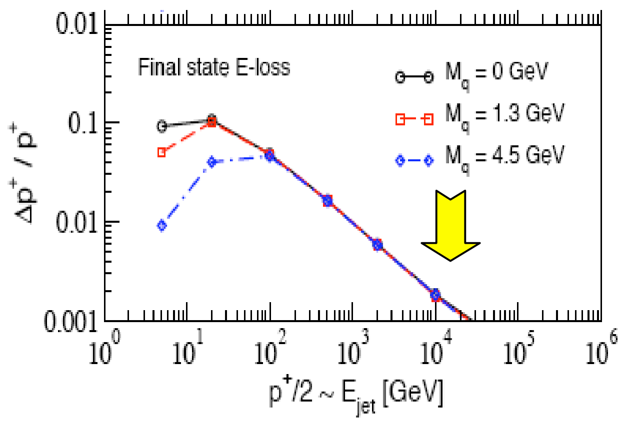


- Very similar jet shapes at the LHC

Medim-Induced Jet Shape Functions

An intuitive approach to medium-induced jet shapes for non-experts

ΔE^{rad} LPM suppressed



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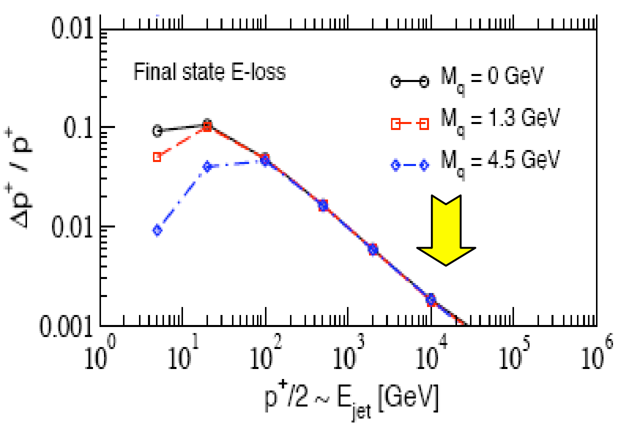

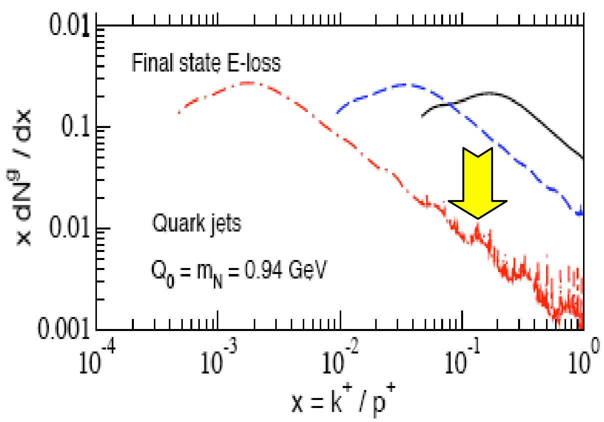

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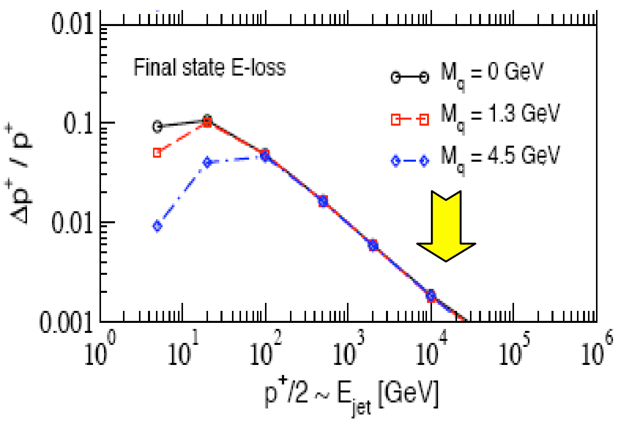
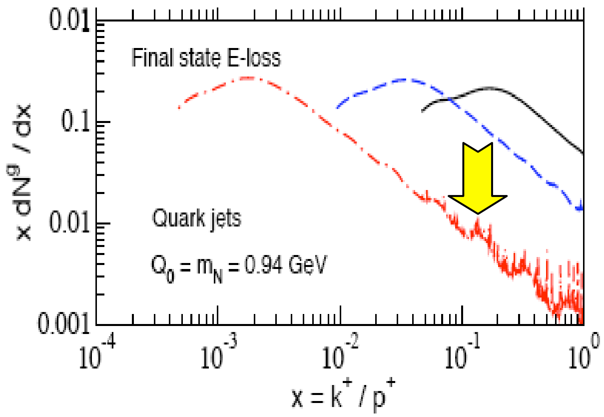
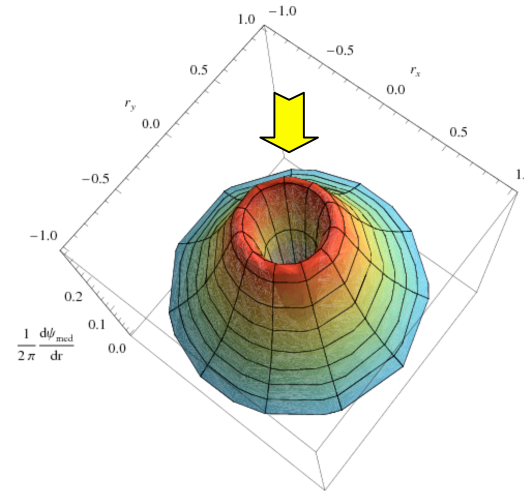
An intuitive approach to medium-induced jet shapes for non-experts

ΔE^{rad} LPM suppressed $\leftarrow$ $\frac{dI^{rad}}{d\omega}(\omega)$ suppressed $\leftarrow$ $\int d\omega \frac{dI^{rad}}{d\omega dr}(r)$ suppressed





V., I. (2005)



E_{jet} = 20 GeV

Medim-Induced Jet Shape Functions

An intuitive approach to medium-induced jet shapes for non-experts

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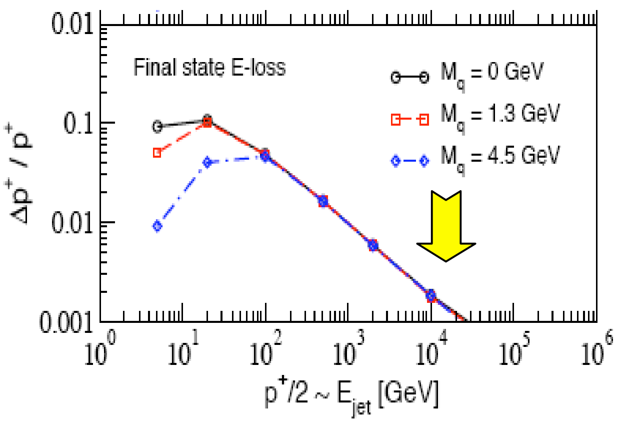
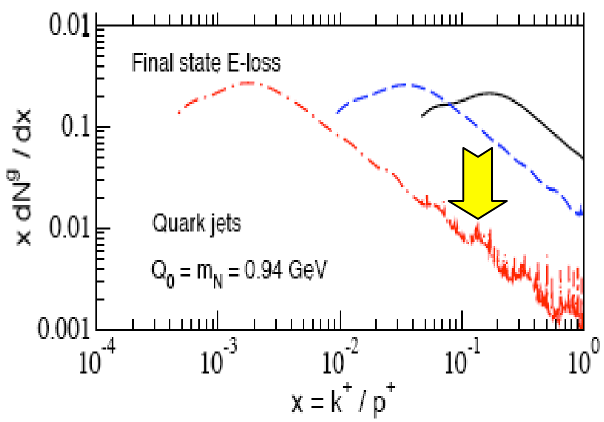
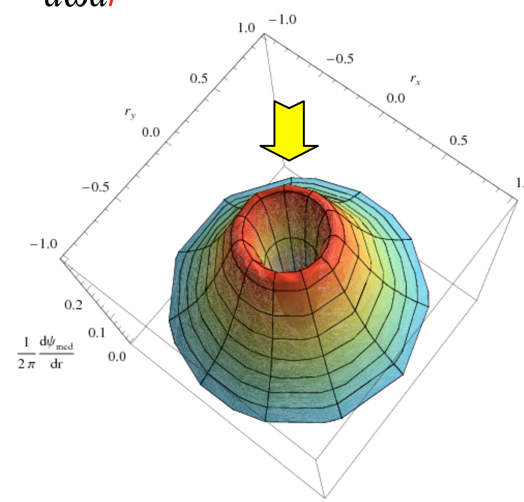






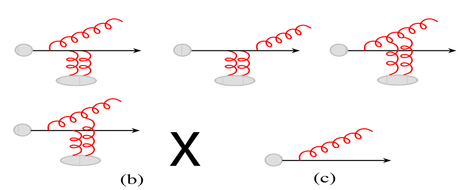
V., I. (2005)

E_{jet} = 20 GeV

- Proven now to all orders in opacity
- Incompatible with Sudakov resummation (absence of large logs)
- Can be see in other approaches to the energy loss

Majumder, A. et al. (2005)

Destructive interference



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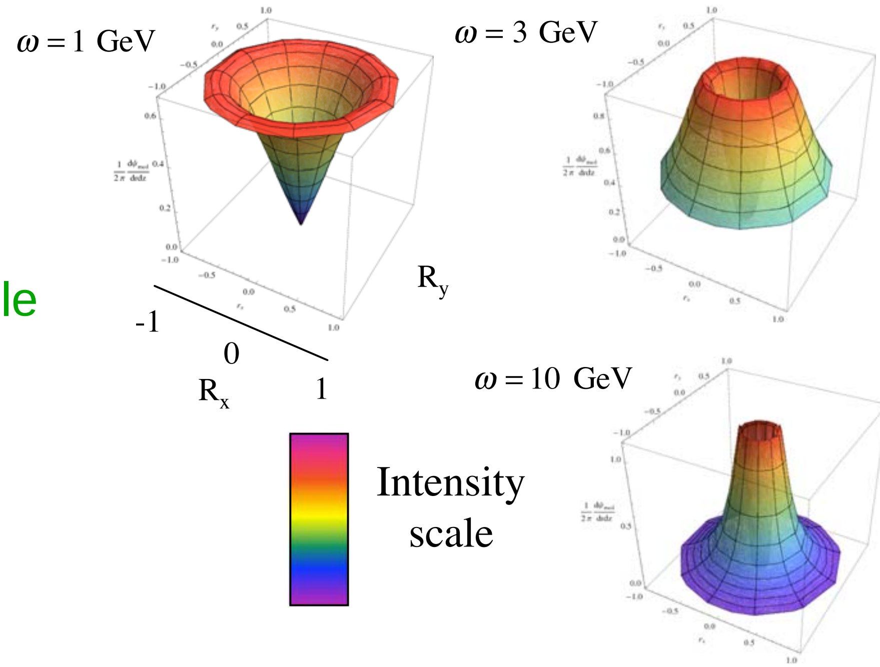
Ivan Vitev

A Differential Approach to Particle Correlations

2D analysis reveals rich structure

$$\frac{1}{2\pi}\frac{d\Psi^{med}}{drdz} = \frac{1}{\Delta E^{rad}}\frac{dI^{rad}}{d(\omega / E_{jet})dr}$$

- May be accessible via intra-jet particle correlations
- Medium-induced part only



A Differential Approach to Particle Correlations

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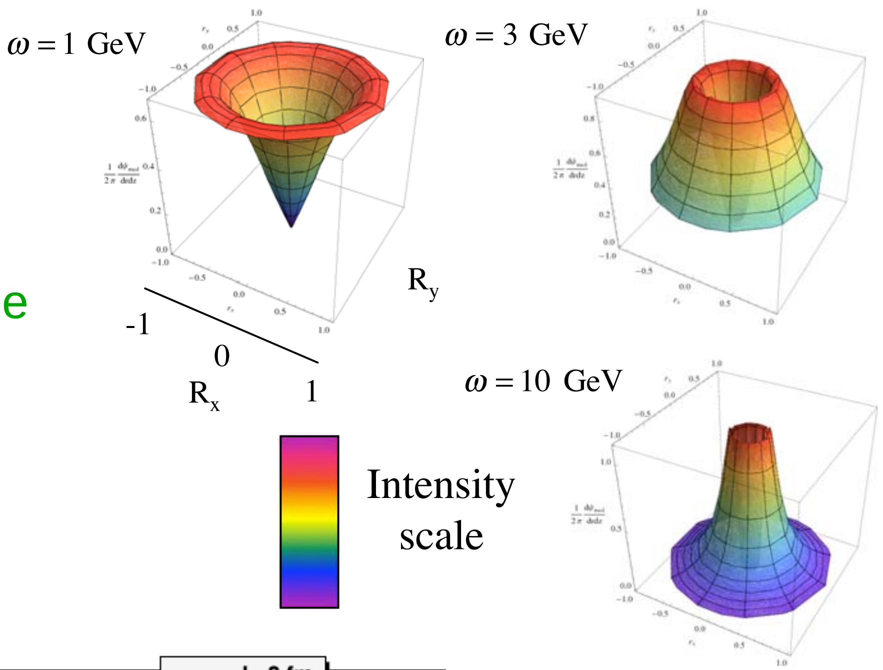
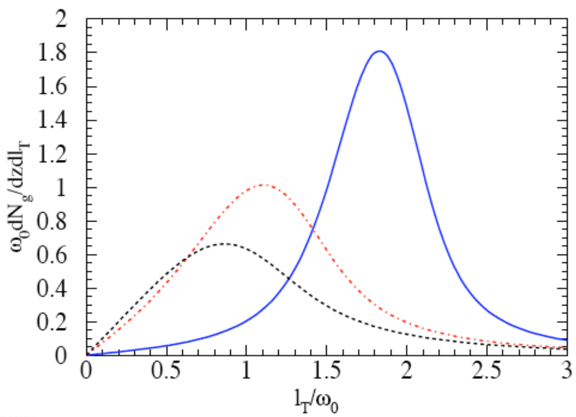
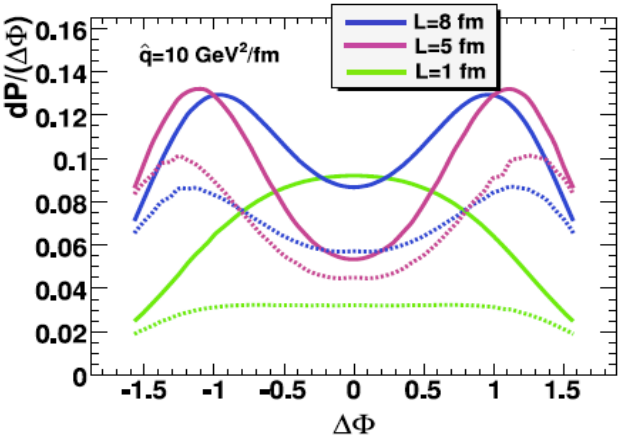


Relation to experimental correlation measurements remains speculative





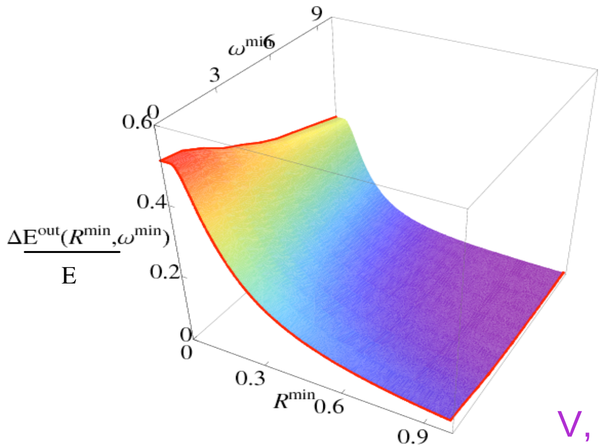
Majumder, A. et al (2005)

Polosa, A. et al (2006)

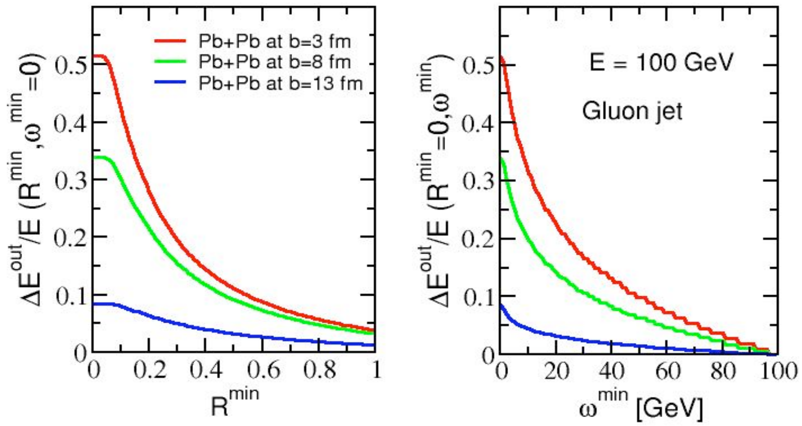
Tomography of Jets

Determination of energy flow

$$\frac{\Delta E^{out}(R^{min},\omega^{min})}{E} = \frac{1}{E}\int_{R^{min}} dr \int_{\omega^{min}} d\omega \; \frac{d\,I^{med}}{d\omega dr}(\omega,r)$$



V, I. et al. (2008)



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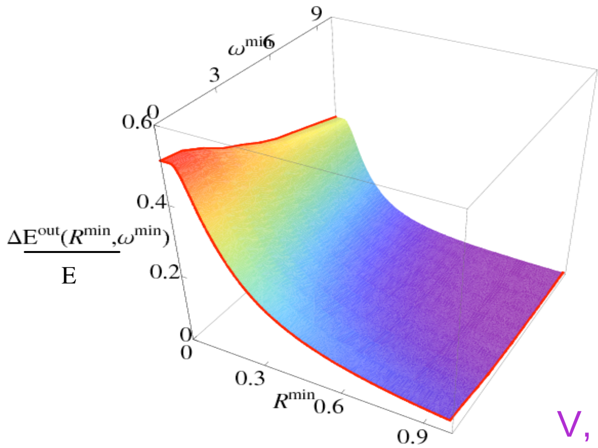
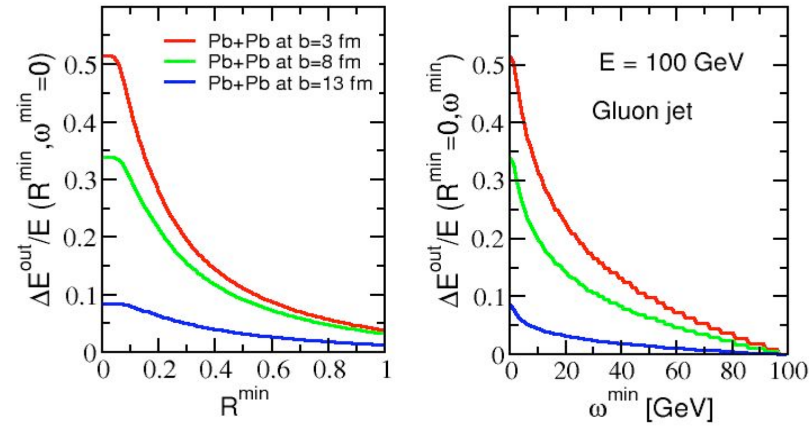


V, I. et al. (2008)

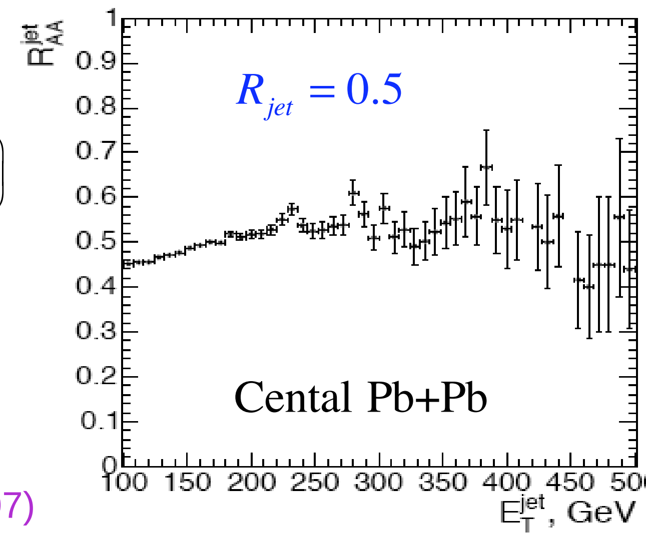


Application to jet cross sections $R_{AA}(R^{min},\omega^{min})$

$$\frac{d\sigma^{AA}(R\;,\omega^{min})}{d^2E_T dy} = \int_{\varepsilon=0}^{1} P(\varepsilon; R\;,\omega^{min}) \left(\frac{1}{(1-\varepsilon)^2} \frac{d\sigma^{pp}(R\;,\omega^{min})}{d^2E_T' dy} + \frac{1}{(\varepsilon\; f(R/\infty;\omega/\infty))^2} \frac{d\sigma^{pp}(R\;,\omega^{min})}{d^2E_T'' dy} \right)$$

- Can be evaluated in MC
- Extendable to tagged, e.g. di-lepton tagged jets

Mironov, C. et al. (2007)



Lokhtin, I. et al. (2007)

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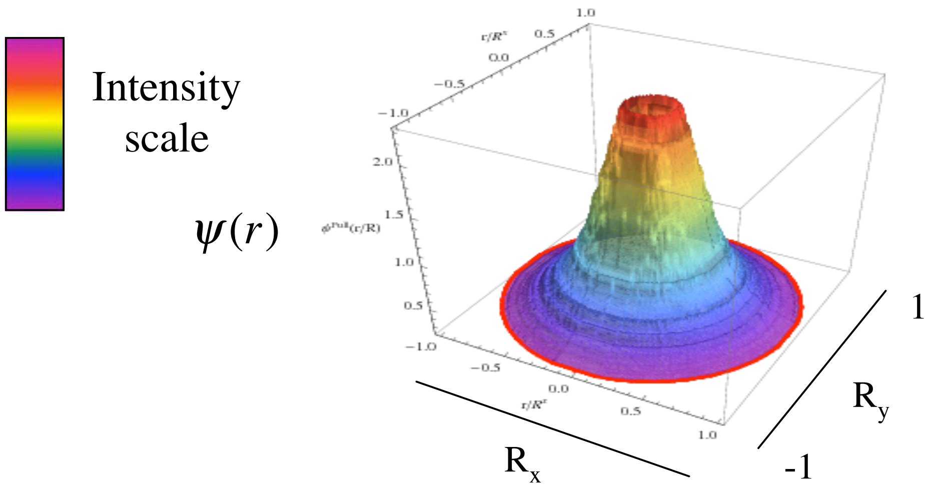
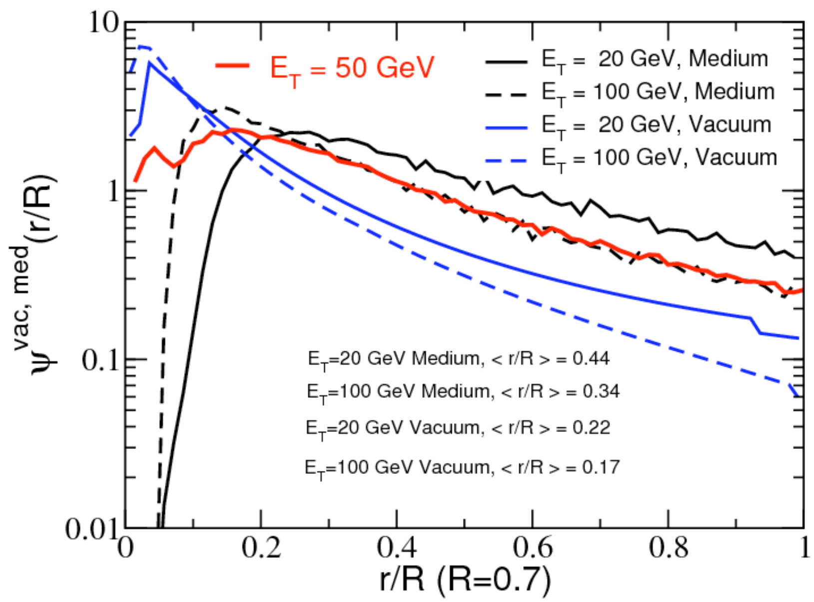
Outlook

Quantitative studies look promising





Outlook

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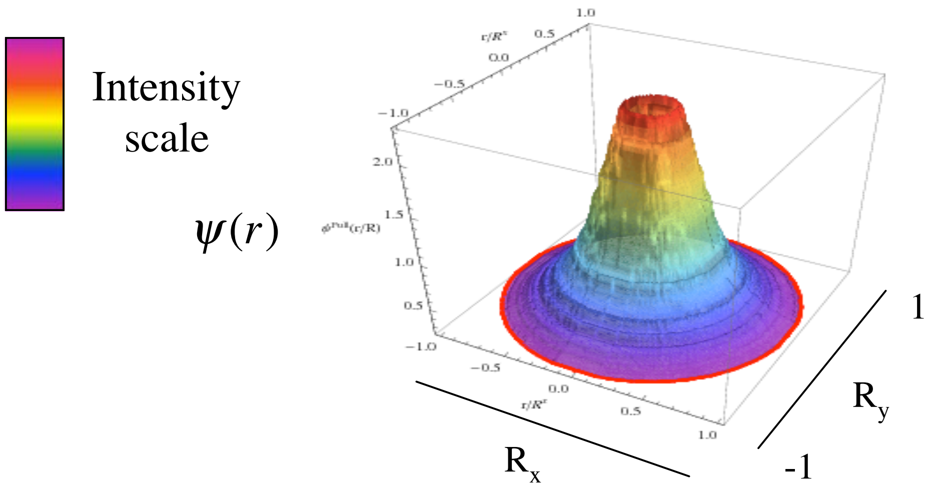
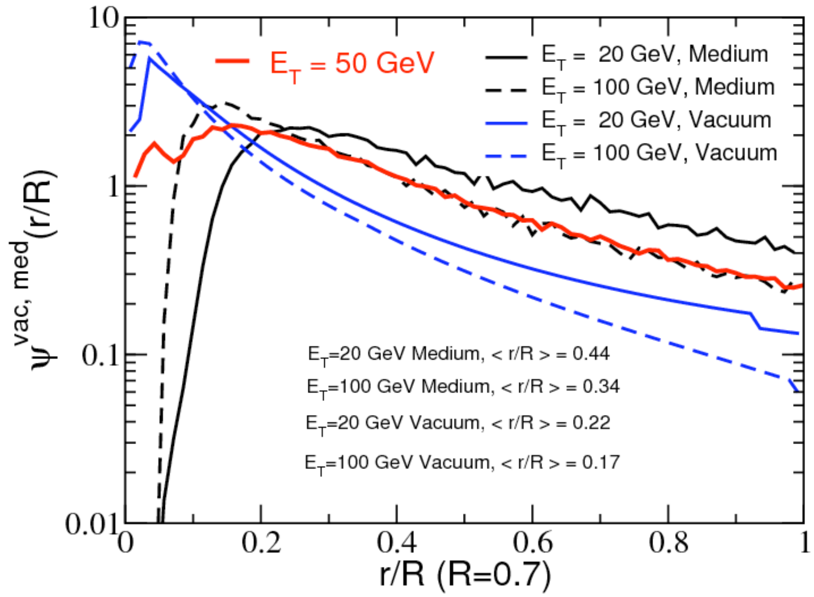




- Shape functions in the medium and their generalization to two dimensional tomography of jets can ultimately reveal the mechanism of particle interactions in matter
- Jet topologies with large number of jets and their modifications will become accessible at the LHC

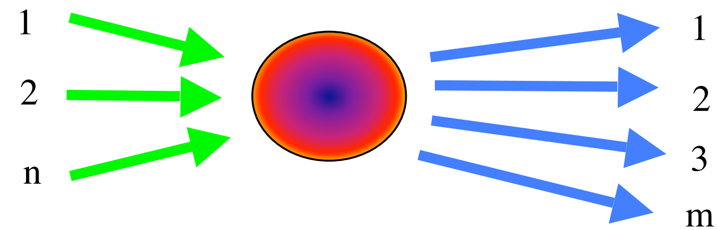
Conclusions

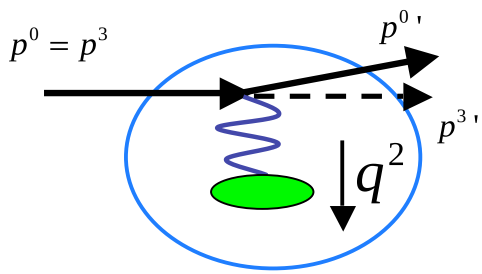
- First treatments of radiative and collisional energy loss of fast quarks and gluons in a consistent framework
- New models of heavy flavor suppression, both perturbative and non-perturbative; require experimental D, and B measurements
- Jet conversion processes in nuclear matter, understanding of SDIS, derivation of the initial state energy loss in large nuclei, valid forward rapidity phenomenology
- Developments of new jet finding algorithms for LHC experiments, seedless cone algorithm
- Determination of baseline jet shapes and jet topologies in p+p consistent with the Tevatron results
- Toward a 2D tomography *of* jets; understanding the medium induced jet shapes, energy corrections versus cone radius R, generalization of jet shape functions

Types of Energy Loss

Elastic interactions: $\sum_{1...n} particles\ \text{in} = \sum_{1...m} particles\ \text{out}$

Inelastic interaction: $\sum_{1...n} particles\ \text{in} < \sum_{1...m} particles\ \text{out}$



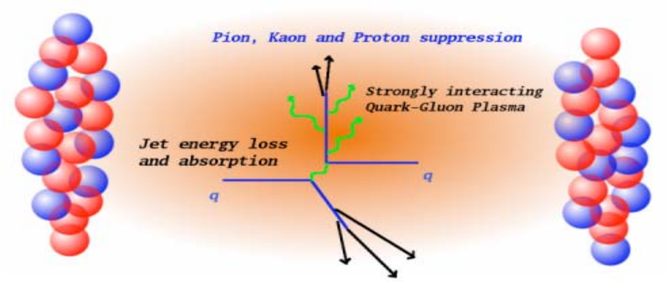


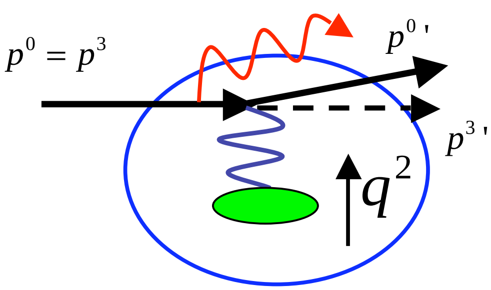
$$\frac{d\Delta E^{coll}}{dz} \approx 4\pi\alpha_{em}^2 z^2 Z \rho_{num} \frac{1}{\beta^2 m} \ln B_q$$

$$\Delta E^{coll} = c_1 L$$

Bethe, H.A. (1930,1932), Bloch, F. (1932)

- Collisional energy loss
  - medium excitation





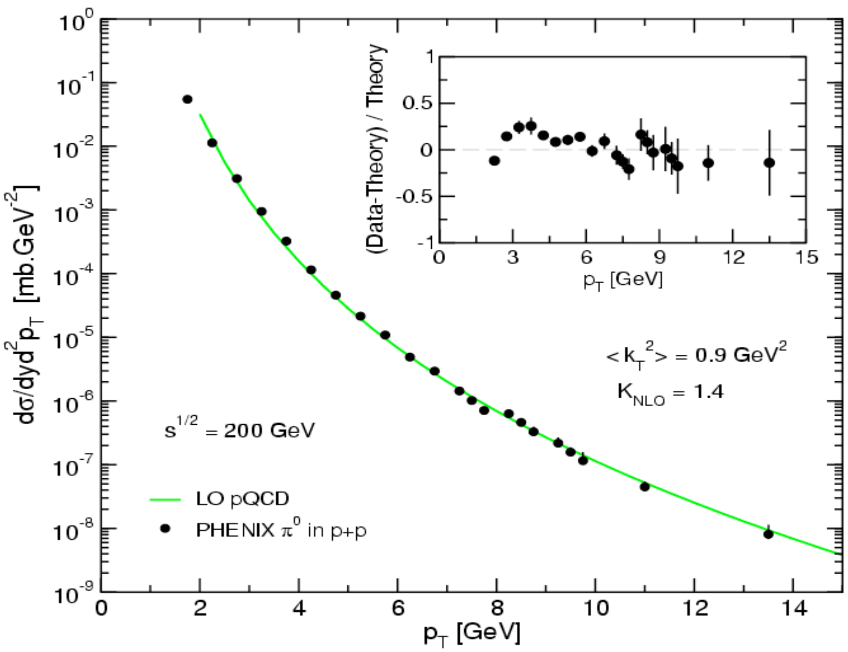
$$\frac{d\Delta E^{rad}}{dz} \approx \frac{16}{3} \alpha_{em}^3 z^4 Z^2 \rho_{num} \frac{1}{M^2} E \ln(\lambda\gamma)$$

$$\Delta E^{rad} = c_2 E L$$

- Radiative energy loss
  - gauge boson bremsstrahlung

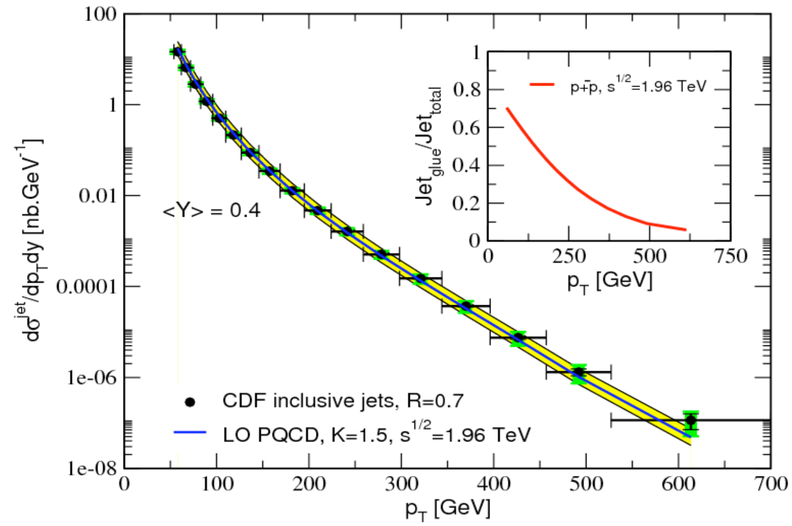
Bethe, H. A. et al. (1934) Weizsacker, C. et al. (1934)

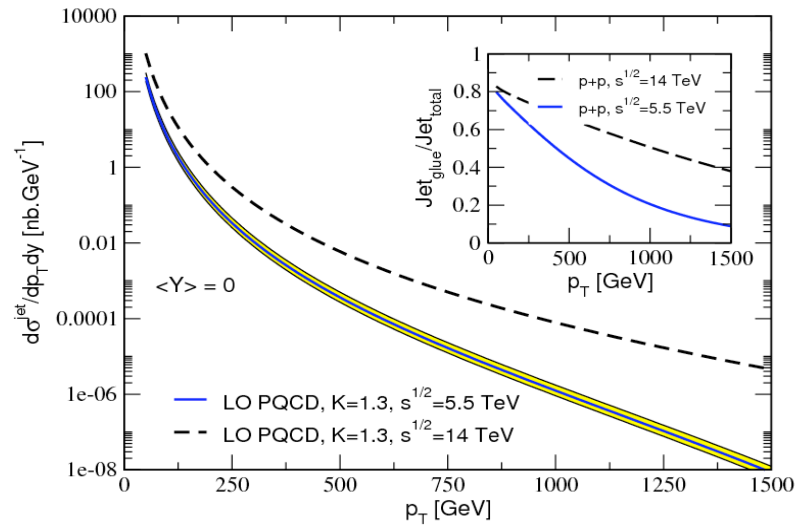
Jet Cross Sections: Comparison to LO and NLO PQCD



• Good comparison to the shape at LO. Meaningful K-factor

• Even better comparison at NLO.





Jet Shapes in QCD: the p-p Baseline

An analytic approach to the energy distribution of jet

Seymour, M. (1998)

QCD splitting kernel

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

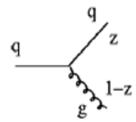
- Note: the Kinoshita, Lee, Nuenberg theorem does not guarantee collinear safety

Kinoshita, T (1962) Lee, T. D. et al. (1962)

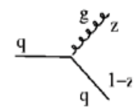
Requires Sudakov resummation

$$P_{Sudakov}(<r,R) = \exp(-P_1(>r,R))$$

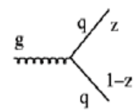
- The collinear divergence is essential



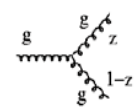
$$P^{(1)}_{qq}(x) = C_2(F)\left[(1+x^2)\left(\frac{1}{1-x}\right)_+ + \frac{3}{2}\delta(1-x)\right]$$



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



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



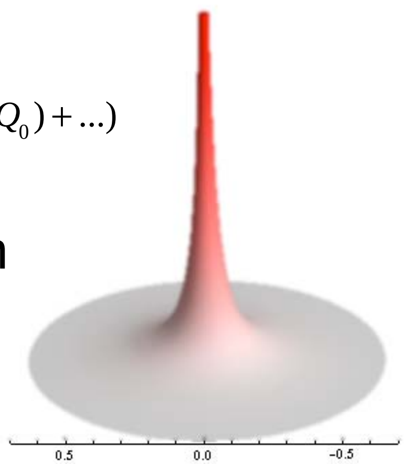
$$P^{(1)}_{gg}(x) = 2C_2(A)\left[\frac{x}{(1-x)_+} + \frac{1-x}{x} + x(1-x)\right] + \left(\frac{11}{6}C_2(A) - \frac{2}{3}T(F)\,n_f\right)\delta(1-x)\,,$$

Power corrections

$$\psi_{pow.}(r,R) \sim \frac{C_i}{2\pi}\frac{2}{r}\left(\frac{Q_0}{rE_T}\right)(\bar{\alpha}_s(Q_0)+\ldots)$$

Initial state radiation

$$\psi_{ini.}(r,R) \sim \frac{C\,\alpha_s}{2\pi}2r\left(\frac{1}{Z^2}-1\right)$$



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Ivan Vitev

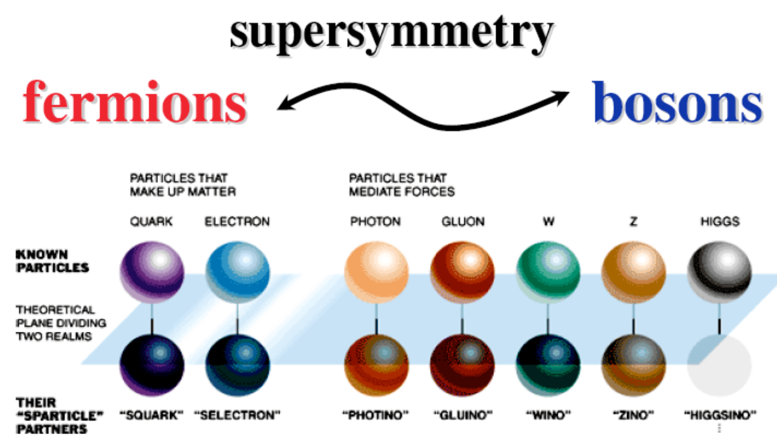
Jet Physics at the LHC

Searches SUSY

- Based on tried and true symmetry principles
- Unification of the coupling constants
- Excellent candidate for cold dark matter (neutralino 30 GeV - 10 TeV)

$$W = \sum_{L,E^c} \lambda_L L E^c H_1 + \sum_{Q,U^c} \lambda_Q Q U^c H_2 + \sum_{Q,D^c} \lambda_Q Q D^c H_1 + \mu H_1 H_2$$

Wess, J. et al. (1974) Georgi, H. et al. (1981)



Photino, Zino and Neutral Higgsino: Neutralinos

Charged Wino, charged Higgsino: Charginos

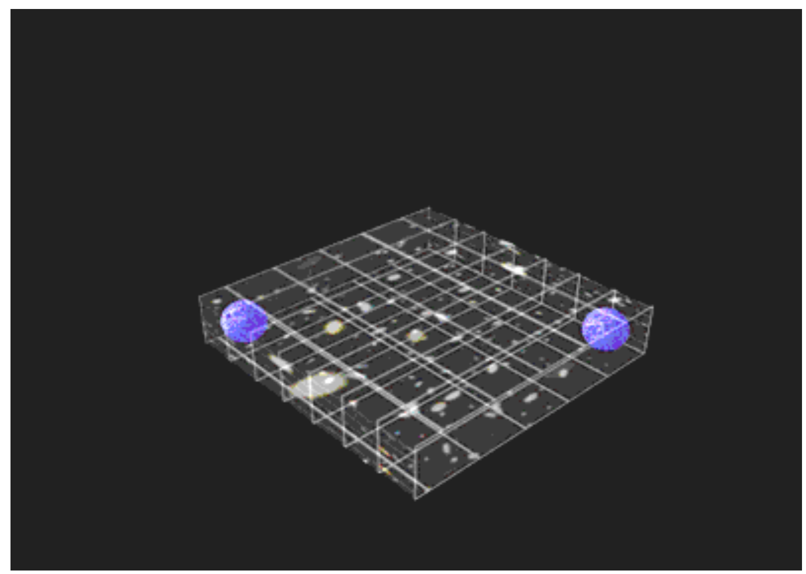
Searches for higher dimensions

- Generalization to 5D E&M+Gravity
- Numerous extensions

$$ds^2 = (e^{-2ky})\eta_{\mu\eta} x^\mu x^\nu - dy^2 \qquad m_n = n / R \ (S^1)$$

Kaluza, T. (1921) Klein, O. (1926)
Overdui, J. M. et al. (1999)

- Connecting HEP and NP



Searching for Extra Diemnsions and SUSY

Observation at colliders
LHC

MSSM

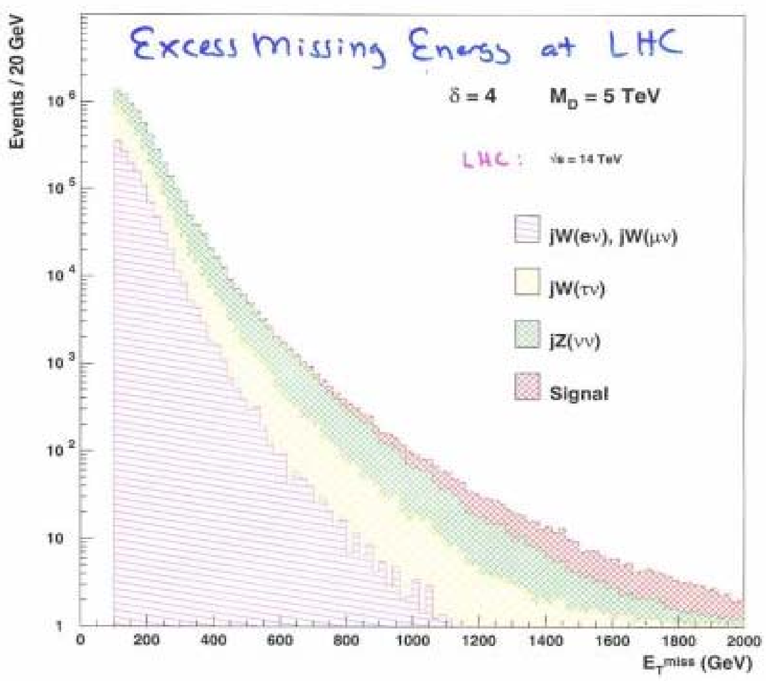
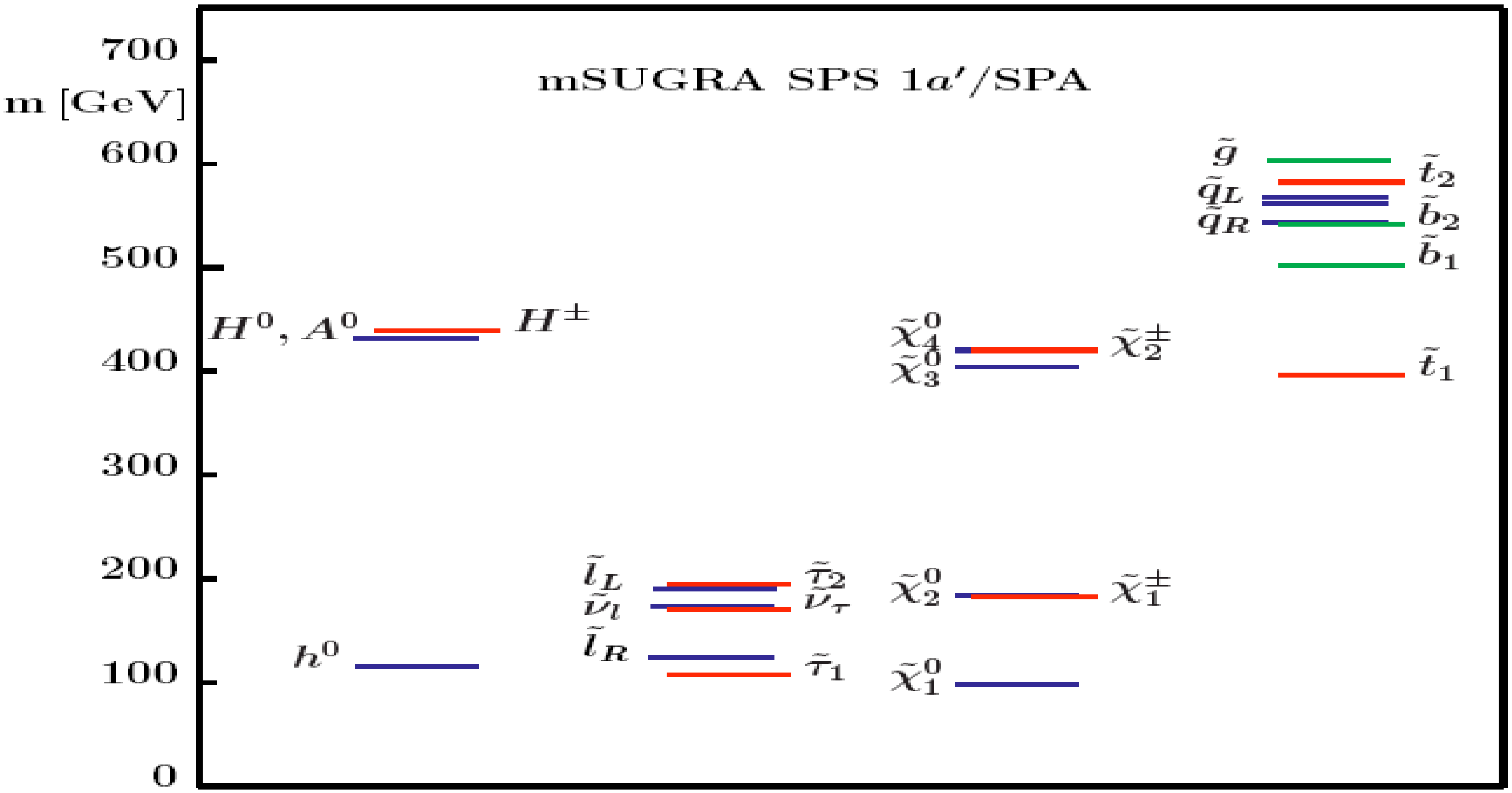


Figure 1: Missing energy spectrum at the LHC.

Field Content of the MSSM					
Super-Multiplets	Boson Fields	Fermionic Partners	SU(3)	SU(2)	U(1)
gluon/gluino	g	$\widetilde{g}$	8	0	0
gauge/	$W^{\pm}, W^0$	$\widetilde{W}^{\pm}, \widetilde{W}^0$	1	3	0
gaugino	B	$\widetilde{B}$	1	1	0
slepton/	$(\widetilde{\nu}, \widetilde{e}^-)_L$	$(\nu, e^-)_L$	1	2	-1
lepton	$\widetilde{e}_R^-$	e_R^-	1	1	-2
squark/	$(\widetilde{u}_L, \widetilde{d}_L)$	$(u, d)_L$	3	2	1/3
quark	$\widetilde{u}_R$	u_R	3	1	4/3
	$\widetilde{d}_R$	d_R	3	1	$-2/3$
Higgs/	(H_d^0, H_d^-)	$(\widetilde{H}_d^0, \widetilde{H}_d^-)$	1	2	-1
higgsino	(H_u^+, H_u^0)	$(\widetilde{H}_u^+, \widetilde{H}_u^0)$	1	2	1

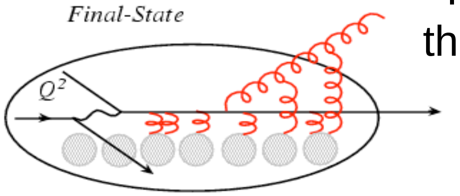
124 parameters (18 are the SM)

Mass Spectrum in Minimal Super Gravity



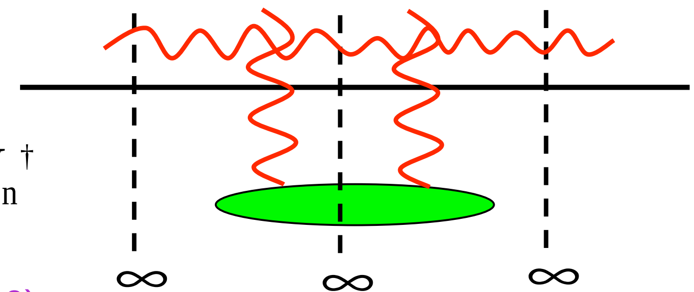
Example of 100 GeV SUSY particles

Medium-Induced Radiation in the Final State



- Includes interference with the radiation from hard scattering

$$-\frac{1}{2}\sigma_{el}\delta^2(q_\perp) \qquad \frac{d\sigma_{el}}{d^2q_\perp} \qquad -\frac{1}{2}\sigma_{el}\delta^2(q_\perp)$$



$$\hat{\mathrm{R}}_\mathrm{n} = \hat{\mathrm{D}}_\mathrm{n}{}^\dagger \hat{\mathrm{D}}_\mathrm{n} + \hat{\mathrm{V}}_\mathrm{n} + \hat{\mathrm{V}}_\mathrm{n}{}^\dagger$$

$$k^+ \frac{dN_g^n}{dk^+ d^2k_\perp} \propto Tr \sum_{i_1 \ldots i_n} \bar{A}^{i_1 \ldots i_n} A_{i_1 \ldots i_n}$$
$$= \bar{A}^{i_1 \ldots i_{n-1}} \left(D^\dagger D + V^\dagger + V \right) A_{i_1 \ldots i_{n-1}}$$
$$= \bar{A}^{i_1 \ldots i_{n-1}} \hat{R} \; A_{i_1 \ldots i_{n-1}}$$

Gyulassy, M. et al. (2000)

Number of scatterings **Momentum transfers**

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

Color current propagators **Coherence phases (LPM effect)**

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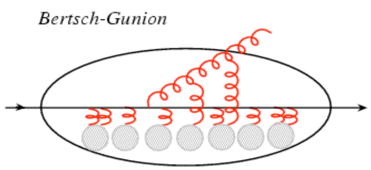
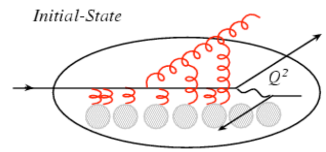
Ivan Vitev

Medium-Induced Radiation in the Initial State



Asymptotic

$t = -\infty, \;\; t = +\infty$



Asymptotic

$t = -\infty$

Large Q^2

$t = z_L = L$

- **Bertsch-Gunion case with interference**

Vitev, I. (2007)

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

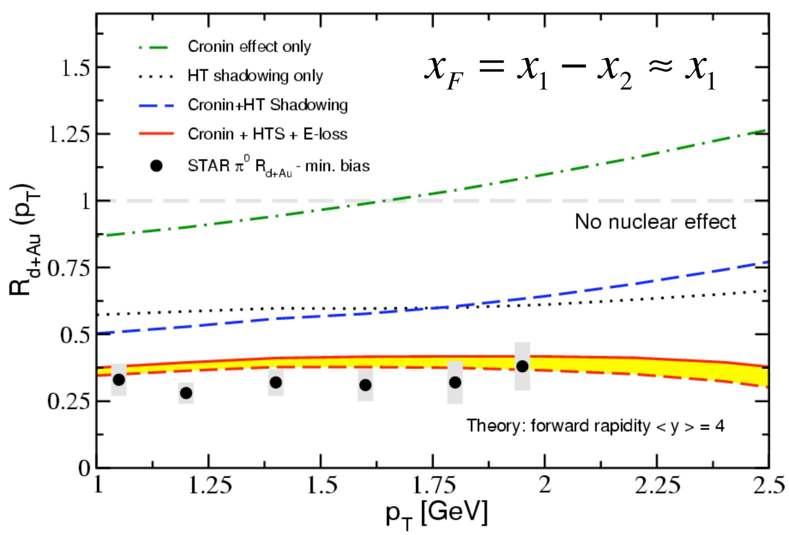
- **Realistic initial state medium induced radiation**

Vitev, I. (2007)

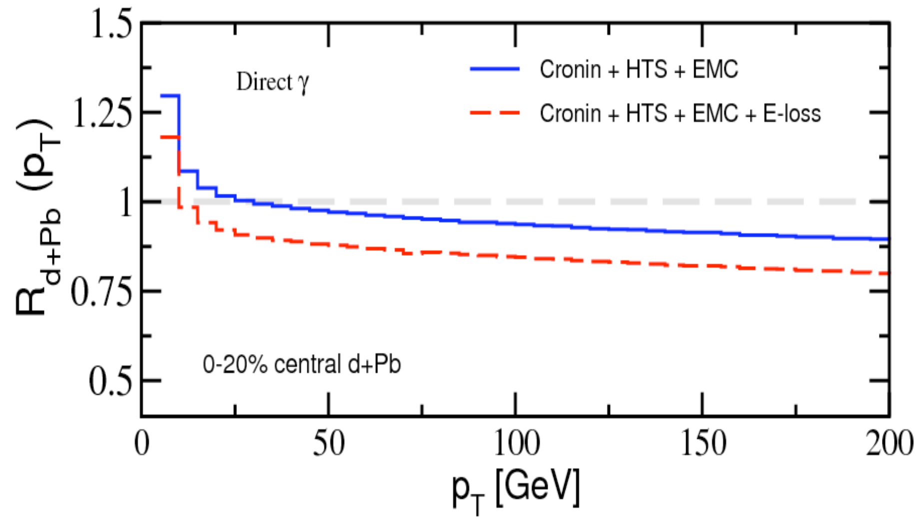
$$k^+ \frac{dN_g}{dk^+ d^2 k_\perp} = \sum_{n=1}^{\infty} k^+ \frac{dN^n{}_g}{dk^+ d^2 k_\perp} = \sum_{n=1}^{\infty} \frac{C_R \alpha_s}{\pi^2} \left[\prod_{i=1}^{n} \int_0^{L-\sum_{j=i+1}^{n} \Delta z_j} \frac{d\Delta z_i}{\lambda_g(z_i)} \int d^2 q_i \left(\frac{1}{\sigma_{el}} \frac{d\sigma_{el}}{d^2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

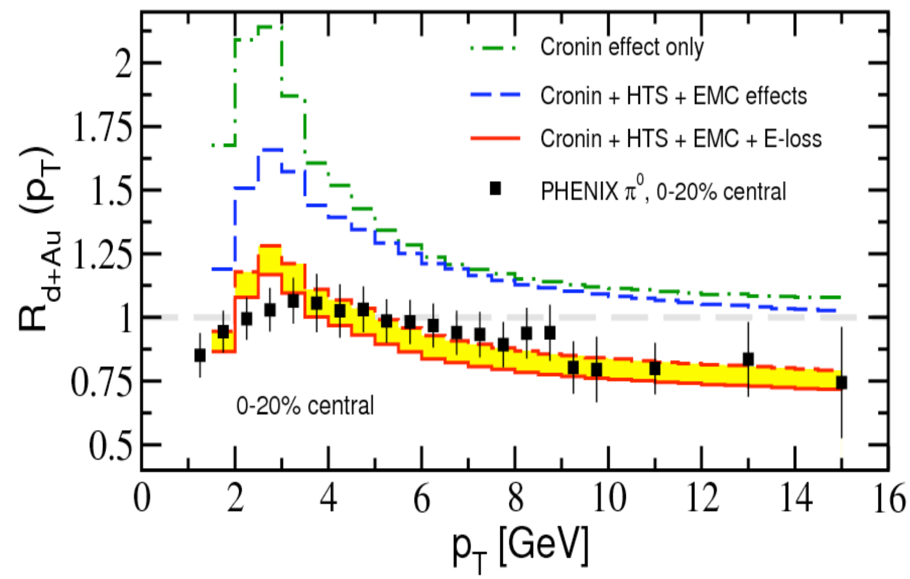
Cold Nuclear Matter Effects for π^0 and Direct γ

- Where it starts from



- Dynamical shadowing (coherent final state scattering)
- Cronin effect (initial state transverse momentum diffusion)
- Initial state energy loss (final state at these energies - negligible)

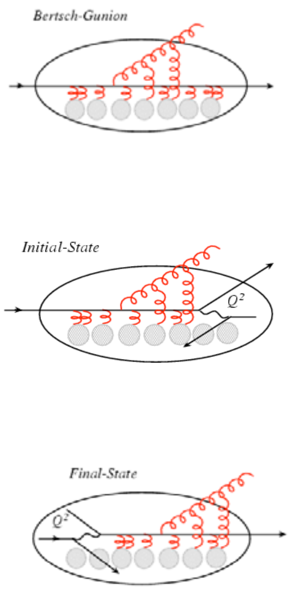


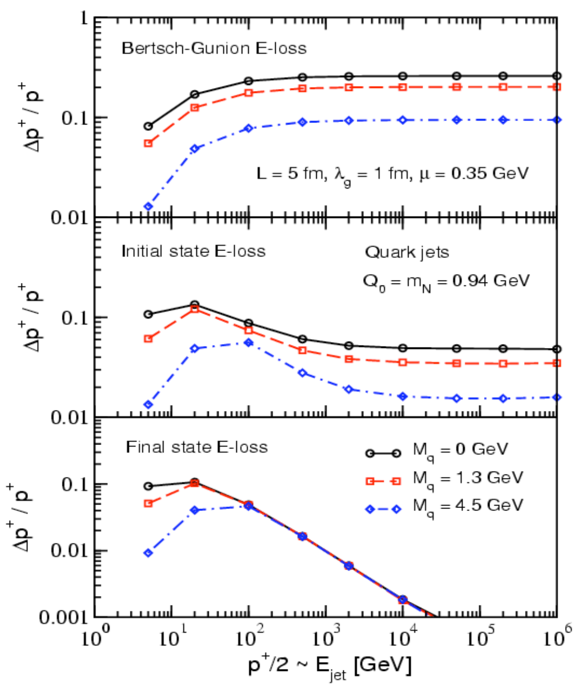


Cold Nuclear Matter Effects

- Initial-state E-loss

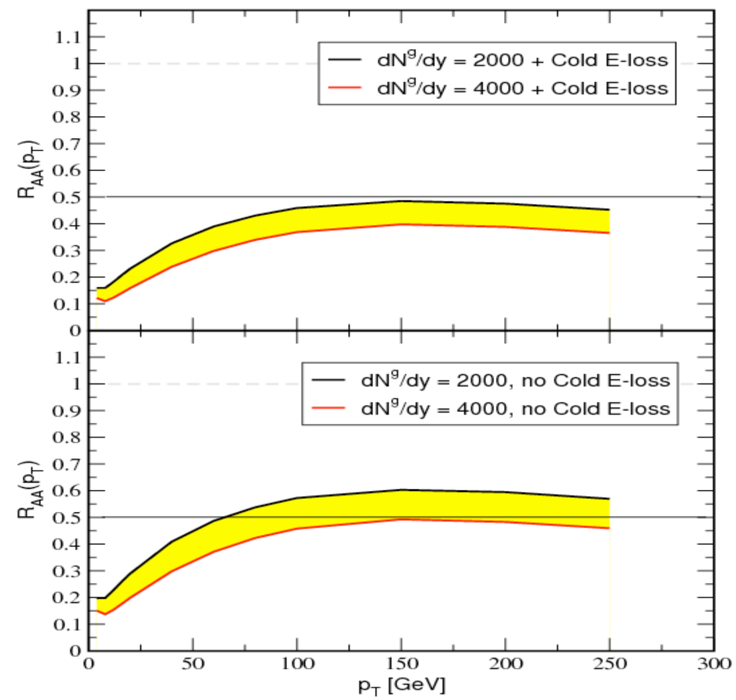
$$\frac{\omega dN^g}{d\omega d^2k_\perp} = \frac{C_R\alpha_s}{\pi^2}\int_0^{s/4} d^2q_\perp \frac{\mu_{eff}^2}{(q_\perp^2+\mu^2)^2}\left[\frac{L}{\lambda_g}\frac{q_\perp^2}{k_\perp^2(k_\perp-q_\perp)^2} - 2\frac{q_\perp^2 - 2k_\perp\cdot q_\perp}{k_\perp^2(k_\perp-q_\perp)^2}\frac{k^+}{k_\perp^2\lambda_g}\sin\frac{k_\perp^2 L}{k^+}\right]$$





Energy scale

$$E = p_T \cosh(y_{\text{jet}} - y_{\text{target}})$$



- Effect of cold nuclear matter energy loss is equal to the doubling of the parton rapidity density

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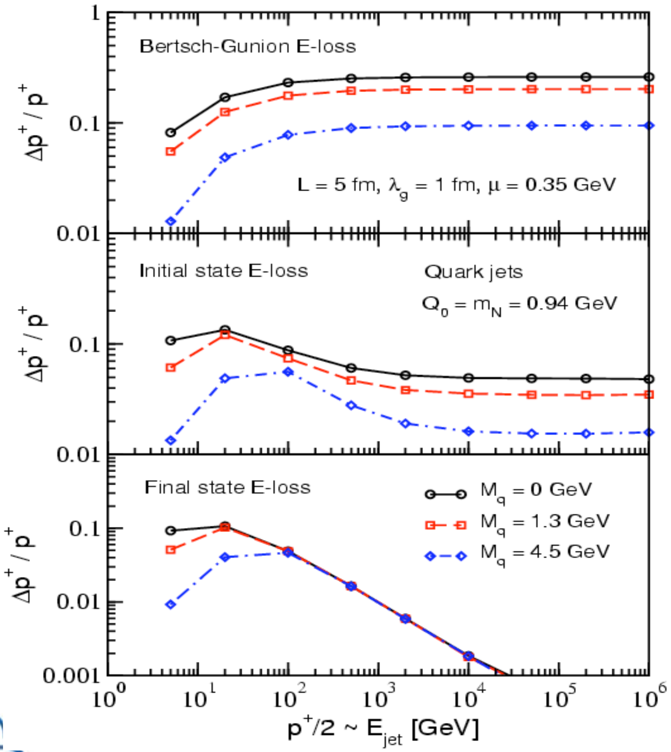
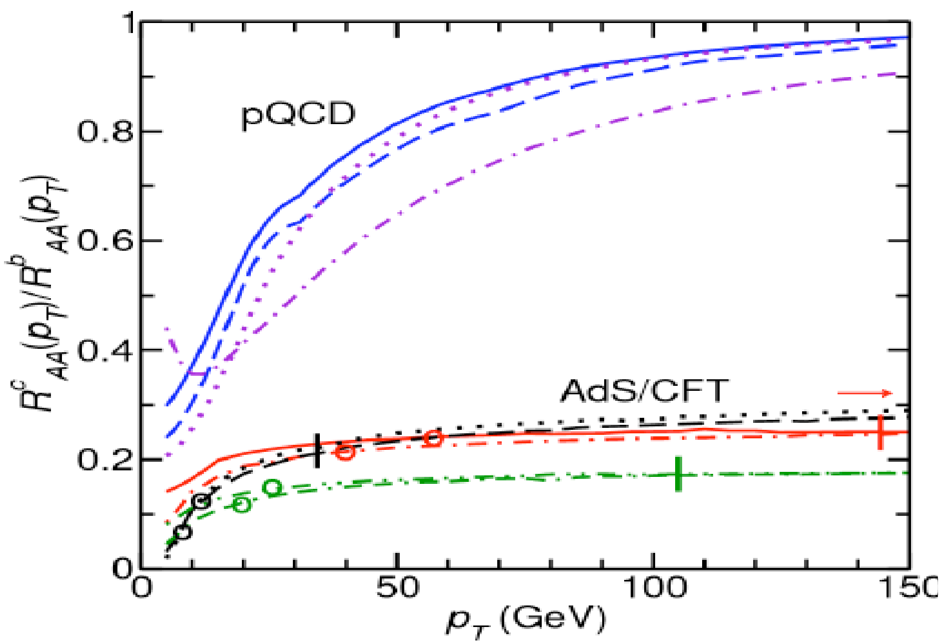
A Note on PQCD Regimes

- An interesting idea $\neq$ valid physics explanation
- We don't know the degree of coherence at the LHC. One has to understand PQCD and its E-loss regimes before embarking on the ambitious task of disproving PQCD itself



I.Vltev, (2007)

Measurable at the LHC



W.Horowitz, M. Gyulassy, (2007)

Light Cone Wave Functions

From general theory of LCWF for the lowest-lying Fock state

S.Brodsky, D.S.Hwang, B.Q.Ma, I.Schmidt, Nucl.Phys.B 592 (2001)

- Expansion in Fock components

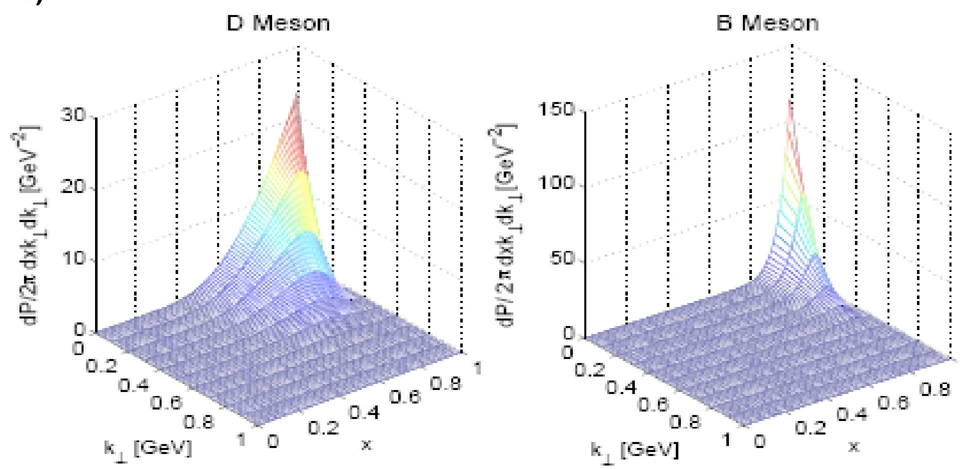
$$\left|\psi_M; P_\perp, P^+\right\rangle = \sum_{i=2}^{n} \int \frac{dx_i}{\sqrt{2x_i}} \frac{d^2 k_{\perp i}}{\sqrt{(2\pi)^3}} \psi_i(k_{\perp i}, x_i)$$

$$\times \delta\left(\sum_{i=2}^{n} x_i - 1\right) \delta\left(\sum_{i=2}^{n} k_{\perp i}\right) \left|i; k_{\perp i} + x_i P_\perp, x_i P^+\right\rangle$$

LO Fock component

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

- Results for heavy flavor



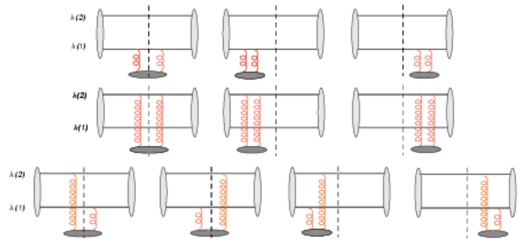
- Models such as coalescence should use plausible wave functions, especially for heavy flavor

Medium-Modified Heavy Meson

Initial distribution:

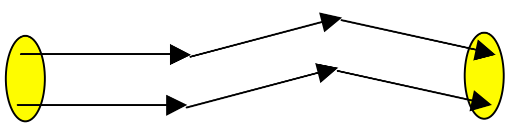
$$|\psi_i(\Delta k_\perp, x)|^2 = \left[\delta^2(K_\perp)\right] \times \left[\mathrm{Norm}^2 e^{-\frac{\Delta k_\perp^2}{4x(1-x)\Lambda^2}} e^{-\frac{m_1^2(1-x)+m_2^2 x}{x(1-x)\Lambda^2}} \right]$$

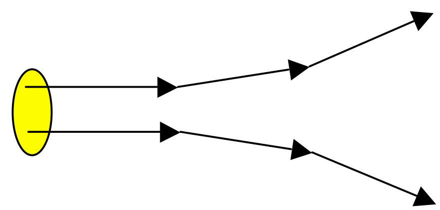
Resum using GLV the multiple scattering in impact parameter (B,b) space



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

- 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:

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

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