Tomography *of* Jets

Ivan Vitev, Nuclear Theory, T-16 , LANL

Work done with S. Wicks

Tata Institute of Fundamental Research

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Outline of the Talk

Motivation

- What I will not talk about - the inclusive particle R_{AA}
- Conceptual differences between E-loss formalisms
- The interface between particle and high energy nuclear physics

Jet shapes in elementary collisions

- Jet finding algorithms and jet shapes in elementary N-N collisions
- Fixed orders, Sudakov resummation, non-perturbative effects and initial state radiation

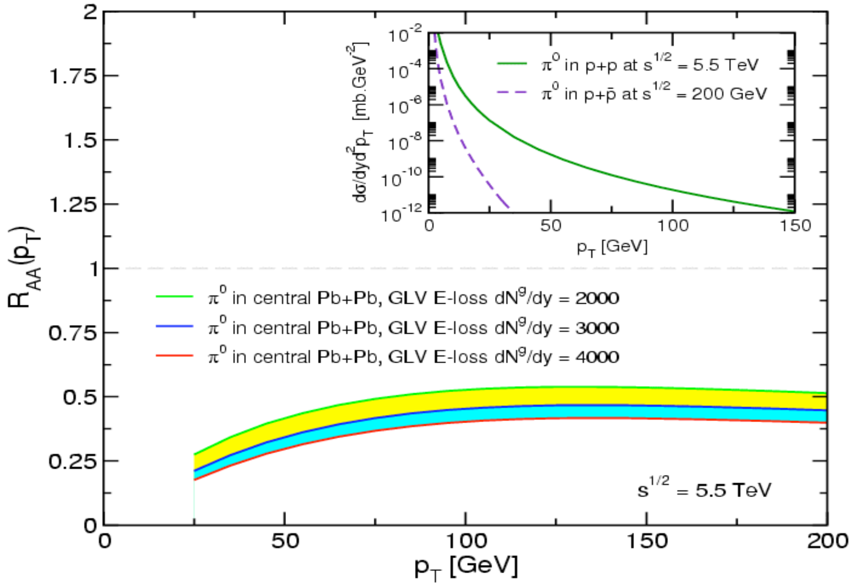
Jets in nuclear collisions

- Medium-induced jet shapes in QGP - a theoretical approach
- Toward a 2D tomography *of* jets - a differential test of parton interactions in the QGP

Conclusions

Not to be Discussed

Running α_s



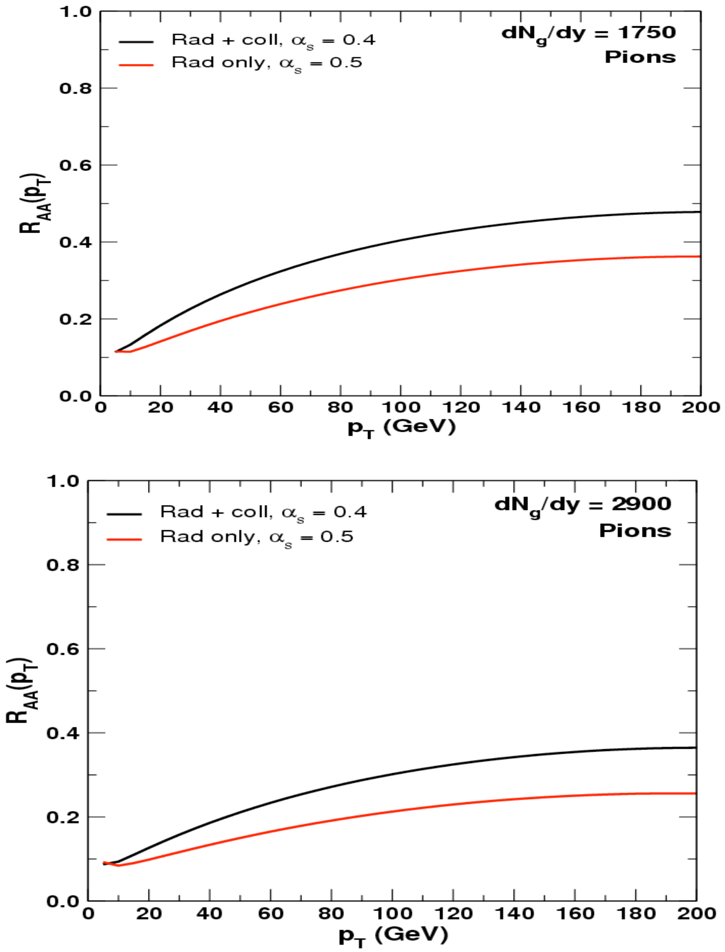
V., I. (2006)

- Possibly exclude some models or at least constrain the parameters in some of them
- For a summary of predictions, see

Armesto, N. (QM 2008)

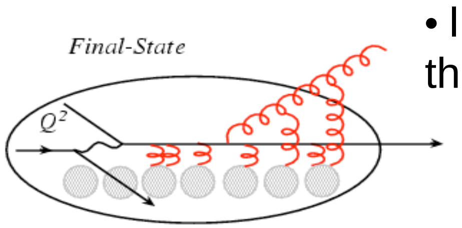
- The difference is NOT the geometry

Fixed α_s

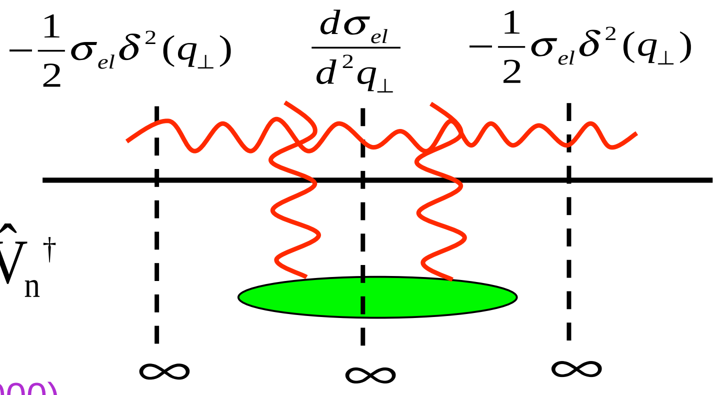


Wicks, S. et al. (2007)

Medium-Induced Radiation in the Final State



- Includes interference with the radiation from hard scattering



$$k^+\frac{dN_g^n}{dk^+d^2k_\perp} \propto Tr\sum_{i_1\ldots i_n}\bar{A}^{i_1\ldots i_n}A_{i_1\ldots i_n}$$

$$= \bar{A}^{i_1\ldots i_{n-1}}\left(D^\dagger D + V^\dagger + V\right)A_{i_1\ldots i_{n-1}}$$

$$= \bar{A}^{i_1\ldots i_{n-1}}\,\hat{R}\;A_{i_1\ldots i_{n-1}}$$

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

Gyulassy, M. et al. (2000)

Number of scatterings

Momentum transfers

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

Color current propagators

Coherence phases (LPM effect)

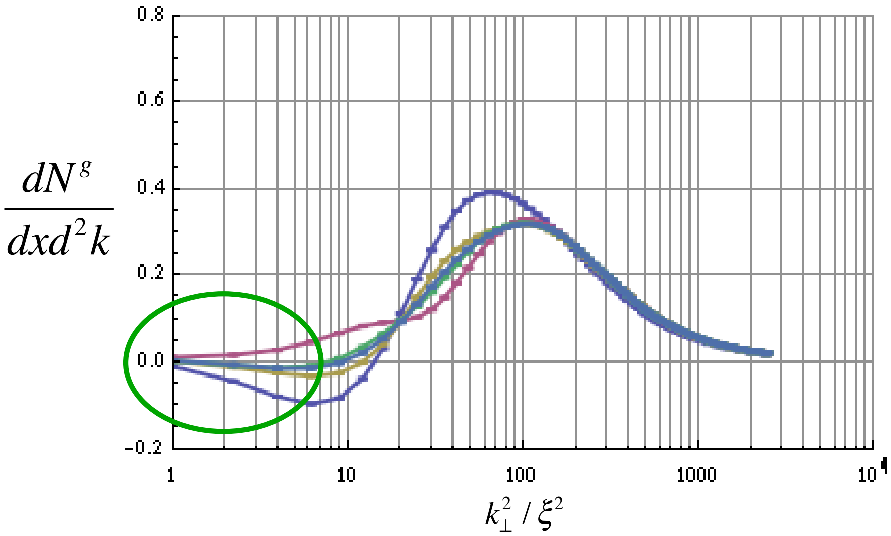
Conceptual Differences between Approaches

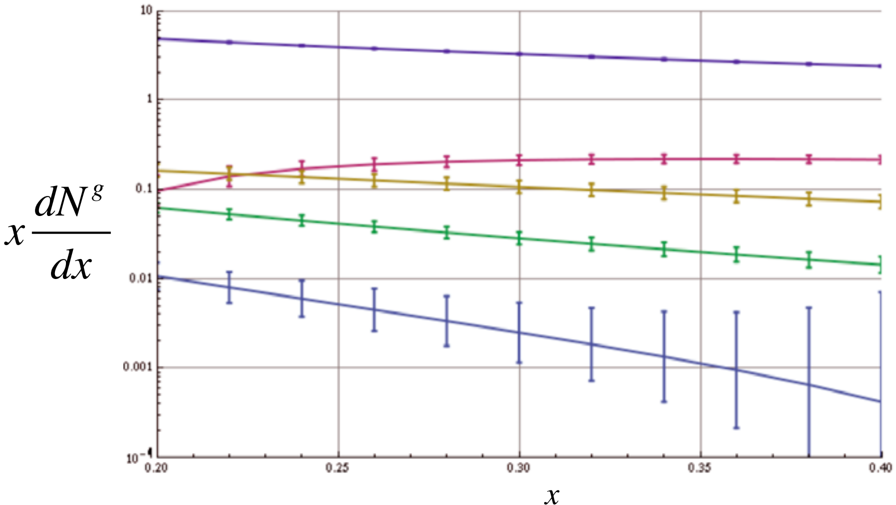
- The reaction operator (Guylassy-Levai-Vitev + Djordjevic) and HT (Wang et al.) approaches expand the radiation in the correlation between multiple scattering centers

- The BDMPS (Baier et al.) approach assumes very large number of scatterings

In the limit $2 \gg 1$ we get $N^{coll}_{\min} > 4$, better $N^{coll} \geq 9$

$x = k^+ / E^+ \approx \omega / E$





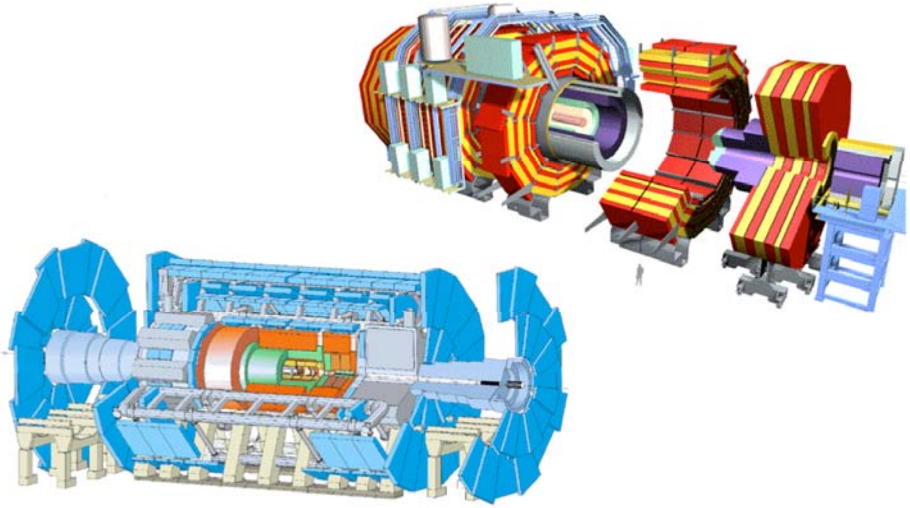
- There is no qualitative change of behavior between n = 1 and n = 5

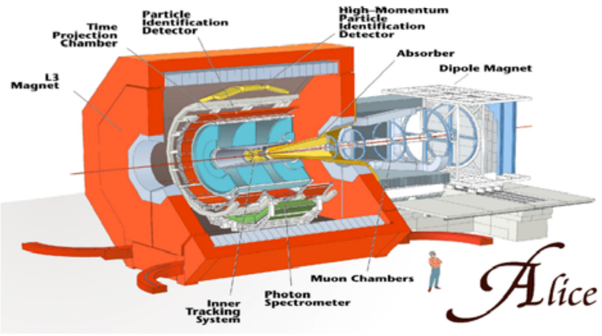
Wicks, S. et al. (2008)

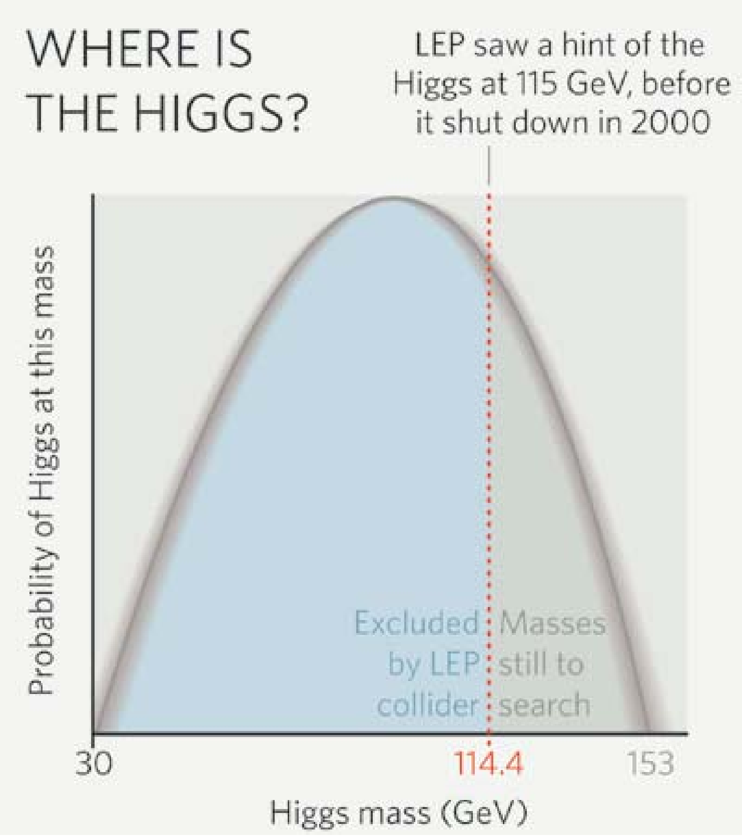
Planned Discovery of the Higgs

The LHC was not built for us

- But we can use its detector capabilities







Hogan, J. (2007)

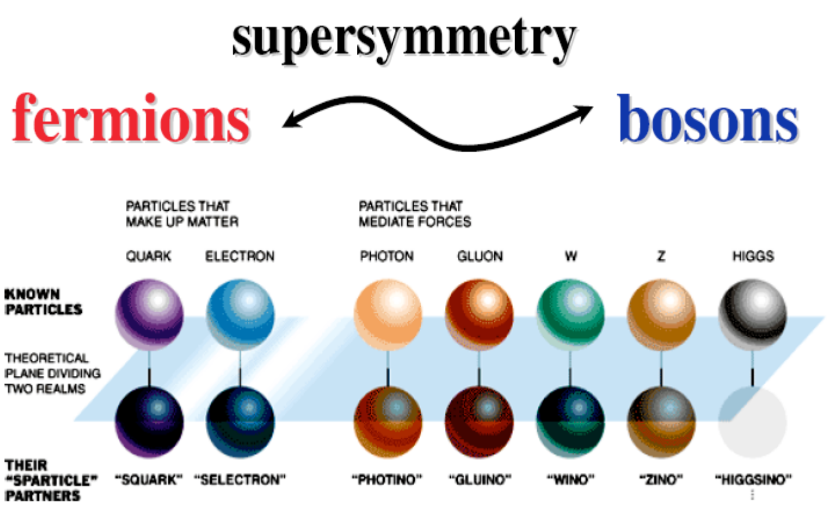
Planned Discovery of Supersymmetry

Theoretical appeal

- Stabilizes the electro-weak symmetry breaking scale against radiative correction
- Unification of the coupling constants
- Excellent candidate for cold dark matter

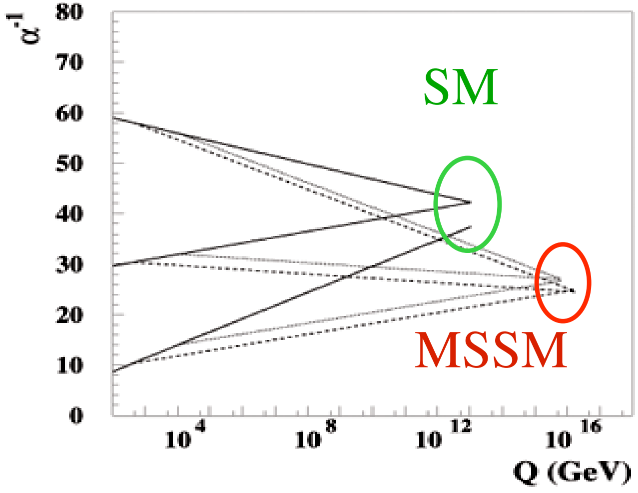
$$W=\sum_{L,E^c}\lambda_L L E^c H_1+\sum_{Q,U^c}\lambda_Q Q U^c H_2+\sum_{Q,D^c}\lambda_Q Q D^c H_1+\mu H_1 H_2$$

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



Photino, Zino and Neutral Higgsino: Neutralinos

Charged Wino, charged Higgsino: Charginos



P. Mercadante (2004)

"I would argue that the *first discovery* at the LHC will not be the Higgs but supersymmetry"

J. Ellis, CERN colloquium

$$M_{SUSY}=1\ TeV\ \ (10\ TeV)$$

Extra Dimensions at the LHC

Searches for higher dimensions

Kaluza, T. (1921) Klein, O. (1926)

Overdui, J. M. et al. (1999)

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

$$ds^2 = (e^{-2ky})\eta_{\mu\eta}x^{\mu}x^{\nu} - dy^2$$

$$m_n = n / R \ (S^1)$$

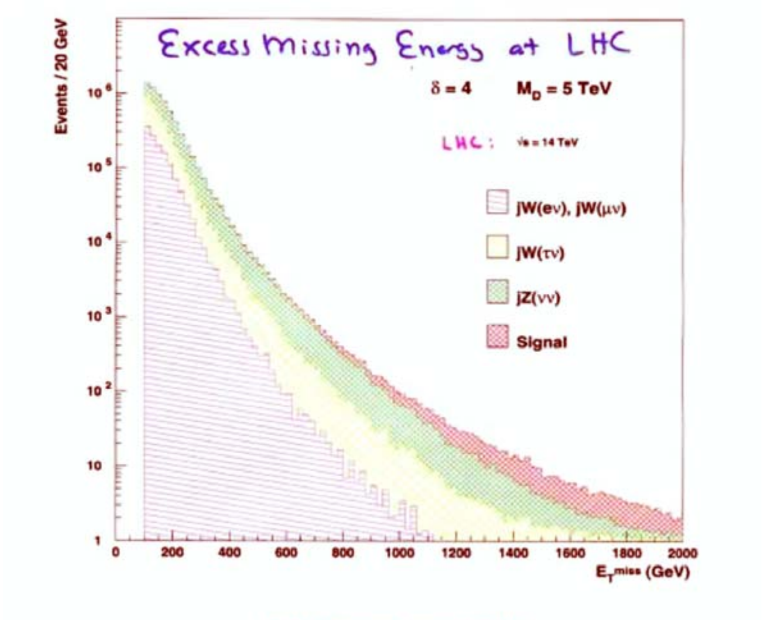
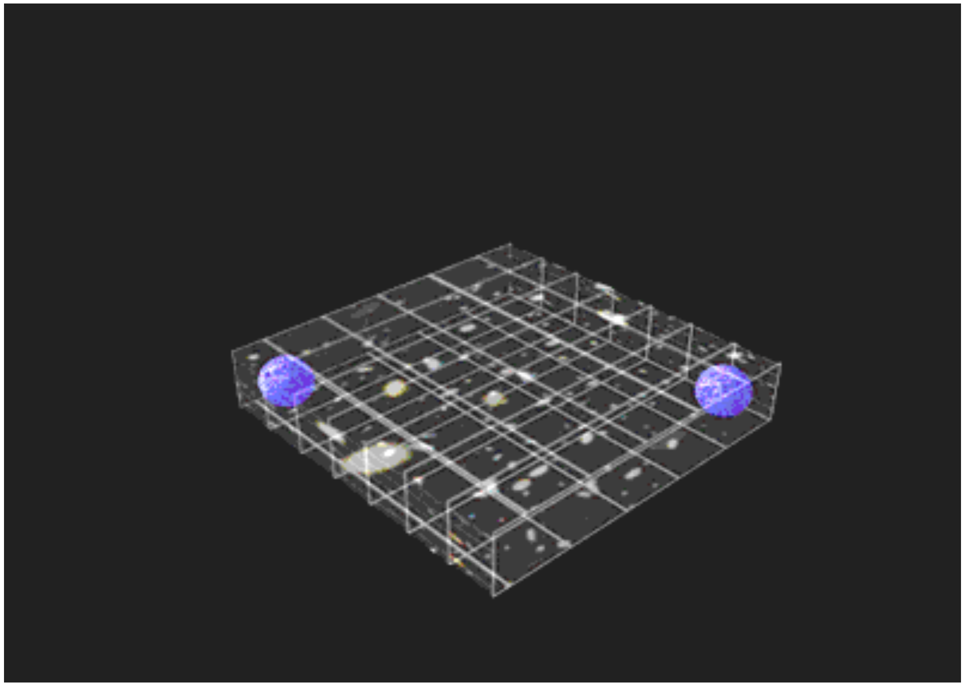


Figure 1: Missing energy spectrum at the LHC.

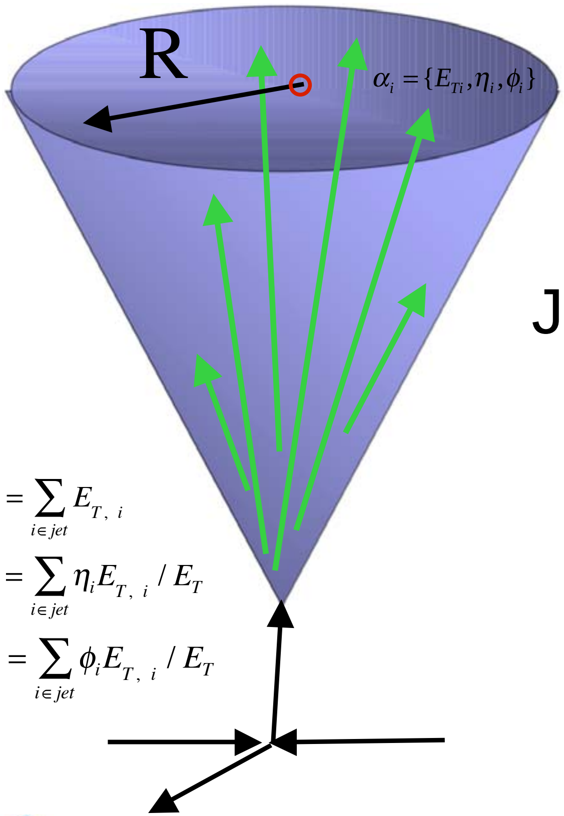


- Connecting HEP and NP

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

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



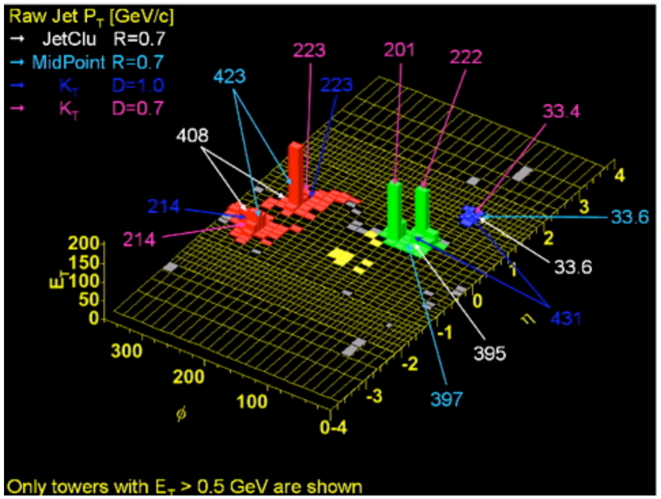
$$\alpha_i=\{E_{Ti},\eta_i,\phi_i\}$$

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

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

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

Sterman, G. et al. (1977)



Only towers with E_T > 0.5 GeV are shown

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)

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

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

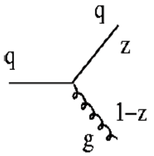
Jet Shapes in QCD: the p+p Baseline I

An analytic approach to the energy distribution of jet

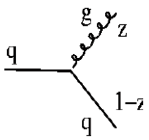
Seymour, M. (1998)

QCD splitting kernel

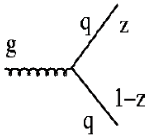
$$dP_a = \frac{\alpha_s}{2\pi}\frac{d\rho^2}{\rho^2}\frac{d\phi}{2\pi}\, dz P_{a\to bc}(z)$$



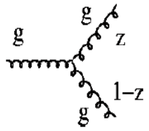
$$P^{(1)}_{qq}(x) = C_2(F)\left[(1+x^2)\left(\frac{1}{1-x}\right)_+ + \frac{3}{2}\delta(1-x)\right]$$



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



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



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

- Note: the Kinoshita, Lee, Neaunberg 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

Jet Shapes in QCD: the p+p Baseline II

Additional contributions have been argued to be important

Power corrections $Q_0 \sim 2\ \mathrm{GeV}$

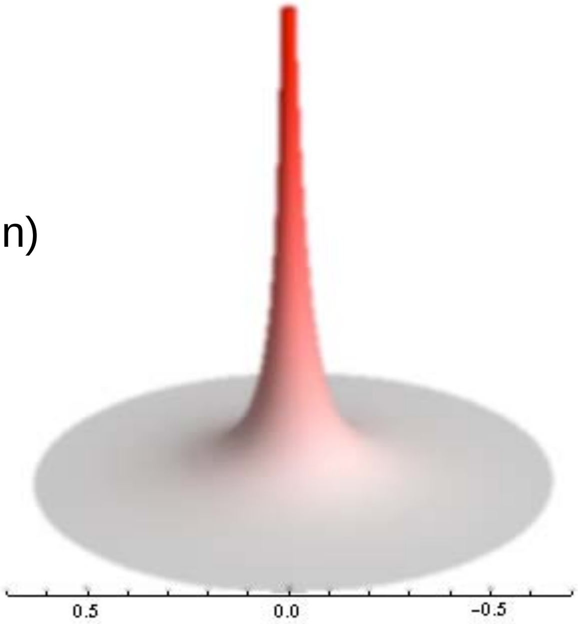
$$\psi_{pow.}(r,R) \sim \frac{C_i}{2\pi}\frac{2}{r}\left(\frac{Q_0}{rE_T}\right)(\bar{\alpha}_s(Q_0)+\ldots)$$

Scale of non-perturbative effects (hadronization)

Initial state radiation

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

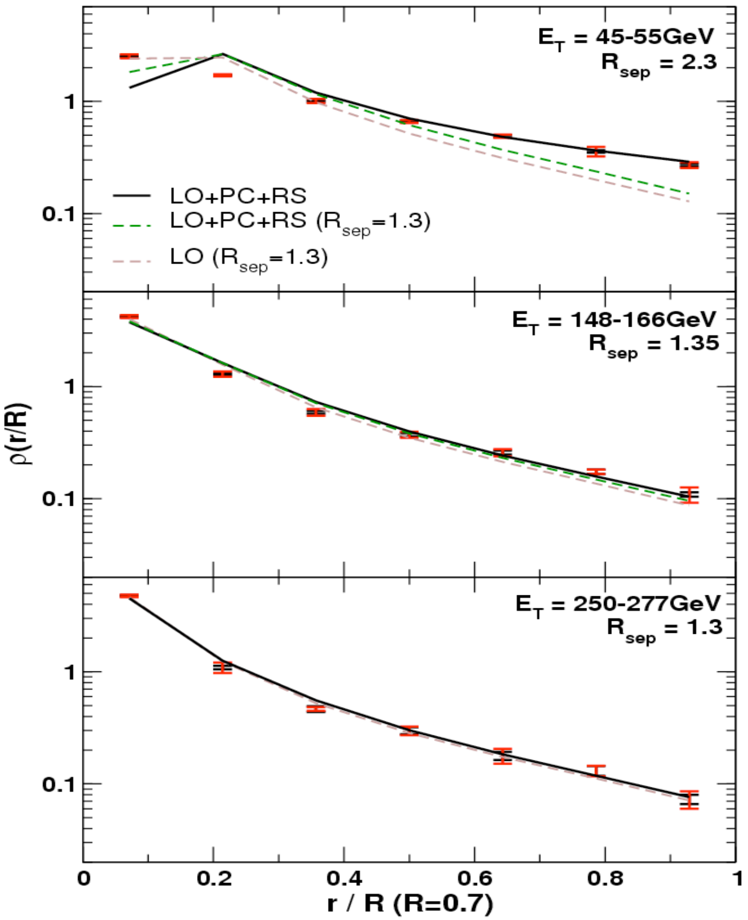
Not important in $e^+ + e^-$ but important in p+p



- Final expression: resummed, matched, and power corrected

$$\psi_{resum}(r,R) = \psi_{soft}(r,R) \otimes P_{Sudakov}(r,R) + (\psi_{LO}(r,R) - \psi_{soft}(r,R)) + \psi_{pow}(r,R)$$

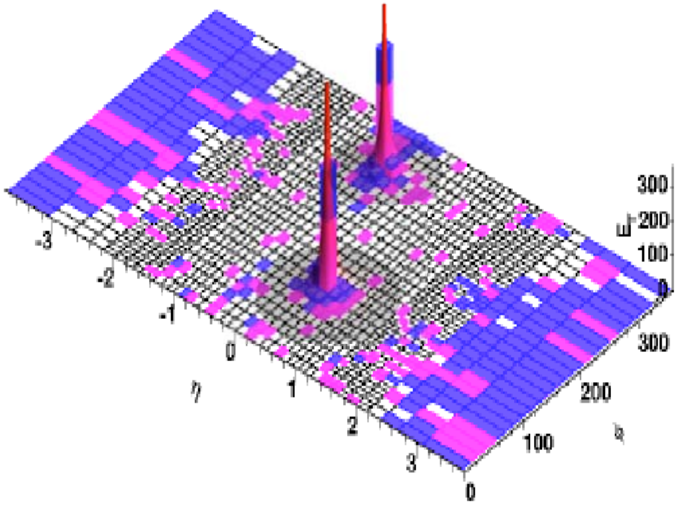
Comparison to the Tevatron Data



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

- Shape function $$\psi(r,R)=\frac{d\Psi(r,R)}{dr}$$

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



V., I et al. (2008)

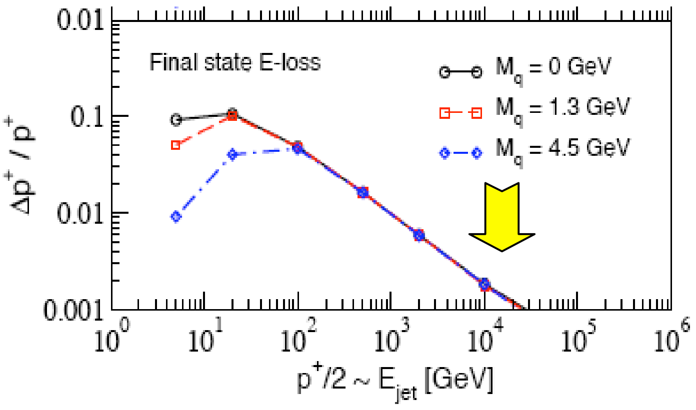
Perez-Ramos, R et al. (2007)

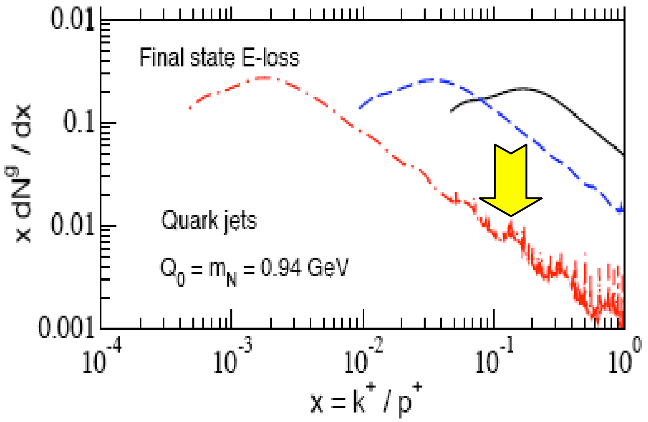
- Very similar jet shapes at the LHC

Medim-Induced Jet Shape Functions

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

ΔE^{rad} LPM suppressed $\leftarrow$ $\dfrac{dI^{rad}}{d\omega}(\omega)$ suppressed

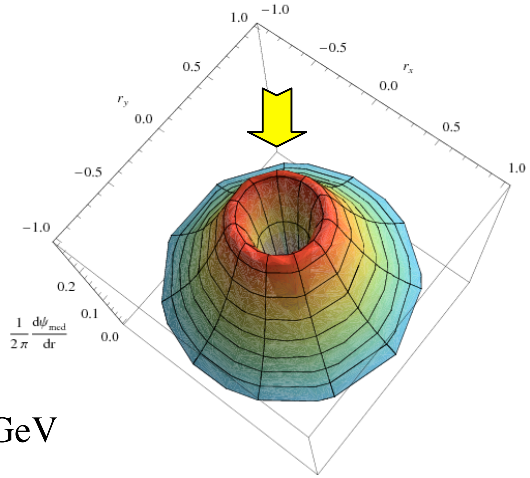




V., I. (2005) $\leftarrow$ $\displaystyle\int d\omega \frac{dI^{rad}}{d\omega dr}(r)$ suppressed

- Can be see in other approaches to the energy loss

Majumder, A. et al. (2005)



E_{jet} = 20 GeV

An Analytic Approach

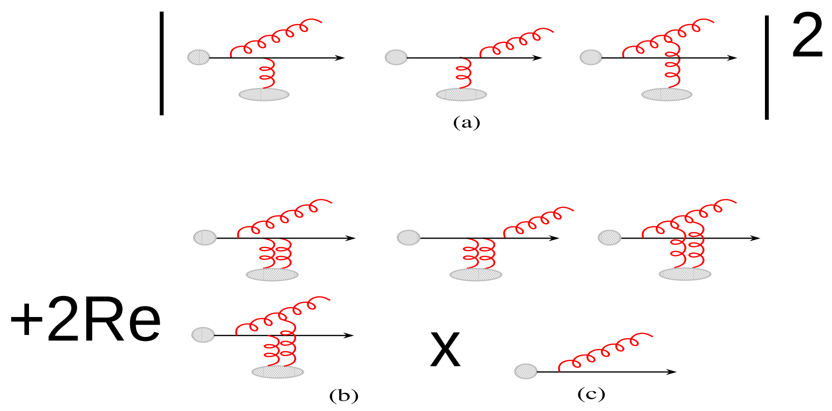
An intuitive approach to medium-induced jet shapes for non-experts

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

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

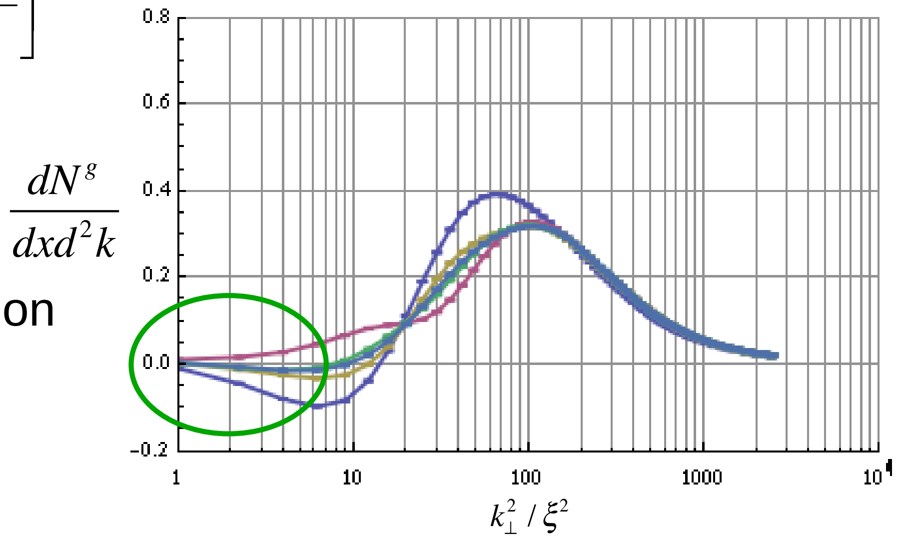
$$\times \int_0^{2\pi} d\alpha \frac{\cos\alpha}{(\omega^2 \sin^2\theta^* - 2q_\perp \omega \sin\theta^* \cos\alpha + q_\perp^2)}$$

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



- Proven now to all orders in opacity

- Incompatible with Sudakov resummation (absence of large logs)



A Differential Approach to Particle Correlations

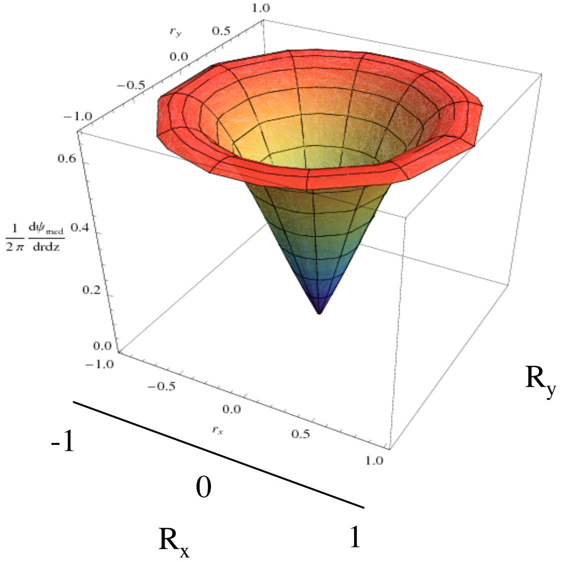
2D analysis reveals rich structure

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

- May be accessible via intra-jet particle correlations

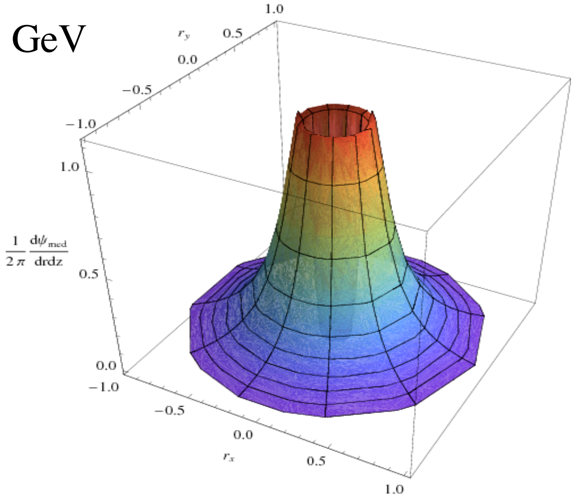
- Medium-induced part only

$\omega = 1$ GeV

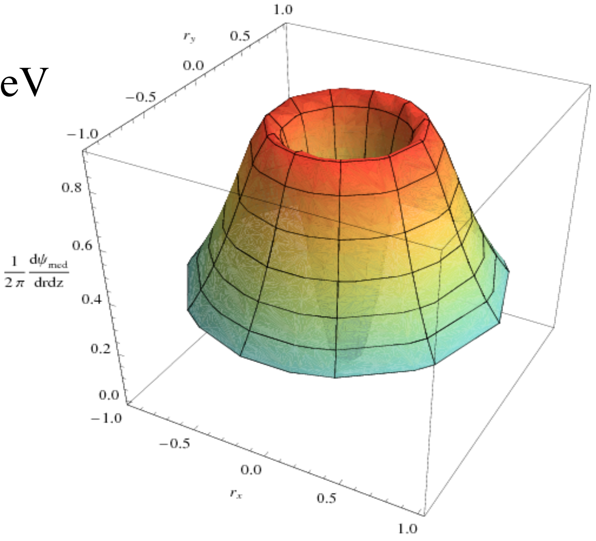


Intensity scale

$\omega = 10$ GeV



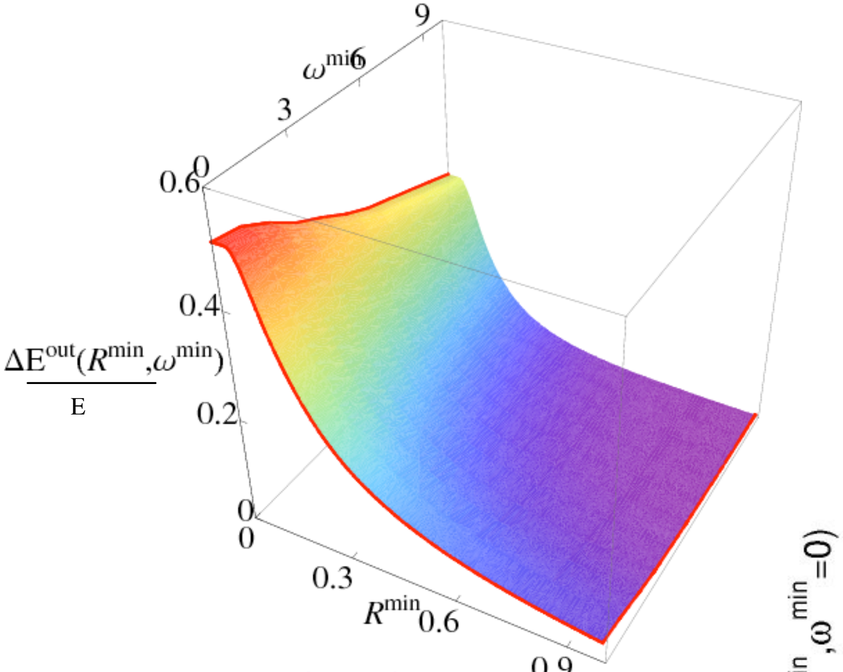
$\omega = 3$ GeV



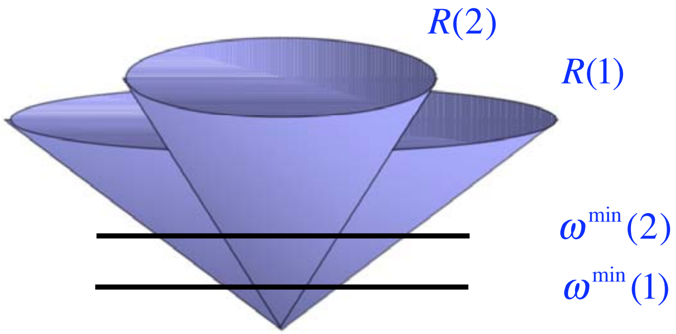
Tomography of Jets I

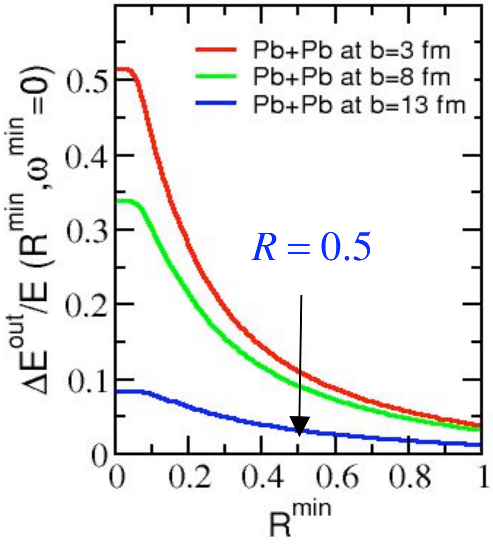
Determination of energy flow

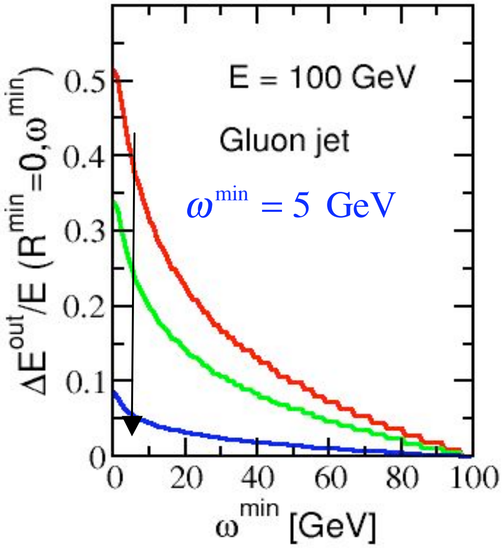
$$\frac{\Delta E^{\mathrm{out}}(R^{\min},\omega^{\min})}{E} = \frac{1}{E}\int_{R^{\min}} dr \int_{\omega^{\min}} d\omega \; \frac{dI^{\mathrm{med}}}{d\omega\, dr}(\omega,r)$$



V, I. et al. (2008)







Large leverage arm

Suppression of backgrounds

Tomography of Jets II

Shape function in heavy ion collisions

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

“Vacuum” contribution

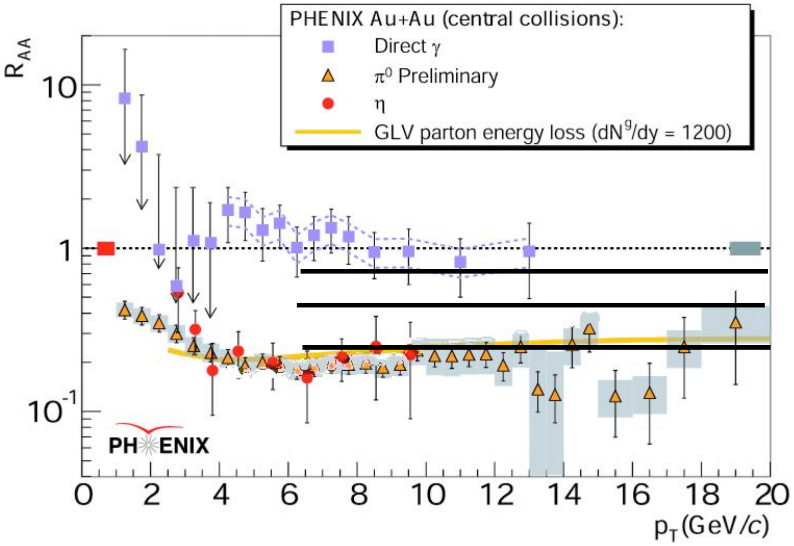
Only a fraction of the lost energy falls in the cone ad above the minimum p_T cut

Medium contribution

$$f(R/\infty;\omega/\infty) = \frac{\Delta E((0,R),(\omega,\infty))}{\Delta E((0,\infty),(0,\infty))}$$

Normalization is the quenched jet cross section

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



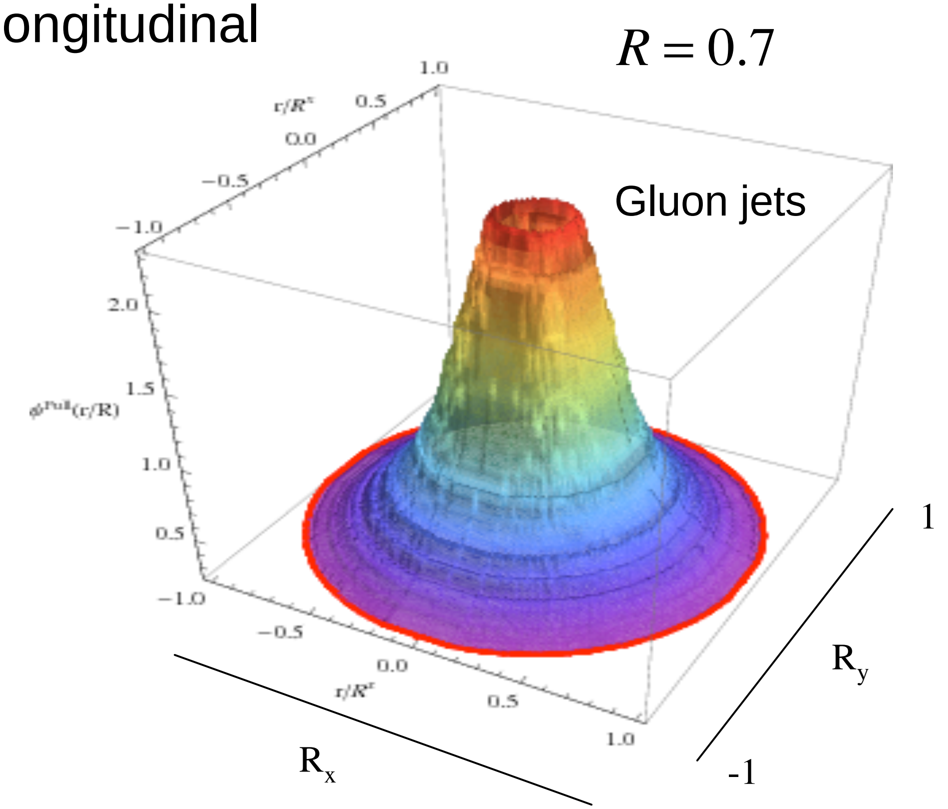
Qualitatively different way of looking at jet suppresion

Numerical Results at the LHC

Shape function: integrated over all longitudinal momenta

Intensity scale

$$\psi(r)$$



- Full numerical simulation:

Jets: $\sim \dfrac{dN^{coll}}{d^2b}$ Medium: $\sim \dfrac{dN^{part}}{d^2b}$

- 1+1D Bjorken, multiple gluon fluctuations and QCD calculations of the p+p jet shape component

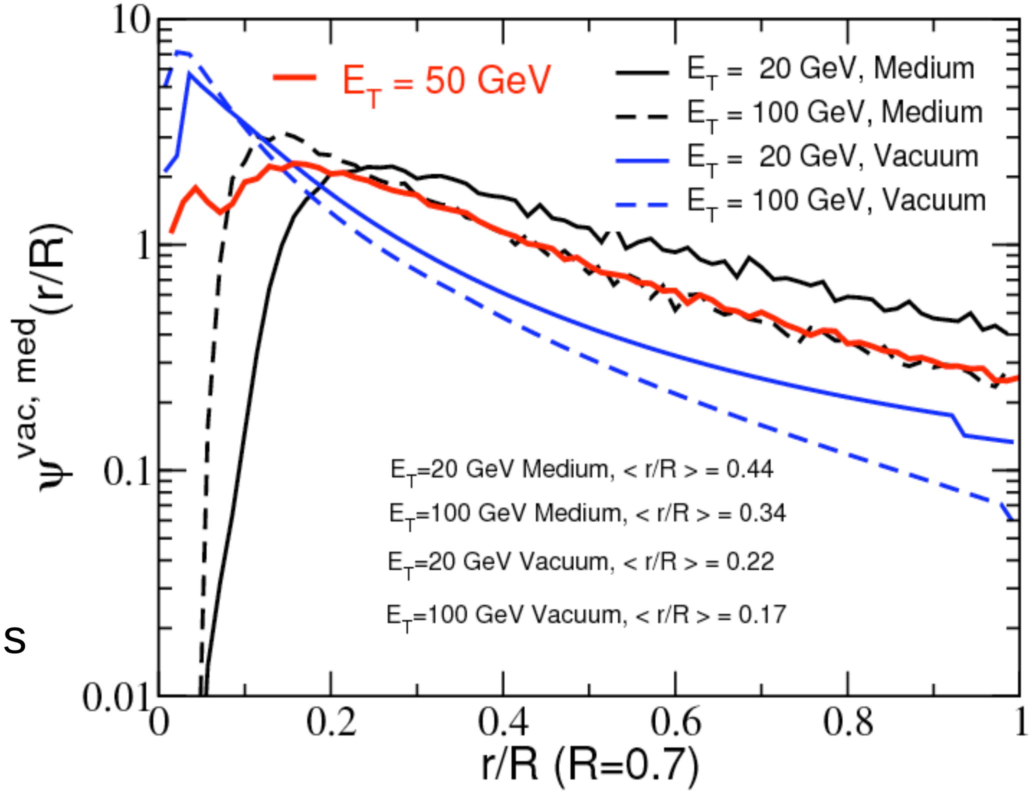
- Such simulations are numerically expensive

Numerical Results

- Average jet radius

$$\langle r / R \rangle = \int_0^1 r / R \; \psi(r / R)$$

(Suggestive of > 50% increase)

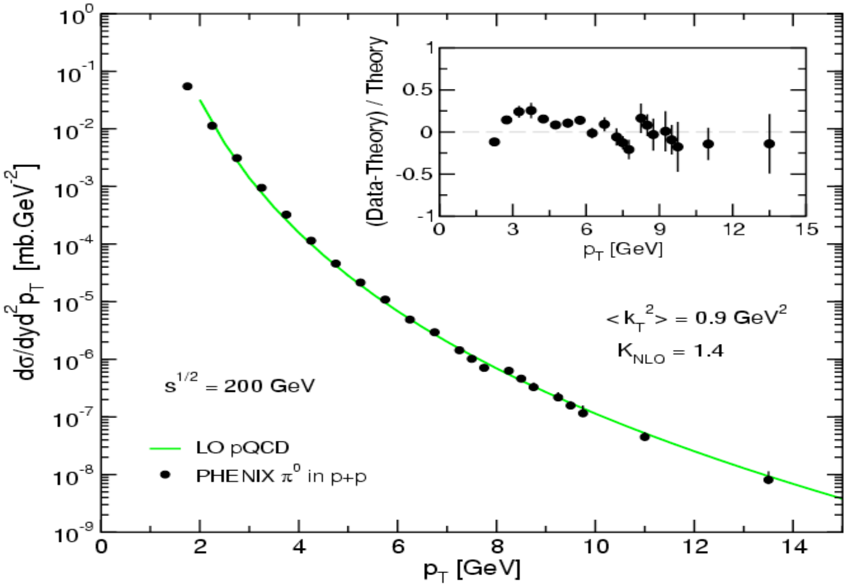


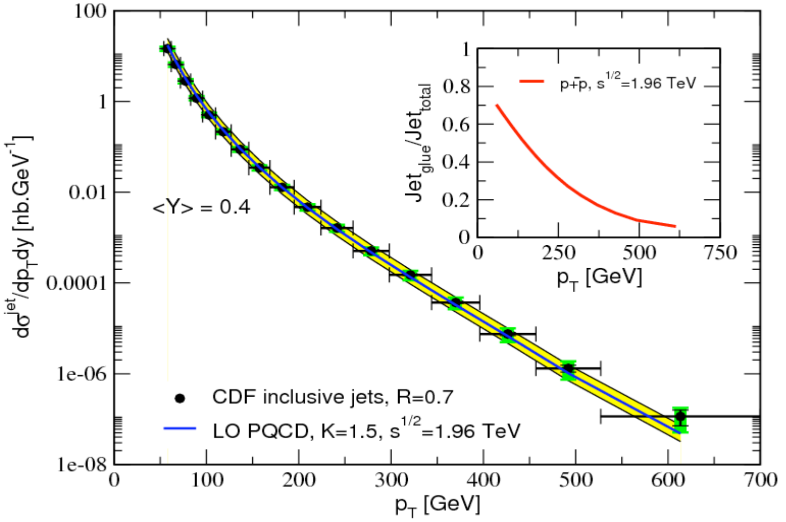
- Shape functions in the medium and their generalization to two dimensional tomography of jets can ultimately reveal the mechanism of particle interactions in matter

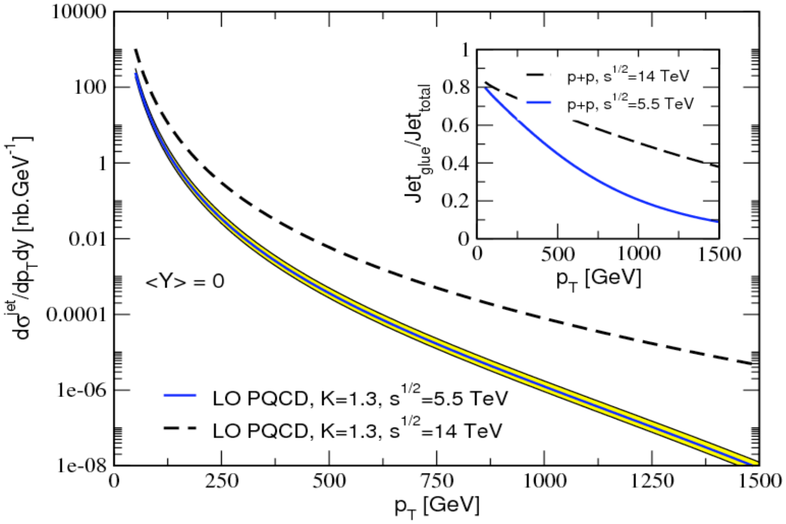
- Results are preliminary. We expect to improve by adding a shape functions for 500 GeV jets

(just checked that the calculation is finished)

Jet Cross Sections: Are these Measurements Feasible







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

- With integrated luminosity $1\ nb^{-1}$

  10% statistical @ 150 GeV inclusive jets

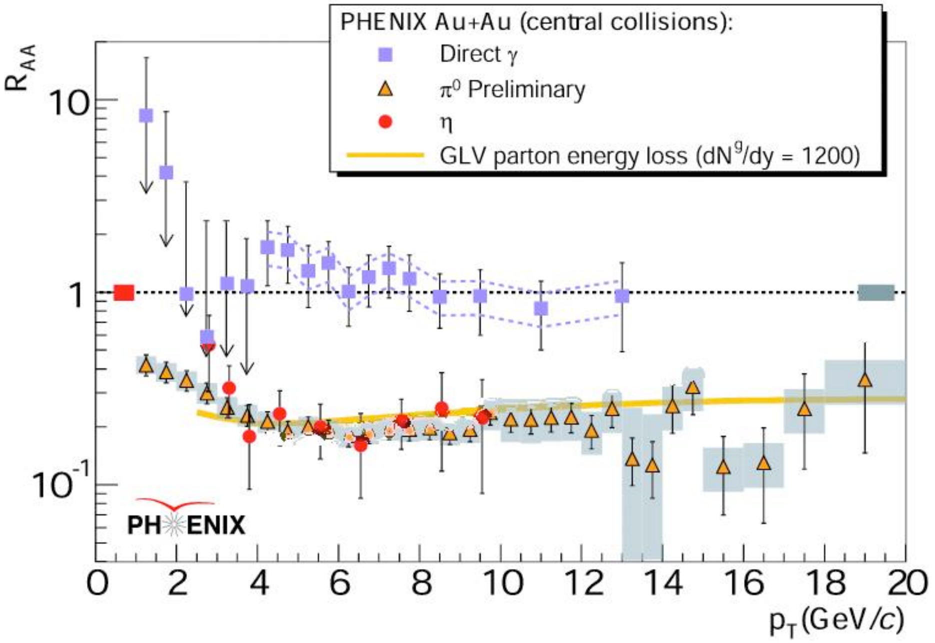
  5% - 30% statistical @ 100 GeV jet shapes

Conclusions

- Developments in studying the effect of high orders in opacity: no qualitative change up to $\langle L/\lambda \rangle = 5$, possible onset of deviations at $\langle L/\lambda \rangle = 8\text{-}10$
- LHC detectors were constructed to measure jets. Best use should be made to use these capabilities.
- Calculations of baseline jet shapes to MLLA, power corrections and initial state radiation for theTevatron and the LHC
- Large angle radiation was proven to all orders in opacity and studied numerically
- Medium induced jet shapes were computed and shown to be significantly different than the "vacuum ones", both in underlying physics and quantitatively
- Important: we have a new calculation at 500 GeV. The final results will be improved (the quantitative aspect)
- Jet cross sections were calculated to demonstrate the feasibility of 2D tomography and jet shape studies in HI collisions to E_T=100 GeV with $\int L dt = 1\ \mathrm{nb}^{-1}$

Another Motivation

This is Dia (S. Reddy's daughter)



Search for Extra Dimensions

Searches for higher dimens

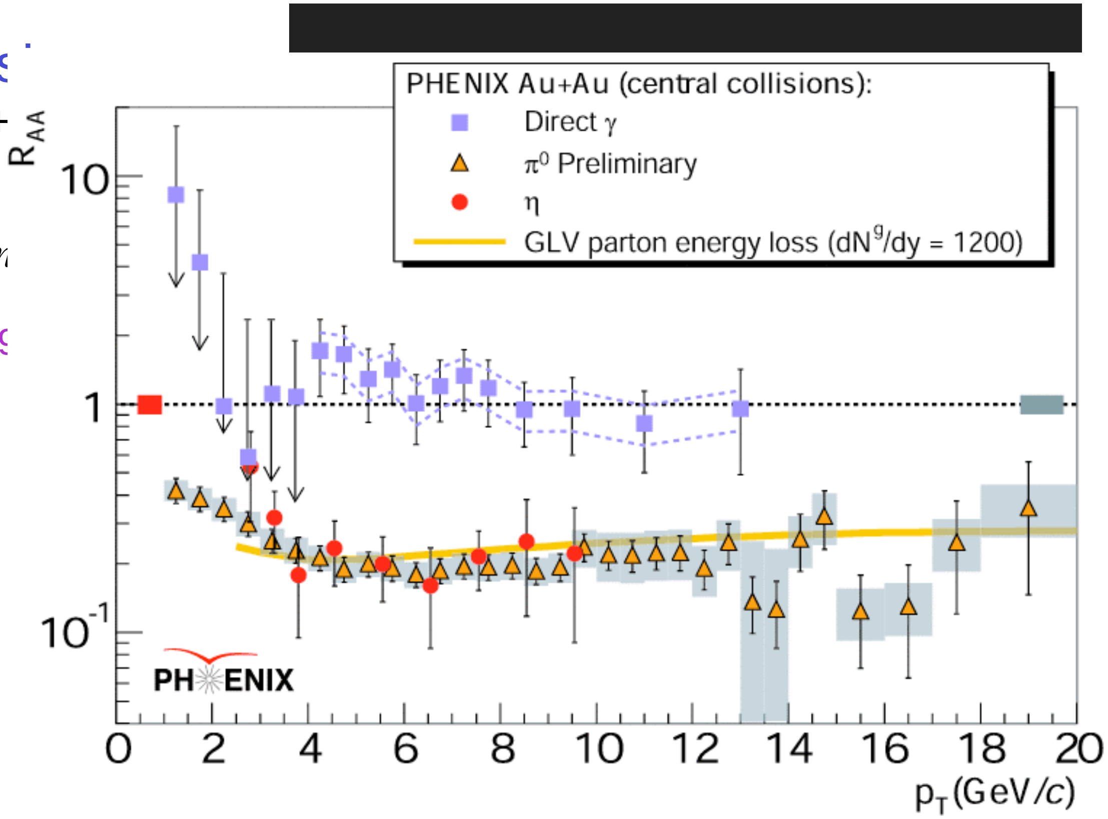
- Generalization to 5D E&M+
- Numerous extensions

$$ds^2 = (e^{-2ky})\eta_{\mu\eta}x^\mu x^\nu - dy^2 \quad m$$

Kaluza, T. (1921) Klein, O. (19

Overdui, J. M. et al. (1999)

- Connecting HEP and NP



Discovery channels (supersymetry)

Rich spectroscopy

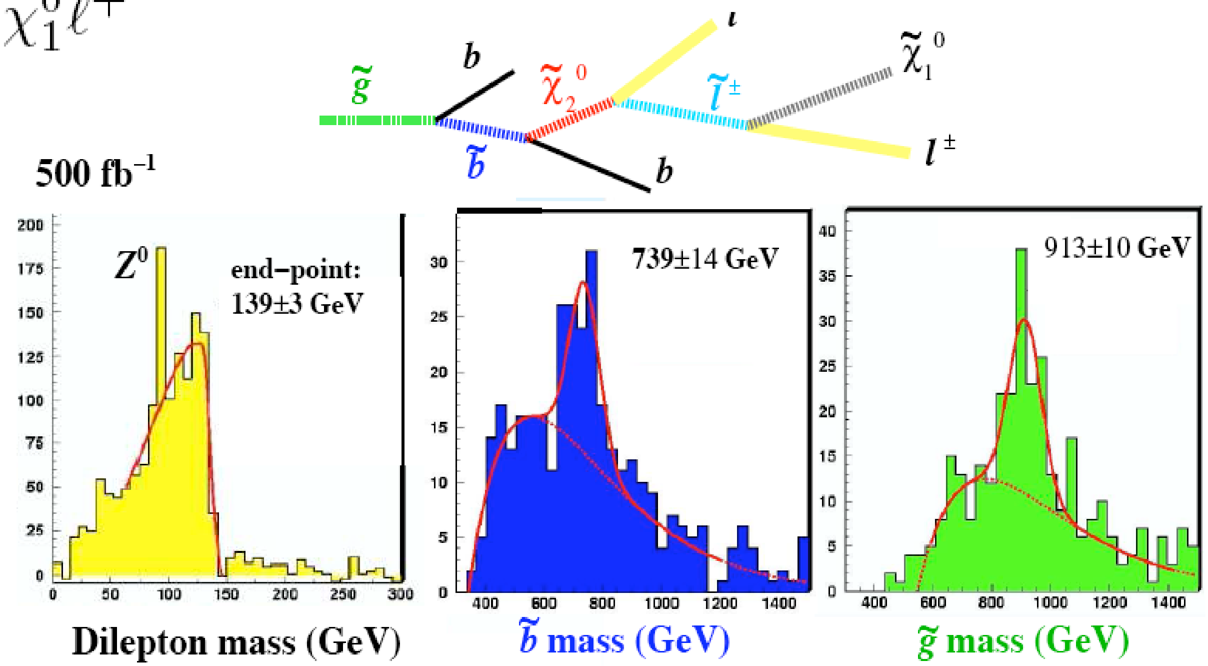
$Example:\ H, h, H^+, H^-, A$

- Detected via high jet multiplicity + missing energy (since there is lightest supersymmetric particle - stable neutralino χ_1^0 $m_\chi > 6\ GeV\ \ for\ m_A \sim 200\ GeV$)

$$\chi_2^1 \to \ell^+\ell^- \to \ell^-\chi_1^0\ell^+$$

Really high (>10) jet multiplicities

Understanding jets, jet energy flow, and QCD backgrounds is critical for discovering physics beyond the standard model

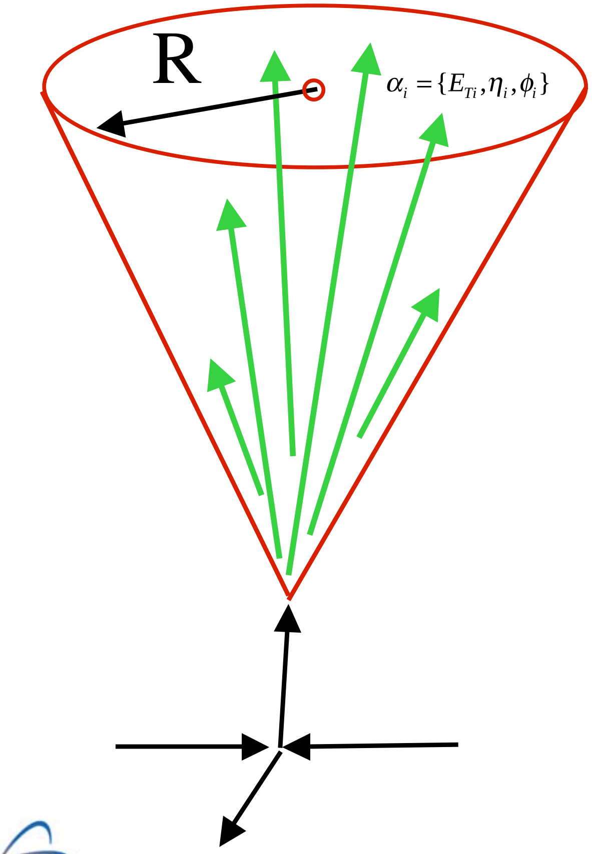


The decay chain of the gluino: $M_{\tilde{g}} \simeq 1\ TeV$

Jet definitions

- Jet variables

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



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

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

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

- Transverse energy
- (Pseudo) Rapidity
- Angle

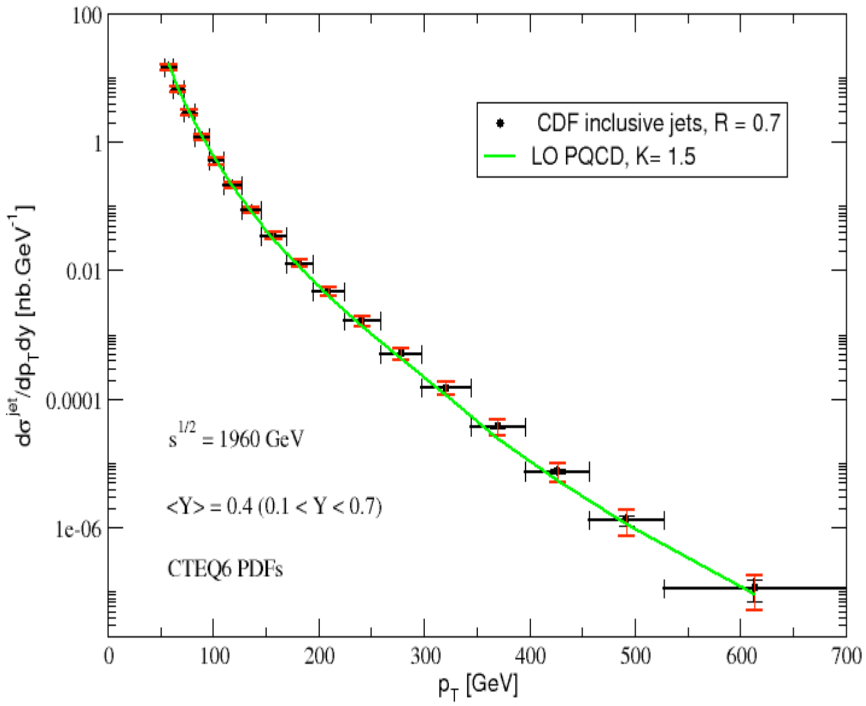
Jets are collimated showers of energetic particles that carry a large fraction of the energy available in the collisions

Jet algorithms:

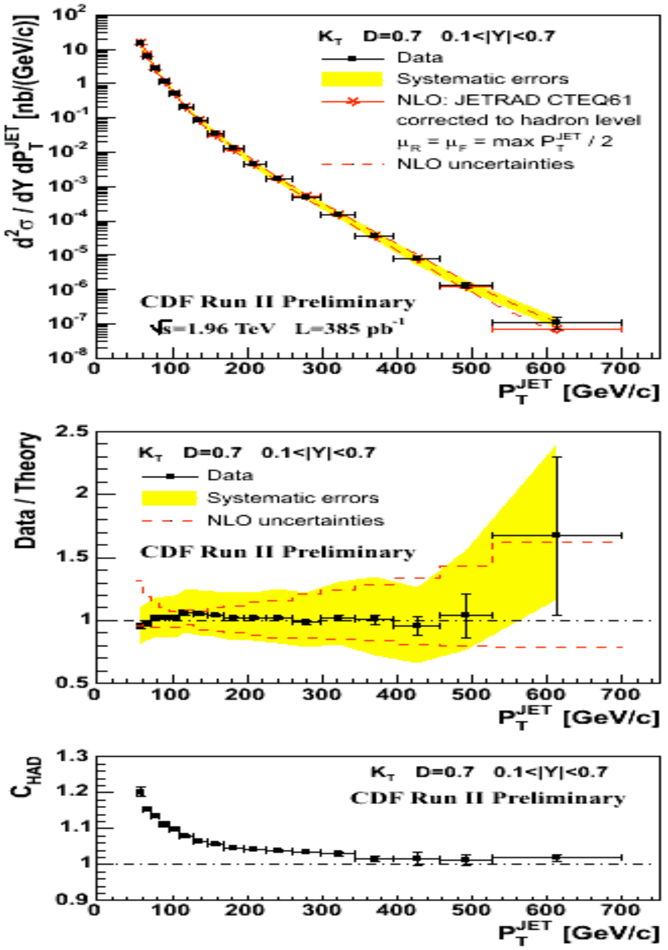
- Kt algorithm: preferred (collinear and infrared safe to all orders in PQCD)
- Cone algorithm:

Jet cross sections: comparison to LO and NLO PQCD

W. Horowitz, I.V., S. Wicks, in preparation

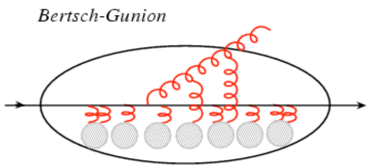


- Good comparison to the shape at LO. Meaningful K-factor



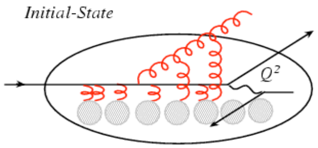
- Even better comparison at NLO.

Medium-Induced Radiation in the Initial State



Asymptotic

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



Asymptotic

$t = -\infty$

Large Q²

$t = z_L = L$

- **Bertsch-Gunion case with interference**

Vitev, I. (2007)

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

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

- **Realistic initial state medium induced radiation**

Vitev, I. (2007)

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

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

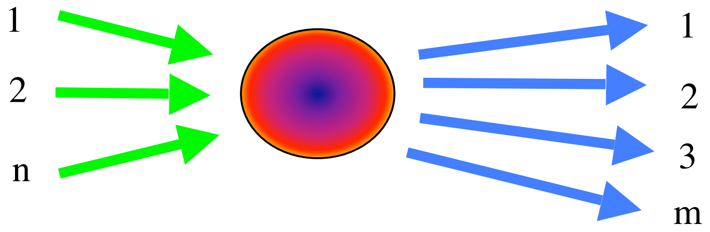
$$\left. - 2 H \cdot B_{(2\ldots n)(1\ldots n)} \left(\cos \left(\sum_{k=2}^{n+1} \omega_{(k\ldots n)} \Delta z_k \right) \right) \right]$$

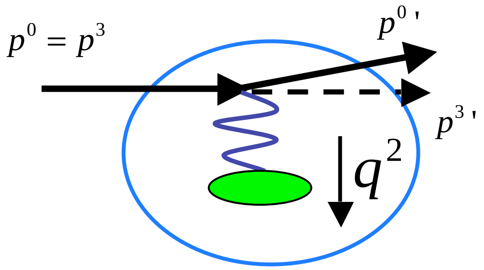
Los Alamos
NATIONAL LABORATORY
EST. 1943

Types of Energy Loss

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

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





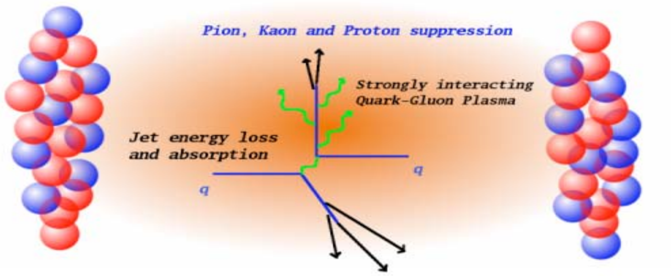
$$\frac{d\Delta E^{coll}}{dz} \approx 4\pi\alpha_{em}^2 z^2 Z \rho_{num} \frac{1}{\beta^2 m} \ln B_q$$

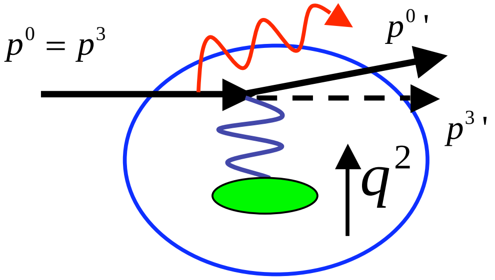
$$\Delta E^{coll} = c_1 L$$

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

- Collisional energy loss

  - medium excitation





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

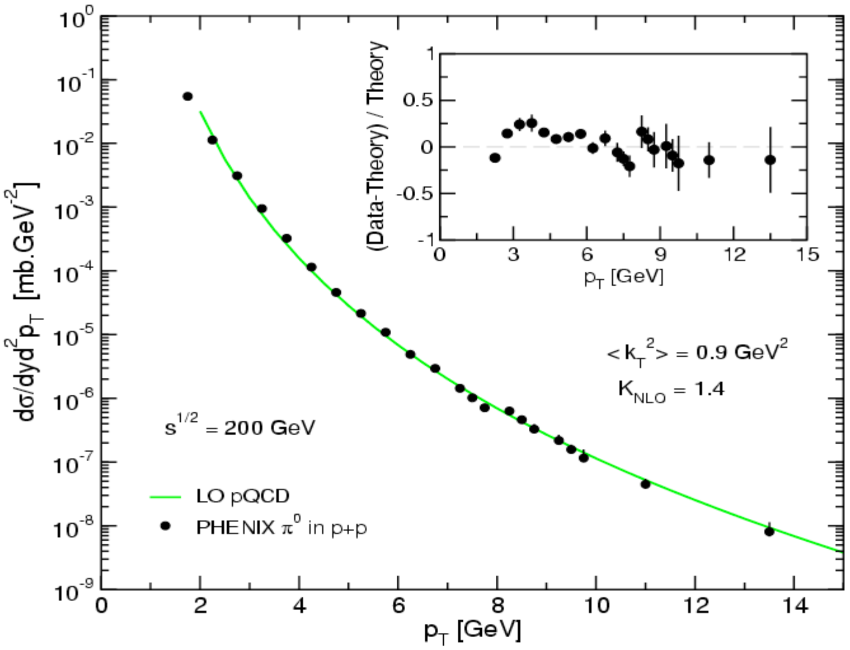
$$\Delta E^{rad} = c_2 E L$$

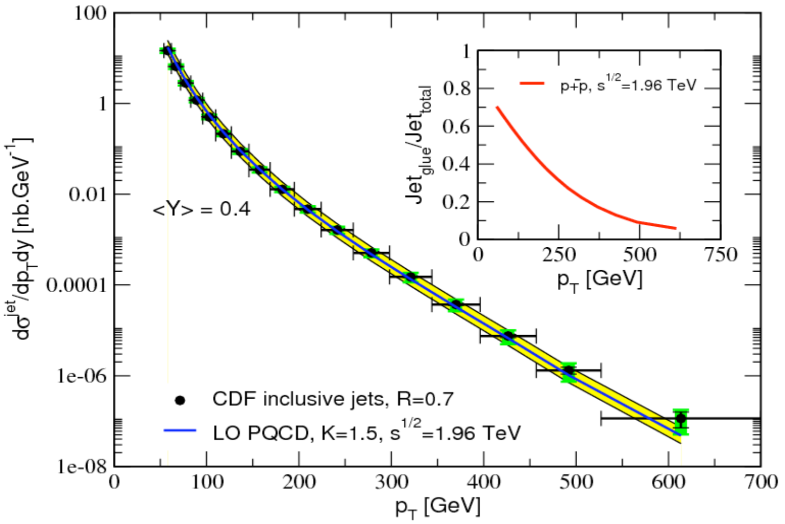
- Radiative energy loss

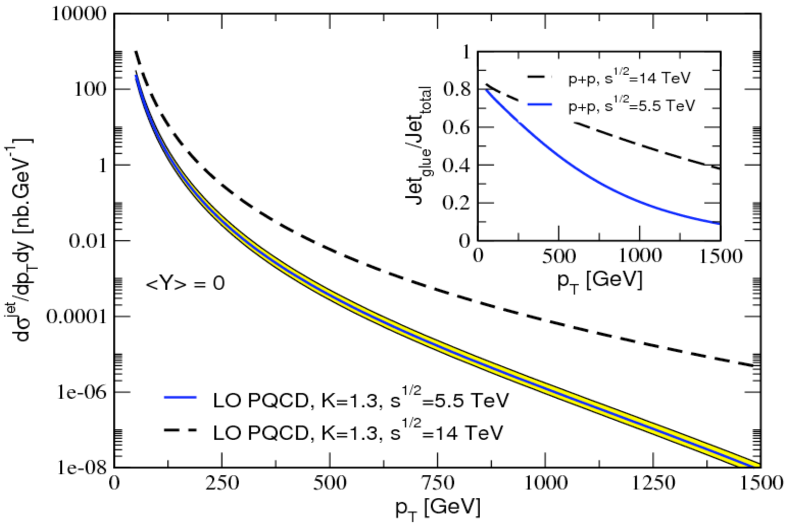
  - gauge boson bremsstrahlung

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.

Searching for Extra Diemnsions and SUSY

Observation at colliders
LHC

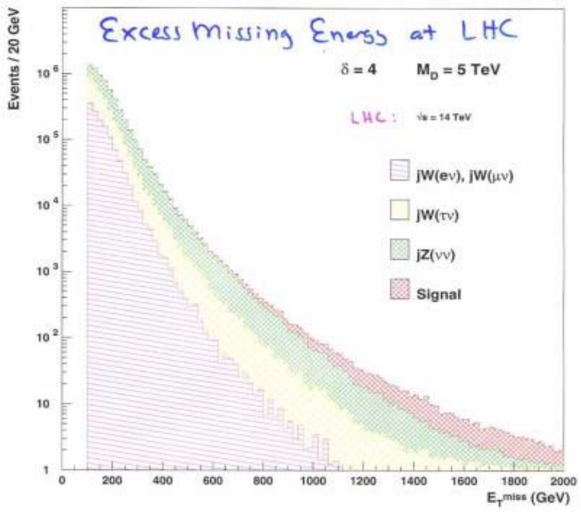


Figure 1: Missing energy spectrum at the LHC.

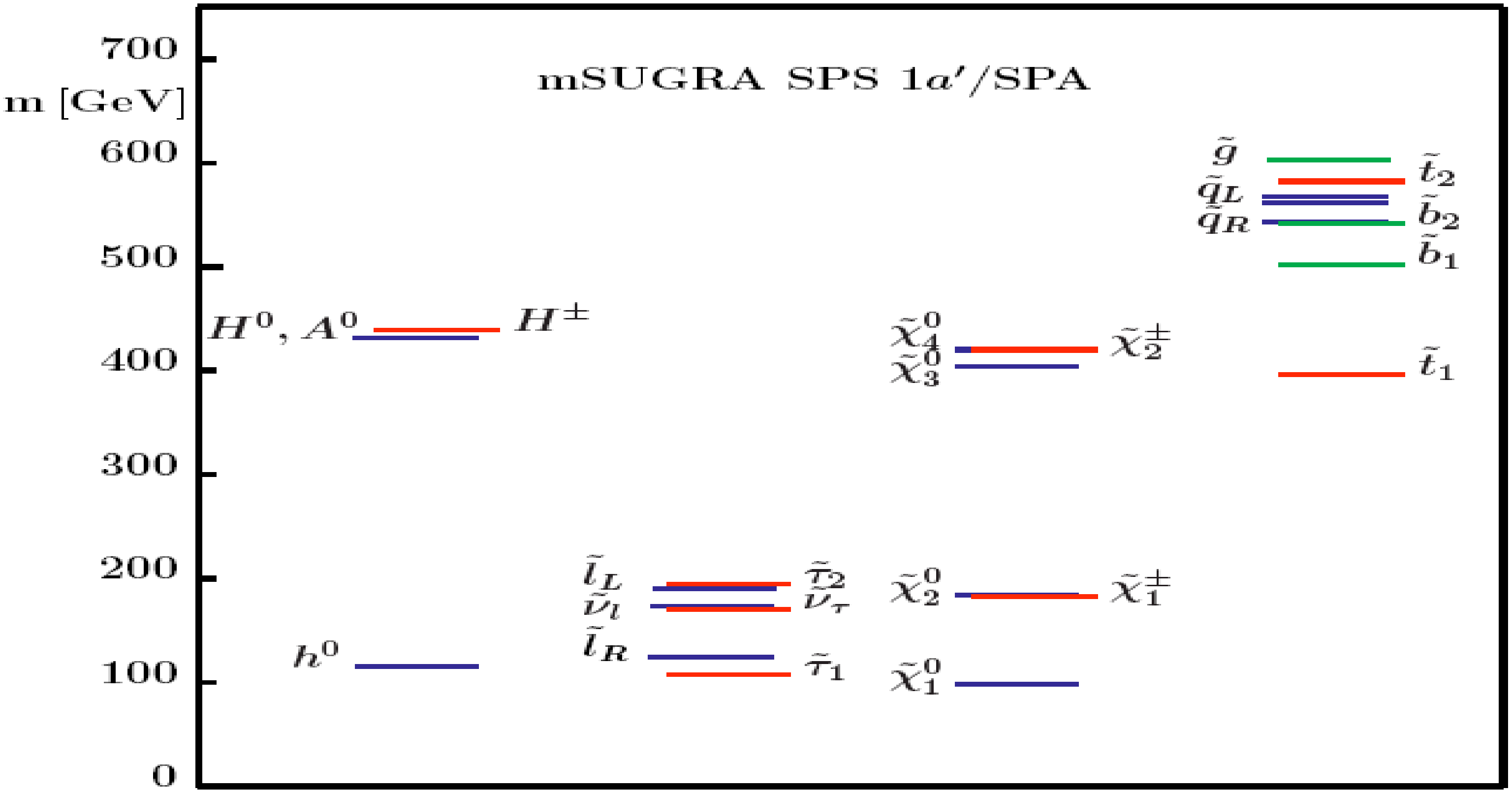
MSSM

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/gaugino	$W^\pm\,,\,W^0$	$\widetilde{W}^\pm\,,\widetilde{W}^0$	1	3	0
	B	$\widetilde{B}$	1	1	0
slepton/lepton	$(\widetilde{\nu},\widetilde{e}^-)_L$	$(\nu,e^-)_L$	1	2	-1
	$\widetilde{e}^-_R$	e^-_R	1	1	-2
squark/quark	$(\widetilde{u}_L,\widetilde{d}_L)$	$(u,d)_L$	3	2	$1/3$
	$\widetilde{u}_R$	u_R	3	1	$4/3$
	$\widetilde{d}_R$	d_R	3	1	$-2/3$
Higgs/higgsino	$(H_d^0\,,\,H_d^-)$	$(\widetilde{H}_d^0,\widetilde{H}_d^-)$	1	2	-1
	$(H_u^+\,,\,H_u^0)$	$(\widetilde{H}_u^+,\widetilde{H}_u^0)$	1	2	1

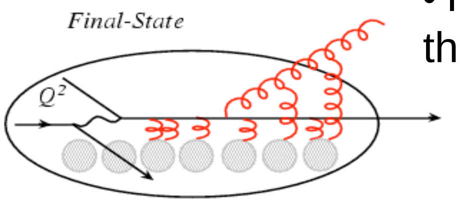
124 parameters (18 are the SM)

Mass Spectrum in Minimal Super Gravity

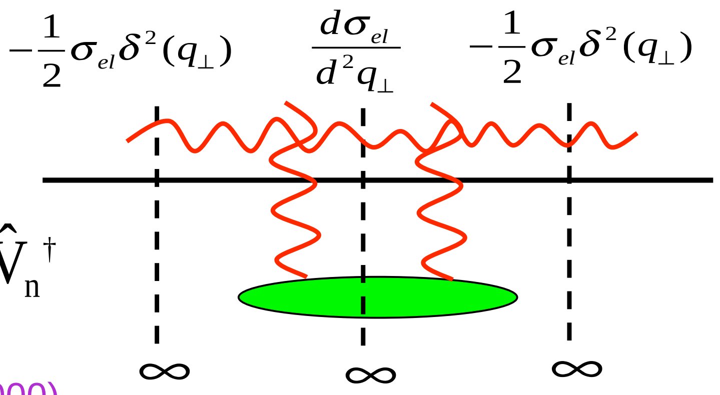


Example of 100 GeV SUSY particles

Medium-Induced Radiation in the Final State



- Includes interference with the radiation from hard scattering



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

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

Gyulassy, M. et al. (2000)

$$k^+\frac{dN_g^n}{dk^+d^2k_\perp} \propto Tr\sum_{i_1\ldots i_n}\bar{A}^{i_1\ldots i_n}A_{i_1\ldots i_n}$$

$$= \bar{A}^{i_1\ldots i_{n-1}}\left(D^\dagger D + V^\dagger + V\right)A_{i_1\ldots i_{n-1}}$$

$$= \bar{A}^{i_1\ldots i_{n-1}}\hat{R}\;A_{i_1\ldots i_{n-1}}$$

Number of scatterings

Momentum transfers

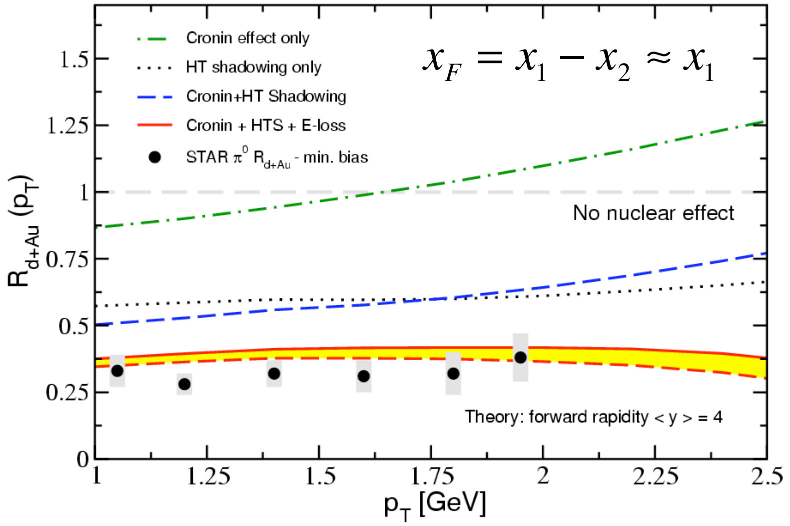
$$k^+\frac{dN_g}{dk^+d^2k_\perp} = \sum_{n=1}^{\infty}k^+\frac{dN^n{}_g}{dk^+d^2k_\perp} = \sum_{n=1}^{\infty}\frac{C_R\alpha_s}{\pi^2}\left[\prod_{i=1}^{n}\int_0^{L-\sum_{j=i+1}^{n}\Delta z_j}\frac{d\Delta z_i}{\lambda_g(z_i)}\int d^2q_i\left(\frac{1}{\sigma_{el}}\frac{d\sigma_{el}}{d^2q_i}-\delta^2(q_i)\right)\right]$$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

Color current propagators

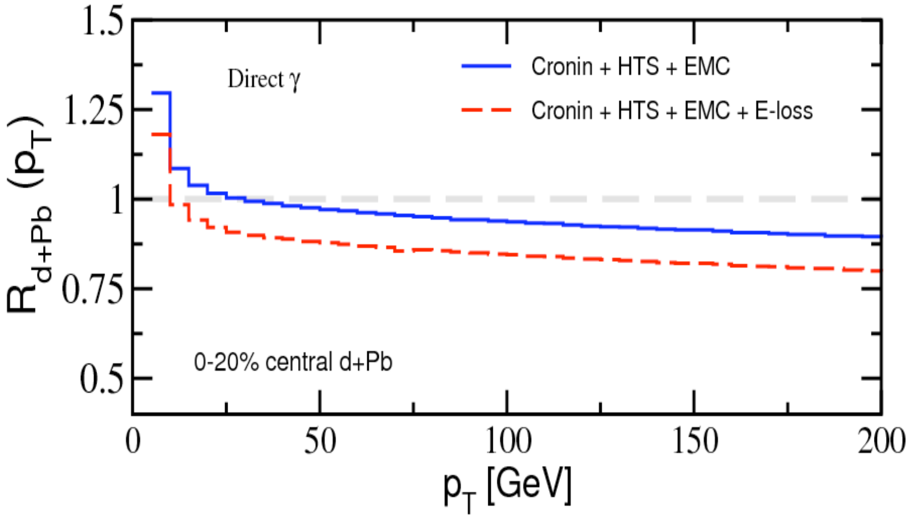
Coherence phases (LPM effect)

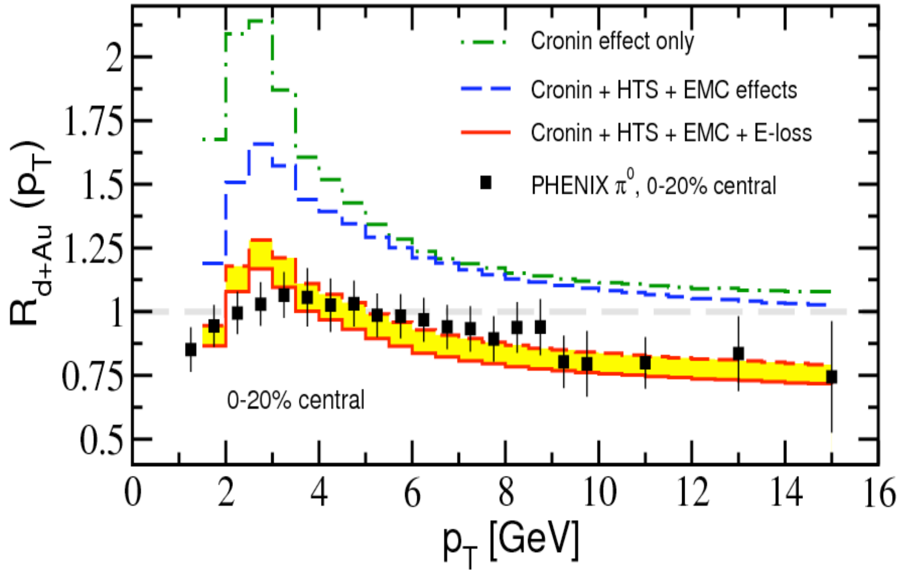
Cold Nuclear Matter Effects for π^0 and Direct γ

- 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)

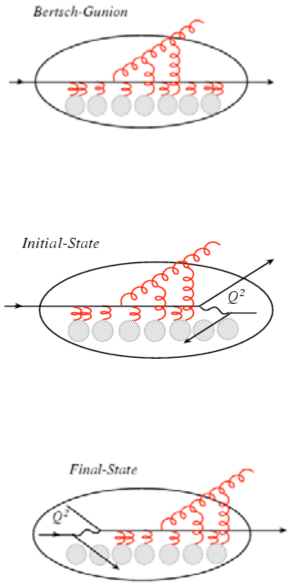


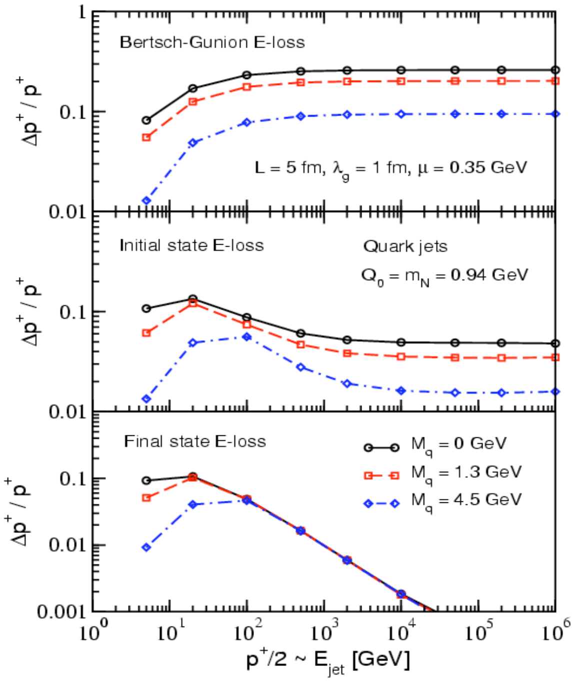


Cold Nuclear Matter Effects

- Initial-state E-loss

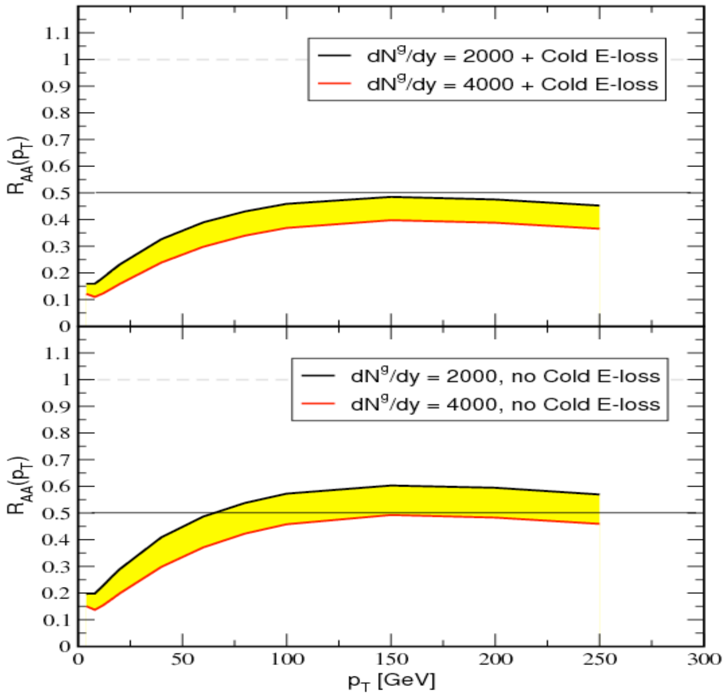
$$\frac{\omega dN^g}{d\omega d^2k_\perp} = \frac{C_R\alpha_s}{\pi^2}\int_0^{s/4} d^2q_\perp \frac{\mu_{eff}^2}{(q_\perp^2+\mu^2)^2}\left[\frac{L}{\lambda_g}\frac{q_\perp^2}{k_\perp^2(k_\perp-q_\perp)^2} - 2\frac{q_\perp^2 - 2k_\perp\cdot q_\perp}{k_\perp^2(k_\perp-q_\perp)^2}\frac{k^+}{k_\perp^2\lambda_g}\sin\frac{k_\perp^2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





Energy scale

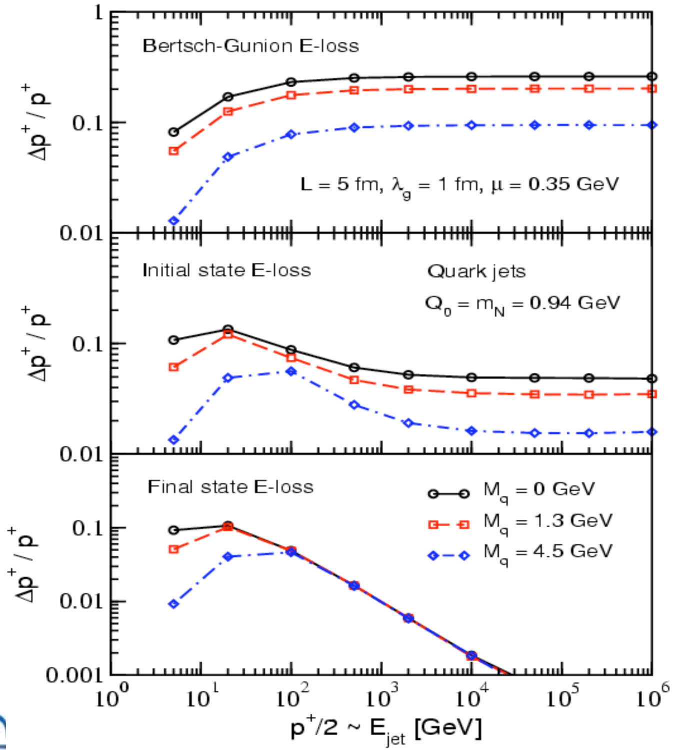
$$E = p_T \cosh(y_{\text{jet}} - y_{\text{target}})$$



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

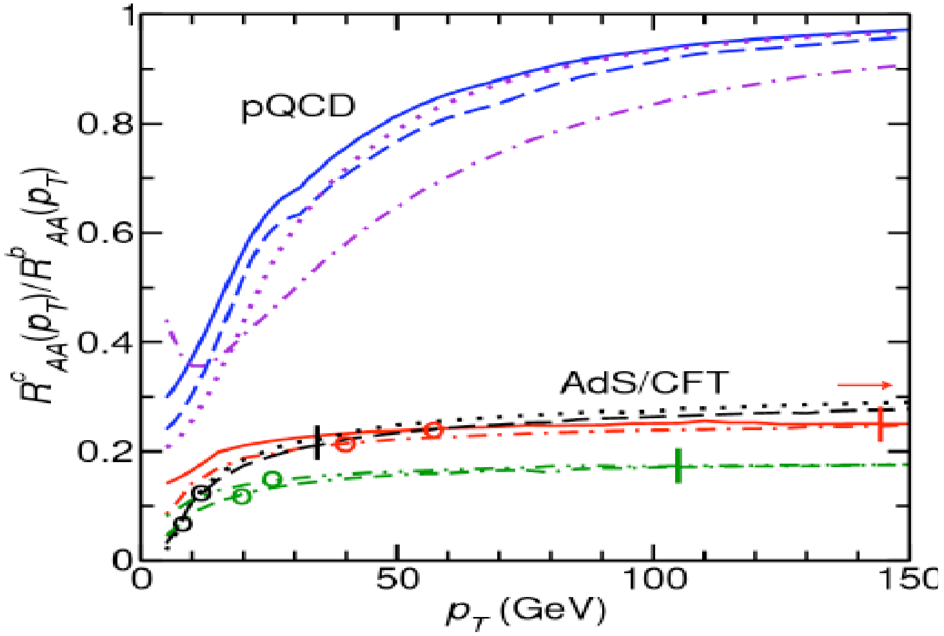
A Note on PQCD Regimes

- An interesting idea ≠ 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.Vitev, (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

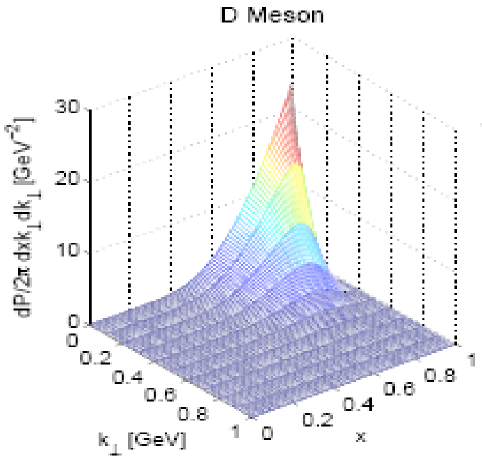
$$\left|\psi_M; P_\perp, P^+\right\rangle = \sum_{i=2}^{n} \int \frac{dx_i}{\sqrt{2x_i}} \frac{d^2k_{\perp i}}{\sqrt{(2\pi)^3}} \psi_i(k_{\perp i}, x_i)$$

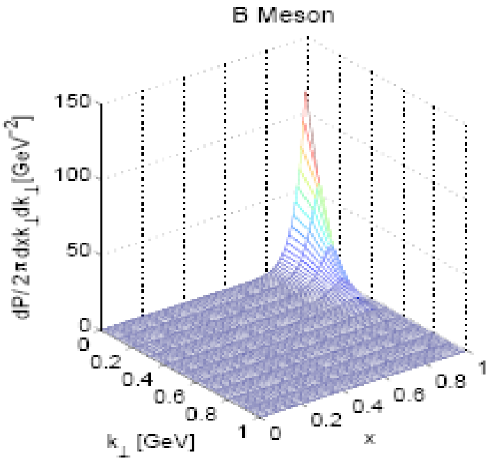
$$\times \delta\left(\sum_{i=2}^{n} x_i - 1\right) \delta\left(\sum_{i=2}^{n} k_{\perp i}\right) \left|i; k_{\perp i} + x_i P_\perp, x_i P^+\right\rangle$$

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





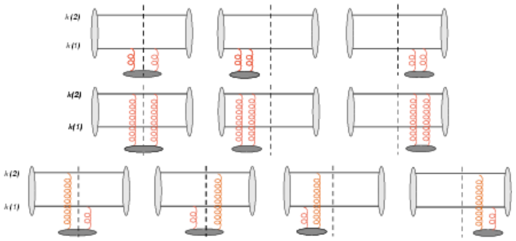
- Models such as coalescence should use plausible wave functions, especially for heavy flavor

Medium-Modified Heavy Meson

Initial distribution:

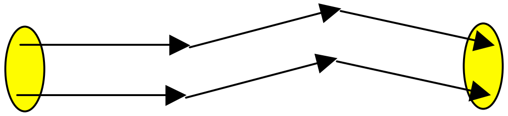
$$\left|\psi_i(\Delta k_\perp,x)\right|^2=\left[\delta^2(K_\perp)\right]\times\left[\mathrm{Norm}^2 e^{-\frac{\Delta k_\perp^2}{4x(1-x)\Lambda^2}}e^{-\frac{m_1^2(1-x)+m_2^2x}{x(1-x)\Lambda^2}}\right]$$

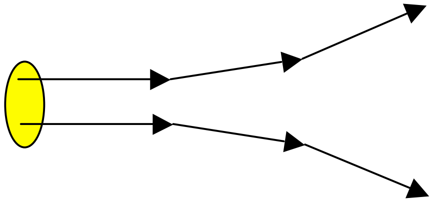
Resum using GLV the multiple scattering in impact parameter (B,b) space



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

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



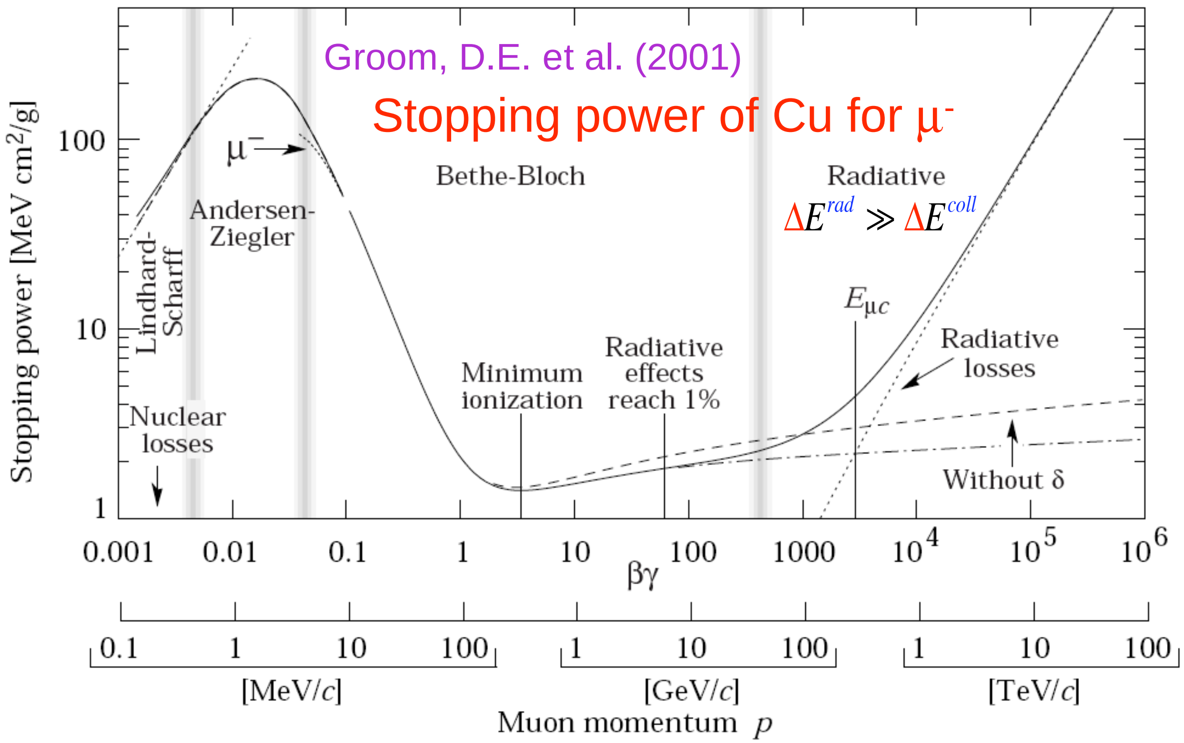


?

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

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

The Stopping Power of Matter



Groom, D.E. et al. (2001)

Stopping power of Cu for μ^-

$\Delta E^{rad} \gg \Delta E^{coll}$

- 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

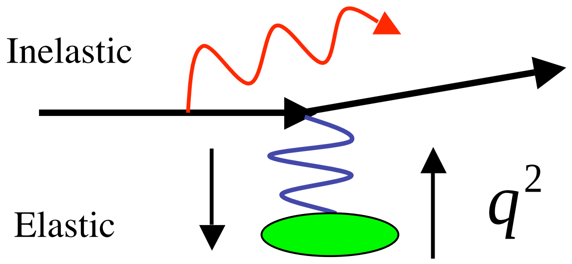
$$\frac{d\Delta E^{rad}}{dz} \approx \frac{16}{3}\alpha_{em}^3 z^4 Z^2 \rho_{num} \frac{1}{M^2} E \ln(\lambda\gamma)$$

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

- 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)



Toward Proper Comparison of ΔE^{rad} / ΔE^{coll}

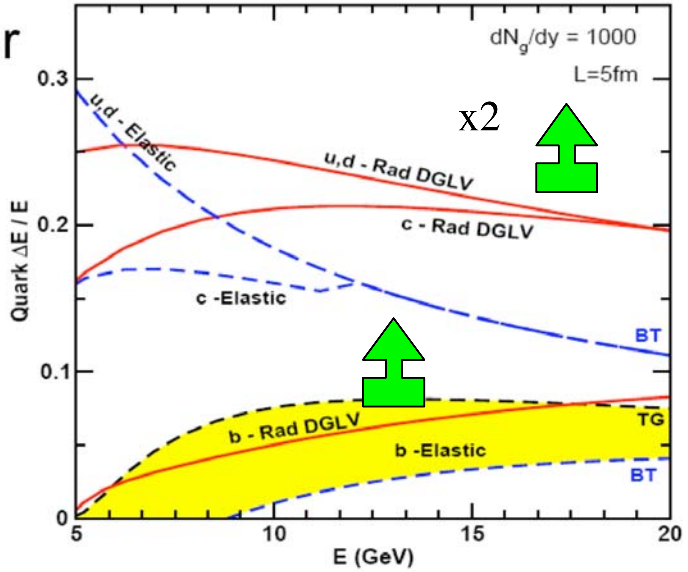
- LPM - new path length and energy behavior

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)



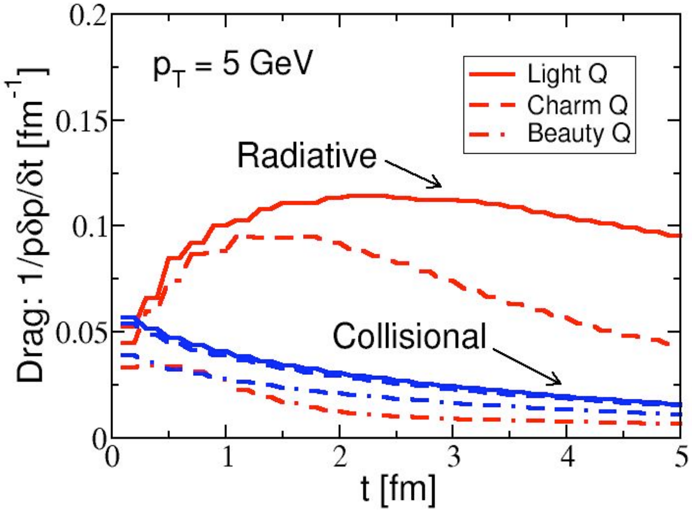
- Comparison in the the same model of the medium / momentum exchanges

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

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

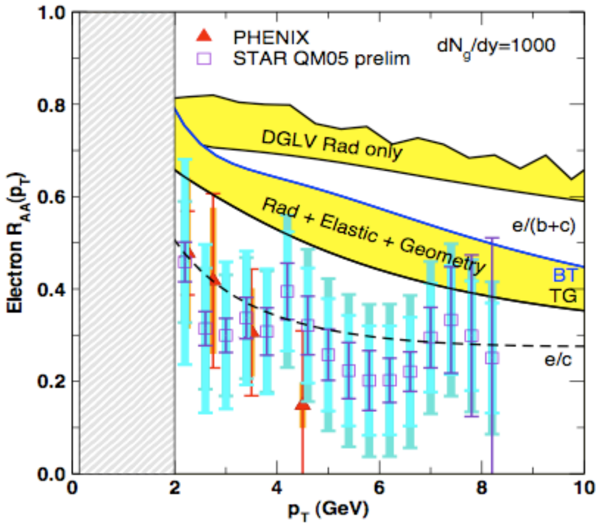
$$\frac{\mu^2}{\pi\left(q^2+\mu^2\right)^2} \to \frac{\mu^2}{\pi q^2\left(q^2+\mu^2\right)}$$

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



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

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± 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)

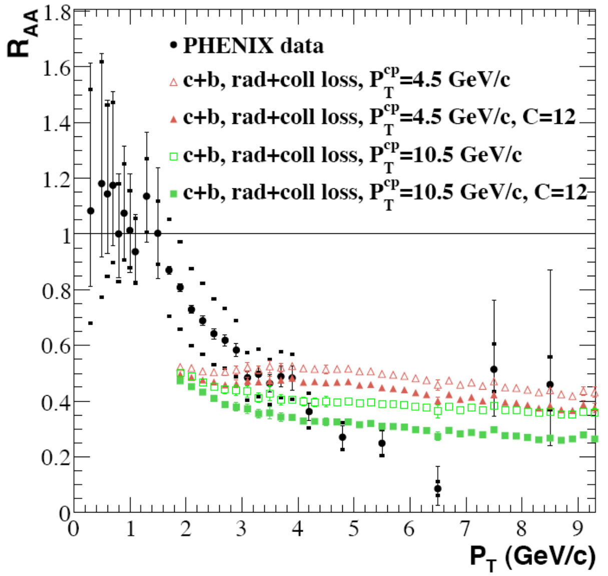
Charm baryon enhancement

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

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

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

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



Heavy Meson Dissociation at RHIC and LHC

Formation times of mesons/baryons

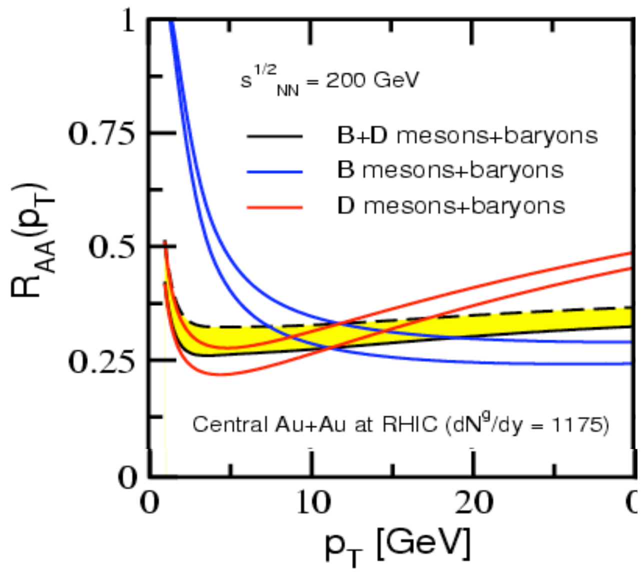
$$\Delta y^{+} = \frac{1}{\Delta p^{-}} = \frac{(0.2\ GeV.fm)\ 2z(1-z)p^{+}}{k_{\perp}^{2} + (1-z)m_{h}^{2} - z(1-z)M_{q}^{2}} \qquad \tau_{\rm form} = \frac{\Delta y^{+}}{1+\beta_{Q}}$$

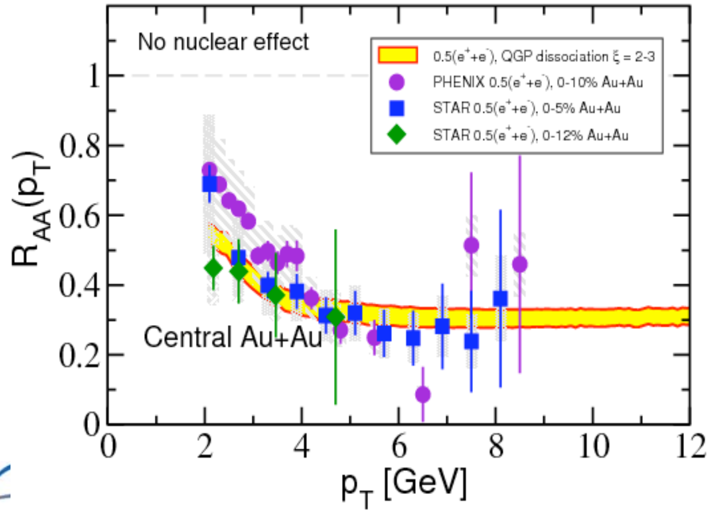
$\tau_{\rm form}(p_T = 10\ GeV)$	π	D	B
	20 fm	**1.5 fm**	**0.4 fm**

Adil, A. et al. (2007)

- Application to heavy resonances

Markert, K. et al. (2008)





- 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

Light hadrons as proxies to jets

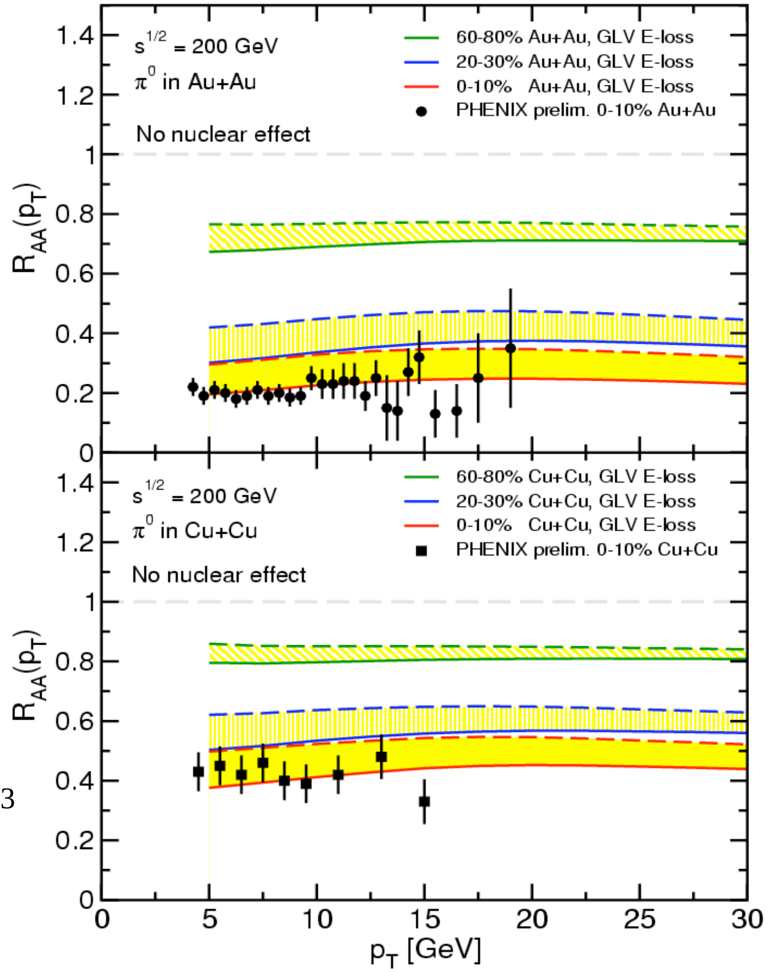
- Very "special" jets: atypical, sensitive to hadronization effects

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

– Static medium

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

– 1+1D Bjorken



$$T = 400 \;\; MeV$$

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

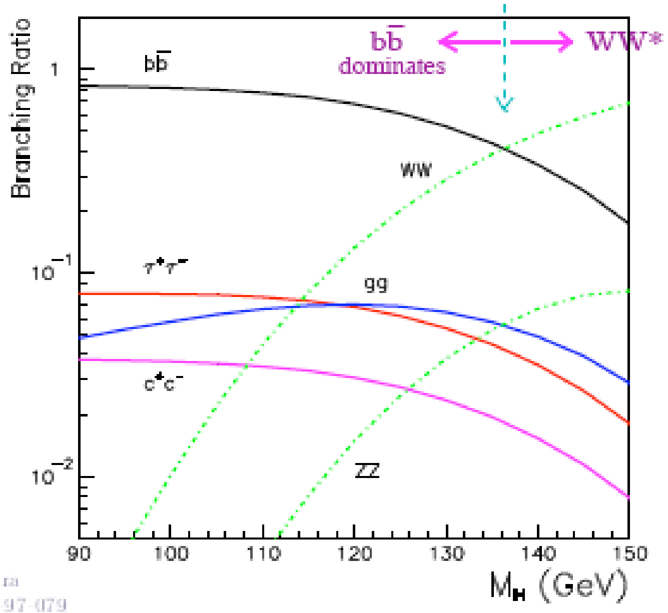
$$\langle\langle \hat{q} \rangle\rangle = 0.35 - 0.85 \;\; GeV^2.fm^{-1}$$

Significantly different values are indicative of theoretical inconsistency

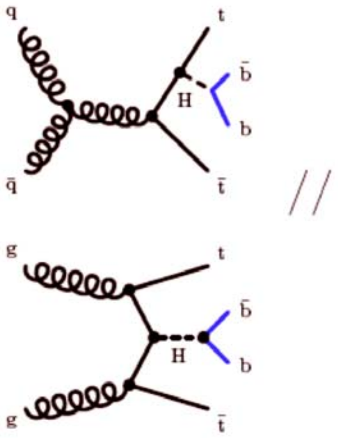
I.V., Phys.Lett.B 639 (2006)

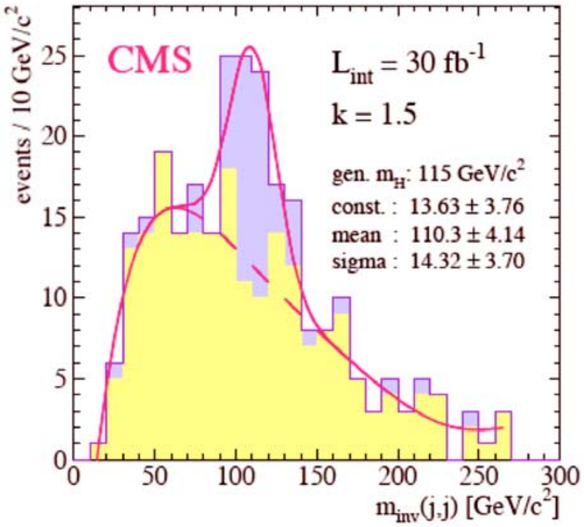
Golden channels (Higgs)

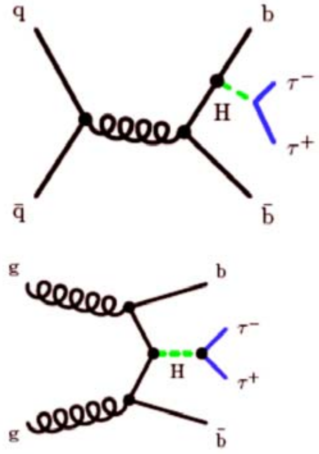
Branching ratios

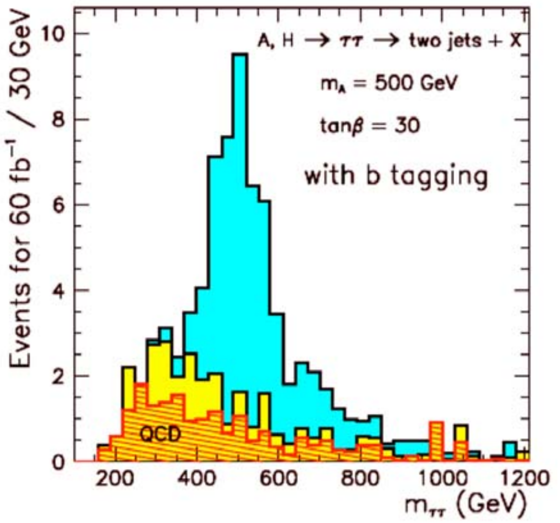


M. Spira
DESY-97-079









- Detected via:

$$b \rightarrow jet \qquad \tau \rightarrow jet$$

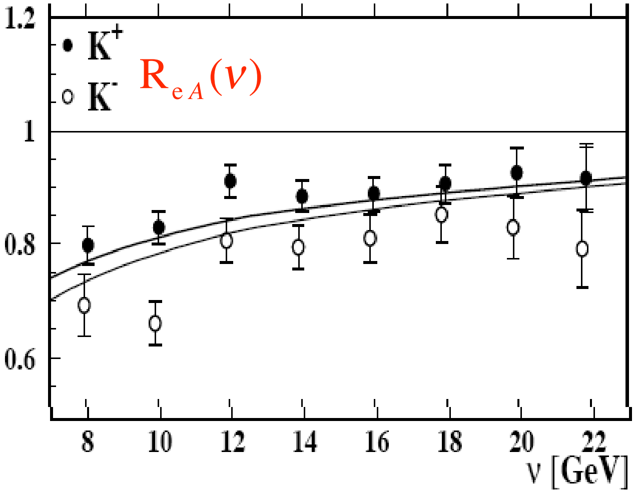
Jet physics as the basis for Higgs searches

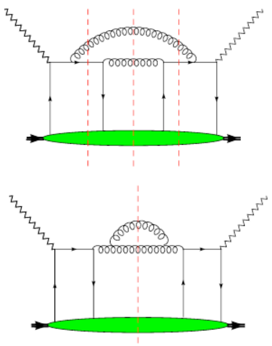
Coupling the Quark and Gluon Energy Loss

Jet quenching in SDIS - cold nuclei

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

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



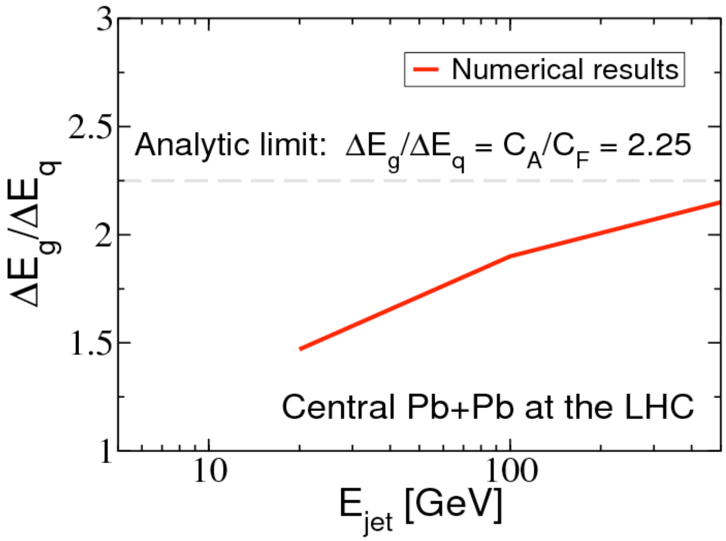


$\phi_q(x) > (\gg) \phi_{\bar{q}}(x)$

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

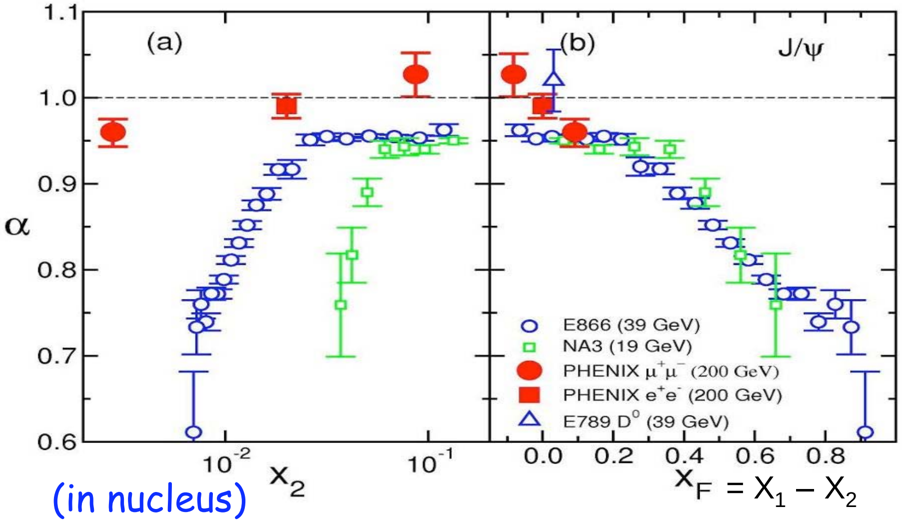
Liu, W. et al. (2007)



Gyulassy, M. et al. (2002)

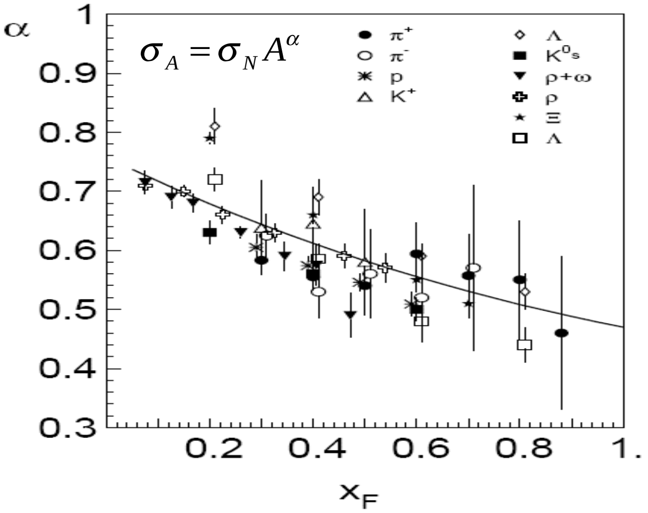
Theory of Cold Nuclear Matter Energy Loss

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



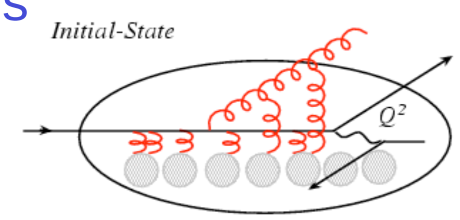
(in nucleus)

Gavin, S. et al. (1992)



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

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

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