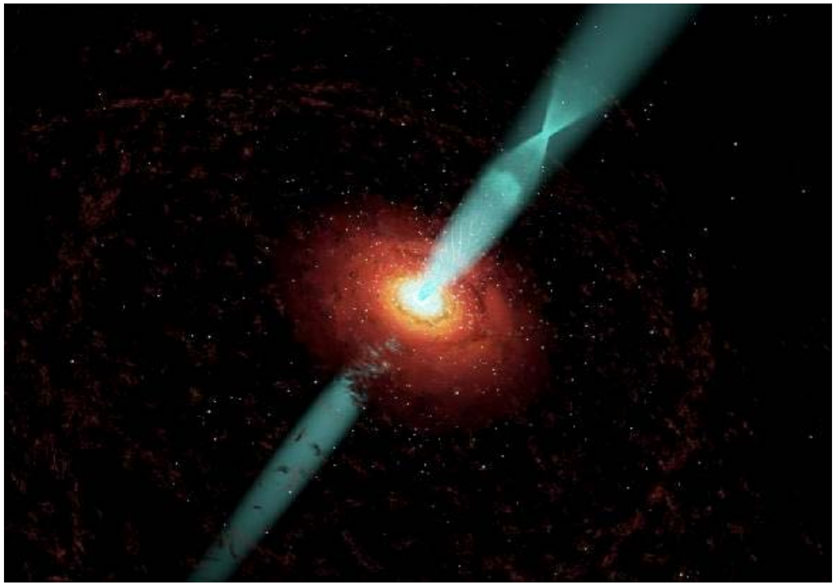
The Theory and Phenomenology of Jets in Nuclear Collisions



Ivan Vitev, Nuclear Theory, T-16 , LANL

Work done with S. Wicks and B. W. Zhang

Key points / preliminary results can be found in arXiv:0806.0003

Hot Quarks 2008

August 18-23, Estes Park, CO

Outline of the Talk

Motivation

- What I will not talk about - the inclusive particle R_{AA}: pros and cons
- The interface between particle and high energy nuclear physics: new opportunities

Jet shapes in elementary collisions

- Jet finding algorithms and jet shapes in elementary N-N collisions
- Theory: fixed order, 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

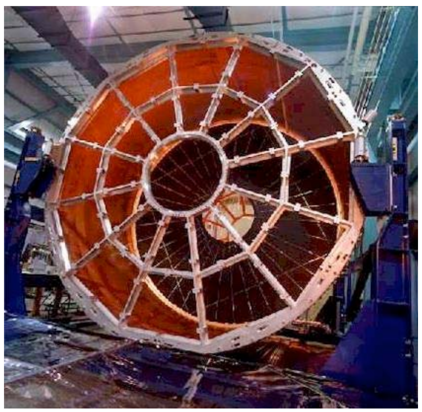
Results, some not so expected

- The (practically) decorrelated quenching of jets and jet shapes

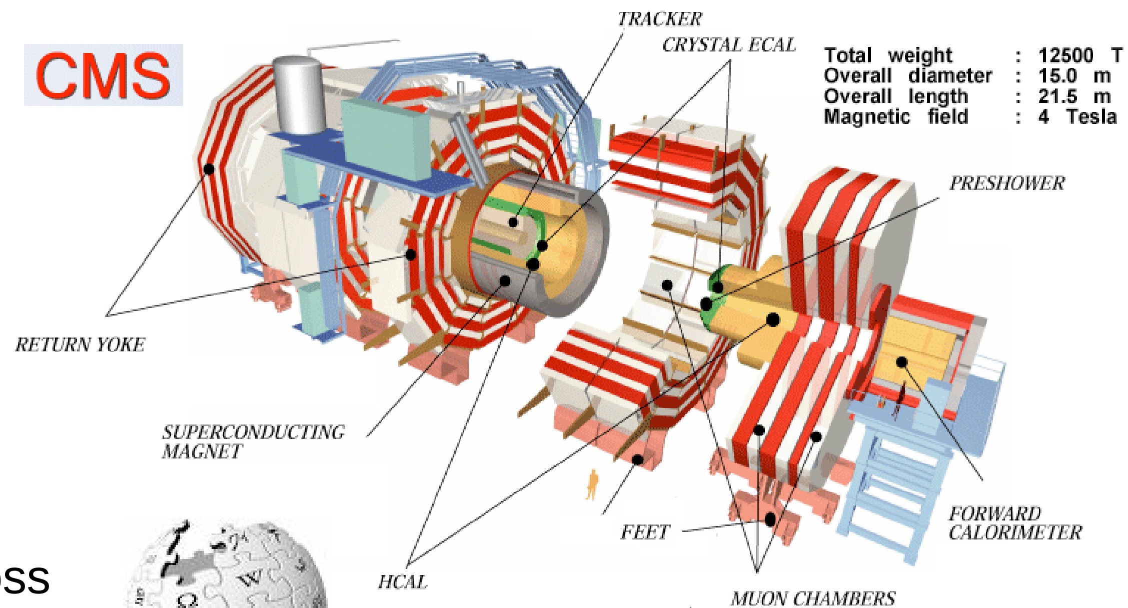
Energy Loss, Significance

Energy Loss: the most significant and experimentally important effect of charged particle propagation in matter

- Keeps in business the larger (experimental) part of the physics community since virtually every detector operates on those principles



TPC: collisional E-loss (ionization)
EMCAL: radiative QED E-loss (EM-shower)
HCAL: QCD E-loss (radiative hadronic shower)



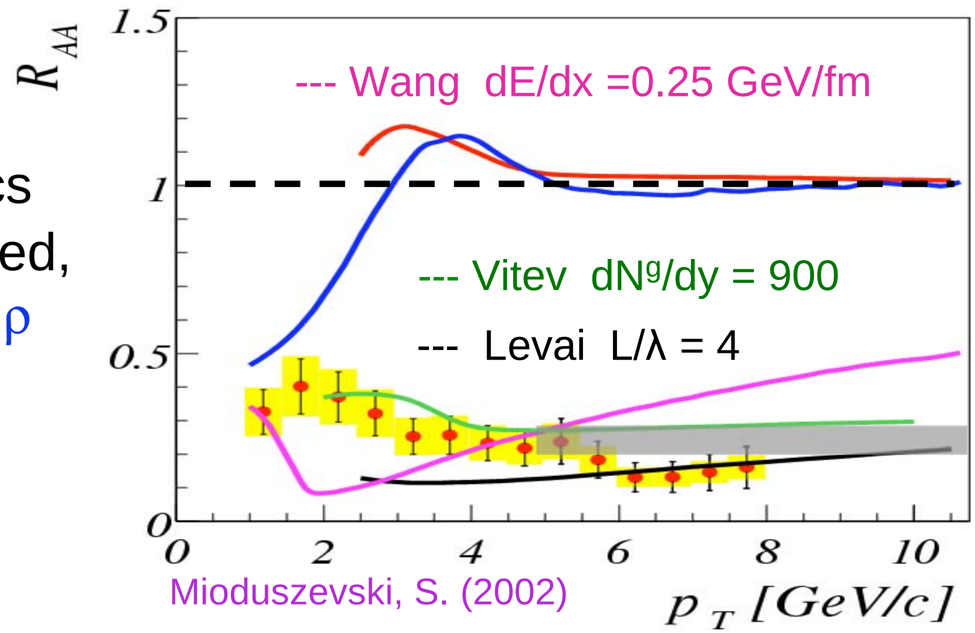
WIKIPEDIA
The Free Encyclopedia

http://en.wikipedia.org/wiki/Particle_detector

Few Real Predictions (Before Mid 2002)

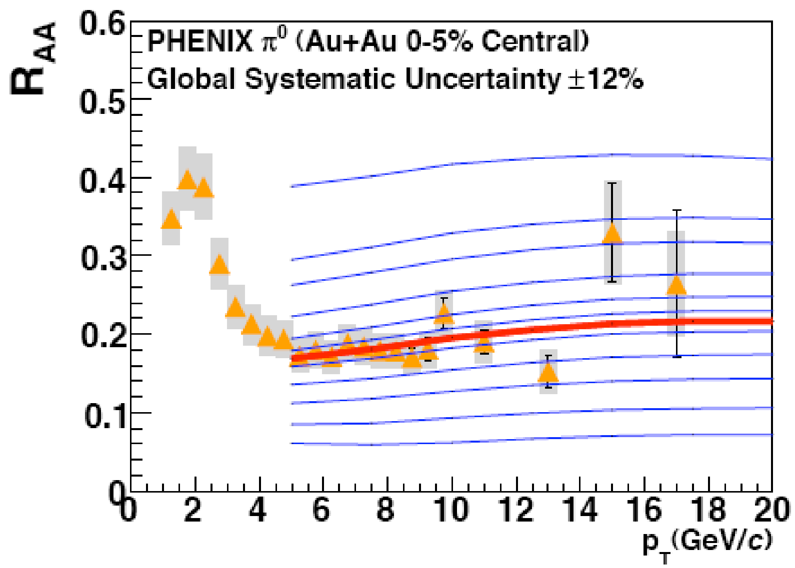
- Before the real high p_T data appeared

- Advantages of R_{AA} : clear physics interpretation, theoretically predicted, experimentally understood, ±30% ρ and ±10% T



Mioduszevski, S. (2002)

Gyulassy, M. et al (2000)



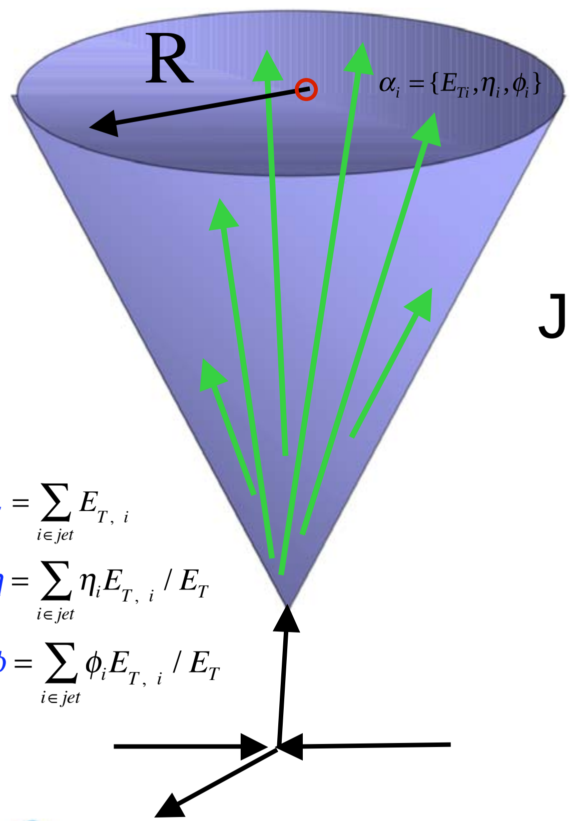
Adare, A. et al. (2008)

- Disadvantages: unable to resolve the order of magnitude systematic uncertainty in the medium density and a factor of two in temperature
- Generalize R_{AA} keeping the best features to a more differential observable

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

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

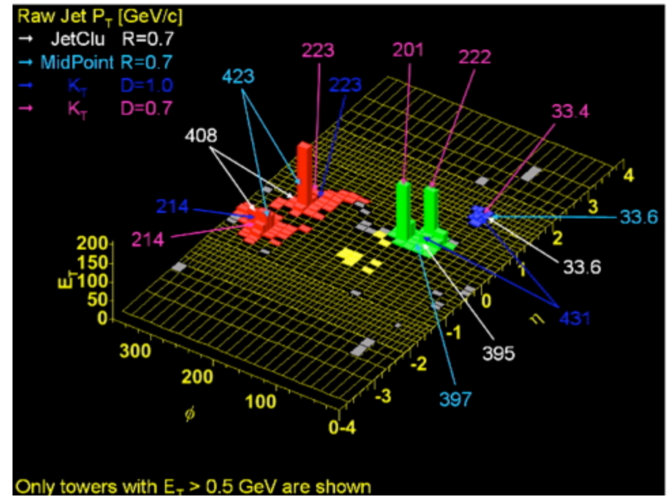


$$E_T = \sum_{i \in jet} E_{T,\,i}$$

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

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

Sterman, G. et al. (1977)



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)

Planned Discovery of Supersymmetry

Theoretical appeal

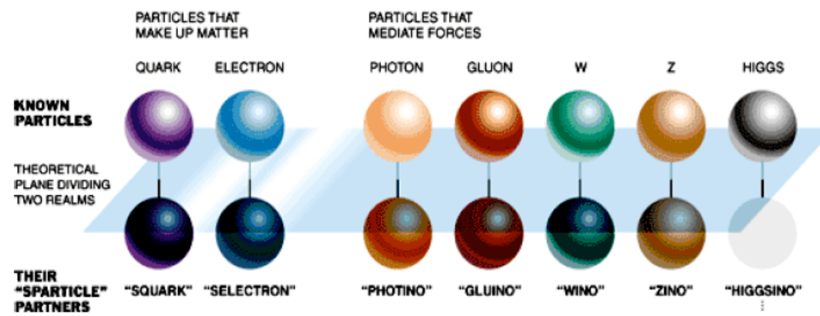
- Stabilizes the electro-weak symmetry breaking scale against radiative correctior
- Unification of the coupling constants
- Excellent candidate for cold dark matter

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

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

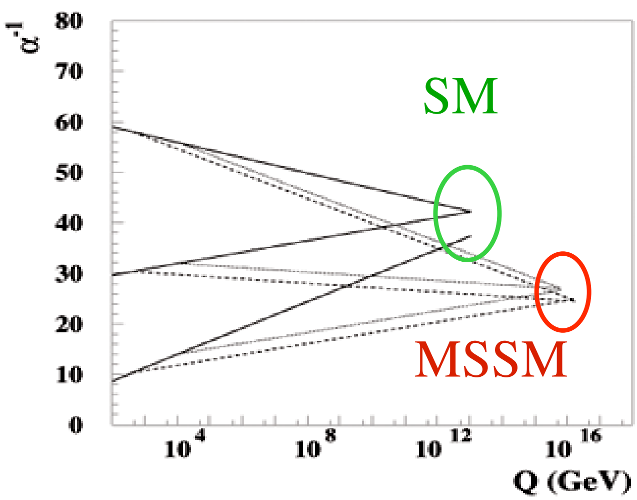
supersymmetry

fermions ⟷ bosons



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

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

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

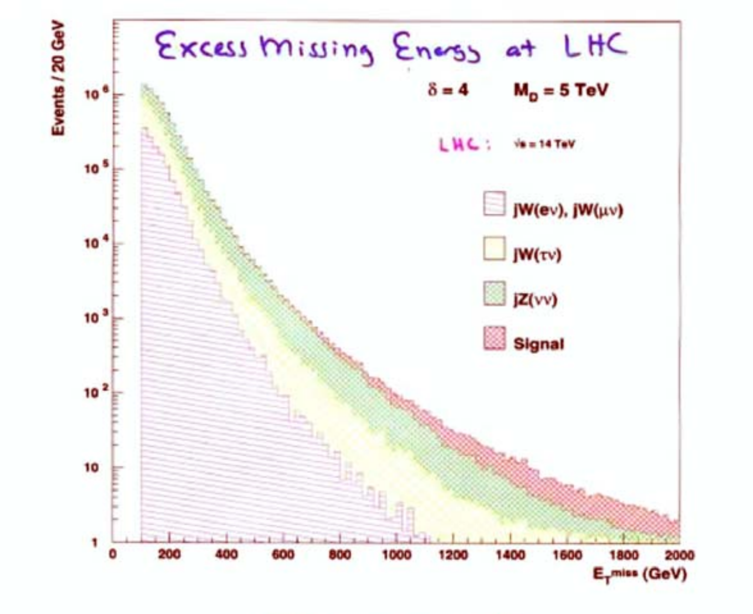
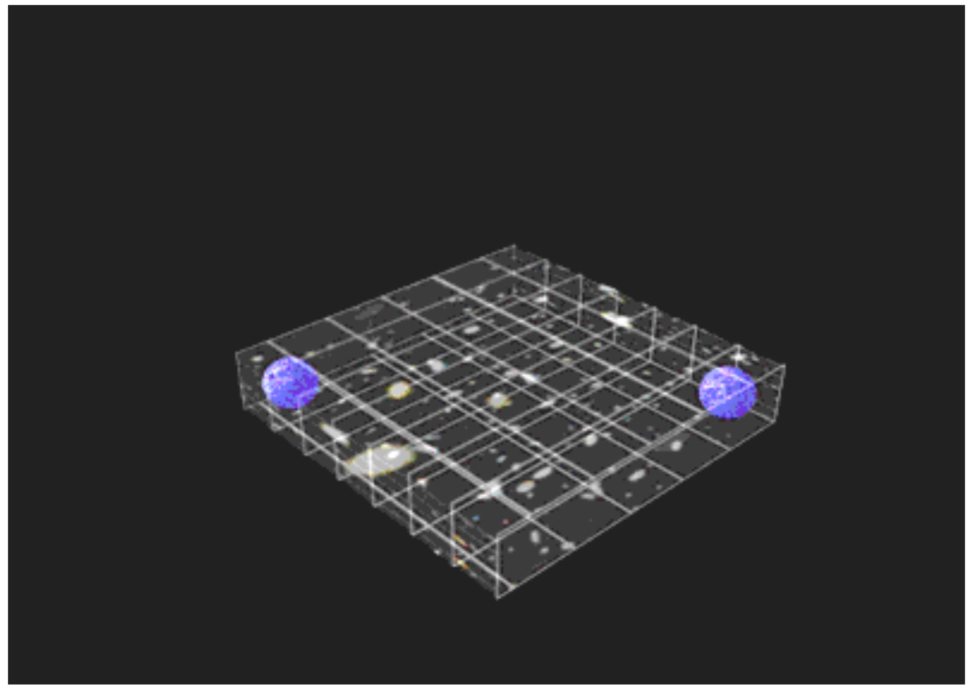


Figure 1: Missing energy spectrum at the LHC.



- Connecting HEP and NP

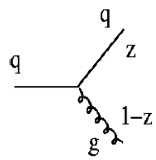
Jet Shapes in QCD: the p+p Baseline I

An analytic approach to the energy distribution of jet

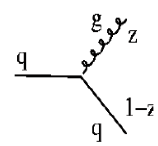
Seymour, M. (1998)

QCD splitting kernel

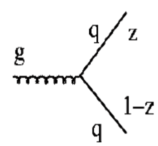
$$dP_a = \frac{\alpha_s}{2\pi}\frac{d\rho^2}{\rho^2}\frac{d\phi}{2\pi}dzP_{a\to bc}(z)$$



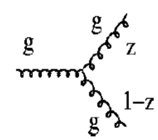
$$P_{qq}^{(1)}(x) = C_2(F)\left[(1+x^2)\left(\frac{1}{1-x}\right)_+ + \frac{3}{2}\delta(1-x)\right]$$



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



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



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

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

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

- LO adapted to heavy ion studies

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

$$z_{\min} = p_{T\,\min}/E$$

- 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

Webber., B. et al. (1986)

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

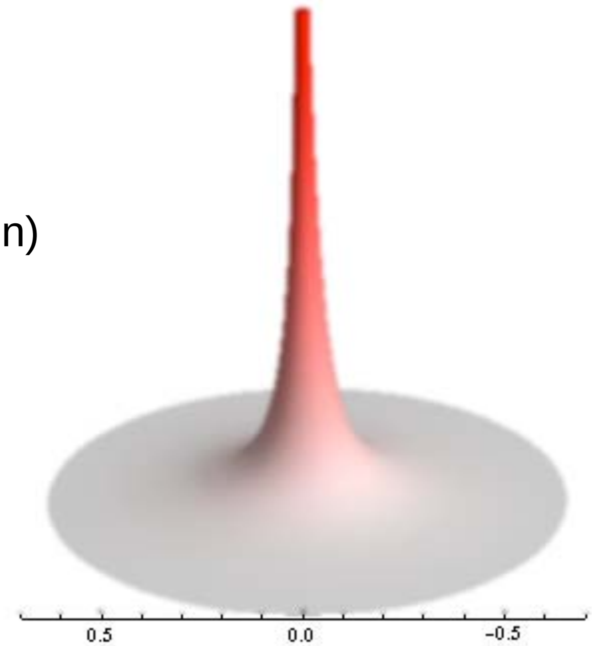
$$\psi_{pow.}(r,R) \sim \frac{C_i}{2\pi}\frac{2}{r}\left(\frac{Q_0}{rE_T}\right)(\bar{\alpha}_s(Q_0)+\ldots)$$

Scale of non-perturbative effects (hadronization)

Initial state radiation

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

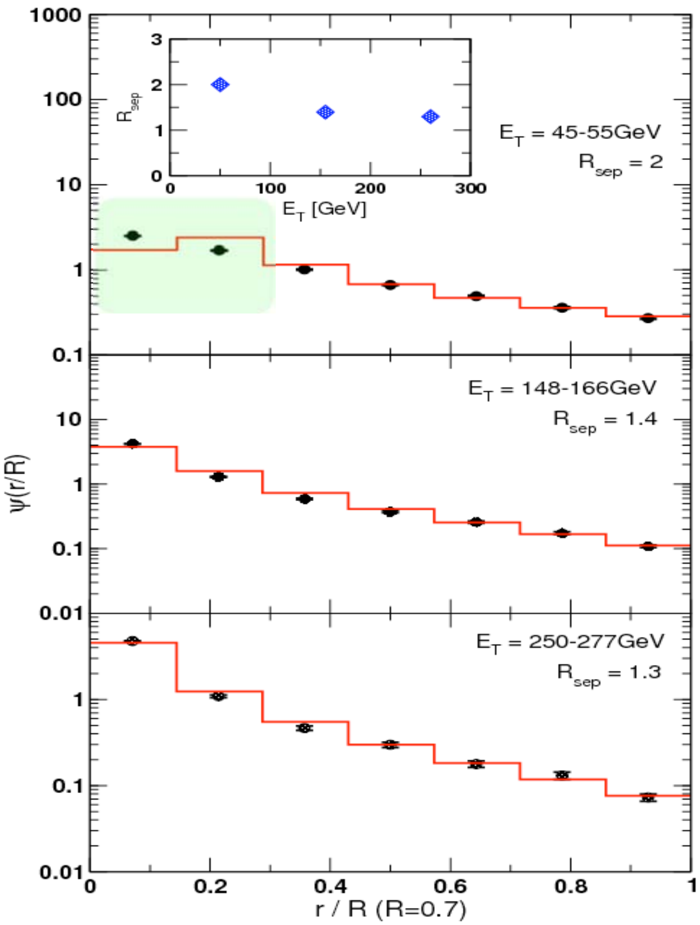
Not important in $e^+ + e^-$ but important in p+p



- Final expression: resummed, matched, and power corrected

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

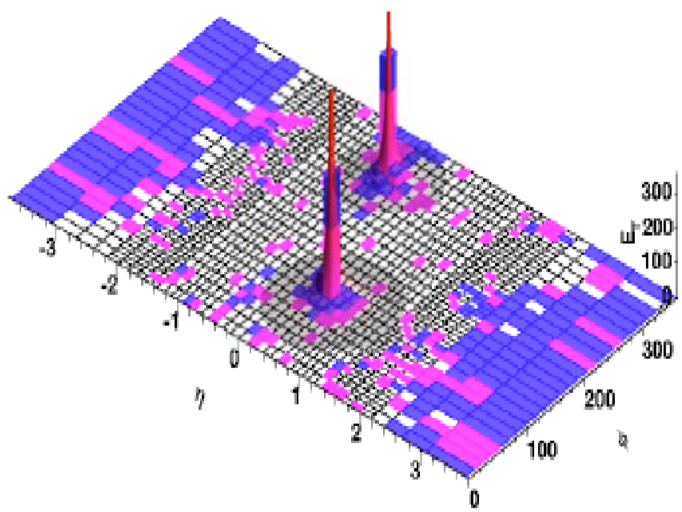
Comparison to the Tevatron Data



Note the logarithmic scale!

- Energy distribution $\Psi(r,R) = \frac{\sum_i E_{Ti}\Theta(r - R_{ijet})}{\sum_i E_{Ti}\Theta(R - R_{ijet})}$
- Shape function $\psi(r,R) = \frac{d\Psi(r,R)}{dr}$
  - Very good description of the "tails" r/R > 0.3
  - For large gluon fractions E_T < 50 GeV and r/R < 0.3 only qualitative description of the flattening

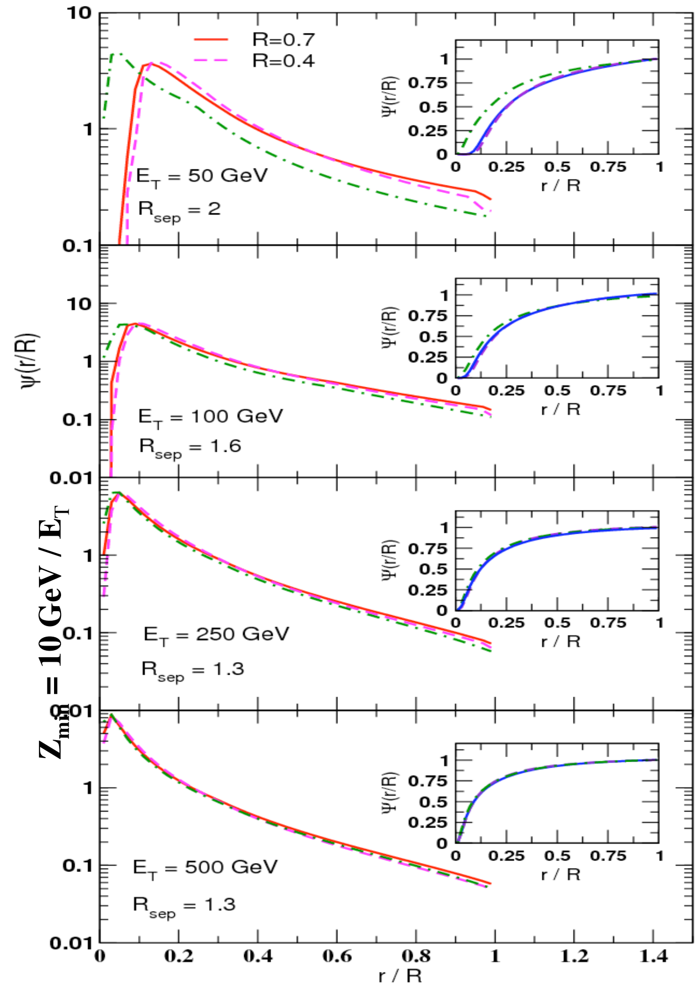
MLLA, initial state contribution, power corrections, \`R_{sep}' algorithm adjustment factor



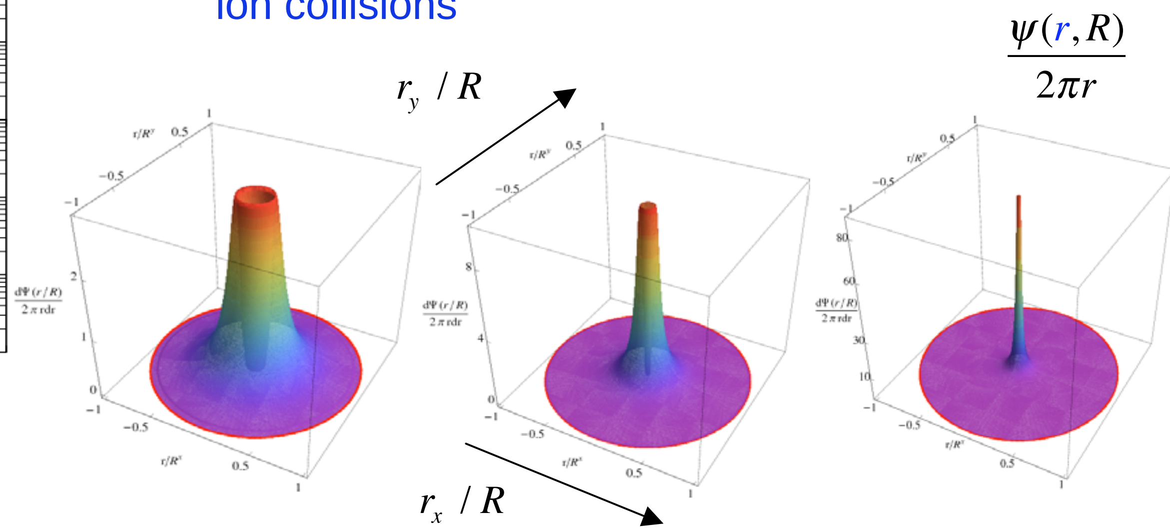
V., I et al. (2008)

Perez-Ramos, R et al. (2007)

Baseline shapes at the LHC



- Very similar jet shapes at the LHC and the Tevatron
  - As a function of the jet opening angle (R=0.7, 0.4 ,…) the jet shapes are self similar
  - First studies have been carried with a z_{min} cut. 10-20% of the energy must be missed to significantly affect the shape
  - The shapes in p+p change significantly with E_T. ~ 10 fold. Very important implications for heavy ion collisions

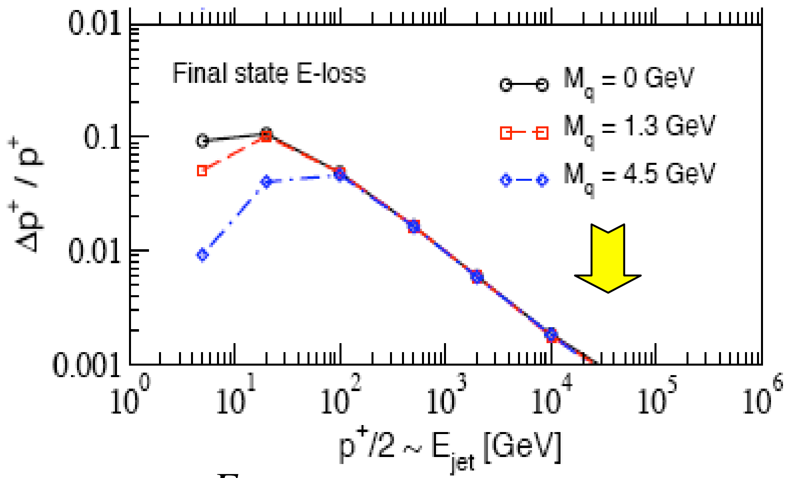


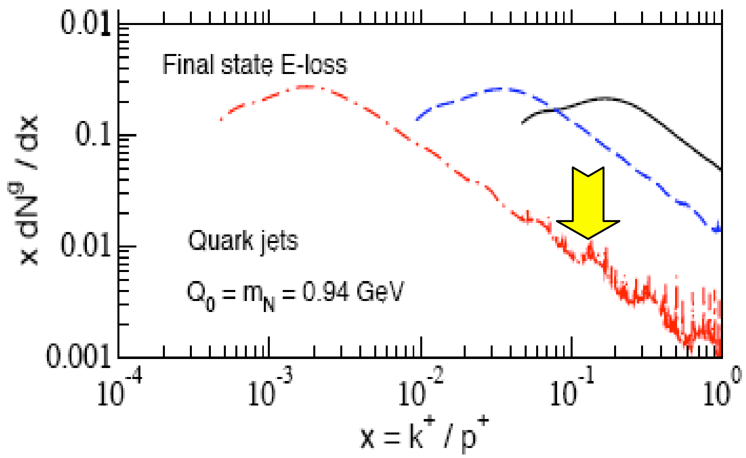
V., I et al. (2008)

Medim-Induced Jet Shape Functions

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

ΔE^{rad} LPM suppressed $\qquad \longleftarrow \quad \dfrac{dI^{rad}}{d\omega}(\omega)$ suppressed

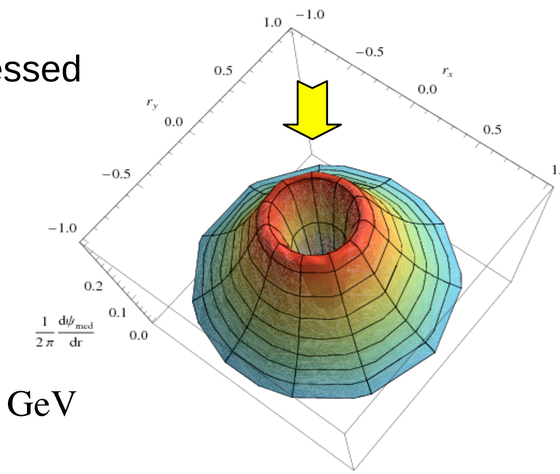




$$\Delta E^{rad} \sim L^2 \ln \frac{E}{E_c}$$

V., I. (2005)

$\longleftarrow \quad \displaystyle\int d\omega \frac{dI^{rad}}{d\omega dr}(r)$ suppressed



- Can be see in other approaches to the energy loss (HT is very similar to GLV, written in different variables)

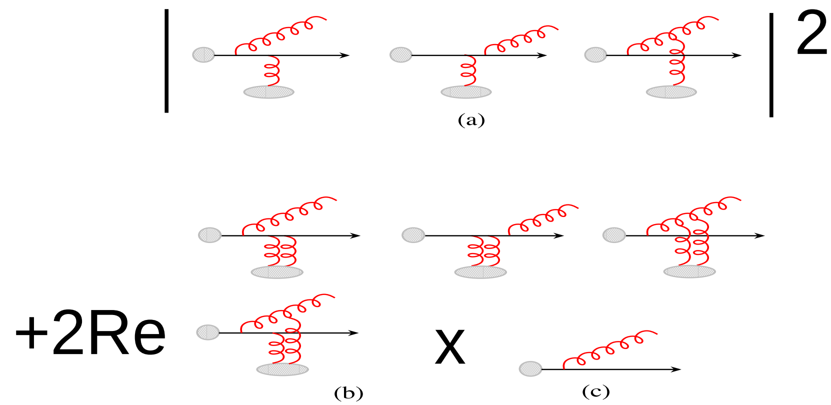
Majumder, A. et al. (2005)

E_{jet} = 20 GeV

An Analytic Approach

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

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



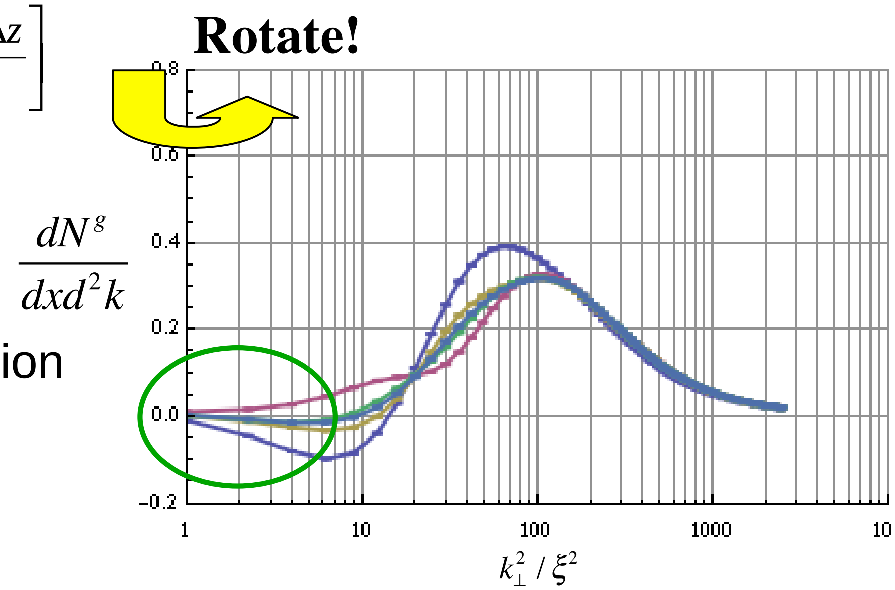
$$\frac{dN^{g}{}_{med}}{d\omega d\sin\theta^* d\delta} \approx \frac{2C_R\alpha_s}{\pi^2} \int_{z_0}^{L} \frac{d\Delta z}{\lambda_g(z)} \int_0^{\infty} dq_\perp q_\perp{}^2 \frac{1}{\sigma_{el}} \frac{d\sigma_{el}}{d^2 q_\perp}$$

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

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

- Proven now to all orders in opacity

- Incompatible with Sudakov resummation (absence of large logs)



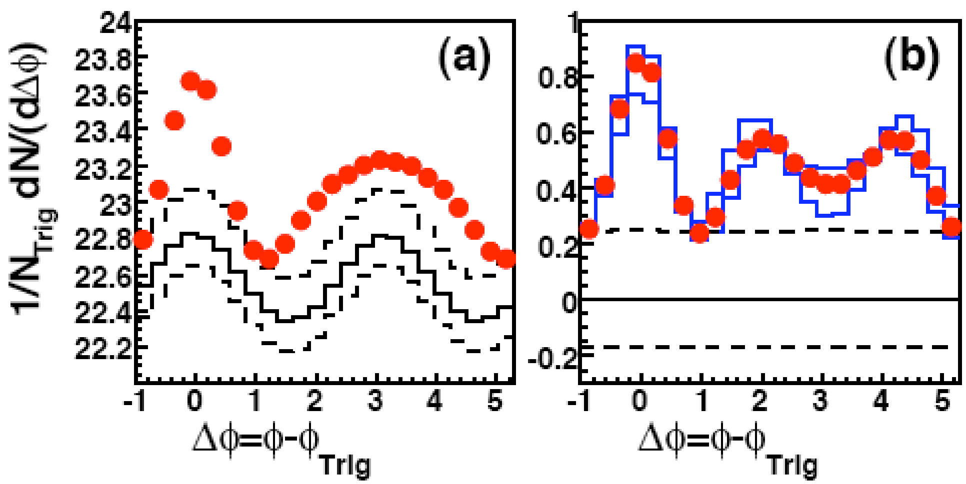
Wicks, S. (2008)

A Differential Approach to Particle Correlations

2D analysis reveals rich structure

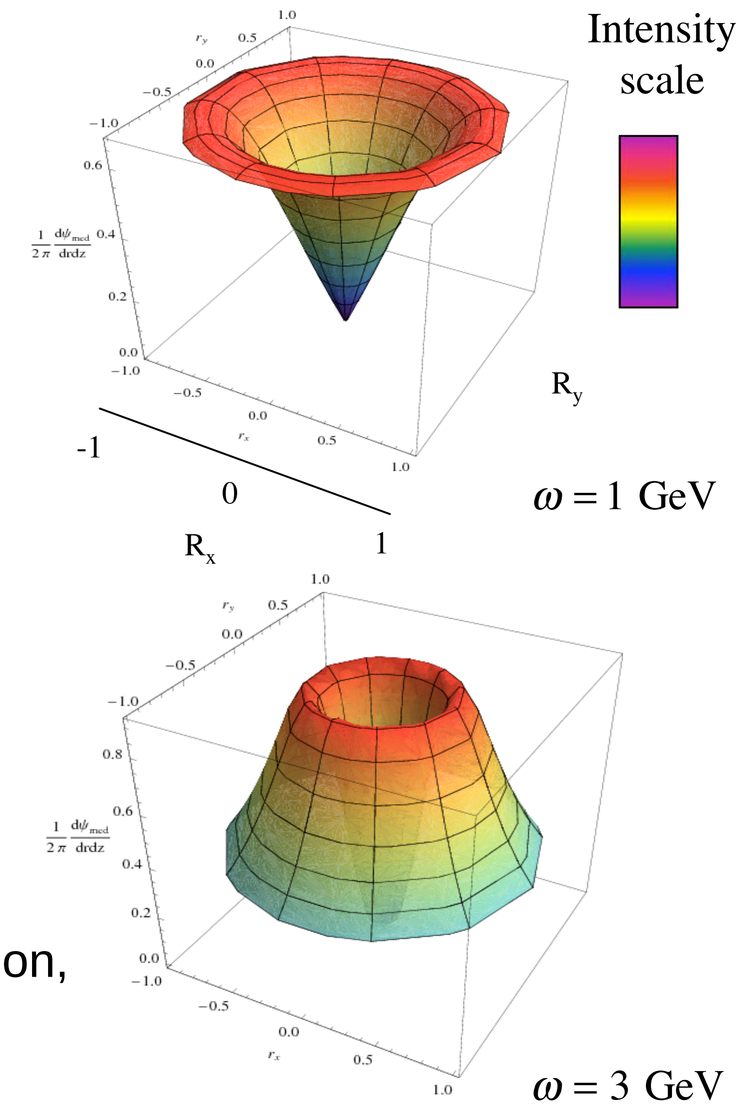
$$\frac{1}{2\pi}\frac{d\Psi^{med}}{drdz} = \frac{1}{\Delta E^{rad}}\frac{dI^{rad}}{d(\omega / E_{jet})dr}$$

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



- However: acoplanarity, rapidity distribution, subtraction of v_2

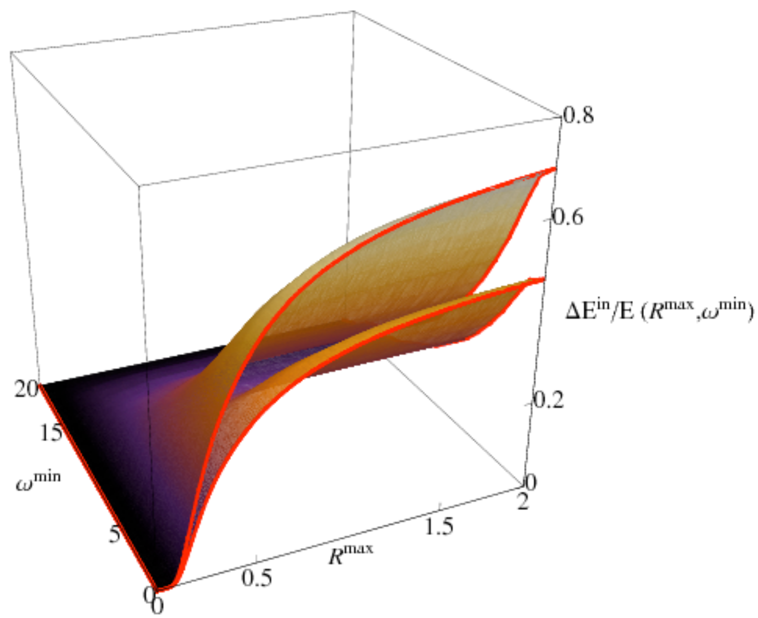
Polosa, A. et al. (2007)

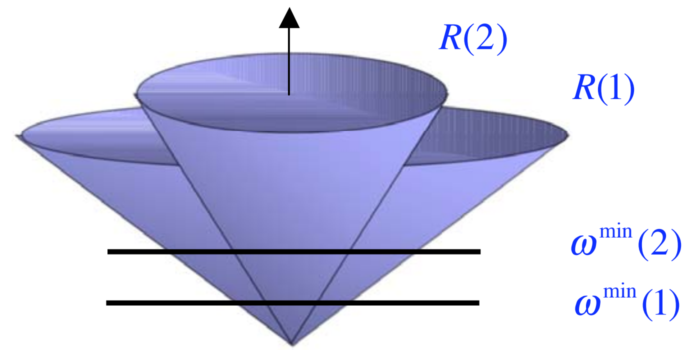


Energy Loss Distribution

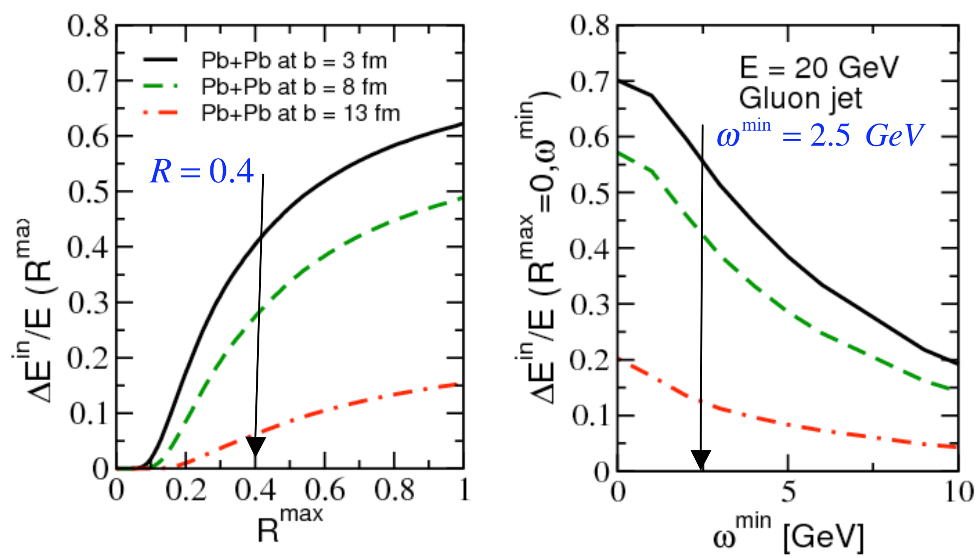
A good energy loss theory should be able to give differential results

$$\frac{\Delta E^{\rm out}(R^{\max},\omega^{\min})}{E} = \frac{1}{E}\int_0^{R^{\min}} dr \int_{\omega^{\min}}^{E} d\omega \;\frac{d\,\mathrm{I}^{\rm med}}{d\omega dr}(\omega,r)$$





V, I. et al. (2008)



Suppression of backgrounds

Large leverage arm

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Generalizing R_{AA}

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

"Vacuum" contribution

May need higher energy

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

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

Guidance: sum rules (approximate and exact, depending on quantum numbers)

$$\int_0^1 zD_{h/q,g}(z)dz = 1$$

"Exact"

$$z = p_{T;h} / p_{T;q,g}$$

$$\int_0^1 D_{h/Q}(z)dz = 1, \;\; Q = c,b$$

"Approximate"

- Energy sum rule:

Note: cross sections and particle numbers not conserved

$$f \to 1$$

Ping $\frac{1}{\sigma}\frac{d\sigma^{pp}}{d^2E_T dy} = \delta^2(\vec{E}_T - \vec{E}_0)$

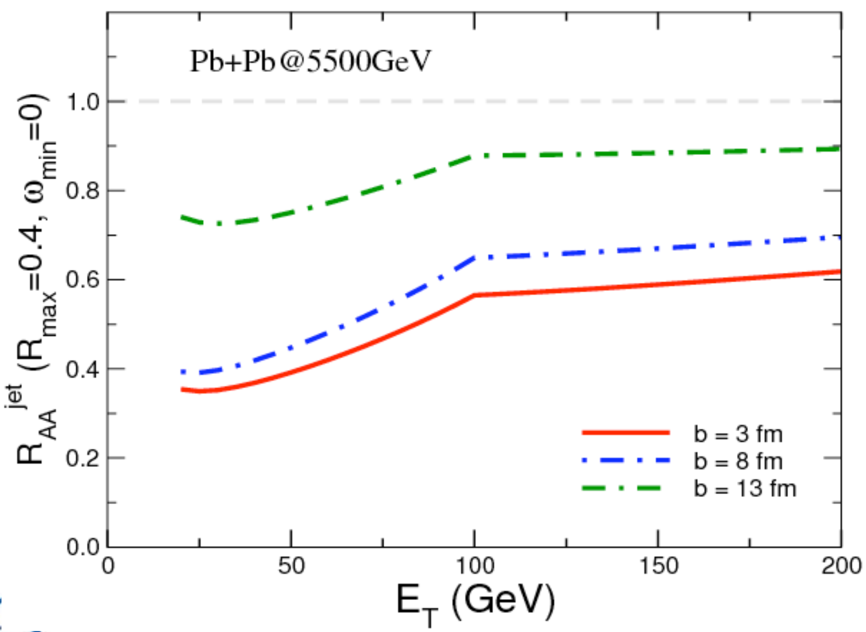
Verify $\int d^2E_T \, \frac{1}{\sigma}\frac{d\sigma^{AA}(R\to\infty,\omega^{\min}\to 0)}{d^2E_T dy} E_T = E_0$

Numerical Results: R_{AA} vs Centrality

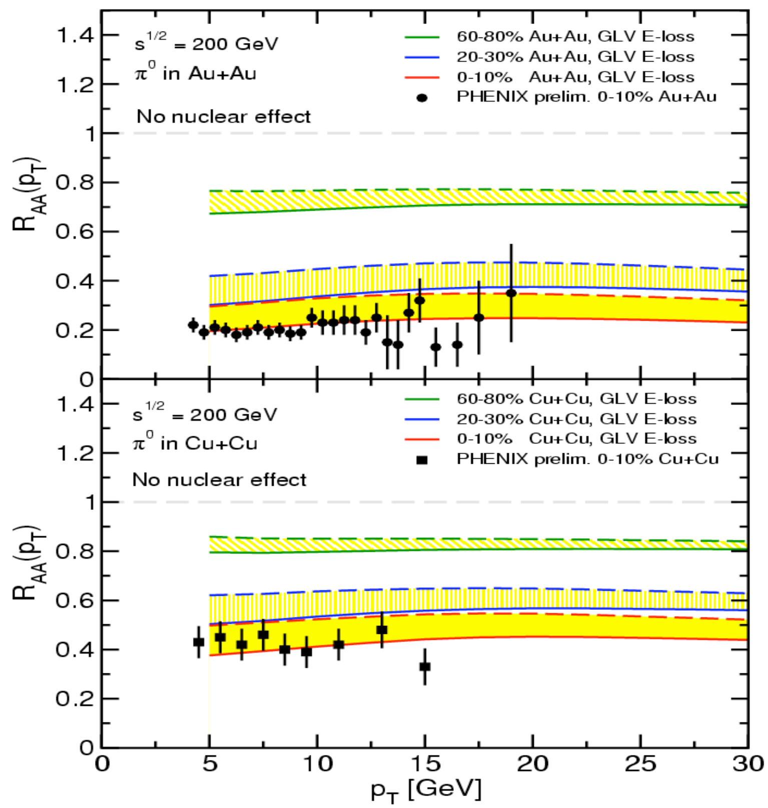
- Full numerical simulation:

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

Note: exact numerical results only 20 GeV, 100 GeV and 500 GeV medium jet



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

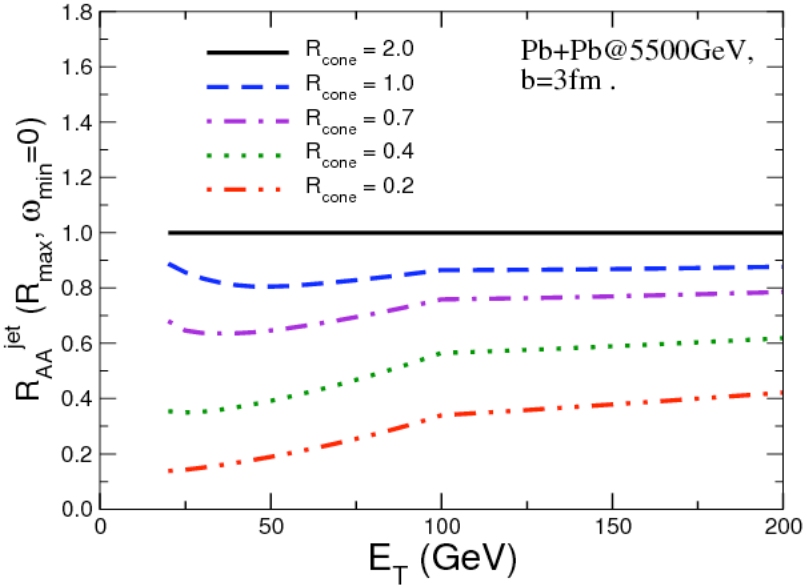


V, I. (2006)

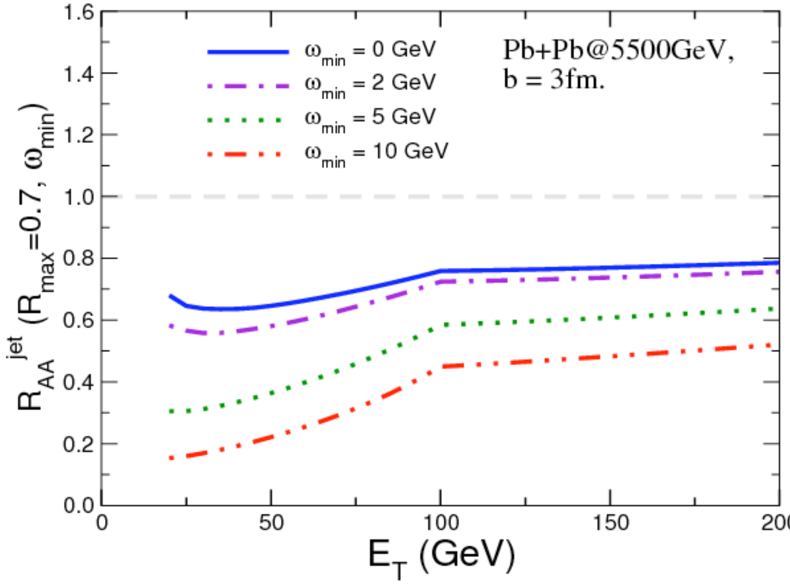
- Retain all known handles from RHIC

New Handles / Results: R_{AA} vs R_{cone} and ω_{min}

- Using R_{cone}



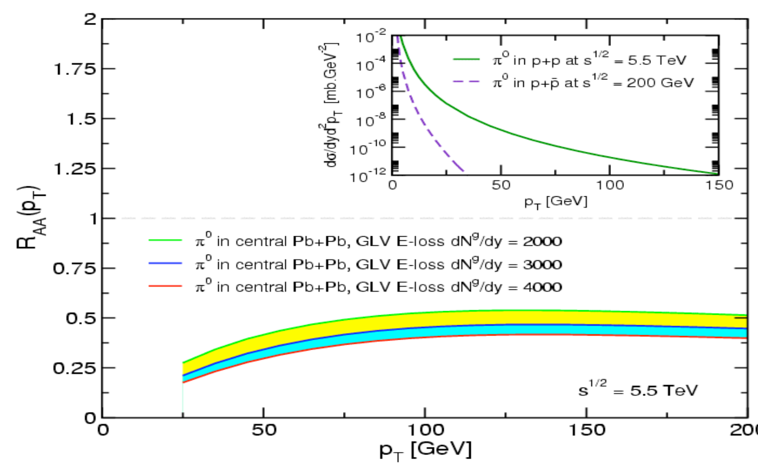
- Using ω_{min}



- At any E_T (20 GeV - 200 GeV shown) there is the ability to reconstruct experimentally the characteristics of energy loss
- Contrast: single result for leading particle

V., I. (2006)

Armesto, N. (ed) et al. (2008)

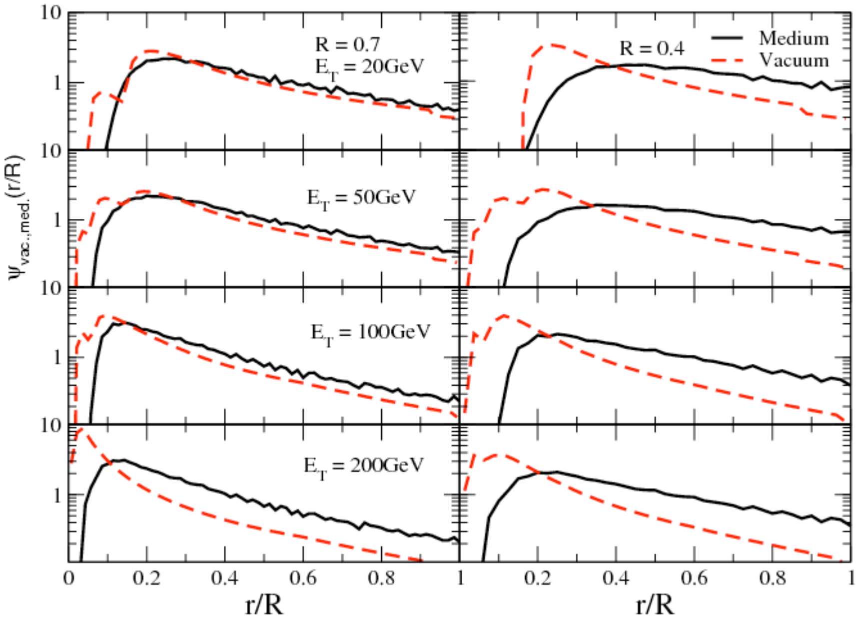


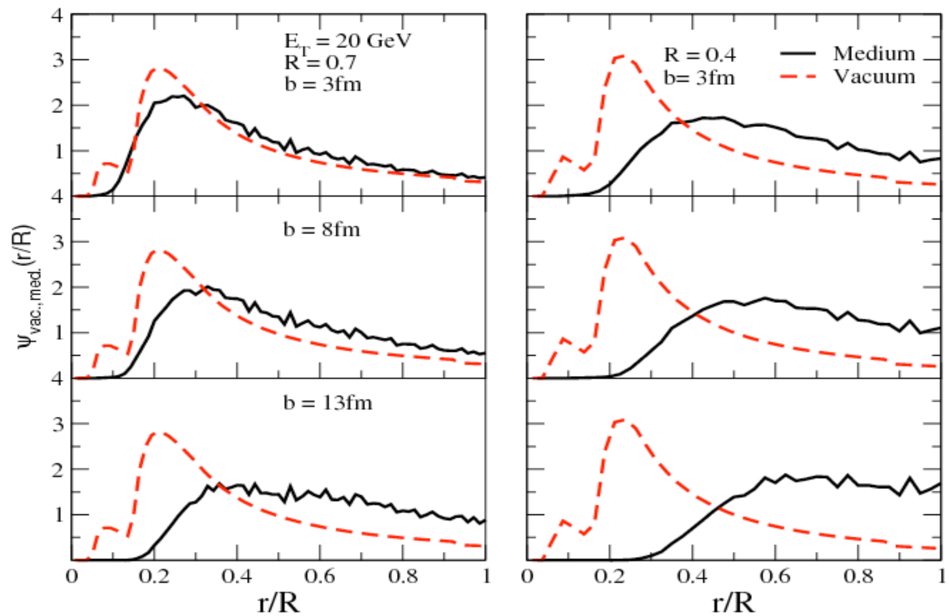
Jet Shapes in the Medium

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

“Vacuum” contribution **Medium contribution**

Normalization is the quenched jet cross section





- If all energy is lost one can easily (e.g. selecting R=0.4) identify this broadening. Note: the broad medium distribution ~ centrality independent

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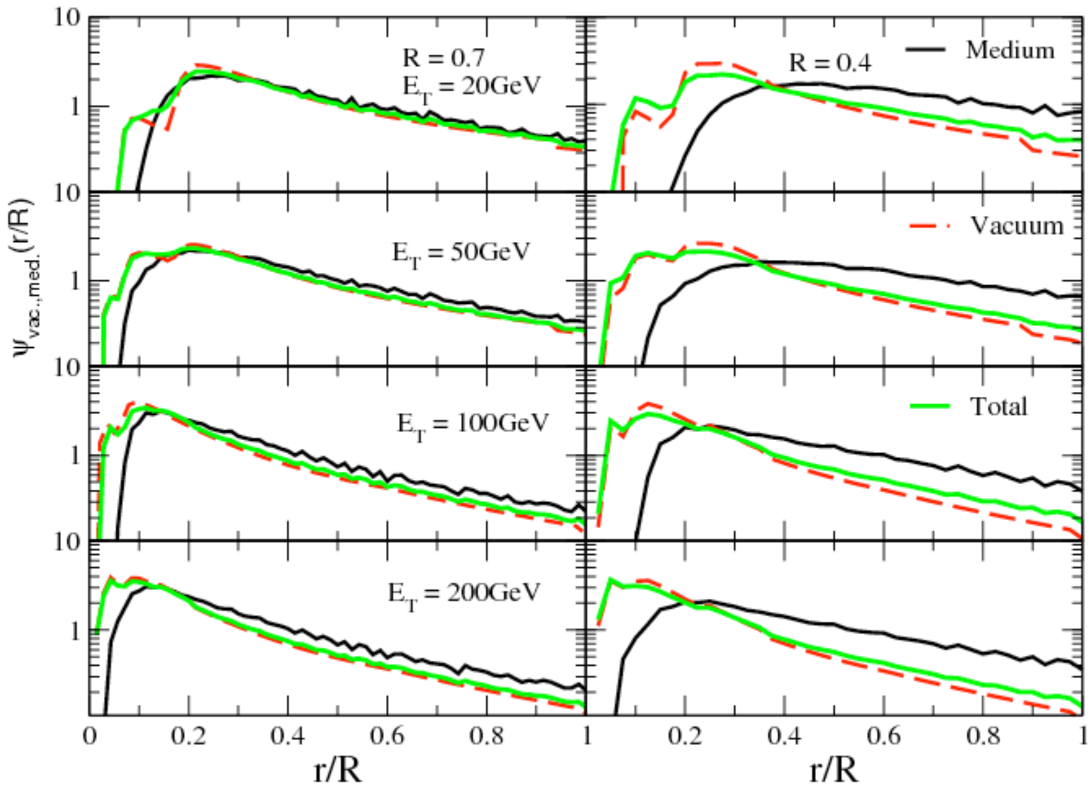
- What you don’t see are the actual energy loss distributions

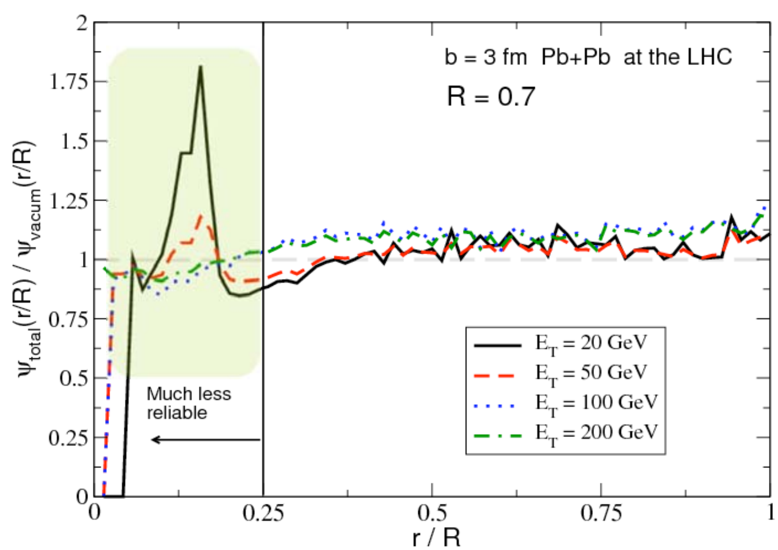
Final Results



- In the limit of 100% E-loss (perfectly opaque, **black**) there can be significant jet broadening ~ 75%

- In reality the jets are similar to the ones in vacuum.

Explanation …



- The larger deviations from unity are a result of uncertainties in the p+p baseline, not the medium-induced contribution

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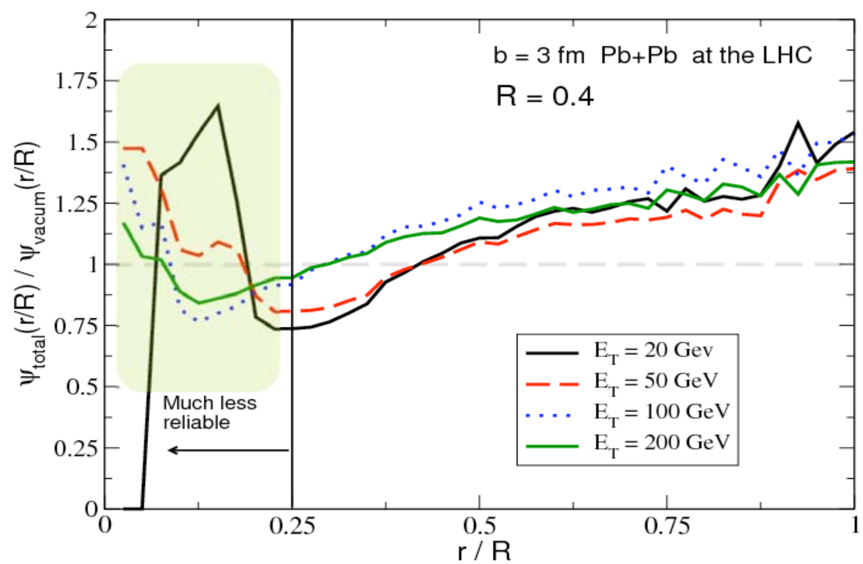
Calculating Mean Jet Radii

R = 0.4	Vacuum	Complete E-loss	Realistic Case
< r / R > E_T = 20 GeV	0.41	0.57	0.43
< r / R > E_T = 50 GeV	0.35	0.53	0.37
< r / R > E_T = 100 GeV	0.28	0.42	0.31
< r / R > E_T = 200 GeV	0.25	0.42	0.27

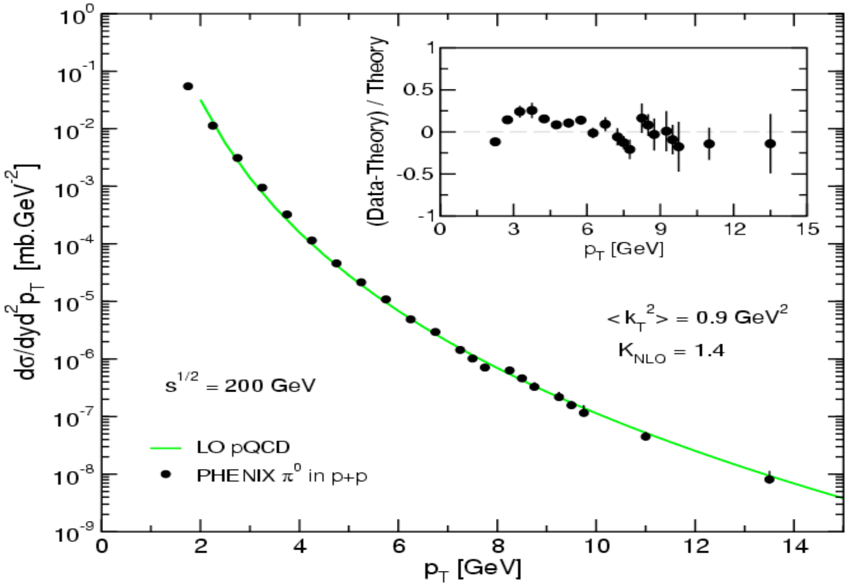
R = 0.7	Vacuum	Complete E-loss	Realistic Case
< r / R > E_T = 20 GeV	0.41	0.45	0.42
< r / R > E_T = 50 GeV	0.33	0.41	0.36
< r / R > E_T = 100 GeV	0.27	0.34	0.29
< r / R > E_T = 200 GeV	0.24	0.32	0.26

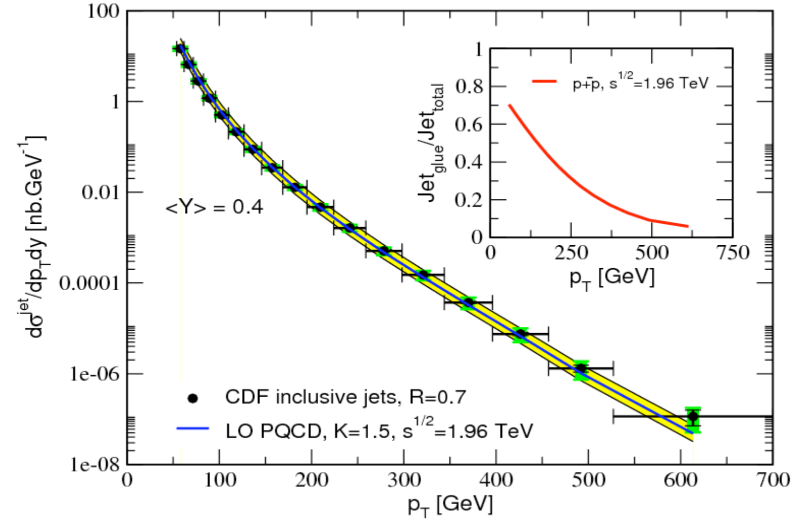
$$\langle r/R \rangle = \int_0^1 r/R \; \psi_{vac.,med.,tot.}(r/R)\, d(r/R)$$

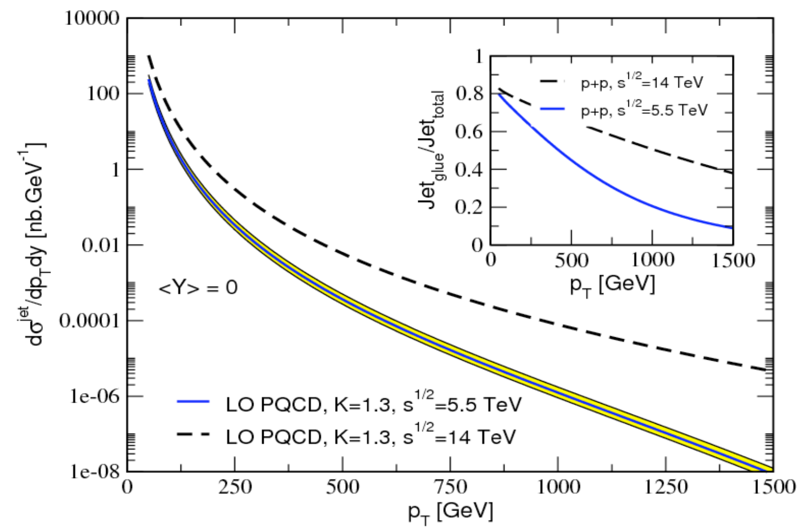


- The medium is gray! The shape is characterized by mean radii and there is very little difference between the vacuum and total shapes.
- Excellent statistics is needed at the LHC to detect the r/R > 0.5 change.

Feasibility of Jet Measurements







- 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

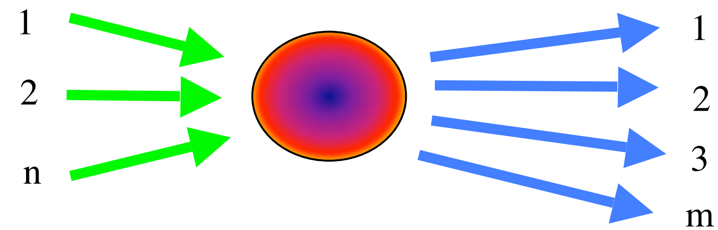
Conclusions

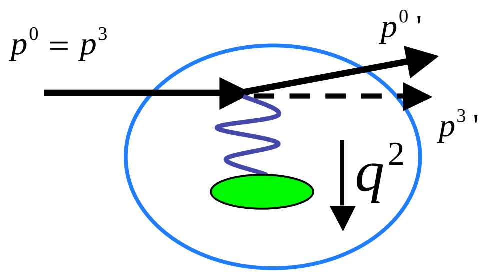
- LHC detectors were constructed to measure jets. Effort should be made to fully use these capabilities in HI collisions.
- The theory of jet shapes was generalized for high multiplicity environments (MLLA, power corrections and initial state radiation). Comparisons at the Tevatron and predictions for the LHC made.
- Medium-induced contribution to jet shapes was computed and shown to be different than the "vacuum one" in underlying physics.
- The (generalized) R_{AA} of jets was studied vs R_{cone} and ω_{min} . The relation to the fully differential distribution of the radiative E-loss was derived and illustrated.
- Little correlation was found between R_{AA} of the jet and the mean measure of the jet shape $<r/R>$ (approximate vacuum width).
- The broadening (up to 50%) is manifested in the "tails" $r/R > 0.5$ (careful selection of R_{cone}). Requires careful studies.
- 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 $\int Ldt = 1\ nb^{-1}$

Types of Energy Loss

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

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



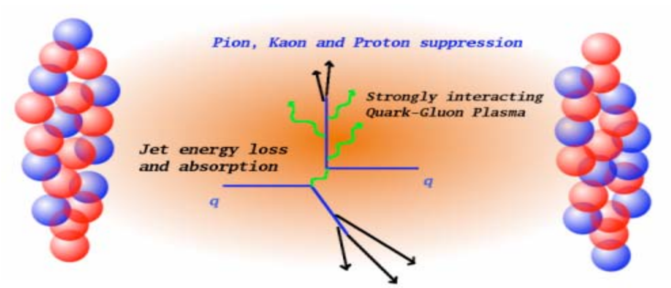


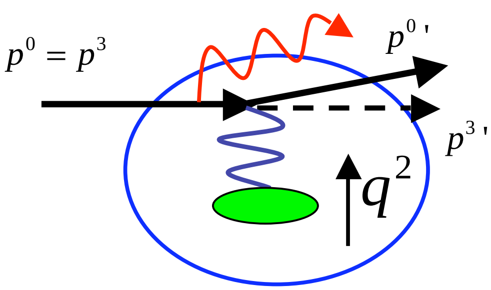
$$\frac{d\Delta E^{coll}}{dz} \approx 4\pi\alpha_{em}^2 z^2 Z \rho_{num} \frac{1}{\beta^2 m} \ln B_q$$

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

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

- Collisional energy loss
  - medium excitation





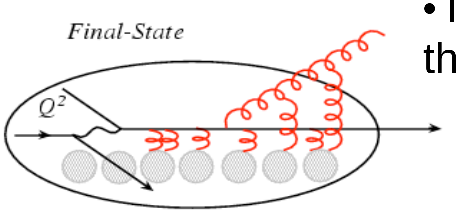
$$\frac{d\Delta E^{rad}}{dz} \approx \frac{16}{3} \alpha_{em}^3 z^4 Z^2 \rho_{num} \frac{1}{M^2} E \ln(\lambda\gamma)$$

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

- Radiative energy loss
  - gauge boson bremsstrahlung

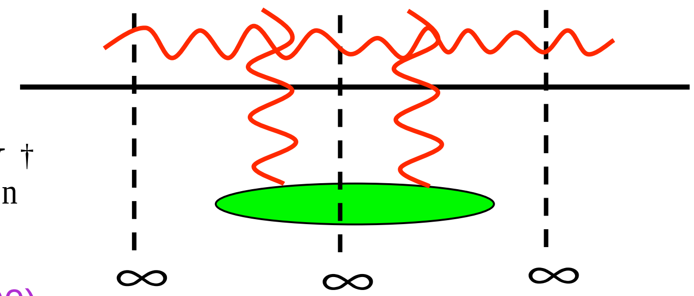
Bethe, H. A. et al. (1934) Weizsacker, C. et al. (1934)

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)

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

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

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

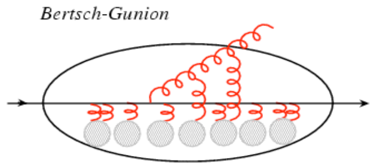
Number of scatterings **Momentum transfers**

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

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

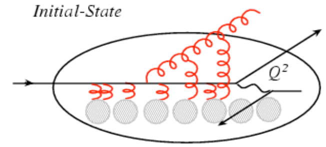
Color current propagators **Coherence phases (LPM effect)**

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)

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

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

- **Realistic initial state medium induced radiation**

Vitev, I. (2007)

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

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

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

Jet Shapes in QCD: the p+p Baseline I

Note that $z_{\min} = p_{T\,\min} / E$

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

- LO adapted to heavy ion studies

$$\begin{aligned}
\psi_q(r) &= \frac{C_F\alpha_s}{2\pi}\frac{2}{r}\left(2\log\frac{1-z_{min}}{Z}\right. \\
&\quad \left. -\frac{3}{2}\left[(1-Z)^2 - z_{min}^2\right]\right) , \\
\psi_g(r) &= \frac{C_A\alpha_s}{2\pi}\frac{2}{r}\left(2\log\frac{1-z_{min}}{Z}\right. \\
&\quad -\left(\frac{11}{6} - \frac{Z}{3} + \frac{Z^2}{2}\right)(1-Z)^2 \\
&\quad \left. +\left(2z_{min}^2 - \frac{2}{3}z_{min}^3 + \frac{1}{2}z_{min}^4\right)\right) \\
&\quad + \frac{T_R N_f \alpha_s}{2\pi}\frac{2}{r}\left(\left(\frac{2}{3} - \frac{2Z}{3} + Z^2\right)(1-Z)^2\right. \\
&\quad \left. -\left(z_{min}^2 - \frac{4}{3}z_{min}^3 + z_{min}^4\right)\right) .
\end{aligned}$$

V., I et al. (2008)

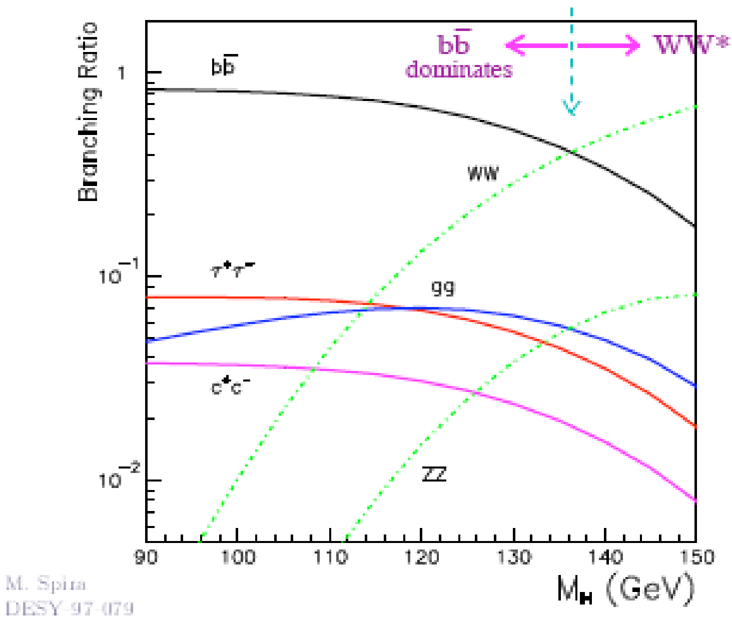
- Sudakov form factors

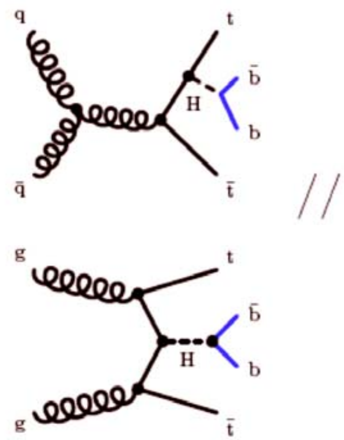
$$\begin{aligned}
P_q(r > z_{min}R) &= \exp\left(2C_F \log\frac{R}{r} f_1\left(2\beta_0\alpha_s \log\frac{R}{r}\right)\right. \\
&\quad -\left[\frac{3}{2}C_F - CR^2 - c_q^>(z_{min})\right] \\
&\quad \left.\times f_2\left(2\beta_0\alpha_s \log\frac{R}{r}\right)\right) , \\
P_g(r > z_{min}R) &= \exp\left(2C_A \log\frac{R}{r} f_1\left(2\beta_0\alpha_s \log\frac{R}{r}\right)\right. \\
&\quad -\left[\frac{1}{2}b_0 - CR^2 - c_g^>(z_{min})\right] \\
&\quad \left.\times f_2\left(2\beta_0\alpha_s \log\frac{R}{r}\right)\right) .
\end{aligned}$$

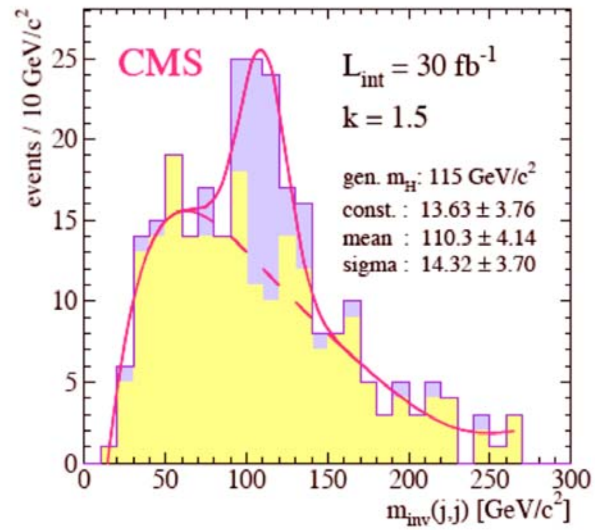
$$\begin{aligned}
P_q(r < z_{min}R) &= P_q(r > z_{min}R; r = z_{min}R) \\
&\quad \times \exp\left(-\left[\frac{3}{2}C_F - c_q^<(z_{min})\right]\right. \\
&\quad \left. \times f_2\left(2\beta_0\tilde{\alpha}_s \log\frac{z_{min}R}{r}\right)\right) , \\
P_g(r < z_{min}R) &= P_g(r > z_{min}R; r = z_{min}R) \\
&\quad \times \exp\left(-\left[\frac{1}{2}b_0 - c_g^>(z_{min})\right]\right. \\
&\quad \left. \times f_2\left(2\beta_0\tilde{\alpha}_s \log\frac{z_{min}R}{r}\right)\right) .
\end{aligned}$$

Golden channels (Higgs)

Branching ratios



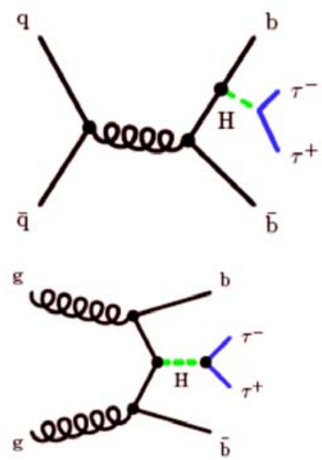


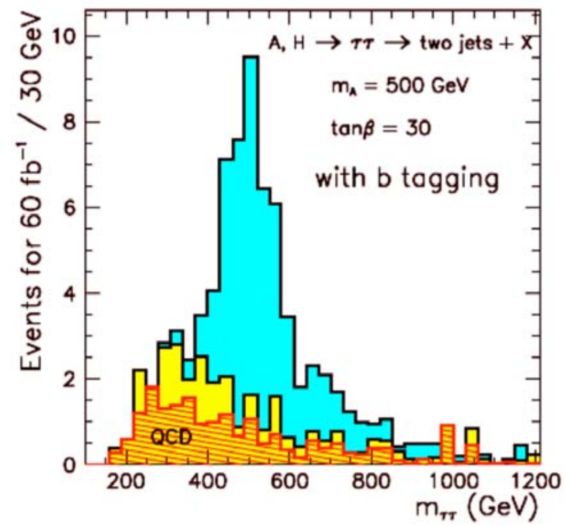


- Detected via:

$$b \longrightarrow jet \qquad \tau \longrightarrow jet$$

Jet physics as the basis for Higgs searches





Discovery channels (supersymetry)

Rich spectroscopy

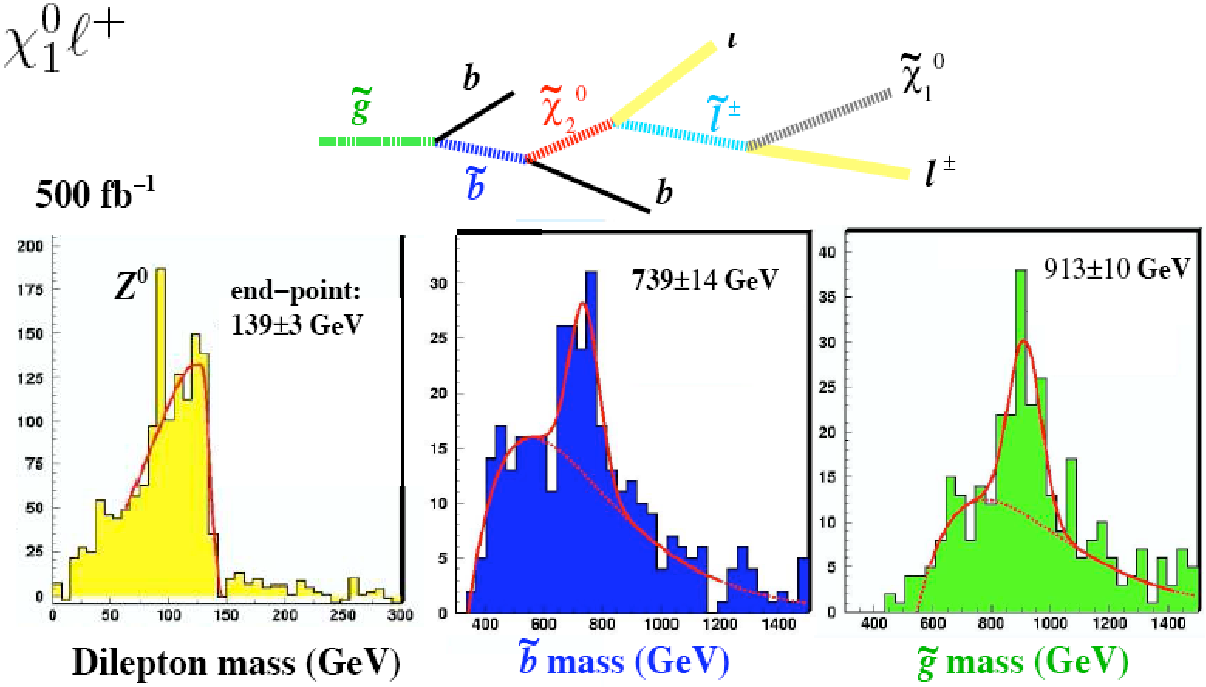
$Example: \ H, h, H^+, H^-, A$

- 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: $M_{\tilde{g}} \simeq 1 \ TeV$