Jet Shape at the LHC

Yang-Ting Chien

Los Alamos National Laboratory

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In collaboration with Ivan Vitev

Outline

In this talk,

- Jet shape $\Psi(r;R)$ in proton collisions
  - quark jet and gluon jet discrimination
- Soft-collinear effective theory (SCET)
  - Resummation of $\log r/R$
- Preliminary results
  - Baseline for heavy ion studies

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- Preliminary results
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Work in progress,

- Jet shape $\Psi(r;R)$ in heavy ion collisions
  - Jet quenching in quark-gluon plasma (QGP)
  - SCET with Glauber gluons ($\mathrm{SCET_G}$)

Motivation

- Quark-gluon discrimination
  - Heavy particles usually decay into quark-heavy final states
  - QCD backgrounds are mostly gluon-heavy

Being able to distinguish quarks from gluons is very important

  - Quark and gluon jet substructures are different
  - *Jet shape* (defined later) probes the energy distribution inside a jet

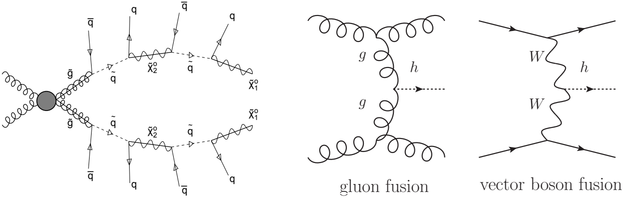


Figure: (Left) Gluino decay chain with a quark-heavy final state. (Right) Different higgs production mechanisms with quark or gluon jets in the final state

Jet shape $\Psi(r;R)$

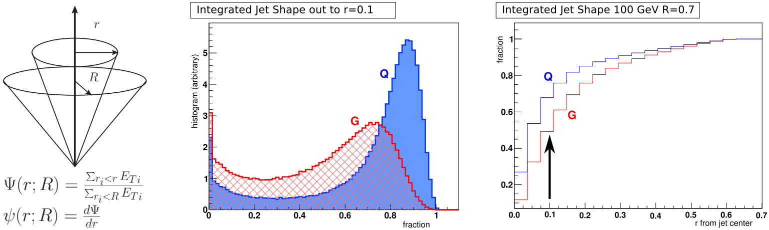
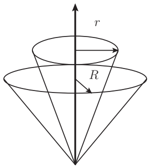


Figure: Jet shape definition, $\Psi(r=0.1)$ and $\langle\Psi\rangle_{all\ jets}(r)$. (Schwartz and Gallicchio)

- Jet shape probes the energy distribution inside a jet
  - $\Psi(r=0.1)$ is an event-by-event jet observable
  - $\langle\Psi\rangle_{all\ jets}(r)$ is the average over all jets

Jet shape $\Psi(r;R)$



$$\Psi(r;R) = \frac{\Sigma_{r_i<r} E_{Ti}}{\Sigma_{r_i<R} E_{Ti}}$$

$$\psi(r;R) = \frac{d\Psi}{dr}$$

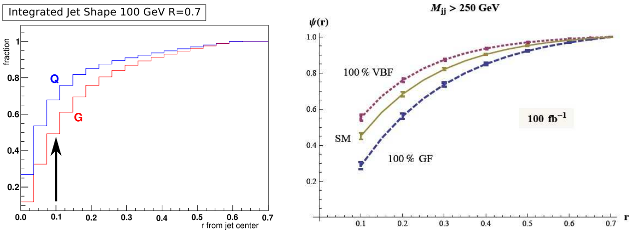


Figure: (Right) Shape of the most central jet in *h*+2*j* events. (Yuan etal)

- Jet shape probes the energy distribution inside a jet
  - $\langle\Psi\rangle_{all\ jets}(r)$ is the average over all jets
  - e.g. discrimination of the higgs production mechanisms

Motivation

- Characterizing the properties of the QGP
  - Medium modifications in jet shape contains information about QGP

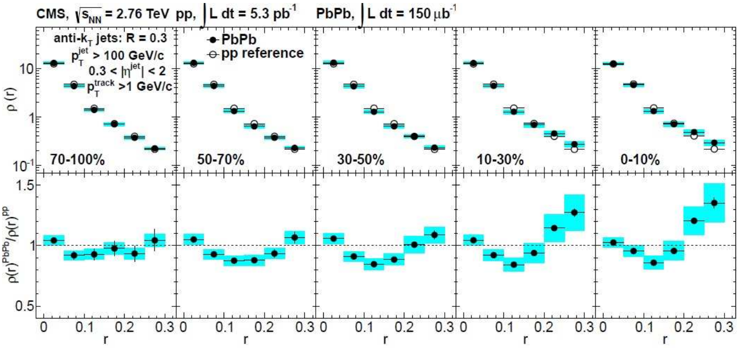
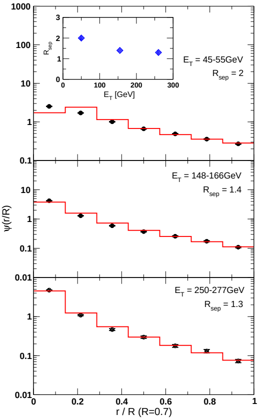
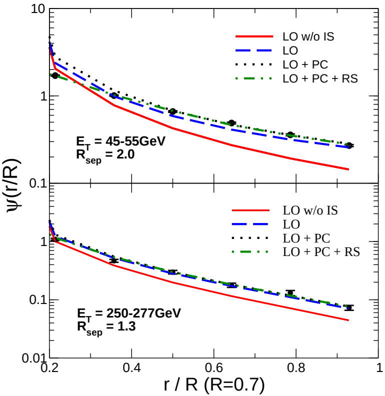


Figure: (Top) The CMS differential jet shape measurements in pp (open circles) and PbPb (filled circles) collisions, and their ratios (bottom). (1310.0878)

Theory calculation of jet shape

- pQCD calculation with a parameter R_{sep} fits the CDF data. (Seymour, Ivan etal)

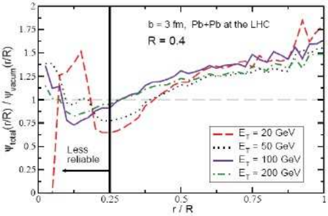




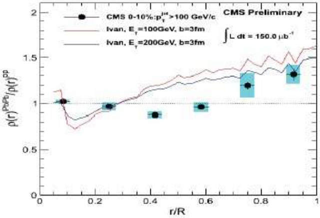
Theory calculation of jet shape

Phenomenology with $SCET_G$

- Qualitative features predicted. Quantitatively, the enhancement near the periphery of the jet
- The exact details of the shape deviate at small and intermediate r/R



"Comparison" to CMS data



- This is the region where we hope we can improve using SCET resummation techniques and full $SCET_G$ medium-induced splittings

See talk by Y.-T. Chien (2014)

Theory calculation of jet shape

- Large logarithms of the form $\alpha_s^n \log^m r/R \ (m \leq 2n)$ need to be resummed
  - pQCD resummation agrees with the CDF data. (Yuan etal)

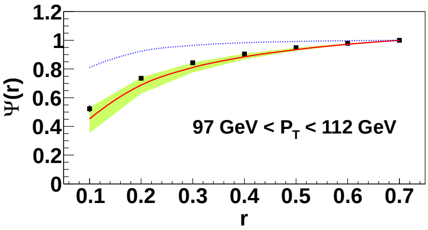


Figure: Comparison between the pQCD resummed result and the CDF data

Resumming phase space logs using EFT techniques

Soft Collinear Effective Theory (SCET)

- Separate physical degrees of freedom by a systematic expansion in power counting
  - Matching SCET with QCD. Integrate out the hard modes.
  - Further integrate out the off-shell modes $\rightarrow$ collinear Wilson lines
  - Soft sector $\rightarrow$ soft Wilson lines
- Soft-collinear decoupling at leading order $\rightarrow$ Factorization theorem

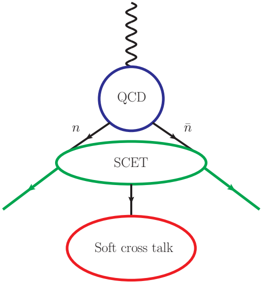


Figure: Factorization in SCET

An attempt to resum $\Psi(r;R)$ using SCET

- Jet shape has dominant contributions from the collinear sector

$$\Psi(r) = \frac{E_c^{<r} + E_s^{<r}}{E_c^{<R} + E_s^{<R}} \sim \frac{E_c^{<r}}{E_c^{<R}} + \mathcal{O}(\lambda)$$

  – Contributions from the (ultra)soft modes are power suppressed
  – Power counting parameter λ is of $\mathcal{O}(R)$ (*threshold enhancement*)

- We use SCET only for averaging over parton shower but not the jet production cross sections (David Farhi's talk)

$$\langle\Psi\rangle = \frac{1}{\sigma}\int d\omega \frac{d\sigma}{d\omega}\Psi_\omega \ , \ \text{where } \Psi_\omega = \frac{\langle E_r\rangle_\omega}{\langle E_R\rangle_\omega} \text{ and } \langle E_r\rangle_\omega = \int dE_r E_r J_\omega(E_r)$$

$$J_\omega(E_r) = \sum_{X_c}\langle 0|\bar{\chi}_\omega(0)|X_c\rangle\langle X_c|\chi_\omega(0)|0\rangle\delta(E_r - \hat{E}^{<r}(X_c, \text{algorithm}))$$

- Using the collinear SCET Feynman rules, the *jet energy function* $J_r^E = \frac{2}{\omega}\langle E_r\rangle_\omega$ is calculated at $\mathcal{O}(\alpha_s)$ for quark jets and gluon jets

Renormalization group evolution of jet energy functions

$$\frac{dJ_r^{qE}(r,R,\mu)}{d\ln\mu} = \Big[-C_F\Gamma_{\text{cusp}}\ln\frac{\omega^2\tan^2\frac{R}{2}}{\mu^2} - 2\gamma_{J^q}\Big]J_r^{qE}(r,R,\mu)$$

$$\frac{dJ_r^{gE}(r,R,\mu)}{d\ln\mu} = \Big[-C_A\Gamma_{\text{cusp}}\ln\frac{\omega^2\tan^2\frac{R}{2}}{\mu^2} - 2\gamma_{J^g}\Big]J_r^{gE}(r,R,\mu)$$

- The anomalous dimensions of the jet energy functions are

$$\gamma_{J^q} = -3C_F\ , \qquad \gamma_{J^g} = -\beta_0 = -\frac{11}{3}C_A + \frac{4}{3}T_F n_f$$

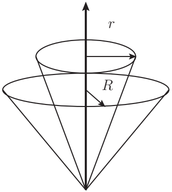
  - The same anomalous dimensions as the unmeasured jet functions
  - The anomalous dimensions are r **independent**
  - J_r^E and J_R^E have the same anomalous dimensions
  - $\Psi_\omega(r;R) = J_r^E/J_R^E$ which we calculate in SCET is RG invariant

Natural scales

- Jet energy functions at $\mathcal{O}(\alpha_s)$

$$J_r^{qE}(r,R,\mu) = \frac{\alpha_s C_F}{2\pi}\left[\frac{1}{2}\ln^2\frac{\omega^2\tan^2\frac{r}{2}}{\mu^2} - \frac{3}{2}\ln\frac{\omega^2\tan^2\frac{r}{2}}{\mu^2} - 2\ln X\ln\frac{\omega^2\tan^2\frac{r}{2}}{\mu^2} + 2 - \frac{3\pi^2}{4}\right.$$
$$\left. + 6X - \frac{3}{2}X^2 - \left(\frac{1}{2}X^2 - 2X^3 + \frac{3}{4}X^4 + 2X^2\log X\right)\tan^2\frac{R}{2}\right], \text{ where } X = \frac{\tan\frac{r}{2}}{\tan\frac{R}{2}}$$

  - The scale $\mu_{j_r} = \omega\tan\frac{r}{2}$ eliminates large logarithms at $\mathcal{O}(\alpha_s)$
  - J_r^E and J_R^E have the same anomalous dimensions but different scales



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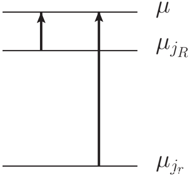

Resummed jet energy functions

- RG evolution between μ_{j_r} and μ_{j_R} resums $\log r/R$

$$\Psi^i_\omega(r,R) = \frac{J^{iE}(r,R,\mu_{j_r})}{J^{iE}(R,\mu_{j_R})}\exp[-2C_iS(\mu_{j_r},\mu_{j_R})+2A_{J^i}(\mu_{j_r},\mu_{j_R})]\left(\frac{\mu_{j_r}^2}{\omega^2\tan^2\frac{R}{2}}\right)^{C_iA_\Gamma(\mu_{j_R},\mu_{j_r})}$$

$$S(\nu,\mu) = -\int_{\alpha_s(\nu)}^{\alpha_s(\mu)} d\alpha\frac{\Gamma_{\rm cusp}(\alpha)}{\beta(\alpha)}\int_{\alpha_s(\nu)}^{\alpha}\frac{d\alpha'}{\beta(\alpha')},\quad A_X(\nu,\mu) = -\int_{\alpha_s(\nu)}^{\alpha_s(\mu)} d\alpha\frac{\gamma_X(\alpha)}{\beta(\alpha)}$$

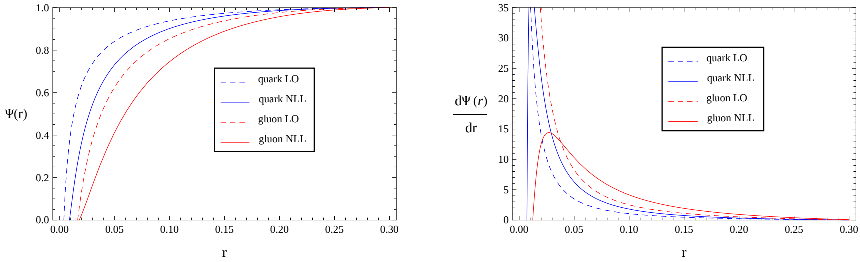

Figure: The LO and NLL jet shapes for quark and gluon jets with E_J=100 GeV.

Numerical results and comparison with the CMS data

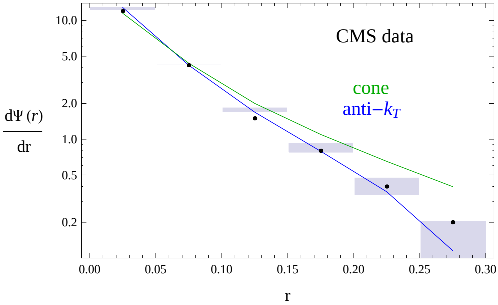

Figure: Differential jet shape for nucleon-nucleon center of mass energy of 2.76 TeV in proton collisions. Jets are reconstructed using the anti-k_T algorithm $R = 0.3$ with, $p_T > 100\ GeV$ and $0.3 < |\eta| < 2$. The curve for jets reconstructed using the recursive cone algorithm is plotted to show the algorithmic dependence in jet shape.

Conclusions and future work

- Jet shape is calculated in the SCET collinear sector
  – Global logarithms of $\log r/R$ are resummed to NLL using RG evolution between the two natural scales $\omega \tan \frac{r}{2}$ and $\omega \tan \frac{R}{2}$
  – Nice agreement with the recent CMS data

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  – Nice agreement with the recent CMS data
- Work in progress and future work
  – Calculate jet shape for jets in heavy ion collisions
  – Glauber gluon contributions and the use of $\mathrm{SCET_G}$
  – Medium modification of parton shower evolution
  – Extracting properties of the quark-gluon plasma