Resummation of Jet Shape and Extracting Properties of Quark-Gluon Plasma

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In collaboration with Ivan Vitev

Outline

In this talk,

- Jet shapes in proton collisions
  - useful in quark jet and gluon jet discrimination
- Resummation of phase space logarithms $\log r/R$ using SCET
  - Factorization theorem
  - Renormalization group evolution
  - Possible issues about non-global logarithms (put aside for now)
- Preliminary results

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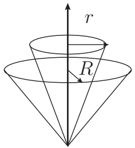
Work in progress,

- Jet shapes in heavy ion collisions
  - Medium induced splitting functions using $\mathrm{SCET_G}$ (known)
  - Medium modifications at first order in opacity $\mathcal{O}(L/\lambda)$
- Preliminary results

Jet shape, integral and differential (Ellis, Kunszt, Soper)



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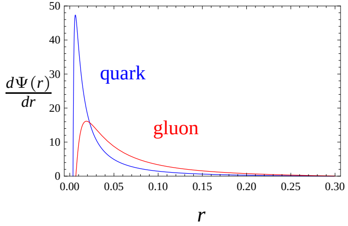

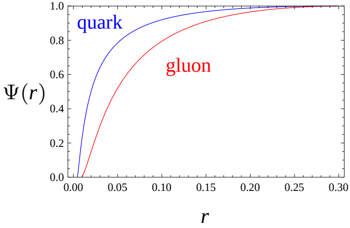

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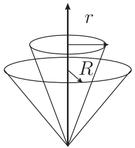

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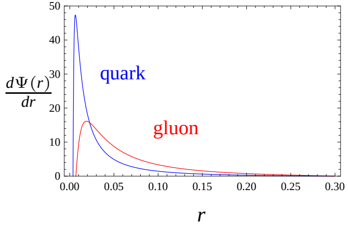

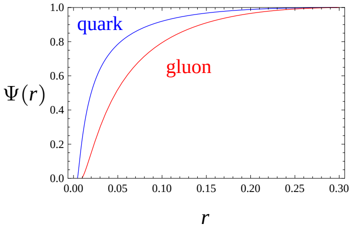

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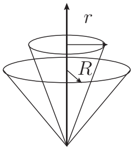

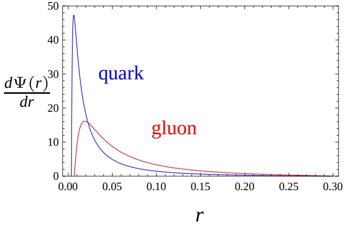

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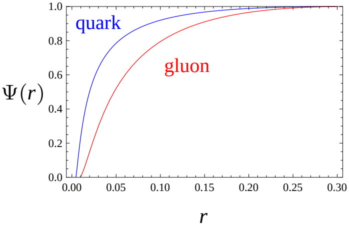

- Jet shape probes the energy distribution inside a jet
  - Quark jets are more localized vs. gluon jets are more spread out
- Large logarithms of the form $\alpha_s^n \log^m r/R$ $(m \leq 2n)$ need to be resummed

Motivation I

- Quark-gluon discrimination
  - Many SM and BSM signals have quark-heavy final states
  - QCD backgrounds are mostly gluon-heavy
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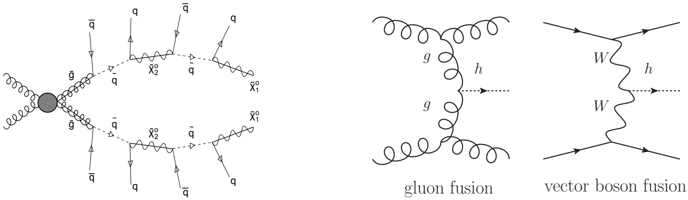

(Left) Gluino decay chain with a quark-heavy final state

(Right) Different higgs production mechanisms with quark or gluon jets in the final state

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  - Modification of jet shapes contains information about the medium
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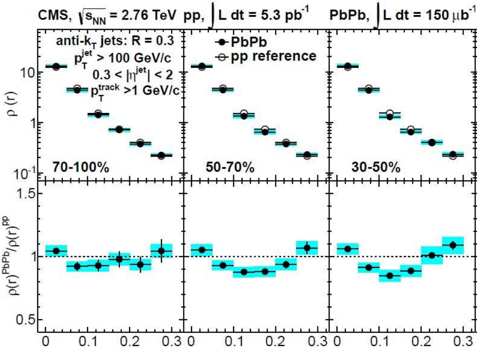
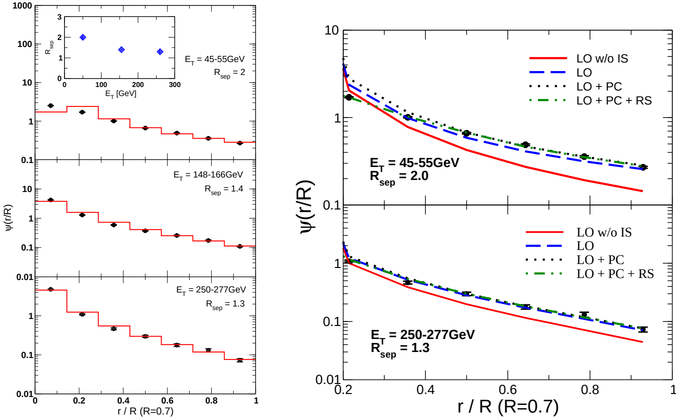


- (Top) The CMS differential jet shape measurements in pp and PbPb collisions with different centralities
- (Bottom) Ratio of medium and vacuum jet shapes (1310.0878)

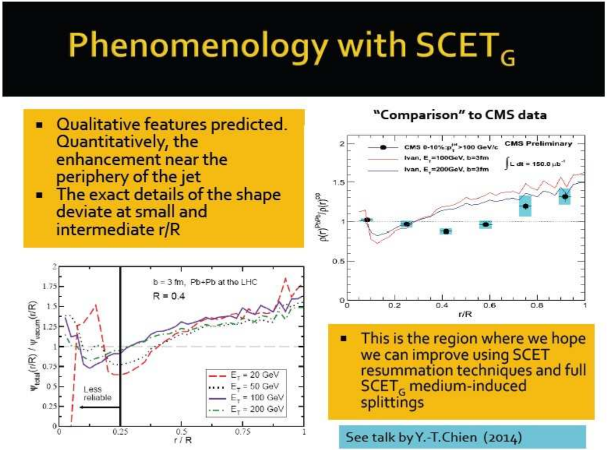
Jet shape calculations in pQCD (Seymour, Vitev et al)

- pQCD calculation with a parameter R_{sep} fits the CDF data.
  – Resummation performed using the modified leading logarithmic approximation
  – Initial state radiation and power corrections examined



Jet shape calculations in pQCD (Vitev, Boston Jet Physics Workshop 2014)

- The CMS jet shape modification data is still not explained very well



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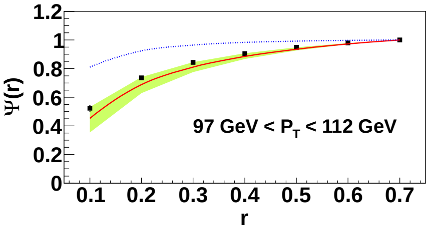

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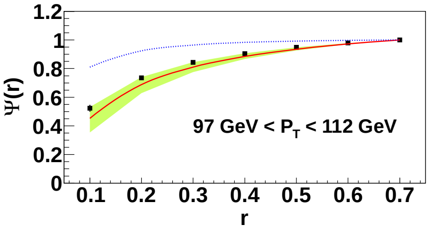

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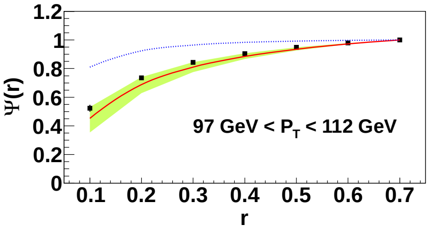

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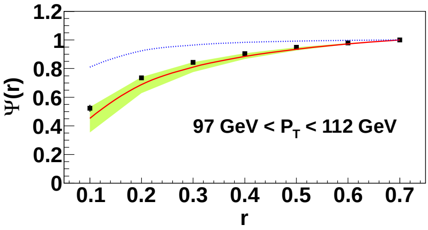

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Let's resum phase space logs using SCET

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 power $\rightarrow$ Factorization theorem

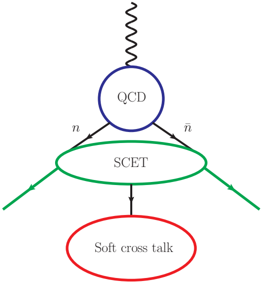

Figure: Factorization in SCET

Power counting

- Jet shape has dominant contributions from the collinear sector

$$\Psi(r)=\frac{E_c^{<r}+E_s^{<r}}{E_c^{<R}+E_s^{<R}}\sim\frac{E_c^{<r}}{E_c^{<R}}+\mathcal{O}(\lambda)\text{ or }\mathcal{O}(\lambda^2)$$

  - Just a reminder, $p_c : Q(1,\lambda^2,\lambda)$ and $p_s : Q(\lambda,\lambda,\lambda)$ or $Q(\lambda^2,\lambda^2,\lambda^2)$
  - Contributions from the (ultra)soft modes are power suppressed
  - λ is of $\mathcal{O}(R)$ because of dynamical threshold enhancement (and Λ)
  - For small jets ($R \ll 1$) the power corrections are small

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$$\Psi(r) = \frac{E_c^{<r} + E_s^{<r}}{E_c^{<R} + E_s^{<R}} \sim \frac{E_c^{<r}}{E_c^{<R}} + \mathcal{O}(\lambda) \text{ or } \mathcal{O}(\lambda^2)$$

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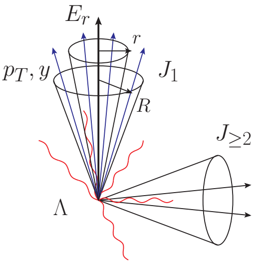
- Terms of $\mathcal{O}(r)$ and $\mathcal{O}(R)$ are small, but $\mathcal{O}(r/R)$ is not necessarily small

Factorization theorem



- Factorization theorem for the differential cross section of an anti-$\mathrm{k_T}$ R jet with p_T, y, energy E_r inside the r cone, and an energy cutoff Λ outside to ensure N-jet configuration

$$\frac{d\sigma}{dp_T dy dE_r} = H(p_T, y, \mu) J_1^{\omega}(E_r, \mu) J_2(\mu) \dots S_{1,2,\dots}(\Lambda, \mu)$$

- For the differential jet rate

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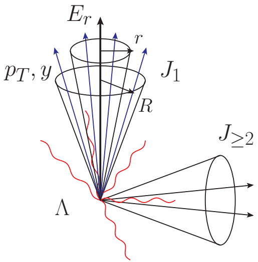

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– Here $J_1^{\omega}(E_r, \mu) = \sum_{X_c} \langle 0|\bar{\chi}_{\omega}(0)|X_c\rangle\langle X_c|\chi_{\omega}(0)|0\rangle \delta(E_r - \hat{E}^{<r}(X_c, \text{algorithm}))$ and $\omega = 2E_J$ is twice the jet energy

– $J_i(\mu)$ are the "unmeasured jet functions" (Ellis, Vermilion, Walsh, Hornig, Lee)

– All the jet and soft functions have R dependence

Jet shape in SCET

The averaged energy inside the r cone for this jet is

$$\langle E_r \rangle_\omega = \frac{1}{\frac{d\sigma}{dp_T dy}} \int dE_r E_r \frac{d\sigma}{dp_T dy dE_r} = \frac{H(p_T, y, \mu) J^E_{r1}(\mu) J_2(\mu) \ldots S_{1,2,\ldots}(\Lambda, \mu)}{H(p_T, y, \mu) J_1(\mu) J_2(\mu) \ldots S_{1,2,\ldots}(\Lambda, \mu)} = \frac{J^E_{r1}(\mu)}{J_1(\mu)}$$

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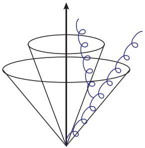
- Non-global logs of the form $\log \Lambda/Q$ in the soft sector cancel, but there are still potential non-global logs in $J^E_r(\mu)$
  - non-global phase space logarithms
  - non-global logarithms in the collinear sector
  - the strong-energy-ordering phase space may not be contributing to the leading non-global logs here



Renormalization group evolution of jet energy functions

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

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

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  - The same anomalous dimensions as the unmeasured jet functions
  - The anomalous dimensions are r independent
  - Ψ_ω is renormalization group invariant

$$\Psi_\omega = \frac{J_r^E(\mu)}{J_R^E(\mu)} = \frac{J_r^E(\mu_{j_r})}{J_R^E(\mu_{j_R})}U_J(\mu_{j_r},\mu_{j_R})$$

  - Choosing natural scales μ_{j_r} and μ_{j_R} to eliminate large logarithms

Natural scales

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

$$\frac{2}{\omega}J_r^{qE}(r,R,\mu) = \frac{\alpha_s C_F}{2\pi}\Big[\frac{1}{2}\ln^2\frac{\omega^2\tan^2\frac{r}{2}}{\mu^2} - \frac{3}{2}\ln\frac{\omega^2\tan^2\frac{r}{2}}{\mu^2} - 2\ln X\ln\frac{\omega^2\tan^2\frac{r}{2}}{\mu^2} + 2 - \frac{3\pi^2}{4}$$
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– The scale $\mu_{j_r} = \omega\tan\frac{r}{2} \approx E_J \times r$ eliminates large logarithms at $\mathcal{O}(\alpha_s)$
– $J_r^E(\mu)$ and $J_R^E(\mu)$ have the same anomalous dimensions but different scales

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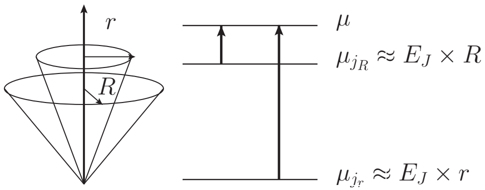
- Jet energy functions at $\mathcal{O}(\alpha_s)$

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

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



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

Resummed jet energy functions

- $\log r/R$'s are resummed using the familiar RG kernels in SCET ($i = q, g$)

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

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

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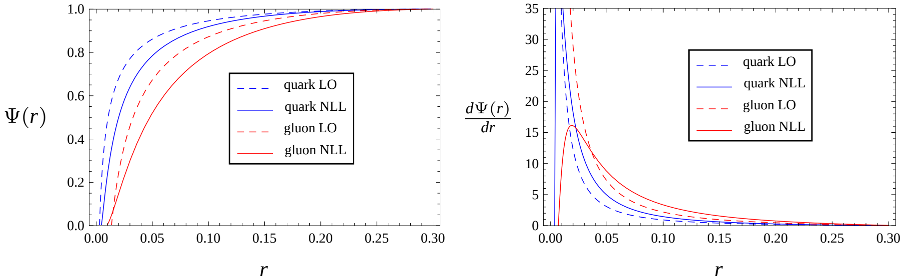
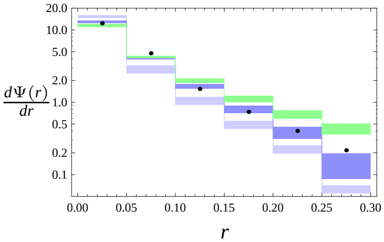


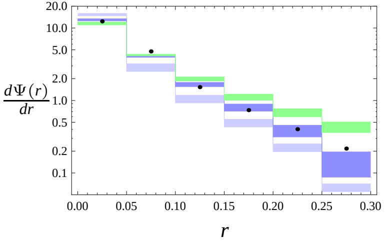
– Integral and differential jet shapes of 100 GeV quark and gluon jets at LO and NLL

Comparison with the CMS data (1310.0878)



– Differential jet shape in proton collisions with center of mass energy of 2.76 TeV

Comparison with the CMS data (1310.0878)

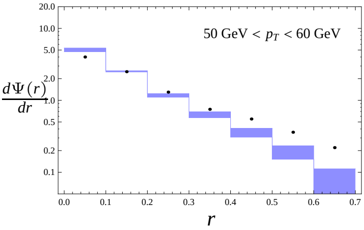


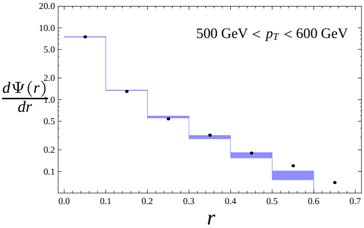
– Differential jet shape in proton collisions with center of mass energy of 2.76 TeV

- The blue bands (LO and NLL) are for R=0.3 anti-$\mathrm{k_T}$ jets with $p_T > 100$ GeV and $0.3 < |\eta| < 2$
- Resummation is important
- The green band is for R=0.3 cone jets

  - The difference for jets reconstructed using different algorithms is of $\mathcal{O}(r/R)$
- Bands are theory uncertainties estimated by varying μ_{j_r} and μ_{j_R}
- For the region $r \approx R$ we need higher order fixed order calculations and power corrections

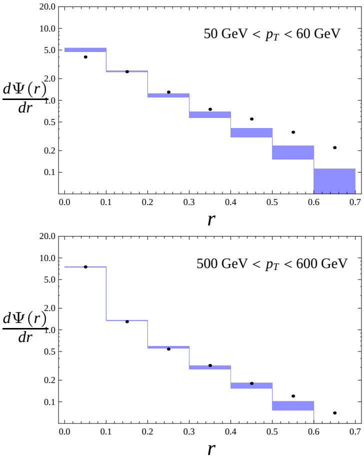
Comparison with the CMS data (1204.3170)





– Differential jet shape in proton collisions with center of mass energy of 7 TeV

Comparison with the CMS data (1204.3170)



– Differential jet shape in proton collisions with center of mass energy of 7 TeV

- The blue band (NLL) is for R=0.7 anti-$\mathrm{k_T}$ jets with $|\eta| < 1$
- For low p_T jets power corrections are significant
- For high p_T jets the SCET calculations reproduce the peak region very well

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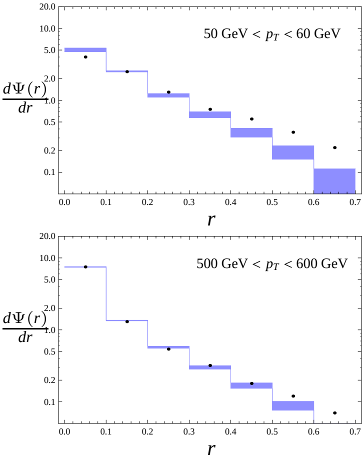

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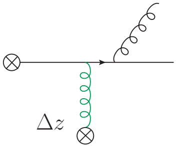
SCET works in jet shape!

Jet shape in heavy ion collisions



– Heavy ion collisions create a strong interacting medium called quark-gluon plasmas
– Jets passing through QGP are observed to be "quenched"
– Glauber gluon interaction provides transverse momentum kicks, $p_G : Q(\lambda^2, \lambda^2, \lambda)$
– $\mathrm{SCET_G}$ describes the in-medium jet formation mechanism

- Jet shape gets modified when the jet passes through QGP

$$\Psi(r) = \frac{J_r^{E,vac} + J_r^{E,med}}{J_R^{E,vac} + J_R^{E,med}} = \frac{J_r^{E,vac}}{J_R^{E,vac}} \frac{J_R^{E,vac}}{J_R^{E,vac} + J_R^{E,med}} + \frac{J_r^{E,med}}{J_R^{E,vac} + J_R^{E,med}}$$

– Large logarithms in $\Psi^{vac}(r) = J_r^{E,vac} / J_R^{E,vac}$ are resummed
– There are no large logarithms in $J_r^{E,med}$ at first order in opacity $\mathcal{O}(L/\lambda)$ (Landau-Pomeranchuk-Migdal effect)

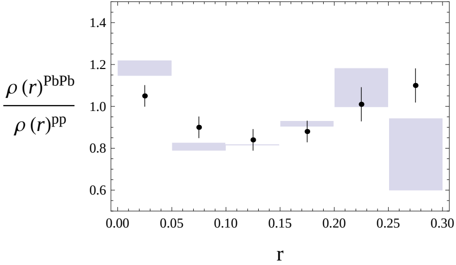
In-medium jet energy functions

- With the medium induced splitting functions at hand, we calculate the medium modifications of jet energy functions
  - In the small x limit, the medium induced splitting functions are

$$\frac{dN_{q\to qg}}{dxd^2k_\perp} = \frac{C_F\alpha_s}{\pi^2}\frac{1}{x}\int_0^L \frac{d\Delta z}{\lambda}\int d^2q_\perp \frac{1}{\sigma_{el}}\frac{d\sigma_{el}}{d^2q_\perp}\frac{2k_\perp\cdot q_\perp}{k_\perp^2(q_\perp-k_\perp)^2}\left[1-\cos\left(\frac{(q_\perp-k_\perp)^2\Delta z}{x\omega}\right)\right]$$

  - We use the effective cross section $\frac{1}{\sigma_{el}}\frac{d\sigma_{el}}{d^2q_\perp} = \frac{m^2}{\pi(q_\perp^2+m^2)^2}$ in static QGP
  - There is no soft-collinear divergence when integrating over x and $k_\perp$
  - The RG evolution of jet energy functions is the same as in vacuum

Preliminary result



- We plot the ratio of the differential jet shapes in lead-lead and proton-proton collisions for gluon jets with $p_T = 100$ GeV and $y = 0$
- For quark jets the curve is quite different
- The data is for the centrality bin between $30 - 50\%$
- We haven't averaged jet shapes with the appropriate cross sections
- Power corrections seem to be important around $r \approx R$
- Calculations evaluated for static QGP with $\lambda_g = 1$ fm, $L = 4.5$ fm, $m = 0.75$ GeV

Conclusions

- Jet shape is calculated in the SCET collinear sector
  - The factorization theorem is written down
  - Jet energy functions are calculated at $\mathcal{O}(\alpha_s)$ for quark and gluon jets
  - Global logarithms are resummed to NLL using RG evolution

Nice agreement with the recent CMS data

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- Work in progress
  - Look into issues about non-global logarithms
  - Calculate jet shapes in heavy ion collisions using $\mathrm{SCET_G}$
  - Help studying the properties of the quark-gluon plasma