HARD PROBES 2018

Confronting Jet Quenching with Jet Grooming: Jet Mass Distribution in Heavy Ion Collisions

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In collaboration with Ivan Vitev (jet mass) and Iain Stewart (collinear drop)
To appear soon

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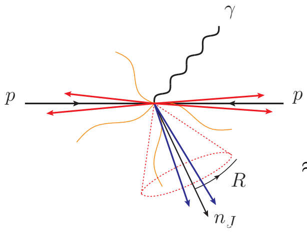
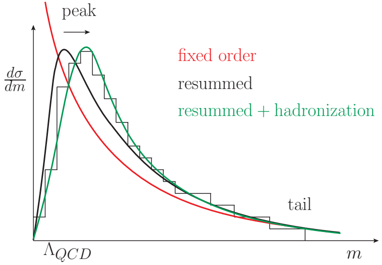
Outline

- Jet mass
- Soft-collinear effective theory (SCET)
  - Factorization and resummation
  - Medium modification by Glauber interactions
- Soft Drop and Collinear Drop
- Preliminary results

Jet mass



$$m^2 = \Big(\sum_{i\in J} p_i\Big)^2$$
$$= \big(p_c + p_s\big)^2$$
$$\approx p_c^2 + 2p_c\cdot p_s$$
$$\approx p_c^2 + 2E_J n_J\cdot p_s$$

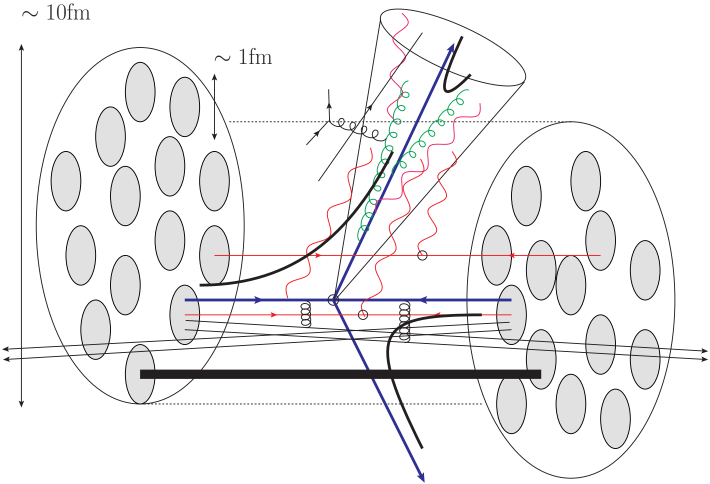


- Jet mass is a soft radiation sensitive jet substructure observable
- The infrared structure of QCD induces Sudakov logarithms
- Fixed order calculation breaks down at small jet mass m
- Large logarithms of the form

  $$\frac{1}{m}\alpha_s^i\Big(\log^j\frac{p_T}{m}\ \text{or}\ \log^j R\Big),\quad j\leq 2i-1$$

  need to be resummed
- Hadronization affects the peak position at small m

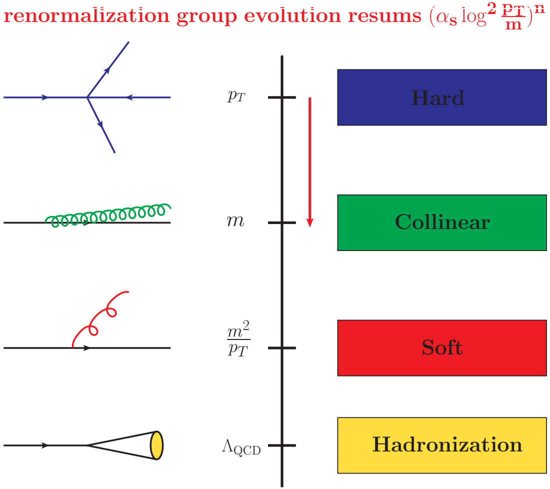
A cartoon of jet mass contributions



Connors et al, *The Definition of Jets in a Large Background*

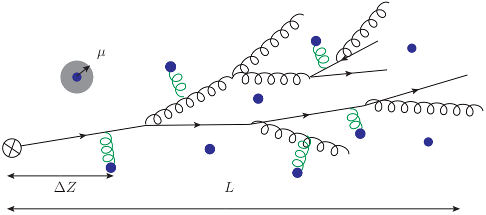
Resummation using Soft-Collinear Effective Theory (SCET)

- Large logarithms of hierarchical scale ratios can be systematically resummed using effective field theory techniques

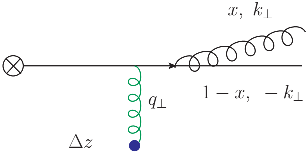


Multiple scattering in a medium and QCD bremsstrahlung

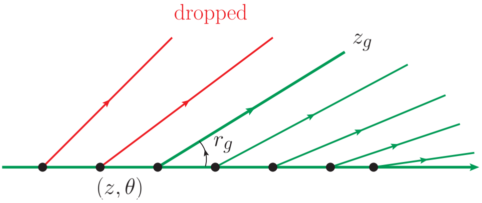
- Coherent multiple scattering and induced bremsstrahlung are the qualitatively new ingredients in the medium parton shower
- Interplay between multiple characteristic scales:
  - Debye screening scale μ
  - Parton mean free path λ
  - Radiation formation time τ

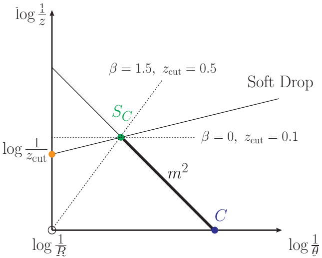


- Jet-medium interaction using SCET with background Glauber gluon fields $\mathrm{SCET_G}$ (Glauber-collinear: Majumder et al, Vitev et al. Glauber-soft: work in progress)
- Leading-order medium induced splitting functions $\mathcal{P}^{med}_{i\to jl}(x, k_\perp)$ were calculated using $\mathrm{SCET_G}$ (Vitev et al)



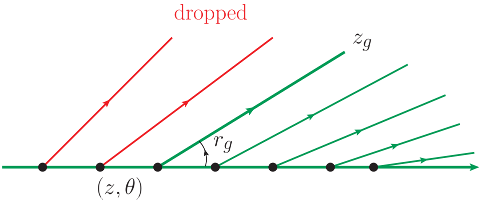
Soft Drop

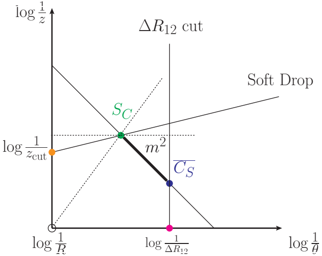




- Tree-based procedure to drop soft radiation (Larkoski et al)
  - Recluster a jet using C/A algorithm: angular ordered
  - For each branching, consider the p_T of each branch and the angle θ
  - Drop the soft branch if $z < z_{cut}\ \theta^\beta$, where $z = \frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}}$

Soft Drop





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Groomed jet mass function

- The process-independent groomed jet mass function $J^{SD}(m^2,\mu)$ captures all the soft-collinear radiation inside jets ($i=q,g$)

$$J_i^{SD}(m^2,\mu)=\int dp^2 dk J_i(p^2,\mu) S_i^{SD}(k,R,z_{cut},\mu)\delta(m^2-p^2-2E_J k)$$

where $S_i^{SD}(k,R,z_{cut},\mu)=S_i^{C}(k,R,z_{cut},\mu)S_i^{G}(R,z_{cut},\mu)$

- Medium-induced splitting functions are used to calculate the modification of $J^{SD}(m^2,\mu)$. At $\mathcal{O}(\alpha_s)$,

$$J_i^{SD}(m^2,\mu)=\sum_{j,k}\int_{PS} dx dk_\perp \mathcal{P}_{i\to jk}(x,k_\perp)\delta(m^2-M^2(x,k_\perp))\Theta_{\rm alg.}\Theta_{SD}$$

$M^2(x,k_\perp)=\frac{k_\perp^2}{x(1-x)}$, $\Theta_{\rm k_T}=\Theta(E_J R x(1-x)-k_\perp)$, $\Theta_{SD}=\Theta(E_J R x(1-x)\left(\frac{x}{z_{cut}}\right)^{1/\beta}-k_\perp)$.

- The full jet mass distribution can be calculated by weighing the groomed jet mass functions with jet cross sections

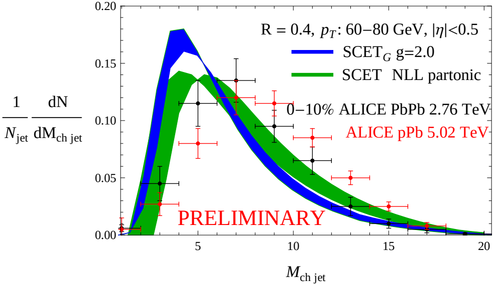
$$\frac{d\sigma}{dm^2}=\sum_{i=q,g}\int_{PS} dp_T dy \frac{d\sigma^i}{dp_T dy} P_i^{SD}(m^2,\mu),\ \text{where}\ P_i^{SD}(m^2,\mu)=\frac{J_i^{SD}(m^2,\mu)}{J_{un}^i(\mu)}$$

Resummed groomed jet mass function

- Each function is calculated at 1-loop and depends on a single scale

$$
\begin{aligned}
& P_i^{SD}(m^2,\mu) \\
= \quad & \exp\Big[2\frac{2+\beta}{1+\beta}C_iS(\mu_{sc},\mu_s) - 4C_iS(\mu_j,\mu_s) + 2C_iS(\mu_{j_R},\mu_s) + 2A_{J_i}(\mu_j,\mu_{j_R}) + 2A_{S_i}(\mu_{sc},\mu_{j_R})\Big] \\
& \times\left(\frac{\mu_j^2 z_{cut}^{\frac{1}{1+\beta}}}{\mu_{sc}^{\frac{2+\beta}{1+\beta}}\,(2E_J\tan\frac{R}{2})^{\frac{\beta}{1+\beta}}}\right)^{2C_iA_\Gamma(\mu_s,\mu_{sc})}\left(\frac{2E_J\tan\frac{R}{2}}{\mu_{j_R}}\right)^{2C_iA_\Gamma(\mu_s,\mu_{j_R})}\frac{S_i^G(\mu_s)}{m^2 J_{\rm un}^i(\mu_{j_R})} \\
& \tilde{J}_i(\partial\eta,\mu_j)\tilde{S}_i^C\Big(\partial\eta + \ln\frac{\mu_j^2 z_{cut}^{\frac{1}{1+\beta}}}{\mu_{sc}^{\frac{2+\beta}{1+\beta}}\,(2E_J\tan\frac{R}{2})^{\frac{\beta}{1+\beta}}},\mu_{sc}\Big)\left(\frac{m^2}{\mu_j^2}\right)^{\eta}\frac{e^{-\gamma_E\eta}}{\Gamma(\eta)}
\end{aligned}
$$

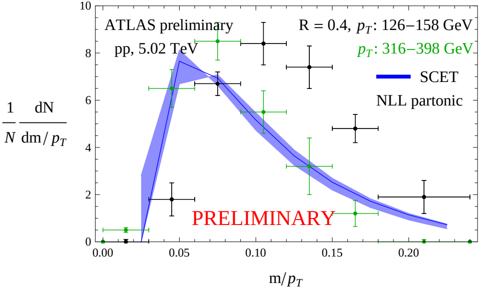
Preliminary results



- Medium-induced radiation enhances small mass region
- Large jet mass requires hard and wide angle radiation
- Soft contributions and hadronization are still under examination

ALICE, Phys. Lett. B776 (2018) 249-264

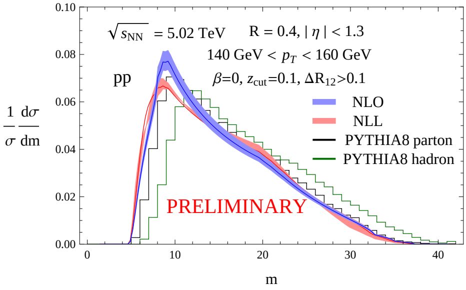
Preliminary results

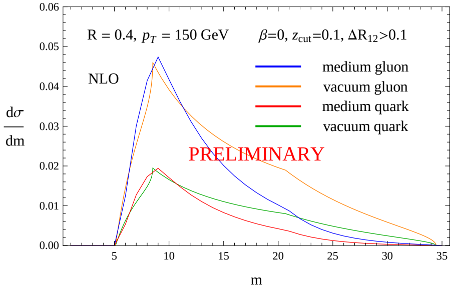


- At parton level, m/p_T distributions mildly scale with p_T
- Hadron mass effect is large at low p_T

ATLAS-CONF-2018-014

Preliminary results

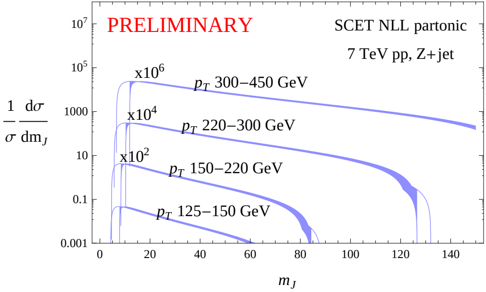


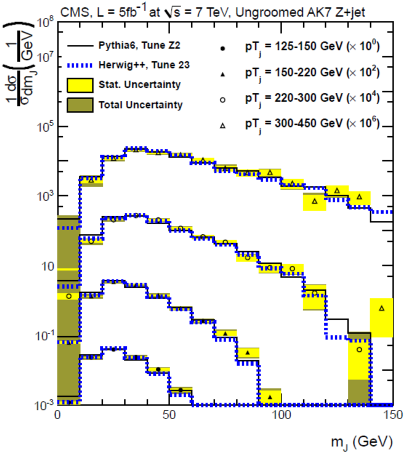


- $\Delta R_{12} > 0.1$ cuts out the Sudakov peak
- Lower and upper limits of jet mass are dictated by kinematics
- Medium perturbative contributions enhance small mass region
- Soft contributions (underlying events, medium recoil, etc), hadronization and background subtraction are still under examination

CMS-HIN-16-024

Preliminary results



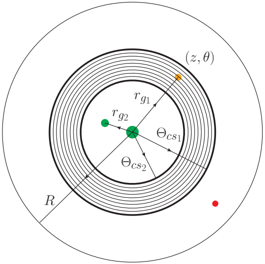


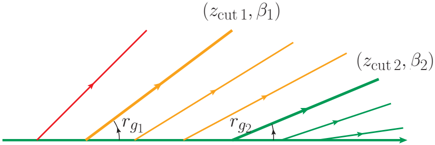
- $Z +$ jet are quark-jet enriched

CMS, JHEP 05 (2013) 090

Collinear drop

An example of CD observable can be constructed using a Soft Drop + an Anti Soft Drop





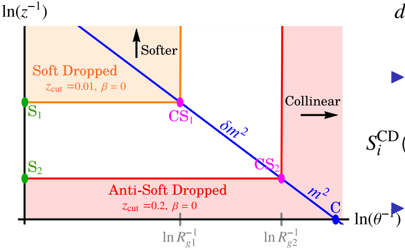
- Consider $\delta m^2 = m^2_{\mathrm{SD}_1} - m^2_{\mathrm{SD}_2}$ to quantify the radiation distribution within the “ring"
- Contributions from collinear radiation to soft-drop jet mass cancel

$$m^2_{\mathrm{SD_i}} \sim p_c^2 + 2E_J n \cdot p_{cs_i}\ , \qquad \delta m^2 \sim 2E_J n \cdot (p_{cs_1} - p_{cs_2})$$

- Phase space constraints on the kinematics of soft emissions,

$$z\theta^2 \approx \frac{\delta m^2}{E_J^2}\ , \qquad z_{\mathrm{cut}\,1}\left(\frac{\theta}{R_0}\right)^{\beta_1} \lesssim z \lesssim z_{\mathrm{cut}\,2}\left(\frac{\theta}{R_0}\right)^{\beta_2}$$

Factorization and resummation of δm^2 using SCET

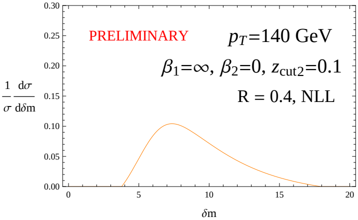


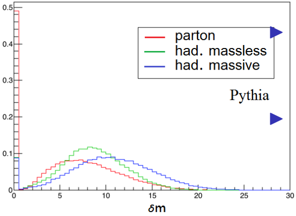
$$\frac{d\sigma}{d\delta m^2} = \sum_{i=q,g} N_i(\mu) J^{\mathrm{SD}}_{\mathrm{un},i}(z_{\mathrm{cut}\,2}, \beta_2, \mu) S^{\mathrm{CD}}_i(\delta m^2, z_{\mathrm{cut}\,i}, \beta_i, \mu)$$

- If two soft-drop conditions are hierarchically separated, collinear-soft sector can be further factorized

$$S^{\mathrm{CD}}_i(\delta m^2, \mu) = \int dk_i \overline{S_{C_2,i}}(k_2, \mu) S_{C_1,i}(k_1, \mu) \delta(\delta m^2 - 2E_J(k_1 + k_2))$$

- Using SCET renormalization group techniques we can resum δm^2





- Massless hadrons are constructed using the p-scheme
- Significant hadronization correction is seen

Conclusions

- Jet mass contains rich information of radiation inside jets
- Jet mass can be systematically resummed using effective field theory techniques
- Jet mass function allows us to calculate for arbitrary hard process at NLL accuracy
- Collinear drop allows us to systematically explore soft phase space regions