Resummation of jet mass in dijet process at hadron colliders

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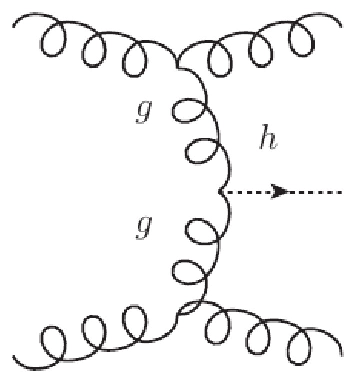
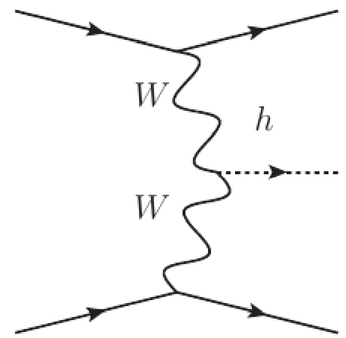
Jet Substructure

- Understanding the substructure of jets is crucial for LHC phenomenology
- It is important for new physics searches
    - **distinguish jets coming from decays of boosted resonances from QCD jets**
- Jet shapes enable us to look at energy distributions inside a jet



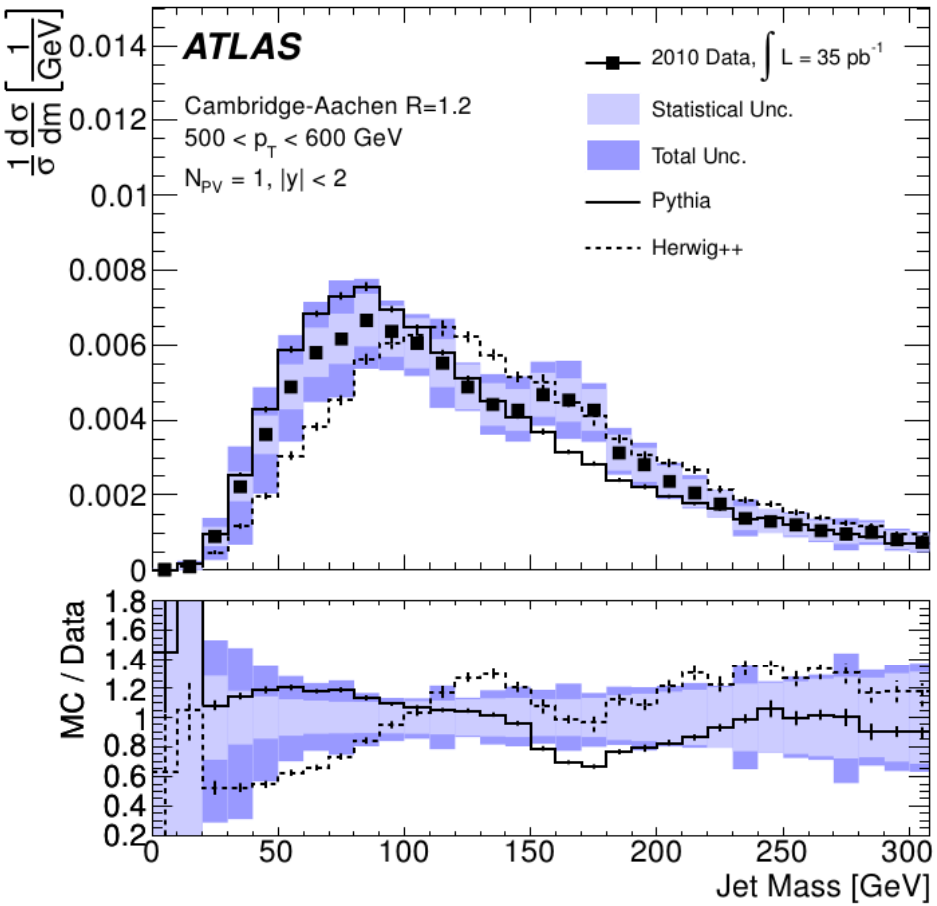


State of art

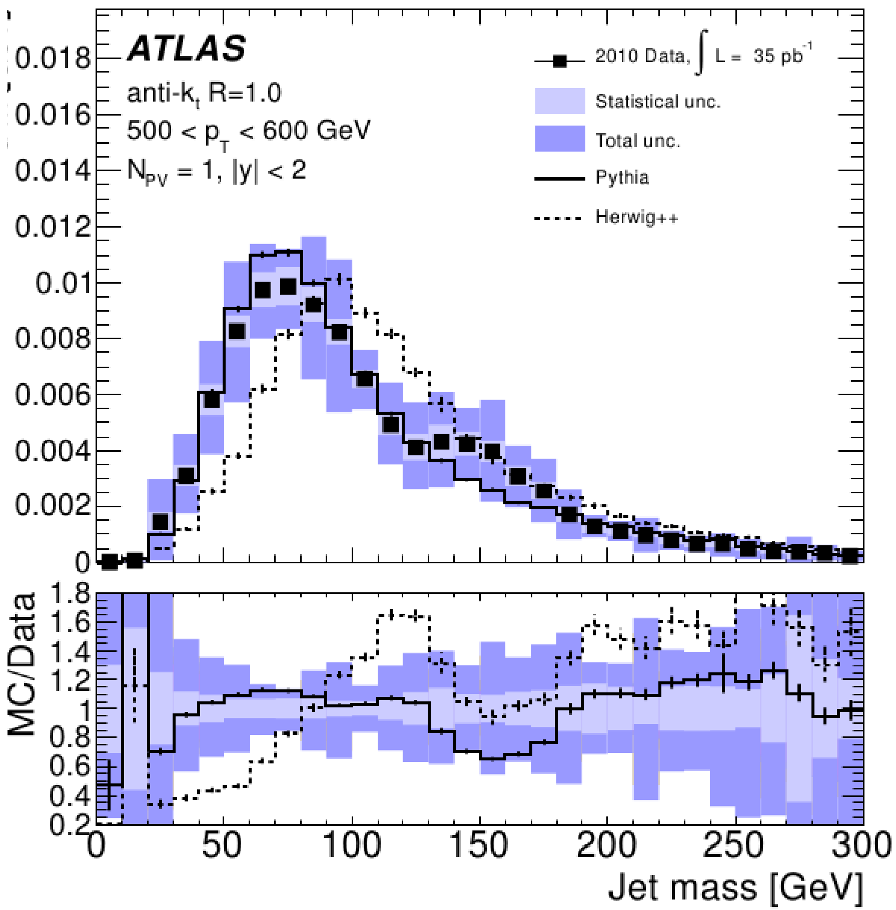
- $e^+ e^-$ Colliders
  - angularities in multi-jet events
    Ellis et al. JHEP1011,101 & PLB689,82-89,2010
  - m_J with a jet veto
    R. Kelley, M. D. Schwartz & H. X. Zhu
  - .....
- Hadron Colliders
  - m_J in Higgs + 1 jet & γ+1 jet
    Stewart et al. Schwartz et al.
  - Jet Energy Profile - $\Psi(r)$ H.-n. Li, Z. Li & C.-P Yuan
  - m_J in Z+ 1 jet & dijet M. Spannowsky et al. JHEP 1210, 126

Jet Mass Spectrum with Experiment

Cambridge-Aachen R=1.2



Anti-kT R=1.0



JHEP 1205, 128

MC vs Analytical Approach

- MC simulations using parton showers
  - **provide fully differential events on which any observable can be measured**
  - **interfaced with hadronisation to give a realistic description**
  - **formally LL (although contain many sub-leading terms)**
- Analytical Calculation
  - **feasible for a limited number of observables**
  - **well defined and improvable accuracy, which often exceeds the MC one**
  - **they can help development and validation of MC tools**

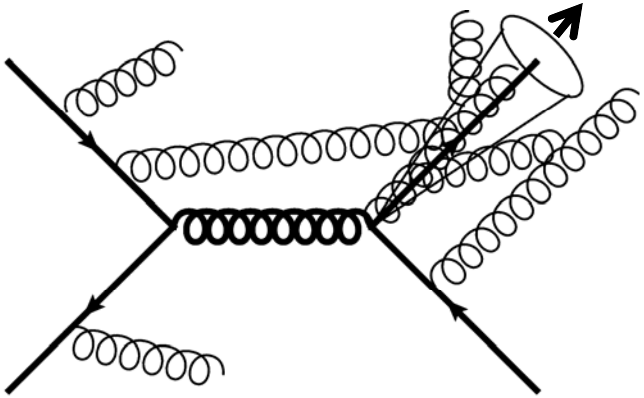
The two approaches are complementary !

Factorization

Large logarithms from fixed-order:

$$\frac{d\sigma}{dm_R^2} = \frac{1}{m_R^2}\left(\alpha_s A \ln\frac{m_R^2}{p_T^2} + \alpha_s^2 B \ln^3\frac{m_R^2}{p_T^2} + \cdots\right)$$

Observed Jet



$\mu_h \sim p_T$

$\mu_{j1} \sim m_R$

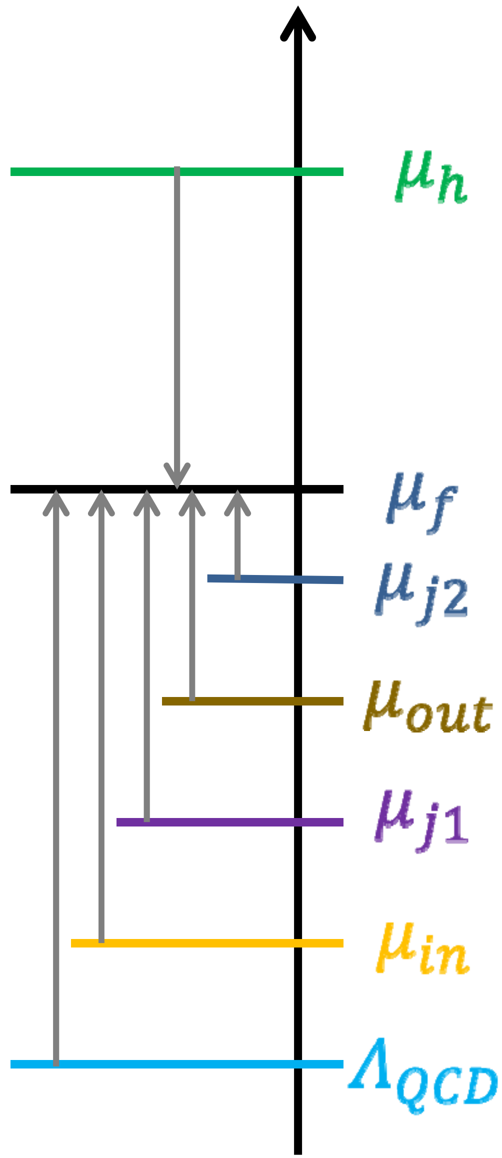
$\mu_{in} \sim m_R^2/p_T$

$$d\sigma = f_a \otimes f_b \otimes H \otimes S \otimes J_{obs} \otimes J$$

f_a, f_b: Λ_{QCD}; H: μ_h; J_{obs}: μ_{j1}; J: μ_{j2}

$$S \Rightarrow S_{in} \otimes S_{out}$$

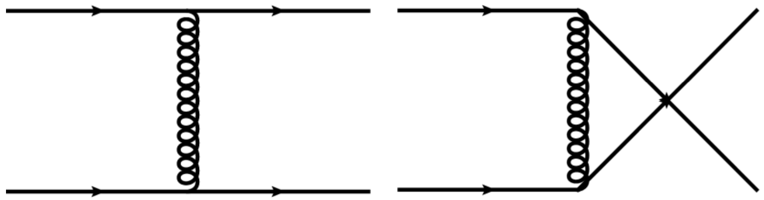
S_{in}: μ_{in}; S_{out}: μ_{out}



Color Structure

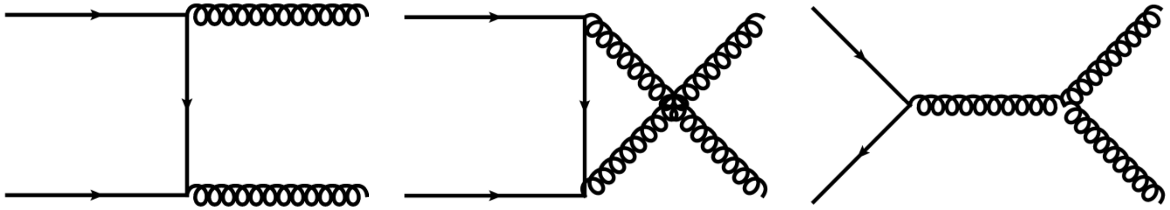
R. Kelley & M. D. Schwartz, PRD83, 045022

$q_i + q_j \to q_i + q_j$



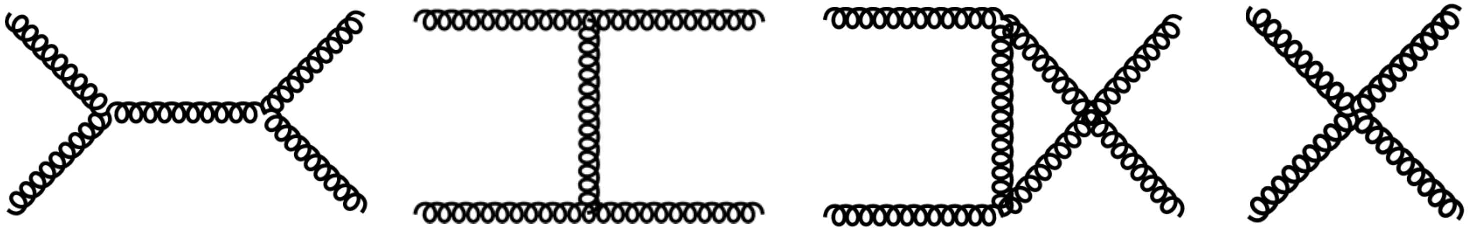
$|c_1\rangle = t^c_{i_3,i_1} t^c_{i_4,i_2}\,, \qquad |c_2\rangle = \delta_{i_3,i_1}\delta_{i_4,i_2}$

$q_i + q_i \to g + g$



$|c_1\rangle = (t^{a_1}t^{a_2})_{i_3,i_4}\,, \qquad |c_2\rangle = (t^{a_2}t^{a_1})_{i_3,i_4}\,, \qquad |c_3\rangle = \delta^{a_1,a_2}\delta_{i_3,i_4}$

$g + g \to g + g$



$|c_1\rangle = \mathrm{Tr}\,(t^{a_1}t^{a_2}t^{a_3}t^{a_4})\,, \qquad |c_2\rangle = \mathrm{Tr}\,(t^{a_1}t^{a_2}t^{a_4}t^{a_3})\,, \qquad |c_3\rangle = \mathrm{Tr}\,(t^{a_1}t^{a_4}t^{a_3}t^{a_2})\,,$

$|c_4\rangle = \mathrm{Tr}\,(t^{a_1}t^{a_4}t^{a_2}t^{a_3})\,, \qquad |c_5\rangle = \mathrm{Tr}\,(t^{a_1}t^{a_3}t^{a_4}t^{a_2})\,, \qquad |c_6\rangle = \mathrm{Tr}\,(t^{a_1}t^{a_3}t^{a_2}t^{a_4})\,,$

$|c_7\rangle = \mathrm{Tr}\,(t^{a_1}t^{a_4})\,\mathrm{Tr}\,(t^{a_2}t^{a_3})\,, \qquad |c_8\rangle = \mathrm{Tr}\,(t^{a_1}t^{a_2})\,\mathrm{Tr}\,(t^{a_3}t^{a_4})\,, \qquad |c_9\rangle = \mathrm{Tr}\,(t^{a_1}t^{a_3})\,\mathrm{Tr}\,(t^{a_2}t^{a_4})$

Hard Function

$$H_{IJ} = \sum_{\Gamma} \mathcal{C}_I^{\Gamma} \mathcal{C}_J^{\Gamma\star} \qquad \frac{d}{d\ln\mu}\mathcal{C}_I^{\Gamma}(\mu) = \Gamma_{IJ}^{H}\mathcal{C}_J^{\Gamma}(\mu)$$

R. Kelley & M. D. Schwartz
PRD83, 045022

$$\Gamma_{IJ}^{H}(\hat{s},\hat{t}_1,\hat{u}_1\mu) = \left(\gamma_{\text{cusp}}\frac{c_H}{2}\ln\frac{-\hat{t}_1}{\mu^2} + \gamma_H - \frac{\beta(\alpha_s)}{\alpha_s}\right)\delta_{IJ} + \gamma_{\text{cusp}} M_{IJ}(s,t,u)$$

$$M_{IJ}(\hat{s},\hat{t}_1,\hat{u}_1) = \begin{pmatrix} 4C_F U - C_A(T+U) & 2U \\ \frac{C_F}{C_A}U & 0 \end{pmatrix}$$

off-diagonal

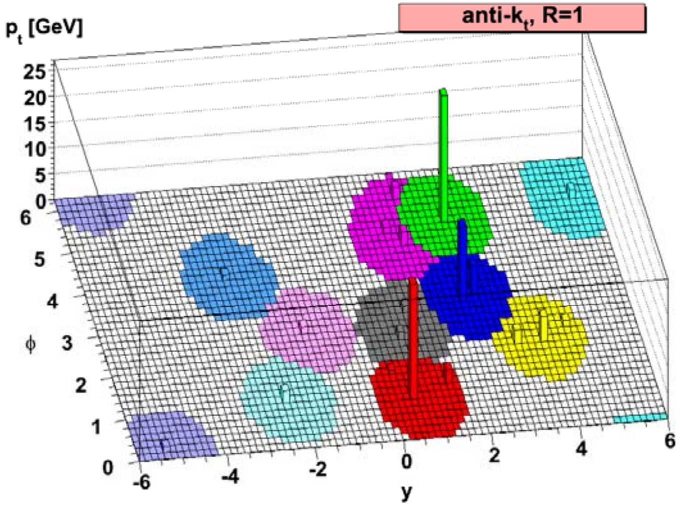
diagonalize

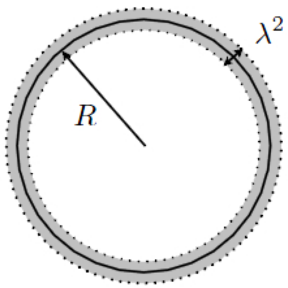
$$\left(\tilde{F}\cdot M\cdot\tilde{F}^{-1}\right)_{KK'} = \begin{pmatrix} \lambda_1 & 0 \\ 0 & \lambda_2 \end{pmatrix}$$

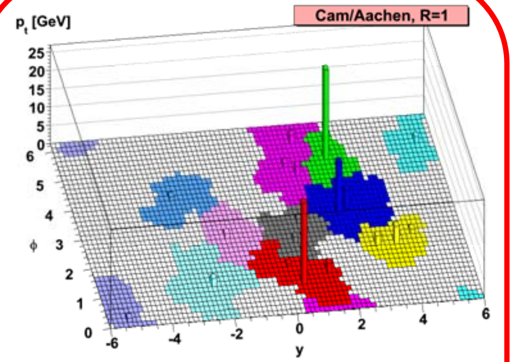
RG equation in diagonalized basis:

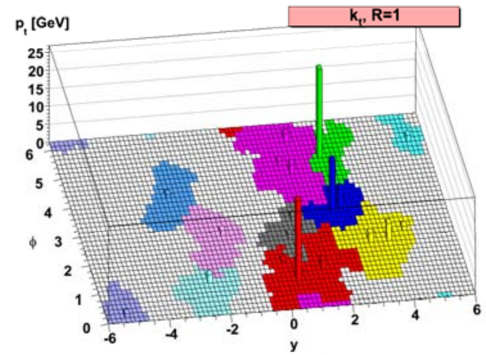
$$\frac{d}{d\ln\mu}\hat{H}_{KK'}(\mu) = \left[\gamma_{\text{cusp}}\left(c_H\ln\left|\frac{\hat{t}_1}{\mu^2}\right| + \lambda_K + \lambda_{K'}^{\star}\right) + 2\gamma_H - \frac{2\beta(\alpha_s)}{\alpha_s}\right]\hat{H}_{KK'}(\mu)$$

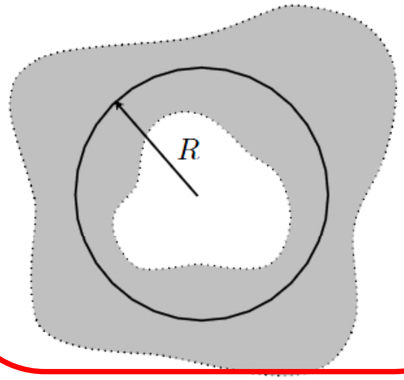
Jet Algorithm











$$d_{ij} = \min(k_{ti}^{2p}, k_{tj}^{2p})\frac{\Delta_{ij}^2}{R^2}$$

$$d_{iB} = k_{ti}^{2p}$$

$$\Delta_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$$

p= -1 : anti-kT

p= 0 : CA

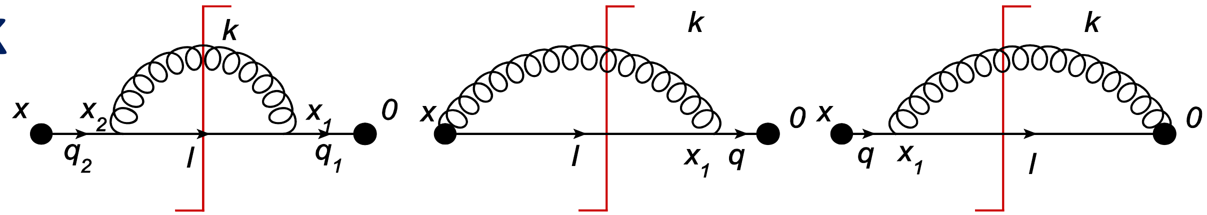
p= 1 : kT

⇨ **boundary clustering change the jet boundary by O(1)**

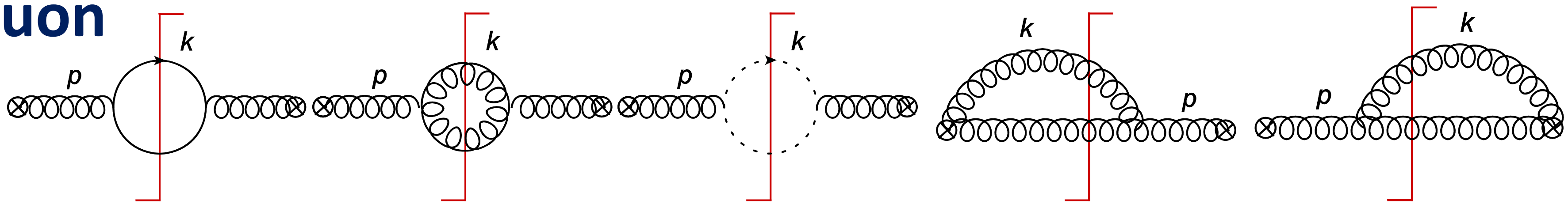
R. Kelley et al., JHEP 1209,117

Jet Function

Quark



Gluon



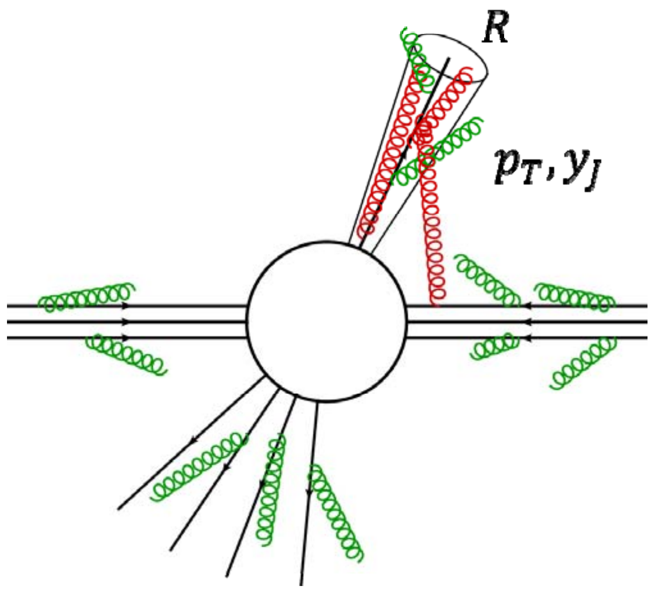
Phase space: $\int \frac{d^D k}{(2\pi)^D}(-2\pi i)\delta(k^2)(-2\pi i)\delta((p-k)^2)\Theta_{\mathrm{k_T}}$

$$\Theta_{\mathrm{k_T}} = \Theta\left(\tan^2\frac{R}{2} > \frac{k^+(p^-)^2}{k^-(p^- - k^-)^2}\right)$$

$$\Theta^{(0)}_{\mathrm{k_T}} = \Theta\left(\tan^2\frac{R}{2} > \frac{k^+}{k^-}\right)$$

Zero-bin subtract:
avoid double counting of soft sector

NLO Soft Function



$$\boldsymbol{S}(k_{\rm in}, k_{\rm out}, \beta, r, \mu) = \sum_{i,j}^{i\neq j} \boldsymbol{w}_{ij} \mathcal{I}_{ij}(k_{\rm in}, k_{\rm out}, \beta, r, \mu)$$

$$\left(\boldsymbol{w}_{ij}\right)_{IJ} = \langle c_I \,|\, \boldsymbol{T}_i \cdot \boldsymbol{T}_j \,|\, c_J \rangle$$

$$\mathcal{I}_{ij}(k_{\rm in}, k_{\rm out}, \beta, r, \mu) = \mathcal{I}_{ij}^{J_1}(k_{\rm in}, \beta, r, \mu)\delta(k_{\rm out}) + \mathcal{I}_{ij}^{out}(k_{\rm out}, \beta, r, \mu)\delta(k_{\rm in})$$

$$\mathcal{I}_{ij}^{J_1}(k, \beta, r, \mu) = -\frac{4\pi\alpha_s}{(2\pi)^{d-1}}\left(\frac{\mu^2 e^{\gamma_E}}{4\pi}\right)^{\epsilon} \int d^d q \; \delta(q^2)\theta(q_0) \mathcal{M}_1(k;q) \frac{n_i \cdot n_j}{(n_i \cdot q)(n_j \cdot q)}$$

$$\mathcal{M}_1(k;q) = \Theta\left(R^2 - (y - y_J)^2 - \phi^2\right)\delta(k - n_J \cdot q)$$

$$\mathcal{I}_{ij}^{out}(k, \beta, r, \mu) = -\frac{4\pi\alpha_s}{(2\pi)^{d-1}}\left(\frac{\mu^2 e^{\gamma_E}}{4\pi}\right)^{\epsilon} \int d^d q \; \delta(q^2)\theta(q_0) \mathcal{M}_{out}(k;q) \frac{n_i \cdot n_j}{(n_i \cdot q)(n_j \cdot q)}$$

$$\mathcal{M}_{out}(k;q) = \Theta\left((y - y_J)^2 + \phi^2 + R^2\right)\delta(k - n_4 \cdot q)$$

Refactorization of Soft Function

The soft gluon in/out the cone correspond to different scales

R. Kelley, M. D. Schwartz & H. X. Zhu PRD87, 014010

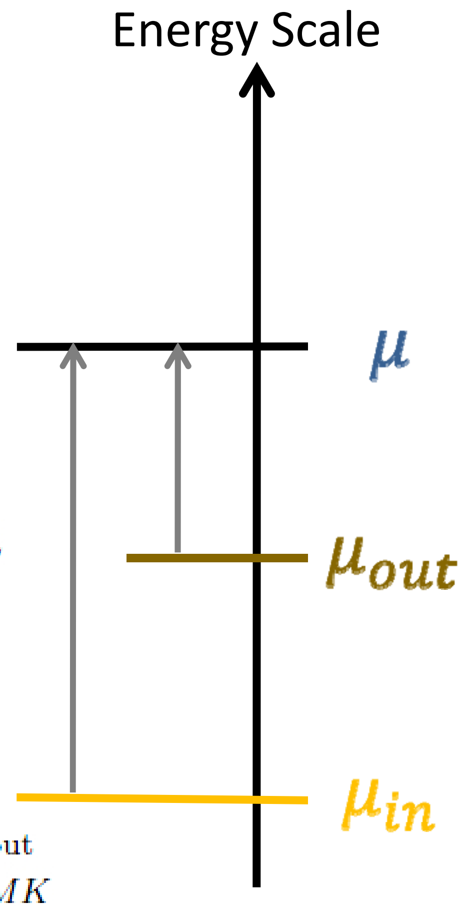
$$\hat{S}_{K'K}(k_{\rm in}, k_{\rm out}, \mu) = \boxed{\hat{S}^{\rm in}_{K'L}(k_{\rm in}, \mu_{\rm in}, \mu)} \left(\hat{S}^{(0)}\right)^{-1}_{LM} \boxed{\hat{S}^{\rm out}_{MK}(k_{\rm out}, \mu_{\rm out}, \mu)}$$

$$\widetilde{\hat{s}}^{\rm in}_{K'L}(\kappa_{\rm in}, \mu) = \widetilde{\hat{s}}^{(0)}_{K'L} + \sum_{i \neq j} [\boldsymbol{w}_{ij}]_{K'L} \, \tilde{I}^{\rm in}_{ij}(\kappa_{\rm in}, \mu)$$

$$\frac{d}{d \ln \mu} \widetilde{\hat{s}}^{\rm in}_{K'L}(L_{\rm in}, \mu) = \left[-2 \widetilde{B}^{\rm in}_{K'L} \gamma_{\rm cusp} \, L_{\rm in} - \widetilde{C}^{\rm in}_{K'L} \gamma_{\rm cusp} - \widetilde{\gamma}^{\rm in}_{K'L}\right] \widetilde{\hat{s}}^{\rm in}_{K'L}$$

$$\widetilde{\hat{s}}^{\rm out}_{MK}(\kappa_{\rm out}, \mu) = \widetilde{\hat{s}}^{(0)}_{MK} + \sum_{i \neq j} [\boldsymbol{w}_{ij}]_{MK} \, \tilde{I}^{\rm out}_{ij}(\kappa_{\rm out}, \mu)$$

$$\frac{d}{d \ln \mu} \widetilde{\hat{s}}^{\rm out}_{MK}(L_{\rm out}, \mu) = \left[-2 \widetilde{B}^{\rm out}_{MK} \gamma_{\rm cusp} \, L_{\rm out} - \widetilde{C}^{\rm out}_{MK} \gamma_{\rm cusp} - \widetilde{\gamma}^{\rm out}_{MK}\right] \widetilde{\hat{s}}^{\rm out}_{MK}$$



RG invariance

$$\frac{d\widetilde{f}_{q/N}(\tau,\mu)}{d\ln\mu} = \left[2C_F\gamma_{\rm cusp}\ln(\tau) + 2\gamma^{f_q}\right]\widetilde{f}_{q/N}(\tau,\mu)$$

$$\frac{d}{d\ln\mu}\hat{H}_{KK'}(\mu) = \left[\gamma_{\rm cusp}\left(c_H\ln\left|\frac{\hat{t}_1}{\mu^2}\right| + \lambda_K + \lambda^\star_{K'}\right) + 2\gamma_H - \frac{2\beta(\alpha_s)}{\alpha_s}\right]\hat{H}_{KK'}(\mu)$$

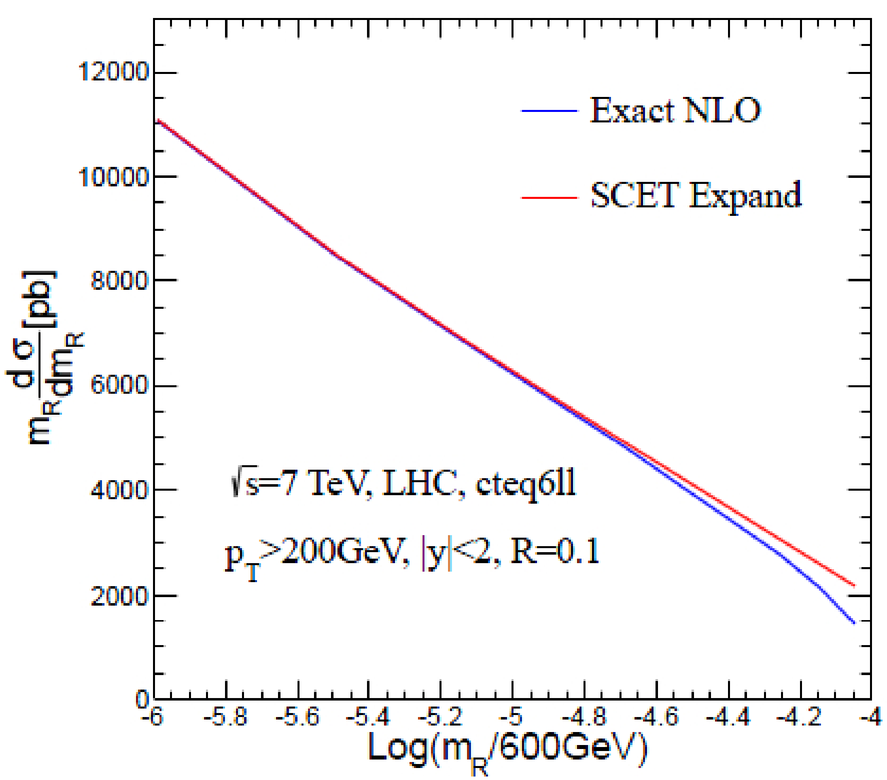
$$\frac{d}{d\ln\mu}\widetilde{j}_g(Q^2,\mu) = \left[-2C_A\gamma_{\rm cusp}\ln\left(\frac{Q^2}{\mu^2}\right) - 2\gamma^{J_g}\right]\widetilde{j}_g(Q^2,\mu)$$

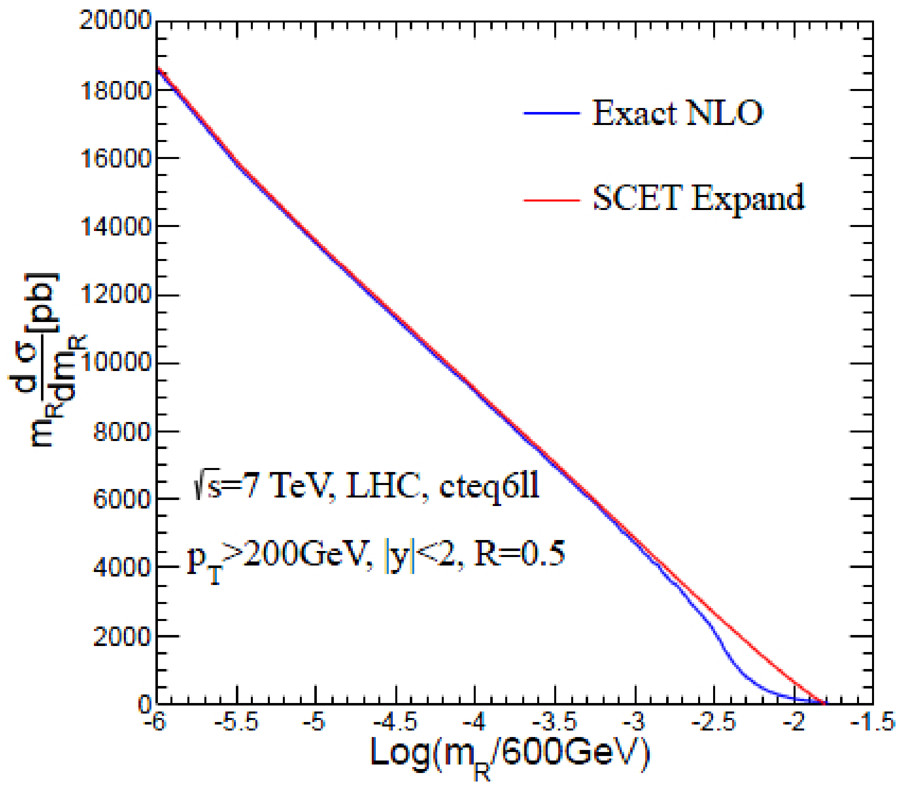
$$\frac{d}{d\ln\mu}\,\hat{\widetilde{s}}_{K'K} = \Big\{\gamma_{\rm cusp}\left[2C_{i_1}L(\hat{u}_1) + (2C_{i_2} - c_H)L(\hat{t}_1) - \lambda_K - \lambda^\star_{K'}\right] - 2\,\gamma_{\rm cusp}\,(C_{i_1} + C_{i_2} - C_{j_1} - C_{j_2})\ln\frac{Q^2}{\mu^2} - 2\gamma^S\Big\}\,\hat{\widetilde{s}}_{K'K}$$

$$\frac{d}{d\ln\mu}\left[H_{IJ}(p_T,v,\mu)\widetilde{s}_{JI}\left(\frac{Q^2}{2E_J^*},\frac{Q^2}{2E_J^*},\mu\right)\widetilde{f}_{i_1/N_1}\left(\frac{Q^2}{p_T^2}\bar{v},\mu\right)\widetilde{f}_{i_2/N_2}\left(\frac{Q^2}{p_T^2}v,\mu\right)\widetilde{j}_1(Q^2,\mu)\widetilde{j}_2(Q^2,\mu)\right] = 0$$

The RG invariance has been checked at $O(\alpha_s)$

Jet Mass Spectrum at Fixed-Order



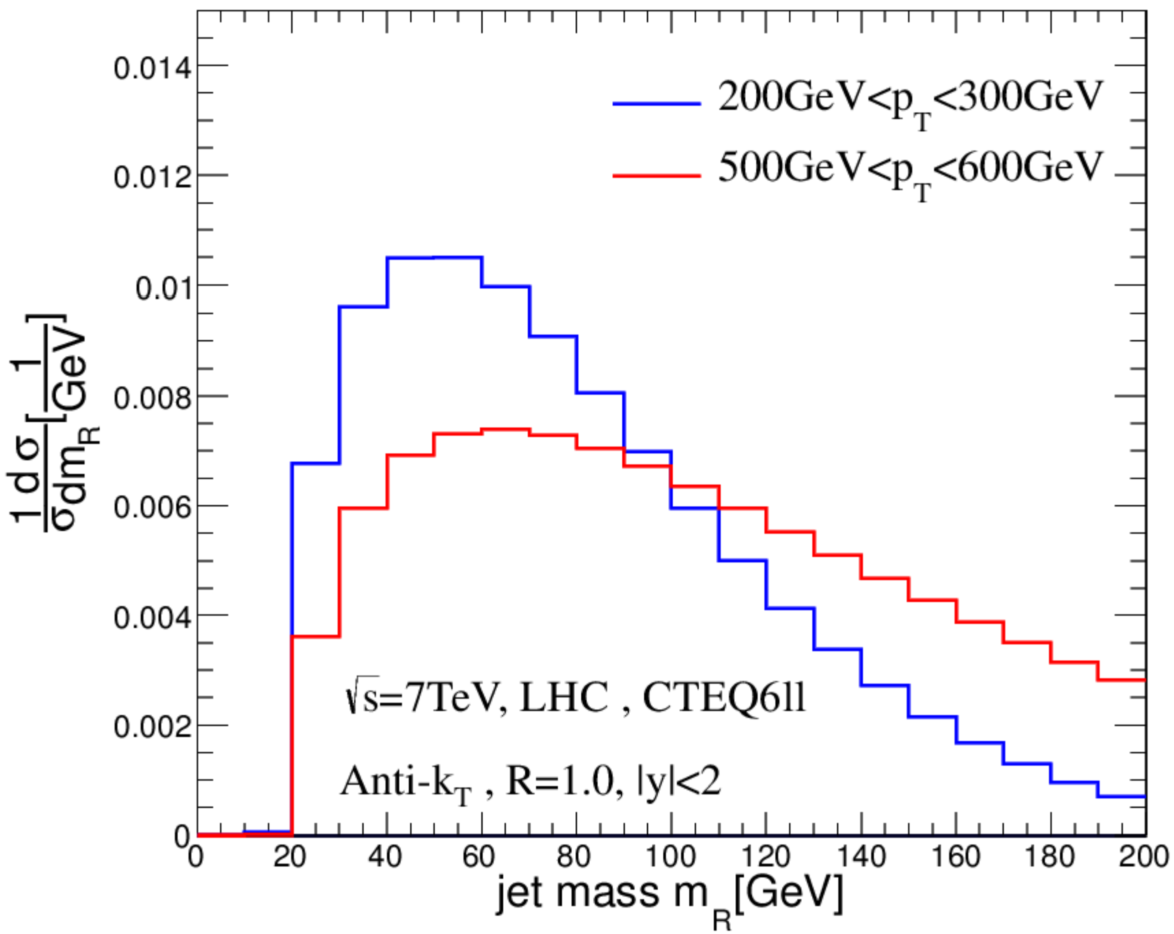


NLL Resummation

$$\mu_h = p_T$$
$$\mu_{j1} = 1.6\, m_R^{1.47}$$
$$\mu_{in} = \mu_{j1}^2/6700$$

R. Kelley, M. D. Schwartz & H. X. Zhu
PRD87, 014010

$$\mu_{out} = \mu_{j2} = \mu_h$$



Out Look

- Resummation at NNLL
- Scale choices and matching
- Non-global logarithms
- Distinguish quark jet and gluon jet
- Compare our results with the experiment and MC tools

Thank you!