Jet substructure measurements in semi-inclusive jet production

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Santa Fe Jets and Heavy Flavor Workshop
01/29/18 - 01/31/18
We want to study semi-inclusive jet production event:
\[ p + p \rightarrow \text{Jet((with/without) substructure)} + X \]

- More statistics. No veto on additional jets.
Plans of this talk

• Inclusive jet production (no substructure)

• Substructure measurements
  - hadron-in-jet (brief)

• Angularities (1801.00790)
  - quark and gluon discrimination
  - Relation to inclusive jet
  - Phenomenology

• Conclusions
Inclusive Jet Production

- A completely perturbative process (IR safe), perturbative computation can be made.
- Fixed order calculation gives:

\[ E \frac{d\sigma^{pp \to \text{jet}X}}{dp_T d\eta} \propto \sum_{a,b} \int \frac{dx_a}{x_a} f^p_a(x_a) \int \frac{dx_b}{x_b} f^p_b(x_b) H_{ab} \]
Inclusive Jet Production

NLO 1990

\[ H_{ab}^{(0)} + \alpha_s H_{ab}^{(1)} + \alpha_s^2 H_{ab}^{(2)} + \ldots \]

\[ H_{ab} \]

\[ \text{has } (\alpha_s \ln R)^n \] which must be resummed.
Factorization

Example of NLO diagrams

- Relevant scales:
  1. Hard scale: \( \mu_H \sim p_T \)
  2. Jet scale: \( \mu_J \sim p_T R \)

- For small-R jet, we have hierarchy between the two different scales and jet cross-section is factorized, \( H_{ab} \to \sum_c \int \frac{dz_c}{z_c^2} H_{ab}^c J_c(z_c) \) giving

\[
E \frac{d\sigma^{pp \to \text{jet} X}}{dp_T d\eta} \propto \sum_{a,b,c} \int \frac{dx_a}{x_a} f_a^p (x_a) \int \frac{dx_b}{x_b} f_b^p (x_b) \int \frac{dz_c}{z_c^2} H_{ab}^c J_c(z_c)
\]
Semi-inclusive jet function \( J_c(z_c, p_T R, \mu) \)

- Using Effective-field theory, we can write operator definition of \( J_c \):

\[
J_q(z, p_T R, \mu) = \frac{z}{2N_c} \text{Tr} \left[ \frac{\gamma \cdot \bar{n}}{2} \langle 0 | \delta (\omega - \bar{n} \cdot \mathcal{P}) \chi_n(0) | JX \rangle \langle JX | \bar{\chi}_n(0) | 0 \rangle \right]
\]

\[
J_g(z, p_T R, \mu) = -\frac{z \omega}{2(N_c^2 - 1)} \langle 0 | \delta (\omega - \bar{n} \cdot \mathcal{P}) \mathcal{B}_{n\perp \mu}(0) | JX \rangle \langle JX | \mathcal{B}_{n\perp \mu}^\mu(0) | 0 \rangle,
\]

- At NLO, (quark initiated) we have the following diagrams:

(A) \hspace{2cm} (B) \hspace{2cm} (C)
Semi-inclusive jet function $J_c(z_c, p_T R, \mu)$

- Using Effective-field theory, we can write operator definition of $J_c$:

$$J_q(z, p_T R, \mu) = \frac{z}{2N_c} \text{Tr} \left[ \gamma \cdot \bar{n} \langle 0 | \delta (\omega - \bar{n} \cdot \mathcal{P}) \chi_n(0) | J X \rangle \langle J X | \chi_n(0) | 0 \rangle \right]$$

$$J_g(z, p_T R, \mu) = -\frac{z \omega}{2(N_c^2 - 1)} \langle 0 | \delta (\omega - \bar{n} \cdot \mathcal{P}) \mathcal{B}_{n \perp \mu}(0) | J X \rangle \langle J X | \mathcal{B}_{n \perp \mu}^\mu(0) | 0 \rangle,$$

Kang, Ringer, Vitev '16

- At NLO, (quark initiated) we have the following diagrams:

$$L = \ln \frac{\mu^2}{p_T^2 R^2}$$

$$J_{q \rightarrow qg}(z, p_T R) = \delta(1 - z) \frac{\alpha_s}{2\pi} \left[ C_F \left( \frac{1}{\epsilon^2} + \frac{3}{2\epsilon} + \frac{1}{\epsilon} L + \frac{1}{2} L^2 + \frac{3}{2} L \right) + d_{qg} \right]$$
Semi-inclusive jet function $J_c(z_c, p_T R, \mu)$

- Using Effective-field theory, we can write operator definition of $J_c$:

$$J_q(z, p_T R, \mu) = \frac{z}{2N_c} \text{Tr} \left[ \frac{\gamma \cdot \vec{n}}{2} \langle 0 | \delta (\omega - \vec{n} \cdot \mathcal{P}) \chi_n(0) | JX \rangle \langle JX | \chi(0) | 0 \rangle \right]$$

$$J_g(z, p_T R, \mu) = -\frac{z \omega}{2(N_c^2 - 1)} \langle 0 | \delta (\omega - \vec{n} \cdot \mathcal{P}) \mathcal{B}_{n\perp\mu}(0) | JX \rangle \langle JX | \mathcal{B}_{n\perp}(0) | 0 \rangle,$$

- At NLO, (quark initiated) we have the following diagrams: ($L = \ln \frac{\mu^2}{p_T^2 R^2}$)

$$J_{q\rightarrow q(g)}(z, p_T R) = \frac{\alpha_s C_F}{2\pi} \left[ \delta(1 - z) \left( -\frac{1}{e^2} - \frac{1}{e} L - \frac{1}{2} L^2 + \frac{\pi^2}{12} \right) + \left( \frac{1}{e} + L \right) \frac{1 + z^2}{(1 - z)_+} - 2(1 + z^2) \left( \frac{\ln(1 - z)}{1 - z} \right)_+ - (1 - z) \right]$$
Semi-inclusive jet function \( J_C(z_c, p_T R, \mu) \)

- Using Effective-field theory, we can write operator definition of \( J_C \):
  \[
  J_q(z, p_T R, \mu) = \frac{z}{2N_c} \text{Tr} \left[ \frac{\gamma \cdot \bar{n}}{2} \left< 0 | \delta (\omega - \bar{n} \cdot \mathcal{P}) \chi_n(0) | JX \right> \left< JX | \bar{\chi}_n(0) | 0 \right> \right]
  \]
  \[
  J_g(z, p_T R, \mu) = -\frac{z \omega}{2(N_c^2 - 1)} \left< 0 | \delta (\omega - \bar{n} \cdot \mathcal{P}) \mathcal{B}_{n \perp \mu}(0) | JX \right> \left< JX | \mathcal{B}_{n \perp}^{\mu}(0) | 0 \right>
  \]

- At NLO, (quark initiated) we have the following diagrams:
  \( L = \ln \frac{\mu^2}{p_T^2 R^2} \)

\[
J_{q\rightarrow(q)g}(z, p_T R) = \frac{\alpha_s}{2\pi} \left( \frac{1}{\epsilon} + L \right) P_{gq}(z) - \frac{\alpha_s}{2\pi} \left[ P_{gq}(z) 2 \ln(1 - z) + C_F z \right]
\]

\[\text{Kang, Ringer, Vitev '16}\]
• Adding the contributions, we have cancellation of $\frac{1}{\epsilon^2}$ and $L^2$:

$$J_q(z, p_{TR}) = J_{q\rightarrow qg}(z, p_{TR}) + J_{q\rightarrow q(g)}(z, p_{TR}) + J_{q\rightarrow (q)g}(z, p_{TR})$$

$$\supset \frac{\alpha_s C_F}{2\pi} \frac{1}{\epsilon} (P_{qq}(z) + P_{gq}(z))$$

$$J_g(z, p_{TR}) \supset \frac{\alpha_s C_F}{2\pi} \frac{1}{\epsilon} (P_{gg}(z) + 2n_f P_{qg}(z))$$

• The UV poles give DGLAP RG equation for $J_c$:

$$\mu \frac{d}{d\mu} J_i(z, p_{TR}, \mu) = \frac{\alpha_s(\mu)}{\pi} \sum_j \int_{z}^{1} d\frac{z'}{z} P_{ji}(\frac{z}{z'}, \mu) J_j(z', p_{TR}, \mu)$$

where $P_{ij}$ are the standard splitting functions.

• Evolution from $\mu J$ to $\mu H$ gives $(\alpha_s \ln R)^n$ resummations.

• See Liu, Moch, Ringer `18 for joint resummation of threshold log and jet radius logs, and phenomenology.
Comparison with the inclusive hadron production case

\[ \frac{d\sigma^{pp\rightarrow jet X}}{dp_Td\eta} = \sum_{a,b,c} f_a \otimes f_b \otimes H_{ab}^c \otimes J_c + \mathcal{O}(R^2) \]

\[ \frac{d\sigma^{pp\rightarrow hX}}{dp_Td\eta} = \sum_{a,b,c} f_a \otimes f_b \otimes H_{ab}^c \otimes D_h^c \]

Factorization

Evolution

\[ \mu \frac{d}{d\mu} J_i = \sum_j P_{ji} \otimes J_j \]

\[ \mu \frac{d}{d\mu} D_i^h = \sum_j P_{ji} \otimes D_j^h \]
Comparison with the exclusive jet production case

\[ d\sigma^{e^+e^- \rightarrow \text{jet}_1 \cdots \text{jet}_N} \propto H_{1,2,\ldots,N} \otimes J_{1}^{\text{excl}} \cdots J_{N}^{\text{excl}} S \]

Ellis, Vermilion, Walsh, Hornig, Lee '10

- The operator definition of the \( J_c^{\text{excl}} \) is similar to the semi-inclusive case, except it has an additional restriction \( \delta(N(X_n)-1) \), which restricts amount of energy outside the jet.
Jet Substructure Measurements
Hadron in jet

- We may try to observe a hadron $H$ inside the jet

- $J_c(z, p_T R, \mu) \rightarrow G^H_c(z, z_h, p_T R, \mu)$

- $G^H_c$ no more completely perturbative:

$$G^h_i(z, z_h, \mu) = \sum_j \int_{z_h}^{1} \frac{dz'_h}{z'_h} J_{ij}(z, z'_h, \mu) D^h_j\left(\frac{z_h}{z'_h}, \mu\right)$$

where $z_h = \frac{\omega_h}{\omega_J}$

- Two DGLAPS

\[ \mu_H \sim p_T \]
\[ \mu_J \sim p_T R \]
\[ \mu_D \sim 1\text{GeV} \]
Hadron in jet

• We may try to observe a hadron H inside the jet

• \( J_c(z, p_T R, \mu) \to G_c^H(z, z_h, p_T R, \mu) \)

• \( G_c^H \) no more completely perturbative:

\[
G_i^h(z, z_h, \mu) = \sum_j \int_{z_h}^{1} \frac{dz_h'}{z_h'} J_{ij}(z, z_h', \mu) D_j^h\left(\frac{z_h}{z_h'}, \mu\right)
\]

where \( z_h = \frac{\omega_h}{\omega_J} \)

• Two DGLAPS

\[ \mu_H \sim p_T \]

\[ \mu_J \sim p_T R \]

\[ \mu_D \sim 1 \text{GeV} \]
Patterns emerging

\[ \frac{d\sigma}{dp_T d\eta d\nu} \]

- When we measure substructure \( \nu \) from the jet, once we evolve to \( \mu_J \) the remaining evolution to \( \mu_H \) is given by DGLAP evolution!
- Two step factorization:
  a) production of a jet
  b) probing the internal structure of the jet produced.
Jet angularity

• Thrust was defined as an event shape parameter to understand radiation pattern

\[ T = \frac{1}{Q} \max_t \sum_{i \in X} |t \cdot p_i| = 1 - \tau_0 \]

• \( \tau_0 \rightarrow 0 \) is equivalent to dijet limit

• A generalized class of IR safe observables, angularity (applied to jet):

\[ \tau_{e^+e^-}^a = \frac{1}{E_J} \sum_{i \in J} E_i \theta_{iJ}^{2-a} \]

\[ \tau_{pp}^a = \frac{1}{p_T} \sum_{i \in J} p_{T,i} (\Delta R_{iJ})^{2-a} \]

• \( a=0 \) related to thrust (jet mass)
• \( a=1 \) related to jet broadening (sensitive to rapidity divergence)
• Many studies done for exclusive case: \textit{Sterman et al. `03, `08, Hornig, C. Lee, Ovanesyan `09, Ellis, Vermilion, Walsh, Hornig, C. Lee `10, Chien, Hornig, C. Lee `15, Hornig, Makris, Mehen `16}
Jet angularity

- When $\frac{1}{\tau_a^{2-a}} \ll R$, $\left(\alpha_s \ln^2 \left(\frac{\tau_a^{2-a}}{R}\right)\right)^n$ resummation becomes important.
- Replace $J_c(z, p_T R, \mu) \rightarrow G_c(z, p_T R, \tau_a, \mu)$
- Refactorize $G_c$ as

$$G_c(z, p_T R, \tau_a, \mu) = \sum_i H_{c \rightarrow i}(z, p_T R, \mu) \times \int d\tau_a C_i \cdot d\tau_a S_i \cdot \delta(\tau_a - \tau_a^{C_i} - \tau_a^{S_i}) \cdot C_i(\tau_a^{C_i}, p_T \tau_a^{2-a}, \mu) \cdot S_i(\tau_a^{S_i}, \frac{p_T \tau_a}{R^{1-a}}, \mu)$$

- Each pieces describe physics at different scales.
- $\mu J \rightarrow \mu_H$ evolution follows DGLAP evolution equation again
- Jointly resums $(\alpha_s \ln R)^n$ and $(\alpha_s \ln^2 \frac{R}{\tau_a^{1/(2-a)}})^n$
Jet angularity

• When $\frac{1}{\tau^a} \ll R$, $(\alpha_s \ln^2 (\frac{1}{\tau^a} / R))^n$ resummation becomes important.

• Replace $J_c(z, p_T R, \mu) \rightarrow G_c(z, p_T R, \tau_a, \mu)$

• Refactorize $G_c$ as

$$G_c(z, p_T R, \tau_a, \mu) = \sum_i \mathcal{H}_{c\rightarrow i}(z, p_T R, \mu)$$

$$\times \int d\tau_a^C_i d\tau_a^S_i \delta(\tau_a - \tau_a^C_i - \tau_a^S_i) C_i(\tau_a^C_i, p_T \tau_a^{2-a}, \mu) S_i(\tau_a^S_i, \frac{p_T \tau_a}{R^{1-a}}, \mu)$$

• $H_{c\rightarrow i}$, $C_i$ and $S_i$ have double poles, which cancel once evolved to $\mu H$.

• $G_c(z, p_T R, \tau_a, \mu)$ follows DGLAP from $\mu J$ to $\mu H$:

$$\mu \frac{d}{d\mu} G_i(z, p_T R, \tau_a, \mu) = \frac{\alpha_s(\mu)}{\pi} \sum_j \int_z^1 \frac{dz'}{z'} P_{ji} \left( \frac{z}{z'}, \mu \right) G_j(z', p_T R, \tau_a, \mu)$$

$$\mu_H \sim p_T$$

$$\mu_J \sim p_T R$$

$$\mu_C \sim p_T \tau_a^{2-a}$$

$$\mu_S \sim \frac{p_T \tau_a}{R^{1-a}}$$
Relation to inclusive jet function

\[
\int \frac{d\sigma}{dp_T d\eta d\tau_a} d\tau_a = \frac{d\sigma}{dp_T d\eta} \Leftrightarrow \int_0^\infty d\tau_a G_i(z, p_T, R, \tau_a, \mu) = J_i(z, p_T, R, \mu)
\]

- Correct integration over substructure should give inclusive case.

\[
G_c(z, p_T R, \tau_a, \mu) = \sum_i \mathcal{H}_{c \rightarrow i}(z, p_T R, \mu) \int d\tau_a^{C_i} d\tau_a^{S_i} \delta(\tau_a - \tau_a^{C_i} - \tau_a^{S_i}) C_i(\tau_a^{C_i}, p_T \tau_a^{1-a}, \mu) S_i(\tau_a^{S_i}, \frac{p_T \tau_a}{R^{1-a}}, \mu)
\]

See also Chien, Hornig, C. Lee `15
Relation to inclusive jet function

\[ \int \frac{d\sigma}{dp_T d\eta_1} d\tau_a = \int_0^\infty d\tau_a G_i(z, p_T, R, \tau_a, \mu) = J_i(z, p_T, R, \mu) \]

- Correct integration over substructure should give inclusive case.

\[ G_c(z, p_T R, \tau_a, \mu) = \sum_i \mathcal{H}_{c \rightarrow i}(z, p_T R, \mu) \int d\tau_a C_i \delta(\tau_0 - \tau_a) \delta(\tau_a - \tau_a^0) C_i(\tau_a^0, p_T \tau_a R, \mu) S_i(\tau_a^0, p_T R, \mu) \]

\[ \mathcal{H}_{q \rightarrow q}(z, p_T R, \mu) = \delta(1 - z) - \frac{\alpha_s C_F}{2\pi} \left\{ \delta(1 - z) \left[ \frac{1}{\epsilon^2} + \frac{3}{2} \frac{1}{\epsilon} + \ln \left( \frac{\mu^2}{p_T R^2} \right) \right] \right. \\
+ \frac{1}{2} \ln^2 \left( \frac{\mu^2}{p_T R^2} \right) + \frac{3}{2} \ln \left( \frac{\mu^2}{p_T R^2} \right) - \frac{\pi^2}{12} \right. \\
+ 2 \left( (1 + z^2) \ln \left( \frac{1 - z}{1 + z} \right) + (1 - z) - P_{qq}(z) \left( \frac{1}{\epsilon} + \ln \left( \frac{\mu^2}{p_T R^2} \right) \right) \right) \}

\[ \mathcal{H}_{g \rightarrow g}(z, p_T R, \mu) = \frac{\alpha_s}{2\pi} P_{gg}(z) \left( \frac{1}{\epsilon} + \ln \left( \frac{\mu^2}{p_T R^2} \right) - \ln(1 - z)^2 \right) - \frac{\alpha_s C_F}{2\pi} z \]

\[ C_q(\tau_0, p_T, R, \mu) = C_q^{l.p.}(\tau_0, p_T, \mu) + \Delta C_q^{\text{alg}}(\tau_0, R) \]

\[ \int_{\tau_0^\text{max}}^\infty d\tau_0 C_q^{l.p.}(\tau_0, p_T, \mu) = 1 + \frac{\alpha_s C_F}{2\pi} \left\{ \frac{2}{\epsilon^2} + \frac{3}{2\epsilon} - \frac{2}{\epsilon} \ln \left( \frac{\tau_0^\text{max} p_T}{\mu^2} \right) + \ln^2 \left( \frac{\tau_0^\text{max} p_T}{\mu^2} \right) \right. \\
- \frac{3}{2} \ln \left( \frac{\tau_0^\text{max} p_T}{\mu^2} \right) + \frac{7}{2} - \frac{\pi^2}{2} \right\} \]

\[ \int_{\tau_0^\text{max}}^\infty d\tau_0 \Delta C_q^{kT}(\tau_0, R) = \frac{\alpha_s C_F}{2\pi} \left( 3 - \frac{\pi^2}{3} - 3 \ln 2 + 4 \ln^2 2 \right) \]

\[ \int_{\tau_0^\text{max}}^\infty d\tau_0 S_q(\tau_0, p_T, R, \mu) = 1 + \frac{\alpha_s C_F}{2\pi} \left\{ \frac{1}{\epsilon^2} + \frac{2}{\epsilon} \ln \left( \frac{\tau_0^\text{max} p_T}{\mu R} \right) + \ln^2 \left( \frac{\tau_0^\text{max} p_T}{\mu R} \right) \right. \\
- \frac{\pi^2}{12} - 2 \ln^2 \left( \frac{\tau_0^\text{max} p_T}{\mu R} \right) \right\} \]
Relation to inclusive jet function

\[
\int \frac{d\sigma}{dp_T d\eta} d\tau_a = \int_0^\infty d\tau_a G_i(z, p_T, R, \tau_a, \mu) = J_i(z, p_T, R, \mu)
\]

See also Chien, Hornig, C. Lee `15

- Correct integration over substructure should give inclusive case.

\[
\mathcal{G}_c(z, p_T R, \tau_a, \mu) = \sum_i \mathcal{H}_{c 	o i}(z, p_T R, \mu) \int d\tau_a C_i \frac{d\tau_a S_i}{d\tau_a} \delta(\tau_a - \tau_a^{C_i} - \tau_a^{S_i}) C_i(\tau_a^{C_i}, p_T^{\tau_a^{C_i}}, \mu) S_i(\tau_a^{S_i}, \frac{p_T \tau_a^{C_i}}{R^{1-a}}, \mu)
\]

\[
\mathcal{H}_{q \to q}(z, p_T R, \mu) = \delta(1-z) - \frac{\alpha_s C_F}{2\pi} \left\{ \delta(1-z) \left[ \frac{1}{\epsilon^2} + \frac{3}{2} \epsilon + \ln \left( \frac{\mu^2}{p_T^2 R^2} \right) \right]
\]

\[
+ \frac{1}{2} \ln^2 \left( \frac{\mu^2}{p_T^2 R^2} \right) + \left[ \frac{3}{2} \ln \left( \frac{\mu^2}{p_T^2 R^2} \right) - \frac{\pi^2}{12} \right]
\]

\[
+ 2 \left( (1+z^2) \ln(1-z) \right) + (1-z) - P_{qq}(z) \left[ \frac{1}{\epsilon} + \ln \left( \frac{\mu^2}{p_T^2 R^2} \right) \right]
\]

\[
\mathcal{H}_{g \to q}(z, p_T R, \mu) = \frac{\alpha_s}{2\pi} P_{gq}(z) \left( \frac{1}{\epsilon} + \ln \left( \frac{\mu^2}{p_T^2 R^2} \right) - \ln(1-z)^2 \right) - \frac{\alpha_s C_F}{2\pi} z
\]

\[
\mathcal{C}_q(\tau_0, p_T, R, \mu) = C_q^{1p}(\tau_0, p_T, \mu) + \Delta C_q^{\text{alg}}(\tau_0, R)
\]

\[
\int_{\tau_0^{\text{max}}}^{\tau_0} d\tau_0 C_q^{1p}(\tau_0, p_T, \mu) = 1 + \frac{\alpha_s C_F}{2\pi} \left\{ \frac{2}{\epsilon^2} + 3 \left[ \frac{2}{\epsilon} + \ln \left( \frac{\tau_0^{\text{max}}}{R} \right) \right] \right\}
\]

\[
- \frac{3}{2} \ln \left( \frac{\tau_0^{\text{max}}}{R} \right) + \frac{7}{2} - \frac{\pi^2}{2}
\]

\[
\int_{\tau_0^{\text{max}}}^{\tau_0} d\tau_0 \Delta C_q^{kt}(\tau_0, R) = \frac{\alpha_s C_F}{2\pi} \left( 3 - \frac{\pi^2}{3} - 3 \ln 2 + 4 \ln^2 2 \right)
\]

\[
\int_{\tau_0^{\text{max}}}^{\tau_0} d\tau_0 S_q(\tau_0, p_T, R, \mu) = 1 + \frac{\alpha_s C_F}{2\pi} \left\{ -\frac{1}{\epsilon^2} + \frac{2}{\epsilon} \ln \left( \frac{\tau_0^{\text{max}}}{R} \right) + \frac{\pi^2}{12} - 2 \ln \left( \frac{\tau_0^{\text{max}}}{R} \right) \right\}
\]
Relation to inclusive jet function

- □ poles except ones associated with DGLAP cancel.
- □ logs except ones associated with the jet scale cancel.
Quark and gluon discrimination

- We can study how well angularity discriminates between quark and gluon jet as a continuous function of ‘a’.
Quark and gluon discrimination

- We can study how well angularity discriminates between quark and gluon jet as a continuous function of ‘a’.
- As 'a' increases, better discrimination but more sensitive to non-perturbative effects.
Non-perturbative Model

• As $\tau_a$ gets smaller, $\mu_S \sim \frac{p_T \tau_a}{R^{1-a}}$ can approach $\Lambda_{QCD}$:

$$S_i(\tau_a, \mu) \rightarrow \int d\tau'_a S_i(\tau_a - \tau'_a, \mu) S^{NP}(\tau'_a)$$

where

$$S^{NP}(\tau_a) = \frac{N(A, B, \Lambda)}{\Lambda} \left( \frac{\frac{p_T \tau_a}{R^{1-a}}}{\Lambda} \right)^{A-1} \exp \left( - \left( \frac{\frac{p_T \tau_a}{R^{1-a}} - B}{\Lambda} \right)^2 \right)$$

• Since we are sensitive to non-perturbative effects at small values of $\tau_a$, the distribution is unaffected at large values of $\tau_a$.

• Profile function is included to prevent soft scale from reaching landau pole and scales involved are varied up and down by factor 2 with respect to the canonical scale.
Phenomenology

200 GeV < $p_T$ < 250 GeV, $|\eta| < 1.2$
$a = -0.5, R = 0.4, \sqrt{s} = 7$ TeV

200 GeV < $p_T$ < 250 GeV, $|\eta| < 1.2$
$a = 0, R = 0.4, \sqrt{s} = 7$ TeV

200 GeV < $p_T$ < 250 GeV, $|\eta| < 1.2$
$a = 0.5, R = 0.4, \sqrt{s} = 7$ TeV

50 GeV < $p_T$ < 100 GeV, $|\eta| < 1.2$
$a = -0.5, R = 0.4, \sqrt{s} = 7$ TeV

50 GeV < $p_T$ < 100 GeV, $|\eta| < 1.2$
$a = 0, R = 0.4, \sqrt{s} = 7$ TeV

50 GeV < $p_T$ < 100 GeV, $|\eta| < 1.2$
$a = 0.5, R = 0.4, \sqrt{s} = 7$ TeV

Kang, KL, Ringer '18
Phenomenology \((a=0, \text{jet mass})\)

- As pointed out yesterday (Prof. Stewart’s talk), NP (both hadronization and MPI) effects in jet mass is well-represented by just shifting first-moments.

- Single parameter NP soft function from \textit{Stewart, Tackmann, Waalewijn `15}:

\[
S_{\kappa}^{NP}(k) = \left(\frac{4k}{\Omega_{\kappa}^2}\right) \exp \left(-\frac{2k}{\Omega_{\kappa}}\right)
\]

- The parameter \(\Omega_{\kappa}\) is associated with the amount of shift.
Phenomenology (a=0, jet mass)

\[ \frac{1}{\sigma} \frac{d\sigma}{dm_J} \]

\( 200 < p_T < 300 \text{ GeV} \)
\( 300 < p_T < 400 \text{ GeV} \)
\( 400 < p_T < 500 \text{ GeV} \)
\( 500 < p_T < 600 \text{ GeV} \)

\( \sqrt{s} = 7 \text{ TeV}, \text{ anti-}k_T, R = 1, |\eta| < 2 \)
• Formalism for studying semi-inclusive jet production with or without substructure measurements were introduced.

• From $\mu_J$ to $\mu_H$, the semi-inclusive jet production follows DGLAP evolution.

• Demonstrated how angularity measured case integrates to inclusive jet case.

• Continuous parameter dependence on quark and gluon discrimination power was considered.

• We now have a consistent baseline calculation for jet mass in pp. Extend to jet mass in heavy ion collisions!