Progress on Jets in SCET

Wouter Waalewijn

University of Amsterdam
Delta Institute for Theoretical Physics
NWO
erc

REF 2020

Goals

- Introduction to Jets in Soft-Collinear Effective Theory (SCET)
- Selection of recent developments, connecting:

Phenomenology:

- Event shapes
- Tagging boosted *H*, *W*
- Grooming
- Probing QGP [Varun's talk]

Theory:

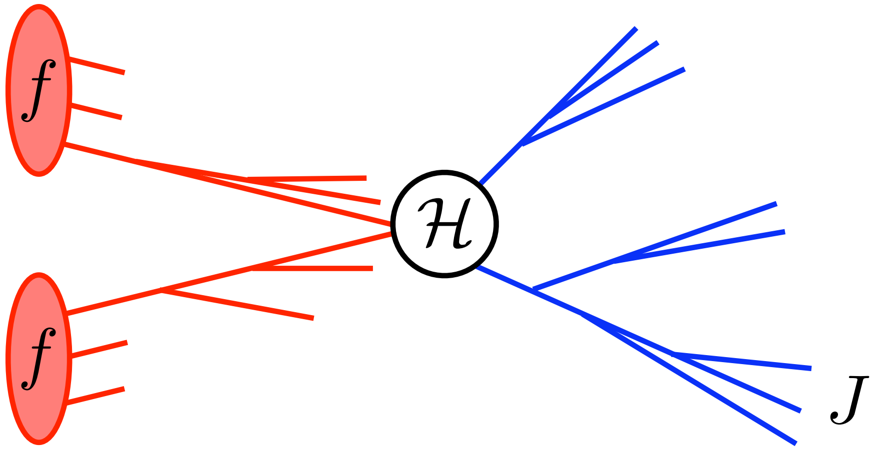
- Higher order calculations [Bernard's talk]
- Non-global logarithms [Thomas' talk]
- Multi-differential resummation
- Recoil

Outline

- Jet production:
  - Inclusive
  - Exclusive
- Jet functions
- Jet substructure:
  - Jet mass
  - Fragmentation
  - Jet shape
  - 2-prong tagging
  - Soft drop
  - V+jet azimuthal decorrelation

Inclusive jet production: formalism

- $pp \to \text{jet} + X$ for jet radius $R \ll 1$
- Power counting: $\theta \sim \Lambda_{\text{QCD}}/p_T, \quad \theta \sim R$
- Factorization:



$$\frac{d\sigma}{d\eta\, dp_T} = \sum_{a,b,c} f_a(x_a) \otimes f_b(x_b) \otimes \mathcal{H}_{ab\to c}\left(x_a, x_b, \eta, \frac{p_T}{z}\right) \otimes J_c(z, p_T R)$$

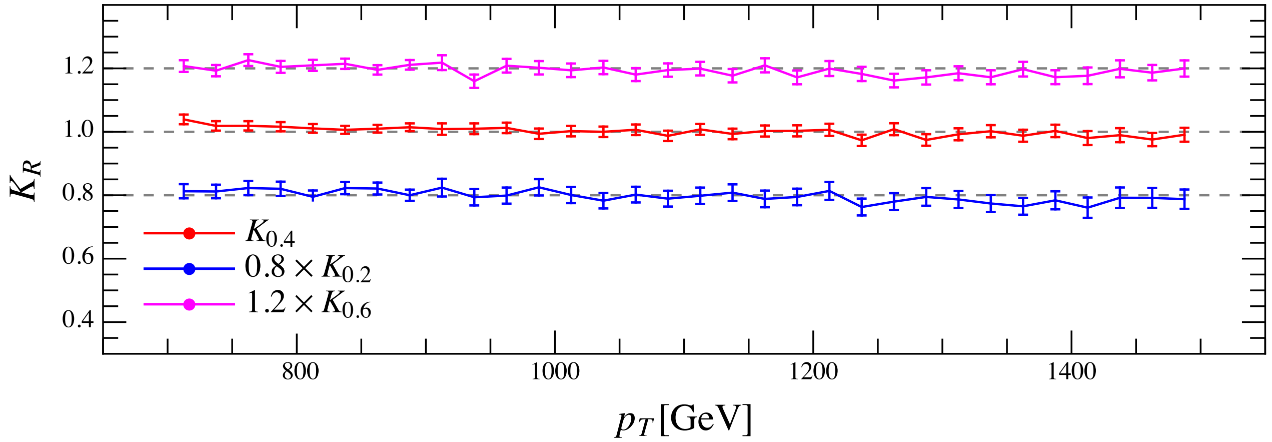
[Kaufmann et al, Kang et al, Dai et al]

- Same factorization as inclusive fragmentation with fragmentation function replaced by a jet function

Inclusive jet production: some results

- Power corrections of $\mathcal{O}(R^2)$ are small for even $R \sim 0.6$

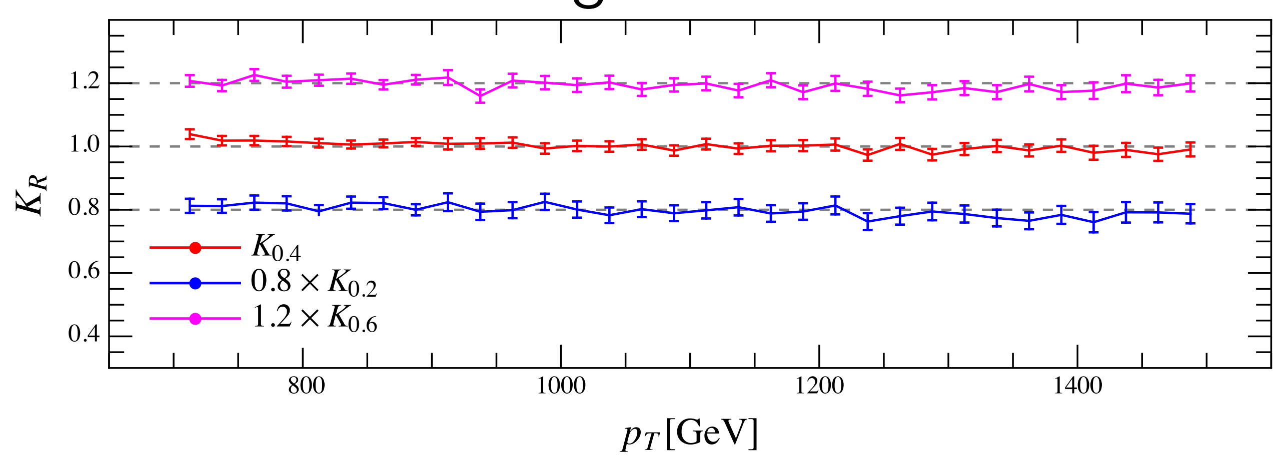
ratio of singular and full NLO



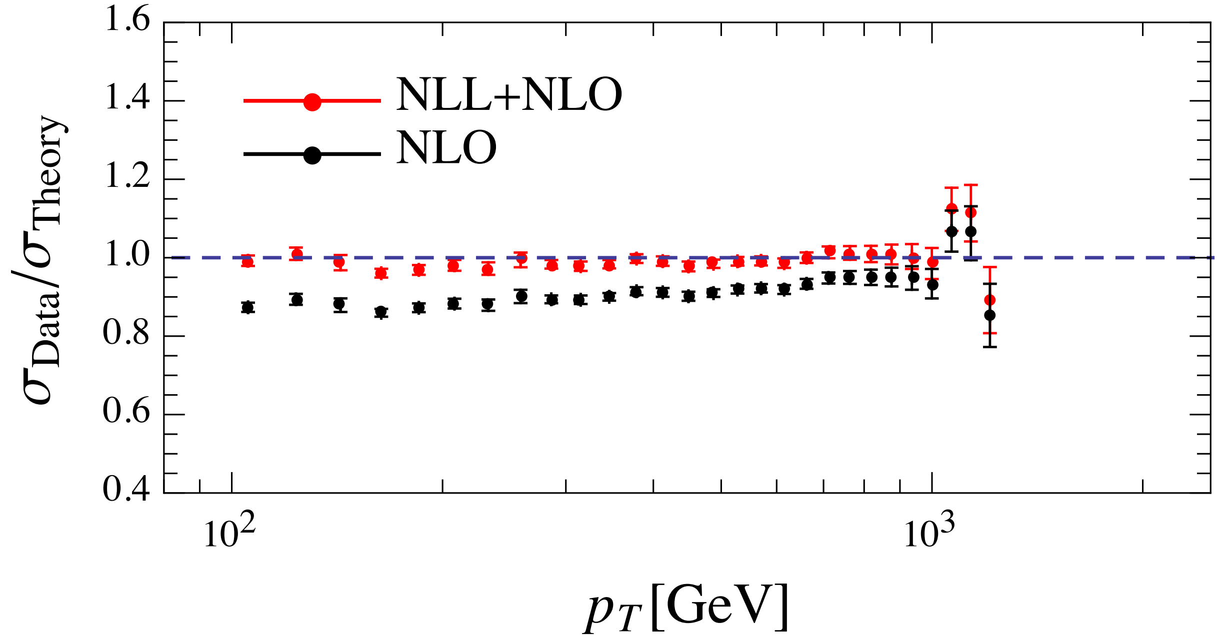
Inclusive jet production: some results

- Power corrections of $\mathcal{O}(R^2)$ are small for even $R \sim 0.6$
- Jet function satisfies DGLAP equation, and evolution between $\mu_J \sim p_T R$, $\mu_{\mathcal{H}} \sim p_T$ resums logarithms of R [Dasgupta et al]
- Threshold logarithms can also be included [Liu, Moch, Ringer] (but numerically less relevant)

ratio of singular and full NLO

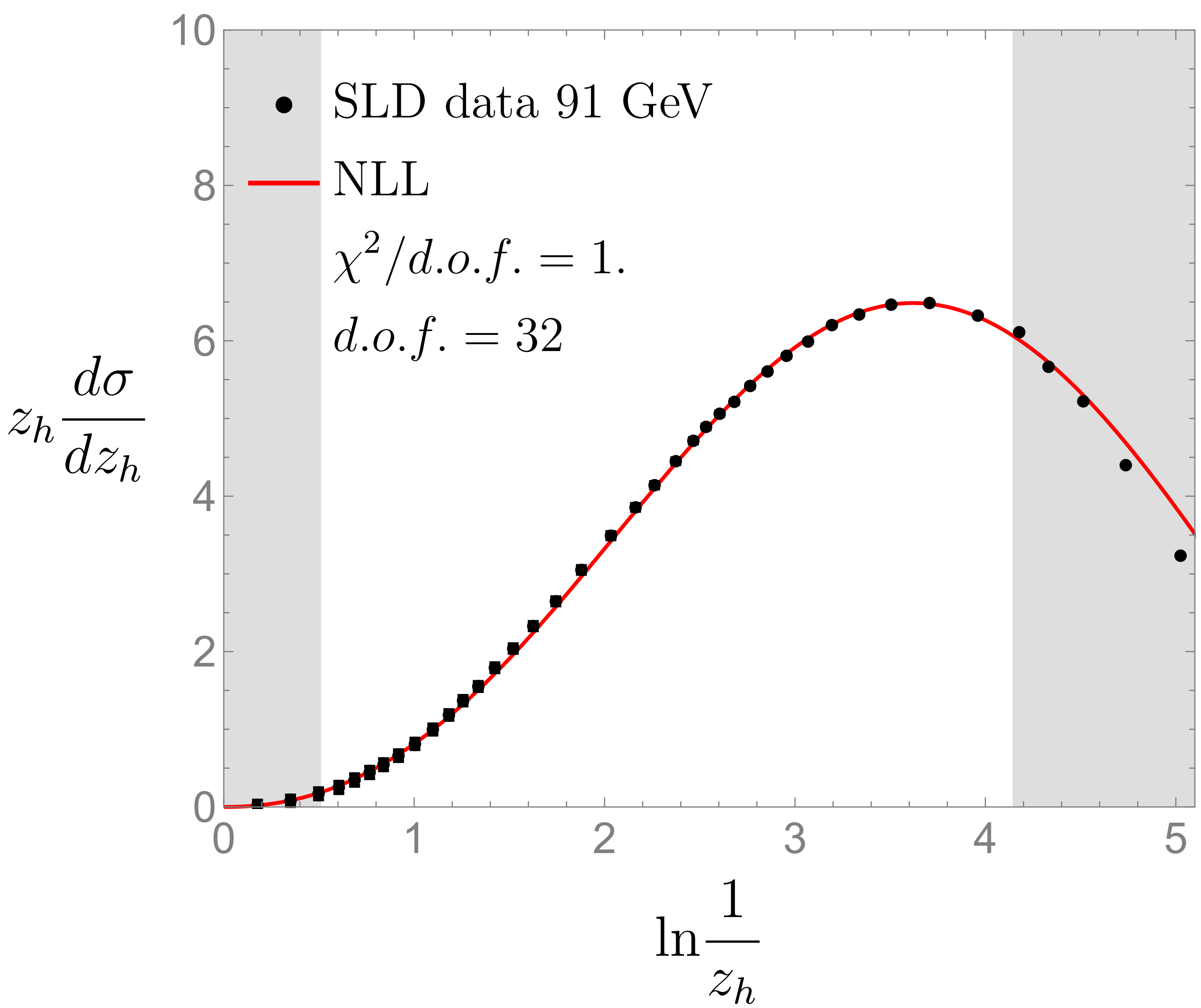


$0.0 \leqslant |\eta| < 0.5$, R = 0.5 @ 7TeV



Inclusive jet production: fragmentation limit

- In limit $R \to 0$, jet function becomes fragmentation function
- Charged hadron spectrum can be obtained using small-*z* resummation of jet, hard and anomalous dimension [Neill]



Inclusive jet production: leading jet

- The leading parton does not have to produce the leading jet, so factorization becomes increasingly nonlinear [Scott, WW]

$$\frac{\mathrm{d}\sigma^{\mathrm{NLO}}_{pp\to HJ}}{\mathrm{d}p_{T,J}} = \sum_{i,j} \int \mathrm{d}p_{T,i}\, \mathrm{d}p_{T,j}\, \frac{\mathrm{d}\tilde{\sigma}_{pp\to Hij}}{\mathrm{d}p_{T,i}\mathrm{d}p_{T,j}} \int \mathrm{d}z_{l,i}\, J_{l,i}(z_{l,i}, p_{T,i}R, \mu)$$
$$\times \int \mathrm{d}z_{l,j}\, J_{l,j}(z_{l,j}, p_{T,j}R, \mu)\delta\big(p_{T,J} - \max\{z_{l,i}p_{T,i}, z_{l,j}p_{T,j}\}\big)$$

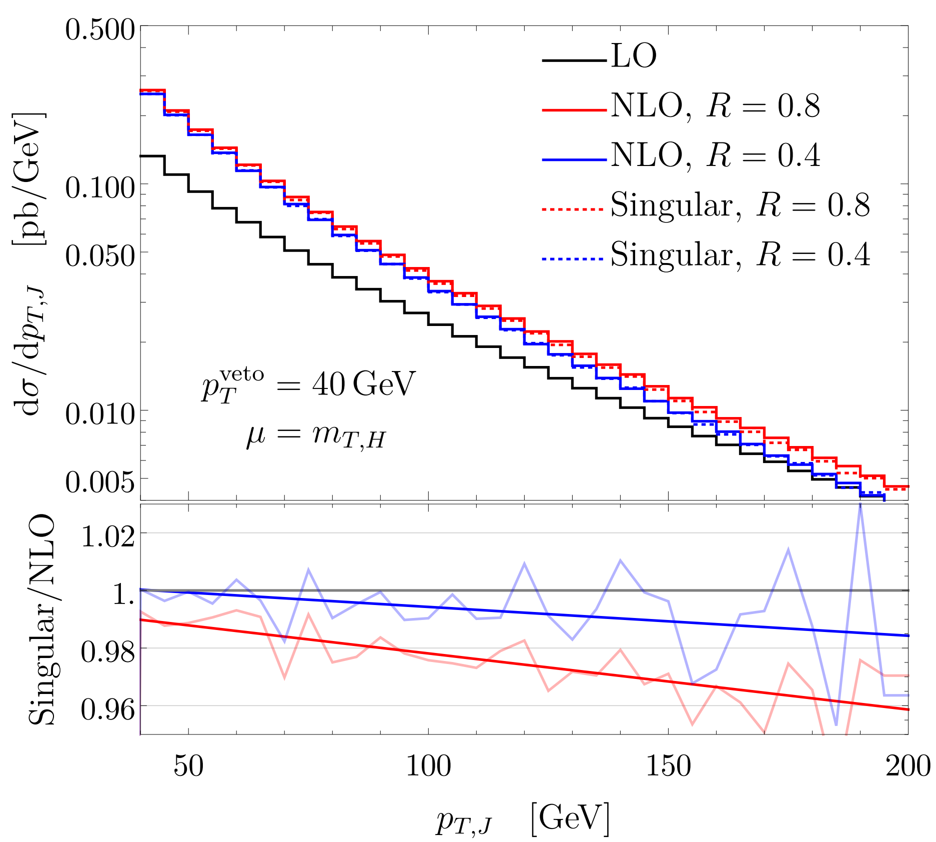
Inclusive jet production: leading jet

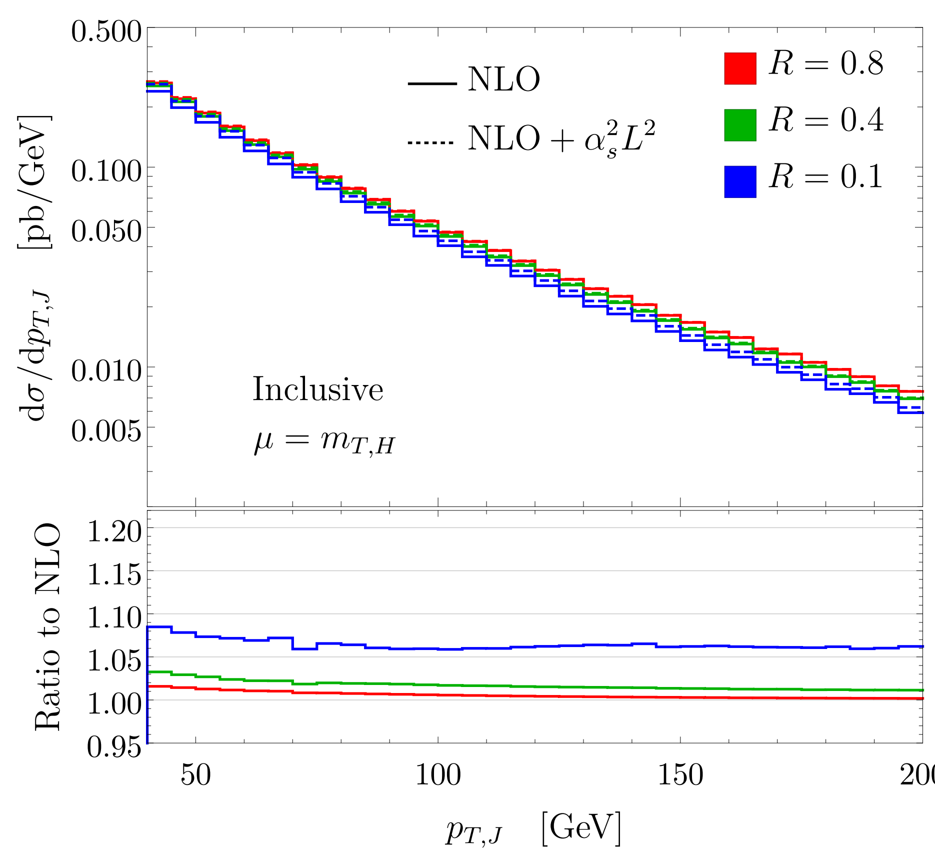
- The leading parton does not have to produce the leading jet, so factorization becomes increasingly nonlinear [Scott, WW]

$$\frac{\mathrm{d}\sigma^{\mathrm{NLO}}_{pp\to HJ}}{\mathrm{d}p_{T,J}} = \sum_{i,j} \int \mathrm{d}p_{T,i}\, \mathrm{d}p_{T,j}\, \frac{\mathrm{d}\tilde{\sigma}_{pp\to Hij}}{\mathrm{d}p_{T,i}\mathrm{d}p_{T,j}} \int \mathrm{d}z_{l,i}\, J_{l,i}(z_{l,i}, p_{T,i}R, \mu)$$

$$\times \int \mathrm{d}z_{l,j}\, J_{l,j}(z_{l,j}, p_{T,j}R, \mu)\delta\big(p_{T,J} - \max\{z_{l,i}p_{T,i}, z_{l,j}p_{T,j}\}\big)$$

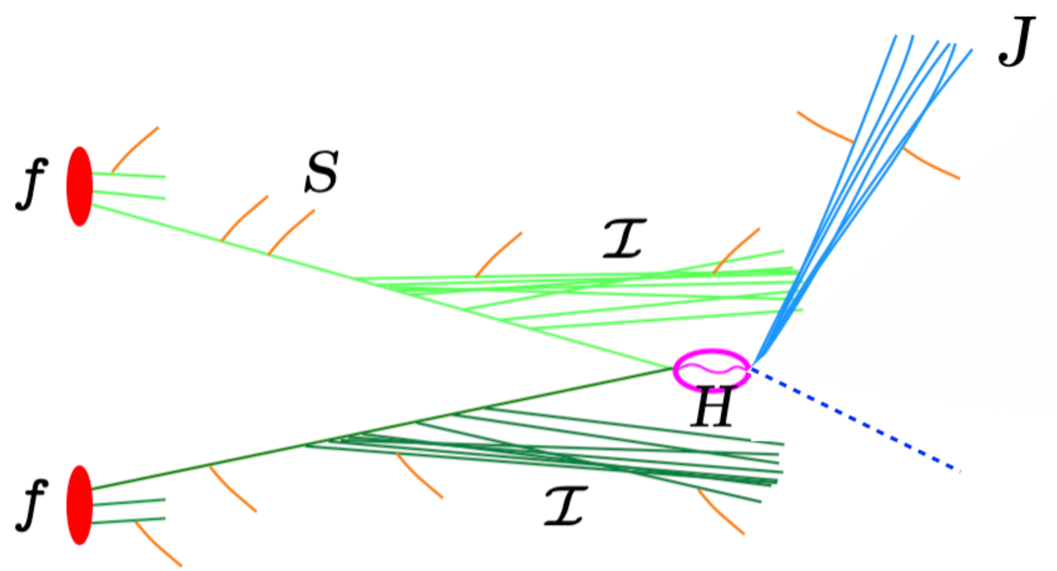
- $\mathcal{O}(R^2)$ corrections and resummation effects small





Exclusive jet production: formalism

- Exactly *N* jets. Veto on extra jets → radiation is collinear or soft
- Power counting: $\theta \sim p_T^{\text{veto}}/Q, \quad \theta \sim R, \quad E \sim p_T^{\text{veto}}$
- Factorization:



$$\sigma(p_T^{\text{veto}}) = f^2\,\mathcal{I}^2(p_T^{\text{veto}})\,H(Q)\,J(p_T R)\,S(p_T^{\text{veto}})$$

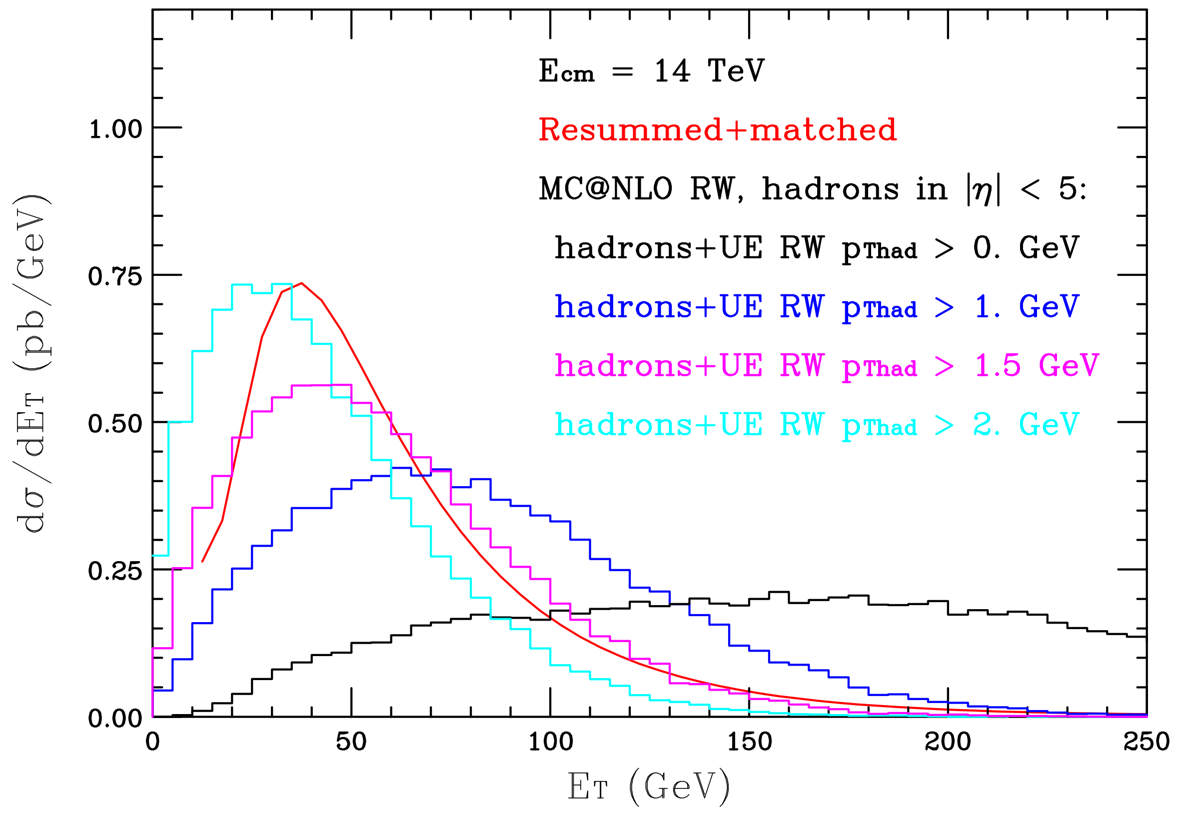
[Becher et al; Stewart et al; see also Banfi et al]

- Fine print: For $R \sim 1$ collinear and soft can cluster

  For $R \ll 1$ clustering logarithms $\ln R$

Exclusive jet production: alternative jet vetoes

- Event shapes in e^+e^-. E.g. thrust $\tau \ll 1$ vetoes a third jet
- Similarly, $p_T^H \ll m_H$ vetoes additional jets in Higgs production
- *N*-jettiness in *pp* [Stewart, Tackmann, WW]
  - Simple factorization, good for slicing IR div. [Boughezal et al; Gaunt et al]
  - But sensitive to underlying event/Glaubers



[Grazzini et al]

Jet function: introduction

- Quark jet function at order α_s (field theory definition in SCET)

$$\int \mathrm{d}\Phi_c \qquad\qquad\qquad\qquad \delta(\text{measurement})$$

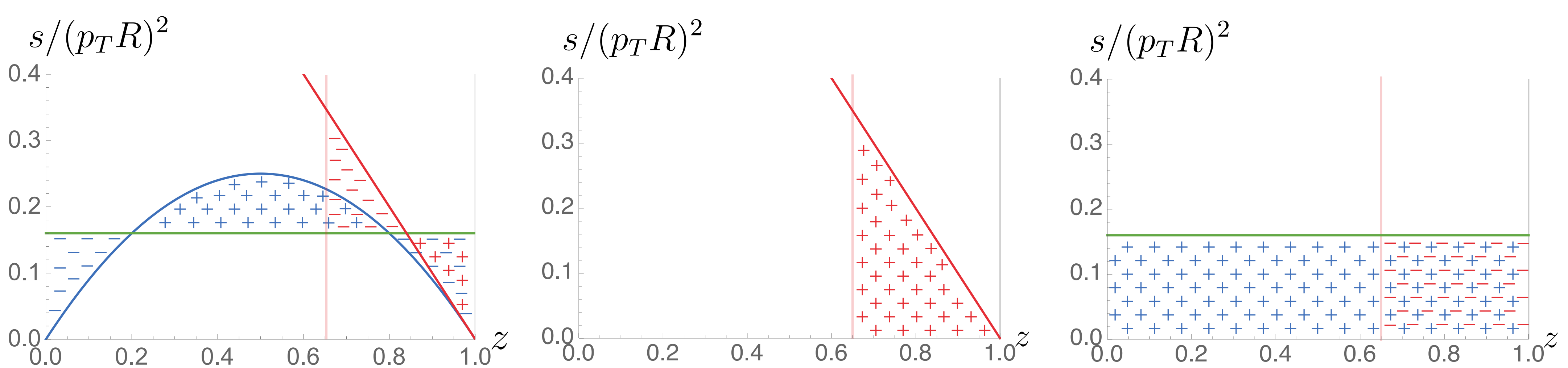
- For inclusive jet production, not all radiation inside jet
- Invariant mass jet function known at α_s^3 [Bruser et al; Banerjee et al]
  $j_{q,3} = -128.651\ldots$
- For many observables (e.g. with a jet algorithm) only one-loop jet functions known. Notorious example: broadening [Becher, Bell]

Jet function: calculation

- For NNLL resummation need two-loop anomalous dimension. Can use consistency of factorization to extract this from automated two-loop soft function code SoftSERVE [Bell, Rahn, Talbert]

$$\gamma_H + \gamma_J + \gamma_S + \cdots = 0$$

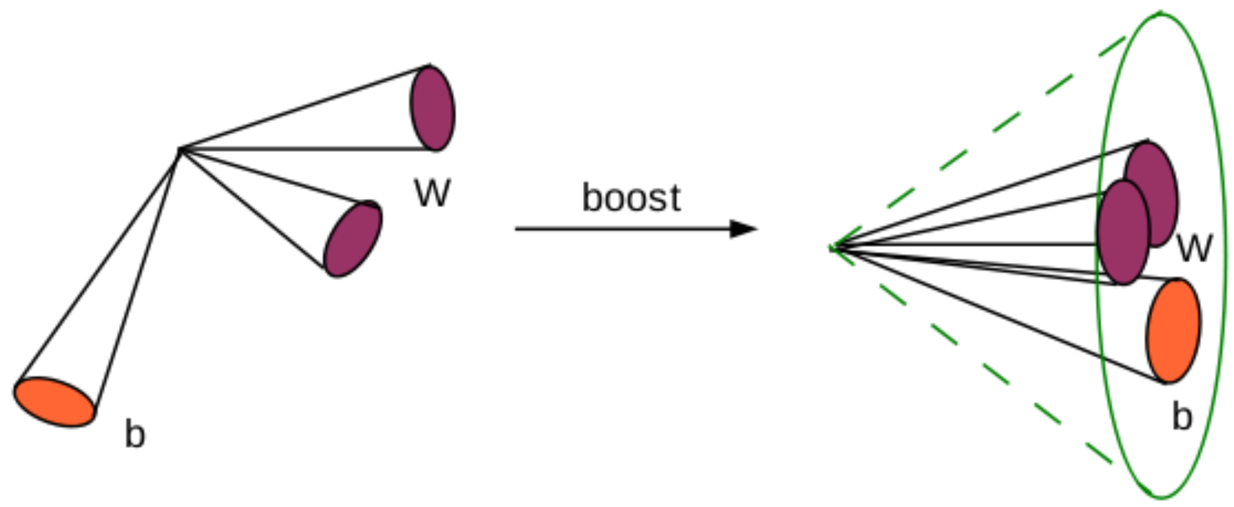
- GOJet package for calculating one-loop jet functions, uses geometric subtraction scheme for IR [Basdew-Sharma et al]



(a) G_1: Numerical contribution (b) G_2: Soft counterterm (c) G_3: Box counterterm

Jet substructure: introduction

- Study properties of the jet: mass, charge, shape…
- Identify what kind of jet it is: quark, gluon or boosted heavy particle?
- E.g. top quark:



3 jets

3 subjets

Jet substructure: jet mass

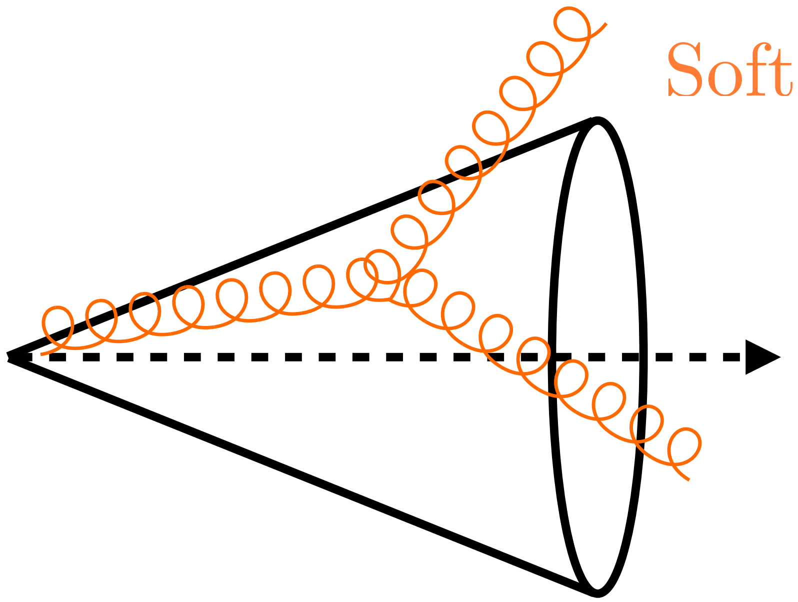
- Example: jet mass: $m_J \ll p_T^J R \ll p_T^J$
- Power counting:

$$\theta \sim R \quad \rightarrow \quad \theta \sim m_J^2/p_T^2, \quad \theta \sim R,\; E \sim m_J^2/(p_T^2 R^2)$$

- Insensitive to details of other jets in small *R* limit, as is clear from boosting.

Jet substructure: nonglobal logarithms

- Nonglobal logarithms arise due to different restrictions on soft radiation in- and outside jets [Dasgupta, Salam]

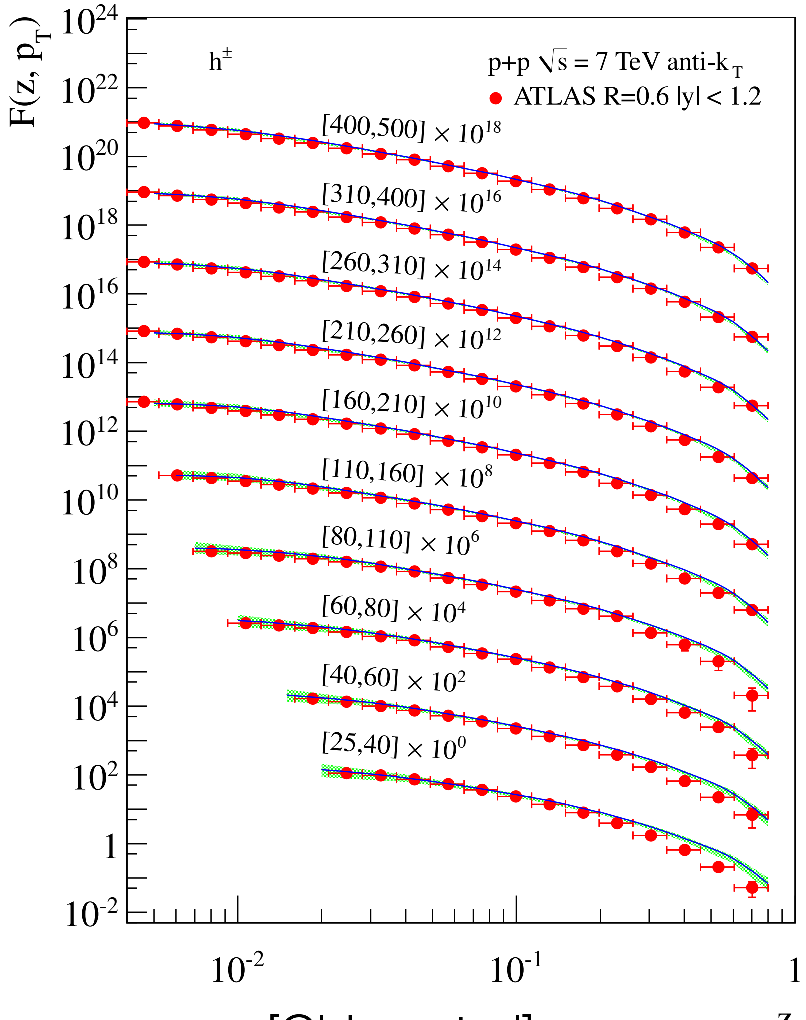


- This can be avoided/reduced for:
  - Purely collinear measurements, e.g. fragmentation in jets
  - Observables that treat soft radiation in- and outside jet the same, e.g. azimuthal angular decorrelation in Z+jet (using special axis)
  - Measurements for which soft radiation is reduced (grooming)

Jet substructure: fragmentation

- Power counting: $\theta \sim R, \quad \theta \sim \Lambda_{\text{QCD}}/p_T$
- Collinear factorization (exclusive jets) [Procura, Stewart; Jain, Procura, WW]

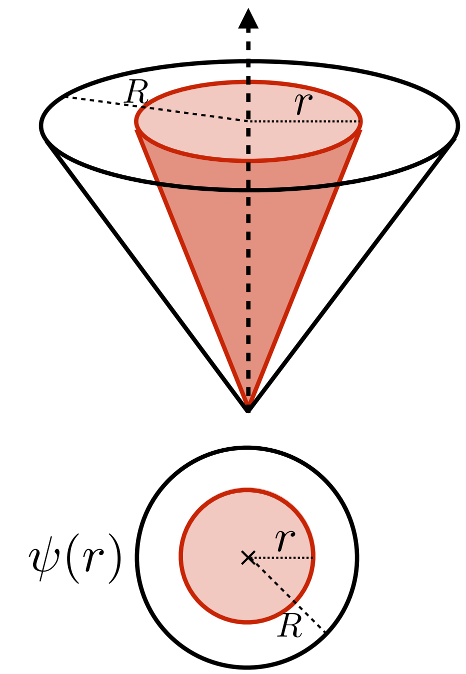
$$\mathcal{G}_{i\to h}(z, p_T R, \mu) = \sum_j \mathcal{J}_{i\to j}(z, p_T R, \mu) \otimes D_{i\to h}(z, \mu)$$



[Chien et al]

- Several extensions:
  - Inclusive jet production [Kang et al]
  - Transverse momenta [Kang et al; Neill et al]
  - Threshold resummation [Procura, WW; Dai et al]
  - Heavy quarks [Bauer, Mereghetti; Dai et al]

Jet substructure: jet shape resummation



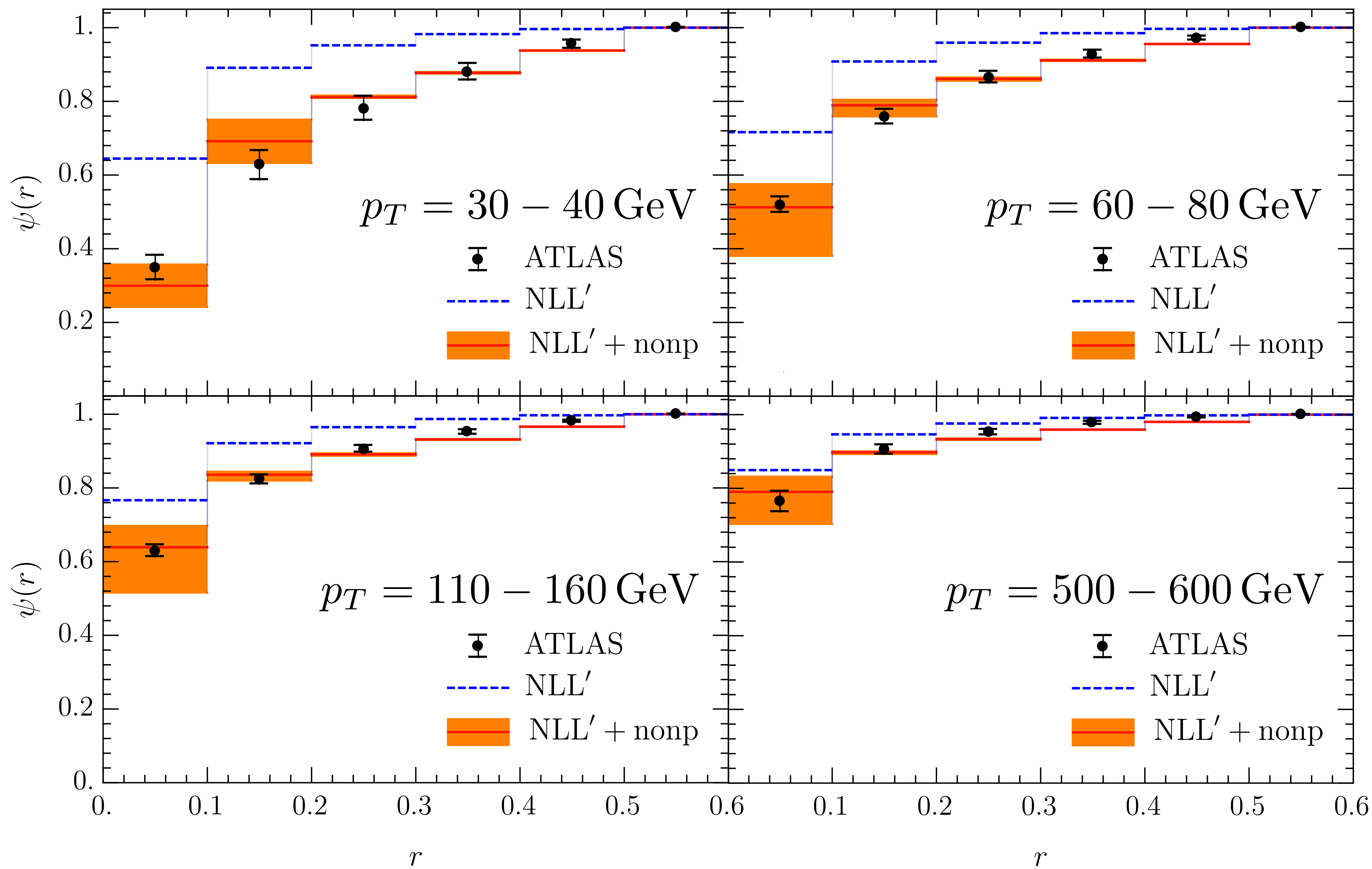
- Average energy fraction inside cone of size $r \leq R$
- Contains large logarithms for $r \ll R$

$$\psi_q(r) = 1 + \frac{\alpha_s C_F}{2\pi}\left(-2\ln^2\frac{r}{R} - 3\ln\frac{r}{R} - \frac{9}{2} + \frac{6r}{R} - \frac{3r^2}{2R^2}\right)$$

- Power counting: $\theta \sim R, \quad \theta \sim r$
- Factorization includes recoil from soft radiation
  [Cal, Ringer, WW; earlier work without recoil: Seymour; Li, Li, Yuan; Chien, Vitev]

$$\mathcal{G}(p_T R, r/R) = H(p_T R)\, C(p_T r, k_\perp) \otimes S(k_\perp, R)$$

Jet substructure: jet shape results



- Good agreement. Perturbative uncertainty largest for small r
- Nonperturbative effects (included) $\propto \Lambda_{\mathrm{QCD}}/p_T$

Jet substructure: soft drop

- Recluster the jet using Cambridge/Aachen (based on angles)
- Traverse the tree, throwing away the less energetic branch until
[Larkoski, Marzani, Soyez, Thaler]

$$\frac{\min(E_i, E_j)}{E_i + E_j} > z_{\mathrm{cut}} \left(\frac{\theta_{ij}}{R} \right)^{\beta}$$

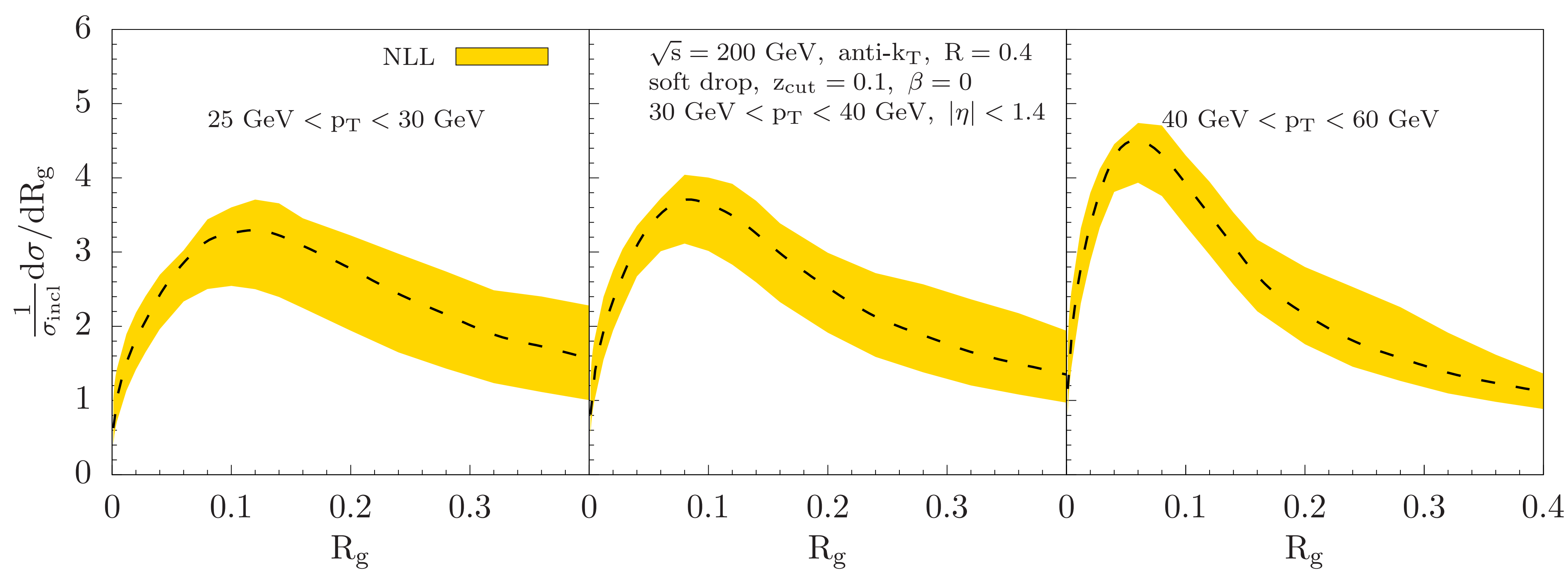
- Parameters $\beta > 0, \quad \frac{1}{2} > z_{\mathrm{cut}} > 0$ specify how much wide-angle soft radiation is removed

Jet substructure: soft drop groomed radius

- Power counting: $\theta \sim R, \quad \theta \sim R_g, \quad \theta \sim R_g, E \sim z_{\text{cut}} \left(\frac{R_g}{R}\right)^\beta$
- Collinear always passes grooming, collinear-soft may not
- Factorization [Kang, Lee, Liu, Neill, Ringer]

$$\mathcal{G}(p_T R, z_{\text{cut}}, \beta, R_g^{\text{cut}}) = H(p_T R)\, C(p_T R_g^{\text{cut}})\, S\left(z_{\text{cut}} p_T R (R_g^{\text{cut}}/R)^{1+\beta}\right)$$

- NLL includes leading non-global and clustering logarithms



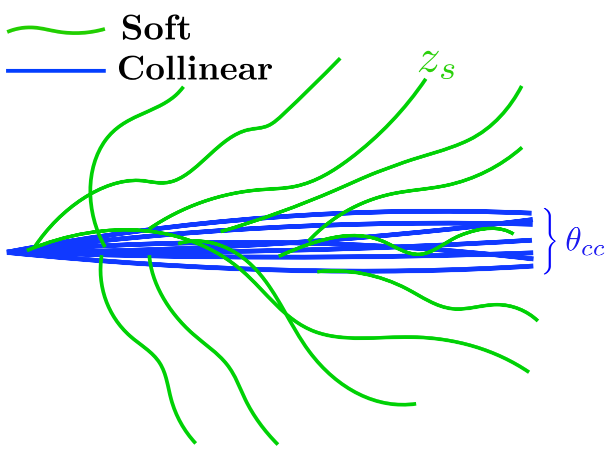
Jet substructure: 2-prong tagging power counting

- Start from energy correlation functions [Larkoski, Salam,Thaler]

$$e_2^{(\beta)} = \sum_{i<j\in J} z_i z_j \theta_{ij}^\beta \qquad e_3^{(\beta)} = \sum_{i<j<k\in J} z_i z_j z_k \theta_{ij}^\beta \theta_{ik}^\beta \theta_{jk}^\beta$$

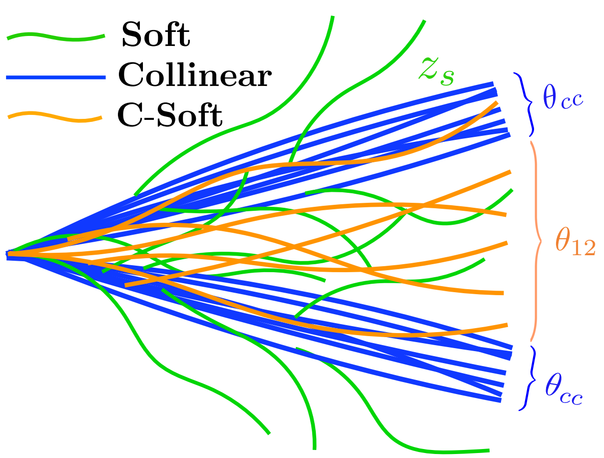
with z_i the energy fraction of *i* and θ_{ij} the angle between *i* and *j*

- Parametric discrimination of 1 vs. 2 prong [Larkoski, Moult, Neill]



$$e_2^{(\beta)} \sim \theta_{cc}^\beta + z_s$$

$$e_3^{(\beta)} \sim \theta_{cc}^{3\beta} + \theta_{cc}^\beta z_s + z_s^2 \qquad (e_2^{(\beta)})^3 \lesssim e_3^{(\beta)}$$



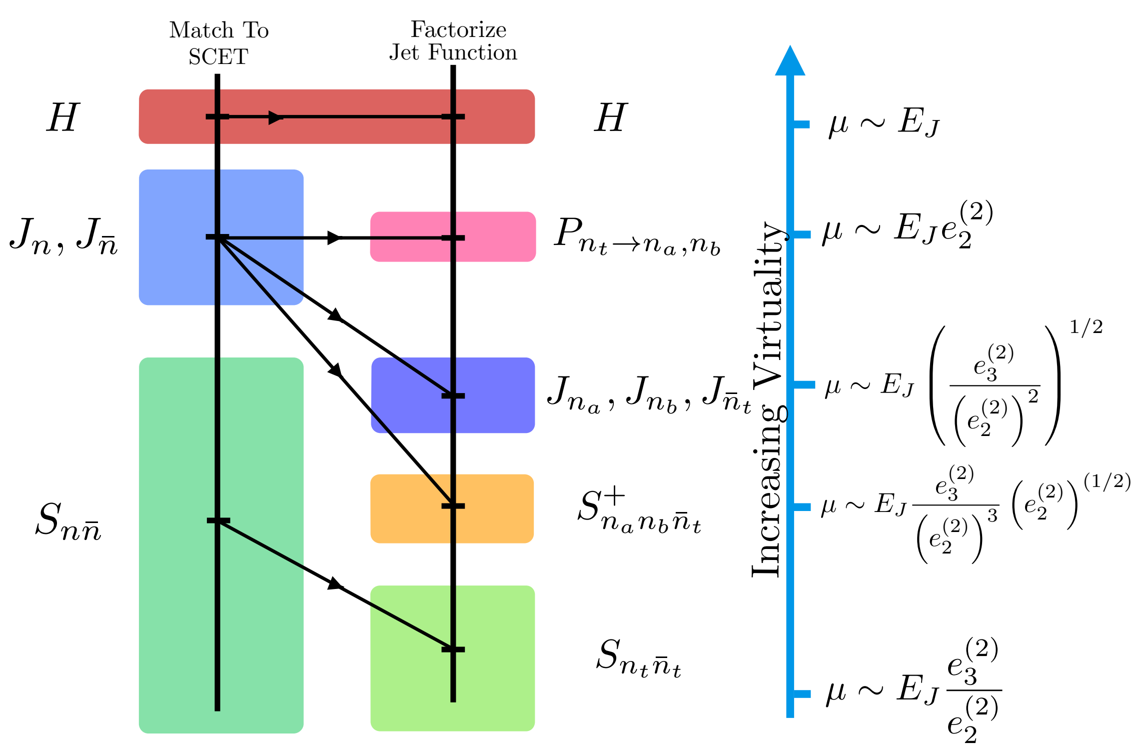
$$e_2^{(\beta)} \sim \theta_{12}^\beta \qquad e_3^{(\beta)} \ll (e_2^{(\beta)})^3$$

$$e_3^{(\beta)} \sim \theta_{12}^\beta z_s + \theta_{12}^{2\beta} \theta_{cc}^\beta + \theta_{12}^{3\beta} z_{cs}$$

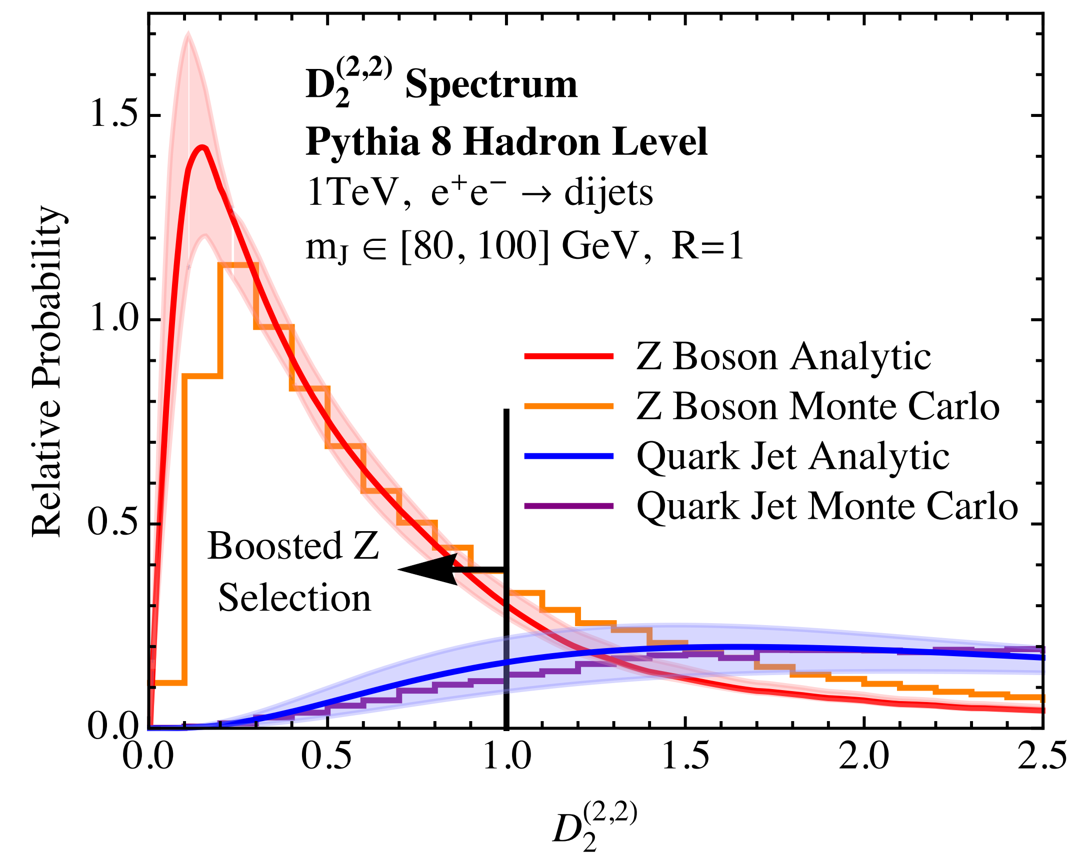
Jet substructure: two prong tagging results

- Tag Z boson jets using $D_2^{(\beta,\beta)} \equiv \dfrac{e_3^{(\beta)}}{(e_2^{(\beta)})^3}$

- SCET yields resummed prediction for the cross section of D_2, compatible with Monte Carlos



It's complicated…



[Larkoski, Moult, Neill]

Jet substructure: recoil-free axes

- Jet axis is along jet momentum: recoiled by soft radiation in jet
  → Theory: non-global logarithms, Exp: contamination.

- Recoil absent for Winner-Take-All (WTA) recombination:

$$E_r = E_1 + E_2$$

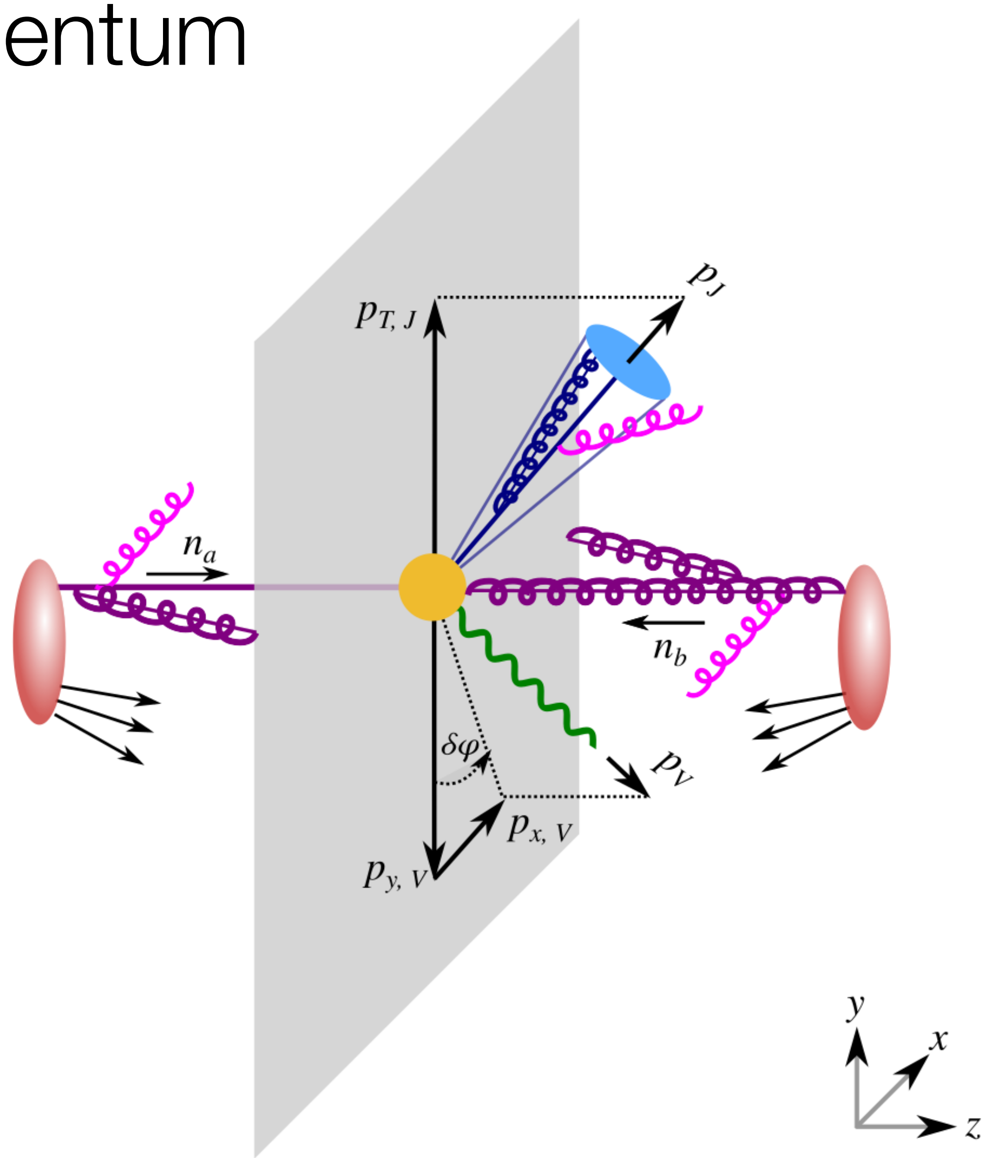
$$\hat{n}_r = \begin{cases} \hat{n}_1 & \text{if } E_1 > E_2 \\ \hat{n}_2 & \text{if } E_2 > E_1 \end{cases}$$

[Salam; Bertolini, Chan, Thaler]

Exclusive jet production: V+jet azimuthal decorrelation

- Azimuthal angle $\Delta\phi = \pi - \delta\phi$ with $\delta\phi \approx |p_{x,V}|/p_{T,V}$
- By using WTA axis, soft radiation **only** provides total recoil, but jet axis not aligned with jet momentum

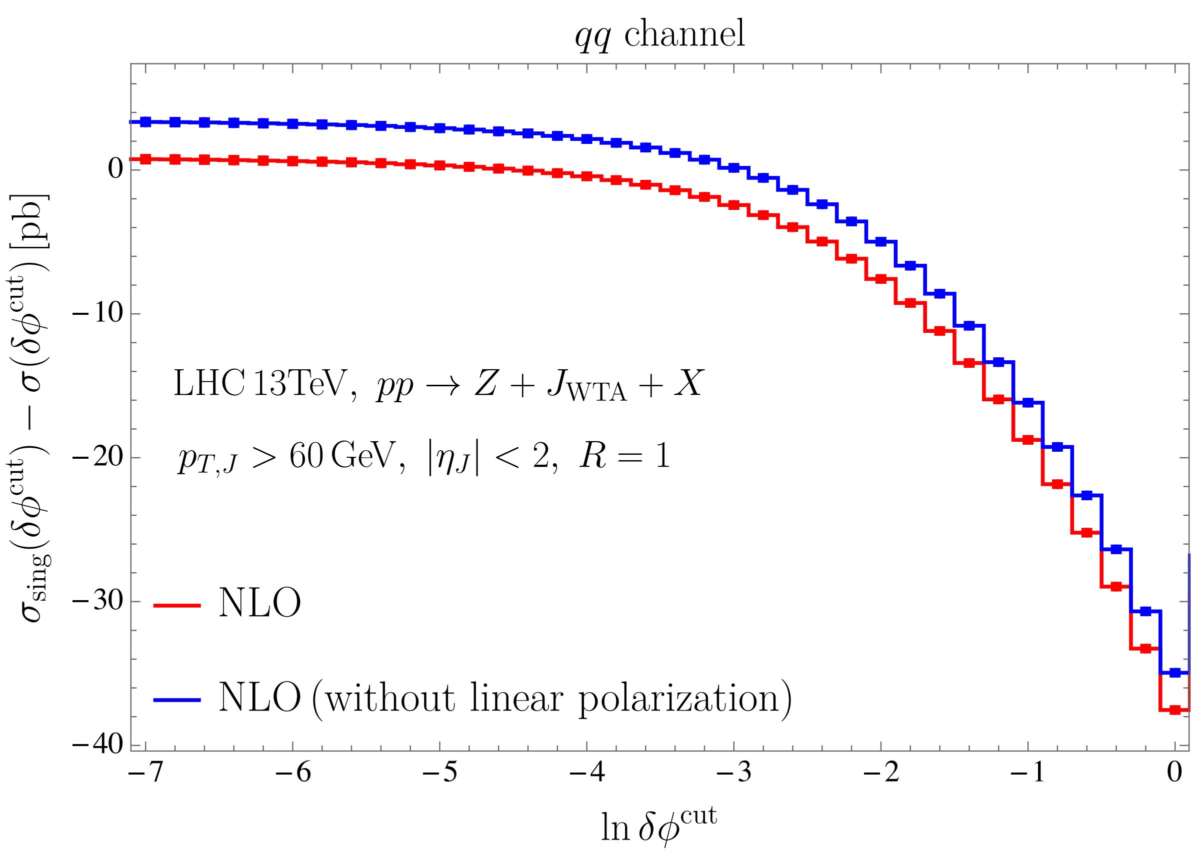
$$\frac{\mathrm{d}\sigma(pp \to VJX)}{\mathrm{d}p_{T,J}\,\mathrm{d}y_V\,\mathrm{d}\eta_J\,\mathrm{d}p_{x,V}} = \sum_{i,j,k} H_{ij\to Vk}(p_{T,J}, y_V - \eta_J) \times \int \frac{\mathrm{d}b_x}{2\pi}\, e^{-\mathrm{i}b_x\, p_{x,V}}\, S_{ijk}(b_x, \eta_J) \times F_i(b_x, x_1)\, F_j(b_x, x_2)\, \mathcal{J}_k(b_x)$$

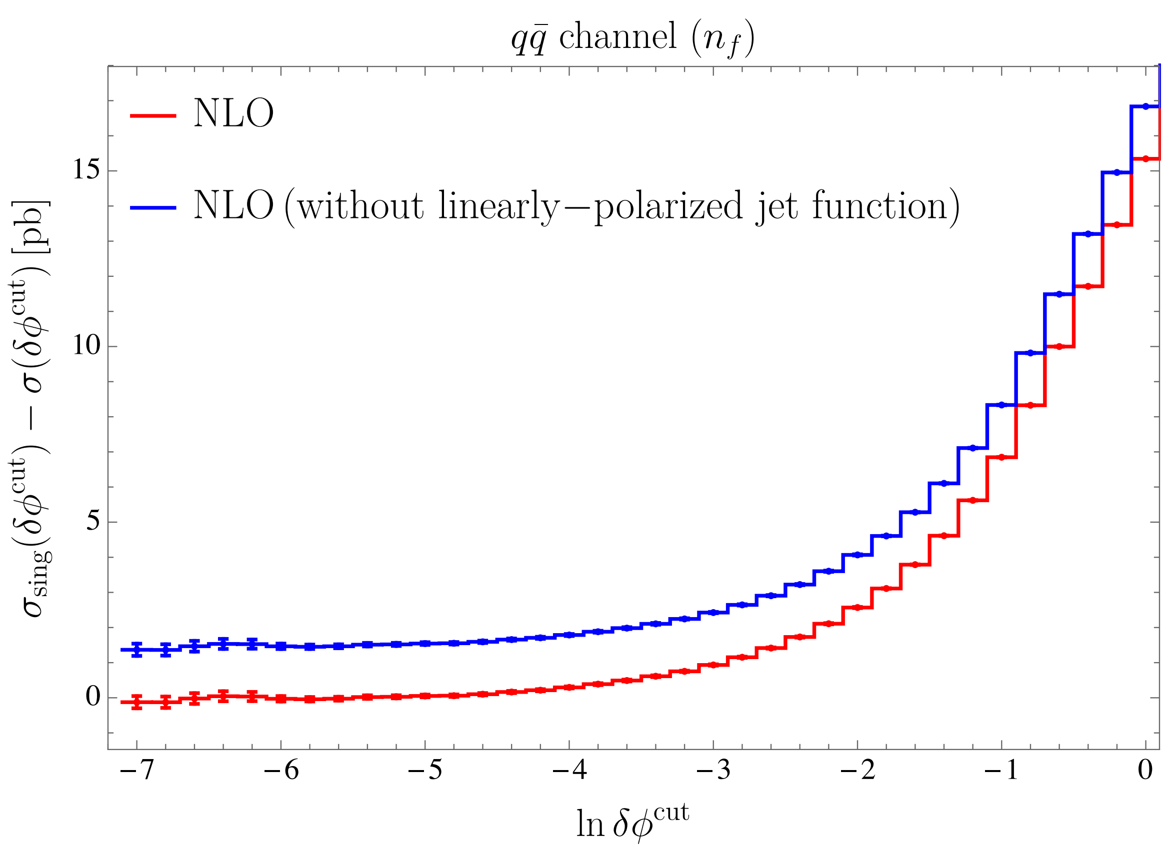


- Standard TMD PDFs with $b_T = (b_x, 0)$

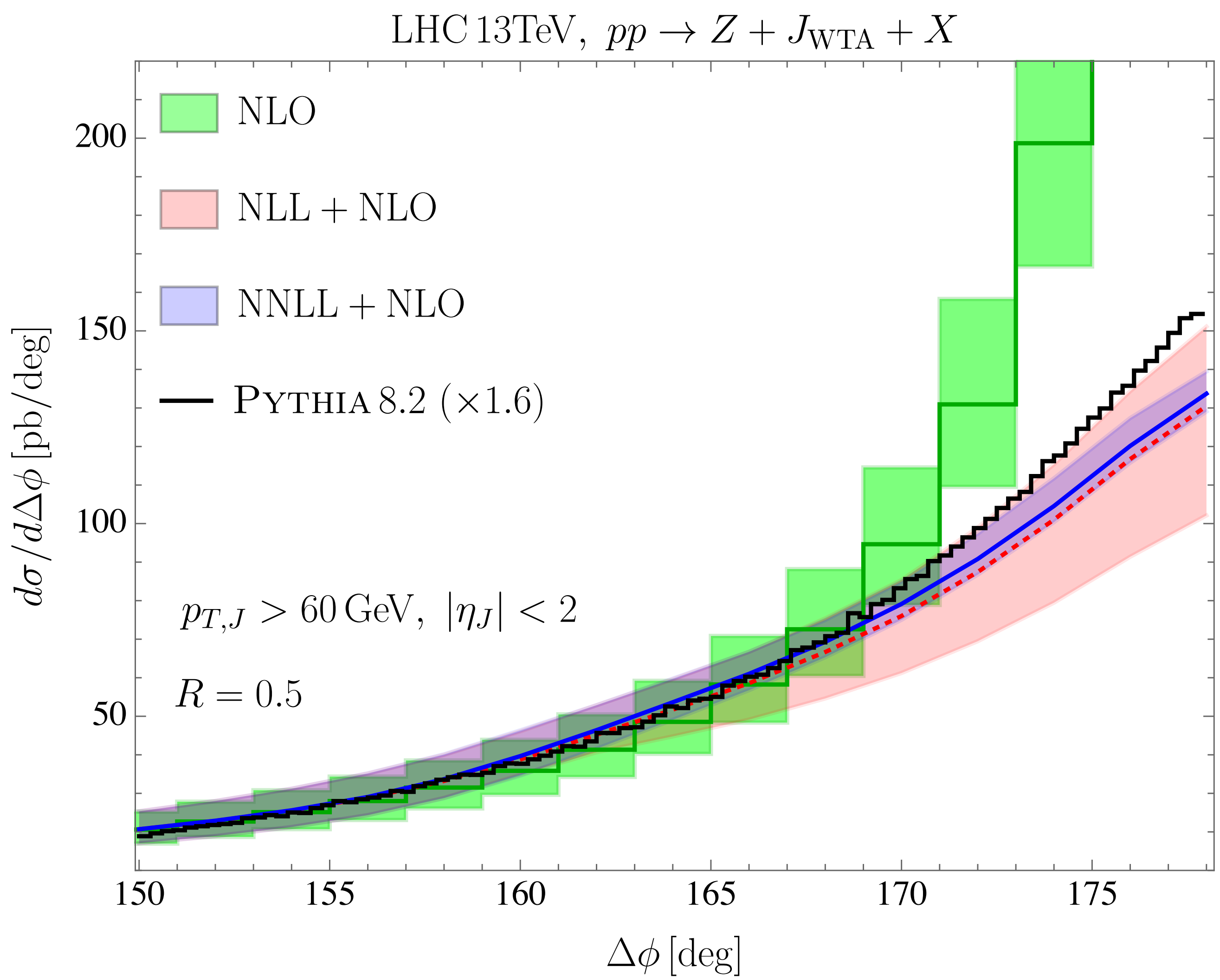
Exclusive jet production: V+jet linear polarization

- Linearly-polarized gluon beam function contributes at NLO. (NNLO for Higgs production) Test using MCFM. [Campbell, Ellis et al]
- Linearly-polarized jet function: $\mathcal{J}_g^L(\vec{b}_\perp) = \frac{\alpha_s}{4\pi}\left(-\frac{1}{3}C_A + \frac{2}{3}T_F n_f\right)$





Exclusive jet production: V+jet results



- Small b_x: match to NLO using transition function.
  Large b_x: avoid Landau pole with b^* prescription. [Collins, Soper, Sterman]

- Good perturbative convergence.

- Pythia (with NLO K-factor) agrees reasonably well. [Sjostrand et al]

Summary

- Jet production:
  - Factorization generally understood
  - Exclusive: Several definitions have factorization issues limiting precision/use in phenomenology
  - Inclusive: Non-global logarithms may come back to bite you for jet substructure
- Jet functions
  - Up to three loop (for jet mass), but much still one loop
- Jet substructure:
  - Lots of progress and new ideas
  - For many observables (N)LL is current limit due to non-global logarithms (though often small)
  - Differential resummation involves more complicated factorization, e.g. 2-prong taggers.
  - Recoil from soft radiation complicates several observables, e.g. azimuthal decorrelation. Reduce by grooming or avoid with recoil-free axis.
  - Grooming important experimentally and can be accounted for in theory.