

# Inclusive jet production and subjets

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DPF Fermilab, 08/02/17



# Outline

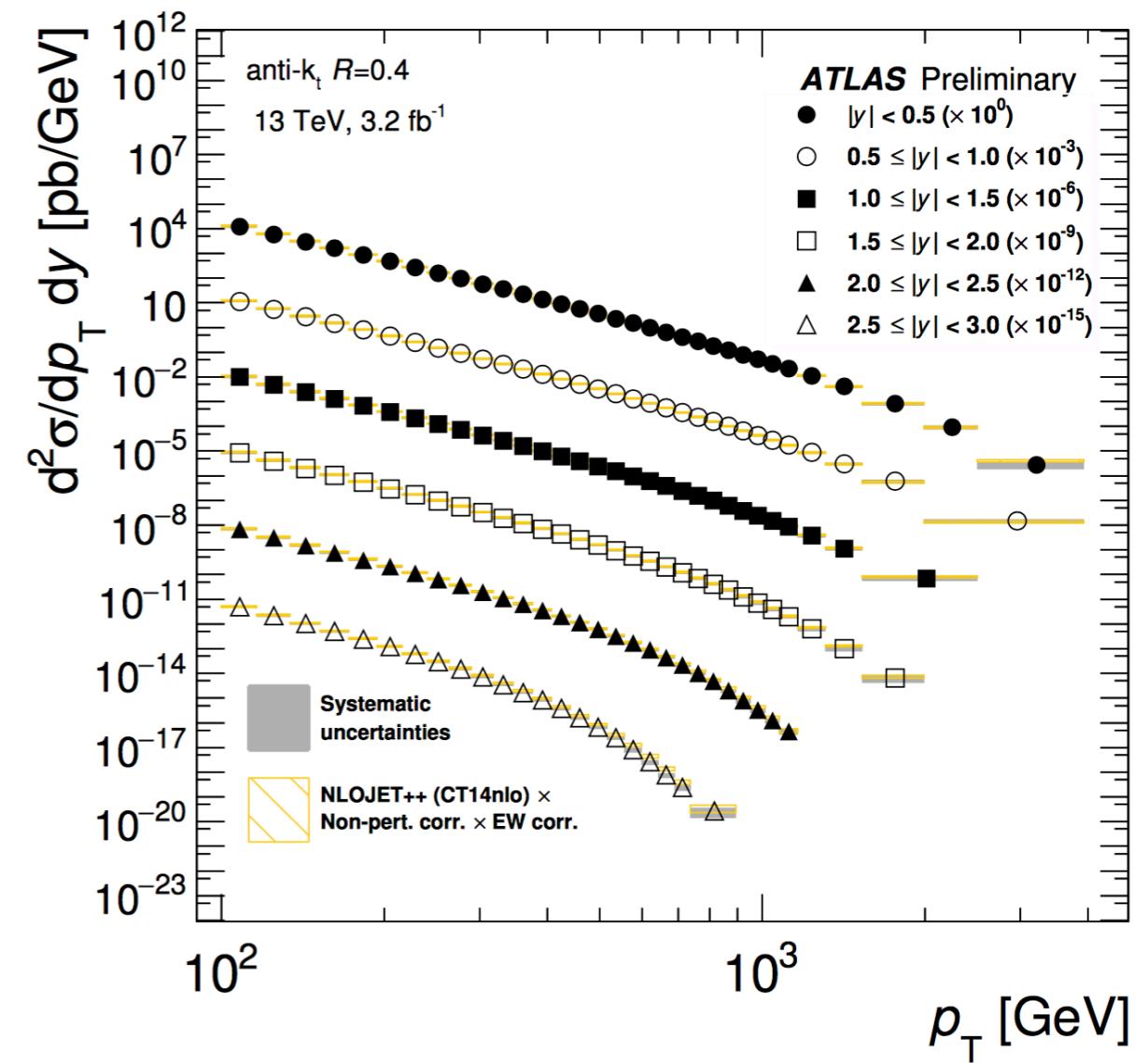
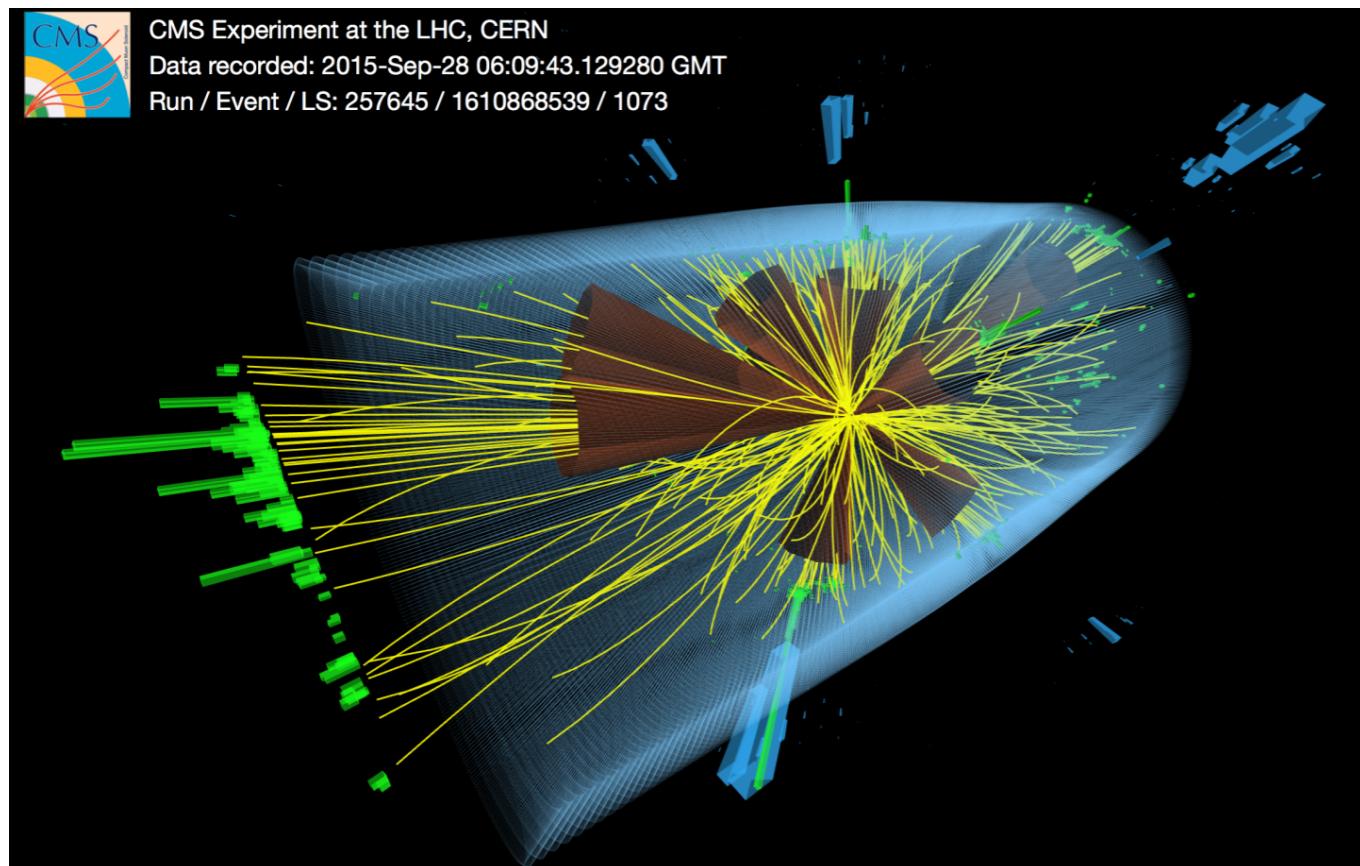
- Inclusive jets
- Subjets *Kang, FR, Vitev '16*
  - Inclusive subjets *Kang, FR, Waalewijn '17*
  - Centered around an axis
- Conclusions

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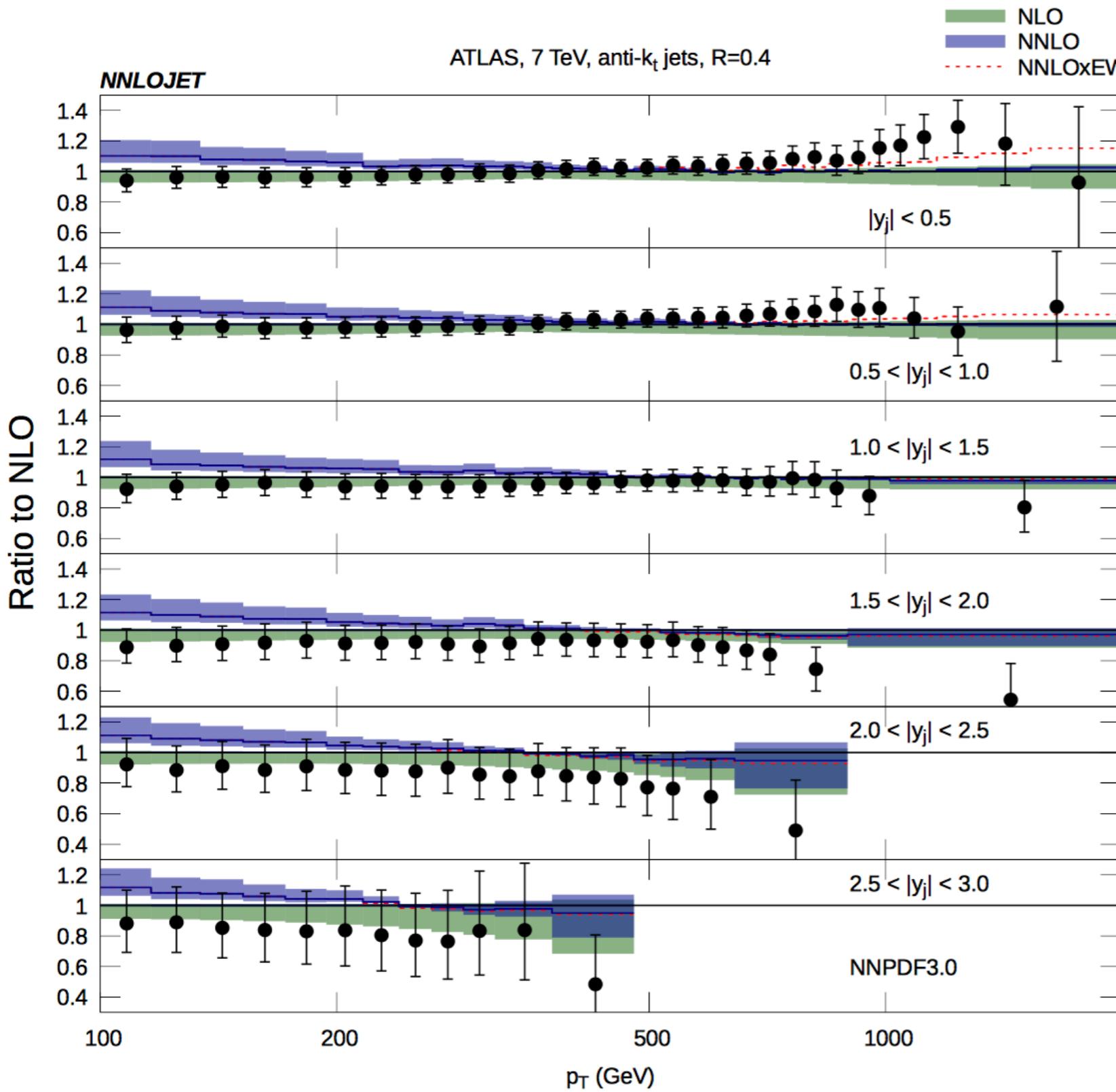
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# Inclusive jet production $pp \rightarrow \text{jet}X$

- PDFs and  $\alpha_s$  are constrained by collider jet data
- High  $p_T$  jets are a promising observable for the search of BSM physics at the LHC
- Baseline for jet quenching in heavy-ion collisions



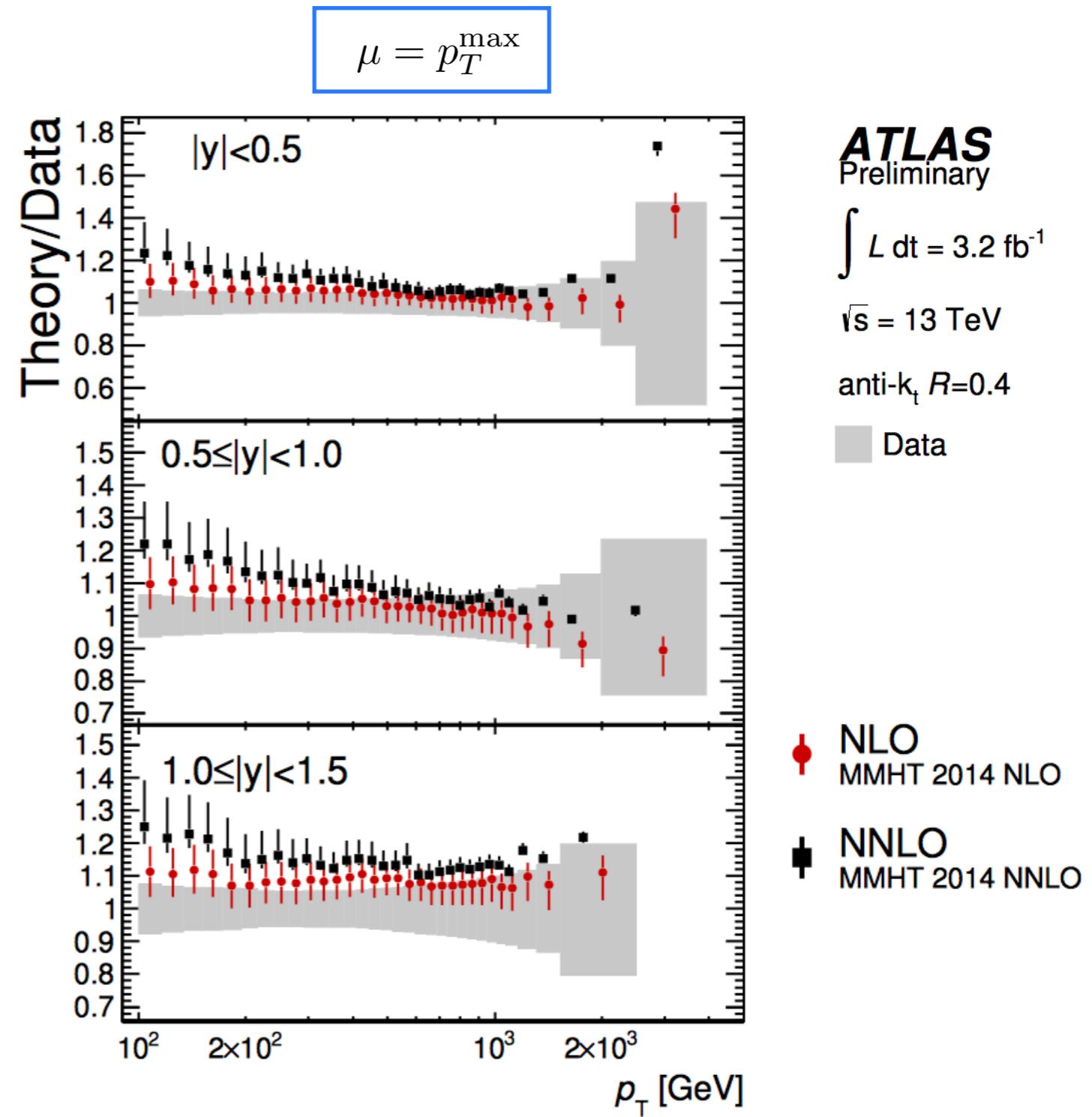
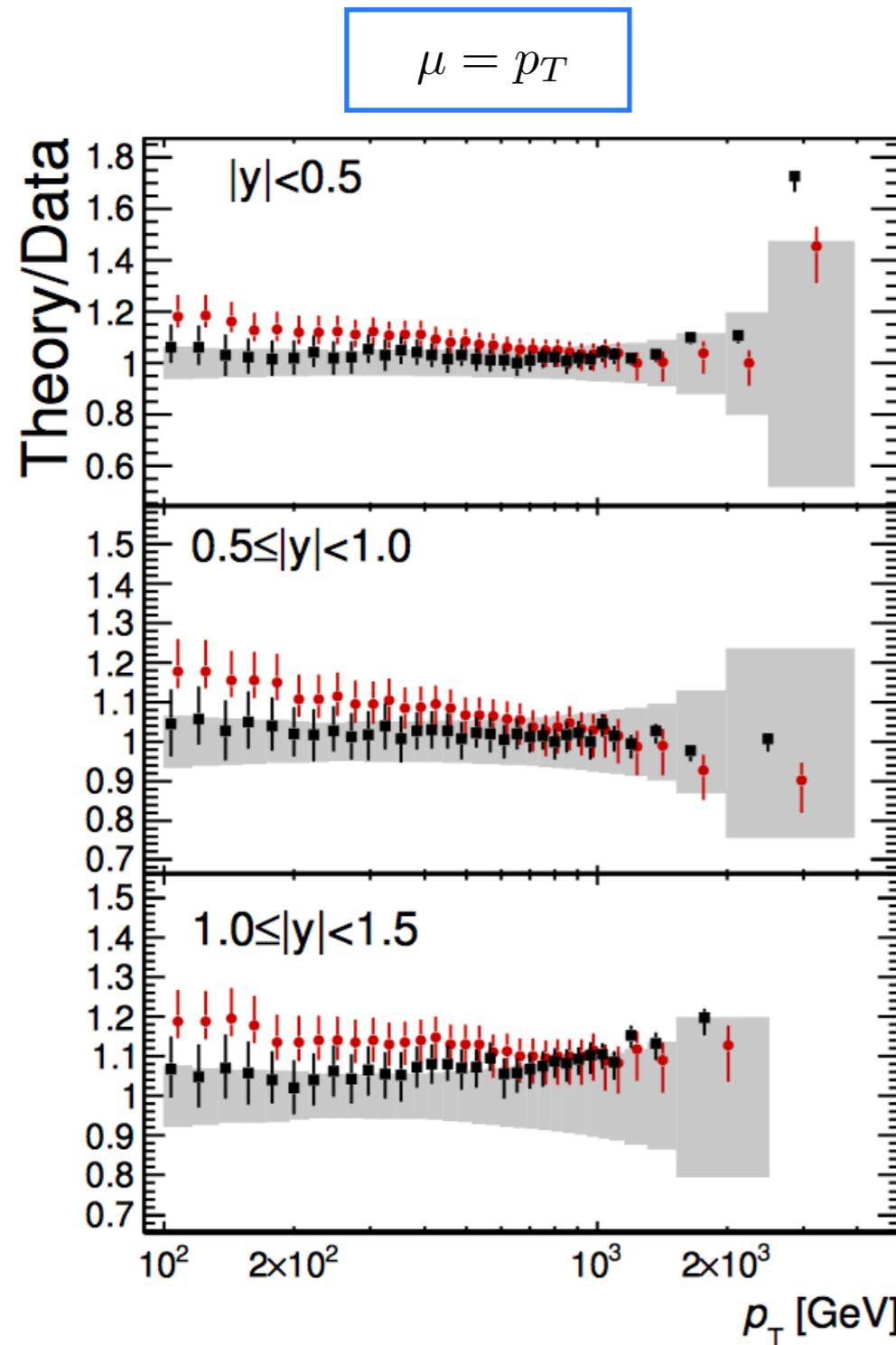
# Inclusive jet production $pp \rightarrow \text{jet}X$ @ NNLO



*Currie, Glover, Pires '16*  
*Currie, Glover, Gehrmann,*  
*Gehrmann-De Ridder, Huss, Pires '17*

leading color approximation

# Inclusive jet production $pp \rightarrow \text{jet}X$ @ NNLO



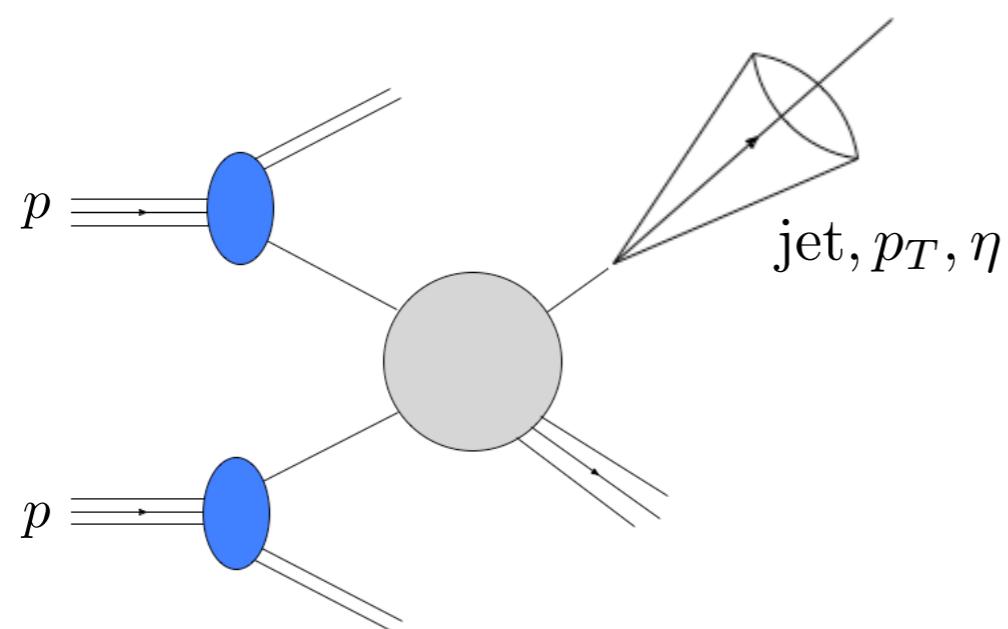
# Inclusive jet production $pp \rightarrow \text{jet}X$

## Factorization

$$R \sim 1$$

$$\frac{d\sigma^{pp \rightarrow \text{jet}X}}{dp_T d\eta} = \sum_{a,b,c} f_a \otimes f_b \otimes H_{ab}$$

Ellis, Kunszt, Soper '90, Aversa, Chiappetta, Greco, Guillet '90,  
Jäger, Stratmann, Vogelsang '04, Currie, Glover, Pires '16, ...



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Kang, FR, Vitev '16

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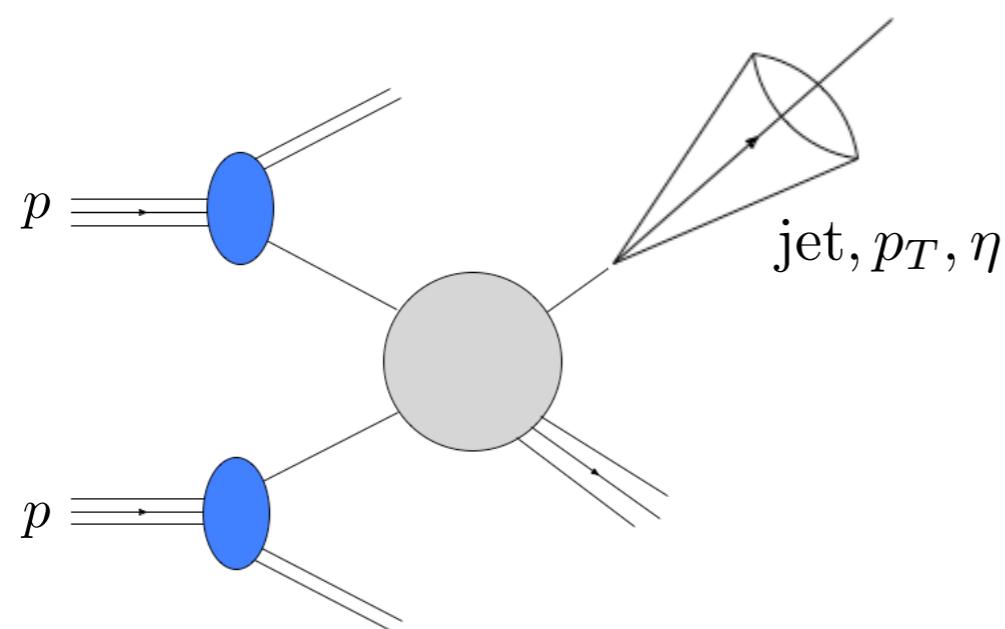
$$\frac{d\sigma^{pp \rightarrow \text{jet}X}}{dp_T d\eta} = \sum_{a,b,c} f_a \otimes f_b \otimes H_{ab}^c \otimes J_c + \mathcal{O}(R^2)$$

(e.g. <4% difference for R=0.7)

Ellis, Kunszt, Soper '90, Aversa, Chiappetta, Greco, Guillet '90,  
Jäger, Stratmann, Vogelsang '04, Currie, Glover, Pires '16, ...

see also:

Kaufmann, Mukherjee, Vogelsang '15  
Dai, Kim, Leibovich '16



# Inclusive jet production $pp \rightarrow \text{jet}X$

Factorization

Kang, FR, Vitev '16

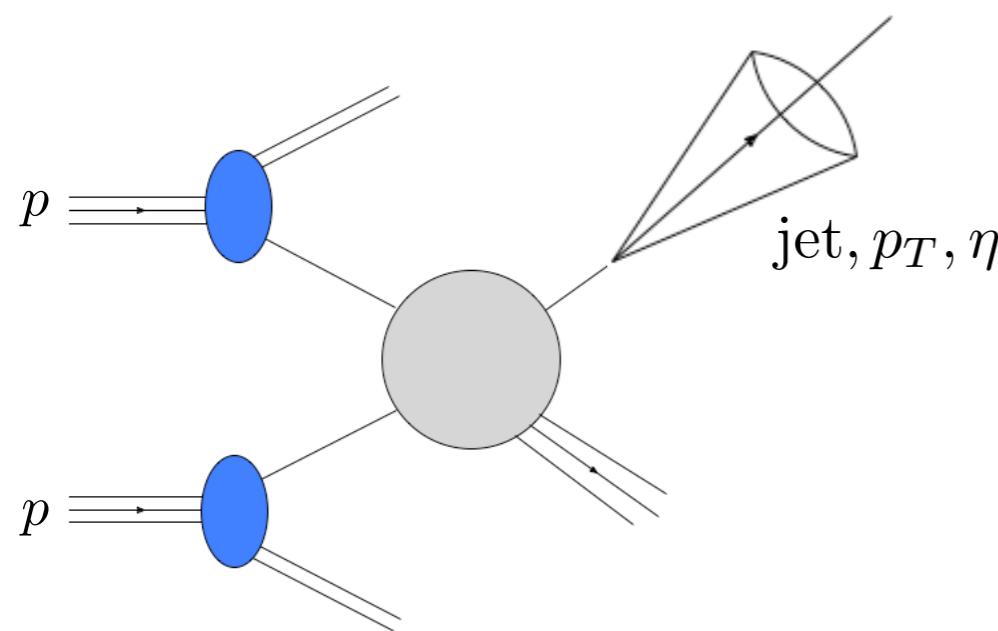
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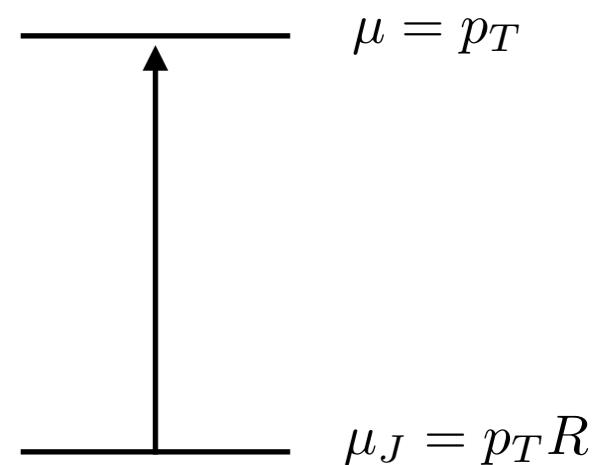
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timelike DGLAP for semi-inclusive jet function



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

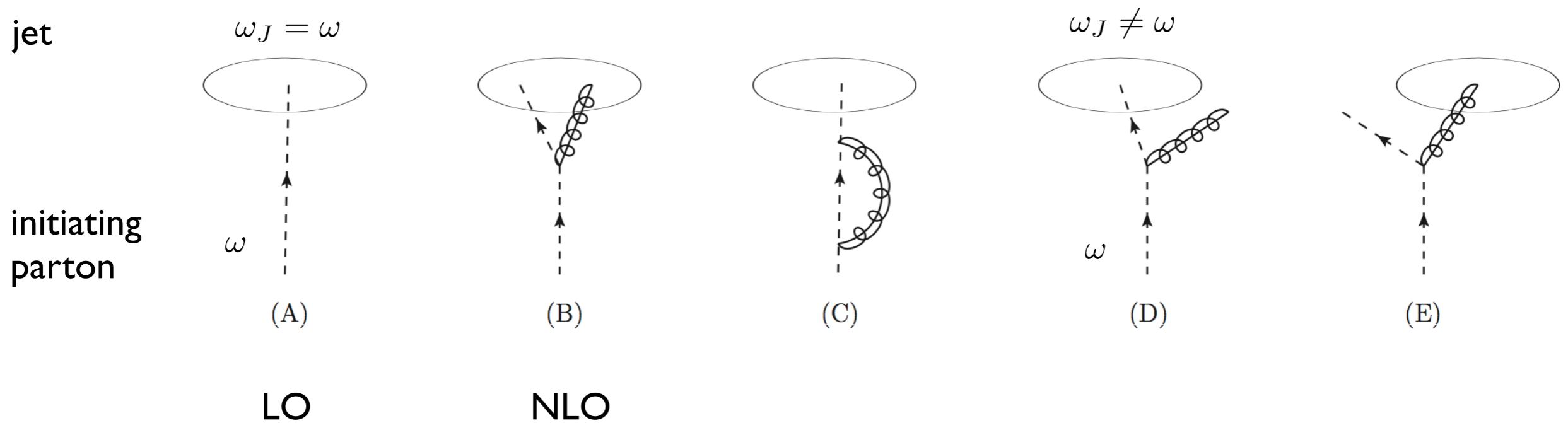


resummation of  $\alpha_s^n \ln^n R$

see also: Dasgupta, Dreyer, Salam, Soyez '15, '16

# The semi-inclusive jet function up to NLO

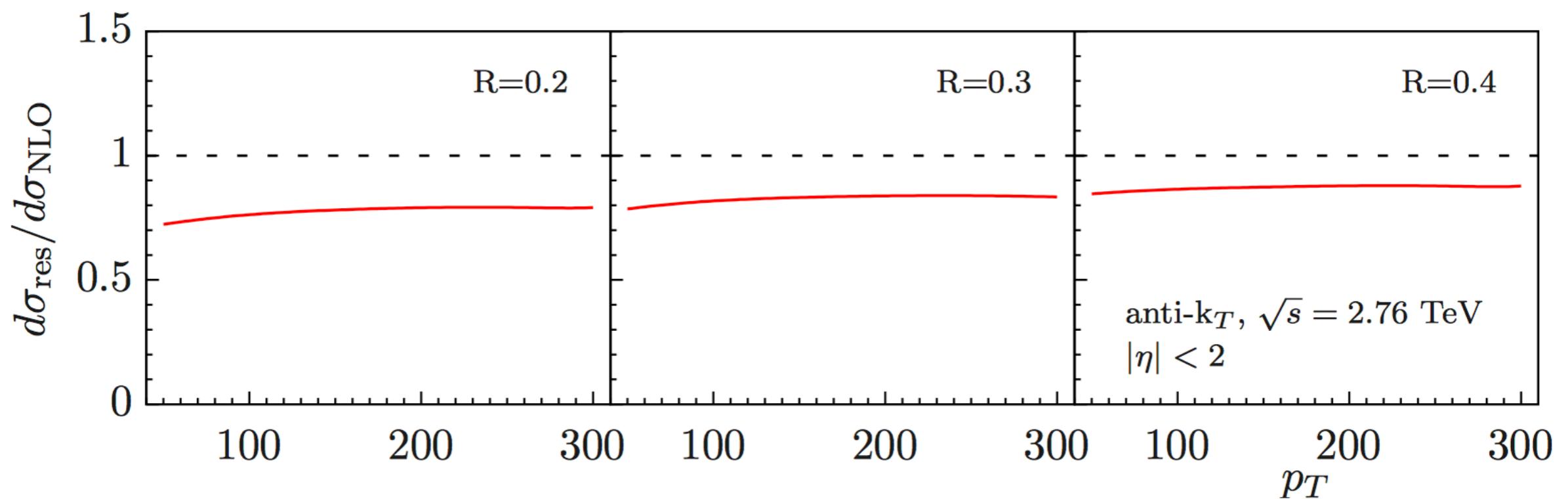
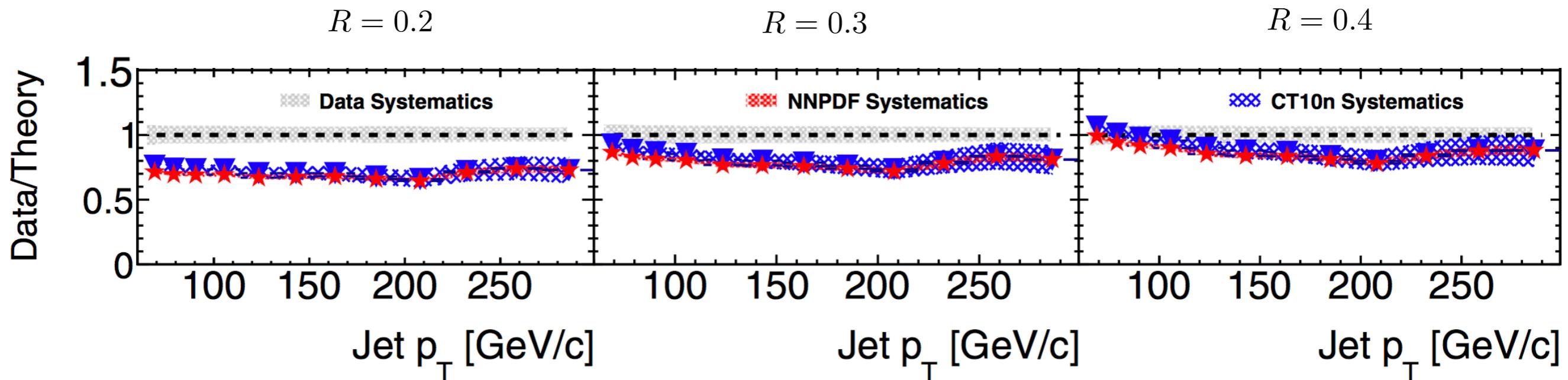
- The siJFs describe how a parton is transformed into a jet with radius  $R$  and energy fraction  $z$



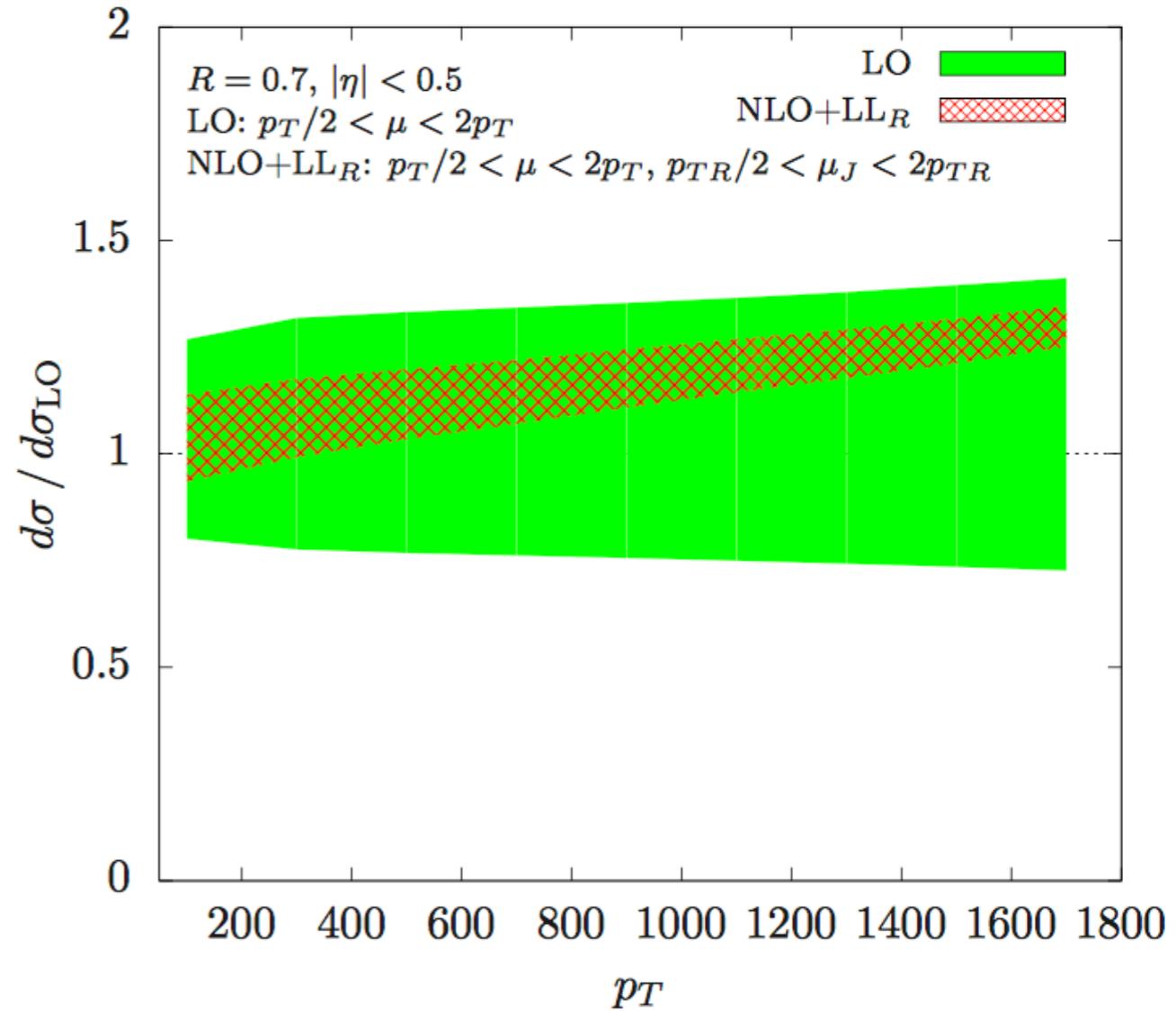
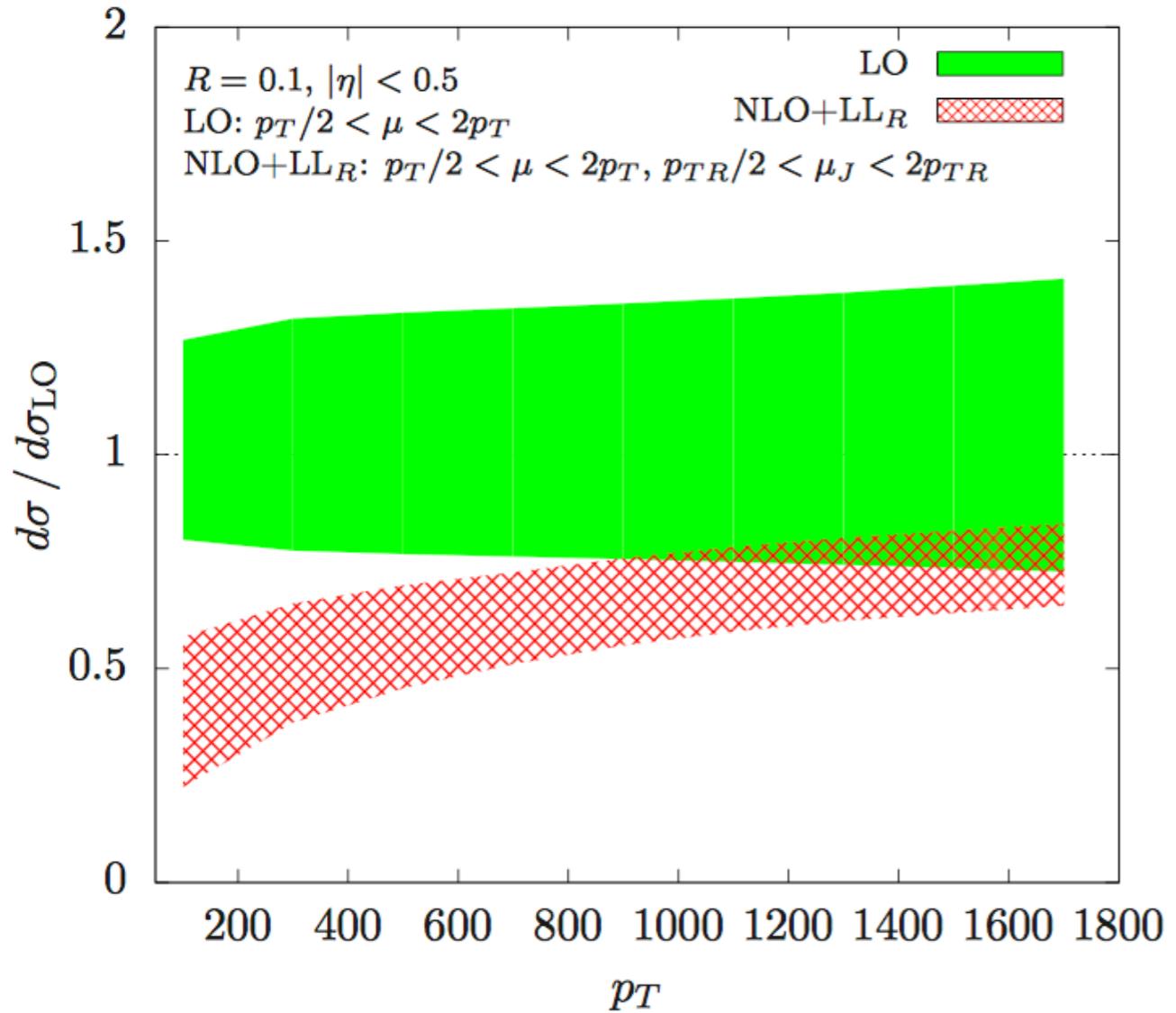
$$J_q(z, \omega_J) = \delta(1 - z) + \frac{\alpha_s}{2\pi} \left[ \frac{1}{\epsilon} + \ln \left( \frac{\mu^2}{p_T^2 R^2} \right) \right] [P_{qq}(z) + P_{gq}(z)] + \dots$$

where  $z = \omega_J/\omega$

# Comparison to LHC data



# QCD scale dependence



see also: Dasgupta, Dreyer, Salam, Soyez '15, '16

# Outline

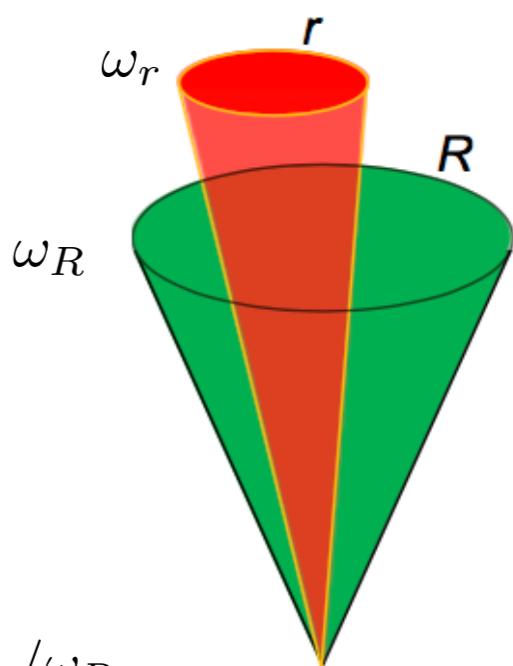
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- Subjets
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  - Centered around an axis *Kang, FR, Waalewijn '17*
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# Inclusive subjets

- Recluster particles of identified jet with a smaller jet parameter  $r < R$
- Longitudinal and transverse energy profile of jets

$$pp \rightarrow (\text{jet } j_r) + X$$

$$F(z_r, r; \eta, p_T, R) = \frac{d\sigma}{d\eta dp_T dz_r} / \frac{d\sigma}{d\eta dp_T}$$



- Applications for tagging and heavy-ion physics
- Measure AP splitting function

$$z_r = \omega_r / \omega_R$$

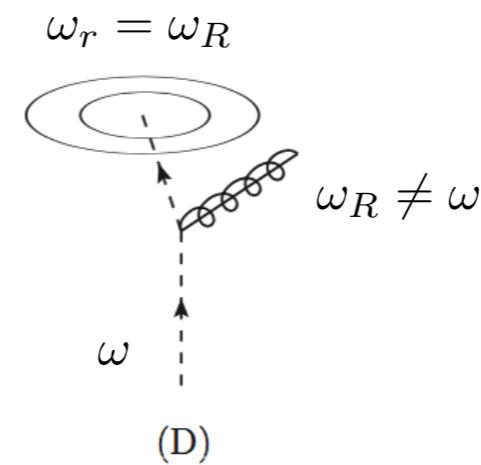
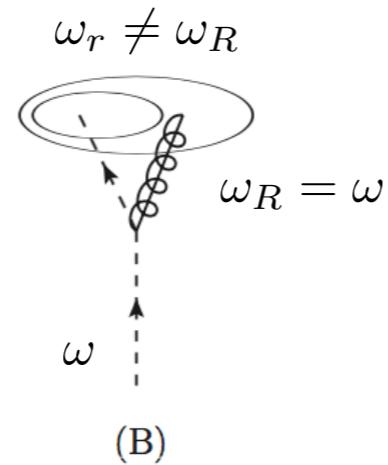
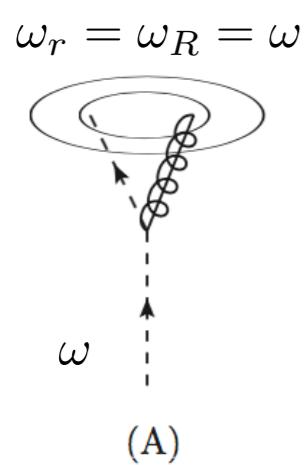
# Inclusive subjets

- Factorization for  $R \ll 1$

$$\frac{d\sigma^{pp \rightarrow (\text{jet } j_r) X}}{dp_T d\eta dz_r} = \sum_{abc} f_a(x_a, \mu) \otimes f_b(x_b, \mu) \otimes H_{ab}^c(x_a, x_b, \eta, p_T/z, \mu) \otimes \mathcal{G}_c^{\text{jet}}(z, z_r, \omega_R, \mu)$$

↑ same hard functions as before      ↑ semi-inclusive subjet function (siSJF)

- The quark siSJF at NLO



$$z = \frac{\omega_R}{\omega}, \quad z_r = \frac{\omega_r}{\omega_R}$$

# Inclusive subjets

$$\begin{aligned}
 \mathcal{G}_{q,\text{bare}}^{\text{jet}}(z, z_r, \omega_R, \mu) = & \delta(1-z)\delta(1-z_r) + \frac{\alpha_s}{2\pi} \left\{ \delta(1-z_r) \left( \frac{1}{\epsilon} + L_R \right) [P_{qq}(z) + P_{gq}(z)] \right. \\
 & + \delta(1-z) L_{r/R} [P_{qq}(z_r) + P_{gq}(z_r)] + C_F \delta(1-z_r) \left[ \delta(1-z) \left( \frac{13}{2} - \frac{2\pi^2}{3} \right) \right. \\
 & \left. \left. - 2(1+z^2) \left( \frac{\ln(1-z)}{1-z} \right)_+ - 2\ln(1-z) \frac{1+(1-z)^2}{z} - 1 \right] \right\}
 \end{aligned}$$

IR UV

where  $L_{r/R} = L_r - L_R$ ,  $L_R = \ln \left( \frac{4\mu^2}{\omega_R^2 R^2} \right)$ ,  $L_r = \ln \left( \frac{4\mu^2}{\omega_R^2 r^2} \right)$

$r \sim R \ll 1$   
 anti-k<sub>T</sub>-in-anti-k<sub>T</sub>

# Inclusive subjets

- Renormalization and RG equation

$$\mu \frac{d}{d\mu} \mathcal{G}_i^{\text{jet}}(\textcolor{blue}{z}, z_r, \omega_R, \mu) = \sum_k \int_{\textcolor{blue}{z}}^1 \frac{d\textcolor{blue}{z}'}{z'} P_{ik} \left( \frac{z}{\textcolor{blue}{z}'}, \mu \right) \mathcal{G}_k^{\text{jet}}(\textcolor{blue}{z}', z_r, \omega_R, \mu)$$

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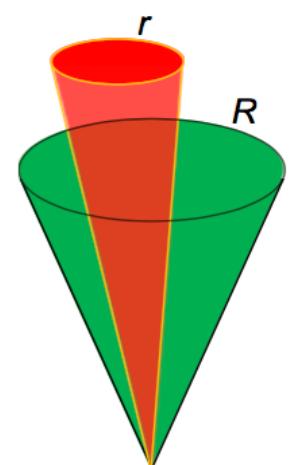
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- Matching for  $r \ll R \ll 1$

$$\mathcal{G}_i^{\text{jet}}(z, \mathbf{z}_r, \omega_R, r, R, \mu) = \sum_j \int_{z_r}^1 \frac{d\mathbf{z}'_r}{z'_r} \mathcal{J}_{ij}(z, \mathbf{z}'_r, \omega_R, R, \mu) J_j \left( \frac{z_r}{z'_r}, \omega_r, r, \mu \right) \left[ 1 + \mathcal{O} \left( \frac{r^2}{R^2} \right) \right]$$

matching coefficients  
same as for hadron-in-jet

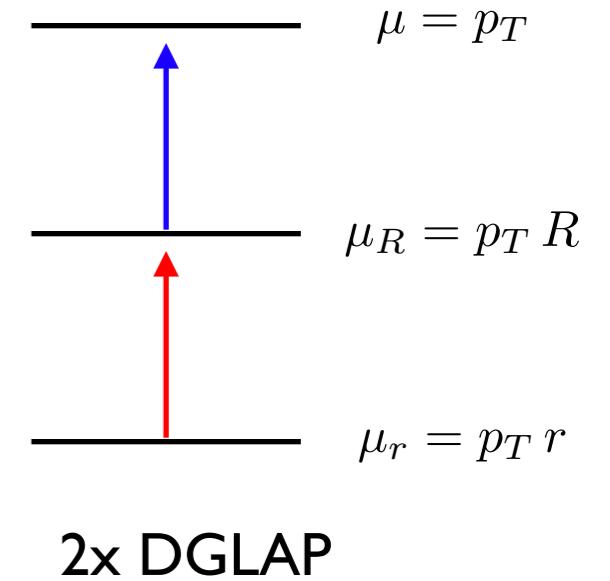
↑  
sjLF for subjet of size  $r$



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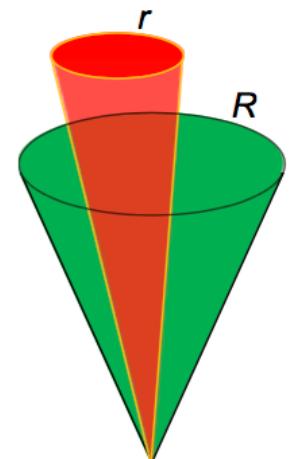


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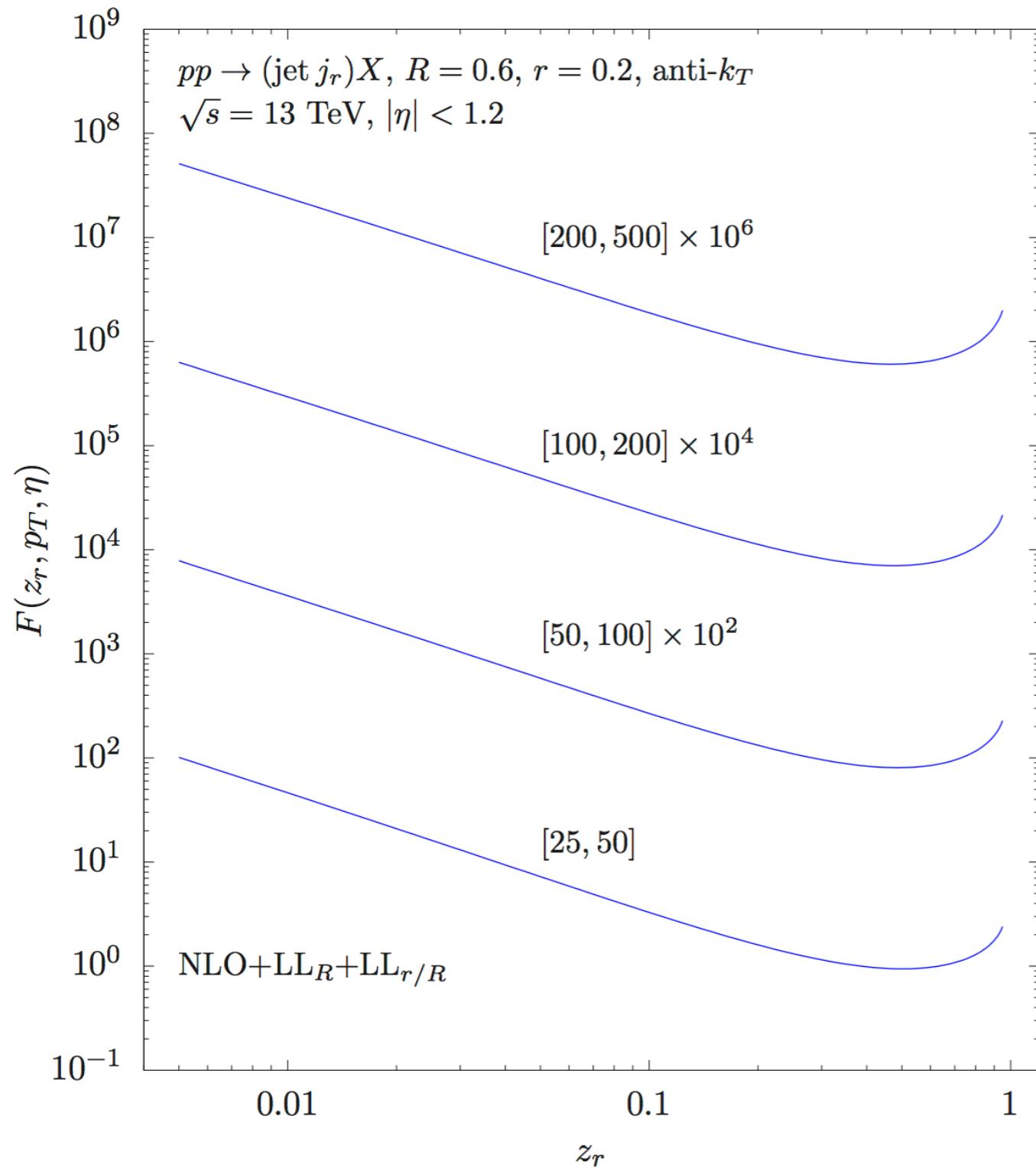
$$\mathcal{G}_i^{\text{jet}}(z, \mathbf{z}_r, \omega_R, r, R, \mu) = \sum_j \int_{z_r}^1 \frac{d\mathbf{z}'_r}{z'_r} \mathcal{J}_{ij}(z, \mathbf{z}'_r, \omega_R, R, \mu) J_j \left( \frac{z_r}{z'_r}, \omega_r, r, \mu \right) \left[ 1 + \mathcal{O} \left( \frac{r^2}{R^2} \right) \right]$$

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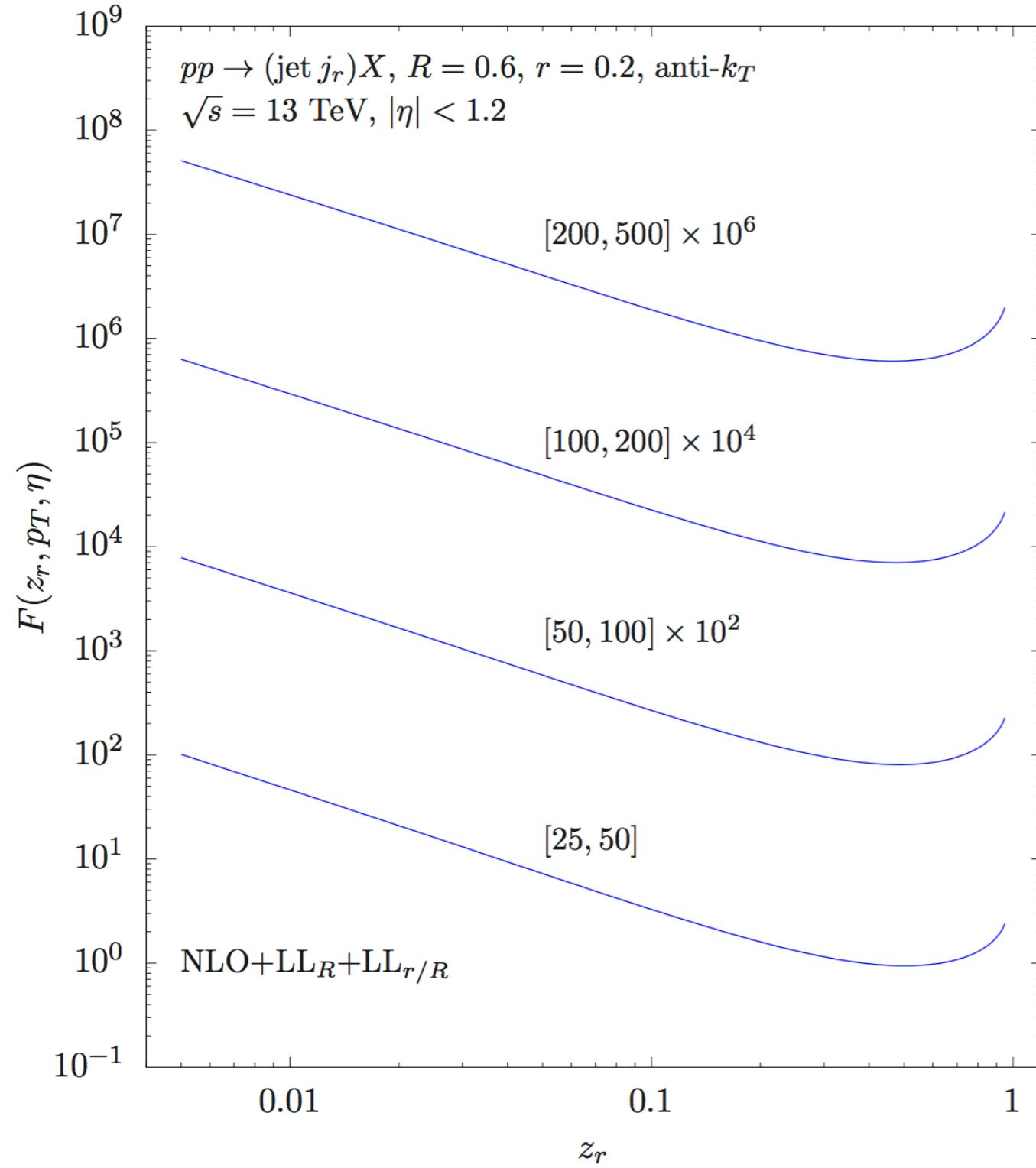


# Inclusive subjets



Joint resummation of  $\ln R, \ln(r/R)$

# Inclusive subjets



Joint resummation of  $\ln R, \ln(r/R)$

Fixed order result:

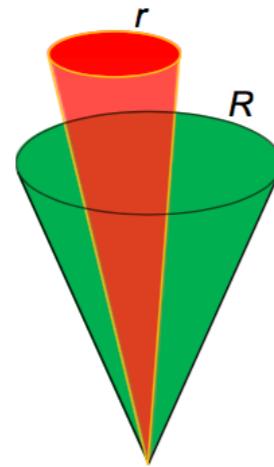
$$\frac{d\sigma}{d\eta \, dp_T \, dz_r} \sim \mathcal{G}_c^{\text{jet}}(z, z_r, \omega_R, \mu)$$

$$\mathcal{G}_q^{\text{jet}}(z, z_r < 1, \omega_R, \mu) =$$

$$\frac{\alpha_s}{2\pi} \delta(1-z) L_{r/R} [P_{qq}(z_r) + P_{gq}(z_r)]$$

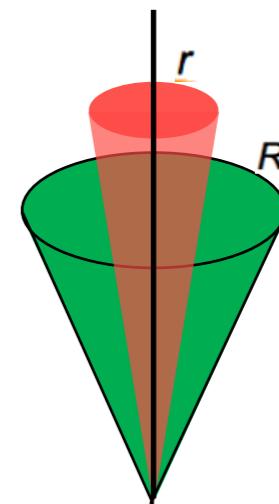
# Subjets centered around a predetermined axis

Inclusive subjets



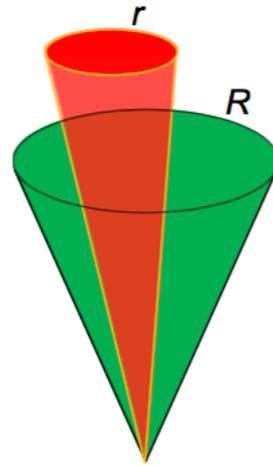
Centered around an axis

- recoil-free axis
- winner-take-all
- standard jet axis



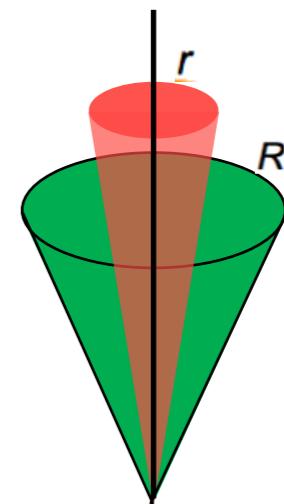
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- recoil-free axis

Refactorization for  $r \ll R$  and  
 $\ln(r/R)$  resummation:

$$\mu \frac{d}{d\mu} \tilde{J}_i^{\text{jet}}(z_r, \omega_r, \mu) = \sum_k \int_z^1 \frac{dz'_r}{z'_r} \tilde{\gamma}_{ik} \left( \frac{z_r}{z'_r}, \mu \right) \tilde{J}_k^{\text{jet}}(z'_r, \omega_r, \mu)$$

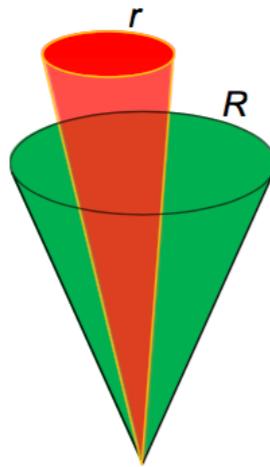
$$\tilde{\gamma}_{ij}^{(1)}(z_r, \mu) = \theta \left( z_r > \frac{1}{2} \right) \frac{\alpha_s}{\pi} P_{ji}(z_r)$$

modified DGLAP

Still hard-collinear factorization only

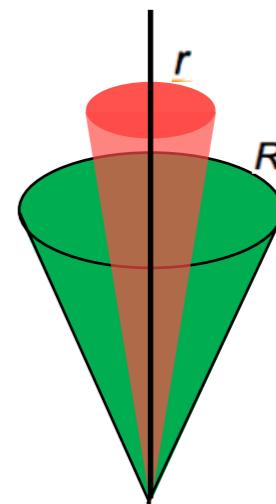
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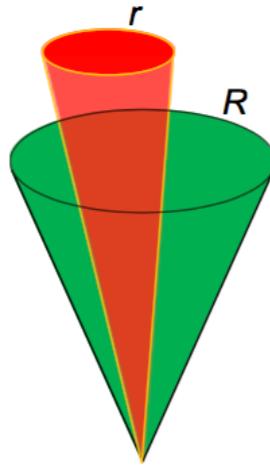
$$\hat{\mathcal{G}}_i^{\text{jet}}(z, z_r, \omega_R, r, R, \mu) = \mathcal{H}_{ij}(z, \omega_R R, \mu) \int d^2 k_{\perp} C_j(z_r, \omega_r r, k_{\perp}, \mu, \nu) S_j(k_{\perp}, R, \mu, \nu)$$

hard	collinear	soft
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RGs and rapidity RGs + non-global logarithms

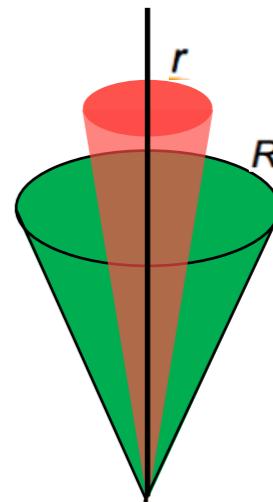
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RGs and rapidity RGs + non-global logarithms

Jet shape,  $z_r$  average:

$$\int_0^1 dz_r z_r \hat{\mathcal{G}}_q^{\text{anti-}k_T}(z, z_r, \omega_R, \mu) = J_q^{\text{anti-}k_T}(z, \omega_R, \mu) + \delta(1-z) \frac{\alpha_s C_F}{2\pi} \left[ -\frac{1}{2} L_{r/R}^2 + \frac{3}{2} L_{r/R} - \frac{9}{2} + \frac{6r}{R} - \frac{3r^2}{2R^2} \right]$$

see also: Seymour '98; Li, Li, Yuan 11;  
Chien, Vitev '14 ...

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# Conclusions

- Inclusive small- $R$  jets and their substructure within SCET
  - Inclusive and central subjets
  - Standard jet shape
- 
- Non-global logarithms
  - Numerical results available soon for central subjets