

# The Latest Developments for Jets as Tools for Precision Physics

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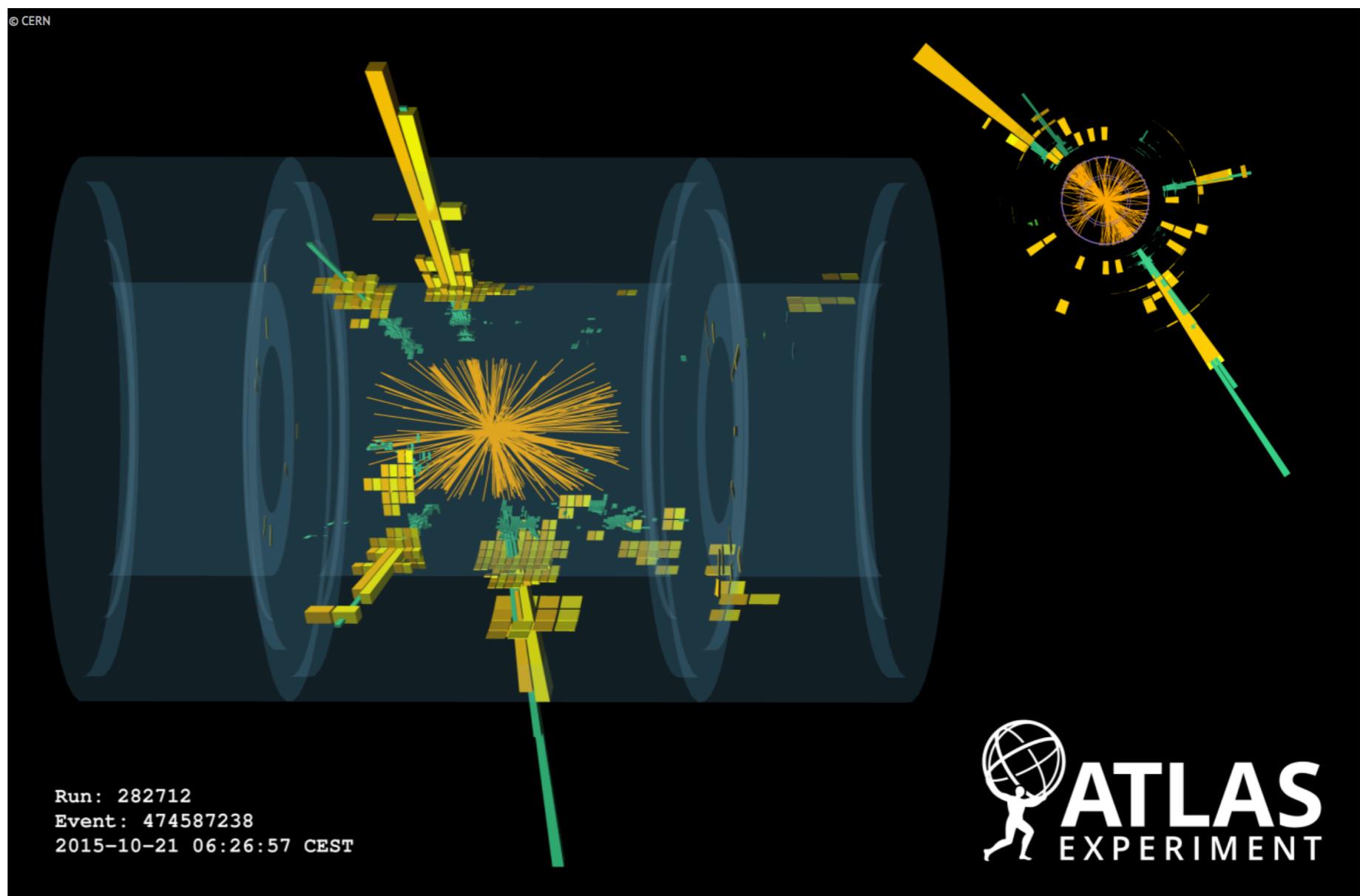
# Jets at the LHC

- Inclusive jet production

$$\xrightarrow{\hspace{1cm}} \frac{d\sigma^{pp \rightarrow \text{jet}+X}}{dp_T d\eta}$$

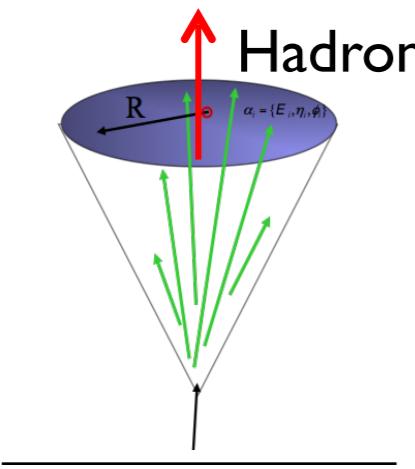
- Measure additional jet substructure

$$\xrightarrow{\hspace{1cm}} \frac{d\sigma^{pp \rightarrow (\text{jet } \tau) X}}{dp_T d\eta d\tau}$$



# Jet substructure

- The jet fragmentation function



$$z = p_T^h / p_T$$

longitudinal structure

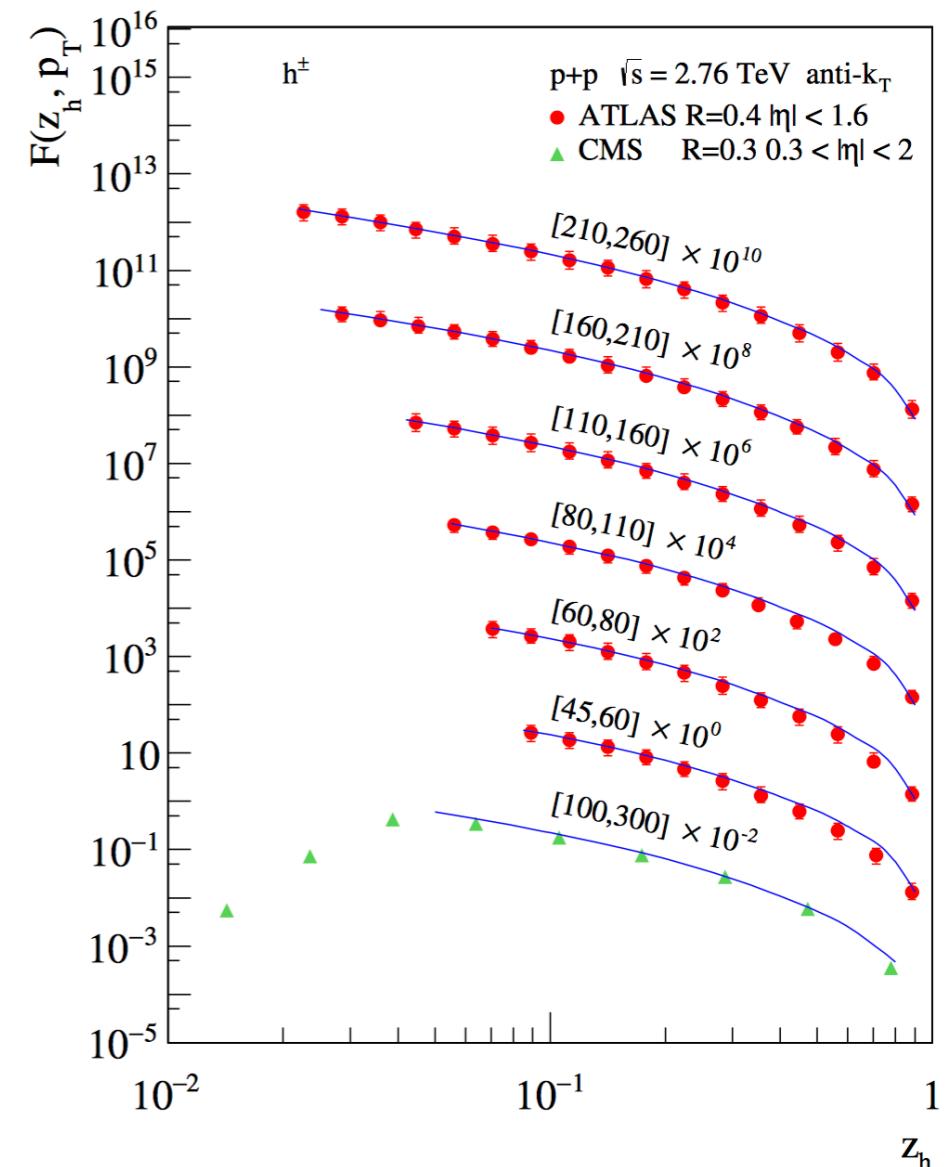
- Extraction of the QCD strong coupling constant

*LesHouches '17*

- Include a grooming procedure

- Tagging see *Ian Moult's talk*

- Differential probe of the QGP in heavy-ion collisions

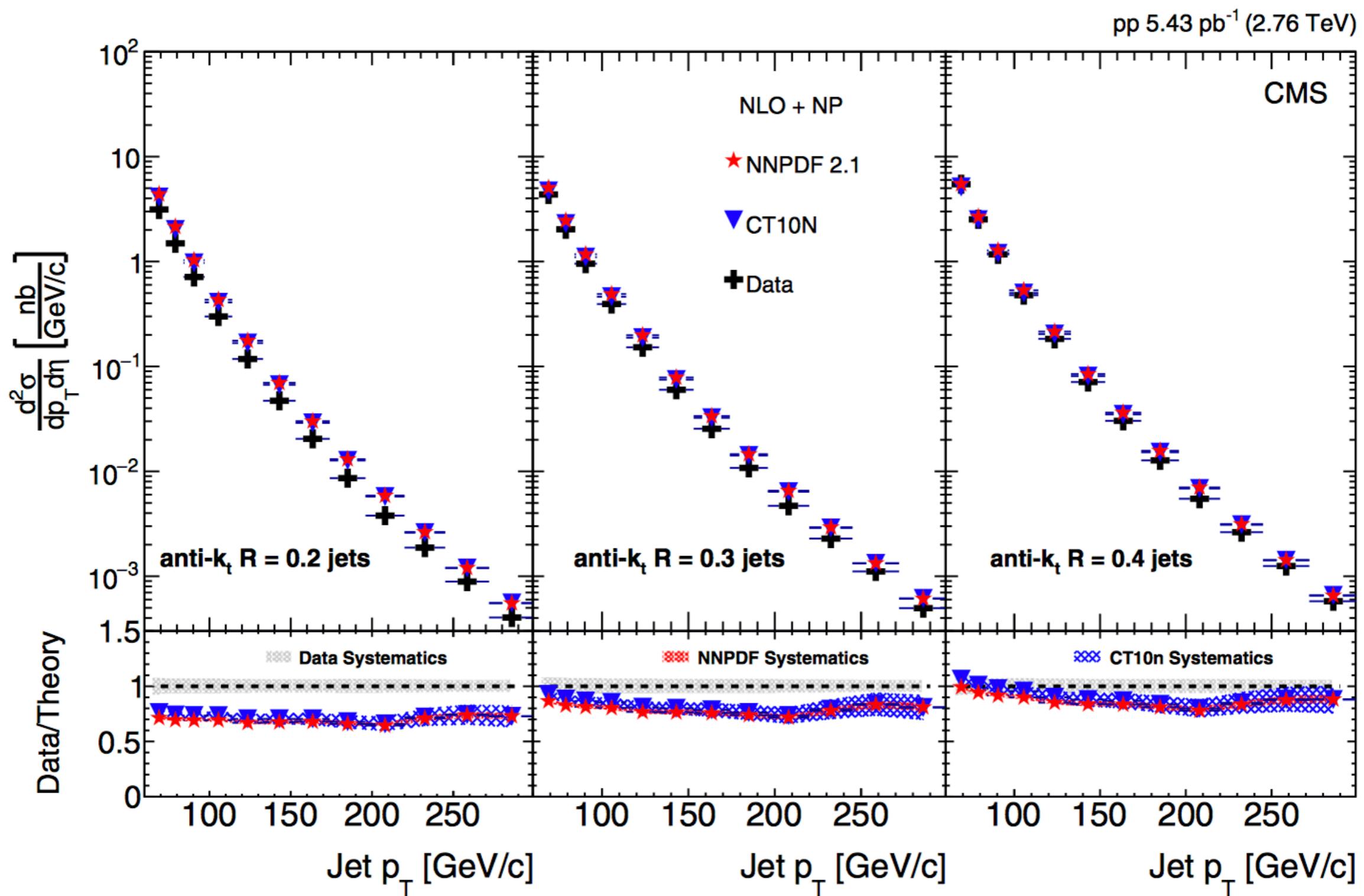


*Kang, FR, Vitev '16*

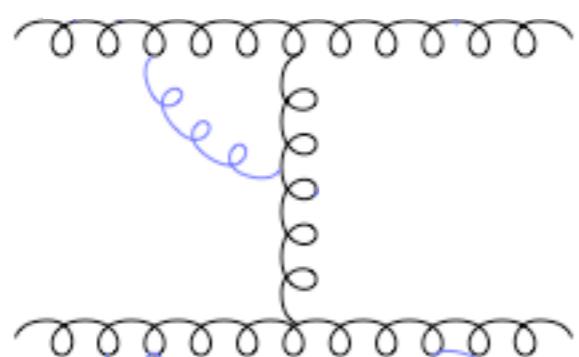
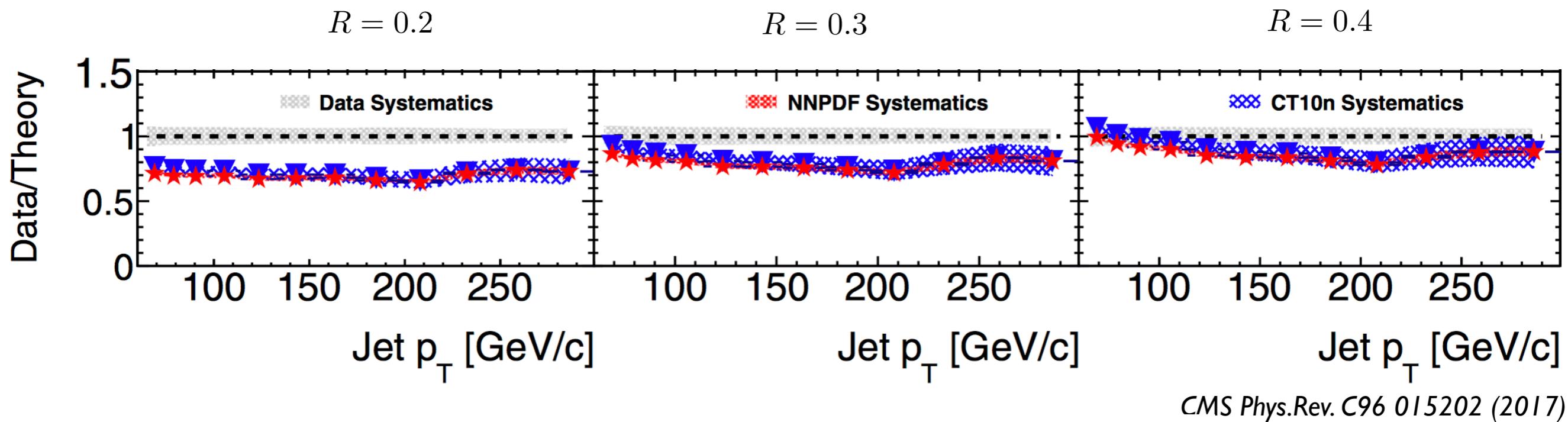
# Outline

- Introduction
- Inclusive jet production
- Groomed jet observables
- The transverse profile of jets
- Conclusions

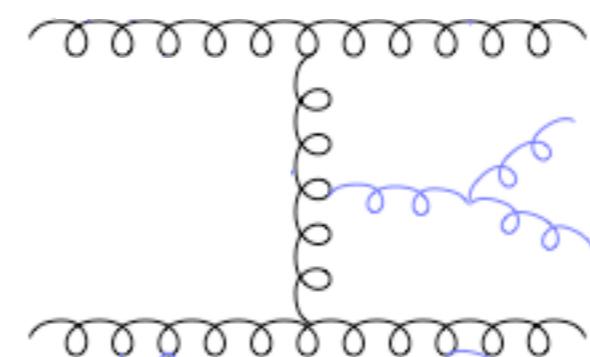
# Jet production at the LHC



# Jet production at the LHC



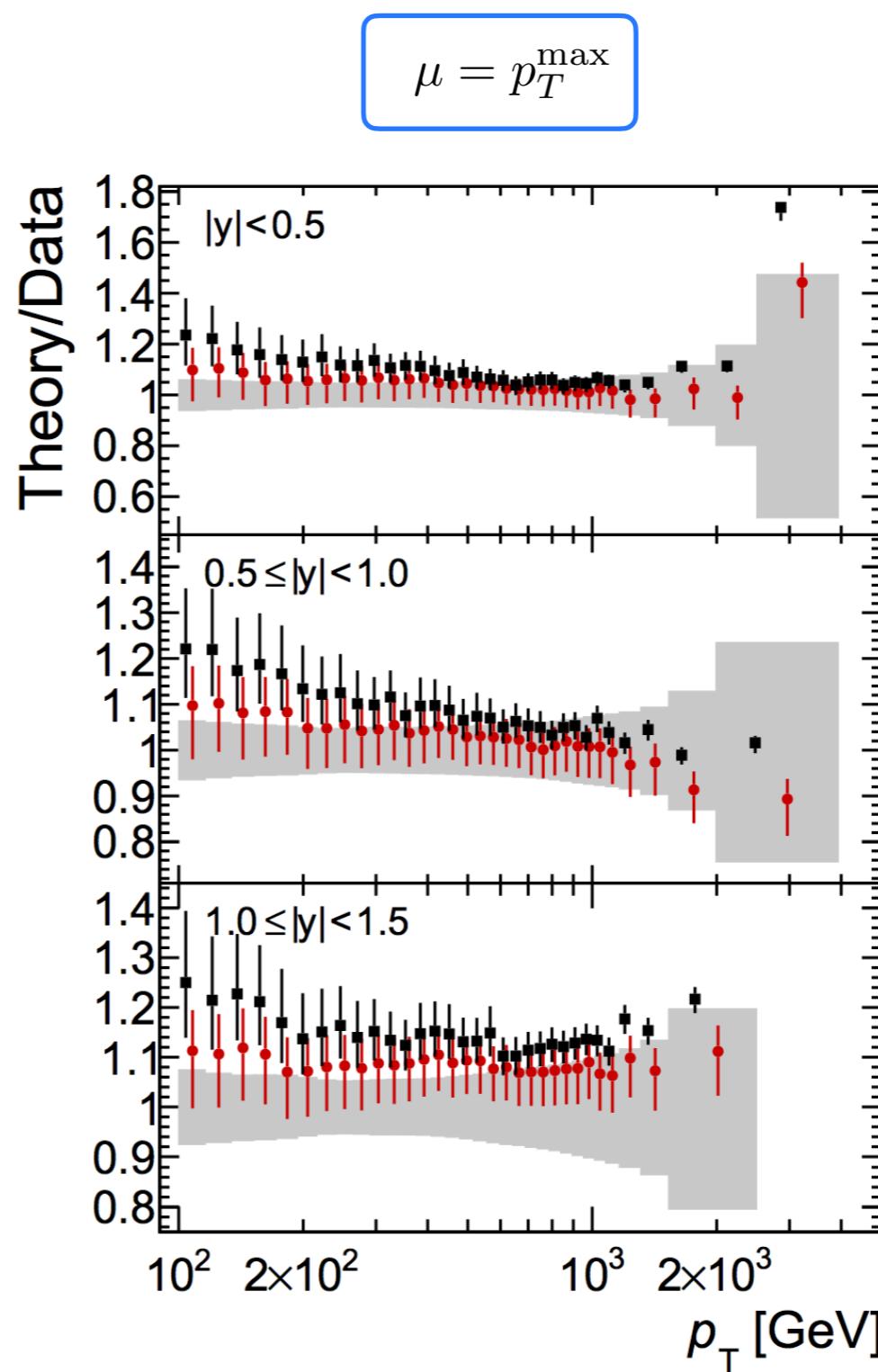
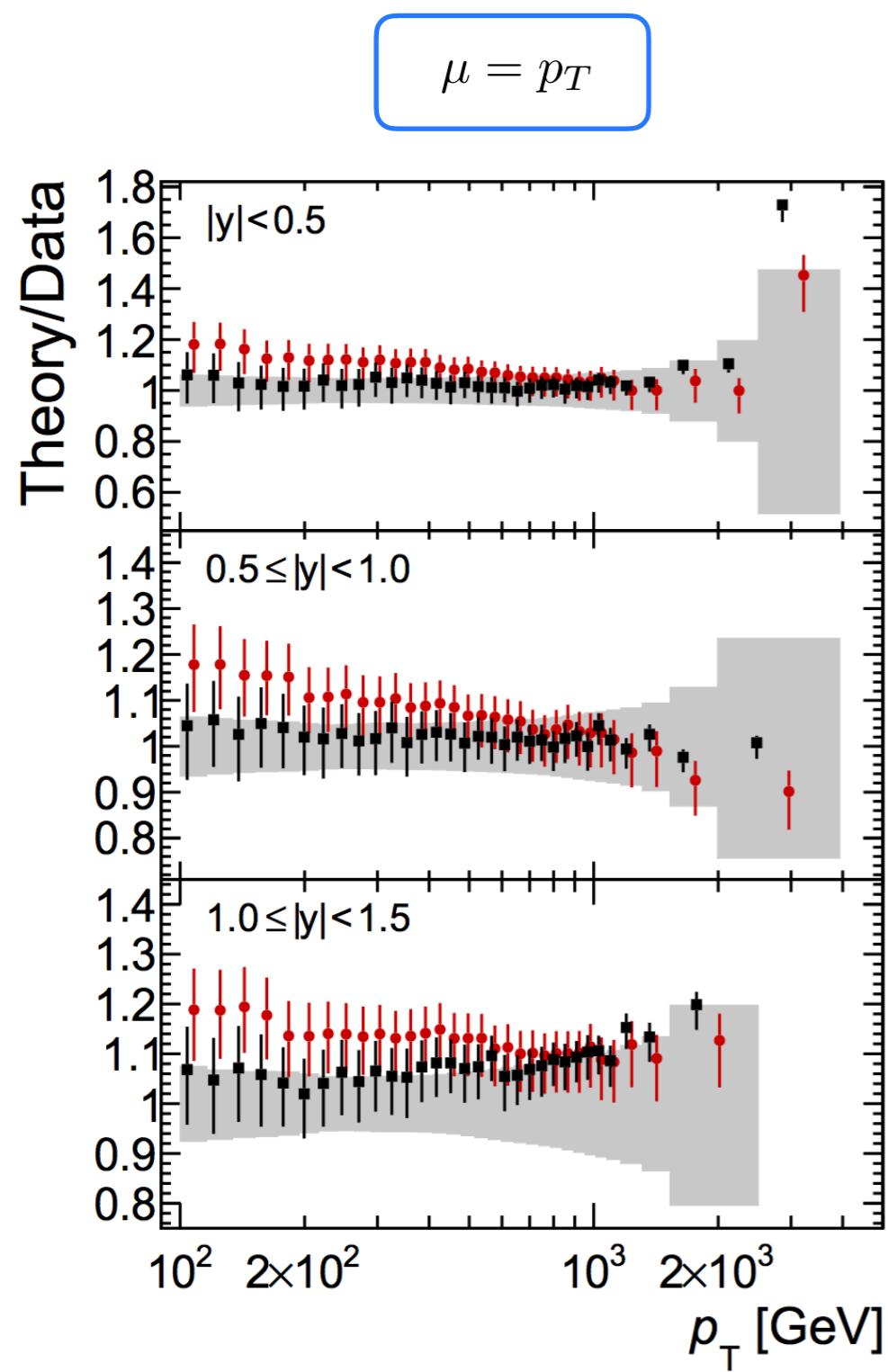
NLO 1990

*Ellis, Kunszt, Soper '90*

NNLO 2016 ...

*Currie, Glover, Pires '16*

# Jet production at the LHC



**ATLAS**

$L = 81\text{nb}^{-1} - 3.2\text{ fb}^{-1}$

$\sqrt{s} = 13\text{ TeV}$

$\text{anti-}k_t R=0.4$

- Data
- NLO QCD
- $\otimes k_{\text{EW}} \otimes k_{\text{NP}}$
- NNLO QCD
- $\otimes k_{\text{EW}} \otimes k_{\text{NP}}$
- NLO MMHT 2014 NLO
- NNLO MMHT 2014 NNLO

# Inclusive jet cross sections

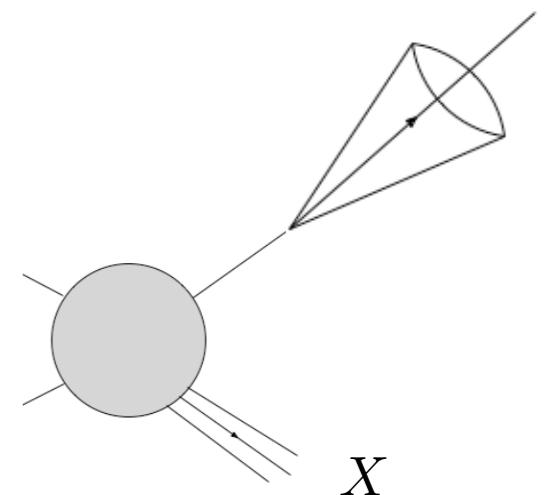
$$pp \rightarrow \text{jet} + X$$

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

↑

partonic hard-scattering cross section

$$H_{ab} = \alpha_s^2 \left( H_{ab}^{(0)} + \alpha_s H_{ab}^{(1)} + \alpha_s^2 H_{ab}^{(2)} + \dots \right)$$



Cross check + resummation of large logarithms found in analytical calculations:

- Jet radius parameter

$$\alpha_s^n \ln^n R$$

]

- Threshold

$$\alpha_s^n \left( \frac{\ln^{2n-1} z}{z} \right)_+$$

- Forward

$$\alpha_s^n \ln^{n,2n}(-t/s)$$

# Joint threshold and small radius resummation

Liu, Moch, FR '17

- Refactorization at threshold

$$\begin{aligned} \frac{d^2\hat{\sigma}_{i_1 i_2}}{dv dz} &= s \int ds_X ds_c ds_G \delta(zs - s_X - s_G - s_c) \\ &\times \text{Tr} [\mathbf{H}_{i_1 i_2}(v, p_T, \mu_h, \mu) \mathbf{S}_G(s_G, \mu_{sG}, \mu)] J_X(s_X, \mu_X, \mu) \\ &\times \sum_m \text{Tr} [J_m(p_T R, \mu_J, \mu) \otimes_\Omega S_{c,m}(s_c R, \mu_{sc}, \mu)] \end{aligned}$$

- Joint resummation  $\alpha_s^n \left( \frac{\ln^{2n-1} z}{z} \right)_+, \quad \alpha_s^n \ln^n R \quad \text{where} \quad z = s_4/s$
- Possible to extend theoretical accuracy beyond NLL

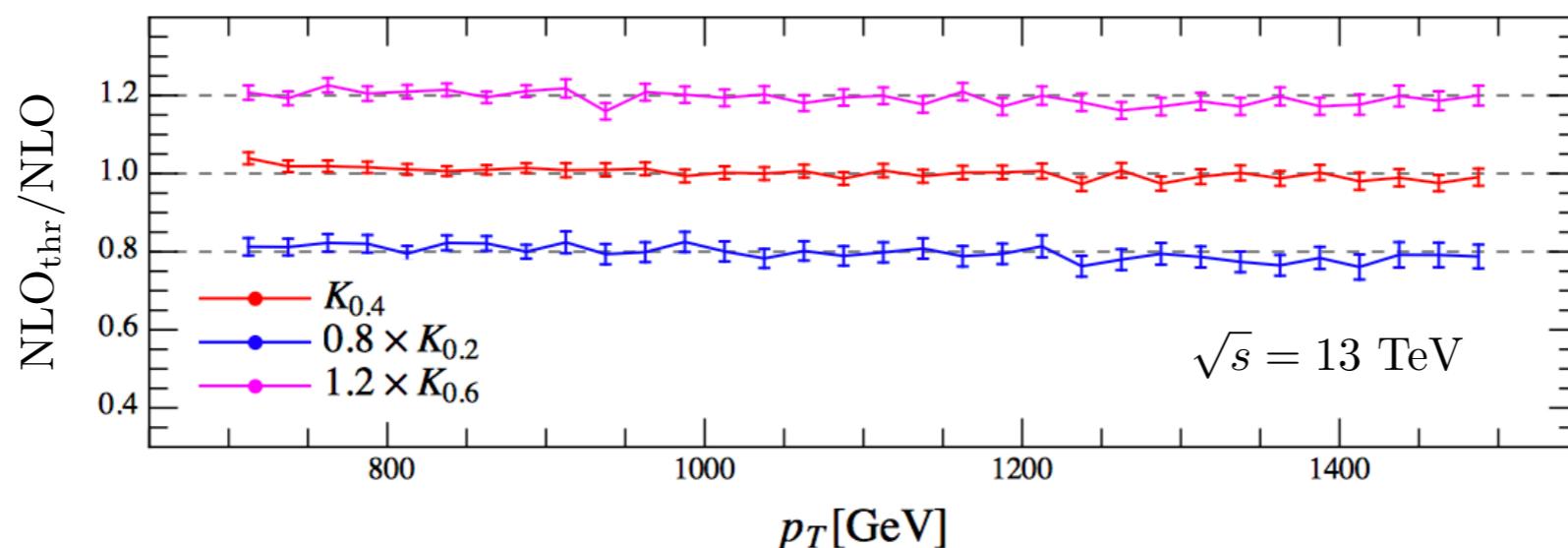
see also: Kidonakis, Sterman '97, Kidonakis, Oderda, Sterman '98  
 Kidonakis, Owens '01, Kumar, Moch '13  
 de Florian, Hinderer, Mukherjee, FR, Vogelsang '14

# Joint threshold and small radius resummation

Liu, Moch, FR '17

- Refactorization at threshold

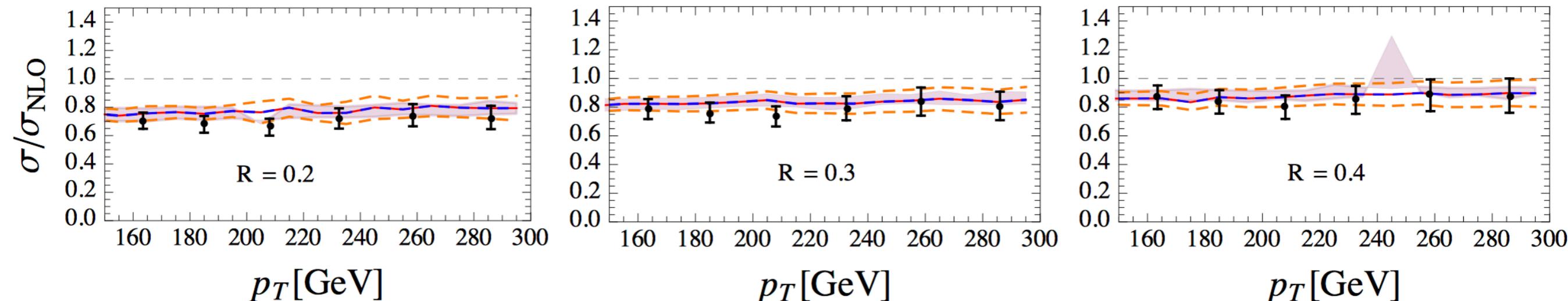
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# Phenomenological results

Liu, Moch, FR '17, '18

CMS Phys.Rev. C96 015202 (2017)

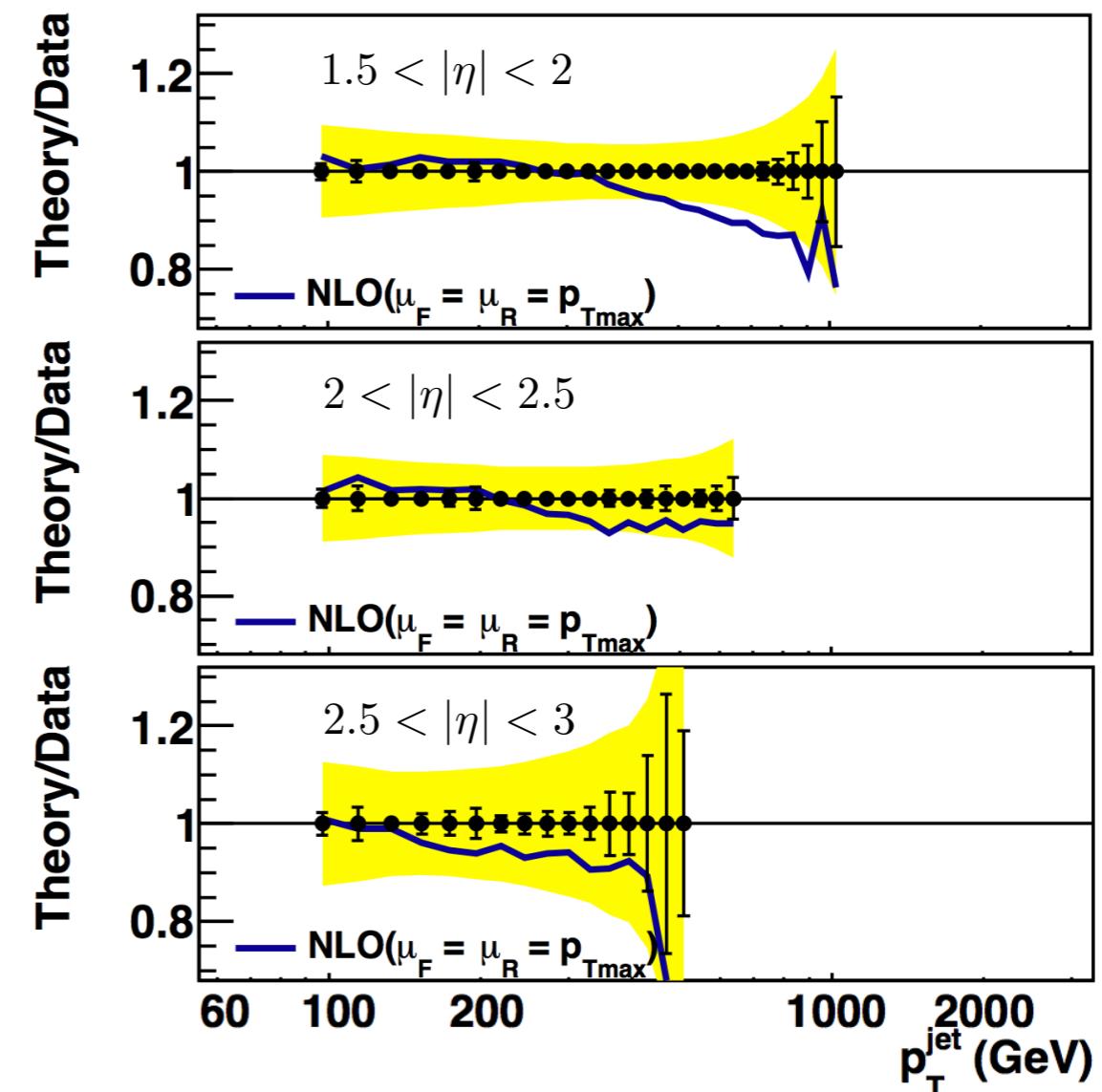
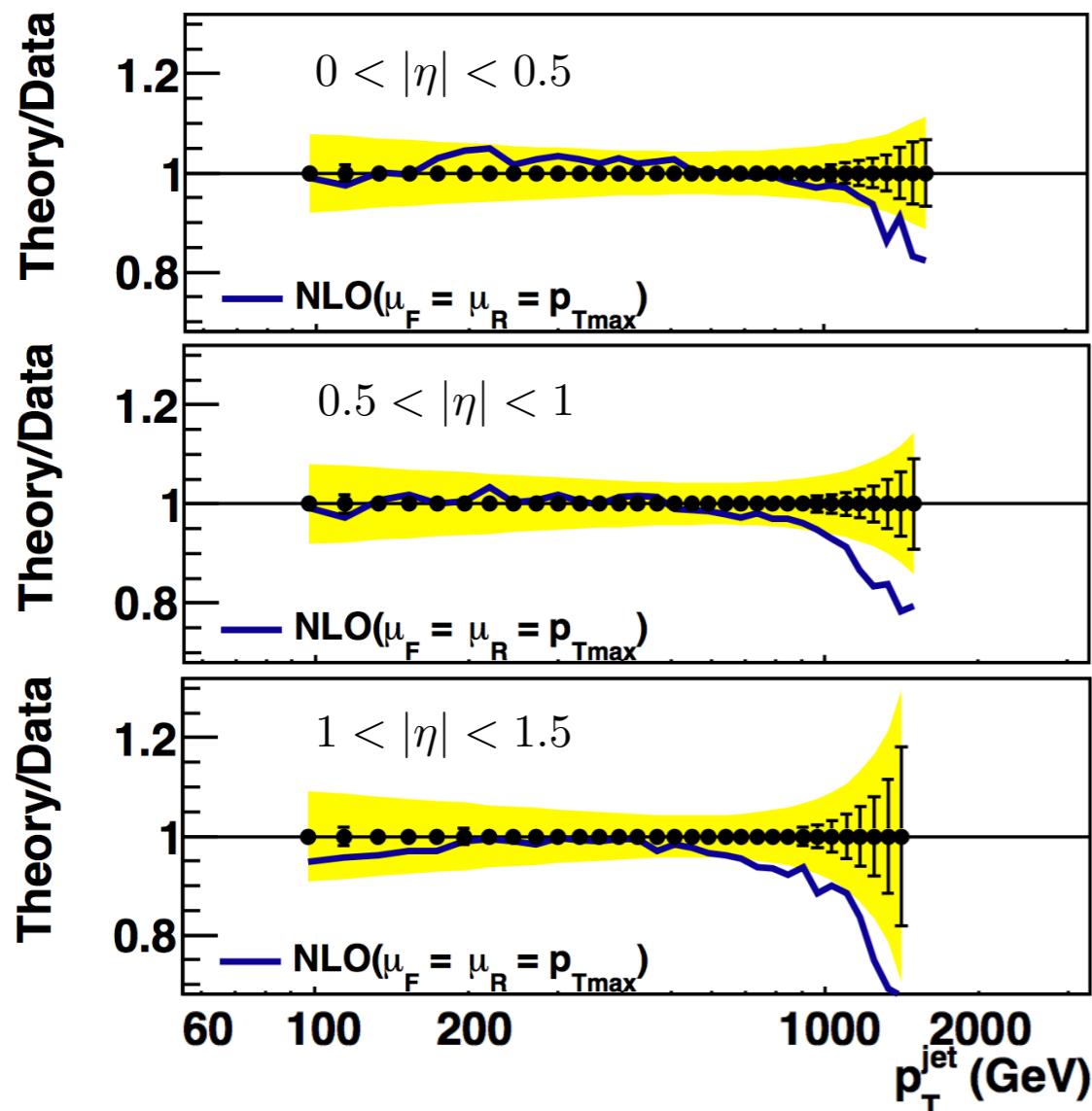


- The QCD scale dependence is still quite large see also: Currie, Gehrmann-de Ridder, Gehrmann, Glover, Huss, Pires '18
- Precision goal is eventually NNLO + NNLL' see also: Hinderer, FR, Sterman, Vogelsang '18

# Comparison to 13 TeV data

Liu, Moch, FR '17, '18

Eren, Lipka, Lipka, Moch, FR '18



CT14 NNLO PDFs  
CMS, 10.3204/PUBDB-2018-03915

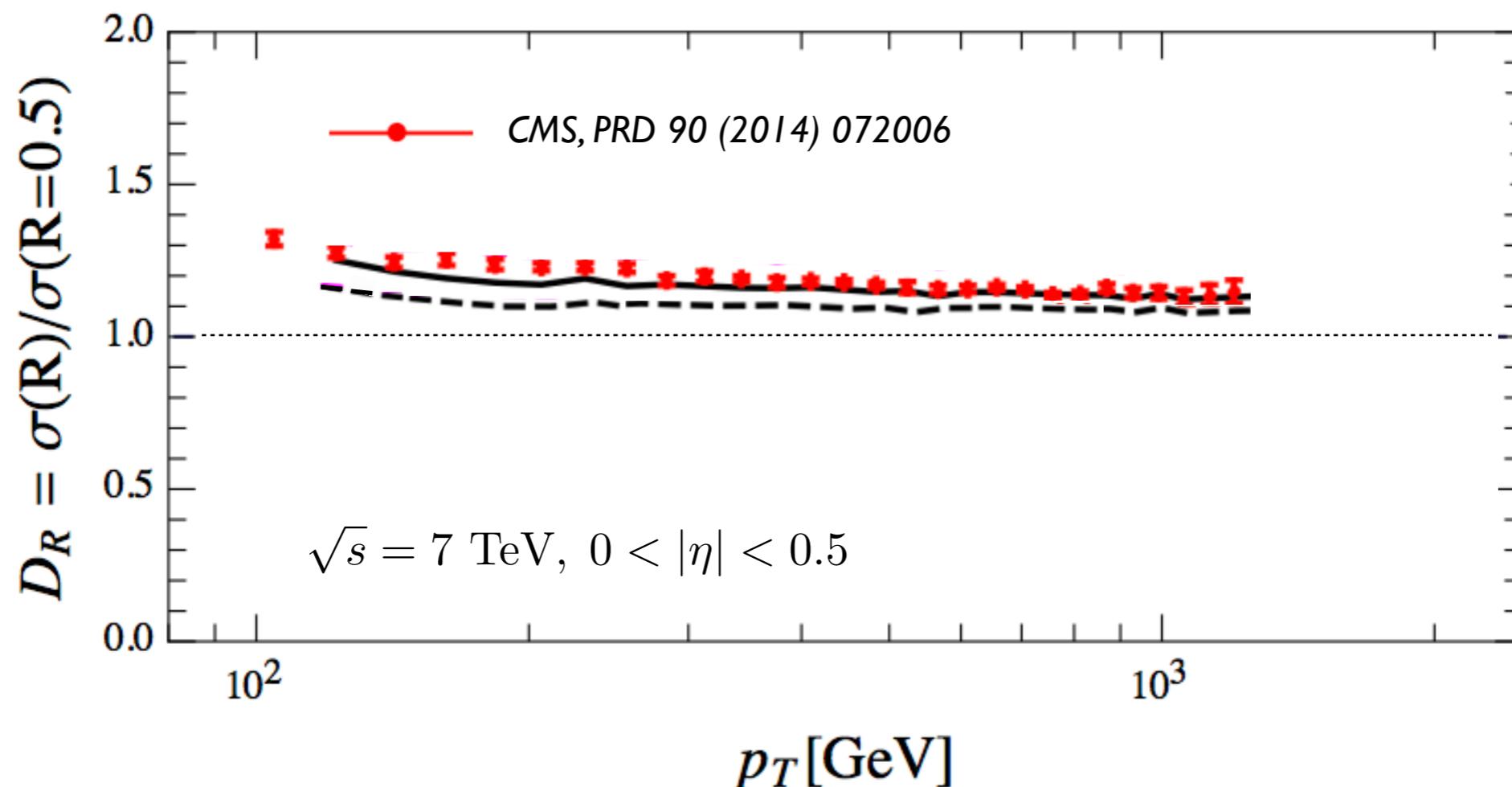
# Phenomenological results

Liu, Moch, FR '17, '18

- Cross section ratios

$$D_R = \frac{\sigma(R=0.7)}{\sigma(R=0.5)}$$

NLO  
 NLO+NLL



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# QCD factorization

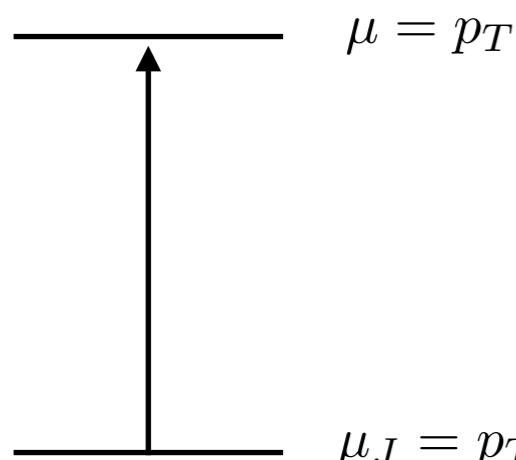
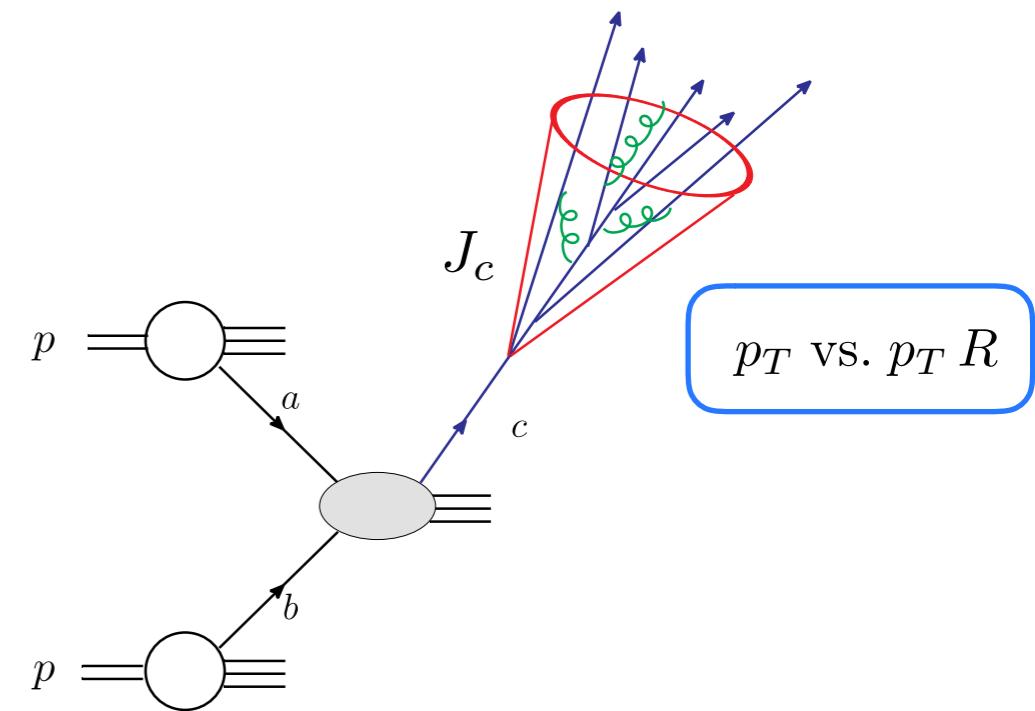
- Inclusive jet production  $pp \rightarrow \text{jet} + X$

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



perturbatively calculable

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



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

*Dasgupta, Dreyer, Salam, Soyez '15*  
*Kaufmann, Mukherjee, Vogelsang '15*  
*Kang, FR, Vitev '16*  
*Dai, Kim, Leibovich '16*

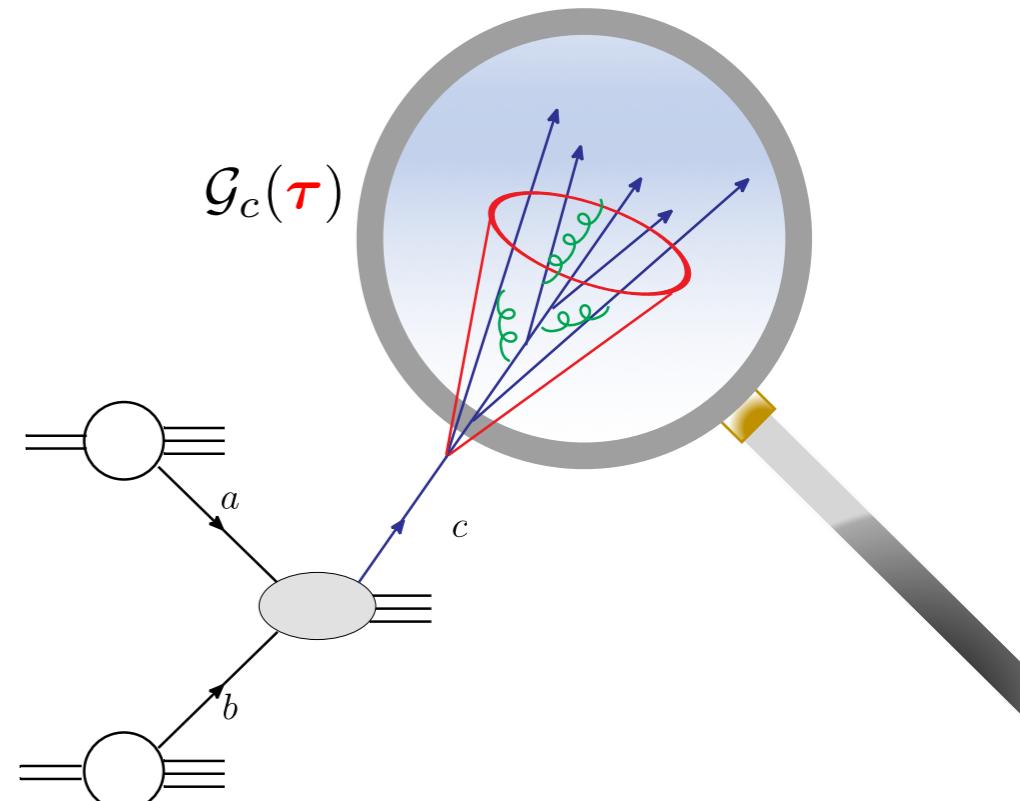
# QCD factorization

- Inclusive jet production  $pp \rightarrow \text{jet} + X$

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

- Jet substructure  $\tau$

$$\frac{d\sigma^{pp \rightarrow (\text{jet } \tau)X}}{dp_T d\eta d\tau} = \sum_{abc} f_a \otimes f_b \otimes H_{ab}^c \otimes \mathcal{G}_c(\tau)$$



- $\ln R$  resummation
- Definition of quark-gluon fractions beyond LO
- Mostly analytical calculations

*Dasgupta, Dreyer, Salam, Soyez '15*  
*Kaufmann, Mukherjee, Vogelsang '15*  
*Kang, FR, Vitev '16*  
*Dai, Kim, Leibovich '16*

# Soft drop grooming

Larkoski, Marzani, Soyez, Thaler '14

- Recluster jet constituents with the C/A algorithm
- Recursively decluster the jet and remove soft branches that fail the soft drop criterion

$$\frac{\min[p_{T1}, p_{T2}]}{p_{T1} + p_{T2}} > z_{\text{cut}} \left( \frac{\Delta R_{12}}{R} \right)^\beta$$

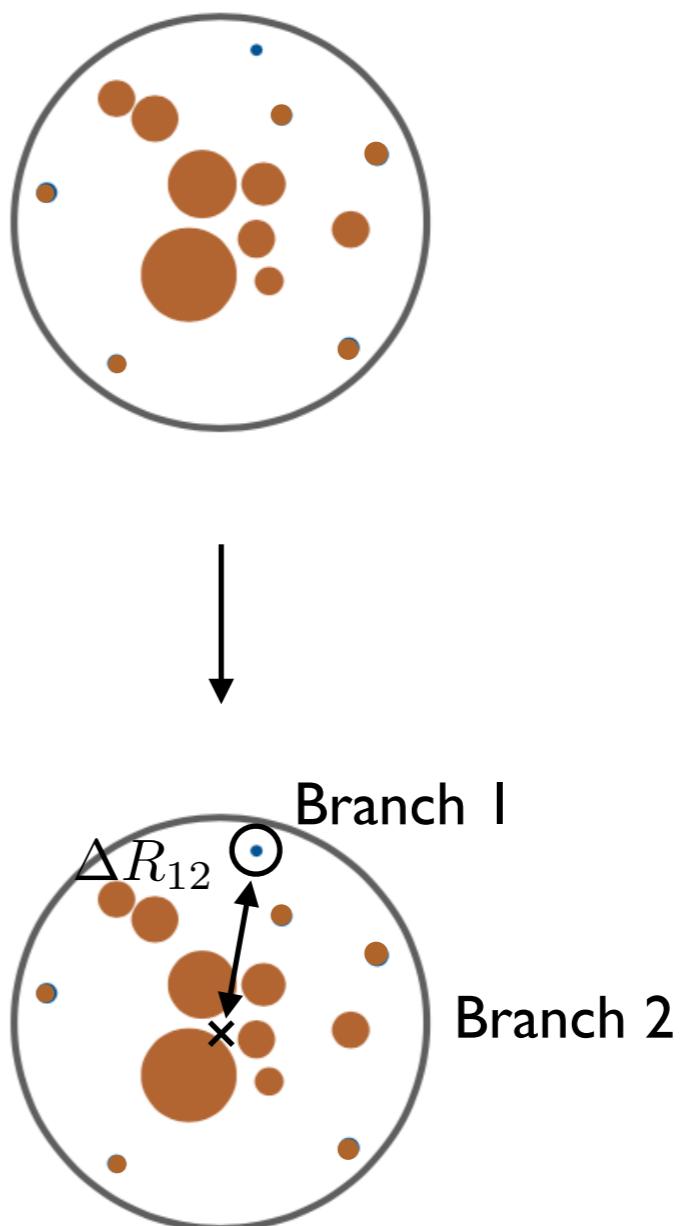
Geometric distance  $\Delta R_{12}^2 = \Delta\eta^2 + \Delta\eta^2$

Soft threshold  $z_{\text{cut}}$

Angular exponent  $\beta$

- See also e.g. trimming, pruning

Krohn, Thaler, Wang '10, Ellis, Vermilion, Walsh '10

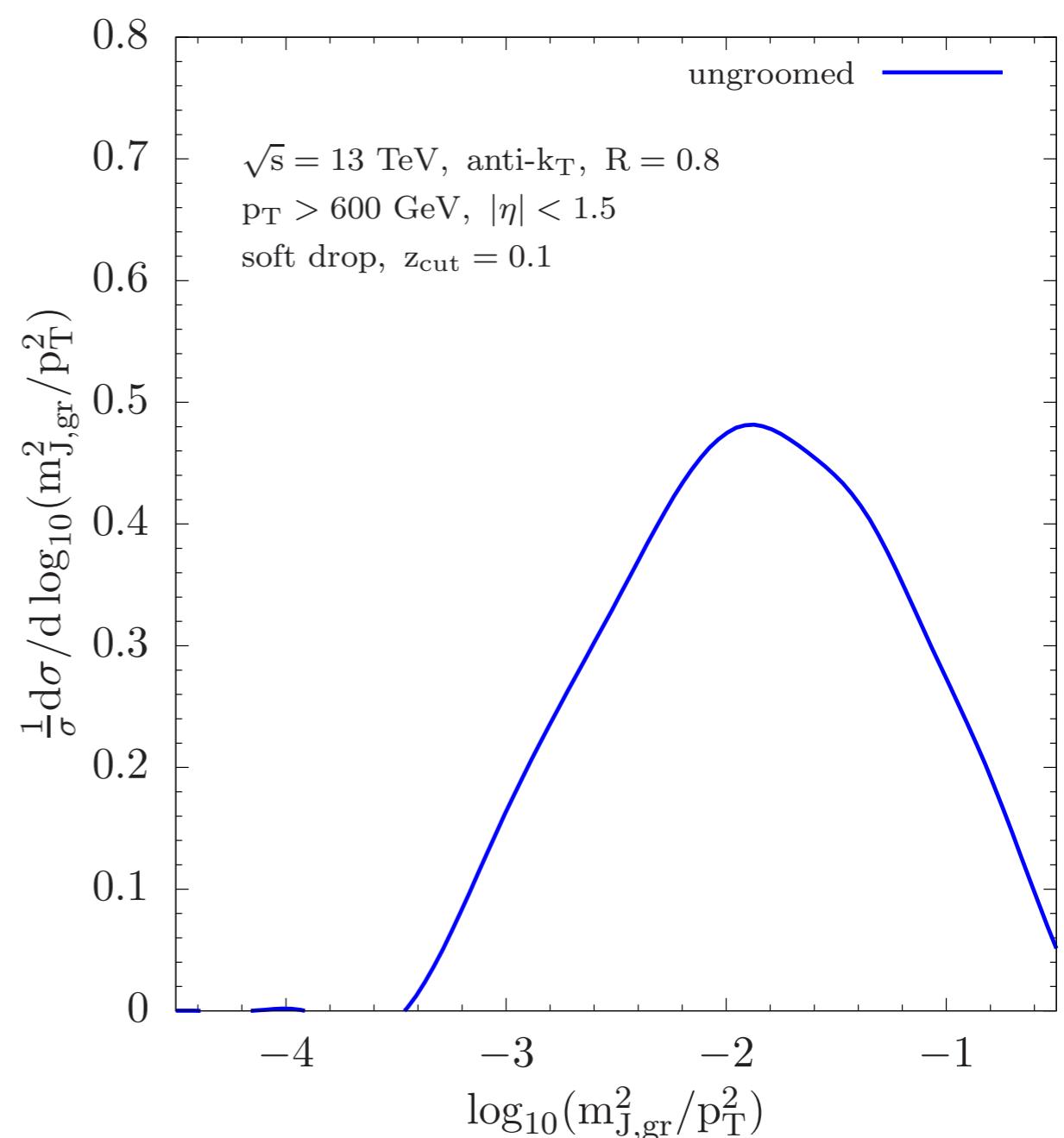
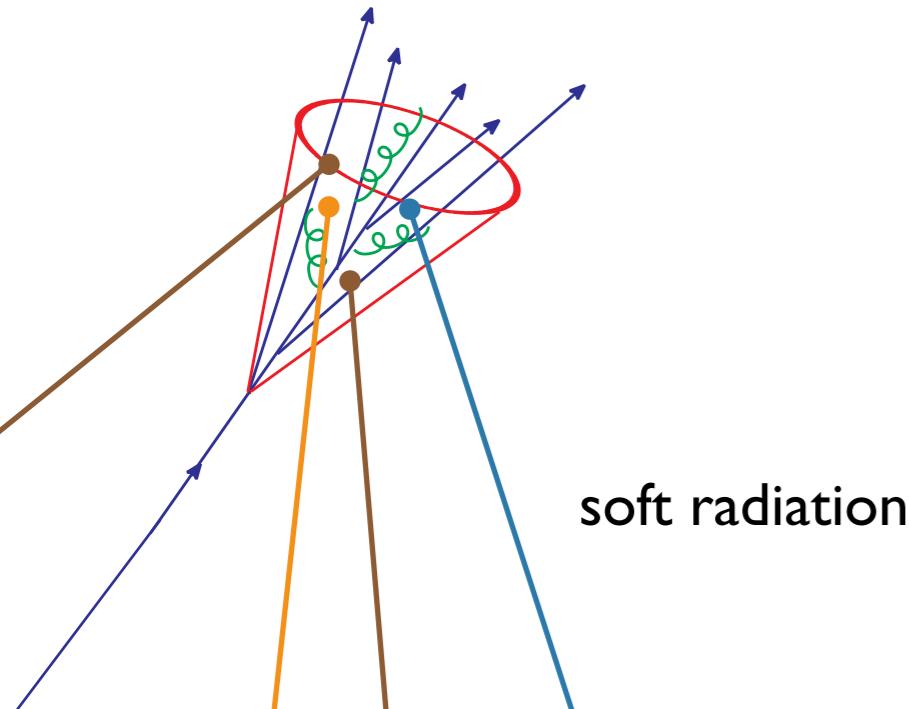


# The soft drop groomed jet mass

- Jet mass  $m_J^2 = \left( \sum_{i \in J} p_i \right)^2$
- Reduced sensitivity to UE, NP, ISR ...  
*Larkoski, Marzani, Soyez, Thaler '14*
- Resummation of logarithms in  $m_J/p_T, R, z_{\text{cut}}$

*Frye, Larkoski, Schwartz, Yan '16  
Marzani, Schunk, Soyez '17  
Kang, Lee, Liu, FR '18*

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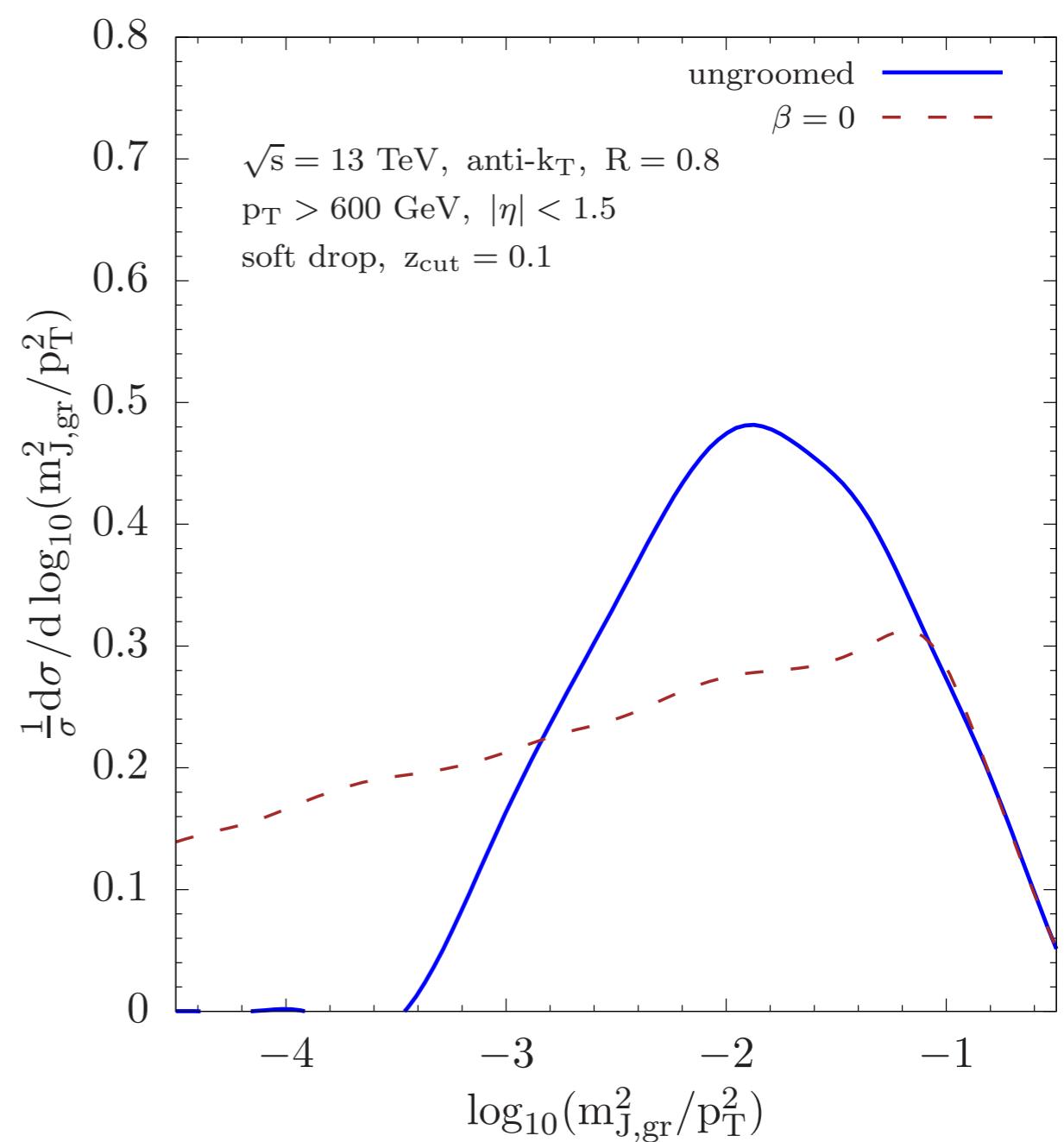
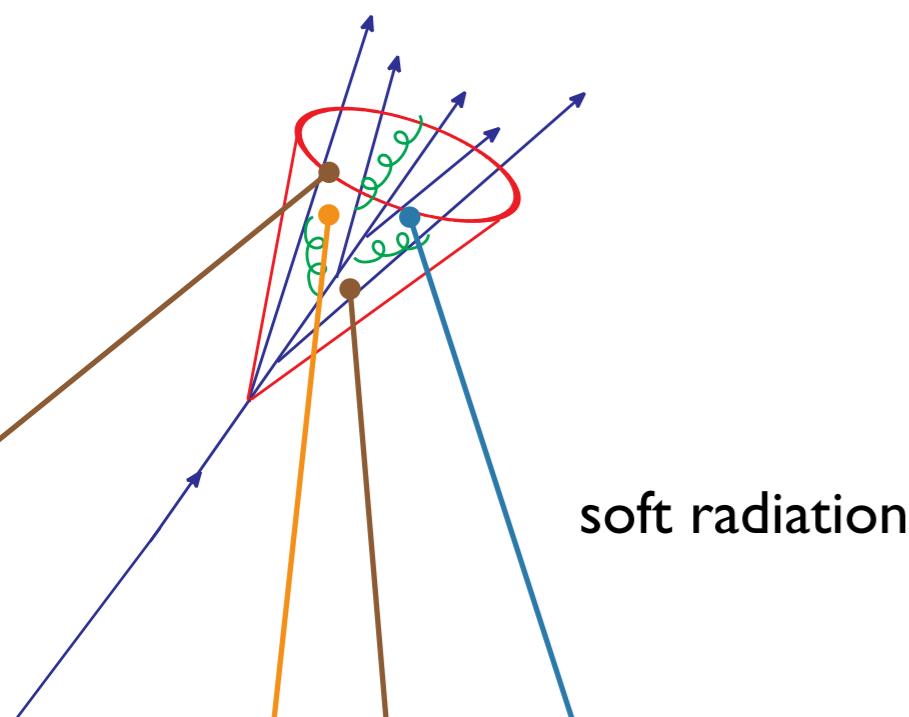


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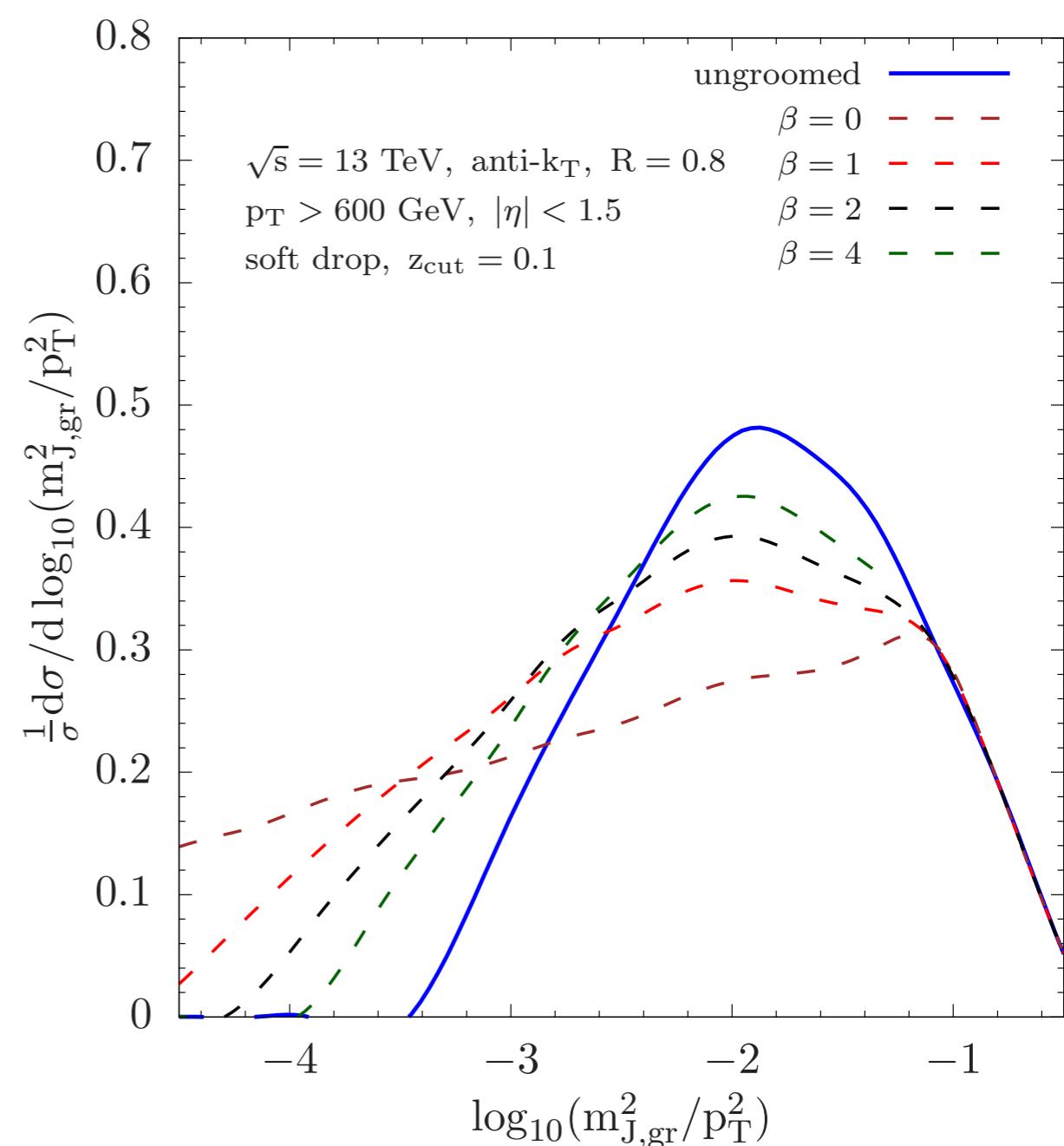
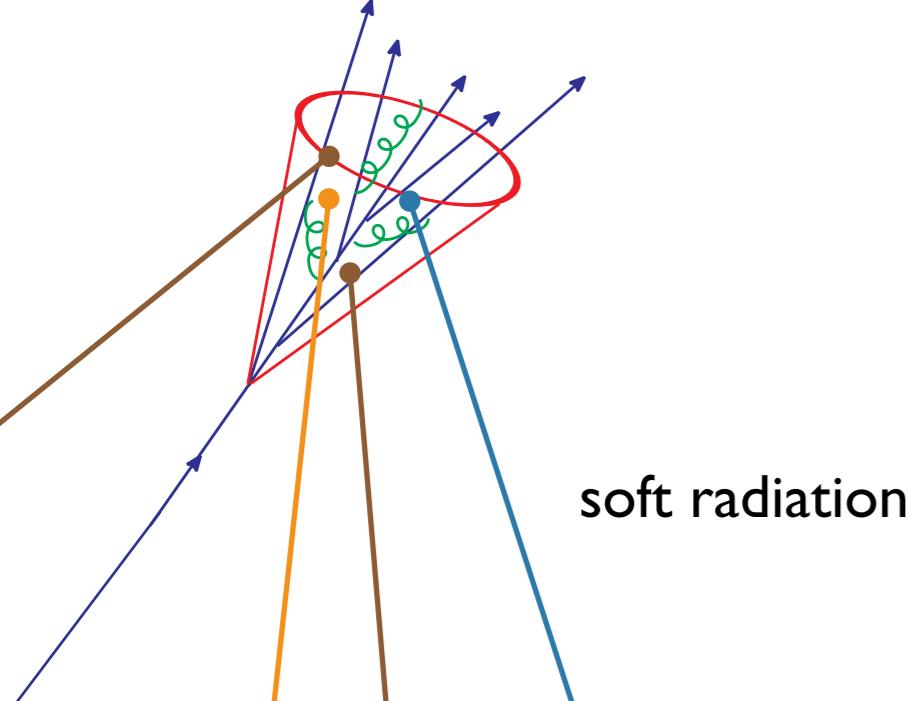
$$\frac{\min[p_{T1}, p_{T2}]}{p_{T1} + p_{T2}} > z_{\text{cut}} \left( \frac{\Delta R_{12}}{R} \right)^\beta$$



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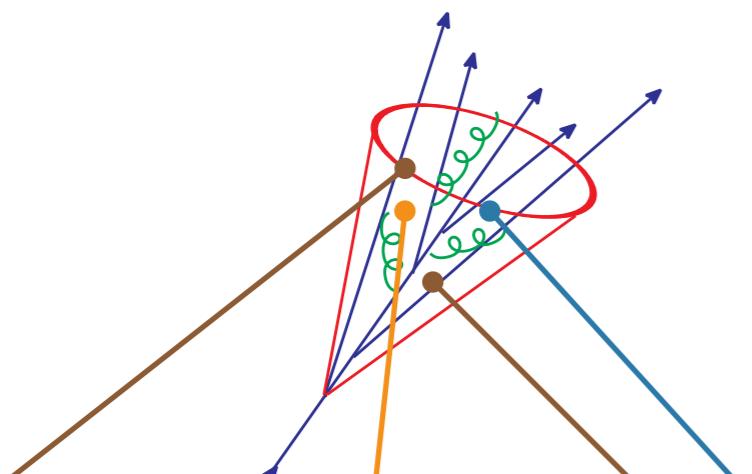
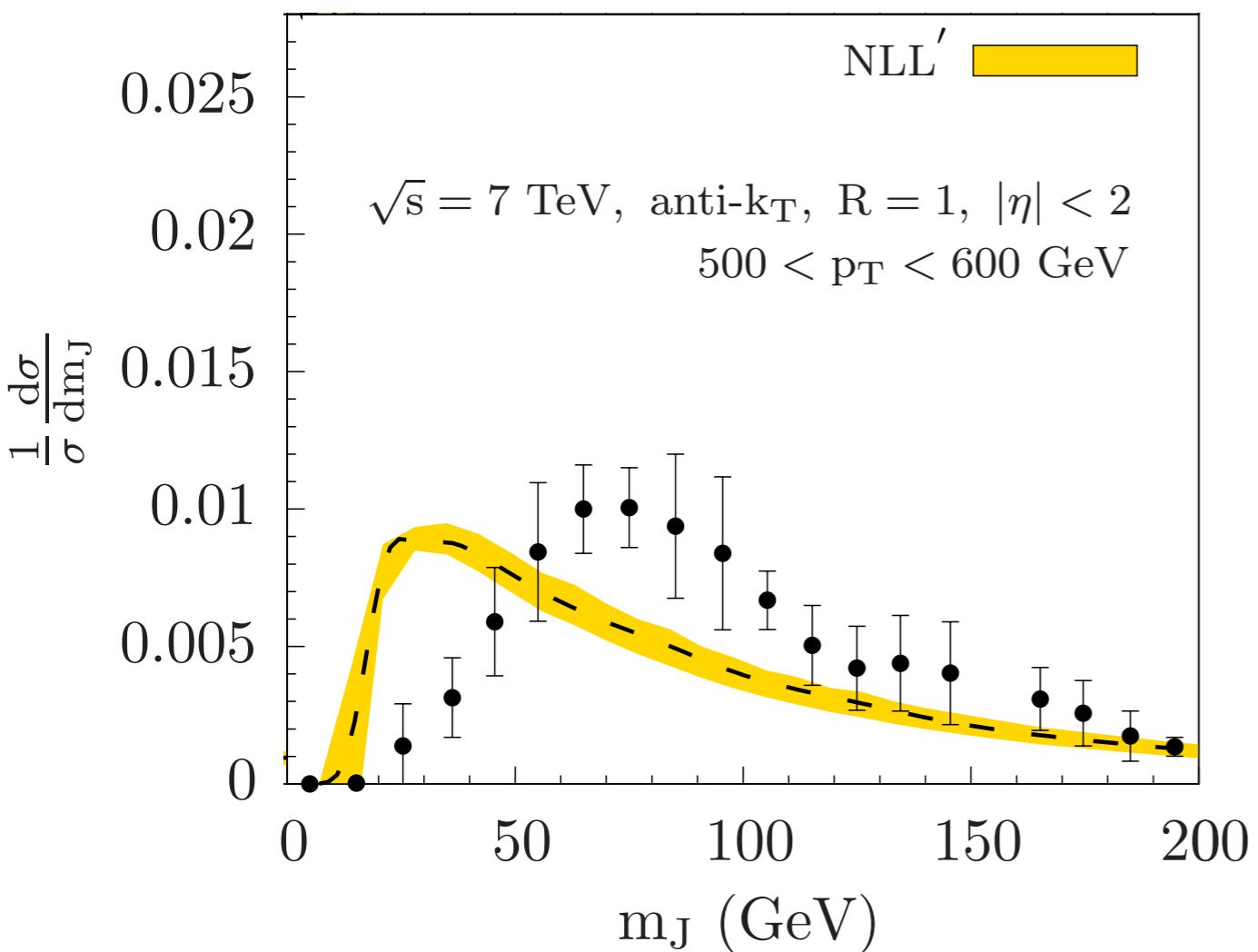
$$\frac{\min[p_{T1}, p_{T2}]}{p_{T1} + p_{T2}} > z_{\text{cut}} \left( \frac{\Delta R_{12}}{R} \right)^\beta$$



# Jet mass distributions

Kang, Lee, Liu, FR '18

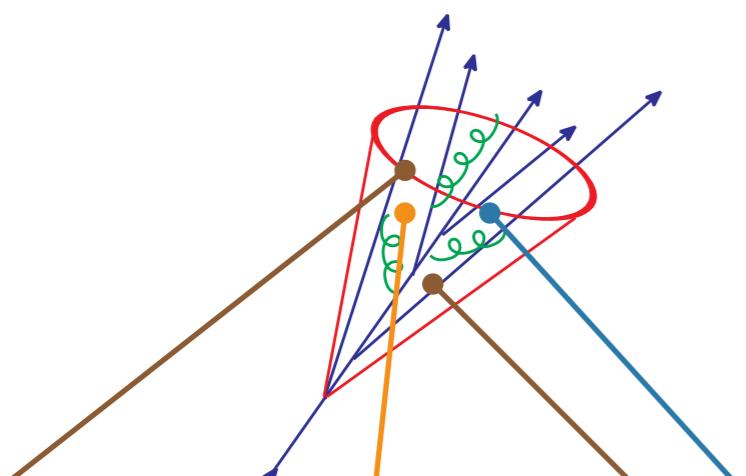
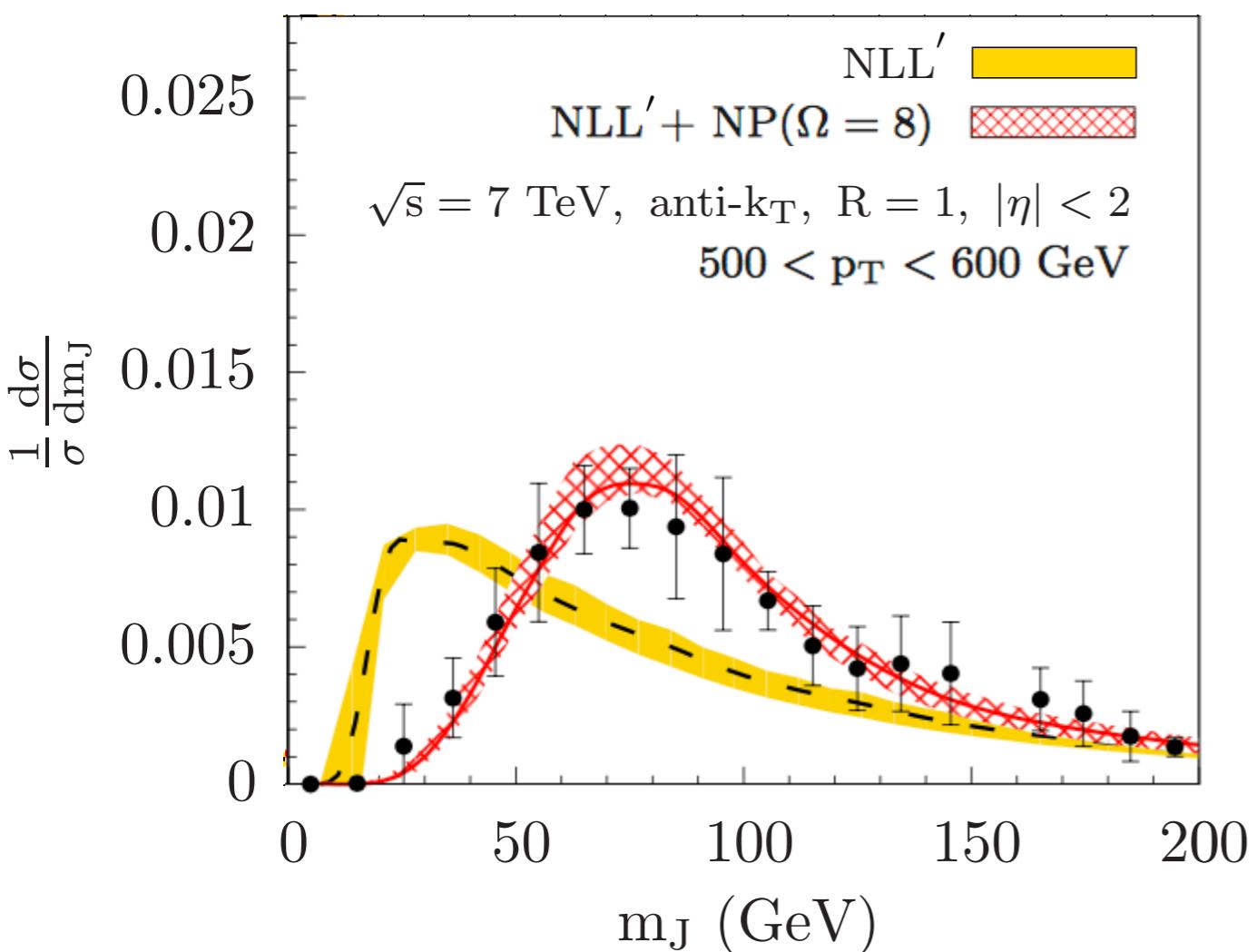
ATLAS, JHEP 05 (2012) 128

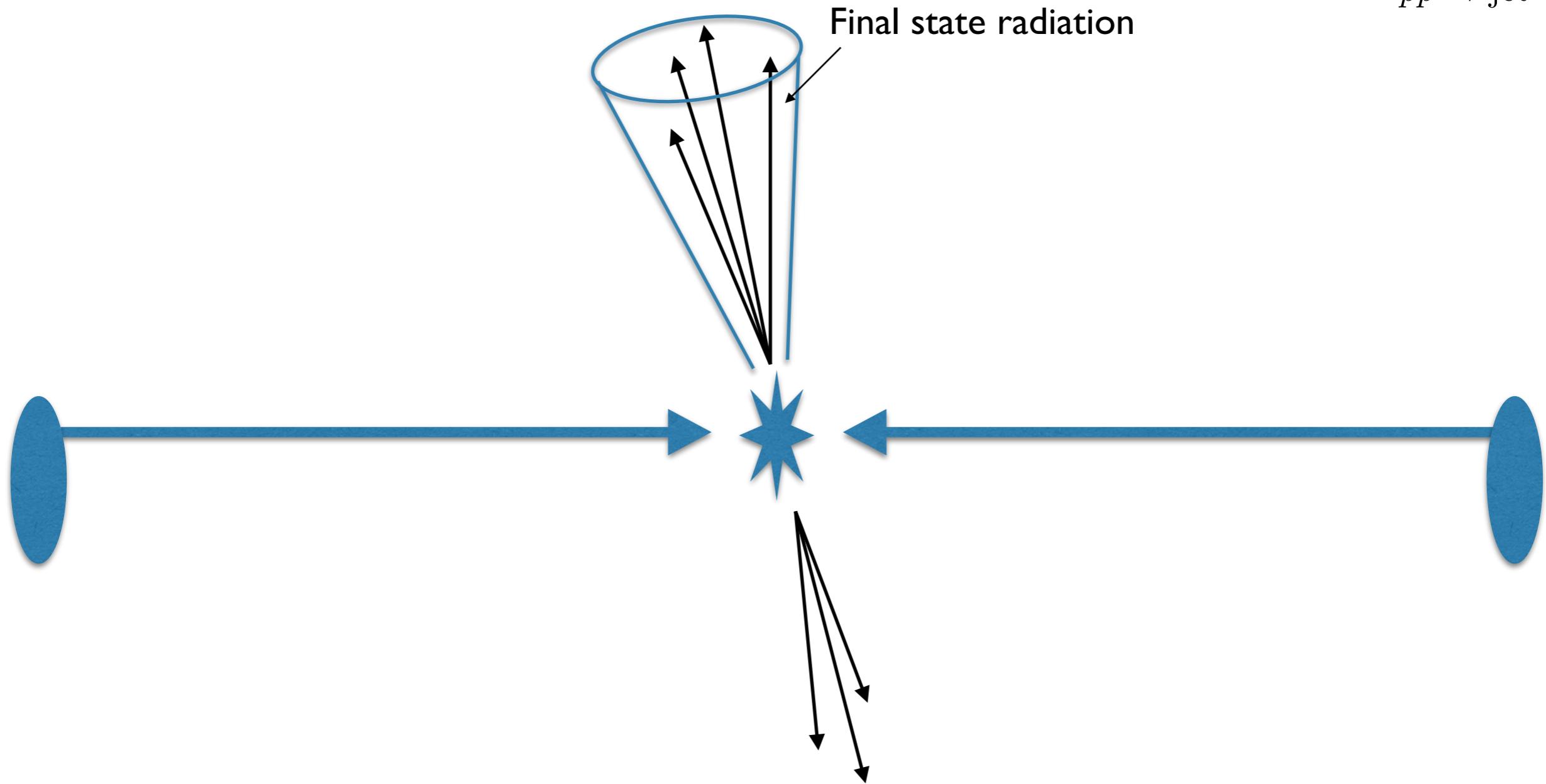


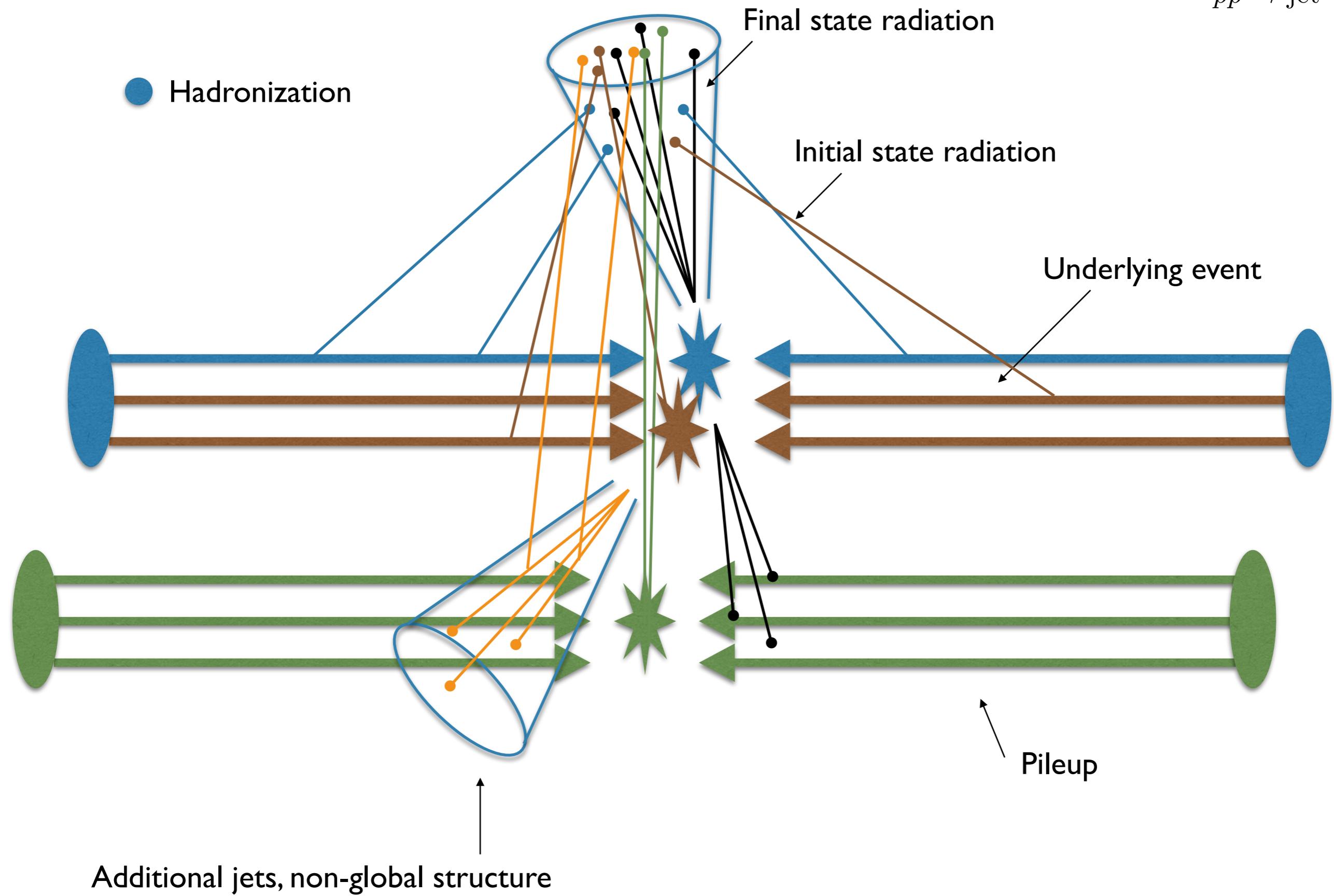
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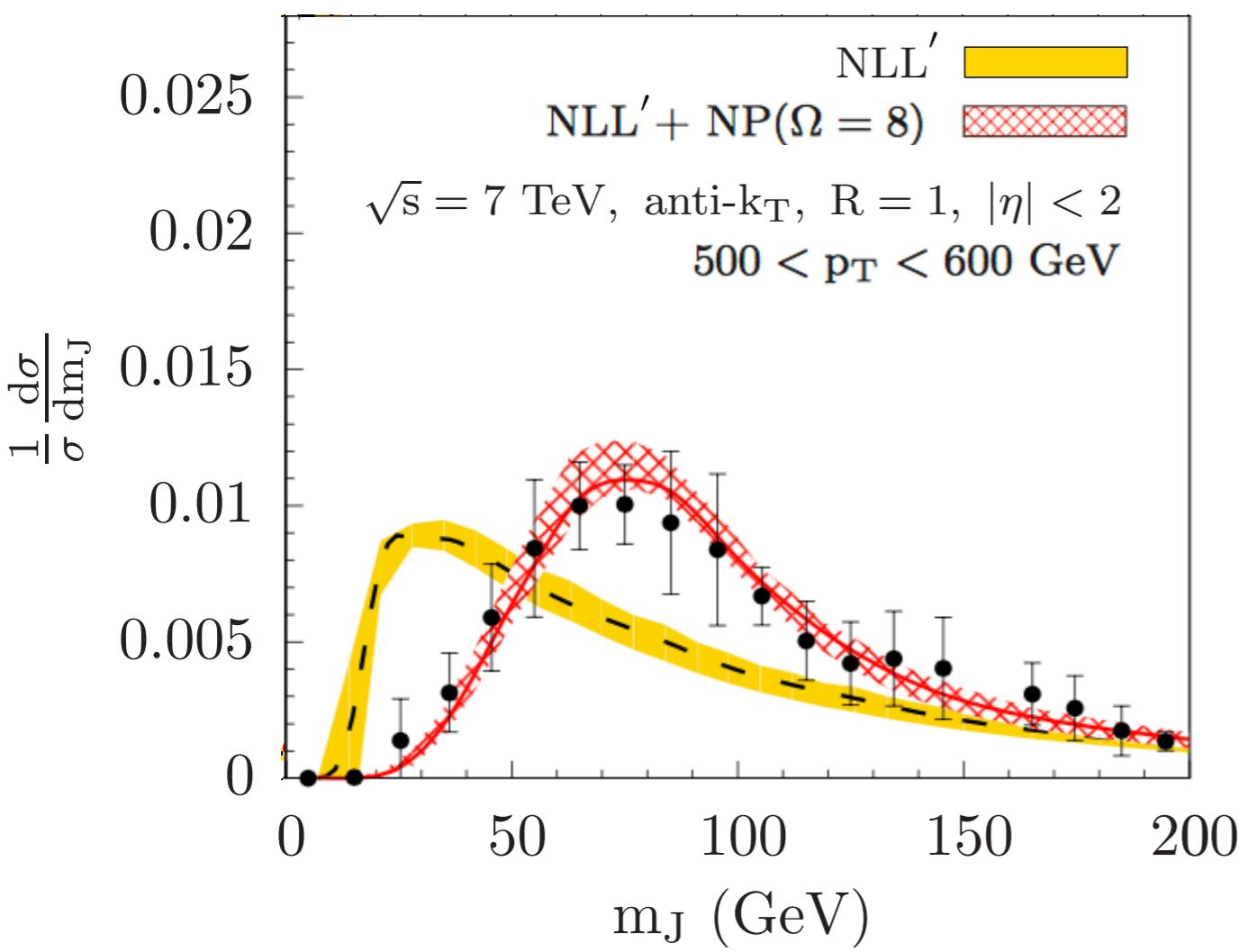
$pp \rightarrow \text{jet} + X$ 

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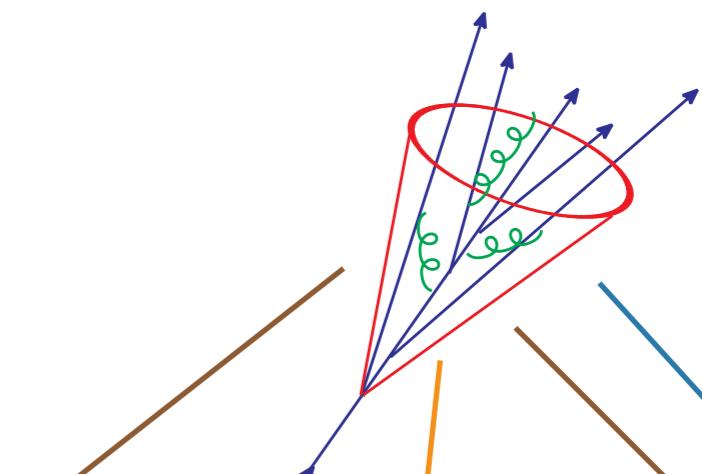
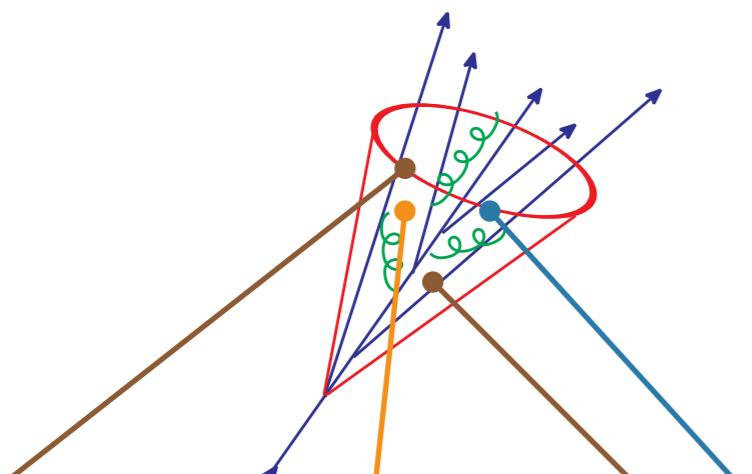
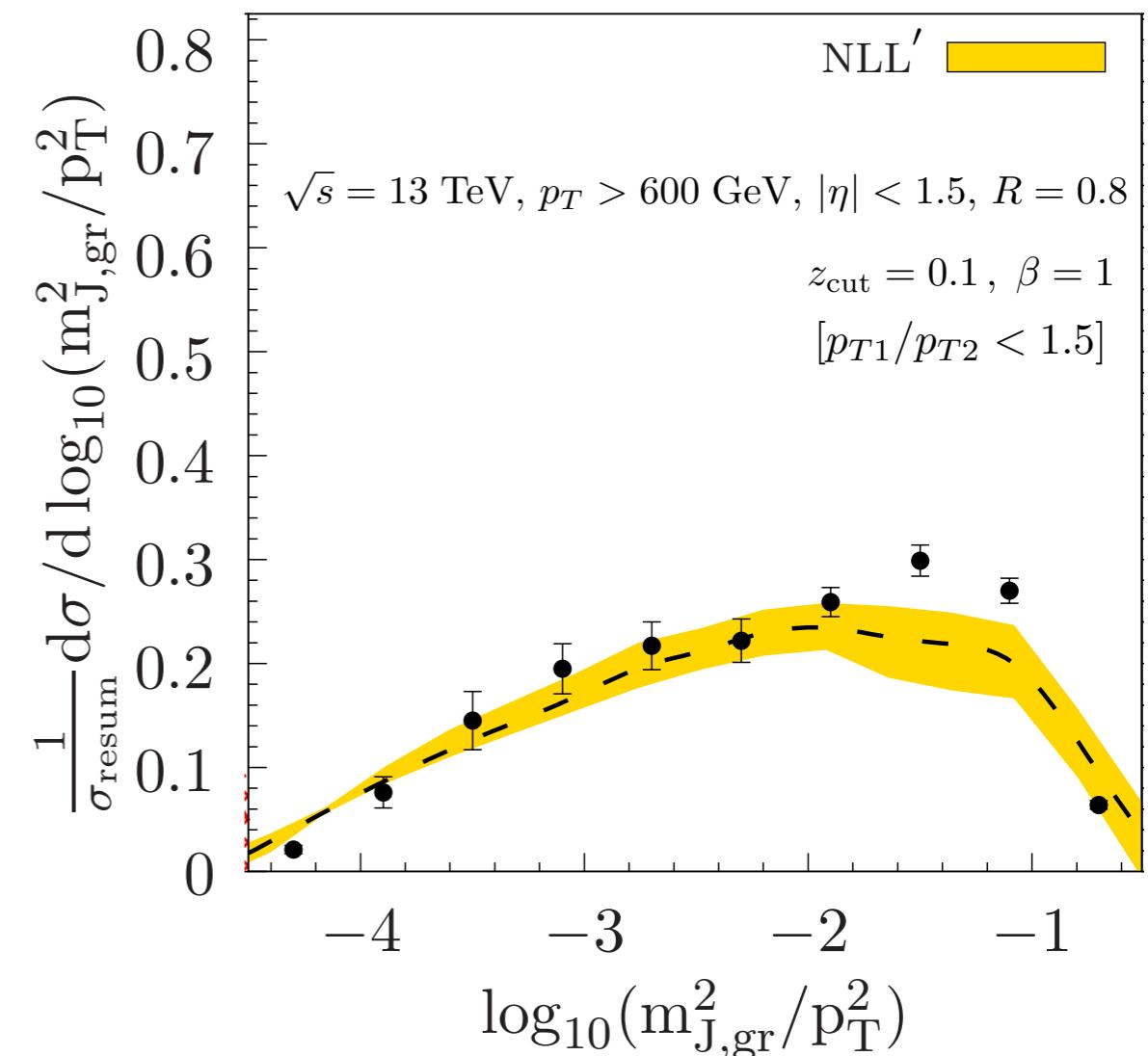
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ATLAS, JHEP 05 (2012) 128



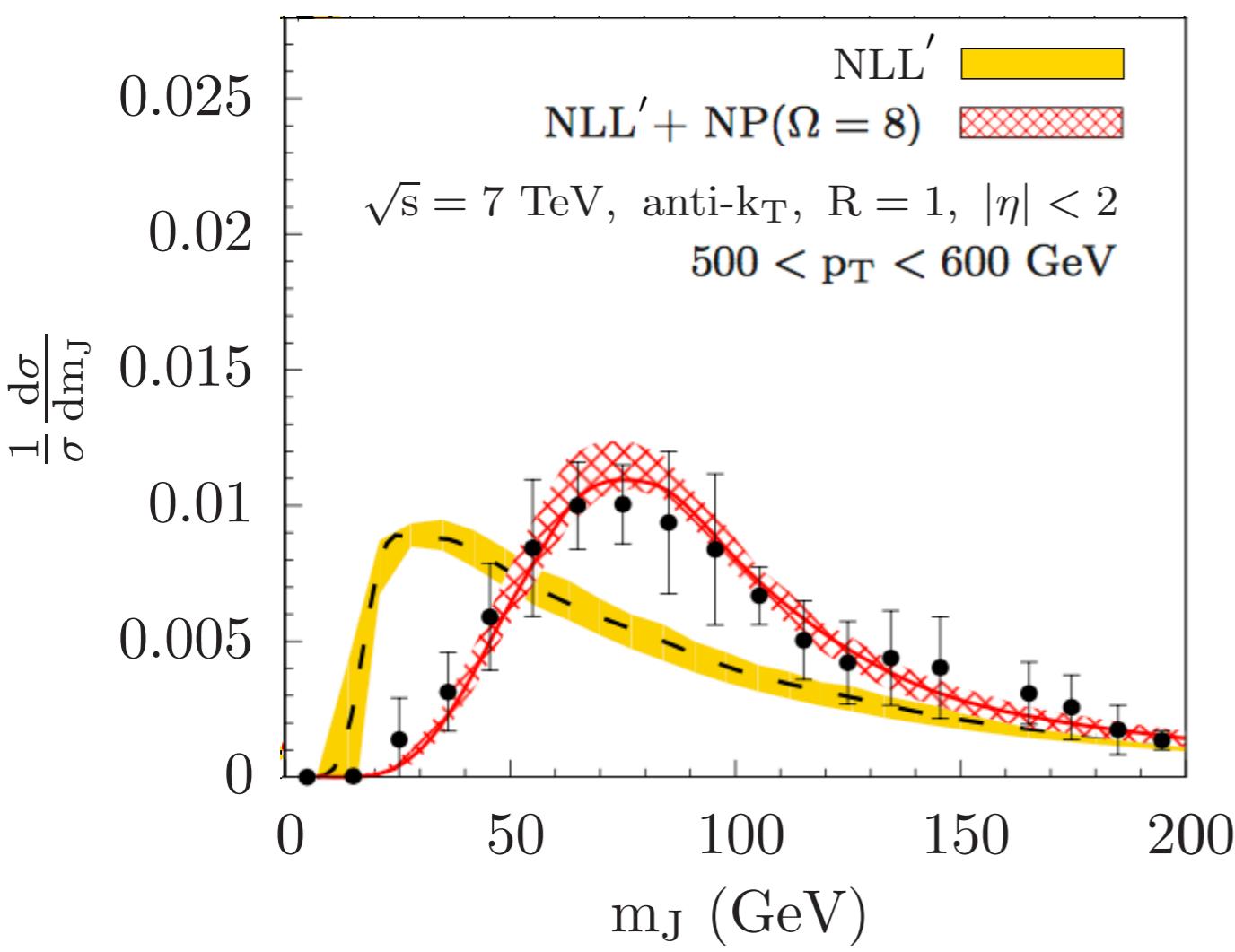
ATLAS, PRL 121 (2018) 092001



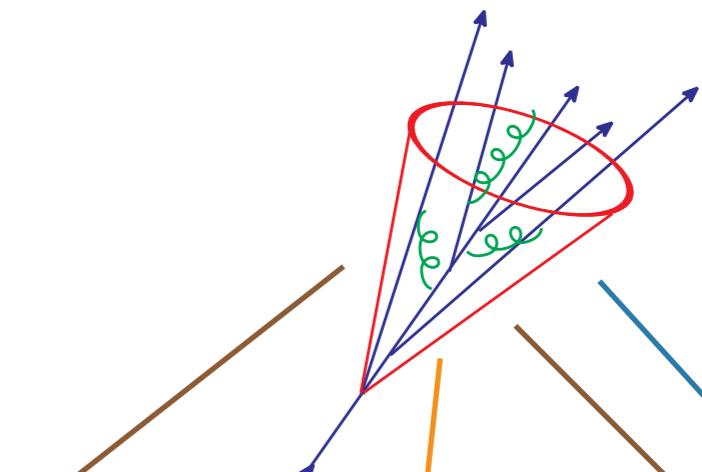
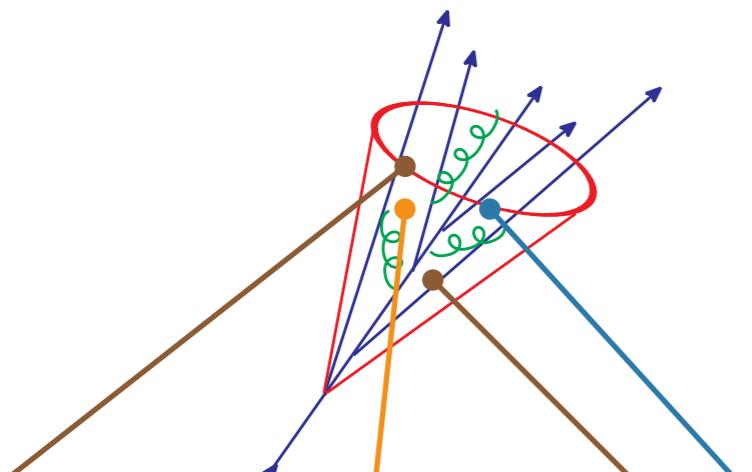
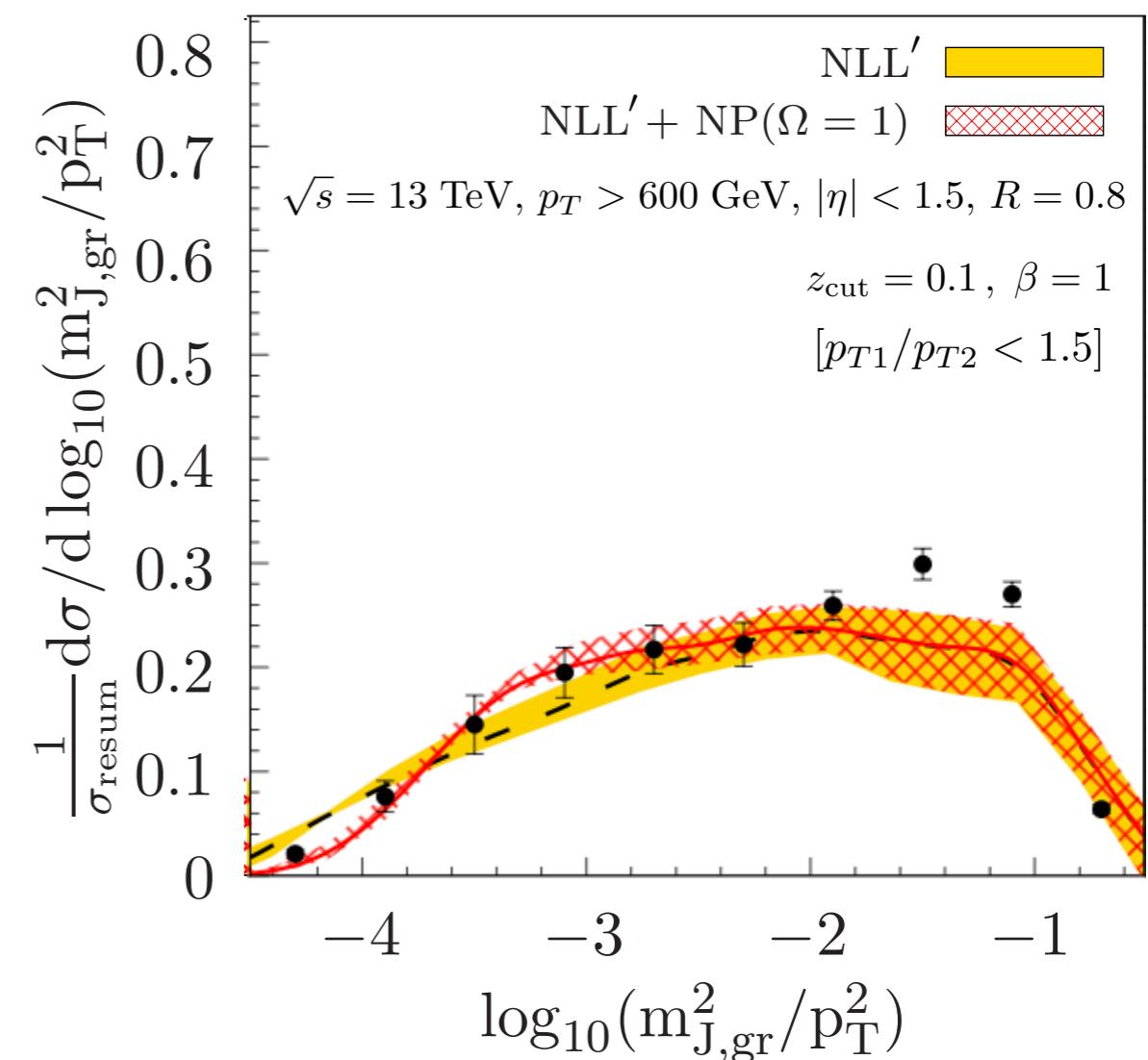
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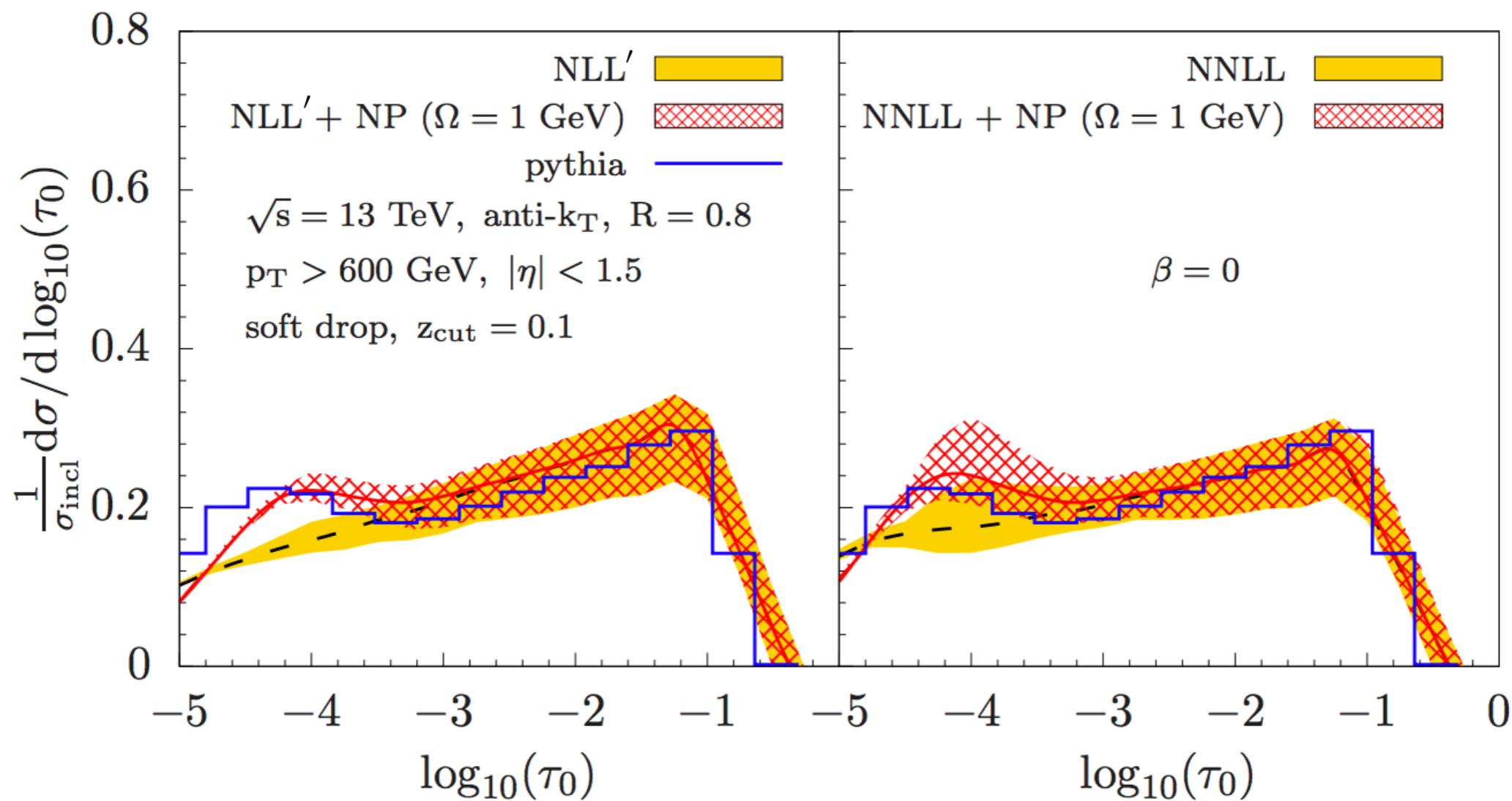
ATLAS, PRL 121 (2018) 092001



# Jet mass distributions

Kang, Lee, Liu, FR '18

- Resummation of 3 classes of logarithms  $\alpha_s^n \ln^n R, \alpha_s^n \ln^{2n}(m_J/p_T), \alpha_s^n \ln^{2n} z_{\text{cut}}$



- Non-perturbative shape functions with grooming

see: Hoang, Mantry, Pathak, Stewart - BOOST18

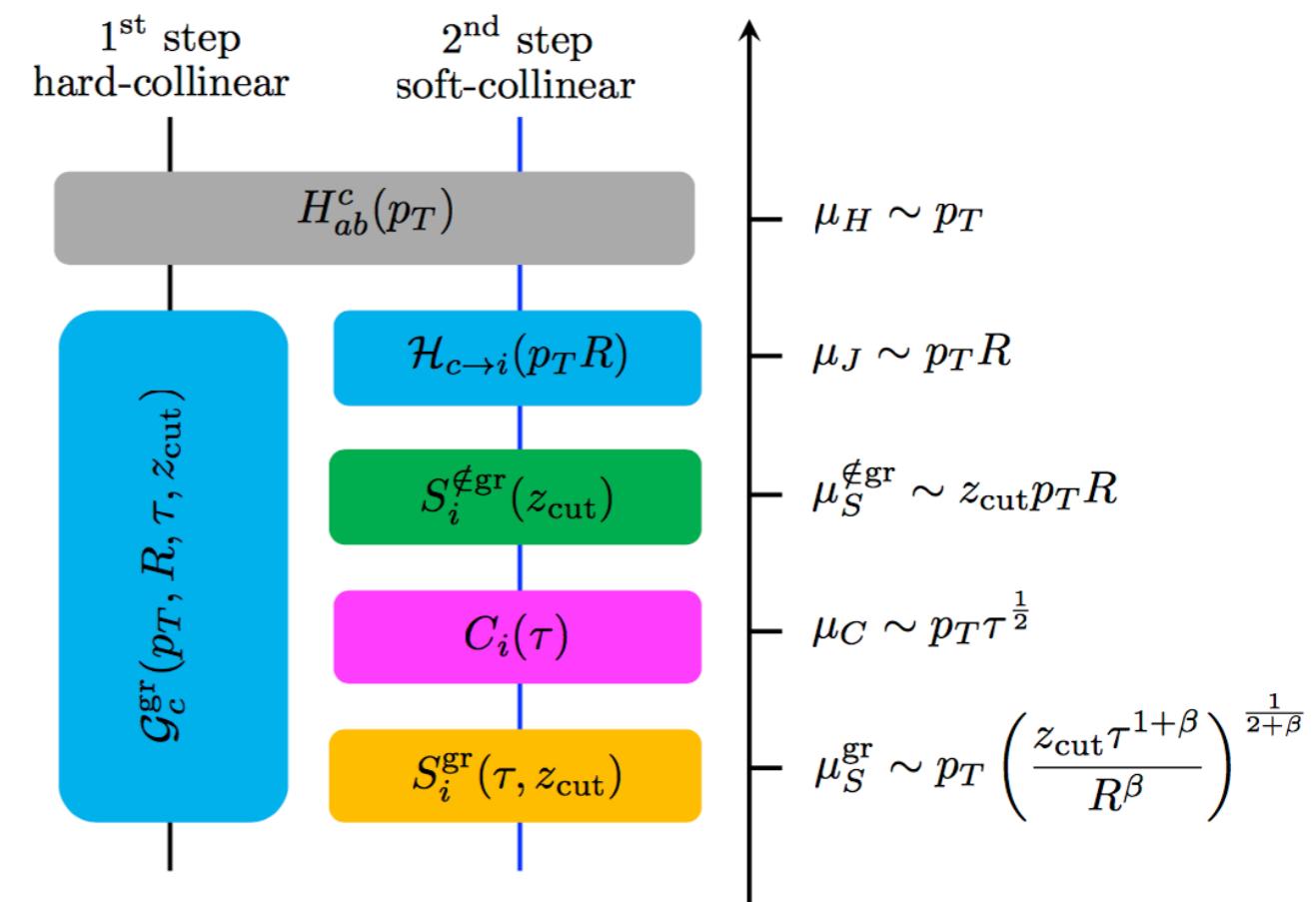
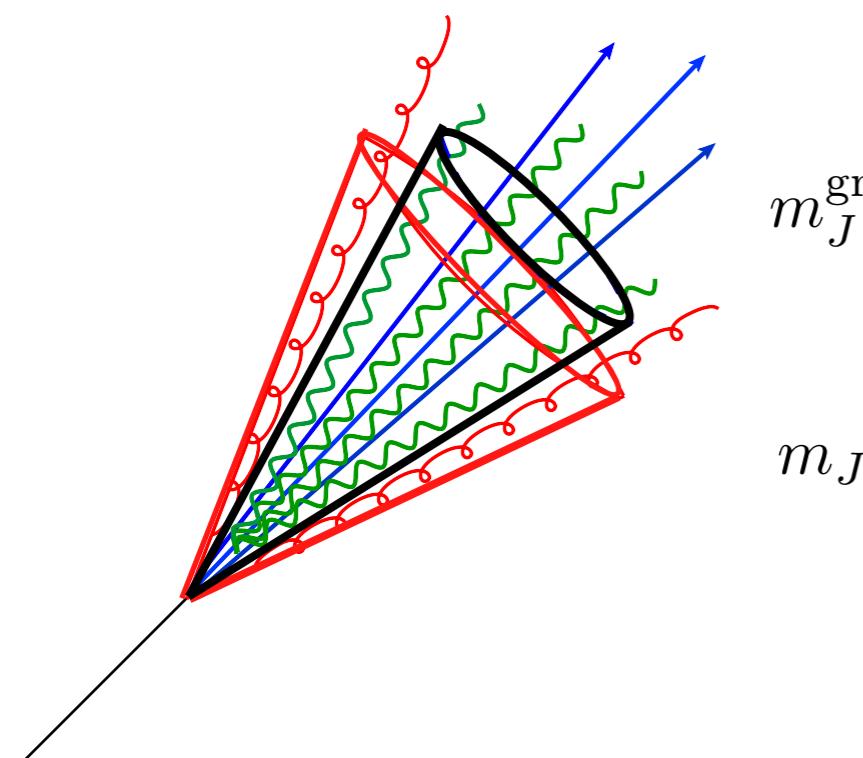
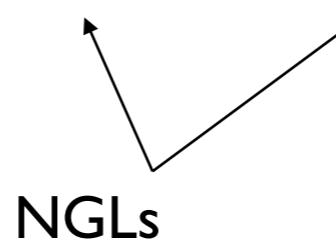
$$\tau_0 = m_J^2/p_T^2$$

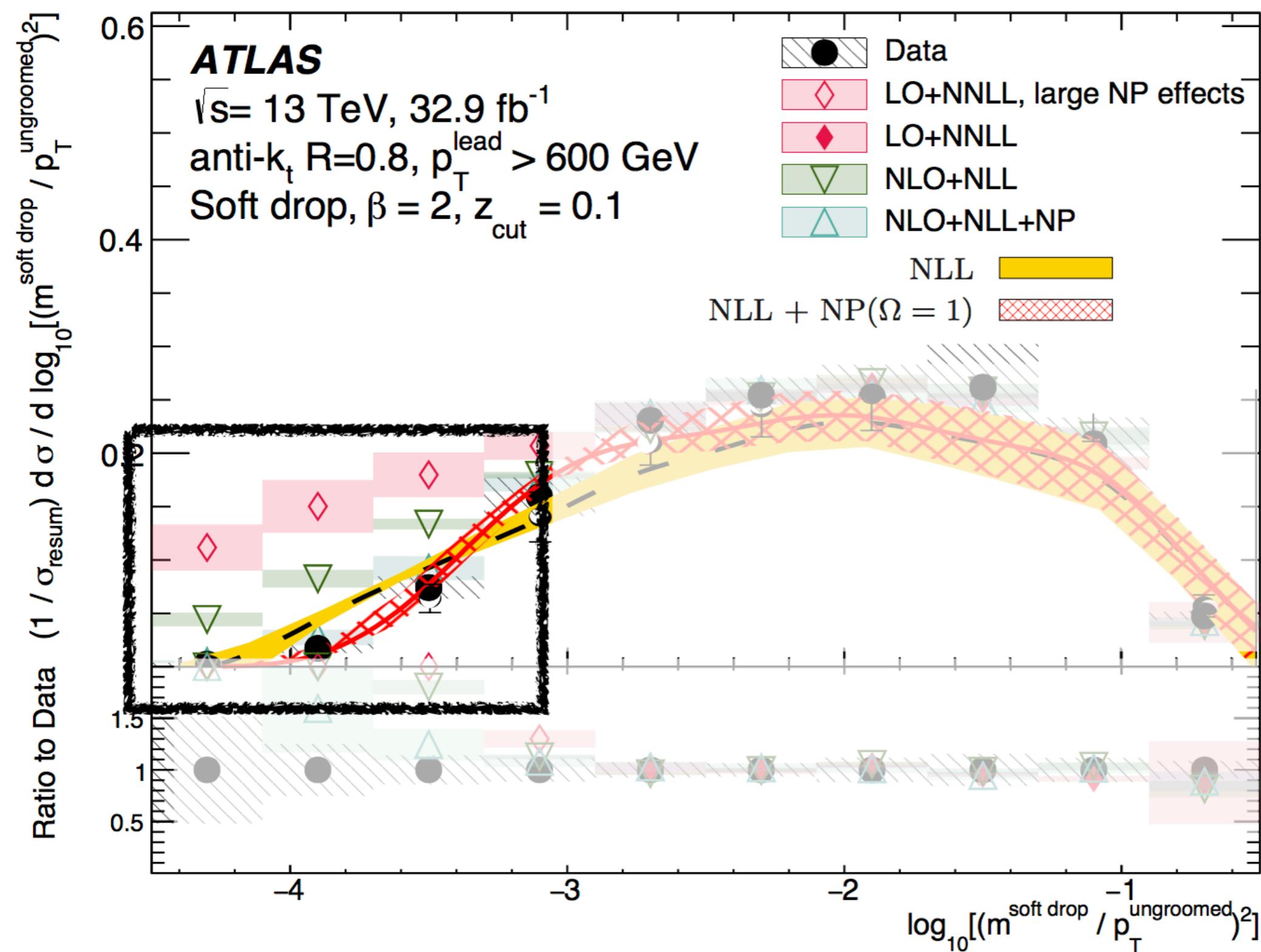
# Jet mass distributions

Kang, Lee, Liu, FR '18

- The groomed case  $R \ll 1, \tau_{\text{gr}}/R^2 \ll z_{\text{cut}} \ll 1$

$$\mathcal{G}_i^{\text{gr}}(z, p_T R, \tau_{\text{gr}}, z_{\text{cut}}, \mu) = \sum_j \mathcal{H}_{i \rightarrow j}(z, p_T R, \mu) S_i^{\notin \text{gr}}(z_{\text{cut}} p_T R, \beta, \mu) C_i(\tau_{\text{gr}}, p_T, \mu) \otimes S_i^{\text{gr}}(\tau_{\text{gr}}, p_T, R, z_{\text{cut}}, \mu)$$





Frye, Larkoski, Schwartz, Yan '16  
 Marzani, Schunk, Soyez '17  
 Kang, Lee, Liu, FR '18

ATLAS, PRL 121 (2018) 092001

A lot of important progress but still work to do!

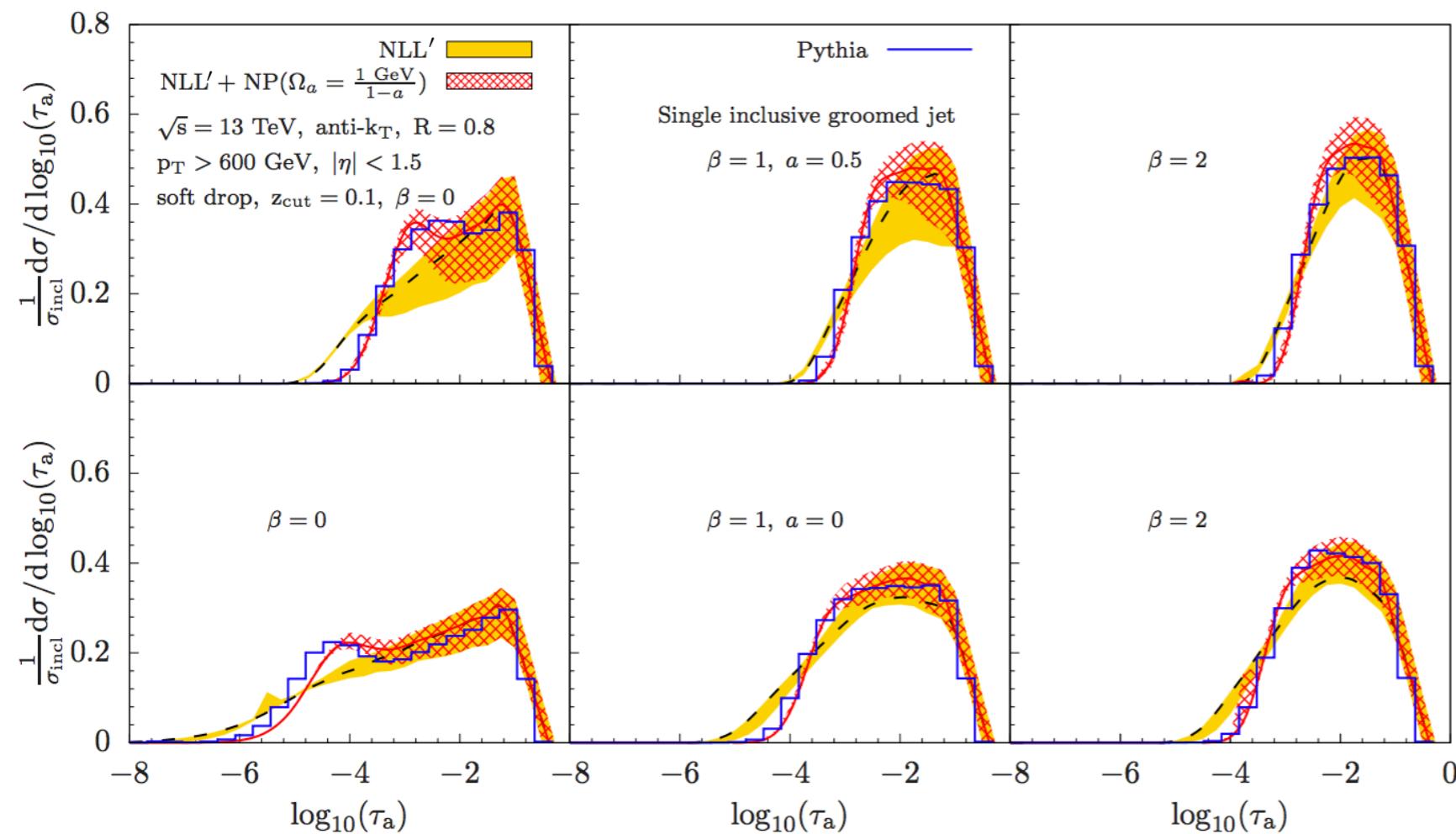
Ben Nachman, BOOST18

# Soft drop groomed jet angularities

Berger, Kucs, Sterman '03  
 Kang, Lee, Liu, FR - in preparation

- Family of observables with a continuous parameter  $a$
- Jet mass ( $a = 0$ ), jet broadening ( $a = 1$ )

$$\tau_a = \frac{1}{p_T} \sum_{i \in J} p_{Ti} \Delta R_{iJ}^{2-a}$$



# The soft drop groomed jet radius

Larkoski, Marzani, Soyez, Thaler '14

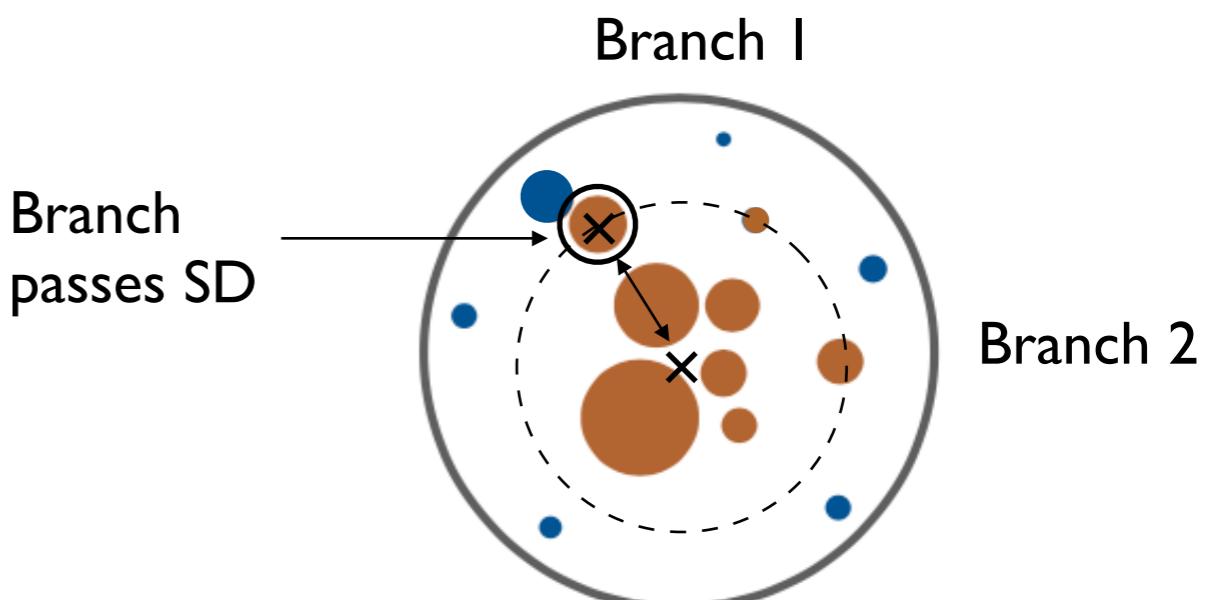
- Groomed radius

$$\theta_g = \frac{\Delta R_{12}}{R} = \frac{R_g}{R}$$

$$\frac{\min[p_{T1}, p_{T2}]}{p_{T1} + p_{T2}} > z_{\text{cut}} \left( \frac{\Delta R_{12}}{R} \right)^\beta$$

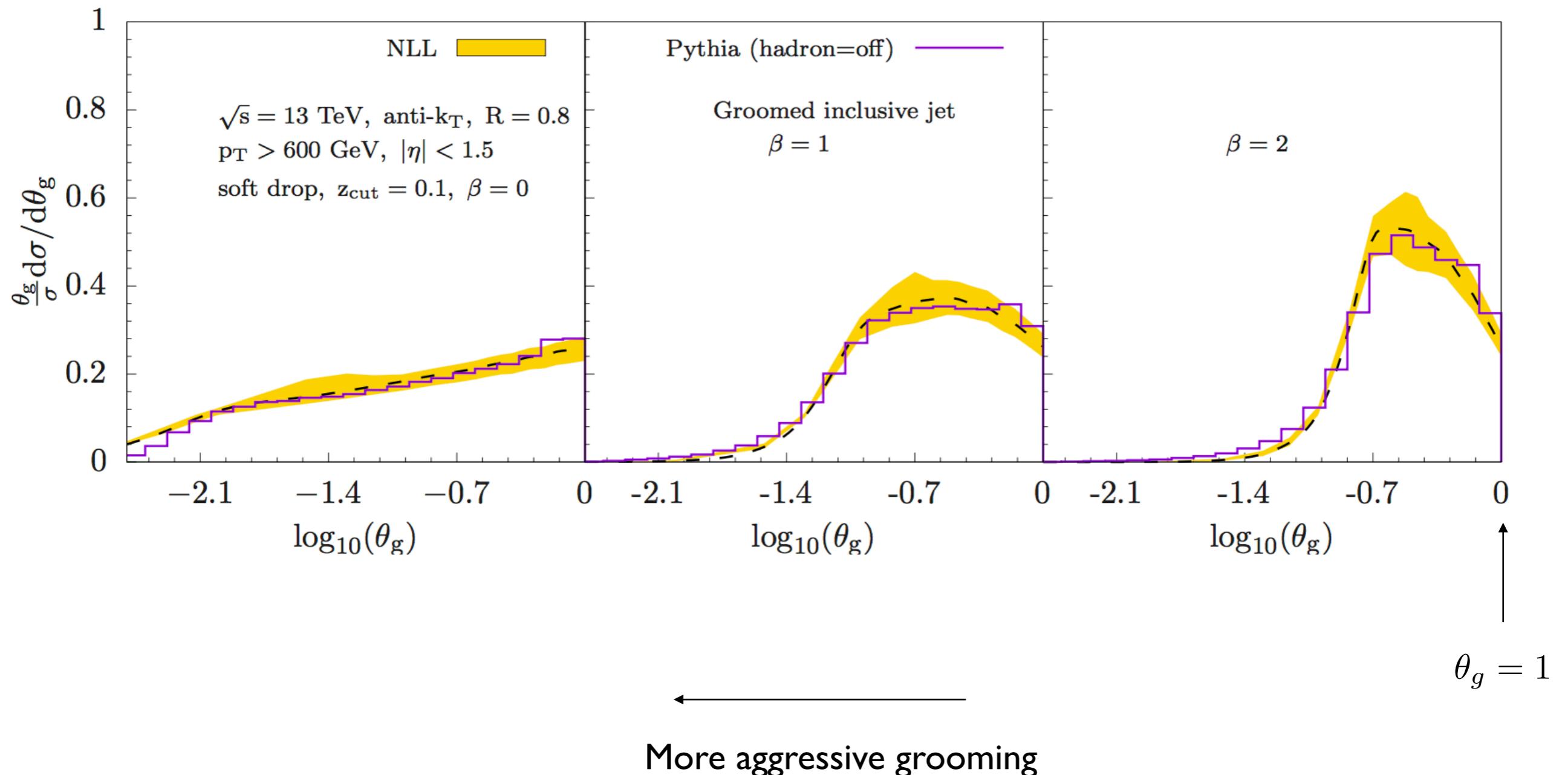
$$\Delta R_{12} = R_g = \sqrt{\Delta\phi^2 + \Delta\eta^2}$$

- Key observable to characterize SD groomed jet
- Related to the active area of the groomed jet  $\sim \pi R_g^2$
- Used to calculate Sudakov safe observables such as  $\Delta_{p_T}$ ,  $z_g$



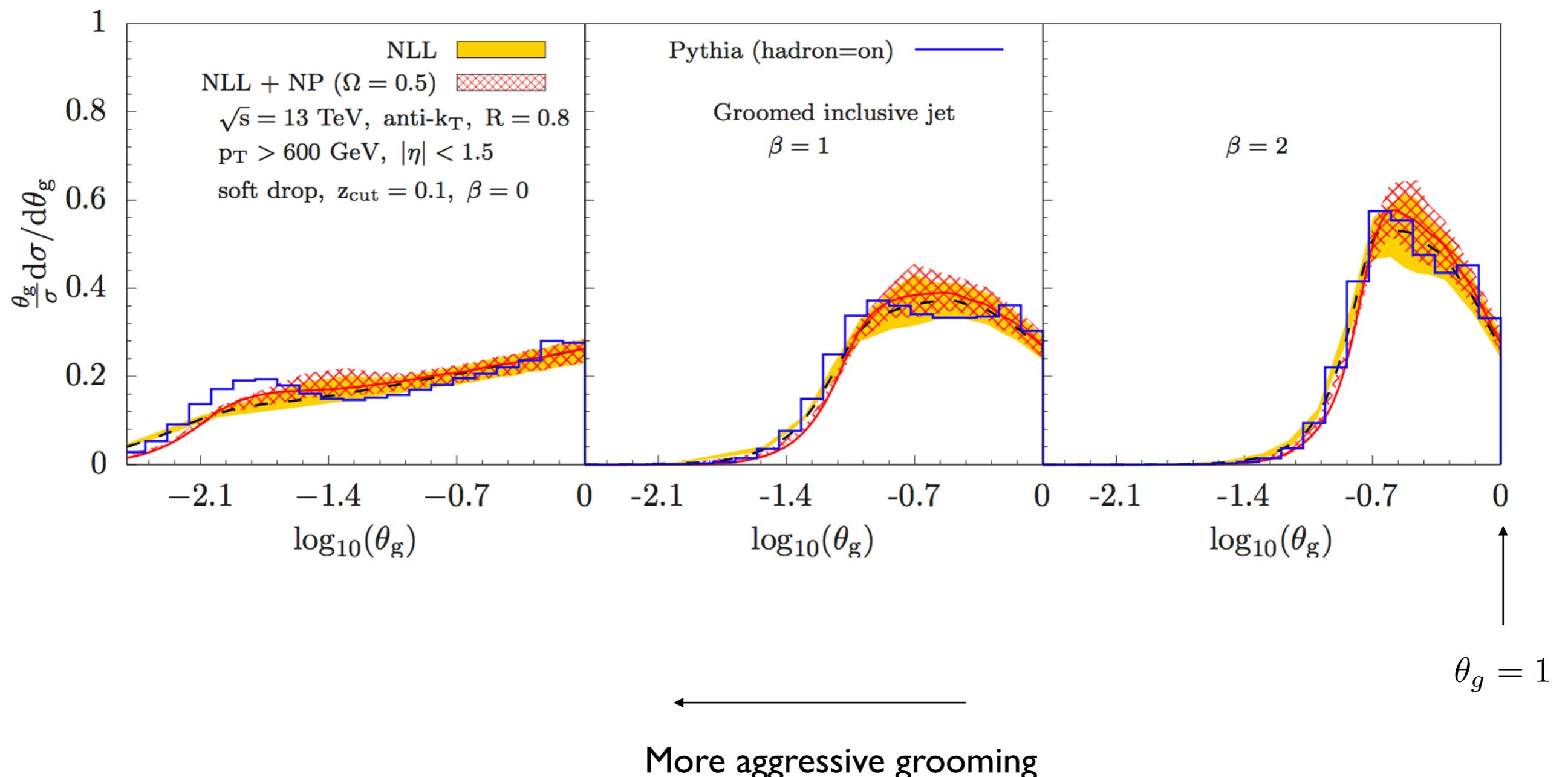
# The soft drop groomed jet radius

Kang, Lee, Liu, FR  
*- in preparation*



# The soft drop groomed jet radius

Kang, Lee, Liu, FR  
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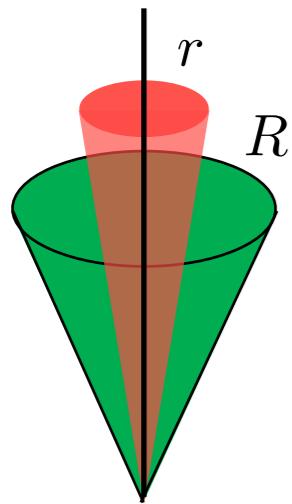


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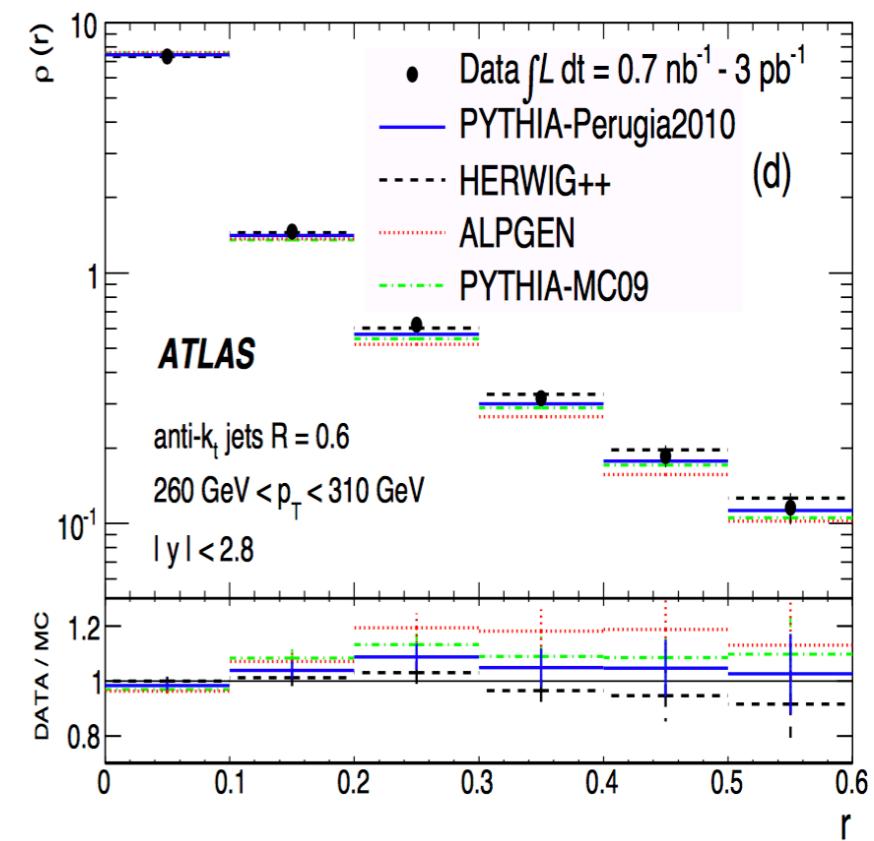
# The transverse profile of jets

- Jet energy profile *ATLAS, Phys.Rev.D 83 (2011) 052003*



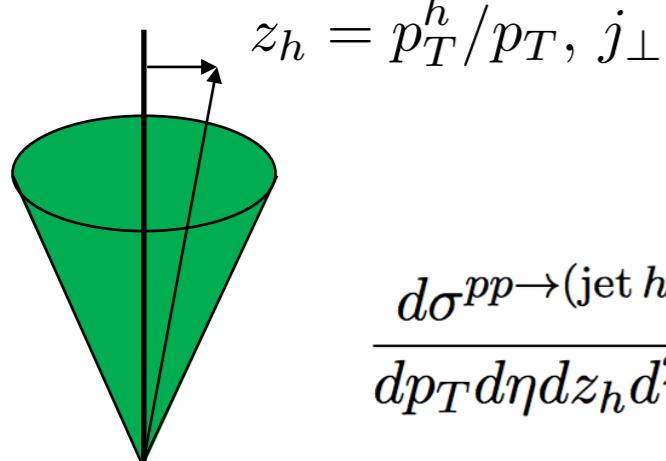
$$\psi(r) = \frac{\sum_{\Delta R_{iJ} < r} p_{Ti}}{\sum_{\Delta R_{iJ} < R} p_{Ti}}$$

$$\rho(r) = \frac{d\psi(r)}{dr}$$

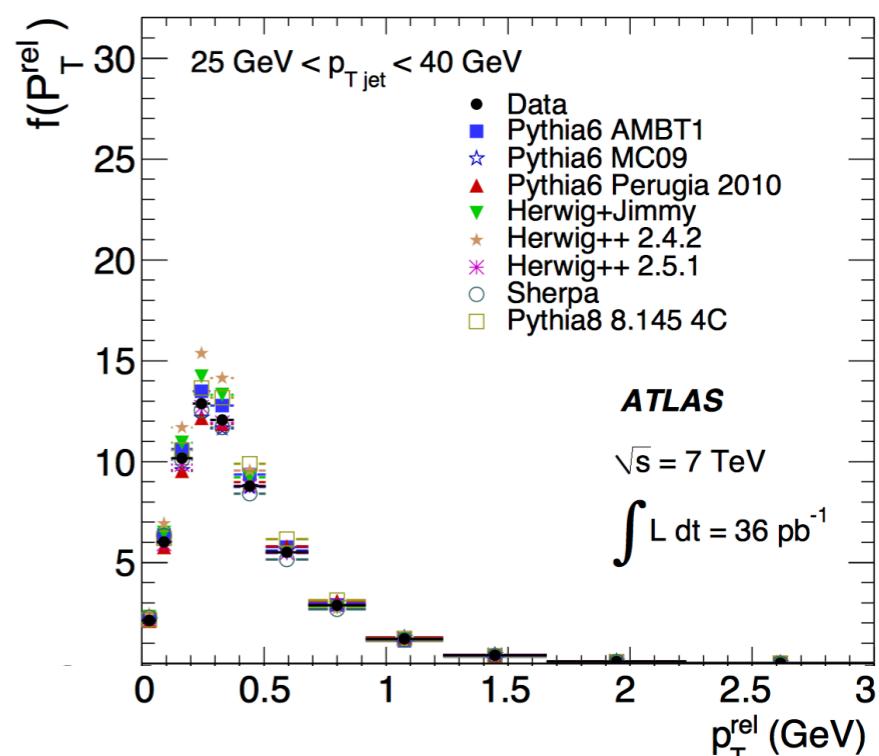


- Transverse momentum distribution (TMDFFs)

*ATLAS, Eur.Phys.J.C. 71 (2011) 1795*

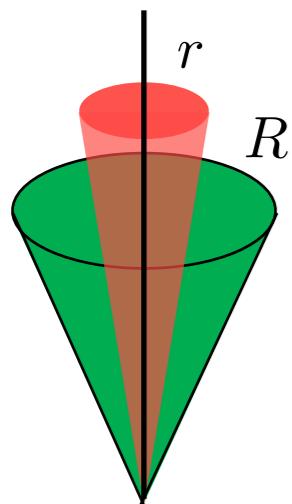


$$\frac{d\sigma^{pp \rightarrow (\text{jet } h)X}}{dp_T d\eta dz_h d^2 j_\perp} \Bigg/ \frac{d\sigma^{pp \rightarrow \text{jet } X}}{dp_T d\eta}$$



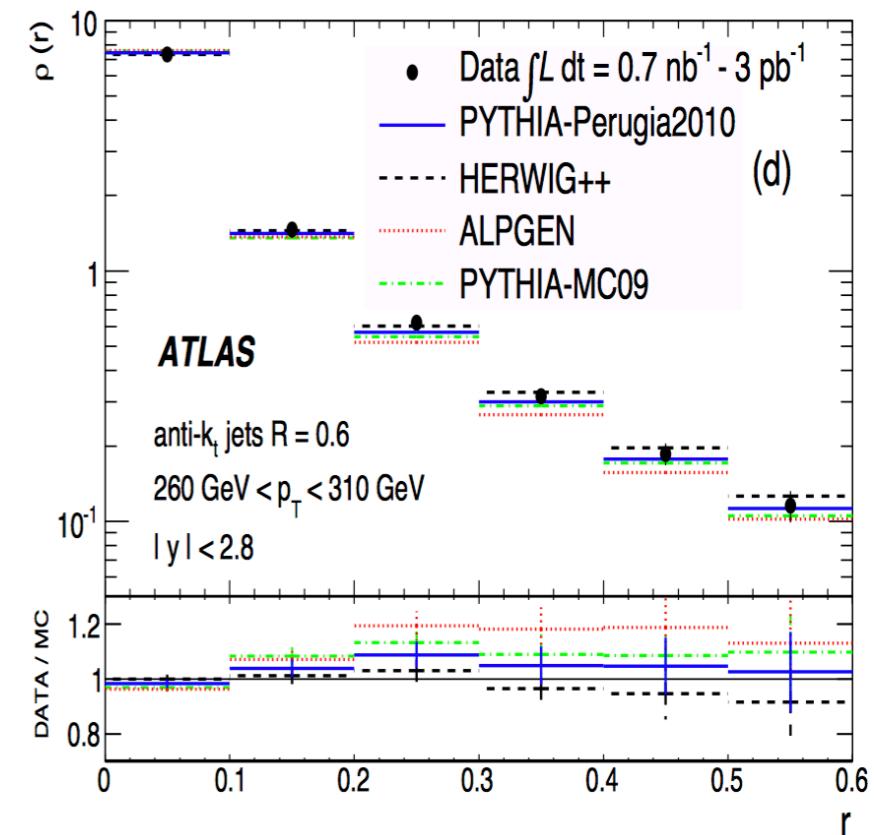
# The transverse profile of jets

- Jet energy profile *ATLAS, Phys.Rev.D 83 (2011) 052003*

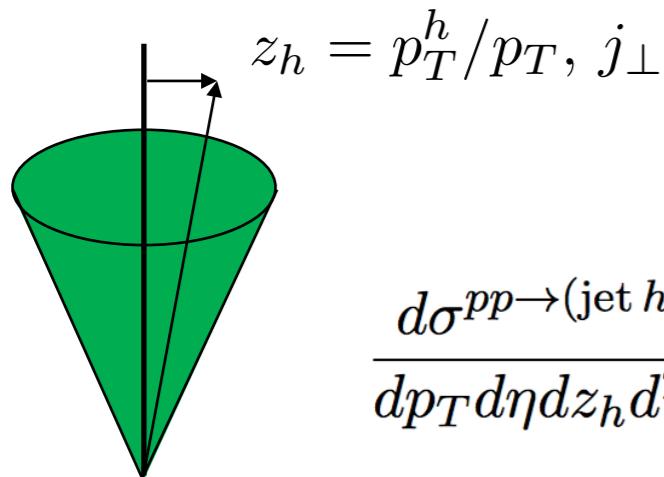


$$\psi(r) = \frac{\sum_{\Delta R_{iJ} < r} p_{Ti}}{\sum_{\Delta R_{iJ} < R} p_{Ti}}$$

$$\rho(r) = \frac{d\psi(r)}{dr}$$



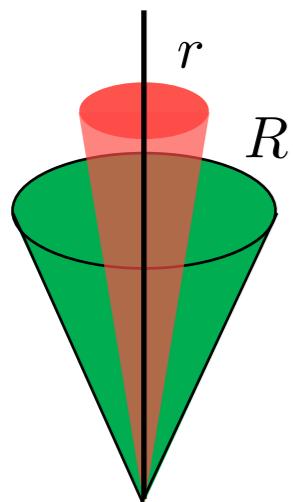
- Transverse momentum distribution (TMDFFs)  
*ATLAS, Eur.Phys.J.C. 71 (2011) 1795*



$$\frac{d\sigma^{pp \rightarrow (\text{jet } h) X}}{dp_T d\eta dz_h d^2 j_\perp} \Bigg/ \frac{d\sigma^{pp \rightarrow \text{jet } X}}{dp_T d\eta}$$

Neill, Scimemi, Waalewijn, '16  
 Kang, Liu, FR, Xing '17  
 Makris, Neill, Vaidya '17  
 Neill, Papaefstathiou, Waalewijn, Zoppi '18

# The jet energy profile

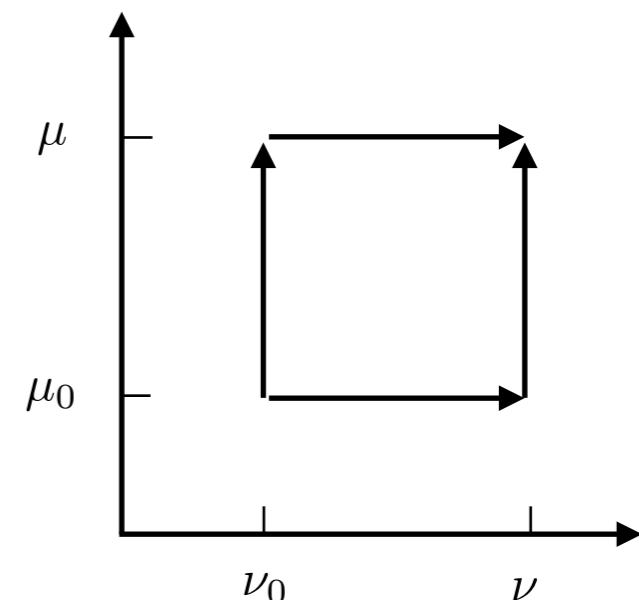


$$\psi(r) = \frac{\sum_{\Delta R_{iJ} < r} p_{Ti}}{\sum_{\Delta R_{iJ} < R} p_{Ti}} \quad \rho(r) = \frac{d\psi(r)}{dr}$$

Kang, FR, Waalewijn '16  
Cal, FR, Waalewijn - in preparation

- Factorization beyond leading-log

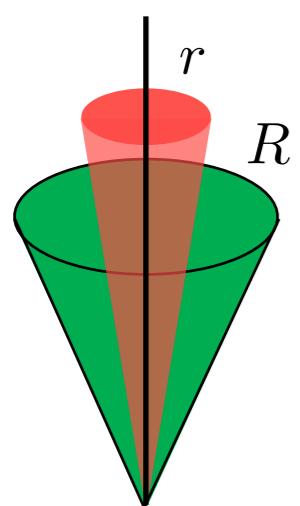
$$\begin{aligned} \mathcal{G}_i(z, p_T R, r/R, \mu) &= \sum_j \mathcal{H}_{i \rightarrow j}(z, p_T R, \mu) \\ &\times \int d^2 k_\perp C_j(p_T r, k_\perp, \mu, \nu) S_j^G(k_\perp, \mu, \nu R) S_j^{\text{NG}}(r/R) \end{aligned}$$



- NLL' resummation  $\ln(r/R)$
- Rapidity RG evolution, SCET<sub>II</sub>
- Soft recoil
- Non-global logarithms

Earlier work see: Seymour '98  
Li, Li, Yuan '11  
Chien, Vitev '14

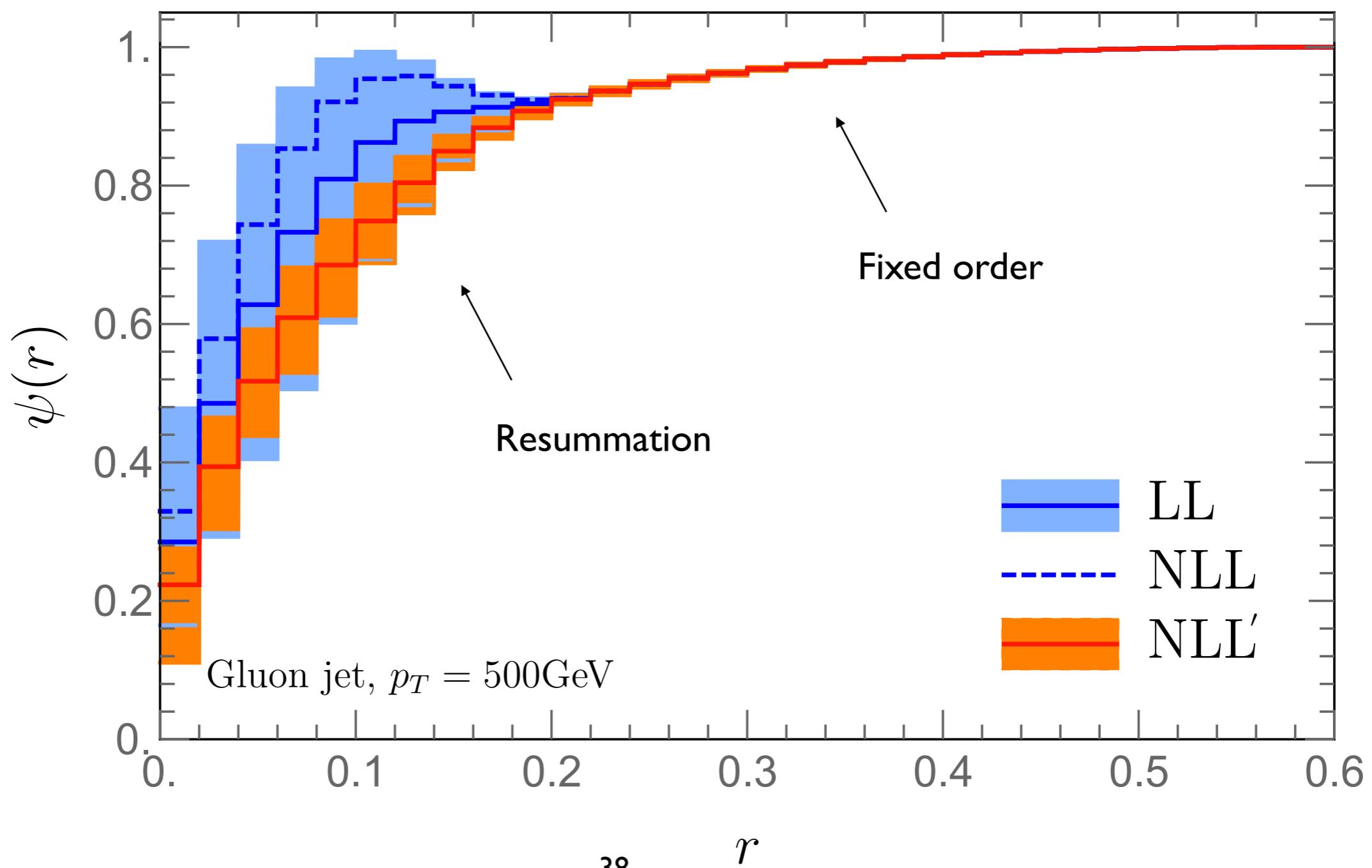
# The jet energy profile



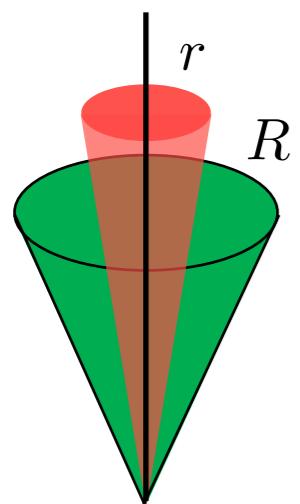
$$\psi(r) = \frac{\sum_{\Delta R_{iJ} < r} p_{Ti}}{\sum_{\Delta R_{iJ} < R} p_{Ti}}$$

Kang, FR, Waalewijn '16  
Cal, FR, Waalewijn - in preparation

$\sqrt{s} = 7$  TeV,  $|\eta| < 2.8$   
 $pp \rightarrow \text{jet} + X, R = 0.6$



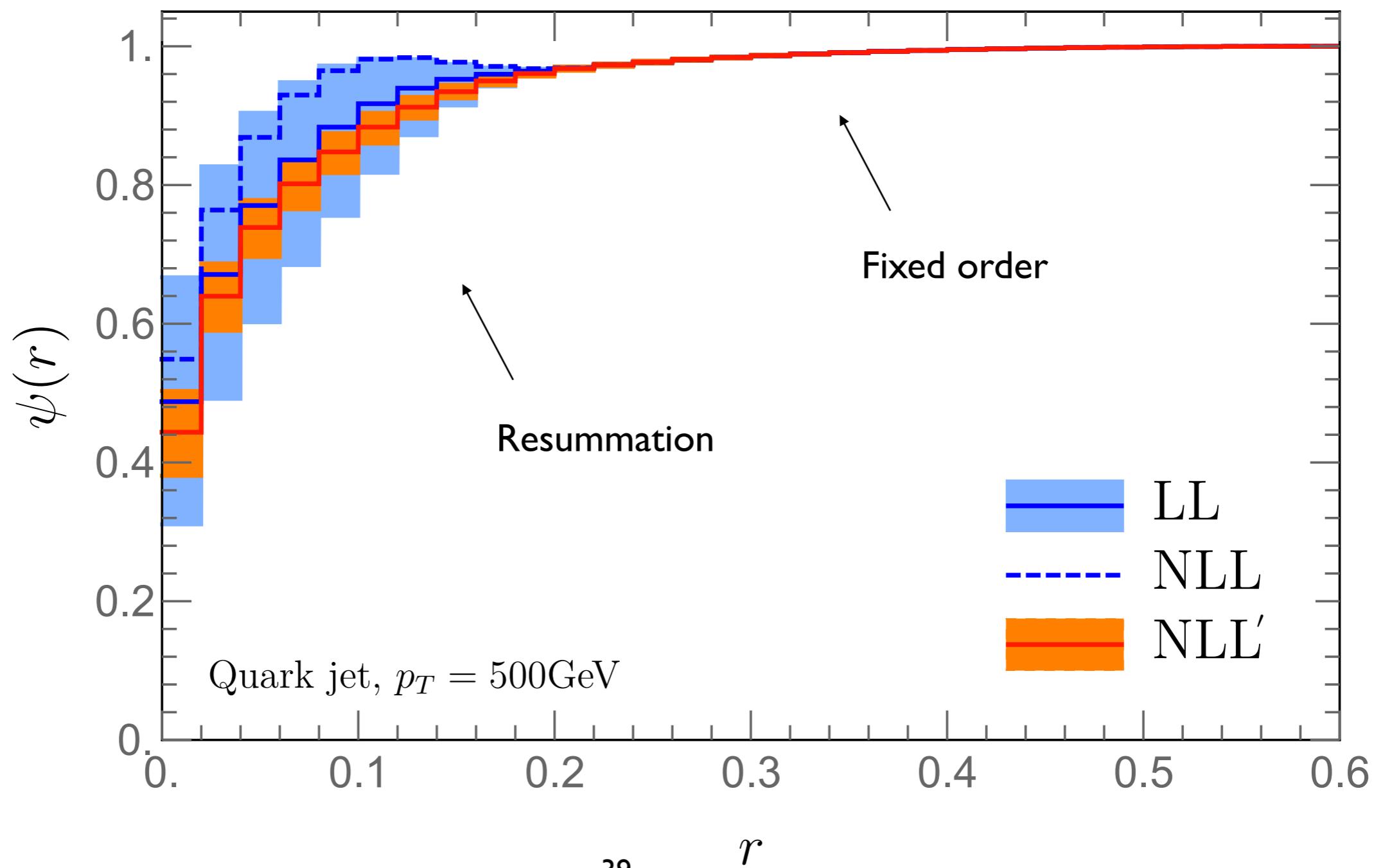
# The jet energy profile



$$\psi(r) = \frac{\sum_{\Delta R_{iJ} < r} p_{Ti}}{\sum_{\Delta R_{iJ} < R} p_{Ti}}$$

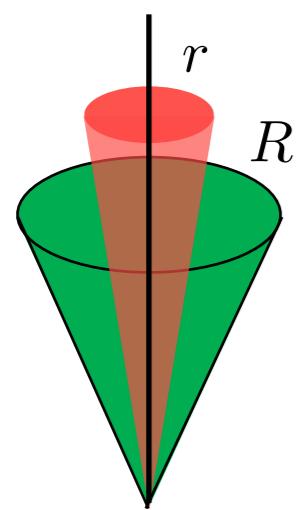
Kang, FR, Waalewijn '16  
Cal, FR, Waalewijn - in preparation

$\sqrt{s} = 7$  TeV,  $|\eta| < 2.8$   
 $pp \rightarrow \text{jet} + X, R = 0.6$

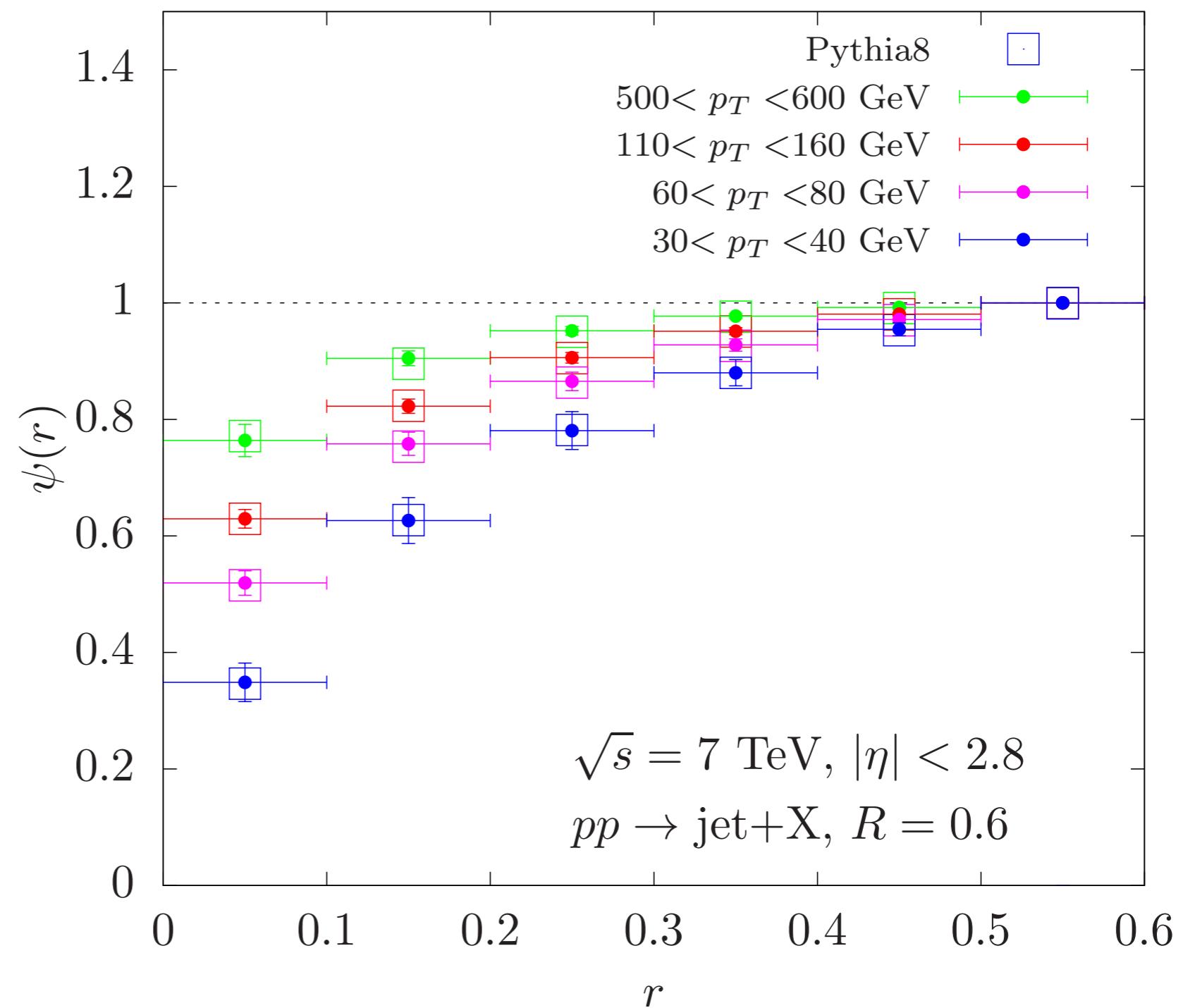


# The jet energy profile

Kang, FR, Waalewijn '16  
Cal, FR, Waalewijn - in preparation



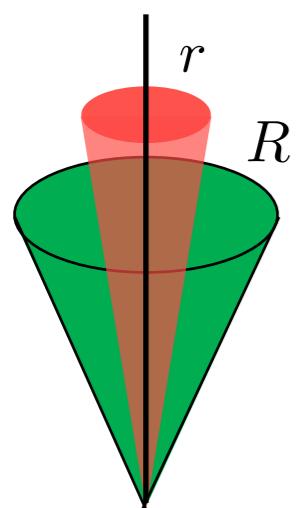
$$\psi(r) = \frac{\sum_{\Delta R_{iJ} < r} p_{Ti}}{\sum_{\Delta R_{iJ} < R} p_{Ti}}$$



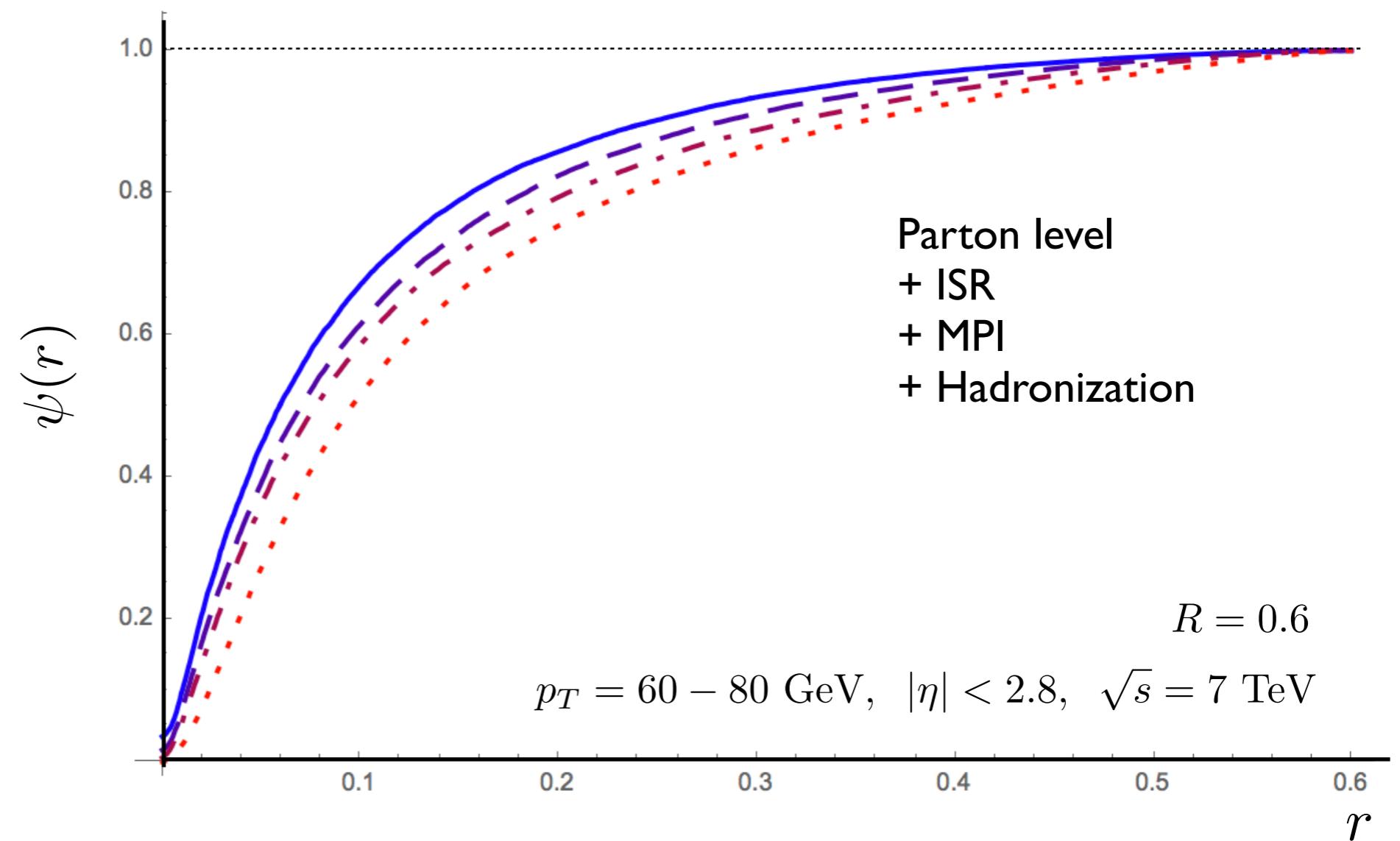
See also data from LEP, HERA, Tevatron

# The jet energy profile

Kang, FR, Waalewijn '16  
Cal, FR, Waalewijn - in preparation



$$\psi(r) = \frac{\sum_{\Delta R_{iJ} < r} p_{Ti}}{\sum_{\Delta R_{iJ} < R} p_{Ti}}$$



- Need high precision calculations
- Grooming needed

# Outline

- Introduction
- Inclusive jet production
- Groomed jet observables
- The transverse profile of jets
- Conclusions

# Conclusions

- Significant progress has been made but more work needed
- Precision goal for inclusive jet production is NNLO + NNLL
- QCD precision jet substructure studies
- Observables mapping out the transverse profile of jets

