

Threshold and jet radius joint resummation for single-inclusive jet production

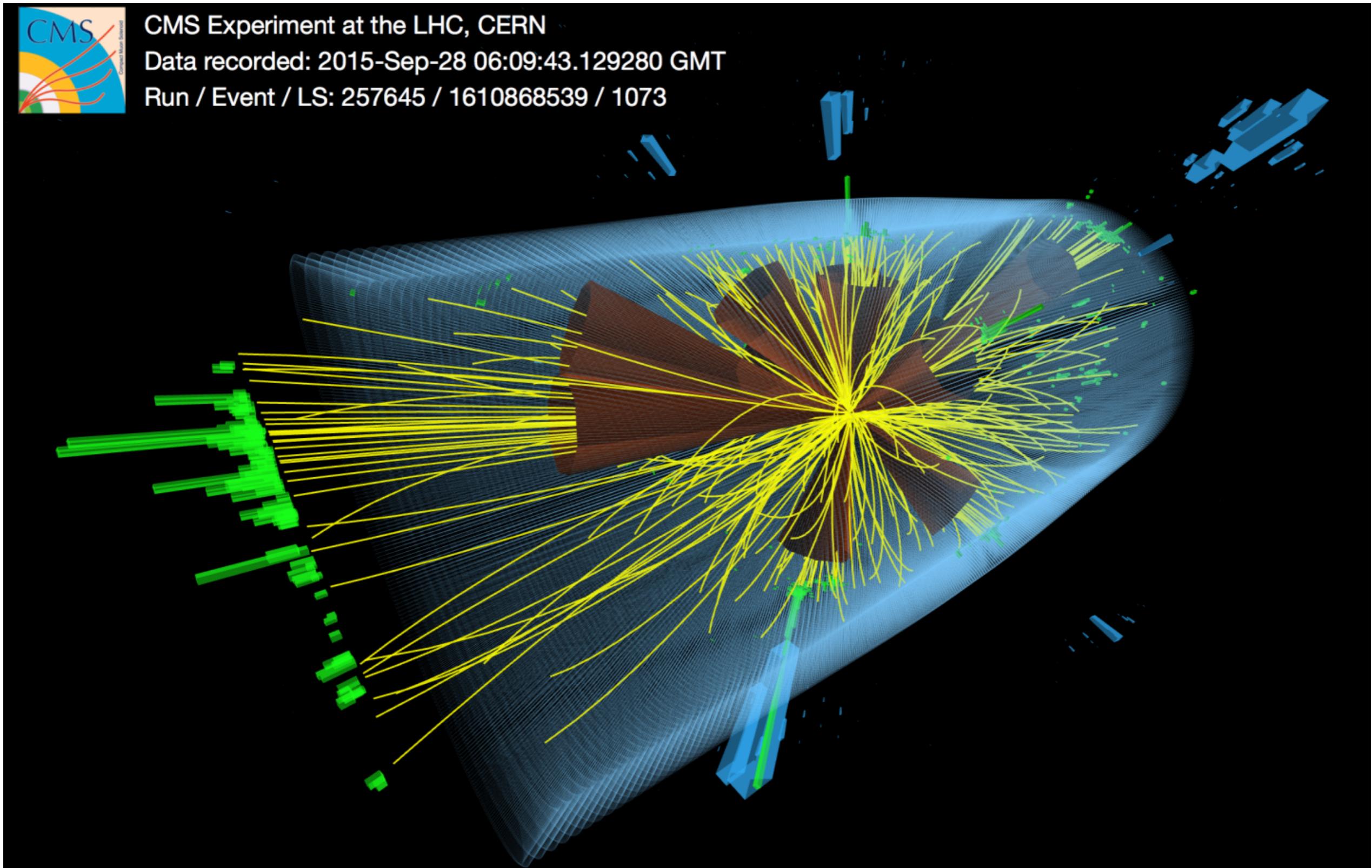
Felix Ringer

Lawrence Berkeley National Laboratory

In collaboration with: Xiaohui Liu, Sven Moch

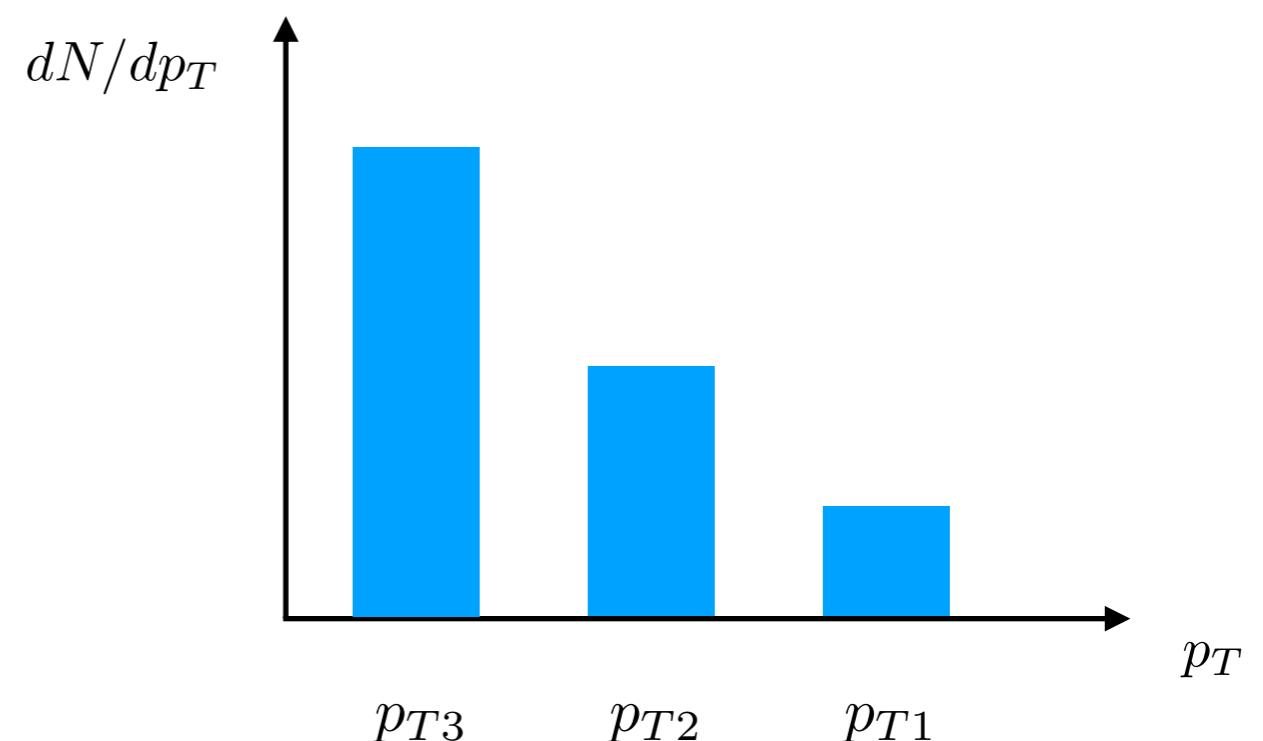
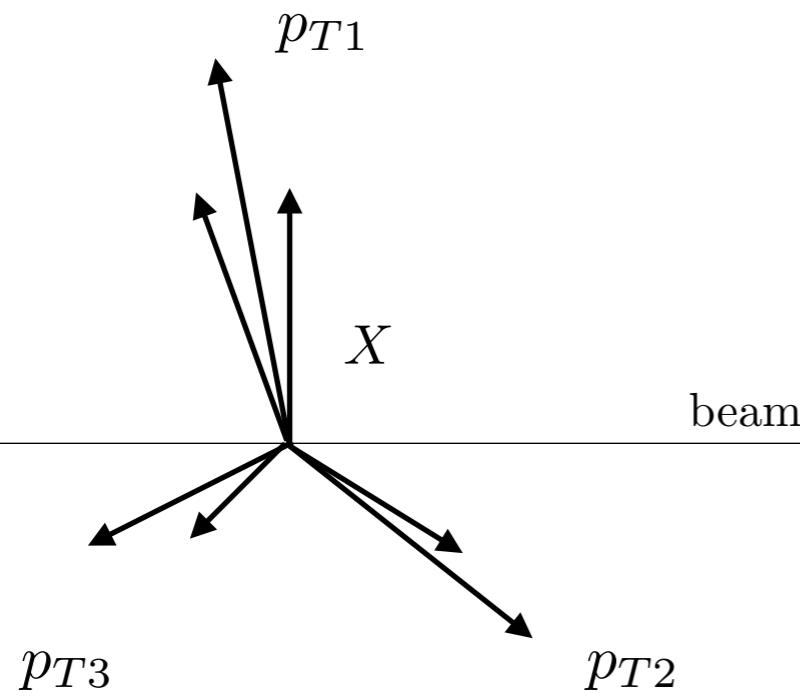
DIS 18, Kobe Japan, 04/18/18



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

Single-inclusive jet production

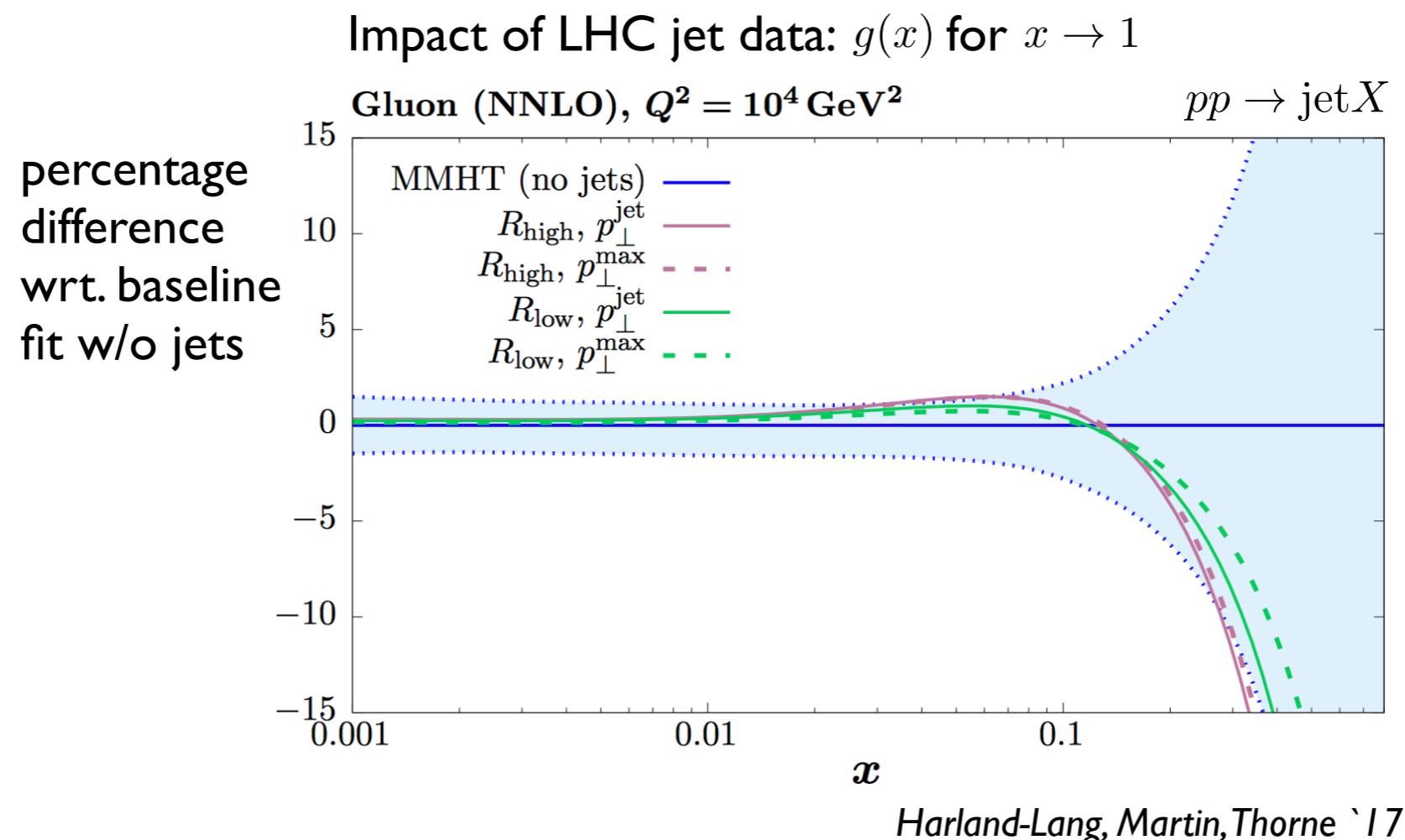
$pp \rightarrow \text{jet} + X$



n jets in n p_T -bins

Single-inclusive jet production

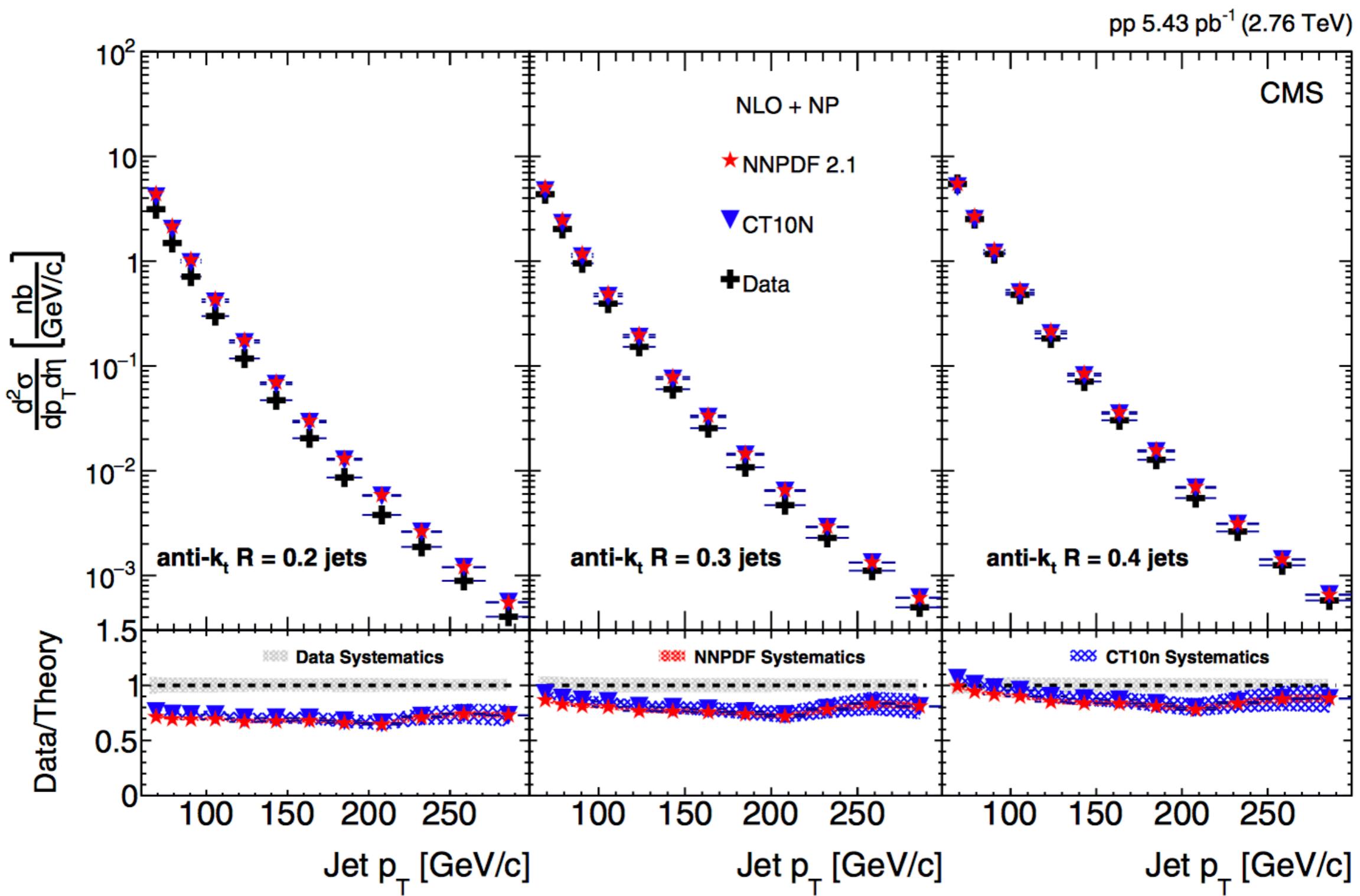
- Baseline process at the LHC: PDFs and α_s
- High precision calculations required at the percent level
- Searches for physics beyond the standard model
- Constrain in particular the gluon PDF



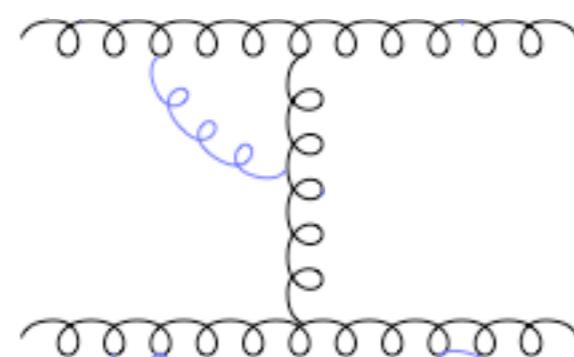
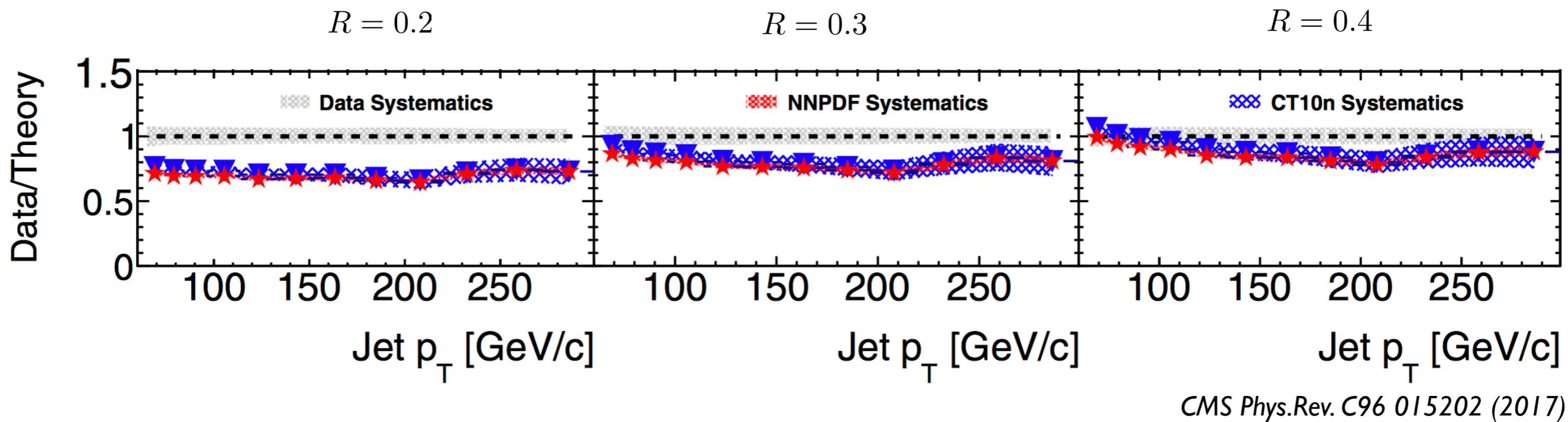
Outline

- Motivation
- Jet radius resummation
- Threshold and jet radius resummation
- Conclusions

Jet production at the LHC



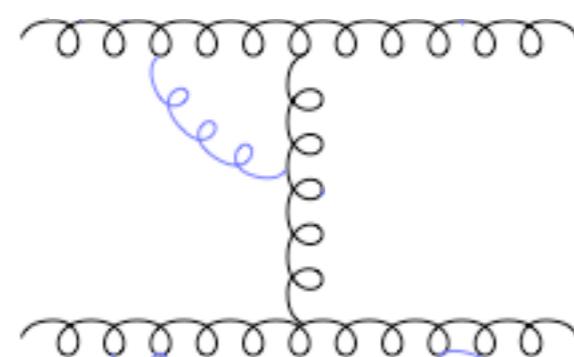
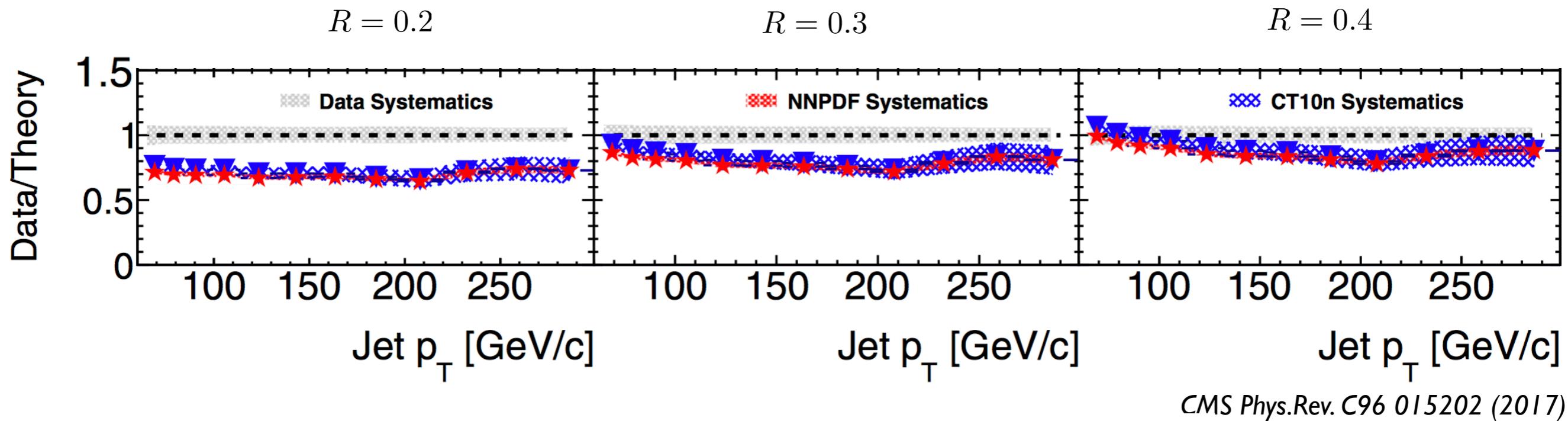
Jet production at the LHC



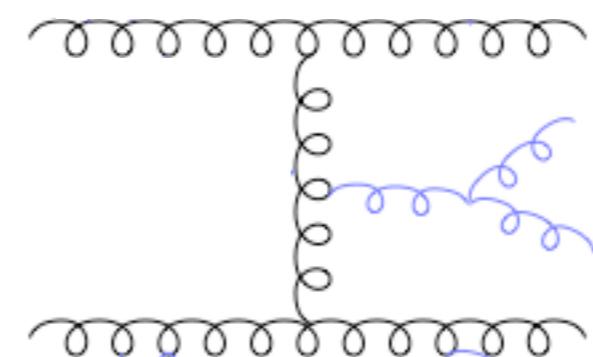
NLO 1990

Ellis, Kunszt, Soper '90

Jet production at the LHC



NLO 1990

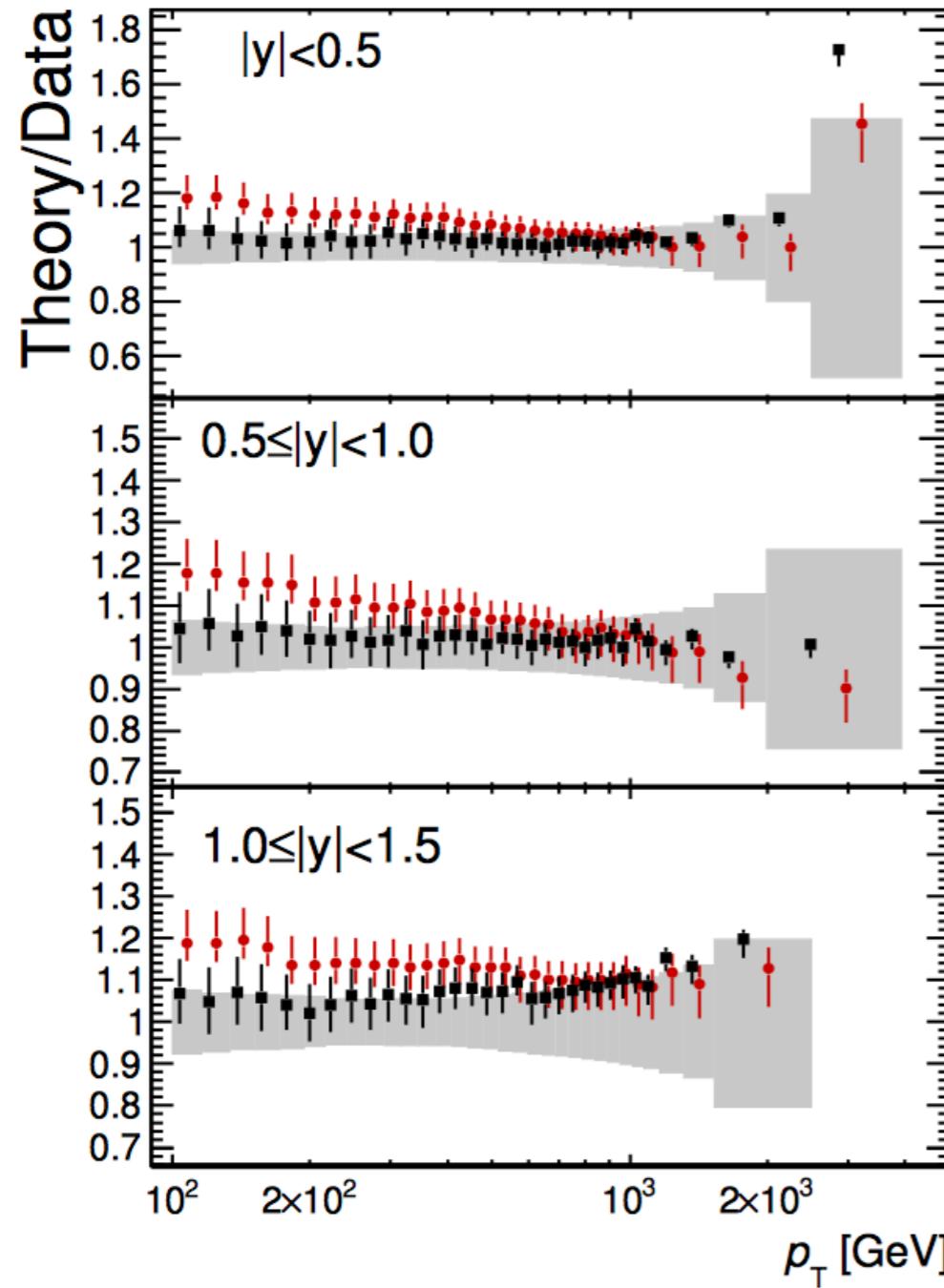
Ellis, Kunszt, Soper '90

NNLO 2016 ...

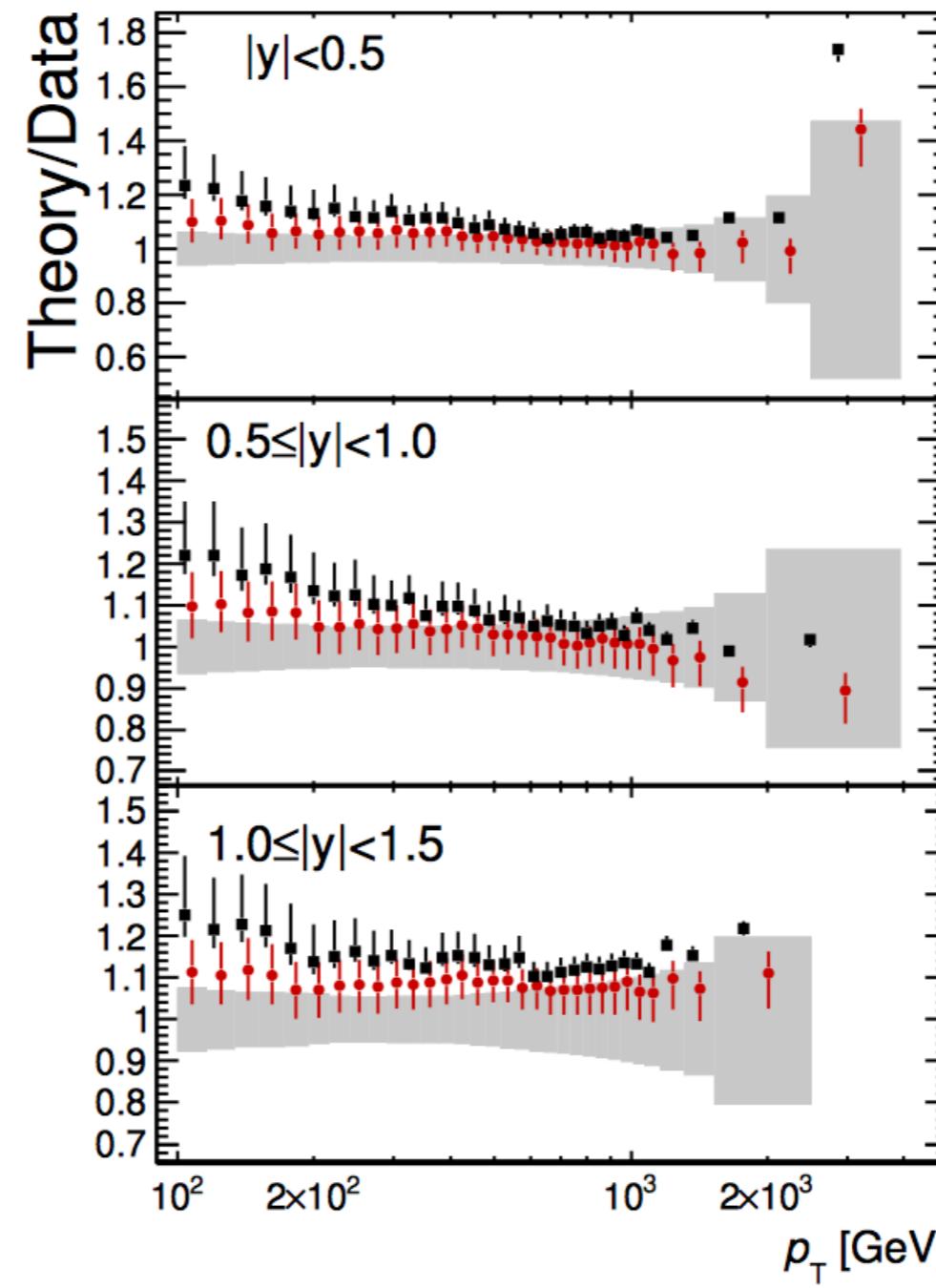
Currie, Glover, Pires '16

Jet production at the LHC

$$\mu = p_T$$



$$\mu = p_T^{\max}$$



ATLAS
Preliminary

$\int L dt = 3.2 \text{ fb}^{-1}$

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

anti- k_t , $R=0.4$

Data

NLO
MMHT 2014 NLO

NNLO
MMHT 2014 NNLO

Inclusive jet cross sections

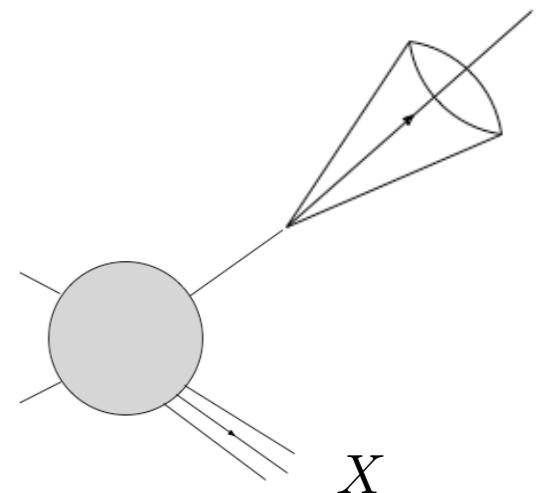
$$pp \rightarrow \text{jet} + X$$

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



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

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

Inclusive jet cross sections

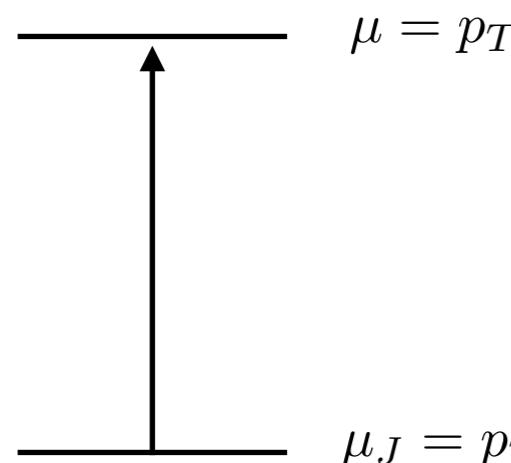
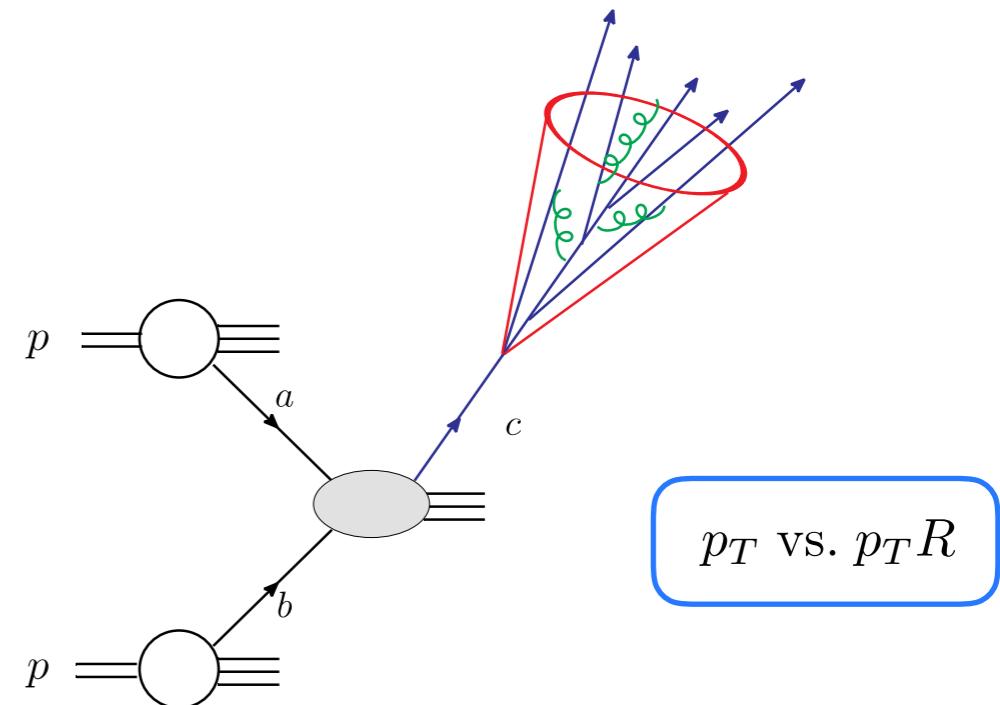
 $pp \rightarrow \text{jet} + X$

- Hard-collinear factorization

$$\frac{d\sigma^{pp \rightarrow \text{jet}X}}{dp_T d\eta} = \sum_{a,b,c} f_a \otimes f_b \otimes H_{ab}^c \otimes J_c + \mathcal{O}(R^2/R_0^2)$$

- RG evolution

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



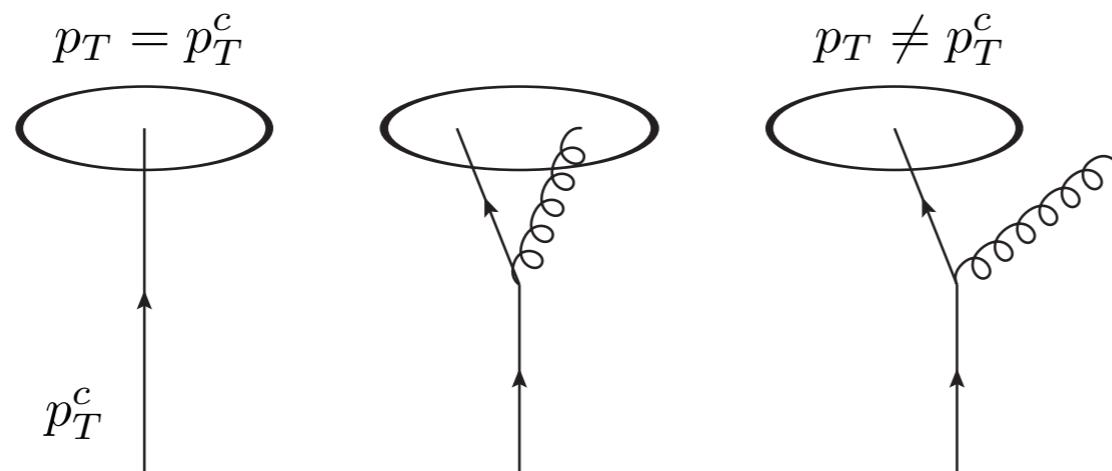
resummation of $\alpha_s^n \ln^n R$ via DGLAP

Dasgupta, Dreyer, Salam, Soyez '14
 Kaufmann, Mukherjee, Vogelsang '15
 Kang, FR, Vitev '16
 Dai, Kim, Leibovich '16

The semi-inclusive jet function

Kang, FR,Vitev '16

- The siJF $J_c(z, p_T R, \mu)$ describes how a parton is transformed into a jet with radius R and carrying an energy fraction z



where
$$z = p_T / p_T^c$$

- NLO result

$$\begin{aligned}
 J_q^{(1)}(z, p_T R, \mu) &= \frac{\alpha_s}{2\pi} \left(\frac{1}{\epsilon} + \ln \left(\frac{\mu^2}{p_T^2 R^2} \right) \right) [P_{qq}(z) + P_{gq}(z)] \\
 &\quad - \frac{\alpha_s}{2\pi} \left\{ C_F \left[2(1+z^2) \left(\frac{\ln(1-z)}{1-z} \right)_+ + (1-z) \right] - \delta(1-z) d_J^{q,\text{alg}} + P_{gq}(z) 2 \ln(1-z) + C_F z \right\}
 \end{aligned}$$

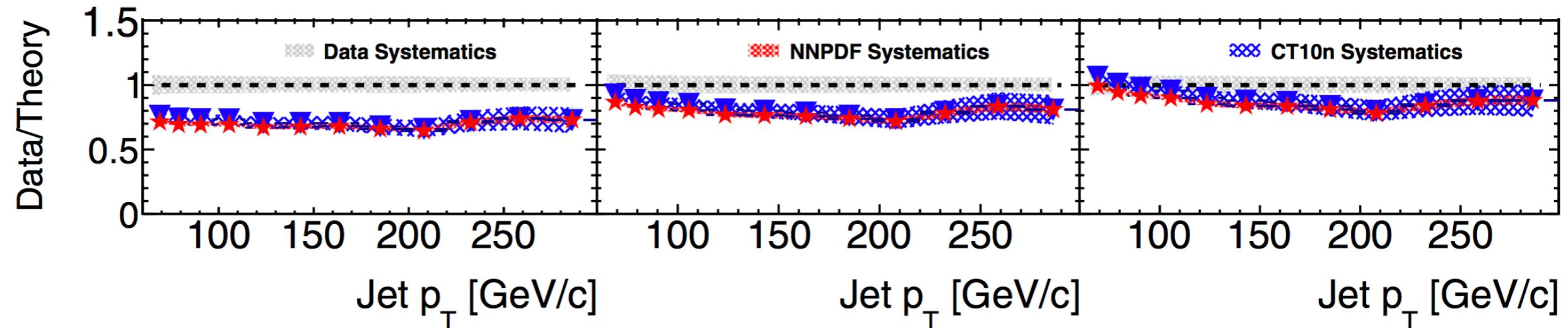
Comparison to LHC data

$$\sum_{a,b,c} f_a \otimes f_b \otimes H_{ab}$$

$R = 0.2$

$R = 0.3$

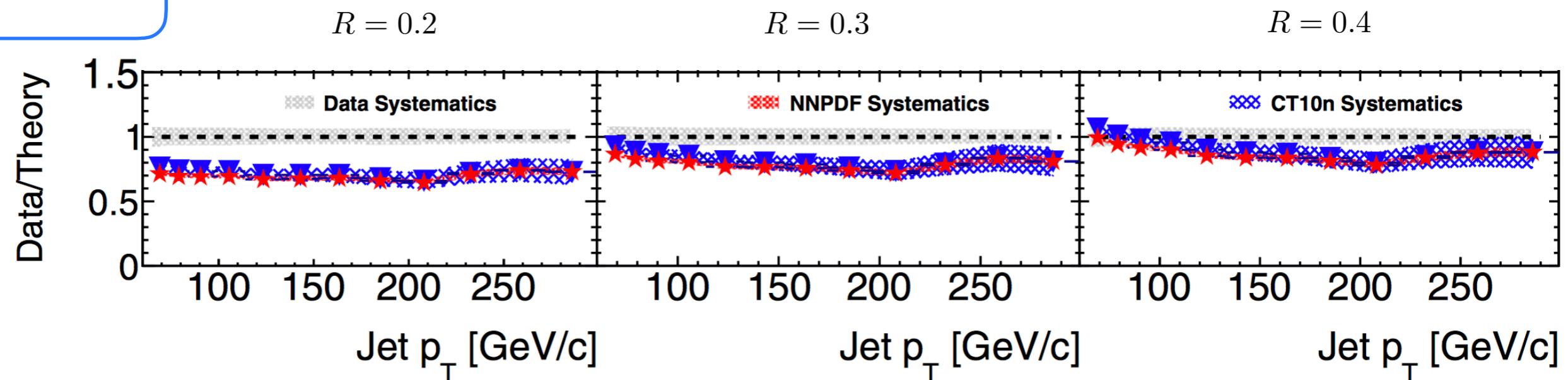
$R = 0.4$



CMS Phys.Rev. C96 015202 (2017)

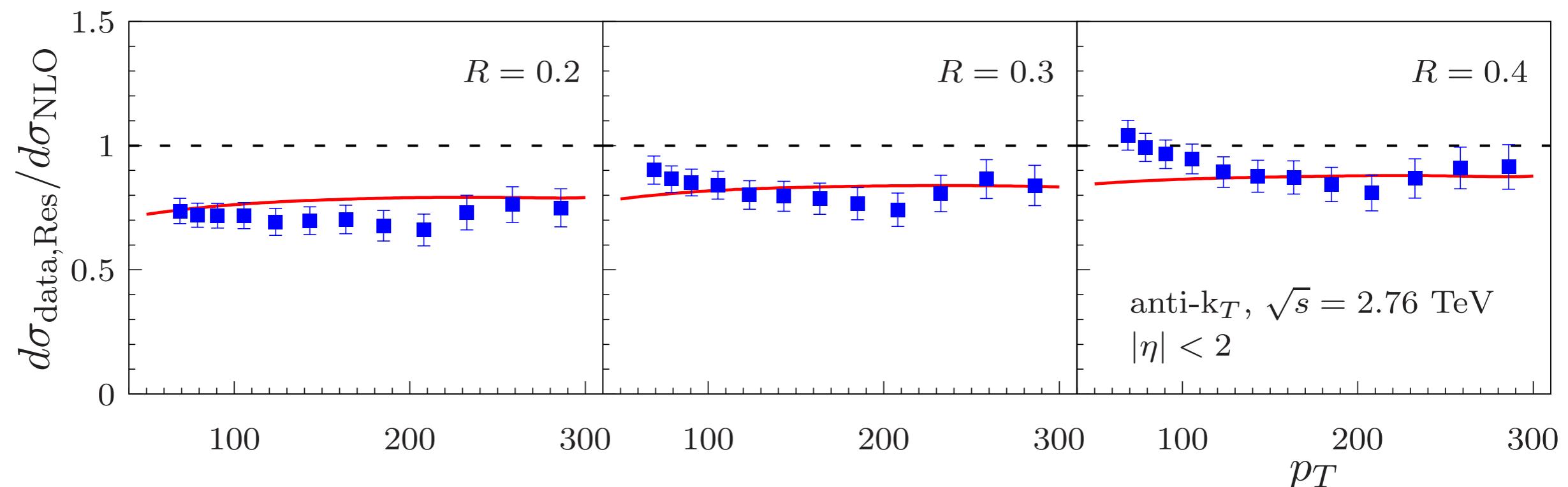
Comparison to LHC data

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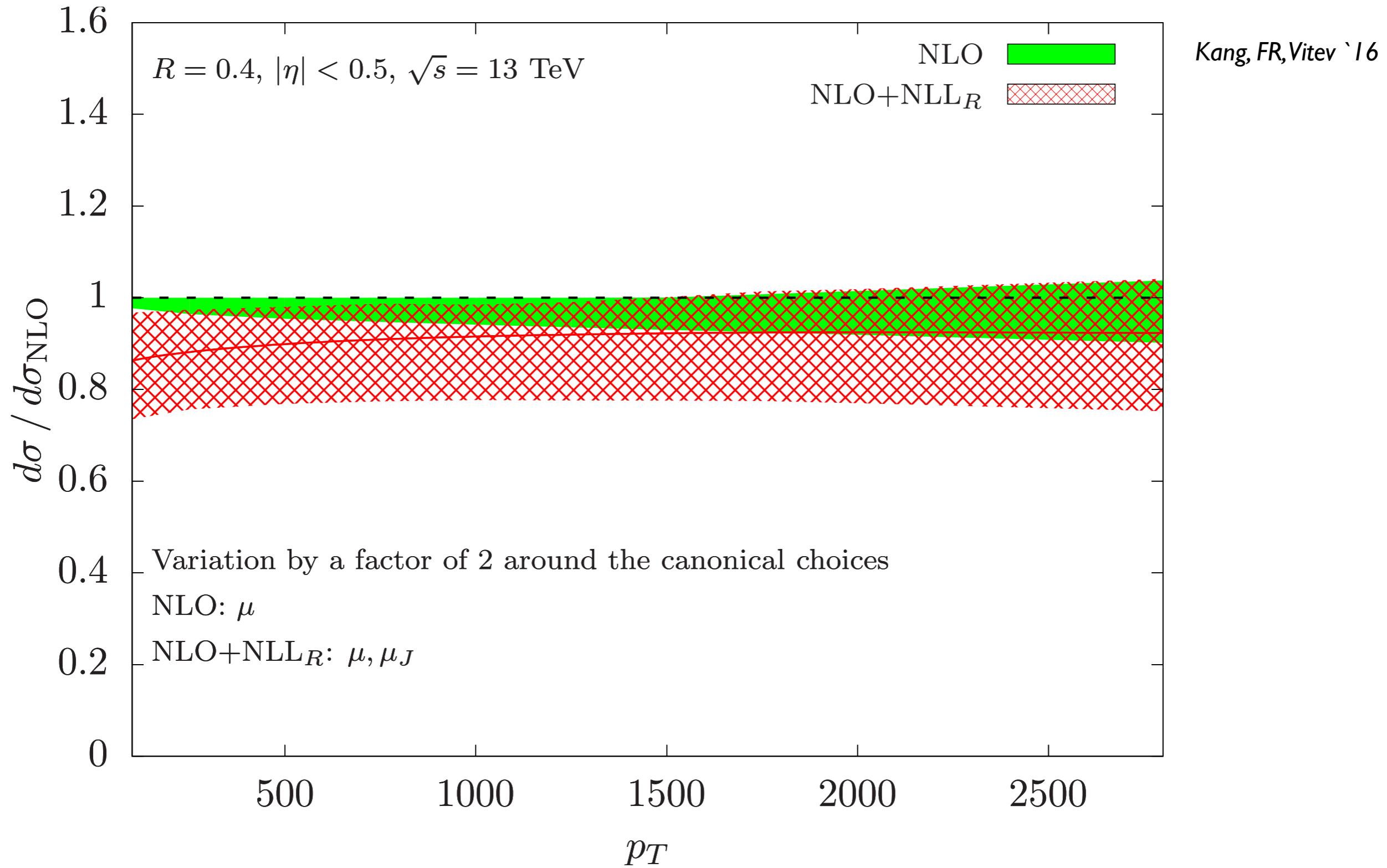


CMS Phys.Rev. C96 015202 (2017)

$$\sum_{a,b,c} f_a \otimes f_b \otimes H_{ab}^c \otimes J_c$$



Residual QCD scale dependence

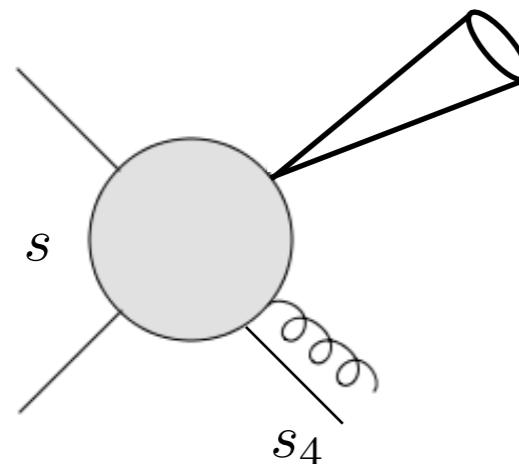


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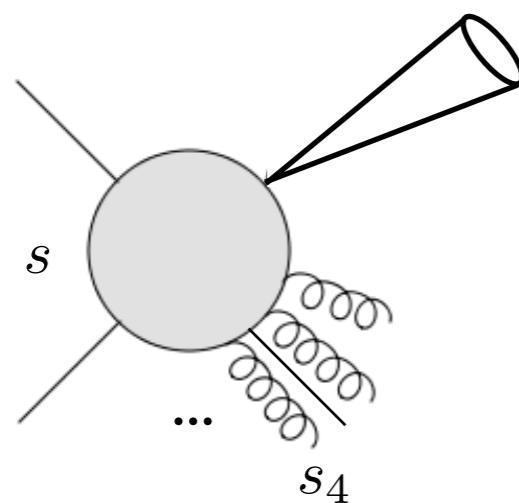
Threshold resummation

NLO:



$$d\hat{\sigma}^{\text{NLO}} \sim \alpha_s \left(\frac{\ln z}{z} \right)_+ + \dots$$

$N^k\text{LO}:$



$$d\hat{\sigma}^{N^k\text{LO}} \sim \alpha_s^k \left(\frac{\ln^{2k-1} z}{z} \right)_+ + \dots$$

$$z = s_4/s \rightarrow 0 \quad \text{partonic threshold}$$

- At threshold all the radiation outside the observed jet is required to be small

→ Threshold resummation

Sterman '87; Catani, Trentadue '89

Joint threshold and small-R resummation

- Non-trivial color structure

Kidonakis, Sterman '97, Kidonakis, Oderda, Sterman '98

- Previously unsolved problems with the inverse transformation

only approximate NNLO results available

Kidonakis, Owens '01, Kumar, Moch '13
de Florian, Hinderer, Mukherjee, FR, Vogelsang '14
Dai, Kim, Leibovich '17

$$\frac{p_T^2 d^2\sigma}{dp_T^2 d\eta} = \sum_{i_1 i_2} \int_0^{V(1-W)} dz \int_{\frac{VW}{1-z}}^{1-\frac{1-V}{1-z}} dv x_1^2 f_{i_1}(x_1) x_2^2 f_{i_2}(x_2) \frac{d^2\hat{\sigma}_{i_1 i_2}}{dv dz}(v, z, p_T, R)$$

where

$$V = 1 - p_T e^{-\eta} / \sqrt{S}$$

$$VW = p_T e^{\eta} / \sqrt{S}$$

threshold $\quad z \rightarrow 0$

$$s = x_1 x_2 S$$

$$v = \frac{u}{u+t}$$

$$z = s_4/s$$

logarithms

$$\left(\frac{\ln z}{z} \right)_+$$

Joint threshold and small-R resummation

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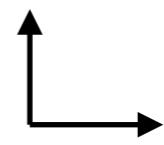
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$$\int_{\mathcal{C}_N} \frac{dN}{2\pi i} (1-z)^{-N} \frac{d\hat{\sigma}_{i_1 i_2}^N}{dv}$$

where

$$V = 1 - p_T e^{-\eta} / \sqrt{S}$$

$$VW = p_T e^{\eta} / \sqrt{S}$$

threshold $\quad z \rightarrow 0$

$$s = x_a x_b S \quad v = \frac{u}{u+t} \quad z = s_4/s$$

logarithms $\left(\frac{\ln z}{z}\right)_+$

Joint threshold and small-R resummation

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Dai, Kim, Leibovich '17*

Refactorize at threshold:

$$\begin{aligned} \frac{d^2\hat{\sigma}_{i_1 i_2}}{dv dz} &= s \int ds_X ds_c ds_G \delta(zs - s_X - s_G - s_c) && \text{Liu, Moch, FR '14} \\ &\times \text{Tr} [\mathbf{H}_{i_1 i_2}(v, p_T, \mu_h, \mu) \mathbf{S}_G(s_G, \mu_{sG}, \mu)] J_X(s_X, \mu_X, \mu) \\ &\times \sum_m \text{Tr} [J_m(p_T R, \mu_J, \mu) \otimes_\Omega S_{c,m}(s_c R, \mu_{sc}, \mu)] \end{aligned}$$

- Derivation within Soft Collinear Effective Theory *Bauer, Stewart et al. '00 - '02*
- Numerical implementation in distribution space *Becher, Neubert '06*

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Liu, Moch, FR '14

$\mathbf{H}_{i_1 i_2}$ hard functions for $2 \rightarrow 2$ scattering: 2-loop results

Broggio, Ferroglia, Pecjak, Zhang '14

J_X recoiling jet function: 2-loop results

Becher, Neuber '06, Becher Bell '11

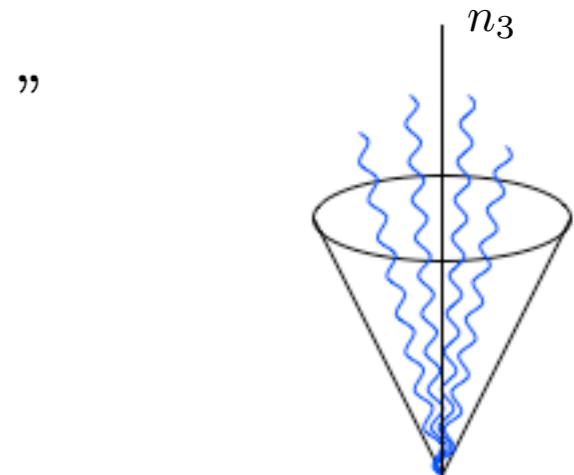
Joint threshold and small-R resummation

Liu, Moch, FR '17

- Joint resummation $\alpha_s^n \ln^{2n} \bar{N}, \quad \alpha_s^n \ln^n R$

- Jet function

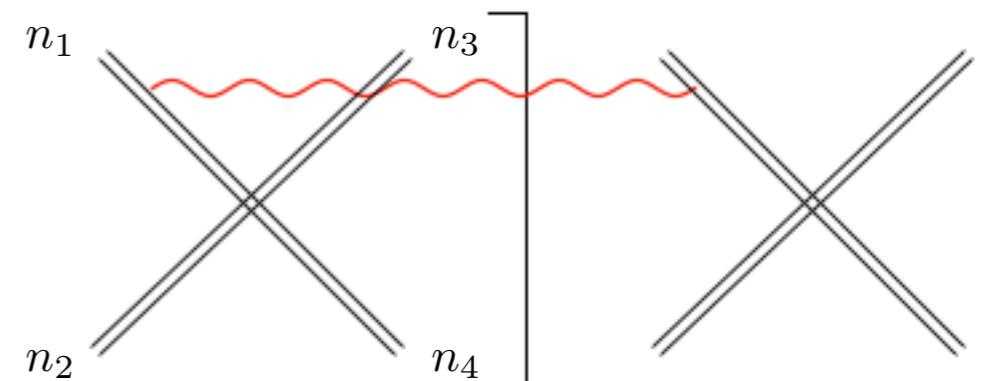
$$J_q(R) = 1 + \frac{\alpha_s}{2\pi} C_F \left[\frac{1}{\epsilon^2} + \frac{3}{2\epsilon} + \frac{1}{\epsilon} L_R + \frac{1}{2} L_R^2 + \frac{3}{2} L_R + \frac{13}{2} - \frac{3\pi^2}{4} \right]$$



- Global-soft function

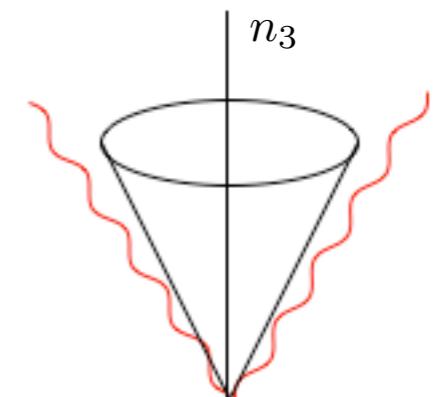
$$\mathbf{S}_G^{(1)} = \frac{\alpha_s}{\pi \epsilon} \frac{e^{\epsilon \gamma_E}}{\Gamma(1-\epsilon)} \sum_{i \neq j \neq 4} \mathbf{T}_i \cdot \mathbf{T}_j \frac{n_{ij}}{\mu_{sG}} \left(\frac{s_G n_{ij}}{\mu_{sG}} \right)^{-1-2\epsilon}$$

$$n_{ij} = \sqrt{s_{ij}/s_{i4}/s_{j4}} \text{ and } s_{ij} = 2p_i \cdot p_j$$

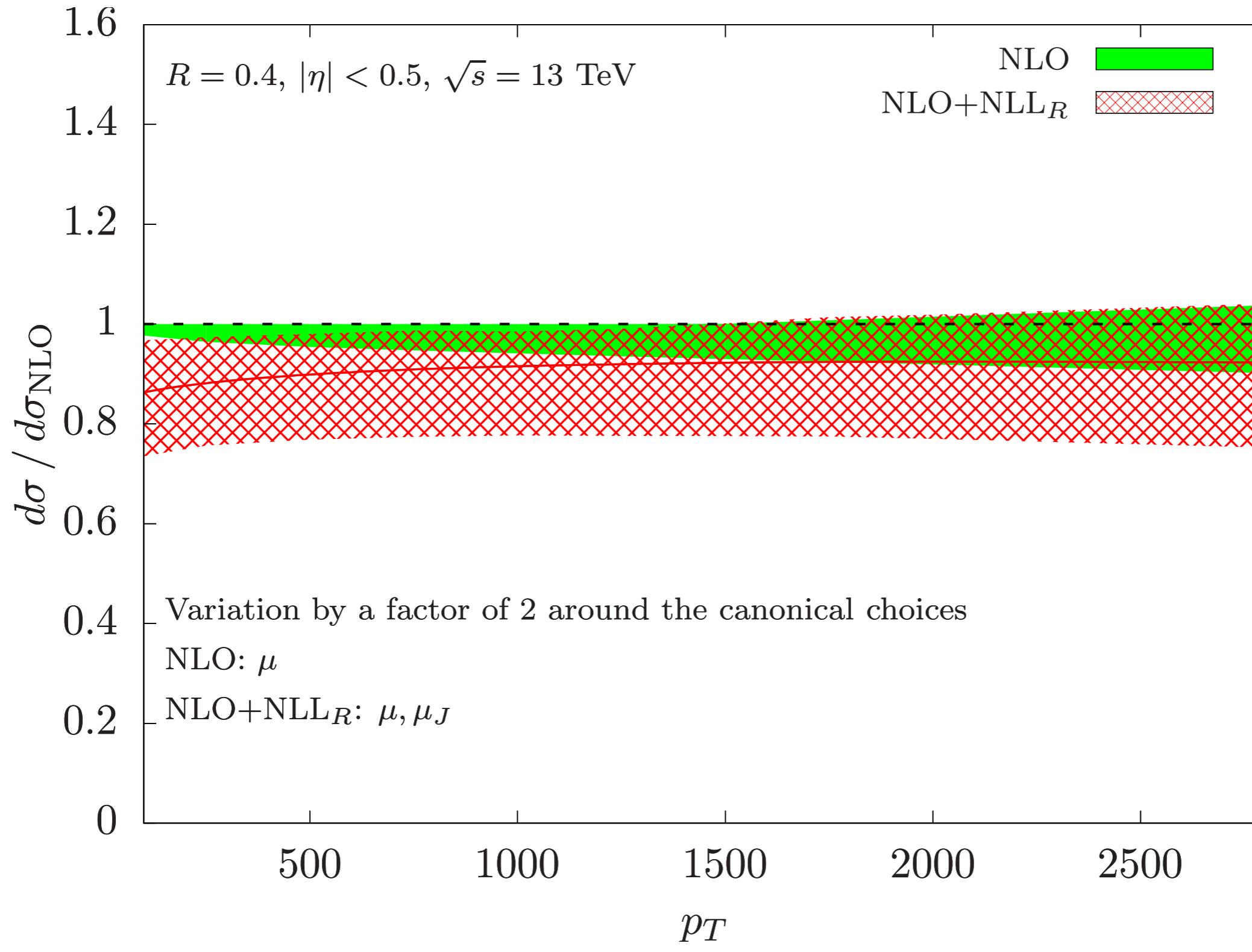


- Soft-collinear function

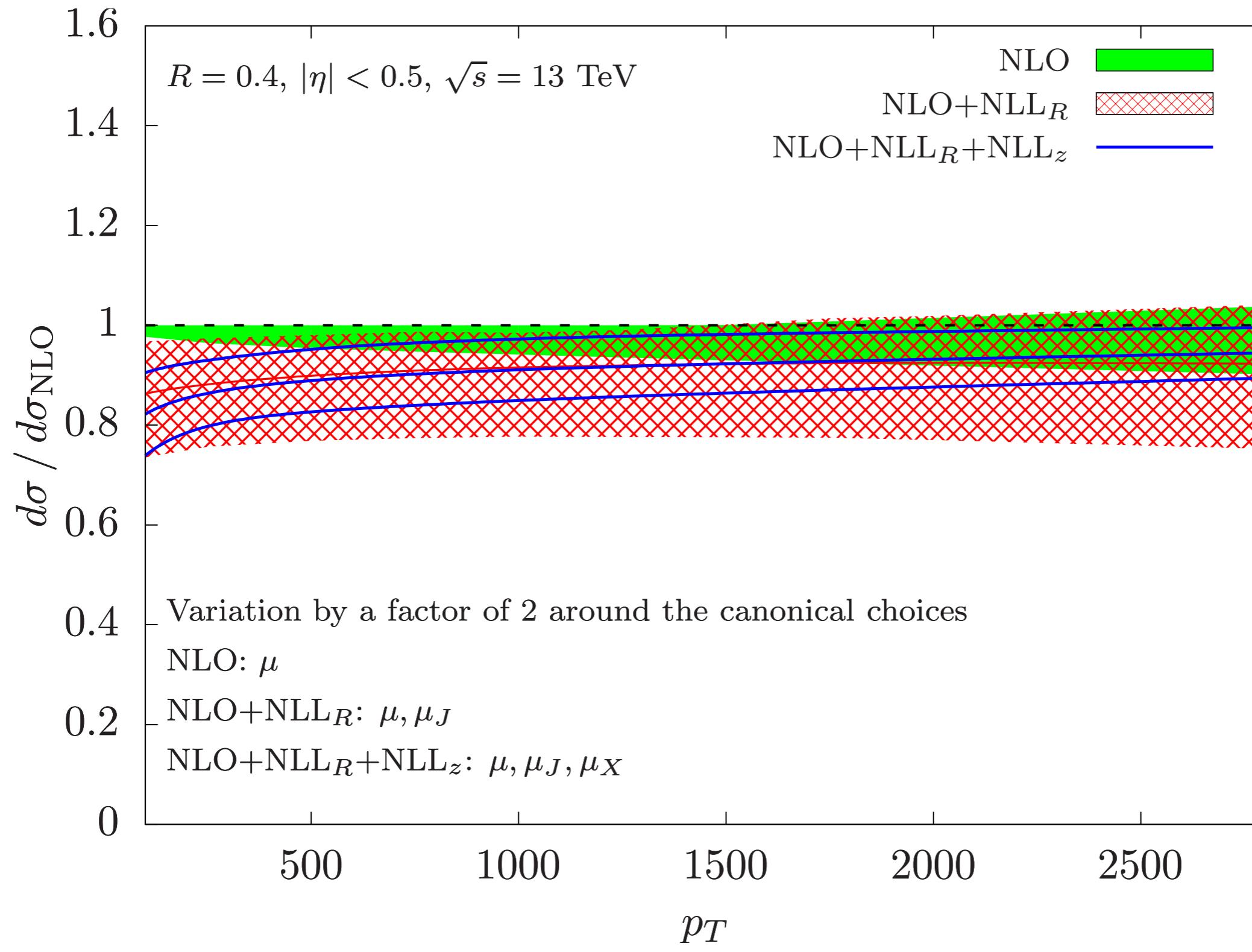
$$S_c^{(1)} = \mathbf{T}_3^2 \frac{\alpha_s}{\pi \epsilon} \frac{e^{\epsilon \gamma_E}}{\Gamma(1-\epsilon)} \frac{p_T R}{s \mu_{sc}} \left(\frac{s_c p_T R}{s \mu_{sc}} \right)^{-1-2\epsilon}$$



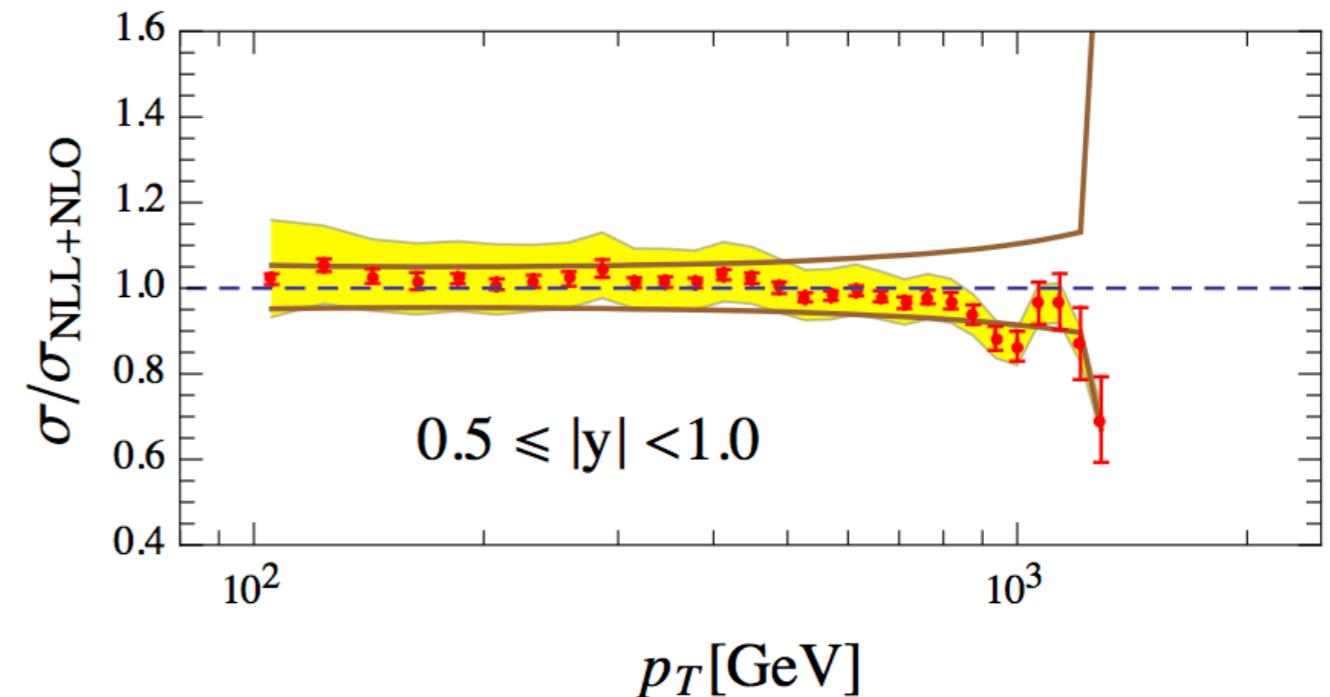
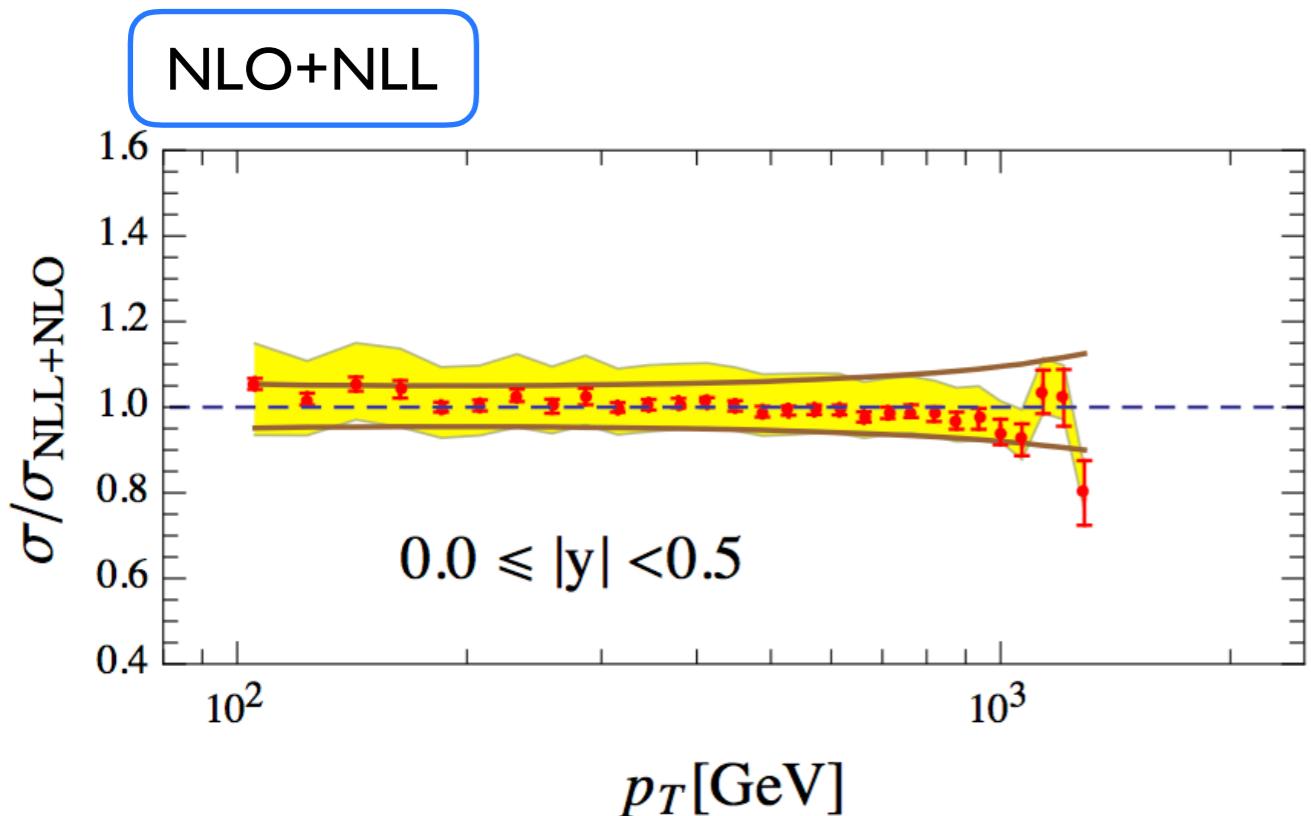
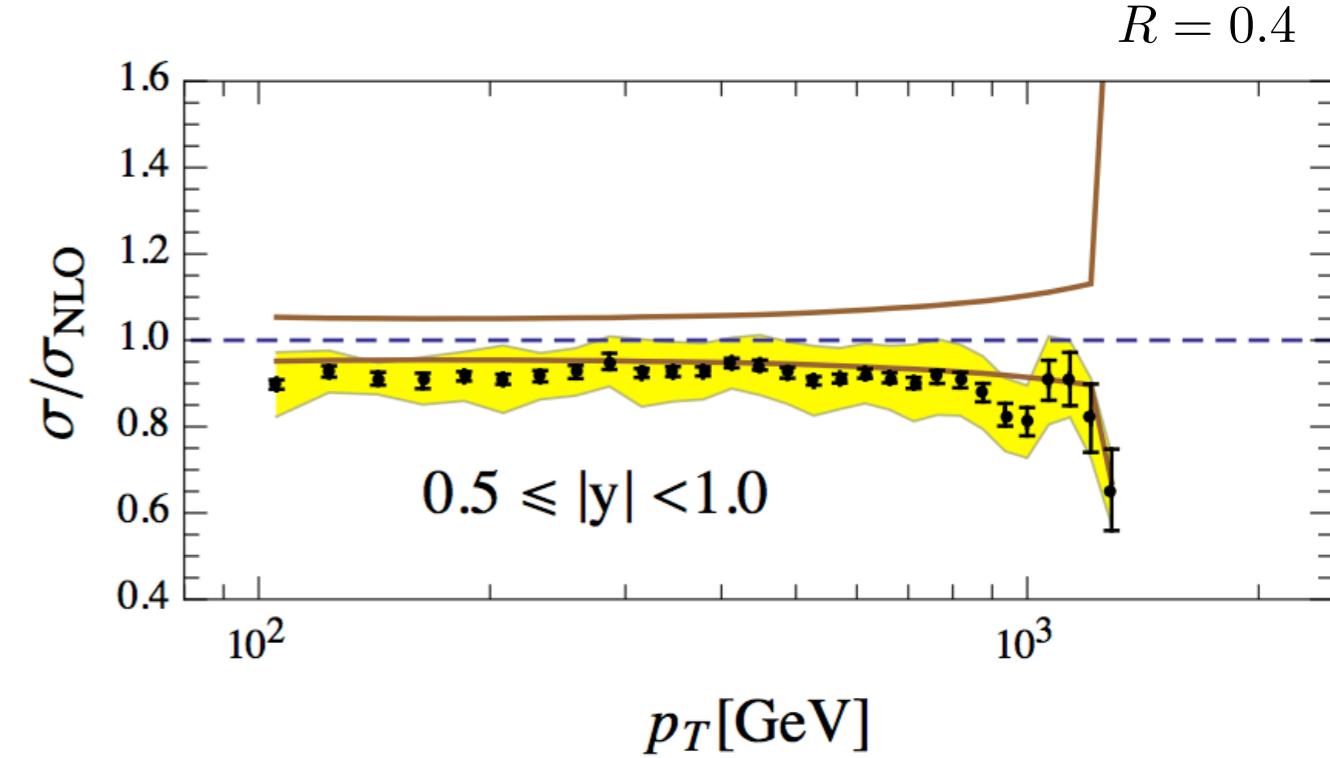
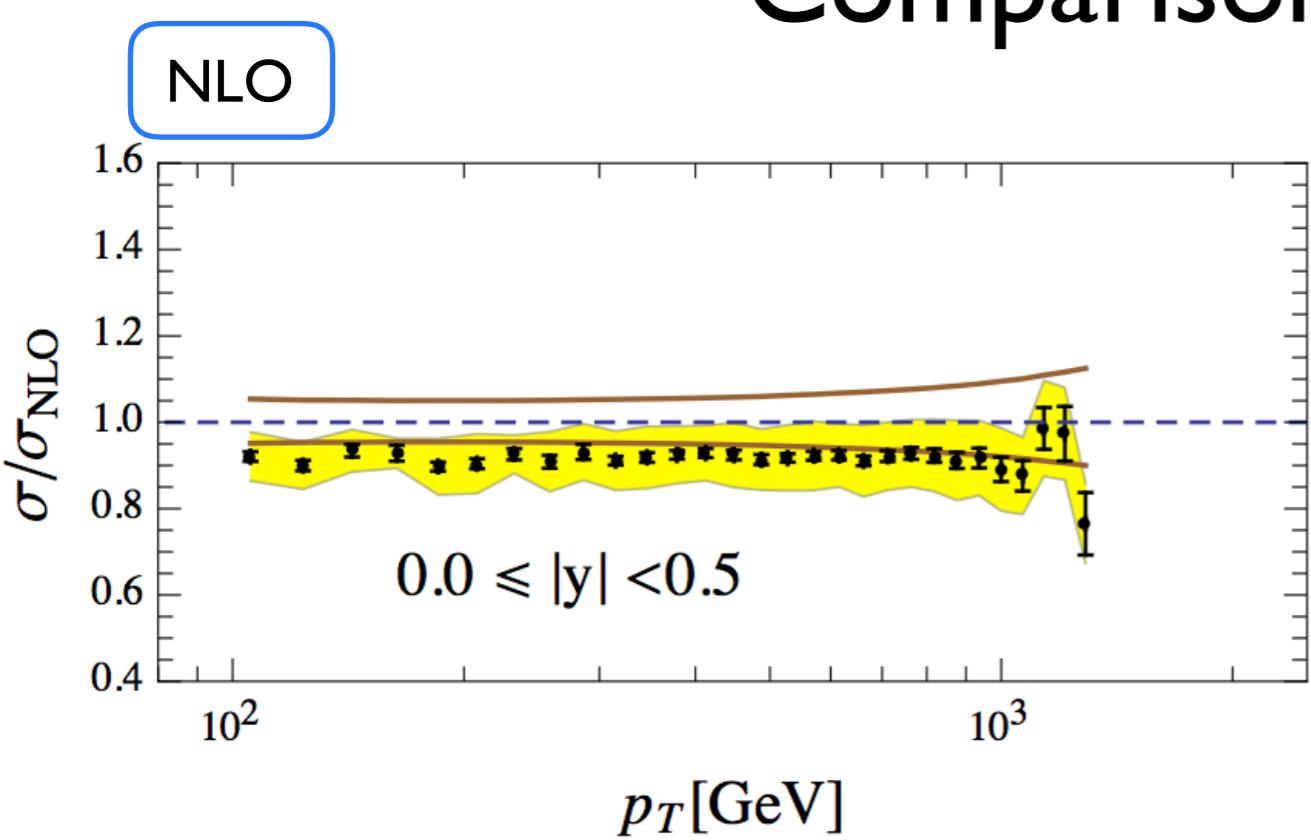
Residual QCD scale dependence



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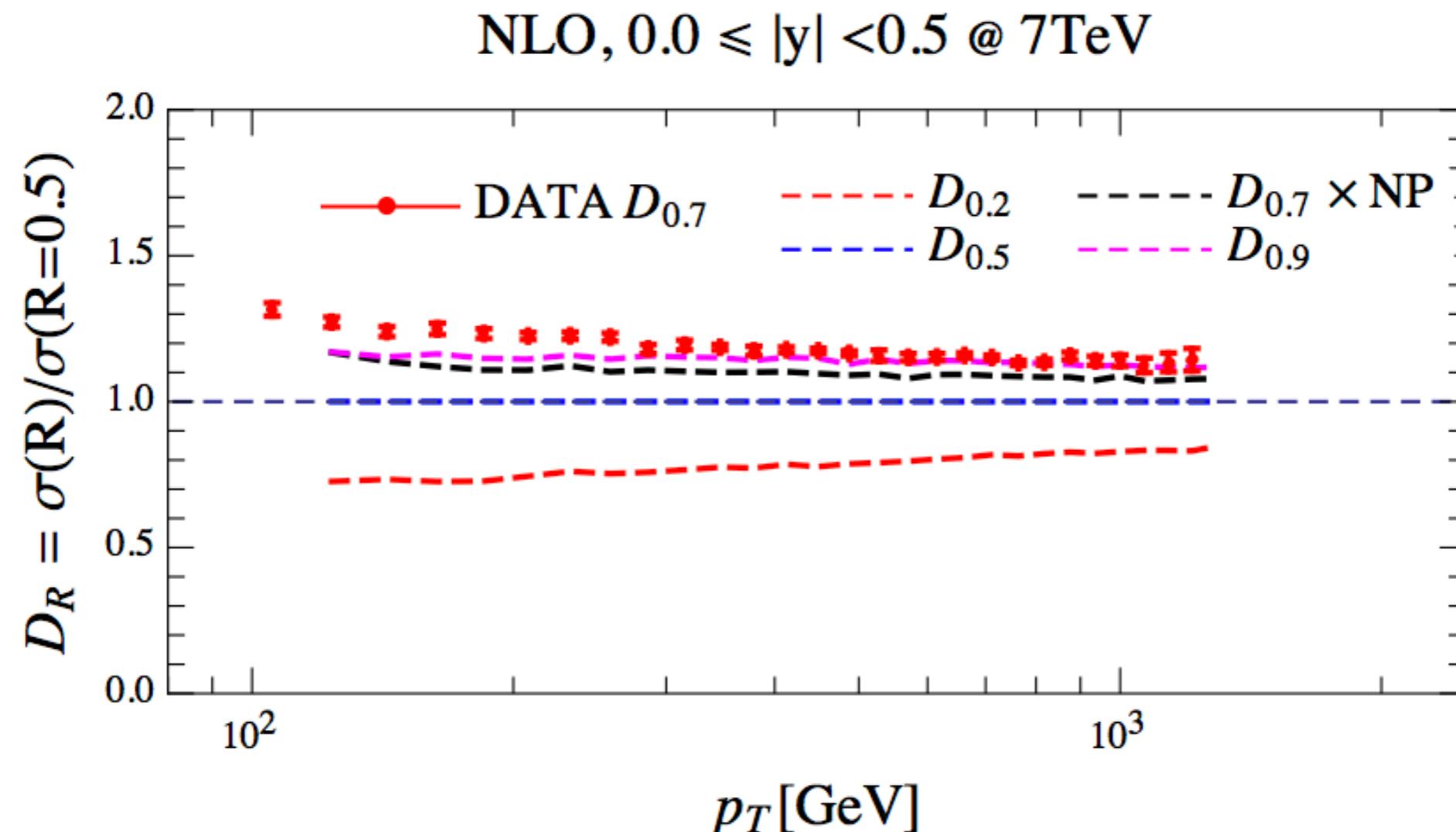
Comparison to LHC data



Comparison to LHC data

- Cross section ratios

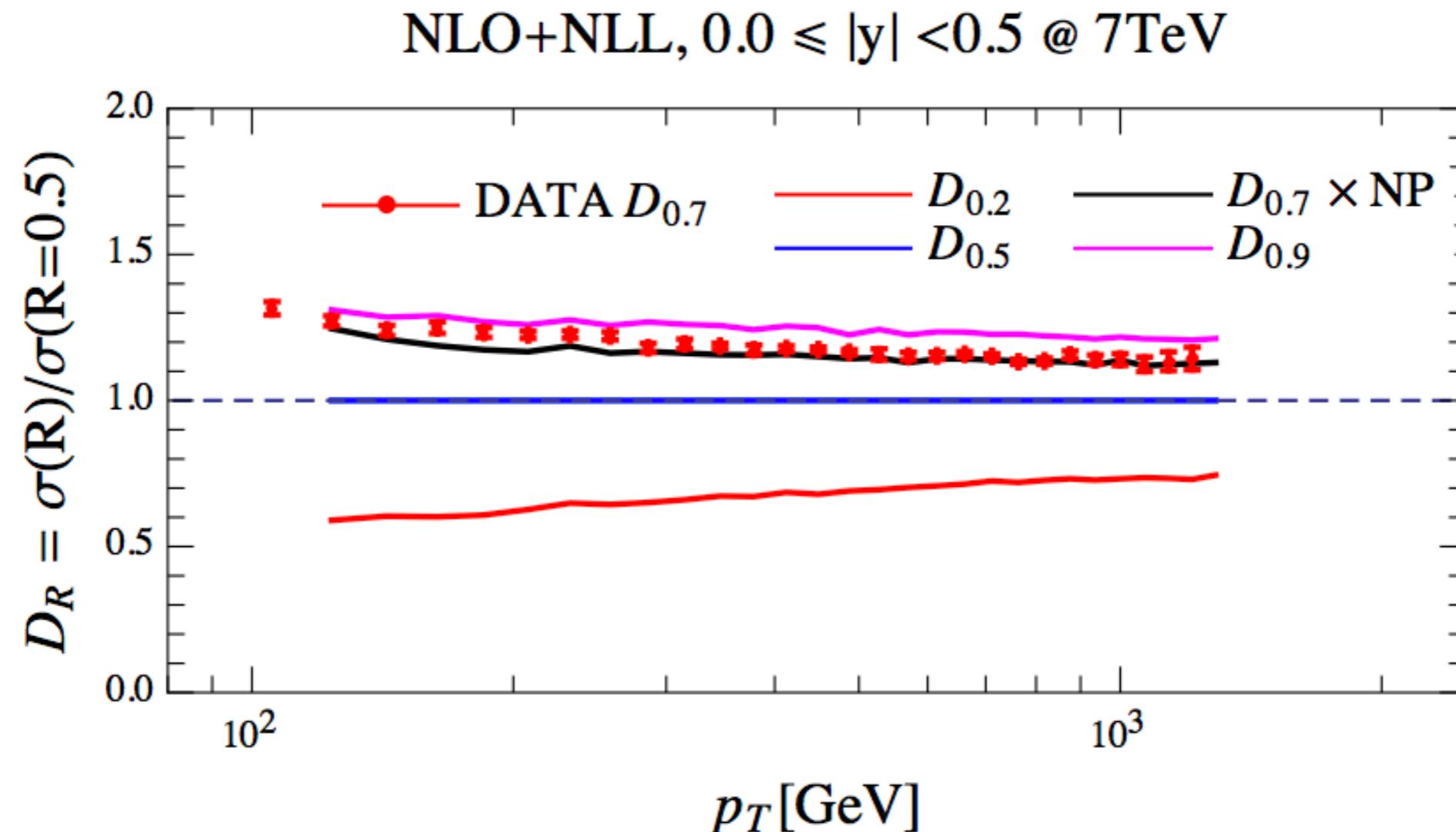
$$D_R = \frac{\sigma(R = 0.7)}{\sigma(R = 0.5)}$$



Comparison to LHC data

- Cross section ratios

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



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Conclusions

- Precision jet physics including resummation
- Joint resummation of jet radius and threshold logarithms
- First numerical results for the double differential jet cross section
- Significantly improved comparison to LHC data
- Allows for a systematic extension beyond NLL

