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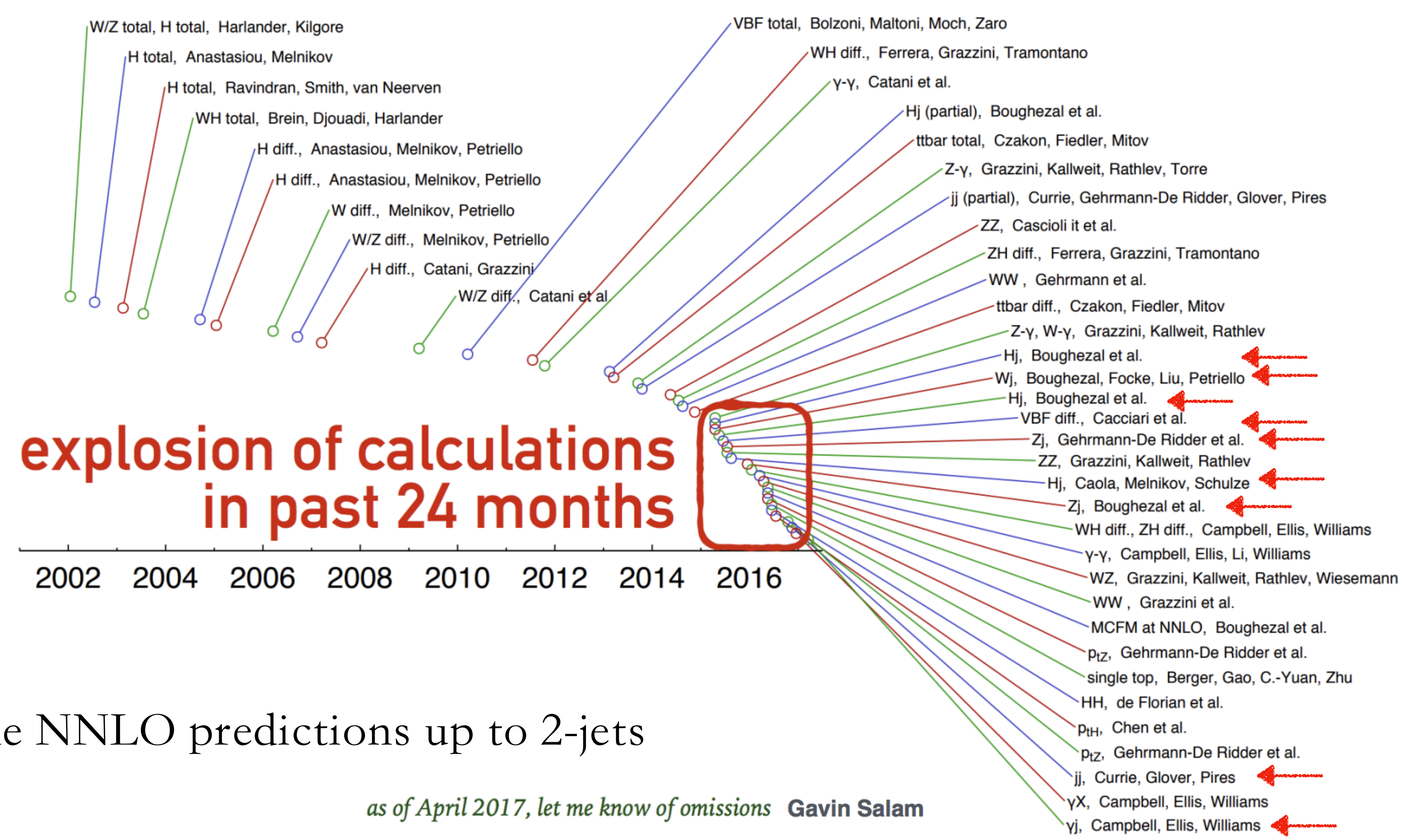
Progress in jet physics at colliders from the LHC to EIC

Xiaohui Liu

Probing Quark-Gluon Matter with Jets
@ BNL 2018

Status of arts

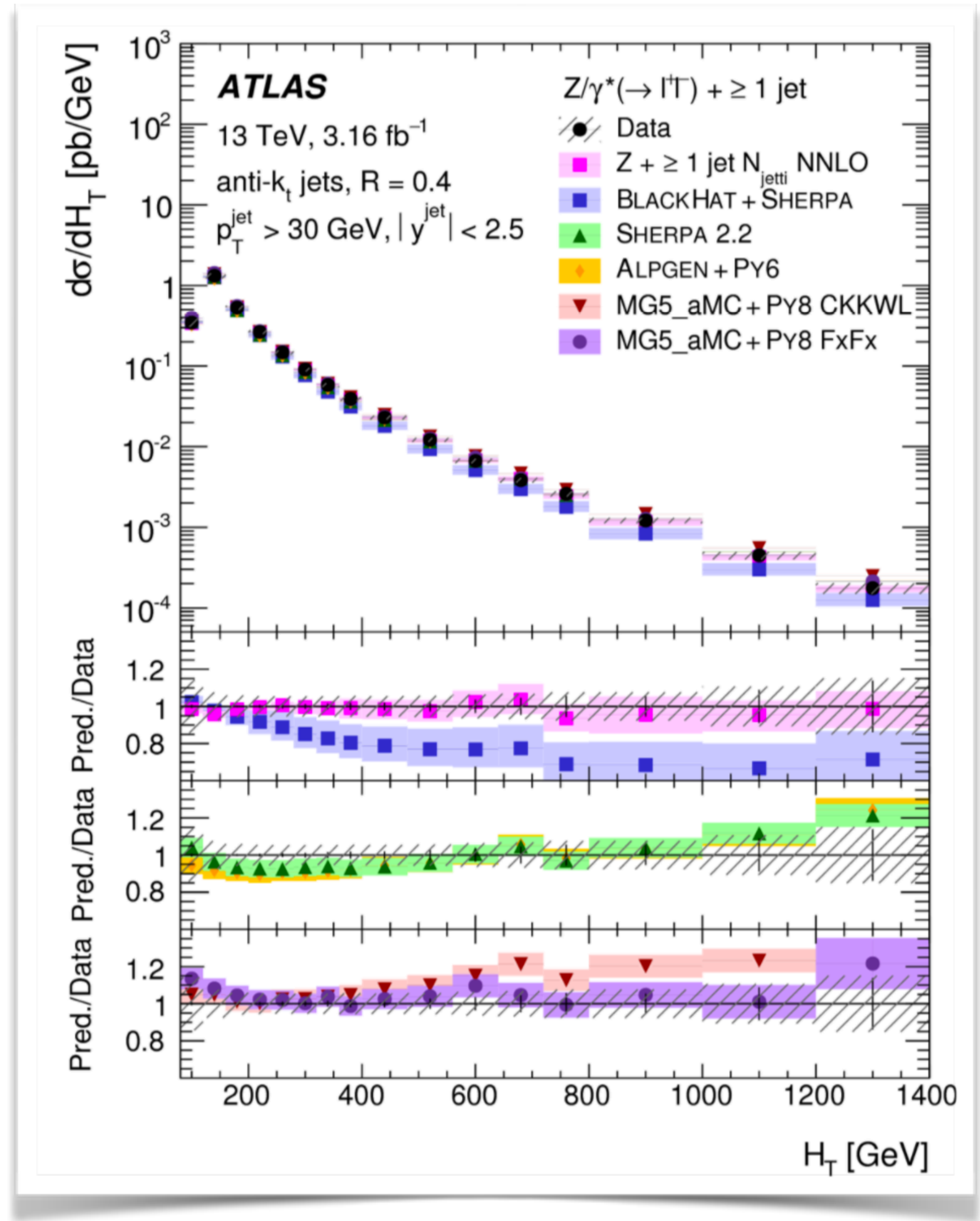
- Rapid progress in jet physics
  - NNLO



Available NNLO predictions up to 2-jets

Status of arts

- Rapid progress in jet physics
  - NNLO Fixed order
    - Improved predictive power
    - Potentially useful for studying jet quenching with V + 1j
    - Good for pT, HT spectrum ⋯ May not be sufficient when sensitive to high multiplicities

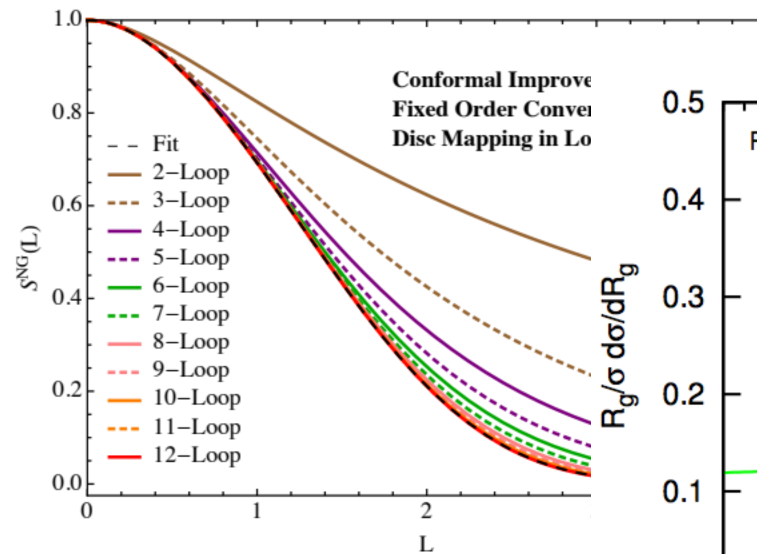


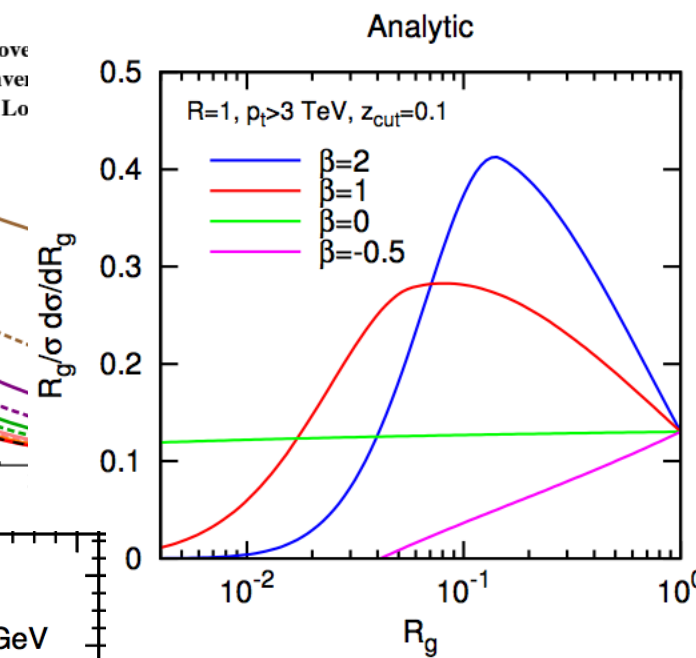
Radja, XL, Petriello

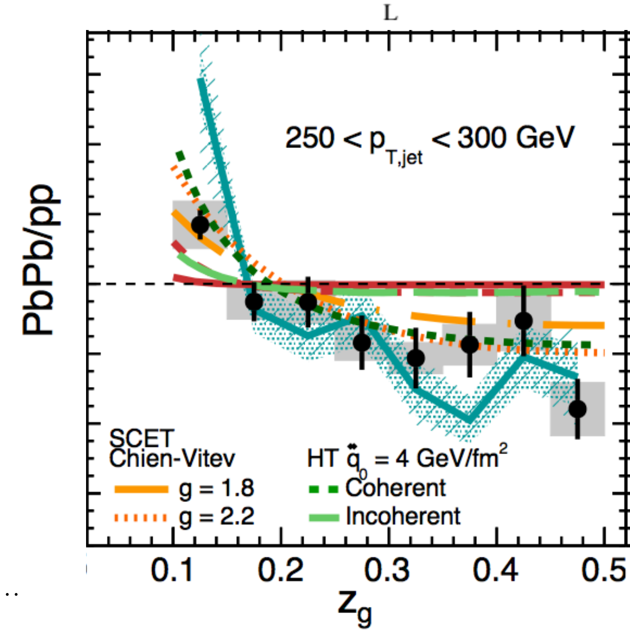
Status of arts

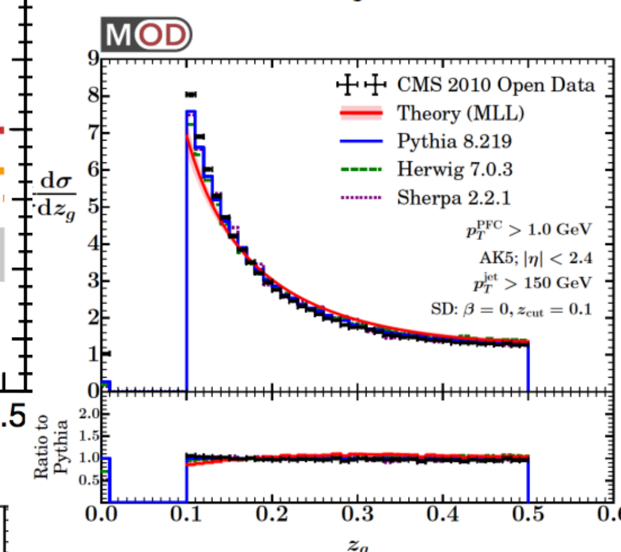
- Rapid progress in jet physics
  - Boost in the jet substructure
    - Sensitive to multiple emissions
    - Resummation

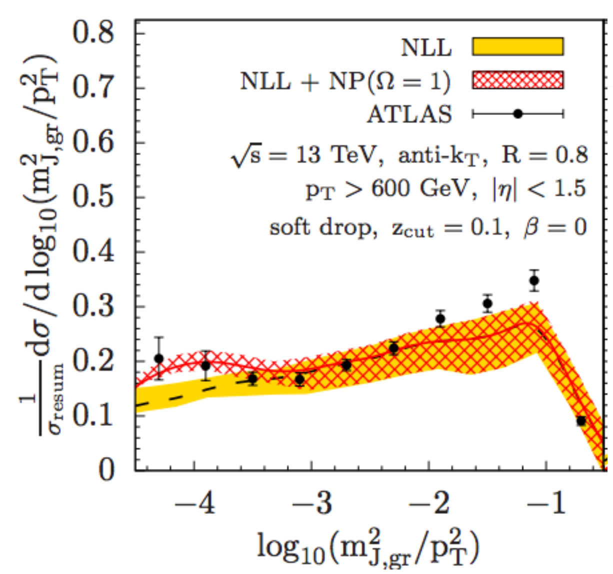
- Jet shape Li, Li, Yuan, Chien, Vitev
- Jet mass/angularity Larkoski, Schwartz, Kang, Lee, Ringer…
- Jet radius Dasgupta, Salam, Soyez, Kang, Ringer, Vitev, Liu, Moch…
- Jet grooming/pruning/trimming Larkoski, Marzani, Soyez, Thaler …
- NGLs Dasgupta, Salam, BMS, Caron-Huot … Becher, Neubert, Shao, Larkoski, Moult, Neill …
- …

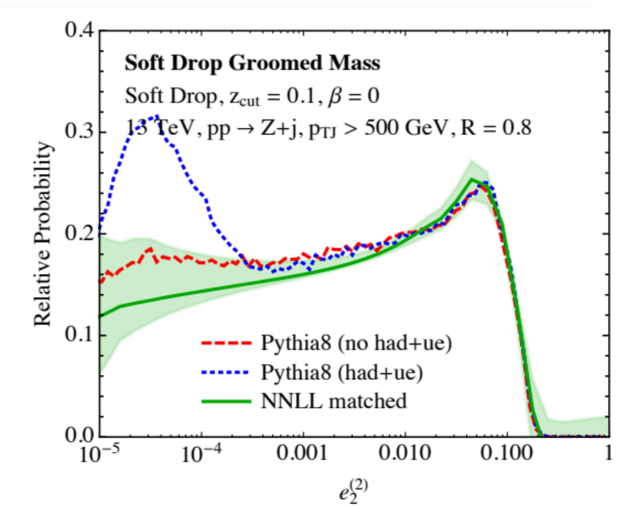












This talk

- Single inclusive jet production
    - small R + threshold
- Jet-lepton p_T imbalance
    - small R + small p_T

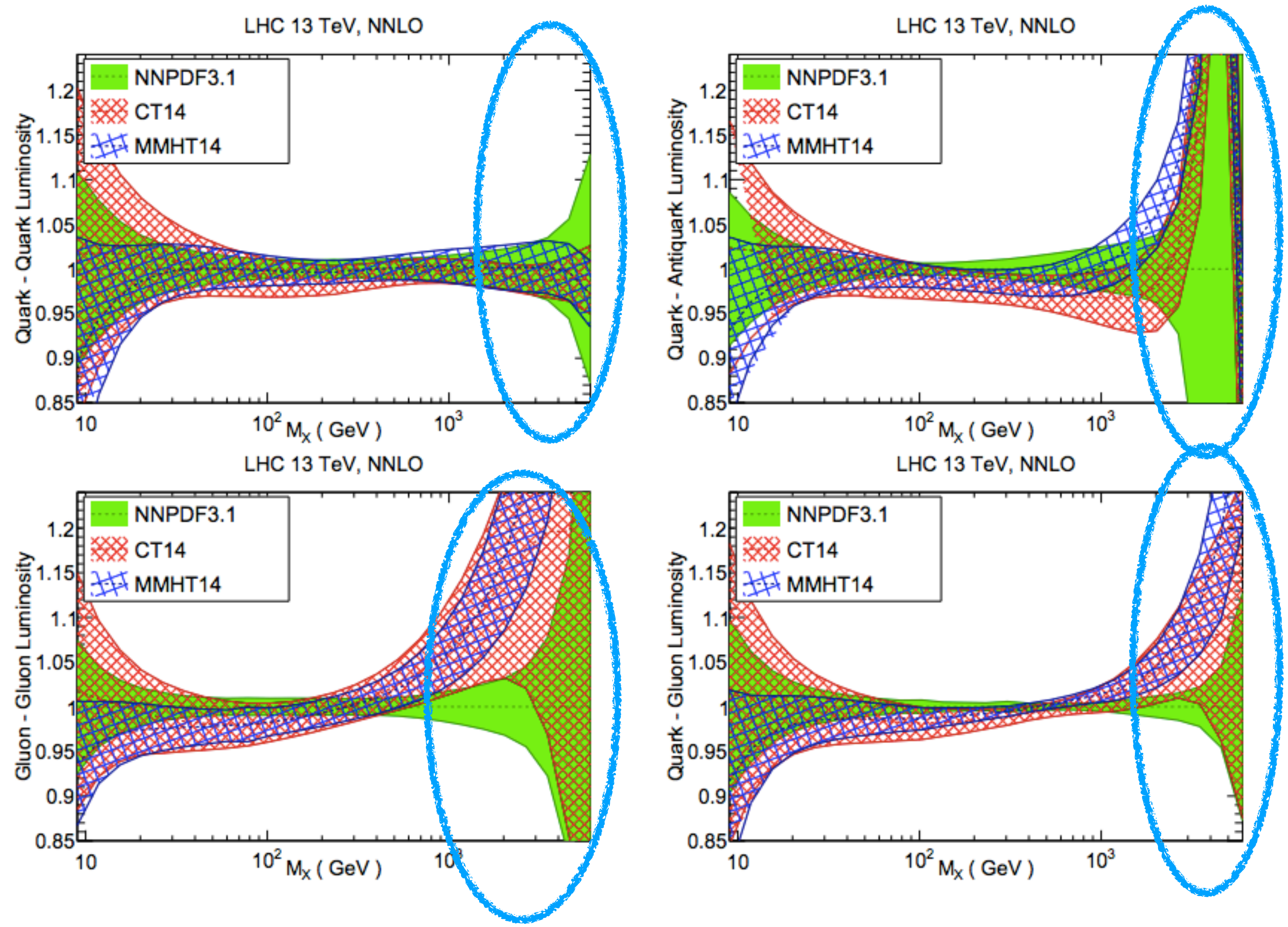
- Jet shape
- Jet mass/angularity
- Jet radius
- Jet grooming/pruning/trimming
- NGLs
- …

Single inclusive jet production

Liu, Felix, Moch

Inclusive jet production

- Benchmark process at the LHC
  - alphas extraction
  - PDF fitting

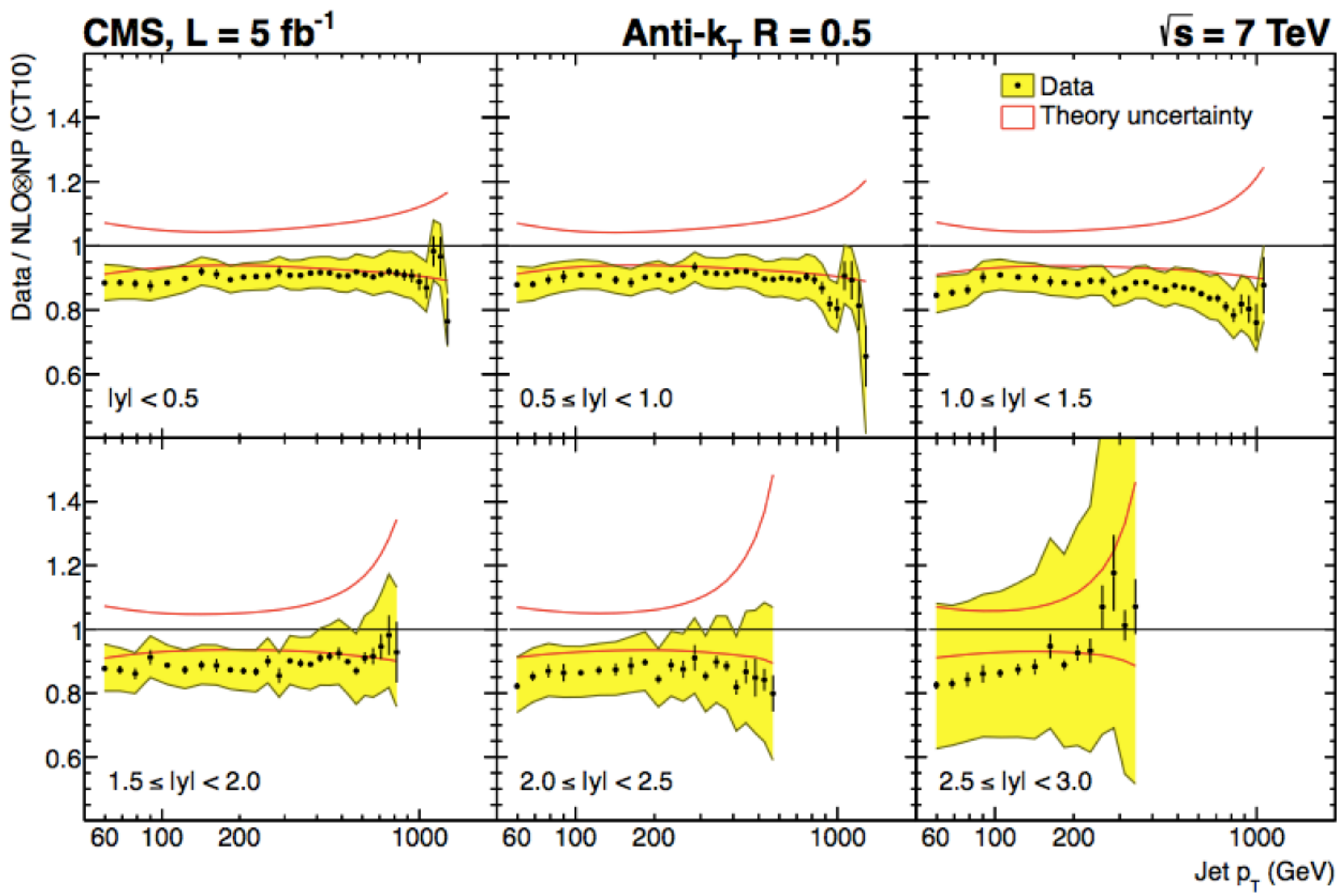


- Still large discrepancies and uncertainties for different PDF fittings in large x region.
- Can be constrained by near future inclusive jet pT analysis.

Inclusive jet production

- Current Status of arts
  - NLO known for decades: NLOJET++ (Nagy, 02), (M)EKS (Ellis, Kunszt, Soper, 92) …

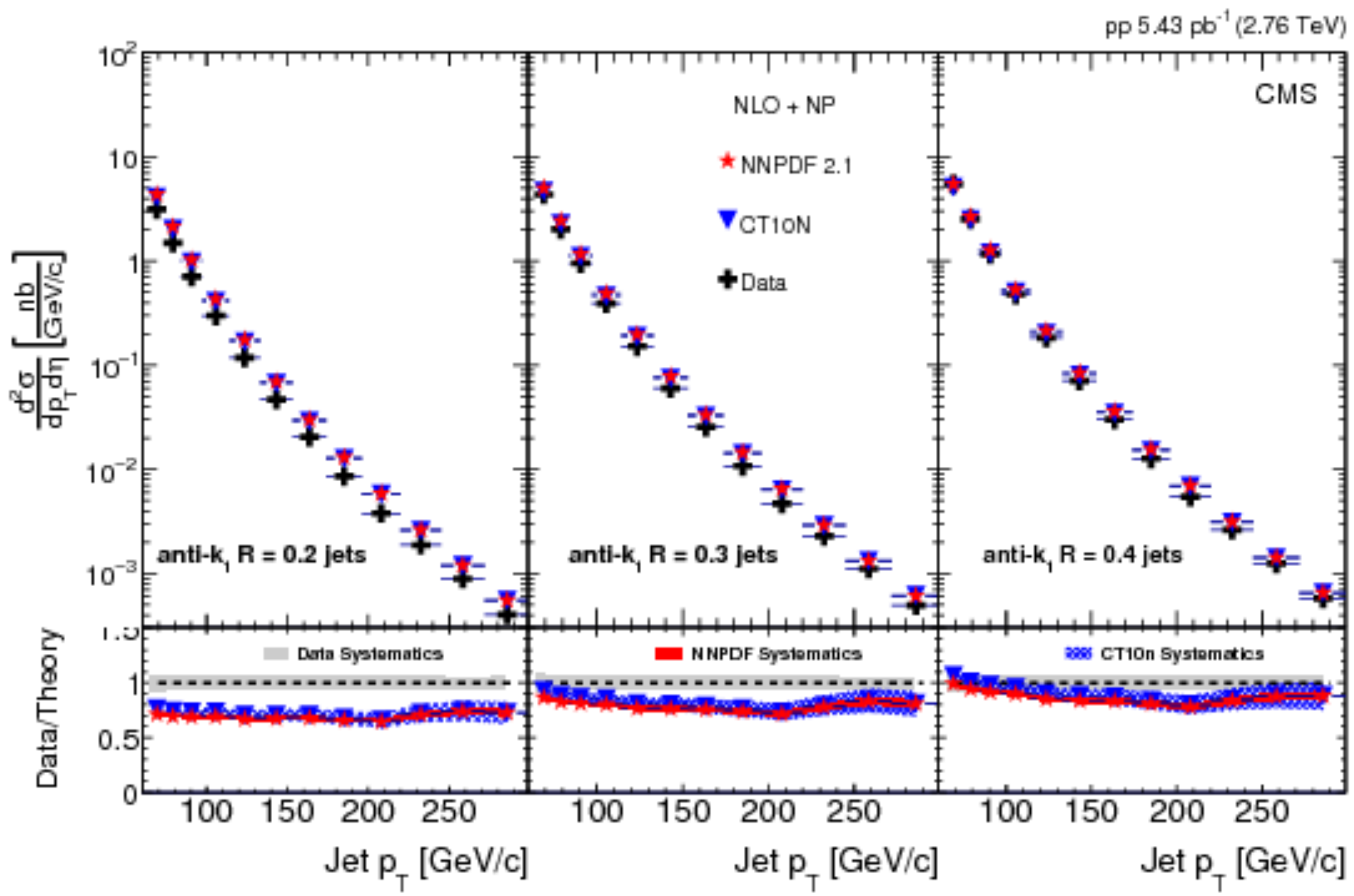
- Theory is systematically higher than the data for all rap bins.
- Also seen in other LHC inclusive jet analyses, with machine energy ranging from 2.76TeV to 13TeV



CMS, 1406.0324

Inclusive jet production

- Current Status of arts
  - NLO known for decades: NLOJET++ (Nagy, 02), (M)EKS (Ellis, Kunszt, Soper, 92) ···

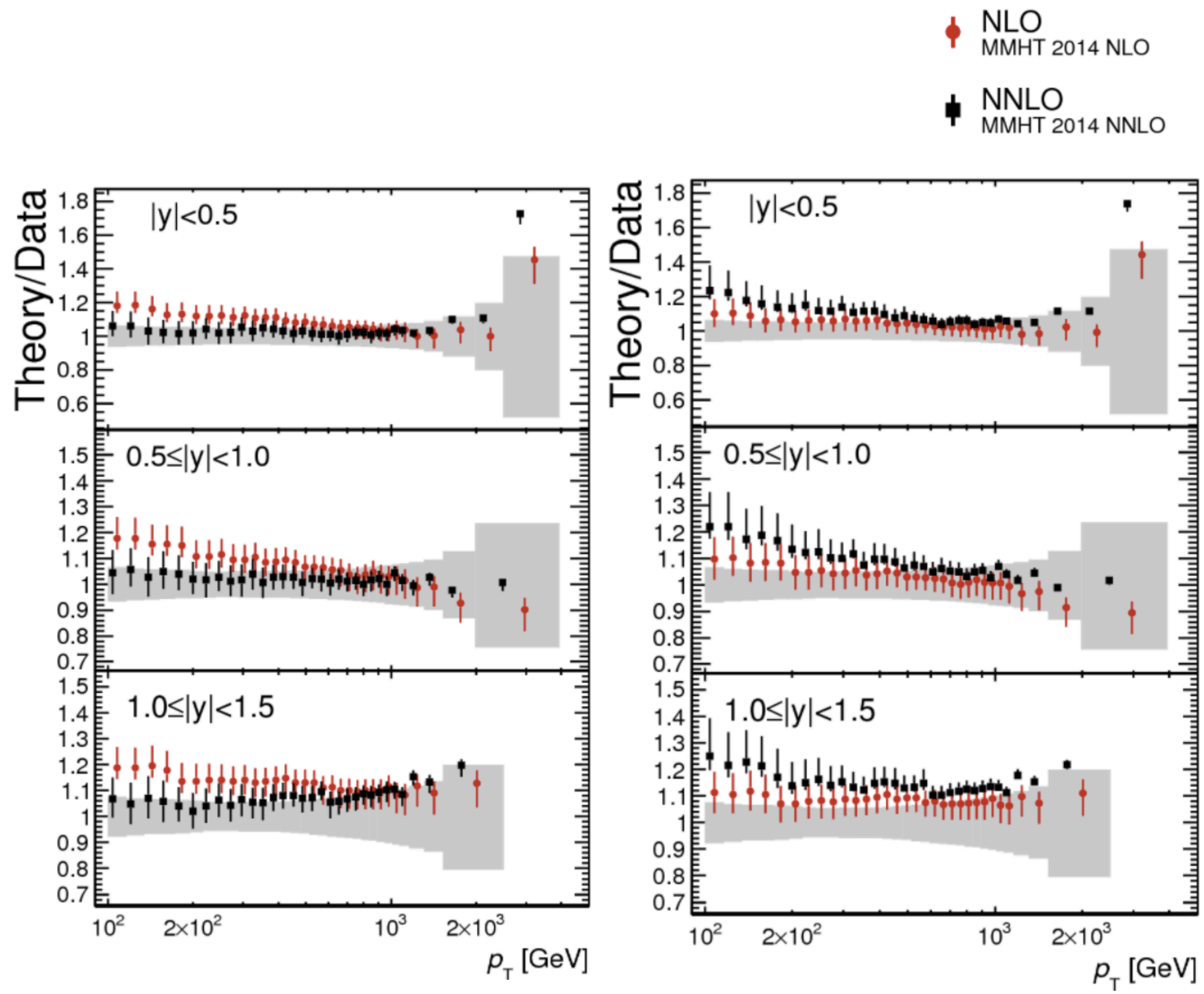


- R-dependent discrepancies between the theory and the data

CMS, 1609.05383

Inclusive jet production

- Current Status of arts
  - NNLO with leading color approximation



- NNLO theory seems to describe the data with a specific scale choice, (still systematically higher than the data).
- Slightly different scale choices lead to different conclusions.

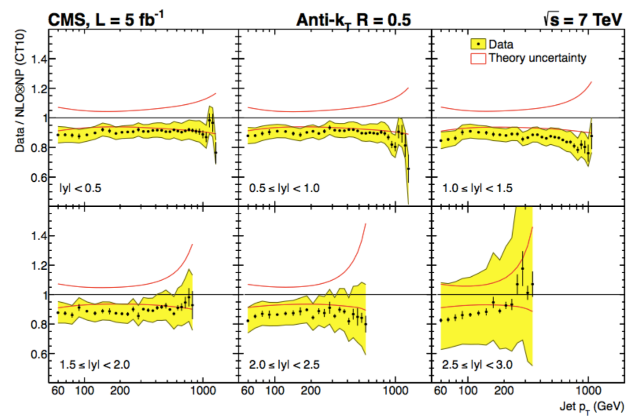
scale = individual jet pT

scale = leading jet pT

Currie, Glover, Pires, 17

Inclusive jet production

- Current Status of arts
  - NLO known for decades: NLOJET++ (Nagy, 02), (M)EKS (Ellis, Kunszt, Soper, 92) $\cdots$
  - NNLO with leading color approximation



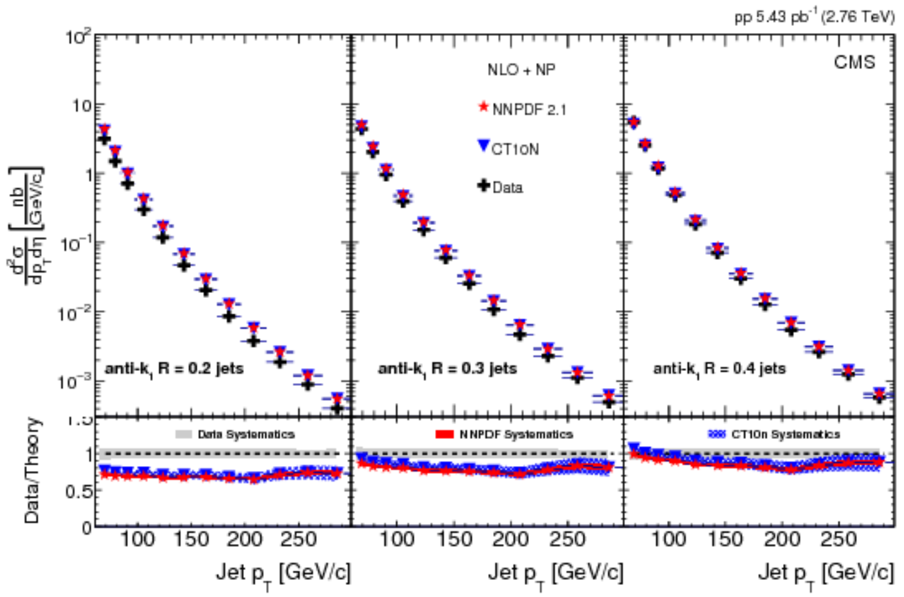
“ While no cuts were applied to all jet datasets included in NNPDF3.1, for the 2011 ATLAS 7 TeV dataset a good agreement between data and theory was obtained when fitting only the central rapidity bin, |yjet| < 0.5. Concurrently, it was found that achieving a good description of the ATLAS 2011 7 TeV data set would be impossible, if all five rapidity bins were included simultaneously and if all cross-correlations among rapidity bins were taken into account accordingly.”

Nocera and Ubiali, 1709.09690

Inclusive jet production

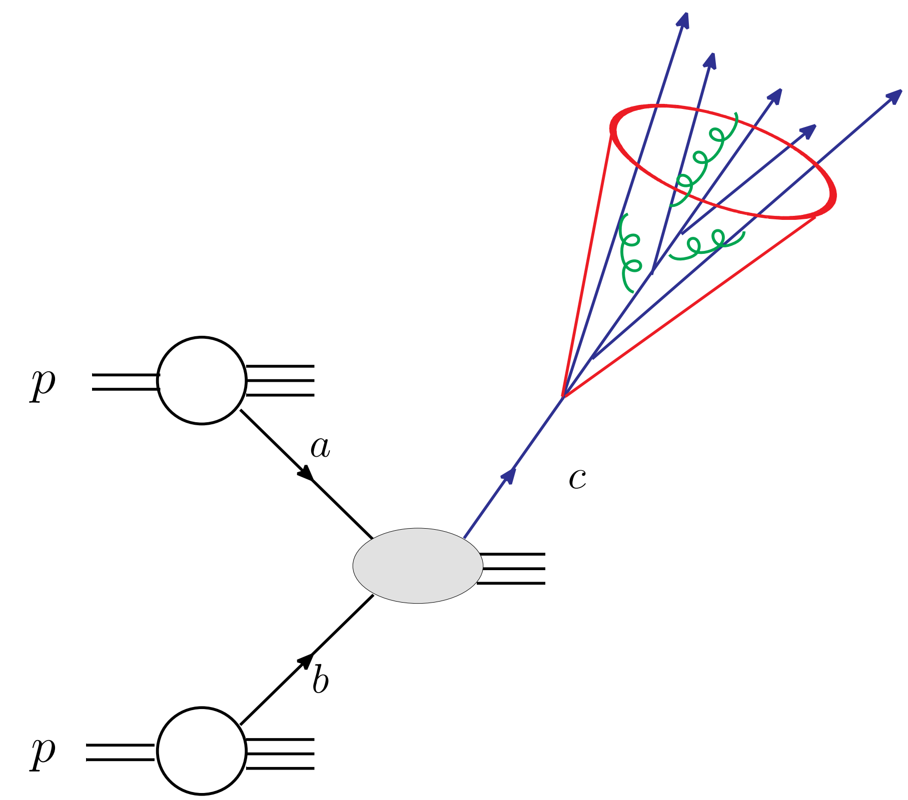
- Current Status of arts
  - persistent tension between NLO/NNLO theory and the LHC data

Large higher order corrections?



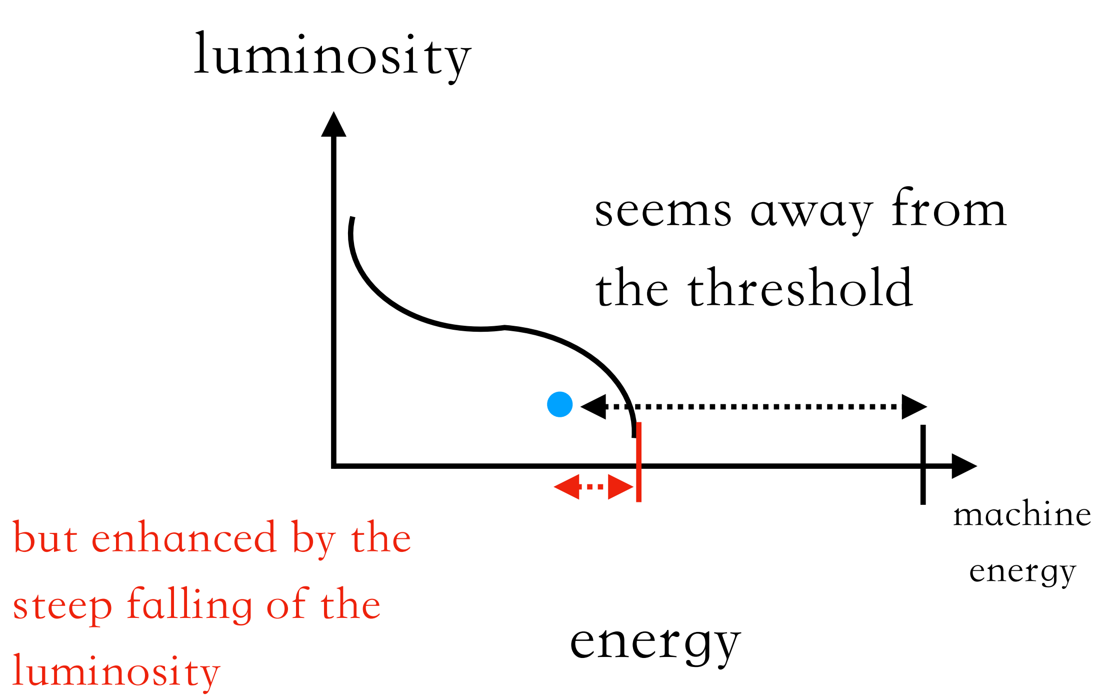
Inclusive jet production

- Possible large corrections
  - small R
  - threshold



$$\sum_{m=0,k=1} \alpha_s^n \left[\frac{\ln^{2n-m-k} z}{z}\right]_+ \ln^m R$$

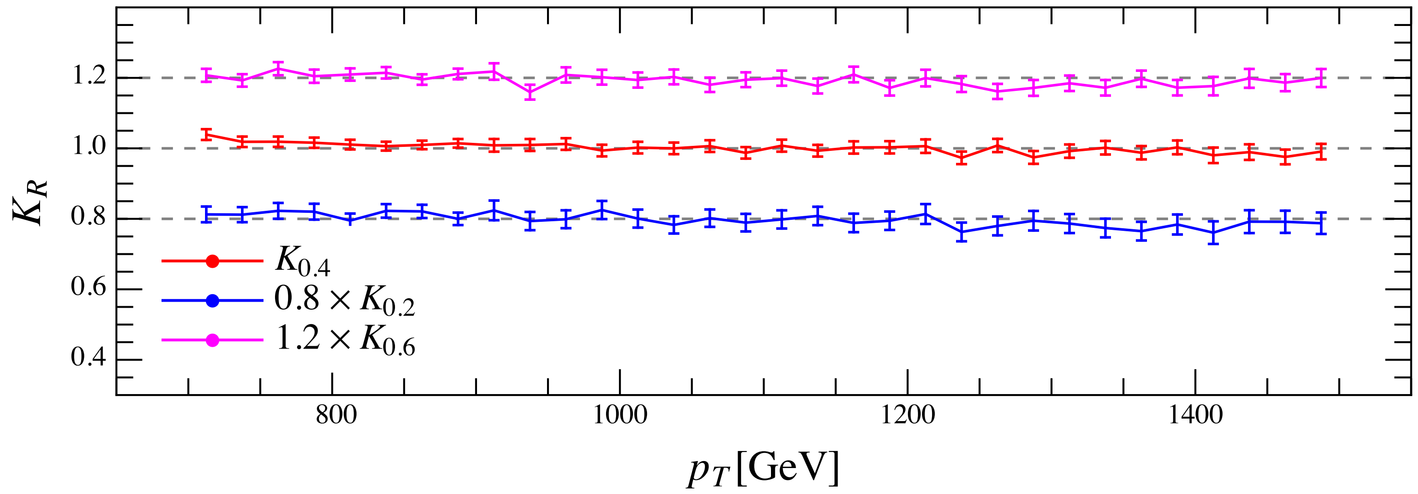
z measures the invariant mass outside the signal jet, characterize the distance to the threshold



Inclusive jet production

- Possible large corrections
  - small R
  - threshold

NLO singular /NLO full



$$\sum_{m=0,k=1} \alpha_s^n \left[\frac{\ln^{2n-m-k} z}{z} \right]_+ \ln^m R$$

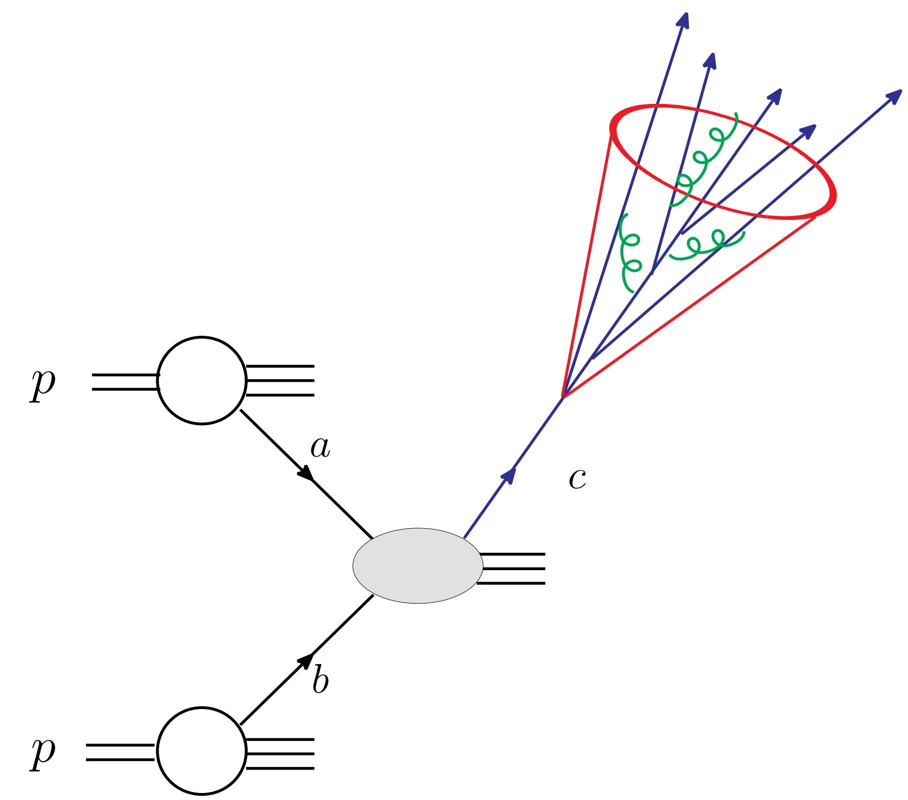
singular terms make up the dominant bulk of the NLO result.

Or, threshold gives a very good approximation of the full calculation

Inclusive jet production

- Factorization and resummation

$$\sum_{m=0,k=1} \alpha_s^n \left[\frac{\ln^{2n-m-k} z}{z}\right]_+ \ln^m R$$



$$\ln R = \ln \frac{p_T R}{p_T} = \ln \frac{p_T R}{\mu} + \ln \frac{\mu}{p_T}$$

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

derived within SCET + Becher, Neubert, Rothen, Shao $\cdots$

Inclusive jet production

- Factorization and resummation

Fixed Order

Resummation

LO	1					
NLO	$\alpha_s L^2$	$\alpha_s L$	α_s			
NNLO	$\alpha_s^2 L^4$	$\alpha_s^2 L^3$	$\alpha_s^2 L^2$	$\alpha_s^2 L$	α_s^2	
...	...	...	...	...	...	
N^{k}LO	$\alpha_s^k L^{2k}$	$\alpha_s^k L^{2k-1}$	$\alpha_s^k L^{2k-2}$	$\alpha_s^k L^{2k-3}$	$\alpha_s^k L^{2k-4}$	...

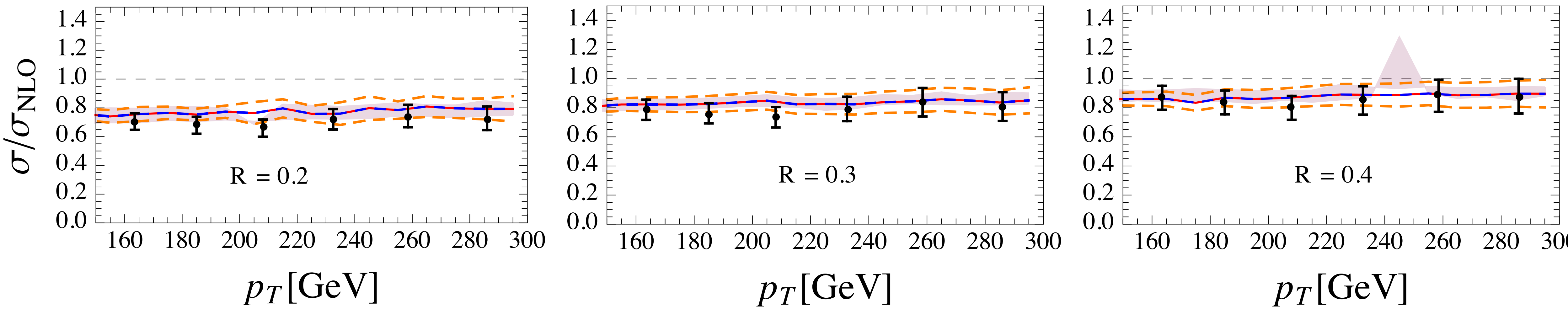
LL NLL NNLL

$$\sigma = \sigma_{\mathrm{NLO}} - \sigma_{\mathrm{sin.}} + \sigma_{\mathrm{NLL}}$$

Inclusive jet production

- Phenomenology
  - compare with 2.76 TeV LHC data

with NLO CT10 PDF sets
NP effects included



- NLO consistently higher than the data for all choices of radii.
- NLL + NLO agrees very well with the data

XL, Moch, Ringer, 2017

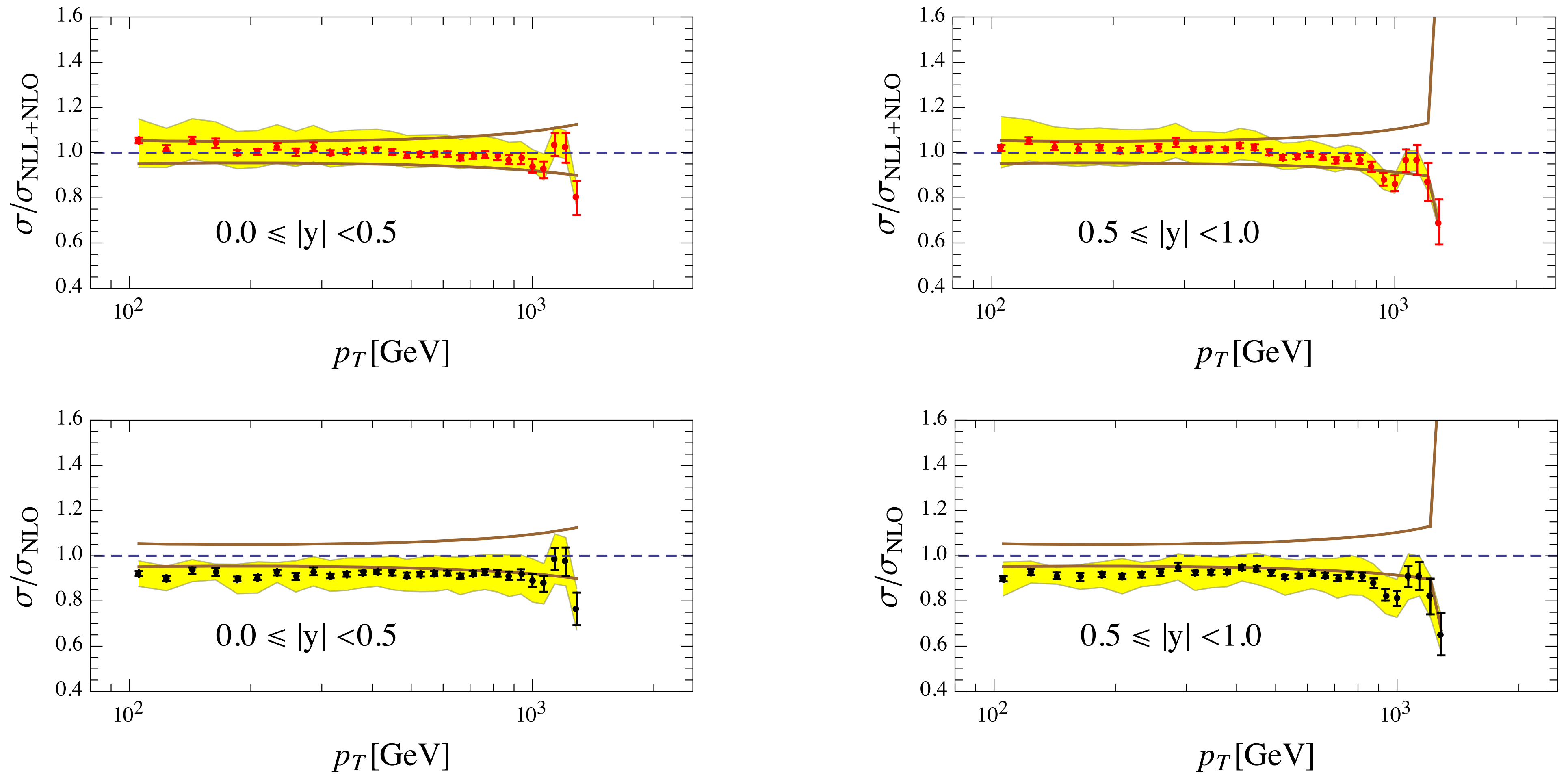
NLO using MEKS, Gao, et. al. 2012

Inclusive jet production

- Phenomenology

  - compare with 7 TeV LHC data

with NLO CT10 PDF sets
NP effects included

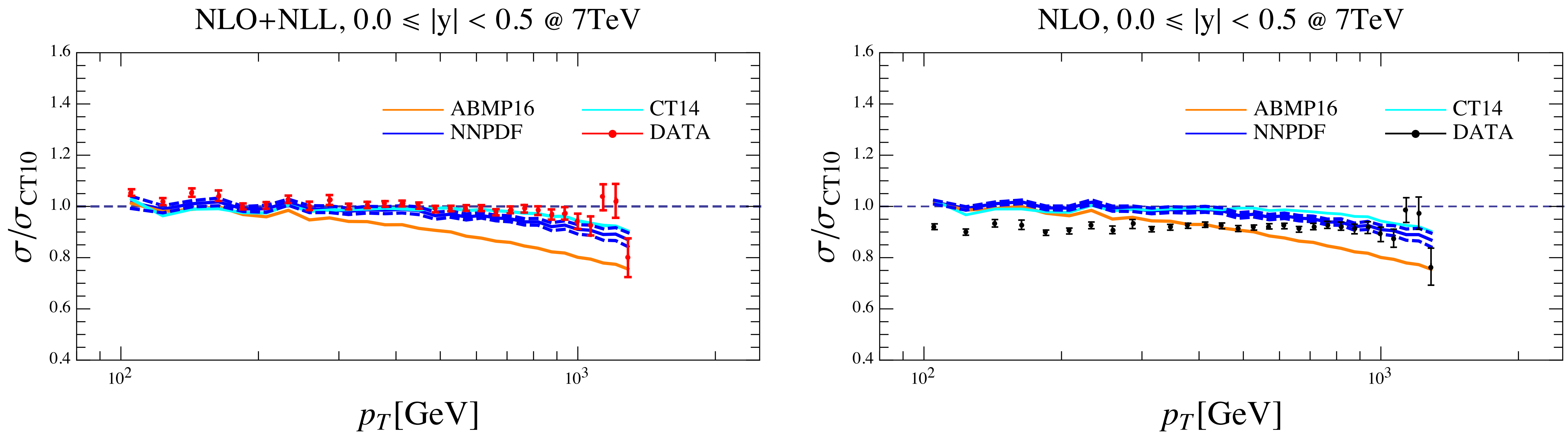


similar story
for higher
rapidity bins

- NLO is higher than the data while NLL + NLO agrees well

Inclusive jet production

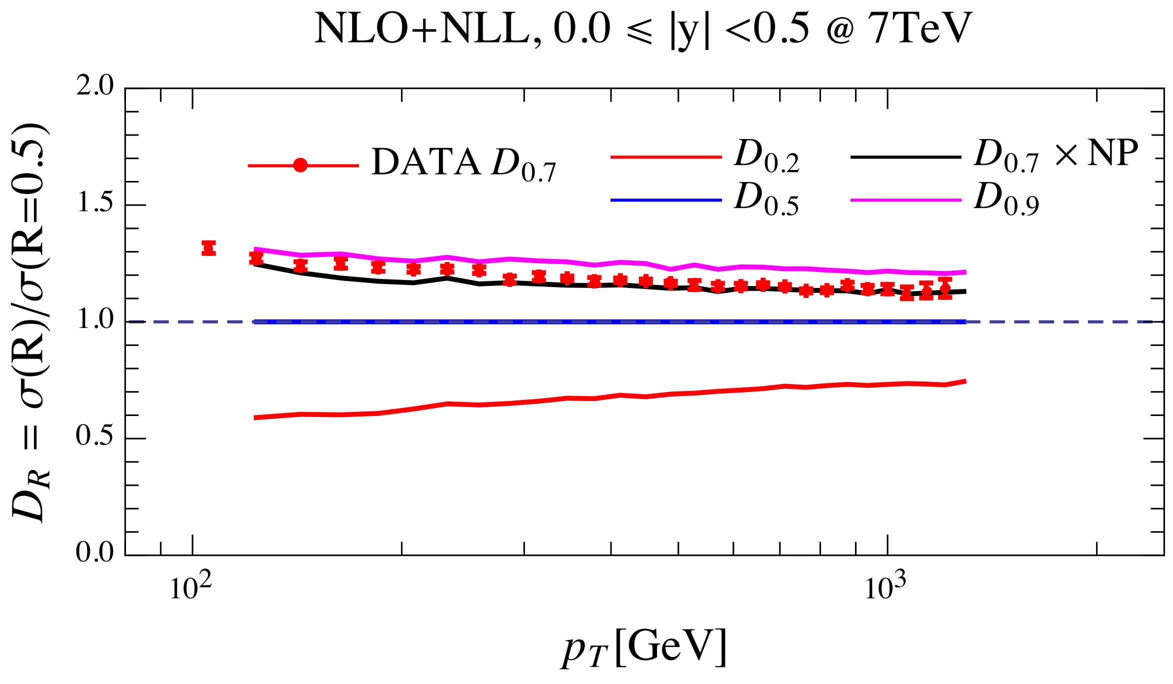
- Phenomenology
  - Impact of PDFs

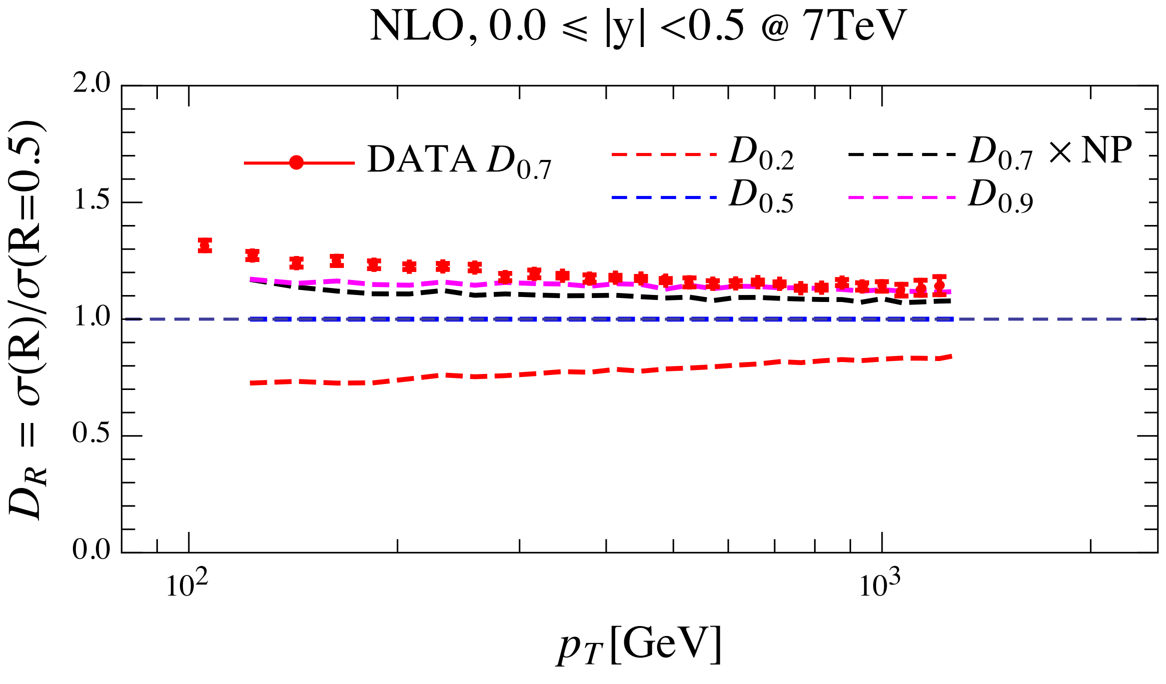


- PDF uncertainty is small
- Considering the impact of PDFs does not change the conclusion: resummation improves the theory prediction quite a lot.

Inclusive jet production

- Phenomenology
  - compare with 7 TeV LHC data





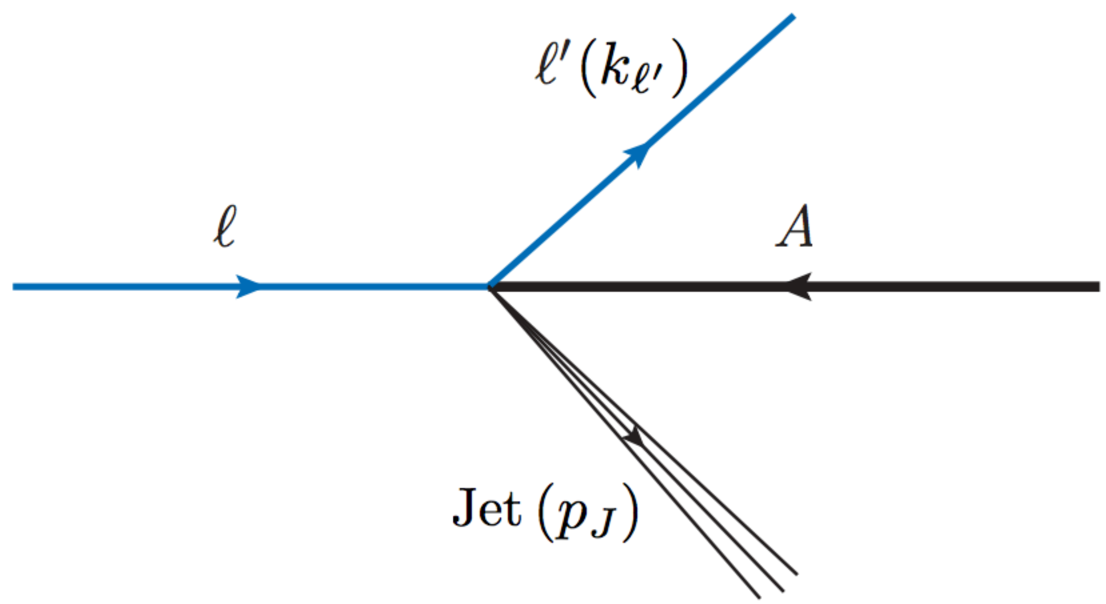
- Take the ratio to reduce the PDF impacts
- NLO does not describe the data while NLO + NLL does a much better job

Jet-lepton pT imbalance

Liu, Felix, Yuan in preparation

Jet-lepton pT imbalance

- Good for spin asymmetries and eA collisions

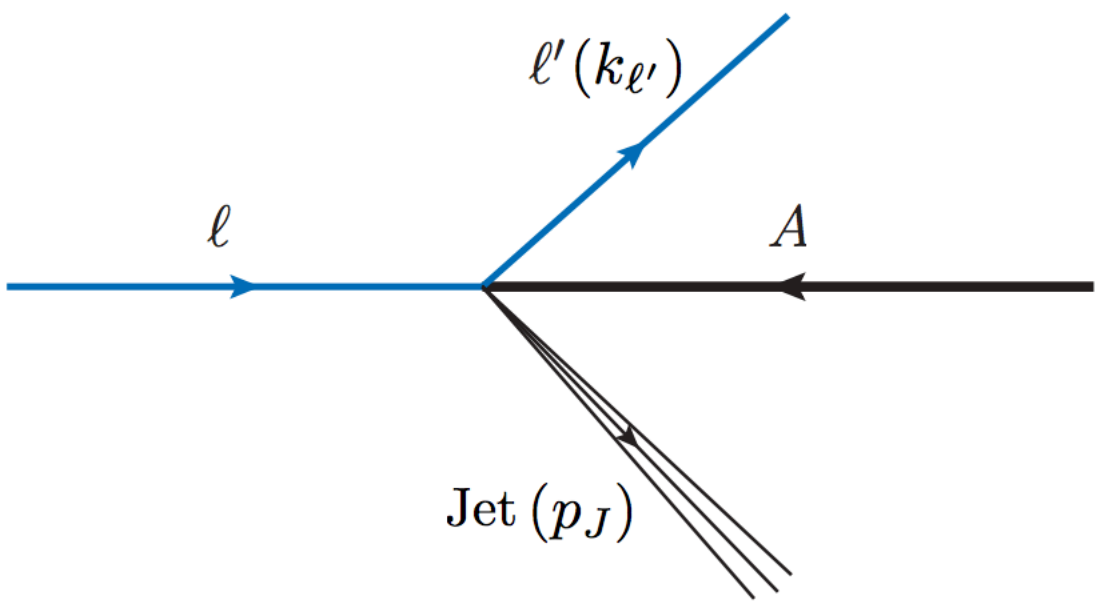


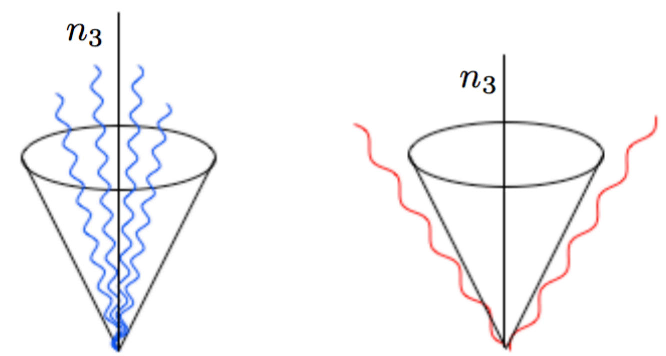
COM or laboratory frame;
analogy to pp collisions

Requires TMD resummation and the small jet radius resummation

Jet-lepton pT imbalance

- Factorization





$$\frac{d\sigma}{dy_{\ell'}d^2k_{\perp\ell'}d^2q_\perp} = H_q(k_{\ell'\perp},\mu)\, J_q(k_{\ell'\perp}R,\mu)$$

$$\int d^2k_\perp d^2\lambda_{1\perp} d^2\lambda_{2\perp}\, x f_q(x,k_\perp,\mu,\nu)\, S_{gl}(\lambda_{1\perp},\mu,\nu)\, S_{sc}(\lambda_{2\perp}R,\mu)\, \delta^{(2)}(q_\perp - k_\perp - \lambda_{1\perp} - \lambda_{2\perp})$$

Rapidity regulator by Chiu, Jain, Neill, Rothstein

Jet-lepton pT imbalance

- Factorization

All components have been calculated to NLO

$$\hat{f}_{q/q}(x,b,\mu) = \delta(1-x) + \frac{\alpha_s}{2\pi}C_F\left\{\left[\frac{2}{\eta}\left(\frac{1}{\epsilon}+\ln\frac{\mu^2}{\mu_b^2}\right)+\frac{2}{\epsilon}\ln\frac{\nu}{p^+}+\frac{3}{2\epsilon}\right]\delta(1-x)\right.$$
$$+\left(-\frac{1}{\epsilon}-\ln\frac{\mu^2}{x^2\mu_b^2}\right)P_{qq}(x)$$
$$\left.+\ln\frac{\mu^2}{\mu_b^2}\left(2\ln\frac{\nu}{p^+}+\frac{3}{2}\right)\delta(1-x)+1-x\right\}.$$

where $\mu_b = 2e^{-\gamma_E}/b$. The hard function

$$H_q(p_{\ell\perp},\mu) = 1+\frac{\alpha_s}{2\pi}C_F\left[-\frac{2}{\epsilon^2}-\frac{1}{\epsilon}\left(2\ln\frac{\mu^2}{k_{\ell\perp}^2}+3\right)-\ln^2\frac{\mu^2}{k_{\ell\perp}^2}-3\ln\frac{\mu^2}{k_{\ell\perp}^2}-8+\frac{\pi^2}{6}\right],$$

and the jet function

$$J_q(p_{\ell\perp}R,\mu) = 1+\frac{\alpha_s}{2\pi}C_F\left[\frac{1}{\epsilon^2}+\frac{1}{\epsilon}\left(\ln\frac{\mu^2}{k_{\ell\perp}^2R^2}+\frac{1}{2}\right)+\frac{1}{2}\ln^2\frac{\mu^2}{k_{\ell\perp}^2R^2}+\frac{3}{2}\ln\frac{\mu^2}{k_{\ell\perp}^2R^2}+\frac{13}{2}-\frac{3\pi^2}{4}\right].$$

The soft functions are

$$\hat{S}_q^{\rm sc}(b,\mu,\nu R) = 1+\frac{\alpha_s}{2\pi}C_F\left[-\frac{1}{\epsilon^2}-\frac{1}{\epsilon}\ln\frac{\mu^2}{\mu_b^2R^2}-\frac{1}{2}\ln^2\frac{\mu^2}{\mu_b^2R^2}+\frac{\pi^2}{12}\right]$$

and

$$\hat{S}_q^{\rm gl}(b,\mu,\nu) = 1+\frac{\alpha_s}{2\pi}C_F\left[\frac{2}{\eta}\left(-\frac{1}{\epsilon}-\ln\frac{\mu^2}{\mu_b^2}\right)+\frac{2}{\epsilon^2}+\frac{1}{\epsilon}\left(-\ln\frac{\nu^2}{\mu^2}+\ln\frac{\mu^2}{\mu_b^2}+2y_J\right)\right.$$
$$\left.-\ln\frac{\mu^2}{\mu_b^2}\ln\frac{\nu^2}{\mu_b^2}+2y_J\ln\frac{\mu^2}{\mu_b^2}+\ln^2\frac{\mu^2}{\mu_b^2}-\frac{\pi^2}{6}\right].$$

- Each function depends only on one single scale.
- Rapidity regulator only in the beam and the global soft function.
- Can check to see all poles cancel.
- Stay tuned for numerics.

Conclusions

- Framework allows to do small R resummation joint with threshold and small pT.
- Can achieve high precision in the future, eg. NNLO + NNLL.
- Applied to the inclusive jet production at the LHC.
- Tensions reduced when joint resummation is considered.