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

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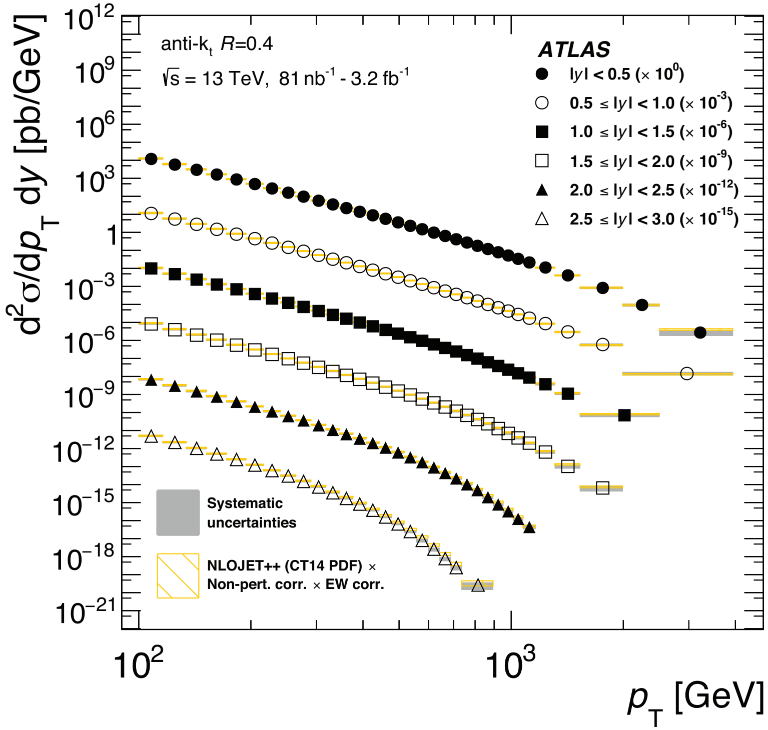
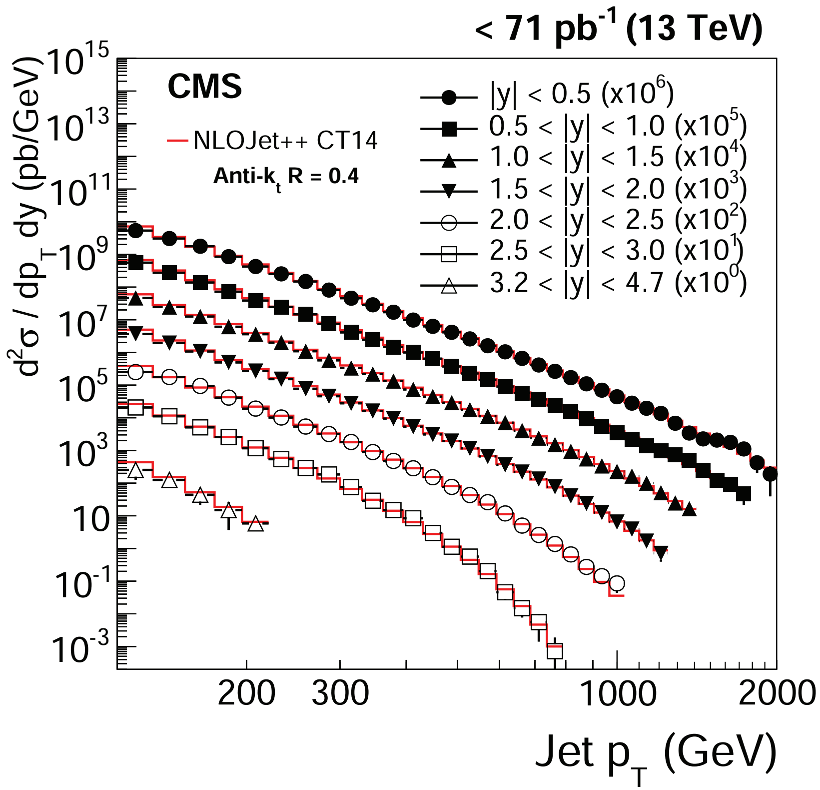
Based on work done in collaboration with:

- *Threshold and jet radius joint resummation for single-inclusive jet production*
  Xiaohui Liu, S. M. and Felix Ringer Phys.Rev.Lett. 119 (2017) no.21, 212001
  arXiv:1708.04641

- *Phenomenology of single-inclusive jet production with jet radius and threshold resummation*
  Xiaohui Liu, S. M. and Felix Ringer arXiv:1801.07284

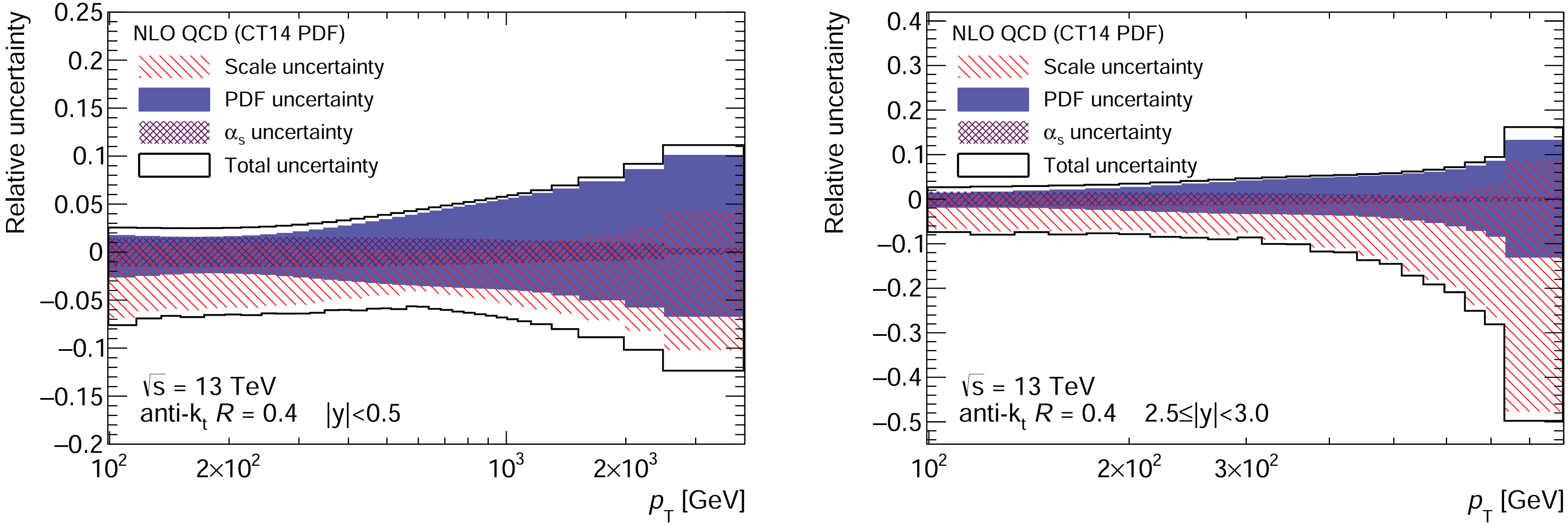
Single-inclusive jet production





- Double differential cross section for $pp \to \text{jet} + X$ at $\sqrt{s} = 13$ TeV
  - transverse momentum p_T and rapidity y of signal-jet
  - ATLAS arXiv:1711.02692 (left), CMS arXiv:1605.04436 (right)
- Comparison with NLO perturbative QCD predictions (NLOJET++ Nagy)
  - impressive agreement over several orders of magnitude

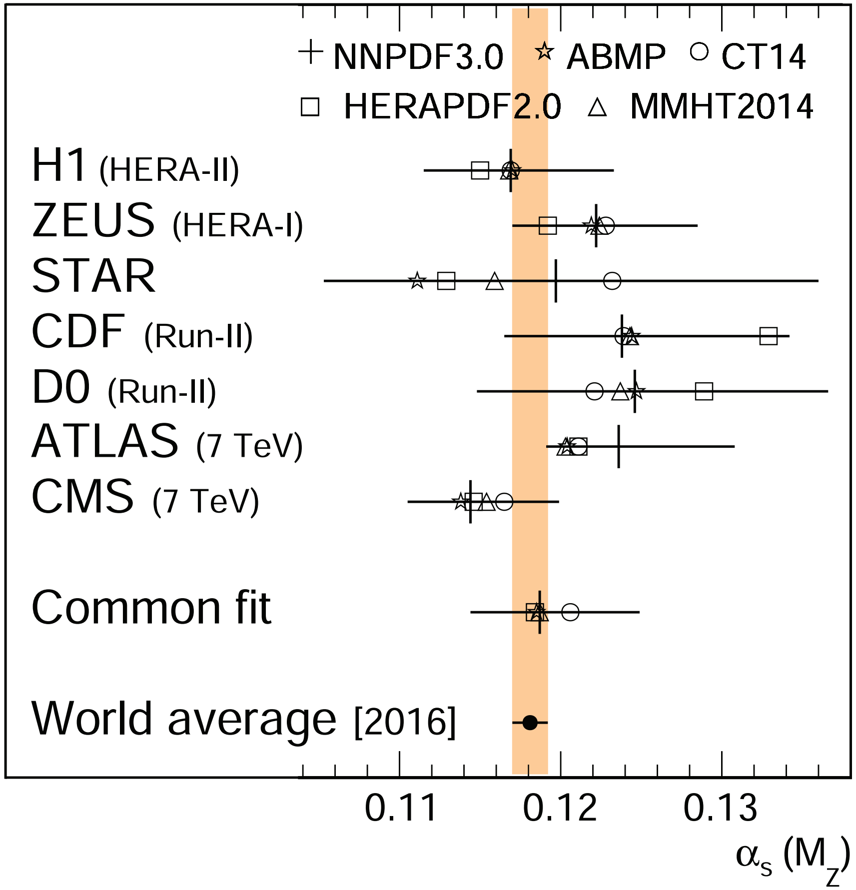
Uncertainties



- Relative QCD uncertainties in single-inclusive jet cross-sections at NLO
  - first and last $|y|$ bins for inclusive jet measurement
  - uncertainties due to renormalization and factorization scales, μ_R, μ_F, the strong coupling α_s with $\Delta\alpha_s = 0.0015$ and PDFs CT14
- Sizable uncertainties
  - $\mathcal{O}(10\%)$ for central rapidities $|y| < 0.5$
  - $\mathcal{O}(30 - 40\%)$ forward $2.5 \leq |y| < 3.0$ at large p_T

Uses of inclusive jet data

- Dermination of $\alpha_s(M_Z)$ and PDFs (gluon at medium to large x)
  - partonic cross sections $\hat{\sigma}_{ij \to \text{jet}} \propto \alpha_s^2(\mu)$
  - jet cross section $d\sigma_{pp \to \text{jet}} = \alpha_s^2(\mu) \sum_{ij} f_i(\mu) \otimes f_j(\mu) \otimes [\dots]$



- $\alpha_s(M_Z)$ at NLO in QCD from inclusive jet cross section data

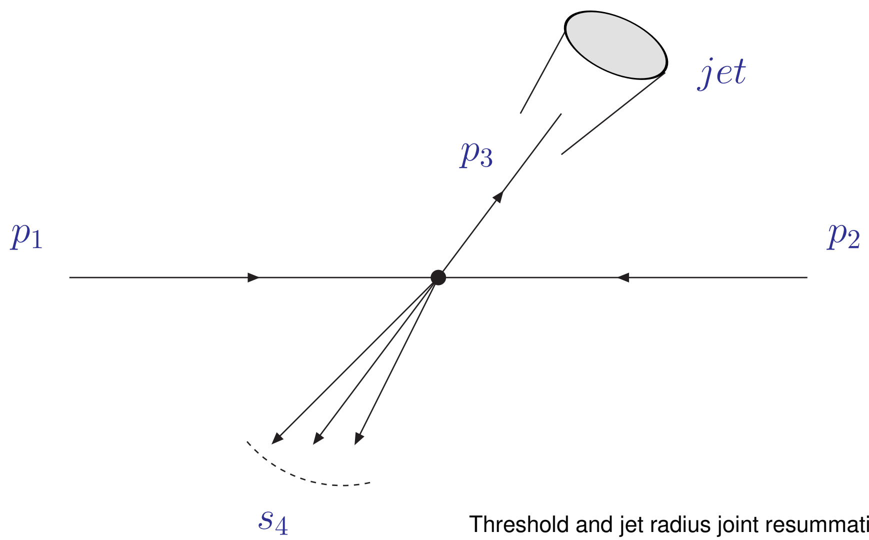
  Britzger, Rabbertz, Savoiu, Sieber '17
- correlations between PDFs and $\alpha_s(M_Z)$ are important

QCD factorization

- Double differential cross section for $pp \to \text{jet} + X$
  - transverse momentum p_T and rapidity η of signal-jet

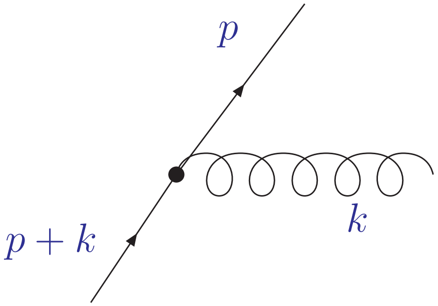
$$\frac{p_T^2 \mathrm{d}^2\sigma}{\mathrm{d}p_T^2 \mathrm{d}\eta} = \sum_{i_1 i_2} \int_0^{V(1-W)} \mathrm{d}z \int_{\frac{VW}{1-z}}^{1-\frac{1-V}{1-z}} \mathrm{d}v \, x_1^2 \, f_{i_1}(x_1) \, x_2^2 \, f_{i_2}(x_2) \, \frac{\mathrm{d}^2\hat{\sigma}_{i_1 i_2}}{\mathrm{d}v \, \mathrm{d}z}(v, z, p_T, R)$$

- PDFs f_i and variables $V = 1 - p_T e^{-\eta}/\sqrt{S}$, $VW = p_T e^{\eta}/\sqrt{S}$
- Partonic cross sections $\hat{\sigma}_{i_1 i_2}$ dependent on partonic kinematic variables on $s = x_1 x_2 S$, $v = u/(u+t)$ and partonic threshold $z = s_4/s \to 0$
- Mandelstam variables $s = (p_1 + p_2)^2$, $t = (p_1 - p_3)^2$ and $u = (p_2 - p_3)^2$ with kinematics constraint $s + t + u = s_4$



Threshold logarithms

- Soft and collinear regions of phase space
  - double logarithms from singular regions in Feynman diagrams
  - propagator vanishes for: $E_g = 0$, soft $\theta_{qg} = 0$ collinear



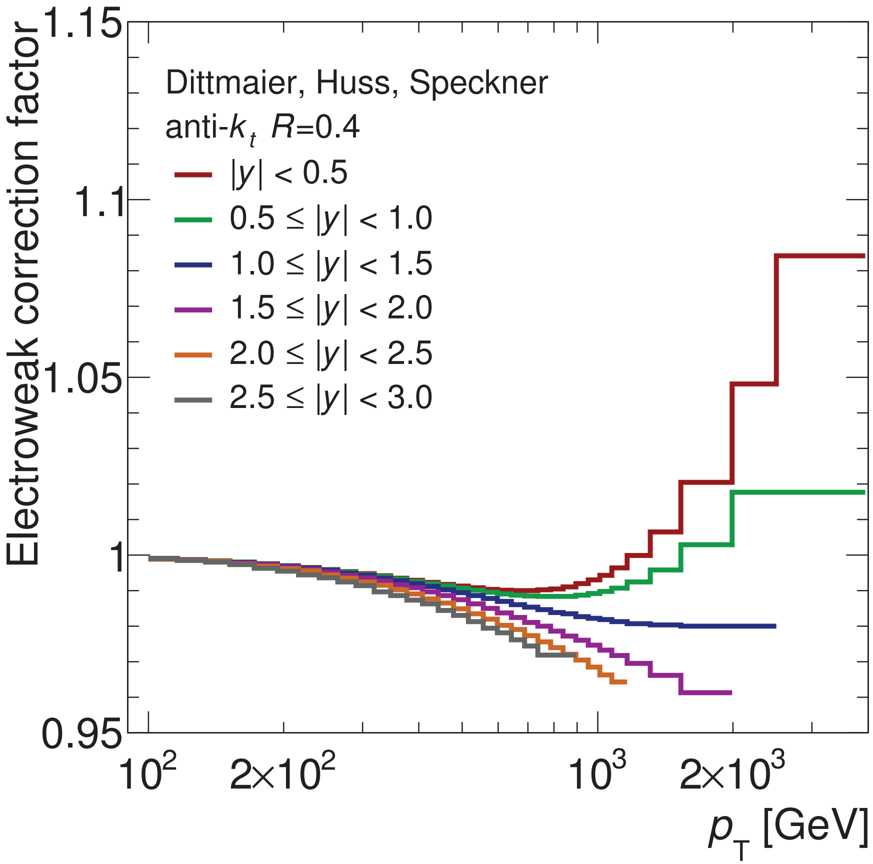
$$\frac{1}{(p+k)^2} = \frac{1}{2p \cdot k} = \frac{1}{2E_q E_g (1 - \cos\theta_{qg})}$$

$$\alpha_s \int d^4k \frac{1}{(p+k)^2} \longrightarrow \alpha_s \int dE_g \, d\sin\theta_{qg} \, \frac{1}{2E_q E_g (1 - \cos\theta_{qg})}$$

$$\longrightarrow \alpha_s \ln^2(\dots)$$

- Large double-logarithmic corrections $\ln(\dots) \gg 1$ near threshold
- Single-inclusive jet production with threshold logarithms $\alpha_s^n (\ln^{2n-1}(z)/z)_+$ for $z = s_4/s \to 0$
  - *positive* corrections enhance partonic cross sections $\hat{\sigma}_{i_1 i_2}$
  - long history of resummation Sterman '87; Catani, Trentadue '88; ...
- Same for weak radiative corrections: positive corrections for large $p_T \gg M_W$ Dittmaier, Huss, Speckner '12

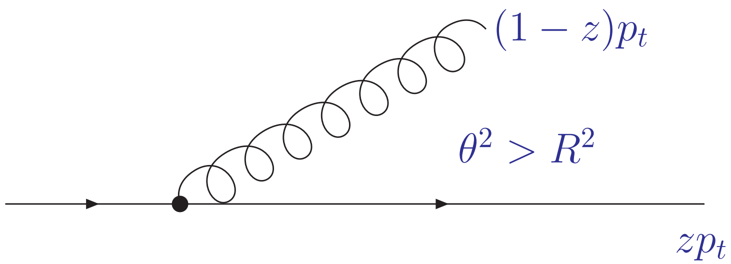
Electroweak corrections at NLO



- Electroweak correction factors for inclusive jet cross-section as function of jet p_T for all $|y|$ bins Dittmaier, Huss, Speckner '12
  - negative corrections $\mathcal{O}(1-3\%)$ for p_T in range $\mathcal{O}(\text{few } 100)$ GeV
  - sizeable (positive) effect $\mathcal{O}(10\%)$ at large $p_T \gg M_W$

Jet radius logarithms (I)

- Collinear singularity when the jet becomes very narrow
  - partons radiated outside of jet (not recombined with jet by chosen jet algorithm) become more and more collinear to emitter
- Example
  - loss of transverse momentum for leading jet
  - quasi-collinear branching of quark with transverse momentum p_T



$$\delta p_T = (1-z)p_T - p_T = -zp_T \text{ for } (1-z) > z$$
$$\delta p_T = (1-z)p_T - p_T = -zp_T \text{ for } z > (1-z)$$

- Perturbative radiation loss for average $\langle \delta p_T \rangle_{\mathrm{q}}$

$$\langle \delta p_T \rangle_{\mathrm{q}} = p_T \frac{\alpha_s}{2\pi} \int_{R^2}^{1} \frac{d\theta^2}{\theta^2} \int dz \big(\max[z, 1-z] - 1 \big) P_{qq}(z)$$

Jet radius logarithms (II)

- Leading order result for quark and gluon jets   Dasgupta, Magnea, Salam '07

$$
\langle \delta p_T \rangle_{\rm q} \;=\; C_F \frac{\alpha_s}{\pi}\, p_T \;\ln(R)\, \left(2\ln 2 - \frac{3}{8}\right) \;=\; 0.43\,\alpha_s \;\ln(R)
$$

$$
\langle \delta p_T \rangle_{\rm g} \;=\; \frac{\alpha_s}{\pi}\, p_T \;\ln(R)\, \left[C_A \left(2\ln 2 - \frac{43}{96}\right) + T_f\, n_f\, \frac{7}{48}\right] \;=\; 1.02\,\alpha_s \;\ln(R)
$$

- Large single-logarithmic corrections $\ln(1/R) \gg 1$ for small R
  - *negative* corrections decrease partonic cross sections $\hat{\sigma}_{i_1 i_2}$
  - resummation …

Joint resummation

SCET factorization

- Factorization in small-R and $z \to 0$ threshold limit
  - assume anti-k_t jet algorithm, $z \sim R$, and small finite mass of jet

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

- Specific functions for individual kinemtic regions
  - hard functions for $2 \to 2$ scattering $\mathbf{H}_{i_1 i_2}$ (known to 2-loops Broggio, Ferroglia, Pecjak, Zhang '14)
  - inclusive jet function $J_X(s_X)$ dependent on invariant mass s_X of the recoiling collimated radiation (known to order α_s^2 Becher, Neubert '06, Becher, Bell '10)
  - global soft function $\mathbf{S}_G$ accounts for wide-angle soft radiation which cannot resolve the small radius R (known to NLO Liu, S.M., Ringer '17)

Joint resummation

SCET factorization

- Factorization in small-R and $z \to 0$ threshold limit
  - assume anti-k_t jet algorithm, $z \sim R$, and small finite mass of jet

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

- Specific functions for individual kinemtic regions
  - signal-jet function $J(p_T\, R)$ accounts for energetic radiation inside jet Becher, Neubert, Rothen, Shao ‘15
  - soft-collinear (“coft”) function $S_c(s_c R)$ captures soft radiation near jet boundary Becher, Neubert, Rothen, Shao ‘15, Chien, Hornig, Lee ‘15
- Sum runs over all collinear splittings and traces taken in color space
- ‘$\otimes_\Omega$’ denotes associated angular integrals Becher, Neubert, Rothen, Shao ‘15

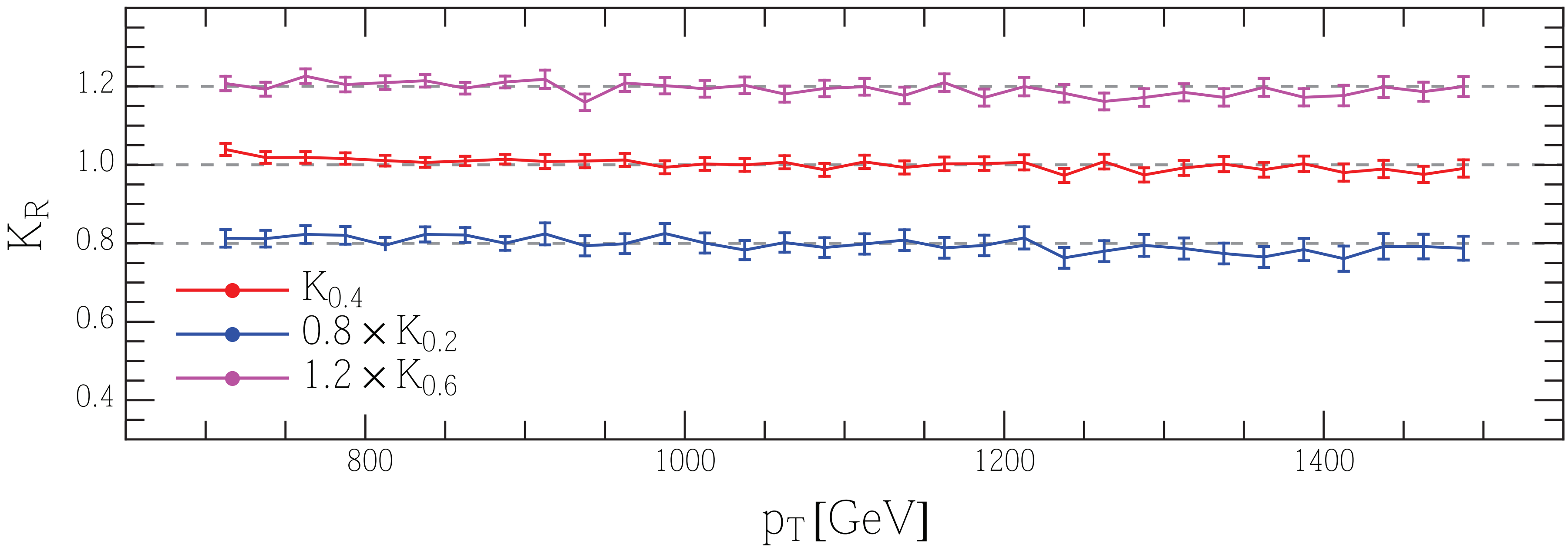
Phenomenology

- Evaluation of cross section in SCET (resummation) with renormalization group equations
  - evolution of all functions from their natural scales μ_i to common hard scale $\mu = p_T^{\max}$
- Matching of NLL resummed results with full NLO calculation (need to avoid double counting)

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

  - resummed cross section $\mathrm{d}\sigma_{\mathrm{NLL}}$
  - fixed order NLO result in singular limit $\mathrm{d}\sigma_{\mathrm{NLO}_{\mathrm{sin}}}$
  - complete fixed order NLO result $\mathrm{d}\sigma_{\mathrm{NLO}}$

Validation

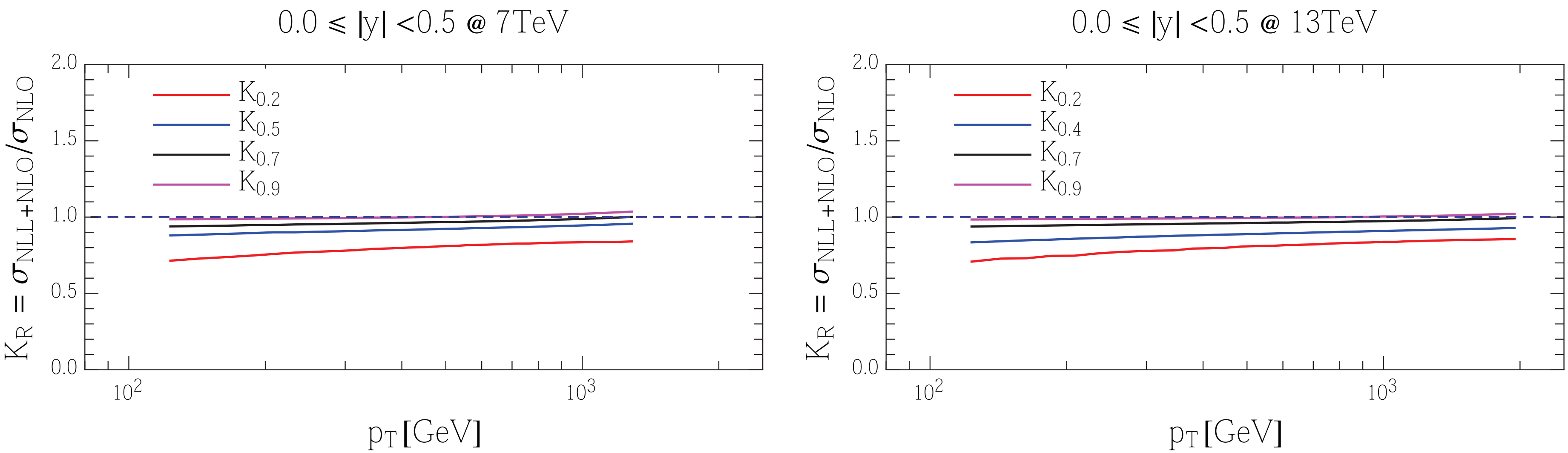


- Comparison of fixed order NLO result in singular limit $\mathrm{d}\sigma_{\mathrm{NLO}_{\mathrm{sin}}}$ with complete fixed order NLO result $\mathrm{d}\sigma_{\mathrm{NLO}}$
- Ratio $K_R = \dfrac{\mathrm{d}\sigma_{\mathrm{NLO}_{\mathrm{sin}}}}{\mathrm{d}\sigma_{\mathrm{NLO}}}$ as function of jet p_T for $1.5 < |\eta| < 2$ at $\sqrt{S} = 13$ TeV (error bars for numerical uncertainty)

Jet radius dependence (I)

Resummation for various R

- Ratio K_R of NLO + NLL and NLO cross sections for different jet radii
  $$K_R = \frac{\sigma_{\mathrm{NLL+NLO}}(R)}{\sigma_{\mathrm{NLO}}(R)}$$
- LHC at $\sqrt{S} = 7$ TeV (left) and 13 TeV (right) with NLO PDF set of MMHT

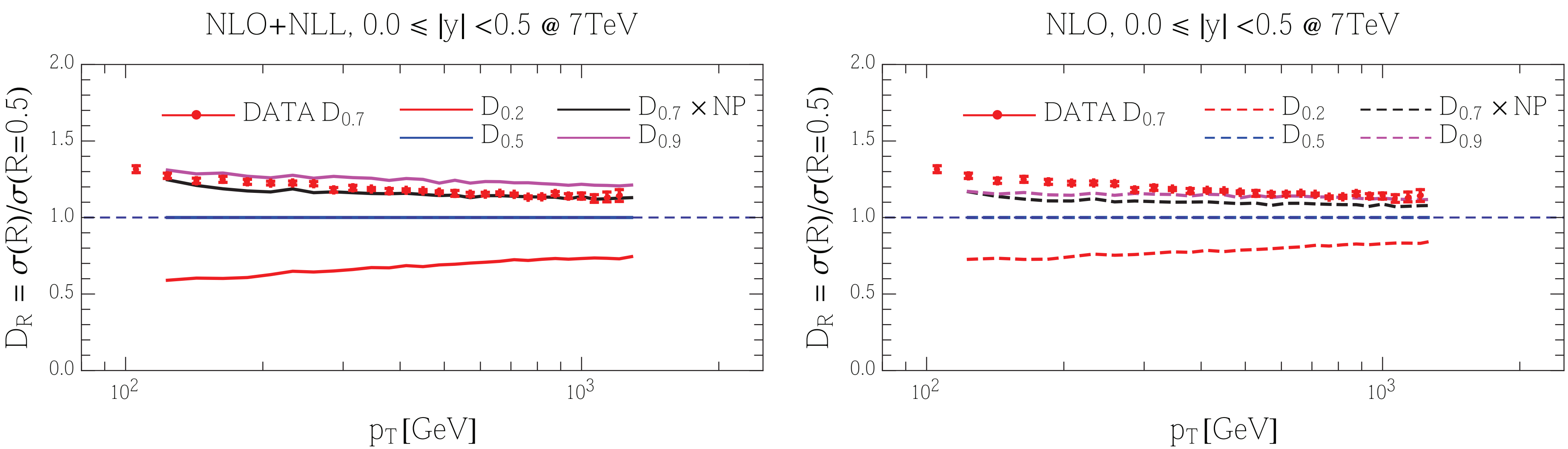


- Significant effect for small jet radii; reduction of $\mathcal{O}(20\%)$ for $R = 0.2$ in entire range of p_T

Jet radius dependence (II)

Impact of joint resummation

- Cross section ratio $D_R = \dfrac{\sigma(R)}{\sigma(R_{\rm fixed})}$
- D_R for NLO + NLL (left) and NLO (right) cross sections for $R_{\rm fixed} = 0.5$ at $\sqrt{S} = 7$ TeV with NLO PDF set of MMHT14
- Single-inclusive jet data from collected at $\sqrt{S} = 7$ TeV with $R = 0.7$ by CMS `arXiv:1406.0324` (with NP correction factors)

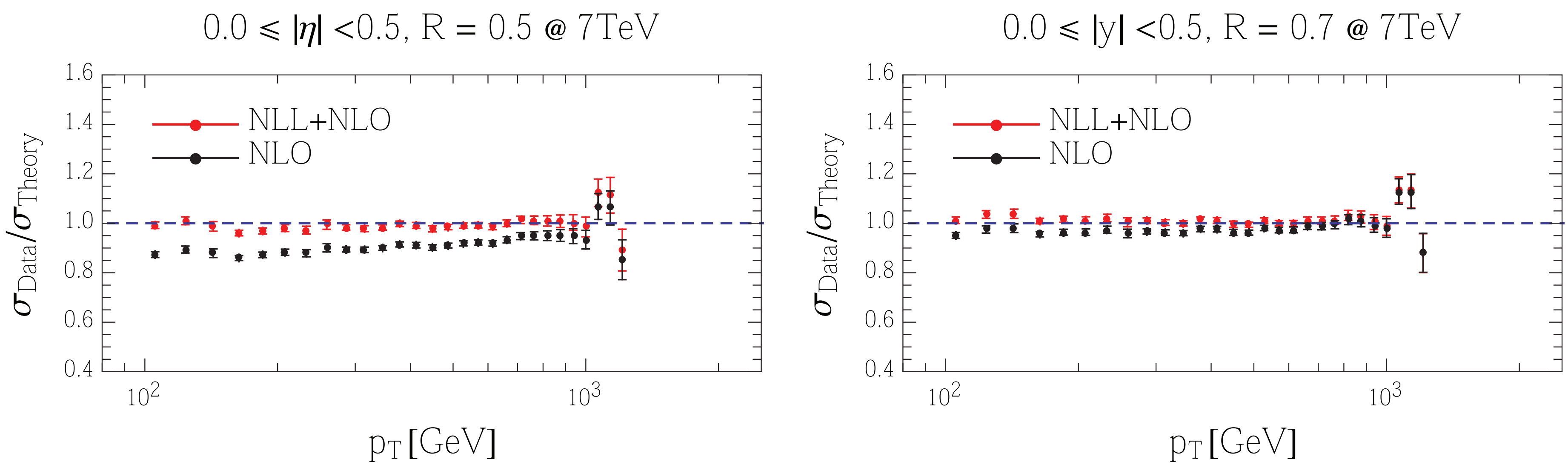


- NLO result overshoots; joint resummation agrees with data for $D_{R=0.7}$

Data vs. theory (I)

LHC data at $\sqrt{S} = 7$ TeV

- Ratio $\sigma_{\rm Data}/\sigma_{\rm Theory}$ with $R = 0.5$ (left) and $R = 0.7$ (right) to theoretical results at NLO (black dots) and at NLO + NLL (red dots) accuracy
    - NLO PDF set of MMHT14
    - data at $\sqrt{S} = 7$ TeV by CMS `arXiv:1406.0324`

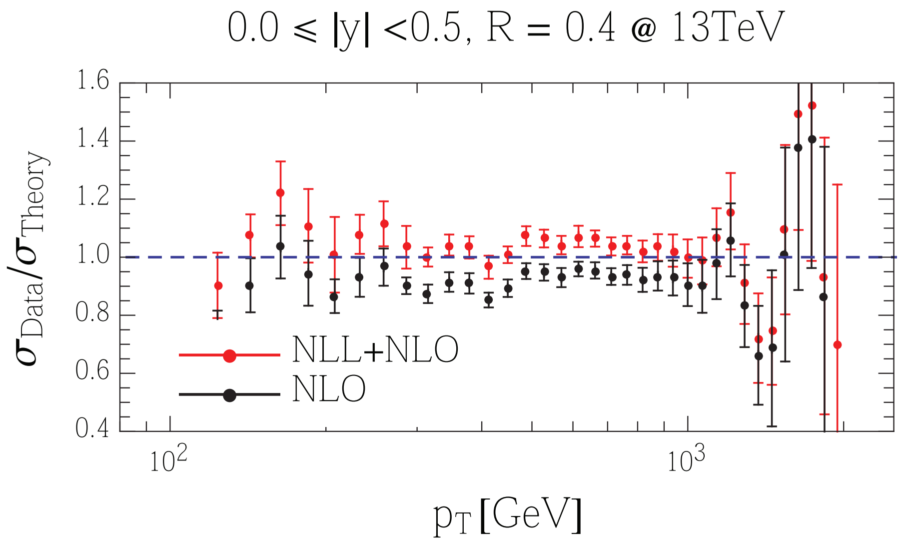


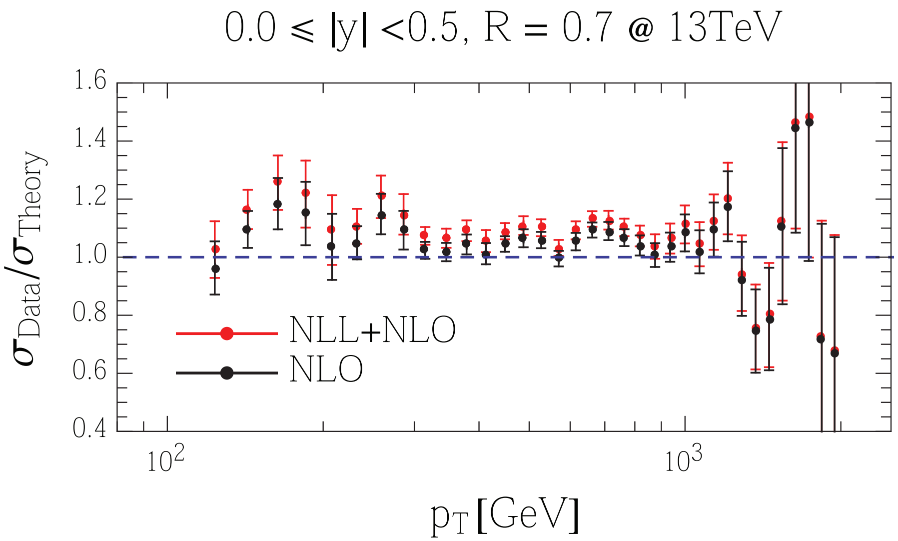
- Joint resummation agrees well with data; ratio with NLO predictions undershoots

Data vs. theory (II)

LHC data at $\sqrt{S} = 13$ TeV

- Ratio $\sigma_{\rm Data}/\sigma_{\rm Theory}$ with $R = 0.4$ (left) and $R = 0.7$ (right) to theoretical results at NLO (black dots) and at NLO $+$ NLL (red dots) accuracy
  - NLO PDF set of MMHT14
  - data at $\sqrt{S} = 13$ TeV by CMS `arXiv:1605.04436`



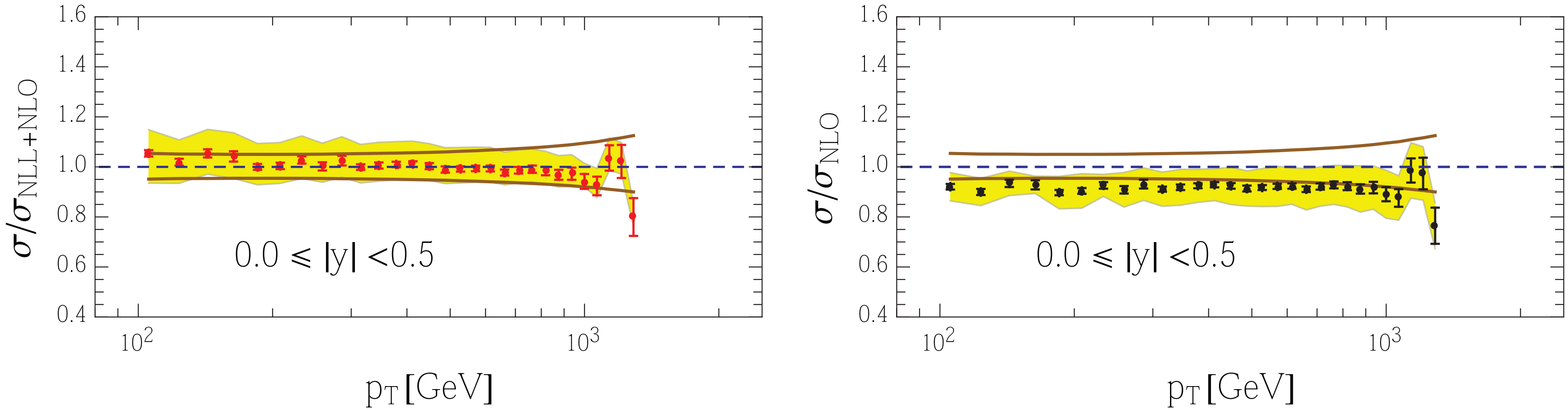


- Same trend as for data at $\sqrt{S} = 7$ TeV, but still large experimental uncertainties

Data vs. theory (III)

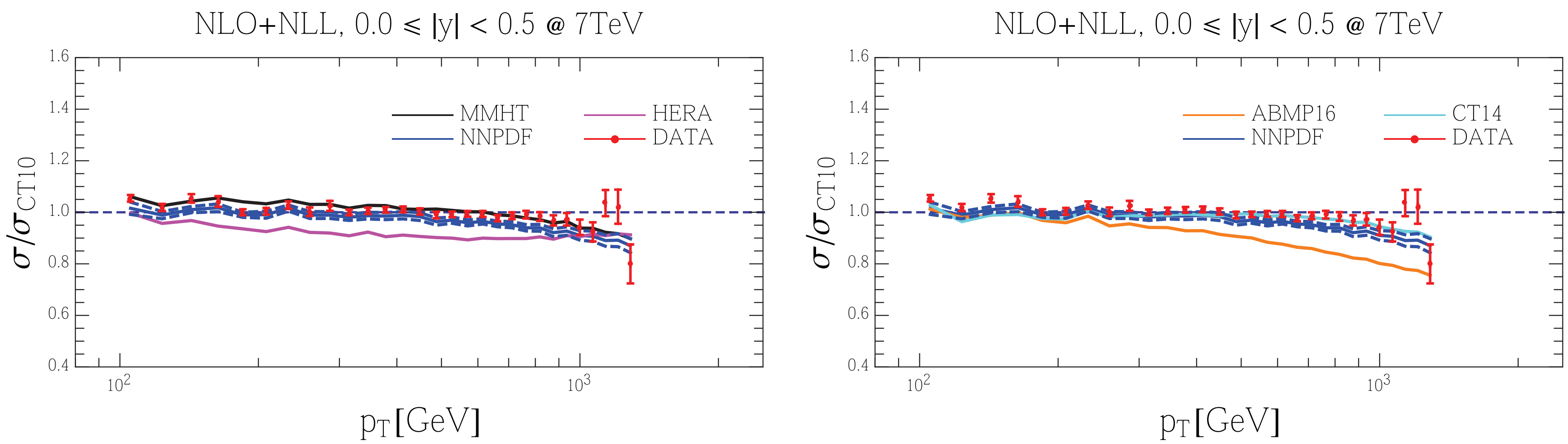
Experimental and theoretical uncertainties

- Ratio $\sigma_{\rm Data}/\sigma_{\rm Theory}$ with $R = 0.5$ to theoretical results at NLO $+$ NLL (left) and at NLO (right) accuracy at $\sqrt{S} = 7$ TeV using the NLO PDF set by CT10 for data collected by CMS `arXiv:1406.0324` (with NP correction factors)
    - error bars represent experimental statistical errors
    - solid (brown) lines represent experimental systematic ones
    - band (yellow) indicates theoretical scale uncertainties



PDF dependence

- Cross sections $\sigma_{\mathrm{NLO+NLL}}$ at NLL + NLO accuracy with $R = 0.5$ at $\sqrt{S} = 7$ TeV normalized to the one with the NLO PDF set by CT10
  - central NLO PDF sets HERAPDF2.0, MMHT14 and NNPDF3.1 (left)
  - central NLO PDF sets ABMP16, CT14 and NNPDF3.1 (right)
  - data collected by CMS `arXiv:1406.0324` (with NP correction factors) is superimposed



Summary

Theory framework

- Joint resummation of threshold logarithms $\alpha_s^n (\ln^{2n-1}(z)/z)_+$ and small jet-radius logarithms $\alpha_s^n \ln^n(R)$ to all orders at NLL accuracy
- Resummation at NLO $+$ NLL accuracy in good agreement with CMS data
- Residual theoretical uncertainties from scale variation still of similar size as experimental systematics

Uses of jet measurements

- Determinations of strong coupling constant $\alpha_s(M_Z)$ and gluon PDF at medium to large-x based on results fixed order perturbation theory likely to incur bias
- Precision of $\lesssim 1\%$ makes resummed theoretical predictions at NNLO $+$ NNLL accuracy in QCD mandatory