Precision Physics at the LHC
Jets theory

João Pires
LIP-Lisbon, Portugal

15th Vienna Central European Seminar on Particle Physics and Quantum Field Theory

particleface

cost
EUROPEAN COOPERATION IN SCIENCE & TECHNOLOGY

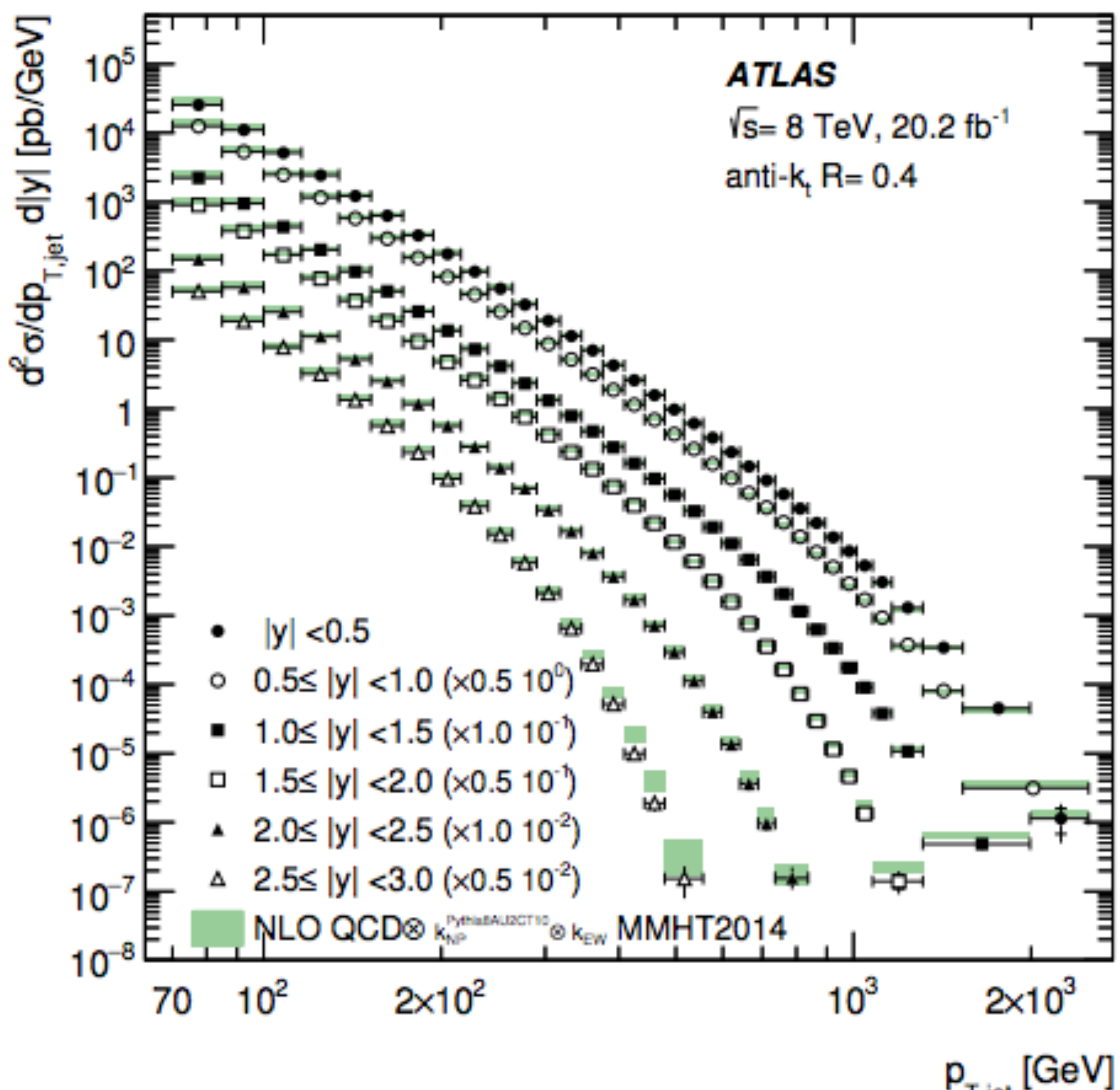
LIP

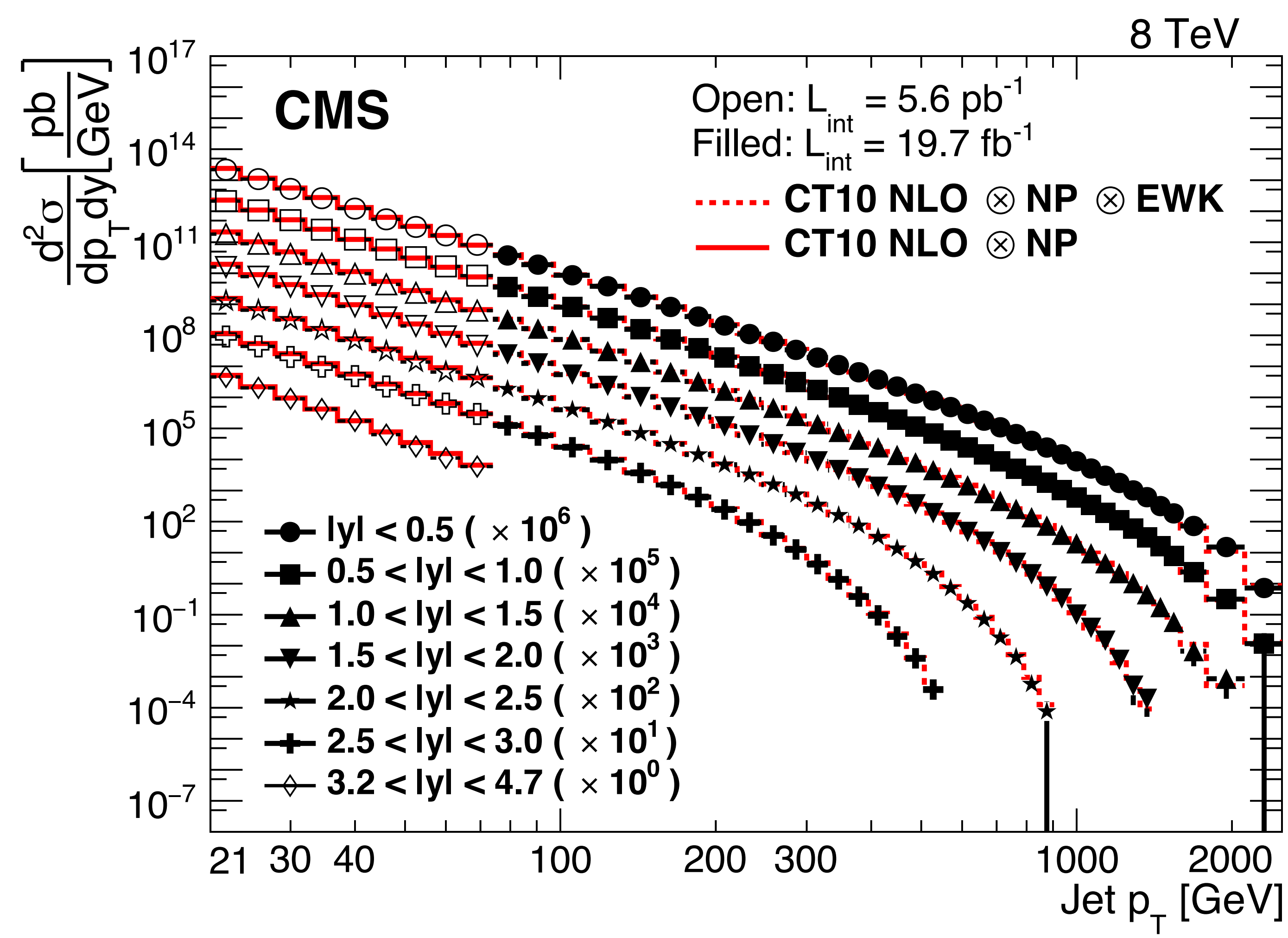
FCT
Fundação para a Ciência e a Tecnologia
MINISTÉRIO DA CIÊNCIA, TECNOLOGIA E ENSINO SUPERIOR

Jet production at the LHC

- look at production of jets of hadrons with large transverse energy in proton-proton collisions
- for sufficiently high transverse momentum $p_T > 20$ GeV high rates and clean and simple cross section definition
- anti-k_t jet definition infrared and collinear safe used in experimental measurements and theory predictions

$$\frac{d\sigma}{dp_T dy} = \frac{1}{\mathcal{L}} \frac{N_{jets}}{\Delta p_T \Delta y} \propto \alpha_s^2$$





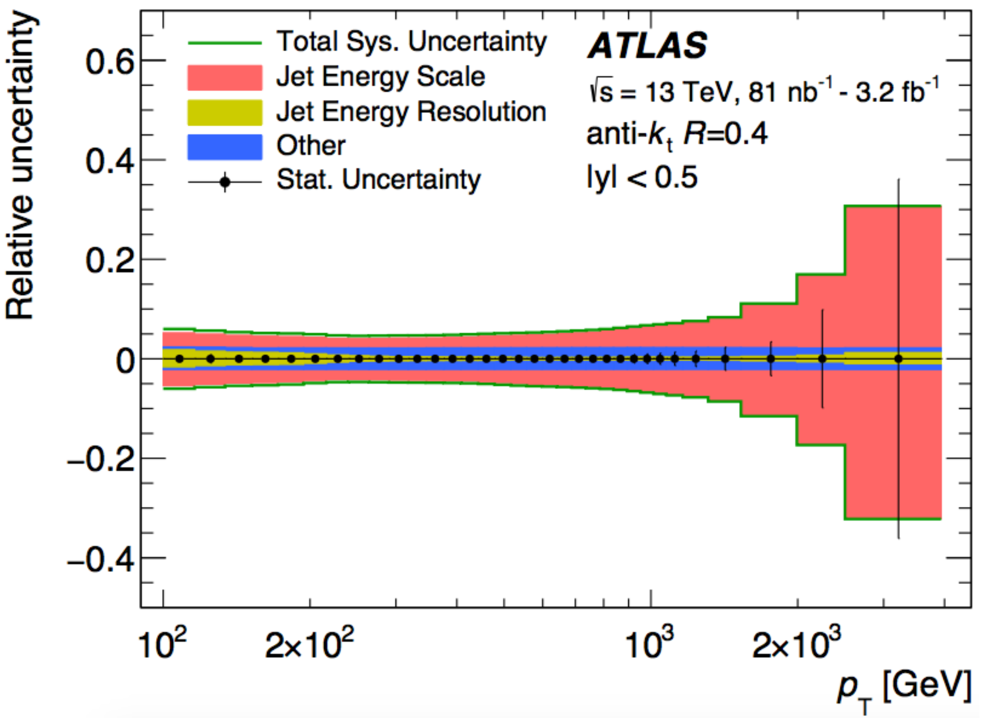
Jet production: uncertainties at the LHC

Jet measurements have become very precise:

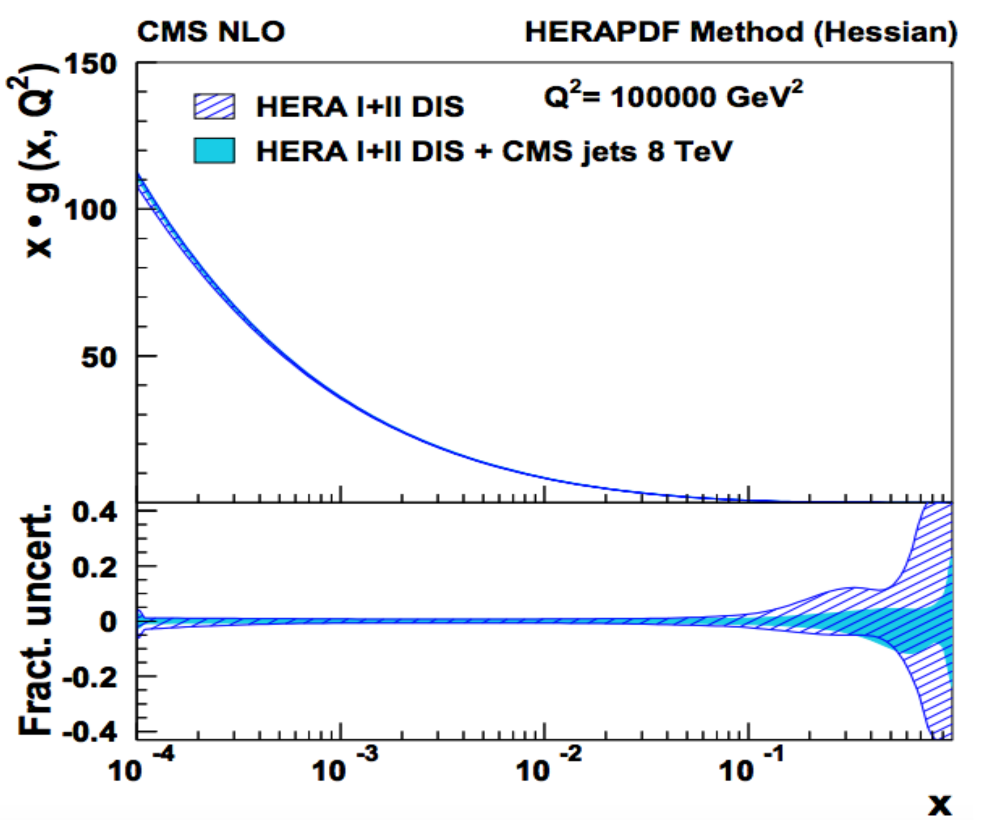
- dominant systematic uncertainty JES ~ 1-2% corresponds to < 10% uncertainty on single jet inclusive cross section
- similar for ATLAS and CMS: 5% systematic on a wide range, and sub-% statistical → allow jet precision physics at the LHC

Ideal testing ground for QCD:

- test perturbative QCD description of jet data at the LHC
- constrain PDFs (sensitive to gluon at LO)



[ATLAS, arXiv:1711.026926]

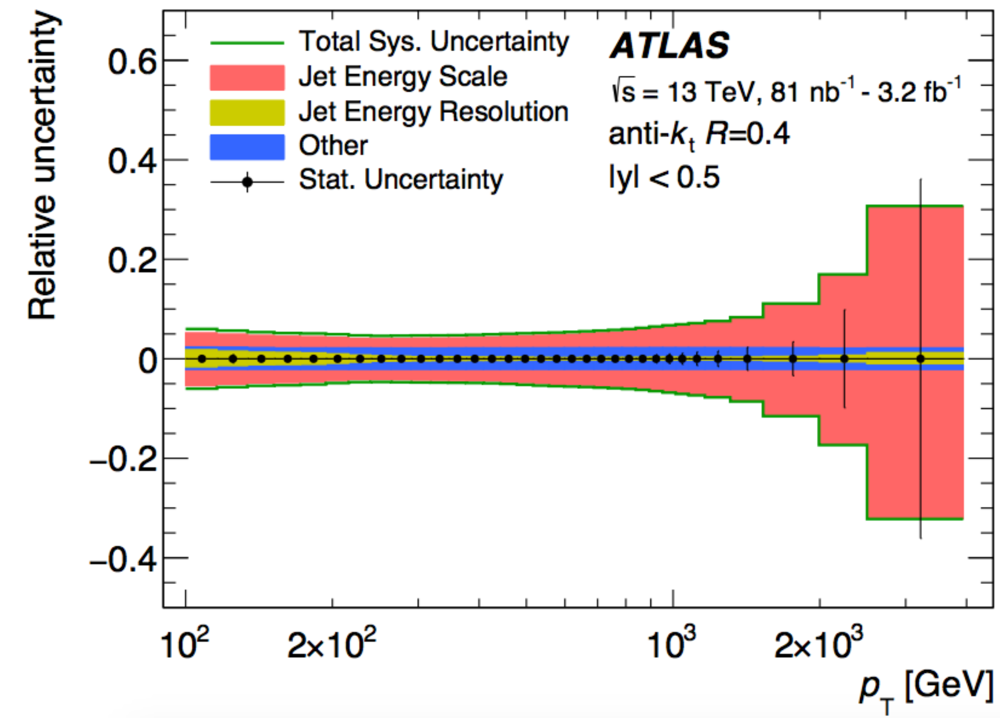


Gluon PDF fractional uncertainty with LHC jet data included CMS (arXiv:1609.5331)

Jet production: uncertainties at the LHC

Jet measurements have become very precise:

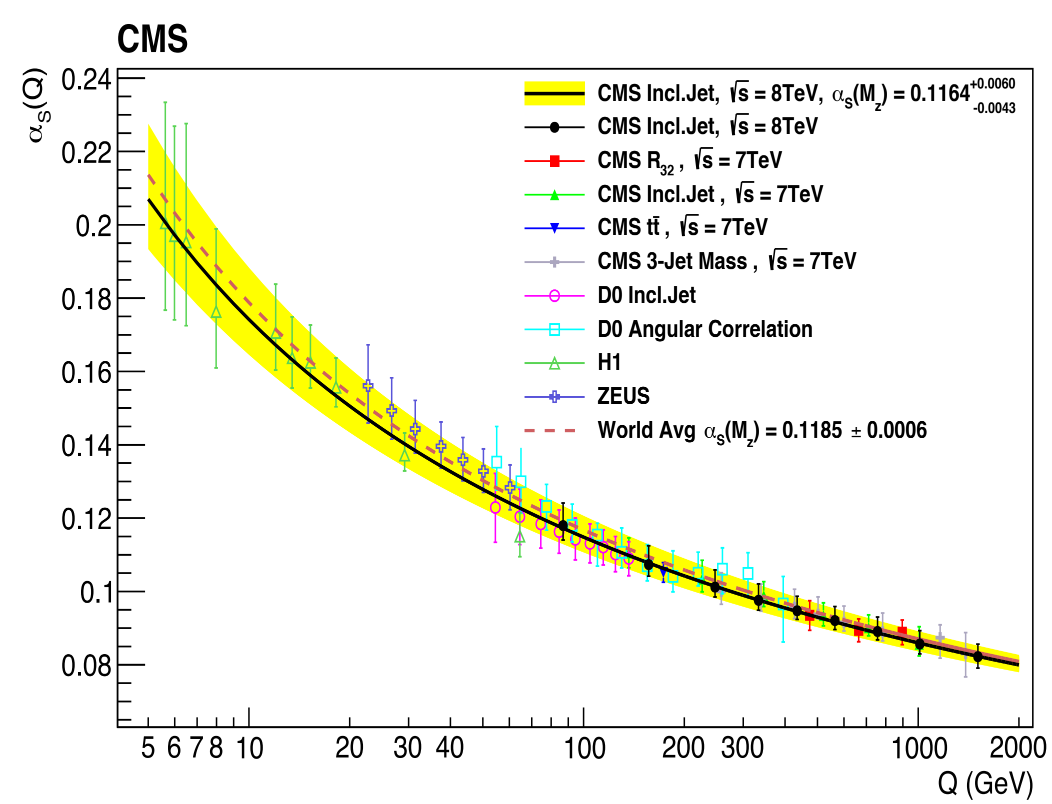
- dominant systematic uncertainty JES ~ 1-2% corresponds to < 10% uncertainty on single jet inclusive cross section
- similar for ATLAS and CMS: 5% systematic on a wide range, and sub-% statistical → allow jet precision physics at the LHC



[ATLAS, arXiv:1711.026926]

Ideal testing ground for QCD:

- test perturbative QCD description of jet data at the LHC
- constrain PDFs (sensitive to gluon at LO)
- determine α_s → huge range in jet p_T directly tests energy dependence/running of α_s from a single experiment



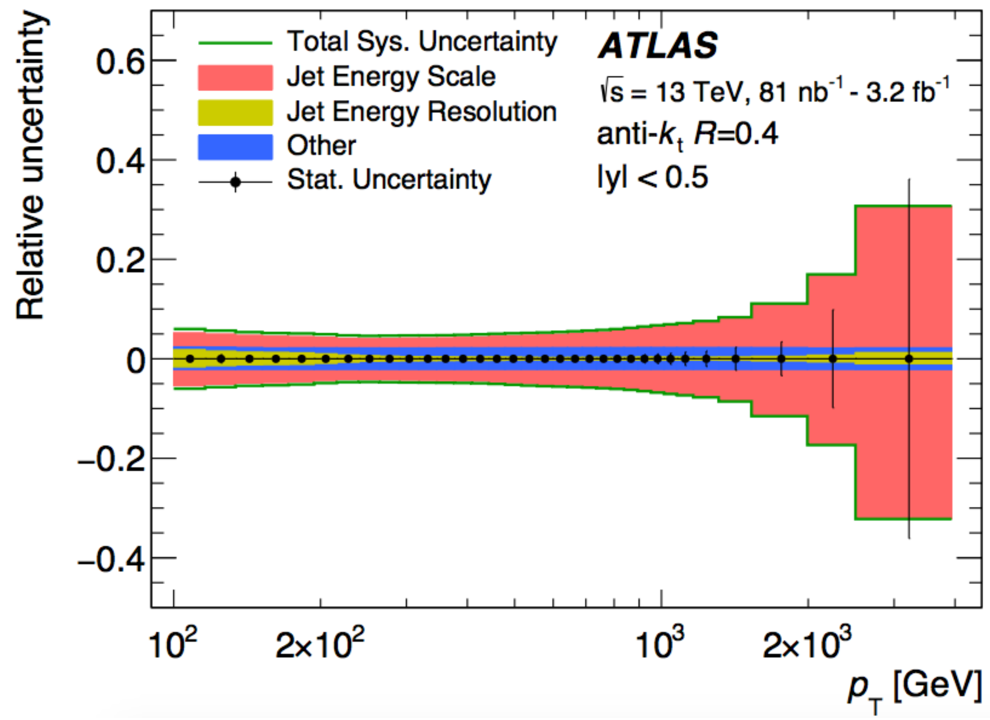
α_s running in the TeV range from LHC jet data

Jet production: uncertainties at the LHC

Jet measurements have become very precise:

- dominant systematic uncertainty JES ~ 1-2% corresponds to < 10% uncertainty on single jet inclusive cross section

- similar for ATLAS and CMS: 5% systematic on a wide range, and sub-% statistical → allow jet precision physics at the LHC



[ATLAS, arXiv:1711.026926]

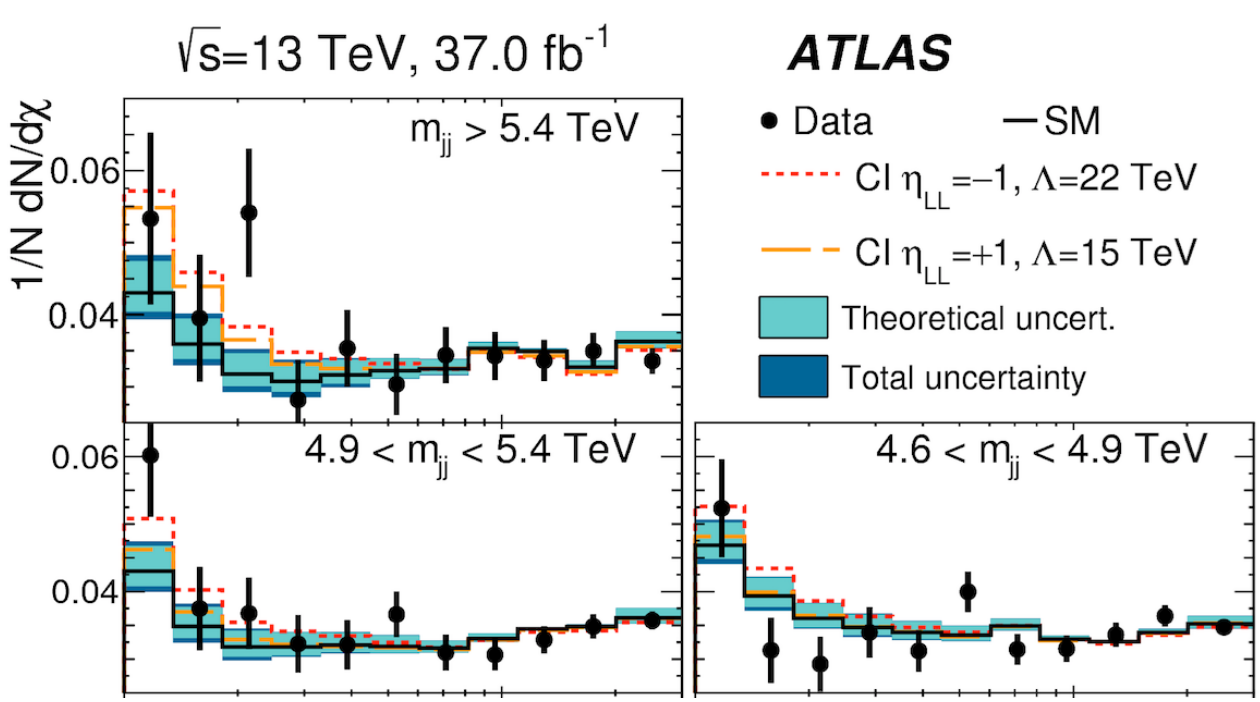
Ideal testing ground for QCD:

- test perturbative QCD description of jet data at the LHC

- constrain PDFs (sensitive to gluon at LO)

- determine α_s → huge range in jet p_T directly tests energy dependence/running of α_s from a single experiment

- a window to new physics e.g.→ bumps in dijet mass distributions → precise BSM searches in dijet angular distributions



[ATLAS, arXiv:1703.09127]

Jet observables

- *Single jet inclusive cross section: $pp \rightarrow jet+X$*

  - inclusive sum of individual jet contributions in the event that pass the jet fiducial cuts

    ⟶ each jet in the event contributes separately, leading to multiple entries of a single event in distributions

  - differential in transverse momentum p_T and rapidity y

Jet observables

- ***Single jet inclusive cross section: pp→jet+X***
  - inclusive sum of individual jet contributions in the event that pass the jet fiducial cuts

    ⟶ each jet in the event contributes separately, leading to multiple entries of a single event in distributions

  - differential in transverse momentum p_T and rapidity *y*

- ***Di-jet inclusive cross section: pp→2 jet+X***
  - consider only the two leading jets (in p_T) in the event

    ⟶ single entry per event in distributions

  - multi-differential measurements possible (M_{jj} ,$p_{T,avg}$, y^*, $y_{boost,...}$)

Jet observables: theory status

- Much progress in fixed-order calculations/resummation and parton shower predictions
  - NLO QCD [Ellis, Kunszt, Soper ’92][Giele, Glover, Kosower ’94] [Nagy 02]
  - NLO QCD + PS [Alioli, Hamilton, Nason, Oleari, Re ’11] [Hoeche, Schonherr ’12] [Herwig7 ‘15]
  - NLO QCD + Resummation (threshold+jet radius) [Dasgupta, Dreyer, Salam, Soyez ’14] [Liu, Moch, Ringer ’17]
  - NLO EW [Dittmaier, Huss, Speckner ’13] [Campbell, Wackeroth, Zhou ’16]
  - NLO QCD+EW [Frederix, Frixione, Hirschi, Pagani, Shao, Zaro ’17]
  - NNLO QCD [Gehrmann-De Ridder, Gehrmann, Glover, JP ’13] [Currie, Glover, JP ’16] [Currie, Gehrmann-De Ridder, Gehrmann, Glover, Huss, JP ’17] [Czakon, van Hameren, Mitov, Poncelet ’19]

NLO QCD + PS (POWHEG)

Nason ***[arXiv:hep-ph/0409146] JHEP 0411 (2004) 040***
Alioli, Hamilton, Nason, Oleari, Re ***[arXiv: 1012.3380] JHEP 1104 (2011) 081***

- hardest emission generated first according to:

$$d\sigma = \bar{B}\left(\Phi_B\right) d\Phi_B \left[\Delta_R\left(p_T^{\mathrm{min}}\right) + \frac{R\left(\Phi_R\right)}{B\left(\Phi_B\right)} \Delta_R\left(k_T\left(\Phi_R\right)\right) d\Phi_{\mathrm{rad}}\right]$$

- with the born cross section replaced with the NLO differential cross section at fixed Born kinematics integrated over single emission → preserves NLO accuracy for inclusive quantities

$$\bar{B}\left(\Phi_B\right) = B\left(\Phi_B\right) + \left[V\left(\Phi_B\right) + \int d\Phi_{\mathrm{rad}}\, R\left(\Phi_R\right)\right]$$

- probability of not having an emission harder than p_T → POWHEG Sudakov

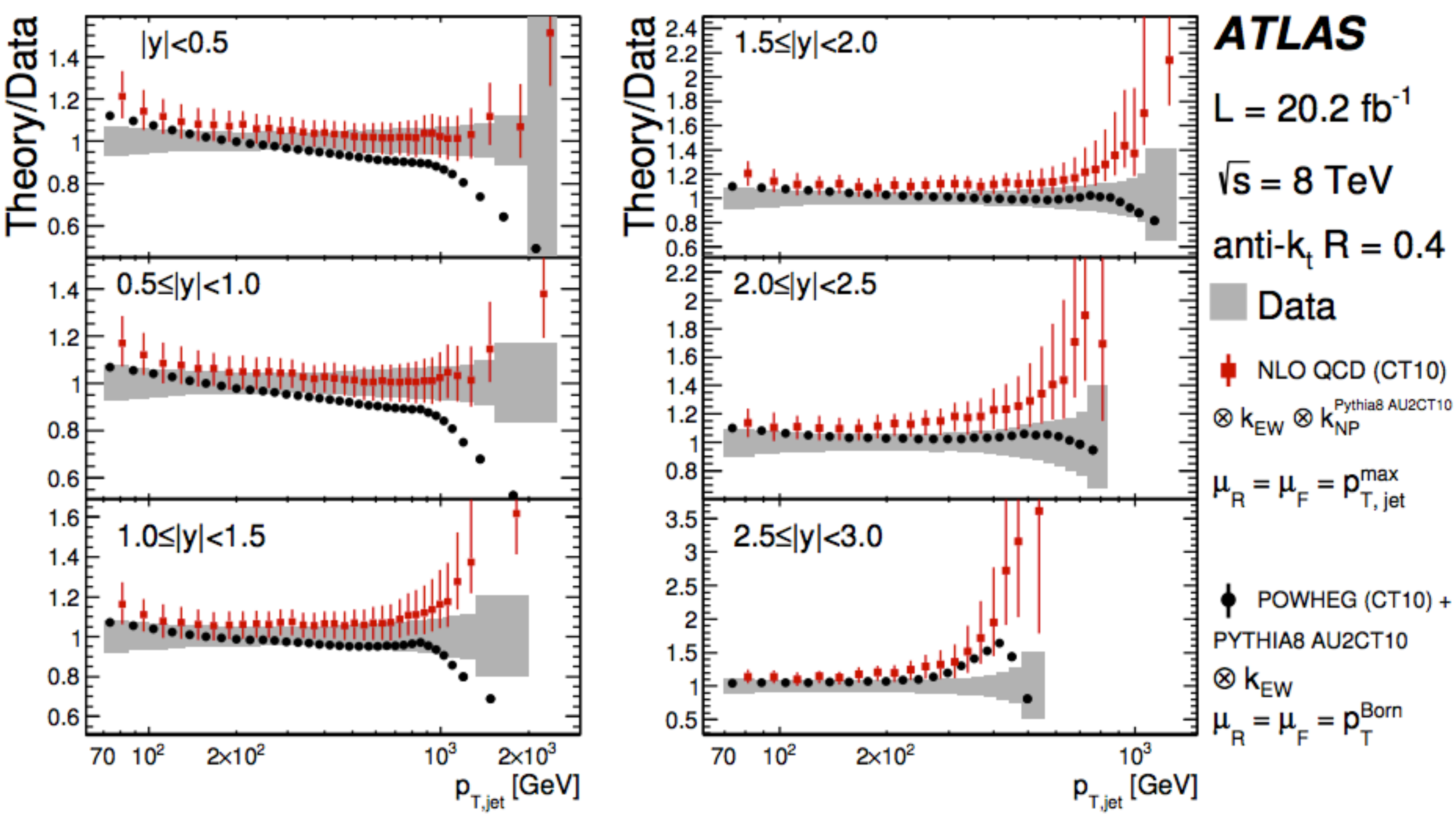
$$\Delta_R\left(p_T\right) = \exp\left[-\int d\Phi_{\mathrm{rad}} \frac{R\left(\Phi_R\right)}{B\left(\Phi_B\right)} \theta\left(k_T\left(\Phi_R\right) - p_T\right)\right]$$

- interface with shower generator to develop the rest of the shower vetoing emissions harder than the first one

NLO QCD + PS (POWHEG)

ATLAS **[arXiv: 1706.03192] JHEP 1709 (2017) 020**

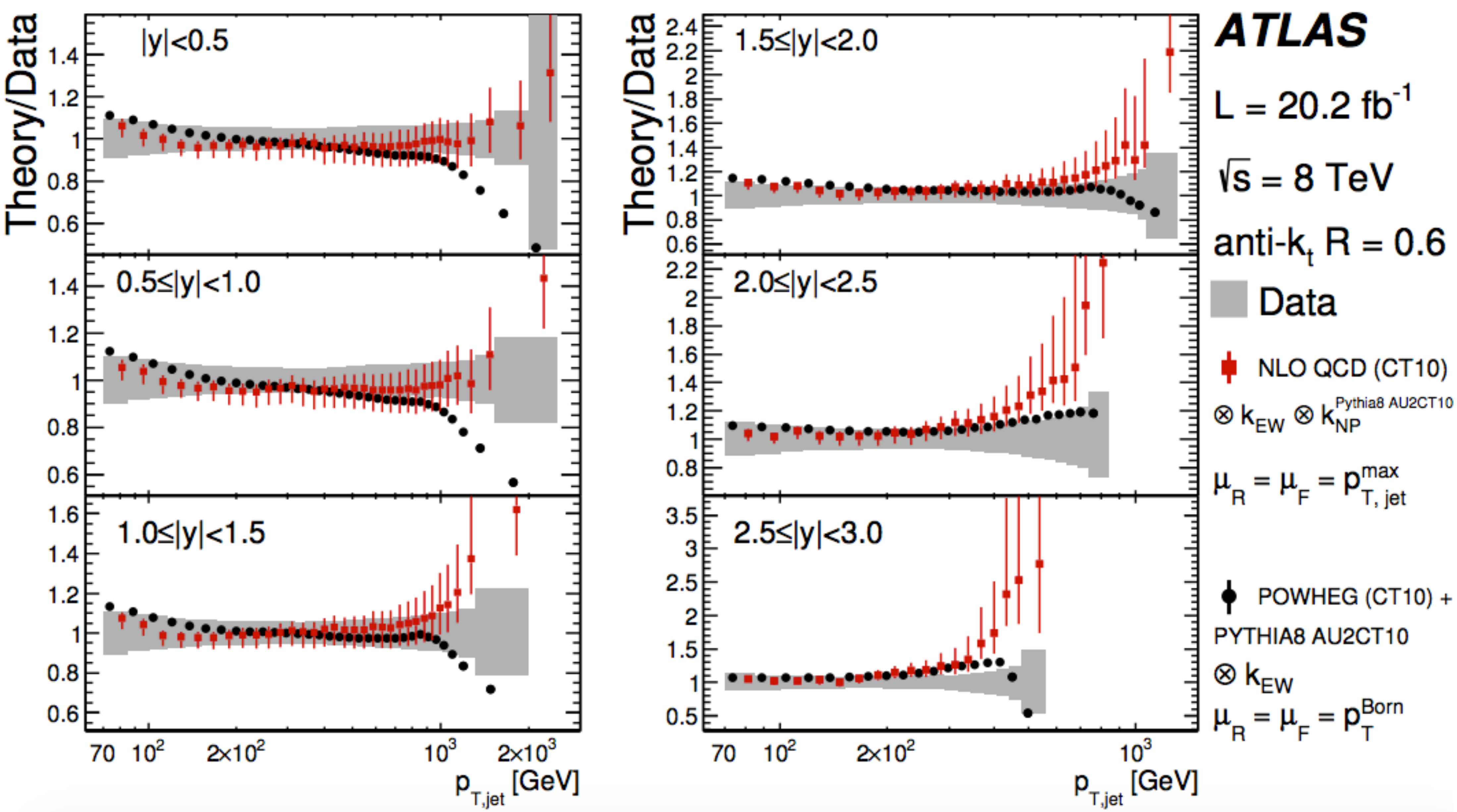
- Comparison to cross section data $R = 0.4; 0.6 \ @ \ 8 \ \mathrm{TeV}$
- POWHEG prediction lower than fixed-order NLO QCDxNPxEW
- Ratio to data less sensitive to the jet radius in POWHEG



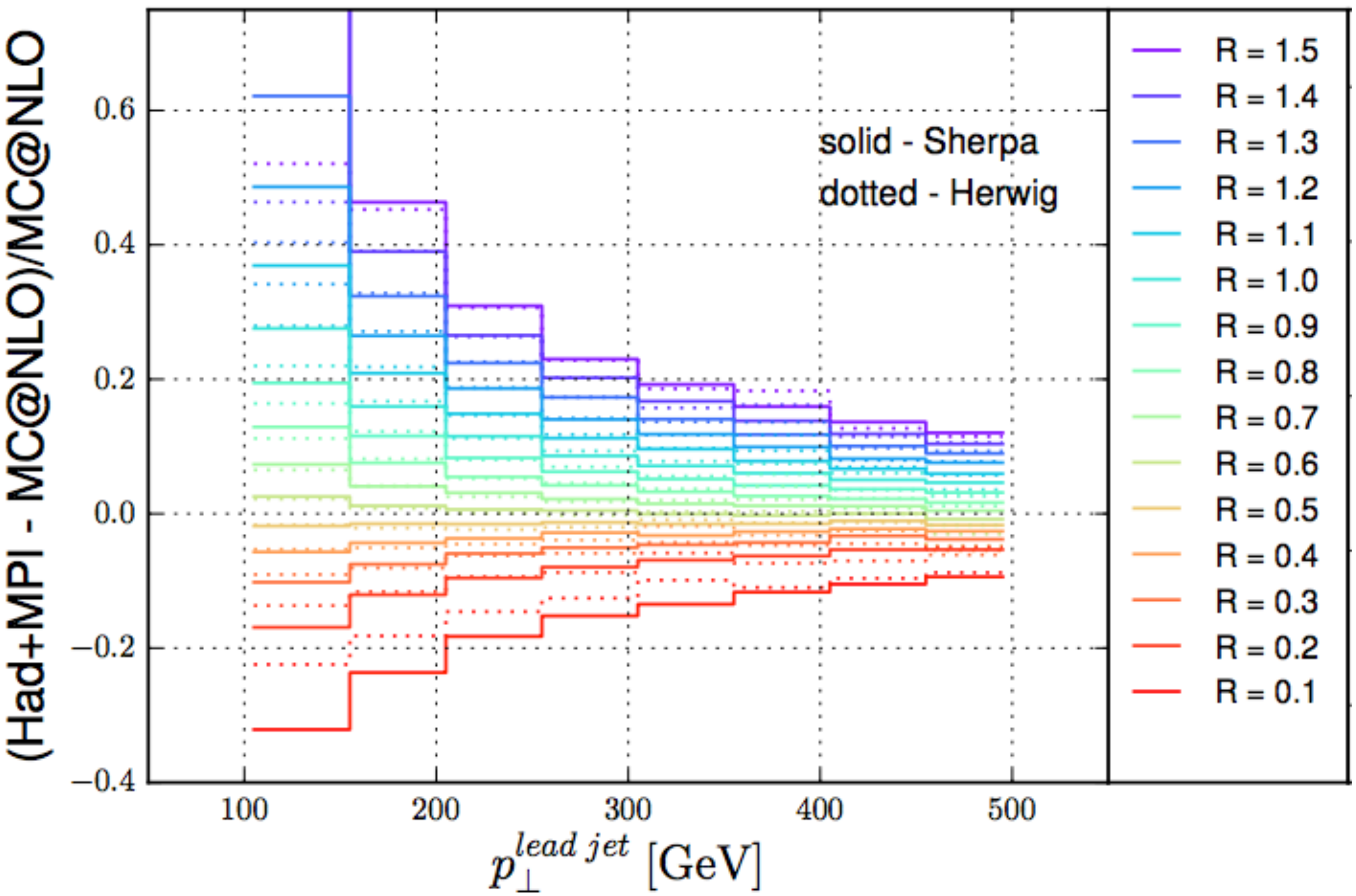
NLO QCD + PS (POWHEG)

ATLAS ***[arXiv: 1706.03192] JHEP 1709 (2017) 020***

- Comparison to cross section data $R = 0.4; 0.6 \ @ \ 8 \ \text{TeV}$
- POWHEG prediction lower than fixed-order NLO QCDxNPxEW
- Ratio to data less sensitive to the jet radius in POWHEG



Jets at the LHC: Fixed-order and Parton Shower descriptions



[Bellm, Buckley, et.al., arXiv:1903.12563]

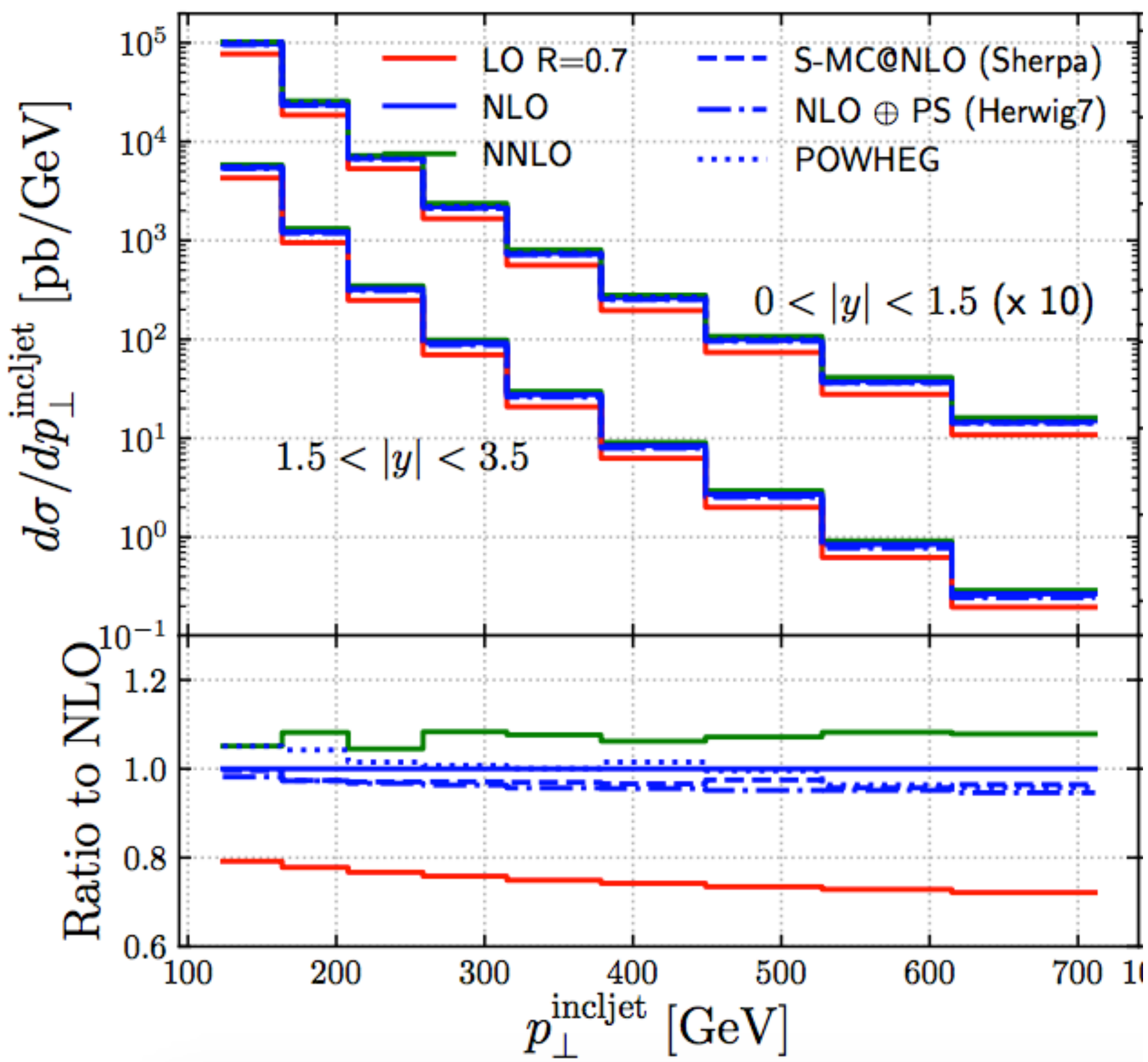
A thorough study of jet cross sections at the LHC **[Bellm, Buckley, et.al., arXiv:1903.12563]**

- Complete analysis of **Hadronization** and **MPI** corrections as a function of the jet size for measurements in:

  ⟶ *Higgs+jet* ; *Z+jet* ; *inclusive jet* production at the LHC

- Compatible results for the combined hadronization and MPI corrections between Sherpa and HERWIG, small for R values around *R=0.4*

Jets at the LHC: Fixed-order and Parton Shower descriptions



[Bellm, Buckley, et.al., arXiv:1903.12563]

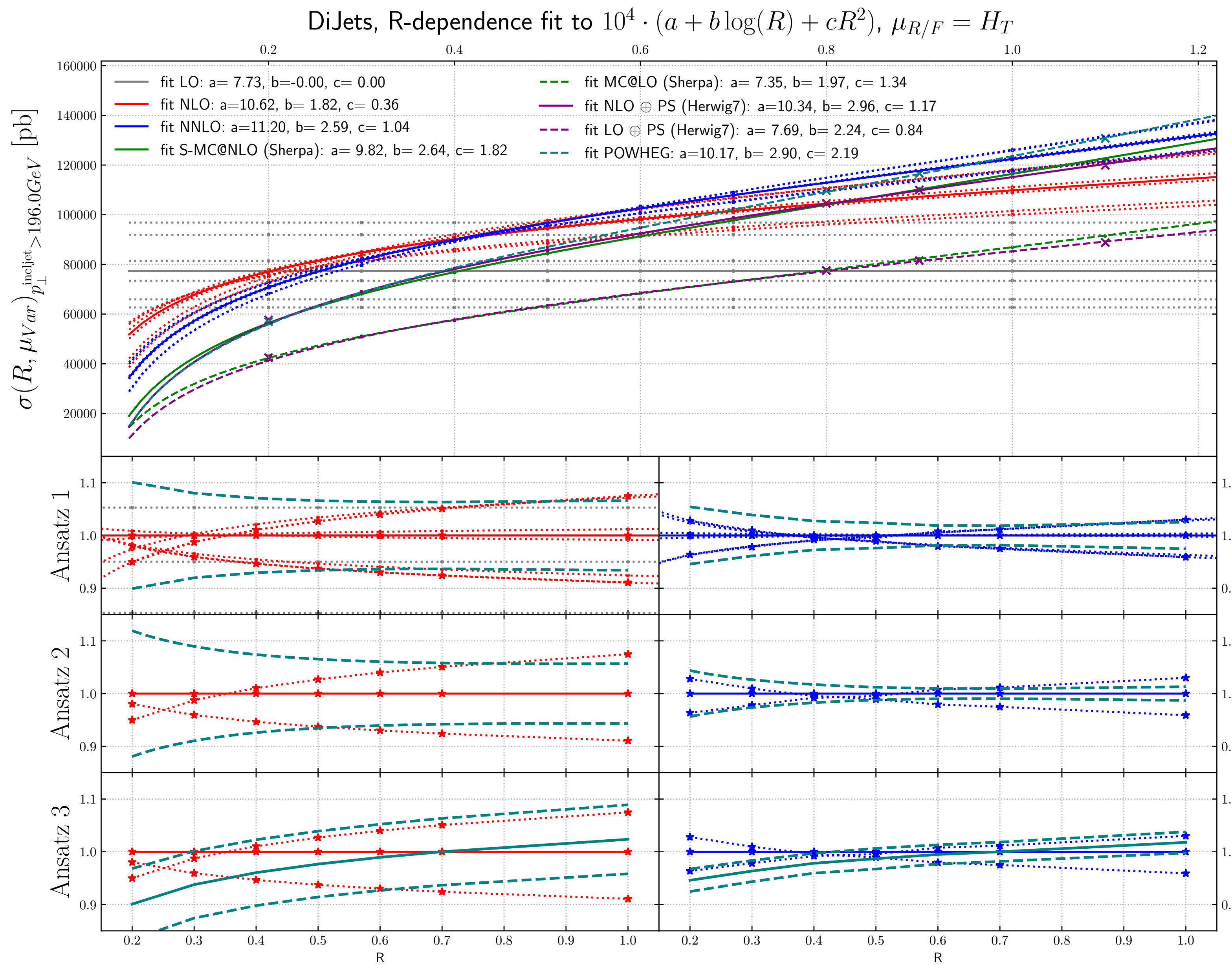
A thorough study of jet cross sections at the LHC **[Bellm, Buckley, et.al., arXiv:1903.12563]**

- PS MC's matched or merged to NLO accuracy and fixed-order LO,NLO,NNLO for:

  ⟶ *Higgs+jet* ; *Z+jet* ; *inclusive jet* production at the LHC

- Observe good agreement between different PS predictions for inclusive jet production reflecting the underlying fixed-order NLO results

Jets at the LHC: Fixed-order and Parton Shower descriptions



[Bellm, Buckley, et.al., arXiv:1903.12563]

Inclusive jet cross section *R*-dependence fits to the functional form $f(R) = a + b\log(R) + cR^2$

- larger slope at NNLO and NLO+PS compared to NLO
- lower panels show scale uncertainty *R*-dependence and alternative uncertainty estimates
  - ansatz 1 uncertainty estimate combines scale uncertainties in $\sigma(R) = \sigma(R_0)\dfrac{\sigma(R)}{\sigma(R_0)}$ in quadrature
  - ansatz 2 uncertainty estimate combines scale uncertainties of *a*,*b*,*c* in quadrature

NLO QCD + Resummation (threshold+jet radius)

Liu, Moch, Ringer **[arXiv: 1708.04641] Phys. Rev. Lett. 119, 212001 (2017)**
Liu, Moch, Ringer **[arXiv: 1801.07284] Phys.Rev. D97 (2018) no.5, 056026**
Dasgupta, Dreyer, Salam, Soyez **[arXiv: 1602.01110] JHEP 1606 (2016) 057**

Double differential single jet inclusive cross section:

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

- $z = s_4/s$ invariant mass recoiling against the jet
- in the small R-limit and threshold limit $z \to 0$ cross section factorizes within SCET

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

- perturbative contributions know at least to NLO
- joint resummation at NLL accuracy $\alpha_s^n \left(\ln^k(z)/z\right)_+$; $\alpha_s^n \ln^k(R)$
- additive matching to fixed-order NLO QCD result

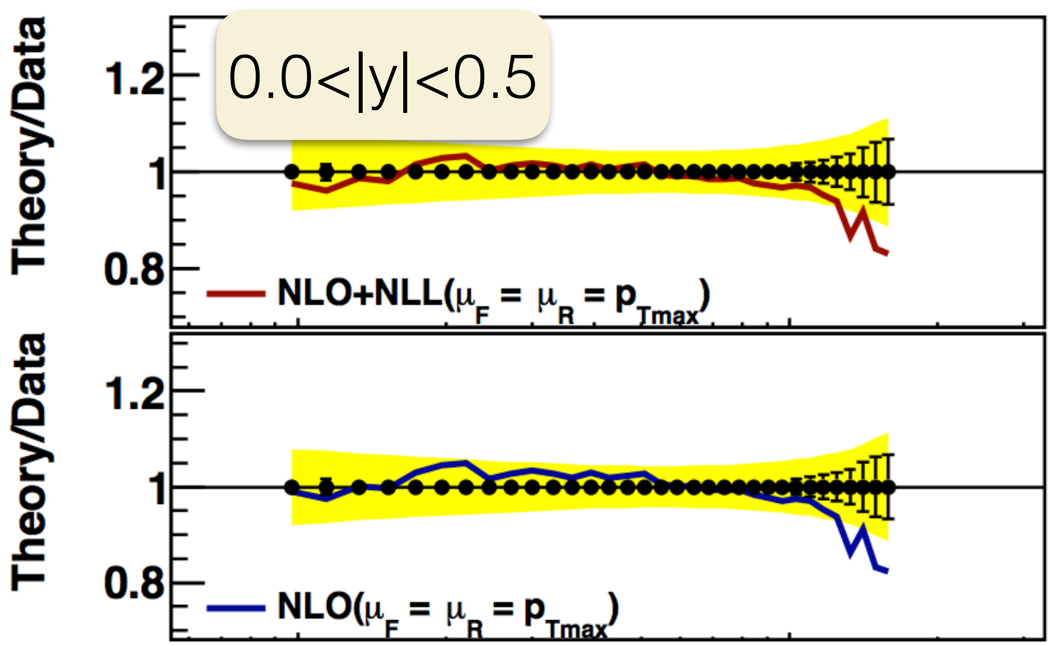
$$\sigma_{\mathrm{NLO+NLL}} = \sigma_{\mathrm{NLO}} - \sigma_{\mathrm{NLO_{sing}}} + \sigma_{\mathrm{NLL}}$$

- resummation scales μ_i evolved through RGE equations to common hard scale $\mu = \mu_h = p_T^{max}$

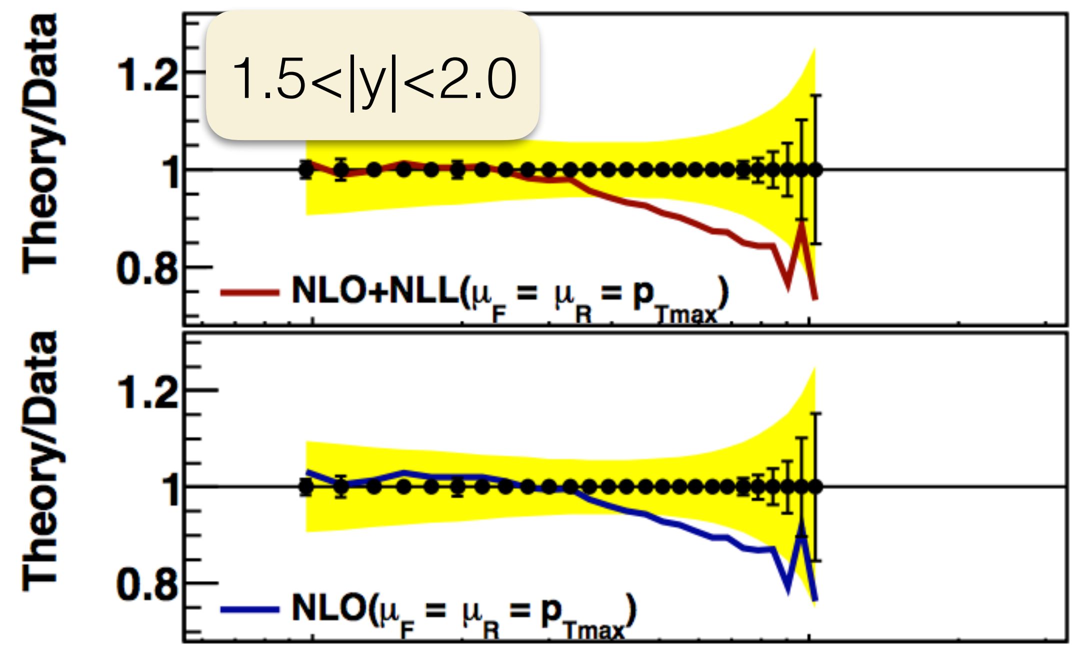
NLO QCD + Resummation (threshold+jet radius)

Liu, Moch, Ringer ***[arXiv: 1801.07284] Phys.Rev. D97 (2018) no.5, 056026***
Liu, Moch, Ringer ***[arXiv: 1808.04574]***

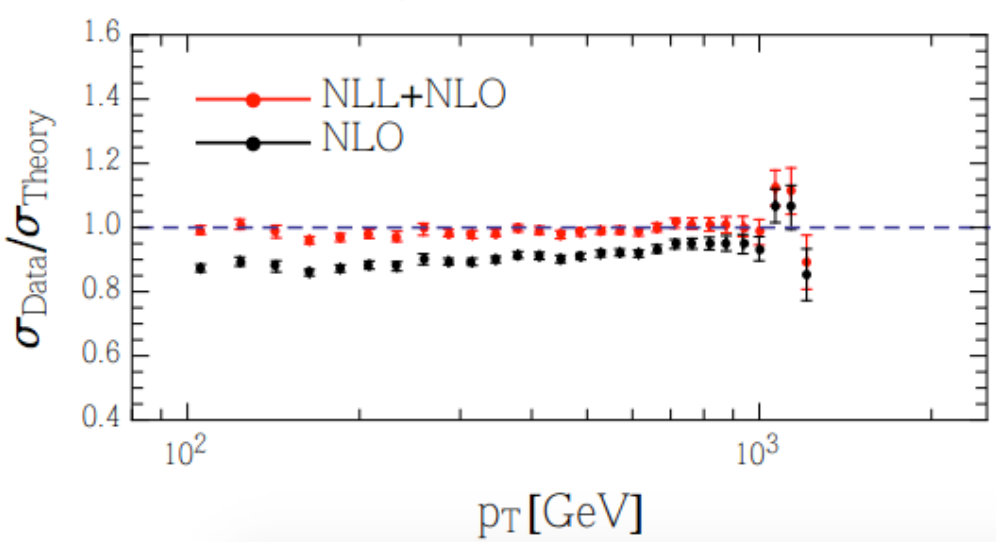
$R = 0.7$ @ 8 TeV



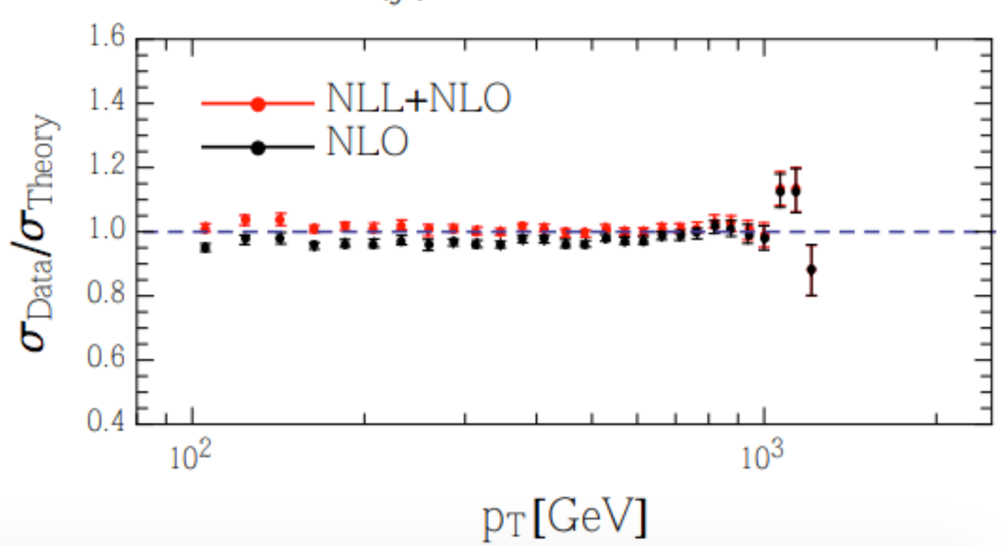
$R = 0.7$ @ 8 TeV



$0.0 \leqslant |\eta| < 0.5$, R = 0.5 @ 7TeV



$0.0 \leqslant |y| < 0.5$, R = 0.7 @ 7TeV



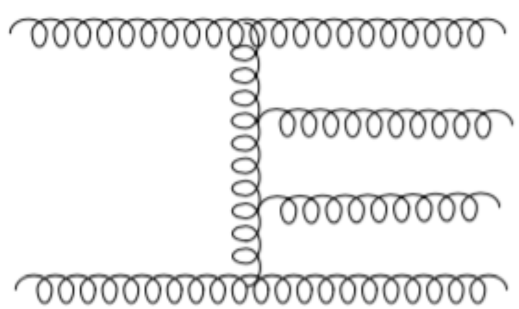
- threshold logs lead to an enhancement of the cross section for large p_T $\quad \mu = \mu_h = p_T^{max}$
- resummation of small R-logs lead to a decrease in the cross section in the entire range p_T

NNLO QCD

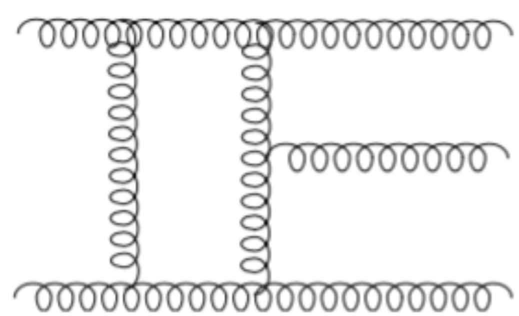
- Perturbative QCD expansion of the inclusive jet cross section at hadron colliders

$$d\sigma = \sum_{i,j} \int \left[d\hat{\sigma}_{ij}^{LO} + \left(\frac{\alpha_s}{2\pi}\right) d\hat{\sigma}_{ij}^{NLO} + \left(\frac{\alpha_s}{2\pi}\right)^2 d\hat{\sigma}_{ij}^{NNLO} + \mathcal{O}(\alpha_s^3) \right] f_i(x_1) f_j(x_2) dx_1 dx_2$$

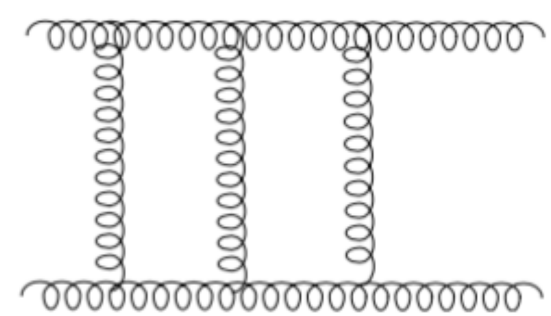
- NNLO gluonic contributions



$A_6^{(0)}(gg \to gggg)$



$A_5^{(1)}(gg \to ggg)$



$A_4^{(2)}(gg \to gg)$

- tree-level 2→4 matrix elements — *[Berends, Giele '87] [Mangano, Parke, Xu '87] [Britto, Cachazo, Feng '06]*
- one-loop 2→3 matrix elements — *[Bern, Dixon, Kosower '93] [Kunszt, Signer, Trocsanyi '94]*
- two-loop 2→2 matrix elements — *[Anastasiou, Glover, Oleari, Tejeda-Yeomans '01] [Bern, De Freitas, Dixon '02]*
- NNLO DGLAP evolution — *[Moch, Vermaseren, Vogt '04]*
- NNLO PDF's — *[ABMP, CT, NNPDF, MMHT]*

NNLO antenna subtraction

$$\begin{aligned} d\hat{\sigma}_{NNLO} &= \int_{d\Phi_4}\left(d\hat{\sigma}^{RR}_{NNLO} - d\hat{\sigma}^{S}_{NNLO}\right) \\ &+ \int_{d\Phi_3}\left(d\hat{\sigma}^{RV}_{NNLO} - d\hat{\sigma}^{T}_{NNLO}\right) \\ &+ \int_{d\Phi_2}\left(d\hat{\sigma}^{VV}_{NNLO} - d\hat{\sigma}^{U}_{NNLO}\right) \end{aligned}$$

$d\hat{\sigma}^{S}_{NNLO}$ $d\hat{\sigma}^{T}_{NNLO}$

- mimic RR,RV in unresolved limits

$d\hat{\sigma}^{T}_{NNLO}$ $d\hat{\sigma}^{U}_{NNLO}$

- analytically cancel the poles in RV and VV matrix elements

For inclusive jet and dijet production: pp→jet +X ; pp→2jet +X

- NNLO corrections known *[Currie, Gehrmann-De Ridder, Gehrmann, Glover, Huss, JP '17]*
- all channels $\{gg, qg, q\bar{q}, qq, qq^{'}, q\bar{q}^{'}\}$ at leading colour $\alpha_s^2 N^2, \alpha_s^2 N N_F, \alpha_s^2 N_F^2$
- gg-channel with full colour
- sub-leading colour contributions: (suppressed by $1/N^2$)
    - below two percent at NLO (all channels)

NNLOJET

NNLO fully differential parton-level generator

- Based on antenna subtraction for the analytic cancellation of IR singularities at NNLO

Infrastructure

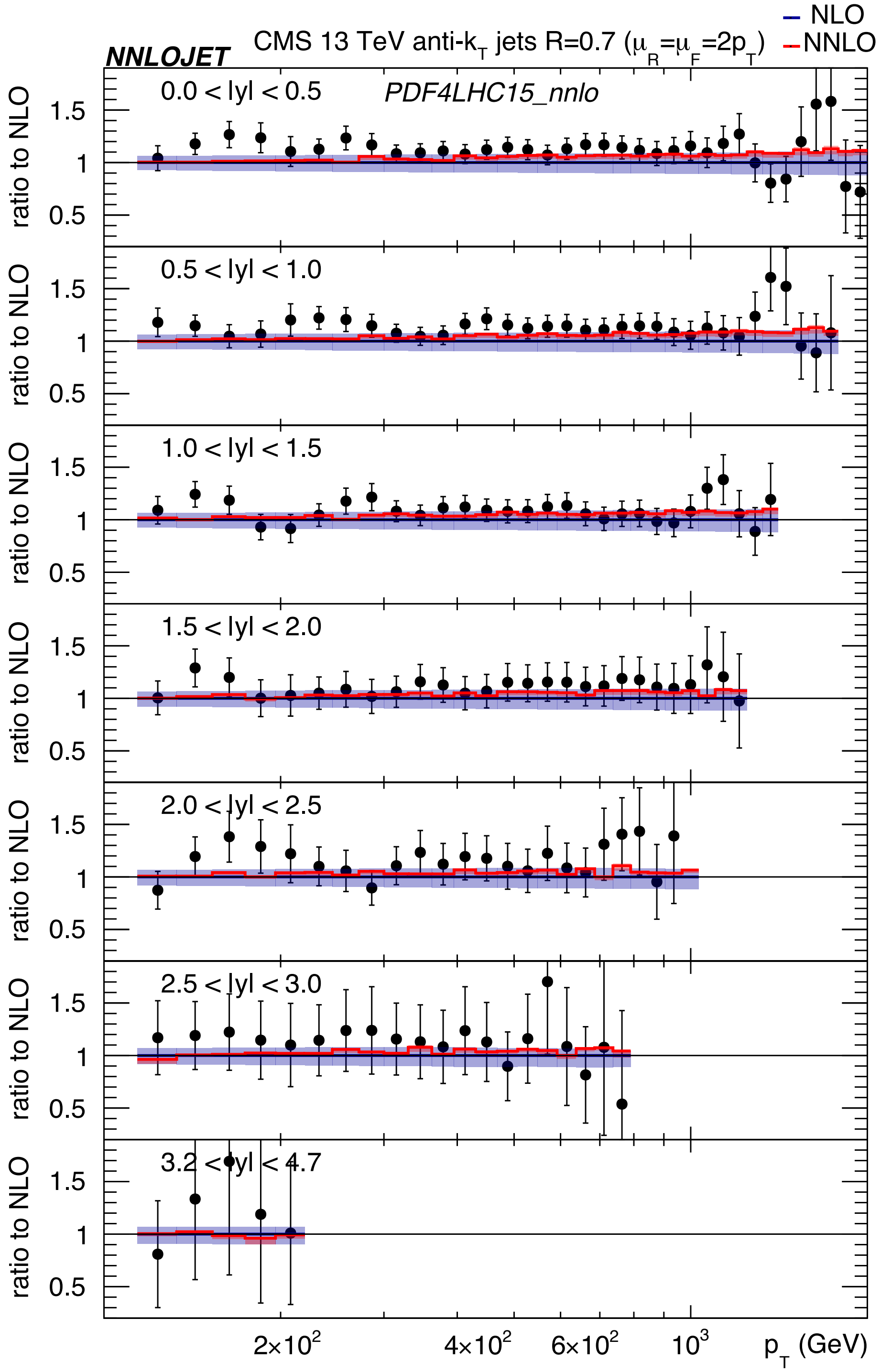
- Process management
- Phase space, histogram routines
- Validation and testing
- ApplFast interface in progress

Processes implemented at NNLO

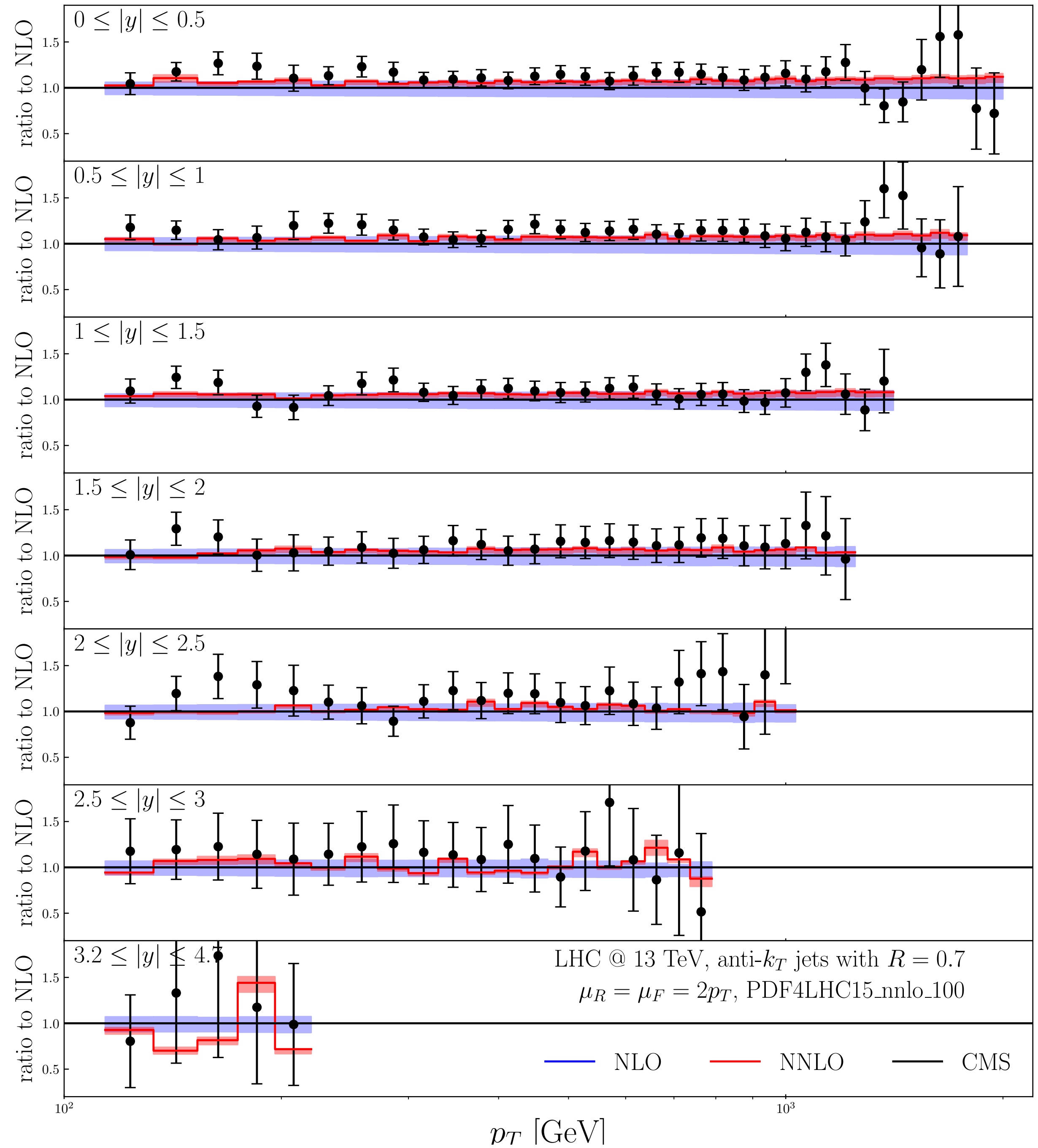
- Z+(0,1) jet, W+(0,1) jet
- H+(0,1) jet
- DIS-2jet
- VBF H+2jet
- Inclusive jet production

X.Chen,J.Cruz-Martinez, J.Currie, R.Gauld, T.Gehrmann, A.Gehrmann-De Ridder,E.W.N.Glover, M.Höfer, A.Huss, T.Morgan, I.Majer, J.Niehues, D.Walker, JP* *[arXiv: 1801.06415]*** *and references therein*

Single-jet inclusive rates at NNLO



Antenna subtraction



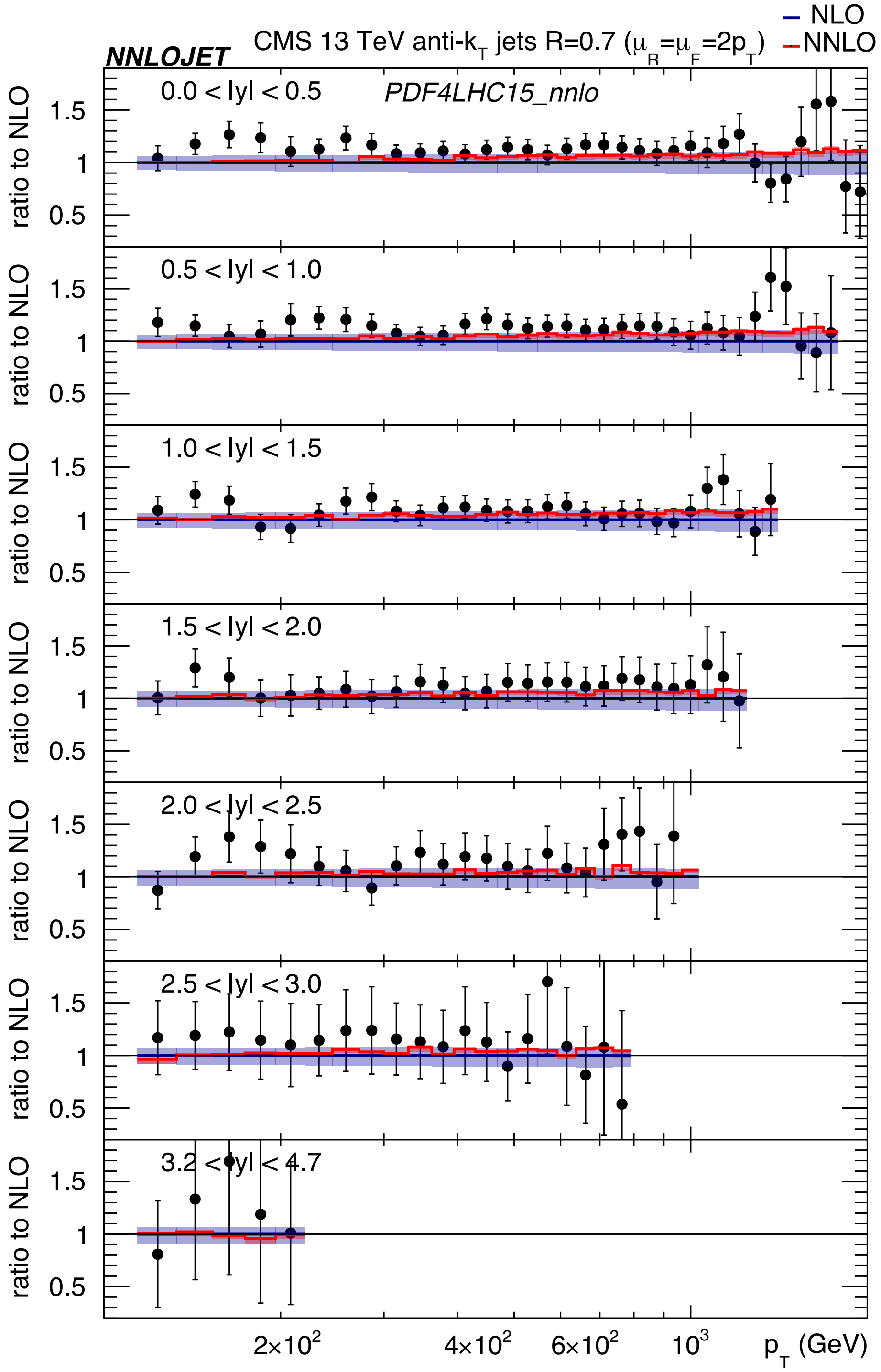
Sector Improved Phase Space for Real Radiation

[Gehrmann-De Ridder, Gehrmann, Glover, JP ’13]

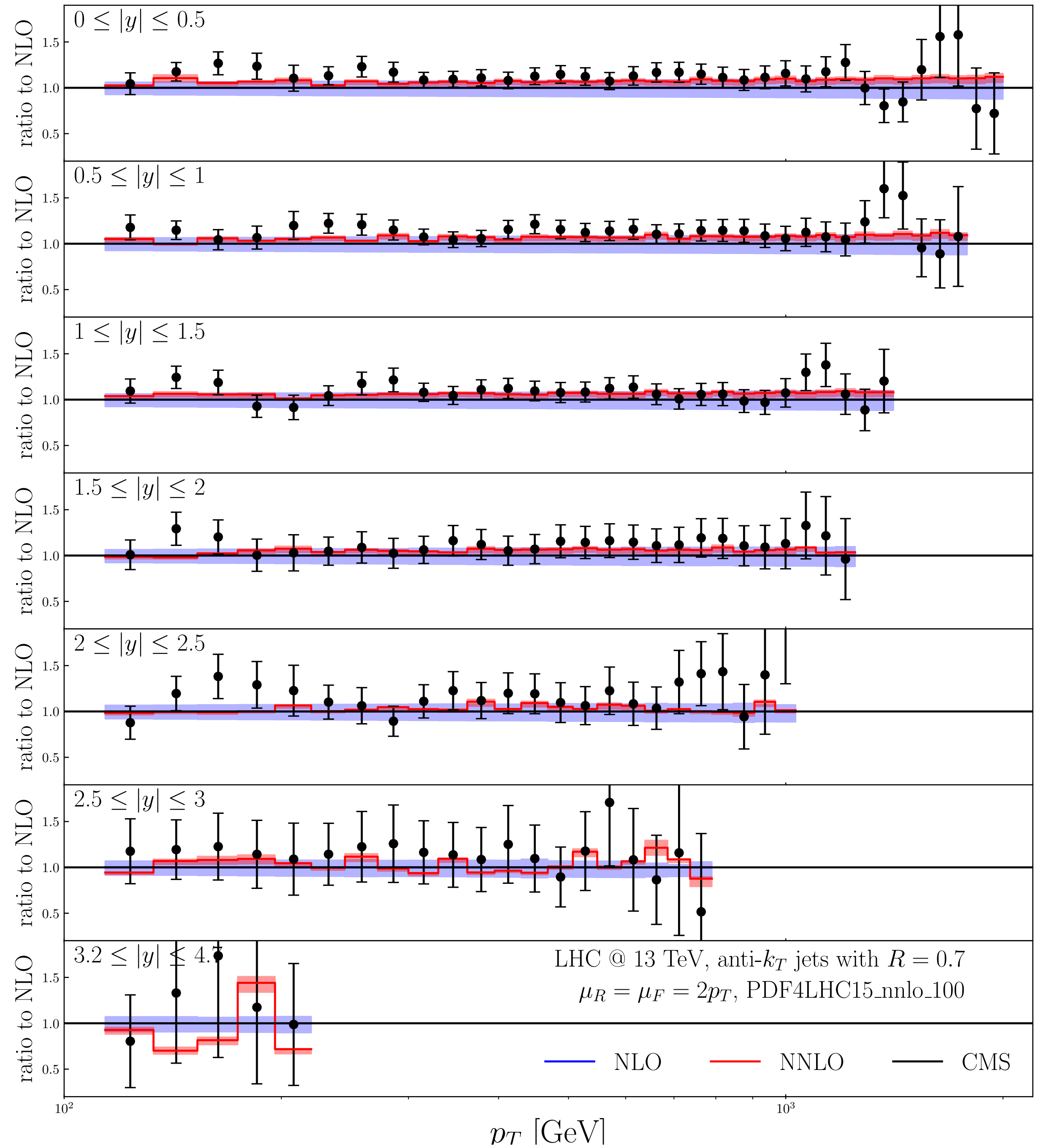
[Currie, Glover, JP ’16] [Currie, Gehrmann-De Ridder, Gehrmann, Glover, Huss, JP ’17]

[Czakon, van Hameren, Mitov, Poncelet ’19]

Single-jet inclusive rates at NNLO



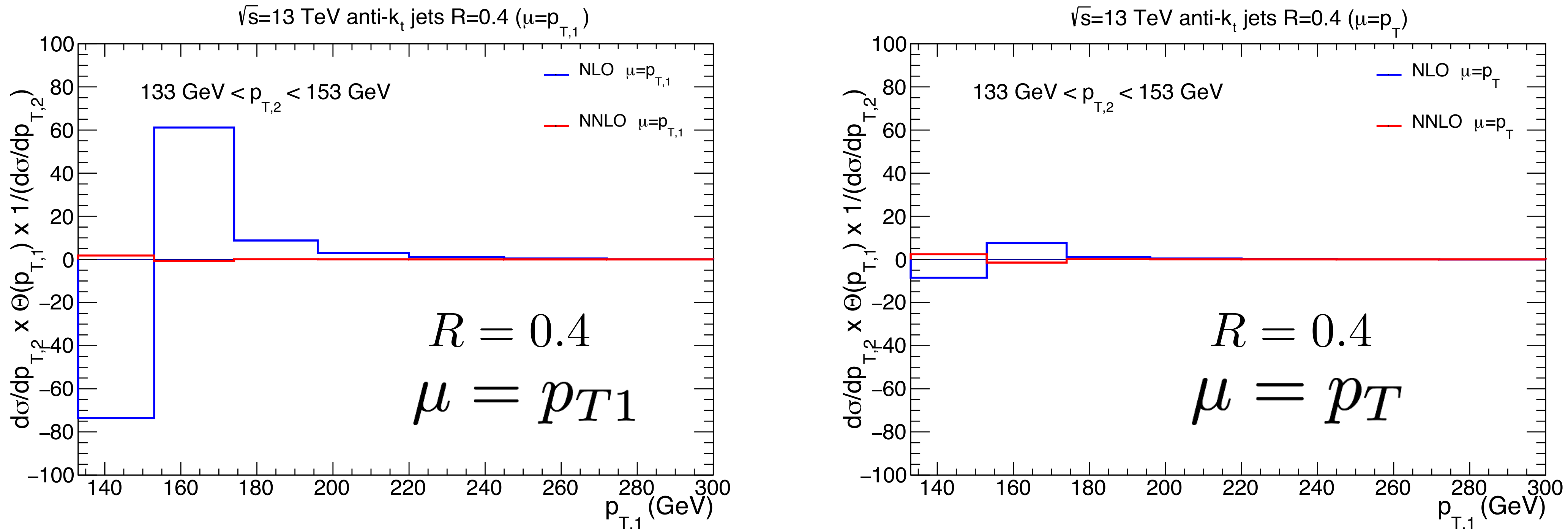
Antenna subtraction



Sector Improved Phase Space for Real Radiation

- Full agreement between two independent calculations using different IR subtraction schemes
- Sub-leading color effects negligible

Second jet transverse momentum - scale choice



Decomposition of events contributing to a single bin in $p_{T2:}$

- bin content above constrained to add up to one by construction
- instability in the second jet p_T distribution from events when additional radiation is not recombined into the outgoing jet

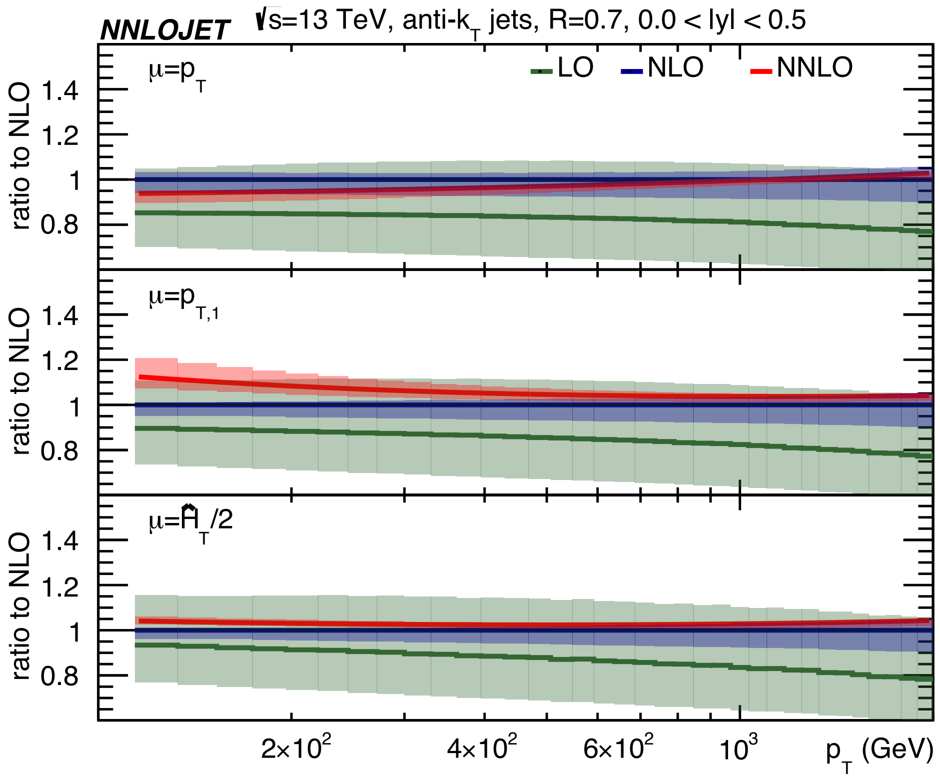
⟶ **Large cancellations** between positive real emission and large negative virtual correction provide a guide to understand the behaviour of the scale choice

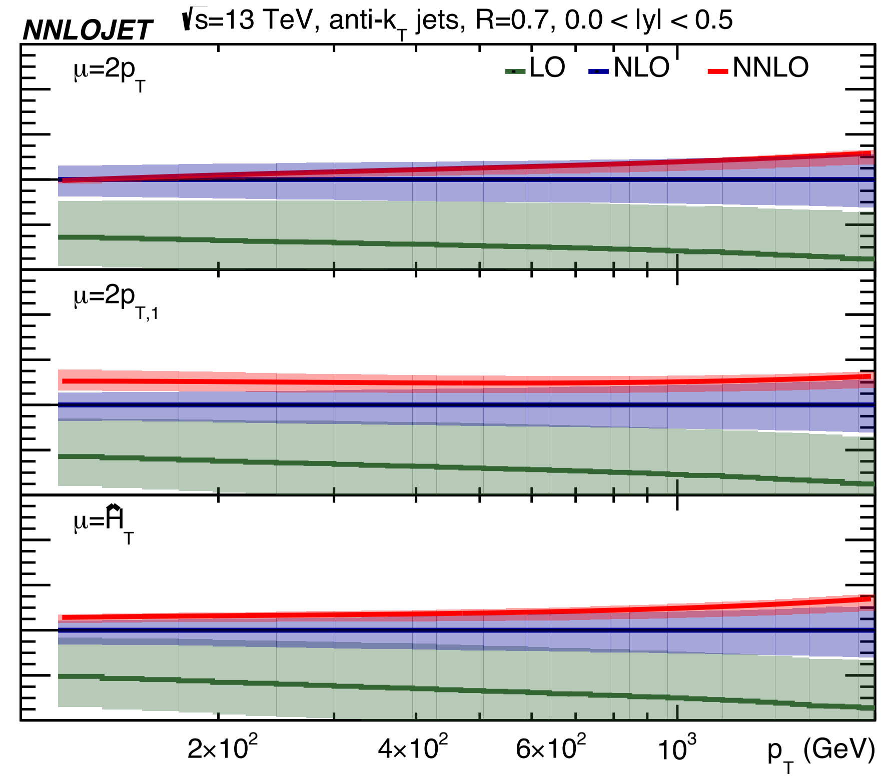
- worse for $\mu = p_{T1}$ that changes event-by-event in the distribution; $\mu = p_T$ remains constant
- detailed single jet inclusive scale study in [J.Currie,T.Gehrmann, A.Gehrmann-De Ridder, E.W.N.Glover,A.Huss, JP ‘18] **[arXiv: 1807.03692] JHEP 1810 (2018) 155**

Single-jet inclusive rates at NNLO - scale choice

0.0<|y|<0.5

$\mu = p_{T,1}$



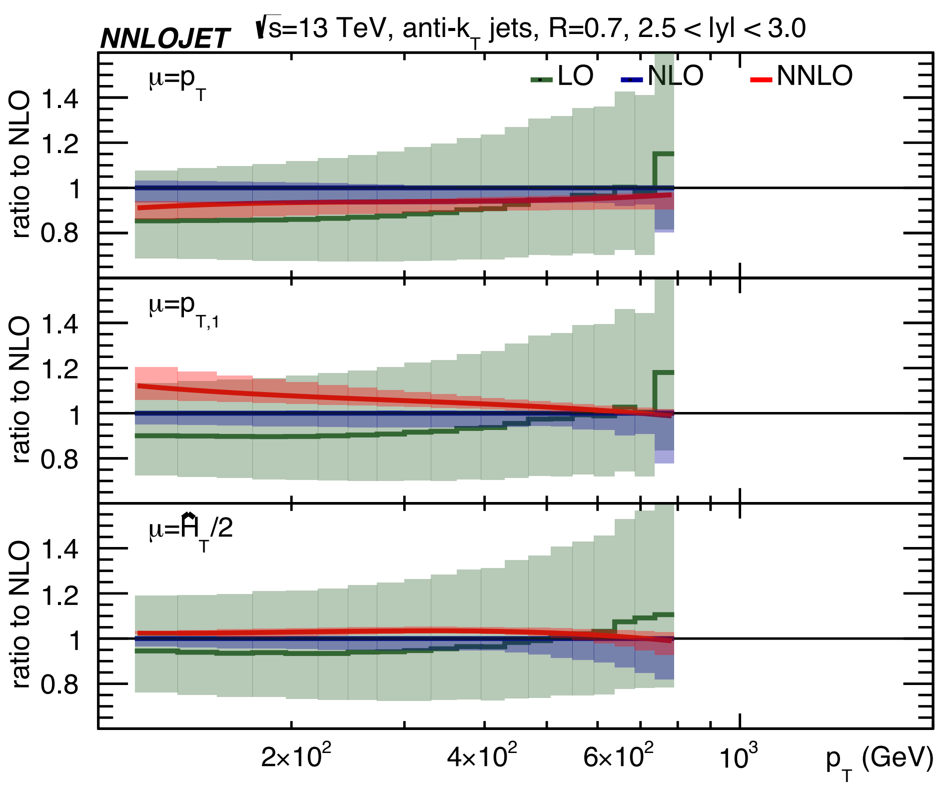


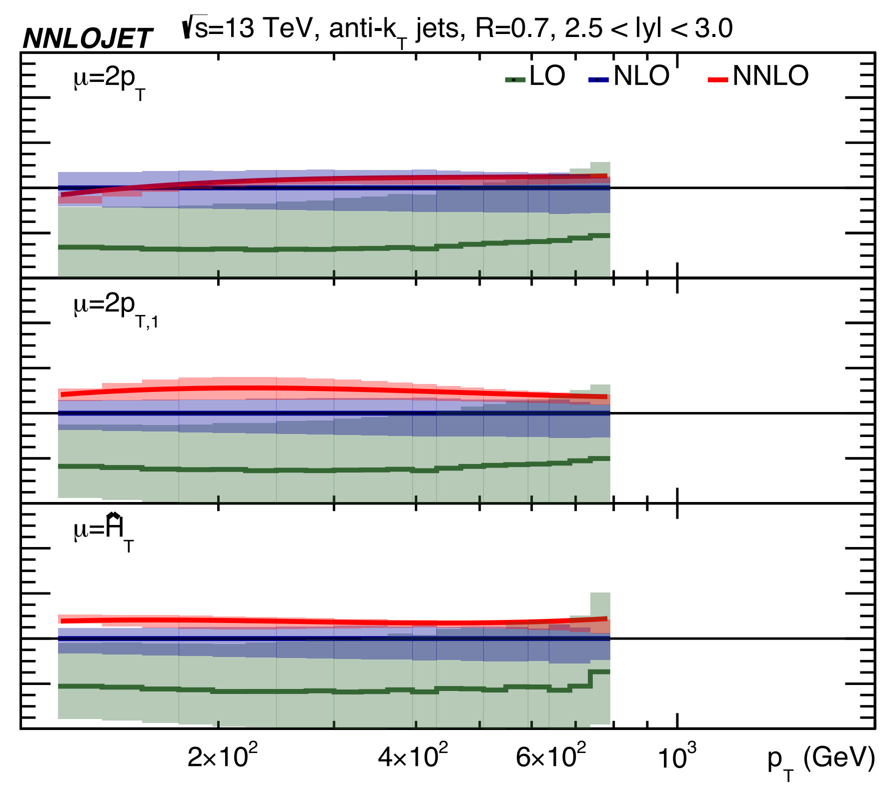
$\mu = 2p_T$

$\mu = \hat{H}_T$

2.5<|y|<3.0

$\mu = p_{T,1}$





$\mu = 2p_T$

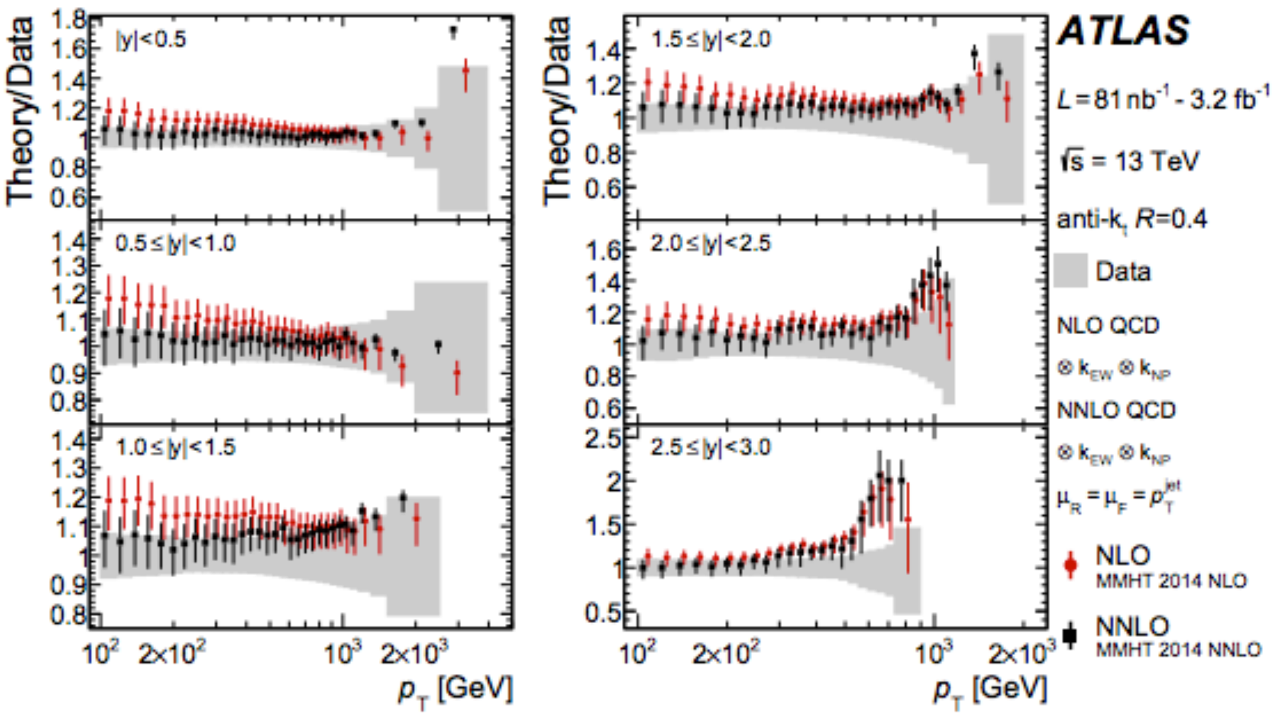
$\mu = \hat{H}_T$

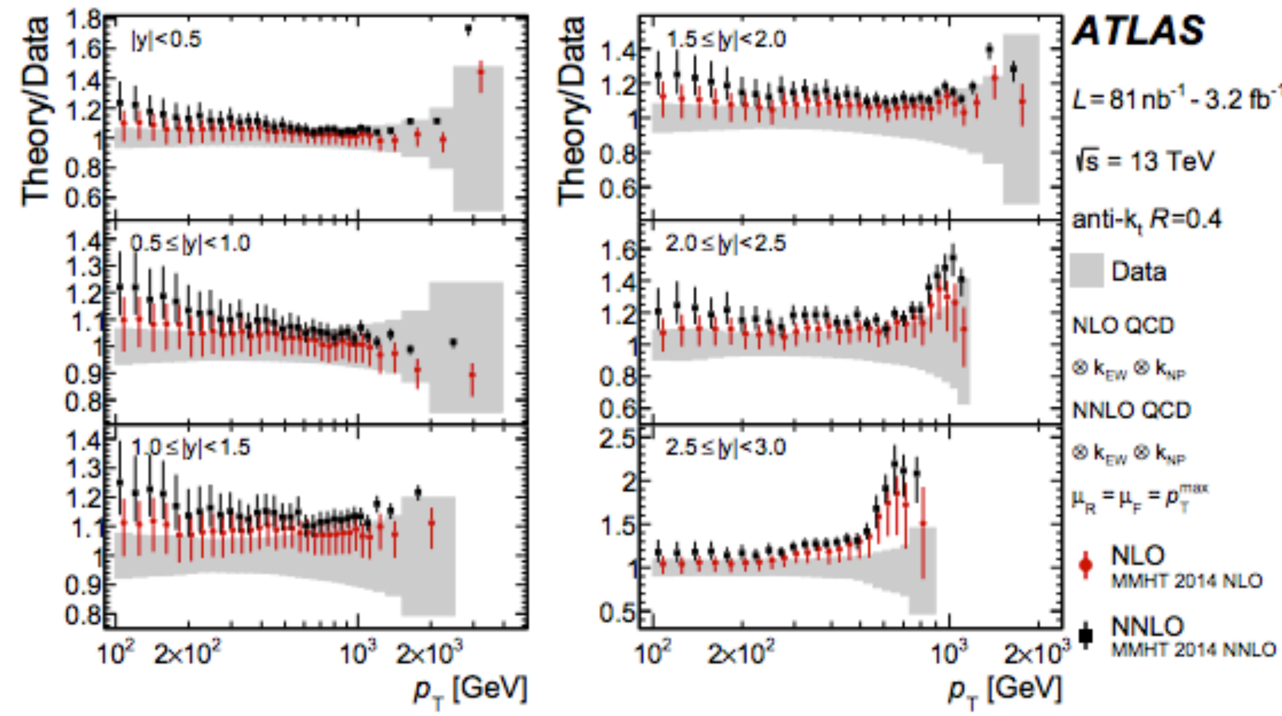
$\mu = p_{T,1}$ ⇒ strongly disfavoured in NNLO predictions for single jet inclusive p_T distributions

[J.Currie,T.Gehrmann, A.Gehrmann-De Ridder, E.W.N.Glover,A.Huss, JP '18] **[arXiv: 1807.03692] JHEP 1810 (2018) 155**

ATLAS $pp \rightarrow$ jet+X, $\sqrt{s}$=13 TeV

ATLAS ***[arXiv: 1711.02692] JHEP 05 (2018) 195***





NLO (μ=p_T)
NNLO (μ=p_T)

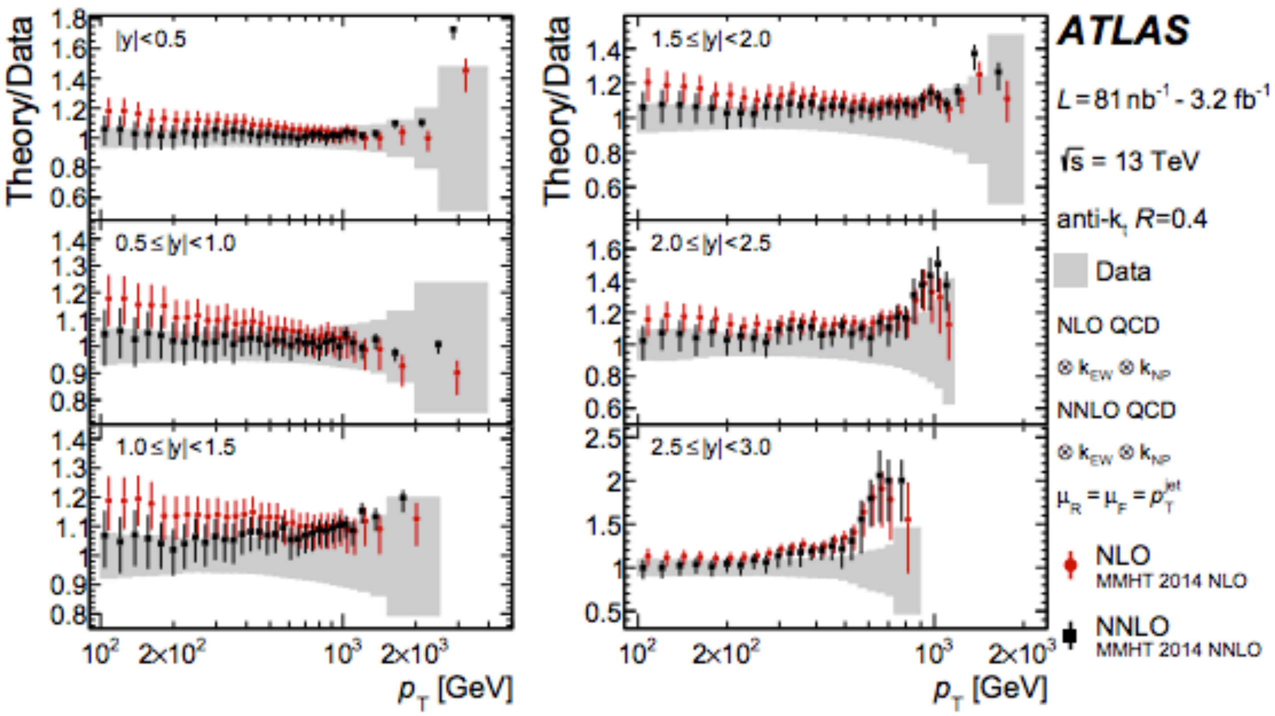
NLO (μ=p_{T1})
NNLO (μ=p_{T1})

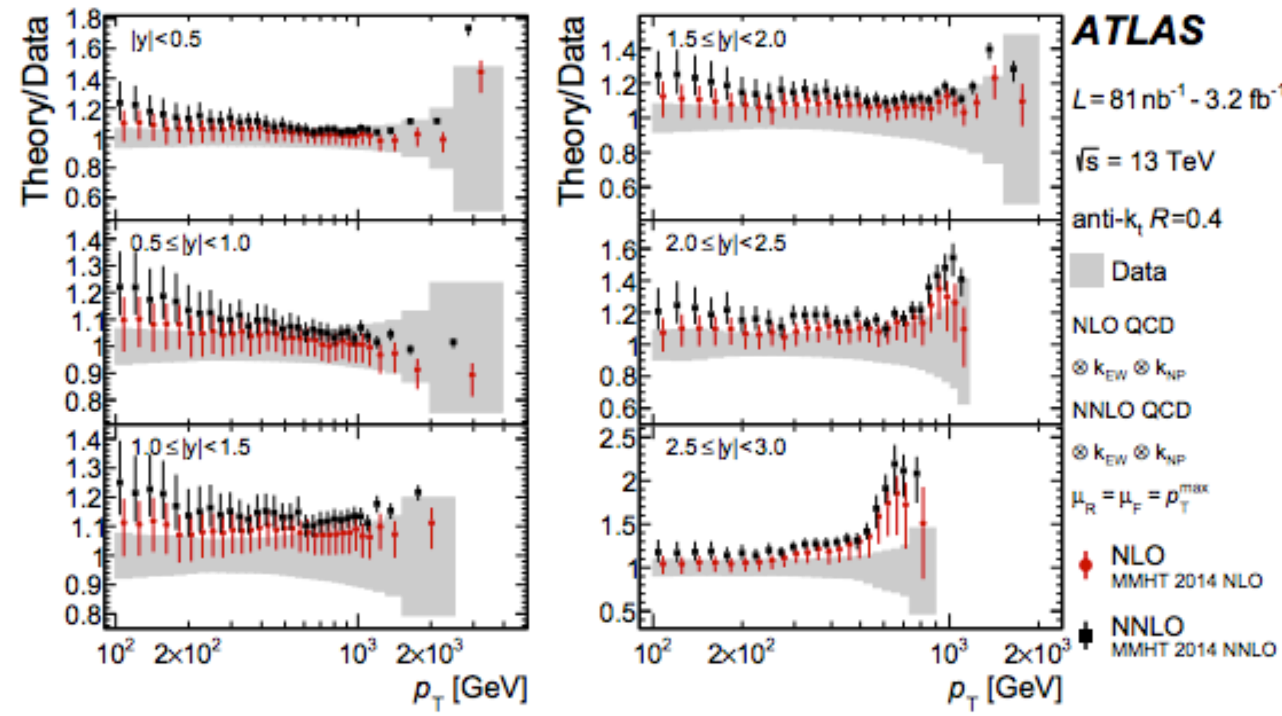
ATLAS ***[arXiv: 1711.02692] JHEP 05 (2018) 195***

$\mu = p_{T,1} \Rightarrow$ strongly disfavoured in NNLO predictions for single jet inclusive p_T distributions

ATLAS $pp \to$ jet+X, $\sqrt{s}$=13 TeV

ATLAS ***[arXiv: 1711.02692] JHEP 05 (2018) 195***





NLO $(\mu = p_T)$
NNLO $(\mu = p_T)$

NLO $(\mu = p_{T1})$
NNLO $(\mu = p_{T1})$

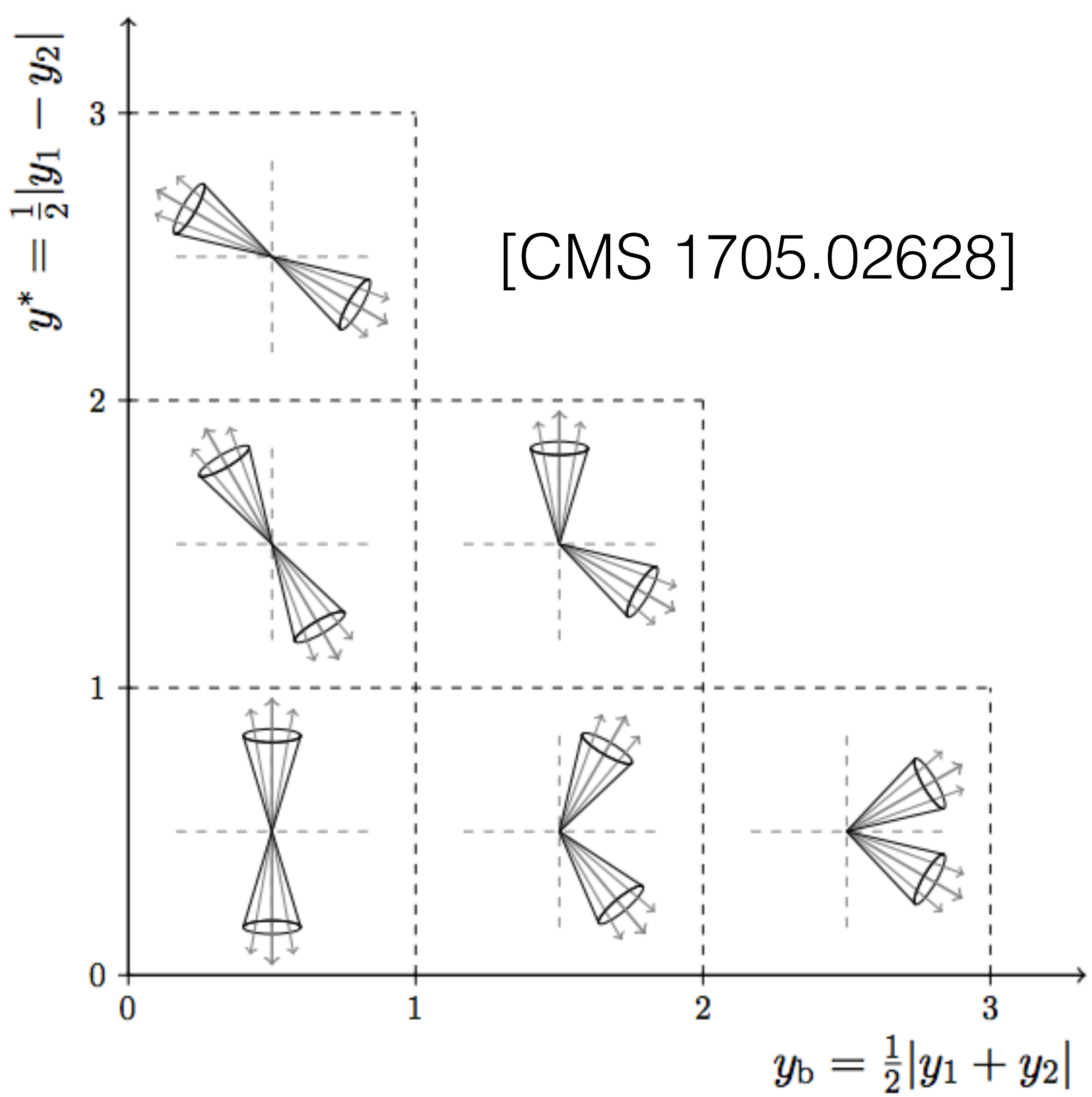
ATLAS ***[arXiv: 1711.02692] JHEP 05 (2018) 195***

- Conclusion in agreement with recent measurements from ATLAS $\sqrt{s}$=13 TeV
- Example of the importante of having **NNLO** effects under control
- **NNLO** theory from NNLOJET

Dijet triple differential measurement - CMS

- Obtain the maximal sensitivity from the dijet cross section to the parton densities from multi-differential distributions

- Explore the shape of the dijet cross section in triple differential form to constrain PDFs at small to moderate x-values: interplay between the parton luminosities and the scattering matrix elements



[CMS 1705.02628]

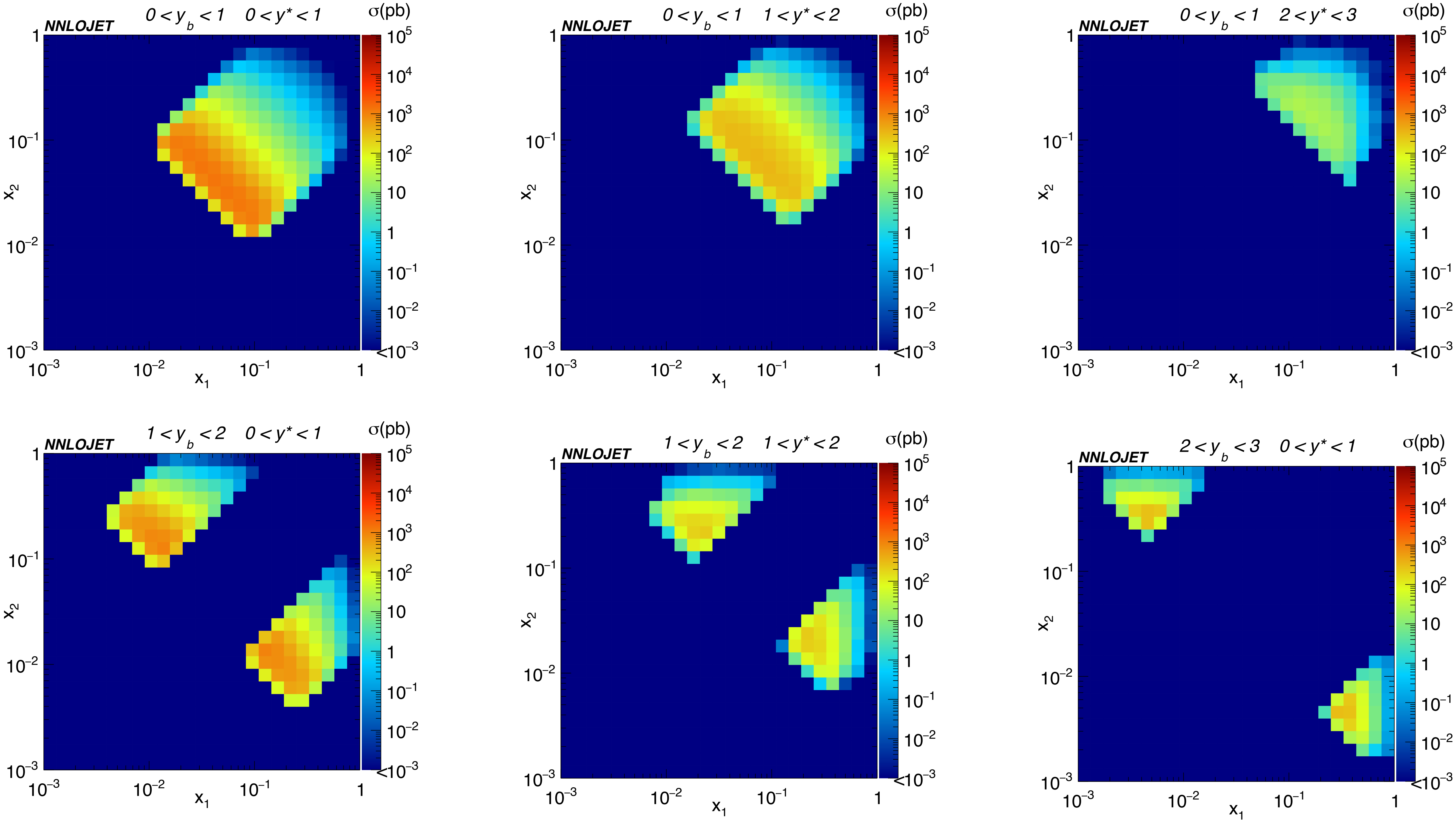
- 2 jet observables built from the two-leading jets in the event, with the caveat that the assignment of the hardest jet in the event is not infra-red safe

- Follow the setup of the 8 TeV CMS measurement that overcomes the problem

$$p_{T,\text{avg}} = (p_{T,1} + p_{T,2})/2$$

$$y^* = |y_1 - y_2|/2$$

$$y_b = |y_1 + y_2|/2$$



$$x_1 = \frac{p_T}{\sqrt{s}} \left(e^{y_1} + e^{y_2}\right) = \frac{2\, p_{T,\mathrm{avg}}}{\sqrt{s}} \, e^{\pm y_b} \cosh(y^*),$$

$$x_2 = \frac{p_T}{\sqrt{s}} \left(e^{-y_1} + e^{-y_2}\right) = \frac{2\, p_{T,\mathrm{avg}}}{\sqrt{s}} \, e^{\mp y_b} \cosh(y^*). \; (1)$$

- density plot in the partonic fractions (x_1,x_2) plane of the triple differential cross section as a function of y^* and y_b for the fiducial cuts of the CMS measurement $p_{T,avg} > 133$ GeV
- cuts on y^* and y_b directly map to surfaces on the x-Q^2 plane where the PDFs are determined; CMS setup

State of the art

Previously studied:

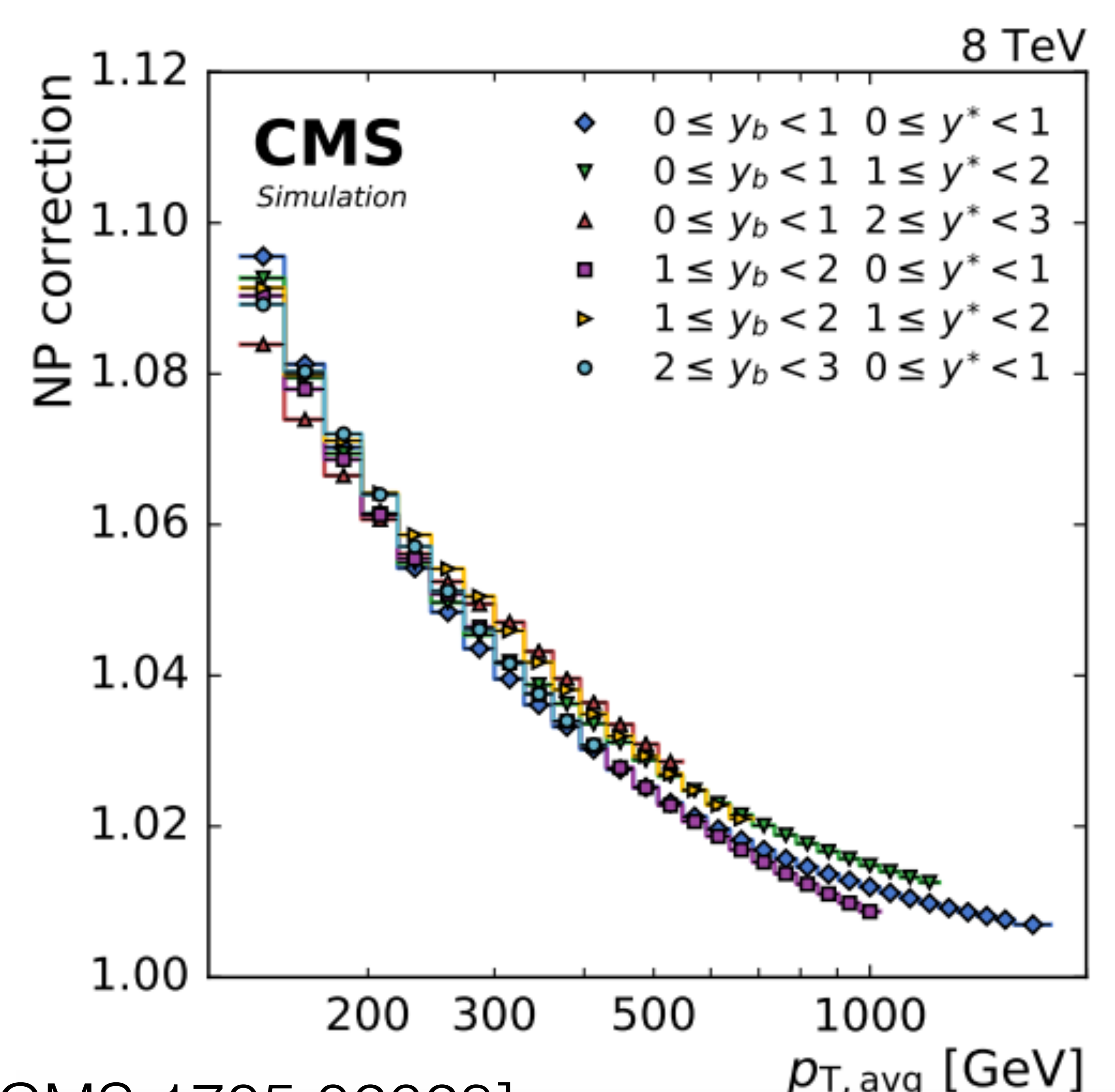
- The NLO inclusive two jet triply differential cross section — *W.Giele, E.W.N.Glover, D.A.Kosower* ***[hep-ph/9403347] Phys.Rev.Lett. 73 (1994) 2019***
  - Scale uncertainties and missing higher order corrections limit the achievable precision
- Measurement from CDF at 1.8 TeV based on an integrated luminosity of 86pb^{-1}

CDF collaboration ***[hep-ex/0012013 Phys.Rev.D64 (2001) 012001***

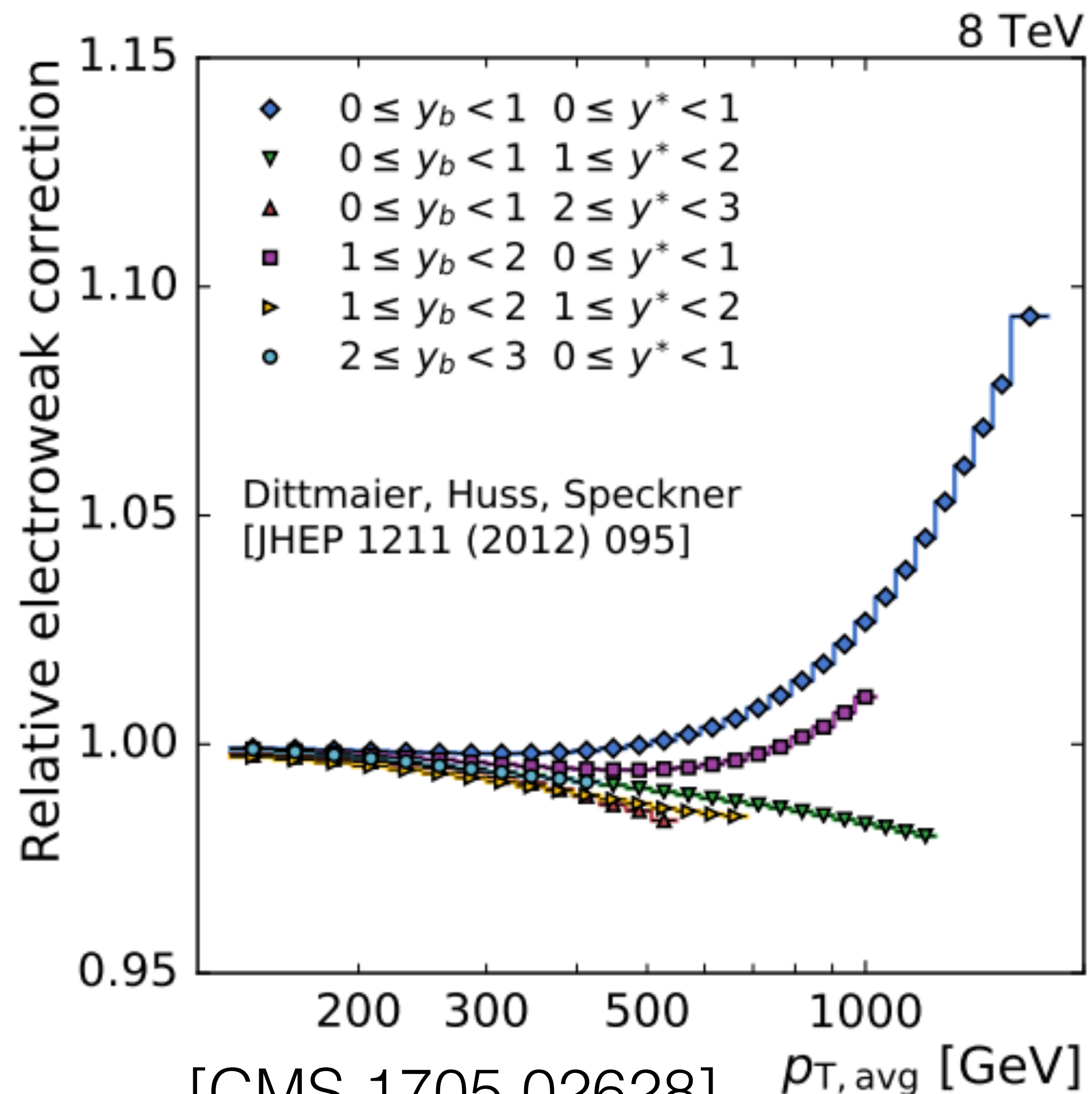
Goal:

- Compute for the first time the triple differential observable at NNLO
- Detailed comparison with CMS 8 TeV data 19.7fb^{-1} dataset at the percent level
- Include an assessment of NP and EW effects

CMS $\sqrt{s}$=8 TeV anti-k_T R=0.7



[CMS 1705.02628]

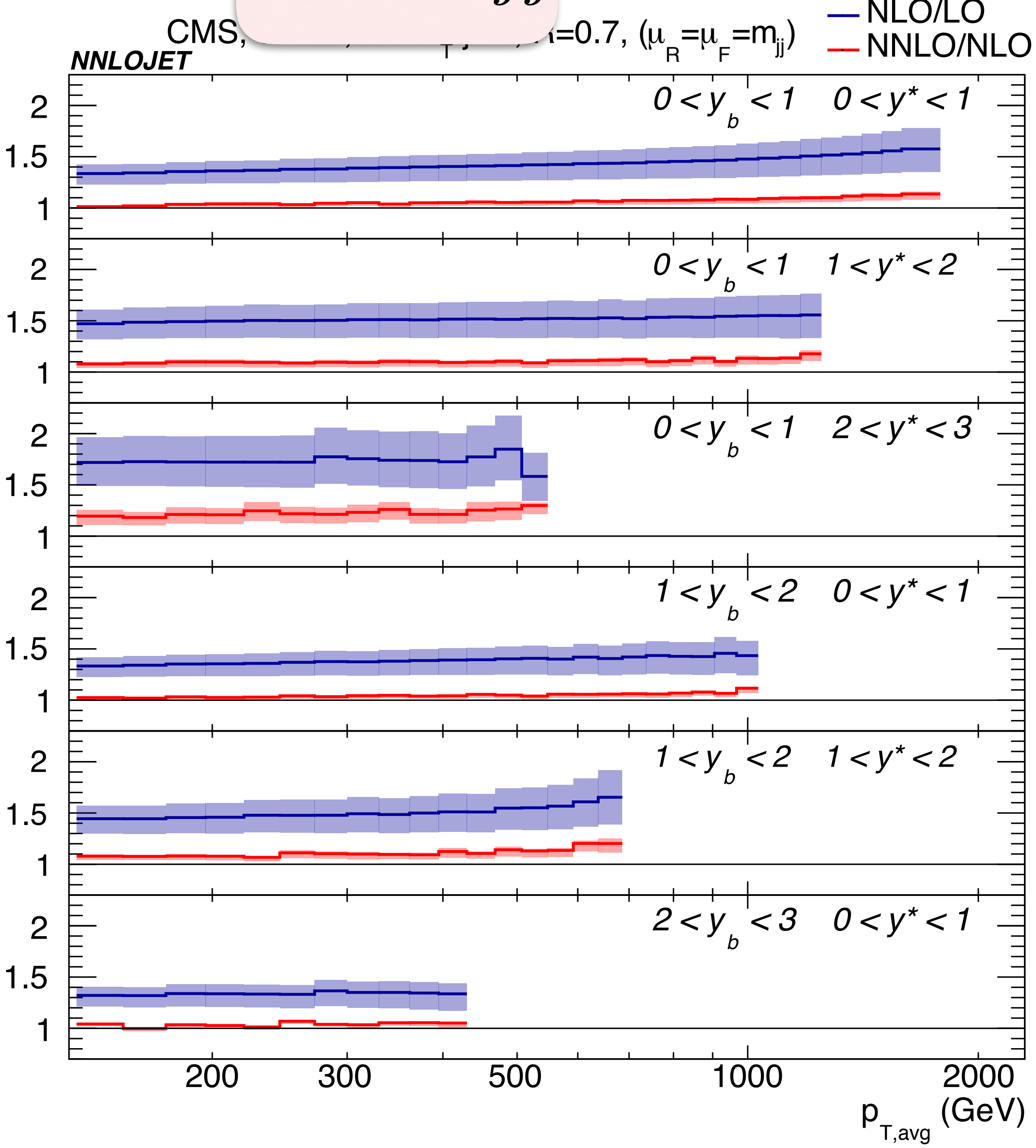


[CMS 1705.02628]

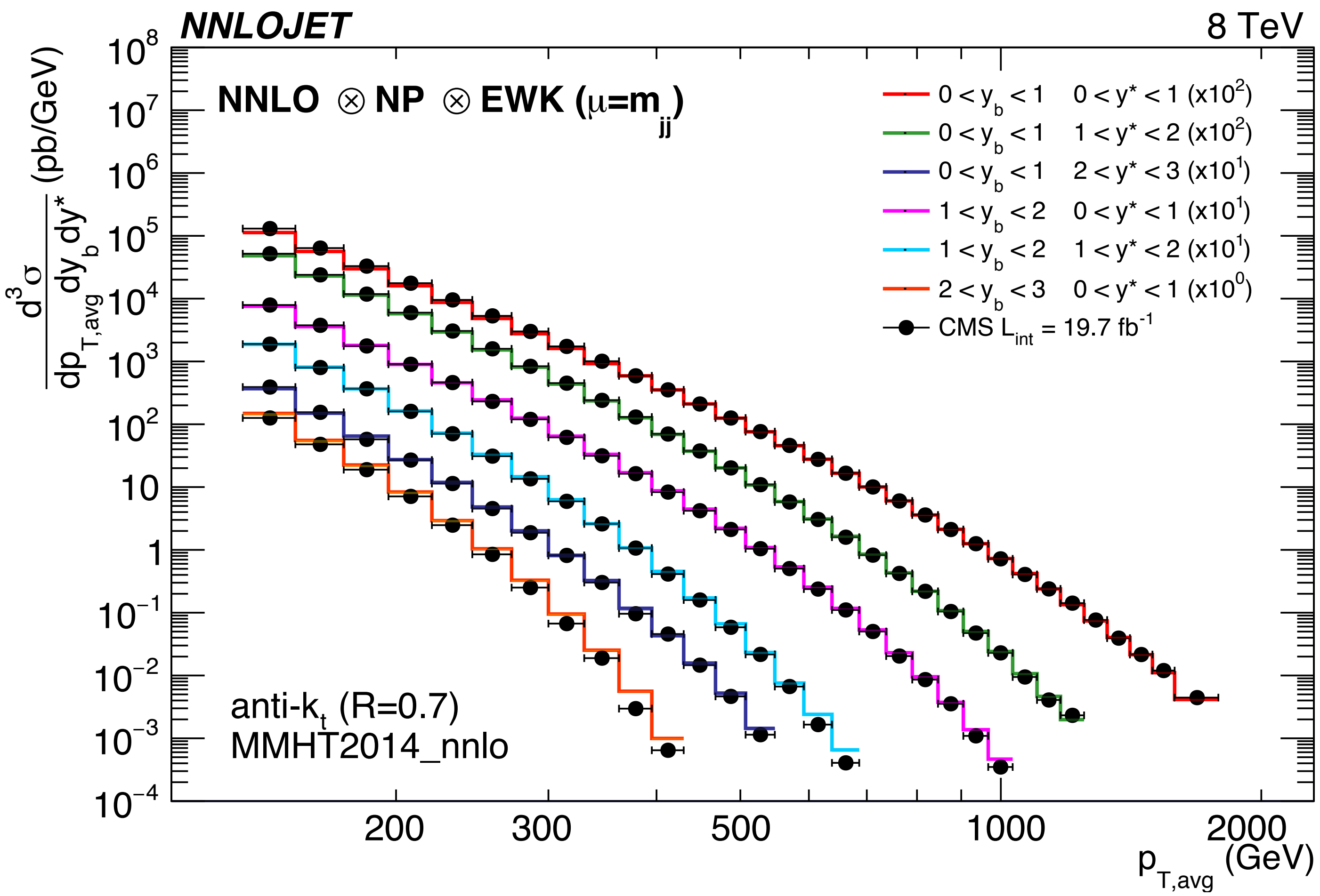
- NP correction 10% in the lowest $p_{T,avg}$ bins, negligible above 1 TeV
  - center of the envelop of HERWIG,PYTHIA and POWHEG with and without hadronization and MPI
- EW correction relevant in the low y* and low y_b rapidity slice reaching 8% at high $p_{T,avg}$
  - EW effects visible in the LHC measurements that reach percent-level precision

CMS $\sqrt{s}$=8 TeV anti-k_T R=0.7

$\mu = m_{jj}$

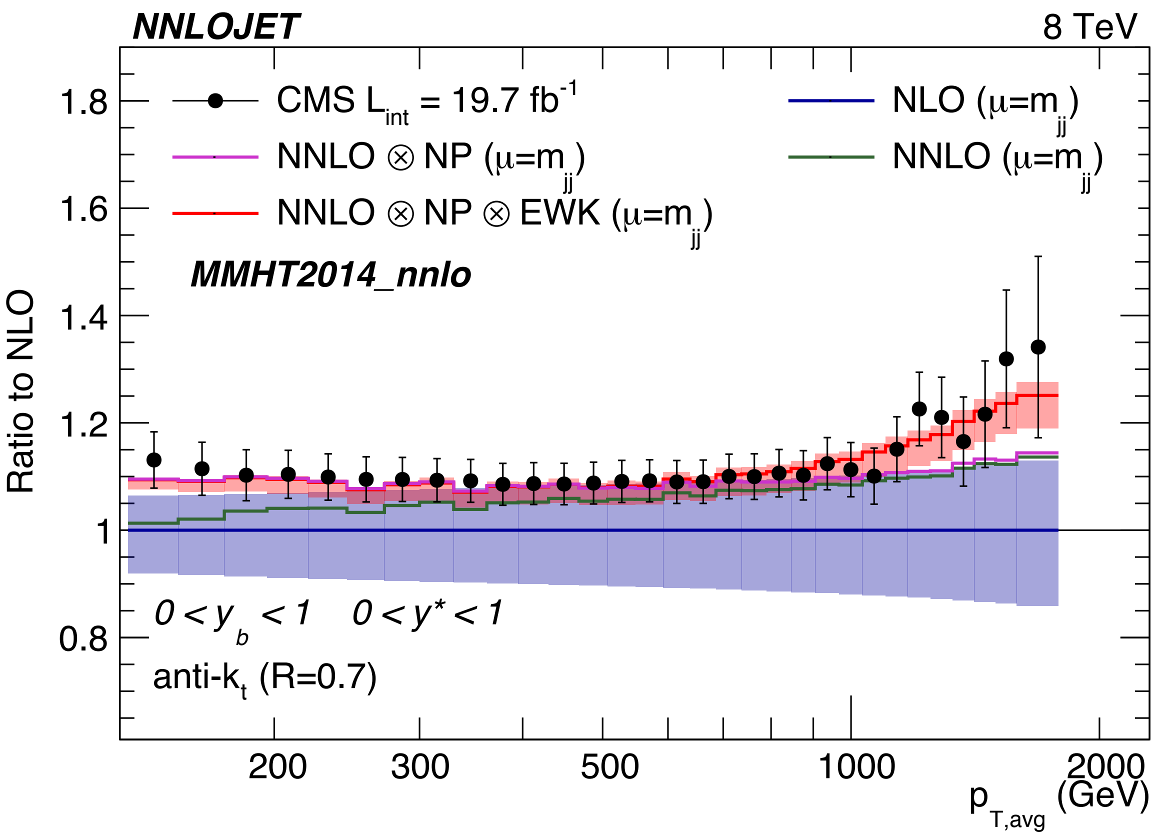


Gehrmann-De Ridder, Gehrmann, Glover, Huss, JP
[arXiv: 1905.09047] Phys. Rev. Lett. 123, 102001 (2019)



- size of the corrections varies significantly as a function of $p_{T,avg}$ and the applied cuts on y^* and y_b
- NNLO correction changes both the shape and normalisation of the NLO result
- QCD scale choice $\mu_R = \mu_F = m_{jj}$

CMS $\sqrt{s}$=8 TeV $0 < y_b < 1$

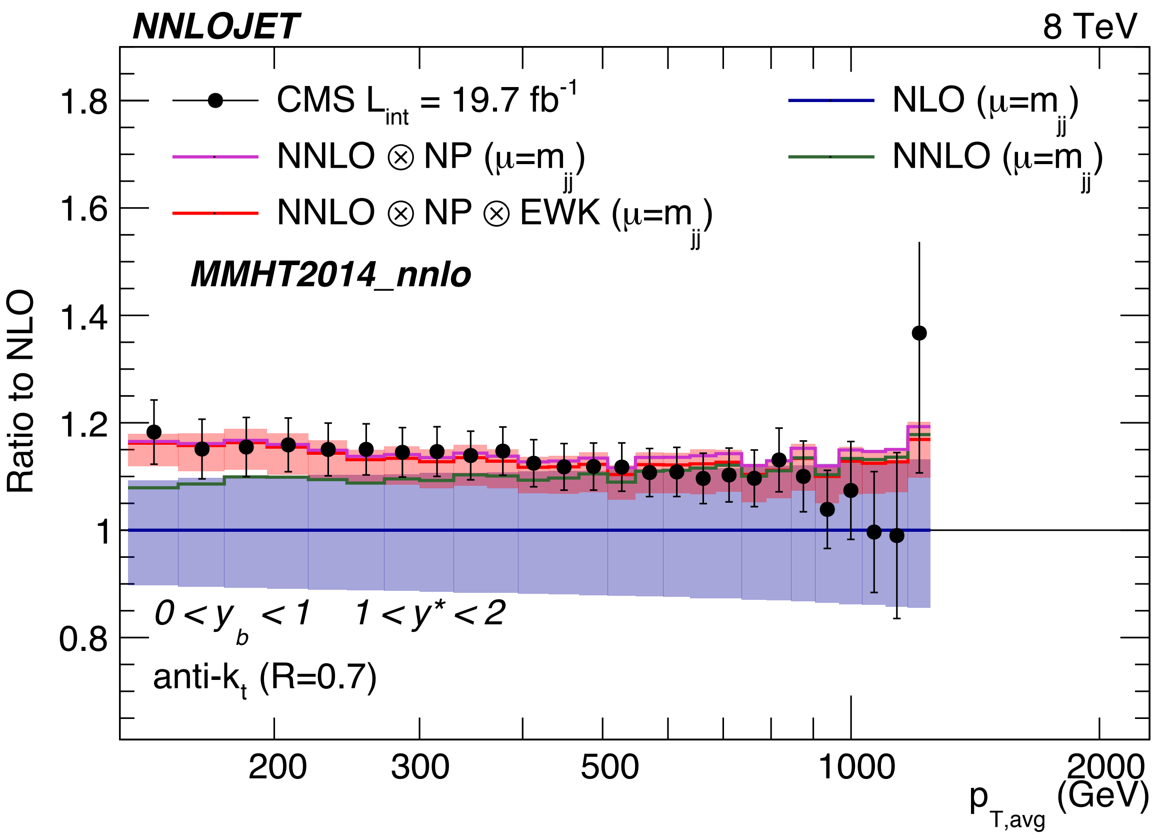


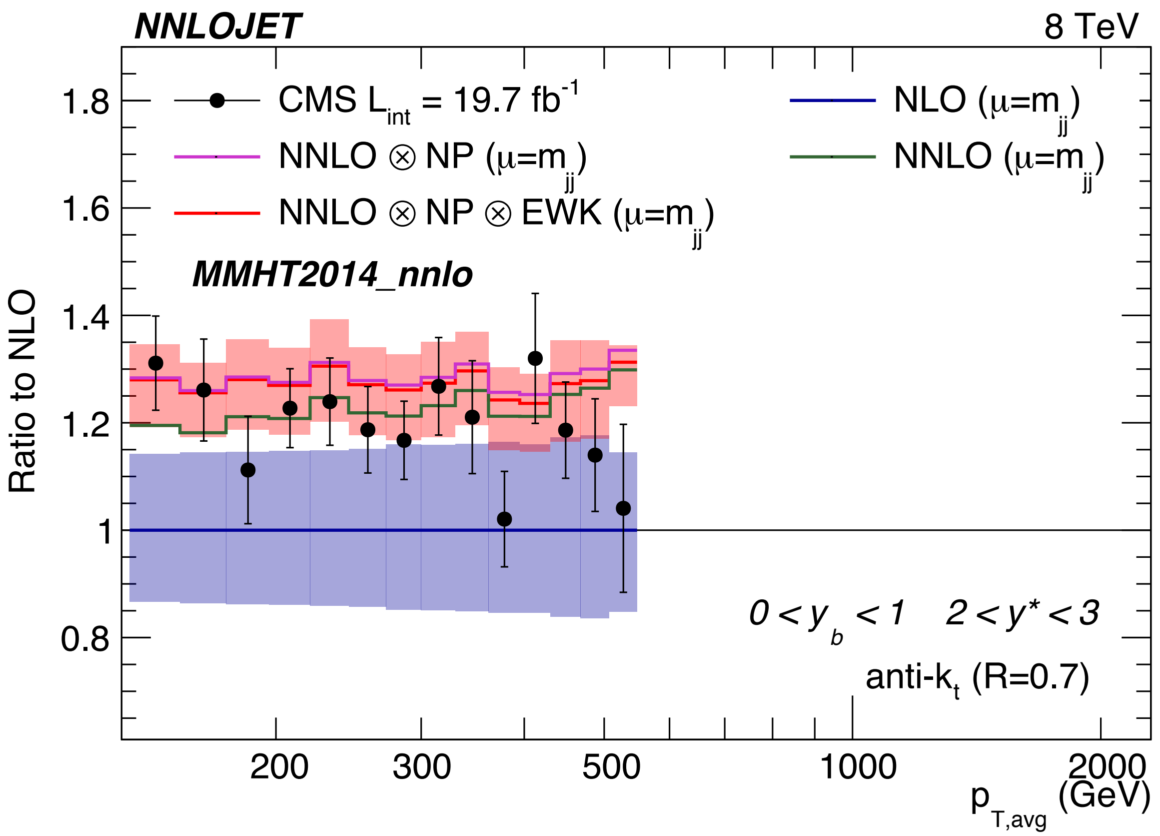
MMHT2014_nnlo

- **NNLO** correction changes both the shape and normalisation of the **NLO** result

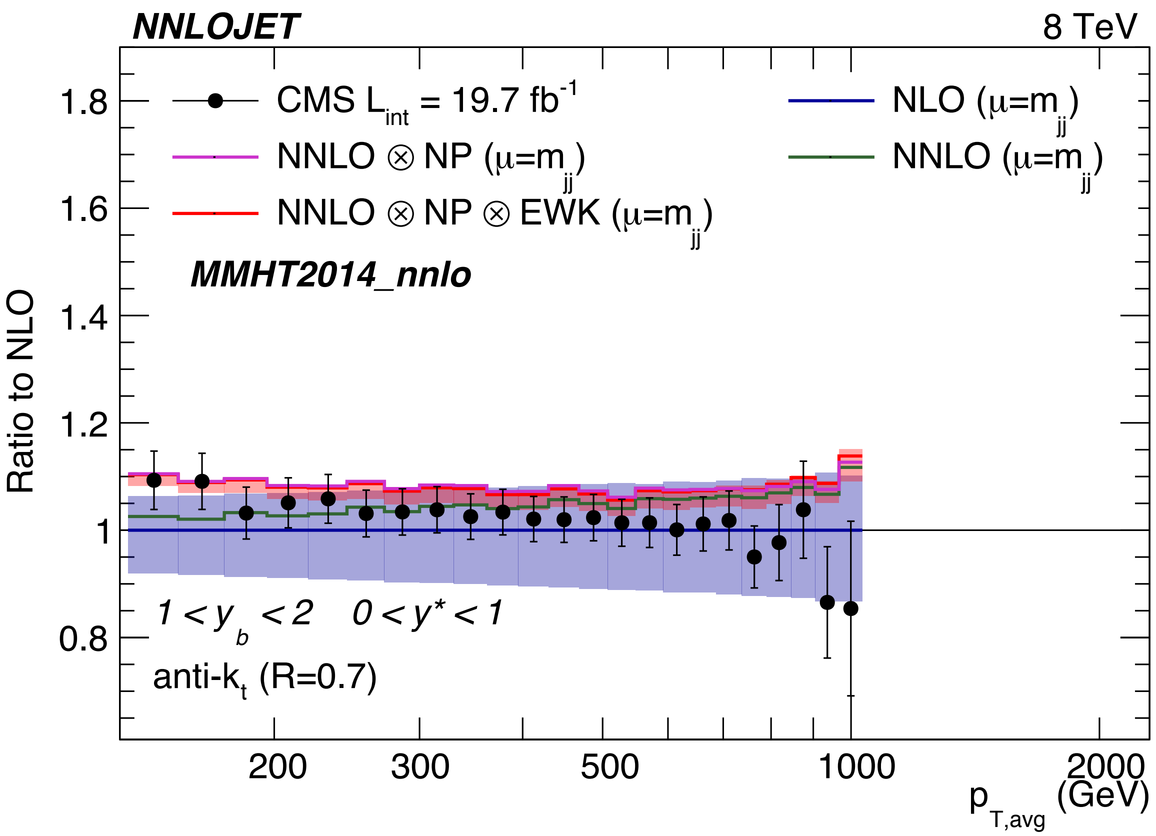
→ good agreement with NNLO⊗NP⊗EWK for the central y_b slice

Gehrmann-De Ridder, Gehrmann, Glover, Huss, JP
[arXiv: 1905.09047] Phys. Rev. Lett. 123, 102001 (2019)



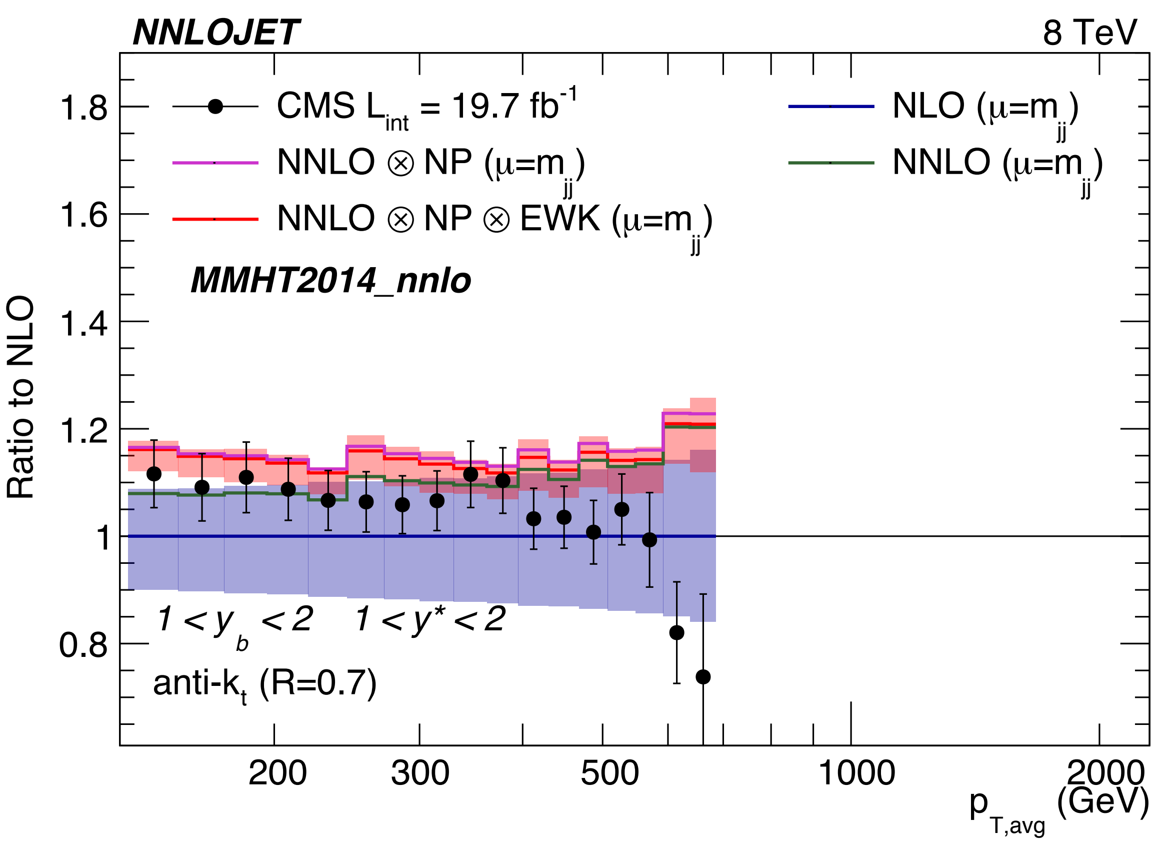


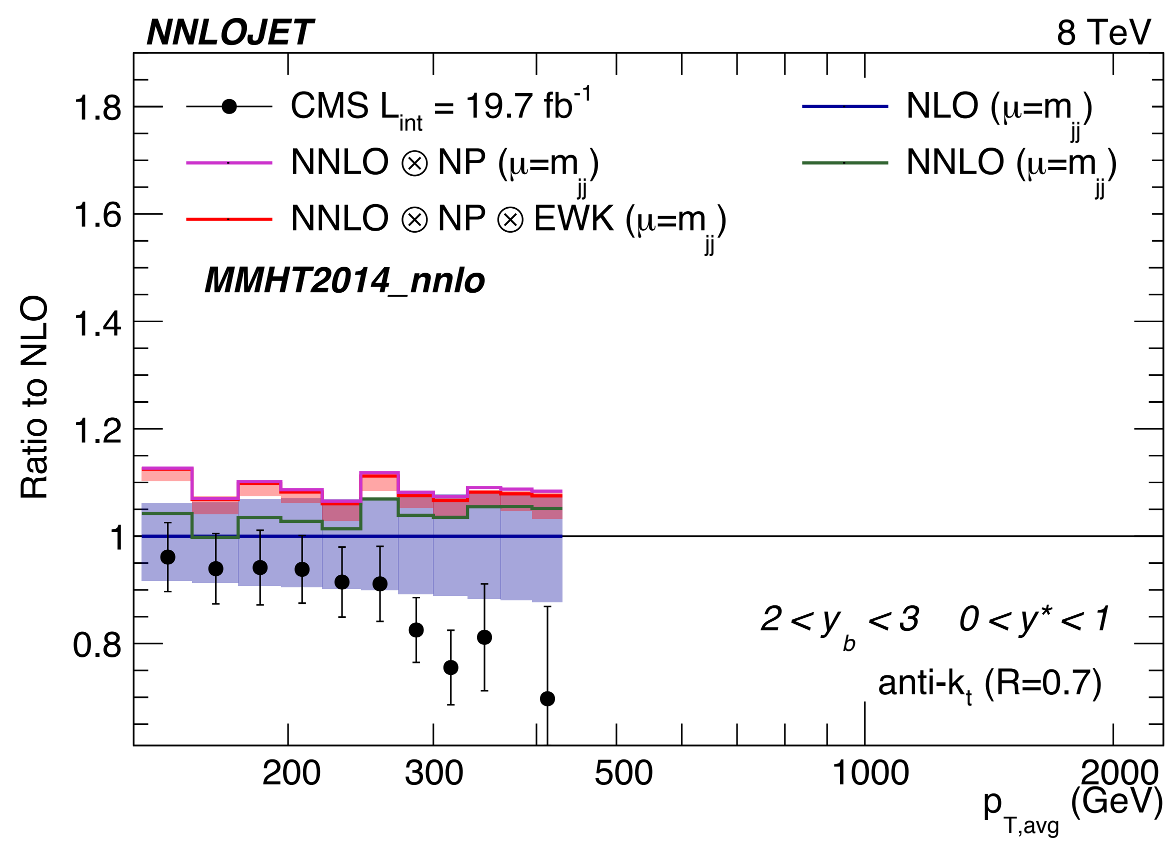
CMS √s=8 TeV $y_b > 1$



MMHT2014_nnlo

- y_b variation probes the scattering of a high-x parton off a low-x parton; → large PDF uncertainty
- data sits below the central value of the MMHT2014 **NNLO** central value
- PDF effect since matrix element contribution invariant under y_b variation





Summary/Outlook

Summary:

- Significant theoretical progress in the description of inclusive jet and dijet production at the LHC
- Theoretical developments driven by the increase in precision of the experimental measurements
- New theoretical calculations available that can be used to understand the impact of the effects of higher order corrections in the description of jet data at hadron colliders

Outlook

- Perform further quantitative comparisons between data and theory i.e., different energies, covering wide jet p_T and rapidity and jet cone sizes
- Use new data to understand effects in tuning of hadronization and underlying event parameters and respective uncertainties
- Extend existing phenomenological predictions to triple-differential measurements and angular observables and jet shapes
- Study sensitivity of jet-based observables to α_s and PDF extractions and assess ultimate reach in precision in a combined fit