Current theory status for jet production

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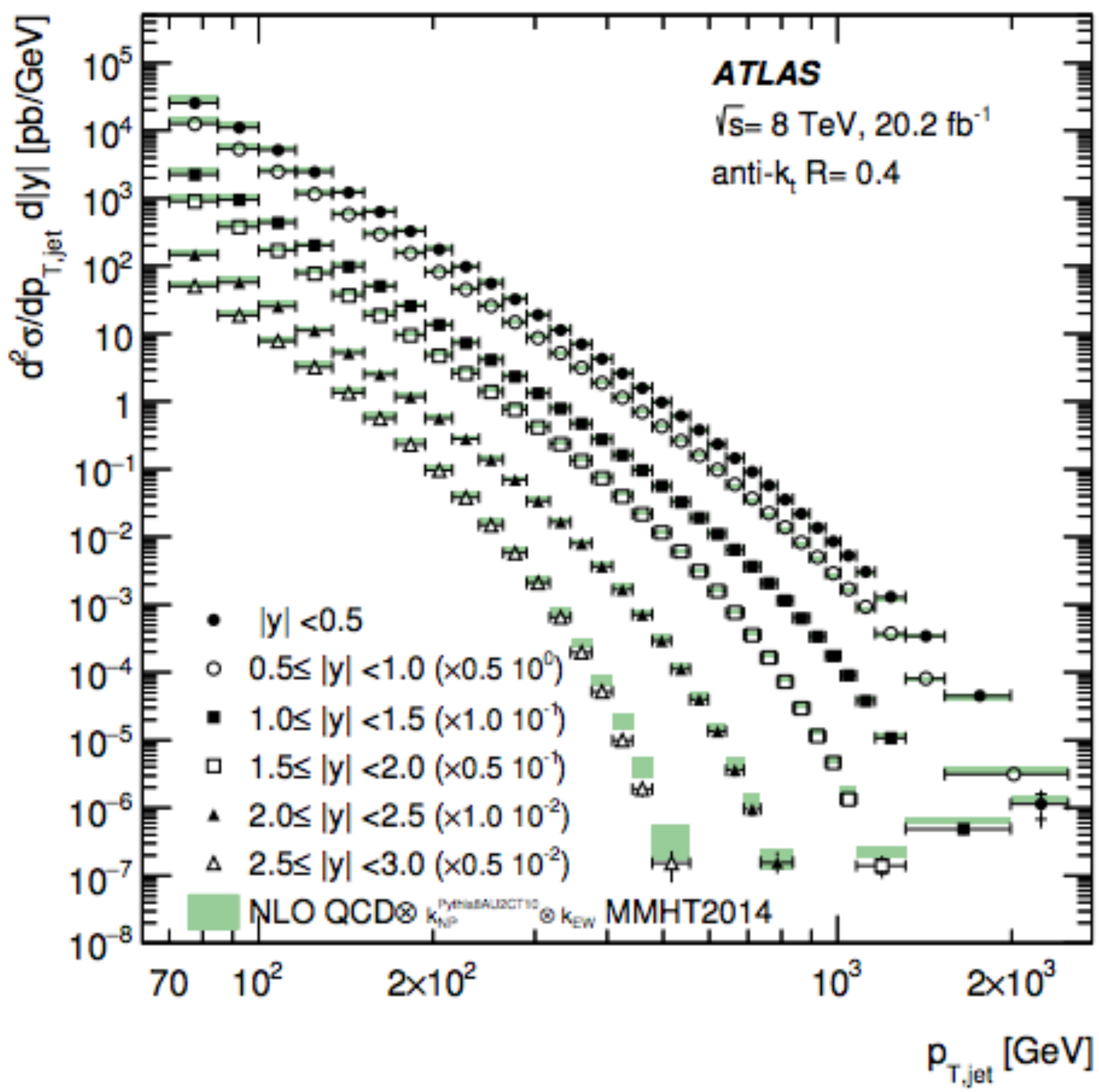
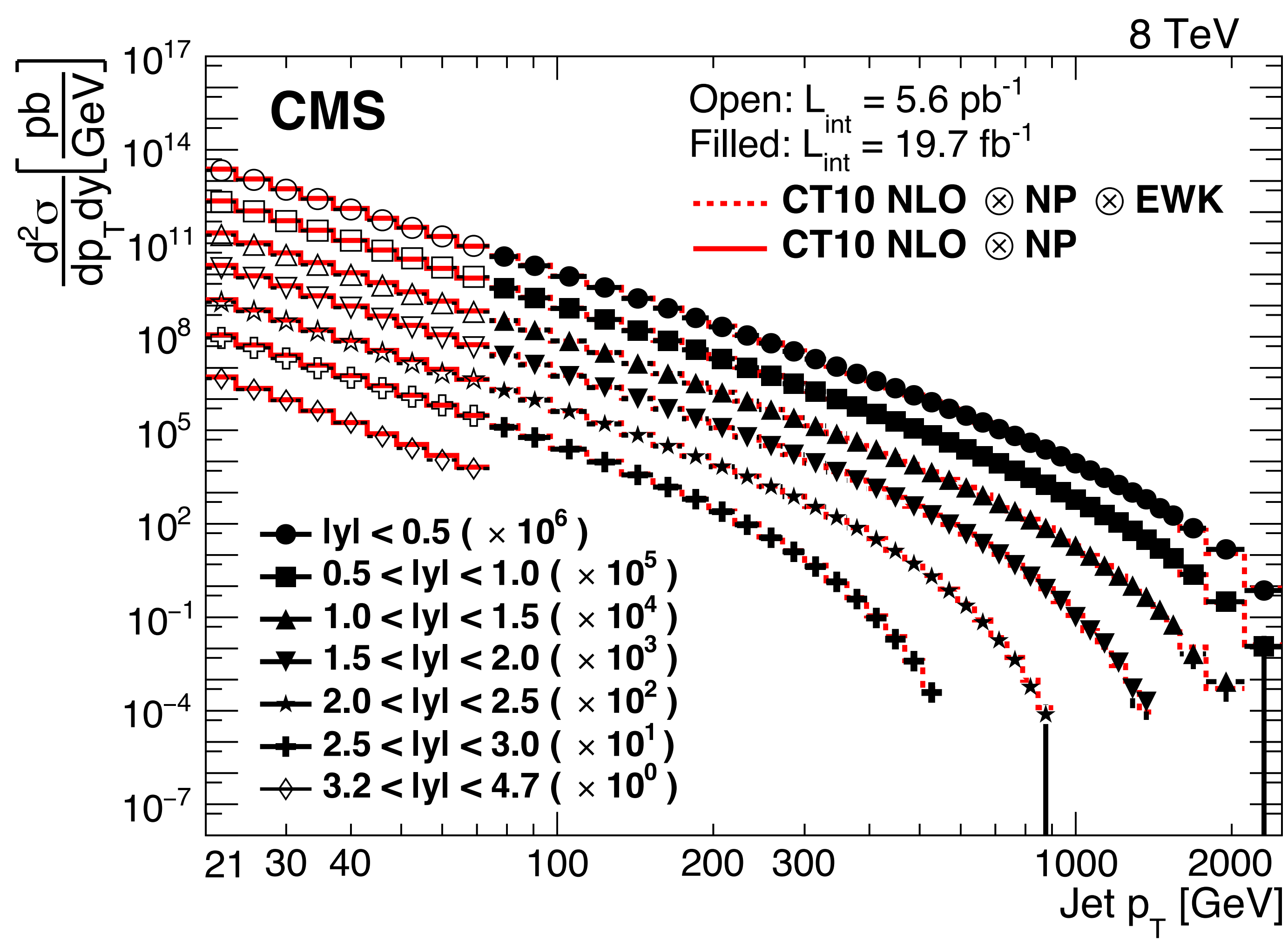
Jet production at the LHC

- 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

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





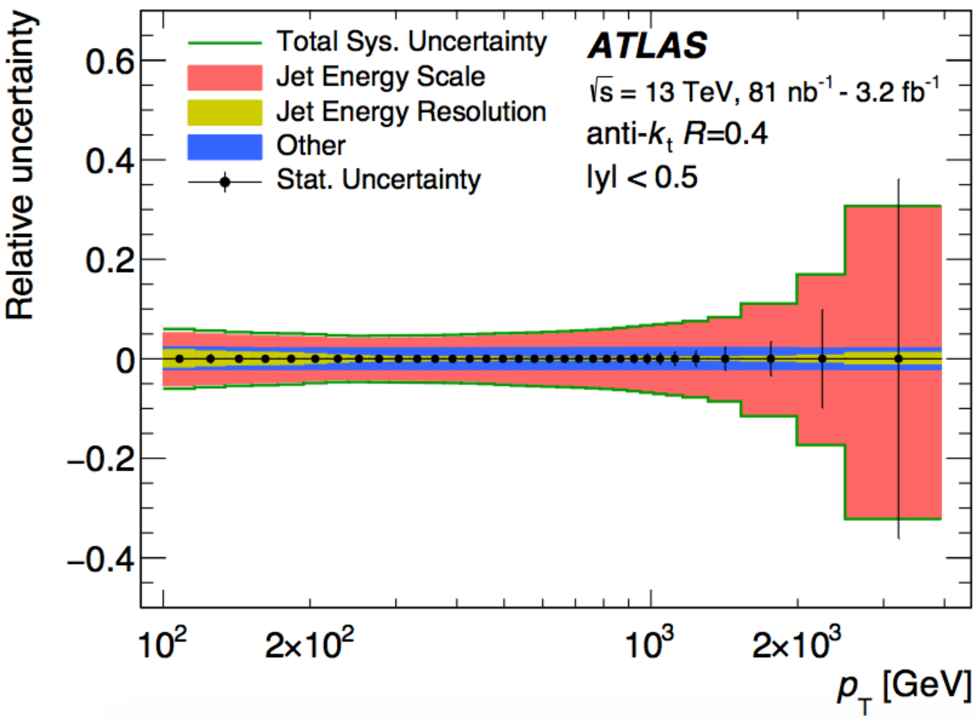
Jet production: uncertainties at the LHC

Jet measurements have become very precise:

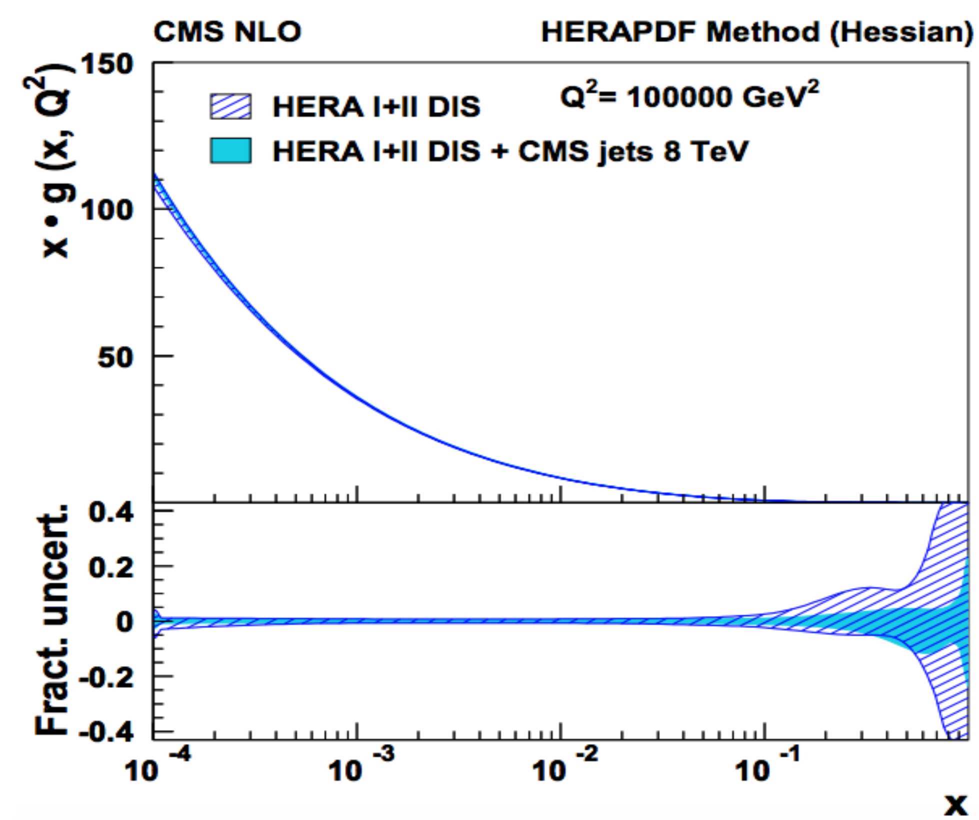
- dominant systematic uncertainty JES ~ 1-2% corresponds to < 10% uncertainty on single jet inclusive cross section
- similar for ATLAS and CMS: 5% systematic on a wide range, and sub-% statistical → allow jet precision physics at the LHC

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)

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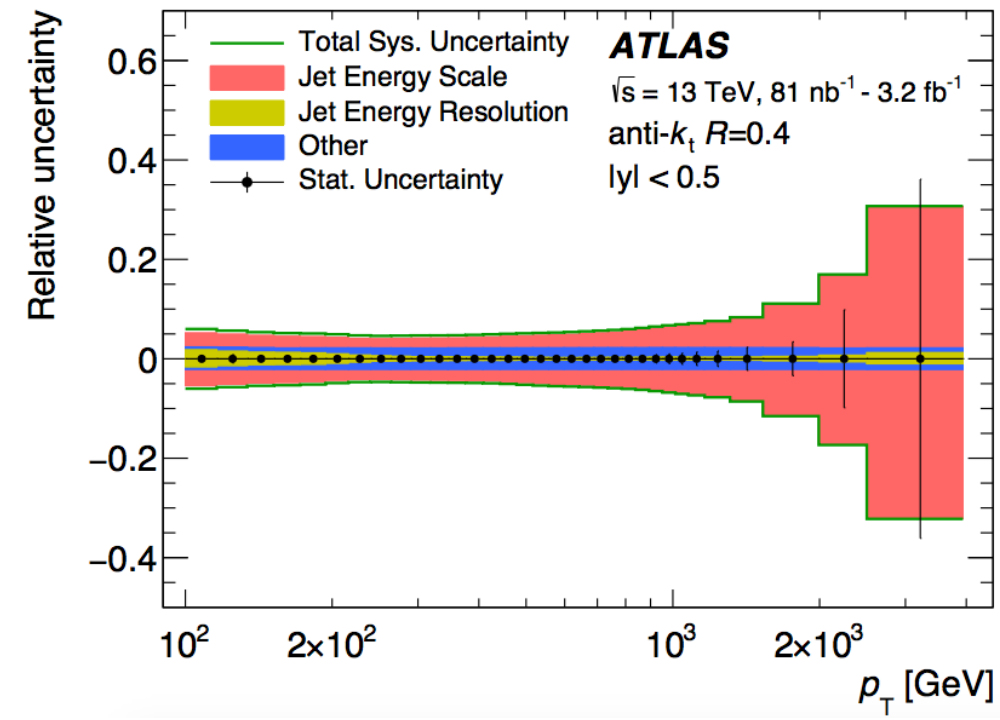

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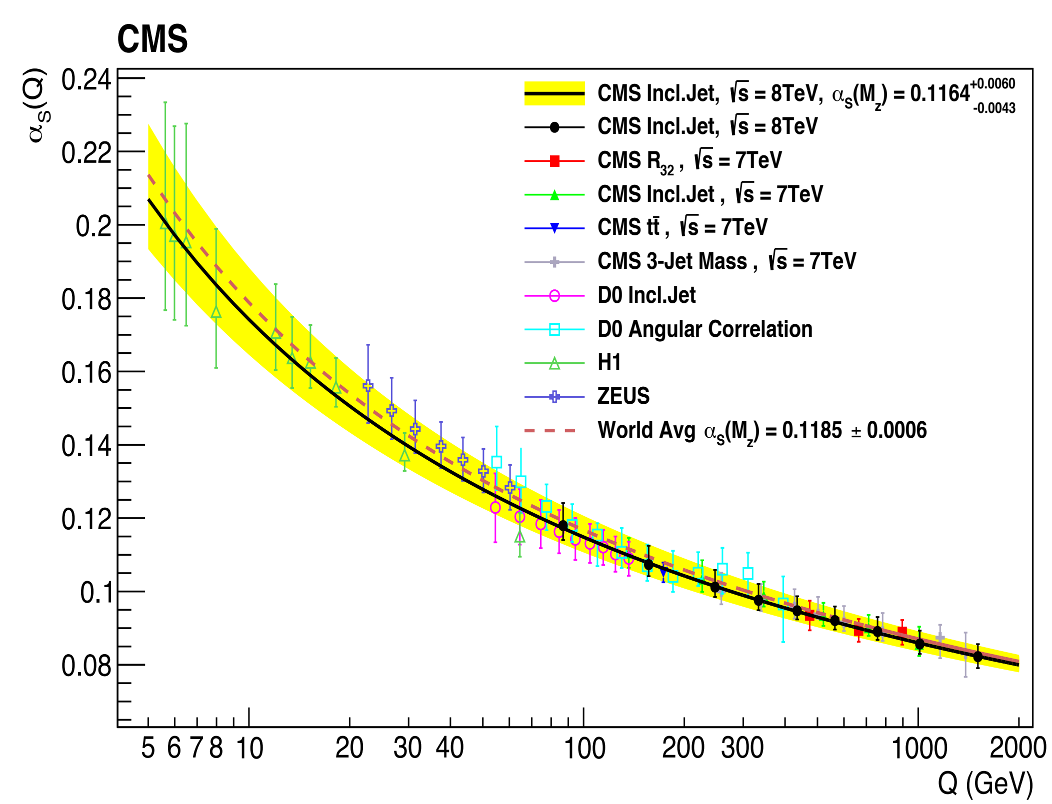
- determine α_s → huge range in jet p_T directly tests energy dependence/running of α_s from a single experiment



α_s running in the TeV range from LHC jet data

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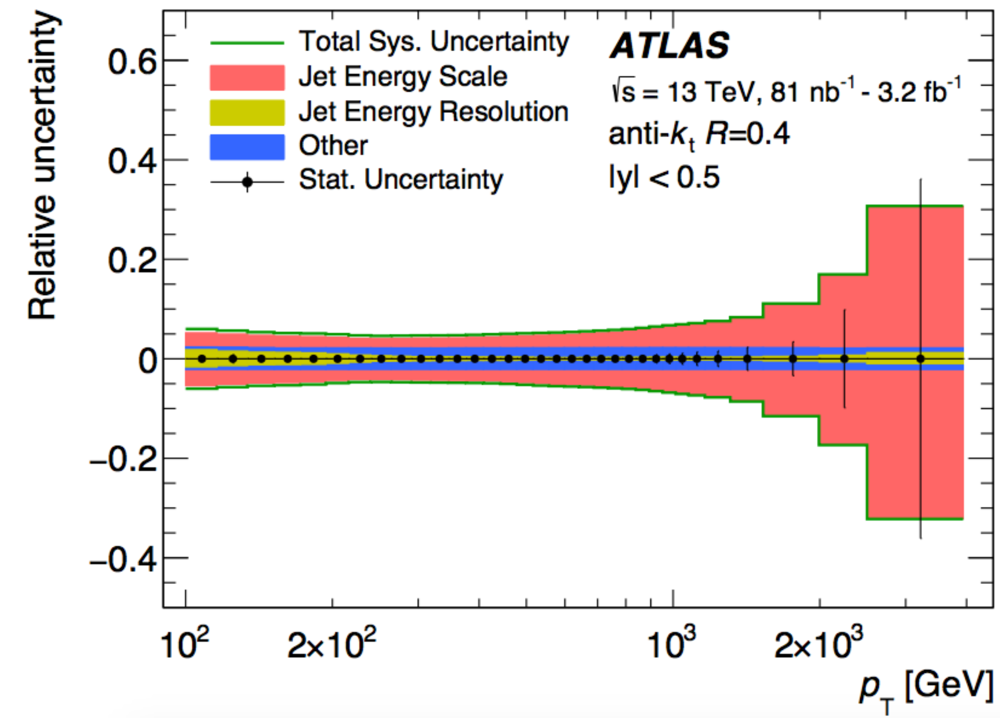

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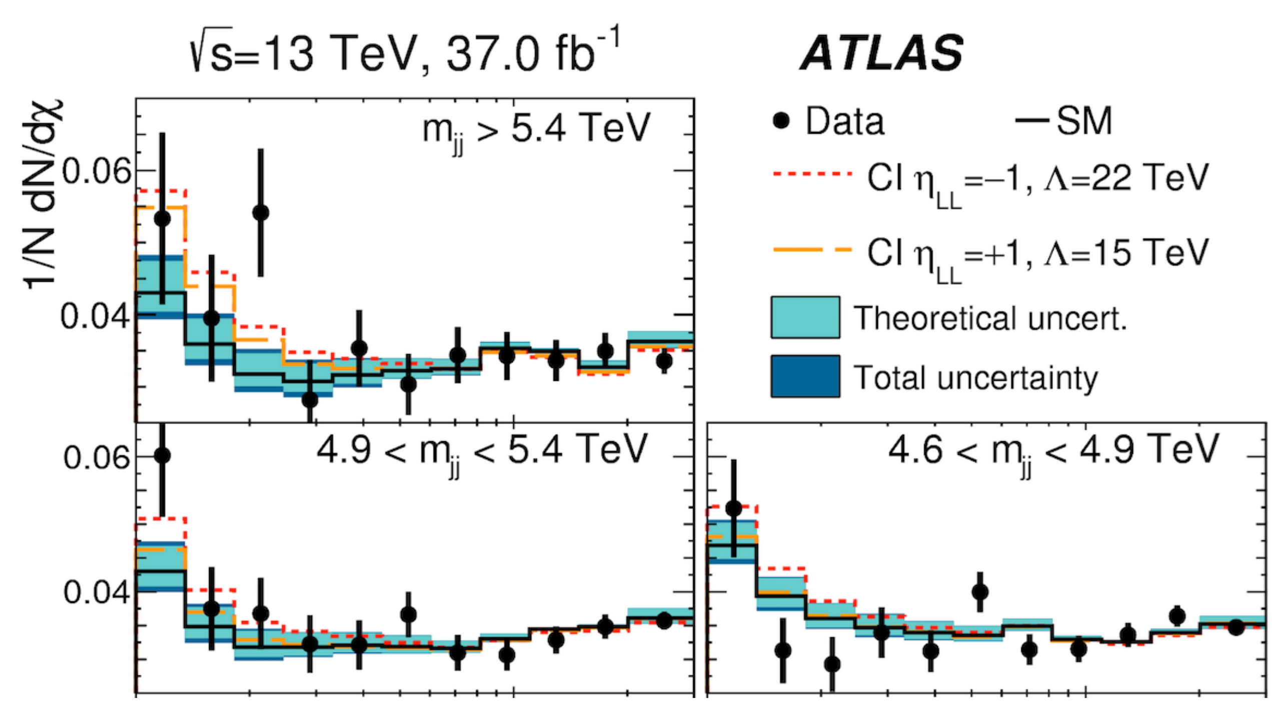
- a window to new physics e.g.→ bumps in dijet mass distributions → precise BSM searches in dijet angular distributions



[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

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  - 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]

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:

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

- 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

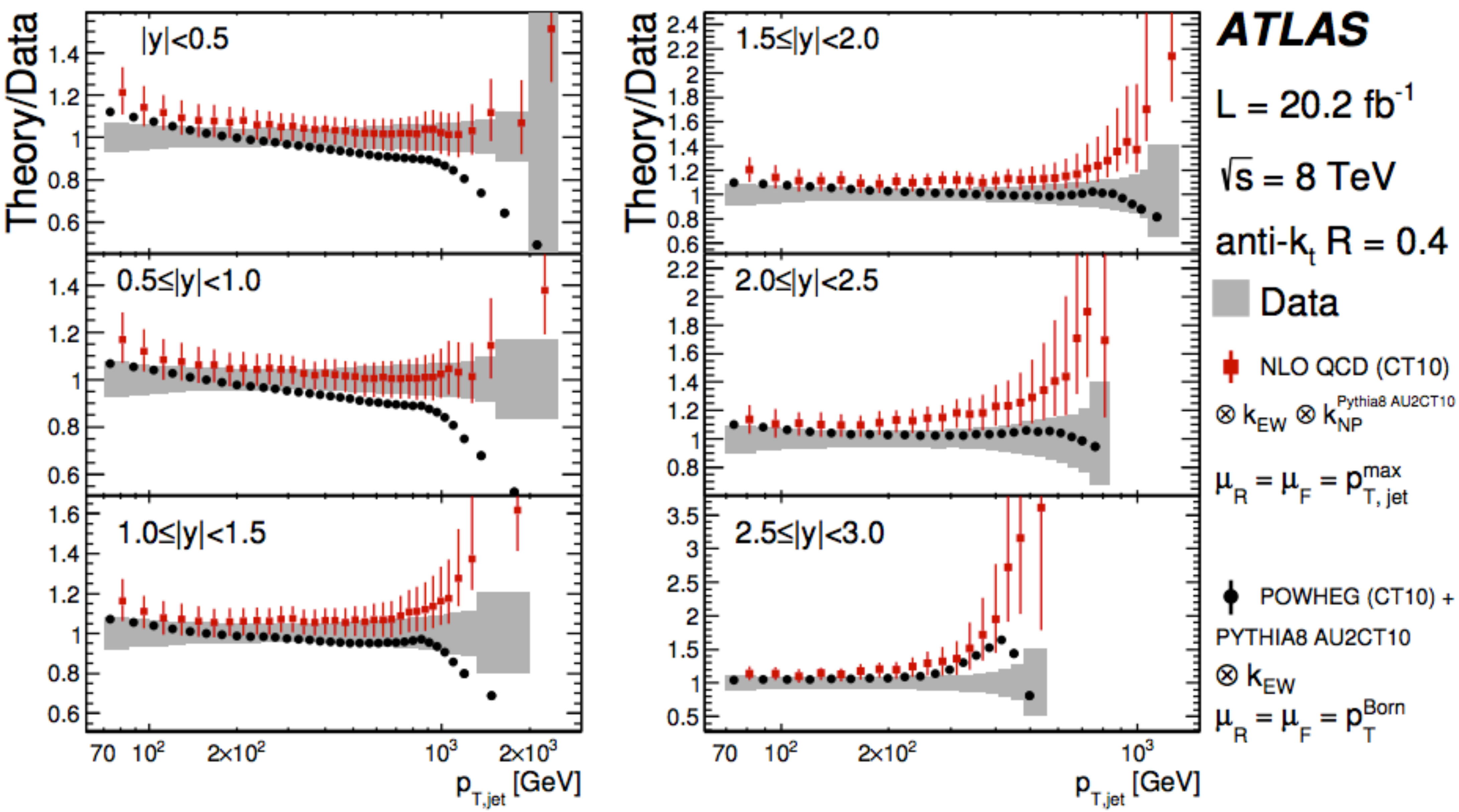
$$\Delta_R\left(p_T\right) = \exp\left[-\int d\Phi_{\mathrm{rad}} \frac{R\left(\Phi_R\right)}{B\left(\Phi_B\right)} \theta\left(k_T\left(\Phi_R\right) - p_T\right)\right]$$

- 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 + 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

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

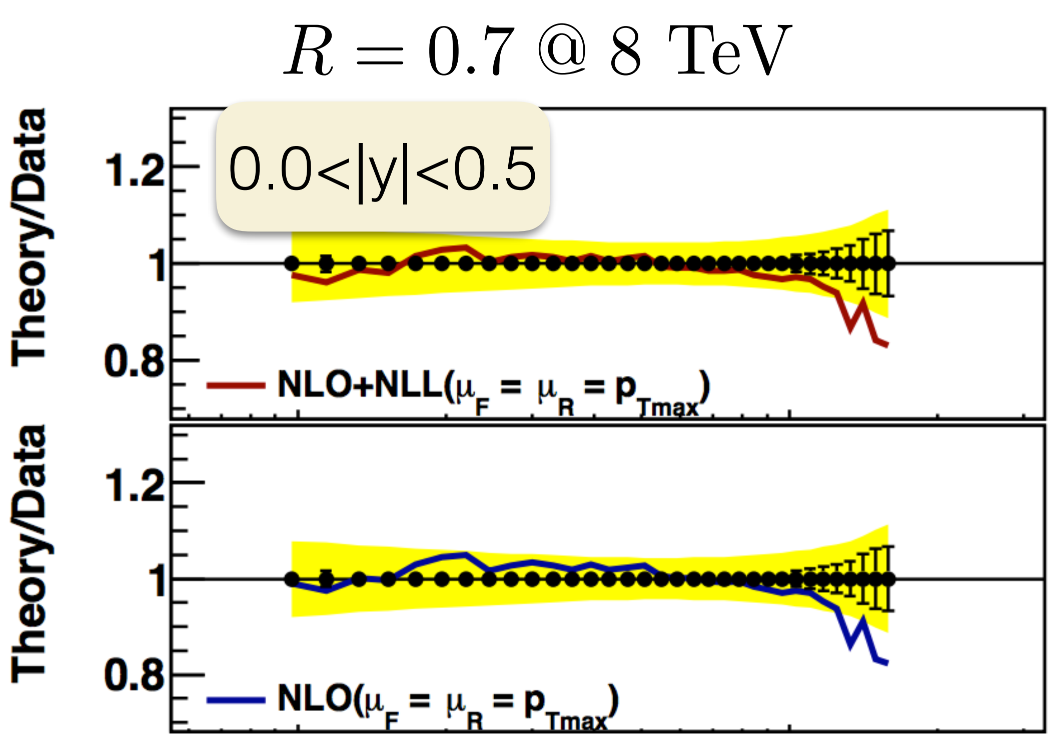
- perturbative contributions know at least to NLO
- joint resummation at NLL accuracy $\alpha_s^n \left(\ln^k(z)/z\right)_+$; $\alpha_s^n \ln^k(R)$
- additive matching to fixed-order NLO QCD result

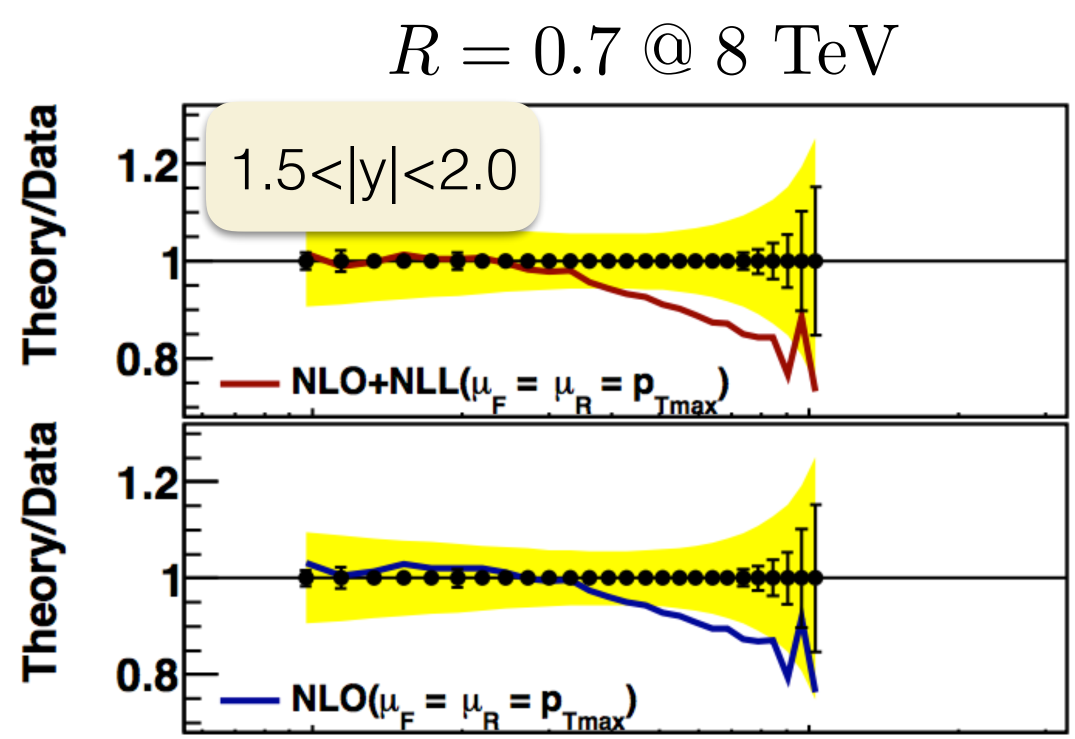
$$\sigma_{\mathrm{NLO+NLL}} = \sigma_{\mathrm{NLO}} - \sigma_{\mathrm{NLO_{sing}}} + \sigma_{\mathrm{NLL}}$$

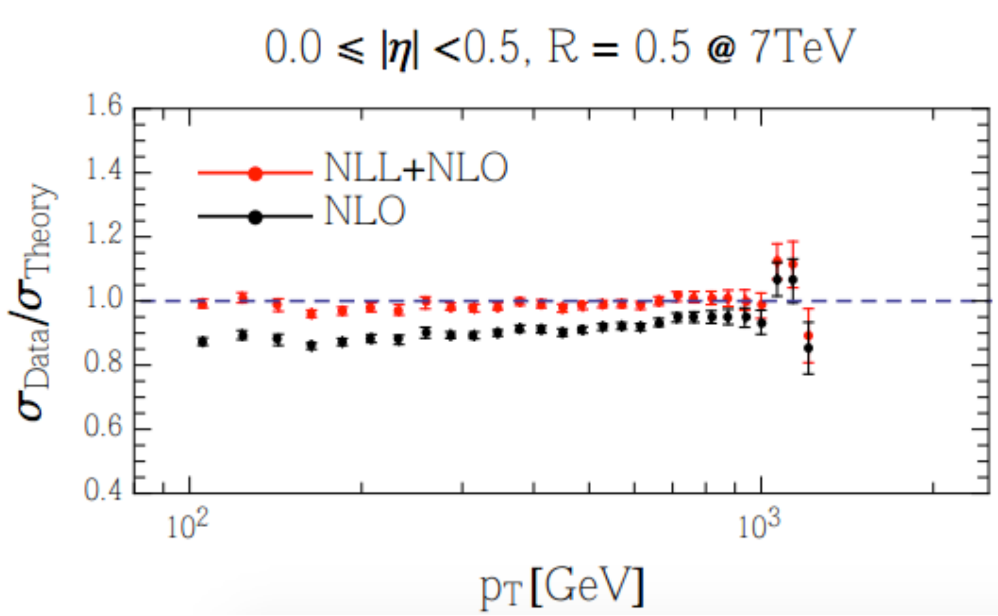
- resummation scales μ_i evolved through RGE equations to common hard scale $\mu = \mu_h = p_T^{max}$

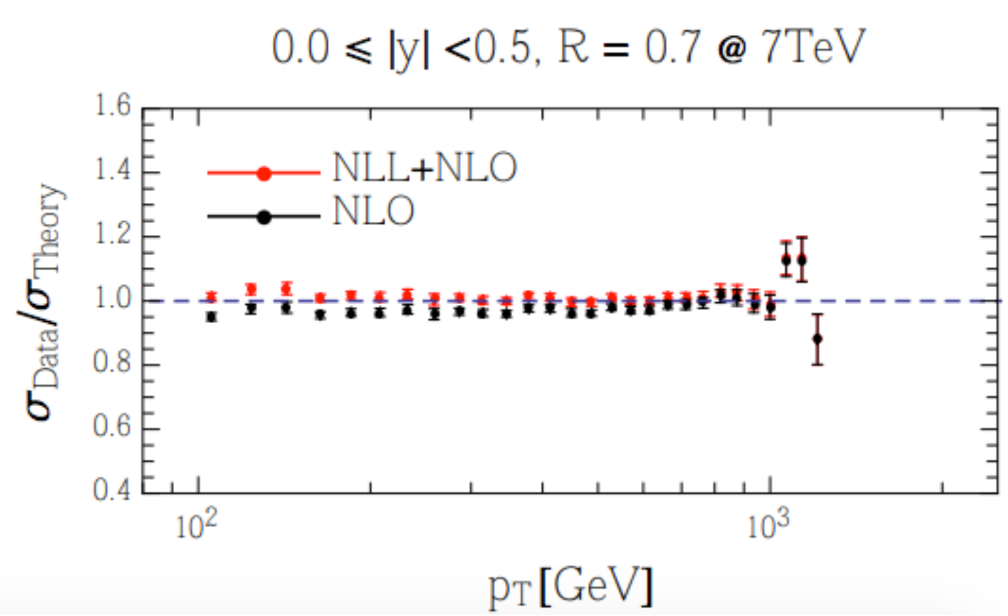
NLO QCD + Resummation (threshold+jet radius)

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









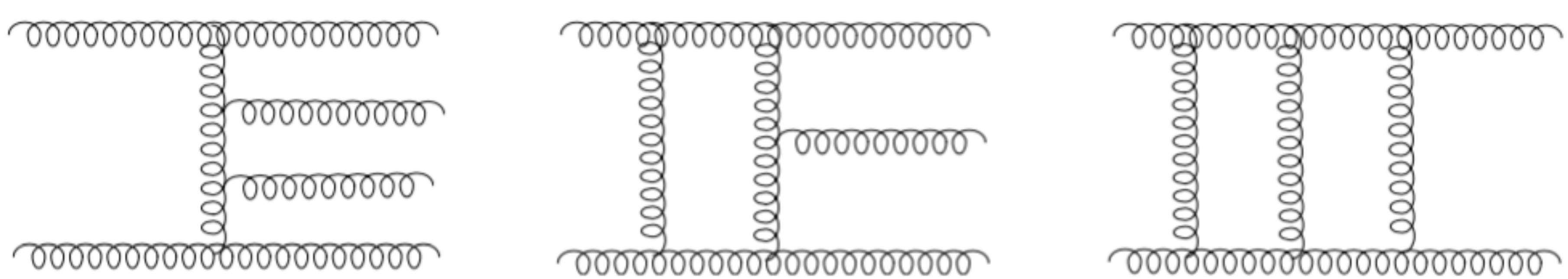
- threshold logs lead to an enhancement of the cross section for large p_T $\mu = \mu_h = p_T^{max}$
- resummation of small R-logs lead to a decrease in the cross section in the entire range p_T

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



$A_6^{(0)}(gg \to gggg)$ $\quad$ $A_5^{(1)}(gg \to ggg)$ $\quad$ $A_4^{(2)}(gg \to gg)$

- 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

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

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

- mimic RR,RV in unresolved limits

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

- 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

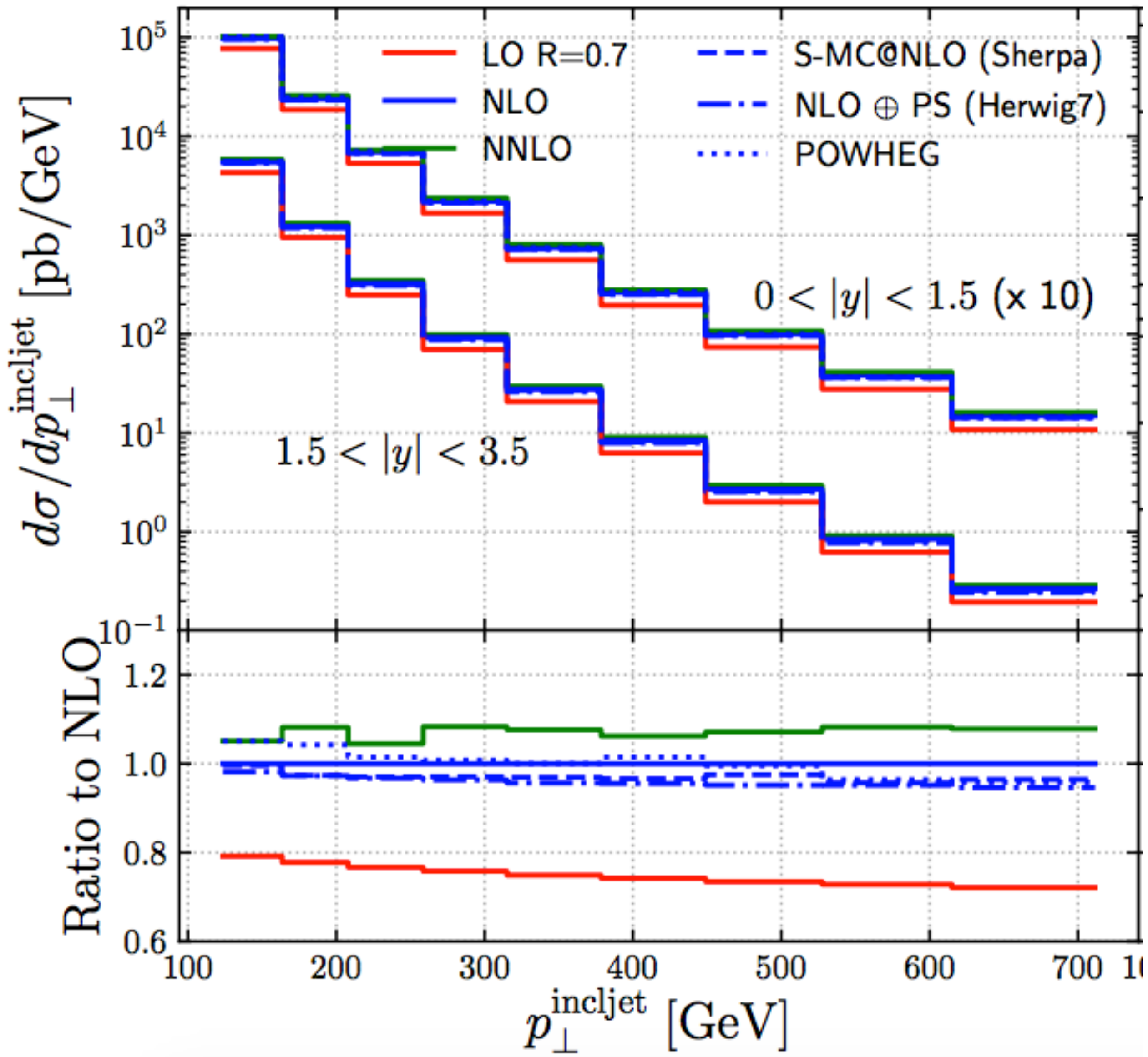
- Process management
- Phase space, histogram routines
- Validation and testing
- ApplFast interface in progress

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*

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

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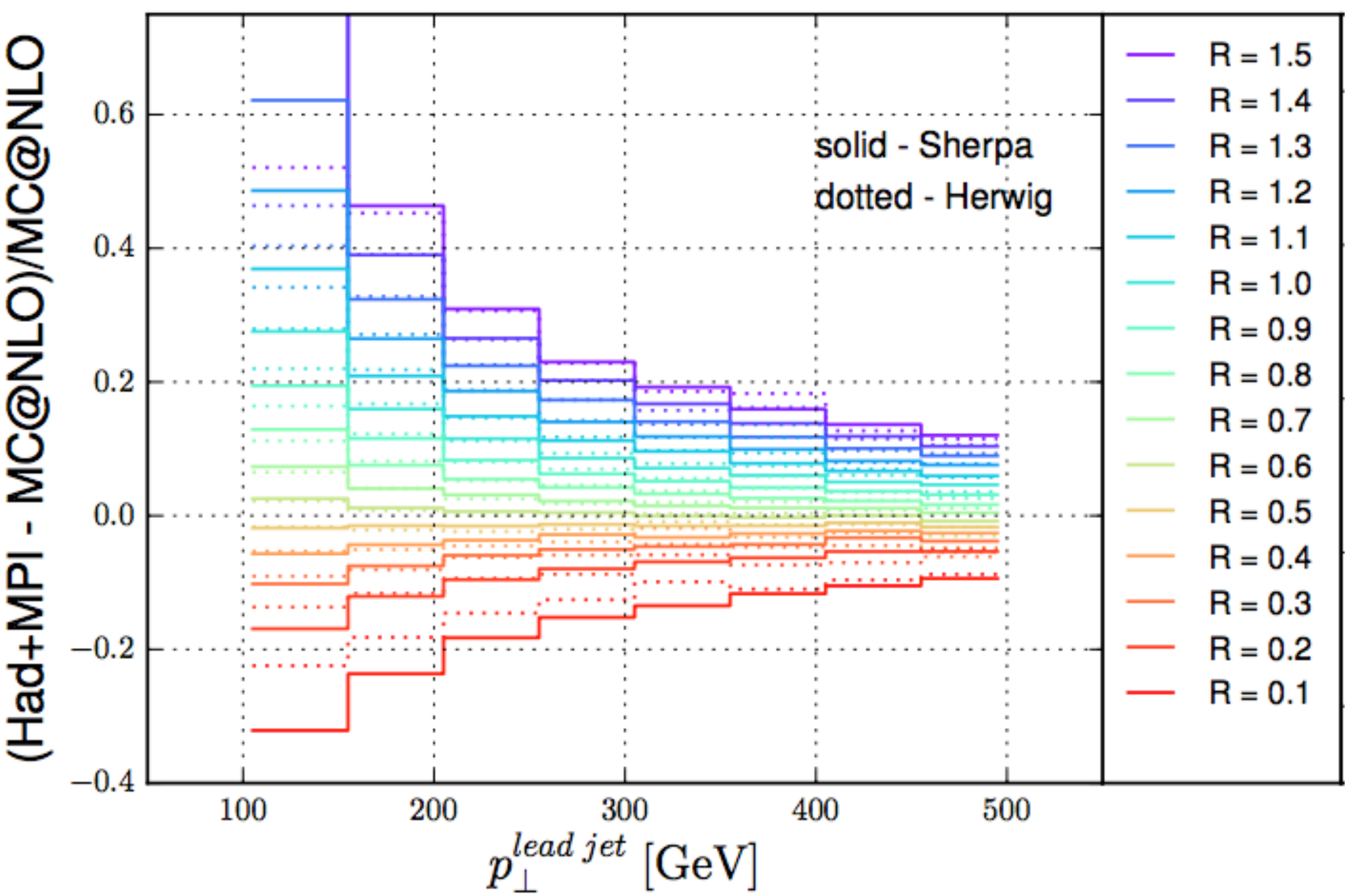

[Bellm, Buckley, et.al., arXiv:1903.12563]

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*

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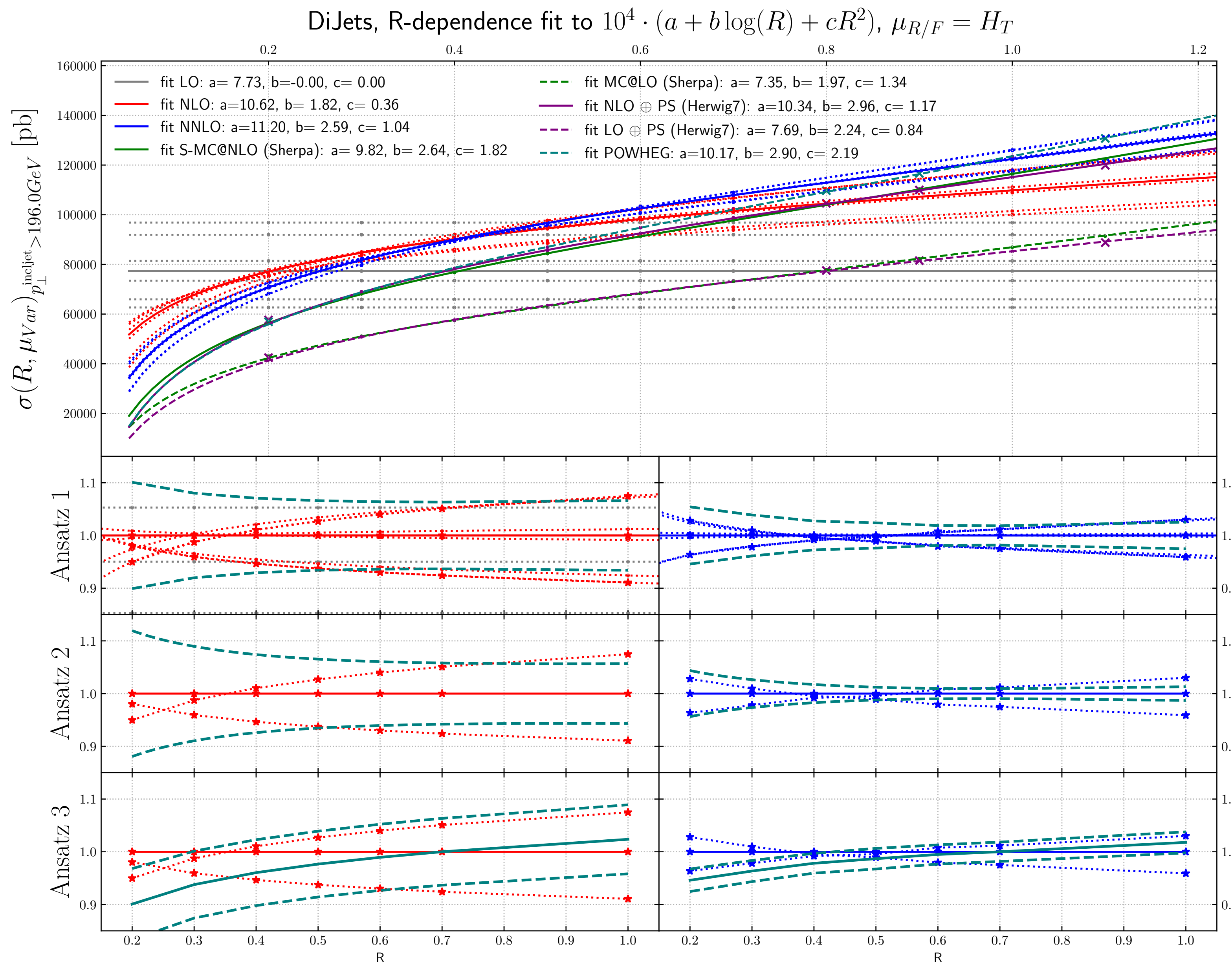


[Bellm, Buckley, et.al., arXiv:1903.12563]

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

Single jet inclusive production: scale choices $\mu_{R,}$ μ_F

- p_T → transverse momentum of the individual jets
- p_{T1} → transverse momentum of the leading jet
- H_T → scalar sum of the transverse momenta of the reconstructed jets
- $\hat{H}_T$ → scalar sum of the transverse momenta of all partons

$$\mu \sim p_T$$
$$\mu \sim p_{T1}$$
$$\mu \sim H_T$$
$$\mu \sim \hat{H}_T$$

- $\mu_{R,}$ μ_F are arbitrary and unphysical parameters and are absent from the true result → *a priori* each scale above is an equally valid scale choice

However, a suitable scale choice would

- minimize ratios of Q^2/μ^2 ,i.e, faster perturbative convergence and smaller scale uncertainties
- avoid scales that introduce pathological behaviours in the prediction, i.e, $\sigma < 0$
- avoid scales that are discontinuous on the phase space of the observable, i.e, no kinks in k-factors

→ recently derived NNLO predictions for inclusive jet production allow for the first time a robust study on scale setting, making use of the knowledge of three orders in the perturbative expansion of the observable

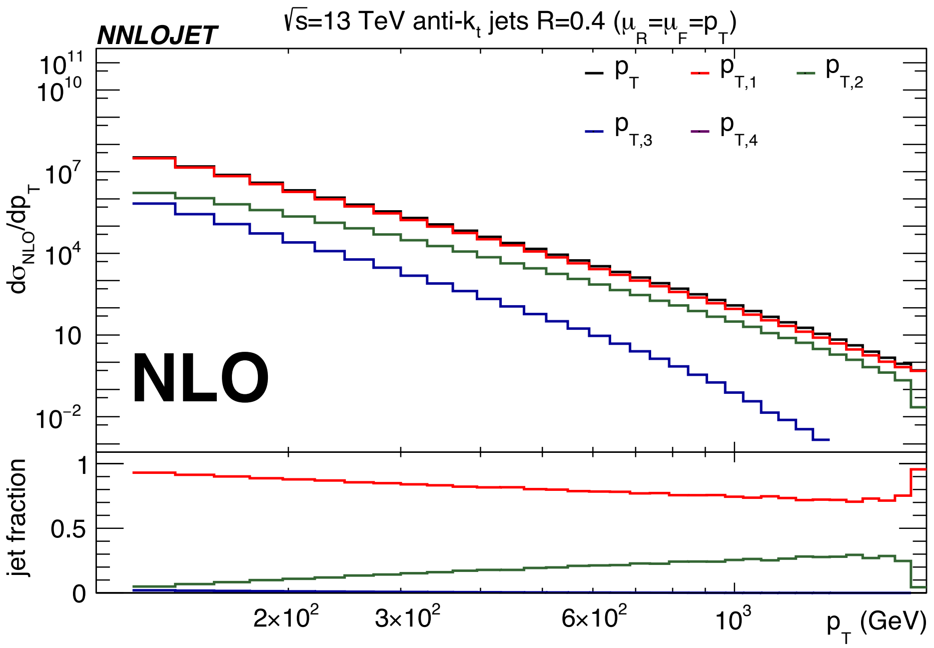
Individual jet contributions and jet fractions

- Single jet inclusive observable receives contributions from all jets in the event, at $O(\alpha_S^4)$

$$\frac{d\sigma}{dp_T}(\mu = p_T) = \frac{d\sigma}{dp_{T1}}(\mu = p_{T1}) + \frac{d\sigma}{dp_{T2}}(\mu = p_{T2}) + \frac{d\sigma}{dp_{T3}}(\mu = p_{T3}) + \frac{d\sigma}{dp_{T4}}(\mu = p_{T4})$$

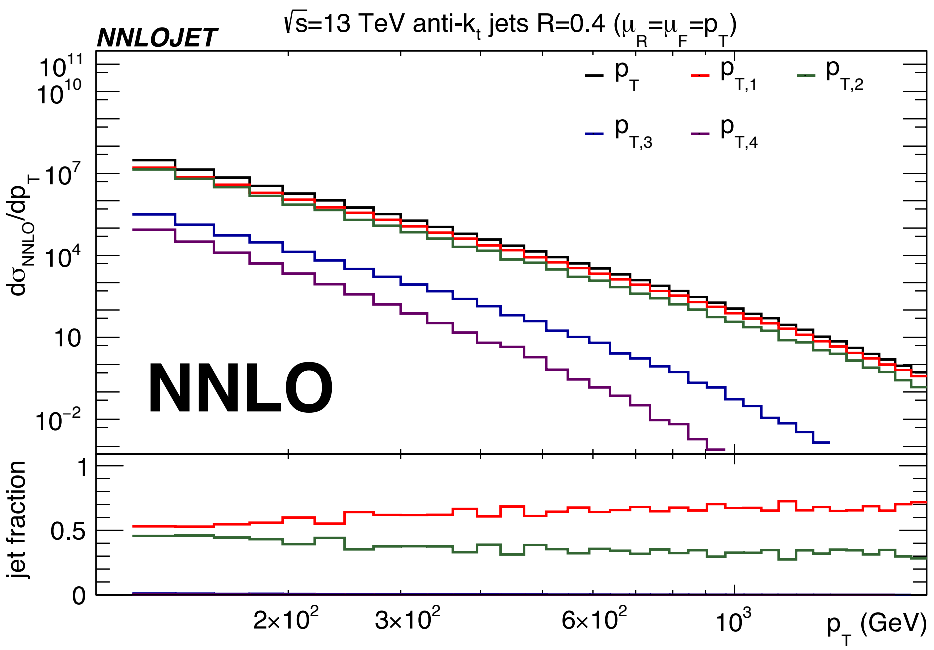
<u>*NLO:*</u>

- leading jet dominates
- third jet negligible
- second jet sizeable at high p_T negligible at low p_T

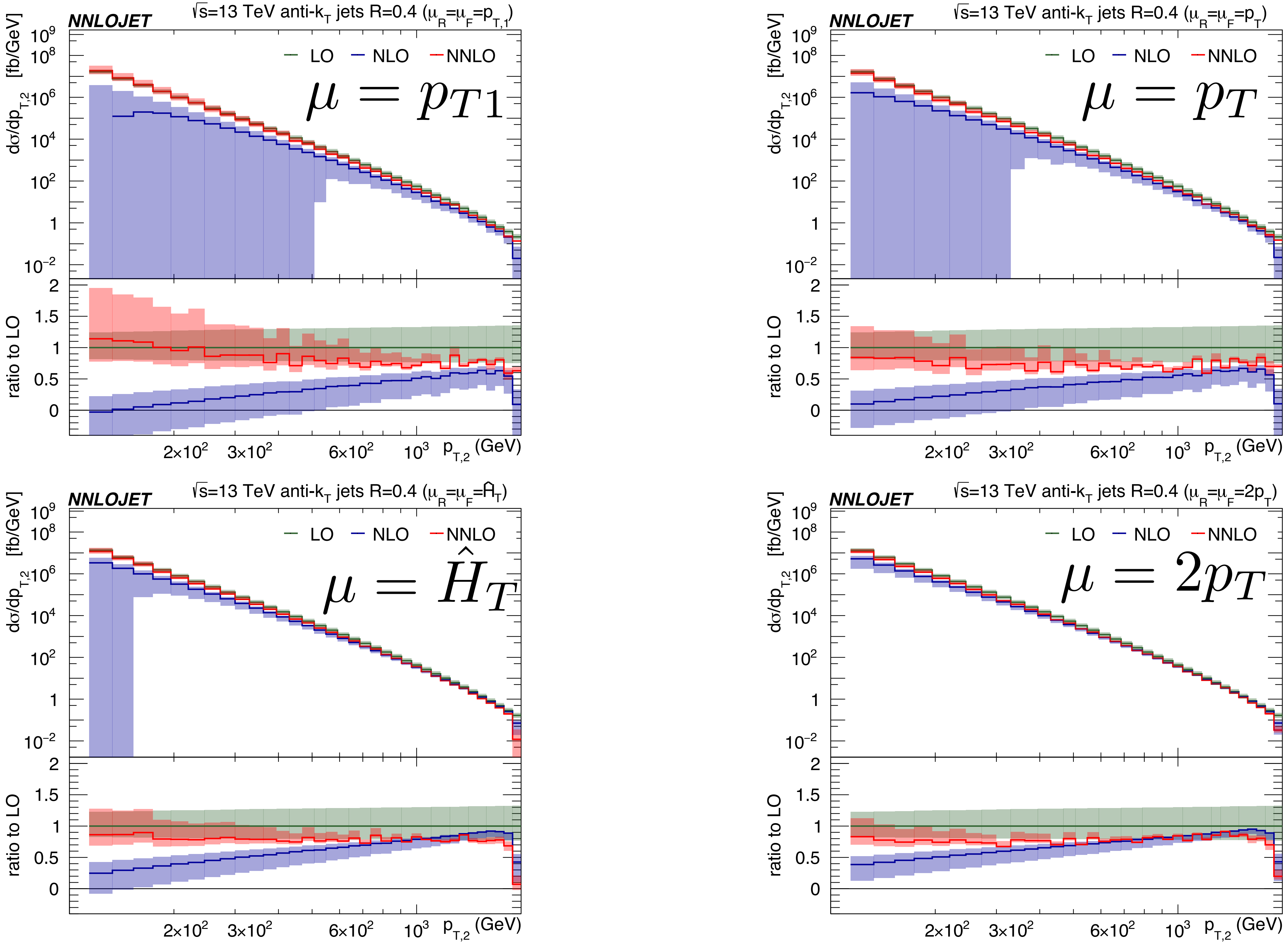


<u>*NNLO:*</u>

- leading and second jet fractions similar over the whole p_T range
- significant increase in second jet p_T contribution to the inclusive jet sample at NNLO with respect to NLO



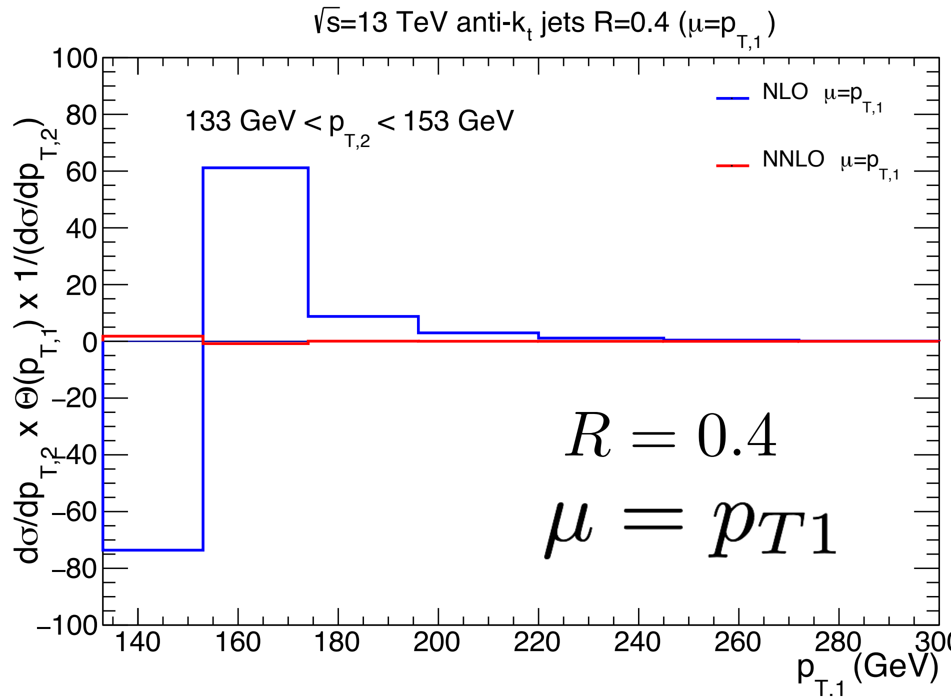
Second jet transverse momentum distribution

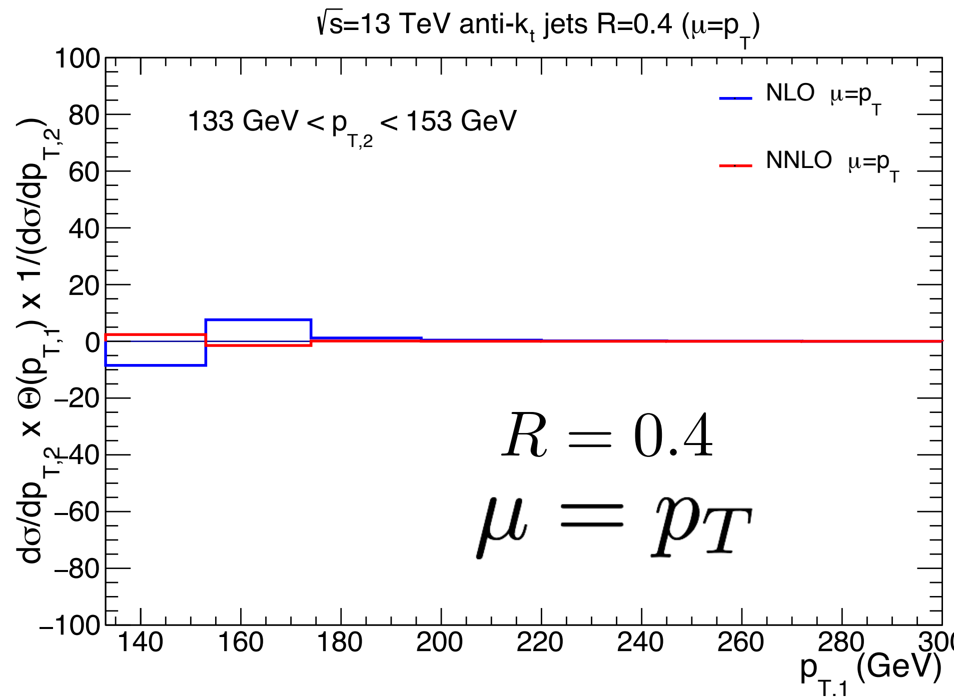


Corrections to second jet distribution integrated over rapidity R=0.4

- **NLO**: large and negative with huge uncertainty → potentially large logs sensitive on IR effects; NNLO: large and positive
- **Stabilization of the predictions at NNLO** (in line with the LO) → functional form of the scale matters

Second jet transverse momentum distribution





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

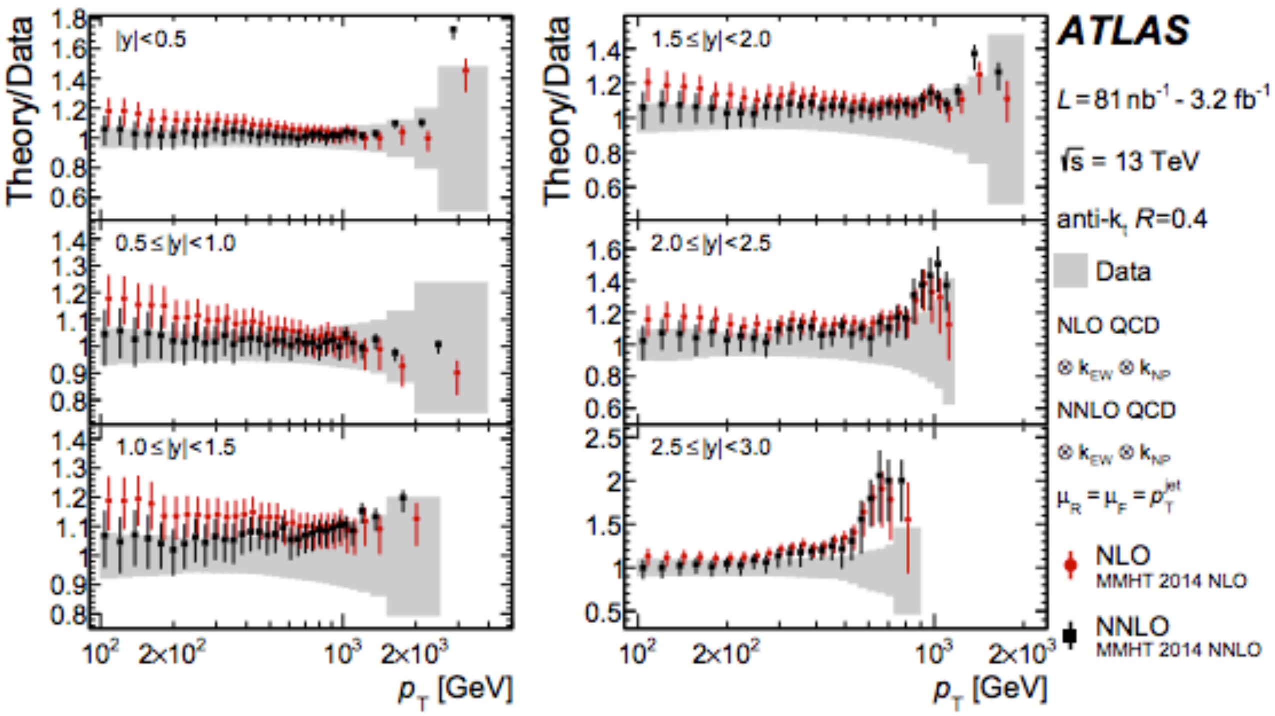
⟶ **Large cancellations** between positive real emission and large negative virtual correction provide a guide to understand the behaviour of the scale choice

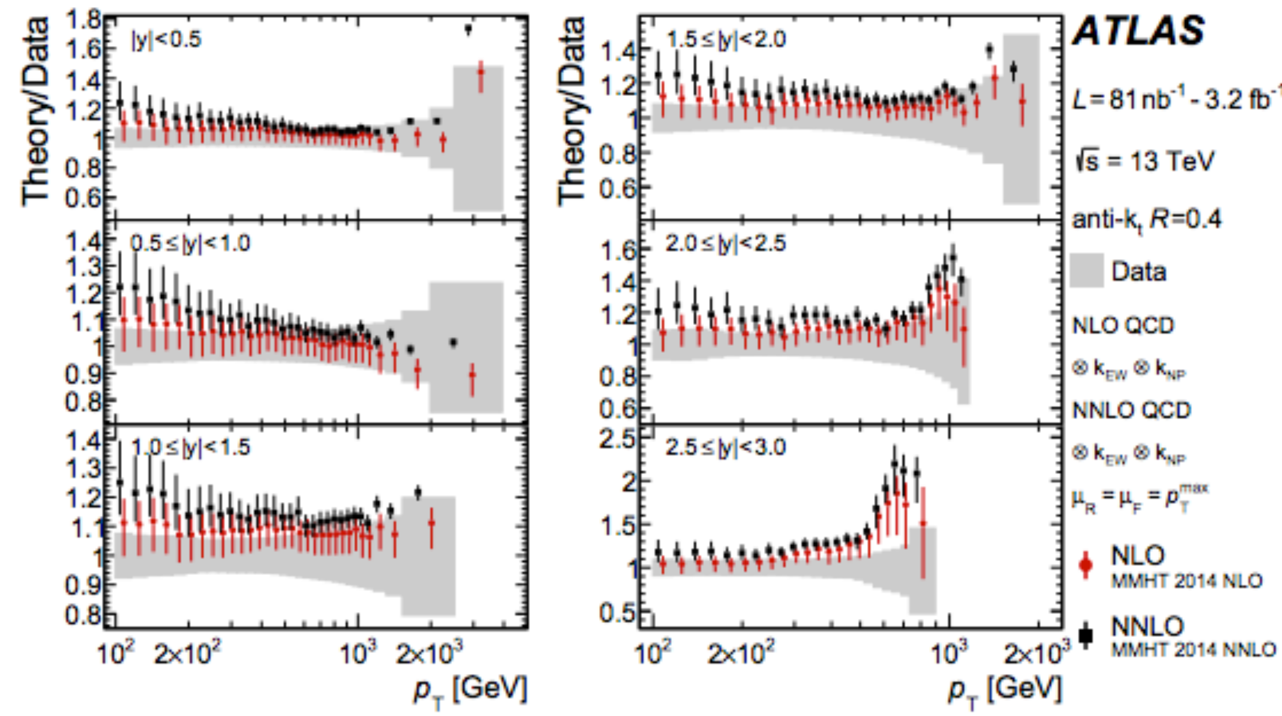
- worse for $\mu = p_{T1}$ that changes event-by-event in the distribution; $\mu = p_T$ remains constant
- detailed single jet inclusive scale study in [J.Currie,T.Gehrmann, A.Gehrmann-De Ridder, E.W.N.Glover,A.Huss, JP ‘18] **[arXiv: 1807.03692] JHEP 1810 (2018) 155**

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

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

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ATLAS *pp*→jet+X, √s=13 TeV

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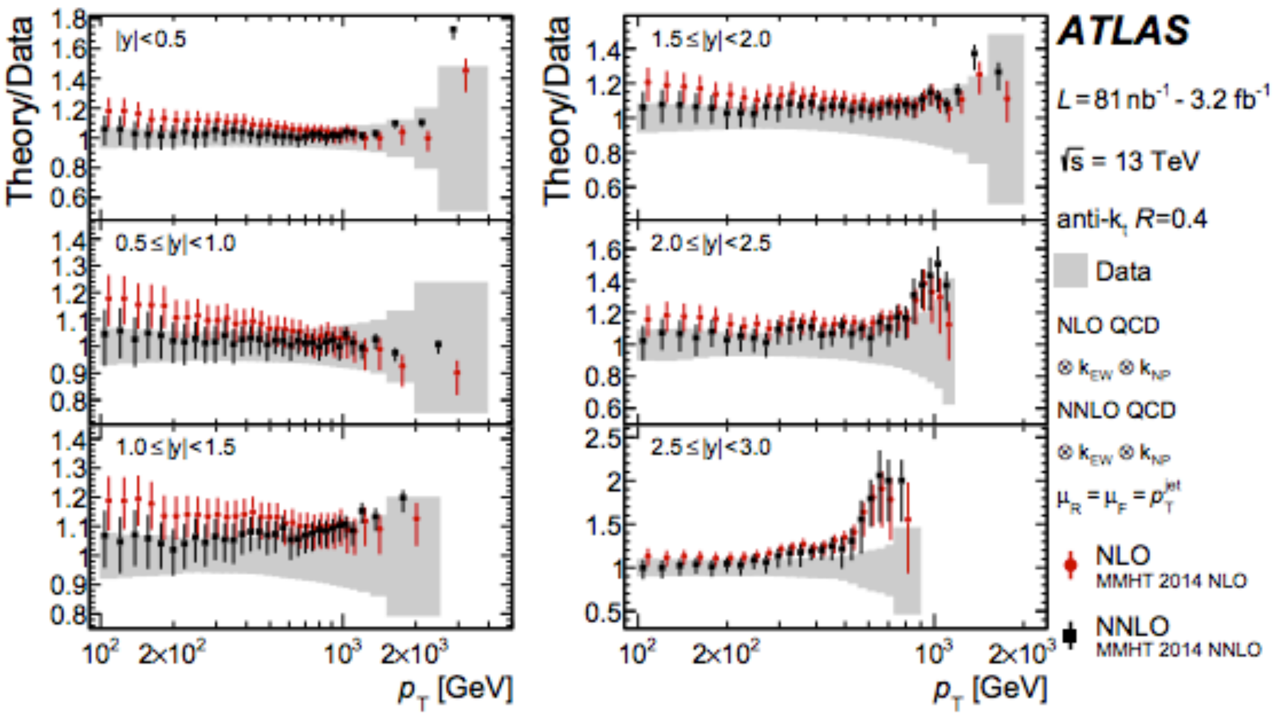
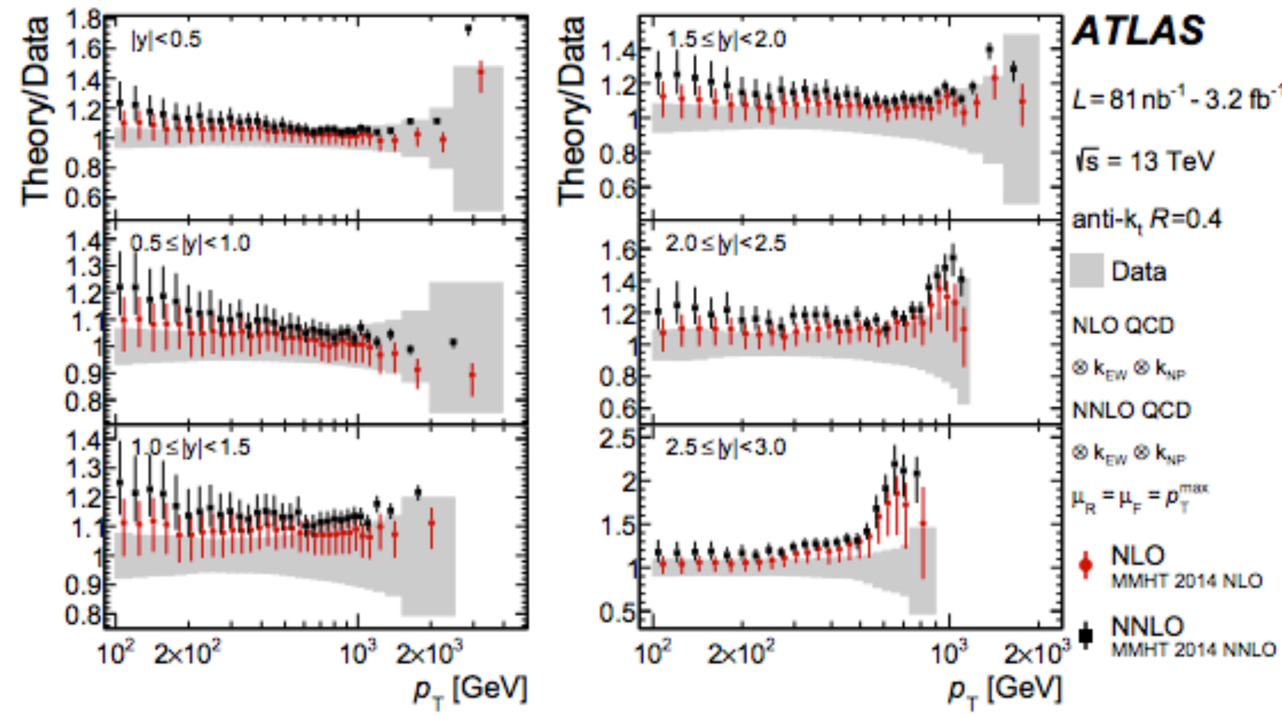




NLO $(\mu = p_T)$
NNLO $(\mu = p_T)$

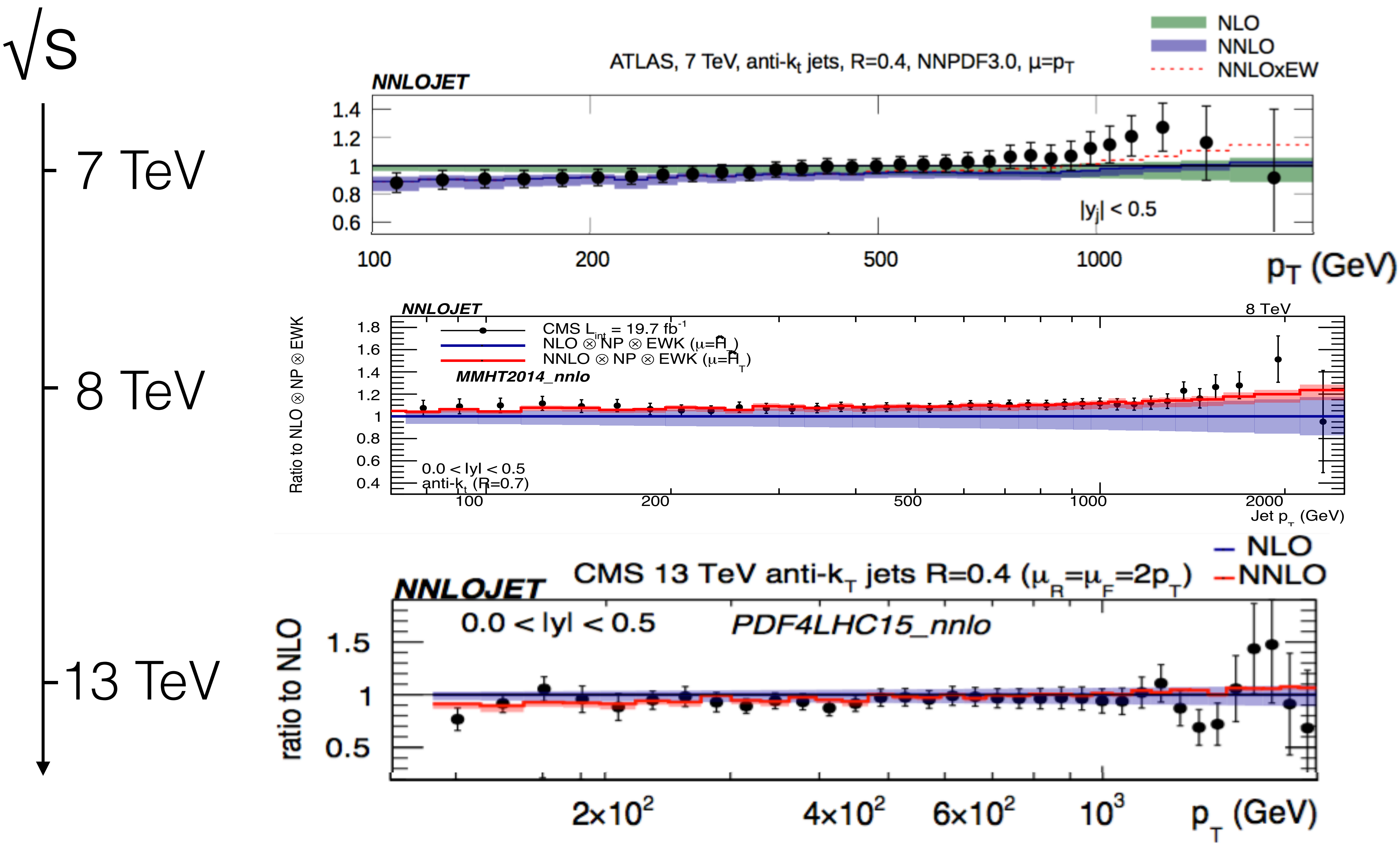
NLO $(\mu = p_{T1})$
NNLO $(\mu = p_{T1})$

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

- Conclusion in agreement with recent measurements from ATLAS √s=13 TeV
- **NNLO** theory from NNLOJET
- Theoretical understanding of the scale choice and precision phenomenology with jet observables at NNLO is just starting

Understanding single jet inclusive production at the LHC - first steps of the NNLO era

Results have appeared in the context of individual theory publications looking at published LHC data



Understanding single jet inclusive production at the LHC - dissemination of NNLO results

Today:

- tables of *k*-factors from NNLO runs, fixed binning, fixed PDF set and scale choice
- determination of (PDF, α_s) require NNLO predictions to be computed multiple times (varying PDF sets, scales, etc.)
- would like to store the perturbative coefficients of the (N)NLO QCD calculations of final state observables in lookup tables or grids once and for all with very high statistical precision

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- would like to store the perturbative coefficients of the (N)NLO QCD calculations of final state observables in lookup tables or grids once and for all with very high statistical precision

Outlook/steps for the coming months:

- single jet inclusive grids generation using APPLFAST-NNLOJET interface in progress [D.Britzger, C.Gwenlan, K. Rabbertz, M.Sutton] cross sections at NNLO available in both formats
  - FASTNLO
  - APPLGRID
  - → First application: H1 determination of α_s from jet production in DIS (H1: arXiv:1709.07251)
  - grids hosted at CERN → ploughshare project: ploughshare.web.cern.ch
  - many grids already available → source for NNLO grids from APPLfast

Understanding single jet inclusive production at the LHC - dissemination of NNLO results

Today:

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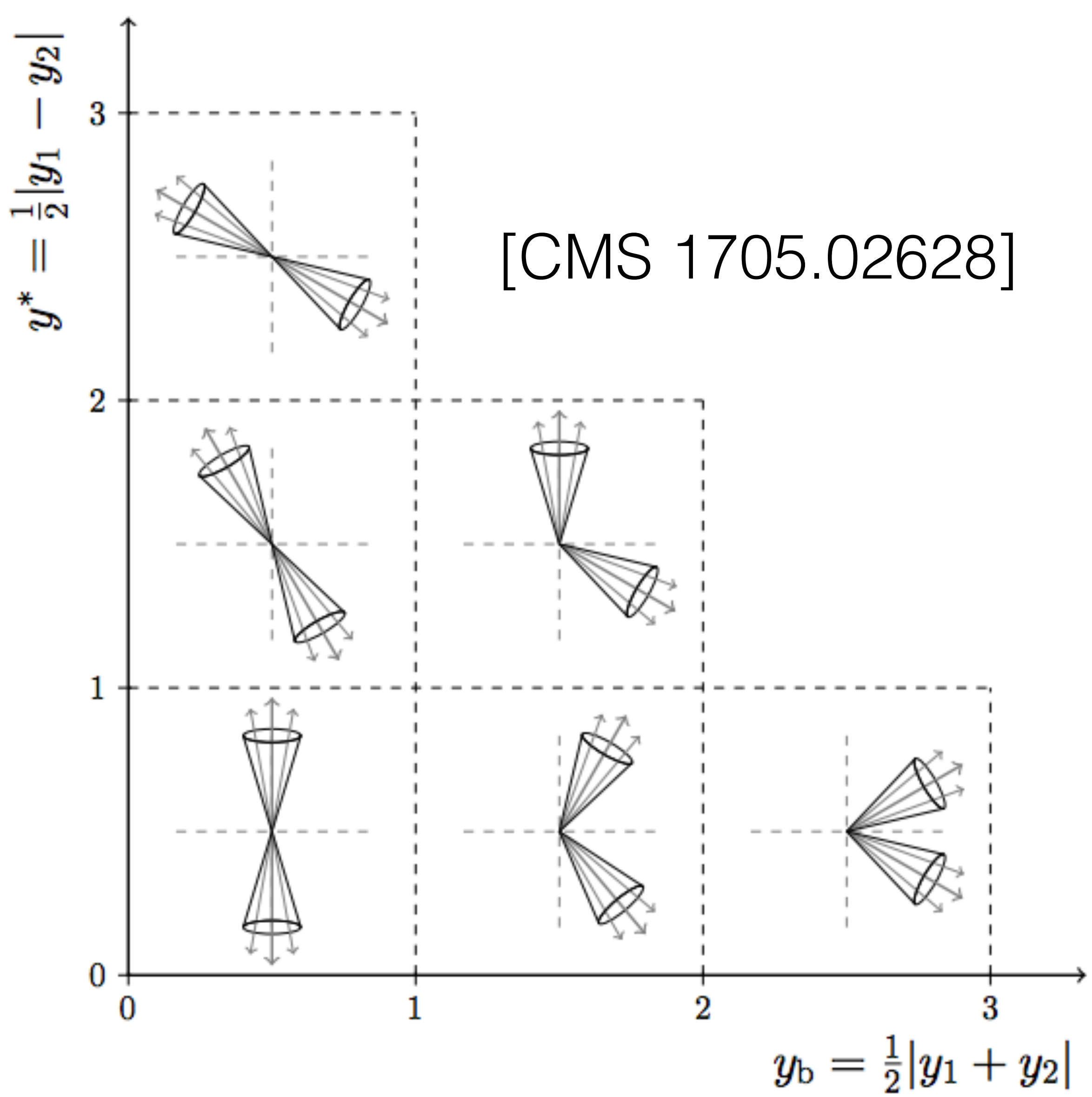
Ultimate goal:

- have a consistent description of jet data at NNLO for all jet datasets (ATLAS,CMS,LHCb,ALICE) at low and high-p_T in the central and forward rapidity regions for multiple jet R cone sizes

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]

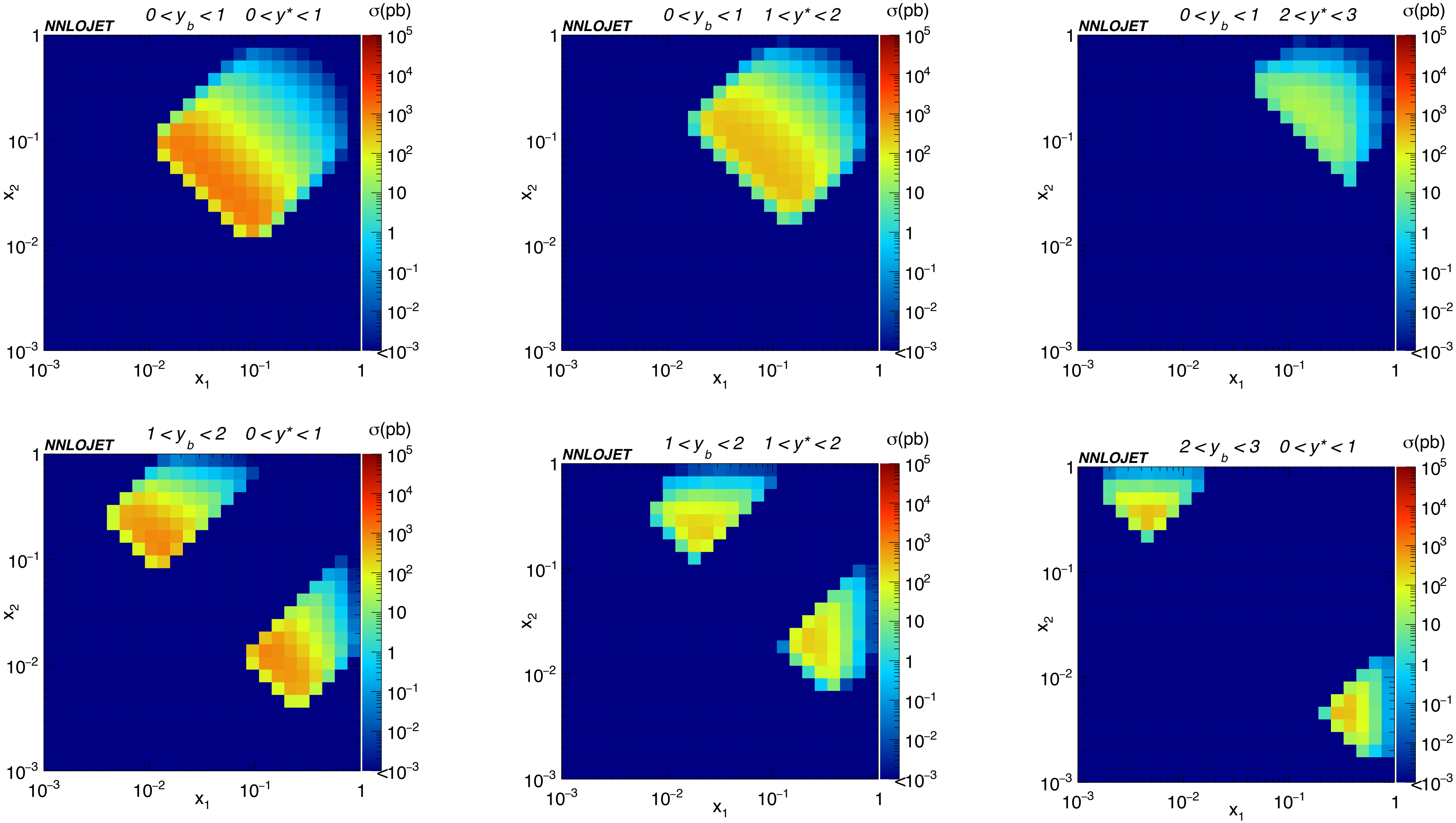
- 2 jet observables built from the two-leading jets in the event, with the caveat that the assignment of the hardest jet in the event is not infra-red safe

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

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

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

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



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

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

- 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:

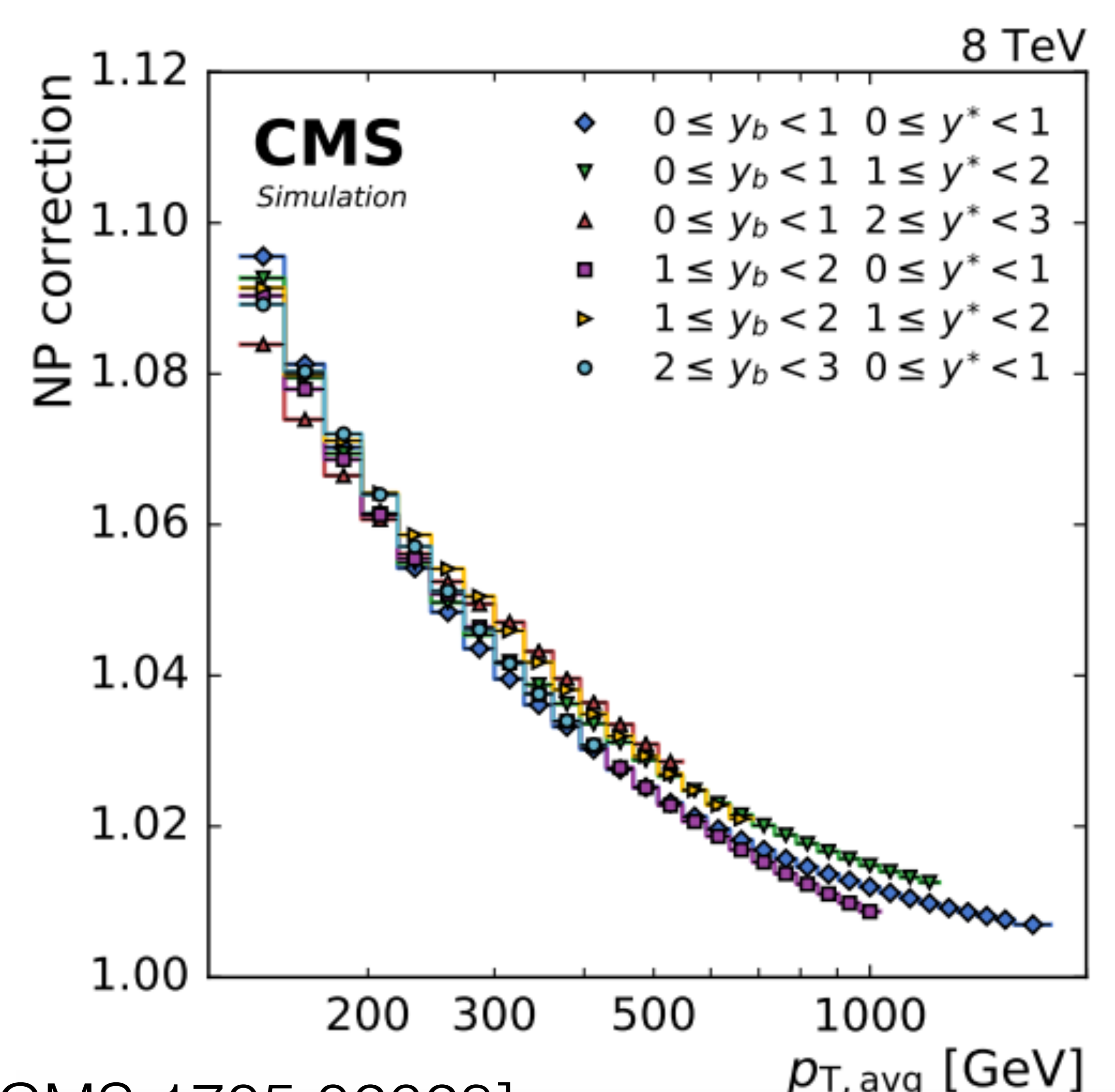
- The NLO inclusive two jet triply differential cross section *W.Giele, E.W.N.Glover, D.A.Kosower* ***[hep-ph/9403347] Phys.Rev.Lett. 73 (1994) 2019***
    - Scale uncertainties and missing higher order corrections limit the achievable precision
- Measurement from CDF at 1.8 TeV based on an integrated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

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

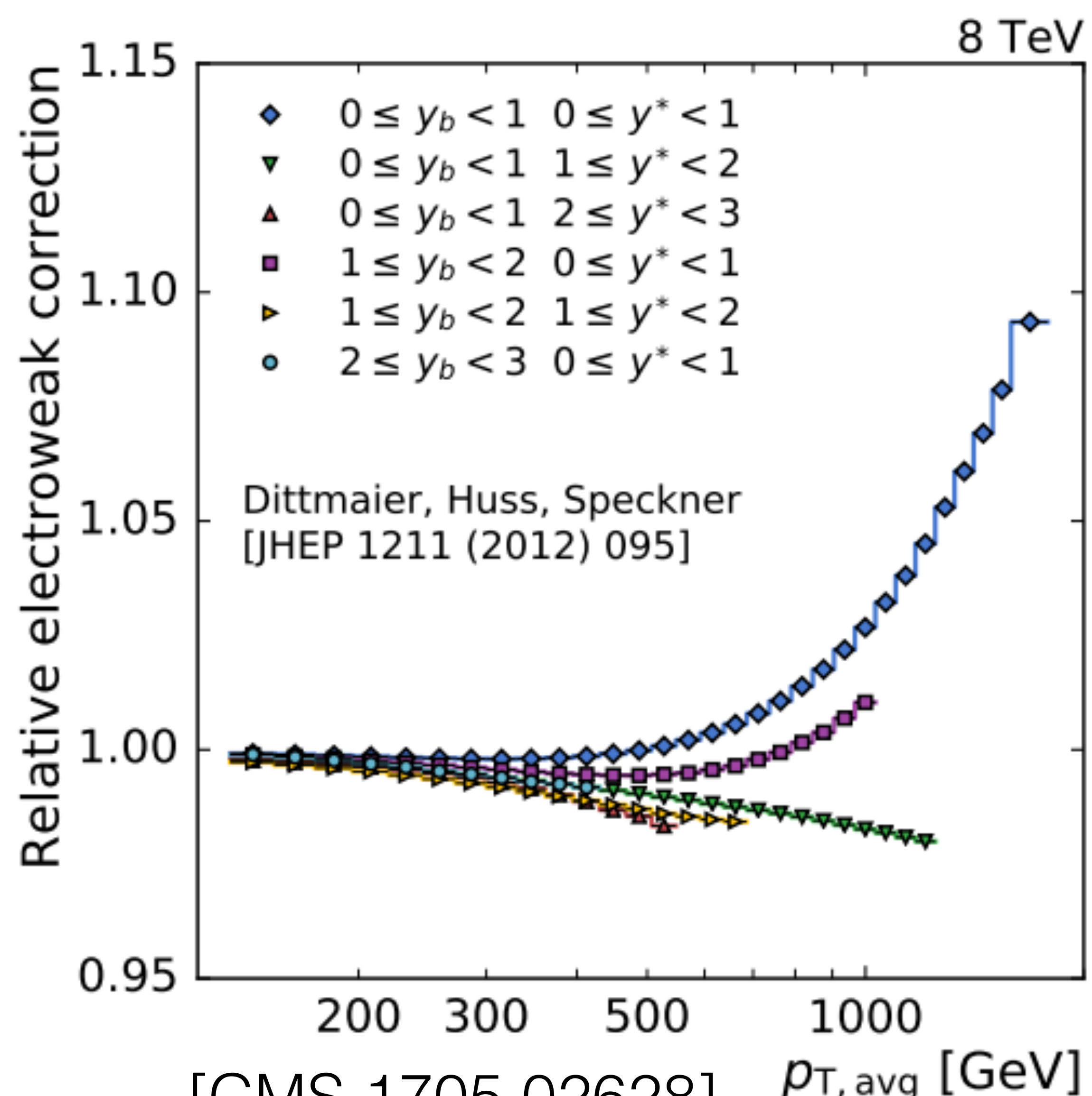
Goal:

- 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]

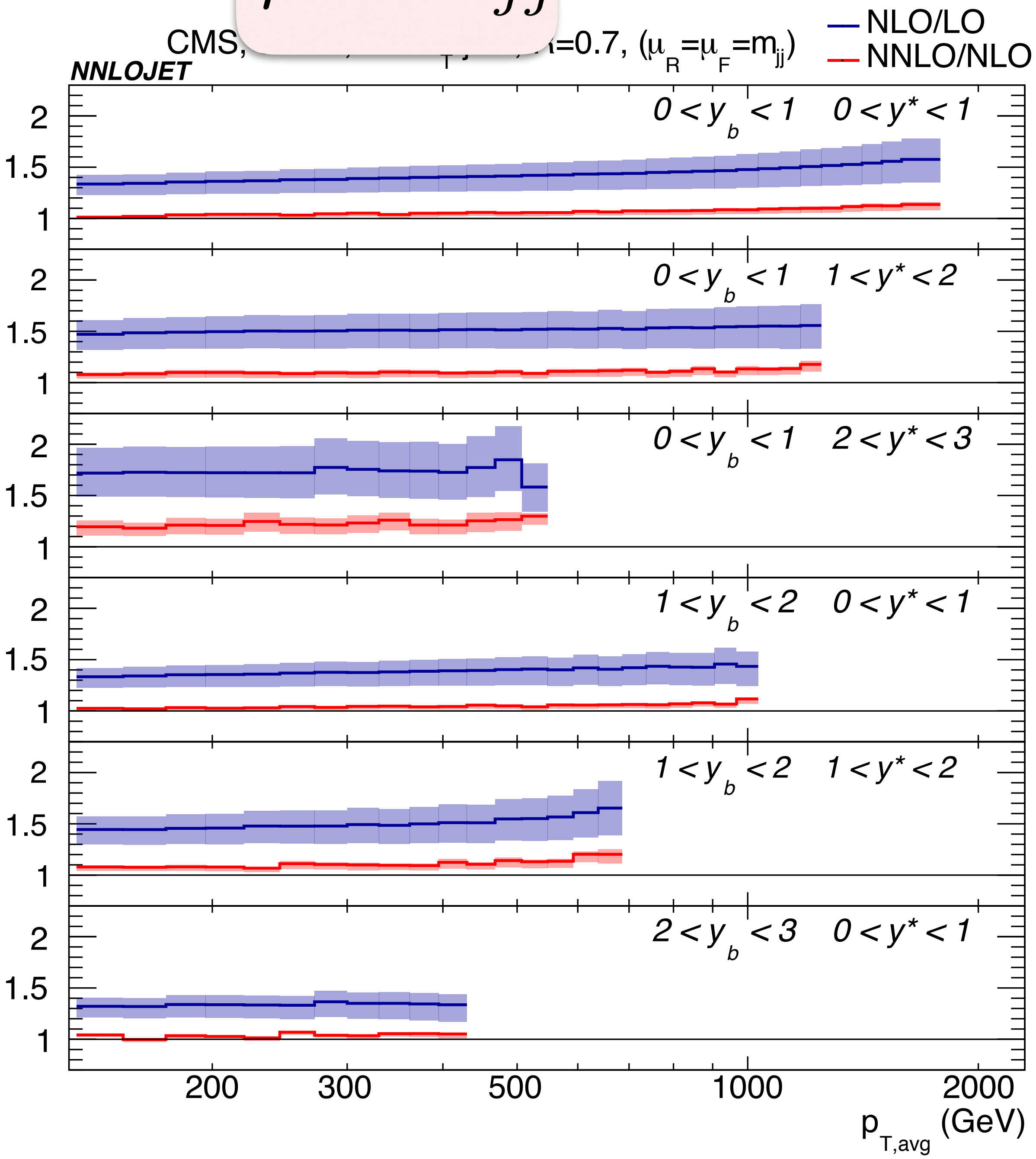


[CMS 1705.02628]

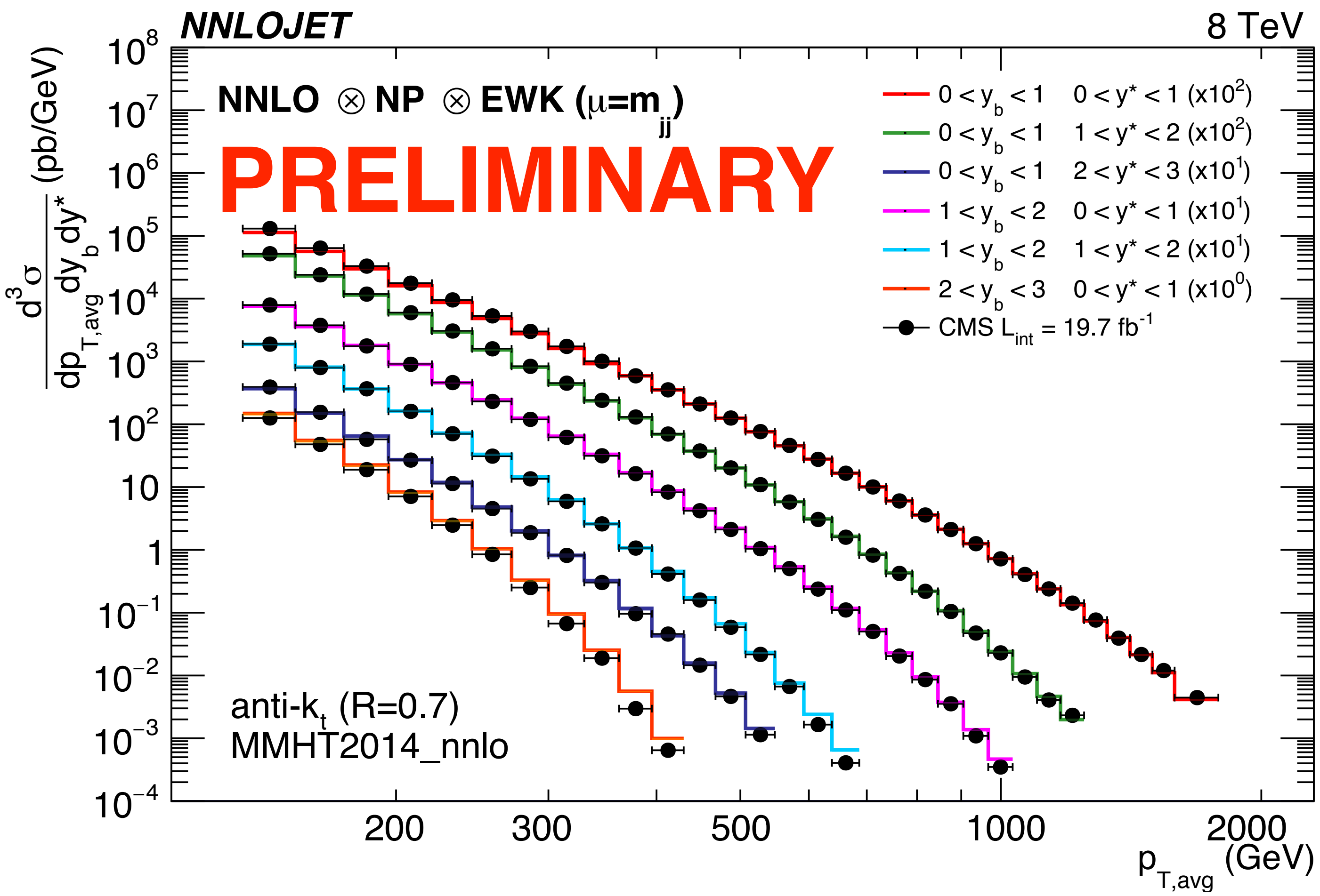
- NP correction 10% in the lowest $p_{T,avg}$ bins, negligible above 1 TeV
  - center of the envelop of HERWIG,PYTHIA and POWHEG with and without hadronization and MPI
- EW correction relevant in the low y* and low y_b rapidity slice reaching 8% at high $p_{T,avg}$
  - EW effects visible in the LHC measurements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

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

$\mu = m_{jj}$

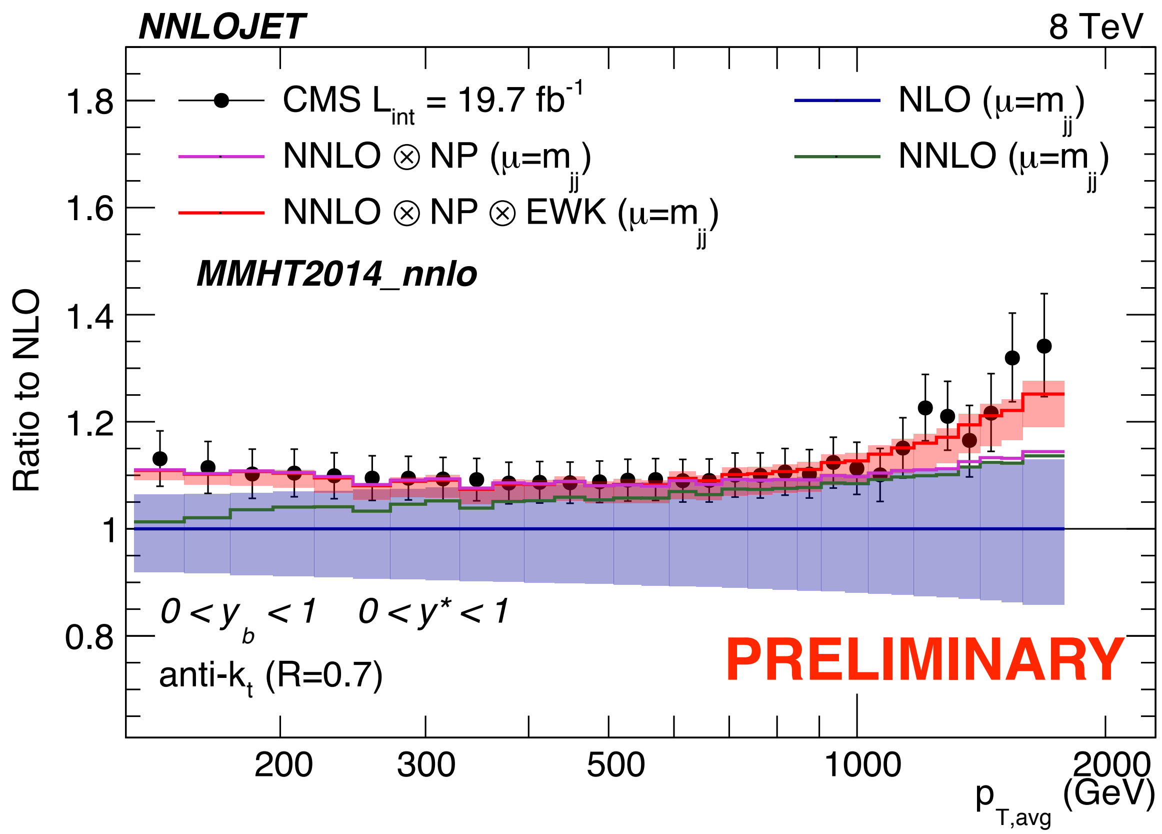


[Gehrmann-De Ridder, Gehrmann, Glover, Huss, JP in preparation '19]



- 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

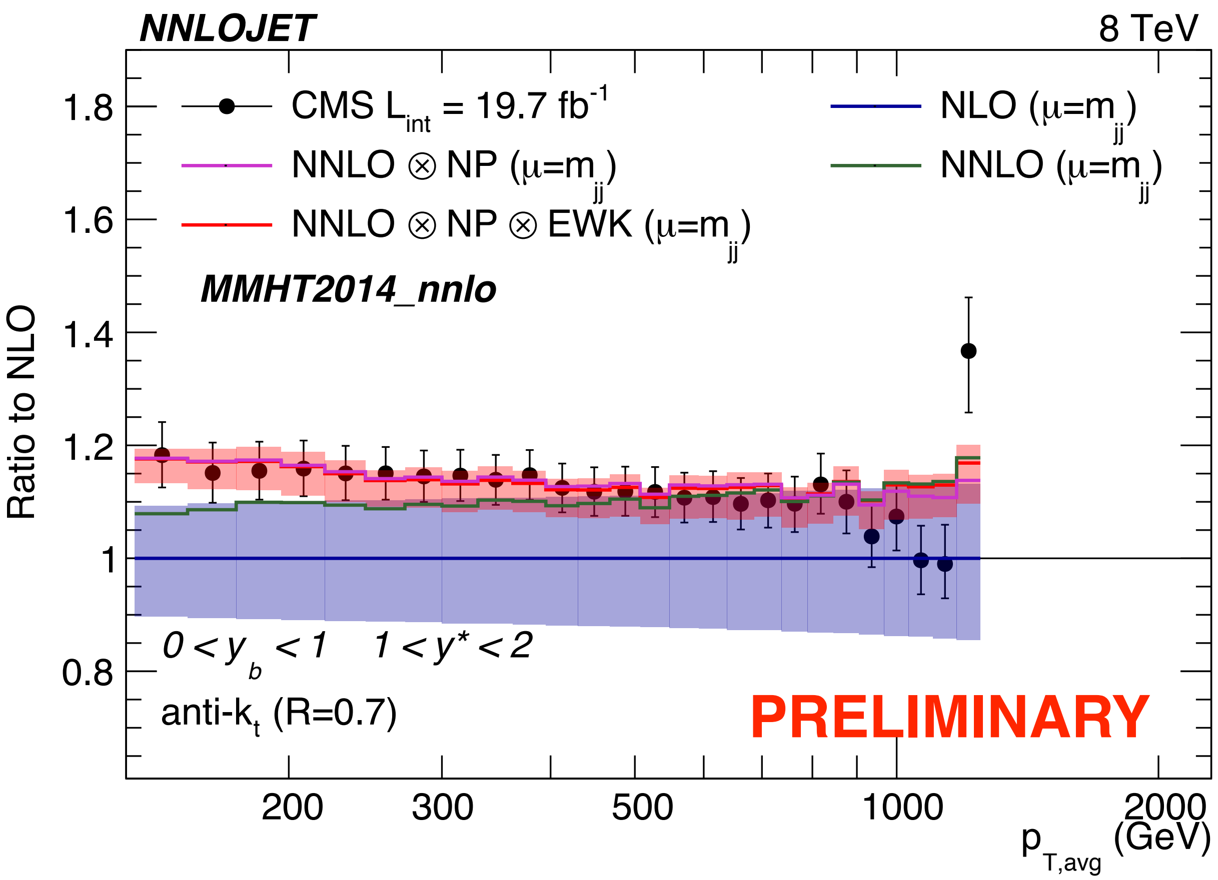


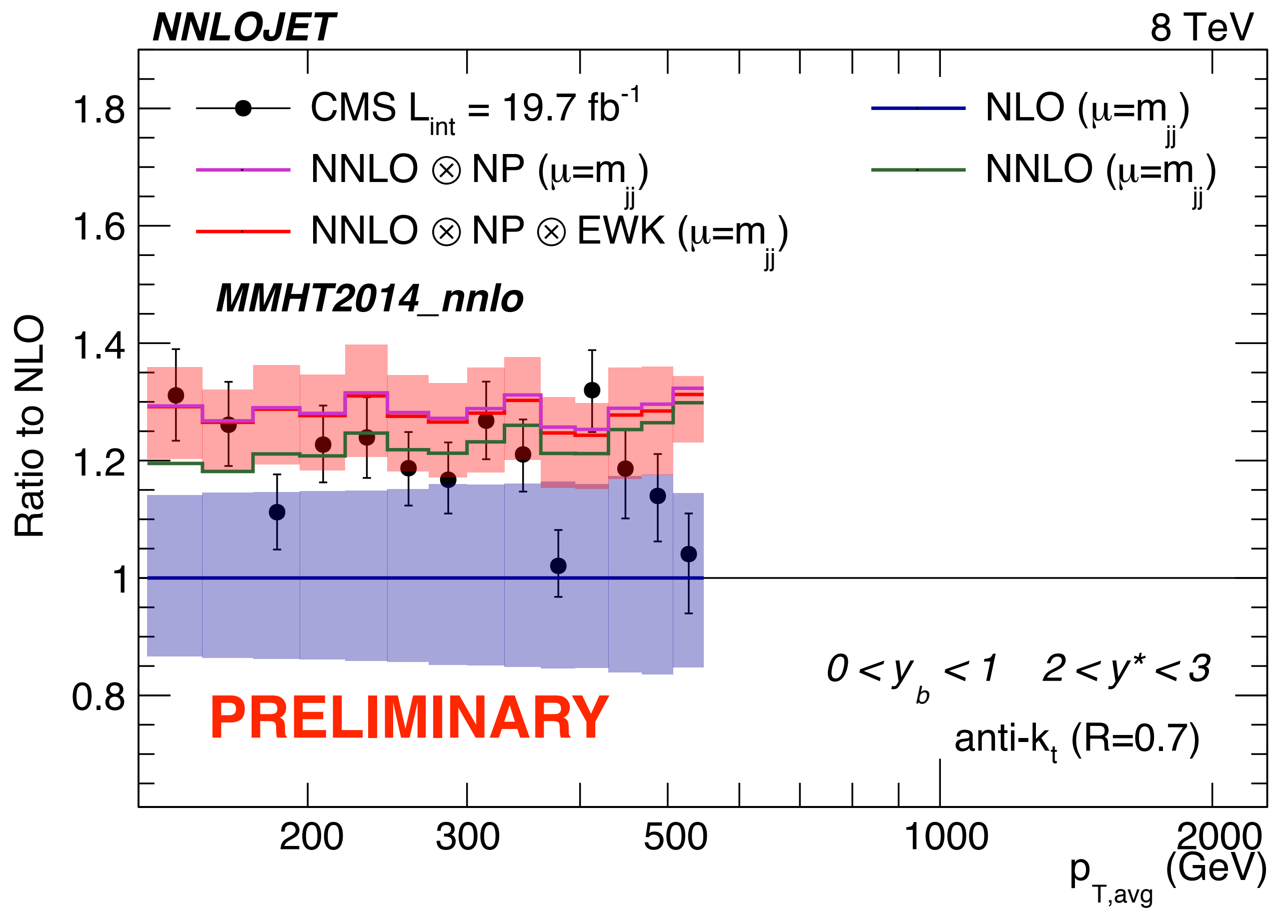
MMHT2014_nnlo

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

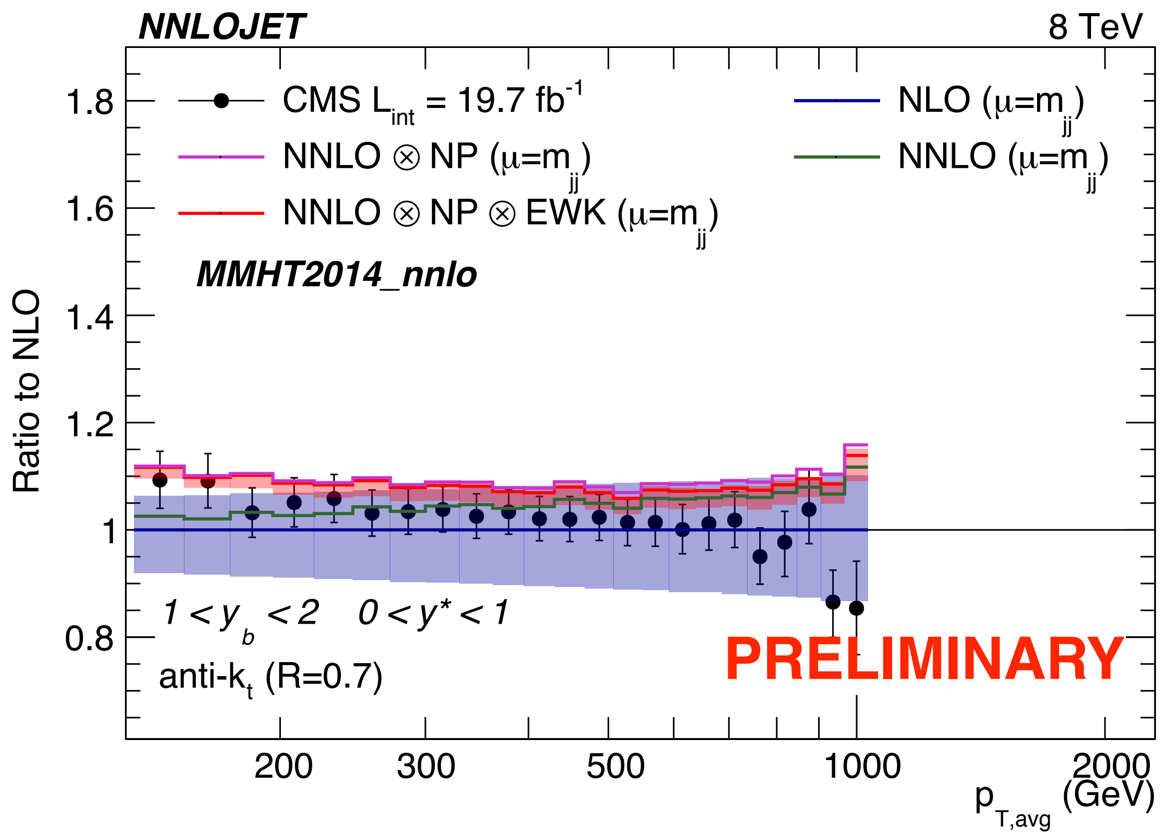
→ good agreement with NNLO⊗NP⊗EWK for the central y_b slice

[Gehrmann-De Ridder, Gehrmann, Glover, Huss, JP in preparation '19]



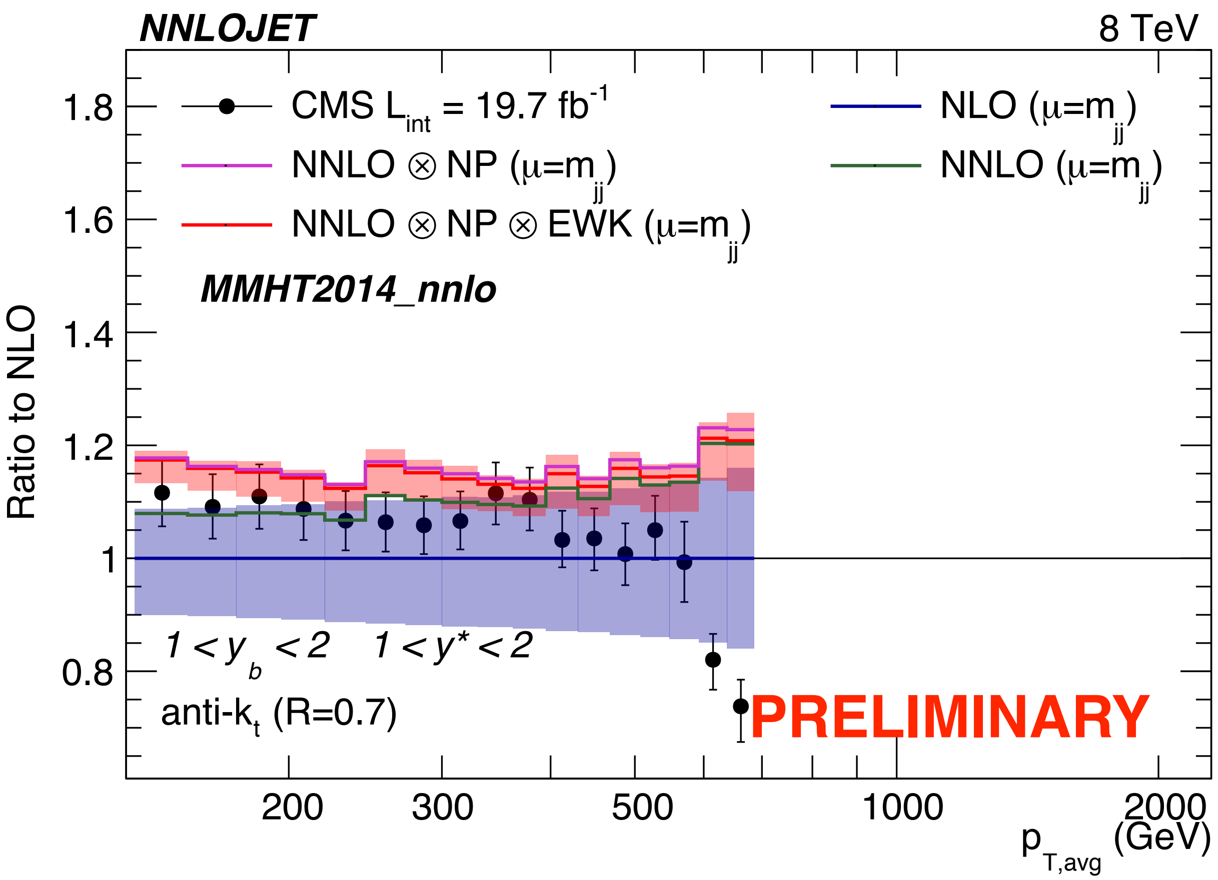


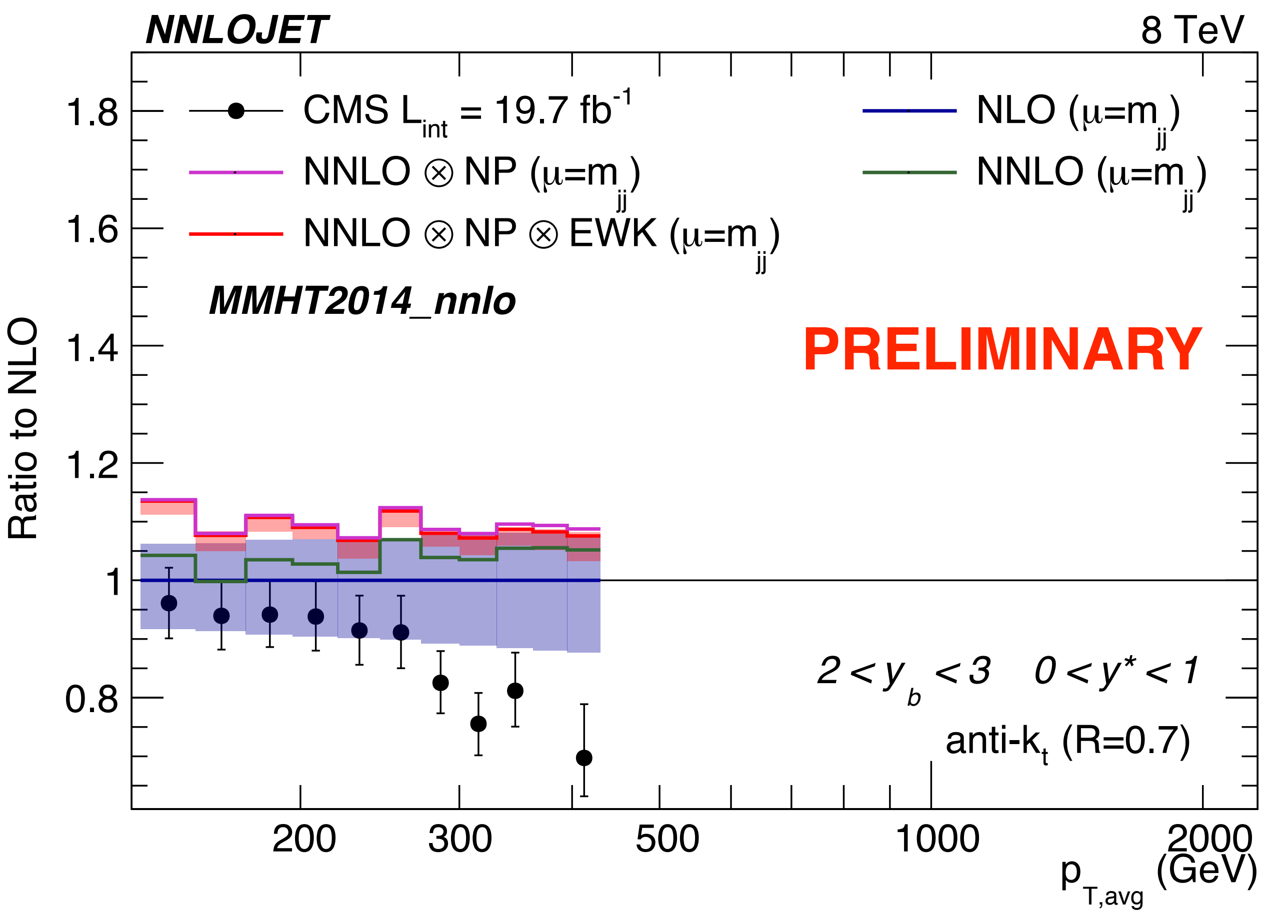
CMS $\sqrt{s}$=8 TeV $y_b > 1$



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 (different energies, covering wide jet p_T and rapidity and jet cone sizes) → APPLFAST interface in progress
- 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