Status of NNLO QCD corrections for process with one or more jets in the final state at the LHC

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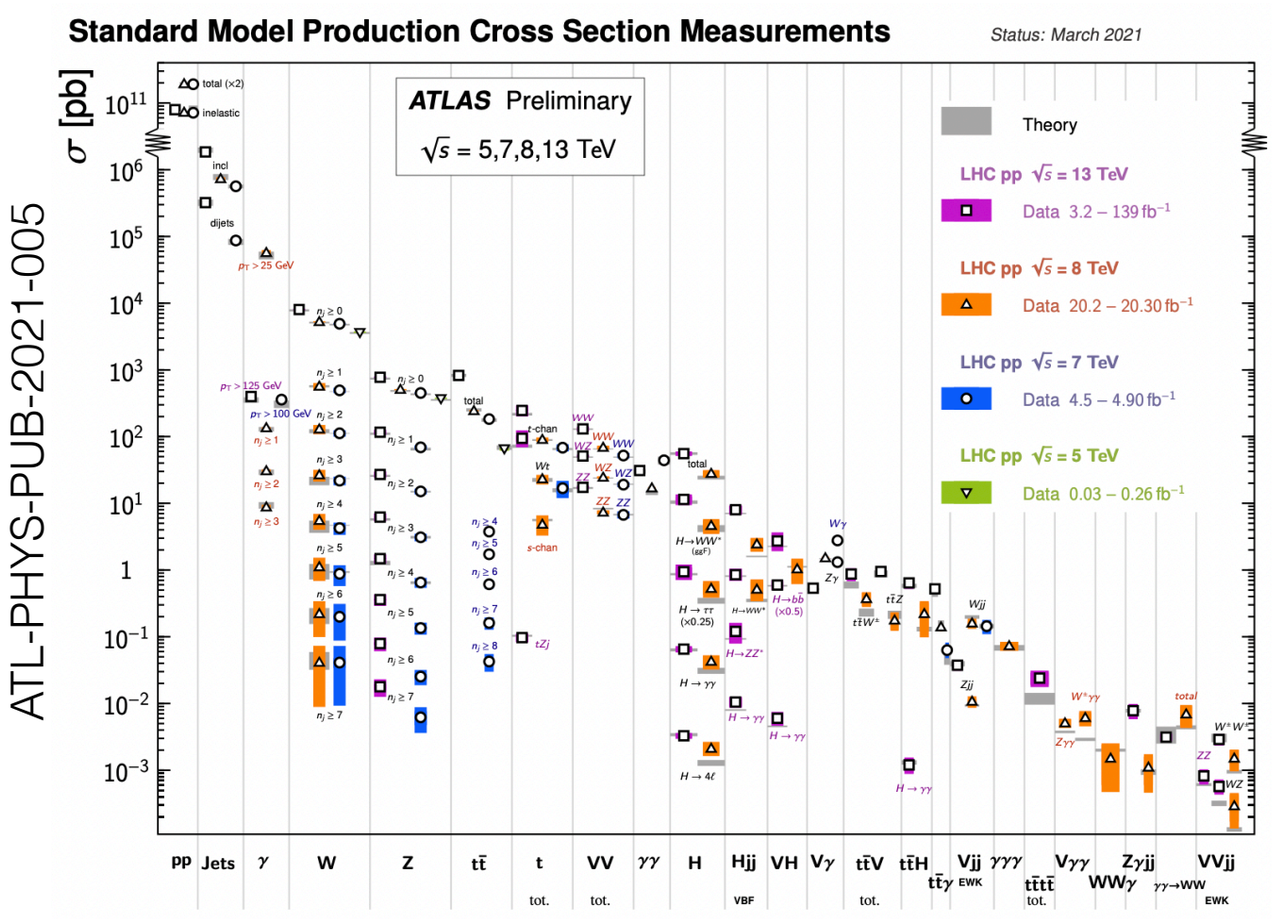
Introduction



- Summary of Standard Model cross section measurements at the LHC

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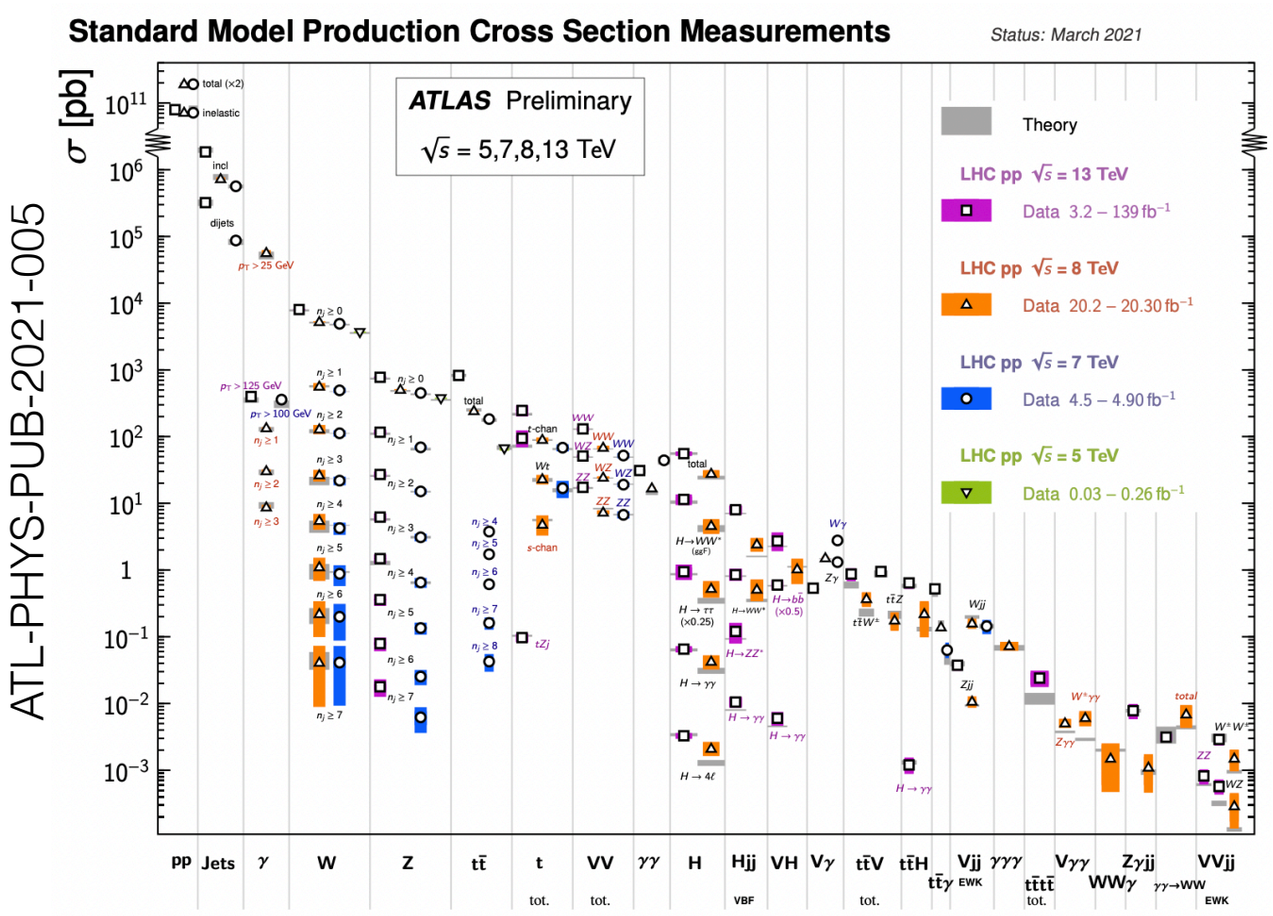

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- Understanding jet production is a key ingredient for several physics measurements

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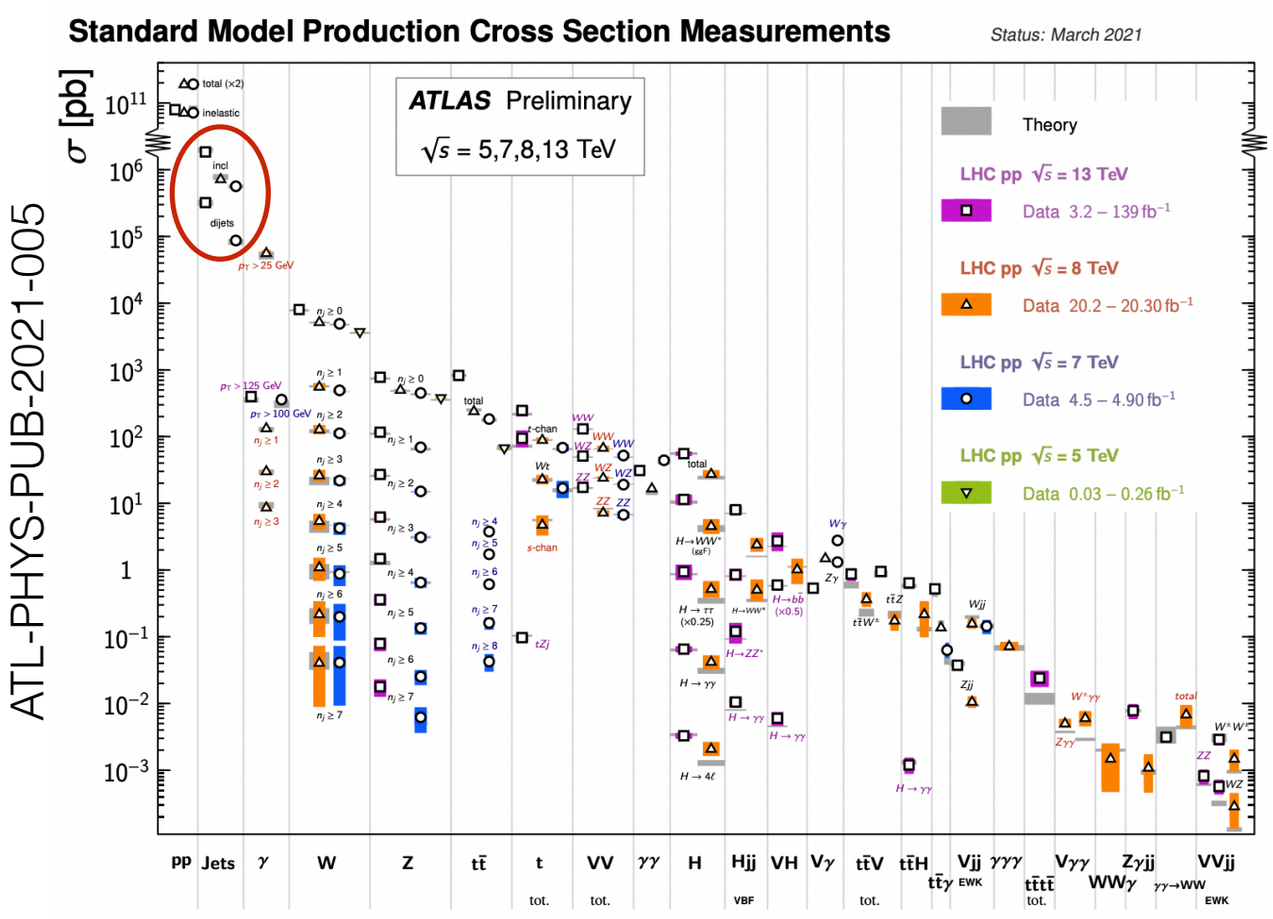

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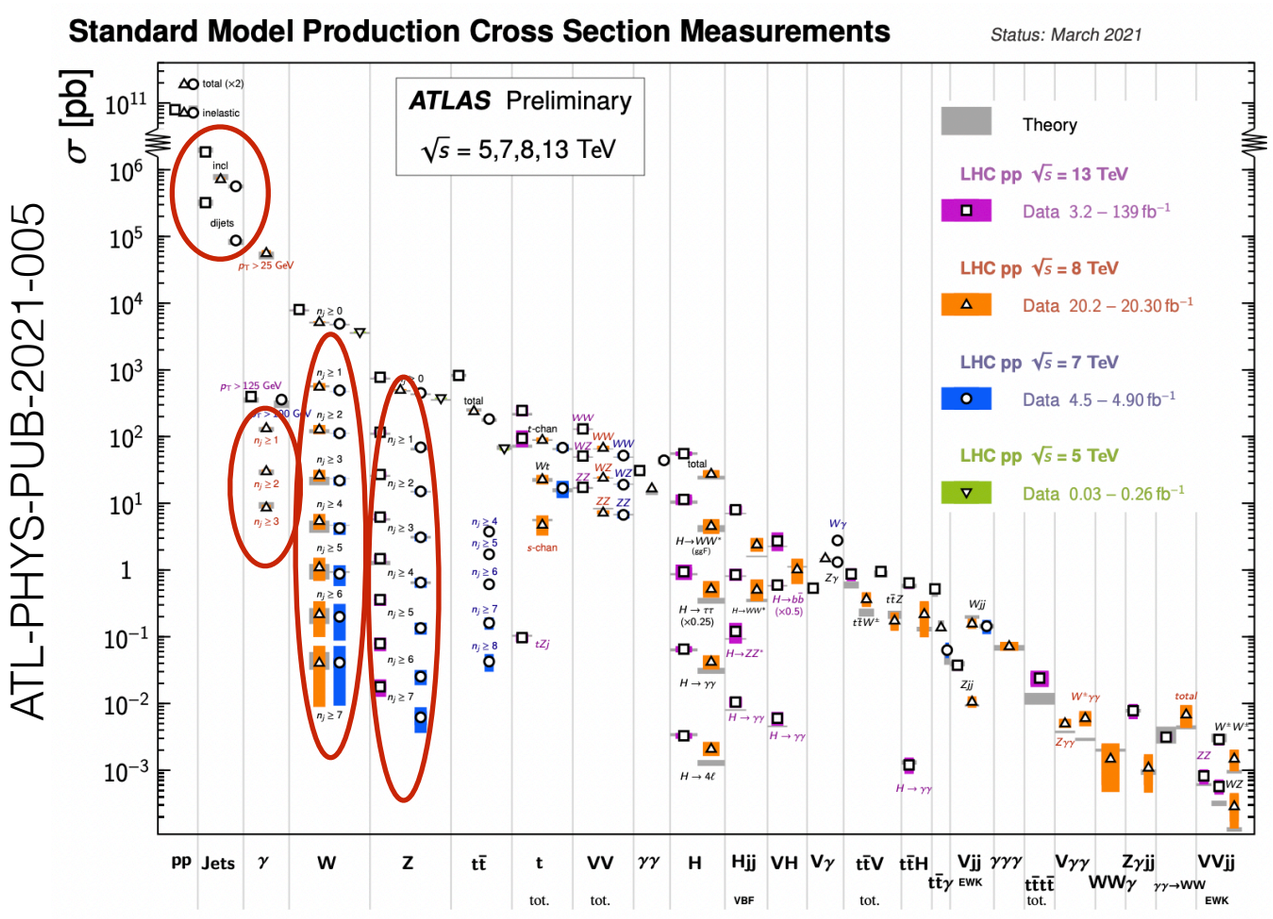

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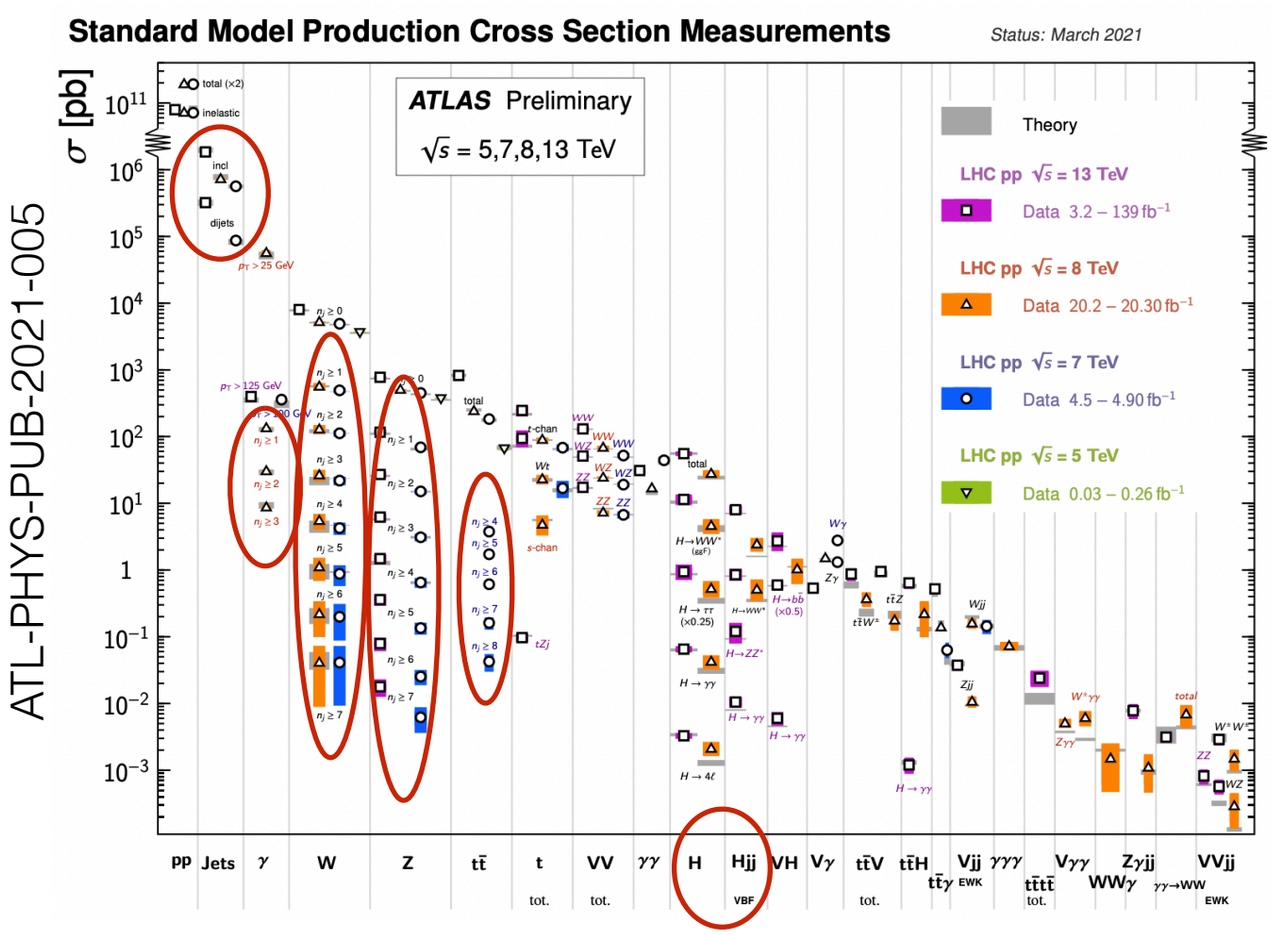

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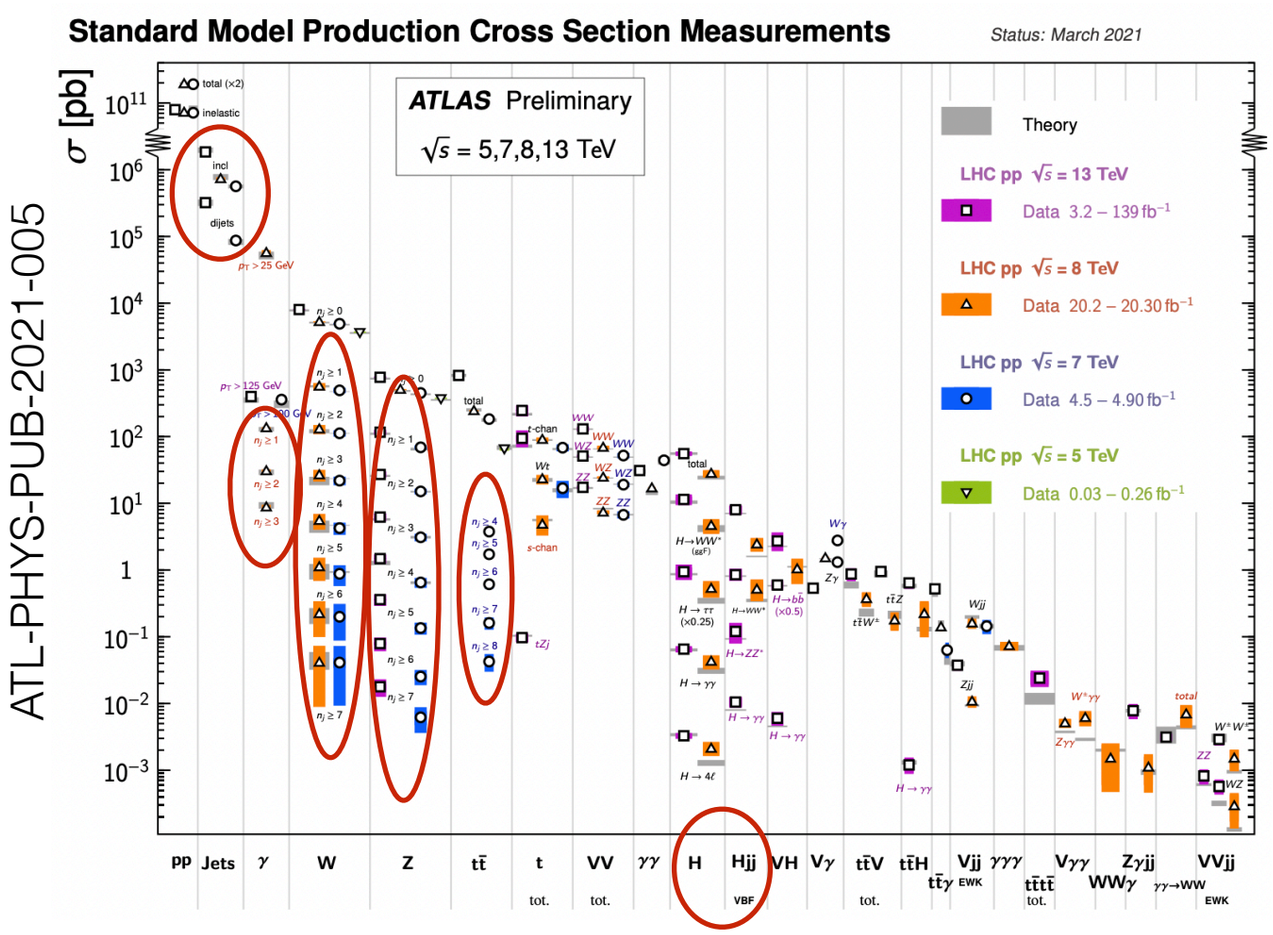

- Summary of Standard Model cross section measurements at the LHC
- Understanding jet production is a key ingredient for several physics measurements
- Goal to test pQCD at unprecedented collider energies, probe proton structure and search for New Physics

Fully differential NNLO$_{QCD}$

- Calculations of fully differential NNLO$_{QCD}$ cross sections for 2→2 processes has had remarkable progress over the past years with many different approaches now applied to LHC processes

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

- Many new different schemes developed to consistently achieve the subtraction of IR-singularities at NNLO$_{QCD}$ between real and virtual matrix elements

- Sector decomposition
  Binoth, Heinrich; Anastasiou, Melnikov, Petriello
- Antenna subtraction
  Gehrmann, Gehrmann-De Ridder, Glover
- Sector-Improved Residue subtraction
  Czakon; Boughezal, Melnikov, Petriello
- q_T
  Catani, Grazzini
- N-jettiness
  Boughezal, Focke, Liu, Petriello; Gaunt, Stahlhofen, Tackmann, Walsh

- Color-full subtraction
  Del Duca, Somogyi, Trocsanyi
- Nested soft-collinear subtraction
  Caola, Melnikov, Röntsch
- Analytic local sector subtraction
  Magnea, Maina, Pelliccioli, Signorile-Signorile, Torrielli, Uccirati
- Projection to Born
  Cacciari, Dreyer, Karlberg, Salam, Zanderighi

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Will present a selection of recent theory developments. Not all topics can be covered, apologies for all omissions

action
Somogyi, Trocsanyi

near subtraction
kov, Röntsch

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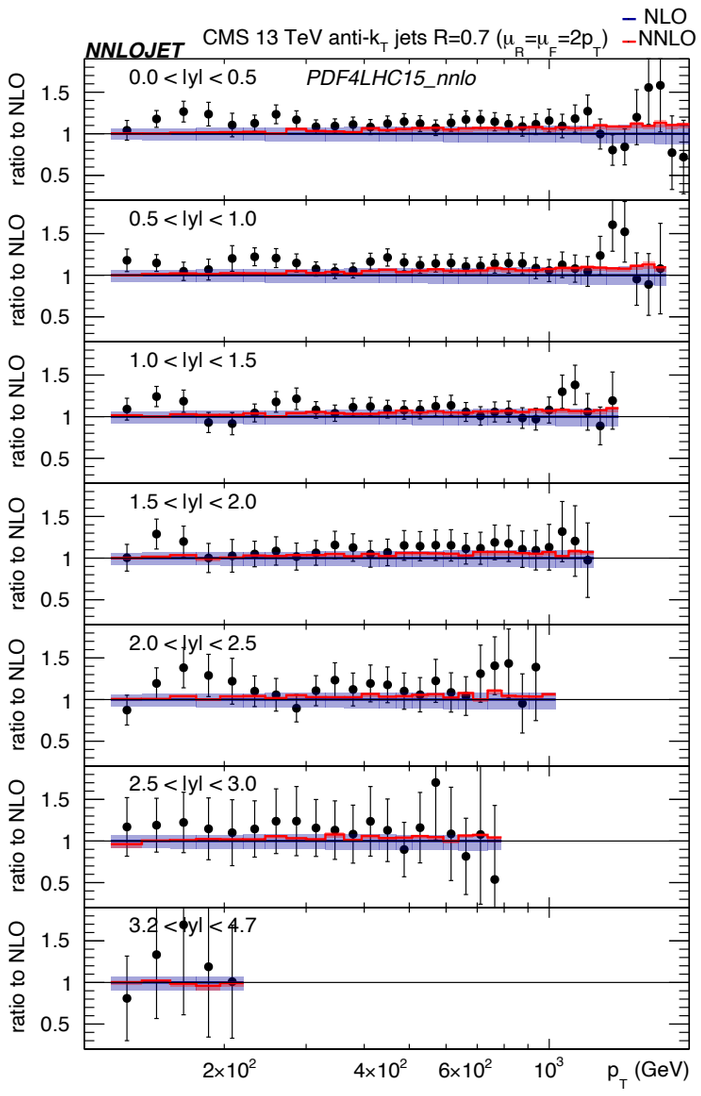
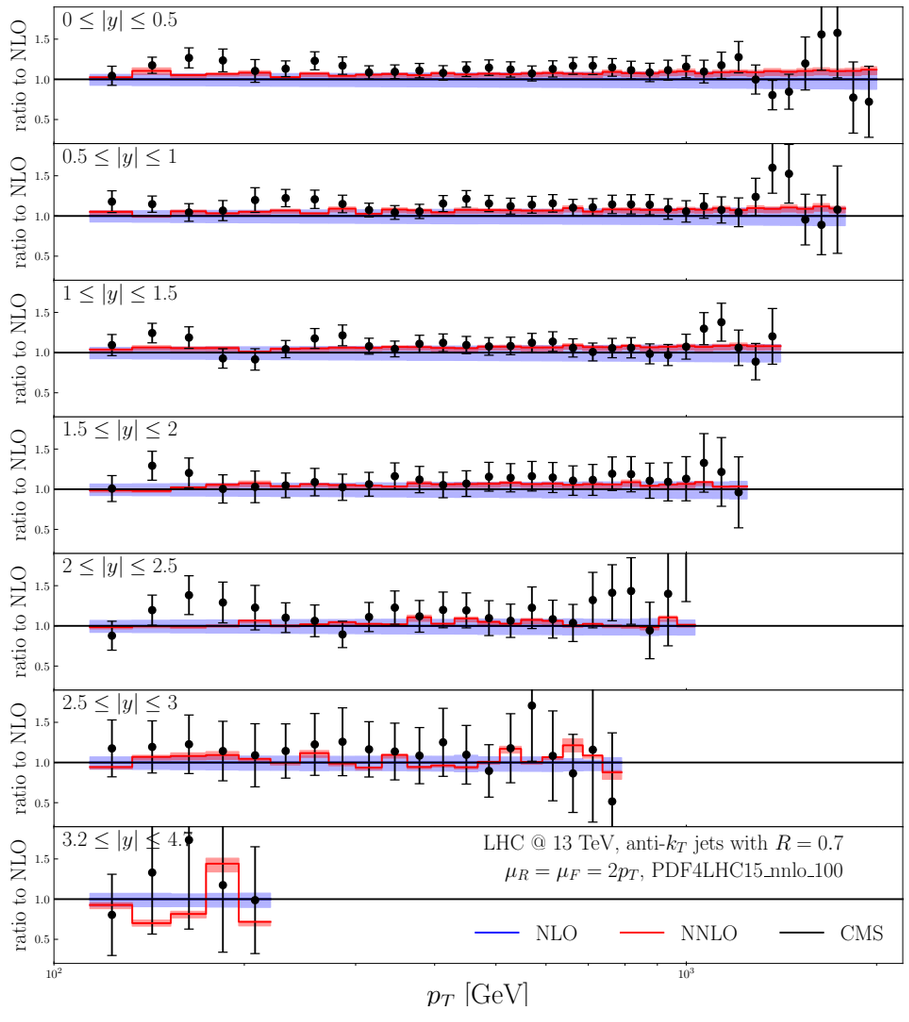
- Projection to Born
  Cacciari, Dreyer, Karlberg, Salam, Zanderighi

Jet final states: *j*+*X*

- Single jet inclusive rates, jet production spectrum differential in jet p_T and rapidity
  - NNLO calculation with NNLOJET:
    J.Currie et al. Phys. Rev. Lett. 118 (2017) 072002
  - NNLO calculation with Sector Improved Phase Space for Real Radiation:
    M.Czakon et al. JHEP 10 (2019) 262
- Sub-leading colour effects negligible



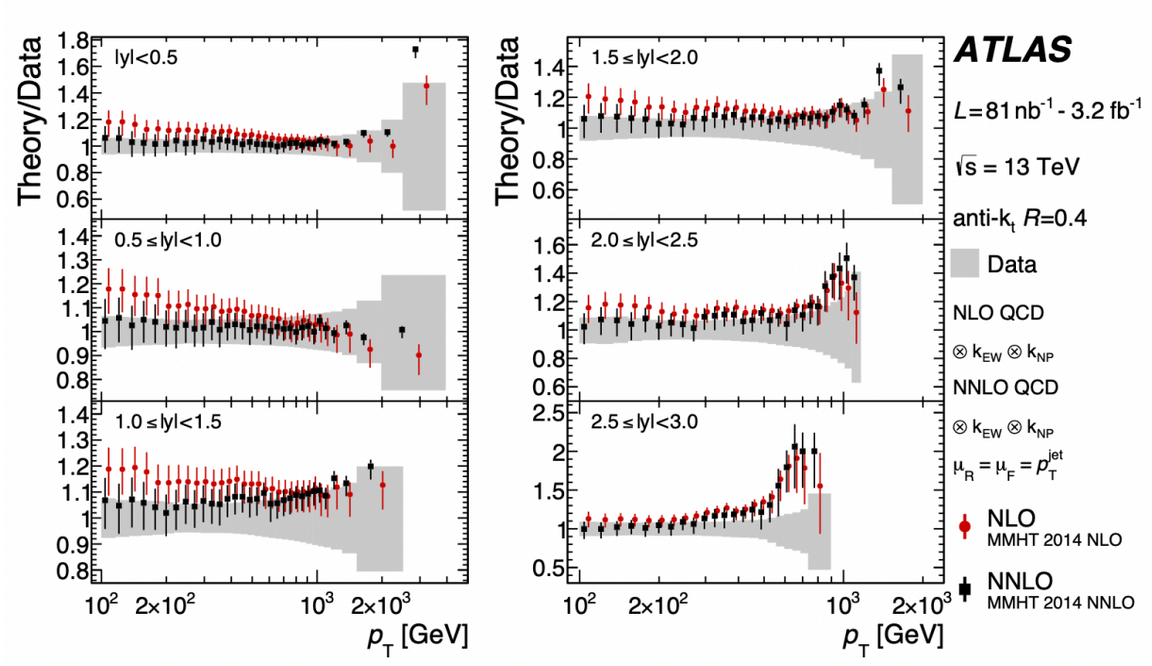
[arXiv:1807.03692]



[arXiv:1907.12911]

Jet final states: *j*+*X*

- Ratios of NNLO pQCD predictions and √s = 13 TeV LHC measurements



- ATLAS anti-k_T R=0.4 measurement
- Significant improvement in the description of the data going from **NLO** to **NNLO**
- Tension with the data in the of the forward ($|y| > 2$) high p_T range

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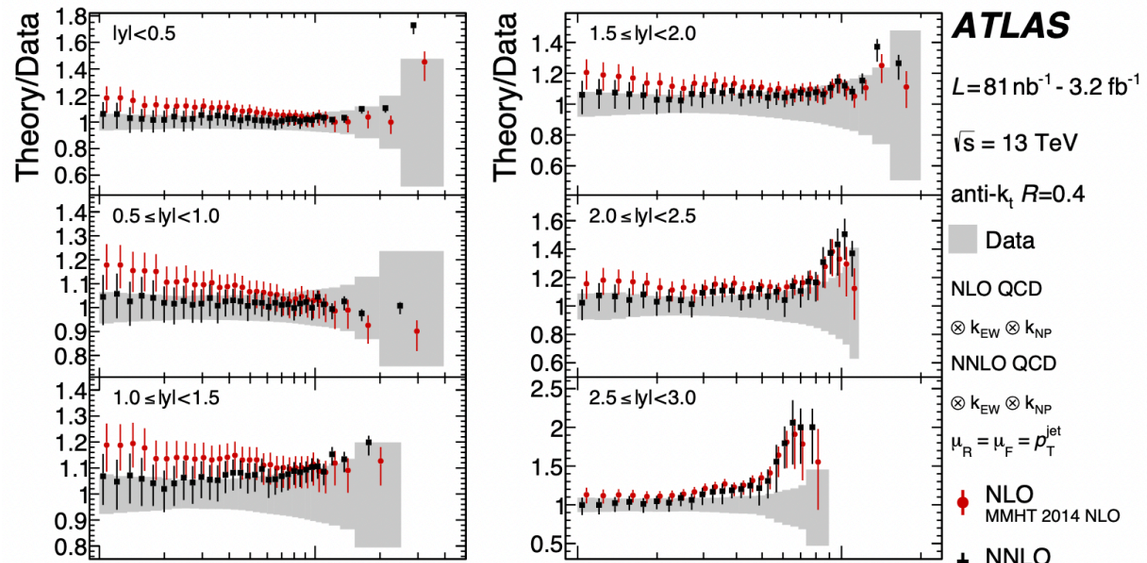
JHEP 05 (2018) 195



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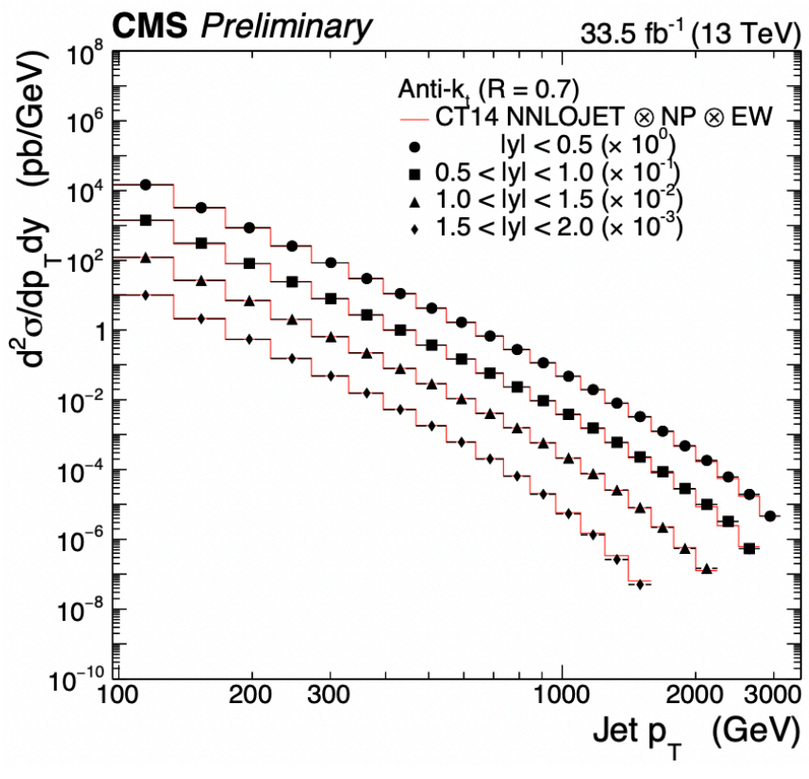
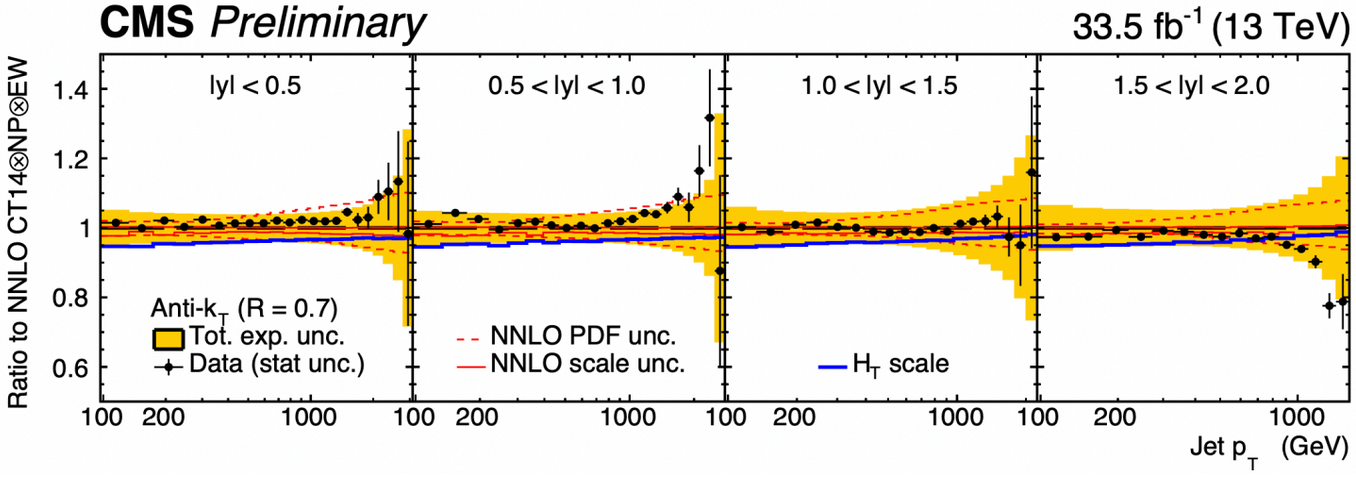
CMS PAS SMP-20-011





- Smaller impact of higher-order corrections for R=0.7
- Good description of the data at NNLO

Triple differential dijet cross section

- Dijet cross section: *pp→2jets+X*
  - Measured triple differentially by CMS at 8 TeV [arXiv:1705.02628] as a function of
    - Average p_T $\quad p_{T,\mathrm{avg}} = (p_{T,1} + p_{T,2})/2$
    - Rapidity separation $\quad y^* = |y_1 - y_2|/2$
    - Boost of the dijet system $\quad y_b = |y_1 + y_2|/2$
  - y_b cut probes parton distribution functions at symmetric and asymmetric x_1,x_2 values

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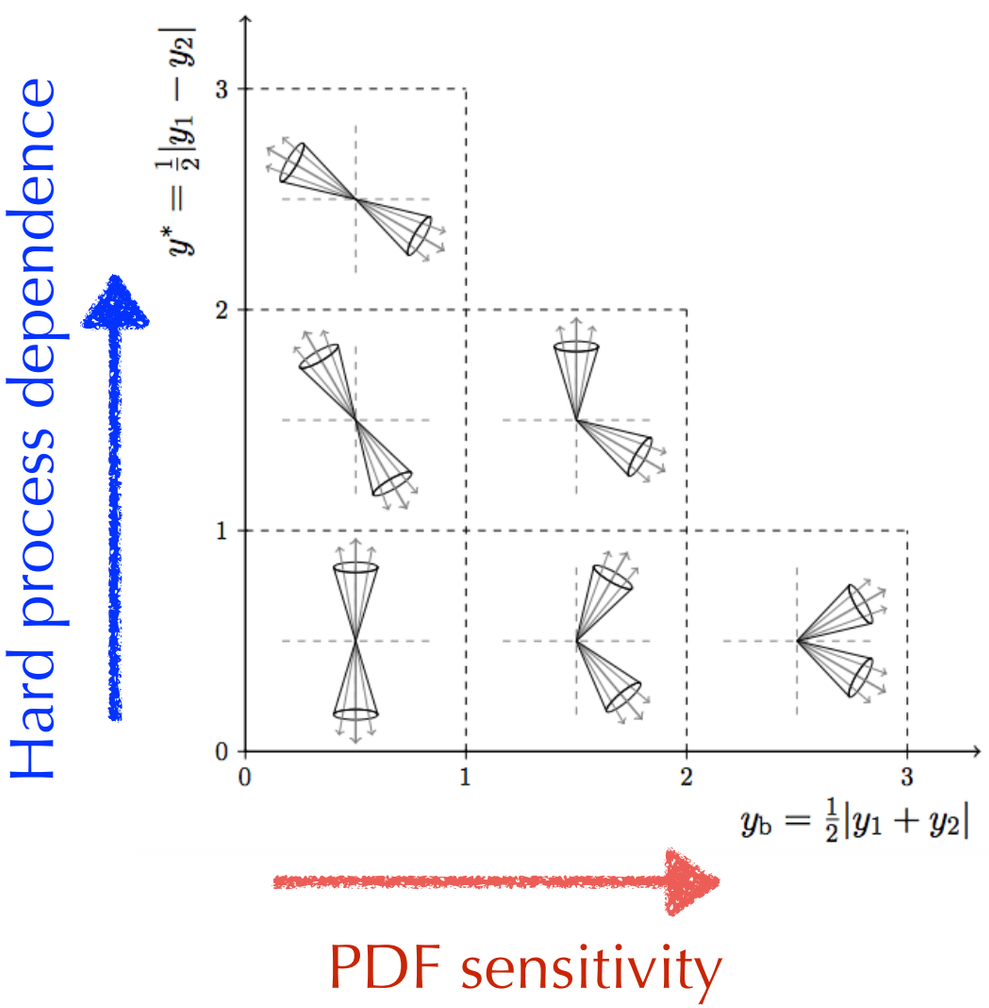
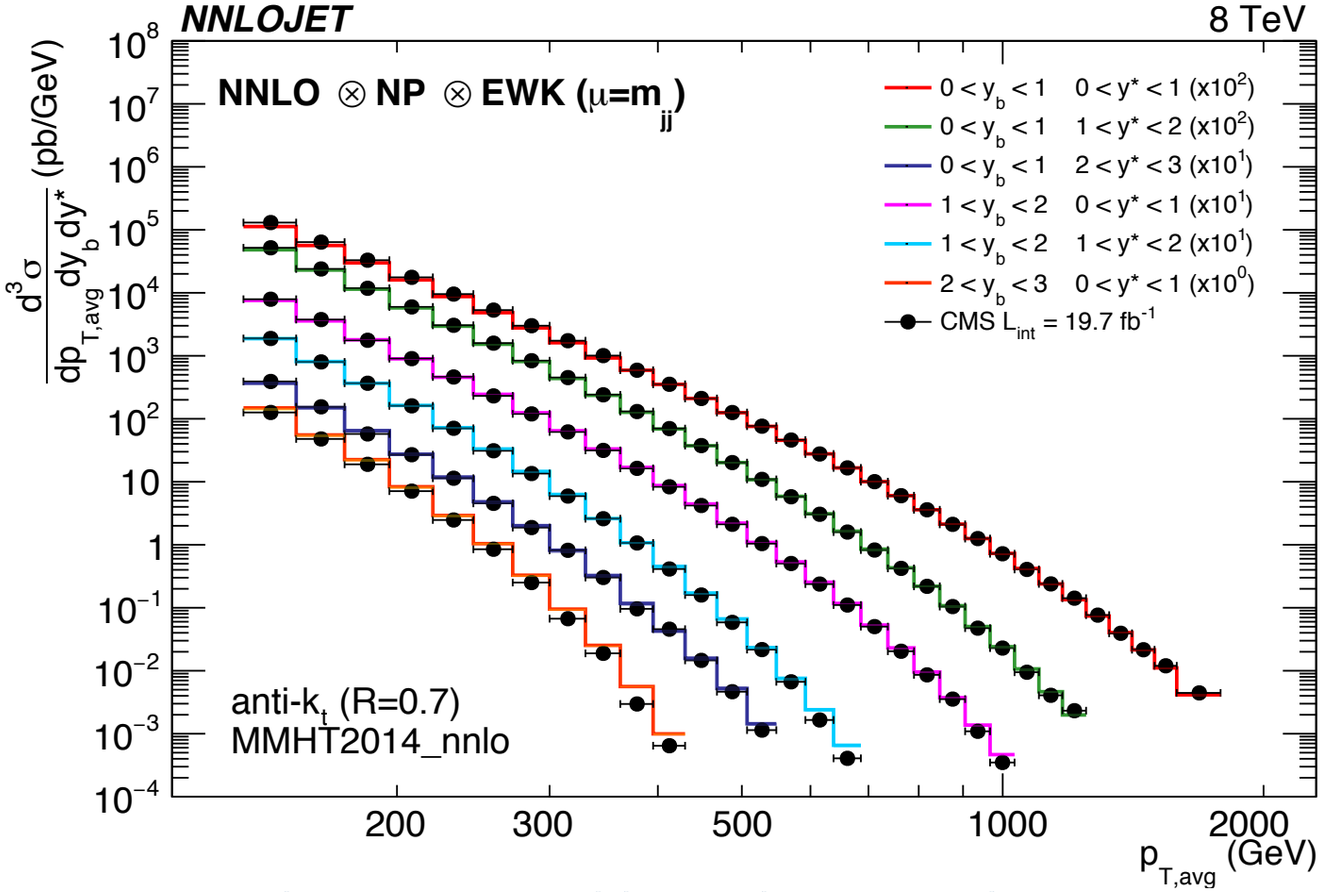
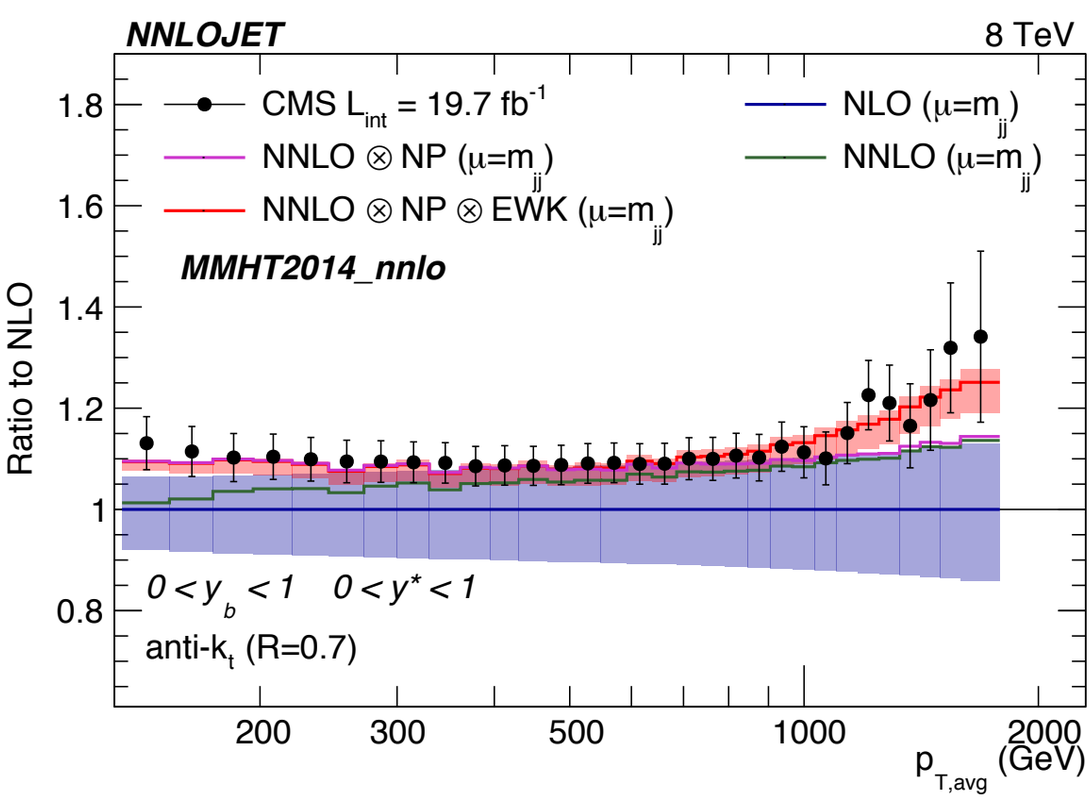
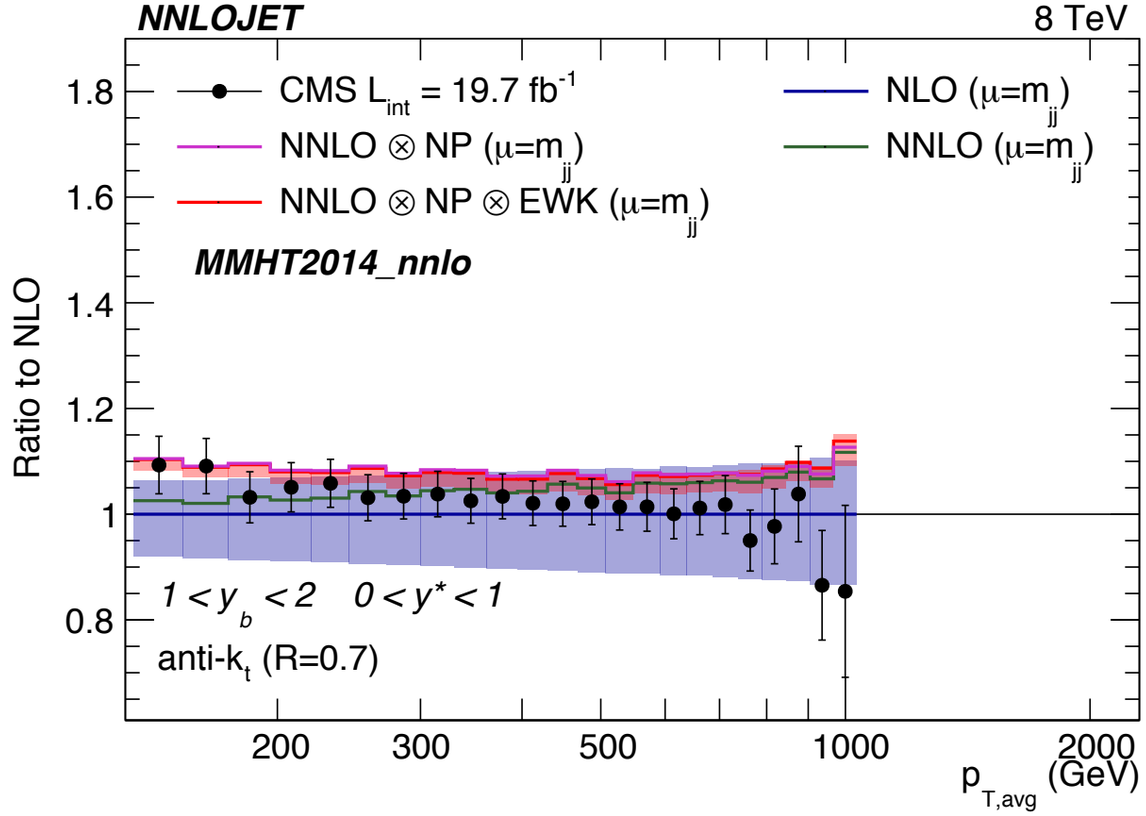




Gehrmann-De Ridder, Gehrmann, Glover, Huss, JP
[arXiv: 1905.09047] Phys. Rev. Lett. 123, 102001 (2019)

Triple differential dijet cross section





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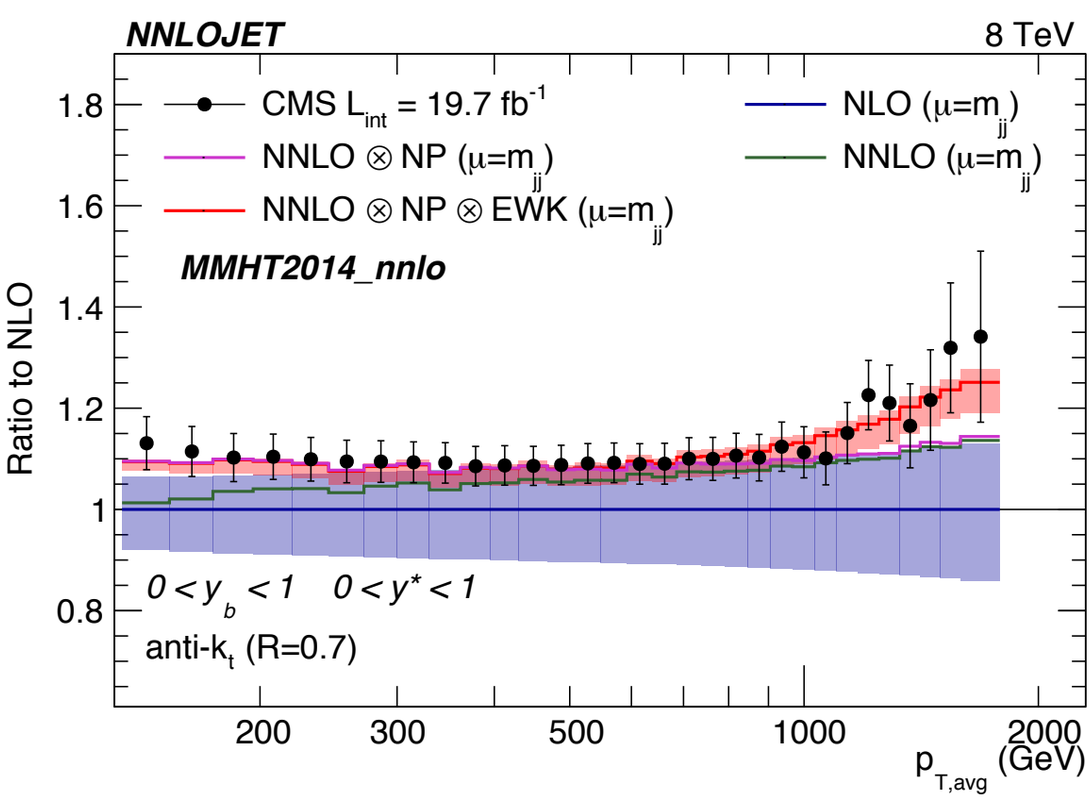
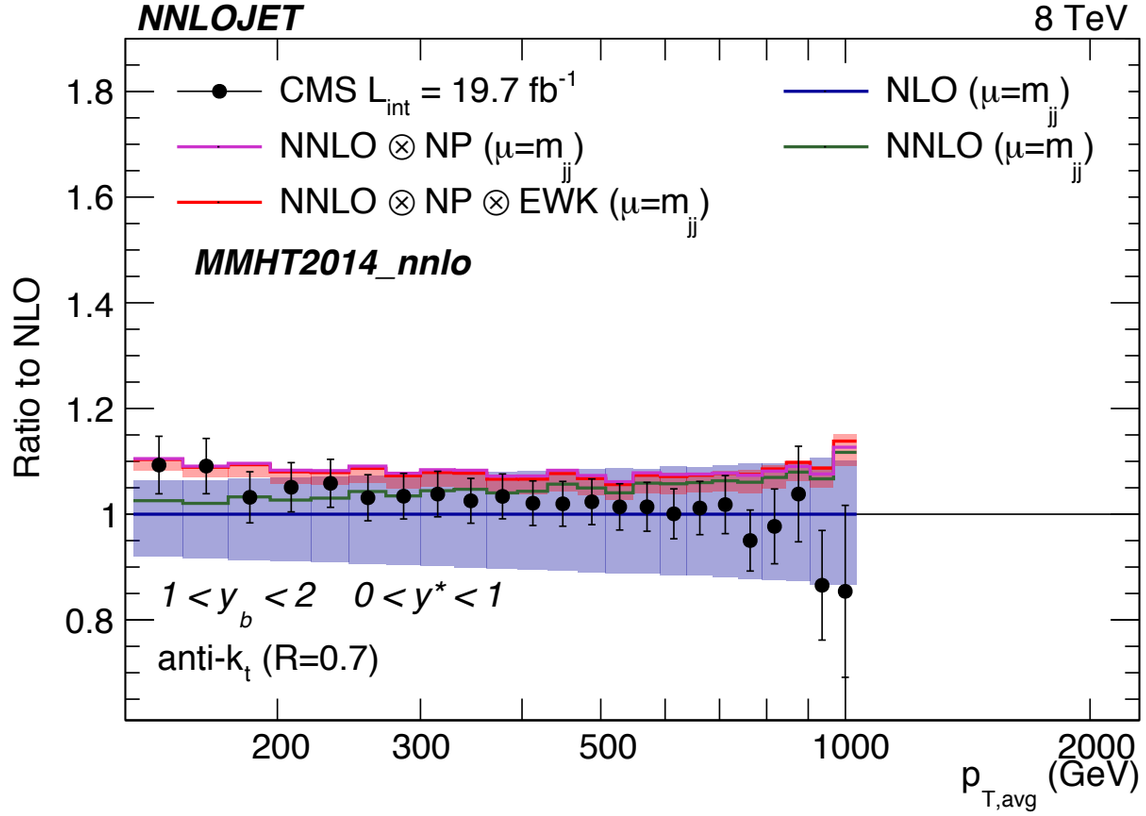
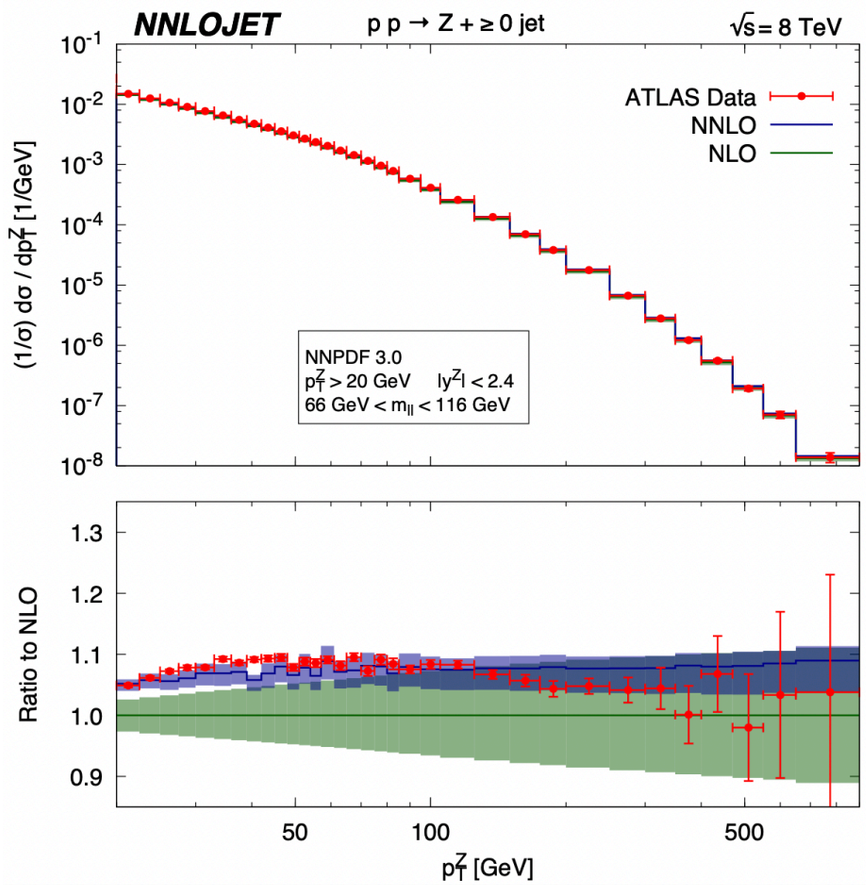




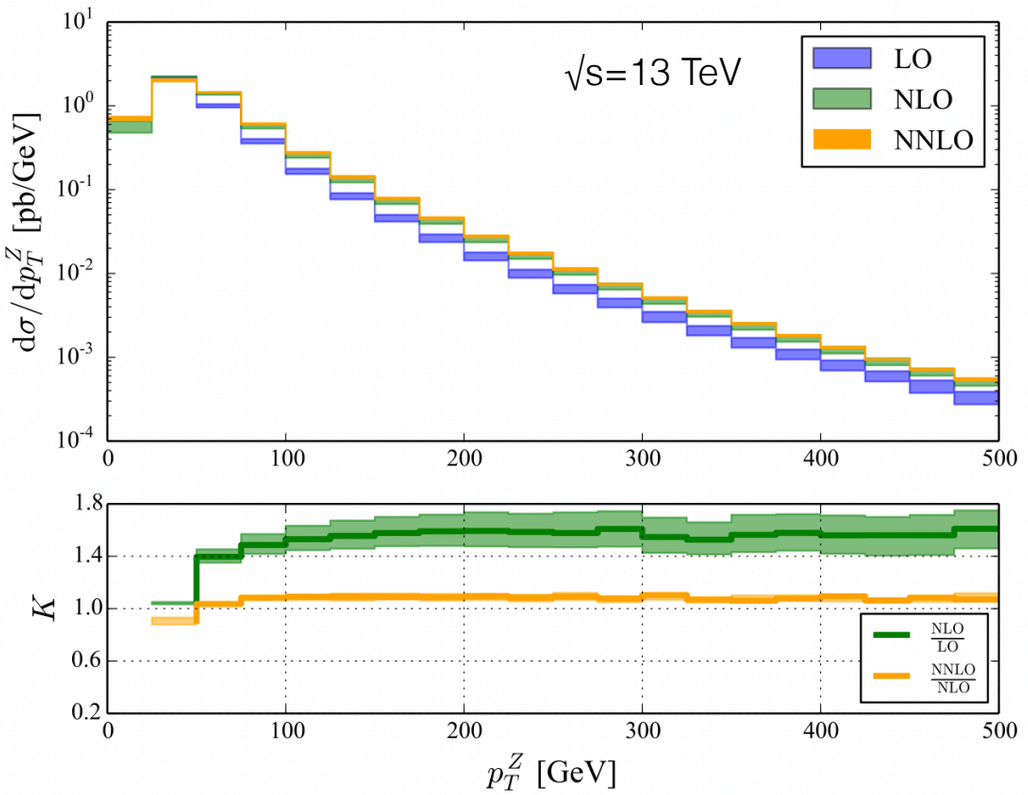
- comparison with triple differential CMS dijet 8 TeV measurement [arXiv:1705.02628]
  - NNLO correction changes both the shape and normalisation of the NLO result
  - Significant reduction in theory uncertainty going from NLO to NNLO
  - $0 < y_b < 1$: good agreement with NNLO⊗NP⊗EWK
  - $1 < y_b < 2$: data below NNLO theory prediction
  - PDF effect since matrix element contribution invariant under y_b variation

Z + jet final states

- Large cross section and clean leptonic signature. Sensitivity to α_s and gluon PDF



Gehrmann-De Ridder, et al. Phys. Rev. Lett. 117, 022001 (2016)
Gehrmann-De Ridder, et al. JHEP 07 (2016) 133



Boughezal et al. Phys. Rev. Lett. 116, 152001 (2016)

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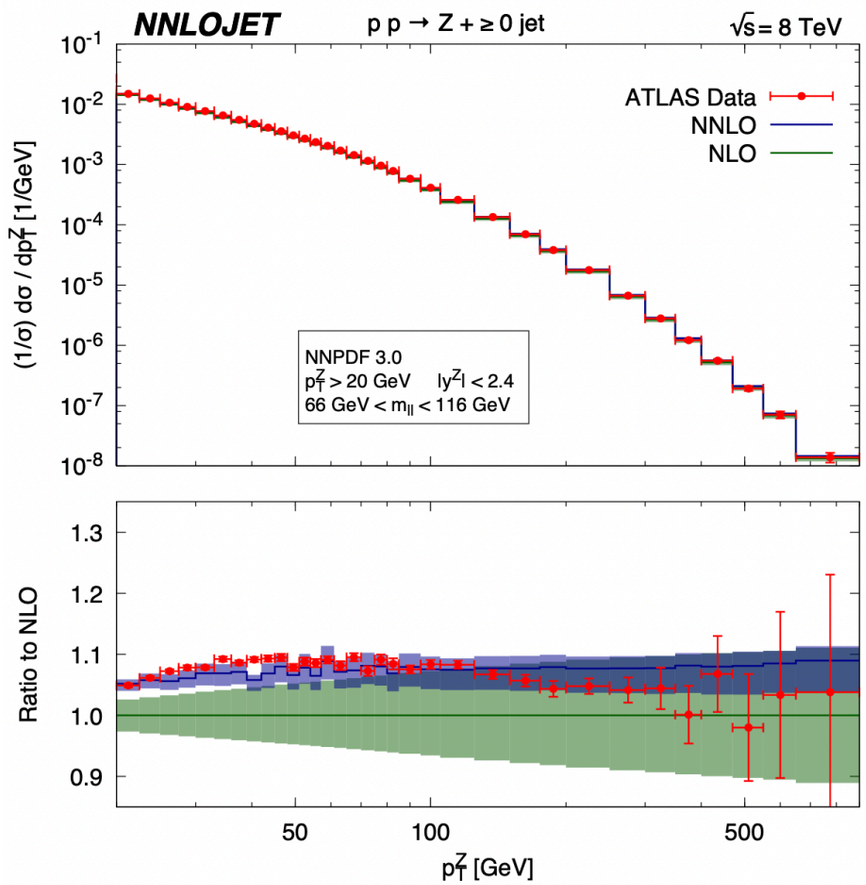

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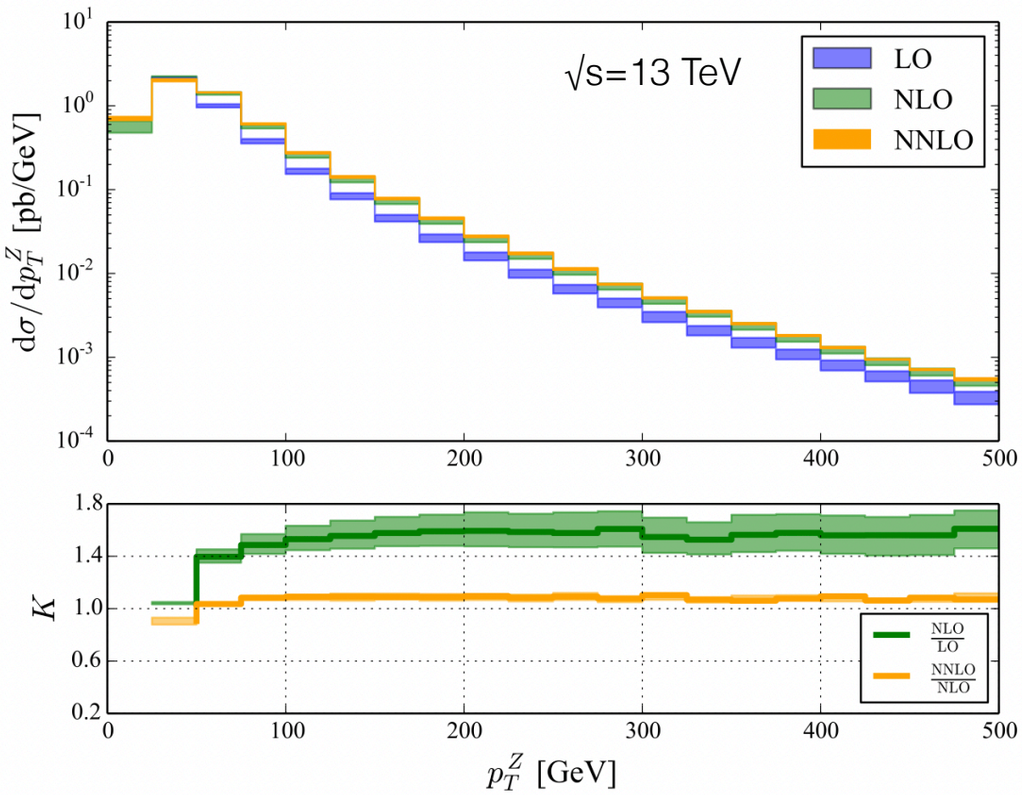
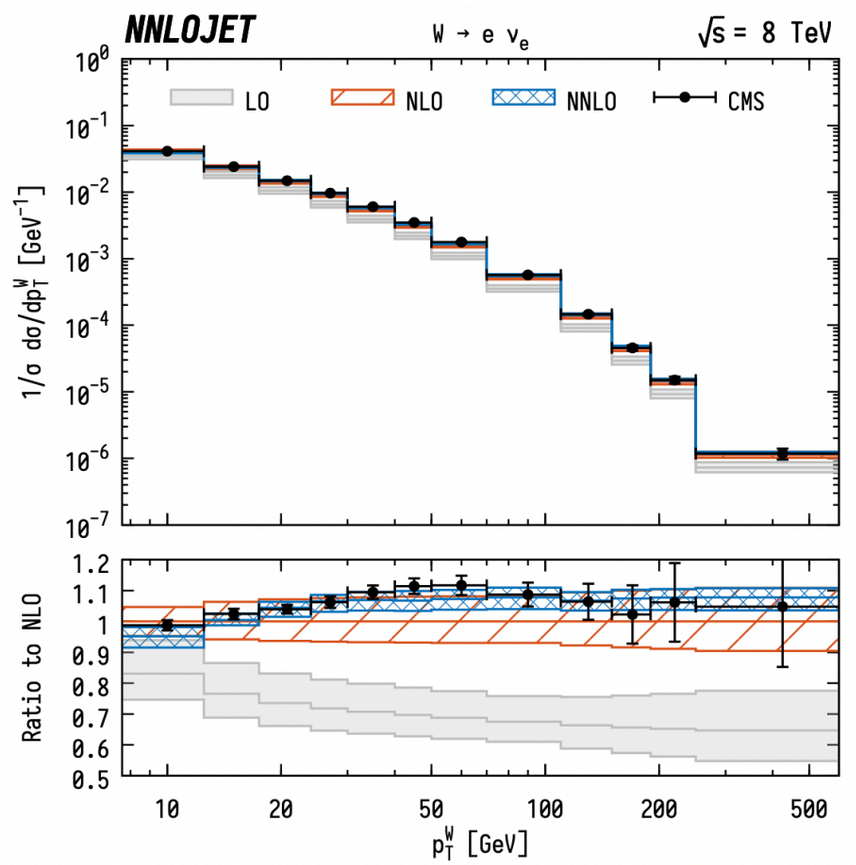


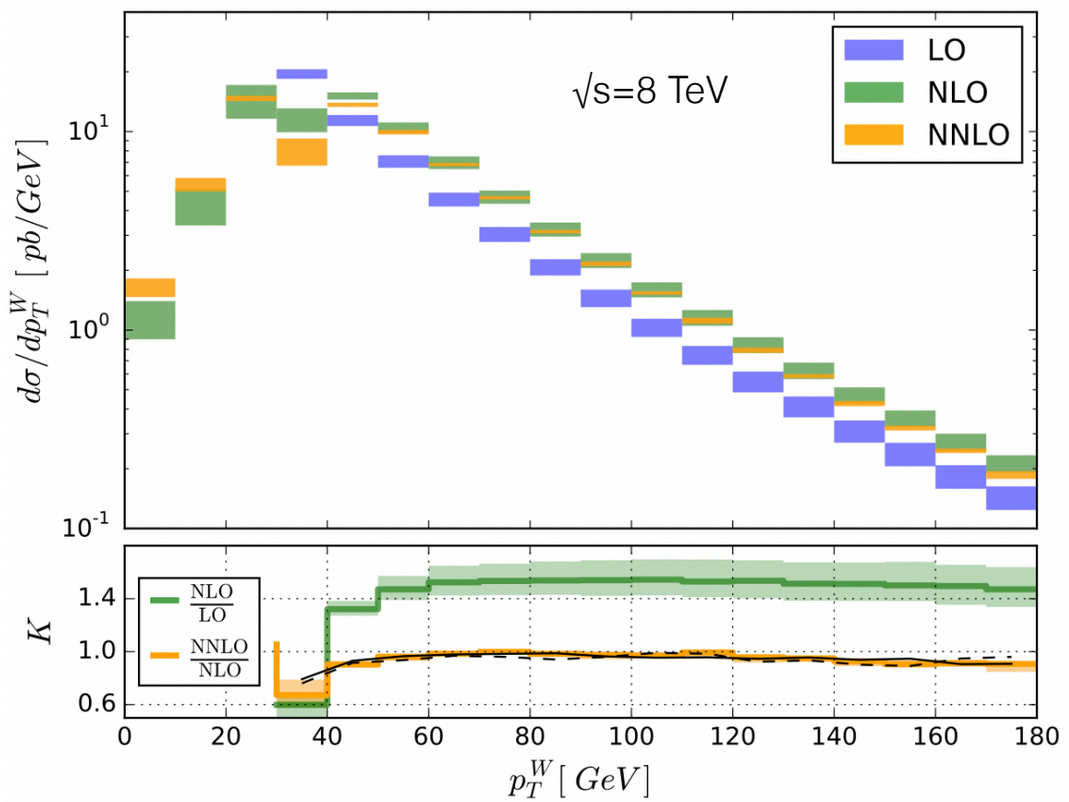
Boughezal et al. Phys. Rev. Lett. 116, 152001 (2016)

- Excellent convergence of the perturbative expansion
- NNLO correction below 10% and large reduction in the scale uncertainty of the NNLO prediction
- Significant improvement in the Data vs Theory comparison at NNLO
- Agreement between two NNLO calculations from NNLOJET and N-jettiness subtraction

W + jet final states



Gehrmann-De Ridder, Gehrmann, Glover, Huss, Morgan
Phys. Rev. Lett. 120, 122001 (2018)



Boughezal, Focke, Liu, Petriello
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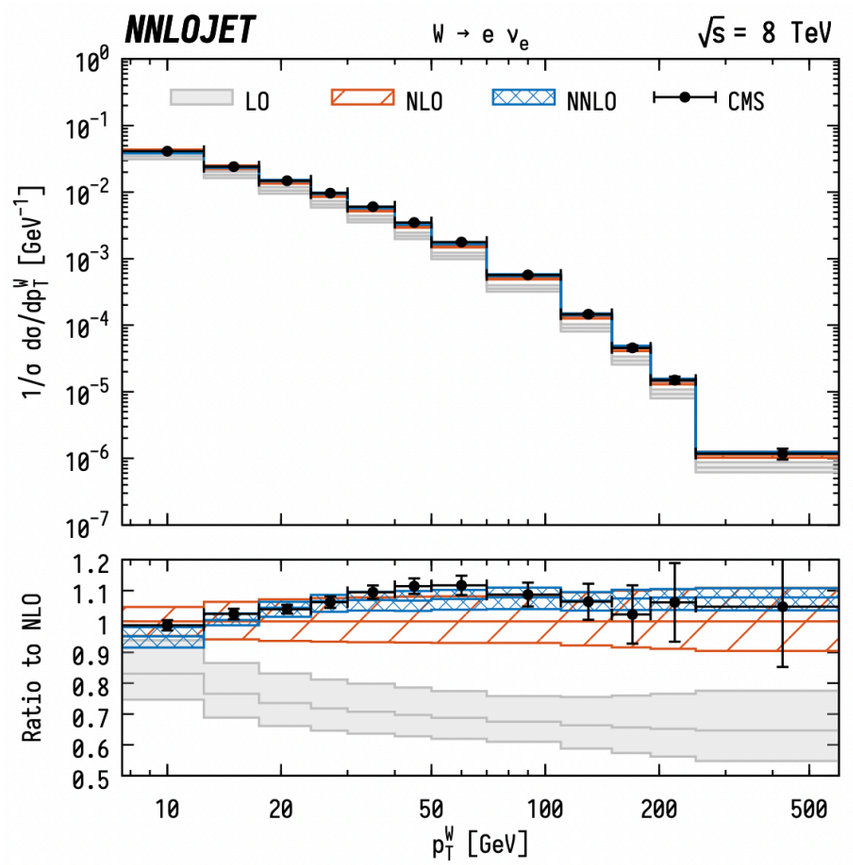

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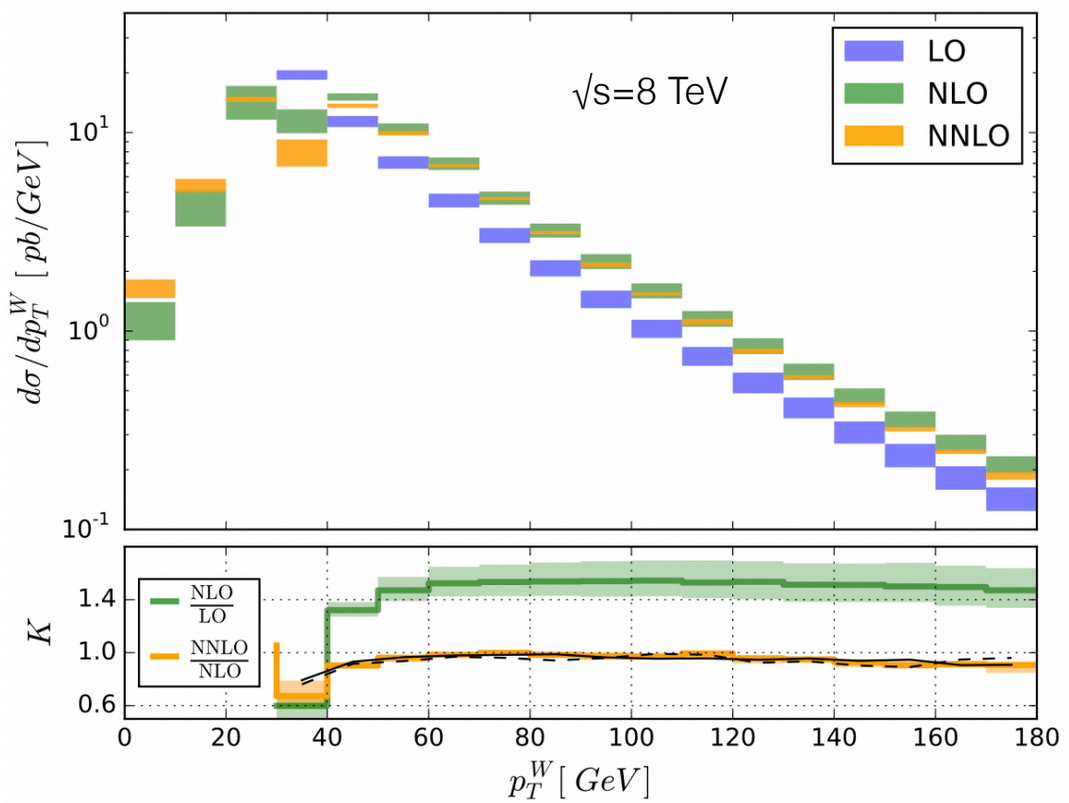
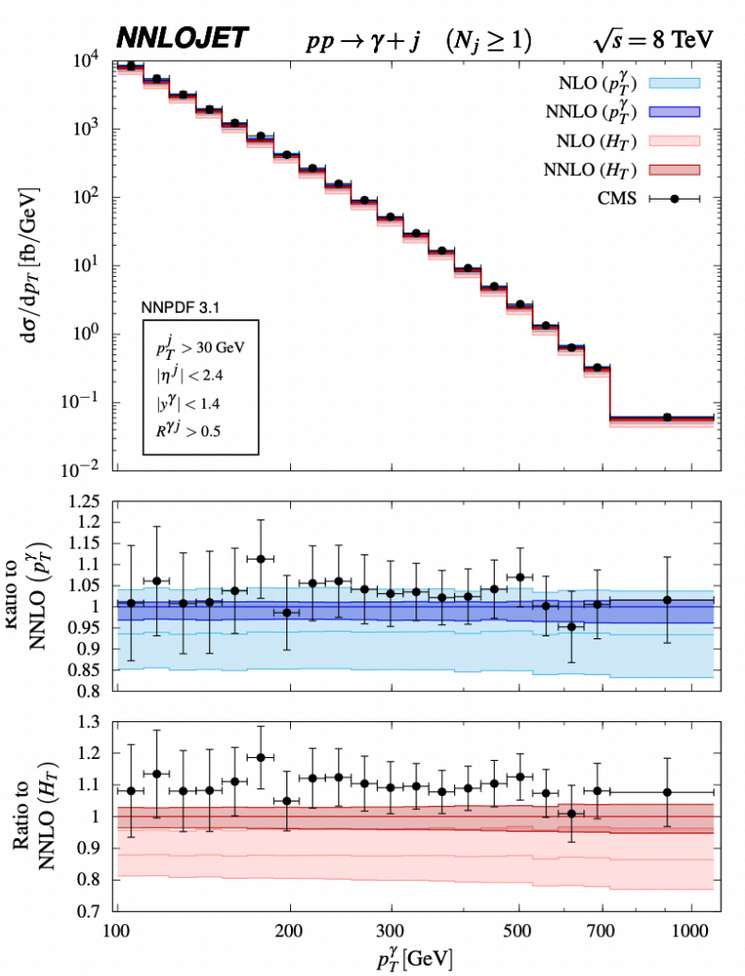


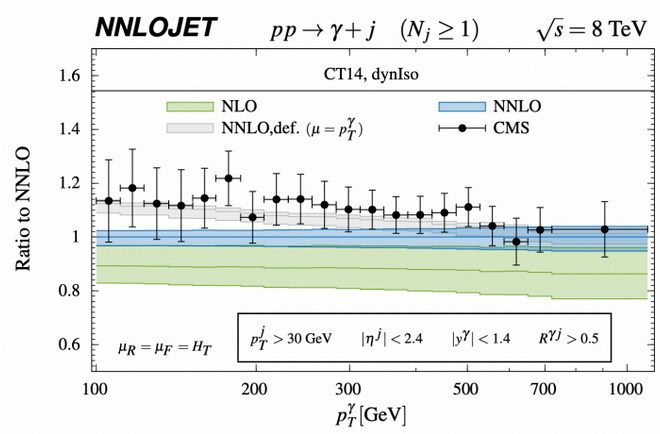
Boughezal, Focke, Liu, Petriello
Phys. Rev. Lett. 115, 062002 (2015)

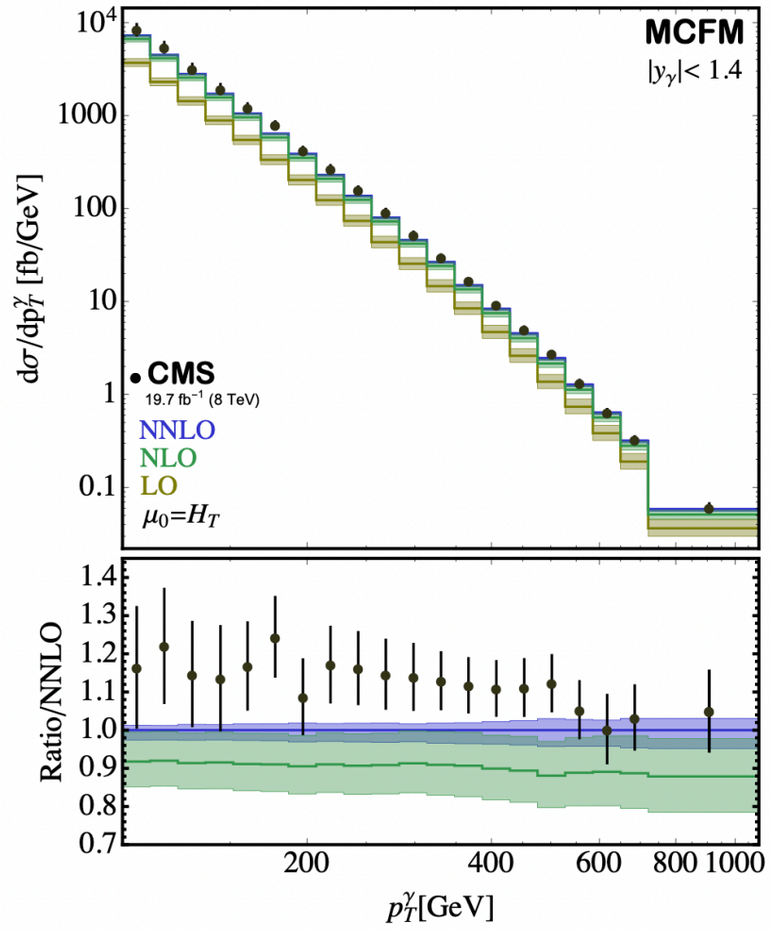
- NLO corrections between 10–40% with residual scale uncertainties at the level of around ±10%
- NNLO corrections at the 5% level change the shape of the NLO result improving the description of the data
- NNLO scale uncertainties at the ±2% level and overlap with the NLO result → good convergence of the perturbative expansion
- Agreement between two NNLO calculations from NNLOJET and N-jettiness subtraction

γ + jet final states



Chen, Gehrmann, Glover, Höfer, Huss
JHEP 04 (2020) 166





Campbell, Ellis, Williams
Phys. Rev. D 96, 014037 (2017)

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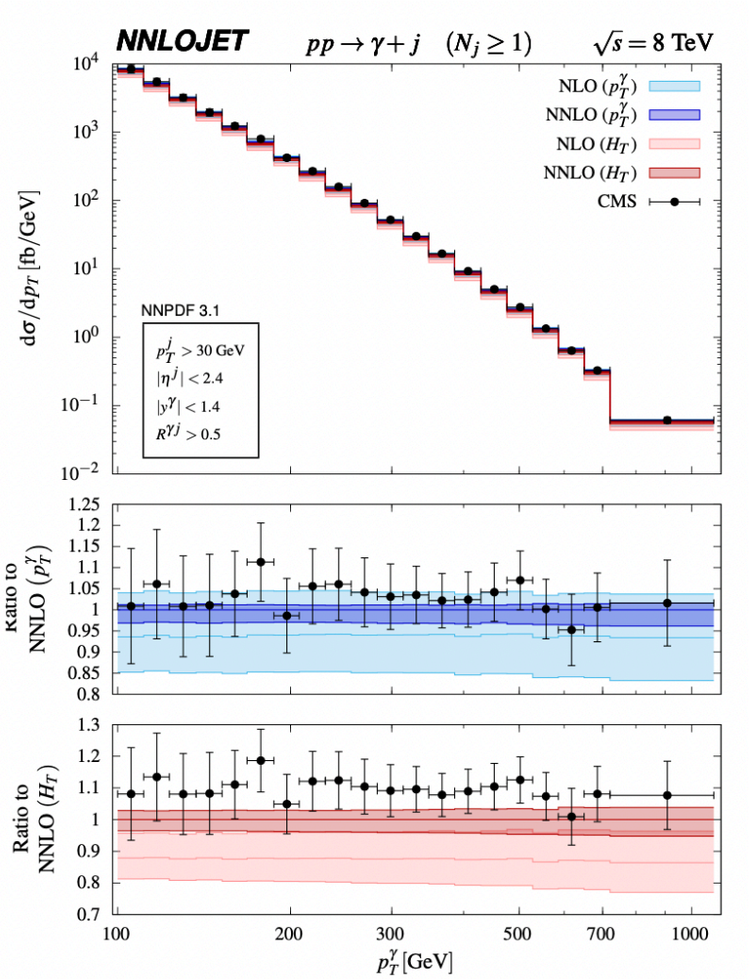

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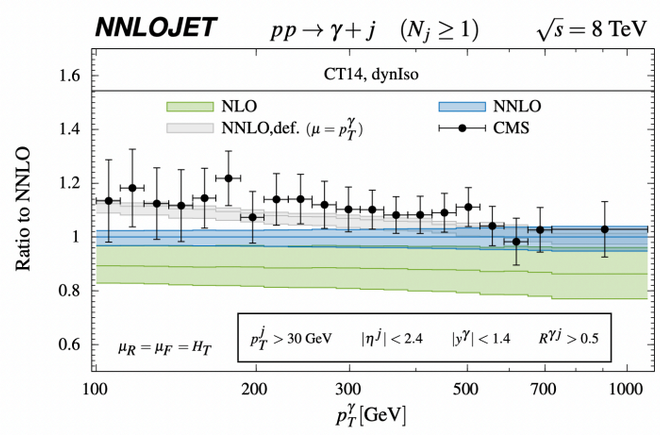

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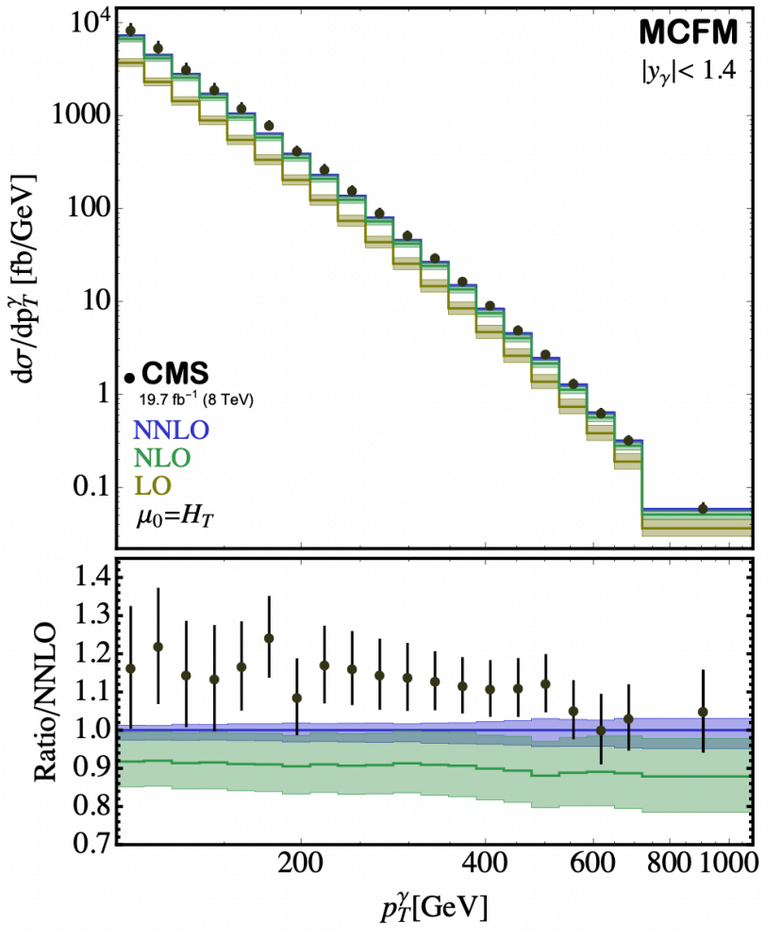
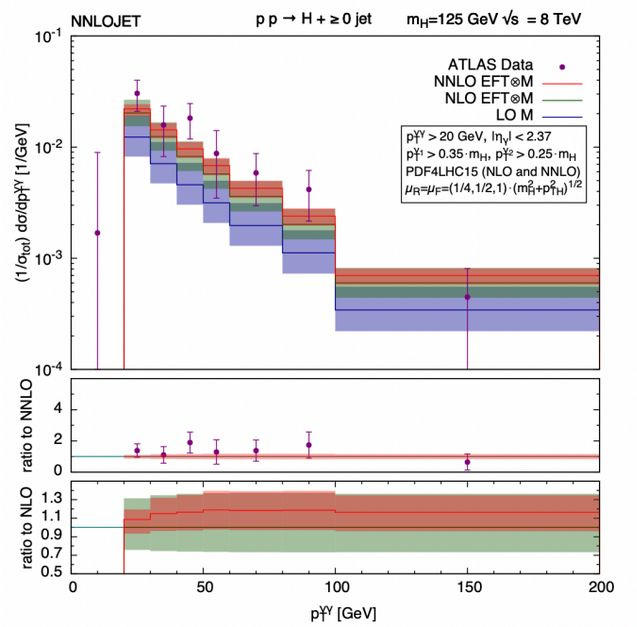


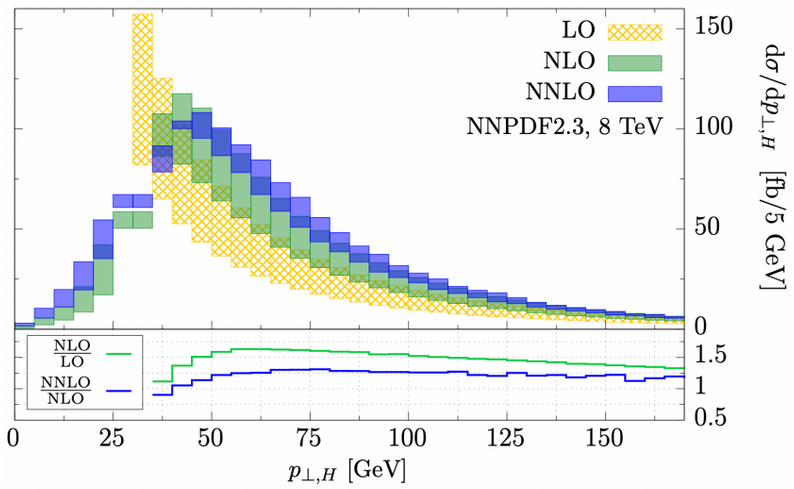
Campbell, Ellis, Williams
Phys. Rev. D 96, 014037 (2017)

- Smooth cone isolation in MCFM, smooth and hybrid isolation in NNLOJET matching the fixed-cone
- Agreement between two NNLO calculations when using same input settings
- $\mu = p_{T,\gamma}$ favoured as central scale choice in terms of perturbative stability
- Residual scale uncertainties at NNLO typically at the level of 3%
- All V+jet processes know now to NNLO QCD

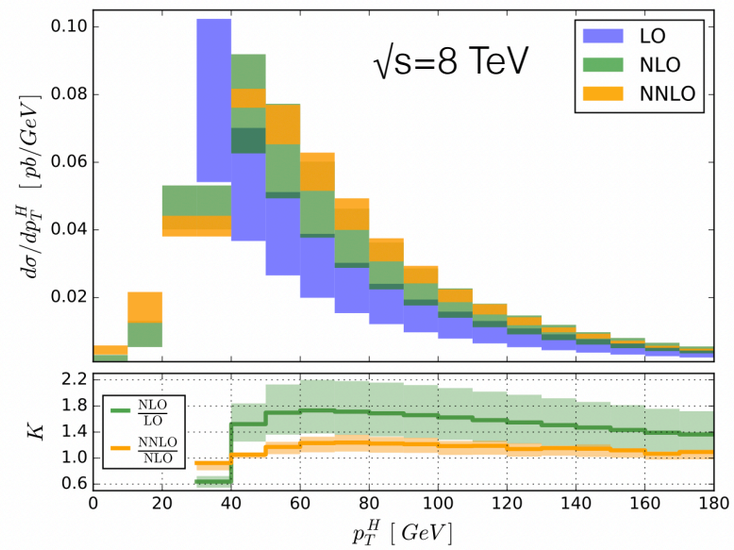
H + jet final states



Chen, Cruz-Martinez, Gehrmann, Glover, Jaquier
JHEP 1610 (2016) 066

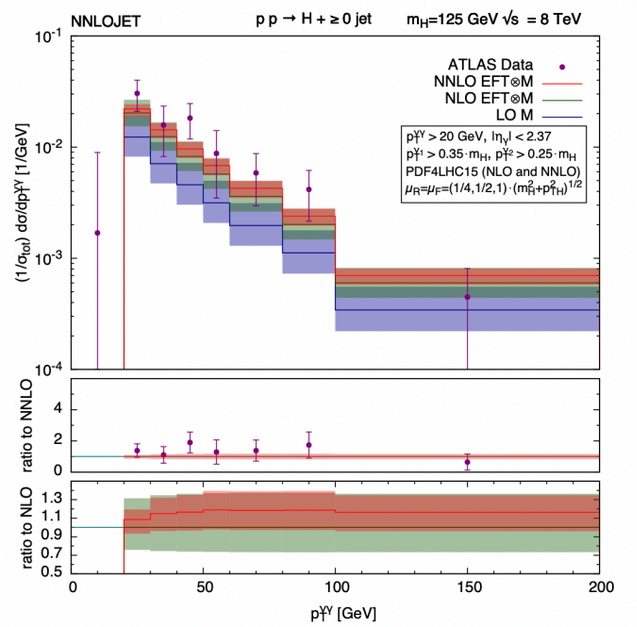


Boughezal, Caola, Melnikov, Petriello, Schulze
Phys. Rev. Lett. 115, 082003 (2015)



Boughezal, Focke, Giele, Liu, Petriello
Phys.Lett.B 748 (2015)

H + jet final states



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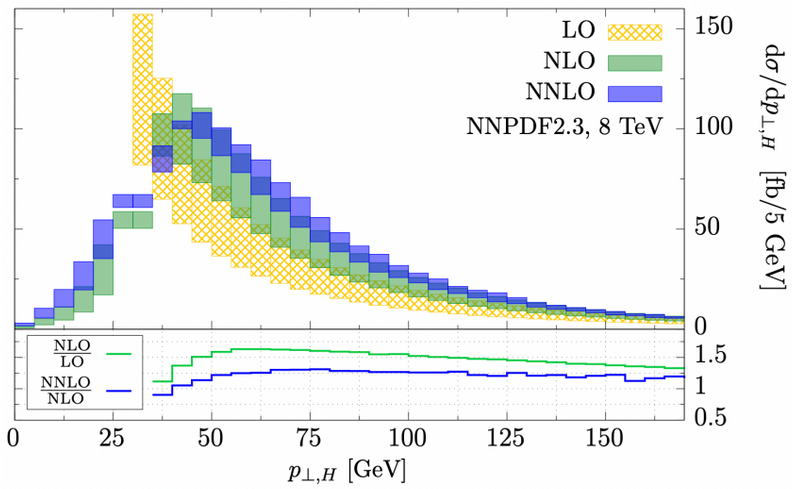

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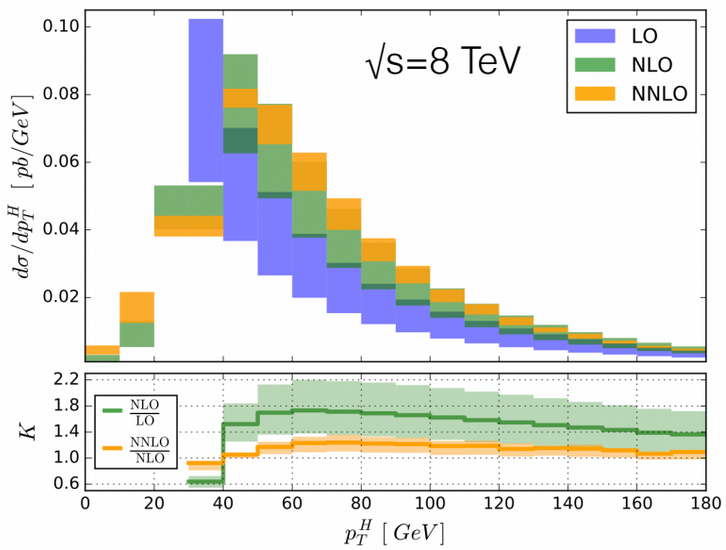


Boughezal, Focke, Giele, Liu, Petriello
Phys.Lett.B 748 (2015)

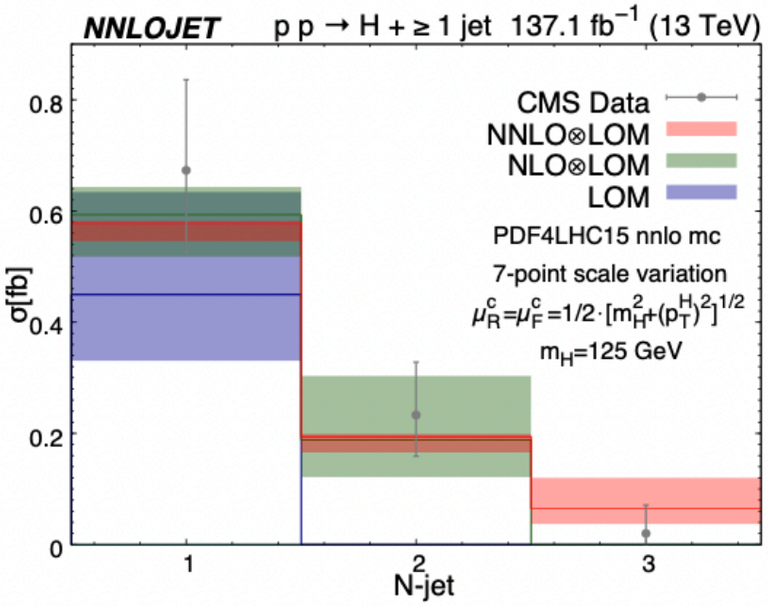
- Improved precision of the Higgs p_T spectrum at NNLO
- Improved description of the Higgs signal under jet cuts, the discrimination power between different Higgs production modes, and background suppression through the application of jet vetoes
- Three different NNLO accurate calculations for H+jet final states performed in the HEFT ($m_t \to \infty$ limit). Full top-quark mass dependence for H+jet known at NLO only
- Substancially larger NNLO corrections observed with respect to V + jet
- Good agreement between NNLO prediction reweighted by exact top-mass dependence at LO and ATLAS data normalized to the total inclusive cross section

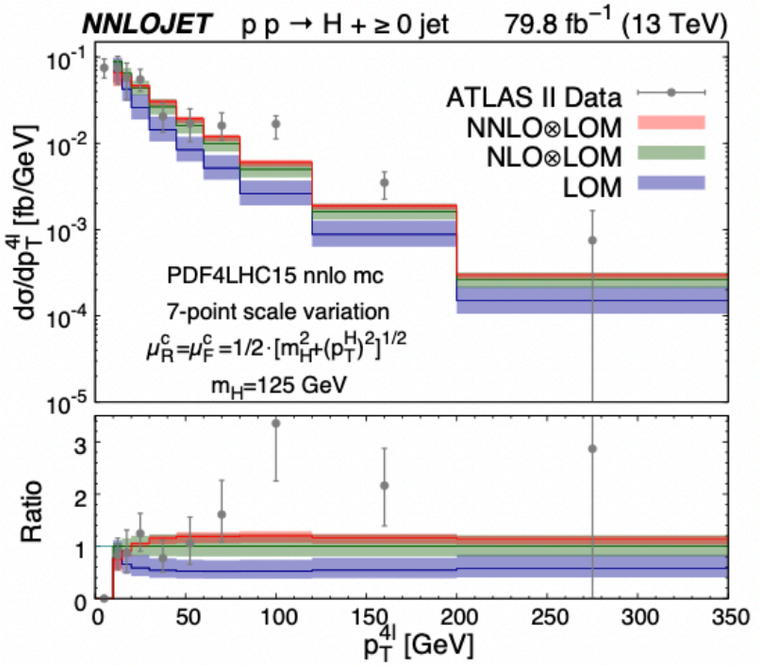
H + jet final states - fiducial cuts

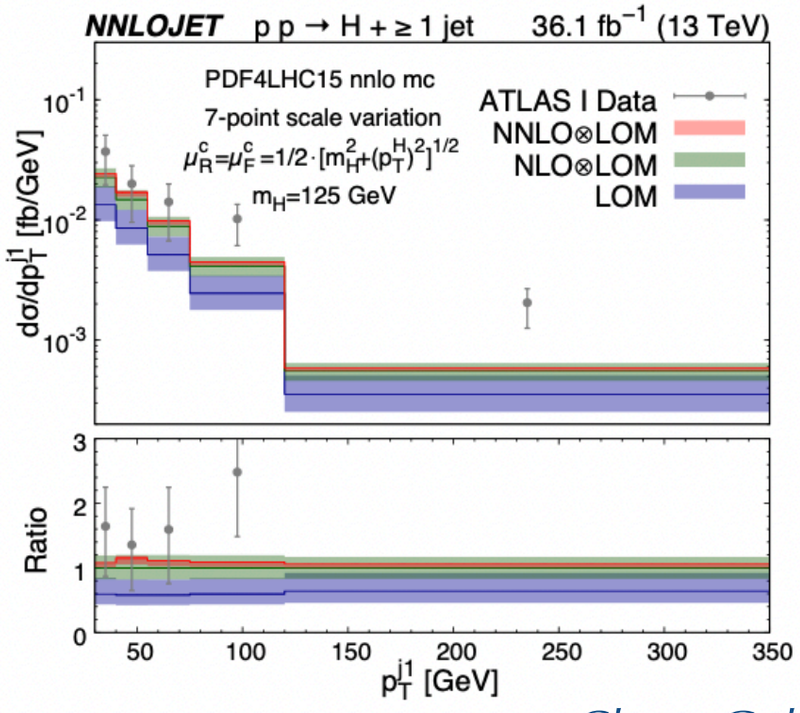
	CMS	ATLAS I	ATLAS II
Lepton Kinematics			
1st lepton $p_T^{l_1}$ (GeV)	> 20	> 20	> 20
2nd lepton $p_T^{l_2}$ (GeV)	> 10	> 15	> 15
3rd lepton $p_T^{l_3}$ (GeV)	—	> 10	> 10
lepton $p_T^{e(\mu)}$ (GeV)	$> 7(5)$	$> 7(5)$	> 5
Rapidity $\lvert y^{e(\mu)}\rvert$	$< 2.5(2.4)$	$< 2.47(2.7)$	< 2.7
Lepton Isolation			
Cone size R^l	0.3	—	—
$\sum_i p_T^i/p_T^l$ ($i \in R^l$)	< 0.35	—	—
$\Delta R^{\mathrm{SF(DF)}}(l_i, l_j)$	> 0.02	$> 0.1(0.2)$	> 0.1
Invariant Mass (GeV)			
Z_1 candidate m_{Z_1}	$[40, 120]$	$[50, 106]$	$[50, 106]$
Z_2 candidate m_{Z_2}	$[12, 120]$	$[12, 115]$	$[12, 115]$
$m_{l^+l'^-}$ (SF+DF)	> 4	—	—
$m_{l^+l^-}$ (SF)	—	> 5	> 5
Four leptons m_{4l}	125	125	125
Jet Definition			
Algorithm	anti-k_T	anti-k_T	anti-k_T
Cone size R	0.4	0.4	0.4
p_T^j (GeV)	> 30	> 30	> 30
Rapidity $\lvert y^j\rvert$	< 2.5	< 4.4	< 4.4
$\Delta R(j, e(\mu))$	—	$> 0.2(0.1)$	> 0.1

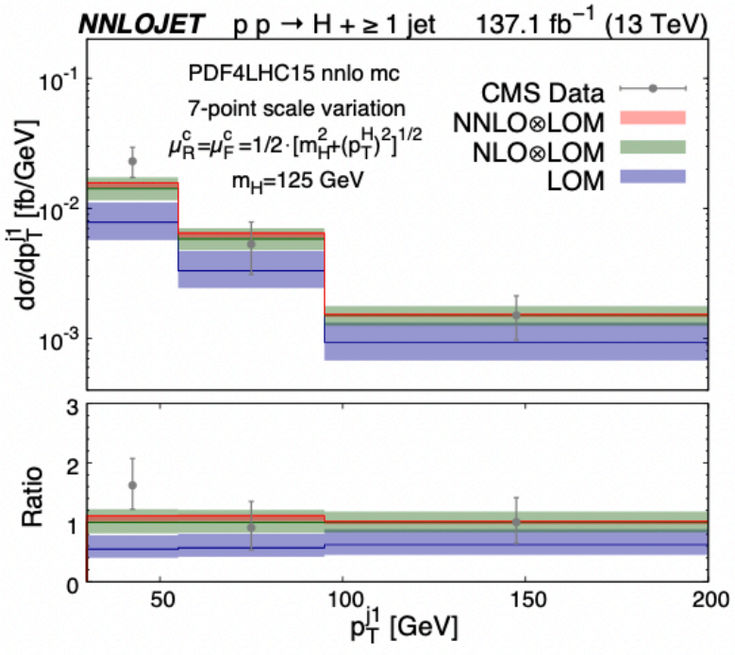
- Fiducial cuts for final state leptons and jets for the four-lepton decay mode of the Higgs boson

H + jet final states - fiducial cross sections at NNLO









Chen, Gehrmann, Glover, Huss JHEP 1907 (2019) 052

- NNLO corrections sizeable and kinematics dependent
- Substantial reduction of scale uncertainties with respect to NLO to a level of about 10% in most distributions

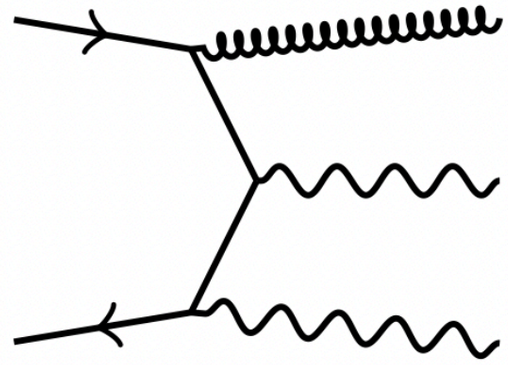
NNLO QCD jet-predictions beyond $2 \to 2$ processes

γγ + jet final states

- Use recently derived two-loop leading-colour QCD helicity amplitudes for γγ+jet production at hadron colliders

  Chawdhry, Czakon, Mitov, Poncelet JHEP 07 (2021) 164

- Reliable description of the diphoton p_T spectrum at NNLO
- Main background to Higgs decay channel



$$pp \to g\gamma\gamma + X$$

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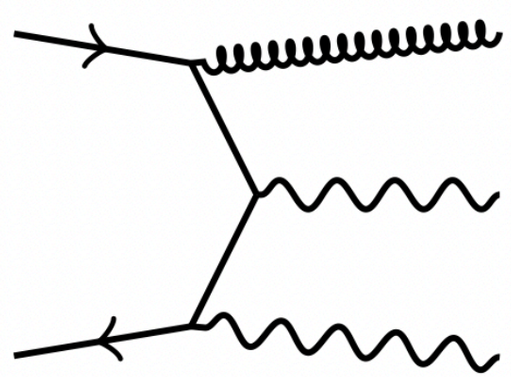

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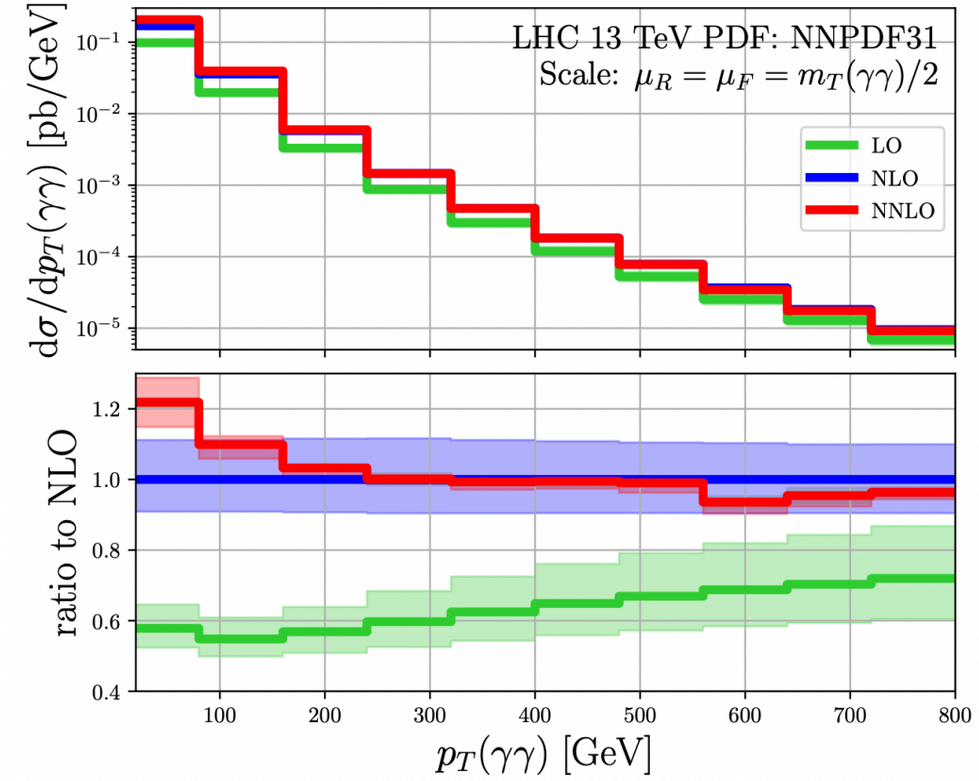


Chawdhry, Czakon, Mitov, Poncelet [arXiv:2105.06940]

- Excellent convergence of the perturbative expansion
- Reliable prediction achieved after the inclusion of NNLO effects
- Scale uncertainty at NNLO at the ~1-2% level

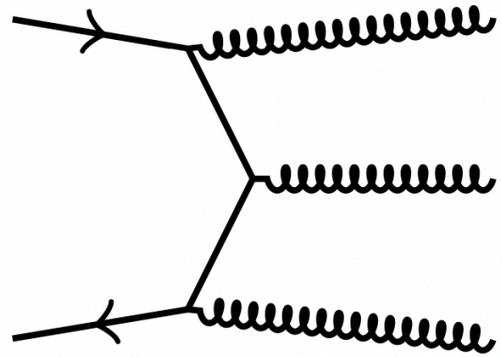
Three-jet production final state

- Use recently derived two-loop leading-colour QCD helicity amplitudes for 5-parton scattering at hadron colliders

  Chicherin, Sotnikov JHEP 12 (2020) 167

  Abreu, Cordero, Ita, Page, Sotnikov JHEP 07 (2021) 095

- Experimental analysis limited by NLO scale uncertainties
- NNLO allows for improved predictions for jet transverse momenta, angular correlations, event-shape observables



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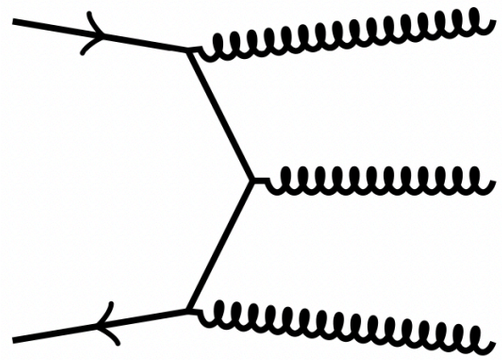

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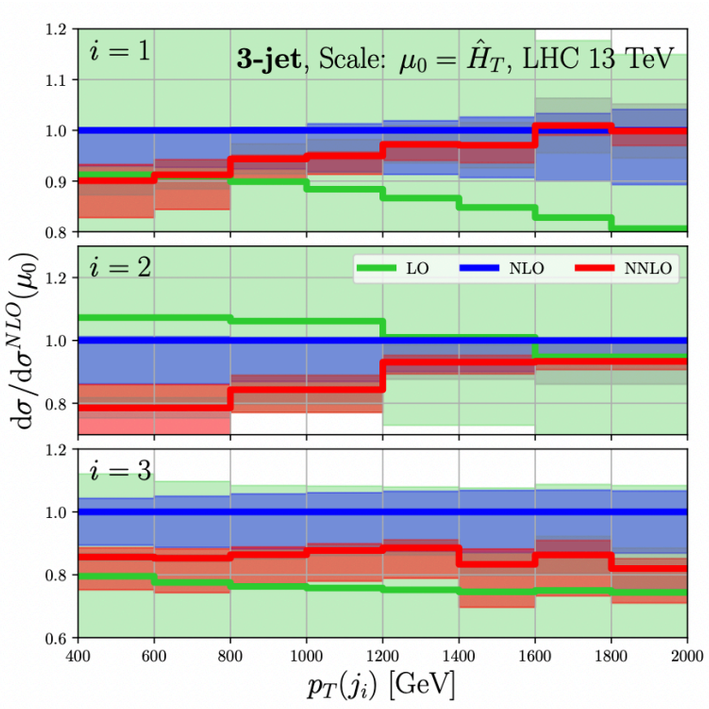

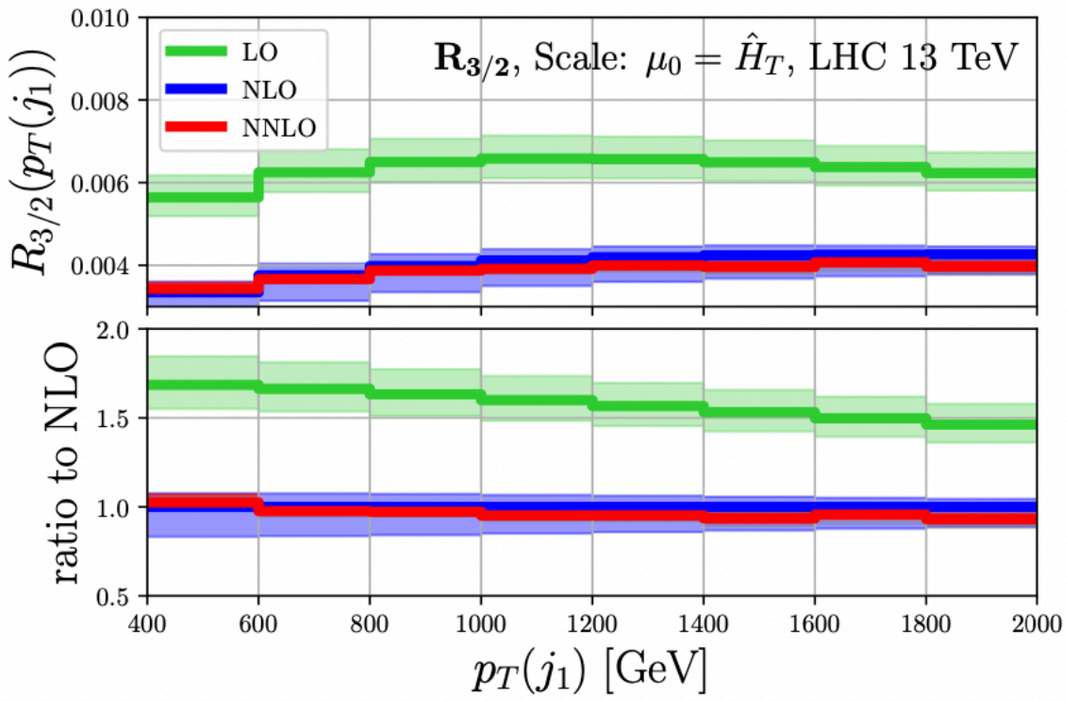

Chawdhry, Czakon, Mitov, Poncelet [arXiv:2106.05331]

- NNLO corrections of the order of -15% at low pT increase steadily at high-p_T for 1st and 2nd jet pT spectrum
- Three-jet to two-jet ratio prediction stabilised at NNLO with scale uncertainties at the 3% level

Summary

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  - pp→3jet..... [Chawdhry, Czakon, Mitov, Poncelet ’21]
  - pp→Z+jet.....[Gehrmann-De Ridder, Gehrmann, Glover, Huss, Morgan ’15]
    [Boughezal, Campbell, Ellis, Focke, Giele, Liu, Petriello ’15]
  - pp→W+jet.....[Boughezal, Liu, Petriello ’16]
    [Gehrmann-De Ridder, Gehrmann, Glover, Huss, Walker ’17]
  - pp→γ+jet.....[Campbell, Ellis, Williams ’16]
    [Chen, Gehrmann, Glover, Höfer, Huss ’20]
  - pp→$\gamma\gamma$+jet.....[Chawdhry, Czakon, Mitov, Poncelet ‘21]
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    [Chen, Cruz-Martinez, Gehrmann, Glover, Jaquier’16]
- Results not covered in this talk
  - pp→Z+b-jet.....[Gauld, Gehrmann-De Ridder, Glover, Huss, Majer ’20]
  - pp→W+c-jet.....[Czakon, Mitov, Pellen, Poncelet ’20]
  - pp→WH+jet.....[Gauld, Gehrmann-De Ridder, Glover, Huss, Majer ’20]