Differential theory predictions for top-quark production and decay

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A bit on stable top production

Brief status

- ✓ Stable top quark pair production is aiming at as high precision as possible
- ✓ Results are becoming "mature" and well established. Computed by two groups with different methods. Impressive agreement!

Czakon, Mitov, Poncelet at al 2013 –
Catani, Devoto, Grazzini, Kallweit, Mazzitelli, Sargsyan 2019

- ✓ At present this means NNLO QCD + EW + resummation (soft and collinear in the high-energy limit)

Czakon et al;
Pagani, Tsinikos, Zaro
Ferrogglia, Pecjak, Scott, Wang, Yang

See also talk by Davide Pagani

- ✓ Calculations are fully differential and can handle any safe observable. Up to two dimensional distributions computed
- ✓ Many interesting applications:
  - ✓ PDFs (studied by all groups: conclusions vary from group to group)
  - ✓ Top parametric impact on Higgs and BSM
  - ✓ Direct searches with tops
  - ✓ Results ready for used by SMEFT fits (theoretical predictions available as fastNLO tables; even more convenient and flexible formats in development)

See also talks by Paolo Nason and Olaf Behnke

Spin-correlations in top-pair production and decay (in NWA)

History of top production and decay

- ✓ Top production and decay was first computed at NLO 10-15 years ago

  Bernreuther, Brandenbourg, Si, Uwer 2004
  Melnikov,Schulze 2008

- ✓ Later expanded to include off-shell/non-resonant effects

  Denner, Dittmaier, Kallweit, Pozzorini 2010-
  Bevilacqua, Czakon, van Hameren, Papadopoulos, Worek 2010
  Frederix 2013
  Cascioli, Kallweit, Maierhöfer, Pozzorini 2013

- ✓ Extension for NLO+PS:

  Campbell, Ellis, Nason, Re 2014
  Jezo, Lindert, Nason, Oleari, Pozzorini 2016

  See also talk by Paolo Nason

  - ✓ NLO is still the state of the art for off-shell calculations

    See talk by Mathieu Pellen

- ✓ Progress to higher orders was made in the Narrow Width Approximation:

  - ✓ approx NNLO (prod) x NNLO (decay)

    Gao, Papanastasiou 2017

  - ✓ Full NNLO (prod) x NNLO (decay)

    Behring, Czakon, Mitov, Papanastasiou, Poncelet 2019

ttbar spin correlations

✓ NNLO QCD corrections to top pair spin-correlations was presented already at Top 2018

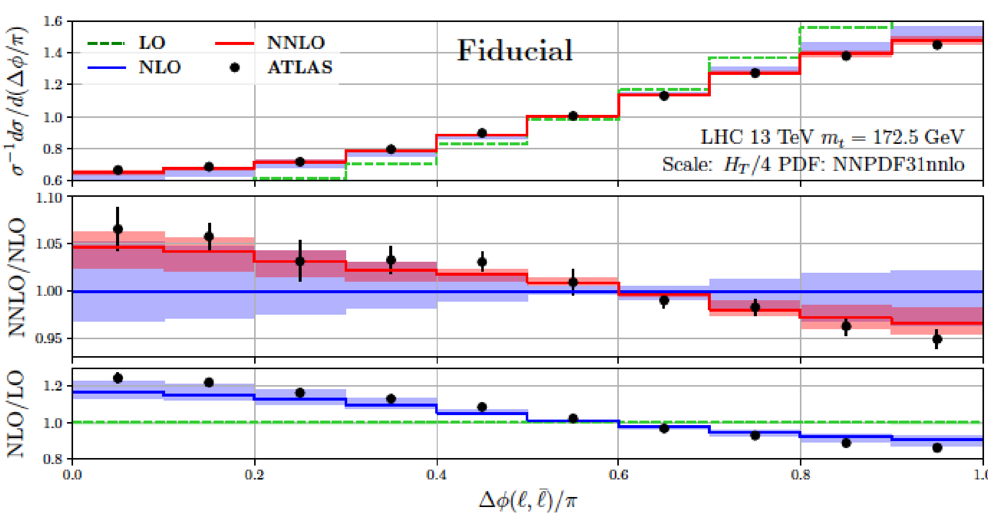
Behring, Czakon, Mitov, Papanastasiou, Poncelet arXiv:1901.05407

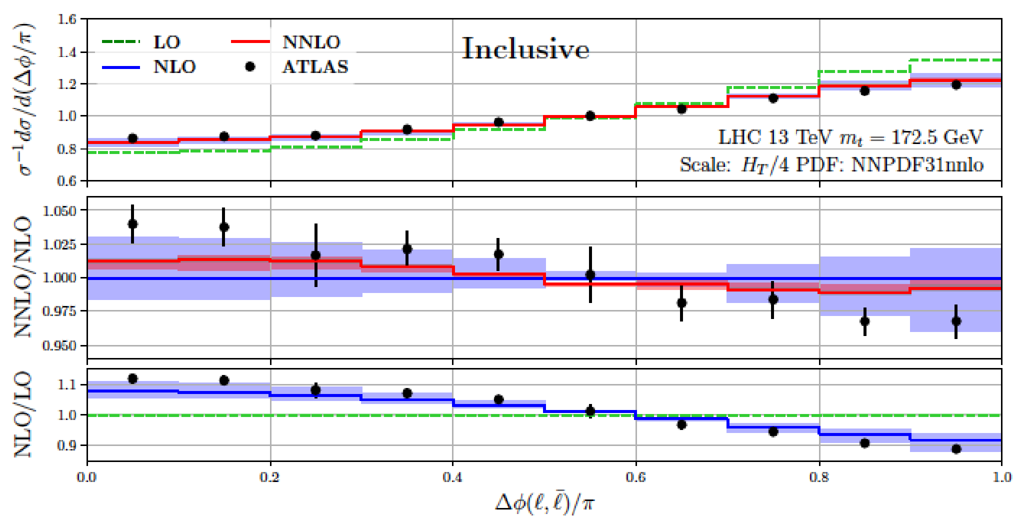
✓ Main finding:
  - ✓ NNLO QCD describes data in the fiducial region
  - ✓ Does not describe it in the extrapolated phase space

✓ An extensive analysis was made. All but one sources were dismissed:

  - ✓ Scale choice
  - ✓ m_{top}
  - ✓ PDF
  - ✓ Finite width and EW corrections

✓ Results point towards the need for improved understanding of modeling of final states

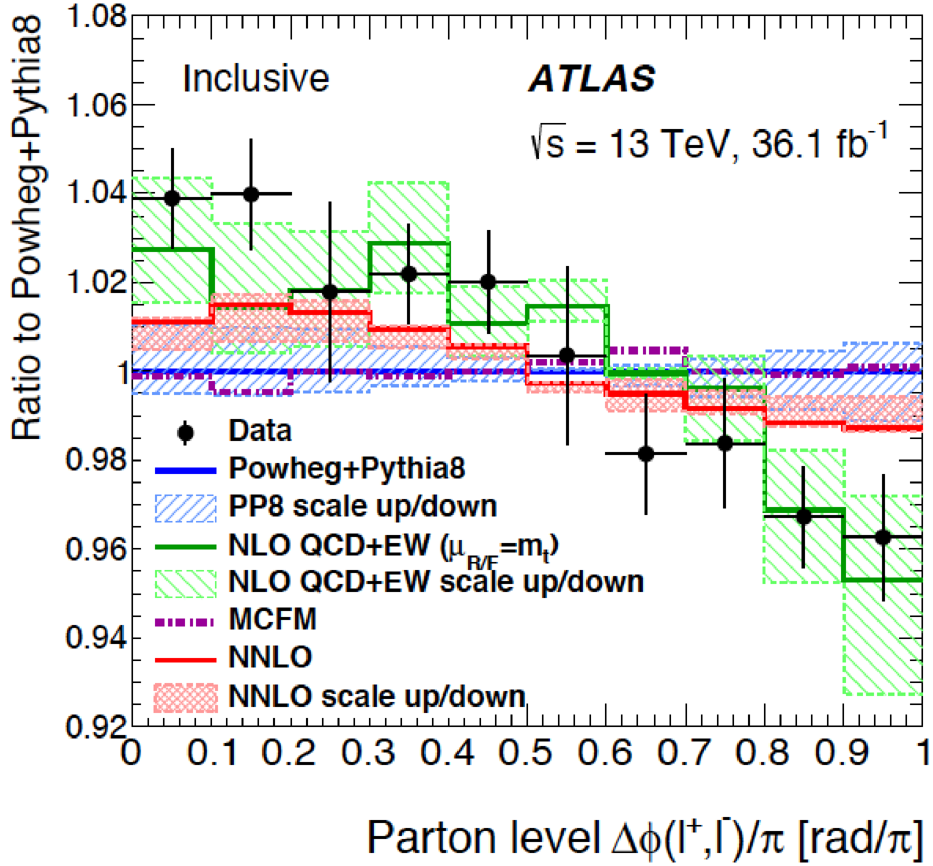




ttbar spin correlations

✓ After our paper appeared, ATLAS published an update for its Inclusive selection

ATLAS: arXiv:1903.07570



Green curve: from Bernreuther and Si

ttbar spin correlations

✓ Based on the green band it is often said that NLO QCD describes data

➢ This is not so!

✓ The green curve is computed by perturbative expansion of the ratio

❖ A normalized distribution through NNLO reads:

$$R = \frac{1}{\sigma^0 + \alpha_S \sigma^1 + \alpha_S^2 \sigma^2} \left(\frac{d\sigma^0}{dX} + \alpha_S \frac{d\sigma^1}{dX} + \alpha_S^2 \frac{d\sigma^2}{dX} \right) + \mathcal{O}\left(\alpha_S^3\right)$$

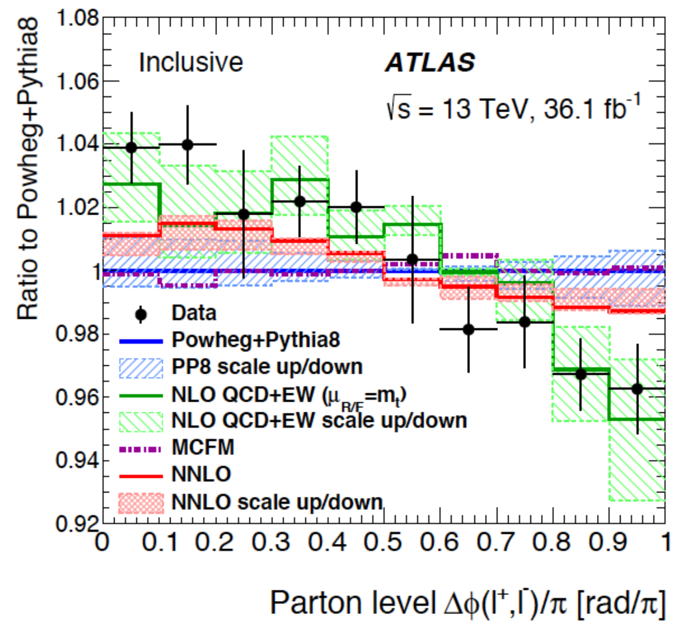
❖ The ratio R can also be expanded in the coupling

$$R^{\text{NNLO,exp}} = R^0 + \alpha_S R^1 + \alpha_S^2 R^2 \,,$$

$$R^0 = \frac{1}{\sigma^0} \frac{d\sigma^0}{dX} \,,$$

$$R^1 = \frac{1}{\sigma^0} \frac{d\sigma^1}{dX} - \frac{\sigma^1}{\sigma^0} \frac{1}{\sigma^0} \frac{d\sigma^0}{dX} \,,$$

$$R^2 = \frac{1}{\sigma^0} \frac{d\sigma^2}{dX} - \frac{\sigma^1}{\sigma^0} \frac{1}{\sigma^0} \frac{d\sigma^1}{dX} + \left(\left(\frac{\sigma^1}{\sigma^0} \right)^2 - \frac{\sigma^2}{\sigma^0} \right) \frac{1}{\sigma^0} \frac{d\sigma^0}{dX}$$

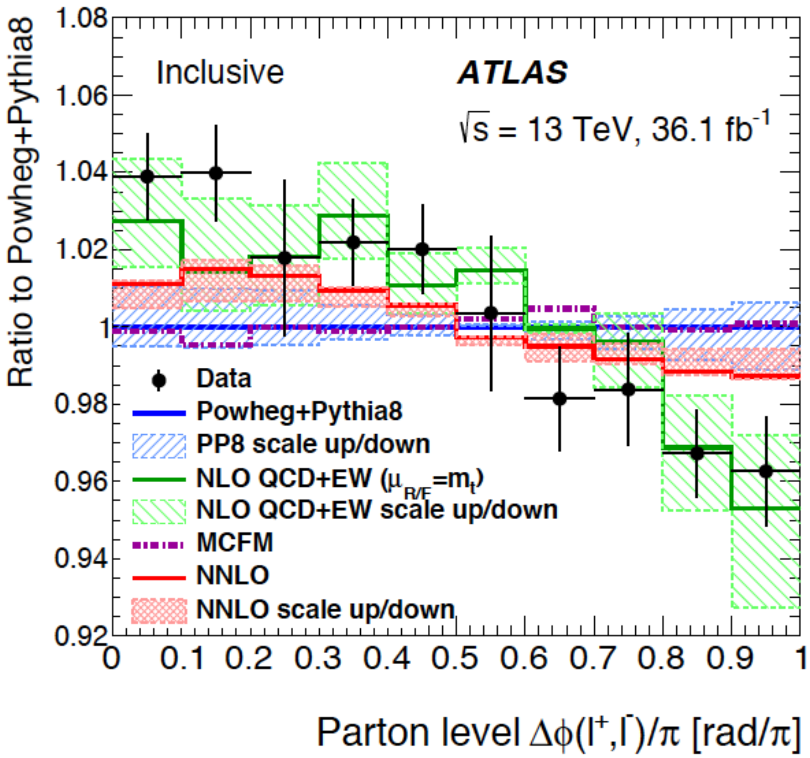


ATLAS: arXiv:1903.07570

ttbar spin correlations

✓ QCD works! One can do the same expansion for the NNLO calculation

Behring, Czakon, Mitov, Papanastasiou, Poncelet arXiv:1901.05407



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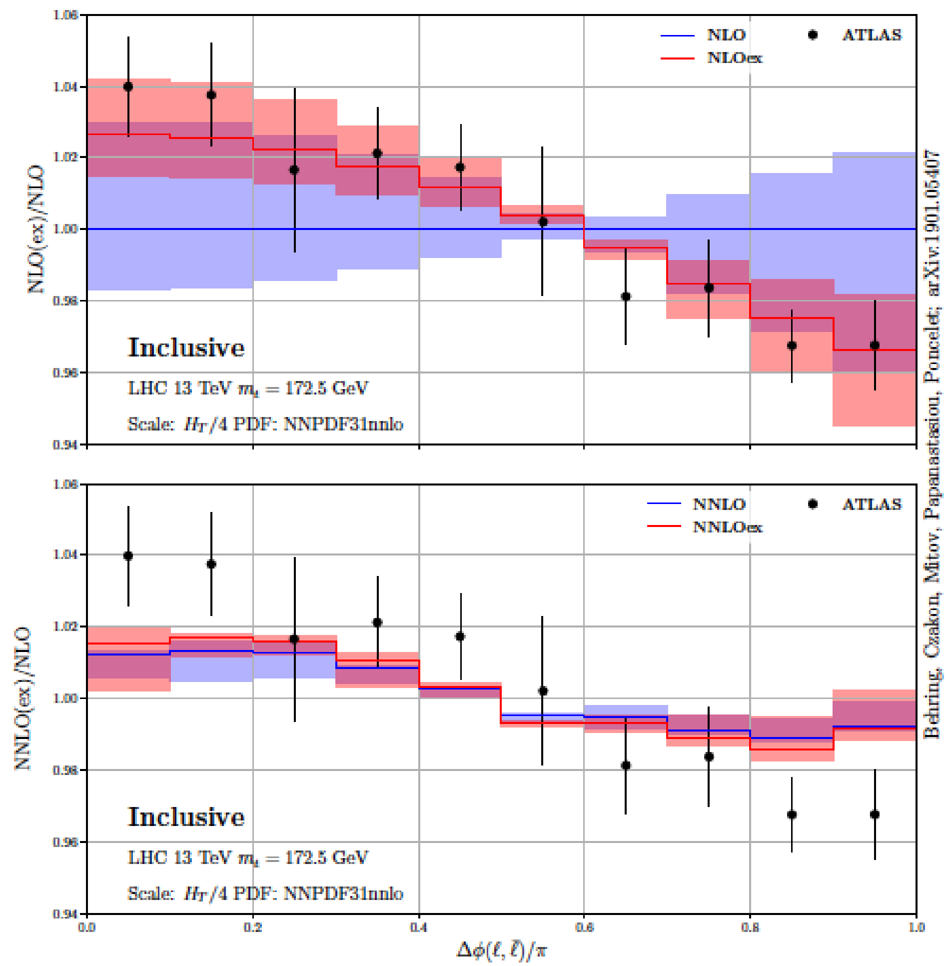


✓ At NLO the expanded definition has big impact. It makes NLO agree with data.

✓ However at NNLO the difference is tiny. This implies, ultimately, there is no th/data agreement

✓ My understanding is the ATLAS plot will be updated given its important implications

Top-pair differential distributions for dilepton final states

Work in progress: Czakon, Mitov, Poncelet

NNLO QCD vs ATLAS data

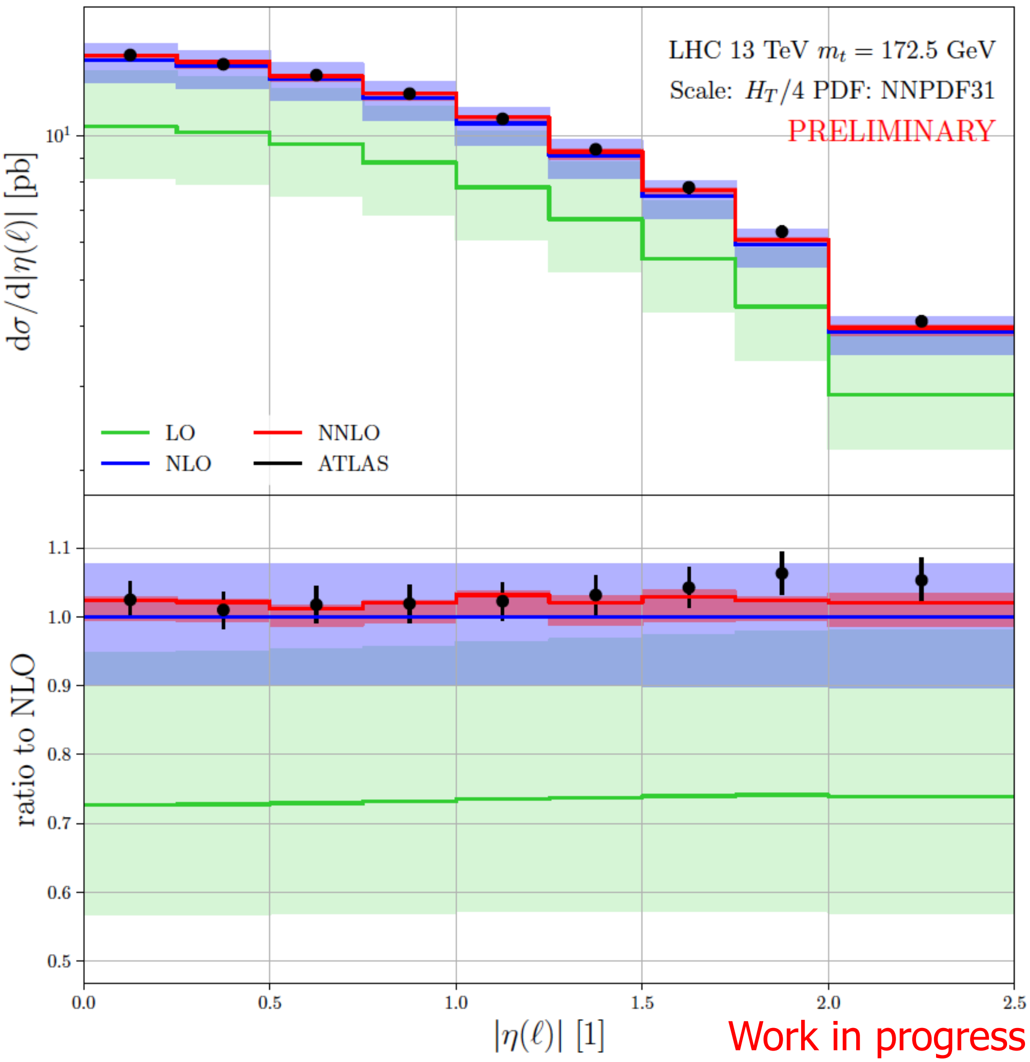
- ✓ Data taken from

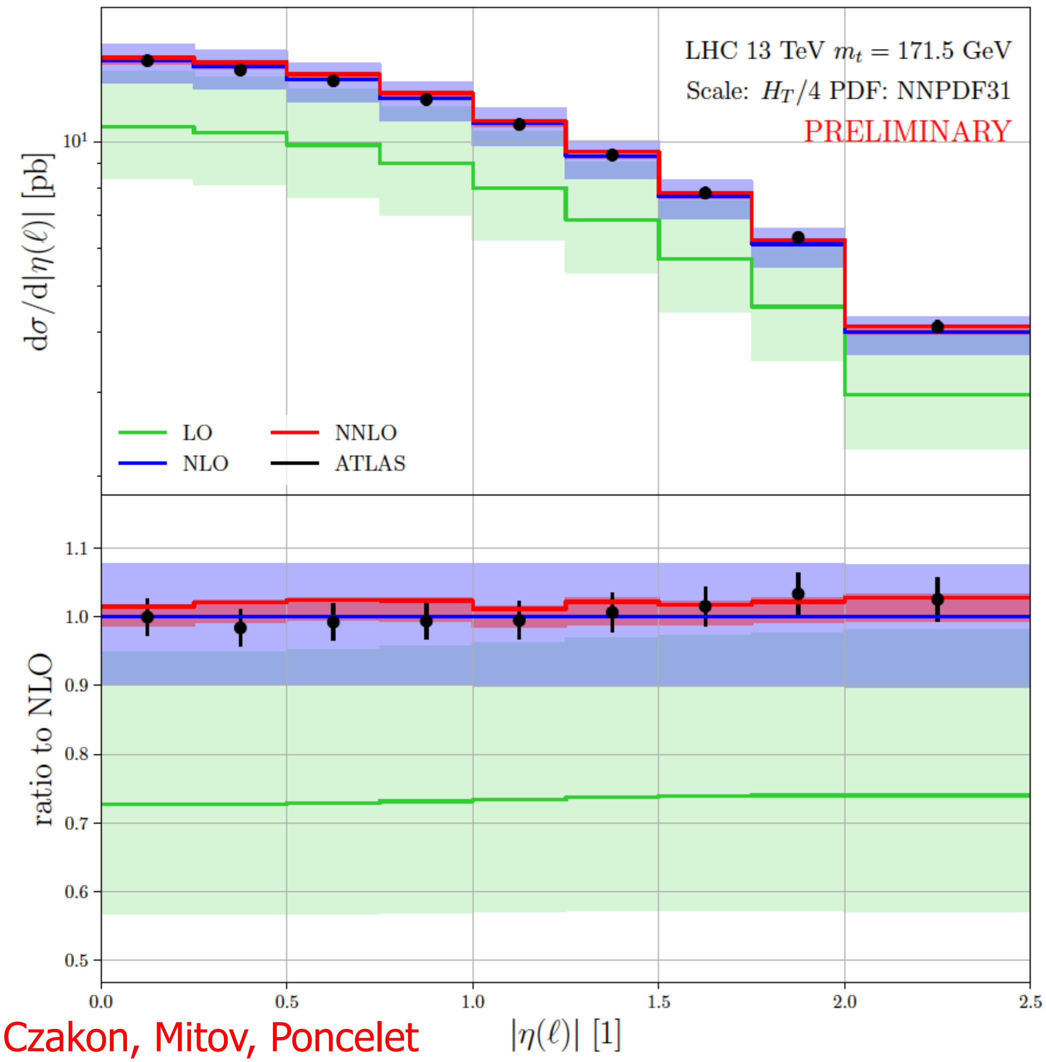
ATLAS-CONF-2019-041

- ✓ Here is our implementation of the fiducial phase space:
  - we require 2 oppositely charged leptons
  - p_T(charged lepton) > 20 GeV
  - |rapidity(charged lepton)| < 2.5
- ✓ Importantly, such calculation is fully inclusive in any hadronic radiation
- ✓ Predictions given for two values of m_t – there is clear sensitivity to its value
- ✓ 7-point scale variation
- ✓ No pdf error included

NNLO QCD vs ATLAS data

- ✓ η(lepton)
  - ✓ MC error of NNLO visible albeit small (work in progress)
  - ✓ Great reduction of scale error at NNLO (vs NLO). Tiny K-factor.
  - ✓ Both m_t=171.5GeV and m_t=172.5GeV work well.

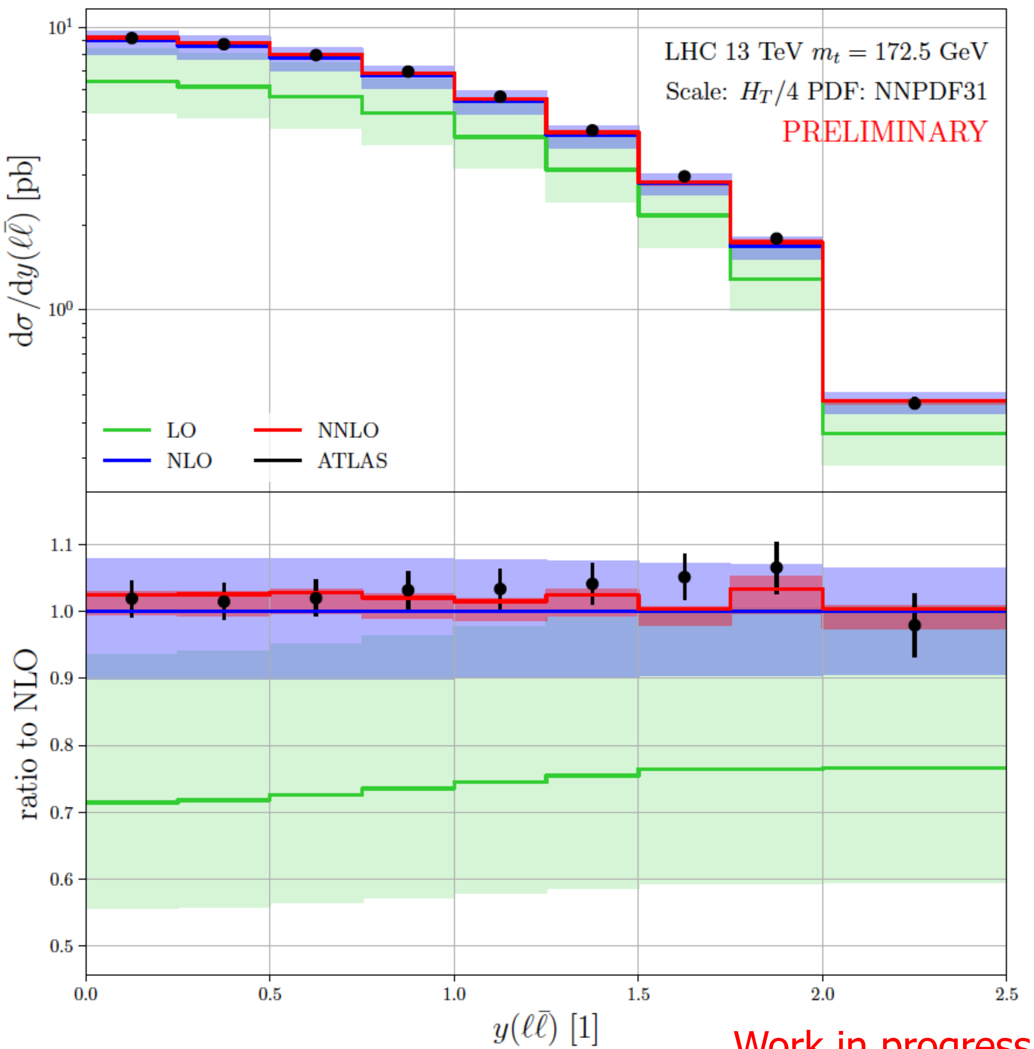


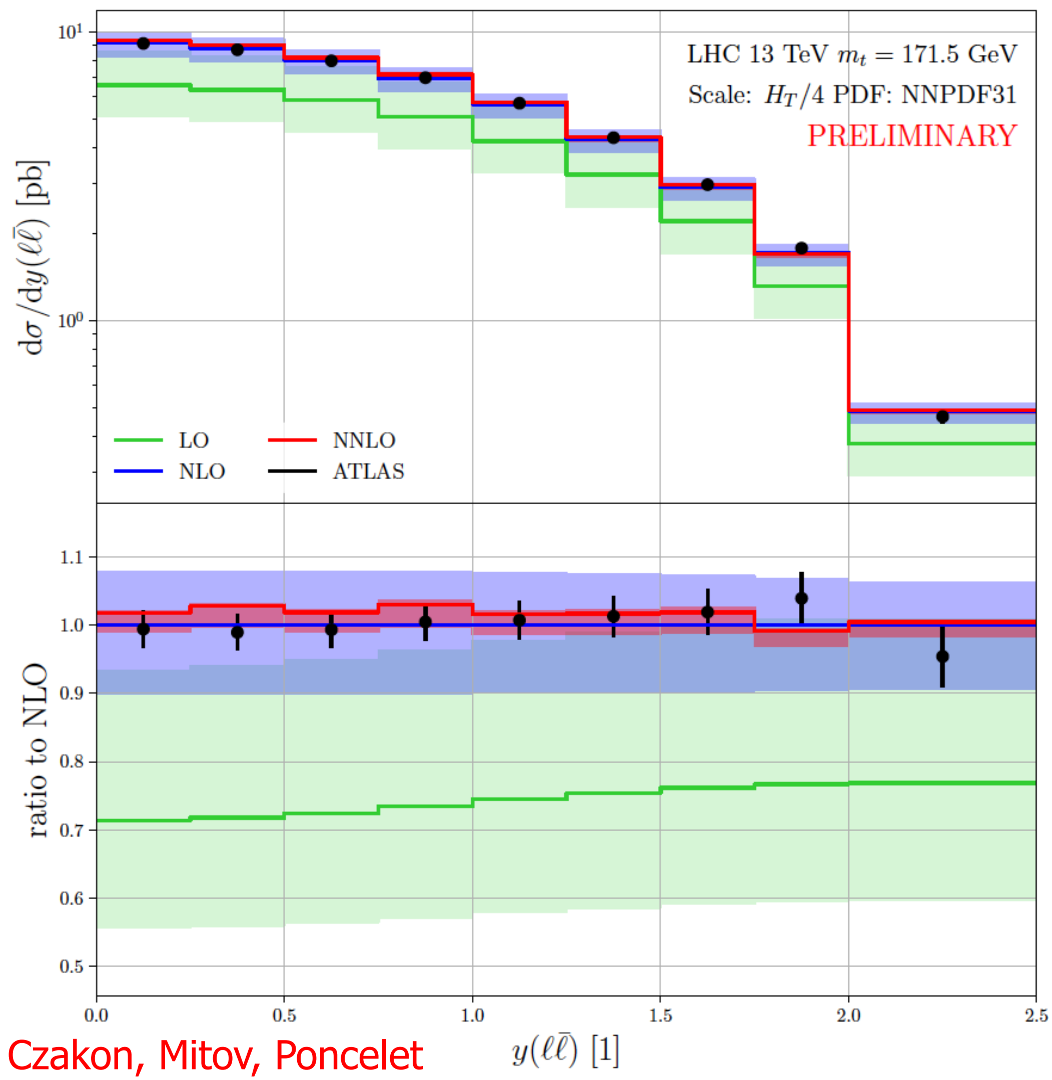


Work in progress: Czakon, Mitov, Poncelet

NNLO QCD vs ATLAS data

- ✓ y(lepton pair)
  - ✓ MC error of NNLO visible albeit small (work in progress)
  - ✓ Great reduction of scale error at NNLO (vs NLO). Tiny K-factor.
  - ✓ Both m_t=171.5GeV and m_t=172.5GeV work well.

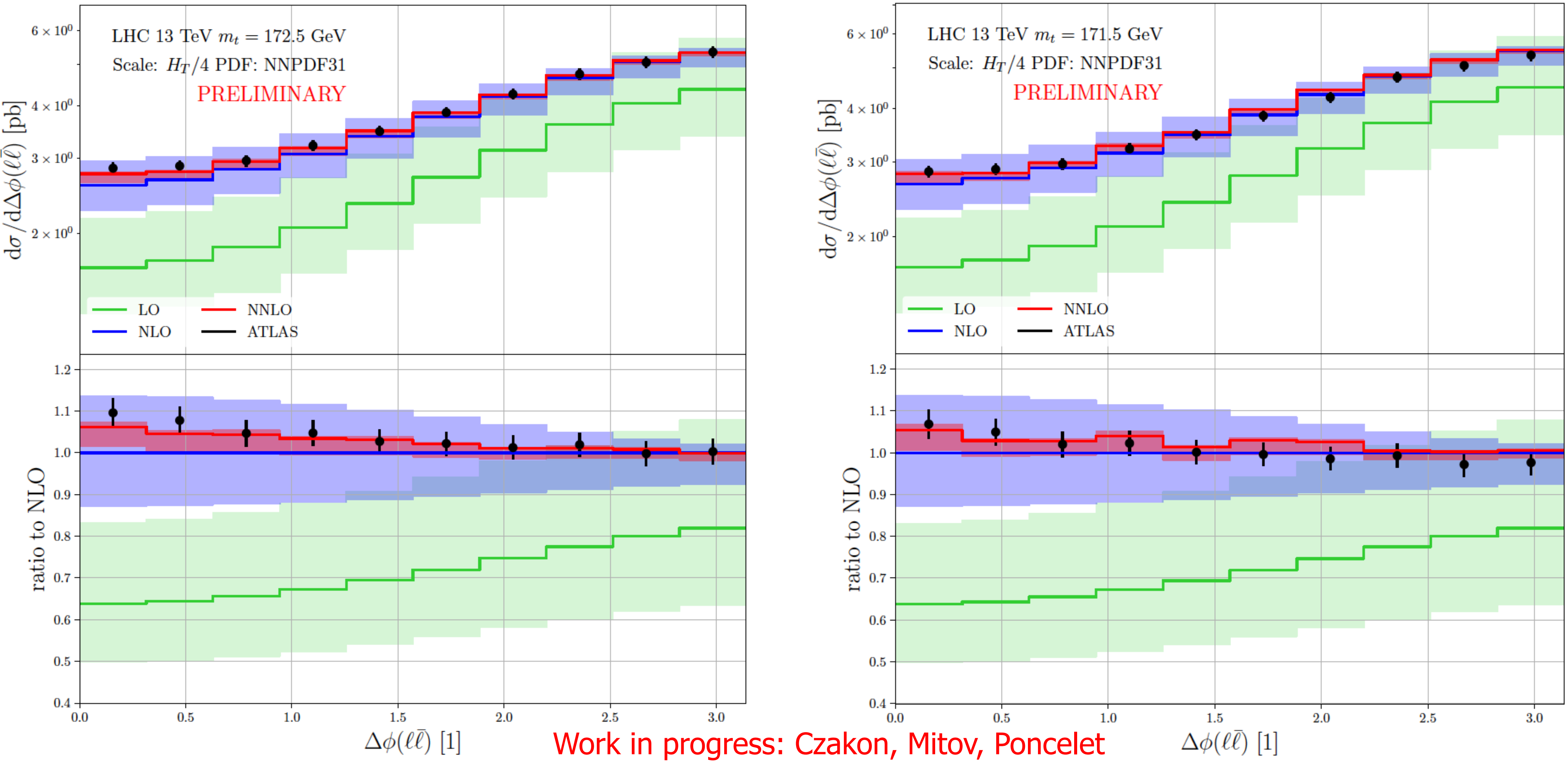




Work in progress: Czakon, Mitov, Poncelet

NNLO QCD vs ATLAS data

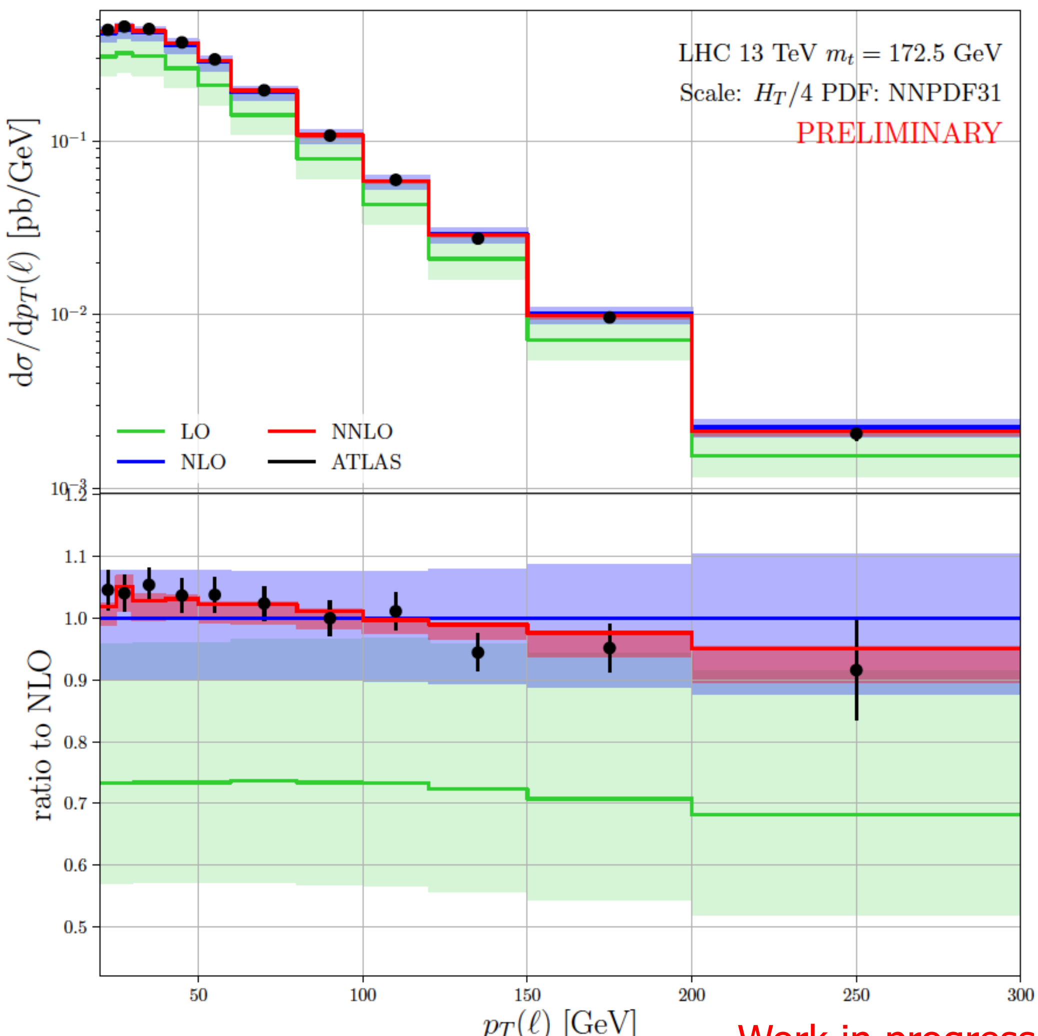
- ✓ Δφ
  - ✓ Great reduction of scale error at NNLO (vs NLO). Tiny K-factor.
  - ✓ m_t=171.5GeV probably a bit better than m_t=172.5GeV.
  - ✓ Improved MC error required to draw quantitative conclusion (which m_t is best)

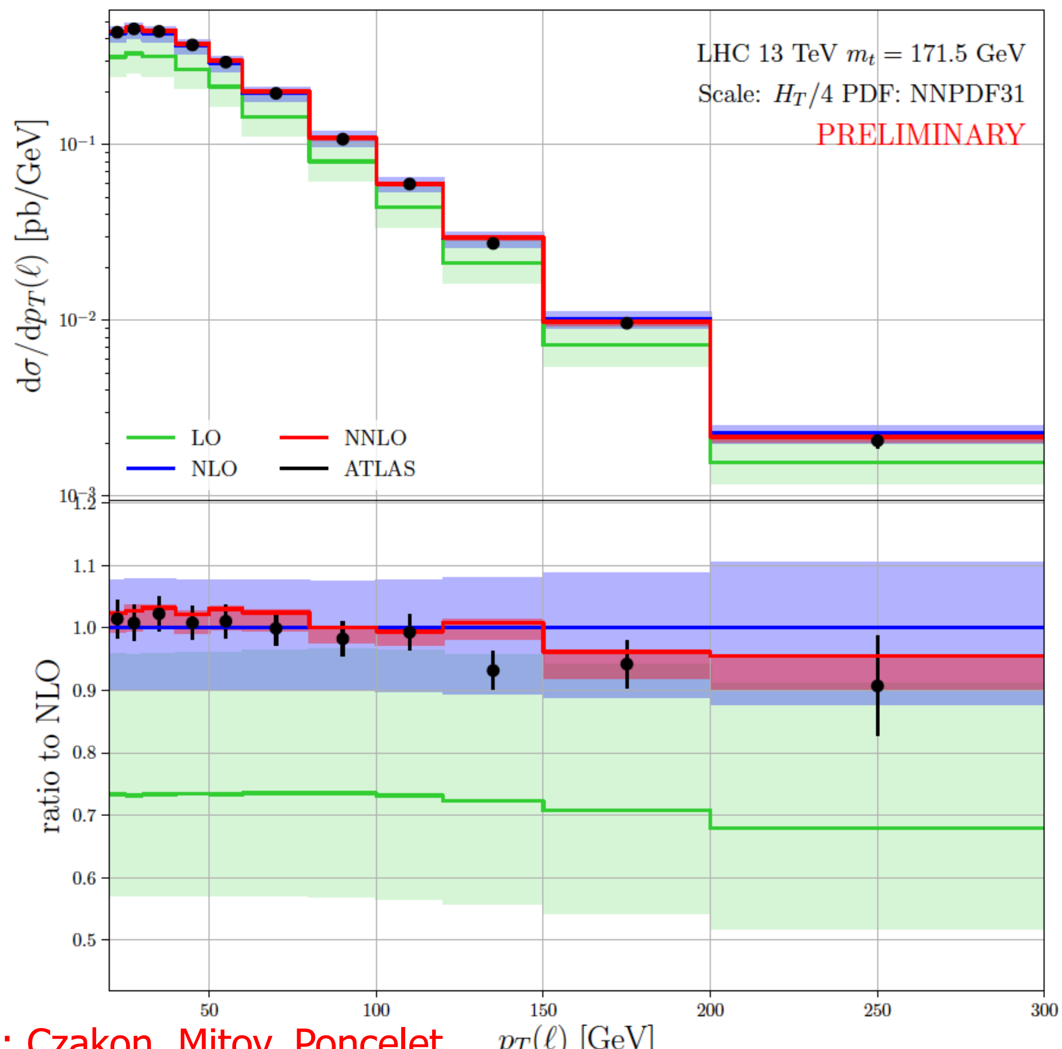


Work in progress: Czakon, Mitov, Poncelet

NNLO QCD vs ATLAS data

- ✓ P_T(lepton)
  - ✓ MC error of NNLO visible albeit small (work in progress)
  - ✓ Great reduction of scale error at NNLO (vs NLO)
  - ✓ m_t=171.5GeV seems better than m_t=172.5GeV





Work in progress: Czakon, Mitov, Poncelet

NNLO QCD vs ATLAS data

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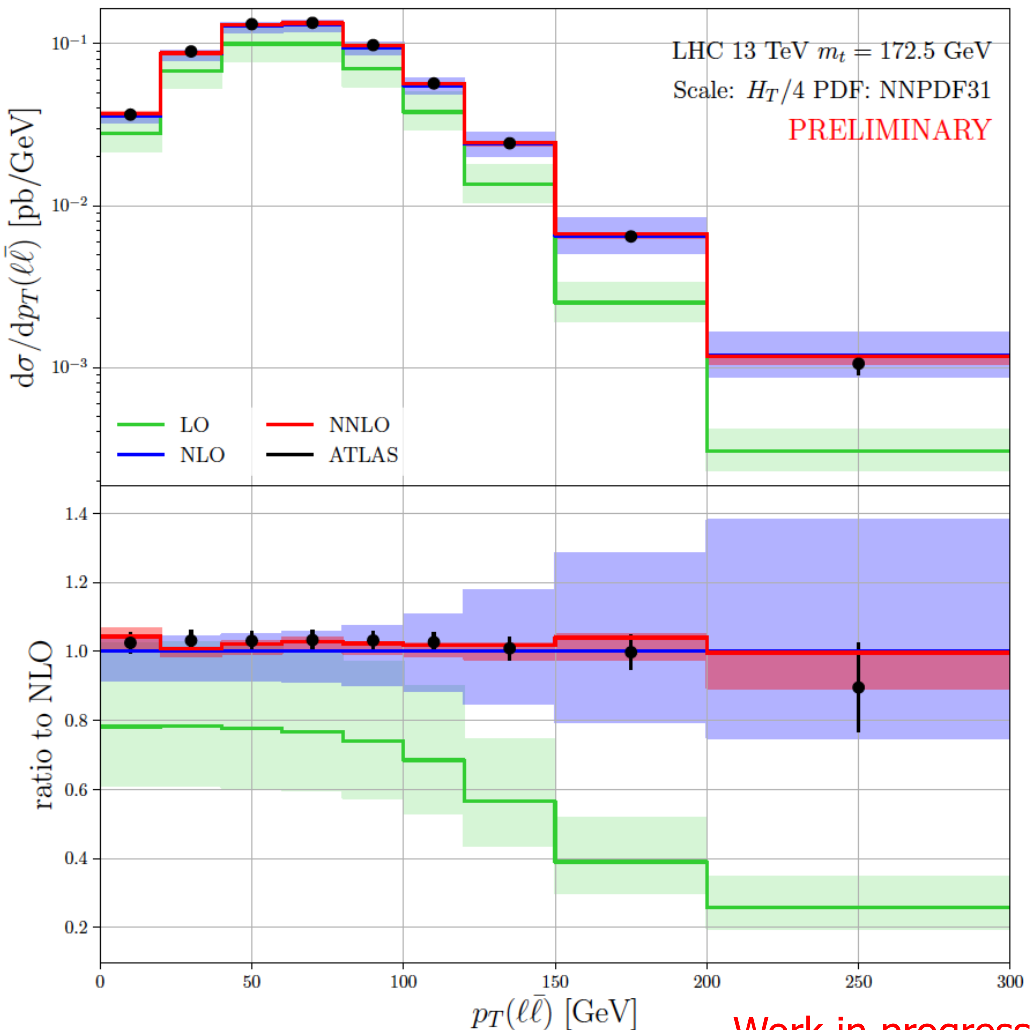
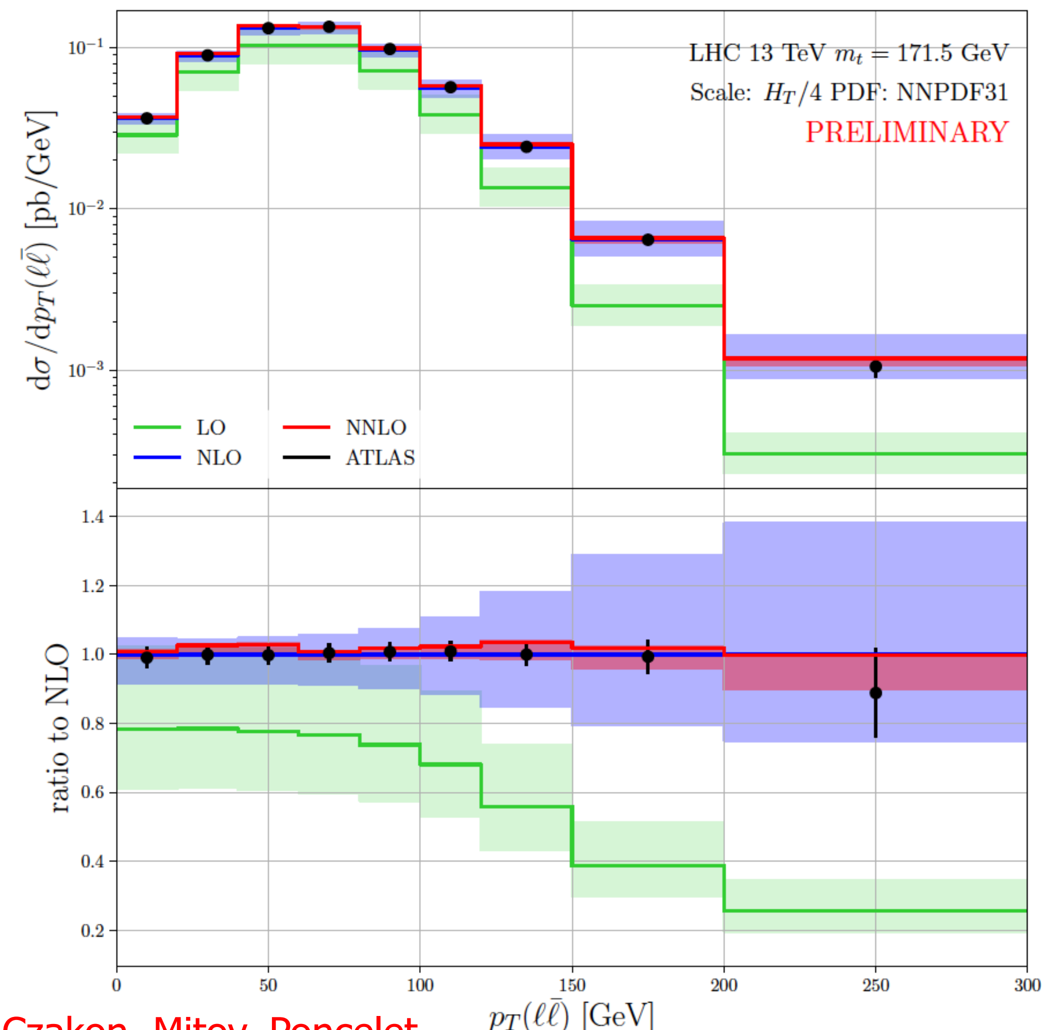


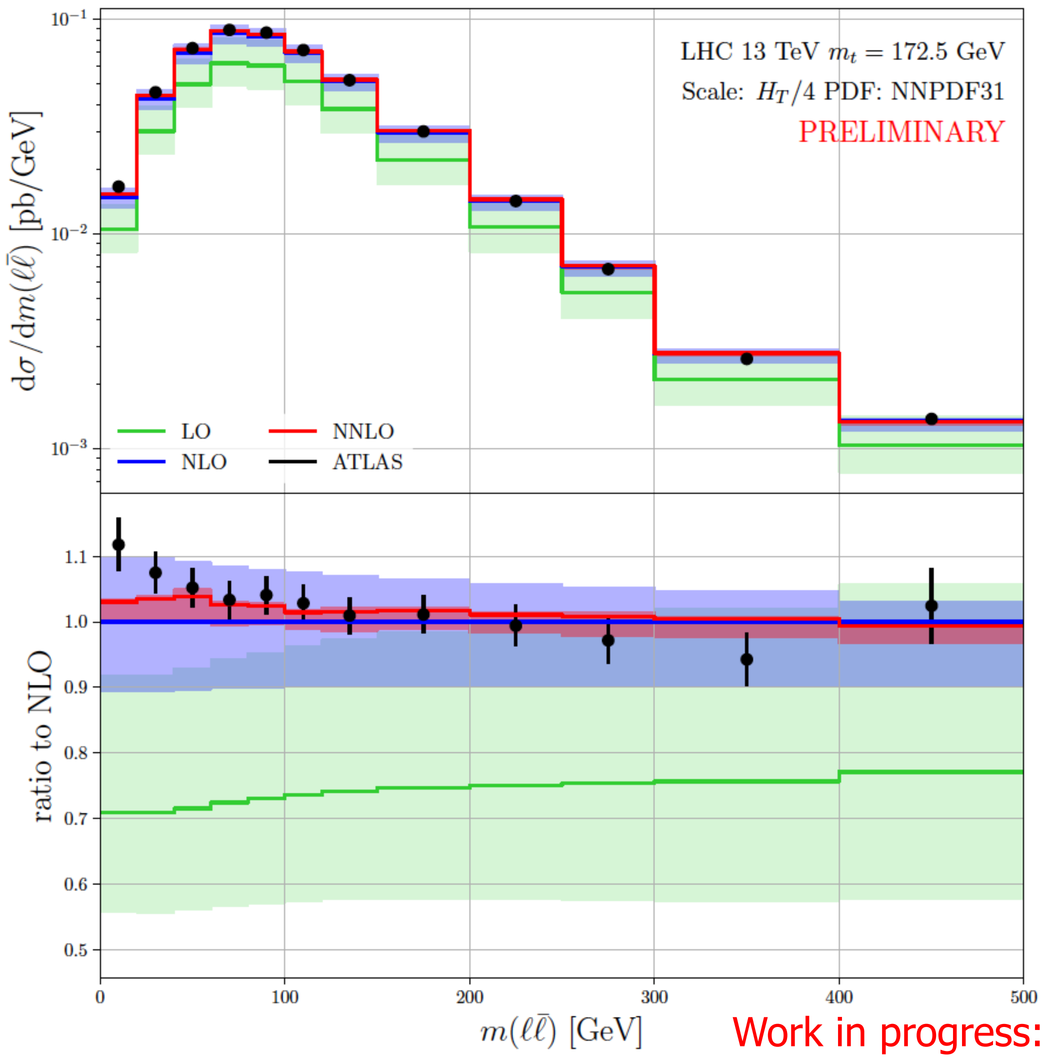


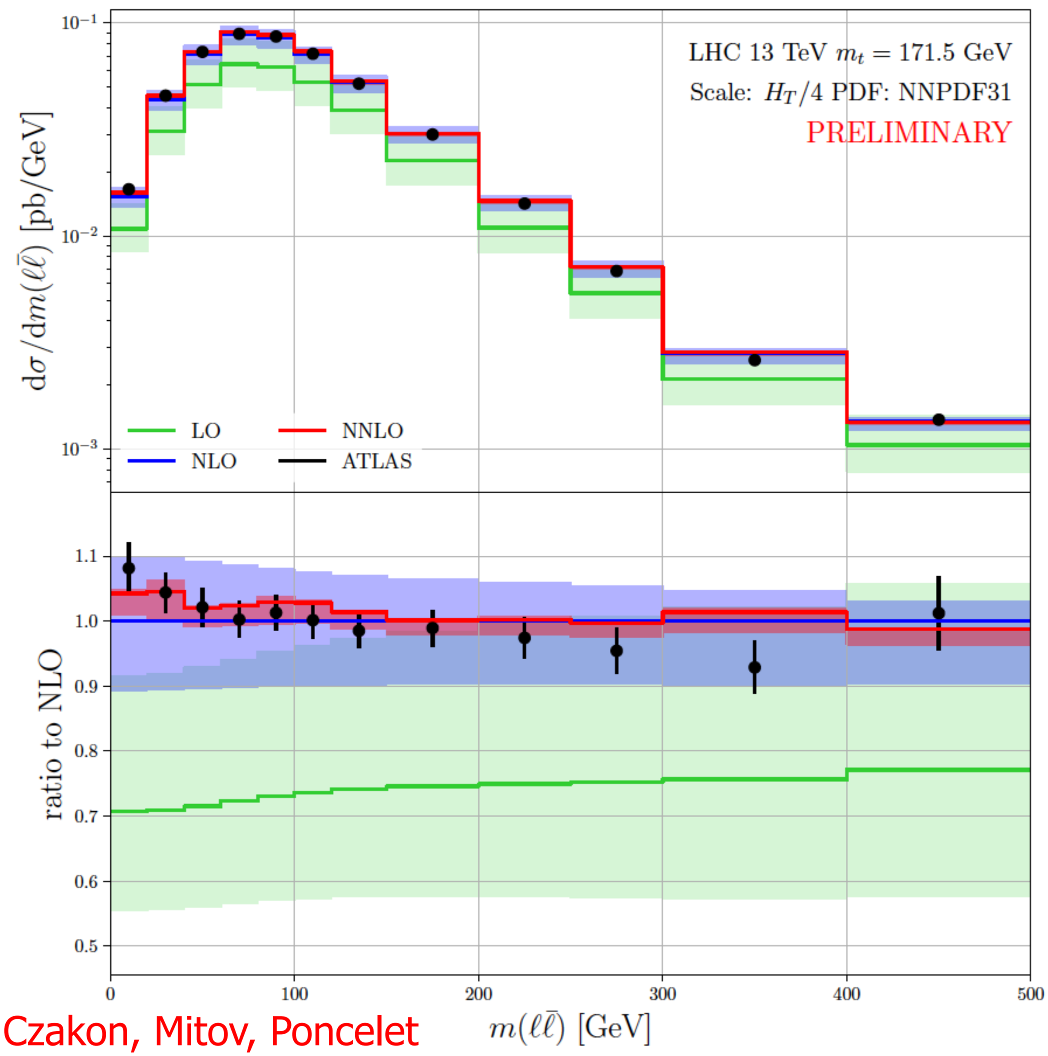
Work in progress: Czakon, Mitov, Poncelet

NNLO QCD vs ATLAS data

✓ m(lepton pair)

- ✓ Great reduction of scale error at NNLO (vs NLO). Tiny K-factor.
- ✓ m_t=171.5GeV better than m_t=172.5GeV.
- ✓ Improved MC error required to draw quantitative conclusion (especially for m_t determ.)

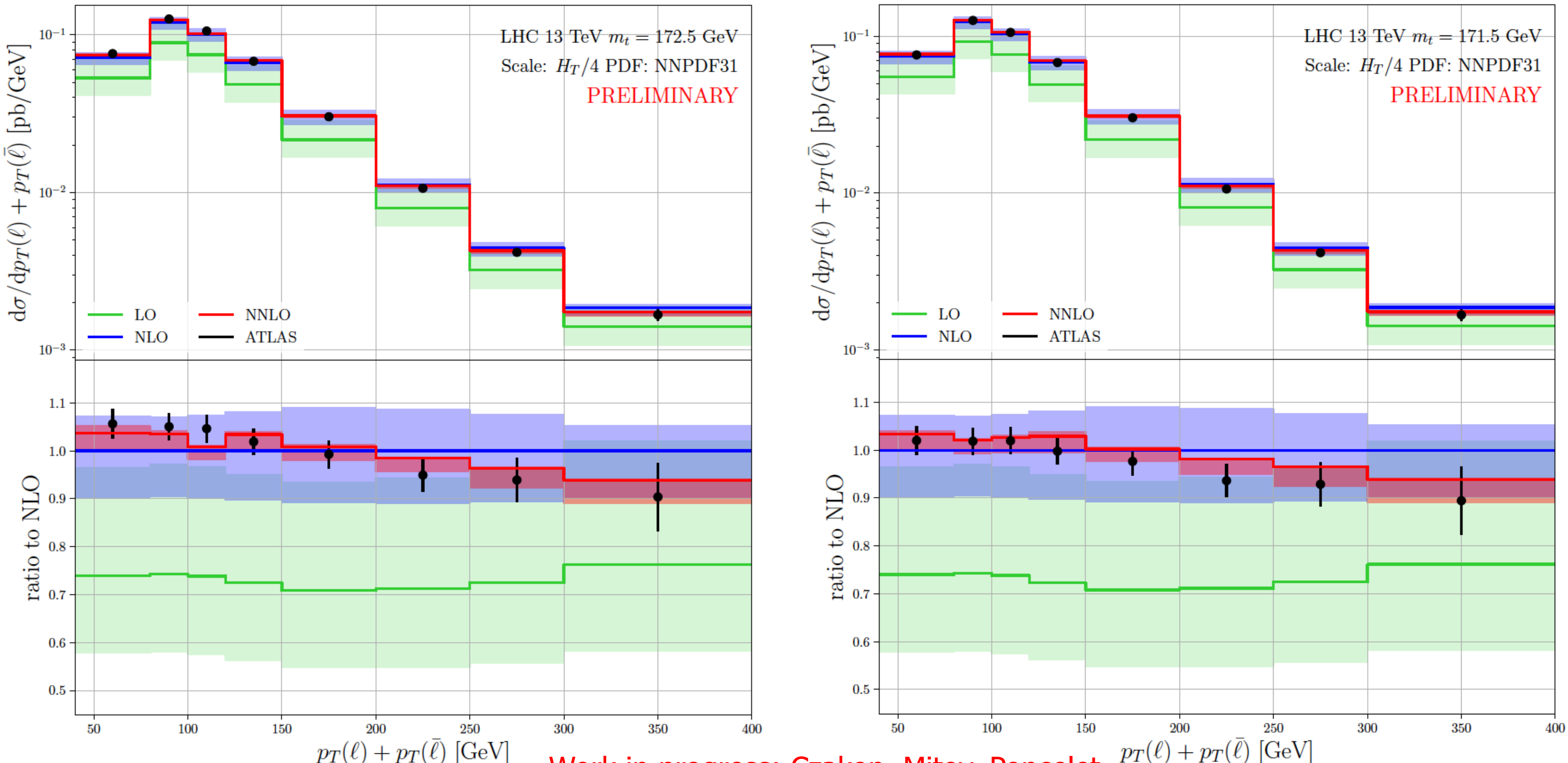




Work in progress: Czakon, Mitov, Poncelet

NNLO QCD vs ATLAS data

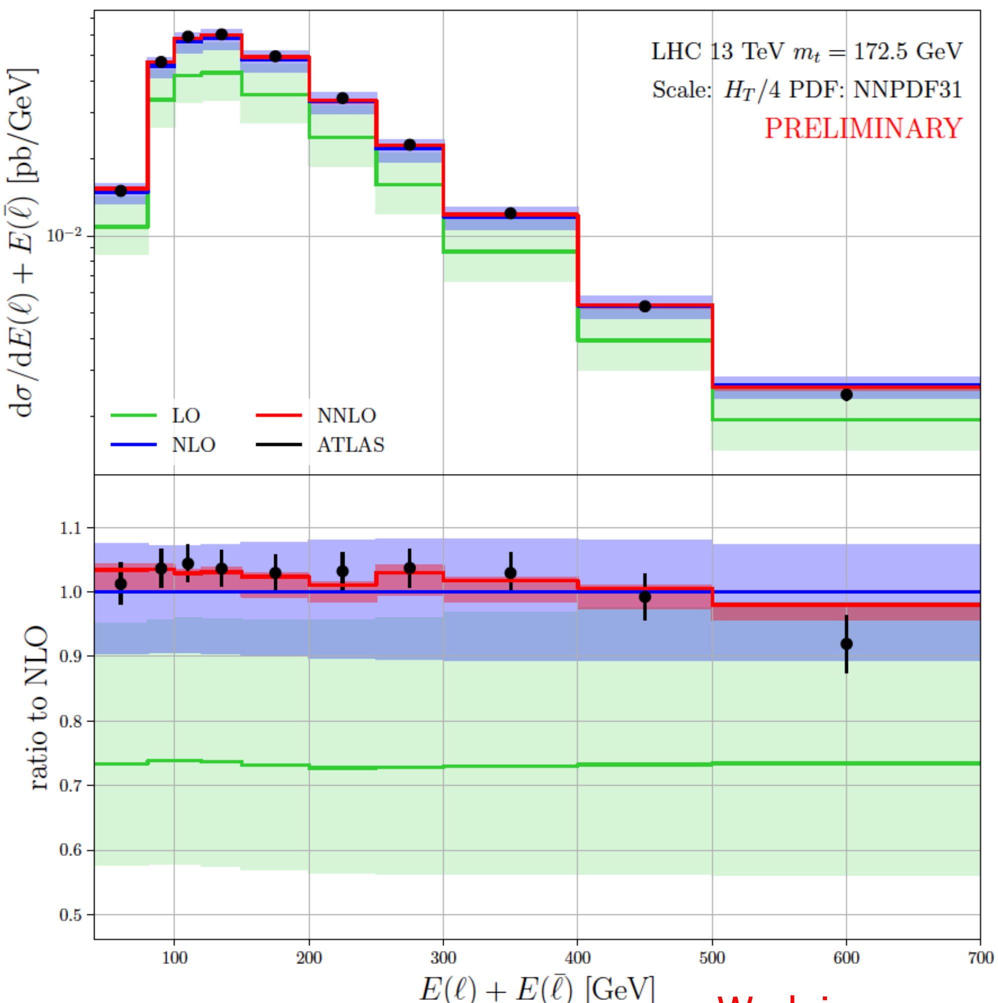
- ✓ (scalar) Sum of the two lepton P_T's
  - ✓ Great reduction of scale error at NNLO (vs NLO). Small K-factor.
  - ✓ Both m_t=171.5GeV and m_t=172.5GeV seem to work
  - ✓ Improved MC error required to draw quantitative conclusion (especially for m_t determin.)

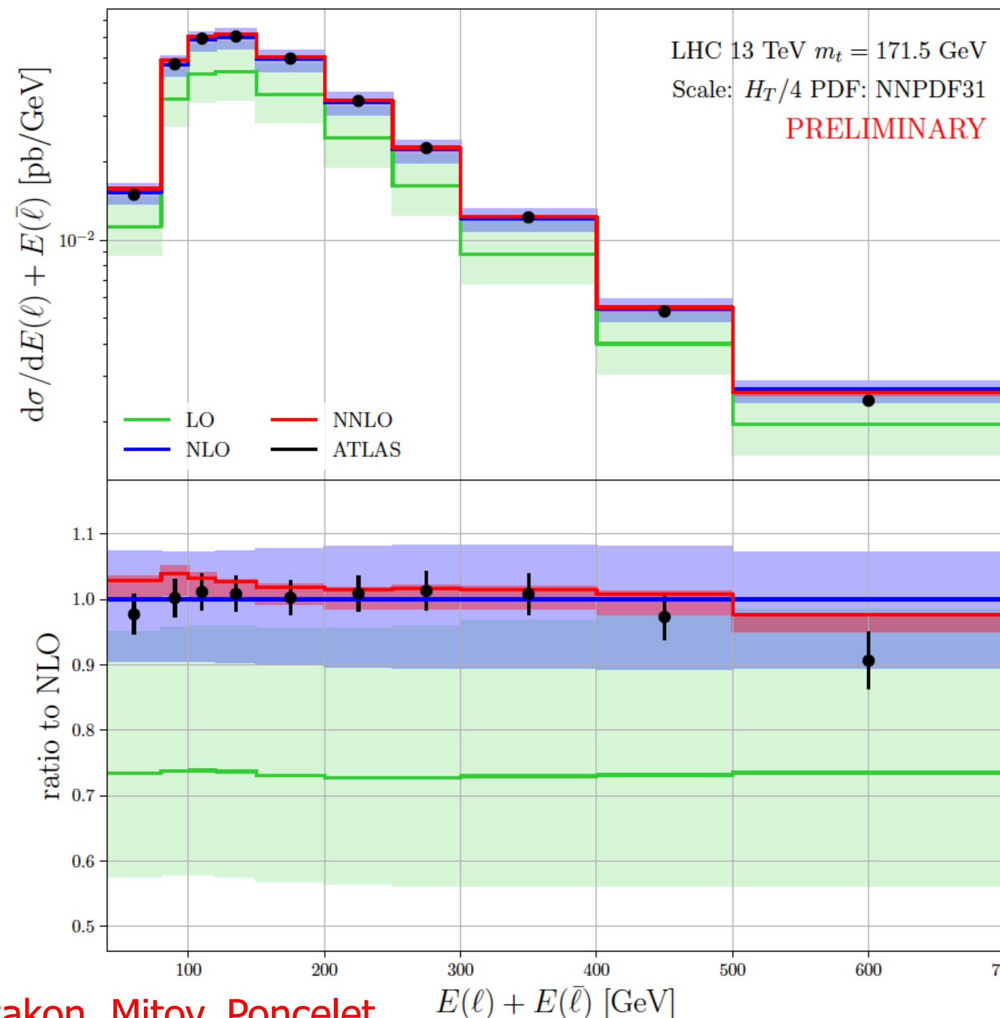


Work in progress: Czakon, Mitov, Poncelet

NNLO QCD vs ATLAS data

- ✓ Sum of the two lepton energies
  - ✓ Great reduction of scale error at NNLO (vs NLO). Small K-factor.
  - ✓ Both m_t=171.5GeV and m_t=172.5GeV seem to work
  - ✓ Improved MC error required to draw quantitative conclusion (especially for m_t determin.)



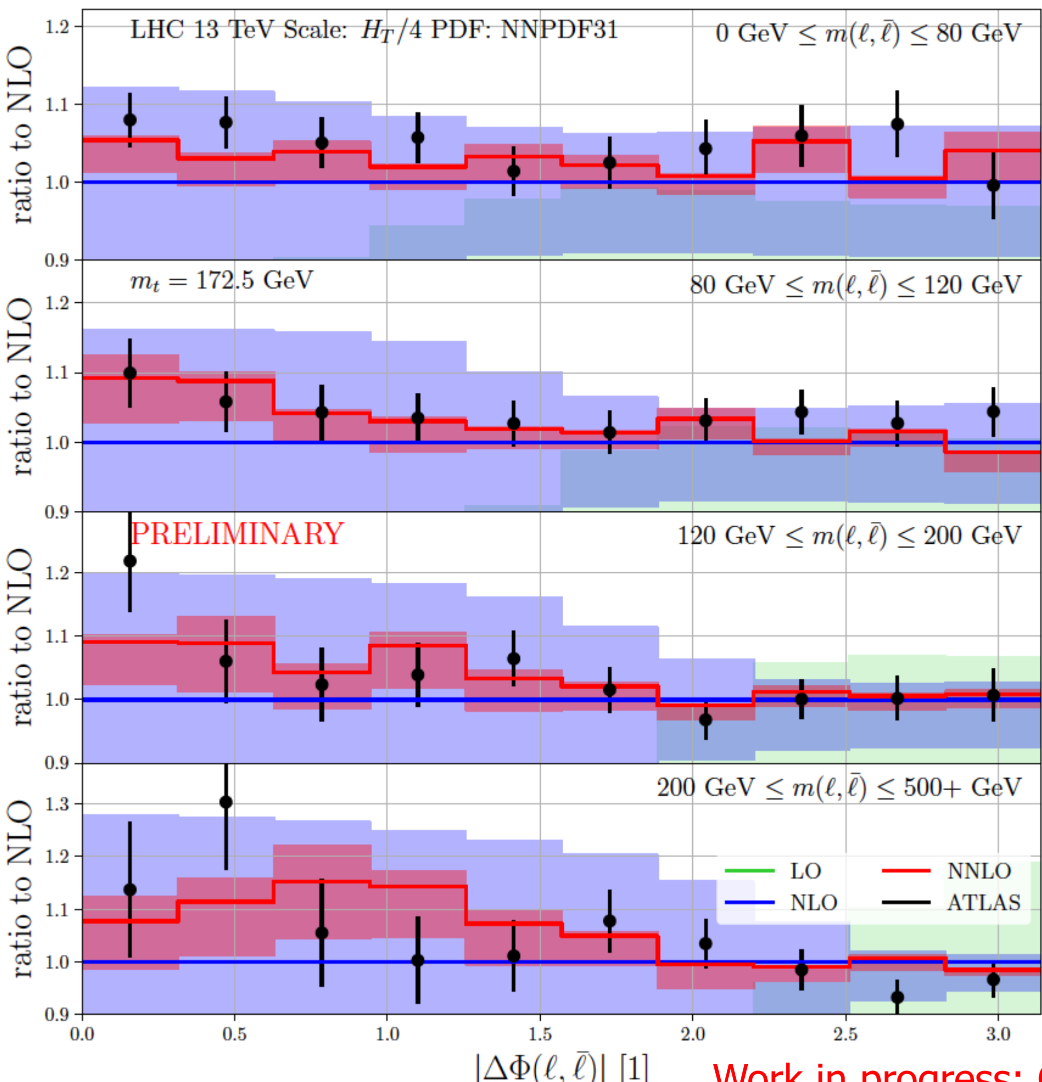


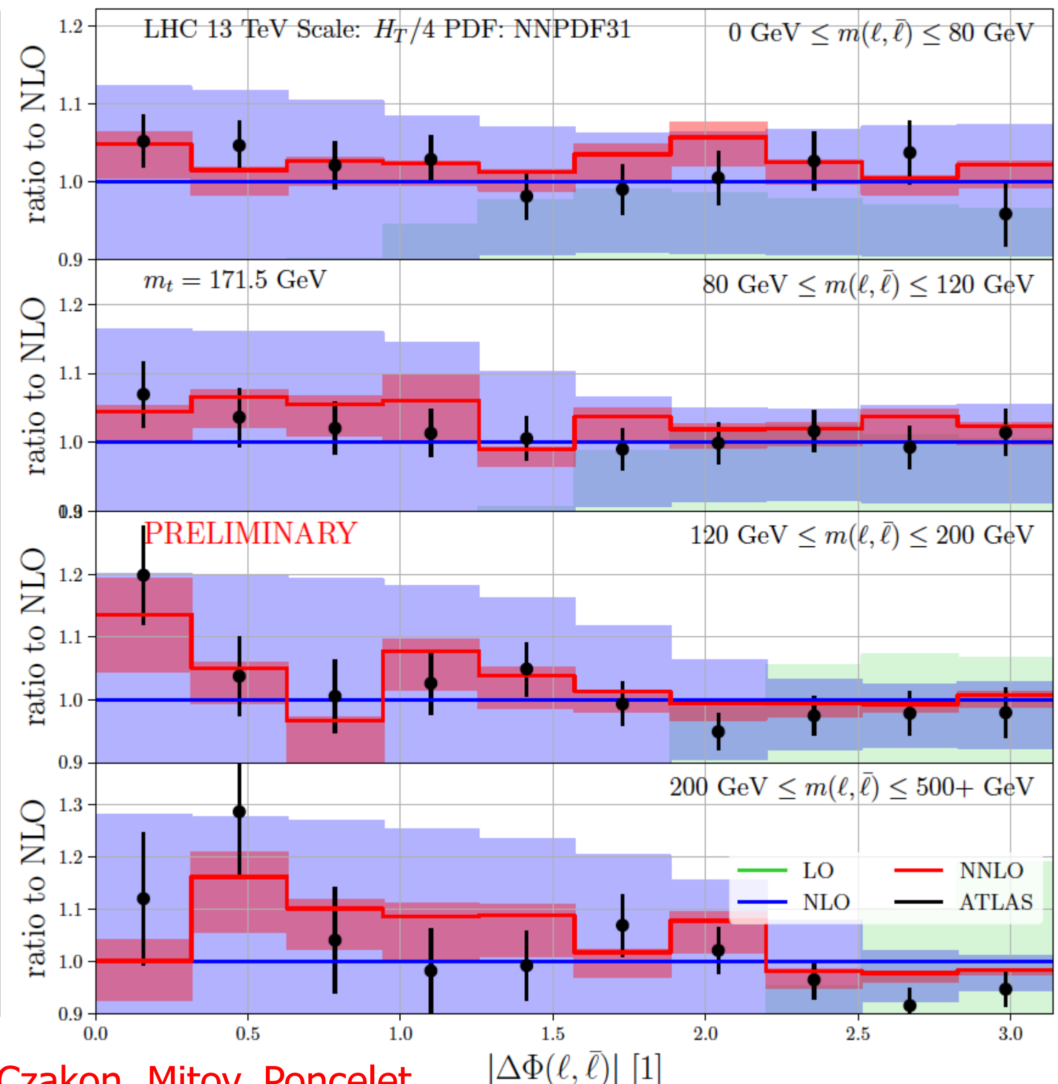
Work in progress: Czakon, Mitov, Poncelet

NNLO QCD vs ATLAS data: 2-dim

✓ $\Delta\varphi$ vs. m(tt) (others are computed, too, not shown)

- ✓ Great reduction of scale error at NNLO (vs NLO). Mostly small K-factors
- ✓ Both m_t=171.5GeV and m_t=172.5GeV seem to work
- ✓ Improved MC error required to draw quantitative conclusion (m_t sensitivity is apparent)





Work in progress: Czakon, Mitov, Poncelet

NNLO QCD vs ATLAS data: 2-dim

- ✓ eta(lepton) vs. m(tt) (others are computed, too, not shown)
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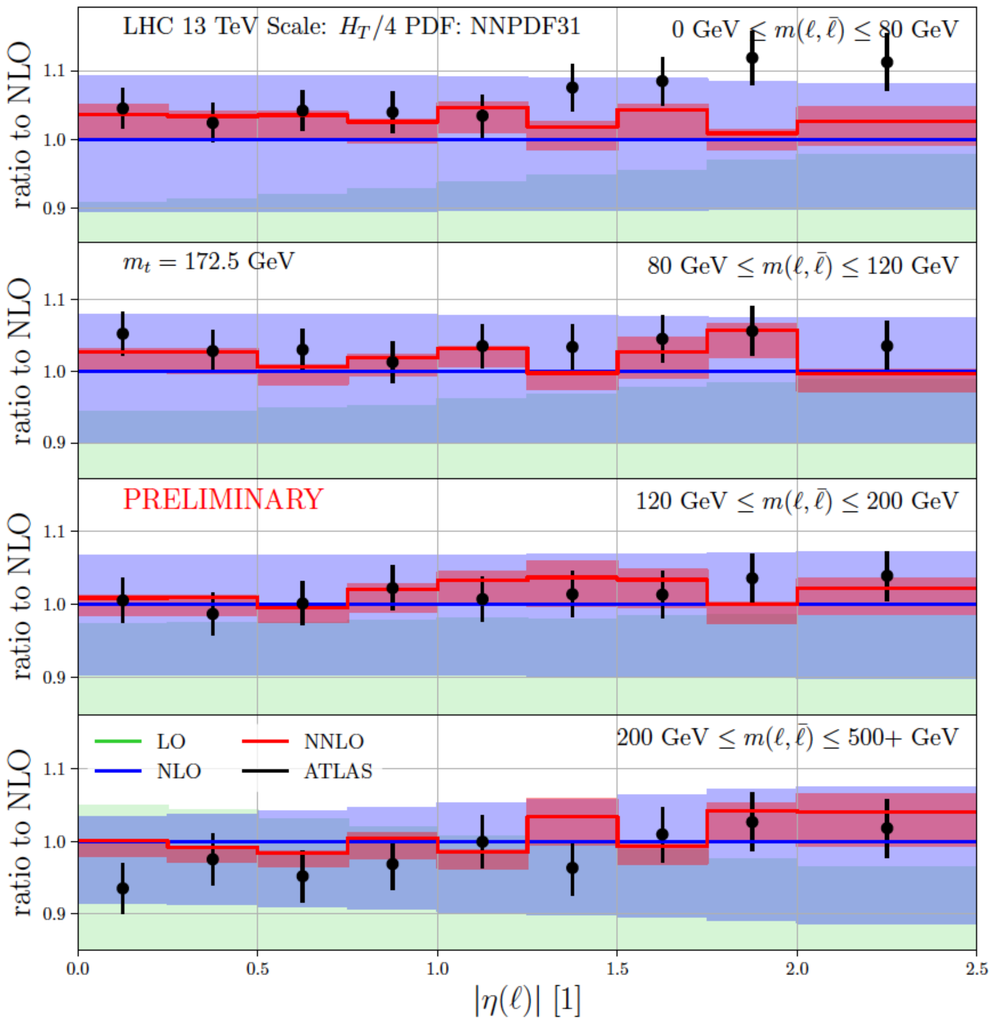
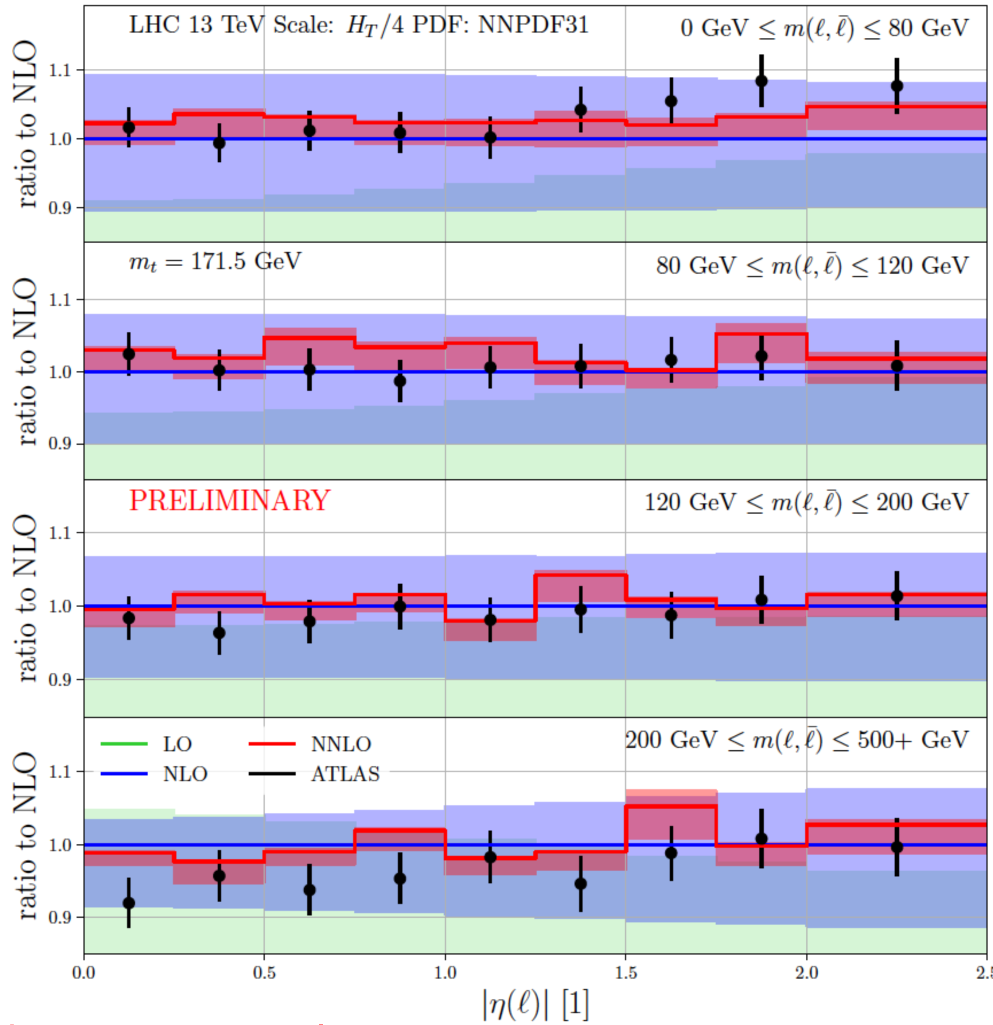
  - ✓ m_t=171.5GeV seem to work
  - ✓ Improved MC error required to draw quantitative conclusion (m_t sensitivity is apparent)





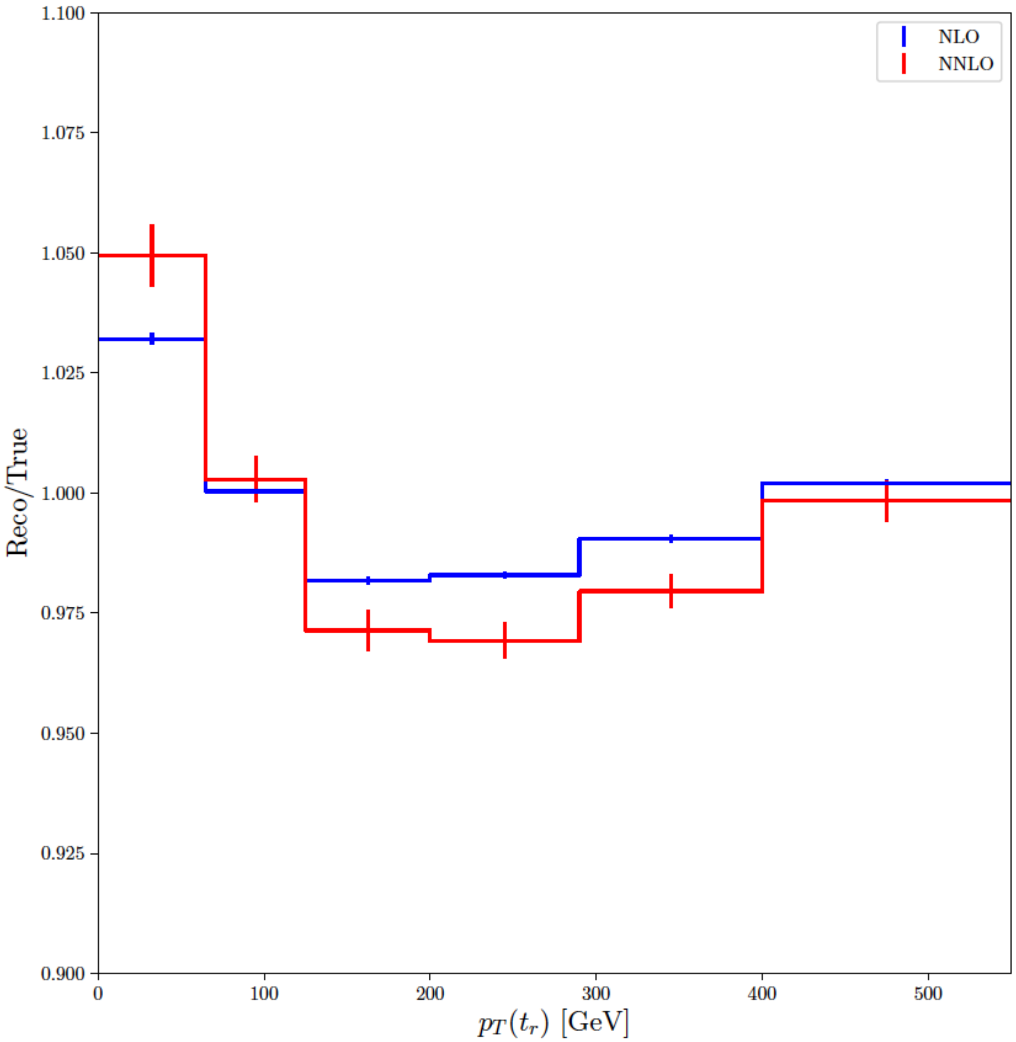
Work in progress: Czakon, Mitov, Poncelet

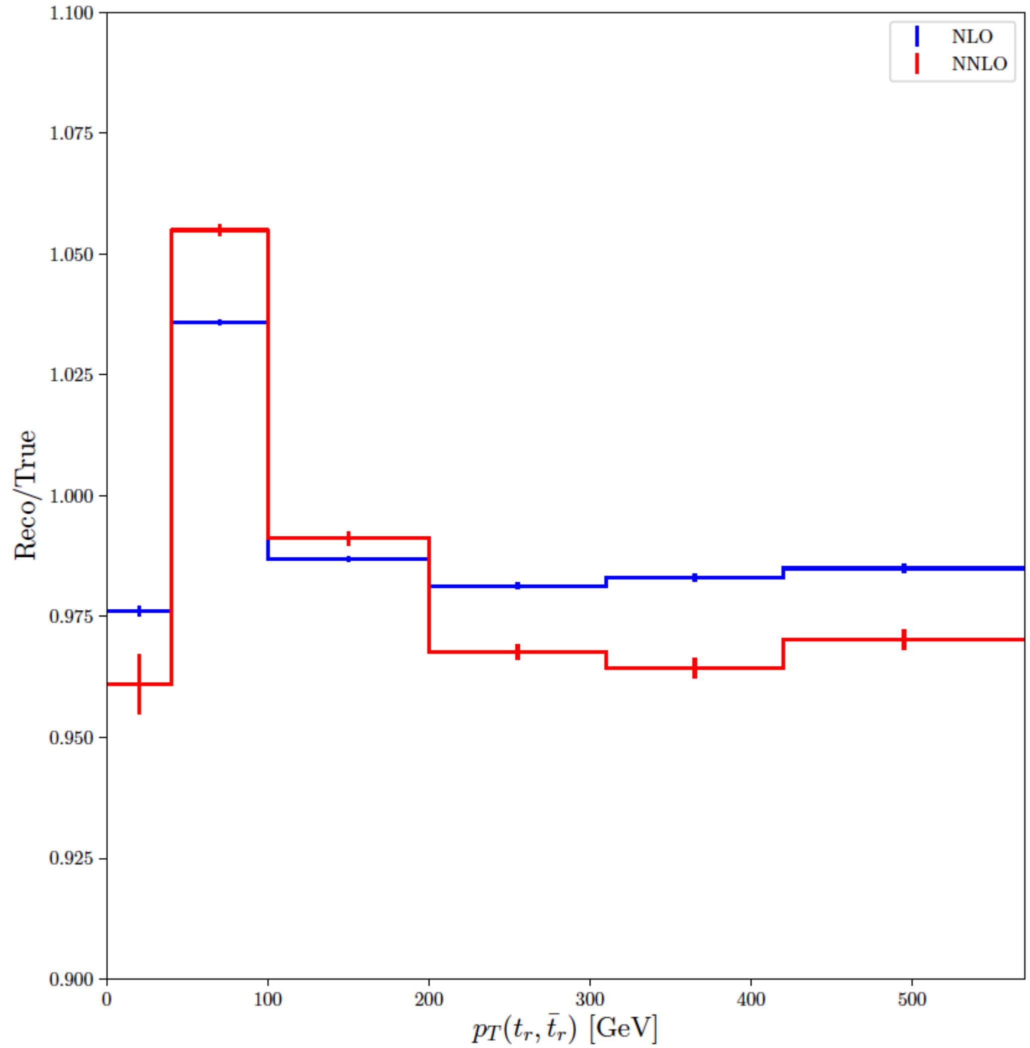
NNLO QCD vs CMS data

- ✓ Comparison in progress
  - ✓ 13 TeV distributions from arXiv:1811.06625
  - ✓ The complete spin-density matrix measured by CMS
- ✓ In the context of comparing with CMS an interesting study was done: compare the distributions of the true top versus the distribution of the reconstructed top (for the CMS selection)
  - ✓ We use the true top (which is known before the decay)
  - ✓ Experimentally the top is reconstructed from the decay products:
    - ➢ Assume neutrino momenta are known
    - ➢ Leptons + neutrinos give the two W's (minimizing the differences from the true W mass). For us this step is unambiguous.
    - ➢ Then combine the two W's with two b-jets that minimize the difference between the reconstructed top masses and "true" mass. In our calculation we can have up to 4 b-quarks so this introduces a potential difference.

NNLO QCD vs CMS data

✓ Here is the ratio between the true top and the constructed top at NLO and NNLO (in the context of the CMS selection)





NNLO QCD vs CMS data

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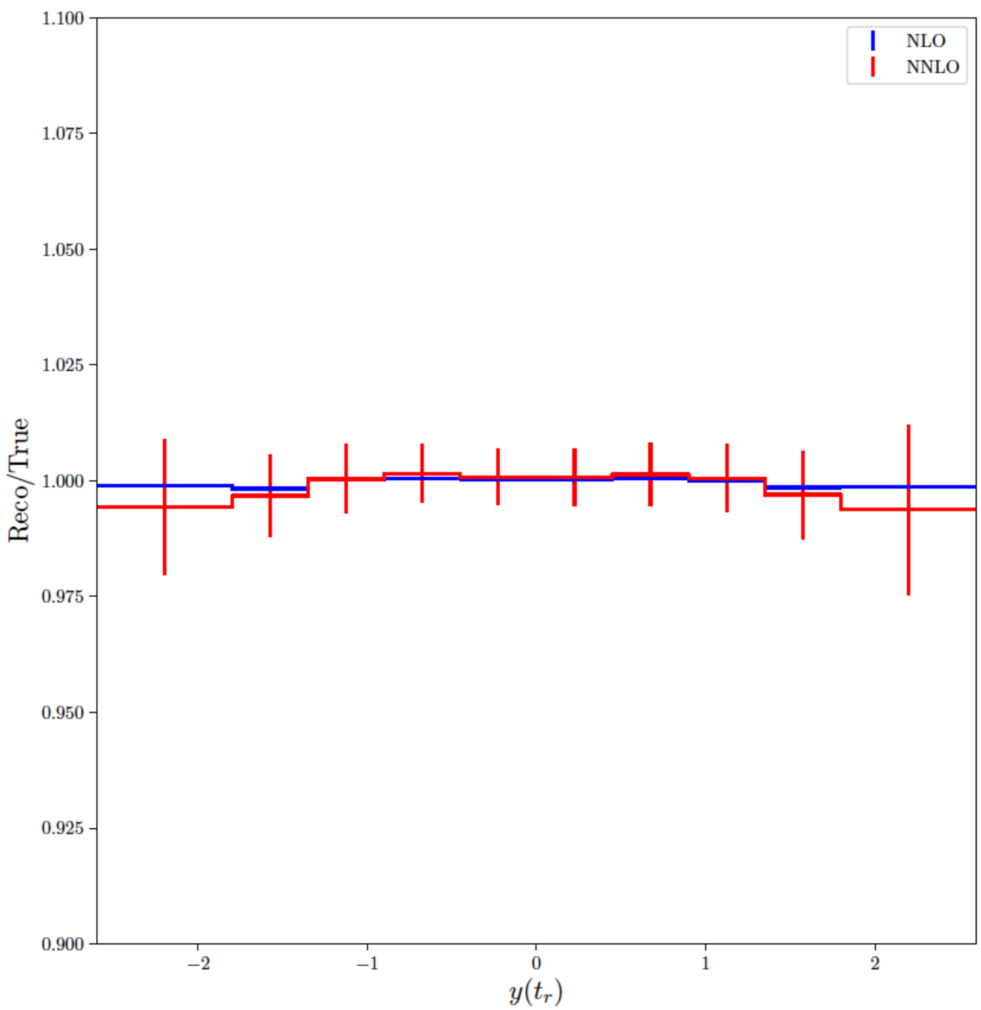

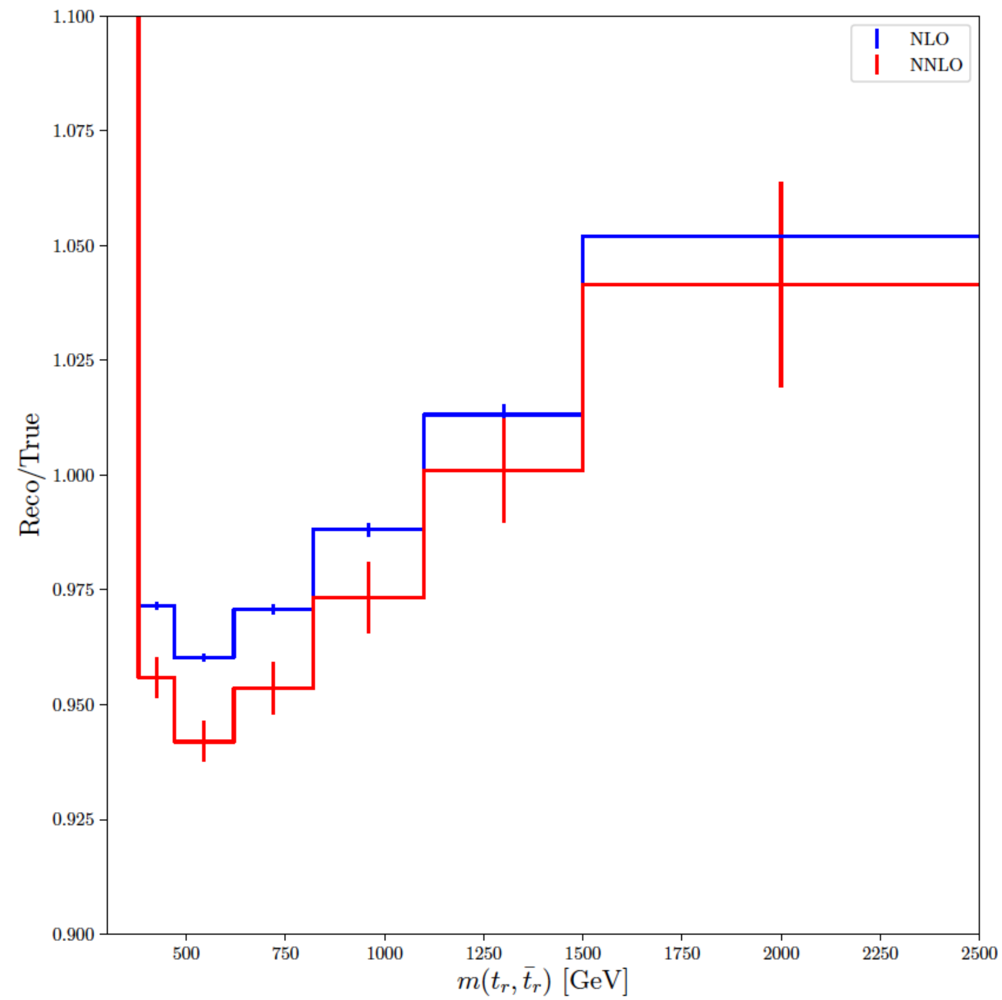

Conclusions

- ✓ Steady progress on calculations of NNLO top production with NNLO top decay.
- ✓ Calculations are in the NWA which is adequate for most applications.
  - ✓ Pure QCD for now.
- ✓ Calculations have been presented for all measured leptonic distributions at ATLAS and CMS.
- ✓ The potential quality of the calculations is very high; comparing them to existing and future precise data will become a great discriminator for:
  - ➢ m_t determination: we often focus solely on precision but leptonic distributions offer an unparalleled robustness which is not present in many other determinations
  - ➢ Monte Carlos/modeling used in top physics (and beyond)
  - ➢ Ultimately, will allow us to test with unparalleled precision the SM in the top quark sector
- ✓ Few immediate (and pressing!) lessons:
  - ❖ At such high level of precision everything matters. Given at present Fixed Order calculations are much more precise than general purpose even generators, an effort must be made to connect such calculations to data.
  - ❖ This is tricky given the amount of interpolation/modeling used in measurements.