Top differential distributions with leptonic decays

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Outline

- ✓ Spin correlations
- ✓ Leptonic differential distributions in NNLO QCD
  - ✓ ATLAS
  - ✓ CMS
- ✓ On tt~ production in the threshold region
- ✓ Summary

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

ttbar spin correlations

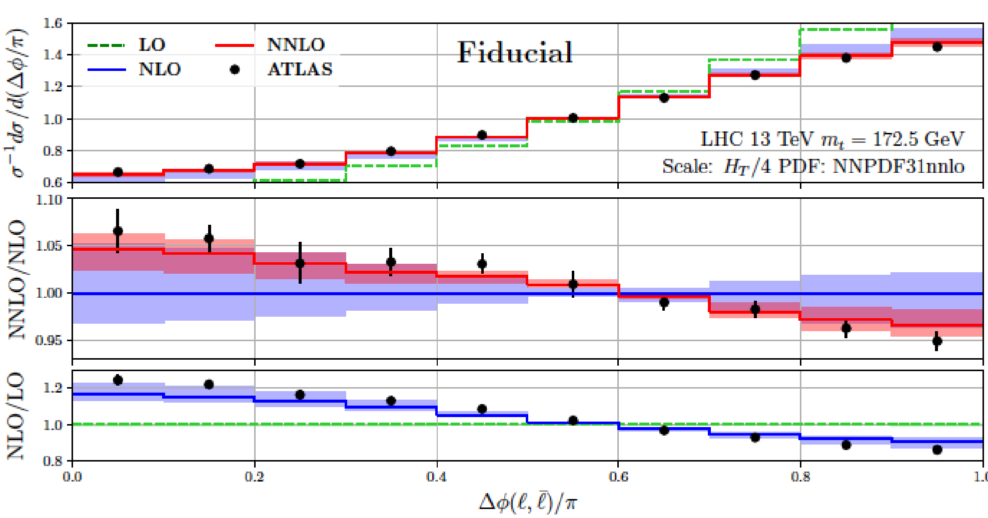
- ✓ NNLO QCD corrections to top pair spin-correlations was presented already at Top 2018

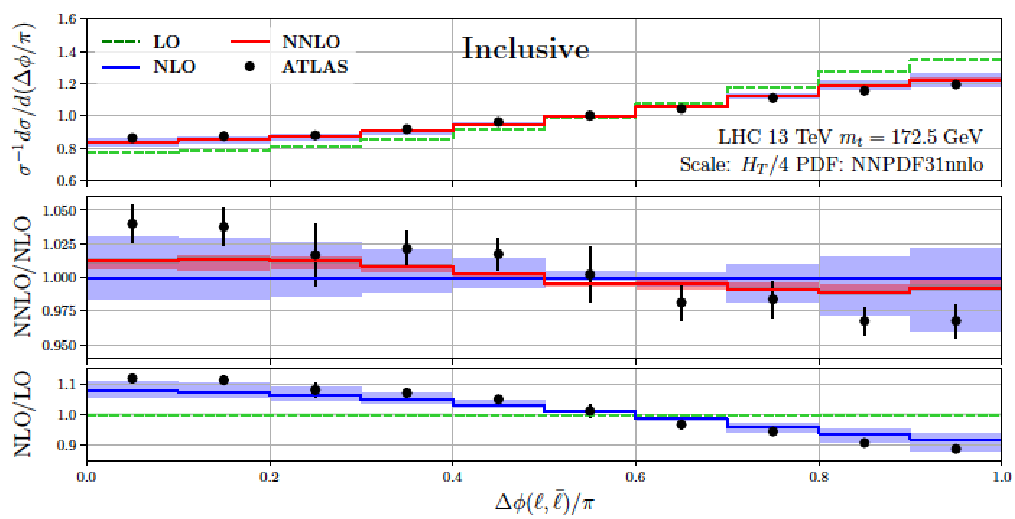
Behring, Czakon, Mitov, Papanastasiou, Poncelet arXiv:1901.05407

- ✓ 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

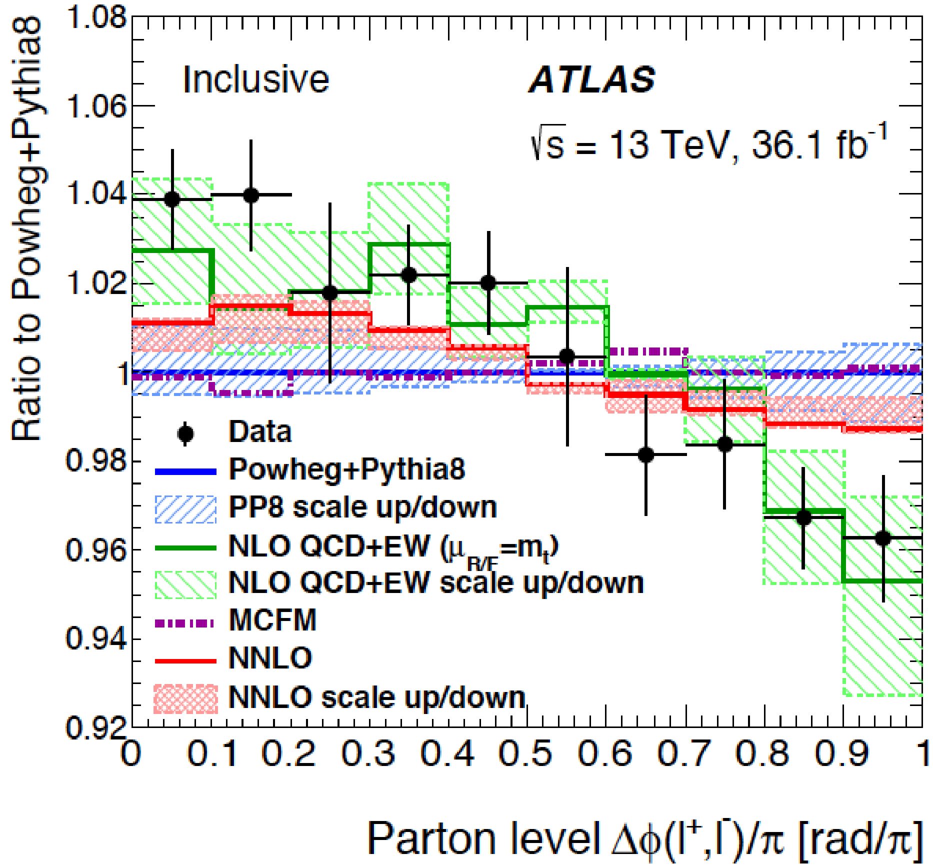




ttbar spin correlations

✓ 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:

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

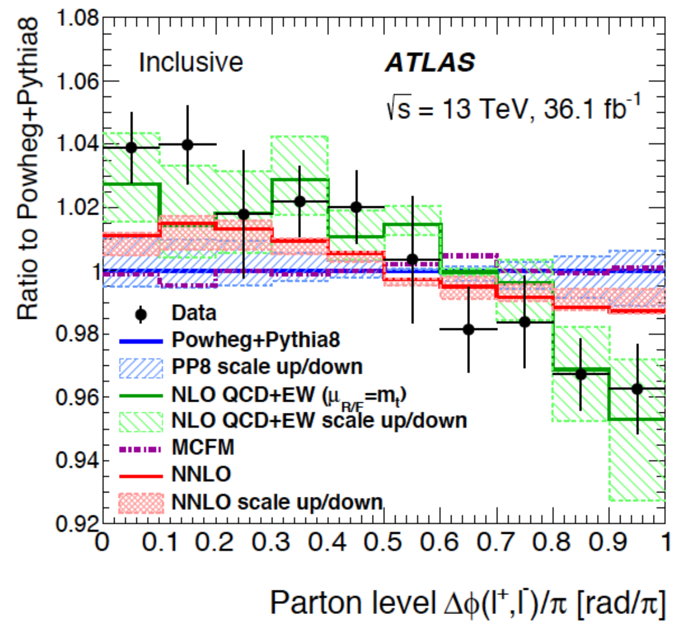
❖ The ratio R can also be expanded in the coupling

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

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

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

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

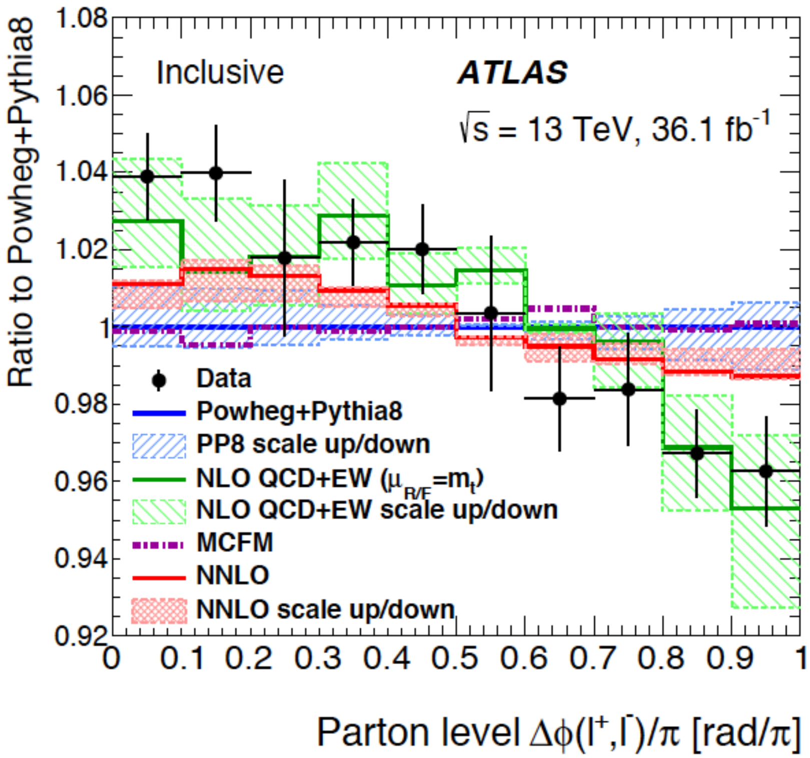


ATLAS: arXiv:1903.07570

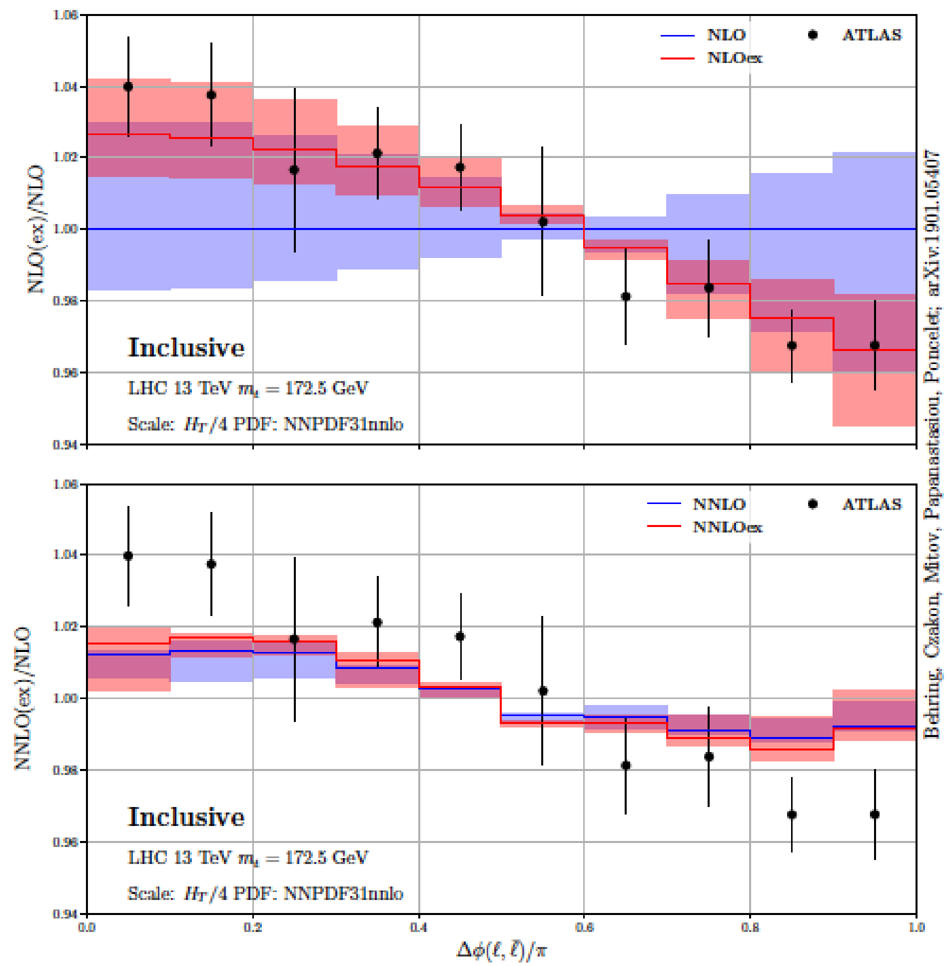
ttbar spin correlations

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

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



ATLAS: arXiv:1903.07570



- ✓ 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
- ✓ Probably this plot needs to 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

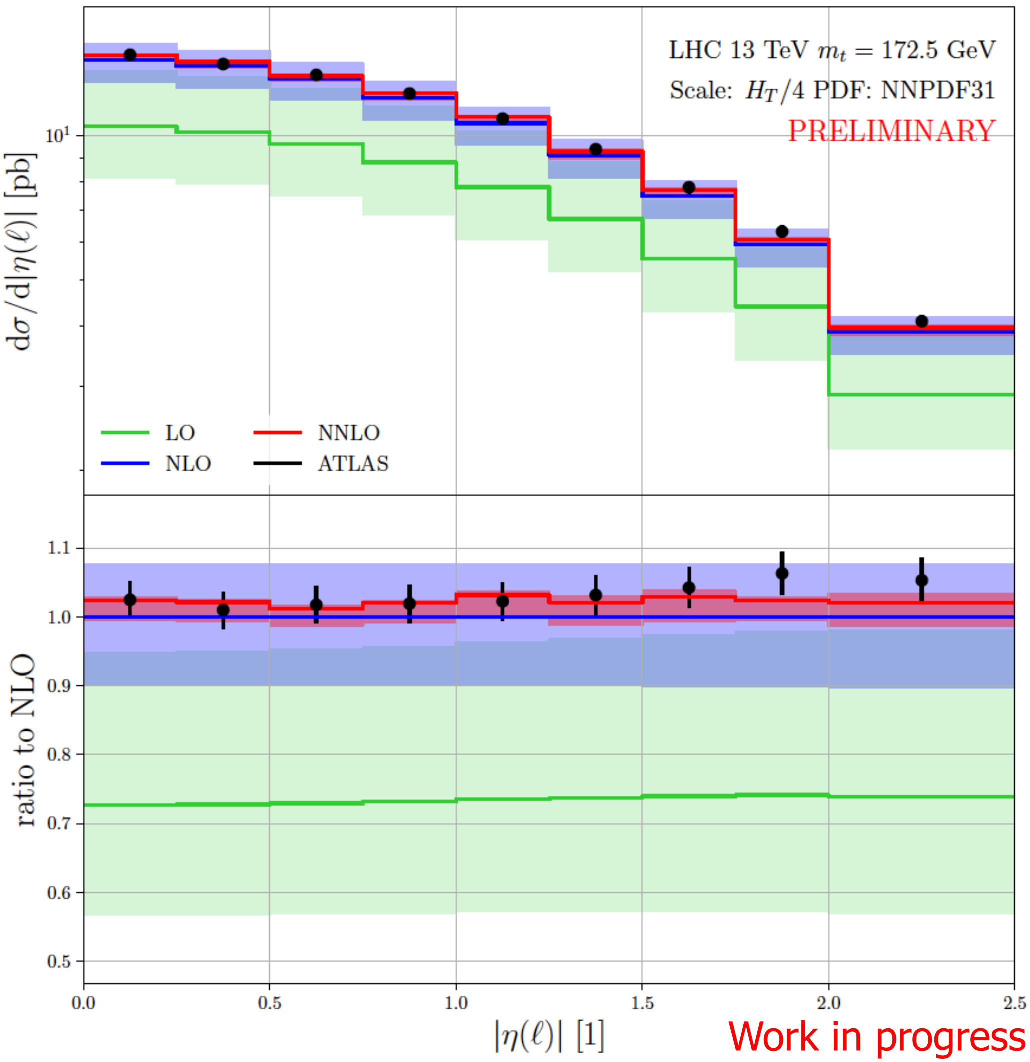
- ✓ Data taken from

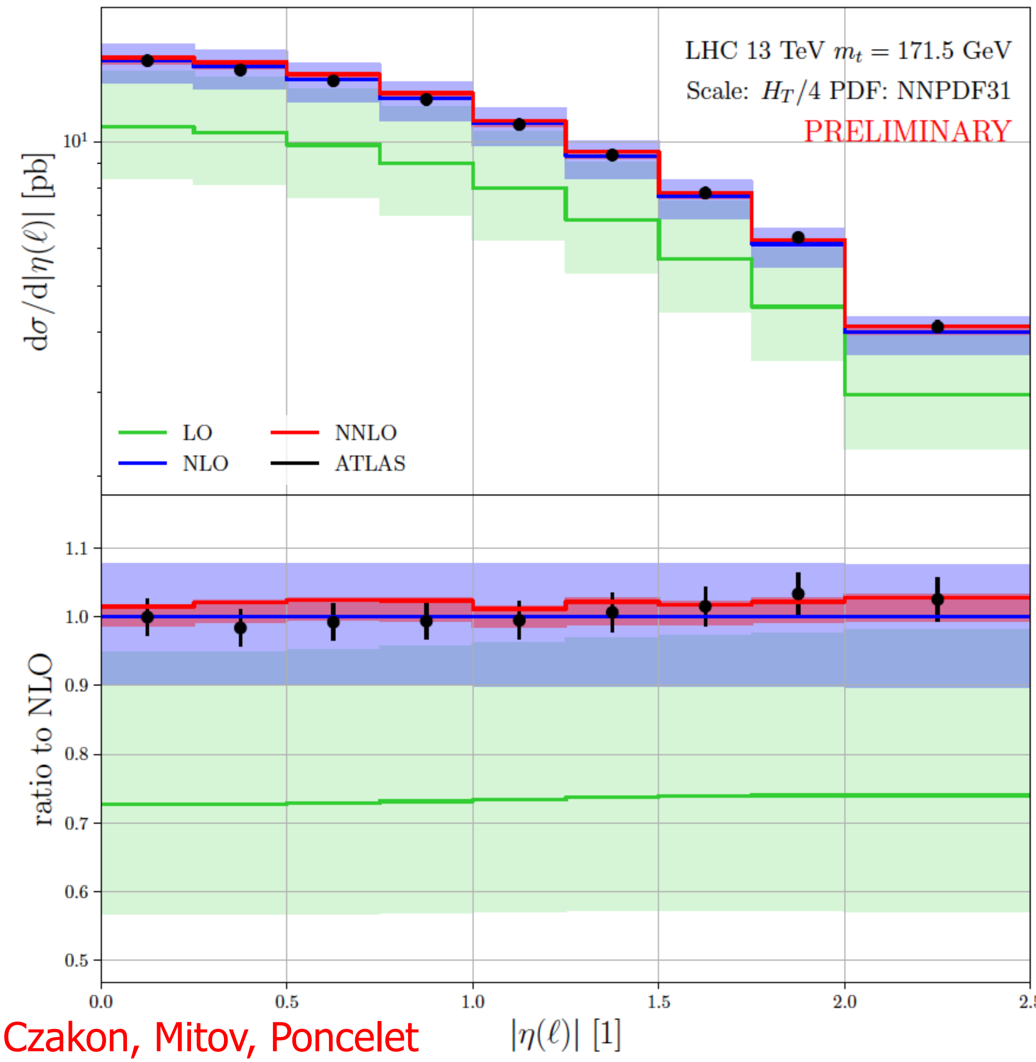
ATLAS-CONF-2019-041

- ✓ 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.

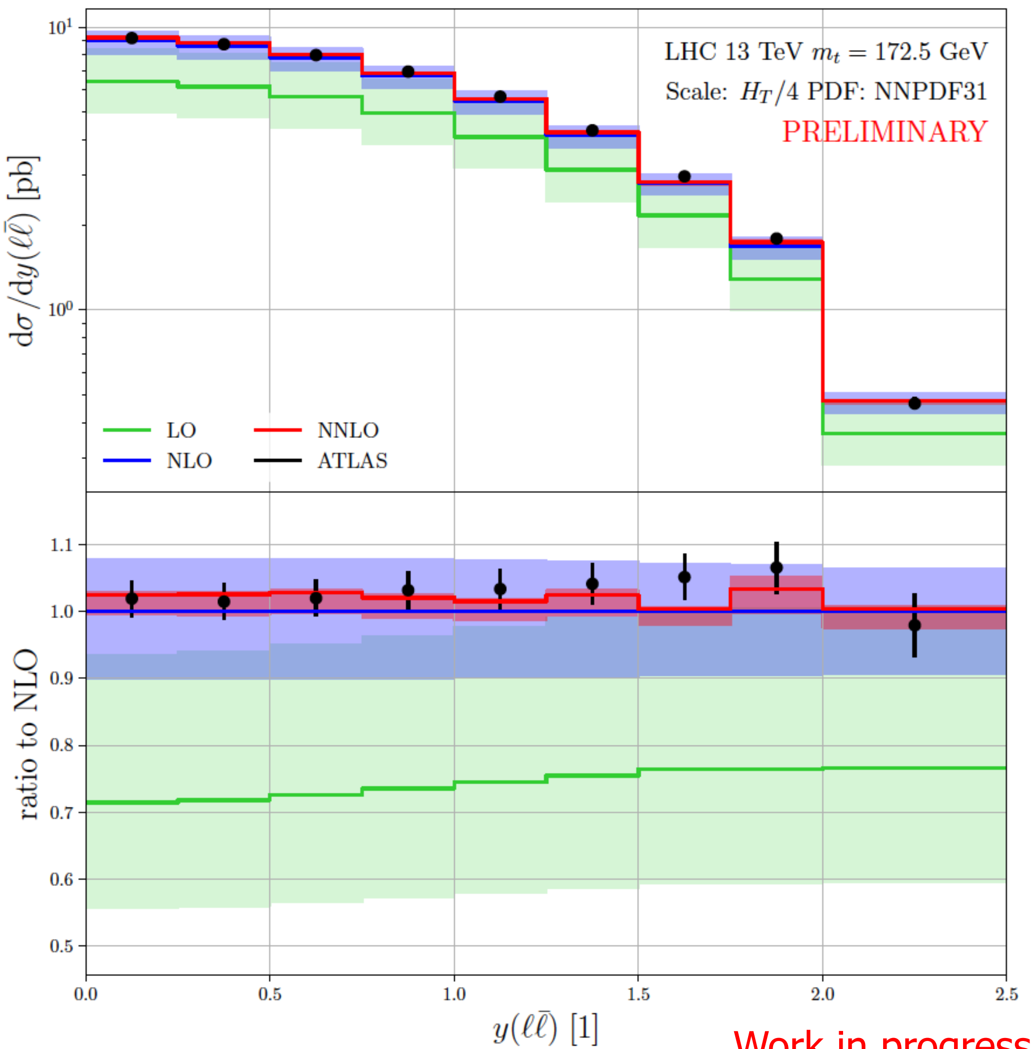


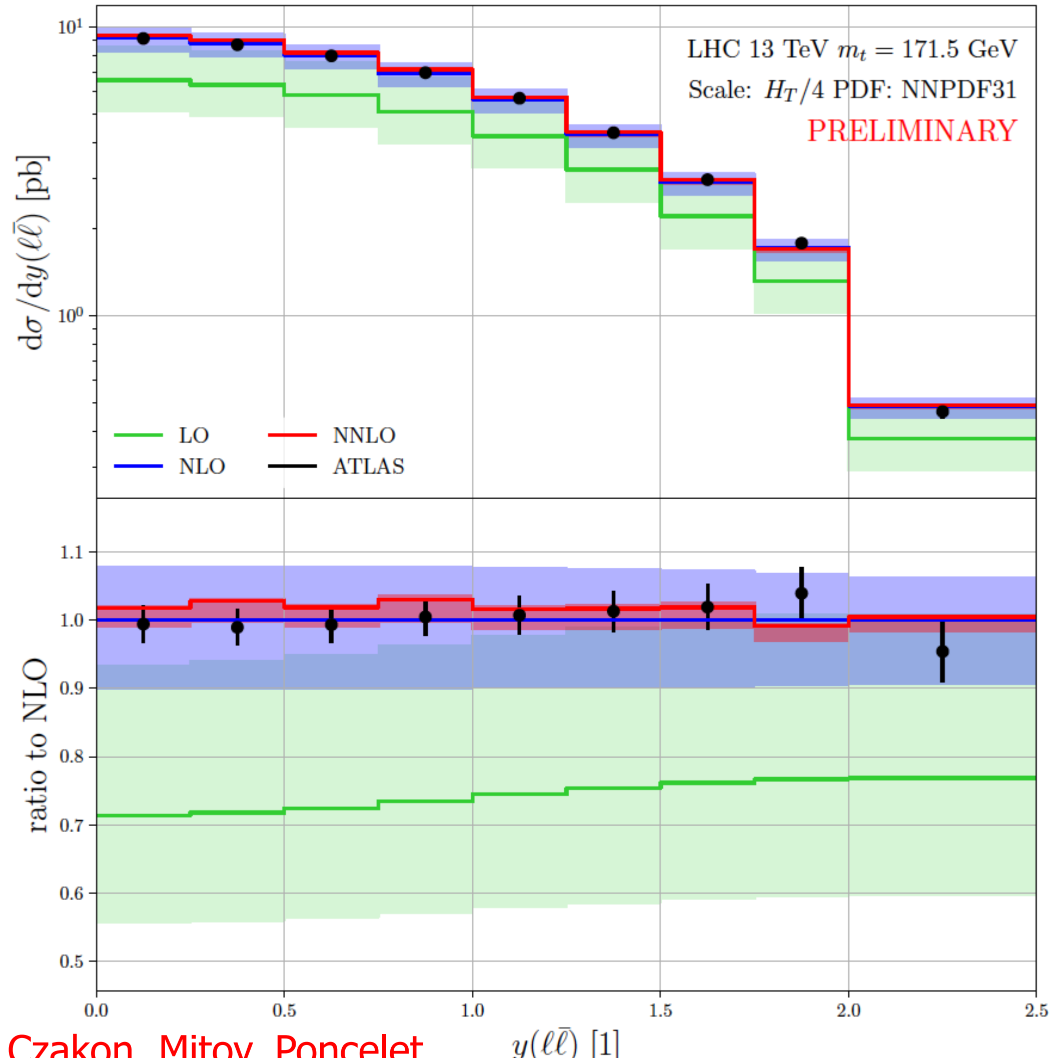


Work in progress: Czakon, Mitov, Poncelet

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.

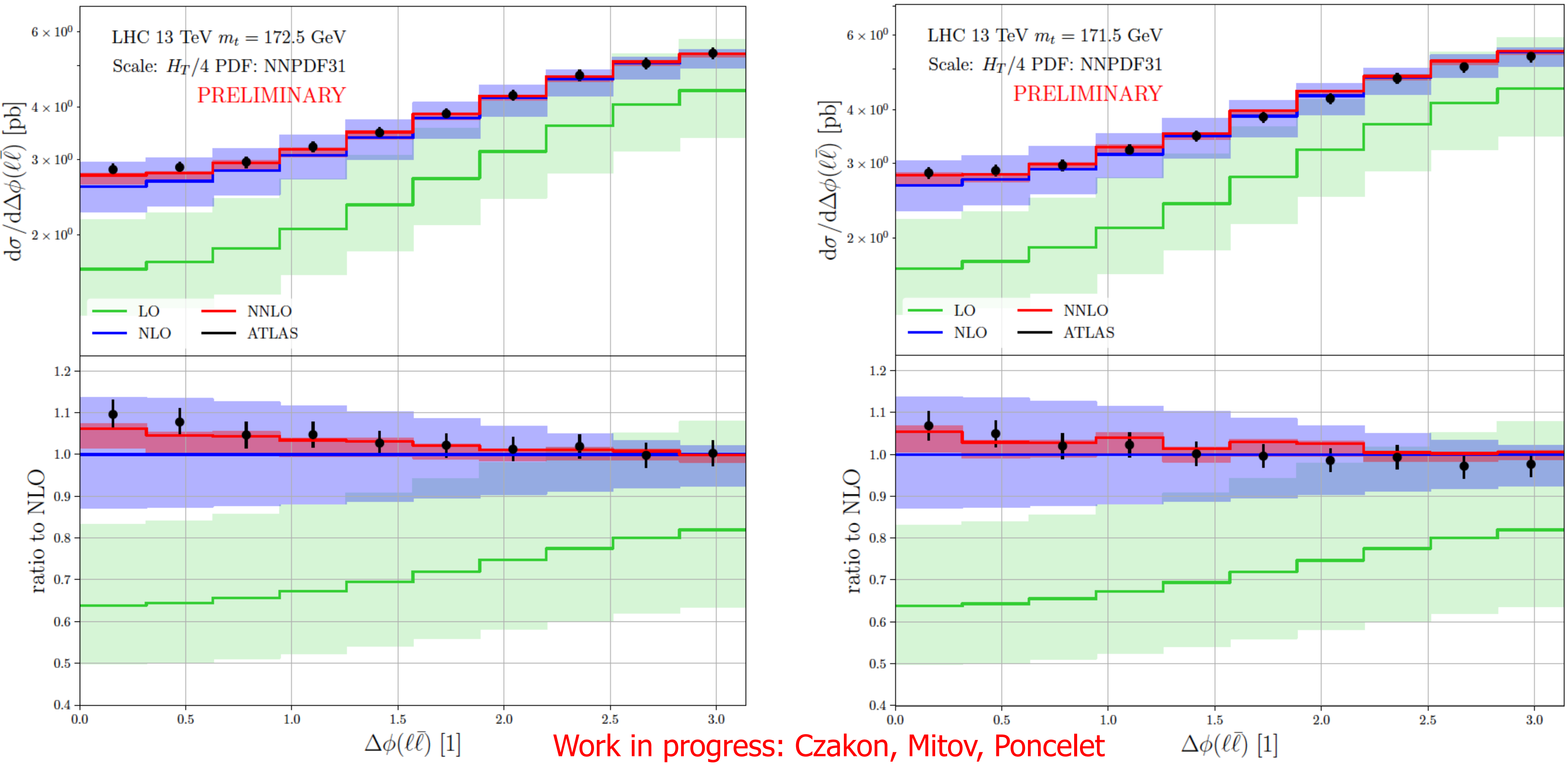




Work in progress: Czakon, Mitov, Poncelet

NNLO QCD vs ATLAS data

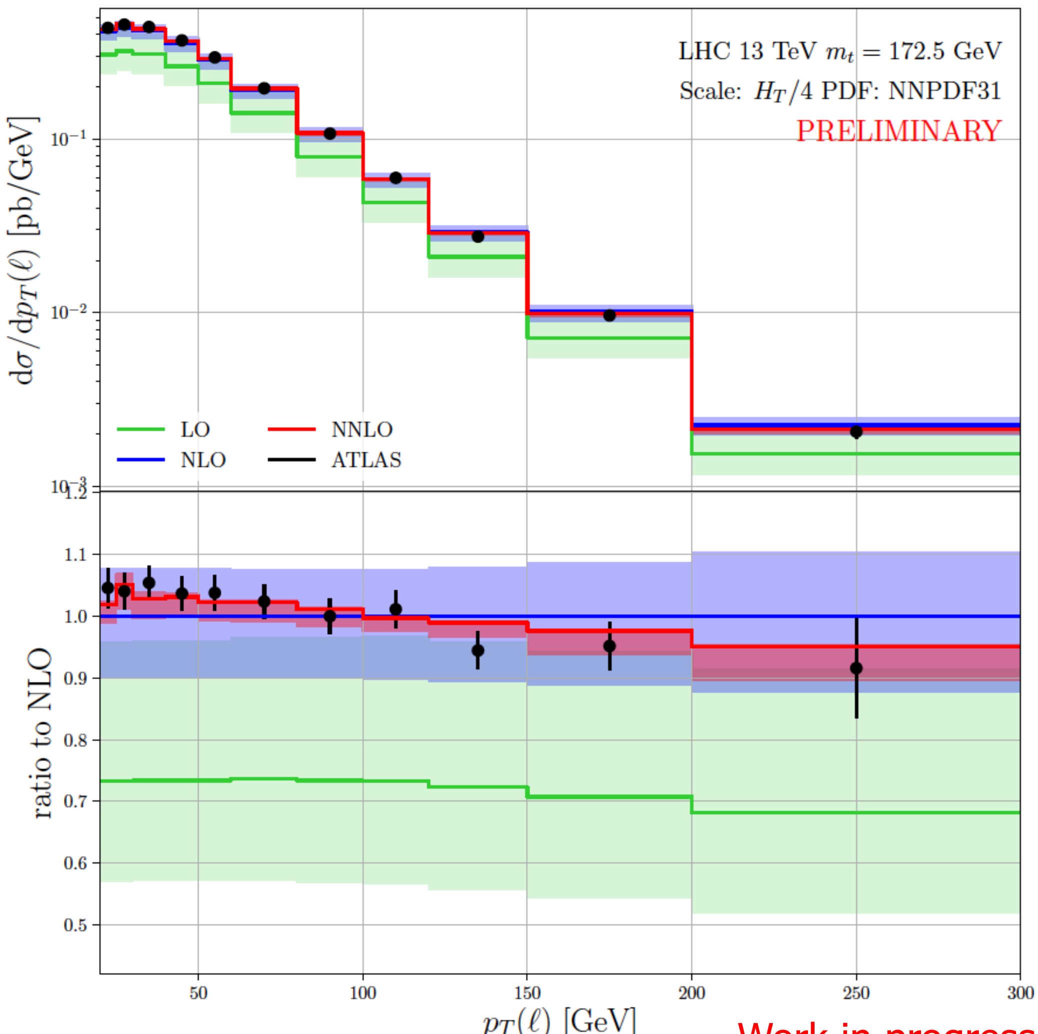
- ✓ Δφ
  - ✓ Great reduction of scale error at NNLO (vs NLO). Tiny K-factor.
  - ✓ m_t=171.5GeV probably a bit better than m_t=172.5GeV.
  - ✓ Improved MC error required to draw quantitative conclusion (which m_t is best)

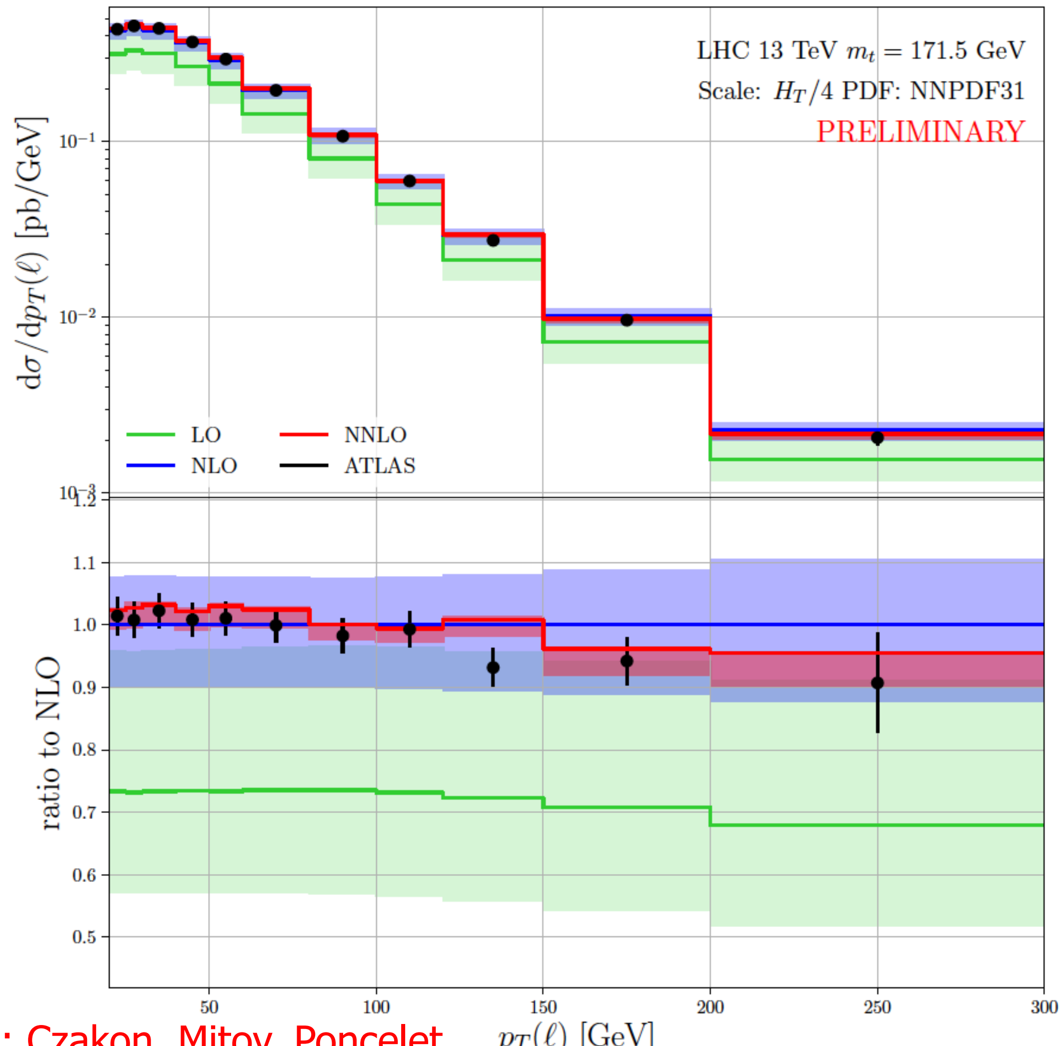


Work in progress: Czakon, Mitov, Poncelet

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

- ✓ P_T(lepton pair)
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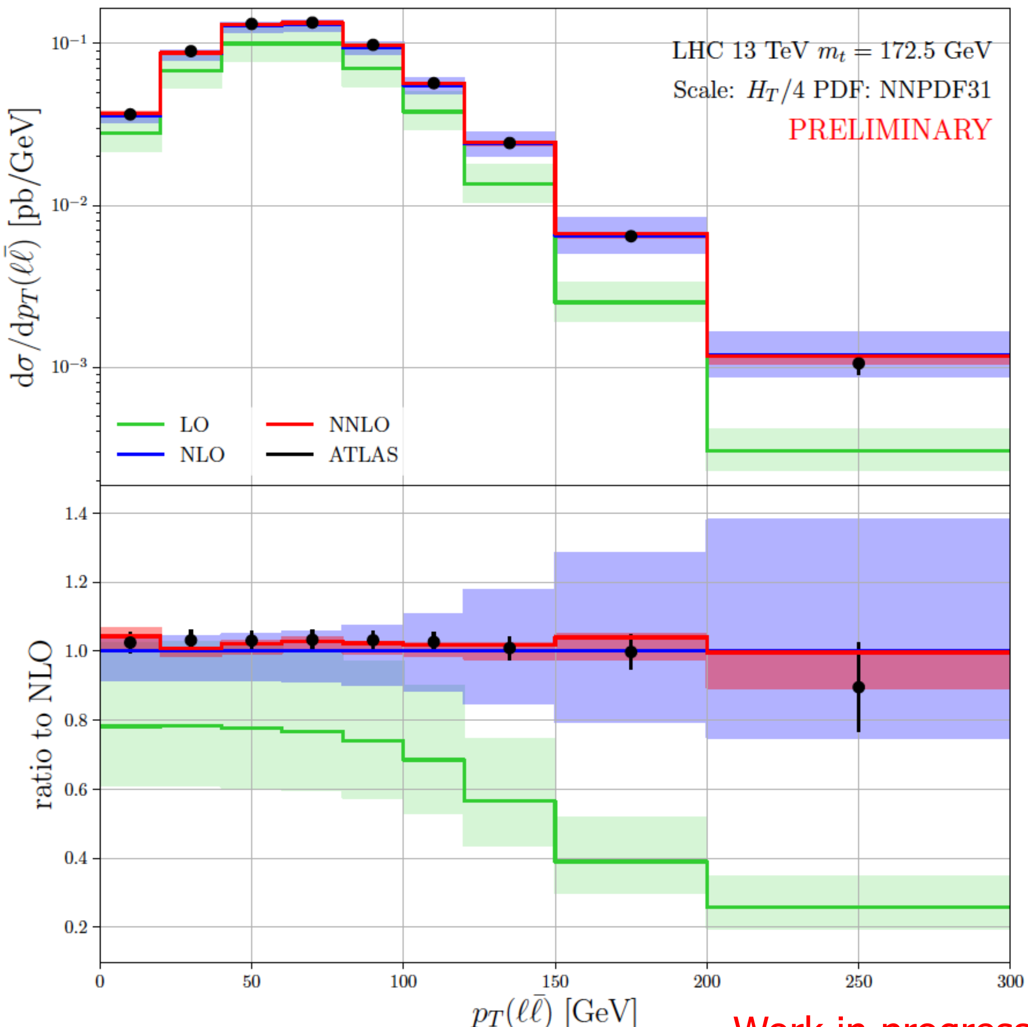
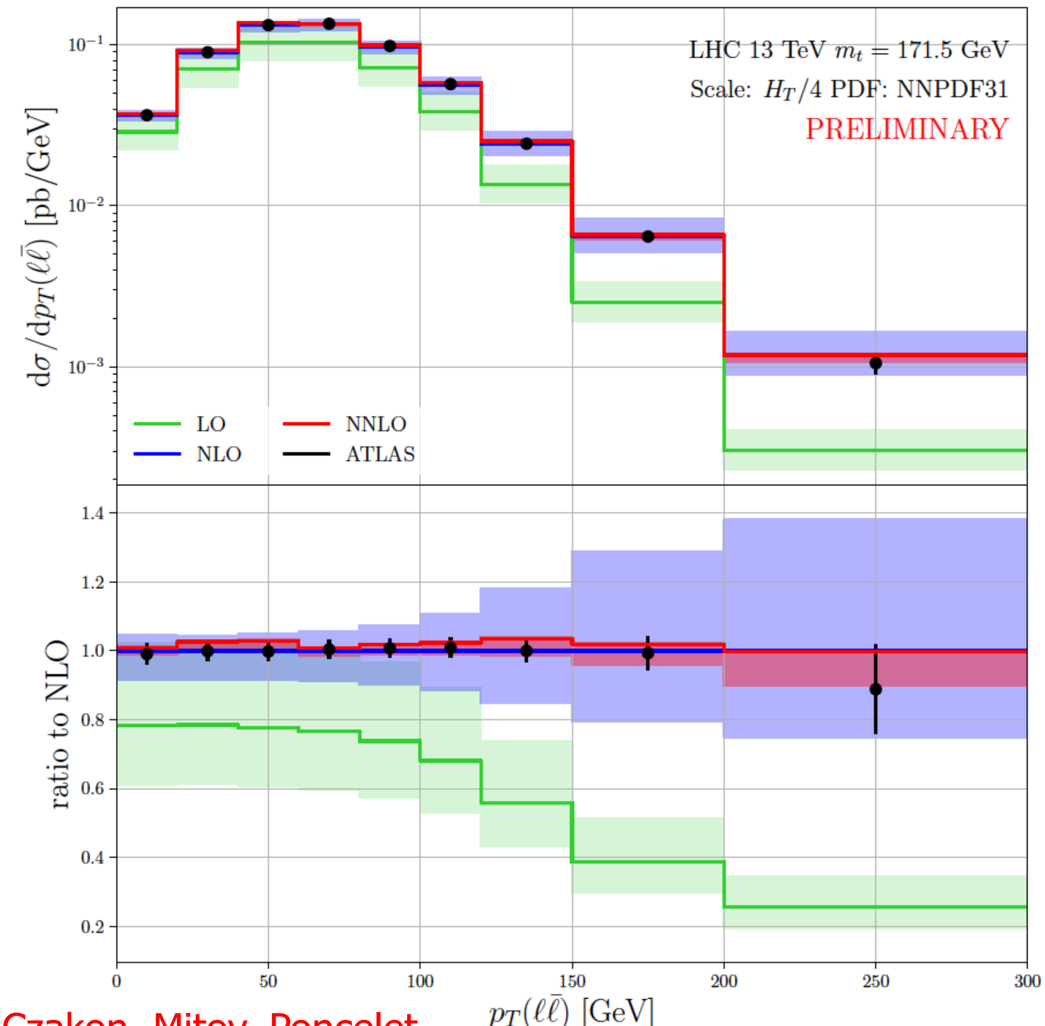


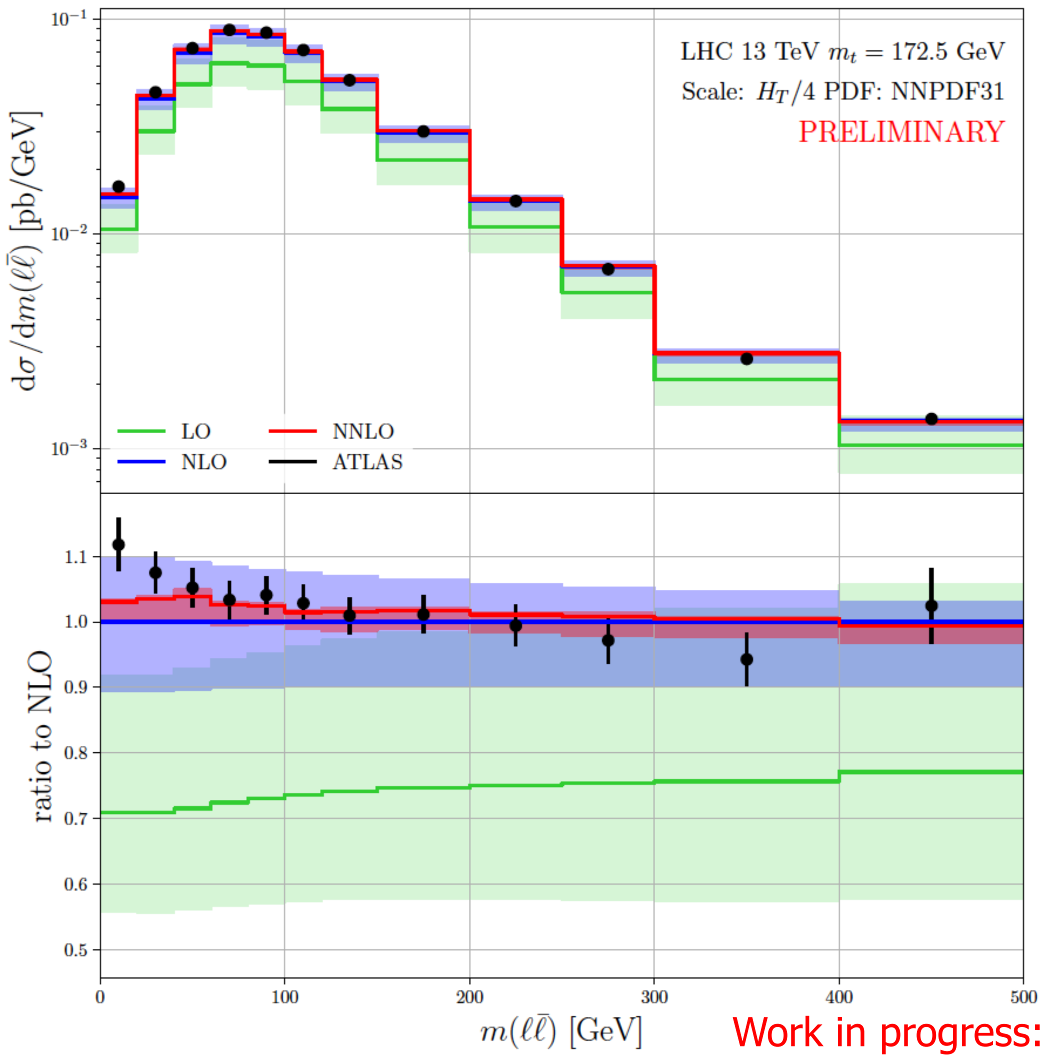


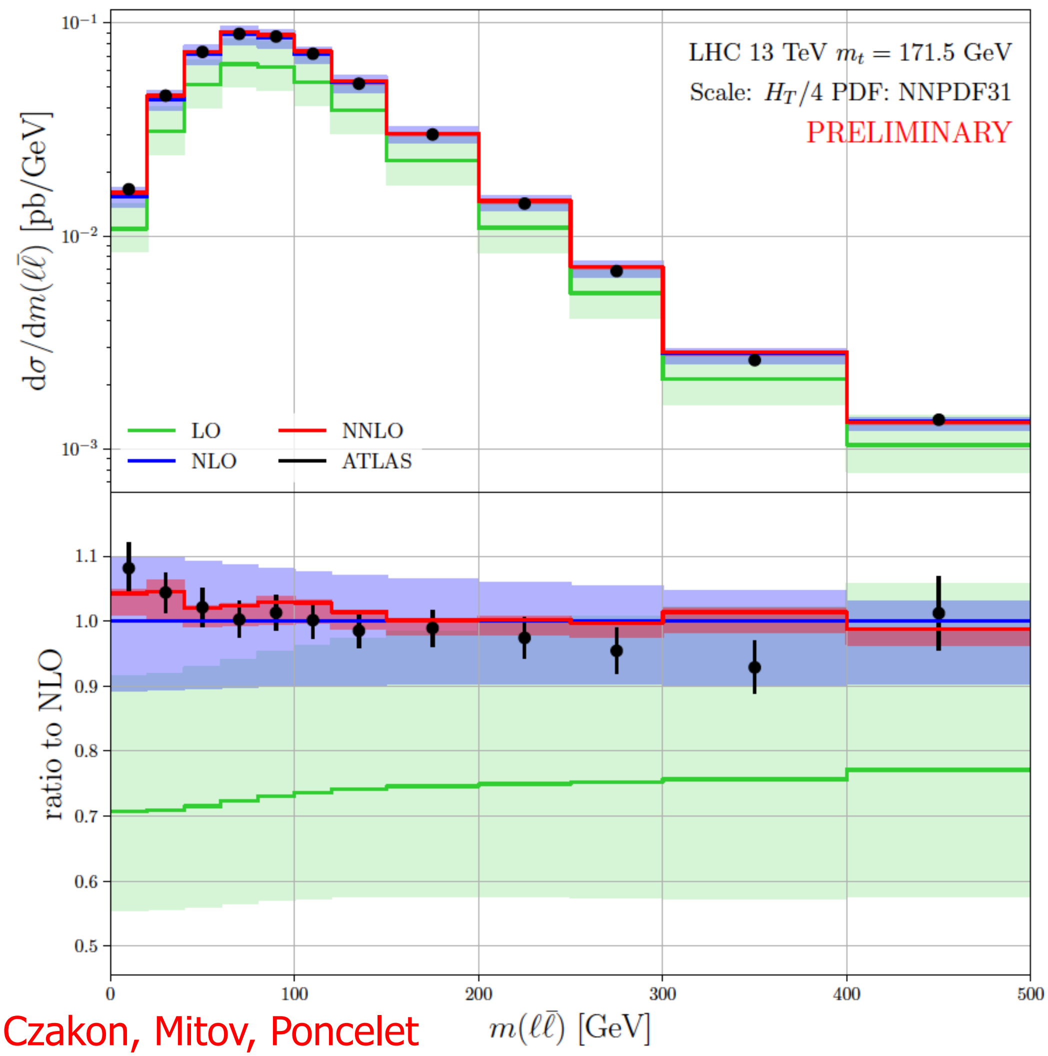
Work in progress: Czakon, Mitov, Poncelet

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 determin'n)

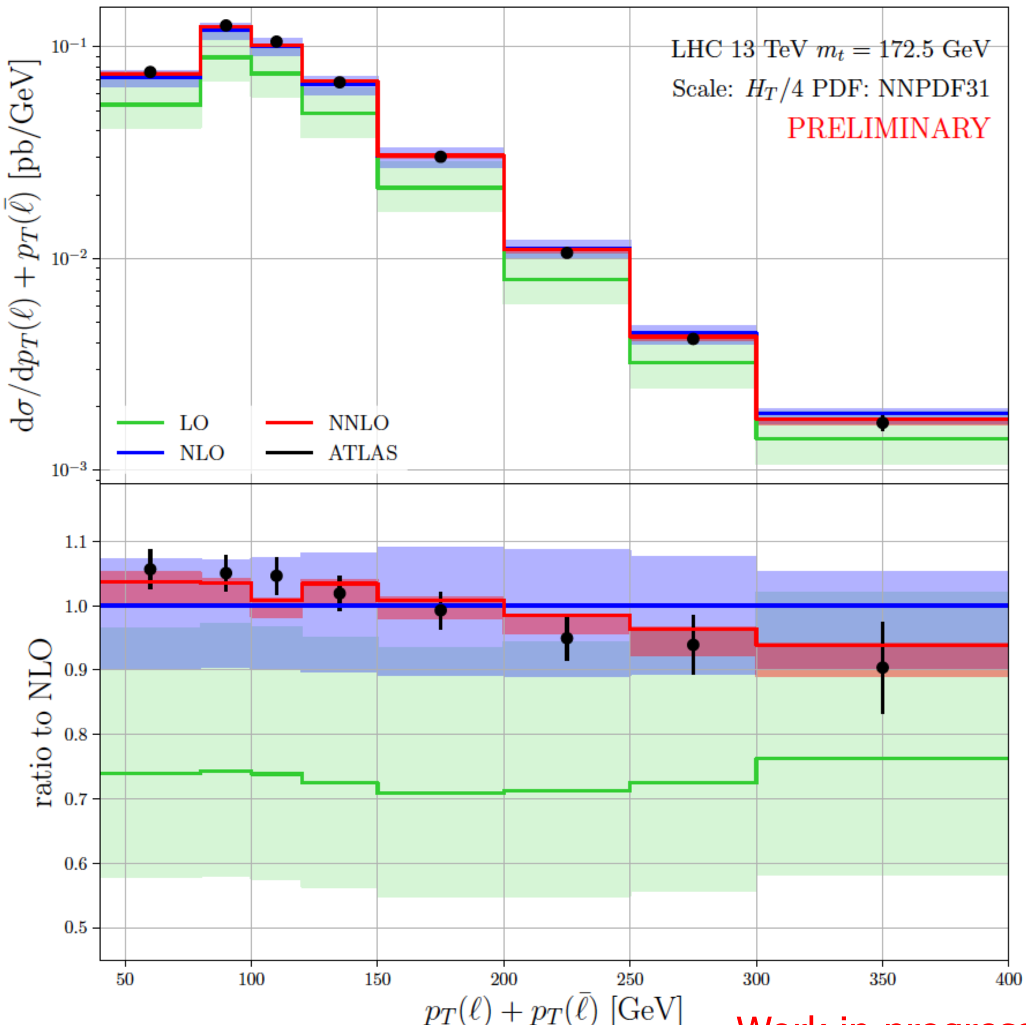


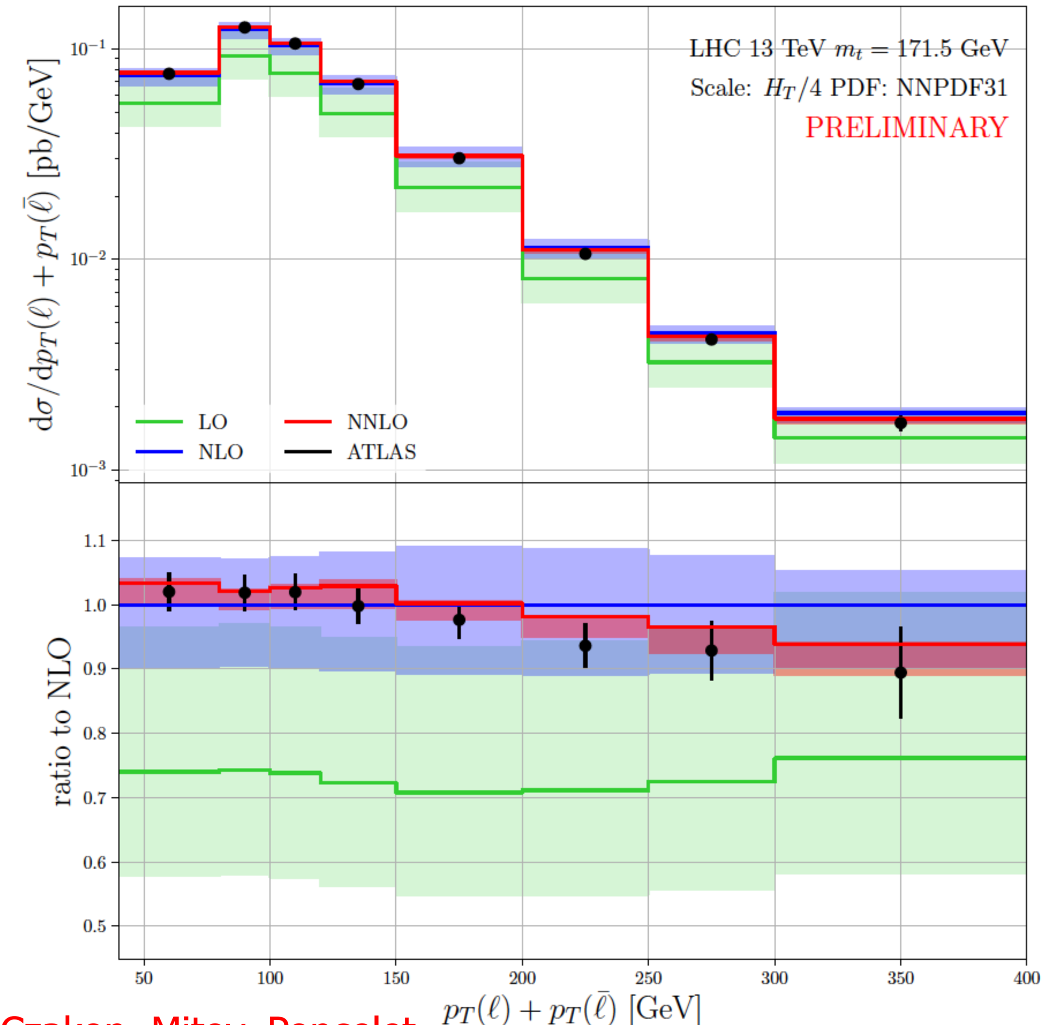


Work in progress: Czakon, Mitov, Poncelet

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'n)

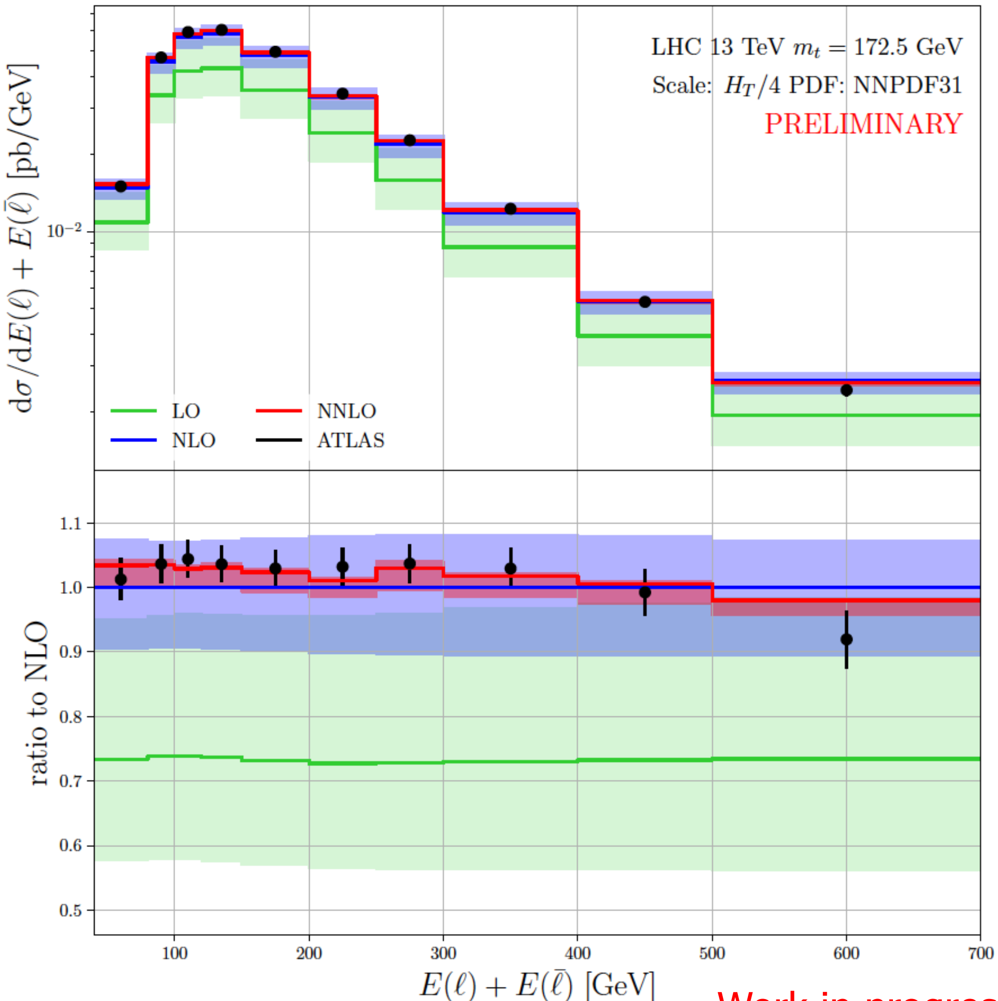


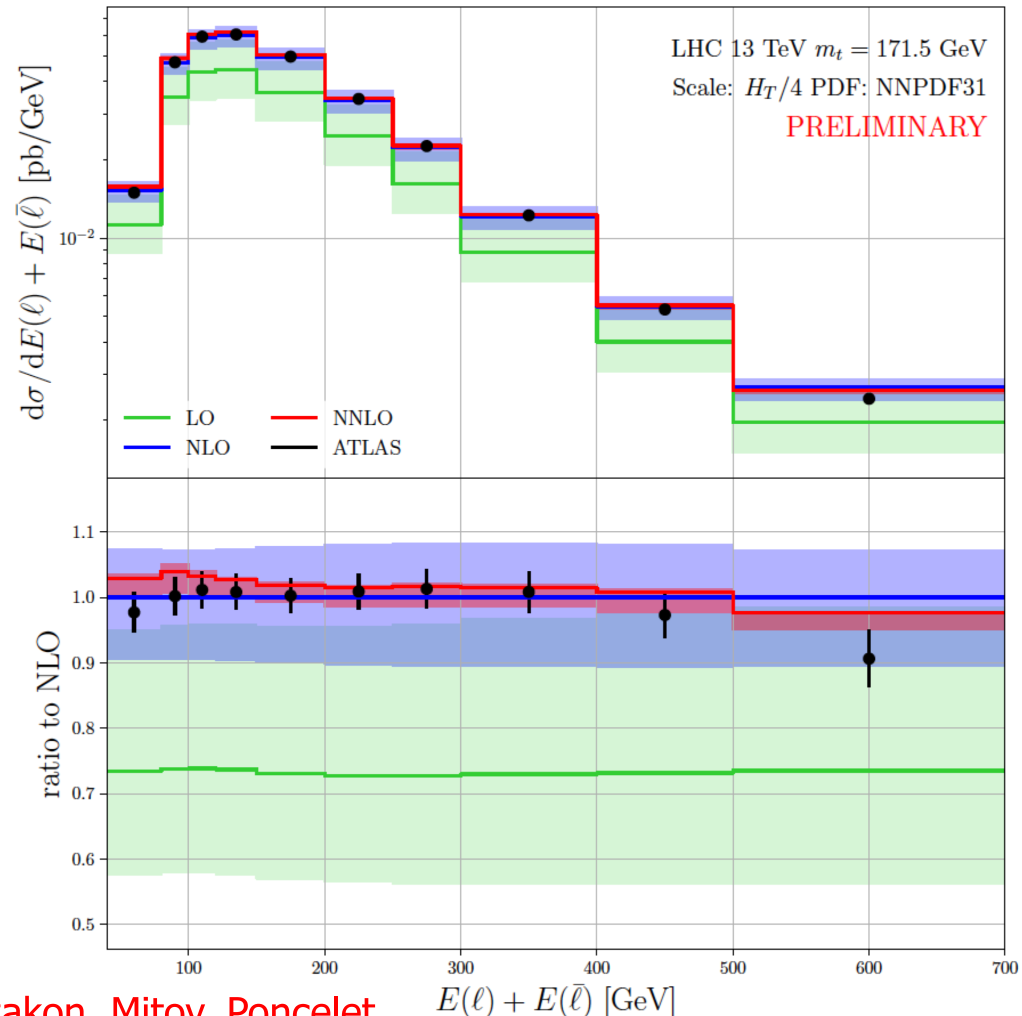


Work in progress: Czakon, Mitov, Poncelet

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'n)

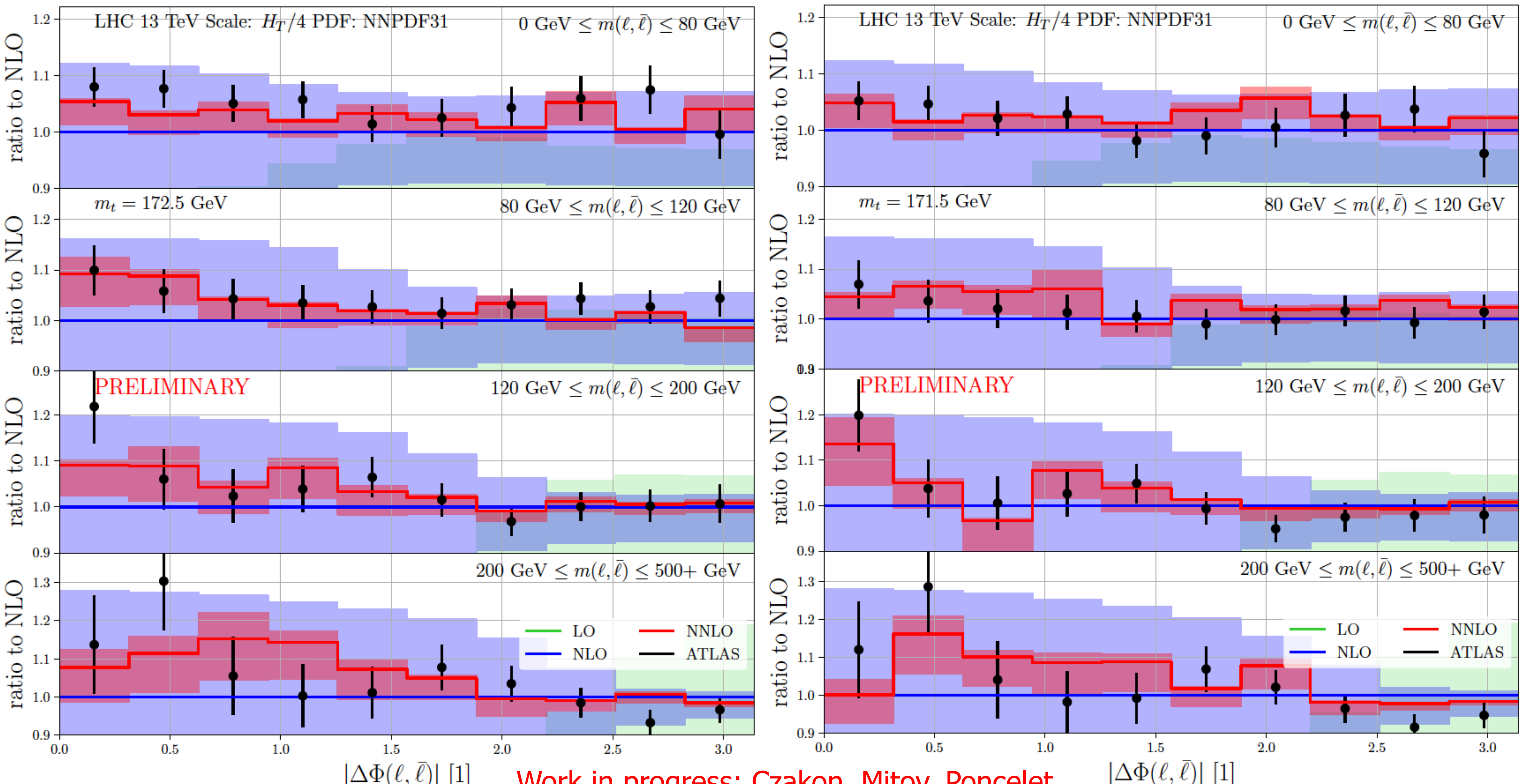




Work in progress: Czakon, Mitov, Poncelet

NNLO QCD vs ATLAS data: 2-dim

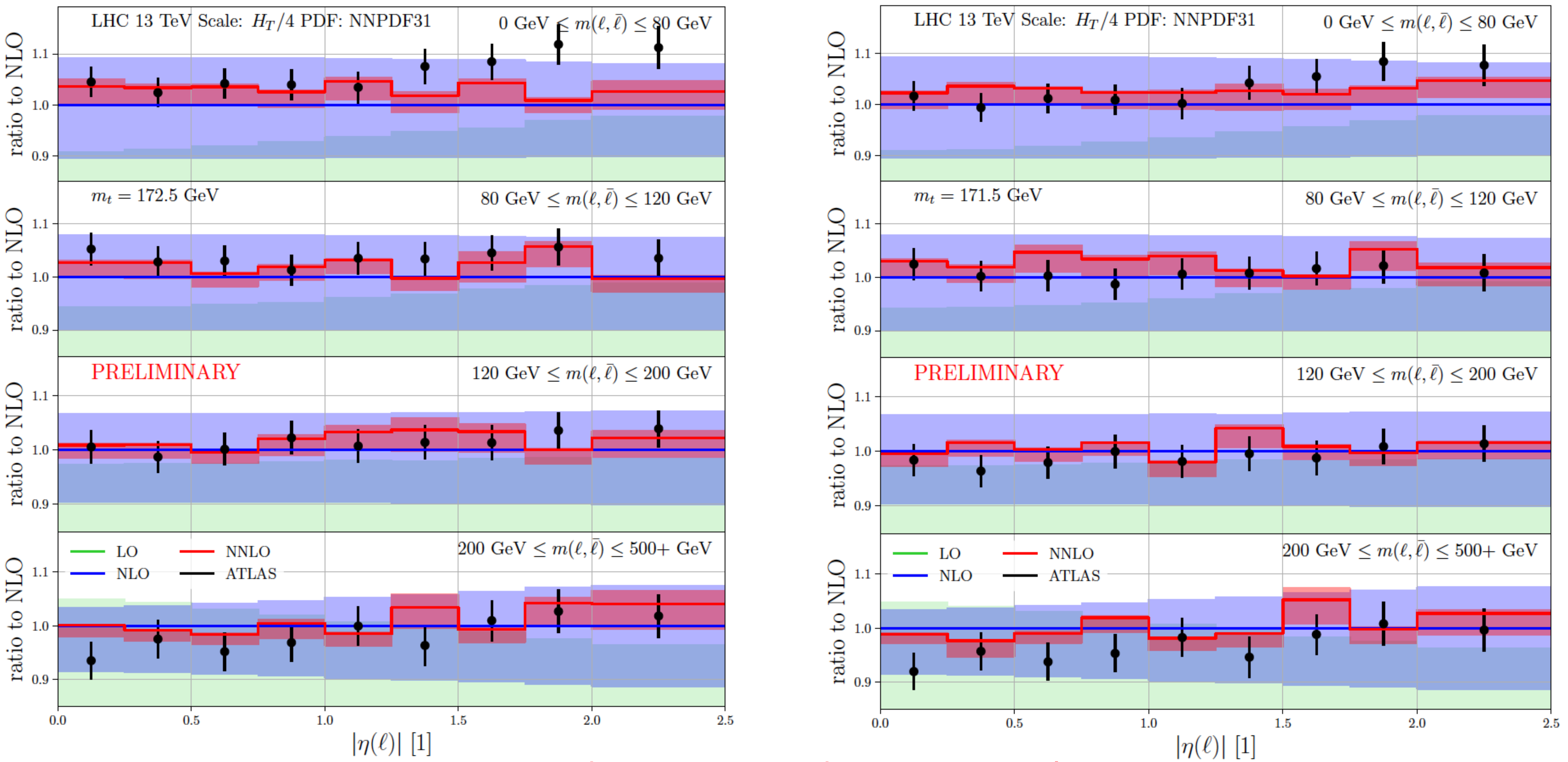
- ✓ Δφ vs. m(tt) (others are computed, too, not shown)
  - ✓ Great reduction of scale error at NNLO (vs NLO). Mostly small K-factors
  - ✓ Both m_t=171.5GeV and m_t=172.5GeV seem to work
  - ✓ Improved MC error required to draw quantitative conclusion (m_t sensitivity is apparent)



Work in progress: Czakon, Mitov, Poncelet

NNLO QCD vs ATLAS data: 2-dim

- ✓ eta(lepton) vs. m(tt) (others are computed, too, not shown)
  - ✓ Great reduction of scale error at NNLO (vs NLO). Mostly small K-factors
  - ✓ 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 data taken from arXiv:1811.06625
- ✓ Here is our implementation of fiducial phase space:
  - Exactly two oppositely charged leptons (four channels: e^+e^-,mu^+mu^-,e^+mu^-, e^-mu^+) with
    - p_T > 20 GeV and |eta| < 2.4
    - m(ll) > 20 GeV
  - At least two b-jets with p_T > 30 GeV and |eta| < 2.4.
  - Jets are well-separated from leptons: ΔR(jet,lepton) > 0.4 for all charged leptons

- Unfortunately, we find no agreement with the CMS measurements.
- The magnitude of the disagreement suggest that, most likely, the fiducial volume definition above is not an apples-to-apples comparison.
- Further discussion on how to make an apples-to-apples comparison needs to happen.

On the tt~ threshold region

- The threshold region $M_{tt} \sim 2m_t$ is of significant interest:
  - Dominant m_t dependence
  - Significant EW corrections, in particular due to Higgs

CMS, arXiv:1907.01590 (Top Yukawa constraint)

  - Significant higher order effects (kinematics) due to:
    - tt bound state effects
    - Soft-gluon emissions

Bonciani, Catani, Mangano, Nason '96
Petrelli, Cacciari, Greco, Maltoni, Mangano '97
Hagiwara, Sumino, Yokoya '08
Kiyo, Kuhn, Moch, Steinhauser, Uwer '09
Beneke, Falgari, Schwinn '10
Ju, Wang, Wang, Xu, Xu, Yang '19

- It has been understood and appreciated for a long time that bound-state effects in tt~ production near threshold must be factorized and resummed in order to have a finite cross-section beyond NNLO in QCD.

- How big are these effects?

- A detailed measurement of the M_{tt} spectrum at the LHC can be very useful. Unfortunately, the bin size is restricted by resolution…

- ✓ A first attempt (to the best of my knowledge) at doing this at hadron colliders was done more than 20 years ago

Catani, Mangano, Nason, Trentadue '96
Bonciani, Catani, Mangano, Nason '98

- ✓ The total inclusive cross-section was studied at NLO. It was found that these "Coulomb" contributions resum to 1% effect, i.e. they are completely negligible.

- ✓ Even at NNLO their effect is negligible

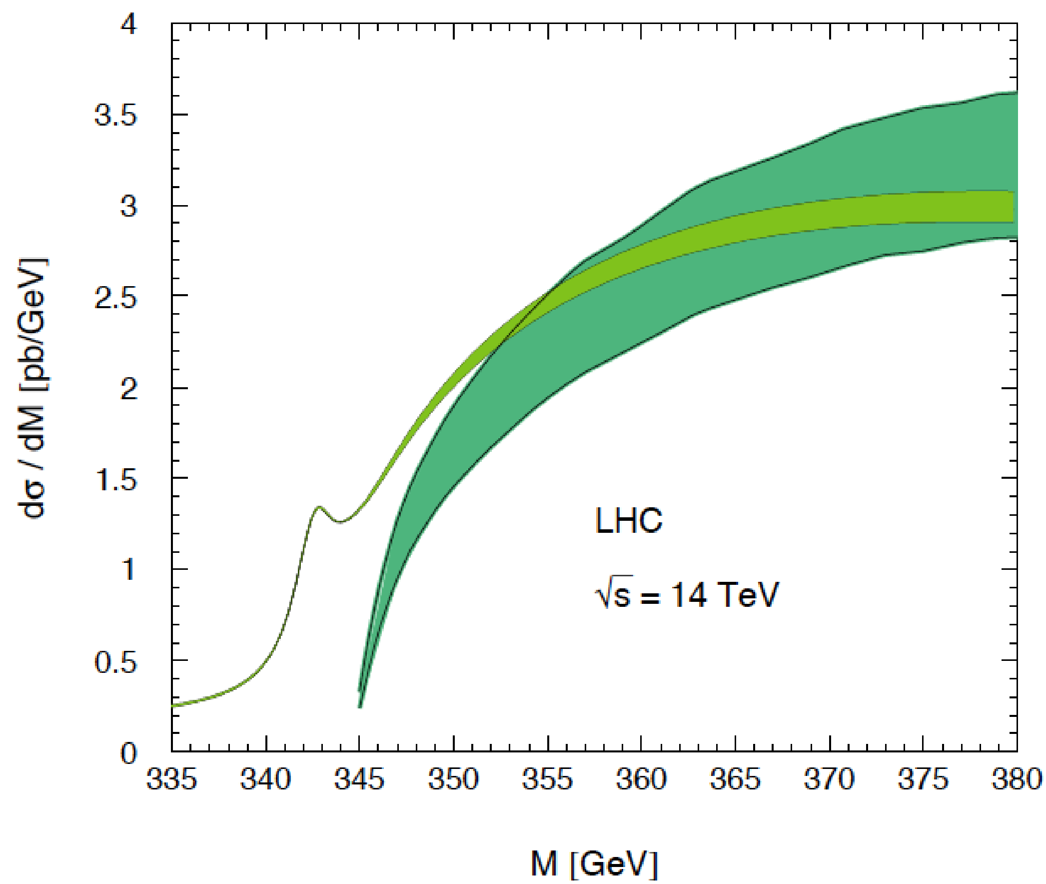
- ✓ A question remains: what is their impact on less inclusive observables, in particular, close to threshold?

- ✓ A rather detailed study was performed in

Hagiwara, Sumino, Yokoya '08
Kiyo, Kuhn, Moch, Steinhauser, Uwer '09

- ✓ The shape of the M_{tt} spectrum was studied at NLO in an EFT framework

- ✓ What was found was that:
  - ✓ Corrections are large close to threshold
  - ✓ The region where these effects are important is small – probably up to O(10 GeV) away from threshold



✓ A new study has recently appeared

Ju, Wang, Wang, Xu, Xu, Yang '19

✓ They follow an approach very similar to the work of: Kiyo, Kuhn, Moch, Steinhauser, Uwer '09

✓ Emphasis is on bound-state effects, not soft-gluon resummation

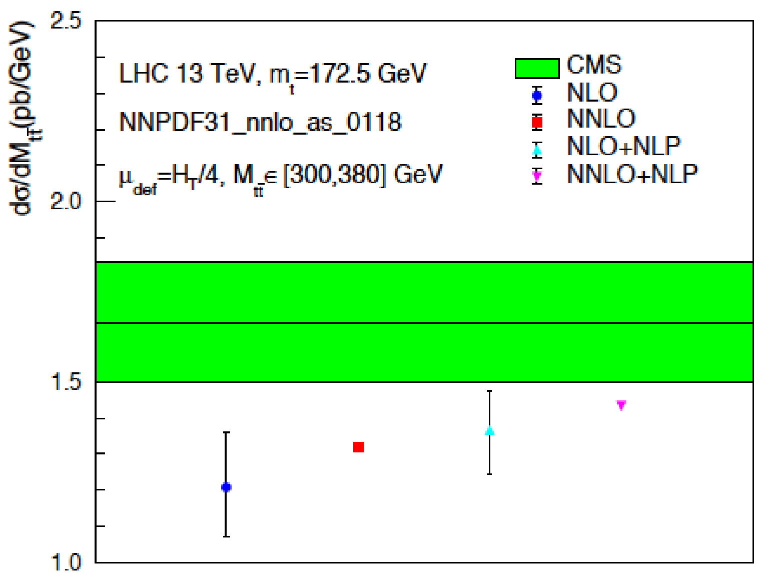
✓ The focus is on the first bin [300,380] GeV of the M_{tt} distribution.

✓ Q: in many tt~ measurements this bin is below data, so could it be due to higher order Coulombic effects? (Or smaller value of m_t?)

✓ The authors find a 9% enhancement in that bin.

✓ This seems significant, given previous work.

✓ It is an interesting finding that deserves further attention.



✓ Q: Can this be an artefact of the matching? Experience with resummation shows that sometimes it can be used beyond its region of validity. It is not clear (to me) from the paper if this may be the case here.

✓ Ultimately precise data will help; trying to determine m_t from differential distribution will make any inconsistency evident.

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 used in top physics (and beyond)
  - ➢ Ultimately, test to unparalleled precision the SM in the top quark sector
- ✓ Few immediate (and pressing!) lessons:
  - ❖ At such high level of precision everything matters. Given Fixed Order calculations may well be more reliable in describing leptonic distributions than showered MC's, an effort must be made to connect such calculations to data.
  - ❖ This is tricky given the amount of interpolation/modeling used in measurements.
  - ❖ But it needs to be done. It can be done. And I think this Workshop can be a beautiful beginning.