Progress in 2→2 and 2→3 NNLO LHC calculations and BSM applications

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Outline

- ✓ 2→2 processes
  - ➢ Update on NNLO top-pair production with NNLO decay
  - ➢ Dijet production at NNLO
- ✓ 2→3 processes
  - ➢ 3-photon production at NNLO in QCD
- ✓ Summary

2→2 processes

Top-pair production and decay in NWA

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

First complete calculation of top-pair production and decay, both at NNLO in QCD

The new kid on the block: ttbar spin correlations

ATLAS

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Updates

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Physics Briefing

Tags: top quark, TOPQ group, ICHEP2018, Physics Results

Precision leads to puzzles

Top quarks spin together more than they should, according to this new ATLAS result.

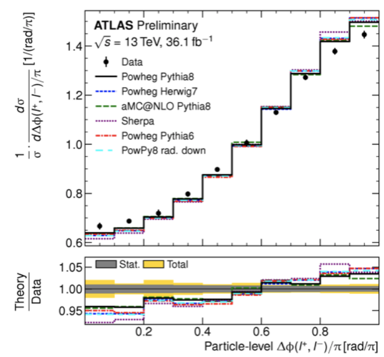
By ATLAS Collaboration, 6th July 2018

The top quark is a unique particle due to its phenomenally high mass. It decays in less than 10-24 seconds, that is, before it had time to interact with any other particles. Therefore many of its quantum numbers, such as its spin, are transferred to its decay particles. When created in matter-antimatter pairs, the spins of the top quark and the antitop quark are expected to be correlated to some degree.

By measuring the angles between the top and antitop decay particles, ATLAS has not only measured this degree of correlation, but found it to be higher than what is predicted by calculations based on the Standard Model.

A long standing mystery

This is not the first time that LHC experiments have probed spin correlation in top events. Both ATLAS and CMS have previously published measurements using the same observable and also found the spin correlation to be higher than expected, but at the time did not have sufficient precision to make a statement. This new result has significantly reduced uncertainty due to a much better understanding of the detector and the vast amount of data now available at the LHC.



The observable used to extract the spin correlation compared to different predictions where the slope in the data (points) relative to the predictions (curves) indicates higher spin correlation. (Image: ATLAS Collaboration/CERN)

So what could it be? What could make top quarks spin together more than they should?

New physics or poor modelling?

ttbar spin correlations

- Some background:

$$|\mathcal{M}(pp \to t\bar{t} \to (\ell^+\ell - \nu\bar{\nu} b\bar{b})|^2 \sim \mathrm{Tr}[\rho R \bar{\rho}]$$

$$R \sim \underbrace{\bar{A}\mathbb{1}\otimes\mathbb{1}}_{\text{spin-averaged}} + \underbrace{\bar{B}_i^+\sigma^i\otimes\mathbb{1} + \bar{B}_i^-\mathbb{1}\otimes\sigma^i}_{\text{top-quark polarization}} + \underbrace{\bar{C}_{ij}\sigma^i\otimes\sigma^j}_{\text{spin-correlation}}$$

  - Individual top quarks are produced unpolarized
  - However the spins of the two top quarks in the pair are strongly correlated
  - Since the top decays very fast (the only quark we could observe as a bare quark) its spin information is passed to its decay products
  - Measuring distributions of decay products one can see the imprint of these spin correlations

- Why is this observable interesting? It can help differentiate non-SM contributions to top pair production:

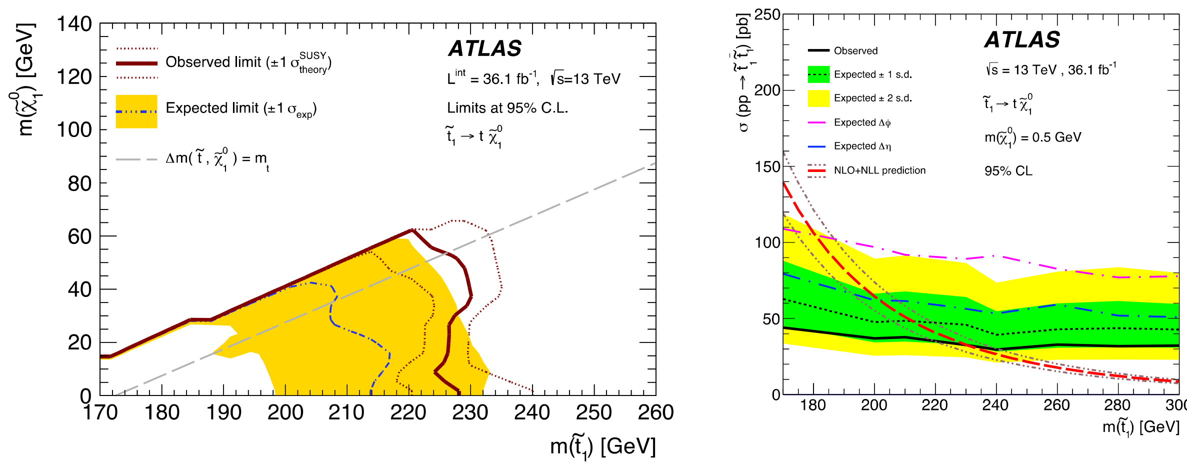
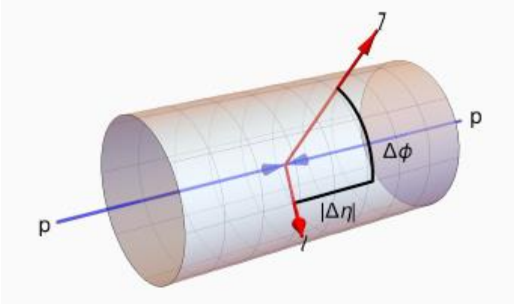


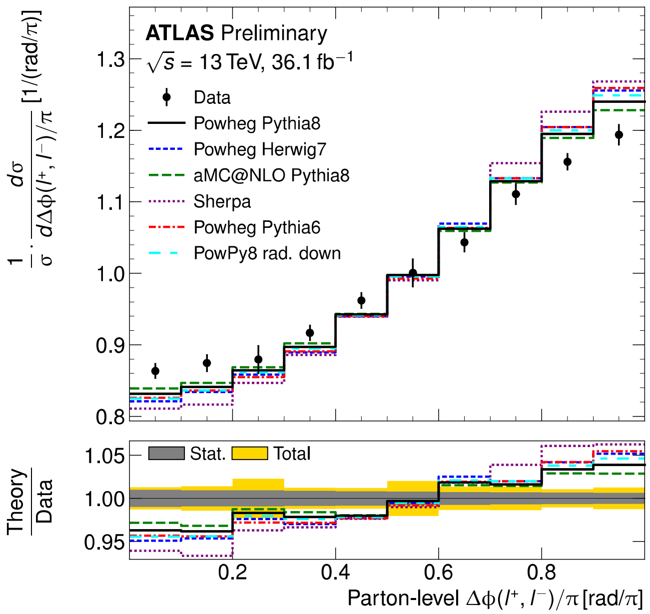
Figure 7 – Left: observed and expected 95% CL exclusion in the plane of $m_{\tilde{t}}$ and $m_{\rm LSP}$ [7]. Right: limits on the $\tilde{t}\tilde{t}^*$ cross section at 95% CL as a function of $m_{\tilde{t}}$, assuming $m_{\rm LSP} = 0.5$ GeV. The expected limits when using the $|\Delta\phi_{\ell\ell}|$ and $|\Delta\eta|$ distributions alone are shown by the magenta and blue dashed lines, respectively [7].

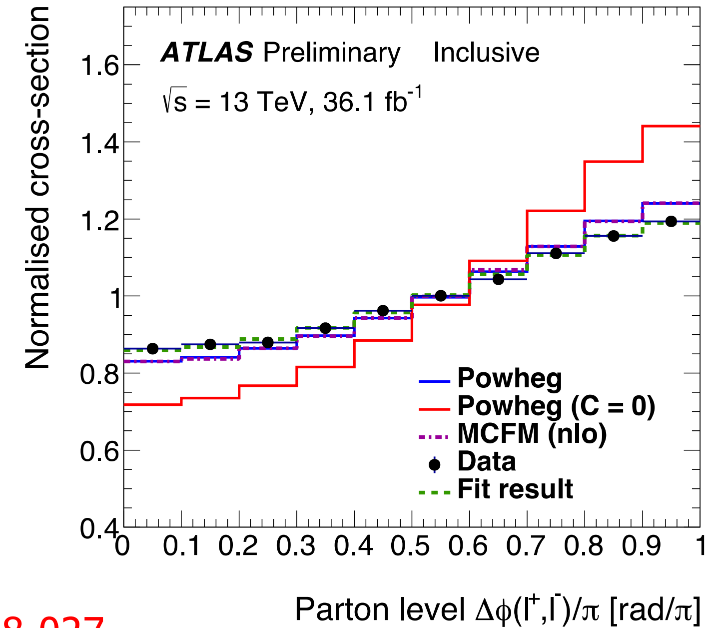
From arXiv:1905.08634

ttbar spin correlations



- ✓ In principle the full spin density matrix can be measured
- ✓ However, precision is low (since special frames are needed)
- ✓ To improve precision, use lab-frame distributions (they mix spin-correlation with kinematics)
- ✓ Best candidate: $\Delta\varphi$ - the angle between the two leptons in the transverse plane





ATLAS-CONF-2018-027

Region	f_{SM}	Significance (incl. theory uncertainties)
$m_{t\bar{t}} < 450$ GeV	$1.11 \pm 0.04 \pm 0.13$	0.85 (0.84)
$450 < m_{t\bar{t}} < 550$ GeV	$1.17 \pm 0.09 \pm 0.14$	1.00 (0.91)
$550 < m_{t\bar{t}} < 800$ GeV	$1.60 \pm 0.24 \pm 0.35$	1.43 (1.37)
$m_{t\bar{t}} > 800$ GeV	$2.2 \pm 1.8 \pm 2.3$	0.41 (0.40)
inclusive	$1.250 \pm 0.026 \pm 0.063$	3.70 (3.20)

Significant deviation!

ttbar spin correlations

- ✓ So, what's the explanation?

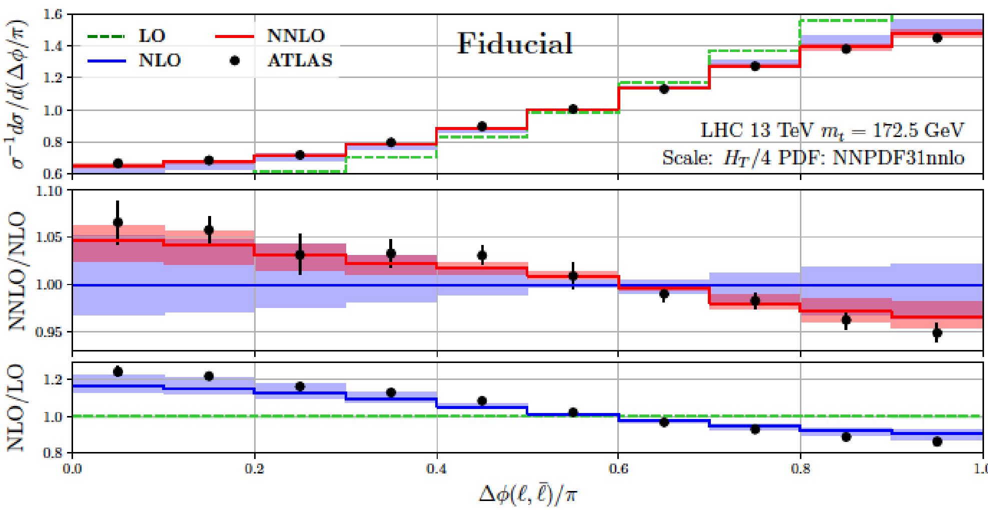
- ✓ Months after ATLAS published, the NNLO calculation with top decay also at NNLO appeared

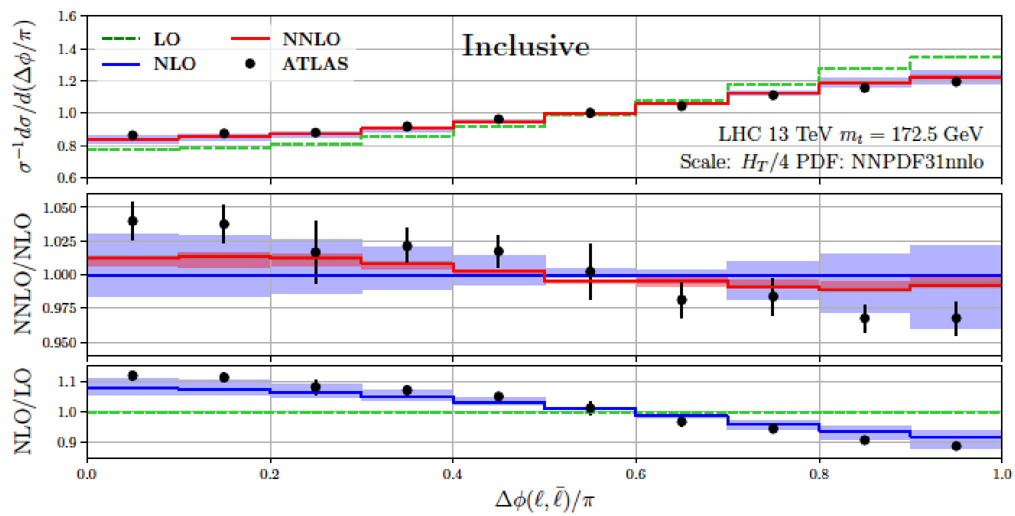
Behring, Czakon, Mitov, Papanastasiou, Poncelet arXiv:1901.05407

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

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

- ✓ What we found was very surprising:





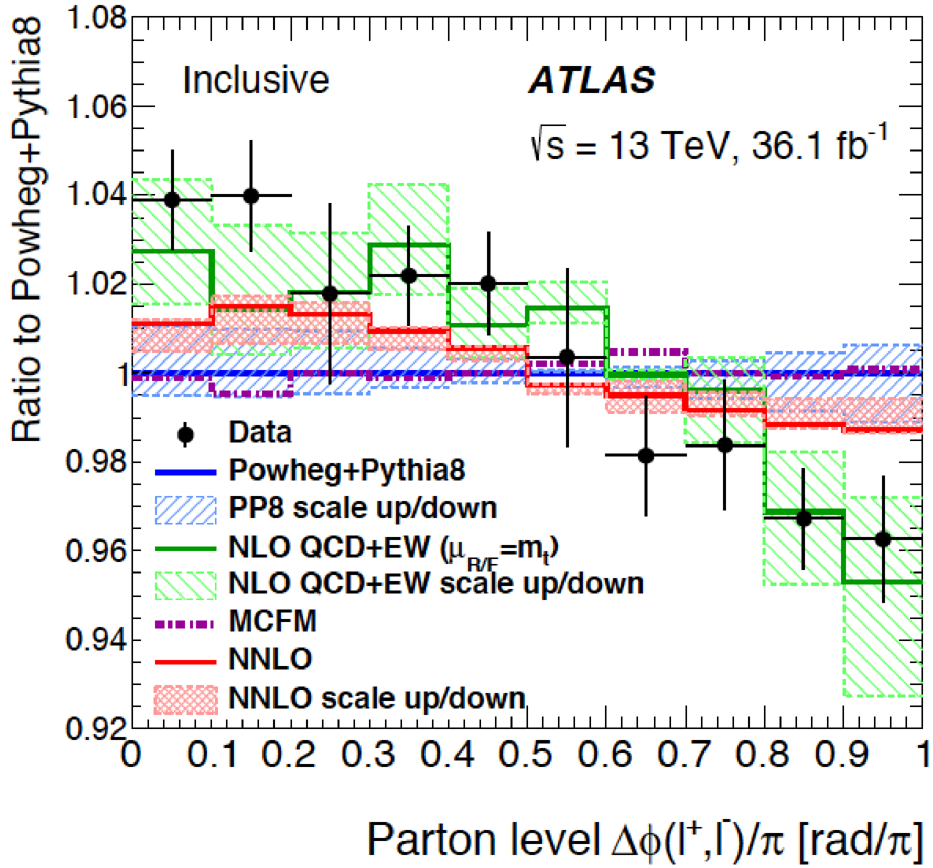
- ✓ NNLO describes the data in fiducial volume but not in the inclusive one! How can that be?

ttbar spin correlations

✓ We concluded that the only explanation is that the MC modeling used in ttbar modeling is not precise enough and we see deviations there

✓ An important effect due to MC modeling is observed. Likely to bring to scrutiny the precision of existing MC generators and further motivate NNLO showers

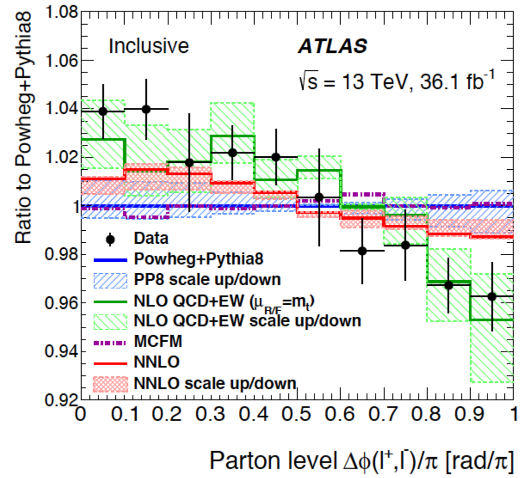
✓ After our paper appeared, ATLAS published an update: use Inclusive selection only + the following plot:



ATLAS: arXiv:1903.07570

ttbar spin correlations

- ✓ The mystery deepens!
- ✓ The green band is a private calculation by Bernreuter et al
- ✓ It is NLO + EW. But we checked this cannot account for it
- ✓ So why the green curve seem to agree with data?



ATLAS: arXiv:1903.07570

- ✓ Turned out the green curve is computed by perturbative expansion of the ratio
- ✓ A normalized distribution at NNLO reads:

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

- ✓ But the ratio R can be expanded in the coupling

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

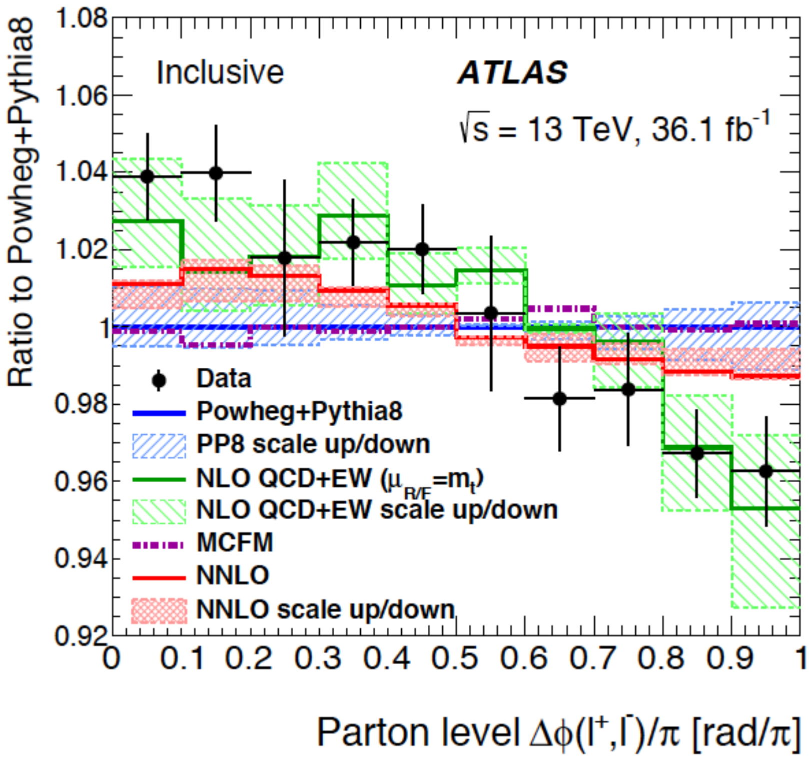
$$R^0 = \frac{1}{\sigma^0} \frac{d\sigma^0}{dX} ,$$

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

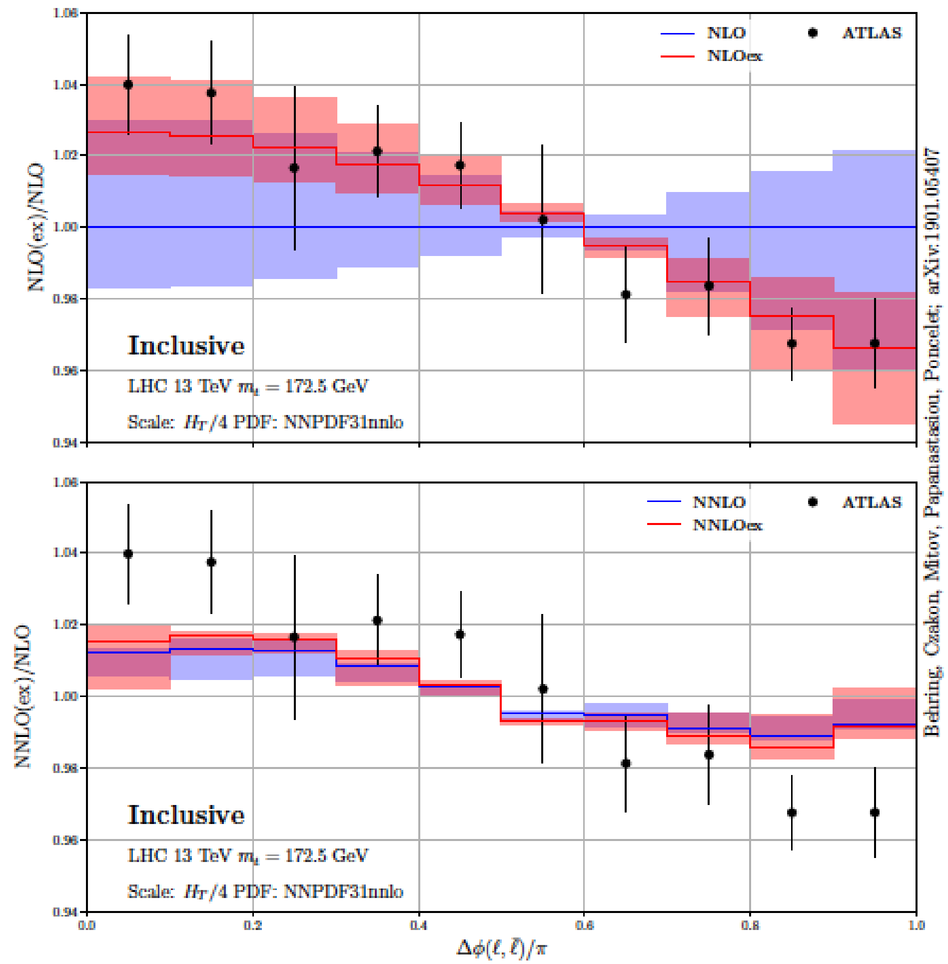
$$R^2 = \frac{1}{\sigma^0} \frac{d\sigma^2}{dX} - \frac{\sigma^1}{\sigma^0} \frac{1}{\sigma^0} \frac{d\sigma^1}{dX} + \left(\left(\frac{\sigma^1}{\sigma^0} \right)^2 - \frac{\sigma^2}{\sigma^0} \right) \frac{1}{\sigma^0} \frac{dX}{dX}$$

ttbar spin correlations

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



ATLAS: arXiv:1903.07570



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

✓ However at NNLO the difference is tiny and thus we conclude there is still no agreement.

✓ A perfect example how NLO can lead to the wrong conclusion and that NNLO is needed!

2→2 processes

Dijet production at NNLO QCD

Czakon, van Hammeren, Mitov, Poncelet arXiv:1907.12911

First complete NNLO calculation of inclusive jet production

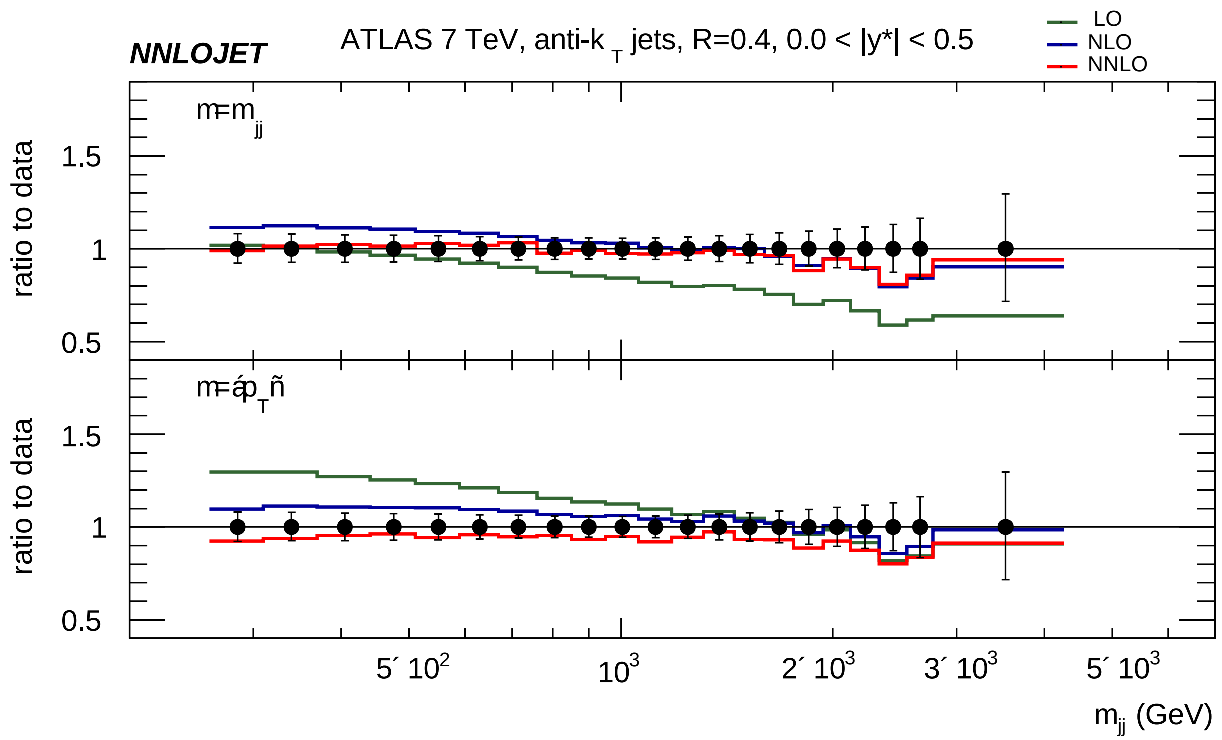
- full color included
- all partonic channels included

Jet production: prior work

✓ A number of publications and results by the NNLOjet collaboration

Currie, Gehrmann-De Ridder, Gehrmann, Glover, Huss, Pires '16-19

- ✓ Computed both dijets and inclusive jet production
- ✓ Studied scale settings in this process



✓ Calculations done within the antenna subtraction formalism
✓ NNLO in leading color approximation (should be sufficiently accurate)
✓ NNLO better than NLO in terms of scale uncertainty and agreement with data
✓ However, strong dependence on the choice of scales.
✓ The prospects for quality theory/data comparison in multi-TeV region is quite promising

Jet production

- ✓ An independent calculation is highly desirable
- ✓ A check on the leading color approximation is needed

- ✓ With this in mind, a brand new calculation of inclusive jet production

Czakon, van Hammeren, Mitov, Poncelet arXiv:1907.12911

- ✓ Calculation within the STRIPPER framework

Czakon, '10

- ✓ Some improvements presented which have already been used in the last two years in top production at NNLO

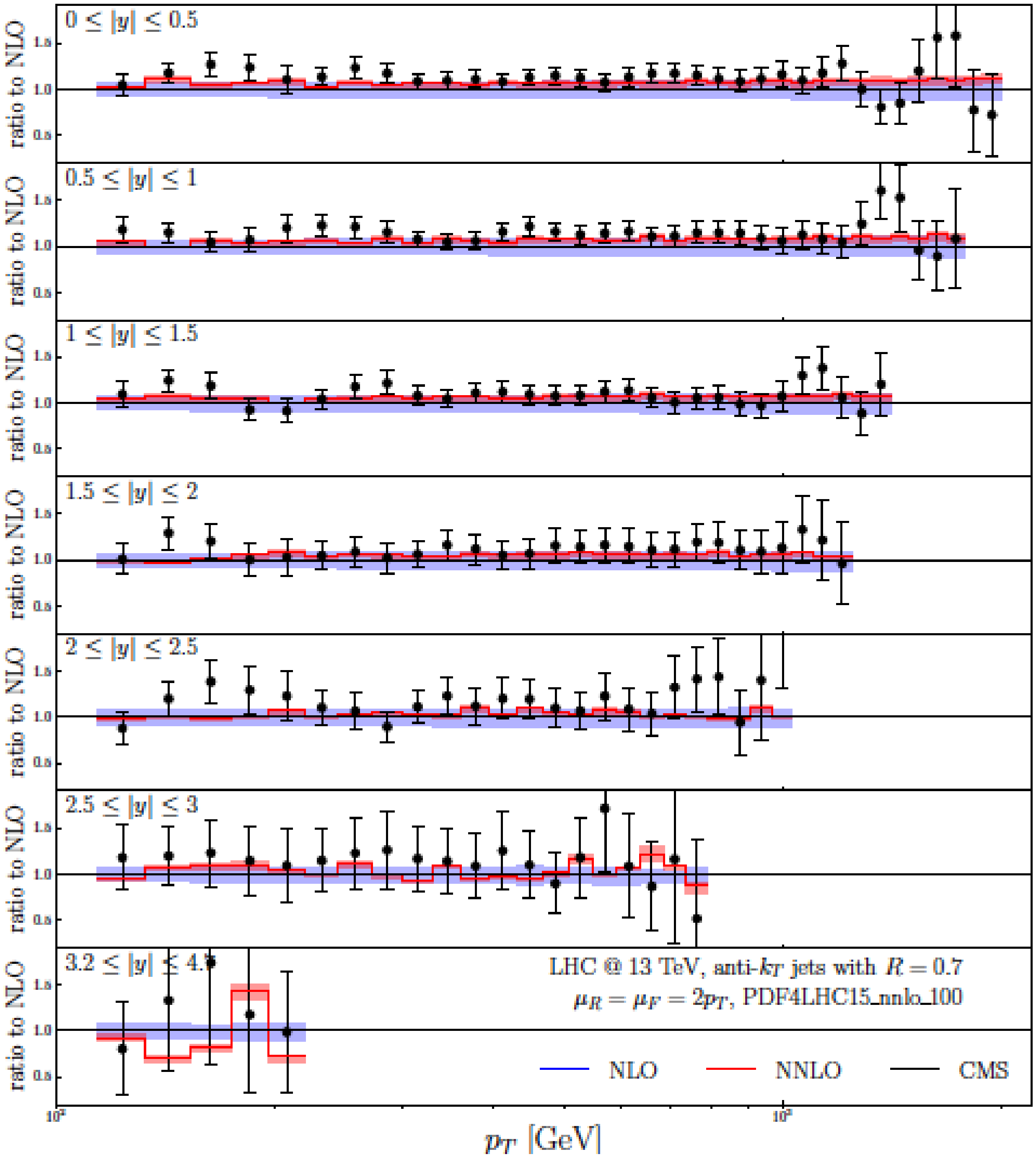
- ✓ Calculation includes:
  - ➢ All partonic channels
  - ➢ Exact in color

- ✓ This is the first complete NNLO jet-production calculation at hadron colliders

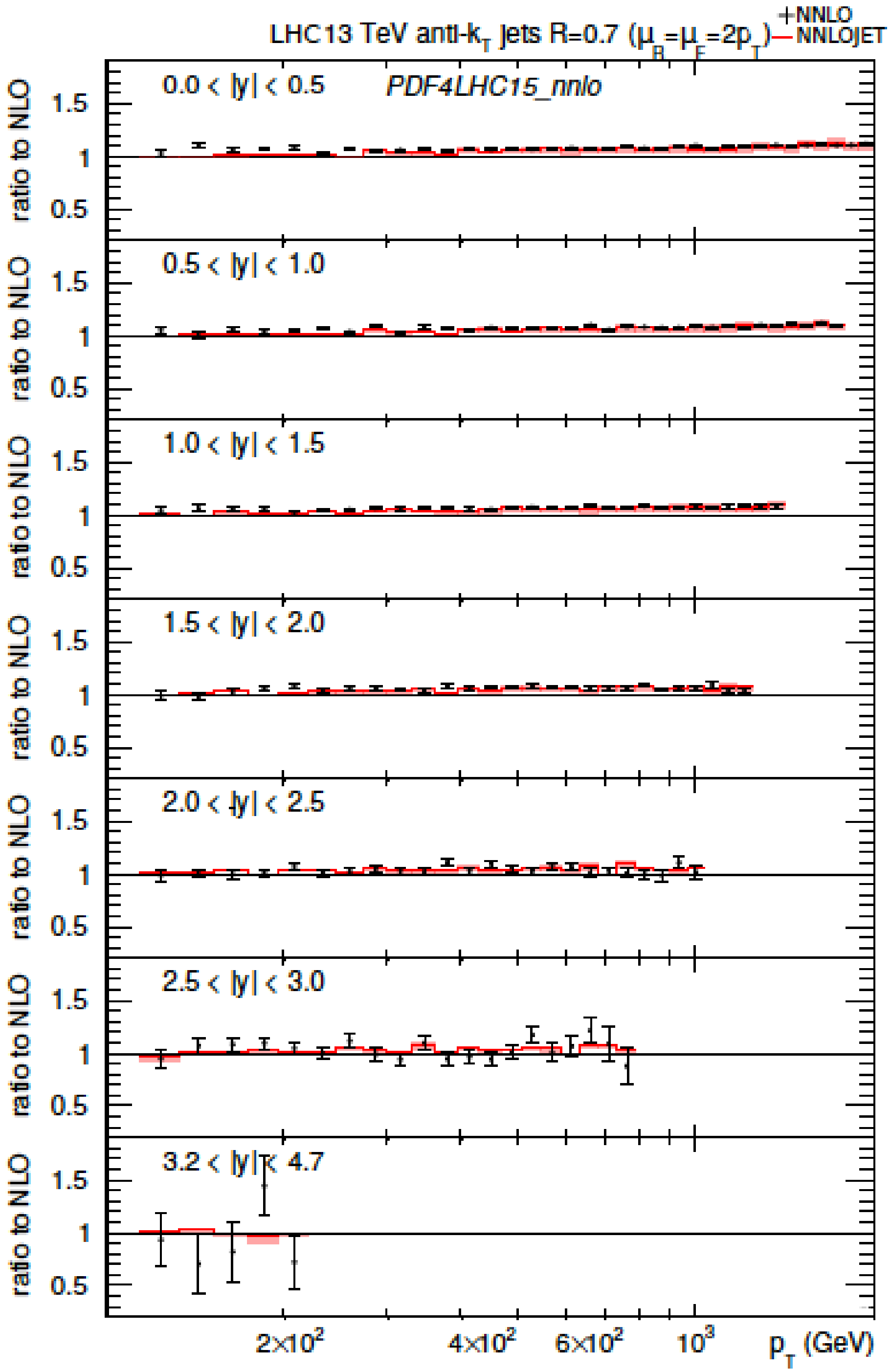
- ✓ Scales: as used by the NNLOjet collaboration

- ✓ NEW: K-factors for each bin published

Jet production: full NNLO vs CMS 13 TeV data



Jet production: full NNLO vs leading color NNLO



Jet production

- ✓ Some notable features:
  - ✓ We have separately checked versus NNLOjet's pure-gluon contribution (with full color) and found agreement
  - ✓ We see fairly good agreement between the two calculations. It is consistent with:
    - ✓ The two calculations agreeing
    - ✓ The subleading color corrections being, indeed, small
  - ✓ The numeric convergence is slow. It scales with the number of events as expected
    - ✓ For this calculation we needed about 350k CPU hours. Increasing it will improve the MC error (which grows at large rapidity)
    - ✓ We believe that for few million CPU hours we can compute all measured distributions (LHC energies, jet sizes, kinematic distributions) with much improved MC quality
    - ✓ A detailed analysis of the dijet invariant mass is possible: improve searches for resonances decaying to hadrons
    - ✓ No fastNLO tables produced in this calculation. But we have the setup in place and could use it if needed (will slightly increase the CPU usage)

2➞3 processes

Towards their first calculation:

3-photon production in NNLO QCD

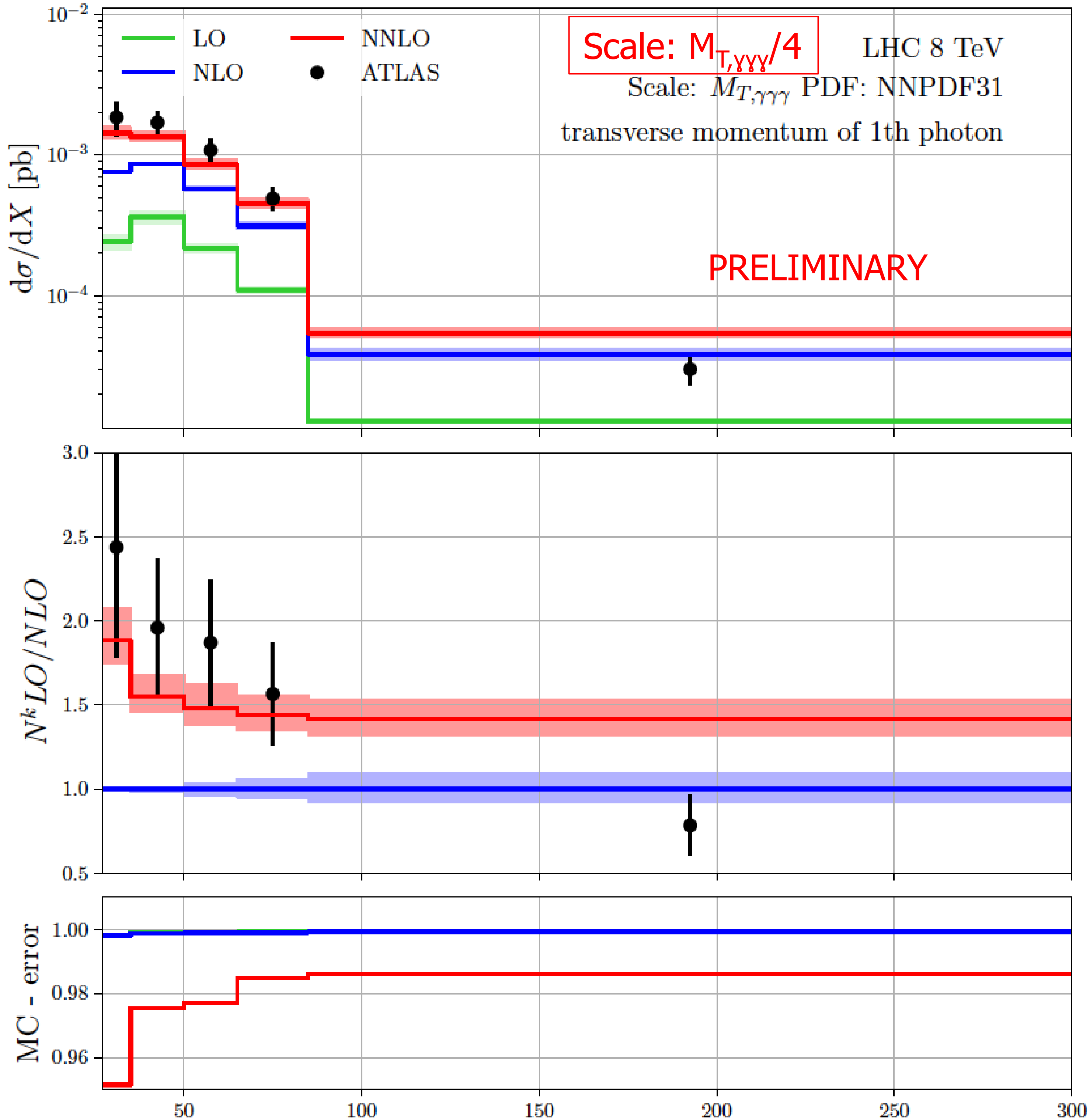
Chawdhry, Czakon, Mitov, Poncelet, in progress

- ✓ As a first application, we are working on the NNLO corrections to 3-photons at the LHC
- ✓ Available detailed differential measurement from ATLAS (8 TeV) arXiv:1712.07291
  - ➢ It shows clear discrepancy between NLO QCD and data
- ✓ Calculation setup:
  - ✓ All channels included
  - ✓ All contributions, except for the 2-loop finite reminder, are included. The plan is to include it in the leading color approximation (subleading non-N_F terms suppressed by $1/N_C^2$)

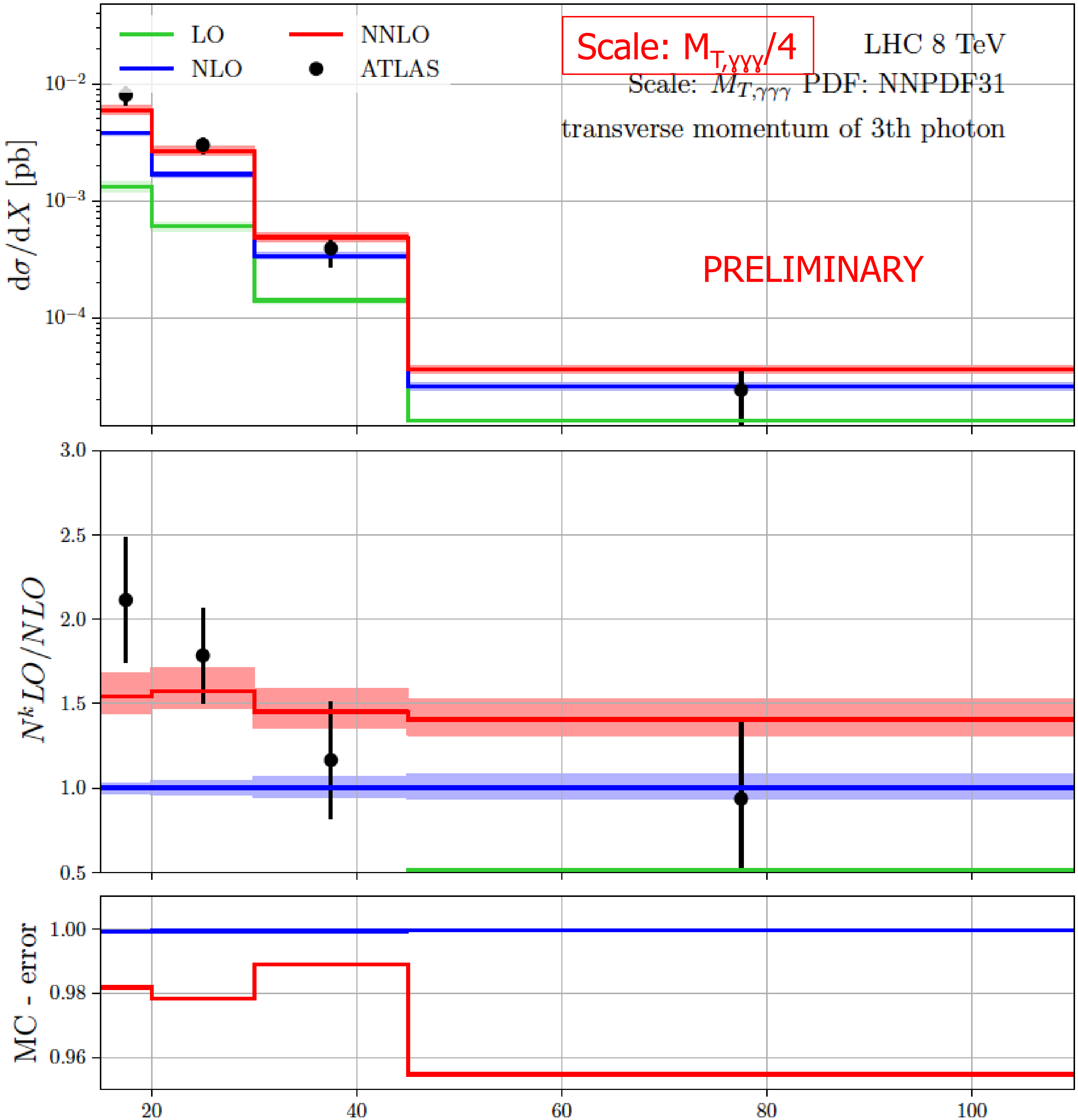
- E_T ($= p_T$) cut for the three photons: $E_{T,\gamma_1} > 27$ GeV, $E_{T,\gamma_2} > 22$ GeV, $E_{T,\gamma_3} > 15$ GeV
- Rapidity: All photons have $|\eta_\gamma| < 2.37$ (+exclusion of $1.37 < |\eta_\gamma| < 1.56$)
- Separation of photons: The angular distance between each two photons ΔR is required to be > 0.45
- Invariant mass: $m_{\gamma\gamma\gamma} > 50$ GeV
- Photon isolation: Using the Frixione isolation [11] as indicated for the MadGraph@NLO setup (see last paragraph in section 3.2. in [1]). This means $R_0 = 0.4$, $E_T^{iso} > 10$ GeV and $\chi(R) = (1 - \cos(\Delta R))/(1 - \cos(\Delta R_0))$.

We use the *NNPDF31_nnlo_as_0118* PDF set and a central scale choice of

$$\mu_0 = \sqrt{p_\gamma^2 + (p_{\gamma,T})^2} \quad \text{with} \quad p_\gamma = \sum_{i=1}^{3} p_{\gamma_i} \, . \tag{3.1}$$



Plot includes everything but the scale-independent part of the 2-loop finite reminder



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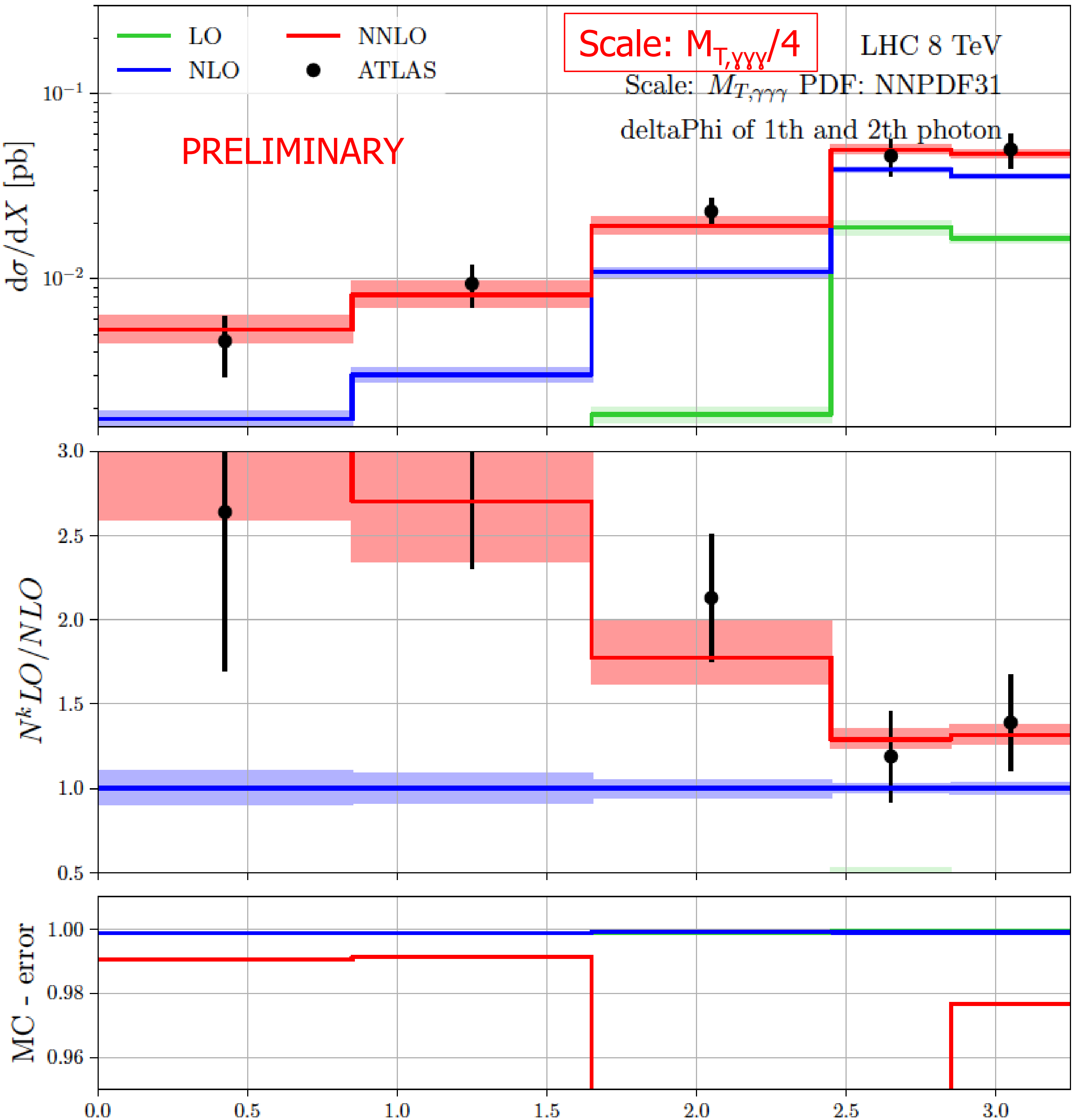

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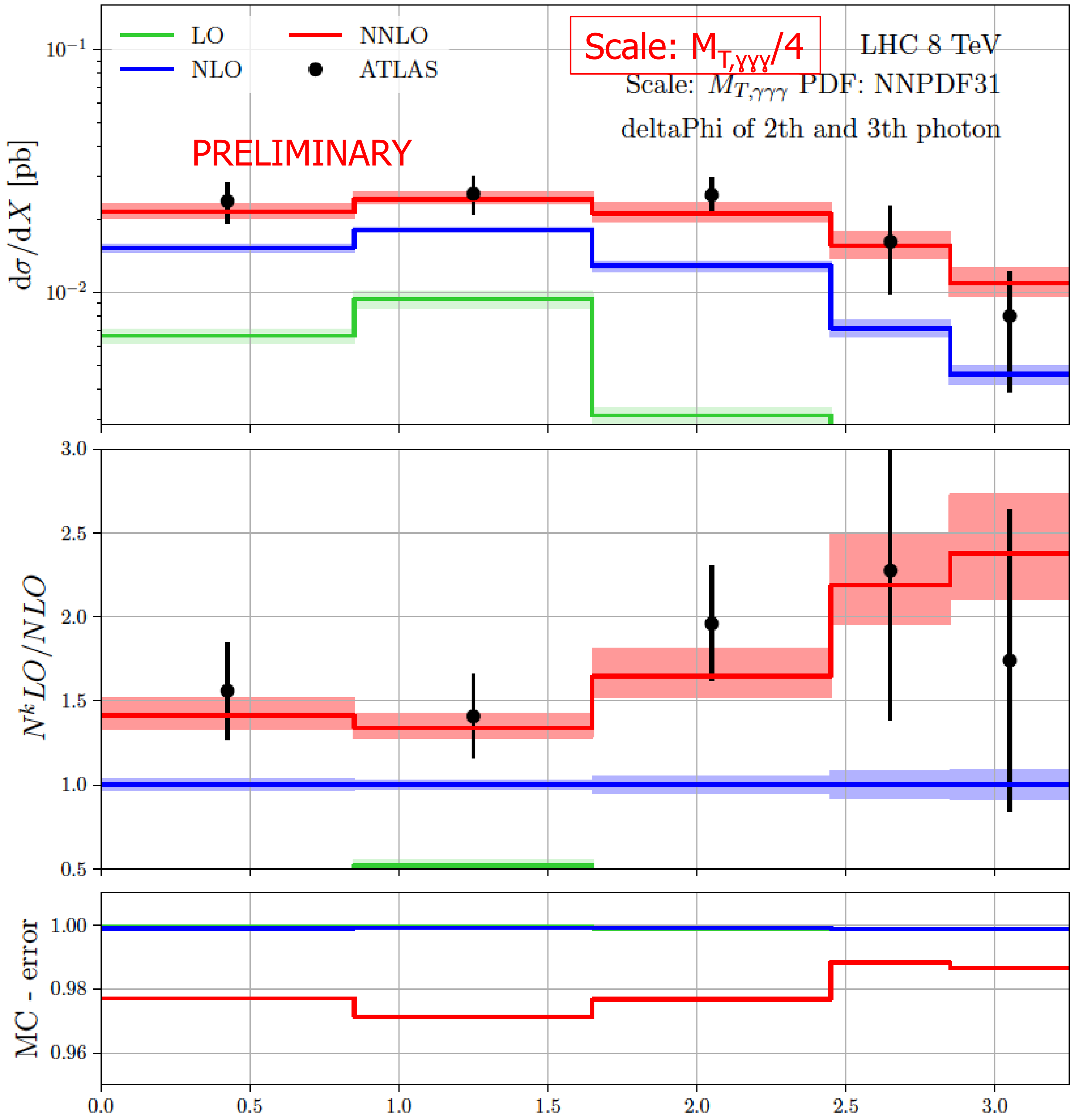

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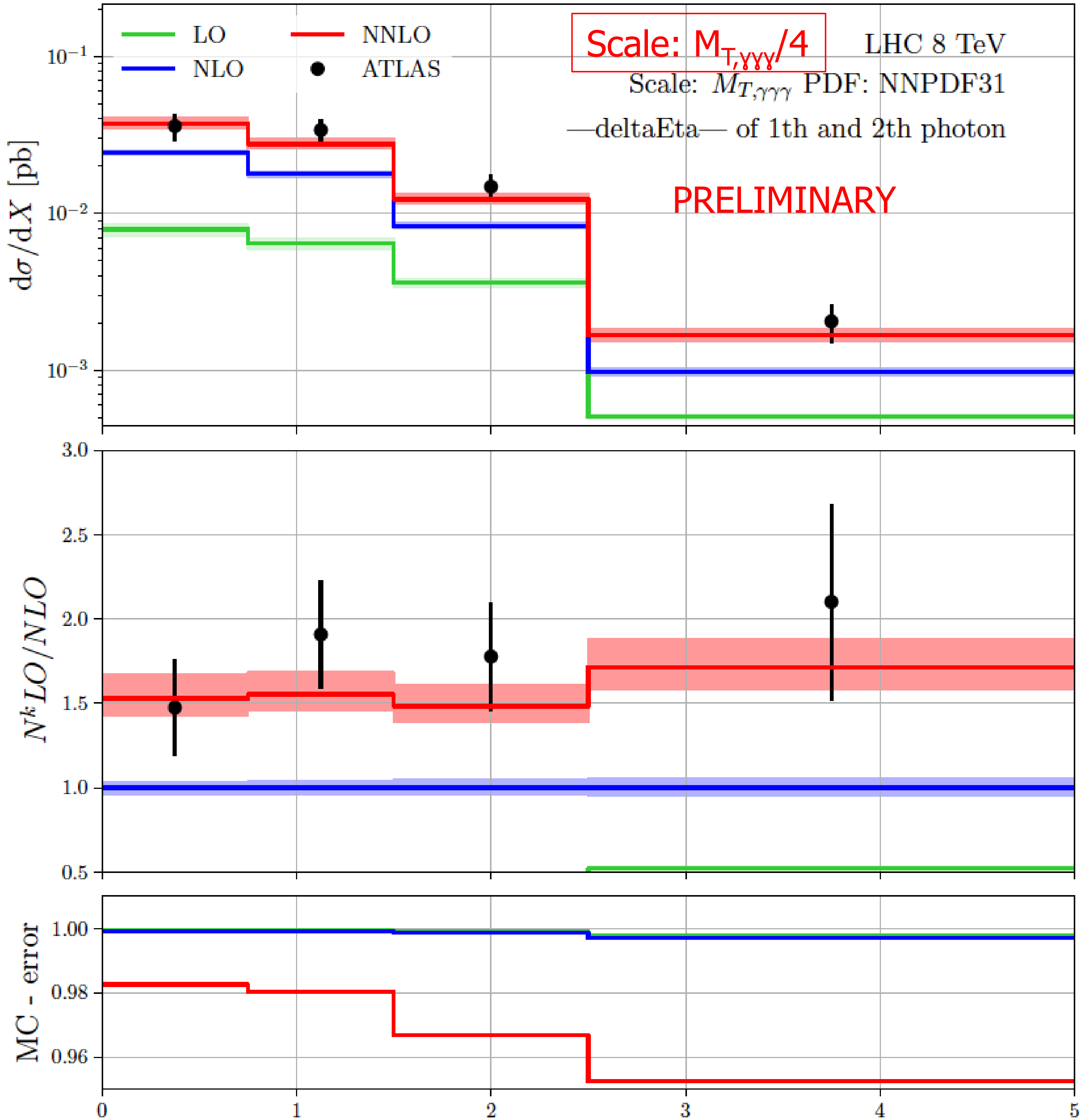

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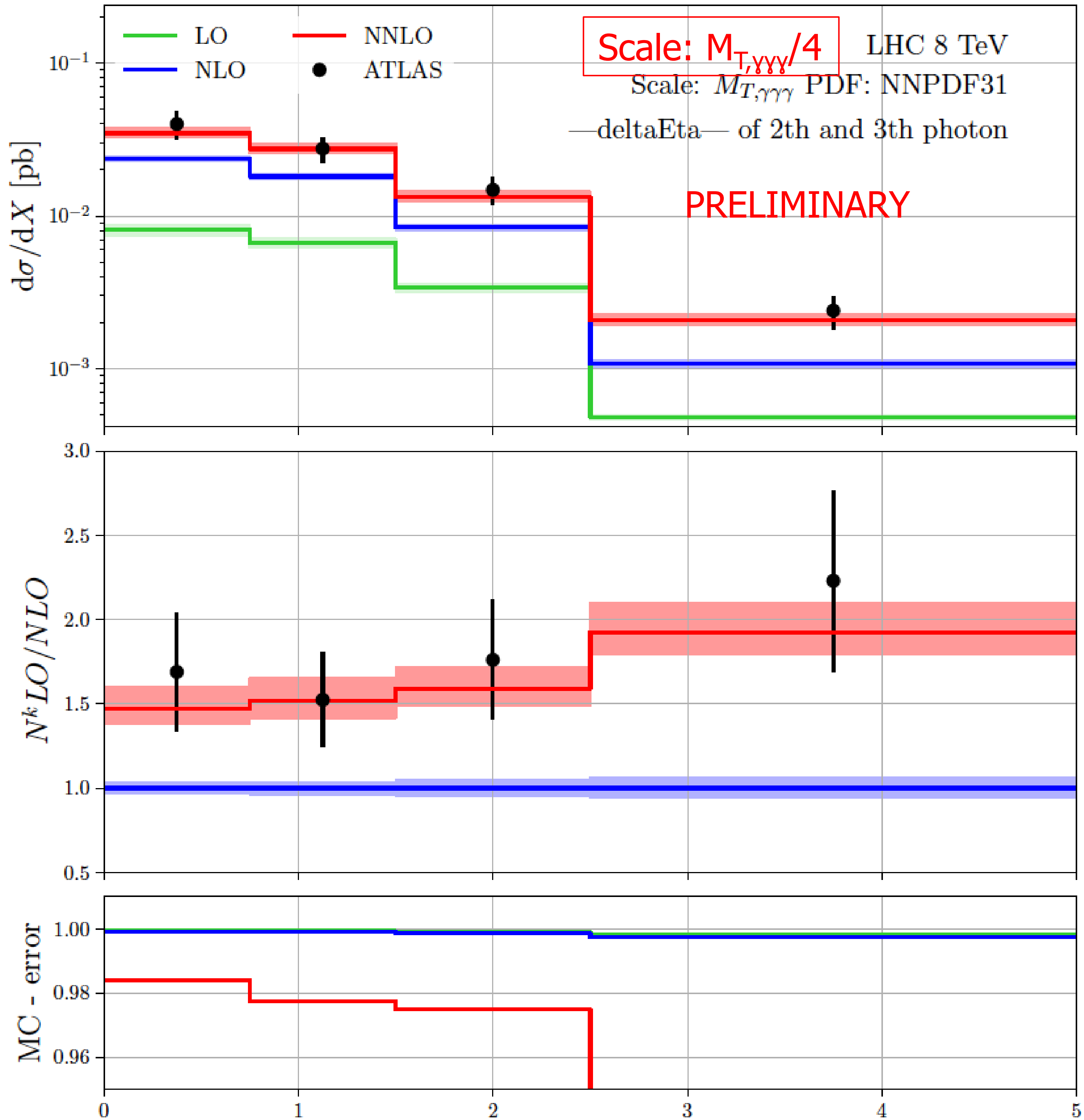

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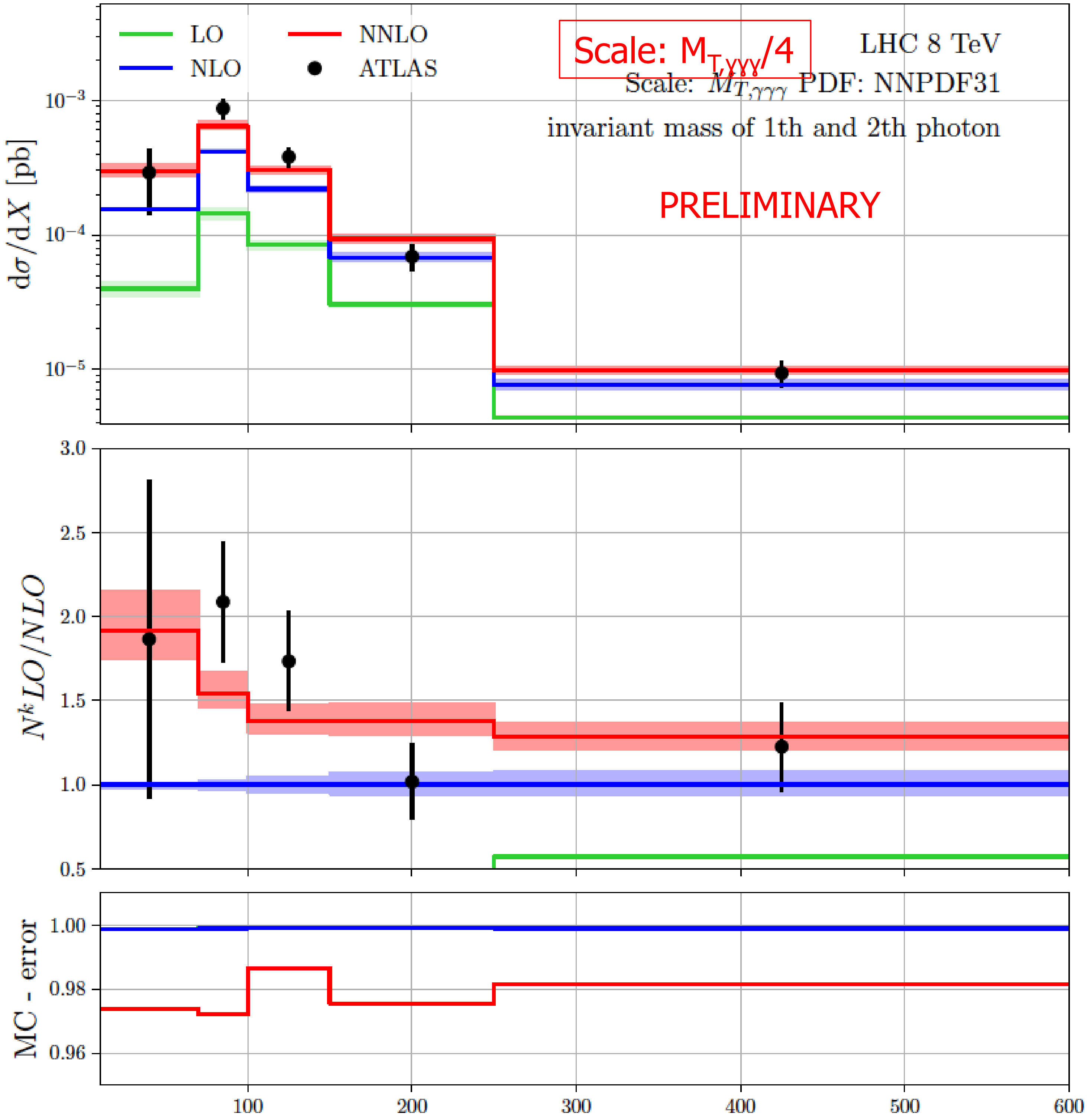

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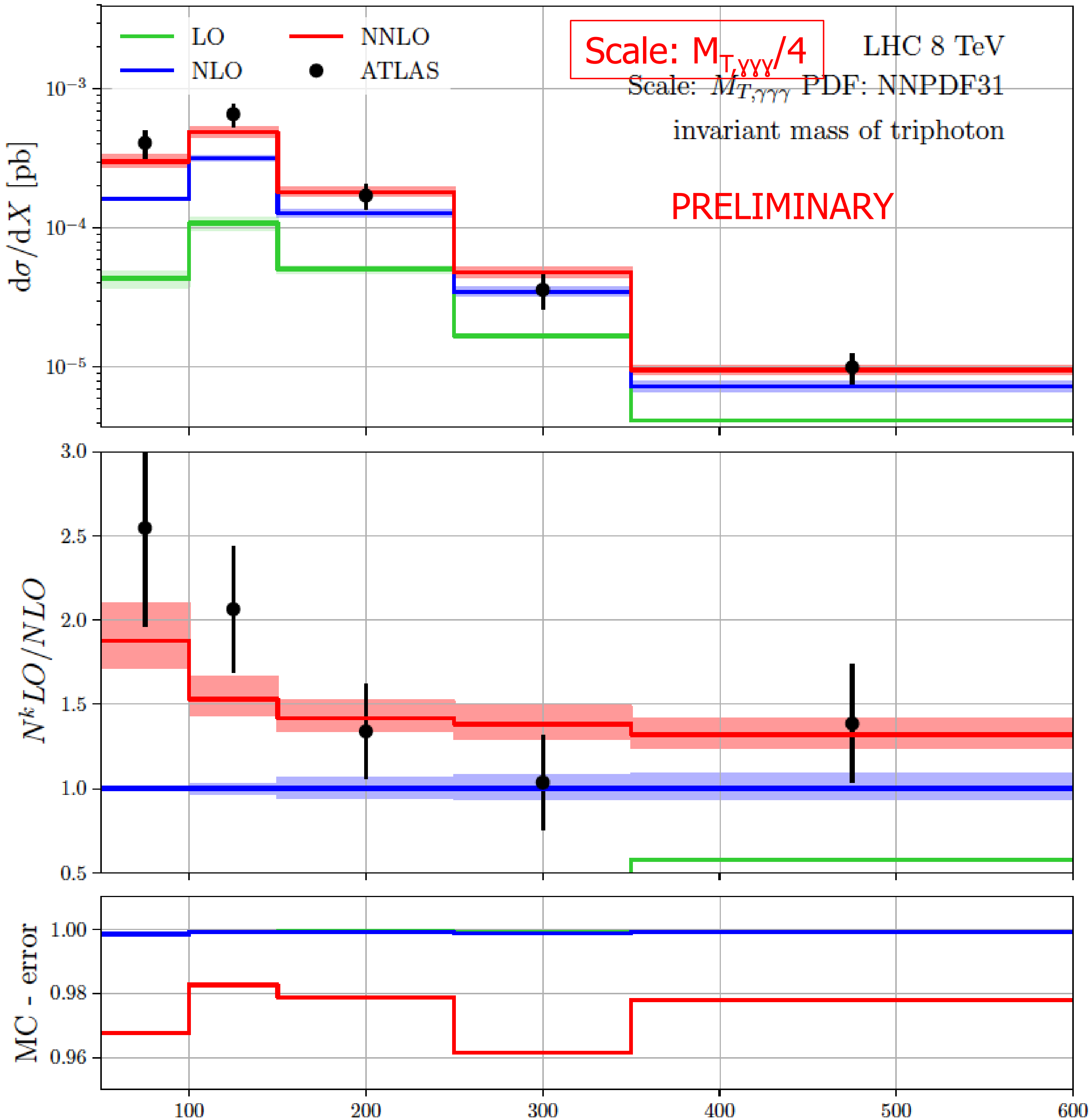
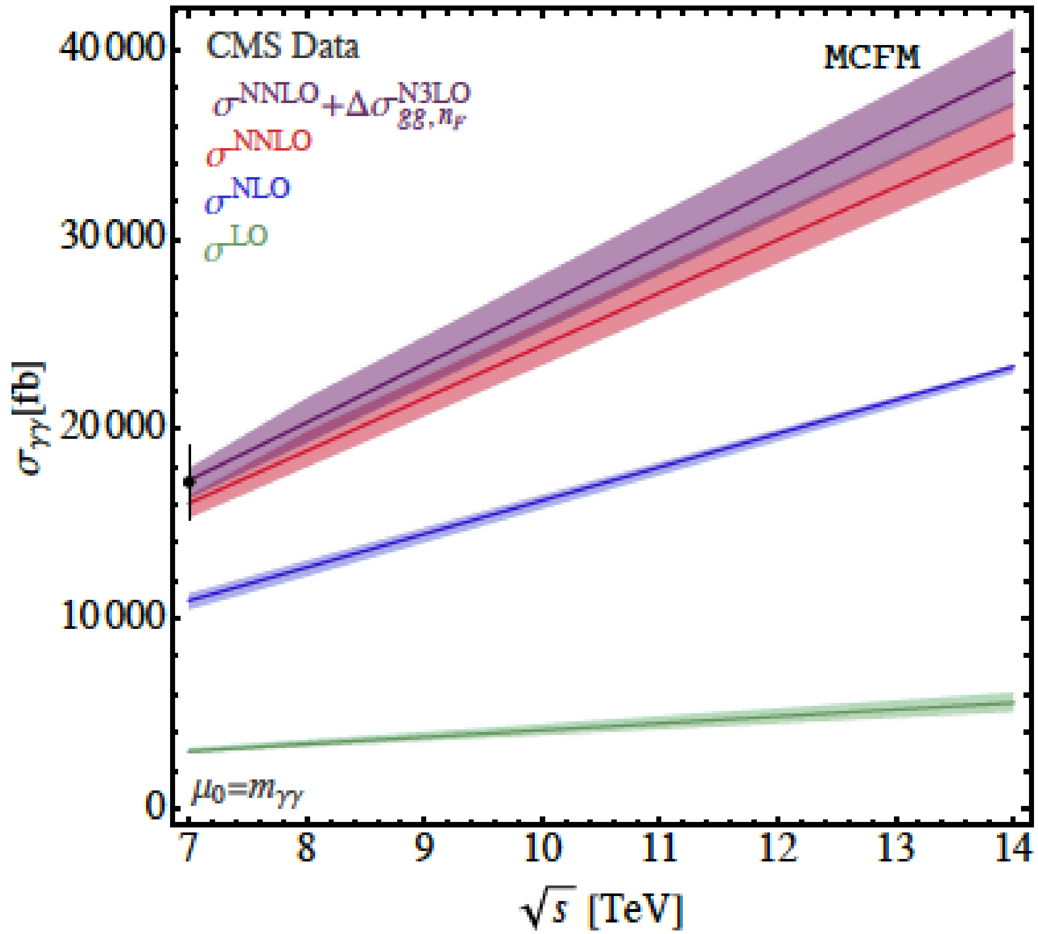


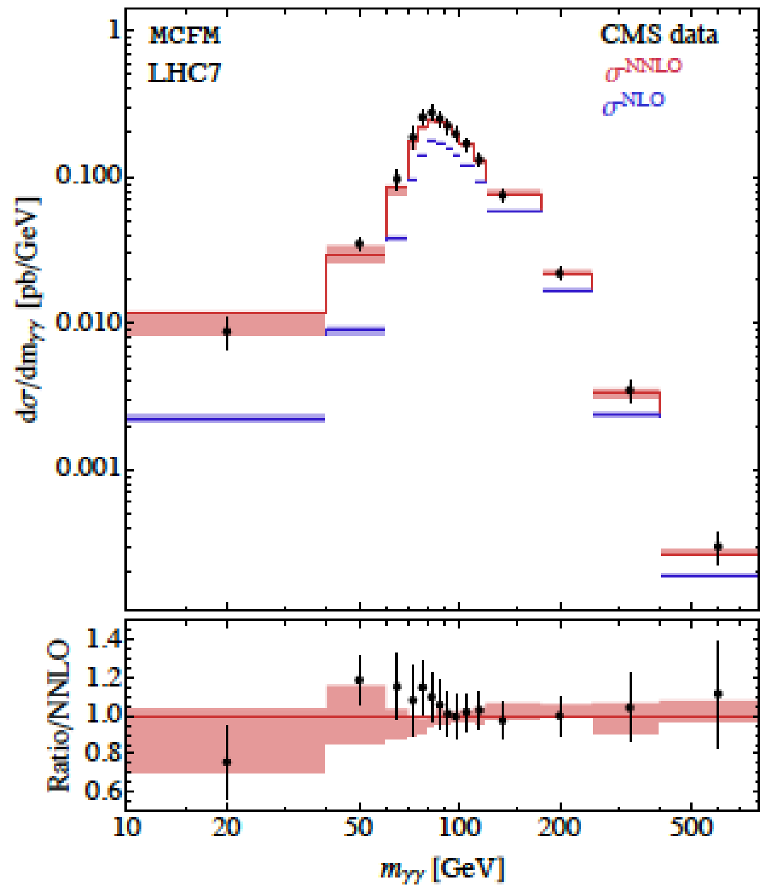
Plot includes everything but the scale-independent part of the 2-loop finite reminder

✓ What about perturbative convergence?

✓ It behaves very similarly to diphoton production:

Catani, Cieri, de Florian, Ferrera, Grazzini '11
Campbell, Ellis , Li, Williams '16





✓ There are some differences: no "box" loop contribution; small gg-contribution but large gq

- What about the two-loop amplitude?

- For the moment only leading color is possible. The subleading color should be less important

- Amplitude is not available (results for jets published)

  Abreu, Dormans, Febres Cordero, Ita, Page, Sotnikov '19

- We are computing it following a traditional approach:

  - Generate diagrams — "DiaGen" by Czakon (private code)
  - Substitute IBPs — Chawdhry, Mitov, Lim arXiv:1805.09182
  - Express masters in terms of known functions (pentagon functions)

    Gehrmann, Henn, Lo Presti arXiv:1807.09812

- We have produced a globally valid expression, i.e. all needed crossings of momenta are performed explicitly

  - This leads to an explosion of number of masters (there are O(70) crossings).
  - As a result, the basis of functions is also very large O(3k)
  - Utilizing the IBP solutions is easy in Mathematica.
  - What is hard is the manipulation of a very large number of terms due to crossings. We have found that finite fields reconstruction helps for adding many simplified expressions
  - The most complex part is the dealing with functions
  - Poles cancellation checked
  - Numeric evaluation is slow but not a show-stopper

Conclusions

- ✓ Steady progress on NNLO calculations
  - ➢ Top-pair production and decay in the NWA. Precision starts to challenge current NLO-accurate event generators. The need for NNLO-accurate MCs becomes clearer.
    - ➢ Another application: reliable and precise top quark mass extraction
  - ➢ A new application: dijet production. First complete NNLO dijet calculation. Currently precision is restricted by MC statistics. All distributions can be computed with more CPU. A great place for resonance searches.
- ✓ Opening a new chapter in precision physics: towards first calculation of a 2➞3 process:
  - ✓ 3-photon production in NNLO QCD
  - ✓ Currently all is included but the 2-loop finite reminder. Work in progress.
  - ✓ Significant NNLO corrections (similarly to diphoton production)
- ✓ Work ongoing for solving the non-planar 2-loop 5-point IBPs. New software developments and improvements. Ultimately, we are constrained by available CPU.
- ✓ Implementing ideas for the usability and user-friendliness of the computed 2-loop amplitudes