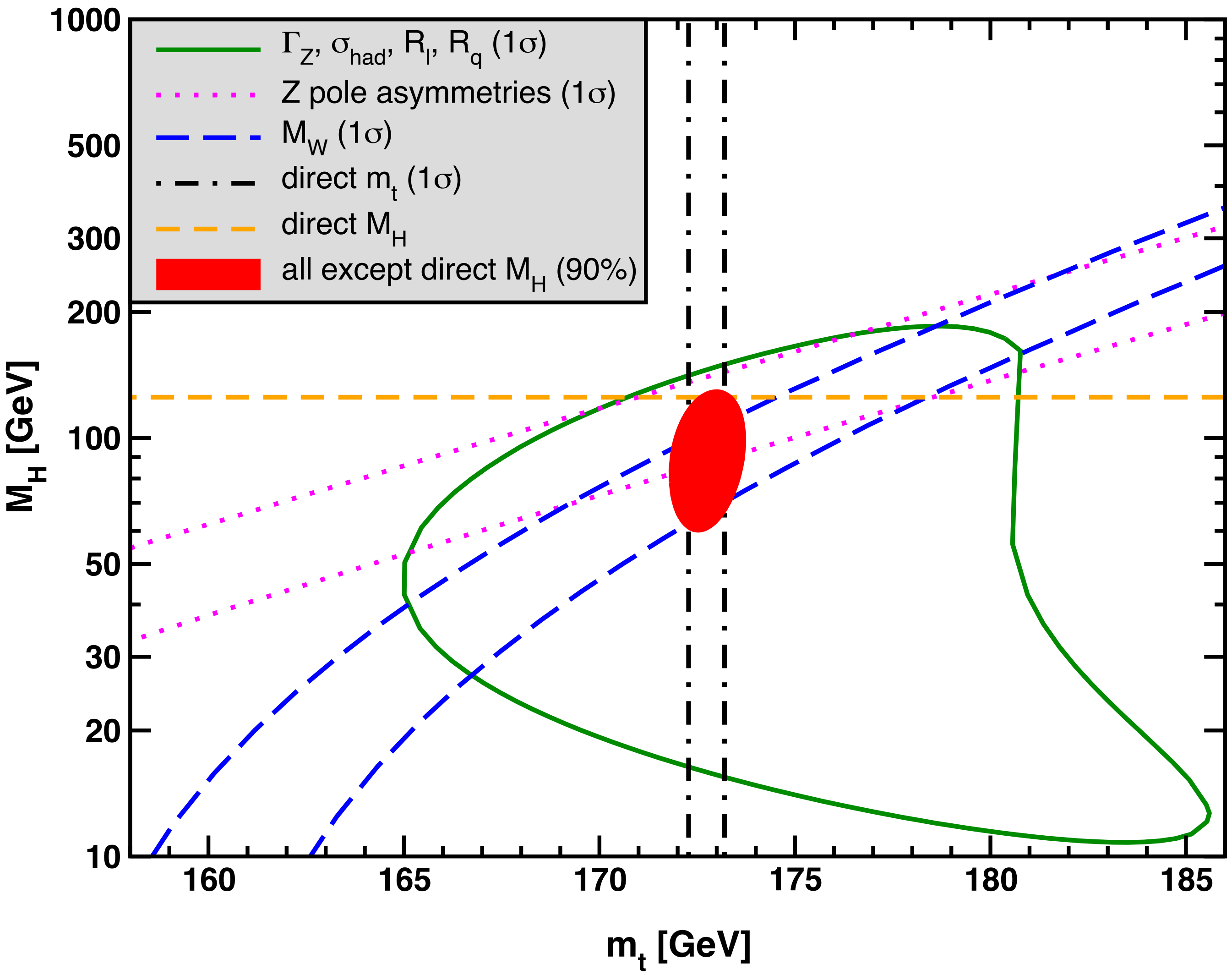
Top quark mass and pair production near threshold

Li Lin Yang
Zhejiang University

Based on Ju, Wang, Wang, Xu, Xu, **LLY**: 1908.02179, 2004.03088

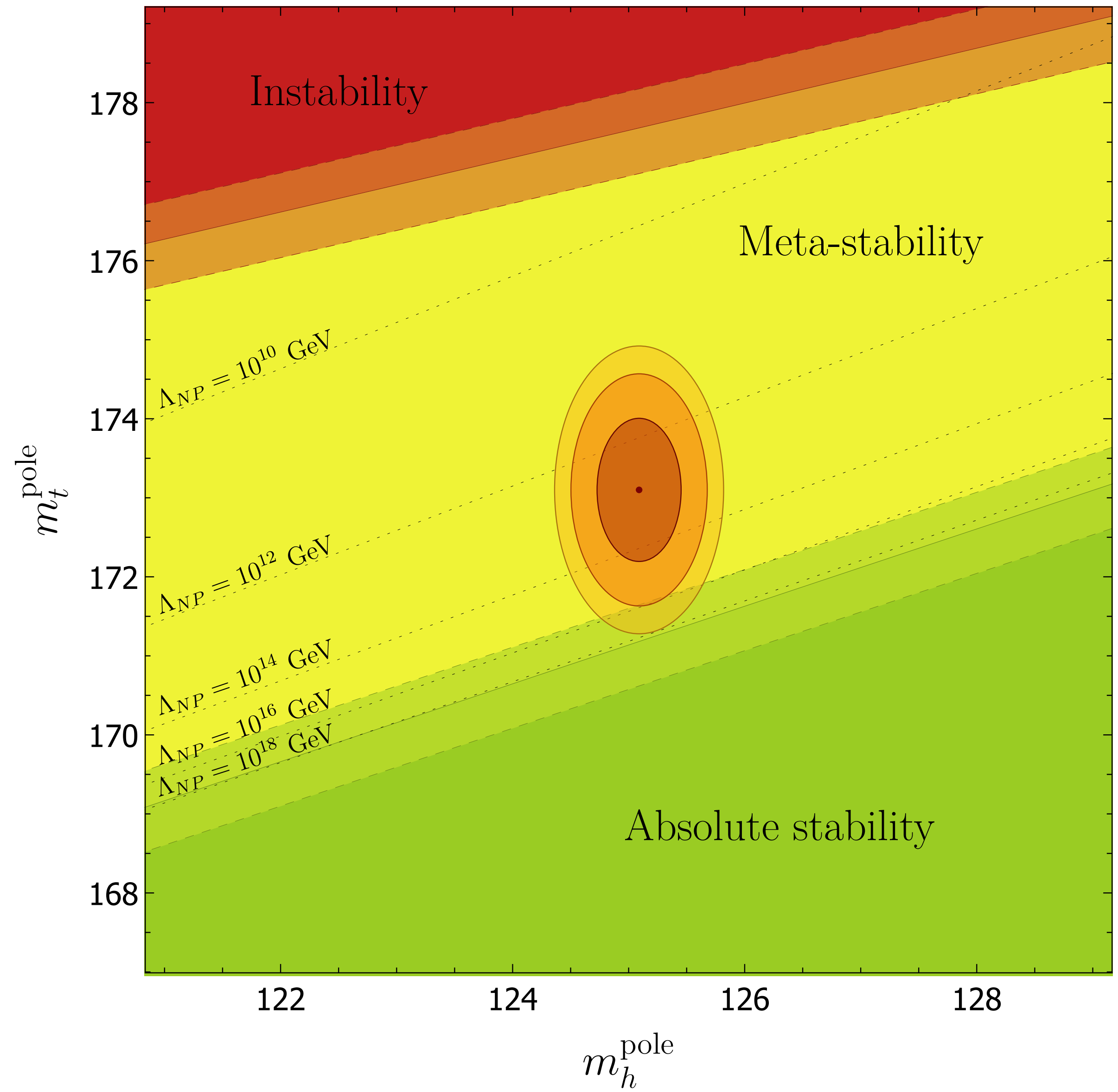
The top quark mass *a highly important parameter of the SM*

Constraints on new physics



2019 Review of Particle Physics

The fate of our universe



A. Andreassen, W. Frost, M. D. Schwartz: 1707.08124

What is the top quark mass?

- There are different definitions for a mass
- Kinematic: reconstructed object fitted to Monte Carlo event generators (so-called MC mass) Direct measurements
- Field theoretic: a (renormalized) parameter in the Lagrangian density (scheme-dependent) Indirect measurements
  - Pole (on-shell) mass
  - $\overline{\text{MS}}$ mass
  - 1S mass
  - MSR mass
  - …

***t*-QUARK MASS**

t-Quark Mass (Direct Measurements)	172.9 ± 0.4 GeV
t-Quark Mass from Cross-Section Measurements	160^{+5}_{-4} GeV
t-Quark Pole Mass from Cross-Section Measurements	173.1 ± 0.9 GeV

2019 Review of Particle Physics

What is the Top Quark Mass?

André H. Hoang[1,2] 2004.12915

[1]University of Vienna
Faculty of Physics, Boltzmanngasse 5, A-1090 Wien,
email: andre.hoang@univie.ac.at
[2]Erwin Schrödinger International Institute for Mathe
Boltzmanngasse 9, A-1090 Wien, Austria

In this review I give an overview on the conceptual issues involved in the question how to interpret so-called 'direct top quark mass measurements', which are based on the kinematic reconstruction of top quark decay products at the Large Hadron Collider (LHC). These measurements quote the top mass parameter $m_t^{\rm MC}$ of Monte-Carlo event generators with current uncertainties of around 0.5 GeV. At present time the problem of finding a rigorous relation between $m_t^{\rm MC}$ and top mass renormalization schemes defined in field theory is unresolved and touches perturbative as well as nonperturbative aspects and the limitations of state-of-the-art Monte-Carlo event generators. I review the status of LHC top mass measurements, illustrate how conceptual limitations enter and explain a controversy that has permeated the community in the context of the interpretation problem related to $m_t^{\rm MC}$. Recent advances in acquiring first principle insights are summarized, and it is outlined what else has to be understood to fully resolve the issue. For the time being, I give a recommendation how to deal with the interpretation problem when making top mass dependent theoretical predictions.

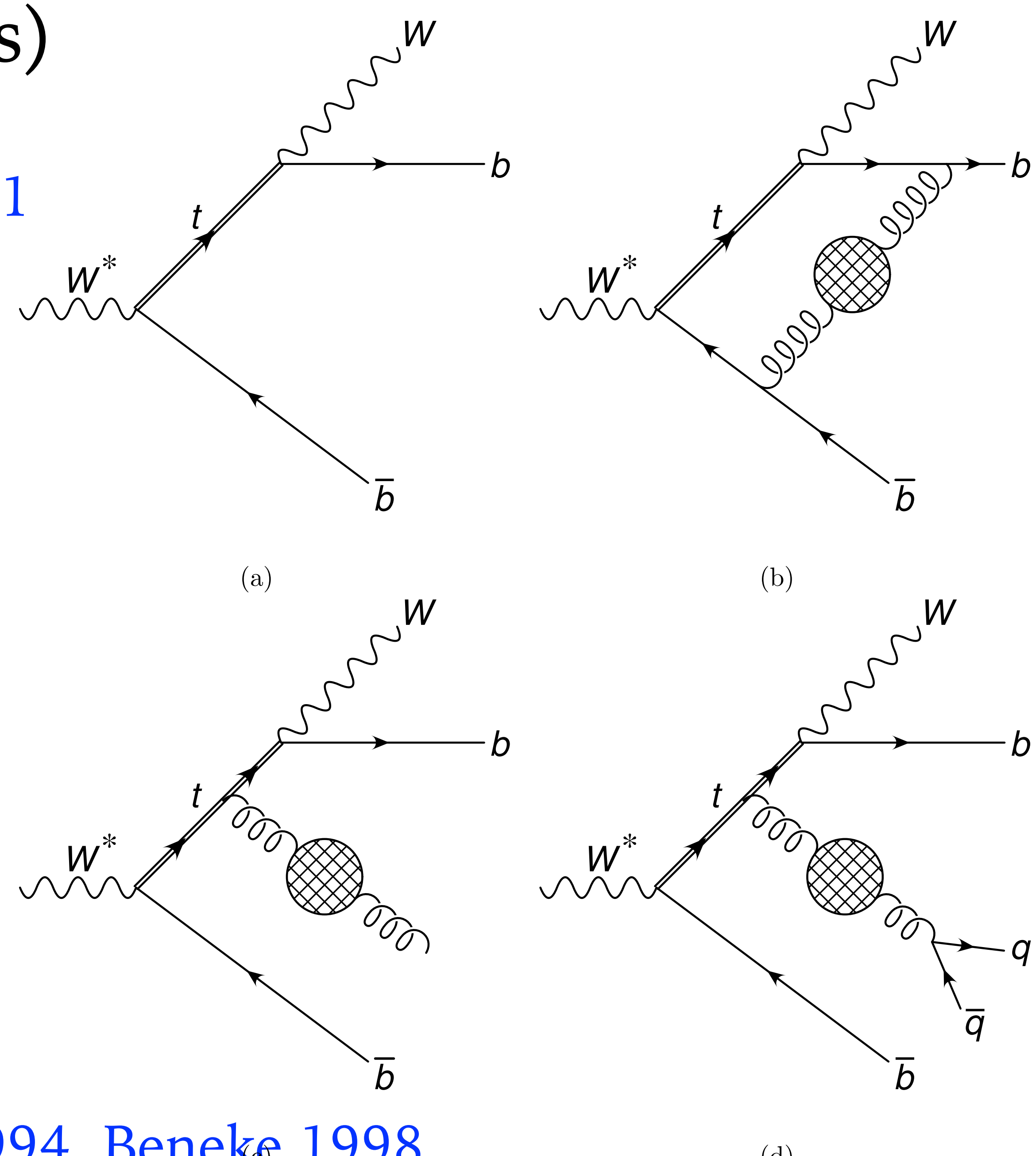
$m_t^{\rm MC} \approx m_t^{\rm pole}$ but the exact relation remains unknown

The top quark (as a colored particle) has no pole mass non-perturbatively

Reflected in perturbation theory as the renormalons (in addition to those associated with the asymptotic perturbative series of observables)

Ravasio, Nason, Oleari: 1810.10931

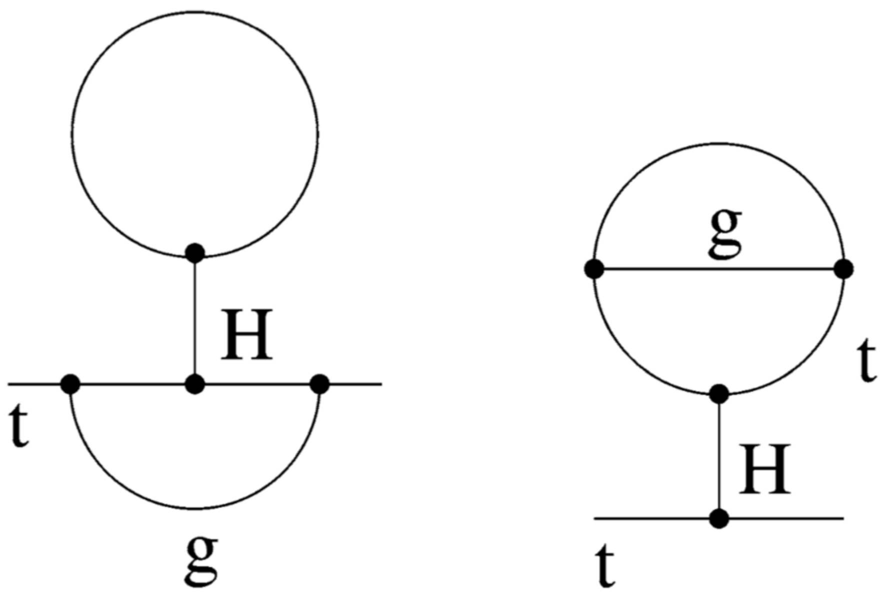
$\mathcal{O}(\Lambda_{\mathrm{QCD}})$ ambiguity



See also: Bigi et al. 1994; Beneke, Braun 1994, Beneke 1998, …

Czakon@TOP2019

The $\overline{\text{MS}}$ mass is not as universal as The $\overline{\text{MS}}$ strong coupling



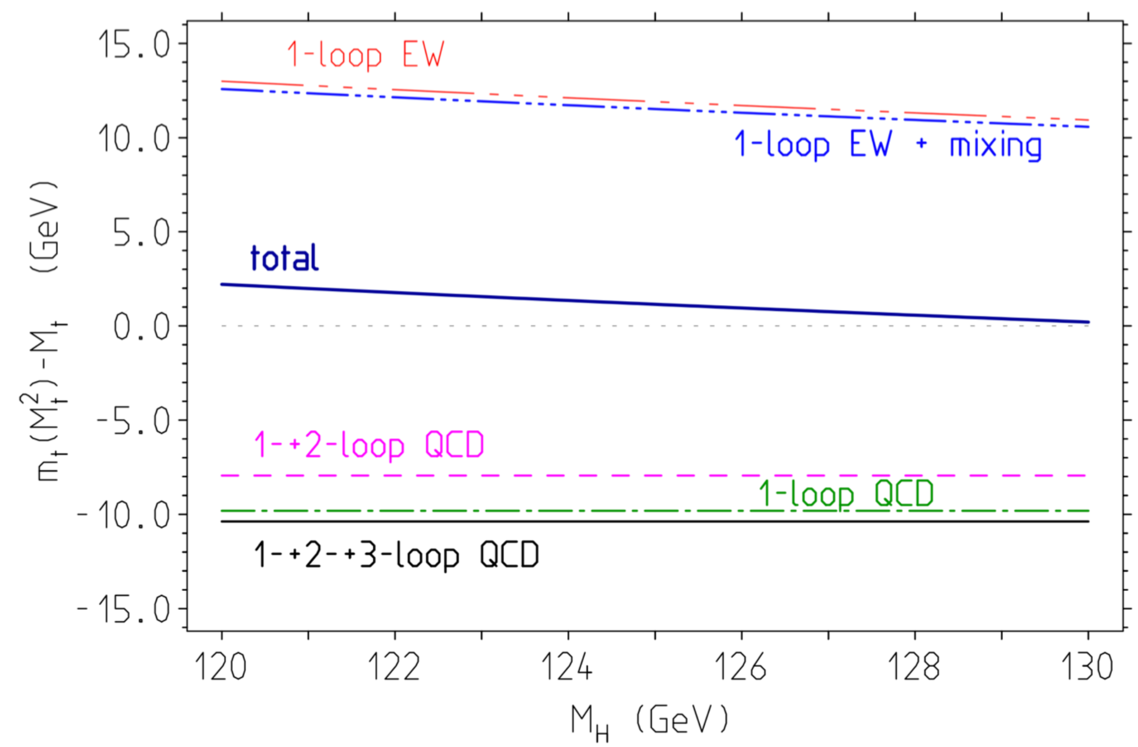


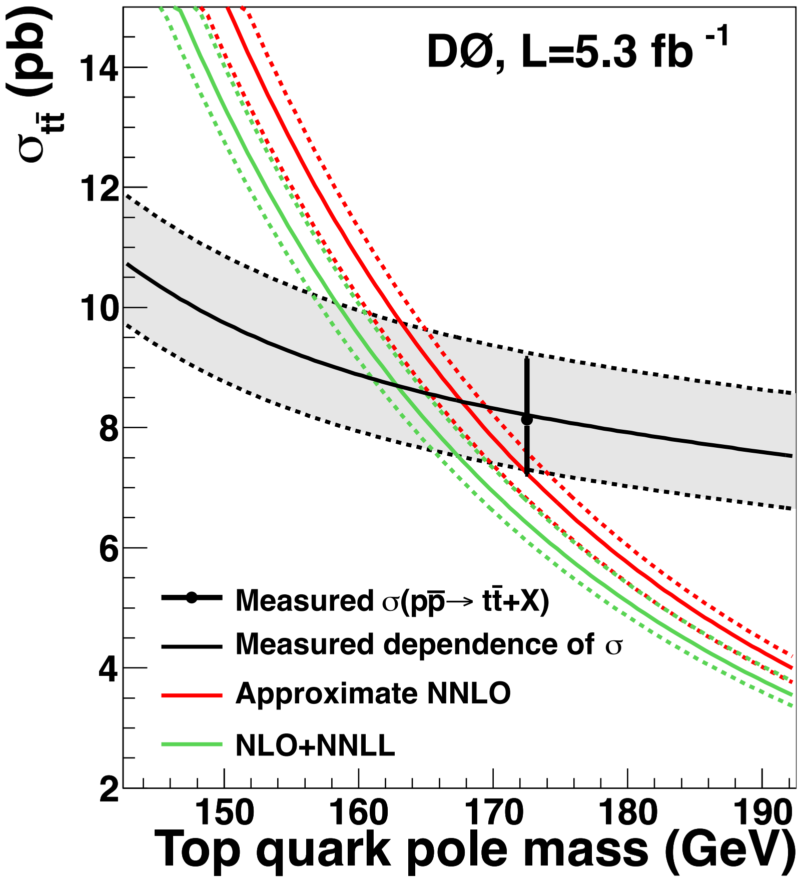
Table 1: The various contributions to $m_t(M_t^2) - M_t$ in GeV.

M_H [GeV]	$O(\alpha)$	$O(\alpha\alpha_s)$	$O(\alpha)+O(\alpha\alpha_s)$	$O(\alpha_s)+O(\alpha_s^2)+O(\alpha_s^3)$	total
124	12.11	−0.39	11.72	−10.38	1.34
125	11.91	−0.39	11.52	−10.38	1.14
126	11.71	−0.38	11.32	−10.38	0.94

Jegerlehner, Kalmykov, Kniehl `12

Indirect measurements of the pole mass

Keeping the $\mathcal{O}(\Lambda_{\rm QCD})$ ambiguity in mind, we should be able to extract $m_t^{\rm pole}$ to good accuracies from cross sections



D0 Collaboration: 1104.2887

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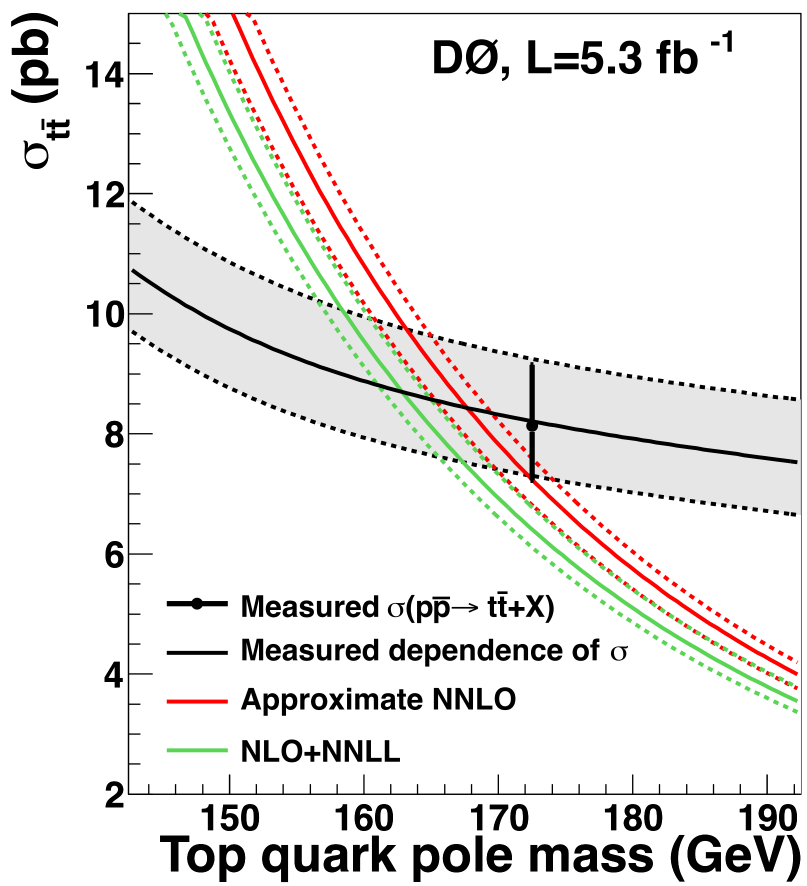


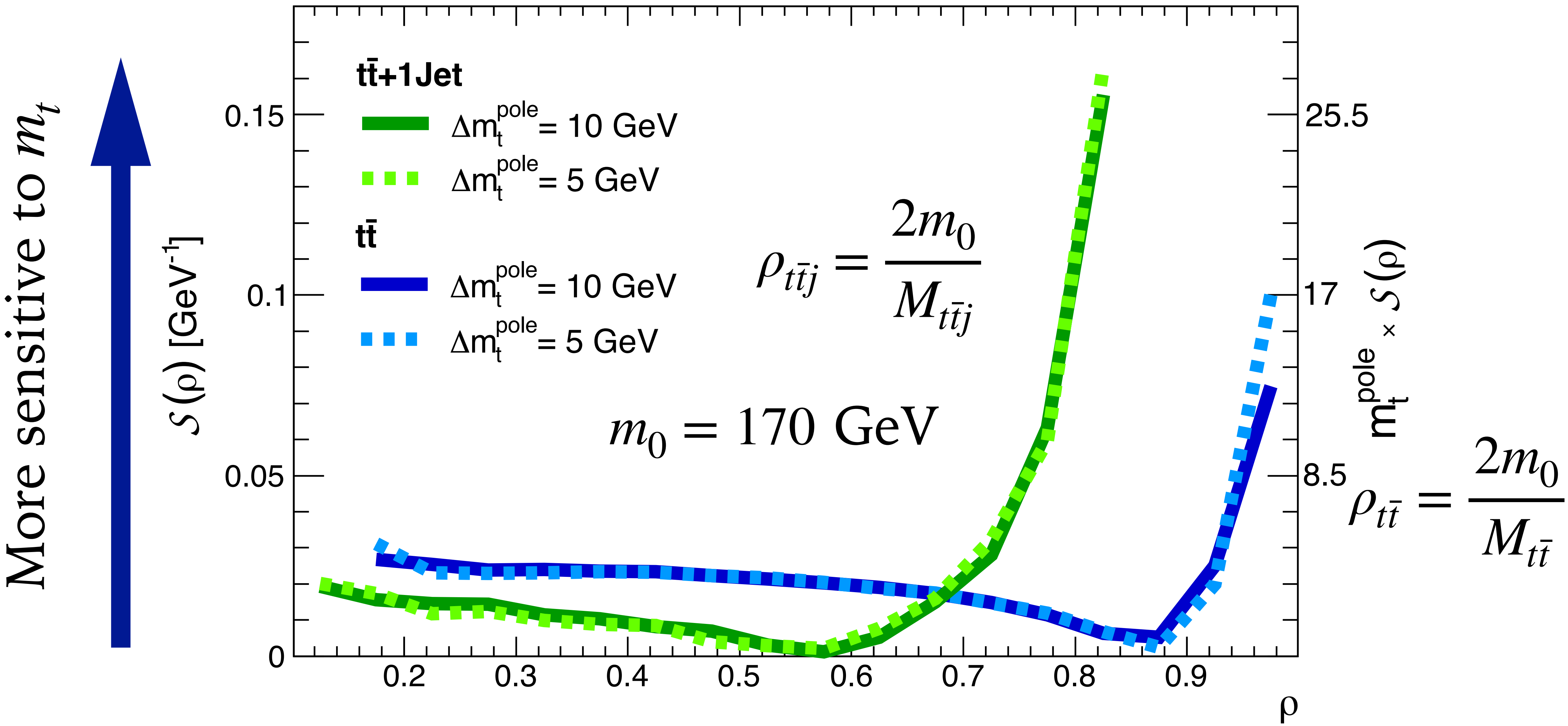
D0 Collaboration: 1104.2887

The next natural step is to use more differential observables…

…should choose observables most sensitive to m_t

Threshold region and top quark mass

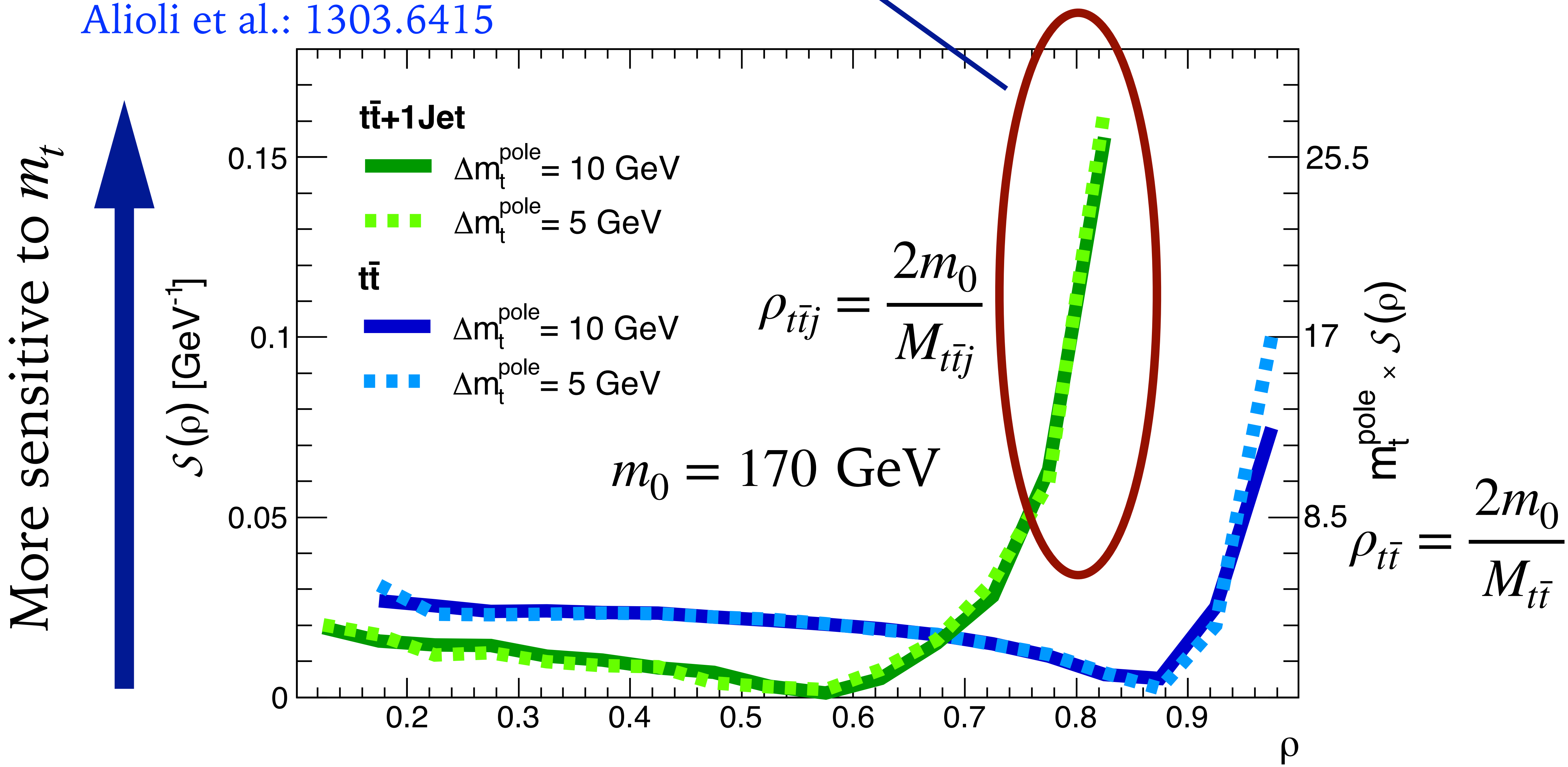
Alioli et al.: 1303.6415



Threshold region and top quark mass

$M_{t\bar{t}} \to 2m_t$ in $t\bar{t}$+jets production

Alioli et al.: 1303.6415



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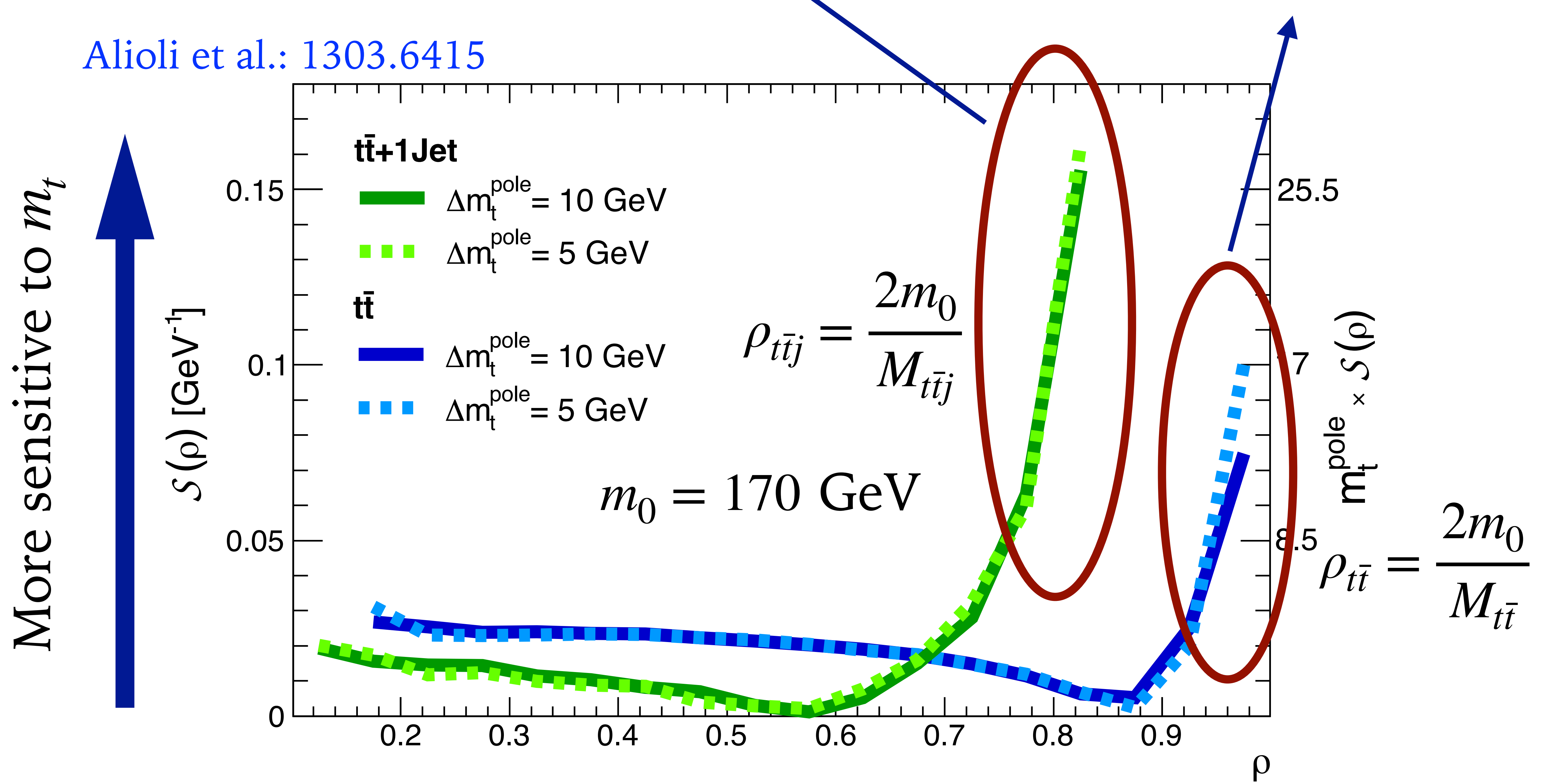

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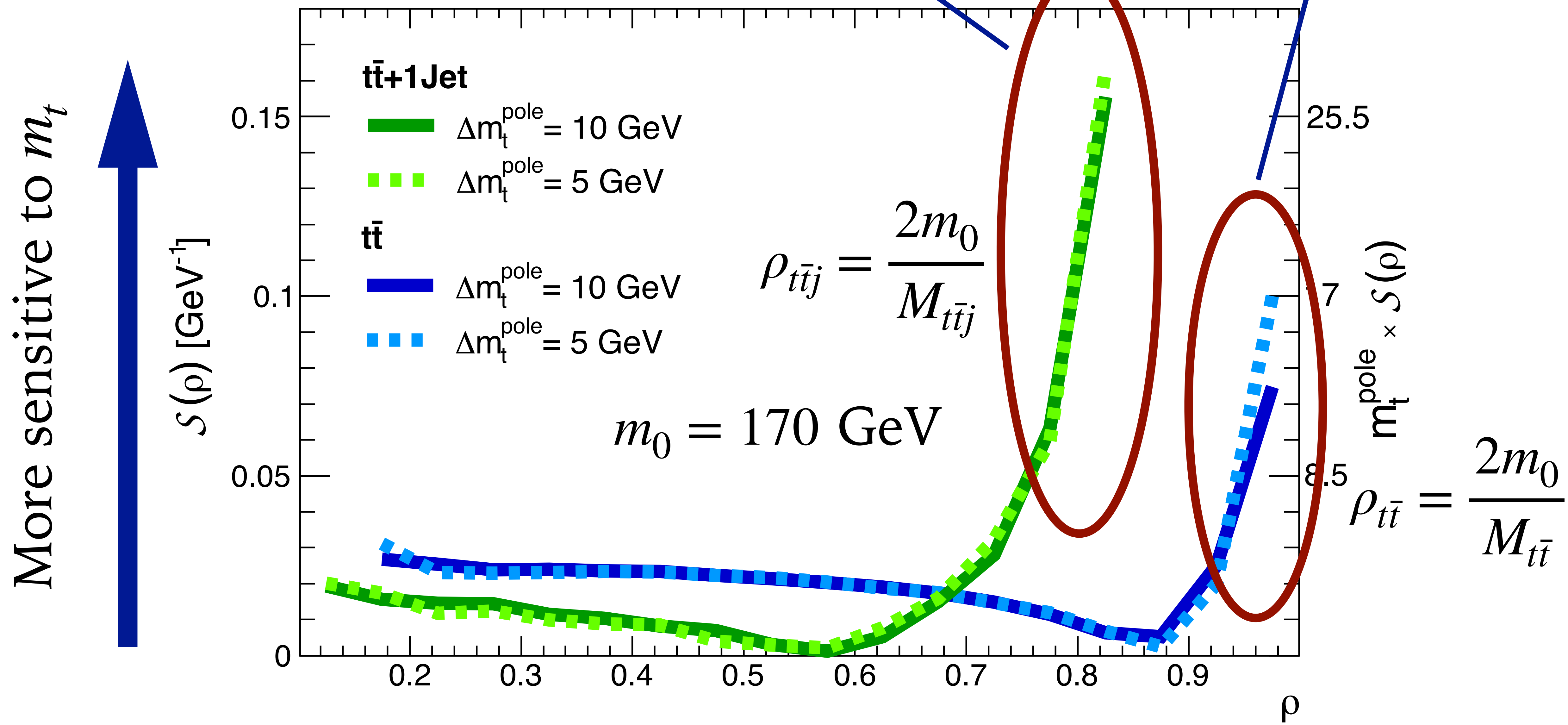
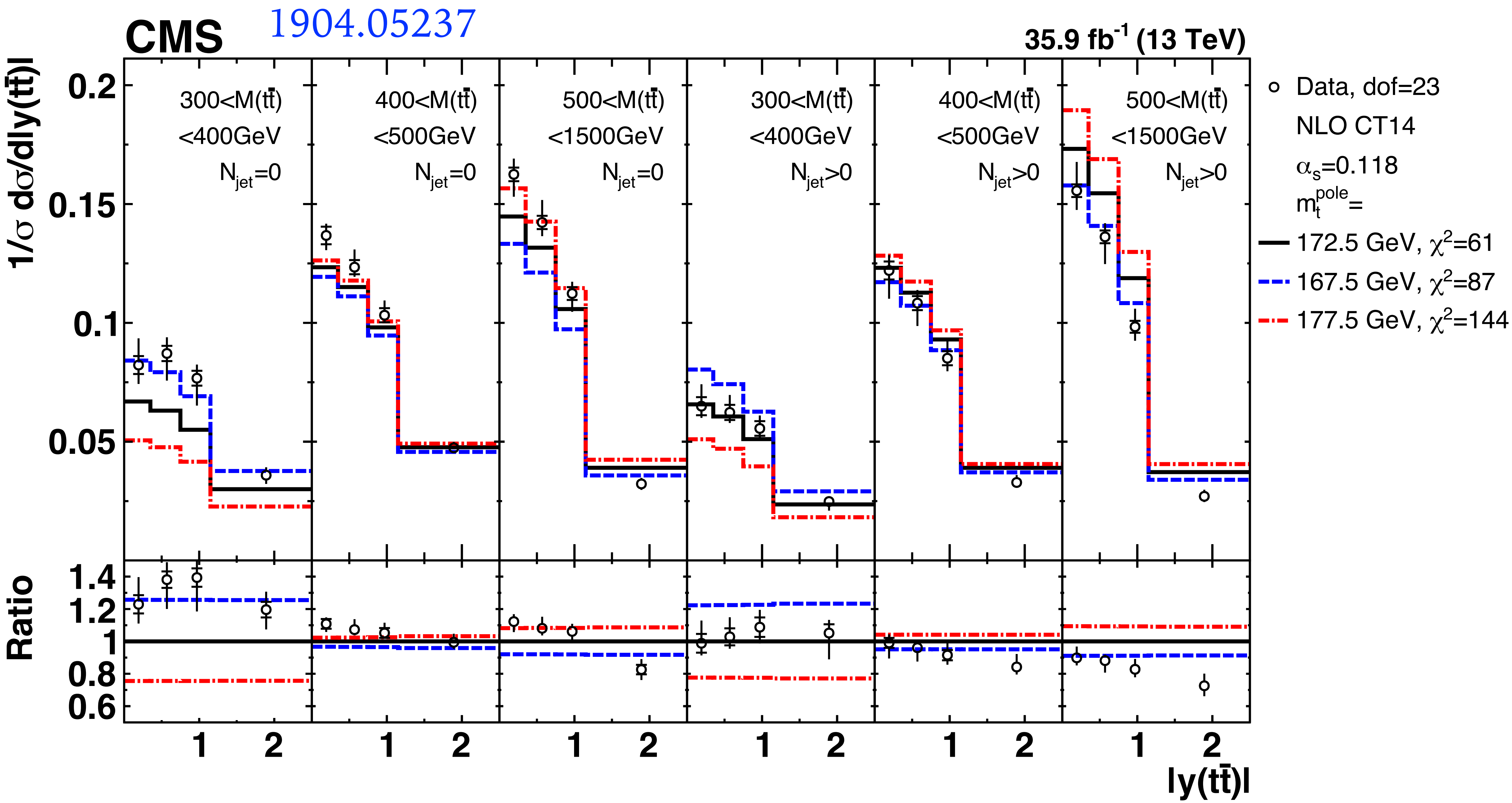


Most of the mass-sensitivity comes from the threshold region

Threshold region and top quark mass



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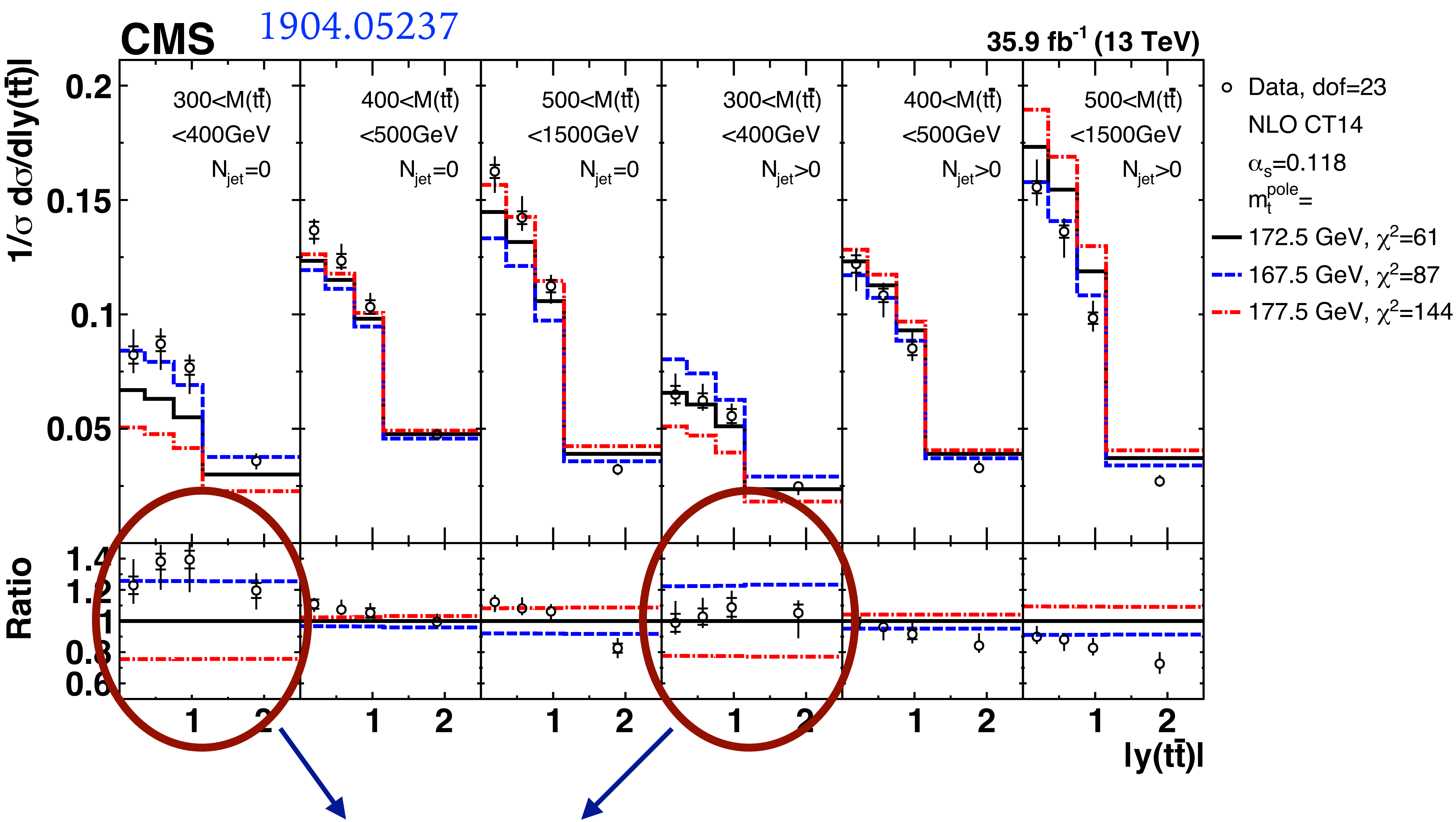

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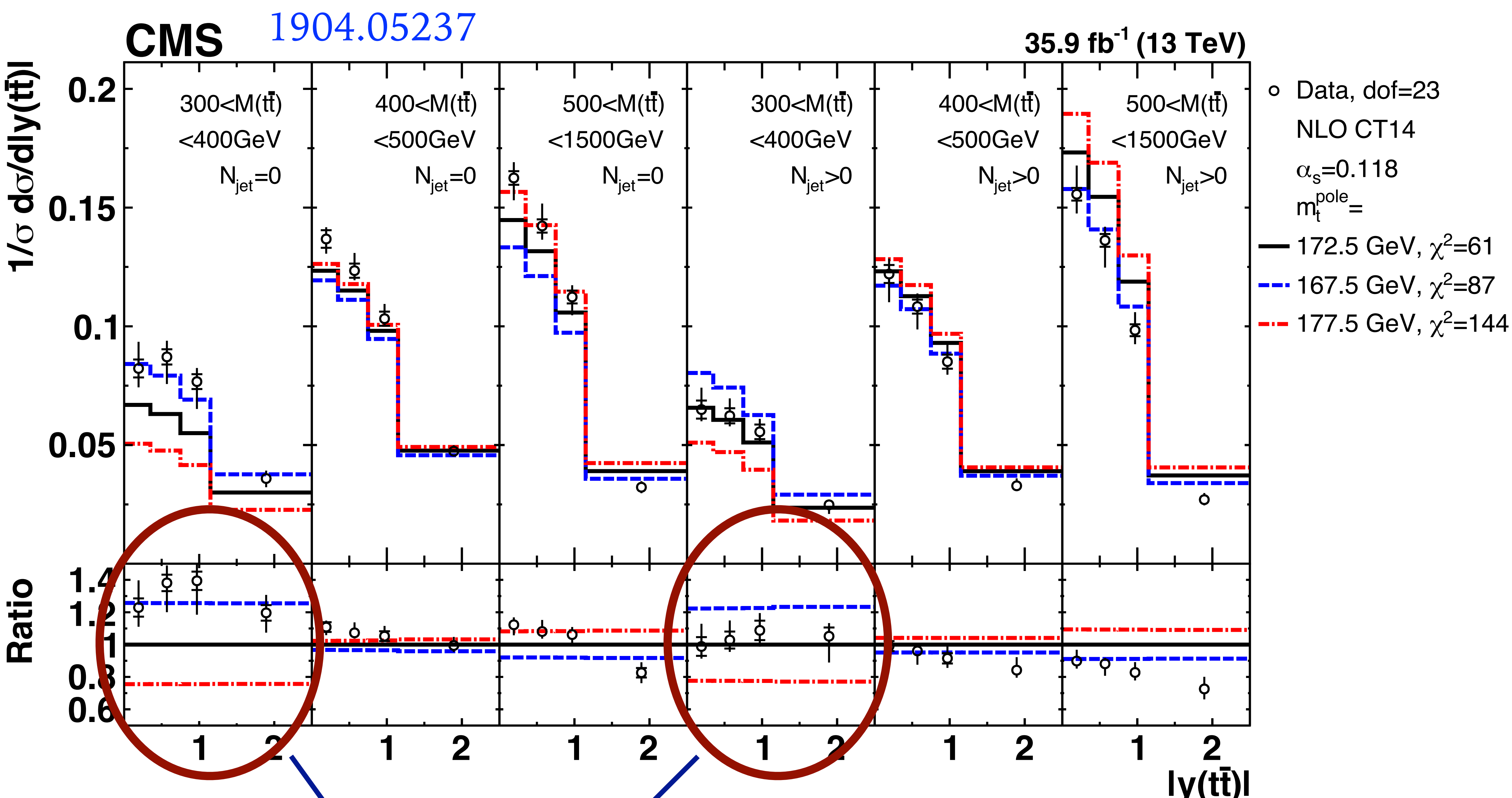

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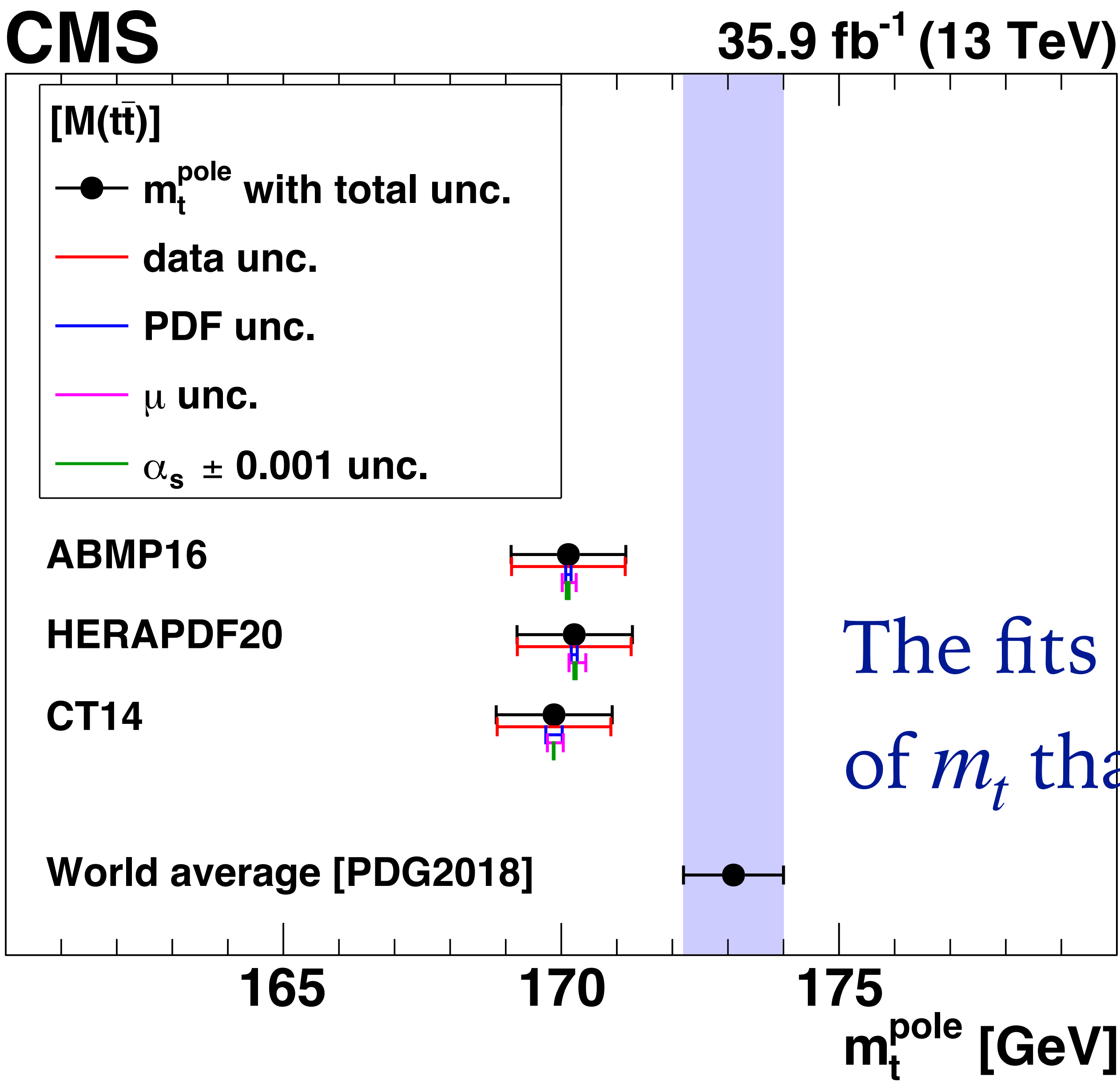
My focus in the rest of the talk

Threshold region and top quark mass

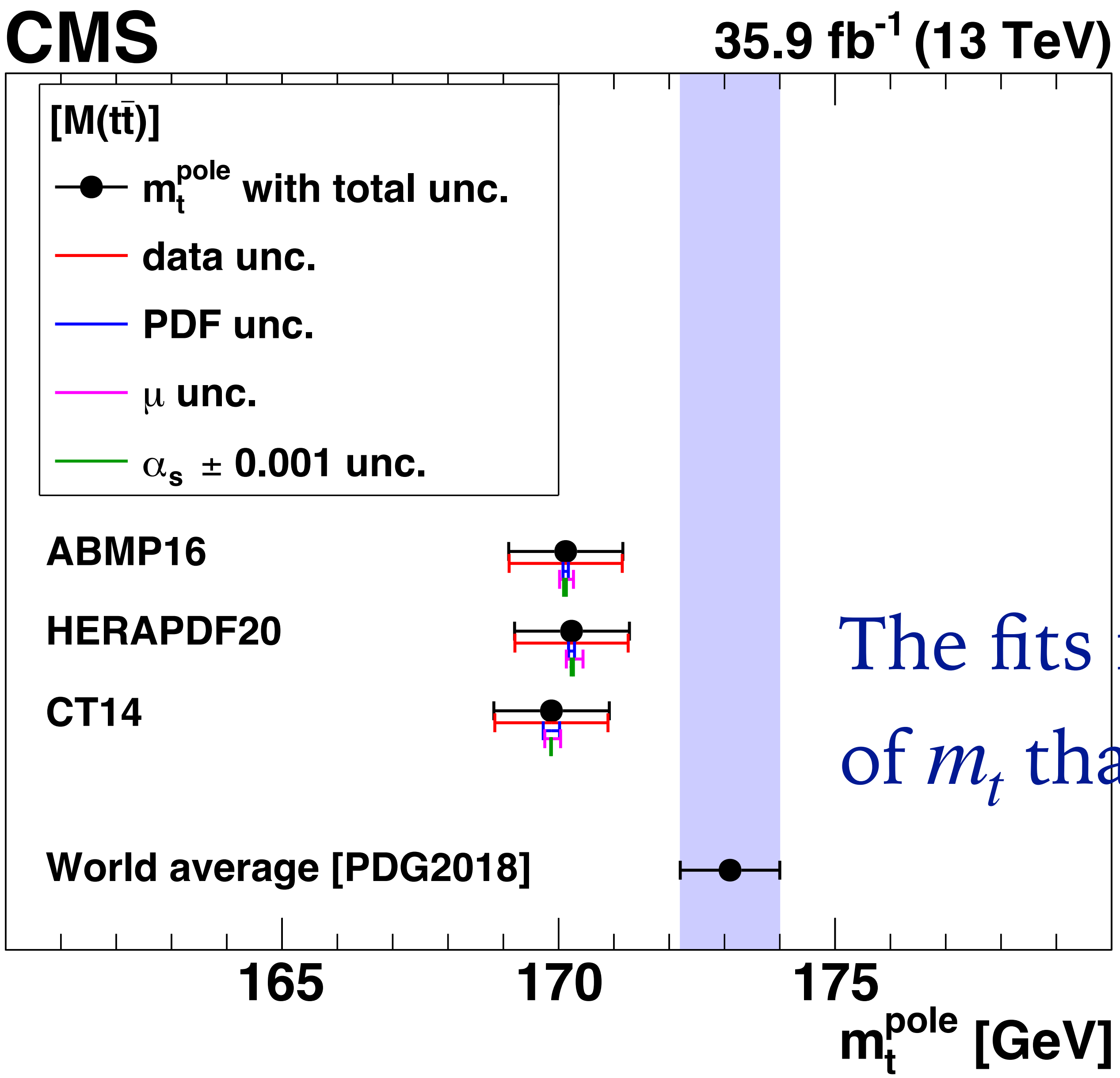


ATLAS collaboration: 1905.02302

CMS collaboration: 1904.05237

The fits favor much lower values of m_t than the world average!

Threshold region and top quark mass



ATLAS collaboration: 1905.02302

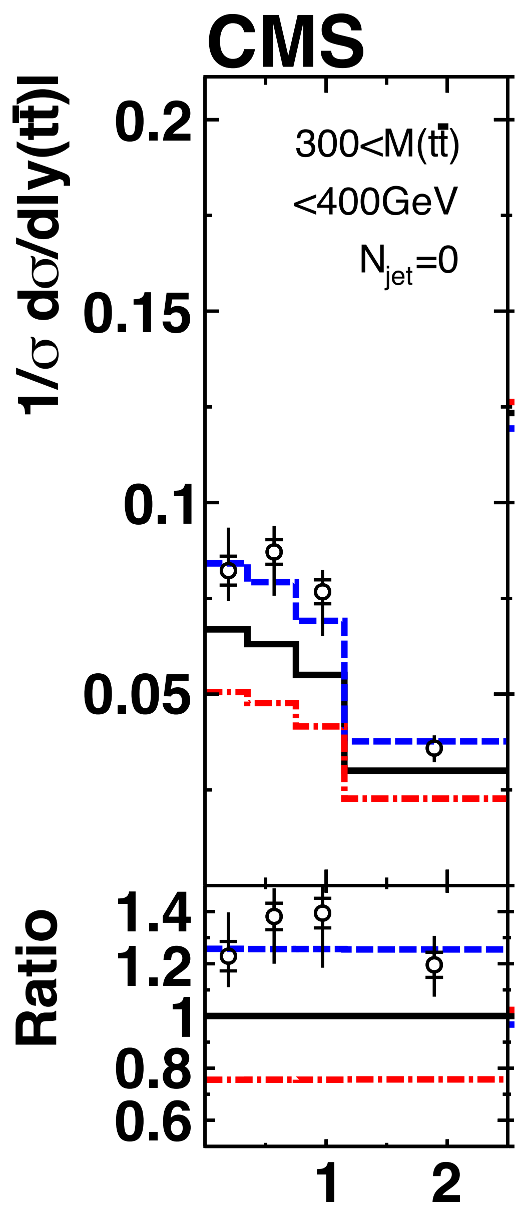
CMS collaboration: 1904.05237

The fits favor much lower values of m_t than the world average!

The difference is much larger than the renormalon ambiguity…

What could possibly be the reason?

The method of indirect mass measurements relies heavily on **both** the experimental side **and** the theoretical side



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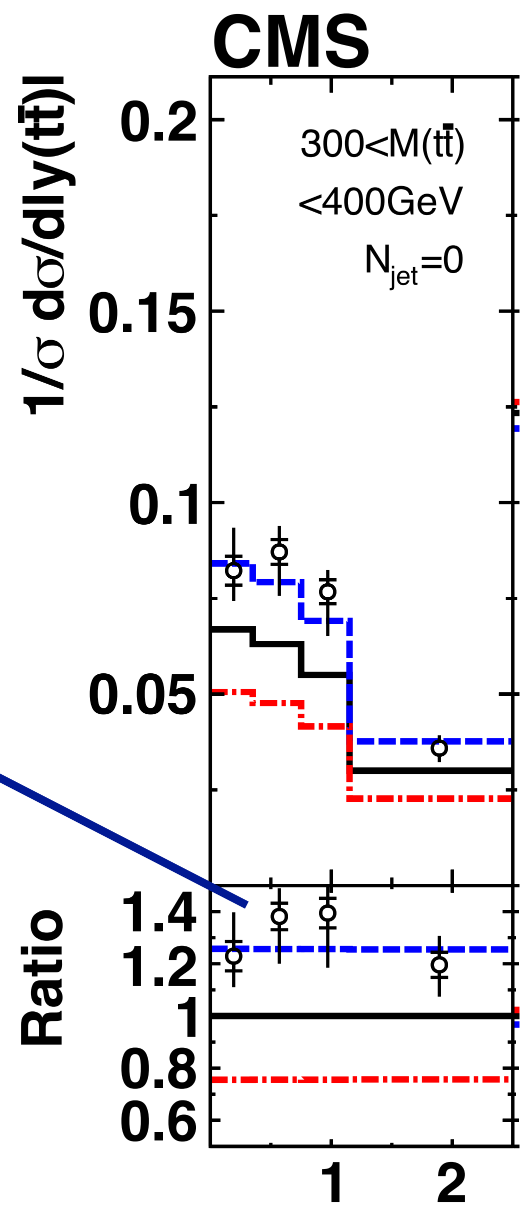
The experimentalists need to measure the mass-sensitive observables to high precisions



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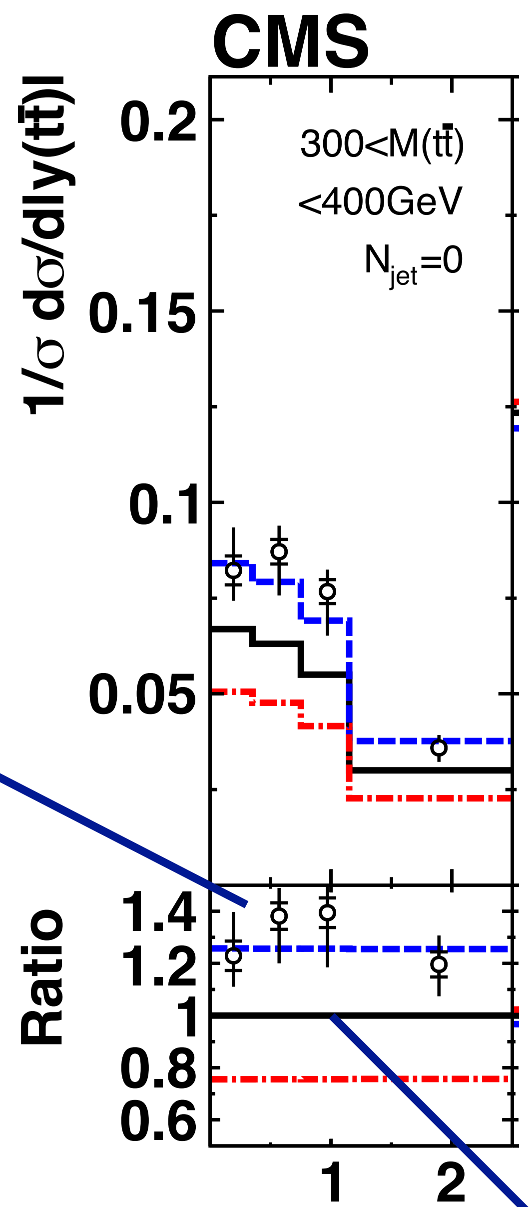

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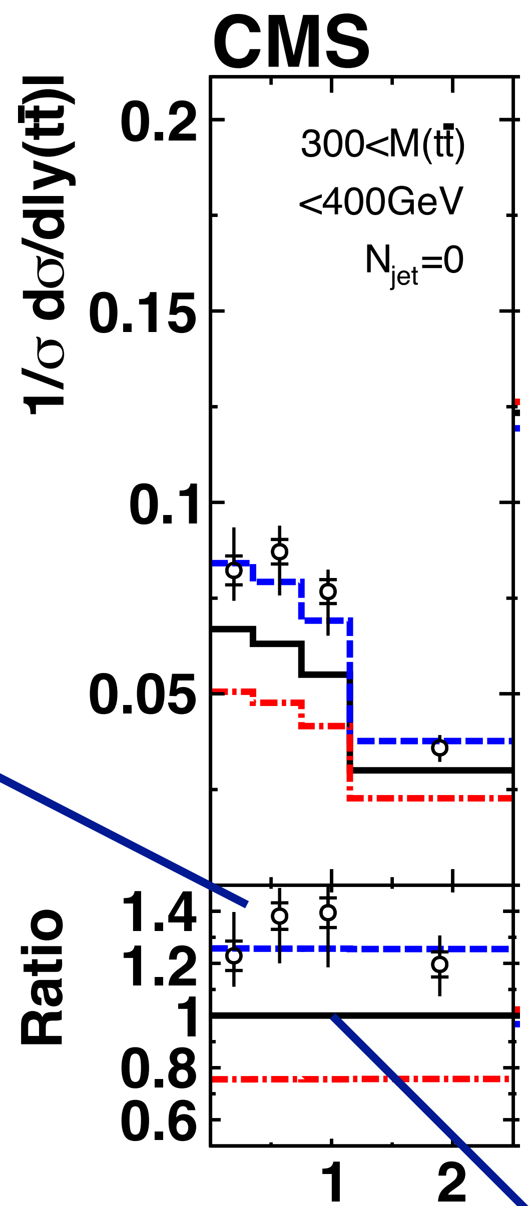


The theorists need to provide high-precision predictions for these observables

I'm a theorist, so I'll only talk about the latter…

Up-to-date perturbative predictions

NNLO+NNLL' in QCD

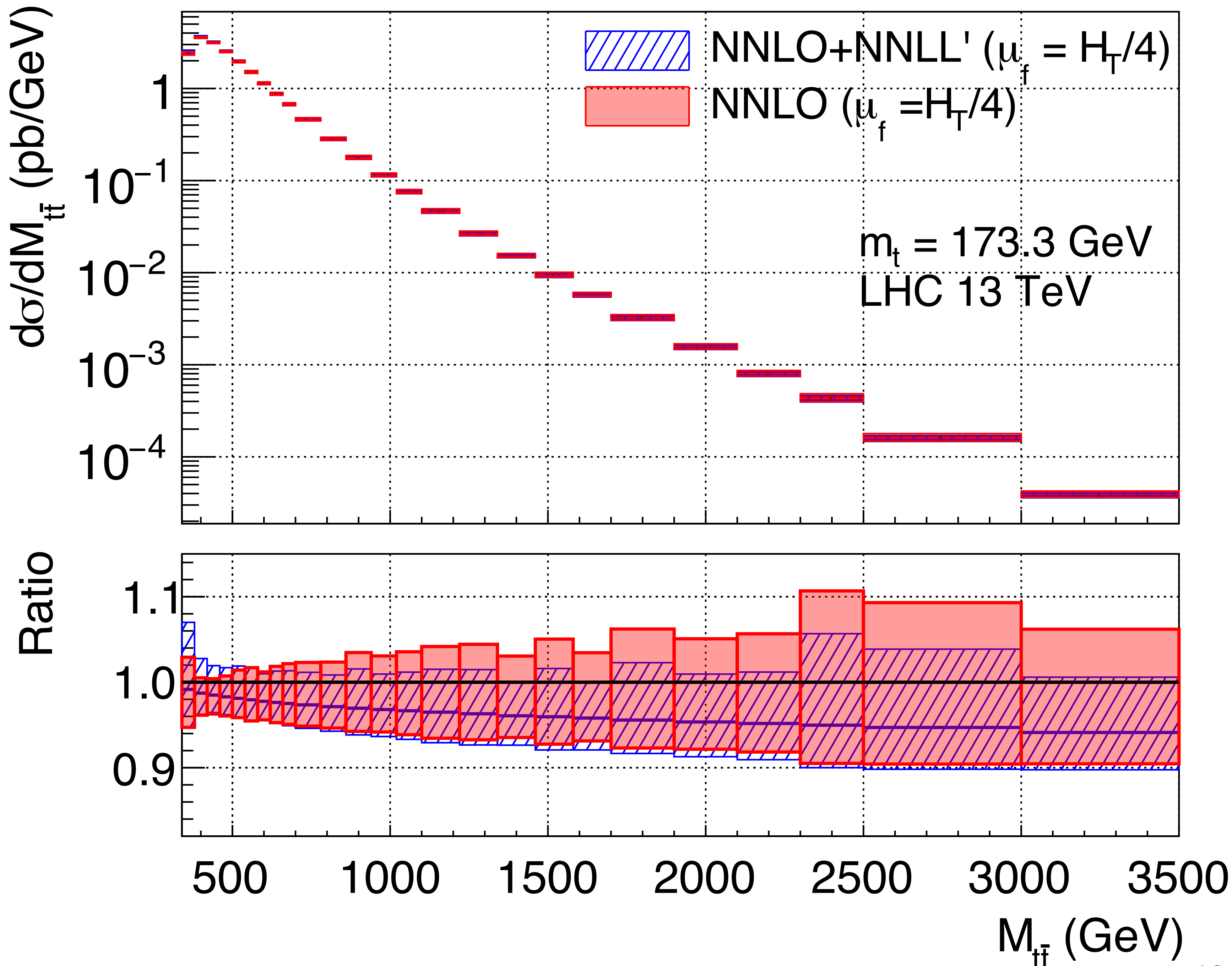
Pecjak, Scott, Wang, **LLY**: 1601.07020

Czakon, Heymes, Mitov: 1606.03350

Czakon, Ferroglia, Heymes, Mitov, Pecjak, Scott, Wang, **LLY**: 1803.07623

Pecjak, Scott, Wang, **LLY**: 1811.10527

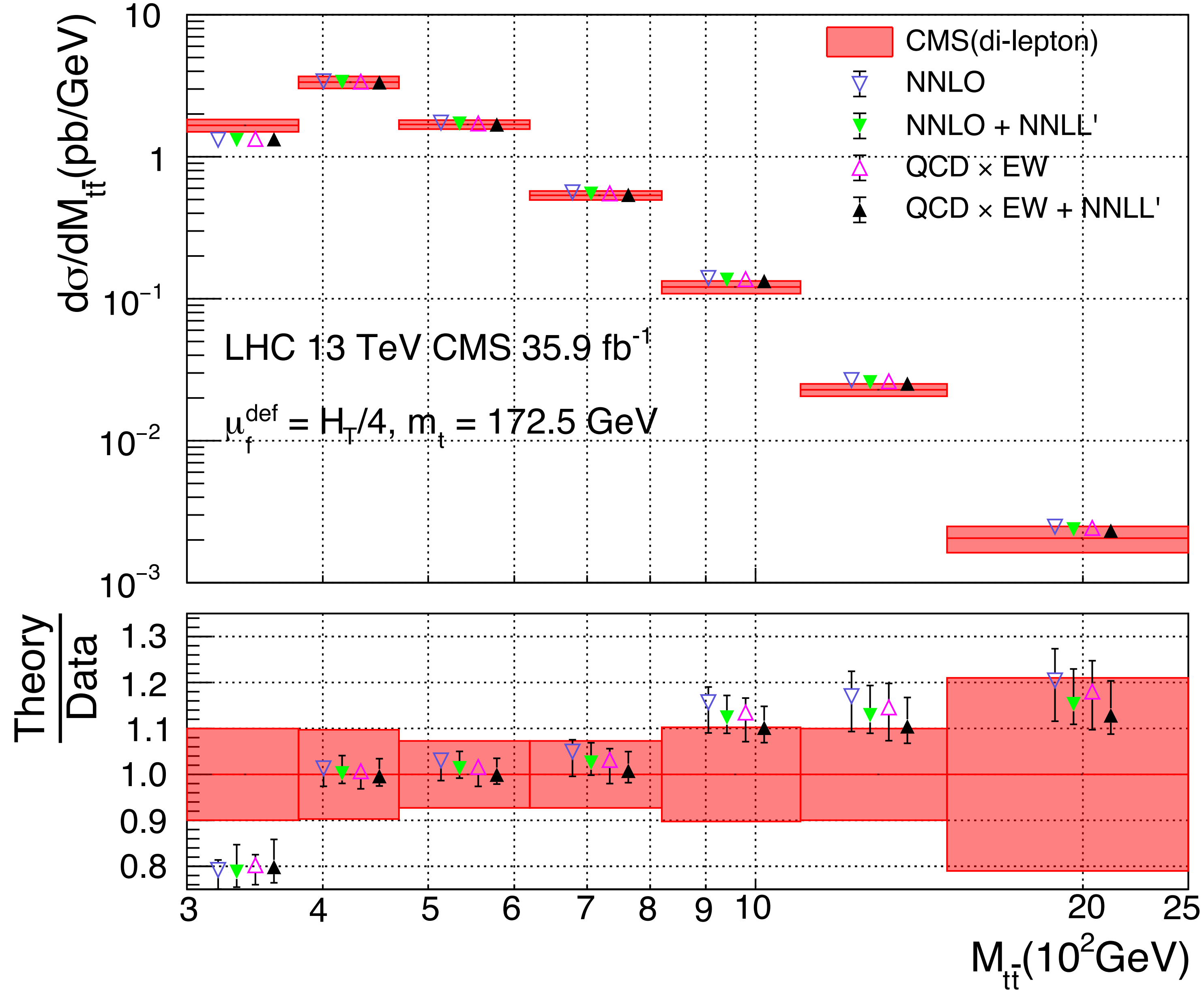
Catani, Devoto, Grazzini, Kallweit, Mazzitelli: 1906.06535



Up-to-date perturbative predictions

Further combined with the full NLO (QCD+electroweak) results

Czakon, Ferroglia, Mitov, Pagani, Papanastasiou, Pecjak, Scott, Tsinikos, Wang, **LLY**, Zaro: 1901.08281



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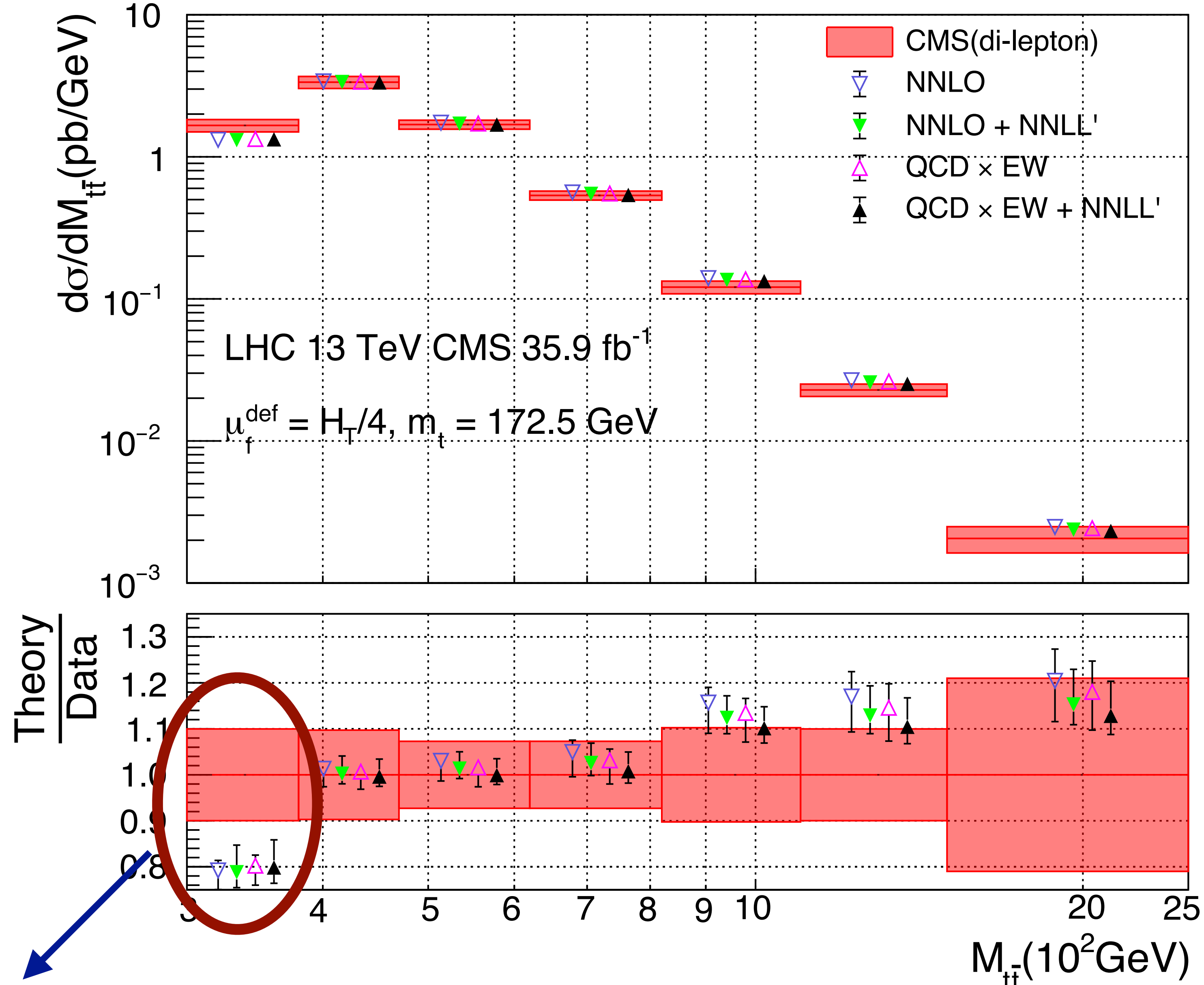

Still a discrepancy precisely in the m_t-sensitive region

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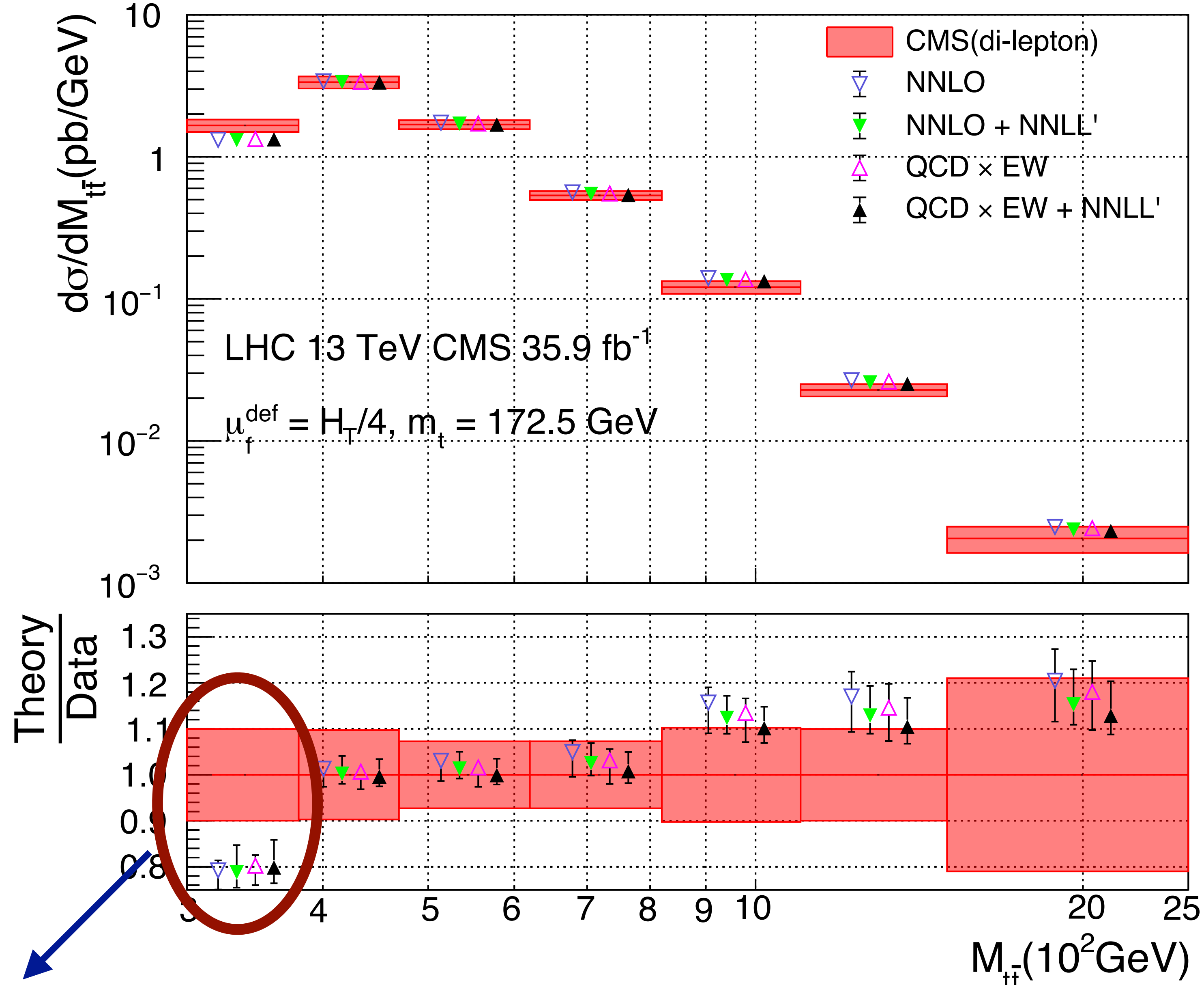
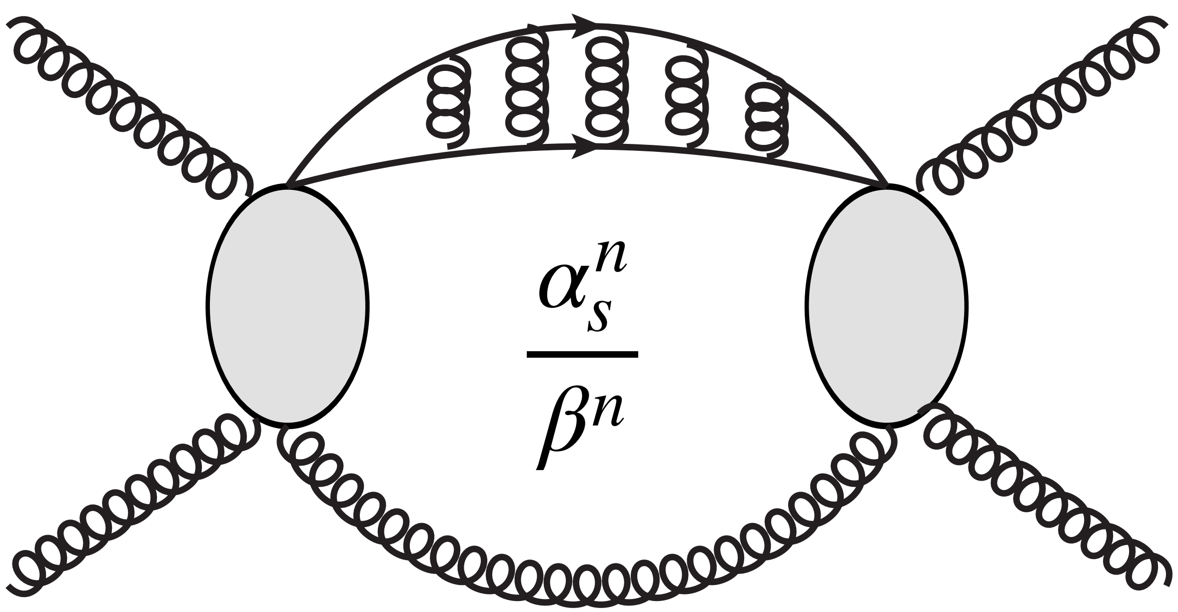


Still a discrepancy precisely in the m_t-sensitive region

What else have we missed?

Non-relativistic Coulomb corrections

When the top and anti-top quarks move slowly with respect to each other, exchanges of gluons in between lead to "Coulomb corrections" or "Sommerfeld enhancement"



$$\beta = \sqrt{1 - \frac{4m_t^2}{M_{t\bar{t}}^2}} \to 0$$

Kind of "non-perturbative" bound-state effects, but still calculable for top quarks

Resummation to all orders in α_s

A note on technical details

The basic EFT framework to resum these Coulomb corrections has been laid out in, e.g., Fadin et al. 1990; Bodwin et al. 1994; Petrelli et al. 1997; Hagiwara et al. 2008; Kiyo et al. 2008; Beneke et al. 2010

- We have performed a thorough assessment of the validity (and invalidity) of the EFTs **in the context of the LHC**
  - The small-β limit is valid up to $M_{t\bar{t}} \sim 380$ GeV **given that we carefully include the exact LO coefficients** (which was not done in previous calculations)
  - One should **NOT** try to resum soft gluons when already taking the $\beta \to 0$ limit (as opposed to some of the existing calculations)

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- We have derived an NLP resummation formula with full kinematic dependence (and have calculated a new hard function for that) which allows us to:
  - Use dynamic renormalization and factorization scales, and consequently combine our resummed result with existing NNLO calculations
  - Study double differential distributions

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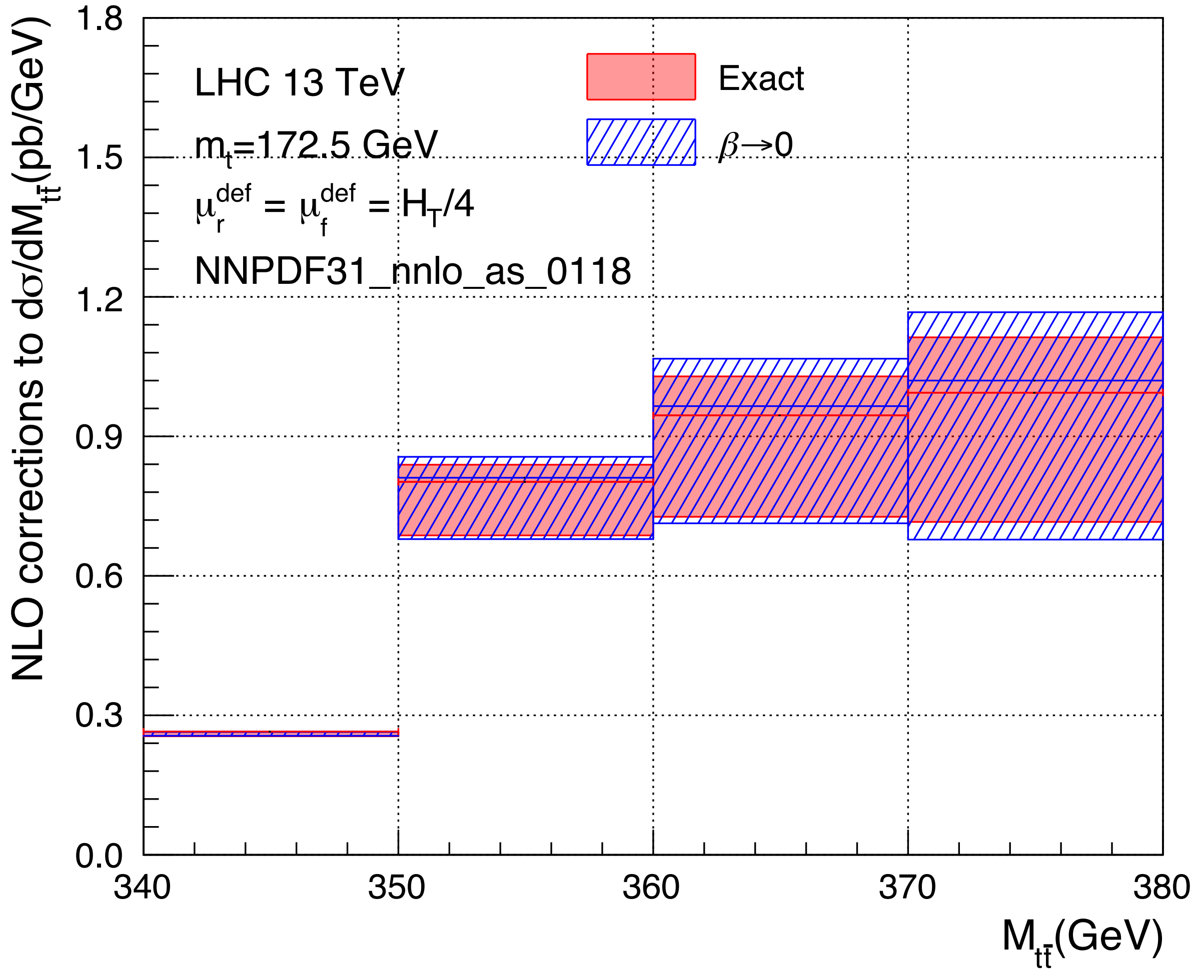
For more technical details, I'll give another talk on May 22 at the CERN QCD "lunch" seminar

https://indico.cern.ch/event/909250/

It’s time to show some plots…

Validity of EFTs



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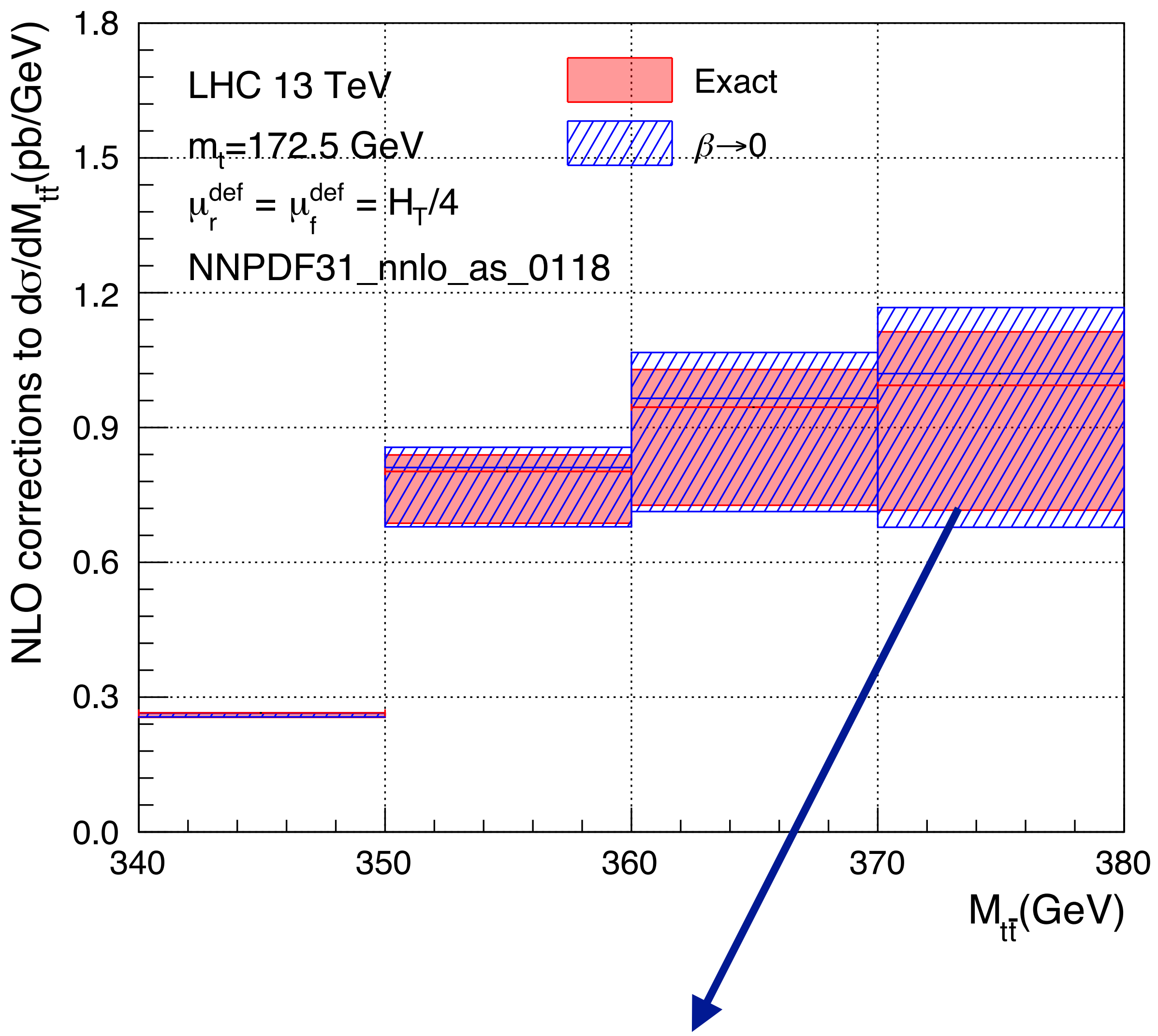
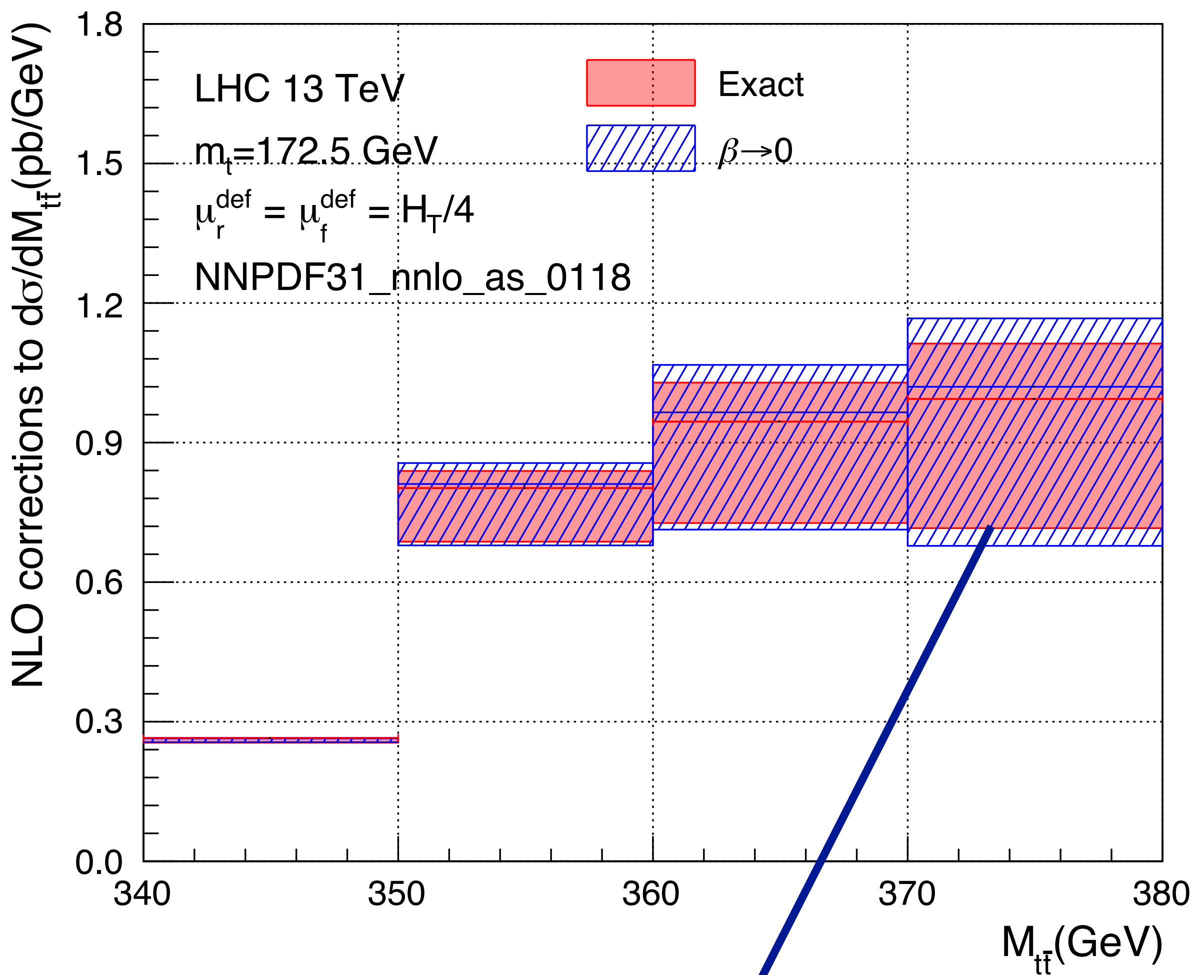
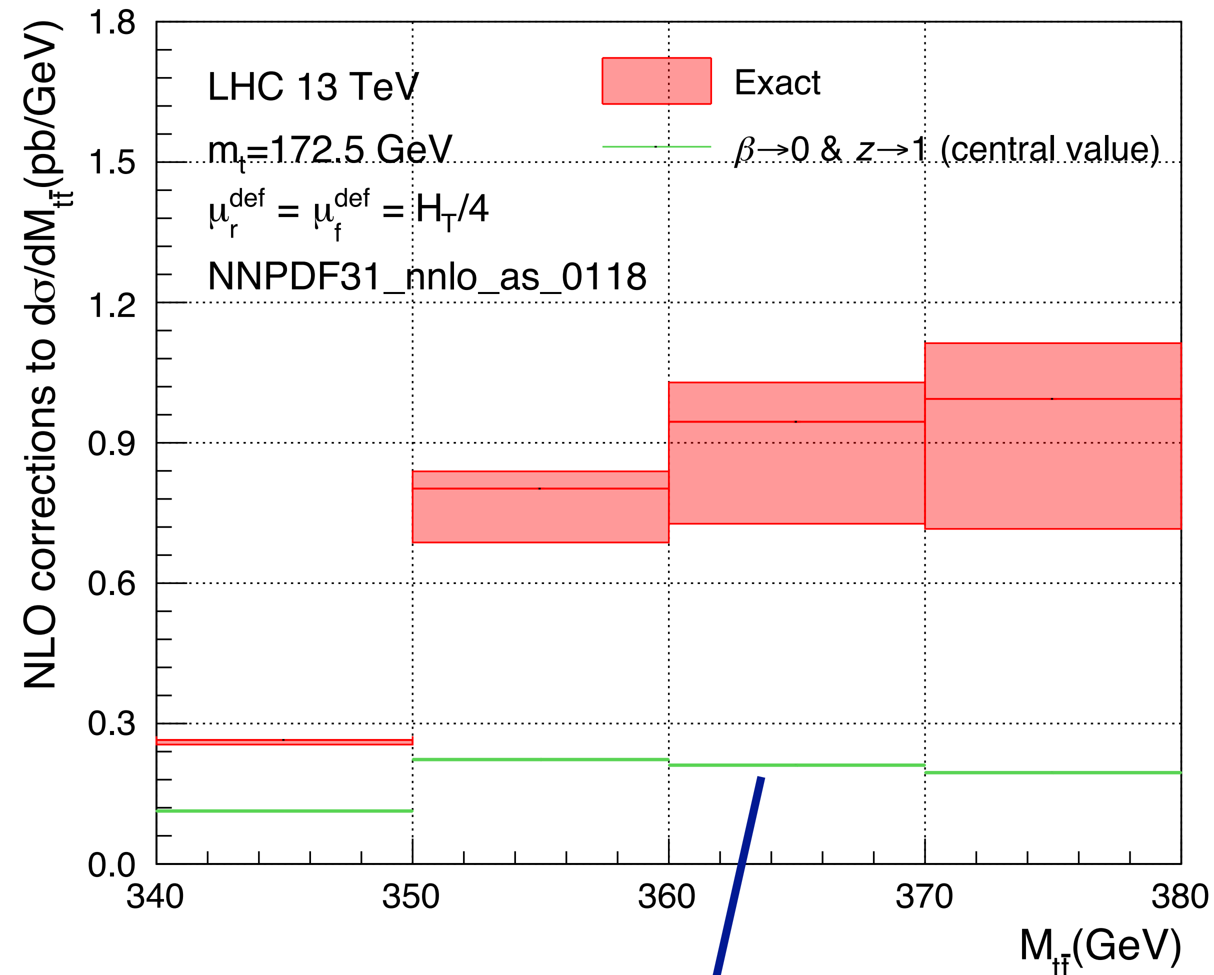


NRQCD ($\beta \to 0$ threshold limit) works well

Validity of EFTs

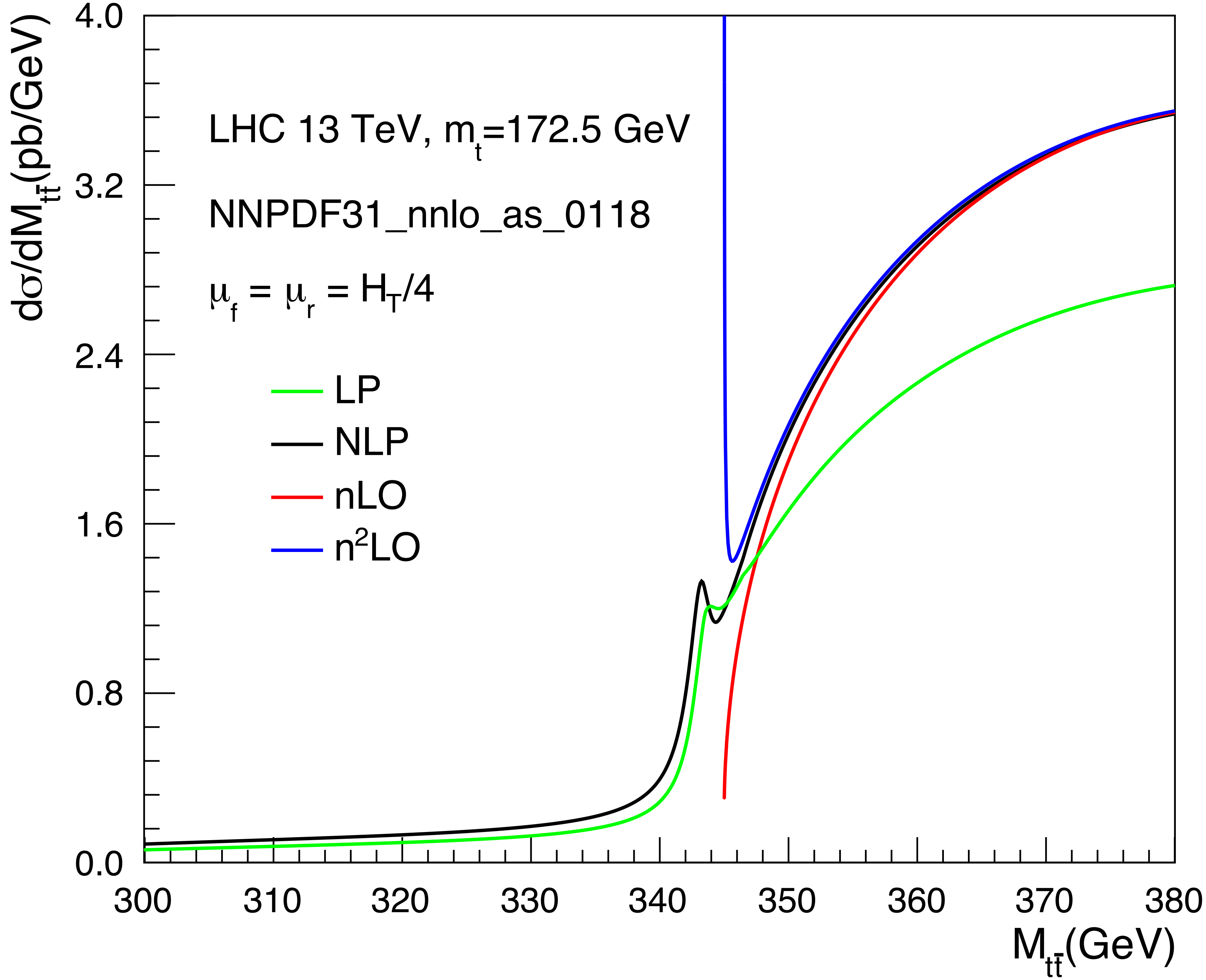




NRQCD ($\beta \to 0$ threshold limit) works well

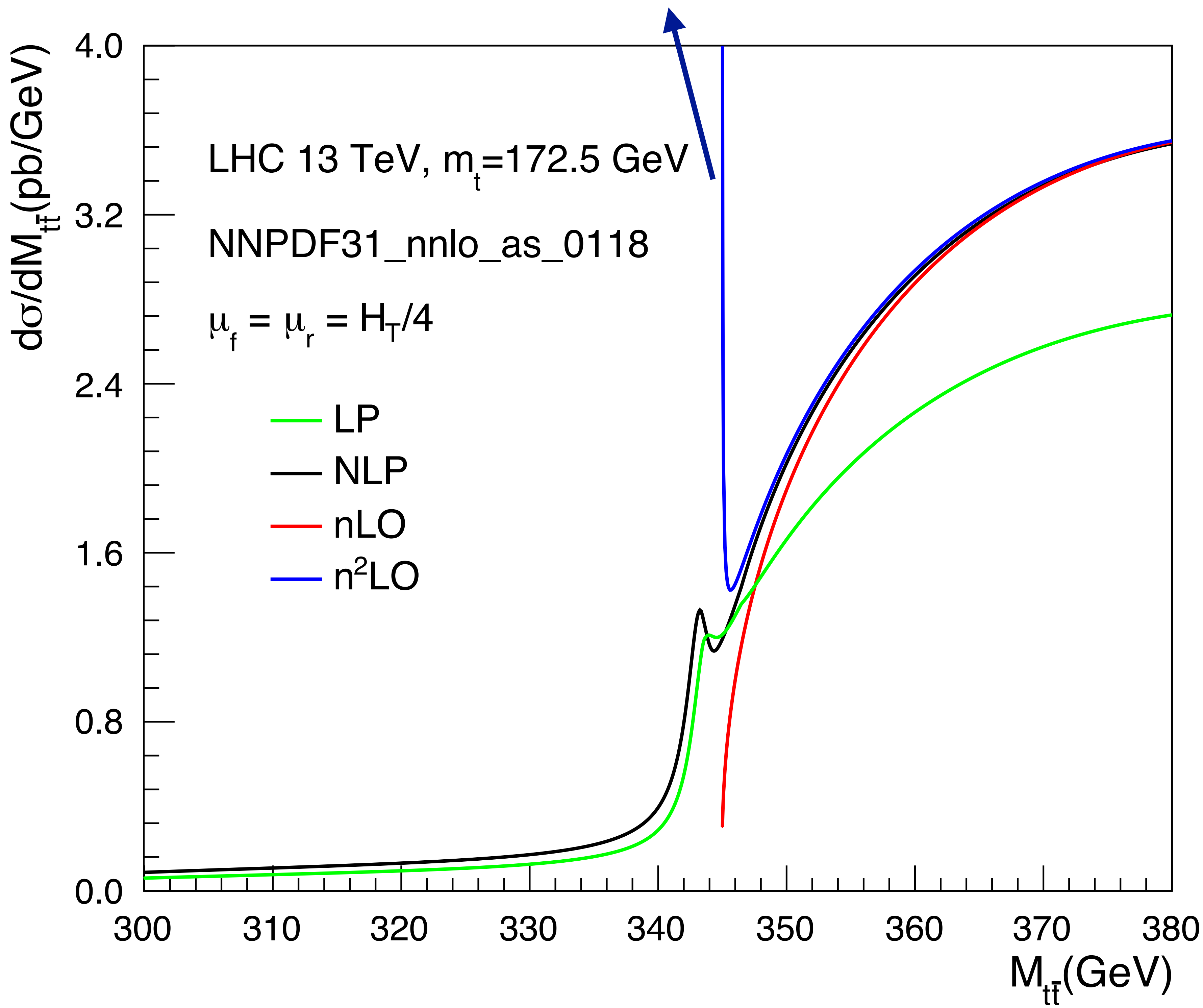
But the simultaneous threshold+soft limit does NOT

Perturbative behavior



Perturbative behavior

Fixed-order expansion divergent in the threshold limit



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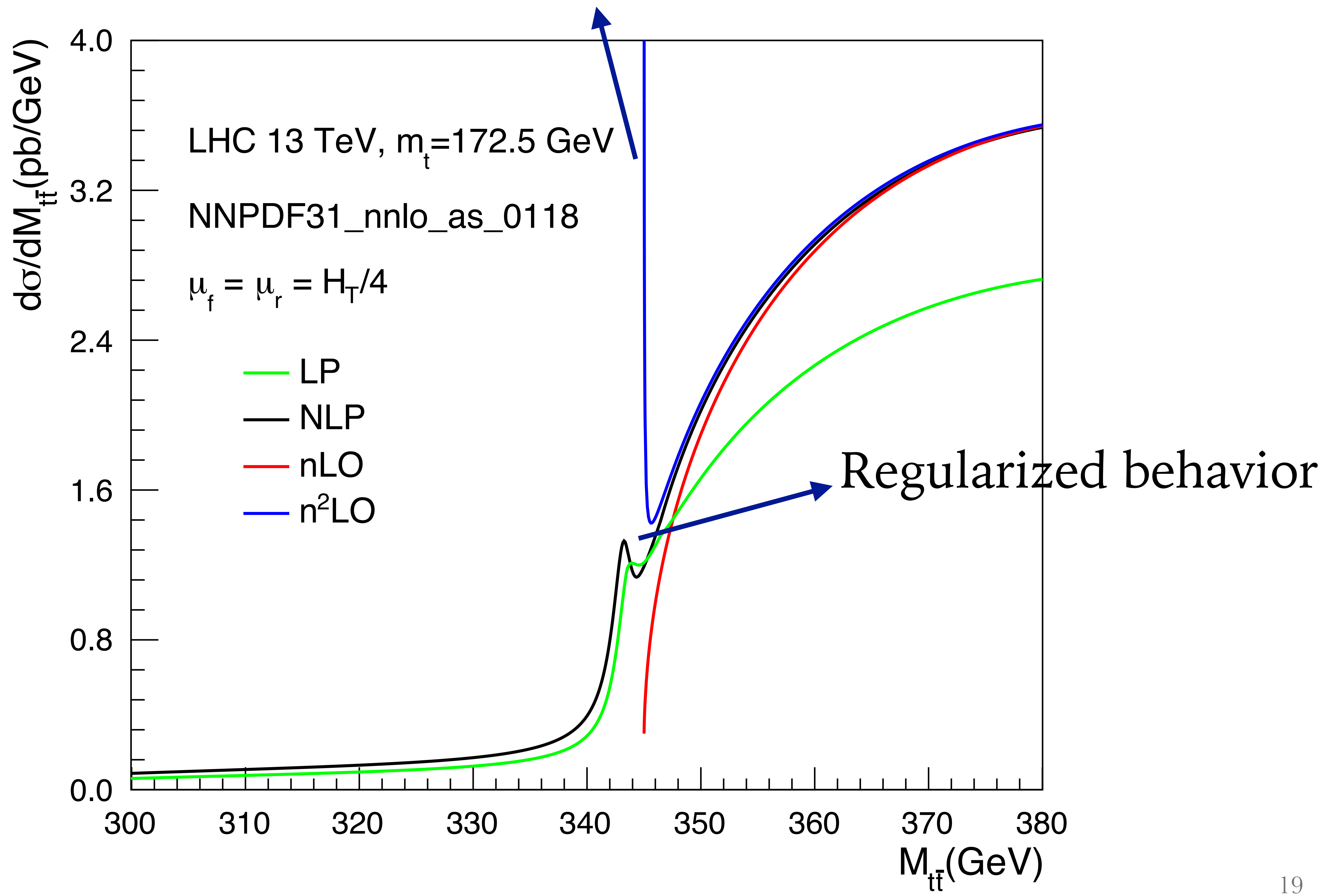

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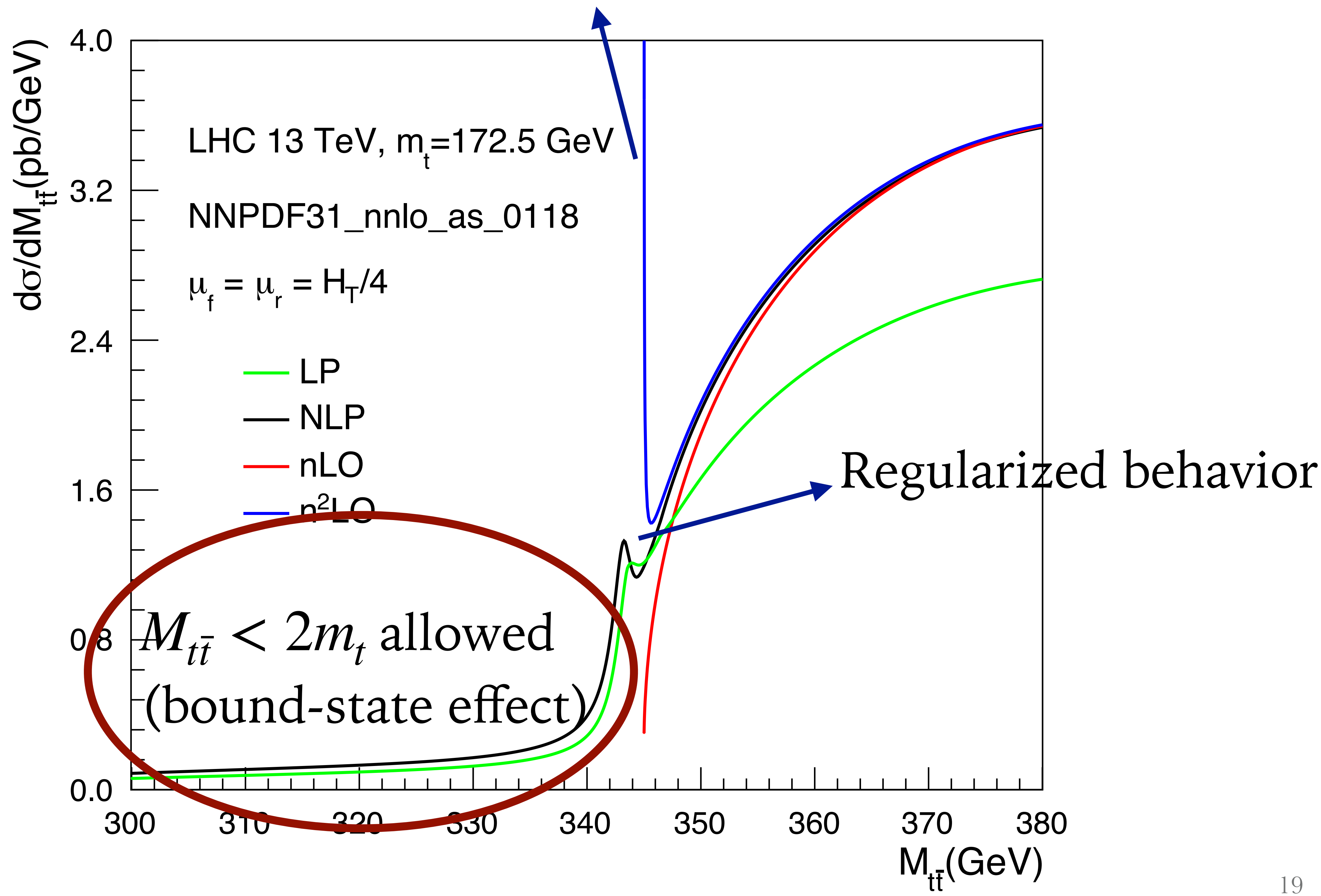
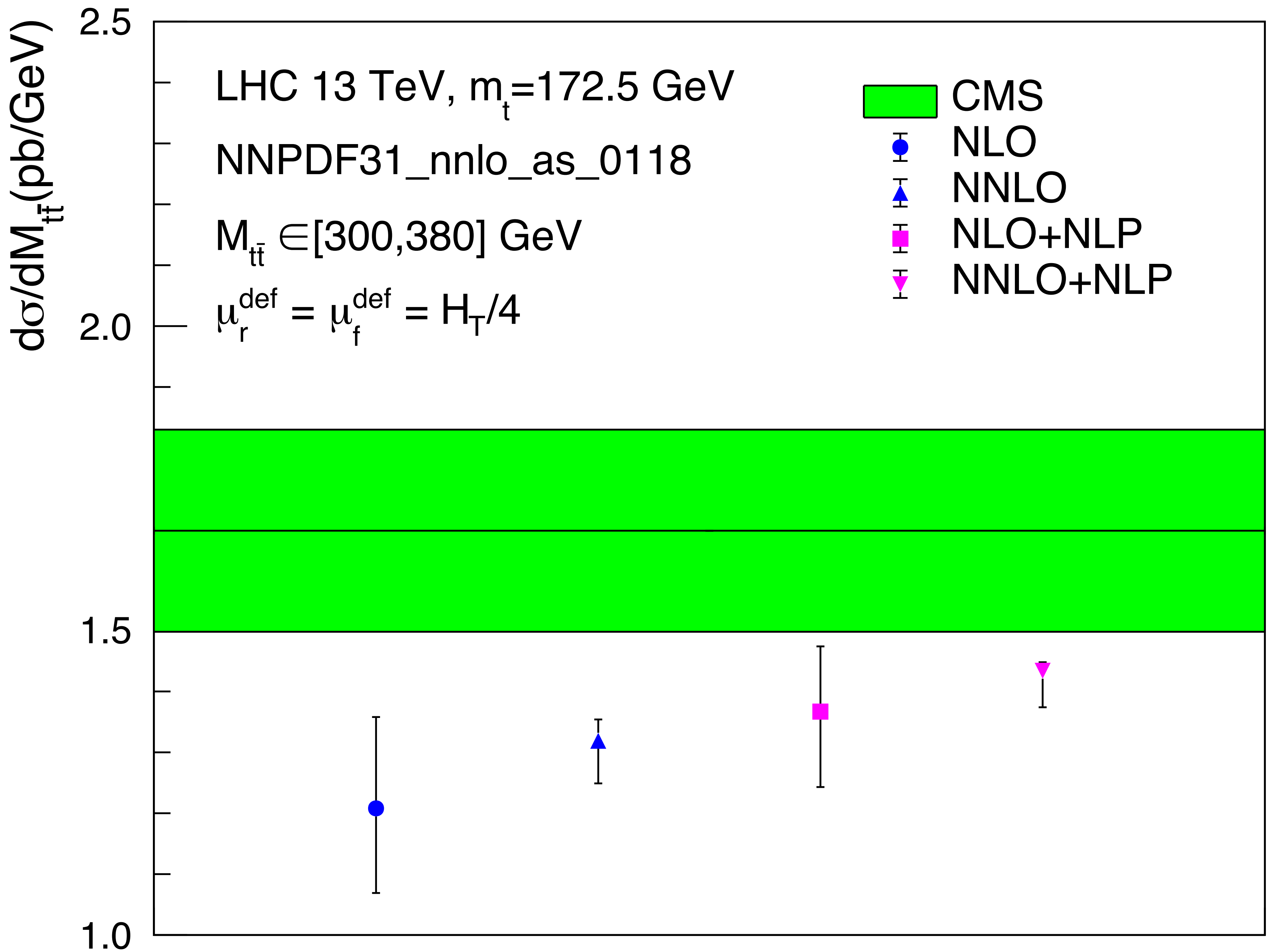


Compare to data: absolute distribution



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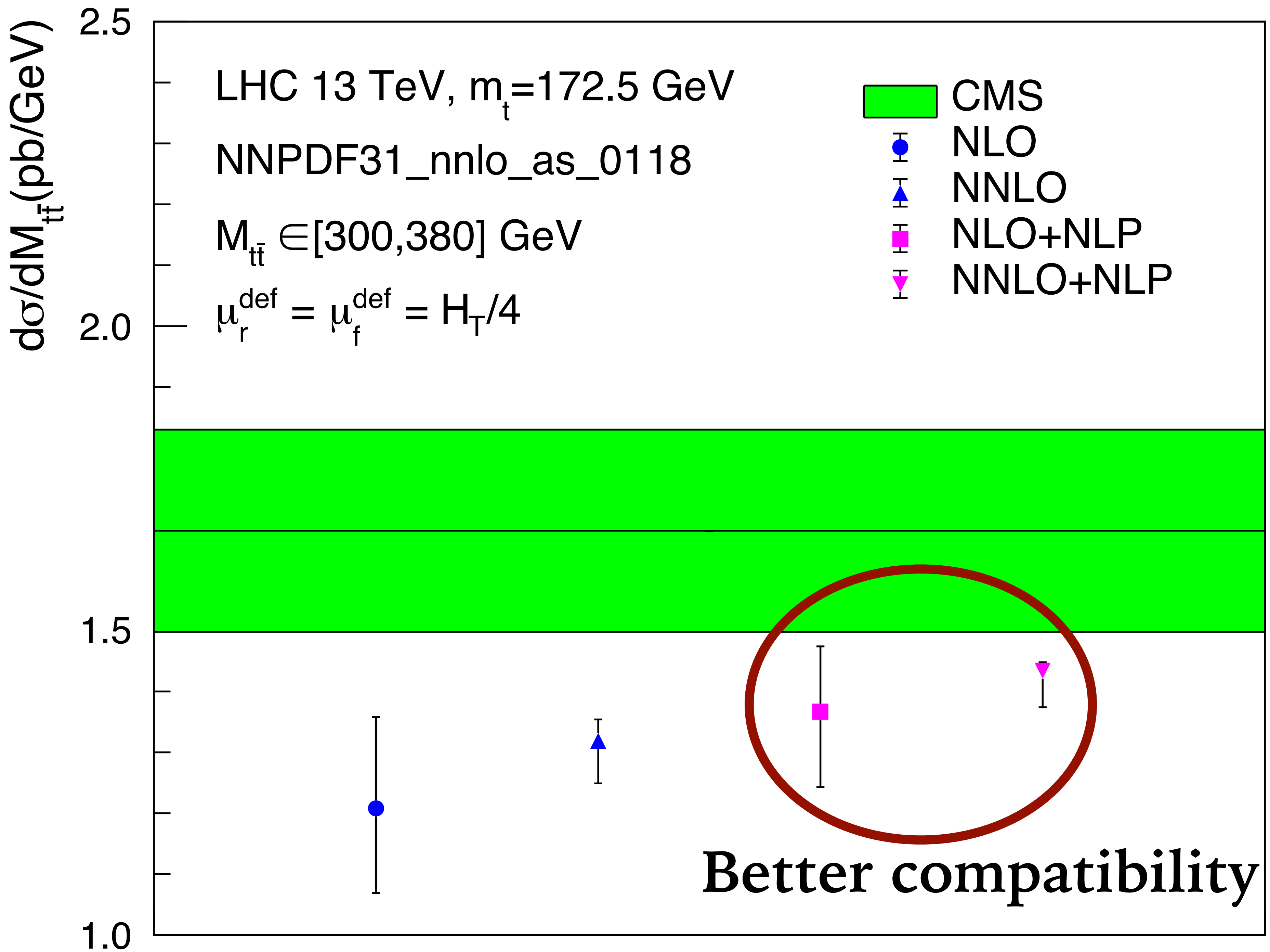
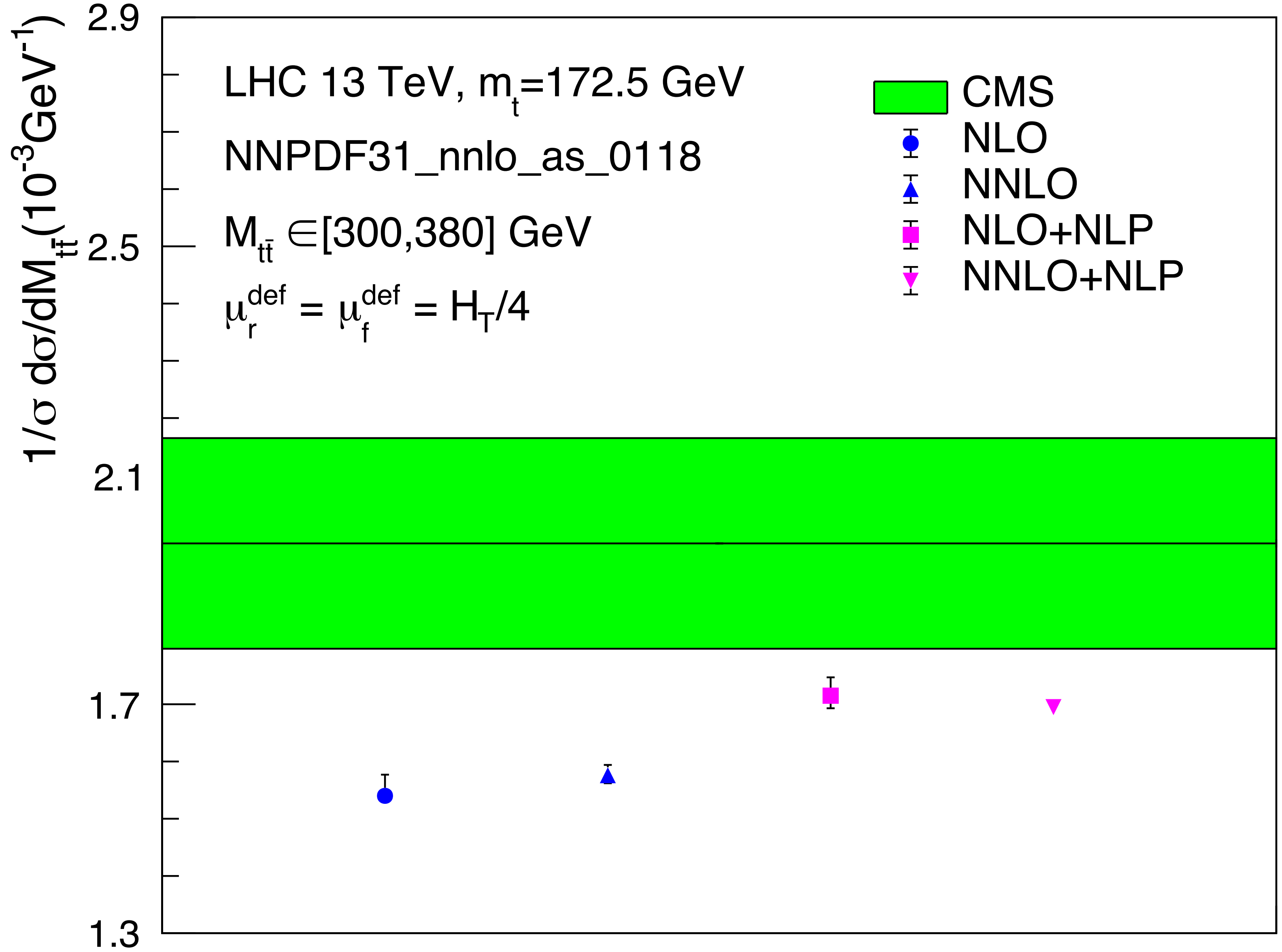


Better compatibility with data

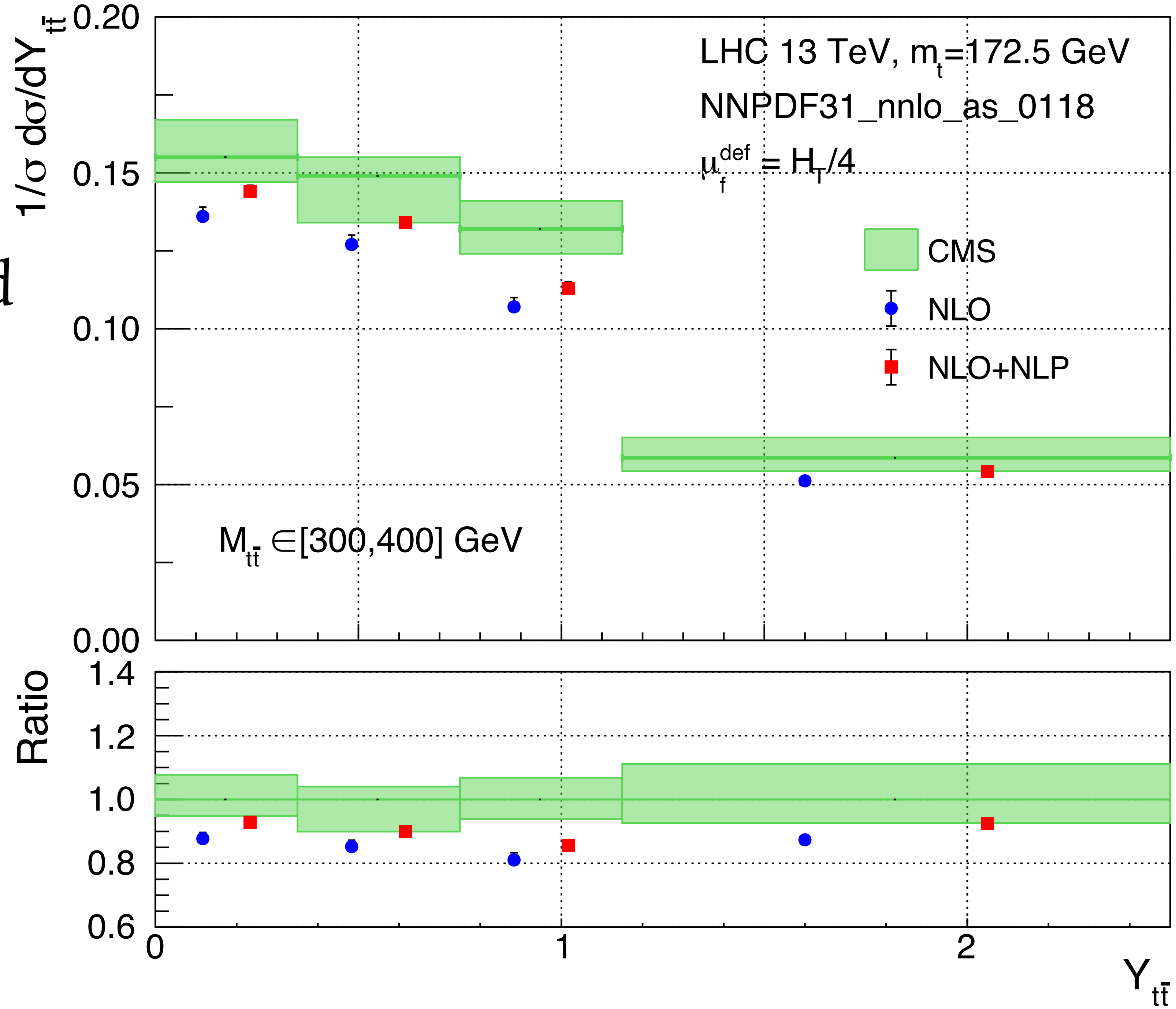
Compare to data: normalized distribution



For normalized distribution, the NNLO corrections are small in this region, but the Coulomb corrections are still significant

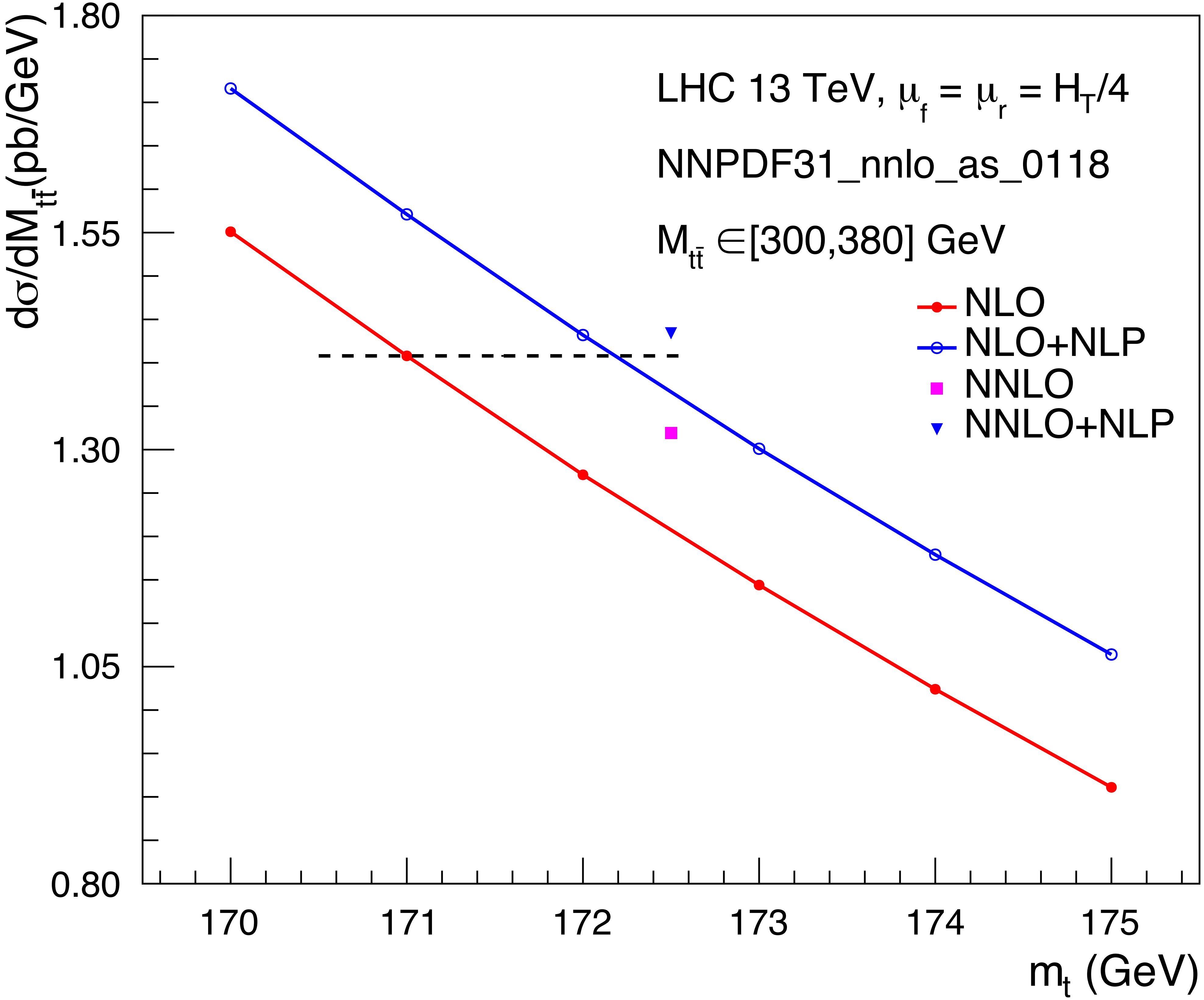
Compare to data: double distribution

Normalized



Observing similar effects as in the single distribution

Influence on mass extraction: absolute distr.



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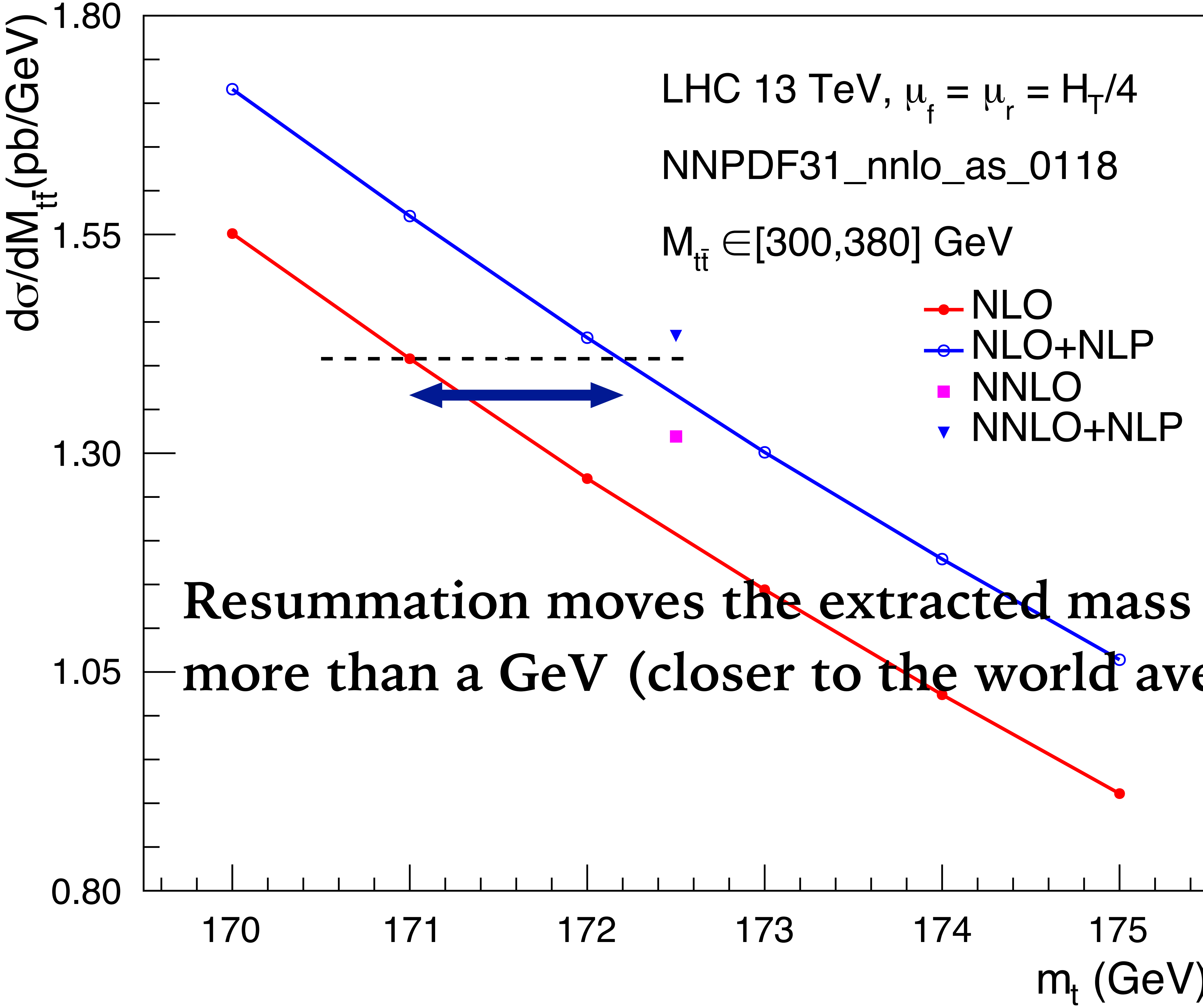
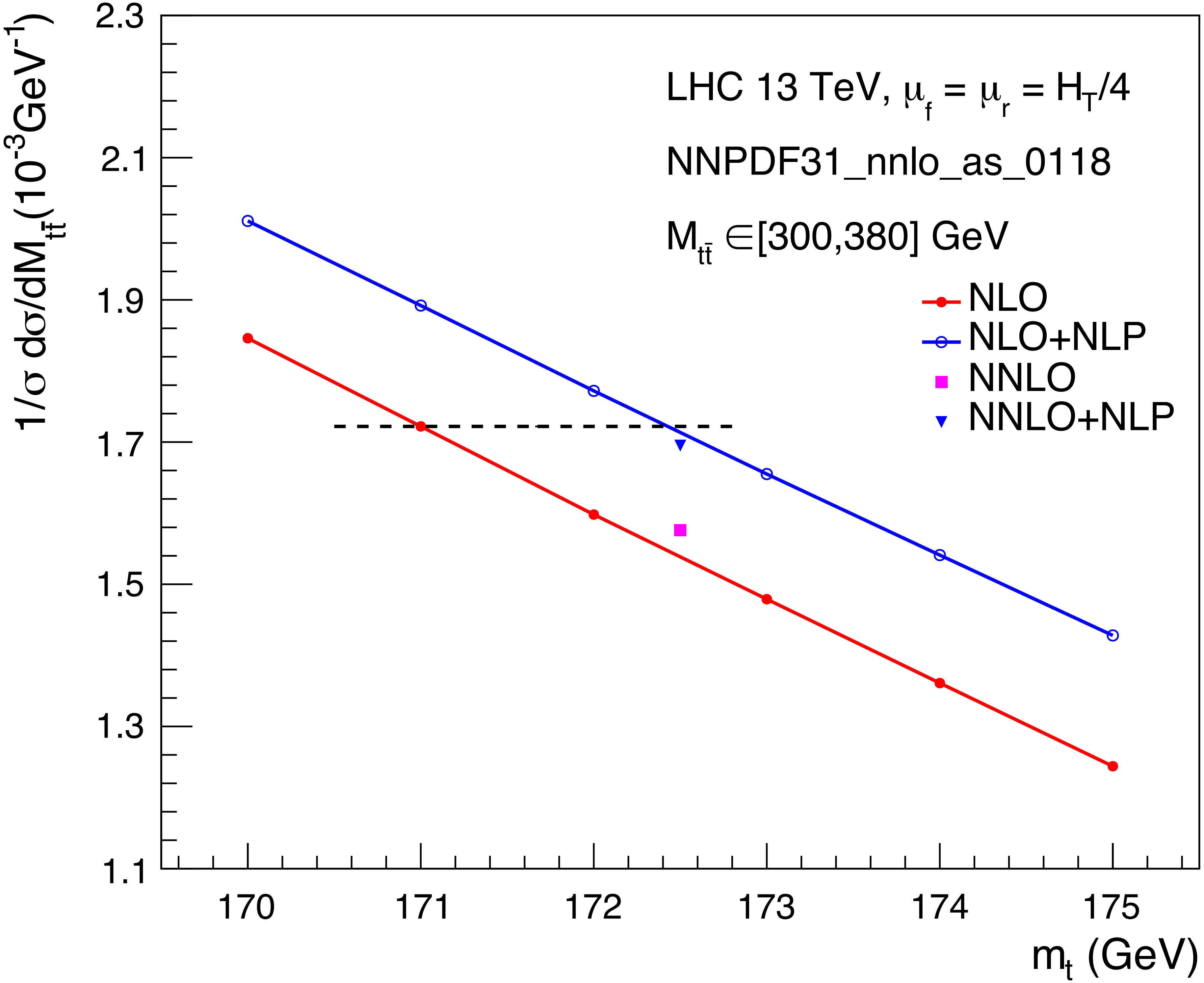


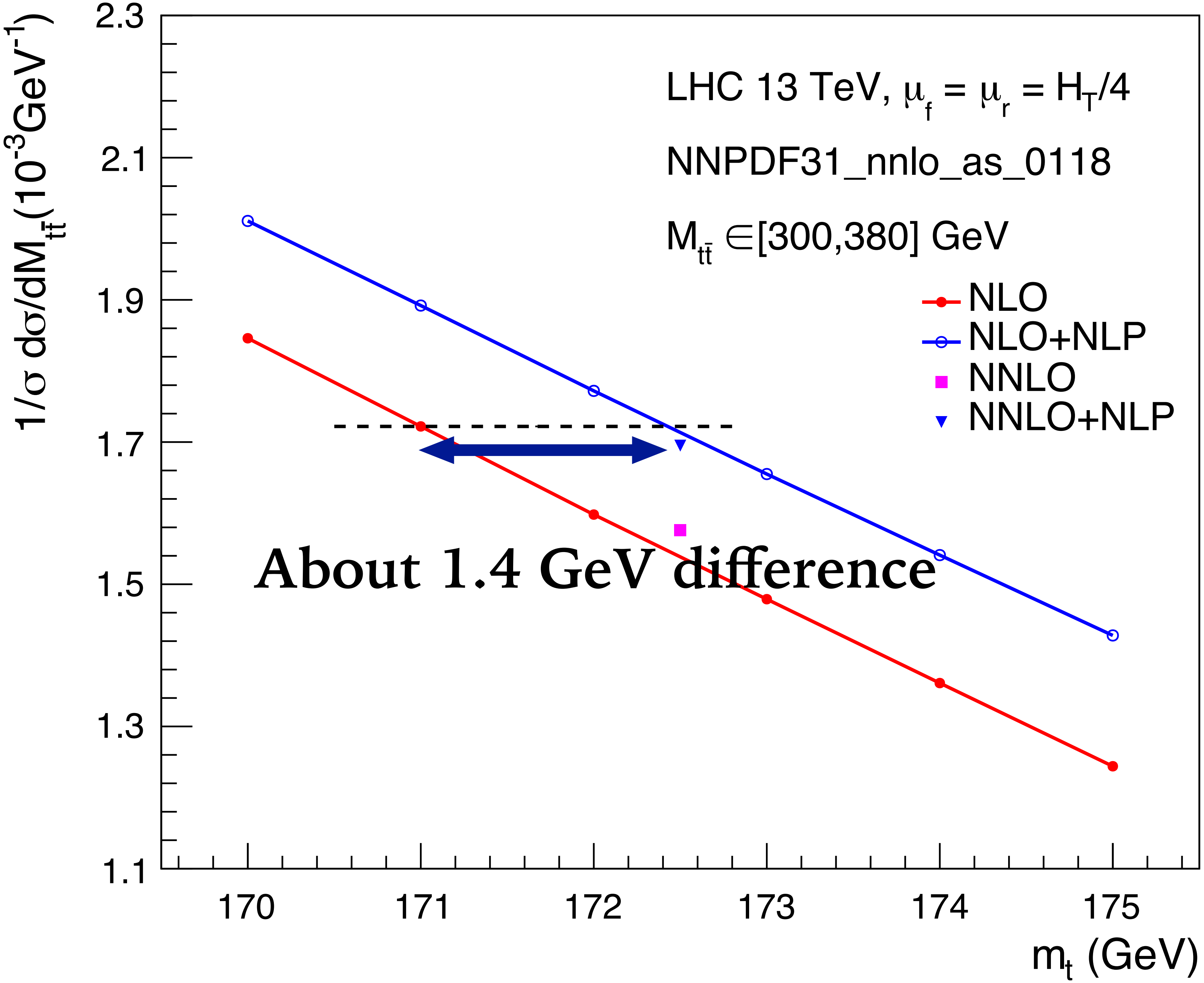
Resummation moves the extracted mass up by more than a GeV (closer to the world average)

Influence on mass extraction: normalized distr.



Similar behavior for [300,400] GeV range

Influence on mass extraction: normalized distr.



Similar behavior for [300,400] GeV range

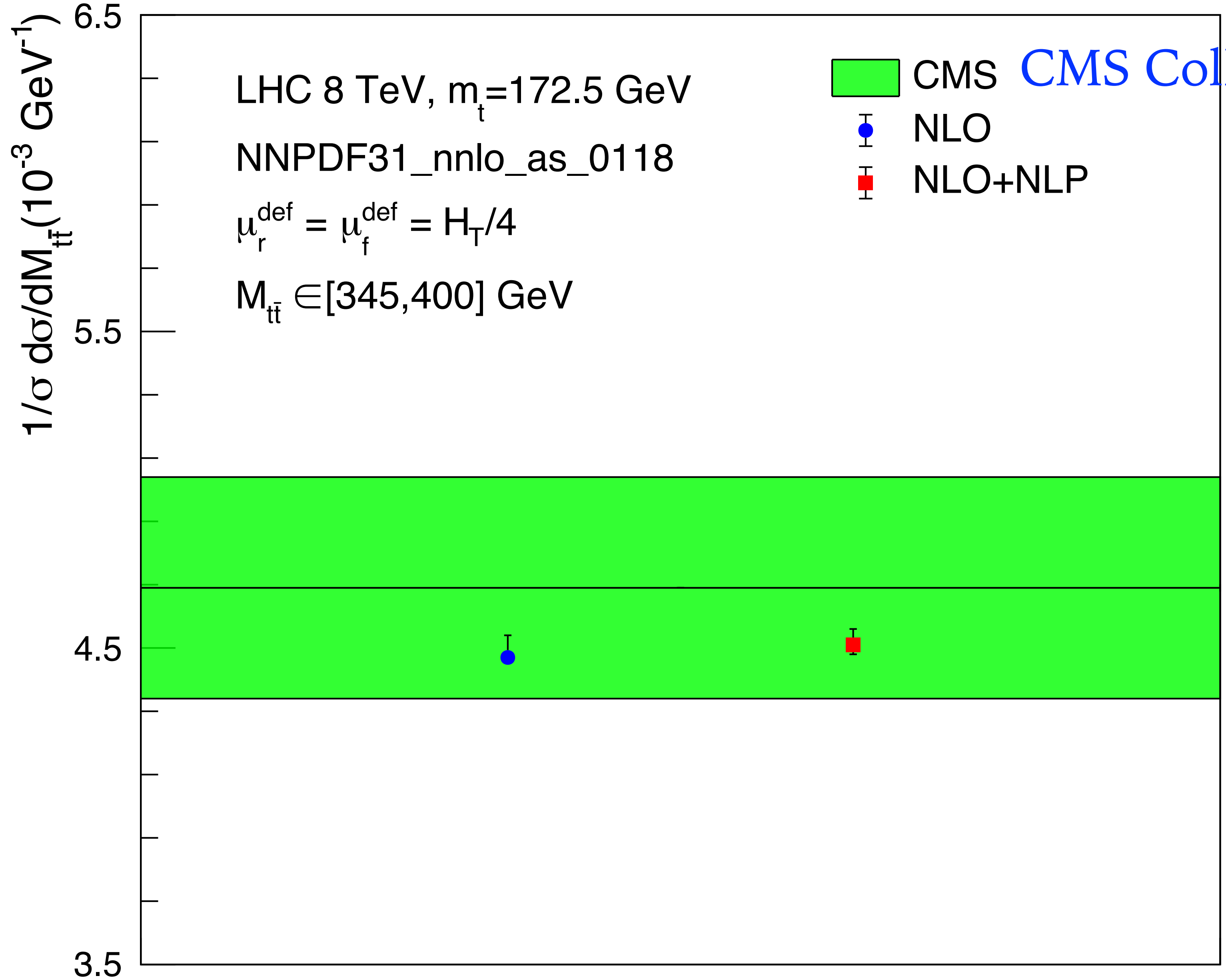
Summary

- The top quark mass, as an important parameter, has been measured to high precisions using different methods
- The results of recent indirect measurements are much smaller than the world average, which are largely related to a gap between theory and data in the low-$M_{t\bar{t}}$ threshold region
- We reanalyzed the Coulomb effects in the threshold region and found that they lead to better compatibilities between the extracted top quark mass and the world average
- Further considerations in the future:
  - QED Coulomb effects which are formally NLP
  - Beyond NLP: NNLP in NRQCD, top quark width as well as electroweak corrections

Backup slides

Results for 8 TeV (note the binning!)

There was a CMS measurement at the 8 TeV LHC which did not find any discrepancy in the low $M_{t\bar{t}}$ region



CMS Collaboration: 1505.04480

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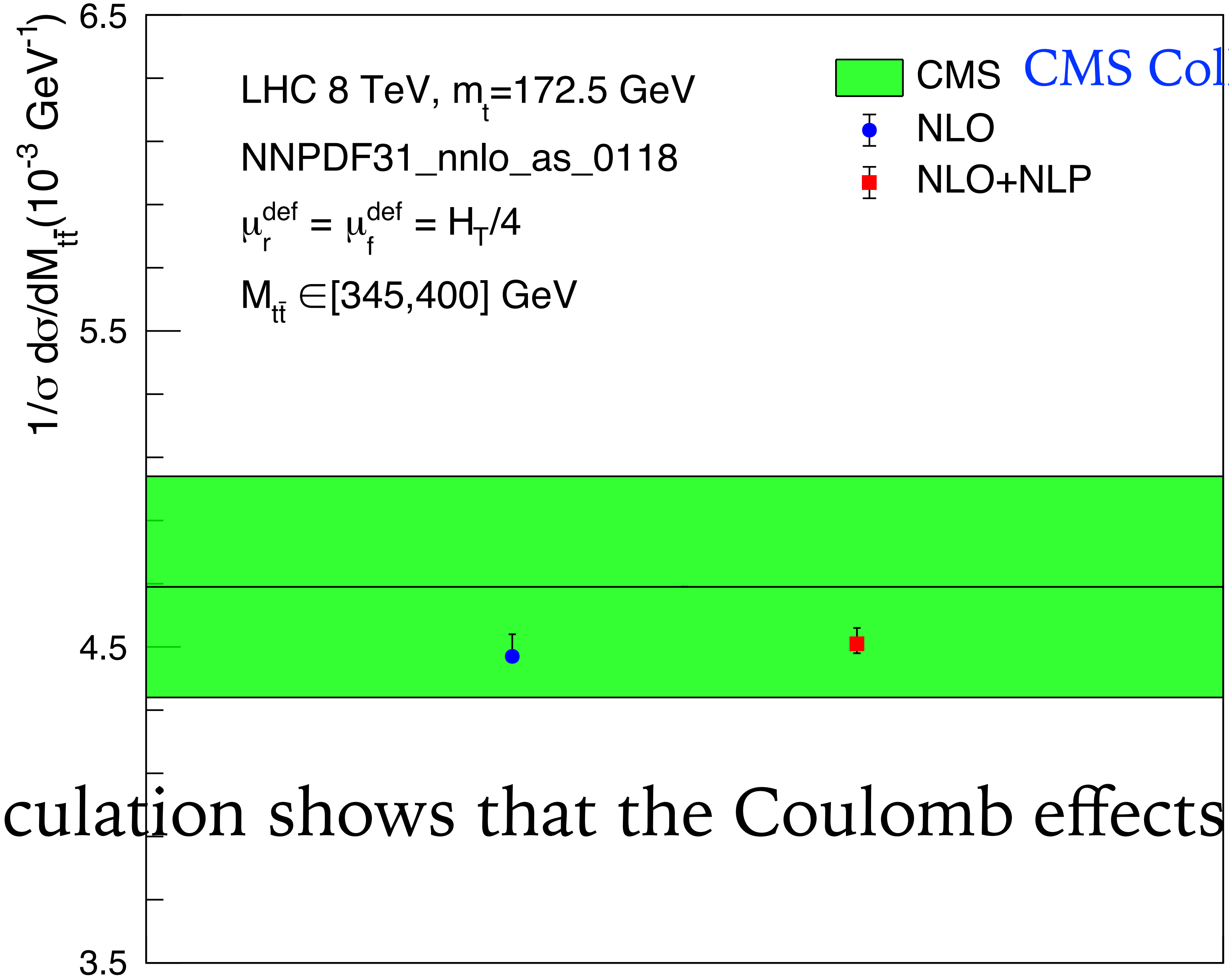

Our calculation shows that the Coulomb effects are also small

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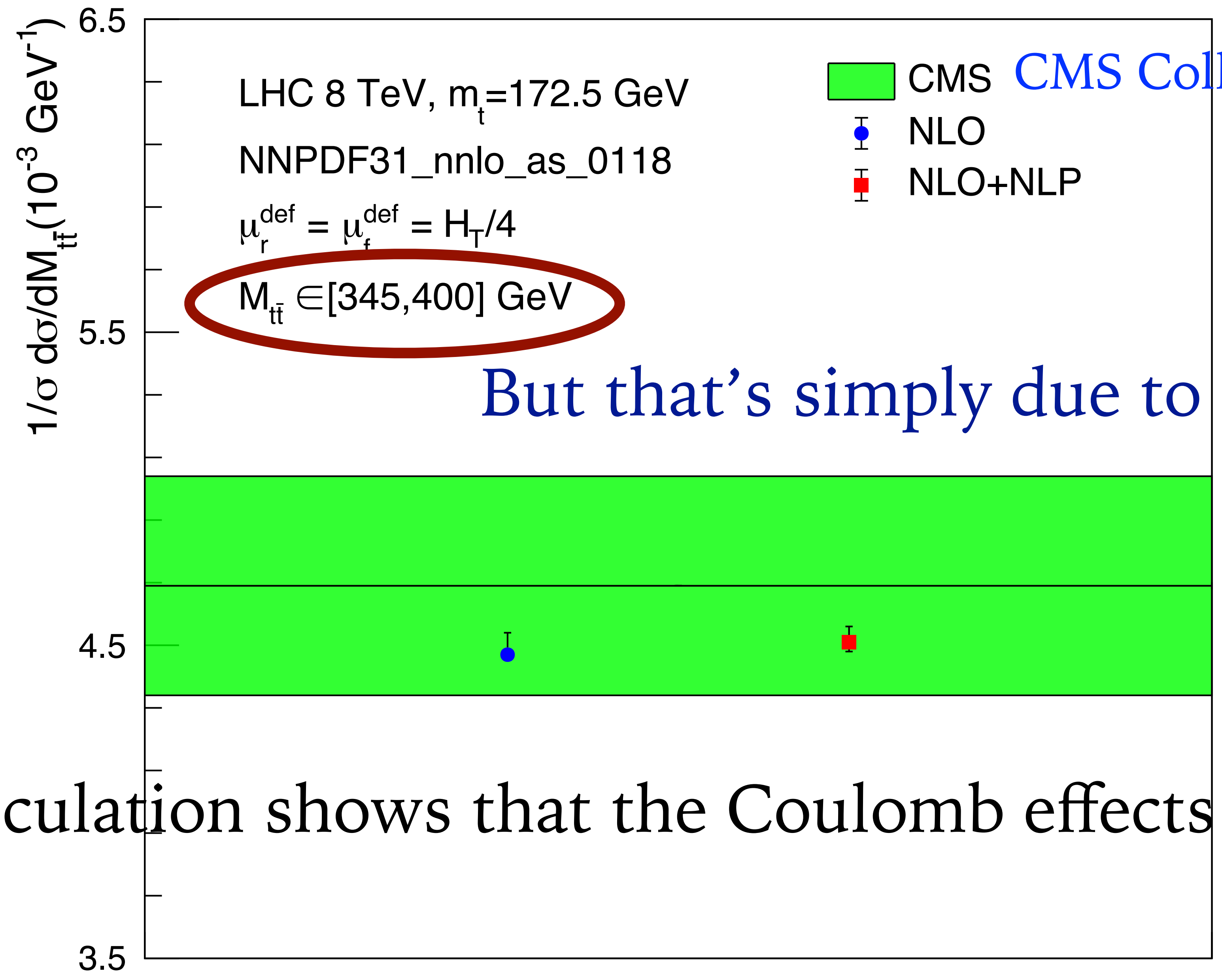

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But that's simply due to the binning!

Our calculation shows that the Coulomb effects are also small

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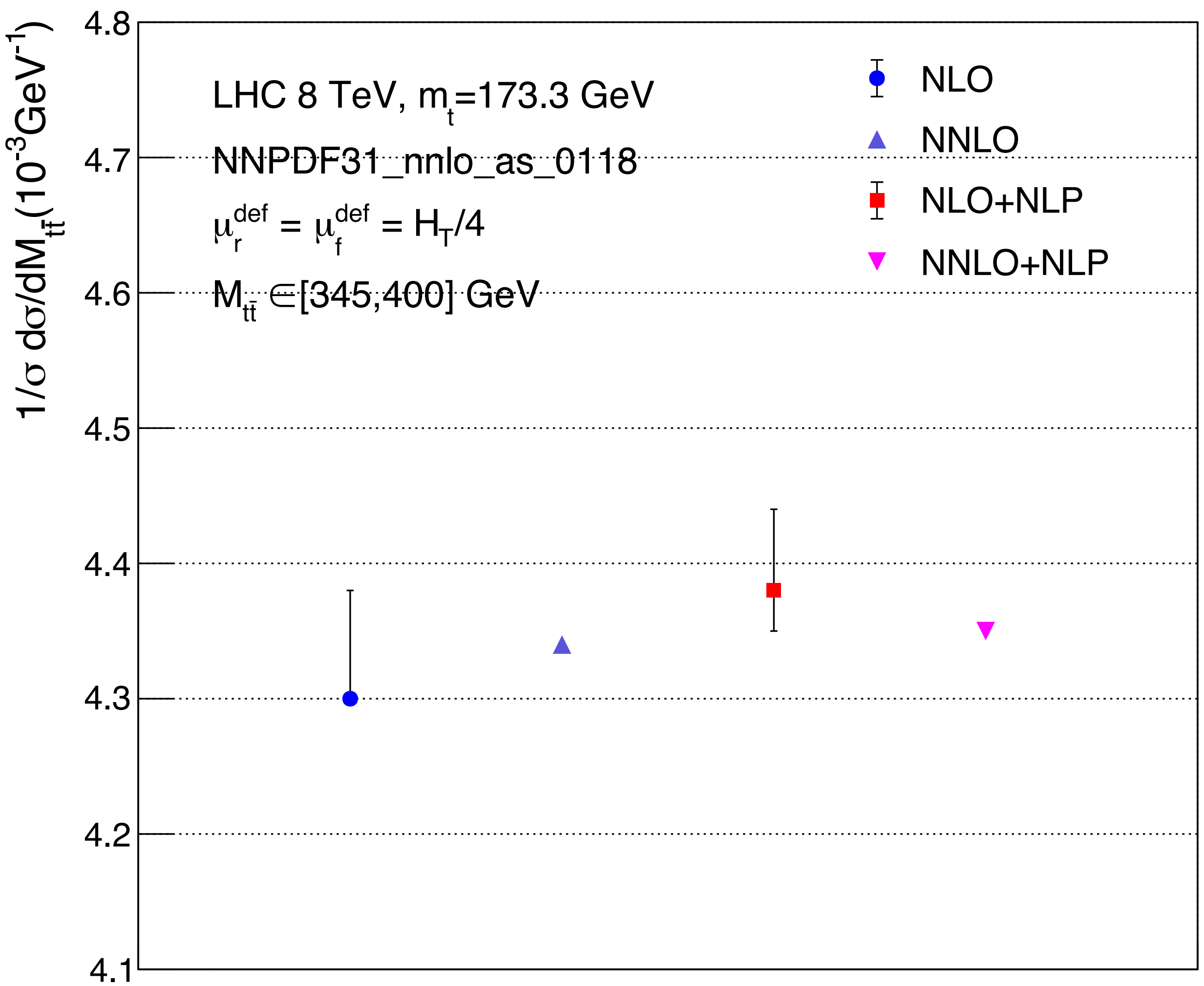

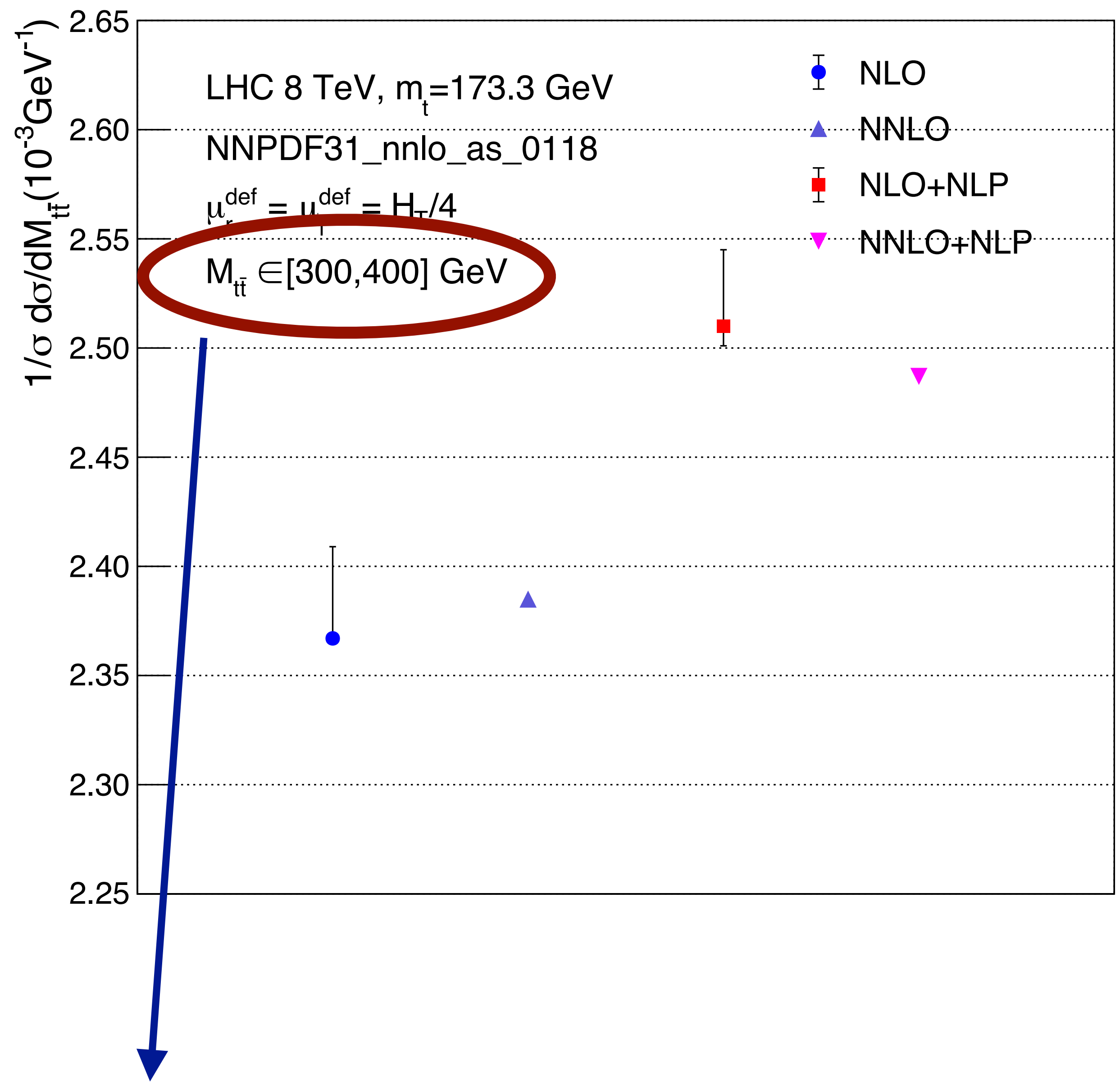

Had one chosen the same binning as 13 TeV, the effects should be visible (with enough statistics)!