Top-quark pair production: fully differential predictions at NNLO

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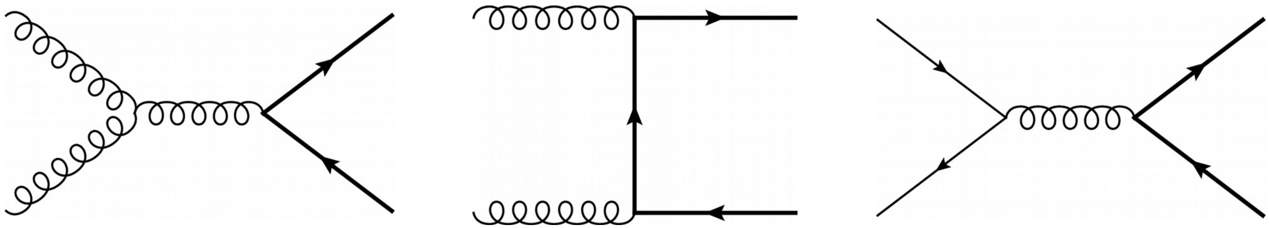
In collaboration with S. Catani, S. Devoto, M. Grazzini, S. Kallweit, H. Sargsyan

Outline

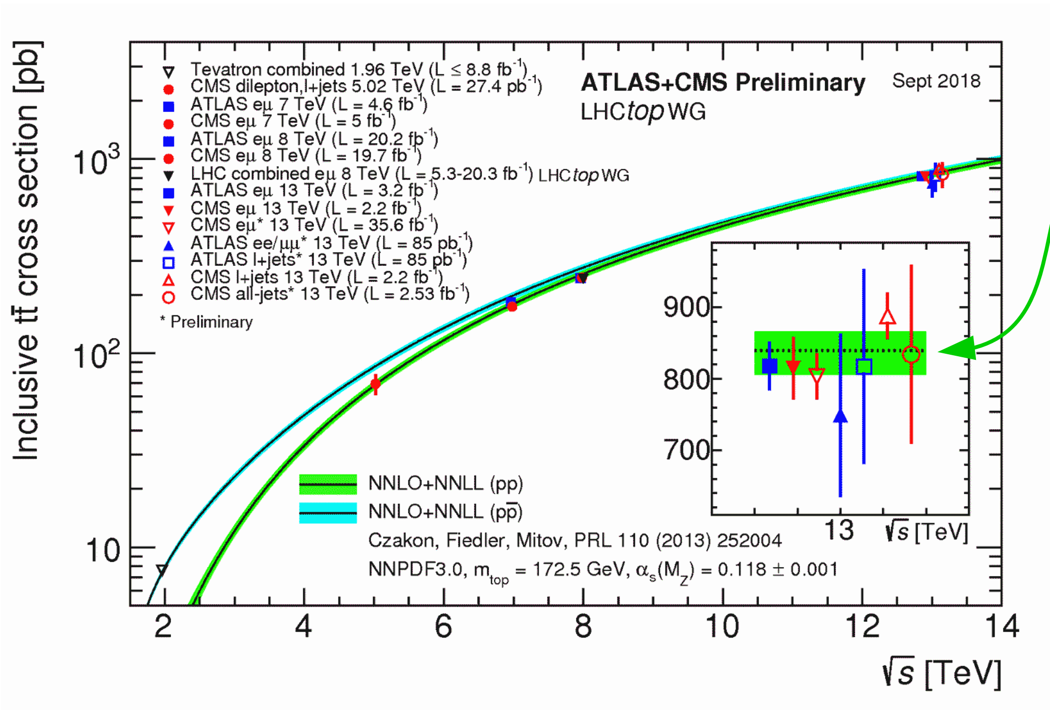
- **Introduction**
- **NNLO corrections with q_T subtraction**
- **Extension to heavy quark production**
- **Results and comparison with data**
- **Conclusions and outlook**

Top-quark pair production

Main production mechanism of top quarks at hadron colliders



- Approx. 3 times larger than single-top production
- About **15** $t\bar{t}$ pairs produced **per second** at the LHC!



Impressive experimental precision

Very precise theoretical predictions are needed

Cross section known at NNLO QCD + NLO EW + resummation

Why a new NNLO QCD calculation?

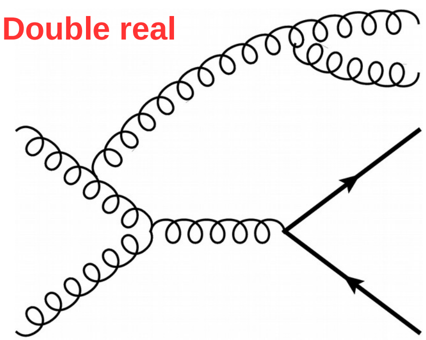
- Very difficult calculation: only one group able to complete it until now
- Independent check is always useful!
- No publicly available tool to produce NNLO distributions yet

Bärnreuther, Czakon, Mitov (2012)
Czakon, Mitov (2012)
Czakon, Fiedler, Mitov (2013)
Czakon, Fiedler, Heymes, Mitov (2015,2016)

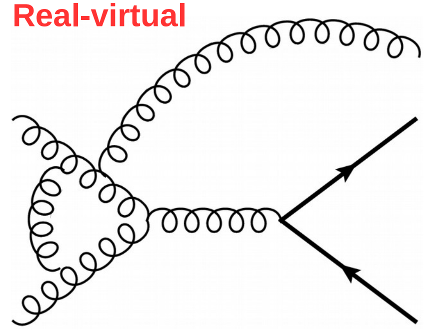
$t\bar{t}$ production at NNLO

We need the scattering amplitudes:

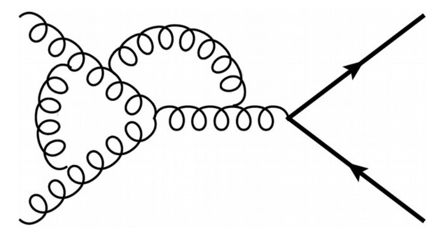
Double real



Real-virtual



Two-loop virtual



Fast and stable evaluation with OpenLoops2

Cascioli et al. (2012), Buccioni et al. (2018)

Available numerically

Czakon (2008)
Barnreuther, Czakon, and Fiedler (2013)

… but we also need to handle their divergencies:

No ε poles, singular in (double) unresolved limit

Explicit $1/\varepsilon^2$ poles, singular in unresolved limit

Explicit $1/\varepsilon^4$ poles, no further PS singularities

$$\Delta\sigma_{\mathrm{NNLO}} = \int_{F+2} d\sigma_{\mathrm{RR}} + \int_{F+1} d\sigma_{\mathrm{RV}} + \int_{F} d\sigma_{\mathrm{VV}}$$

Finite

Individually divergent contributions

We need **subtraction methods** that allow us to perform these calculations numerically

q_T subtraction

Originally developed for the hadroproduction of **colourless** final states Catani, Grazzini (2007)

Implemented as slicing method, slicing parameter: $\mathbf{q_T}$ (transverse momentum of final state *F*)

Master formula:

Difference computed with a cut on r = q_T/M

$$d\sigma^{F}_{\mathrm{NNLO}} = \mathcal{H}^{F}_{\mathrm{NNLO}} \otimes d\sigma^{F}_{\mathrm{LO}} + \left[d\sigma^{F+\mathrm{jet}}_{\mathrm{NLO}} - d\sigma^{\mathrm{CT}}_{\mathrm{NNLO}} \right]$$

Process dependent hard-collinear function

Restores correct normalization, includes the 2-loop corrections

NLO *F*+jet cross section (using dipole subtraction)

Universal counterterm to cancel qT → 0 divergencies

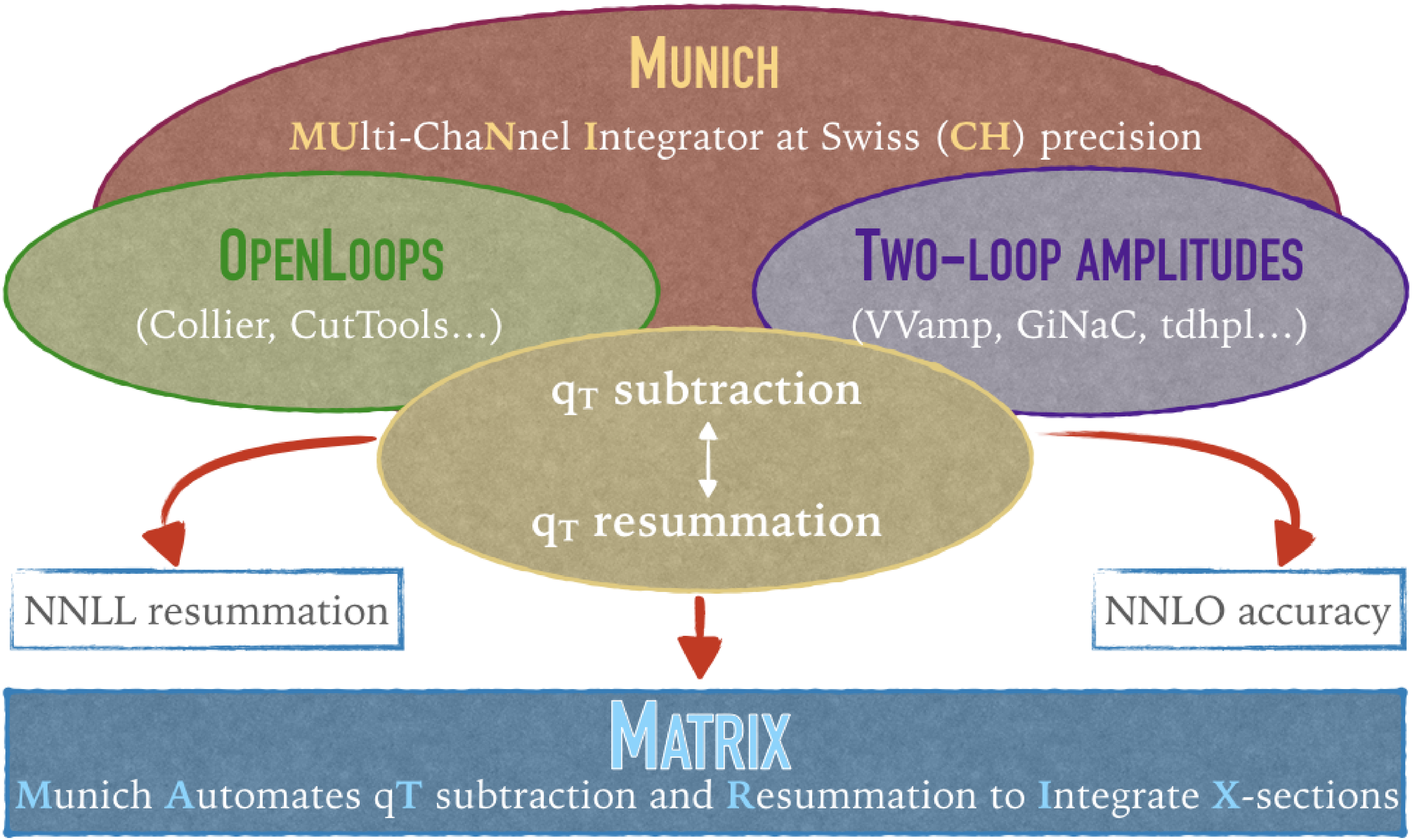
Based on known low qT behaviour from resummation

General form of hard-collinear function known at NNLO for colourless *F*

Method can be applied to the production of arbitrary colour singlets once the relevant amplitudes are available → MATRIX

Grazzini, Kallweit, Wiesemann (2017)

The MATRIX project



The MATRIX project

Status:

- $Z/\gamma^*(\to \ell^+\ell^-)$
- $W(\to \ell\nu)$
- H
- $\gamma\gamma$
- $W\gamma \to \ell\nu\gamma$
- $Z\gamma \to \ell^+\ell^-\gamma$
- $ZZ(\to 4\ell)$ Plus NLO gg [not in public release]
- $WW(\to \ell\nu\ell'\nu')$
- $ZZ/WW \to \ell\ell\nu\nu$
- $WZ \to \ell\nu\ell\ell$
- HH [not in public release]

First public release out in November 2017

Grazzini, Kallweit, Wiesemann

What about heavy quark production?

Extension to heavy-quark production

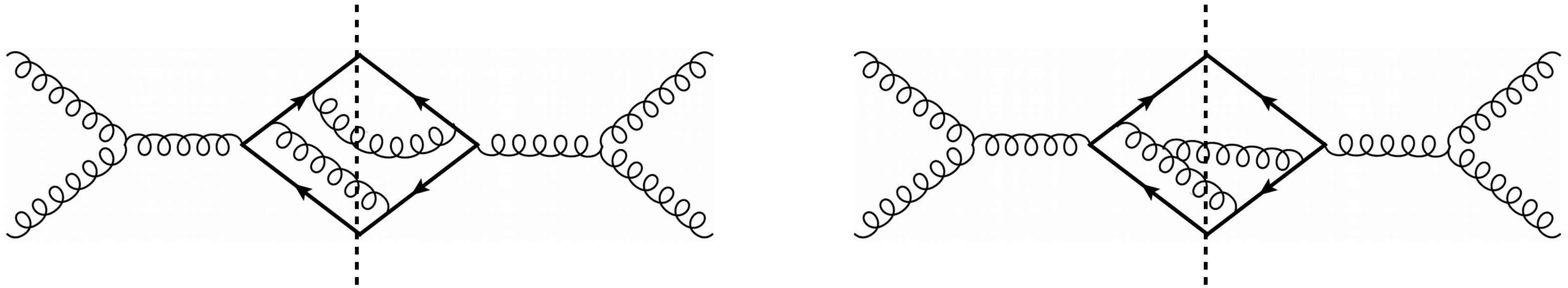
Analogous formula, but with new contributions coming from **final state radiation**

$$d\sigma^{t\bar{t}}_{\rm NNLO} = \mathcal{H}^{t\bar{t}}_{\rm NNLO} \otimes d\sigma^{t\bar{t}}_{\rm LO} + \left[d\sigma^{t\bar{t}+{\rm jet}}_{\rm NLO} - d\sigma^{t\bar{t},{\rm CT}}_{\rm NNLO} \right]$$

- Modified subtraction counterterm fully known
  (ingredient: NNLO soft anomalous dimension $\mathbf{\Gamma}_t$)

- The structure of the hard-collinear function *H* also changes:

Integration of additional **final-state soft singularities** that redefine *H* needed:



We have recently completed their computation

Catani, Devoto, Grazzini, JM (to appear)
See also Angeles-Martinez, Czakon, Sapeta (2018)

Thanks to these results, **q_T subtraction** can now deal with **$Q\bar{Q}$ production**

Our calculation is implemented within the MATRIX framework

First inclusive and differential results recently published, presented in the following slides

Catani, Devoto, Grazzini, Kallweit, JM, Sargsyan (2019); Catani, Devoto, Grazzini, Kallweit, JM (2019)

MATRIX at work

```
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|                                                                     |
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|         | _\/_ |   / _ \    |_____|   / _ \    ||    \\   //       |
|         || \/ ||  | |_| |     ||     ||_||     ||     \\ //        |
|         ||    ||  |  ___ |    ||     ||\\      ||     // \\        |
|         ||    ||  ||    ||    ||     || \\     ||    //   \\       |
|                                                                     |
|          Version: 1.0.1                         June 2018           |
|          Reference: arXiv:1711.06631                                |
|                                                                     |
| Munich -- the MUlti-chaNnel Integrator at swiss (CH) precision --   |
| Automates qT-subtraction and Resummation to Integrate X-sections    |
|                                                                     |
| \          \ ____      \          \ ____      \ ____      \         |
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|  /          /          |/          /____      |/          |/        |
| /          /          /          /          /          /            |
|                                                                     |
| M. Grazzini                              (grazzini@physik.uzh.ch)   |
| S. Kallweit                             (stefan.kallweit@cern.ch)   |
| M. Wiesemann                           (marius.wiesemann@cern.ch)   |
|---------------------------------------------------------------------|
| MATRIX is based on a number of different computations and tools     |
| from various people and groups. Please acknowledge their efforts    |
| by citing the list of references which is created with every run.   |
\---------------------------------------------------------------------/

<<MATRIX-MAKE>> This is the MATRIX process compilation.
<<MATRIX-READ>> Type process_id to be compiled and created. Type "list" to show
                available processes. Try pressing TAB for auto-completion. Type
                "exit" or "quit" to stop.
|============>>
```

```
|============>> list
------------------------------------------------------------------------------------------------------------
process_id         ||   process                         ||   description
------------------------------------------------------------------------------------------------------------
pph21              >>   p p --> H                       >>   on-shell Higgs production
ppz01              >>   p p --> Z                       >>   on-shell Z production
ppw01              >>   p p --> W^-                     >>   on-shell W- production with CKM
ppwx01             >>   p p --> W^+                     >>   on-shell W+ production with CKM
ppeex02            >>   p p --> e^- e^+                 >>   Z production with decay
ppnenex02          >>   p p --> v_e^- v_e^+             >>   Z production with decay
ppenex02           >>   p p --> e^- v_e^+               >>   W- production with decay and CKM
ppexne02           >>   p p --> e^+ v_e^-               >>   W+ production with decay and CKM
ppaa02             >>   p p --> gamma gamma             >>   gamma gamma production
ppaa02             >>   p p --> gamma gamma             >>   gamma gamma production
ppeexa03           >>   p p --> e^- e^+ gamma           >>   Z gamma production with decay
ppnenexa03         >>   p p --> v_e^- v_e^+ gamma       >>   Z gamma production with decay
ppenexa03          >>   p p --> e^- v_e^+ gamma         >>   W- gamma production with decay
ppexnea03          >>   p p --> e^+ v_e^- gamma         >>   W+ gamma production with decay
ppzz02             >>   p p --> Z Z                     >>   on-shell ZZ production
ppwxw02            >>   p p --> W^+ W^-                 >>   on-shell WW production
ppemexmx04         >>   p p --> e^- mu^- e^+ mu^+       >>   ZZ production with decay
ppemexmx04NLOgg    >>   p p --> e^- mu^- e^+ mu^+ NLOgg >>   ZZ production with decay (NLO gg)
ppeeexex04         >>   p p --> e^- e^- e^+ e^+         >>   ZZ production with decay
ppeexnmnmx04       >>   p p --> e^- e^+ v_mu^- v_mu^+   >>   ZZ production with decay
ppemxnmnex04       >>   p p --> e^- mu^+ v_mu^- v_e^+   >>   WW production with decay
ppeexnenex04       >>   p p --> e^- e^+ v_e^- v_e^+     >>   ZZ/WW production with decay
ppemexnmx04        >>   p p --> e^- mu^- e^+ v_mu^+     >>   W-Z production with decay
ppeeexnex04        >>   p p --> e^- e^- e^+ v_e^+       >>   W-Z production with decay
ppeexmxnm04        >>   p p --> e^- e^+ mu^+ v_mu^-     >>   W+Z production with decay
ppeexexne04        >>   p p --> e^- e^+ e^+ v_e^-       >>   W+Z production with decay
ppttx20            >>   p p --> top anti-top            >>   on-shell top-pair production  <-----
|============>> ppttx20
<<MATRIX-MAKE>> MATRIX usage agreements:
<<MATRIX-MAKE>> MATRIX is based on several computations, studies and tools from
                various people and groups. When using results obtained by MATRIX
                these efforts must be acknowledged by citing the list of
                references in the CITATION.bib file, which is created in the
                result folder with every run.
<<MATRIX-READ>> Do you agree with these terms? Type "y" to agree, or "n" to
                abort the code.
<<MATRIX-MAKE>> You have agreed with all MATRIX usage terms.
<<MATRIX-MAKE>> Starting compilation...
<<MATRIX-MAKE>> Using compiled LHAPDF installation under
                (config/MATRIX_configuration) path_to_lhapdf=/home/grazzini
                /lhapdf-local/bin/lhapdf-config
<<MATRIX-MAKE>> Download and Compilation of OpenLoops via svn checkout from
                http://openloops.hepforge.org/svn/OpenLoops/branches/public into
                /mnt/runs2/grazzini/develop/munich/MATRIX/external/OpenLoops-
                install...
<<MATRIX-MAKE>> Downloading OpenLoops...
<<MATRIX-MAKE>> Compiling OpenLoops...
```

```
                 /----------------------------------------------------\
                 |                 Final result for:                   |
                 |        p p --> top anti-top  @ 100 TeV LHC          |
                 \----------------------------------------------------/

<MATRIX-RESULT> 3 separate runs were made

                #--------\
                # LO-run |
                #--------/
<MATRIX-RESULT> PDF: NNPDF31_lo_as_0118
<MATRIX-RESULT> Total rate (possibly within cuts):
<MATRIX-RESULT> LO:  2.381e+07 fb +/- 2.2e+04 fb (muR, muF unc.: +21.1% -16.0%)

                #---------\
                # NLO-run |
                #---------/
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<MATRIX-RESULT> Total rate (possibly within cuts):
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<MATRIX-RESULT> NLO: 3.234e+07 fb +/- 2.7e+04 fb (muR, muF unc.: +11.3% -10.4%)

                #----------\
                # NNLO-run |
                #----------/
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<MATRIX-RESULT> NLO: 3.187e+07 fb +/- 2.8e+03 fb (muR, muF unc.: +11.3% -10.5%)
<MATRIX-RESULT> NNLO:3.527e+07 fb +/- 4.5e+04 fb (muR, muF unc.:  +2.9%  -4.8%)
<MATRIX-RESULT>      (computed with finite qT-subtraction cut-off r_cut=0.0015)
<MATRIX-RESULT> NNLO:3.522e+07 fb +/- 7.4e+04 fb (muR, muF unc.:  +2.8%  -4.7%)
<MATRIX-RESULT>      (extrapolated to r_cut=0 -- final result with uncertainty)
```

Per-mille level accuracy for total XS in ~1000CPU days, including differential distributions and scale uncertainties

Inclusive cross section

Catani, Devoto, Grazzini, Kallweit, JM, Sargsyan (2019)

Excellent agreement with Top++

$\sigma_{\rm NNLO}$ [pb]	MATRIX	TOP++
8 TeV	$238.5(2)^{+3.9\%}_{-6.3\%}$	$238.6^{+4.0\%}_{-6.3\%}$
13 TeV	$794.0(8)^{+3.5\%}_{-5.7\%}$	$794.0^{+3.5\%}_{-5.7\%}$
100 TeV	$35215(74)^{+2.8\%}_{-4.7\%}$	$35216^{+2.9\%}_{-4.8\%}$

Statistical+systematic uncertainties

Scale uncertainties

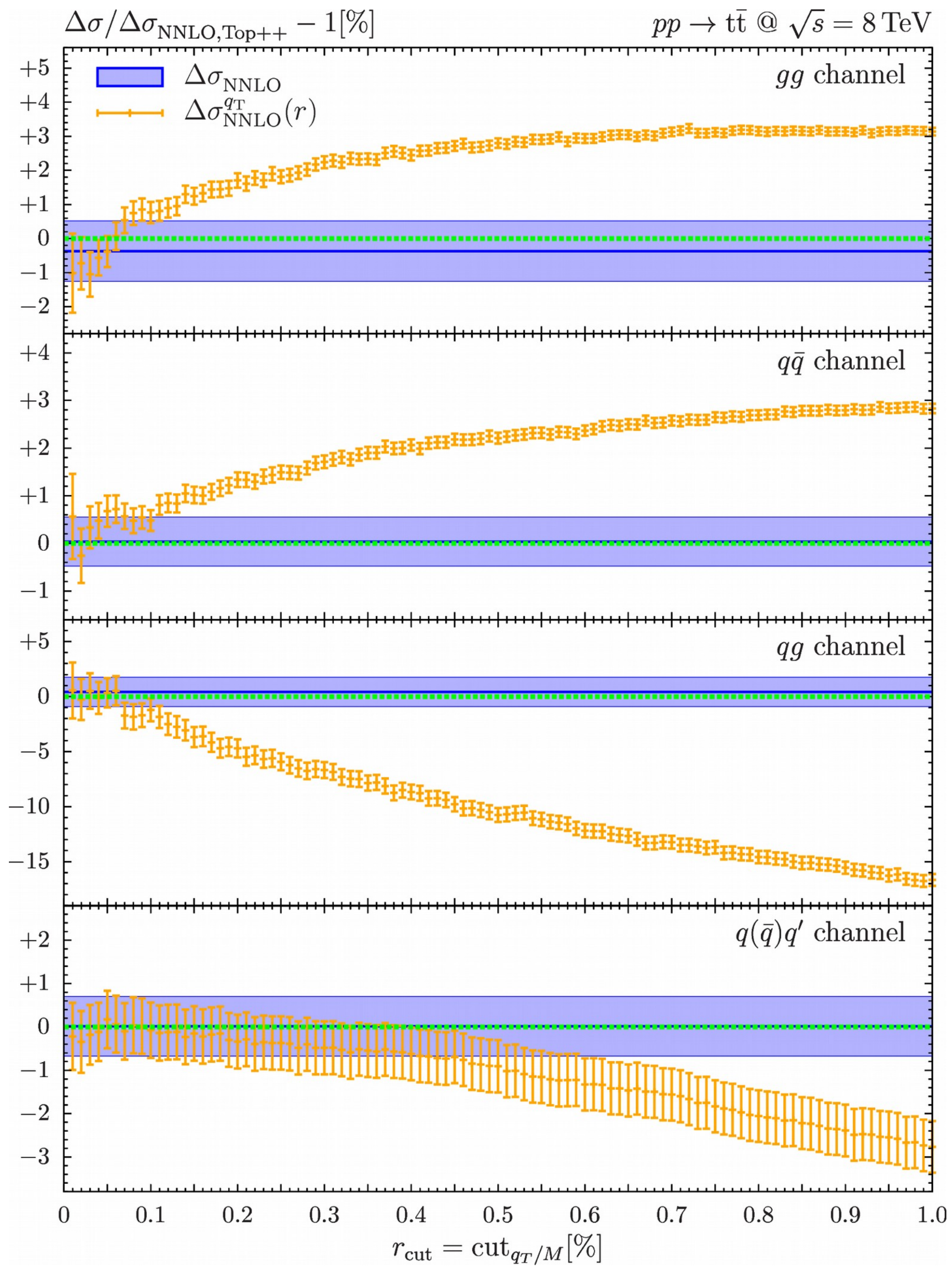
NNPDF31 sets, m_t=173.3GeV

Scale uncertainties: $\mu_0=m_t$

$\mu_0 < \mu_F,\mu_R < 2\mu_0$ $\quad 0.5 < \mu_F/\mu_R < 2$

Per-mille accuracy in ~1000CPU days

Quality of the $q_T \to 0$ extrapolation can be understood looking at the $r_{\rm cut}$ dependence



Differential results

We compute single and double differential distributions

We compare our results with recent measurements from CMS
in the lepton+jets channel [CMS-TOP-17-002]

CMS measurements are extrapolated to parton level in the inclusive phase space

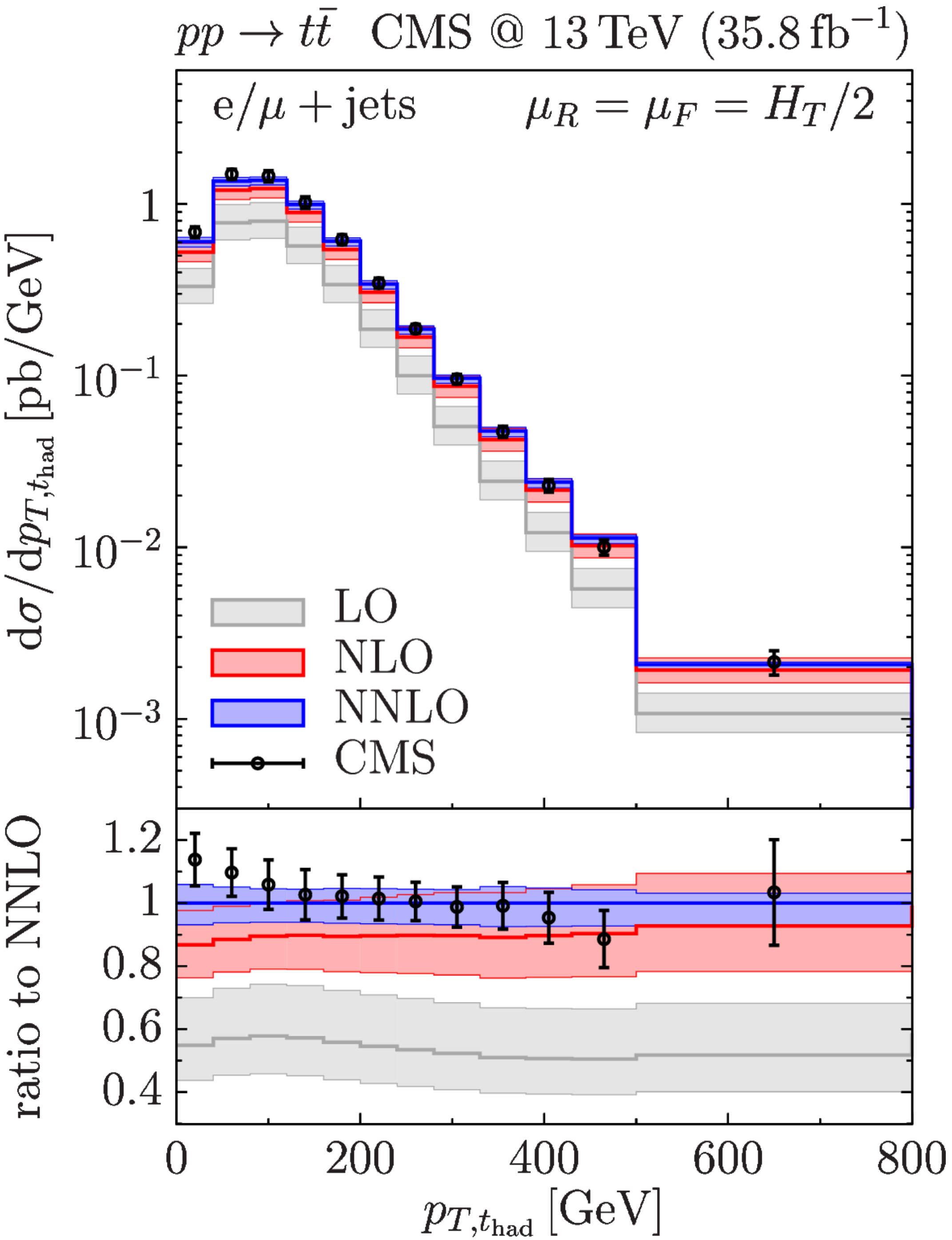
→ we carry out our calculation without cuts

Perturbative results depend on the choice of scales μ_F, μ_R
which should be chosen of the order of the characteristic hard scale

- Total cross section and rapidity distribution: m_t
- Invariant mass distribution: $m_{t\bar{t}}$
- Transverse momentum distribution: m_T

The dynamical scale $\mu_0 = H_T/2 = (m_{T,t} + m_{T,\bar{t}})/2$ is a good approximation to all these scales

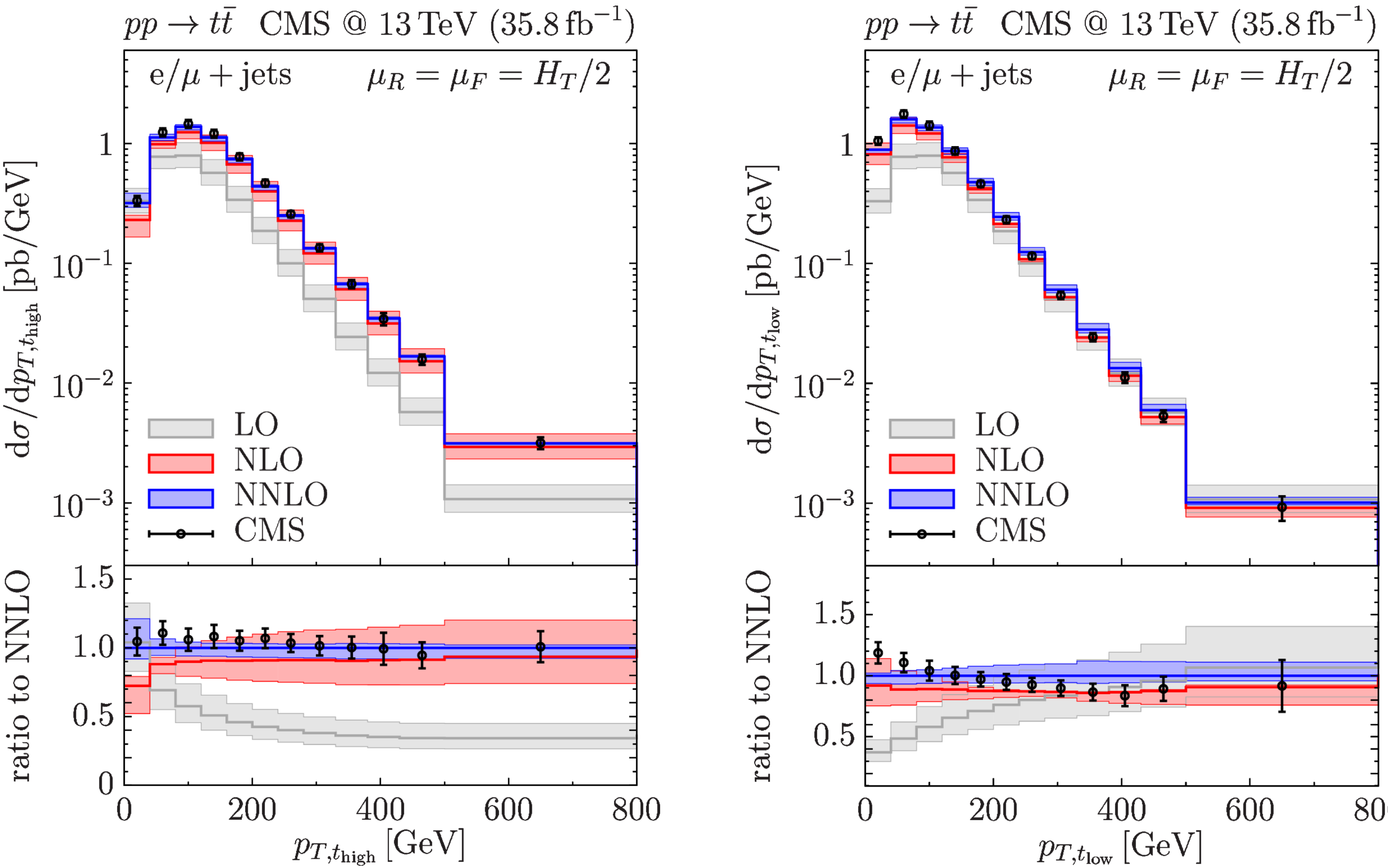
Single-differential distributions



- Good perturbative behaviour, large overlap between NLO and NNLO bands
- As noted in previous analysis the measured p_T is slightly softer than the NNLO prediciton
- Data and theory consistent within uncertainties

Single-differential distributions

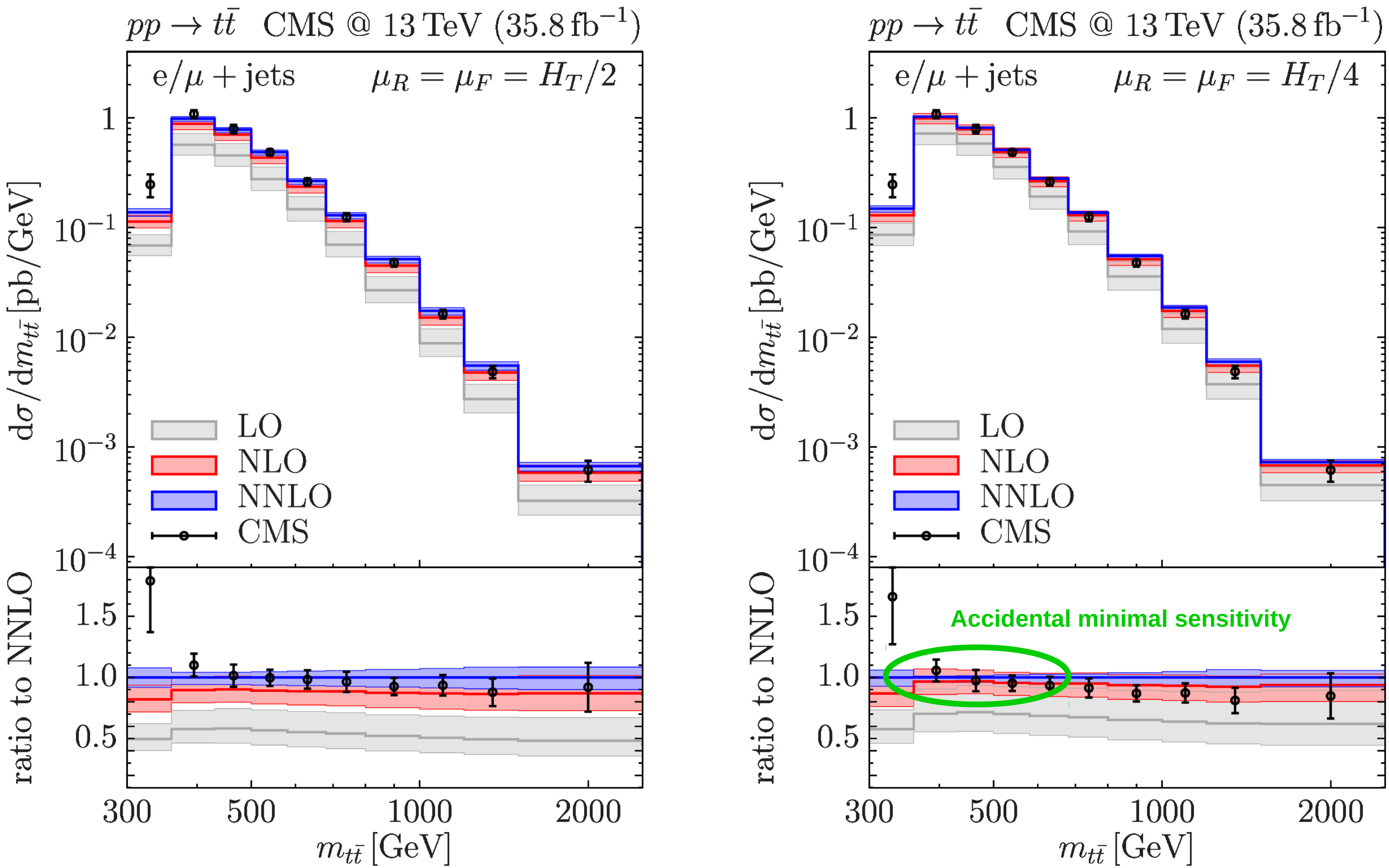
Catani, Devoto, Grazzini, Kallweit, JM (2019)



- Higher order corrections have a larger effect on the shape
- Low $p_T(t_{high})$ region: FO instabilities associated with low $p_T(t\bar{t})$
- Good agreement with data

Single-differential distributions

Catani, Devoto, Grazzini, Kallweit, JM (2019)



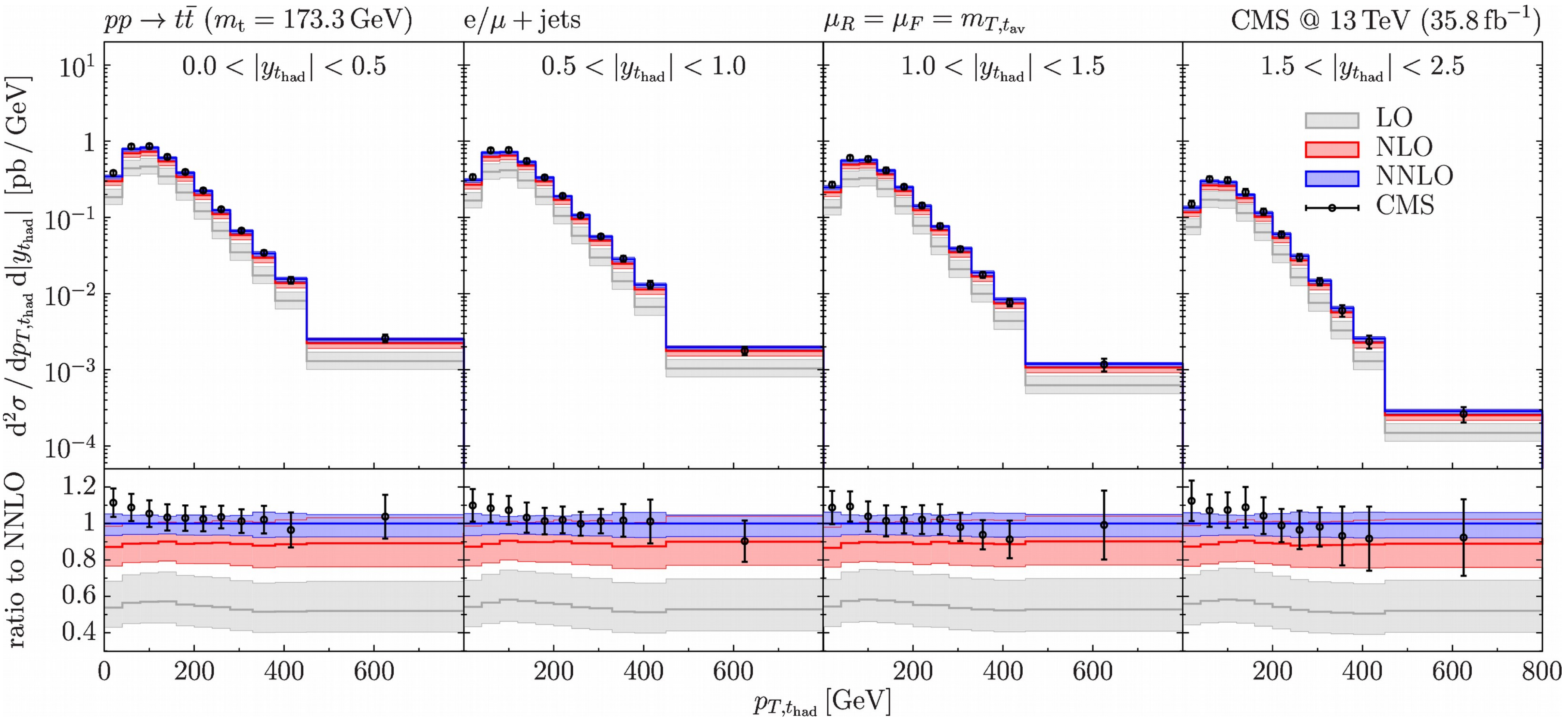
- Lower scale $H_T/4$ (usually used as a benchmark) seems to lead to underestimation of perturbative uncertainties in certain $m_{t\bar{t}}$ regions

- Good description of data except for first bin ($m_{t\bar{t}}$<360GeV)
  Resummation effects? Smaller m_t?

CMS-TOP-18-004: leptonic channel, fit m_t=170.81±0.68GeV

Double-differential distributions

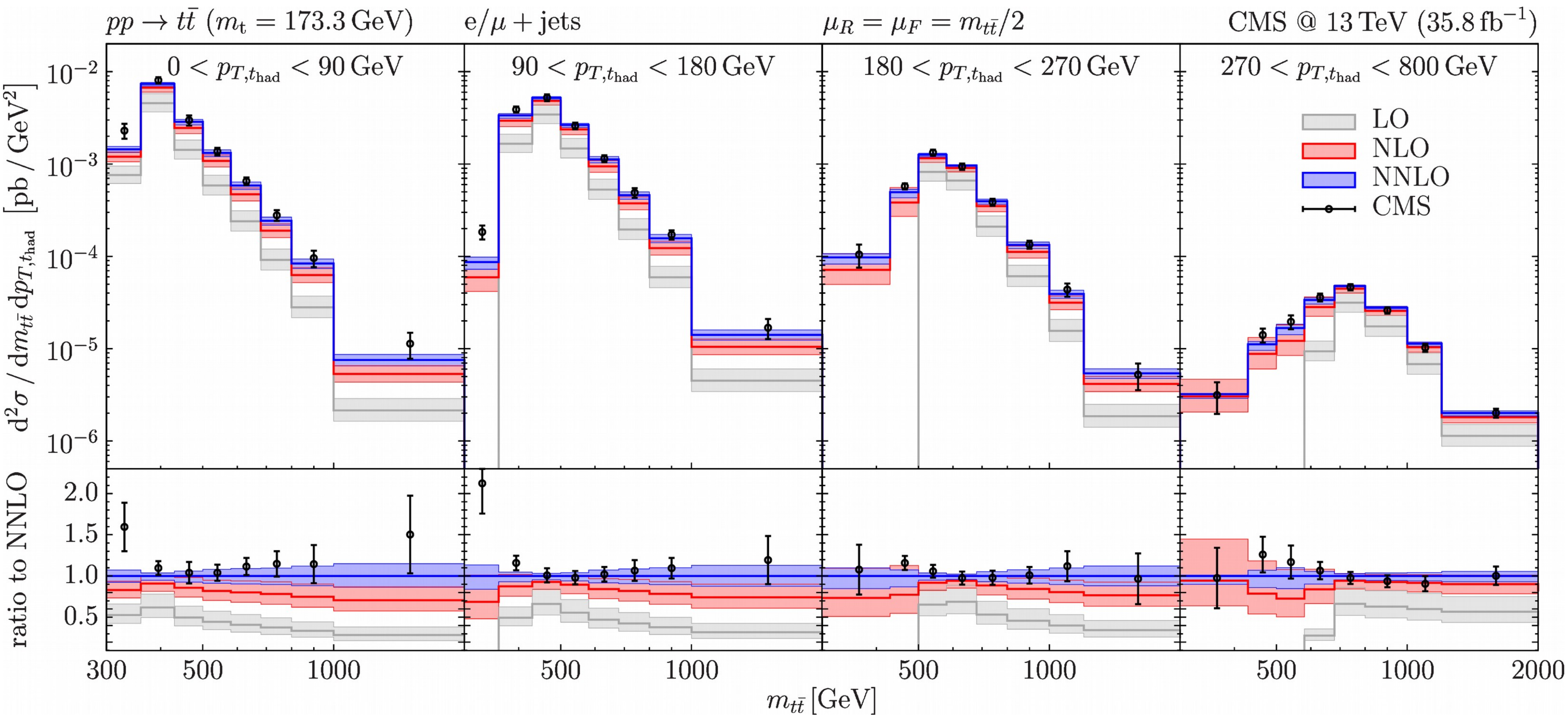
Catani, Devoto, Grazzini, Kallweit, JM (2019)



- As for single differential distribution, p_T data softer than NNLO
- This feature holds in all the rapidity intervals

Double-differential distributions

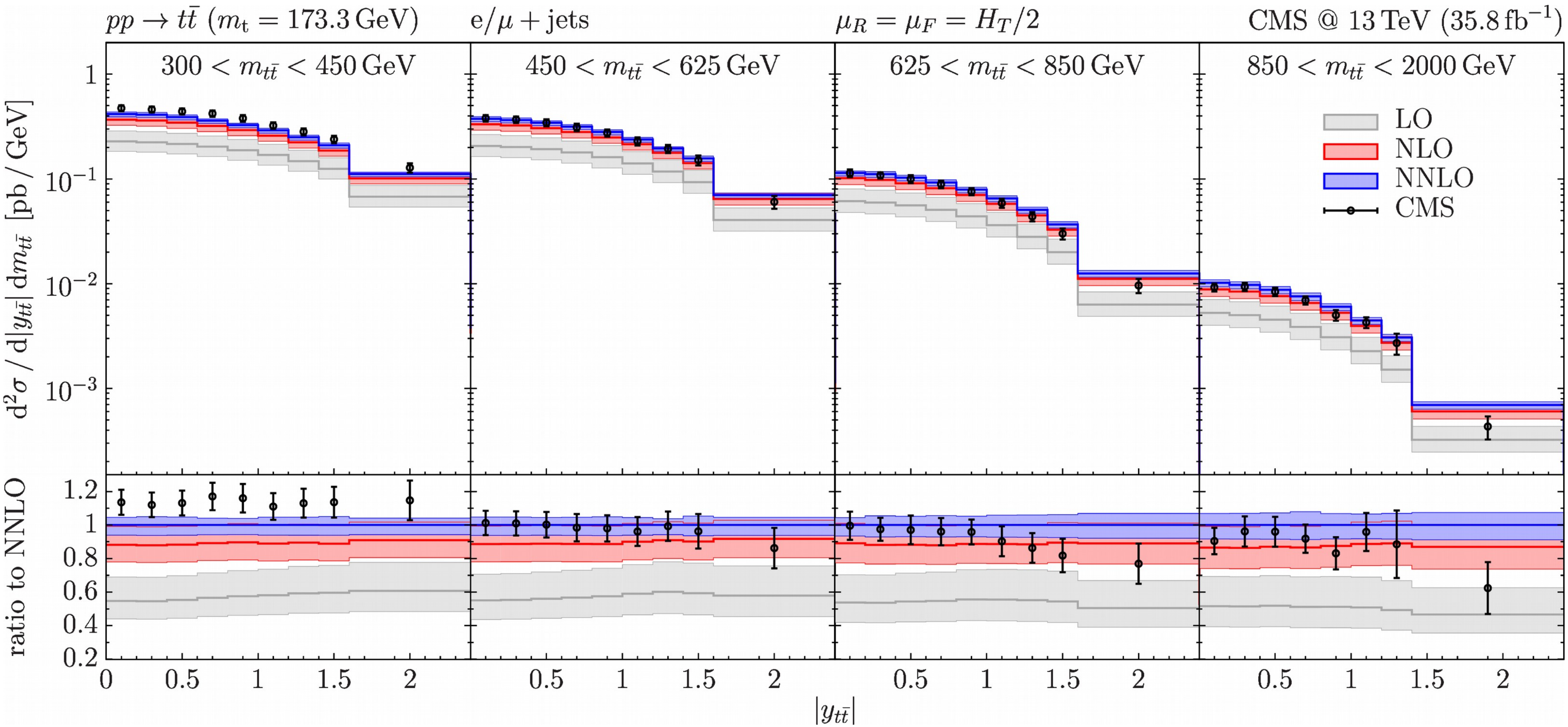
Catani, Devoto, Grazzini, Kallweit, JM (2019)



- Kinematical boundary at LO: $m_{t\bar{t}} > 2\, m_{T,min}$
- NLO (NNLO) is effectively LO (NLO) below that threshold → larger uncertainties
- NNLO nicely describes the data (except only close to the physical $m_{t\bar{t}}$ threshold)

Double-differential distributions

Catani, Devoto, Grazzini, Kallweit, JM (2019)

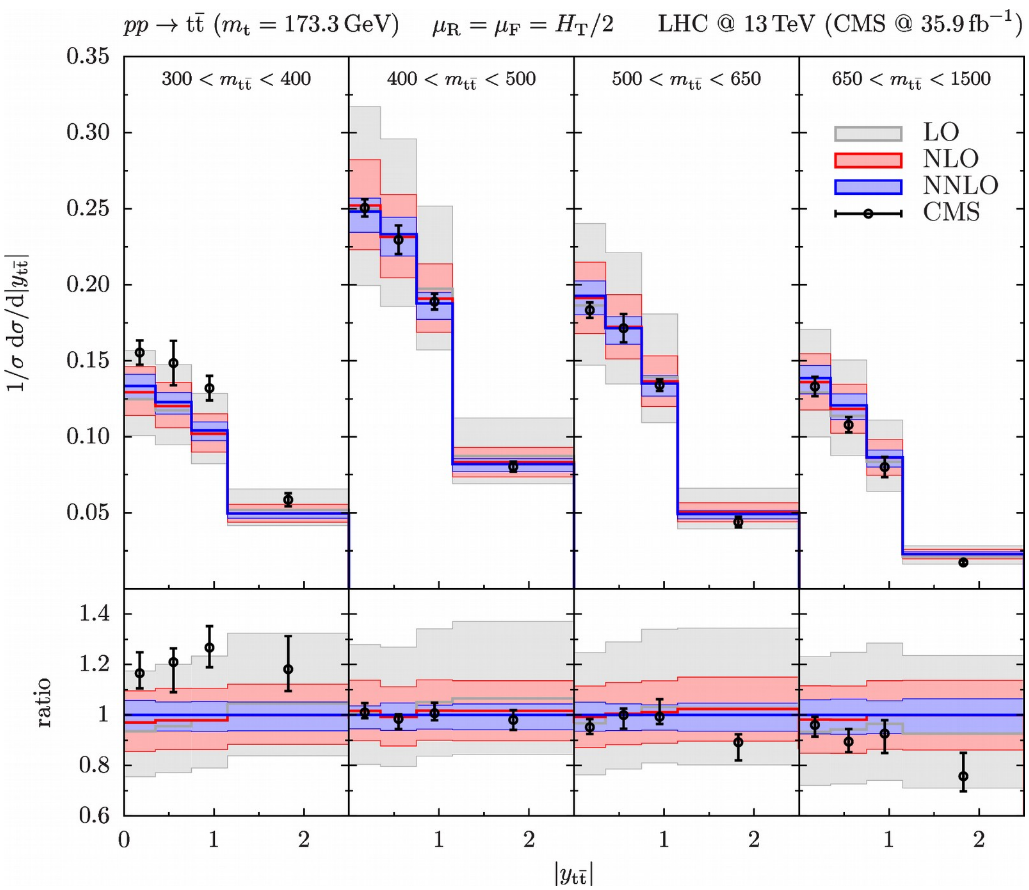


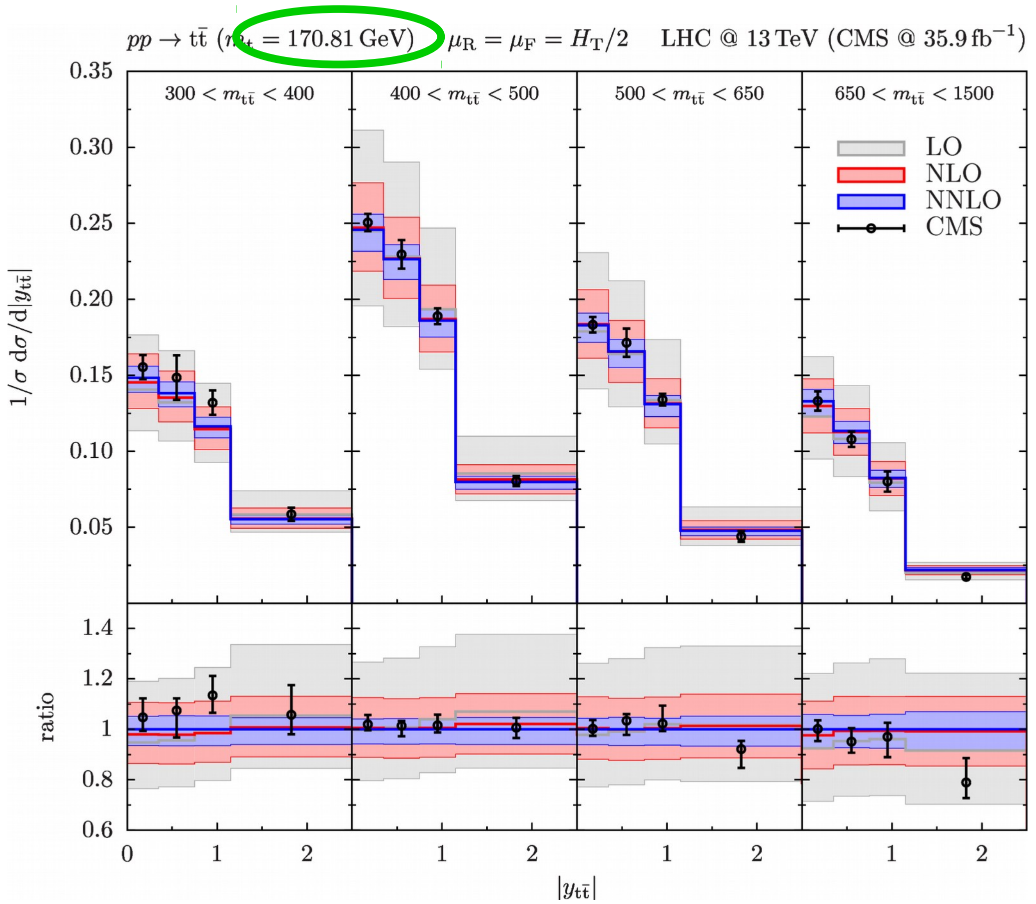
- Again some discrepancy in the low $m_{t\bar{t}}$ region, smaller effect due to larger bin size
- Impact of radiative corrections relatively uniform in both variables

Double-differential distributions

NEW: predictions for parton level CMS measurements using fully leptonic final state

[CMS-TOP-18-004]

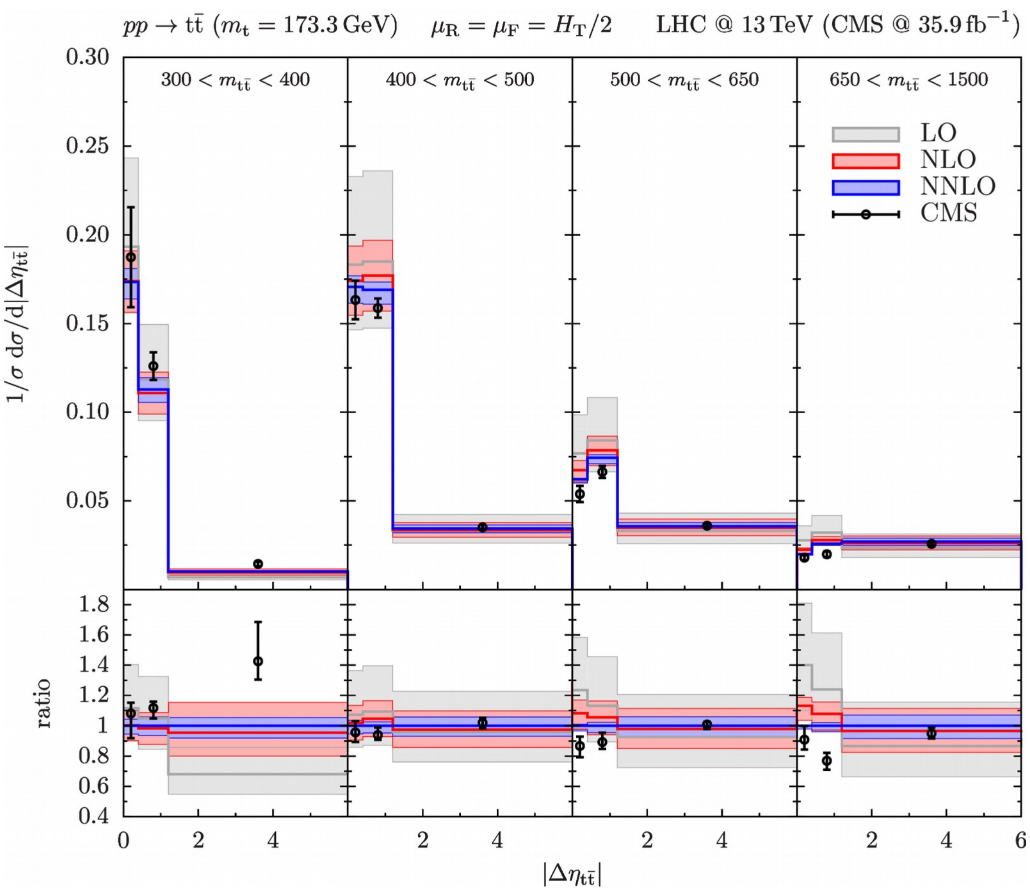


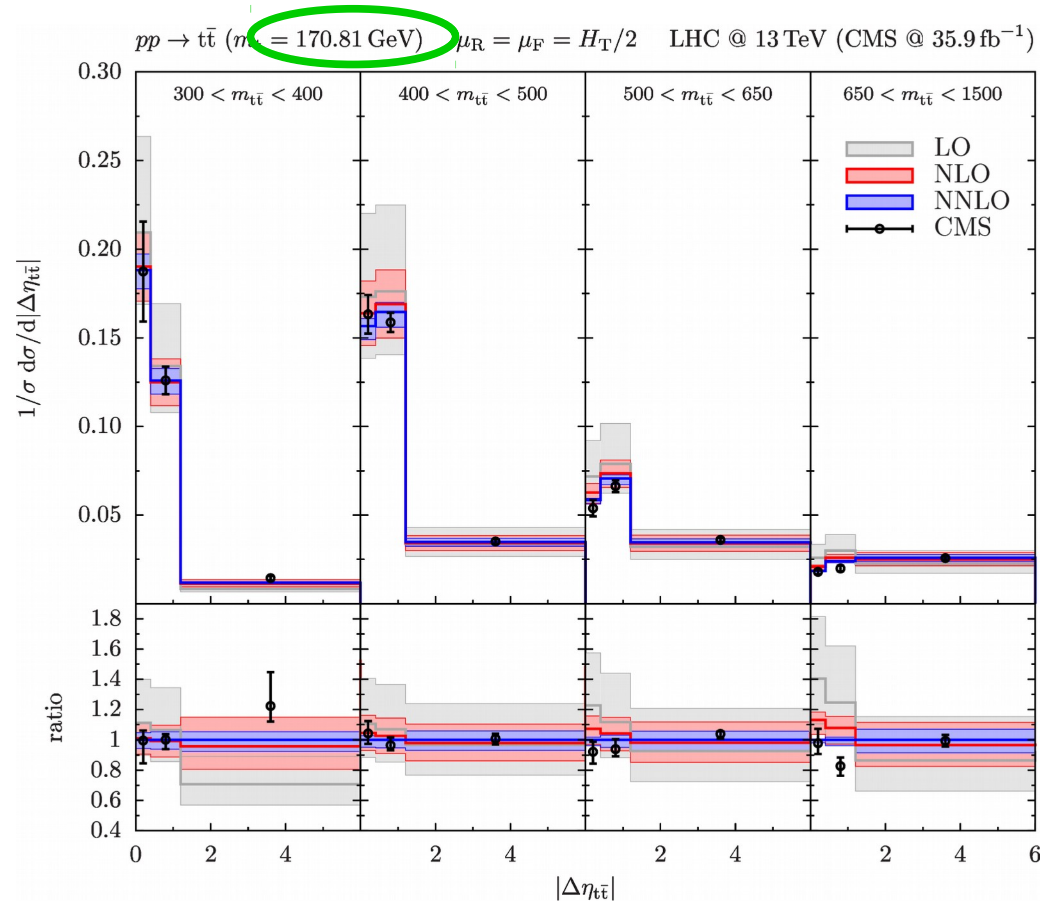


- Similar features compared to semileptonic channel (note these are normalized distributions)
- Using fitted top mass by CMS (170.81GeV) leads to a better agreement with data
- Same improvement observed in m_{tt}-$|y_t|$ distribution (see backup slides)

Double-differential distributions

NEW: predictions for parton level CMS measurements using fully leptonic final state [CMS-TOP-18-004]



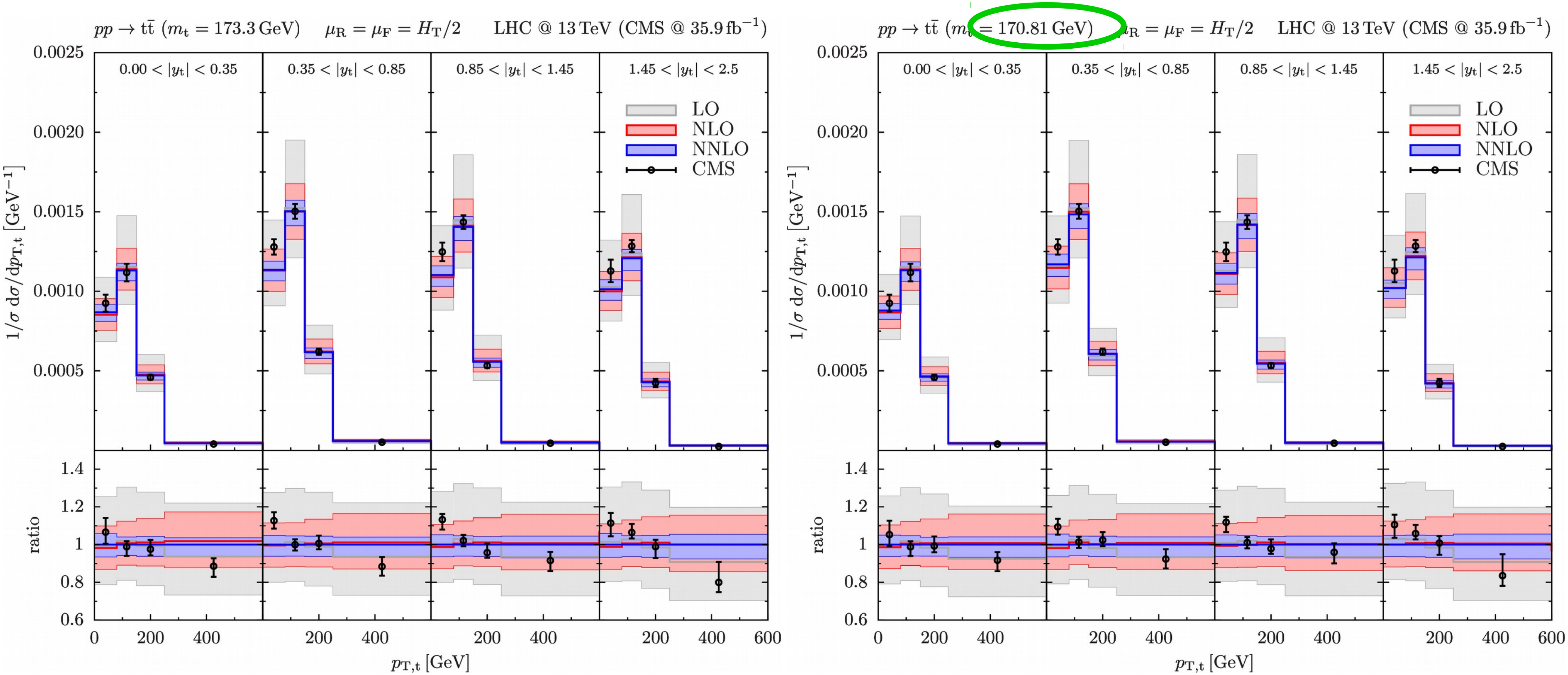


- Again significant improvement in the first invariant mass panel
- Smaller differences in the other invariant mass regions

Double-differential distributions

NEW: predictions for parton level CMS measurements using fully leptonic final state

[CMS-TOP-18-004]



- Mass value has smaller impact in transverse momentum distribution
- Data still softer than prediction, though slightly better agreement with lower mass

Summary and outlook

- We have presented a new computation of **top-quark pair** production at **NNLO**
- First complete application of **q_T subtraction** to colourful final states at NNLO
- Calculation fully implemented within the **MATRIX** framework
- We are able to evaluate arbitrary IR safe observables for stable top quarks

  - multi-differential distributions

  - cross sections with cuts in the top quarks and jets kinematics
- NNLO differential distributions in 1000-2000 CPU days
- Nice description of parton level CMS data
- **Outlook:**

  - inclusion of EW corrections

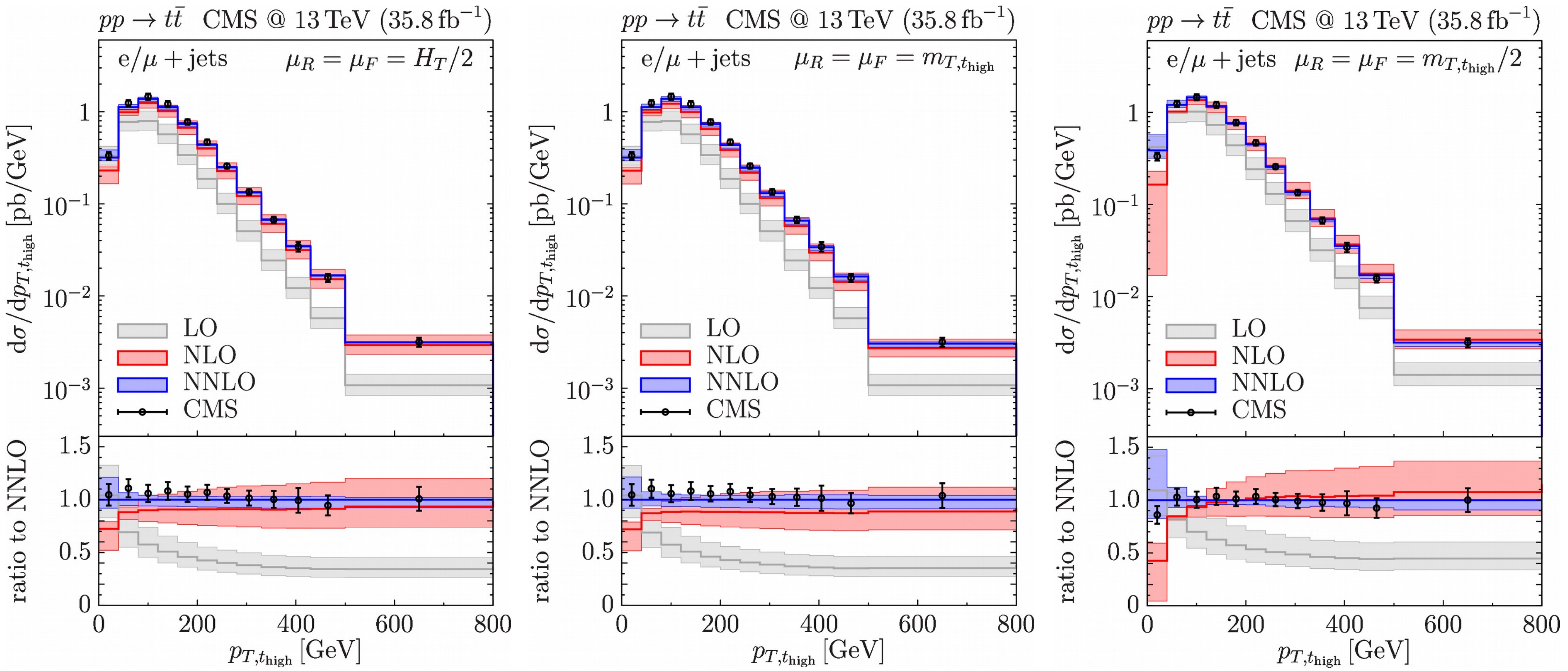
  - inclusion of top-quark decays

Thanks!

Backup slides

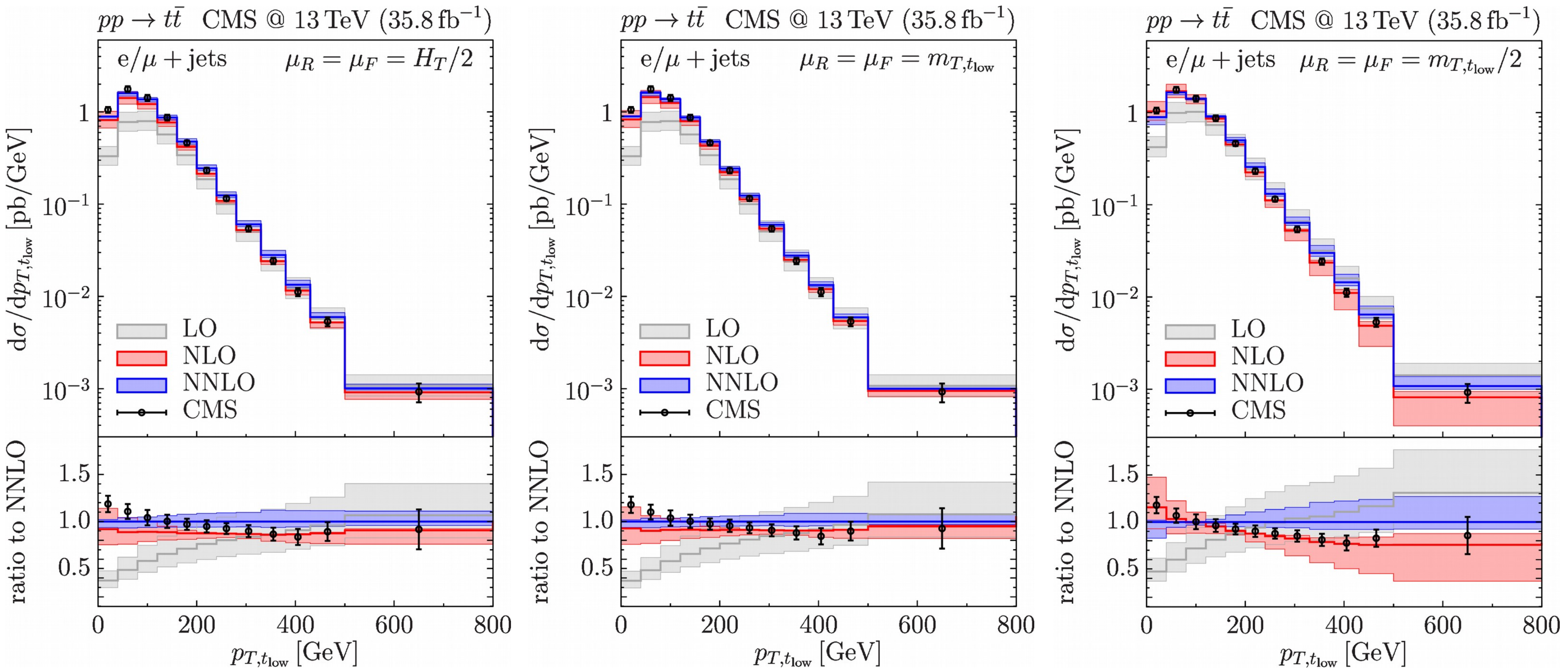
Other scale choices

$p_T(t_{high})$



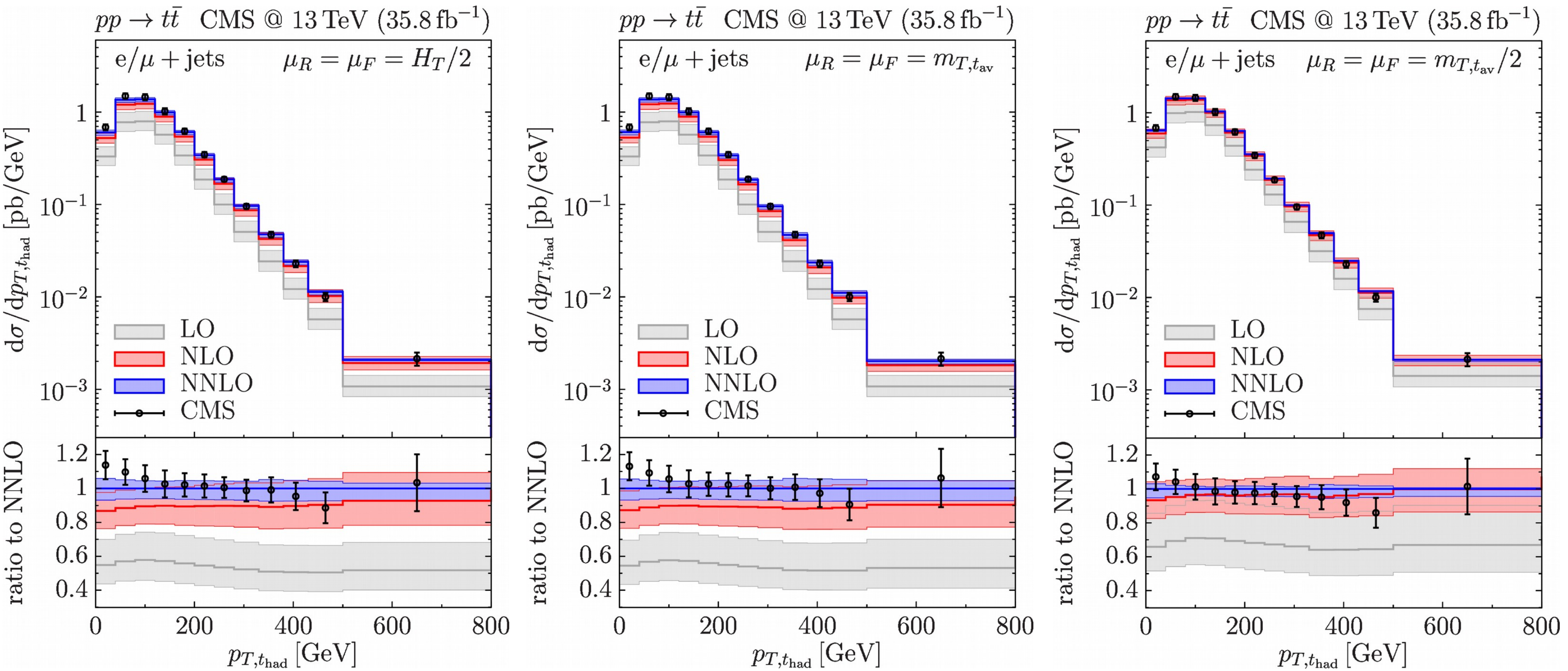
Other scale choices

$p_T(t_{low})$



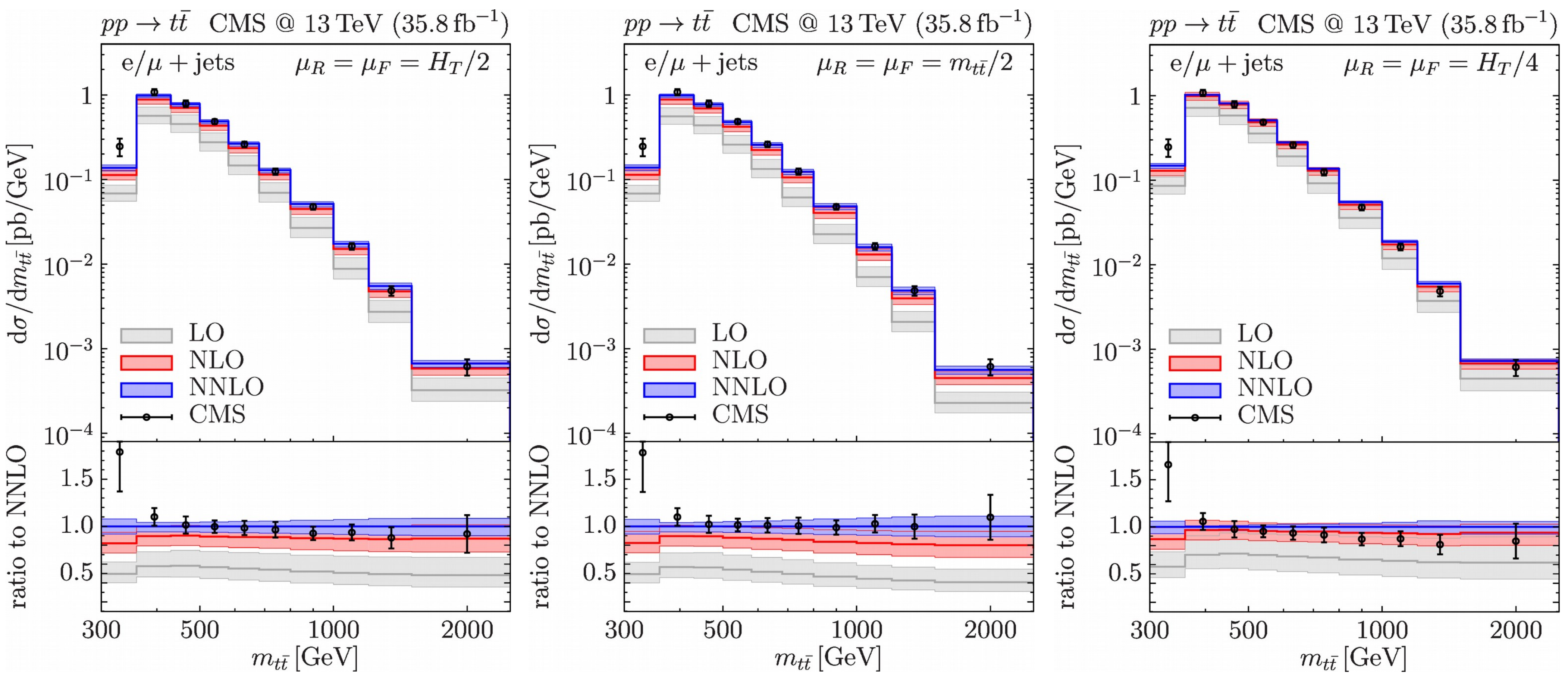
Other scale choices

$p_T(t_{had})$



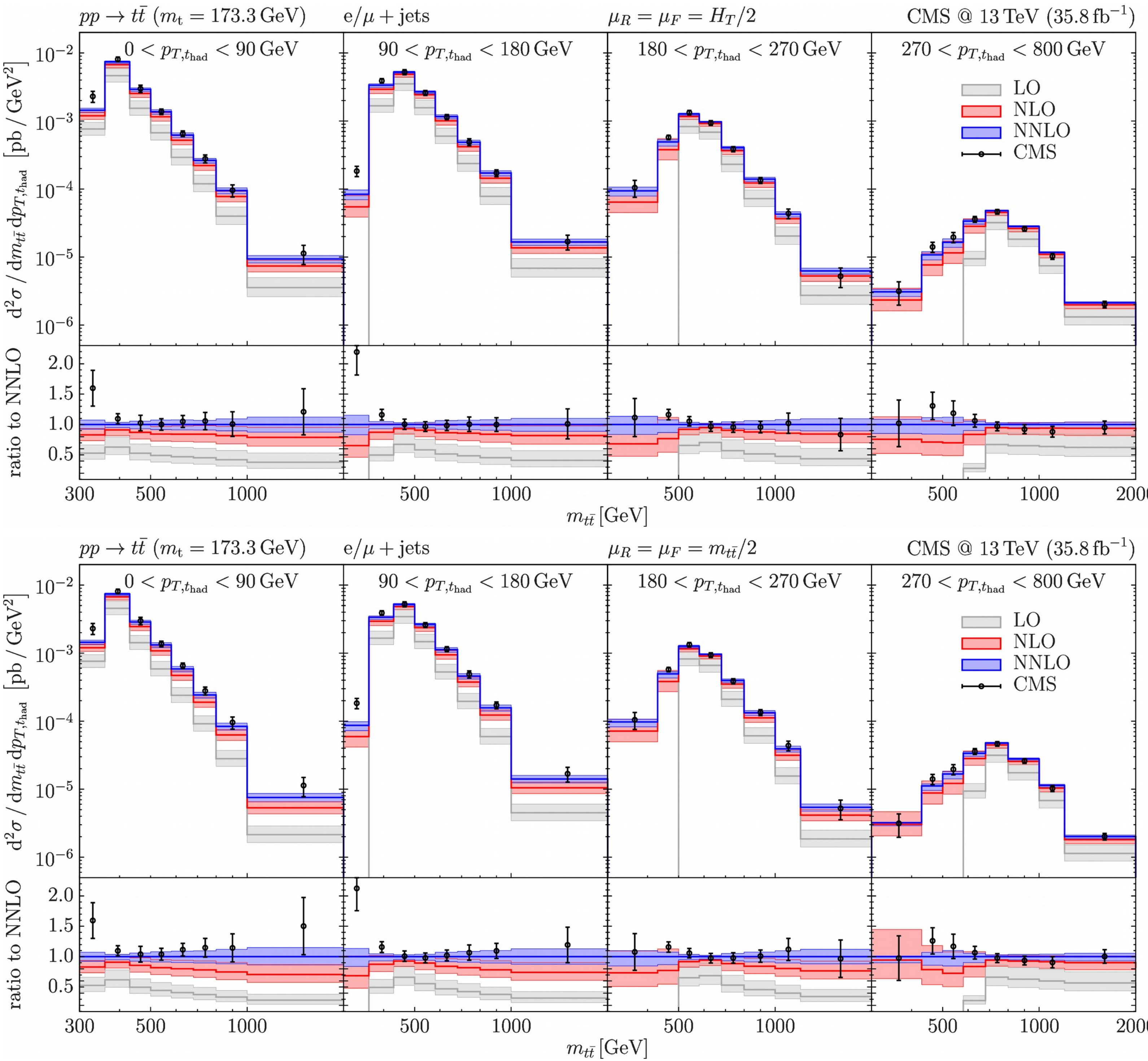
Other scale choices

m_{tt}



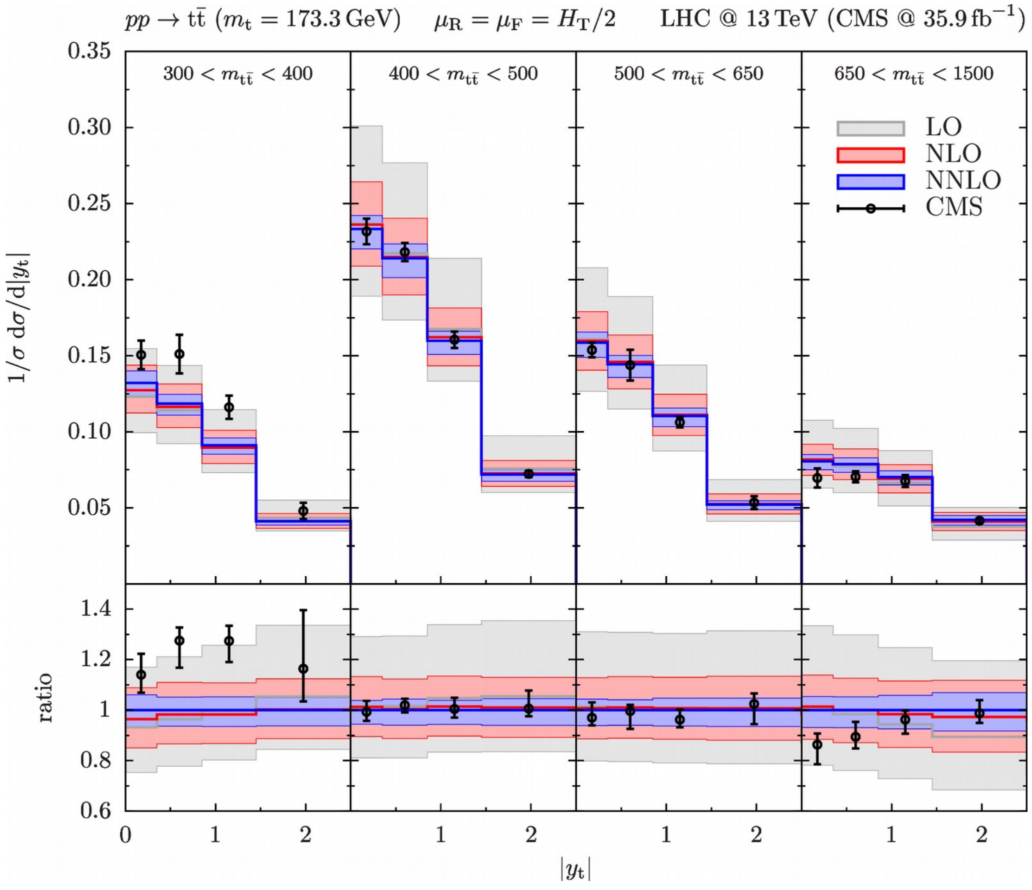
Other scale choices

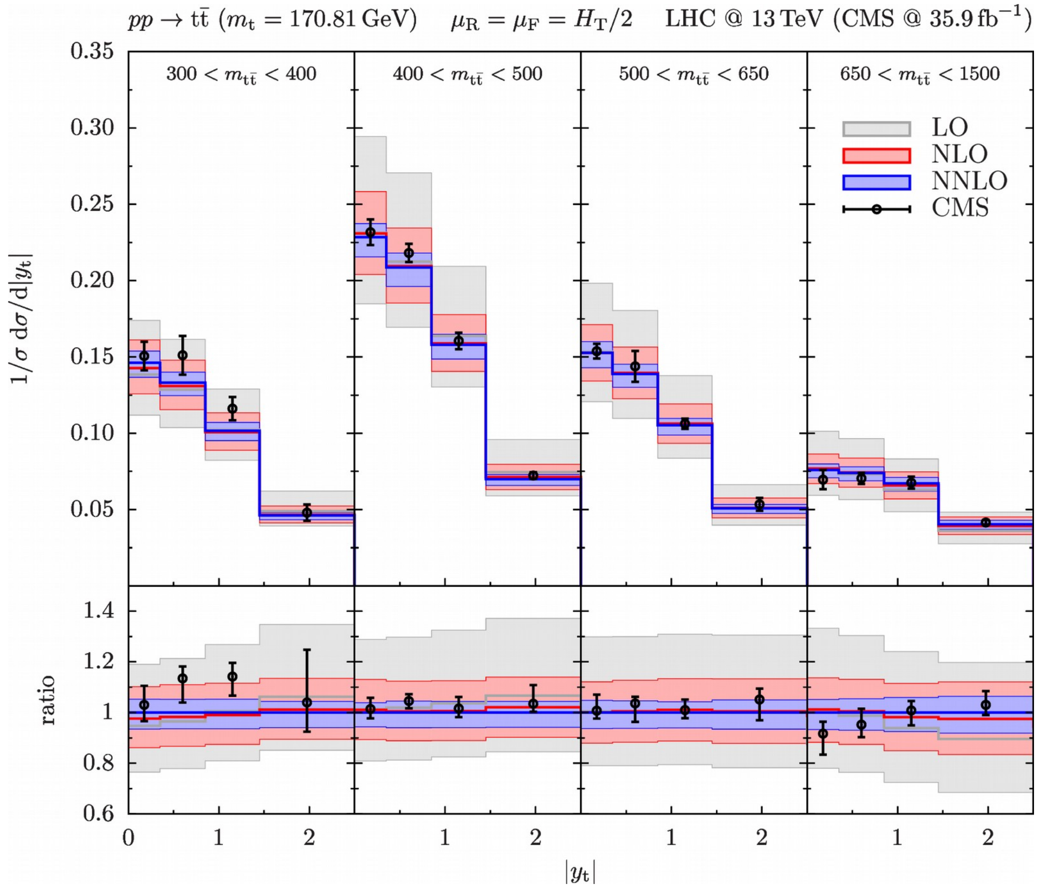
m_{tt} vs $p_T(t_{had})$



Double-differential distributions

NEW: predictions for parton level CMS measurements using fully leptonic final state
[CMS-TOP-18-004]

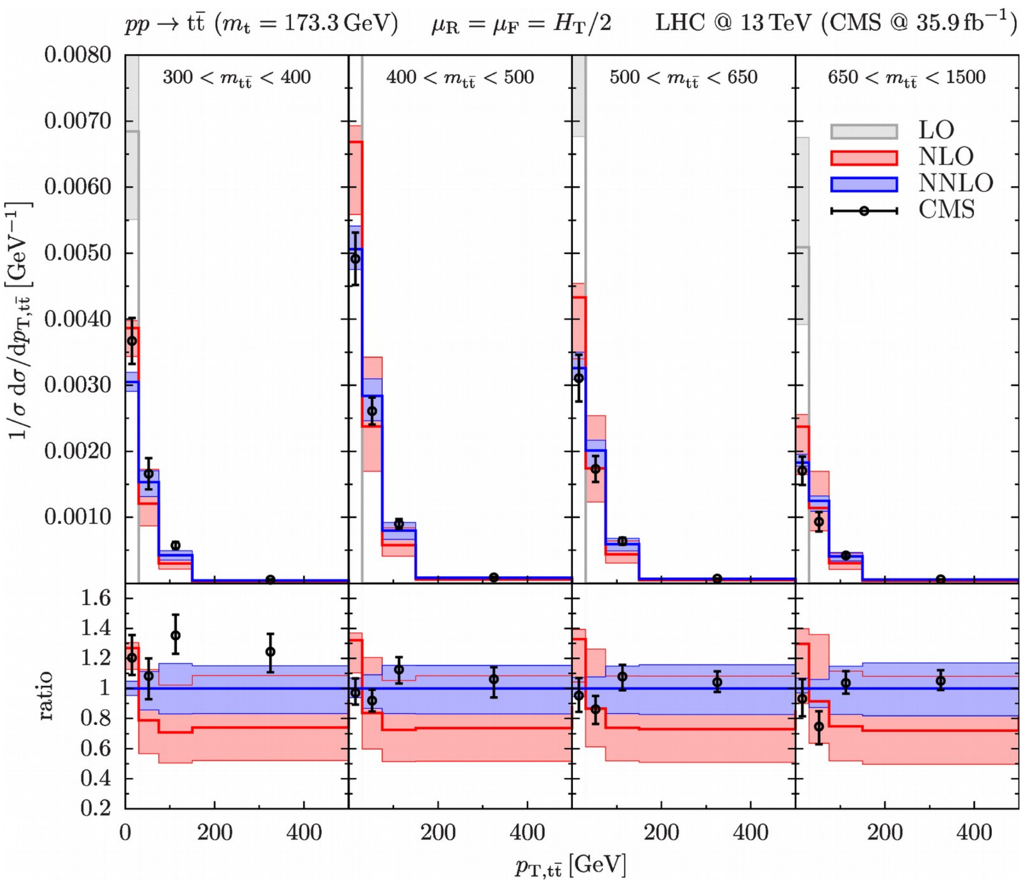


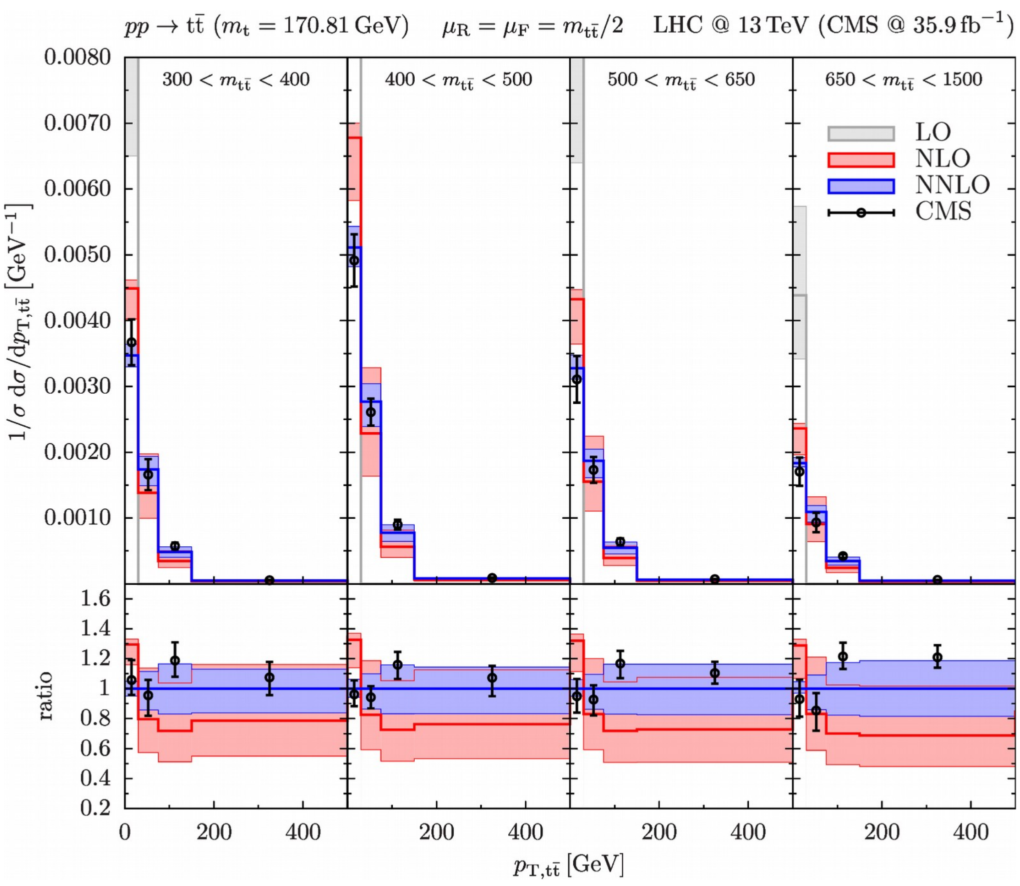


Double-differential distributions

NEW: predictions for parton level CMS measurements using fully leptonic final state

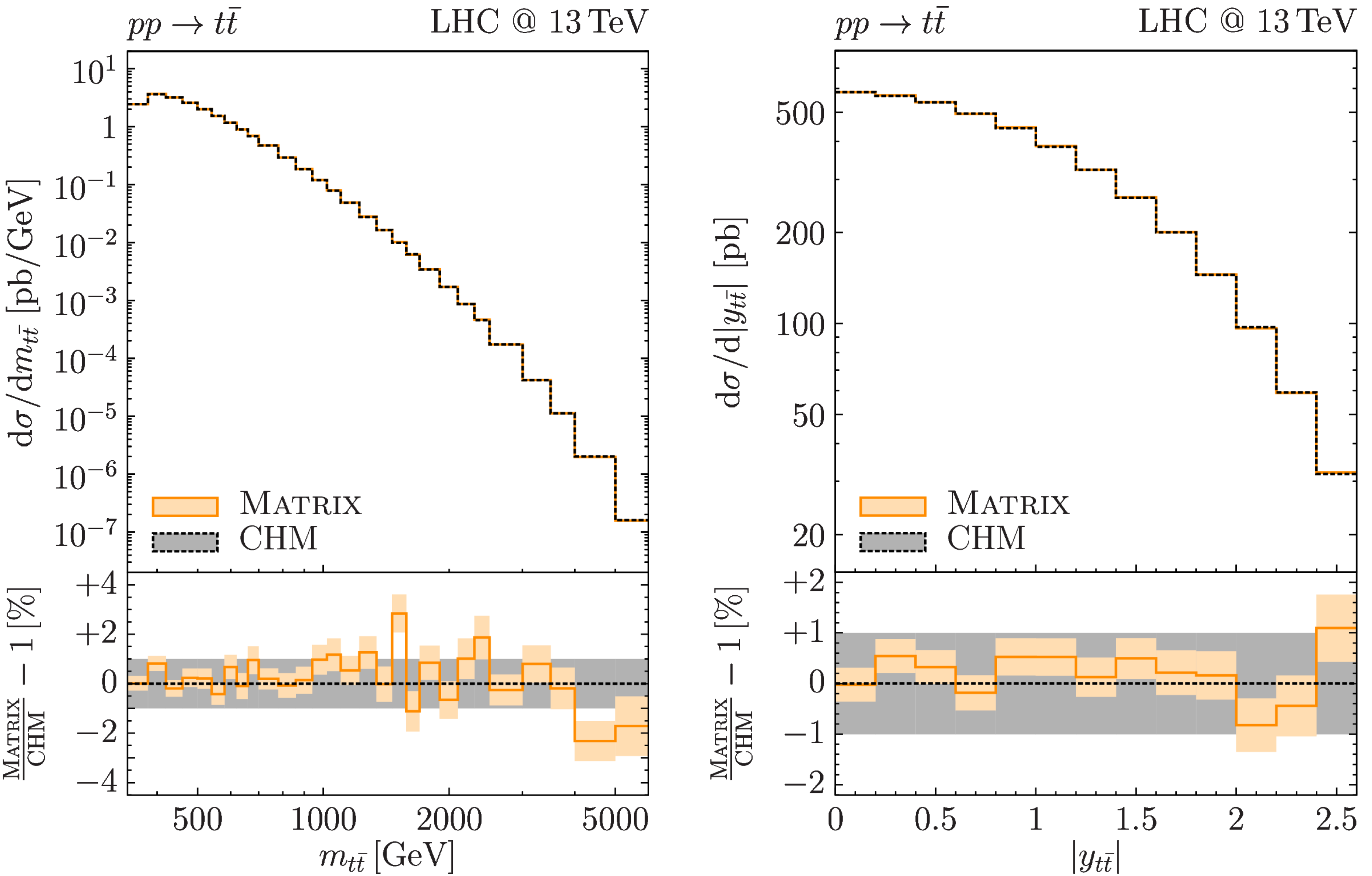
[CMS-TOP-18-004]





Comparison to existing results

CHM = [Czakon, Heymes, Mitov, 1606.03350]



Excellent agreement even in extreme kinematical regions

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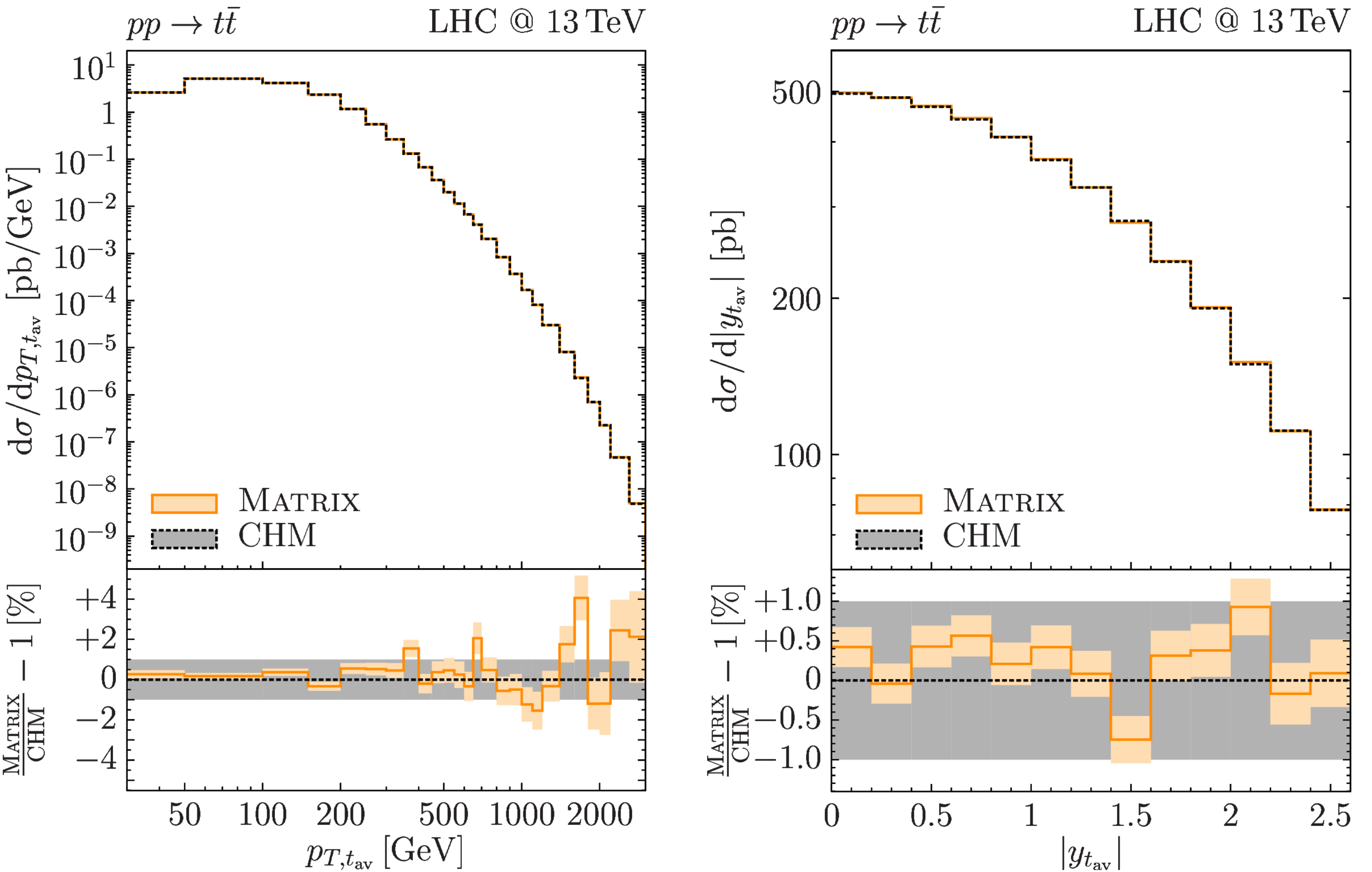

Excellent agreement even in extreme kinematical regions