Top-quark production at NNLO using q_T subtraction

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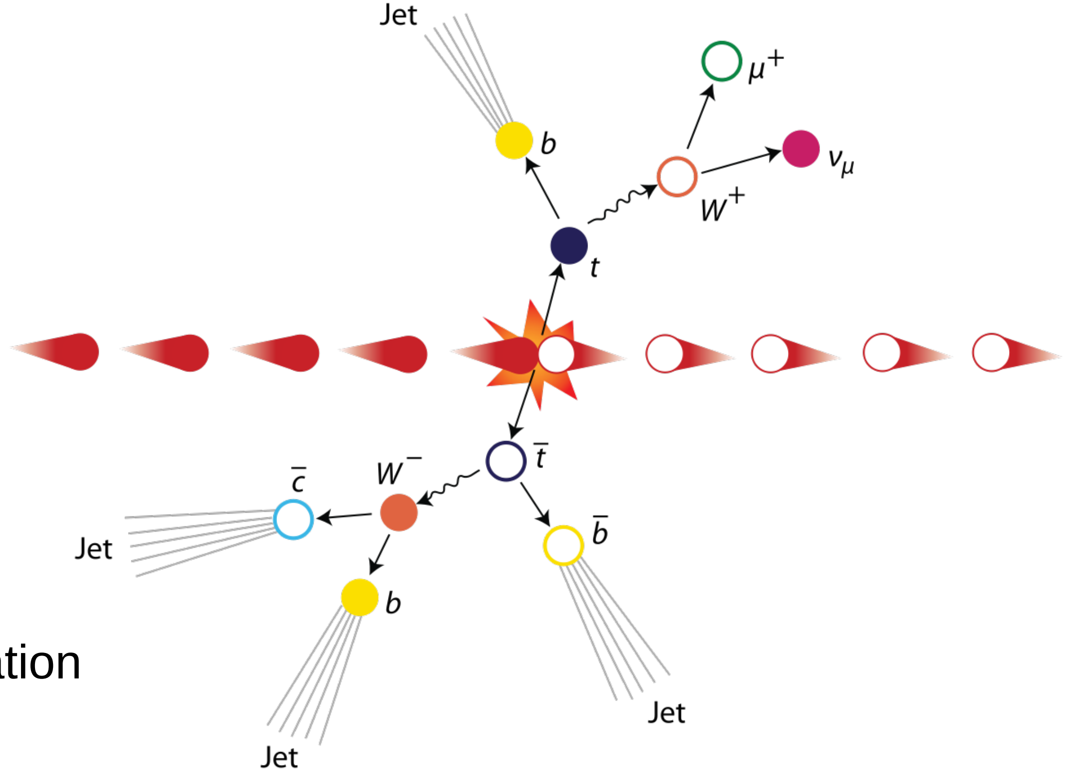
Outline

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

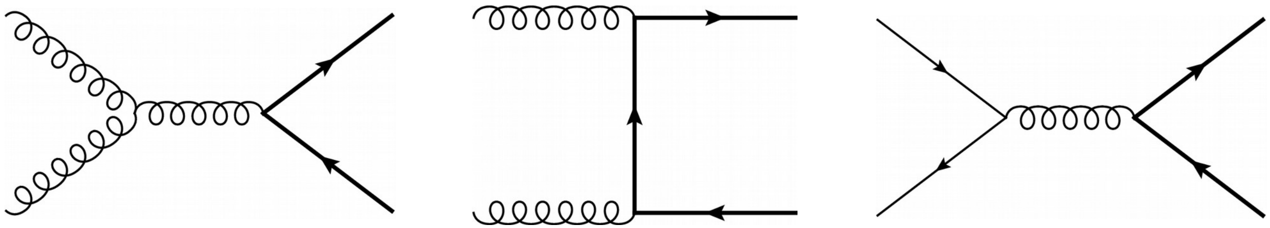
The top quark



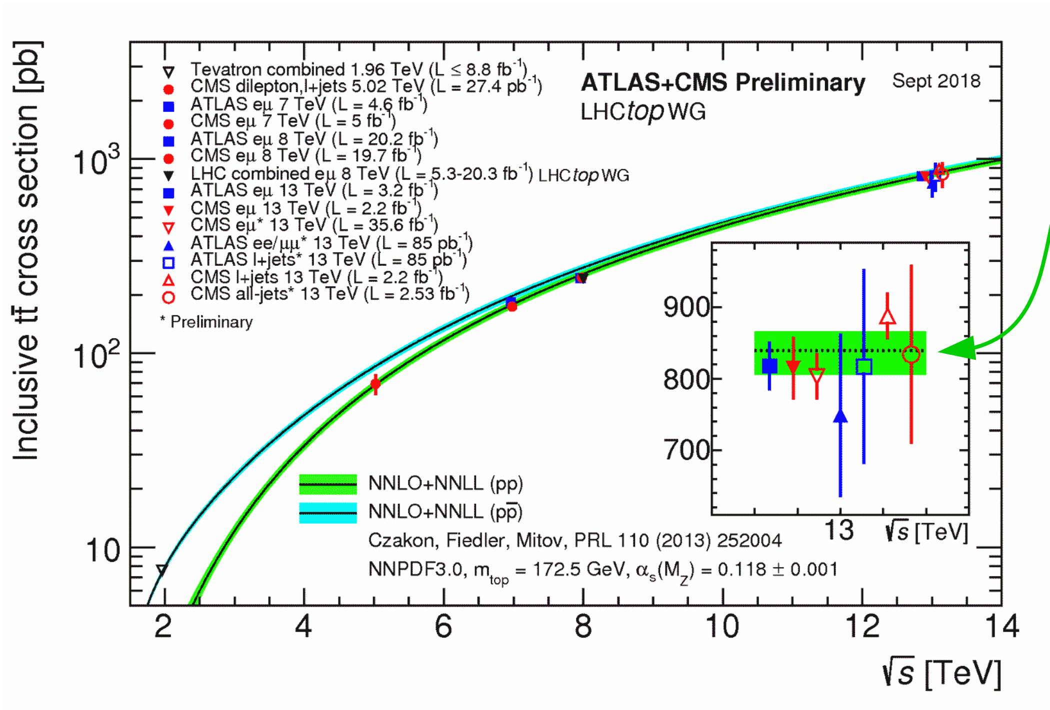
- Heaviest particle in the SM
- Strongest coupling to Higgs boson
- Only quark that decays before hadronization
- Possible window to new physics
- Important background in many searches
- Standard candle at the LHC (triggering, tracking, b-tagging, energy and jet calibration)

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
(see talk by D. Melini)

Very precise theoretical predictions are needed

Cross section known at NNLO QCD + NLO EW + resummation
(see talk by D. Scott)

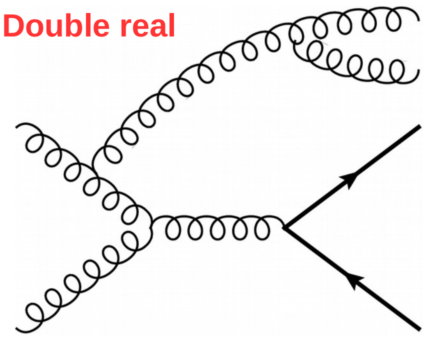
Why a new NNLO QCD calculation?

- Very difficult calculation: only one group able to complete it until now
  - Bärnreuther, Czakon, Mitov (2012)
  - Czakon, Mitov (2012)
  - Czakon, Fiedler, Mitov (2013)
  - Czakon, Fiedler, Heymes, Mitov (2015,2016)
- Independent check is always useful!
- No publicly available tool to produce NNLO distributions yet

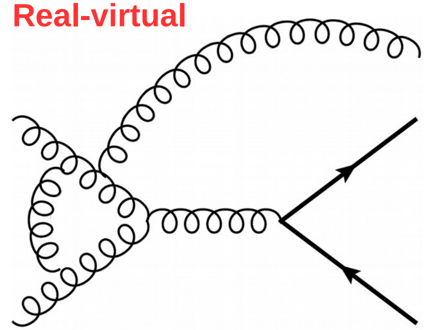
$t\bar{t}$ production at NNLO

We need the scattering amplitudes:

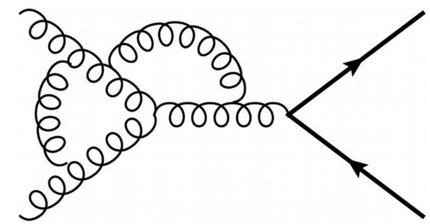
Double real



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

Subtraction methods

NLO: solved, Dipole subtraction, FKS, …

NNLO:

- Antenna [Gehrmann-de Ridder, Gehrmann, Glover ‘05, …]
- CoLoRFulNNLO [Somogyi, Trócsányi, Del Duca ‘05, …]
- q_T subtraction [Catani, Grazzini ‘07, …]
- STRIPPER [Czakon ‘10, ‘11]
- Projection-to-Born [Cacciari et al. ‘15]
- N-jettiness [Gaunt et al. ‘15; Boughezal et al. ‘15, …]
- Nested soft-collinear [Caola, Melnikov, Roentsch ‘17]
- Geometric [Herzog ‘18]
- Local analytic sector [Magnea et al. ‘18]

q_T subtraction

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

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

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

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

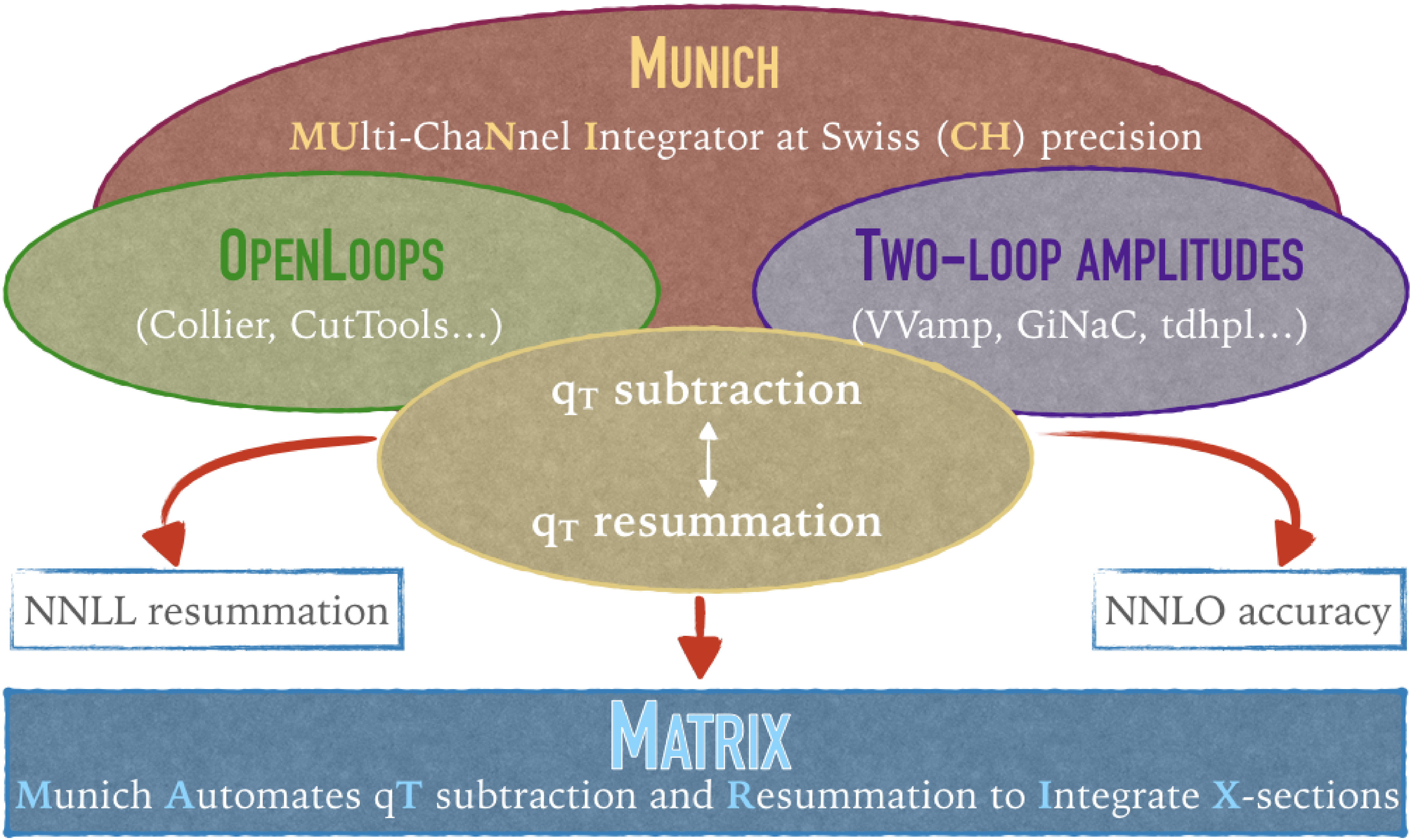
General form of hard-collinear function known at NNLO for colourless *F*

Implies knowledge of ***correct*** subtraction operator for virtual corrections

$$H \sim \langle \tilde{\mathcal{M}} | \tilde{\mathcal{M}} \rangle \quad \text{with} \quad |\tilde{\mathcal{M}}\rangle = \left(1 - \tilde{I}\right) |\mathcal{M}\rangle$$

Method can be applied to the production of arbitrary colour singlets at NNLO 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

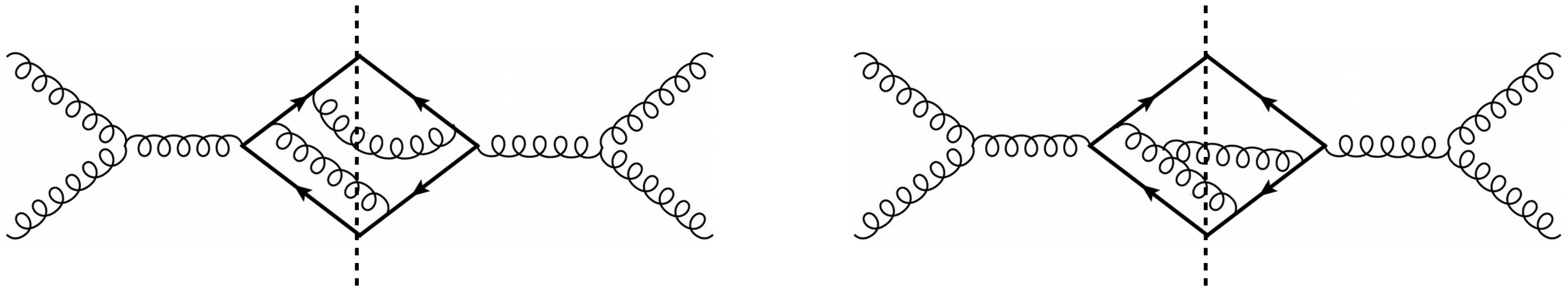
Analogous formula, but with new contributions coming from **final state radiation**

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

- 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:



$$H \sim \langle \tilde{\mathcal{M}} | \tilde{\mathcal{M}} \rangle \longrightarrow (\mathbf{H\Delta}) \sim \langle \tilde{\mathcal{M}} | \mathbf{\Delta} | \tilde{\mathcal{M}} \rangle \quad \left(\begin{array}{c} \text{Equivalent to:} \\ \tilde{I} \longrightarrow \tilde{\mathbf{I}} \end{array} \right)$$

Additional radiative soft factor **Δ** which includes **colour correlations**

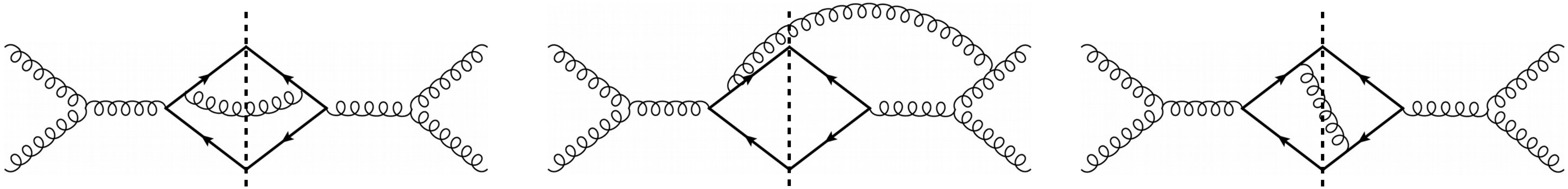
Extension to heavy-quark production

- Specifically, we have to compute $d\sigma/d^2q_T$

- Only new soft singularities → integrate the (subtracted) **soft current**

E.g. at NLO:

$$-\mathbf{J}(k)^2|_{\text{sub}} = \sum_{J=3,4}\left[\frac{p_J^2}{(p_J\cdot k)^2}\mathbf{T}_J^2 + \sum_{i=1,2}\left(\frac{p_i\cdot p_J}{p_J\cdot k} - \frac{p_1\cdot p_2}{(p_1+p_2)\cdot k}\right)\frac{2\,\mathbf{T}_i\cdot\mathbf{T}_J}{p_i\cdot k}\right] + \frac{2p_3\cdot p_4}{(p_3\cdot k)(p_4\cdot k)}\mathbf{T}_3\cdot\mathbf{T}_4$$



- After integration the following NLO subtraction operator can be obtained:
  [Catani, Grazzini, Torre; 1408.4564]

Purely initial-state — New soft contributions

$$\widetilde{\mathbf{I}}^{(1)}_{c\bar{c}\to Q\bar{Q}}\left(\epsilon,\frac{M^2}{\mu_R^2}\right) = -\frac{1}{2}\left(\frac{M^2}{\mu_R^2}\right)^{-\epsilon}\left\{\left(\frac{1}{\epsilon^2}+i\pi\frac{1}{\epsilon}-\frac{\pi^2}{12}\right)(\mathbf{T}_1^2+\mathbf{T}_2^2)+\frac{2}{\epsilon}\gamma_c-\frac{4}{\epsilon}\,\mathbf{\Gamma}_t^{(1)}(y_{34})+\mathbf{F}_t^{(1)}(y_{34})\right\}$$

Pole structure agrees with studies on one-loop amplitudes
[Catani, Dittmaier, Trocsanyi, 0011222]

Finite piece: only from direct computation

- We had to **extend** the above results **to NNLO**

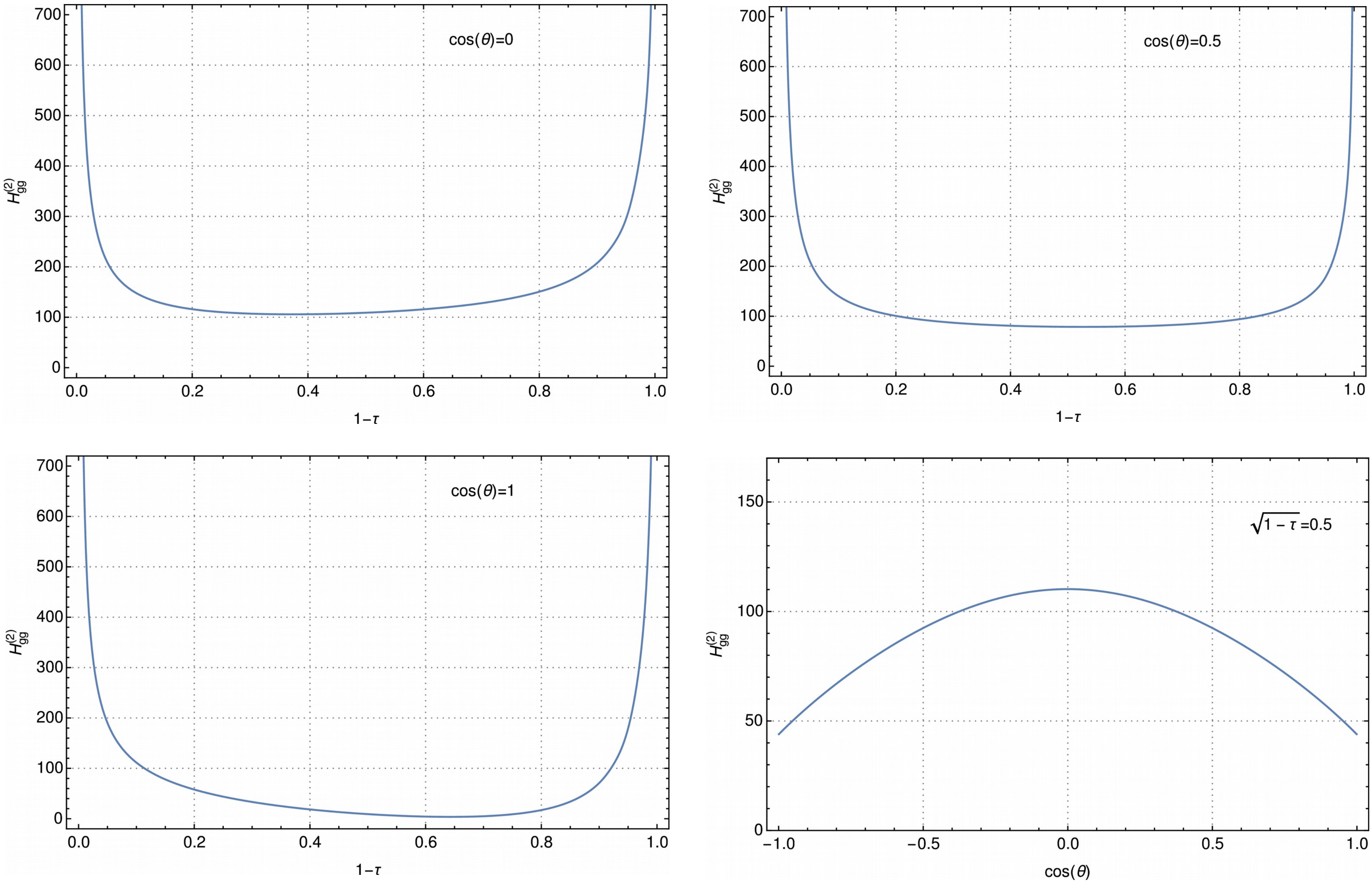
Final result - $H^{(2)}$

$\tau = 4m^2/s$, $\cos\theta$ scattering angle

- We have recently finished their computation

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

- Results mostly analytical, numerical integration for some pieces



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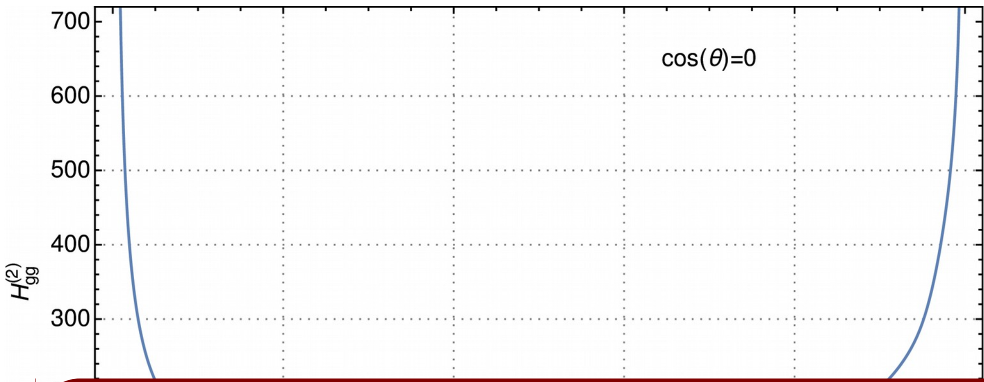
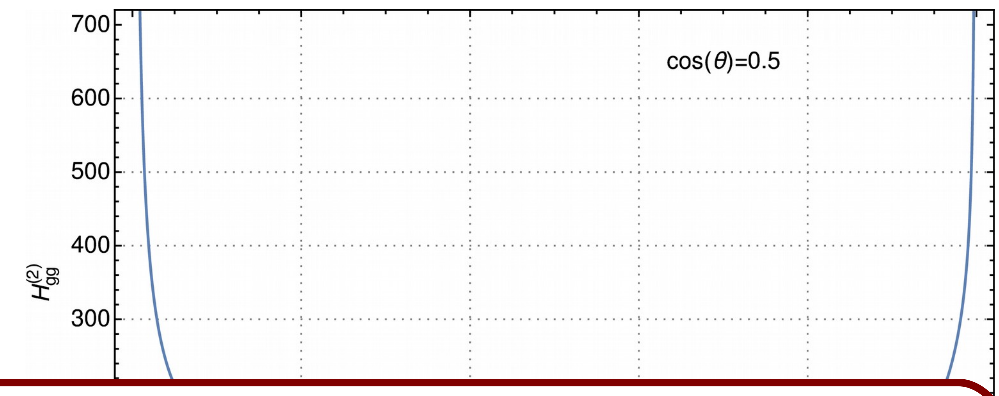


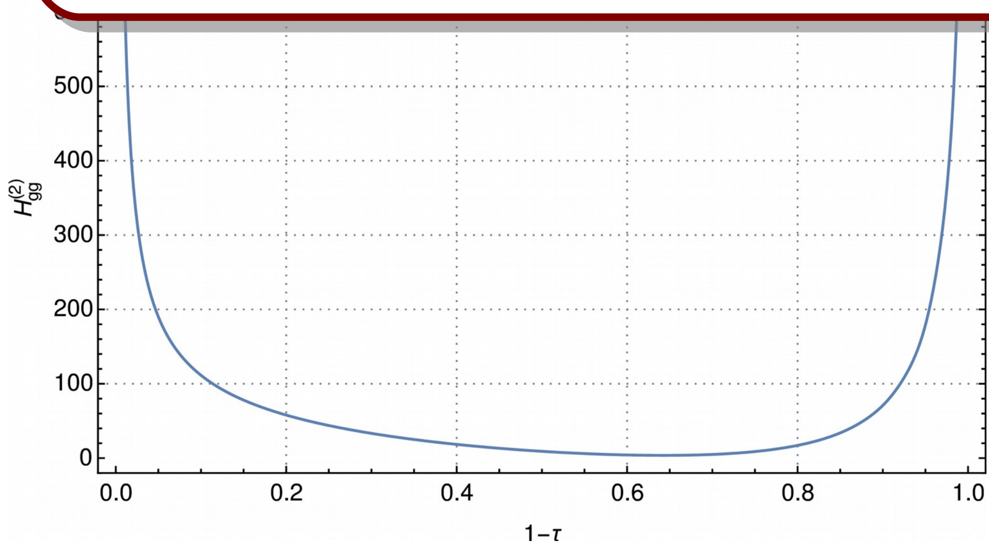


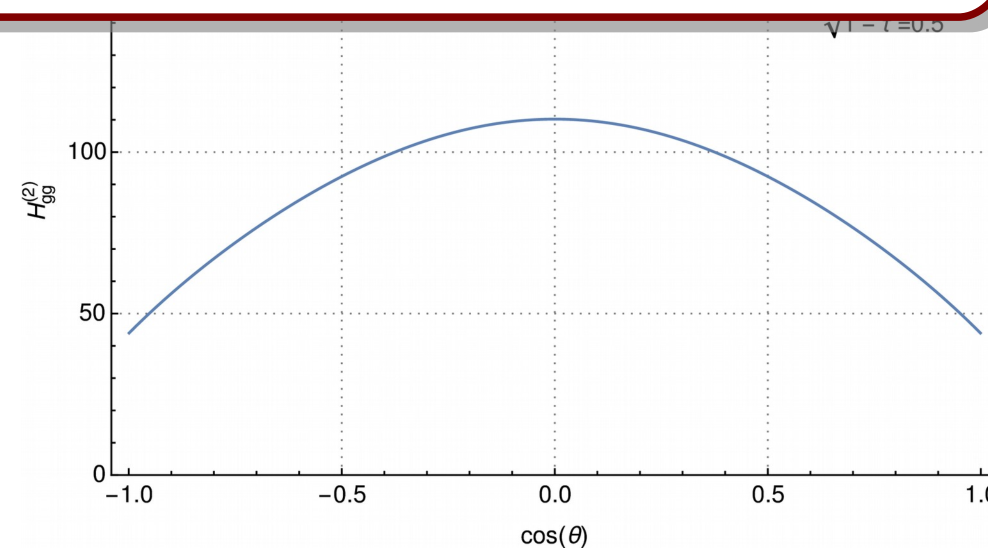
Thanks to these results, **q_T subtraction** can now deal with **$Q\bar{Q}$ production**

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)





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

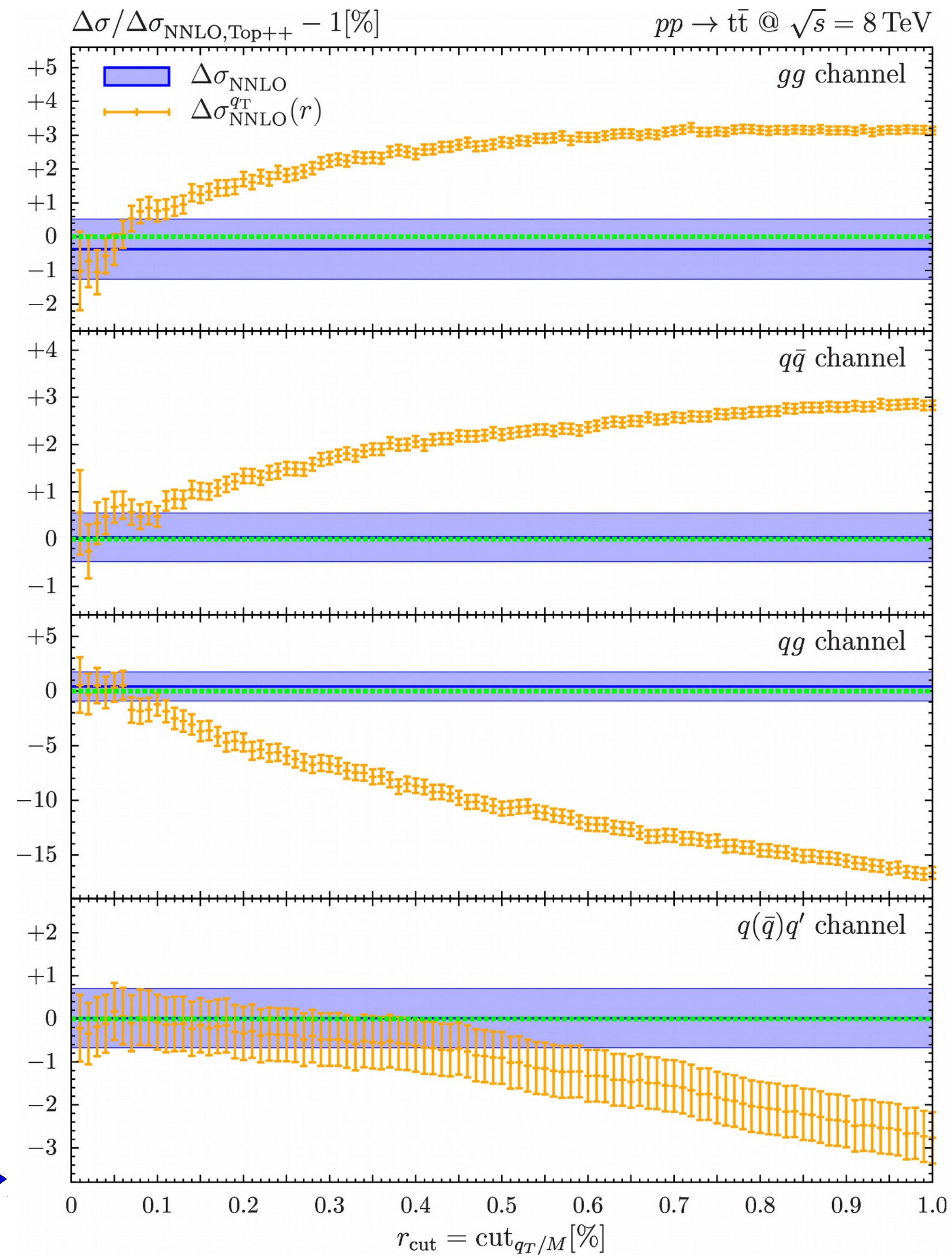
NNPDF31 sets, m_t=173.3GeV

Scale uncertainties: $\mu_0=m_t$

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

Per-mille accuracy in ~1000CPU days

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

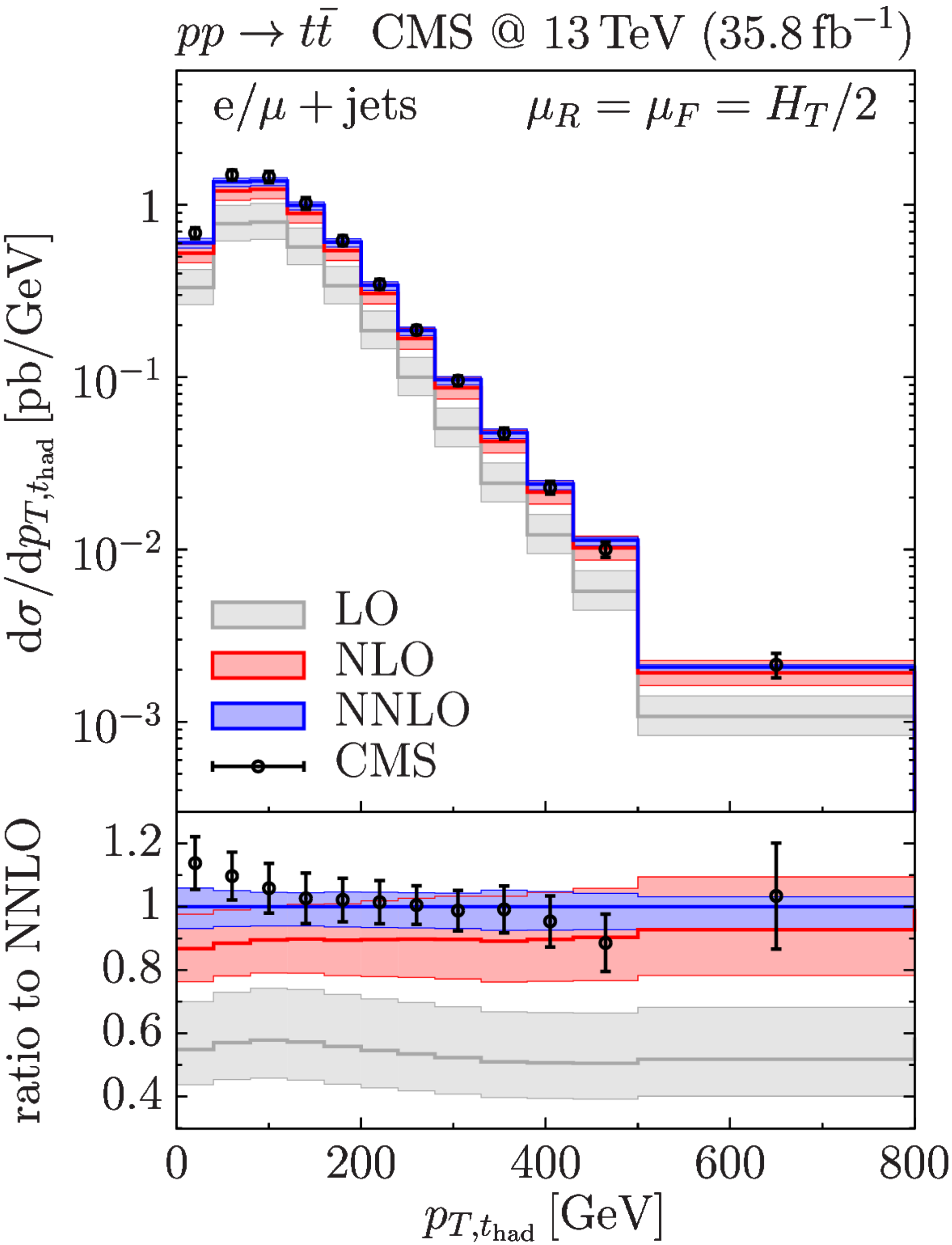
Perturbative results depend on the choice of scales μ_F, μ_R
which should be chosen of the order of the characteristic hard scale

- 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

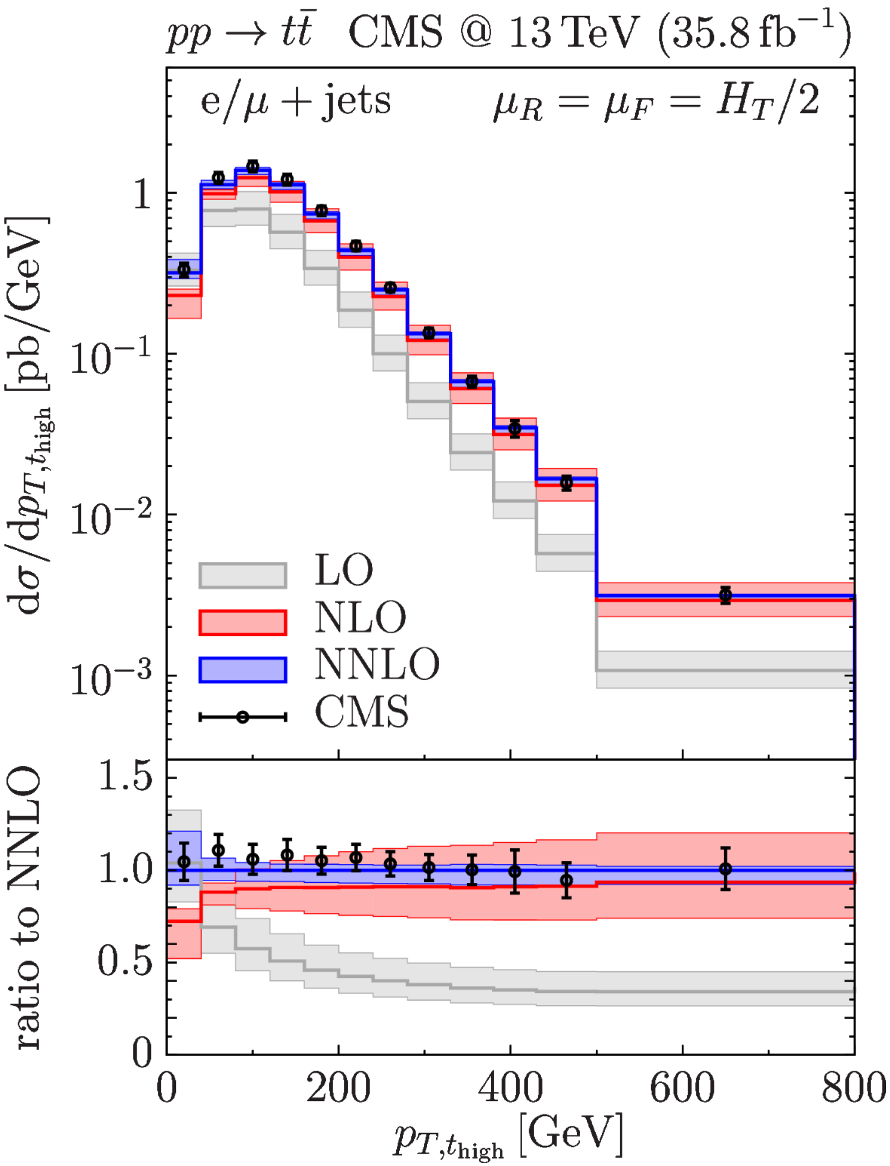
Catani, Devoto, Grazzini, Kallweit, JM (2019)

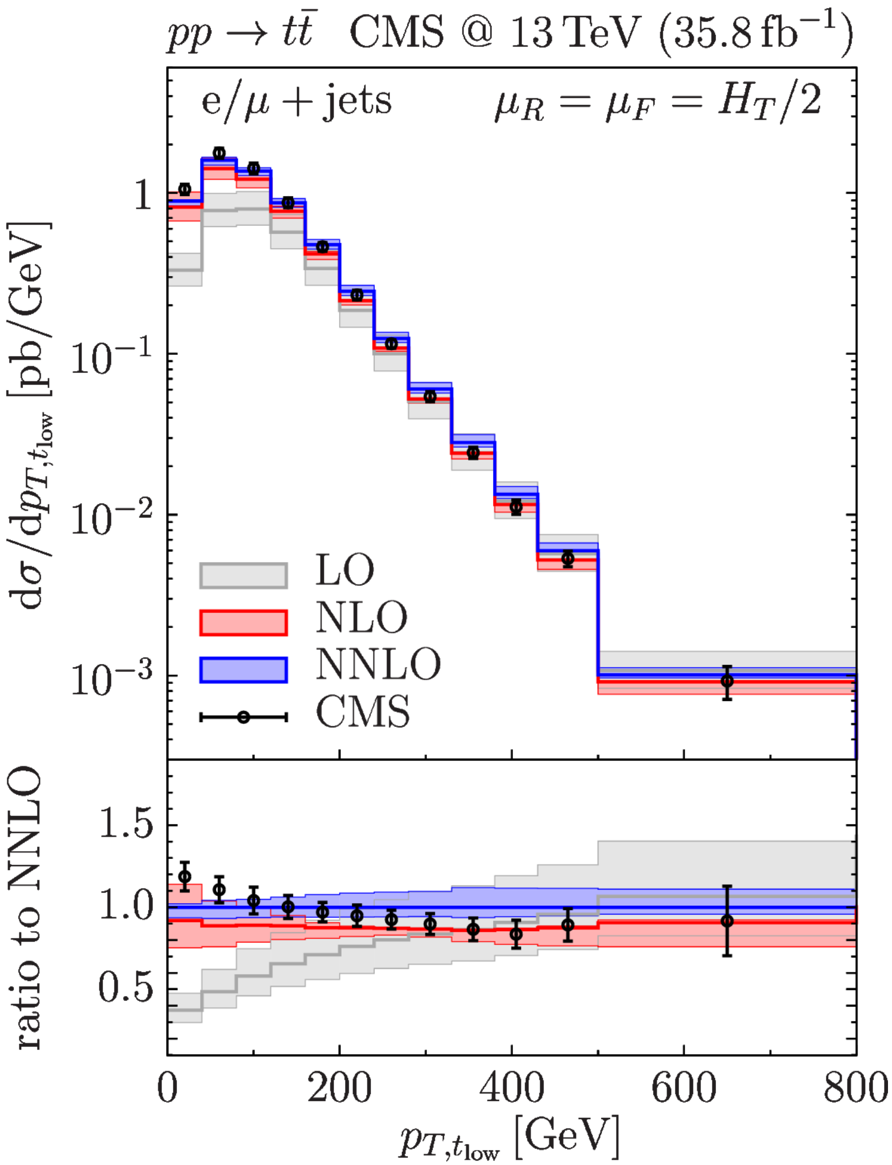


- Good perturbative behaviour, large overlap between NLO and NNLO bands
- As noted in previous analysis the measured p_T is slightly softer than the NNLO prediciton
- Data and theory consistent within uncertainties

Single-differential distributions

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

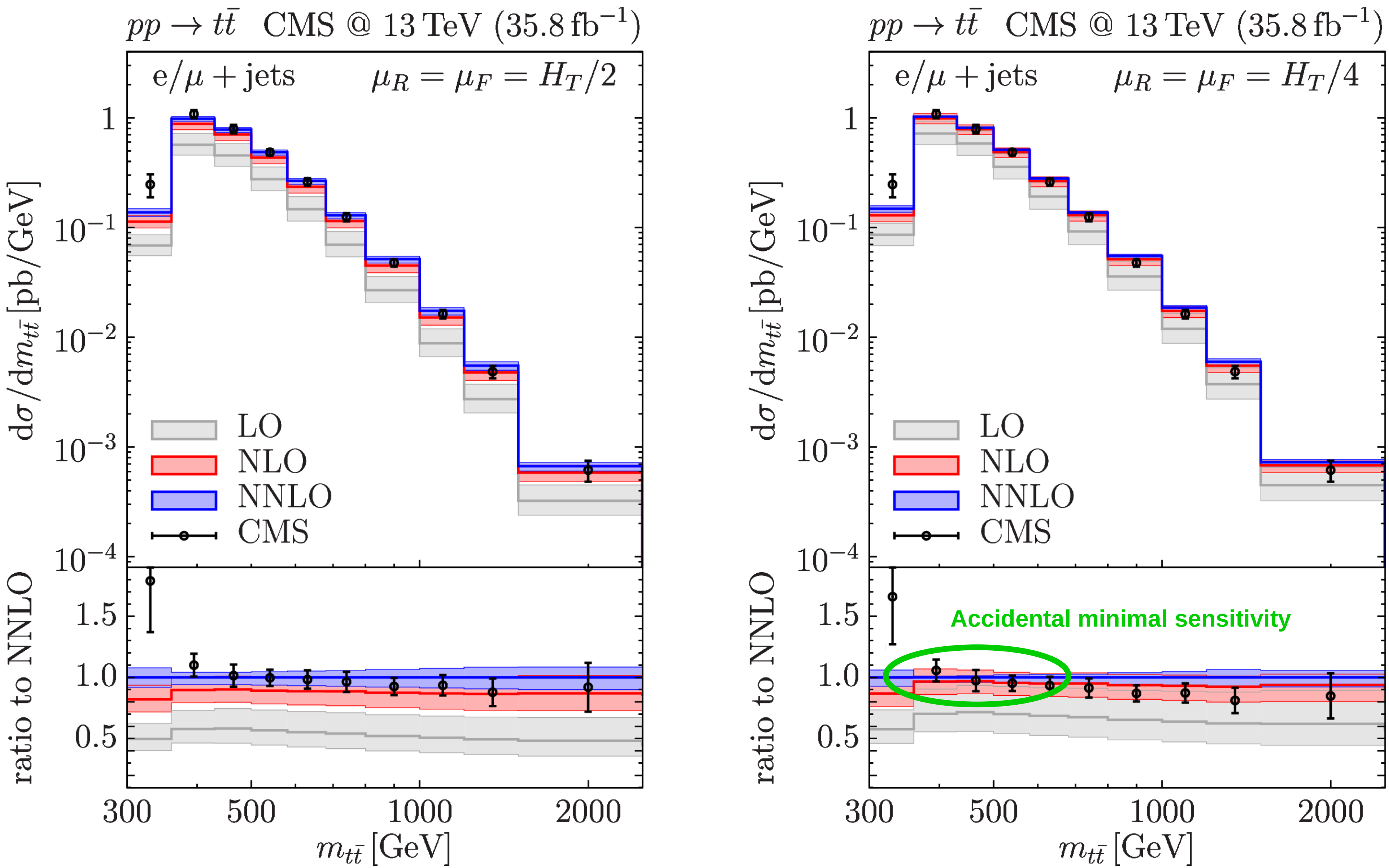




- Higher order corrections have a larger effect on the shape
- Low $p_T(t_{high})$ region: FO instabilities associated with low $p_T(t\bar{t})$
- Good agreement with data

Single-differential distributions

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

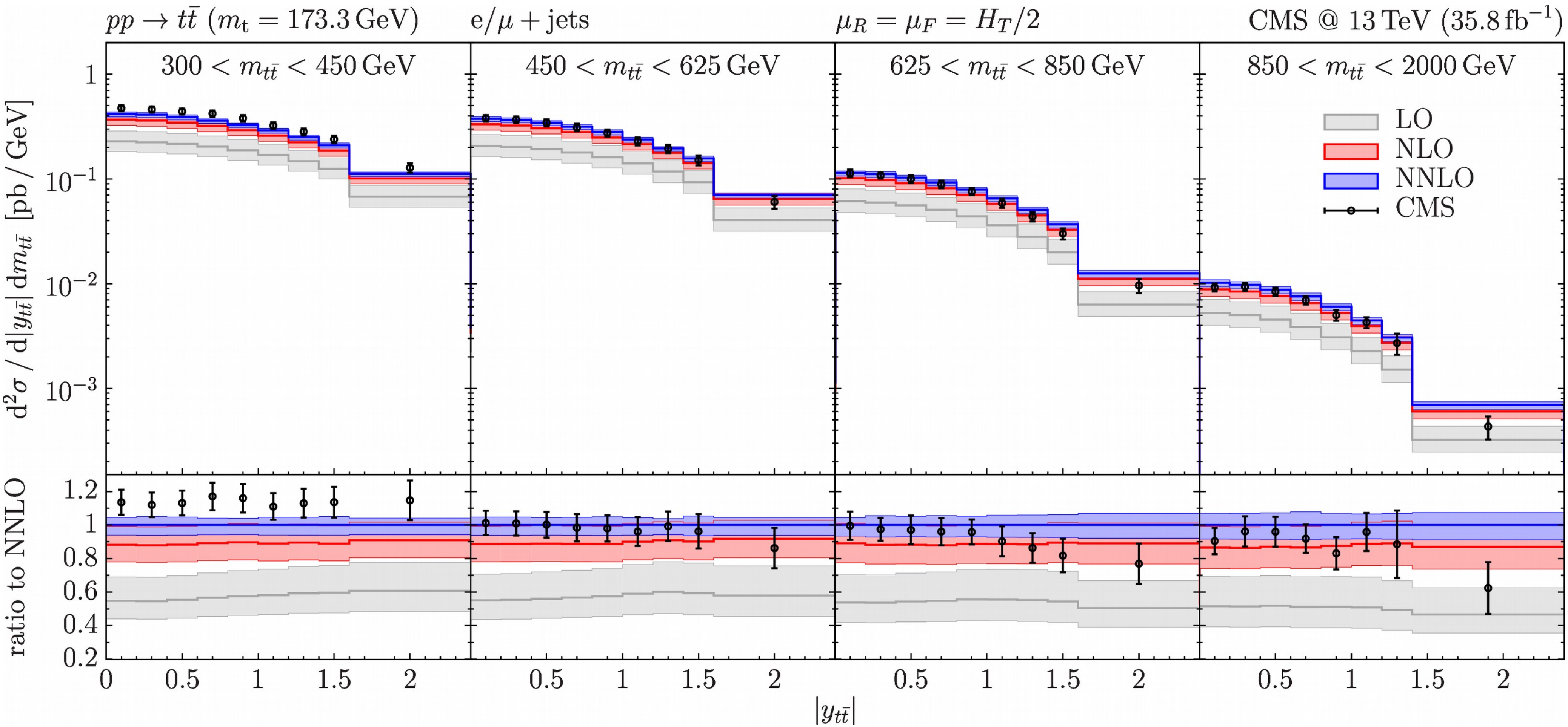


- Lower scale $H_T/4$ (usually used as a benchmark) seems to lead to underestimation of perturbative uncertainties in certain $m_{t\bar{t}}$ regions

- Good description of data except for first bin ($m_{t\bar{t}}$<360GeV)
  Issues in extrapolation? Smaller m_t? CMS-TOP-18-004: leptonic channel, fit m_t=170.81±0.68GeV

Double-differential distributions

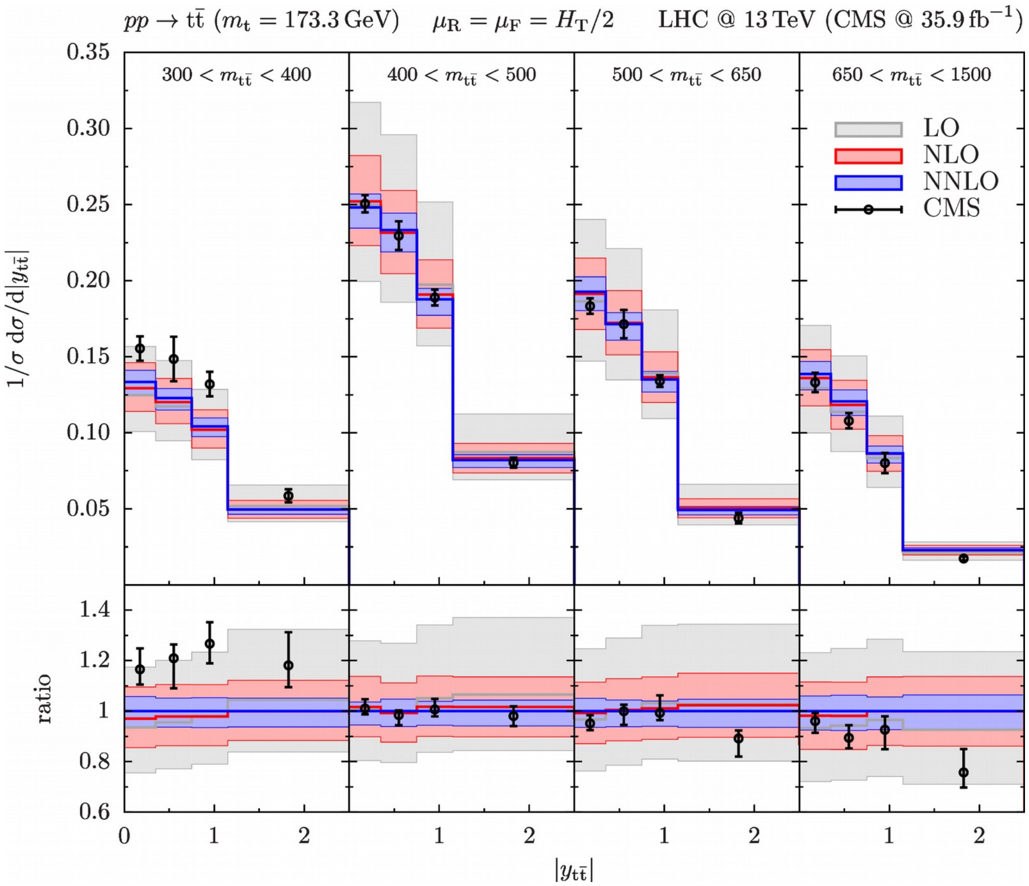
Catani, Devoto, Grazzini, Kallweit, JM (2019)

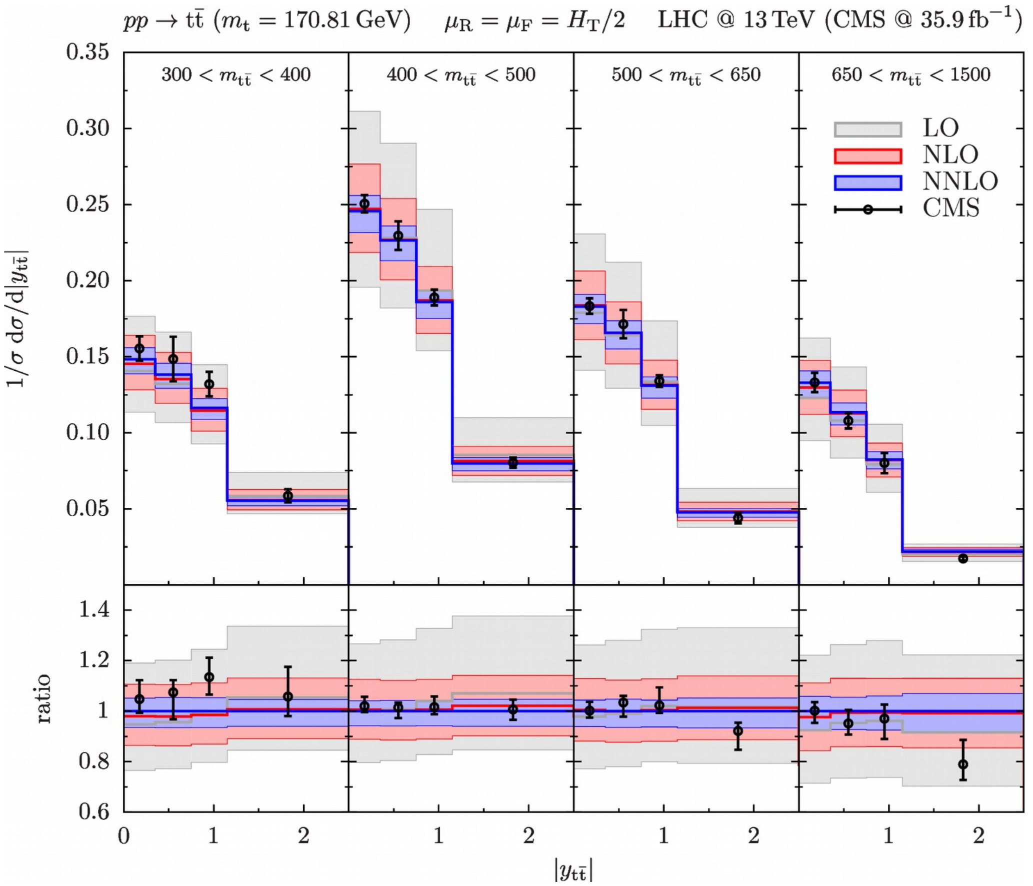


- Again some discrepancy in the low $m_{t\bar{t}}$ region, smaller effect due to larger bin size
- Impact of radiative corrections relatively uniform in both variables

Double-differential distributions

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

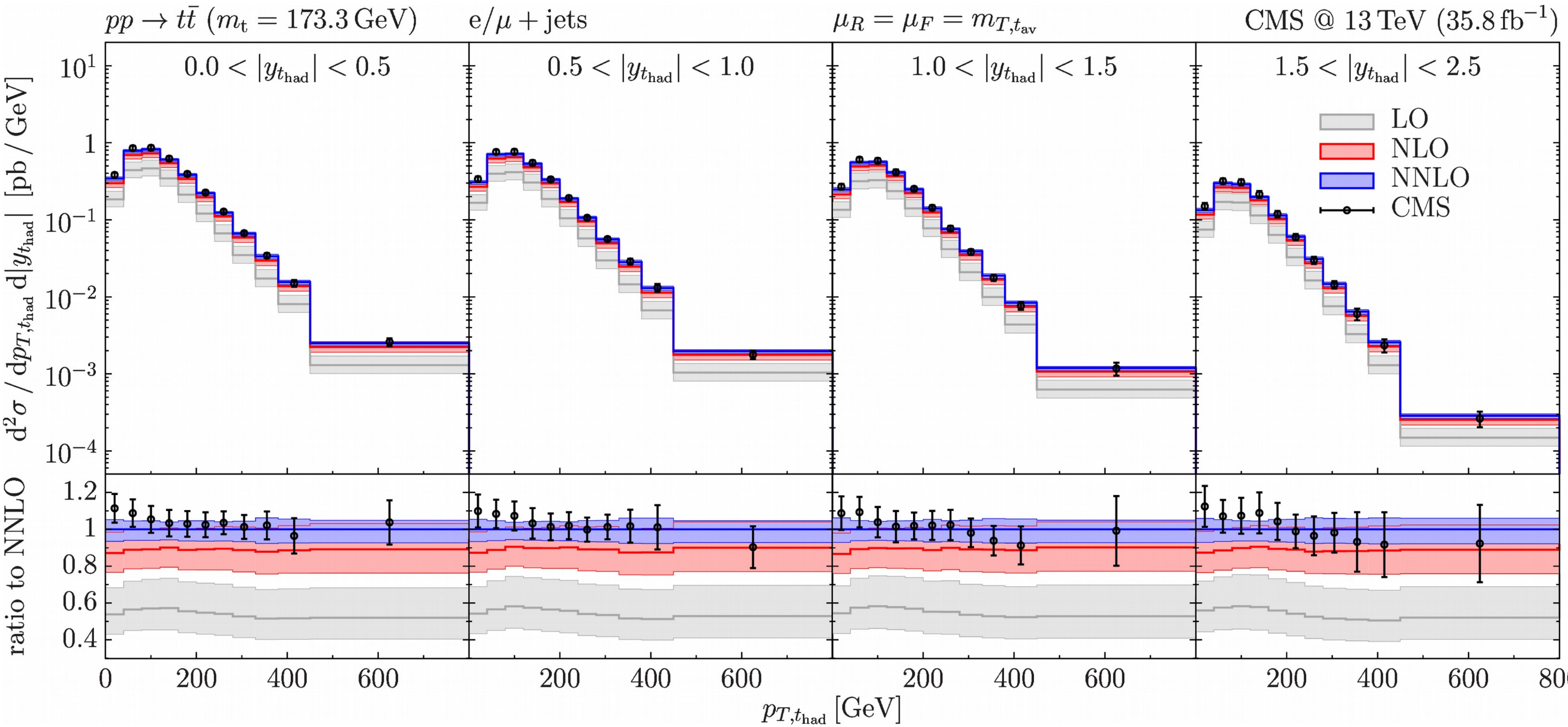




- Similar features in this decay channel (note these are normalized distributions)
- Using fitted top mass by CMS (170.81GeV) leads to a better agreement with data

Double-differential distributions

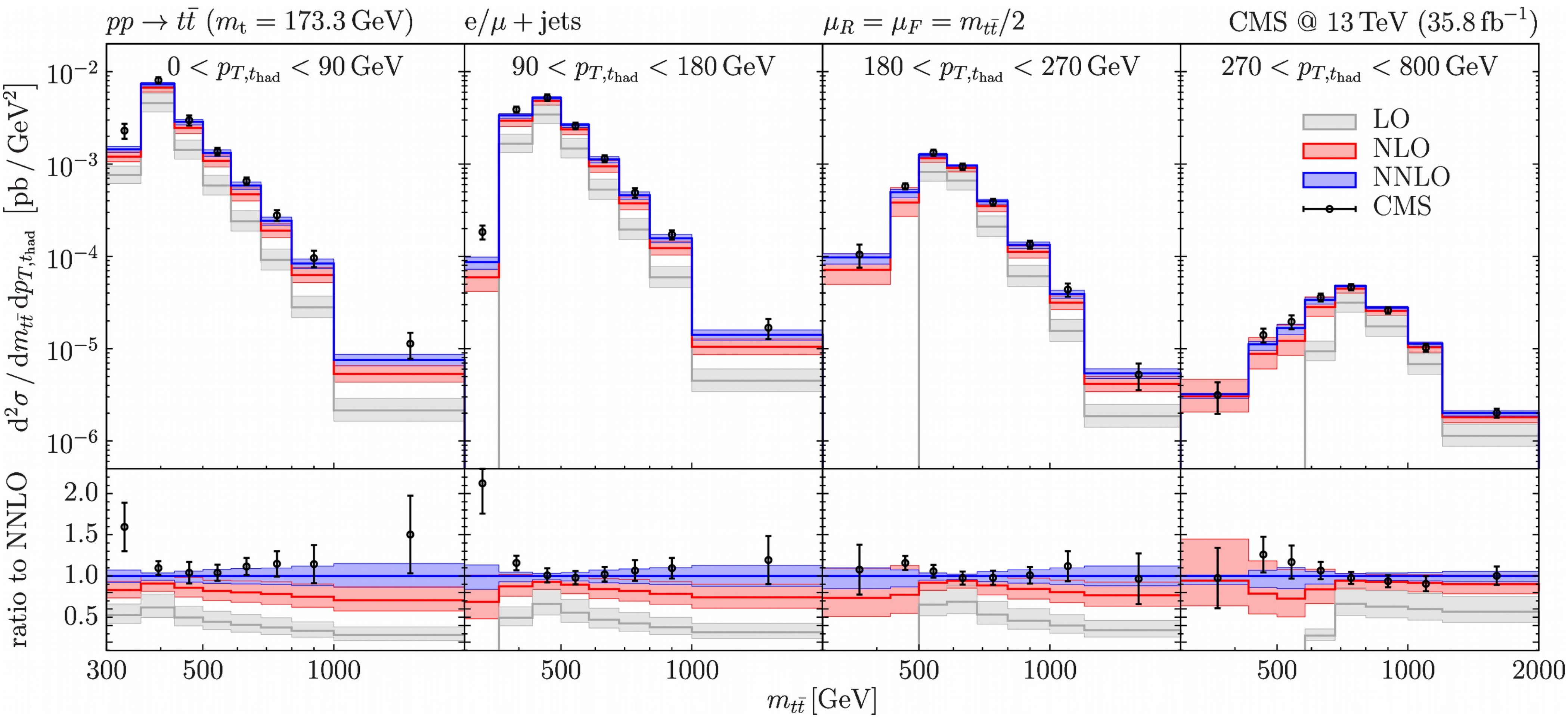
Catani, Devoto, Grazzini, Kallweit, JM (2019)



- 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)

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

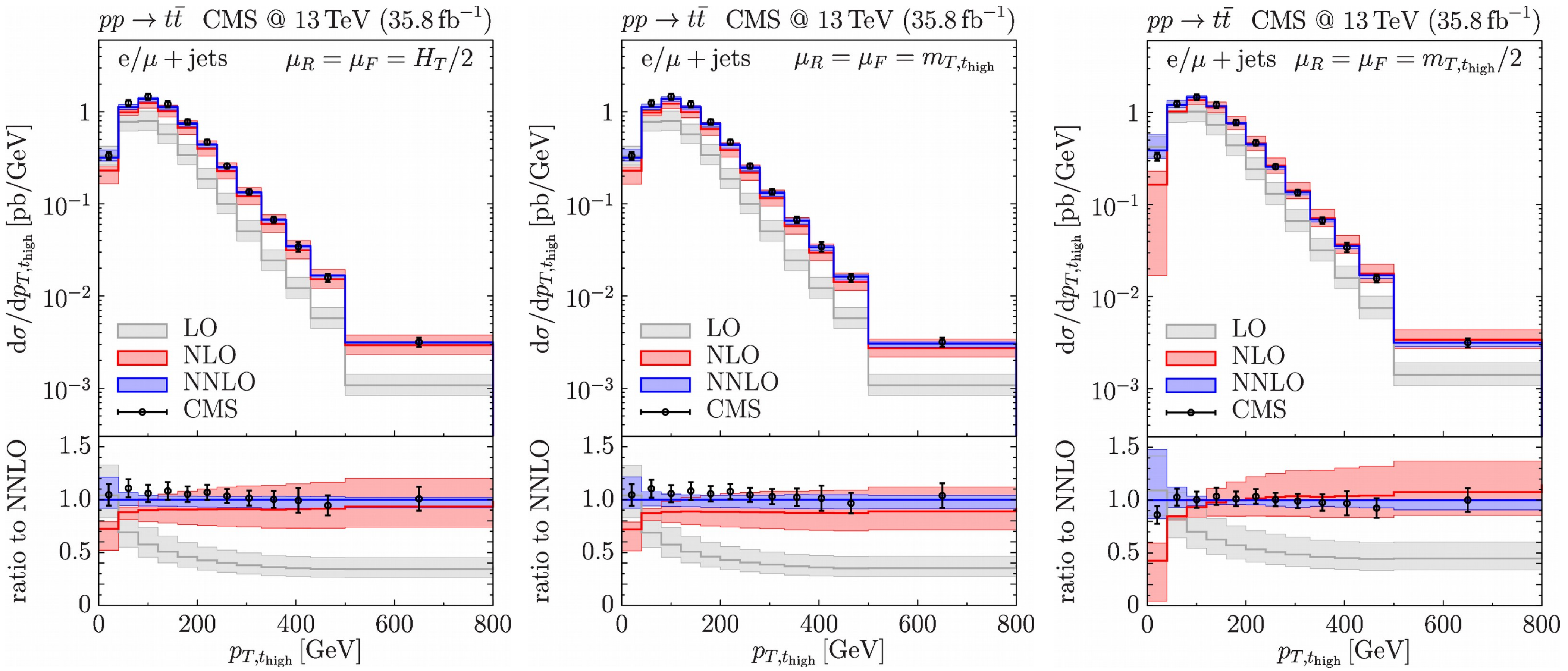
  - inclusion of top-quark decays

Thanks!

Backup slides

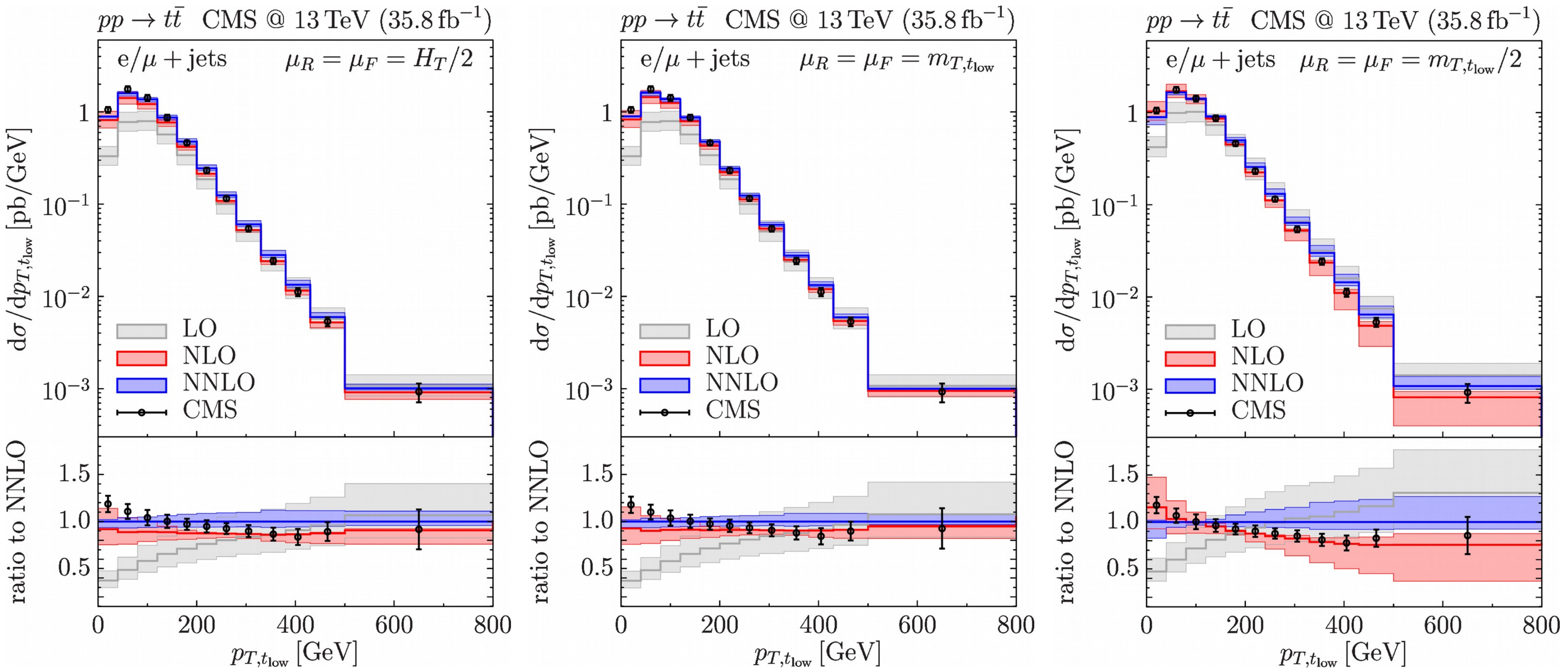
Other scale choices

$p_T(t_{high})$



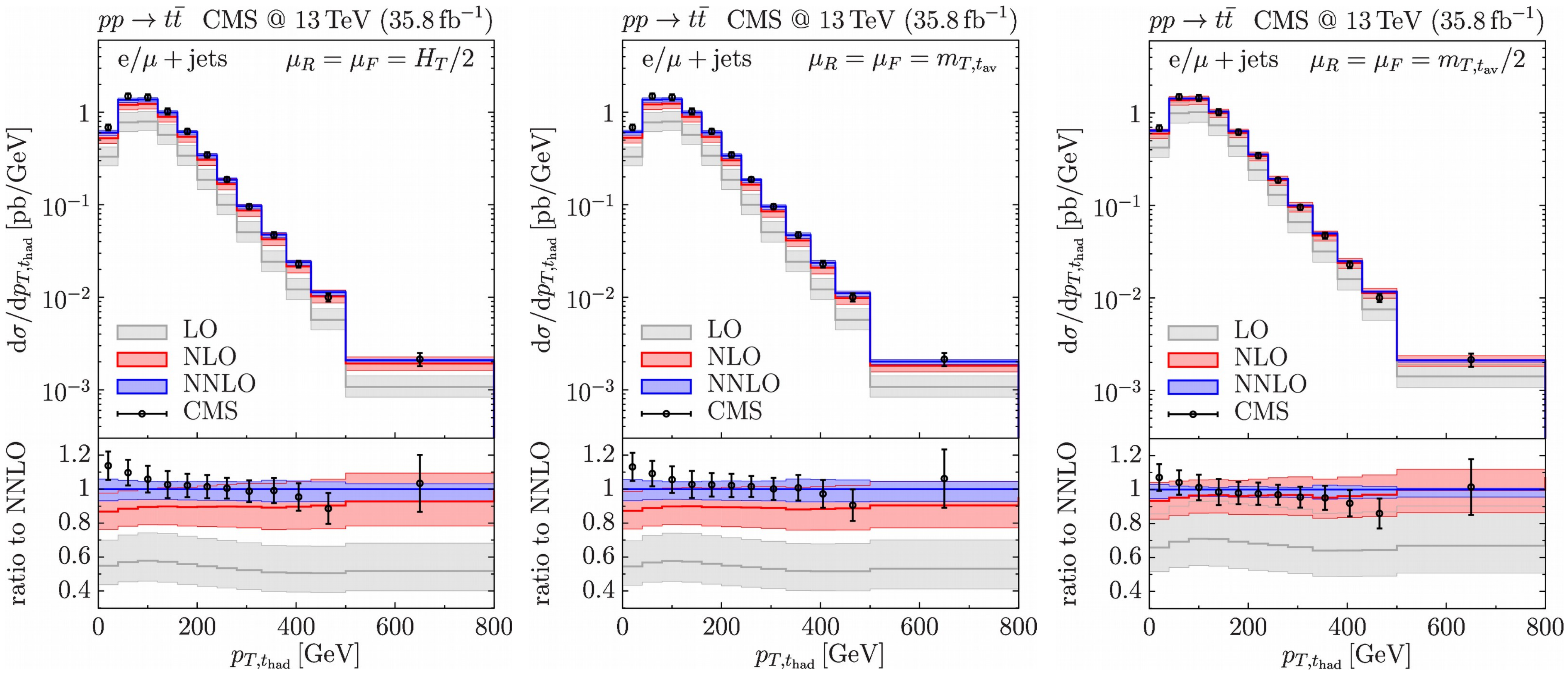
Other scale choices

$p_T(t_{low})$



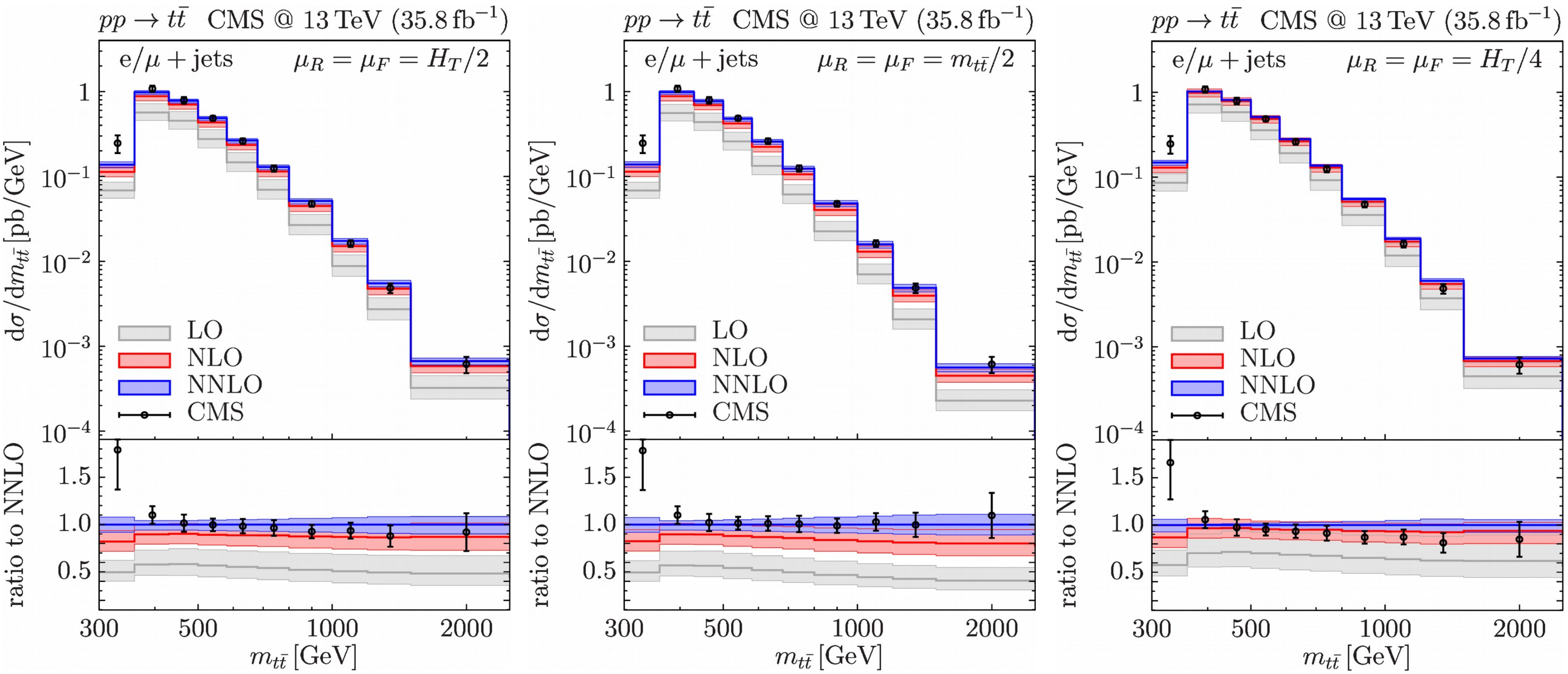
Other scale choices

$p_T(t_{had})$



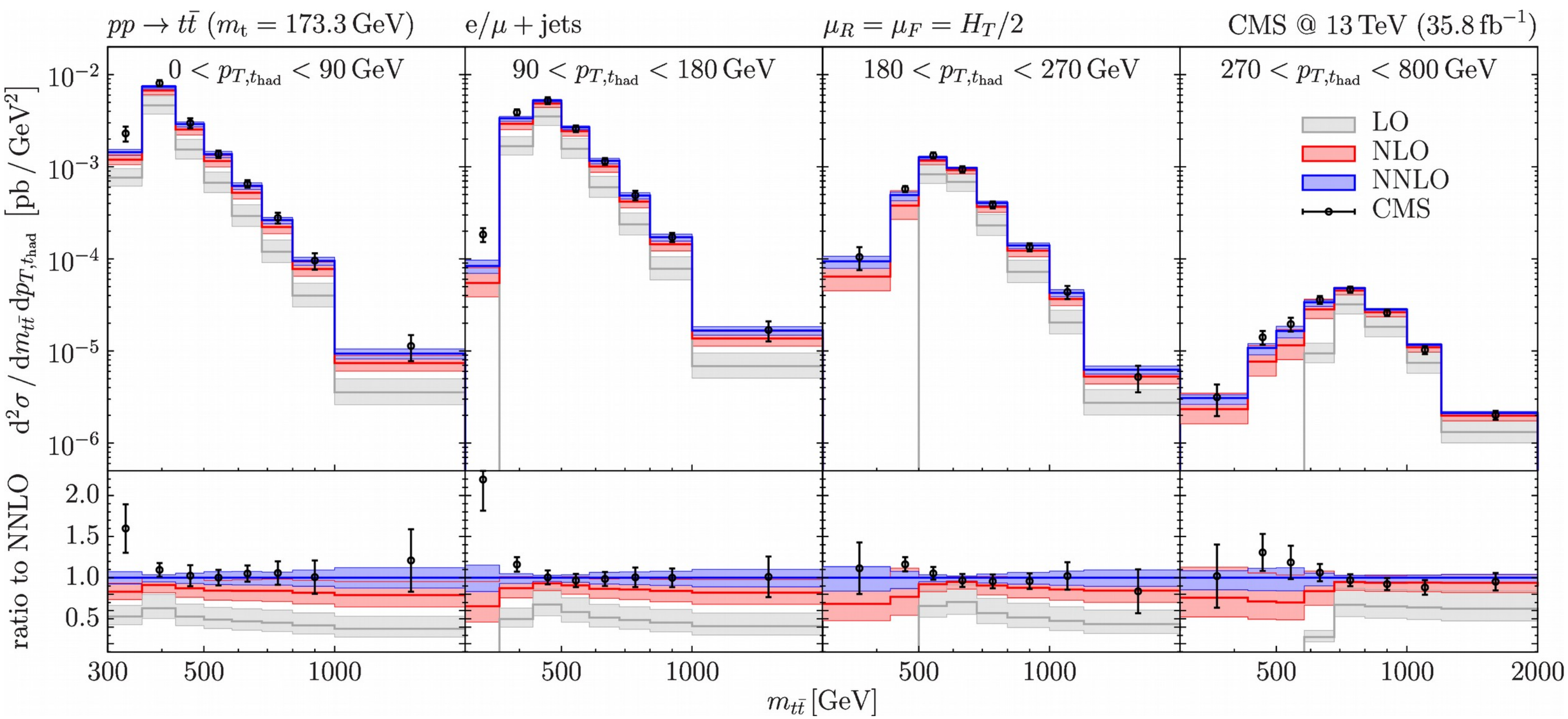
Other scale choices

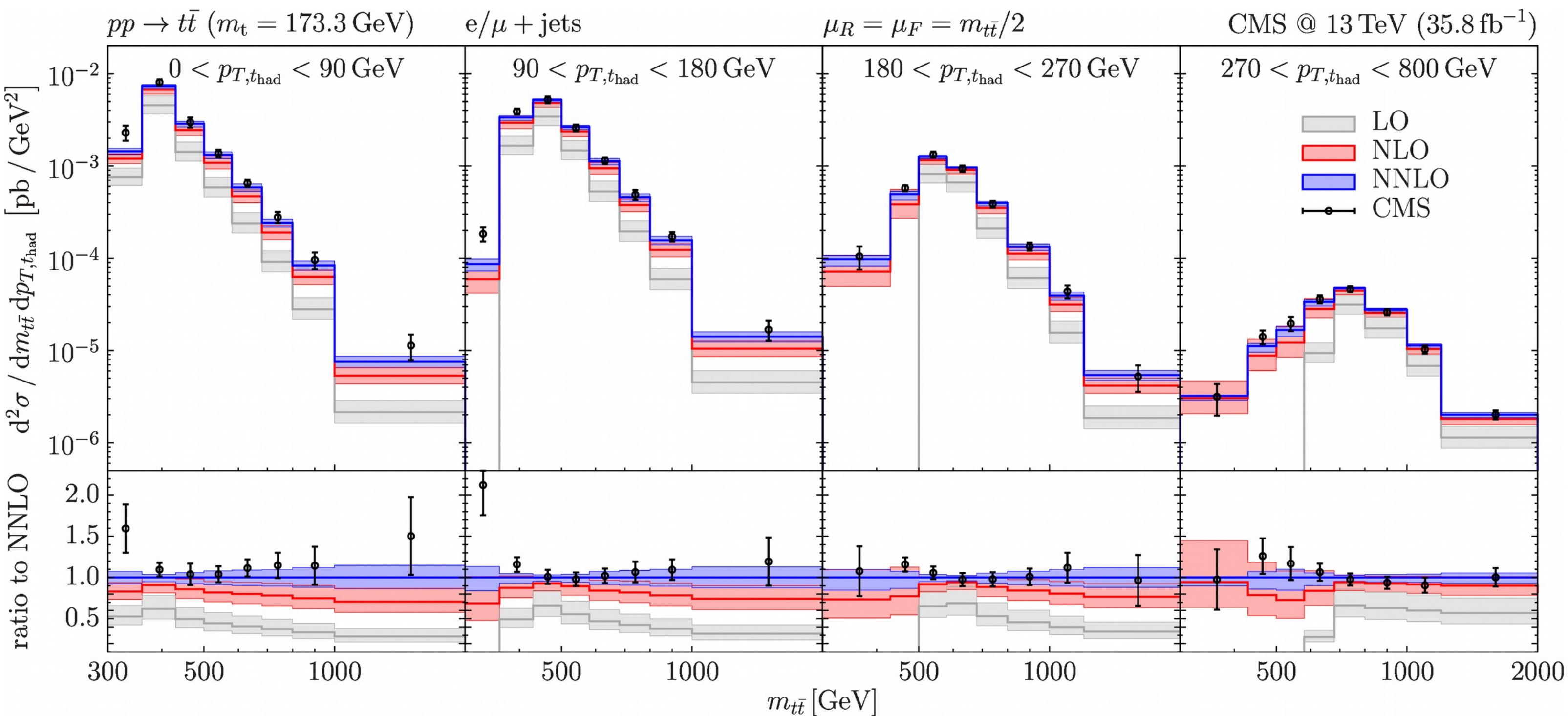
m_{tt}



Other scale choices

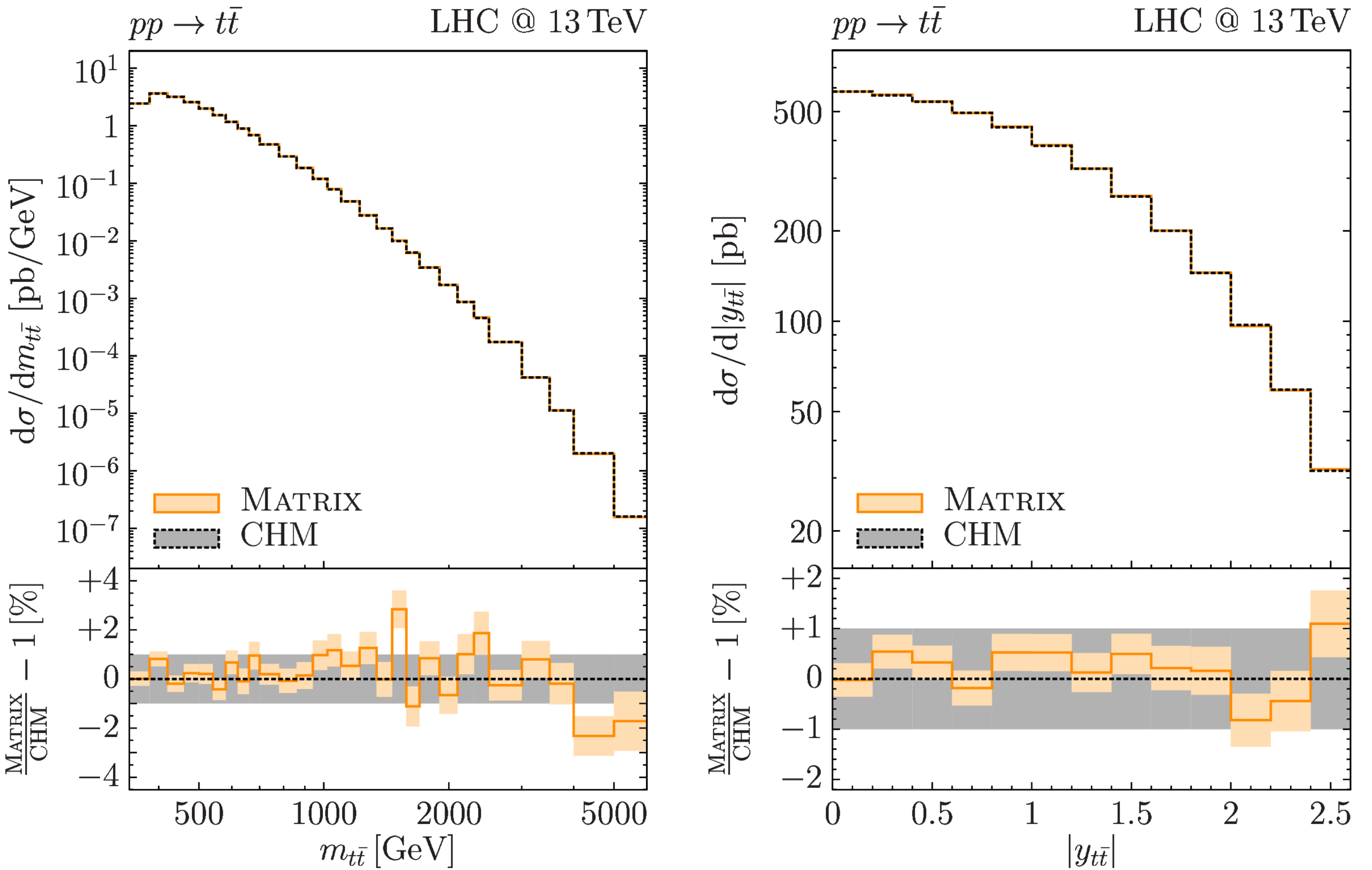
m_{tt} vs $p_T(t_{had})$





Comparison to existing results

CHM = [Czakon, Heymes, Mitov, 1606.03350]



Excellent agreement even in extreme kinematical regions

Comparison to existing results

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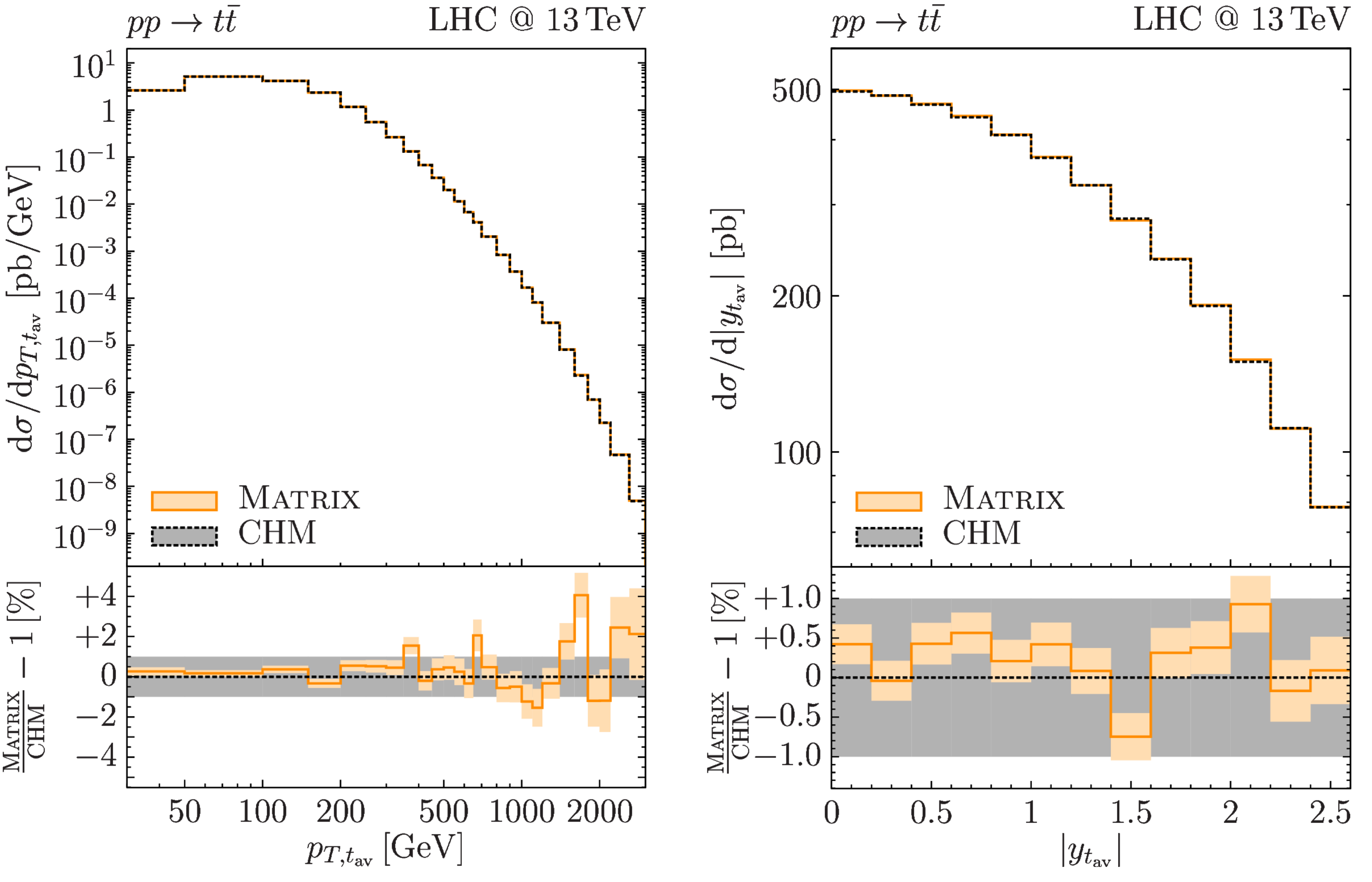

Excellent agreement even in extreme kinematical regions