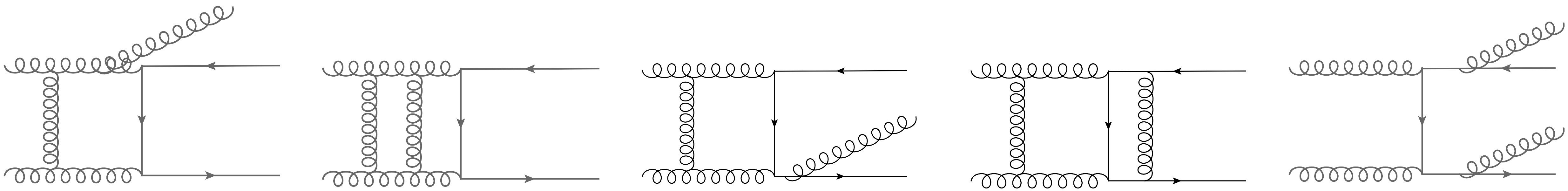
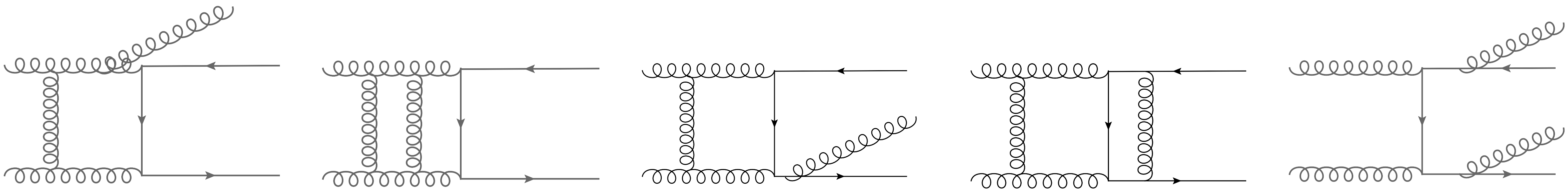


TOP-QUARK HADROPRODUCTION IN NNLO QCD

LoopFest XVIII, 14.08.19

Simone Devoto - University of Zürich

In collaboration with:
S. Catani, M. Grazzini, S. Kallweit, J. Mazzitelli, H. Sargsyan



CONTENTS

- Introduction;
- q_T subtraction formalism;
- q_T subtraction formalism for heavy quark production;
- Inclusive cross section;
- Differential distributions;
- Summary and outlook.

WHY TOP PAIR PRODUCTION AT NNLO?

Top quark production is of great importance at hadron colliders:

Standard Model Studies	
	➤ strong coupling with the Higgs boson;
	➤ top mass is a fundamental parameter;
	➤ standard candle at LHC.

BSM Studies	
	➤ possible window on new physics;
	➤ background to new physics searches.

Top pair production is the main source of top events at LHC:

- **3 times larger than single top production;**
- **at LHC about 15 $t\bar{t}$ pairs produced per second .**

QCD CORRECTIONS: THEORETICAL STATUS

Focusing on on-shell top pair production:

- **NLO QCD:**
  - Total Cross Section *[P. Nason, S. Dawson, R. K. Ellis (1988)],[…]*
  - Differential distribution *[M. L. Mangano, P. Nason and G. Ridolfi (1992)], […]*
- **NNLO QCD:**
  - Total Cross Section *[M. Czakon, P. Fiedler, A. Mitov (2013)]*
  - Differential distributions *[M. Czakon, P. Fiedler and A. Mitov (2015), M. Czakon, P. Fiedler, D. Heymes and A. Mitov (2016); M. Czakon, D. Heymes and A. Mitov (2017)]*
- **NEW: NNLO QCD using qT subtraction**
  [S. Catani, SD, M. Grazzini, S. Kallweit, J. Mazzitelli, H. Sargsyan: 1901.04005; S. Catani, SD, M. Grazzini, S. Kallweit, J. Mazzitelli: 1906.06535]

WHY TOP PAIR PRODUCTION AT NNLO… AGAIN?

NNLO QCD corrections for on shell $t\bar{t}$ production are known.

Why a new computation?

↓

Very difficult computation, 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); …]*

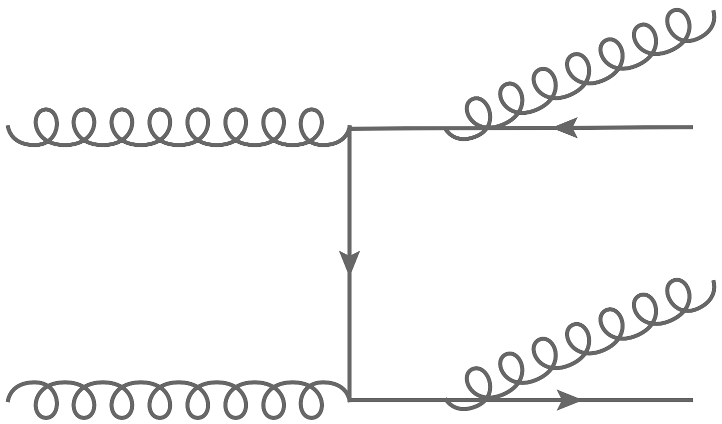
See talk by A. Mitov for recent developments!

↓

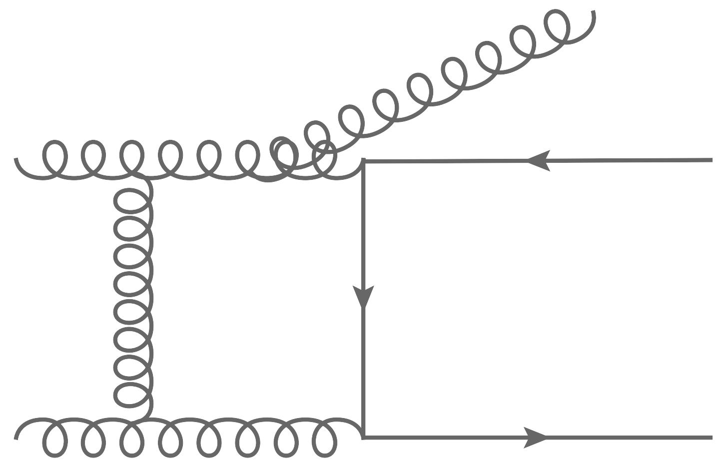
- An independent check is always useful;
- No public available NNLO generator yet.

TOP PAIR PRODUCTION AT NNLO – INGREDIENTS

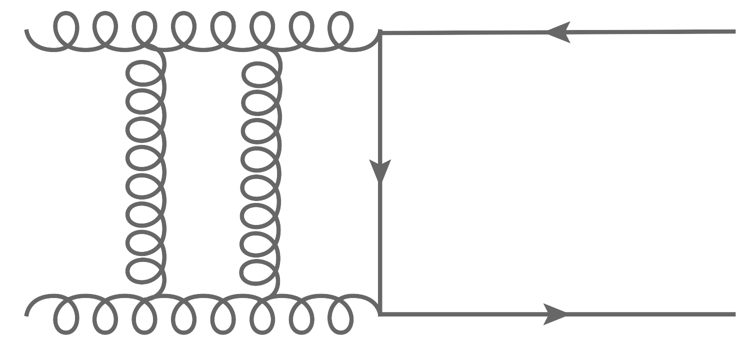
Double real



Real -virtual



Two loop virtual



Fast and stable evaluation with OpenLoops 2
[Cascioli et al. (2012), Buccioni et al. (2018), Buccioni et al. (2019)]

Numerically available
[Czakon (2008); Barnreuther et al.(2013)]

See talk by M. Zoller!

IR divergent

IR divergent

IR divergent

IR divergences cancel once all contributions are combined (KLN theorem) but they do not allow a straightforward implementation of numerical techniques.

We need a method to handle and cancel IR singularities

Q_T SUBTRACTION FORMALISM

[S. Catani, M. Grazzini (2007)]

The q_T subtraction formalism is a method to handle and cancel IR divergences, originally developed for **colorless** final states.

$$d\sigma^F_{(N)NLO} = d\sigma^F_{(N)NLO}\Big|_{q_T=0} + d\sigma^F_{(N)NLO}\Big|_{q_T\neq 0}$$

qt = transverse momentum of the system F

$$d\sigma^{F+jets}_{(N)LO}$$

$$d\sigma^F_{(N)NLO} = \mathscr{H}^F_{(N)NLO} \otimes d\sigma^F_{LO} + \left[d\sigma^{F+jets}_{(N)LO} - d\sigma^{CT}_{(N)LO}\right]$$

HARD COLLINEAR COEFFICIENT
Contains information on virtual corrections to the process.

Singularities for $q_t \neq 0$ can be computed with NLO subtraction techniques.

Extra singularities of NNLO type associated to the $q_t \to 0$ limit need additional subtraction. IR behaviour known from q_t resummation formalism allow us to construct a counterterm.
[J. C. Collins, D. E. Soper, G. Sterman (1985); G. Bozzi, S. Catani, D. de Florian, M. Grazzini (2005)]

MATRIX

[M.Grazzini, S. Kallweit, M. Wiesemann: arXiv 1711.06631]

Computational framework which, implementing q_T subtraction, allows us to evaluate fully differential cross sections for a wide class of processes at hadron colliders ***where the final state is a color singlet*** *in next-to-next-to-leading order (NNLO) QCD.*

MATRIX

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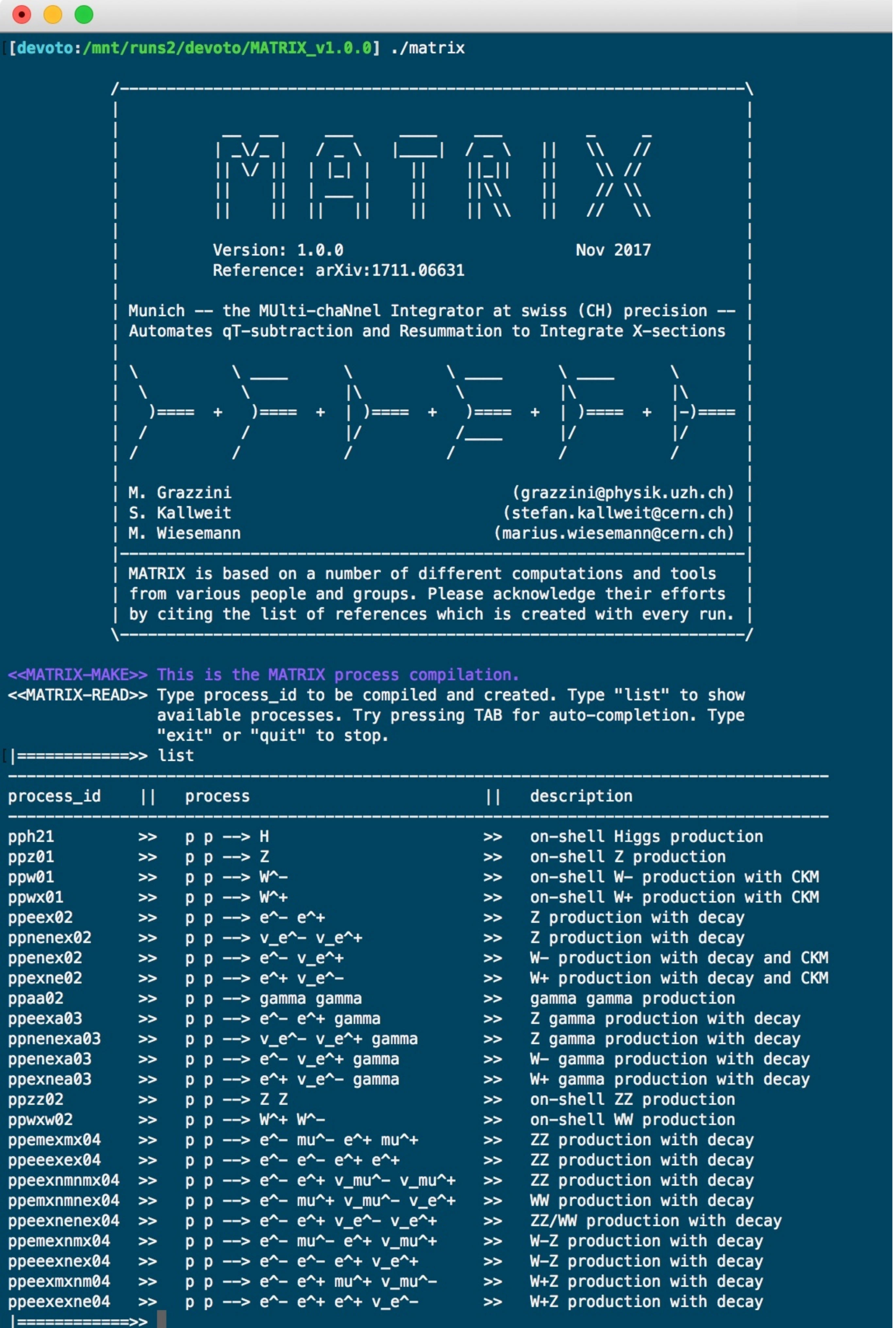

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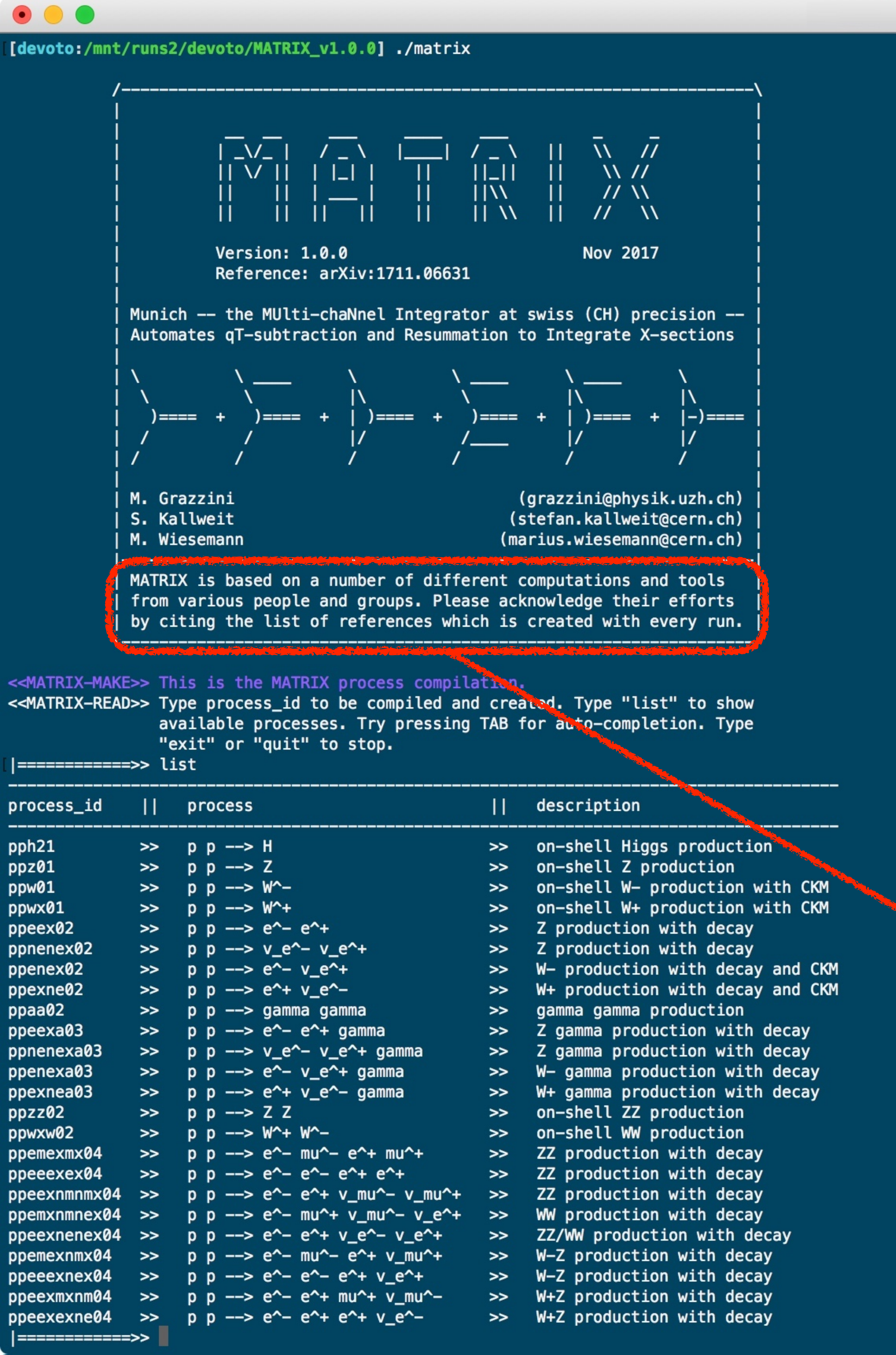

```
[devoto:/mnt/runs2/devoto/MATRIX_v1.0.0] ./matrix

Version: 1.0.0                                   Nov 2017
Reference: arXiv:1711.06631

Munich -- the MUlti-chaNnel Integrator at swiss (CH) precision --
Automates qT-subtraction and Resummation to Integrate X-sections

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
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
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
|============>>
```

MATRIX

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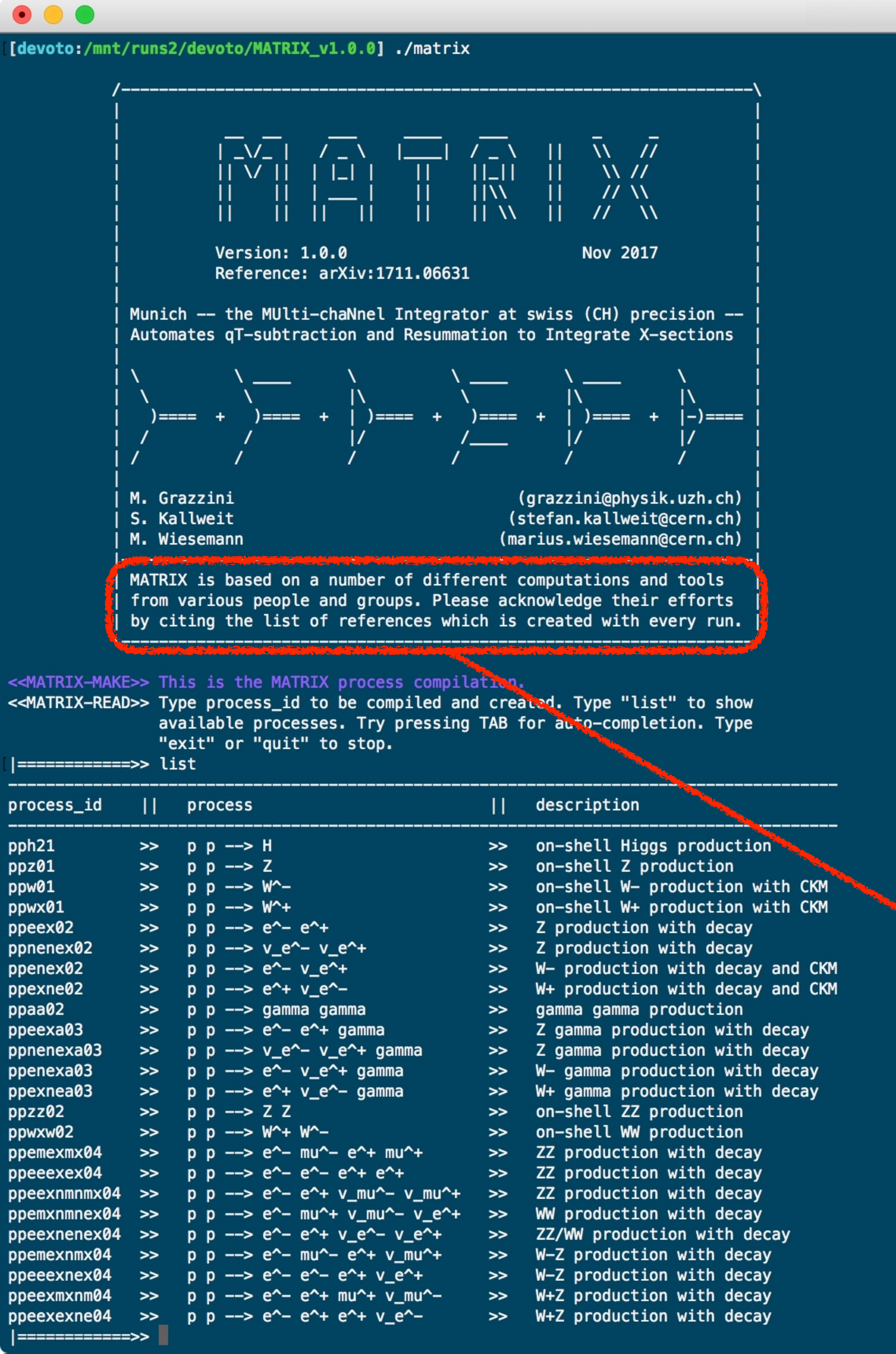
Computational framework which, implementing q_T subtraction, allows us to evaluate fully differential cross sections for a wide class of processes at hadron colliders ***where the final state is a color singlet*** *in next-to-next-to-leading order (NNLO) QCD.*

- *Munich (S. Kallweit);*
- *OpenLoops2 (F. Buccioni, J.N. Lang, J.Lindert, P. Maierhofer, S. Pozzorini, H. Zhang, M. F. Zoller);*
- *TDHPL, GiNaC, VVAMP, …*



MATRIX

[M.Grazzini, S. Kallweit, M. Wiesemann: arXiv 1711.06631]

WHAT ABOUT TOP PAIR PRODUCTION?

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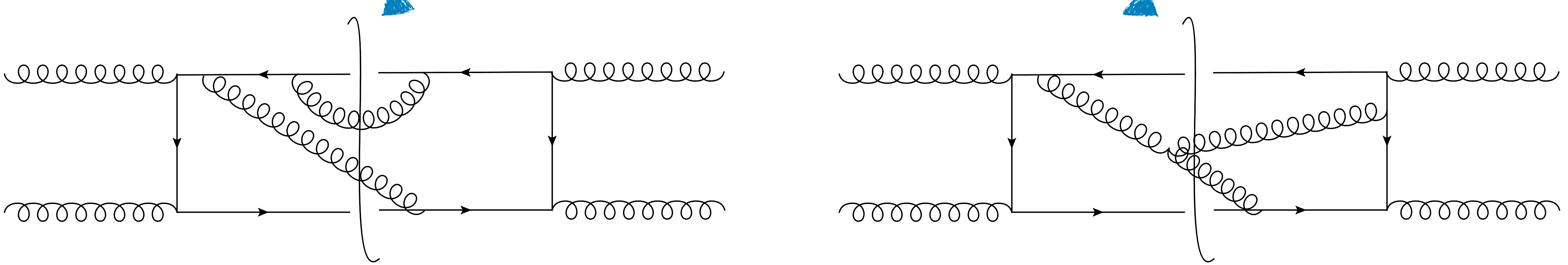
- *TDHPL, GiNaC, VVAMP, …*

q_T SUBTRACTION FOR COLORFUL MASSIVE FINAL STATES

With the inclusion of extra contributions, q_T subtraction formalism can be extended to **massive colored** final states.

- *Successfully applied to top pair production at NLO and NNLO considering only off-diagonal channels.* *[R. Bonciani, S. Catani, M. Grazzini, H. Sargsyan, A. Torre (2015)]*

The extension to colored final state requires the inclusion of additional final-state soft singularities.



… and so on…

Q_T SUBTRACTION FOR COLORFUL MASSIVE FINAL STATES

- What was missing to fully implement q_T subtraction at NNLO for top pair production?

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

HARD COLLINEAR COEFFICIENT ✘

Computable with NLO subtraction techniques. ✔

IR behaviour known from studies in q_t resummation
[A. Ferroglia, M. Neubert, B. D. Pecjak, L. L. Yang (2009)];
[Hai Tao Li, Chong Sheng Li, Ding Yu Shao, Li Lin Yang, Hua Xing Zu (2013)];
[S. Catani, M. Grazzini, A. Torre (2014)] ✔

Contains the integrations of the additional final-state soft singularities.
We recently completed their computation. *[S. Catani, SD, M.Grazzini, J.Mazzitelli, in preparation. See also R. Angeles-Martinez, M. Czakon, S. Sapeta (2018)]*

HARD COLLINEAR COEFFICIENT

Colourless final state

Colourless subtraction operator

Specified up to order α_s^2 in [S.Catani, L. Cieri, D. De Florian, G. Ferrera, M. Grazzini (2013)].

$$\mathcal{H} \propto \langle \tilde{M} | \tilde{M} \rangle$$

$$|\tilde{M}\rangle = (1 - I_C)\, |M\rangle$$

All loop renormalised virtual amplitude

Colourful final state

Additional soft radiative factor

$$\mathcal{H} \propto \langle \tilde{M} | \Delta | \tilde{M} \rangle$$

- We are only interested in the low q_T behaviour → soft limit;
- We need to integrate the **soft current** in the case of:
  - Double gluon emission; *[S.Catani, M.Grazzini (1999); M. Czakon (2011)]*
  - Light quark pair production; *[S.Catani, M.Grazzini (1999)]*
  - Gluon emission at one loop. *[I. Bierenbaum, M. Czakon, A. Mitov (2011); M. Czakon, A Mitov (2019)]*

HARD COLLINEAR COEFFICIENT – NLO

[S. Catani, M. Grazzini, A. Torre: arXiv 1408:4564]

Example: $t\bar{t}$ production at **NLO** within q_T subtraction formalism:

Computation of the soft contribution → *Integration of a suitably subtracted soft current.*

$$\int \frac{d^n k}{2\pi^{n-1}} \delta_+(k) \left| J_{sub}(k) \right|^2 e^{i \vec{b} \cdot \vec{k}_T}$$

- J_{sub} is the soft current after a proper subtraction of the (known) colourless contribution:

$$\left| J_{sub}(k) \right|^2 = \sum_{j=3,4} \frac{m_j^2}{(p_j \cdot k)^2} \mathbf{T}_j^2 + \frac{2\, p_3 \cdot p_4}{p_3 \cdot k\, p_4 \cdot k} \mathbf{T}_3 \cdot \mathbf{T}_4 + \sum_{\substack{i=1,2 \\ j=3,4}} \frac{2}{p_i \cdot k} \left(\frac{p_i \cdot p_j}{p_j \cdot k} - \frac{p_1 \cdot p_2}{(p_1 + p_2) \cdot k} \right) \mathbf{T}_i \cdot \mathbf{T}_j$$

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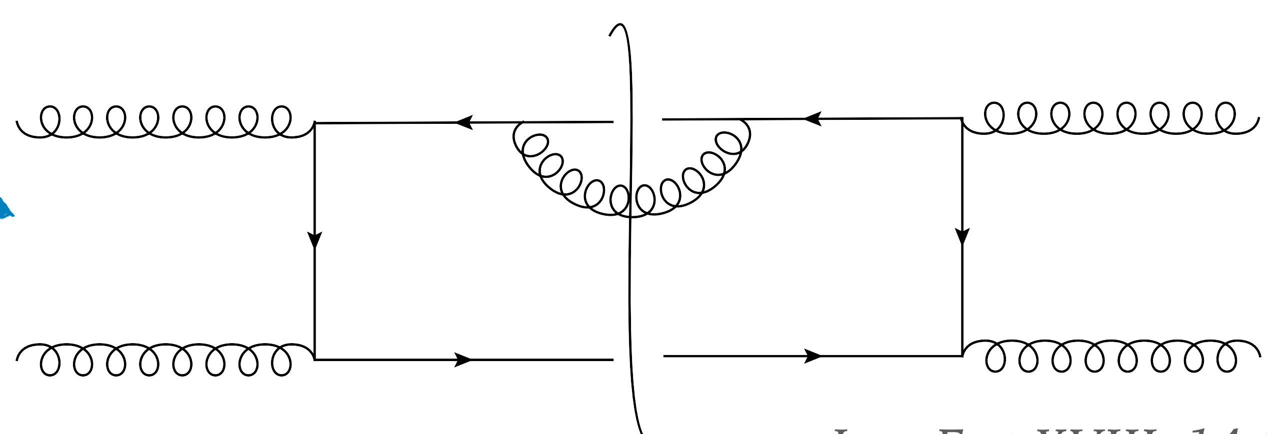

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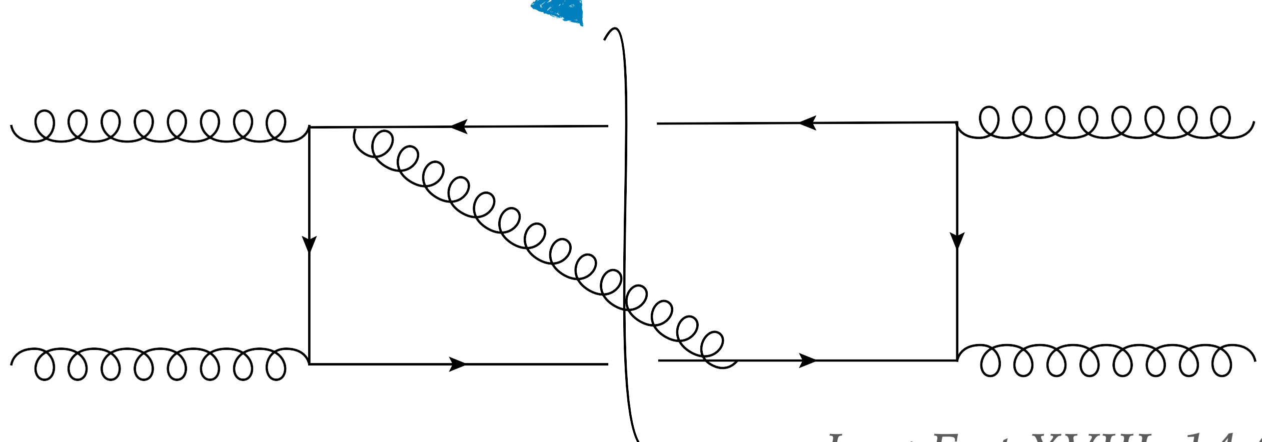

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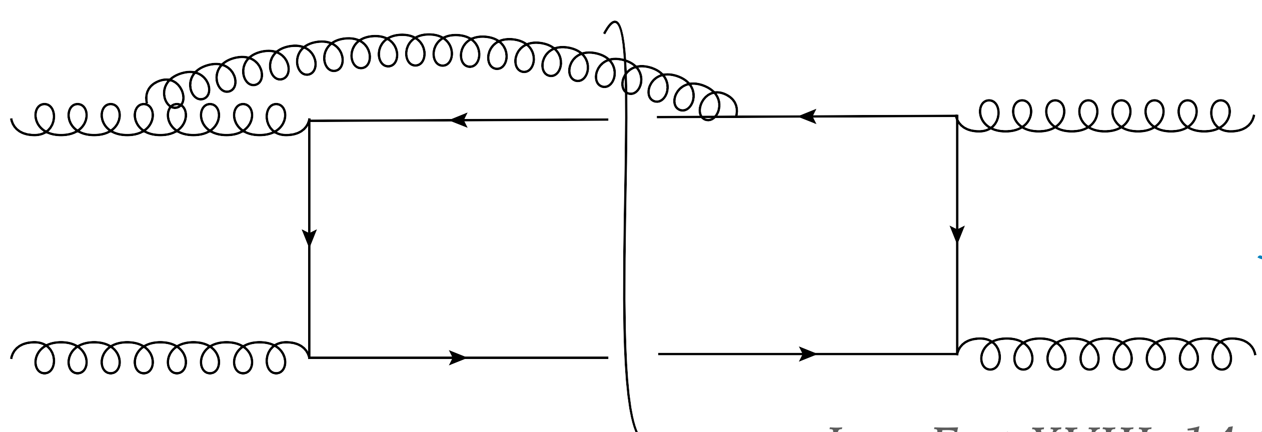


HARD COLLINEAR COEFFICIENT – NNLO

[S. Catani, SD, M.Grazzini, J.Mazzitelli, in preparation.]

NNLO: the soft current is more complicated. Contributions from:

- Light quark pair production:

$$\int \frac{d^n k_1}{2\pi^{n-1}} \frac{d^n k_2}{2\pi^{n-1}} \delta_+(k_1)\delta_+(k_2) \left| J_{sub}^{NNLO(q\bar{q})}(k_1,k_2) \right|^2 e^{i\vec{b}\cdot\left(\vec{k}_{T1}+\vec{k}_{T2}\right)}$$

[S.Catani, M.Grazzini (1999)]

- Double gluon emission:

$$\int \frac{d^n k_1}{2\pi^{n-1}} \frac{d^n k_2}{2\pi^{n-1}} \delta_+(k_1)\delta_+(k_2) \left| J_{sub}^{NNLO(gg)}(k_1,k_2) \right|^2 e^{i\vec{b}\cdot\left(\vec{k}_{T1}+\vec{k}_{T2}\right)}$$

[S.Catani, M.Grazzini (1999); M. Czakon (2011)]

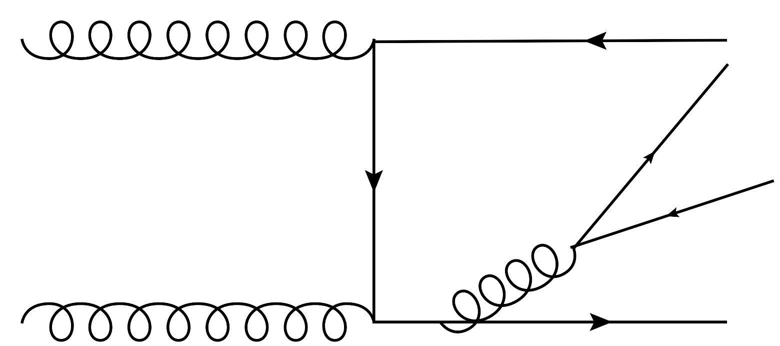
- One gluon emission at 1 loop:

$$\int \frac{d^n k}{2\pi^{n-1}} \delta_+(k) \left| J_{sub}^{NNLO(1L)}(k) \right|^2 e^{i\vec{b}\cdot\vec{k}_T}$$

[I. Bierenbaum, M. Czakon, A. Mitov (2011)]

$$\left| J_{sub}^{NNLO(q\bar{q})}(k_1,k_2) \right|^2 = J_{\mu,sub}^{NLO}(k_1+k_2)\Pi^{\mu\nu}(k_1,k_2) J_{\nu,sub}^{NLO}(k_1+k_2)$$

$$\Pi^{\mu\nu}(k_1,k_2) = \frac{T_R(-g^{\mu\nu}k_1\cdot k_2 + k_1^\mu k_2^\nu + k_1^\nu k_2^\mu)}{(k_1\cdot k_2)^2}$$



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[S.Catani, M.Grazzini (1999)]

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[S.Catani, M.Grazzini (1999); M. Czakon (2011)]

- One gluon emission at 1 loop:

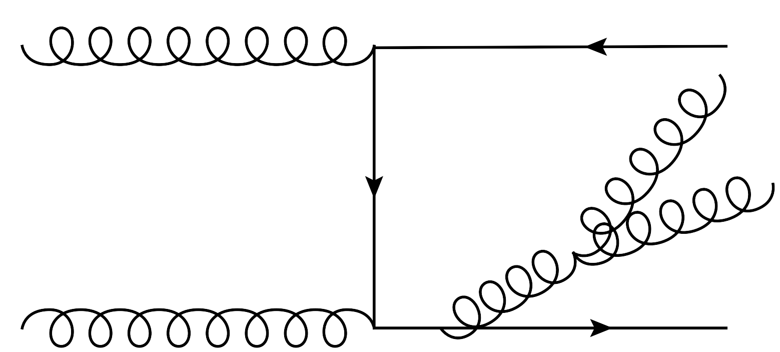
$$\int \frac{d^nk}{2\pi^{n-1}}\delta_+(k)\left|J_{sub}^{NNLO(1L)}(k)\right|^2 e^{i\vec{b}\cdot\vec{k}_T}$$

[I. Bierenbaum, M. Czakon, A. Mitov (2011)]

$$\left|J_{sub}^{NNLO(gg)}(k_1,k_2)\right|^2 = \frac{1}{2}\left\{\mathbf{J}^2(k_1),\mathbf{J}^2(k_2)\right\} - C_a\sum_{i,j=1}^{n}\mathbf{T}_i\cdot\mathbf{T}_j\,\mathcal{S}_{ij}(k_1,k_2)$$

Iteration of NLO results — *New part*

$$\mathcal{S}_{ij}(k_1,k_2) = \mathcal{S}_{ij}^{m=0}(k_1,k_2) + \left(m_i^2\mathcal{S}_{ij}^{m\neq0}(k_1,k_2) + m_j^2\mathcal{S}_{ji}^{m\neq0}(k_1,k_2)\right)$$



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[S.Catani, M.Grazzini (1999); M. Czakon (2011)]

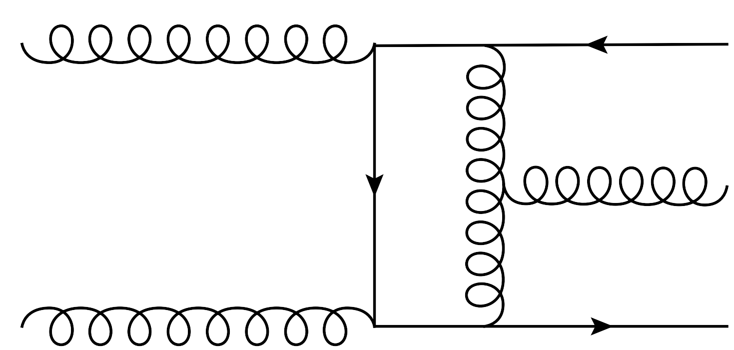
- One gluon emission at 1 loop:

$$\int \frac{d^n k}{2\pi^{n-1}} \delta_+(k) \left| J_{sub}^{NNLO(1L)}(k) \right|^2 e^{i\vec{b}\cdot\vec{k}_T}$$

[I. Bierenbaum, M. Czakon, A. Mitov (2011)]

$$\left| J_{sub}^{NNLO(1L)}(k) \right|^2 = \langle M_a^{(0)}(n+1;k) | M_a^{(1)}(n+1;k) \rangle + c.c.$$

$$\begin{aligned}\langle M_a^{(0)}(n+1;k) | M_a^{(1)}(n+1;k) \rangle + c.c. = & -4\pi\alpha_S \mu^{2\epsilon} \\ & \times \Bigg\{ 2C_A \sum_{i\neq j=1}^{n} \left(e_{ij} - e_{ii}\right) R_{ij} \langle M^{(0)}(n) | T_i \cdot T_j | M^{(0)}(n) \rangle \\ & -4\pi \sum_{i\neq j\neq k=1}^{n} e_{ik} I_{ij} \langle M^{(0)}(n) | f^{abc} T_i^a T_j^b T_k^c | M^{(0)}(n) \rangle \\ & + \left(\sum_{i\neq j=1}^{n} e_{ij} \langle M^{(0)}(n) | T_i \cdot T_j | M^{(1)}(n) \rangle + c.c. \right) \\ & + \left(\sum_{i=1}^{n} \mathscr{C}_i e_{ii} \langle M^{(0)}(n) | M^{(1)}(n) \rangle + c.c. \right) \Bigg\}\end{aligned}$$

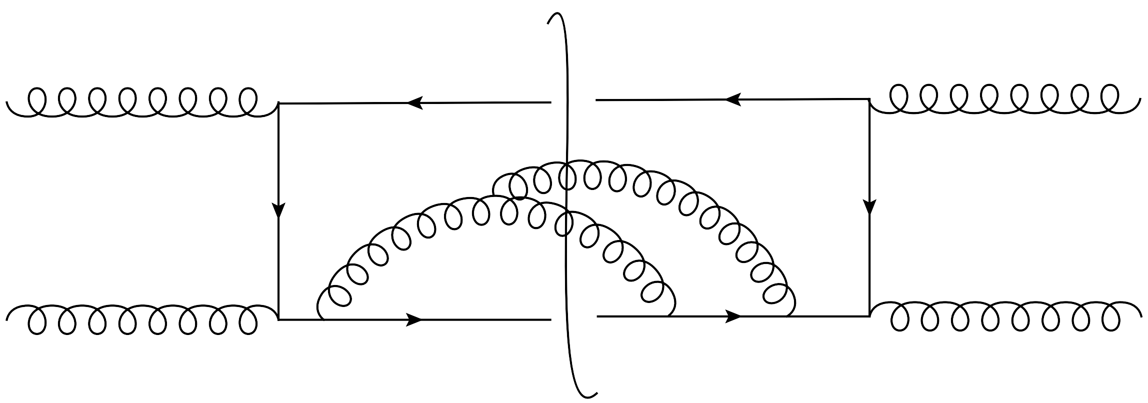


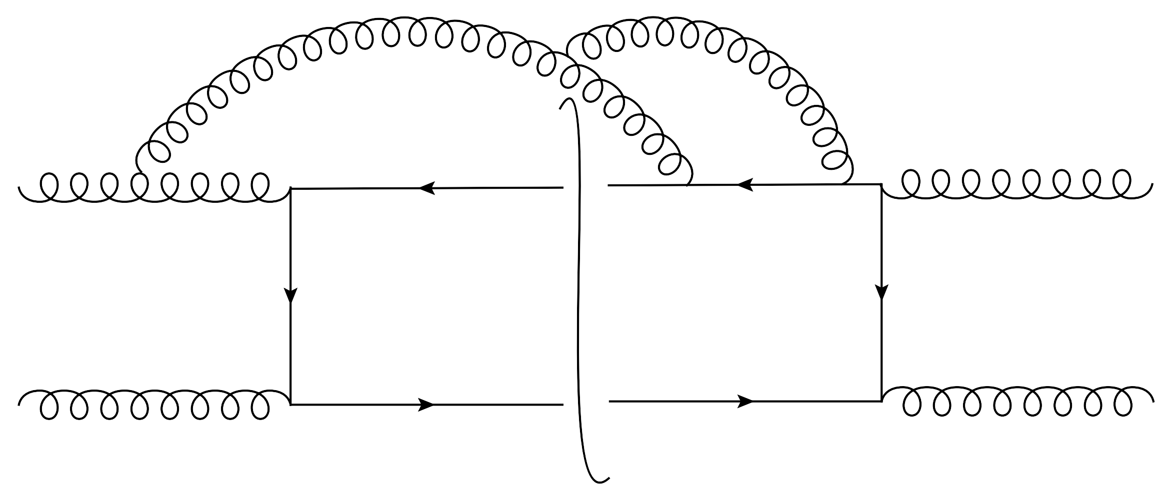
HARD COLLINEAR COEFFICIENT - NNLO

[S. Catani, SD, M.Grazzini, J.Mazzitelli, in preparation.]

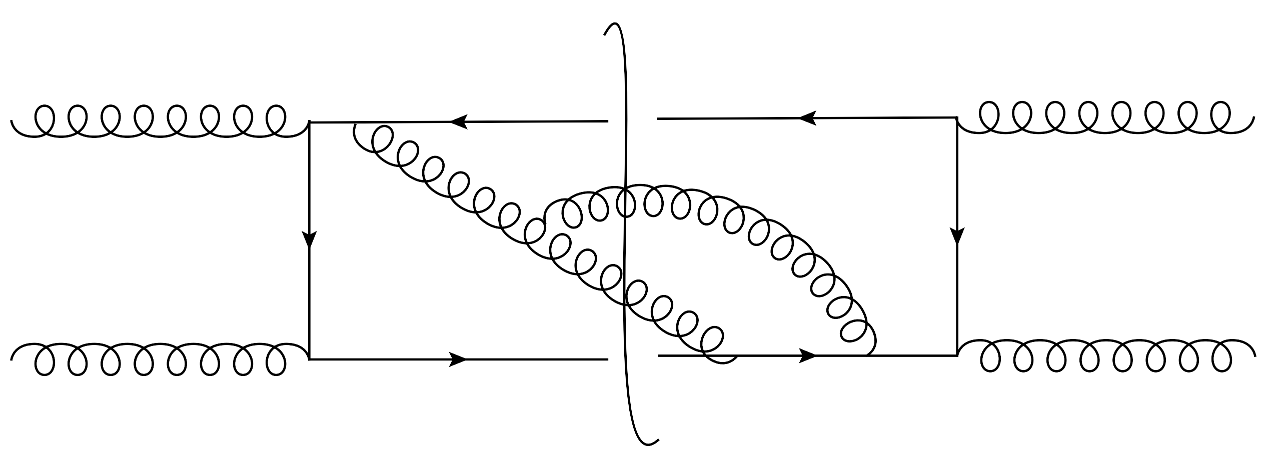
We computed all the needed integrals:

- Analytic expression for $\mathbf{T}_i\mathbf{T}_j$,$\mathbf{T}_j\mathbf{T}_j$ contributions:



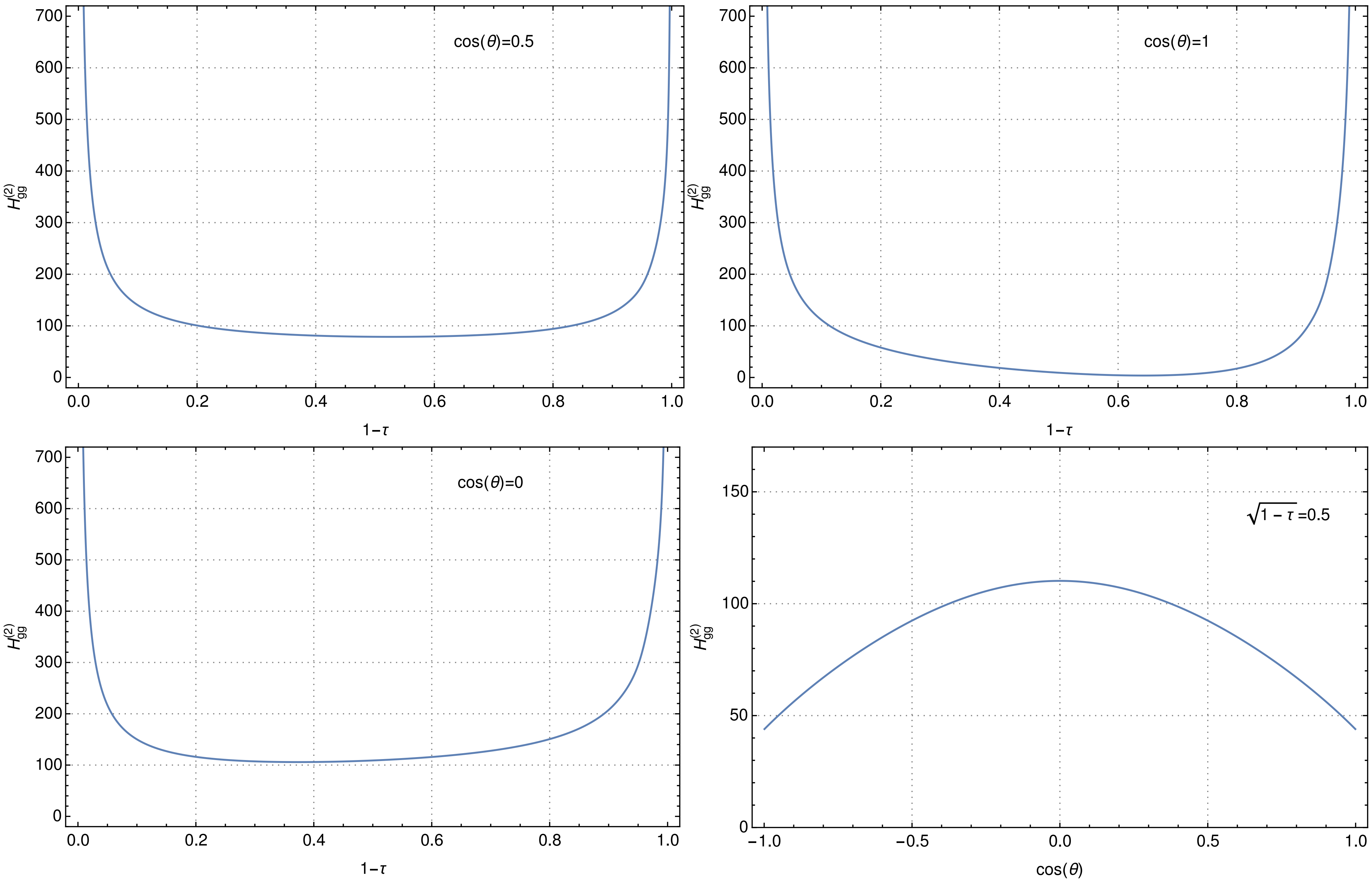


- Numerical expression for some pieces of the $\mathbf{T}_3\mathbf{T}_4$ contribution:



HARD COLLINEAR COEFFICIENT – NNLO

[S. Catani, SD, M.Grazzini, J.Mazzitelli, in preparation.]



$$H^{(2)}_{gg}$$

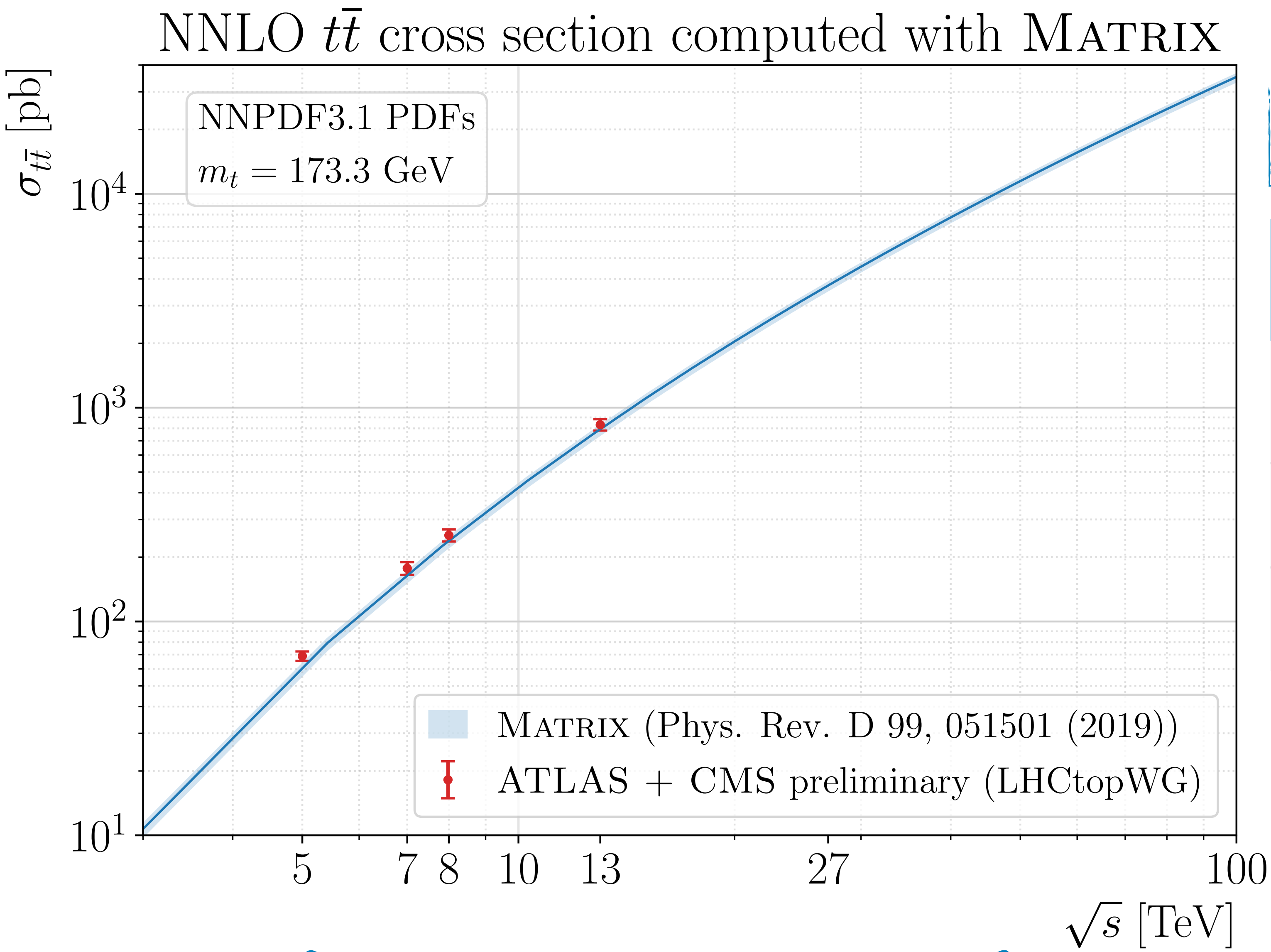
$$\tau = 4m_t^2/s$$

$\cos\theta$
scattering angle

The completion of this calculation allowed the implementation of top pair production in the **MATRIX** framework!

INCLUSIVE CROSS SECTION

[S. Catani, SD, M. Grazzini ,S.Kallweit, J. Mazzitelli, H. Sargsyan (2019)]



Excellent agreement with TOP++!

σ_{NNLO} [pb]	MATRIX	TOP++
8 TeV	$238.5(2)^{+3.9\%}_{-6.3\%}$	$238.6^{+4\%}_{-6.3\%}$
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

$$\mu_0 = m_t$$

$$\frac{1}{2}\mu_0 < \mu_F, \mu_R < 2\mu_0 \qquad \frac{1}{2} < \frac{\mu_F}{\mu_R} < 2$$

Per-mille accuracy in ~1000 CPU days

DIFFERENTIAL DISTRIBUTIONS

[S. Catani, SD, M. Grazzini ,S.Kallweit, J. Mazzitelli (2019)]

- **We computed single and double differential distributions;**
- **We compared with recent measurements from CMS in the leptons+jet channels** *[CMS-TOP-17-002]*.

Renormalization and factorization scales, μ_R and μ_F, should be chosen of the order of the characteristic hard scale:

Hard scale	
Total cross section	m_t
Rapidity distribution	m_t
Invariant mass distribution	$m_{t\bar{t}}$
Transverse momentum distribution	m_T

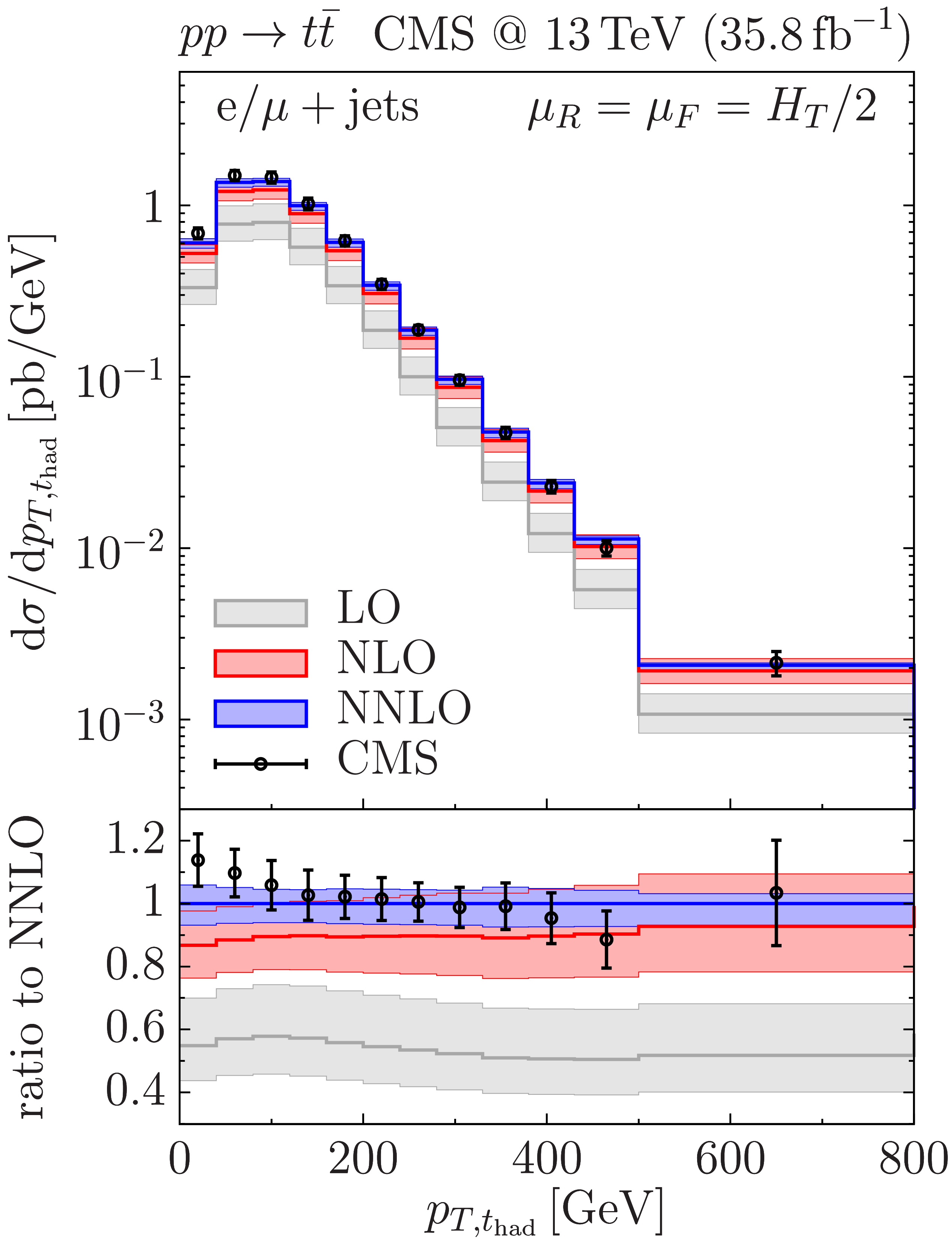
→ The dynamical scale $\mu_0 = \frac{1}{2} H_T = \frac{1}{2}(m_{T,t} + m_{T,\bar{t}})$ is a good approximation of all these scales.

The comparison with CMS is performed:

- Without cuts (extrapolation to parton level in the inclusive phase space);
- Multiplying our predictions by 0.438 (semileptonic BR of the $t\bar{t}$ pair) times 2/3 (only electron and muons).

SINGLE DIFFERENTIAL DISTRIBUTIONS

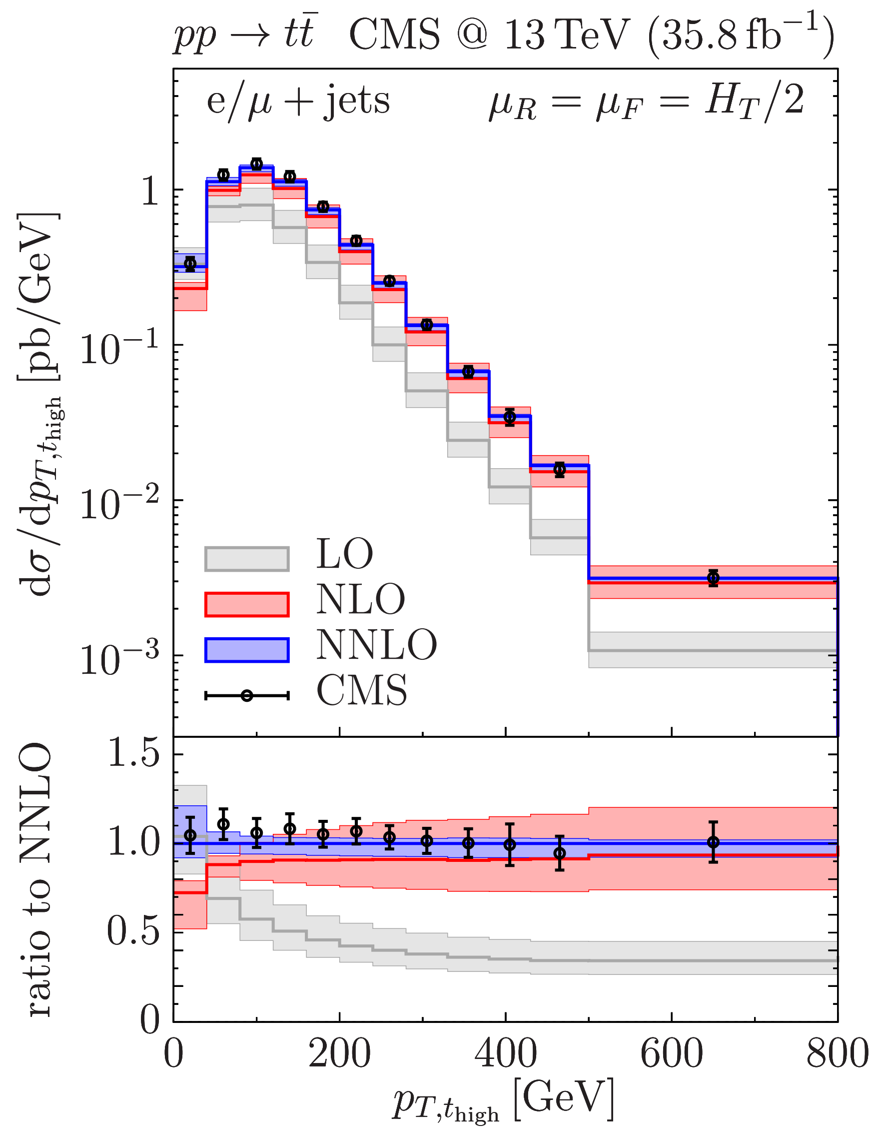
[S. Catani, SD, M. Grazzini ,S.Kallweit, J. Mazzitelli (2019)]

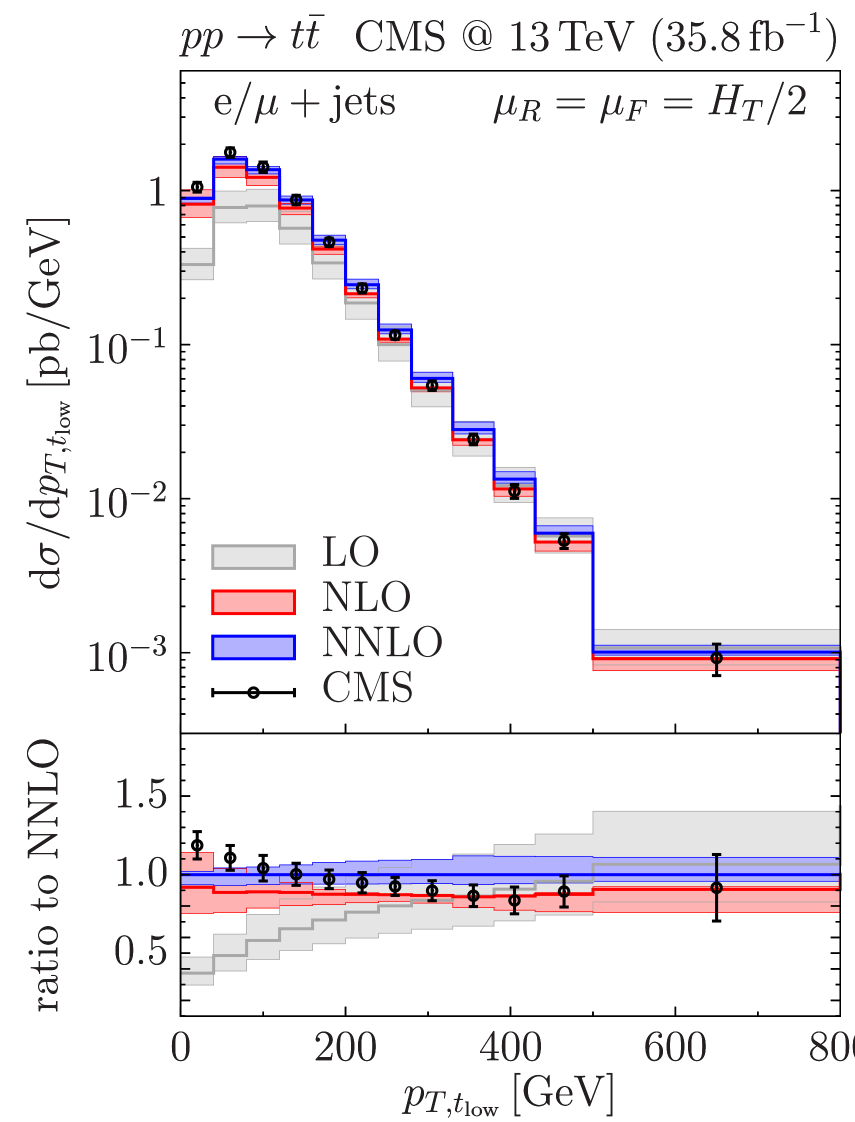


- LO and NLO bands do not overlap (consistent with total cross sections),
- NLO and NNLO bands overlap, suggesting convergence of the perturbative expansion;
- Measured distribution is slightly softer than the theoretical prediction, as already observed in several analyses;
- Data and theory are consistent within uncertainties.

SINGLE DIFFERENTIAL DISTRIBUTIONS

[S. Catani, SD, M. Grazzini ,S.Kallweit, J. Mazzitelli (2019)]

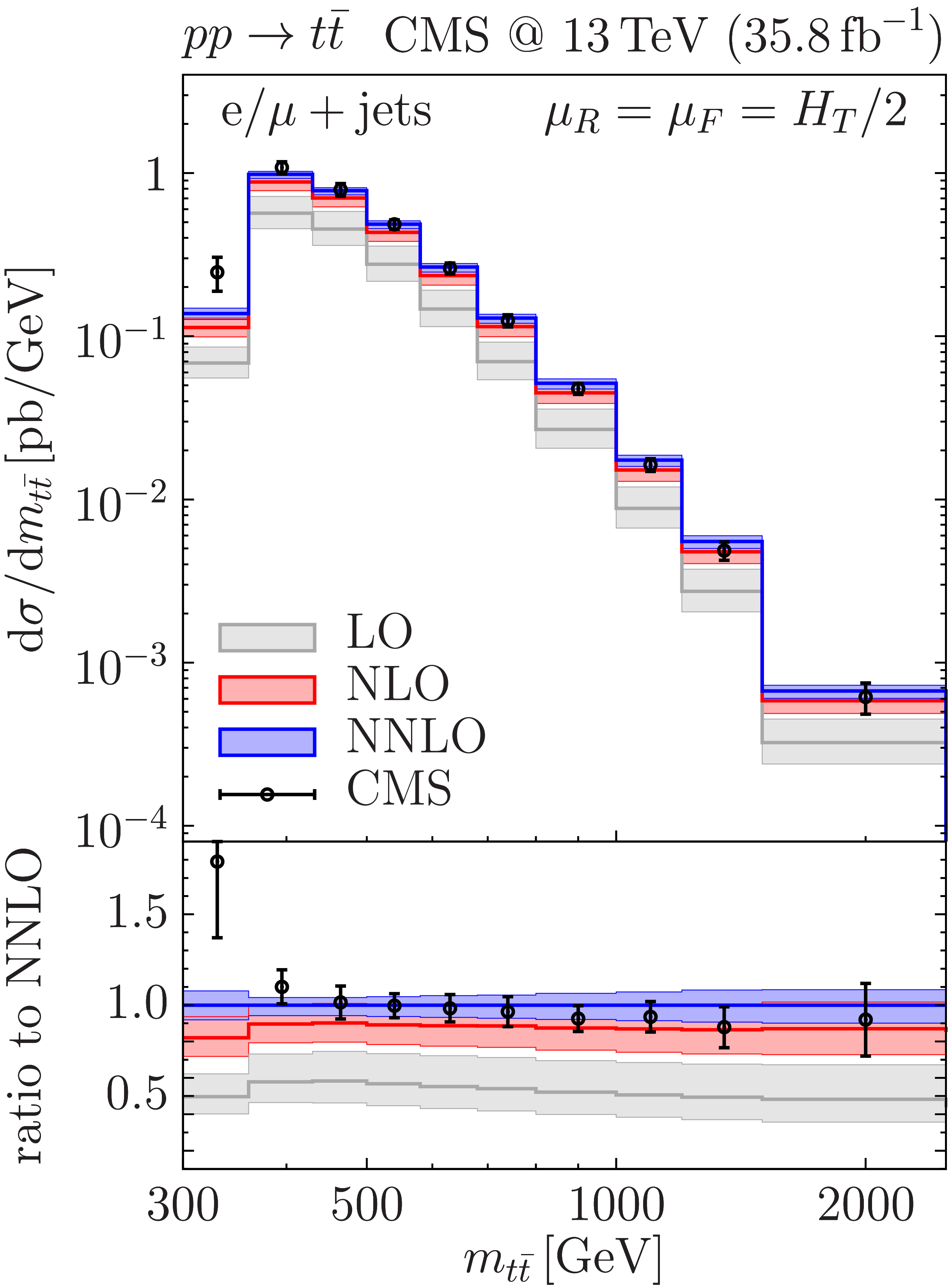




- Higher order corrections have big effect on the shape:
  - $p_{T,t_{high}}$: at small p_T the p_T of the pair is forced to be small;
  - $p_{T,t_{low}}$: the effect is spread over the entire p_T region.

SINGLE DIFFERENTIAL DISTRIBUTIONS

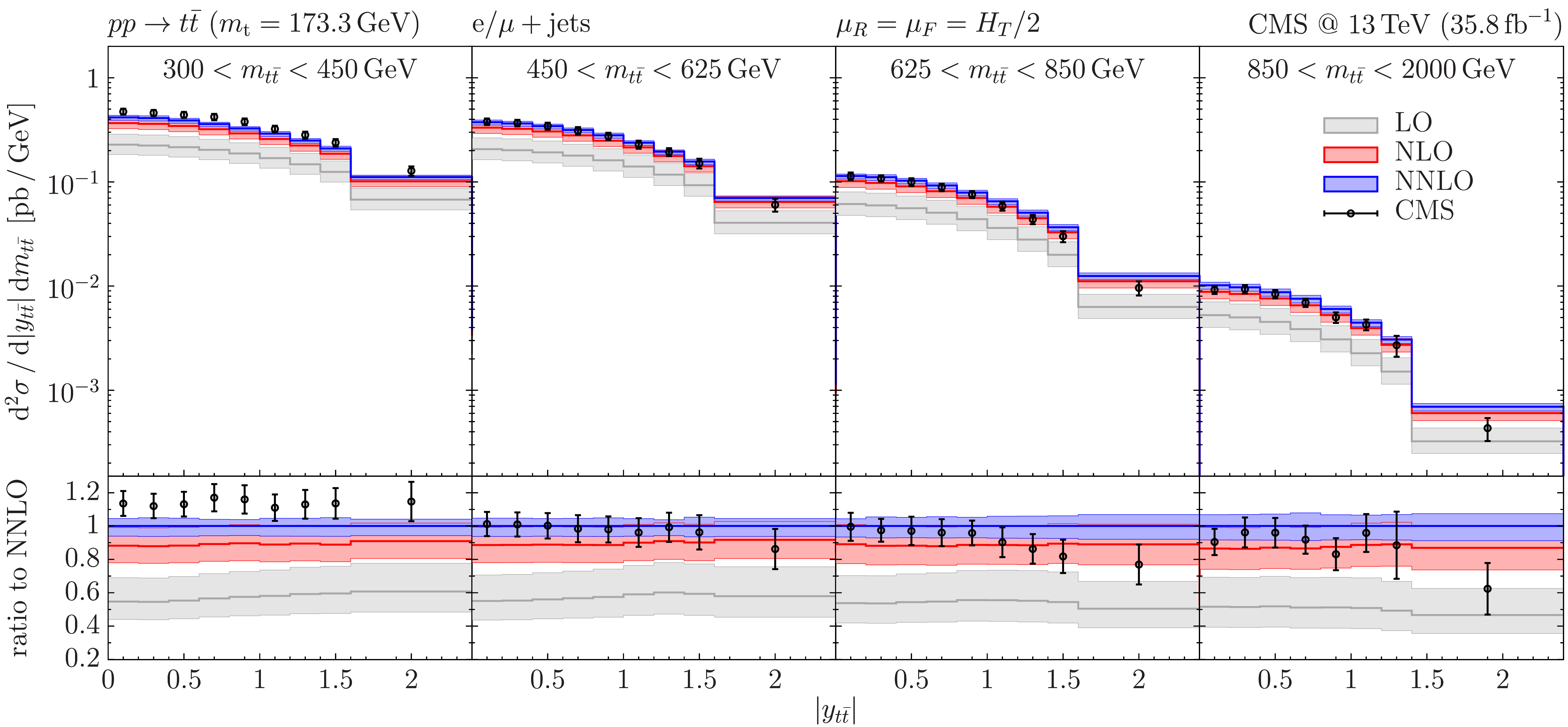
[S. Catani, SD, M. Grazzini ,S.Kallweit, J. Mazzitelli (2019)]



- Good convergence of the perturbative expansion;
- Good agreement with the data, neglecting the first bin. Possible causes:
  - Threshold region: issues in experimental extrapolation?
  - Smaller top mass?

DOUBLE DIFFERENTIAL DISTRIBUTIONS

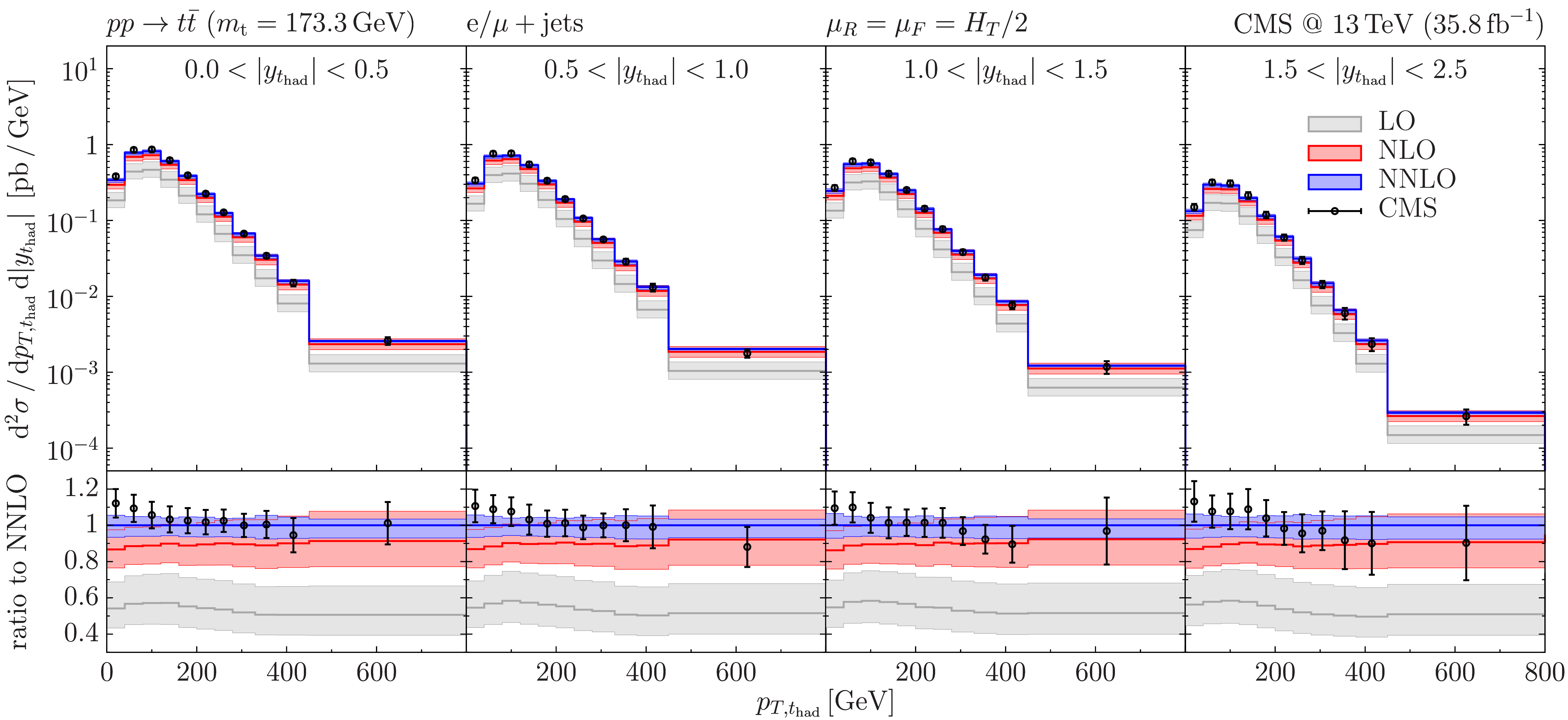
[S. Catani, SD, M. Grazzini ,S.Kallweit, J. Mazzitelli (2019)]



- First bin in the $m_{t\bar{t}}$ distribution overshoots again the theoretical prediction, smaller effect due to larger bin size.
- Relatively uniform impact of radiative corrections in both variables.

DOUBLE DIFFERENTIAL DISTRIBUTIONS

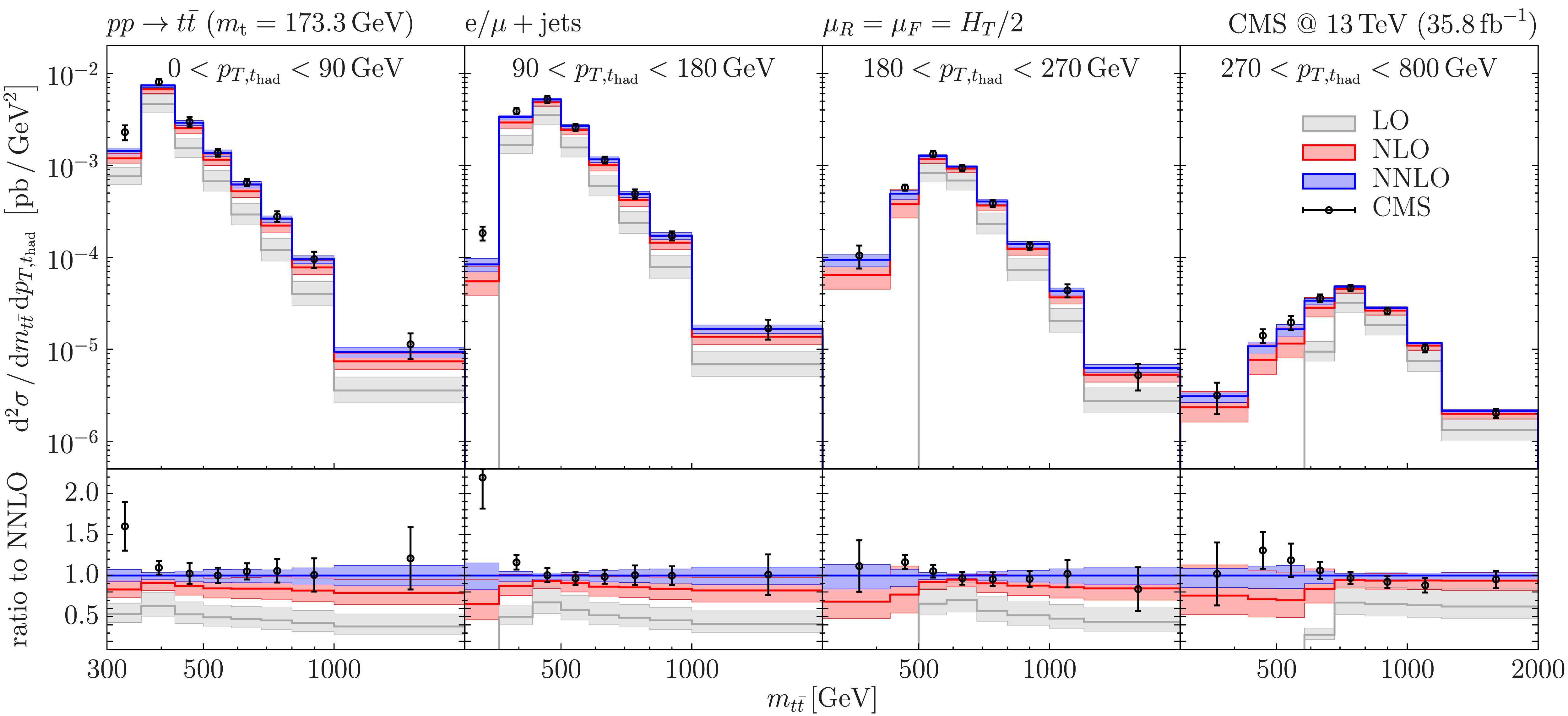
[S. Catani, SD, M. Grazzini ,S.Kallweit, J. Mazzitelli (2019)]



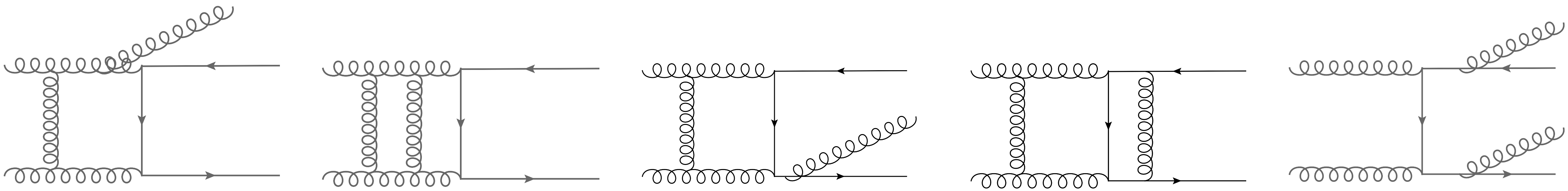
➤ As for single differential distributions, p_T data softer than NNLO.

DOUBLE DIFFERENTIAL DISTRIBUTIONS

[S. Catani, SD, M. Grazzini ,S.Kallweit, J. Mazzitelli (2019)]

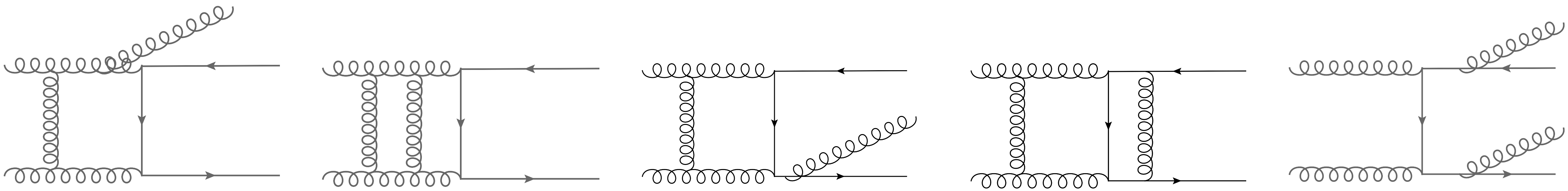


- Kinematical boundary at LO: $m_{t\bar{t}} > 2m_{T\,min}$;
- Below the threshold, NLO (NNLO) is effectively LO (NLO) → larger uncertainties;
- NNLO nicely describes the data except near threshold.



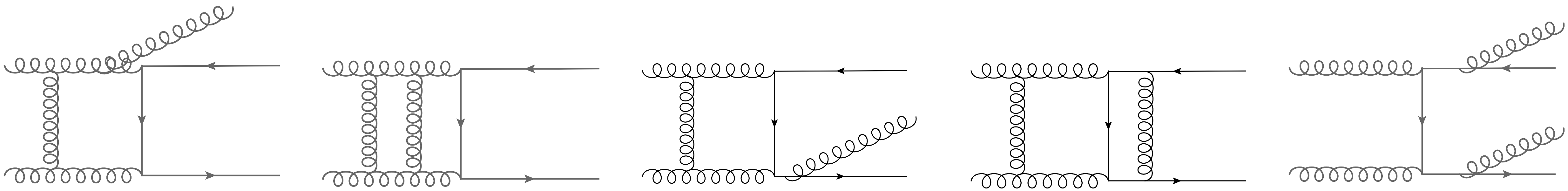
SUMMARY & OUTLOOK

- We have presented a new computation for top-quark production at NNLO;
- First complete application of q_T-subtraction formalism for massive colourful final state at NNLO;
- The process has been implemented into the MATRIX framework;
- Results for NNLO inclusive and multi-differential cross section: NNLO differential distributions in 1000-2000 CPU days.



SUMMARY & OUTLOOK

- New public MATRIX release with the inclusion of $t\bar{t}$ production;
- Improve NNLO QCD:
  - NLO EW?
  - Inclusion of top decays?
- Extend to different processes:
  - $b\bar{b}$ production?
  - $t\bar{t}$ + colorless?



SUMMARY & OUTLOOK

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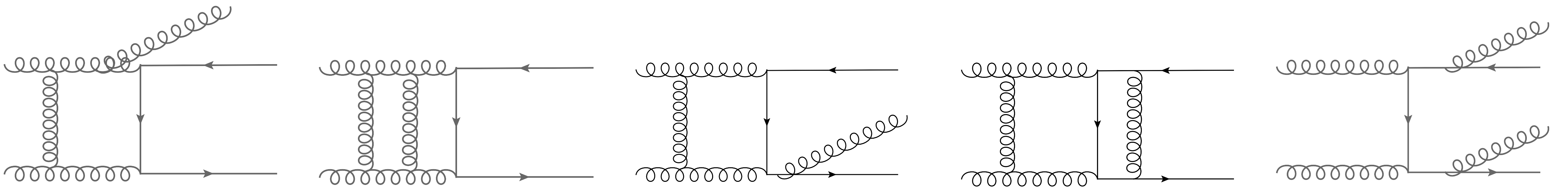
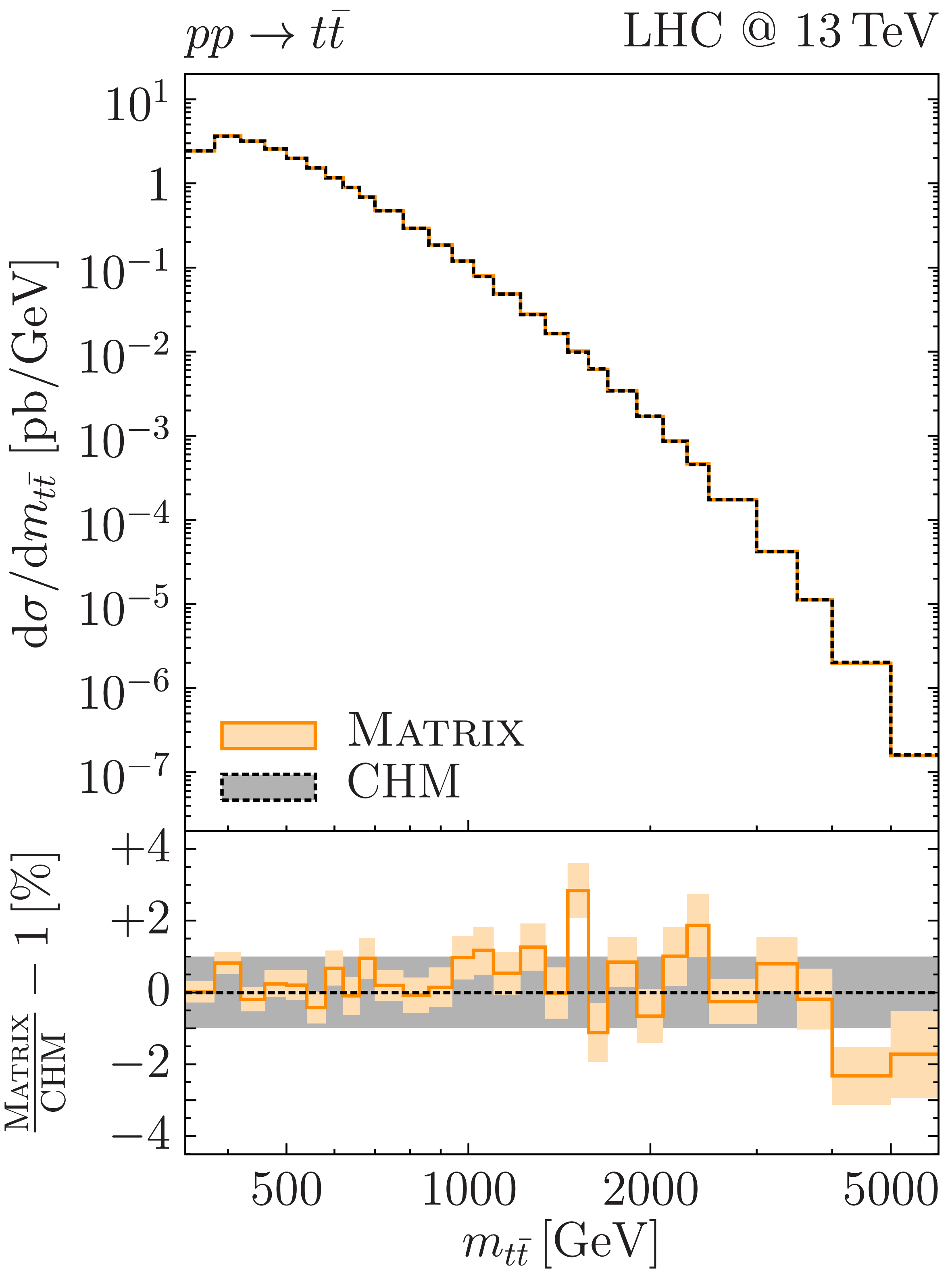
THANKS!

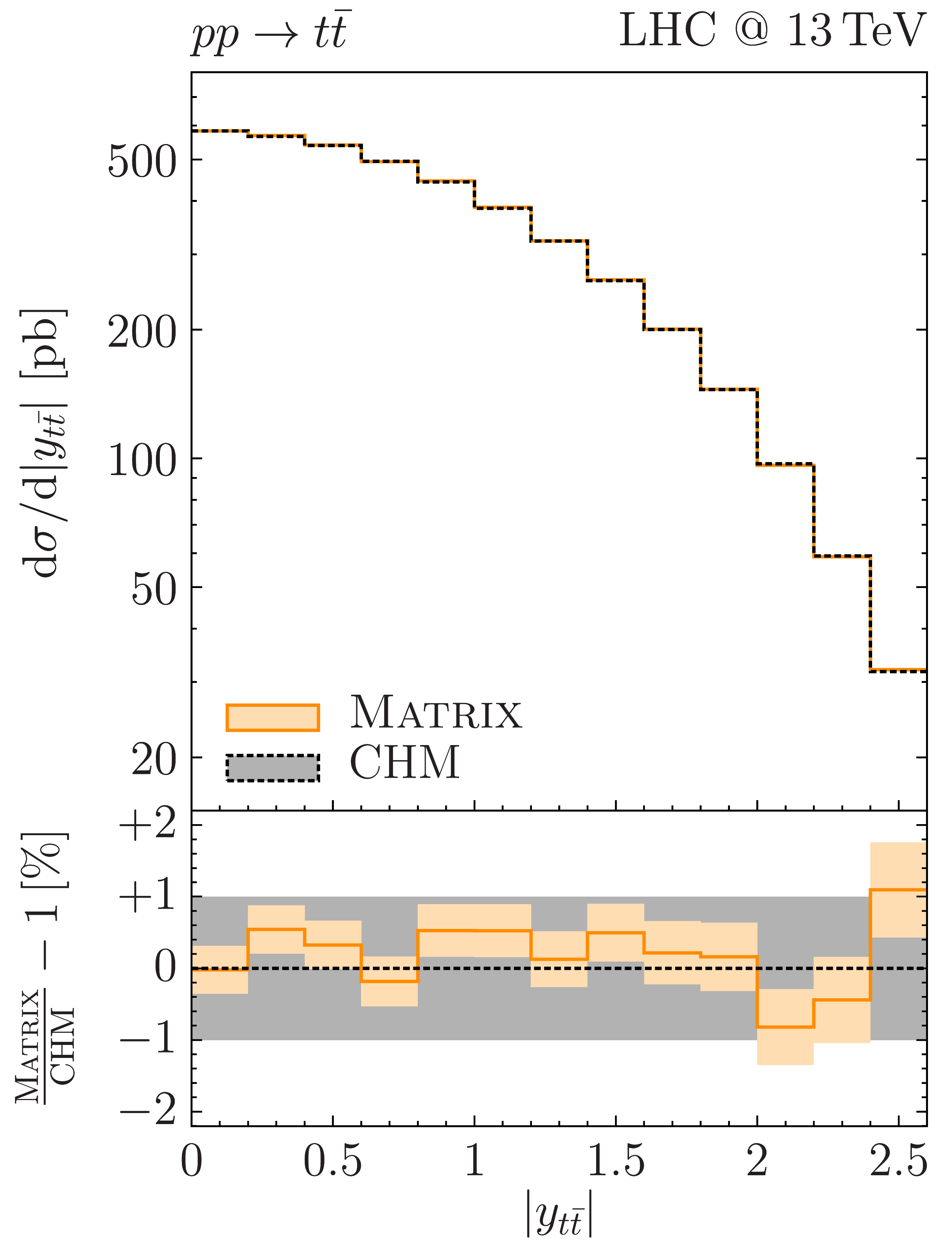


BACKUP SLIDES

COMPARISON TO EXISTING RESULTS

CHM: [M. Czakon, D. Heymes, A. Mitov (2017)]





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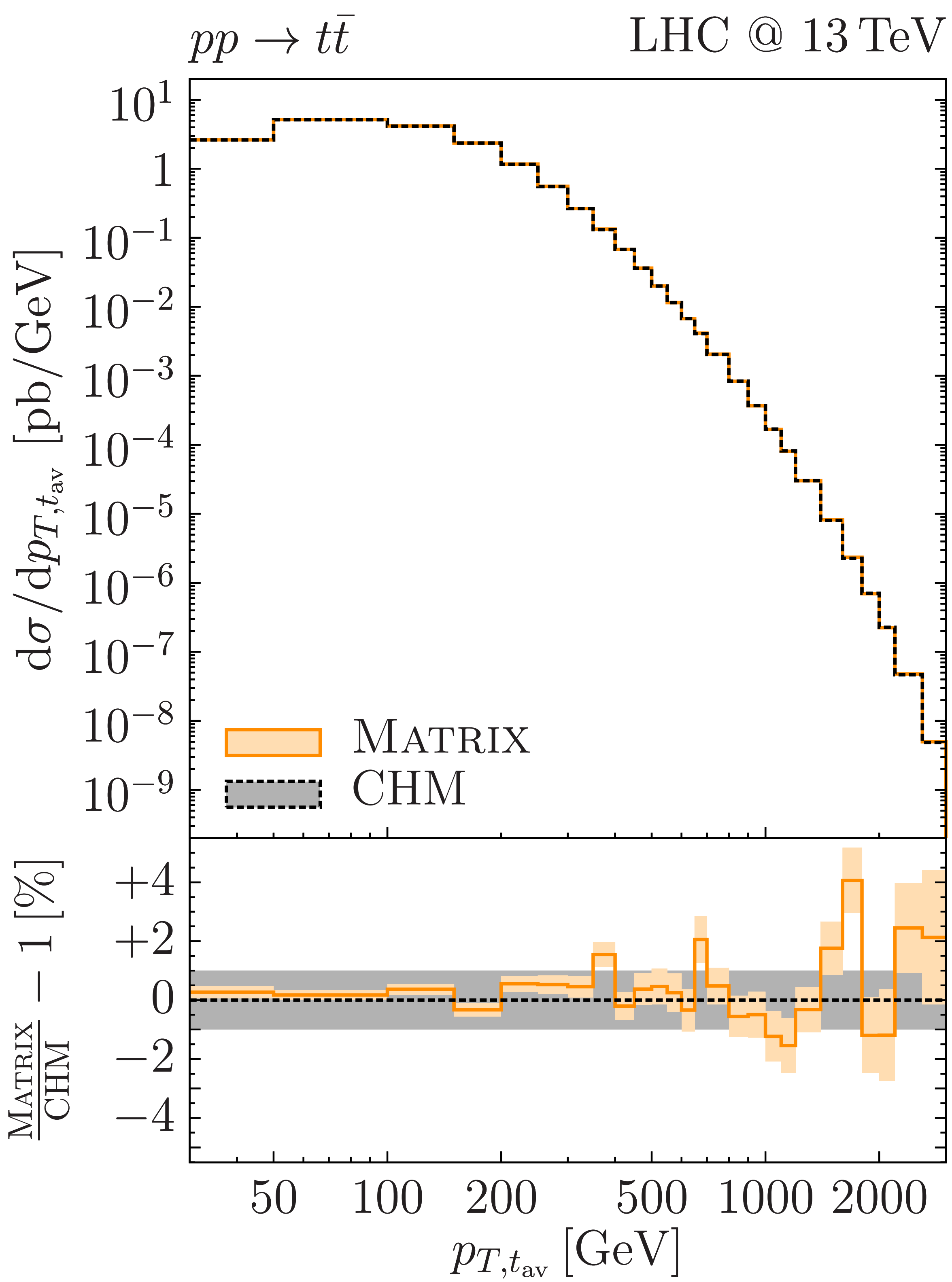
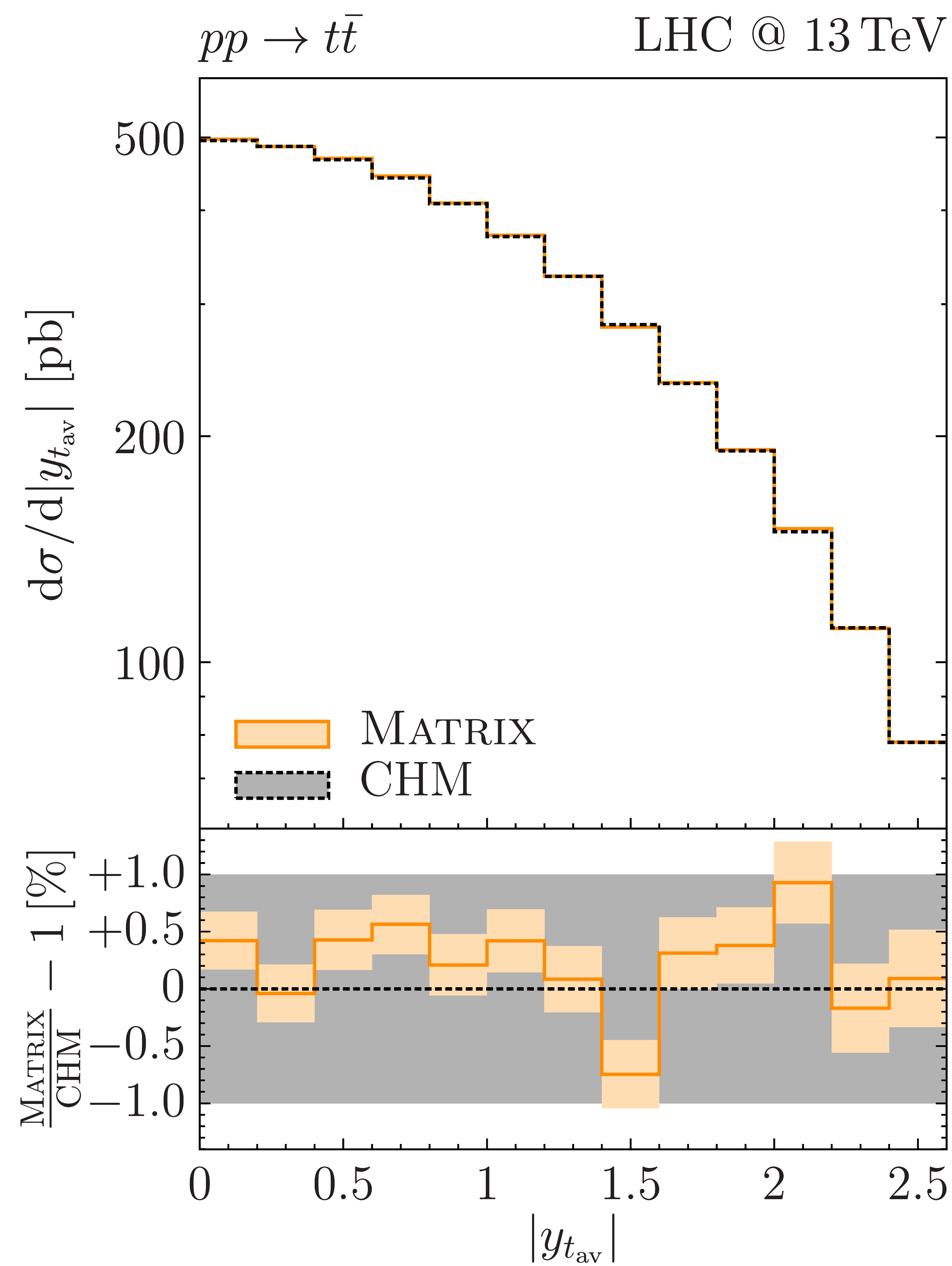
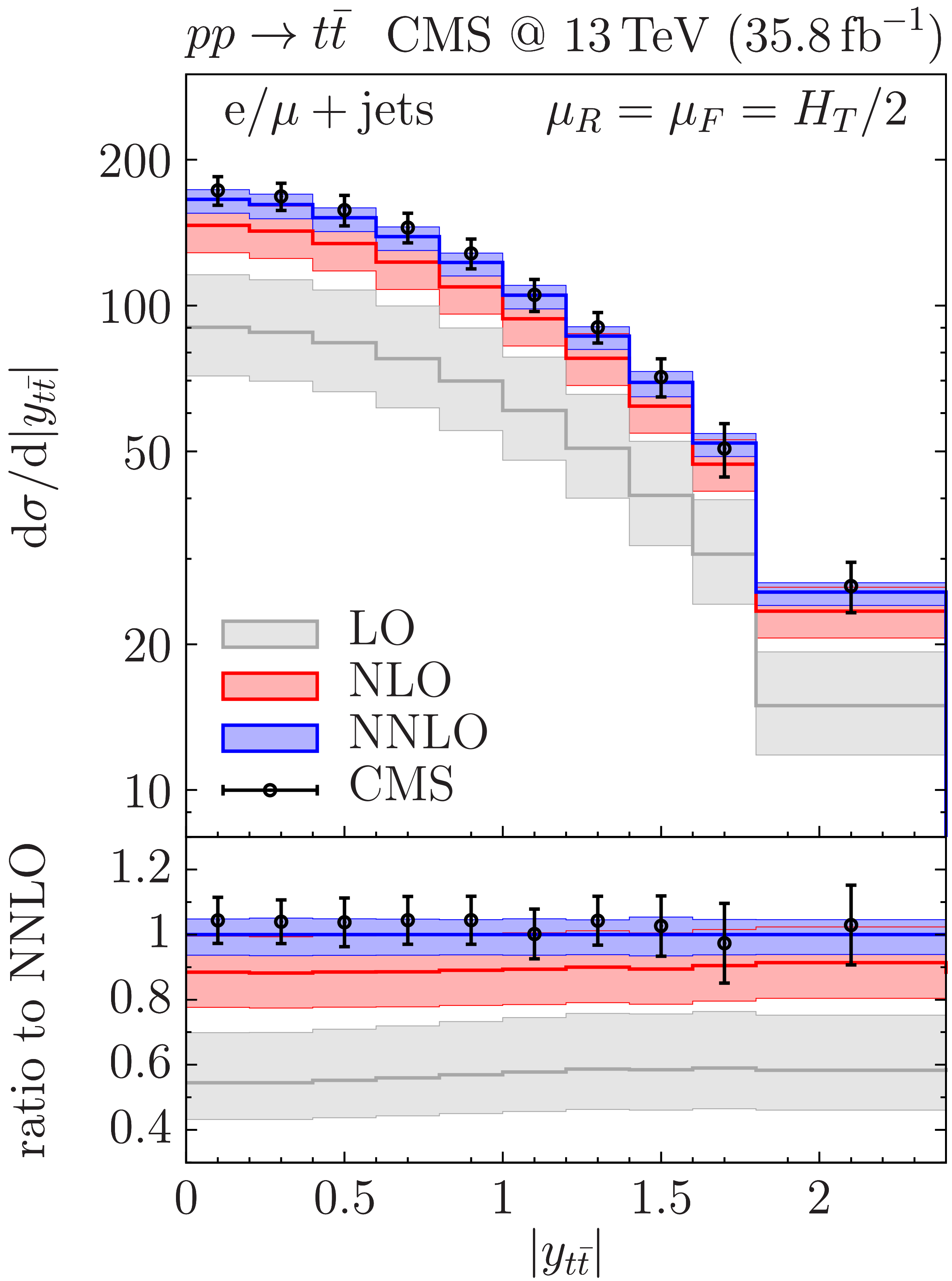




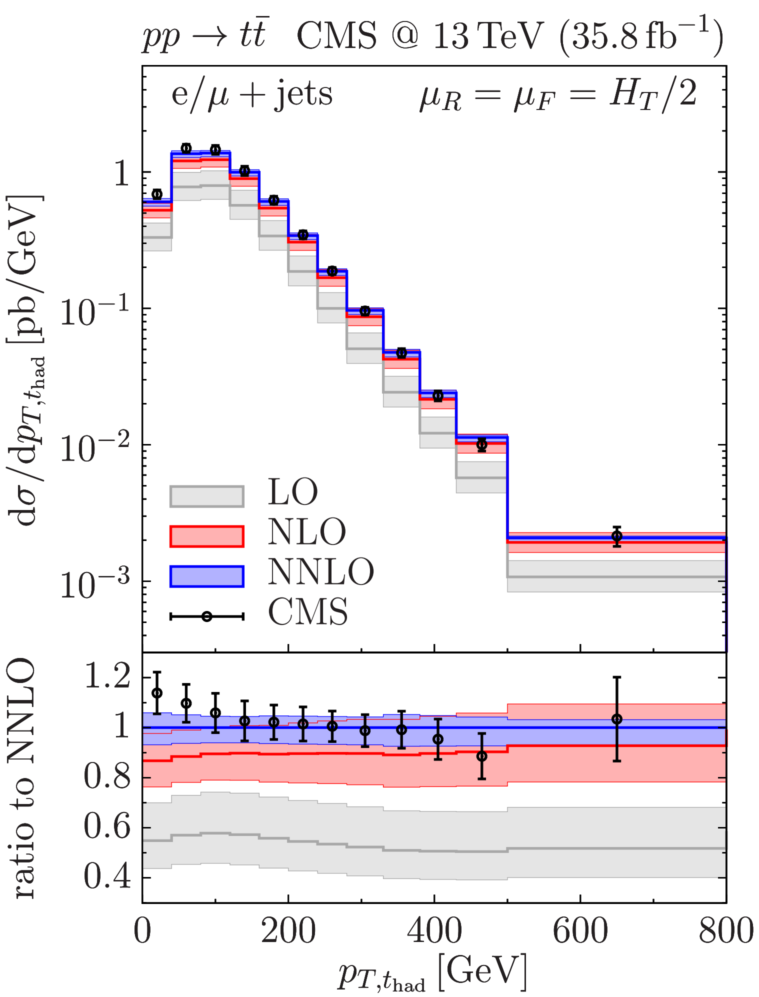
MORE DISTRIBUTIONS



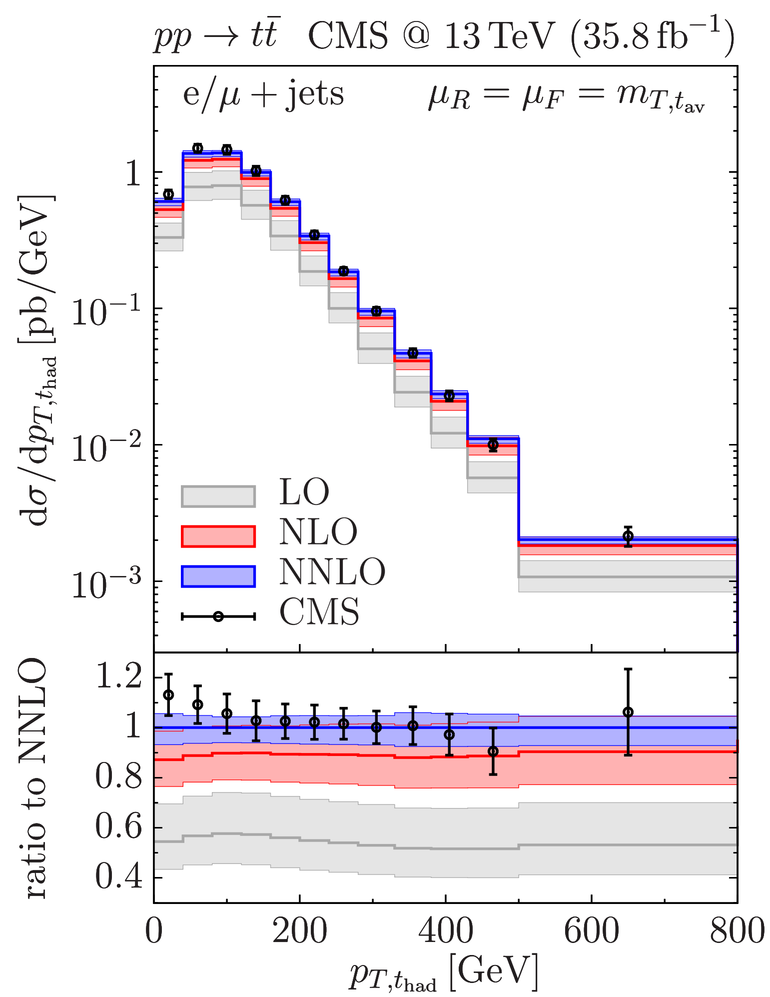
- LO and NLO bands do not overlap (consistent with total cross sections),
- NLO and NNLO bands overlap, suggesting convergence of the perturbative expansion;
- Good agreement data-theory.

DIFFERENT SCALE CHOICES

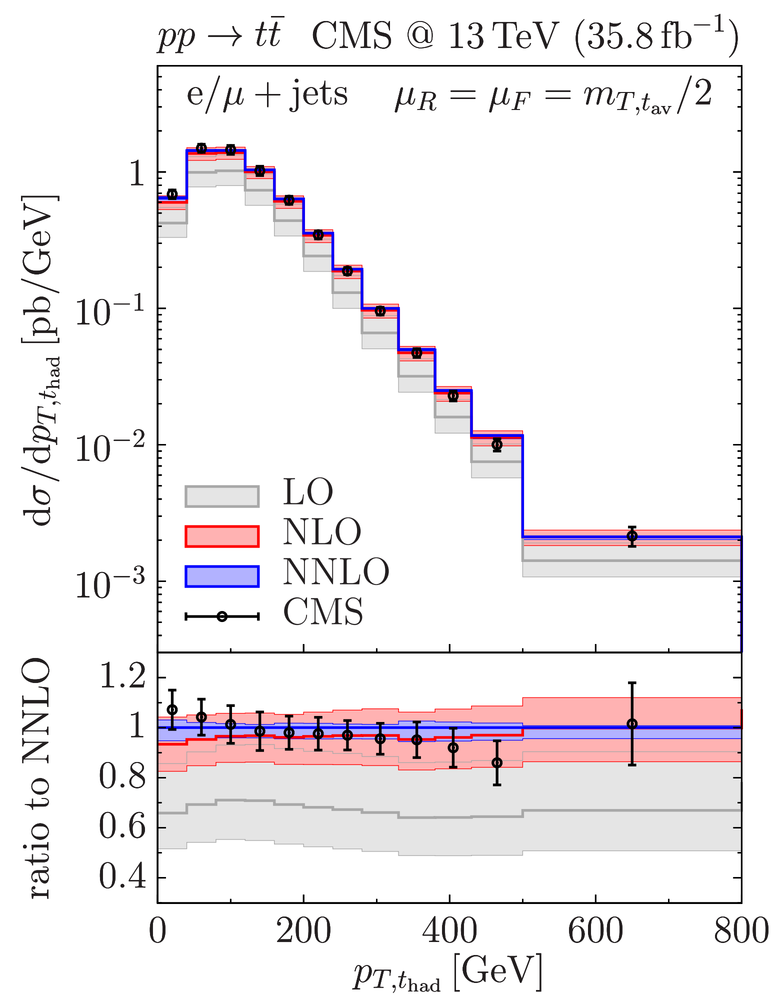
$\mu_R = \mu_F = H_T/2$



$\mu_R = \mu_F = m_{T,t_{av}}$



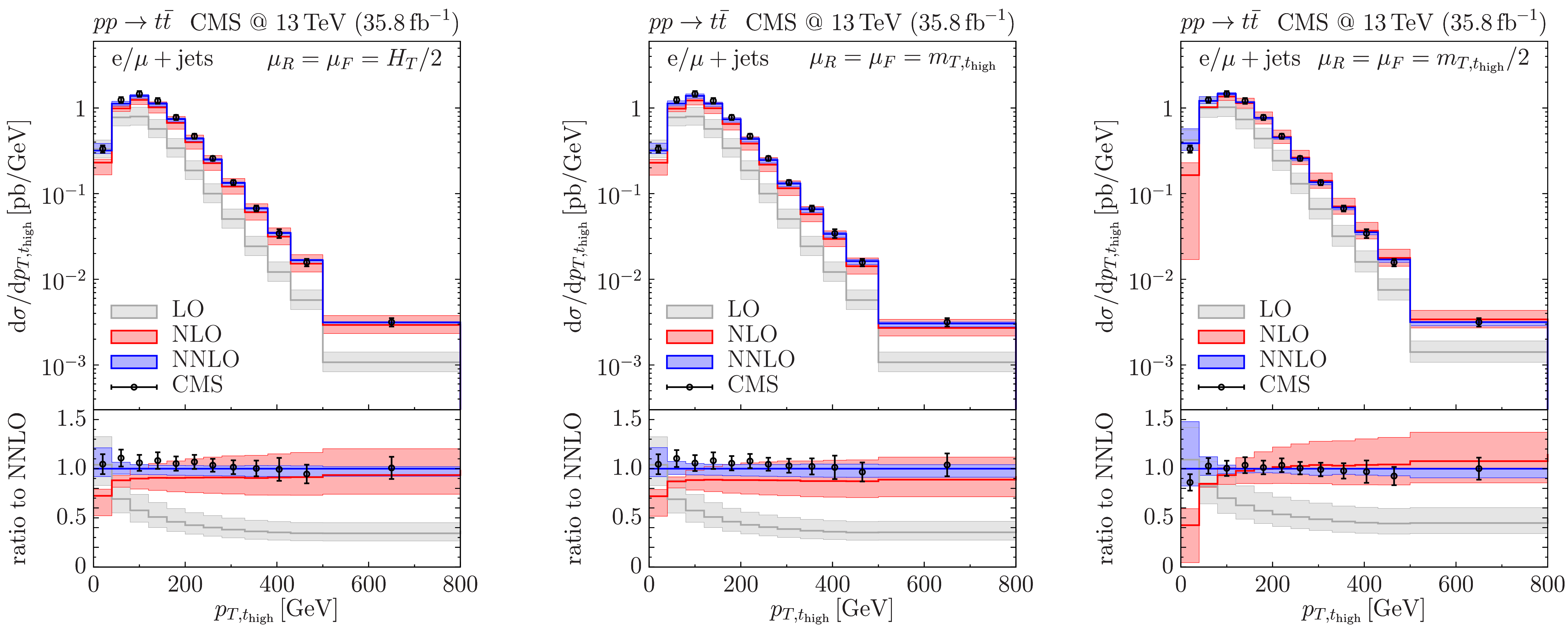
$\mu_R = \mu_F = m_{T,t_{av}}/2$



$p_{T,t_{had}}$ *distributions*

DIFFERENT SCALE CHOICES

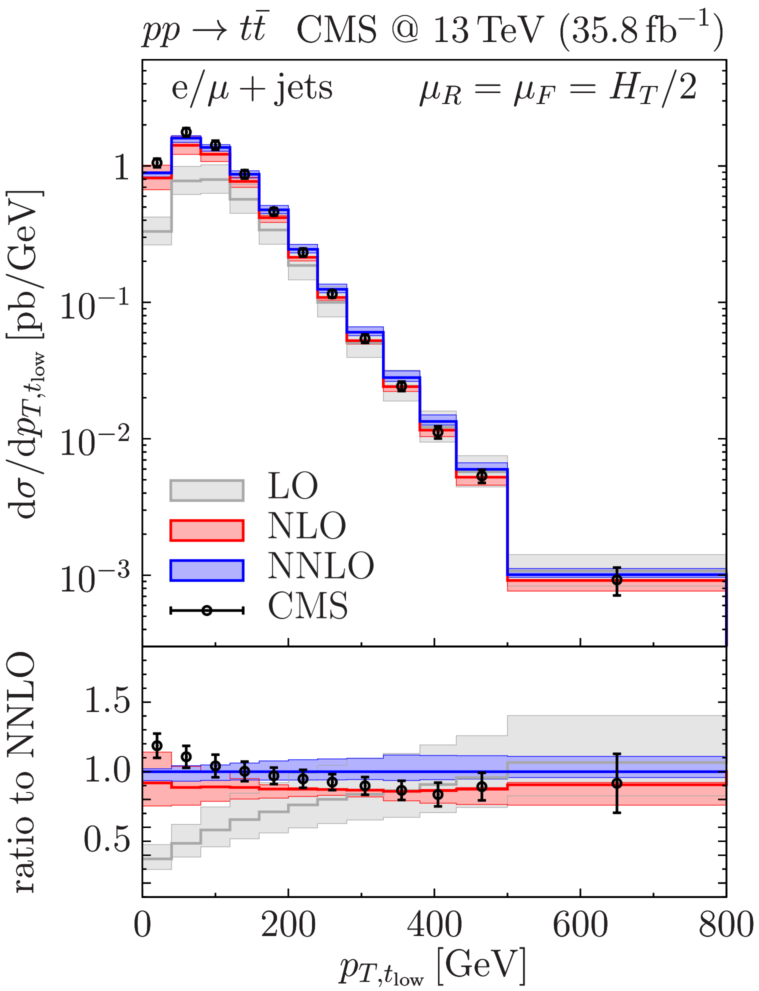
$\mu_R = \mu_F = H_T/2$ $\mu_R = \mu_F = m_{T,t_{high}}$ $\mu_R = \mu_F = m_{T,t_{high}}/2$



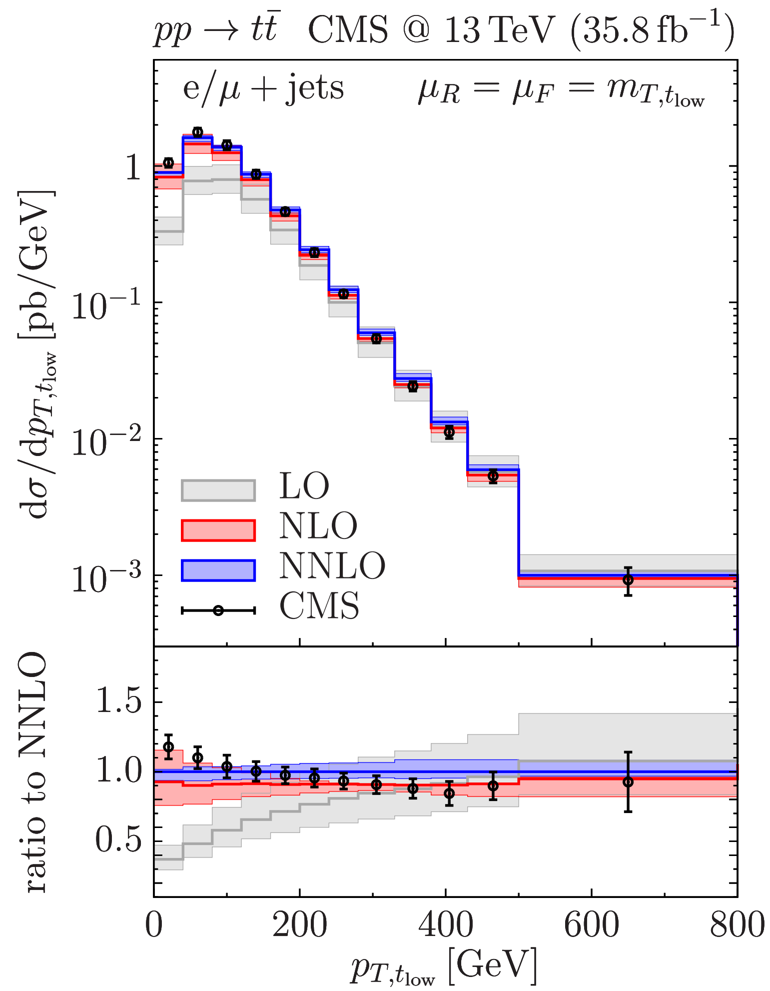
$p_{T,t_{high}}$ *distributions*

DIFFERENT SCALE CHOICES

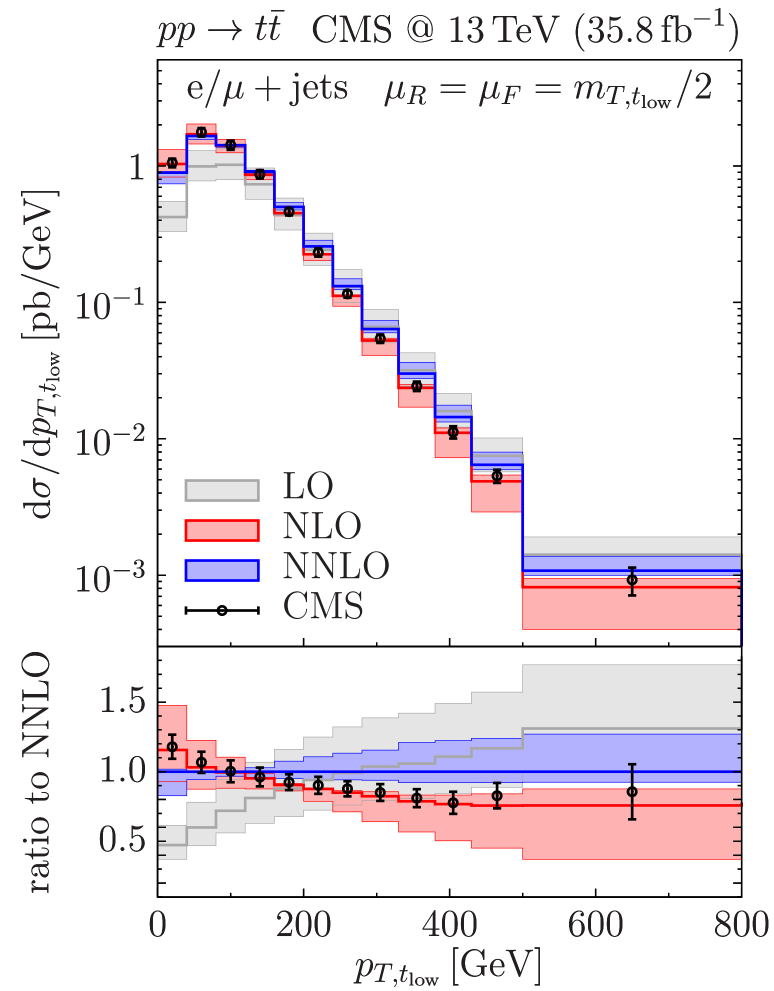
$\mu_R = \mu_F = H_T/2$



$\mu_R = \mu_F = m_{T,t_{low}}$



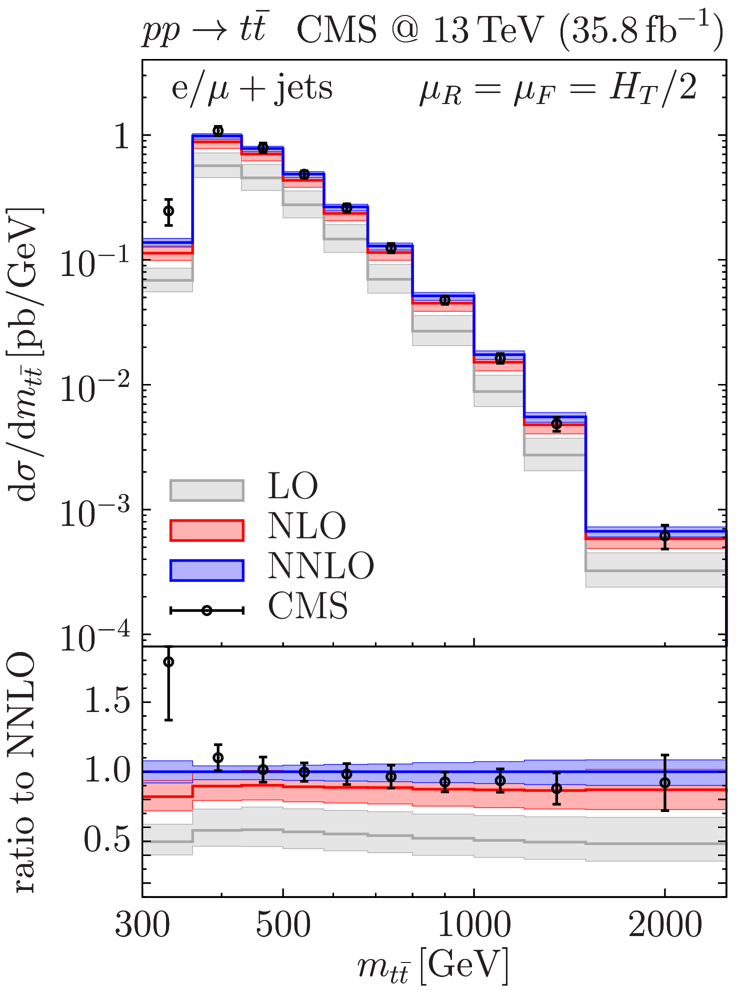
$\mu_R = \mu_F = m_{T,t_{low}}/2$



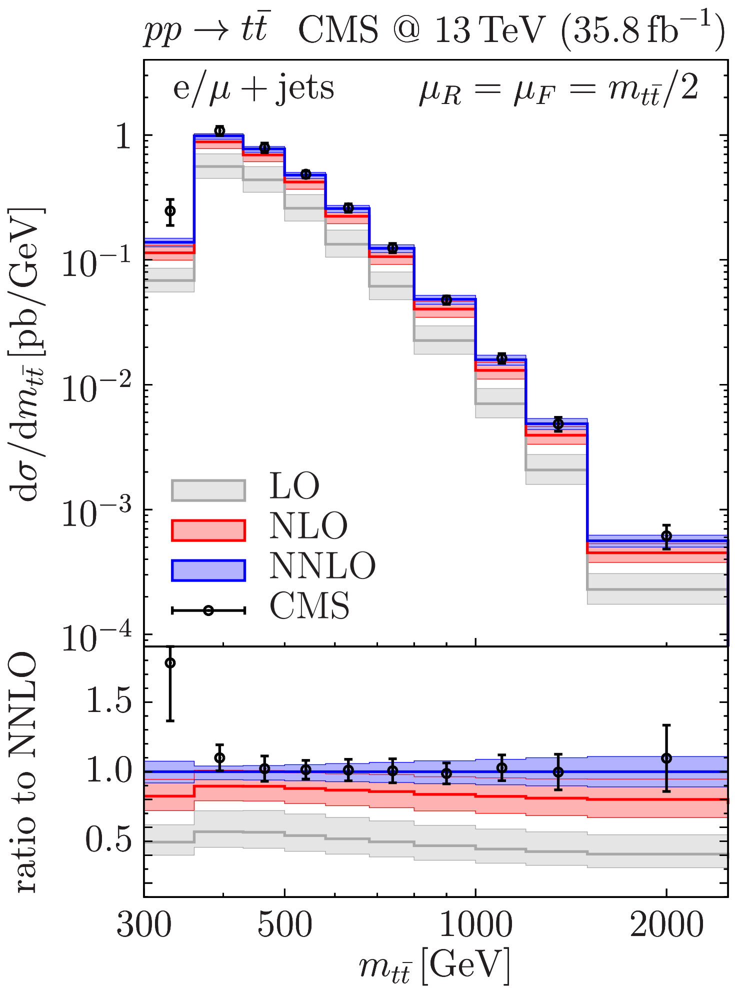
$p_{T,t_{low}}$ *distributions*

DIFFERENT SCALE CHOICES

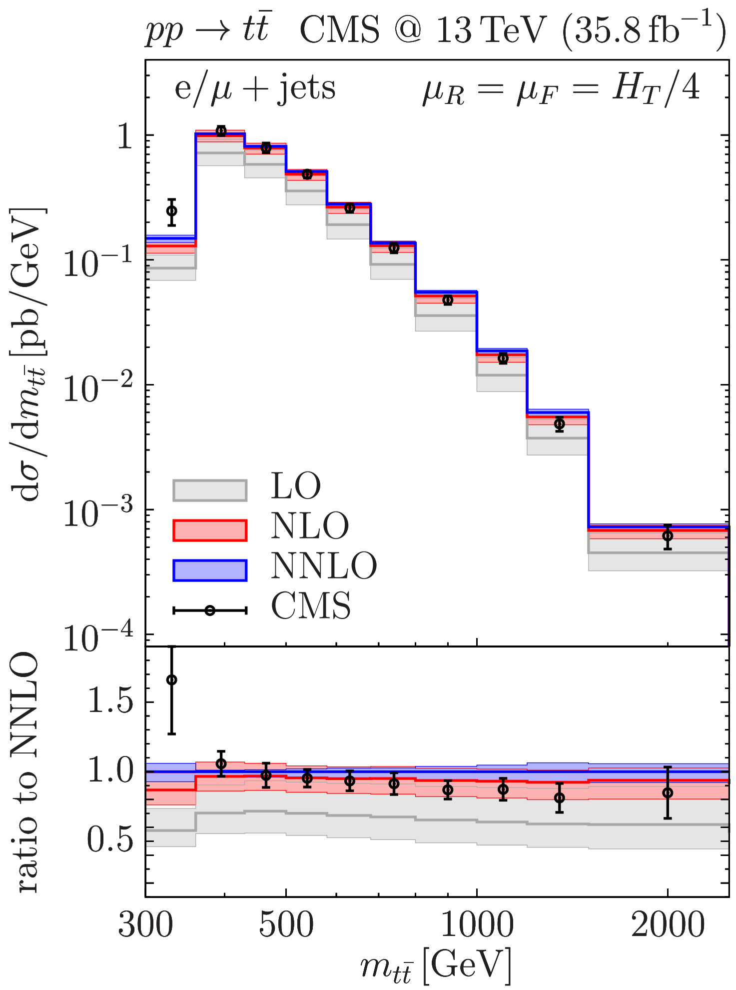
$\mu_R = \mu_F = H_T/2$



$\mu_R = \mu_F = m_{t\bar{t}}$

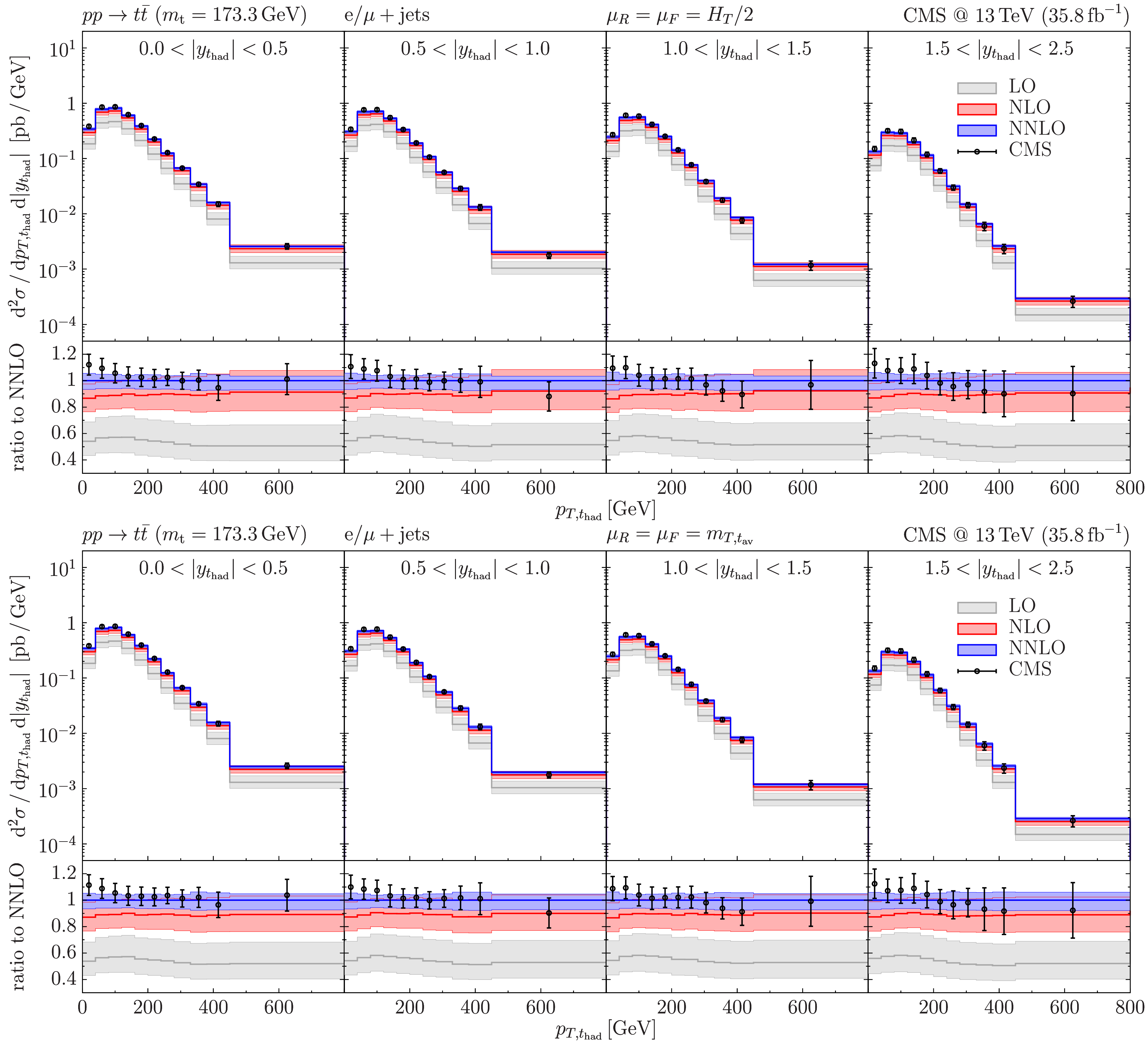


$\mu_R = \mu_F = H_T/4$

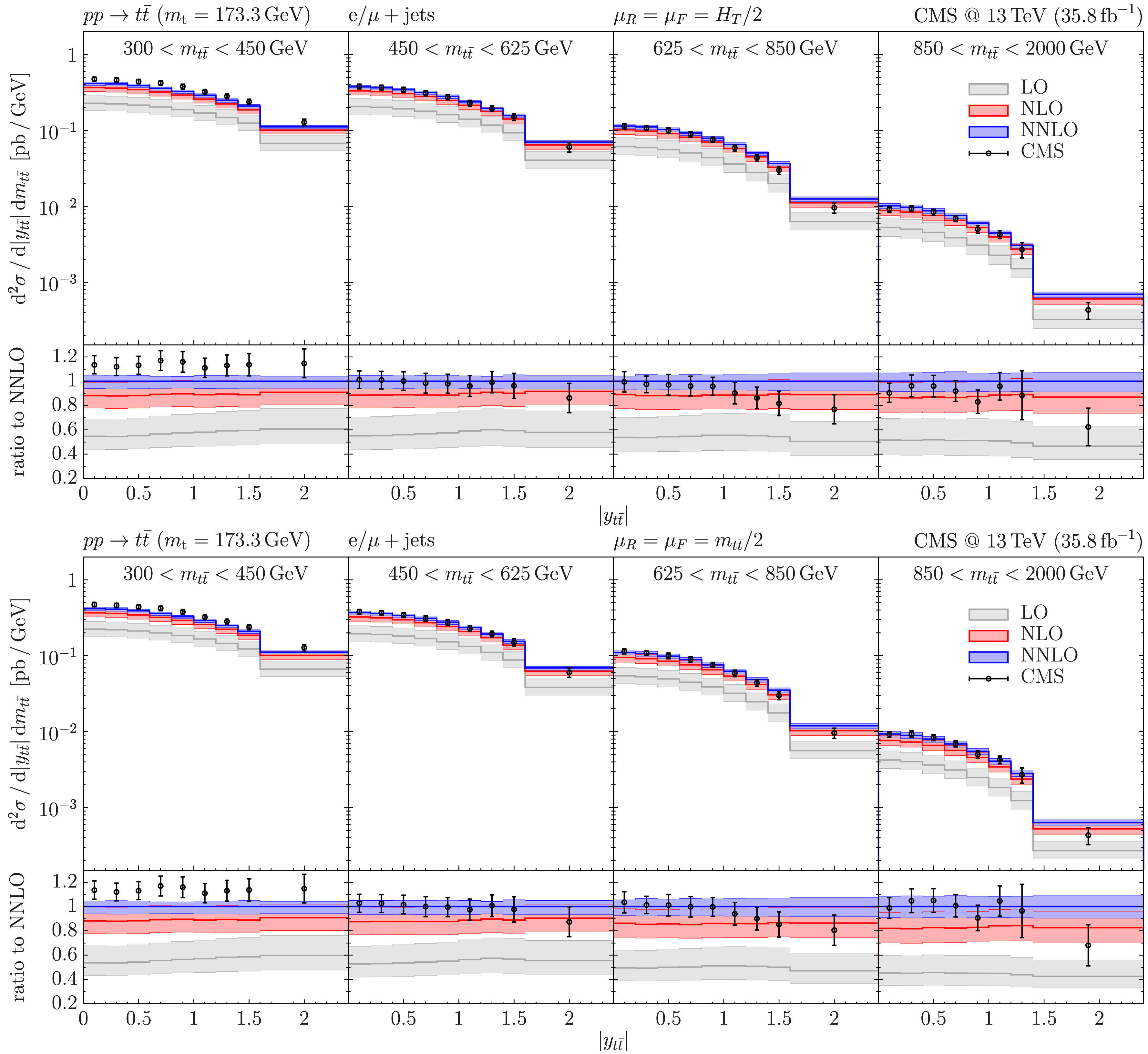


$m_{t\bar{t}}$ distributions

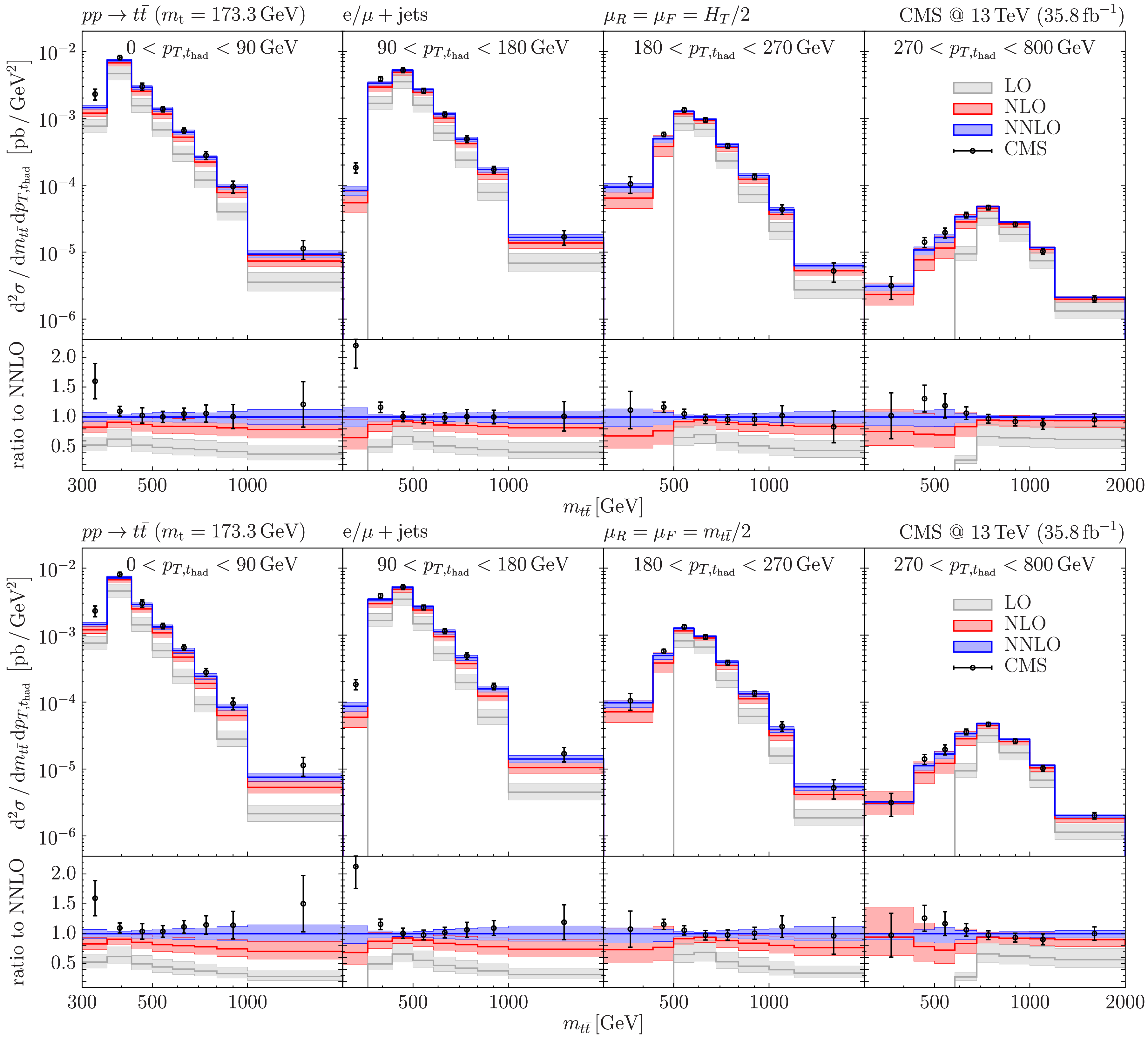
DIFFERENT SCALE CHOICES



DIFFERENT SCALE CHOICES



DIFFERENT SCALE CHOICES



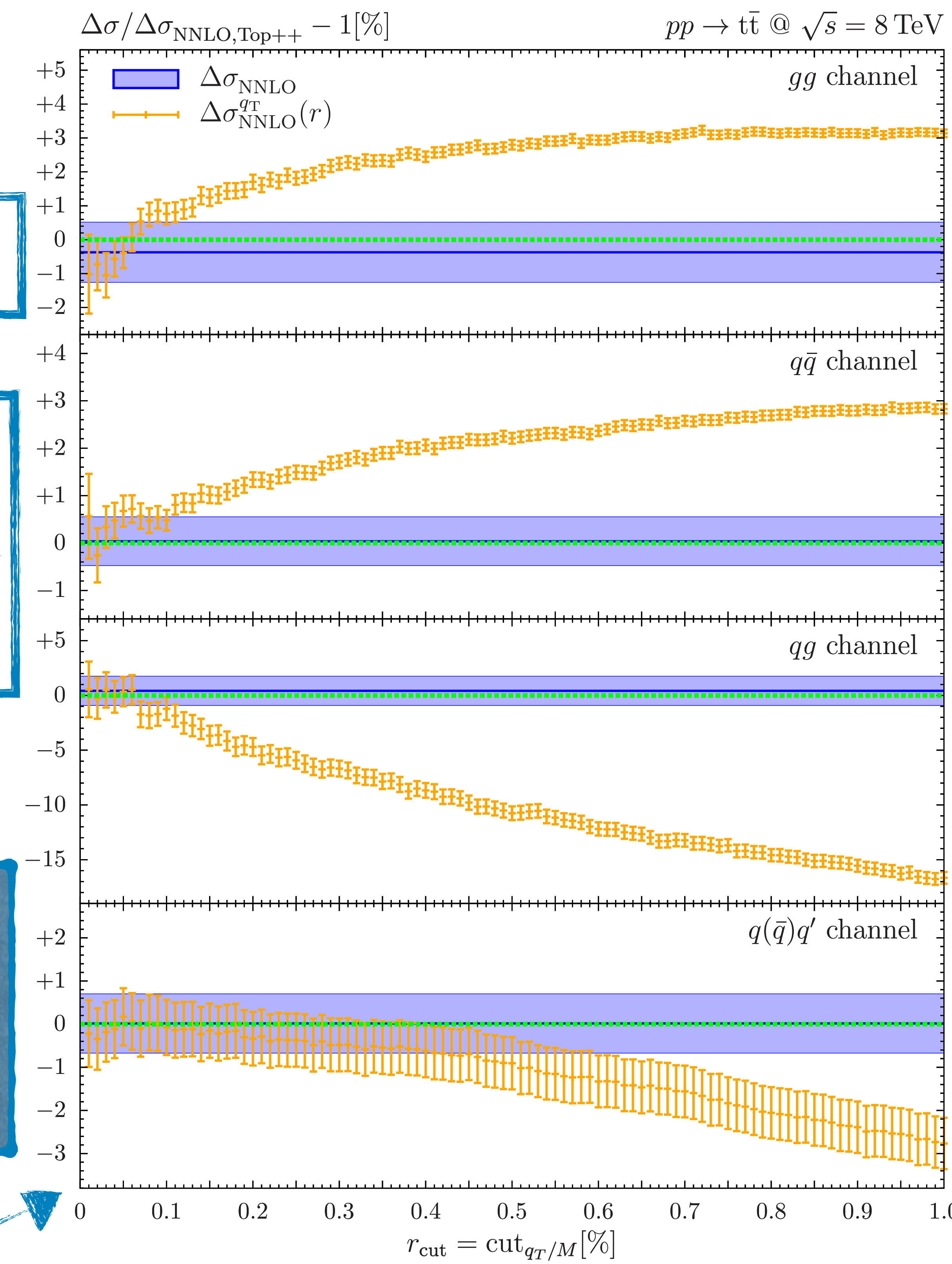
INCLUSIVE CROSS SECTION

[S. Catani, SD, M. Grazzini ,S.Kallweit, J. Mazzitelli, H. Sargsyan (2019)]

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

Separately divergent.
In practice, q_T subtraction implemented as a slicing method, introducing a cutoff $r_{cut} = Q/M$ and performing the limit $r_{cut} \to 0$.

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



DOUBLE GLUON EMISSION

[S. Catani, M. Grazzini: arXiv:9908523; M. Czakon: arXiv:1101.0642]

$$\mathcal{S}_{ij}^{m=0}(q_1,q_2) = \frac{(1-\epsilon)}{(q_1\cdot q_2)^2}\frac{p_i\cdot q_1\; p_j\cdot q_2 + p_i\cdot q_2\; p_j\cdot q_1}{p_i\cdot(q_1+q_2)\; p_j\cdot(q_1+q_2)}$$
$$-\frac{(p_i\cdot p_j)^2}{2\,p_i\cdot q_1\; p_j\cdot q_2\; p_i\cdot q_2\; p_j\cdot q_1}\left[2-\frac{p_i\cdot q_1\; p_j\cdot q_2 + p_i\cdot q_2\; p_j\cdot q_1}{p_i\cdot(q_1+q_2)\; p_j\cdot(q_1+q_2)}\right]$$
$$+\frac{p_i\cdot p_j}{2\,q_1\cdot q_2}\left[\frac{2}{p_i\cdot q_1\; p_j\cdot q_2}+\frac{2}{p_j\cdot q_1\; p_i\cdot q_2}-\frac{1}{p_i\cdot(q_1+q_2)\; p_j\cdot(q_1+q_2)}\right.$$
$$\left.\times\left(4+\frac{(p_i\cdot q_1\; p_j\cdot q_2 + p_i\cdot q_2\; p_j\cdot q_1)^2}{p_i\cdot q_1\; p_j\cdot q_2\; p_i\cdot q_2\; p_j\cdot q_1}\right)\right]$$

$$\mathcal{S}_{ij}^{m\neq 0}(q_1,q_2) = -\frac{1}{4\,q_1\cdot q_2\; p_i\cdot q_1\; p_i\cdot q_2}+\frac{p_i\cdot p_j\; p_j\cdot(q_1+q_2)}{2\,p_i\cdot q_1\; p_j\cdot q_2\; p_i\cdot q_2\; p_j\cdot q_1\; p_i\cdot(q_1+q_2)}$$
$$-\frac{1}{2\,q_1\cdot q_2\; p_i\cdot(q_1+q_2)\; p_j\cdot(q_1+q_2)}\left(\frac{(p_j\cdot q_1)^2}{p_i\cdot q_1\; p_j\cdot q_2}+\frac{(p_j\cdot q_2)^2}{p_i\cdot q_2\; p_j\cdot q_1}\right)$$

DOUBLE GLUON EMISSION

[S. Catani, M. Grazzini: arXiv:9908523; M. Czakon: arXiv:1101.0642]

$$\tilde{\mathcal{S}}_{ij}^{m=0}(q_1,q_2) = -\frac{(p_i\cdot p_j)^2}{2(p_i\cdot k)(p_j\cdot k)}\left(\frac{2}{(p_i\cdot q_1)(p_j\cdot q_1)}+\frac{1}{(p_i\cdot q_1)(p_j\cdot q_2)}\right)+\frac{(p_i\cdot p_j)}{k^2}\frac{2}{(p_i\cdot q_1)(p_j\cdot q_2)}$$
$$-\frac{(p_i\cdot p_j)}{2k^2(p_i\cdot k)(p_j\cdot k)}\frac{((p_i\cdot q_1)(p_j\cdot q_2)-(p_i\cdot q_2)(p_j\cdot q_1))^2}{(p_i\cdot q_1)(p_j\cdot q_2)(p_i\cdot q_2)(p_j\cdot q_1)}+(1\leftrightarrow 2)$$

$$\tilde{\mathcal{S}}_{ij}^{m\neq 0}(q_1,q_2) = \frac{(p_i\cdot p_j)}{2(p_i\cdot k)^2}\left(\frac{1}{(p_i\cdot q_1)(p_j\cdot q_1)}+\frac{1}{(p_i\cdot q_1)(p_j\cdot q_2)}\right)$$
$$-\frac{1}{k^2(p_i\cdot k)}\frac{1}{(p_i\cdot q_1)}\left(\frac{(p_j\cdot q_1)^2}{(p_j\cdot k)(p_j\cdot q_2)}-\frac{(p_i\cdot q_1)^2}{(p_i\cdot k)(p_i\cdot q_2)}\right)+(1\leftrightarrow 2)$$

$$k = q_1 + q_2$$

ONE GLUON EMISSION AT 1 LOOP

[I. Bierenbaum, M.Czakon, A. Mitov: arXiv:1107.4384; M. Czakon, A.Mitov: arXiv:1804.02069]

$$\left| J_{sub}^{NNLO(1L)}(k) \right|^2 = \langle M_a^{(0)}(n+1;k) \,|\, M_a^{(1)}(n+1;k) \rangle + c.c.$$

$$\langle M_a^{(0)}(n+1;k) \,|\, M_a^{(1)}(n+1;k) \rangle + c.c. = -4\pi\alpha_S \mu^{2\epsilon}$$

$$\times \left\{ 2C_A \sum_{i \neq j = 1}^{n} \left(e_{ij} - e_{ii} \right) R_{ij} \langle M^{(0)}(n) \,|\, T_i \cdot T_j \,|\, M^{(0)}(n) \rangle - 4\pi \sum_{i \neq j \neq k = 1}^{n} e_{ik} I_{ij} \langle M^{(0)}(n) \,|\, f^{abc} T_i^a T_j^b T_k^c \,|\, M^{(0)}(n) \rangle \right.$$

The expansion in ε of R_{ij}, I_{ij} can be found in *[I. Bierenbaum, M.Czakon, A. Mitov: arXiv:1107.4384]*.
Simplified expressions recently published in *[M. Czakon, A.Mitov: arXiv:1804.02069]*.

$$\left. + \left(\sum_{i \neq j = 1}^{n} e_{ij} \langle M^{(0)}(n) \,|\, T_i \cdot T_j \,|\, M^{(1)}(n) \rangle + c.c. \right) + \left(\sum_{i=1}^{n} \mathscr{C}_i e_{ii} \langle M^{(0)}(n) \,|\, M^{(1)}(n) \rangle + c.c. \right) \right\}$$

NLO-like contributions

$$e_{ij} = \frac{\left(p_i \cdot p_j\right)}{\left(p_i \cdot k\right)\left(p_j \cdot k\right)} \qquad e_{ii} = \frac{m_i^2}{\left(p_i \cdot k\right)^2}$$