Top at NNLOPS

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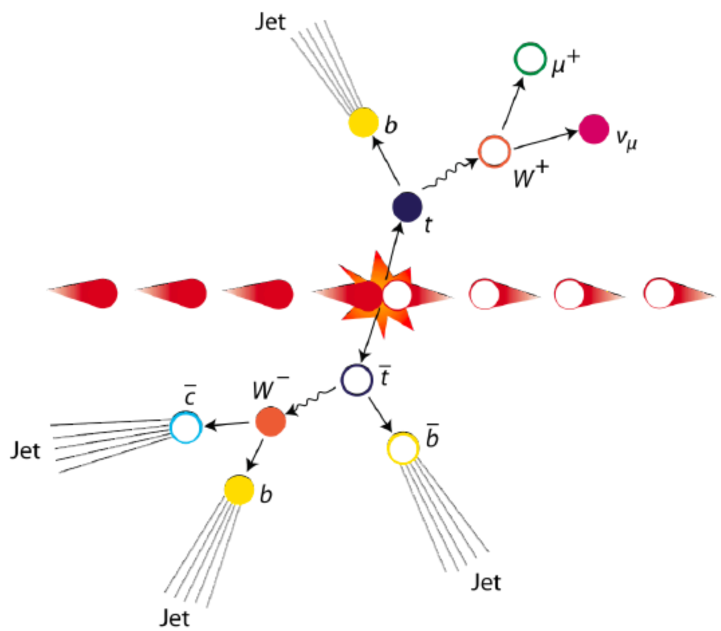

Top 2021, September 2021

The top quark

- No need to remind this audience of the crucial role of the top quark in the SM

  heaviest particle in the SM, strongest coupling to the Higgs, decays before hadronizing, possible window to new physics, produced abundantly at the LHC (omnipresent background), …

- Accordingly, large effort of theory community to provide most accurate perturbative predictions

  [NLO QCD, NNLO QCD, NLO EW, NNLO QCD+ NLO EW, analytic resummations, NLO QCD + PS]

- Besides fixed-order calculations, for experimental analyses fully exclusive event generators combining best perturbative accuracy and parton shower+hadronization are required, i.e. NNLO + PS accurate Monte Carlos

NNLO+PS for top-pairs

- Top-pair at NNLO [Czakon Mitov '12]; [Czakon, Fiedler, Mitov '13]; [Czakon, Fiedler Heymes, Mitov '15,'16]; [Catani, Devoto, Grazzini, Kallweit, Mazzitelli, Sargsyan '19]; [Catani, Devoto, Grazzini, Kallweit, Mazzitelli, '20]

- NNLO+PS for colour singlet MiNLO+reweight [Hamilton, Nason, GZ '12]; Geneva [Alioli, Bauer, Berggren, Tackmann, Walsh, Zuberi '13], UNNLOPS [Hoeche Prestel '14]; MiNNLOPS [Monni, Re, Wiesemann, Zanderighi '19], [Monni, Re, Wiesemann '20]

Both available since almost a decade but NNLO+PS for top-pair developed only recently in

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extending the MiNNLO$_{PS}$ method to top-pair production

MiNNLO$_{PS}$ method

MiNNLO$_{PS}$ was first developed for colour singlet production and is built upon the MiNLO procedure in POWHEG

POWHEG: hardest emission generator at NLO accuracy, events subsequently fed to parton shower for softer radiation to achieve NLO+PS accuracy

[Nason'04; Alioli, Nason, Oleari, Re '07; Alioli, Frixione, Nason, Oleari, Re'10]

POWHEG master formula:

$$d\sigma = d\Phi_B \bar{B} \left[\Delta_{\text{pwg}}(\Lambda) + \Delta_{\text{pwg}}(p_T) \frac{R}{B} d\Phi_{\text{rad}} \right]$$

$$\bar{B} = B + V + \int d\Phi_{\text{rad}} R \qquad \Delta_{\text{pwg}}(p_T) = exp\left[- \int d\Phi_{\text{rad}} \frac{R}{B} \theta\left(p_T(\phi_{\text{rad}}) - p_T\right) \right]$$

MiNLO

MiNLO (Multi scale Improved NLO): suitable modification of the POWHEG $\bar{B}$ function such that the inclusive colour-singlet (F) + jet cross section remains finite when the jet p_T vanishes

[Hamilton, Nason, GZ '12]

$$\bar{B} = e^{-S(p_T)} \left[B \left(1 + S(p_T)^{(1)} \right) + V + \int d\Phi_{\rm rad} R \right]$$

Here: $S(p_T)$ Sudakov form factor obtained from transverse momentum resummation

MiNLO': adjustment of the Sudakov form factor such that the inclusive cross-section is NLO accurate (requires B_2 resummation coefficient and appropriate scale setting)

[Hamilton, Nason, Oleari, GZ '12]

	F+2j	F+jet	F
Fj-MiNLO	LO	NLO	NLO

MiNNLOPS

[Monni, Nason, Re, Wiesemann, GZ '20; Monni, Re, Wiesemann,'20]

MiNNLOPS: further modification of MiNLO' formula to obtain

	F+2j	F+jet	F
Fj-MiNLO	LO	NLO	NLO
MiNNLOPS	LO	NLO	NNLO

Starting point of MiNNLOPS is the transverse momentum resummation formula for colour singlet production, differential in the Born phase space

$$d\sigma^{(\mathrm{sing})} \sim d\sigma^{(0)}_{c\bar{c}} \times \exp[-S_c(b)] \times [HC_1C_2]_{c\bar{c};a_1a_2} \times f_{a_1} f_{a_2}$$

MiNNLOPS

[Monni, Nason, Re, Wiesemann, GZ '20; Monni, Re, Wiesemann,'20]

MiNNLOPS: further modification of MiNLO' formula to obtain

	F+2j	F+jet	F
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Starting point of MiNNLOPS is the transverse momentum resummation formula for colour singlet production, differential in the Born phase space

$$d\sigma_{\mathrm{F}}^{\mathrm{res}} = \frac{d}{dp_{\mathrm{T}}}\left\{e^{-S}\mathcal{L}\right\} = e^{-S}\underbrace{\left\{-S'\mathcal{L} + \mathcal{L}'\right\}}_{\equiv D}$$

$\mathcal{L}$: luminosity factor, computed up to NNLO (includes hard virtual matrix elements for F and convolution of collinear coefficient functions with PDFs)

S: Sudakov form factor

MiNNLO$_{\rm PS}$

Match to fixed order, *keeping the Sudakov factored out*

$$\mathrm{d}\sigma_{\mathrm{F}}^{\mathrm{res}} + [\mathrm{d}\sigma_{\mathrm{FJ}}]_{\mathrm{f.o.}} - [\mathrm{d}\sigma_{\mathrm{F}}^{\mathrm{res}}]_{\mathrm{f.o.}} = e^{-S}\Bigg\{D + [\mathrm{d}\sigma_{\mathrm{FJ}}]_{\mathrm{f.o.}} \underbrace{\frac{1}{[e^{-S}]_{\mathrm{f.o.}}}}_{1+S^{(1)}\dots} \underbrace{-\frac{[\mathrm{d}\sigma_{\mathrm{F}}^{\mathrm{res}}]_{\mathrm{f.o.}}}{[e^{-S}]_{\mathrm{f.o.}}}}_{-D^{(1)}-D^{(2)}\dots}\Bigg\}$$

$$= e^{-S}\left\{\mathrm{d}\sigma_{\mathrm{FJ}}^{(1)}\left(1+S^{(1)}\right) + \mathrm{d}\sigma_{\mathrm{FJ}}^{(2)} + \left(D - D^{(1)} - D^{(2)}\right) + \mathcal{O}(\alpha_s^4)\right\}$$

Nothing but the MiNLO formula

New terms required to preserve the NNLO accuracy

Results in the MiNNLO$_{\rm PS}$ formula for $\bar{\mathrm{B}}$

$$\bar{B}^{\,\mathrm{MiNNLO_{PS}}} \sim e^{-S}\left\{\mathrm{d}\sigma_{\mathrm{FJ}}^{(1)}\left(1+S^{(1)}\right) + \mathrm{d}\sigma_{\mathrm{FJ}}^{(2)} + \left(D - D^{(1)} - D^{(2)}\right) \times F^{\mathrm{corr}}\right\}$$

$F^{\rm corr}$: factor required to spear the “D”-terms in the full FJ phase space

MiNNLO$_{\text{PS}}$

Note that $(D - D^{(1)} - D^{(2)}) = \mathcal{O}(\alpha_s^3 L)$

but these terms contribute at NNLO since

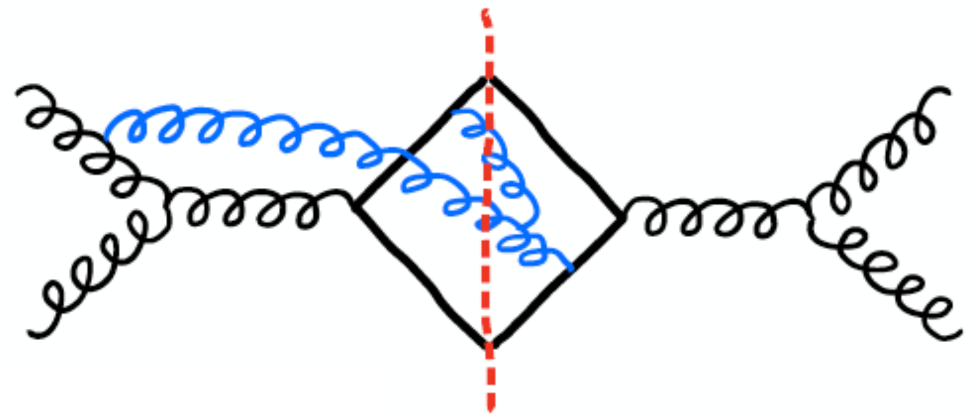
$$\int dL \alpha_s^n L^m e^{-\alpha_s L^2} = \alpha_s^{n-(m+1)/2}$$

⇛ Setting n = 3 and m=1 one obtains a NNLO contribution

Two remarks:

- all $\mathcal{O}(\alpha_s^3)$ terms required are those already present in a NNLO matched resummed calculation
- it is possible to either expand and keep only terms of $\mathcal{O}(\alpha_s^3)$ or include all higher-order terms. The latter choice is preferred since it preserved the total derivative, and is adopted here

MiNNLO$_{\mathrm{PS}}$ for tt



The resummation for top-pair production is more complicated and involves ISR, FSR and interference (soft, large angle). Since there are 4 emitters, it involves matrices/vectors in colour space (denoted in bold):

[Catani, Grazzini, Torre '14]

$$\frac{d\sigma}{d^2\vec{p}_T\, d\Phi_{t\bar{t}}} = \sum_{c=q,\bar{q},g} \frac{|M^{(0)}_{c\bar{c}}|^2}{2m^2_{t\bar{t}}} \int \frac{d^2\vec{b}}{(2\pi)^2} e^{i\vec{b}\cdot\vec{p}_T} e^{-S_c\left(\frac{b_0}{b}\right)} \times \sum_{i,j} \mathrm{Tr}(\mathbf{H}_c \boldsymbol{\Delta}) (C_{ci} \otimes f_i)(C_{\bar{c}j} \otimes f_j)$$

Born

Sudakov

Hard function

Soft large angle (quantum interference)

Collinear coefficients

Parton distribution functions

MiNNLO$_{\text{PS}}$ for tt

The goal is to write the previous equation as a total derivative, up to higher-order terms. This is not trivial, but can be achieved with suitable rotations in colour space and expansions (keeping in mind that the logarithmic accuracy beyond (N)LL does not need to be preserved and NNLO singular terms must be kept).

Input required to obtain the correct (azimuthally averaged) NNLO result available

[Catani, Devoto, Grazzini, Kallweit, Mazzitelli, Sargsyan '19]

The above procedure leads to our master formula for top-pair production:

$$\frac{d\sigma}{dp_T\, d\Phi_{t\bar{t}}} = \frac{d}{dp_T}\left\{ \sum_c \frac{e^{-\tilde{S}_c(p_T)}}{2m_{t\bar{t}}^2} \langle M_{c\bar{c}}^{(0)}| \left(\mathbf{V}_{\rm NLL}\right)^\dagger \mathbf{V}_{\rm NLL} |M_{c\bar{c}}^{(0)}\rangle \sum_{i,j} \left[\mathrm{Tr}(\tilde{\mathbf{H}}_c \mathbf{D})\ (\tilde{C}_{ci} \otimes f_i)\, (\tilde{C}_{\bar{c}j} \otimes f_j) \right]_\phi \right\} + R_f + \mathcal{O}(\alpha_s^5)$$

here $V_{\rm NLL}$ encodes leading effects of Δ and “tilde” denotes a suitable modification of the given function. All formulae are given in 2012.14267.

The integral in p_T of the above equation provides NNLO accurate description of top-pair production, differential in the Born phase space, and provides the standard basis on how to modify the POWHEG $\bar{\text{B}}$-function of the ttJ generator.

Numerical results

Settings:

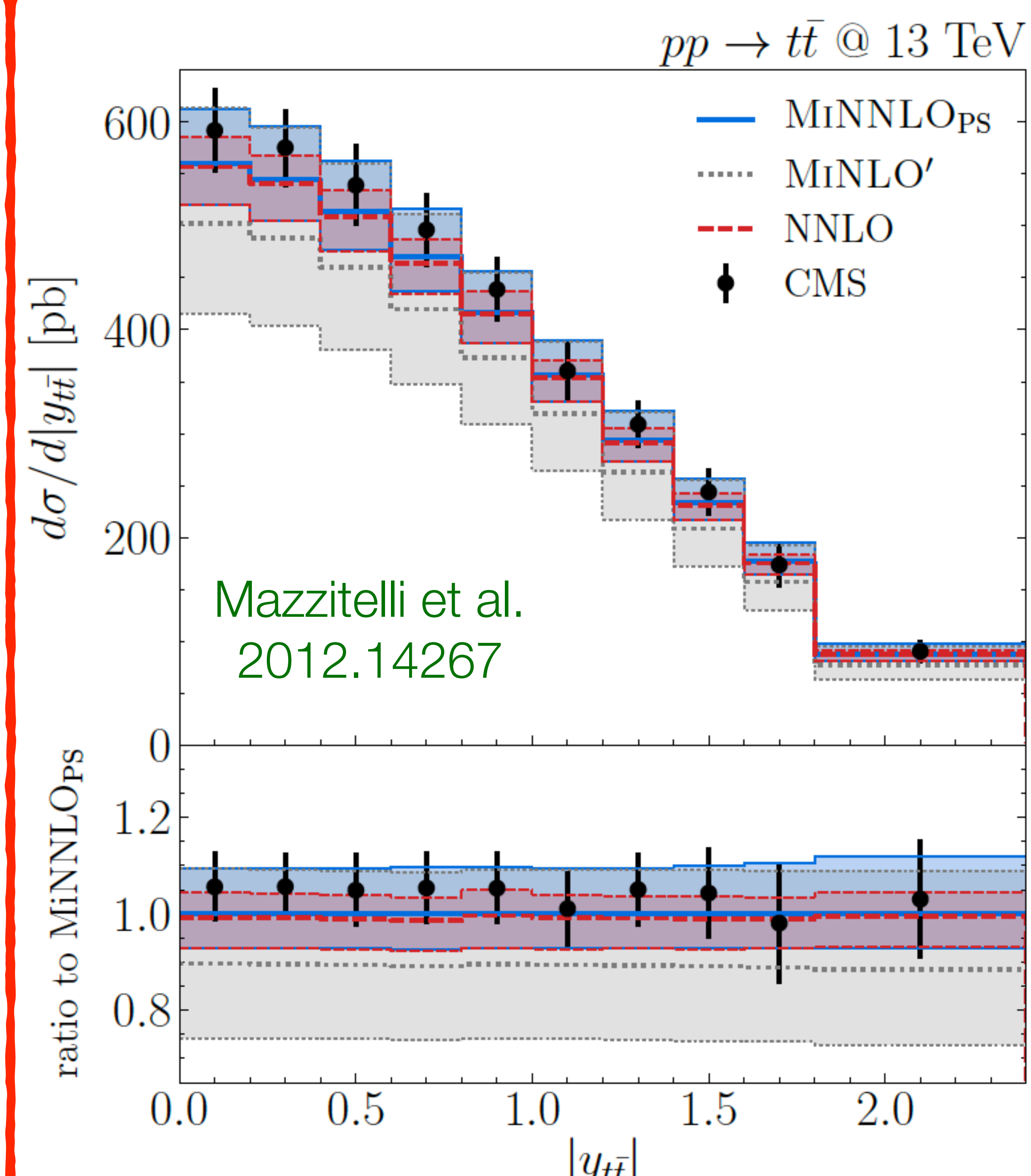
- 13 TeV LHC collisions, stable tops
- n_f =5, NNPDF31 with $\alpha_s(M_Z) = 0.118$
- μ_F, μ_R scales follow the MiNLO procedure: overall couplings evaluated at $m_{tt}/2$, other couplings at $\mu_R = \mu_F = m_{tt}/2e^{-L}$
- We set $L = \ln(Q/p_T)$ with $Q = m_{tt}/2$ at low p_T and modify it to vanish at high-p_T
- Scales in NNLO predictions set to $m_{tt}/2$
- Uncertainty bands: 7 scale variation with $1/2 \leq K_R/K_F \leq 2$
- Showering done with Pythia8 keeping top stable
- For comparison to NNLO hadronization switched off

Numerical results

Total cross section

MiNLO′	NNLO	MiNNLOPS
$695.6(3)^{+22\%}_{-17\%}$ pb	$769.8(9)^{+5.0\%}_{-6.5\%}$ pb	$775.5(2)^{+9.8\%}_{-7.2\%}$ pb

- Excellent agreement between NNLO and MiNNLOPS (despite different scale setting) for the total rate and shape of y_{tt}
- $\text{MiNNLO}_{\text{PS}}$ band slightly larger (reflects additional sources of scale variations)
- Substantial reduction of scale uncertainty w.r.t. MiNLO’
- Perfect agreement with CMS data (unfolded and extrapolated to the total phase space)



Numerical results

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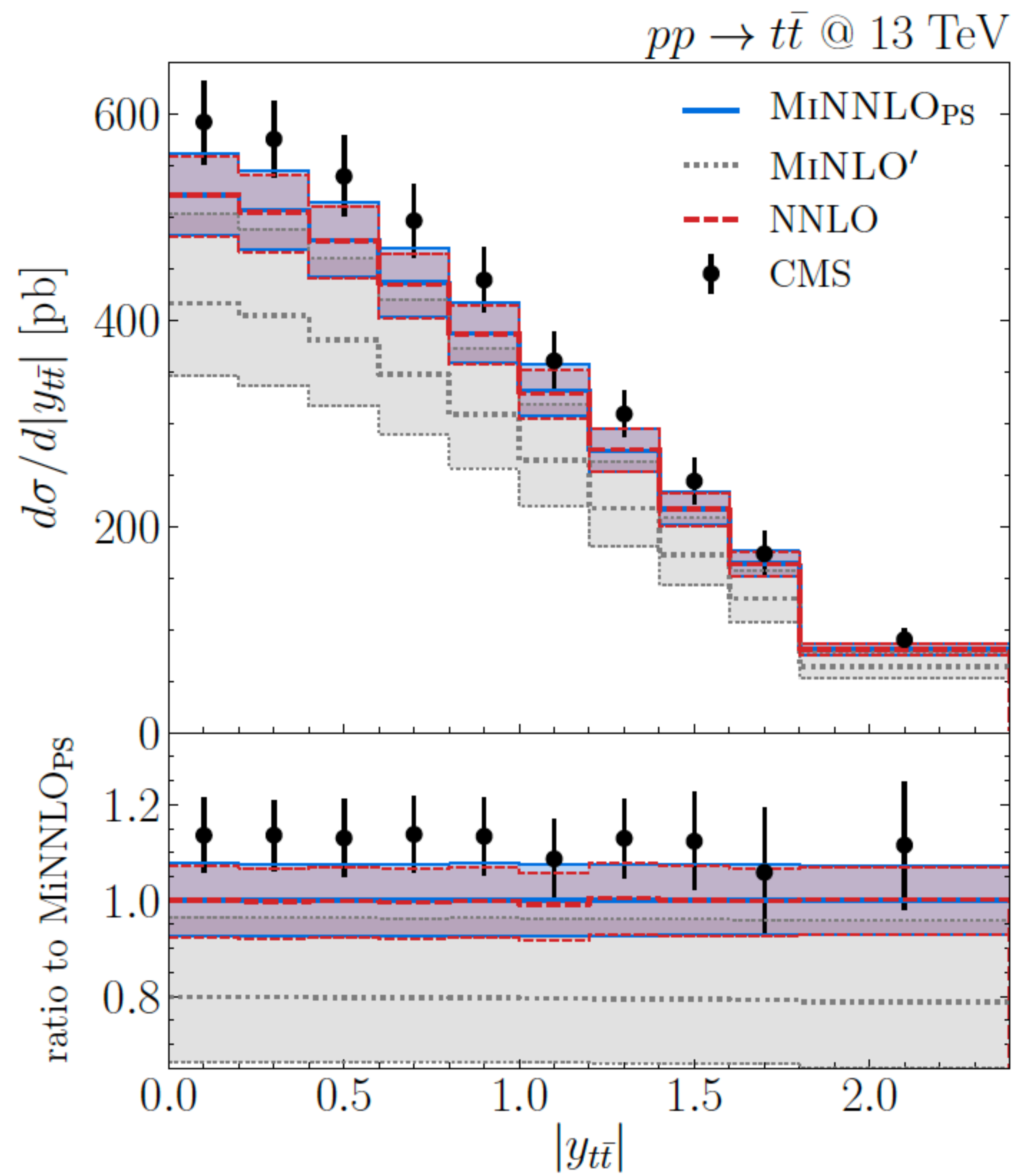
Changing central scales in the overall coupling and MiNLO scales from $m_{tt}/2$ to m_{tt} gives:

MiNLO′	NNLO	MiNNLO$_{PS}$
$572.9(2)^{+21\%}_{-17\%}$ pb	$719.1(8)^{+7.0\%}_{-7.6\%}$ pb	$719.8(2)^{+7.6\%}_{-7.4\%}$ pb



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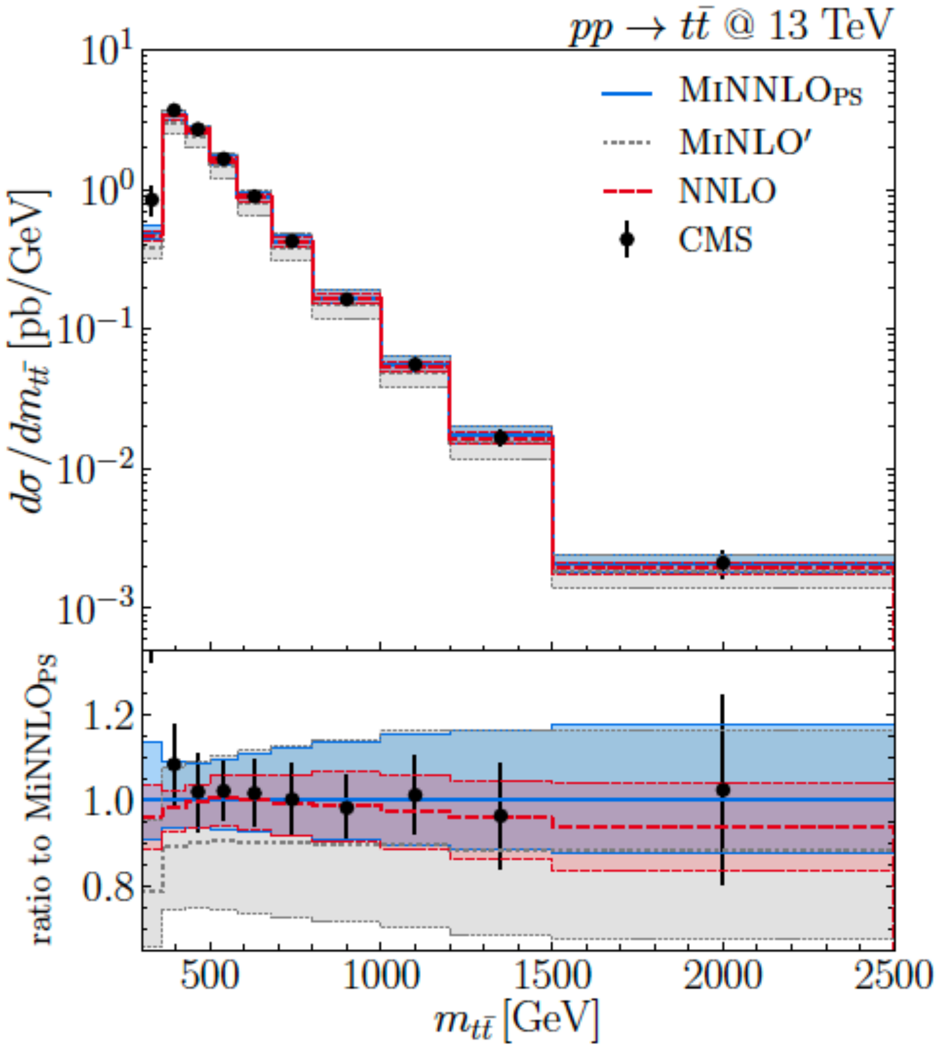
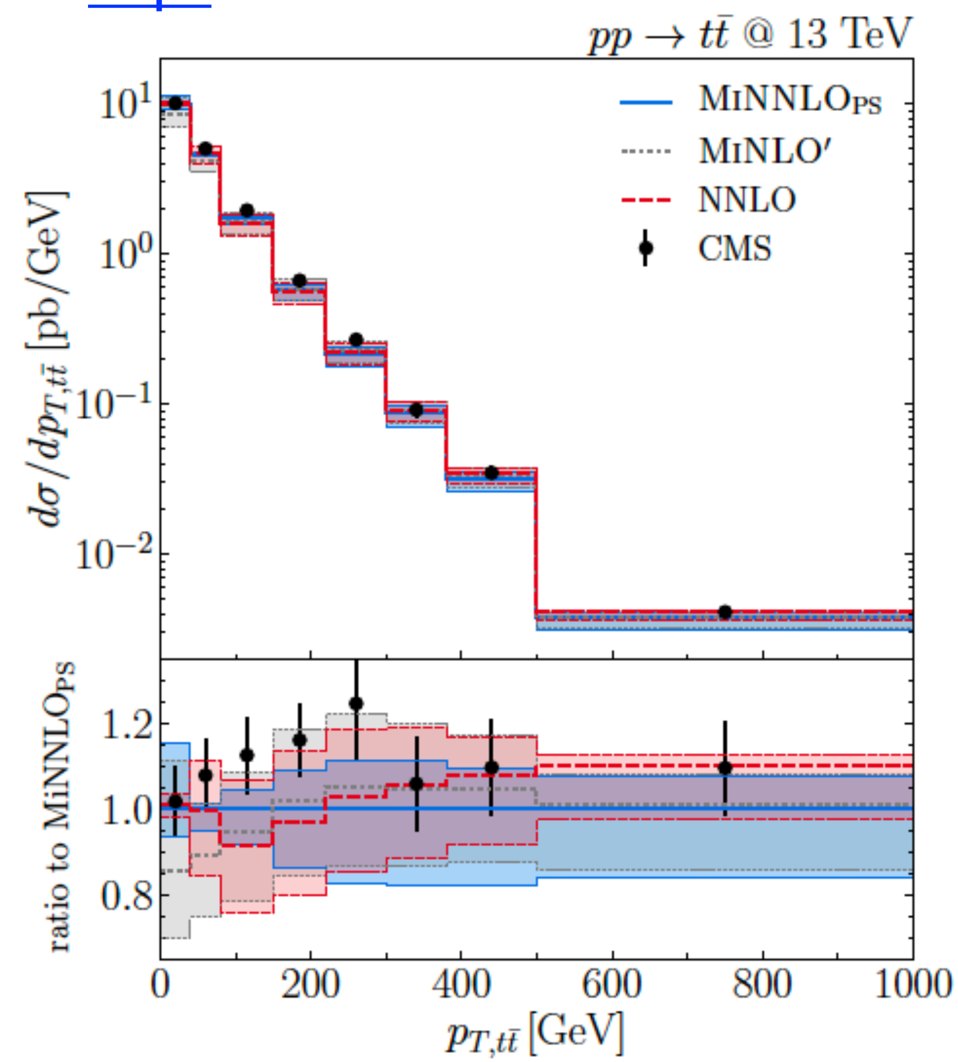
[$t\bar{t}$-mass]



[$t\bar{t}$-pt]



- Agreement with NNLO within uncertainty bands
- Good description of CMS data [1803.08856] unfolded and extrapolated to the full phase space

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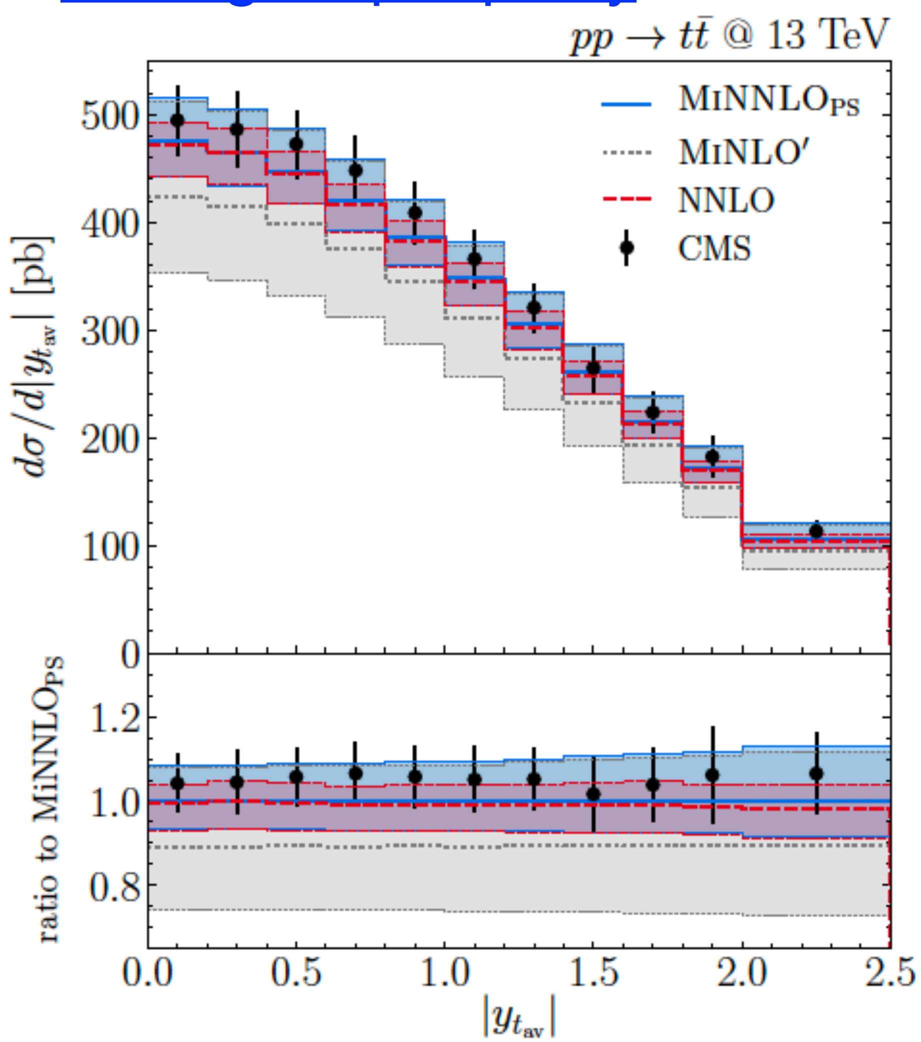
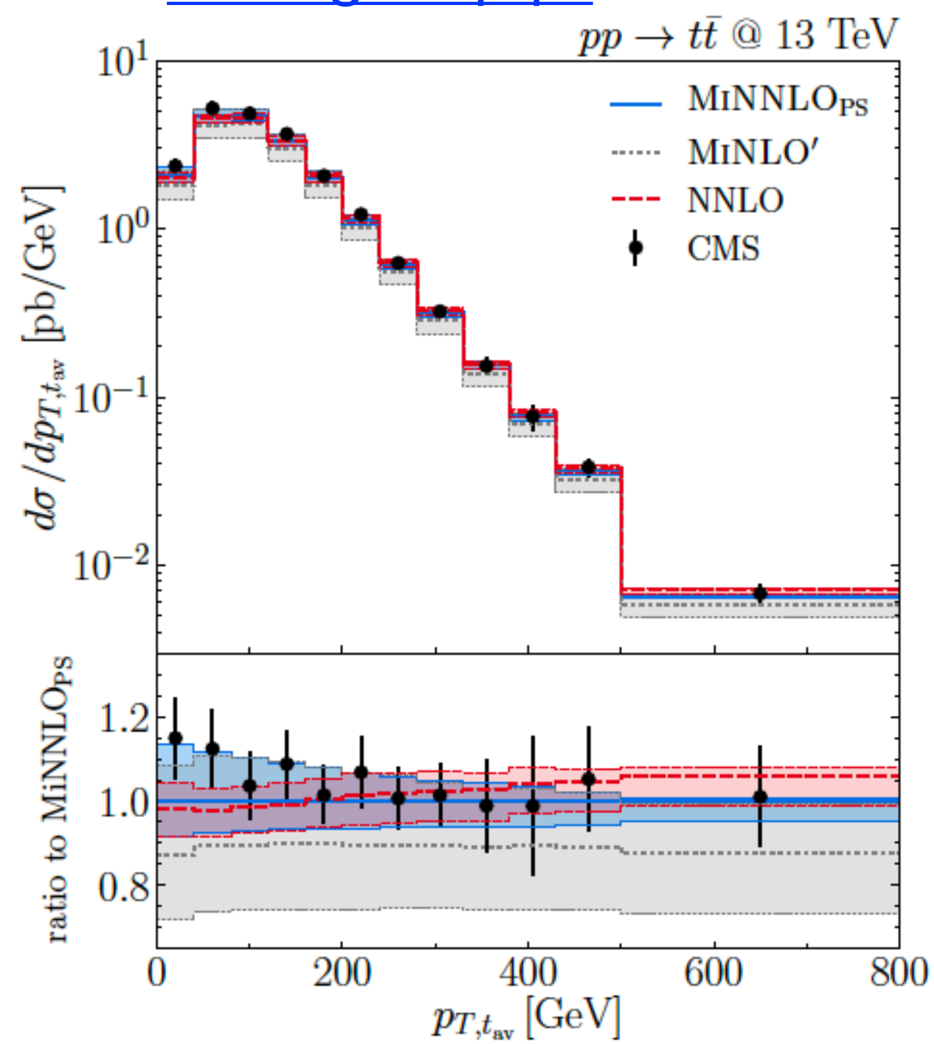
Average top rapidity



Average top p_T



- Agreement with NNLO within uncertainty bands
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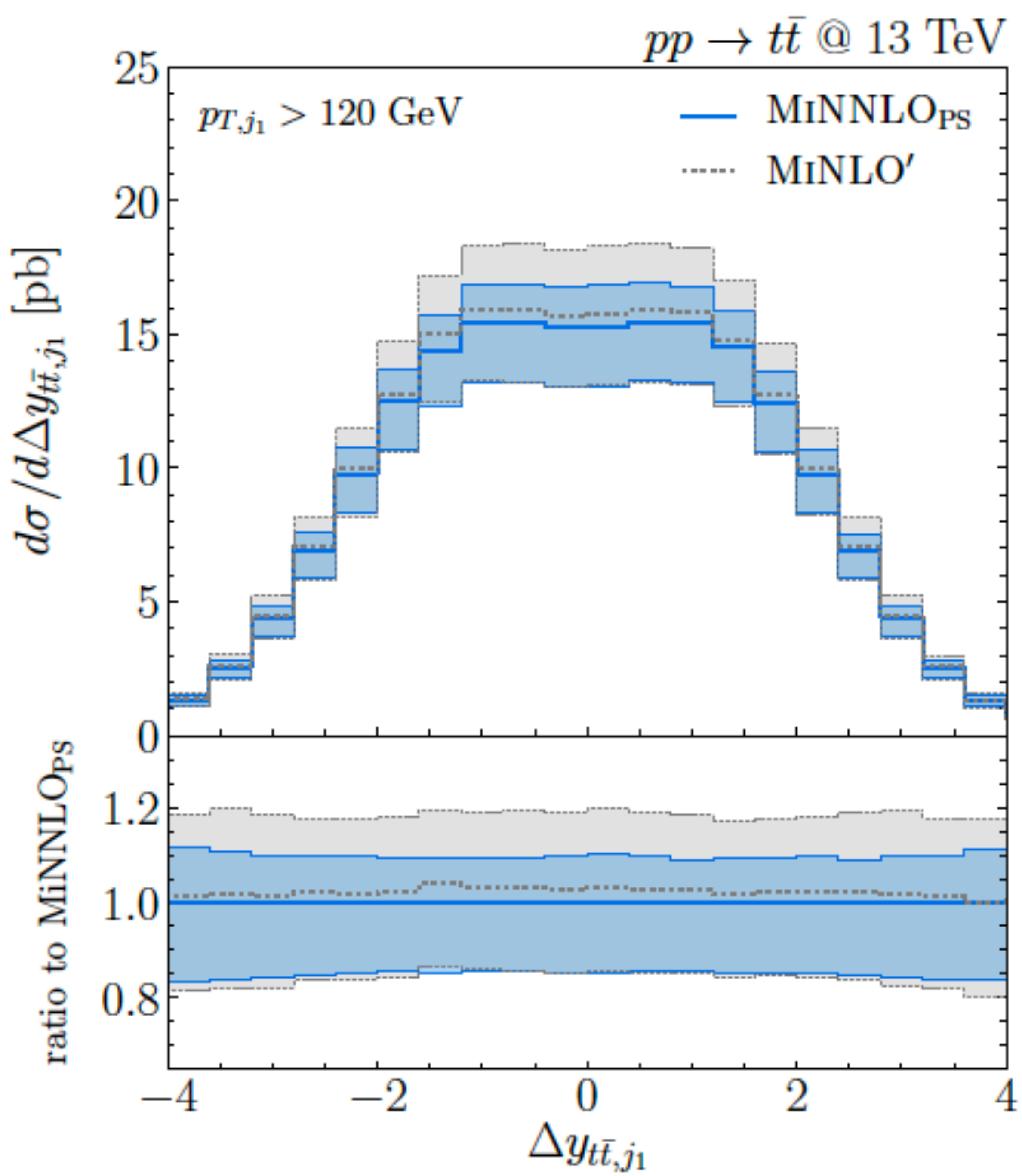
Distance in rapidity between jet and top-system



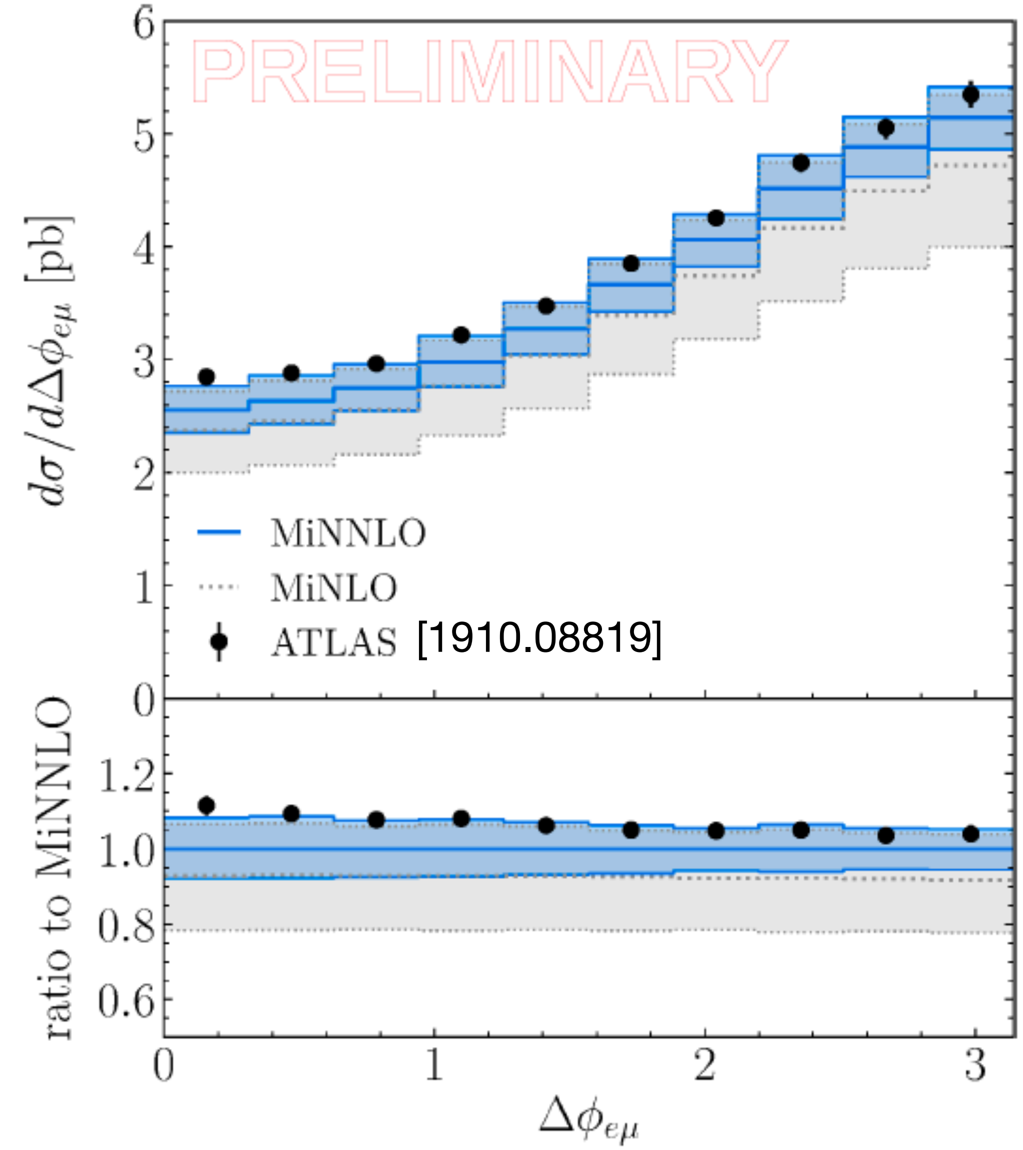
- Large $p_{T,j1}$-cut to be insensitive to NNLO effects
- Good agreement with MiNLO' and MiNNLOPS (both NLO accurate)

Preliminary results

Top-decays included using ratio of tree-level decays and undecayed matrix elements (like Madspin with spin correlations)

[Following the ttJ implementation in POWHEG of Alioli, Moch, Uwer 1110.5251]

Azimuthal angle between muon and electron in fully leptonic decay mode



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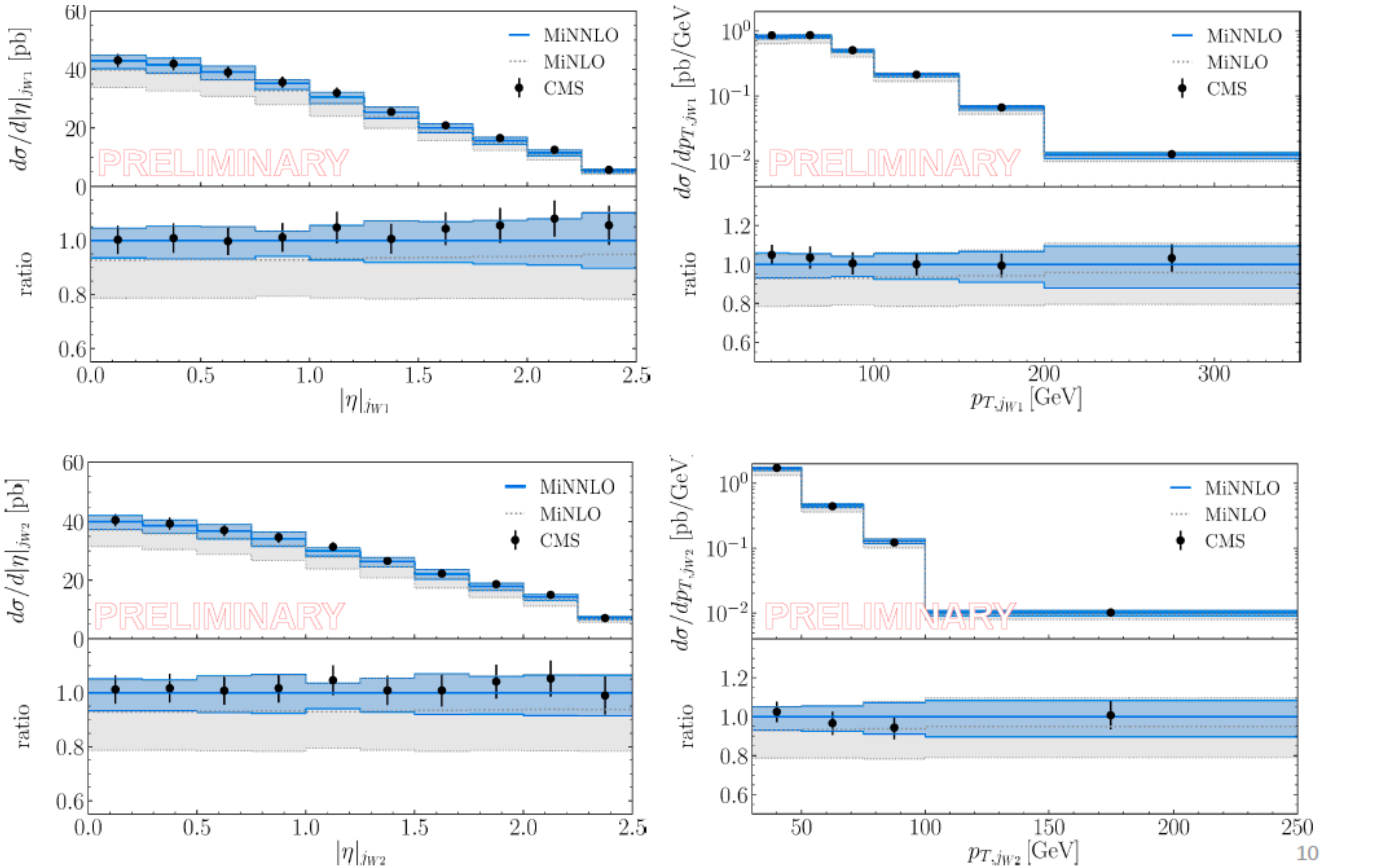
Pseudorapidity and transverse momentum of jets from hadronically decaying W (ordered in p_T, j_{W1}, j_{W2}), data from CMS semileptonic analysis of 1803.08856]



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Conclusions

- Presented results for $t\bar{t}$ matched to parton shower preserving NNLO accuracy using MiNNLO$_{\text{PS}}$ procedure
- Code implemented in POWHEG BOX V2 and publicly available upon request
- First NNLO+PS generator for a coloured process
- Validation with NNLO results
- Good agreement with ATLAS/CMS data
- Preliminary results including top-decays with spin correlations
- Further phenomenological studies (e.g. scale settings) and further validation to come