Top pair production at NNLO matched to parton showers

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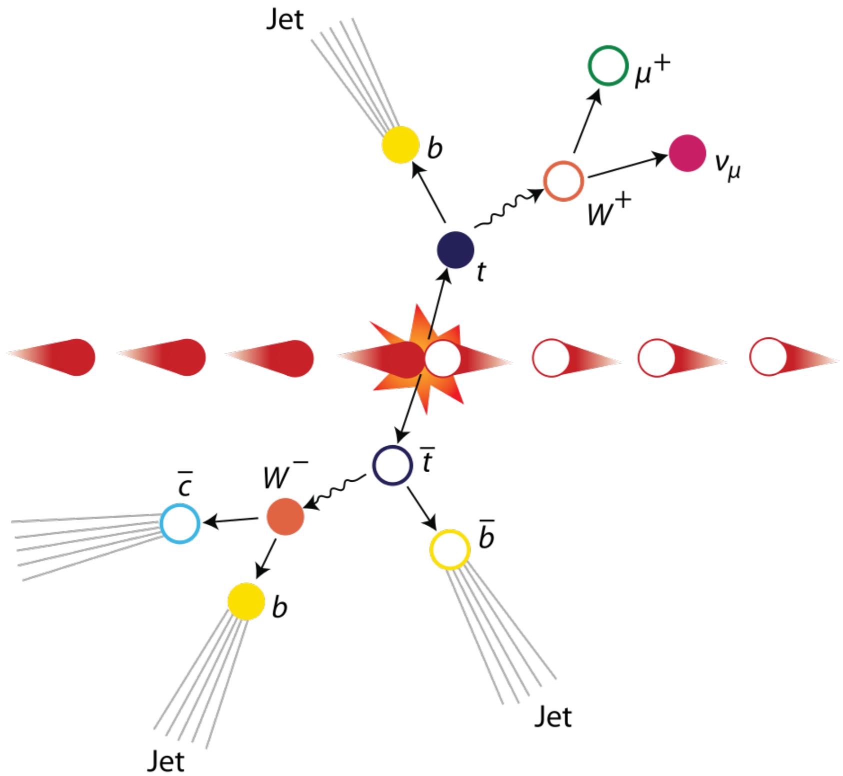
Introduction

- Top-quark pair production is the main source of top quarks at the LHC

- Small experimental uncertainties need to be matched with precise theory predictions

- Event generators combining hard scattering with PS and hadronization are crucial in the analyses and for a more direct theory-experiment comparison

- However, when computing inclusive observables current $t\bar{t}$ MC generators are only NLO accurate



- A NNLO+PS formulation for $t\bar{t}$ was long awaited, but highly non trivial!

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

NNLO+PS for color singlets
MiNLO+reweight [Hamilton, Nason, Zanderighi '12]
Geneva [Alioli, Bauer, Berggren, Tackmann, Walsh, Zuberi '13]
UNNLOPS [Höche, Prestel '14]
MiNNLOPS [Monni, Nason, Re, Wiesemann, Zanderighi '19]
[Monni, Re, Wiesemann '20]

Known for almost a decade, however NNLO+PS for $t\bar{t}$ available only now!
[JM, Monni, Nason, Re, Wiesemann, Zanderighi; 2012.14267]

MiNNLO$_{PS}$ method for $t\bar{t}$

MiNNLO$_{PS}$ originally developed for the production of a **colour singlet F**

It is built upon **MiNLO** procedure implemented within the **POWHEG** method

POWHEG

[Nason 2004]

- NLO event generator interfaced to parton showers
- Hardest emission generated first at NLO accuracy
- Event subsequently fed to shower for softer emissions
- POWHEG method for F+jet:

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

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

- Cutoff on p_T needed to avoid jet being unresolved

MiNLO

[Hamilton, Nason, Oleari, Zanderighi, 2012]

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

- Thanks to Sudakov, MiNLO for F+j is finite even when 1$^{\rm st}$ jet is unresolved
- Inclusive NLO accuracy is achieved by including B_2 term in the Sudakov and setting scales (in R, V and Sudakov expansion) to p_T

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

MiNNLO method extends inclusive accuracy to **NNLO** while keeping NLO accuracy for F+J

MiNNLO$_{\text{PS}}$ method

[Monni, Nason, Re, Wiesemann, Zanderighi '19]
[Monni, Re, Wiesemann '20]

- Derivation based on the connection between **MiNLO** and **q_T-resummation**

Starting point: factorization formula at low transverse momentum

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

The following identity can be derived for the differential NNLO cross section

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Phi_{\mathrm{F}}\mathrm{d}p_{\mathrm{T}}} = \frac{\mathrm{d}}{\mathrm{d}p_{\mathrm{T}}}\left\{\exp[-\tilde{S}(p_{\mathrm{T}})]\mathcal{L}(p_{\mathrm{T}})\right\} + R_f(p_{\mathrm{T}})$$

Finite remainder

After some manipulation

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Phi_{\mathrm{F}}\mathrm{d}p_{\mathrm{T}}} = \exp[-\tilde{S}(p_{\mathrm{T}})]\left\{\frac{\alpha_s(p_{\mathrm{T}})}{2\pi}\left[\frac{\mathrm{d}\sigma_{\mathrm{FJ}}}{\mathrm{d}\Phi_{\mathrm{F}}\mathrm{d}p_{\mathrm{T}}}\right]^{(1)}\left(1+\frac{\alpha_s(p_{\mathrm{T}})}{2\pi}[\tilde{S}(p_{\mathrm{T}})]^{(1)}\right) + \left(\frac{\alpha_s(p_{\mathrm{T}})}{2\pi}\right)^2\left[\frac{\mathrm{d}\sigma_{\mathrm{FJ}}}{\mathrm{d}\Phi_{\mathrm{F}}\mathrm{d}p_{\mathrm{T}}}\right]^{(2)} + \left(\frac{\alpha_s(p_{\mathrm{T}})}{2\pi}\right)^3[D(p_{\mathrm{T}})]^{(3)} + \text{regular terms}\right\}$$

Already in MiNLO

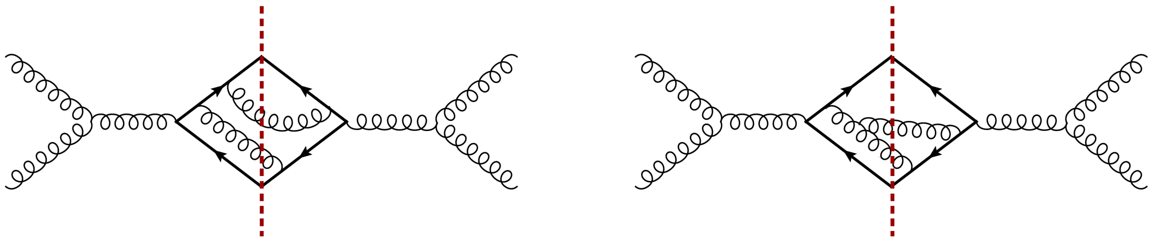
Beyond accuracy

Extra term to achieve NNLO accuracy, depending on NNLL resummation coeffs

Finally the $D^{(3)}$ terms are embedded in the POWHEG $\overline{B}$ function

Extending MiNNLO for $t\bar{t}$

[JM, Monni, Nason, Re, Wiesemann, Zanderighi '20]



More complicated IR structure due to final state soft radiation

Color singlet:

$$d\sigma^{(\mathrm{sing})} \sim d\sigma^{(0)}_{c\bar{c}} \times \exp\left[-S_c(b)\right] \times \left[H C_1 C_2\right]_{c\bar{c};a_1 a_2} \times f_{a_1} f_{a_2}$$

Heavy quark:

Operator in color space leading to color correlations

$$d\sigma^{(\mathrm{sing})} \sim d\sigma^{(0)}_{c\bar{c}} \times \exp\left[-S_c(b)\right] \times \left[\mathrm{Tr}(\mathbf{H}\boldsymbol{\Delta}) C_1 C_2\right]_{c\bar{c};a_1 a_2} \times f_{a_1} f_{a_2}$$

$$\mathrm{Tr}(\mathbf{H}\boldsymbol{\Delta}) \sim \langle \mathcal{M} | \boldsymbol{\Delta} | \mathcal{M} \rangle$$

IR regulated virtual corrections

$$\boldsymbol{\Delta} \sim \exp\left\{ -\int_{b_0^2/b^2}^{M} \frac{dq^2}{q^2} \boldsymbol{\Gamma}(\alpha_s(q)) \right\}^{\dagger} \mathbf{D}(\alpha_s(b_0/b), \phi) \exp\left\{ -\int_{b_0^2/b^2}^{M} \frac{dq^2}{q^2} \boldsymbol{\Gamma}(\alpha_s(q)) \right\}$$

Exponential of soft anomalous dimension matrix

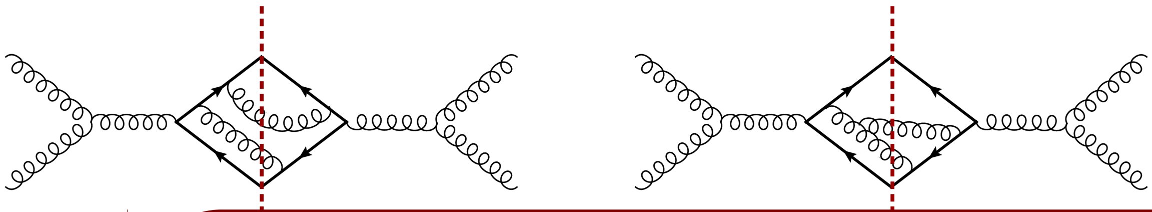
Operator leading to azimuthal correlations

In particular it is not straightforward to describe the NNLO cross section as

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Phi_{\mathrm{F}}\mathrm{d}p_{\mathrm{T}}} = \frac{\mathrm{d}}{\mathrm{d}p_{\mathrm{T}}} \left\{ \exp[-\tilde{S}(p_{\mathrm{T}})] \mathcal{L}(p_{\mathrm{T}}) \right\} + R_f(p_{\mathrm{T}}) \qquad (1)$$

Extending MiNNLO for $t\bar{t}$

[JM, Monni, Nason, Re, Wiesemann, Zanderighi '20]



More complicated IR structure due to final state soft radiation

Color sin

Heavy qu

Exp

However, in eq. (1) we are only interested in the fixed order accuracy

We can modify the $t\bar{t}$ factorization formula as long as we keep NNLO accuracy (and LL in view of the matching with the shower)

We can take it into a shape that resembles the colorless final state case (sum of colour-singlet-like factorization formulas with complex exponentials)

Connection to colour singlet case becomes simpler and MiNNLO$_{PS}$ for $t\bar{t}$ can be derived!

Obs: perturbative ingredients in MiNNLO$_{PS}$ for $t\bar{t}$ are the same that are needed to apply q_T-subtraction to $t\bar{t}$
[Catani, Devoto, Grazzini, Kallweit, JM, Sargsyan '19]

In particular it is not straightforward to describe the NNLO cross section as

$$\frac{d\sigma}{d\Phi_F dp_T} = \frac{d}{dp_T}\left\{\exp[-\tilde{S}(p_T)]\mathcal{L}(p_T)\right\} + R_f(p_T) \qquad (1)$$

Numerical results

Modified logarithm:

$$L = \begin{cases} \log(Q/p_T) & \text{for } p_T<Q/2 \\ 0 & \text{for } p_T>Q \\ \text{Smooth interpolation in the middle} \end{cases}$$

Scale setting:

- Overall Born coupling: $\alpha_s(m_{t\bar{t}})$
- MiNNLO scale setting: $\mu_R = \mu_F = m_{t\bar{t}}\, e^{-L}$, $Q = m_{t\bar{t}}/2$
- Scale uncertainties through 7-point variation
- No direct correspondence between MiNNLO scales and NNLO scales
- Upon integration over p_T they are of the order of $m_{t\bar{t}}$

Comparison to NNLO (computed with MATRIX) with $\mu_0 = m_{t\bar{t}}$

Showering:

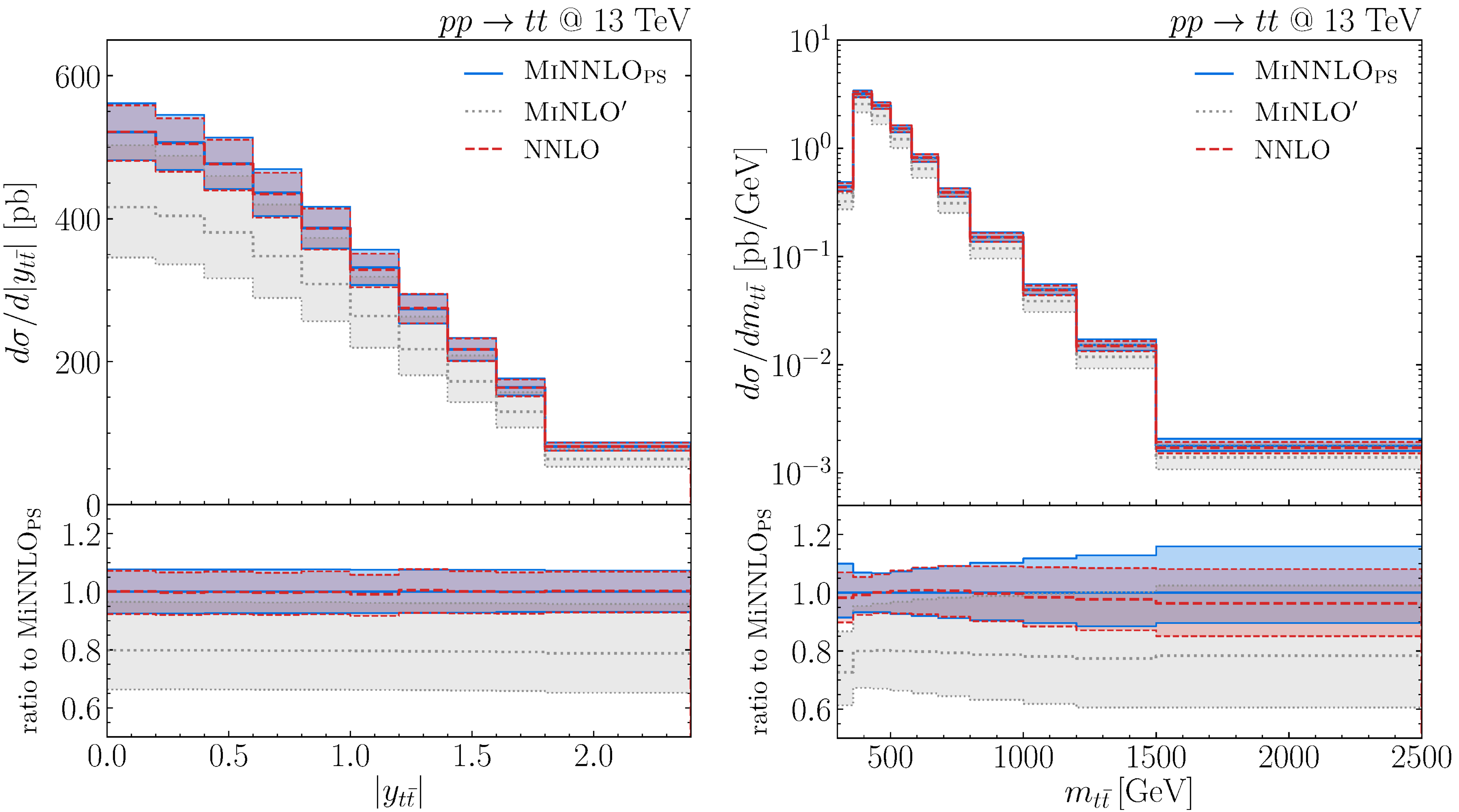
We shower with Pythia8, keeping top quarks stable for comparison against FO

Total cross section:

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

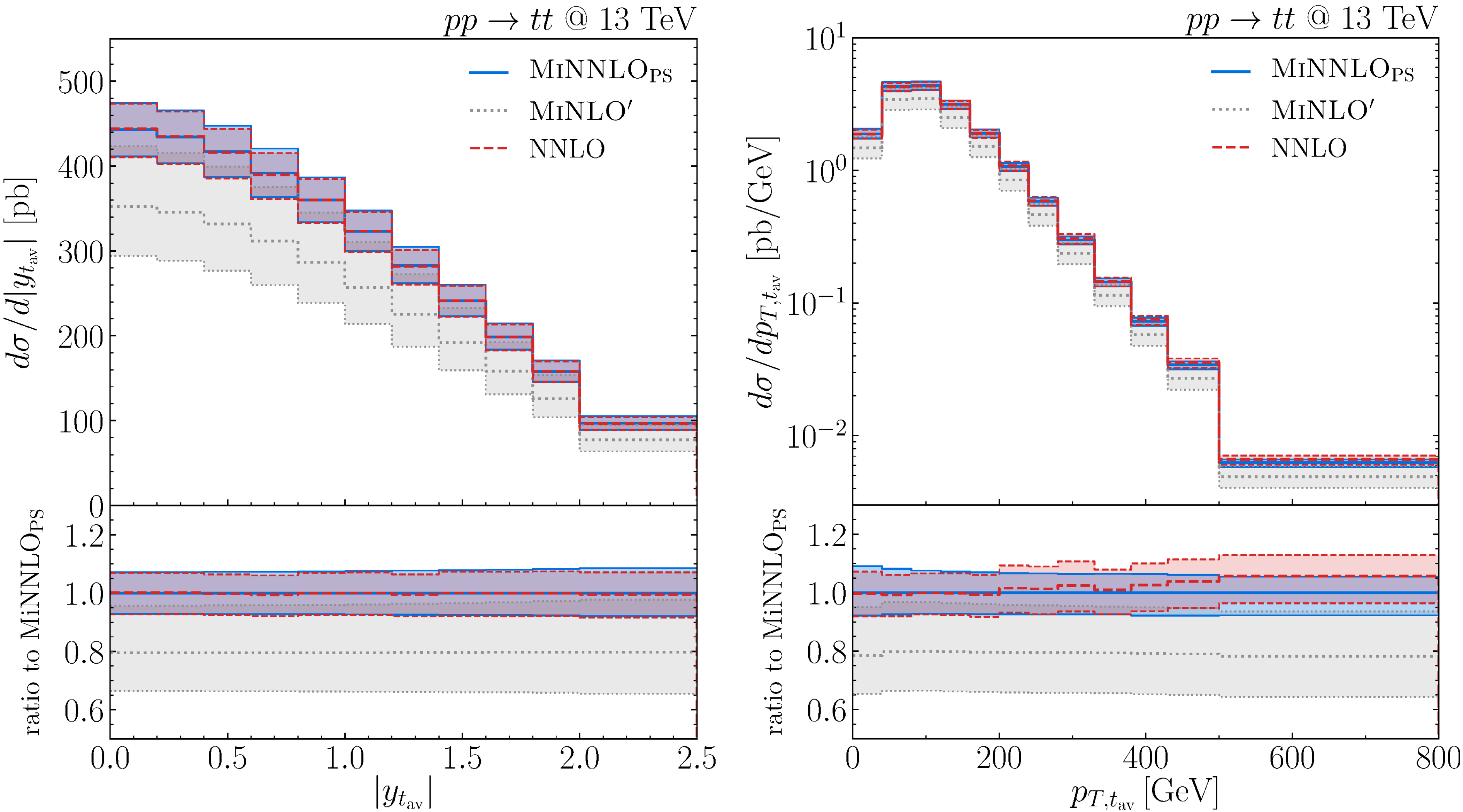
- Excellent agreement between MiNNLO and NNLO, differences at the per-mille level
- Similar size of uncertainties between MiNNLO and NNLO results, large reduction w.r.t. MiNLO’

[JM, Monni, Nason, Re, Wiesemann, Zanderighi ‘20, see supp. material in journal version]



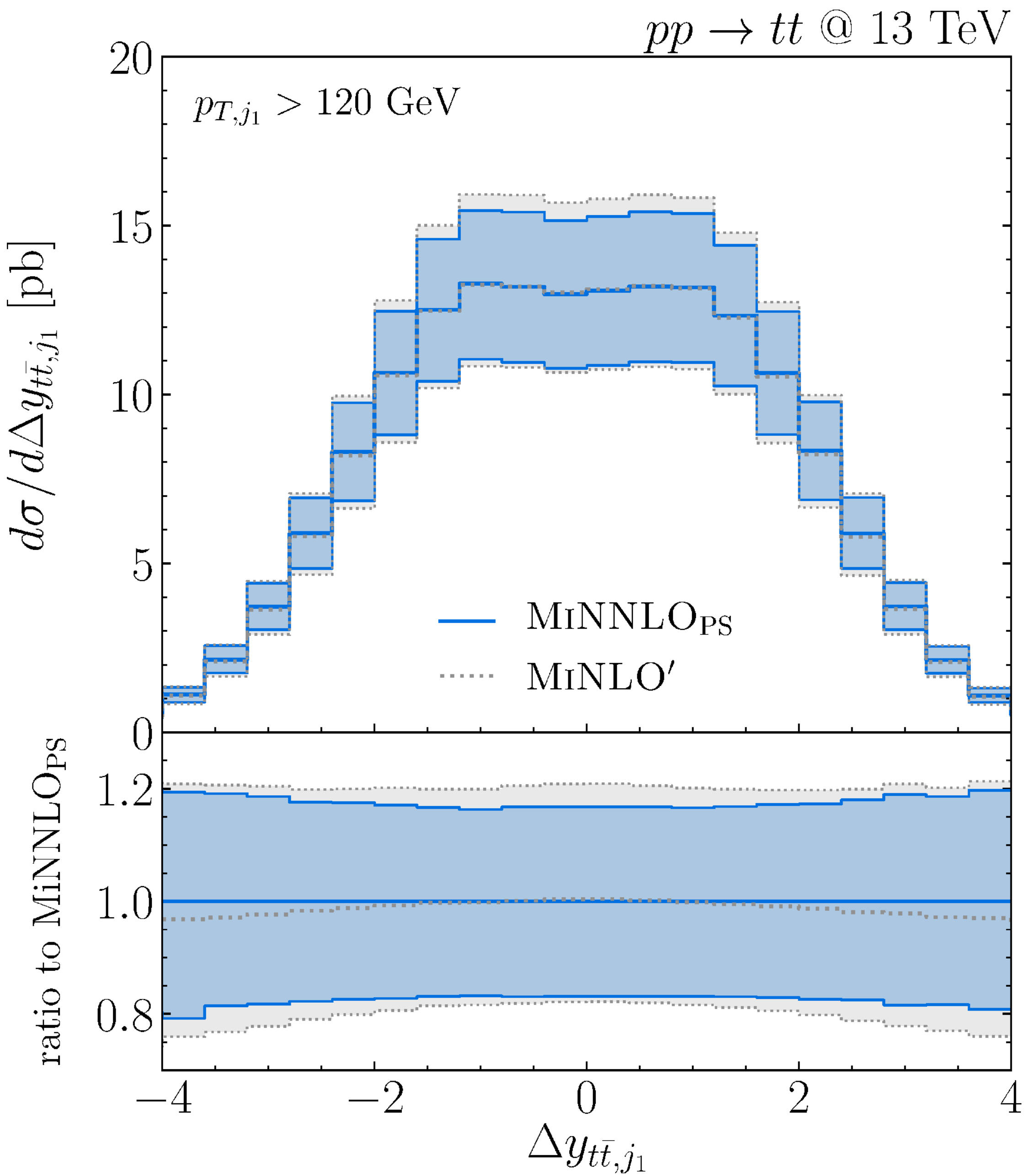
- Rapidity and invariant mass of the $t\bar{t}$ system
- Full compatibility between MiNNLO and NNLO results in the whole range, excellent description of the shapes
- Large reduction of the scale uncertainties compared to MiNLO’
- Obs: small differences can be expected since scale settings are not equivalent

[JM, Monni, Nason, Re, Wiesemann, Zanderighi ‘20, see supp. material in journal version]



- Average of top and anti-top rapidity and transverse momentum distributions
- Excellent agreement between NNLO and MiNNLO
- MiNNLO scale uncertainties of similar size as NNLO ones

[JM, Monni, Nason, Re, Wiesemann, Zanderighi '20, see supp. material in journal version]

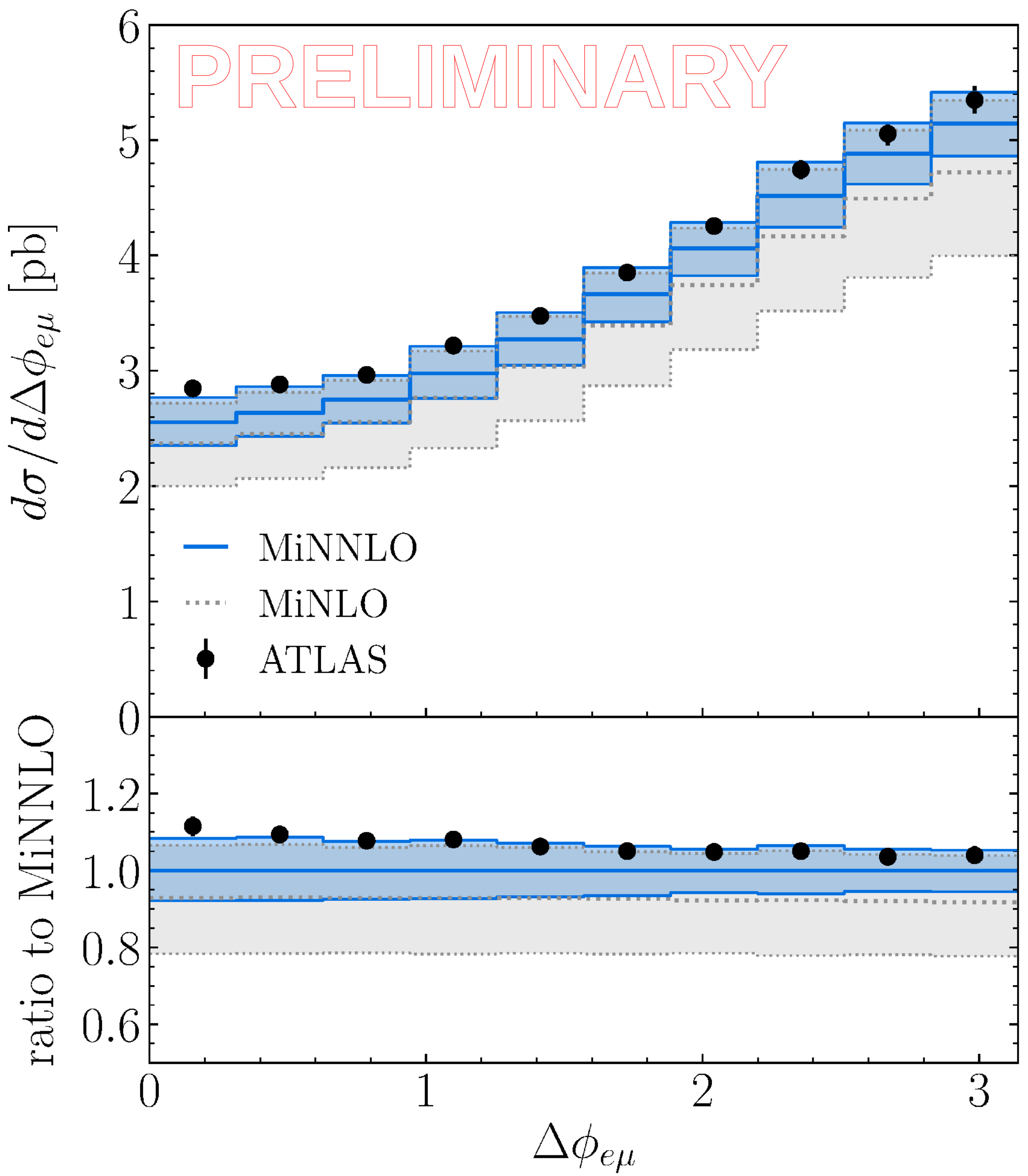


- Rapidity difference between leading jet and $t\bar{t}$ system
- 1-jet observable
- MiNLO' is NLO accurate already
- MiNNLO preserves NLO accuracy
- Obs: relatively large p_T jet in order to be insensitive to NNLO effects

Preliminary results: including top decays using ratio of tree-level decayed and undecayed MEs

[As implemented in POWHEG ttbarj, Alioli, Moch, Uwer 1110.5251]

Azimuthal angle between electron and muon, data from ATLAS fully leptonic analysis [1910.08819]



Preliminary results: including top decays using ratio of tree-level decayed and undecayed MEs

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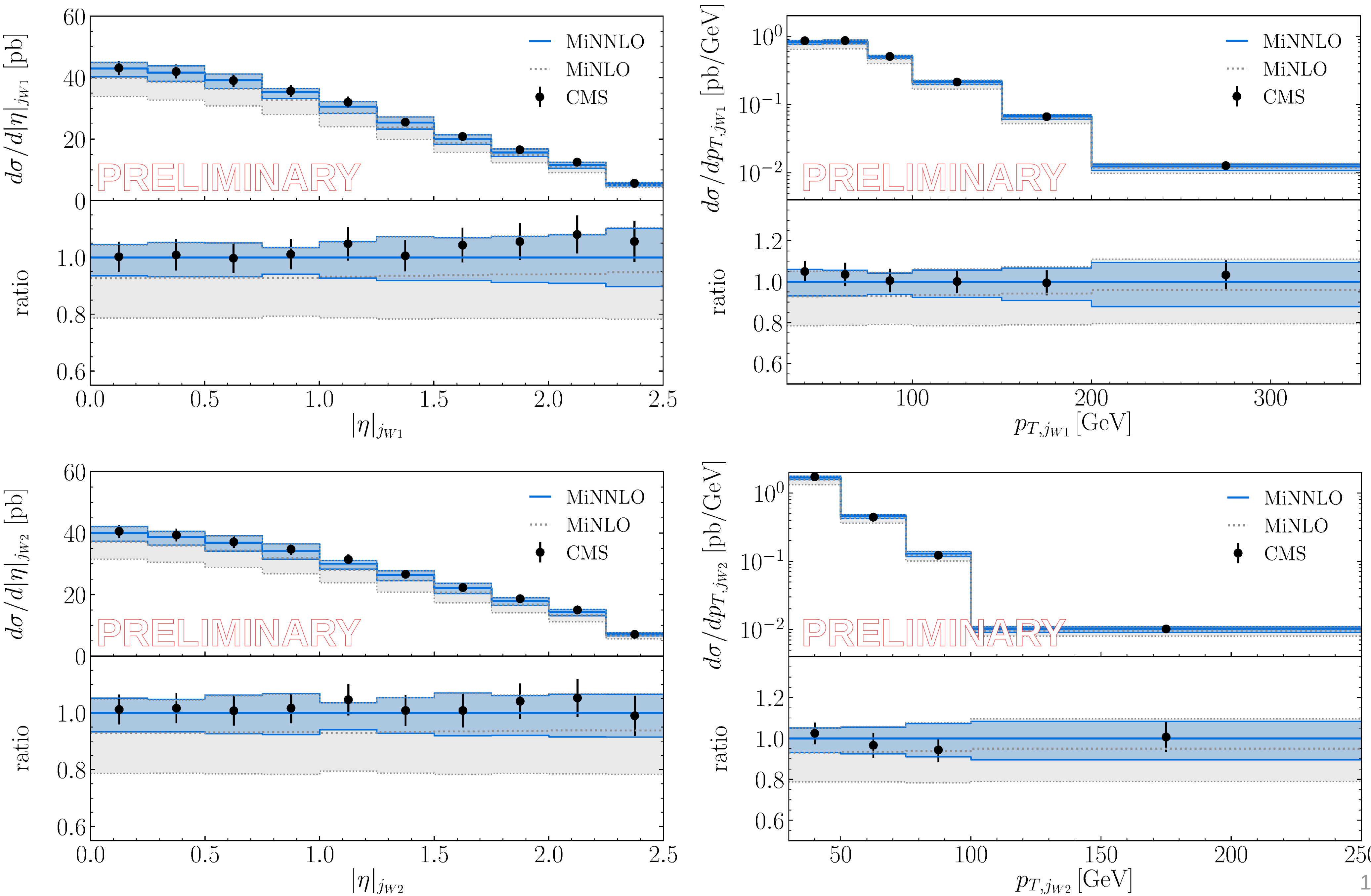
Pseudorapidity and p_T of jets from hadronically decaying W (ordered by p_T, j_{W1} and j_{W2}), data from CMS semileptonic analysis [1803.08856]



Conclusions

- We have presented the matching of the NNLO to parton showers for $t\bar{t}$ based on MiNNLO procedure and implemented in POWHEG-BOX-V2
- MiNNLO method had to be suitable extended to deal with FS radiation
- First case of a NNLO+PS generator for colored final states
- Our results open the way for accurate event generation for $t\bar{t}$
- First comparison with data promising, further phenomenological studies are underway (scale settings, top decays)
- Stay tuned for new results!

Thanks!