Progress in $t\bar{t}$@NNLO+PS

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Standard Model at the LHC 2021

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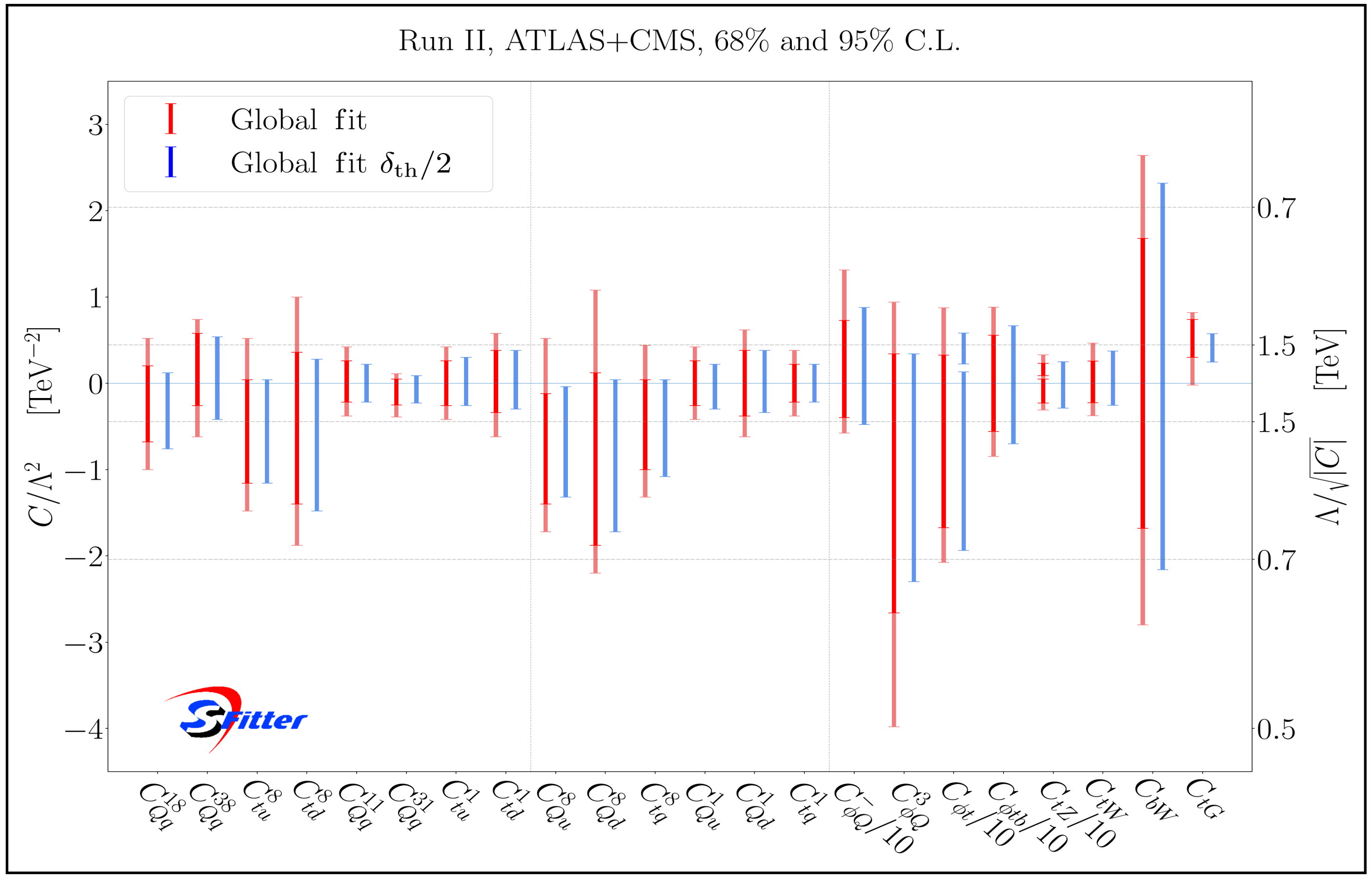
Importance of $t\bar{t}$ at LHC

✦ probe of new physics (top sector: rich BSM/SMEFT sensitivity)

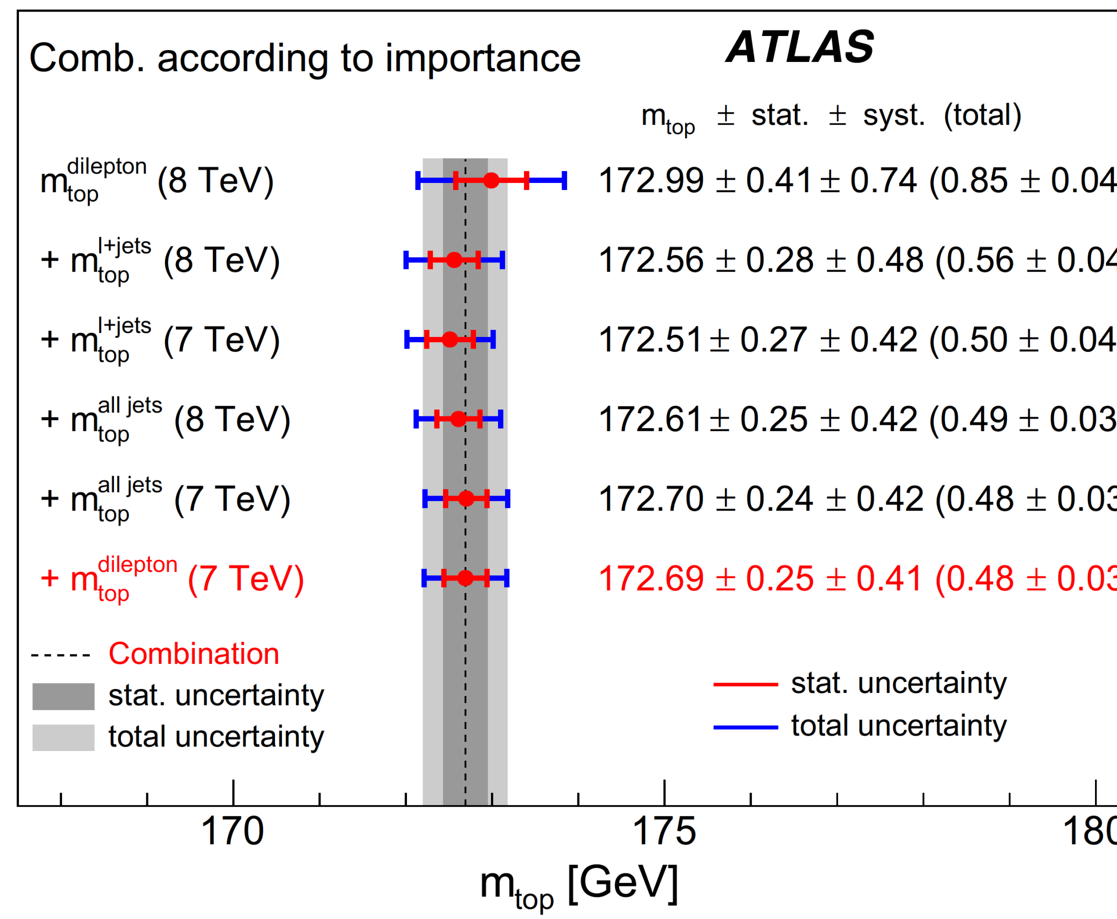
e.g. [Brivio, Bruggisser, Maltoni, Moutafis, Plehn, Vryonidou, Westhoff, Zhang '19]



✦ SM precision measurements

e.g. top mass (or α_s) extraction

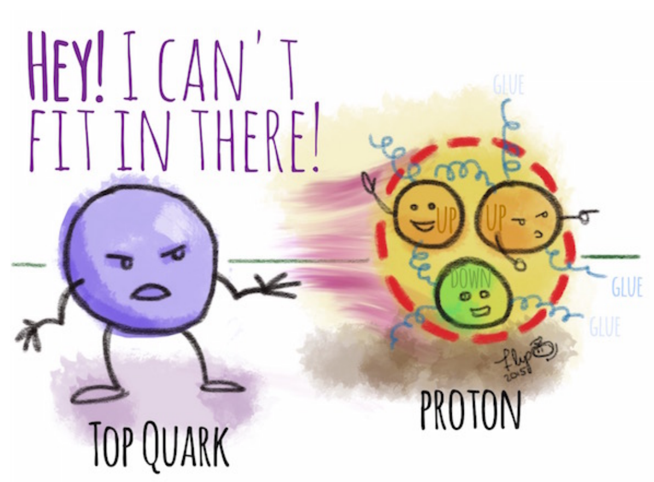
[ATLAS EPJC (2019) 290]



✦ PDF fits

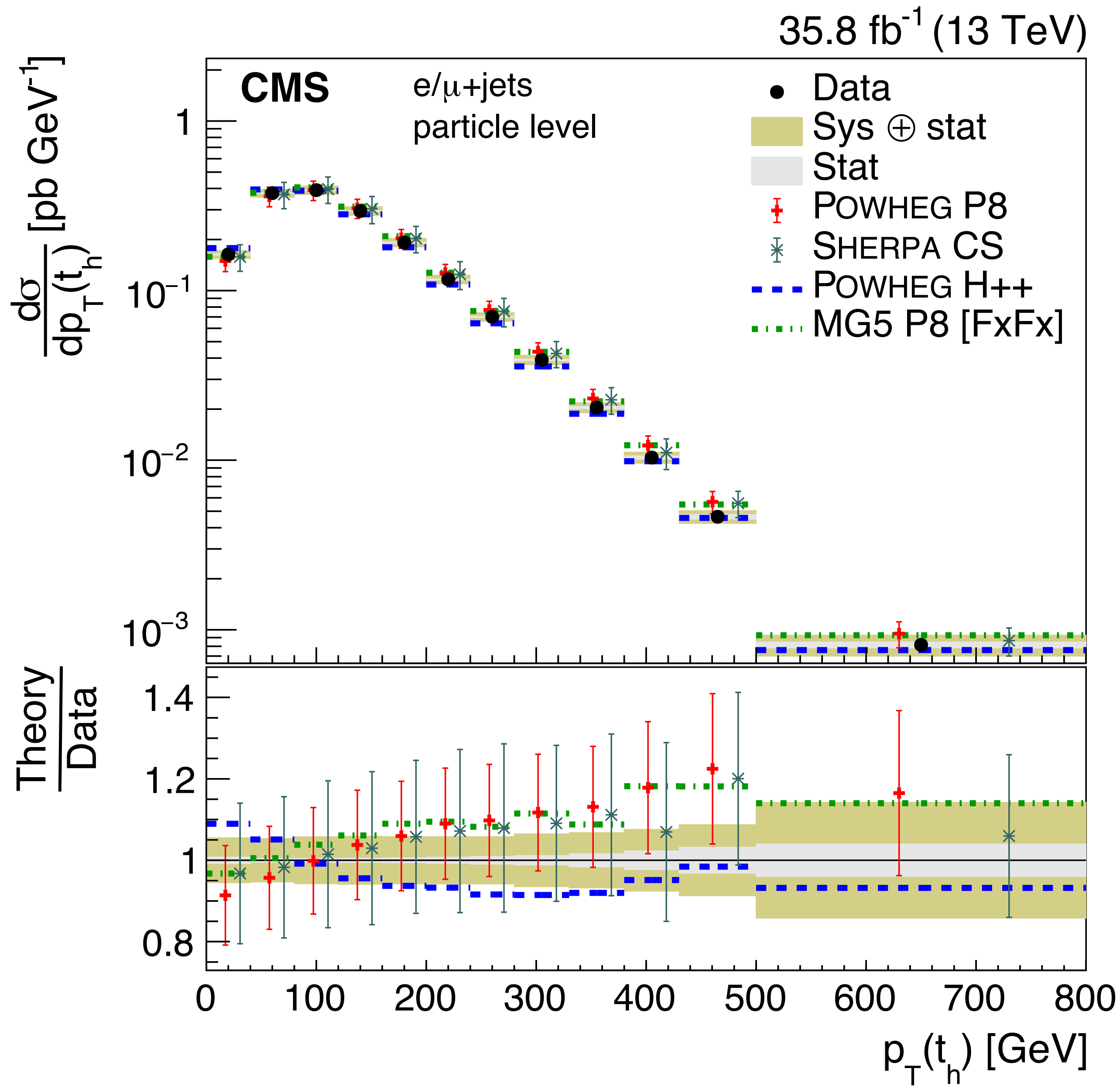
(gluon PDF at large x)

e.g. [Czakon, Mangano, Mitov. Rojo '13]

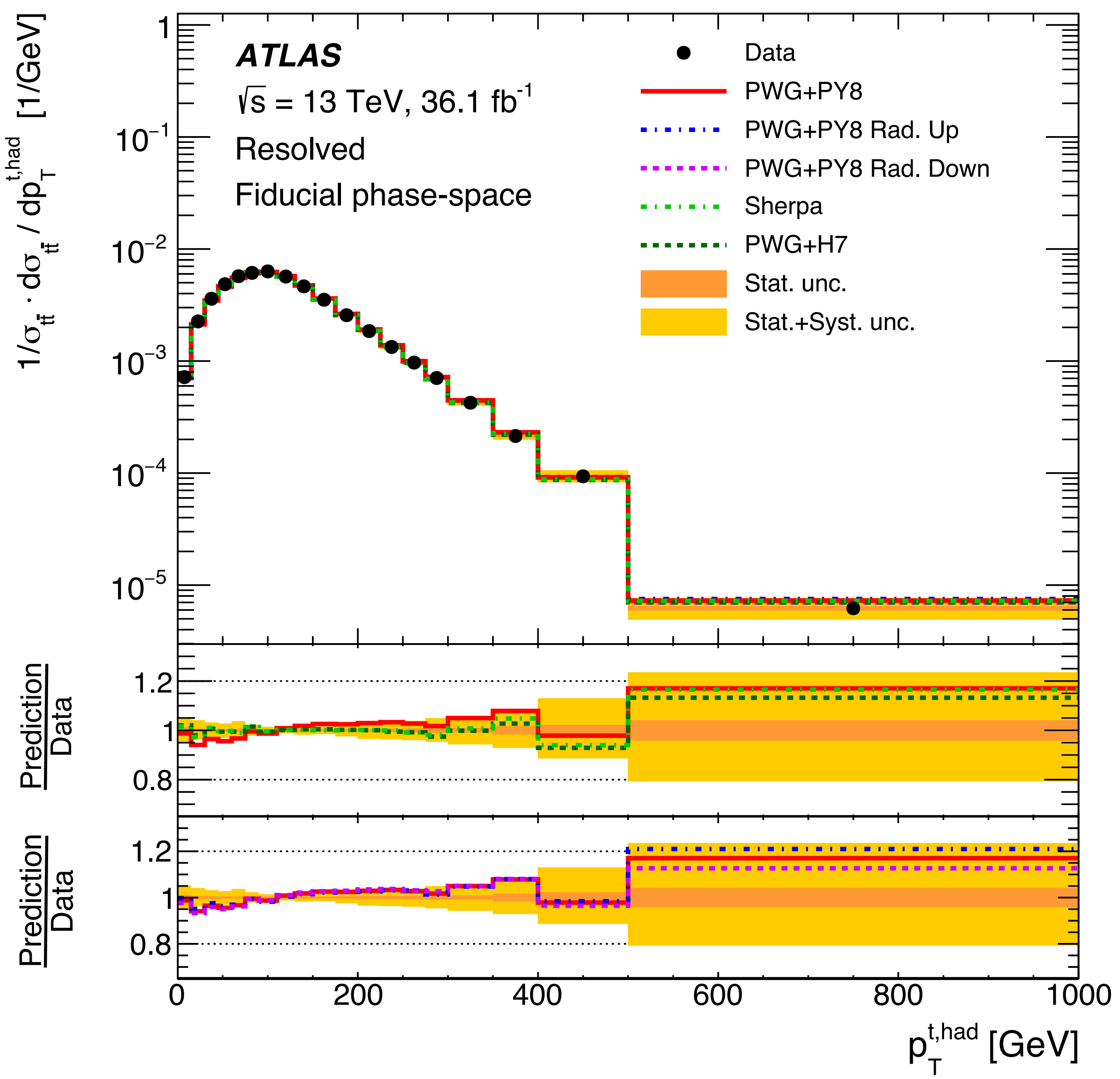


Data/Theory differences in $t\bar{t}$ at LHC

[CMS PRD 97 (2018) 112003]



[ATLAS EPJC 79 (2019) 1028]

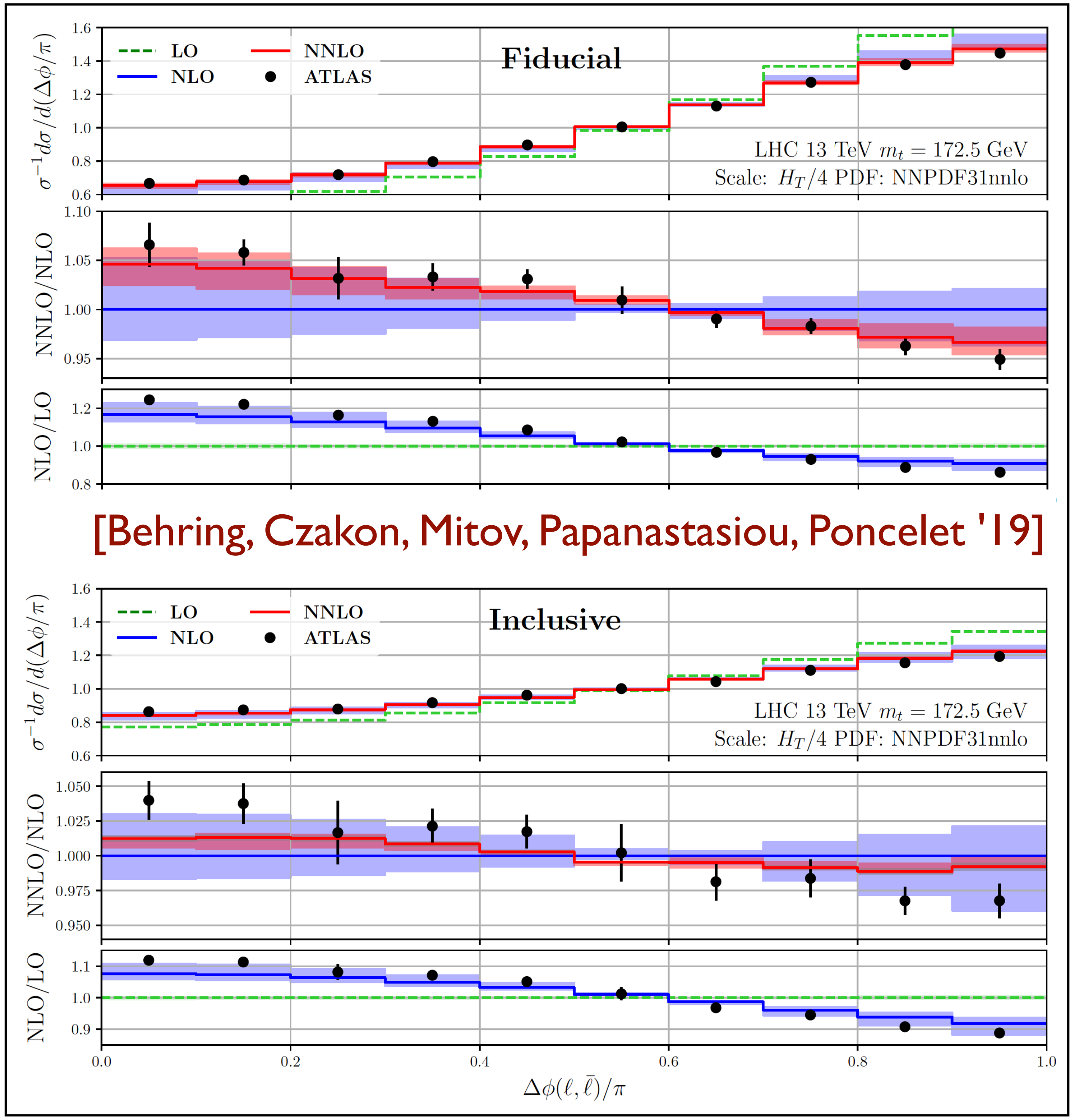


Theory predictions

✦ $t\bar{t}$ at NNLO QCD

[Bärnreuther, Czakon, Mitov '12],
[Czakon, Mitov '12],
[Czakon, Fiedler, Mitov '13],
[Czakon, Fiedler, Heymes, Mitov '15 '16],
... and many more applications/advancements ...

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



[Behring, Czakon, Mitov, Papanastasiou, Poncelet '19]

✦ NNLO+PS for colour singlets

- ***MiNLO+reweight*** [Hamilton, Nason, Zanderighi '12]
- ***Geneva*** [Alioli, Bauer, Berggren, Tackmann, Walsh, Zuberi '13]
- ***UNNLOPS*** [Höche, Prestel '14]
- ***MiNNLO$_{PS}$*** [Monni, Nason, Re, MW, Zanderighi '19], [Monni, Re, MW '20]

Theory predictions

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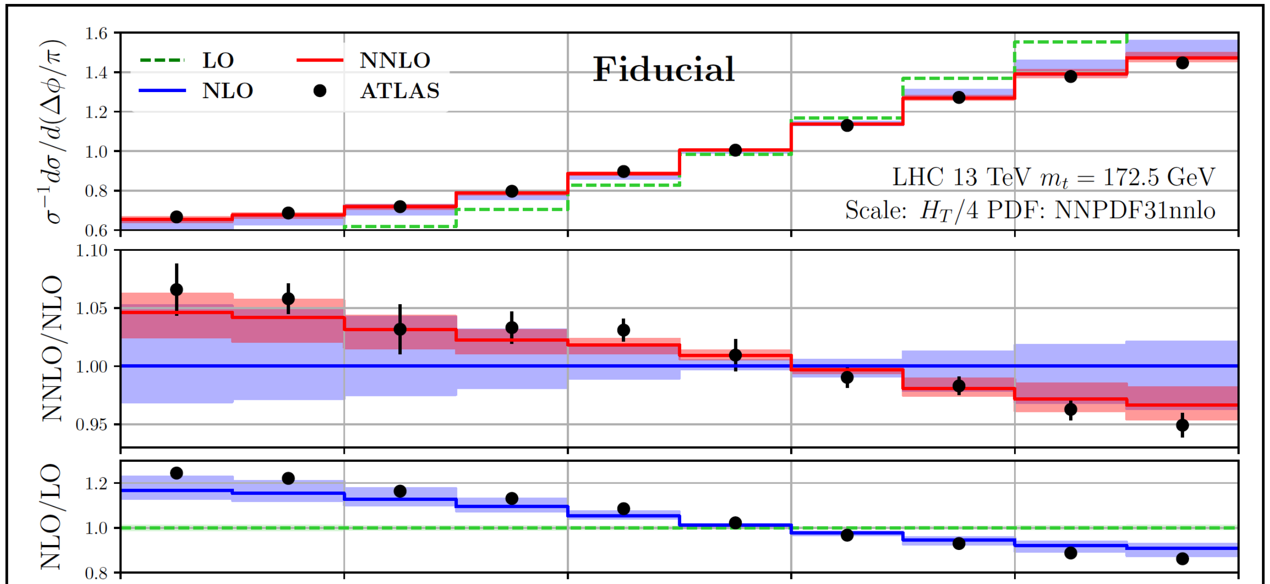
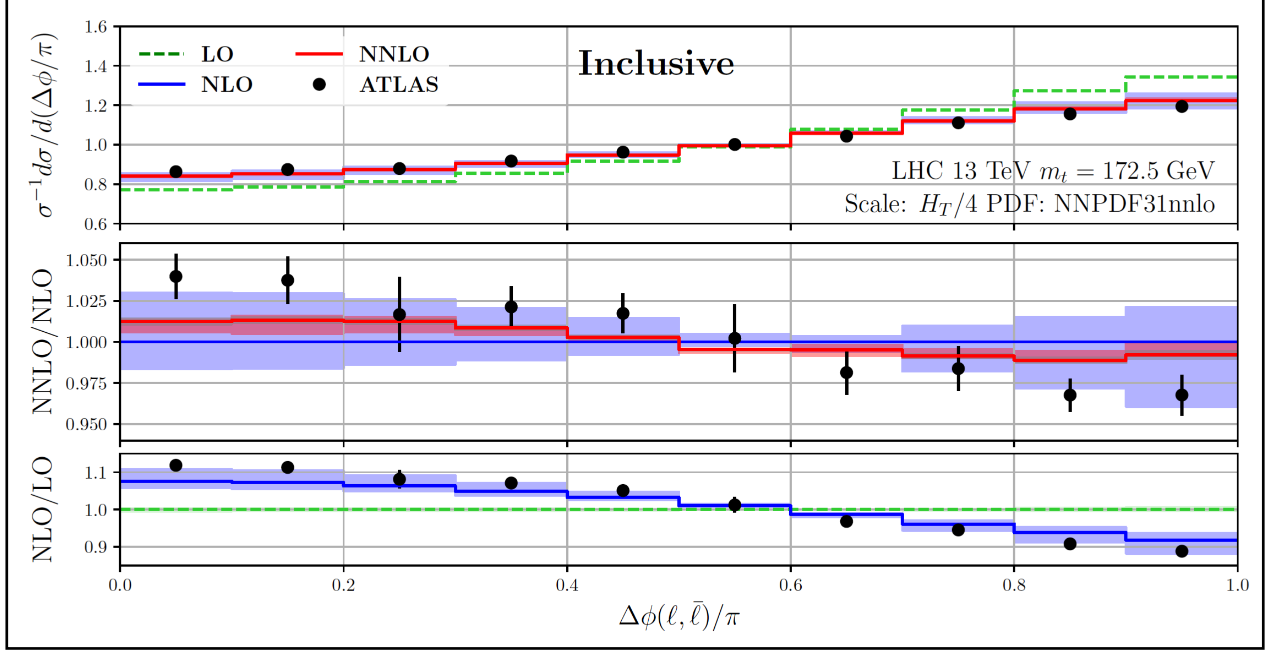
known for almost 10 years !
→ yet $t\bar{t}$ NNLO+PS only now



[Behring, Czakon, Mitov, Papanastasiou, Poncelet '19]



✦ NNLO+PS for colour singlets

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- ❖ ***MiNNLO$_{PS}$*** [Monni, Nason, Re, MW, Zanderighi '19], [Monni, Re, MW '20]

NNLO+PS: What do we want to achieve?

- NNLO accuracy for observables inclusive on radiation. $[d\sigma/dy_F]$
- NLO(LO) accuracy for $F+1(2)$ jet observables (in the hard region). $[d\sigma/dp_{T,j_1}]$
  - appropriate scale choice for each kinematics regime
- resummation from the Parton Shower (PS) $[\sigma(p_{T,j} < p_{T,\text{veto}})]$
- preserve the PS accuracy (leading log - LL)
- possibly, no merging scale required.

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<u>This talk:</u>

★ NNLO+PS for colour singlets

- ❖ MiNNLO$_{\text{PS}}$ formalism
- ❖ some examples

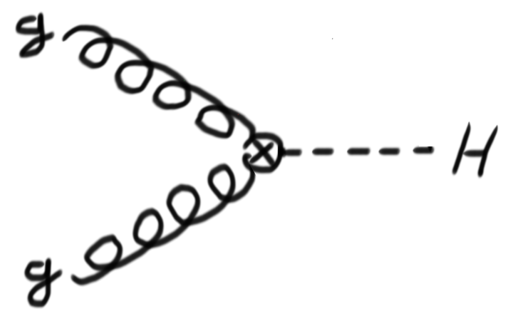
★ NNLO+PS for heavy quarks

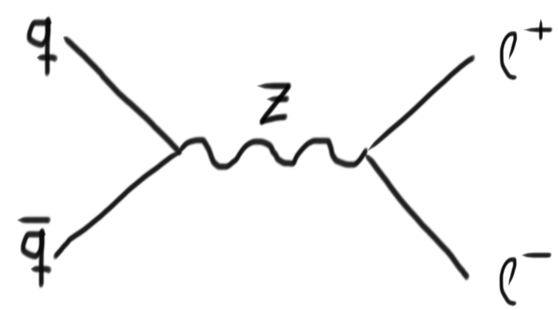
- ❖ complications & formalism
- ❖ results

NNLO+PS

- seminal approaches for NLO+PS many years ago (POWHEG, MC@NLO)

- first NNLO+PS for simple 2→1 processes
  - ***MiNLO+reweighting*** [Hamilton, Nason, Zanderighi '12, + Re '13], [Karlberg, Hamilton, Zanderighi '14]
  - ***Geneva*** [Alioli, Bauer, Berggren, Tackmann, Walsh, Zuberi '13], [Alioli, Bauer, Berggren, Tackmann, Walsh '15]
  - ***UNNLOPS*** [Höche, Prestel '14]





- ***MiNNLO$_{PS}$***: new approach with enormous potential
  [Monni, Nason, Re, MW, Zanderighi '19], [Monni, Re, MW '20]
  - physically sound (no new unphysical scale)
  - applicable beyond 2→1 processes (even beyond colour-singlet)
  - numerically efficient

MiNNLO$_{\text{PS}}$ for colour singlets

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

✦ starting equation:

$$\frac{d\sigma_F^{\text{res}}}{dp_T\, d\Phi_B} = \frac{d}{dp_T}\left\{e^{-S}\mathscr{L}\right\} = e^{-S}\underbrace{\left\{S'\mathscr{L} + \mathscr{L}'\right\}}_{\equiv D}$$

$$\mathscr{L} \sim H\,(C \otimes f)\,(C \otimes f)$$

(symbolically)

✦ combine with F + jet fixed order $d\sigma_{FJ}$:

$$d\sigma^F = d\sigma_F^{\text{res}} + [d\sigma_{FJ}]_{\text{f.o.}} - [d\sigma_F^{\text{res}}]_{\text{f.o.}} = e^{-S}\left\{ D + \frac{[d\sigma_{FJ}]_{\text{f.o.}}}{\underbrace{[e^{-S}]_{\text{f.o.}}}_{1-S^{(1)}\ldots}} \underbrace{- \frac{[d\sigma_F^{\text{res}}]_{\text{f.o.}}}{[e^{-S}]_{\text{f.o.}}}}_{-D^{(1)}-D^{(2)}\ldots} \right\}$$

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- expanded up to $\alpha_s^3(p_T)$ we have: (resummation scheme: $\mu_R = \mu_F \sim p_T$)

(very symbolic/simplified)

$$d\sigma_F^{\text{MiNNLO}} \sim e^{-S}\left\{ \underbrace{d\sigma_{FJ}^{(1)}}_{\sim\alpha_s(p_T)}\underbrace{\left(1 + S^{(1)}\right) + d\sigma_{FJ}^{(2)}}_{\sim\alpha_s^2(p_T)} + \underbrace{\left(D - D^{(1)} - D^{(2)}\right)}_{\sim\alpha_s^3(p_T)} + \text{regular} \right\}$$

$\rightarrow D^{(3)} + \mathcal{O}(\alpha_s^4)$

MiNNLO$_{PS}$ for colour singlets

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

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MiNLO

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MiNNLO$_{\text{PS}}$ for colour singlets

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

- starting equation: $$\frac{d\sigma_F^{\text{res}}}{dp_T\, d\Phi_B} = \frac{d}{dp_T}\left\{e^{-S}\mathscr{L}\right\} = e^{-S}\underbrace{\left\{S'\mathscr{L} + \mathscr{L}'\right\}}_{\equiv D}$$

$$\mathscr{L} \sim H\,(C \otimes f)\,(C \otimes f)$$

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- combine with F + jet fixed order $d\sigma_{FJ}$:

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MiNLO **NNLO correction**

$$d\sigma_F^{\text{MiNNLO}} \sim \boxed{e^{-S}\left\{\underbrace{d\sigma_{FJ}^{(1)}}_{\sim\alpha_s(p_T)}\left(1 + S^{(1)}\right) + \underbrace{d\sigma_{FJ}^{(2)}}_{\sim\alpha_s^2(p_T)}\right.} + \boxed{\underbrace{\left(D - D^{(1)} - D^{(2)}\right)}_{\sim\alpha_s^3(p_T)}} + \left.\boxed{\text{regular}}\right\}$$

beyond accuracy

MiNNLO$_{\text{PS}}$ for colour singlets

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

$$\mathrm{d}\sigma_F^{\mathrm{MiNNLO}} \sim e^{-S} \left\{ \mathrm{d}\sigma_{FJ}^{(1)}\left(1 + S^{(1)}\right) + \mathrm{d}\sigma_{FJ}^{(2)} + \left(D - D^{(1)} - D^{(2)}\right) + \mathrm{regular} \right\}$$

✦ Why singular $\alpha_s^3(p_T)$ terms needed for NNLO in $\alpha_s(Q)$ (after p_T integration) ?

→ ***power counting:*** $\int_{\Lambda_{\mathrm{QCD}}}^{Q} \mathrm{d}p_T\, e^{-S}\, \alpha_s^n(p_T) \frac{1}{p_T} \log^m \frac{Q}{p_T} \sim \mathcal{O}\left(\alpha_s^{n-\frac{m+1}{2}}(Q)\right)$

MiNNLO$_{\text{PS}}$ for colour singlets

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✦ NNLO+PS by constructing POWHEG weight ($\bar{B}$ function) using MiNNLO:

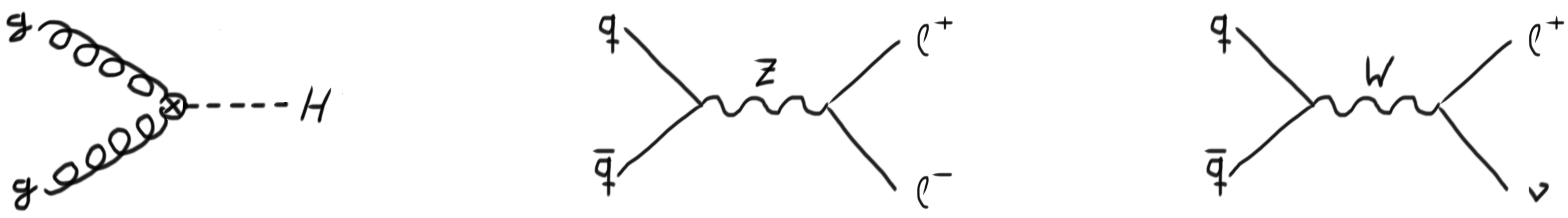
$$\mathrm{d}\sigma_F^{\text{MiNNLO}_{\text{PS}}} = \bar{B}^{\,\text{MiNNLO}_{\text{PS}}} \times \left\{\Delta_{\text{pwg}}(\Lambda_{\text{pwg}}) + \int \mathrm{d}\Phi_{\text{rad}}\Delta_{\text{pwg}}(p_{T,\text{rad}})\frac{R_{FJ}}{B_{FJ}}\right\}$$

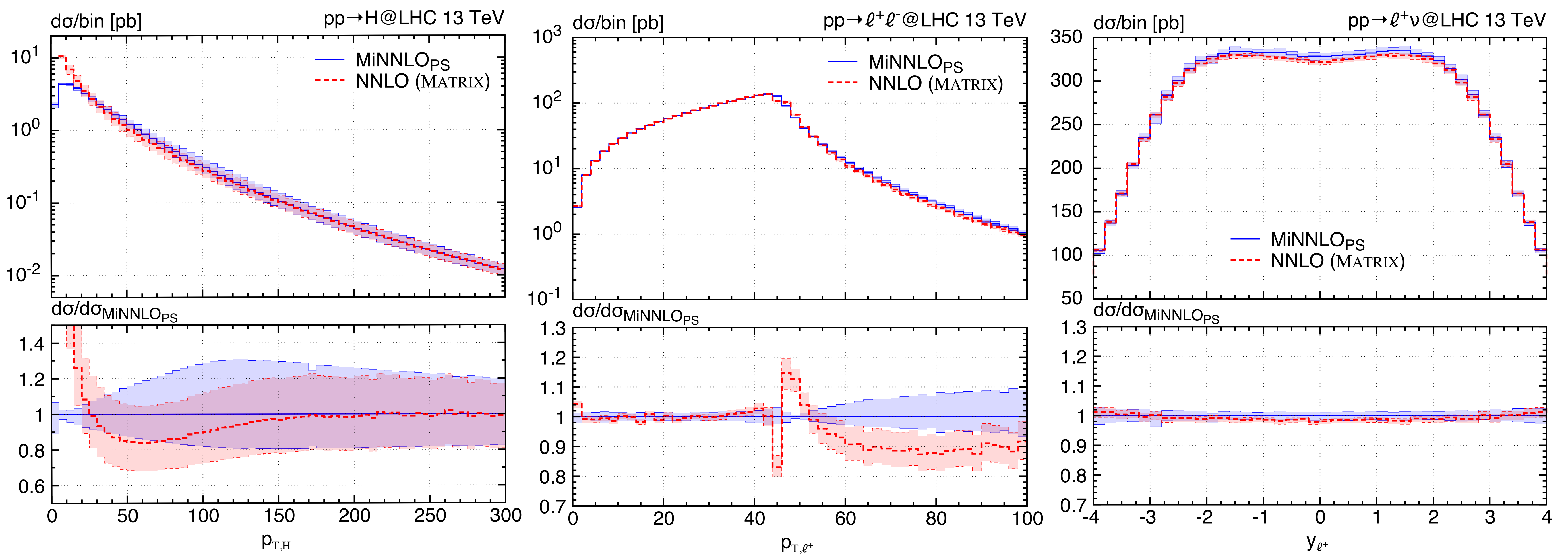
$$\bar{B}^{\,\text{MiNNLO}_{\text{PS}}} \sim e^{-S}\left\{\mathrm{d}\sigma_{FJ}^{(1)}\left(1+S^{(1)}\right)+\mathrm{d}\sigma_{FJ}^{(2)}+\left(D-D^{(1)}-D^{(2)}\right)\times F^{\text{corr}}\right\}$$

→ *spreads NNLO corrections in the F + jet phase space*

MiNNLOPS for 2→1 colour singlets

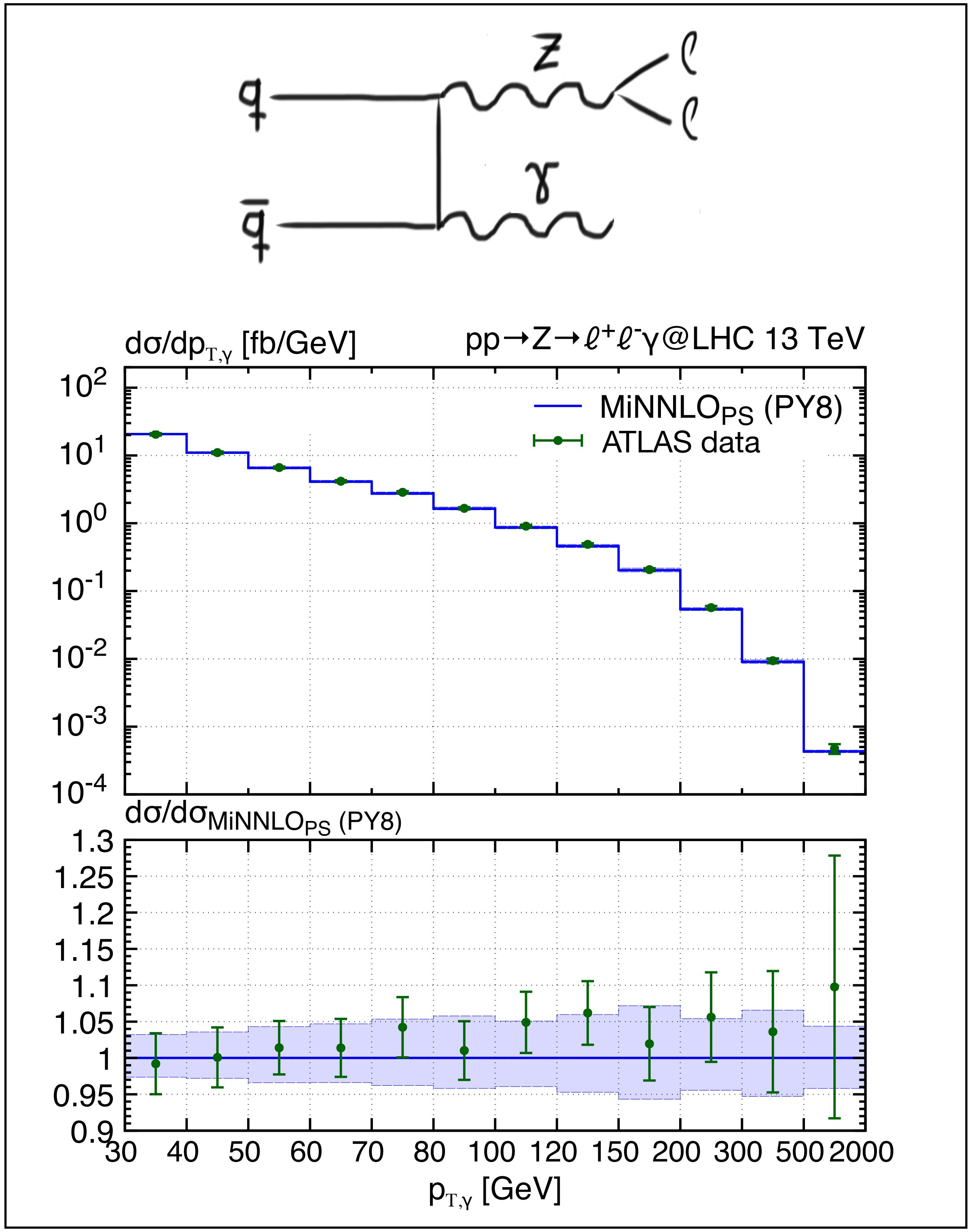
[Monni, Nason, Re, MW, Zanderighi '19], [Monni, Re, MW '20]



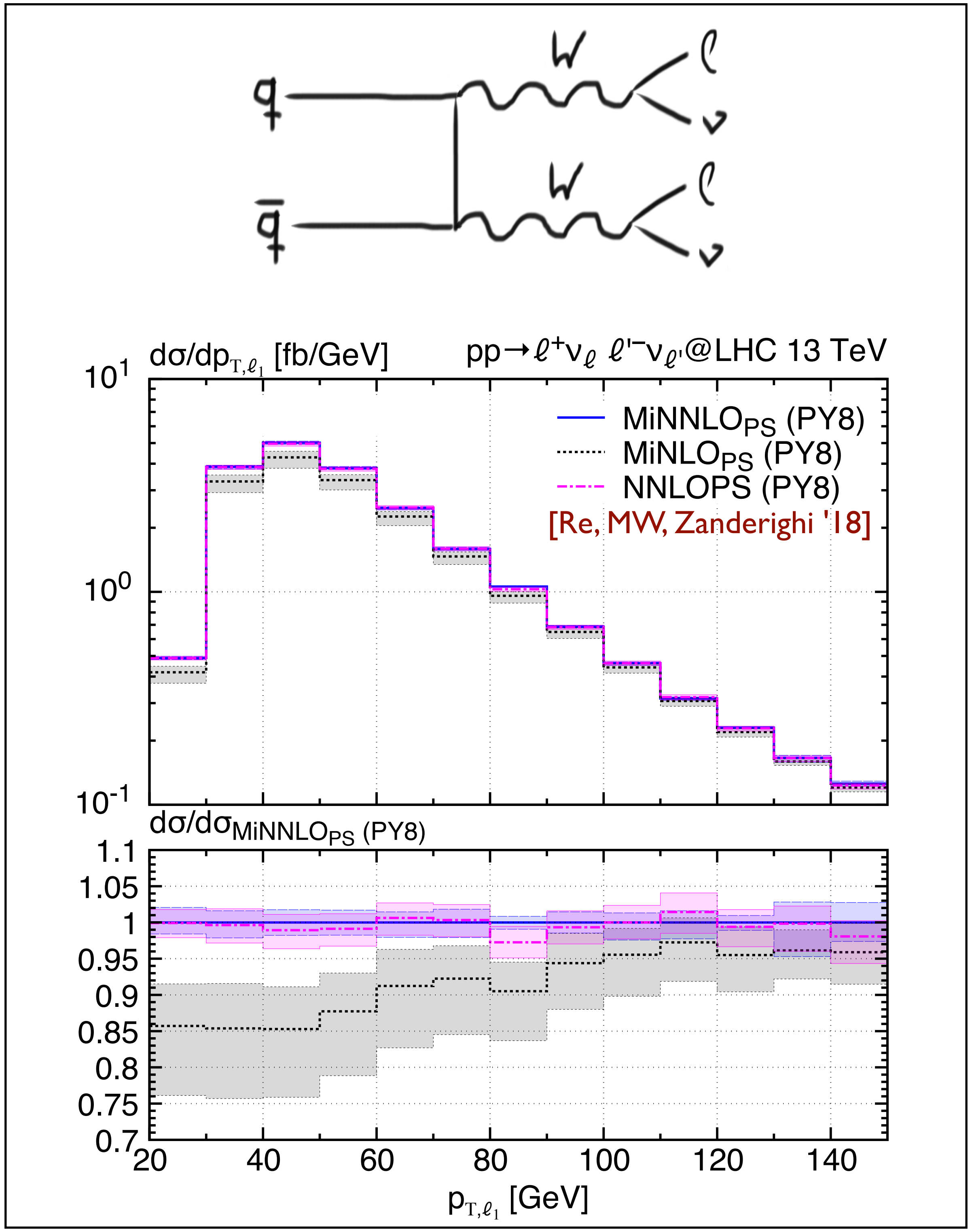


MiNNLO$_{PS}$ for 2→2 colour singlets

[Lombardi, MW, Zanderighi '20]



[Lombardi, MW, Zanderighi '21]



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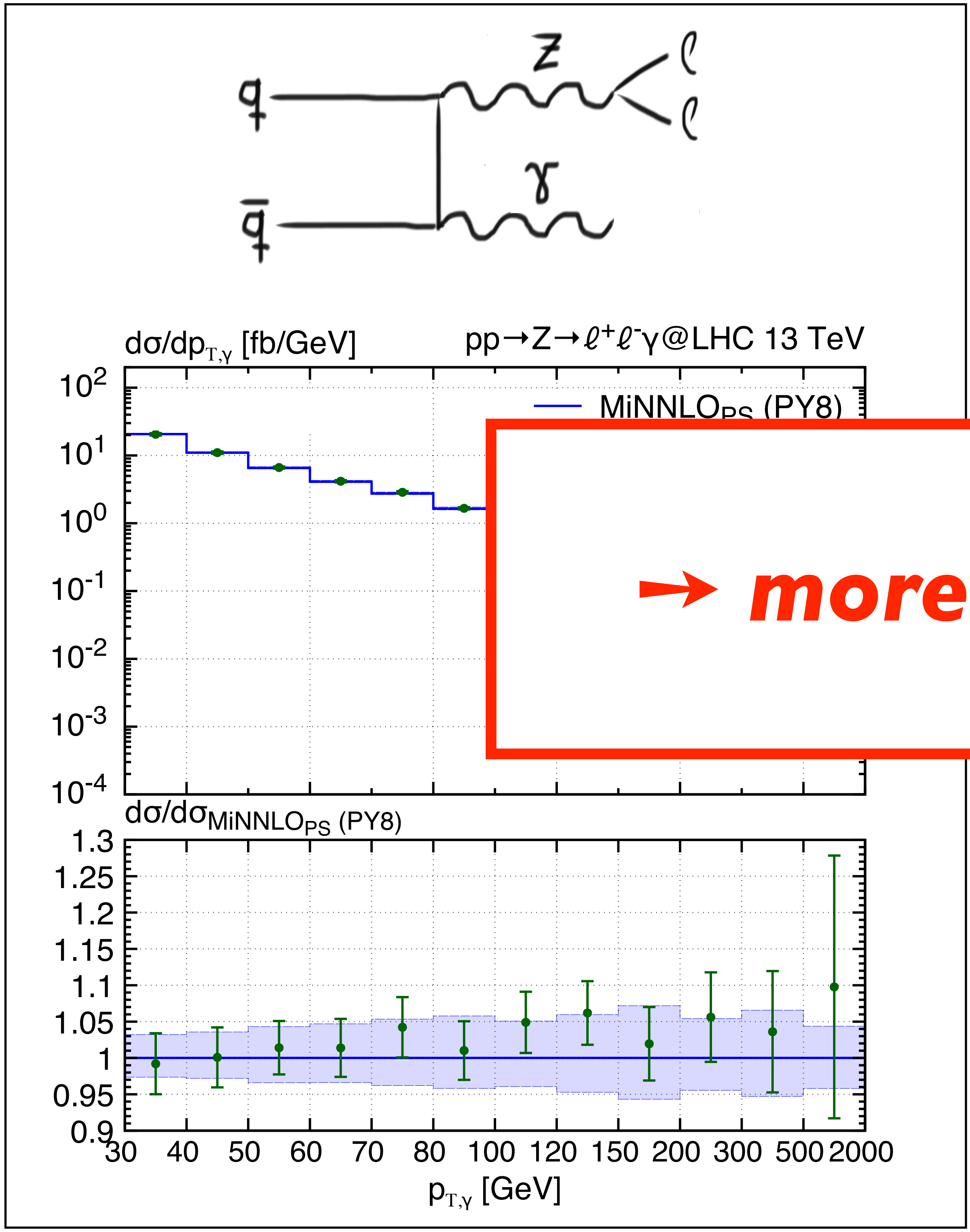

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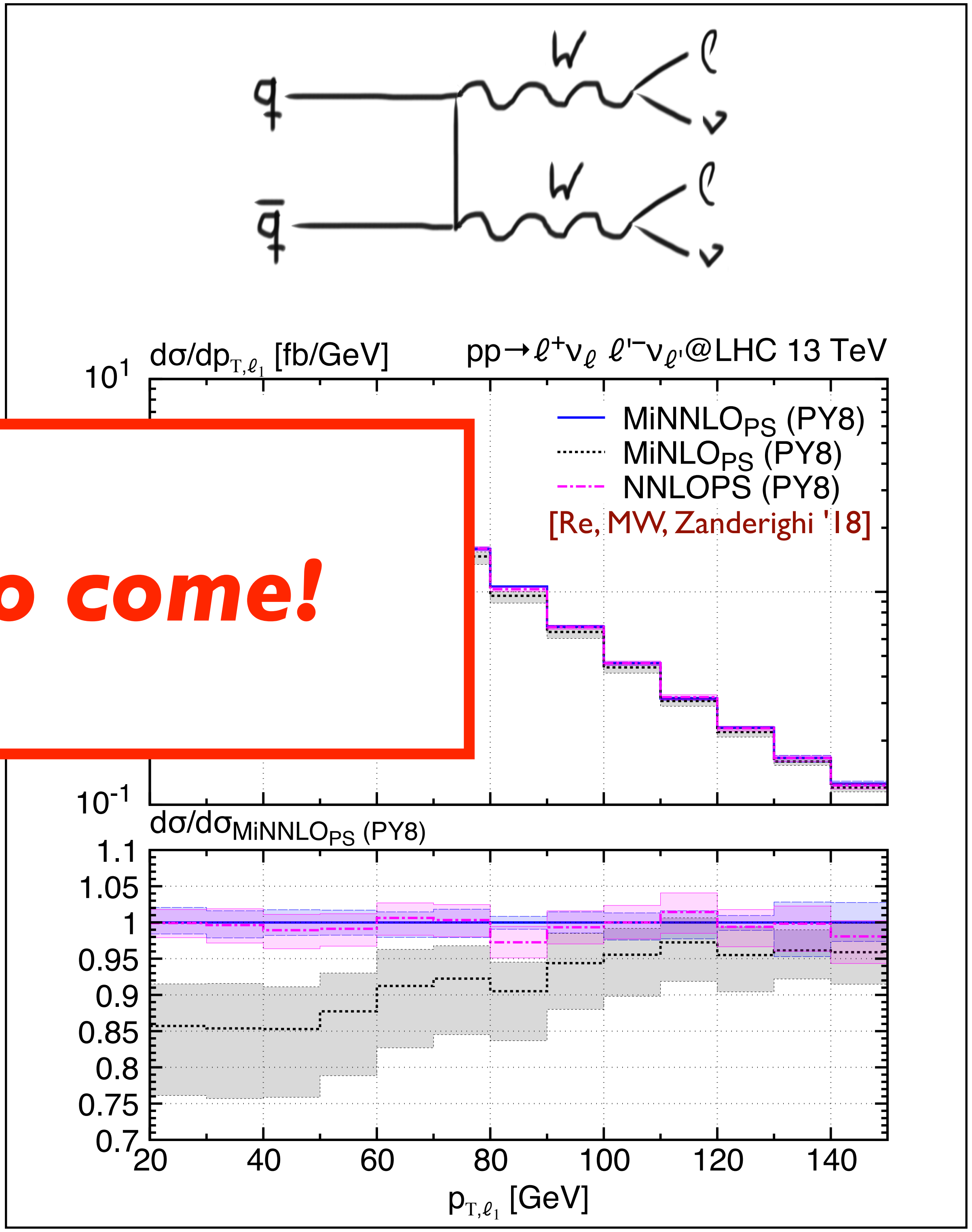
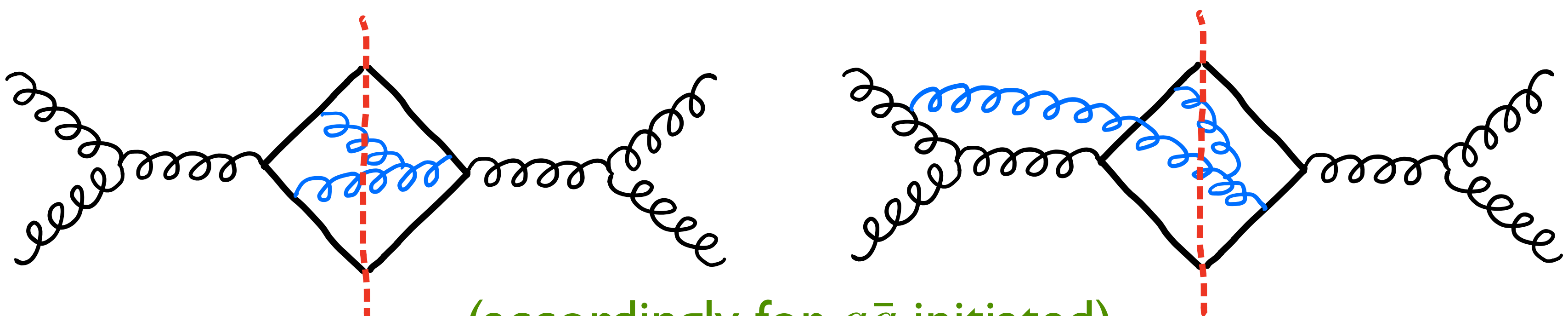


→ more to come!

MiNNLO$_{PS}$ for heavy quarks

[Mazzitelli, Monni, Nason, Re, MW, Zanderighi '20]

- ✦ substantial complication due to final-state radiation and interferences



(accordingly for $q\bar{q}$ initiated)

- ✦ compare resummation formulas (very schematic):

colour singlet: $$\mathrm{d}\sigma^F_{\mathrm{res}} \sim \frac{\mathrm{d}}{\mathrm{d}p_T}\left\{ e^{-S} \quad H \quad (C\otimes f)(C\otimes f)\right\}$$

heavy quark pair: $$\mathrm{d}\sigma^F_{\mathrm{res}} \sim \frac{\mathrm{d}}{\mathrm{d}p_T}\left\{ e^{-S}\, \mathrm{Tr}(\mathbf{H}\boldsymbol{\Delta})\, (C\otimes f)(C\otimes f)\right\}$$

[Catani, Grazzini, Torre '14]

$\boldsymbol{\Delta}$: operator/matrix in colour space that encodes soft emissions of $t\bar{t}$ and interferences

MiNNLOPS for heavy quarks

[Mazzitelli, Monni, Nason, Re, MW, Zanderighi '20]

$$d\sigma^F_{\rm res} \sim \frac{d}{dp_T}\left\{e^{-S}\,\mathrm{Tr}(\mathbf{H}\boldsymbol{\Delta})\,(C\otimes f)\,(C\otimes f)\right\}$$

$$S = -\int \frac{dq^2}{q^2}\left[\frac{\alpha_s(q)}{2\pi}\left(A^{(1)}\log(M/q)+B^{(1)}\right)+\frac{\alpha_s^2(q)}{(2\pi)^2}\left(A^{(2)}\log(M/q)+B^{(2)}\right)+\ldots\right]$$

'B-type' correction to Sudakov

$$\mathrm{Tr}(\mathbf{H}\boldsymbol{\Delta}) = \langle M|\,\boldsymbol{\Delta}\,|M\rangle,\quad \boldsymbol{\Delta}=\mathbf{V}^\dagger\,\mathbf{D}\,\mathbf{V},\quad \mathbf{V}=\exp\left\{-\int\frac{dq^2}{q^2}\left[\frac{\alpha_s(q)}{2\pi}\boldsymbol{\Gamma}_{\mathbf{t}}^{(1)}+\frac{\alpha_s^2(q)}{(2\pi)^2}\boldsymbol{\Gamma}_{\mathbf{t}}^{(2)}\right]\right\}$$

matrix in colour space

MiNNLOPS for heavy quarks

[Mazzitelli, Monni, Nason, Re, MW, Zanderighi '20]

$$d\sigma^{F}_{\rm res} \sim \frac{d}{dp_T}\left\{e^{-S}\,{\rm Tr}(\mathbf{H\Delta})\,(C\otimes f)\,(C\otimes f)\right\}$$

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$${\rm Tr}(\mathbf{H\Delta}) = \langle M|\mathbf{\Delta}|M\rangle, \quad \mathbf{\Delta} = \mathbf{V}^\dagger\,\mathbf{D}\,\mathbf{V}, \quad \mathbf{V} = \exp\left\{-\int\frac{dq^2}{q^2}\left[\frac{\alpha_s(q)}{2\pi}\mathbf{\Gamma}_{\mathbf{t}}^{(1)}+\frac{\alpha_s^2(q)}{(2\pi)^2}\mathbf{\Gamma}_{\mathbf{t}}^{(2)}\right]\right\}$$

- approximations keeping NNLO and (N)LL
  - azimuthal average with $[\mathbf{D}]_\phi = 1$ ➞ modifies $H \to \overline{H}$ and $(C\otimes f)\to\overline{(C\otimes f)}$ at α_s^2
    see [Catani, Devoto, Grazzini, Kallweit, Mazzitelli, Sargsyan '19]
  - $\langle M|\mathbf{\Delta}|M\rangle \approx \underbrace{\langle M|M\rangle}_{=H}\frac{\langle M^{(0)}|\mathbf{\Delta}|M^{(0)}\rangle}{\langle M^{(0)}|M^{(0)}\rangle}$ ← re-absorb mistake at NNLO in $B^{(2)}$
  - expand $\mathbf{V} = \underbrace{\exp\left\{-\int\frac{dq^2}{q^2}\frac{\alpha_s(q)}{2\pi}\mathbf{\Gamma}_{\mathbf{t}}^{(1)}\right\}}_{\equiv\mathbf{V}_{\rm NLL}}\times\left(1-\int\frac{dq^2}{q^2}\frac{\alpha_s^2(q)}{(2\pi)^2}\mathbf{\Gamma}_{\mathbf{t}}^{(2)}\right)+\mathcal{O}(\mathrm{N^3LL})$ ← re-absorb in $B^{(2)}$ coefficient

MiNNLOPS for heavy quarks

[Mazzitelli, Monni, Nason, Re, MW, Zanderighi '20]

$$\mathrm{d}\sigma^{F}_{\mathrm{res}} \sim \frac{\mathrm{d}}{\mathrm{d}p_T}\left\{e^{-S}\,\mathrm{Tr}(\mathbf{H}\boldsymbol{\Delta})\,(C\otimes f)\,(C\otimes f)\right\}$$

$$S = -\int \frac{\mathrm{d}q^2}{q^2}\left[\frac{\alpha_s(q)}{2\pi}\left(A^{(1)}\log(M/q)+B^{(1)}\right)+\frac{\alpha_s^2(q)}{(2\pi)^2}\left(A^{(2)}\log(M/q)+B^{(2)}\right)+\ldots\right]$$

✦ using those approximations (exact up to NNLO & (N)LL) we have:

$$\tilde{B}^{(2)} = B^{(2)} + \frac{\langle M^{(0)}|\,\mathbf{\Gamma}^{(2)\dagger}+\mathbf{\Gamma}^{(2)}\,|M^{(0)}\rangle}{\langle M^{(0)}|M^{(0)}\rangle} + \frac{2\,\mathrm{Re}\left\{\langle M^{(1)}|\,\mathbf{\Gamma}^{(1)\dagger}+\mathbf{\Gamma}^{(1)}\,|M^{(0)}\rangle\right\}}{\langle M^{(0)}|M^{(0)}\rangle} - \frac{2\,\langle M^{(0)}|\,\mathbf{\Gamma}^{(1)\dagger}+\mathbf{\Gamma}^{(1)}\,|M^{(0)}\rangle\,\mathrm{Re}\left\{\langle M^{(1)}|M^{(0)}\rangle\right\}}{\langle M^{(0)}|M^{(0)}\rangle^2}$$

and $$e^{-S}\langle M|\,\boldsymbol{\Delta}\,|M\rangle = e^{-\tilde{S}}\,\frac{\langle M^{(0)}|\,\mathbf{V}^{\dagger}_{\mathrm{NLL}}\mathbf{V}_{\mathrm{NLL}}\,|M^{(0)}\rangle}{\langle M^{(0)}|M^{(0)}\rangle}\,H + \mathcal{O}(\alpha_s^5)$$

(reminder: $\mathbf{V}_{\mathrm{NLL}} \equiv \exp\left\{-\int\frac{\mathrm{d}q^2}{q^2}\frac{\alpha_s(q)}{2\pi}\mathbf{\Gamma}^{(1)}_{\mathbf{t}}\right\}$)

MiNNLOPS for heavy quarks

[Mazzitelli, Monni, Nason, Re, MW, Zanderighi '20]

$$d\sigma^F_{\rm res} \sim \frac{d}{dp_T}\left\{e^{-S}\,{\rm Tr}(\mathbf{H}\boldsymbol{\Delta})\,(C\otimes f)\,(C\otimes f)\right\}$$

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✦ using those approximations (exact up to NNLO & (N)LL) we have:

$$\tilde{B}^{(2)} = B^{(2)} + \frac{\langle M^{(0)}|\boldsymbol{\Gamma}^{(2)\dagger}+\boldsymbol{\Gamma}^{(2)}|M^{(0)}\rangle}{\langle M^{(0)}|M^{(0)}\rangle} + \frac{2\,{\rm Re}\left\{\langle M^{(1)}|\boldsymbol{\Gamma}^{(1)\dagger}+\boldsymbol{\Gamma}^{(1)}|M^{(0)}\rangle\right\}}{\langle M^{(0)}|M^{(0)}\rangle} - \frac{2\,\langle M^{(0)}|\boldsymbol{\Gamma}^{(1)\dagger}+\boldsymbol{\Gamma}^{(1)}|M^{(0)}\rangle\,{\rm Re}\left\{\langle M^{(1)}|M^{(0)}\rangle\right\}}{\langle M^{(0)}|M^{(0)}\rangle^2}$$

and $$e^{-S}\langle M|\boldsymbol{\Delta}|M\rangle = e^{-\tilde{S}}\underbrace{\frac{\langle M^{(0)}|\mathbf{V}^\dagger_{\rm NLL}\mathbf{V}_{\rm NLL}|M^{(0)}\rangle}{\langle M^{(0)}|M^{(0)}\rangle}}\,H+\mathcal{O}(\alpha_s^5)$$

use basis $|M^{(0)}\rangle$ where $\boldsymbol{\Gamma}^{(1)}$ diagonal

$$= \sum_{i\in\text{colours}} c_i\,\underbrace{e^{-\tilde{S}+S_i}}_{\equiv e^{\bar{S}_i}}$$

eigenvalues of $\mathbf{V}^\dagger_{\rm NLL}\mathbf{V}_{\rm NLL}$ exponent

(reminder: $\mathbf{V}_{\rm NLL} \equiv \exp\left\{-\int\frac{dq^2}{q^2}\frac{\alpha_s(q)}{2\pi}\boldsymbol{\Gamma}^{(1)}_{\mathbf{t}}\right\}$)

MiNNLO$_{\text{PS}}$ for heavy quarks

[Mazzitelli, Monni, Nason, Re, MW, Zanderighi '20]

$$\mathrm{d}\sigma^F_{\mathrm{res}} \sim \frac{\mathrm{d}}{\mathrm{d}p_T}\left\{e^{-S}\,\mathrm{Tr}(\mathbf{H\Delta})\,(C\otimes f)\,(C\otimes f)\right\}$$

$$\ldots{}^{(2)}\log(M/q) + B^{(2)}\big) + \ldots \Big]$$

MiNNLO$_{\text{PS}}$ for colour singlets

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

✦ starting equation:

$$\frac{\mathrm{d}\sigma_F^{\mathrm{res}}}{\mathrm{d}p_T\,\mathrm{d}\Phi_{\mathrm{B}}} = \frac{\mathrm{d}}{\mathrm{d}p_T}\left\{e^{-S}\mathscr{L}\right\} = e^{-S}\underbrace{\left\{S'\mathscr{L} + \mathscr{L}'\right\}}_{\equiv D}$$

$$\mathscr{L} \sim H\,(C\otimes f)\,(C\otimes f)$$

…LL) we have:

$$\frac{\ldots\,\mathbf{\Gamma}^{(1)\dagger} + \mathbf{\Gamma}^{(1)}\,|M^{(0)}\rangle\,\mathrm{Re}\left\{\langle M^{(1)}|M^{(0)}\rangle\right\}}{\langle M^{(0)}|M^{(0)}\rangle^2}$$

and $$e^{-S}\langle M|\,\mathbf{\Delta}\,|M\rangle = \underbrace{e^{-\tilde{S}}\frac{\langle M^{(0)}|\,\mathbf{V}^\dagger_{\mathrm{NLL}}\mathbf{V}_{\mathrm{NLL}}\,|M^{(0)}\rangle}{\langle M^{(0)}|M^{(0)}\rangle}}\,H + \mathcal{O}(\alpha_s^5)$$

$$= \sum_{i\in\mathrm{colours}} c_i\,\underbrace{e^{-\tilde{S}+S_i}}_{\equiv e^{\bar{S}_i}}$$

simplified to sum of terms with same structure as starting formula for colour singlet case

$$\Rightarrow\ \mathrm{d}\sigma^F_{\mathrm{res}} \sim \frac{\mathrm{d}}{\mathrm{d}p_T}\left\{\sum_{i\in\mathrm{colours}} e^{-\bar{S}_i}\,\underbrace{c_i\,\overline{H}\,\overline{(C\otimes f)}\,\overline{(C\otimes f)}}_{\equiv\overline{\mathscr{L}}_i}\right\} + \text{terms beyond NNLO \& (N)LL}$$

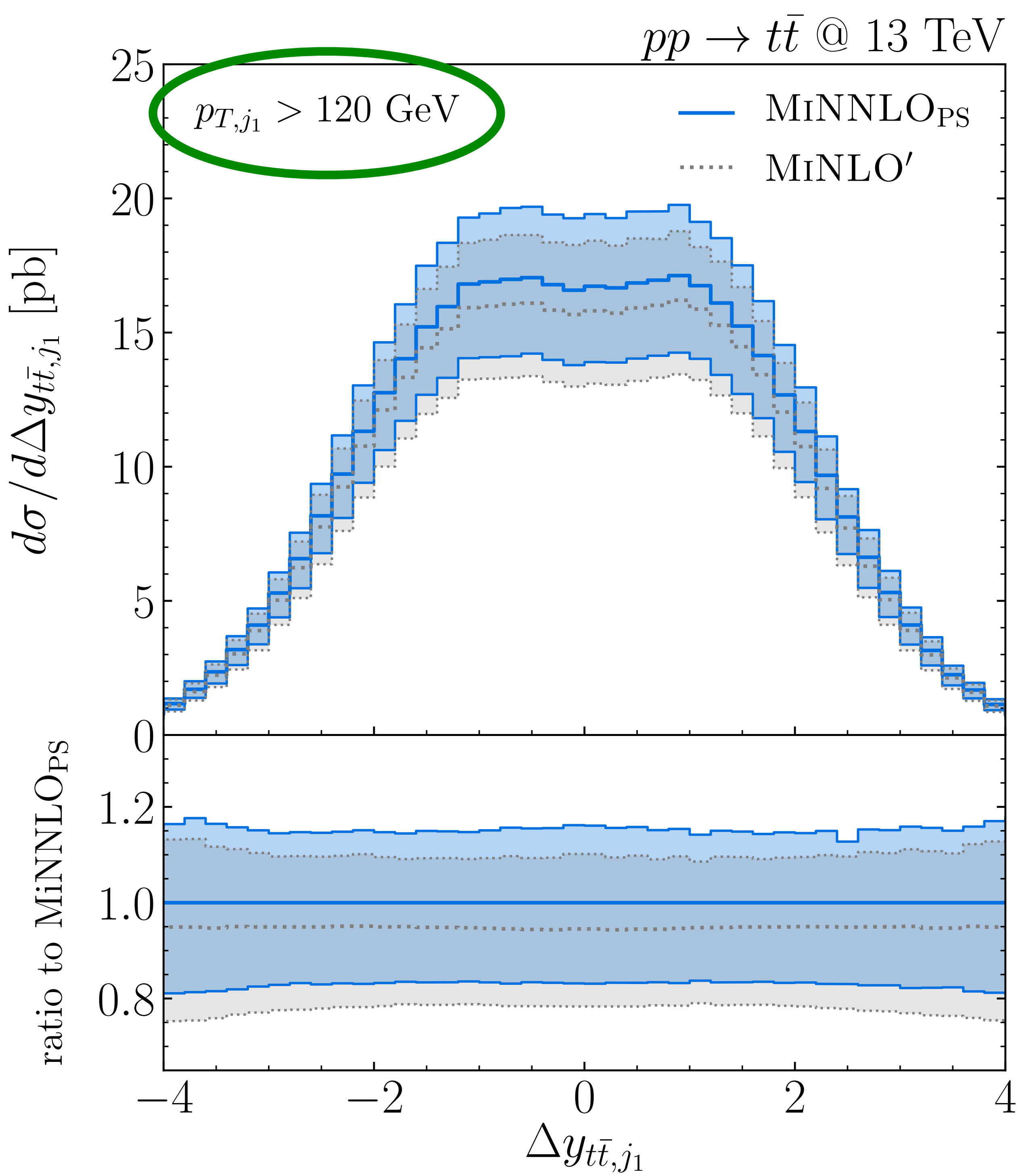
Setup for $t\bar{t}$ MiNNLO$_{\rm PS}$

[Mazzitelli, Monni, Nason, Re, MW, Zanderighi '20]

- scale setting:
  - overall factor in Born: $\alpha_s^2(m_{t\bar{t}}/2)$
  - MiNNLO$_{\rm PS}$ scales: $\mu_R = \mu_F = \frac{m_{t\bar{t}}}{2} e^{-L}, \quad Q = \frac{m_{t\bar{t}}}{2}$
    (no direct correspondence to fixed-order → differences within uncertainties expected)
  - 7-point scale variation
    (including scales in Sudakov → slightly more conservative than in NNLO)
- new modified logarithm: $L = \begin{cases} \log\left(\frac{Q}{p_T}\right) & \text{for } p_T \leq Q/2 \\ 0 & \text{for } p_T \geq Q \end{cases}$
- showered with Pythia8, keeping top quarks stable
- comparison to data unfolded to inclusive phase space [CMS PRD 97 (2018) 112003]

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

[Mazzitelli, Monni, Nason, Re, MW, Zanderighi '20]



- ✦ NLO accurate observable
- ✦ MiNNLO$_{PS}$ agrees well with MiNLO′
- ✦ shows that the way NNLO corrections included does not alter 1-jet observables (especially not in terms of shape)
- ✦ note: relatively large jet p_T threshold (not to become sensitive to NNLO effects)

MiNNLOPS for $t\bar{t}$ production

[Mazzitelli, Monni, Nason, Re, MW, Zanderighi '20]

- total cross section:

MiNLO′	NNLO	MiNNLOPS
$695.6(3)^{+22\%}_{-17\%}$ pb	$769.8(9)^{+5.0\%}_{-6.5\%}$ pb	$772.8(3)^{+7.2\%}_{-5.9\%}$ pb

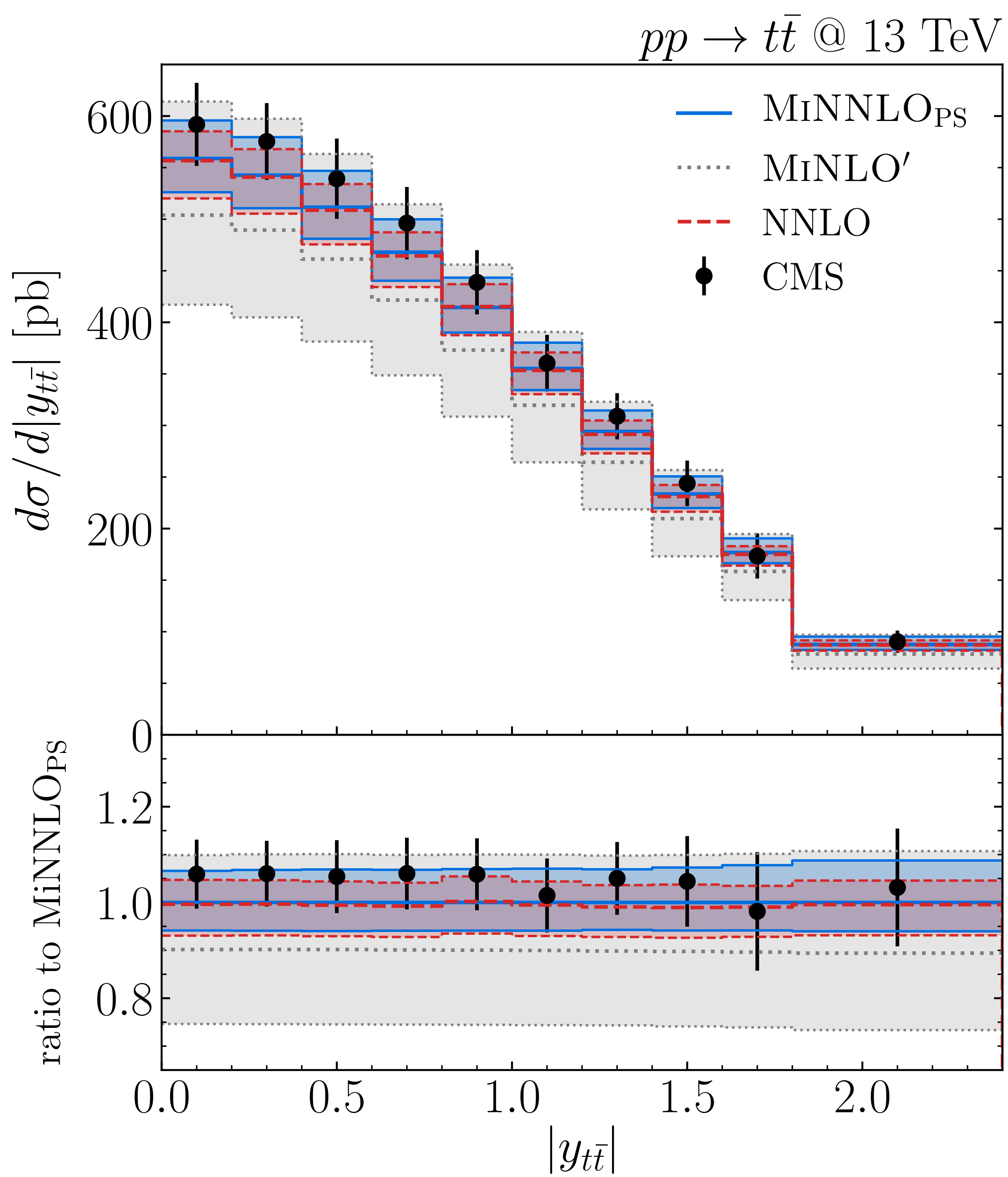
MiNNLOPS about 0.4% above NNLO
(expected due to different scale settings)

- excellent agreement of MiNNLOPS with NNLO for $t\bar{t}$ rapidity
(especially in terms of shape)

- similar size of scale uncertainties between MiNNLOPS and NNLO

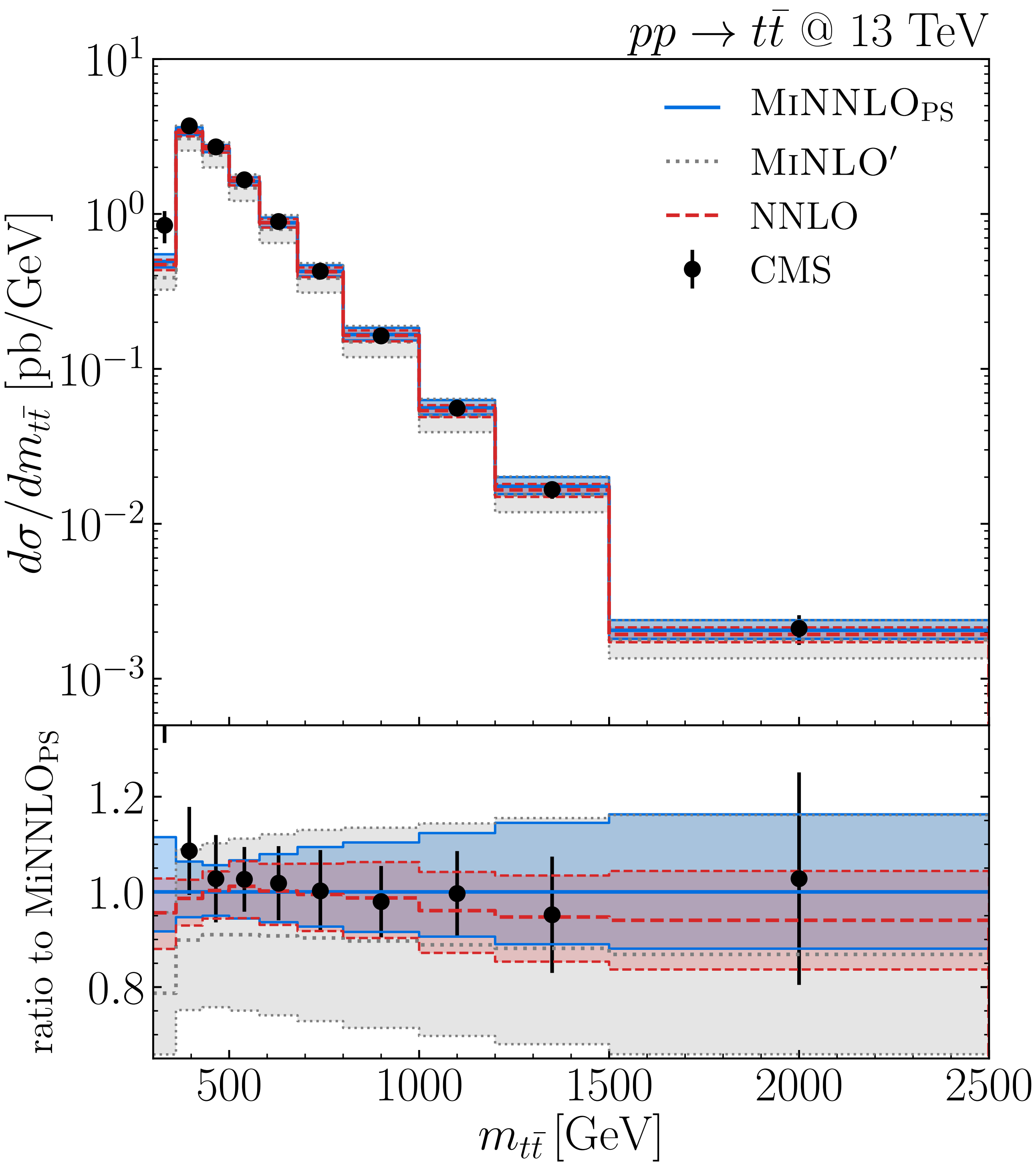
- substantial reduction of scale uncertainties w.r.t. MiNLO′

- perfect agreement with CMS data



MiNNLOPS for $t\bar{t}$ production

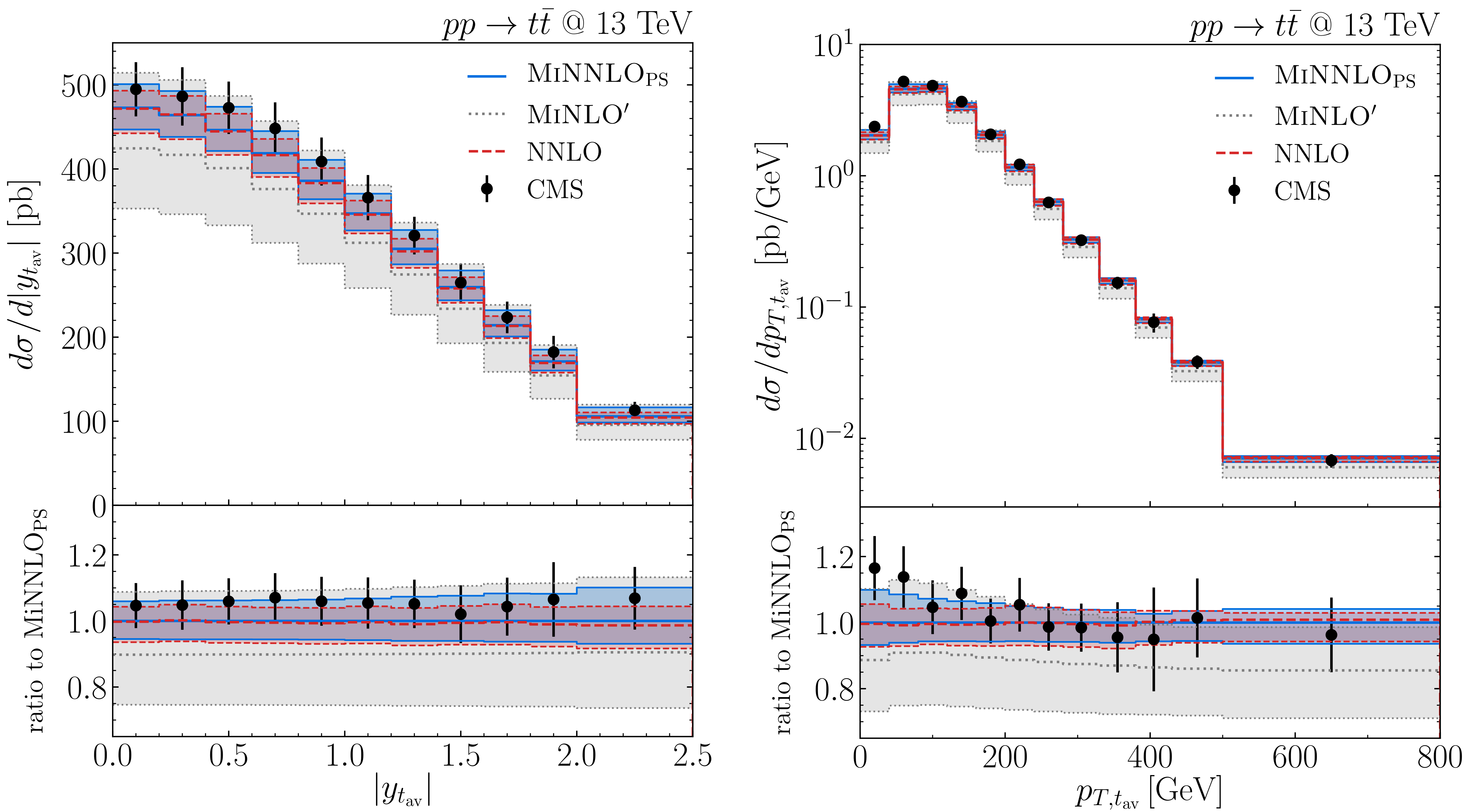
[Mazzitelli, Monni, Nason, Re, MW, Zanderighi '20]



- ✦ good description of measured $t\bar{t}$ invariant-mass spectrum
- ✦ except for first bin at $t\bar{t}$ threshold (finite width & non-relativistic effects)
- ✦ MiNNLOPS and NNLO compatible within uncertainties
- ✦ slightly different shape (different treatment of higher-order terms)
- ✦ slightly larger uncertainties in tail (reflects additional sources of scale variations)

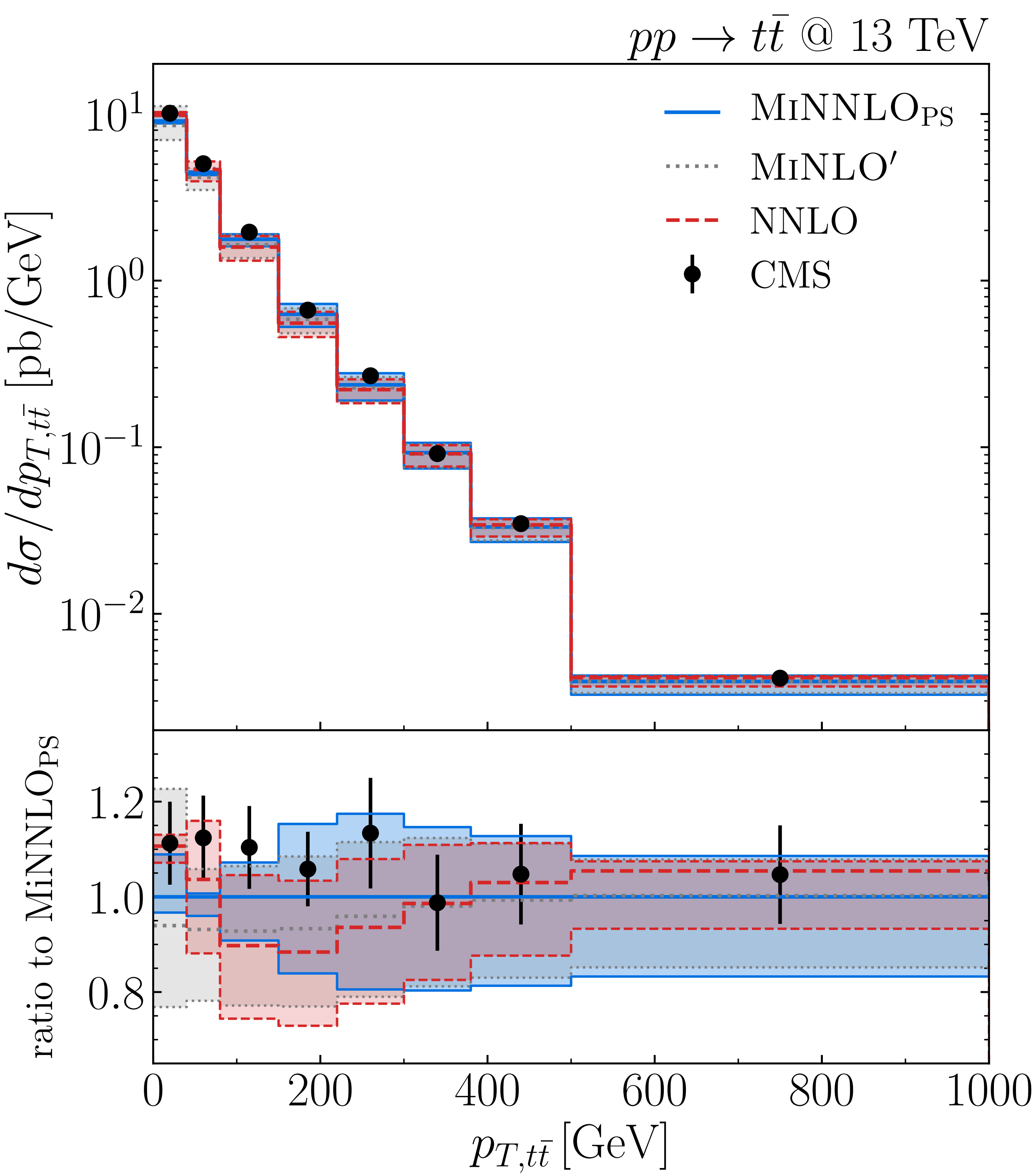
MiNNLO$_{PS}$ for $t\bar{t}$ production

[Mazzitelli, Monni, Nason, Re, MW, Zanderighi '20]



MiNNLOPS for $t\bar{t}$ production

[Mazzitelli, Monni, Nason, Re, MW, Zanderighi '20]



- NLO accurate at large p_T and full agreement of MiNNLOPS with MiNLO′
- also here: larger uncertainties in tail reflect additional sources of scale variations
- fixed-order unphysical at small p_T
- MiNNLOPS improves shape w.r.t. NNLO
- good description of data (especially in terms of shape!)

Summary & Outlook

★ NNLO+PS becoming available for "all" colour-singlet processes

★ First NNLO+PS for coloured final states

★ Top-quark pair production (most awaited application) now available!
(NNLO+PS $t\bar{t}$ code within POWHEG-BOX-V2)

★ opens up new avenues in

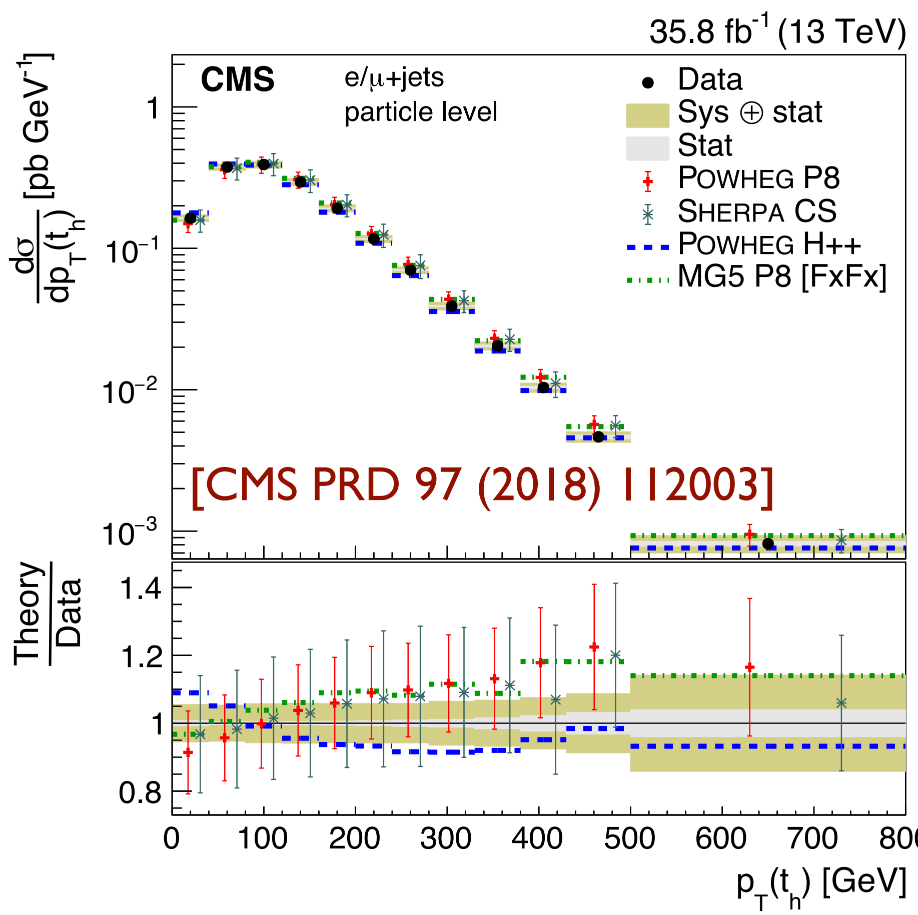
- ❖ studying top quarks
- ❖ lifting (small) tension in current measurements
- ❖ considering other processes at NNLO+PS: $b\bar{b}, F + Q\bar{Q}, ...$

★ consider top decays

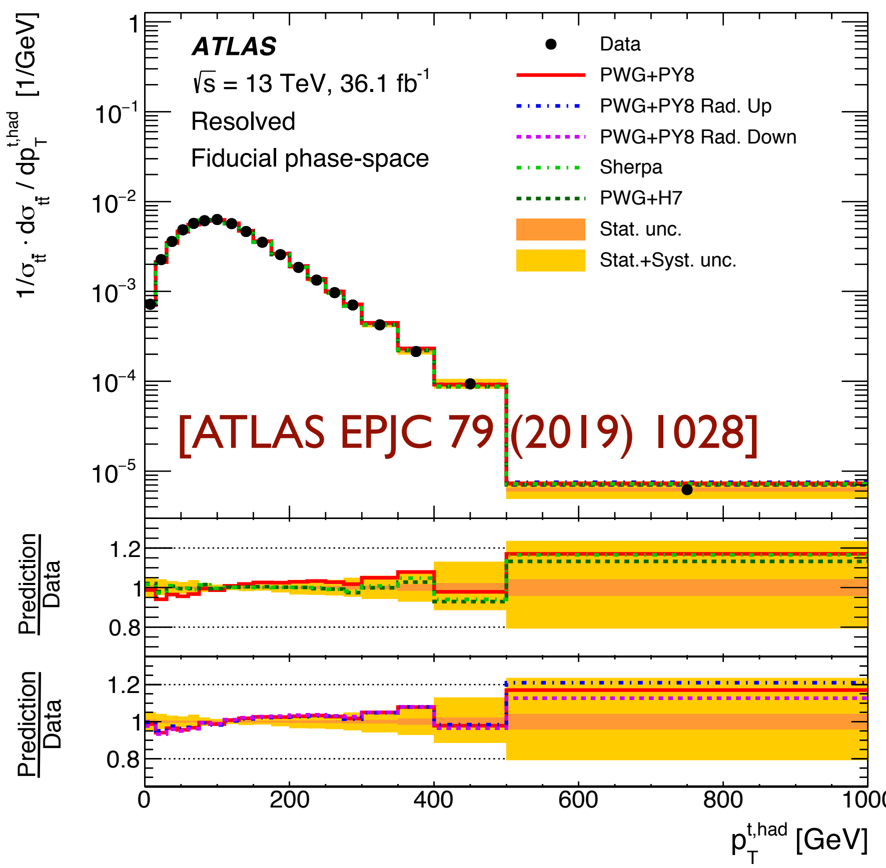
- ❖ through shower (limited perturbative accuracy) + "MadSpin" (fix spin correlations)
- ❖ more sophisticated: exact NLO+PS & NWA at NNLO (substantial work)

Back Up

Data/Theory differences in $t\bar{t}$ at LHC

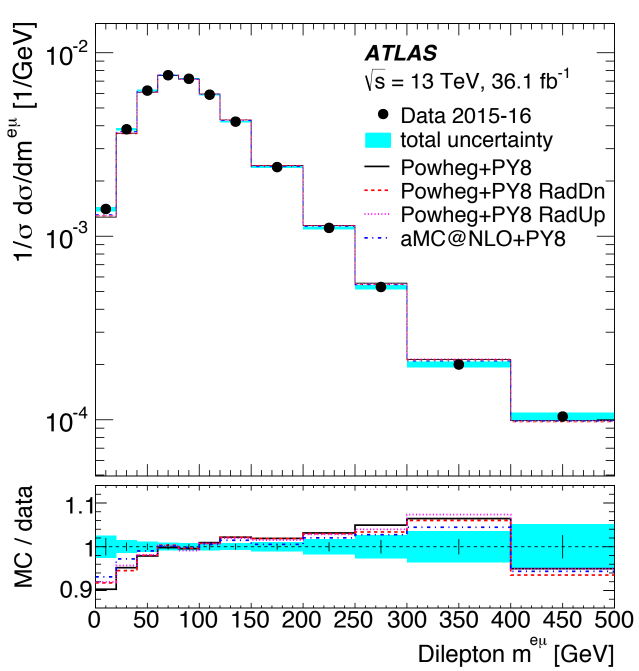


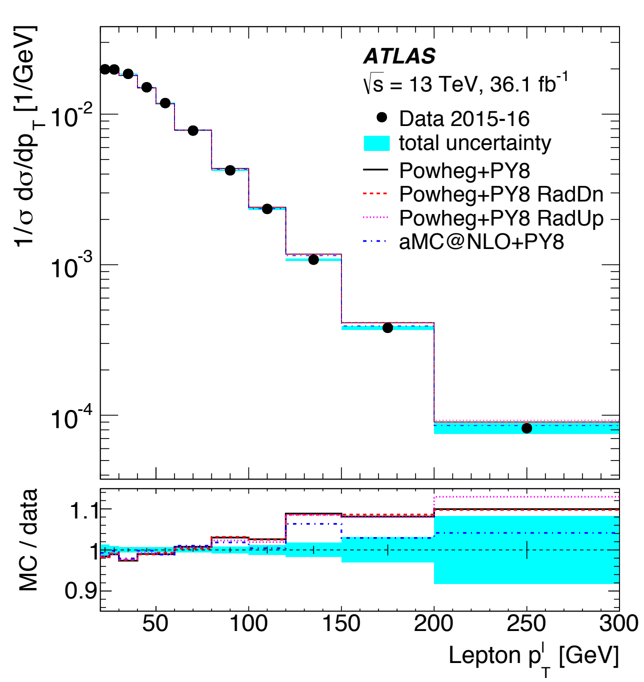
[CMS PRD 97 (2018) 112003]



[ATLAS EPJC 79 (2019) 1028]

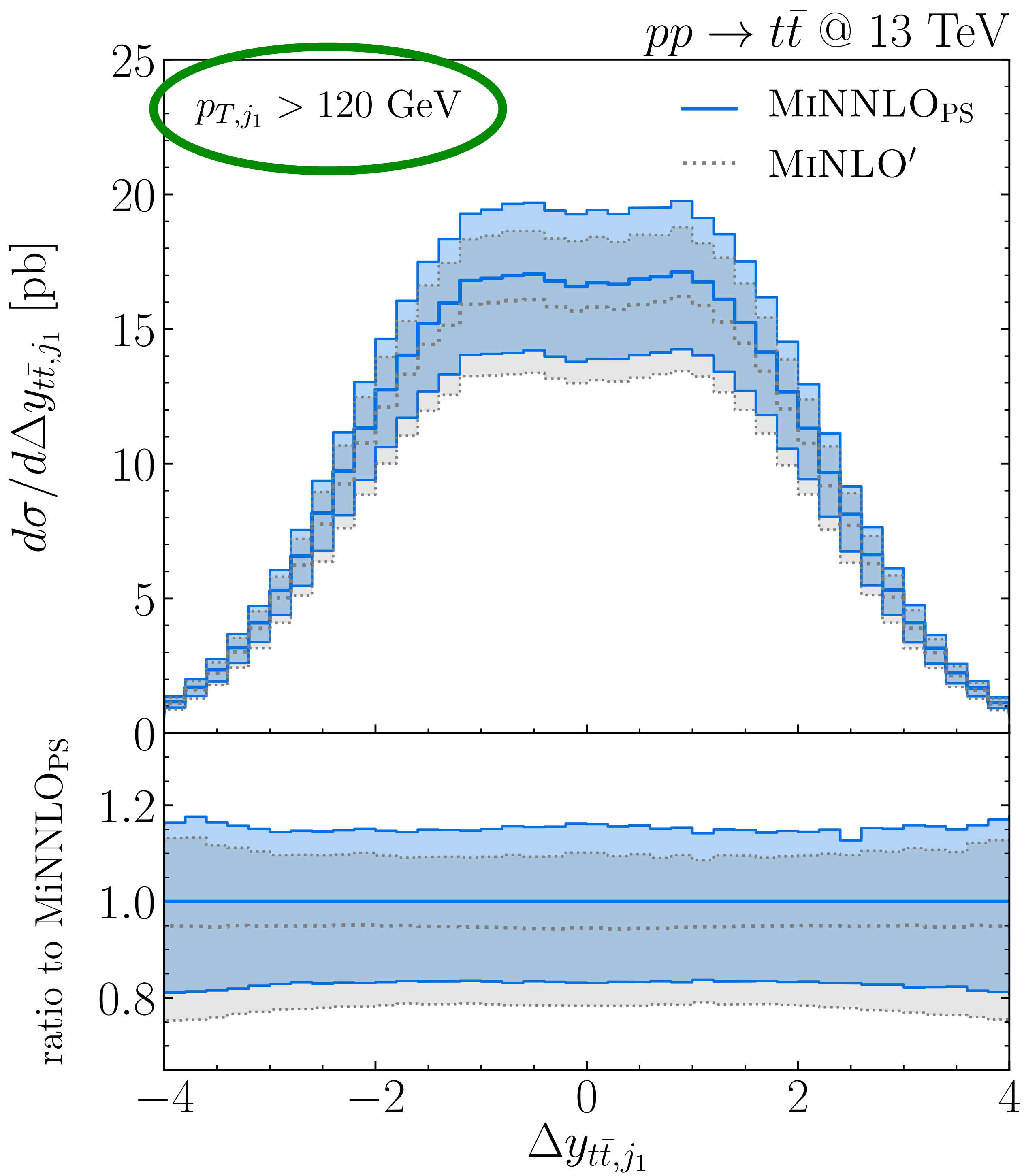
see also: [ATLAS EPJC 80 (2020) 528]





MiNNLOPS for $t\bar{t}$ production

[Mazzitelli, Monni, Nason, Re, MW, Zanderighi '20]



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