MiNNLO

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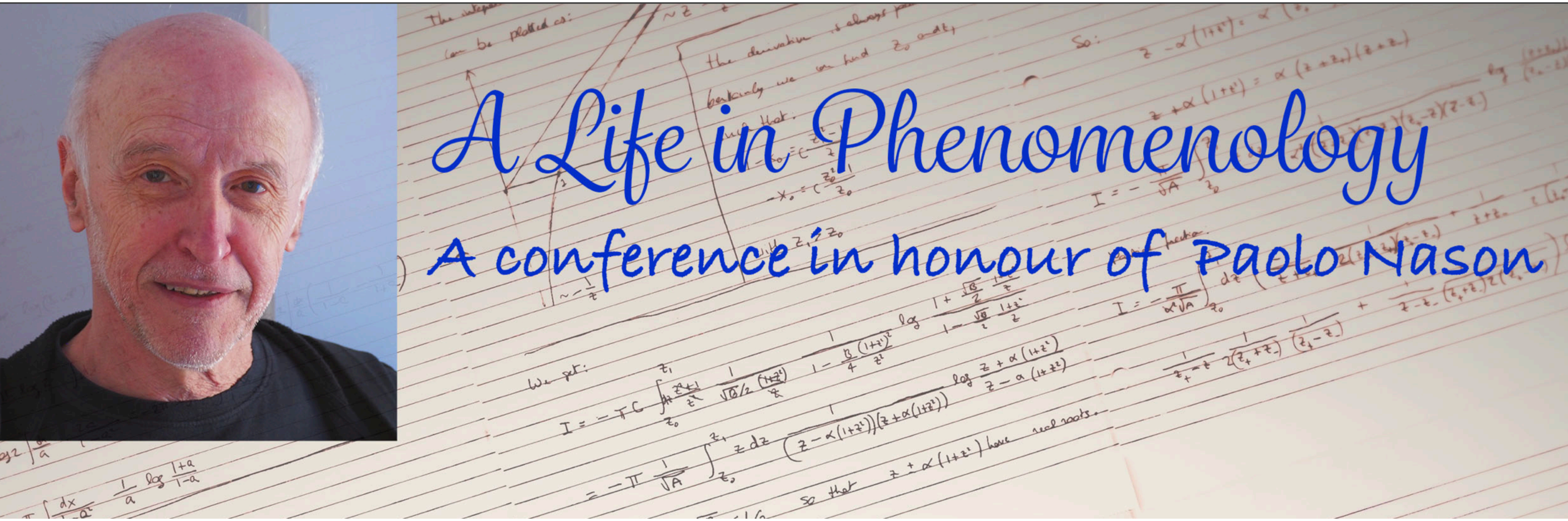

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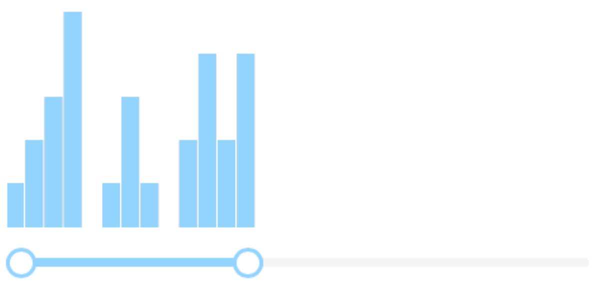

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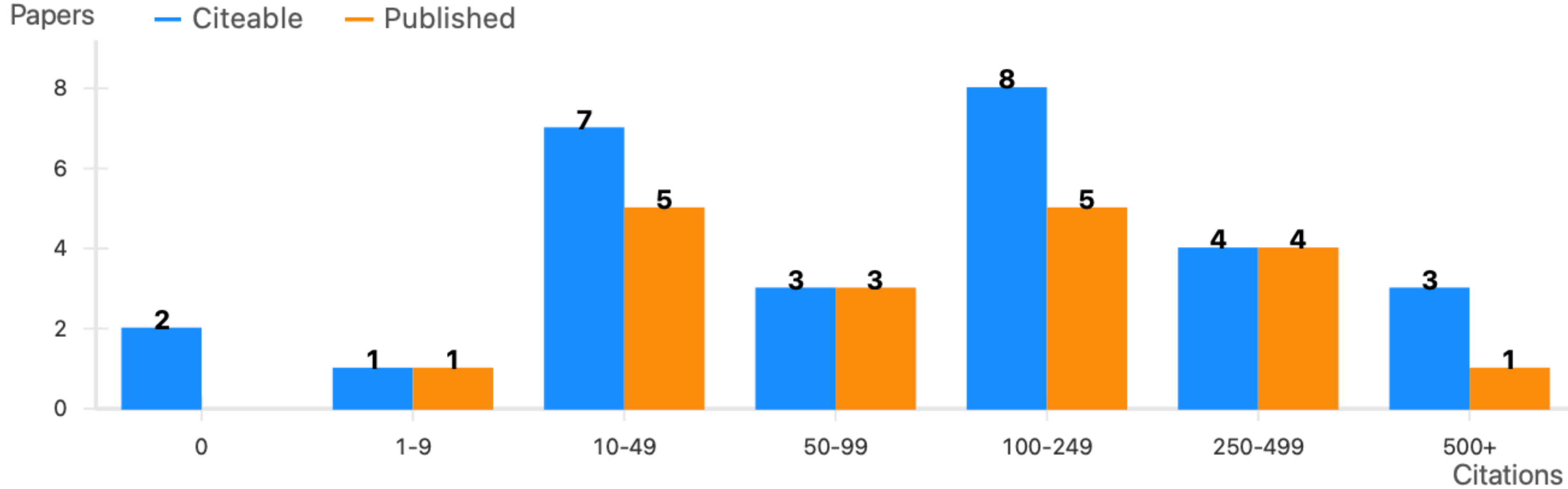

Resonant leptoquark at NLO with POWHEG

#1

Luca Buonocore (Zurich U.), Admir Greljo (U. Bern, AEC and Basel U.), Peter Krack (U. Bern, AEC), Paolo Nason (INFN, Milan Bicocca and Munich, Max Planck Inst.), Nudzeim Selimovic (Zurich U.) et al. (Sep 6, 2022)

e-Print: 2209.02599 [hep-ph]

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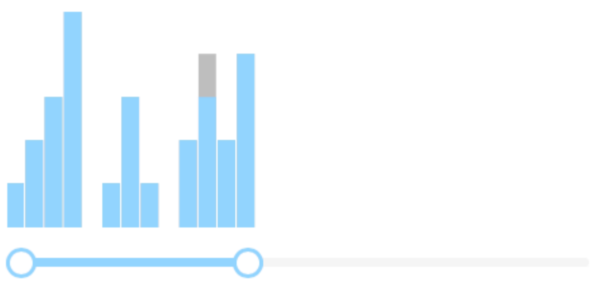

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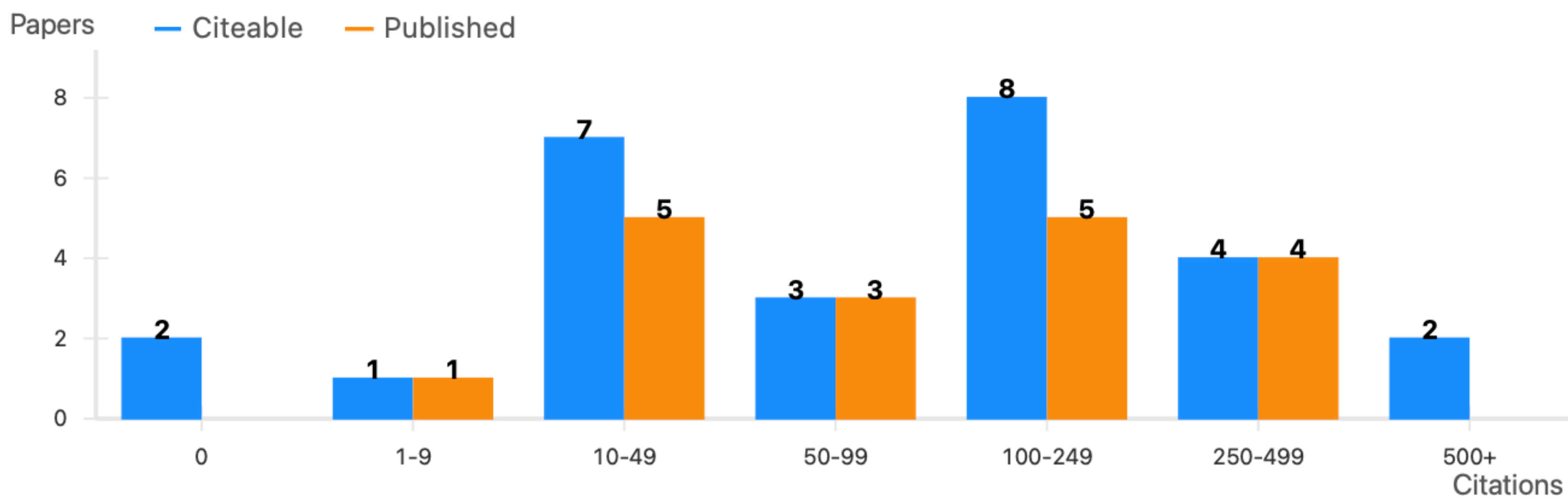

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e-Print: 2209.02599 [hep-ph]

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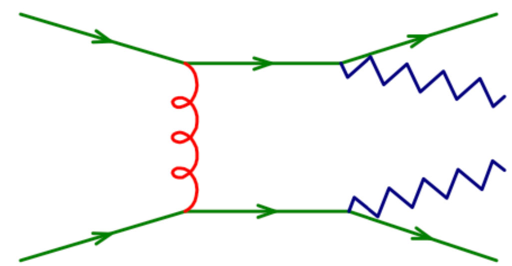
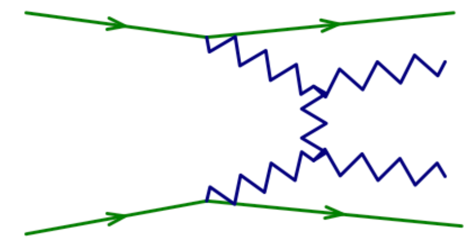
My first work with Paolo

W^+W^+ plus dijet production in the POWHEGBOX

Tom Melia (Oxford U., Theor. Phys.), Paolo Nason (INFN, Milan Bicocca), Raoul Rontsch (O
Theor. Phys.), Giulia Zanderighi (Oxford U., Theor. Phys.) (Feb, 2011)

Published in: *Eur.Phys.J.C* 71 (2011) 1670 • e-Print: 1102.4846 [hep-ph]





ABSTRACT: We present an implementation of the calculation of the production of W^+W^+ plus two jets at hadron colliders, at next-to-leading order (NLO) in QCD, in the POWHEG framework, which is a method that allows the interfacing of NLO calculations to shower Monte Carlo programs. This is the first $2 \to 4$ process to be described to NLO accuracy within a shower Monte Carlo framework. The implementation was built within the POWHEG BOX package. We discuss a few technical improvements that were needed in the POWHEG BOX to deal with the computer intensive nature of the NLO calculation, and argue that further improvements are possible, so that the method can match the complexity that is reached today in NLO calculations. We have interfaced our POWHEG implementation with PYTHIA and HERWIG, and present some phenomenological results, discussing similarities and differences between the pure NLO and the POWHEG+PYTHIA calculation both for inclusive and more exclusive distributions. We have made the relevant code available at the POWHEG BOX web site.

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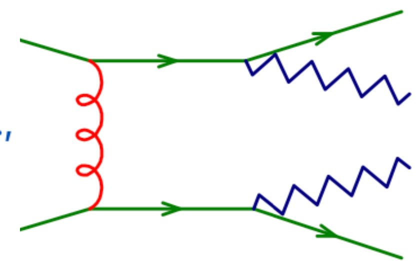

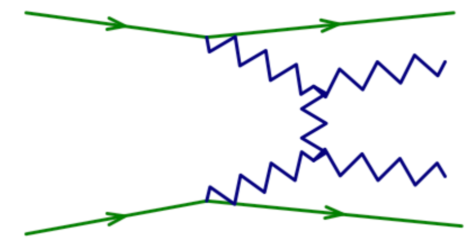

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My first work with Paolo

Main problems faced:

- calculation of virtual corrections very slow hard to compute reliable upper bounds
- with very low generation efficiency

Both problems solved by adding new features/options to the POWHEG BOX which are now largely standard

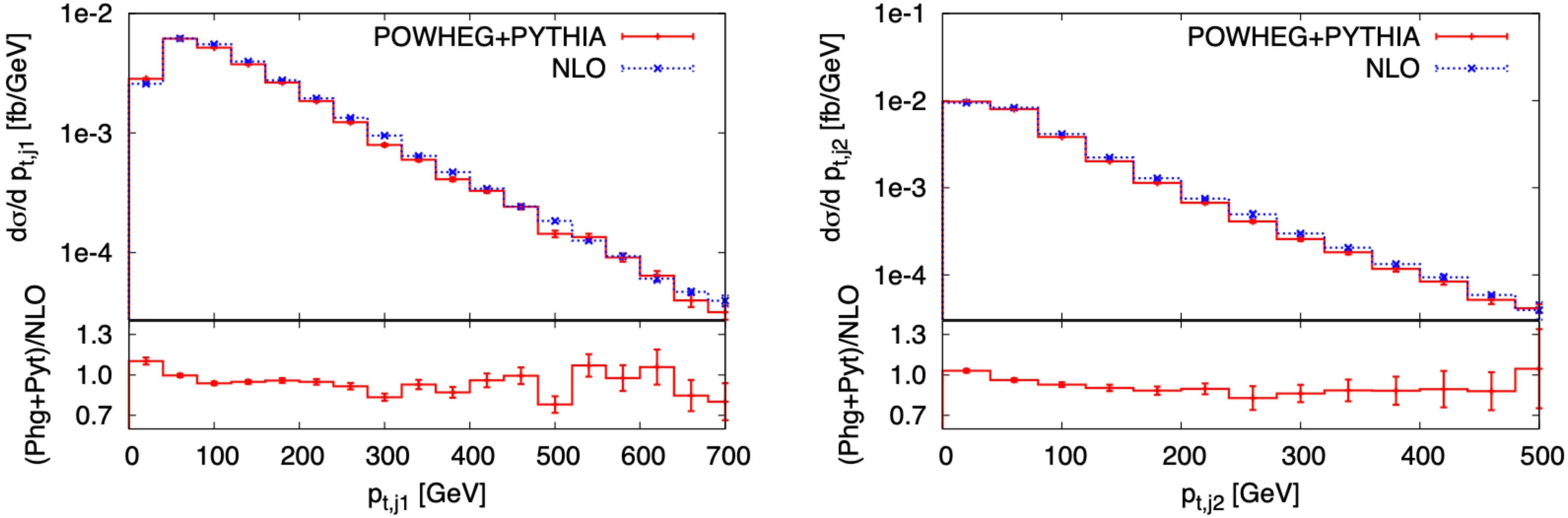
A. Raising the generation efficiency

...

My first work with Paolo

<u>Sample results</u>

Melia, Nason, Rontsch, GZ 1102.4846



- A work that set the ground to the implementation of more complicated process in the POWHEG BOX
- For myself: the beginning of a long lasting collaboration with Paolo

MiNNLO$_{PS}$

POWHEG

A New method for combining NLO QCD with shower Monte Carlo algorithms #1

Paolo Nason (INFN, Milan) (Sep, 2004)

Published in: *JHEP* 11 (2004) 040 • e-Print: hep-ph/0409146 [hep-ph]

pdf DOI cite 3,454 citations

Matching NLO QCD computations with Parton Shower simulations: the POWHEG method #1

Stefano Frixione (INFN, Genoa), Paolo Nason (INFN, Milan Bicocca), Carlo Oleari (INFN, Milan Bicocca and Milan Bicocca U.) (Sep, 2007)

Published in: *JHEP* 11 (2007) 070 • e-Print: 0709.2092 [hep-ph]

pdf DOI cite 4,067 citations

A general framework for implementing NLO calculations in shower Monte Carlo programs: the POWHEG BOX #3

Simone Alioli (DESY, Zeuthen and INFN, Milan Bicocca), Paolo Nason (INFN, Milan Bicocca), Carlo Oleari (Milan Bicocca U. and INFN, Milan Bicocca), Emanuele Re (Durham U., IPPP and INFN, Milan Bicocca) (Feb, 2010)

Published in: *JHEP* 06 (2010) 043 • e-Print: 1002.2581 [hep-ph]

pdf DOI cite 3,785 citations

POWHEG

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

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

POWHEG master formula:

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

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

SINLO: Sudakov Improved NLO

Giulia Zanderighi
University of Oxford & STFC

Work done in collaboration with Keith Hamilton and Paolo Nason 1206.xxxx

Convegno Informale di Fisica Teorica
Cortona, 30 Maggio 2012

SiNLO

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

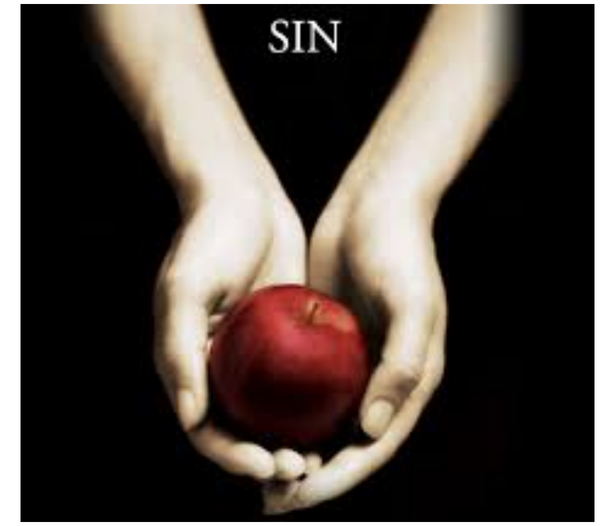
[Hamilton, Nason, GZ '12]

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

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

⇛ **see talk by Keith Hamilton**

SiNLO



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⇛ **see talk by Keith Hamilton**

M ~~S~~iNLO

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

⇛ **see talk by Keith Hamilton**

$\overset{\textbf{M}}{\not{\text{S}}}$iNLO

MiNLO (Multi scale Improved NLO): suitable modification of the POWHEG $\bar{\text{B}}$ 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

⇛ **see talk by Keith Hamilton**

NNLOPS

For Higgs production, the Born kinematics is fully specified by the Higgs rapidity. Consider the following distributions:

$\left(\frac{d\sigma}{dy}\right)_{\rm NNLO}$ → inclusive Higgs rapidity computed at NNLO

$\left(\frac{d\sigma}{dy}\right)_{\rm HJ-MiNLO}$ → inclusive Higgs rapidity from H+1jet-MiNLO

Since H+1jet-MiNLO (HJ-MiNLO) is NLO accurate, it follows that

$$\frac{\left(\frac{d\sigma}{dy}\right)_{\rm NNLO}}{\left(\frac{d\sigma}{dy}\right)_{\rm HJ\text{-}MiNLO}} = \frac{c_2\alpha_s^2 + c_3\alpha_s^3 + c_4\alpha_s^4}{c_2\alpha_s^2 + c_3\alpha_s^3 + d_4\alpha_s^4} \approx 1 + \frac{c_4 - d_4}{c_2}\alpha_s^2 + \mathcal{O}(\alpha_s^3)$$

Thus, reweighing HJ-MiNLO events with this factor, and applying a parton shower to the events, one obtains NNLO+PS accuracy

Hamilton, Nason, Re, GZ 1309.0017

Variants of the method

Variants of the method are possible. One splits the cross-section as

$$d\sigma = d\sigma_A + d\sigma_B \qquad d\sigma_A = d\sigma \cdot h(p_T) \qquad d\sigma_B = d\sigma \cdot (1 - h(p_T))$$

with h a function between 1 and 0, e.g. $h(p_T) = \frac{(c\, m_H)^\gamma}{(c\, m_H)^\gamma + p_T^\gamma}$

And one can re-weight the $\texttt{HJ-MiNLO}$ events with the factor

$$\mathcal{W}(y, p_T) = h(p_T) \frac{\int d\sigma^{\rm NNLO} \delta(y - y(\Phi)) - \int d\sigma_B^{\rm MINLO} \delta(y - y(\Phi))}{\int d\sigma_A^{\rm MINLO} \delta(y - y(\Phi))} + (1 - h(p_T))$$

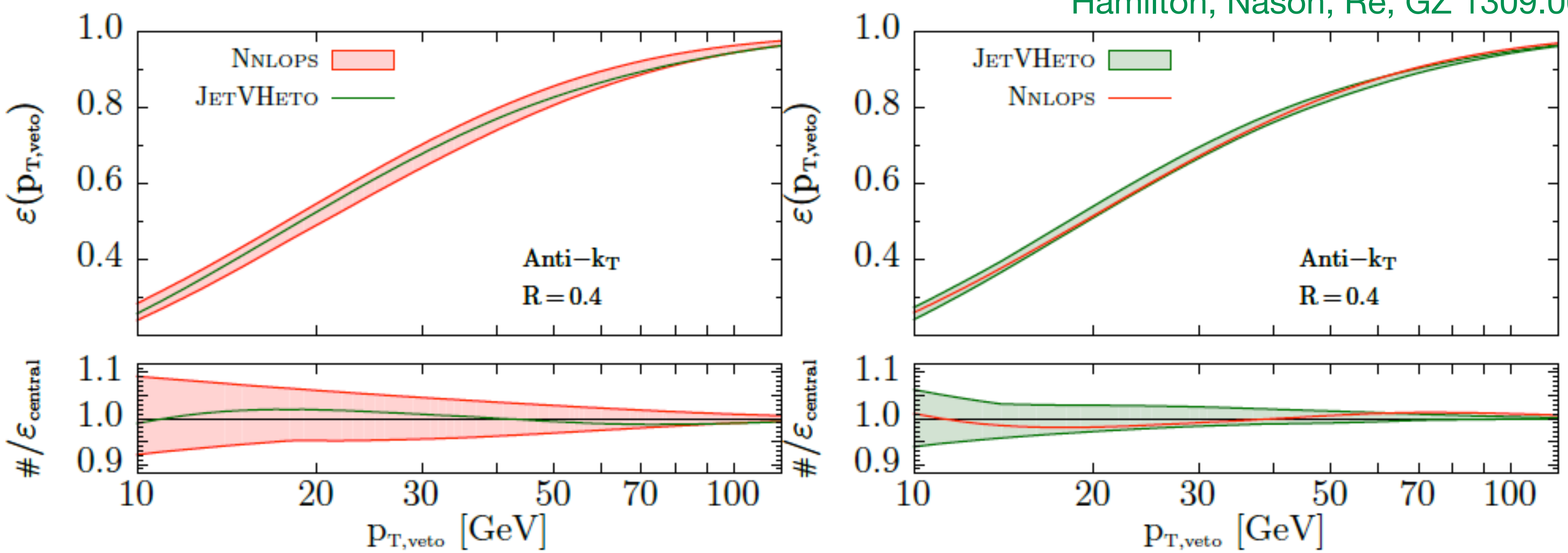
The idea is to distribute the virtual correction only in the low-p_t region (in the high p_t region no improvement) and to preserve exactly the NNLO rapidity distribution

Hamilton, Nason, Re, GZ 1309.0017

NNLOPS results

<u>Jet-veto efficiency</u>: validation from comparison to JetVHeto

Hamilton, Nason, Re, GZ 1309.0017



- JetVHeto: NNLO+NNLL [Banfi, Salam, Monni, GZ]
- agreement at the level of 2-3% everywhere

NNLOPS: other processes

Key ingredient of NNLOPS is the reweighing to the Born phase space

	Dimension of [ϕ_B]	Improvements
Higgs	1	
Drell Yan	3	2 angles parametrised with 8 Collins-Soper coeffs.
HW/HZ	4	8 CS coeffs. + 2 variables
WW	9	64 CS coeffs + 4 variables

It is clear that the need for an a-posteriori reweighting, besides being impractical, becomes the limiting feature of the approach

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 ’19; 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

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

$\mathcal{L}$: 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$_{PS}$

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

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

$$= e^{-S}\left\{\mathrm{d}\sigma_{\mathrm{FJ}}^{(1)}\big(1+S^{(1)}\big) + \mathrm{d}\sigma_{\mathrm{FJ}}^{(2)} + \Big(D - D^{(1)} - D^{(2)}\Big)\right\}$$

Nothing but the MiNLO formula

New terms required to preserve the NNLO accuracy

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

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

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

MiNNLOPS

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

but these terms contribute at NNLO since

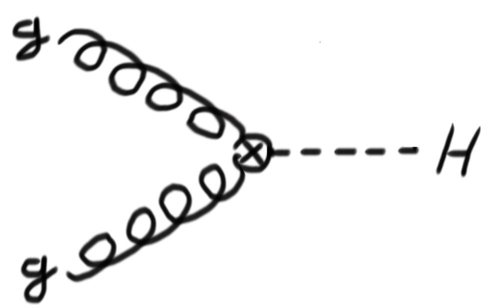
$$\int dL \alpha_s^n L^m e^{-\alpha_s L^2} = \alpha_s^{n-(m+1)/2}$$

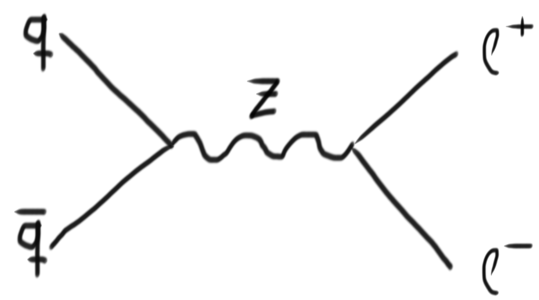
⇛ Setting n = 3 and m=1 one obtains a NNLO contribution

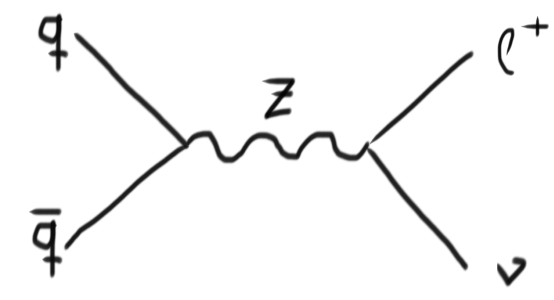
<u>Two remarks:</u>

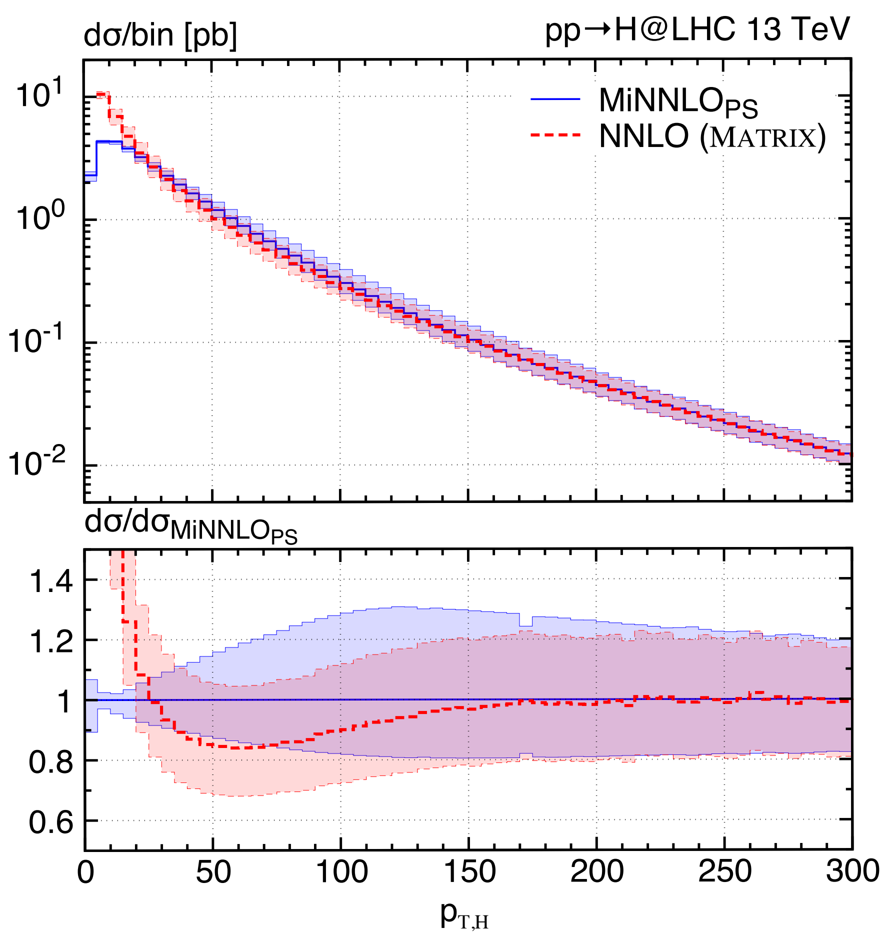
- all $\mathcal{O}(\alpha_s^3)$ terms required are those already present in a NNLO matched resummed calculation
- it is possible to either expand (1) and keep only terms of $\mathcal{O}(\alpha_s^3)$ or include all higher-order terms. The latter choice is preferred since it preserved the total derivative.

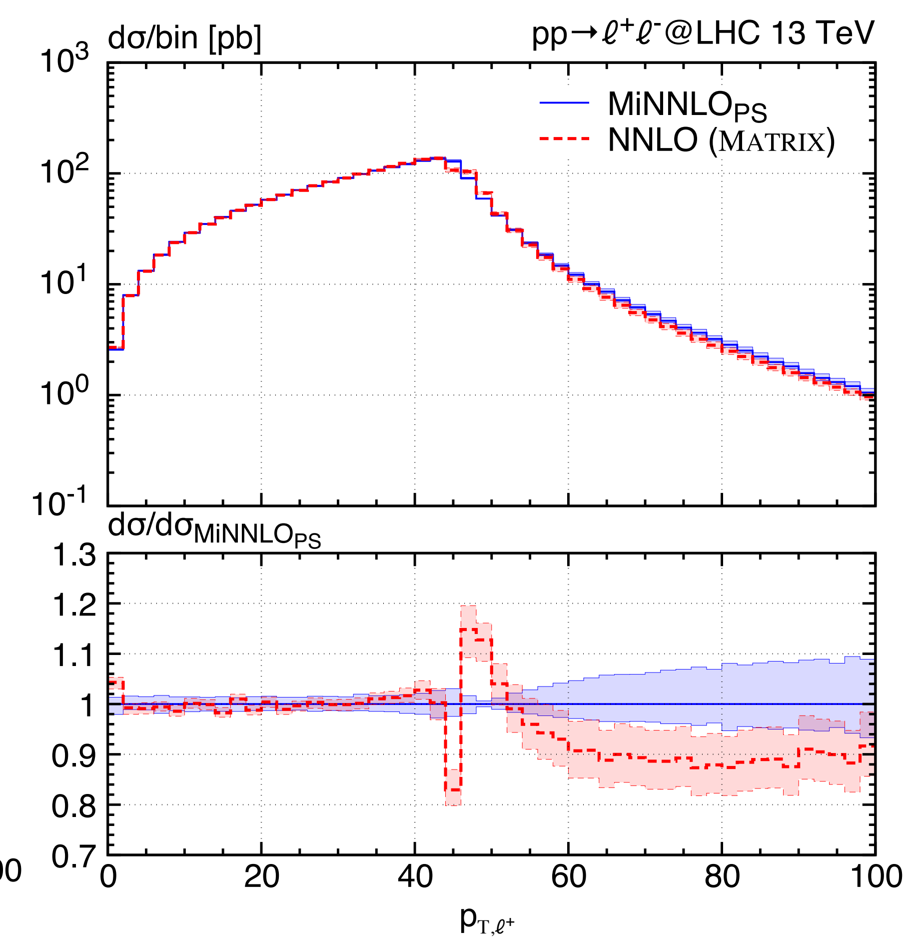
MiNNLO$_{PS}$: 2 →1

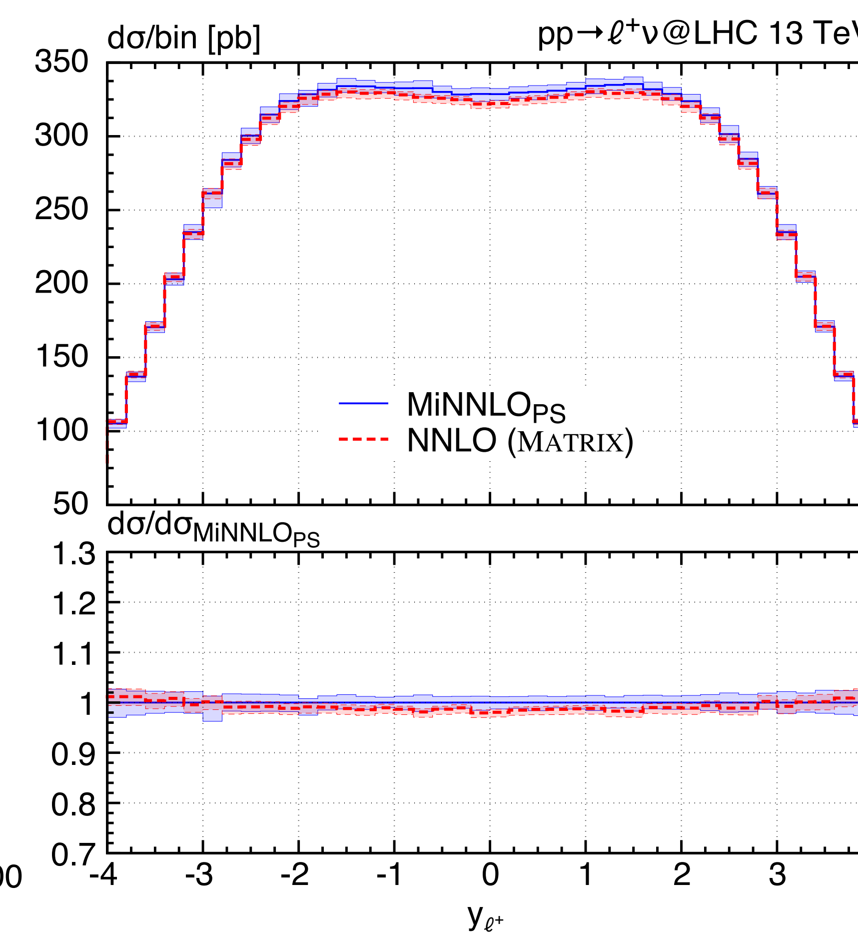








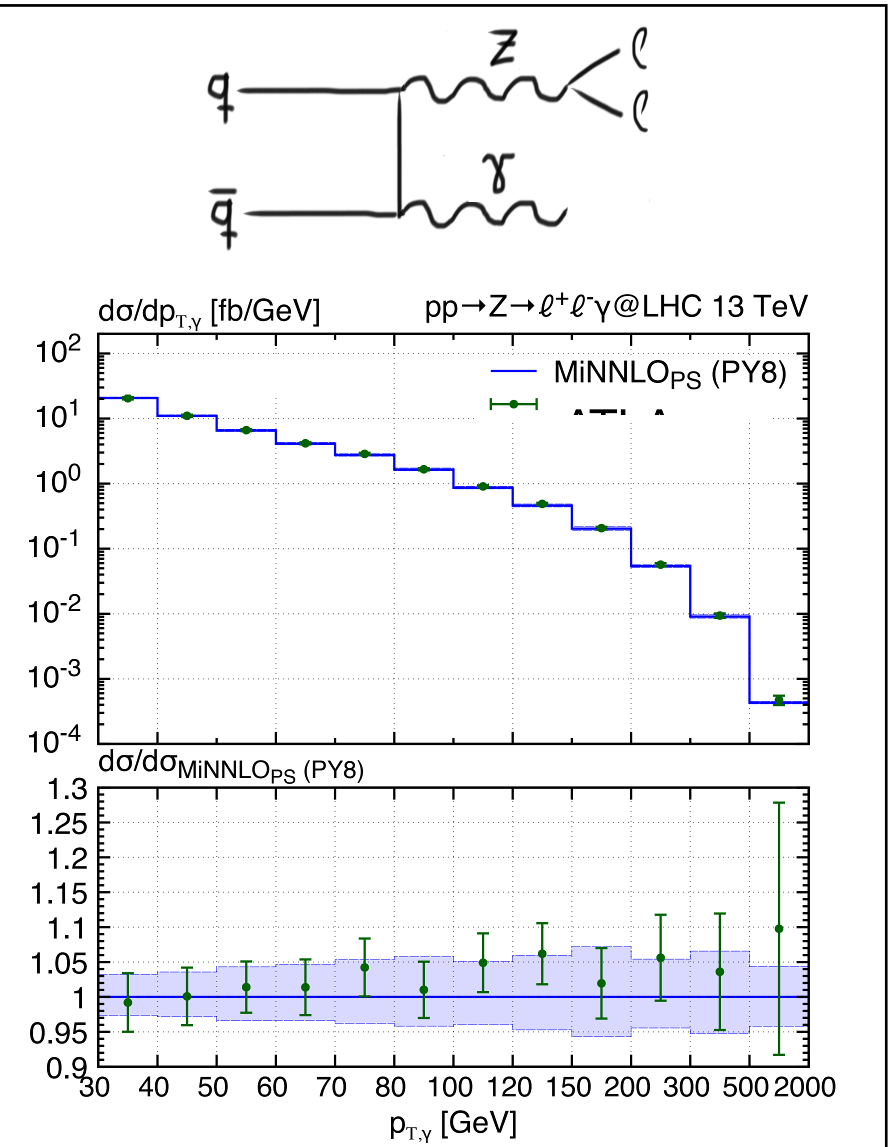




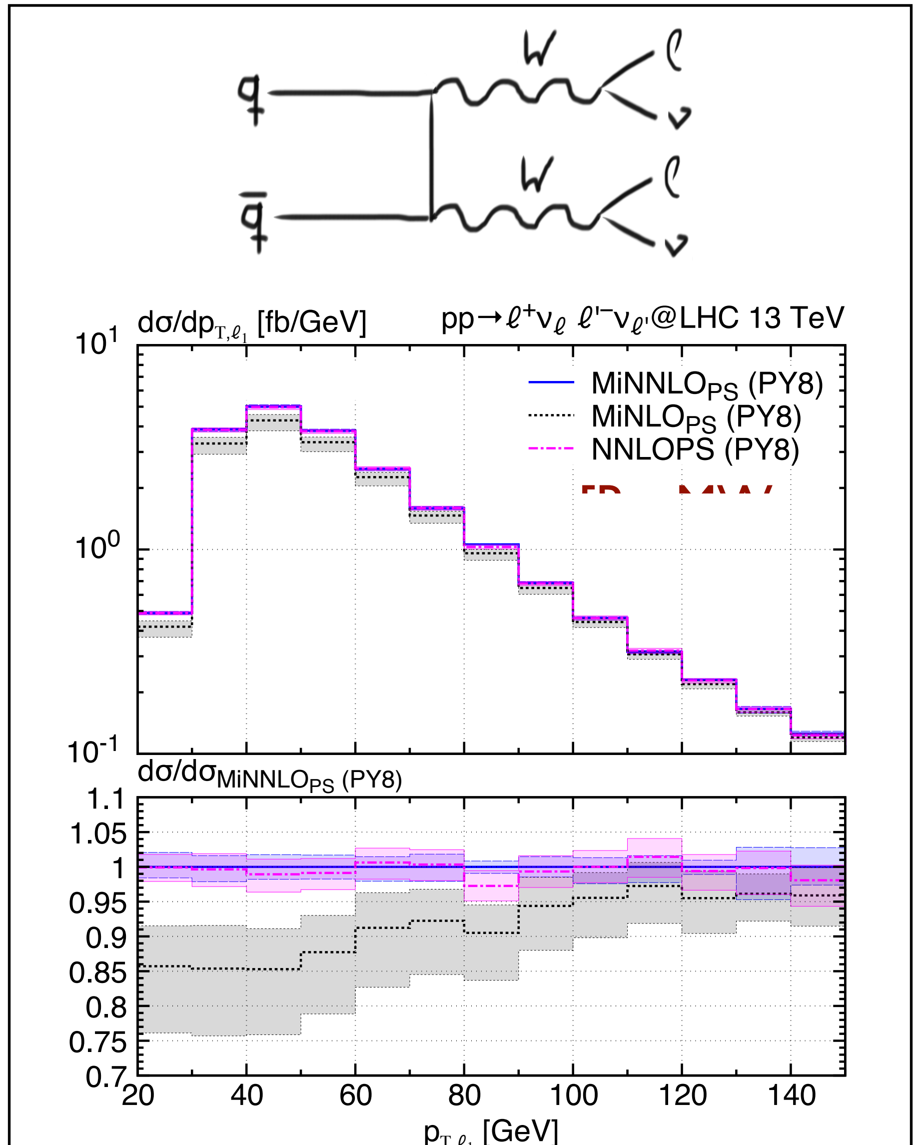
[Monni, Nason, Re, Wiesemann, GZ ’19; Monni, Re, Wiesemann,’20]

MiNNLO$_{PS}$: 2 → 2

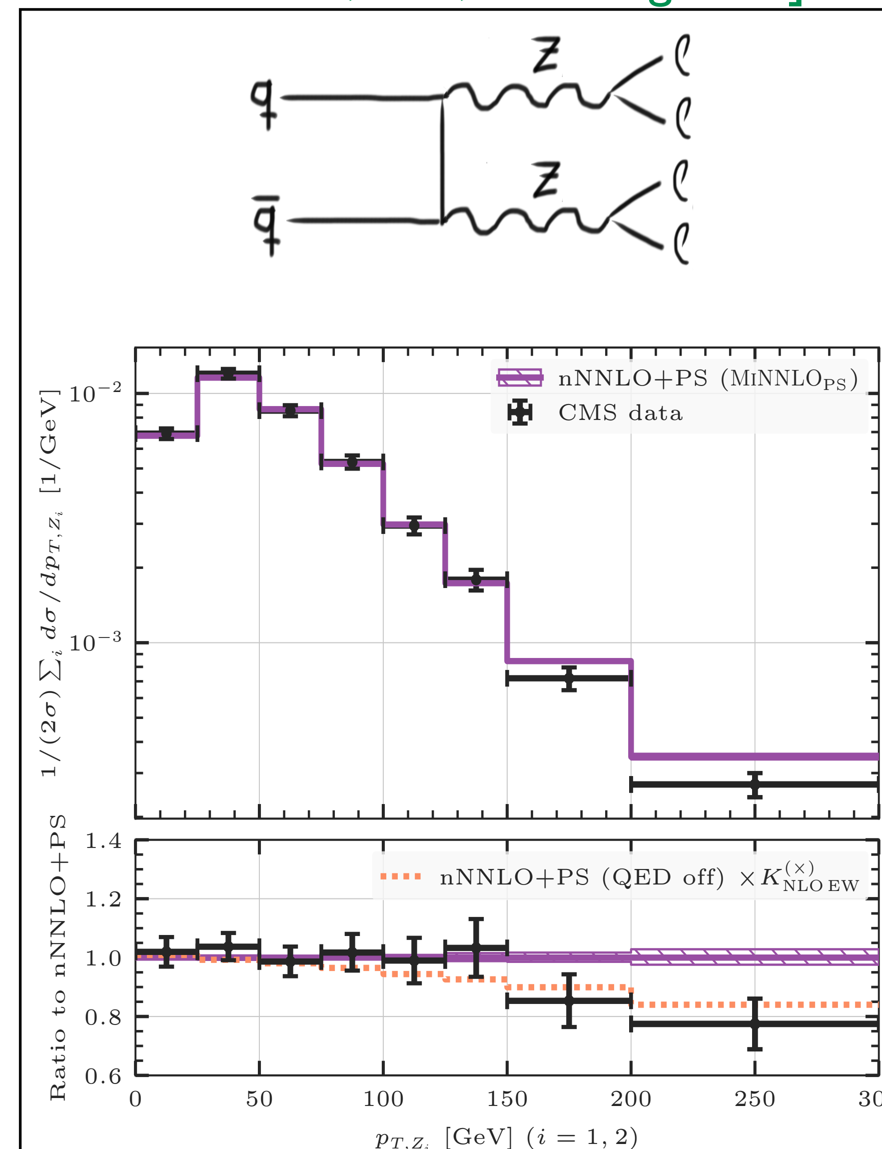
[Lombardi, MW, Zanderighi '20 '21]



[Lombardi, MW, Zanderighi '21]

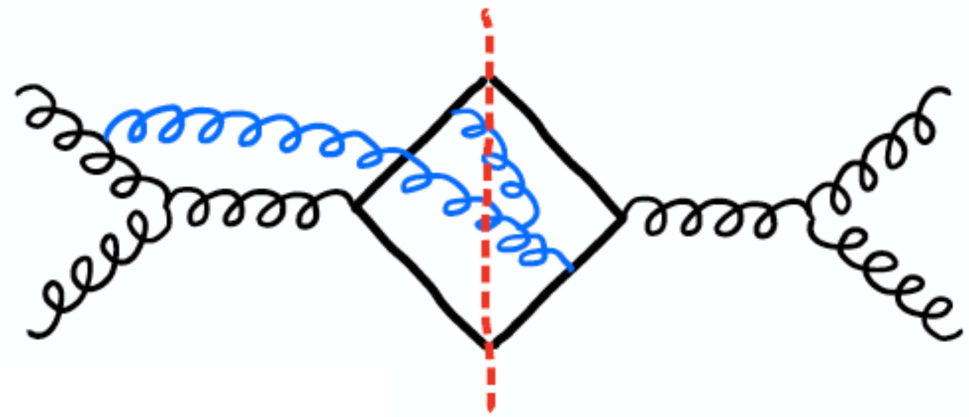


[Buonocore, Koole, Lombardi, Rottoli, MW, Zanderighi '21]



also $\gamma\gamma$ production [Gavardi, Oleari, Re '22] and VH with $H \to b\bar{b}$ in SM [Zanoli, Chiesa, Re, MW, Zanderighi '21] and in SMEFT [Haisch, MW, Zanderighi, Zanoli'22]

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: $|M^{(0)}_{c\bar{c}}|^2$

Sudakov: $S_c\left(\frac{b_0}{b}\right)$

Hard function: $\mathbf{H}_c$

Soft large angle (quantum interference): $\boldsymbol{\Delta}$

Collinear coefficients: C_{ci}, $C_{\bar{c}j}$

Parton distribution functions: f_i, f_j

MiNNLO$_{PS}$ for tt

The goal:
write the previous equation as a total derivative, up to higher-order terms.

Not trivial, but can be achieved with suitable rotations in colour space and expansions

Note: the logarithmic accuracy beyond LL does not need to be preserved and only NNLO singular terms must be kept

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

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

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

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

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

V_{NLL} encodes leading effects of Δ and “tilde” denotes a suitable modification of the given function.

all details in Mazzitelli, Monni, Nason, Re, Wiesemann, GZ 2012.14267, 2112.12135

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 $\bar{B}$-function of the ttJ generator.

Extension to bb-production in progress

Mazzitelli, Ratti, Wiesemann, GZ 22xx.xxxx

Numerical results

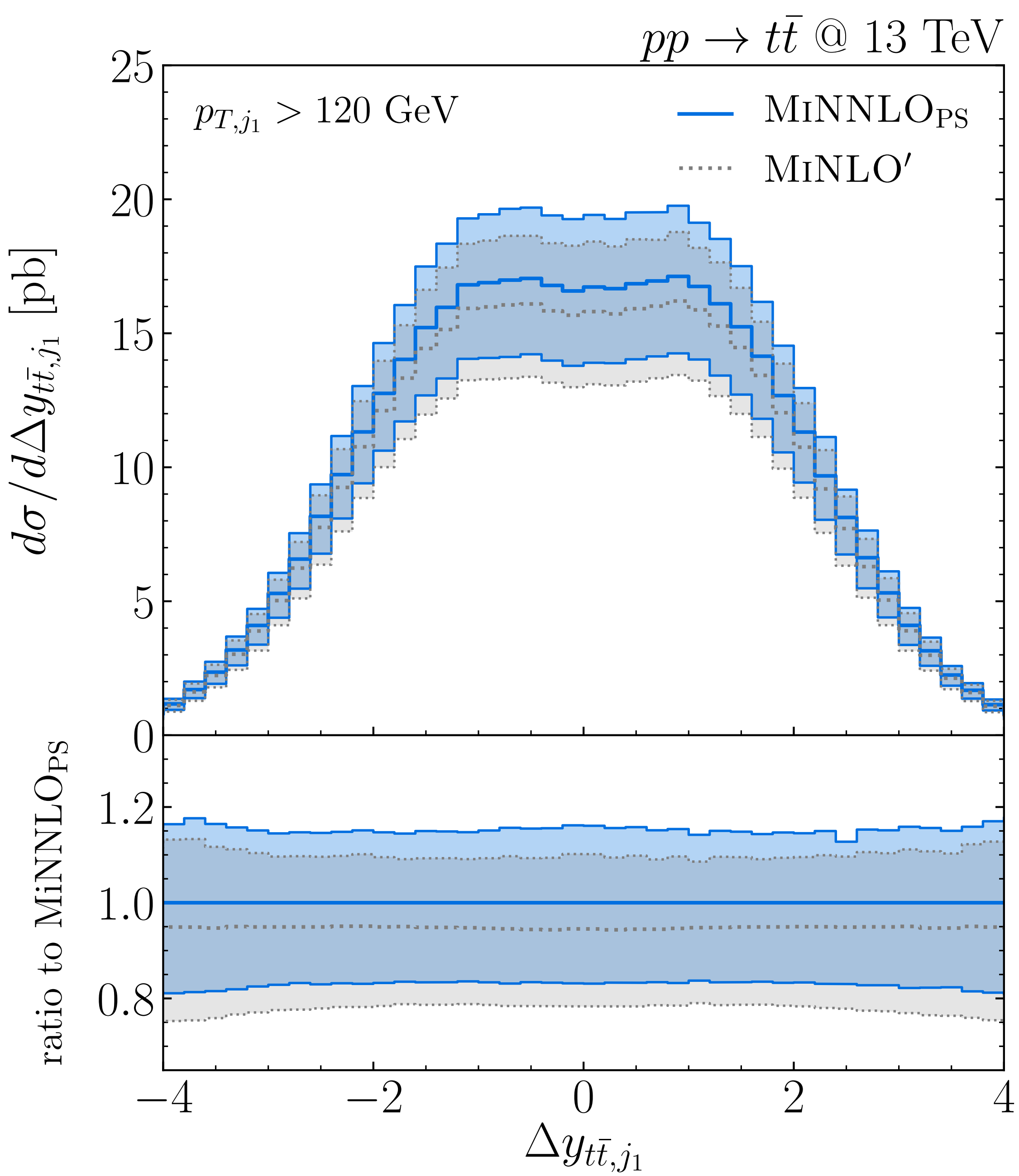
Settings:

- 13 TeV LHC collisions
- Scale setting:
  - Overall scales in Born: $\alpha_s(\mu_R^0)$ with $\mu_R^0 = H_T^{tt}/4 = \frac{1}{4}\left(\sqrt{m_t^2 + p_{T,t}^2} + \sqrt{m_{\bar{t}}^2 + p_{T,\bar{t}}^2}\right)$
  - MiNNLOPS scales: $\mu_R^0 = \mu_F^0 = m_{tt} e^{-L}$
  - We use a new form of modified logarithm $L \equiv \begin{cases} \ln \frac{Q}{p_{\mathrm{T}}} & \text{if } p_{\mathrm{T}} \leq \frac{Q}{2}\,, \\ \ln\left(a_0 + a_1 \frac{p_{\mathrm{T}}}{Q} + a_2 \left(\frac{p_{\mathrm{T}}}{Q}\right)^2\right) & \text{if } \frac{Q}{2} < p_{\mathrm{T}} \leq Q \\ 0 & \text{if } p_{\mathrm{T}} > Q\,, \end{cases}$
  - Standard 7-point scale variation
  - Shower done by Pythia 8 (Monash tune, dipole recoil)
  - Comparison to data unfolded to inclusive tt and fiducial top-decay phase space

Numerical results

Mazzitelli, Monni, Nason, Re, Wiesemann, GZ, 2012.14267

Distance in rapidity between jet and top-system



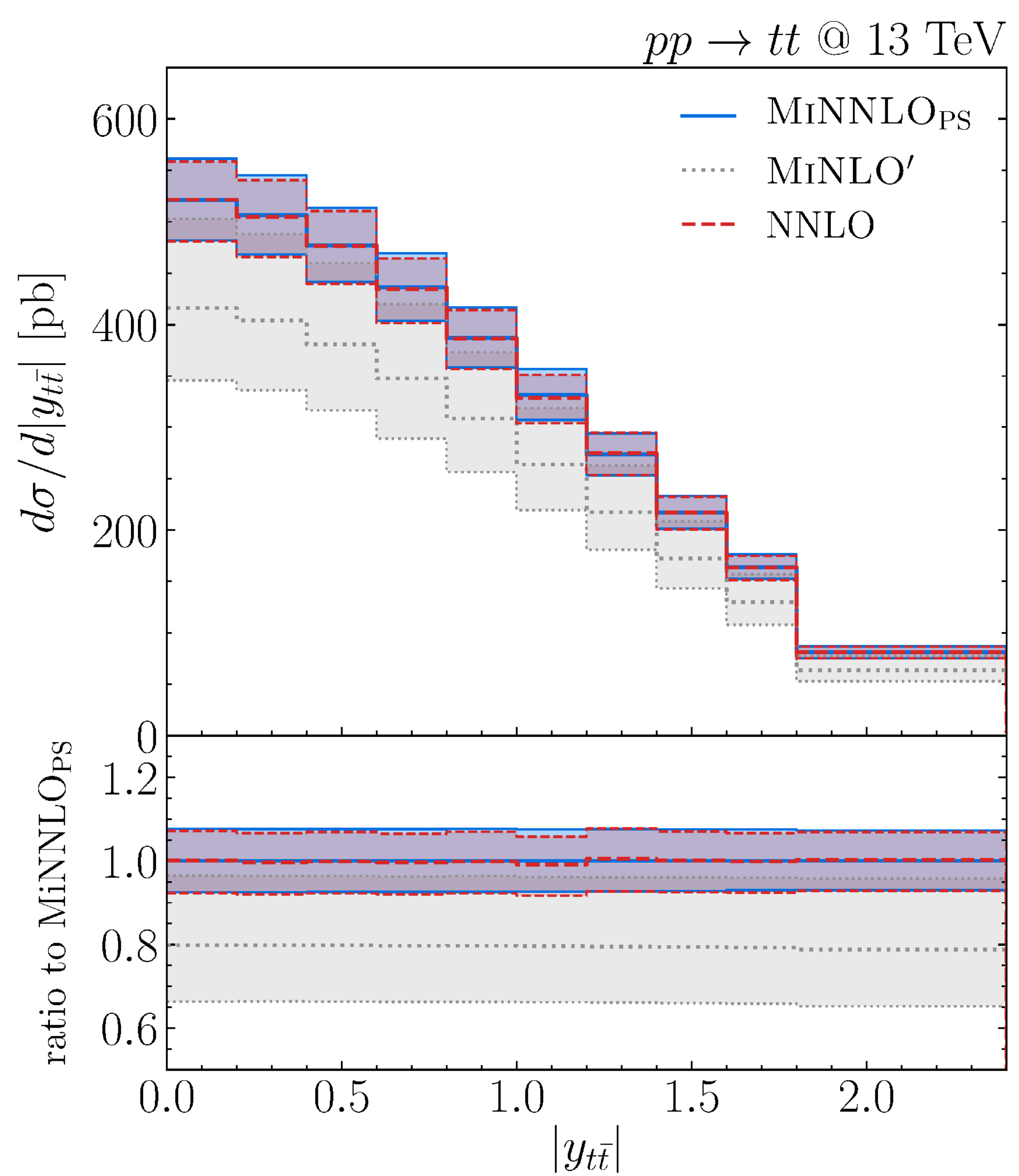
- Large $p_{T,j1}$-cut to be insensitive to NNLO effects
- Good agreement with MiNLO' and MiNNLOPS (both NLO accurate)

Numerical results

Total cross section

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

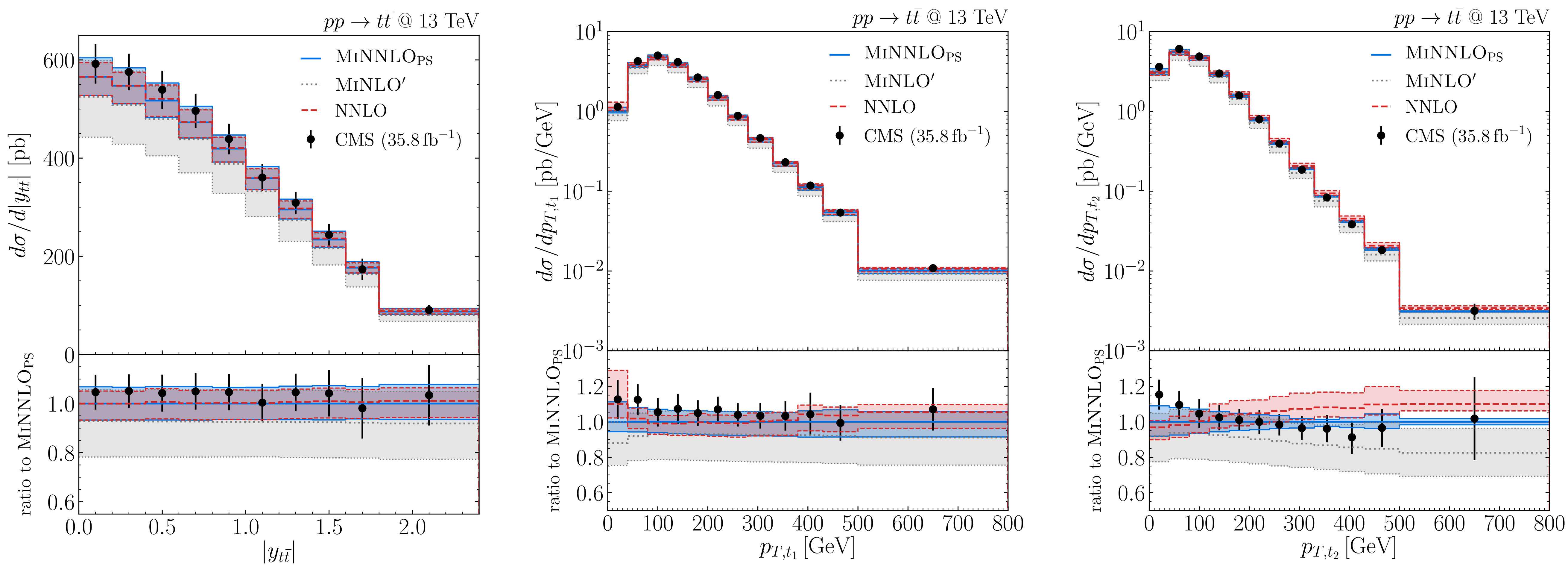
- MiNNLO$_{PS}$ and NNLO agree at permille level (note: despite different scale settings)
- excellent agreement of MiNNLO$_{PS}$ with NNLO for $t\bar{t}$ rapidity
- substantial reduction of scale uncertainties w.r.t. MiNLO′



Numerical results

Data unfolded to inclusive $t\bar{t}$ phase space from [CMS PRD 97 (2018) 112003]

[Mazzitelli, Monni, Nason, Re, MW, Zanderighi '21]



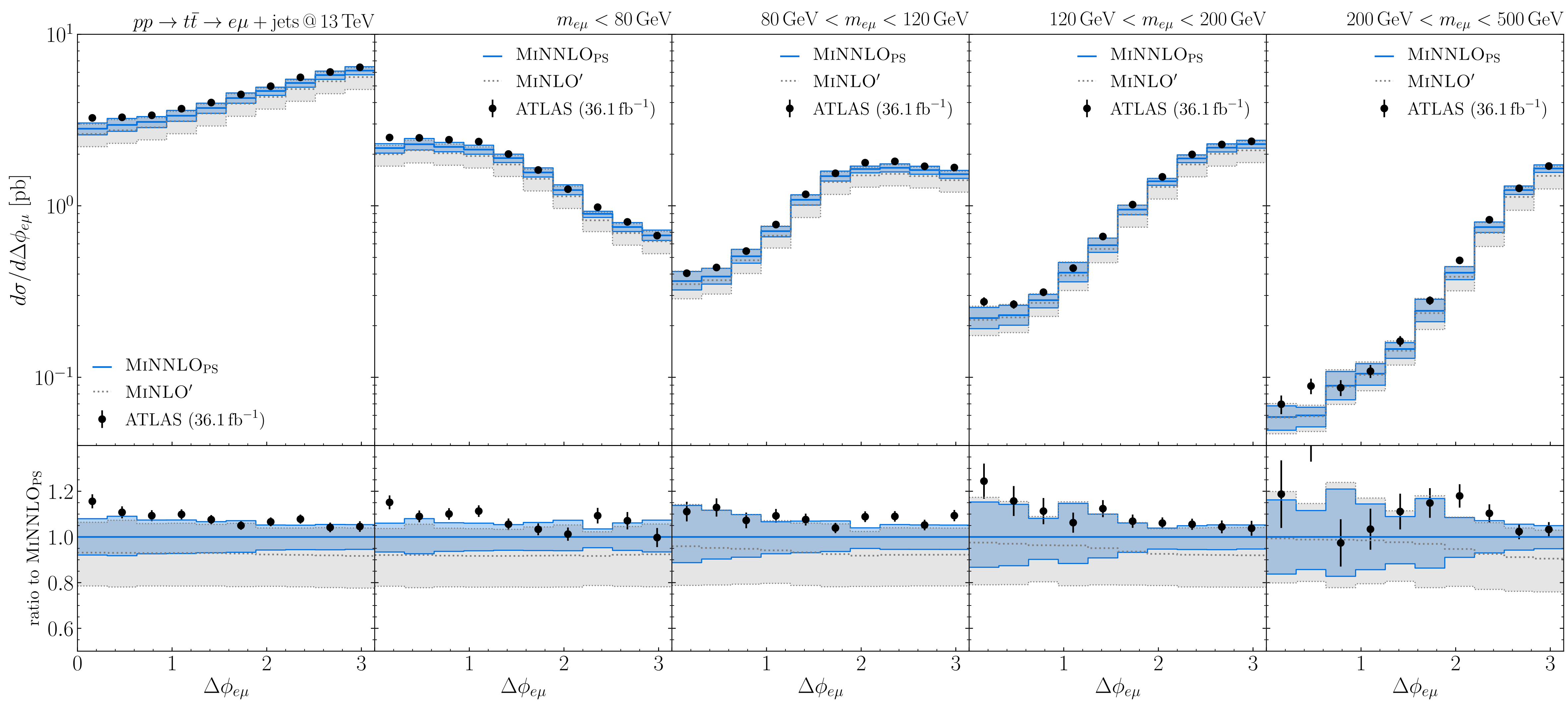
- ☑ excellent agreement of MiNNLO$_{PS}$ with NNLO at inclusive level
- ☑ improved description of top transverse momenta w.r.t. NNLO

Including top decays

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]

Data unfolded to fiducial $\ell^+\nu\ell^-\bar{\nu}b\bar{b}$ phase space from [ATLAS EPJC 80 (2020) 528]



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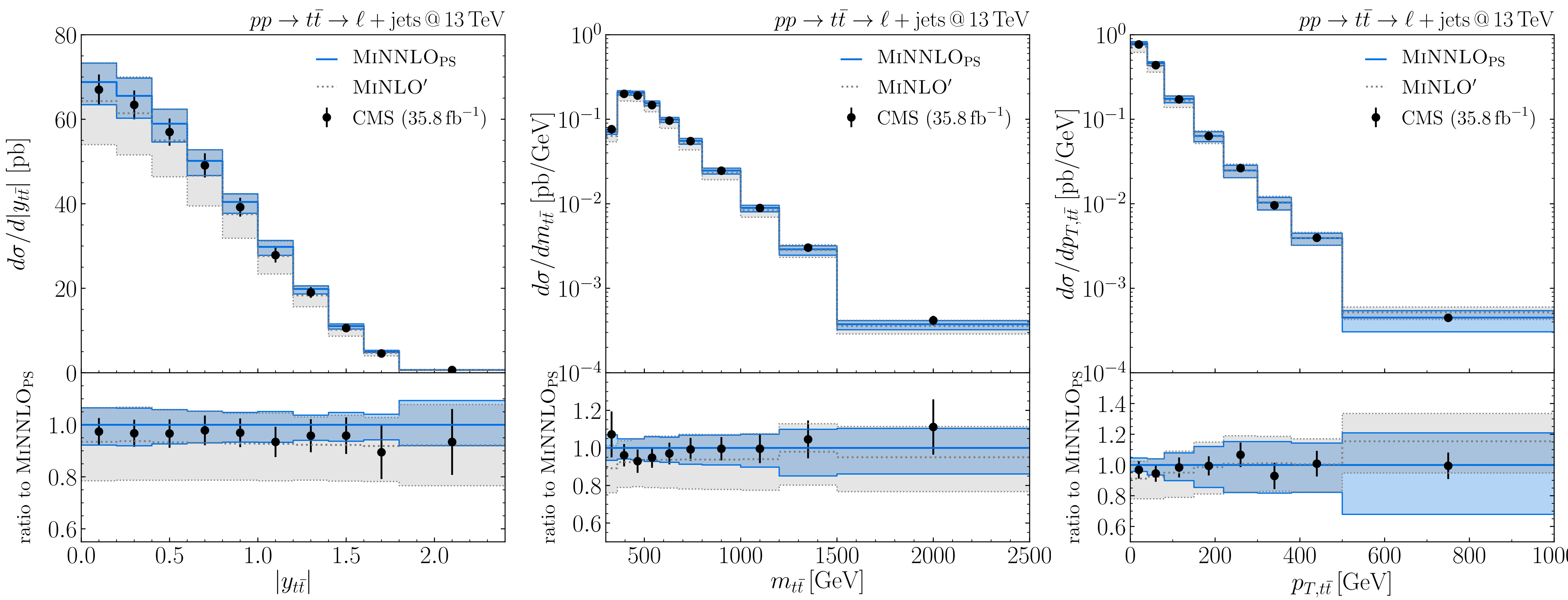
[Following the ttJ implementation in POWHEG of Alioli, Moch, Uwer 1110.5251]

Data unfolded to fiducial $\ell\nu q\bar{q}'b\bar{b}$ phase space from [CMS PRD 97 (2018) 112003]



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Including top decays

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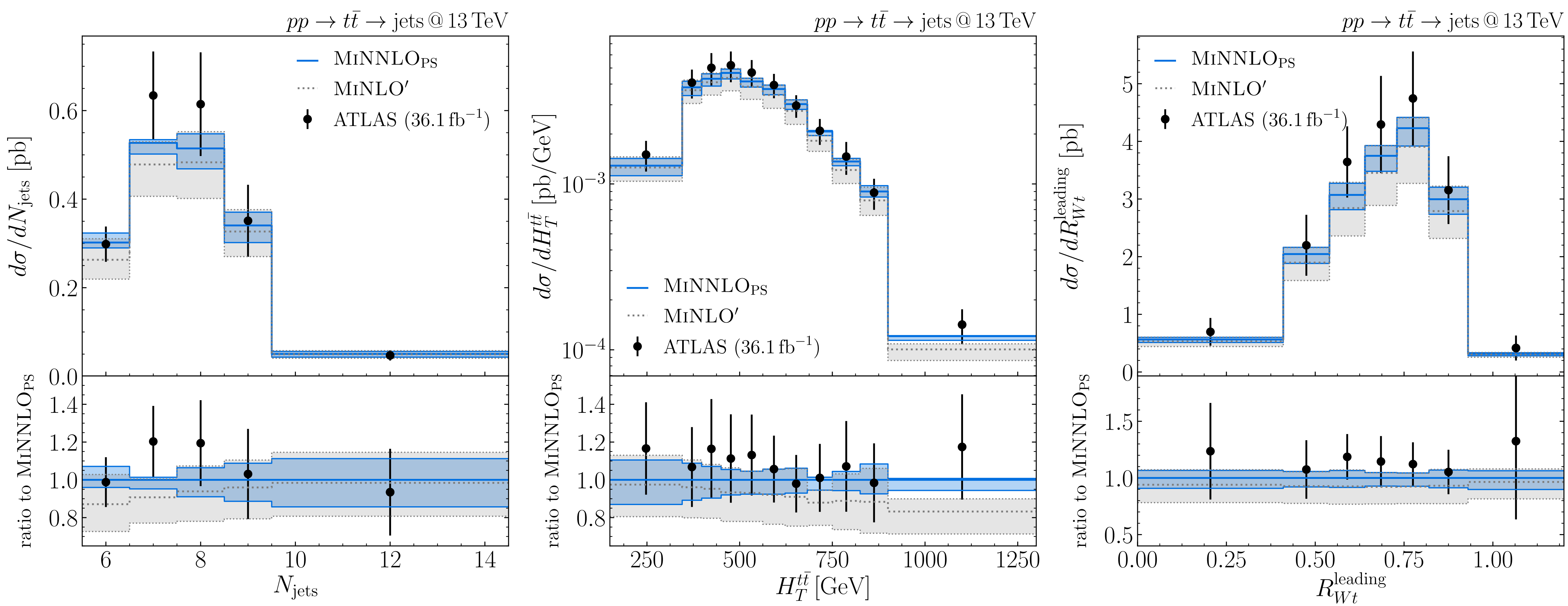
[Following the ttJ implementation in POWHEG of Alioli, Moch, Uwer 1110.5251]

Data unfolded to fiducial $q\bar{q}'q''\bar{q}'''b\bar{b}$ phase space from [ATLAS JHEP 01 (2021) 033]



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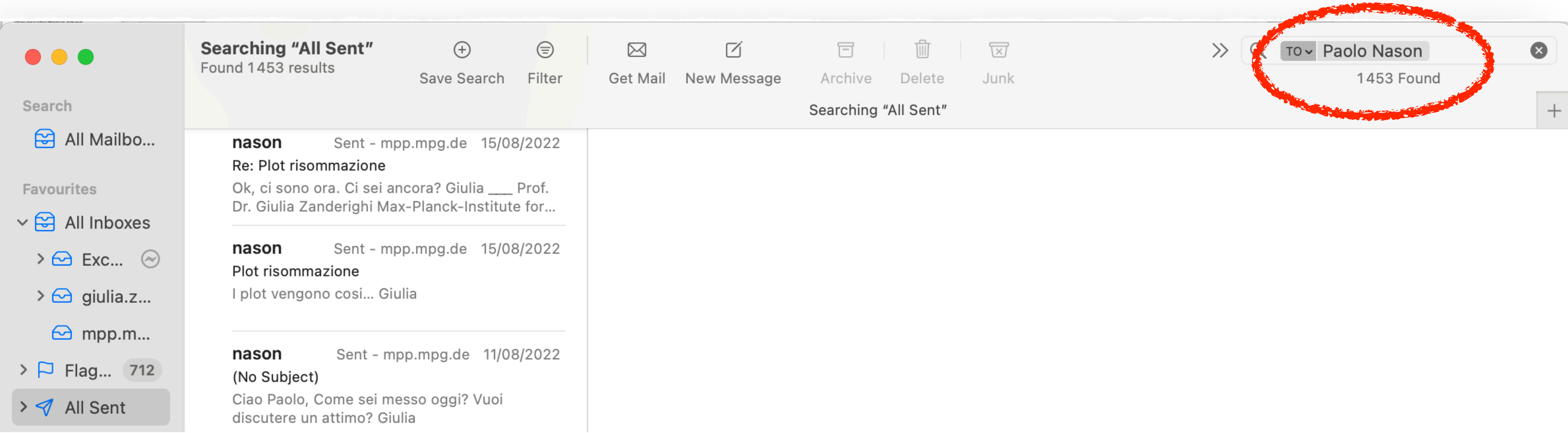
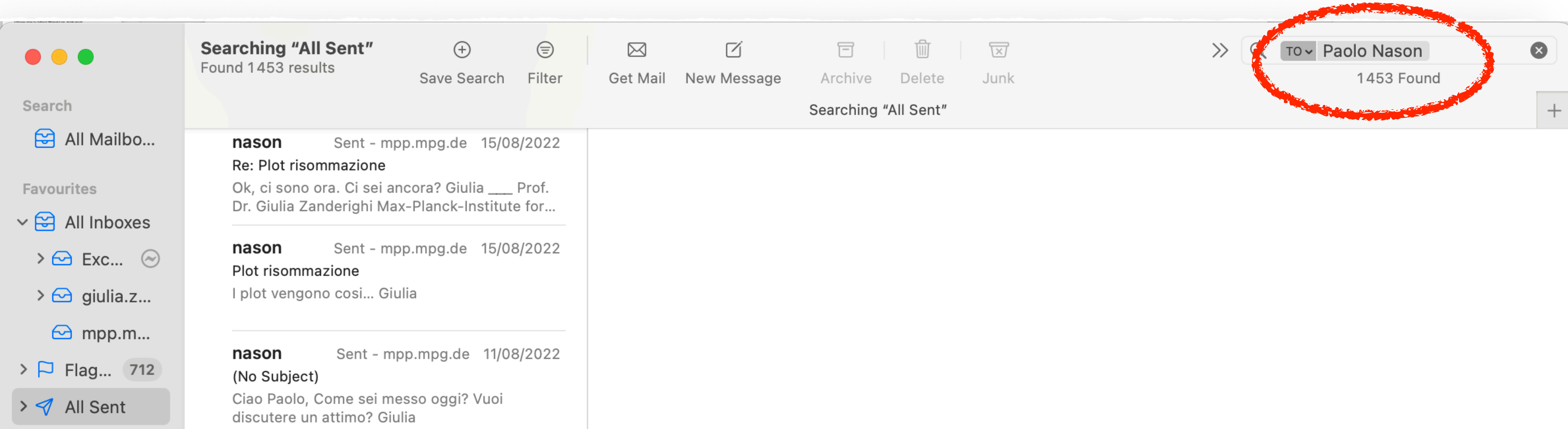
Conclusions

- Presented MiNNLO$_{PS}$ methods, relying on MiNLO and POWHEG
- Focused on results for top pair production
  - First NNLO+PS generator for a coloured process
  - Good agreement with ATLAS/CMS data
  - Code implemented in POWHEG BOX V2 and public
  - Results include top-decays with spin correlations
  - Method allow the inclusion of decays at NNLO, once the relevant input becomes available
- A few concluding remarks …

Since January 2019 ...



Since January 2019 …



Thank you Paolo!