QCD@LHC - FREIBURG - 8th OCTOBER 2024

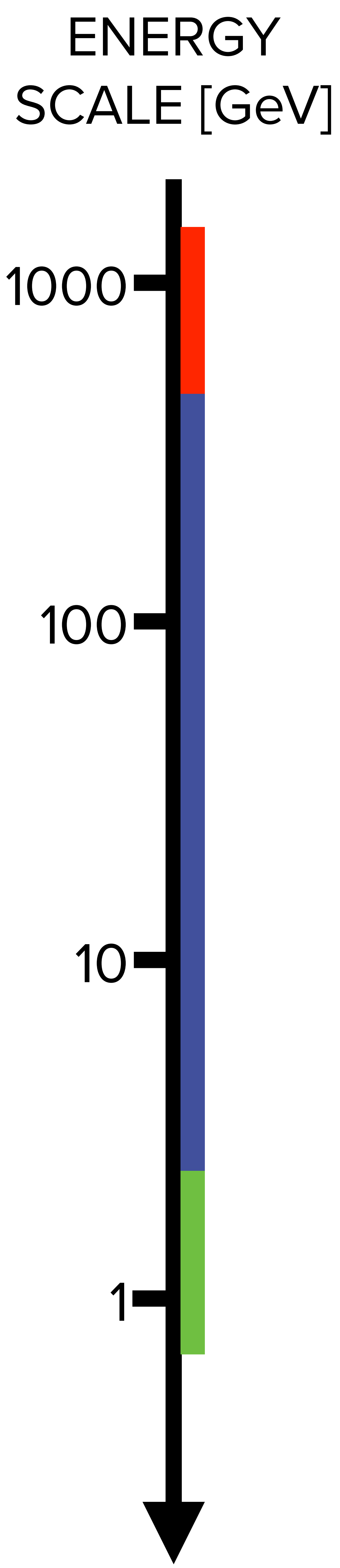
MiNNLO$_{PS}$ EVENT GENERATOR: COLOUR SINGLET PLUS ONE JET EVENTS

SILVIA ZANOLI
University of Oxford

UNIVERSITY OF OXFORD

Based on **2402.00596** Ebert, Rottoli, Wiesemann, Zanderighi, **SZ**

LHC EVENT

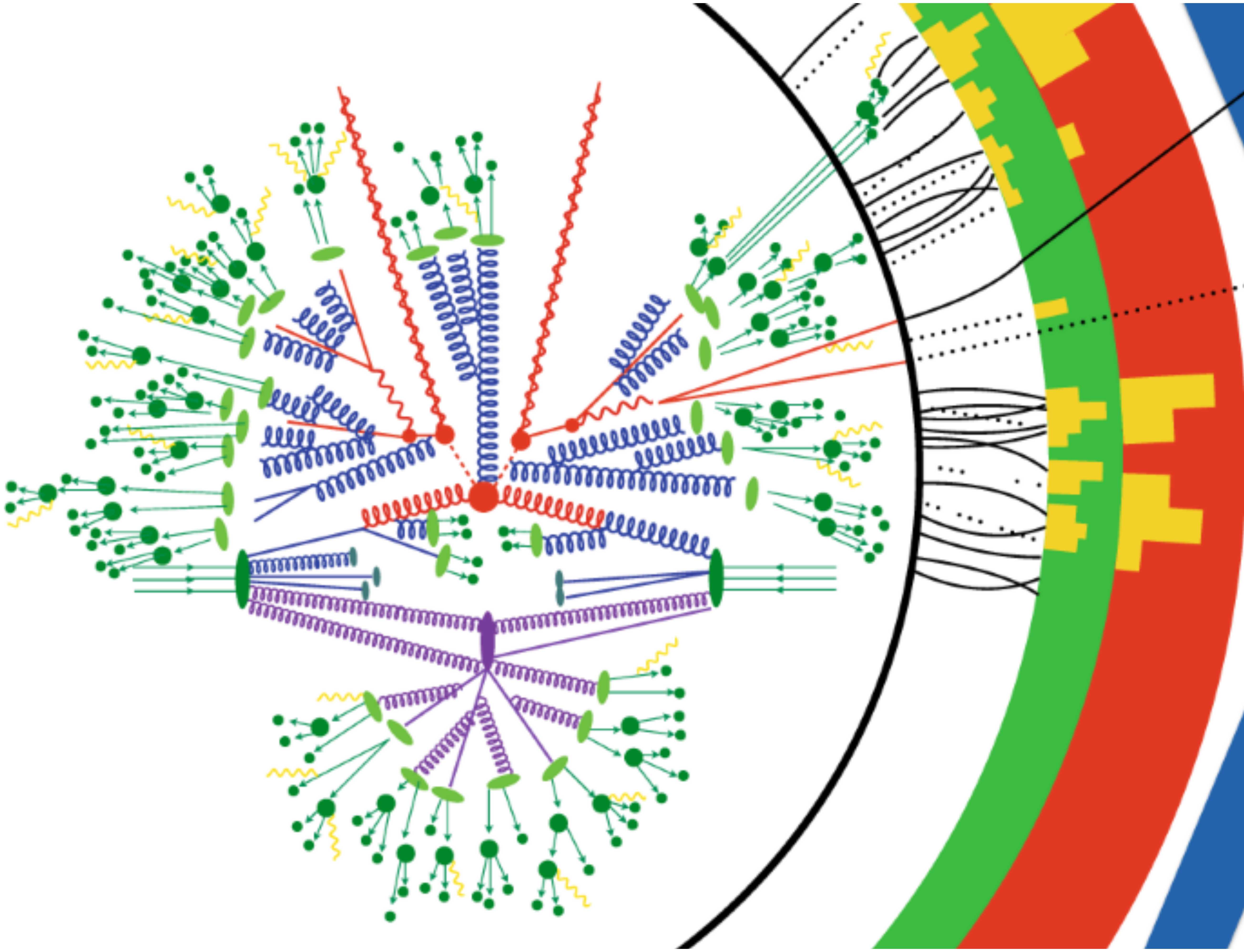


1. HARD SCATTERING

2. PARTON SHOWER

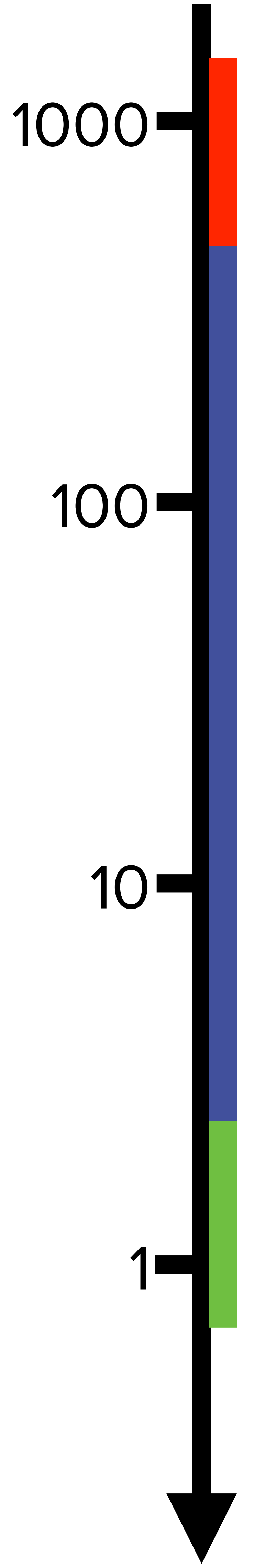
3. HADRONIZATION

4. UNDERLYING EVENT



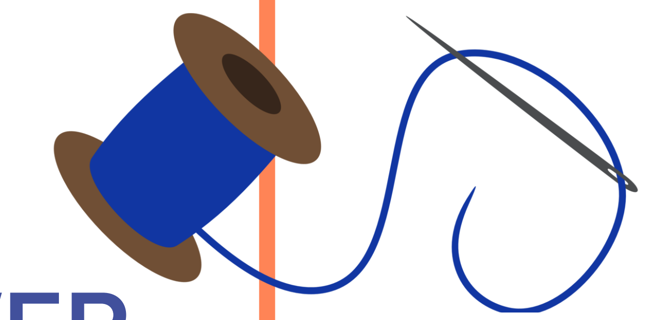
LHC EVENT

ENERGY
SCALE [GeV]

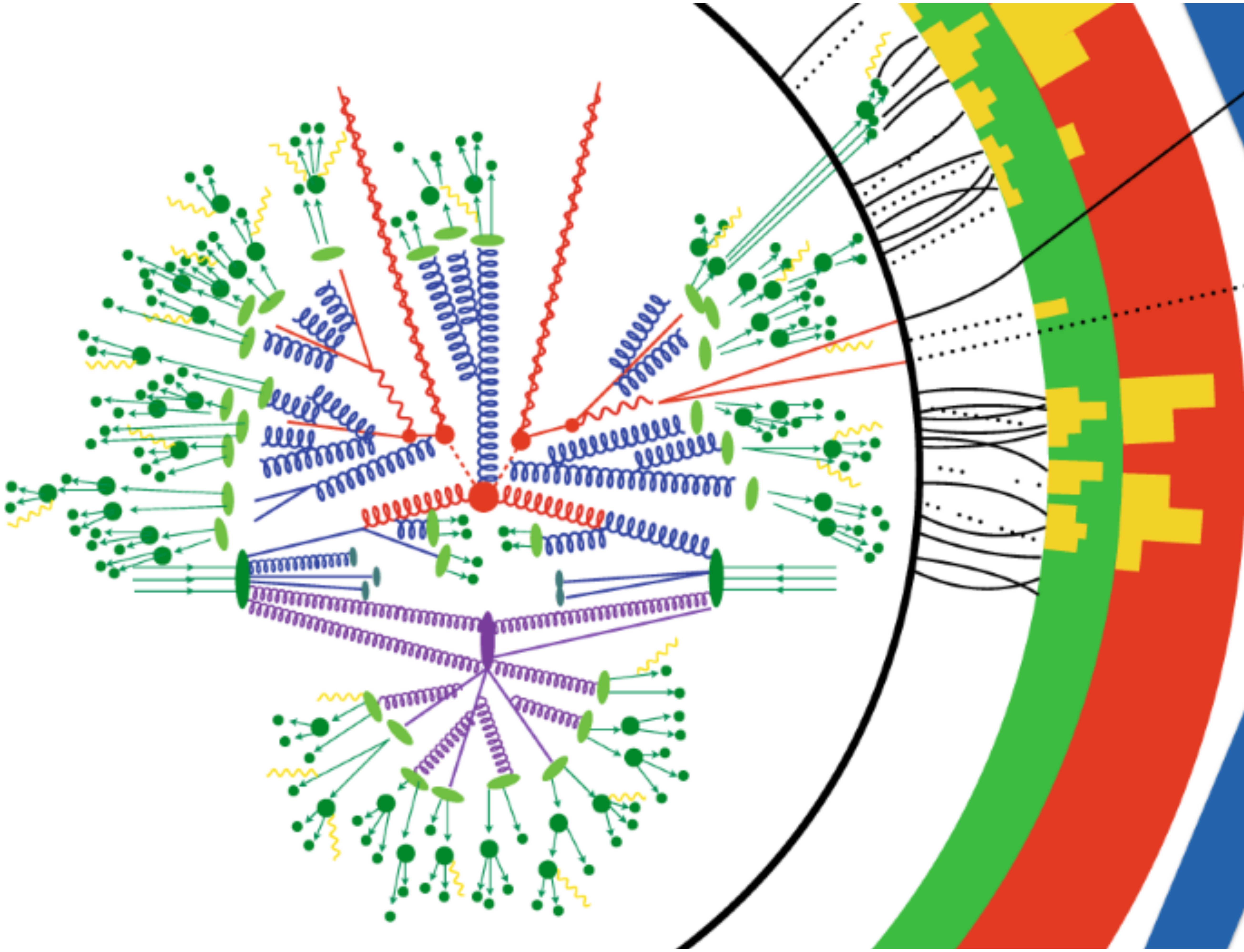


MATCHING

1. HARD SCATTERING



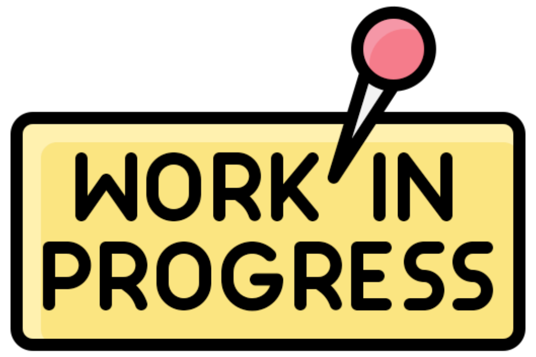
2. PARTON SHOWER
3. HADRONIZATION
4. UNDERLYING EVENT



MATCHING

NLO+LL$_{PS}$

- A **solved problem** for long time.
- Completely understood and **fully automatized**.
- Two main approaches available: POWHEG [Nason ’04; Frixione, Nason, Oleari ’07; Alioli, Nason, Oleari, Re ’10] and MC@NLO [Frixione, Webber ’02].



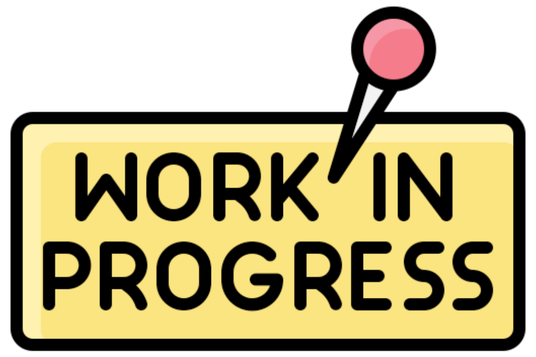
NNLO+LL$_{PS}$

- **State-of-the-art** for precision LHC phenomenology.
- Lots of ongoing effort, **many processes already implemented**.
- Two main methods available: MiNNLO$_{PS}$ [Monni, Nason, Re, Wiesemann, Zanderighi ’19] and Geneva [Alioli, Bauer, Berggren, Tackmann, Walsh, Zuberi ’13, + subsequent papers].

MATCHING

NLO+LL$_{PS}$

- A **solved problem** for long time.
- Completely understood and **fully automatized**.
- Two main approaches available: POWHEG [Nason '04; Frixione, Nason, Oleari '07; Alioli, Nason, Oleari, Re '10] and MC@NLO [Frixione, Webber '02].

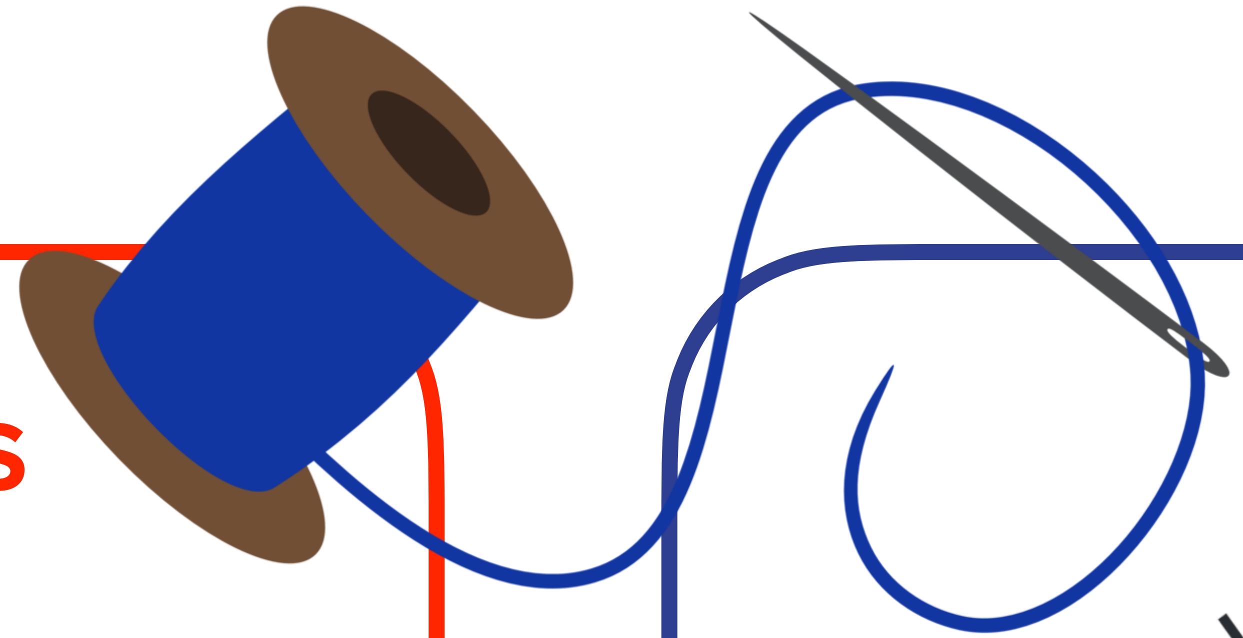


NNLO+LL$_{PS}$

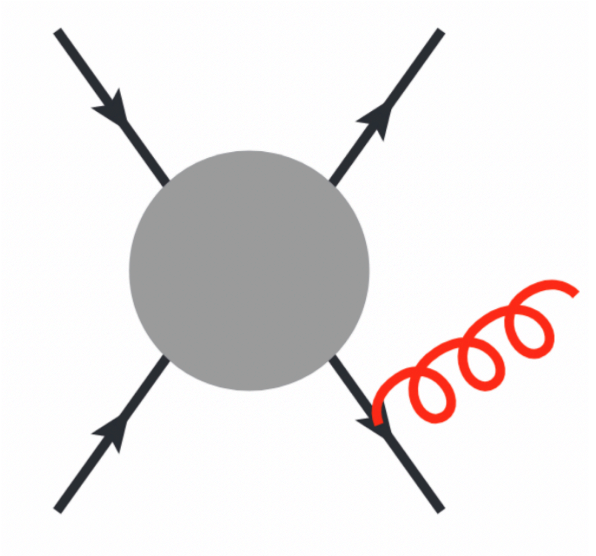
- **State-of-the-art** for precision LHC phenomenology.
- Lots of ongoing effort, **many processes already implemented**.
- Two main methods available: MiNNLO$_{PS}$ [Monni, Nason, Re, Wiesemann, Zanderighi '19] and Geneva [Alioli, Bauer, Berggren, Tackmann, Walsh, Zuberi '13, + subsequent papers].

Logarithmically accurate showers are now available, but matching is still under investigation (at NLO). The method I am presenting today does not directly apply to matching with NLL showers!

WHAT'S THE PROBLEM?

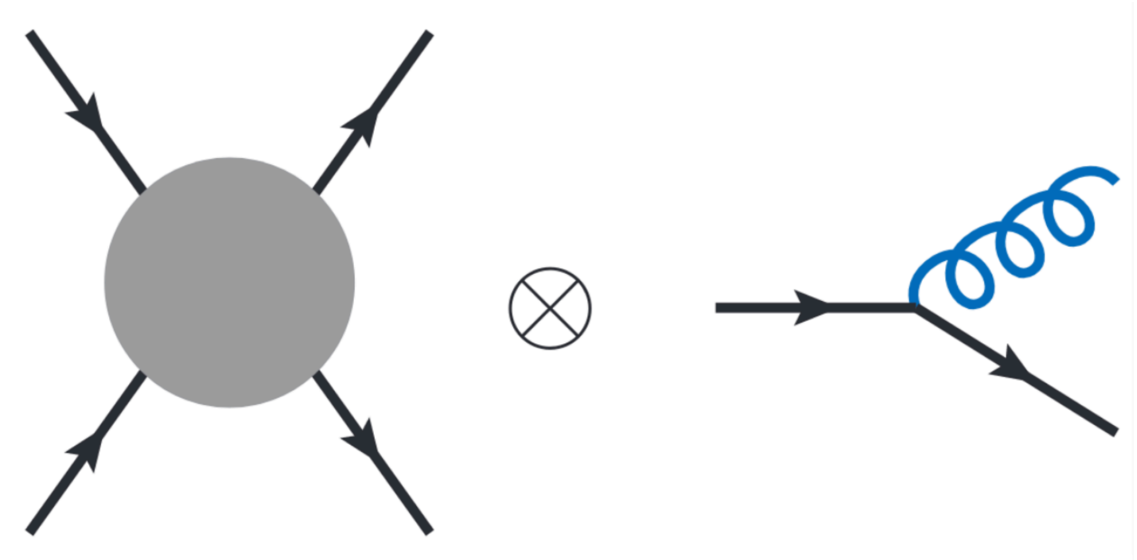


FIXED-ORDER CALCULATIONS



Correct real emission

PARTON SHOWER



Approximate real emission

!! DOUBLE COUNTING !!

NLO+PS

THE POWHEG METHOD

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

Master Formula

$$d\sigma_{\rm pwg} = d\Phi_F\, \bar{B}(\Phi_F) \left\{ \Delta_{\rm pwg}(\Lambda_{\rm pwg}) + \int d\Phi_{\rm rad} \Delta_{\rm pwg}(p_{T,\rm rad}) \frac{R(\Phi_F, \Phi_{\rm rad})}{B(\Phi_F)} \right\}$$

NLO NORMALIZATION (= xs)

$$\bar{B}(\Phi_F) = B(\Phi_F) + V(\Phi_F) + \int d\Phi_{\rm rad} \left[R(\Phi_{FJ}) - C(\Phi_{FJ}) \right]$$

FIRST (= hardest) EMISSION
obtained with the correct matrix element R/B

$$\Delta(p_T) = \exp\left\{ - \int d\Phi'_{\rm rad} \frac{R(\Phi_F, \Phi'_{\rm rad})}{B(\Phi_F)} \Theta(p'_T - p_T) \right\}$$

When using a p_T-ordered shower (most common option, like PYTHIA), we apply a p_T-veto: all the emissions produced by the shower must be softer than the first emission produced by POWHEG.

NNLO+PS

THE MiNNLO$_{PS}$ METHOD

[Monni, Nason, Re, Wiesemann, Zanderighi ’19]

Master Formula

$$d\sigma_F^{\mathrm{MiNNLO_{PS}}} = d\Phi_{FJ} \; \bar{B}^{\mathrm{MiNNLO_{PS}}}(\Phi_{FJ}) \left\{ \Delta_{pwg}(\Lambda_{pwg}) + \int d\Phi_{rad} \Delta_{pwg}(p_{T,rad}) \frac{R(\Phi_{FJ}, \Phi_{rad})}{B(\Phi_{FJ})} \right\}$$

NNLO NORMALIZATION (= xs)

SECOND EMISSION
obtained à la POWHEG

$$\bar{B}^{\mathrm{MiNNLO_{PS}}}(\Phi_{FJ}) =$$

NNLO+PS

THE MiNNLOPS METHOD

[Monni, Nason, Re, Wiesemann, Zanderighi ’19]

Master Formula

$$d\sigma_F^{\mathrm{MiNNLO_{PS}}} = d\Phi_{FJ} \; \bar{B}^{\mathrm{MiNNLO_{PS}}}(\Phi_{FJ}) \left\{ \Delta_{pwg}(\Lambda_{pwg}) + \int d\Phi_{rad} \Delta_{pwg}(p_{T,rad}) \frac{R(\Phi_{FJ}, \Phi_{rad})}{B(\Phi_{FJ})} \right\}$$

NNLO NORMALIZATION (= xs)

SECOND EMISSION obtained à la POWHEG

$$\bar{B}^{\mathrm{MiNNLO_{PS}}}(\Phi_{FJ}) = \left(B(\Phi_{FJ}) + V(\Phi_{FJ}) + \int d\Phi_{rad} R(\Phi_{FJJ}) \right)$$

Born FJ

DIVERGENT

Virtual+Real on FJ

	F	F+J	F+JJ	F+(>3J)
F@NNLO+PS	-	NLO	LO	PS (LL)

THE MiNNLO$_{PS}$ METHOD

[Monni, Nason, Re, Wiesemann, Zanderighi ’19]

Master Formula

$$d\sigma_F^{\mathrm{MiNNLO_{PS}}} = d\Phi_{FJ}\ \bar{B}^{\mathrm{MiNNLO_{PS}}}(\Phi_{FJ}) \left\{ \Delta_{pwg}(\Lambda_{pwg}) + \int d\Phi_{rad} \Delta_{pwg}(p_{T,rad}) \frac{R(\Phi_{FJ}, \Phi_{rad})}{B(\Phi_{FJ})} \right\}$$

NNLO NORMALIZATION (= xs)

SECOND EMISSION obtained à la POWHEG

$$\bar{B}^{\mathrm{MiNNLO_{PS}}}(\Phi_{FJ}) = e^{-\tilde{S}(p_T)} \left(B(\Phi_{FJ})\left(1 + \alpha_s \tilde{S}^{(1)}\right) + V(\Phi_{FJ}) + \int d\Phi_{rad} R(\Phi_{FJJ}) \right)$$

Sudakov form factor

$$\tilde{S}(p_T) = \int_{p_T^2}^{Q^2} \frac{dq^2}{q^2}\left[A \log\frac{Q^2}{q^2} + B\right]$$

Born FJ

DIVERGENT

Correct NLO on FJ

Virtual+Real on FJ

	F	F+J	F+JJ	F+(>3J)
F@NNLO+PS	NLO	NLO	LO	PS (LL)

NNLO+PS

THE MiNNLO$_{PS}$ METHOD

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

Master Formula

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

NNLO NORMALIZATION (= xs)

SECOND EMISSION obtained à la POWHEG

$$\bar{B}^{\text{MiNNLO}_{\text{PS}}}(\Phi_{FJ}) = e^{-\tilde{S}(p_T)} \left(B(\Phi_{FJ})\left(1 + \alpha_s \tilde{S}^{(1)}\right) + V(\Phi_{FJ}) + \int d\Phi_{rad} R(\Phi_{FJJ}) + \left(D(p_T) - \alpha_s D^{(1)}(p_T) - \alpha_s^2 D^{(2)}(p_T)\right) \mathscr{F} \right)$$

Sudakov form factor

$$\tilde{S}(p_T) = \int_{p_T^2}^{Q^2} \frac{dq^2}{q^2} \left[A \log \frac{Q^2}{q^2} + B \right]$$

Born FJ

DIVERGENT

Correct NLO on FJ

Virtual+Real on FJ

α_s^3 correction needed for NNLO normalization

spreading $\Phi_F \to \Phi_{FJ}$

	F	F+J	F+JJ	F+(>3J)
F@NNLO+PS	NNLO	NLO	LO	PS (LL)

NNLO+PS

THE MiNNLO$_{PS}$ METHOD

- Analytic all-order formula:

$$D(\mathrm{p_T}) \equiv -\frac{\mathrm{d}\tilde{S}(\mathrm{p_T})}{\mathrm{dp_T}}\mathscr{L}(\mathrm{p_T}) + \frac{d\mathscr{L}\mathrm{p_T}}{\mathrm{dp_T}}$$

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Phi_\mathrm{F}\mathrm{dp_T}} = \frac{\mathrm{d}\sigma^\mathrm{sing}}{\mathrm{d}\Phi_\mathrm{F}\mathrm{dp_T}} + R(\mathrm{p_T}) = \frac{\mathrm{d}}{\mathrm{dp_T}}\left\{e^{-\tilde{S}(\mathrm{p_T})}\mathscr{L}(\mathrm{p_T})\right\} + R(\mathrm{p_T}) = e^{-\tilde{S}(\mathrm{p_T})}\left[D(p_T) + \frac{R(p_T)}{e^{-\tilde{S}(\mathrm{p_T})}}\right]$$

NNLO+PS

THE MiNNLOPS METHOD

$$D(p_T) \equiv -\frac{d\tilde{S}(p_T)}{dp_T}\mathscr{L}(p_T) + \frac{d\mathscr{L}p_T}{dp_T}$$

- Analytic all-order formula:

$$\frac{d\sigma}{d\Phi_F dp_T} = \frac{d\sigma^{\mathrm{sing}}}{d\Phi_F dp_T} + R(p_T) = \frac{d}{dp_T}\left\{e^{-\tilde{S}(p_T)}\mathscr{L}(p_T)\right\} + R(p_T) = e^{-\tilde{S}(p_T)}\left[D(p_T) + \frac{R(p_T)}{e^{-\tilde{S}(p_T)}}\right]$$

- Combine with FJ fixed-order $d\sigma_{FJ}$ and expand up to α_s^3:

$\mu_R = \mu_F = p_T$

$$\int \frac{dp_T}{p_T}\alpha_s^m(p_T)\ \ln^n\frac{p_T}{Q}\ e^{-\tilde{S}(p_T)} \approx \mathcal{O}\left(\alpha_s^{m-\frac{n+1}{2}}\right)$$

$$d\sigma_F = d\sigma_F^{\mathrm{sing}} + [d\sigma_{FJ}]_{\mathrm{f.o.}} - [d\sigma_F^{\mathrm{sing}}]_{\mathrm{f.o.}} = e^{-\tilde{S}(p_T)}\left\{D + \underbrace{\frac{[d\sigma_{FJ}]_{\mathrm{f.o.}}}{[e^{-\tilde{S}(p_T)}]_{\mathrm{f.o.}}}}_{1-\alpha_s\tilde{S}^{(1)}} - \underbrace{\frac{[d\sigma_F^{\mathrm{sing}}]_{\mathrm{f.o.}}}{[e^{-\tilde{S}(p_T)}]_{\mathrm{f.o.}}}}_{-\alpha_s D^{(1)}(p_T) - \alpha_s^2 D^{(2)}(p_T)}\right\}$$

NNLO+PS

THE MiNNLO$_{PS}$ METHOD

$D(p_T) \equiv -\frac{d\tilde{S}(p_T)}{dp_T}\mathscr{L}(p_T) + \frac{d\mathscr{L}p_T}{dp_T}$

- Analytic all-order formula:

$$\frac{d\sigma}{d\Phi_F dp_T} = \frac{d\sigma^{sing}}{d\Phi_F dp_T} + R(p_T) = \frac{d}{dp_T}\left\{e^{-\tilde{S}(p_T)}\mathscr{L}(p_T)\right\} + R(p_T) = e^{-\tilde{S}(p_T)}\left[D(p_T) + \frac{R(p_T)}{e^{-\tilde{S}(p_T)}}\right]$$

- Combine with FJ fixed-order $d\sigma_{FJ}$ and expand up to α_s^3:

$\mu_R = \mu_F = p_T$

$\int \frac{dp_T}{p_T}\alpha_s^m(p_T)\ \ln^n\frac{p_T}{Q}\ e^{-\tilde{S}(p_T)} \approx \mathscr{O}\left(\alpha_s^{m-\frac{n+1}{2}}\right)$

$$d\sigma_F = d\sigma_F^{sing} + [d\sigma_{FJ}]_{f.o.} - [d\sigma_F^{sing}]_{f.o.} = e^{-\tilde{S}(p_T)}\left\{D + \underbrace{\frac{[d\sigma_{FJ}]_{f.o.}}{[e^{-\tilde{S}(p_T)}]_{f.o.}}}_{1-\alpha_s\tilde{S}^{(1)}} - \underbrace{\frac{[d\sigma_F^{sing}]_{f.o.}}{[e^{-\tilde{S}(p_T)}]_{f.o.}}}_{}\right\}$$

$$-\alpha_s D^{(1)}(p_T) - \alpha_s^2 D^{(2)}(p_T)$$

$$\bar{B}^{MiNNLO_{PS}}(\Phi_{FJ}) = e^{-\tilde{S}(p_T)}\left(B(\Phi_{FJ})\left(1+\alpha_s\tilde{S}^{(1)}\right) + V(\Phi_{FJ}) + \int d\Phi_{rad}R(\Phi_{FJJ}) + \left(D(p_T) - \alpha_s D^{(1)}(p_T) - \alpha_s^2 D^{(2)}(p_T)\right)\mathscr{F}\right)$$

WHAT CAN WE DO WITH MiNNLO$_{PS}$?

2 → 1 PROCESSES

H [1908.06987, 2407.01354] ✓
Z [1908.06987] ✓
W [2006.04133] ✓
bb→H [2402.04025]

2 → 2 PROCESSES

Zγ [2010.10478] ✓
$\gamma\gamma$ [2204.12602] ✓
ZZ [2108.05337] ✓
VH (H→bb) [2112.04168]
(+SMEFT [2204.00663] **)**
WW [2103.12077] ✓
WZ [2208.12660] ✓

QQ PRODUCTION

tt [2012.14267, 2112.12135] ✓
bb [2112.04168]

QQF PRODUCTION

bbZ [2404.08598]

INCLUSION NLO EW

WZ [2208.12660] ✓
Z ongoing

THIS TALK!

EXTENSION TO PROCESSES WITH JETS

[2402.00596]

✓ = **publicly available at https://powhegbox.mib.infn.it/**

MiNLO$_{PS}$ FOR PROCESSES WITH JETS

- **We now aim to target NNLO+PS accuracy in processes with a jet.**
- N-jettiness (τ_N) is a suitable observable to study processes with jets, and the resummation is known at a sufficient order for a NNLO+PS accurate formalism.

τ_N represents how "N-jet-like" an event looks.

$$\tau_N = \frac{2}{Q^2} \sum_k \min\{q_a \cdot p_k, q_b \cdot p_k, q_1 \cdot p_k, \ldots, q_N \cdot p_k\}$$

q_a, q_b = incoming particles
q_i = signal jets
p_k = hadronic fs particles

$\tau_N \longrightarrow 0$: exactly N jet in the event
$\tau_N \longrightarrow 1$: the event has hard radiation between the N signal jets

THE PLAN

MiNNLO$_{PS}$-p_T : NNLO accuracy on F

↓

MiNNLO$_{PS}$-τ_0 : NNLO accuracy on F

↓

MiNNLO$_{PS}$-τ_1 : NNLO accuracy on FJ

THE PLAN

MiNNLO$_{PS}$-p_T : NNLO accuracy on F

↓

MiNNLO$_{PS}$-τ_0 : NNLO accuracy on F

- ✓ Theoretical formalism
- ✓ Implementation for H/Z production
- ✓ Phenomenological analysis

- **Problems in the matching with the shower**
- **Large discrepancies in the 1 jet bin for H production**

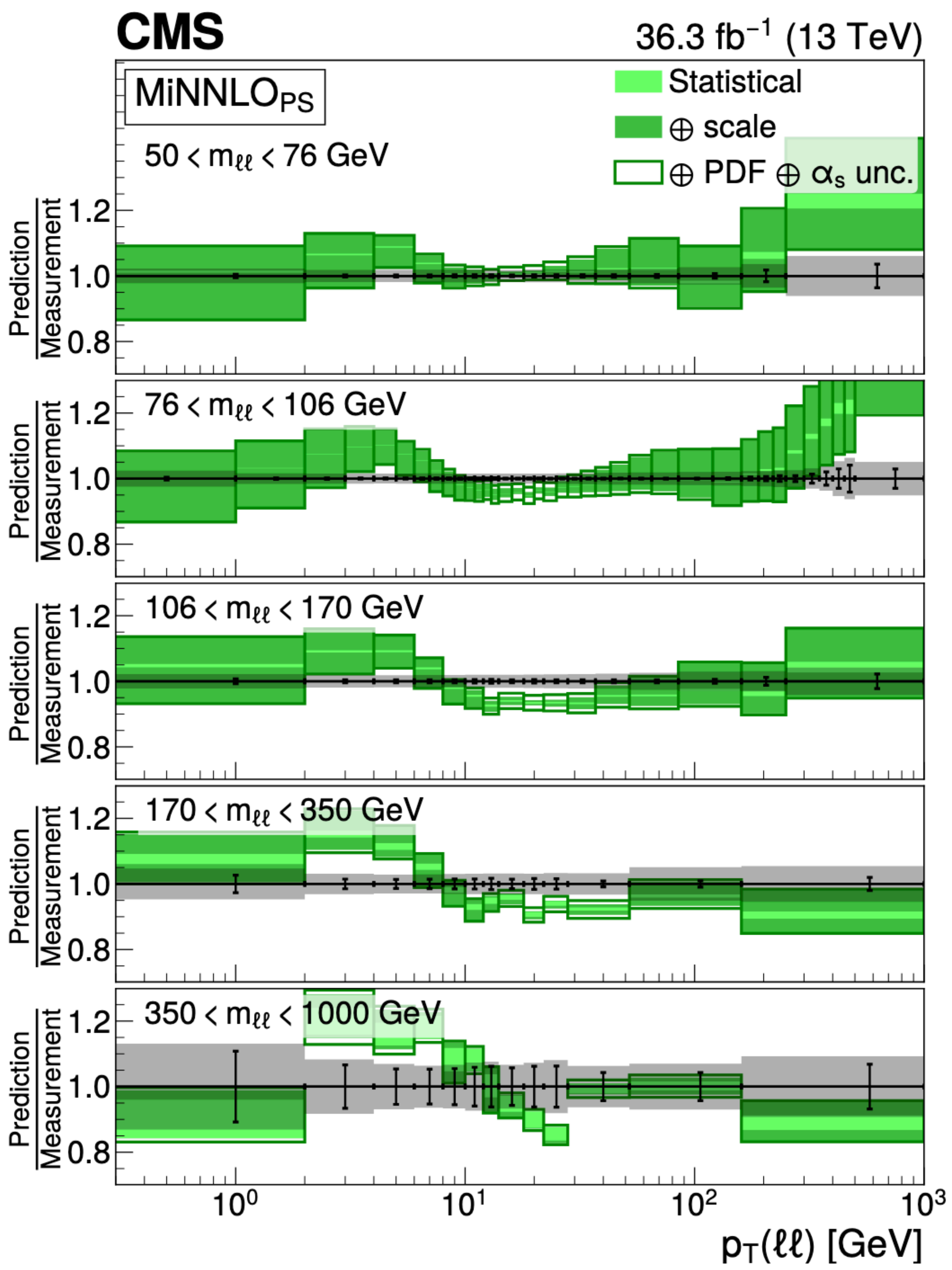
↓

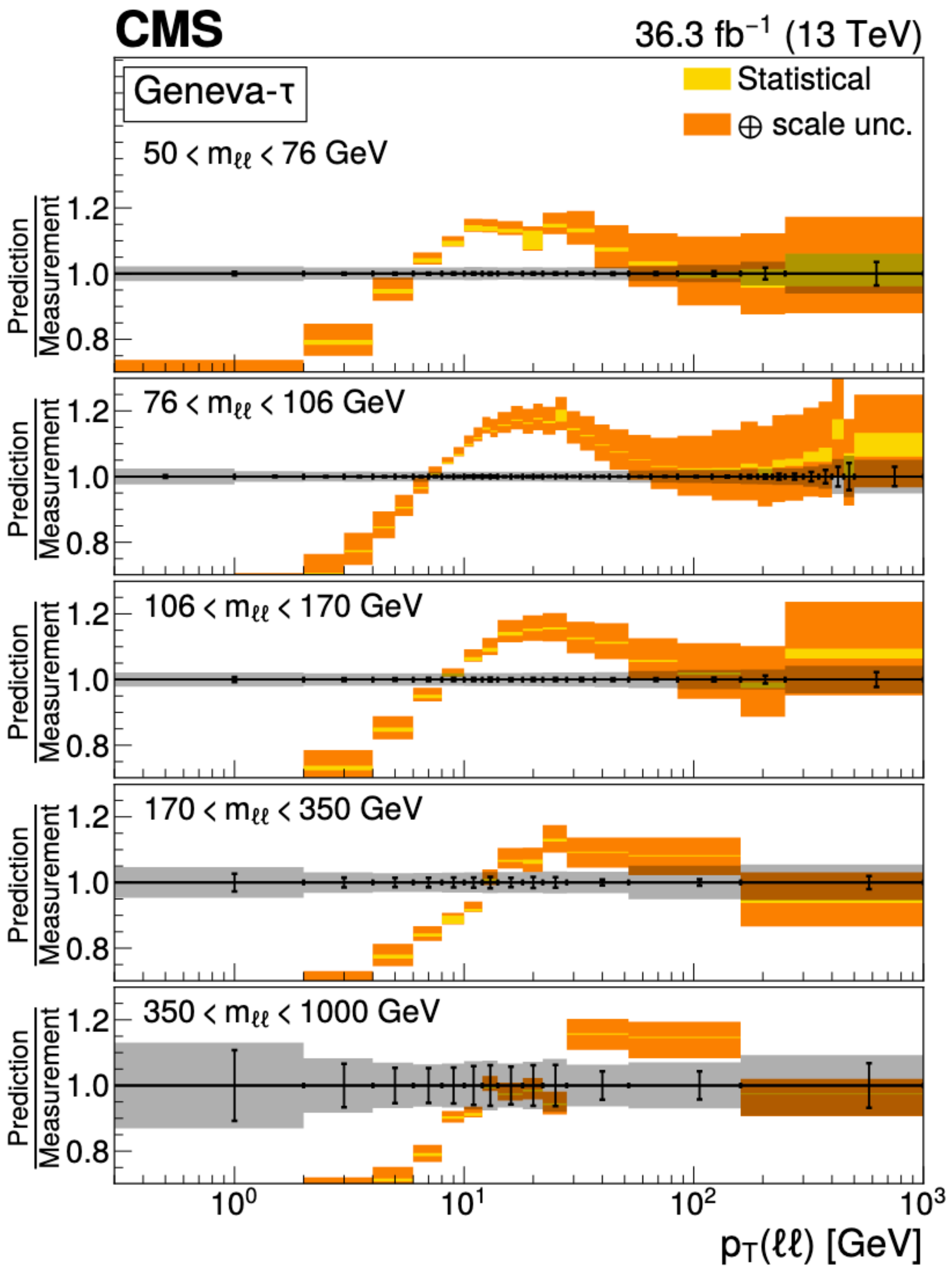
MiNNLO$_{PS}$-τ_1 : NNLO accuracy on FJ

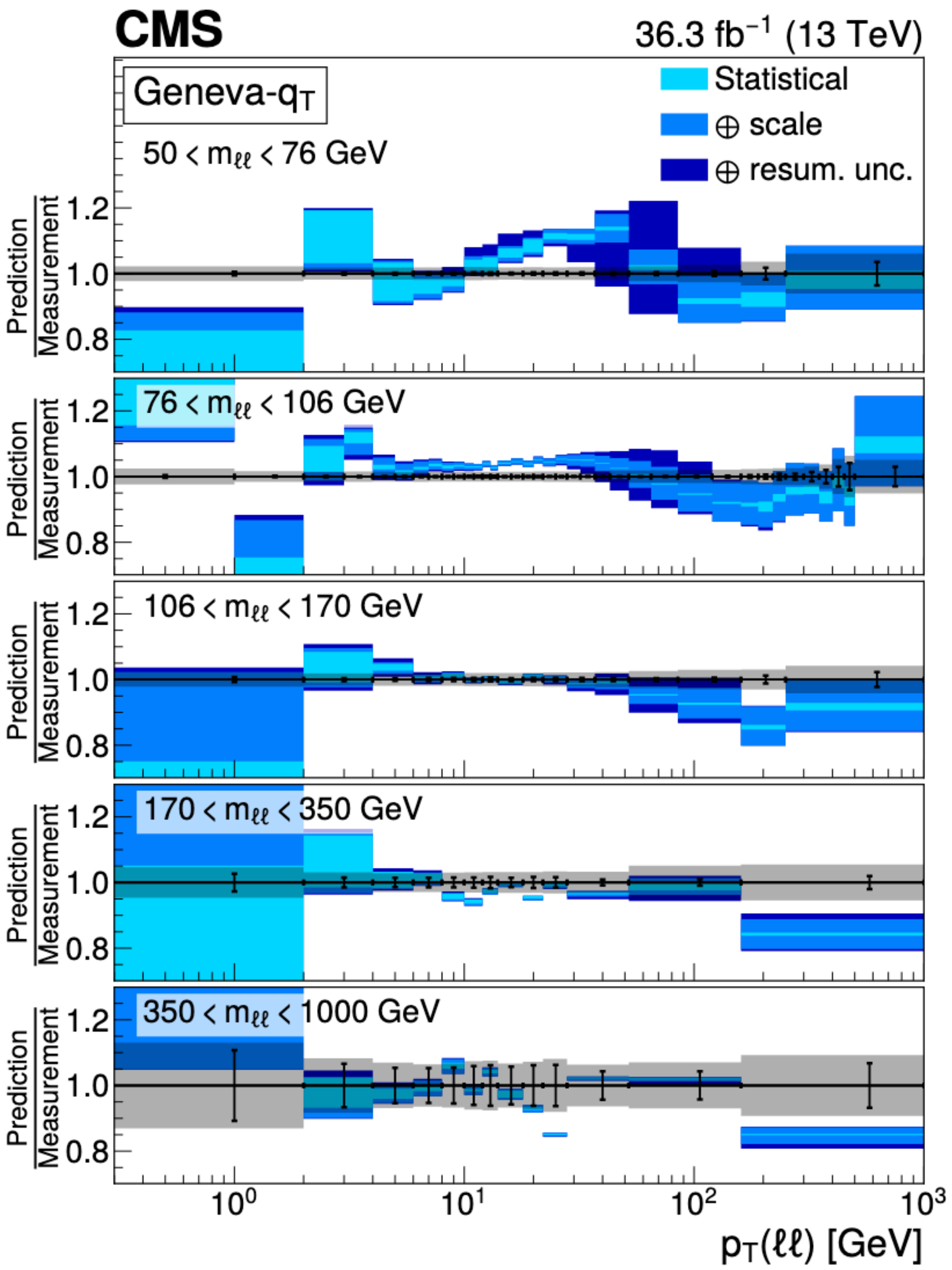
- ✓ Theoretical formalism

DY - CMS 2205.04897

MiNNLOPS-pT GENEVA-τ0 GENEVA-pT







THE MiNNLO$_{\text{PS}}$-τ_0 METHOD

[Ebert, Rottoli, Wiesemann, Zanderighi, SZ '24]

- We start from the factorization formula of 0-jettiness at NNLL' (for 1-jettiness, include also jet function)

$$\frac{d\sigma}{d\Phi_F d\tau_0} = \frac{d\sigma^{\text{sing}}}{d\Phi_F d\tau_0} + R_f(\tau_0) \qquad \frac{d\sigma^{\text{sing}}}{d\Phi_F d\tau_0} = \sum_{a,b} \frac{d|M_{a,b}|^2}{d\Phi_F} H_{a,b}(Q,\mu) \int dt_a dt_b B_a(t_a, x_a, \mu)\, B_b(t_b, x_b, \mu)\, S\left(\tau_0 - \frac{t_a}{Q} - \frac{t_b}{Q}, \mu\right)$$

- We evolve and expand all the needed ingredients in order to obtain: $\frac{d\sigma^{\text{sing}}}{d\Phi_F d\tau_0} = \frac{d}{d\tau_0}\left(e^{-\tilde{S}(\tau_0)} \mathscr{L}(\tau_0)\right)$

- We follow all the steps presented for MiNNLO$_{\text{PS}}$-p$_{\text{T}}$ to obtain:

$$\bar{B}^{\text{MiNNLO}_{\text{PS}}}(\Phi_{\text{FJ}}) = e^{-\tilde{S}(\tau_0)}\left(B(\Phi_{\text{FJ}})\left(1 + \alpha_s \tilde{S}^{(1)}\right) + V(\Phi_{\text{FJ}}) + \int d\Phi_{\text{rad}} R(\Phi_{\text{FJJ}}) + \left(D(\tau_0) - \alpha_s D^{(1)}(\tau_0) - \alpha_s^2 D^{(2)}(\tau_0)\right) \mathscr{F}\right)$$

THE MiNNLO$_{PS}$-τ_0 METHOD

[Ebert, Rottoli, Wiesemann, Zanderighi, SZ ’24]

- We start from the factorization formula of 0-jettiness at NNLL’ (for 1-jettiness, include also jet function)

$$\frac{d\sigma}{d\Phi_F d\tau_0} = \frac{d\sigma^{\rm sing}}{d\Phi_F d\tau_0} + R_f(\tau_0) \qquad \frac{d\sigma^{\rm sing}}{d\Phi_F d\tau_0} = \sum_{a,b} \frac{d|M_{a,b}|^2}{d\Phi_F} H_{a,b}(Q,\mu) \int dt_a dt_b B_a(t_a, x_a, \mu)\, B_b(t_b, x_b, \mu)\, S\left(\tau_0 - \frac{t_a}{Q} - \frac{t_b}{Q}, \mu\right)$$

- We evolve and expand all the needed ingredients in order to obtain: $\frac{d\sigma^{\rm sing}}{d\Phi_F d\tau_0} = \frac{d}{d\tau_0}\left(e^{-\tilde{S}(\tau_0)} \mathscr{L}(\tau_0)\right)$

- We follow all the steps presented for MiNNLO$_{PS}$-p_T to obtain:

$$\bar{B}^{\rm MiNNLO_{PS}}(\Phi_{FJ}) = e^{-\tilde{S}(\tau_0)}\left(B(\Phi_{FJ})\left(1 + \alpha_s \tilde{S}^{(1)}\right) + V(\Phi_{FJ}) + \int d\Phi_{\rm rad} R(\Phi_{FJJ}) + \left(D(\tau_0) - \alpha_s D^{(1)}(\tau_0) - \alpha_s^2 D^{(2)}(\tau_0)\right) \mathscr{F}\right)$$

The logarithmic structure in transverse momentum and jettiness resummation is different!
The MiNNLO$_{PS}$ formulae in the two cases are the same in the structure, but contain different ingredients.

MATCHING WITH THE SHOWER

[Ebert, Rottoli, Wiesemann, Zanderighi, SZ ’24]

The accuracy of the parton shower is not fully preserved because we rely on the POWHEG formalism.

Fix this issue requires a deep **modification of the POWHEG method**, mainly modifying the mappings and/or including truncated-vetoed showers. **We plan to implement these changes when matching with NLL accurate showers.**

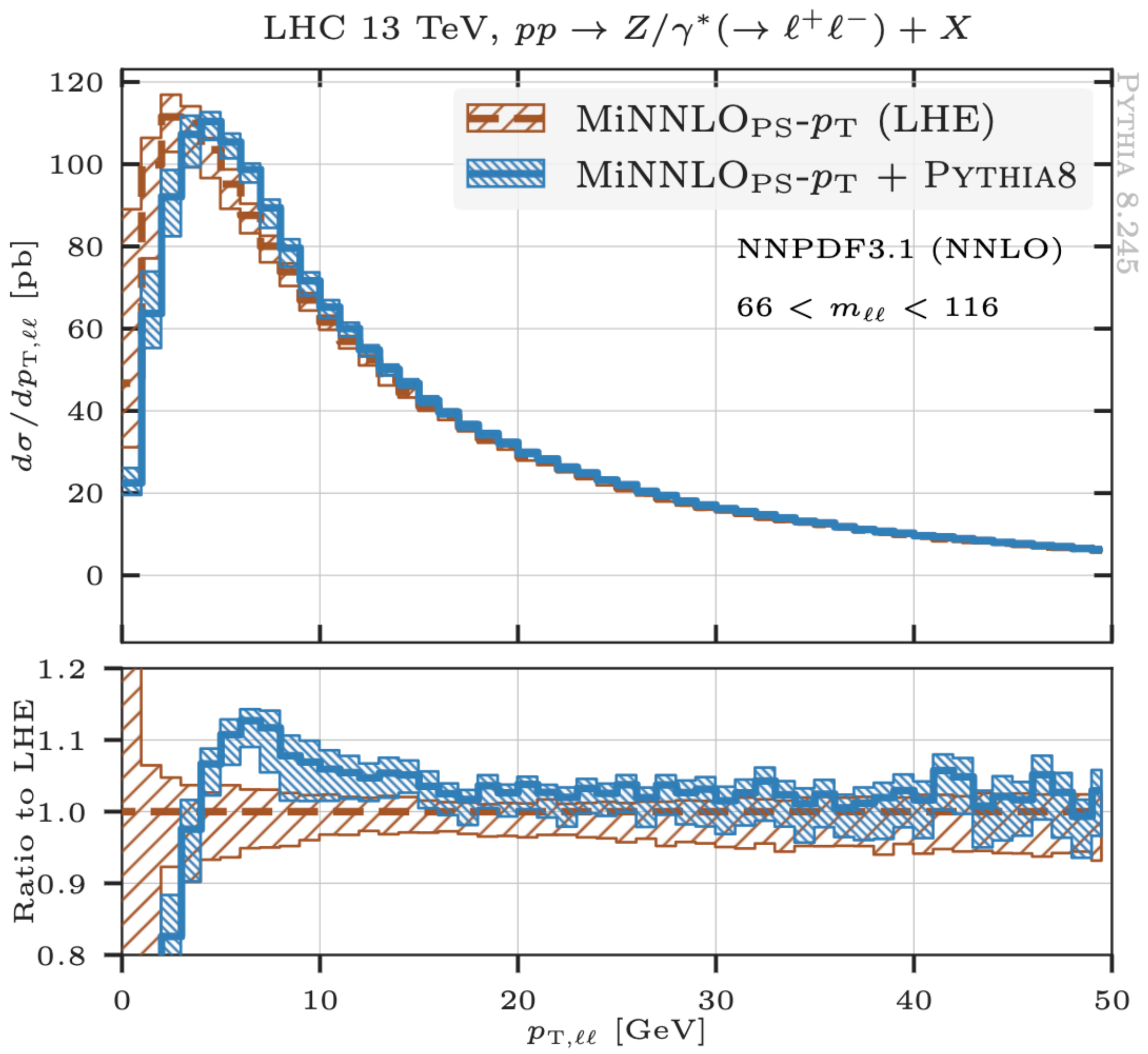
MATCHING WITH THE SHOWER

[Ebert, Rottoli, Wiesemann, Zanderighi, SZ ’24]

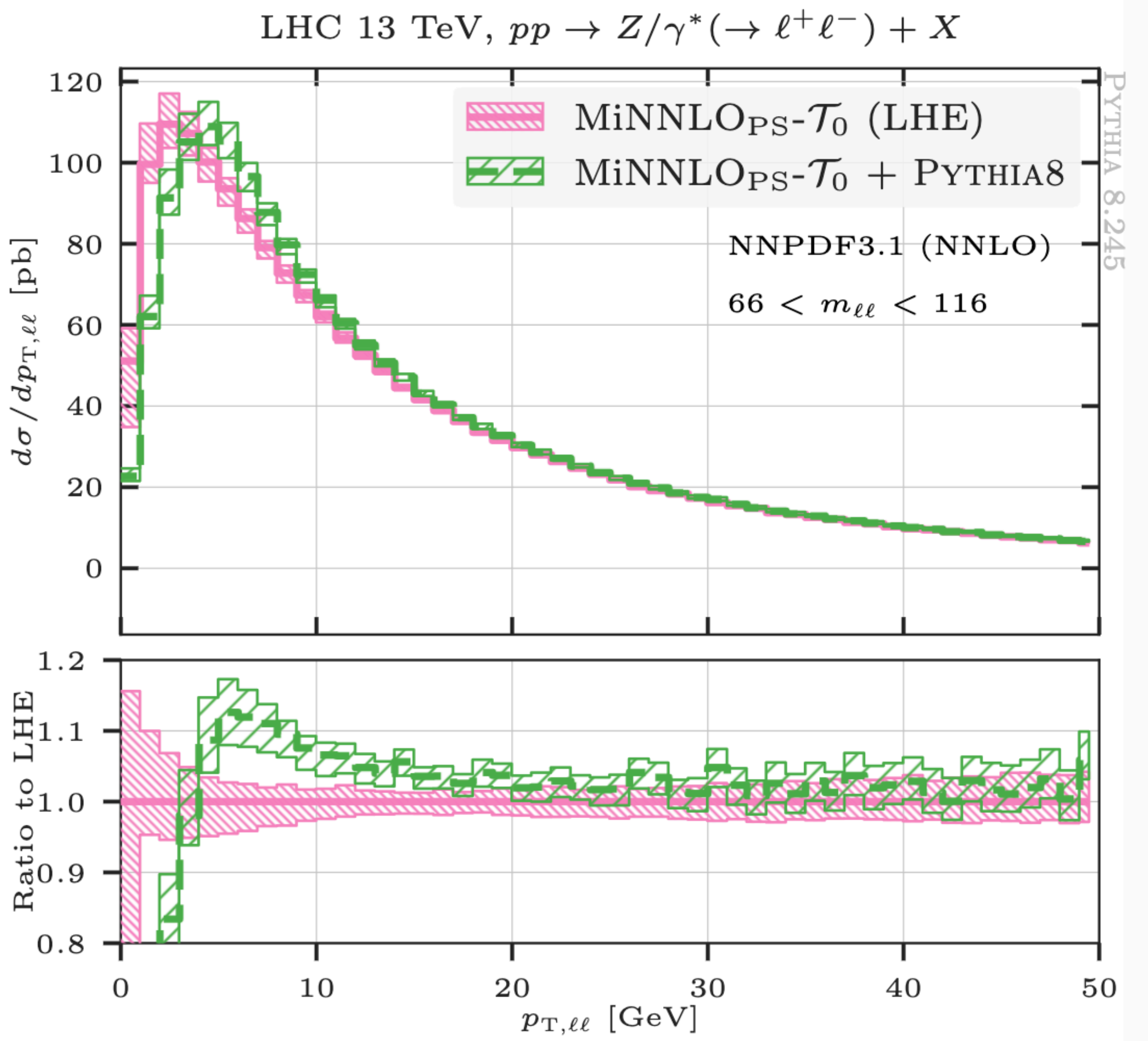
The accuracy of the parton shower is not fully preserved because we rely on the POWHEG formalism.

Fix this issue requires a deep **modification of the POWHEG method**, mainly modifying the mappings and/or including truncated-vetoed showers. **We plan to implement these changes when matching with NLL accurate showers.**

Our results are anyway reliable because the showers effects are small and they have the same impact in MiNNLO$_{PS}$-p_T and MiNNLO$_{PS}$-τ_0.



$p_{T,Z}$



$p_{T,Z}$

- MiNNLO$_{PS}$-p_T (LHE)
- MiNNLO$_{PS}$-p_T (PY8)
- MiNNLO$_{PS}$-τ_0 (LHE)
- MiNNLO$_{PS}$-τ_0 (PY8)

CROSS SECTIONS

[Ebert, Rottoli, Wiesemann, Zanderighi, SZ '24]

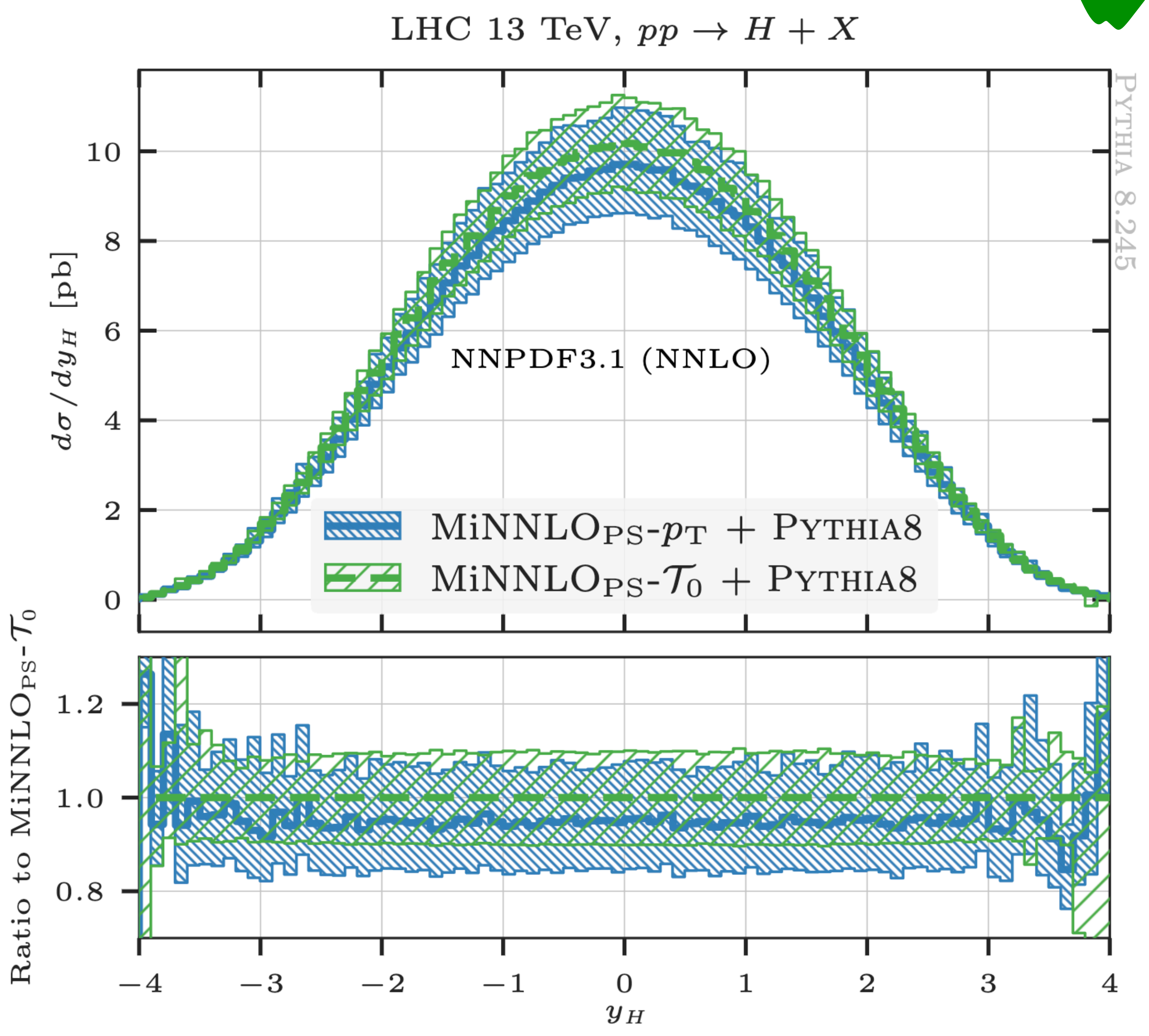
	$pp \to H$ (on-shell)		$pp \to Z \to \ell^+\ell^-$	
	σ [pb]	$\sigma/\sigma_{\text{NNLO}}$	σ [fb]	$\sigma/\sigma_{\text{NNLO}}$
NNLO	$40.32(2)^{+10.7\%}_{-10.4\%}$	1.000	$1919(1)^{+0.9\%}_{-1.1\%}$	1.000
MiNNLO$_{\text{PS}}$-p_{T}	$39.33(1)^{+12.2\%}_{-11.0\%}$	0.975	$1907(2)^{+1.1\%}_{-1.2\%}$	0.994
MiNNLO$_{\text{PS}}$-$\mathcal{T}_0$	$41.56(2)^{+9.4\%}_{-10.1\%}$	1.031	$1925(1)^{+1.2\%}_{-1.2\%}$	1.003

NOTE: the two MiNNLOPS descriptions differ by terms beyond accuracy, so they are expected to agree within error bands.

NNLO OBSERVABLES

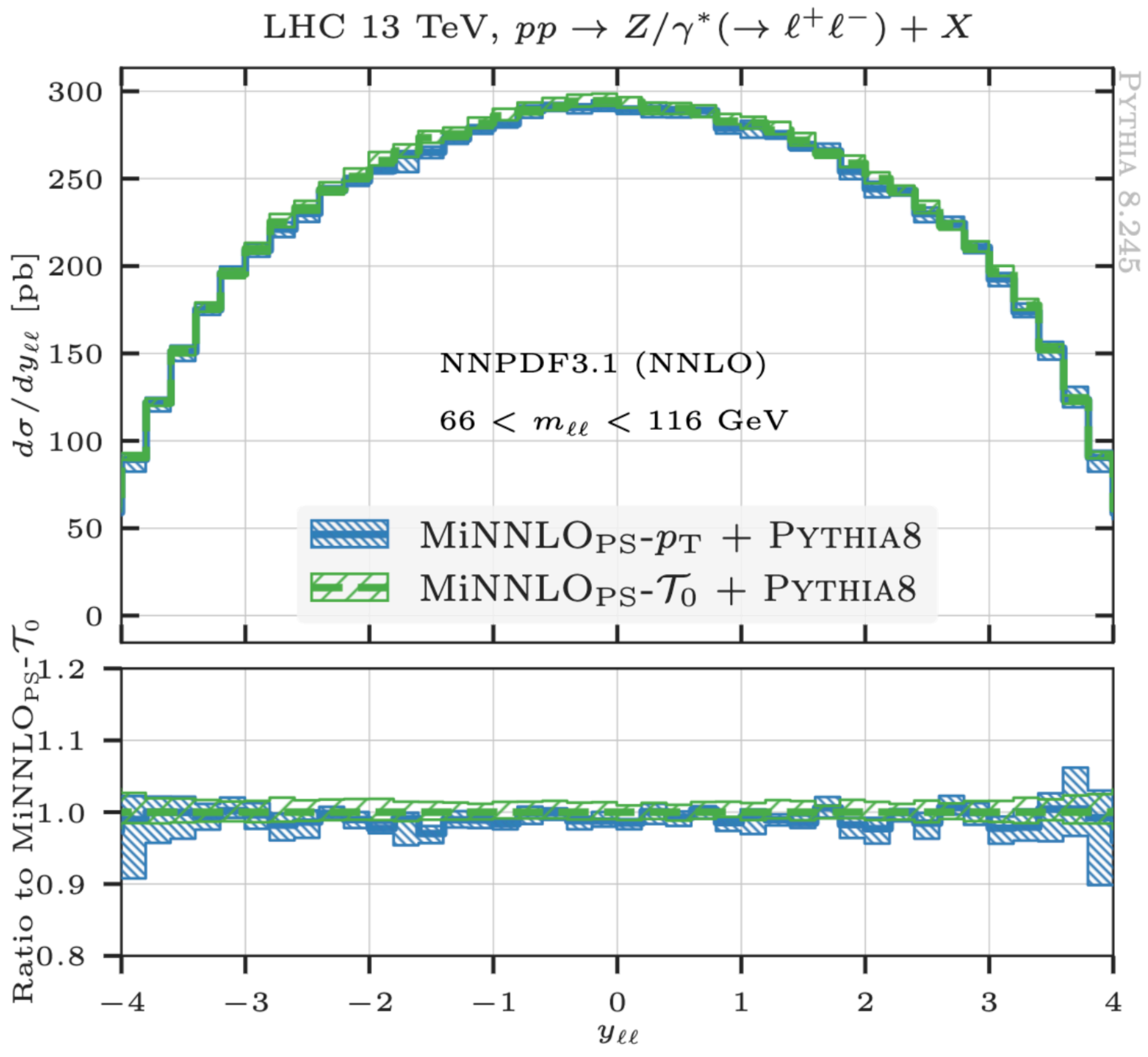
[Ebert, Rottoli, Wiesemann, Zanderighi, SZ '24]

H PRODUCTION



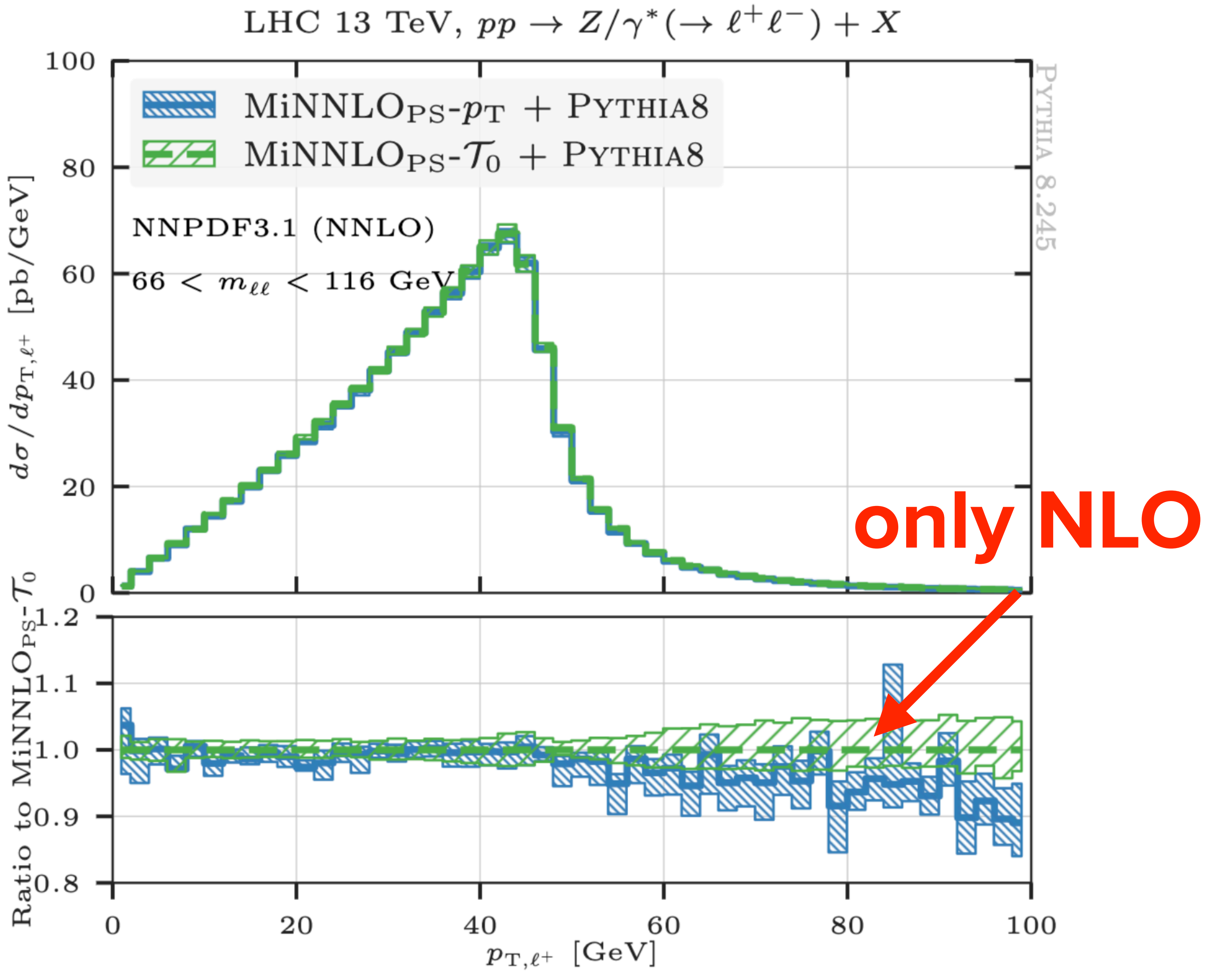
y_H

DRELL-YAN



y_Z

DRELL-YAN

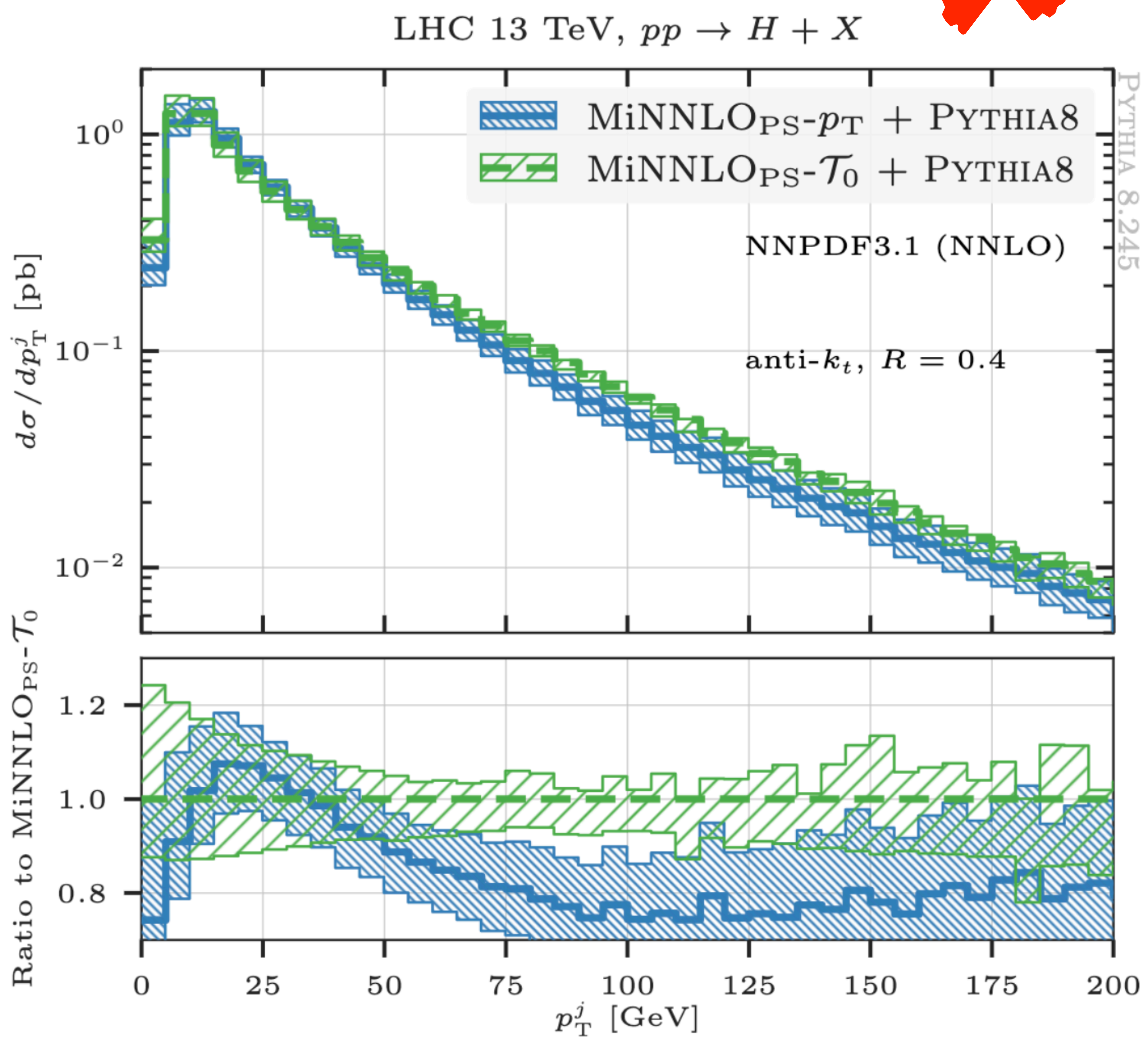


$p_{T,e+}$

NLO OBSERVABLES

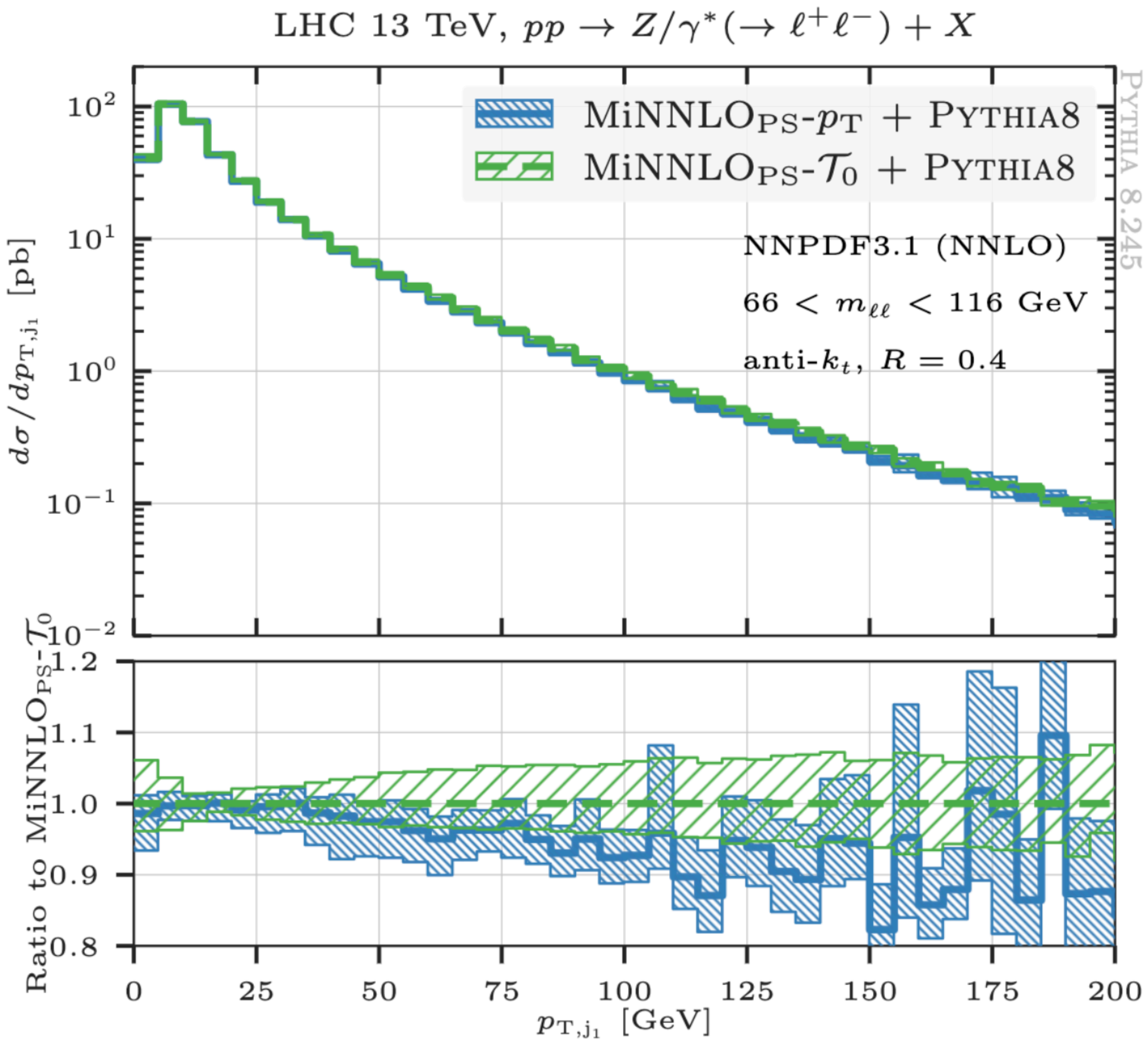
[Ebert, Rottoli, Wiesemann, Zanderighi, SZ ’24]

H PRODUCTION ✗



$p_{T,j}$

DRELL-YAN ✓



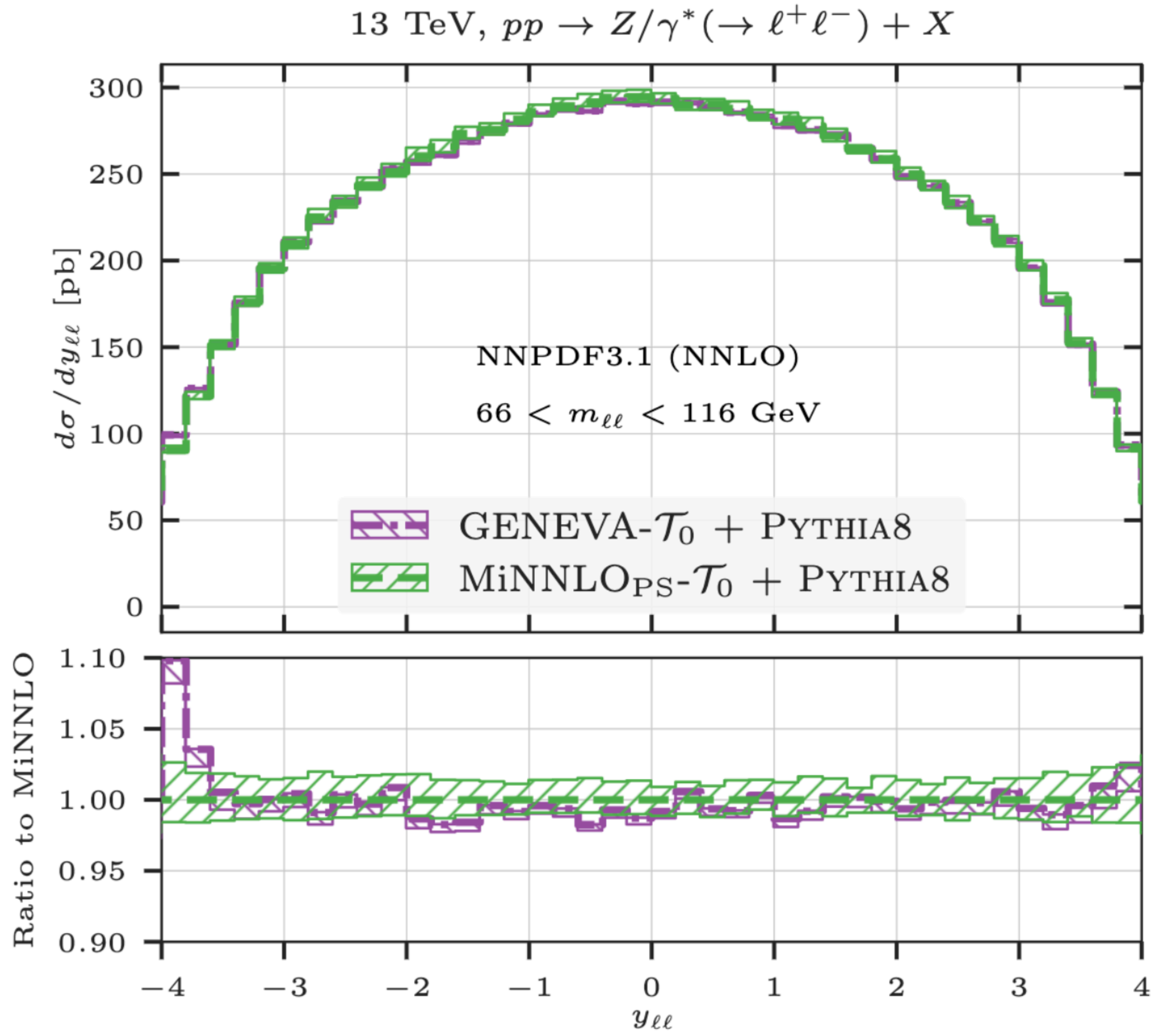
$p_{T,j}$

Large differences between MiNNLO-p_T and MiNNLO-τ_0 for H production **not covered by scale variation.**

COMPARISON WITH GENEVA - DY

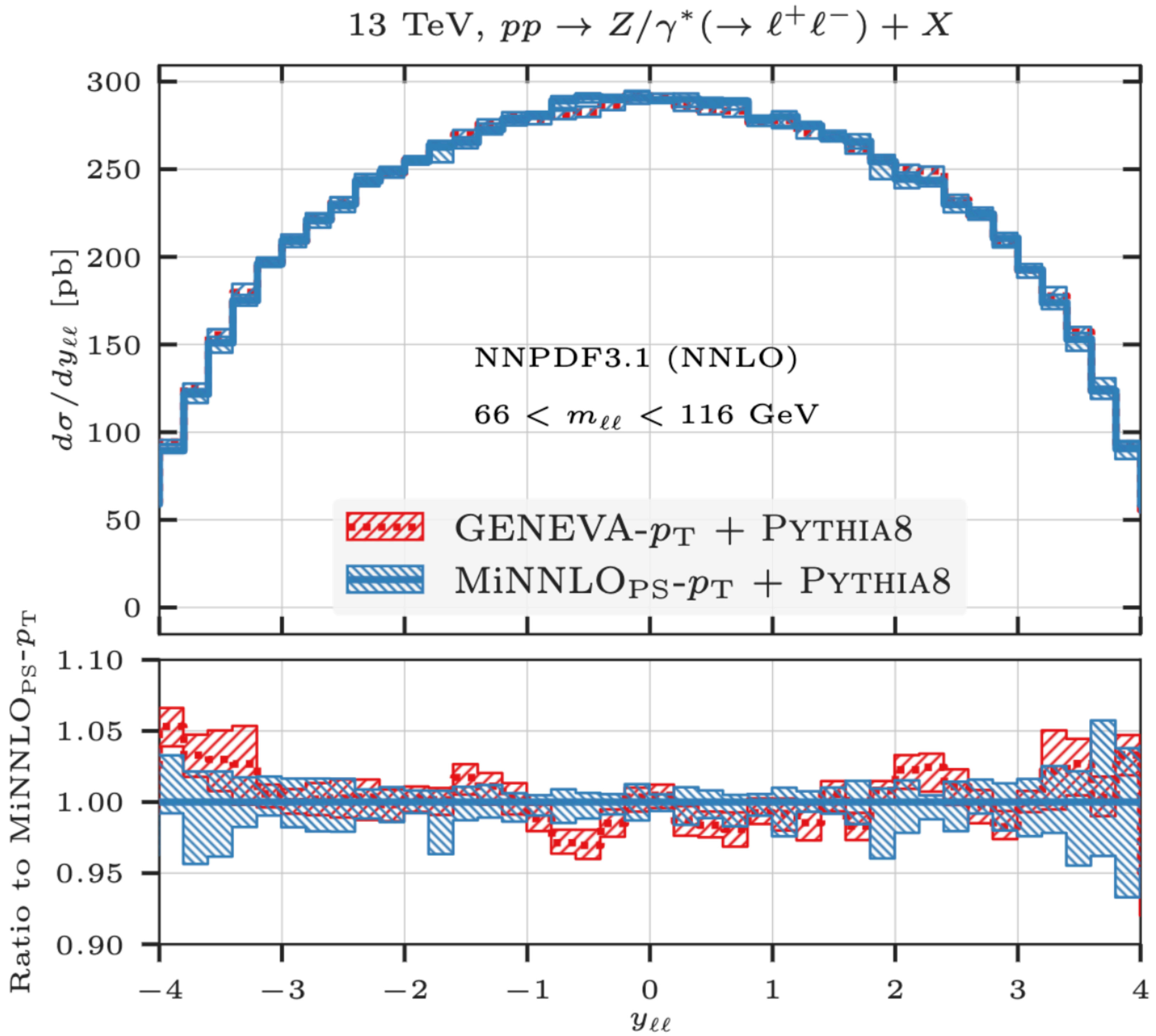
[Ebert, Rottoli, Wiesemann, Zanderighi, SZ ’24]

MiNNLO$_{PS}$-τ_0 vs GENEVA-τ_0 ✔



y_Z

MiNNLO$_{PS}$-p_T vs GENEVA-p_T ✔



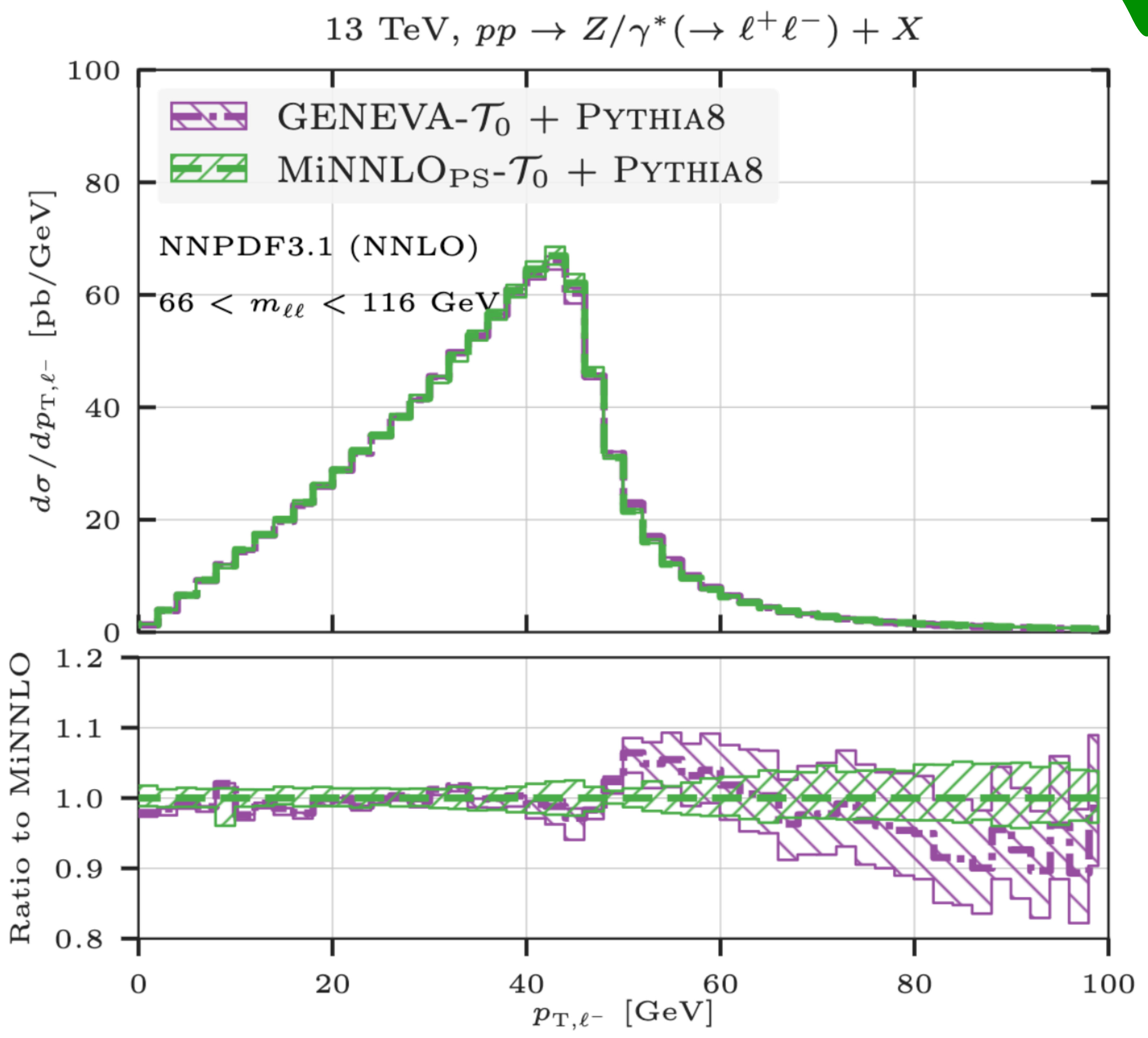
y_Z

NOTE: GENEVA error bars are obtained through 3-point scale variation.

COMPARISON WITH GENEVA - DY

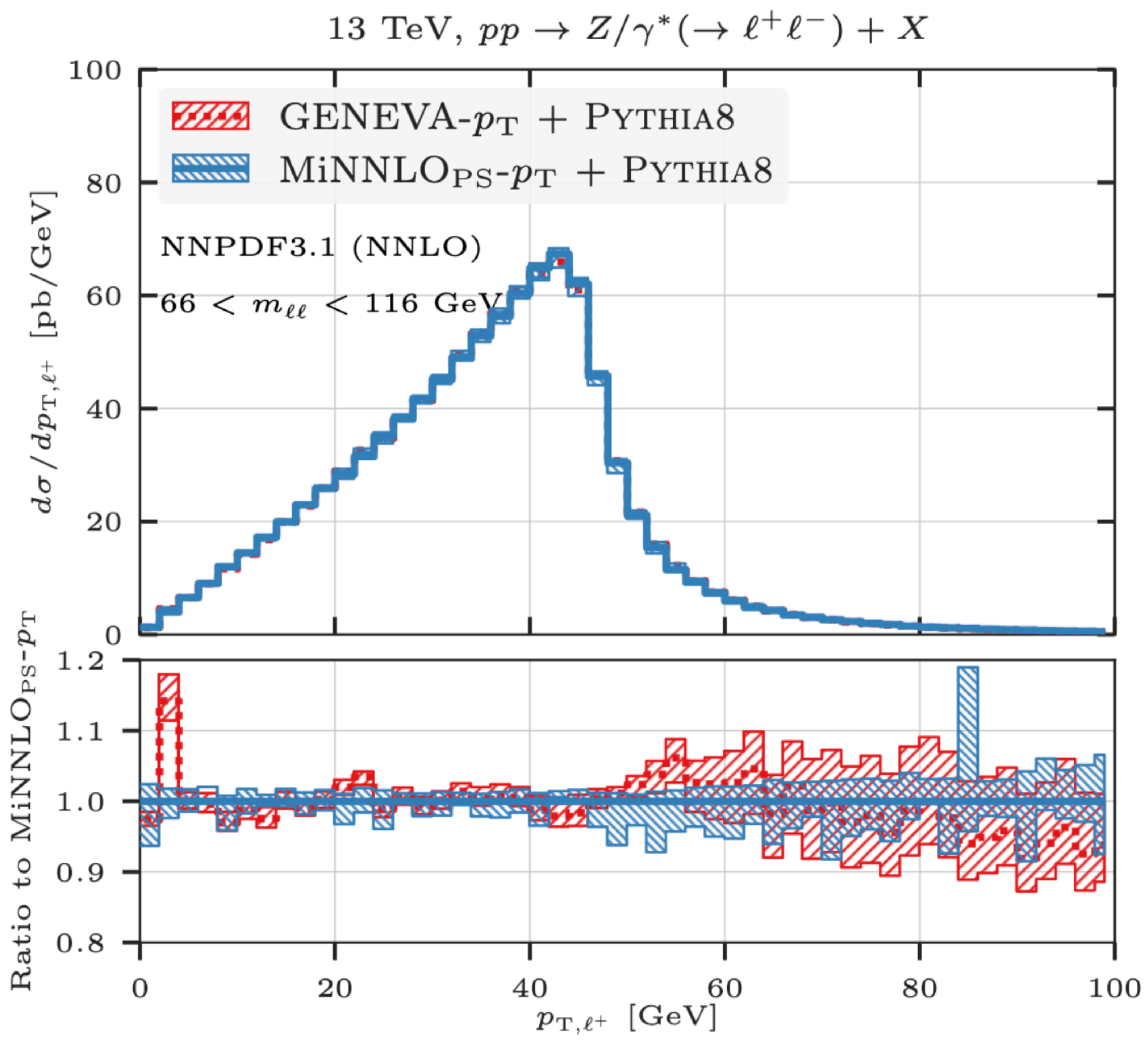
[Ebert, Rottoli, Wiesemann, Zanderighi, SZ ’24]

MiNNLO$_{PS}$-τ_0 vs GENEVA-τ_0 ✓



$p_{T,e+}$

MiNNLO$_{PS}$-p_T vs GENEVA-p_T ✓



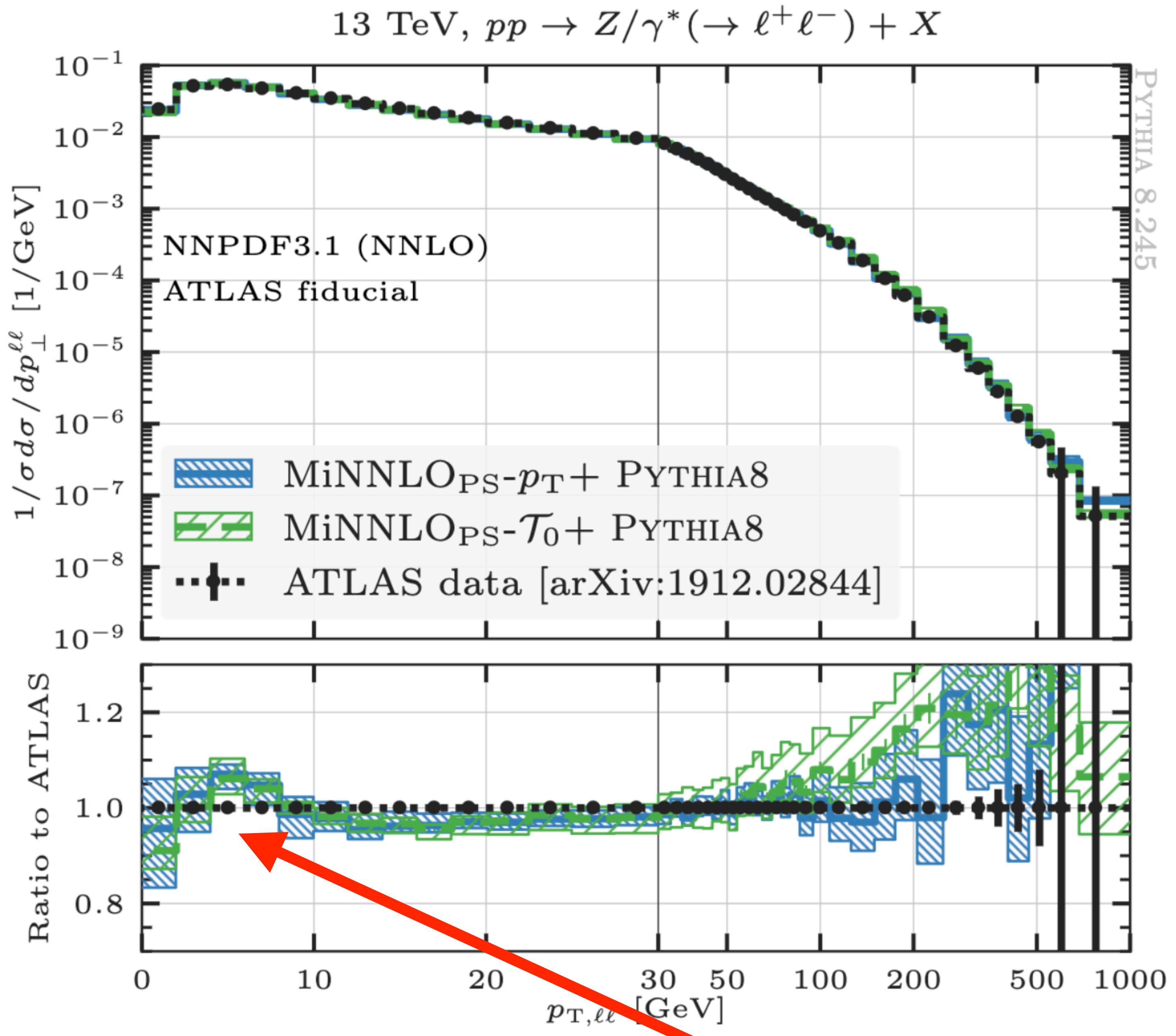
$p_{T,e+}$

NOTE: GENEVA error bars are obtained through 3-point scale variation.

COMPARISON WITH DY DATA ✓

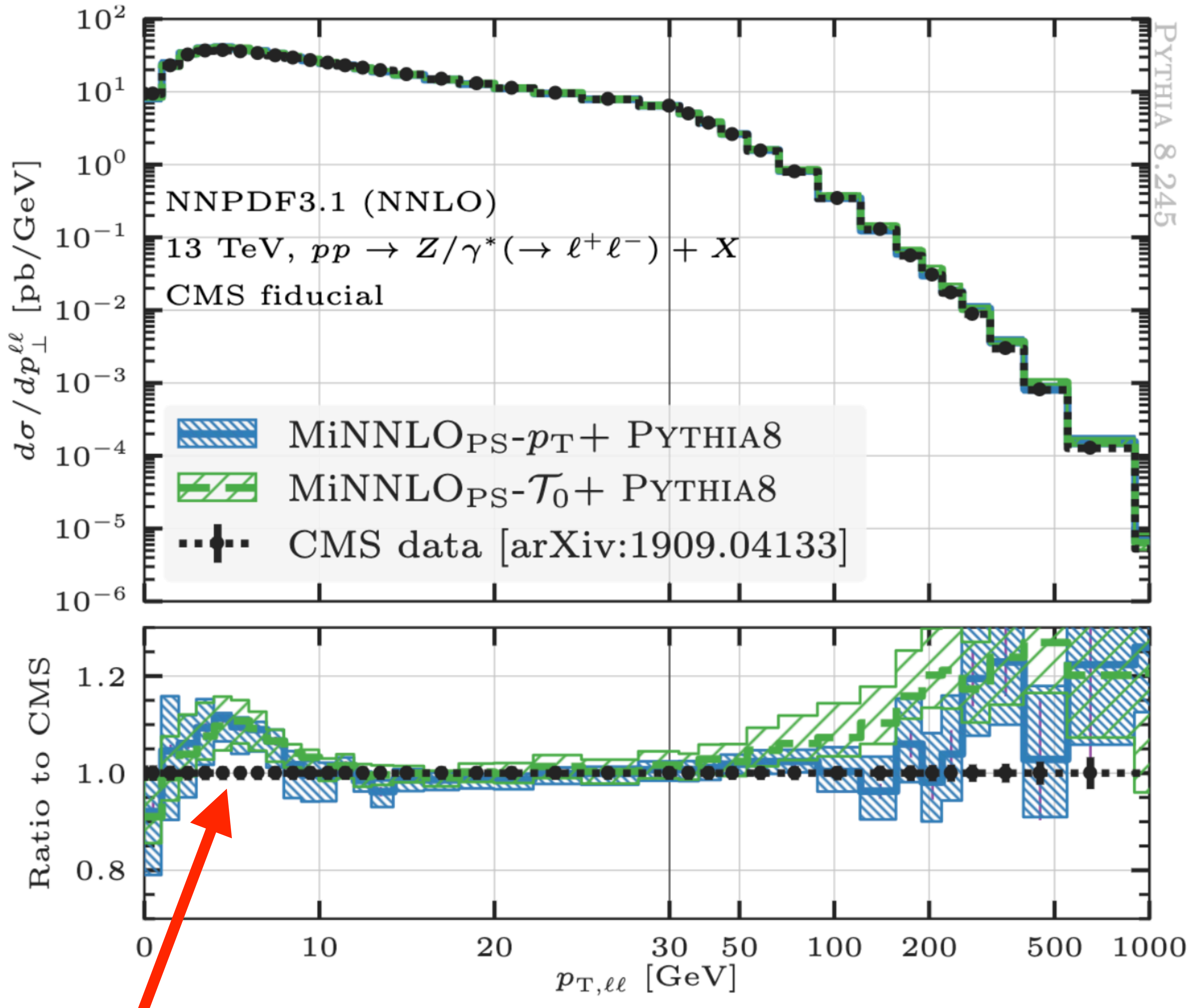
[Ebert, Rottoli, Wiesemann, Zanderighi, SZ ’24]

ATLAS



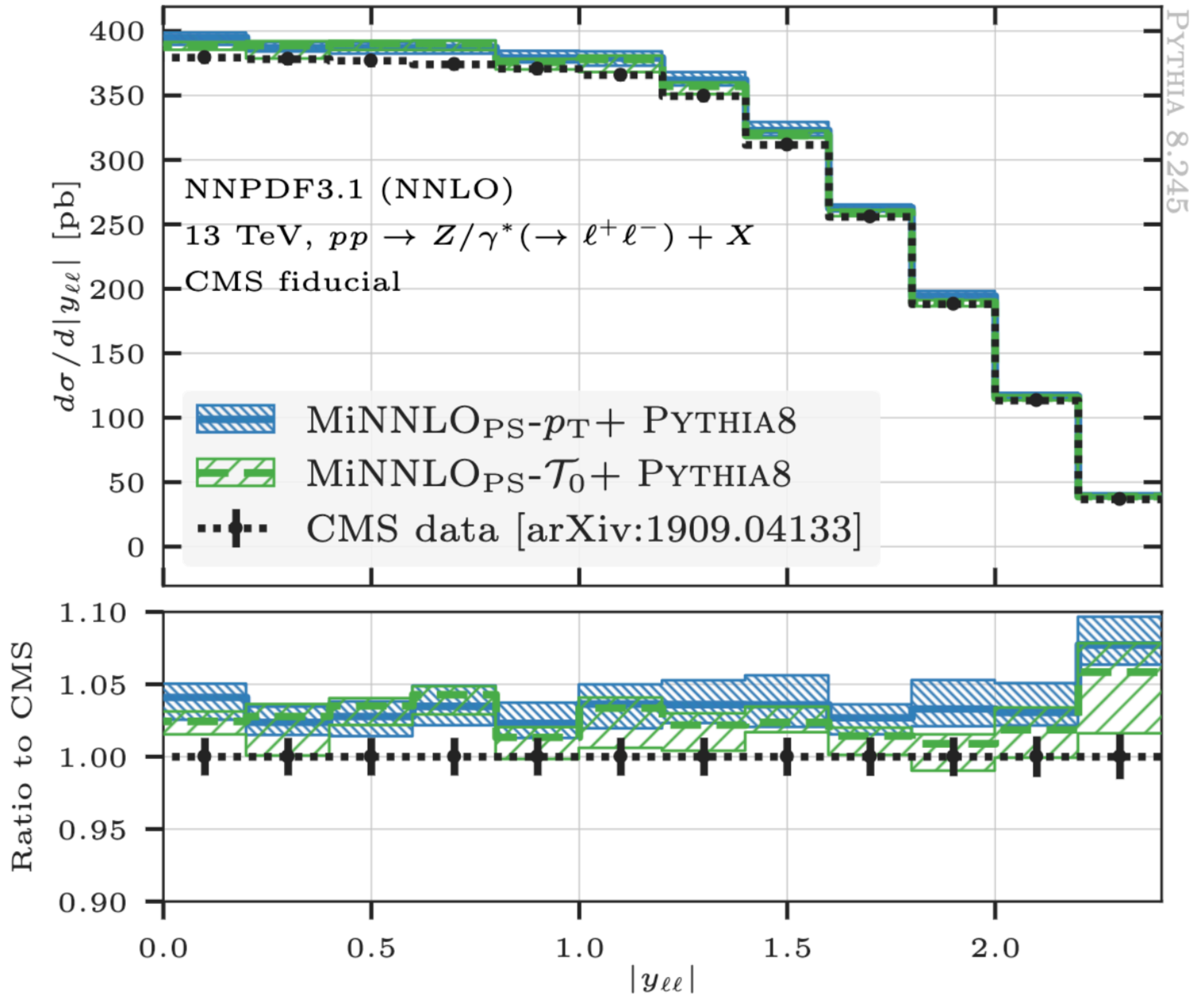
$p_{T,Z}$

CMS



$p_{T,Z}$

CMS



y_Z

Accurate resummation needed

Good agreement (1-2 σ) between MiNNLO$_{PS}$ predictions and data.

SUMMARY

- **NNLO+PS** accuracy is the **state-of-the art** for precision physics at the LHC.
- **The MiNNLO$_{PS}$ method is a powerful framework** to reach this accuracy.
- **Extending MiNNLO$_{PS}$ to processes with jets is not trivial.**
  - MiNNLO$_{PS}$ based on 0-jettiness resummation: I presented the theoretical formalism and discussed phenomenological results for Higgs production and Drell-Yan process. We found **very good agreement for NNLO observables, while discrepancies are present for NLO ones (in the Higgs case).**
  - The **comparison with GENEVA shows a nice agreement between the two methods**, both for the p_T and the jettiness formalisms.
  - **We obtained a good agreement with ATLAS and CMS data.**
  - MiNNLO$_{PS}$ based on 1-jettiness resummation: I (briefly) presented the theoretical formalism.

SUMMARY

- **NNLO+PS** accuracy is the **state-of-the art** for precision physics at the LHC.
- **The MiNNLO$_{PS}$ method is a powerful framework** to reach this accuracy.
- **Extending MiNNLO$_{PS}$ to processes with jets is not trivial.**
  - MiNNLO$_{PS}$ based on 0-jettiness resummation: I presented the theoretical formalism and discussed phenomenological results for Higgs production and Drell-Yan process. We found **very good agreement for NNLO observables, while discrepancies are present for NLO ones (in the Higgs case).**
  - The **comparison with GENEVA shows a nice agreement between the two methods**, both for the p_T and the jettiness formalisms.
  - **We obtained a good agreement with ATLAS and CMS data.**
  - MiNNLO$_{PS}$ based on 1-jettiness resummation: I (briefly) presented the theoretical formalism.

Thank you!