PYTHIA WEEK 2024, OXFORD - 2nd MAY 2024

MiNNLOPS (& PYTHIA)

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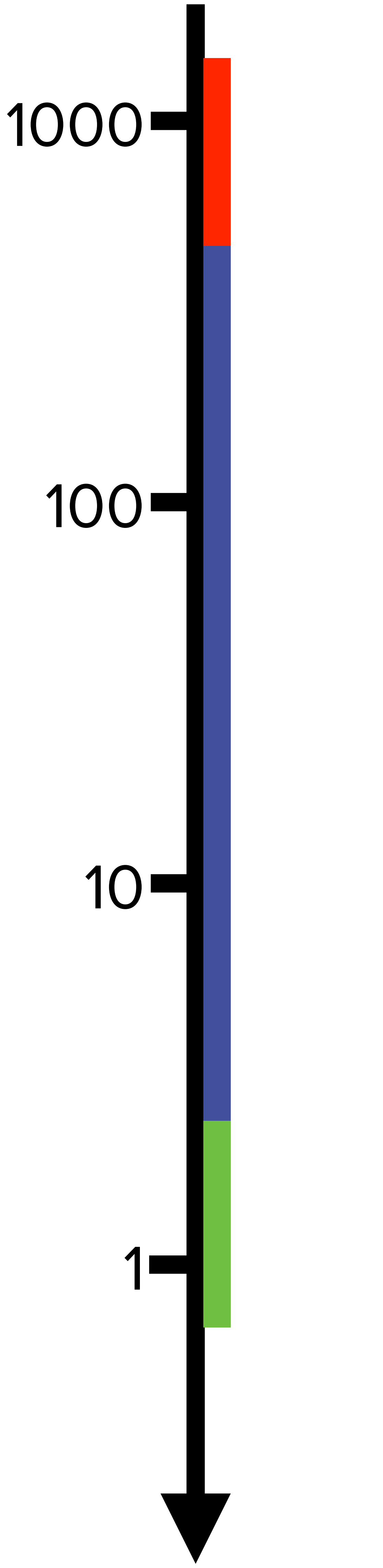
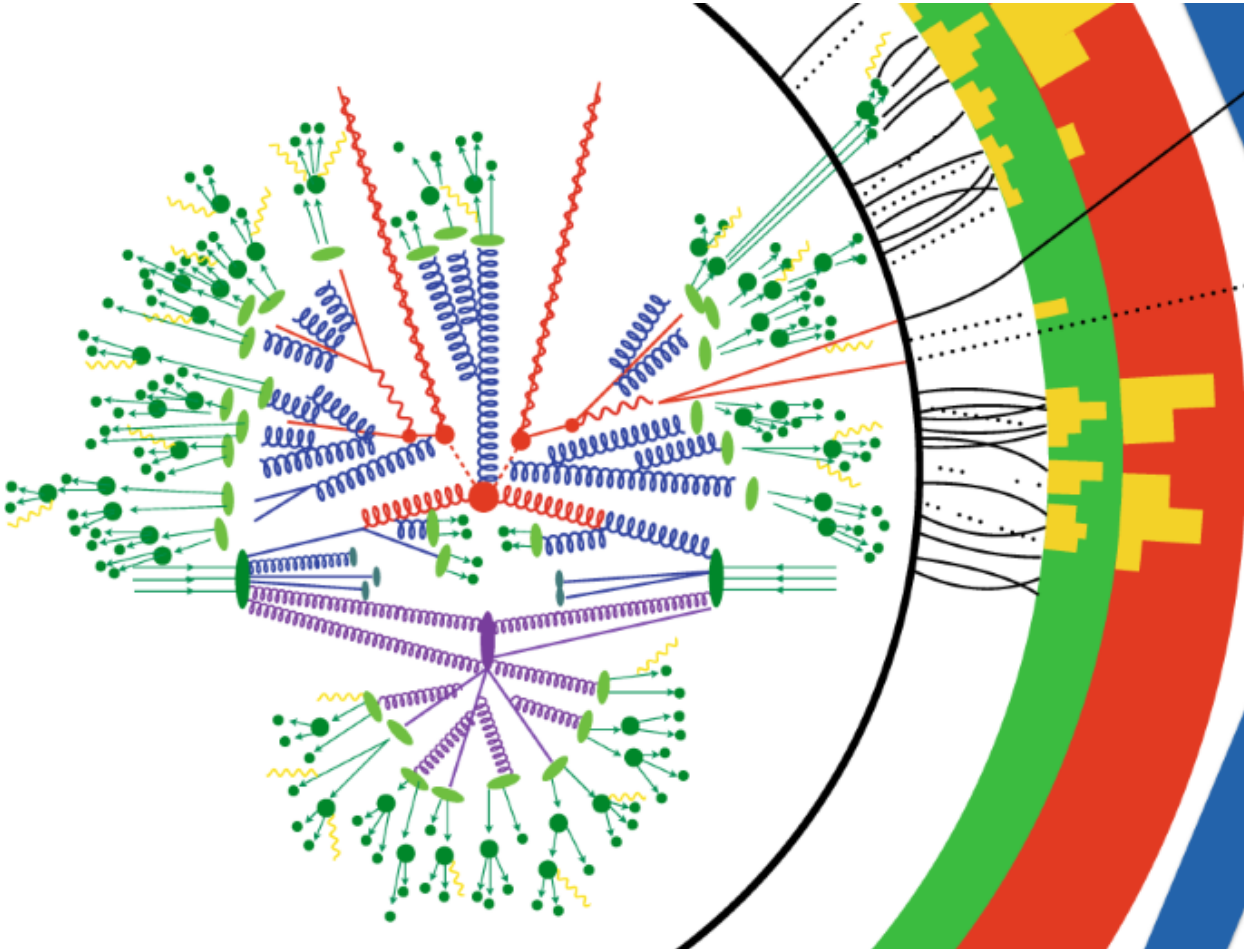
1. THE PROBLEM

LHC EVENT

ENERGY SCALE [GeV]

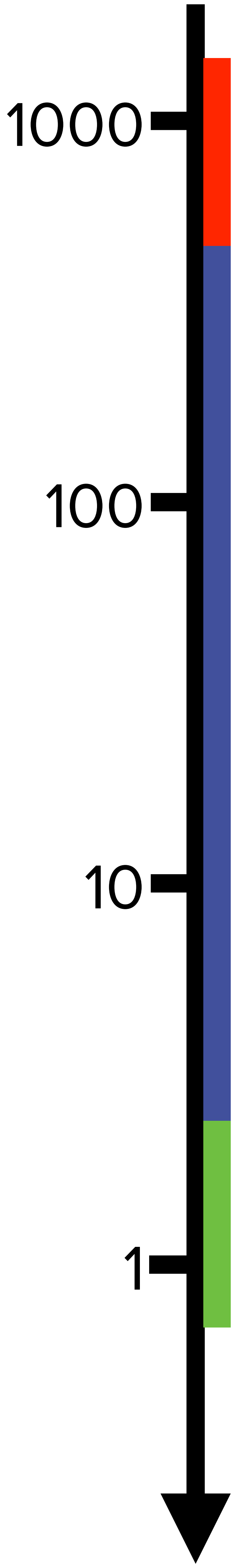


1. HARD SCATTERING
2. PARTON SHOWER
3. HADRONIZATION
4. UNDERLYING EVENT

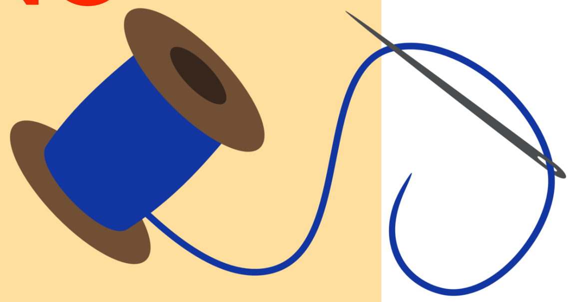


LHC EVENT

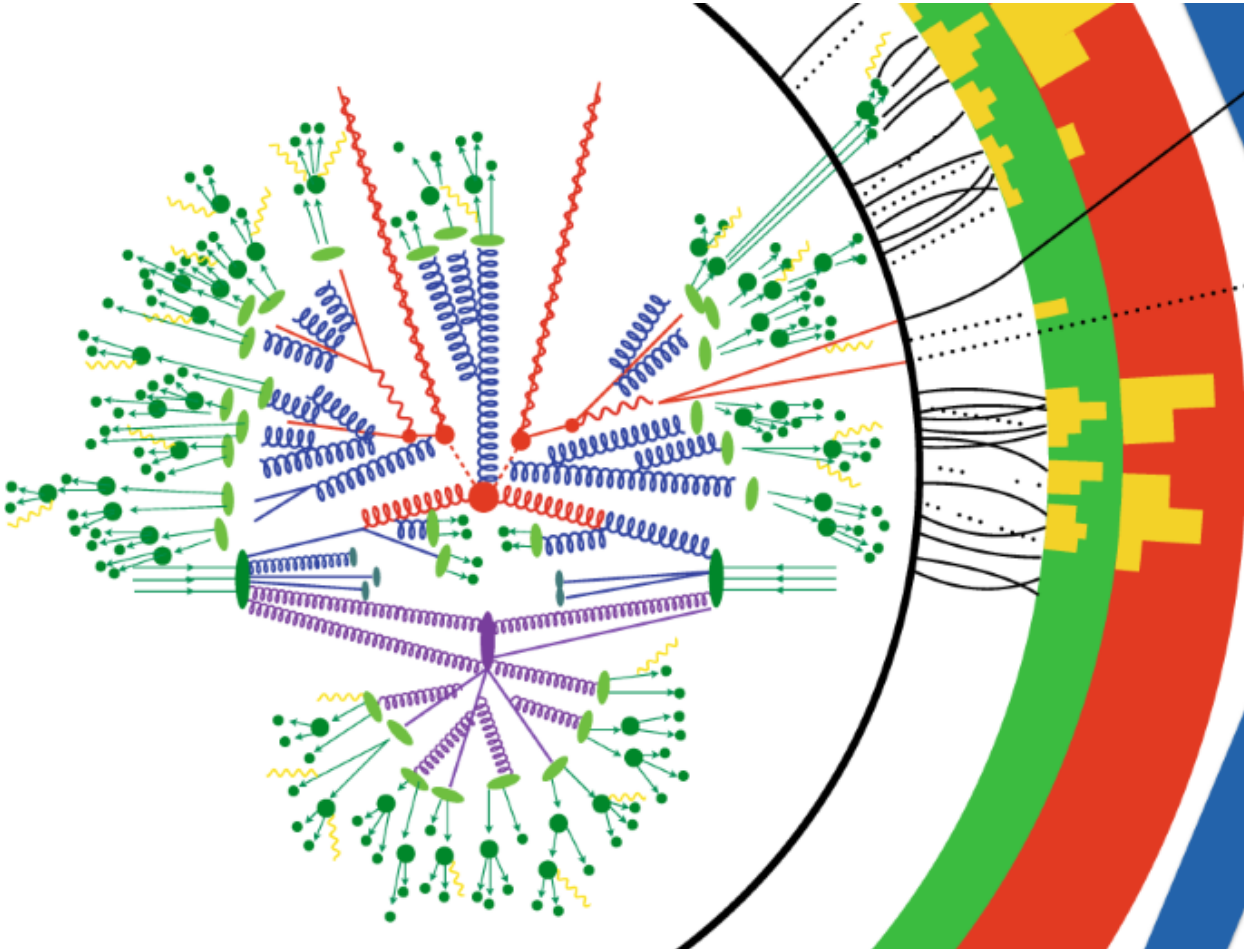
ENERGY SCALE [GeV]



1. HARD SCATTERING



2. PARTON SHOWER
3. HADRONIZATION
4. UNDERLYING EVENT

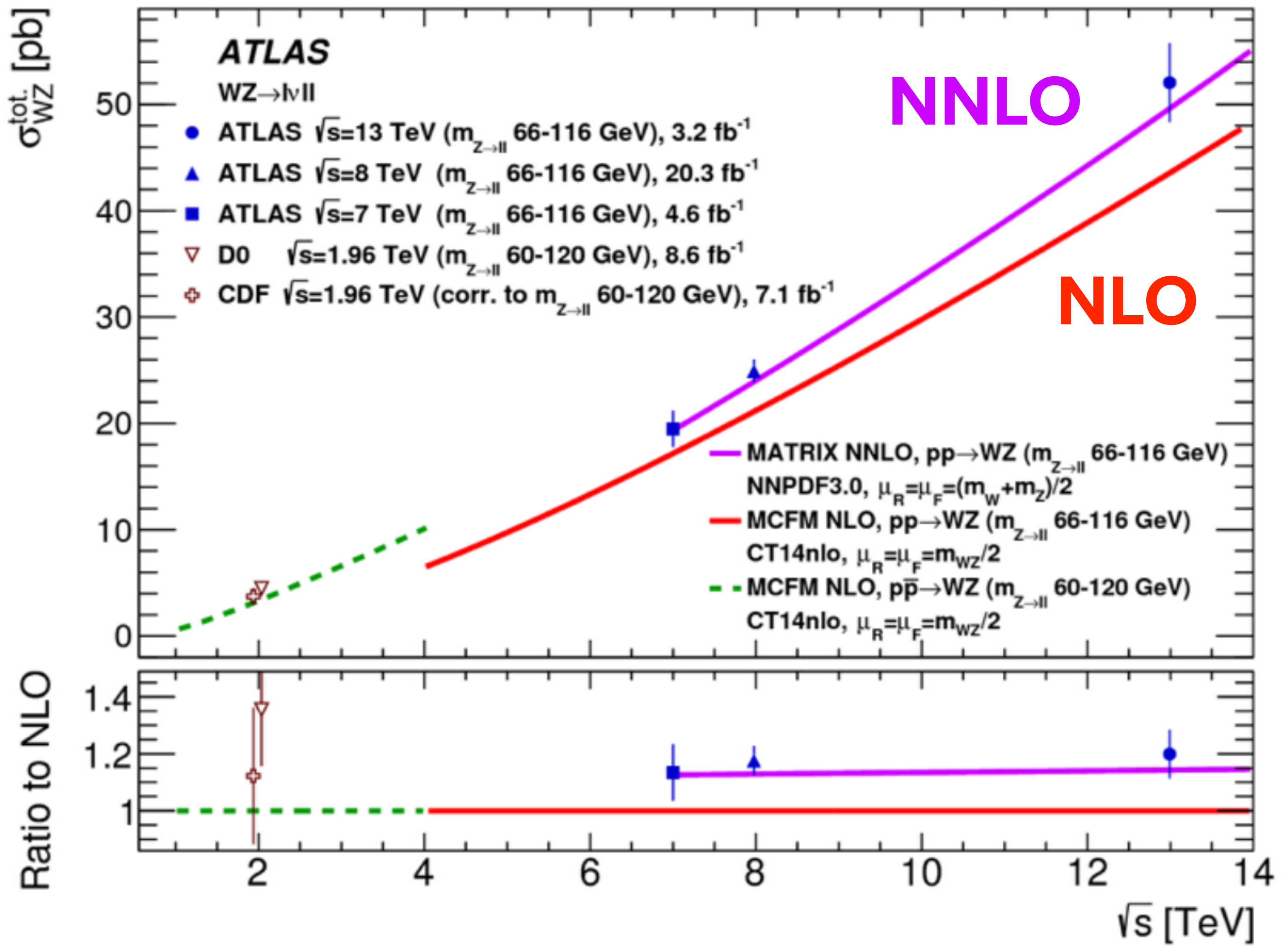


HARD SCATTERING

$\mu \sim Q \gg \Lambda_{QCD}$

Studied with fixed-order calculations. Precision is reached through perturbation theory:

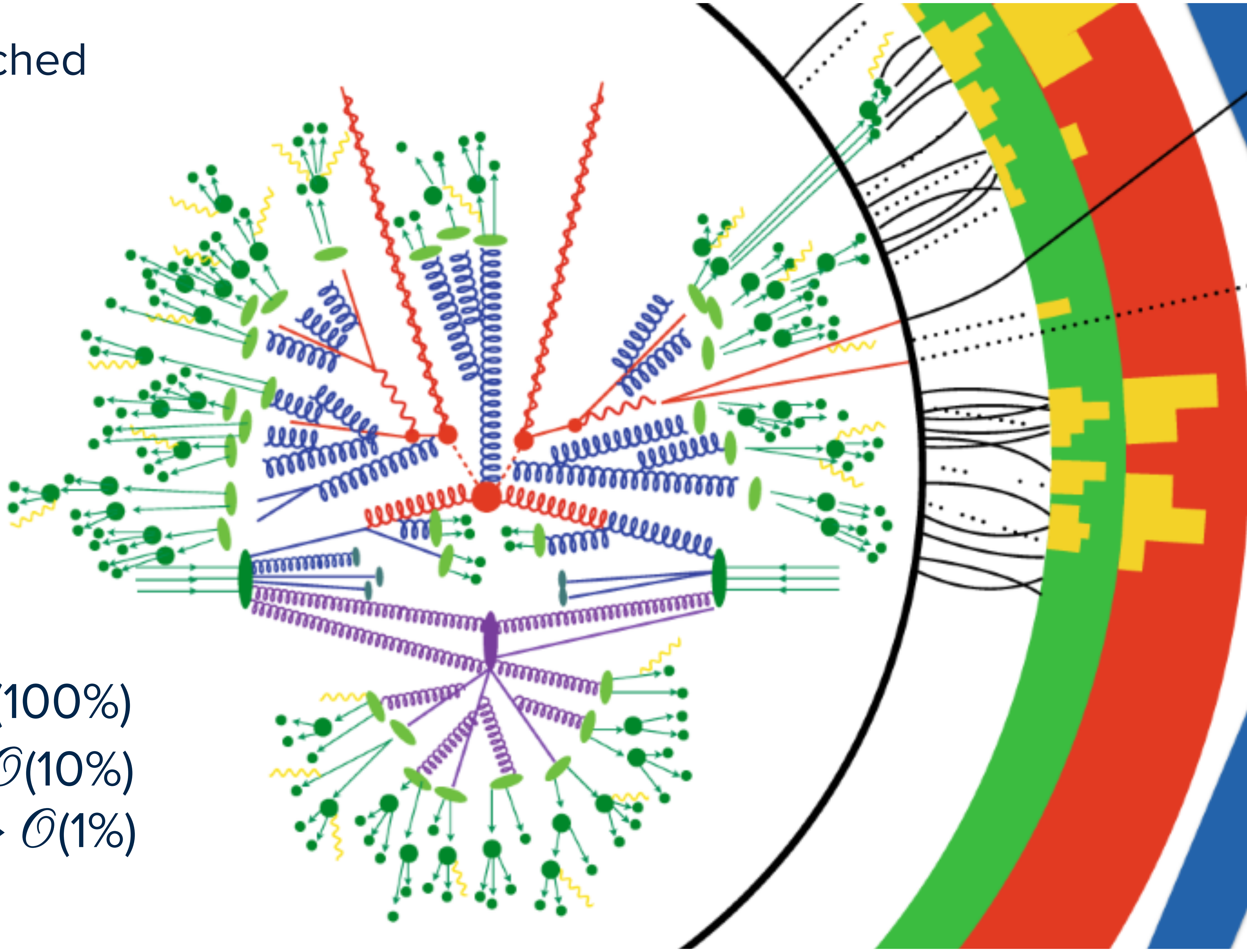
$$\sigma = \sigma_{LO}(1+\alpha_s\delta_{NLO} + \alpha_s^2\delta_{NNLO}+\mathcal{O}(\alpha_s^3))$$



LO → $\mathcal{O}$(100%)

NLO → $\mathcal{O}$(10%)

NNLO → $\mathcal{O}$(1%)



PARTON SHOWER

$\Lambda_{QCD} < \mu < Q$

Cascade of particles from the high-energy limit to the detector level. It is constructed starting from the factorization of QCD amplitudes in the infra-red limit:

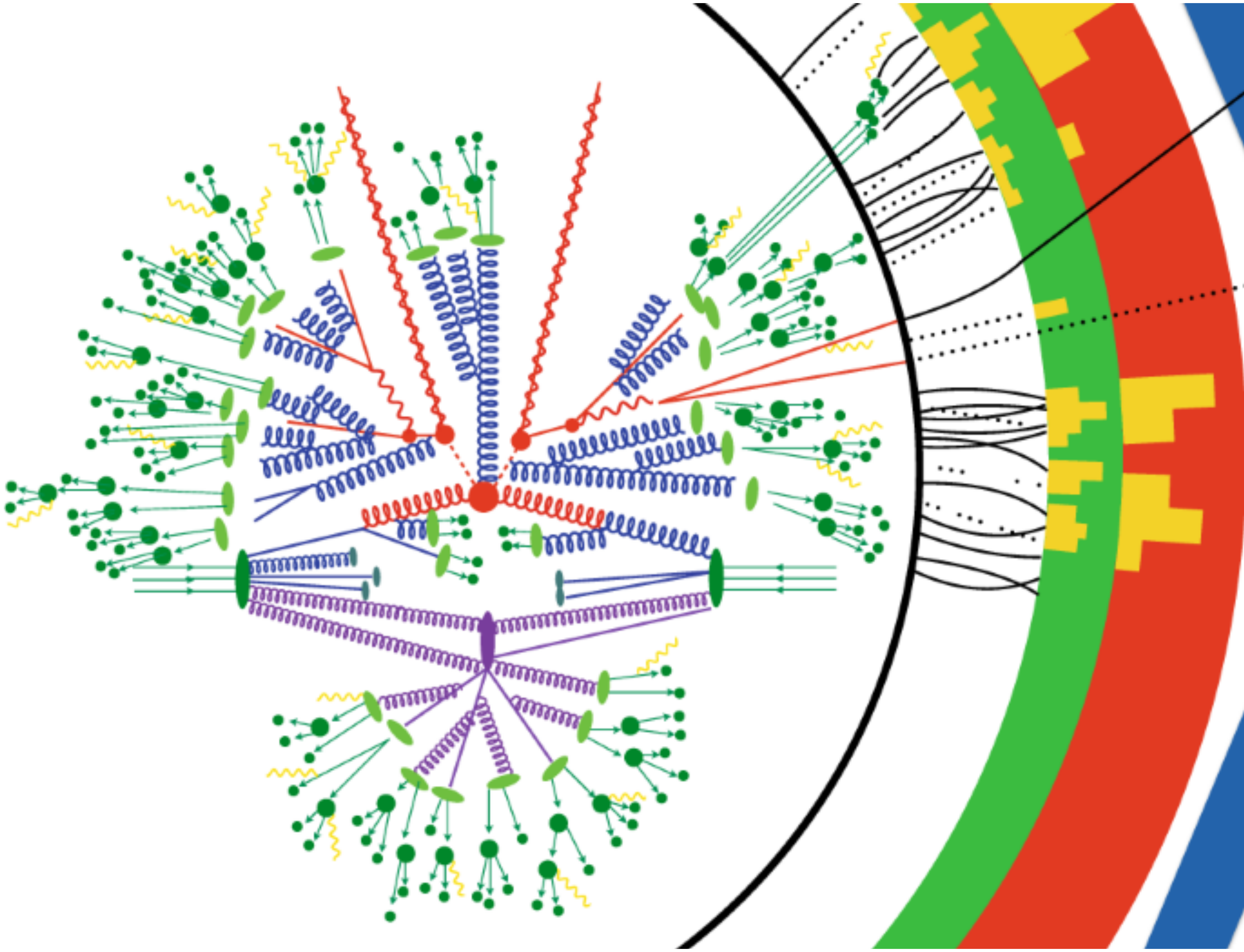
$$|M_{n+1}|^2 \to |M_n|^2 \cdot K$$

For a specific observable (e.g. event-shape V):

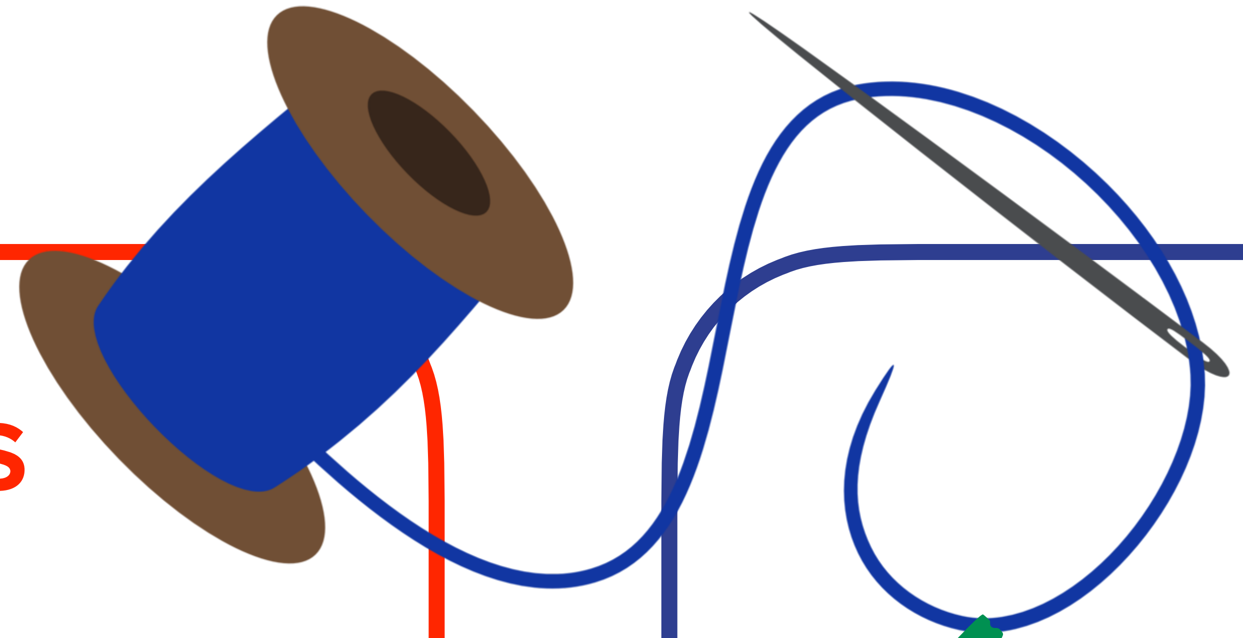
$$\Sigma(V < e^{-|L|}) = \exp\Big(\underbrace{L g_1(\alpha_s L)}_{\text{LL}} + \underbrace{g_2(\alpha_s L)}_{\text{NLL}} + \underbrace{\alpha_s\, g_3(\alpha_s L)}_{\text{NNLL}} + \dots\Big)$$

Most showers are only LL accurate.

Lots of progress done in recent years to improve the accuracy of parton showers (**NLL showers are available**). However, LHC phenomenology is not possible with these new tools yet.



MATCHING



FIXED-ORDER CALCULATIONS

✔ Systematically improvable accuracy.
State of the art: NNLO.

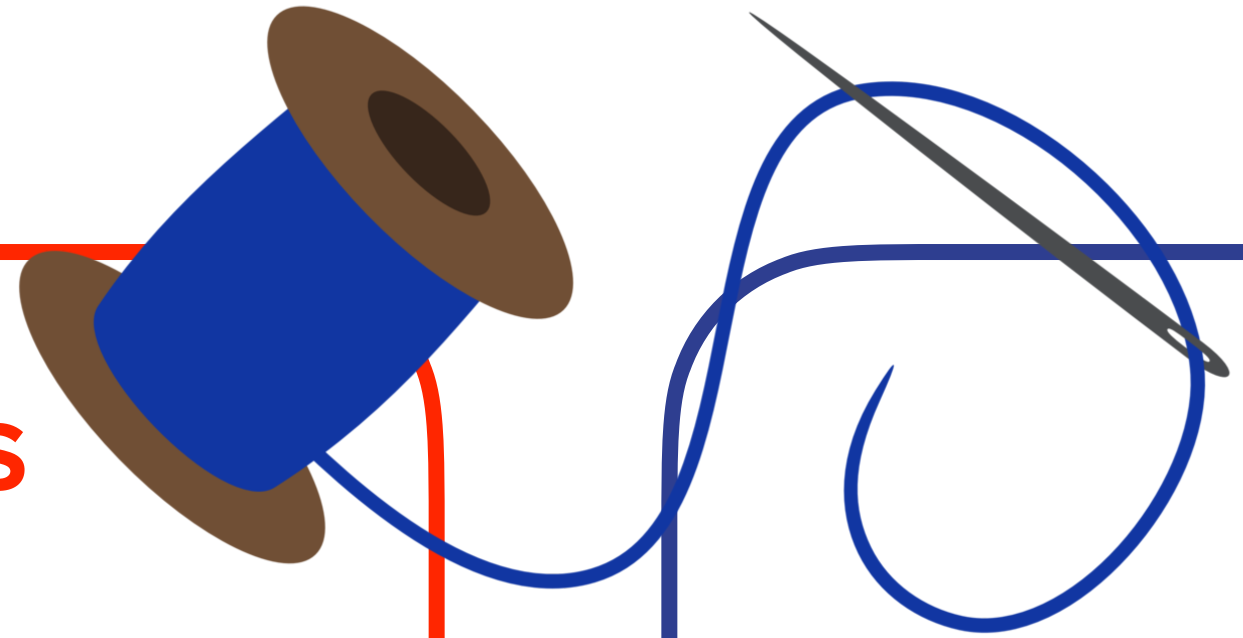
✘ Not realistic (few final state particles, not suitable for exclusive observables).

PARTON SHOWER

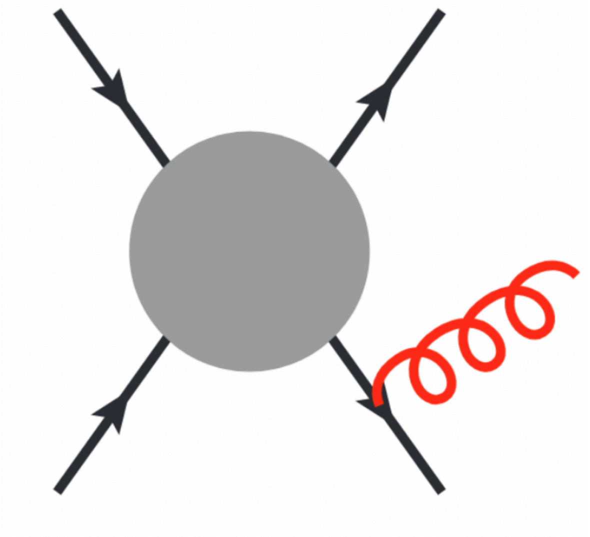
✔ Realistic final states.
Flexible in MC codes.

✘ Low accuracy, usually only LL.

WHAT'S THE PROBLEM?

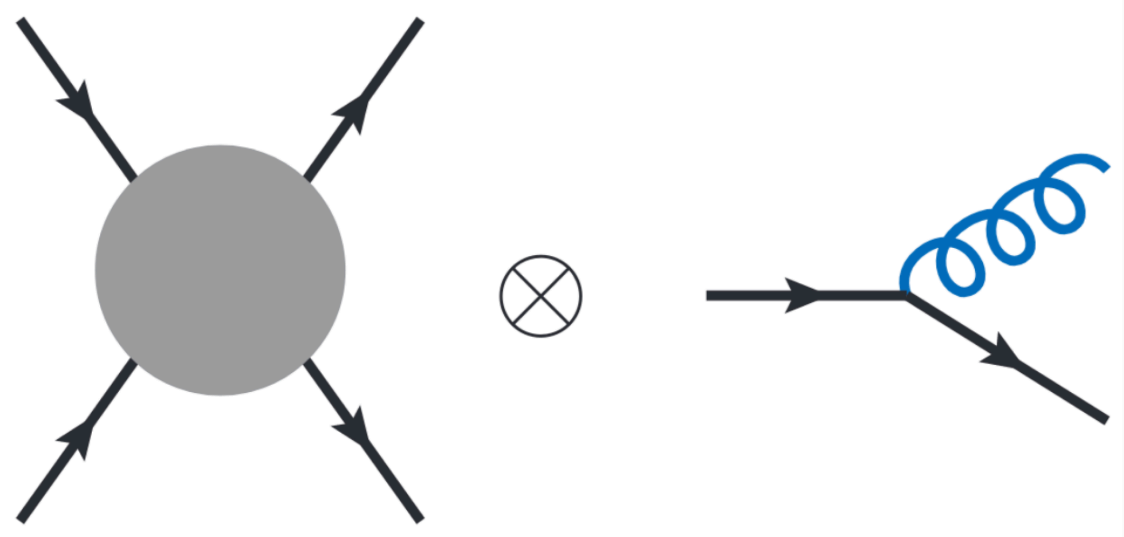


FIXED-ORDER CALCULATIONS



Correct real emission

PARTON SHOWER



Approximate real emission

!! DOUBLE COUNTING !!

2. THE SOLUTION

THE POWHEG METHOD

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

Master Formula

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

NLO NORMALIZATION (= xs)

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

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

$$\Delta(p_{\rm T}) = \exp\left\{ - \int d\Phi'_{\rm rad} \frac{R(\Phi_{\rm F}, \Phi'_{\rm rad})}{B(\Phi_{\rm F})} \Theta(p'_{\rm T} - p_{\rm T}) \right\}$$

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.

THE POWHEG METHOD

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

Master Formula

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

NLO NORMALIZATION (= xs)

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

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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.

NLO+PS ACCURACY

THE MiNNLOPS METHOD

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

Master Formula

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

SECOND EMISSION
obtained à la POWHEG

NNLO NORMALIZATION (= xs)

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

THE MiNNLO$_{PS}$ METHOD

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

Master Formula

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

SECOND EMISSION obtained à la POWHEG

NNLO NORMALIZATION (= xs)

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

Born contribution that already has an emission J

Virtual+Real correction on F+J

⚠ DIVERGENT

THE MiNNLO$_{PS}$ METHOD

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

Master Formula

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

SECOND EMISSION obtained à la POWHEG

NNLO NORMALIZATION (= xs)

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

Appropriate 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 contribution that already has an emission J

DIVERGENT

Correct NLO on F+J

Virtual+Real correction on F+J

THE MiNNLO$_{PS}$ METHOD

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

Master Formula

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

SECOND EMISSION obtained à la POWHEG

NNLO NORMALIZATION (= xs)

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

Appropriate 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 contribution that already has an emission J

~~DIVERGENT~~

Correct NLO on F+J

Virtual+Real correction on F+J

α_s^3 correction needed for NNLO normalization

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

THE MiNNLO$_{\mathrm{PS}}$ METHOD

- Starting equation from p_{T}-resummation:

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

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

- Combine with FJ fixed-order $d\sigma_{\mathrm{FJ}}$:

$$d\sigma_F = d\sigma_F^{\mathrm{sing}} + [d\sigma_{\mathrm{FJ}}]_{\mathrm{f.o.}} - [d\sigma_F^{\mathrm{sing}}]_{\mathrm{f.o.}}$$

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

THE MiNNLO$_{\text{PS}}$ METHOD

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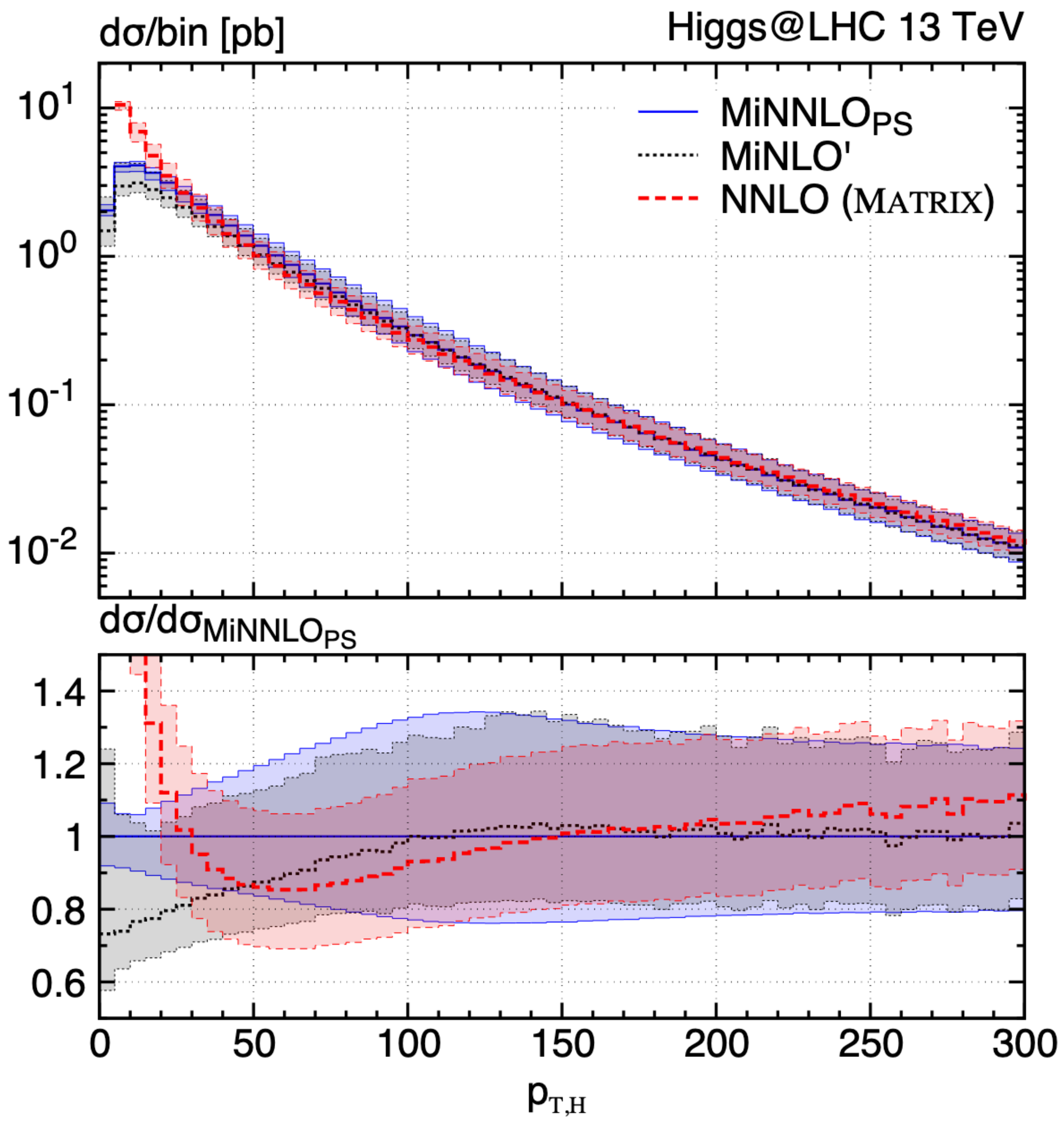
NNLO+PS ACCURACY

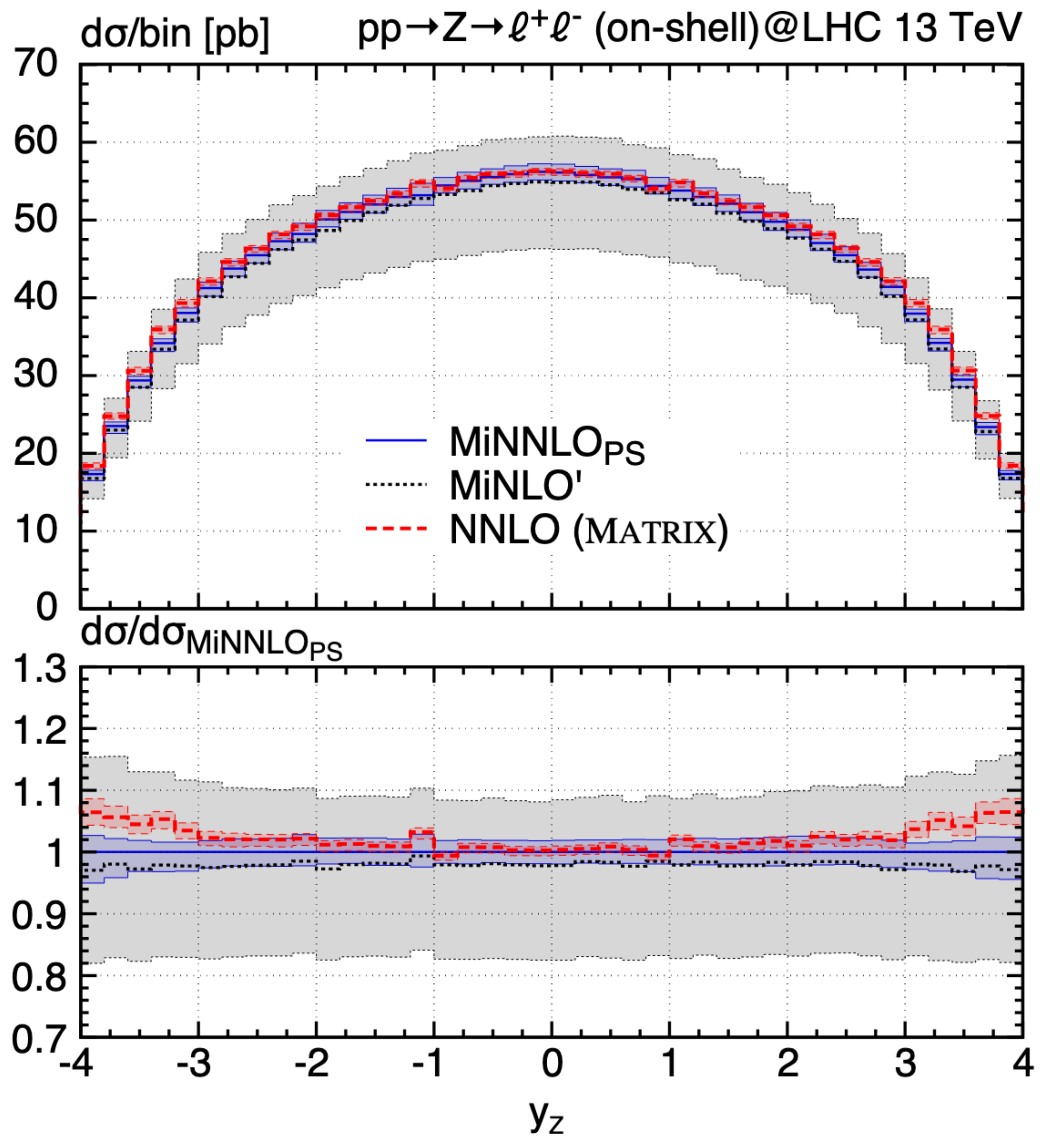
3. WHAT CAN WE DO WITH MINNLO$_{PS}$?

2 → 1 PROCESSES

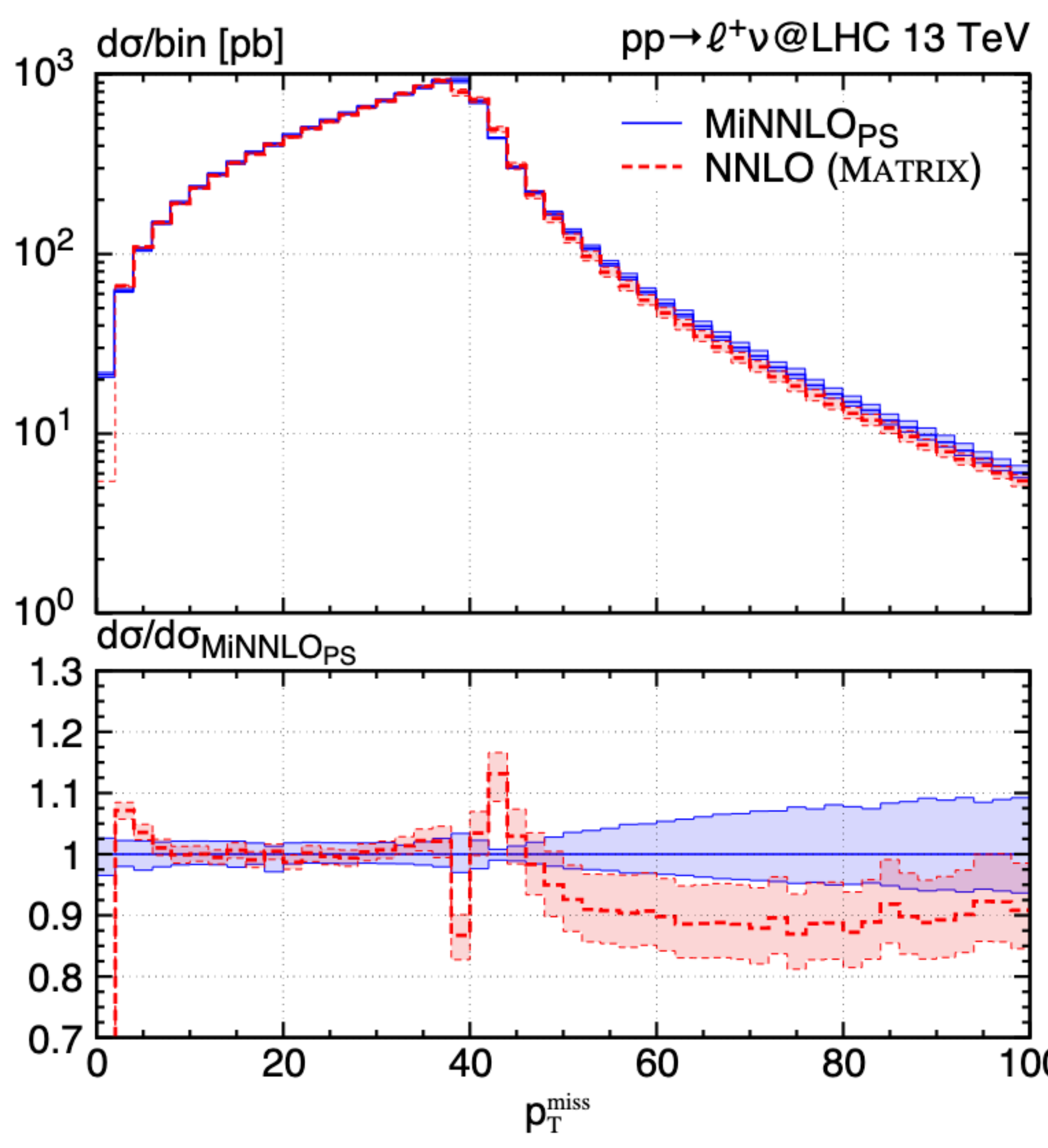
H production
[1908.06987]



Z production
[1908.06987]



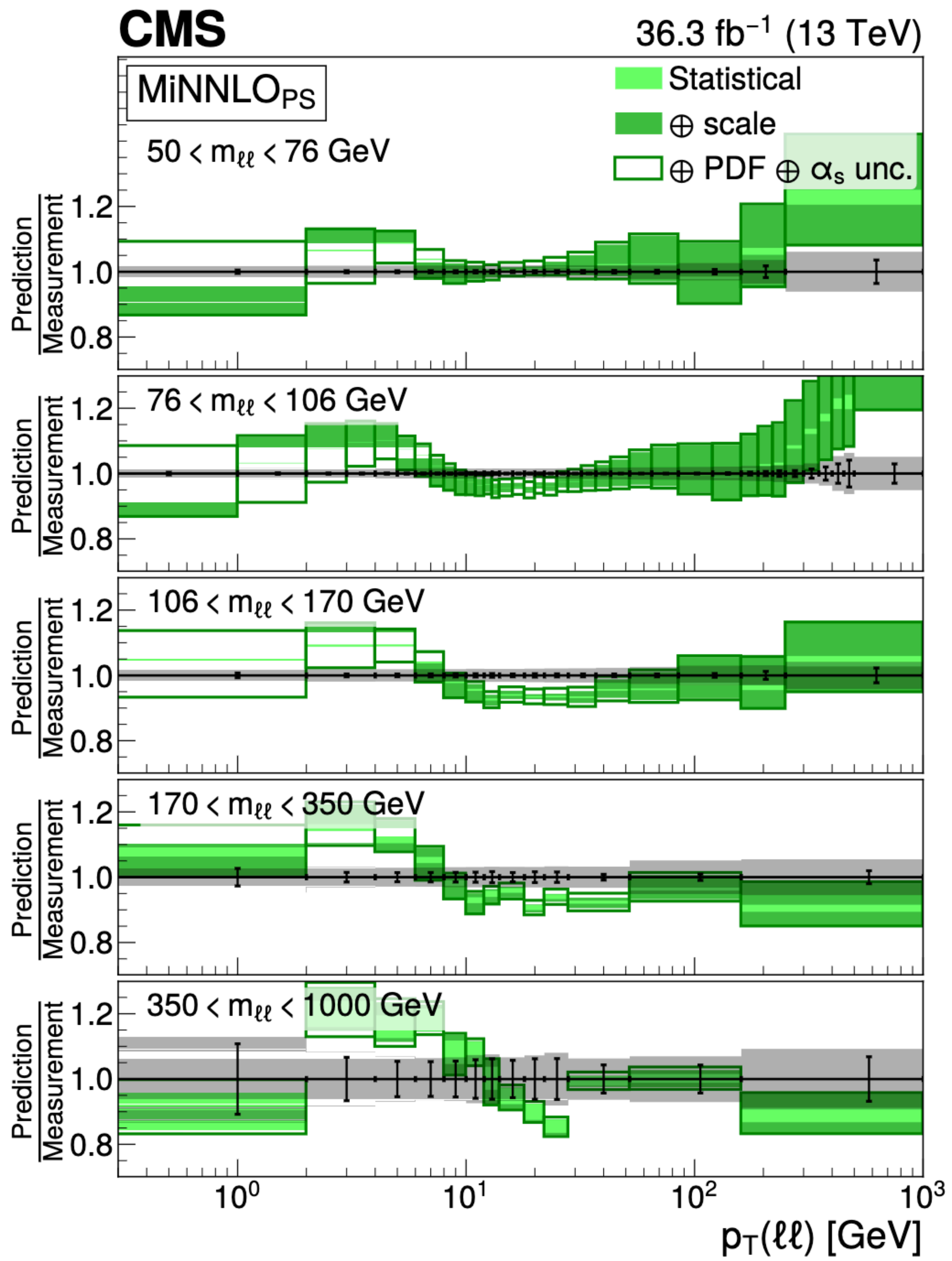
W production
[2006.04133]



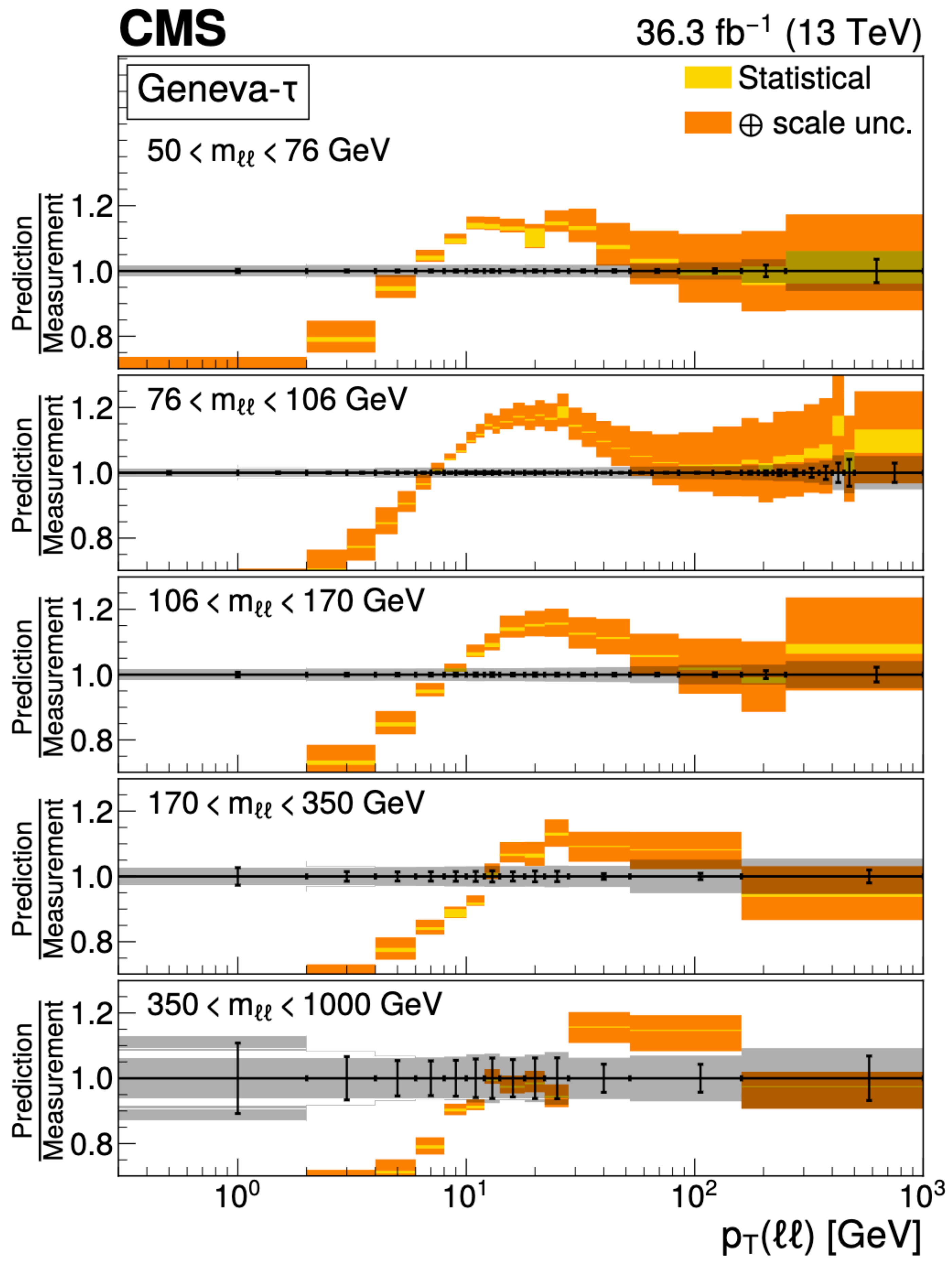
DY: COMPARISON TO DATA

[CMS 2205.04897]

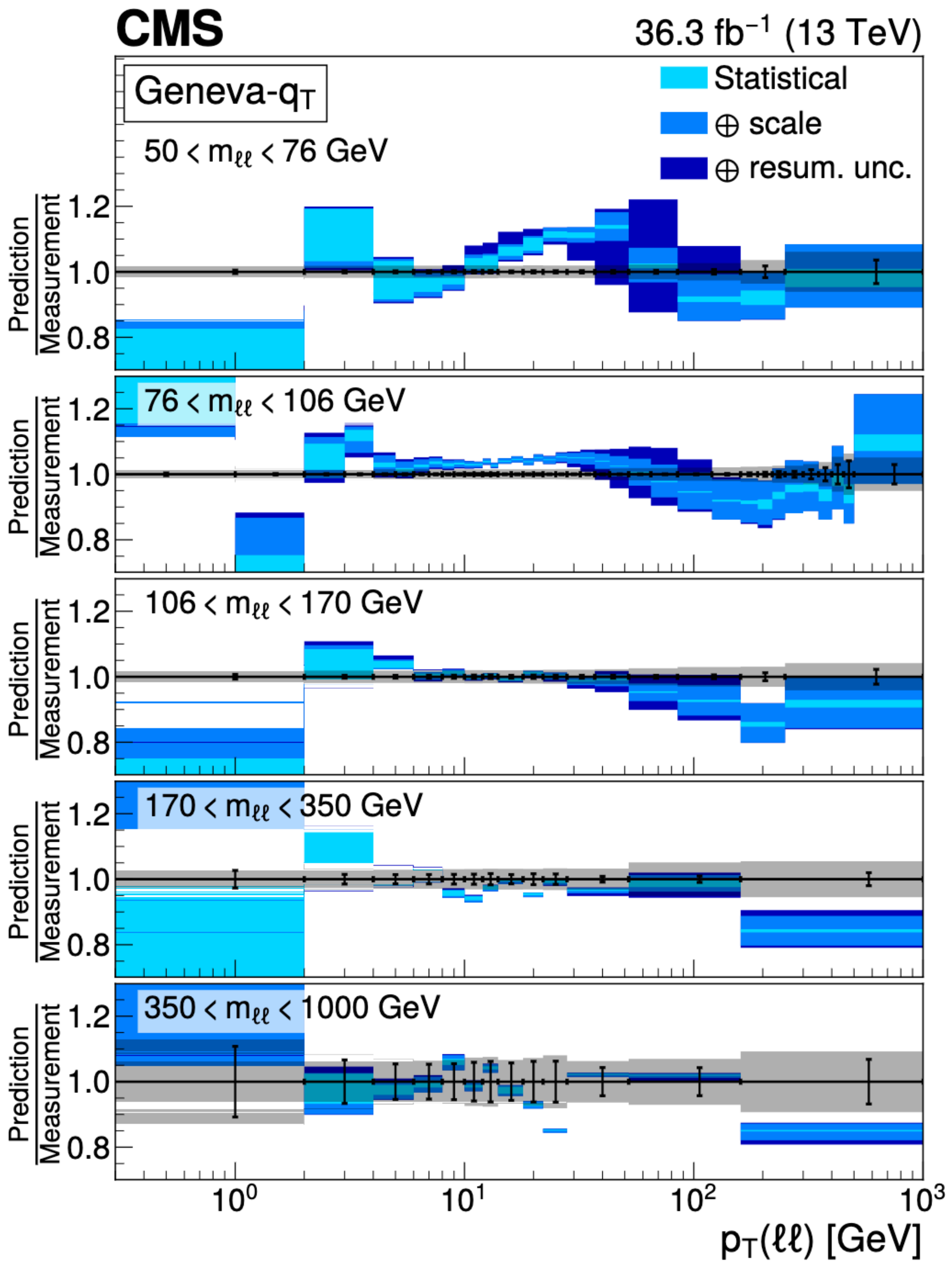
MiNNLO$_{PS}$



GENEVA



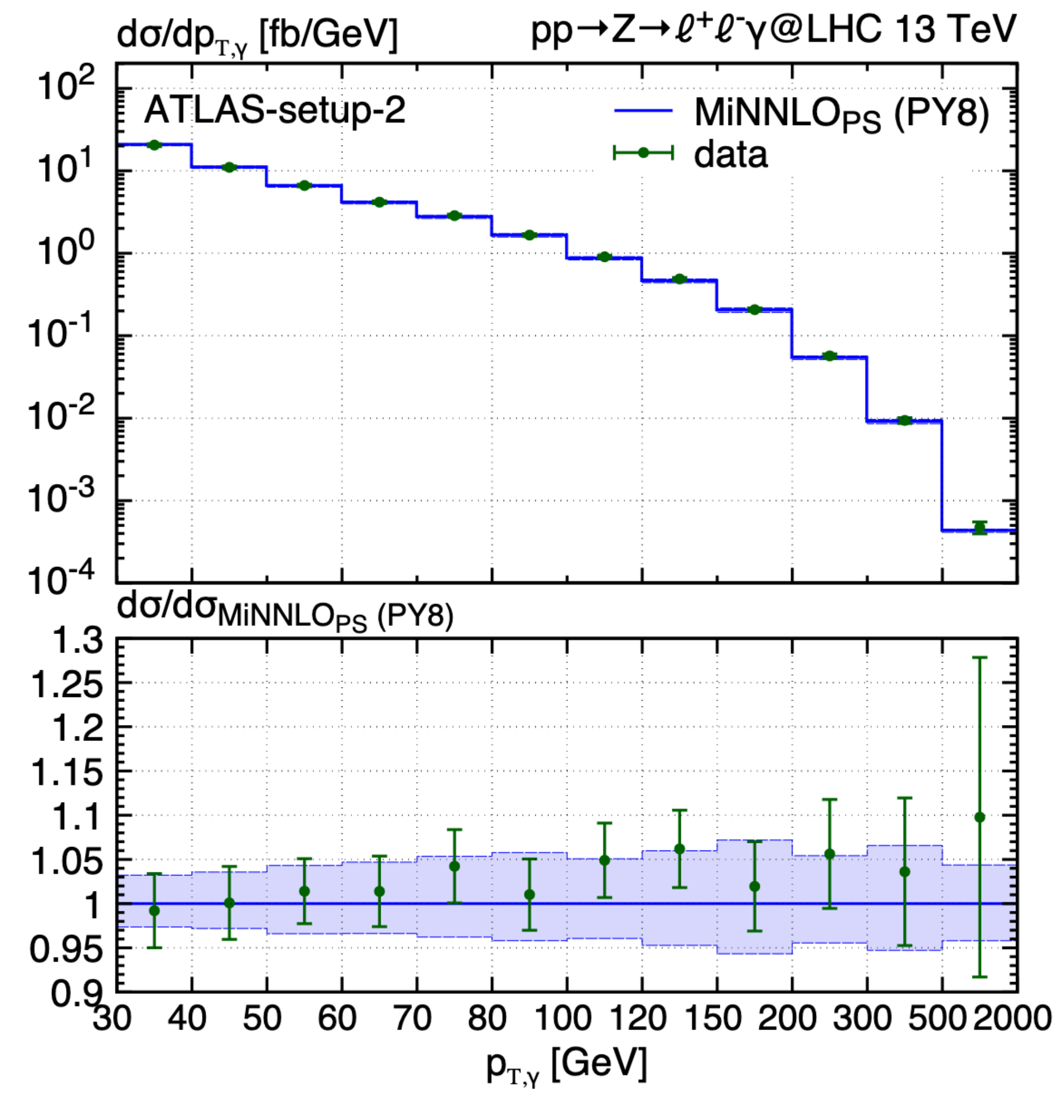
GENEVA-q$_T$



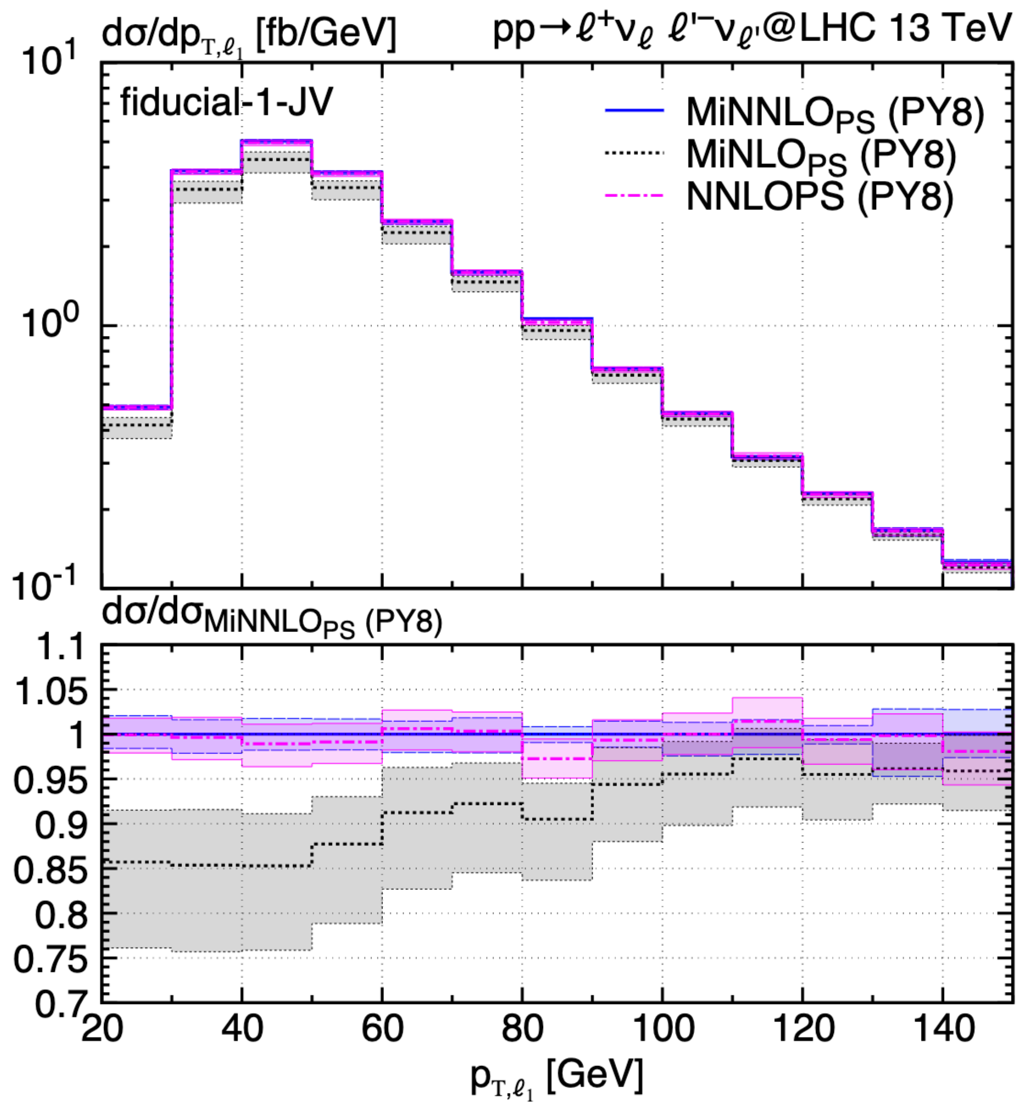
2 → 2 PROCESSES

https://powhegbox.mib.infn.it/

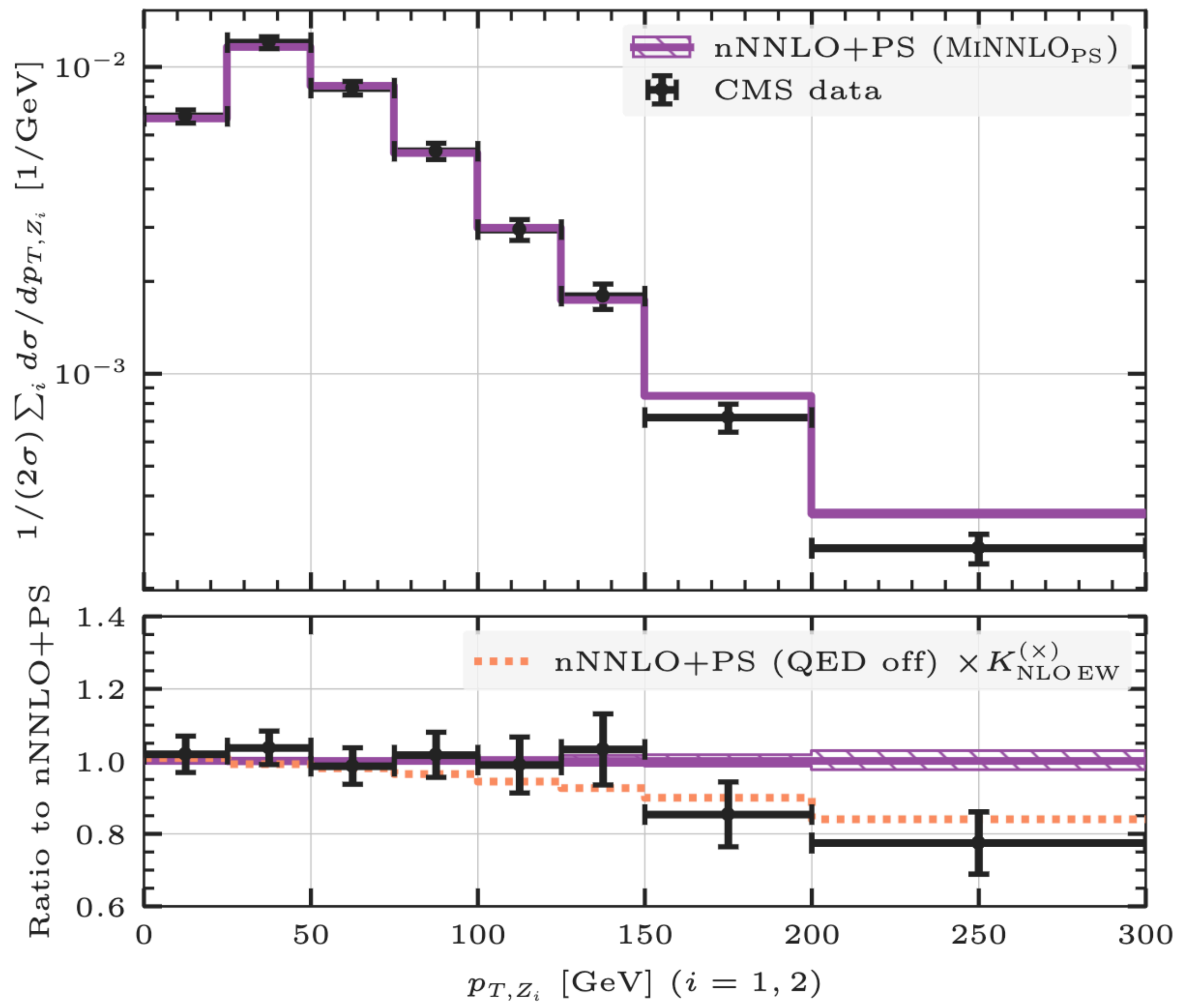
Zγ [2010.10478]



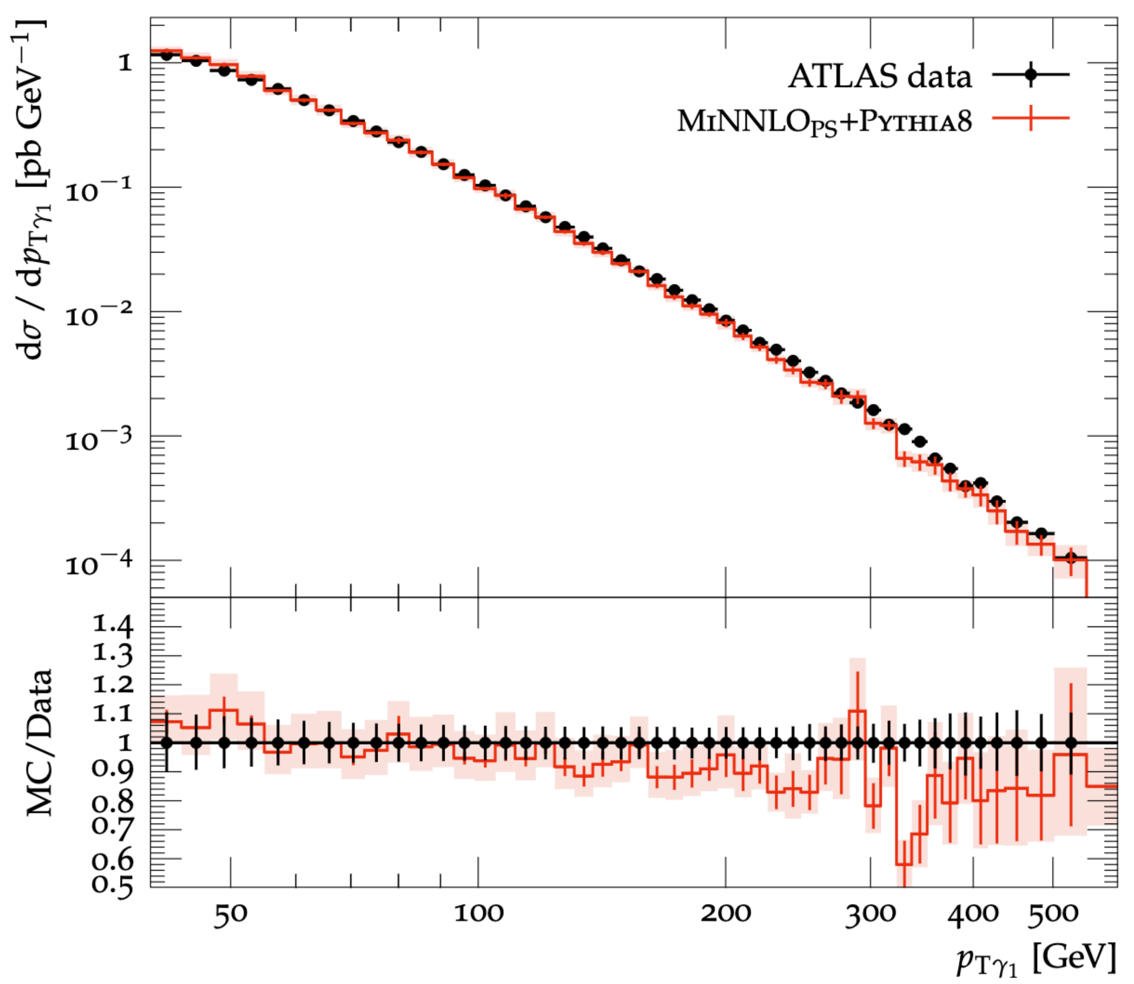
ZZ [2108.05337]



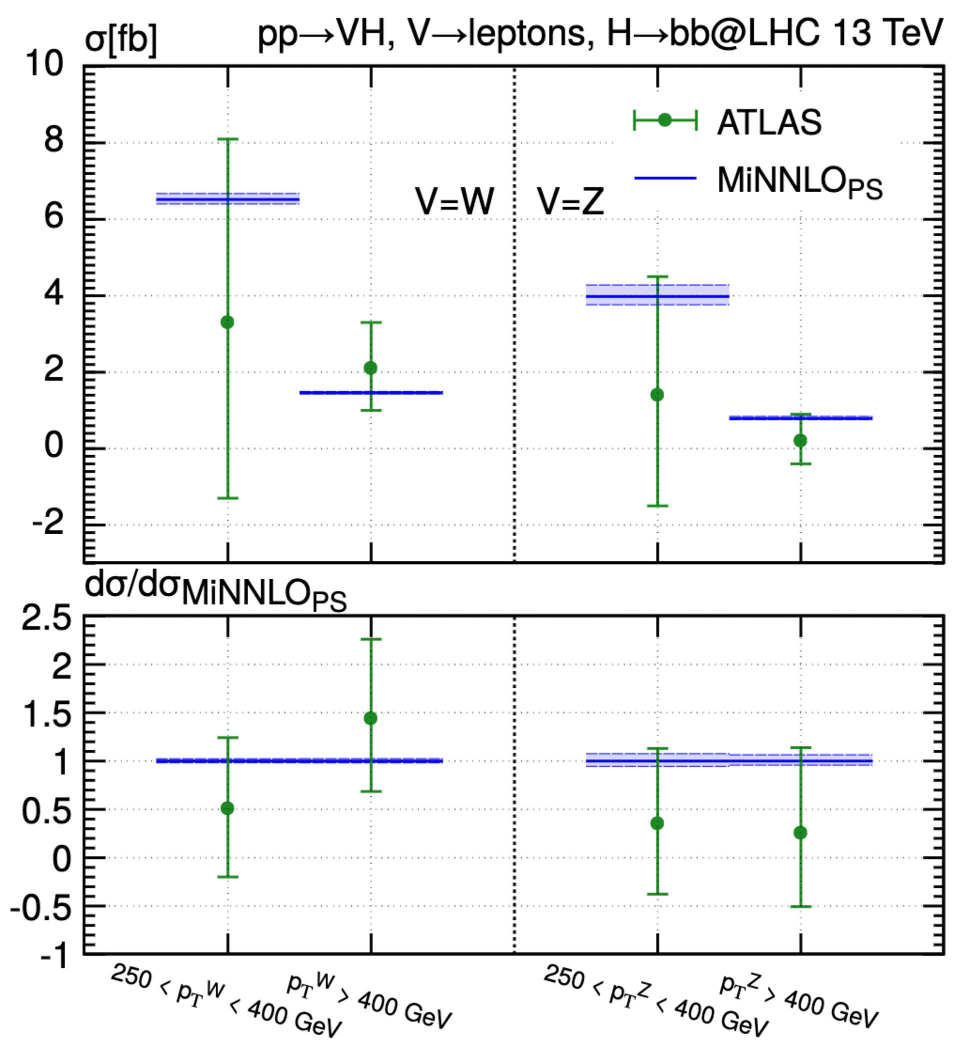
WW [2103.12077]



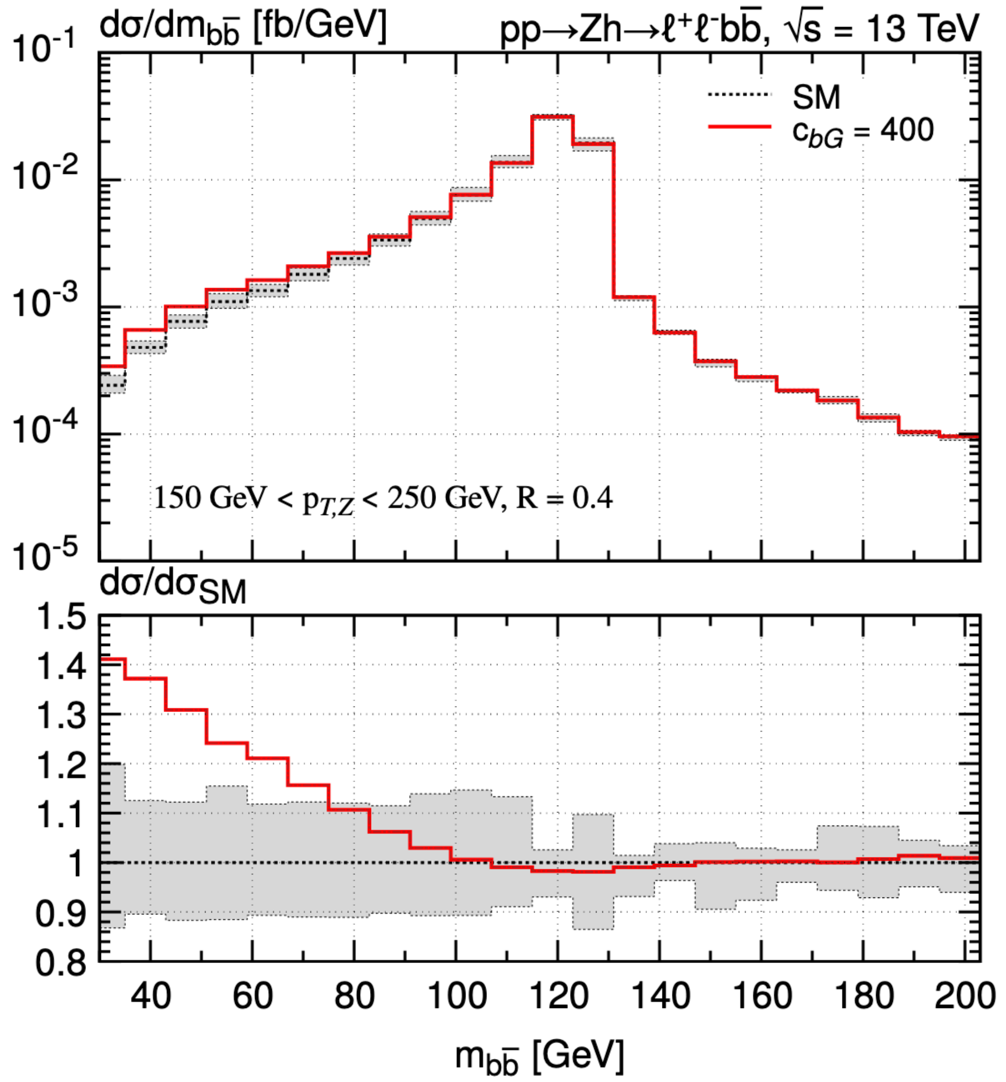
γγ [2204.12602]



VH (H→bb) [2112.04168]

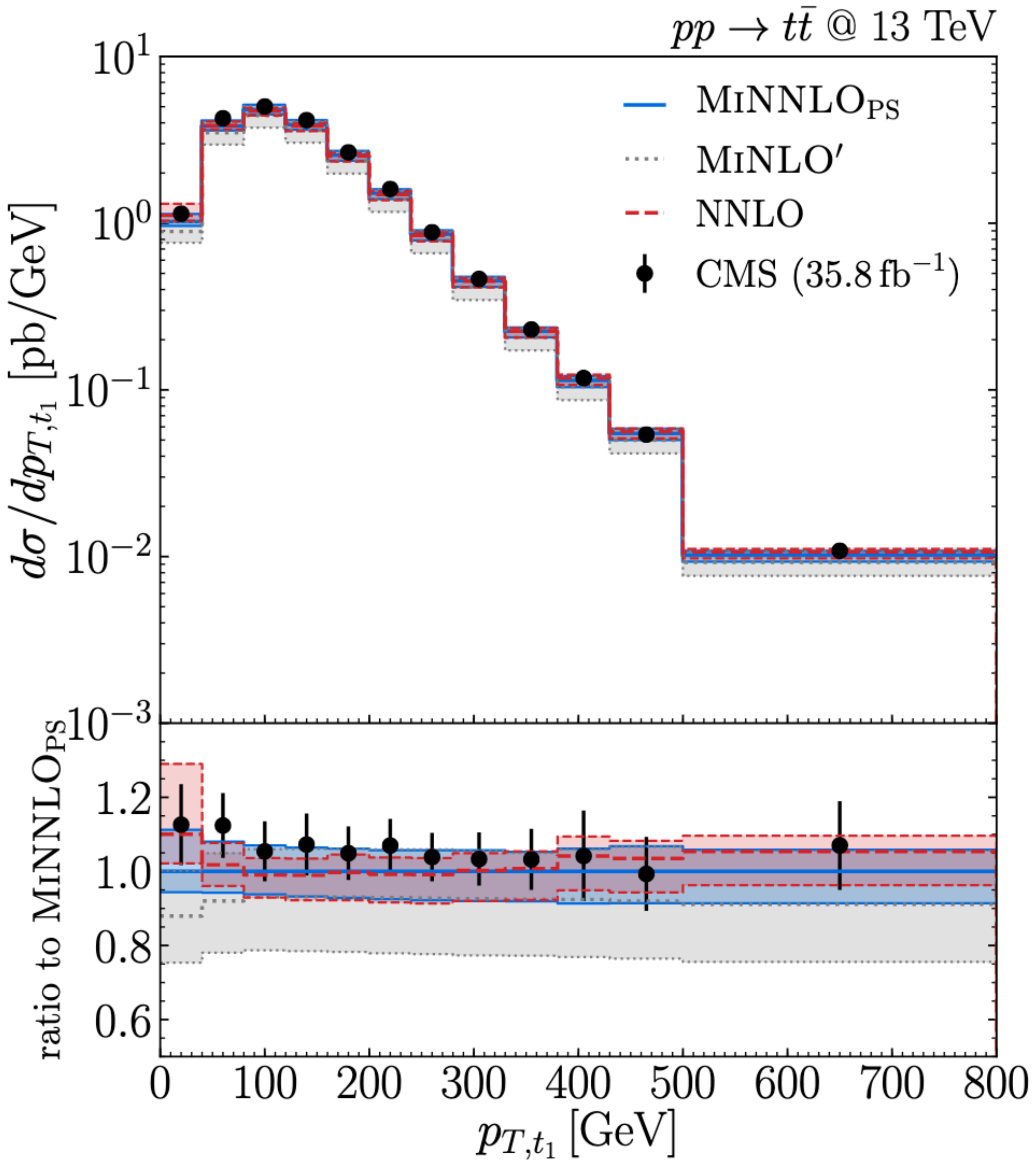


ZH (H→bb) SMEFT [2204.00663]

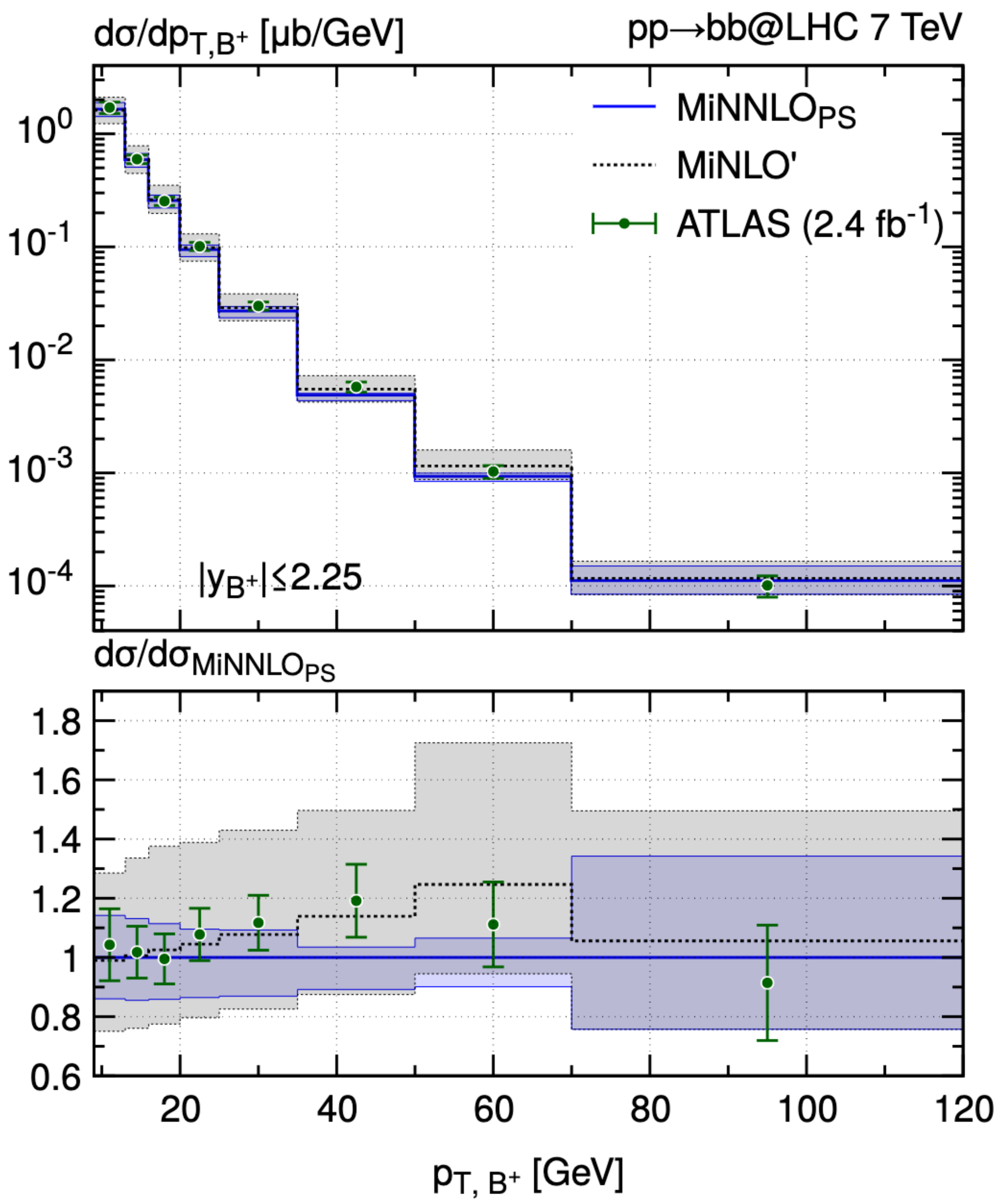


QQ PRODUCTION

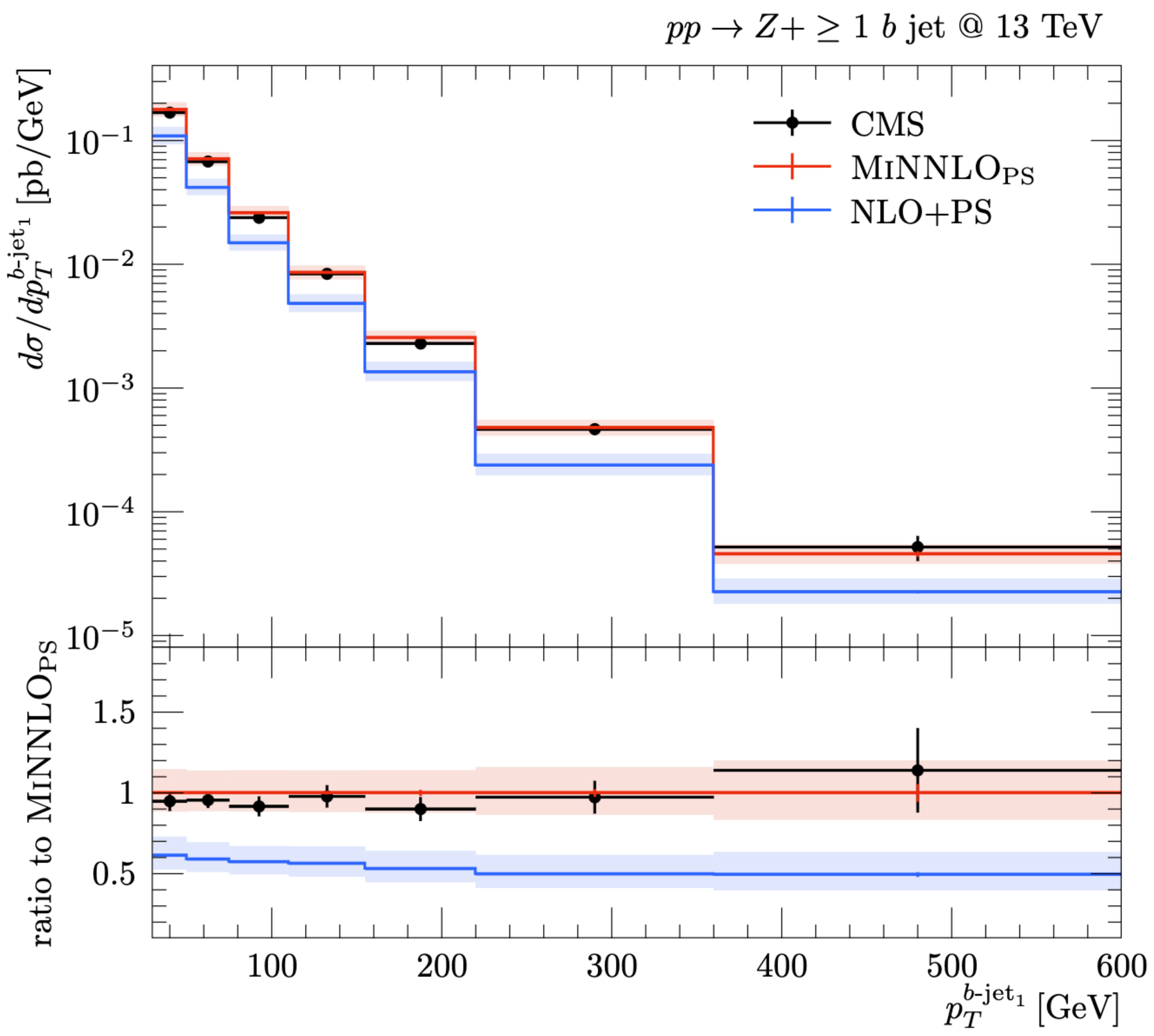
tt production
[2012.14267, 2112.12135]



bb production
[2112.04168]



NEW **bbZ production**
[2404.08598]

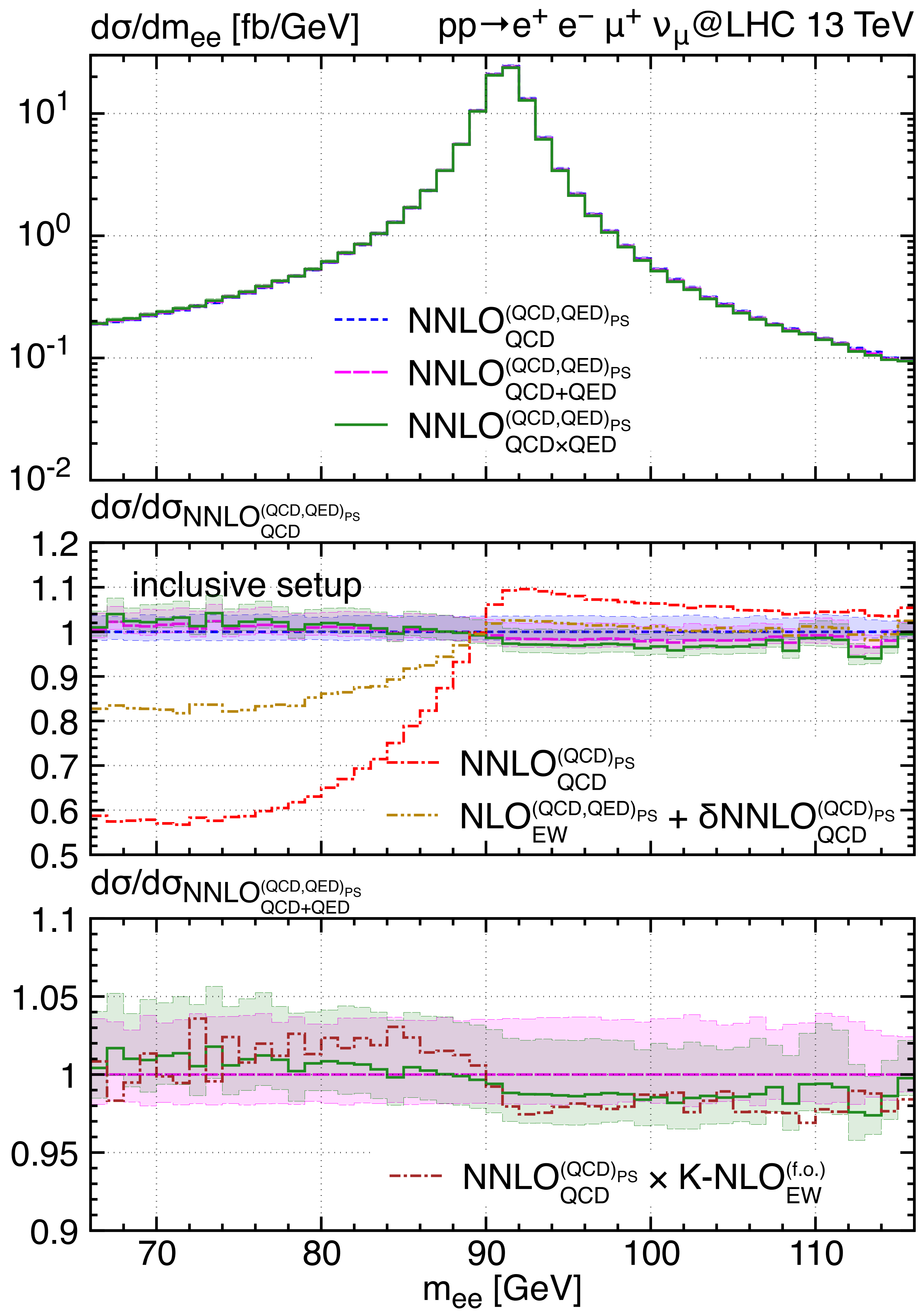


4. WHAT ARE THE NEXT STEPS?

INCLUSION OF NLO EW CORRECTIONS

WZ production

[2208.12660]



NNLO(QCD) & NLO(EW) matched to PS

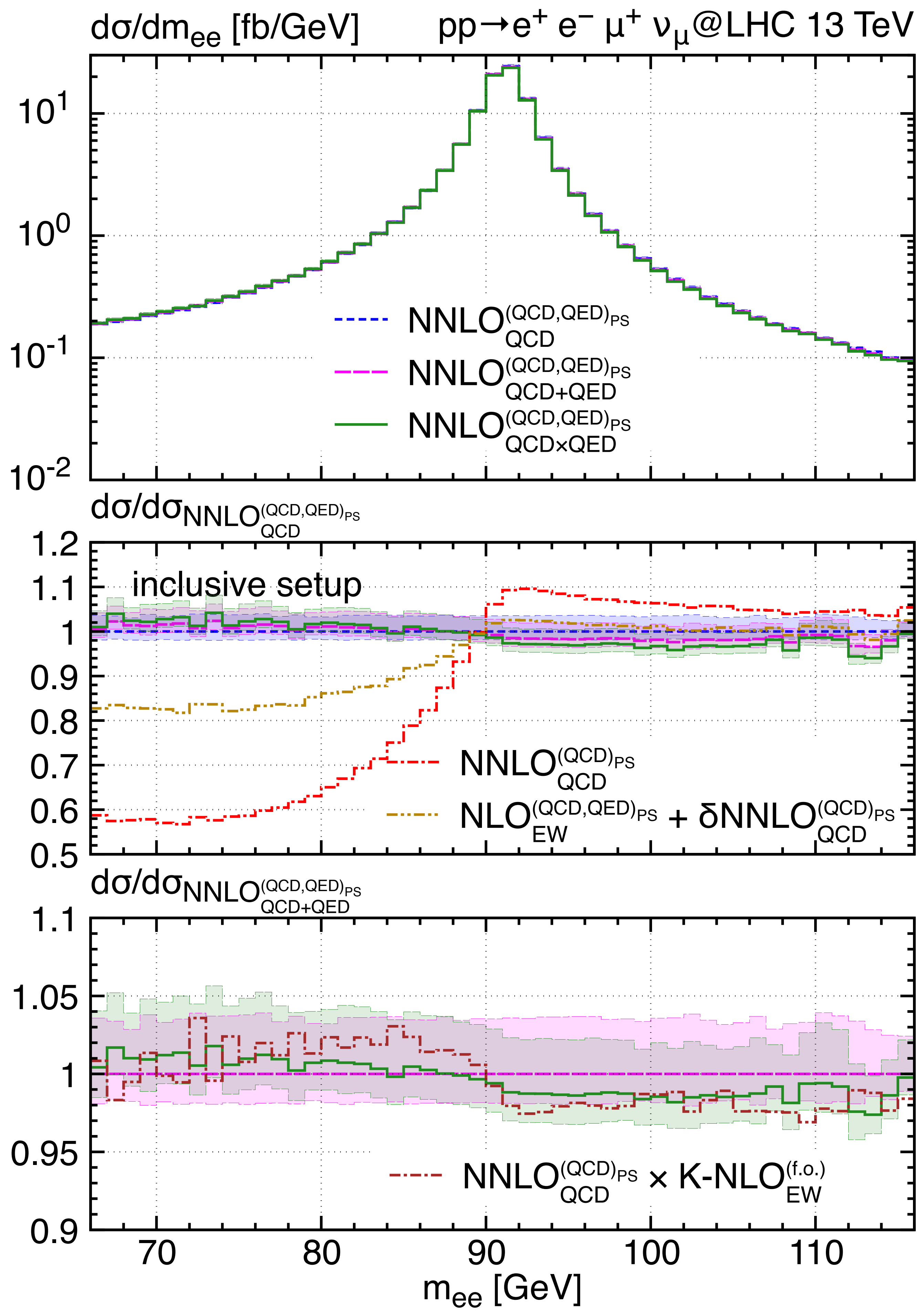
through a-posteriori reweighting

1. $\mathrm{NNLO}_{\mathrm{QCD}}^{(\mathrm{QCD,\,QED})_{\mathrm{PS}}} + \mathrm{NLO}_{\mathrm{EW}}^{(\mathrm{QCD,\,QED})_{\mathrm{PS}}} - \mathrm{LO}^{(\mathrm{QCD,\,QED})_{\mathrm{PS}}} = \mathrm{NNLO}_{\mathrm{QCD+EW}}^{(\mathrm{QCD,\,QED})_{\mathrm{PS}}}$
2. $\mathrm{NNLO}_{\mathrm{QCD}}^{(\mathrm{QCD,\,QED})_{\mathrm{PS}}} + \mathrm{NLO}_{\mathrm{EW}}^{(\mathrm{QED})_{\mathrm{PS}}} - \mathrm{LO}^{(\mathrm{QED})_{\mathrm{PS}}}$
3. $\mathrm{NNLO}_{\mathrm{QCD}}^{(\mathrm{QCD})_{\mathrm{PS}}} + \mathrm{NLO}_{\mathrm{EW}}^{(\mathrm{QCD,\,QED})_{\mathrm{PS}}} - \mathrm{LO}^{(\mathrm{QCD})_{\mathrm{PS}}}$
4. $\mathrm{NNLO}_{\mathrm{QCD}}^{(\mathrm{QCD,\,QED})_{\mathrm{PS}}} \times \mathrm{NLO}_{\mathrm{EW}}^{(\mathrm{QCD,\,QED})_{\mathrm{PS}}} / \mathrm{LO}^{(\mathrm{QCD,\,QED})_{\mathrm{PS}}} = \mathrm{NNLO}_{\mathrm{QCD\times EW}}^{(\mathrm{QCD,\,QED})_{\mathrm{PS}}}$
5. $\mathrm{NNLO}_{\mathrm{QCD}}^{(\mathrm{QCD,\,QED})_{\mathrm{PS}}} \times \mathrm{NLO}_{\mathrm{EW}}^{(\mathrm{QED})_{\mathrm{PS}}} / \mathrm{LO}^{(\mathrm{QED})_{\mathrm{PS}}}$
6. $\mathrm{NLO}_{\mathrm{EW}}^{(\mathrm{QCD,\,QED})_{\mathrm{PS}}} \times \mathrm{NNLO}_{\mathrm{QCD}}^{(\mathrm{QCD})_{\mathrm{PS}}} / \mathrm{LO}^{(\mathrm{QCD})_{\mathrm{PS}}}$
7. $\mathrm{NNLO}_{\mathrm{QCD}}^{(\mathrm{QCD})_{\mathrm{PS}}} \times \mathrm{NLO}_{\mathrm{EW}}^{\mathrm{f.o.}} / \mathrm{LO}^{\mathrm{f.o.}}$

INCLUSION OF NLO EW CORRECTIONS

WZ production

[2208.12660]



NNLO(QCD) & NLO(EW) matched to PS

through a-posteriori reweighting

1. $\mathrm{NNLO}_{\mathrm{QCD}}^{(\mathrm{QCD,\,QED})_{\mathrm{PS}}} + \mathrm{NLO}_{\mathrm{EW}}^{(\mathrm{QCD,\,QED})_{\mathrm{PS}}} - \mathrm{LO}^{(\mathrm{QCD,\,QED})_{\mathrm{PS}}} = \mathrm{NNLO}_{\mathrm{QCD+EW}}^{(\mathrm{QCD,\,QED})_{\mathrm{PS}}}$
2. $\mathrm{NNLO}_{\mathrm{QCD}}^{(\mathrm{QCD,\,QED})_{\mathrm{PS}}} + \mathrm{NLO}_{\mathrm{EW}}^{(\mathrm{QED})_{\mathrm{PS}}} - \mathrm{LO}^{(\mathrm{QED})_{\mathrm{PS}}}$
3. $\mathrm{NNLO}_{\mathrm{QCD}}^{(\mathrm{QCD})_{\mathrm{PS}}} + \mathrm{NLO}_{\mathrm{EW}}^{(\mathrm{QCD,\,QED})_{\mathrm{PS}}} - \mathrm{LO}^{(\mathrm{QCD})_{\mathrm{PS}}}$
4. $\mathrm{NNLO}_{\mathrm{QCD}}^{(\mathrm{QCD,\,QED})_{\mathrm{PS}}} \times \mathrm{NLO}_{\mathrm{EW}}^{(\mathrm{QCD,\,QED})_{\mathrm{PS}}} / \mathrm{LO}^{(\mathrm{QCD,\,QED})_{\mathrm{PS}}} = \mathrm{NNLO}_{\mathrm{QCD\times EW}}^{(\mathrm{QCD,\,QED})_{\mathrm{PS}}}$
5. $\mathrm{NNLO}_{\mathrm{QCD}}^{(\mathrm{QCD,\,QED})_{\mathrm{PS}}} \times \mathrm{NLO}_{\mathrm{EW}}^{(\mathrm{QED})_{\mathrm{PS}}} / \mathrm{LO}^{(\mathrm{QED})_{\mathrm{PS}}}$
6. $\mathrm{NLO}_{\mathrm{EW}}^{(\mathrm{QCD,\,QED})_{\mathrm{PS}}} \times \mathrm{NNLO}_{\mathrm{QCD}}^{(\mathrm{QCD})_{\mathrm{PS}}} / \mathrm{LO}^{(\mathrm{QCD})_{\mathrm{PS}}}$
7. $\mathrm{NNLO}_{\mathrm{QCD}}^{(\mathrm{QCD})_{\mathrm{PS}}} \times \mathrm{NLO}_{\mathrm{EW}}^{\mathrm{f.o.}} / \mathrm{LO}^{\mathrm{f.o.}}$

TOWARDS AN ON-THE-FLY GENERATION

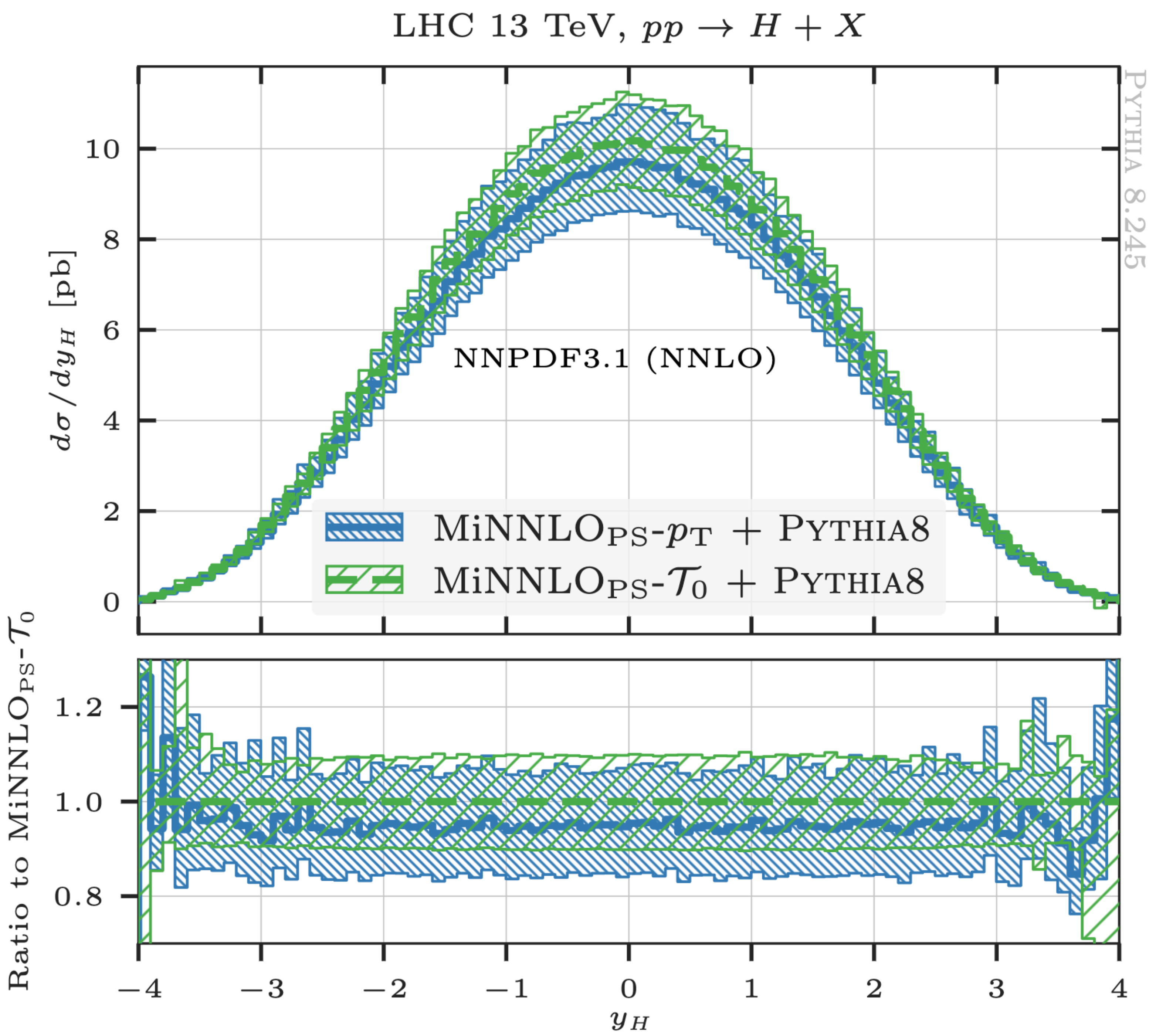
ongoing!

PROCESSES WITH JETS

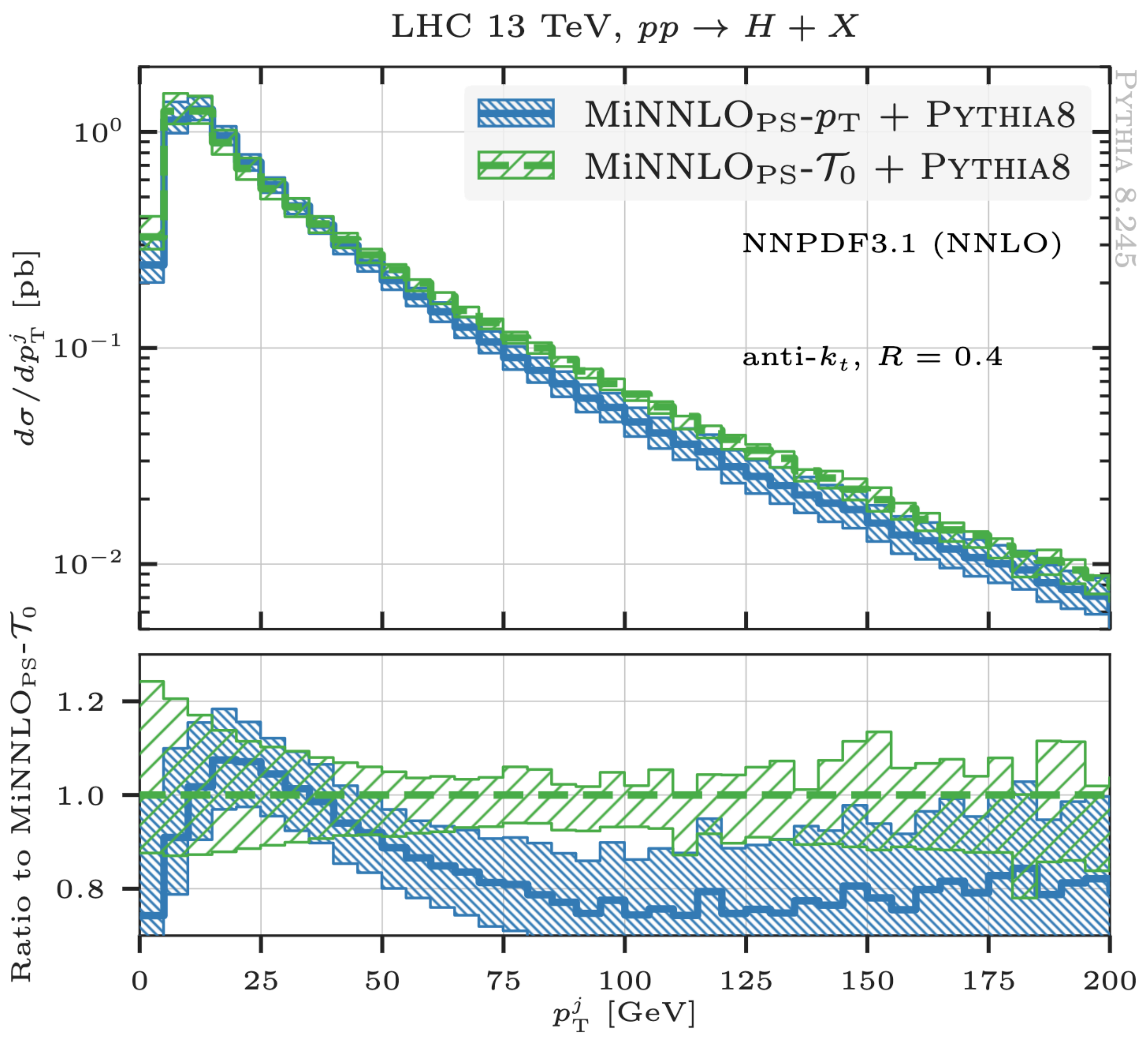
[2402.00596]

H production (τ_0)

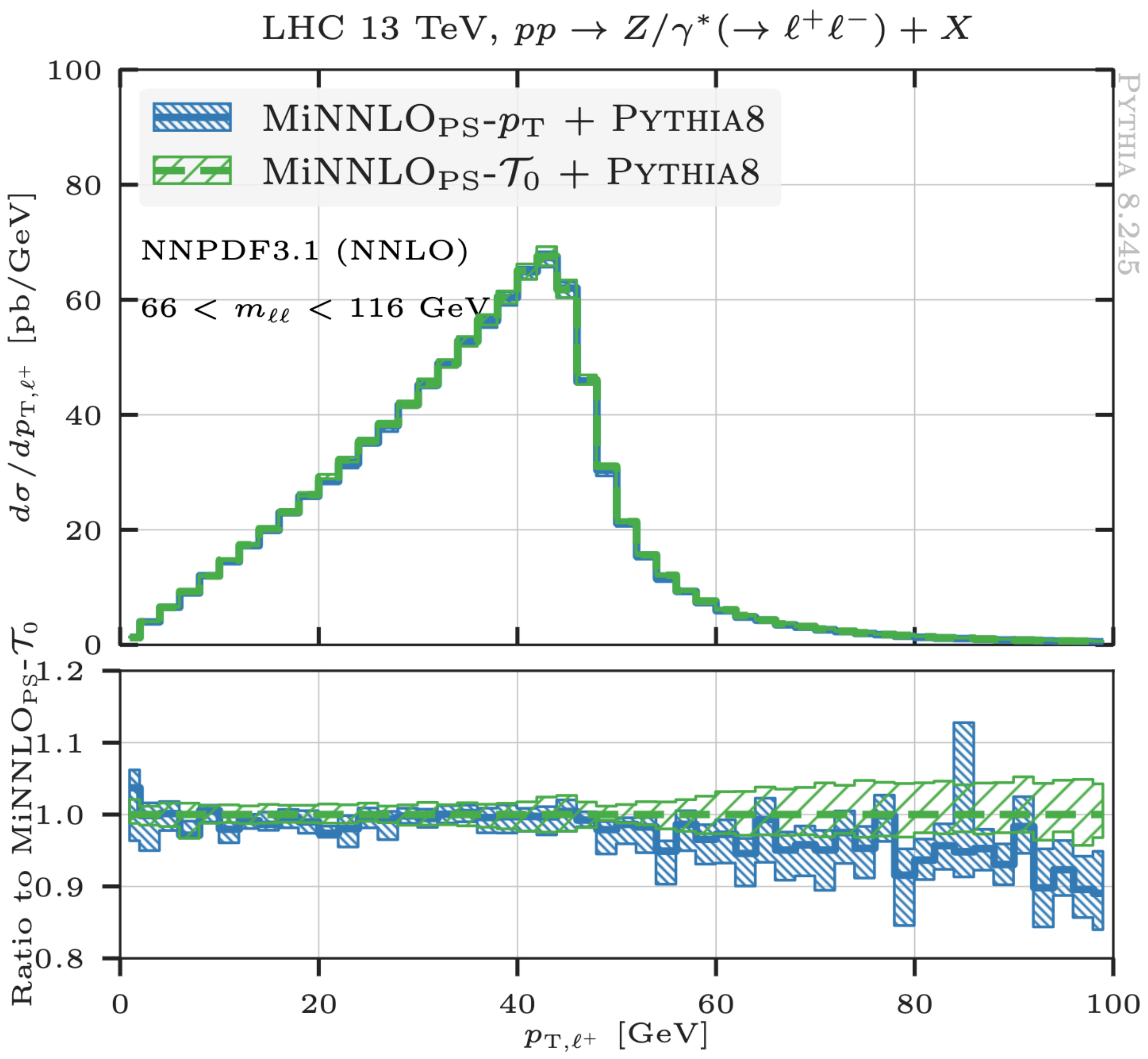
Z production (τ_0)



NNLO observable



NLO observable



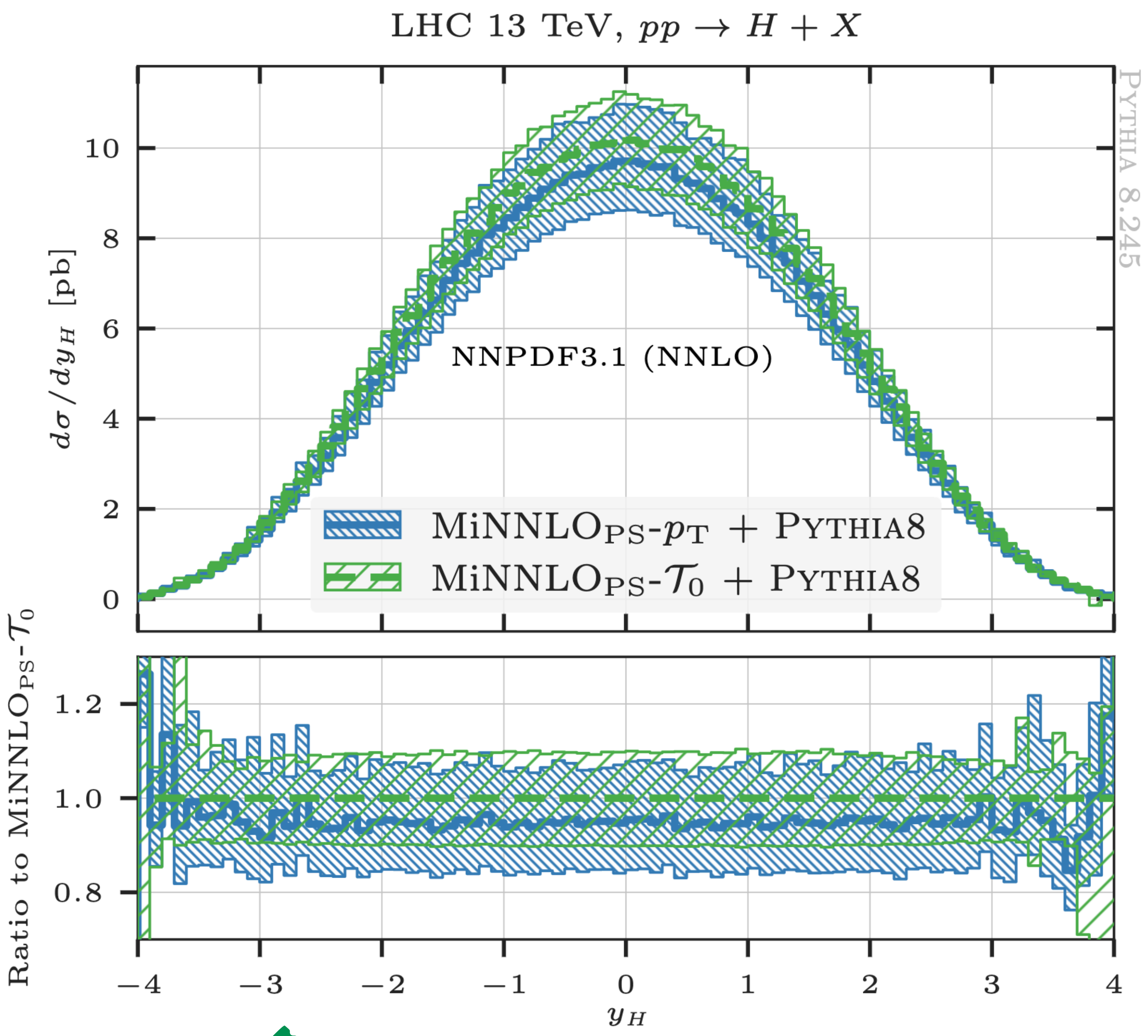
NNLO observable

PROCESSES WITH JETS

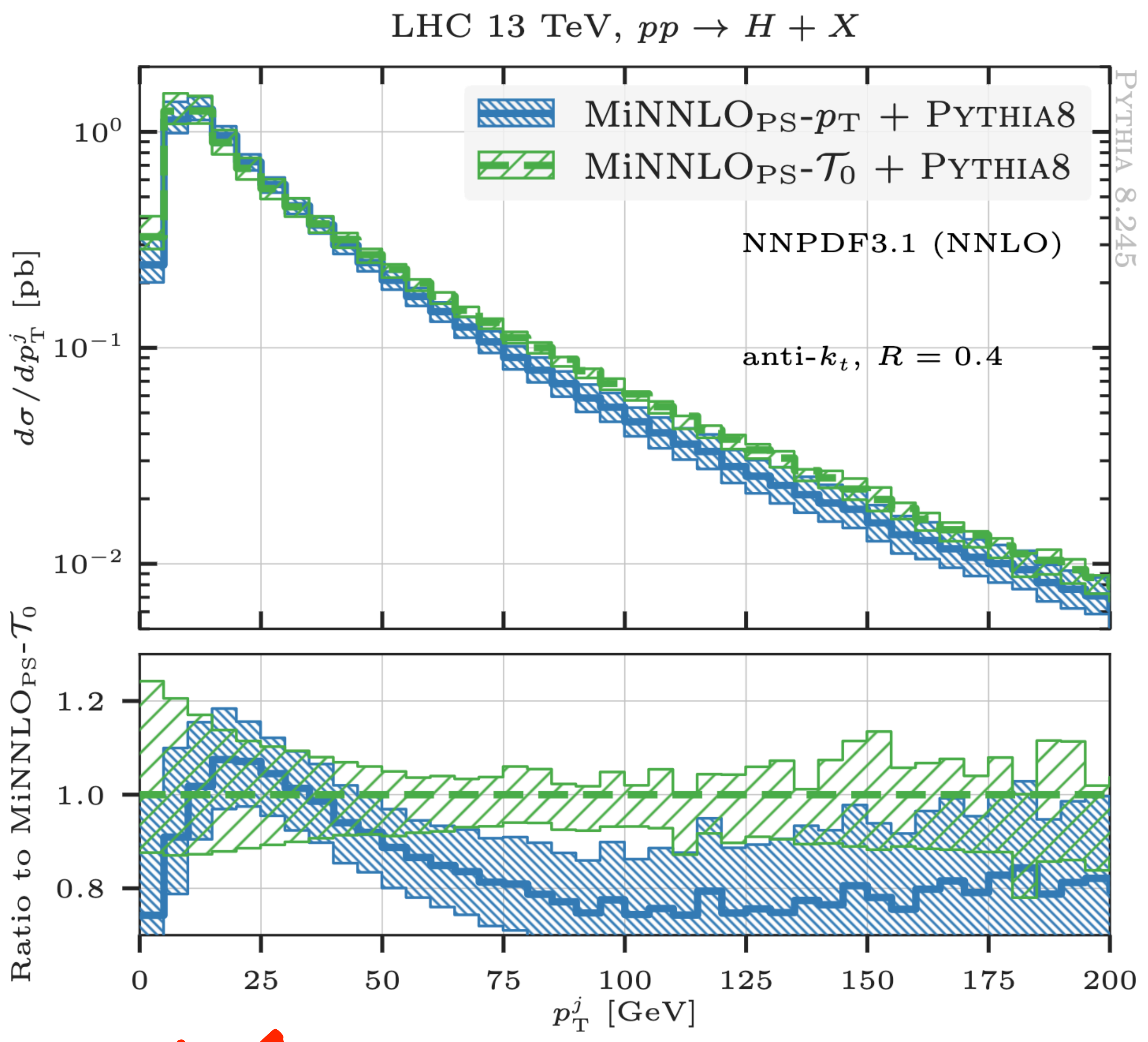
[2402.00596]

H production (τ_0)

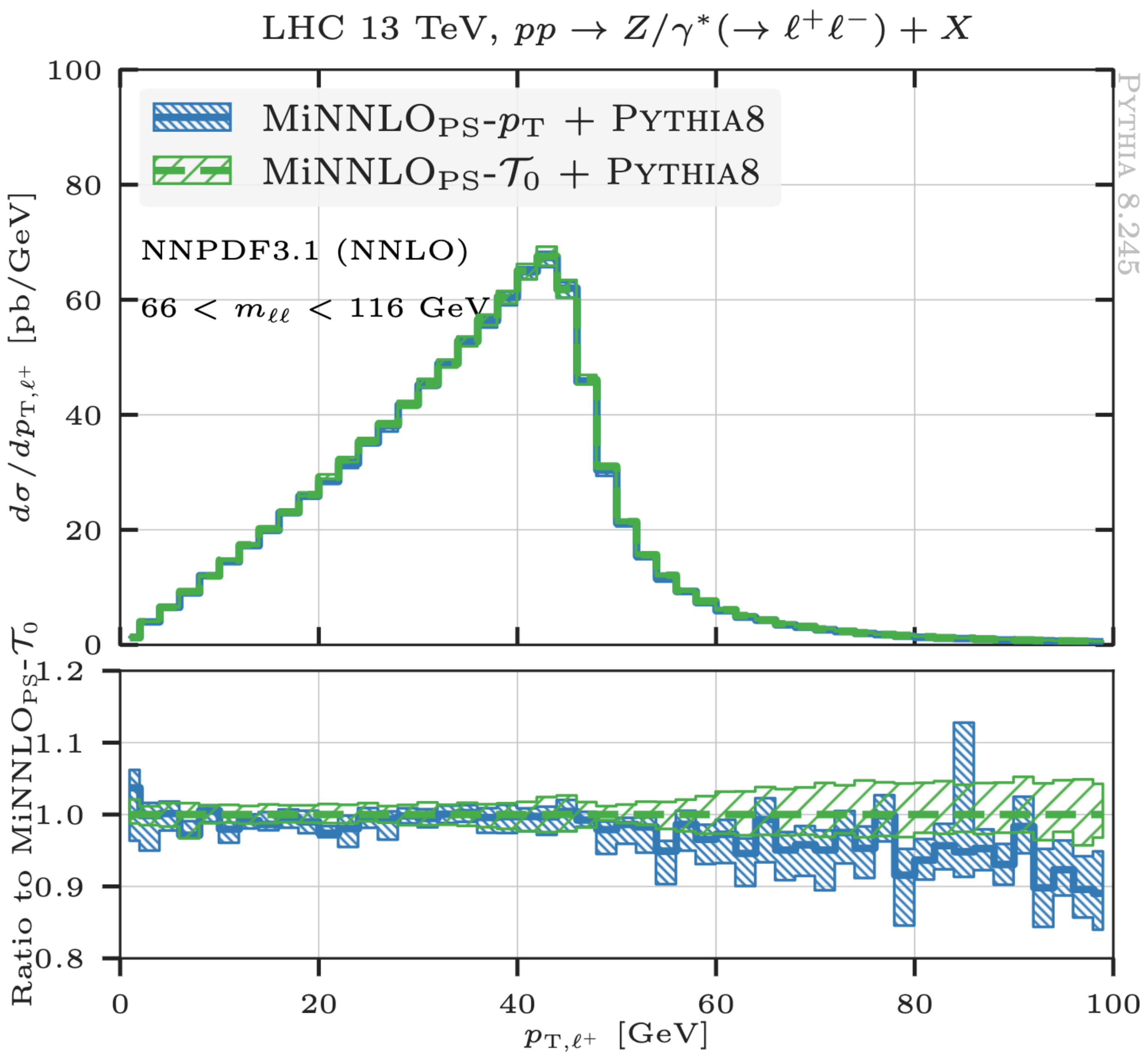
Z production (τ_0)



✔ NNLO observable



✘ NLO observable



✔ NNLO observable

!! The matching with the shower is NOT trivial !!

SUMMARY

https://powhegbox.mib.infn.it/

2019	H/Z	[1908.06987]
2020	$Z\gamma$ tt W	[2010.10478] [2012.14267] [2006.04133]
2021	WW ZZ VH (H→bb)	[2103.12077] [2108.05337] [2112.04168]
2022	VH (H→bb)(SMEFT) $\gamma\gamma$ WZ	[2204.00663] [2204.12602] [2208.12660]
2023	bb	[2302.01645]
2024	H/Z (jettiness) bb→H bbZ	[2402.00596] [2402.04025] [2404.08598]

Different possible outlooks:

1. Inclusion of EW effects
2. Extension to processes with jets
3. NNLO+PS for LEP
4. “FONLL” approach for 5FS/4FS
5. …

MAIN MESSAGE:

NNLO+PS IS POSSIBLE NOWADAYS

5. HOW TO RUN MiNNLO$_{PS}$

(VERY COMPLICATED) STEPS TO FOLLOW

1. DOWNLOAD THE CODE
2. COMPILE THE CODE
3. RUN THE CODE

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1. DOWNLOAD THE CODE
2. COMPILE THE CODE
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EXAMPLE: DY with MiNNLO$_{PS}$

```
$ svn checkout --username anonymous --password anonymous svn://powhegbox.mib.infn.it/trunk/POWHEG-BOX-V2
$ cd POWHEG-BOX-V2
$ svn co --username anonymous --password anonymous svn://powhegbox.mib.infn.it/trunk/User-Processes-V2/Zj
$ cd Zj/ZjMiNNLO
$ make (make main-PYTHIA8-lhef)
$ cd suggested-run
$ cp powheg.input-save powheg.input
$ ../pwhg_main (echo pwgevents.lhe | ../main-PYTHIA8-lhef)
```

```
! MINLO SETTINGS
minlo 1         ! (default 0) if 1, activate minlo
minnlo 1        ! (default 0) if 1, activate miNNlo
largeptscales 0  ! (default 0) if 0, at large pt, use muR=muF~Q in fixed order
                 !              if 1, at large pt, use muR=muF=pt in the fixed-o
```

(VERY COMPLICATED) STEPS TO FOLLOW

1. DOWNLOAD THE CODE
2. COMPILE THE CODE
3. RUN THE CODE

Have fun!

EXAMPLE: DY with MiNNLO$_{PS}$

```
$ svn checkout --username anonymous --password anonymous svn://powhegbox.mib.infn.it/trunk/POWHEG-BOX-V2
$ cd POWHEG-BOX-V2
$ svn co --username anonymous --password anonymous svn://powhegbox.mib.infn.it/trunk/User-Processes-V2/Zj
$ cd Zj/ZjMiNNLO
$ make (make main-PYTHIA8-lhef)
$ cd suggested-run
$ cp powheg.input-save powheg.input
$ ../pwhg_main (echo pwgevents.lhe | ../main-PYTHIA8-lhef)
```

```
alphas_from_pdf 1 ! (default 0) if 1, uses alphas from PDF evolution tool (e.g.

! MINLO SETTINGS
minlo 1         ! (default 0) if 1, activate minlo
minnlo 1        ! (default 0) if 1, activate miNNlo
largeptscales 0  ! (default 0) if 0, at large pt, use muR=muF~Q in fixed order
                 !             if 1, at large pt, use muR=muF=pt in the fixed-o
#Q0 0.5          ! (default 0.) Q0 value used in profiled scales (see 2006.041
```