Julius-Maximilians-
UNIVERSITÄT
WÜRZBURG

MAX-PLANCK-INSTITUT
FÜR PHYSIK

The numerous faces of Precise Phenomenology for LHC Physics

Presented by

Daniele Lombardi

Giornate di Studio sulla Fisica Teorica

Fondazione Cesare Pavese

Santo Stefano Belbo (CN)

November 15th, 2025

UNIVERSITÀ
DI TORINO

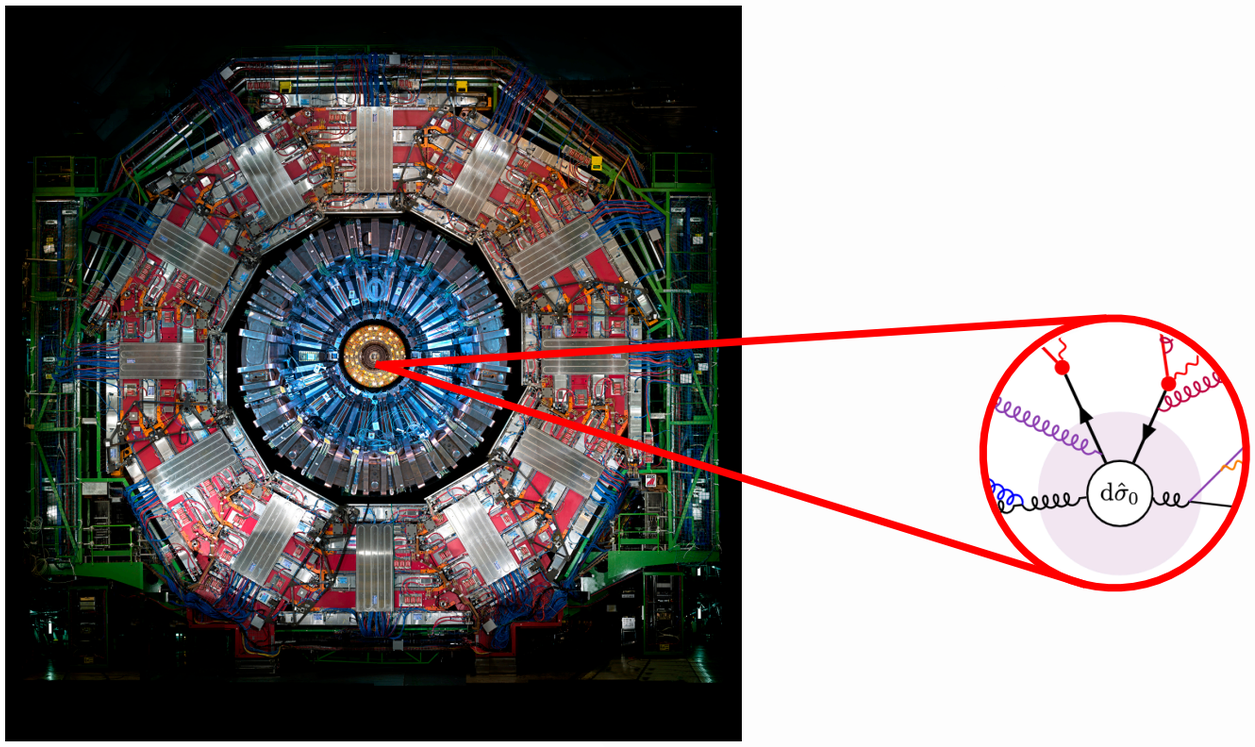
INFN
Istituto Nazionale di Fisica Nucleare

High accuracy for LHC Phenomenology

$$d\hat{\sigma} = d\hat{\sigma}_{(0,0)} + \alpha_S \cdot d\hat{\sigma}_{(1,0)} + \alpha_S^2 \cdot d\hat{\sigma}_{(2,0)} + \dots$$

LO NLO NNLO

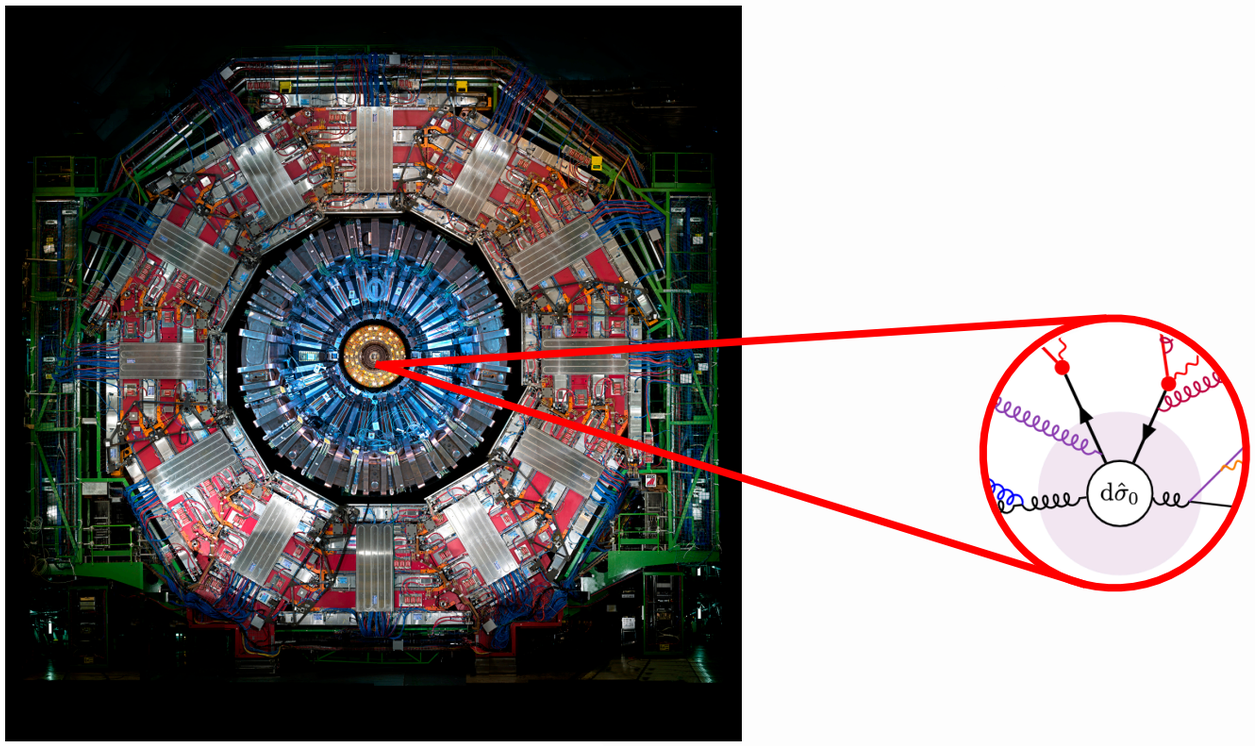
Fixed-order (FO) predictions, based on perturbation theory $\alpha_S \ll 1$



High accuracy for LHC Phenomenology

$$d\hat{\sigma} = \underset{\text{LO}}{d\hat{\sigma}_{(0,0)}} + \alpha_S \cdot \underset{\text{NLO}}{d\hat{\sigma}_{(1,0)}} + \alpha_S^2 \cdot \underset{\text{NNLO}}{d\hat{\sigma}_{(2,0)}} + \ldots + \alpha_{EW} \cdot d\hat{\sigma}_{(0,1)} + \ldots$$

- Fixed-order (FO) predictions, based on perturbation theory $\alpha_S \ll 1$



- Subleading corrections from expansion in the electroweak coupling $\alpha_{EW} \sim \alpha_S^2$

High accuracy for LHC Phenomenology

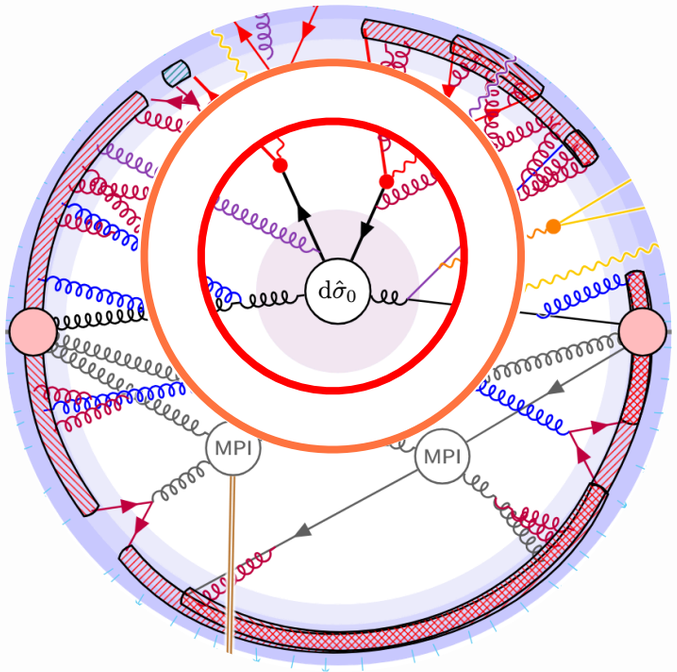
Fixed-order (FO) predictions, based on perturbation theory $\alpha_S \ll 1$

Resummation of large logarithmic contributions
$\alpha_S \log(Q_1/Q_2) \sim 1 \quad \rightarrow$ Parton Showers (PS)

Subleading corrections from expansion in the electroweak coupling $\alpha_{EW} \sim \alpha_S^2$

LO NLO NNLO

$$d\hat{\sigma} = d\hat{\sigma}_{(0,0)} + \alpha_S \cdot d\hat{\sigma}_{(1,0)} + \alpha_S^2 \cdot d\hat{\sigma}_{(2,0)} + \dots + \alpha_{EW} \cdot d\hat{\sigma}_{(0,1)} + \dots$$



High accuracy for LHC Phenomenology

Matching/Merging: combine the two predictions

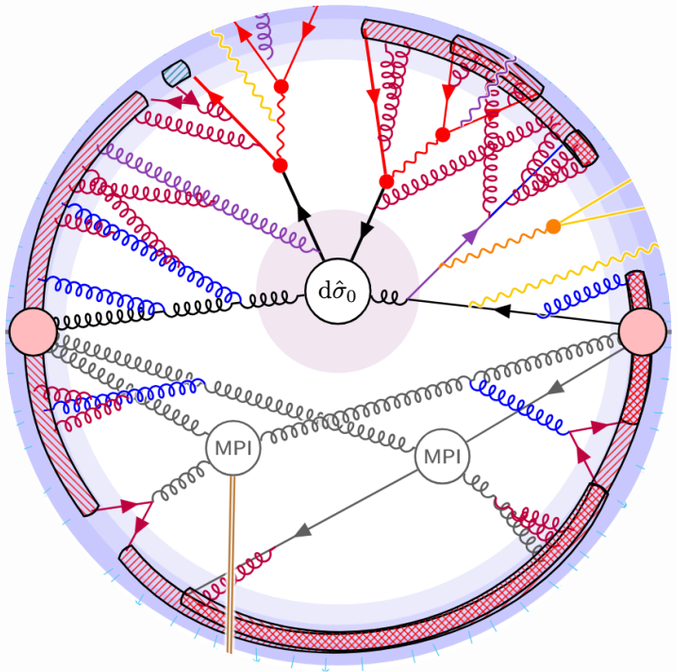
Fixed-order (FO) predictions, based on perturbation theory $\alpha_S \ll 1$

Resummation of large logarithmic contributions
$\alpha_S \log(Q_1/Q_2) \sim 1 \quad \rightarrow$ Parton Showers (PS)

Subleading corrections from expansion in the electroweak coupling $\alpha_{EW} \sim \alpha_S^2$

LO NLO NNLO

$$d\hat{\sigma} = d\hat{\sigma}_{(0,0)} + \alpha_S \cdot d\hat{\sigma}_{(1,0)} + \alpha_S^2 \cdot d\hat{\sigma}_{(2,0)} + \dots$$
$$+\alpha_{EW} \cdot d\hat{\sigma}_{(0,1)} + \dots$$



High accuracy for LHC Phenomenology

Matching/Merging: combine the two predictions

Fixed-order (FO) predictions, based on perturbation theory $\alpha_S \ll 1$

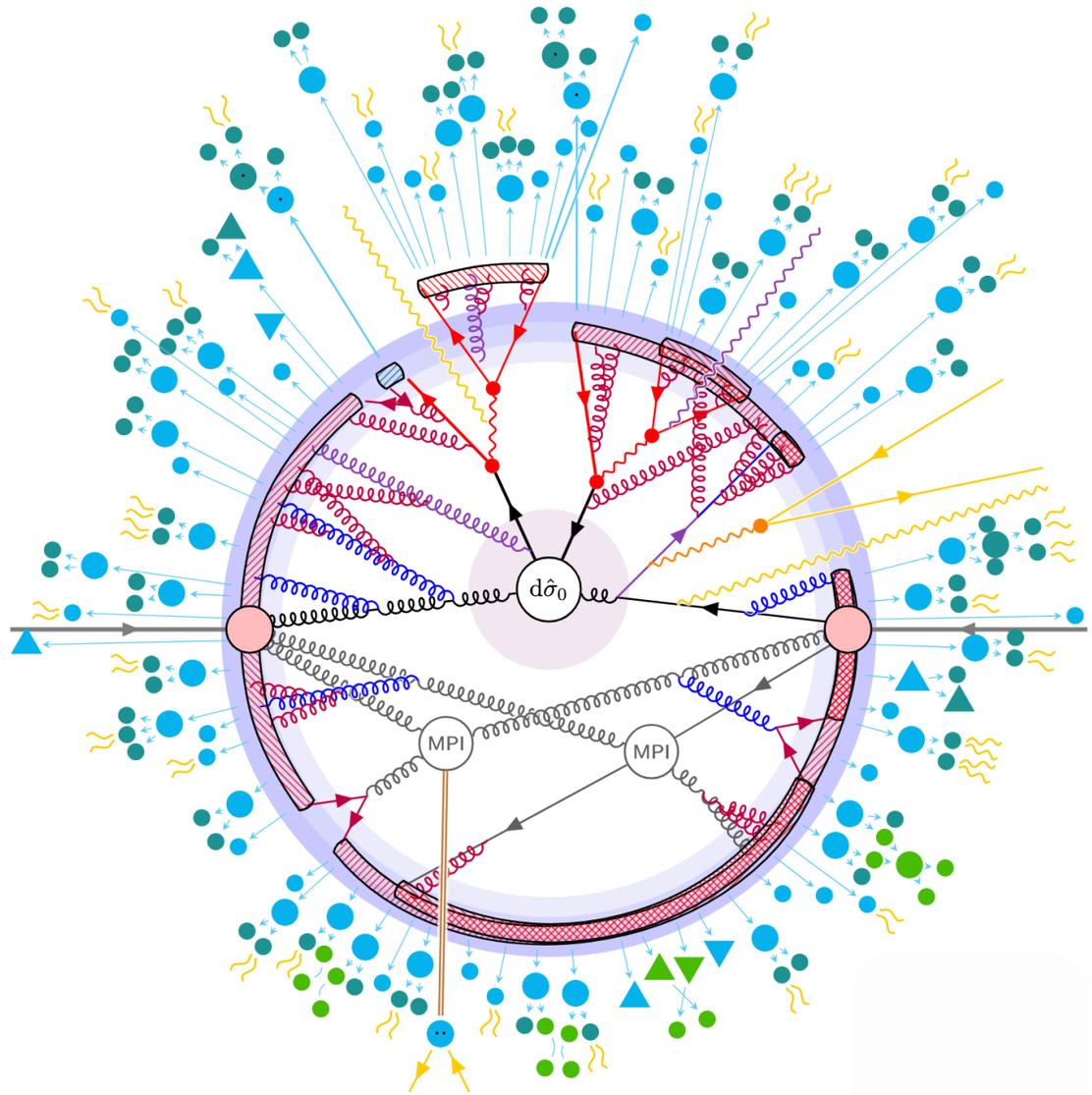
Resummation of large logarithmic contributions
$\alpha_S \log(Q_1/Q_2) \sim 1 \quad \rightarrow$ Parton Showers (PS)

Non-perturbative physics $\alpha_S \gtrsim 1$

Subleading corrections from expansion in the electroweak coupling $\alpha_{EW} \sim \alpha_S^2$

LO NLO NNLO

$$d\hat{\sigma} = d\hat{\sigma}_{(0,0)} + \alpha_S \cdot d\hat{\sigma}_{(1,0)} + \alpha_S^2 \cdot d\hat{\sigma}_{(2,0)} + \dots$$
$$+\alpha_{EW} \cdot d\hat{\sigma}_{(0,1)} + \dots$$



High accuracy for LHC Phenomenology: this talk

Matching/Merging: combine the two predictions

$$d\hat{\sigma} = \underset{\text{LO}}{d\hat{\sigma}_{(0,0)}} + \underset{\text{NLO}}{\alpha_S \cdot d\hat{\sigma}_{(1,0)}} + \underset{\text{NNLO}}{\alpha_S^2 \cdot d\hat{\sigma}_{(2,0)}} + \ldots + \alpha_{EW} \cdot d\hat{\sigma}_{(0,1)} + \ldots$$

Fixed-order (FO) predictions, based on perturbation theory $\alpha_S \ll 1$

Resummation of large logarithmic contributions $\alpha_S \log(Q_1/Q_2) \sim 1 \quad \rightarrow$ Parton Showers (PS)

NNLO$_{QCD}$+PS accuracy

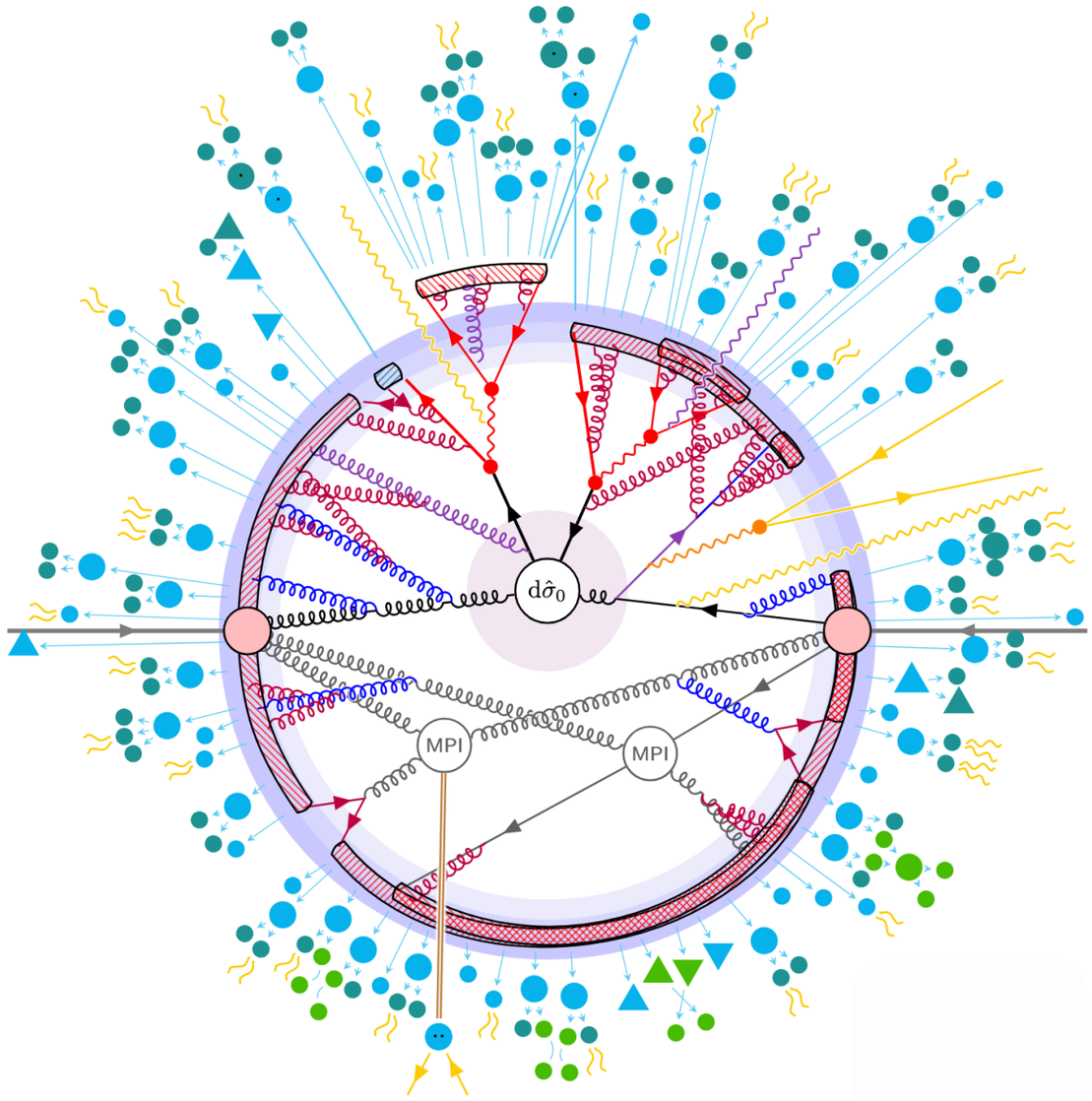
Match NNLO predictions for colour-singlet processes using POWHEG + MiNNLO$_{PS}$: 2γ, W^+W^-, ZZ, and $W^\pm Z$.

Non-perturbative physics $\alpha_S \gtrsim 1$

Subleading corrections from expansion in the electroweak coupling $\alpha_{EW} \sim \alpha_S^2$

MoCaNLO NLO corrections to multi-leg processes

Full off-shell effects at NLO for processes with intricate resonance structure: $t\bar{t}Z$, semi-leptonic vector-boson scattering (VBS) and tri-boson.



NNLO$_{QCD}$+PS

$Z\gamma$	Lombardi, Wiesemann, Zanderighi [arXiv:2010.10478, arXiv:2108.11315]
W^+W^-	Lombardi, Wiesemann, Zanderighi [arXiv:2103.12077]
ZZ	Buonocore, Koole, Lombardi, Rottoli, Wiesemann, Zanderighi [arXiv:2108.05337]
$W^\pm Z$	Lindert, Lombardi, Wiesemann, Zanderighi, Zanoli [arXiv:2208.12660]

NNLO$_{QCD}$+PS

Match NNLO predictions for colour-singlet processes using POWHEG + MiNNLO$_{PS}$: $Z\gamma$, W^+W^-, ZZ, and $W^\pm Z$.

Matching/Merging: combine the two predictions

- The accuracy of predictions based on perturbation theory depends on how many orders in α_S are computed

$$d\hat{\sigma} = \underbrace{d\hat{\sigma}_{(0,0)}}_{\text{LO}} + \alpha_S \cdot \underbrace{d\hat{\sigma}_{(1,0)}}_{\text{NLO}} + \alpha_S^2 \cdot \underbrace{d\hat{\sigma}_{(2,0)}}_{\text{NNLO}} + \dots$$

Fixed-Order (FO) prediction

- The accuracy of a Parton shower (PS) is named after the class of logarithmic contributions it resums

$$\int d\hat{\sigma} \cdot \theta(O < e^{-L}) = \exp\{\underbrace{L\, g_1(\alpha_S L)}_{\text{LL}} + \underbrace{g_2(\alpha_S L)}_{\text{NLL}} + \underbrace{\alpha_S\, g_3(\alpha_S L)}_{\text{NNLL}} + \dots\}$$

Resummed prediction

POWHEG combines calculations up to NLO to PS (general) + **MiNNLO$_{PS}$** combines calculations up to NNLO to PS (only for some processes)

NNLO$_{QCD}$+PS

$Z\gamma$	Lombardi, Wiesemann, Zanderighi [arXiv:2010.10478, arXiv:2108.11315]
W^+W^-	Lombardi, Wiesemann, Zanderighi [arXiv:2103.12077]
ZZ	Buonocore, Koole, Lombardi, Rottoli, Wiesemann, Zanderighi [arXiv:2108.05337]
$W^\pm Z$	Lindert, Lombardi, Wiesemann, Zanderighi, Zanoli [arXiv:2208.12660]

NNLO$_{QCD}$+PS

Match NNLO predictions for colour-singlet processes using POWHEG + MiNNLO$_{PS}$: $Z\gamma$, W^+W^-, ZZ, and $W^\pm Z$.

Matching/Merging: combine the two predictions

- The accuracy of predictions based on perturbation theory depends on how many orders in α_S are computed

$$d\hat{\sigma} = \underbrace{d\hat{\sigma}_{(0,0)}}_{\text{LO}} + \underbrace{\alpha_S \cdot d\hat{\sigma}_{(1,0)}}_{\text{NLO}} + \underbrace{\alpha_S^2 \cdot d\hat{\sigma}_{(2,0)}}_{\text{NNLO}} + \dots$$

Fixed-Order (FO) prediction

- The accuracy of a Parton shower (PS) is named after the class of logarithmic contributions it resums

$$\int d\hat{\sigma} \cdot \theta(O < e^{-L}) = \exp\{\underbrace{L\, g_1(\alpha_S L)}_{\text{LL}} + \underbrace{g_2(\alpha_S L)}_{\text{NLL}} + \underbrace{\alpha_S\, g_3(\alpha_S L)}_{\text{NNLL}} + \dots\}$$

Resummed prediction

POWHEG combines calculations up to NLO to PS (general) + **MiNNLO$_{PS}$** combines calculations up to NNLO to PS (only for some processes)

NNLO$_{QCD}$+PS

$Z\gamma$	Lombardi, Wiesemann, Zanderighi [arXiv:2010.10478, arXiv:2108.11315]
W^+W^-	Lombardi, Wiesemann, Zanderighi [arXiv:2103.12077]
ZZ	Buonocore, Koole, Lombardi, Rottoli, Wiesemann, Zanderighi [arXiv:2108.05337]
$W^\pm Z$	Lindert, Lombardi, Wiesemann, Zanderighi, Zanoli [arXiv:2208.12660]

NNLO$_{QCD}$+PS

Match NNLO predictions for colour-singlet processes using POWHEG + MiNNLO$_{PS}$: $Z\gamma$, W^+W^-, ZZ, and $W^\pm Z$.

Matching/Merging: combine the two predictions

- The accuracy of predictions based on perturbation theory depends on how many orders in α_S are computed

$$d\hat{\sigma} = \underbrace{d\hat{\sigma}_{(0,0)}}_{\text{LO}} + \underbrace{\alpha_S \cdot d\hat{\sigma}_{(1,0)}}_{\text{NLO}} + \underbrace{\alpha_S^2 \cdot d\hat{\sigma}_{(2,0)}}_{\text{NNLO}} + \dots$$

Fixed-Order (FO) prediction

- The accuracy of a Parton shower (PS) is named after the class of logarithmic contributions it resums

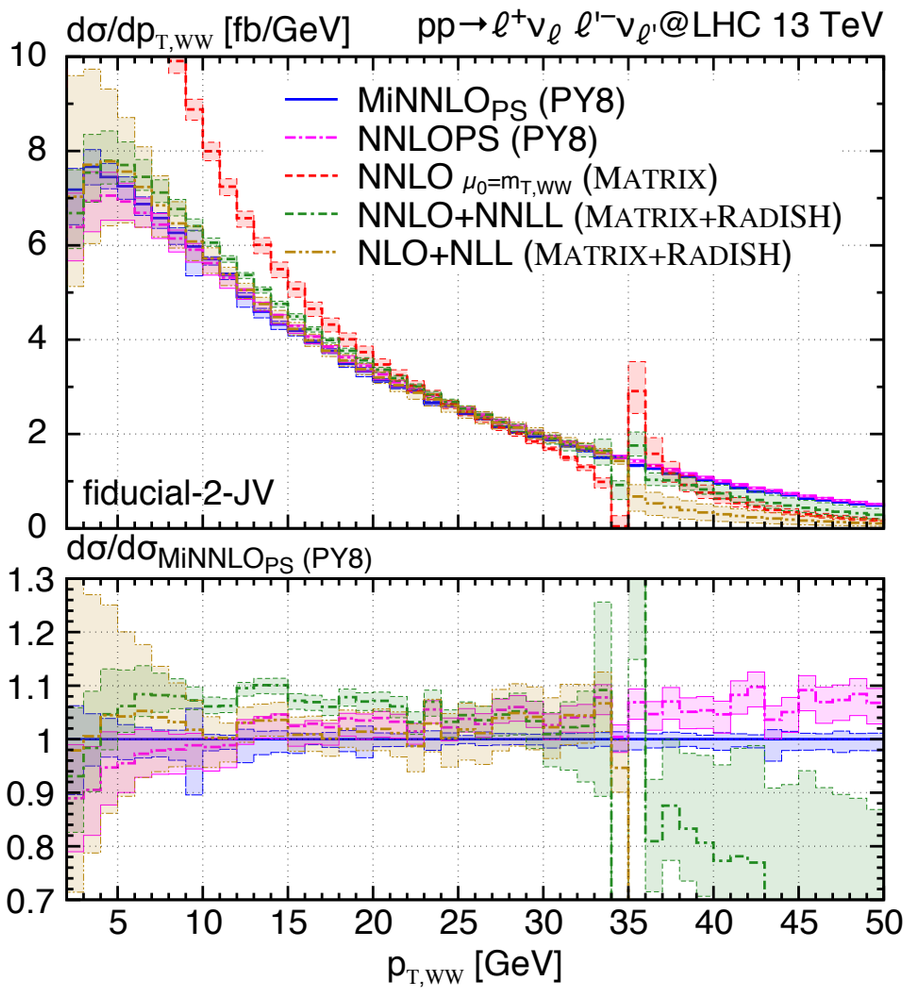
$$\int d\hat{\sigma} \cdot \theta(O < e^{-L}) = \exp\{\underbrace{L\, g_1(\alpha_S L)}_{\text{LL}} + \underbrace{g_2(\alpha_S L)}_{\text{NLL}} + \underbrace{\alpha_S\, g_3(\alpha_S L)}_{\text{NNLL}} + \dots\}$$

Resummed prediction

POWHEG combines calculations up to NLO to PS (general) + **MiNNLO$_{PS}$** combines calculations up to NNLO to PS (only for some processes)

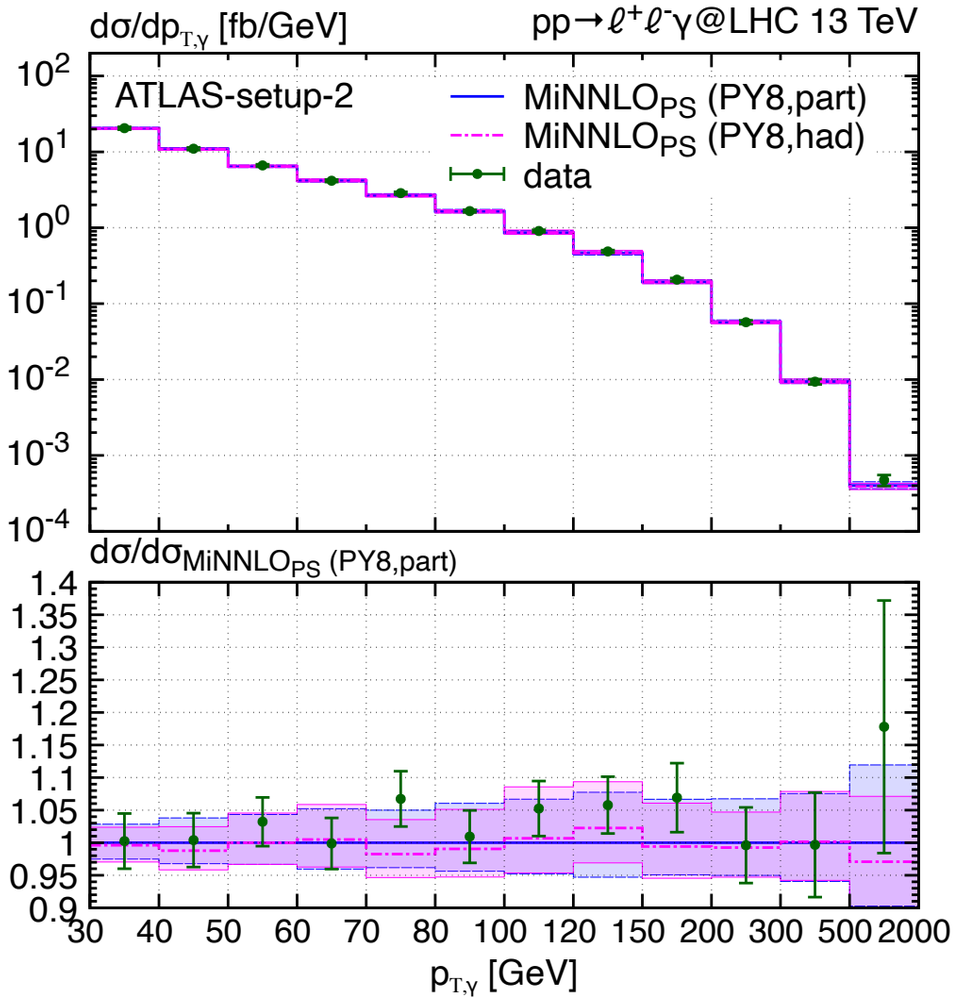
NNLO+PS for di-bosons (I)

W+W- Lombardi, Wiesemann, Zanderighi [arXiv:2103.12077]



Fiducial phase-space with jet-veto cut at 35 GeV: NNLO+PS results provide physical description both below and above jet-veto threshold

Zγ Lombardi, Wiesemann, Zanderighi [arXiv:2010.10478]

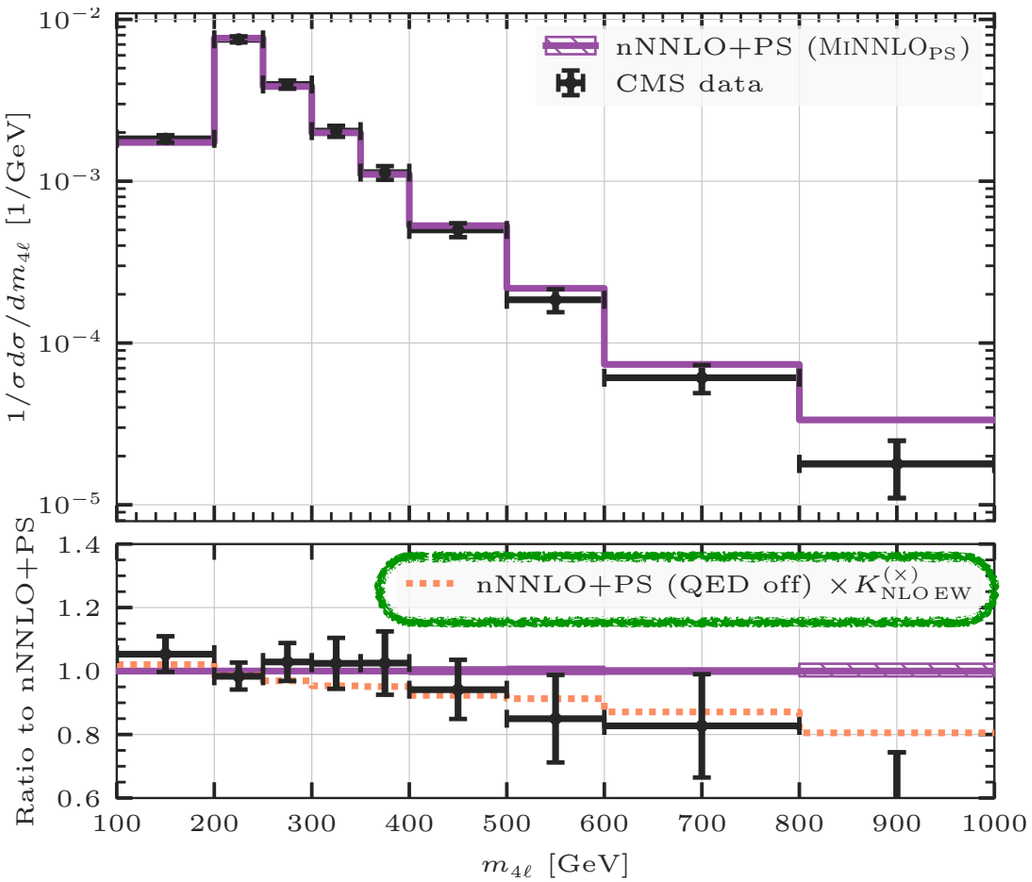


First MiNNLOps extension to general colour-singlet processes compared to ATLAS data!

NNLO+PS for di-bosons (2)

ZZ

Buonocore, Koole, Lombardi, Rottoli, Wiesemann, Zanderighi [arXiv:2108.05337]

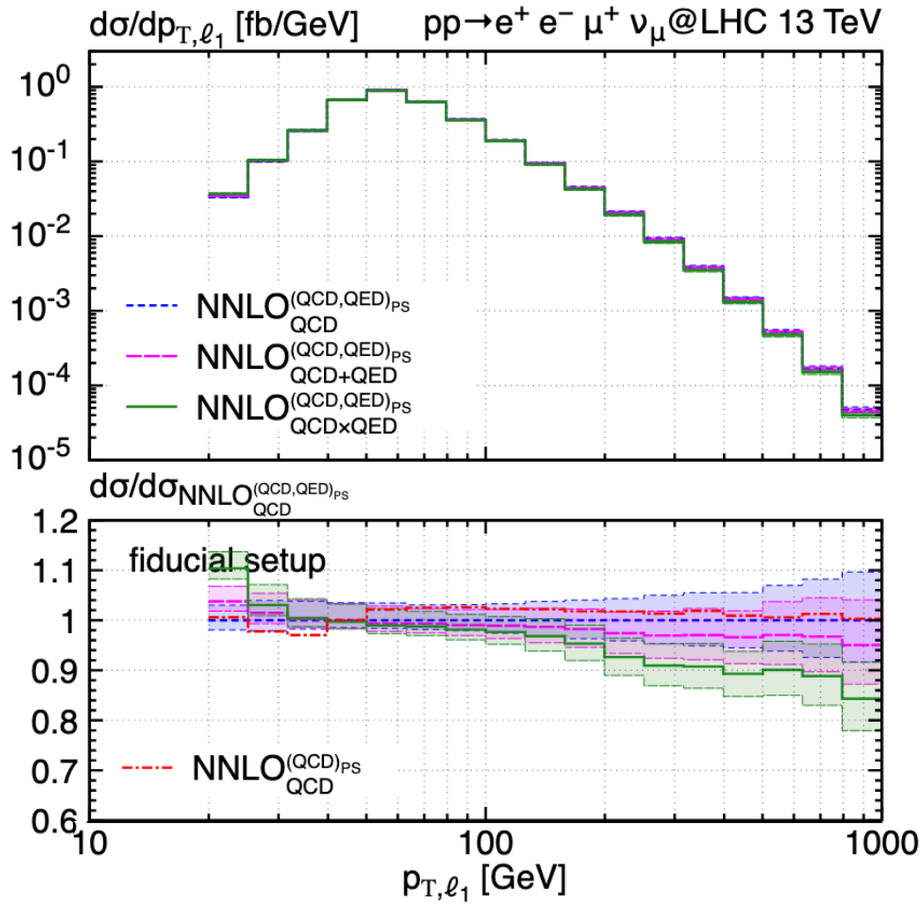


nNNLO + PS generator: combination of

- qq-induced channels at NNLO+PS with MiNNLO$_{PS}$
- gg-induced channels at NLO+PS with POWHEG

W±Z

Lindert, Lombardi, Wiesemann, Zanderighi, Zanoli [arXiv:2208.12660]



Inclusion of **EW corrections** in NNLO+PS generator with two independent generators:

- NNLO$_{QCD}$ + PS with MiNNLO$_{PS}$
- NLO$_{EW}$ + PS with POWHEG

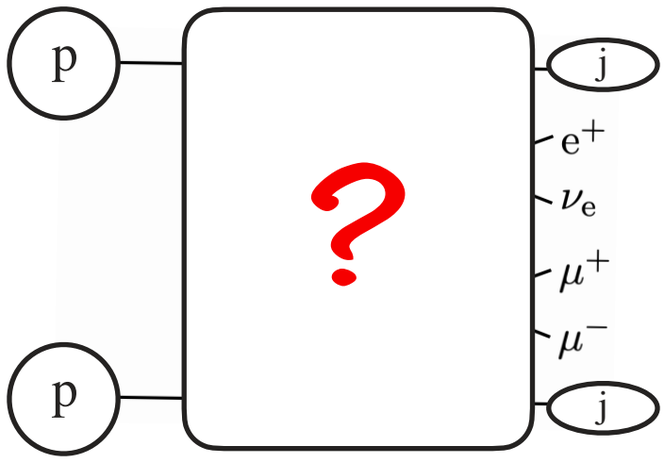
Additive scheme NNLO$_{QCD}$ + NLO$_{EW}$ - LO

Multiplicative scheme NNLO$_{QCD}$ x (NLO$_{EW}$ / LO)

Off-shell and EW effects for multi-leg processes

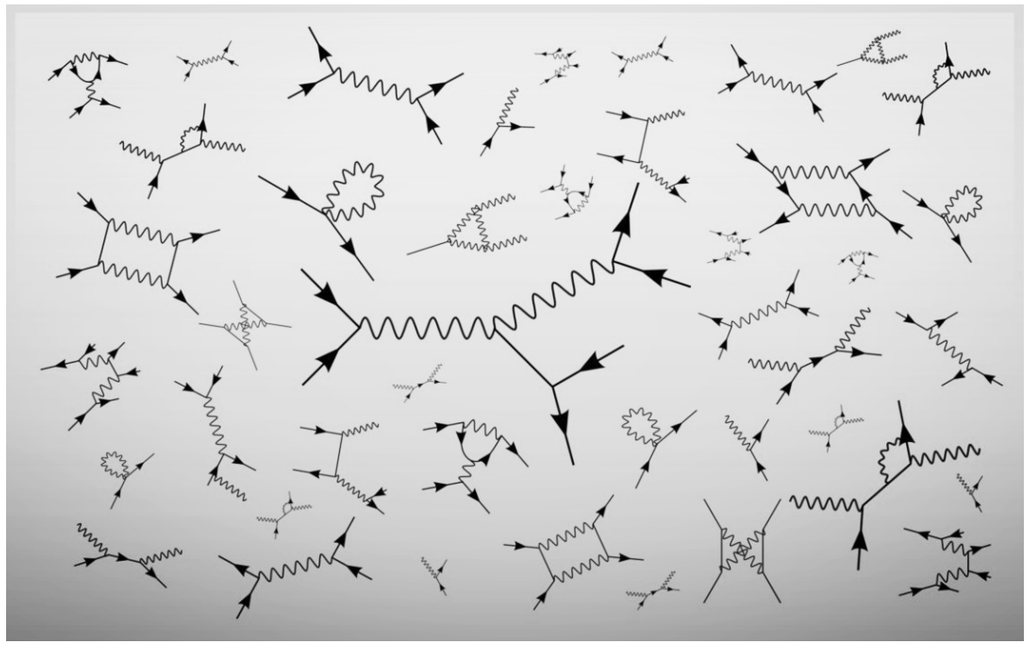
Associated top-pair production: $t\bar{t}Z$	Denner, Lombardi, Pelliccioli [arXiv:2306.13535]
Semi-leptonic VBS at LO	Denner, Lombardi, Schwan [arXiv:2406.12301]
Tri-boson production: $WZ + jj$	Denner, Lombardi, Lopez, Pelliccioli [arXiv:2407.21558]
Doubly-Polarised WZ production	Denner, Franken, Haitz, Lombardi, Pelliccioli [arXiv:2510.26462]

Realistic event description must account for experimental definition of signal: only access to final states



MoCaNLO NLO corrections to multi-leg processes

Full off-shell effects at NLO for processes with intricate resonance structure: $t\bar{t}Z$, semi-leptonic vector-boson scattering (VBS) and tri-boson.



Typically small impact at the integrated level, but crucial for precision physics at the differential level:

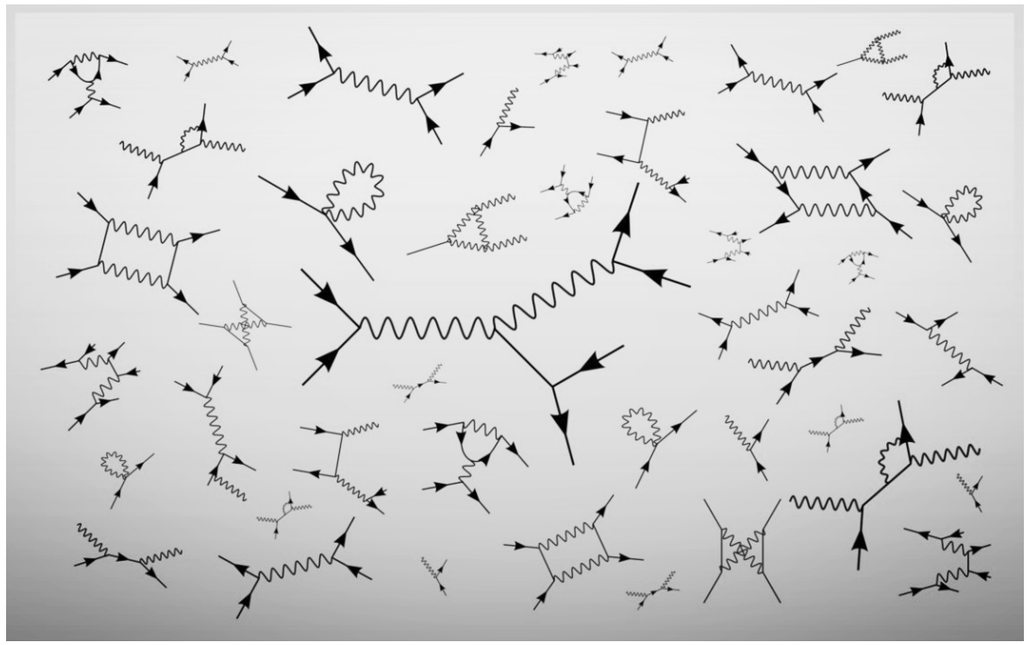
- EW corrections have a prominent role in tails of distributions;
- QED radiation significantly distorts shape of observables;
- Off-shell effects crucial in high p_T regions or close to kinematical boundaries.

Off-shell and EW effects for multi-leg processes

Associated top-pair production: $t\bar{t}Z$	Denner, Lombardi, Pelliccioli [arXiv:2306.13535]
Semi-leptonic VBS at LO	Denner, Lombardi, Schwan [arXiv:2406.12301]
Tri-boson production: $WZ + jj$	Denner, Lombardi, Lopez, Pelliccioli [arXiv:2407.21558]
Doubly-Polarised WZ production	Denner, Franken, Haitz, Lombardi, Pelliccioli [arXiv:2510.26462]

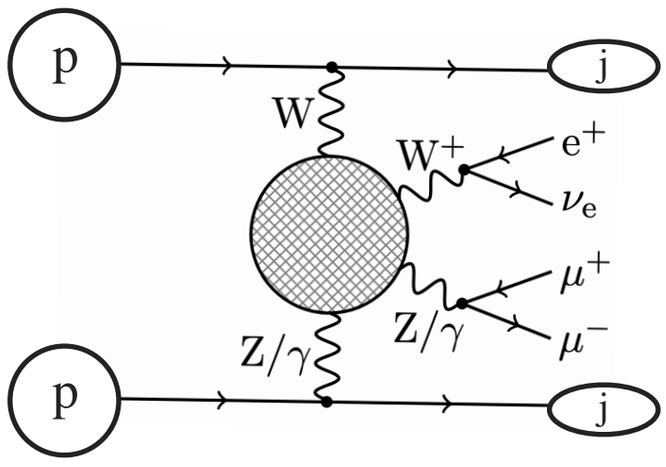
MoCaNLO NLO corrections to multi-leg processes

Full off-shell effects at NLO for processes with intricate resonance structure: $t\bar{t}Z$, semi-leptonic vector-boson scattering (VBS) and tri-boson.



Realistic event description must account for experimental definition of signal: only access to final states

VBS



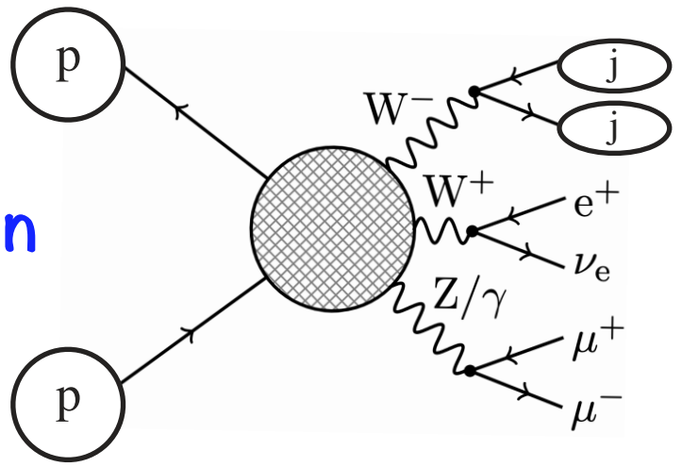
Typically small impact at the integrated level, but crucial for precision physics at the differential level:

- EW corrections have a prominent role in tails of distributions;
- QED radiation significantly distorts shape of observables;
- Off-shell effects crucial in high p_T regions or close to kinematical boundaries.

Off-shell and EW effects for multi-leg processes

Associated top-pair production: $t\bar{t}Z$	Denner, Lombardi, Pelliccioli [arXiv:2306.13535]
Semi-leptonic VBS at LO	Denner, Lombardi, Schwan [arXiv:2406.12301]
Tri-boson production: $WZ+jj$	Denner, Lombardi, Lopez, Pelliccioli [arXiv:2407.21558]
Doubly-Polarised WZ production	Denner, Franken, Haitz, Lombardi, Pelliccioli [arXiv:2510.26462]

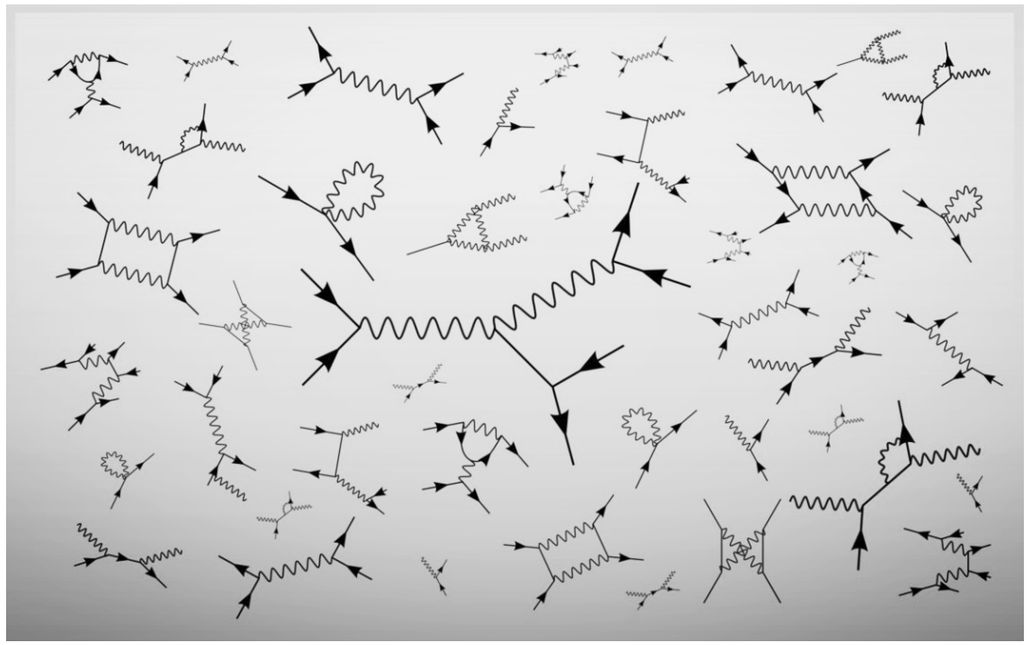
Realistic event description must account for experimental definition of signal: only access to final states



Tri-boson

MoCaNLO NLO corrections to multi-leg processes

Full off-shell effects at NLO for processes with intricate resonance structure: $t\bar{t}Z$, semi-leptonic vector-boson scattering (VBS) and tri-boson.



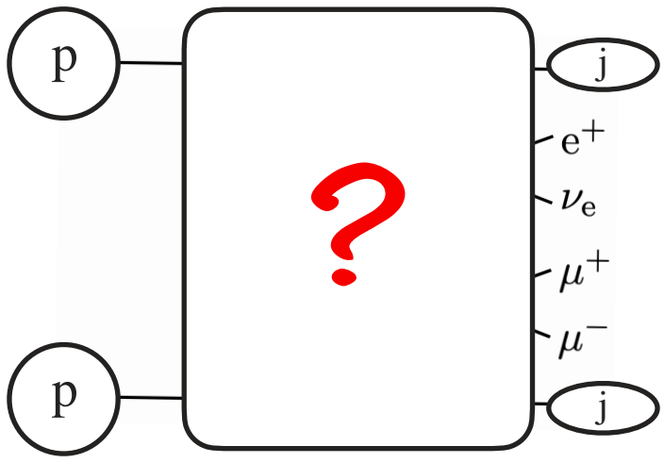
Typically small impact at the integrated level, but crucial for precision physics at the differential level:

- EW corrections have a prominent role in tails of distributions;
- QED radiation significantly distorts shape of observables;
- Off-shell effects crucial in high p_{T} regions or close to kinematical boundaries.

Off-shell and EW effects for multi-leg processes

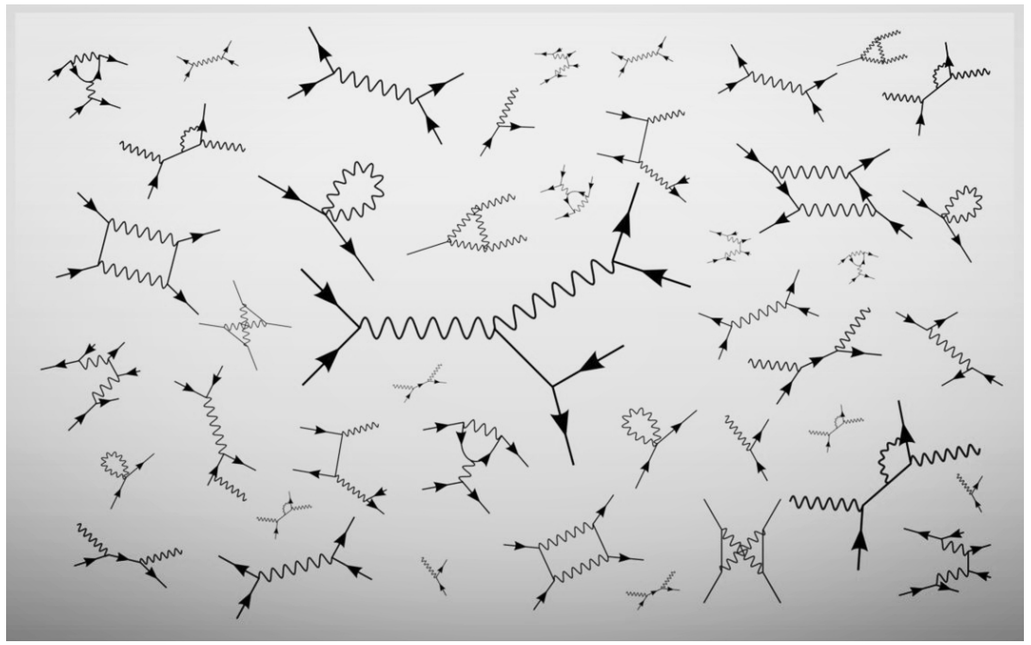
Associated top-pair production: $t\bar{t}Z$	Denner, Lombardi, Pelliccioli [arXiv:2306.13535]
Semi-leptonic VBS at LO	Denner, Lombardi, Schwan [arXiv:2406.12301]
Tri-boson production: $WZ+jj$	Denner, Lombardi, Lopez, Pelliccioli [arXiv:2407.21558]
Doubly-Polarised WZ production	Denner, Franken, Haitz, Lombardi, Pelliccioli [arXiv:2510.26462]

Realistic event description must account for experimental definition of signal: only access to final states



MoCaNLO NLO corrections to multi-leg processes

Full off-shell effects at NLO for processes with intricate resonance structure: $t\bar{t}Z$, semi-leptonic vector-boson scattering (VBS) and tri-boson.



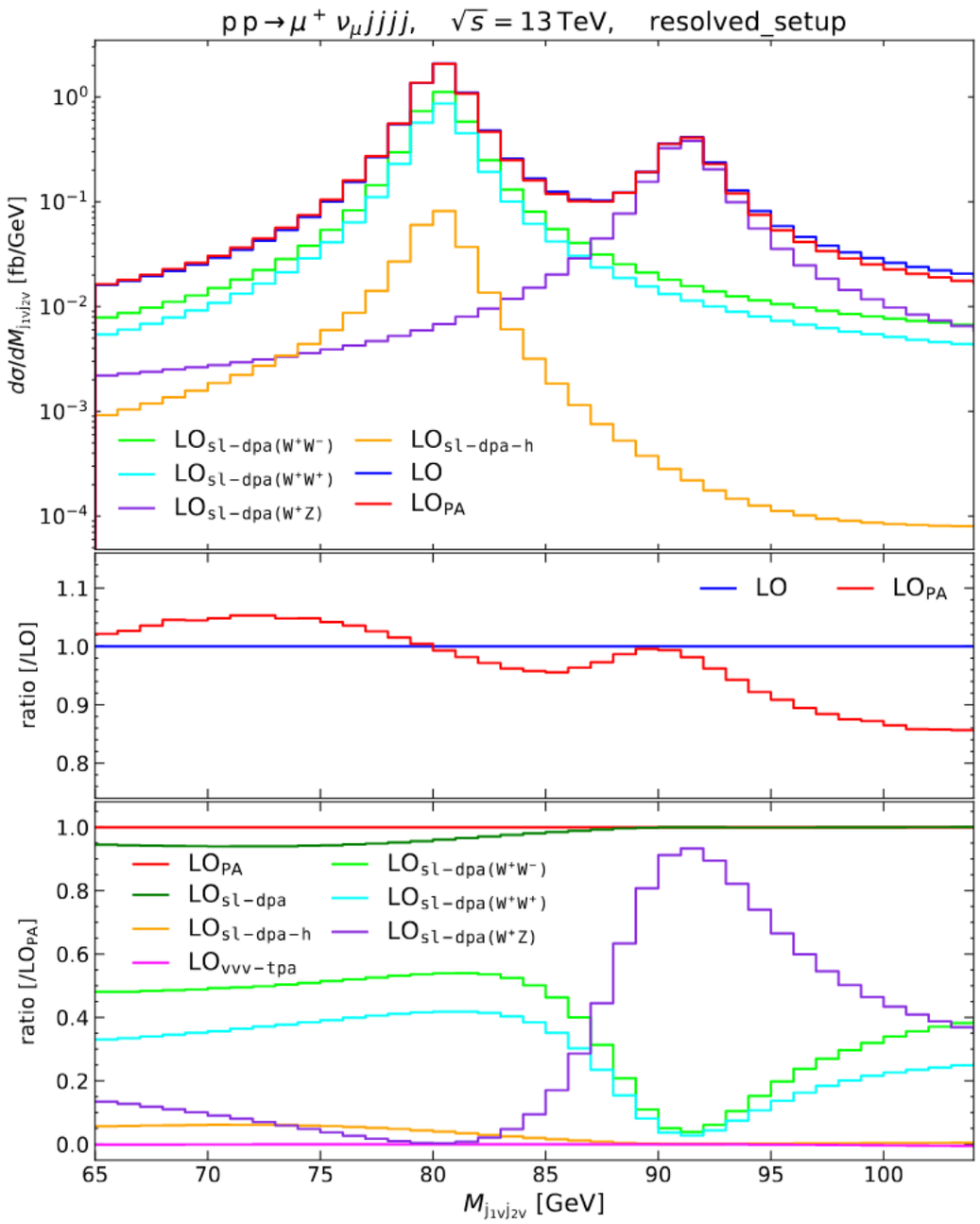
Typically small impact at the integrated level, but crucial for precision physics at the differential level:

- EW corrections have a prominent role in tails of distributions;
- QED radiation significantly distorts shape of observables;
- Off-shell effects crucial in high p_T regions or close to kinematical boundaries.

Off-shell effects in semi-leptonic VBS

Semi-leptonic VBS at LO

Denner, Lombardi, Schwan [arXiv:2406.12301]



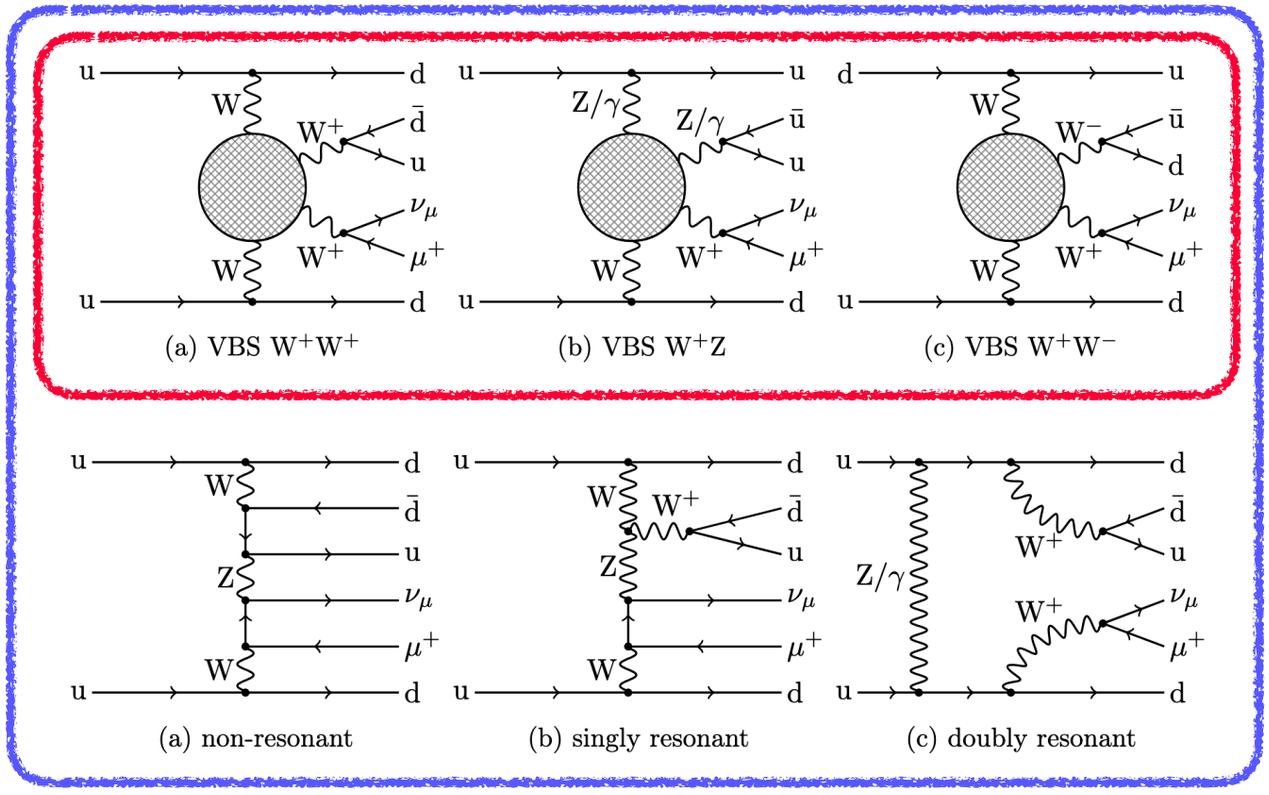
MoCaNLO NLO corrections to multi-leg processes

Full off-shell effects at NLO for processes with intricate resonance structure: ttZ, semi-leptonic vector-boson scattering (VBS) and tri-boson.

- $pp \to W^+(\ell^+\nu_\ell)W^-(jj)jj$, — $LO_{sl-dpa(W^+W^-)}$
- $pp \to W^+(\ell^+\nu_\ell)W^+(jj)jj$, — $LO_{sl-dpa(W^+W^+)}$
- $pp \to W^+(\ell^+\nu_\ell)Z(jj)jj$, — $LO_{sl-dpa(W^+Z)}$
- $pp \to H(\ell^+\nu_\ell W^-(jj))jj$, — $LO_{sl-dpa-h}$

$=$

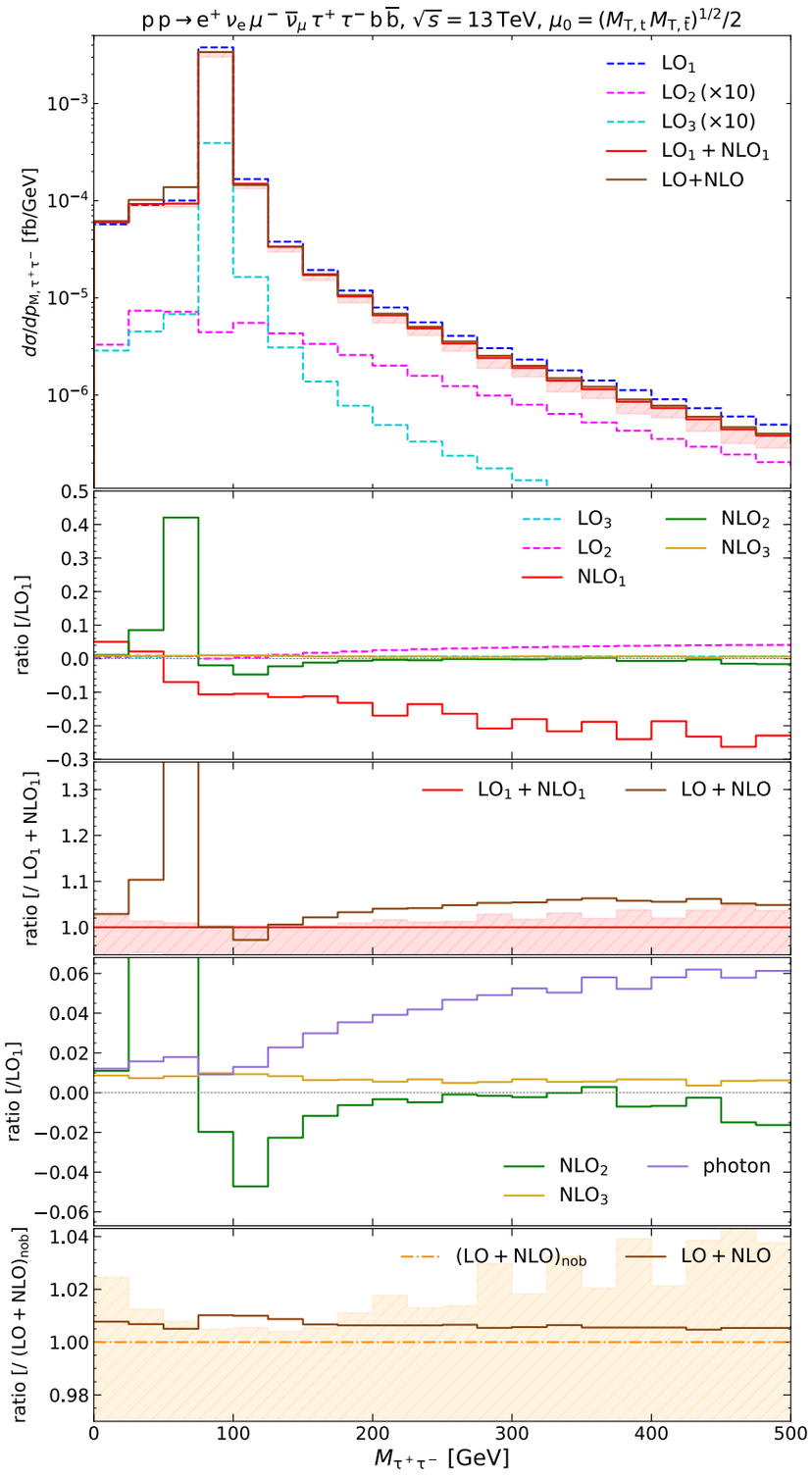
— $LO_{PA} = \mathcal{O}(\alpha^6)$ in DPA vs — $LO = \mathcal{O}(\alpha^6)$ full off-shell



Beyond NLO QCD corrections

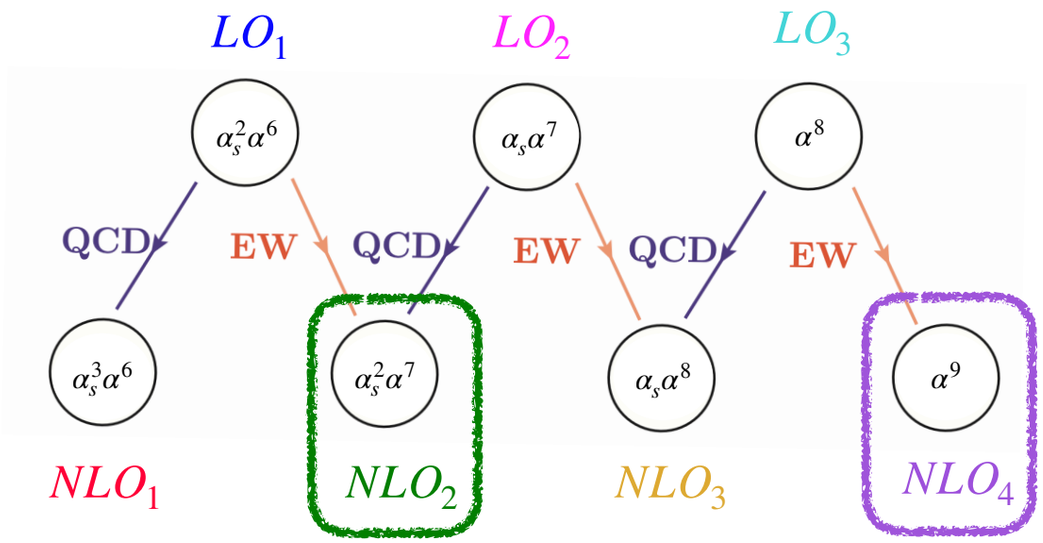
Associated top-pair production: ttZ

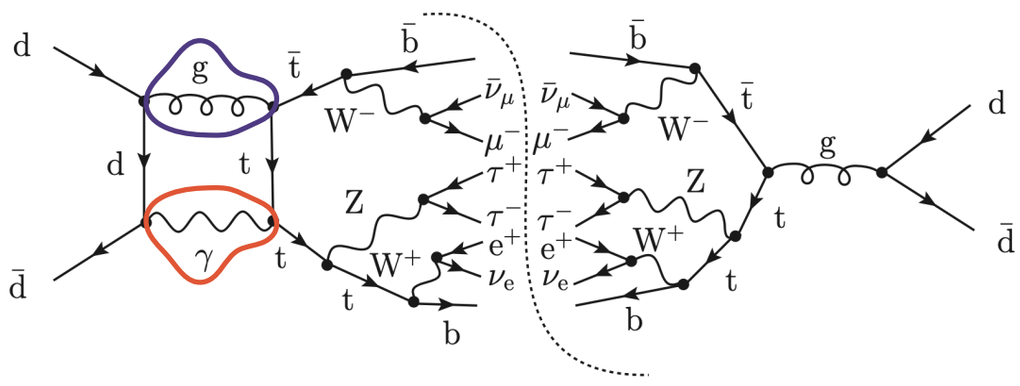
Denner, Lombardi, Pelliccioli [arXiv:2306.13535]



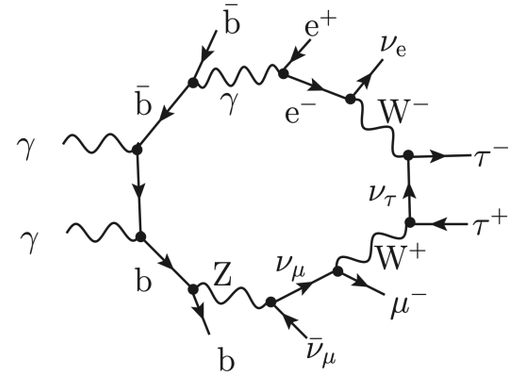
MoCaNLO NLO corrections to multi-leg processes

Full off-shell effects at NLO for processes with intricate resonance structure: ttZ, semi-leptonic vector-boson scattering (VBS) and tri-boson.





QCD correction to LO_2
or
EW correction to LO_1 ?

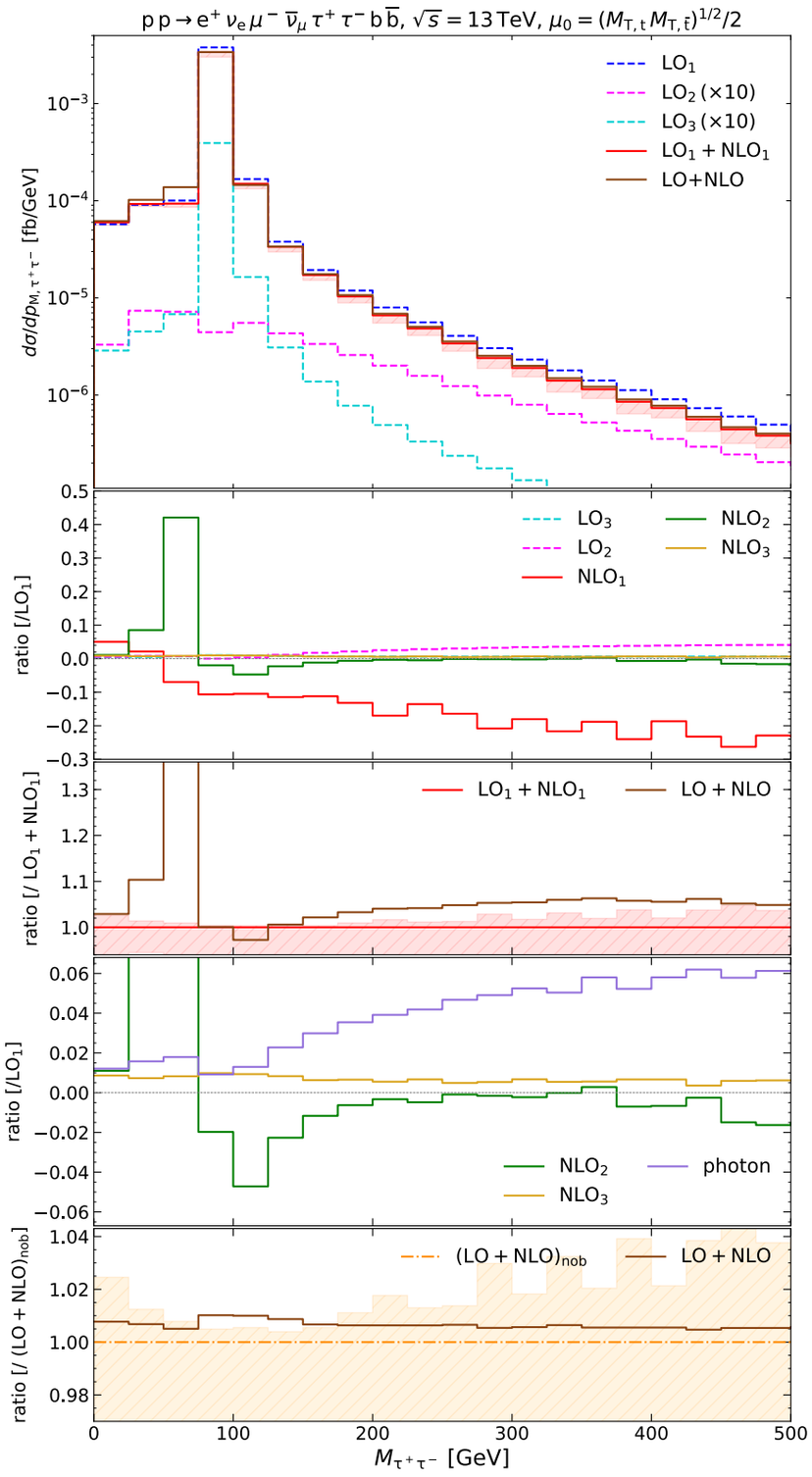


Computationally challenging virtual terms: high number of rank-6 10-point 1-loop functions to be evaluated!

Beyond NLO QCD corrections

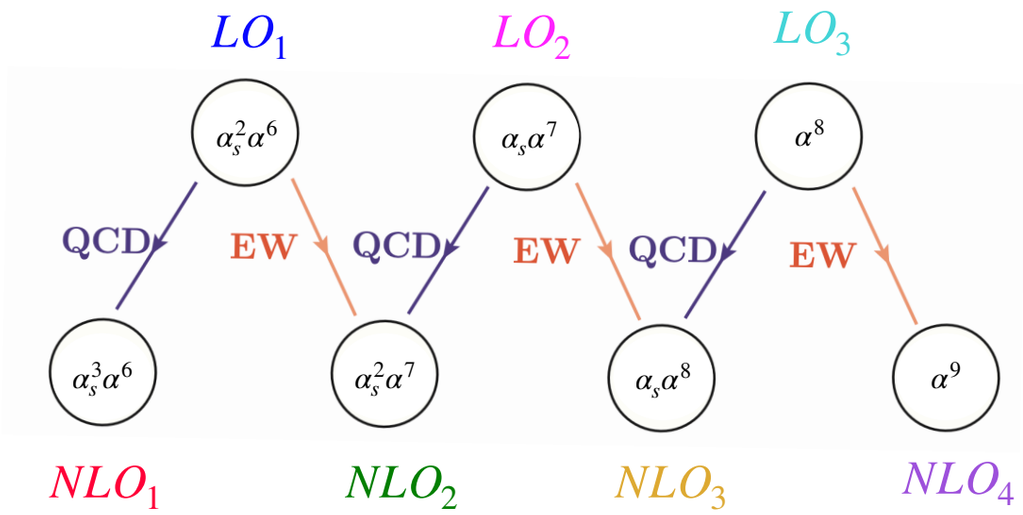
Associated top-pair production: ttZ

Denner, Lombardi, Pelliccioli [arXiv:2306.13535]

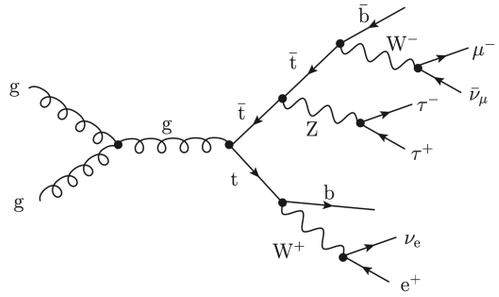


MoCaNLO NLO corrections to multi-leg processes

Full off-shell effects at NLO for processes with intricate resonance structure: ttZ, semi-leptonic vector-boson scattering (VBS) and tri-boson.

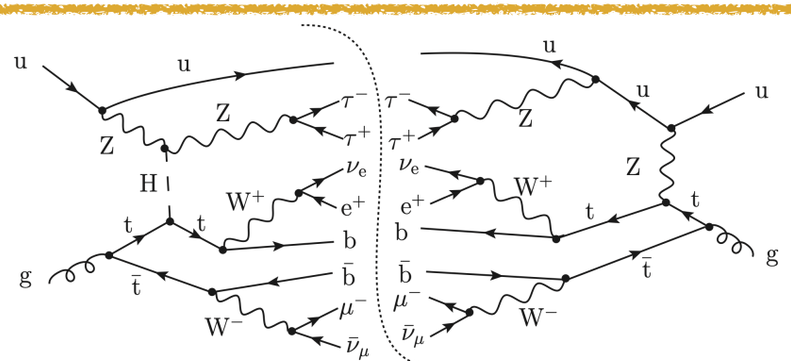


- Negative NLO_1 corrections in the far off-shell region.



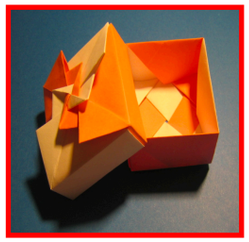
- NLO_2 corrections are the dominant ones around the Z-mass pole (radiative return due to real-photon radiation).

- Flat QCD-like corrections from NLO_3 terms.



Conclusions

- NNLO+PS generators using NLO POWHEG matching and MiNNLO$_{PS}$ method
  - Inclusion of NLO$_{EW}$ corrections at generation level directly starting from simpler processes
  - Matching to PS with new NLL (or higher) logarithmic accuracy

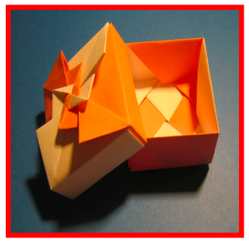


- General treatment of NLO corrections and off-shell effects with MoCaNLO
  - Moving beyond LO for semi-leptonic VBS
  - Using DPA for definition of polarised cross sections at NLO
  - NLO matching using CS-based MC@NLO

MoCaNLO

Conclusions

- NNLO+PS generators using NLO POWHEG matching and MiNNLO$_{PS}$ method
  - Inclusion of NLO$_{EW}$ corrections at generation level directly starting from simpler processes
  - Matching to PS with new NLL (or higher) logarithmic accuracy



- General treatment of NLO corrections and off-shell effects with MoCaNLO
  - Moving beyond LO for semi-leptonic VBS
  - Using DPA for definition of polarised cross sections at NLO
  - NLO matching using CS-based MC@NLO

MoCaNLO

Thank you for your attention