Status of vector-boson pair production at the LHC

Marius Wiesemann

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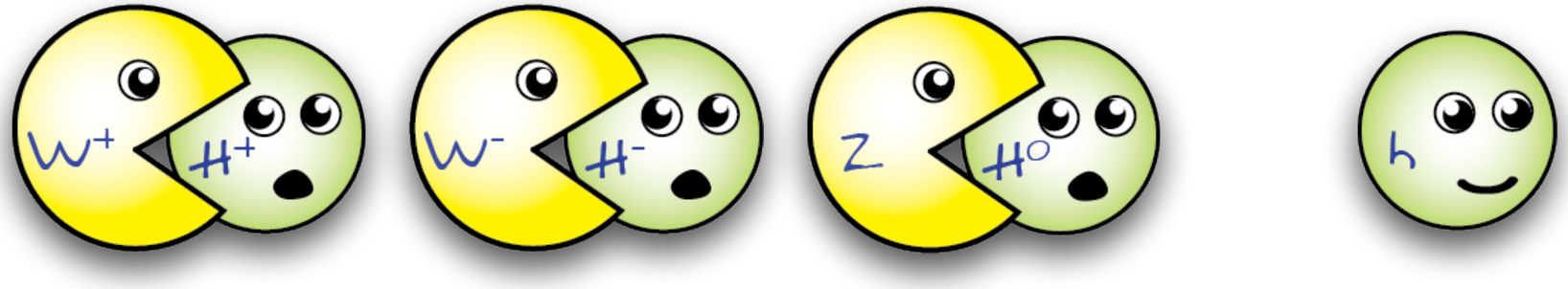
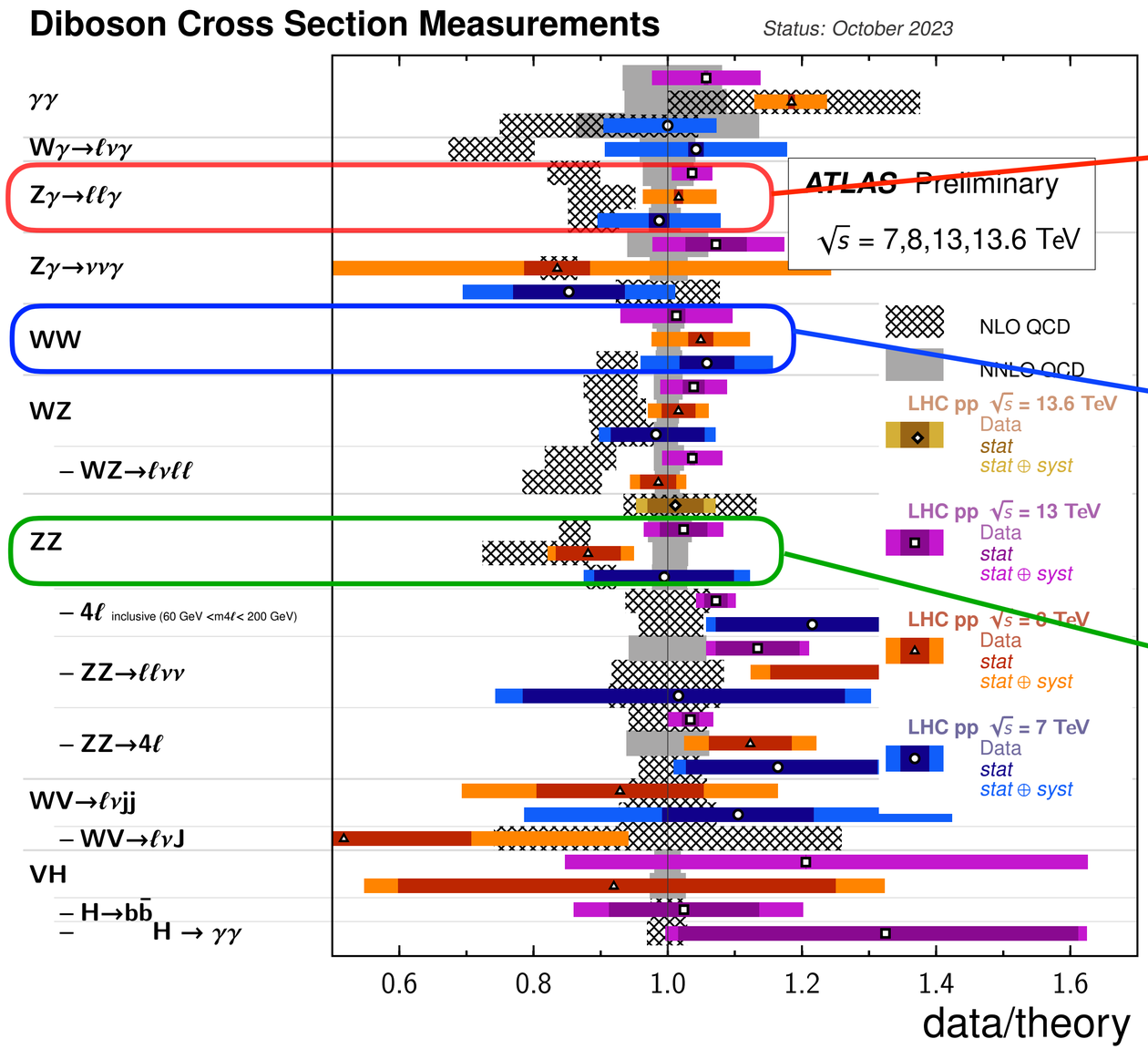
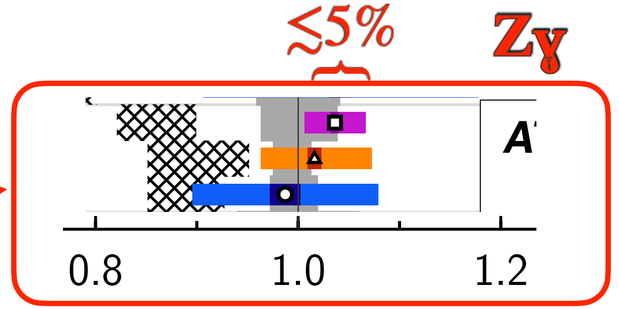


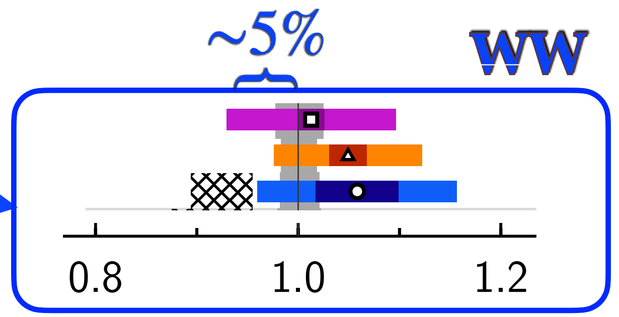
COMETA WG1 meeting

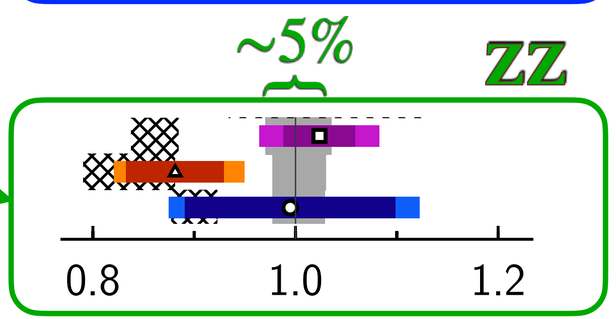
online, January 17, 2024

Diboson precision measurements at the LHC





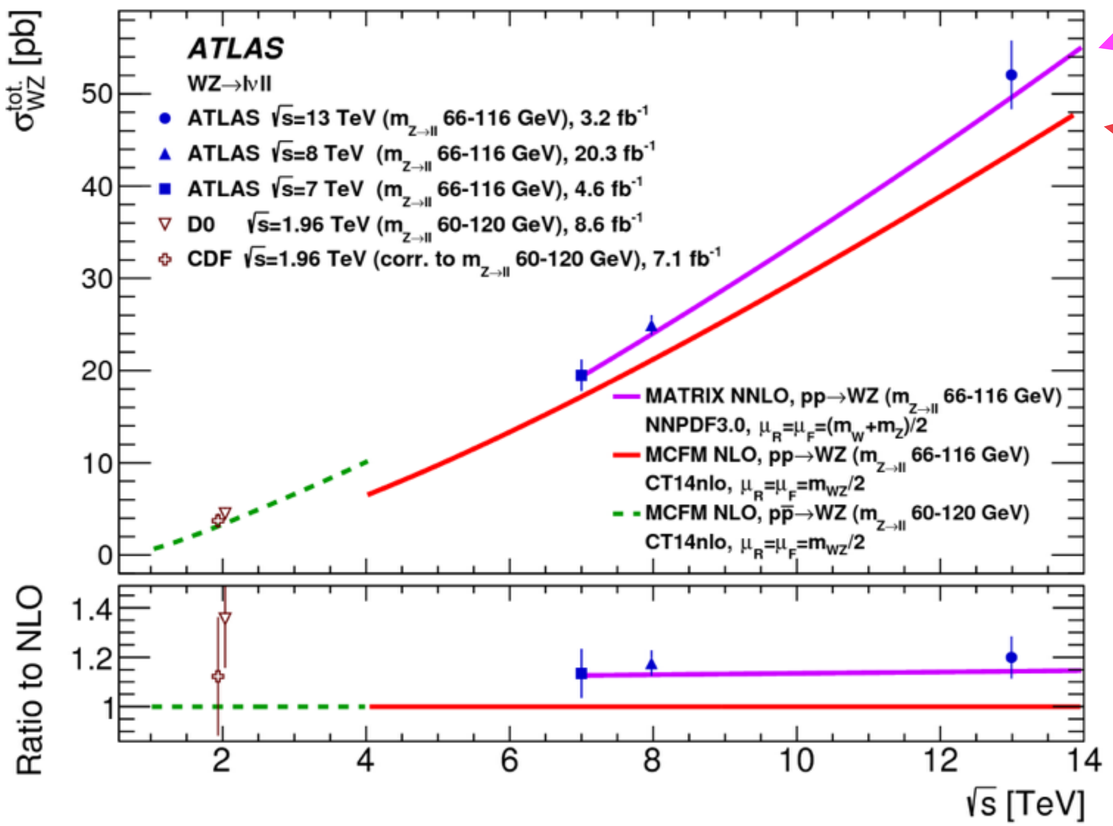




Experiment demands $\mathcal{O}(1\%)$ theoretical precision

Importance of higher-order calculations
(example WZ)

[Grazzini, Kallweit, Rathlev, MW '16]



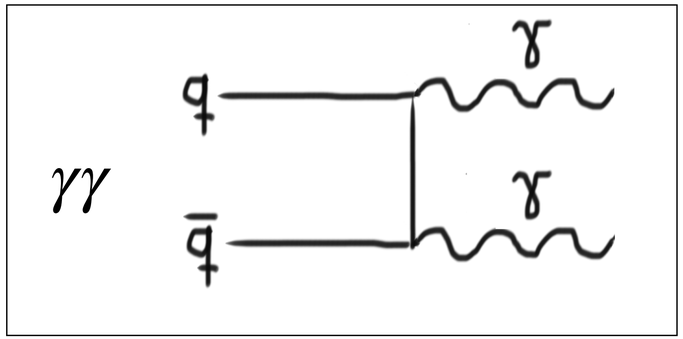
NNLO

NLO

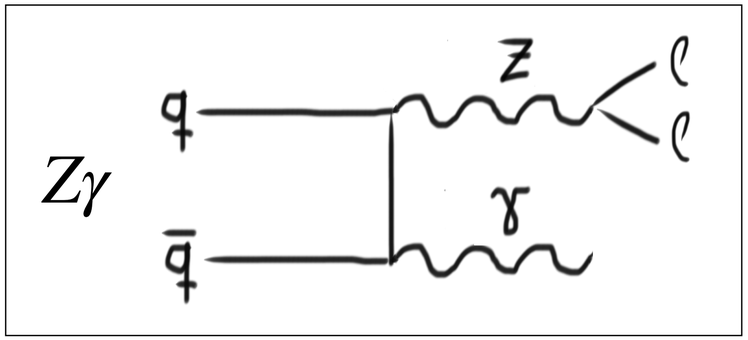
➔ ***NNLO crucial for accurate description of data***

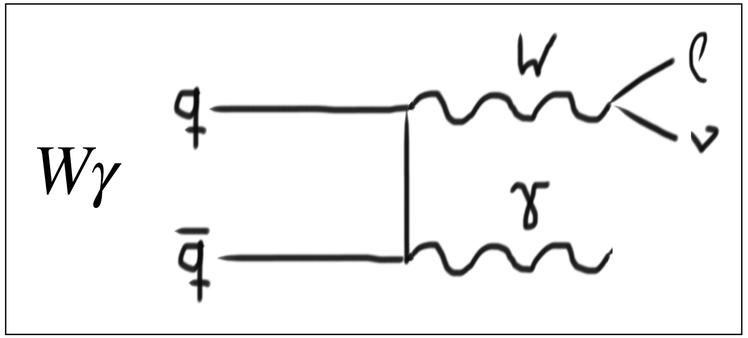
VV production: Which processes?

diphoton

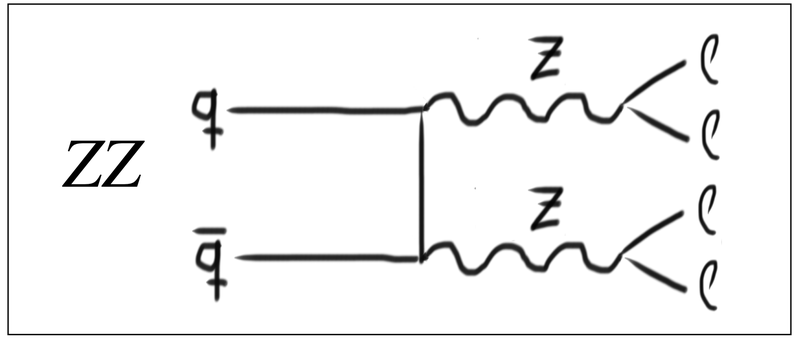


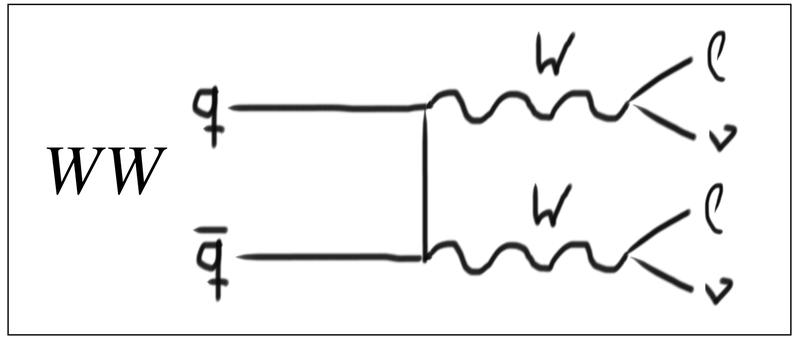
photon + massive vector boson

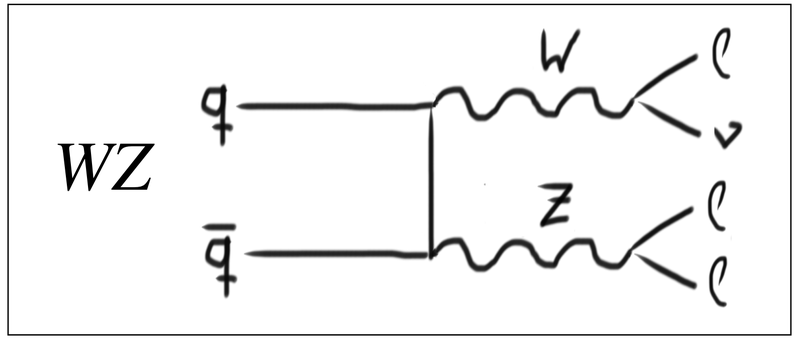




massive vector boson pair







VV production: What is state of the art?

fixed order

- NNLO QCD for $q\bar{q} \to VV$
- NLO EW for $q\bar{q} \to VV$
- NLO QCD for $gg \to VV$ (loop induced)

resummation

- N^{3}LL in diboson p_T
- NNLL in jet p_T / jet veto
- NNLL in double resummation of diboson p_T & jet p_T / jet veto

shower matching

- NNLO+PS in QCD for $q\bar{q} \to VV$
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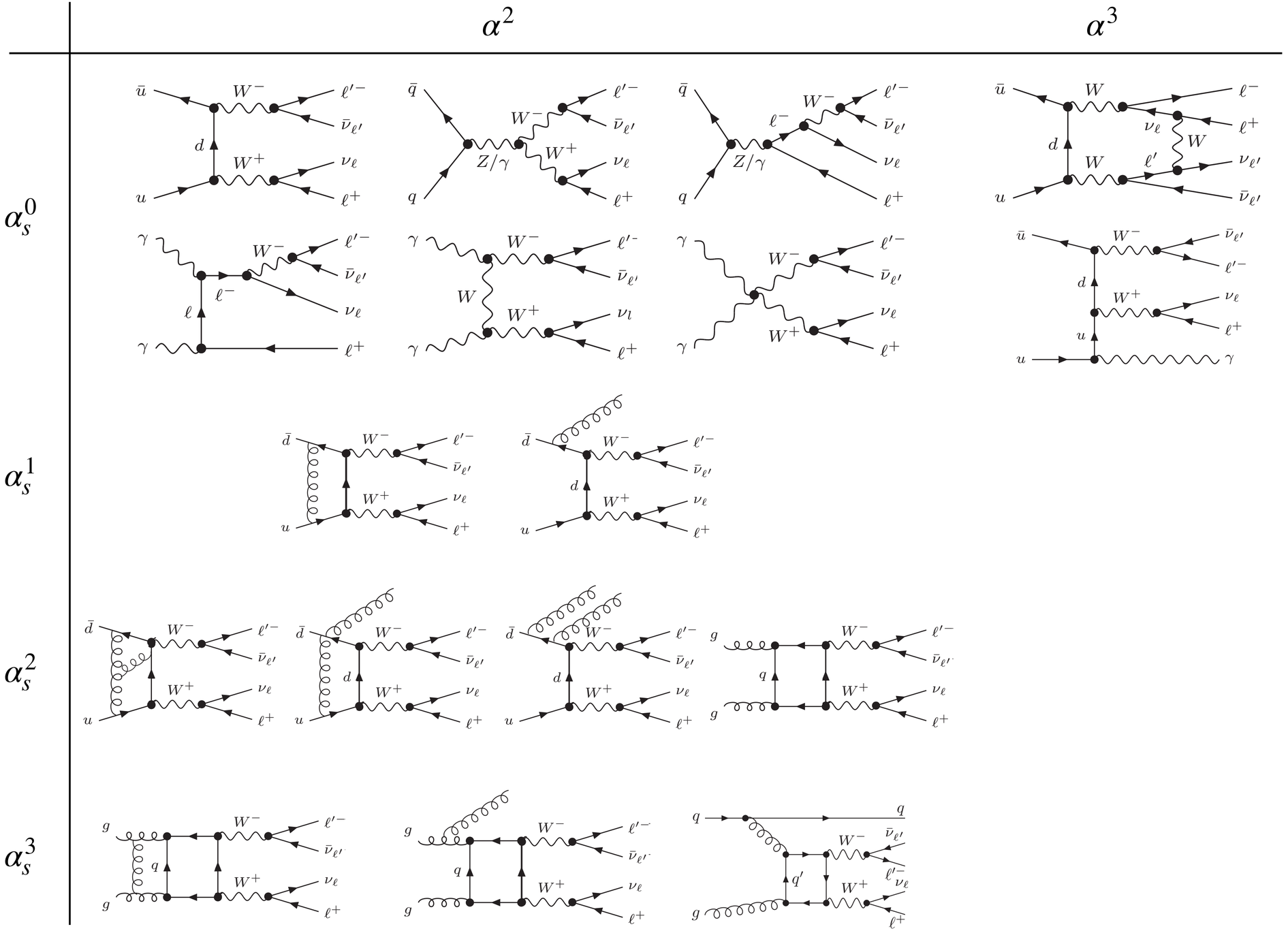
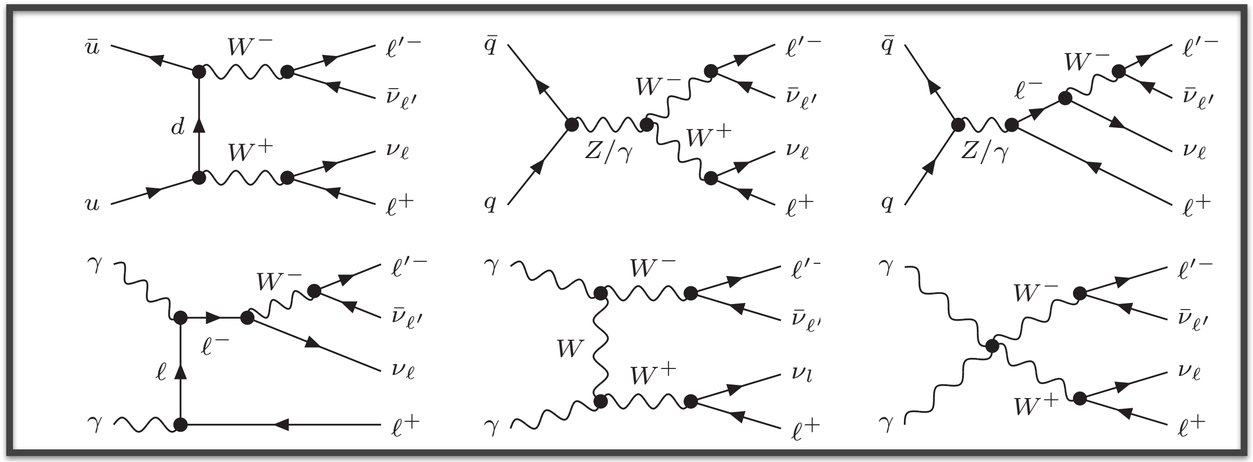
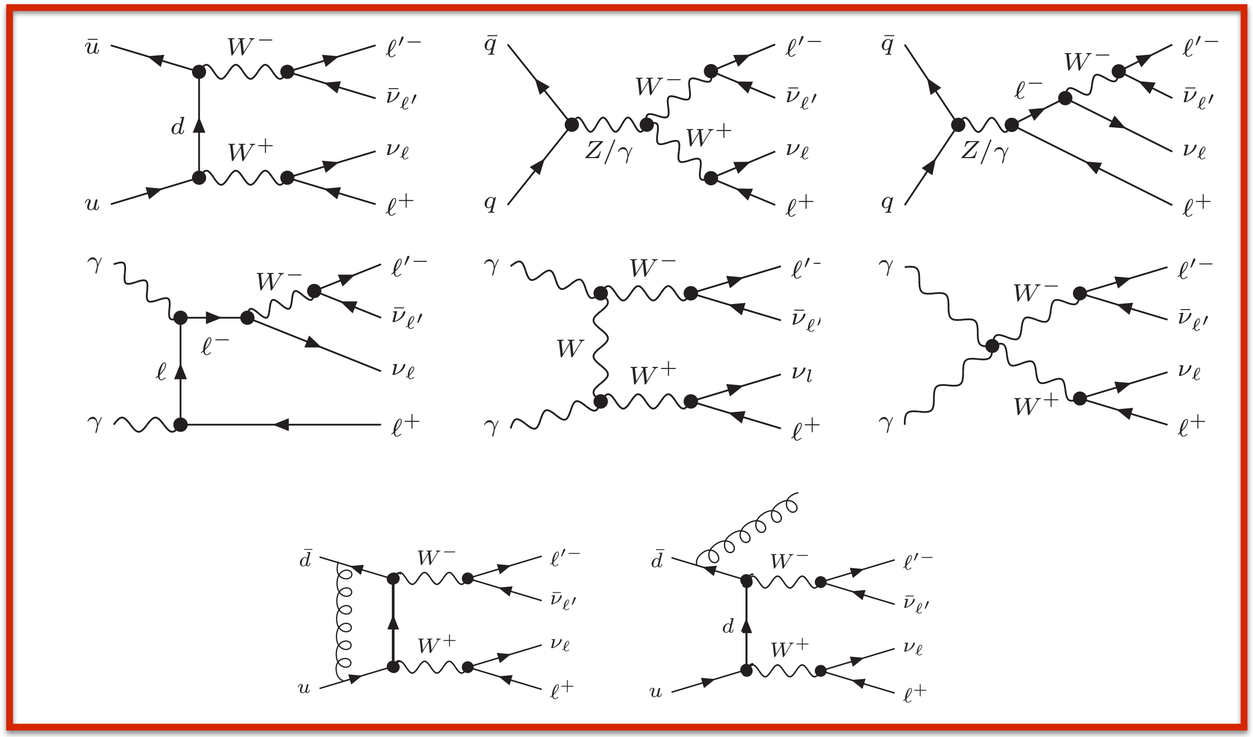
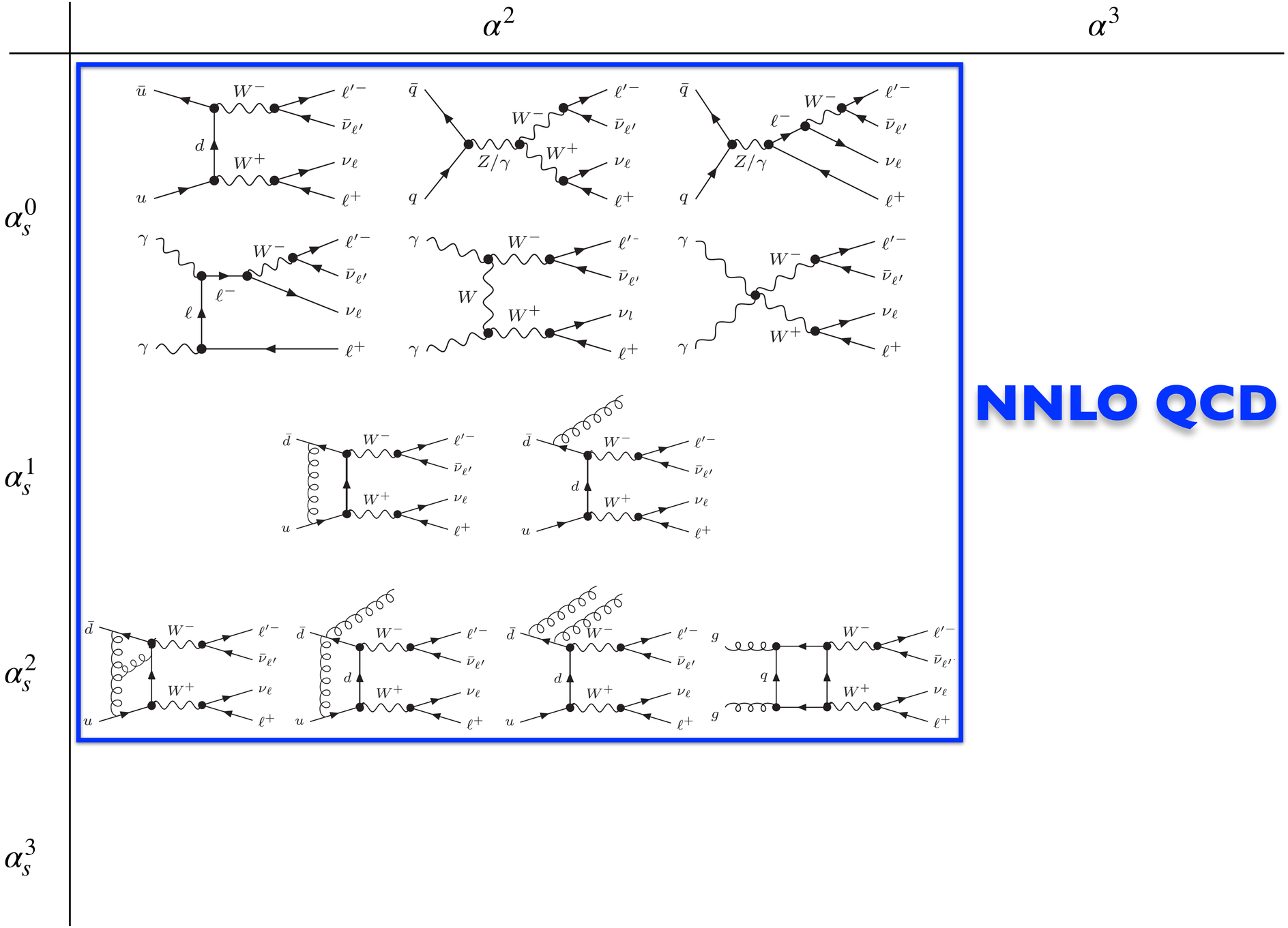
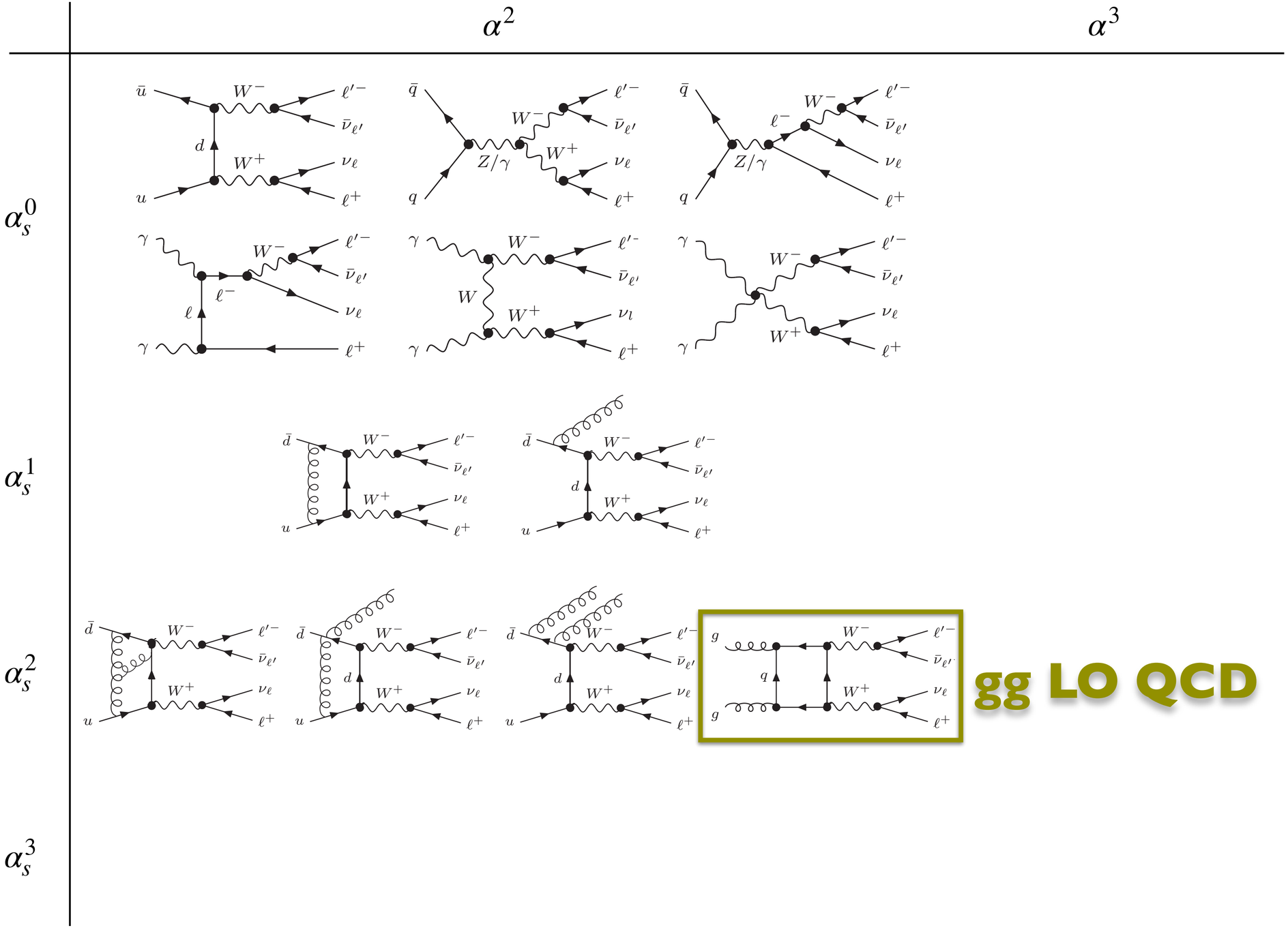

α^2
α^3
α_s^0
α_s^1
α_s^2
α_s^3
$\bar{u}$ W^- ℓ'^- $\bar{\nu}_{\ell'}$ d W^+ ν_ℓ u ℓ^+
$\bar{q}$ W^- ℓ'^- $\bar{\nu}_{\ell'}$ Z/γ W^+ ν_ℓ q ℓ^+
$\bar{q}$ W^- ℓ'^- $\bar{\nu}_{\ell'}$ ℓ^- Z/γ ν_ℓ q ℓ^+
$\bar{u}$ W ℓ^- ν_ℓ W ℓ^+ d W ℓ' $\nu_{\ell'}$ u $\bar{\nu}_{\ell'}$
γ W^- ℓ'^- $\bar{\nu}_{\ell'}$ ℓ^- ℓ ν_ℓ γ ℓ^+
γ W^- ℓ'^- $\bar{\nu}_{\ell'}$ W W^+ ν_l γ ℓ^+
γ W^- ℓ'^- $\bar{\nu}_{\ell'}$ ν_ℓ W^+ γ ℓ^+
$\bar{u}$ W^- $\bar{\nu}_{\ell'}$ ℓ'^- d W^+ ν_ℓ u ℓ^+ u γ
$\bar{d}$ W^- ℓ'^- $\bar{\nu}_{\ell'}$ W^+ ν_ℓ u ℓ^+
$\bar{d}$ W^- ℓ'^- $\bar{\nu}_{\ell'}$ d W^+ ν_ℓ u ℓ^+
$\bar{d}$ W^- ℓ'^- $\bar{\nu}_{\ell'}$ d W^+ ν_ℓ u ℓ^+
g W^- ℓ'^- $\bar{\nu}_{\ell'}$ q W^+ ν_ℓ g ℓ^+
$\bar{d}$ W^- ℓ'^- $\bar{\nu}_{\ell'}$ d W^+ ν_ℓ u ℓ^+
g W^- ℓ'^- $\bar{\nu}_{\ell'}$ q W^+ ν_ℓ g ℓ^+
g W^- ℓ'^- $\bar{\nu}_{\ell'}$ q W^+ ν_ℓ g ℓ^+
q q W^- $\bar{\nu}_{\ell'}$ q' ℓ'^- W^+ ν_ℓ g ℓ^+

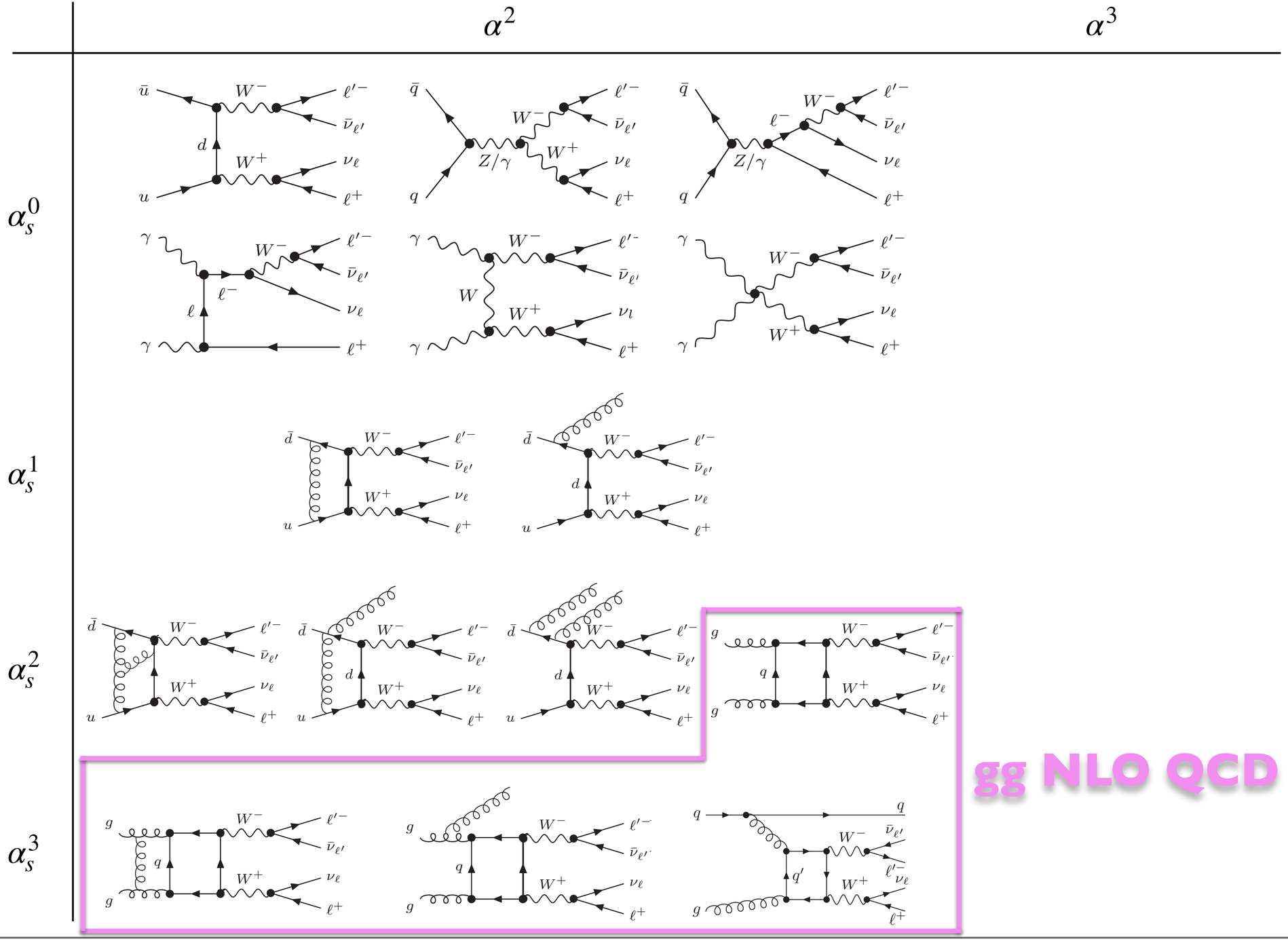
	α^2	α^3
α_s^0		**LO**
α_s^1		
α_s^2		
α_s^3		

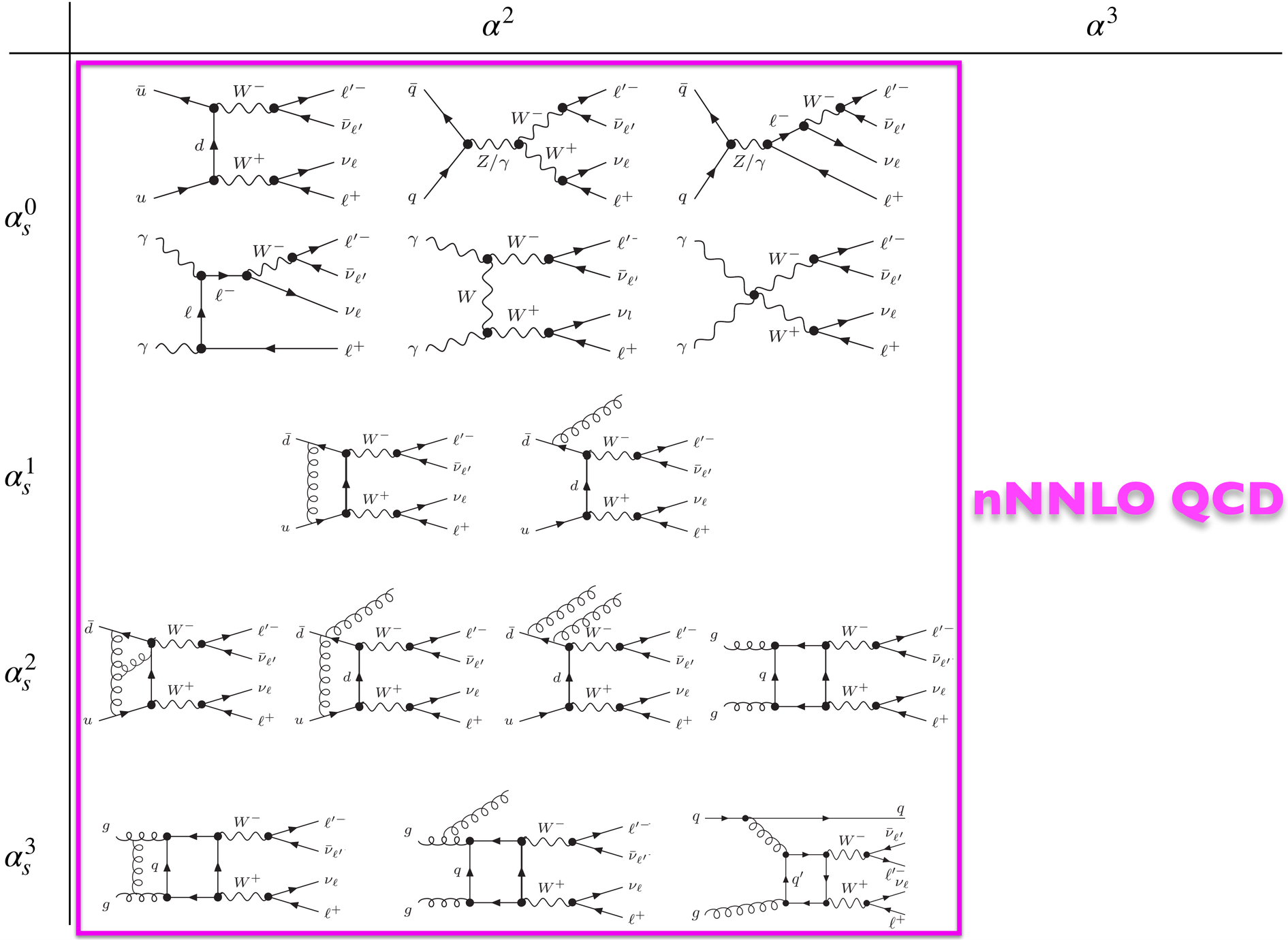
	α^2	α^3
α_s^0		**NLO QCD**
α_s^1		
α_s^2		
α_s^3		

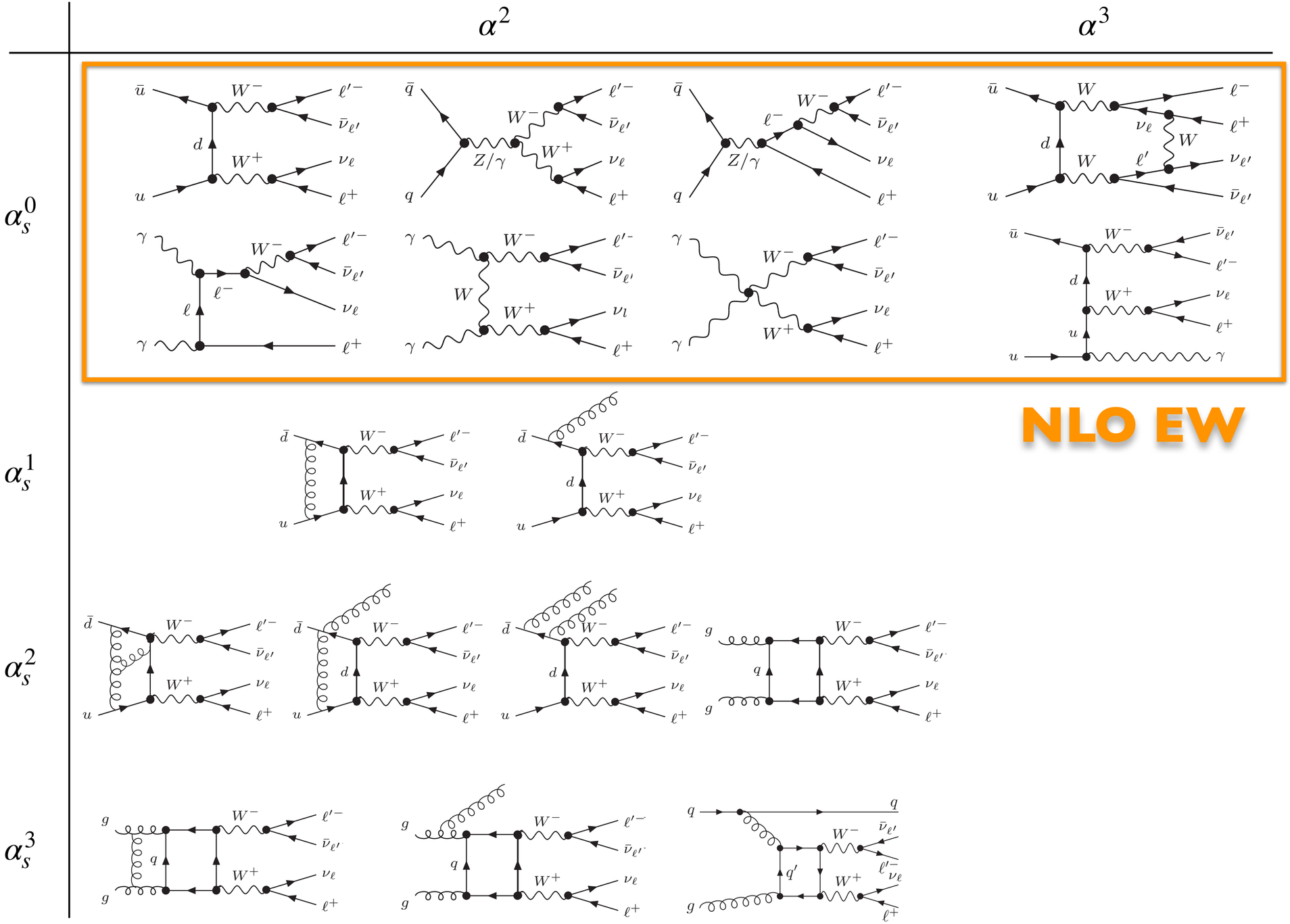

α^2
α^3
α_s^0
α_s^1
α_s^2
α_s^3
$\bar{u}$ W^- ℓ'^- $\bar{\nu}_{\ell'}$ d W^+ ν_ℓ u ℓ^+
$\bar{q}$ W^- ℓ'^- $\bar{\nu}_{\ell'}$ Z/γ W^+ ν_ℓ q ℓ^+
$\bar{q}$ W^- ℓ^- ℓ'^- $\bar{\nu}_{\ell'}$ Z/γ ν_ℓ q ℓ^+
γ W^- ℓ'^- $\bar{\nu}_{\ell'}$ ℓ^- ℓ ν_ℓ γ ℓ^+
γ W^- ℓ'^- $\bar{\nu}_{\ell'}$ W W^+ ν_l γ ℓ^+
γ W^- ℓ'^- $\bar{\nu}_{\ell'}$ W^+ ν_ℓ γ ℓ^+
$\bar{d}$ W^- ℓ'^- $\bar{\nu}_{\ell'}$ W^+ ν_ℓ u ℓ^+
$\bar{d}$ W^- ℓ'^- $\bar{\nu}_{\ell'}$ d W^+ ν_ℓ u ℓ^+
$\bar{d}$ W^- ℓ'^- $\bar{\nu}_{\ell'}$ W^+ ν_ℓ u ℓ^+
$\bar{d}$ W^- ℓ'^- $\bar{\nu}_{\ell'}$ d W^+ ν_ℓ u ℓ^+
$\bar{d}$ W^- ℓ'^- $\bar{\nu}_{\ell'}$ d W^+ ν_ℓ u ℓ^+
g W^- ℓ'^- $\bar{\nu}_{\ell'}$ q W^+ ν_ℓ g ℓ^+

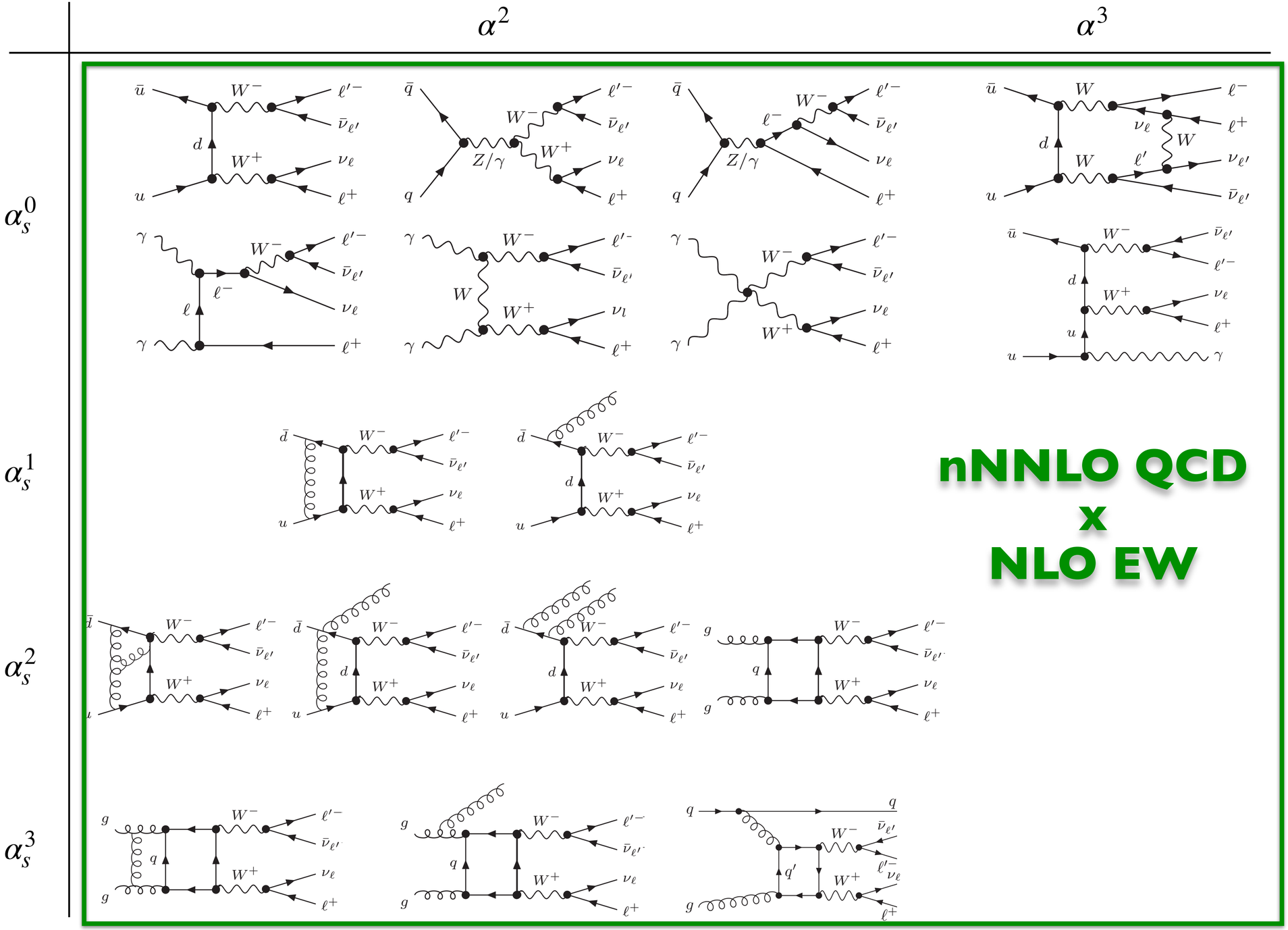
NNLO QCD


α^2
α^3
α_s^0
α_s^1
α_s^2
α_s^3
gg LO QCD


α^2
α^3
α_s^0
α_s^1
α_s^2
α_s^3
gg NLO QCD


α^2
α^3
α_s^0
α_s^1
α_s^2
α_s^3
nNNLO QCD


α^2
α^3
α_s^0
α_s^1
α_s^2
α_s^3
NLO EW


α^2
α^3
α_s^0
α_s^1
α_s^2
α_s^3
nNNLO QCD
x
NLO EW

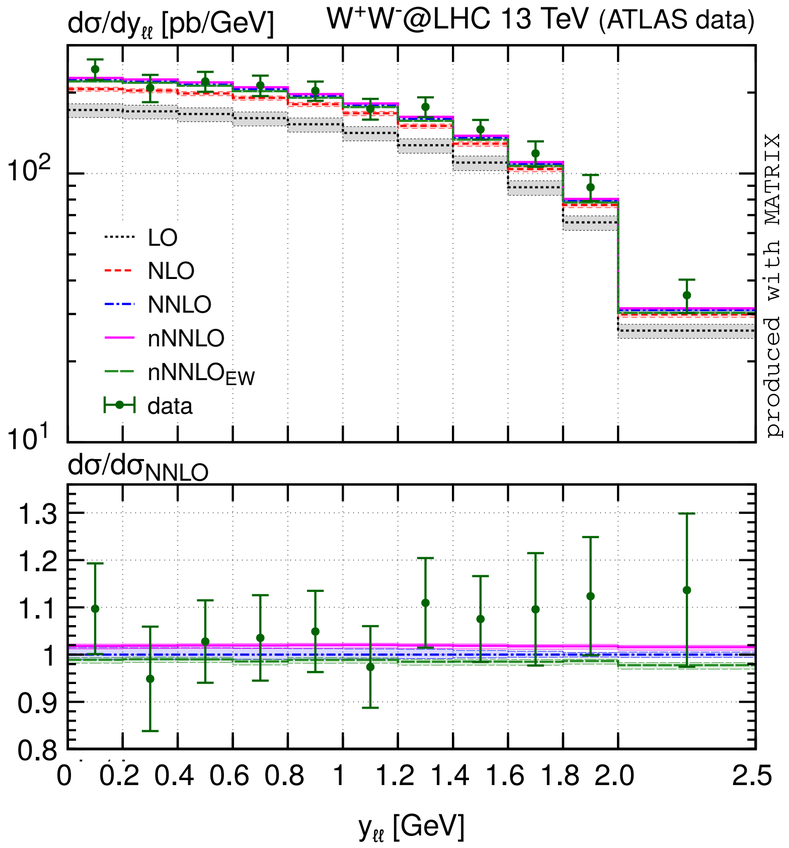
Example: pp → 2ℓ2ν (WW)

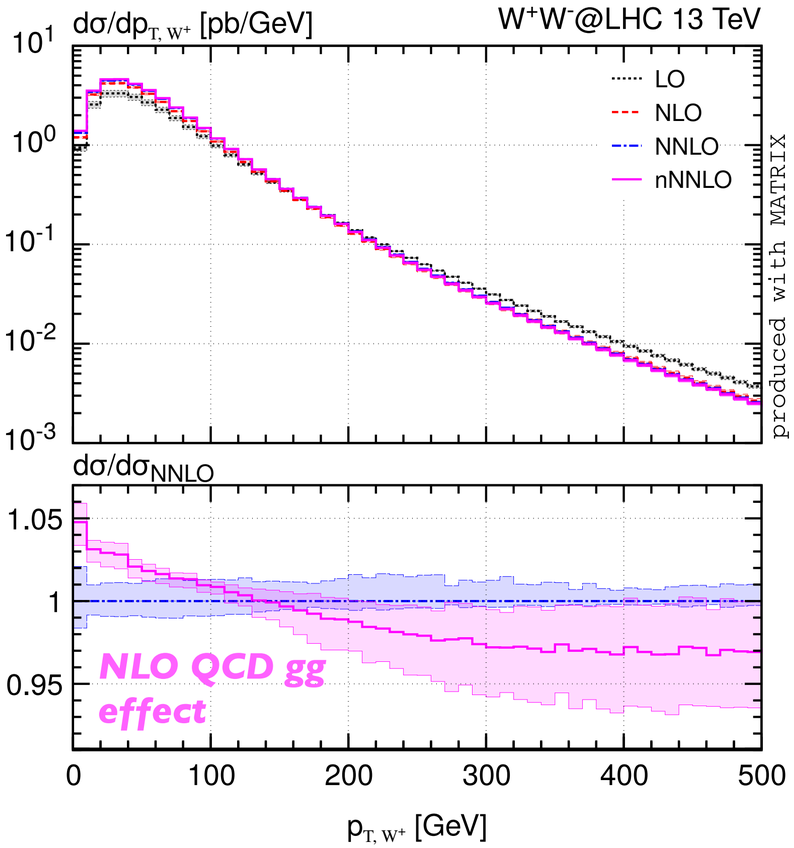
NNLO QCD × **gg NLO QCD** × **NLO EW**

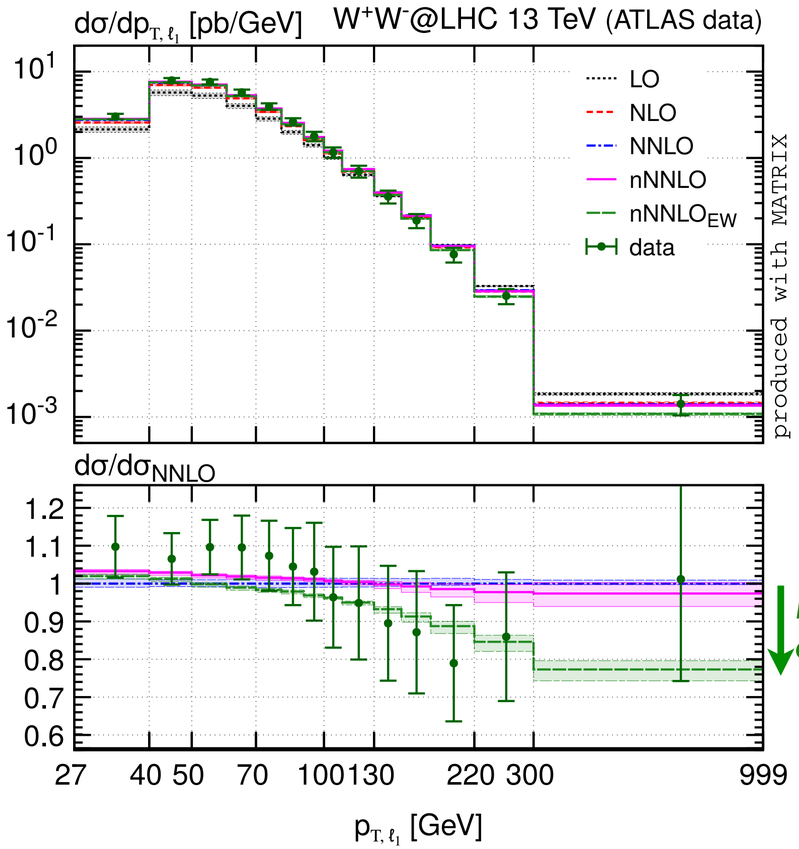
ZZ, WW, WZ
→ [various calculations within MATRIX]

ZZ → [Grazzini, Kallweit, MW, Yook '18]
WW → [Grazzini, Kallweit, MW, Yook '20]

ZZ, WW, WZ
→ [Grazzini, Kallweit, Lindert, Pozzorini, MW '19]







Public fixed-order codes

MATRIX

- automated NNLO QCD framework
- based on q_T subtraction
- all VV processes at NNLO QCD
- NLO EW for all massive VV processes
- NLO QCD for loop-induced gluon-fusion channel

MCFM

MCFM 10.3

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Ciaran Williams (ciaranwi@buffalo.edu)
Tobias Neumann (tneumann@bnl.gov)

MCFM is a parton-level Monte Carlo program that gives predictions for a wide range of processes at hadron colliders. Almost all processes are available at NLO, but some processes are also available at NNLO or N^{3}LO in QCD. The calculation of some processes can also account for NLO electroweak effects. Transverse momentum and jet veto resummation is available for the production of color singlet final states.
Please look at the list of available processes.
This document is available as a series of webpages and as a pdf file.
Download and installation instructions are in Section 1.

January 30, 2023

- extensive NLO QCD process library
- all VV processes now included at NNLO QCD
- based on N-jettiness & q_T subtraction

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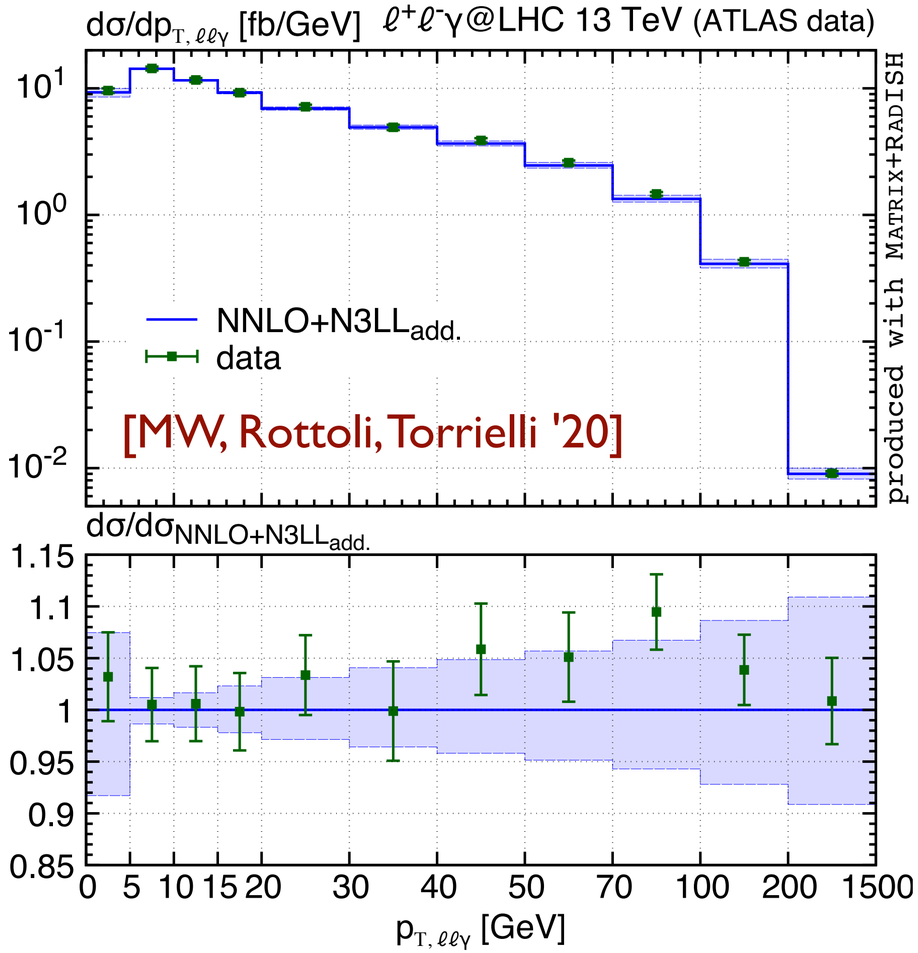
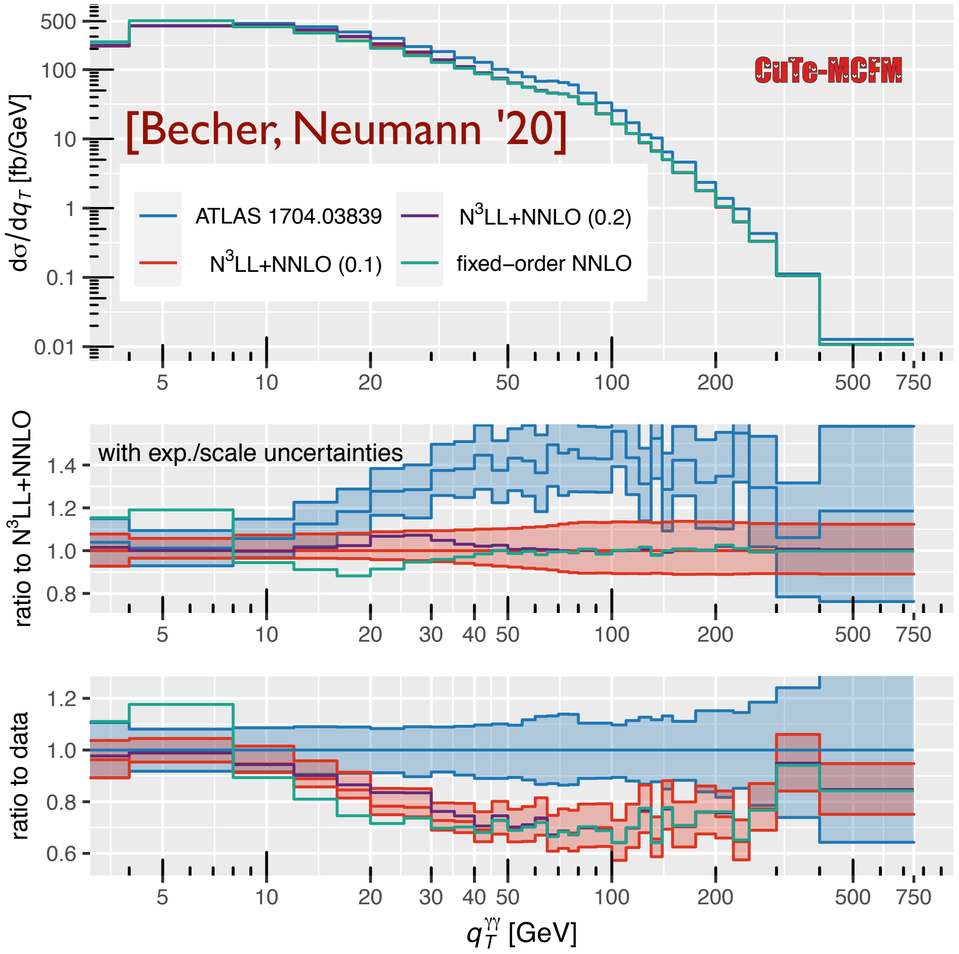
Examples: Zγ & γγ p_T spectrum at NNLO+N3LL

MATRIX+RADISH



CuTe-MCFM



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NNLO+PS methods

NNLOPS: MiNLO+reweighting

[Hamilton, Nason, Oleari, Zanderighi '12, + Re '13], [Karlberg, Re, Zanderighi '14]

- LL accuracy (+ simple NLL terms) from PS
- no new unphysical scale (i.e. physically sound)
- numerically very intensive
- applied beyond 2→1 processes

Geneva

[Alioli, Bauer, Berggren, Tackmann, Walsh '15 + Zuberi '13]

- LL accuracy from PS (at most! no NNLL nonesense!)
- slicing cutoff (missing power corrections)
- numerical cancellations in slicing parameter
- applied beyond 2→1 processes

MiNNLOPS

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

- LL accuracy (+ simple NLL terms) from PS
- no new unphysical scale (i.e. physically sound)
- numerically efficient
- applied beyond 2→1 and even beyond colour singlet

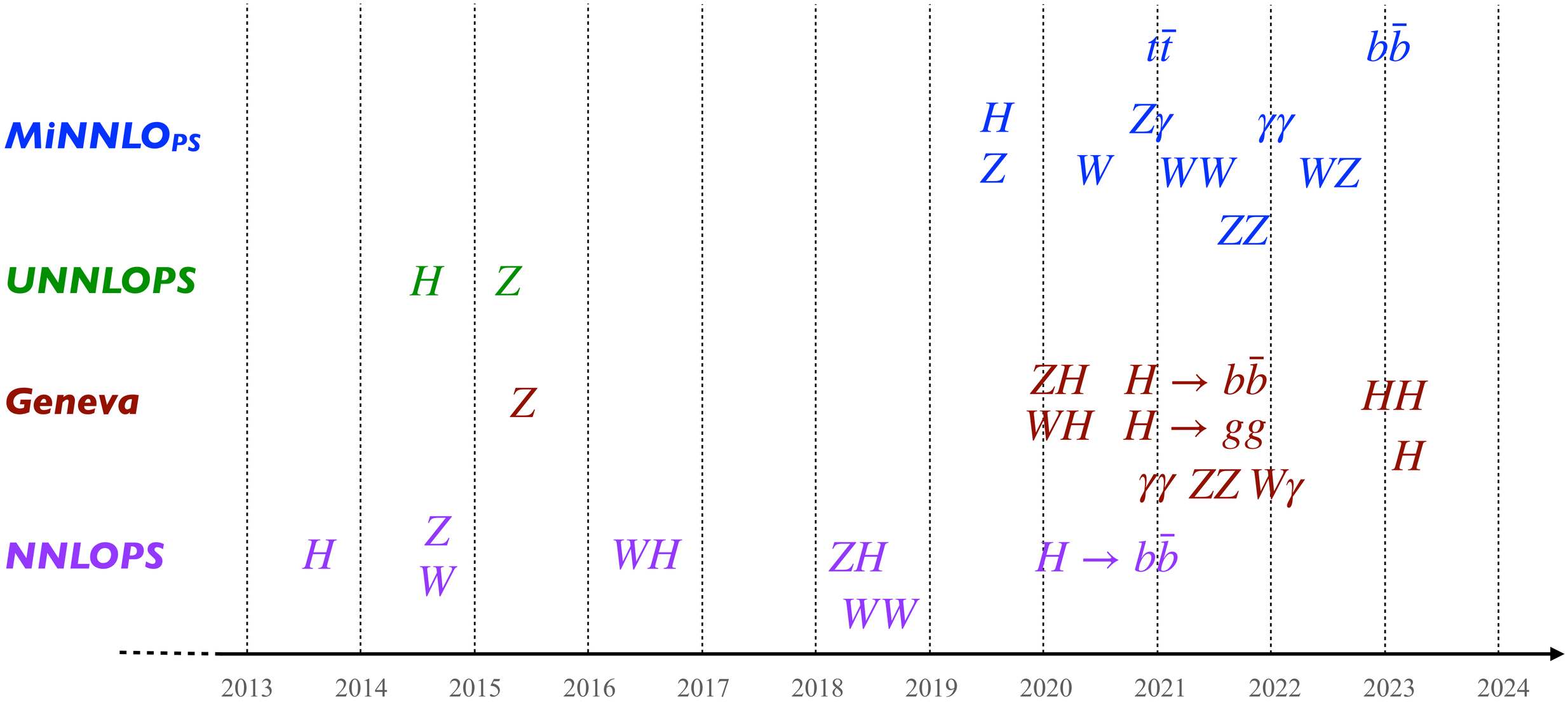
UNNLOPS

[Höche, Prestel '14 '15]

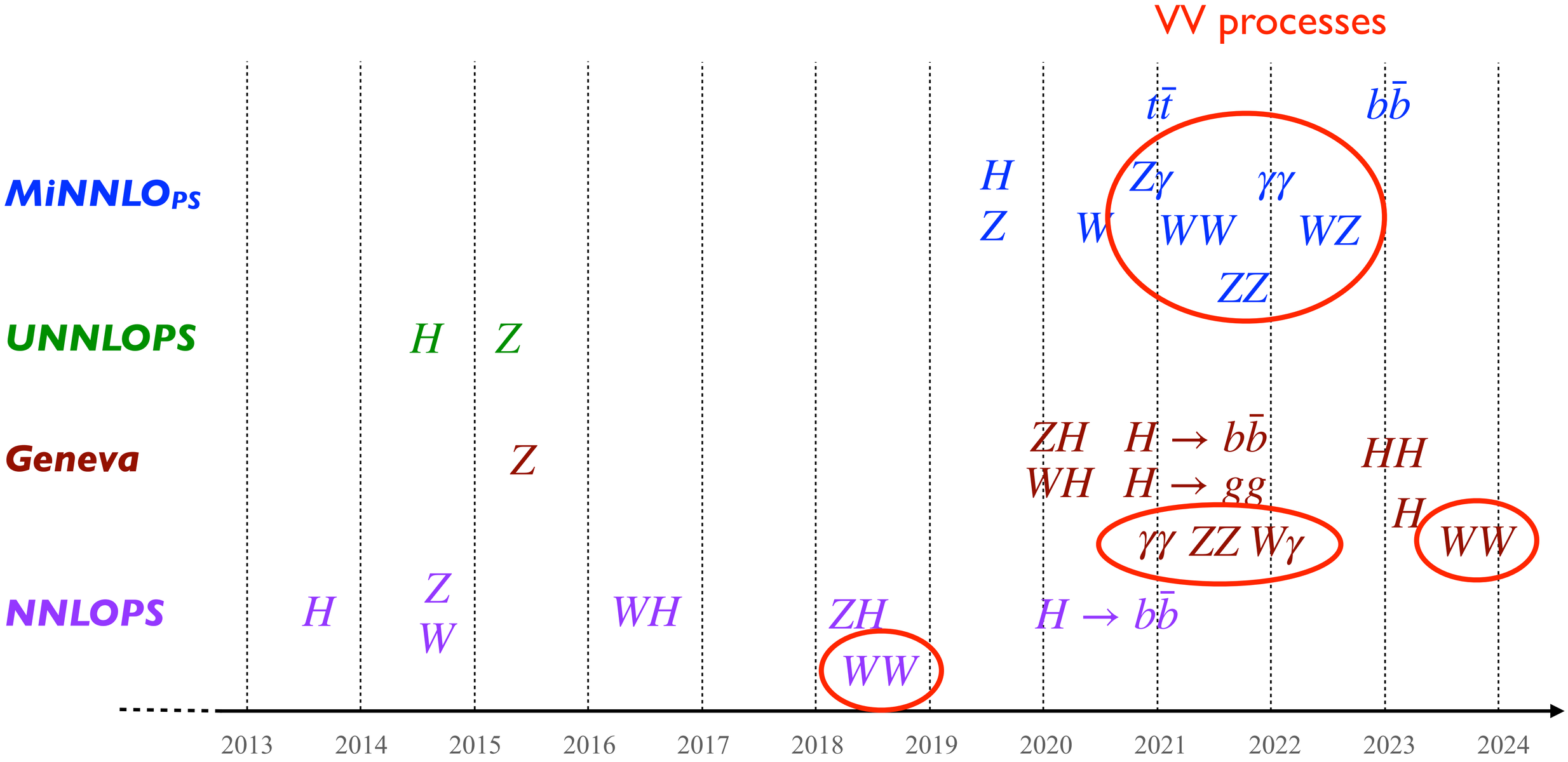
- extension of UNLOPS merging of event samples
- two-loop corrections entirely in 0-jet bin
- only applied to 2→1 processes

there was also some progress on NNLO+PS for sector showers [Campbell, Höche, Li, Preuss, Slands '21]

NNLO+PS timeline

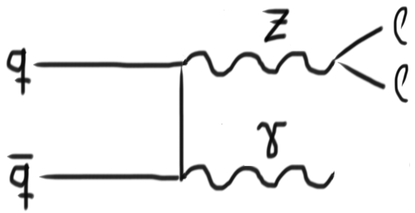


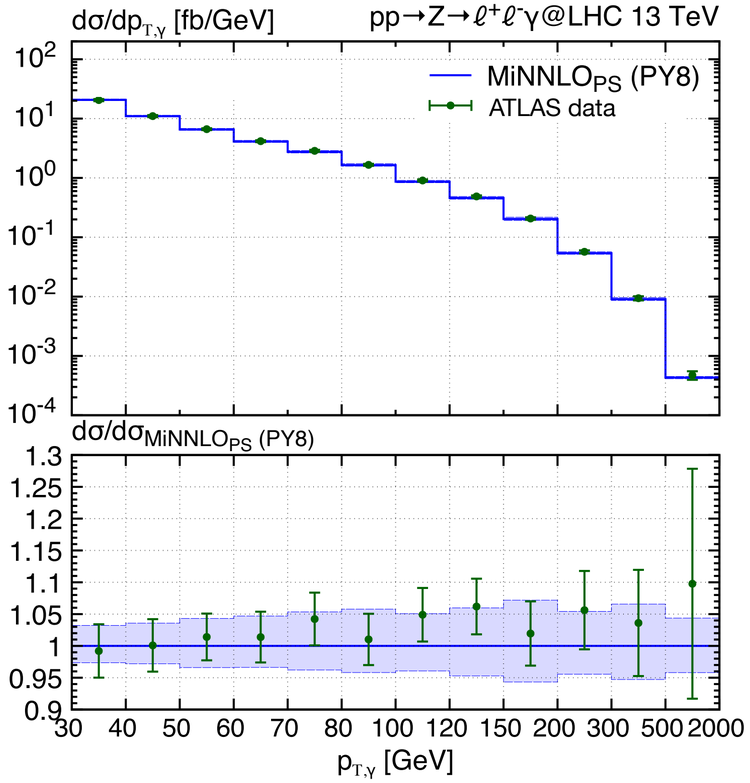
NNLO+PS timeline



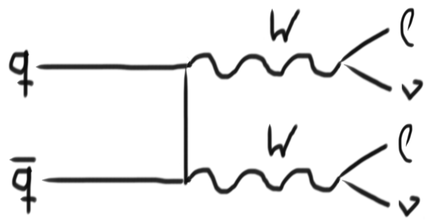
MiNNLO$_{PS}$: diboson processes

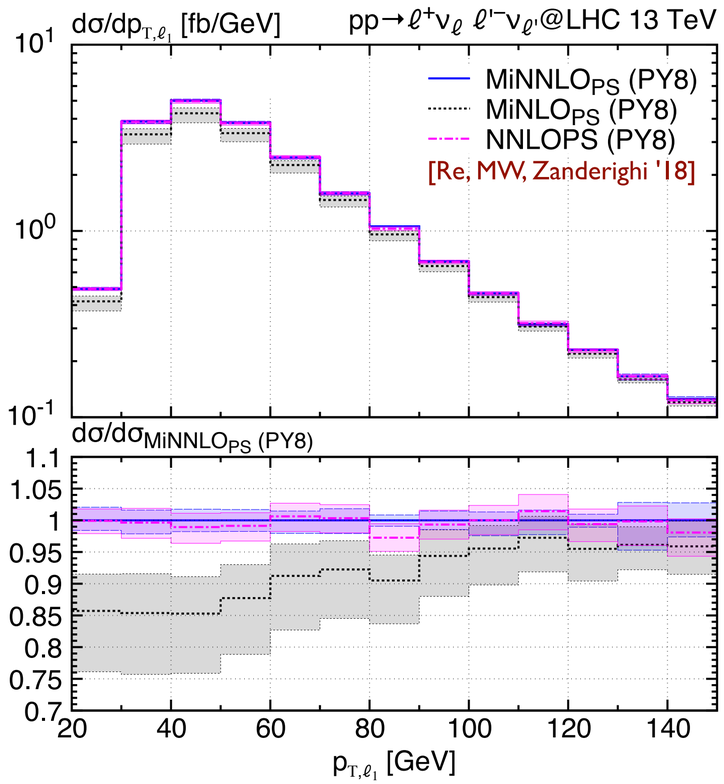
[Lombardi, MW, Zanderighi '20 '21]



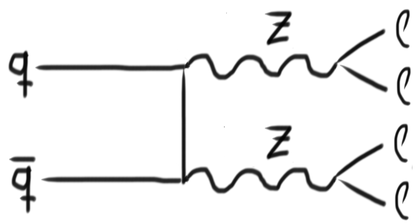


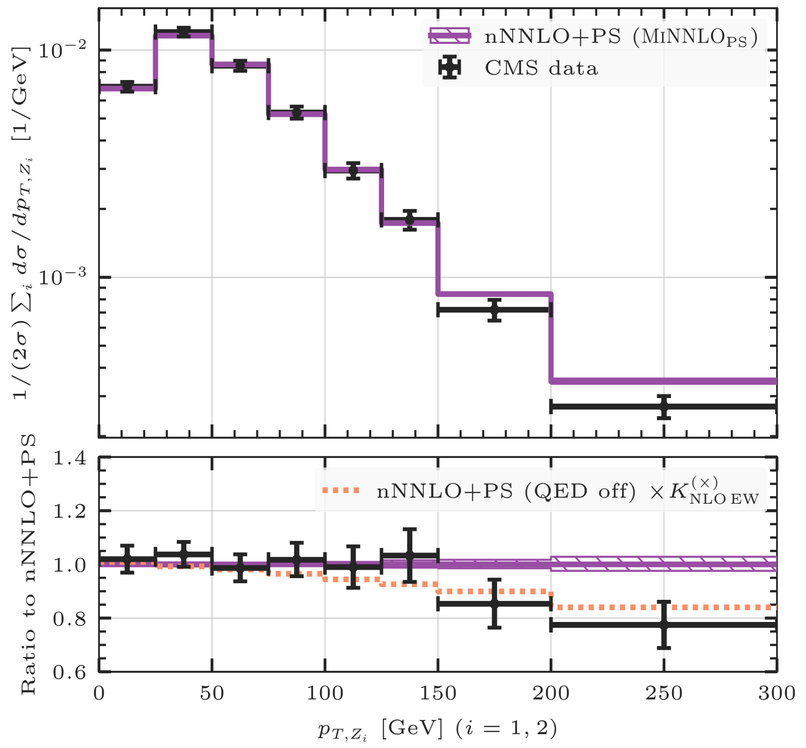
[Lombardi, MW, Zanderighi '21]





[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$_{PS}$: $W^{\pm}Z$ production (NNLO$_{QCD}$+PS & NLO$_{EW}$+PS)

[Lindert, Lombardi, MW, Zanderighi, Zanoli '22]

additive schemes:

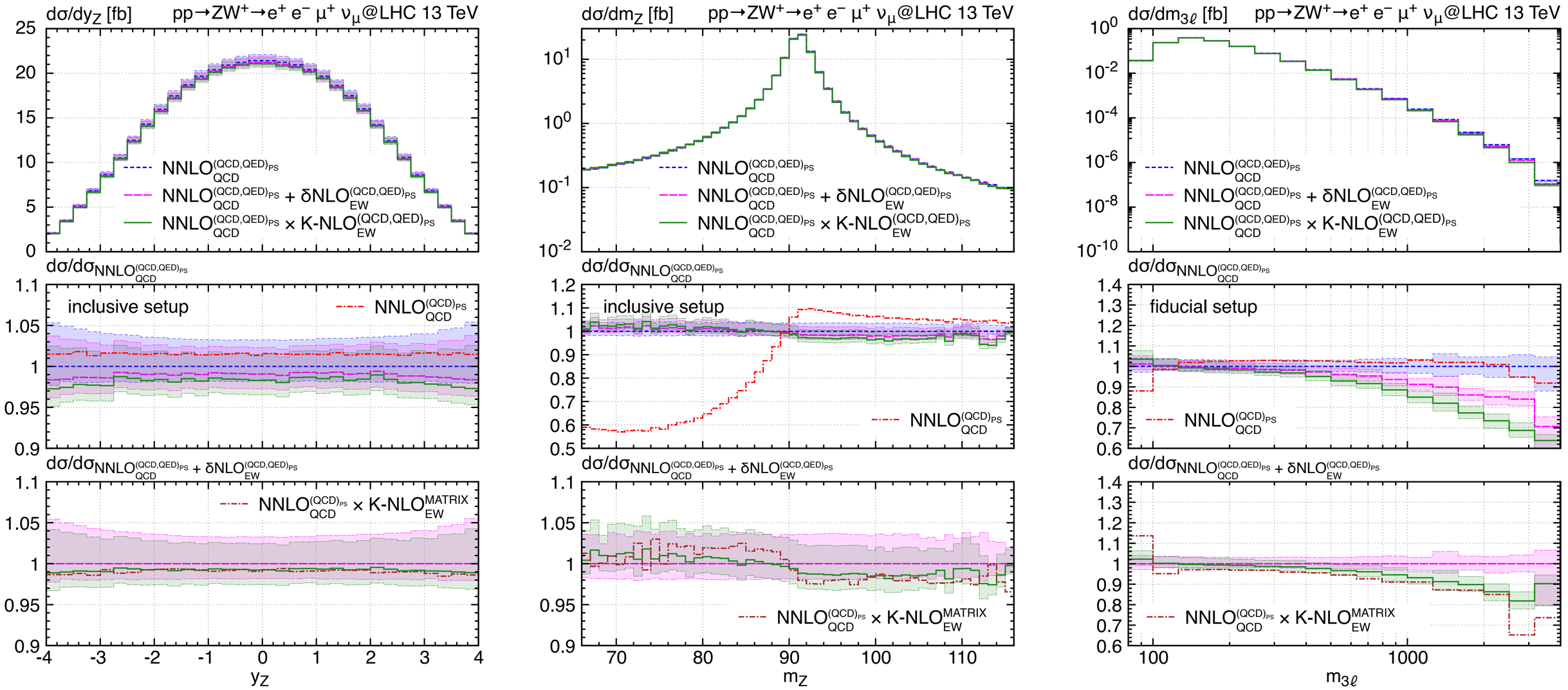
1. $\mathrm{NNLO}_{\mathrm{QCD}}^{(\mathrm{QCD},\mathrm{QED})_{\mathrm{PS}}} + \delta\mathrm{NLO}_{\mathrm{EW}}^{(\mathrm{QCD},\mathrm{QED})_{\mathrm{PS}}}$
2. $\mathrm{NNLO}_{\mathrm{QCD}}^{(\mathrm{QCD},\mathrm{QED})_{\mathrm{PS}}} + \delta\mathrm{NLO}_{\mathrm{EW}}^{(\mathrm{QED})_{\mathrm{PS}}}$
3. $\mathrm{NLO}_{\mathrm{EW}}^{(\mathrm{QCD},\mathrm{QED})_{\mathrm{PS}}} + \delta\mathrm{NNLO}_{\mathrm{QCD}}^{(\mathrm{QCD})_{\mathrm{PS}}}$

multiplicative schemes:

4. $\mathrm{NNLO}_{\mathrm{QCD}}^{(\mathrm{QCD},\mathrm{QED})_{\mathrm{PS}}} \times \text{K-NLO}_{\mathrm{EW}}^{(\mathrm{QCD},\mathrm{QED})_{\mathrm{PS}}}$
5. $\mathrm{NNLO}_{\mathrm{QCD}}^{(\mathrm{QCD},\mathrm{QED})_{\mathrm{PS}}} \times \text{K-NLO}_{\mathrm{EW}}^{(\mathrm{QED})_{\mathrm{PS}}}$
6. $\mathrm{NLO}_{\mathrm{EW}}^{(\mathrm{QCD},\mathrm{QED})_{\mathrm{PS}}} \times \text{K-NNLO}_{\mathrm{QCD}}^{(\mathrm{QCD})_{\mathrm{PS}}}$

MiNNLO$_{PS}$: $W^{\pm}Z$ production (NNLO$_{QCD}$+PS & NLO$_{EW}$+PS)

[Lindert, Lombardi, MW, Zanderighi, Zanoli '22]



MiNNLO$_{PS}$: $W^{\pm}Z$ production (NNLO$_{QCD}$+PS & NLO$_{EW}$+PS)

[Lindert, Lombardi, MW, Zanderighi, Zanoli '22]

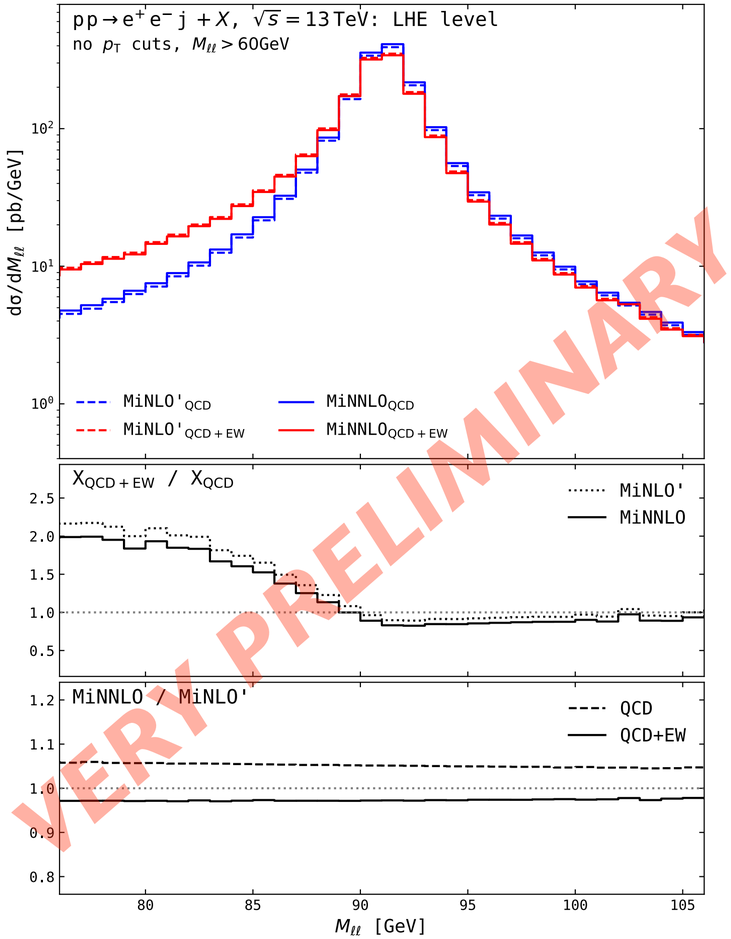
new development:

[Lombardi, Pelliccioli, MW, Zanderighi, Zanoli 'in progress]

MiNNLO$_{PS}^{QCDxEW}$ → simultaneous NNLO$_{QCD}$+NLO$_{EW}$+PS event generation

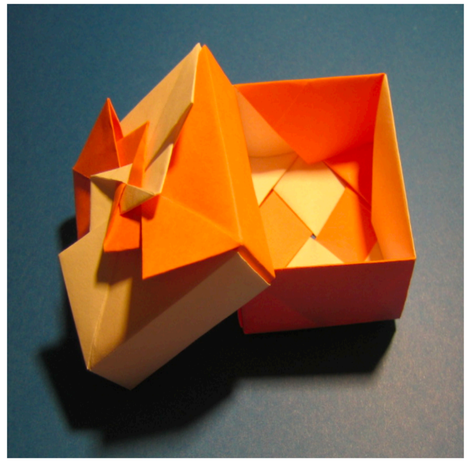
accuracy:

1. QCD: NNLO 0-jet, NLO 1-jet, LO 2-jet
2. EW: NLO 0-jet & 1-jet



MiNNLO$_{PS}$ generators public in POWHEG BOX

The POWHEG BOX



Project

The POWHEG BOX is a general computer framework for implementing NLO calculations in shower Monte Carlo programs according to the POWHEG method. It is also a library, where previously included processes are made available to the users. It can be interfaced with all modern shower Monte Carlo programs that support the Les Houches Interface for User Generated Processes.

Index:

- Available NLO+PS processes
- NNLOps using MiNNLOps
- Proper references
- Downloads
- Version 2
- Version RES
- Bugs
- Licence
- Contributing Authors

or click here: https://powhegbox.mib.infn.it/#MiNNLOps

MiNNLO$_{PS}$ for $2 \to 1$ processes (H, Z, W) in POWHEG-BOX-V2

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

NEW

Top-quark pair *generator*

[Mazzitelli, Monni, Nason, Re, MW, Zanderighi '20 '21]

MiNNLO$_{PS}$ has been extended to $2 \to 2$ colour-singlet processes in POWHEG-BOX-RES

NEW

Zγ *generator (both $Z \to \ell^+\ell^-$ and $Z \to \bar{\nu}\nu$ + aTGC @NNLO)*

[Lombardi, MW, Zanderighi '20, '21]

NEW

WW *generator [Lombardi, MW, Zanderighi '21]*

NEW

ZZ *generator with incoherent combination of $q\bar{q}$ and gg channels*

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

NEW

γγ *generator (t.b.a.) [Gavardi, Oleari, Re '22]*

NEW

VH *generator interfaced with* ***H→bb*** *decay and SMEFT effects (t.b.a.)*

[Zanoli, Chiesa, Re, MW, Zanderighi '21], [Haisch, Scott, MW, Zanderighi, Zanoli '22]

NEW

WZ *generator for NNLO$_{QCD}$+PS and NLO$_{EW}$+PS (t.b.a.)*

[Lindert, Lombardi, MW, Zanderighi, Zanoli 'to appear]

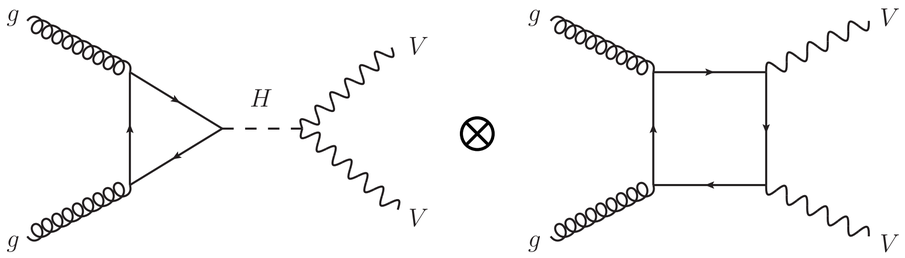
VV production: What is state of the art?

fixed order	***resummation***	***shower matching***
NNLO QCD for $q\bar{q} \to VV$	N³LL in diboson p_T	NNLO+PS in QCD for $q\bar{q} \to VV$
NLO EW for $q\bar{q} \to VV$	NNLL in jet p_T / jet veto	NLO+PS in EW for $q\bar{q} \to VV$
NLO QCD for $gg \to VV$ (loop induced)	NNLL in double resummation of diboson p_T & jet p_T / jet veto	NLO+PS in QCD for $gg \to VV$ (loop induced)

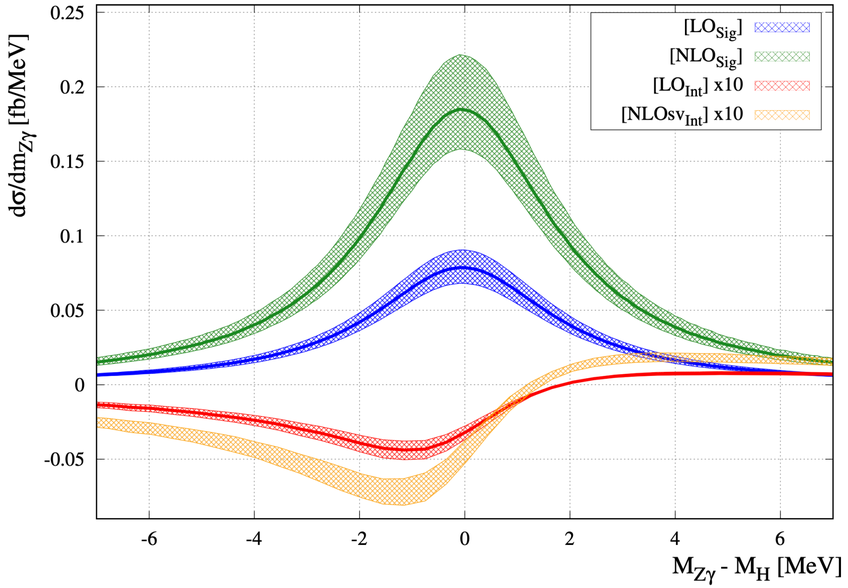
other/new developments:

- Higgs interference effects in $gg \to VV$ at NLO QCD ($\gamma\gamma, Z\gamma, ZZ$)
- inclusion of top-mass effects at 2-loop level ($\gamma\gamma, ZZ$)
- NNLO QCD for $\gamma\gamma + \text{jet}$

Higgs interference

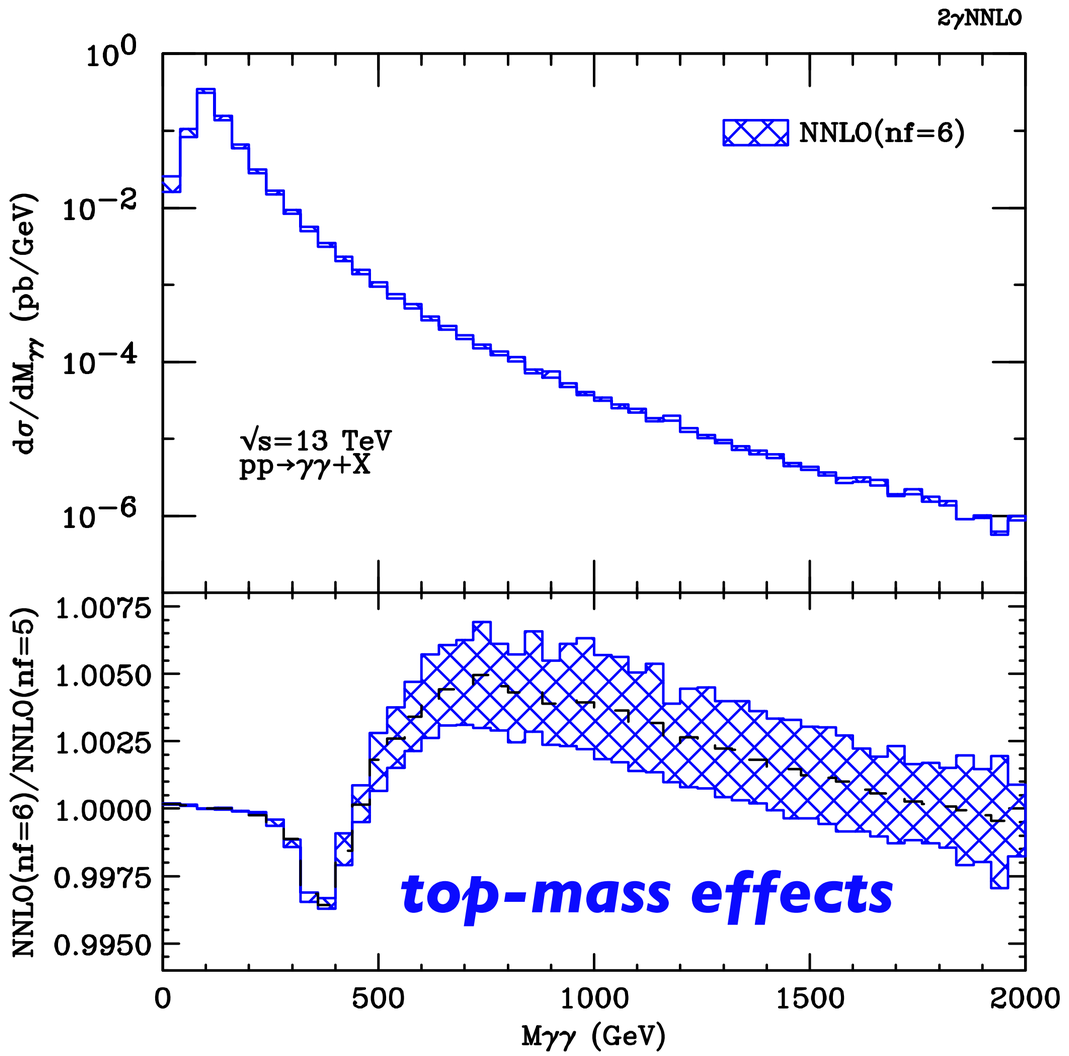


- $gg \to ZZ, gg \to WW$ @ NLO QCD
  [Caola, Dowling, Melnikov, Röntsch, Tancredi '16], [Grazzini, Kallweit MW, Yook '21]
- $gg \to \gamma\gamma$ @ $\mathrm{NNLO_{SV}}$ QCD
  [Bargiela, Buccioni, Caola, Devoto, von Manteuffel, Tancredi '22]
- $gg \to Z\gamma$ @ $\mathrm{NLO_{SV}}$ QCD
  [Buccioni, Devoto, Djouadi, Ellis, Quevillon, Tancredi '23]



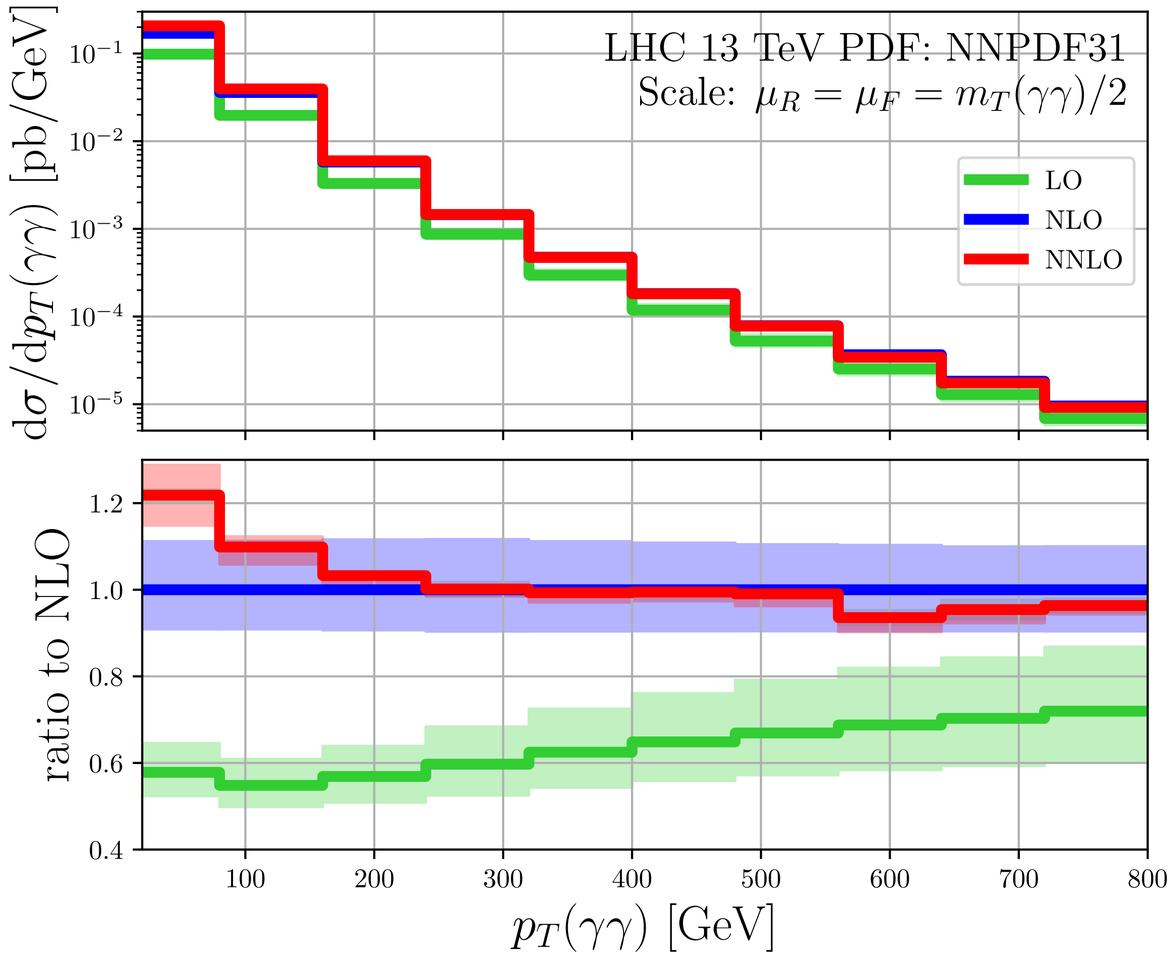
$pp \to \gamma\gamma$ @ NNLO QCD

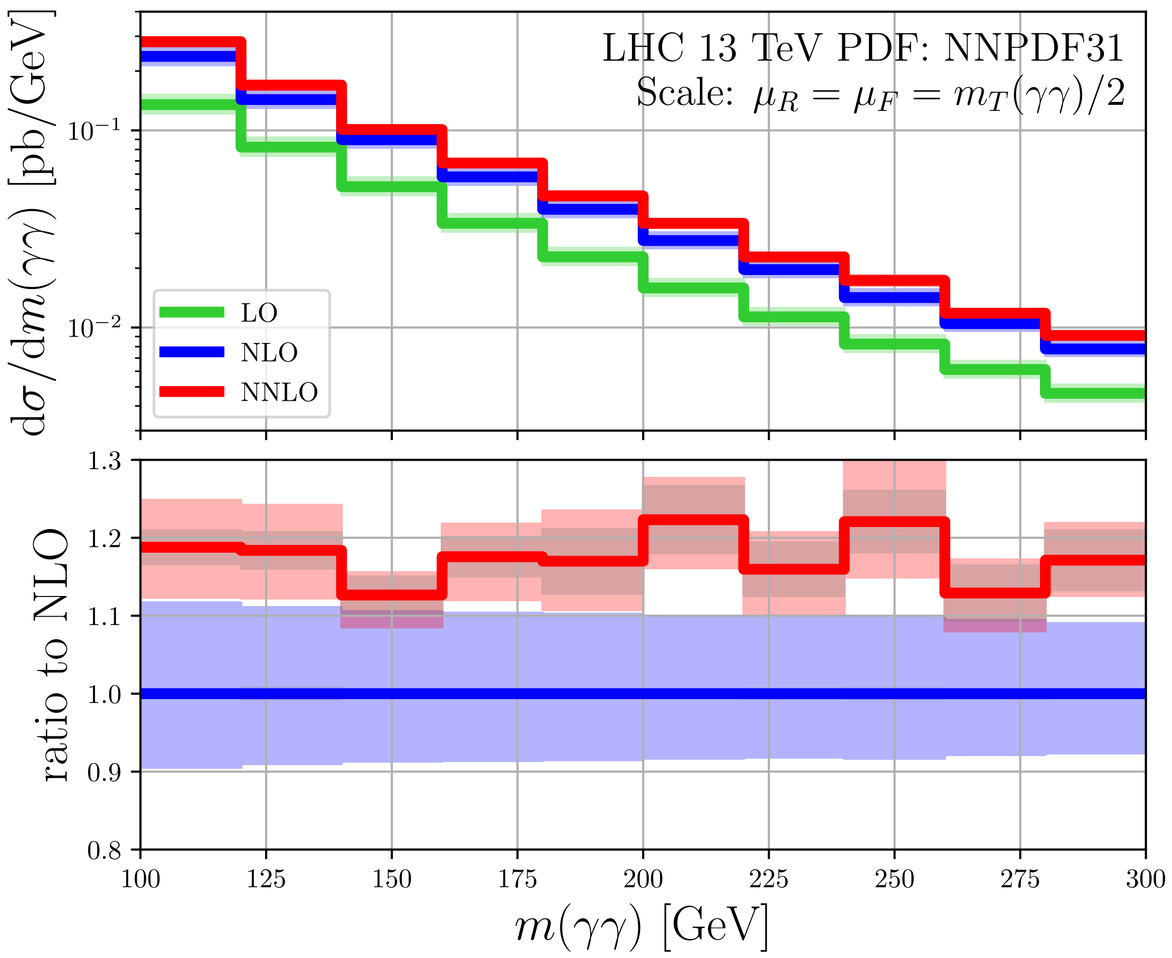
[Becchetti, Bonciani, Cieri, Coro, Ripani '23]



NNLO QCD for diphoton + jet

[Chawdhry,a Czakon, Mitov, Poncelet '21]



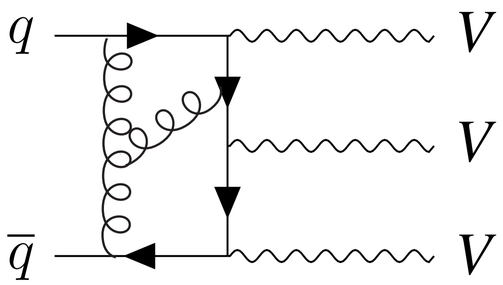


Common technical features with triboson processes

- triboson processes:
  $\gamma\gamma\gamma, Z\gamma\gamma, W\gamma\gamma, ZZ\gamma, WW\gamma, WZ\gamma, ZZZ, WWW, ZZW, WWZ$

- subtraction for colour-singlet production fully understood & automated within MATRIX

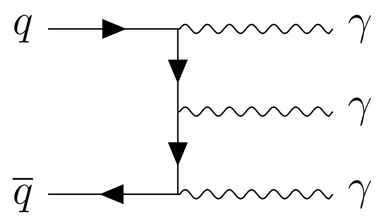
- only missing ingredient: 2-loop amplitudes
  ➞ very complicated ! (five-point functions with external masses)

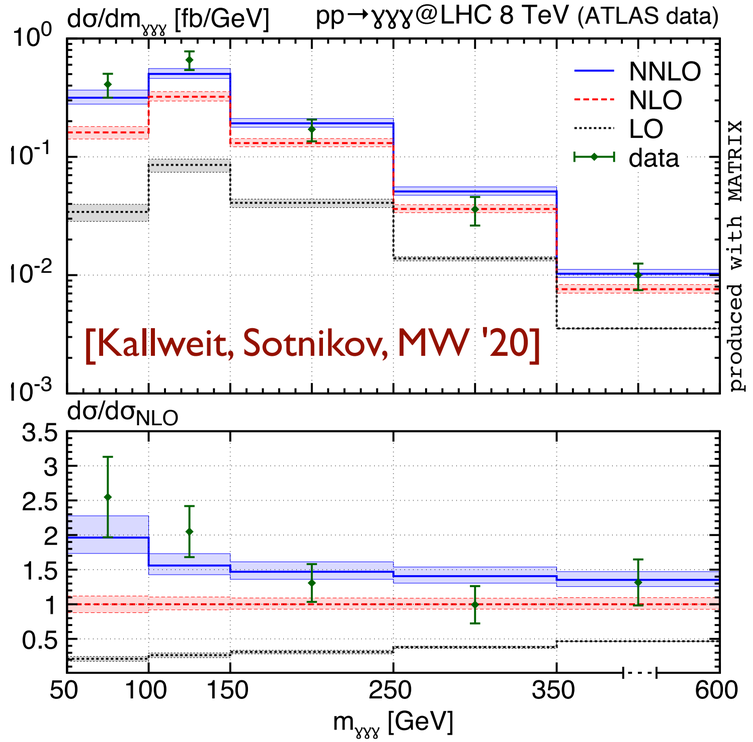


  ➞ known for $\gamma\gamma\gamma$, feasible for $Z\gamma\gamma$ & $W\gamma\gamma$ (one external mass), but needs significant progress for the other processes on the 2-loop side (two and even three external masses)

- NLO QCD & NLO EW exists [MG5_aMC@NLO, Sherpa], [Schönherr et al. '17 '18 '19]

$pp \to \gamma\gamma\gamma$@NNLO





see also: [Chawdhry, Czakon, Mitov, Poncelet '19]

Combined interpretation of VV, VH and HH

Combined interpretation of VV, VH and HH

➙ ***SMEFT !***

Combined interpretation of VV, VH and HH

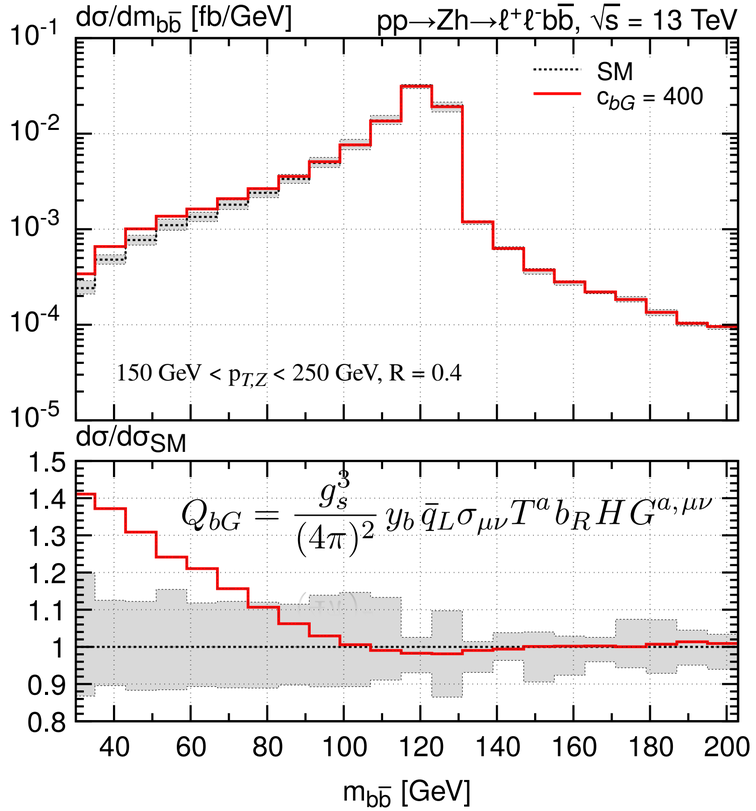
➙ *SMEFT !*

- many implementations: automated at LO QCD and NLO QCD, dedicated ones at NNLO QCD
  ➙ too many to cover here…

- first NNLO+PS in SMEFT: $pp \to VH$ production & $H \to b\bar{b}$ decay
  [Gauld, Haisch, Schnell '23] [Haisch, Scott, MW, Zanderighi, Zanoli '22]

- important at higher orders: consistent input scheme, with input scale and RGE running of SMEFT operators
  see for instance [Battaglia, Grazzini, Spira, MW, '21]

- recently NLL RGE running automated within MG5_aMC@NLO
  [Aoude, Maltoni, Mattelaer, Severi, Vryonidou '23]



Summary

★ fixed order: NNLO QCD, NLO EW and gg NLO QCD for all VV processes
(public in MATRIX, NNLO QCD also in MCFM)

★ resummation (MATRIX & MCFM); NNLO+PS QCD (MiNNLO$_{PS}$ & Geneva); NLO+PS EW

★ new developments: Higgs interference at NLO QCD; top-mass effects in diphoton;
diphoton+jet at NNLO QCD

Outlook

★ feasible (all ingredients available): $gg \to \gamma\gamma$ at NNLO QCD; $q\bar{q} \to \gamma\gamma$ at N^{3}LO QCD

★ top-mass effects in massive diboson processes

★ Sophisticated inclusion of NLO EW corrections in NNLO+PS predictions

★ SMEFT effects at NNLO+PS

Summary

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★ SMEFT effects at NNLO+PS

Stay tuned !

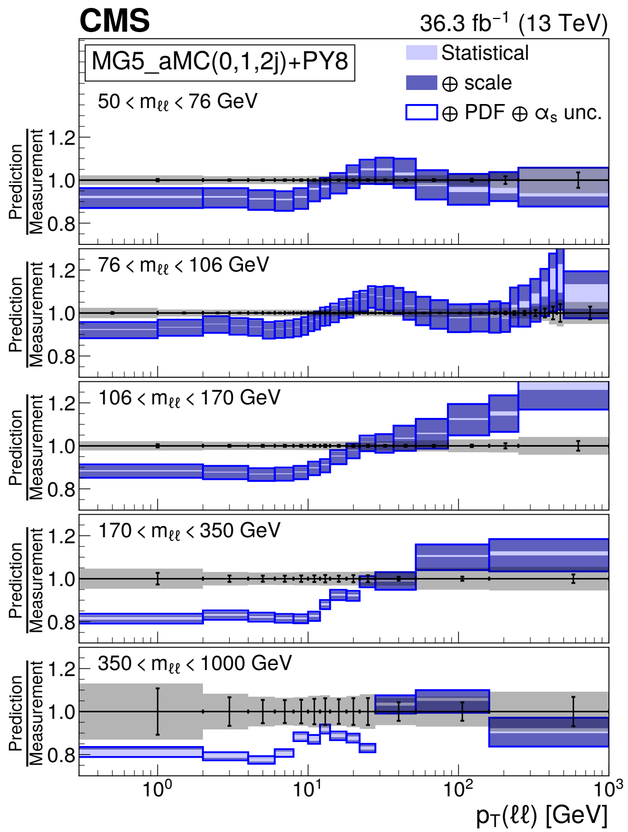
Back Up

Comparison to high-precision Drell-Yan data

[CMS '22 - arXiv:2205.04897]

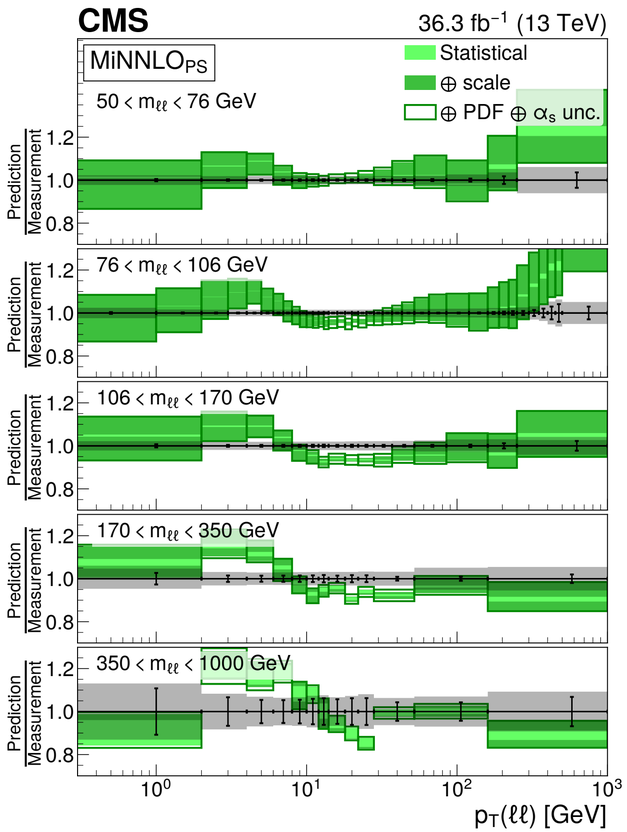
MG5_aMC

[Alwall et al. '14]



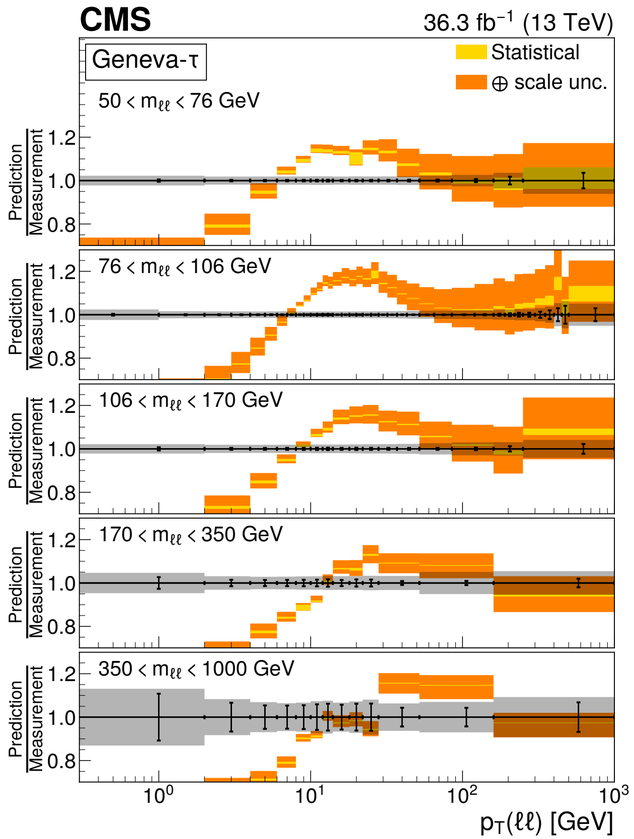
MiNNLO$_{PS}$

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



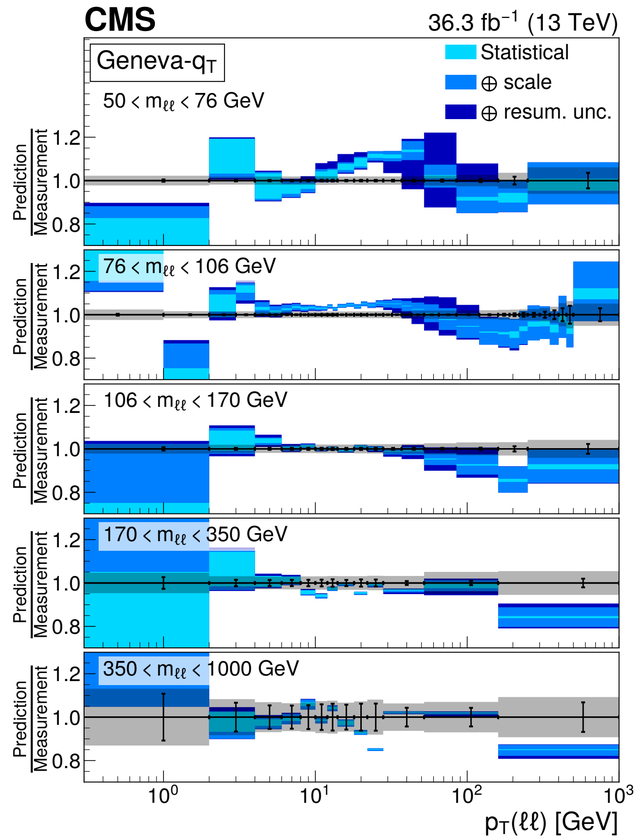
Geneva-τ_0

[Alioli et al. '13 '15]



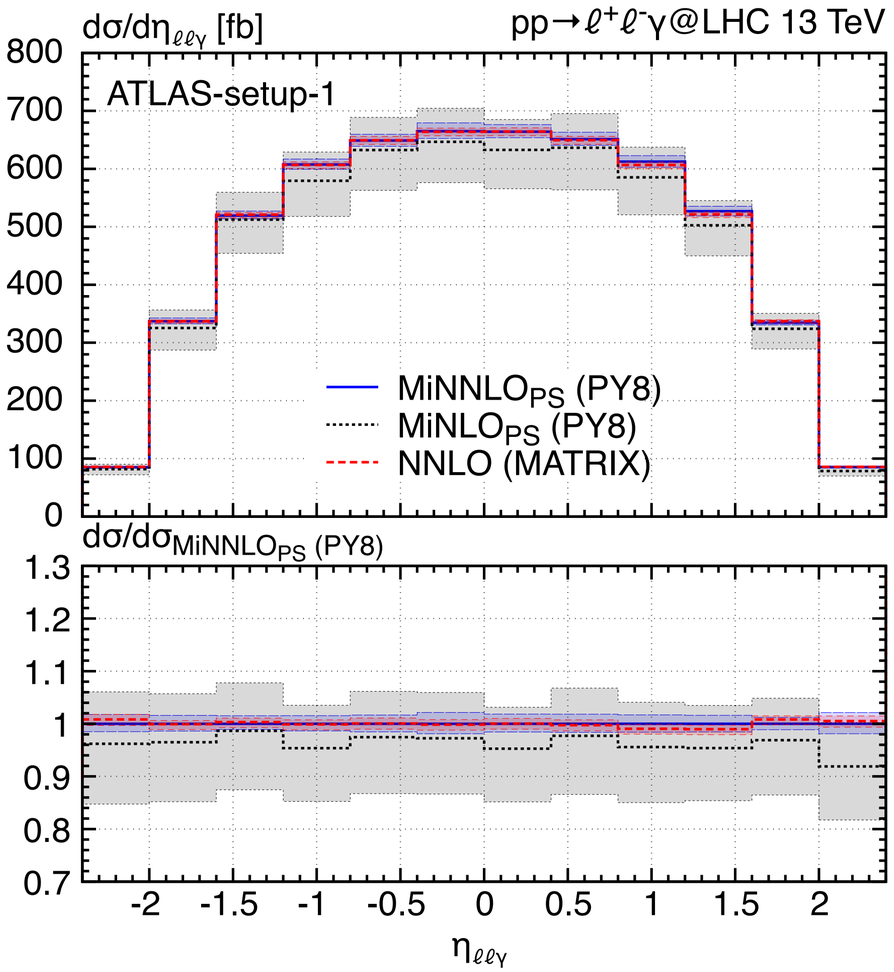
Geneva-p_T^Z

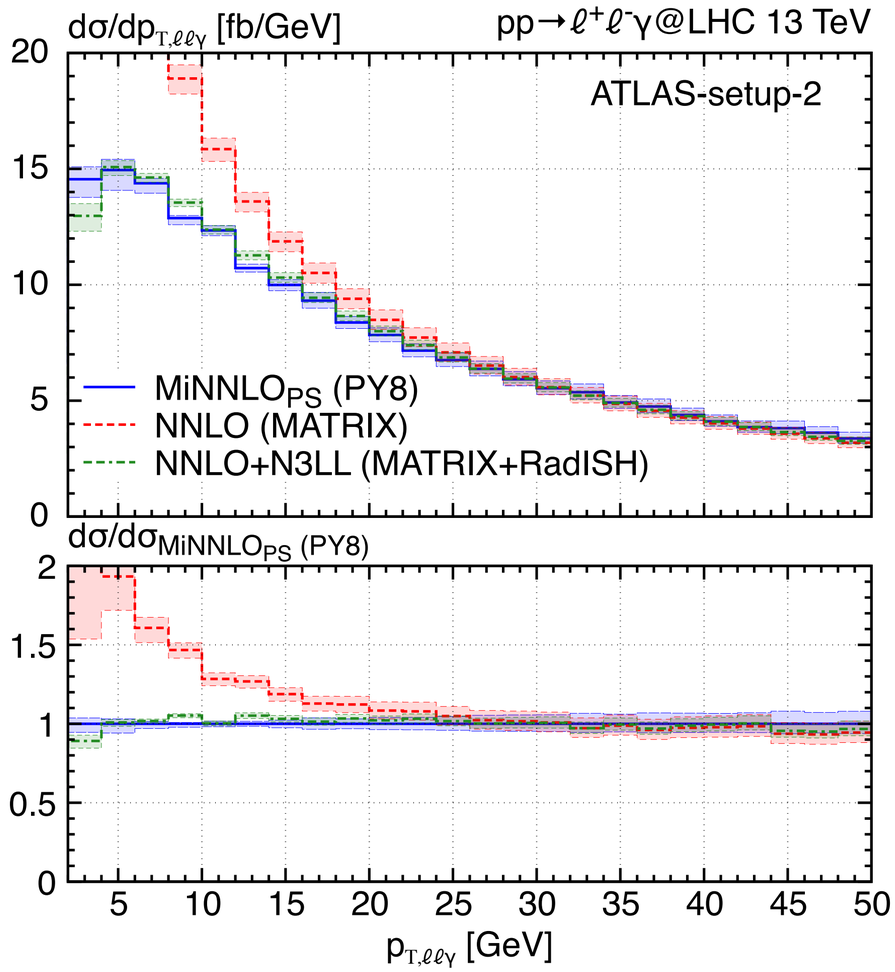
[Alioli, Bauer, Broggio, Gavardi, Kallweit, Lim, Nagar, Napoletano, Rotolli '21]



MiNNLO$_{PS}$: $Z\gamma\,(\ell\ell\gamma)$ production

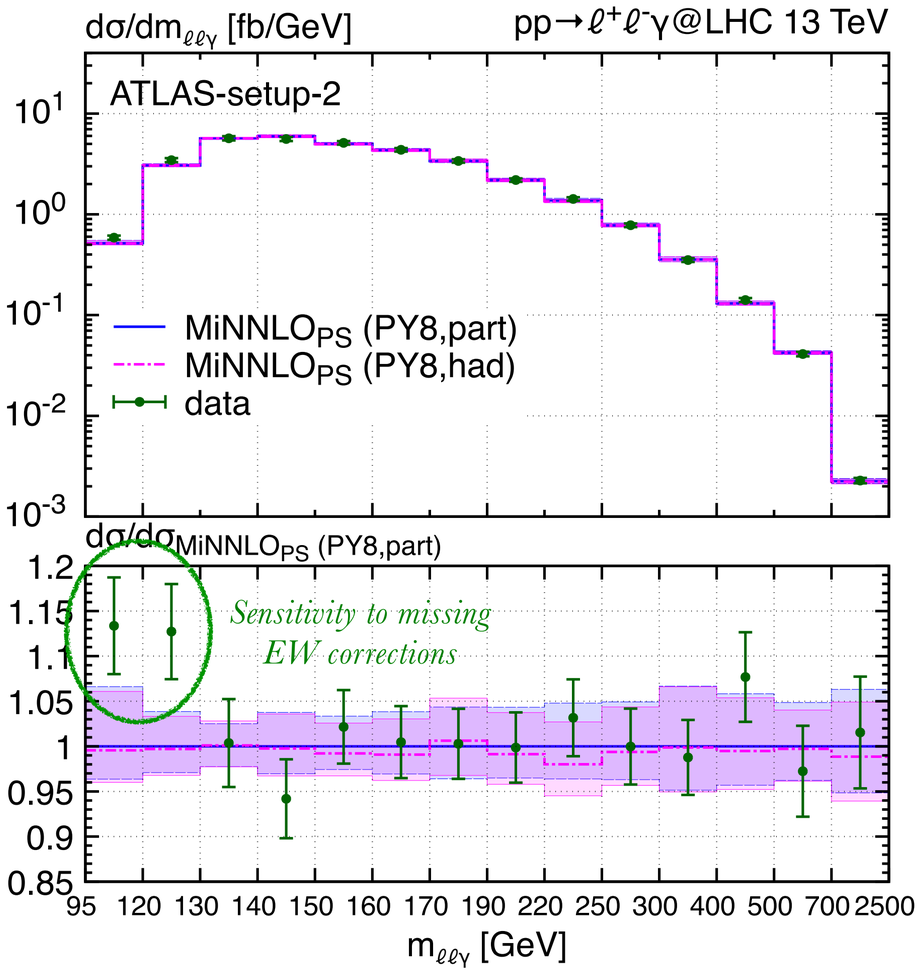
[Lombardi, MW, Zanderighi '20]

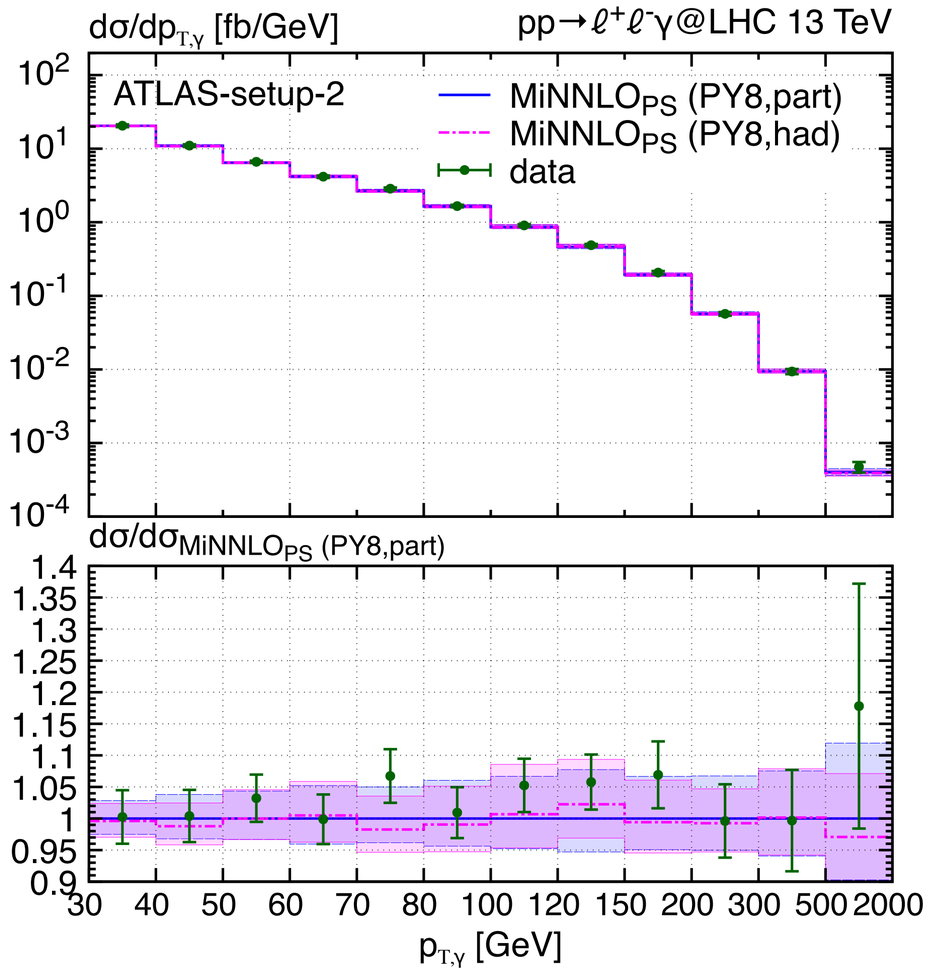




MiNNLO$_{PS}$: $Z\gamma\,(\ell\ell\gamma)$ production

[Lombardi, MW, Zanderighi '20]



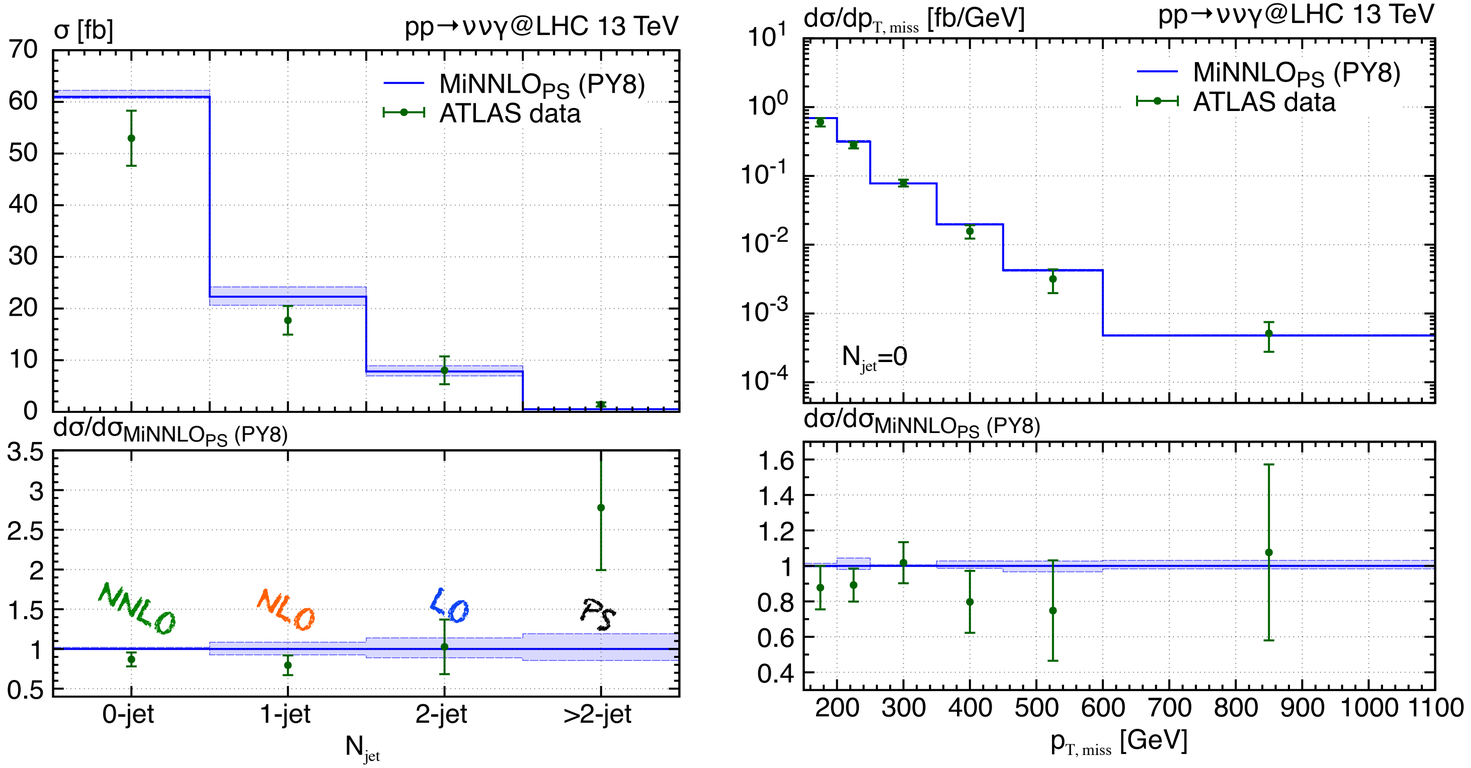


MiNNLO$_{PS}$: $Z\gamma$ ($\nu\nu\gamma$) production

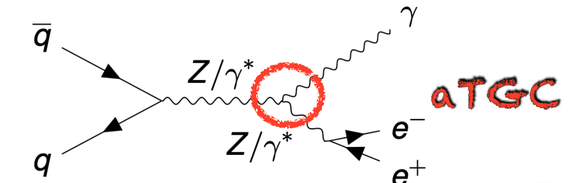
[Lombardi, MW, Zanderighi '21]

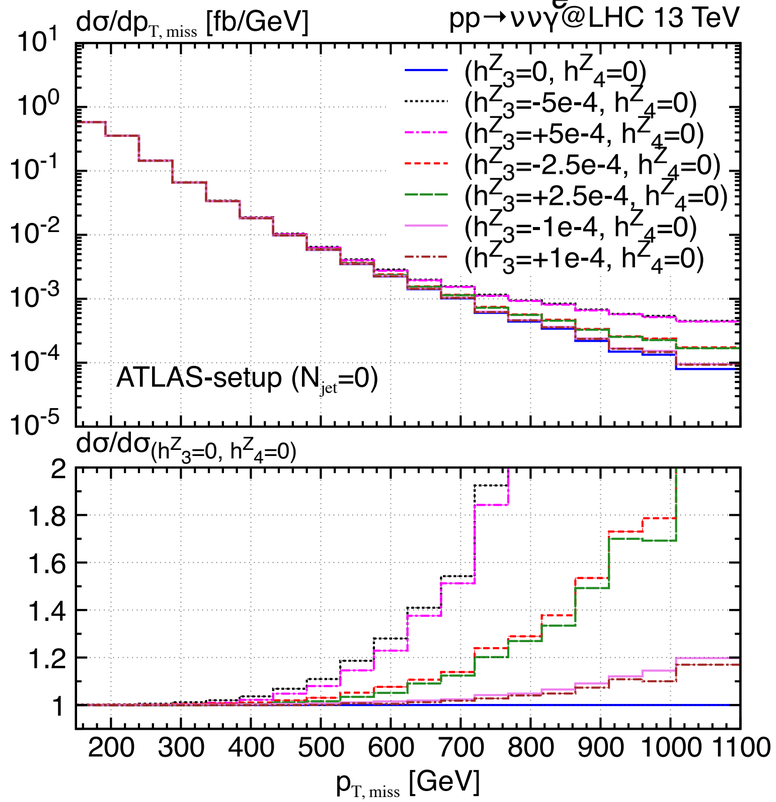
- *presence of isolated photon → theoretically challenging*
- *highly relevant as a* ***probe for BSM*** *(especially $Z \to \nu\bar{\nu}$)*

Good agreement with experimental data from ATLAS 36.1fb^{-1} analysis!

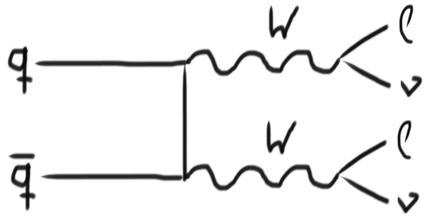


$$\Gamma^{\alpha\beta\mu}_{Z\gamma V}(q_1,q_2,p) = \frac{i(p^2-m_V^2)}{\Lambda^2}\Big(h_1^V\big(q_2^\mu g^{\alpha\beta} - q_2^\alpha g^{\mu\beta}\big) + \\ + \frac{h_2^V}{\Lambda^2}p^\alpha\Big(p\cdot q_2\; g^{\mu\beta} - q_2^\mu p^\beta\Big) - h_3^V\varepsilon^{\mu\alpha\beta\nu}q_{2\,\nu} - \frac{h_4^V}{\Lambda^2}\varepsilon^{\mu\beta\nu\sigma}p^\alpha p_\nu q_{2\,\sigma}\Big)$$



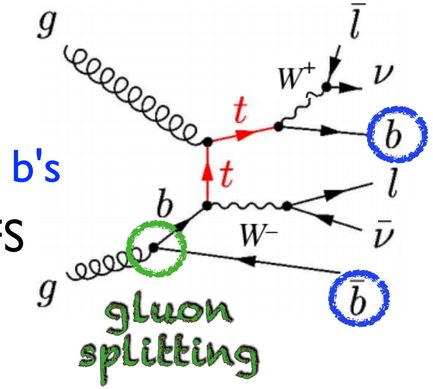


Massive VV production at (n)NNLO+PS

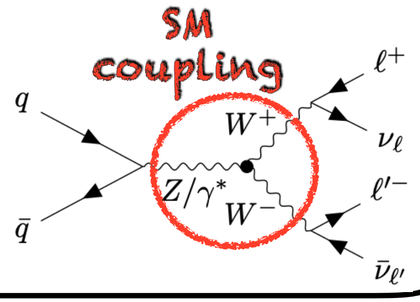


[Lombardi, MW, Zanderighi '21]

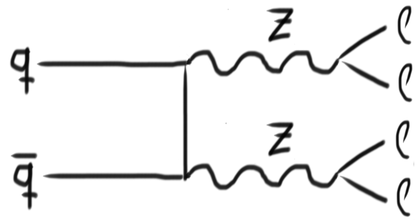
- largest cross section of massive VV processes
- no full event reconstruction due to neutrinos
- jet-veto requirement to suppress top backgrounds
  - remove diagrams with external b's
  - not finite for massless b's → 4FS
    (top-free 5FS in good agreement)
    [Grazzini, Kallweit, Pozzorini, Rathlev, MW '17]



- important Higgs background

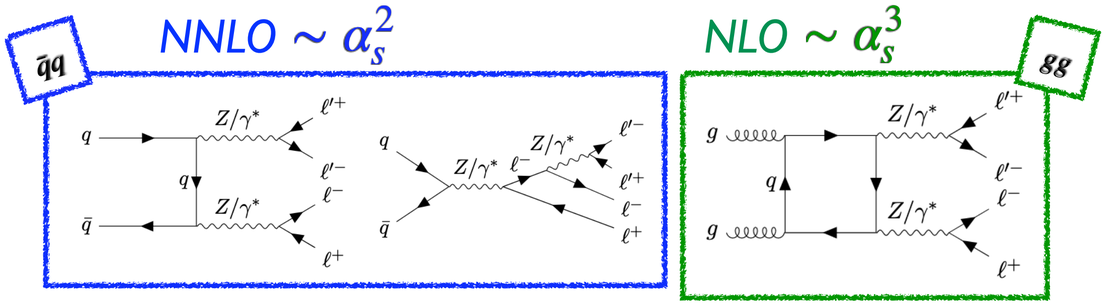


- direct access at LO to anomalous triple gauge couplings



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

- smallest cross section of massive VV, but very clean
- relevant background for Higgs and BSM



$$pp \to \ell^+\ell^-\ell^{(\prime)+}\ell^{(\prime)-}$$

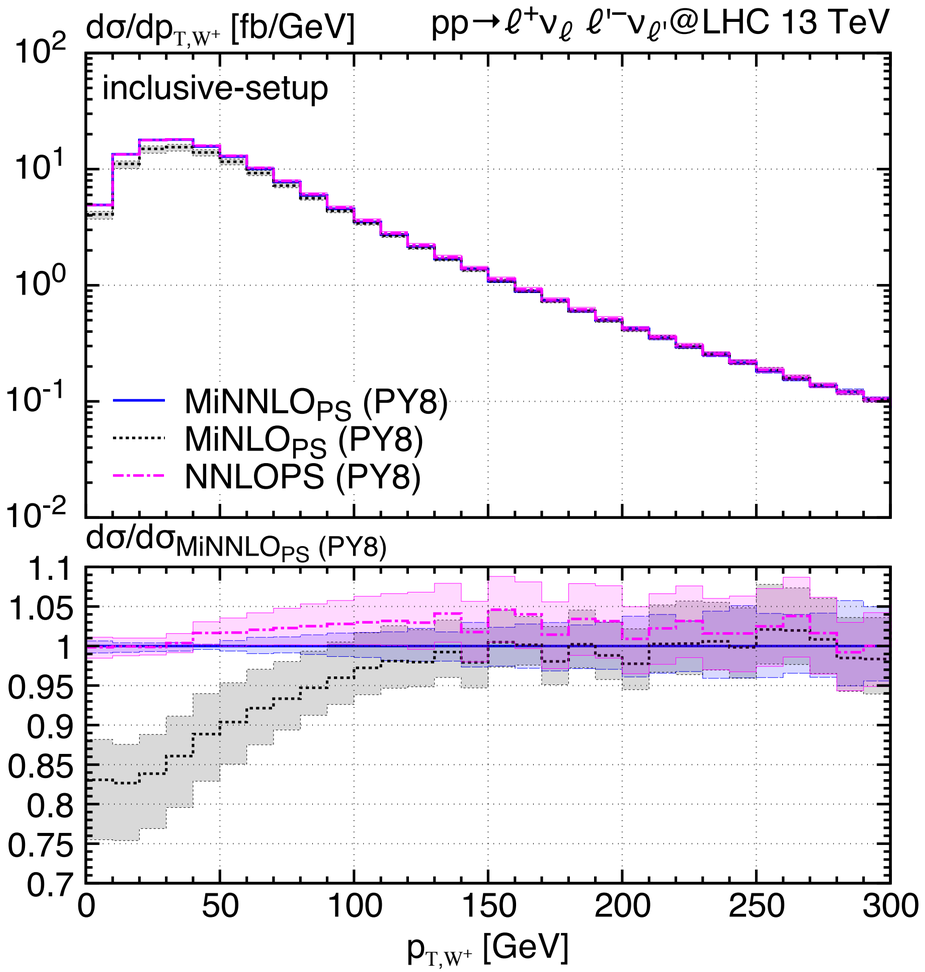
Incoherent combination → nNNLO+PS

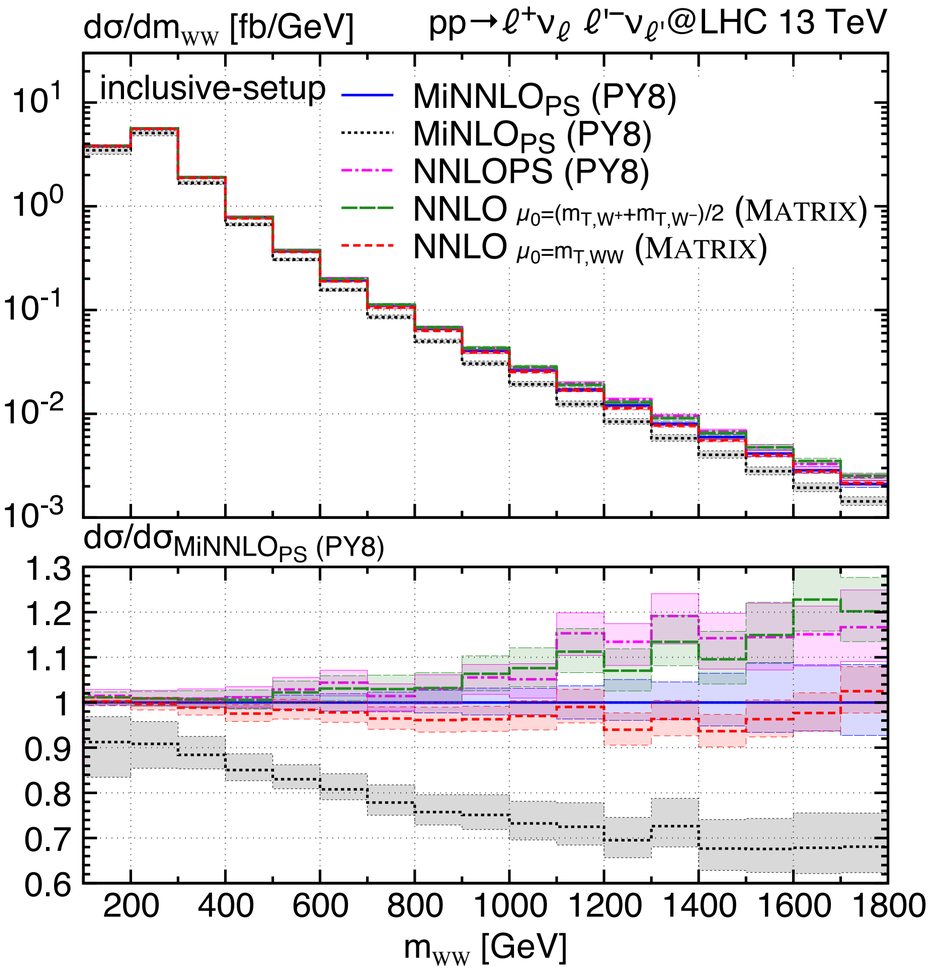
* also in [Alioli et al. '21]

* also in [Alioli, Ferrario Ravasio, Lindert, Röntsch '21]

MiNNLO$_{PS}$: $WW(\ell\nu\ell'\nu')$ production

[Lombardi, MW, Zanderighi '21]

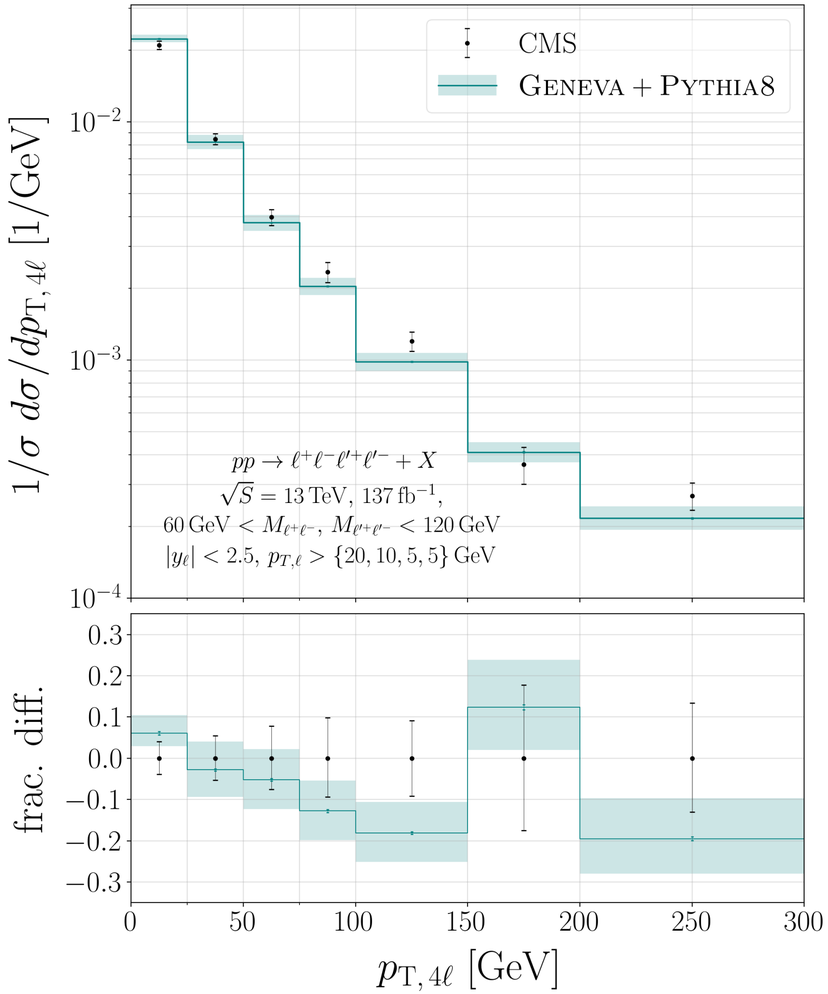




$ZZ(\ell\ell\ell'\ell')$ production

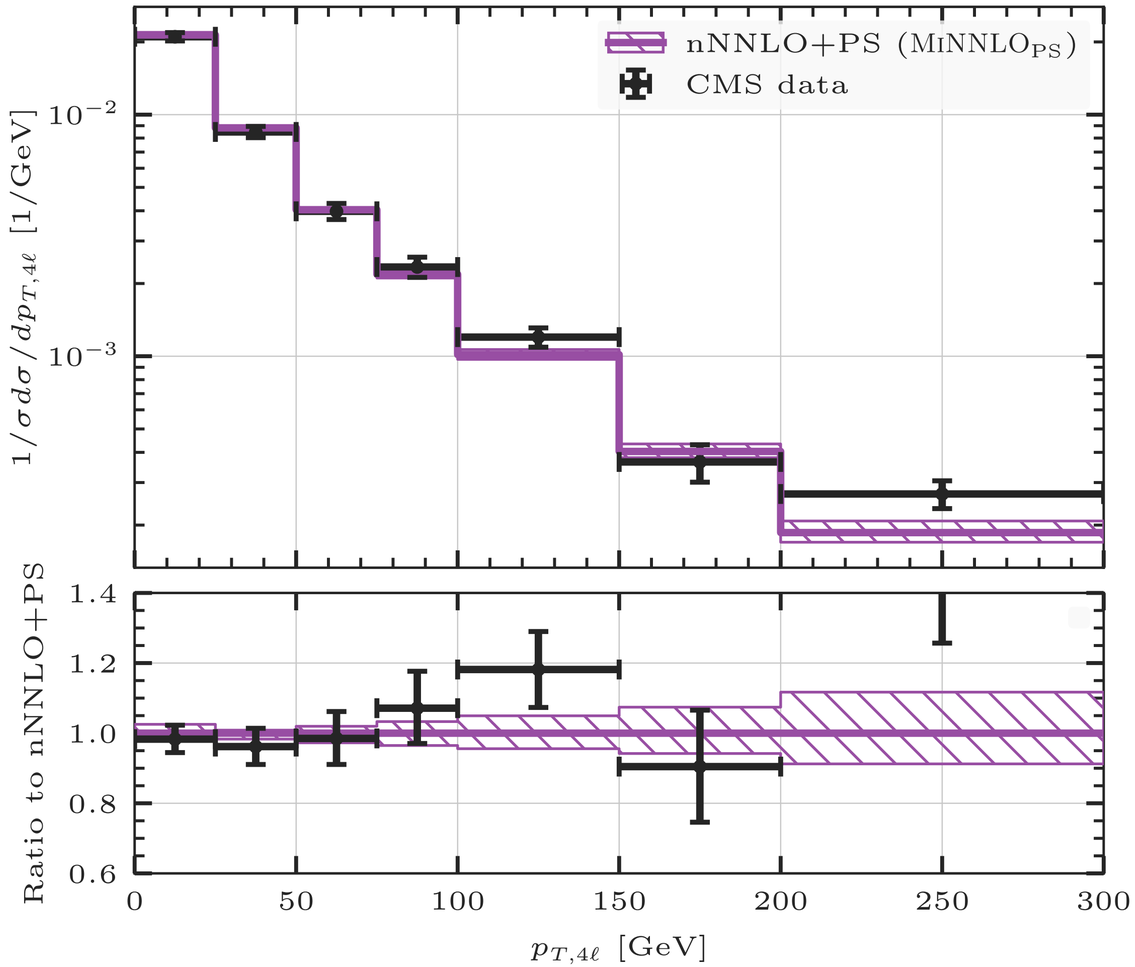
Geneva: NNLO+PS

[Alioli et al. '21]



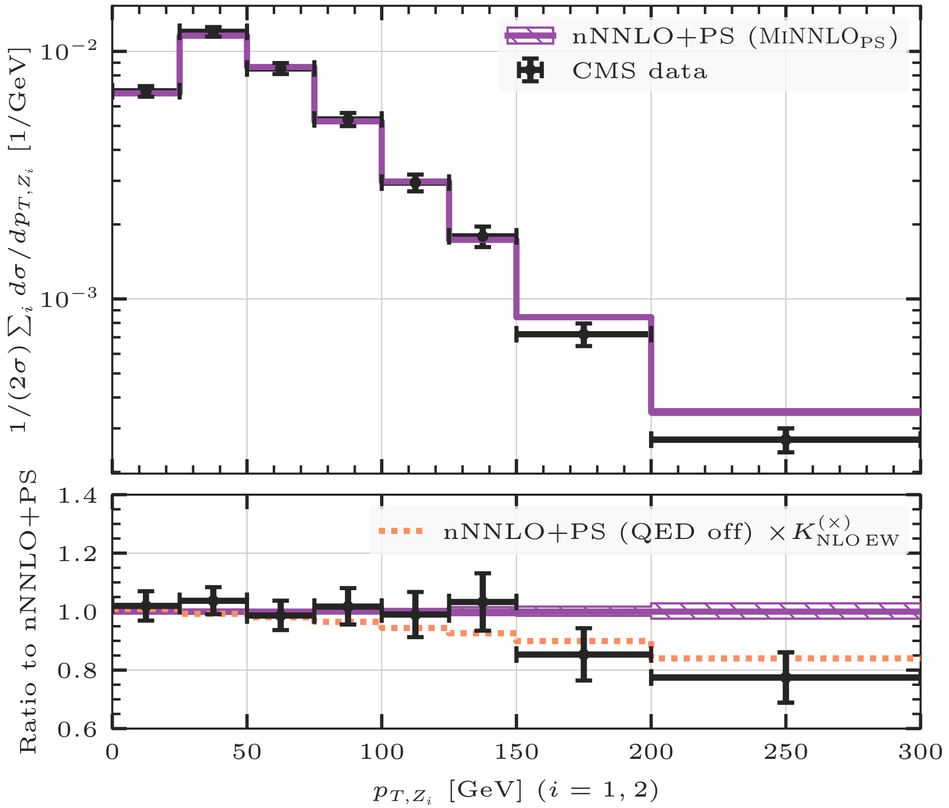
MiNNLO$_{PS}$: nNNLO+PS

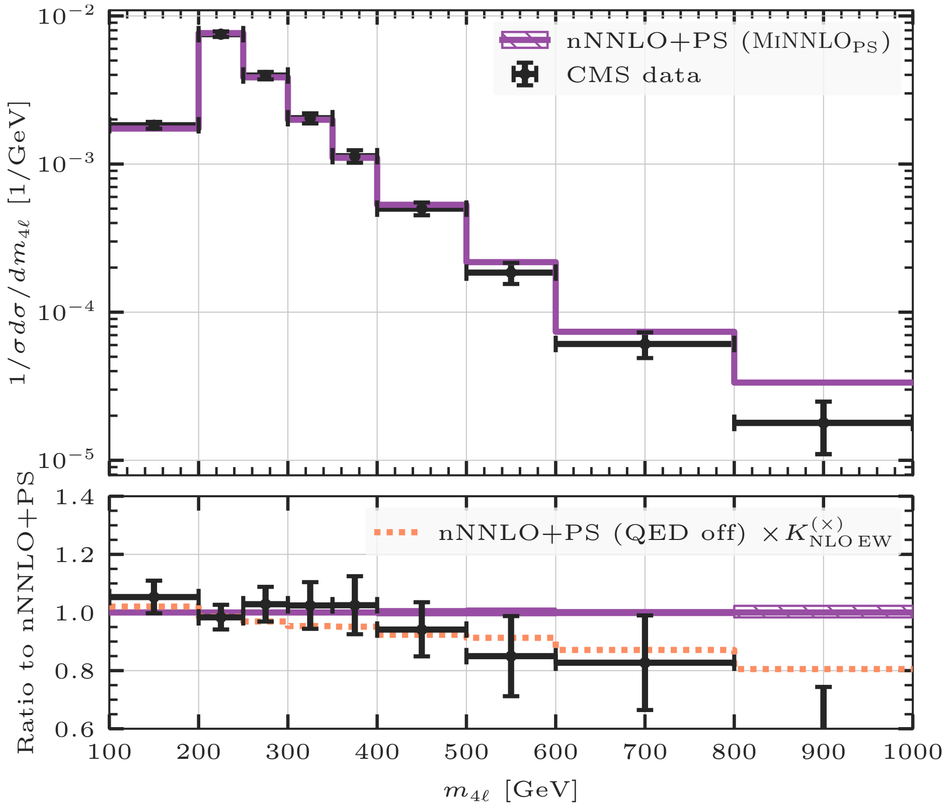
[Buonocore, Koole, Lombardi, Rottoli, MW, Zanderighi '21]



MiNNLO$_{PS}$: nNNLO+PS (x EW) for $ZZ(\ell\ell\ell'\ell')$

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

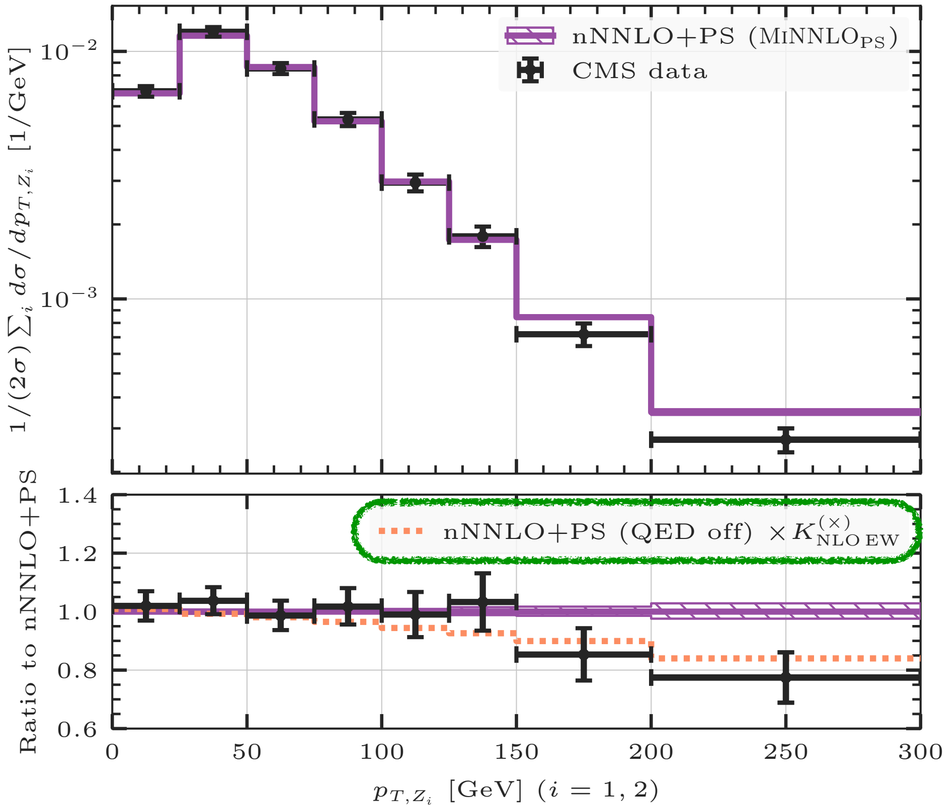


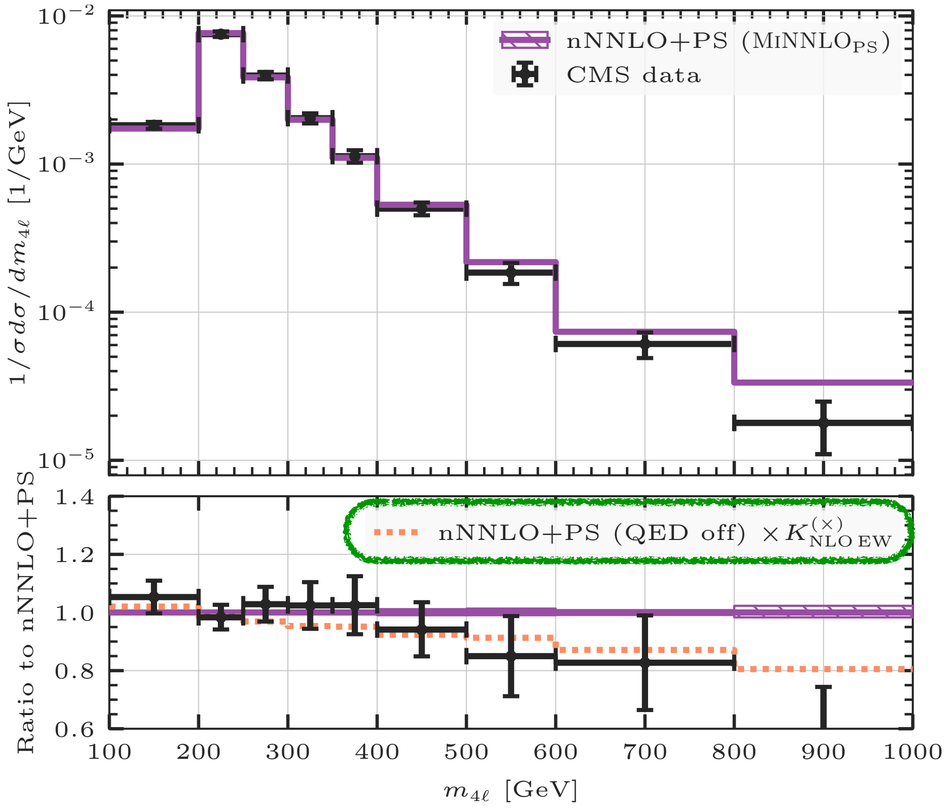


✓ *nNNLO+PS predictions in good agreement with CMS results, based on the a137fb^{-1} 13TeV analysis ([arXiv:2009.01186])!*

MiNNLO$_{PS}$: nNNLO+PS (x EW) for $ZZ(\ell\ell\ell'\ell')$

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

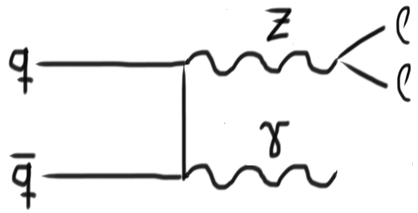


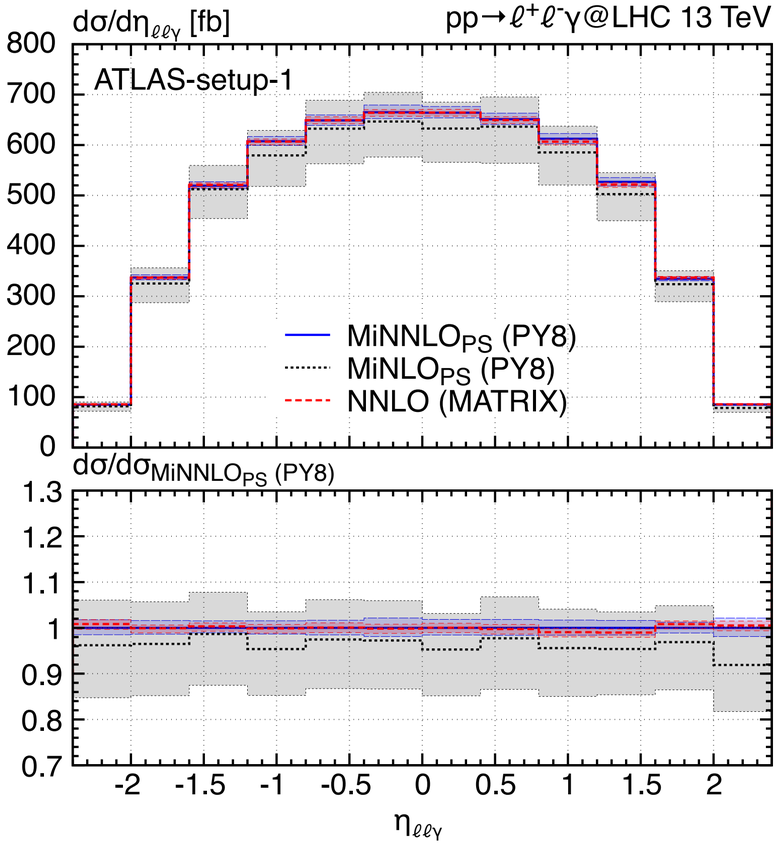


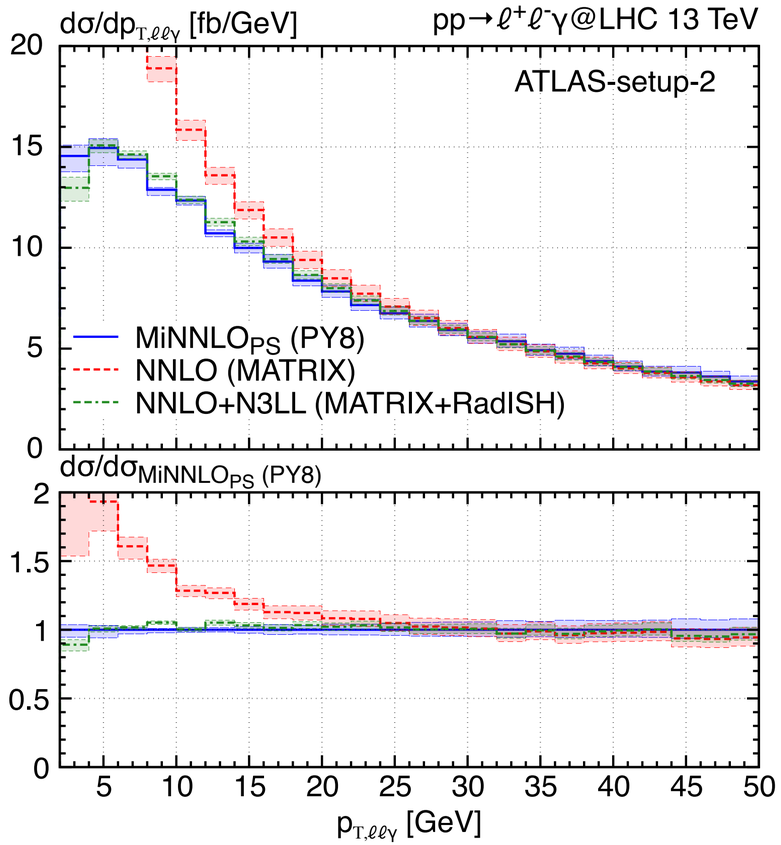
- ✓ *nNNLO+PS predictions in good agreement with CMS results, based on the a137fb^{-1} 13TeV analysis ([arXiv:2009.01186])!*
- ✓ *inclusion of EW corrections (through fixed order NLO K factor) to describe tails of distributions*

MiNNLO$_{PS}$ for 2→2 colour singlets

[Lombardi, MW, Zanderighi '20]

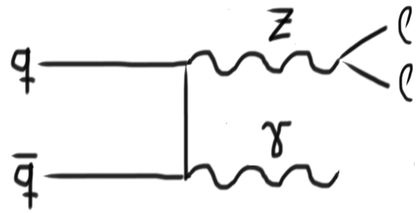


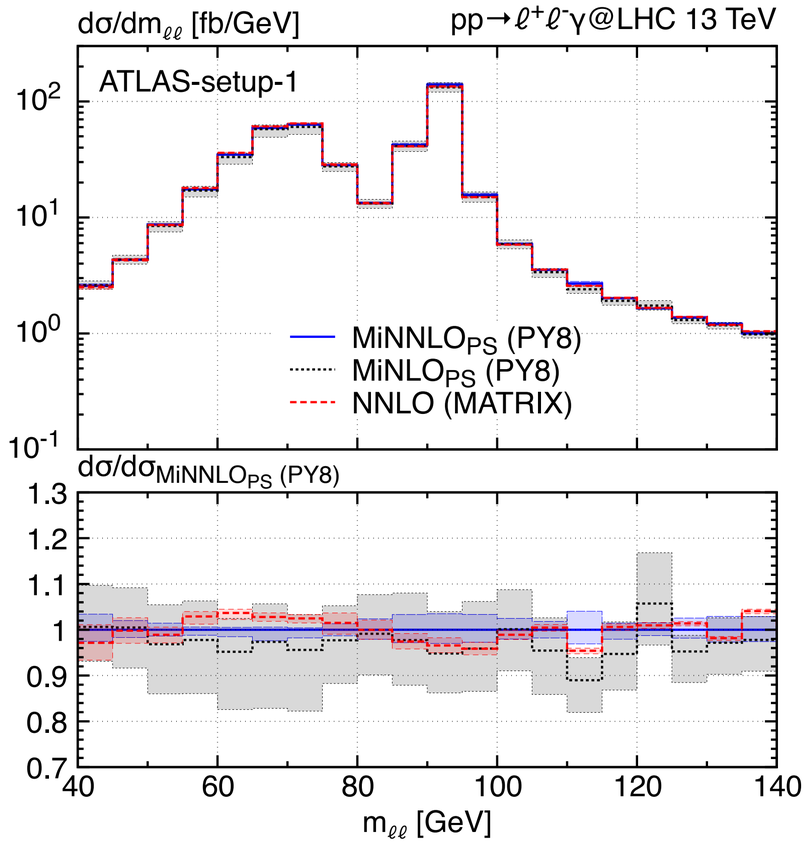


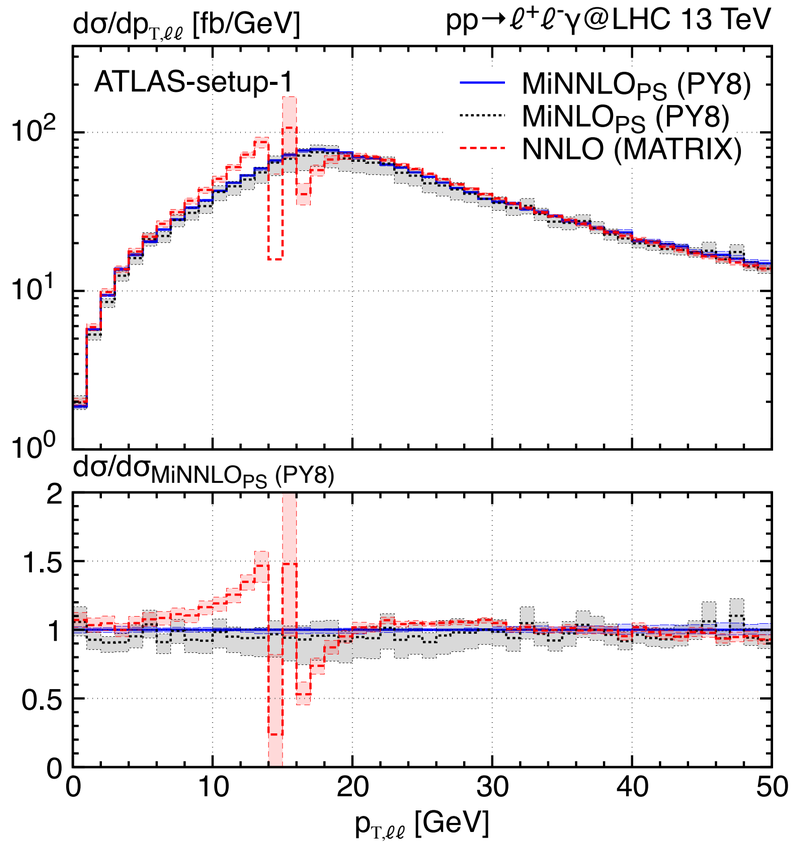


MiNNLO$_{PS}$ for 2→2 colour singlets

[Lombardi, MW, Zanderighi '20]

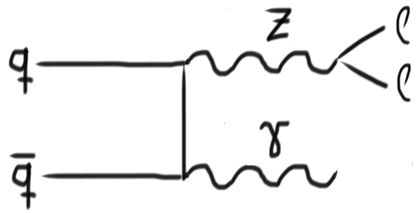


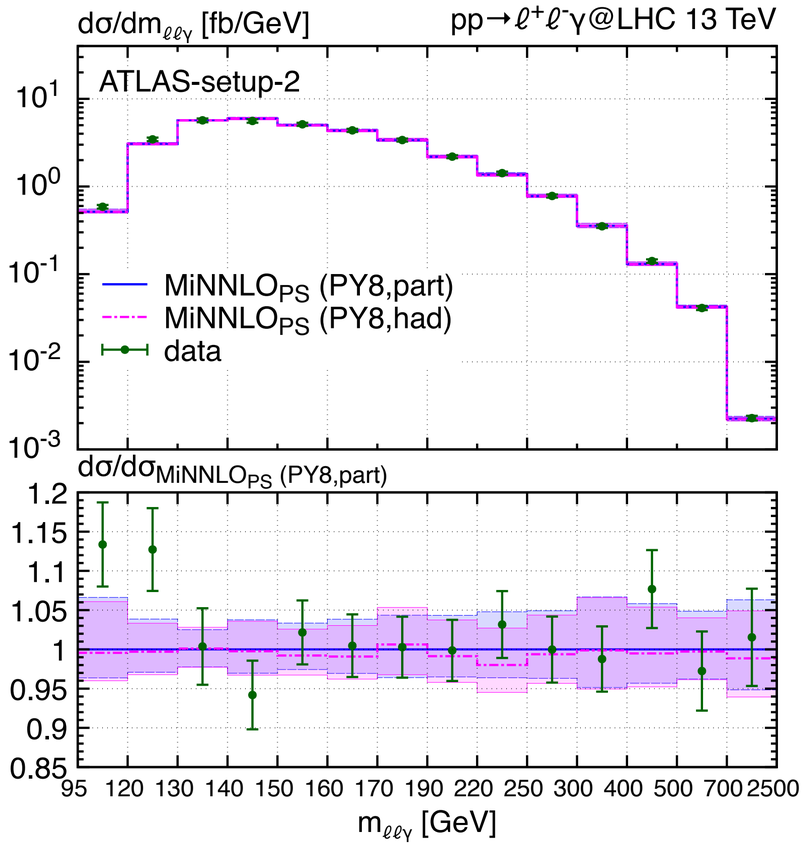


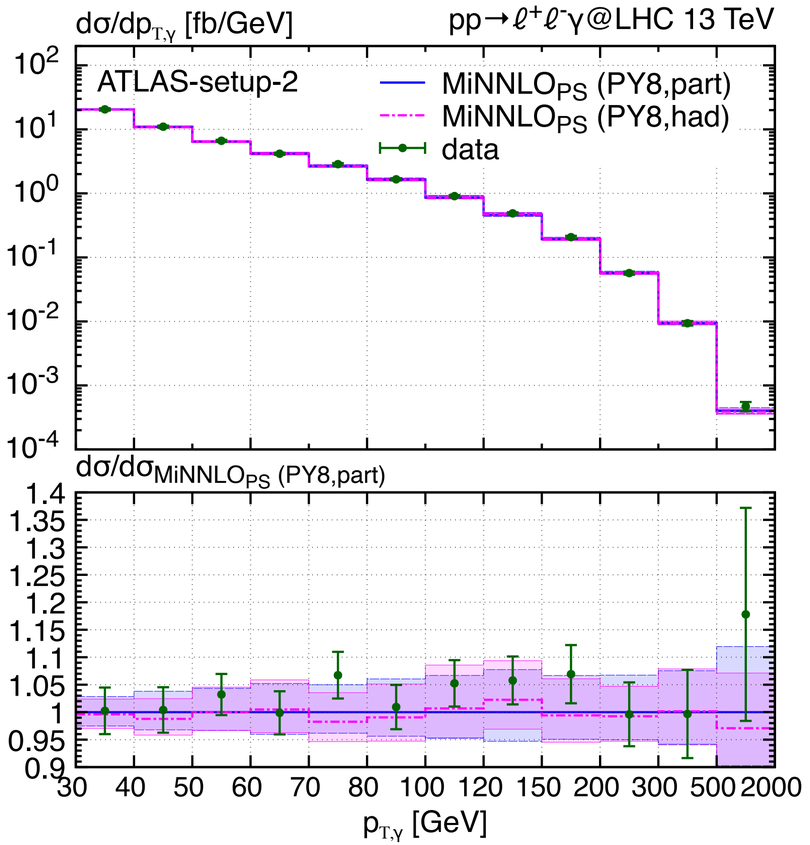


MiNNLO$_{PS}$ for 2→2 colour singlets

[Lombardi, MW, Zanderighi '20]

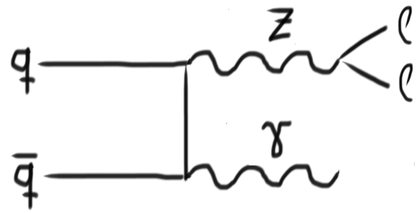


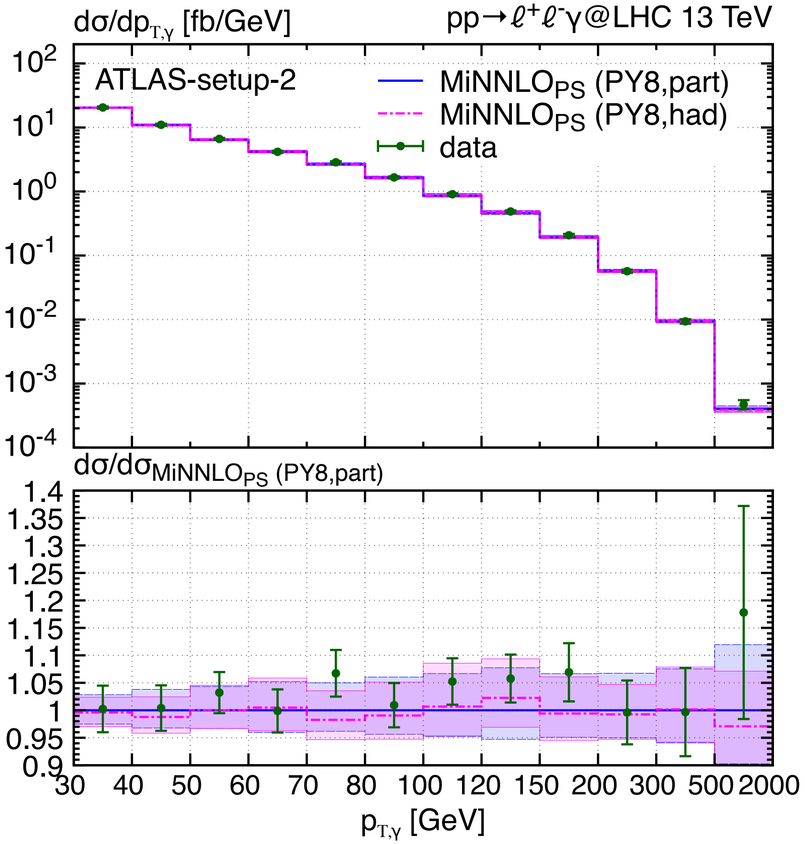


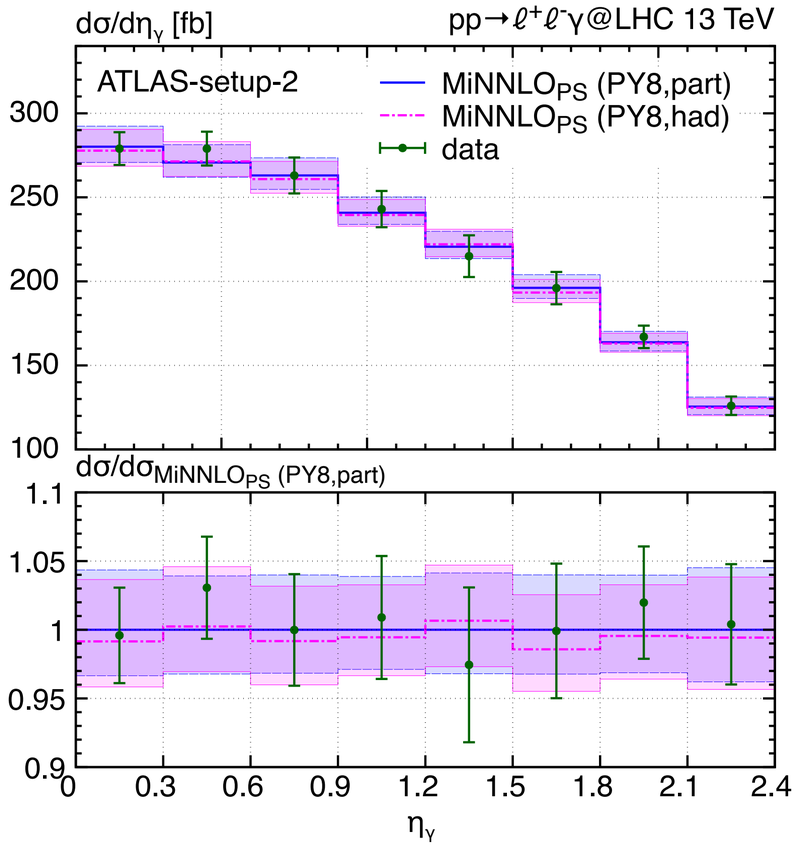


MiNNLO$_{PS}$ for 2→2 colour singlets

[Lombardi, MW, Zanderighi '20]

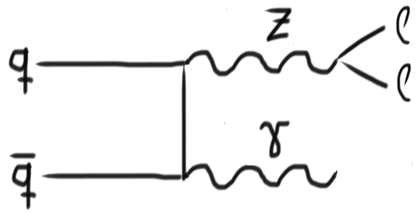


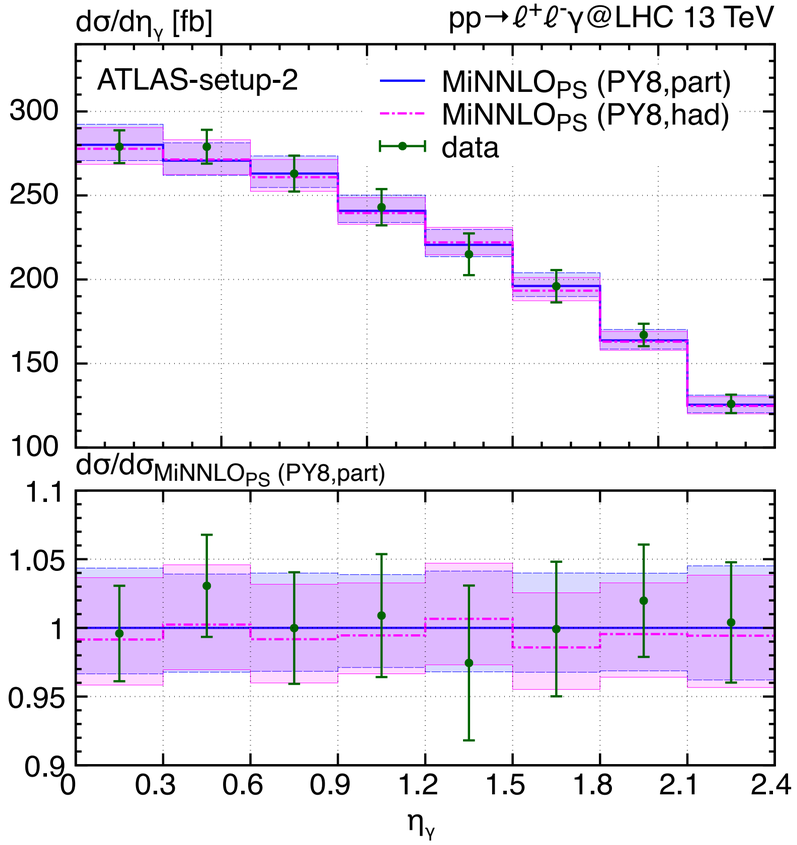


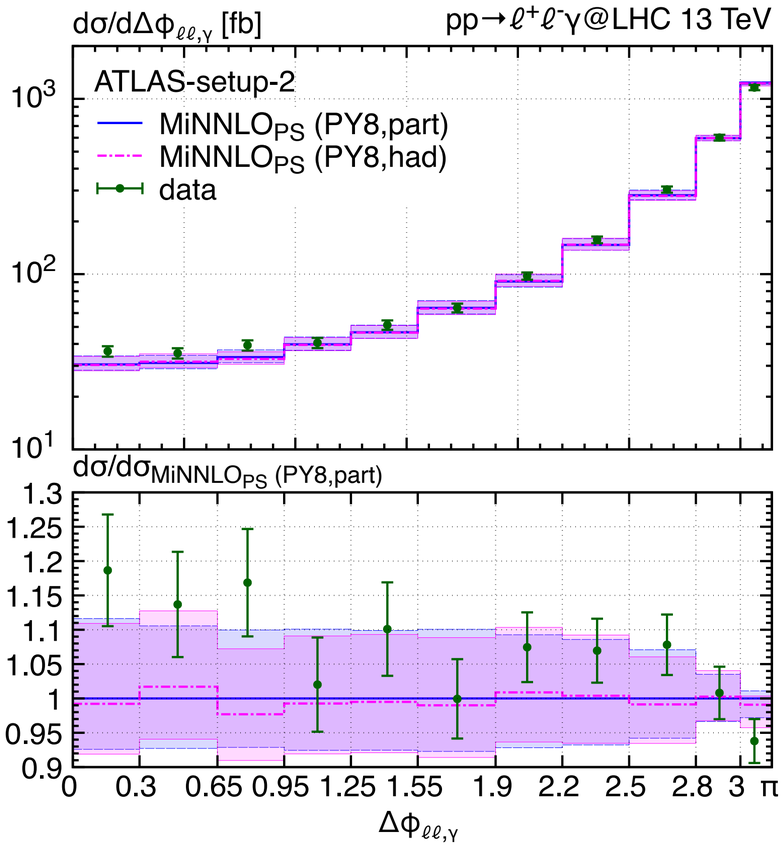


MiNNLO$_{PS}$ for 2→2 colour singlets

[Lombardi, MW, Zanderighi '20]

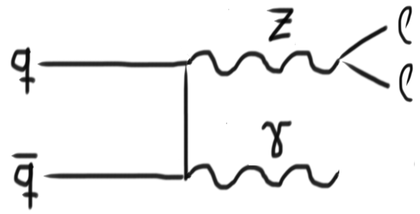


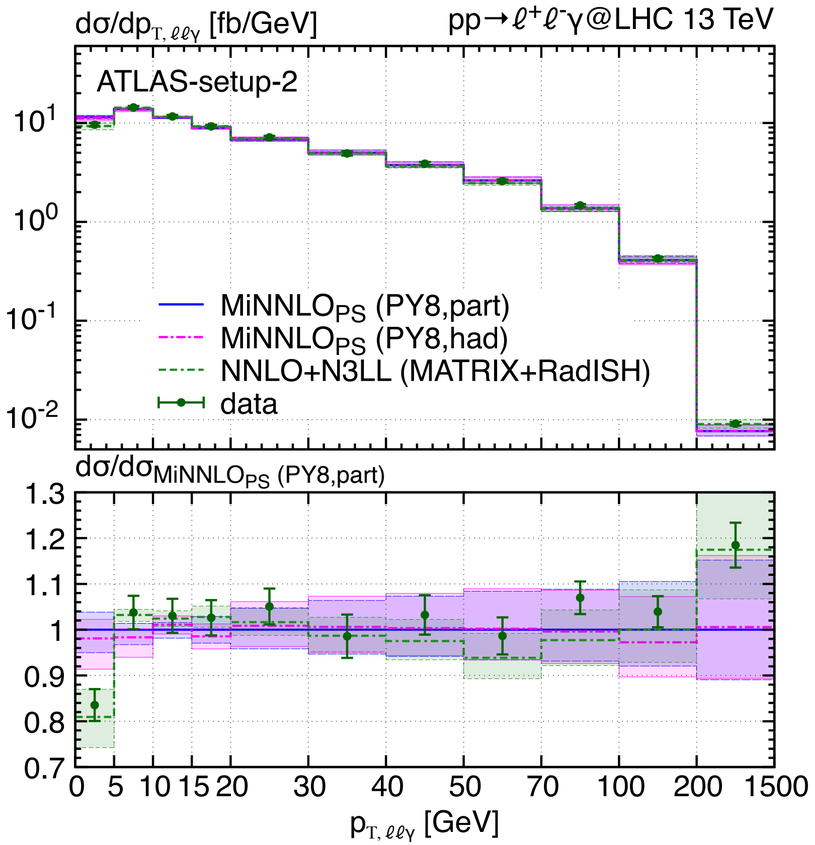




MiNNLO$_{PS}$ for 2→2 colour singlets

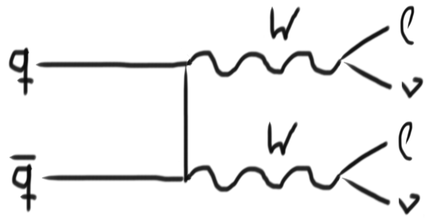
[Lombardi, MW, Zanderighi '20]





MiNNLO$_{PS}$ for 2→2 colour singlets

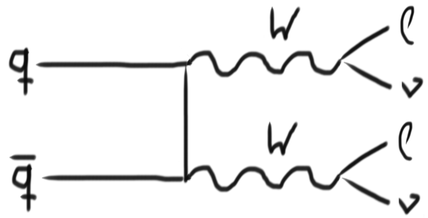
[Lombardi, MW, Zanderighi '21]



$\sigma(pp \to \ell^+\nu_\ell\,\ell'^-\nu_{\ell'})$ [fb]	`setup-inclusive`	`fiducial-1-JV`	`fiducial-2-JV`
MiNLO′	$1156.6(4)^{+5.4\%}_{-5.7\%}$	$185.0(2)^{+8.8\%}_{-6.5\%}$	$143.2(2)^{+4.9\%}_{-8.1\%}$
MiNNLO$_{\rm PS}$	$1292.2(7)^{+0.6\%}_{-0.7\%}$	$207.7(2)^{+1.6\%}_{-1.7\%}$	$159.2(4)^{+1.0\%}_{-1.4\%}$
NNLOPS *[arXiv:1805.09857]*	$1308.9(3)^{+1.7\%}_{-1.6\%}$	$206.4(1)^{+2.2\%}_{-2.3\%}$	$159.0(1)^{+1.7\%}_{-1.8\%}$
NNLO $\mu_0 = (m_{{\rm T},W^+} + m_{{\rm T},W^-})/2$	$1306.5(5)^{+1.6\%}_{-1.6\%}$	$206.5(1)^{+1.0\%}_{-0.7\%}$	$158.9(5)^{+0.8\%}_{-0.6\%}$
NNLO $\mu_0 = m_{{\rm T},WW}$	$1284.9(10)^{+1.4\%}_{-1.3\%}$	—	$160.8(3)^{+1.0\%}_{-0.8\%}$
ATLAS$-gg$ *[arXiv:1702.04519]*	$1481 \pm 59_{\rm (stat)} \pm 154_{\rm (syst)} \pm 108_{\rm (lumi)}$	$236.5 \pm 10_{\rm (stat)} \pm 25_{\rm (syst)} \pm 5.5_{\rm (lumi)}$	—
ATLAS$-gg$ *[arXiv:1905.04242]*	—	—	$178.5 \pm 2.5_{\rm (stat)} \pm 12.7_{\rm (syst)} \pm 4_{\rm (lumi)}$
CMS$-gg$ *[CMS-PAS-SMP-16-006]*	$1289 \pm 68_{\rm (stat)} {}^{\pm 67_{\rm (exp.\ syst)}}_{\pm 76_{\rm (th.\ syst)}} \pm 42_{\rm (lumi)}$	—	—
CMS$-gg$ *[arXiv:2009.00119]*	$1316 \pm 65_{\rm (stat)} \pm 23_{\rm (syst)} \pm 38_{\rm (lumi)}$	—	—

MiNNLO$_{PS}$ for 2→2 colour singlets

[Lombardi, MW, Zanderighi '21]



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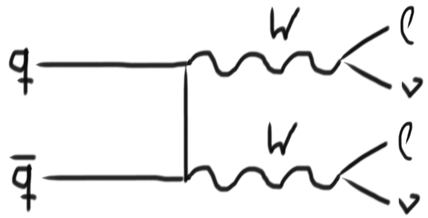
MiNNLO$_{PS}$	$1292.2(7)^{+0.6\%}_{-0.7\%}$ ↘ 10 %	$207.7(2)^{+1.6\%}_{-1.7\%}$ ↘ 10 %	$159.2(4)^{+1.0\%}_{-1.4\%}$ ↘ 10 %
NNLOPS *[arXiv:1805.09857]*	$1308.9(3)^{+1.7\%}_{-1.6\%}$	$206.4(1)^{+2.2\%}_{-2.3\%}$	$159.0(1)^{+1.7\%}_{-1.8\%}$
NNLO $\mu_0 = (m_{T,W^+} + m_{T,W^-})/2$	$1306.5(5)^{+1.6\%}_{-1.6\%}$	$206.5(1)^{+1.0\%}_{-0.7\%}$	$158.9(5)^{+0.8\%}_{-0.6\%}$
NNLO $\mu_0 = m_{T,WW}$	$1284.9(10)^{+1.4\%}_{-1.3\%}$	—	$160.8(3)^{+1.0\%}_{-0.8\%}$
ATLAS−gg *[arXiv:1702.04519]*	$1481 \pm 59_{(\text{stat})} \pm 154_{(\text{syst})} \pm 108_{(\text{lumi})}$	$236.5 \pm 10_{(\text{stat})} \pm 25_{(\text{syst})} \pm 5.5_{(\text{lumi})}$	—
ATLAS−gg *[arXiv:1905.04242]*	—	—	$178.5 \pm 2.5_{(\text{stat})} \pm 12.7_{(\text{syst})} \pm 4_{(\text{lumi})}$
CMS−gg *[CMS-PAS-SMP-16-006]*	$1289 \pm 68_{(\text{stat})}{}^{\pm 67_{(\text{exp. syst})}}_{\pm 76_{(\text{th. syst})}} \pm 42_{(\text{lumi})}$	—	—
CMS−gg *[arXiv:2009.00119]*	$1316 \pm 65_{(\text{stat})} \pm 23_{(\text{syst})} \pm 38_{(\text{lumi})}$	—	—

- *sizeable NNLO corrections + improved accuracy*

MiNNLOPS for 2→2 colour singlets

[Lombardi, MW, Zanderighi '21]



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ATLAS−gg [arXiv:1905.04242]	—	—	$178.5 \pm 2.5_{(\mathrm{stat})} \pm 12.7_{(\mathrm{syst})} \pm 4_{(\mathrm{lumi})}$
CMS−gg [CMS-PAS-SMP-16-006]	$1289 \pm 68_{(\mathrm{stat})} {}^{\pm 67_{(\mathrm{exp.\ syst})}}_{\pm 76_{(\mathrm{th.\ syst})}} \pm 42_{(\mathrm{lumi})}$	—	—
CMS−gg [arXiv:2009.00119]	$1316 \pm 65_{(\mathrm{stat})} \pm 23_{(\mathrm{syst})} \pm 38_{(\mathrm{lumi})}$	—	—

1.3 %

1.7 %

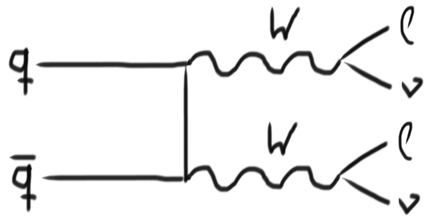
0.1 %

1.2 %

- *sizeable NNLO corrections + improved accuracy*
- *good agreement among NNLO predictions (differences induced by scale settings)*

MiNNLO$_{PS}$ for 2→2 colour singlets

[Lombardi, MW, Zanderighi '21]



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CMS−gg *[CMS-PAS-SMP-16-006]*	$1289 \pm 68_{\rm (stat)}{}^{\pm 67_{\rm (exp.\ syst)}}_{\pm 76_{\rm (th.\ syst)}} \pm 42_{\rm (lumi)}$	—	—
CMS−gg *[arXiv:2009.00119]*	$1316 \pm 65_{\rm (stat)} \pm 23_{\rm (syst)} \pm 38_{\rm (lumi)}$	—	—

- *sizeable NNLO corrections + improved accuracy*
- *good agreement among NNLO predictions (differences induced by scale settings)*
- 1-2 σ *agreement with data in all setups*

MiNNLO$_{PS}$: $WW(\ell\nu\ell'\nu')$ production

[Lombardi, MW, Zanderighi '21]

- ✓ *Normalization and accuracy improvement by including NNLO corrections*
- ✓ *Parton shower cures perturbative instabilities due to a fiducial $p_{T,miss}$ cut of 20GeV*