High precision for vector-boson pair production at the LHC

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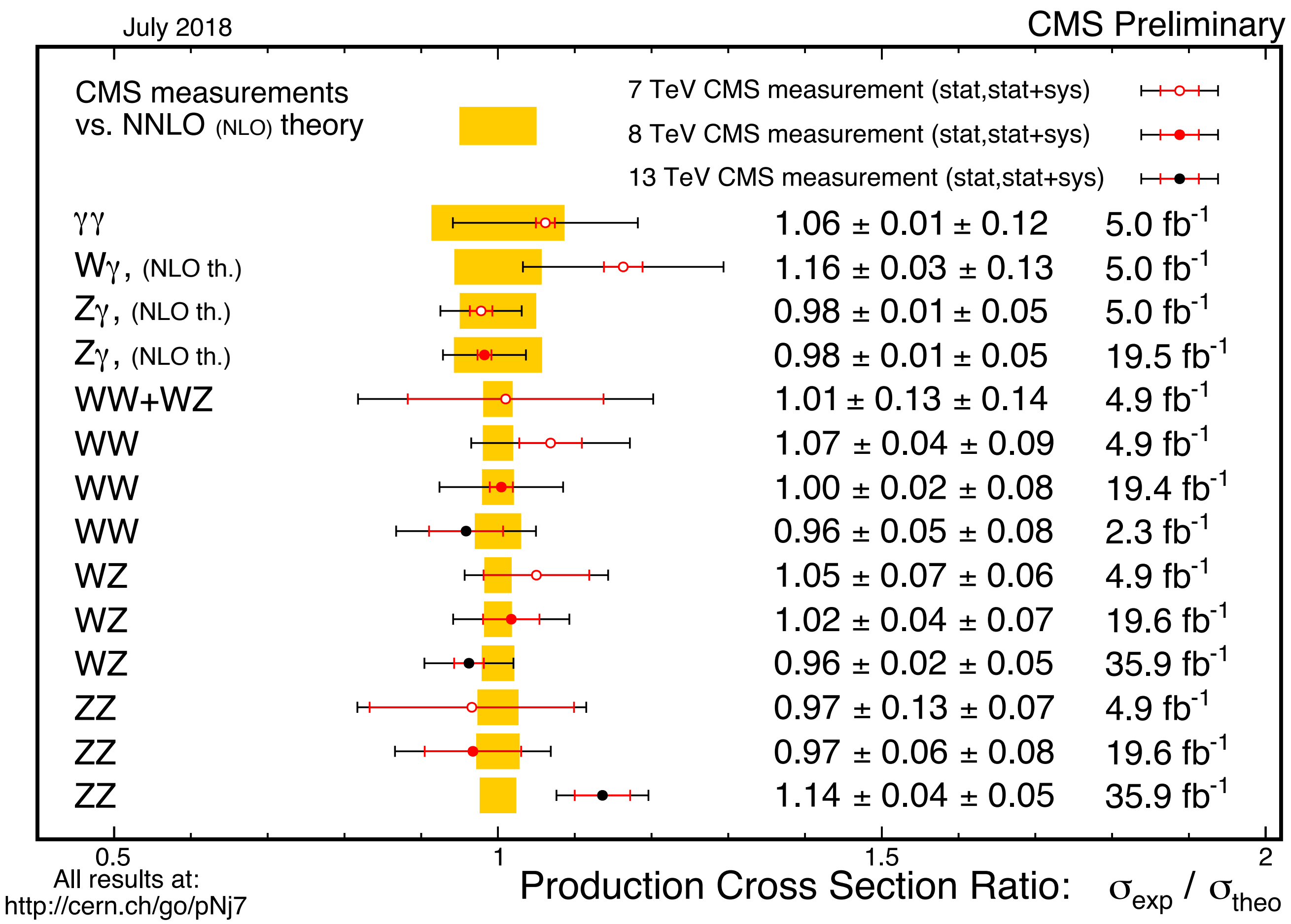
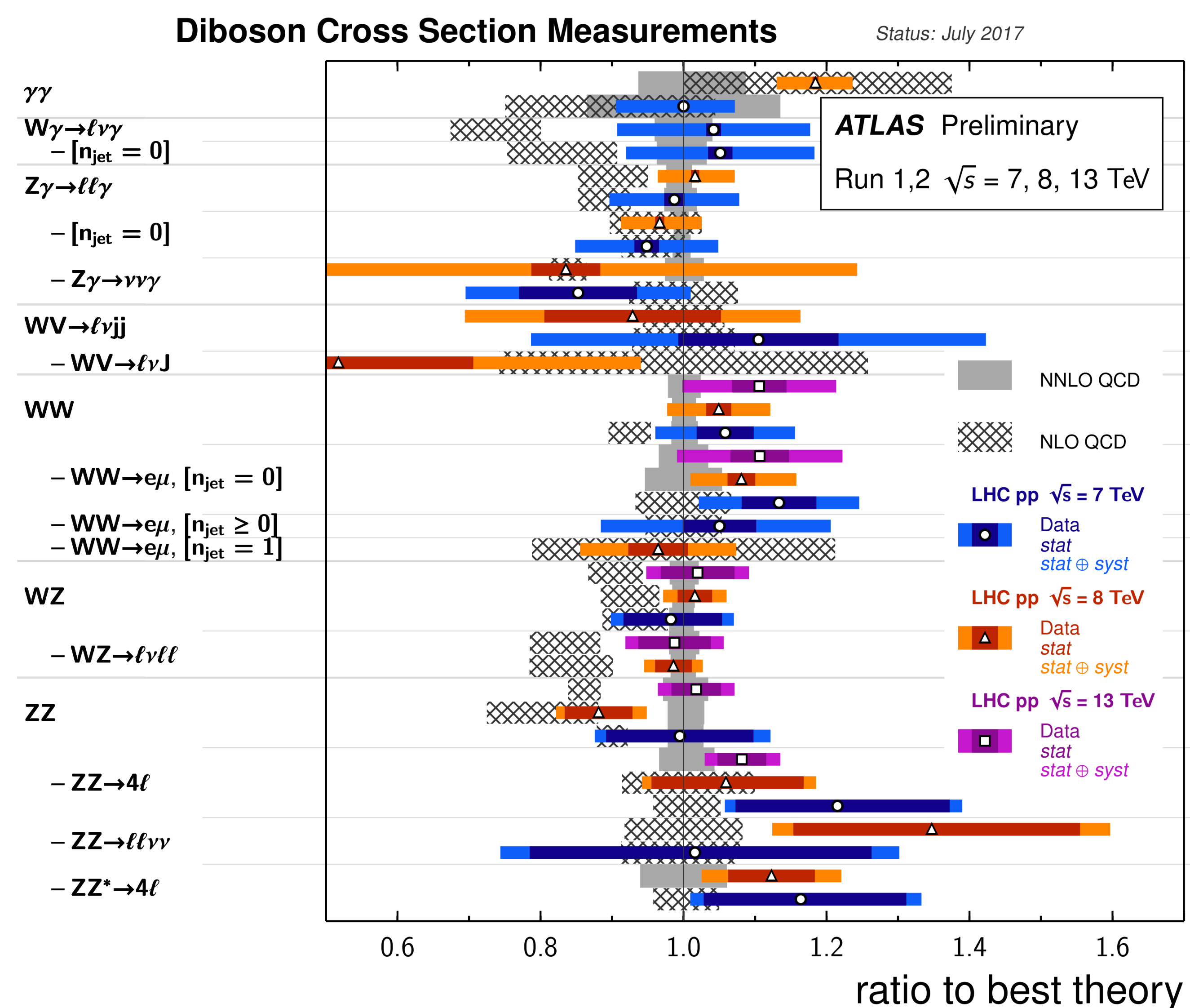
Max-Planck-Institut
für Physik

Standard Model at the LHC 2019

Zurich (Switzerland), April 23th-26th, 2019

Measured diboson cross sections





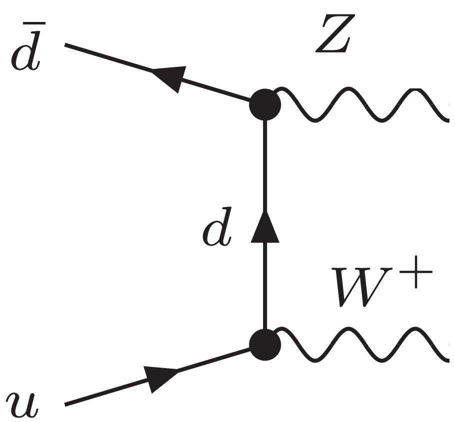
→ ***talks by Evgenii Baldin and Pietro Vischia...***

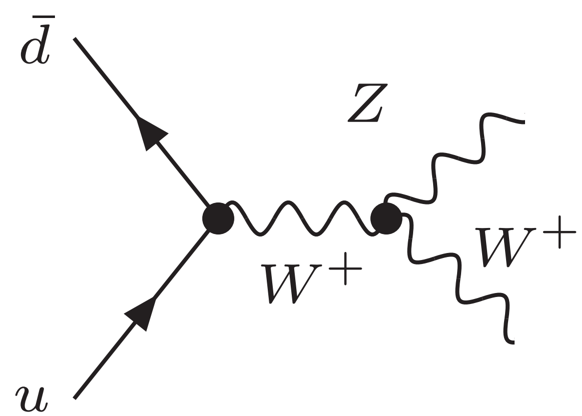
VV production in a nutshell

example: WZ production

VV production in a nutshell

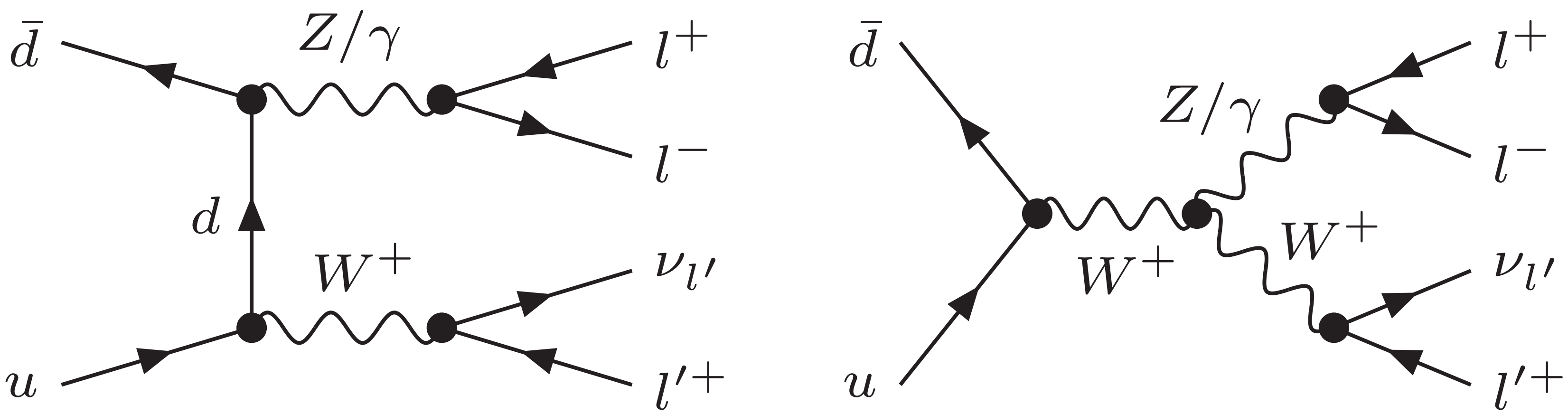
example: WZ production (on-shell)





VV production in a nutshell

example: WZ production (off-shell)



- EW decays of heavy bosons (W, Z, γ^*) ✓ (only isolated photons in the final state)

VV production in a nutshell

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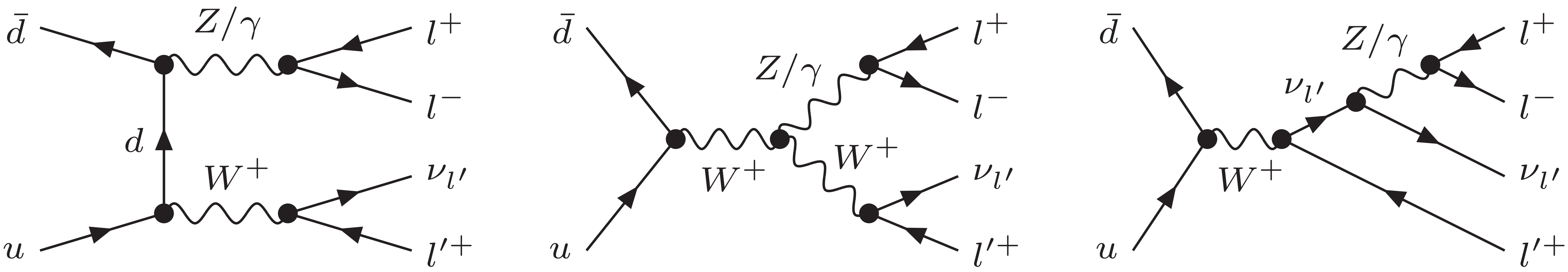

- EW decays of heavy bosons (W, Z, γ^*) ✓ (only isolated photons in the final state)
- all topologies to same leptonic final state (with spin correlations & off-shell effects) ✓

VV production in a nutshell

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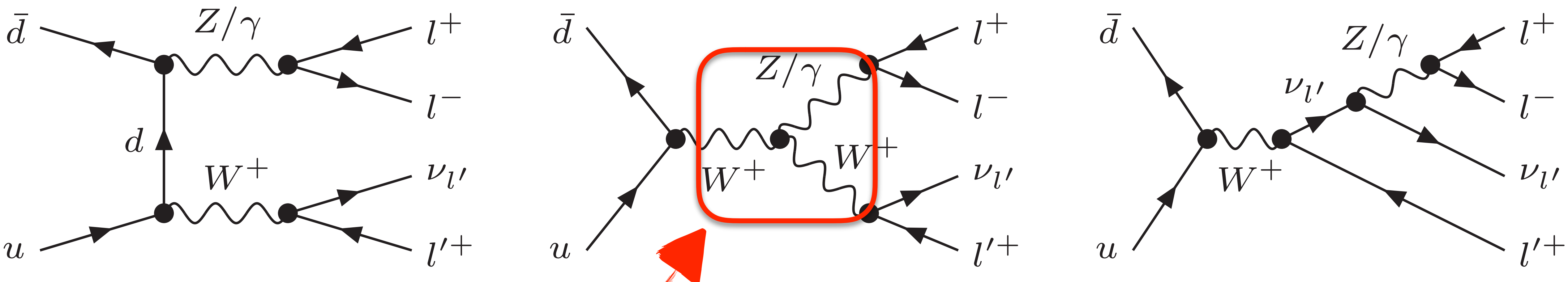

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→ access to triple gauge couplings (TGCs) → high relevance for BSM physics

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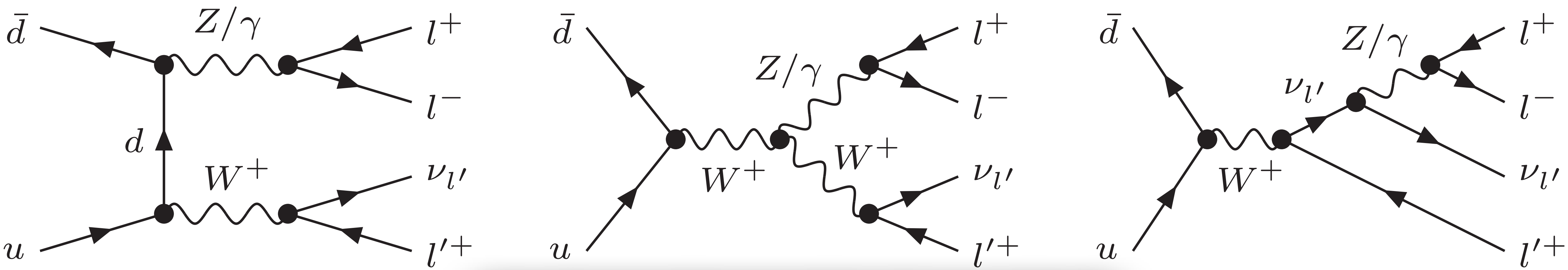
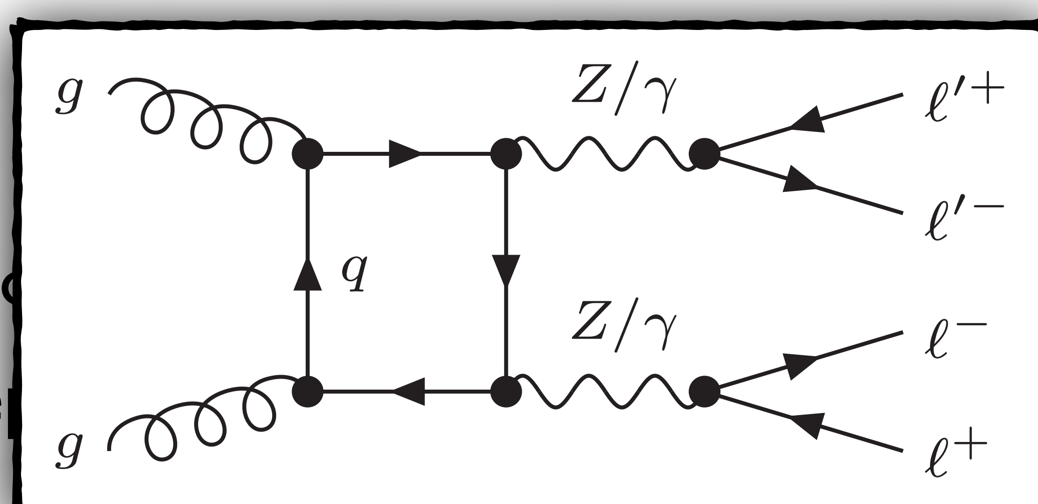
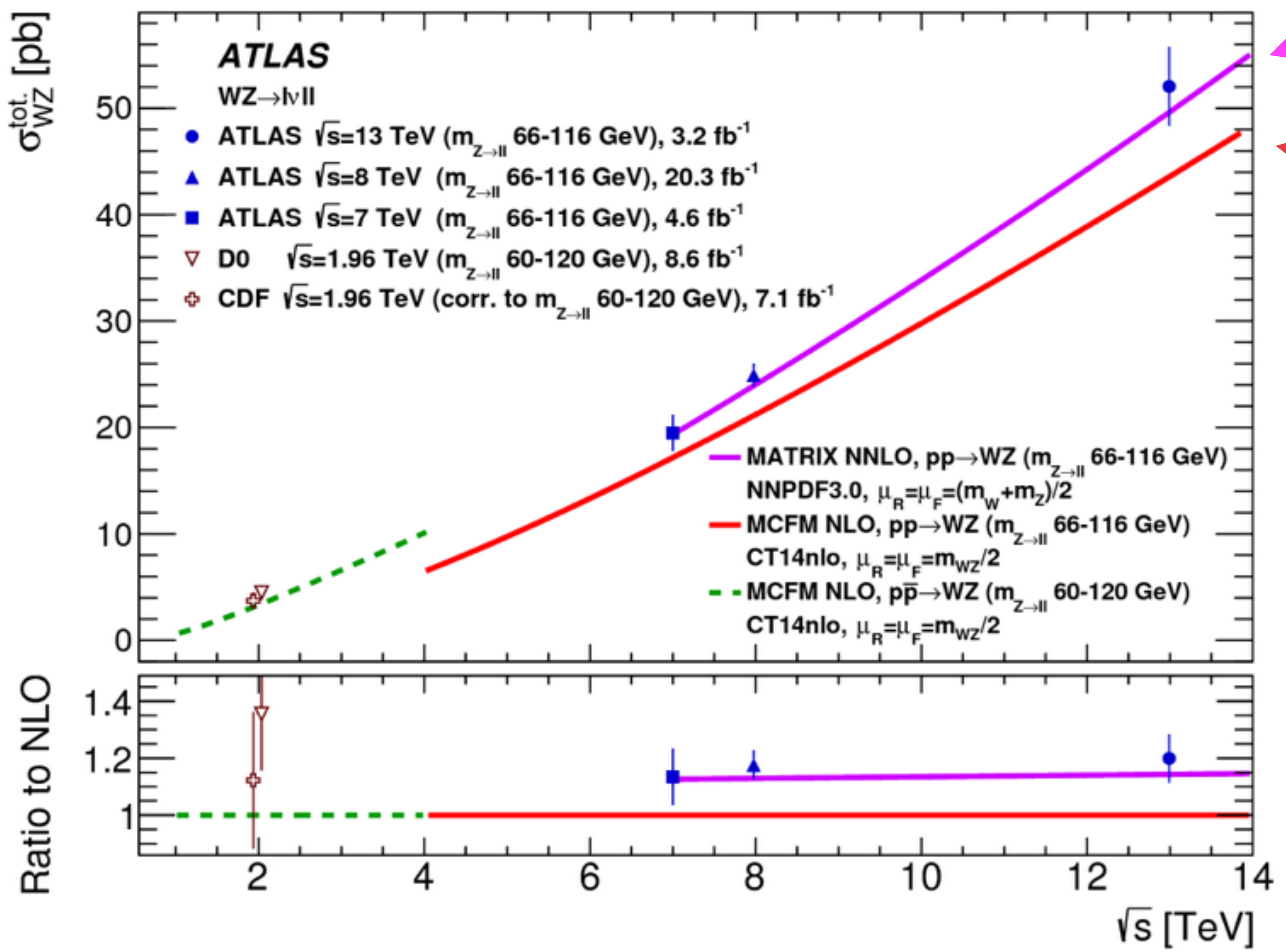
example: WZ production (off-shell)





- EW decays of heavy bos[...] photons in the final state)
- all topologies to same le[...]tions & off-shell effects) ✓
  → access to triple gauge couplings (TGCs) → high relevance for BSM physics
- loop-induced gg channel enters NNLO for charge-neutral processes ✓ (eg, for ZZ)

Importance of QCD corrections
(example WZ)



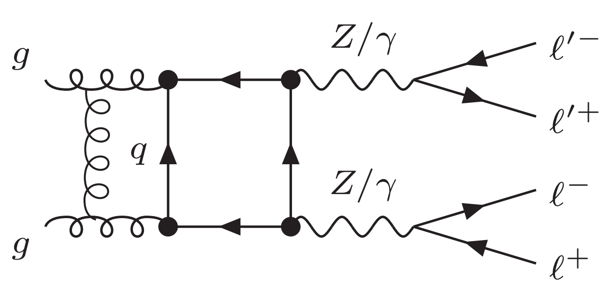
NNLO crucial for accurate description of data

SM predictions: what is there?

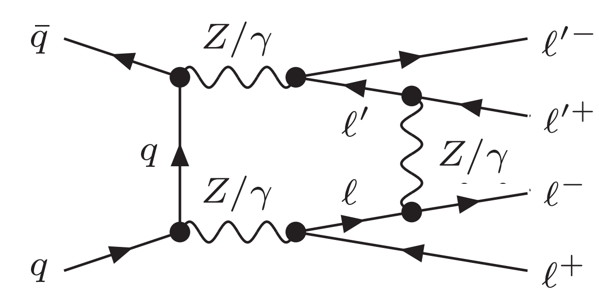
NNLO QCD

NLO QCD gg

NLO EW



NNLO+PS



not in this talk: BSM effects

Higher-order QCD corrections

All VV processes known through NNLO QCD:

→ inclusive/on-shell Z,W & differential/off-shell Z,W (leptonic)

γγ - inclusive and differential [Catani, Cieri, de Florian, Ferrera, Grazzini '12], [Campbell, Ellis, Li, Williams '16], [Grazzini, Kallweit, MW '17]

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ZZ - inclusive/on-shell [Cascioli, Gehrmann, Grazzini, Kallweit, Maierhöfer, von Manteuffel, Pozzorini, Rathlev, Tancredi, Weihs '14]; see also: [Heinrich et al. '17]

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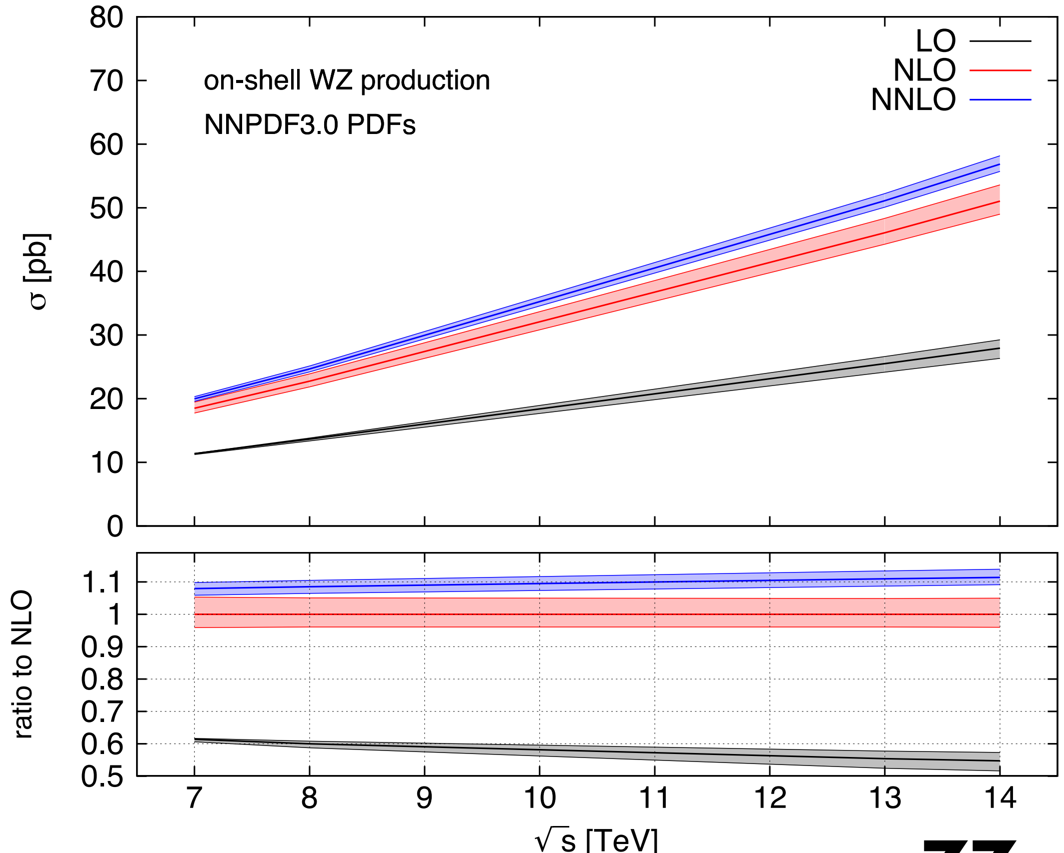
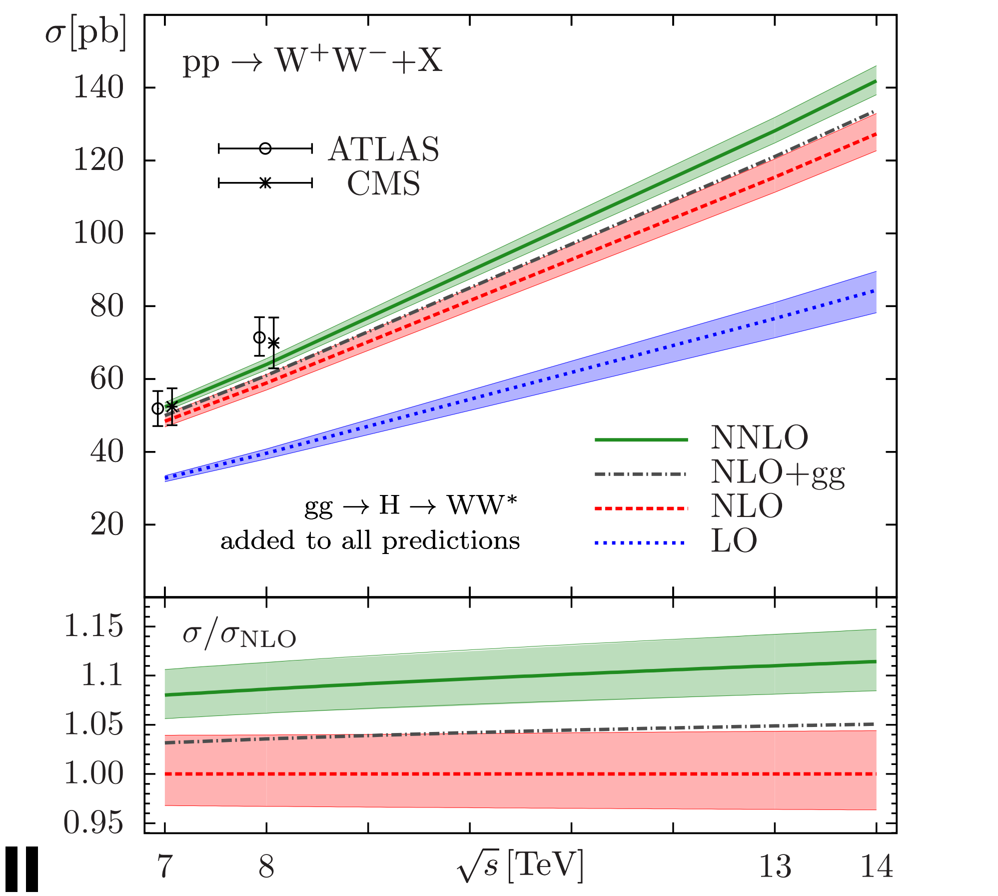
WZ - inclusive/on-shell

[Grazzini, Kallweit, Rathlev, MW '16]



WW - inclusive/on-shell

[Gehrmann, Grazzini, Kallweit, Maierhöfer, von Manteuffel, et al. '14]



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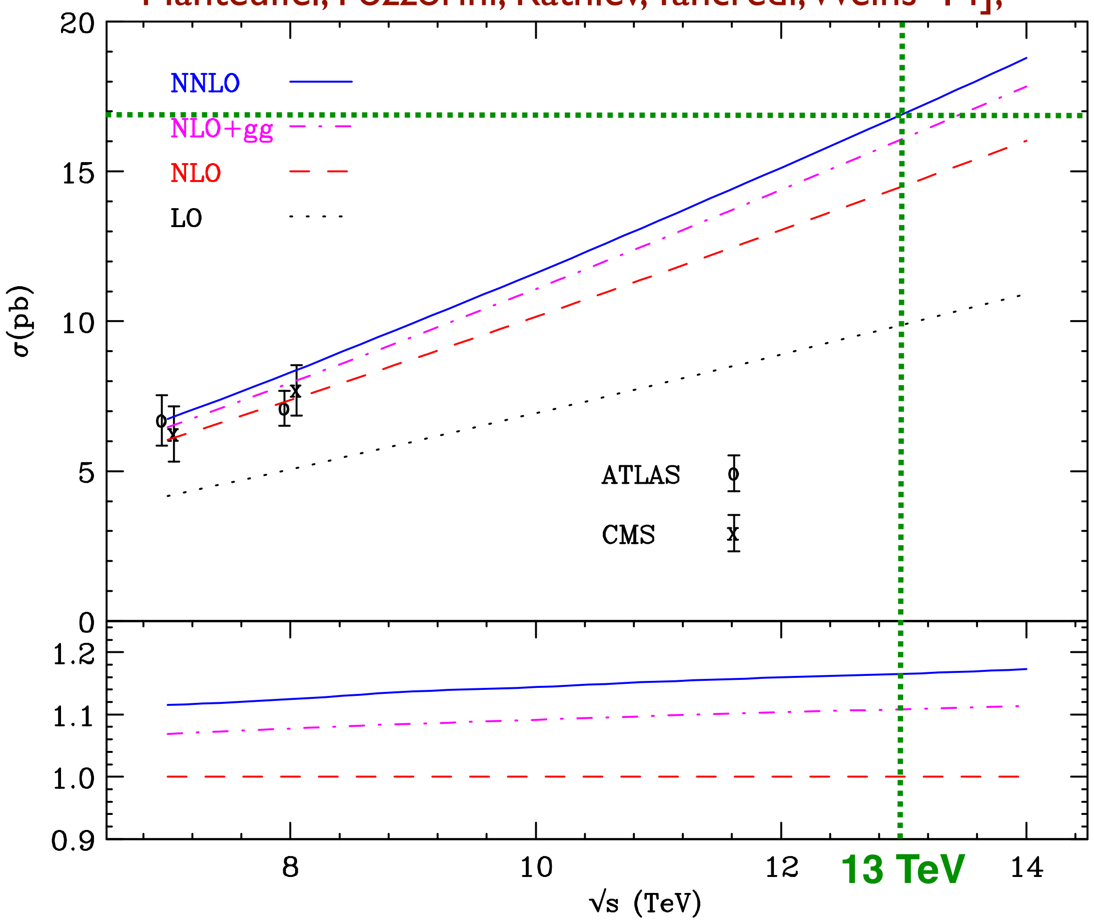
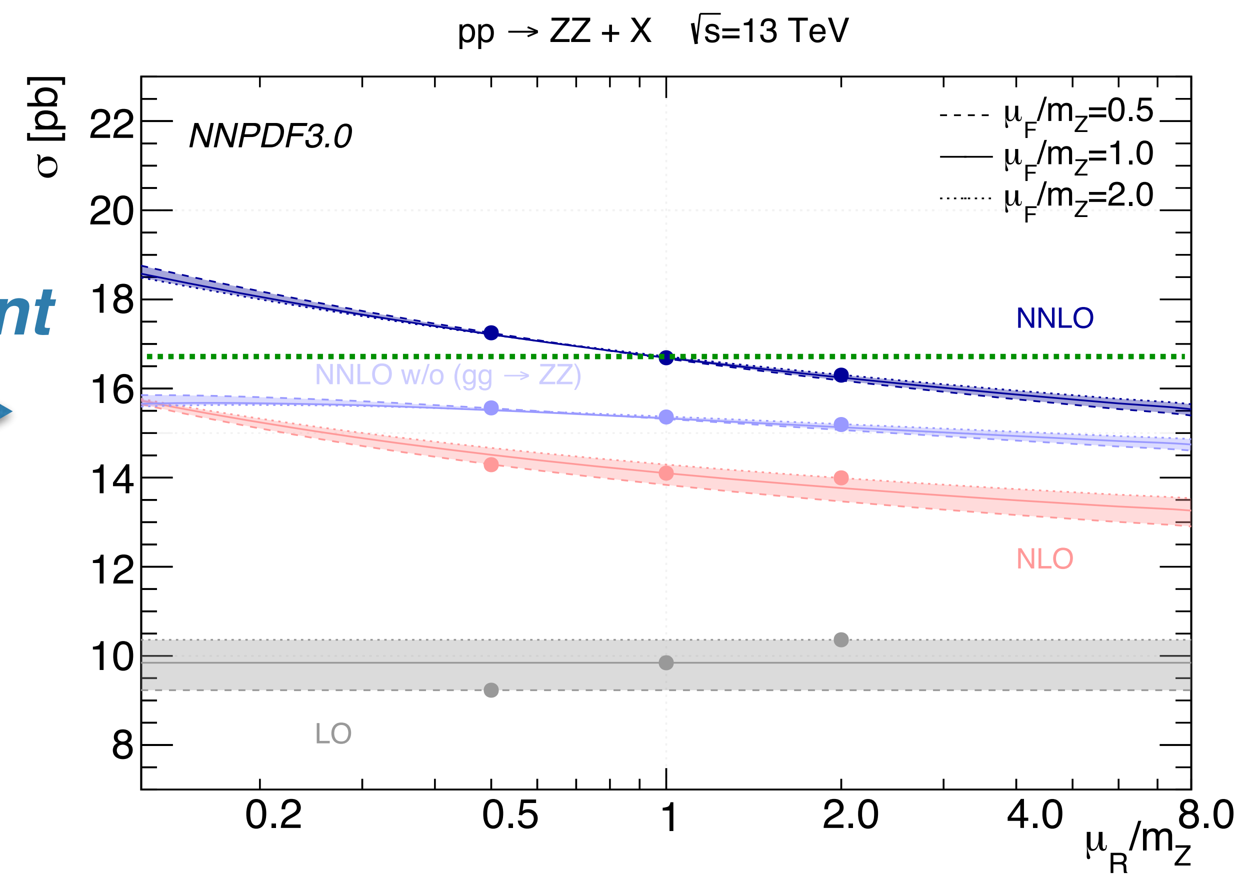


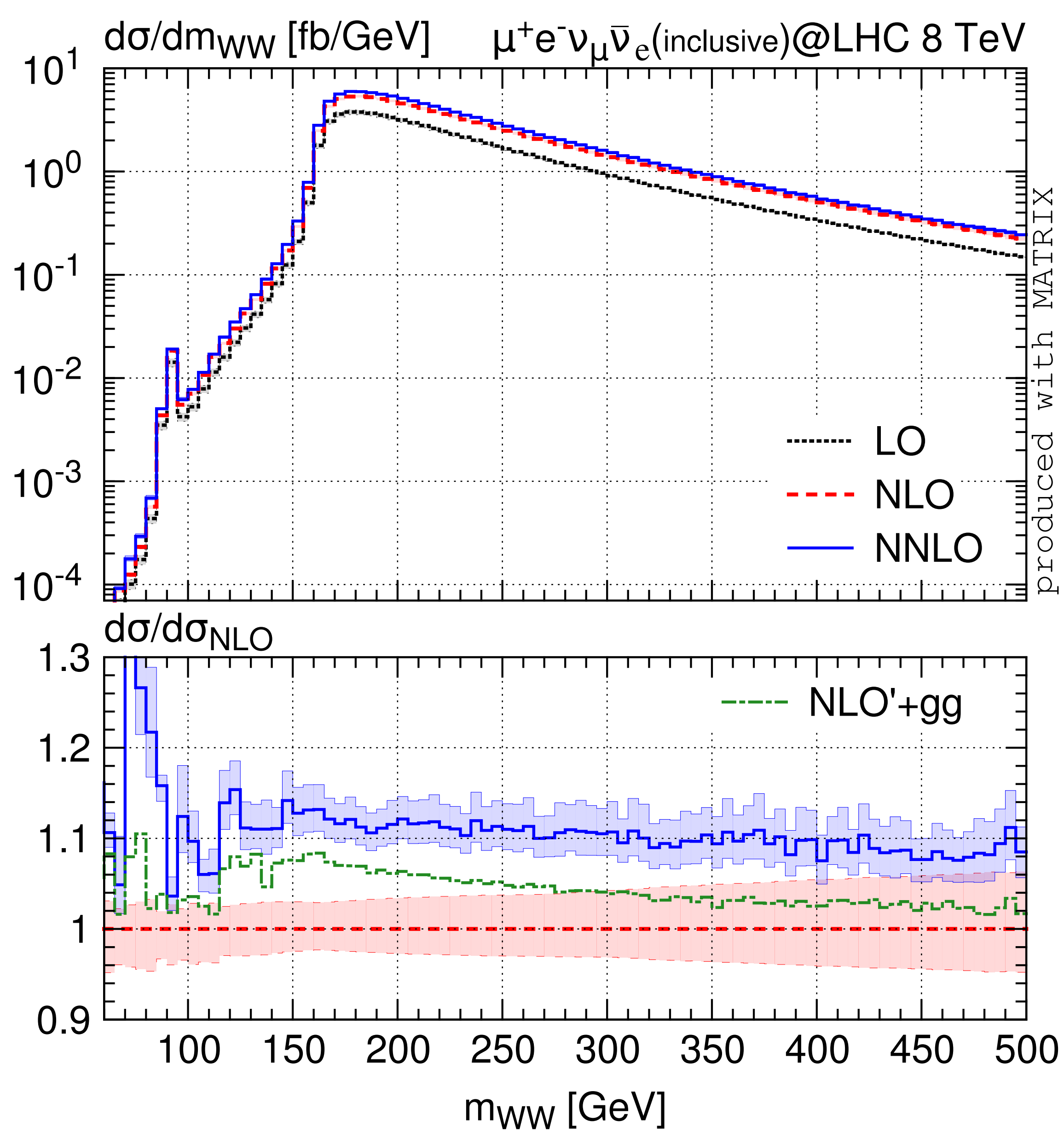
in well agreement

[Heinrich, Jahn, Jones, Kerner, Pires '17]



WW - differential/off-shell

[Grazzini, Kallweit, Pozzorini, Rathlev, MW '15]



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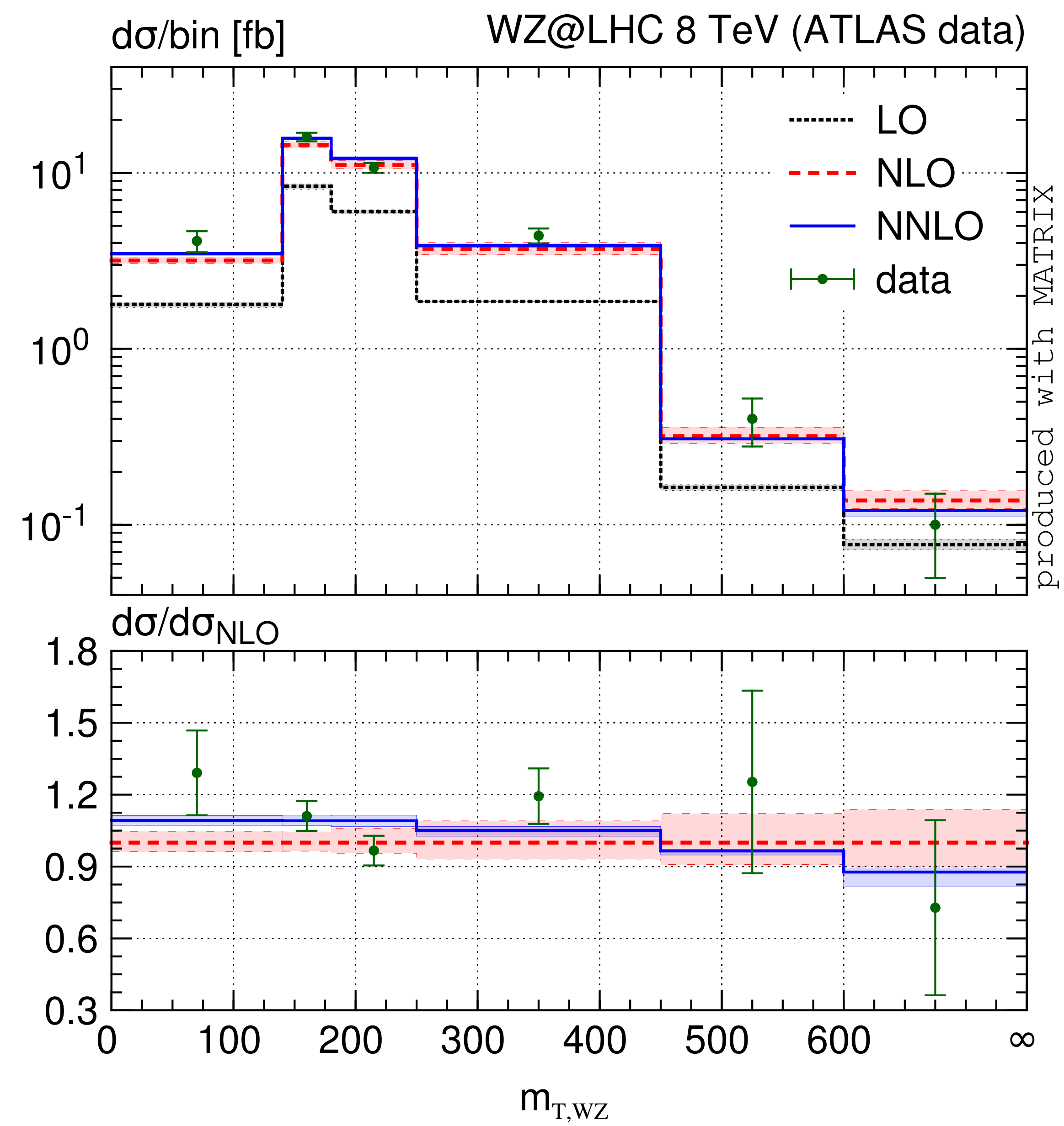
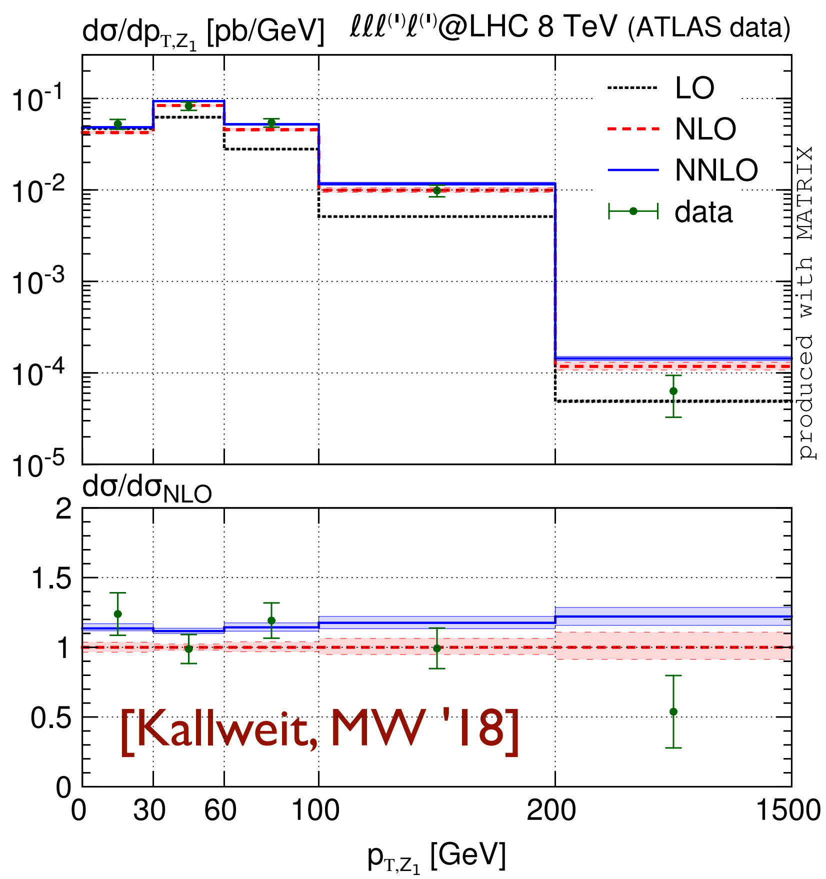
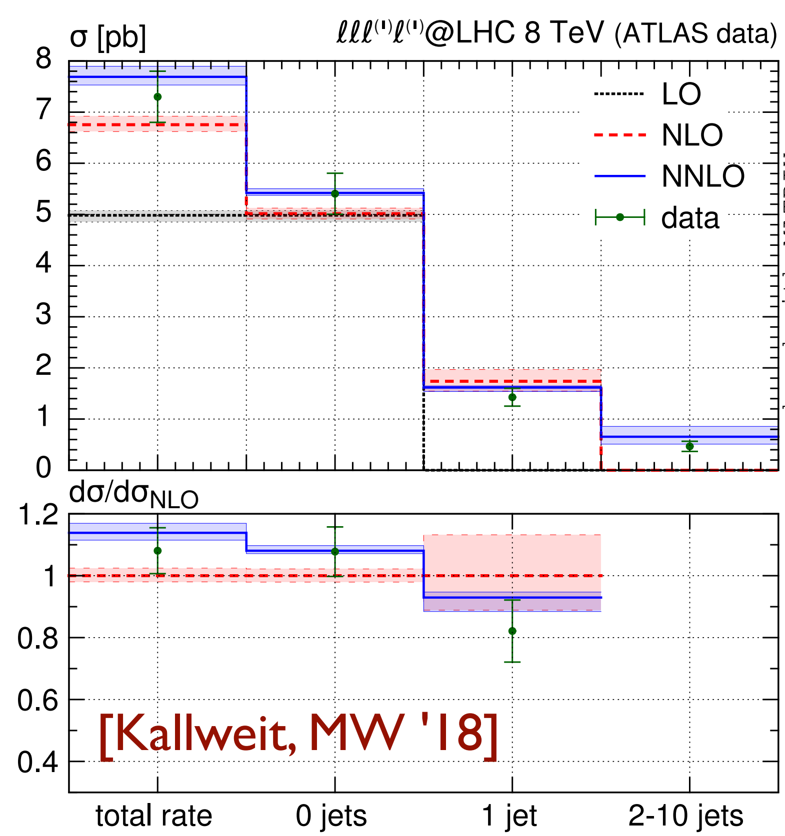


ZZ - differential/off-shell

$ZZ \to 4\ell$

[Grazzini, Kallweit, Rathlev '15], [Kallweit, MW '18]

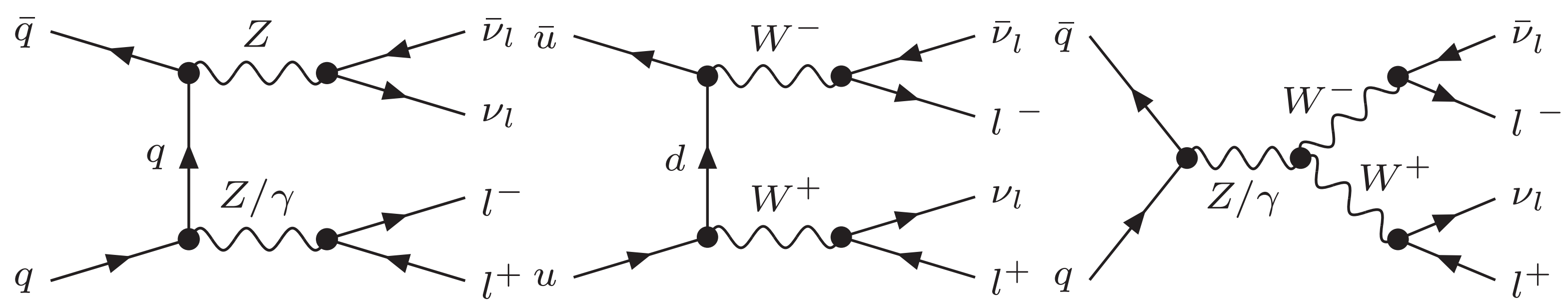




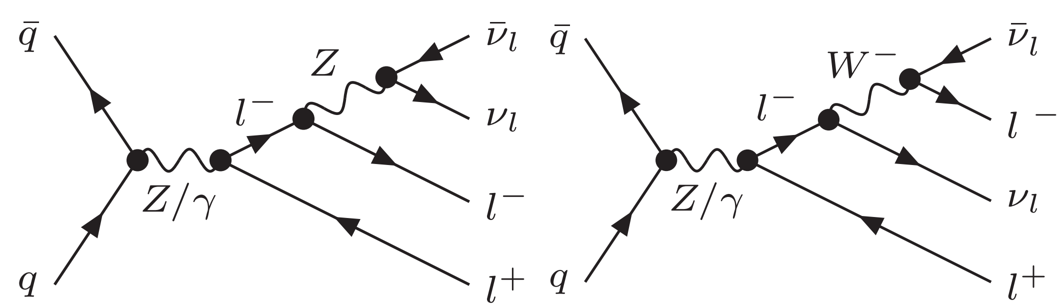
NEW: $ZZ/WW \to \ell\ell + E_{T,miss}$

[Kallweit, MW '18]

- mixes ZZ and WW topologies:



($pp \to ZZ/\gamma^*Z/WW \to \ell\ell\nu\nu$)



($pp \to Z/\gamma^* \to \ell\ell Z/\ell\nu W \to \ell\ell\nu\nu$)

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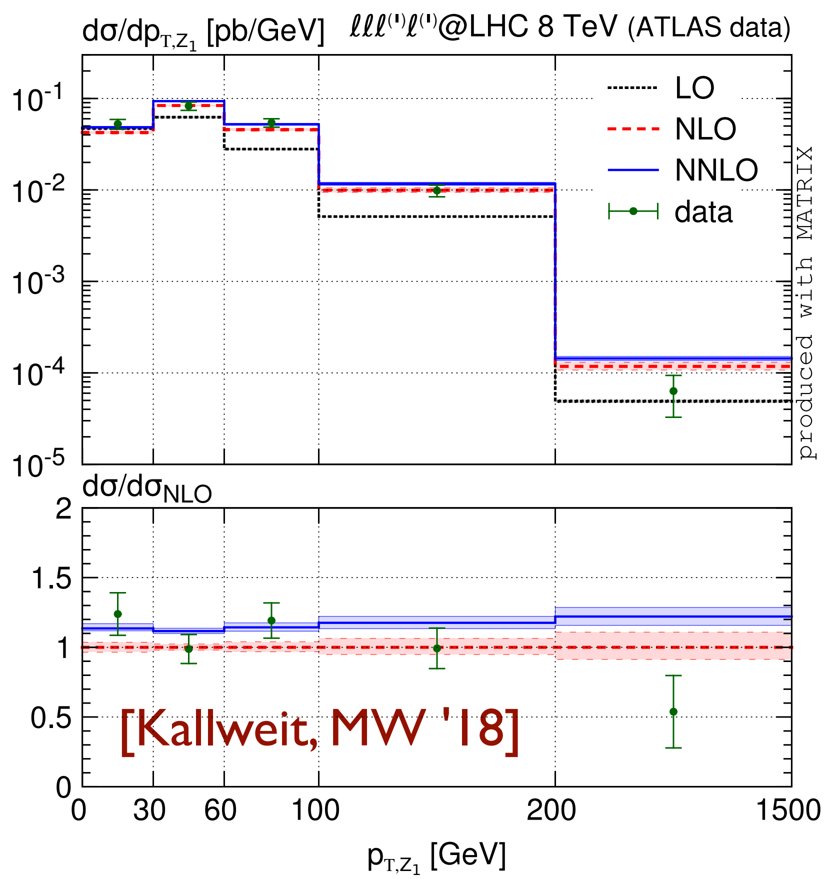
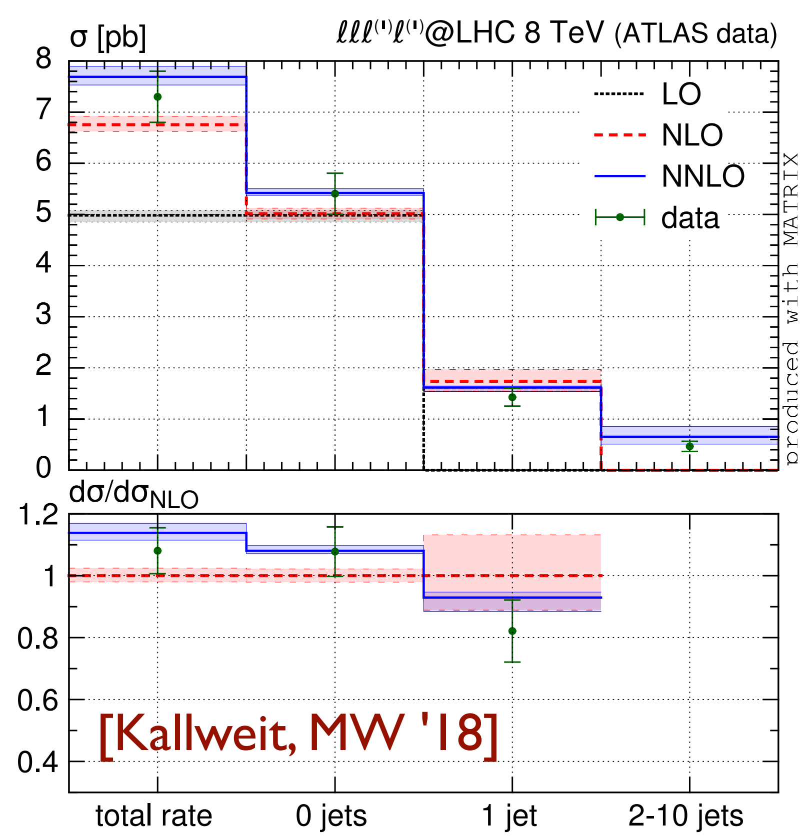
[Grazzini, Kallweit, Rathlev '15], [Kallweit, MW '18]



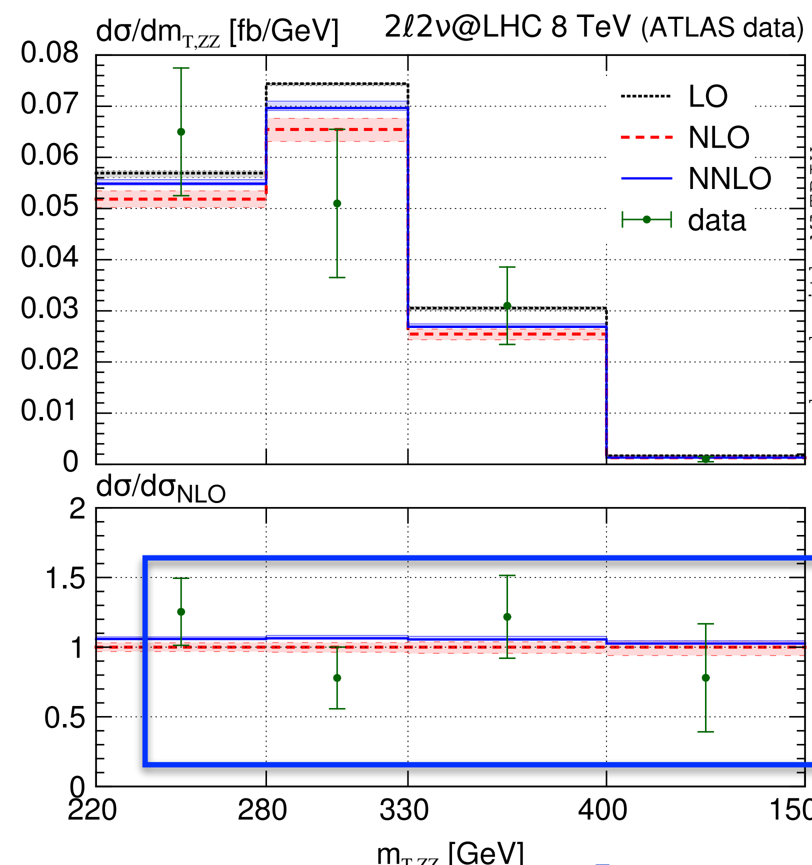


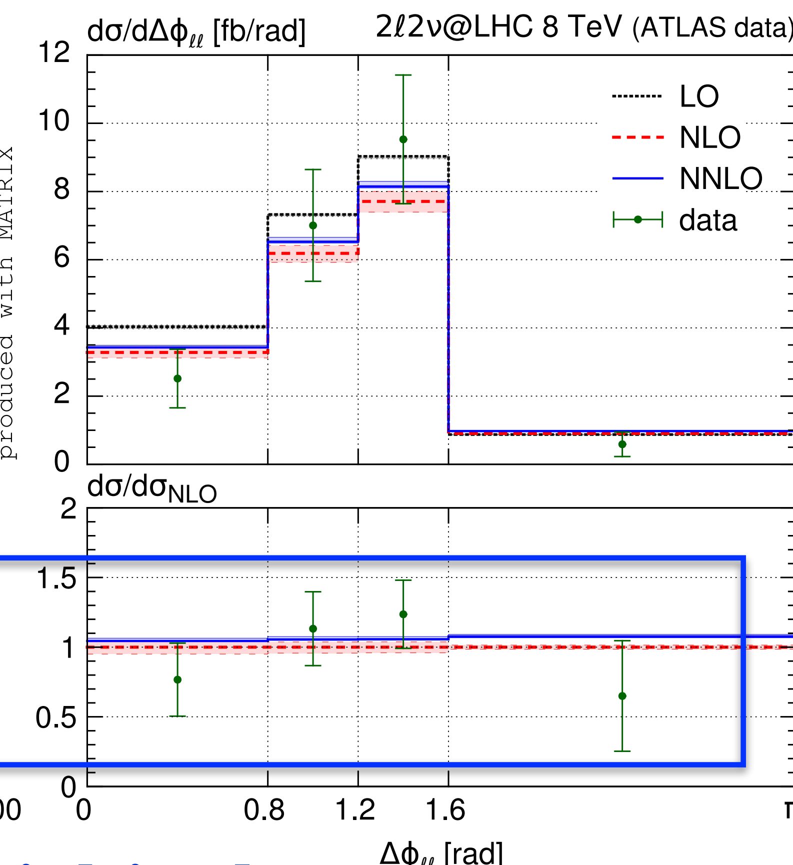
NEW: $ZZ/WW \to \ell\ell + E_{T,miss}$

[Kallweit, MW '18]

channel	σ_{LO} [fb]	σ_{NLO} [fb]	σ_{NNLO} [fb]	σ_{ATLAS} [fb]
$e^+e^-\nu\nu$	$5.558(0)^{+0.1\%}_{-0.5\%}$	$4.806(1)^{+3.5\%}_{-3.9\%}$	$5.083(8)^{+1.9\%}_{-0.6\%}$	$5.0\ ^{+0.8}_{-0.7}(\mathrm{stat})\ ^{+0.5}_{-0.4}(\mathrm{syst}) \pm 0.1(\mathrm{lumi})$
$\mu^+\mu^-\nu\nu$	$5.558(0)^{+0.1\%}_{-0.5\%}$	$4.770(4)^{+3.6\%}_{-4.0\%}$	$5.035(9)^{+1.8\%}_{-0.5\%}$	$4.7\ ^{+0.7}_{-0.7}(\mathrm{stat})\ ^{+0.5}_{-0.4}(\mathrm{syst}) \pm 0.1(\mathrm{lumi})$
total rate	$4982(0)^{+1.9\%}_{-2.7\%}$	$6754(2)^{+2.4\%}_{-2.0\%}$	$7690(5)^{+2.7\%}_{-2.1\%}$	$7300\ ^{+400}_{-400}(\mathrm{stat})\ ^{+300}_{-300}(\mathrm{syst})\ ^{+200}_{-100}(\mathrm{lumi})$

Excellent agreement between NNLO and data





data within 1σ

(better than comparison to MC [JHEP 1701 (2017) 099])

Higher-order QCD corrections

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- differential/off-shell [Grazzini, Kallweit, Rathlev, MW '17]

→ **all publicly available within MATRIX**

process	status	comment
single boson processes		
$pp \to Z/\gamma^*(\to \ell\ell/\nu\nu)$	✓	validated analytically + FEWZ
$pp \to W(\to \ell\nu)$	✓	validated with FEWZ, NNLOjet
$pp \to H$	✓	validated analytically (by SusHi)
photon processes		
$pp \to \gamma\gamma$	✓	validated with 2γNNLO
$pp \to Z\gamma \to \ell\ell\gamma$	✓	[Grazzini, Kallweit, Rathlev '15]
$pp \to Z\gamma \to \nu\nu\gamma$	✓	[Grazzini, Kallweit, Rathlev '15]
$pp \to W\gamma \to \ell\nu\gamma$	✓	[Grazzini, Kallweit, Rathlev '15]
massive diboson processes		
$pp \to ZZ$	✓	[Cascioli et al. '14]
$pp \to ZZ \to \ell\ell\ell\ell$	✓	[Grazzini, Kallweit, Rathlev '15], [Kallweit, MW '18]
$pp \to ZZ \to \ell\ell\ell'\ell'$	✓	[Grazzini, Kallweit, Rathlev '15], [Kallweit, MW '18]
$pp \to ZZ \to \ell\ell\nu'\nu'$	✓	[Kallweit, MW '18]
$pp \to ZZ/WW \to \ell\ell\nu\nu$	✓	[Kallweit, MW '18]
$pp \to WW$	✓	[Gehrmann et al. '14]
$pp \to WW \to \ell\nu\,\ell'\nu'$	✓	[Grazzini, Kallweit, Pozzorini, Rathlev, MW '16]
$pp \to WZ$	✓	[Grazzini, Kallweit, Rathlev, MW '16]
$pp \to WZ \to \ell\nu\ell\ell$	✓	[Grazzini, Kallweit, Rathlev, MW '17]
$pp \to WZ \to \ell'\nu'\ell\ell$	✓	[Grazzini, Kallweit, Rathlev, MW '17]
$pp \to HH$	(✓)	not in public release

The MATRIX framework

[Grazzini, Kallweit, MW '17] https://matrix.hepforge.org/

Amplitudes

OpenLoops	Dedicated 2-loop codes
(Collier, CutTOols, ...)	(VVamp, GiNaC, tdhpl, ...)

Munich

MUlti-cha**N**nel **I**ntegrator at Swiss (**CH**) precision

q_T subtraction $\Leftrightarrow$ q_T resummation

NNLO

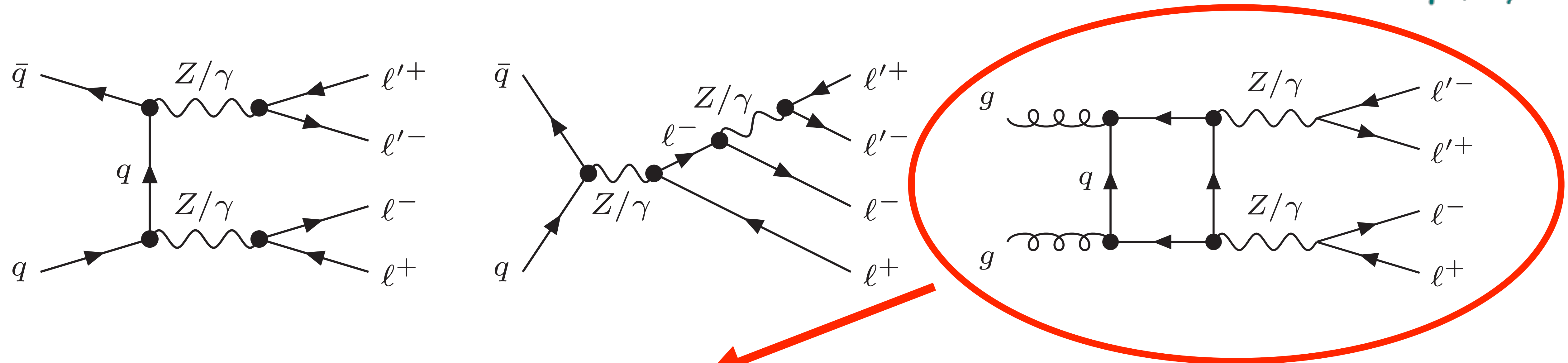
NNLL

Matrix

Munich **A**utomates q**T** Subtraction and **R**esummation to **I**ntegrate **X**-sections.

Recent developments for VV production

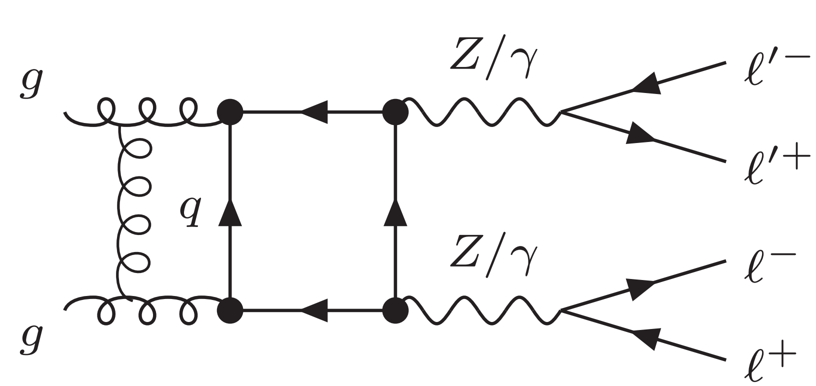
gg→ZZ→4ℓ at NLO [Grazzini, Kallweit, MW, Yook '18]



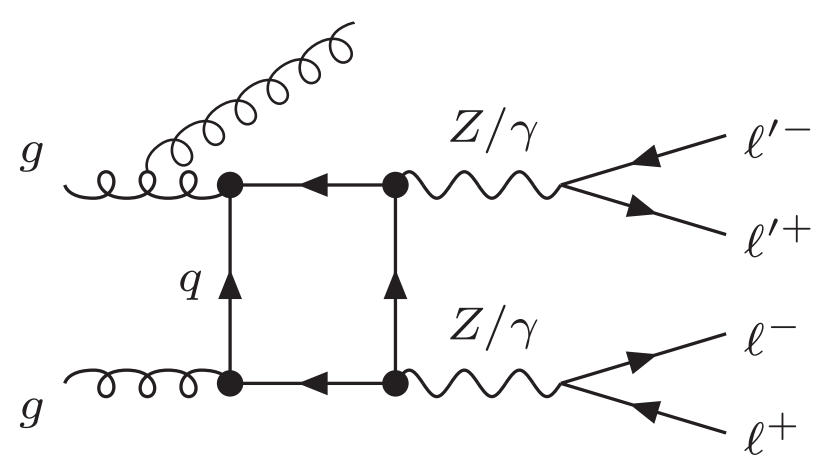
gg NLO:

see also:
[Caola, Melnikov, Röntsch, Tancredi '15]

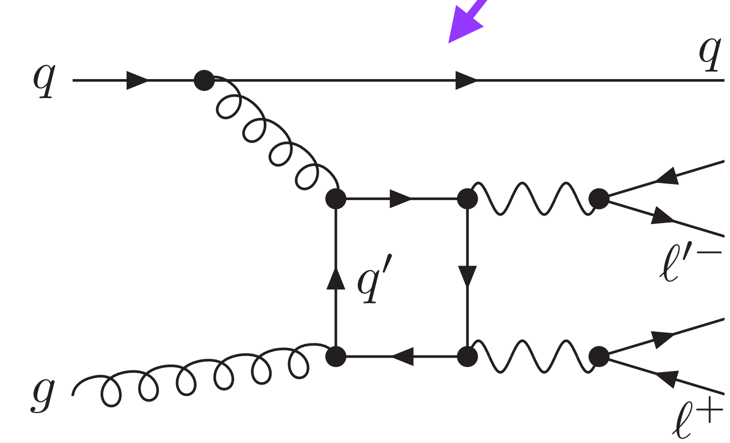
virtuals:



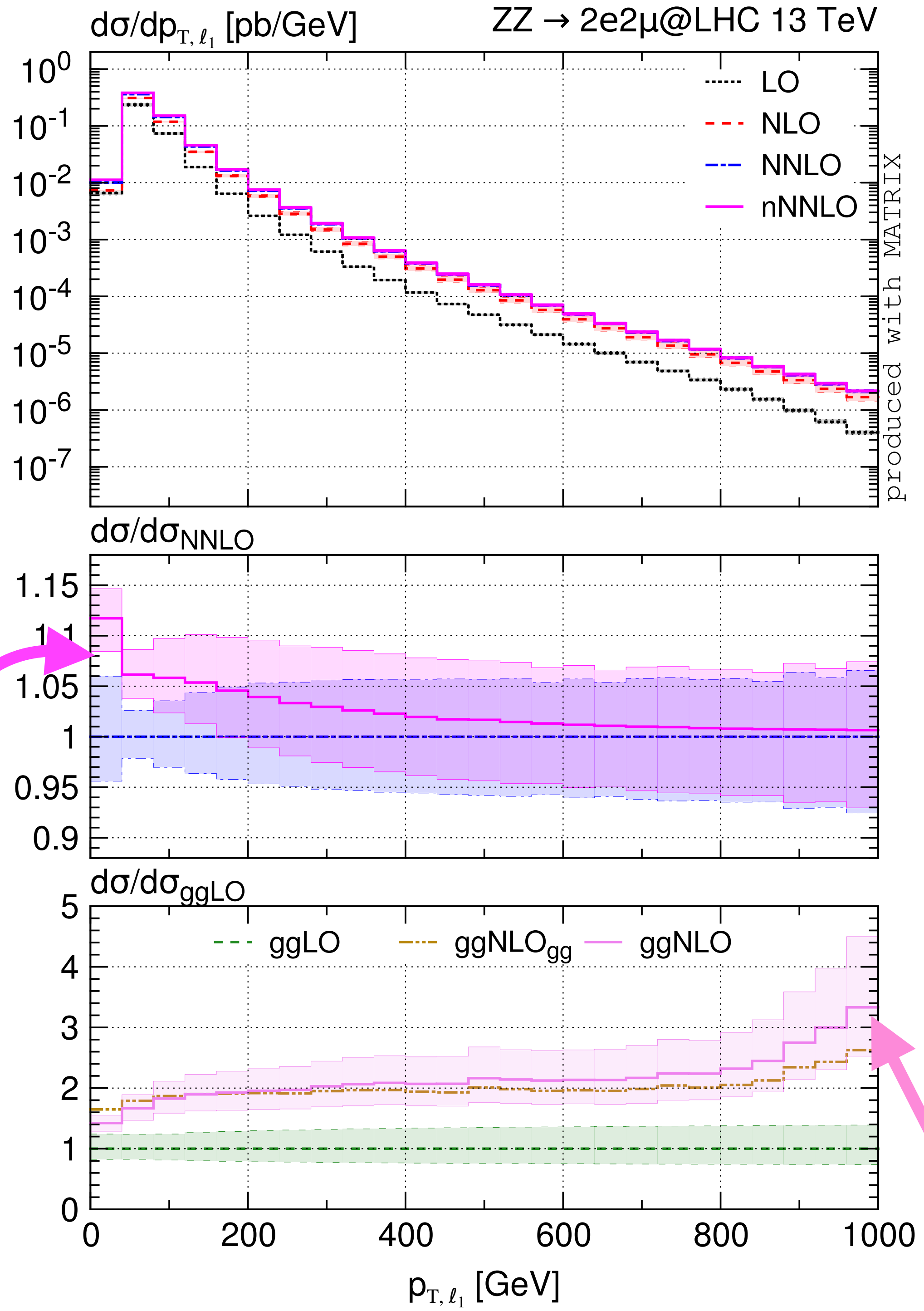
reals:



NEW: qg contributions



gg→ZZ→4ℓ at NLO [Grazzini, Kallweit, MW, Yook '18]



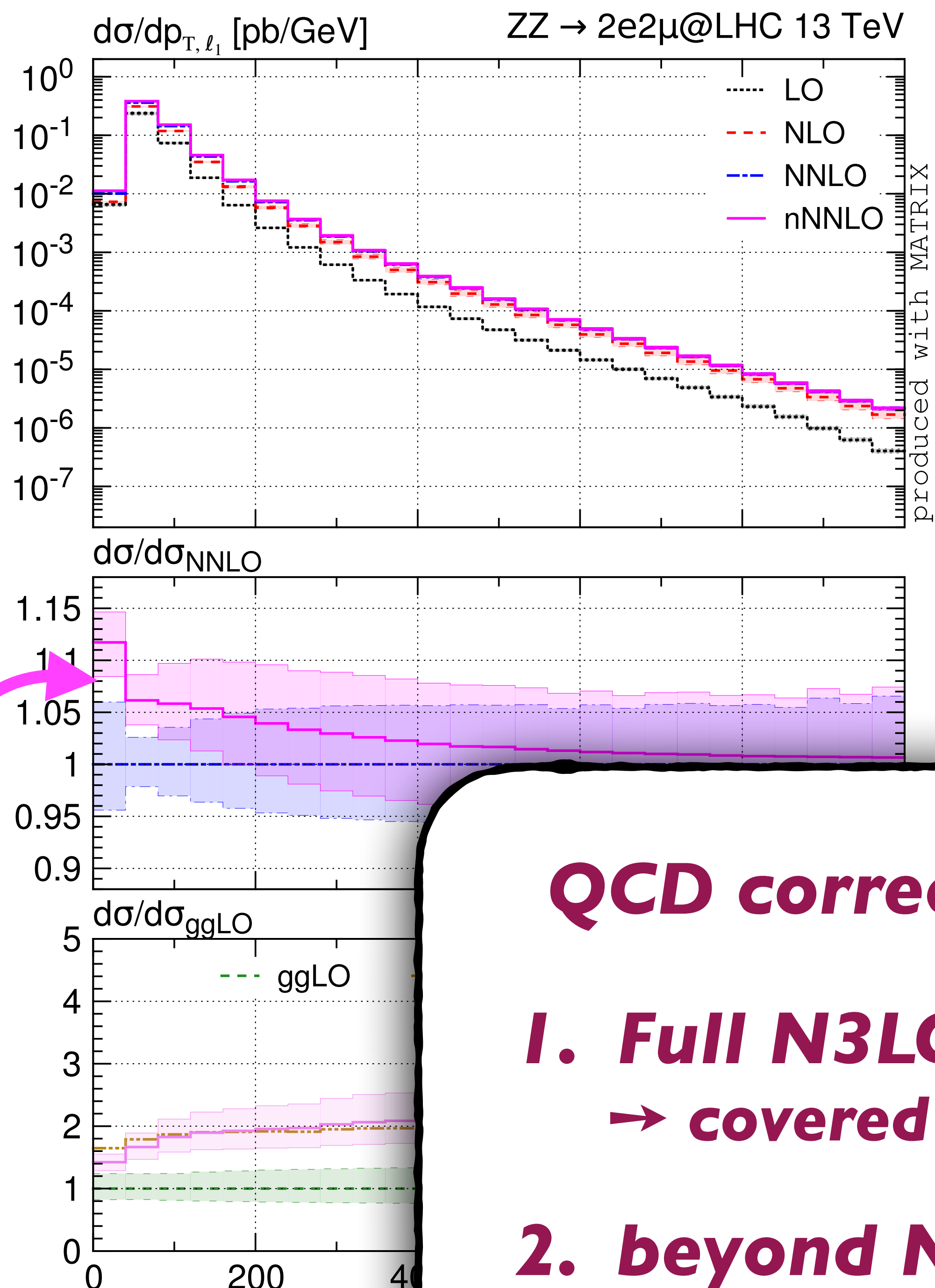
$\sqrt{s}$	8 TeV	13 TeV	8 TeV	13 TeV
	σ [fb]		$\sigma/\sigma_{\mathrm{ggLO}} - 1$	
ggLO	$0.79354(8)^{+28.2\%}_{-20.9\%}$	$2.0054(2)^{+23.5\%}_{-17.9\%}$	0%	0%
ggNLO	$1.3901(9)^{+15.4\%}_{-13.6\%}$	$3.423(3)^{+13.9\%}_{-12.0\%}$	+75.2%	+70.7%
	σ [fb]		$\sigma/\sigma_{\mathrm{NLO}} - 1$	
NLO	$11.2958(4)^{+2.5\%}_{-2.0\%}$	$19.8454(7)^{+2.5\%}_{-2.1\%}$	0%	0%
NNLO	$12.87(3)^{+2.8\%}_{-2.1\%}$	$23.55(2)^{+3.0\%}_{-2.6\%}$	+13.9%	+18.7%
nNNLO	$13.47(3)^{+2.6\%}_{-2.2\%}$	$24.97(2)^{+2.9\%}_{-2.7\%}$	+19.2%	+25.8%

+5-6% effect due to NLO correction to gg compared to NNLO

NLO gg correction large+not flat; moves nNNLO outside uncertainty band of NNLO

huge NLO gg K-factor (~2 & more); impact of newly computed fermionic channels clearly visible

gg→ZZ→4ℓ at NLO [Grazzini, Kallweit, MW, Yook '18]



$\sqrt{s}$	8 TeV	13 TeV	8 TeV	13 TeV
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ggLO	$0.79354(8)^{+28.2\%}_{-20.9\%}$	$2.0054(2)^{+23.5\%}_{-17.9\%}$	0%	0%
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NLO	$11.2958(4)^{+2.5\%}_{-2.0\%}$	$19.8454(7)^{+2.5\%}_{-2.1\%}$	0%	0%
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correction to gg

QCD corrections beyond nNNLO?

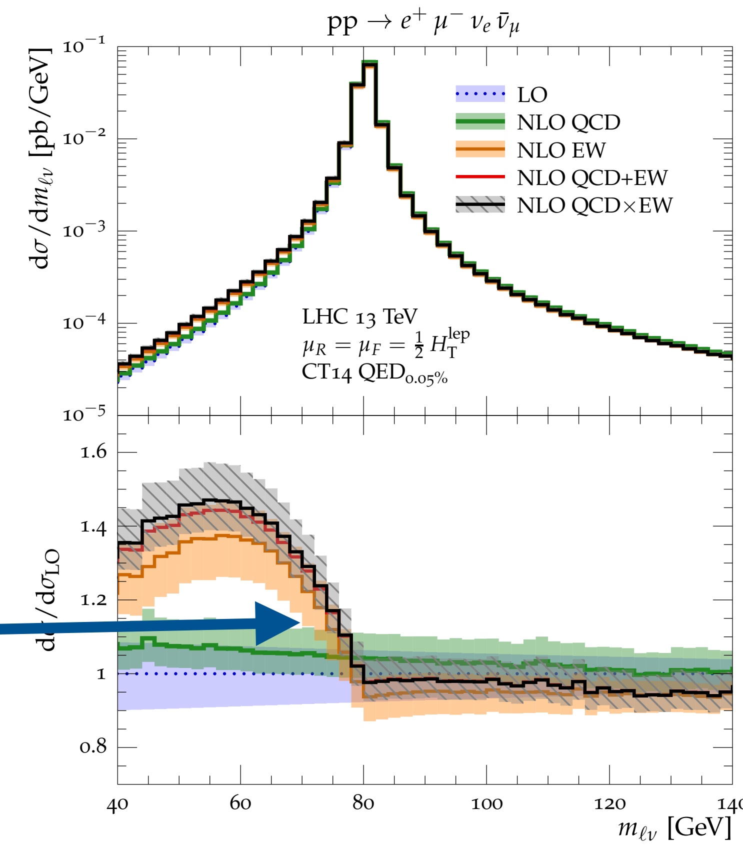
1. ***Full N3LO (qq + mixing with gg)?***
   → *covered by qq scale variations*
2. ***beyond NLO gg: "ggNNLO"?***
   → *NLO K-factor ~1.7*
   → *if NNLO K-factor ~O(1.2-1.3), then nnNNLO/nNNLO~O(1.02-1.04)*

NLO gg correcti … ***& more);***
moves nNNLO ou … ***d fermionic***
band of NNLO … ***channels clearly visible***

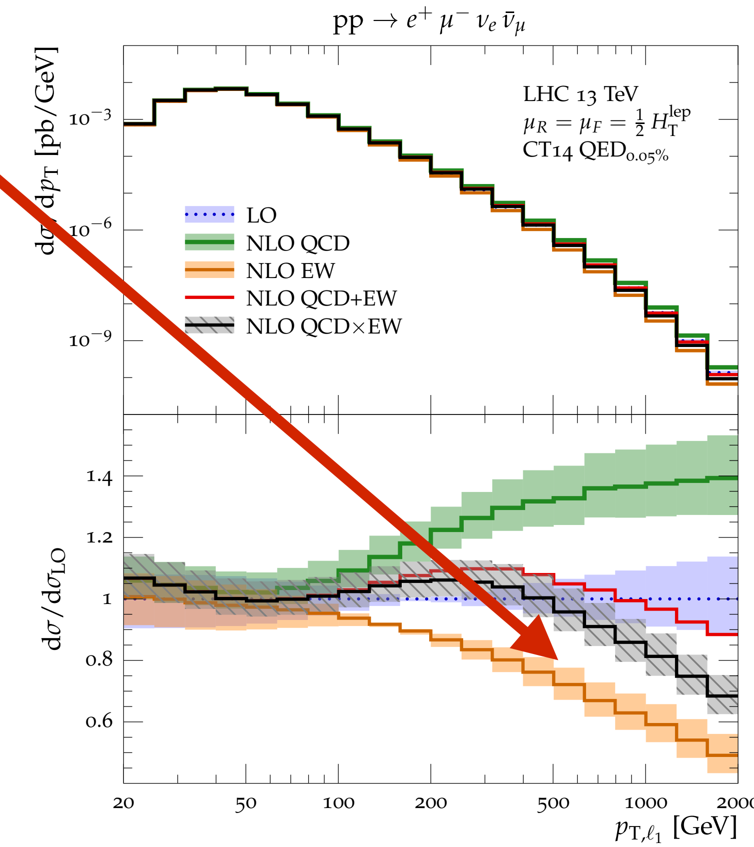
Combination: NNLO QCD and NLO EW

[Grazzini, Kallweit, Lindert, Pozzorini, MW]

- ***why adding NLO EW?***
  - → ***needed for percent-level precision (inclusive)***
  - → ***distortion of line shapes (EW resonances)***
    due to photon FSR from leptons: **QED effect**
  - → ***sizable negative correction in tails***
    due to large Sudakov logarithms: **genuine EW effect**



[SK, Lindert, Pozzorini, Schönherr (2017)]



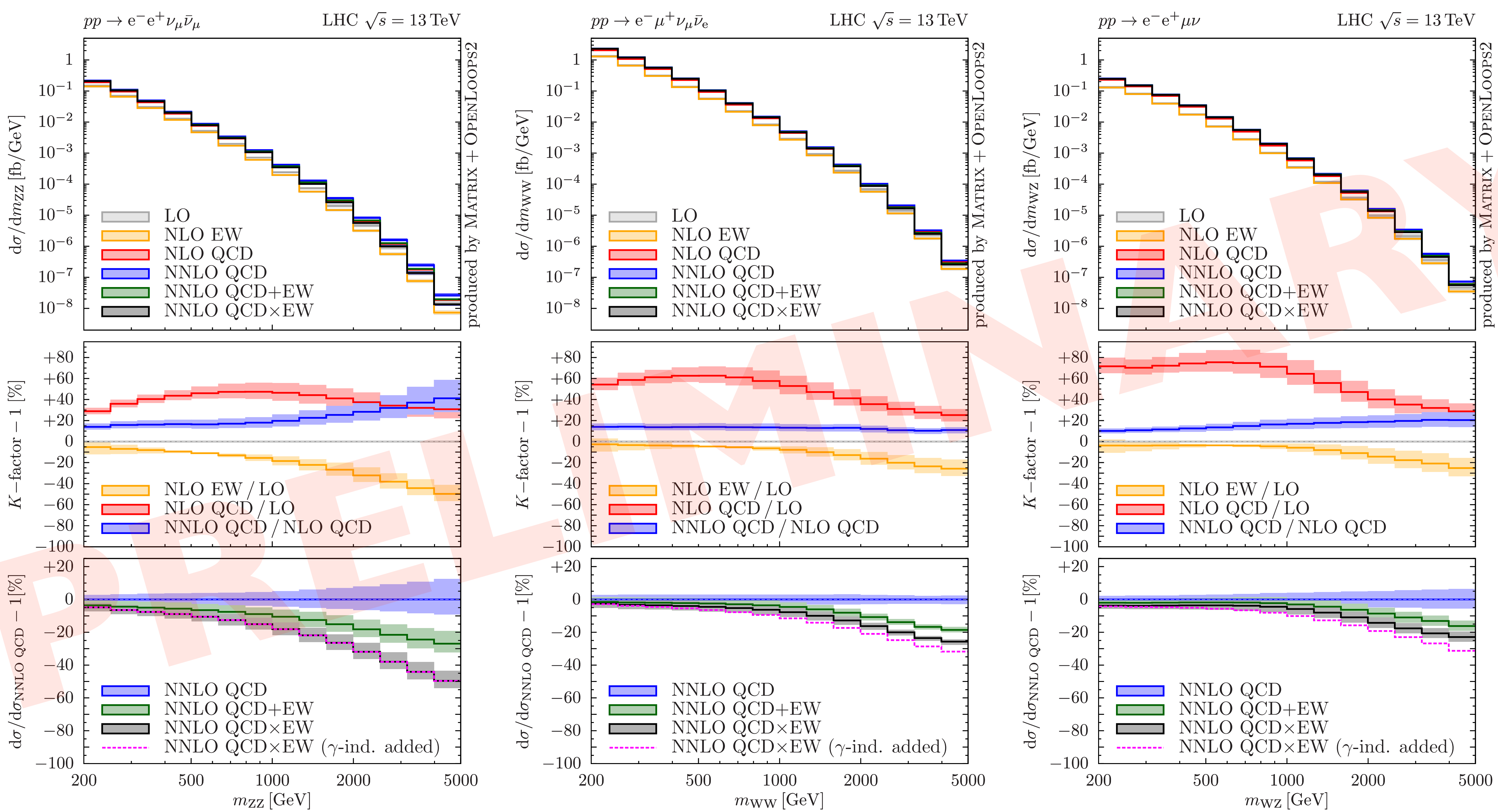
[SK, Lindert, Pozzorini, Schönherr (2017)]

Combination: NNLO QCD and NLO EW

[Grazzini, Kallweit, Lindert, Pozzorini, MW]

- ***all vector-boson pair production processes***
- combination? additive: $d\sigma^{\rm (N)NLO}_{\rm QCD+EW} = d\sigma^{\rm LO}(1+\delta_{\rm QCD}+\delta_{\rm EW})$

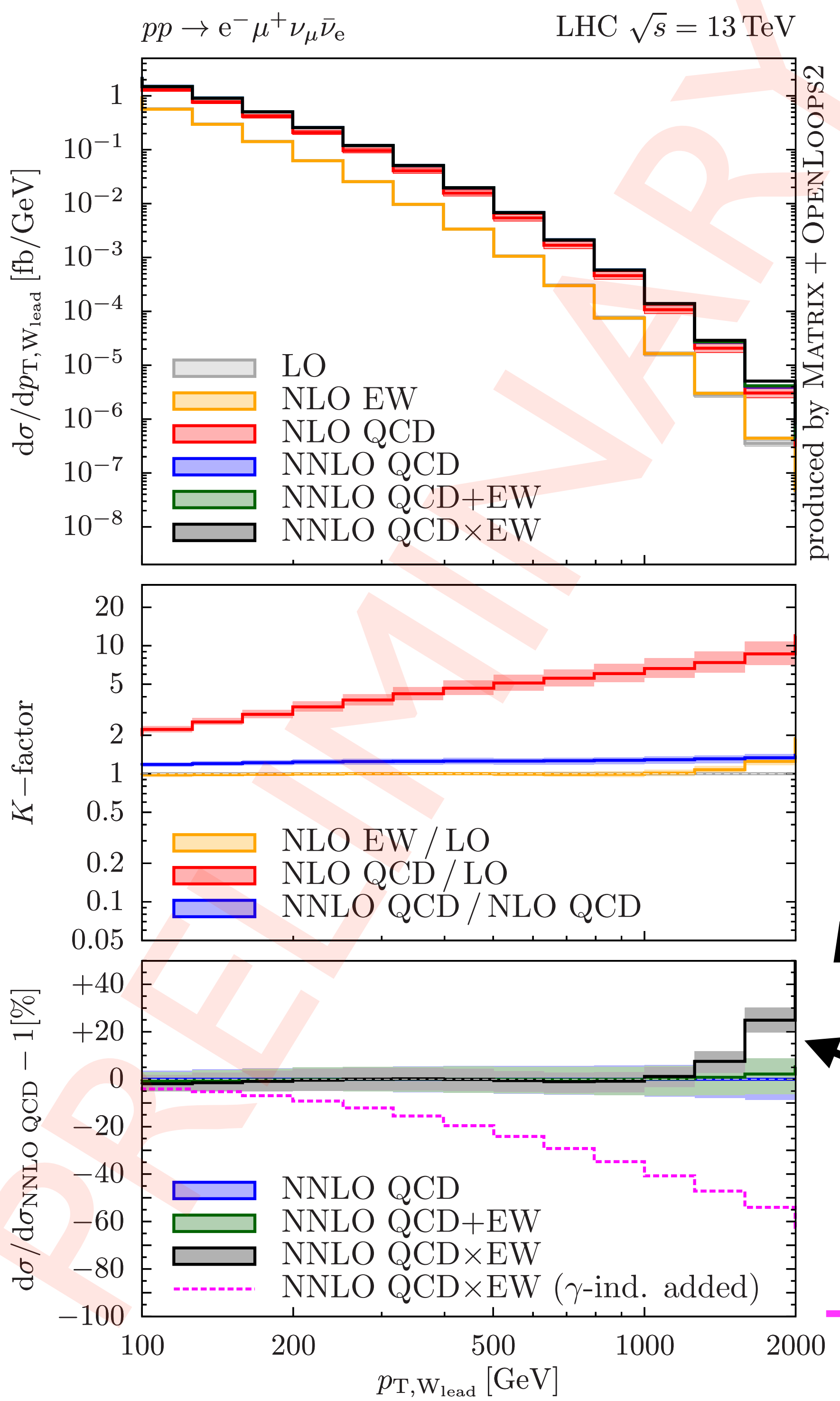
  multiplicative: $d\sigma^{\rm (N)NLO}_{\rm QCD\times EW} = d\sigma^{\rm LO}(1+\delta_{\rm QCD})(1+\delta_{\rm EW})$



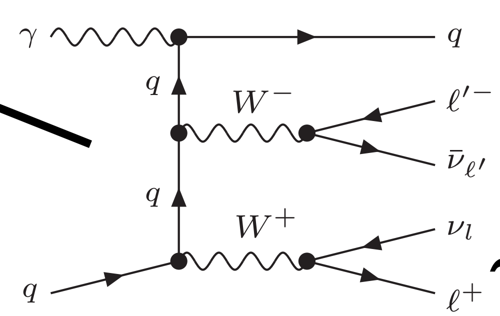
Combination: NNLO QCD and NLO EW

[Grazzini, Kallweit, Lindert, Pozzorini, MW]

- *let's look in detail on one interesting aspect:* ***photon-induced + giant K-factor***



high p_T dominated by V+jet



~ $\ln^2(p_T/m_W)$

→ don't include γ in multiplicative combination!

Combination: NNLO QCD and NLO EW

[Grazzini, Kallweit, Lindert, Pozzorini, MW]

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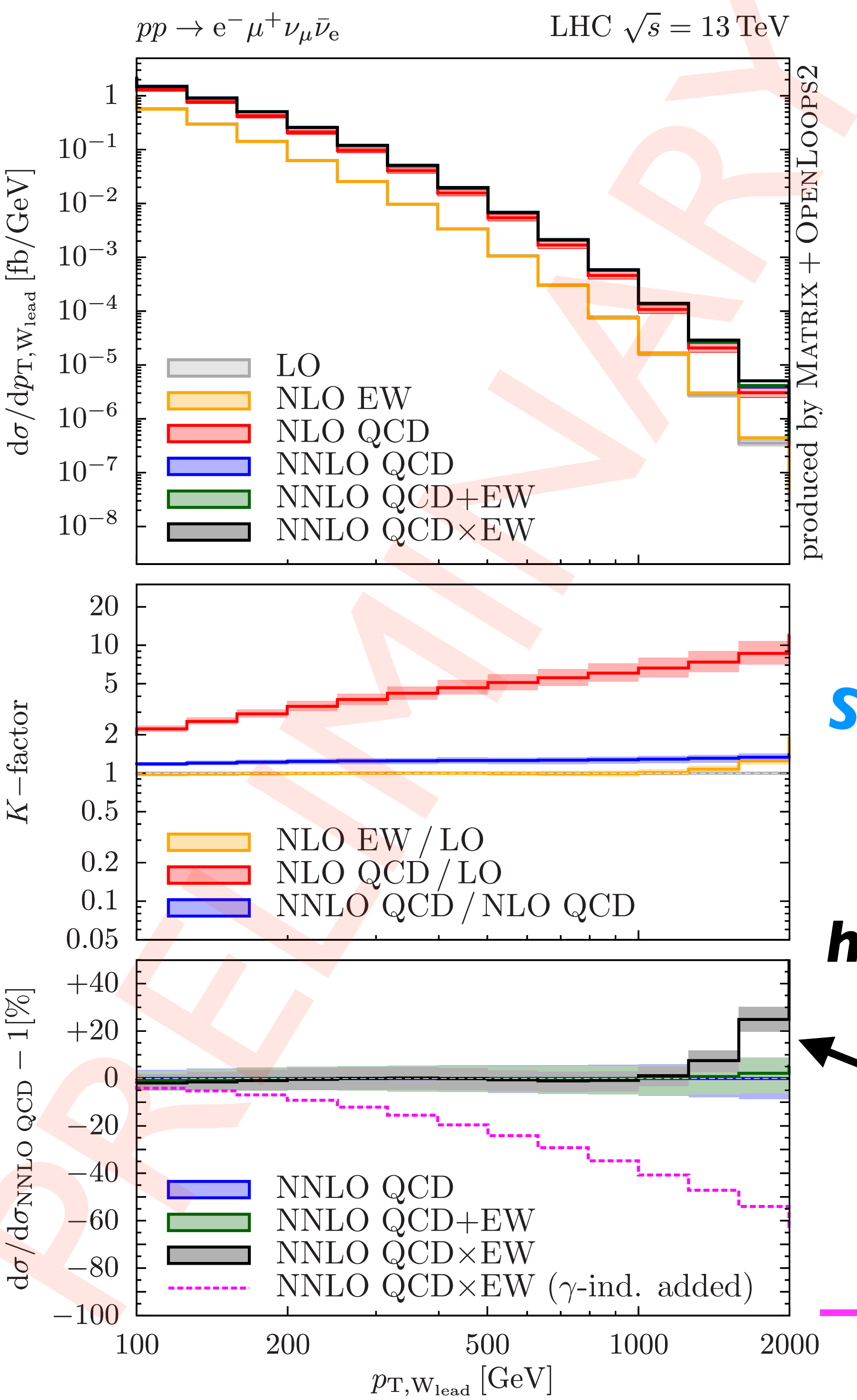
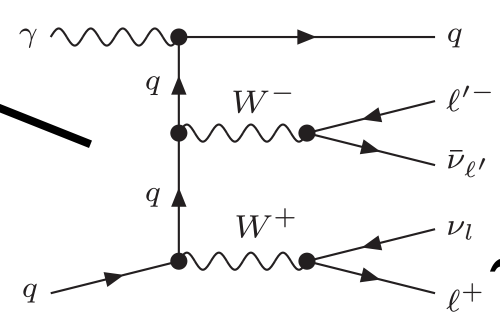


jet-veto ($H_{T,jet}$< 0.2 $H_{T,lep}$)

Sudakov suppression restored

high p_T dominated by V+jet



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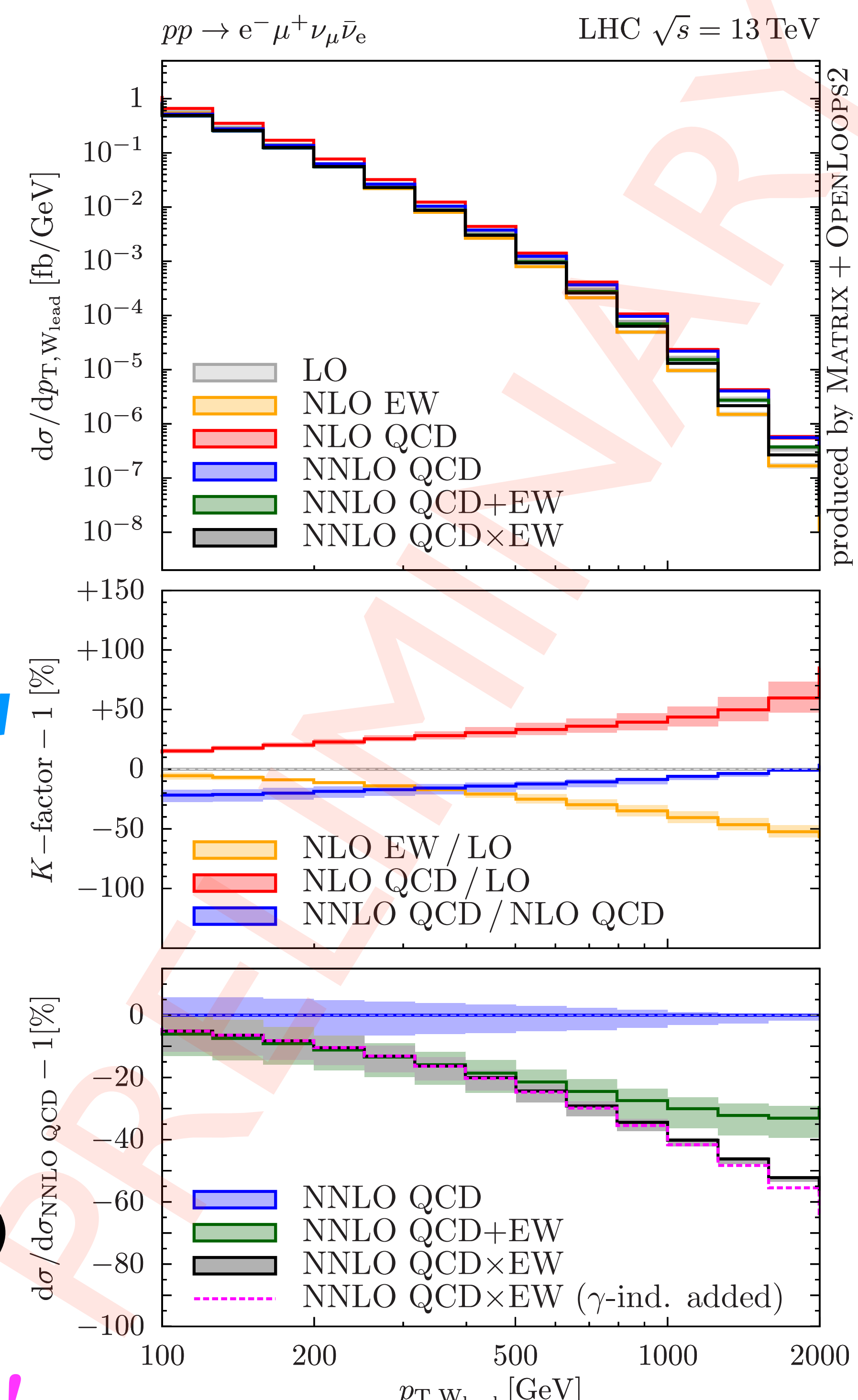


Combination: NNLO QCD and NLO EW

[Grazzini, Kallweit, Lindert, Pozzorini, MW]

Many unanswered questions for final combination

$$\sigma \sim \sigma^{\mathrm{LO}}_{q\bar{q}} + \sigma^{\mathrm{LO}}_{\gamma\gamma} + \Delta^{\mathrm{NLO_{QCD}}}_{q\bar{q}} + \Delta^{\mathrm{NNLO_{QCD}}}_{q\bar{q}} + \Delta^{\mathrm{NLO_{EW}}}_{q\bar{q}/\gamma\gamma} + \Delta^{\mathrm{LO}}_{gg} + \Delta^{\mathrm{NLO_{QCD}}}_{gg}$$

$$\sigma \sim \left(\sigma^{\mathrm{LO}}_{q\bar{q}} + \sigma^{\mathrm{LO}}_{\gamma\gamma}\right)\left(1 + \frac{\Delta^{\mathrm{NLO_{QCD}}}_{q\bar{q}} + \Delta^{\mathrm{NNLO_{QCD}}}_{q\bar{q}} + \Delta^{\mathrm{LO}}_{gg} + \Delta^{\mathrm{NLO_{QCD}}}_{gg}}{\sigma^{\mathrm{LO}}_{q\bar{q}} + \sigma^{\mathrm{LO}}_{\gamma\gamma}}\right)\left(1 + \frac{\Delta^{\mathrm{NLO_{EW}}}_{q\bar{q}/\gamma\gamma}}{\sigma^{\mathrm{LO}}_{q\bar{q}} + \sigma^{\mathrm{LO}}_{\gamma\gamma}}\right)$$

1. ***best approach to combine QCD and EW?***
2. ***how to treat photon initial states?***
3. ***how to treat QCD-EW mixing in qγ channels?***
4. ***how to treat (NLO) gg contributions?***

NNLOPS for WW

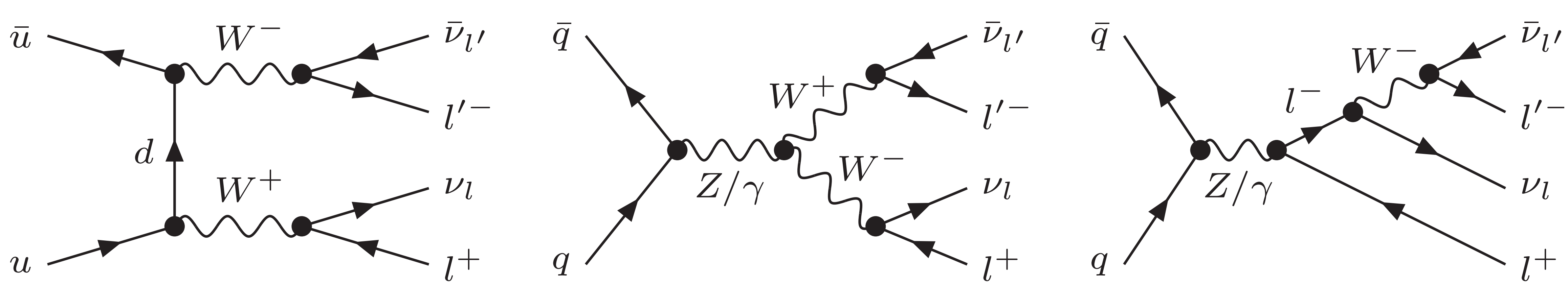
[Re, MW, Zanderighi '18]

- using MiNLO+reweighting approach to reach NNLOPS:

$$W(\Phi_B) = \frac{\left(\frac{d\sigma}{d\Phi_B}\right)_{\rm NNLO}}{\left(\frac{d\sigma}{d\Phi_B}\right)_{\rm XJ-MiNLO'}} = \frac{c_0 + c_1\alpha_S + c_2\alpha_S^2}{c_0 + c_1\alpha_S + d_2\alpha_S^2} \simeq 1 + \frac{c_2 - d_2}{c_0}\alpha_S^2 + \mathcal{O}(\alpha_S^3)$$

- NNLO for WW production from: $pp \to \ell^- \bar{\nu}_\ell \, \ell'^+ \nu_{\ell'} + X$
  - → first fully differential NNLO computation for [Grazzini, Kallweit, Rathlev, MW '16]
  - → publicly available within MATRIX [Grazzini, Kallweit, MW '17]

- matched to parton showering within MiNLO [Hamilton, Monni, Re, Zanderighi '12]

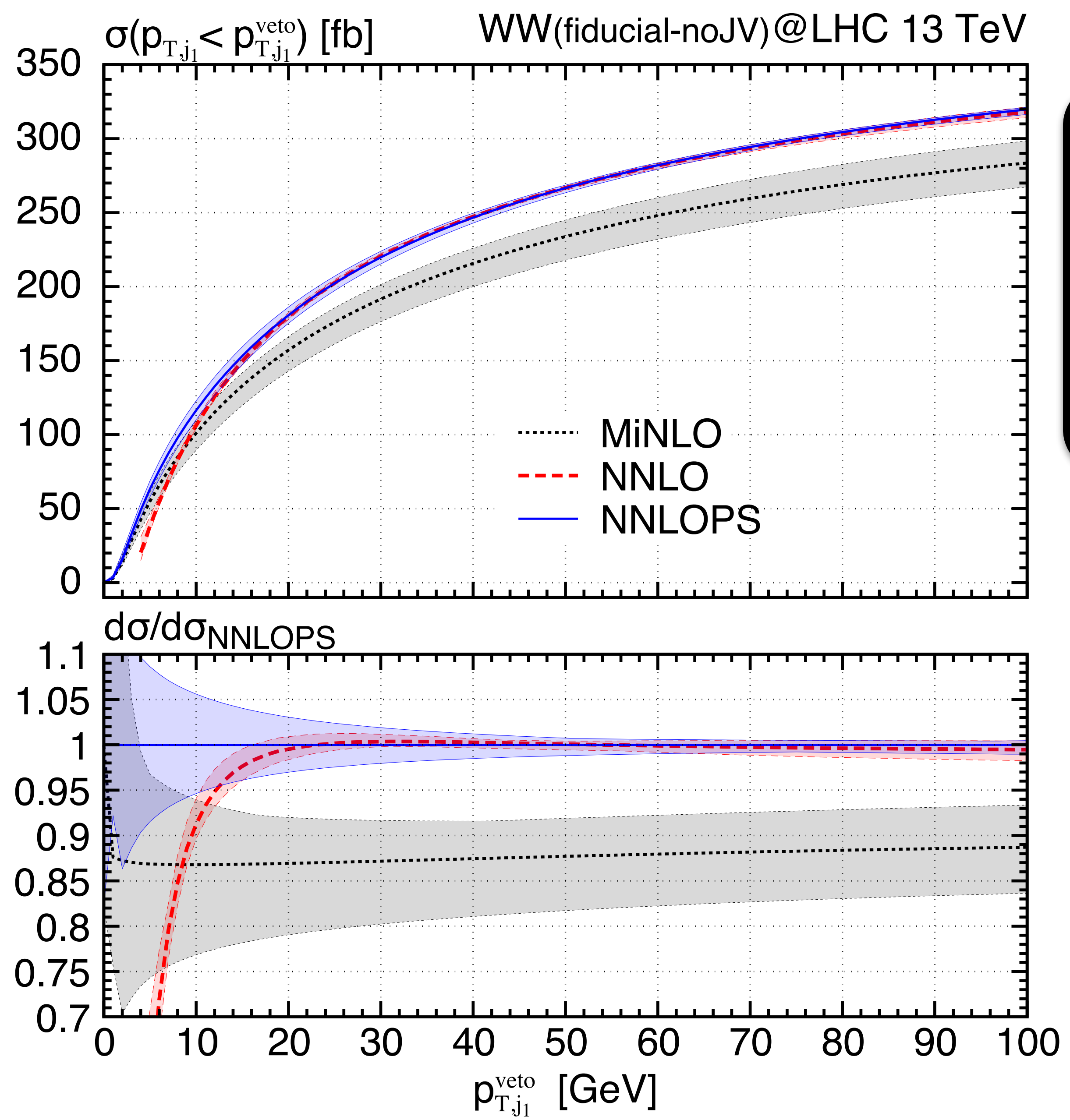


First NNLOPS accurate computation for 2→4 process

NNLOPS for WW

[Re, MW, Zanderighi '18]

jet veto (IR sensitive)



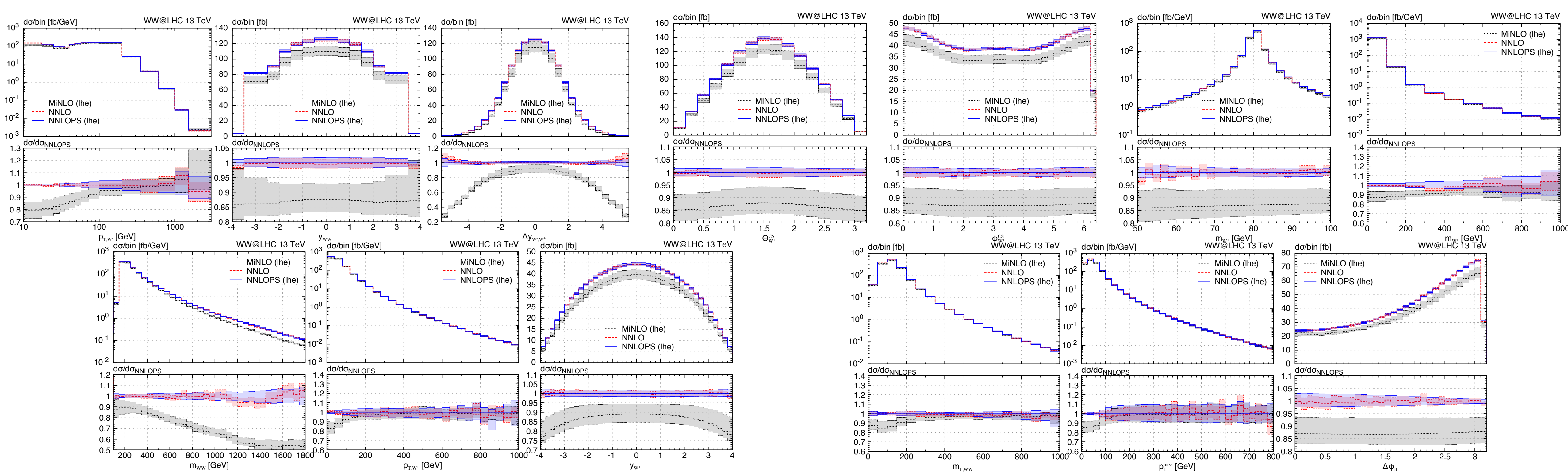
Many other distributions shown in Re, MW, Zanderighi; arXiv:1805.09857

→ **NNLO provides adequate description of jet veto down to ~15 GeV, below NNLO is unphysical**

NNLOPS without reweighting

- despite physical sound results, numerical reweighting induces limitations:
  - ➞ approximation: m_W flat & CS angles [Collins, Soper '77]
    $$\frac{d\sigma}{d\Phi_B} = \frac{d^9\sigma}{dp_{T,W^-}\, dy_{WW}\, d\Delta y_{W^+W^-}\, d\cos\theta^{CS}_{W^+}\, d\phi^{CS}_{W^+}\, d\cos\theta^{CS}_{W^-}\, d\phi^{CS}_{W^-}\, dm_{W^+}\, dm_{W^-}}$$
    to convert the 9D Born phase space into the computation of 81 3D moments
  - ➞ discrete binning limits applicability in less populated phase-space regions of NNLOPS
    $$\begin{aligned} p_{T,W^-} &: \quad [0., 17.5, 25., 30., 35., 40., 47.5, 57.5, 72.5, 100., 200., 350., 600., 1000., 1500., \infty]\,; \\ y_{WW} &: \quad [-\infty, -3.5, -2.5, -2.0, -1.5, -1.0, -0.5, 0.0, 0.5, 1.0, 1.5, 2.0, 2.5, 3.5, \infty]\,; \\ \Delta y_{W^+W^-} &: \quad [-\infty, -5.2, -4.8, -4.4, -4.0, -3.6, -3.2, -2.8, -2.4, -2.0, -1.6, -1.2, \\ &\qquad -0.8, -0.4, 0.0, 0.4, 0.8, 1.2, 1.6, 2.0, 2.4, 2.8, 3.2, 3.6, 4.0, 4.4, 4.8, 5.2, \infty]\,. \end{aligned}$$
  - ➞ reweighting still numerically intensive
  - ➞ thorough validation required

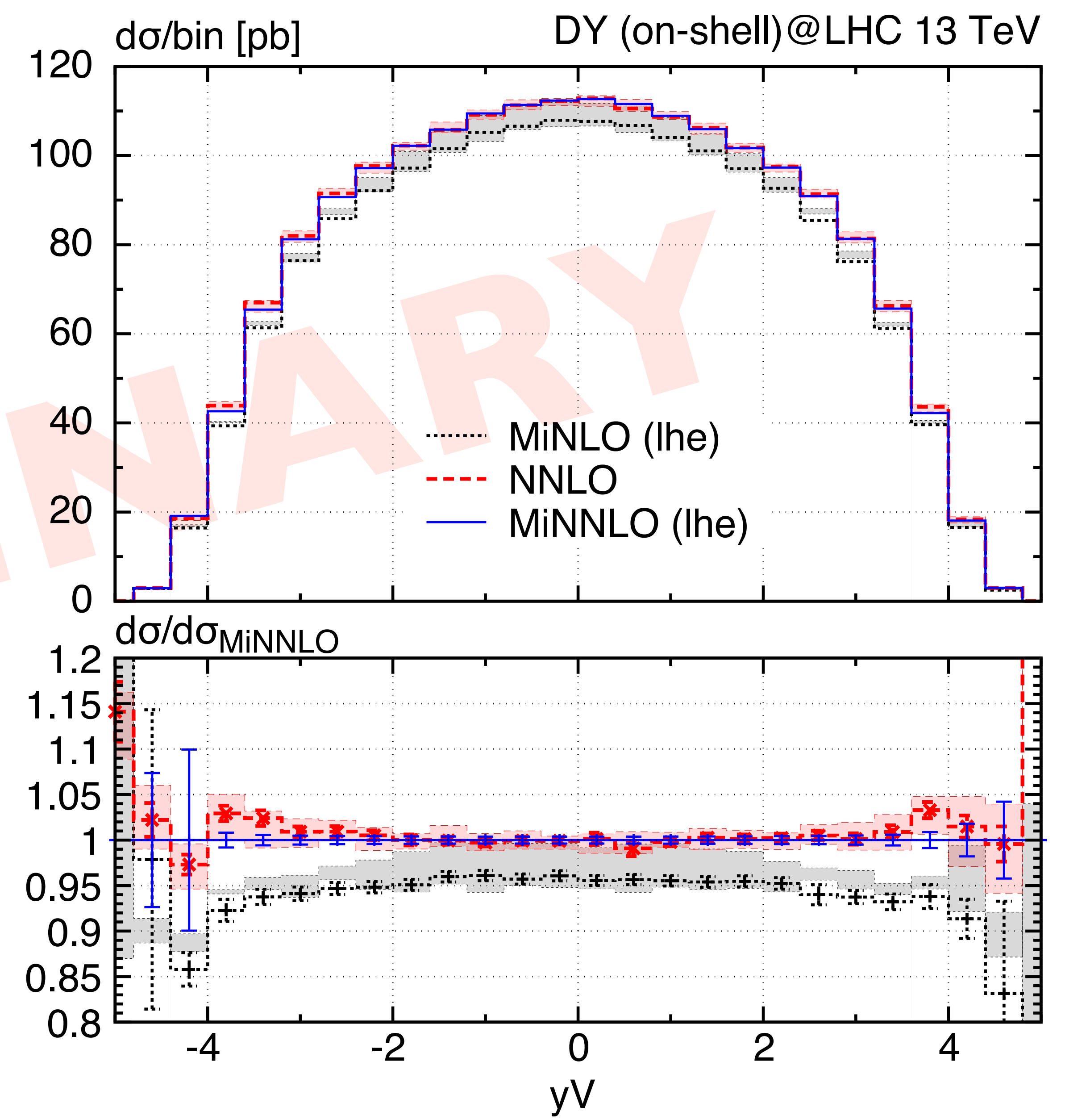
Issue in experimental NNLOPS event production already for DY



NNLOPS without reweighting

- despite physical sound results, numerical reweighting induces limitations
- new idea to avoid reweighting: [Monni, Nason, Re, MW, Zanderighi]
  - ➙ compare MiNLO with resummation formula at sufficient accuracy
  - ➙ identify missing terms for NNLO accuracy
  - ➙ add them explicitly to MiNLO

first results for DY look promising:



Conclusions

- **Theory predictions under excellent control:**
  - ***NNLO QCD for VV done!*** → publicly available within **MATRIX**
  - $\ell\ell$+ET,miss signature studied at NNLO, mixes ZZ and WW resonances
  - combination with NLO QCD for loop-induced gg and with NLO EW ongoing
  - **first NNLOPS computation for a 2→4 process (WW)**

- **Several open issues/questions remain:**
  - corrections beyond nNNLO (NLO gg) relevant? especially "NNLO gg"?
  - how to combine NNLO, NLO gg and NLO EW? photon contributions?
  - how to avoid numerically heavy reweighting for NNLOPS?
    (most important for complicated processes such as dibosons)

FREE YOUR MIND.

```
[wiesemann:~/different-branch-munich/MATRIX] ./matrix

          /---------------------------------------------------------------------\
          | MATRIX: A fully-differential NNLO(+NNLL) process library             |
          |                                                                     |
          |          ___  ___    ____    _____   ____    __   __   __          |
          |         | _\/_ |   / __ \  |____|  / __ \   ||   \\  //          |
          |         || \/ ||   | |_| |    ||    ||_||    ||    \\ //          |
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          |                                                                     |
          |          Version: 1.0.0.release_candidate4      Aug 2017            |
          |                                                                     |
          | Munich -- the MUlti-chaNnel Integrator at swiss (CH) precision --   |
          | Automates qT-subtraction and Resummation to Integrate X-sections    |
          |                                                                     |
          | \          \ ____     \          \ ____     \ ____      \           |
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          |  /          /         |/          /____     |/          |/          |
          | /          /          /          /          /           /           |
          |                                                                     |
          | M. Grazzini                            (grazzini@physik.uzh.ch)    |
          | S. Kallweit                         (stefan.kallweit@cern.ch)      |
          | M. Wiesemann                      (marius.wiesemann@cern.ch)       |
          |---------------------------------------------------------------------|
          | MATRIX is based on a number of different computations and tools    |
          | from various people and groups. Please acknowledge their efforts   |
          | by citing the list of references which is created with every run.  |
          \---------------------------------------------------------------------/

<<MATRIX-MAKE>> This is the MATRIX process compilation.
<<MATRIX-READ>> Type process_id to be compiled and created. Type "list" to show
                available processes. Try pressing TAB for auto-completion. Type
                "exit" or "quit" to stop.
|============>> list
-------------------------------------------------------------------------------------
process_id    ||   process                          ||   description
-------------------------------------------------------------------------------------
pph21         >>   p p --> H                        >>   on-shell Higgs production
ppz01         >>   p p --> Z                        >>   on-shell Z production
ppw01         >>   p p --> W^-                      >>   on-shell W- production with CKM
ppwx01        >>   p p --> W^+                      >>   on-shell W+ production with CKM
ppeex02       >>   p p --> e^- e^+                  >>   Z production with decay
ppnenex02     >>   p p --> v_e^- v_e^+              >>   Z production with decay
ppenex02      >>   p p --> e^- v_e^+                >>   W- production with decay and CKM
ppexne02      >>   p p --> e^+ v_e^-                >>   W+ production with decay and CKM
ppaa02        >>   p p --> gamma gamma              >>   gamma gamma production
ppeexa03      >>   p p --> e^- e^+ gamma            >>   Z gamma production with decay
```

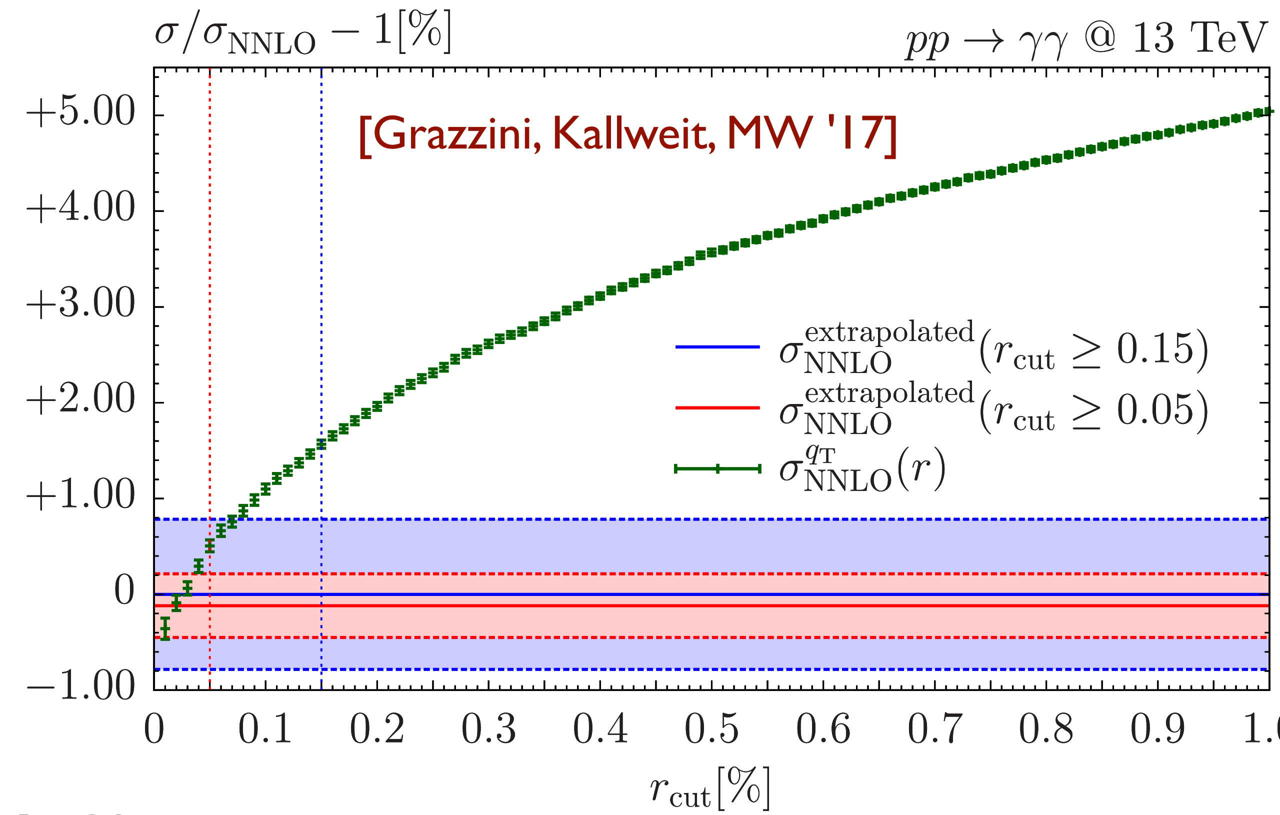
Thank You !

Back Up

γγ - inclusive and differential

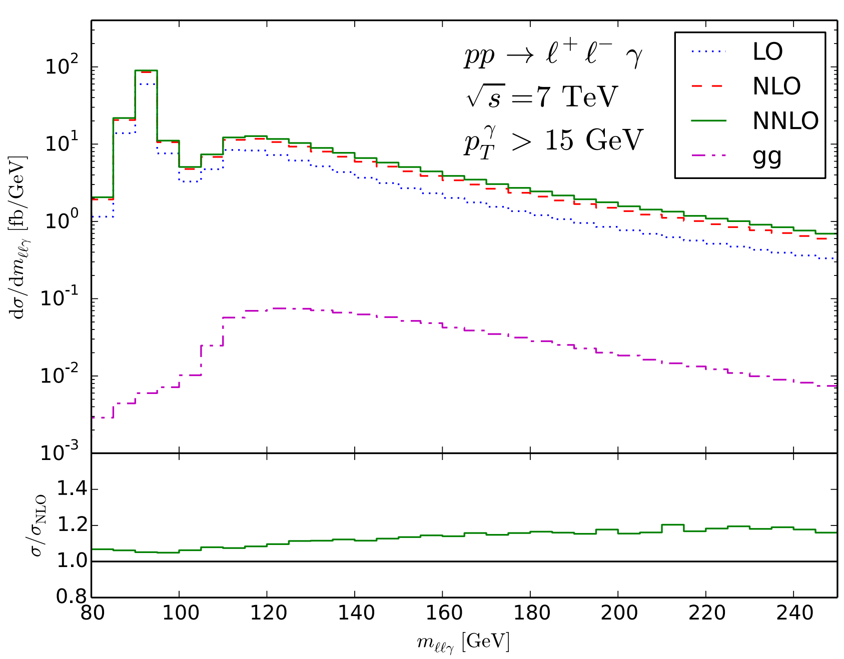
[Catani, Cieri, de Florian, Ferrera, Grazzini '12], [Campbell, Ellis, Li, Williams '16], [Grazzini, Kallweit, MW '17]

- known only with slicing techniques
- photon processes quite delicate dependence on slicing parameter due to photon isolation
- well under control in state-of-the-art tools like MATRIX (see plot on the right)
- systematic uncertainties still larger than for other diboson processes, but few permille possible
- agreement among computation within respective uncertainties

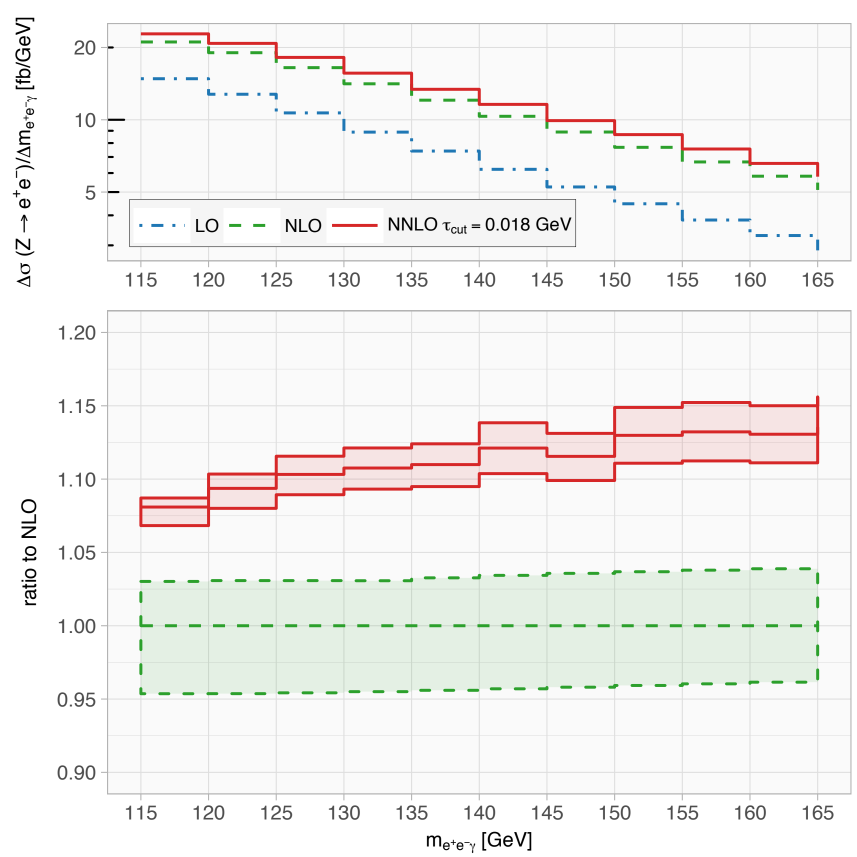


Zγ - inclusive/on-shell and differential/off-shell

[Grazzini, Kallweit, Rathlev '15]



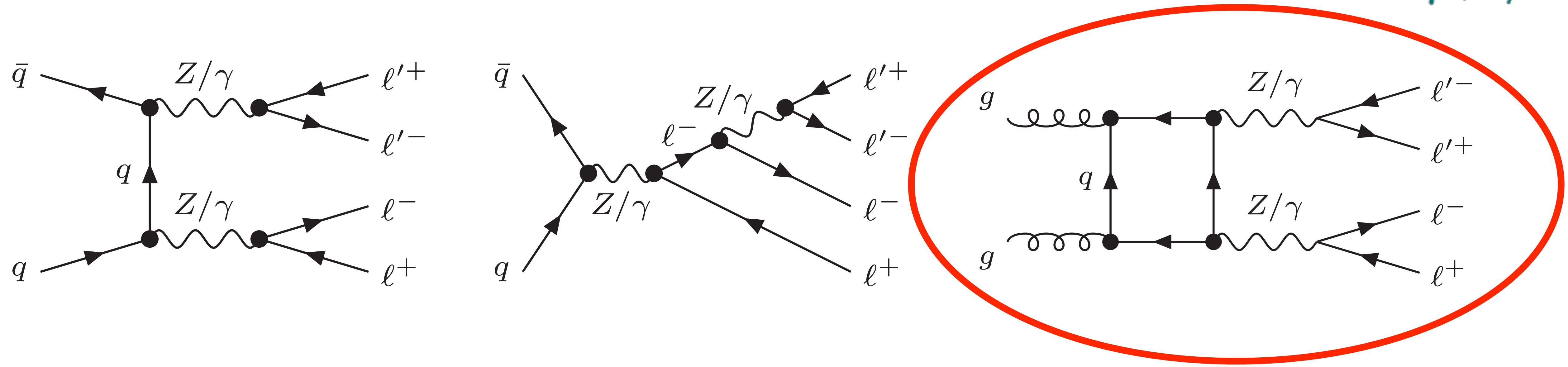
[Campbell, Neumann, Williams '17]



[Grazzini, Kallweit, MW '17]

process (${process_id})	$\sigma^{\rm extrapolated}_{\rm NNLO}$	$K_{\rm NLO}$	$K_{\rm NNLO}$
$pp \to \gamma\gamma$ (ppaa02)	$40.28(30)^{+8.7\%}_{-7.0\%}$ pb	+361%	+56.4%
$pp \to e^-e^+\gamma$ (ppeexa03)	$2316(5)^{+1.1\%}_{-1.2\%}$ fb	+44.3%	+9.29%
$pp \to \nu_e\bar{\nu}_e\gamma$ (ppnenexa03)	$113.5(6)^{+2.9\%}_{-2.4\%}$ fb	+55.2%	+15.0%
$pp \to e^-\bar{\nu}_e\gamma$ (ppenexa03)	$2256(15)^{+3.7\%}_{-3.5\%}$ fb	+155%	+22.0%
$pp \to e^+\nu_e\gamma$ (ppexnea03)	$2671(35)^{+3.8\%}_{-3.6\%}$ fb	+154%	+22.1%

gg→ZZ→4ℓ at NLO QCD



- gg→ZZ contribution part of NNLO corrections to ZZ production
  BUT: significant impact ~50% of the (large) NNLO correction, due to gluon PDFs
- NLO corrections to gg→ZZ are formally part of N3LO cross section
  BUT: still important due to large K-factor
- computed without fermionic channels [Caola, Melnikov, Röntsch, Tancredi '15]
- so far NNLO qq and NLO gg (uncertainty) combined as independent processes
  HOWEVER: their diagrams mix/interfere already at NNLO

→ **consistent impementation of both in single code desirable**

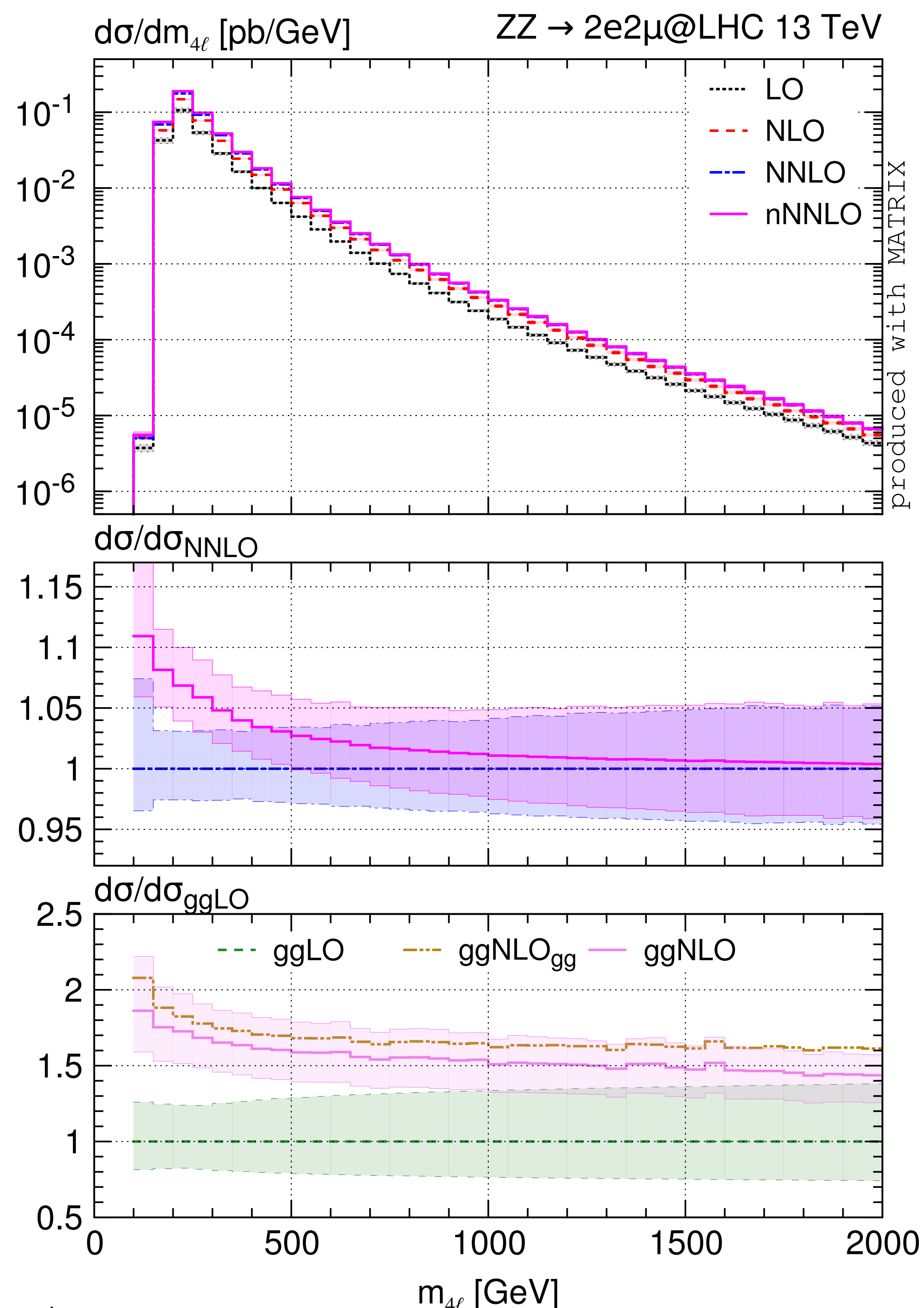
$gg \to ZZ \to 4\ell$ at NLO [Grazzini, Kallweit, MW, Yook '18]

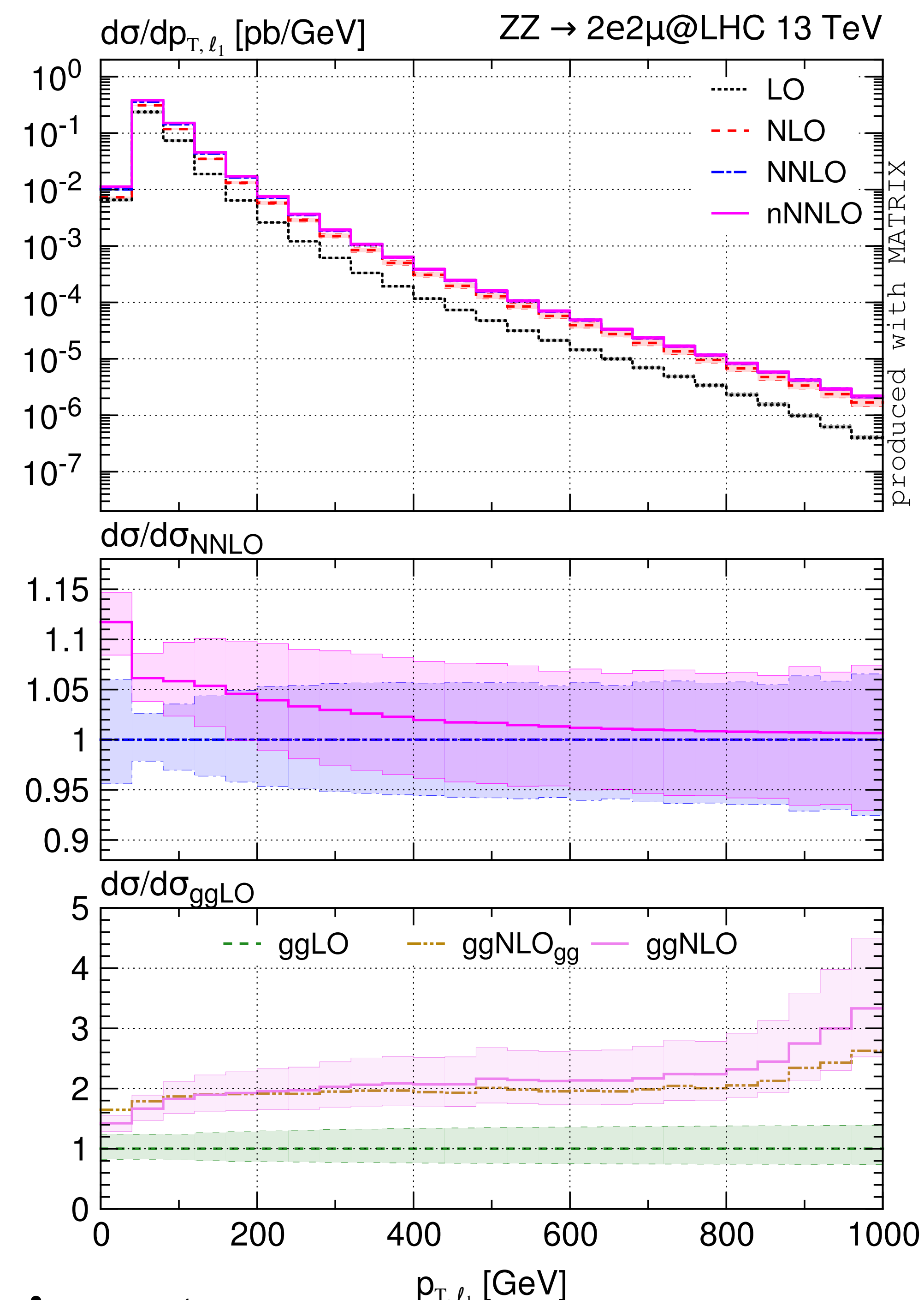
included in the MATRIX framework

$\sqrt{s}$	8 TeV	13 TeV	8 TeV	13 TeV
	σ [fb]		$\sigma/\sigma_{\mathrm{NLO}} - 1$	
LO	$8.1881(8)^{+2.4\%}_{-3.2\%}$	$13.933(7)^{+5.5\%}_{-6.4\%}$	-27.5%	-29.8%
NLO	$11.2958(4)^{+2.5\%}_{-2.0\%}$	$19.8454(7)^{+2.5\%}_{-2.1\%}$	0%	0%
$q\bar{q}$NNLO	$12.08(3)^{+1.1\%}_{-1.1\%}$	$21.54(2)^{+1.1\%}_{-1.2\%}$	$+6.9\%$	$+8.6\%$
	σ [fb]		$\sigma/\sigma_{\mathrm{ggLO}} - 1$	
ggLO	$0.79354(8)^{+28.2\%}_{-20.9\%}$	$2.0054(2)^{+23.5\%}_{-17.9\%}$	0%	0%
ggNLO$_{gg}$	$1.4810(9)^{+16.0\%}_{-13.2\%}$	$3.627(3)^{+15.2\%}_{-12.8\%}$	$+86.6\%$	$+80.9\%$
ggNLO	$1.3901(9)^{+15.4\%}_{-13.6\%}$	$3.423(3)^{+13.9\%}_{-12.0\%}$	$+75.2\%$	$+70.7\%$
	σ [fb]		$\sigma/\sigma_{\mathrm{NLO}} - 1$	
NNLO	$12.87(3)^{+2.8\%}_{-2.1\%}$	$23.55(2)^{+3.0\%}_{-2.6\%}$	$+13.9\%$	$+18.7\%$
nNNLO	$13.47(3)^{+2.6\%}_{-2.2\%}$	$24.97(2)^{+2.9\%}_{-2.7\%}$	$+19.2\%$	$+25.8\%$

+5-6% effect due to NLO correction to gg compared to NNLO

$gg \to ZZ \to 4\ell$ at NLO [Grazzini, Kallweit, MW, Yook '18]





1. inset:
NLO gg correction large+not flat; moves nNNLO outside uncertainty band of NNLO

2. inset:
huge NLO gg K-factor (~2 & more); impact of newly computed fermionic channels clearly visible

gg→ZZ→4ℓ at NLO [Grazzini, Kallweit, MW, Yook '18]

Setup (8 TeV ATLAS ZZ measurement):

definition of the fiducial volume for $pp \to e^+e^-\mu^+\mu^- + X$
$p_{T,e/\mu} > 7\,\text{GeV}$, one electron with $\vert\eta_e\vert < 4.9$, the others $\vert\eta_e\vert < 2.5$, $\vert\eta_\mu\vert < 2.7$
$\Delta R_{ee/\mu\mu} > 0.2$, $\Delta R_{e\mu} > 0.2$, $66\,\text{GeV} \le m_{e^+e^-/\mu^+\mu^-} \le 116\,\text{GeV}$,

Top quark, and Higgs (interference) contribution:

- full top-quark dependence **everywhere, but** in the 2-loop amplitudes (true for both NNLO qq and NLO gg)
- **2-loop NNLO qq:** closed (massless) fermion loops small → top neglected
- **2-loop NLO gg:** top dependence approximated by rescaling massless 2-loop amplitude with the full Born-level amplitude
- Higgs (interference) contribution fully included following this approximation → applicable to Higgs studies; validity of approximation around and beyond top threshold is to be tested; in ZZ signal region, Higgs contribution about -5%

Combination: NNLO QCD and NLO EW

[Grazzini, Kallweit, Lindert, Pozzorini, MW]

Setup of calculation (simplified selection, only for illustration purposes):

- **EW input and renormalization** in G_μ scheme.
- **Uncertainties from 7-point scale variation** around $\mu_\mathrm{R} = \mu_\mathrm{F} = \frac{1}{2}(E_{\mathrm{T,V_1}} + E_{\mathrm{T,V_2}})$.
- **PDF set** `NNPDF31_nnlo_as_0118_luxqed(_nf_4)` at each order.
- **Only very basic set of phase-space selections:**
  - $60\,\mathrm{GeV} < m_{\ell\ell} < 120\,\mathrm{GeV}$ for each SFOS lepton pair,
  - $p_{\mathrm{T},\ell} > 25\,\mathrm{GeV}$ for each lepton, $p_{\mathrm{T,miss}} > 25\,\mathrm{GeV}$,
  - lepton–photon recombination for $dR(\gamma,\ell) < 0.1$.
- **Two setups: inclusive** and **with jet-veto** ($H_{\mathrm{T,jet}} < 0.2\,H_{\mathrm{T,lep}}$).

NNLOPS for VV production

- Use knowledge of fully differential NNLO cross section
- Use MiNLO to consistently merge VV+0,1 jet at NLO
  [Hamilton, Nason, Zanderighi '12]
  - → no merging scale
  - → NLO accurate in the entire VV+0,1 phase space
- Use reweighting to promote MiNLO samples to NNLOPS

→ **yields fully exclusive (hadron-level) events with NNLO accuracy**

(the same way as POWHEG/MC@NLO are NLO+PS accurate)

NNLOPS procedure

- MiNLO is general for colour singlets (X=H,V, VH,VV, ...)
  [Hamilton, Nason, Zanderighi '12] **(only B2 NNLL coefficient becomes non-trivial starting from 2→2)**

	X	X+jet	X+2jets	X+nj (n>2)
XJ (NLO)	—	NLO	LO	—
XJ-MiNLO	NLO	NLO	LO	PS
X@NNLO	NNLO	NLO	LO	—

- XJ-MiNLO already almost right accuracy, only $\mathcal{O}(\alpha_s^2)$ terms missing to obtain NNLO accuracy at Born level

NNLOPS procedure

- MiNLO is general for colour singlets (X=H,V, VH,VV, ...)
  [Hamilton, Nason, Zanderighi '12] **(only B2 NNLL coefficient becomes non-trivial starting from 2→2)**

	X	X+jet	X+2jets	X+nj (n>2)
XJ (NLO)	—	NLO	LO	—
XJ-MiNLO	NLO	NLO	LO	PS
X@NNLO	NNLO	NLO	LO	—
X@NNLOPS	NNLO	NLO	LO	PS

- solution: reweighting MiNLO events in Born phase space to correct for $\mathcal{O}(\alpha_s^2)$ terms by the following ratio:

$$W(\Phi_B) = \frac{\left(\frac{d\sigma}{d\Phi_B}\right)_{\rm NNLO}}{\left(\frac{d\sigma}{d\Phi_B}\right)_{\rm XJ-MiNLO'}} = \frac{c_0 + c_1\alpha_{\rm S} + c_2\alpha_{\rm S}^2}{c_0 + c_1\alpha_{\rm S} + d_2\alpha_{\rm S}^2} \simeq 1 + \frac{c_2 - d_2}{c_0}\alpha_{\rm S}^2 + \mathcal{O}(\alpha_{\rm S}^3)$$

NNLOPS procedure

already used for processes with simpler Born kinematics:

- Higgs (only rapitidy) → 1D reweighting
  [Hamilton, Nason, Re, Zanderighi '13],
  [Hamilton, Nason, Zanderighi '15],

- Drell-Yan (dilepton system) → 3D reweighting
  [Karlberg, Hamilton, Zanderighi '14]

- Higgsstrahlung ($H\ell\ell/H\ell\nu$ system) → 6D reweighting
  [Astill, Bizoń, Re, Zanderigh '16 '18]

NNLOPS for WW

[Re, MW, Zanderighi '18]

- in principle, requires 9D reweighting (numerically impossible)

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Phi_{\mathrm{B}}} = \frac{\mathrm{d}^9\sigma}{\mathrm{d}p_{T,W^-}\,\mathrm{d}y_{WW}\,\mathrm{d}\Delta y_{W^+W^-}\,\mathrm{d}\cos\theta^{\mathrm{CS}}_{W^+}\,\mathrm{d}\phi^{\mathrm{CS}}_{W^+}\,\mathrm{d}\cos\theta^{\mathrm{CS}}_{W^-}\,\mathrm{d}\phi^{\mathrm{CS}}_{W^-}\,\mathrm{d}m_{W^+}\,\mathrm{d}m_{W^-}}$$

- drop invariant masses which are flat (in particular around the peak)

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Phi_{\mathrm{B}}} = \frac{\mathrm{d}^{\cancel{9}\,7}\sigma}{\mathrm{d}p_{T,W^-}\,\mathrm{d}y_{WW}\,\mathrm{d}\Delta y_{W^+W^-}\,\mathrm{d}\cos\theta^{\mathrm{CS}}_{W^+}\,\mathrm{d}\phi^{\mathrm{CS}}_{W^+}\,\mathrm{d}\cos\theta^{\mathrm{CS}}_{W^-}\,\mathrm{d}\phi^{\mathrm{CS}}_{W^-}\,\cancel{\mathrm{d}m_{W^+}}\,\cancel{\mathrm{d}m_{W^-}}}$$

- Collins-Soper angles [Collins, Soper '77] are used to describe both W decays in terms of spherical harmonics and parametrize angular dependence by

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Phi_{\mathrm{B}}} = \frac{9}{256\pi^2}\sum_{i=0}^{8}\sum_{j=0}^{8} AB_{ij}\, f_i(\theta^{\mathrm{CS}}_{W^-},\phi^{\mathrm{CS}}_{W^-})\, f_j(\theta^{\mathrm{CS}}_{W^+},\phi^{\mathrm{CS}}_{W^+})$$

$$AB_{ij}(p_{T,W^-},y_{WW},\Delta y_{W^+W^-}) = \int \frac{\mathrm{d}\sigma}{\mathrm{d}\Phi_B}\, g_i(\theta^{\mathrm{CS}}_{W^-},\phi^{\mathrm{CS}}_{W^-})\, g_j(\theta^{\mathrm{CS}}_{W^+},\phi^{\mathrm{CS}}_{W^+})\,\mathrm{d}\cos\theta^{\mathrm{CS}}_{W^-}\,\mathrm{d}\phi^{\mathrm{CS}}_{W^-}\,\mathrm{d}\cos\theta^{\mathrm{CS}}_{W^+}\,\mathrm{d}\phi^{\mathrm{CS}}_{W^+}$$

$$\begin{aligned}
f_0(\theta,\phi) &= \left(1-3\cos^2\theta\right)/2\,, & f_1(\theta,\phi) &= \sin 2\theta\cos\phi\,, & f_2(\theta,\phi) &= (\sin^2\theta\cos 2\phi)/2\,,\\
f_3(\theta,\phi) &= \sin\theta\cos\phi\,, & f_4(\theta,\phi) &= \cos\theta\,, & f_5(\theta,\phi) &= \sin\theta\sin\phi\,,\\
f_6(\theta,\phi) &= \sin 2\theta\sin\phi\,, & f_7(\theta,\phi) &= \sin^2\theta\sin 2\phi\,, & f_8(\theta,\phi) &= 1+\cos^2\theta\,.
\end{aligned}$$

→ compute 81 3D distributions (numerically feasible)

NNLOPS for WW

[Re, MW, Zanderighi '18]

Setup:

The remaining three variables and their binning chosen to be

$$p_{T,W^-} : [0., 17.5, 25., 30., 35., 40., 47.5, 57.5, 72.5, 100., 200., 350., 600., 1000., 1500., \infty];$$
$$y_{WW} : [-\infty, -3.5, -2.5, -2.0, -1.5, -1.0, -0.5, 0.0, 0.5, 1.0, 1.5, 2.0, 2.5, 3.5, \infty];$$
$$\Delta y_{W^+W^-} : [-\infty, -5.2, -4.8, -4.4, -4.0, -3.6, -3.2, -2.8, -2.4, -2.0, -1.6, -1.2, -0.8, -0.4, 0.0, 0.4, 0.8, 1.2, 1.6, 2.0, 2.4, 2.8, 3.2, 3.6, 4.0, 4.4, 4.8, 5.2, \infty].$$

Cuts inspired by ATLAS 13 TeV study (1702.04519):

lepton cuts	$p_{T,\ell} > 25\,\text{GeV}$, $\lvert\eta_\ell\rvert < 2.4$, $m_{\ell^-\ell^+} > 10\,\text{GeV}$
lepton dressing	add photon FSR to lepton momenta with $\Delta R_{\ell\gamma} < 0.1$ *(our results do not include photon FSR, see text)*
neutrino cuts	$p_T^{\text{miss}} > 20\,\text{GeV}$, $p_T^{\text{miss,rel}} > 15\,\text{GeV}$
	anti-k_T jets with $R = 0.4$;
jet cuts	$N_{\text{jet}} = 0$ for $p_{T,j} > 25\,\text{GeV}$, $\lvert\eta_j\rvert < 2.4$ and $\Delta R_{ej} < 0.3$
	$N_{\text{jet}} = 0$ for $p_{T,j} > 30\,\text{GeV}$, $\lvert\eta_j\rvert < 4.5$ and $\Delta R_{ej} < 0.3$

NNLO uses the central scale

$$\mu_R = \mu_F = \mu_0 \equiv \frac{1}{2}\left(\sqrt{m^2_{e^-\bar{\nu}_e} + p^2_{T,e^-\bar{\nu}_e}} + \sqrt{m^2_{\mu^+\nu_\mu} + p^2_{T,\mu^+\nu_\mu}}\right)$$

All uncertainty bands are the envelop of 7-scales. In the NNLOPS scales in MiNLO and NNLO are varied in a correlated way

gg-channel not included in our study, as it can it is know at one-loop and can be added incoherently

NNLOPS for WW

[Re, MW, Zanderighi '18]

Validation:

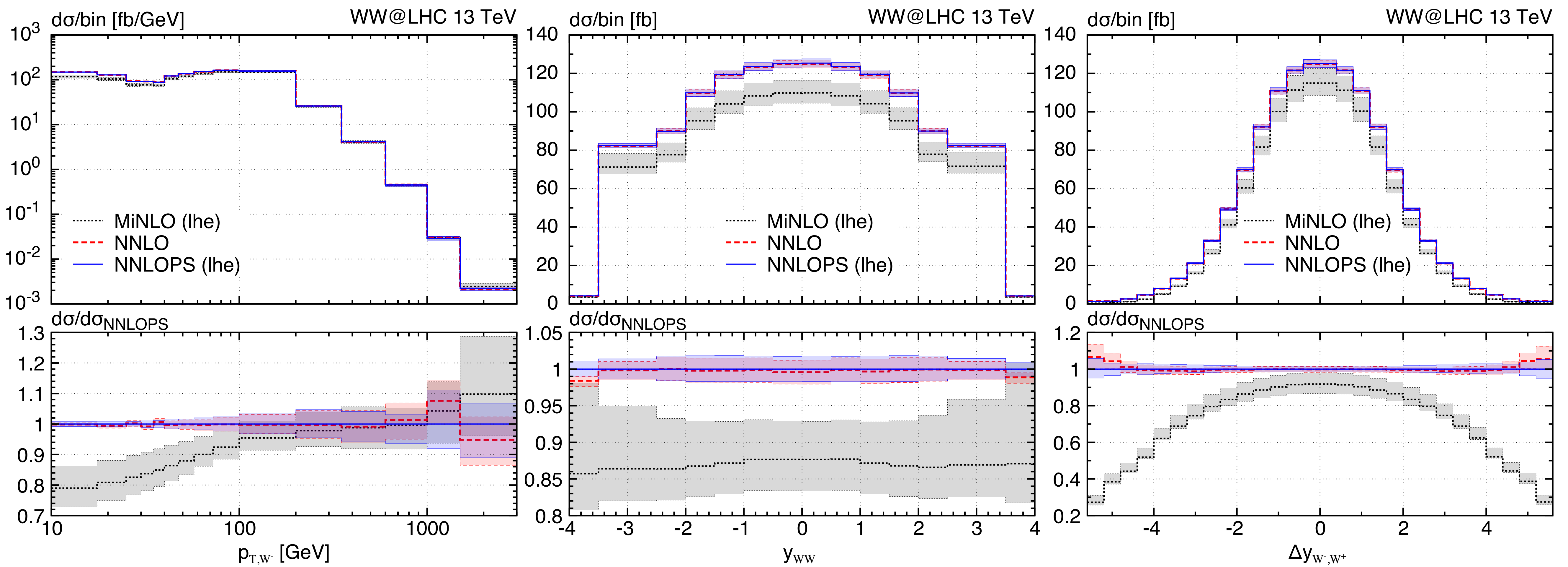
1. Total inclusive NNLO cross section reproduced by NNLOPS sample ✓
2. NNLO distributions for observables used for reweighting reproduced ✓
3. NNLO distributions for CS angles reproduced ✓
4. NNLO distributions for invariant masses of W's reproduced ✓
5. NNLO distributions for other Born-level observables reproduced ✓

NNLOPS for WW

[Re, MW, Zanderighi '18]

Validation at LHE level:

2. NNLO distributions for observables used for reweighting reproduced ✓

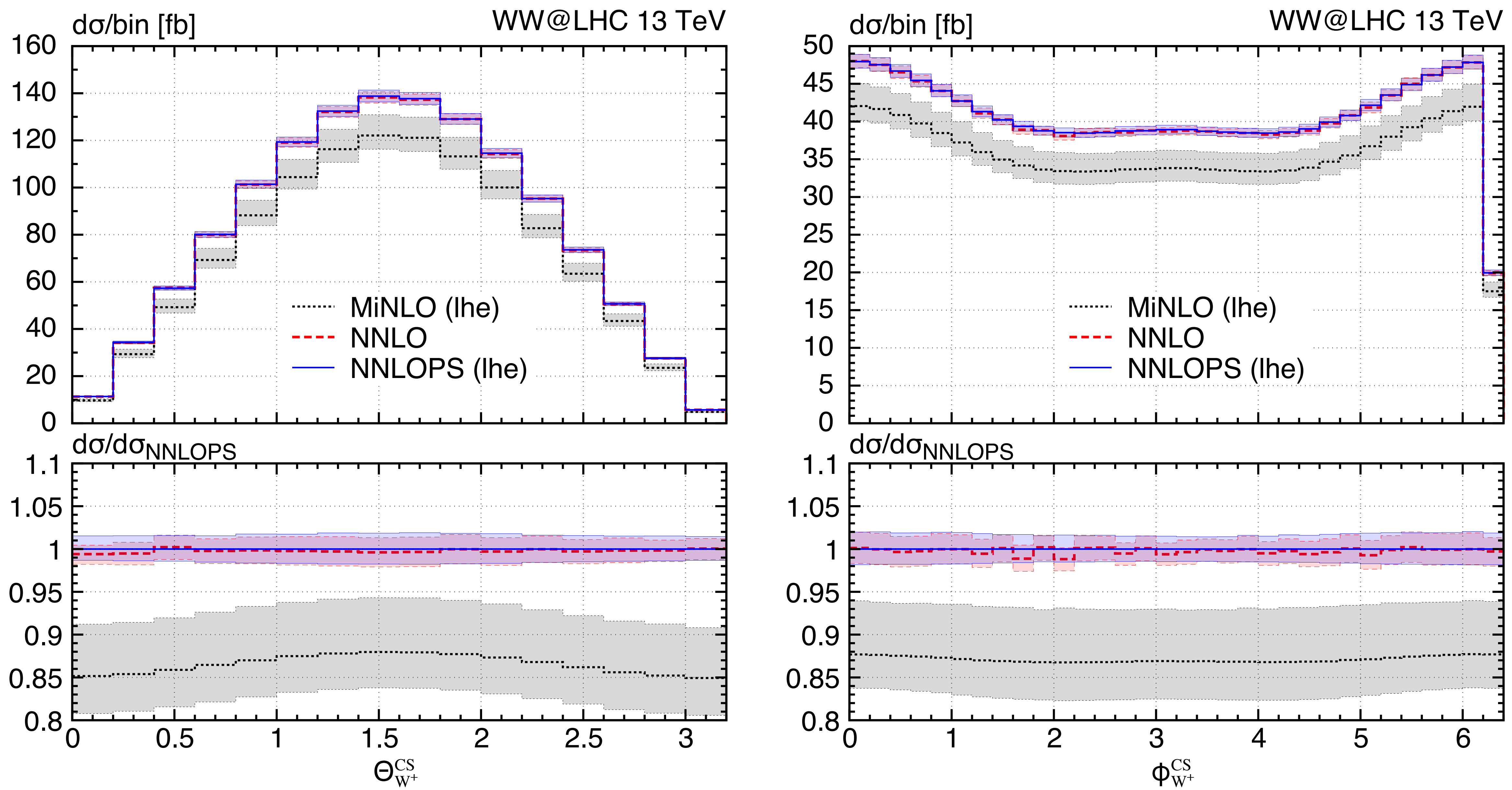


NNLOPS for WW

[Re, MW, Zanderighi '18]

Validation at LHE level:

3. NNLO distributions for CS angles reproduced ✓

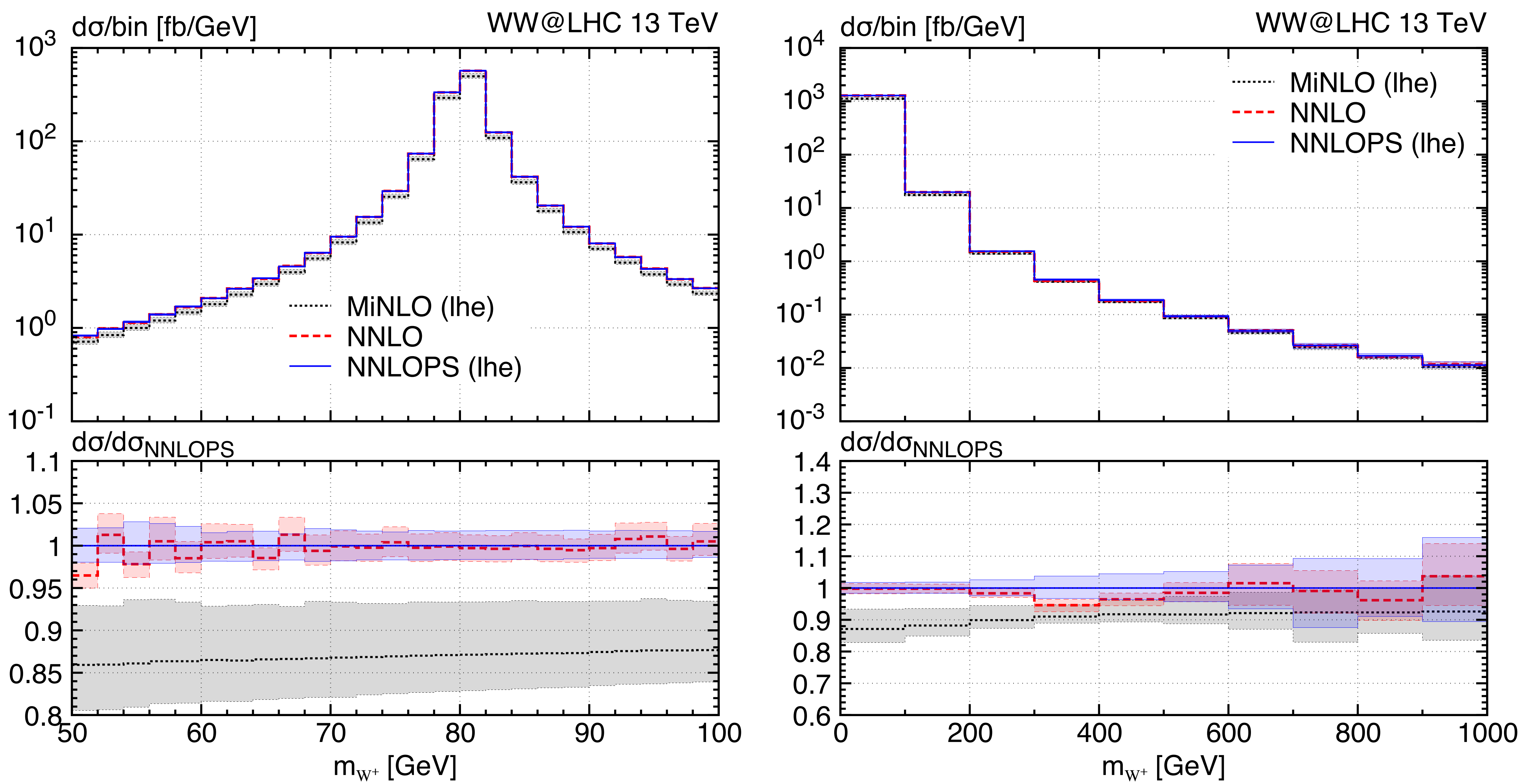


NNLOPS for WW

[Re, MW, Zanderighi '18]

Validation at LHE level:

4. NNLO distributions for invariant masses of W's reproduced ✓

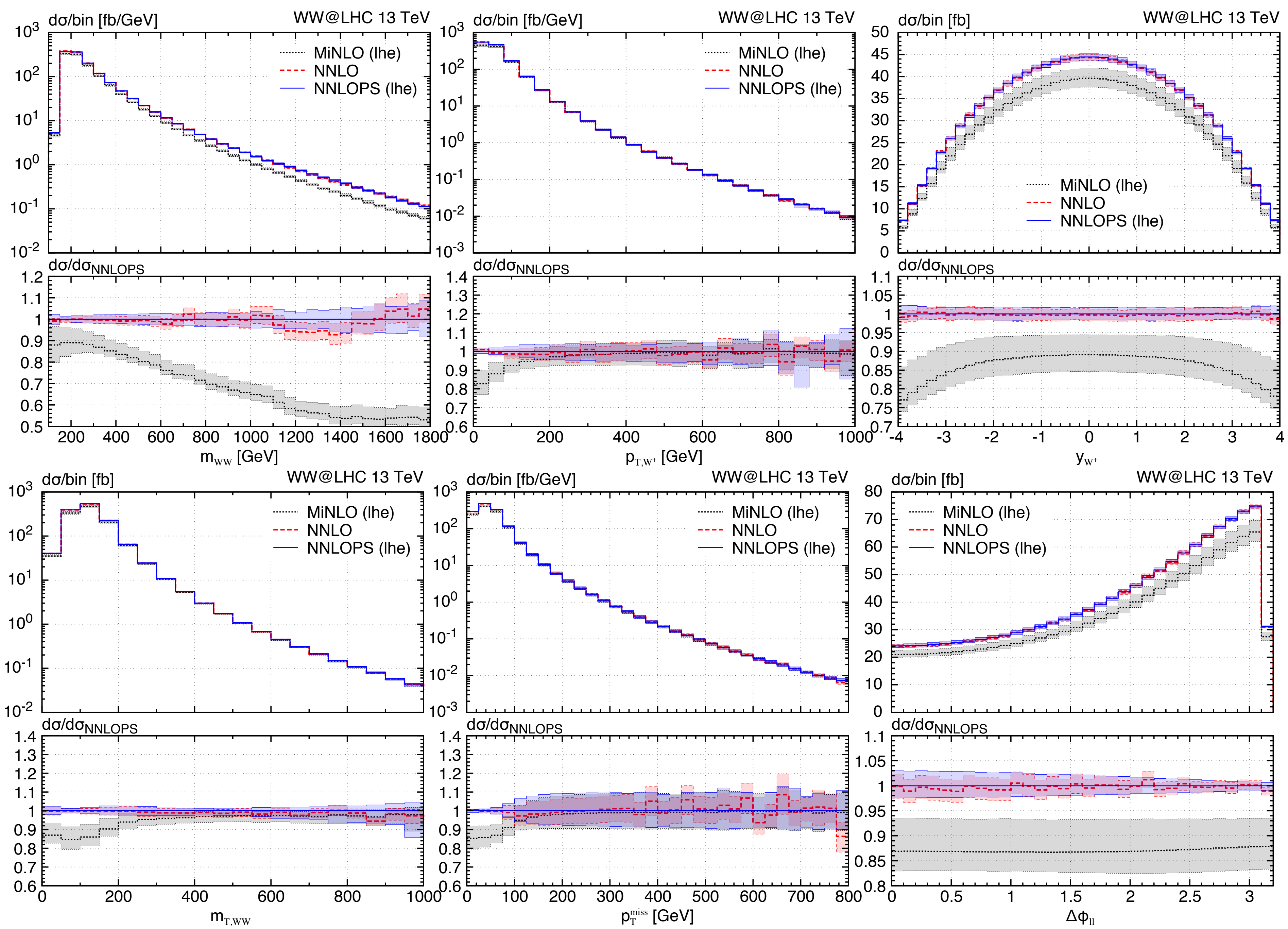


NNLOPS for WW

[Re, MW, Zanderighi '18]

Validation at LHE level:

5. NNLO distributions for other Born-level observables reproduced ✓



NNLOPS for WW

[Re, MW, Zanderighi '18]

Phenomenological results:

Integrated cross sections

$q\bar{q}$ (no loop^2 gg)	$\sigma_{\mathrm{incl}}(pp \to W^+W^-)$ [pb]	$\sigma_{\mathrm{fid}}(pp \to e^{\mp}\nu_e\,\mu^{\pm}\nu_\mu)$ [fb]	$\mathrm{A} = \sigma_{\mathrm{fid}}/\sigma_{\mathrm{incl}}$ [%]
LO	$70.66(1)^{+5.1\%}_{-6.2\%}$	$440.5(0)^{+6.0\%}_{-7.1\%}$	0.623
NLO	$99.96(3)^{+3.5\%}_{-2.8\%}$	$411.8(1)^{+2.7\%}_{-2.3\%}$	0.412
NNLO	$110.0(1)^{+1.6\%}_{-1.6\%}$	$413.1(2)^{+1.0\%}_{-0.7\%}$	0.376
MiNLO	$96.05(1)^{+7.1\%}_{-4.9\%}$	$359.6(1)^{+5.4\%}_{-8.3\%}$	0.374
NNLOPS	$110.2(2)^{+1.7\%}_{-1.6\%}$	$413.0(2)^{+2.2\%}_{-2.3\%}$	0.375
ATLAS$-gg$ [9]	$124.7 \pm 5\,(\mathrm{stat}) \pm 13\,(\mathrm{syst}) \pm 3\,(\mathrm{lumi})$	$473 \pm 20\,(\mathrm{stat}) \pm 50\,(\mathrm{syst}) \pm 11\,(\mathrm{lumi})$	0.379
CMS$-gg$ [10]	$108.5 \pm 5.8\,(\mathrm{stat})\ {}^{\pm 5.7(\mathrm{exp.\,syst})}_{\pm 6.4(\mathrm{theo.\,syst})} \pm 3.6\,(\mathrm{lumi})$	—	—

Annotations: inclusive LO→NLO +40%, NLO→NNLO +10%; fiducial LO→NLO -6.5%, NLO→NNLO +0.3%

→ **inclusive: large QCD corrections; fiducial: strongly reduced by the jet veto**

→ **MiNLO, NLO quite different in fiducial ← poor jet-veto modelling at NLO (acceptance too high)**

→ **NNLO, NNLOPS in excellent agreement (by construction for inclusive, but also in fiducial)**

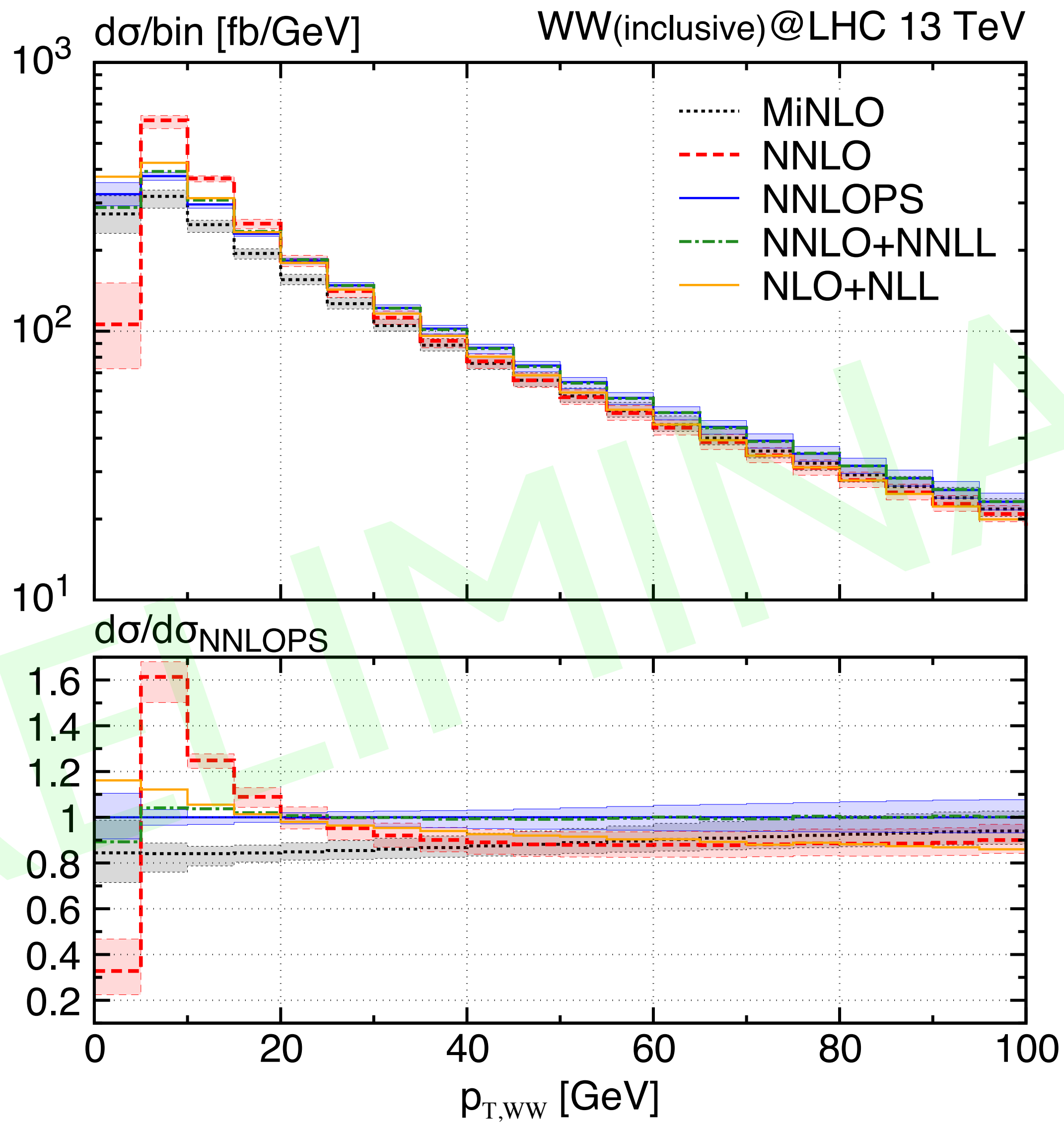
→ **MiNLO, NNLO, NNLOPS yield very similar acceptances, in agreement with data**

NNLOPS for WW

[Re, MW, Zanderighi '18]

Phenomenological results:

$p_{T,WW}$ (IR sensitive) compared to NNLO+NNLL



not completely fair comparison yet:
- on-shell WW for analytic resummation
- slightly different setups
→ full comparison will be done

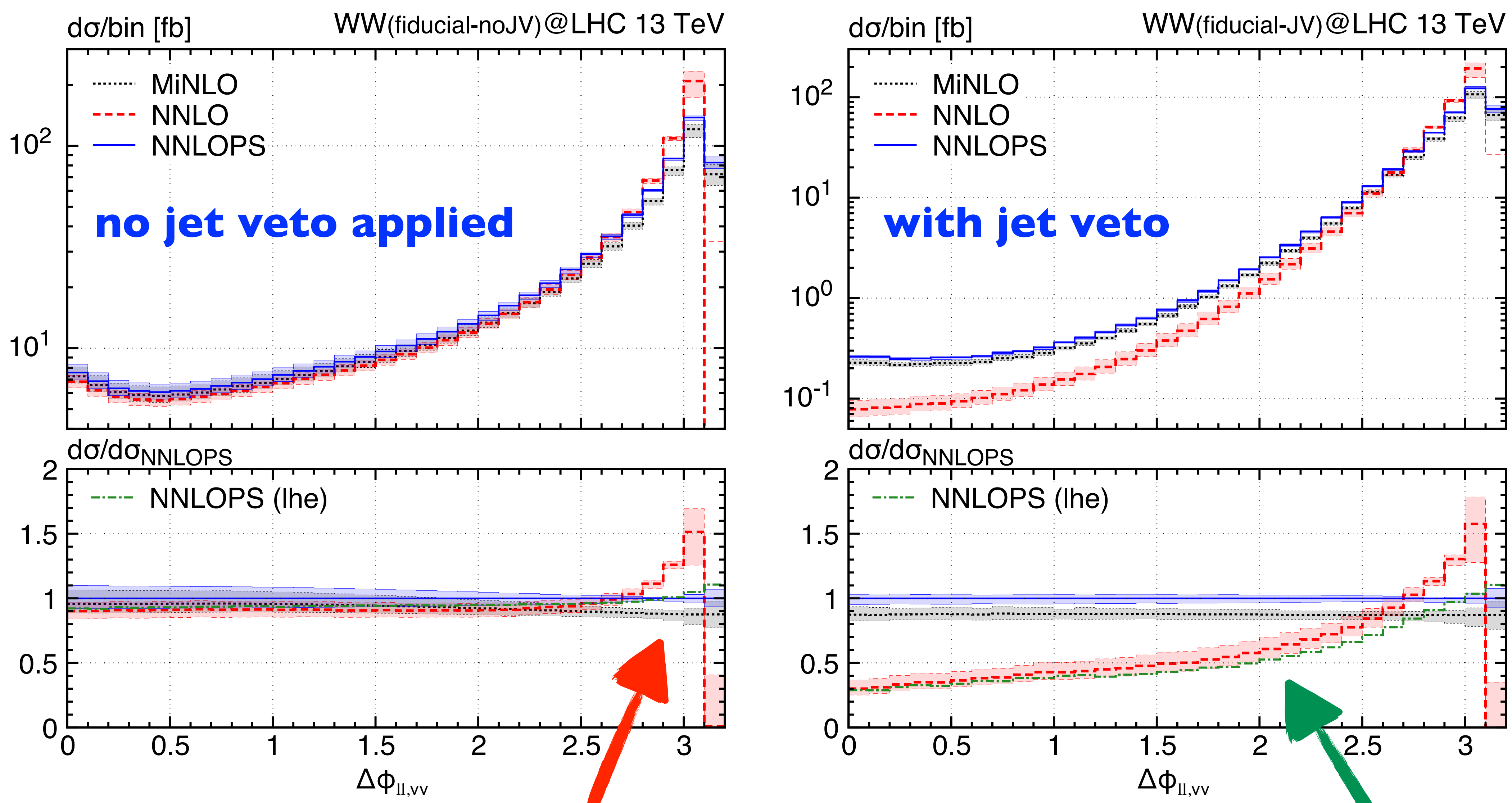
→ Resummation (analytic or shower) crucial at low p_T; NNLOPS in decent agreement with NNLL

NNLOPS for WW

[Re, MW, Zanderighi '18]

Phenomenological results:

$\Delta\Phi_{\ell\ell,\nu\nu}$ (*IR sensitive*)



→ **NNLOPS corrects regions sensitive to soft-gluon effects**

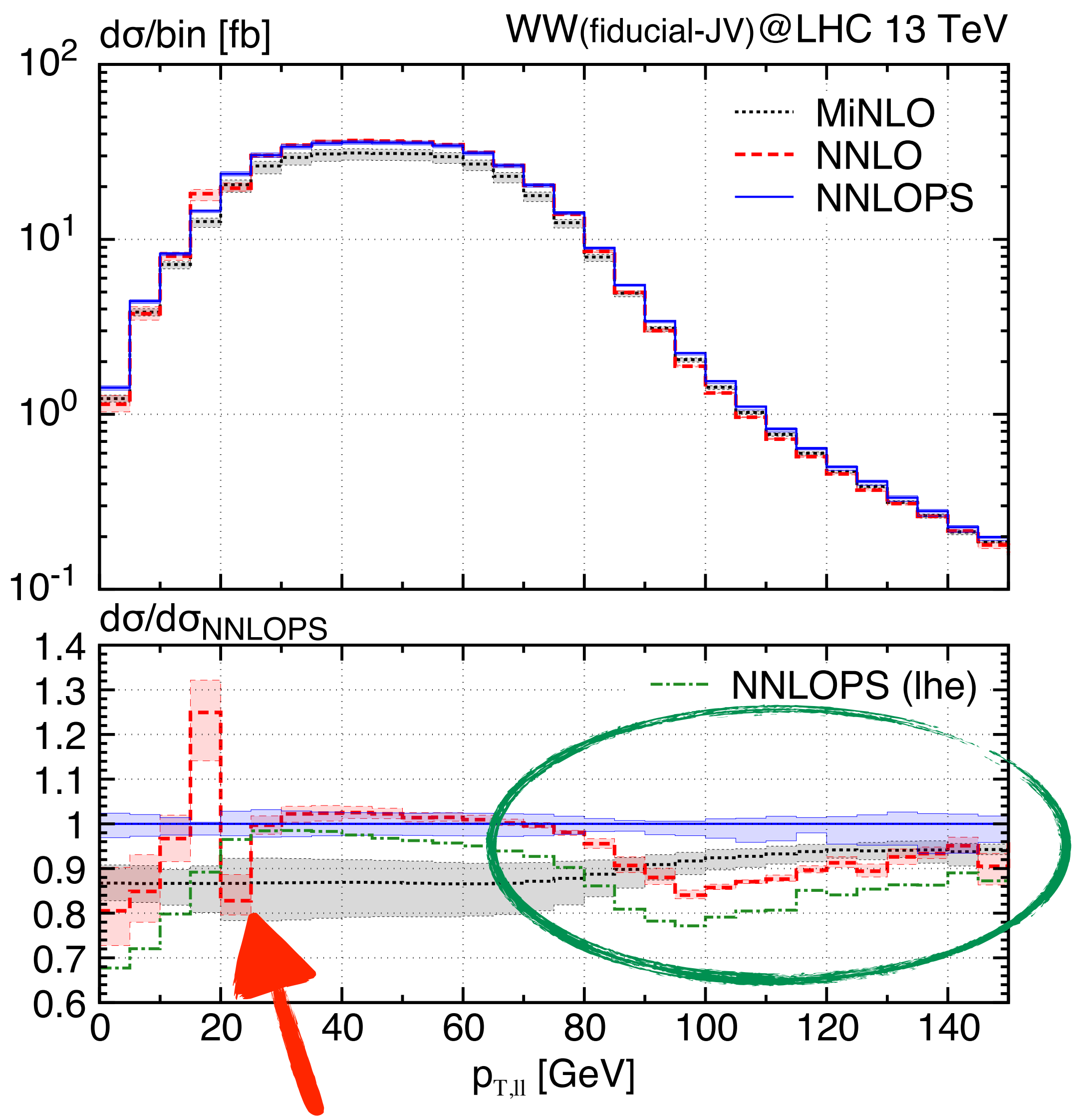
→ **jet veto can turn observables sensitive soft-gluon emissions everywhere**

NNLOPS for WW

[Re, MW, Zanderighi '18]

Phenomenological results:

p_T of dilepton system



Many other distributions shown in Re, MW, Zanderighi; arXiv:1805.09857

→ **NNLOPS cures perturbative instabilities (sudakov shoulder; due to fiducial missing p_T cut)**

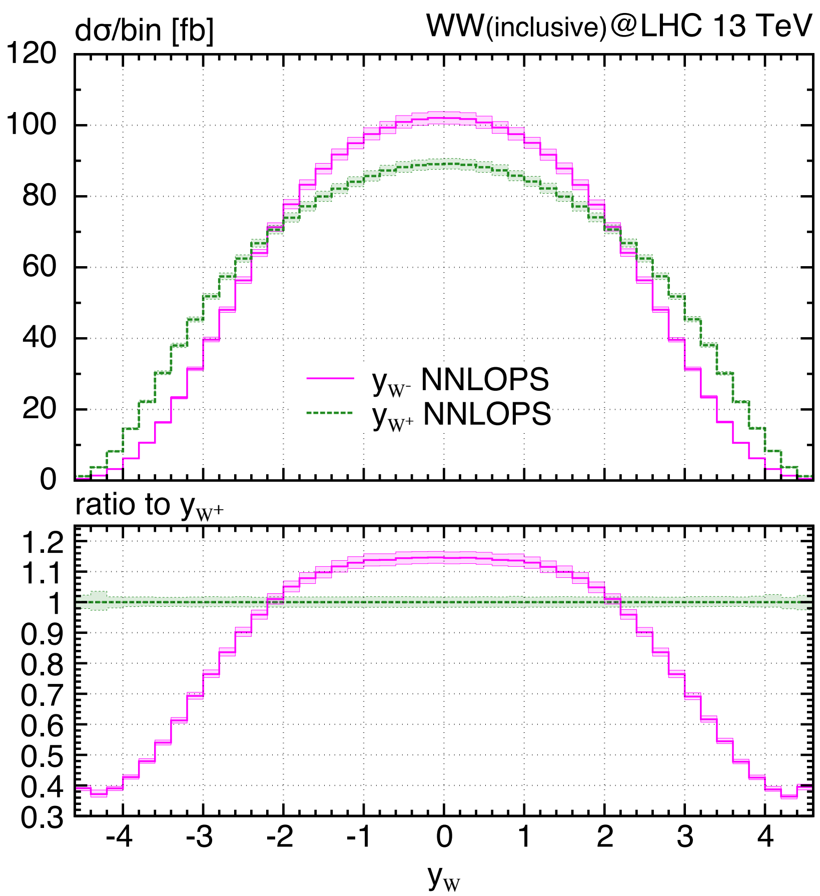
→ **NNLOPS can induce additional shape effects due to recoil/migration**

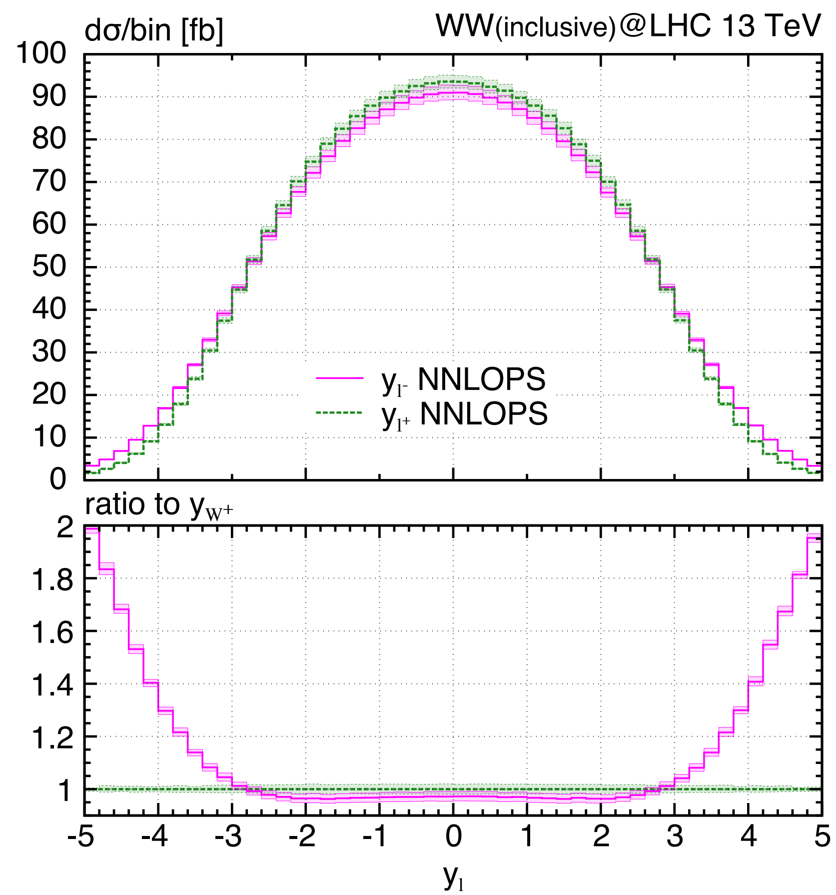
NNLOPS for WW

[Re, MW, Zanderighi '18]

Phenomenological results:

Charge asymmetry





- **W momentum cannot be reconstructed → use leptons**
- **lepton asymmetry smaller; almost vanishes in fiducial**
- **can be recovered by widening rapidity range of leptons or by considering boosted regime**
- **sensitive to W polarizations → powerful probe of new physics**

$$A_C^W = \frac{\sigma(|y_{W^+}| > |y_{W^-}|) - \sigma(|y_{W^+}| < |y_{W^-}|)}{\sigma(|y_{W^+}| > |y_{W^-}|) + \sigma(|y_{W^+}| < |y_{W^-}|)},$$

$$A_C^\ell = \frac{\sigma(|y_{\ell^+}| > |y_{\ell^-}|) - \sigma(|y_{\ell^+}| < |y_{\ell^-}|)}{\sigma(|y_{\ell^+}| > |y_{\ell^-}|) + \sigma(|y_{\ell^+}| < |y_{\ell^-}|)}.$$

NNLOPS	inclusive phase space	fiducial phase space
A_C^W	$0.1263(1)^{+2.1\%}_{-1.8\%}$	$0.0726(3)^{+2.0\%}_{-2.6\%}$
A_C^ℓ	$-[0.0270(1)^{+5.0\%}_{-6.4\%}]$	$-[0.0009(4)^{+72\%}_{-87\%}]$

q_T subtraction

$$d\sigma_{\rm NNLO} = \left[d\sigma^{F+1\rm jet}_{\rm NLO} - \Sigma_{\rm NNLO} \otimes d\sigma_{\rm LO}\right] + \mathcal{H}_{\rm NNLO} \otimes d\sigma_{\rm LO}$$

[Catani, Grazzini '07]

subtraction terms known from resummation:

$$d\sigma^{F+1\rm jet} \xrightarrow{p_T \ll Q} \left[d\sigma^{(\rm res)}\right]_{\rm f.o.} \equiv \Sigma(p_T/Q) \otimes d\sigma_{\rm LO}$$

NNLO accuracy consequence of unitarity:

$$\int dp_T^2 \, \frac{d\sigma^{(\rm res)}}{dp_T^2 \, dy \, dM \, d\Omega} = \mathcal{H} \otimes d\sigma_{\rm LO} \qquad \left(\ln(Q^2b^2/b_0^2) \to \ln(Q^2b^2/b_0^2 + 1)\right)$$

Resummation formula:

$$\frac{d\sigma^{(\rm res)}}{dp_T^2 \, dy \, dM \, d\Omega} \sim \int db \, \frac{b}{2} \, J_0(b\, p_T) \, S(b, A, B) \, \mathcal{H}_{N_1,N_2} \, f_{N_1} \, f_{N_2}$$

[Collins, Soper, Sterman '85], [Bozzi, Catani, de Florian, Grazzini '06]

q_T subtraction

$$d\sigma_{\mathrm{NNLO}} = \left[d\sigma^{F+1\mathrm{jet}}_{\mathrm{NLO}} - \Sigma_{\mathrm{NNLO}} \otimes d\sigma_{\mathrm{LO}} \right] + \mathcal{H}_{\mathrm{NNLO}} \otimes d\sigma_{\mathrm{LO}}$$

[Catani, Grazzini '07]

practical implementation:

- subtraction not local
- both terms in squared brackets separately divergent
- introduce lower cut-off r_{cut} on dimensionless quantity $r = p_{T,WW}/m_{WW}$
- use very small r_{cut} value and integrate both terms separately down to $r \geq r_{\mathrm{cut}}$
- assumption: for $r \leq r_{\mathrm{cut}}$ terms cancel (true up to power-suppressed terms)
- numerics forbids arbitrarily small r_{cut} values: use fit towards $r_{\mathrm{cut}} \to 0$ limit
- MATRIX uses extrapolation $r_{\mathrm{cut}} \to 0$ to obtain the final prediction

q_T subtraction

$$d\sigma_{\rm NNLO} = \Big[\underbrace{d\sigma_{\rm NLO}^{F+1\rm jet}}_{(r > r_{\rm cut})} - \underbrace{\Sigma_{\rm NNLO} \otimes d\sigma_{\rm LO}}_{(r > r_{\rm cut})}\Big] + \mathcal{H}_{\rm NNLO} \otimes d\sigma_{\rm LO}$$

[Catani, Grazzini '07]

practical implementation:

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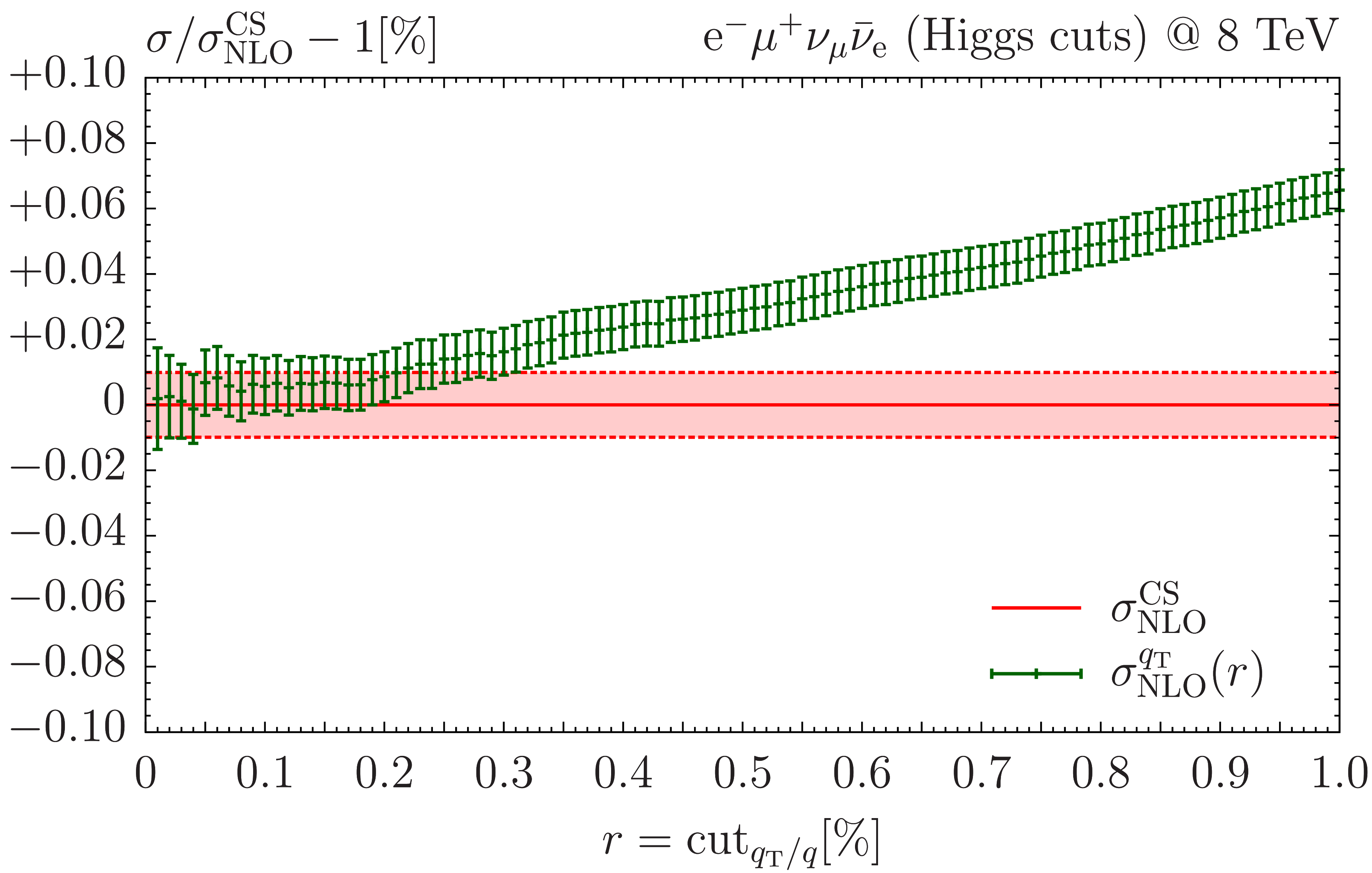
- numerics forbids arbitrarily small r_{cut} values: use fit towards $r_{cut} \to 0$ limit
- MATRIX uses extrapolation $r_{cut} \to 0$ to obtain the final prediction

r_{cut} dependence at NLO

(example from WW)

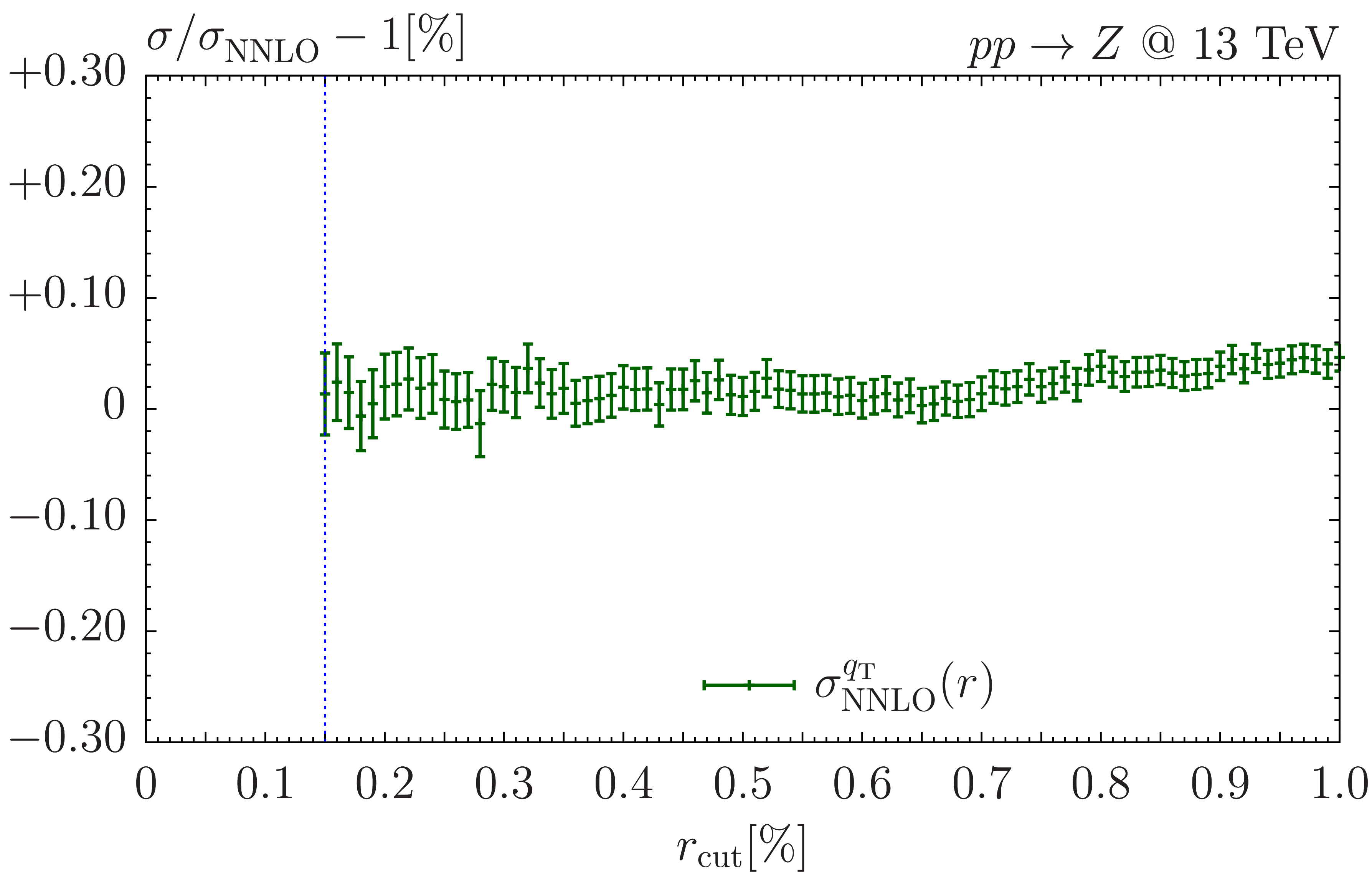


$$d\sigma_{\rm NNLO}(r_{\rm cut}) = \left[d\sigma_{\rm NLO}^{F+\rm jet}(r>r_{\rm cut}) - \Sigma_{\rm NNLO}\otimes d\sigma_{\rm LO}(r>r_{\rm cut})\right] + \mathcal{H}_{\rm NNLO}\otimes d\sigma_{\rm LO}$$

$r_{cut} \to 0$ extrapolation in MATRIX

[Grazzini, Kallweit, MW '17]

automatically computed in every single MATRIX NNLO run

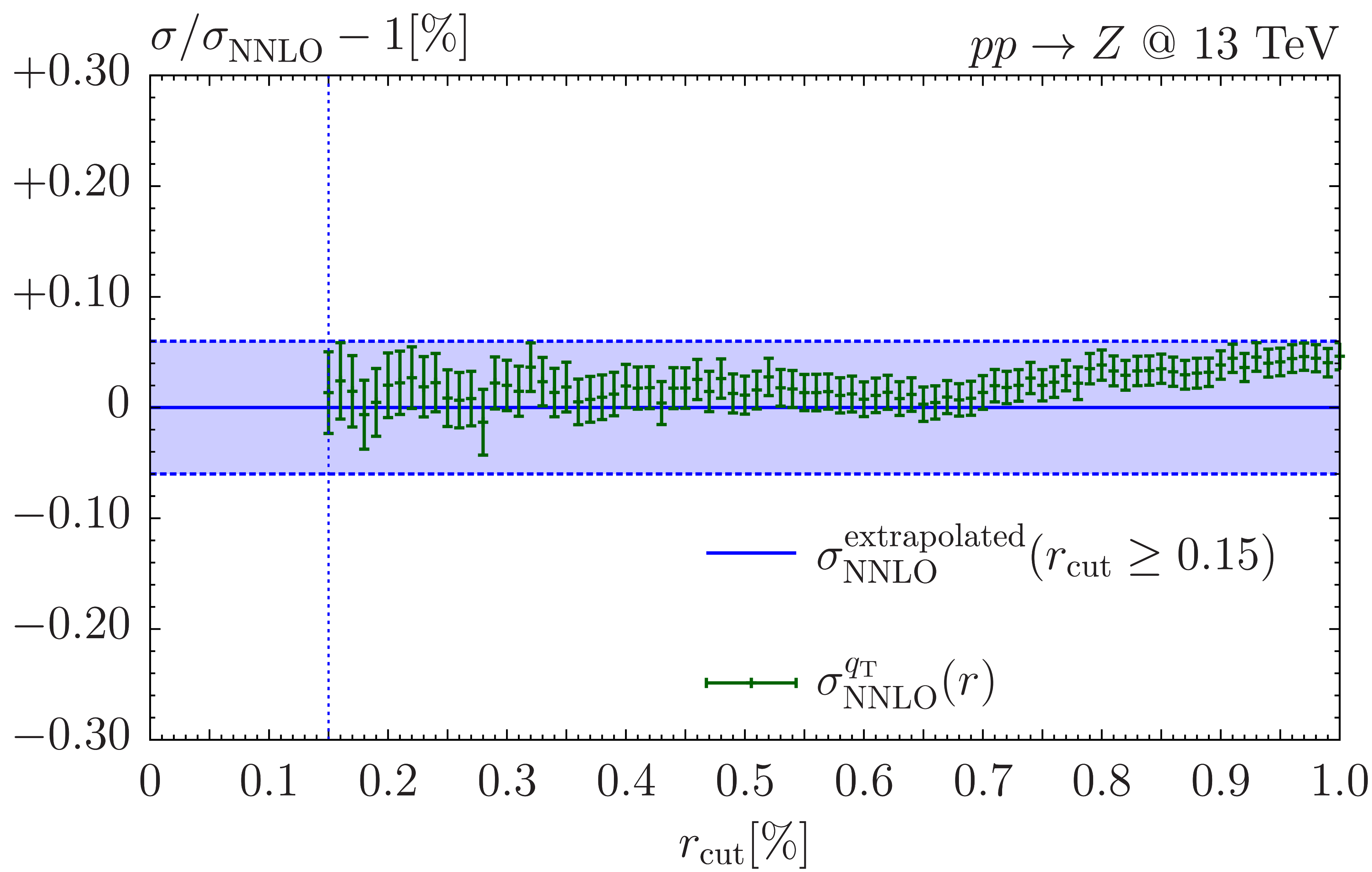


$$d\sigma_{\mathrm{NNLO}}(r_{\mathrm{cut}}) = \left[d\sigma^{F+\mathrm{jet}}_{\mathrm{NLO}}(r > r_{\mathrm{cut}}) - \Sigma_{\mathrm{NNLO}} \otimes d\sigma_{\mathrm{LO}}(r > r_{\mathrm{cut}})\right] + \mathcal{H}_{\mathrm{NNLO}} \otimes d\sigma_{\mathrm{LO}}$$

$r_{cut} \to 0$ extrapolation in MATRIX

[Grazzini, Kallweit, MW '17]

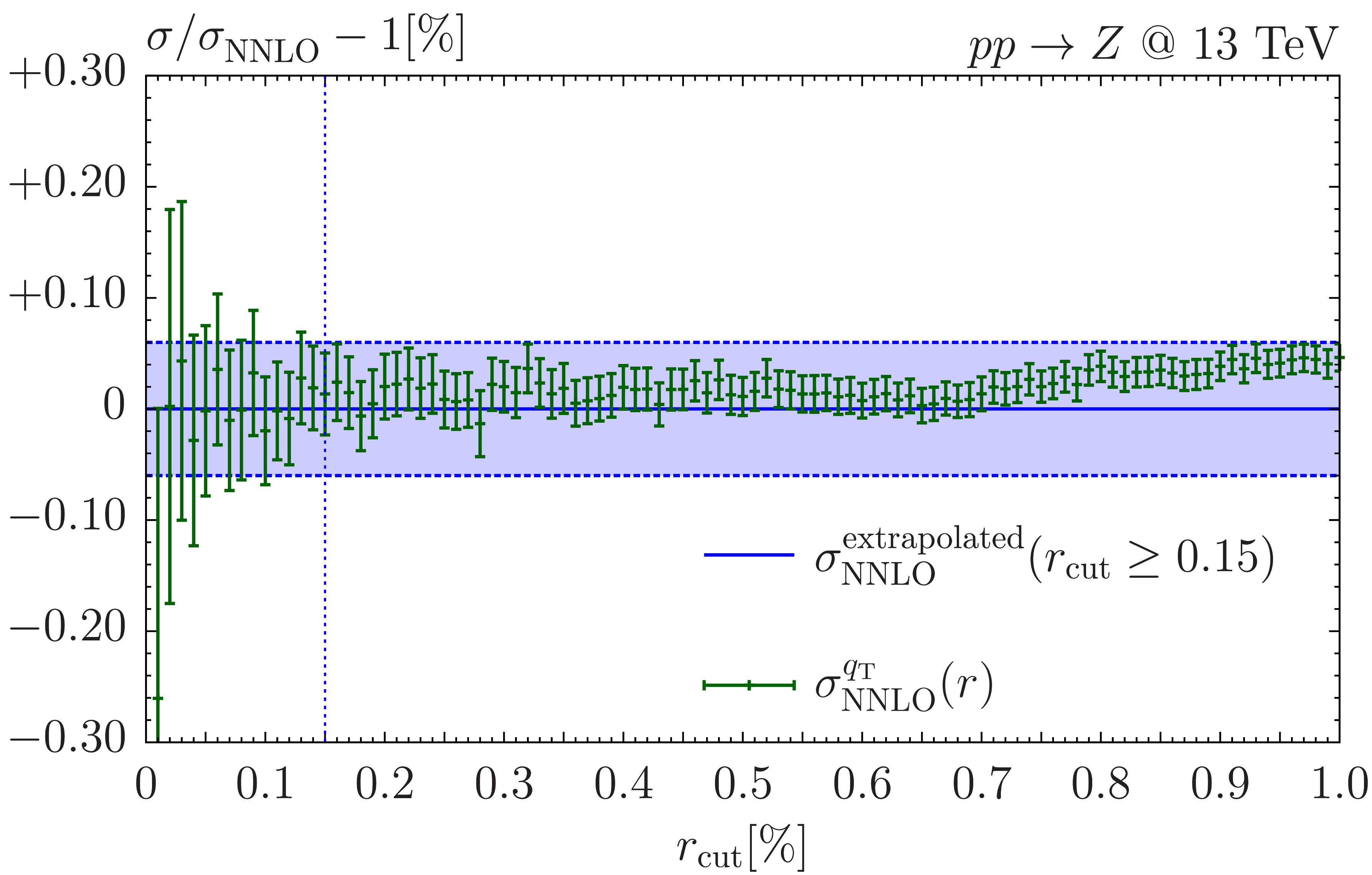
simple quadratic fit ($A * r_{cut}^2 + B * r_{cut} + C$) to extrapolate to $r_{cut}=0$



$$d\sigma_{\mathrm{NNLO}}(r_{\mathrm{cut}}) = \left[d\sigma^{F+\mathrm{jet}}_{\mathrm{NLO}}(r > r_{\mathrm{cut}}) - \Sigma_{\mathrm{NNLO}} \otimes d\sigma_{\mathrm{LO}}(r > r_{\mathrm{cut}})\right] + \mathcal{H}_{\mathrm{NNLO}} \otimes d\sigma_{\mathrm{LO}}$$

$r_{cut} \to 0$ extrapolation in MATRIX

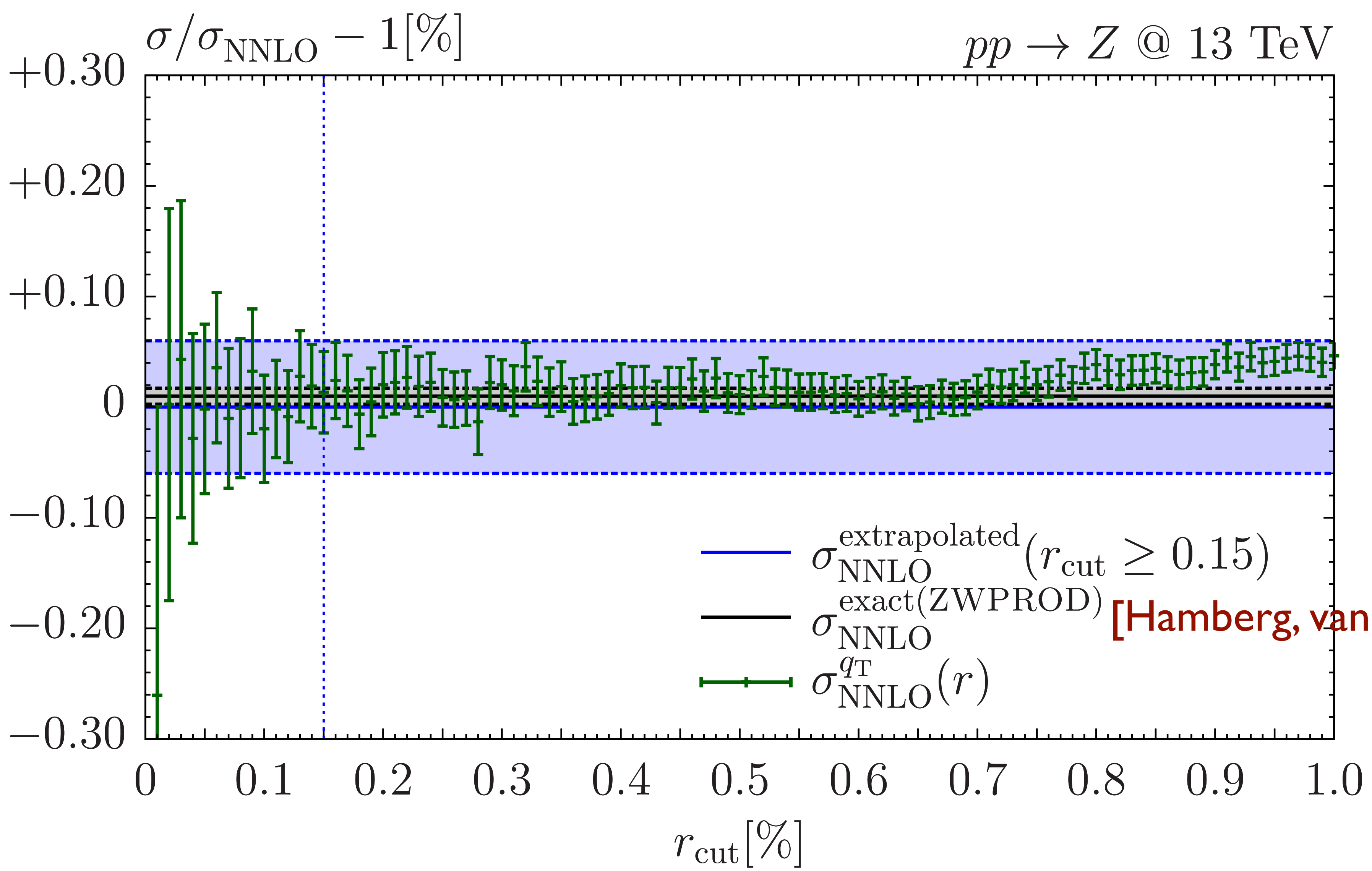
[Grazzini, Kallweit, MW '17]



$$d\sigma_{\mathrm{NNLO}}(r_{\mathrm{cut}}) = \left[d\sigma^{F+\mathrm{jet}}_{\mathrm{NLO}}(r > r_{\mathrm{cut}}) - \Sigma_{\mathrm{NNLO}} \otimes d\sigma_{\mathrm{LO}}(r > r_{\mathrm{cut}})\right] + \mathcal{H}_{\mathrm{NNLO}} \otimes d\sigma_{\mathrm{LO}}$$

$r_{cut} \to 0$ extrapolation in MATRIX

[Grazzini, Kallweit, MW '17]



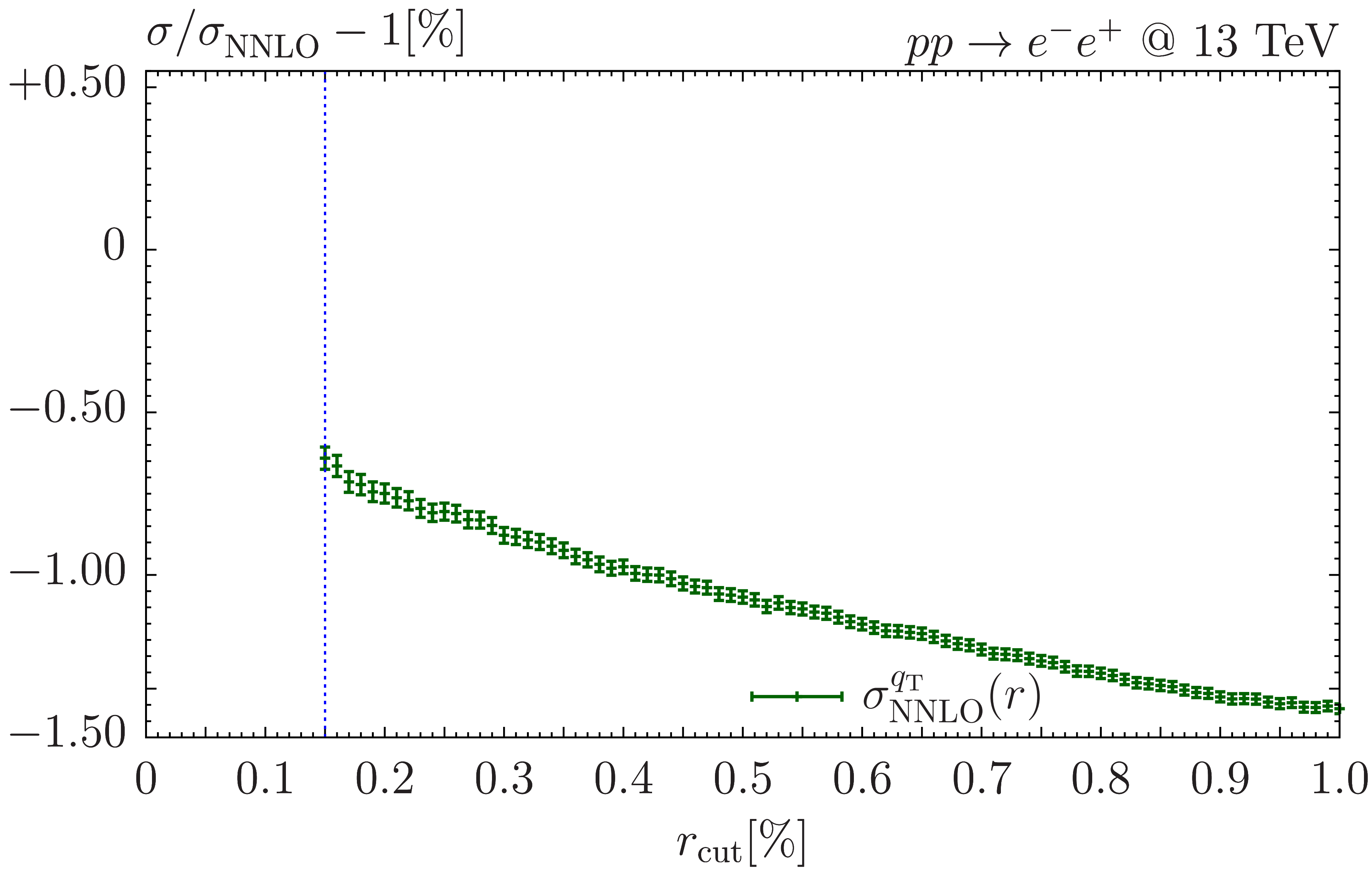
[Hamberg, van Neerven, Matsuura '91]

$$d\sigma_{\mathrm{NNLO}}(r_{\mathrm{cut}}) = \left[d\sigma_{\mathrm{NLO}}^{F+\mathrm{jet}}(r > r_{\mathrm{cut}}) - \Sigma_{\mathrm{NNLO}} \otimes d\sigma_{\mathrm{LO}}(r > r_{\mathrm{cut}})\right] + \mathcal{H}_{\mathrm{NNLO}} \otimes d\sigma_{\mathrm{LO}}$$

$r_{cut}\rightarrow 0$ extrapolation in MATRIX

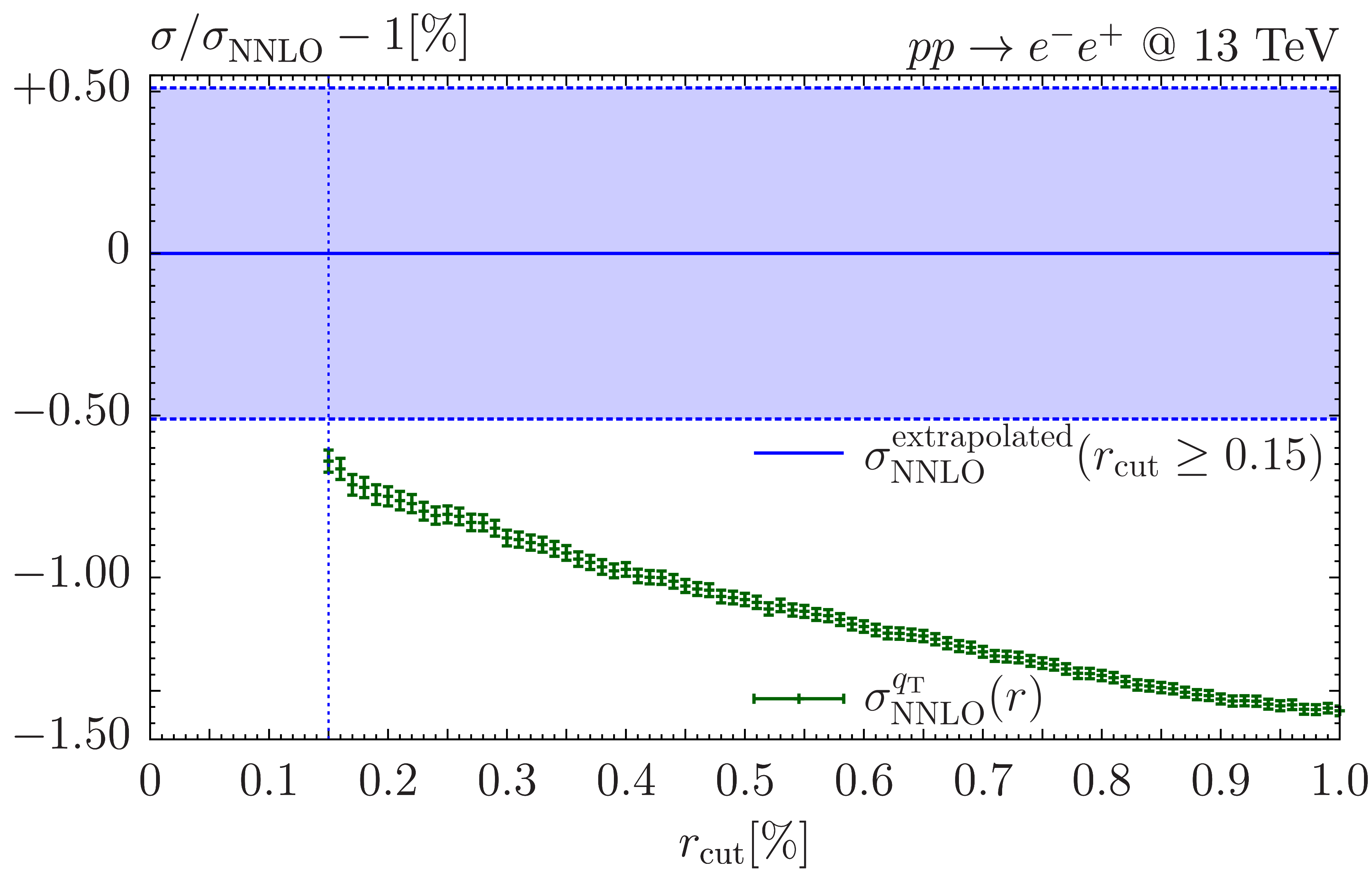
[Grazzini, Kallweit, MW '17]

dileptons with certain cuts (and photon final states) are special



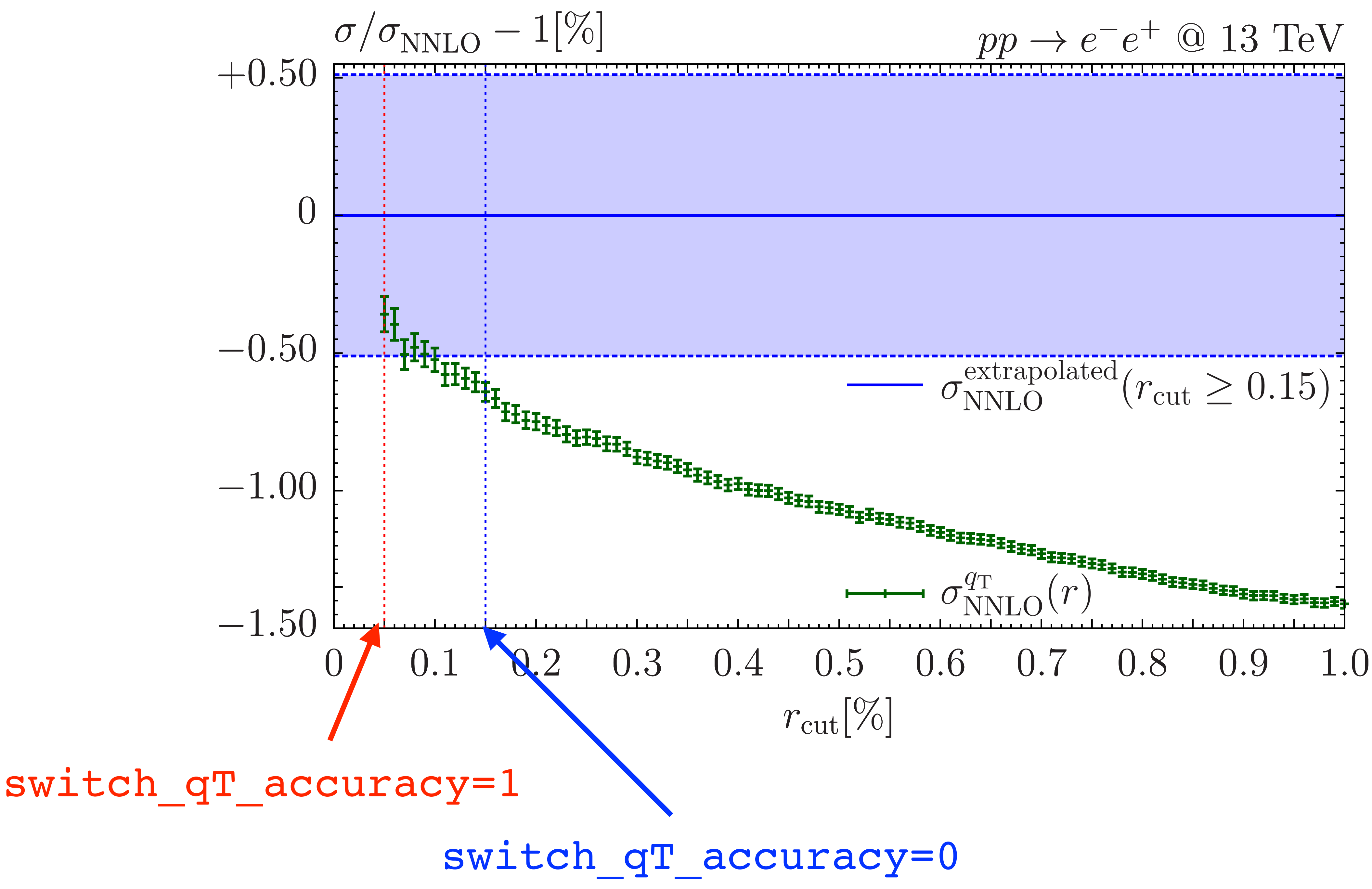
$r_{cut}\rightarrow 0$ extrapolation in MATRIX

[Grazzini, Kallweit, MW '17]



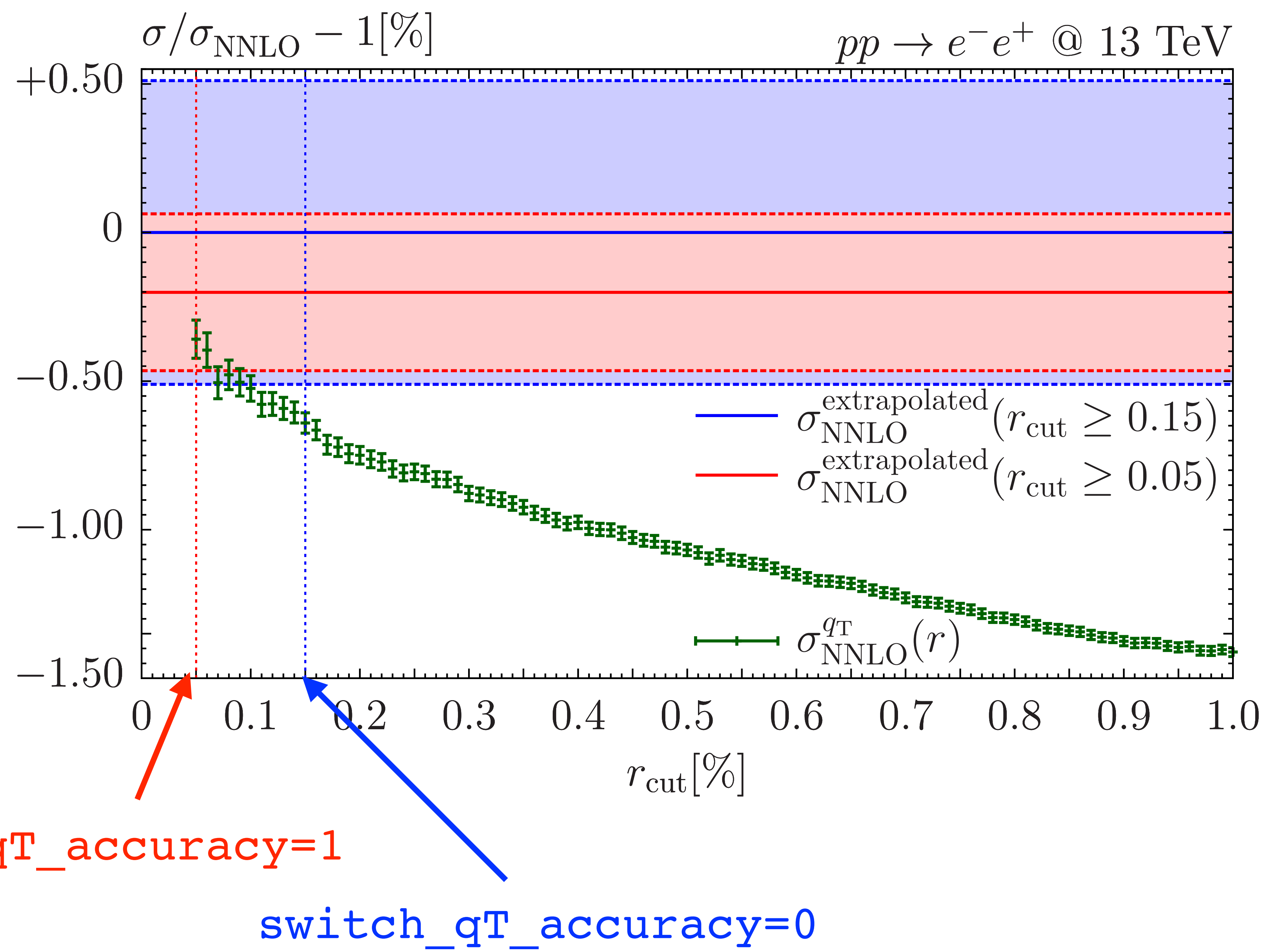
$r_{cut} \rightarrow 0$ extrapolation in MATRIX

[Grazzini, Kallweit, MW '17]



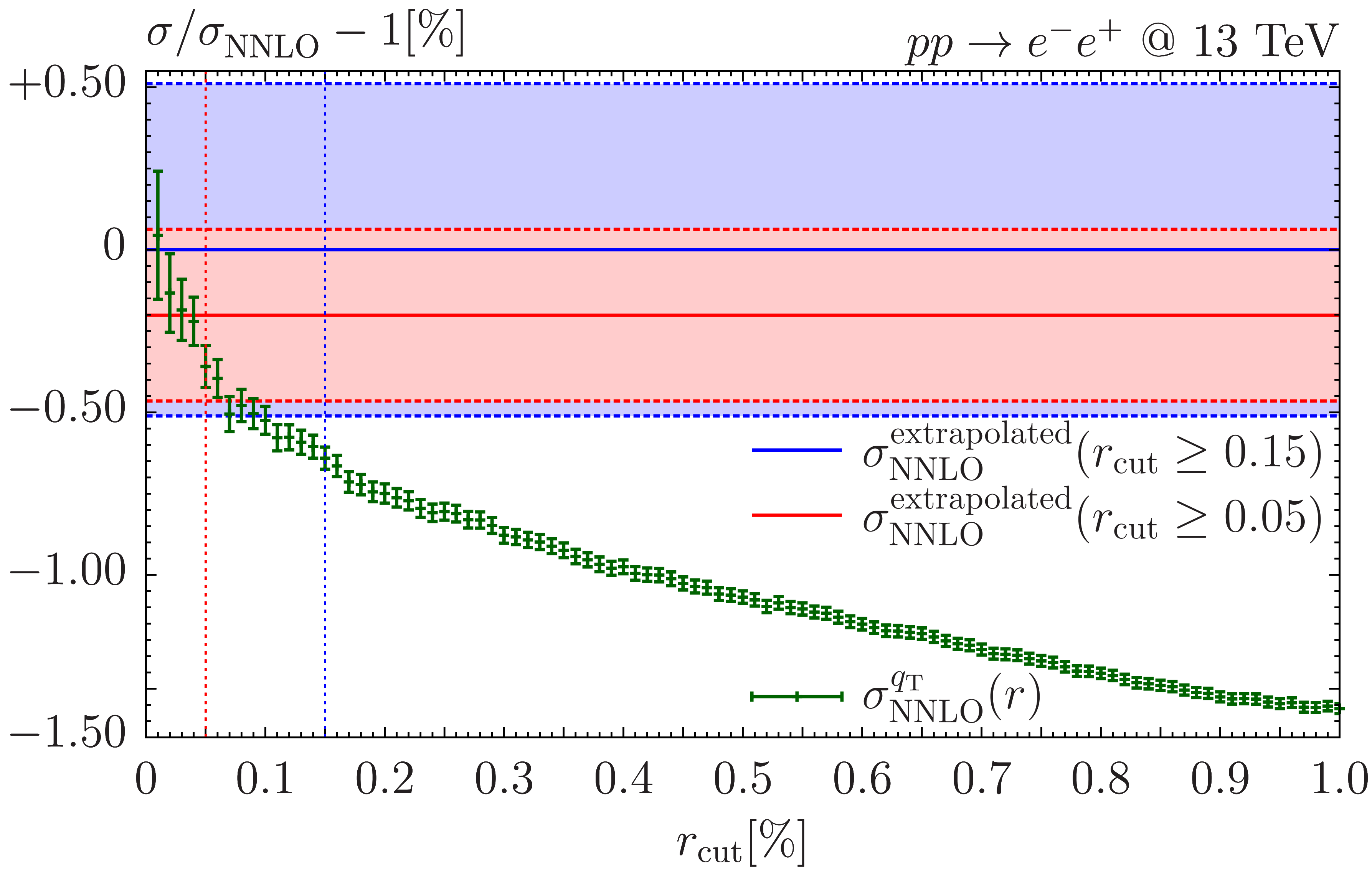
$r_{cut} \to 0$ extrapolation in MATRIX

[Grazzini, Kallweit, MW '17]



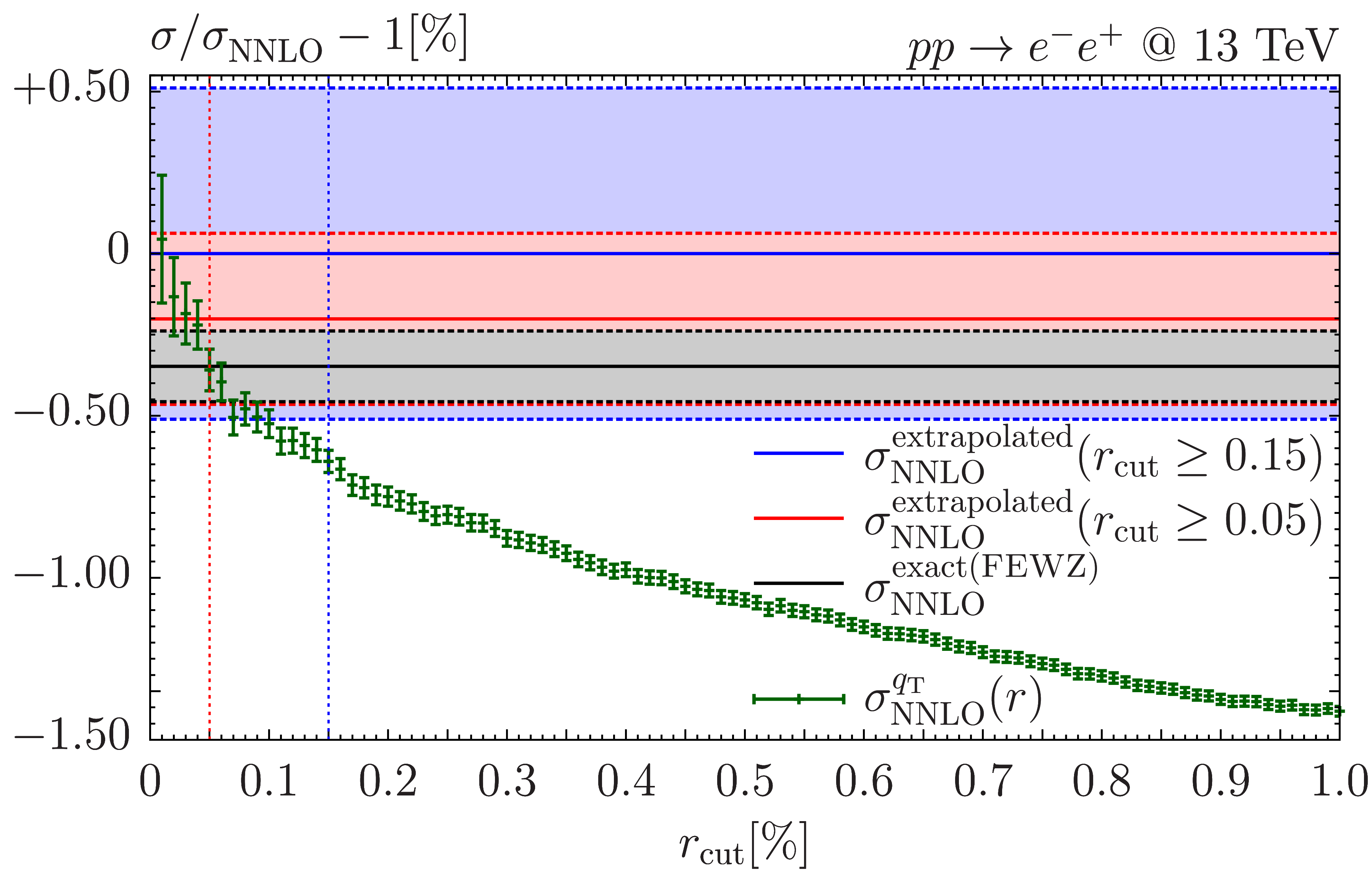
$r_{cut} \to 0$ extrapolation in MATRIX

[Grazzini, Kallweit, MW '17]



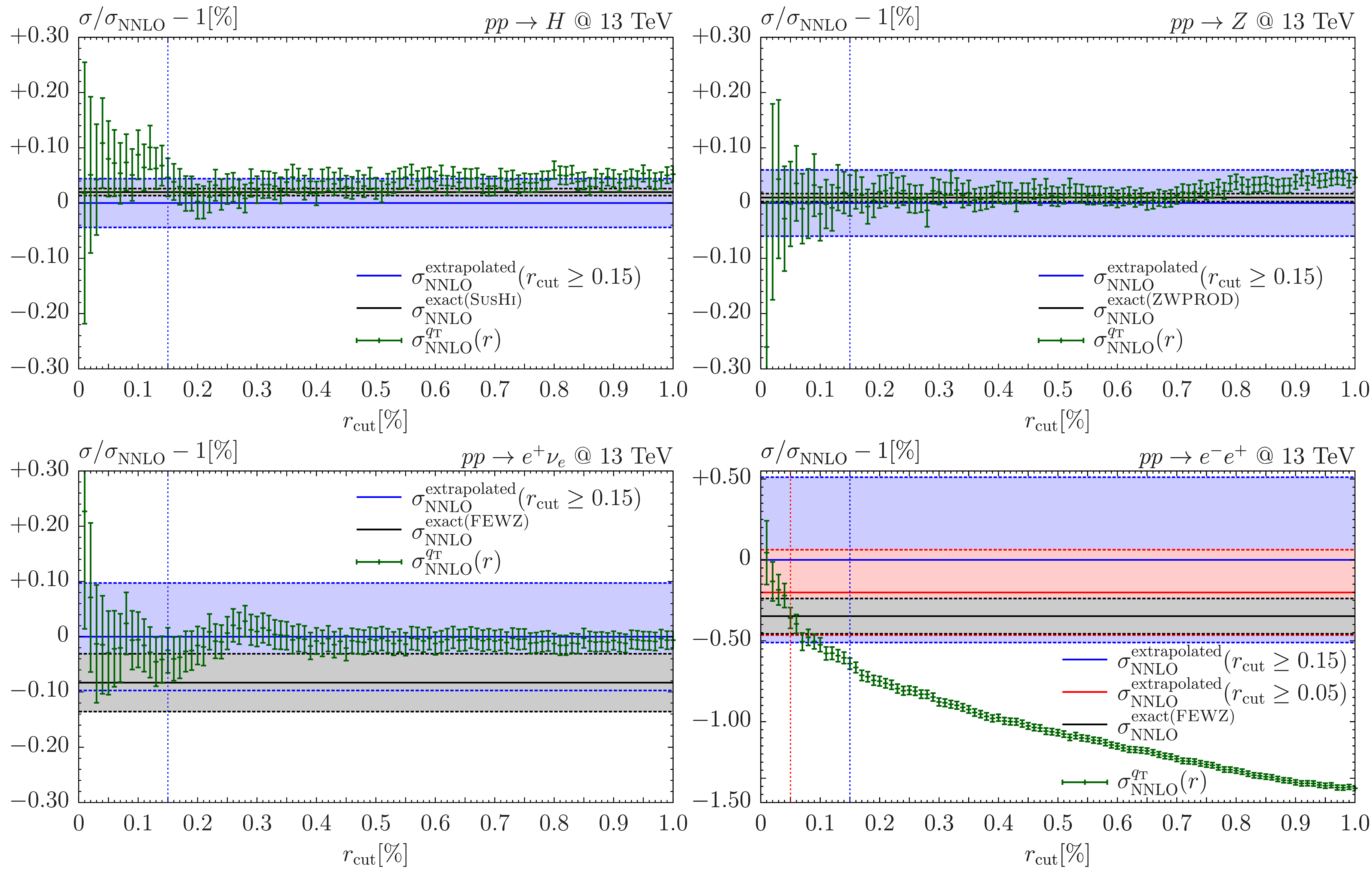
$r_{cut} \to 0$ extrapolation in MATRIX

[Grazzini, Kallweit, MW '17]



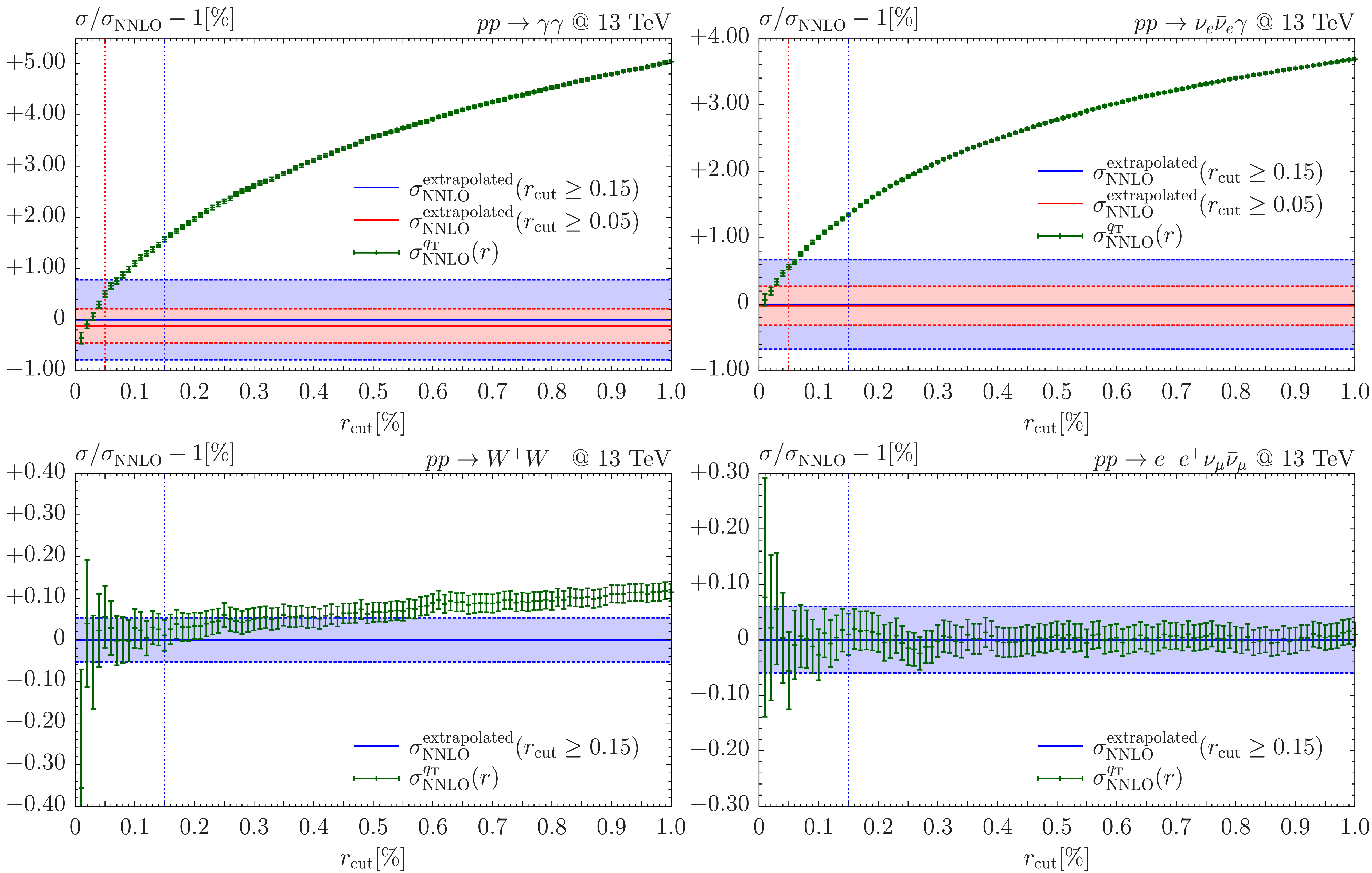
$r_{cut} \to 0$ extrapolation in MATRIX

[Grazzini, Kallweit, MW '17]



$r_{cut} \to 0$ extrapolation in MATRIX

[Grazzini, Kallweit, MW '17]

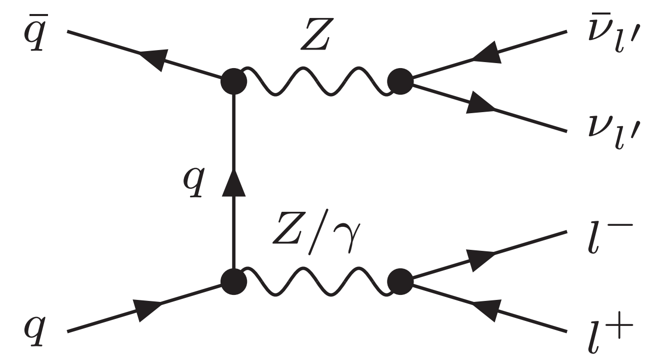


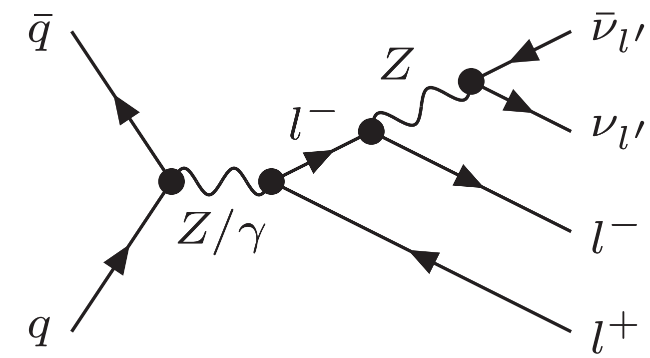
MATRIX features on one slide

- Colourless 2→1 and 2→2 reactions (decays, off-shell effects, spin correlations; previous slide)
- **physics features:**
  - NNLO accuracy based on q_T subtraction
  - loop-induced gg component part of NNLO cross section (effectively LO accurate)
  - CKM for W-boson production
  - essential fiducial cuts, dynamical scales and distributions already pre-defined for each process
  - final-state particles directly accessible (for distributions, cuts, scales)
  - scale uncertainty estimated automatically estimated (7- or 9-point) with every run
  - **NEW:** automatic extrapolation of q_T-subtraction cut-off to zero (with extrapolation uncertainty)
- **technical features:**
  - Core: C++ code; steered by Python interface (compilation/running/job submission/result collection)
  - **only requirements:** LHAPDF 5 or 6 pre-installed & Python 2.7 with numpy
  - **Otherwise fully automatic!** (download/compilation of external packages; inputs via interface etc.)
  - local and cluster support: LSF (lxplus), HT-Condor (lxplus), condor, SLURM, Torque/PBS, SGE
    → missing your favourite cluster? Let us know!
  - option to reduce workload (output) on slow file systems
  - **all relevant references in CITATION.bib** (provided with every run)
  - comprehensive manual shipped with the code

$\ell\ell$+$E_{T,miss}$ at NNLO [Kallweit, MW '18]

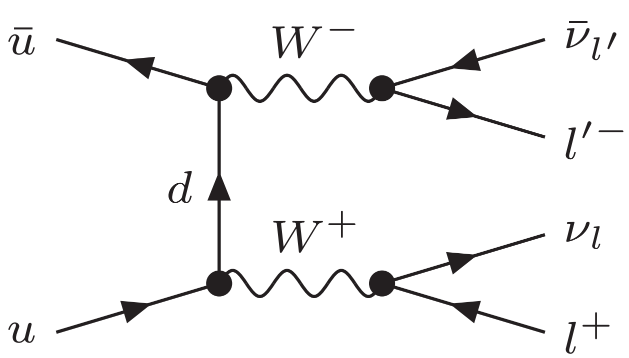
- DF ($\ell\ell\,\nu'\nu'$): double-resonant ZZ (**pp→ZZ/γ*Z→$\ell\ell\,\nu'\nu'$**) and single-resonant DY-like (**pp→Z/γ*→$\ell\ell$ Z→$\ell\ell\,\nu'\nu'$**)

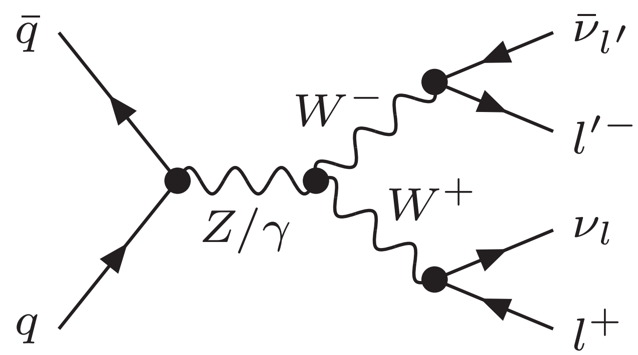


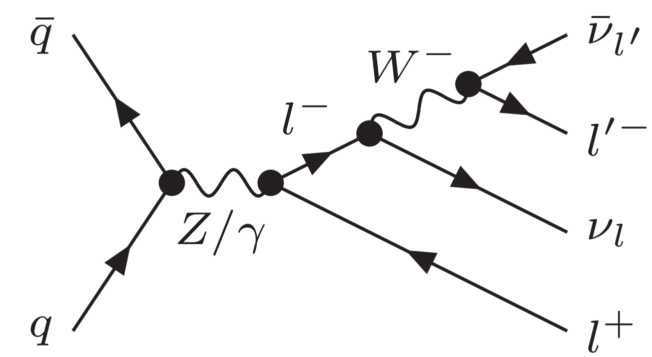


- DF ($\ell\nu\,\ell'\nu'$): double-resonant WW and single-resonant DY-like

(pp→WW→$\ell\nu\,\ell'\nu'$) **(pp→Z/γ*→$\ell\nu$W→$\ell\nu\,\ell'\nu'$)**

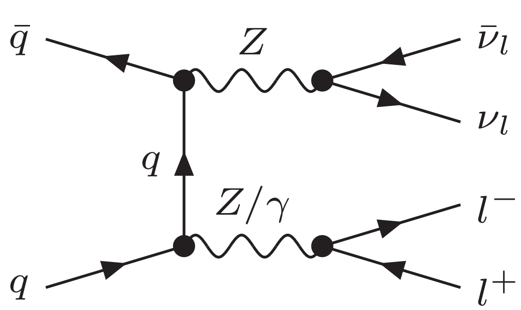


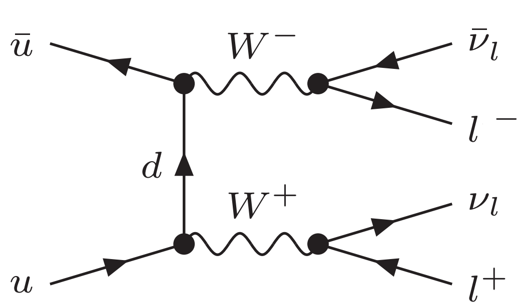


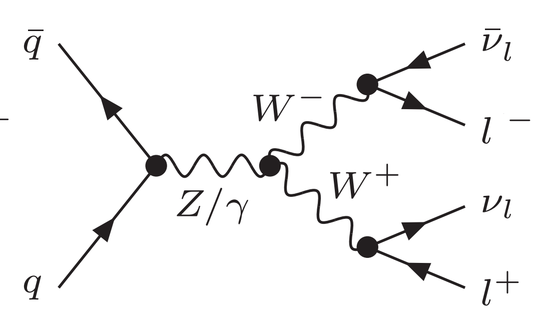


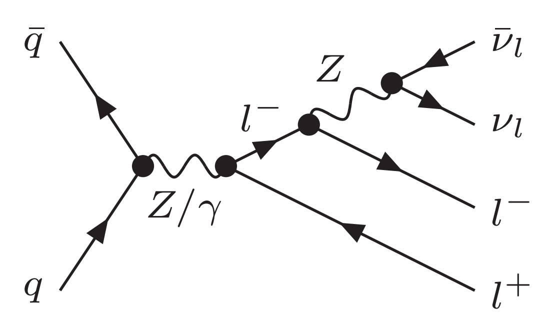
- SF ($\ell\ell\,\nu\nu$): mixes all ZZ, WW and DY-like contributions

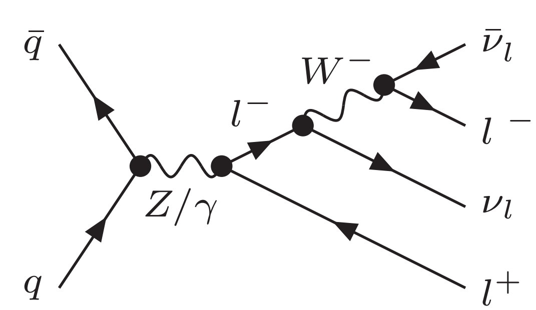
(pp→ZZ/γ*Z/WW→$\ell\ell\,\nu\nu$) **(pp→Z/γ*→$\ell\ell$ Z/$\ell\nu$W→$\ell\ell\,\nu\nu$)**











$\ell\ell+E_{T,\mathrm{miss}}$ at NNLO [Kallweit, MW '18]

Comparison against ATLAS 8 TeV data [JHEP 1701 (2017) 099]

- **fiducial cuts:**

definition of the fiducial volume for $pp \to \ell^+\ell^-\nu\bar{\nu} + X$, $\quad \ell \in \{e,\mu\}$ and $\nu \in \{\nu_e,\nu_\mu,\nu_\tau\}$
$p_{T,\ell} > 25\,\mathrm{GeV}$, $\quad |\eta_\ell| < 2.5$, $\quad \Delta R_{\ell\ell} > 0.3$, $\quad 76\,\mathrm{GeV} \le m_{\ell^+\ell^-} \le 106\,\mathrm{GeV}$,
Axial-$p_T^{\mathrm{miss}} > 90\,\mathrm{GeV}$, $\quad p_T$-balance < 0.4,
$N_{\mathrm{jets}} = 0$, anti-k_T jets with $R = 0.4$, $p_{T,j} > 25\,\mathrm{GeV}$, $|\eta_j| < 4.5$ and $\Delta R_{ej} > 0.3$

jet veto

prefers Z bosons in back-to-back like configurations

$\ell\ell$+E$_{T,miss}$ at NNLO [Kallweit, MW '18]

Comparison against ATLAS 8 TeV data [JHEP 1701 (2017) 099]

- **our setup:**
  - $\mu_R = \mu_F = \dfrac{m_{ZZ}}{2}$ (uncertainties: 7-point scale variation)
  - NNPDF 3.0 (set consistent at each perturbative order) with $\alpha_s(m_Z) = 0.118$
  - 5-flavour scheme

$\ell\ell$+E$_{T,\text{miss}}$ at NNLO [Kallweit, MW '18]

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    $\longrightarrow$ top-quark contamination included in SF ($\ell\ell\nu_\ell\nu_\ell$) channel

    BUT: suppressed by jet veto

    AND: W^+W^- ($\ell\nu_\ell\ell'\nu_{\ell'}$) and top contributions subtracted as background

    $\longrightarrow$ compute SF $\ell\ell\nu_\ell\nu_\ell$ channel and subtact DF $\ell\nu_\ell\ell'\nu_{\ell'}$ (also in 5FS)

    $\longrightarrow$ removes subtracted backgrounds, but keeps all interference contributions!

$$\sigma(\ell\ell\,\nu_{e/\mu/\tau}\nu_{e/\mu/\tau}) = \sigma(\ell\ell\,\nu_\ell\nu_\ell) - \sigma(\ell\nu_\ell\,\ell'\nu_{\ell'}) + 2\cdot\sigma(\ell\ell\,\nu_{\ell'}\nu_{\ell'})$$

$\ell\ell + E_{T,miss}$ at NNLO [Kallweit, MW '18]

Comparison against ATLAS 8 TeV data

- **fiducial cross section (POWHEG+gg+EW):** [JHEP 1701 (2017) 099]

		Measurement	Prediction
$\sigma^{\rm fid}_{ZZ\to e^-e^+\nu\bar{\nu}}$	=	$5.0\ ^{+0.8}_{-0.7}$ (stat) $^{+0.5}_{-0.4}$ (syst) $\pm$ 0.1 (lumi) fb	3.7 ± 0.3 fb
$\sigma^{\rm fid}_{ZZ\to \mu^-\mu^+\nu\bar{\nu}}$	=	4.7 ± 0.7 (stat) $^{+0.5}_{-0.4}$ (syst) $\pm$ 0.1 (lumi) fb	3.5 ± 0.3 fb
$\sigma^{\rm total}_{pp\to ZZ}$	=	7.3 ± 0.4 (stat) $\pm$ 0.3 (syst) $^{+0.2}_{-0.1}$ (lumi) pb	$6.6\ ^{+0.7}_{-0.6}$ pb

$\ell\ell$+E$_{T,miss}$ at NNLO [Kallweit, MW '18]

Comparison against ATLAS 8 TeV data

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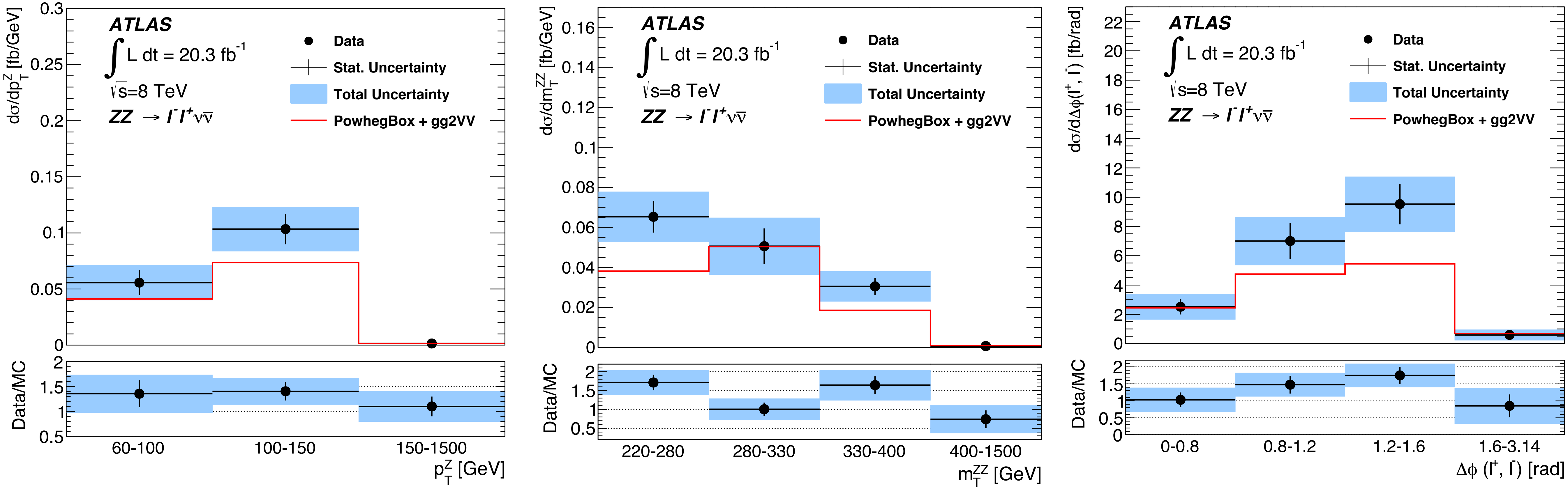
- **fiducial cross section (fixed order):** [Kallweit, MW '18]

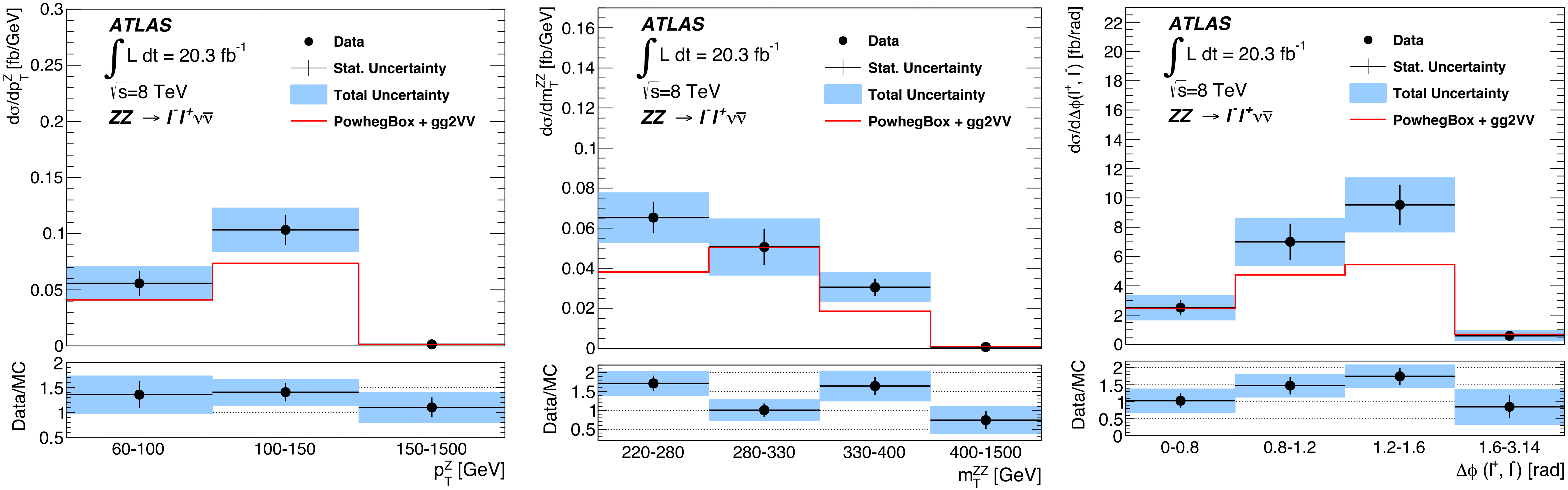
channel	σ_{LO} [fb]	σ_{NLO} [fb]	σ_{NNLO} [fb]	σ_{ATLAS} [fb]
$e^+e^-\nu\nu$	$5.558(0)^{+0.1\%}_{-0.5\%}$	$4.806(1)^{+3.5\%}_{-3.9\%}$	$5.083(8)^{+1.9\%}_{-0.6\%}$	$5.0\ ^{+0.8}_{-0.7}(\text{stat})\ ^{+0.5}_{-0.4}(\text{syst}) \pm 0.1(\text{lumi})$
$\mu^+\mu^-\nu\nu$	$5.558(0)^{+0.1\%}_{-0.5\%}$	$4.770(4)^{+3.6\%}_{-4.0\%}$	$5.035(9)^{+1.8\%}_{-0.5\%}$	$4.7\ ^{+0.7}_{-0.7}(\text{stat})\ ^{+0.5}_{-0.4}(\text{syst}) \pm 0.1(\text{lumi})$
total rate	$4982(0)^{+1.9\%}_{-2.7\%}$	$6754(2)^{+2.4\%}_{-2.0\%}$	$7690(5)^{+2.7\%}_{-2.1\%}$	$7300\ ^{+400}_{-400}(\text{stat})\ ^{+300}_{-300}(\text{syst})\ ^{+200}_{-100}(\text{lumi})$

fiducial distributions (POWHEG+gg+EW): [JHEP 1701 (2017) 099]

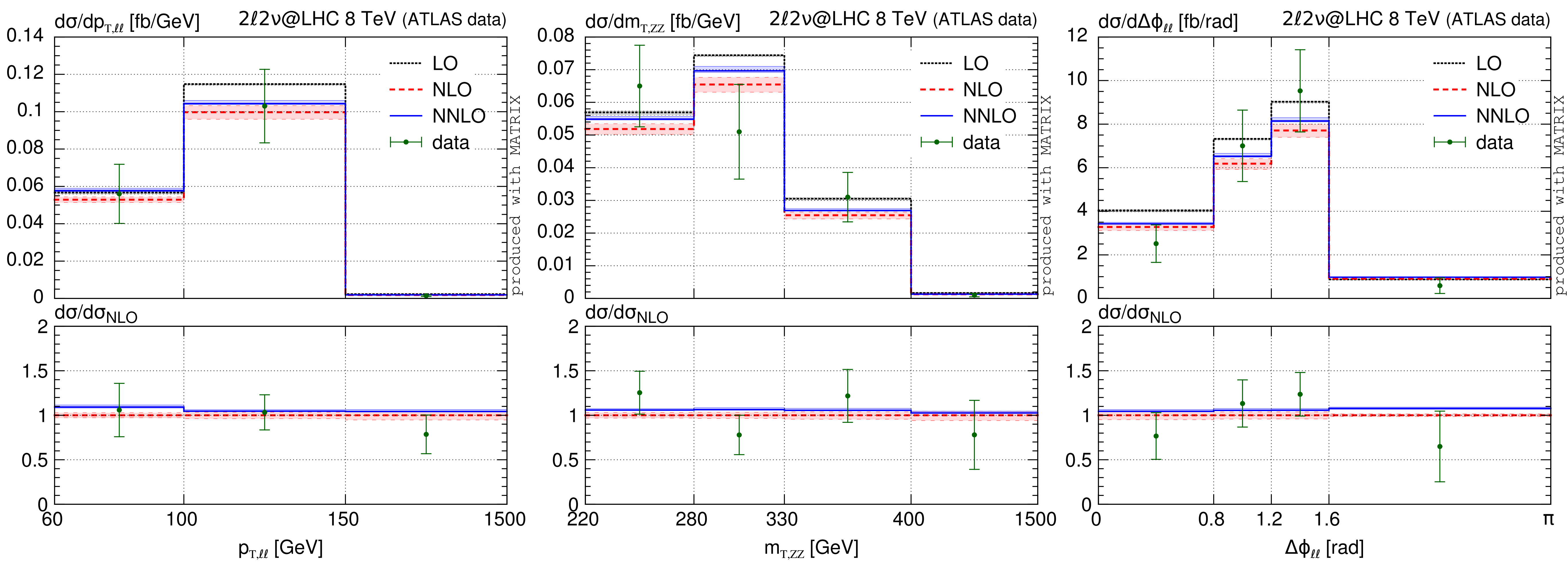


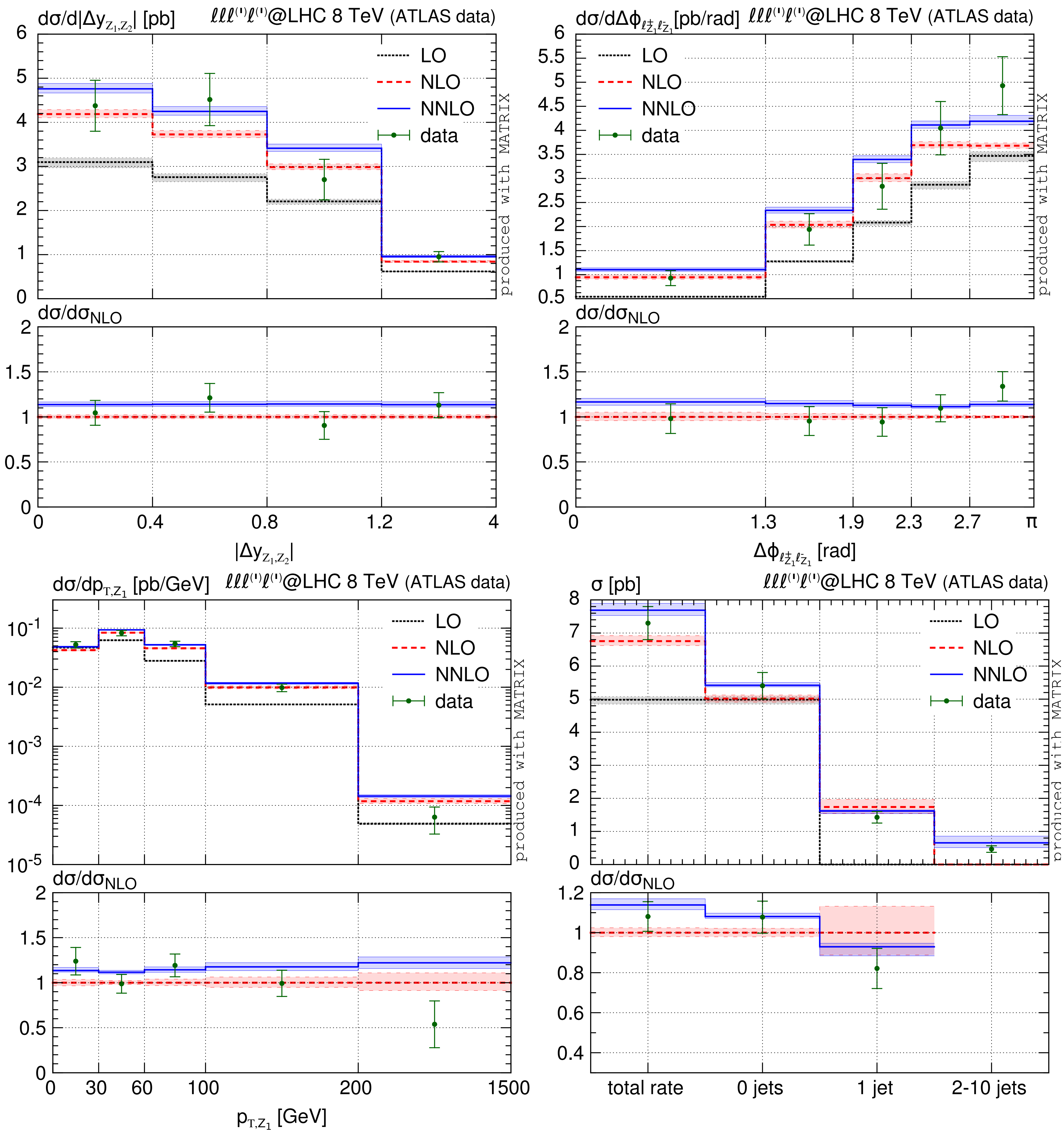
$$m_{T,ZZ} = \sqrt{\left(\sqrt{p_{T,\ell\ell}^2 + m_Z^2} + \sqrt{(p_T^{\text{miss}})^2 + m_Z^2}\right)^2 - (\mathbf{p_{T,\ell\ell}} + \mathbf{p_T^{\text{miss}}})^2}$$

fiducial distributions (POWHEG+gg+EW): [JHEP 1701 (2017) 099]



fiducial distributions (fixed order): [Kallweit, MW '18]

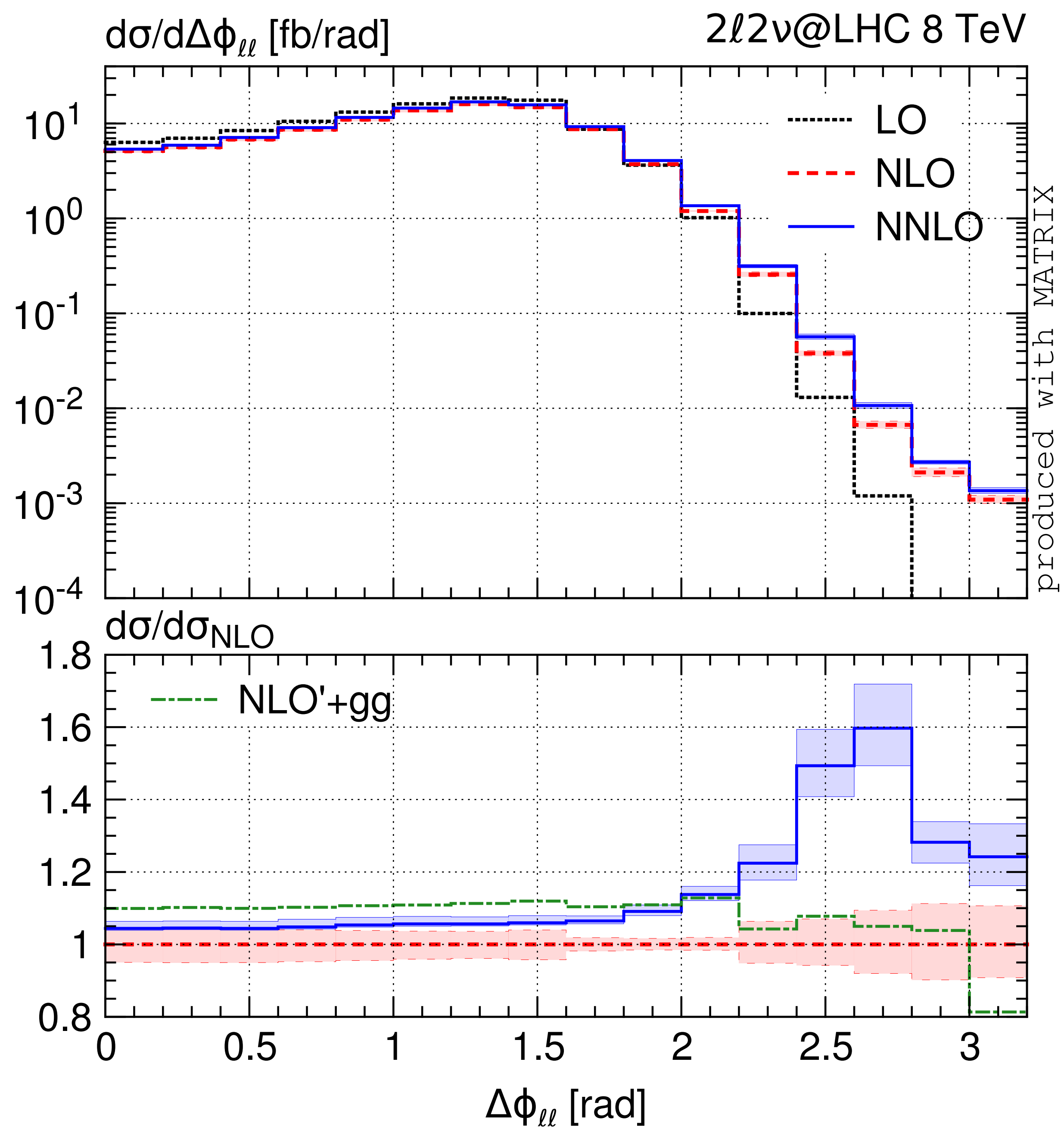




dσ/d|Δy_{Z1,Z2}| [pb]
ℓℓℓ⁽'⁾ℓ⁽'⁾@LHC 8 TeV (ATLAS data)
LO
NLO
NNLO
data
produced with MATRIX
dσ/dσ_NLO
|Δy_{Z1,Z2}|
dσ/dΔφ [pb/rad]
ℓℓℓ⁽'⁾ℓ⁽'⁾@LHC 8 TeV (ATLAS data)
Δφ [rad]
dσ/dp_{T,Z1} [pb/GeV]
ℓℓℓ⁽'⁾ℓ⁽'⁾@LHC 8 TeV (ATLAS data)
p_{T,Z1} [GeV]
σ [pb]
ℓℓℓ⁽'⁾ℓ⁽'⁾@LHC 8 TeV (ATLAS data)
total rate
0 jets
1 jet
2-10 jets

$\ell\ell$+$E_{T,miss}$ at NNLO [Kallweit, MW '18]

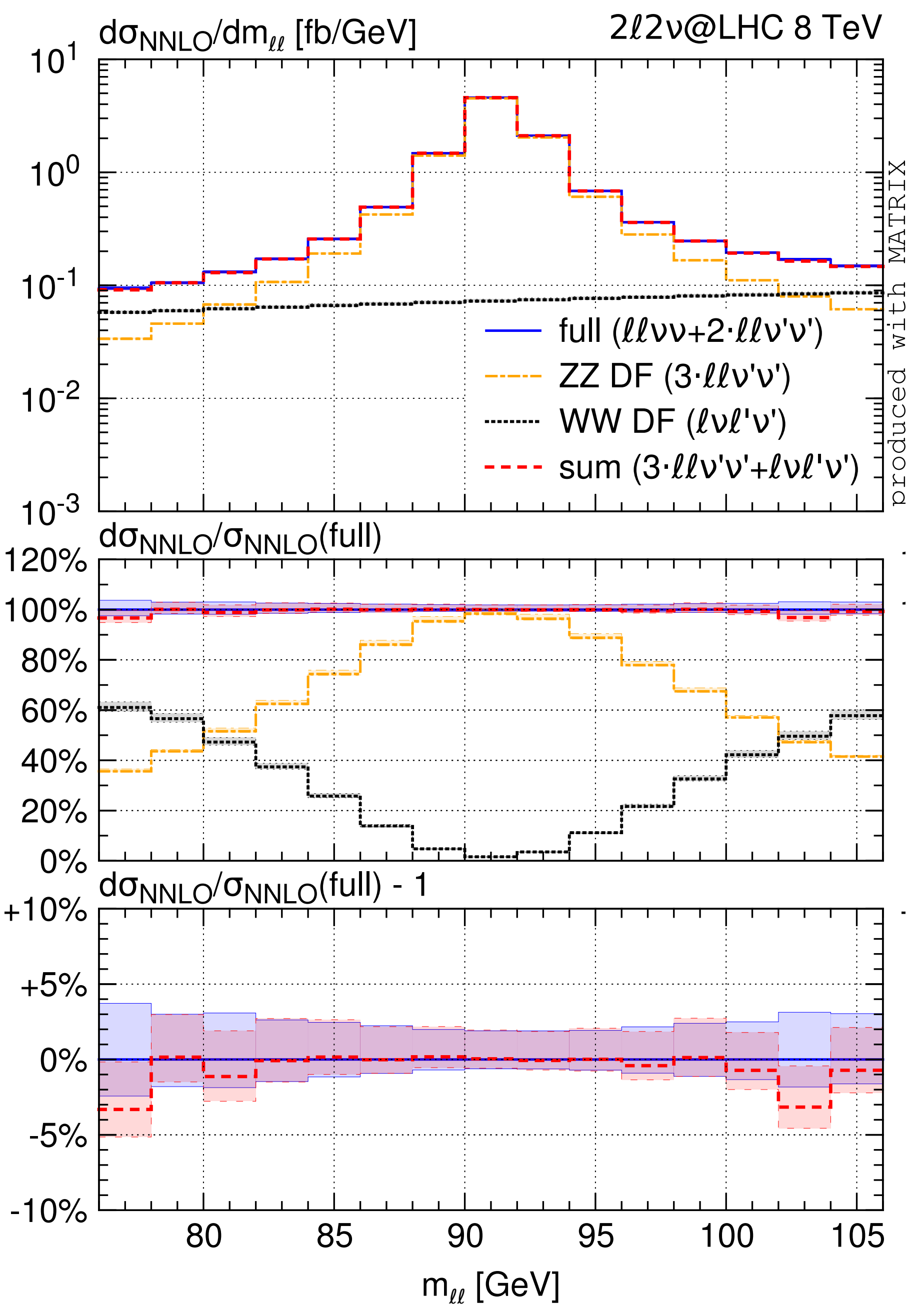
Impact of NNLO on fiducial distributions (same cuts as before)



despite jet veto, NNLO corrections quite large

$\ell\ell$+E$_{T,miss}$ at NNLO [Kallweit, MW '18]

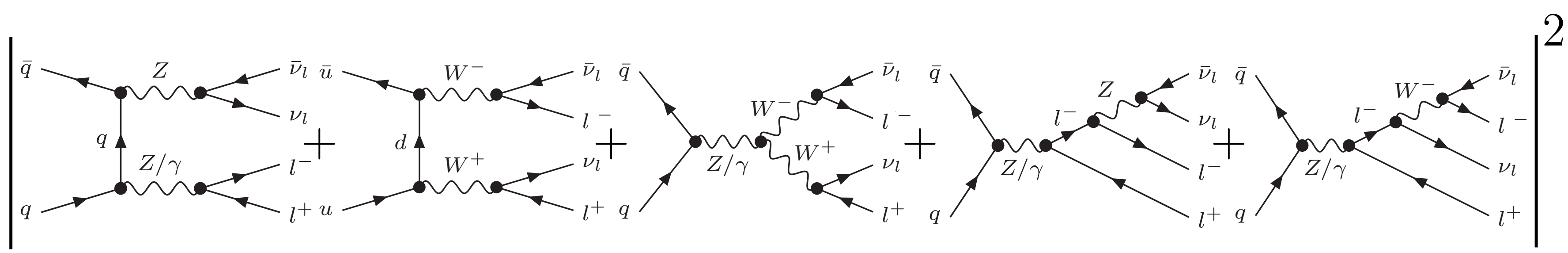
Relative size of ZZ and WW contributions (same cuts as before)



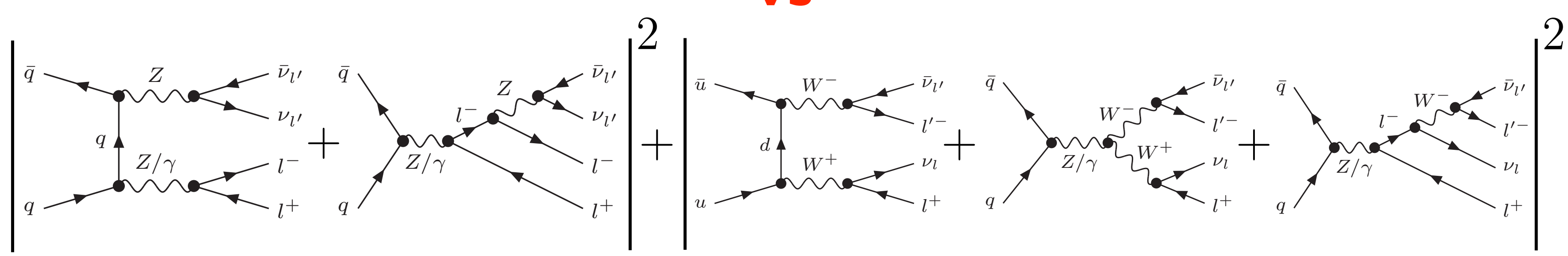
$$\sigma(\ell\ell\,\nu_{e/\mu/\tau}\nu_{e/\mu/\tau}) = \sigma(\ell\ell\,\nu_\ell\nu_\ell) + 2\cdot\sigma(\ell\ell\,\nu_{\ell'}\nu_{\ell'})$$

vs

$$\sigma(\ell\ell\,\nu_{e/\mu/\tau}\nu_{e/\mu/\tau}) \approx 3\cdot\sigma(\ell\ell\,\nu_{\ell'}\nu_{\ell'}) + \sigma(\ell\nu_\ell\,\ell'\nu_{\ell'})$$



vs



incoherent sum of ZZ+WW good approximation

$\ell\ell+E_{T,miss}$ at NNLO [Kallweit, MW '18]

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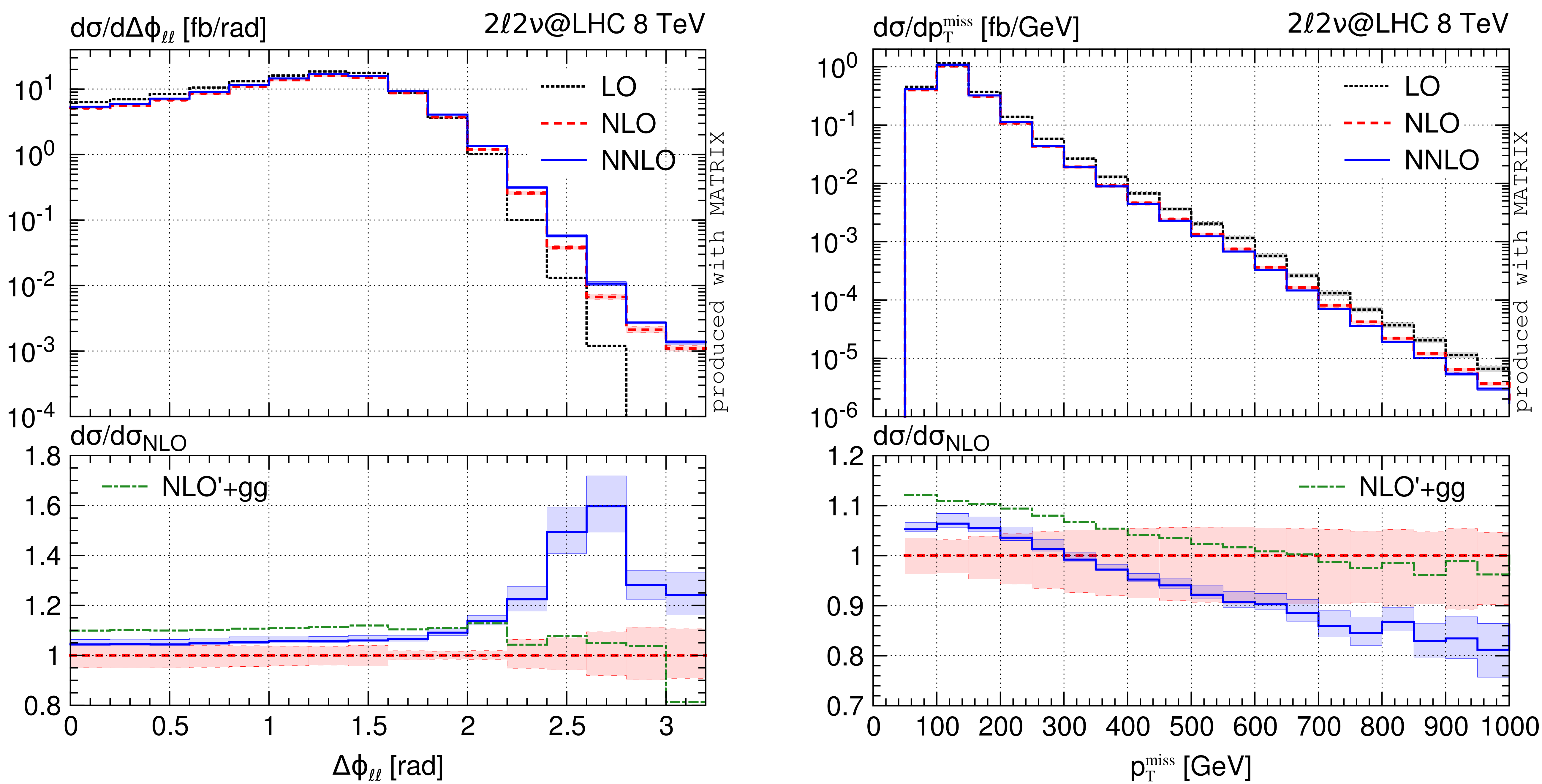

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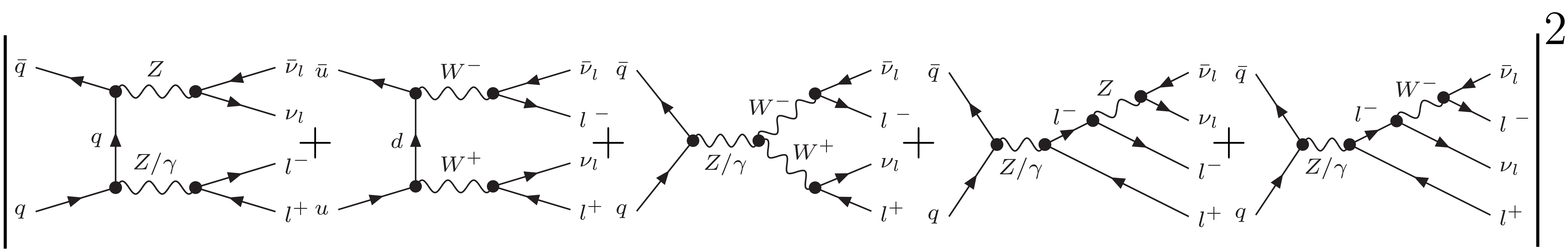
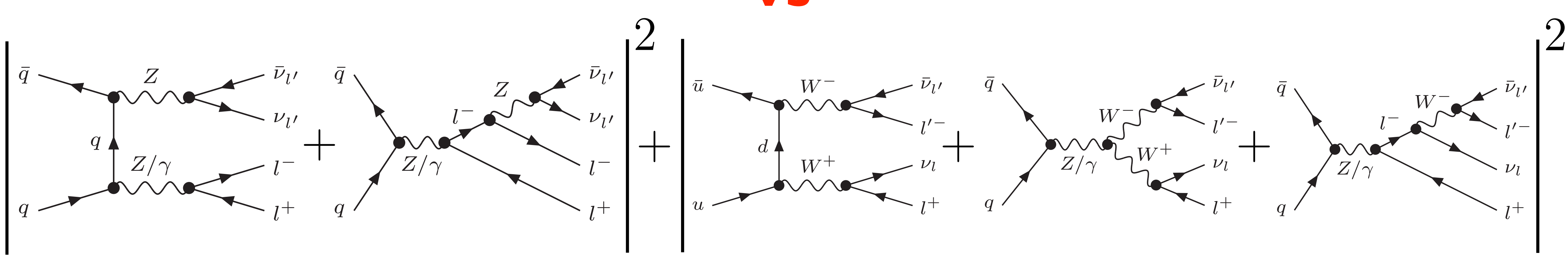


vs



$\ell\ell$+E$_{T,miss}$ at NNLO [Kallweit, MW '18]

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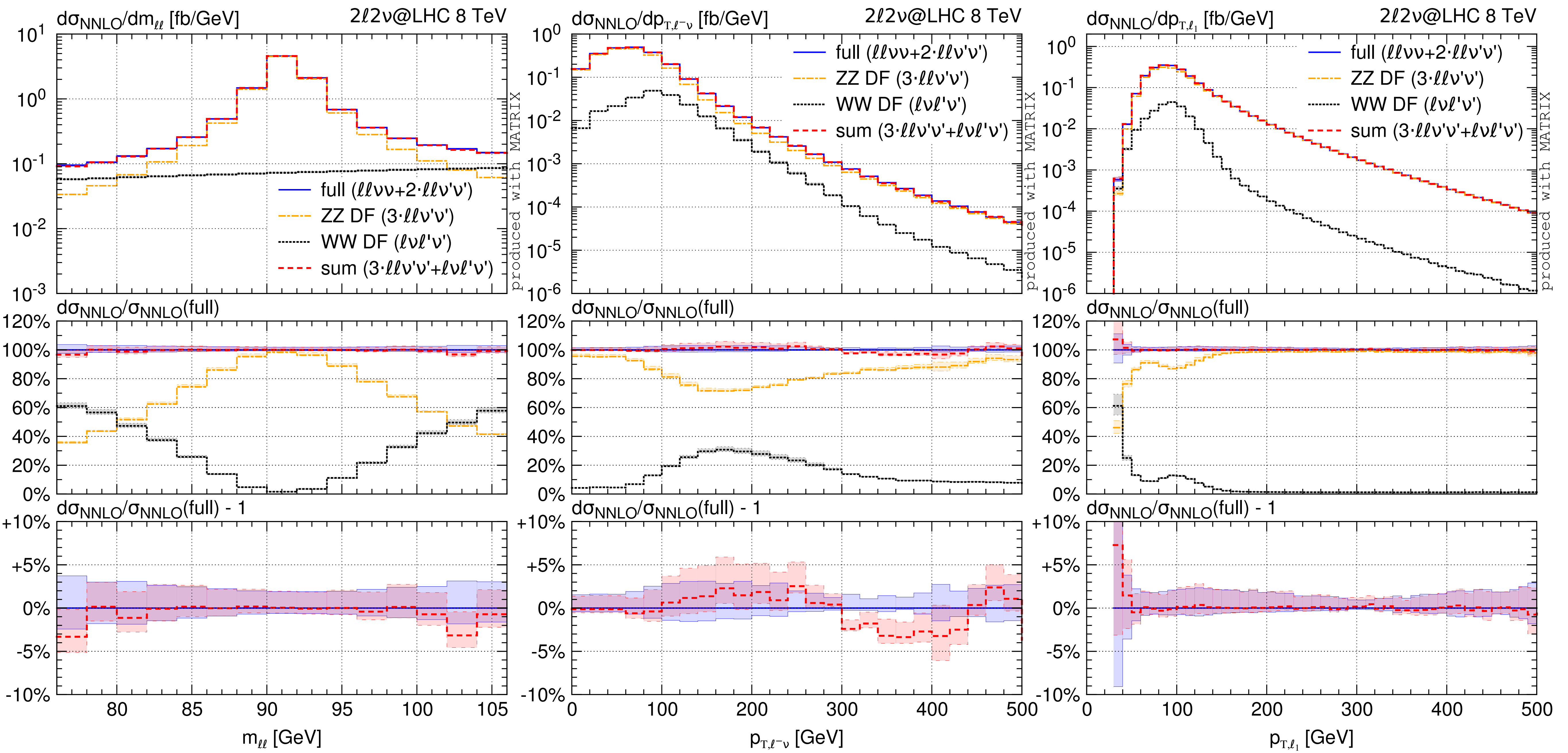

→ incoherent sum of ZZ+WW good approximation