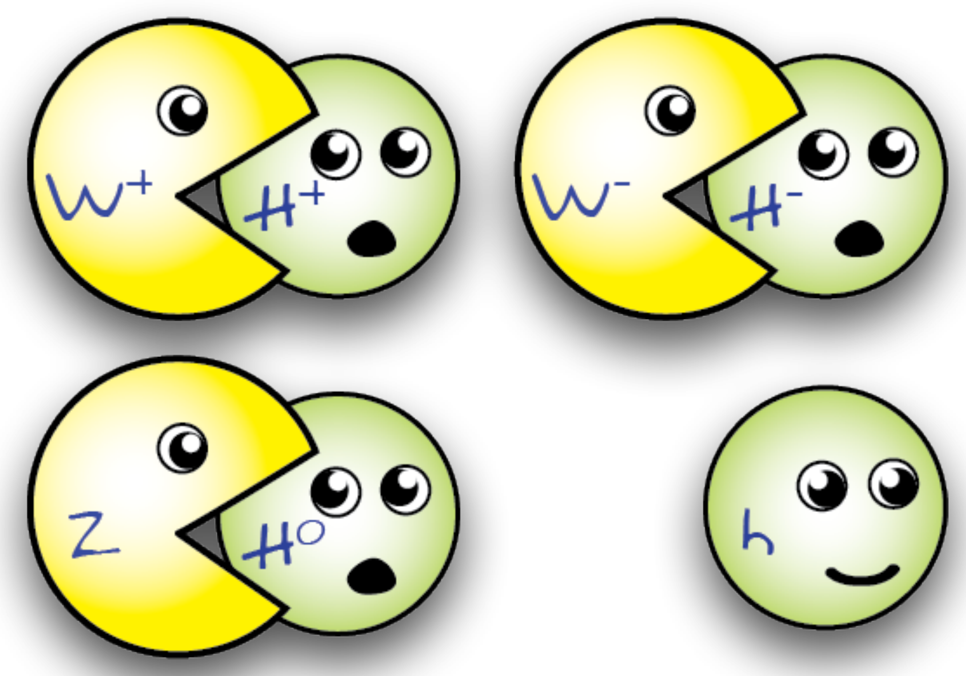
Status of (n)NNLO QCD for Dibosons

Marius Wiesemann

Max-Planck-Institut für Physik



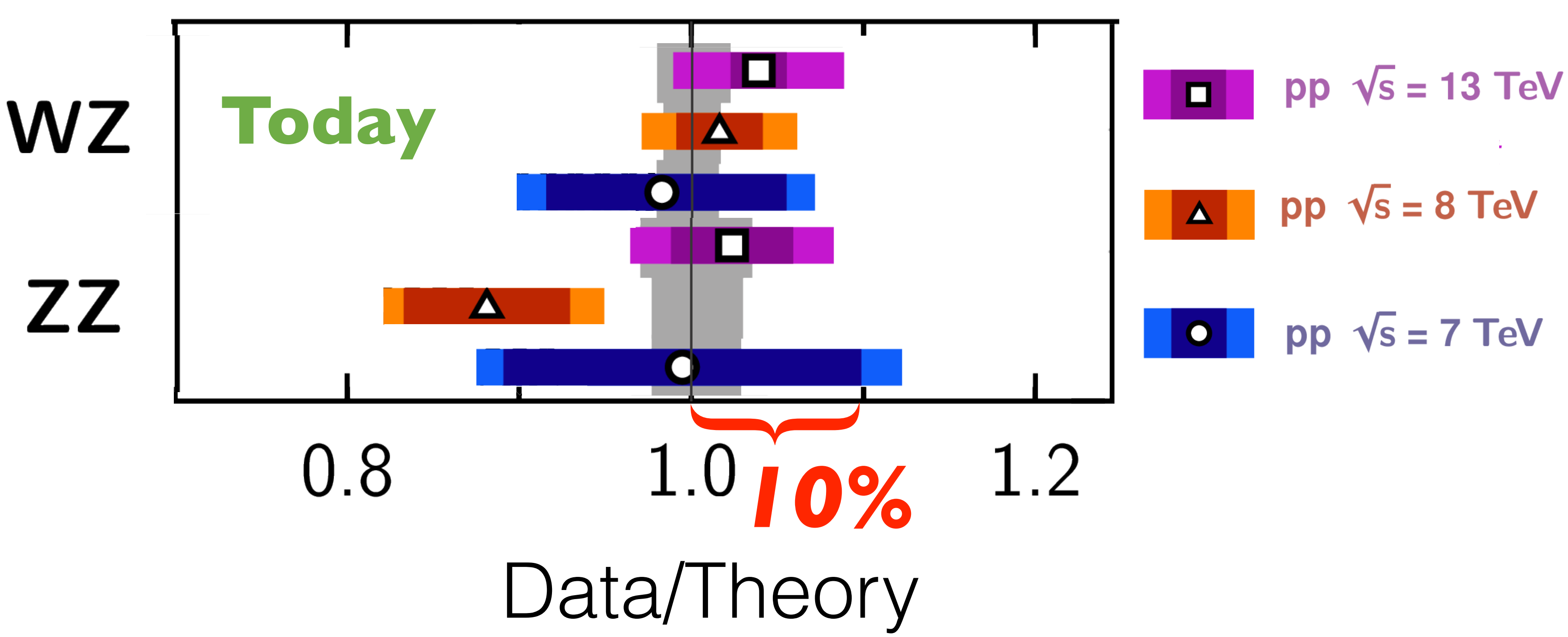
Multi-Boson Interactions 2019

Thessaloniki (Greece), August 26th - 28th, 2019

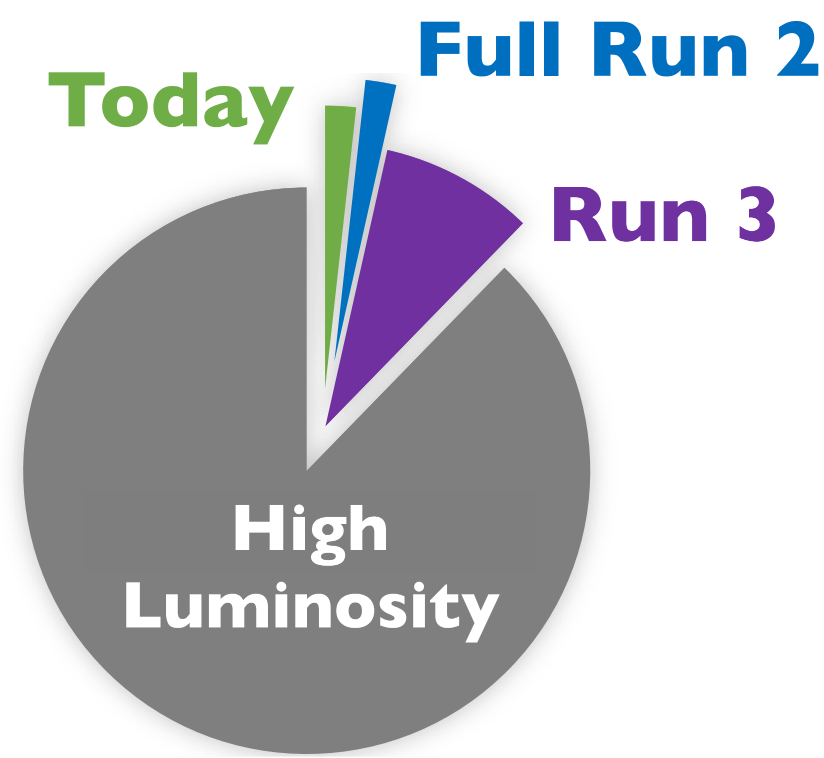
Precision at the LHC

- Production of vector bosons (γ,W, Z) and Higgs
  - → deep test of the fundamental laws of physics
  - → high ***experimental precision*** already now

Diboson Cross Section Measurements



LHC data:

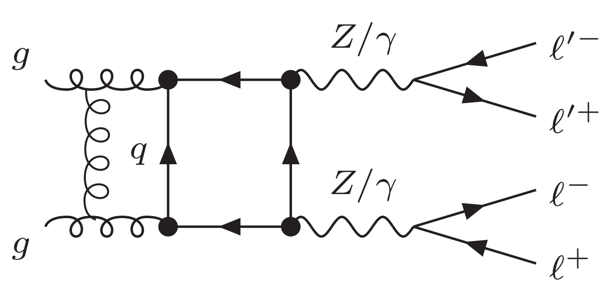


Experiment demands $\mathcal{O}(1\%)$ theoretical precision

SM predictions: what is there?

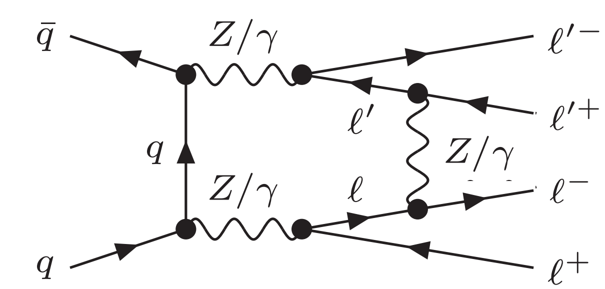
NNLO QCD

NLO QCD gg



NNLO+PS

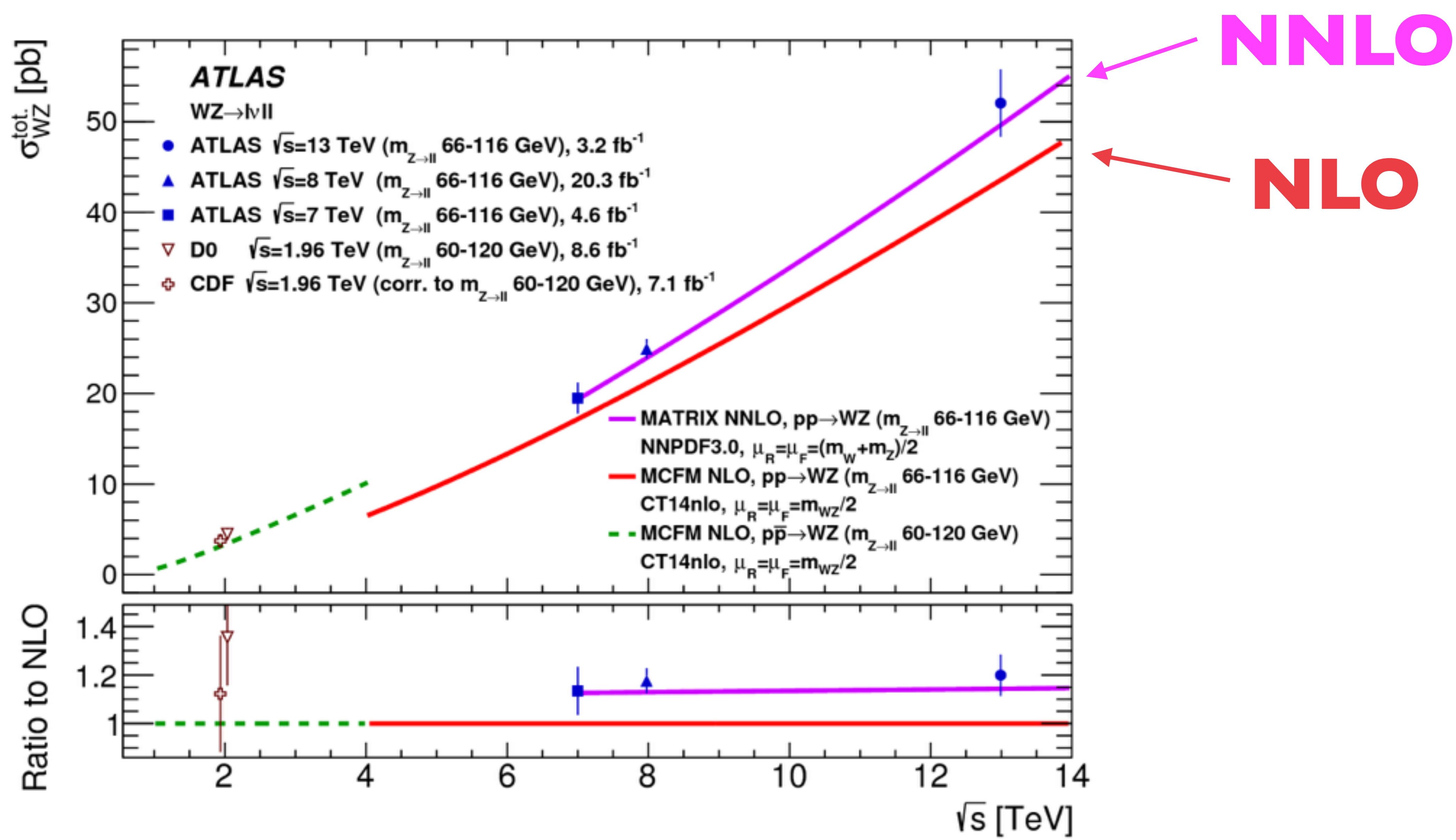
NLO EW



→ Jonas Lindert's talk

not in this talk: BSM effects

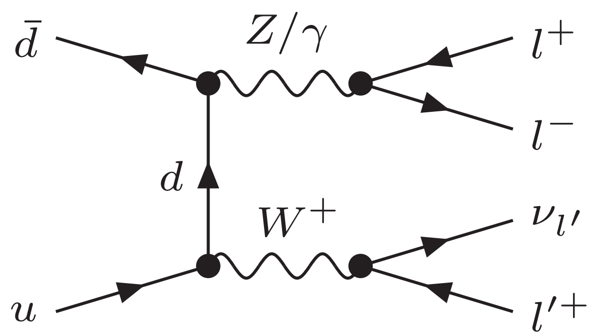
Importance of QCD corrections
(example WZ)



NNLO crucial for accurate description of data

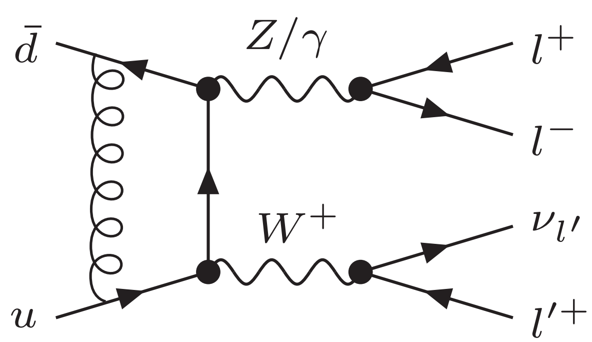
NNLO through X+jet at NLO + Slicing

LO (pp→X)

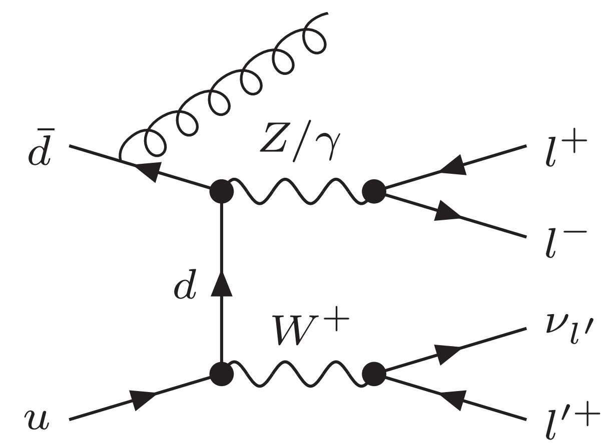


$\rightarrow \mathrm{d}\sigma^{\mathrm{B}}$

NLO (pp→X)

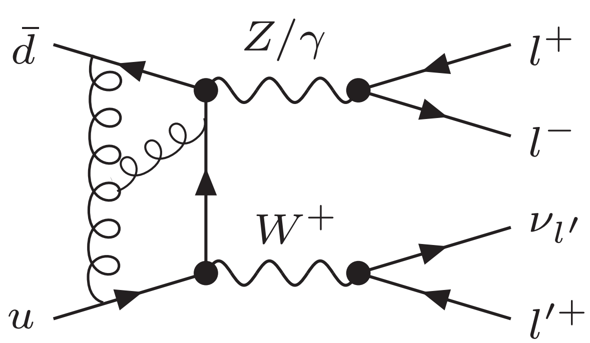


$\rightarrow \mathrm{d}\sigma^{\mathrm{V}}$

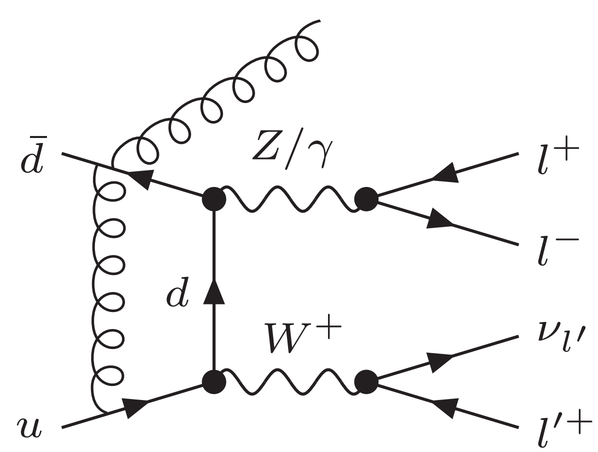


$\rightarrow \mathrm{d}\sigma^{\mathrm{R}}$

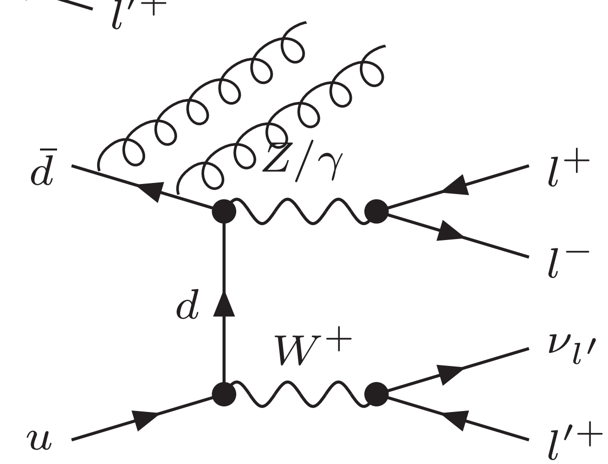
NNLO (pp→X)



$\rightarrow \mathrm{d}\sigma^{\mathrm{VV}}$



$\rightarrow \mathrm{d}\sigma^{\mathrm{RV}}$



$\rightarrow \mathrm{d}\sigma^{\mathrm{RR}}$

NNLO through X+jet at NLO + Slicing

$$\sigma_{\rm NLO}^{\rm X+jet} = \int_{\Phi_{\rm RV}} {\rm d}\sigma^{\rm RV} + \int_{\Phi_{\rm RV+1}} \left({\rm d}\sigma^{\rm RR} - {\rm d}\sigma^{\rm S}\right) + \int_{\Phi_{\rm RV}} \left({\rm d}\sigma^{\rm RV} + \int_1 {\rm d}\sigma^{\rm S}\right)$$

$\mathrm{d}\sigma^{\rm S}$: subtraction term

→ CS [Catani, Seymour '96]

→ FKS [Frixione, Kunszt, Signer '96]

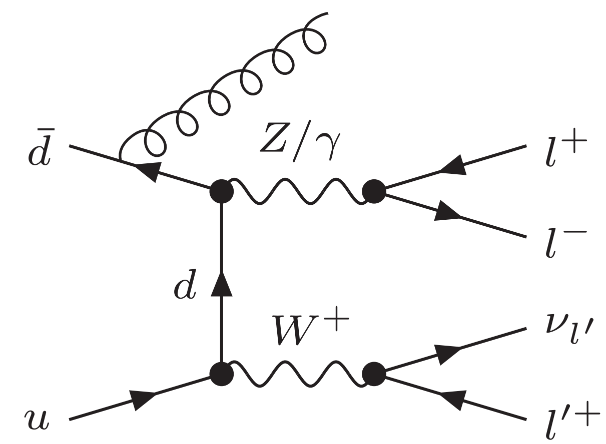
→ Antenna [Gehrmann et al. '05]

→ ...

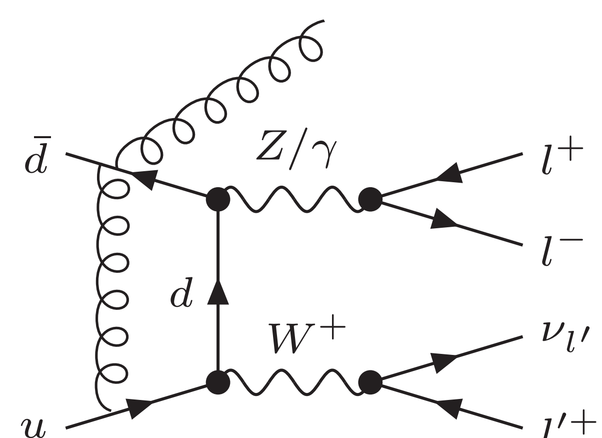
~~LO (pp→X)~~

~~N~~LO (pp→X+jet)

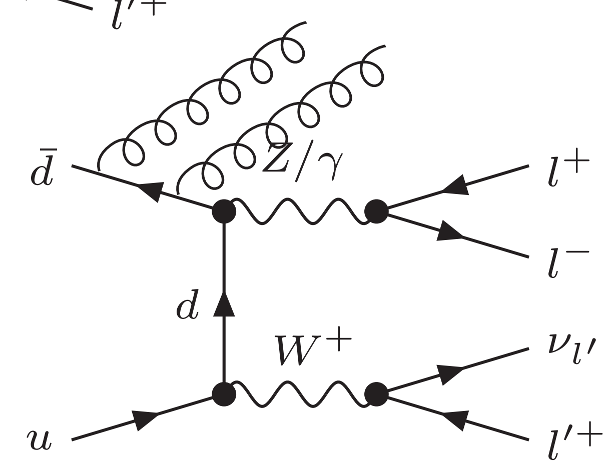
~~N~~NLO (pp→X+jet)



$\rightarrow \mathrm{d}\sigma^{\rm R}$



$\rightarrow \mathrm{d}\sigma^{\rm RV}$

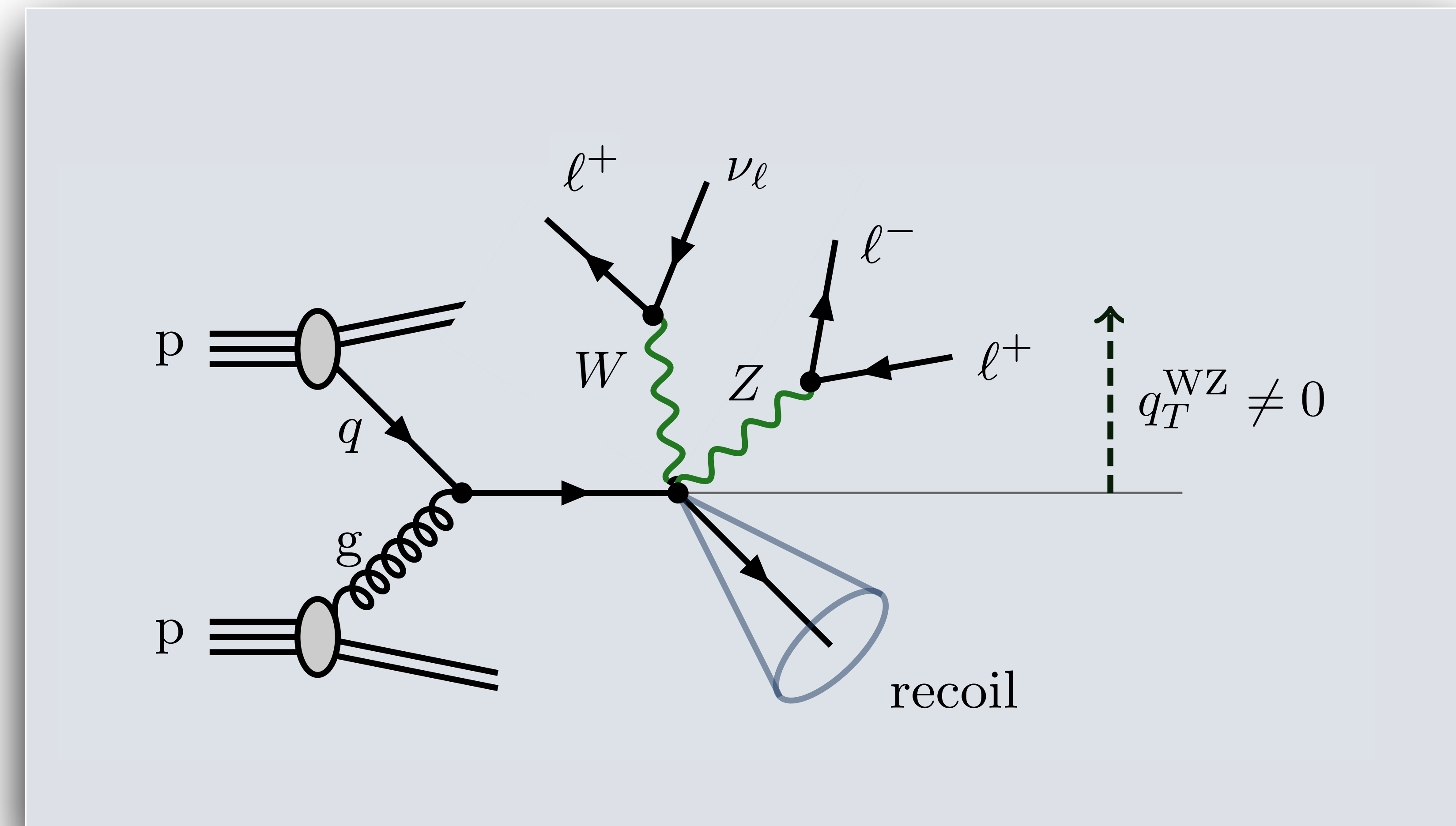


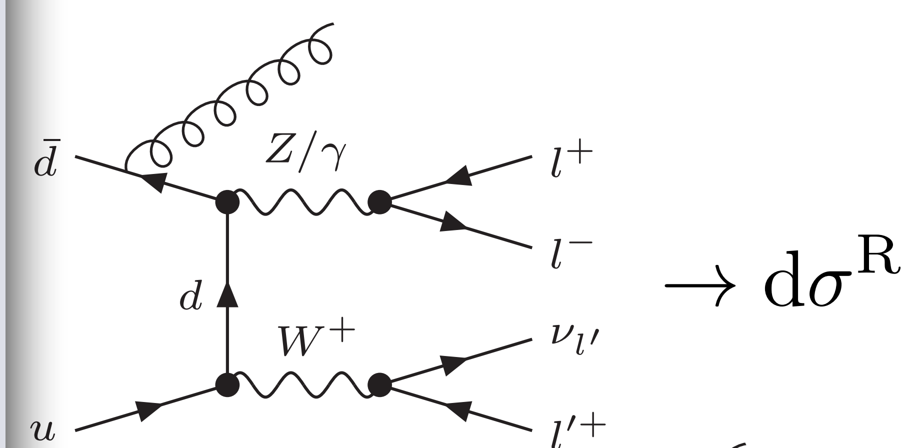
$\rightarrow \mathrm{d}\sigma^{\rm RR}$

NNLO through X+jet at NLO + Slicing

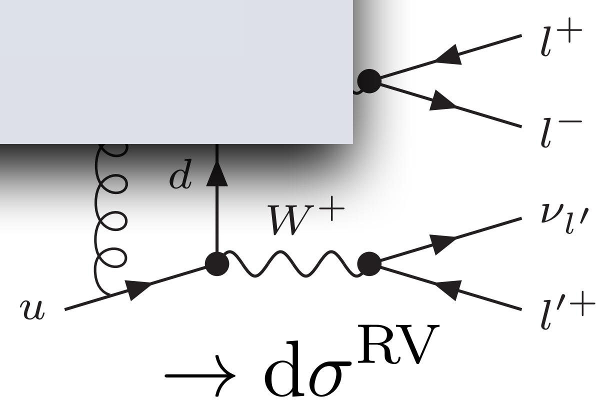
$$\sigma_{\mathrm{NLO}}^{\mathrm{X+jet}} = \left[\int_{\Phi_{\mathrm{RV}}} \mathrm{d}\sigma^{\mathrm{RV}} + \int_{\Phi_{\mathrm{RV+1}}} \left(\mathrm{d}\sigma^{\mathrm{RR}} - \mathrm{d}\sigma^{\mathrm{S}}\right) + \int_{\Phi_{\mathrm{RV}}} \left(\mathrm{d}\sigma^{\mathrm{RV}} + \int_1 \mathrm{d}\sigma^{\mathrm{S}}\right)\right]_{\frac{q_T}{Q} \equiv r > r_{\mathrm{cut}}}$$

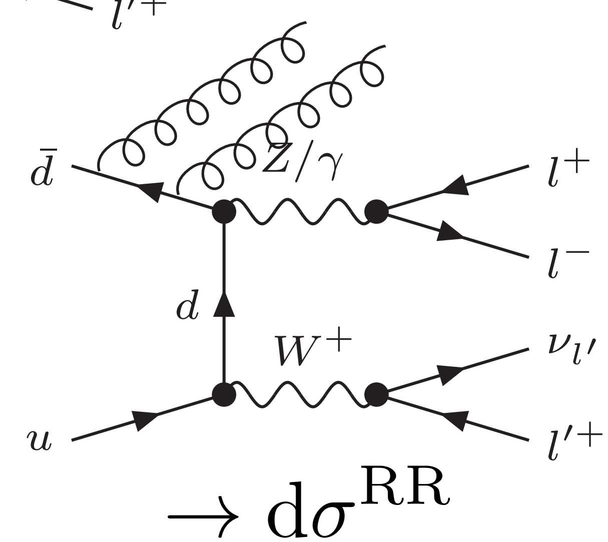
$$\xrightarrow{r_{\mathrm{cut}} \ll 1} \left[A \cdot \log^4(r_{\mathrm{cut}}) + B \cdot \log^3(r_{\mathrm{cut}}) + C \cdot \log^2(r_{\mathrm{cut}}) + D \cdot \log(r_{\mathrm{cut}})\right] \otimes \mathrm{d}\sigma^{\mathrm{B}}$$





NNLO
(pp→X+jet)





NNLO through X+jet at NLO + Slicing

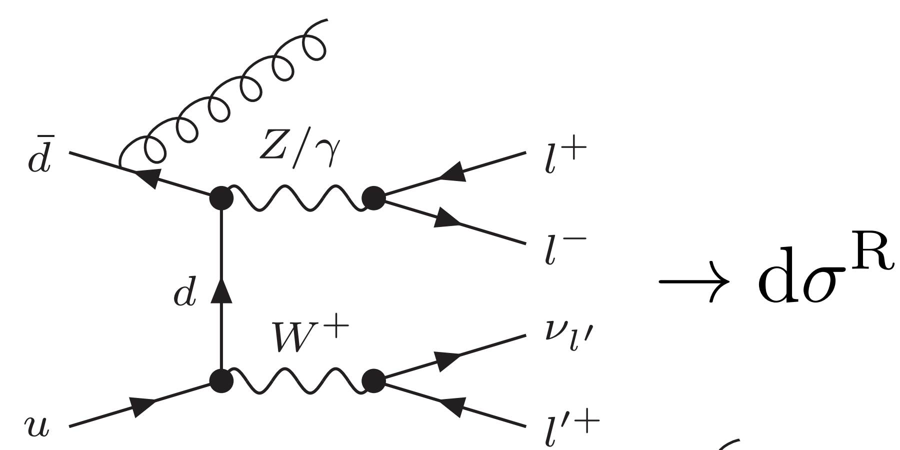
$$\sigma^{\text{X+jet}}_{\text{NLO}} = \left[\int_{\Phi_{\text{RV}}} \mathrm{d}\sigma^{\text{RV}} + \int_{\Phi_{\text{RV}+1}} \left(\mathrm{d}\sigma^{\text{RR}} - \mathrm{d}\sigma^{\text{S}}\right) + \int_{\Phi_{\text{RV}}} \left(\mathrm{d}\sigma^{\text{RV}} + \int_1 \mathrm{d}\sigma^{\text{S}}\right)\right]_{\frac{q_T}{Q} \equiv r > r_{\text{cut}}}$$

$$\xrightarrow{r_{\text{cut}} \ll 1} \left[A \cdot \log^4(r_{\text{cut}}) + B \cdot \log^3(r_{\text{cut}}) + C \cdot \log^2(r_{\text{cut}}) + D \cdot \log(r_{\text{cut}})\right] \otimes \mathrm{d}\sigma^{\text{B}}$$

$$= \int_{r > r_{\text{cut}}} \left[d\sigma^{(\text{res})}\right]_{\text{f.o.}} \equiv \Sigma_{\text{NNLO}}(r_{\text{cut}}) \otimes \mathrm{d}\sigma^{\text{B}}$$

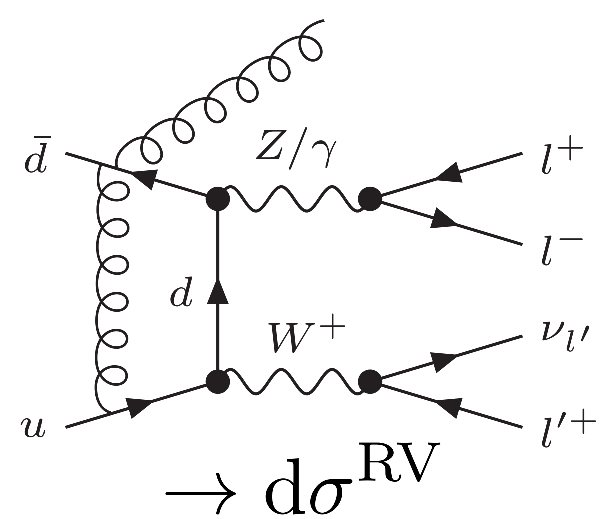
[Collins, Soper, Sterman '85]
[Bozzi, Catani, de Florian, Grazzini '06]

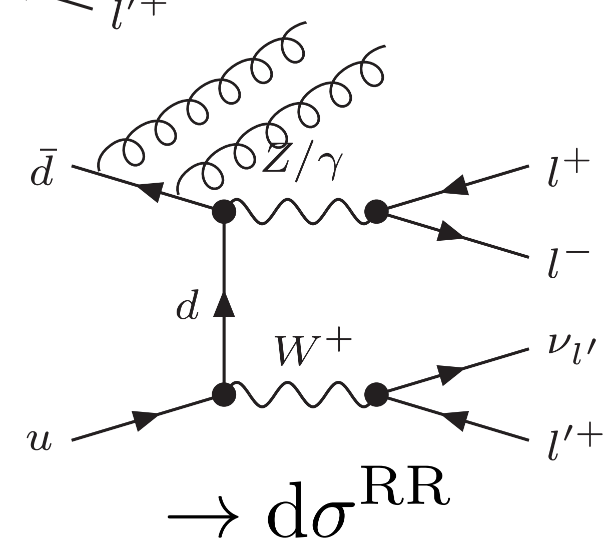
~~LO (pp→X)~~



~~N~~LO (pp→X+jet)

~~N~~NLO (pp→X+jet)





NNLO through X+jet at NLO + Slicing

$$\sigma^{\mathrm{X+jet}}_{\mathrm{NLO}} = \left[\int_{\Phi_{\mathrm{RV}}} \mathrm{d}\sigma^{\mathrm{RV}} + \int_{\Phi_{\mathrm{RV}+1}} \left(\mathrm{d}\sigma^{\mathrm{RR}} - \mathrm{d}\sigma^{\mathrm{S}}\right) + \int_{\Phi_{\mathrm{RV}}} \left(\mathrm{d}\sigma^{\mathrm{RV}} + \int_1 \mathrm{d}\sigma^{\mathrm{S}}\right)\right]_{\frac{q_T}{Q} \equiv r > r_{\mathrm{cut}}}$$

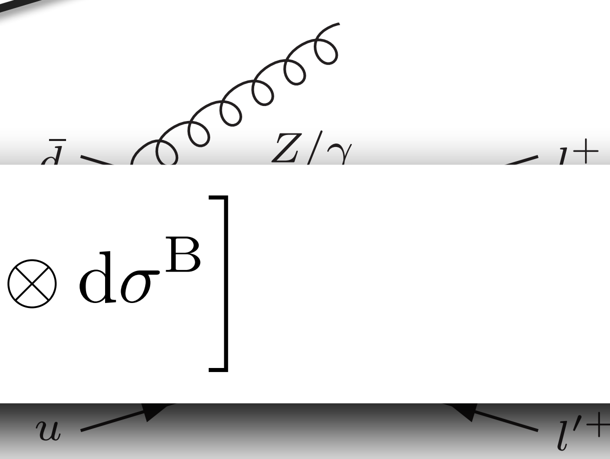
$$\xrightarrow{r_{\mathrm{cut}} \ll 1} \left[A \cdot \log^4(r_{\mathrm{cut}}) + B \cdot \log^3(r_{\mathrm{cut}}) + C \cdot \log^2(r_{\mathrm{cut}}) + D \cdot \log(r_{\mathrm{cut}})\right] \otimes \mathrm{d}\sigma^{\mathrm{B}}$$

$$= \int_{r > r_{\mathrm{cut}}} \left[d\sigma^{(\mathrm{res})}\right]_{\mathrm{f.o.}} \equiv \Sigma_{\mathrm{NNLO}}(r_{\mathrm{cut}}) \otimes \mathrm{d}\sigma^{\mathrm{B}}$$

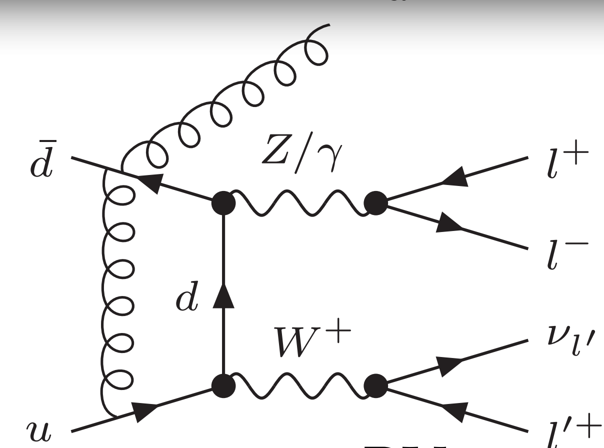
~~LO~~
~~(pp→X)~~

$$\mathrm{d}\sigma^{\mathrm{X}}_{\mathrm{NNLO}} = \left[\mathrm{d}\sigma^{\mathrm{X+jet}}_{\mathrm{NLO}}\Big|_{r > r_{\mathrm{cut}}} - \Sigma_{\mathrm{NNLO}}(r_{\mathrm{cut}}) \otimes \mathrm{d}\sigma^{\mathrm{B}}\right]$$

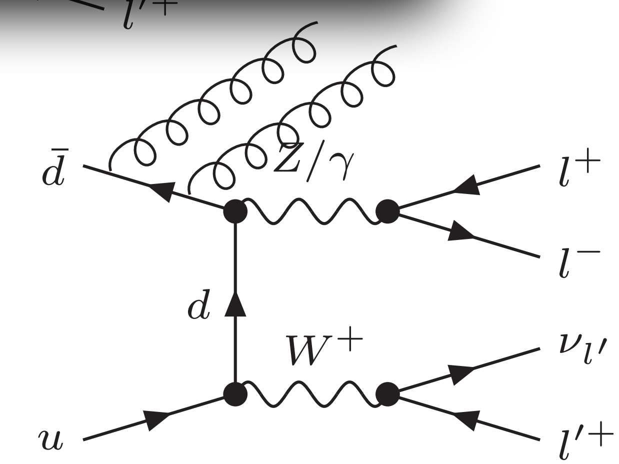
~~N~~
(pp X+jet)



~~N~~NLO
(pp→X+jet)



$\to \mathrm{d}\sigma^{\mathrm{RV}}$



$\to \mathrm{d}\sigma^{\mathrm{RR}}$

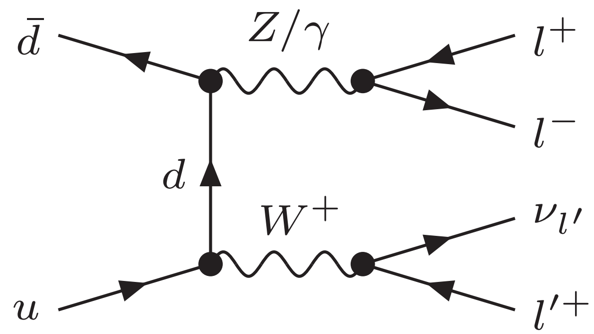
NNLO through X+jet at NLO + Slicing

$$d\sigma^{\mathrm{X}}_{\mathrm{NNLO}} = \left[d\sigma^{\mathrm{X+jet}}_{\mathrm{NLO}} \Big|_{r > r_{\mathrm{cut}}} - \Sigma_{\mathrm{NNLO}}(r_{\mathrm{cut}}) \otimes d\sigma^{\mathrm{B}} \right] + $$

q_T subtraction

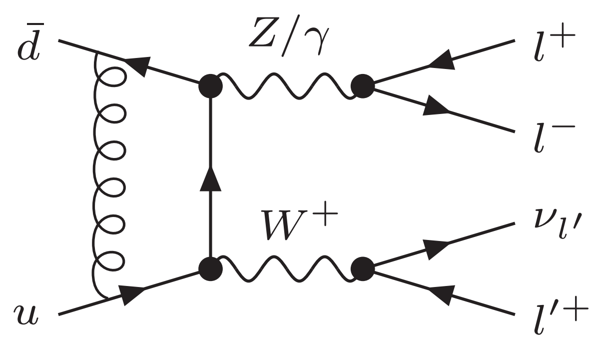
[Catani, Grazzini '07]

LO (pp→X)

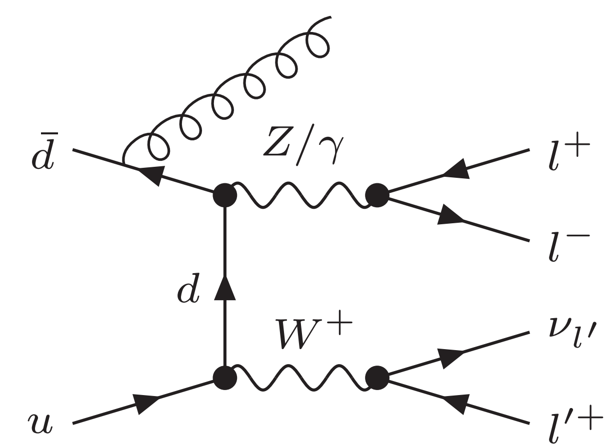


$\rightarrow d\sigma^{\mathrm{B}}$

NLO (pp→X)

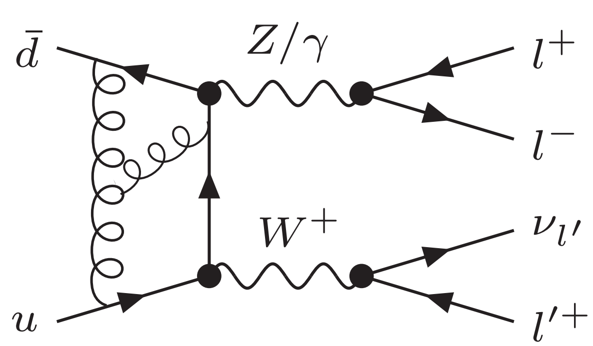


$\rightarrow d\sigma^{\mathrm{V}}$

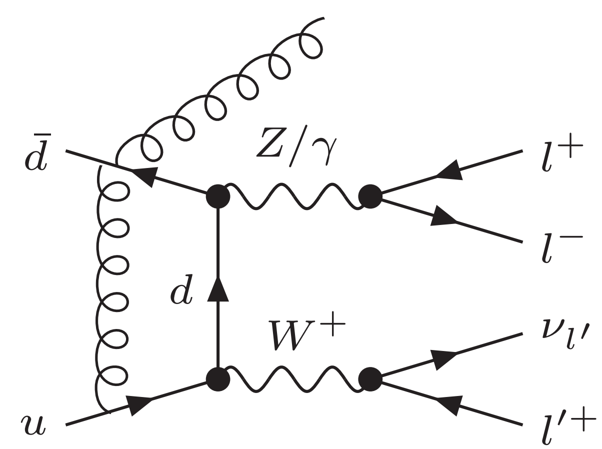


$\rightarrow d\sigma^{\mathrm{R}}$

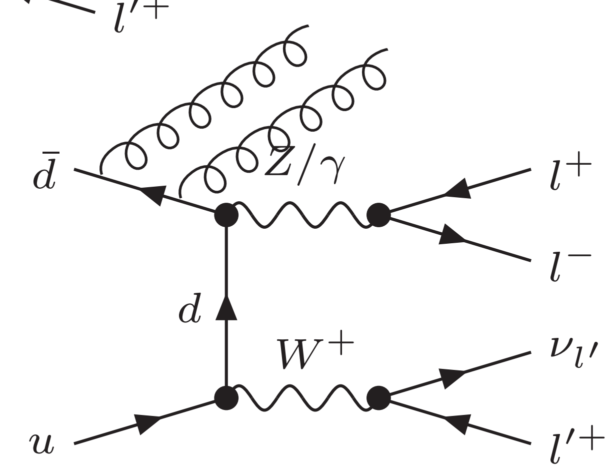
NNLO (pp→X)



$\rightarrow d\sigma^{\mathrm{VV}}$



$\rightarrow d\sigma^{\mathrm{RV}}$



$\rightarrow d\sigma^{\mathrm{RR}}$

NNLO through X+jet at NLO + Slicing

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

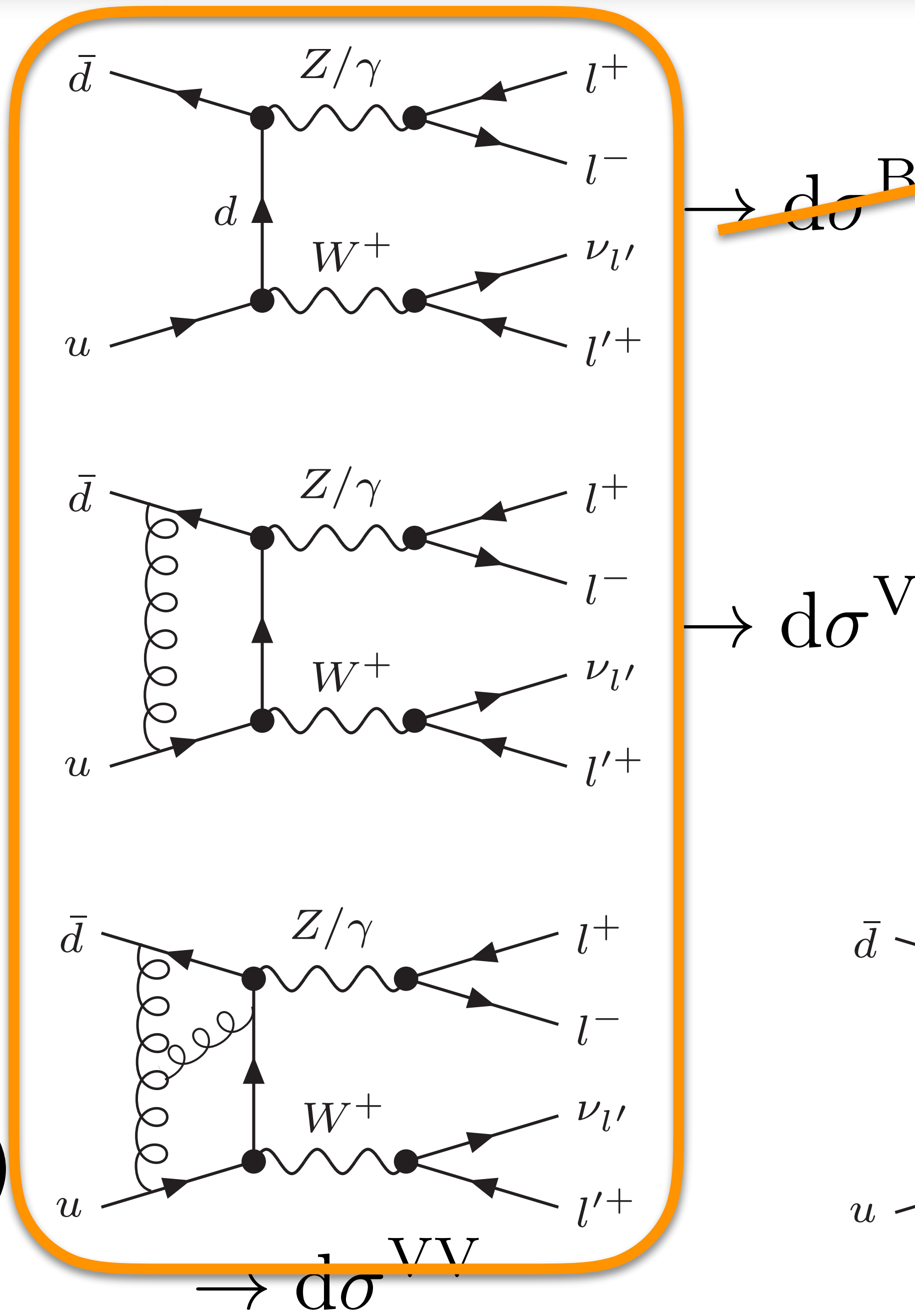
q_T subtraction

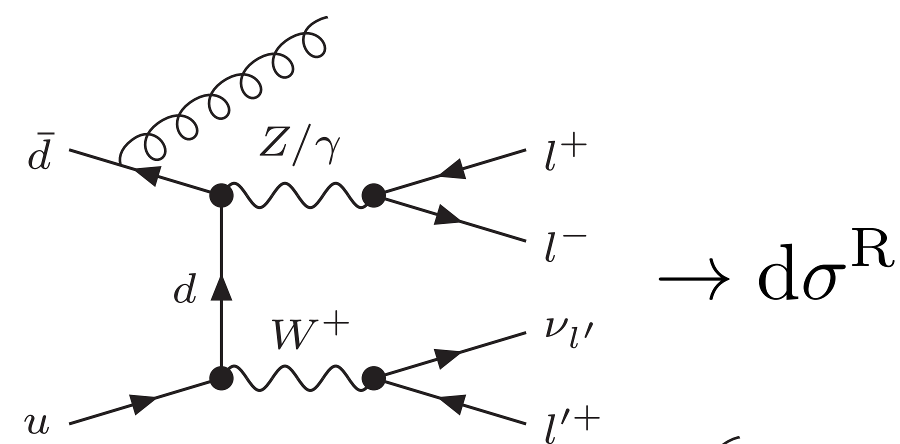
[Catani, Grazzini '07]

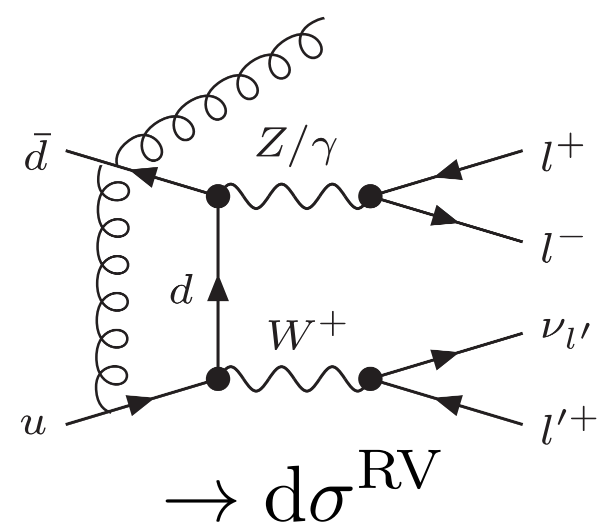
LO (pp→X)

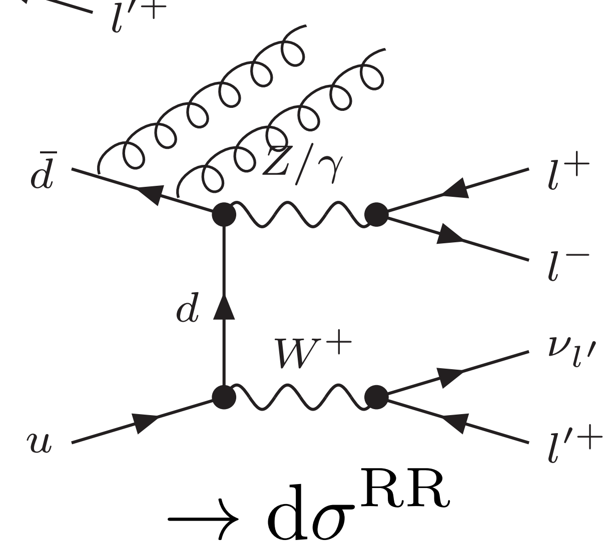
NLO (pp→X)

NNLO (pp→X)





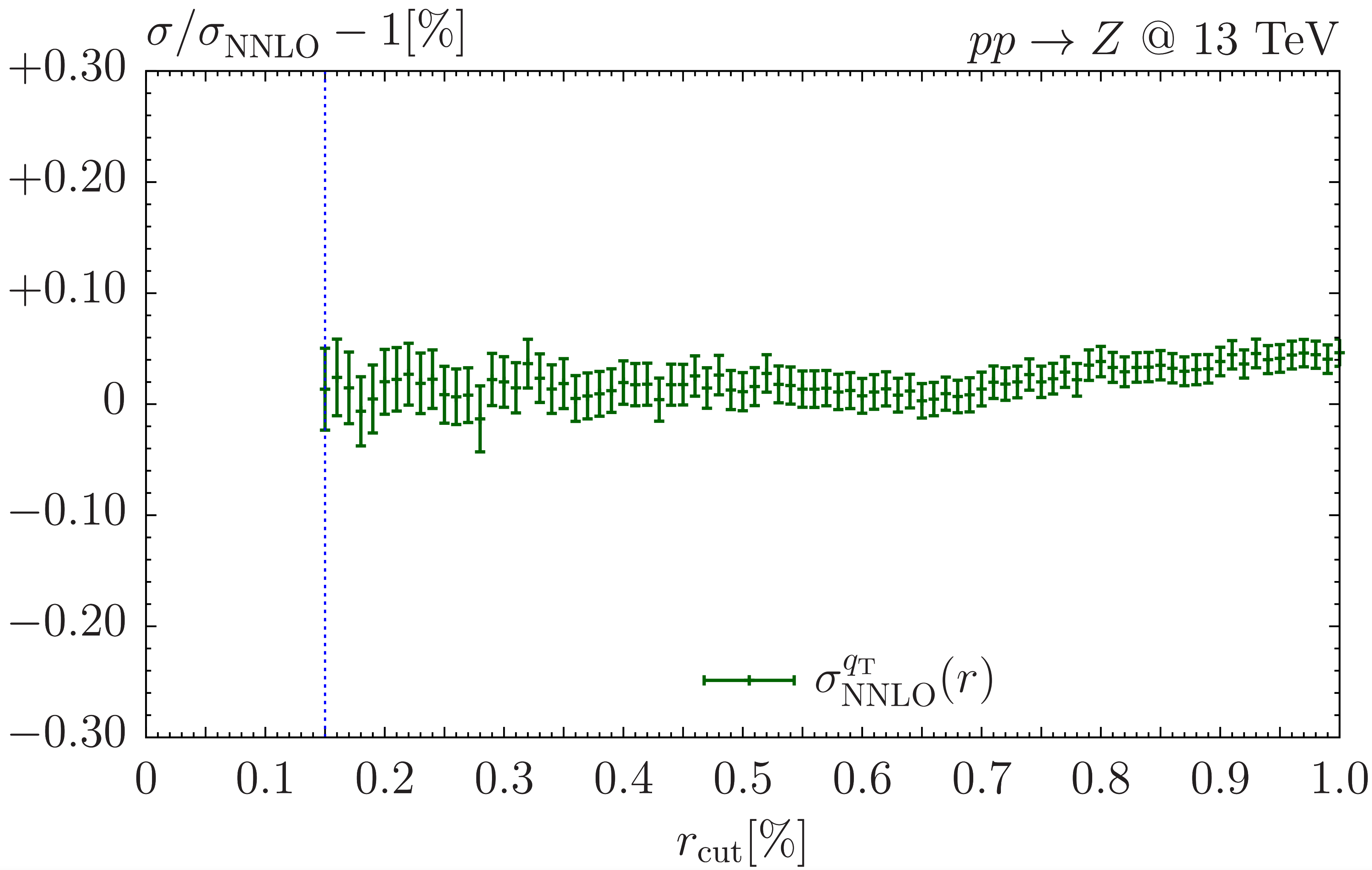




$r_{cut} \to 0$ extrapolation in MATRIX

[Grazzini, Kallweit, MW '17]

automatically computed in every single MATRIX NNLO run

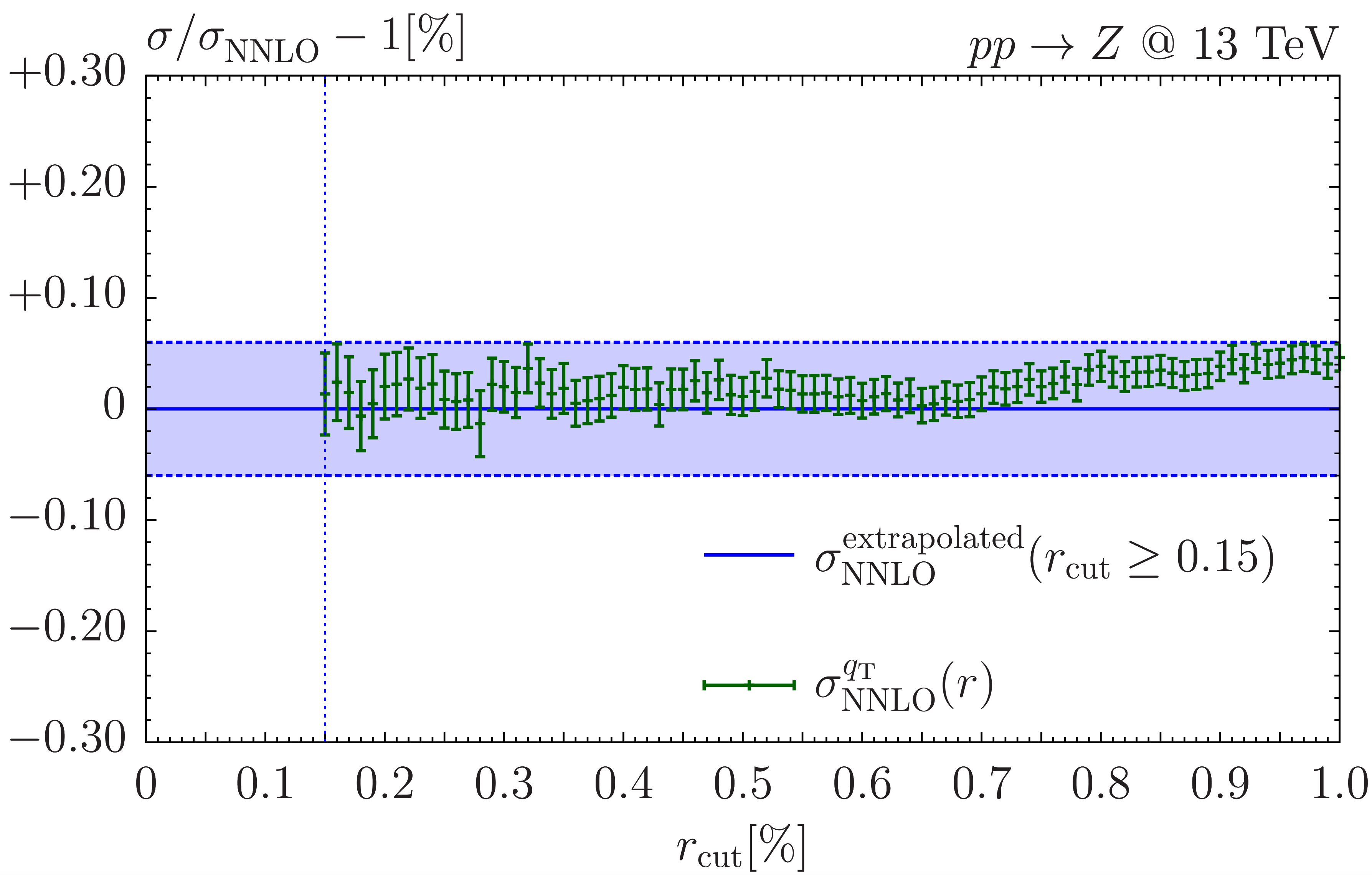


$$\mathrm{d}\sigma^{\mathrm{X}}_{\mathrm{NNLO}} = \left[\mathrm{d}\sigma^{\mathrm{X+jet}}_{\mathrm{NLO}} \Big|_{r > r_{\mathrm{cut}}} - \Sigma_{\mathrm{NNLO}}(r_{\mathrm{cut}}) \otimes \mathrm{d}\sigma^{\mathrm{B}} \right] + \mathcal{H}_{\mathrm{NNLO}} \otimes \mathrm{d}\sigma^{\mathrm{B}}$$

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

[Grazzini, Kallweit, MW '17]

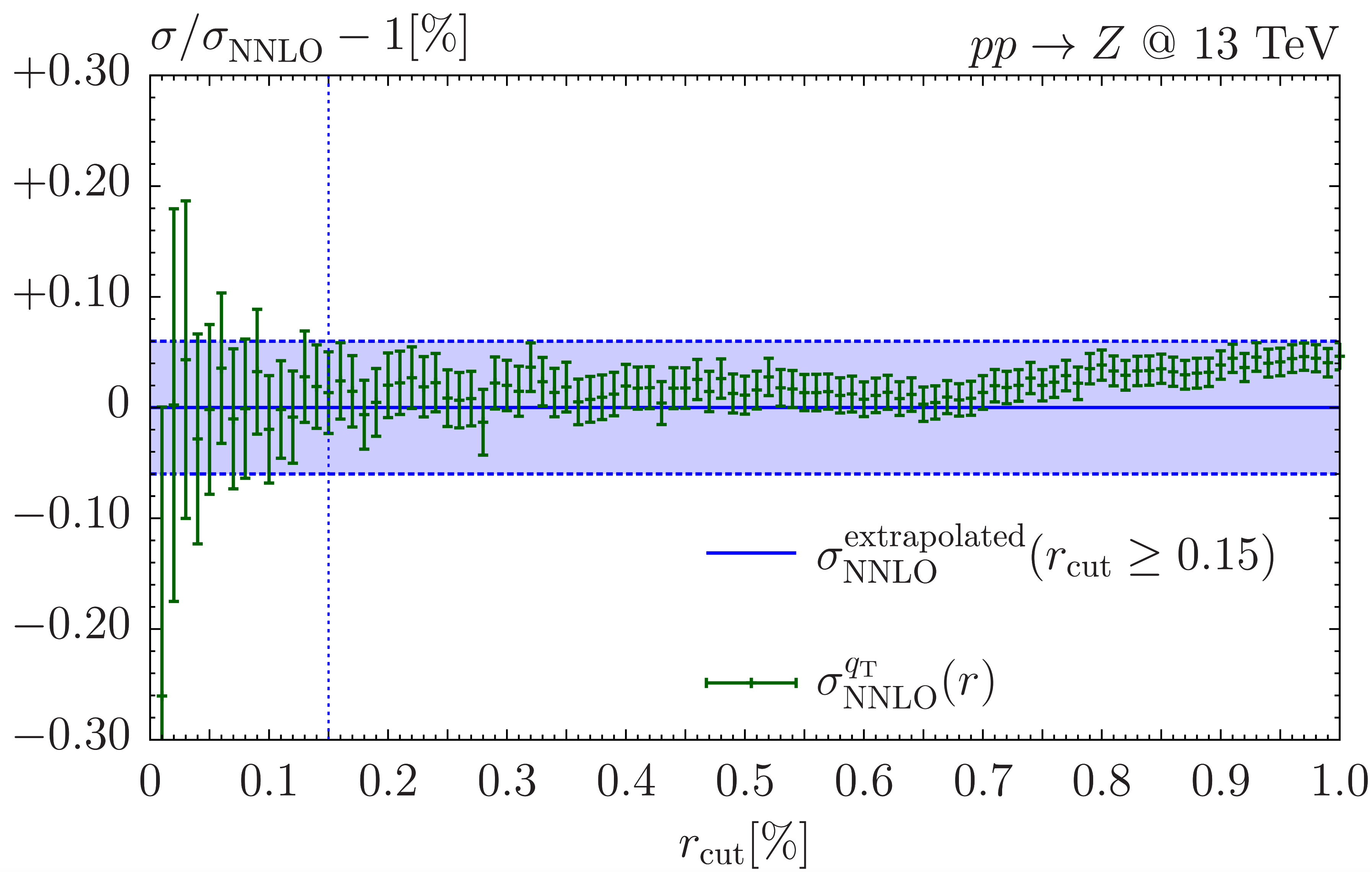
simple quadratic fit ($A * r_{cut}^2 + B * r_{cut} + C$) to extrapolate to $r_{cut}=0$



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

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

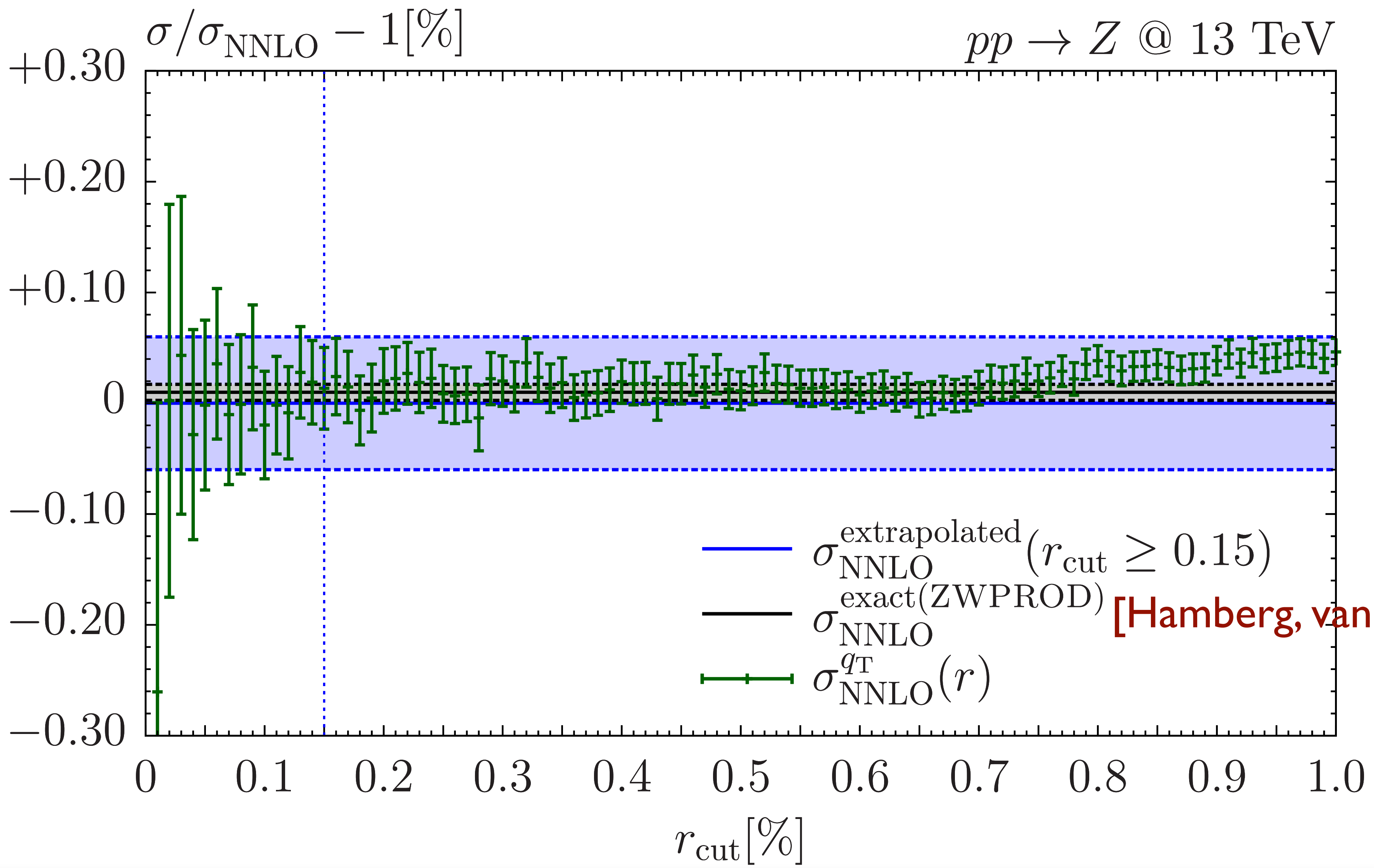
[Grazzini, Kallweit, MW '17]



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

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

[Grazzini, Kallweit, MW '17]



[Hamberg, van Neerven, Matsuura '91]

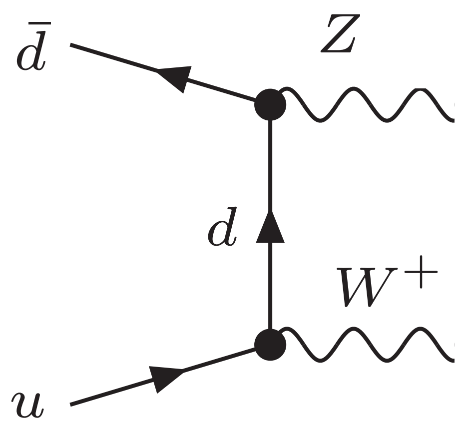
$$d\sigma_{\text{NNLO}}^{\text{X}} = \left[d\sigma_{\text{NLO}}^{\text{X+jet}}\Big|_{r > r_{\text{cut}}} - \Sigma_{\text{NNLO}}(r_{\text{cut}}) \otimes d\sigma^{\text{B}} \right] + \mathcal{H}_{\text{NNLO}} \otimes d\sigma^{\text{B}}$$

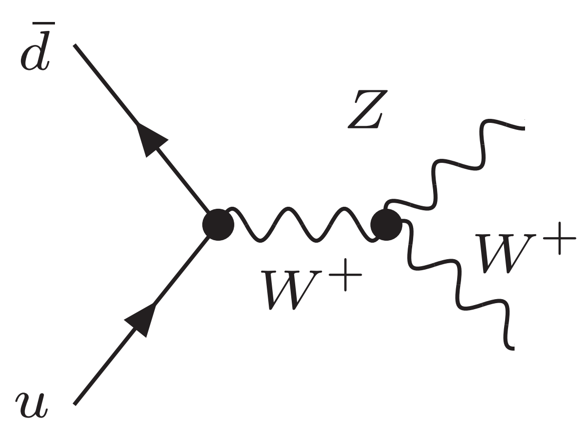
VV production in a nutshell

example: WZ production

VV production in a nutshell

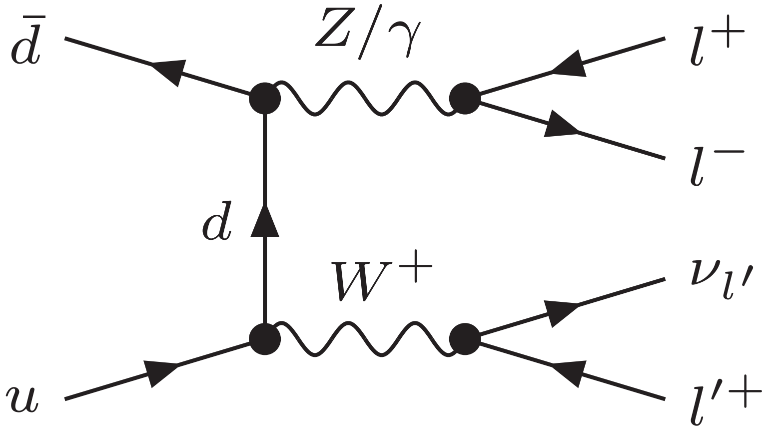
example: WZ production (on-shell)

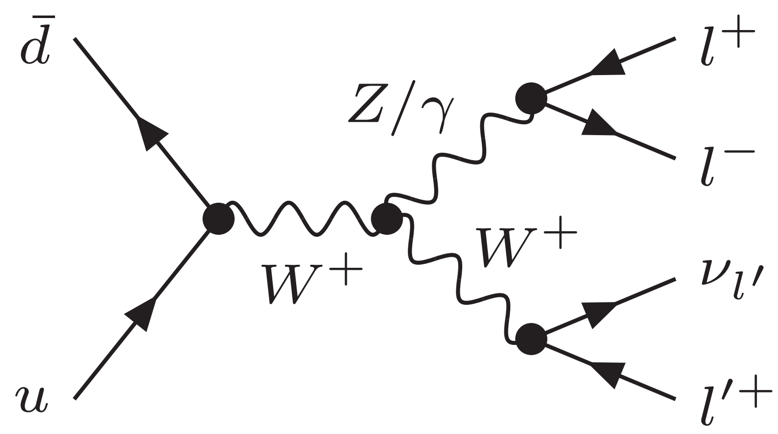




VV production in a nutshell

example: WZ production (off-shell)

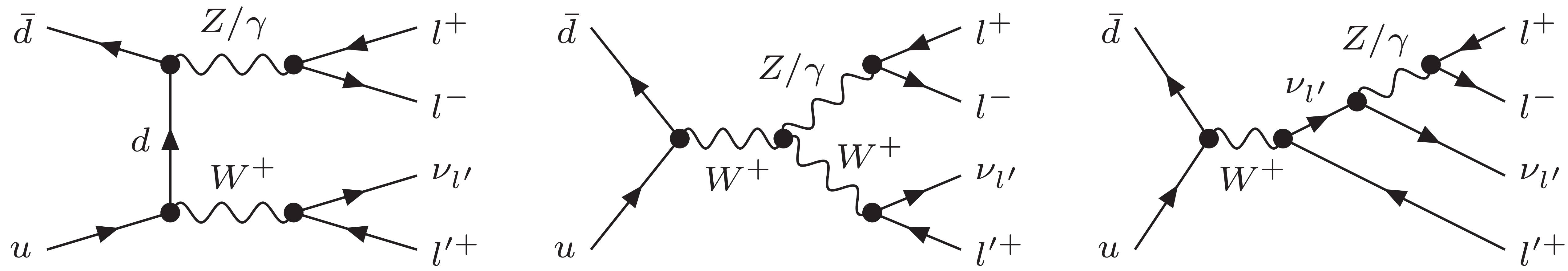




- EW decays of heavy bosons (W, Z, γ^*) ✓ (only isolated photons in the final state)

VV production in a nutshell

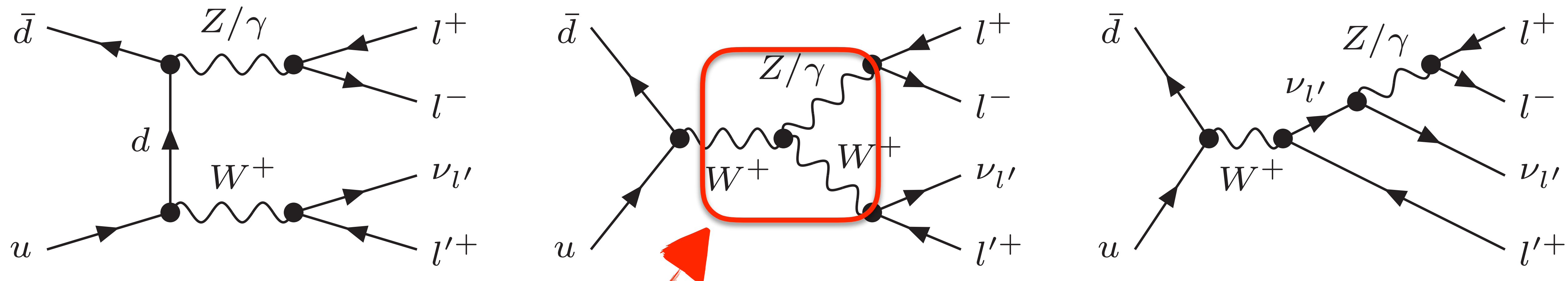
example: WZ production (off-shell)



- 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

example: WZ production (off-shell)

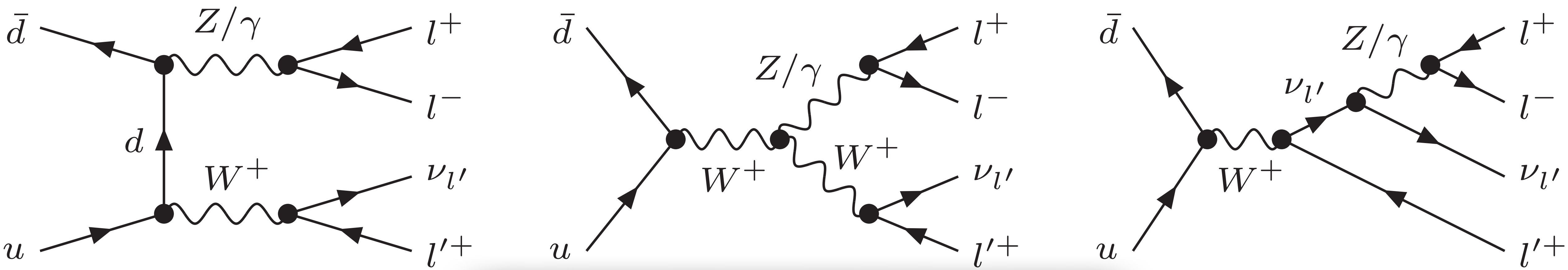


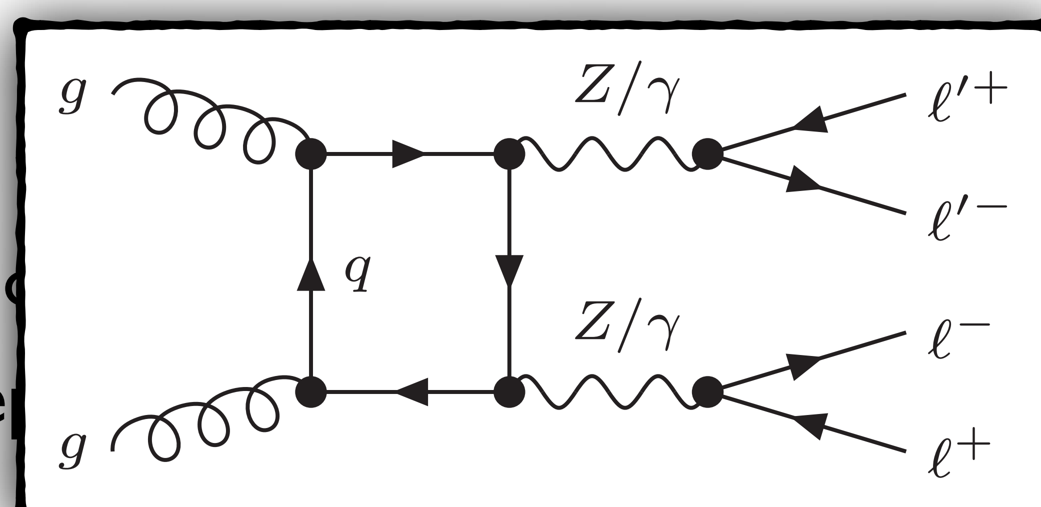
- EW decays of heavy bosons (W, Z, γ^*) ✓ (only isolated photons in the final state)
- all topologies to same leptonic final state (with spin correlations & off-shell effects) ✓

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

VV production in a nutshell

example: WZ production (off-shell)

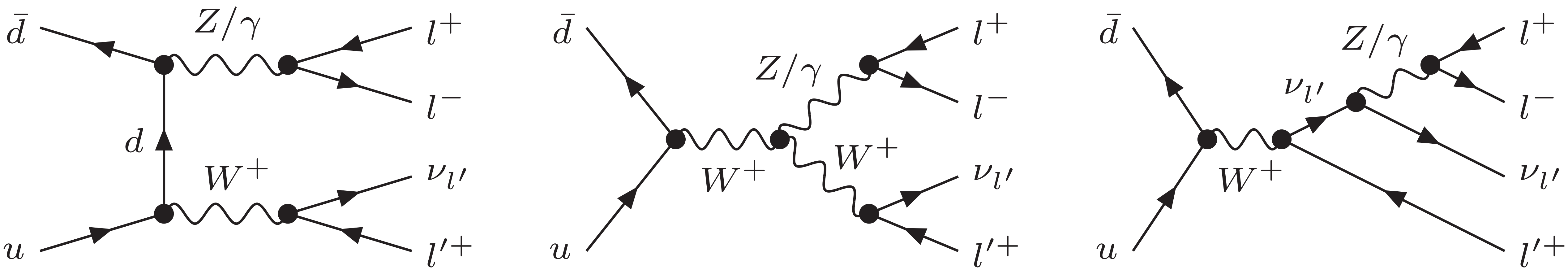




- EW decays of heavy bos… photons in the final state)
- all topologies to same le… …tions & off-shell effects) ✓
  → access to triple gauge couplings (TGCs) → high relevance for BSM physics
- loop-induced gg channel enters NNLO for charge-neutral processes ✓ (eg, for ZZ)

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)
- all topologies to same leptonic final state (with spin correlations & 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)
- important background for Higgs measurements (H→VV) and BSM searches

NNLO QCD corrections vor VV

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]

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

[Grazzini, Kallweit, Rathlev, Torre '13], [Grazzini, Kallweit, Rathlev '15]; see also: [Campbell et al. '17]

Wγ - inclusive/on-shell and differential/off-shell
[Grazzini, Kallweit, Rathlev, Torre '13], [Grazzini, Kallweit, Rathlev '15]

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

- differential/off-shell [Grazzini, Kallweit, Rathlev '15], [Kallweit, MW '18]

WW - inclusive/on-shell [Gehrmann, Grazzini, Kallweit, Maierhöfer, von Manteuffel, et al. '14]

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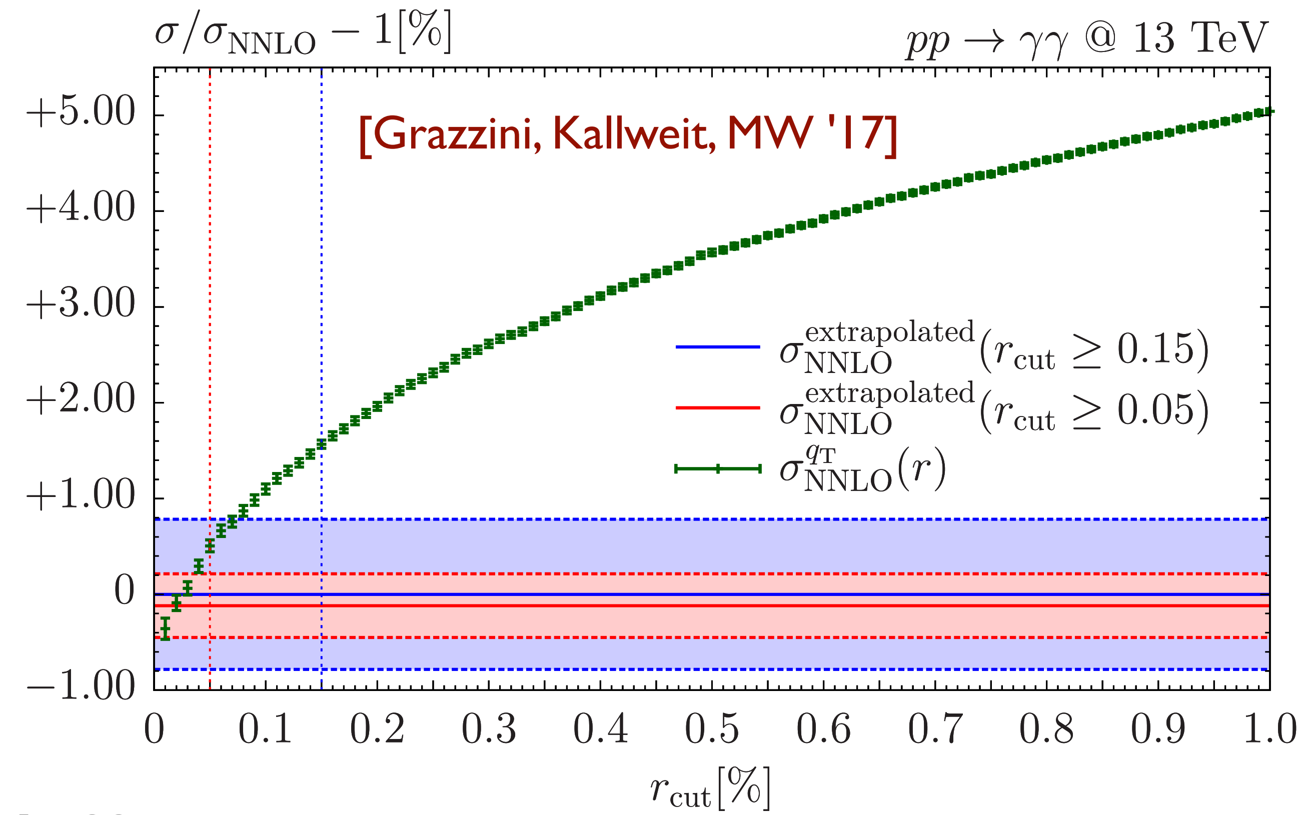
WZ - inclusive/on-shell [Grazzini, Kallweit, Rathlev, MW '16]

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

γγ - inclusive and differential

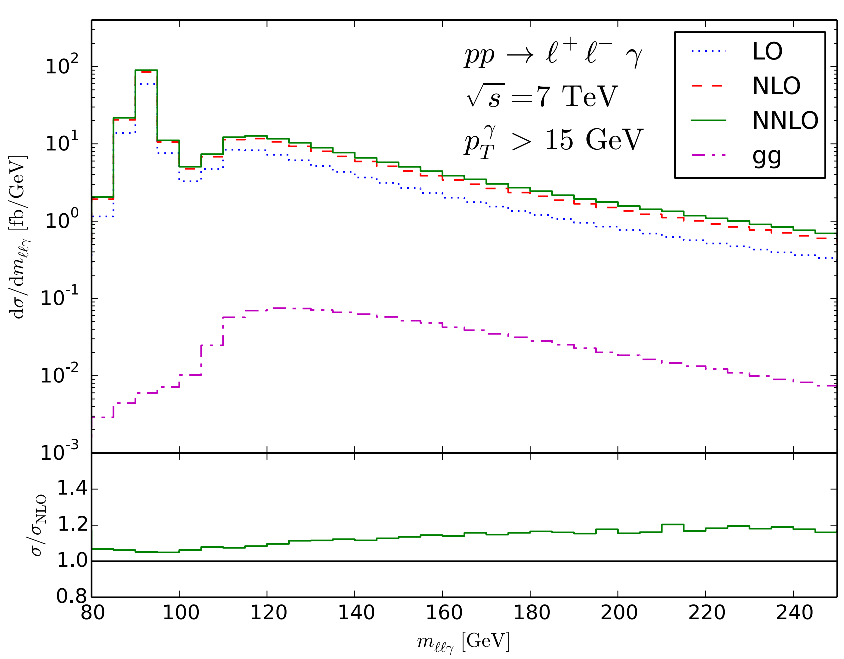
[Catani, Cieri, de Florian, Ferrera, Grazzini '12], [Campbell, Ellis, Li, Williams '16], [Grazzini, Kallweit, MW '17]

- 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

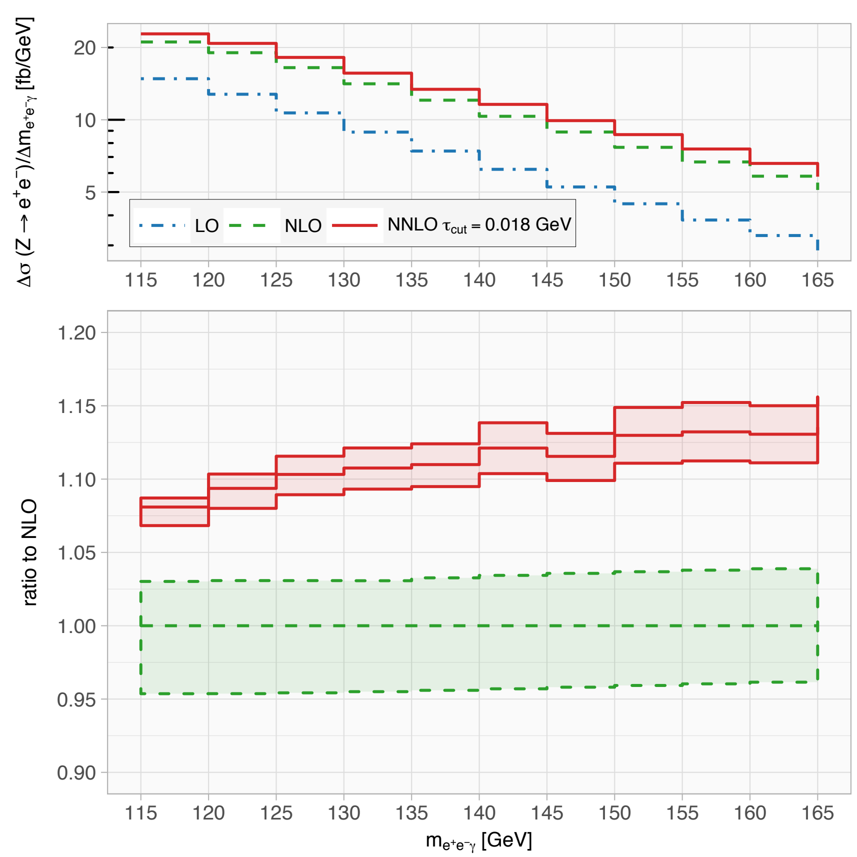


Zγ - inclusive/on-shell and differential/off-shell

[Grazzini, Kallweit, Rathlev '15]



[Campbell, Neumann, Williams '17]

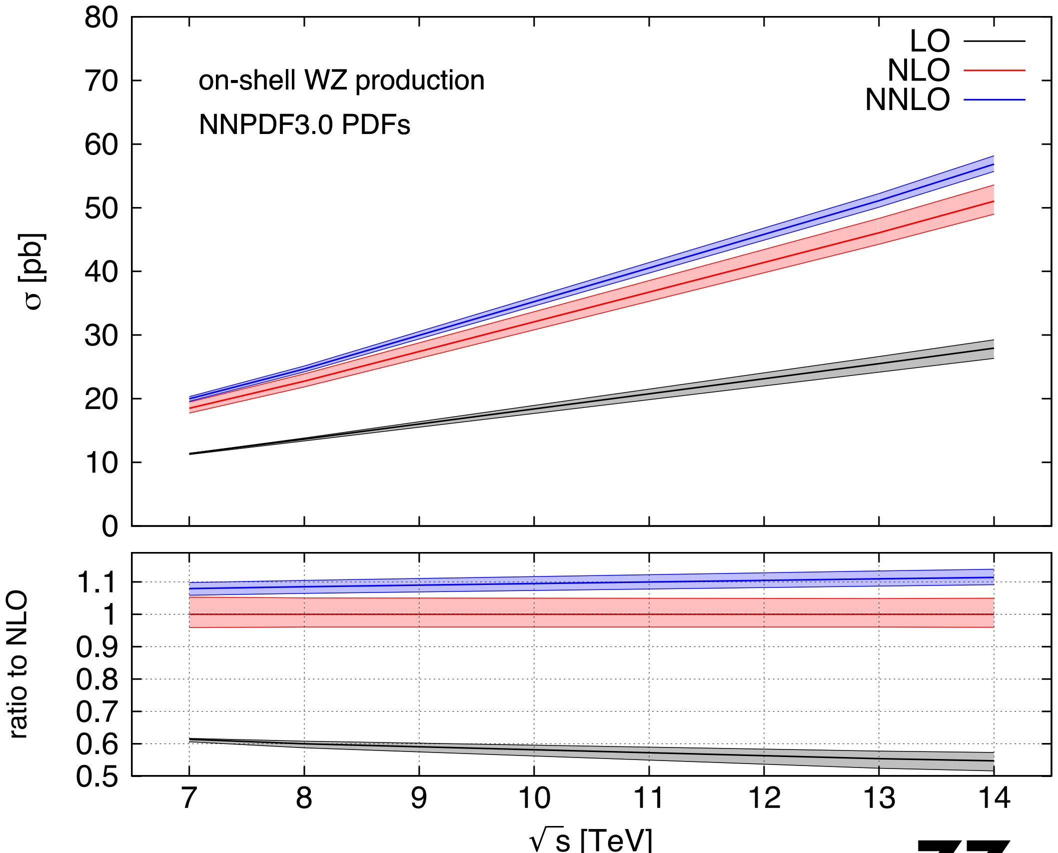


[Grazzini, Kallweit, MW '17]

process (${process_id})	$\sigma^{\mathrm{extrapolated}}_{\mathrm{NNLO}}$	K_{NLO}	K_{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%

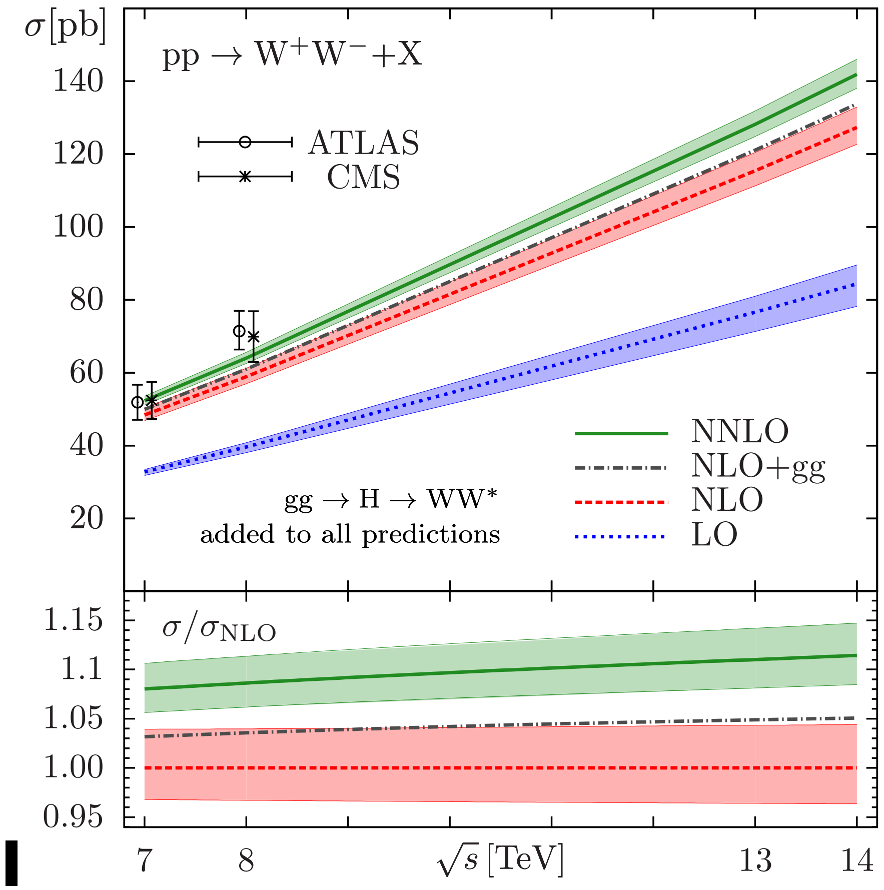
WZ - inclusive/on-shell

[Grazzini, Kallweit, Rathlev, MW '16]



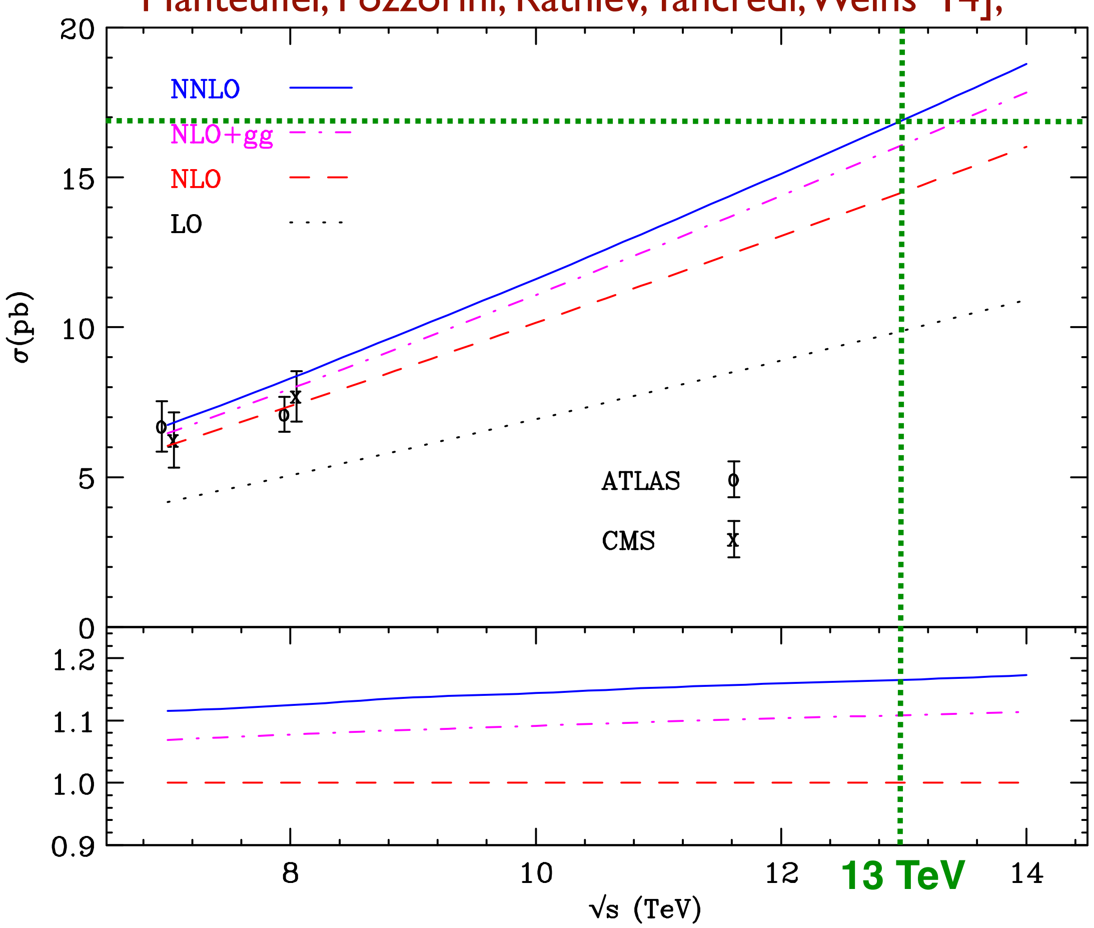
WW - inclusive/on-shell

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



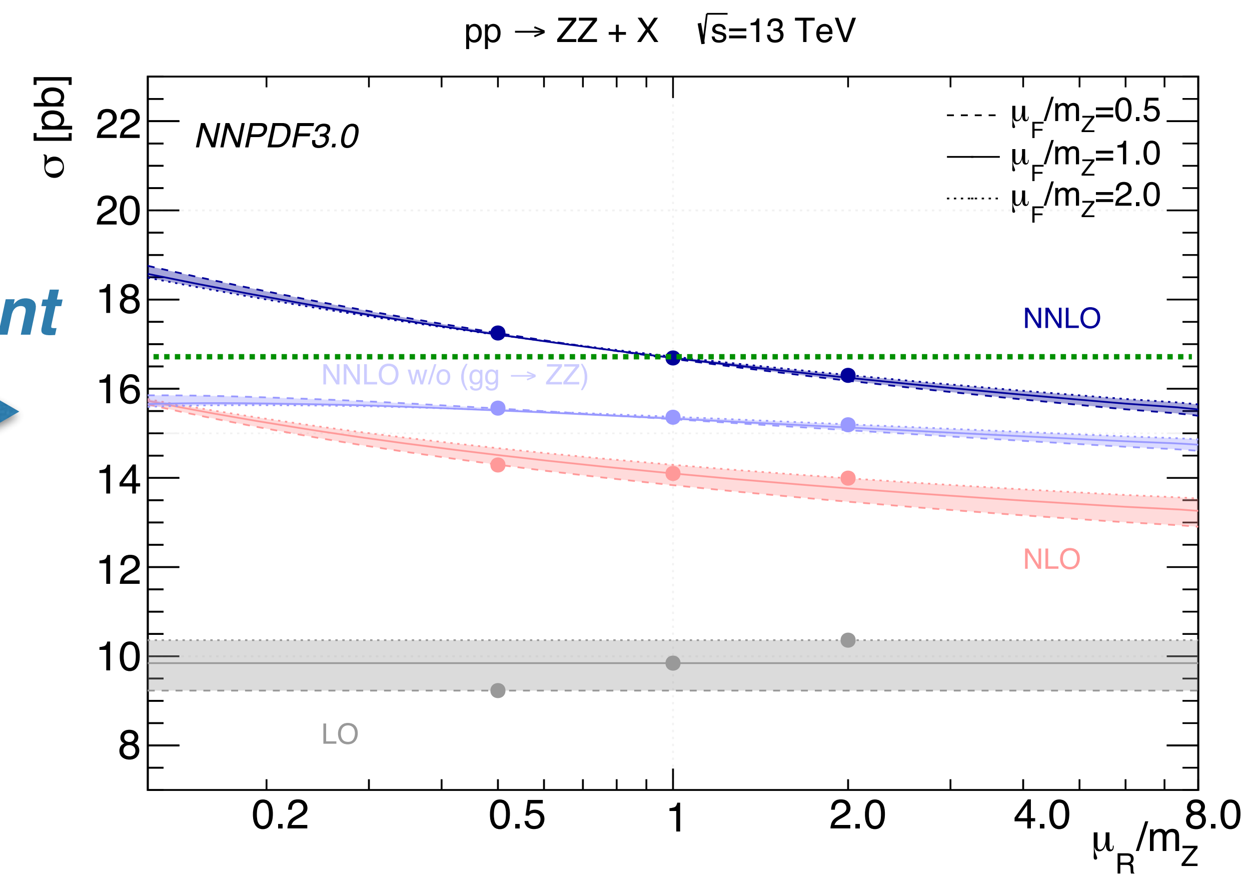
ZZ - inclusive/on-shell

[Cascioli, Gehrmann, Grazzini, Kallweit, Maierhöfer, Manteuffel, Pozzorini, Rathlev, Tancredi, Weihs '14];



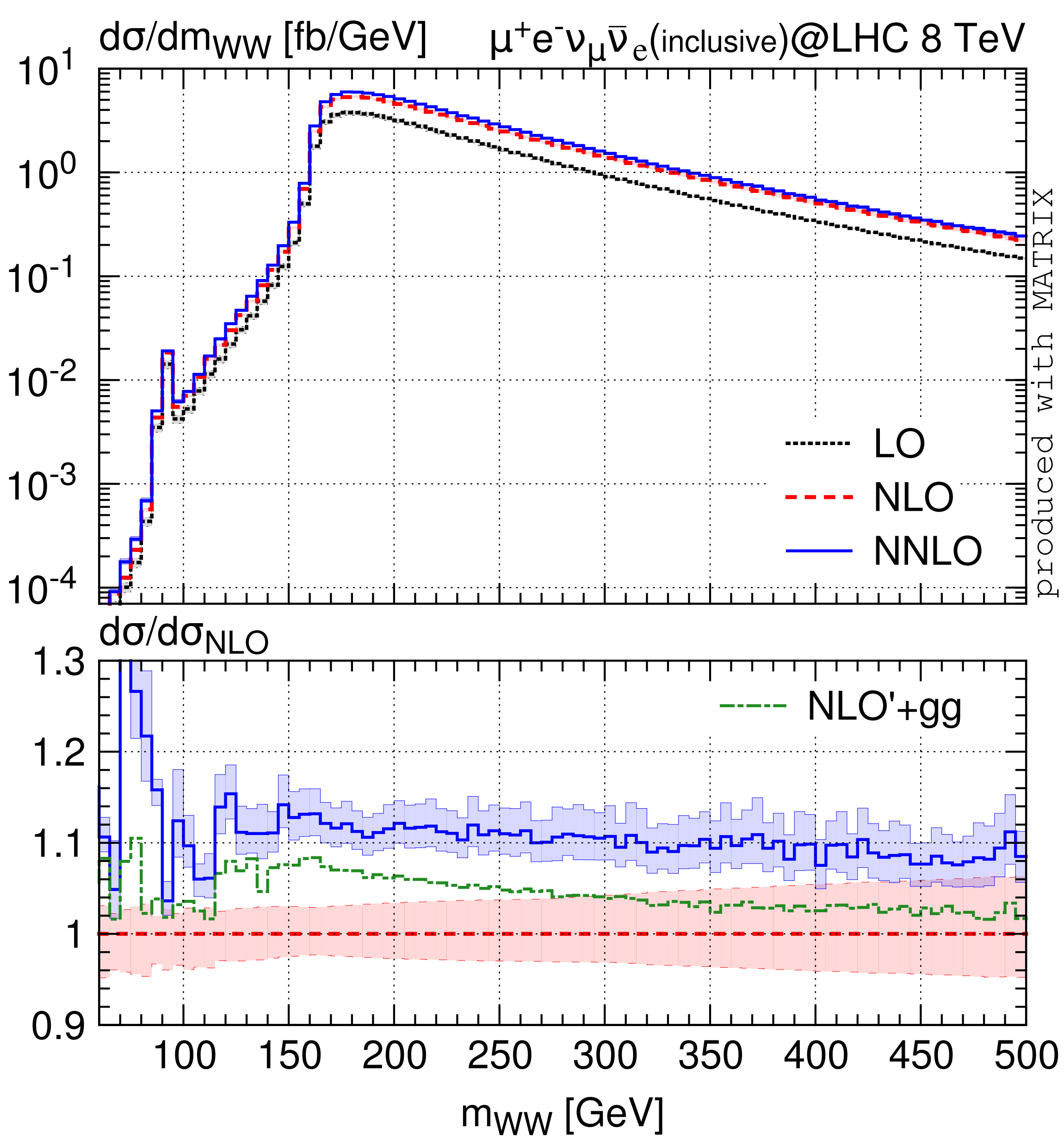
in well agreement

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



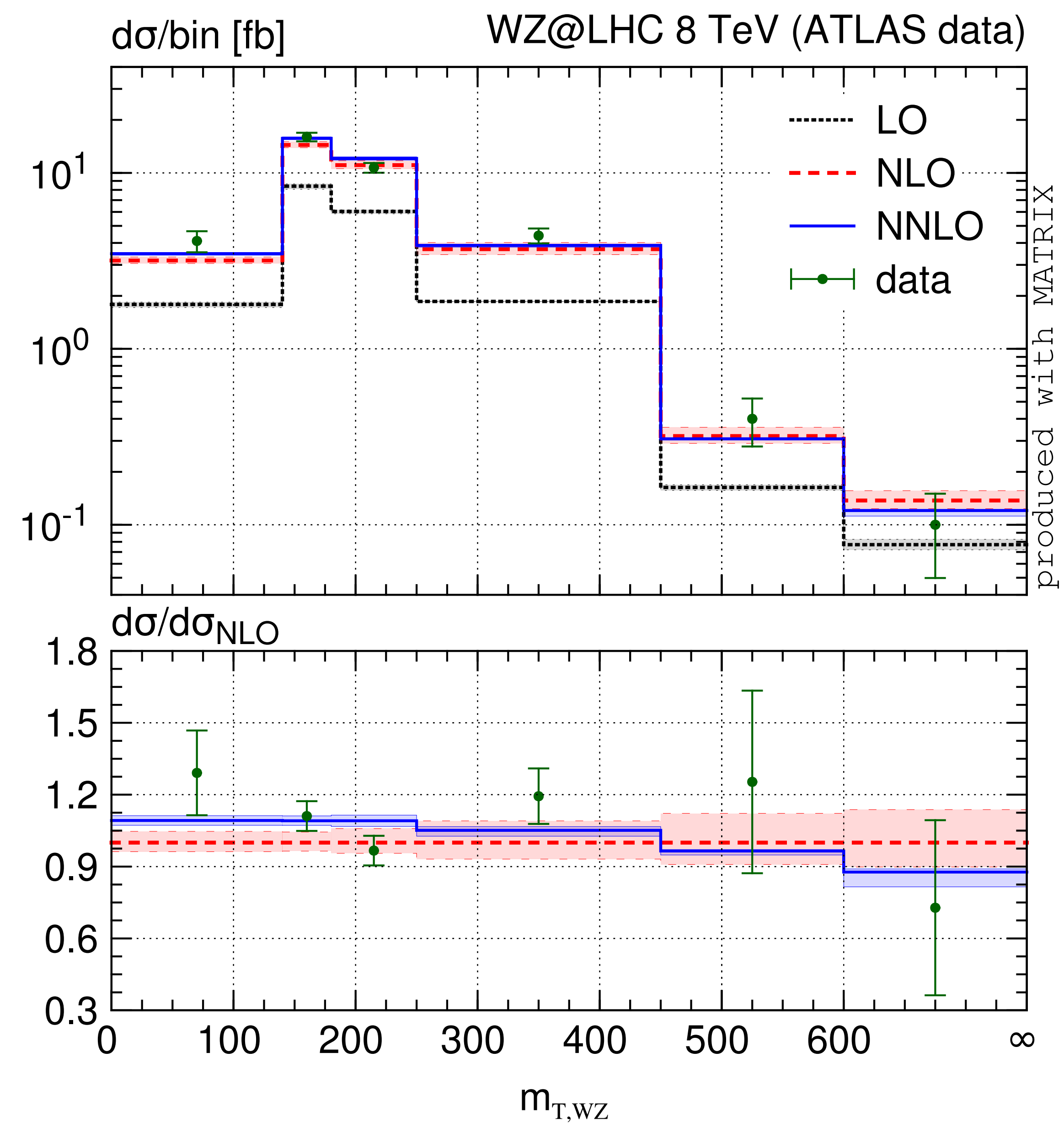
WW - differential/off-shell

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



WZ - differential/off-shell

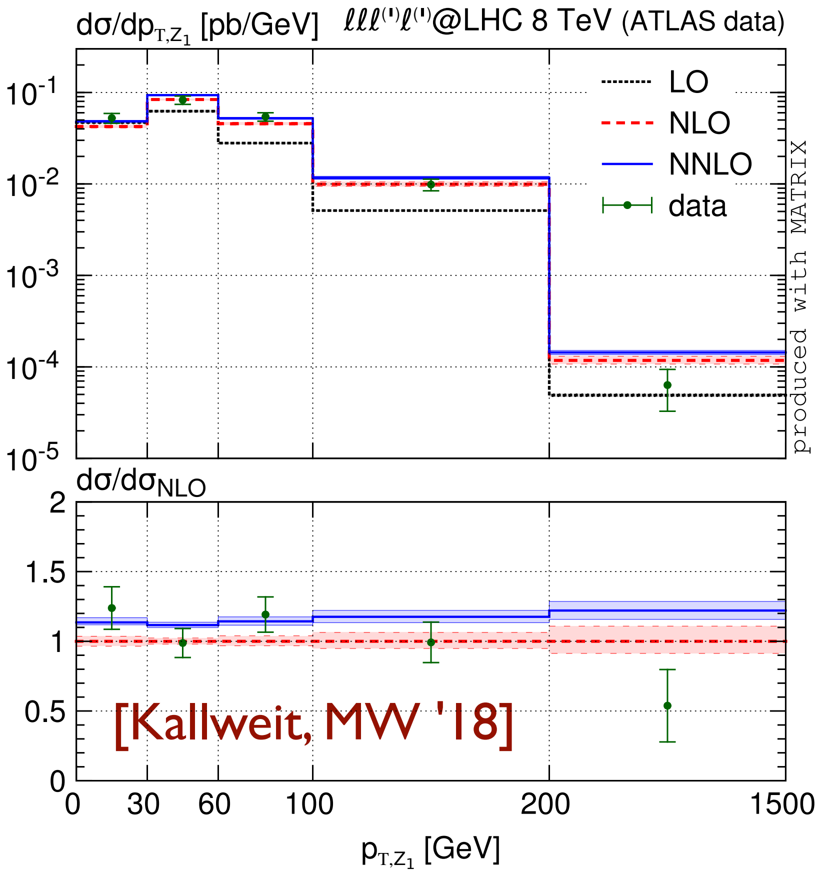
[Grazzini, Kallweit, Rathlev, MW '17]

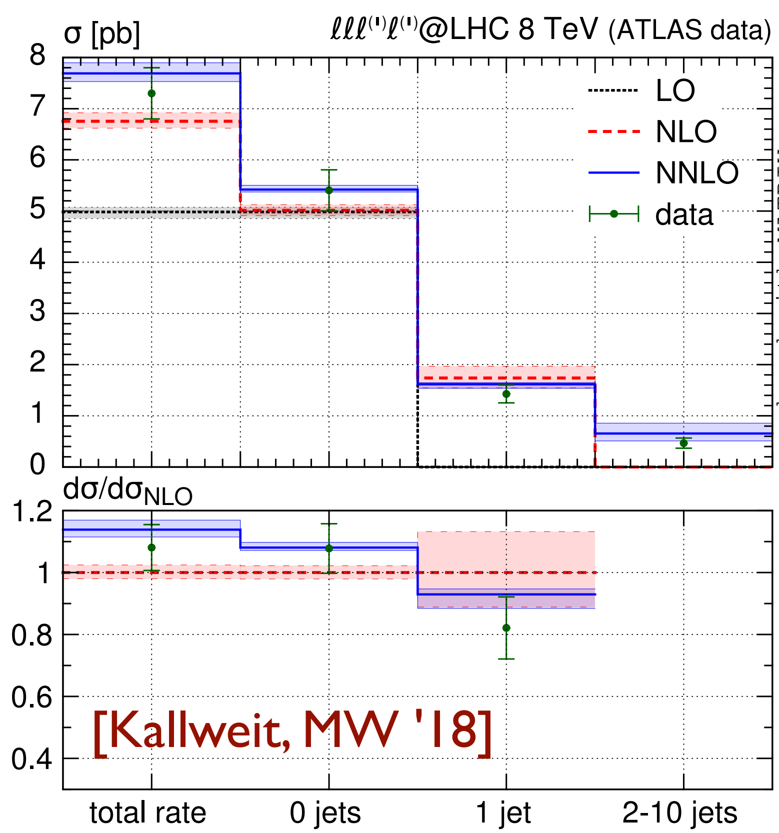


ZZ - differential/off-shell

$ZZ \to 4\ell$

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

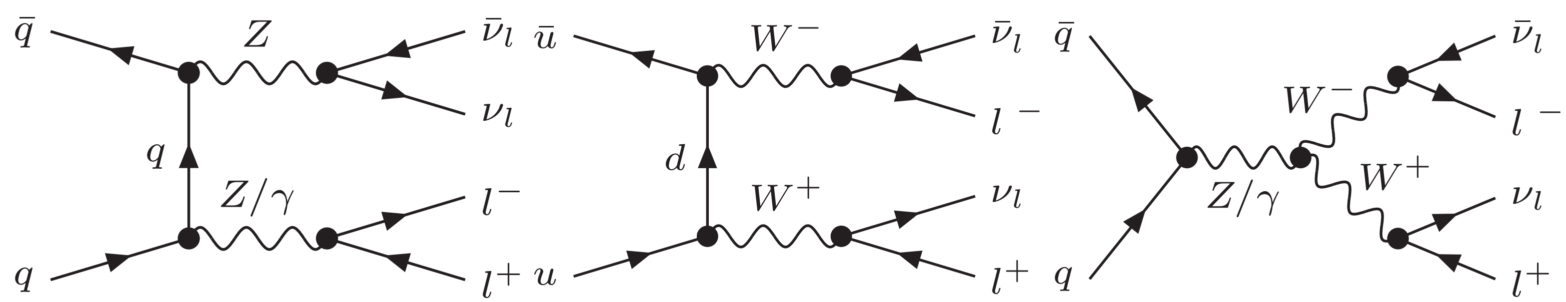




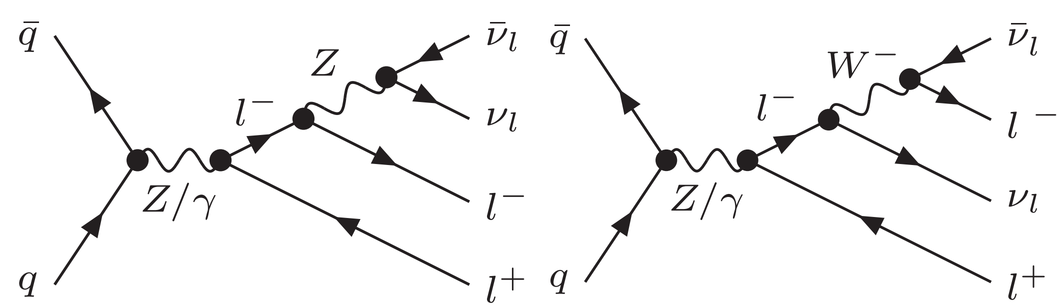
NEW: $ZZ/WW \to \ell\ell + E_{T,miss}$

[Kallweit, MW '18]

- mixes ZZ and WW topologies:



(pp→**ZZ/γ*Z/WW**→$\ell\ell$ νν)

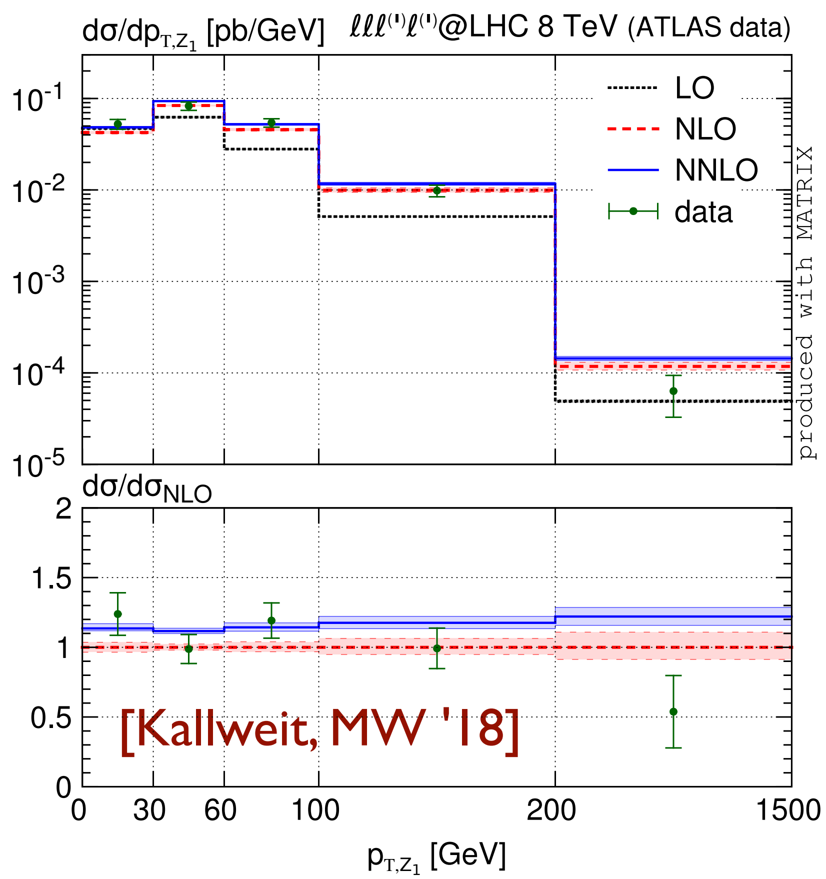


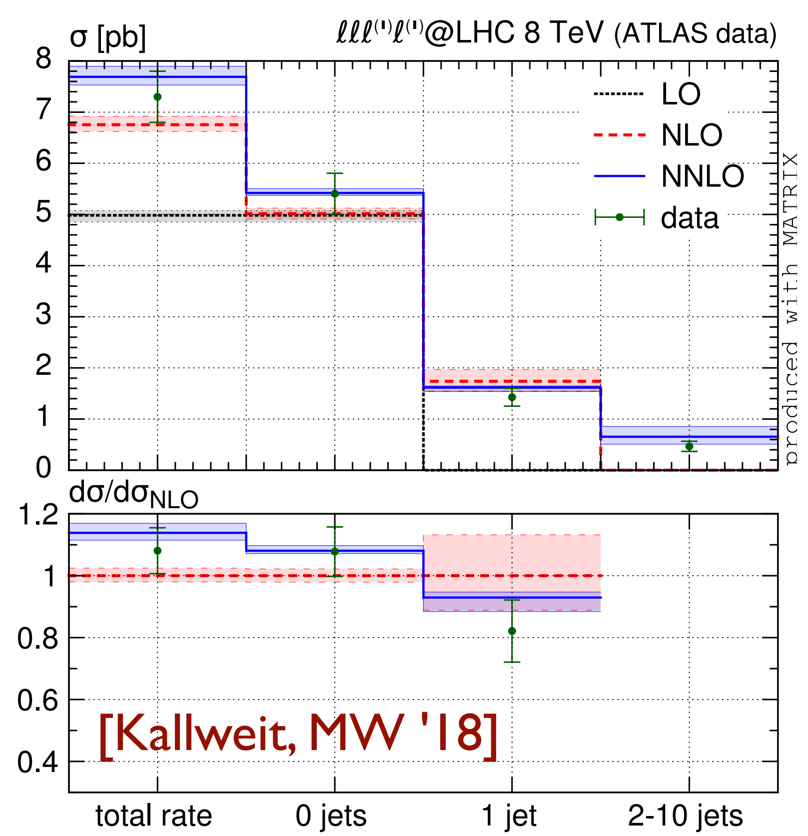
(pp→**Z/γ***→$\ell\ell$ **Z**/ℓν **W**→$\ell\ell$ νν)

ZZ - differential/off-shell

$ZZ \to 4\ell$

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

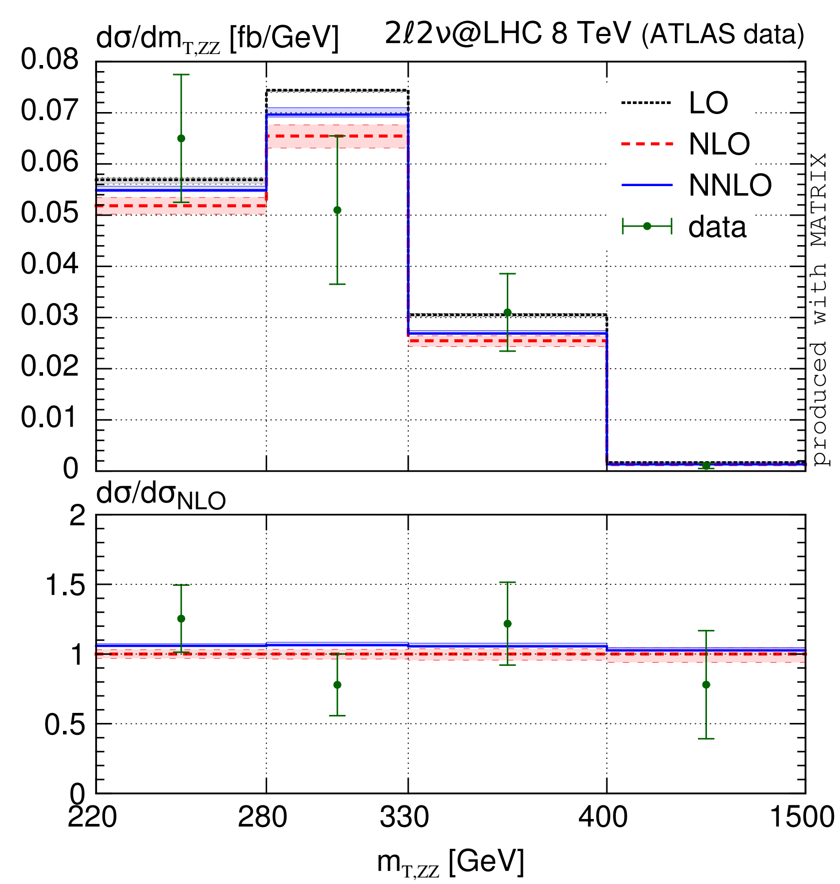


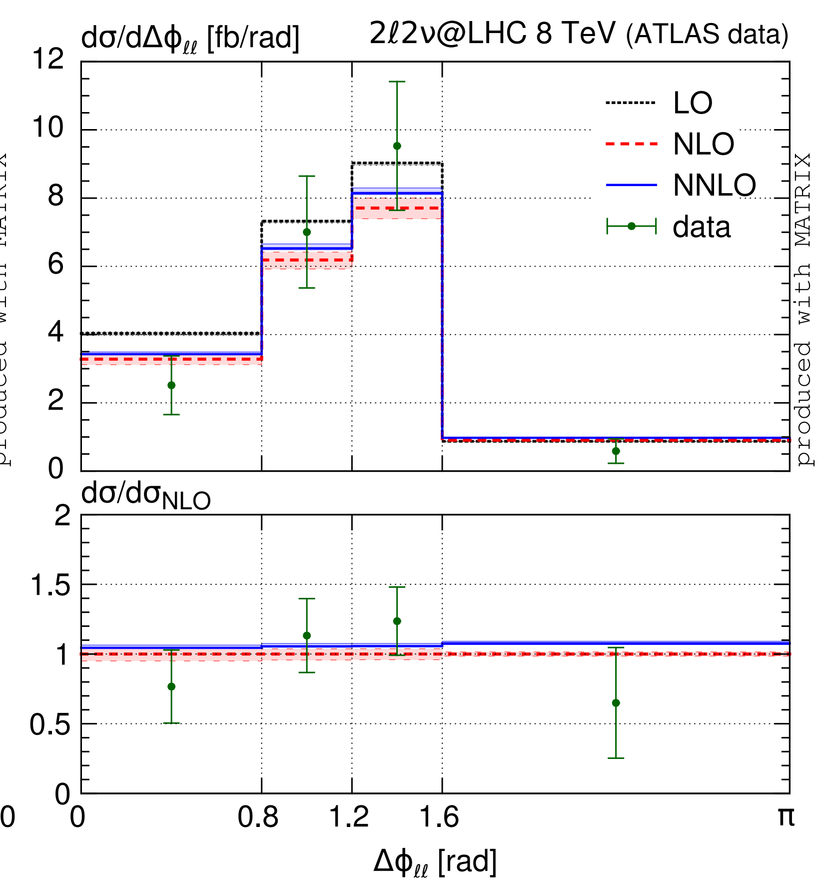


NEW: $ZZ/WW \to \ell\ell + E_{T,miss}$

[Kallweit, MW '18]

channel	$\sigma_{\rm LO}$ [fb]	$\sigma_{\rm NLO}$ [fb]	$\sigma_{\rm NNLO}$ [fb]	$\sigma_{\rm ATLAS}$ [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	$4982(0)^{+1.9\%}_{-2.7\%}$	$6754(2)^{+2.4\%}_{-2.0\%}$	$7690(5)^{+2.7\%}_{-2.1\%}$	$7300\ ^{+400}_{-400}(\text{stat})\ ^{+300}_{-300}(\text{syst})\ ^{+200}_{-100}(\text{lumi})$

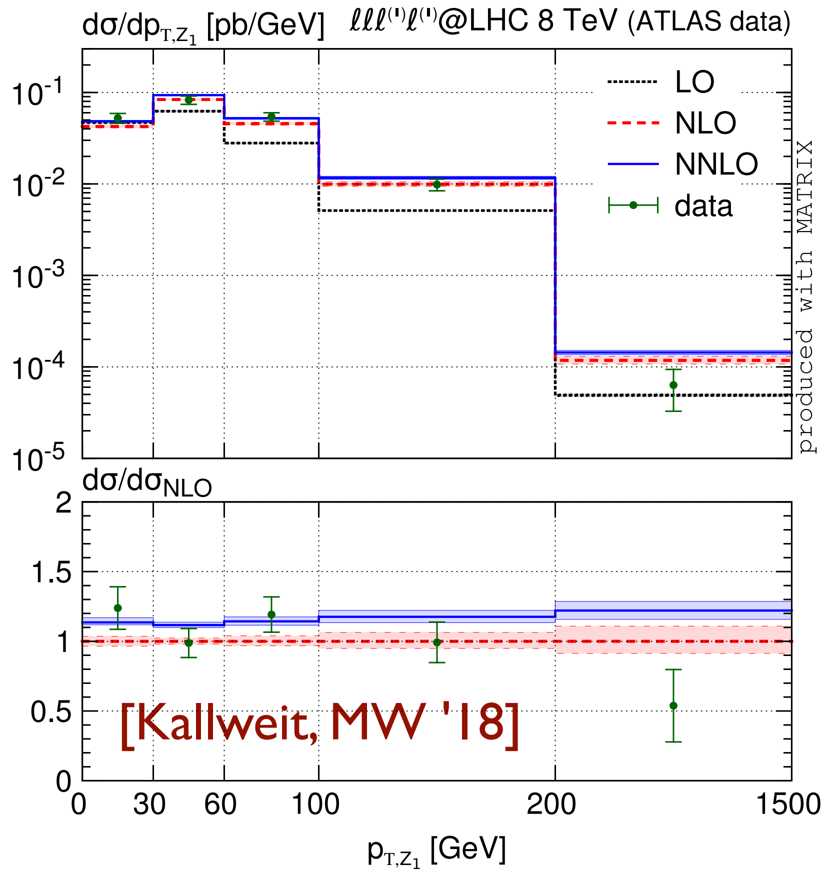


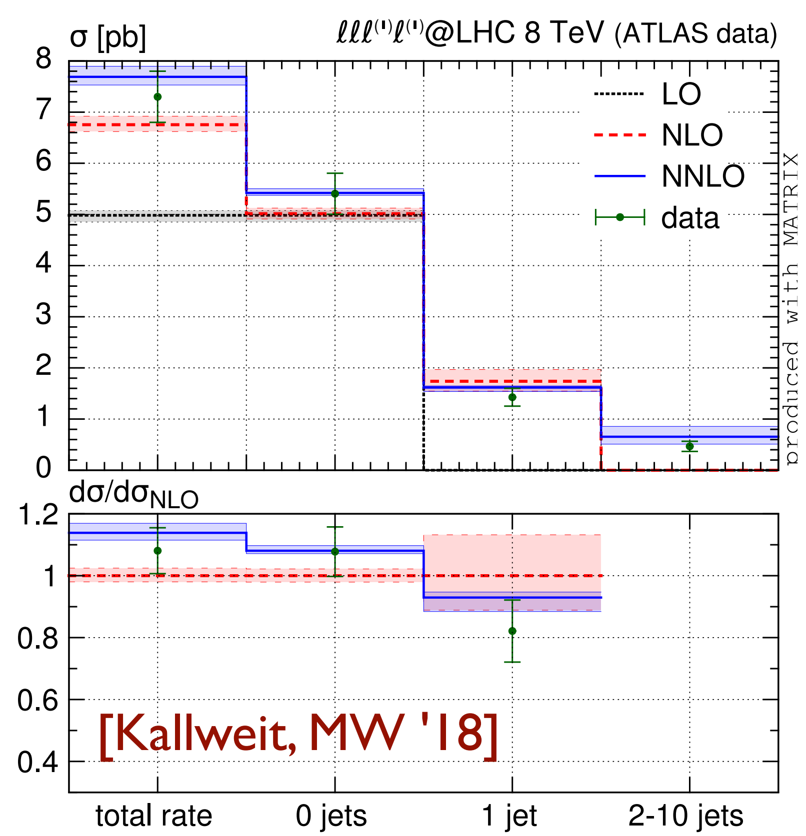


ZZ - differential/off-shell

$ZZ \rightarrow 4\ell$

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





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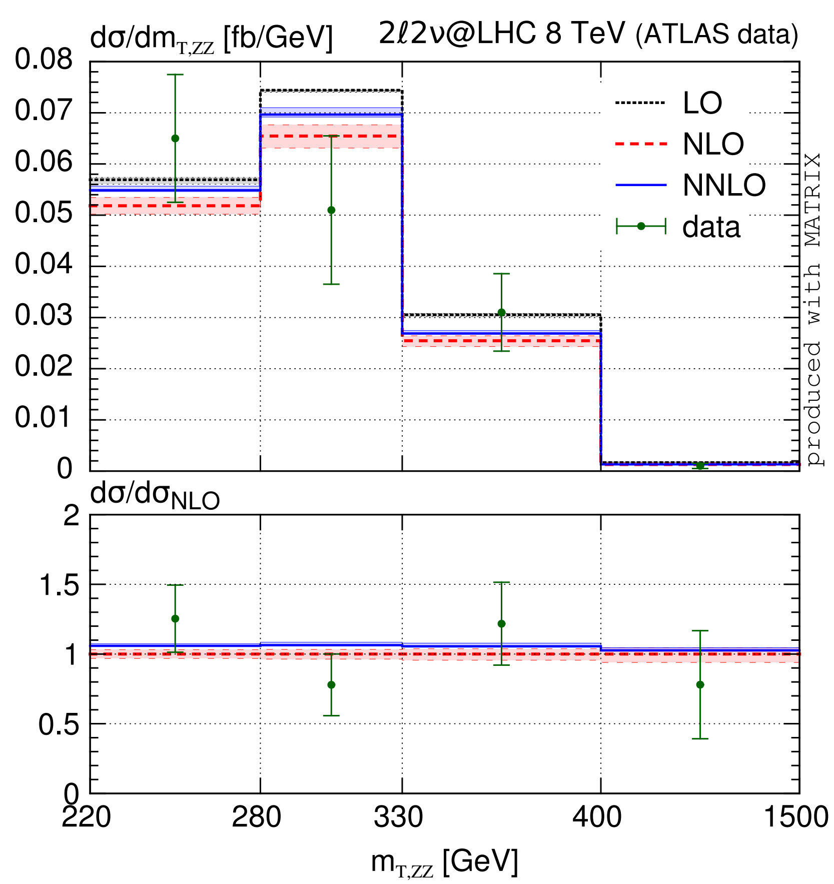
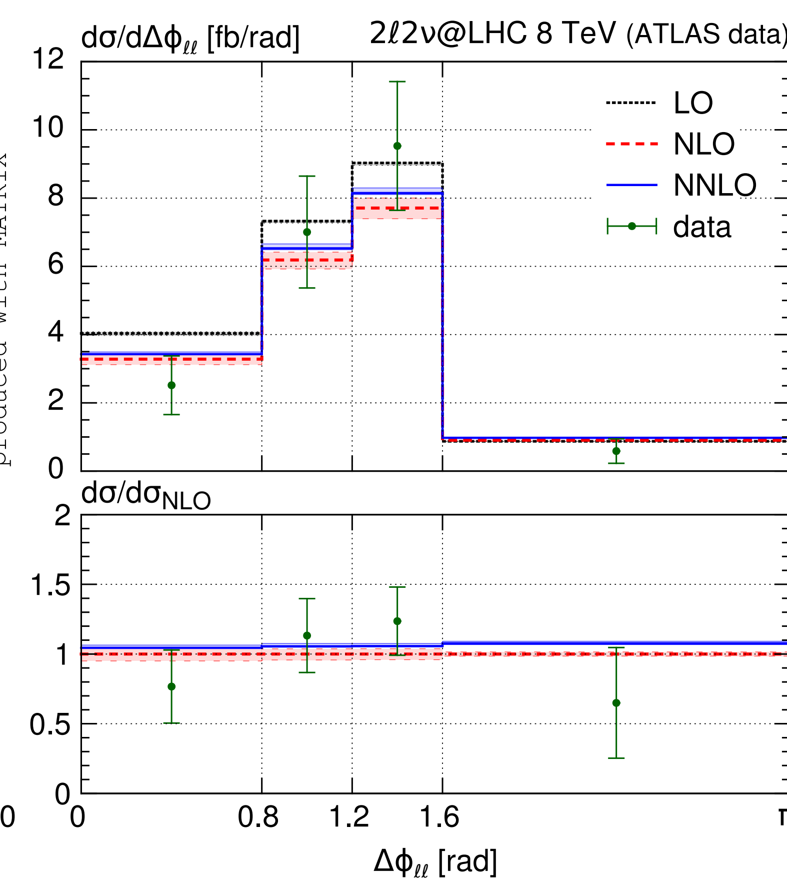
Excellent agreement between NNLO and data





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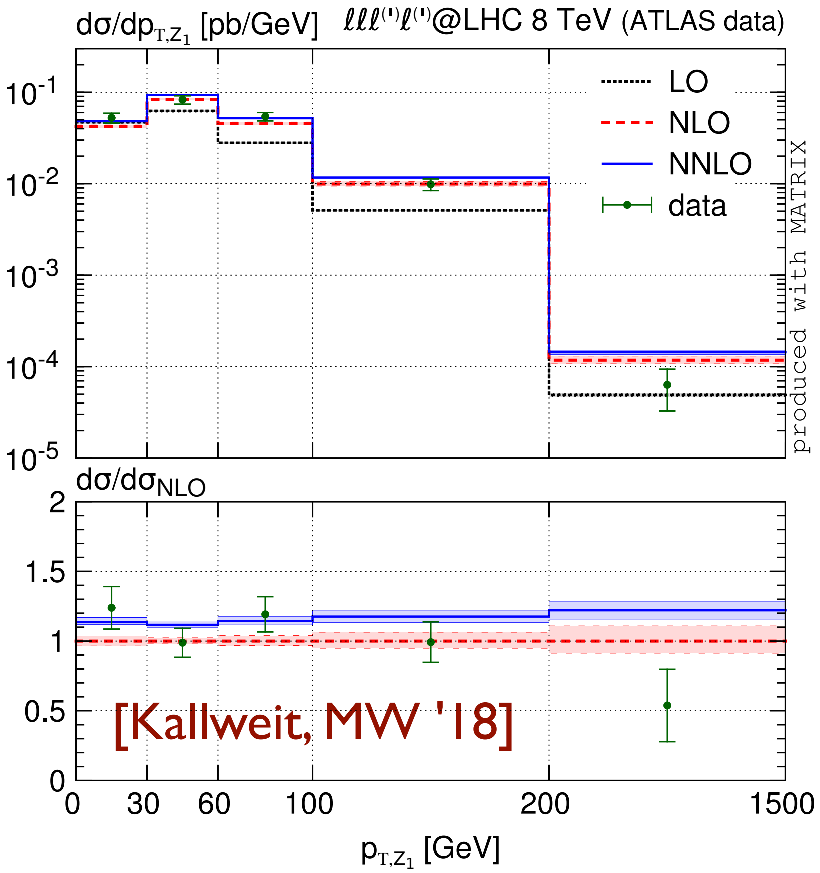
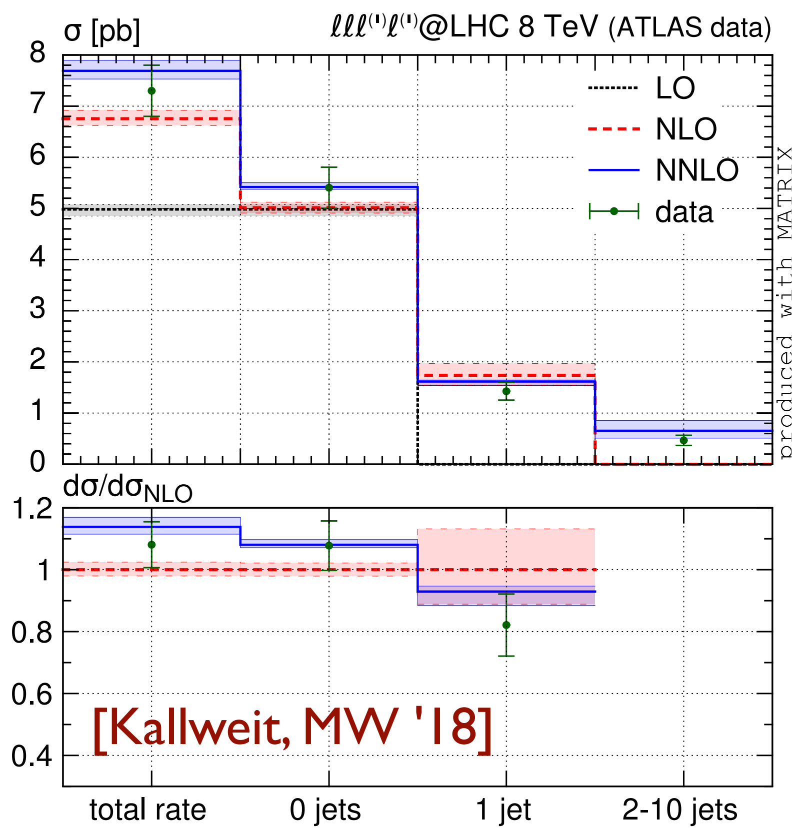
[Grazzini, Kallweit, Rathlev '15], [Kallweit, MW '18]





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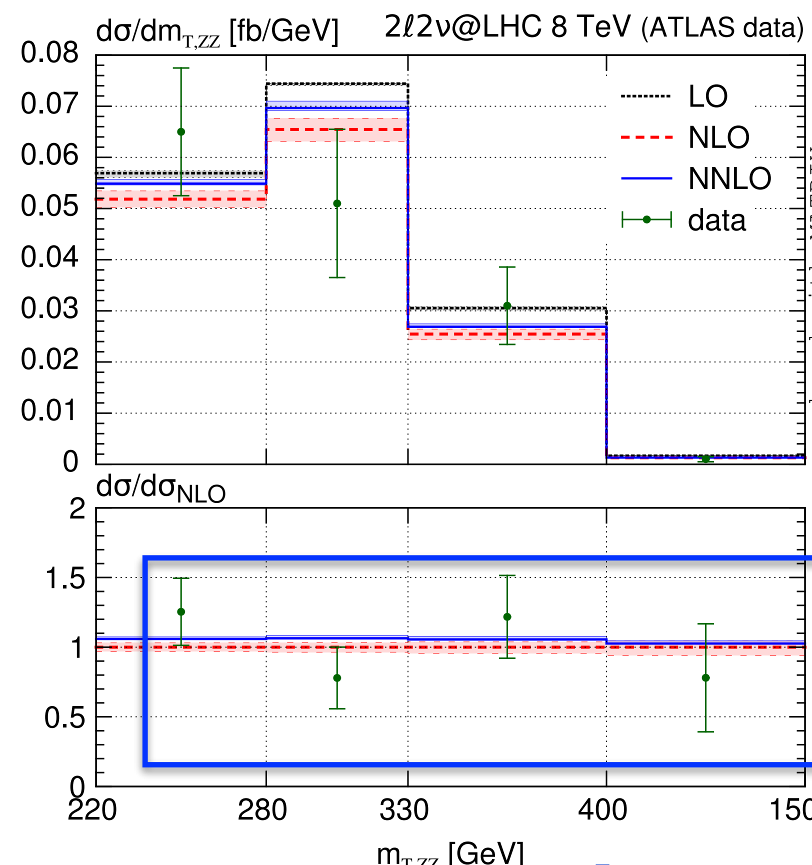

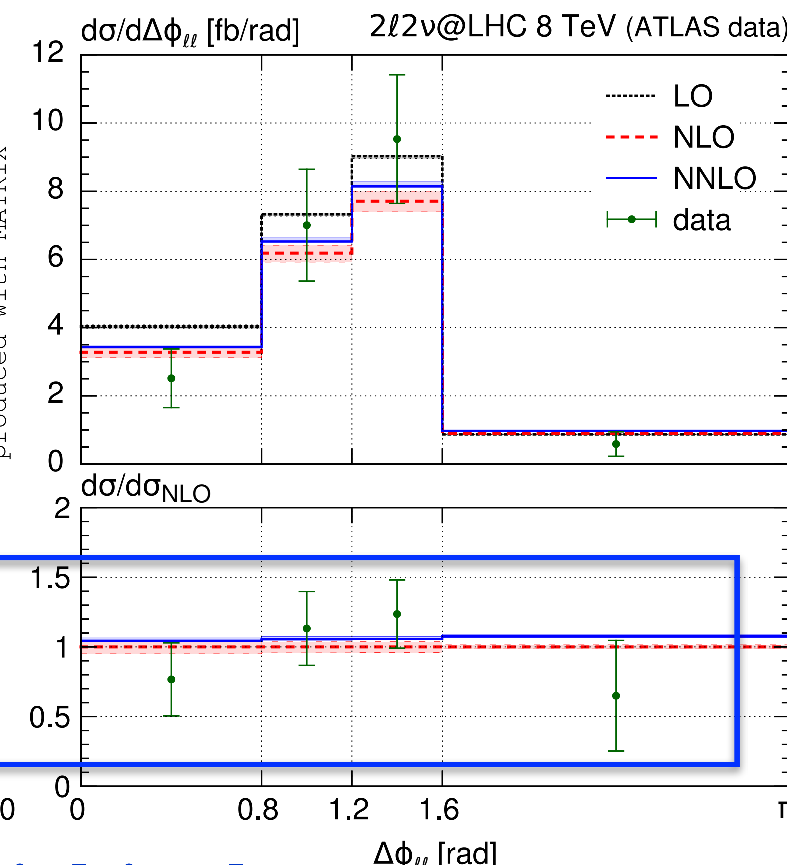

data within 1σ

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

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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-chaNnel Integrator at Swiss (CH) precision

q_T subtraction $\Leftrightarrow$ q_T resummation

NNLO

NNLL

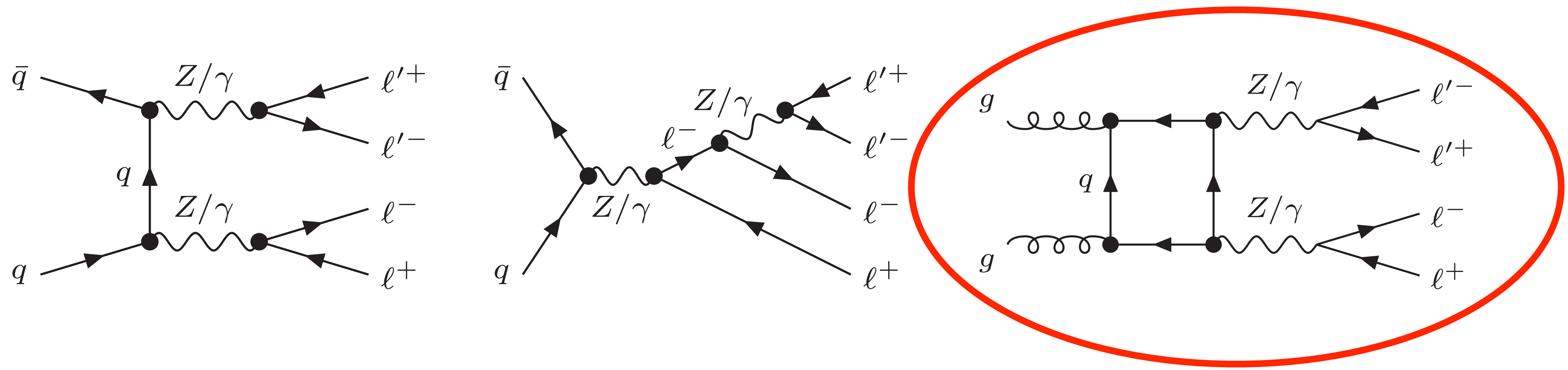
Matrix

Munich Automates qT Subtraction and Resummation to Integrate X-sections.

Recent developments for VV at the QCD front

gg→4ℓ (ZZ) and gg→2ℓ2ν (WW) at NLO

[Grazzini, Kallweit, MW, Yook '18] and [Grazzini, Kallweit, MW, Yook 'to appear]



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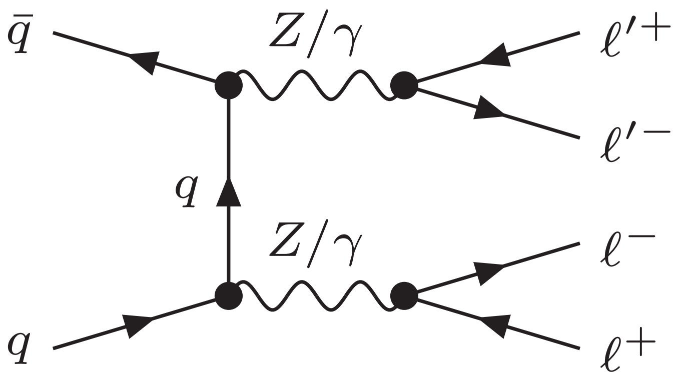
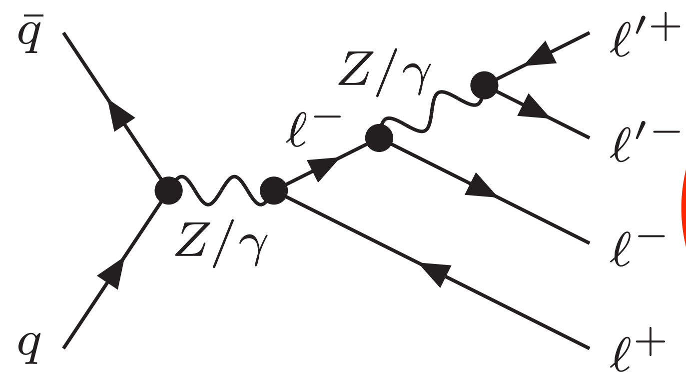
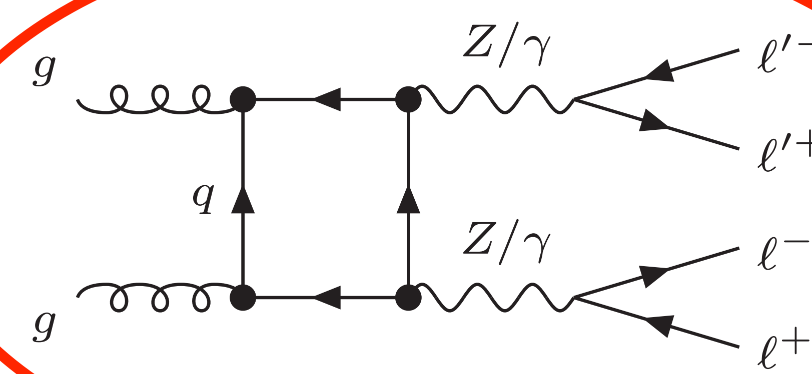


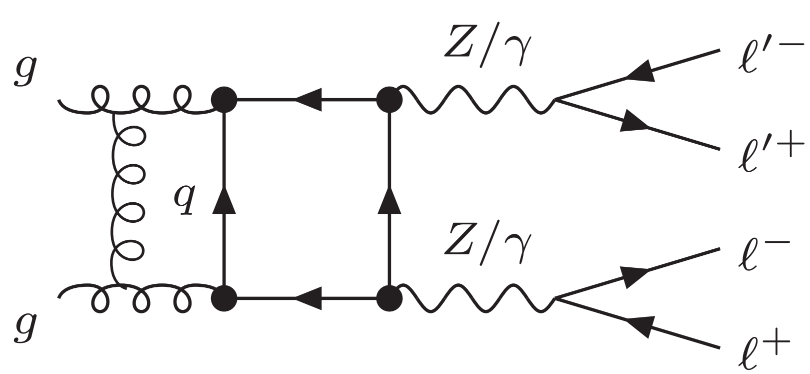




gg NLO:

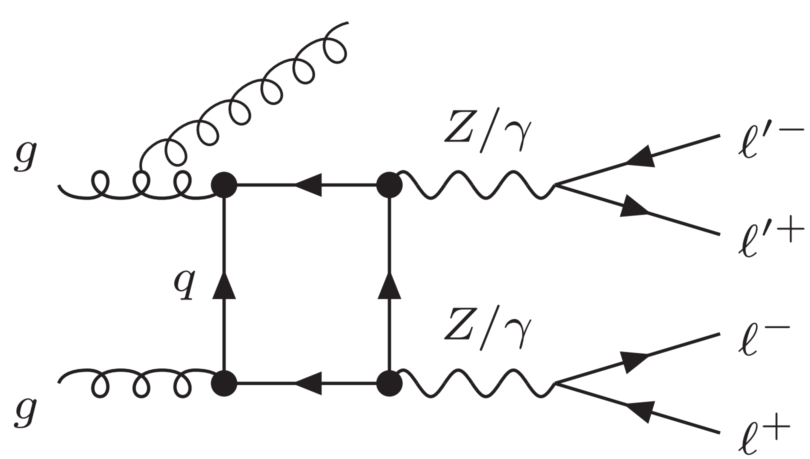
see also:
[Caola, Melnikov, Röntsch, Tancredi '15 '16]

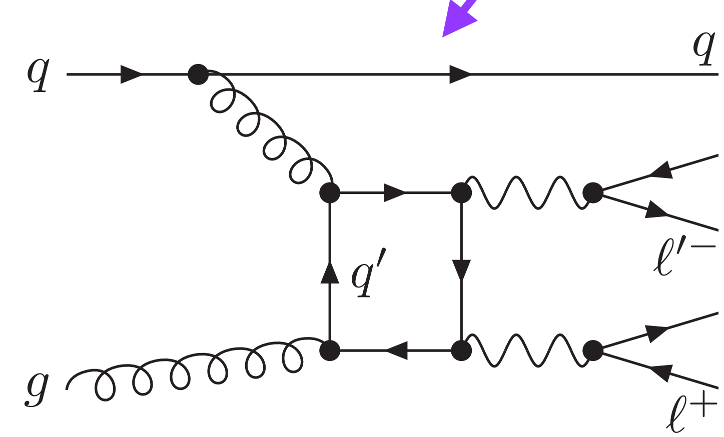
virtuals:



NEW:
qg contributions

reals:





gg→4ℓ (ZZ) at NLO

[Grazzini, Kallweit, MW, Yook '18]

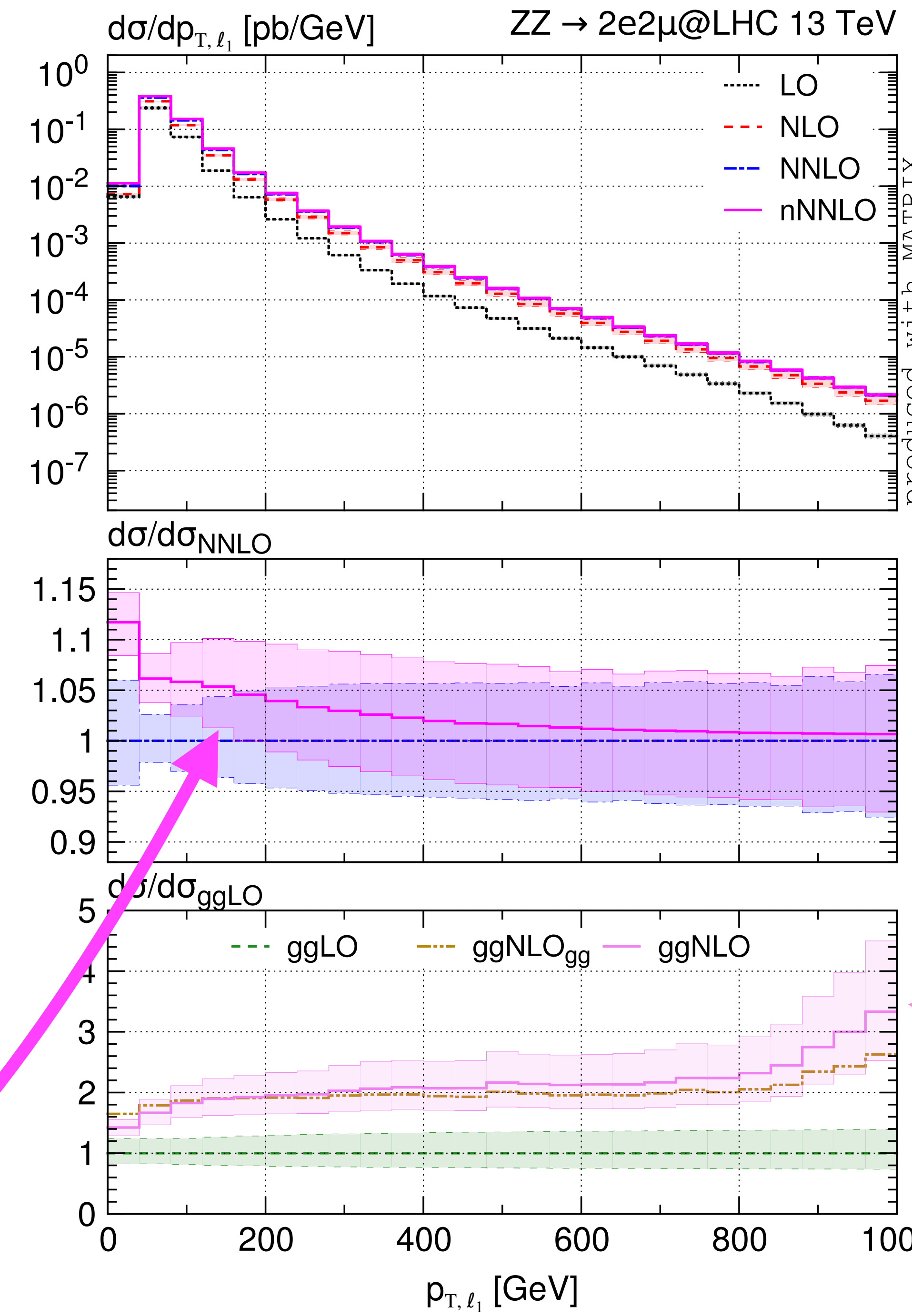
$\sqrt{s}$	8 TeV	13 TeV	8 TeV	13 TeV
	σ [fb]		$\sigma/\sigma_{\mathrm{NLO}} - 1$	
LO	$8.1881(8)^{+2.4\%}_{-3.2\%}$	$13.933(7)^{+5.5\%}_{-6.4\%}$	-27.5%	-29.8%
NLO	$11.2958(4)^{+2.5\%}_{-2.0\%}$	$19.8454(7)^{+2.5\%}_{-2.1\%}$	0%	0%
$q\bar{q}$NNLO	$12.08(3)^{+1.1\%}_{-1.1\%}$	$21.54(2)^{+1.1\%}_{-1.2\%}$	$+6.9\%$	$+8.6\%$
	σ [fb]		$\sigma/\sigma_{\mathrm{ggLO}} - 1$	
ggLO	$0.79354(8)^{+28.2\%}_{-20.9\%}$	$2.0054(2)^{+23.5\%}_{-17.9\%}$	0%	0%
$gg\mathrm{NLO}_{gg}$	$1.4810(9)^{+16.0\%}_{-13.2\%}$	$3.627(3)^{+15.2\%}_{-12.8\%}$	$+86.6\%$	$+80.9\%$
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→4ℓ (ZZ) at NLO

[Grazzini, Kallweit, MW, Yook '18]

$\sqrt{s}$	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

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

NEW: gg→2ℓ2ν (WW) at NLO

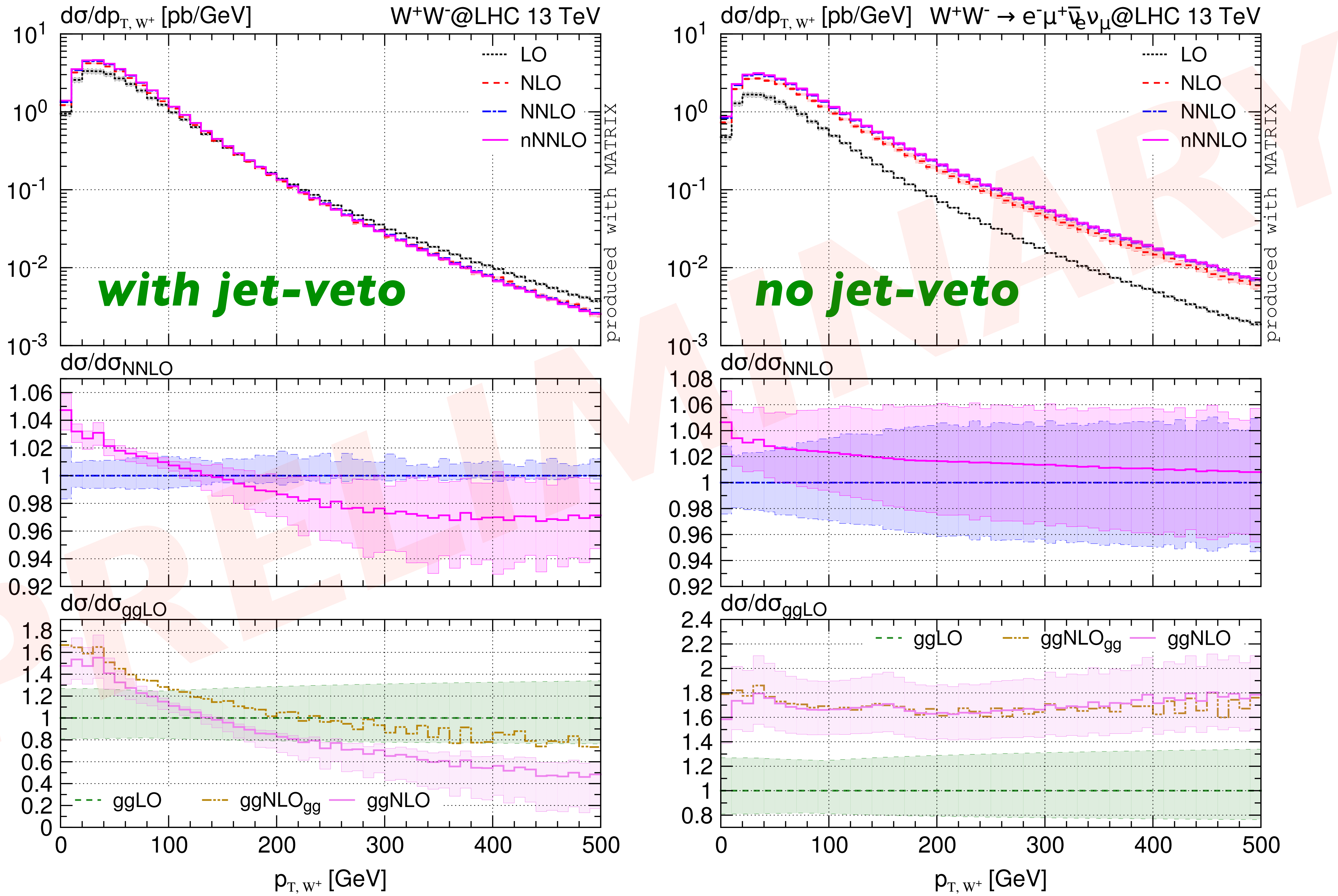
[Grazzini, Kallweit, MW, Yook 'to appear]

$\sqrt{s} = 13$ TeV	jet veto	no jet veto	jet veto	no jet veto
	σ [fb]		$\sigma/\sigma_{\mathrm{NLO}} - 1$	
LO	$284.2(2)^{+5.6\%}_{-6.5\%}$	$284.2(2)^{+5.6\%}_{-6.5\%}$	-15.6%	-43.7%
NLO	$336.6(4)^{+1.6\%}_{-2.0\%}$	$504.6(4)^{+4.1\%}_{-3.3\%}$	0%	0%
$q\bar{q}$NNLO	$337.0(2)^{+0.7\%}_{-0.5\%}$	$559.0(4)^{+2.1\%}_{-2.0\%}$	$+1.2\%$	$+10.8\%$
	σ [fb]		$\sigma/\sigma_{\mathrm{ggLO}} - 1$	
ggLO	$21.96(2)^{+25.7\%}_{-18.4\%}$	$21.96(2)^{+25.7\%}_{-18.4\%}$	0%	0%
$gg\mathrm{NLO}_{gg}$	$31.70(2)^{+10.8\%}_{-10.6\%}$	$38.4(1)^{+15.8\%}_{-13.3\%}$	$+44.4\%$	$+74.7\%$
ggNLO	$28.76(4)^{+7.8\%}_{-9.0\%}$	$37.42(4)^{+15.2\%}_{-12.9\%}$	$+31.0\%$	$+70.4\%$
	σ [fb]		$\sigma/\sigma_{\mathrm{NLO}} - 1$	
NNLO	$359.0(2)^{+1.2\%}_{-0.9\%}$	$581.0(4)^{+2.9\%}_{-2.6\%}$	$+6.7\%$	$+15.1\%$
nNNLO	$365.8(2)^{+0.4\%}_{-0.6\%}$	$596.6(4)^{+2.8\%}_{-2.7\%}$	$+8.7\%$	$+18.2\%$

+2(3)% effect due to NLO correction to gg compared to NNLO with(out) jet veto

NEW: gg→2ℓ2ν (WW) at NLO

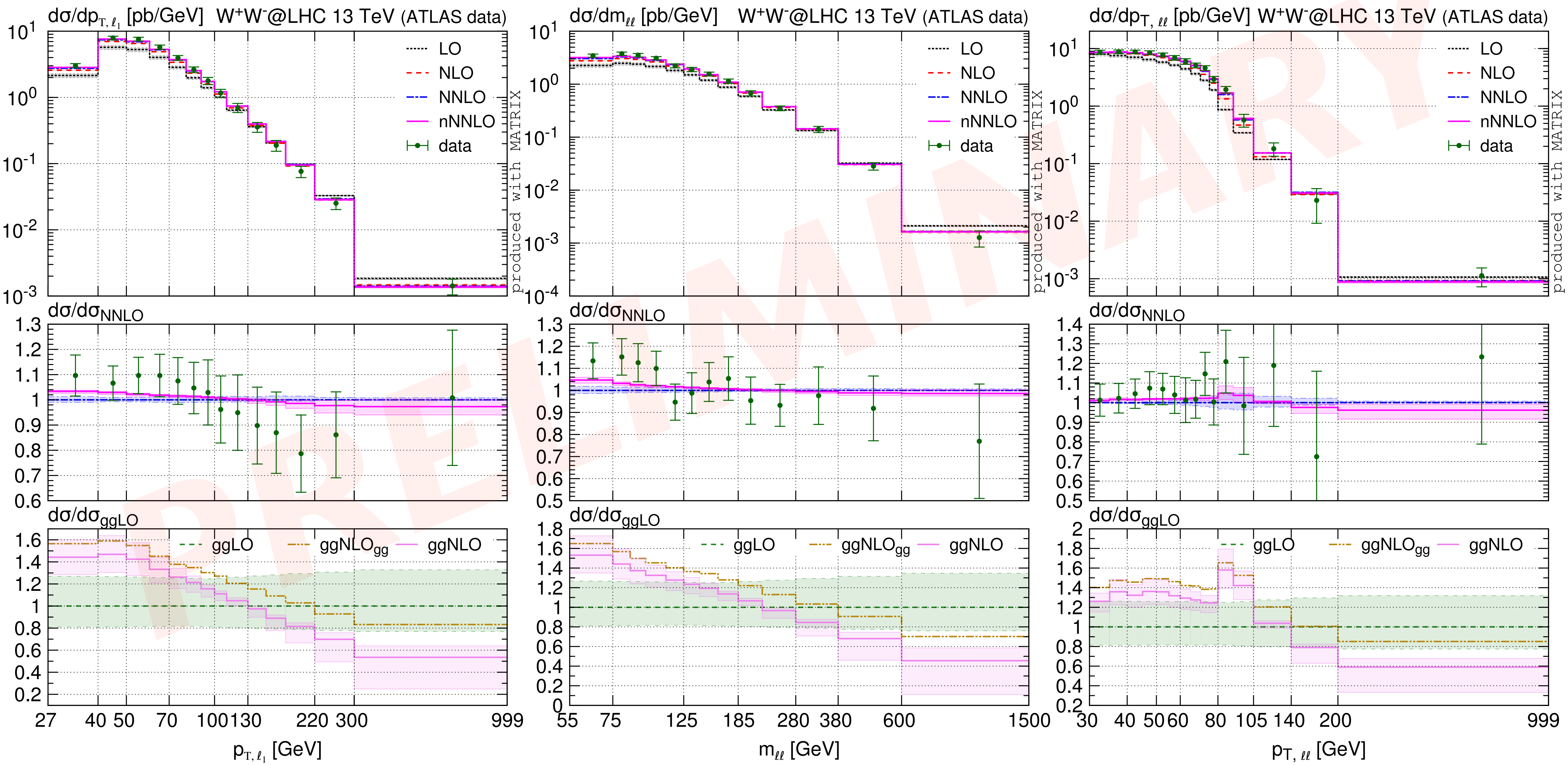
[Grazzini, Kallweit, MW, Yook 'to appear]



shape of nNNLO and NLO gg K-factor strongly affected by jet veto; large impact of newly computed fermionic channels clearly visible

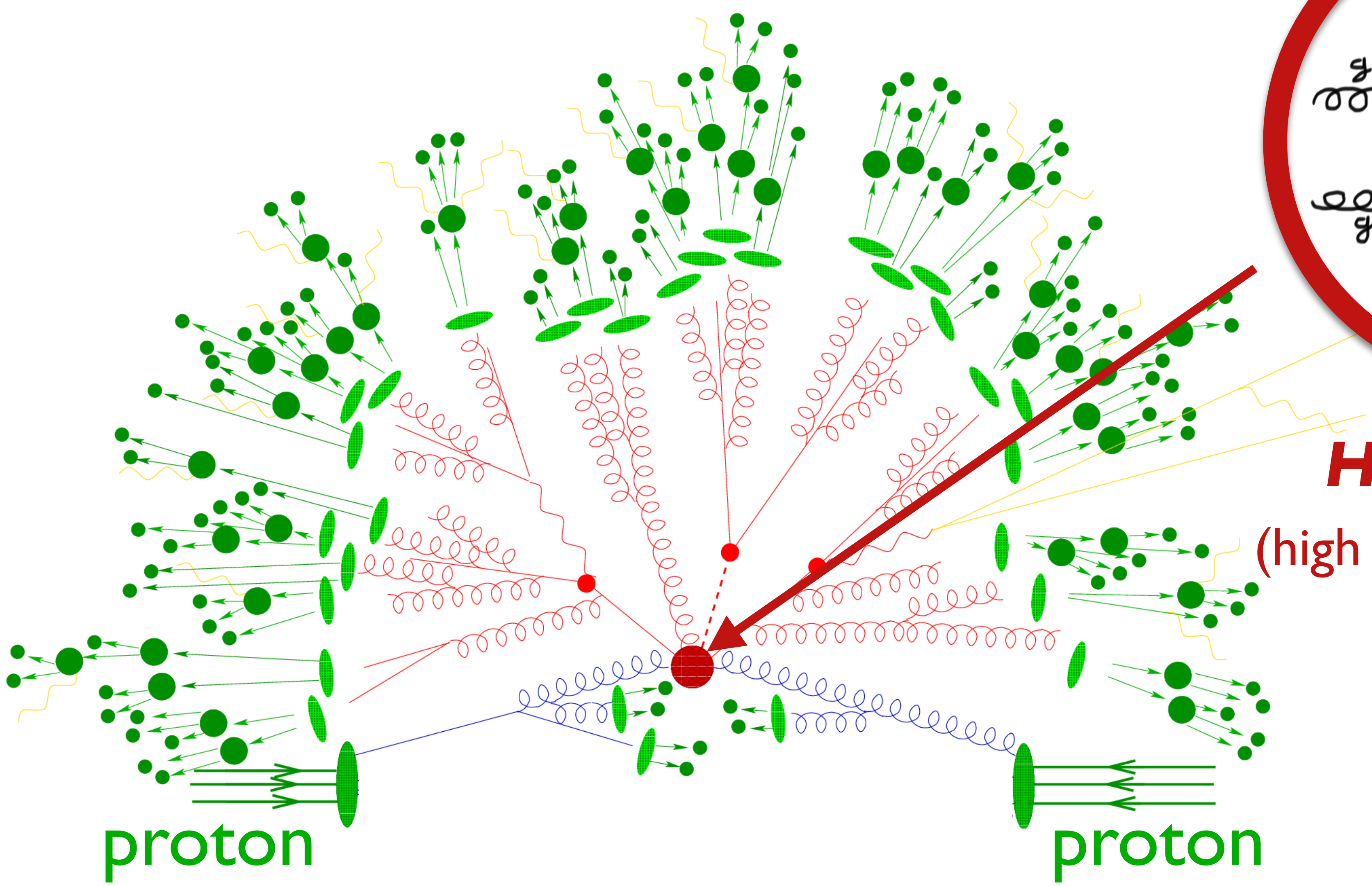
NEW: gg→2ℓ2ν (WW) at NLO

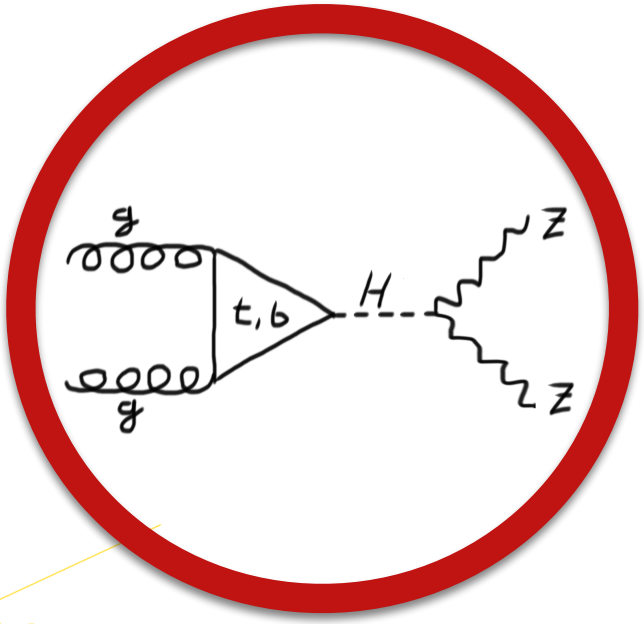
[Grazzini, Kallweit, MW, Yook 'to appear]



good agreement between nNNLO and recent 13 TeV ATLAS data;
tails could further improve due to EW corrections (Jonas Lindert's talk)

Event simulation

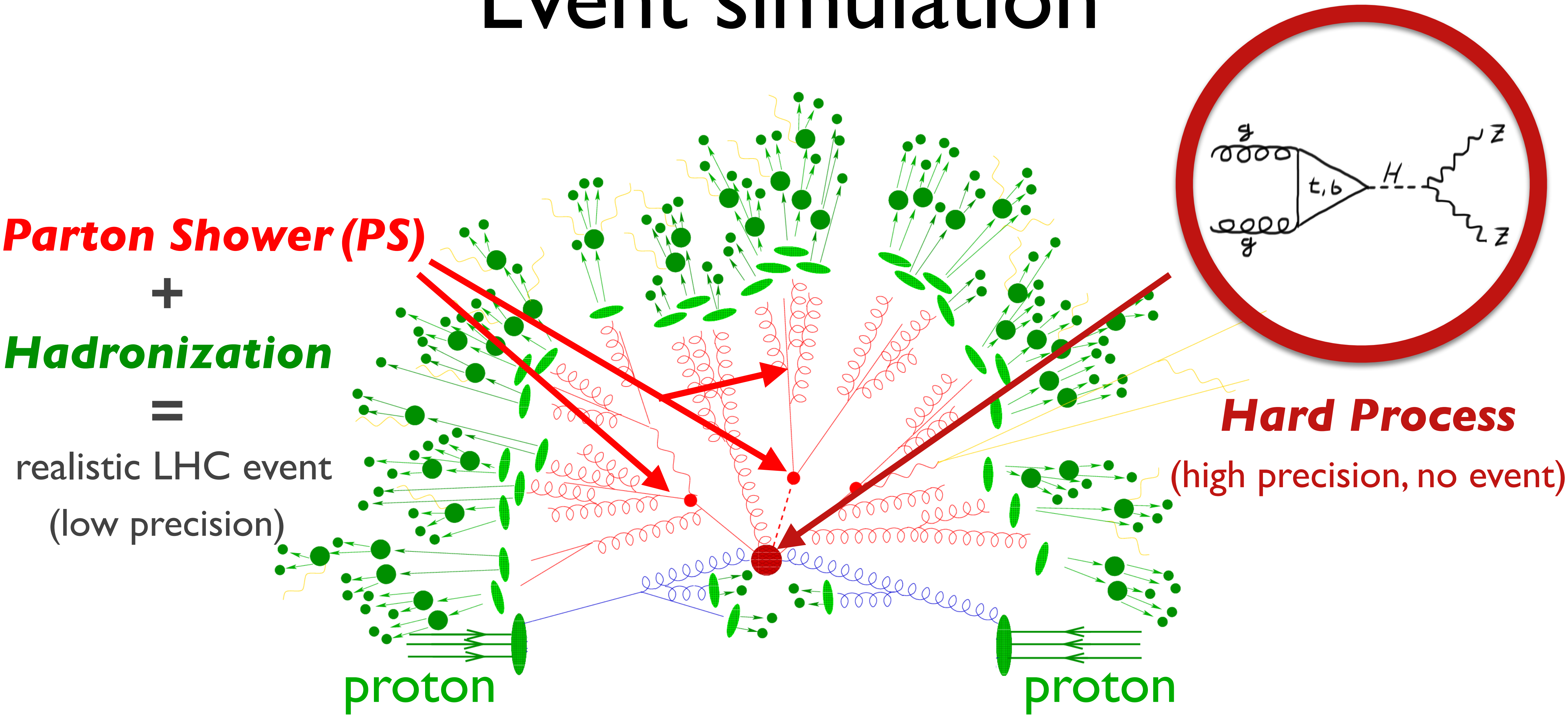




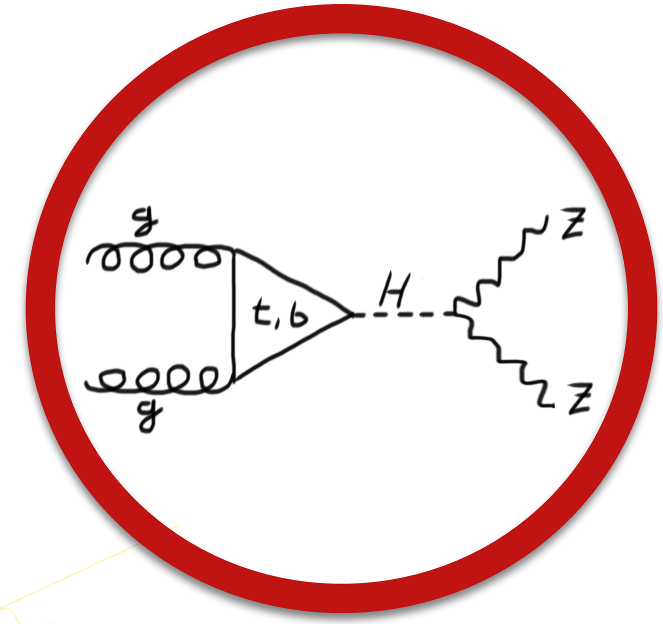
Hard Process

(high precision, no event)

Event simulation



Event simulation



Parton Shower (PS)

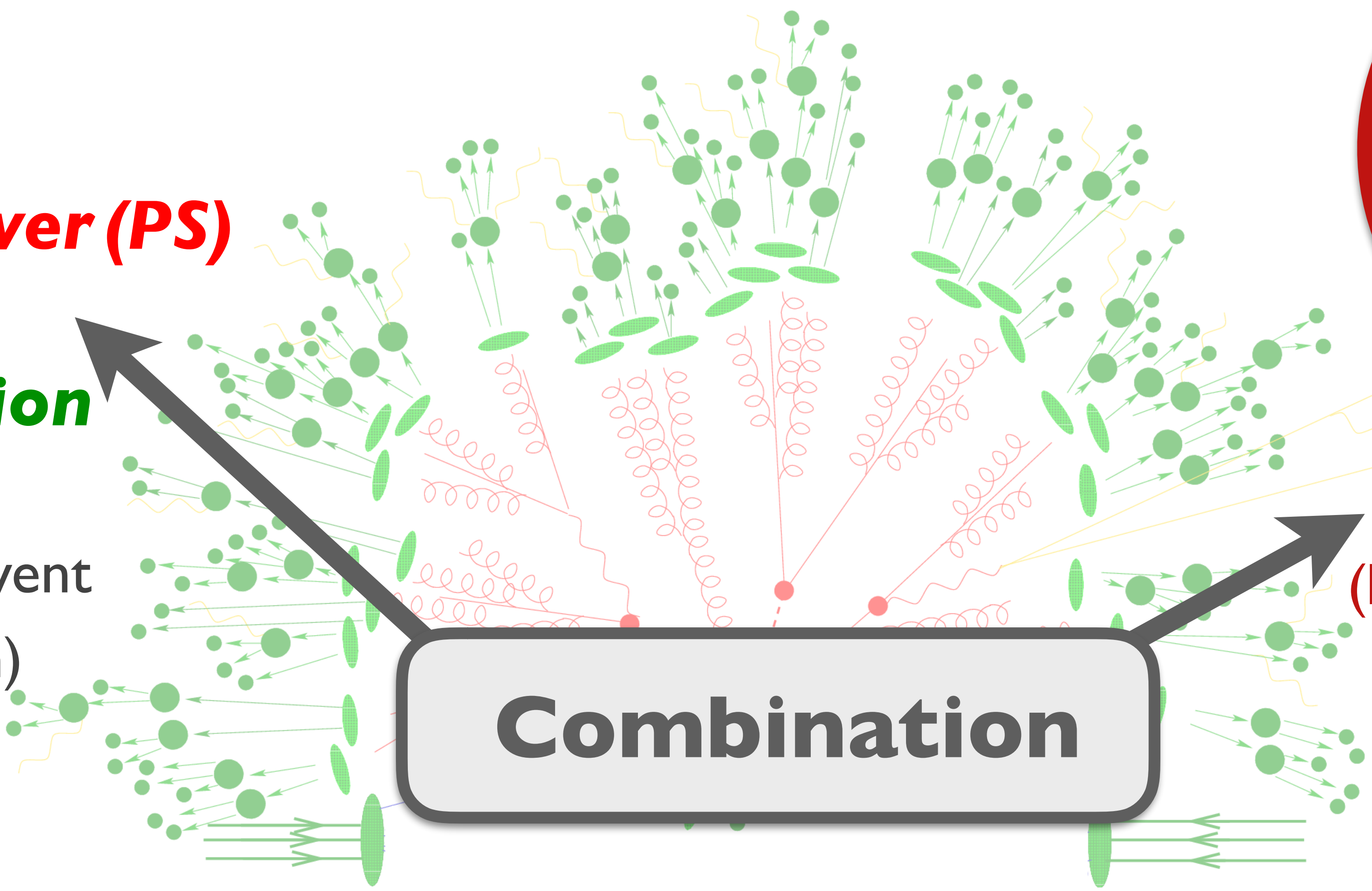
+

Hadronization

=

realistic LHC event

(low precision)



Hard Process

(high precision, no event)

NLO+PS (~10%): *long-standing issue ➙ groundbreaking ~15 years; standard today*

NNLO+PS(~1%): *extremely challenging; no general application to involved processes*

NNLO+PS approaches

- ***MiNLO+reweighting*** [Hamilton, Nason, Zanderighi '12]
  - $pp \to H$ [Hamilton, Nason, Re, Zanderighi '13]
  - $pp \to \ell\ell$ (Z) [Karlberg, Hamilton, Zanderighi '14]
  - $pp \to \ell\ell H/\ell\nu H$ (ZH/WH) [Astill, Bizoń, Re, Zanderigh '16 '18]
  - $pp \to \ell\nu\ell'\nu'$ (WW) [Re, MW, Zanderighi '18]

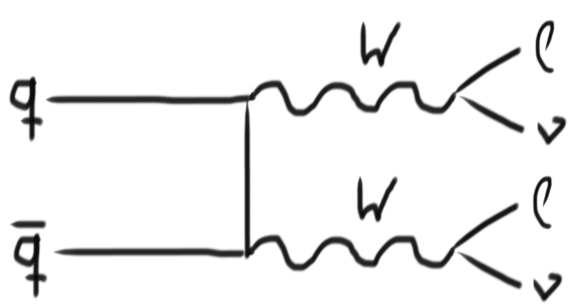
- ***Geneva*** [Alioli, Bauer, Berggren, Tackmann, Walsh, Zuberi '13]
  - $pp \to \ell\ell$ (Z) [Alioli, Bauer, Berggren, Tackmann, Walsh '15]

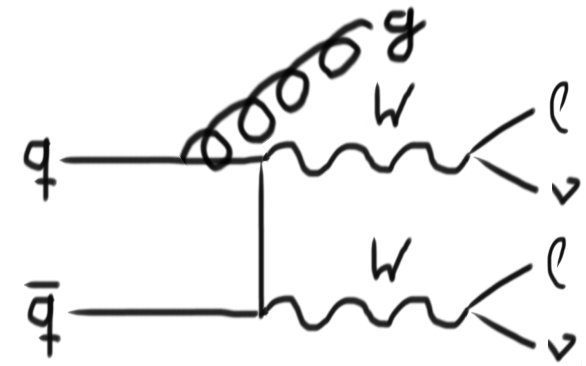
- ***UNNLOPS*** [Höche, Prestel '14]
  - $pp \to H$ [Höche, Prestel '14]
  - $pp \to \ell\ell$ (Z) [Höche, Prestel '14]

MiNLO+reweighting

	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

1. merge *pp → WW* *and* *pp → WW+jet* *(both at NLO+PS)*

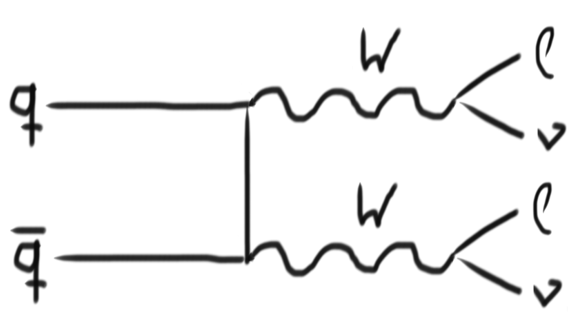


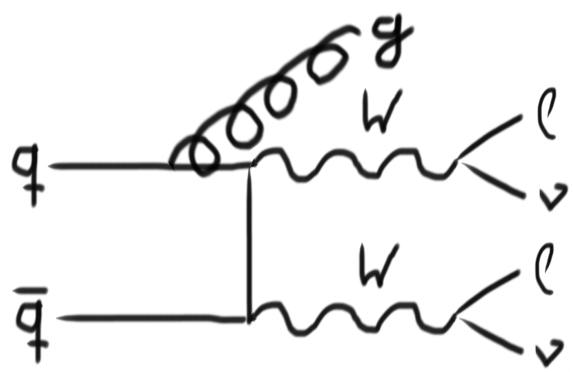


MiNLO+reweighting

	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

1. merge *pp* ➞ *WW* *and* *pp* ➞ *WW+jet* *(both at NLO+PS)*





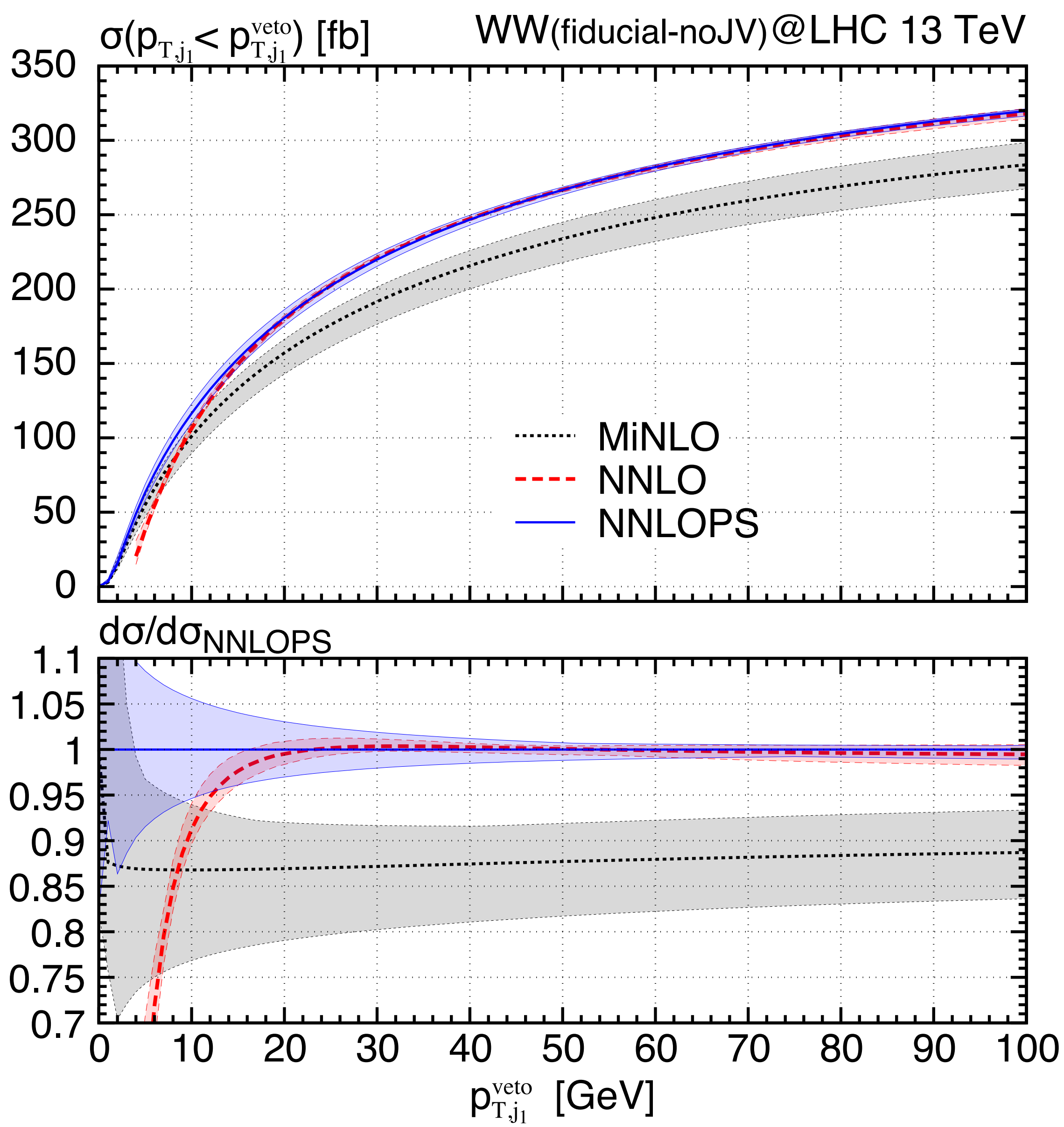
2. reweight to NNLO in born phase space

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

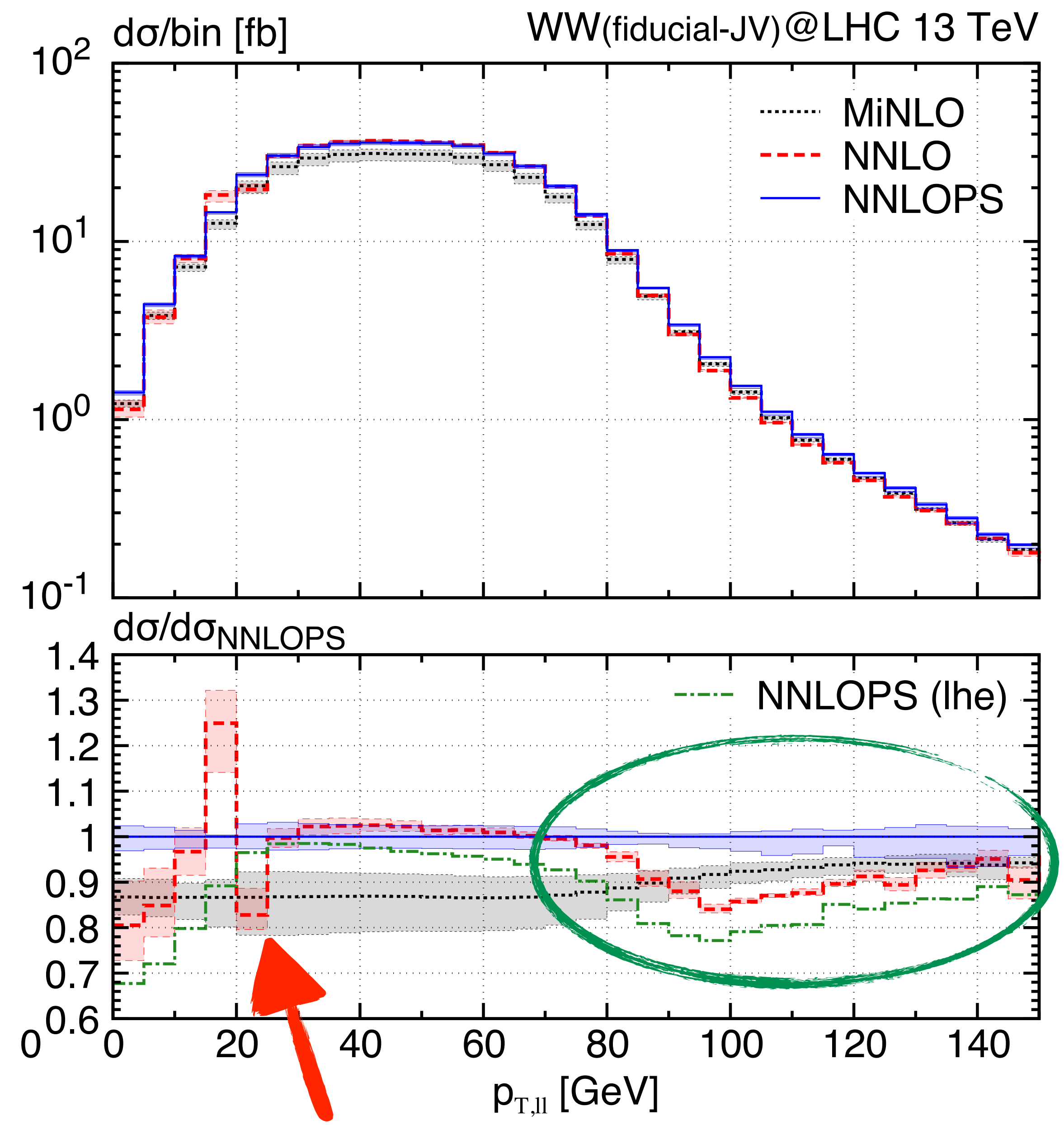
NNLO+PS for WW

[Re, MW, Zanderighi '18]

Jet veto



p_T of dilepton system



→ **NNLOPS physical down to $p_T = 0$**

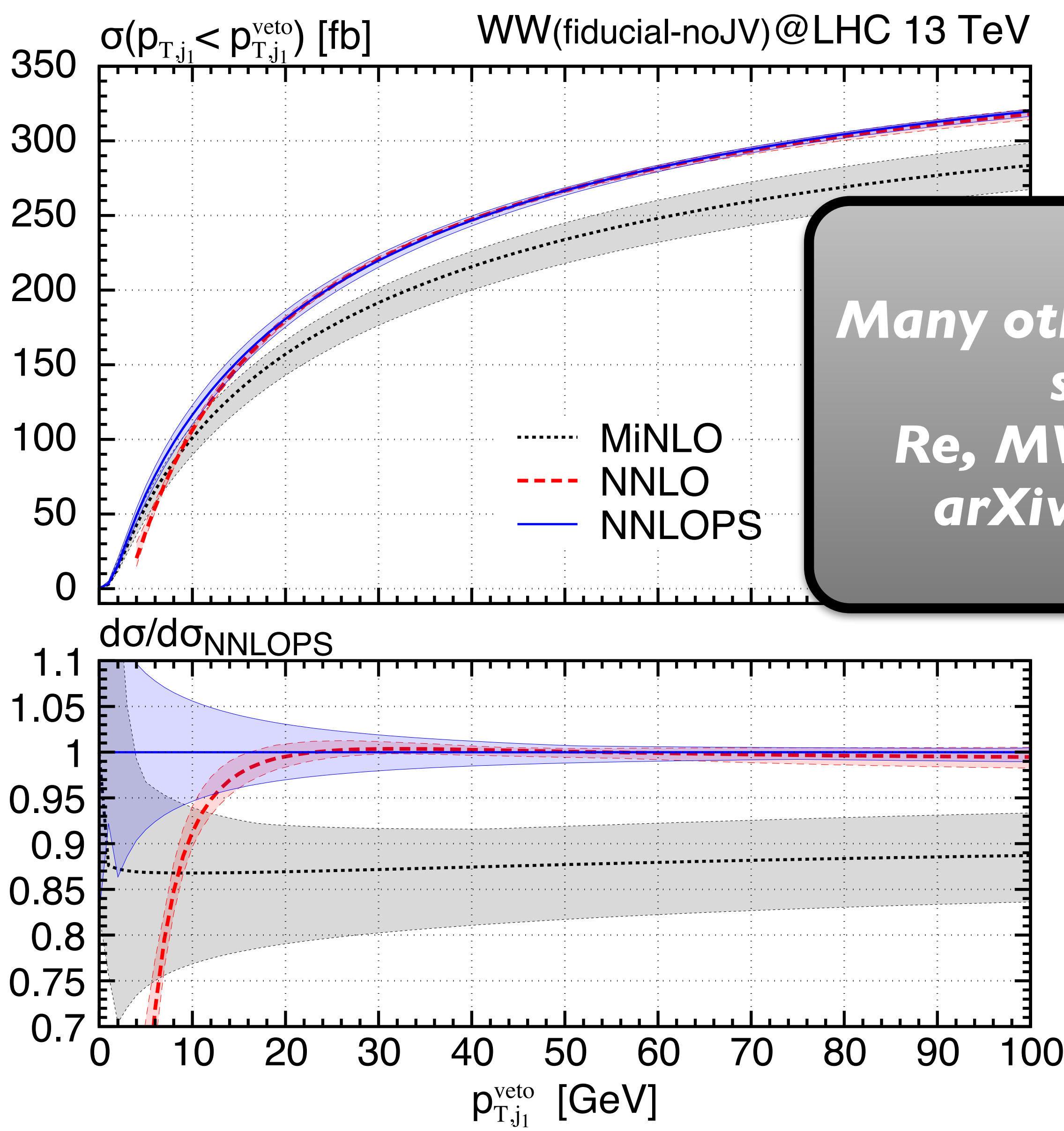
→ **NNLOPS cures perturbative instabilities (p_T^{miss} cut)**

→ **NNLOPS induces additional shape effects**

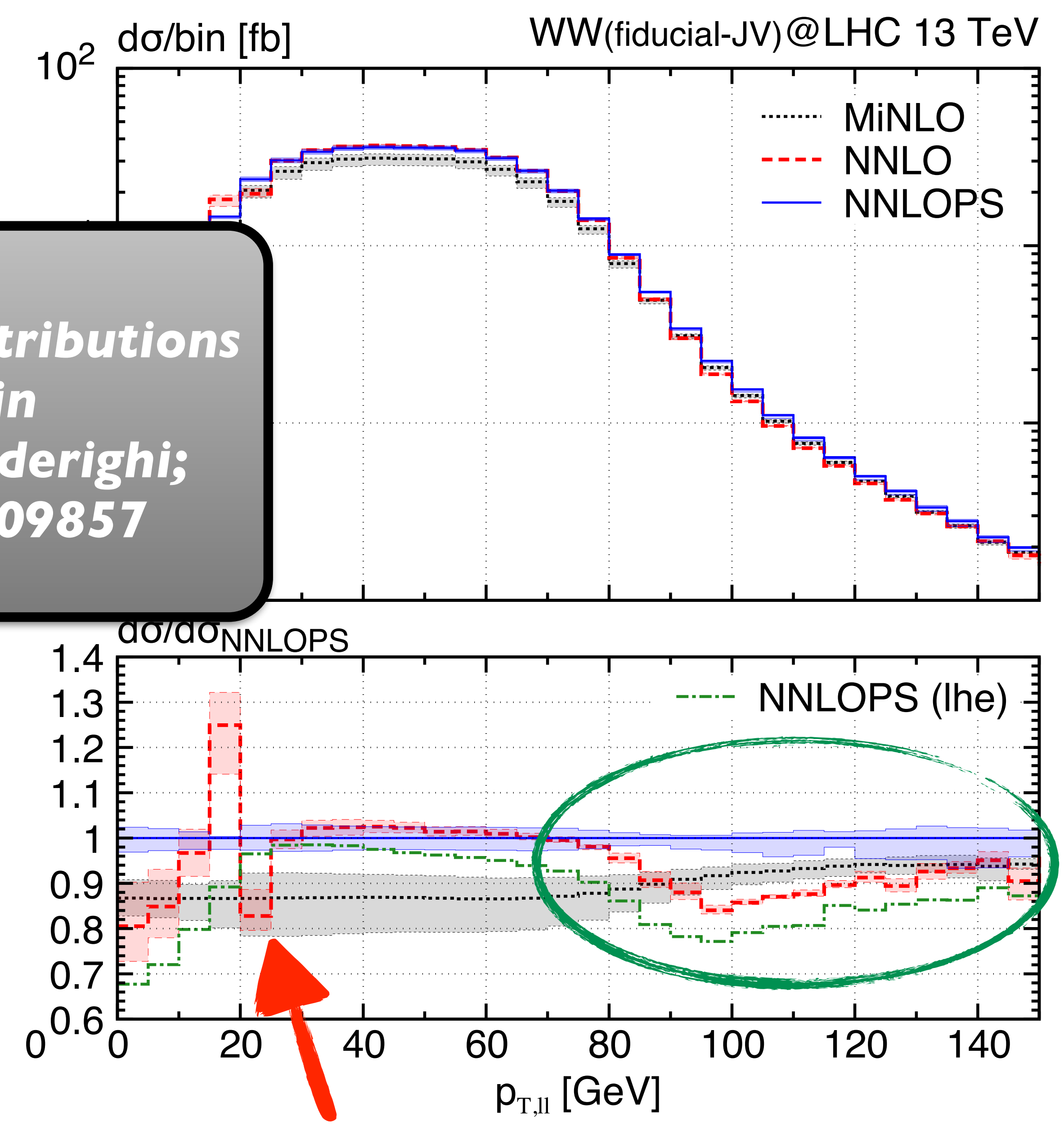
NNLO+PS for WW

[Re, MW, Zanderighi '18]

Jet veto



p_T of dilepton system



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

→ **NNLOPS physical down to $p_T = 0$**

→ **NNLOPS cures perturbative instabilities (p_T^{miss} cut)**

→ **NNLOPS induces additional shape effects**

The problem with reweighting

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

- approximation: m_W flat & CS angles [Collins, Soper '77] to convert to 81 3D moments

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

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

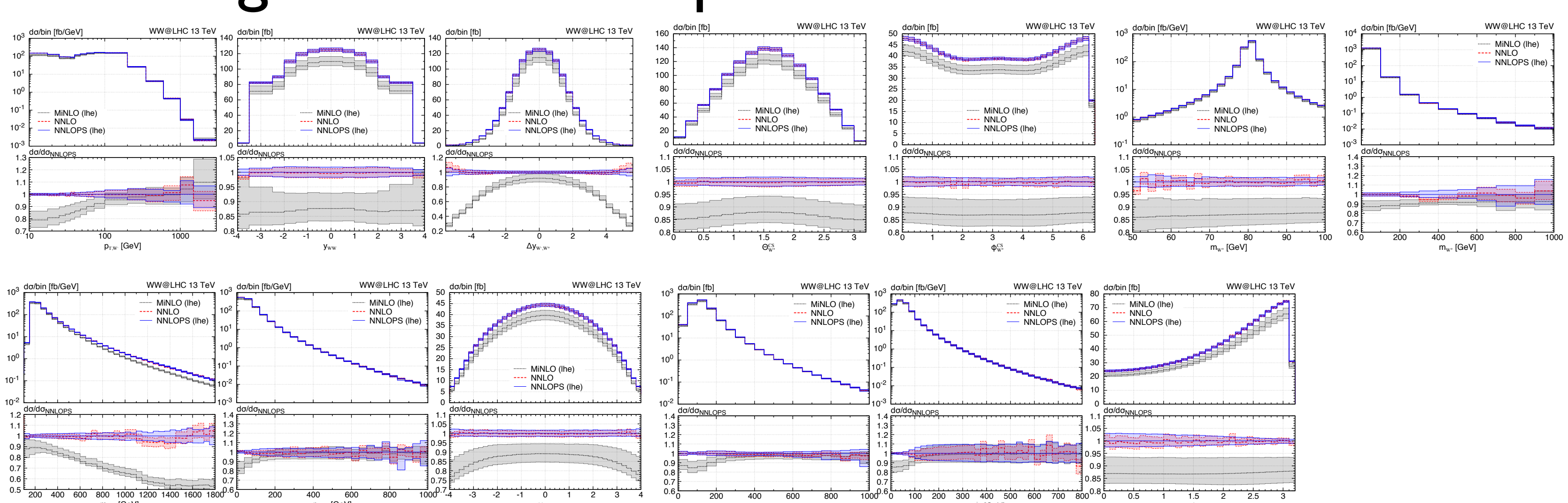
$$AB_{ij}(p_{T,W^-}, y_{WW}, \Delta y_{W^+W^-}) = \int \frac{\mathrm{d}\sigma}{\mathrm{d}\Phi_B}\, g_i(\theta^{\mathrm{CS}}_{W^-},\phi^{\mathrm{CS}}_{W^-})\, g_j(\theta^{\mathrm{CS}}_{W^+},\phi^{\mathrm{CS}}_{W^+})\,\mathrm{d}\cos\theta^{\mathrm{CS}}_{W^-}\,\mathrm{d}\phi^{\mathrm{CS}}_{W^-}\,\mathrm{d}\cos\theta^{\mathrm{CS}}_{W^+}\,\mathrm{d}\phi^{\mathrm{CS}}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

- discrete binning limits applicability in less populated regions

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

- reweighting still numerically intensive

- thorough validation required



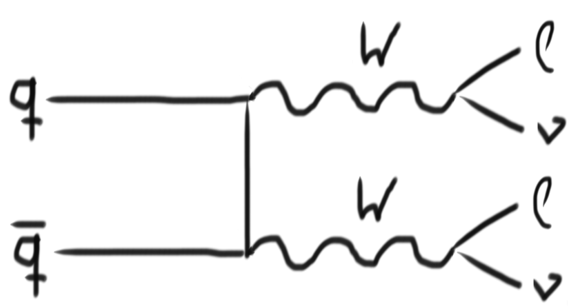
Issue in NNLOPS event production of experiments already for DY

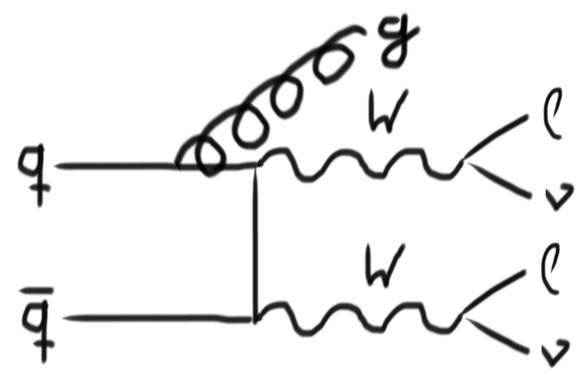
New approach: MiNNLOPS

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

	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

1. merge *pp → WW* *and* *pp → WW+jet* *(both at NLO+PS)*





2. reweight to NNLO in born phase space

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

New approach: MiNNLOPS

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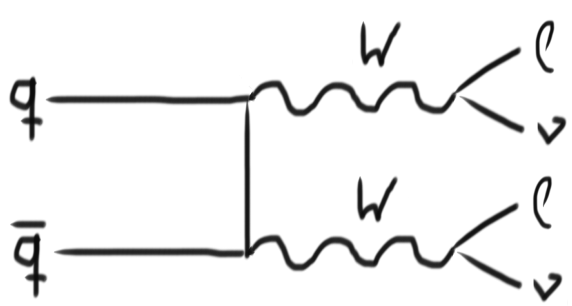
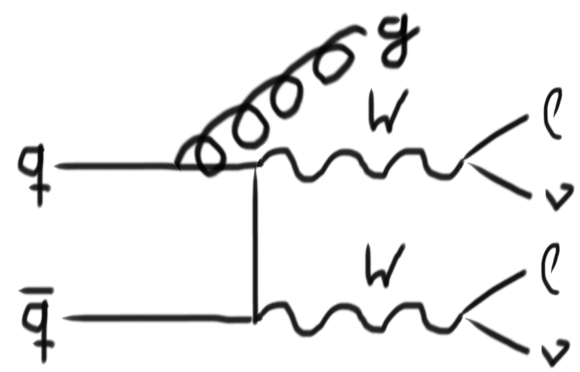
1. merge *pp* ➞ *WW* *and* *pp* ➞ *WW+jet* *(both at NLO+PS)*





2. ~~reweight to NNLO in born phase space~~

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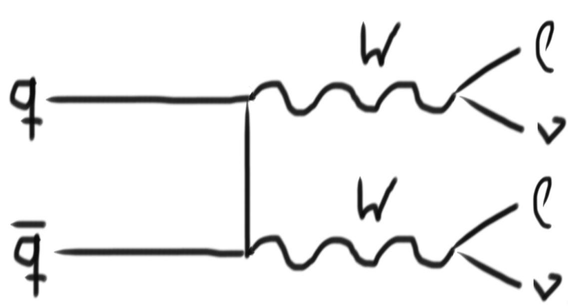
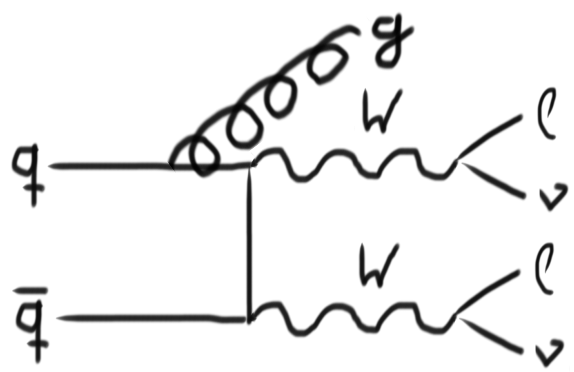
New approach: MiNNLO$_{\text{PS}}$

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

	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

1. merge *pp → WW* *and* *pp → WW+jet* *(both at NLO+PS)*





2. add ***missing terms*** explicitly (from analytic all-order formula)

$$\frac{d\sigma}{d\Phi_B dp_T} = \frac{d}{dp_T}\left\{\exp[-S(p_T)]\mathcal{L}(\Phi_B, p_T)\right\} + R_f(p_T) \;\; = \exp[-S(p_T)]\left\{D(p_T) + \frac{R_f(p_T)}{\exp[-S(p_T)]}\right\}$$

New approach: MiNNLO$_{\text{PS}}$

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

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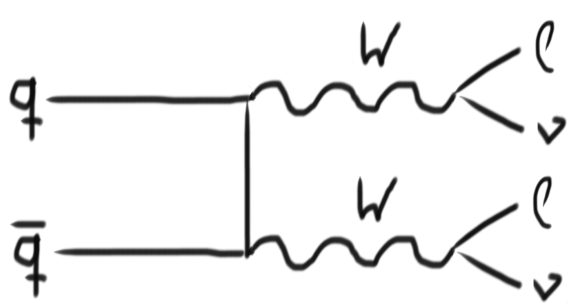
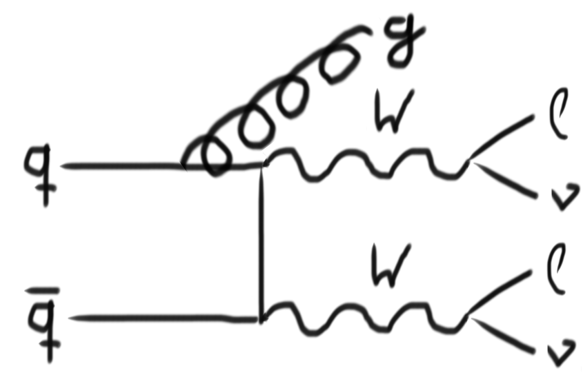
XJ-MiNLO	NLO	NLO	LO	PS
X@NNLO	NNLO	NLO	LO	—
X@NNLOPS	NNLO	NLO	LO	PS

1. merge *pp → WW* *and* *pp → WW+jet* *(both at NLO+PS)*





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$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Phi_{\mathrm{B}}\mathrm{d}p_{\mathrm{T}}} = \frac{\mathrm{d}}{\mathrm{d}p_{\mathrm{T}}}\left\{\exp[-S(p_{\mathrm{T}})]\mathcal{L}(\Phi_{\mathrm{B}},p_{\mathrm{T}})\right\} + R_f(p_{\mathrm{T}}) \;= \exp[-S(p_{\mathrm{T}})]\left\{D(p_{\mathrm{T}}) + \frac{R_f(p_{\mathrm{T}})}{\exp[-S(p_{\mathrm{T}})]}\right\}$$

$$= \exp[-S(p_{\mathrm{T}})]\left\{\frac{\alpha_s(p_{\mathrm{T}})}{2\pi}\left[\frac{\mathrm{d}\sigma_{FJ}}{\mathrm{d}\Phi_{\mathrm{F}}\mathrm{d}p_{\mathrm{T}}}\right]^{(1)}\left(1+\frac{\alpha_s(p_{\mathrm{T}})}{2\pi}[S(p_{\mathrm{T}})]^{(1)}\right) + \left(\frac{\alpha_s(p_{\mathrm{T}})}{2\pi}\right)^2\left[\frac{\mathrm{d}\sigma_{FJ}}{\mathrm{d}\Phi_{\mathrm{F}}\mathrm{d}p_{\mathrm{T}}}\right]^{(2)} + \left(\frac{\alpha_s(p_{\mathrm{T}})}{2\pi}\right)^3[D(p_{\mathrm{T}})]^{(3)} + \text{regular terms}\right\}$$

New approach: MiNNLOPS

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

	X	X+jet	X+2jets	X+nj (n>2)
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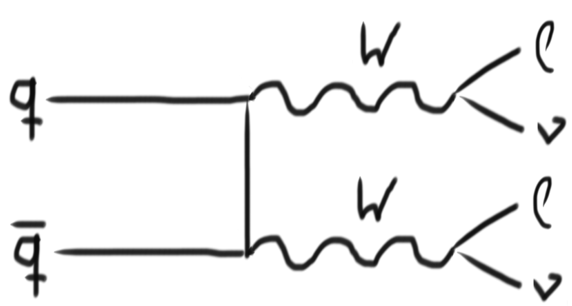
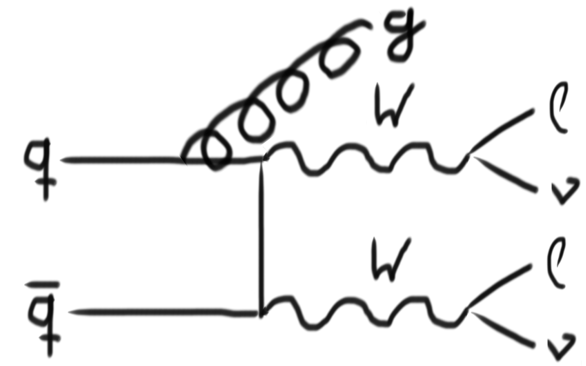
1. merge *pp → WW* *and* *pp → WW+jet* *(both at NLO+PS)*





2. add ***missing terms*** explicitly (from analytic all-order formula)

$$\frac{d\sigma}{d\Phi_B dp_T} = \frac{d}{dp_T}\left\{\exp[-S(p_T)]\mathcal{L}(\Phi_B, p_T)\right\} + R_f(p_T) = \exp[-S(p_T)]\left\{D(p_T) + \frac{R_f(p_T)}{\exp[-S(p_T)]}\right\}$$

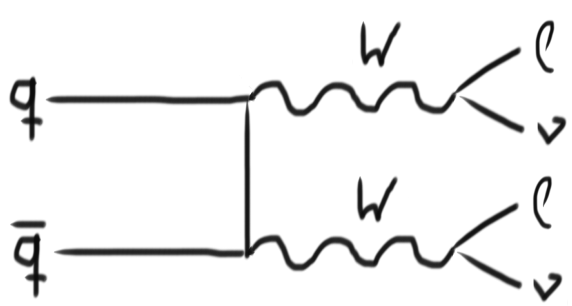
$$= \underbrace{\exp[-S(p_T)]\left\{\frac{\alpha_s(p_T)}{2\pi}\left[\frac{d\sigma_{FJ}}{d\Phi_F dp_T}\right]^{(1)}\left(1+\frac{\alpha_s(p_T)}{2\pi}[S(p_T)]^{(1)}\right) + \left(\frac{\alpha_s(p_T)}{2\pi}\right)^2\left[\frac{d\sigma_{FJ}}{d\Phi_F dp_T}\right]^{(2)}\right.}_{\textbf{MiNLO}} \left. + \left(\frac{\alpha_s(p_T)}{2\pi}\right)^3 [D(p_T)]^{(3)} + \text{regular terms}\right\}$$

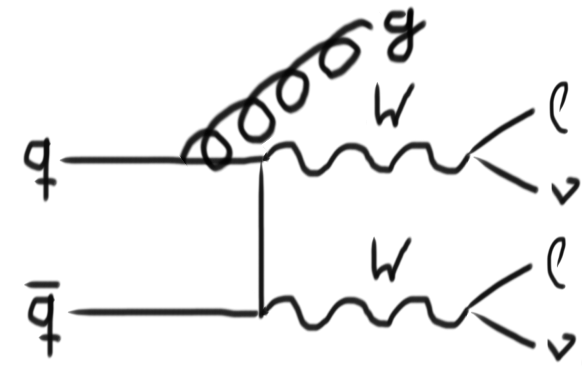
New approach: MiNNLO$_{\rm PS}$

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

	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

1. merge *pp → WW* *and* *pp → WW+jet* *(both at NLO+PS)*





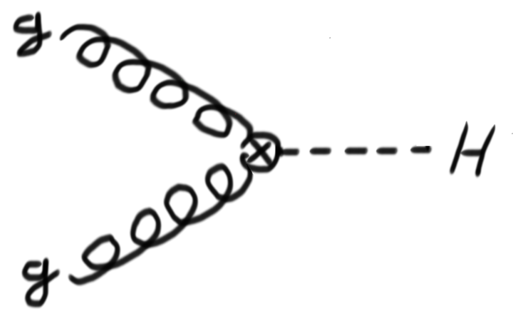
2. add ***missing terms*** explicitly (from analytic all-order formula)

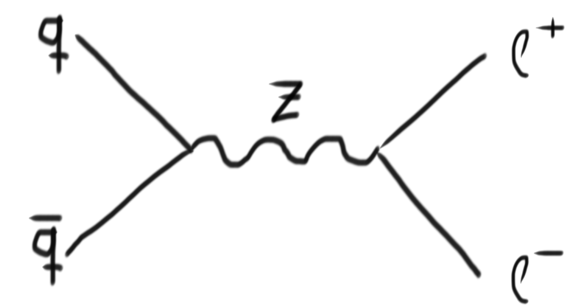
$$\frac{d\sigma}{d\Phi_{\rm B}dp_{\rm T}} = \frac{d}{dp_{\rm T}}\left\{\exp[-S(p_{\rm T})]\mathcal{L}(\Phi_{\rm B},p_{\rm T})\right\} + R_f(p_{\rm T}) \;= \exp[-S(p_{\rm T})]\left\{D(p_{\rm T}) + \frac{R_f(p_{\rm T})}{\exp[-S(p_{\rm T})]}\right\}$$

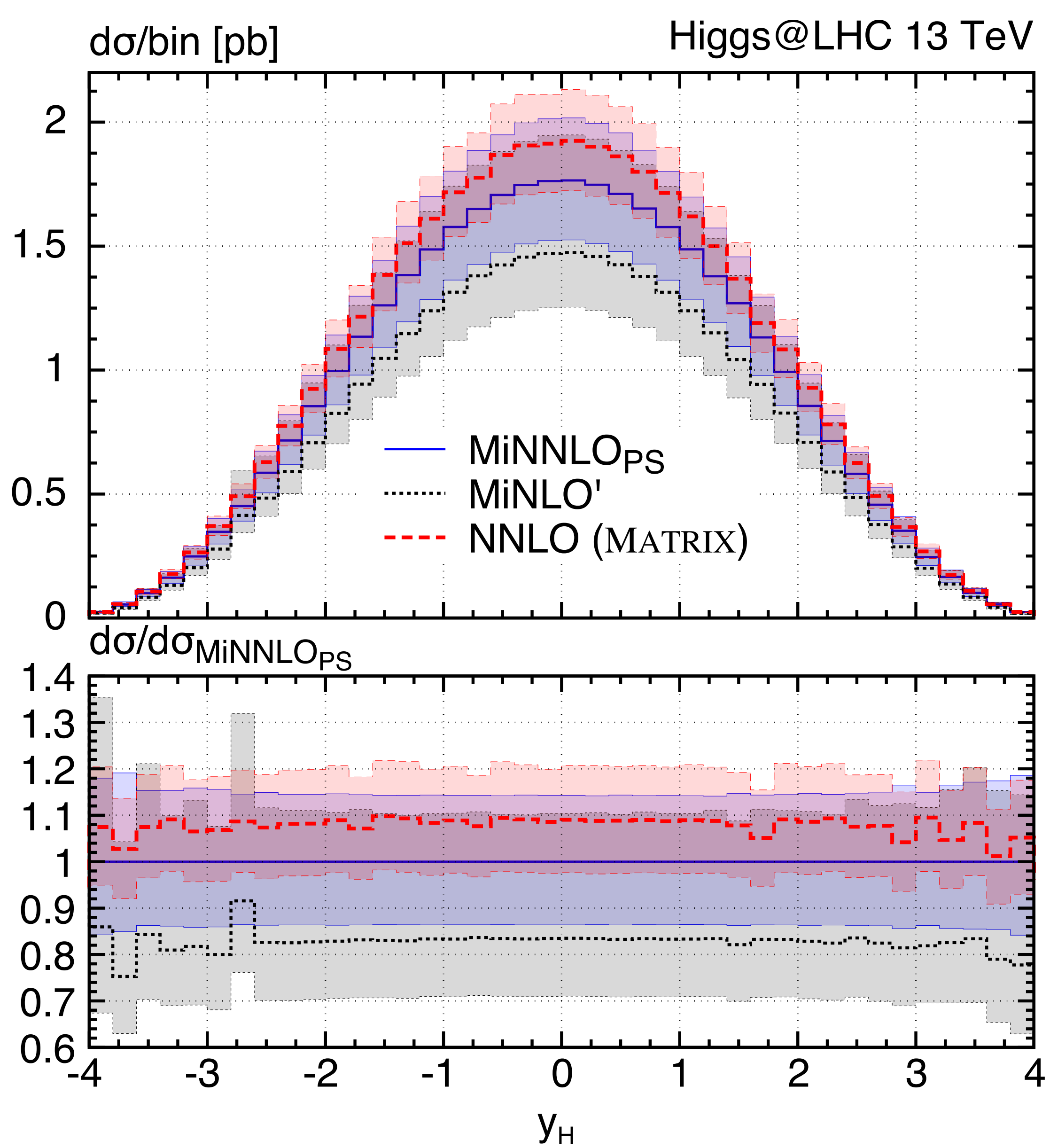
$$= \underbrace{\boxed{\exp[-S(p_{\rm T})]\left\{\frac{\alpha_s(p_{\rm T})}{2\pi}\left[\frac{d\sigma_{FJ}}{d\Phi_{\rm F}dp_{\rm T}}\right]^{(1)}\left(1+\frac{\alpha_s(p_{\rm T})}{2\pi}[S(p_{\rm T})]^{(1)}\right) + \left(\frac{\alpha_s(p_{\rm T})}{2\pi}\right)^2\left[\frac{d\sigma_{FJ}}{d\Phi_{\rm F}dp_{\rm T}}\right]^{(2)}}}_{\textbf{MiNLO}} + \underbrace{\boxed{\left(\frac{\alpha_s(p_{\rm T})}{2\pi}\right)^3[D(p_{\rm T})]^{(3)}}}_{\textbf{missing NNLO terms}} + \text{regular terms}\right\},$$

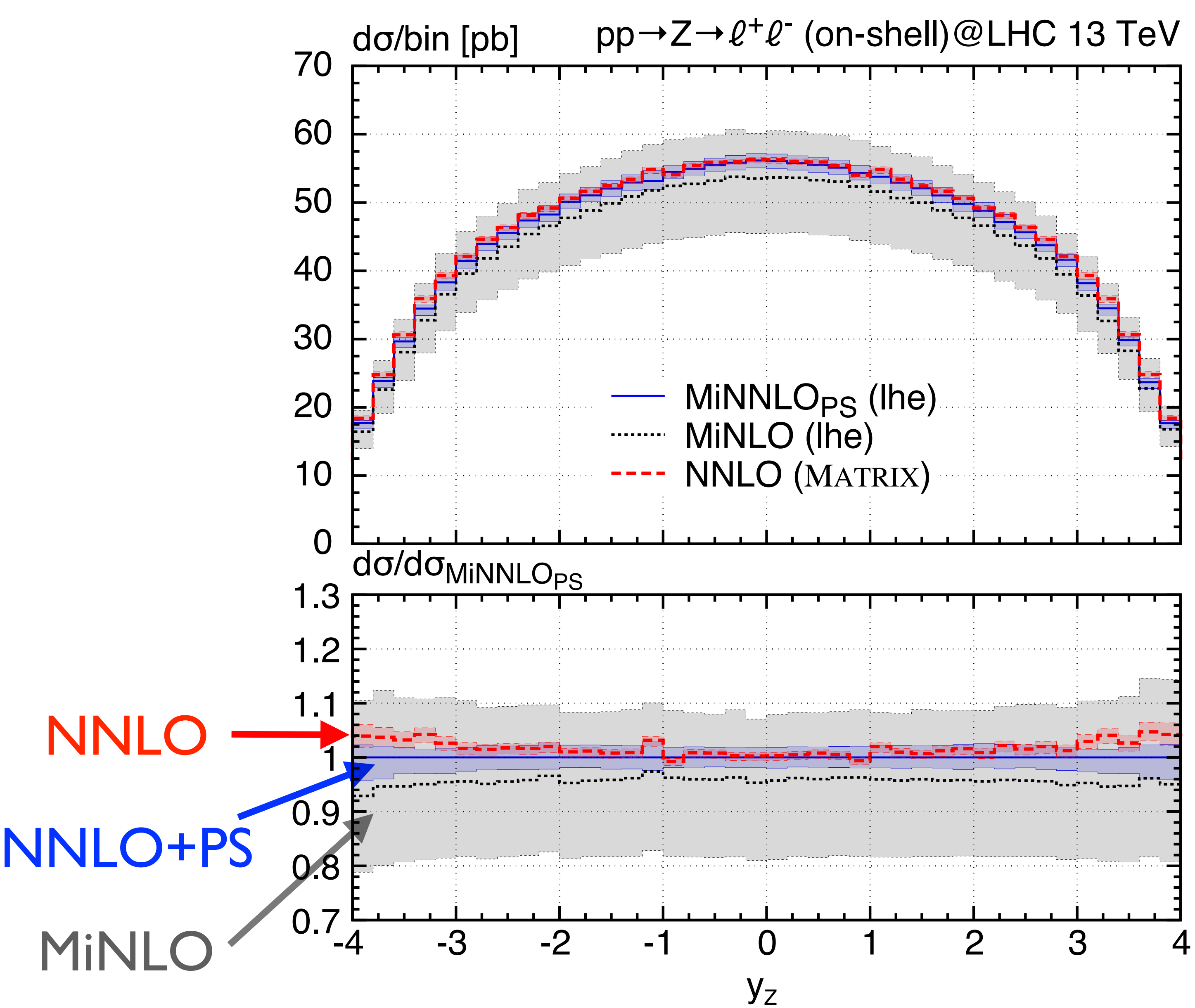
MiNNLO$_{PS}$ results

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









Conclusions

- **Diboson theory predictions under excellent control:**
  - ***NNLO QCD done!*** → publicly available within **MATRIX**
  - $\ell\ell$+ET,miss signature studied at NNLO, mixes ZZ and WW resonances
  - NLO QCD corrections for loop-induced gg contribution
  - first NNLO+PS computation for a 2→4 process (WW)
- **MiNNLO$_{\text{PS}}$: New NNLO+PS approach (no reweighting)**
- **Open issues/ongoing work for dibosons:**
  - best way to combine NNLO, NLO EW and NLO gg
  - NLO gg Higgs interference for ZZ and WW
  - combination of NNLO QCD with state-of-the-art (N3LL) resummation
  - MiNNLO$_{\text{PS}}$ for diboson processes

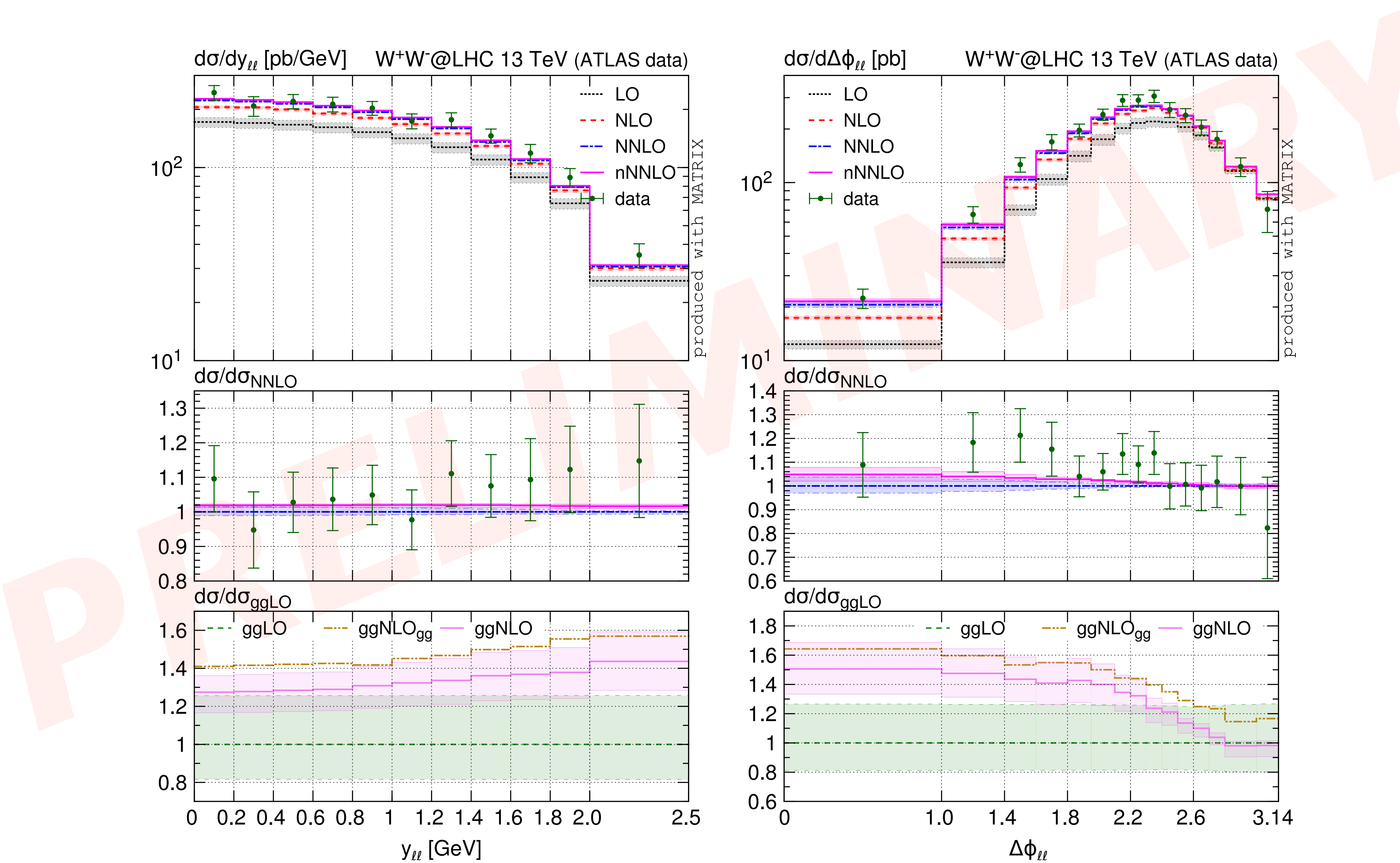

FREE YOUR MIND.
THE MATRIX

Thank You !

Back Up

NEW: $gg \to 2\ell 2\nu$ (WW) at NLO

[Grazzini, Kallweit, MW, Yook 'to appear]



NNLOPS for WW

[Re, MW, Zanderighi '18]

Setup:

The remaining three variables and their binning chosen to be

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

Cuts inspired by ATLAS 13 TeV study (1702.04519):

lepton cuts	$p_{T,\ell} > 25\,\text{GeV}, \quad \lvert\eta_\ell\rvert < 2.4, \quad m_{\ell^-\ell^+} > 10\,\text{GeV}$
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	$p_T^{\text{miss}} > 20\,\text{GeV}, \quad p_T^{\text{miss,rel}} > 15\,\text{GeV}$
jet cuts	anti-k_T jets with $R = 0.4$; $N_{\text{jet}} = 0$ 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

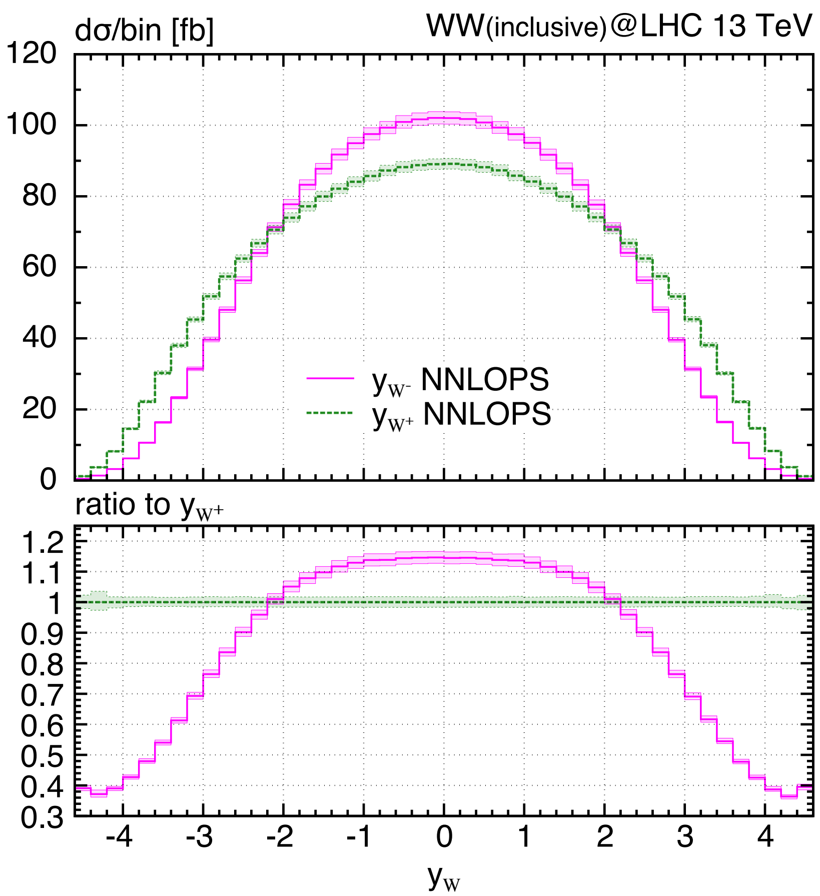
gg-channel not included in our study, as it can it is know at one-loop and can be added incoherently

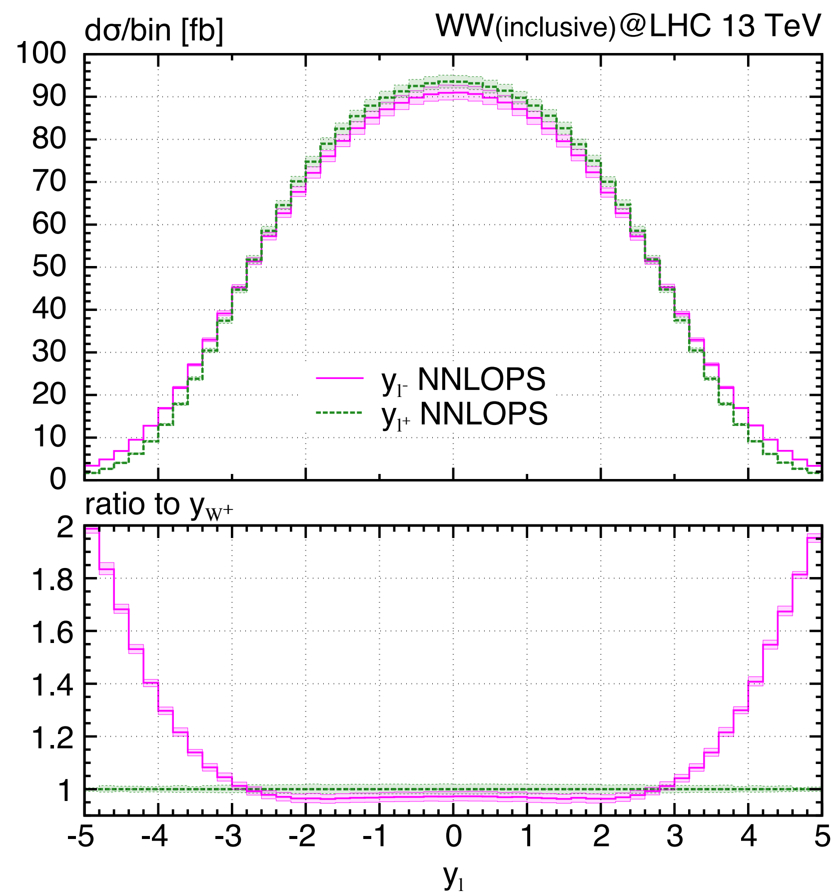
NNLOPS for WW

[Re, MW, Zanderighi '18]

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	$-[0.0270(1)^{+5.0\%}_{-6.4\%}]$	$-[0.0009(4)^{+72\%}_{-87\%}]$

New approach: MiNNLO$_{\text{PS}}$

* NLO (F+jet): $\frac{d\sigma_{FJ}^{(\text{NLO})}}{d\Phi_{\text{F}} dp_{\text{T}}} = \frac{\alpha_s(p_{\text{T}})}{2\pi} \left[\frac{d\sigma_{FJ}}{d\Phi_{\text{F}} dp_{\text{T}}}\right]^{(1)} + \left(\frac{\alpha_s(p_{\text{T}})}{2\pi}\right)^2 \left[\frac{d\sigma_{FJ}}{d\Phi_{\text{F}} dp_{\text{T}}}\right]^{(2)}$

New approach: MiNNLOPS

- NLO (F+jet): $$\frac{\mathrm{d}\sigma_{FJ}^{(\mathrm{NLO})}}{\mathrm{d}\Phi_{\mathrm{F}}\mathrm{d}p_{\mathrm{T}}} = \frac{\alpha_s(p_{\mathrm{T}})}{2\pi}\left[\frac{\mathrm{d}\sigma_{FJ}}{\mathrm{d}\Phi_{\mathrm{F}}\mathrm{d}p_{\mathrm{T}}}\right]^{(1)} + \left(\frac{\alpha_s(p_{\mathrm{T}})}{2\pi}\right)^2\left[\frac{\mathrm{d}\sigma_{FJ}}{\mathrm{d}\Phi_{\mathrm{F}}\mathrm{d}p_{\mathrm{T}}}\right]^{(2)}$$
- MiNLO: $$\frac{\mathrm{d}\sigma}{\mathrm{d}\Phi_{\mathrm{F}}\mathrm{d}p_{\mathrm{T}}} = \exp[-S(p_{\mathrm{T}})]\left\{\frac{\alpha_s(p_{\mathrm{T}})}{2\pi}\left[\frac{\mathrm{d}\sigma_{FJ}}{\mathrm{d}\Phi_{\mathrm{F}}\mathrm{d}p_{\mathrm{T}}}\right]^{(1)}\left(1+\frac{\alpha_s(p_{\mathrm{T}})}{2\pi}[S(p_{\mathrm{T}})]^{(1)}\right) + \left(\frac{\alpha_s(p_{\mathrm{T}})}{2\pi}\right)^2\left[\frac{\mathrm{d}\sigma_{FJ}}{\mathrm{d}\Phi_{\mathrm{F}}\mathrm{d}p_{\mathrm{T}}}\right]^{(2)}\right\}$$

$$S(p_{\mathrm{T}}) = 2\int_{p_{\mathrm{T}}}^{Q}\frac{\mathrm{d}q}{q}\left(A(\alpha_s(q))\ln\frac{Q^2}{q^2} + B(\alpha_s(q))\right),$$

$$A(\alpha_s) = \sum_{k=1}^{2}\left(\frac{\alpha_s}{2\pi}\right)^k A^{(k)}, \quad B(\alpha_s) = \sum_{k=1}^{2}\left(\frac{\alpha_s}{2\pi}\right)^k B^{(k)},$$

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$$S(p_{\mathrm{T}}) = 2\int_{p_{\mathrm{T}}}^{Q}\frac{dq}{q}\left(A(\alpha_s(q))\ln\frac{Q^2}{q^2} + B(\alpha_s(q))\right),$$

$$A(\alpha_s) = \sum_{k=1}^{2}\left(\frac{\alpha_s}{2\pi}\right)^k A^{(k)}, \quad B(\alpha_s) = \sum_{k=1}^{2}\left(\frac{\alpha_s}{2\pi}\right)^k B^{(k)},$$

- analytic all-order formula:

$$\frac{d\sigma}{d\Phi_{\mathrm{B}} dp_{\mathrm{T}}} = \frac{d}{dp_{\mathrm{T}}}\left\{\exp[-S(p_{\mathrm{T}})]\mathcal{L}(\Phi_{\mathrm{B}}, p_{\mathrm{T}})\right\} + R_f(p_{\mathrm{T}})$$

New approach: MiNNLOPS

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$$S(p_{\mathrm{T}}) = 2\int_{p_{\mathrm{T}}}^{Q}\frac{dq}{q}\left(A(\alpha_s(q))\ln\frac{Q^2}{q^2} + B(\alpha_s(q))\right),$$

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counting:

$$\int_{\Lambda}^{Q} dp_{\mathrm{T}}\frac{1}{p_{\mathrm{T}}}\alpha_s^m(p_{\mathrm{T}})\ln^n\frac{p_{\mathrm{T}}}{Q}\exp(-S(p_{\mathrm{T}})) \approx \alpha_s^{m-\frac{n+1}{2}}(Q)$$

$$D(p_{\mathrm{T}}) \equiv -\frac{dS(p_{\mathrm{T}})}{dp_{\mathrm{T}}}\mathcal{L}(p_{\mathrm{T}}) + \frac{d\mathcal{L}(p_{\mathrm{T}})}{dp_{\mathrm{T}}}$$

- analytic all-order formula:

$$\frac{d\sigma}{d\Phi_{\mathrm{B}} dp_{\mathrm{T}}} = \frac{d}{dp_{\mathrm{T}}}\left\{\exp[-S(p_{\mathrm{T}})]\mathcal{L}(\Phi_{\mathrm{B}}, p_{\mathrm{T}})\right\} + R_f(p_{\mathrm{T}}) = \exp[-S(p_{\mathrm{T}})]\left\{D(p_{\mathrm{T}}) + \frac{R_f(p_{\mathrm{T}})}{\exp[-S(p_{\mathrm{T}})]}\right\}$$

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- MiNLO: $$\frac{\mathrm{d}\sigma}{\mathrm{d}\Phi_\mathrm{F}\mathrm{d}p_\mathrm{T}} = \exp[-S(p_\mathrm{T})]\left\{\frac{\alpha_s(p_\mathrm{T})}{2\pi}\left[\frac{\mathrm{d}\sigma_{FJ}}{\mathrm{d}\Phi_\mathrm{F}\mathrm{d}p_\mathrm{T}}\right]^{(1)}\left(1+\frac{\alpha_s(p_\mathrm{T})}{2\pi}[S(p_\mathrm{T})]^{(1)}\right) + \left(\frac{\alpha_s(p_\mathrm{T})}{2\pi}\right)^2\left[\frac{\mathrm{d}\sigma_{FJ}}{\mathrm{d}\Phi_\mathrm{F}\mathrm{d}p_\mathrm{T}}\right]^{(2)}\right\}$$

$$S(p_\mathrm{T}) = 2\int_{p_\mathrm{T}}^{Q}\frac{\mathrm{d}q}{q}\left(A(\alpha_s(q))\ln\frac{Q^2}{q^2} + B(\alpha_s(q))\right),$$

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$$\int_\Lambda^Q \mathrm{d}p_\mathrm{T}\frac{1}{p_\mathrm{T}}\alpha_s^m(p_\mathrm{T})\ln^n\frac{p_\mathrm{T}}{Q}\exp(-S(p_\mathrm{T})) \approx \alpha_s^{m-\frac{n+1}{2}}(Q)$$

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$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Phi_\mathrm{B}\mathrm{d}p_\mathrm{T}} = \frac{\mathrm{d}}{\mathrm{d}p_\mathrm{T}}\left\{\exp[-S(p_\mathrm{T})]\mathcal{L}(\Phi_\mathrm{B},p_\mathrm{T})\right\} + R_f(p_\mathrm{T}) = \exp[-S(p_\mathrm{T})]\left\{D(p_\mathrm{T}) + \frac{R_f(p_\mathrm{T})}{\exp[-S(p_\mathrm{T})]}\right\}$$

$$= \exp[-S(p_\mathrm{T})]\left\{\frac{\alpha_s(p_\mathrm{T})}{2\pi}\left[\frac{\mathrm{d}\sigma_{FJ}}{\mathrm{d}\Phi_\mathrm{F}\mathrm{d}p_\mathrm{T}}\right]^{(1)}\left(1+\frac{\alpha_s(p_\mathrm{T})}{2\pi}[S(p_\mathrm{T})]^{(1)}\right) + \left(\frac{\alpha_s(p_\mathrm{T})}{2\pi}\right)^2\left[\frac{\mathrm{d}\sigma_{FJ}}{\mathrm{d}\Phi_\mathrm{F}\mathrm{d}p_\mathrm{T}}\right]^{(2)} + \left(\frac{\alpha_s(p_\mathrm{T})}{2\pi}\right)^3[D(p_\mathrm{T})]^{(3)} + \text{regular terms}\right\}$$

New approach: MiNNLOPS

- NLO (F+jet): $$\frac{d\sigma_{FJ}^{(\mathrm{NLO})}}{d\Phi_F dp_T} = \frac{\alpha_s(p_T)}{2\pi}\left[\frac{d\sigma_{FJ}}{d\Phi_F dp_T}\right]^{(1)} + \left(\frac{\alpha_s(p_T)}{2\pi}\right)^2\left[\frac{d\sigma_{FJ}}{d\Phi_F dp_T}\right]^{(2)}$$

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$$D(p_T) \equiv -\frac{dS(p_T)}{dp_T}\mathcal{L}(p_T) + \frac{d\mathcal{L}(p_T)}{dp_T}$$

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$$= \underbrace{\boxed{\exp[-S(p_T)]\left\{\frac{\alpha_s(p_T)}{2\pi}\left[\frac{d\sigma_{FJ}}{d\Phi_F dp_T}\right]^{(1)}\left(1+\frac{\alpha_s(p_T)}{2\pi}[S(p_T)]^{(1)}\right) + \left(\frac{\alpha_s(p_T)}{2\pi}\right)^2\left[\frac{d\sigma_{FJ}}{d\Phi_F dp_T}\right]^{(2)}\right.}}_{\textbf{MiNLO}} \left. + \left(\frac{\alpha_s(p_T)}{2\pi}\right)^3[D(p_T)]^{(3)} + \text{regular terms}\right\}$$

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- MiNLO: $\frac{d\sigma}{d\Phi_{\mathrm{F}} dp_{\mathrm{T}}} = \boxed{\exp[-S(p_{\mathrm{T}})]\left\{\frac{\alpha_s(p_{\mathrm{T}})}{2\pi}\left[\frac{d\sigma_{FJ}}{d\Phi_{\mathrm{F}} dp_{\mathrm{T}}}\right]^{(1)}\left(1+\frac{\alpha_s(p_{\mathrm{T}})}{2\pi}[S(p_{\mathrm{T}})]^{(1)}\right) + \left(\frac{\alpha_s(p_{\mathrm{T}})}{2\pi}\right)^2\left[\frac{d\sigma_{FJ}}{d\Phi_{\mathrm{F}} dp_{\mathrm{T}}}\right]^{(2)}\right\}}$

$$S(p_{\mathrm{T}}) = 2\int_{p_{\mathrm{T}}}^{Q}\frac{dq}{q}\left(A(\alpha_s(q))\ln\frac{Q^2}{q^2} + B(\alpha_s(q))\right),$$

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$$D(p_{\mathrm{T}}) \equiv -\frac{dS(p_{\mathrm{T}})}{dp_{\mathrm{T}}}\mathcal{L}(p_{\mathrm{T}}) + \frac{d\mathcal{L}(p_{\mathrm{T}})}{dp_{\mathrm{T}}}$$

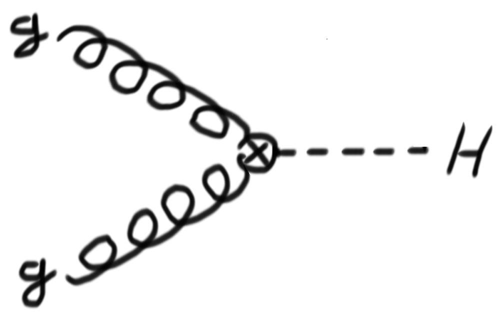
- analytic all-order formula:

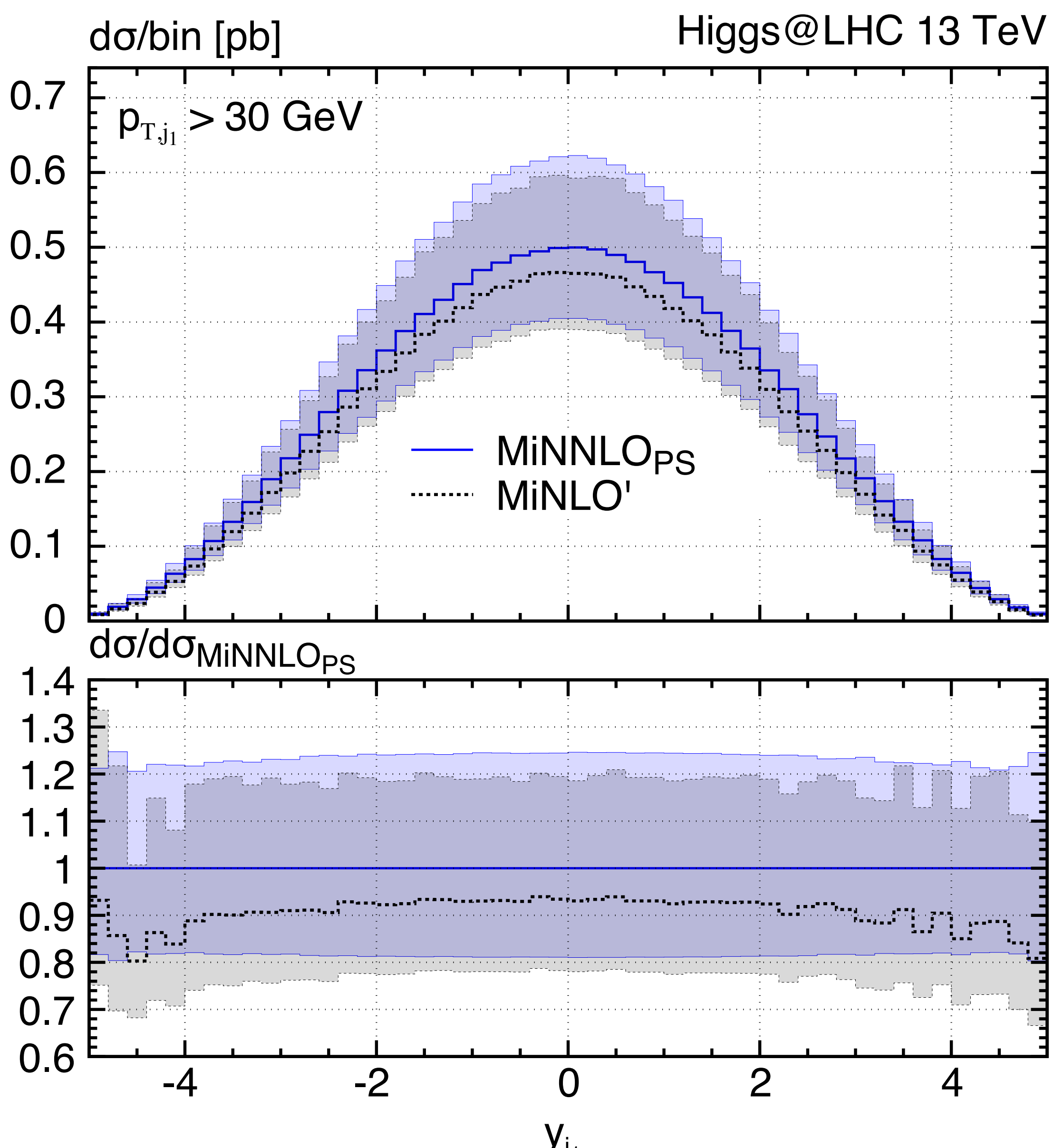
$$\frac{d\sigma}{d\Phi_{\mathrm{B}} dp_{\mathrm{T}}} = \frac{d}{dp_{\mathrm{T}}}\left\{\exp[-S(p_{\mathrm{T}})]\mathcal{L}(\Phi_{\mathrm{B}}, p_{\mathrm{T}})\right\} + R_f(p_{\mathrm{T}}) = \exp[-S(p_{\mathrm{T}})]\left\{D(p_{\mathrm{T}}) + \frac{R_f(p_{\mathrm{T}})}{\exp[-S(p_{\mathrm{T}})]}\right\}$$

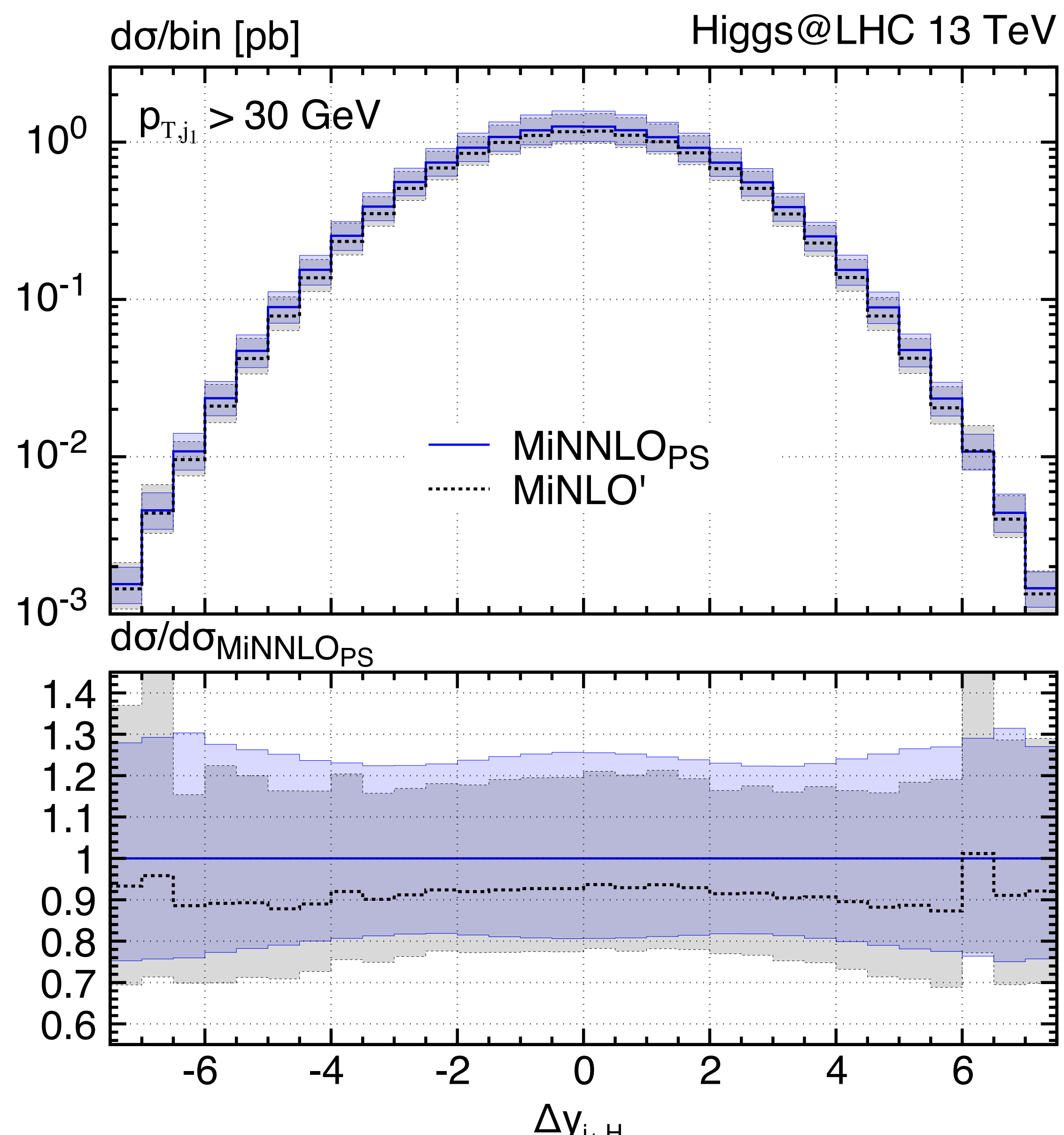
$$= \underbrace{\exp[-S(p_{\mathrm{T}})]\left\{\frac{\alpha_s(p_{\mathrm{T}})}{2\pi}\left[\frac{d\sigma_{FJ}}{d\Phi_{\mathrm{F}} dp_{\mathrm{T}}}\right]^{(1)}\left(1+\frac{\alpha_s(p_{\mathrm{T}})}{2\pi}[S(p_{\mathrm{T}})]^{(1)}\right) + \left(\frac{\alpha_s(p_{\mathrm{T}})}{2\pi}\right)^2\left[\frac{d\sigma_{FJ}}{d\Phi_{\mathrm{F}} dp_{\mathrm{T}}}\right]^{(2)}\right.}_{\textit{MiNLO}} + \underbrace{\left(\frac{\alpha_s(p_{\mathrm{T}})}{2\pi}\right)^3[D(p_{\mathrm{T}})]^{(3)}}_{\textit{missing terms for NNLO accuracy}} \left. + \text{regular terms}\right\}$$

MiNNLO$_{PS}$ results

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

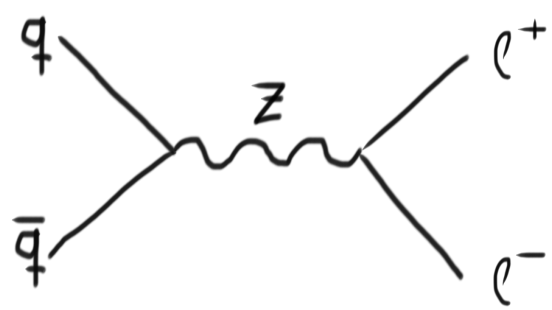


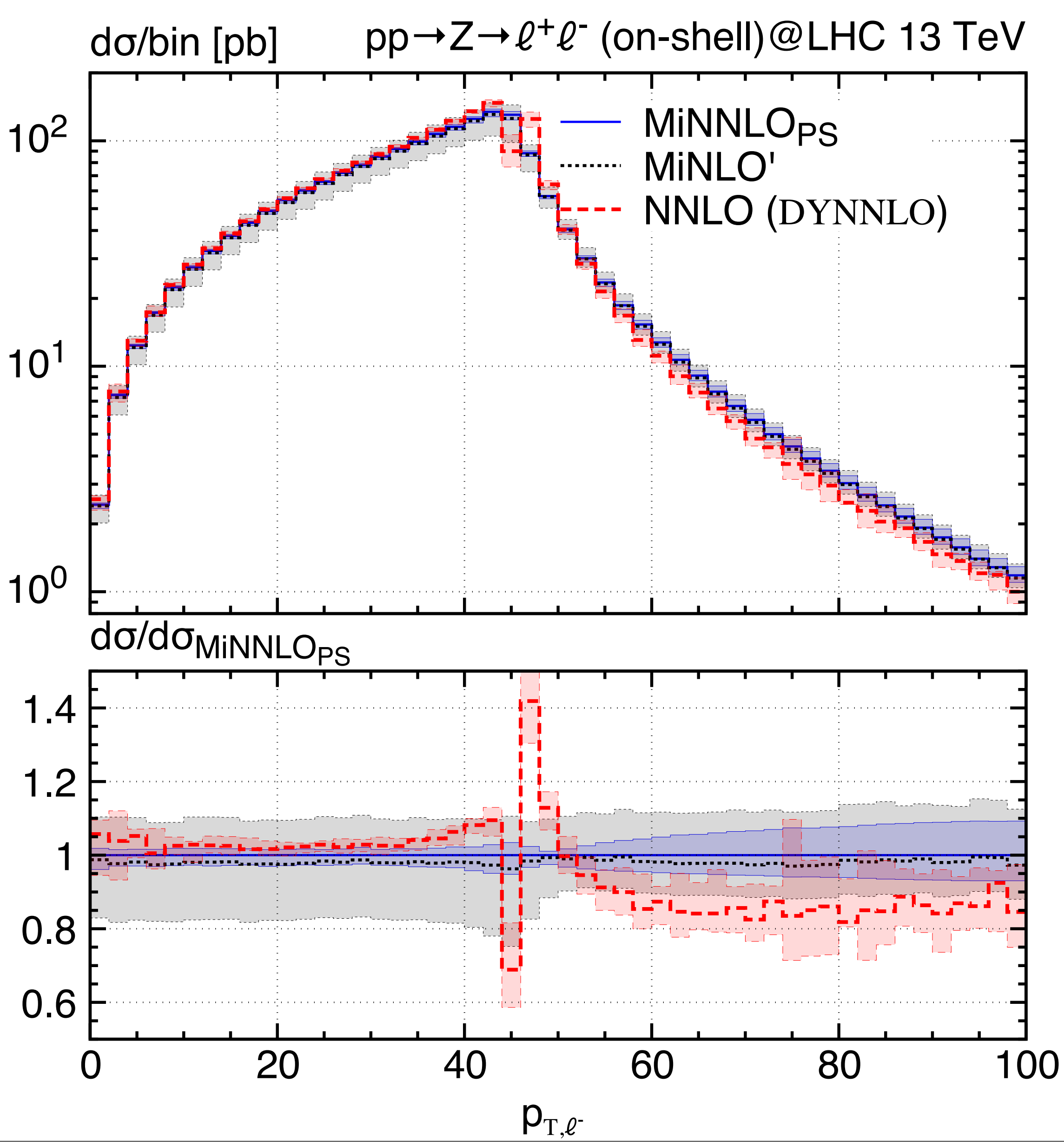


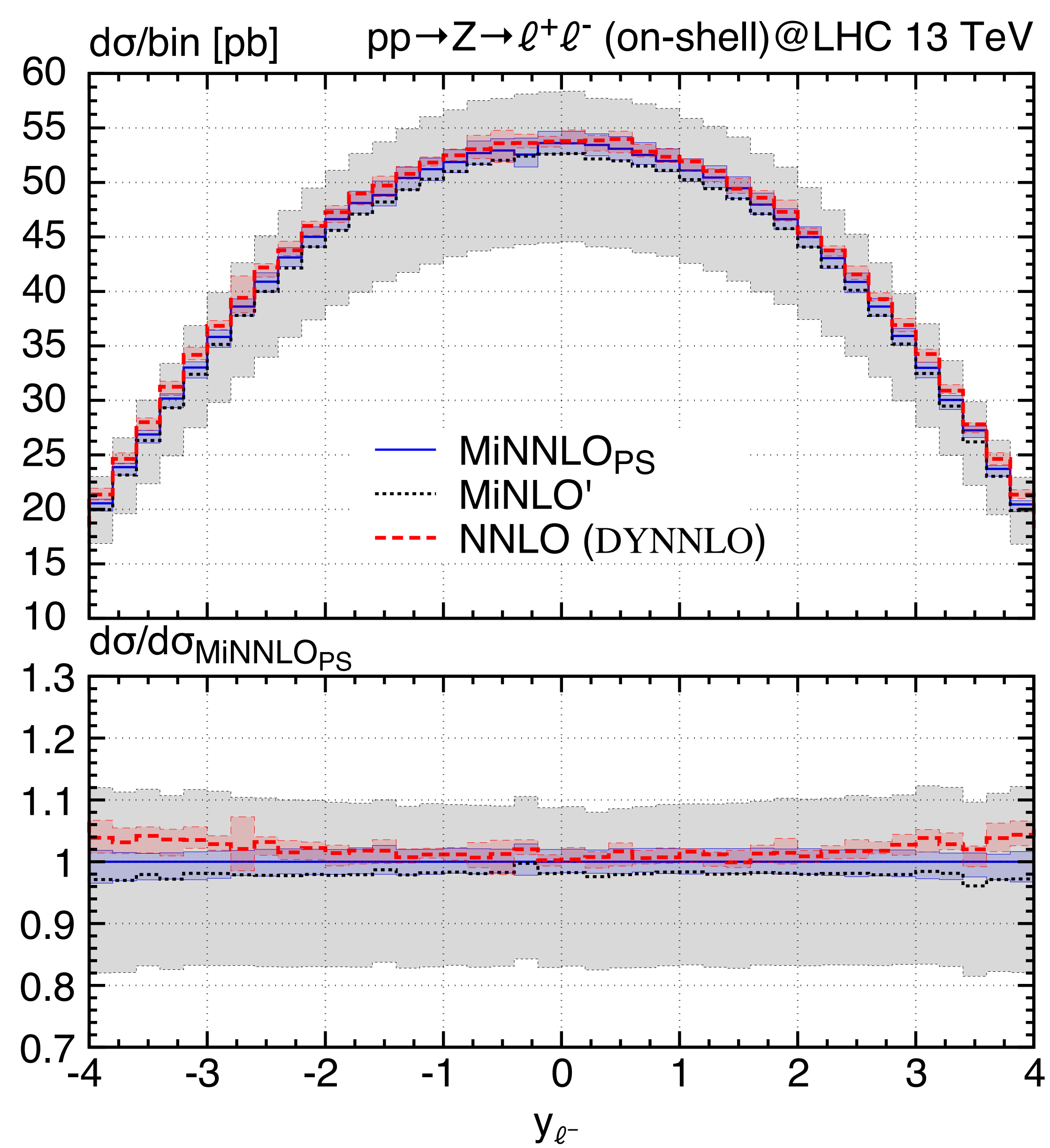


MiNNLO$_{PS}$ results

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

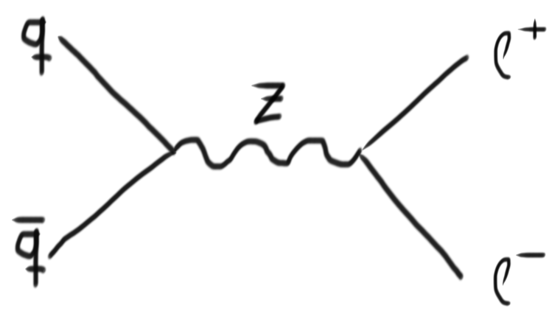


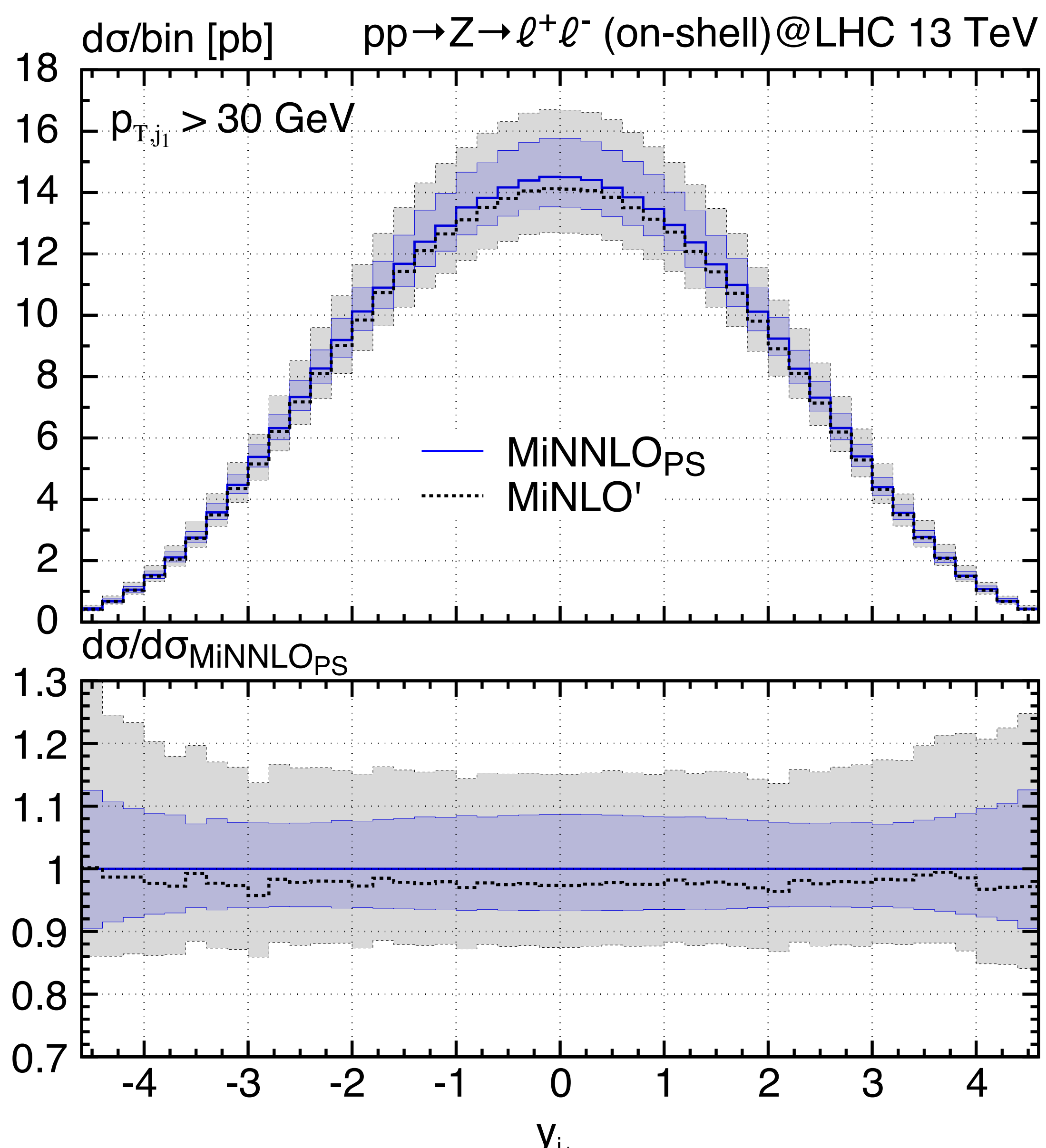


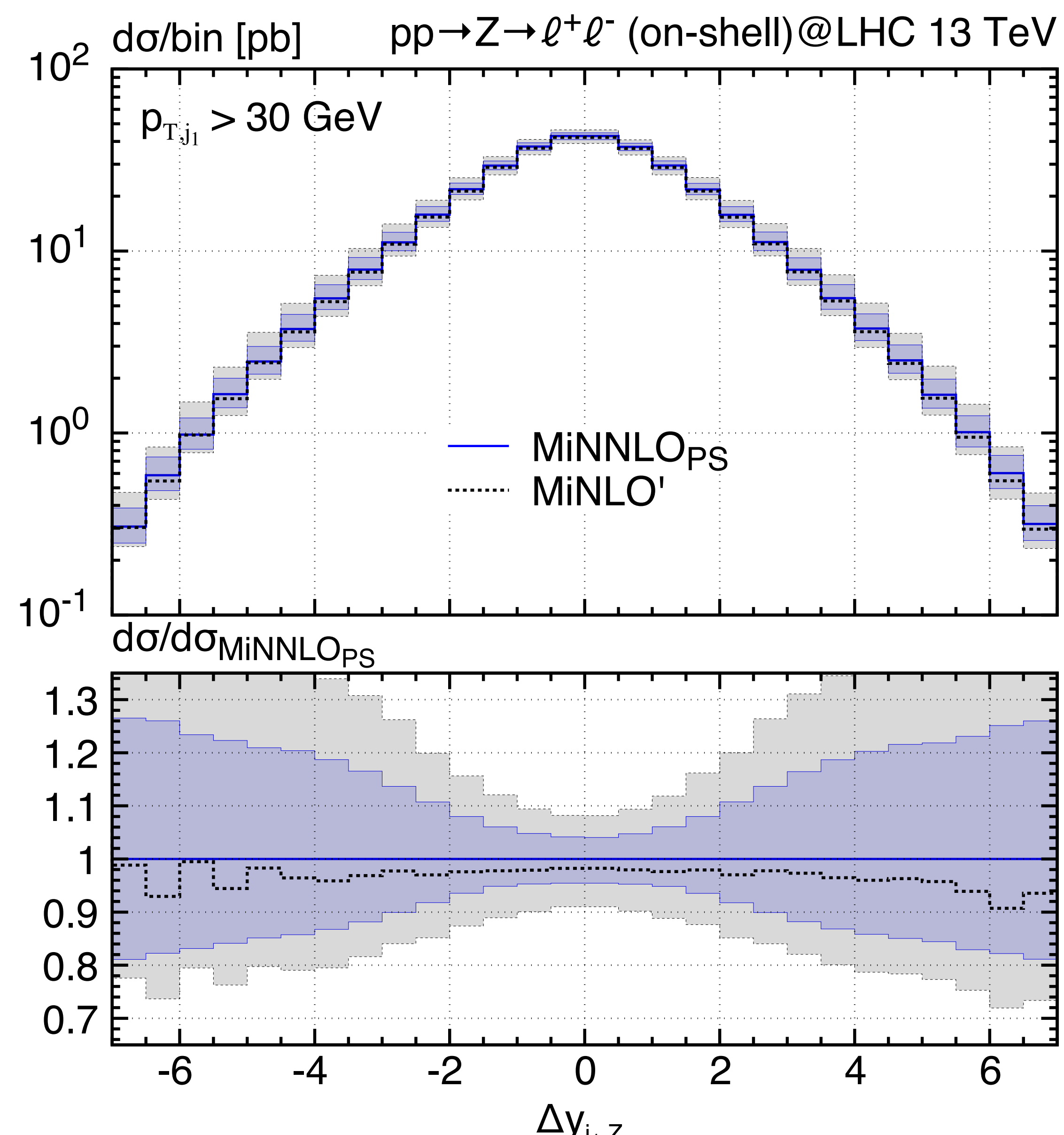


MiNNLO$_{PS}$ results

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



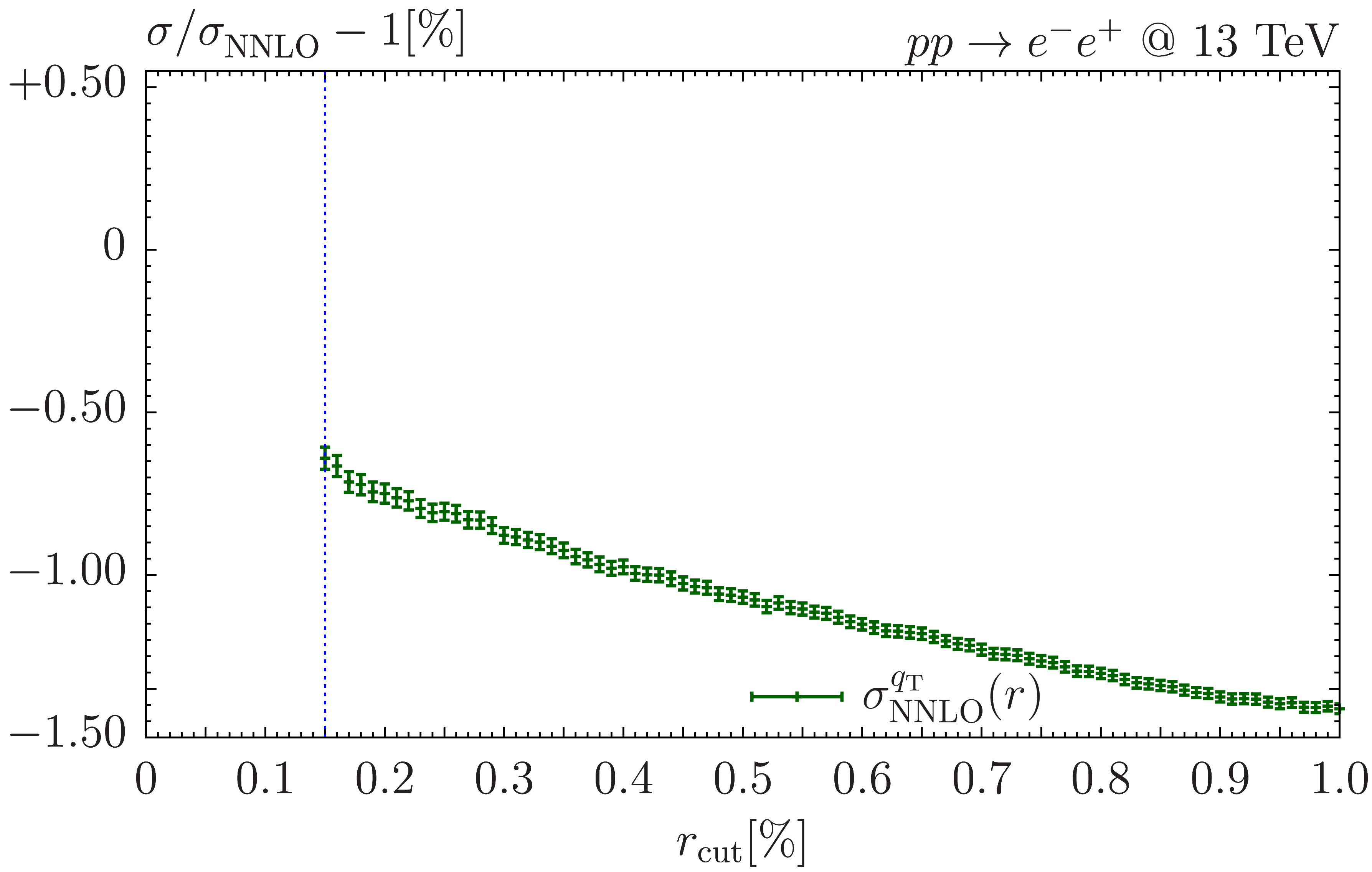




$r_{cut}\to 0$ extrapolation in MATRIX

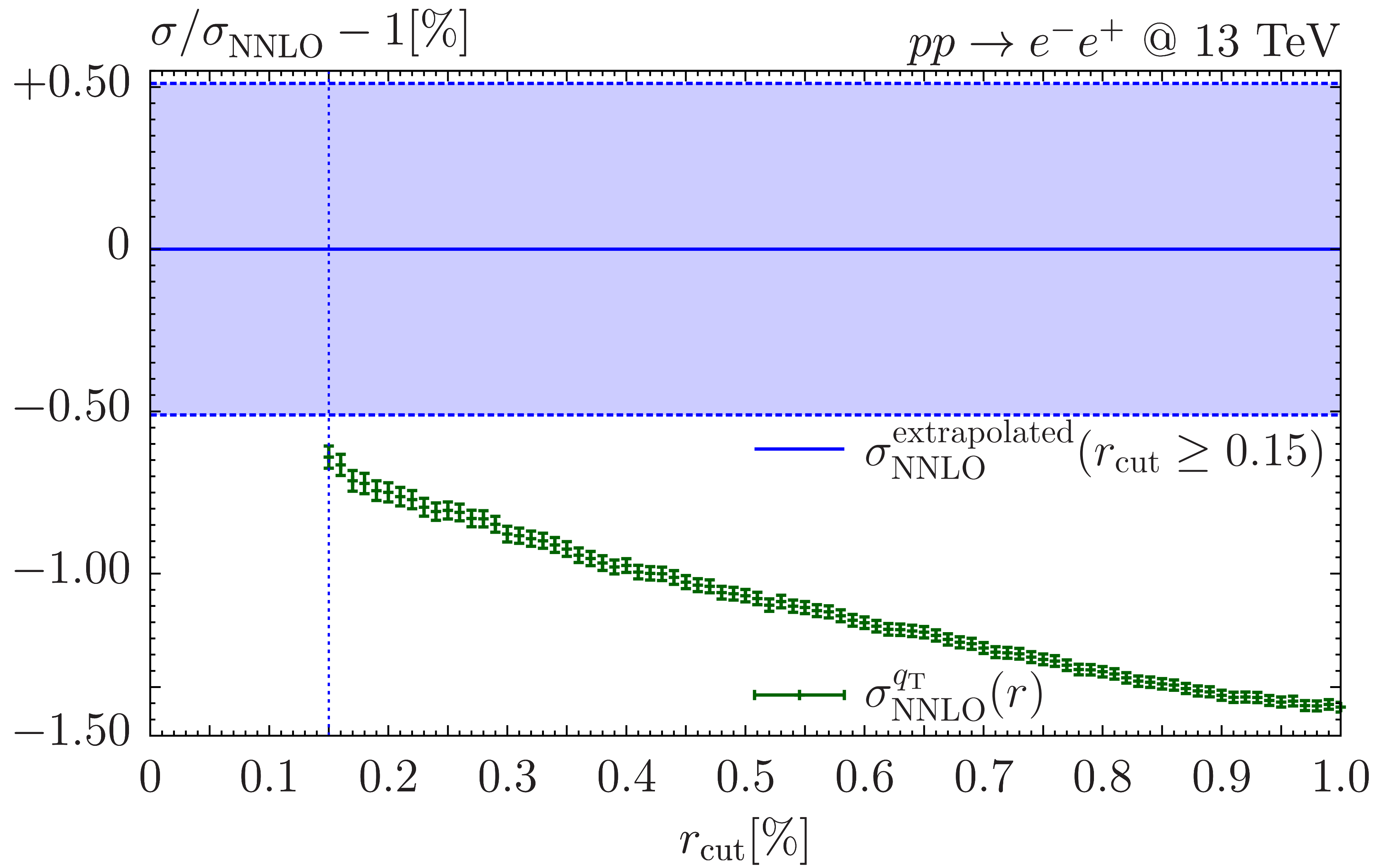
[Grazzini, Kallweit, MW '17]

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



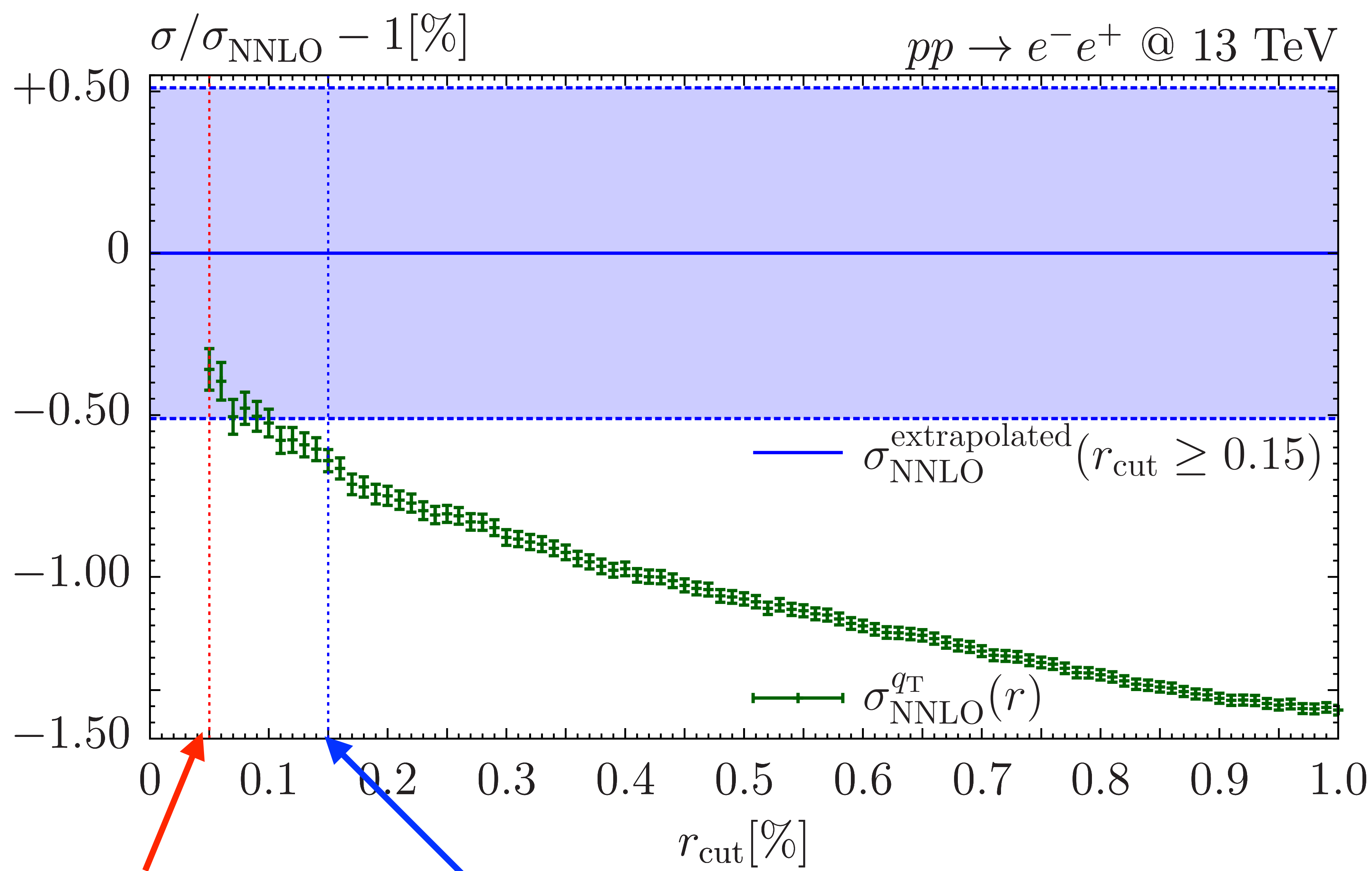
$r_{cut} \to 0$ extrapolation in MATRIX

[Grazzini, Kallweit, MW '17]



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

[Grazzini, Kallweit, MW '17]

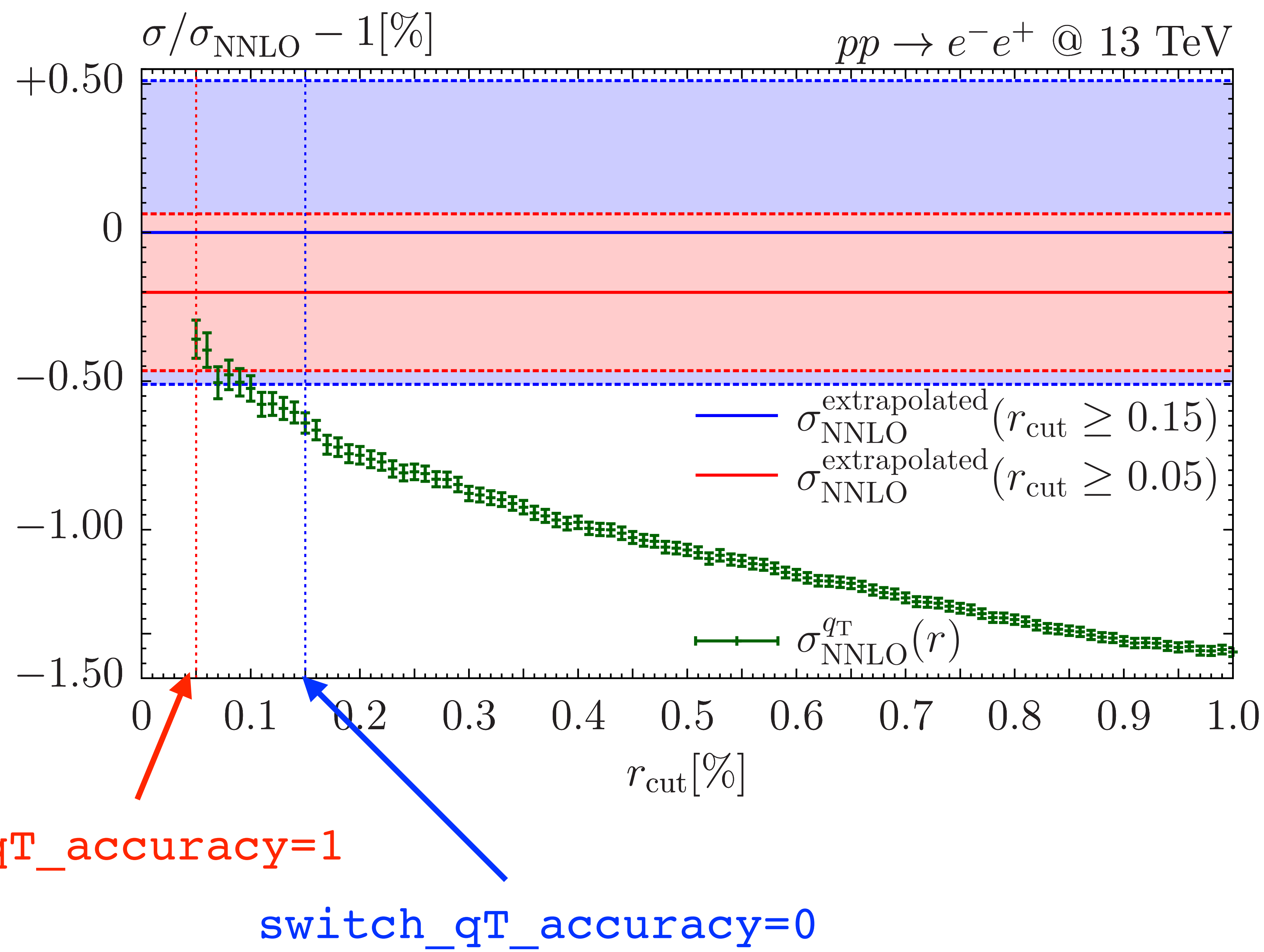


switch_qT_accuracy=1

switch_qT_accuracy=0

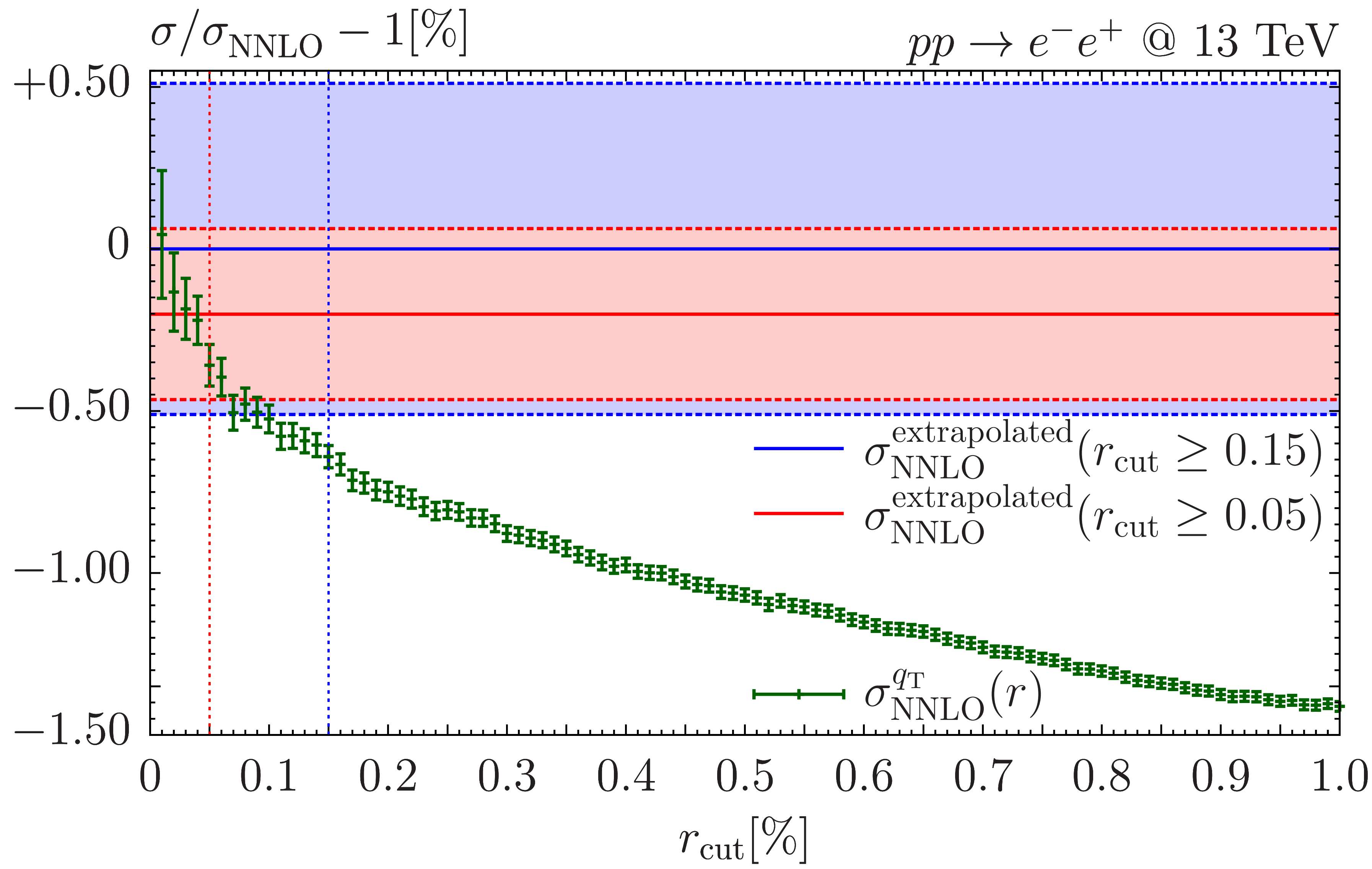
$r_{cut} \to 0$ extrapolation in MATRIX

[Grazzini, Kallweit, MW '17]



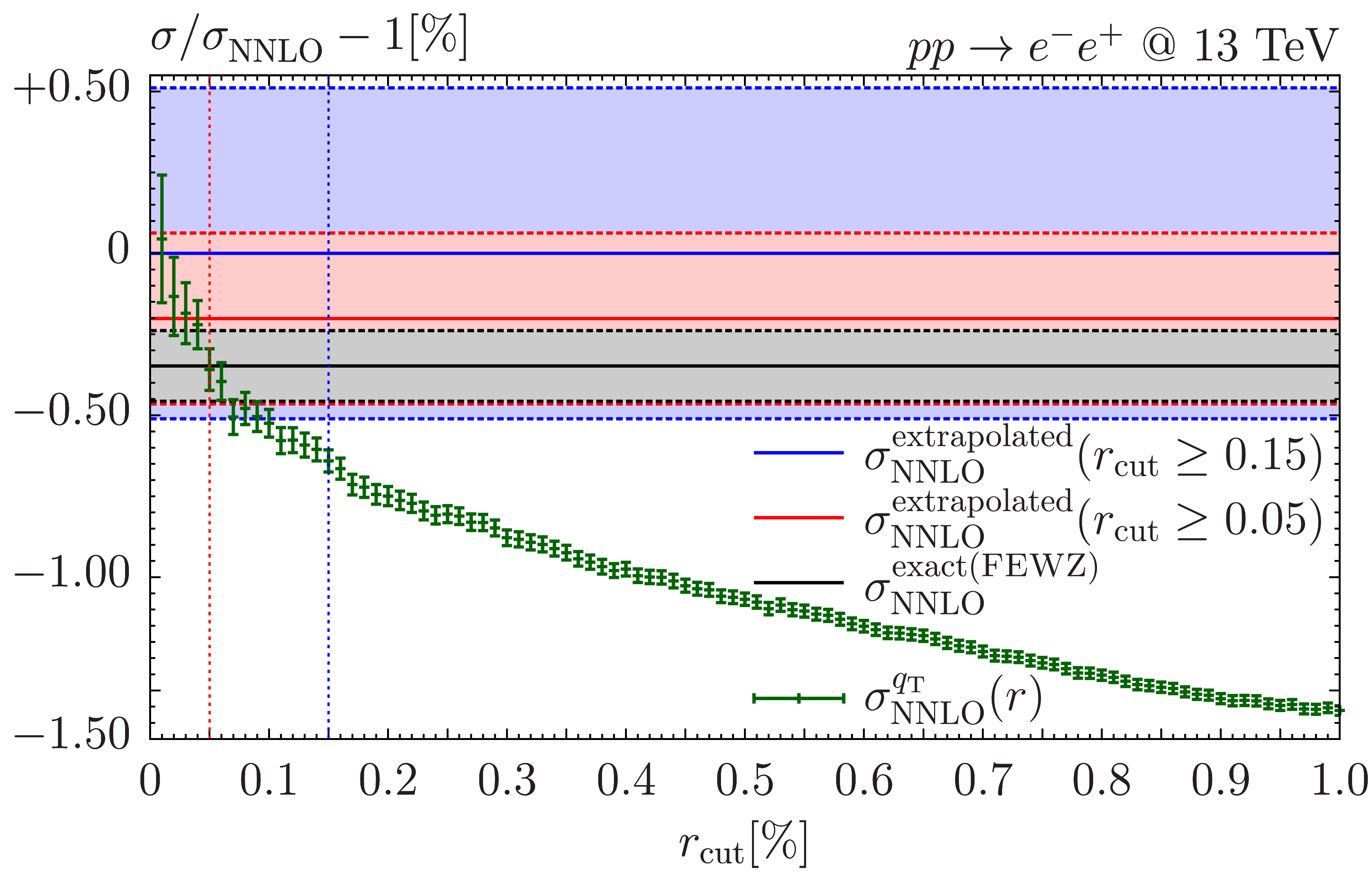
$r_{cut} \to 0$ extrapolation in MATRIX

[Grazzini, Kallweit, MW '17]



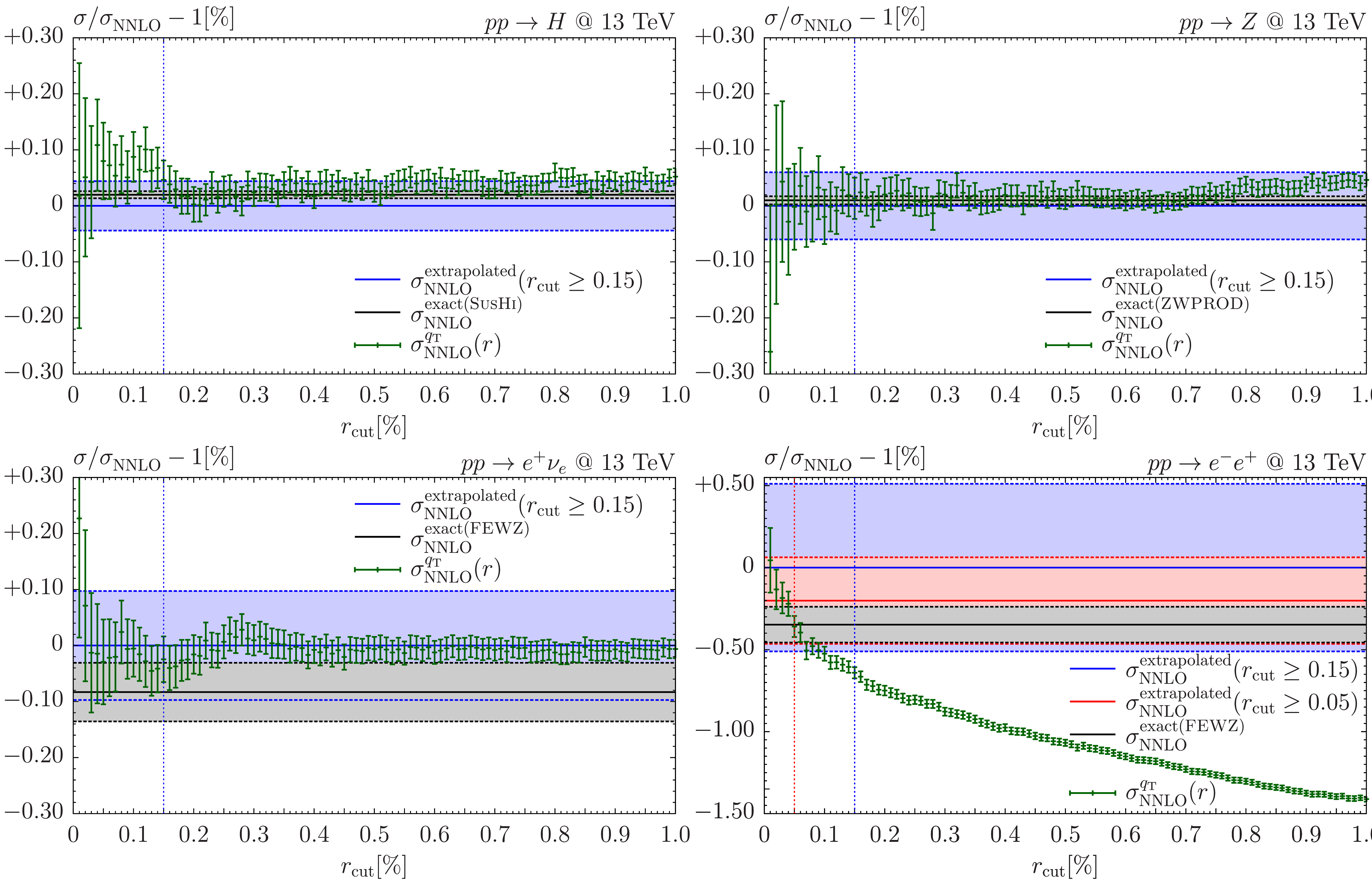
$r_{cut}\rightarrow 0$ extrapolation in MATRIX

[Grazzini, Kallweit, MW '17]



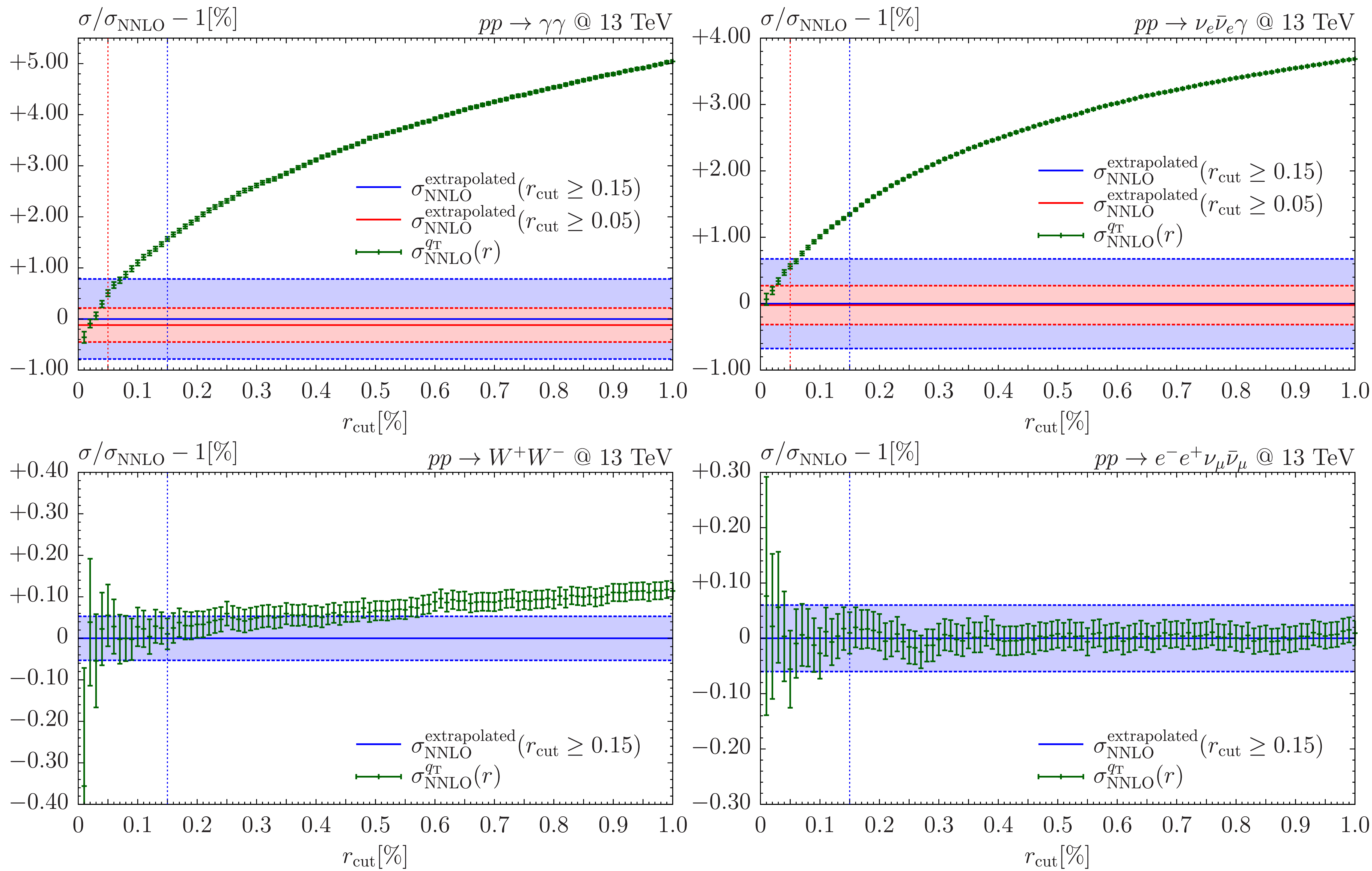
$r_{cut}\rightarrow 0$ extrapolation in MATRIX

[Grazzini, Kallweit, MW '17]



$r_{cut} \rightarrow 0$ 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