NLO EW overview for multi-bosons and VBS at LHCb

Mathieu PELLEN

University of Freiburg

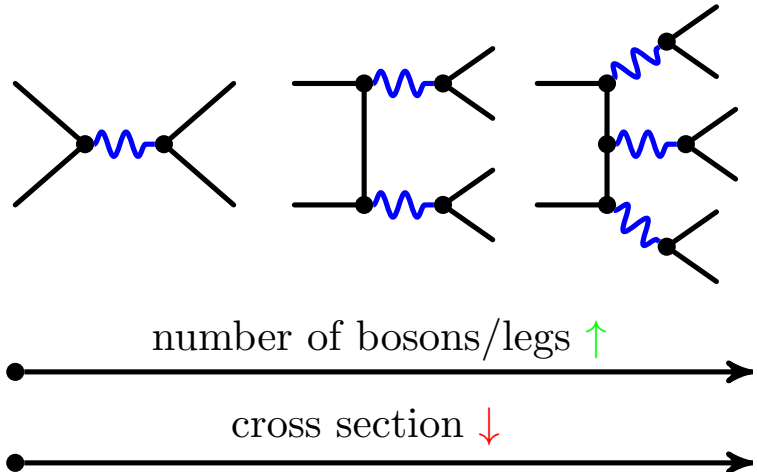
Multi-boson interaction 2022

Shanghai, China

23rd of August 2022

Precision for multiboson processes?!

- More bosons/couplings $\rightarrow$ Smaller cross sections!



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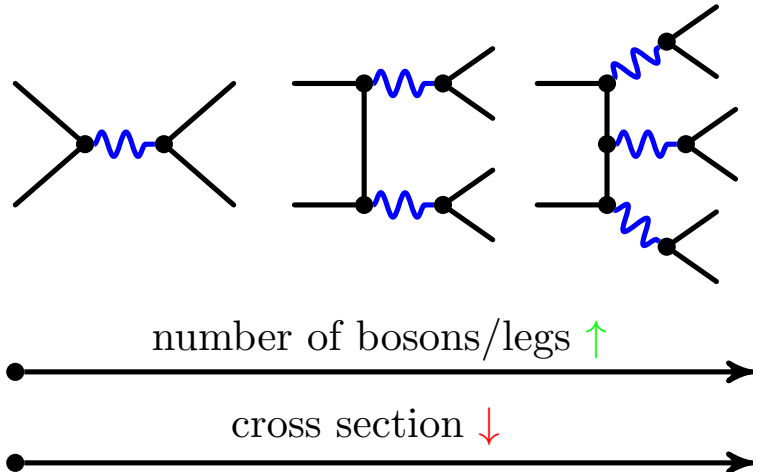

- Even VBS will enter the precision era at HL-LHC!

Integrated Luminosity	36 fb	150 fb	300 fb	3000 fb-
Year	2016	2019	2022	2038
EW(VBS) W±W±	20%	10%	7%	2%
EW (VBS) ZZ	35%	18%	13%	6%
EW (VBS) WZ	35% personally anticipated	18%	13%	6%

Jakob Salfeld-Nebgen in https://indico.cern.ch/event/711256 and CMS-PAS-SMP-14-008

Why EW corrections?

- $\alpha \sim \alpha_s^2 \rightarrow$ NLO EW as necessary as NNLO QCD

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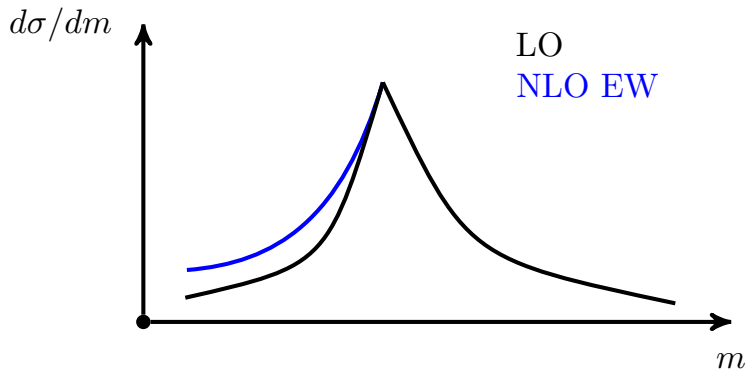

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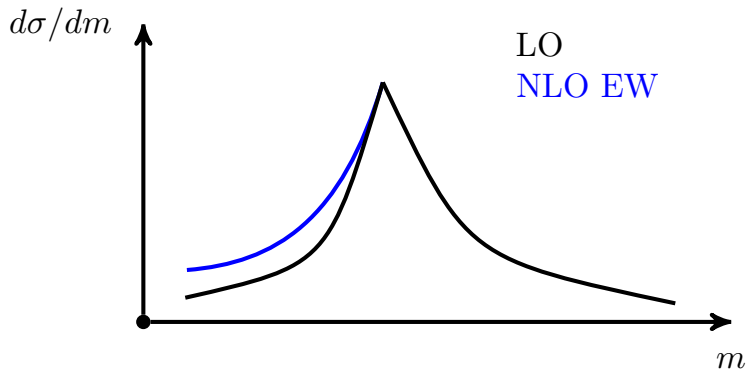
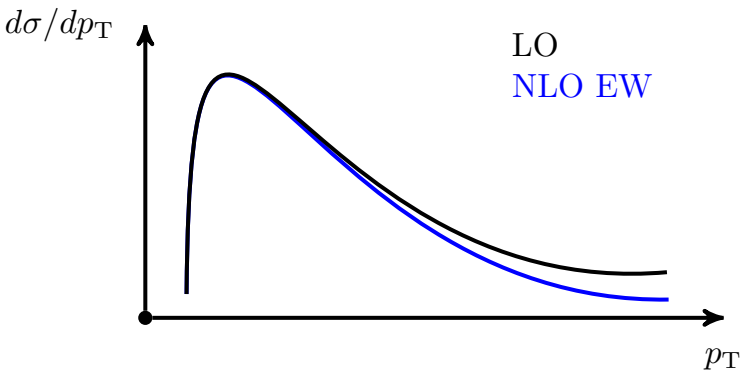
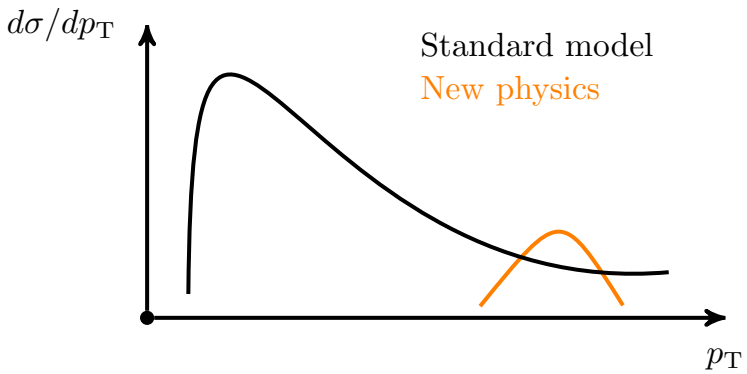
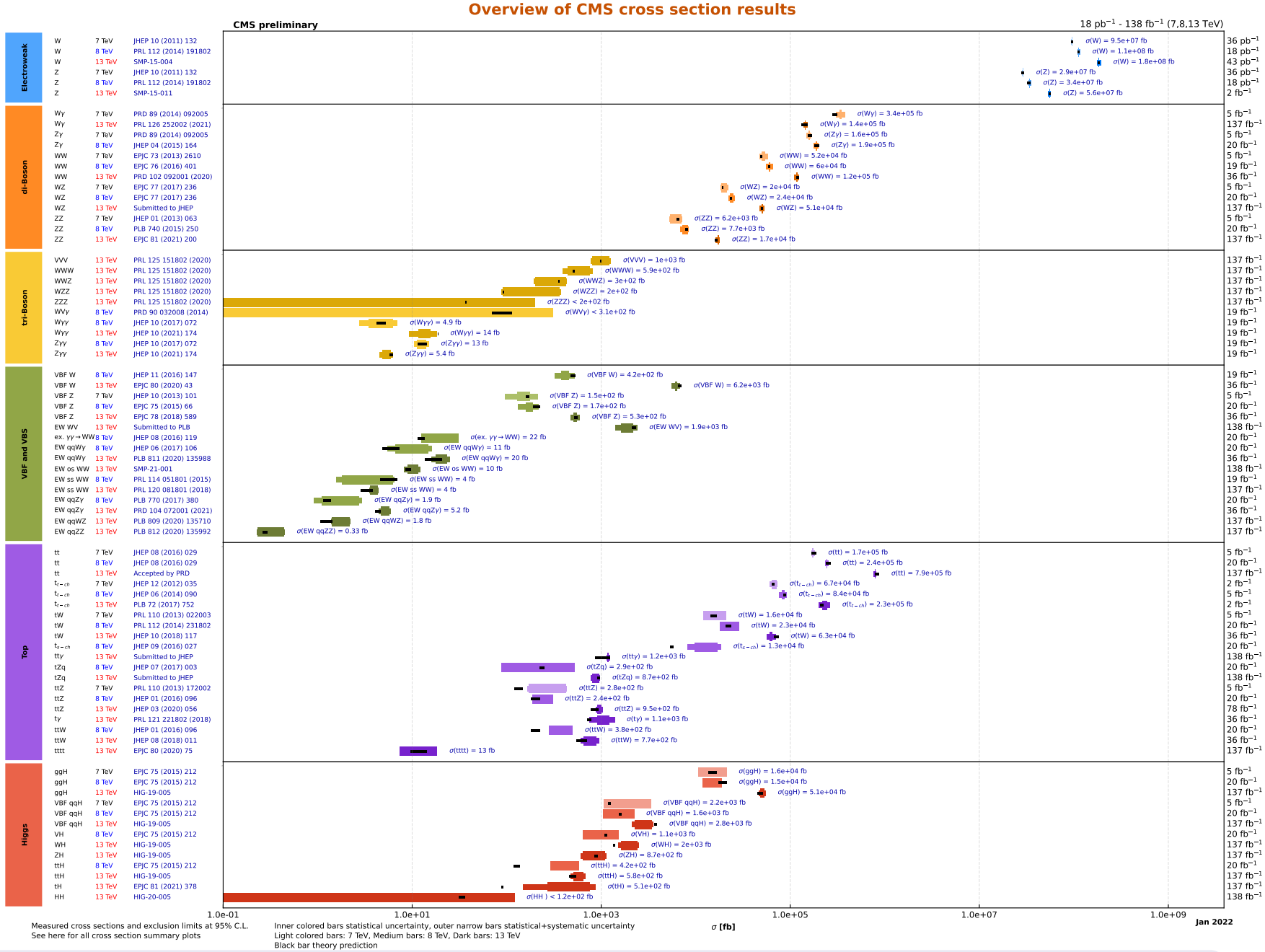


- Crucial for BSM searches







→ **Theory precision is required everywhere!**

Available (best) precision:

- VV:
  - NNLO QCD with PS $\sim$**2018** [Re, Wiesemann, Zanderighi; 1805.09857]
  - NLO EW $\sim$**2014** [Denner, Dittmaier, Hecht, Pasold; 1412.7421]
  - NLO QCD + EW with PS $\sim$**2020** [Chiesa, Oleari, Re; 2005.12146]

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- VV+j
  - NLO QCD + EW $\sim$**2015** [Li, Zhang, Ma, Guo, Li, Zhang; 1507.07332]
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- VV+jj
  - Full NLO QCD + EW ∼**2017** [Biedermann, Denner, MP; 1708.00268]
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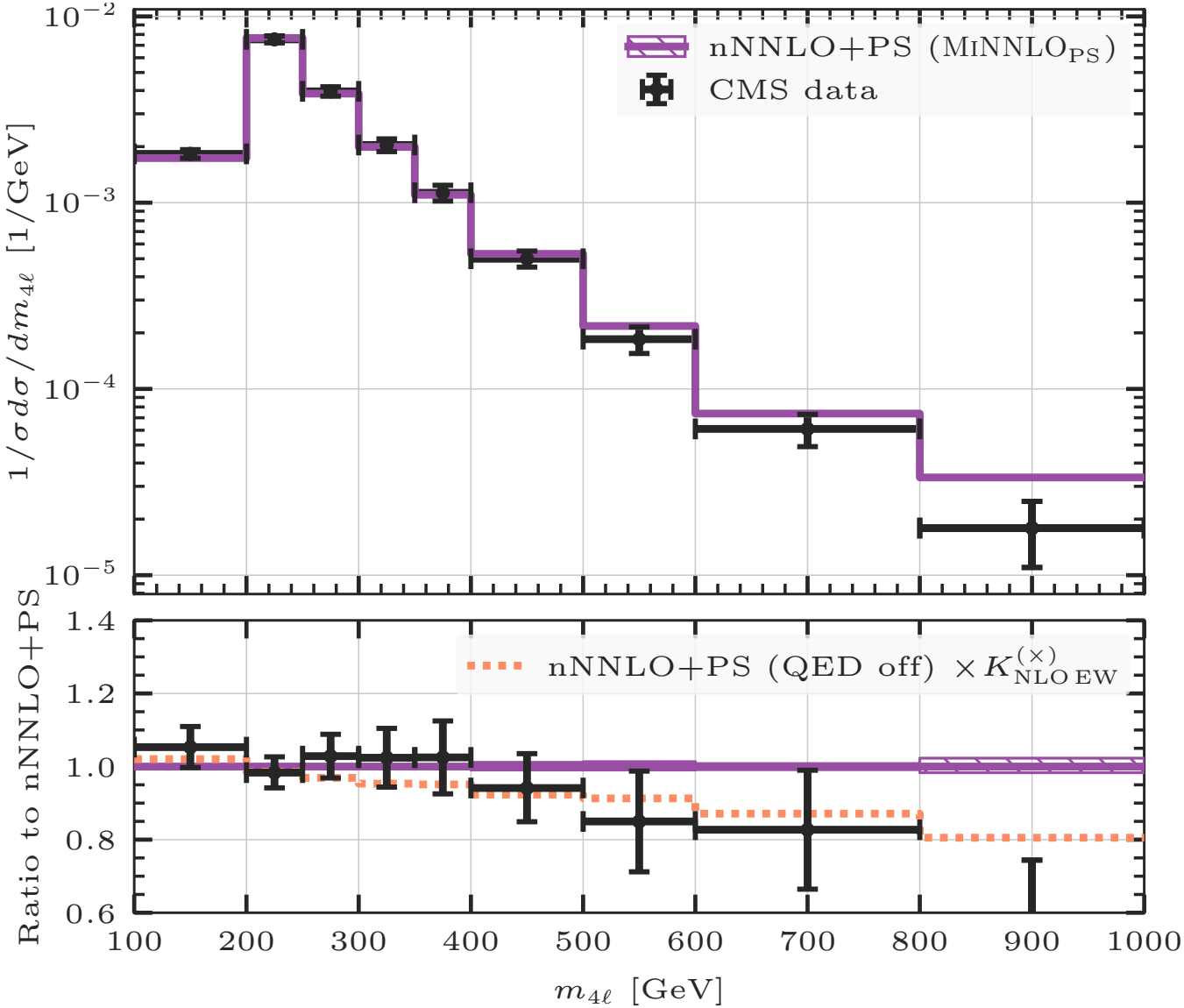
- VVV
  - NLO QCD ∼**2007** [Lazopoulos, Melnikov, Petriello; hep-ph/0703273]
    + EW ∼**2013** [Dao Thi, Le Duc, Weber; 1307.7403]

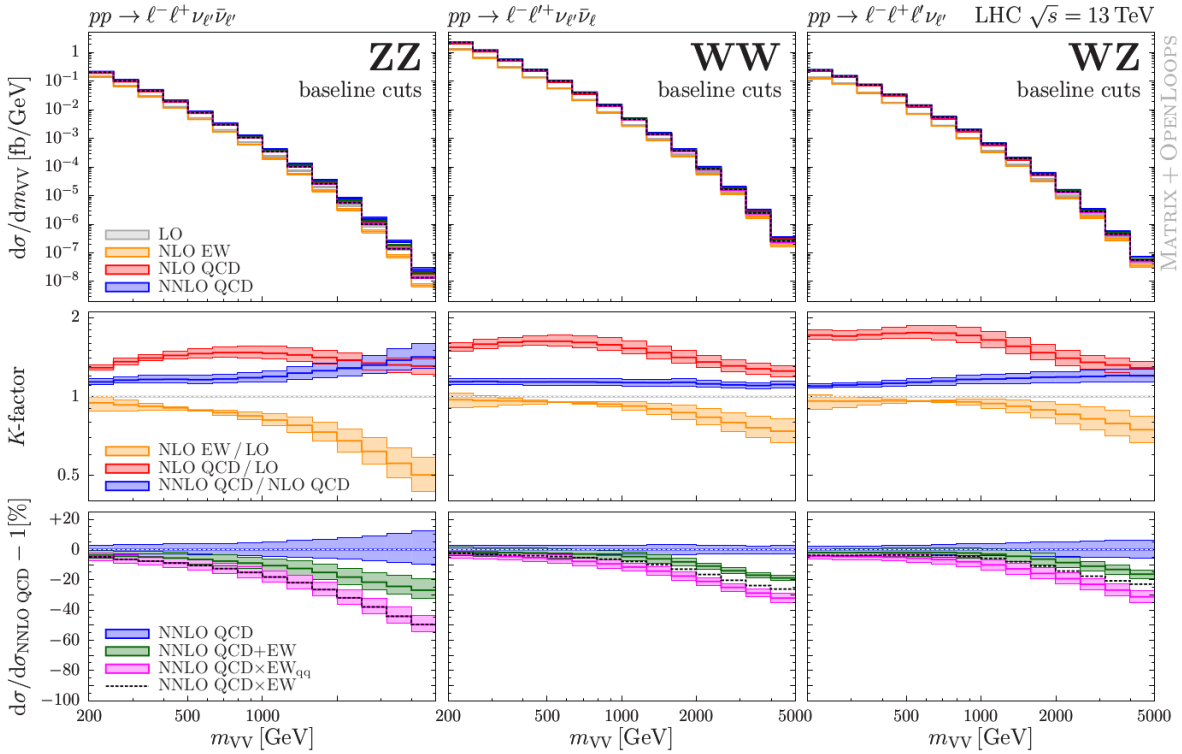
- VV(+j)
  - Fixed order
  - Matching to parton/photon shower
  - Multi-jet merging



[Buonocore, Koole, Lombardi, Rottoli, Wiesemann; 2108.05337]

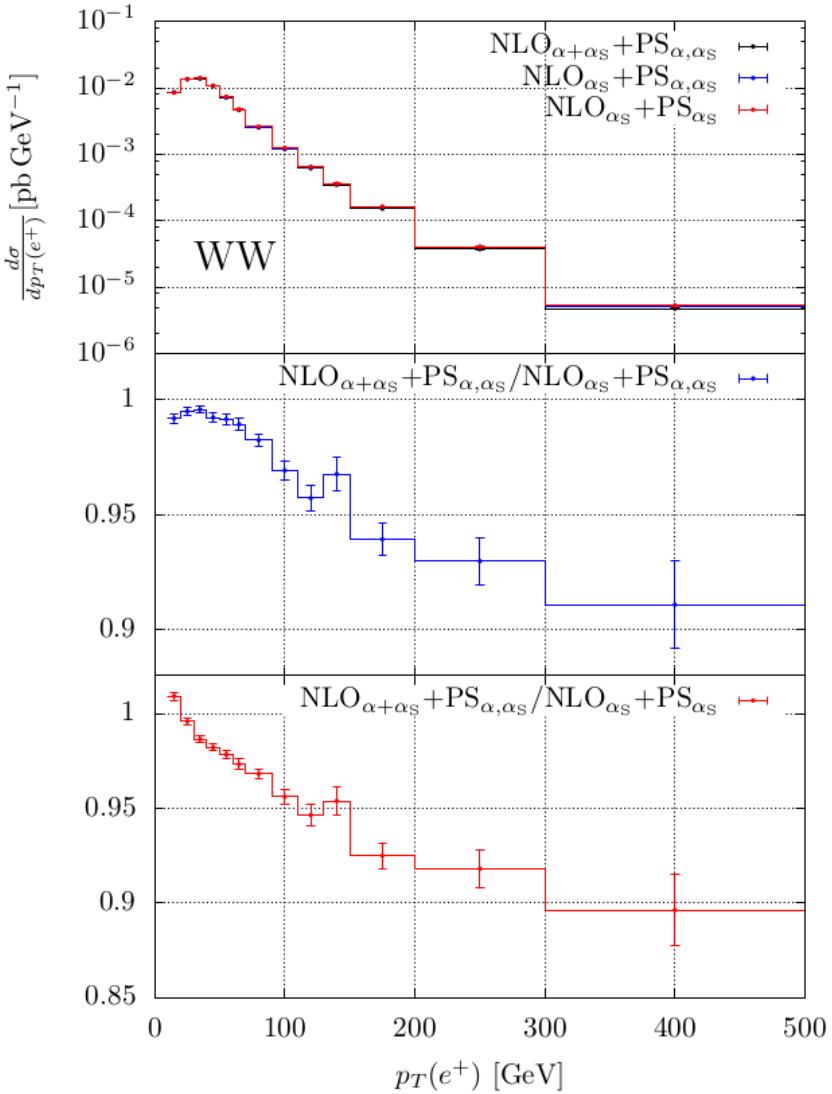
- Good agreement with data [CMS; 2009.01186] @13TeV ...
  ... up to EW corrections → critical for good data description

Fixed order



- State of the art (NNLO QCD+NLO EW) available in MATRIX+OPENLOOPS [Grazzini, Kallweit, Lindert, Wiesemann; 1912.00068]
- NLO EW also publicly available in:
  - MADGRAPH5_AMC@NLO [Frederix et al.; 1804.10017]
  - SHERPA+OPENLOOPS [Kallweit et al.; 1705.00598]
  - SHERPA+RECOLA [Biedermann, MP et al.; 1704.05783]

Matching to parton/photon shower



- Consistent matching of NLO QCD + EW to QCD/QED PS
  → Only available in POWHEG [Chiesa, Oleari, Re; 2005.12146]

Multi-jet merging

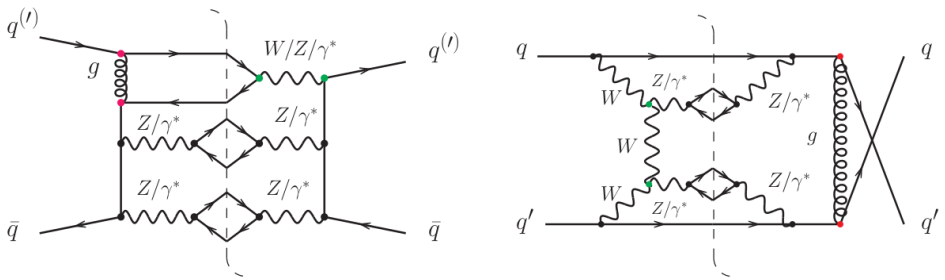
Higher-order EW corrections in ZZ and ZZj production at the LHC

Enrico Bothmann*[1], Davide Napoletano†[2], Marek Schönherr‡[3], Steffen Schumann§[1], and Simon Luca Villani¶[1]

[1] *Institut für Theoretische Physik, Georg-August-Universität Göttingen, 37077 Göttingen, Germany*
[2] *Università degli Studi di Milano-Bicocca & INFN, Piazza della Scienza 3, Milano 20126, Italy*
[3] *Institute for Particle Physics Phenomenology, Department of Physics, Durham University, Durham DH1 3LE, United Kingdom*

Motivation: include EW corrections along with QCD corrections

- Non trivial for QCD multi-merged samples
  → Extension of [Bräuer, Denner, MP, Schönherr, Schumann; 2005.12128] for WWj
- Complicated task due to interferences
- CPU costly for high multiplicity



NLO EW

Full V^{EW} + full real photon emission

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$\rightarrow$ real-emission approx. integrated (IR finite) [Kallweit et al.; 1511.08692]

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Only NLL part of V^{EW}

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NLO EW + NLL $\mathrm{EW}^{\mathrm{exp}}_{\mathrm{Sud}}$

$$\mathrm{d}\sigma^{\mathrm{NLO\ EW+NLL\ EW}^{\mathrm{exp}}_{\mathrm{sud}}} \sim \left[\exp\left(\delta^{\mathrm{EW}}_{\mathrm{Sud}}\right) - \delta^{\mathrm{EW}}_{\mathrm{Sud}} + \delta^{\mathrm{EW}}\right]$$

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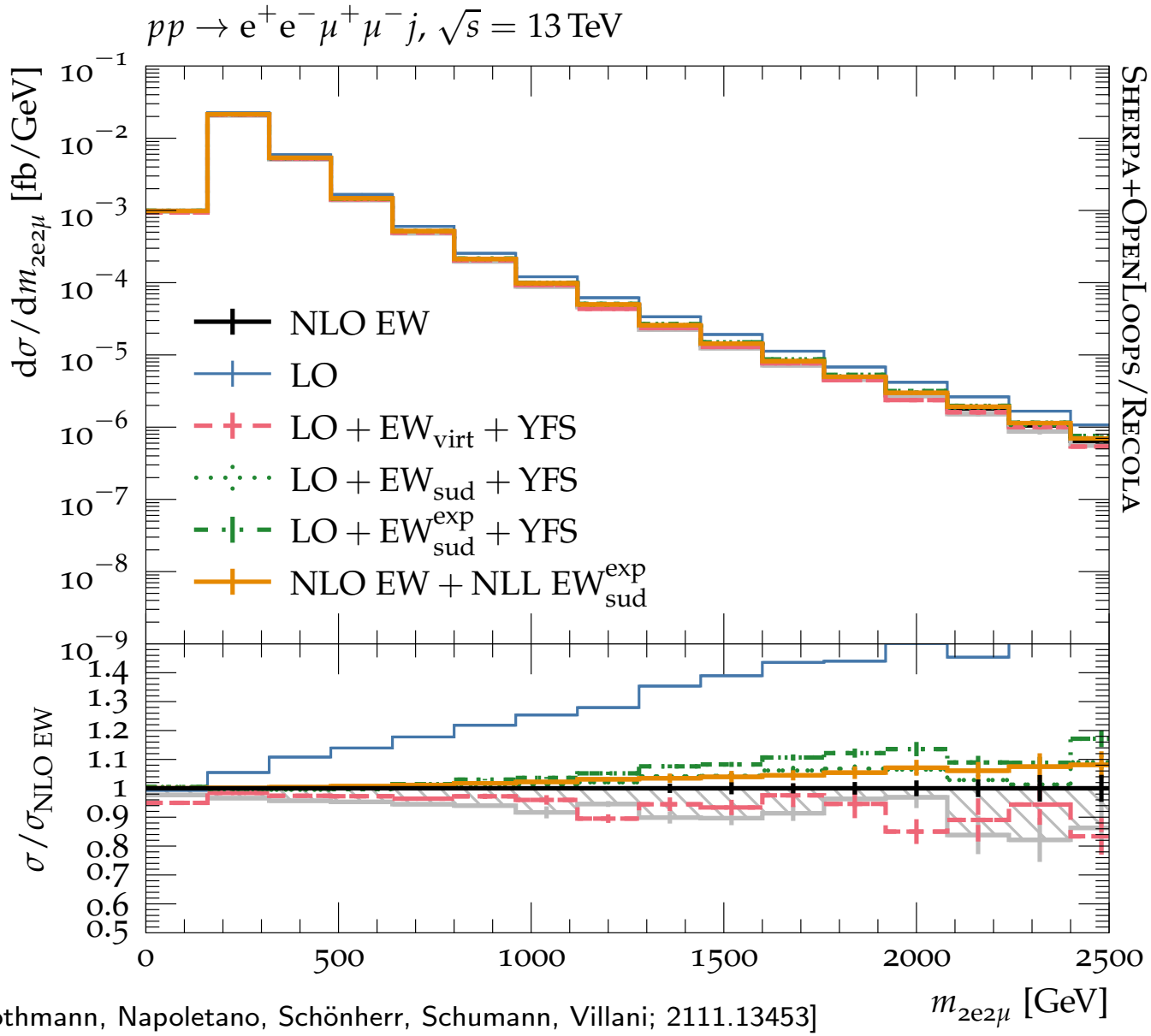
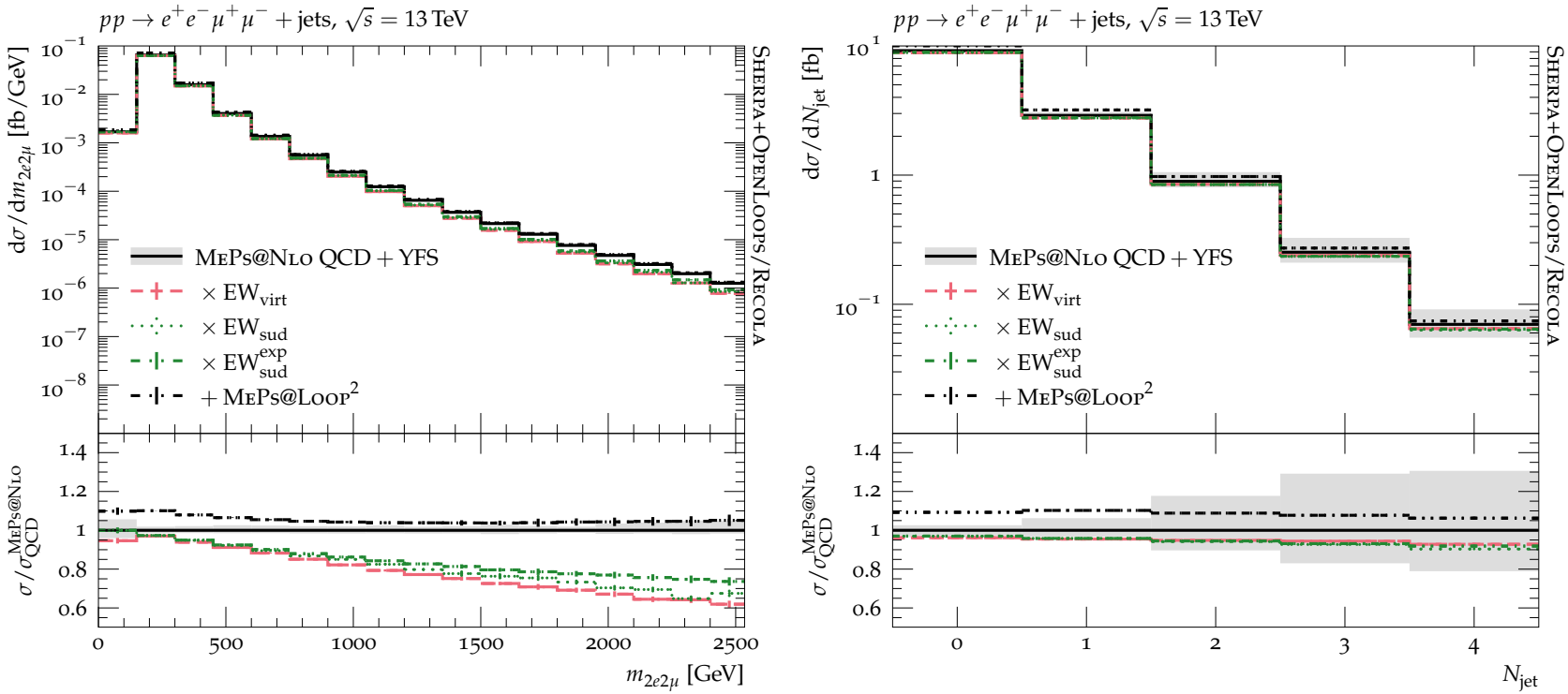
+YFS

Approximately account for photon radiation



[Bothmann, Napoletano, Schönherr, Schumann, Villani; 2111.13453]

- Rather good approximation(s)



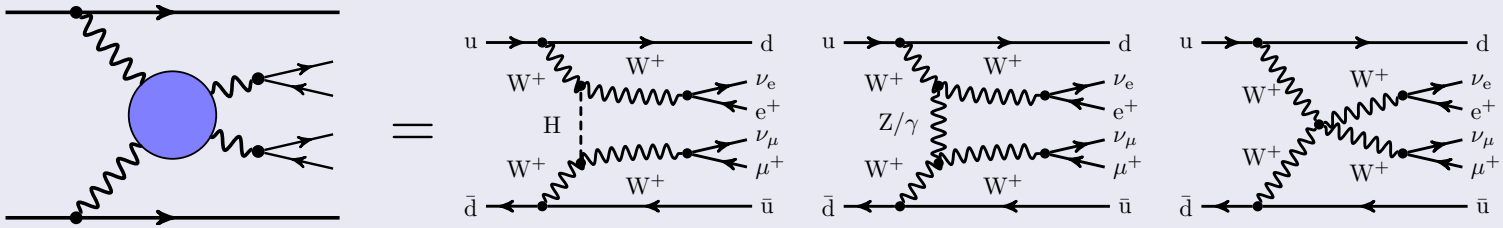
[Bothmann, Napoletano, Schönherr, Schumann, Villani; 2111.13453]

- Multi-merged predictions including approximate EW corrections for ZZ+(jets)

- VV+jj

Example: $pp \to \mu^+\nu_\mu e^+\nu_e jj$ (aka *same-sign WW VBS*)

VBS diagrams



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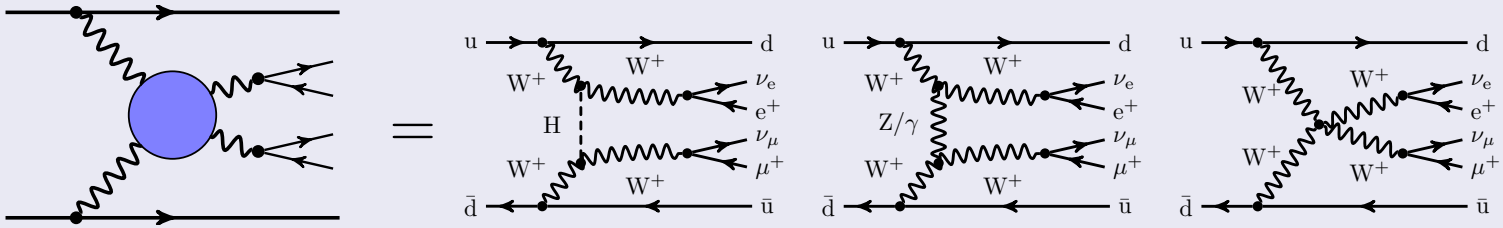
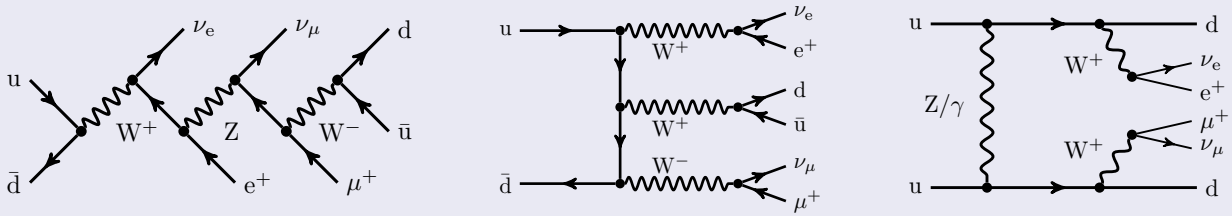


More diagrams contribute ...

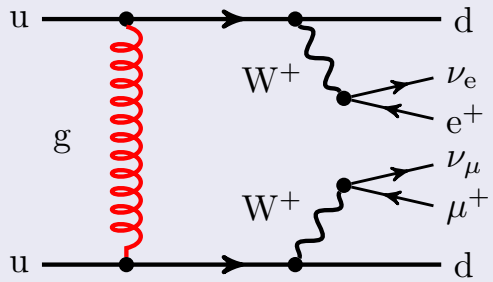


⚠ Gauge invariance: diagrams cannot be cherry picked!

VBS *signatures* possess more than VBS *contributions*:
→ All contributions are experimentally measured

(VBS, tri-boson, decay chains, etc.)

Even more (QCD) diagrams ...



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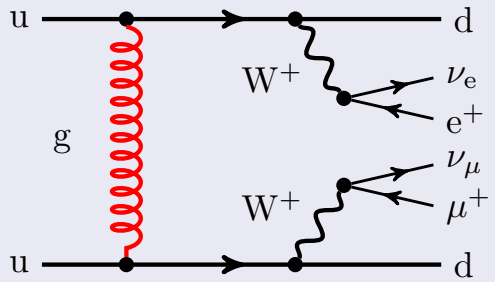
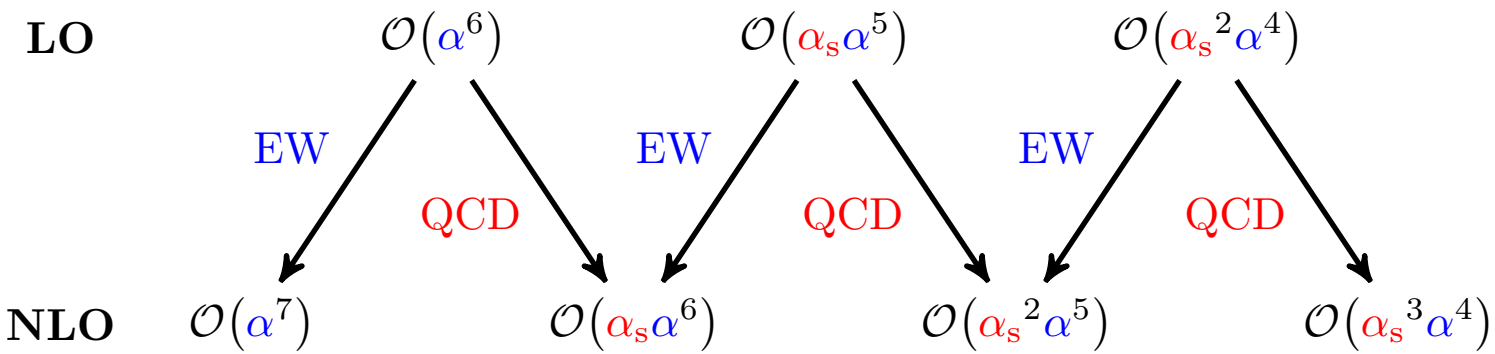


With 2 different amplitudes $\rightarrow$ 3 different contributions:

- $\mathcal{O}\left(\alpha^6\right)$: EW contribution/signal
- $\mathcal{O}\left(\alpha_s\alpha^5\right)$: interference
- $\mathcal{O}\left(\alpha_s{}^2\alpha^4\right)$: QCD contribution/background



Understanding ∼2017

→ Example: $\mathrm{W^+W^+}$

- LO

Order	$\mathcal{O}(\alpha^6)$	$\mathcal{O}(\alpha_s\alpha^5)$	$\mathcal{O}(\alpha_s^2\alpha^4)$
fraction [%]	86.5	2.9	10.5

Understanding ∼2017

→ Example: W^+W^+

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Order	$\mathcal{O}(\alpha^6)$	$\mathcal{O}(\alpha_s\alpha^5)$	$\mathcal{O}(\alpha_s^2\alpha^4)$
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- NLO

Order	$\mathcal{O}(\alpha^7)$	$\mathcal{O}(\alpha_s\alpha^6)$	$\mathcal{O}(\alpha_s^2\alpha^5)$	$\mathcal{O}(\alpha_s^3\alpha^4)$
$\delta\sigma_{\mathrm{NLO}}/\sigma_{\mathrm{LO}}$[%]	−13.2	−3.5	0.0	−0.4

[Biedermann, Denner, MP; 1708.00268]

- Large EW corrections as intrinsic feature of VBS [Biedermann, Denner, MP; 1611.02951]
- EW corrections are the dominant NLO correction

  → Confirmed in [Denner, Dittmaier, Maierhöfer, MP, Schwan; 1611.02951] where $\mathcal{O}\left(\alpha^7\right)$ and $\mathcal{O}\left(\alpha_s\alpha^6\right)$ were computed for WZ

Understanding ∼2021

→ Example: ZZ for $m_{jj} > 100\,\text{GeV}$

- LO

Order	$\mathcal{O}(\alpha^6)$	$\mathcal{O}(\alpha_s\alpha^5)$	$\mathcal{O}(\alpha_s^2\alpha^4)$
fraction [%]	8.36	0.74	90.91

Understanding ∼2021

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- NLO

Order	$\mathcal{O}(\alpha^7)$	$\mathcal{O}(\alpha_s\alpha^6)$	$\mathcal{O}(\alpha_s^2\alpha^5)$	$\mathcal{O}(\alpha_s^3\alpha^4)$
$\delta\sigma_{\text{NLO}}/\sigma_{\text{LO}}$[%]	−1.33	1.98	−7.14	−4.5

[Denner, Franken, MP, Schmidt; 2107.10688]

- Small $\mathcal{O}(\alpha_s^2\alpha^5)$ in W^+W^+ due to accidental cancellation
- ⚠ All NLO corrections are relevant and dependent on phase-space

Understanding ∼2021

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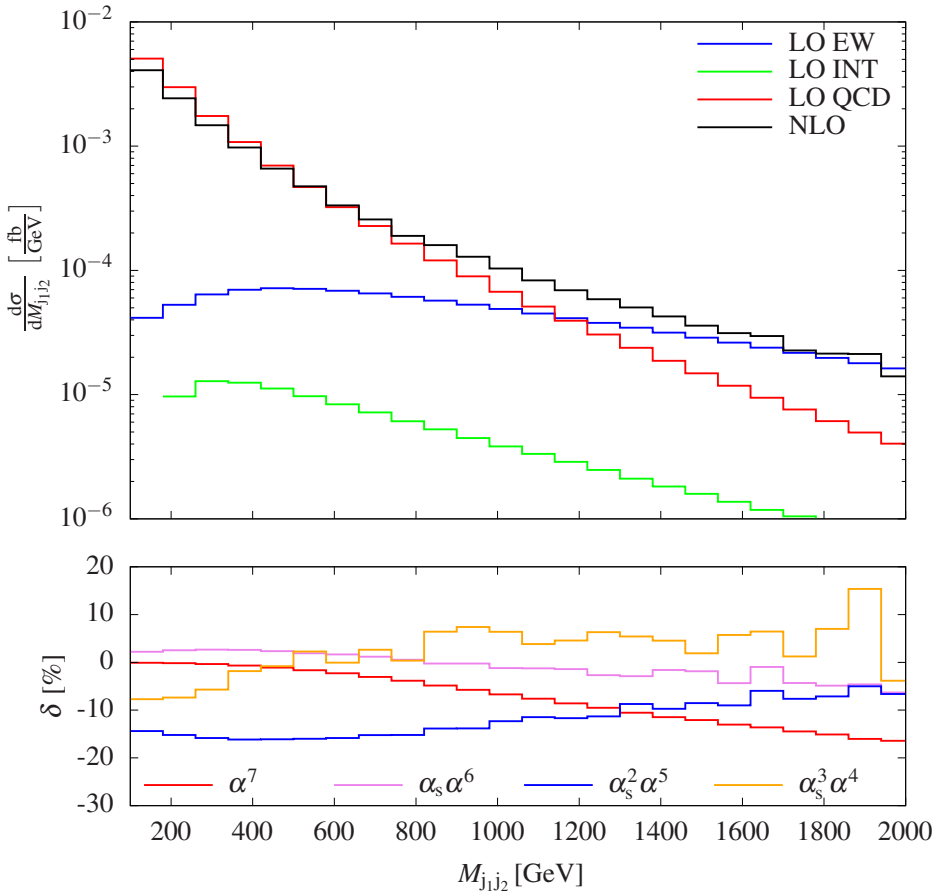


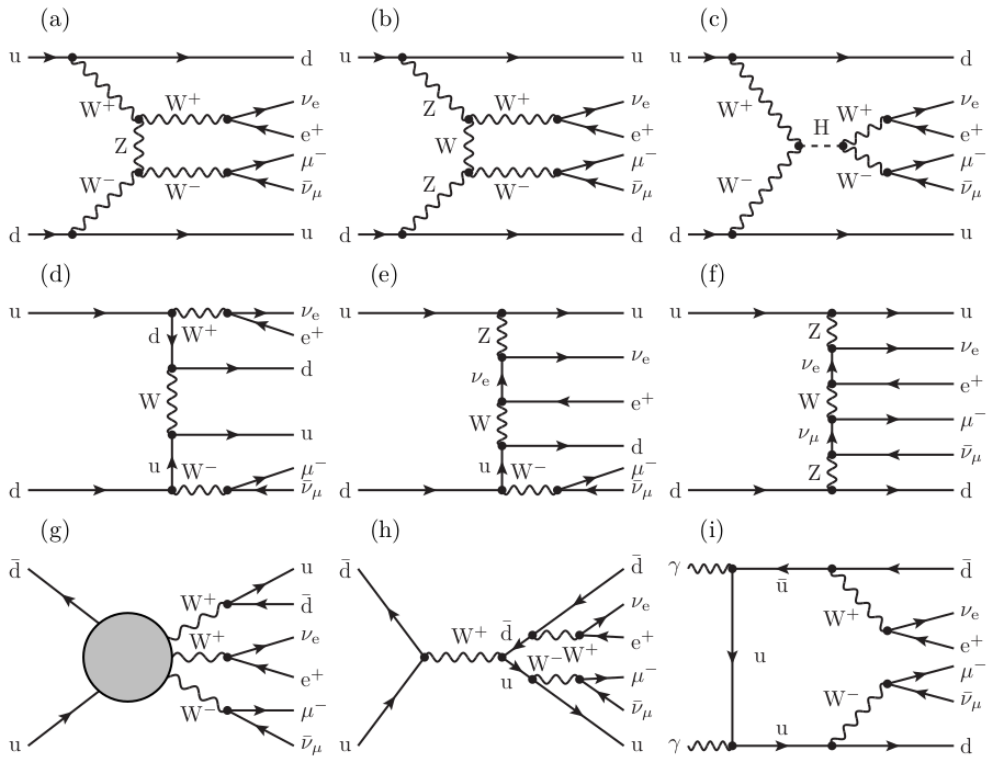
[Denner, Franken, MP, Schmidt; 2107.10688]

- ⚠ Non-trivial structure differentially

Understanding ∼2022

- NLO QCD and EW for VBS W^+W^-

  [Denner, Franken, Schmidt, Schwan; 2207.11264]



- Interplay between VBS ($H \to W^+W^-$) and VBS W^+W^-
  $\to$ NLO EW corrections are large for VBS
  $\to$ NLO EW corrections are moderate for VBF

Understanding ∼2022

Process	W^+W^+	W^+Z	ZZ	W^+W^- (VBS setup)	W^+W^- (Higgs setup)
$\Delta\sigma^{\alpha^7}_{\text{NLO}}$[fb]	−0.2169(3)	−0.04091(2)	−0.015573(5)	−0.307(1)	−0.103(1)
$\sigma^{\alpha^6}_{\text{LO}}$[fb]	1.4178(2)	0.25511(1)	0.097683(2)	2.6988(3)	1.5322(2)
δ^{α^7}[%]	−15.3	−16.0	−15.9	−11.4	−6.7

→ Size of corrections driven by typical scales of the process

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δ^{α^7}[%]	−15.3	−16.0	−15.9	−11.4	−6.7

- Applying unphysical cut:

$$|M_{4\ell} - M_{\text{H}}| \leqslant 20\Gamma_{\text{H}}$$

→ in the VBS setup:

- Excluding resonance: $\delta_{\text{NLOEW}} = -13.2\%$
- Selection only resonance: $\delta_{\text{NLOEW}} = -6.5\%$

→ Size of corrections driven by typical scales of the process

→ Status for ss-WW (best known channel):

Order	$\mathcal{O}\left(\alpha^7\right)$	$\mathcal{O}\left(\alpha_s\alpha^6\right)$	$\mathcal{O}\left(\alpha_s{}^2\alpha^5\right)$	$\mathcal{O}\left(\alpha_s{}^3\alpha^4\right)$
NLO	✓	✓	✓	✓
NLO+PS	✓	✓*	X	✓

(*) Computations in the VBS-approximation *i.e. t-u* interferences and tri-boson contributions neglected

→ See [Covarelli, MP, Zaro; 2102.10991] for review and more references

- For HL LHC, we should tick all boxes!
  → Experimental uncertainty $\sim$ few per cent

Comparison with data

ss-WW and WZ analysis of CMS with 137 fb^{-1} [2005.01173]

Process	$\sigma\,\mathcal{B}$ (fb) CMS exp.	Theory LO (fb)	Theory NLO (fb)
EW WW	$3.98 \pm 0.37\ \text{stat} \pm 0.25\ \text{syst}$	3.93 ± 0.57	3.31 ± 0.47
EW+QCD WW	$4.42 \pm 0.39\ \text{stat} \pm 0.25\ \text{syst}$	4.34 ± 0.69	3.72 ± 0.59
EW WZ	$1.81 \pm 0.39\ \text{stat} \pm 0.14\ \text{syst}$	1.41 ± 0.21	1.24 ± 0.18
EW+QCD WZ	$4.97 \pm 0.40\ \text{stat} \pm 0.23\ \text{syst}$	4.54 ± 0.90	4.36 ± 0.88
QCD WZ	$3.15 \pm 0.45\ \text{stat} \pm 0.18\ \text{syst}$	3.12 ± 0.70	3.12 ± 0.70

→ LO: MadGraph5_aMC@NLO+PYTHIA

→ NLO: MadGraph5_aMC@NLO+PYTHIA + NLO corr. from [Biedermann, Denner, MP; 1708.00268] or [Denner, Dittmaier, Maierhöfer, MP, Schwan; 1904.00882] but only to EW signal

NB: Uncertainty for the NLO numbers are from the LO 7-scales variation.

→ Set basis of future precision measurements

VBS @ LHCb [MP; 1908.06805]

⚠ No EW corrections

- VBS at LHC: large M_{jj} and large $|\Delta y_{jj}|$
  $\rightarrow$ jets clos to the beam line

  (inaccessible in ATLAS and CMS)

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$\rightarrow$ Not the case at LHCb!

- Idea: measure VBS at LHCb
  - Further test of the SM/ESWB ...
    ... in a different kinematic regime than ATLAS/CMS
    $\rightarrow$ enhanced sensitivity to particular BSM models?

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$\rightarrow$ Similar idea for top-quark processes at LHCb

[Gauld; 1311.1810], [LHCb; 1808.08865]

→ Golden channel for VBS at LHC: same-sign signature

(due to low irreducible background)

⚠ LHCb detector only on one side

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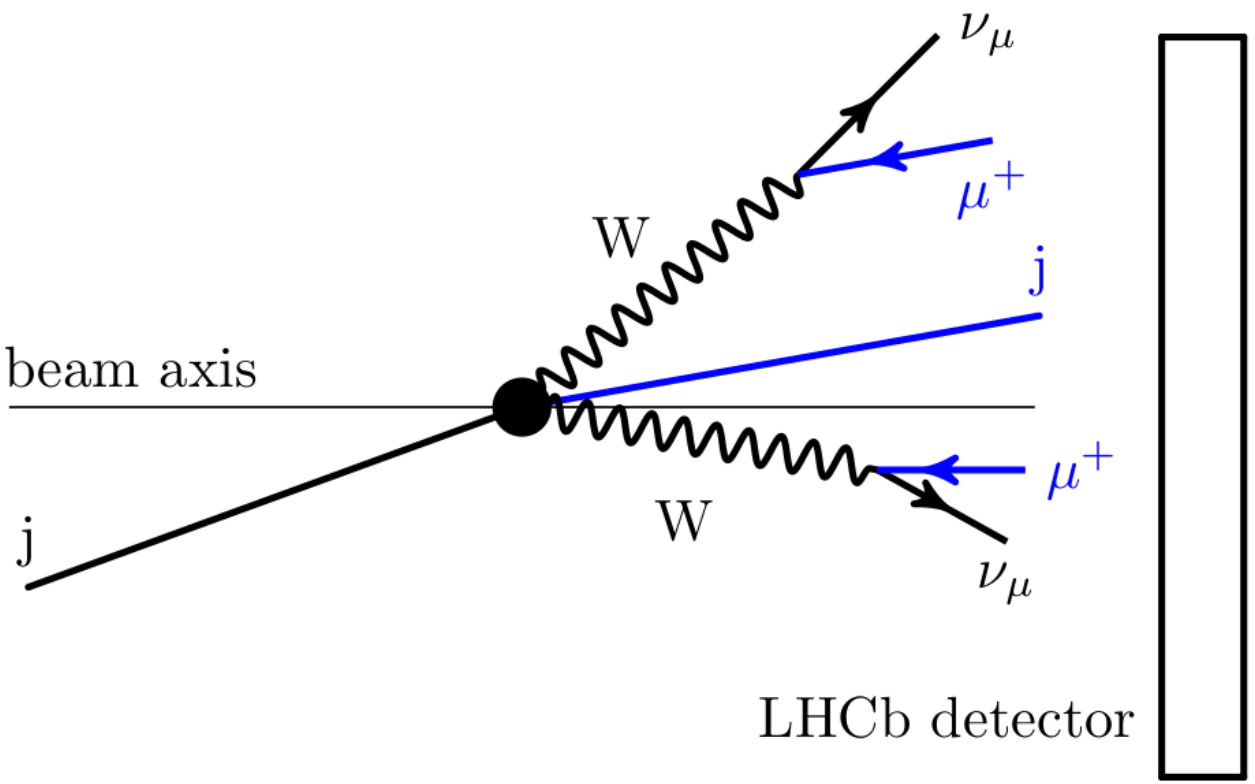
⚠ LHCb detector only on one side

→ experimental signature: $\ell^{\pm}\ell^{\pm} + \mathrm{j}$



- Event selection:

$$
\begin{aligned}
p_{\mathrm{T,j}} &> 20\,\mathrm{GeV}, \quad 2.2 < \eta_{\mathrm{j}} < 4.2, \\
p_{\mathrm{T},\mu^+} &> 20\,\mathrm{GeV}, \quad 2.0 < y_{\mu^+} < 4.5, \\
\Delta R_{\mathrm{j}\mu^+} &> 0.5.
\end{aligned}
$$

+ veto for extra OS lepton of with $2.0 < \eta_\ell < 4.5$

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$$\begin{aligned} \mathrm{pp} &\to \mu^+\nu_\mu\mu^+\nu_\mu\mathrm{jj} \quad (\mathrm{ss\ WW}), \\ \mathrm{pp} &\to \mu^+\nu_\mu\mu^+\mu^-\mathrm{jj} \quad (\mathrm{WZ}), \\ \mathrm{pp} &\to \mu^+\mu^-\mu^+\mu^-\mathrm{jj} \quad (\mathrm{ZZ}), \end{aligned}$$

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- Irreducible QCD background (⚠ only one jet tagged):

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Results (cross sections)

→ For $\mu^+\mu^+$:

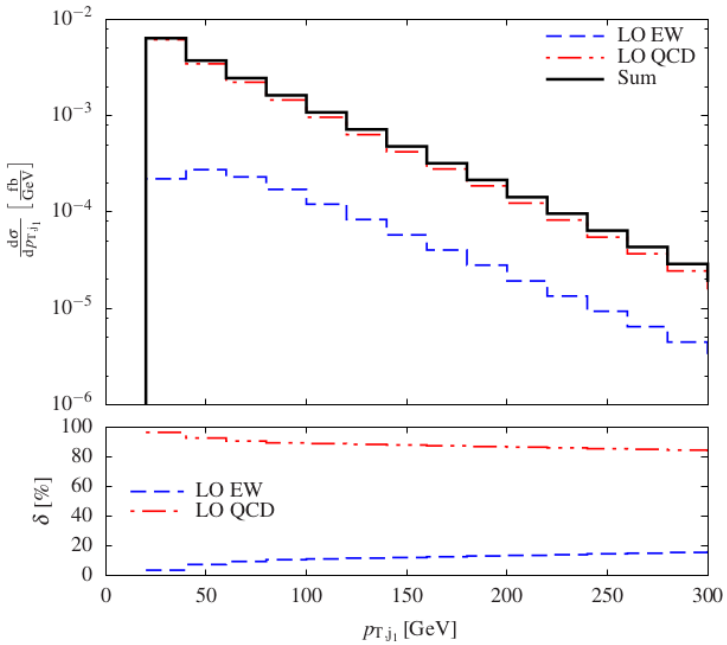
Channel	σ_{EW} [fb]	σ_{QCD} [fb]	$\sigma_{\text{EW}}/\sigma_{\text{QCD}}$
ss WW	0.0185(1)	0.0104(1)	1.78
WZ	0.0071(1)	0.2952(4)	0.02
ZZ	0.0003(1)	0.0161(1)	0.02
Sum	0.0258(1)	0.3217(4)	0.08

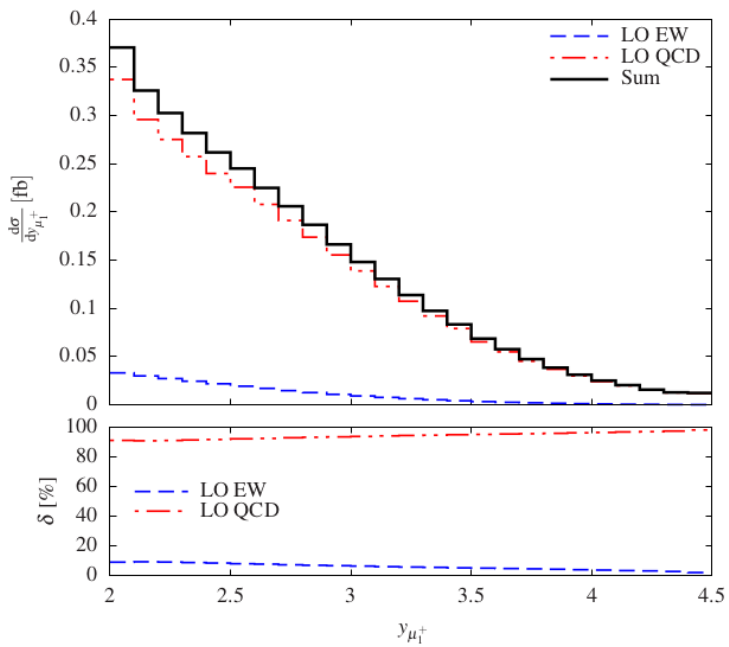
- Cross section for $\ell = \mu$, e:

$$\sigma_{\ell^+\ell^+} \simeq 1.4\,\text{fb with 7.5\% of EW component}$$

NB: $\sigma_{\ell^-\ell^-} \sim \frac{1}{3}\sigma_{\ell^+\ell^+}$ [Chiesa, Denner, Lang, MP; 1906.01863]

Results (differential distributions)





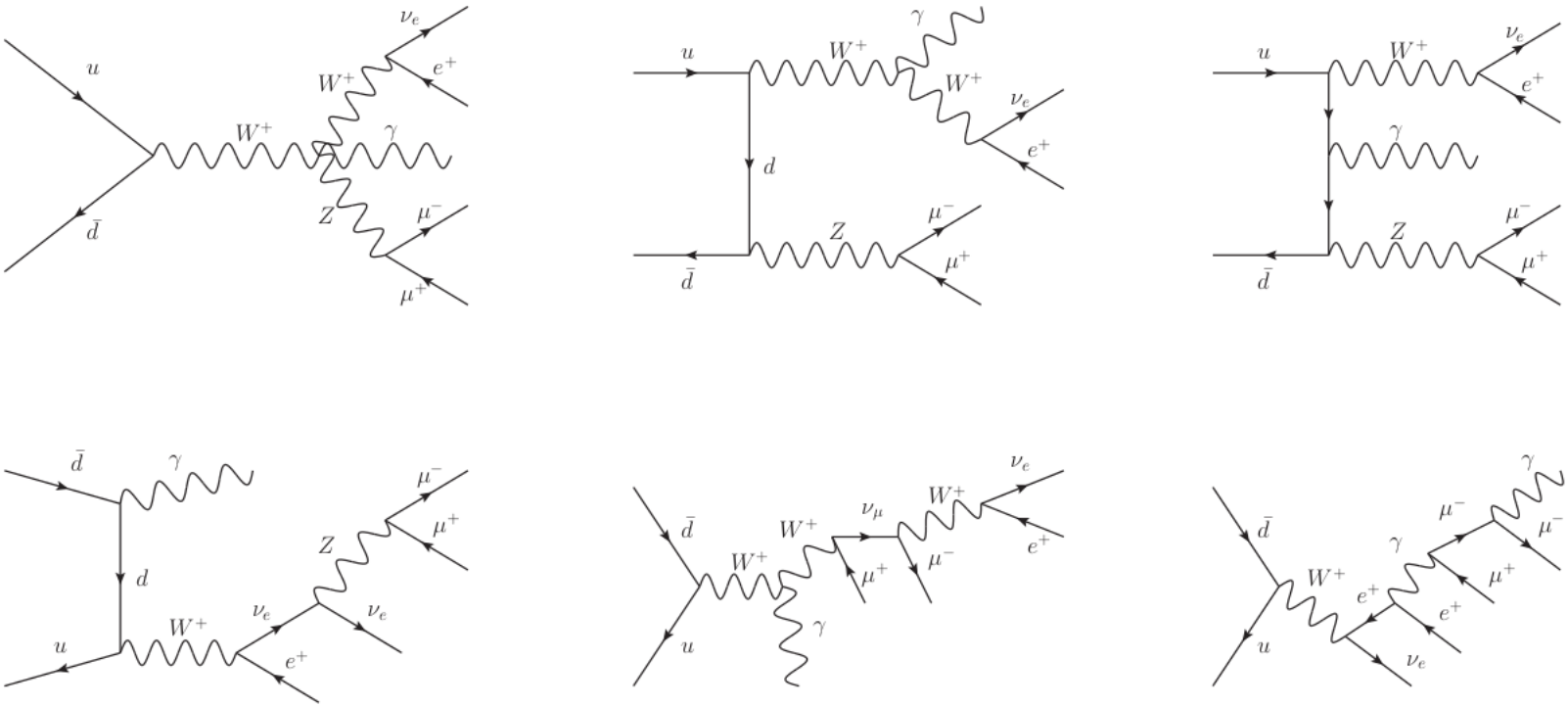
→ Indication for improvement of signal/bck ratio

Conclusion (VBS @ LHCb)

- New idea for measuring VBS @ LHCb
- Challenging but probably feasible ...
  ... with future $50\,\text{fb}^{-1}$ and $300\,\text{fb}^{-1}$ runs
- More realistic estimate is needed
  $\rightarrow$ further test of SM/ESWB
  $\rightarrow$ stringent test of some BSM models?

- VVV
  - NLO QCD + NLO EW

NLO QCD + EW to pp $\to e^+\nu_e\mu^+\mu^-\gamma$ [Cheng, Wackeroth; 2112.12052]



- Off-shell effects, spin correlations, and non-resonance contributions **accounted**

Results

σ_{LO} [fb]	σ_{QCD} [fb]	K-factor	σ_{EW} [fb]	δ_{EW} [%]	$\delta_{\text{EW}}^{q\bar{q}}$ [%]	$\delta_{\text{EW}}^{\gamma q(\bar{q})}$ [%]
0.20869(5)	$0.3588^{+3.90\%}_{-3.23\%}(2)$	1.719(1)	0.2101(1)	0.97(1)	-3.99(4)	+4.96(1)

→ At NLO EW:
large cancellation between $q\bar{q}$ and photon-induced contributions

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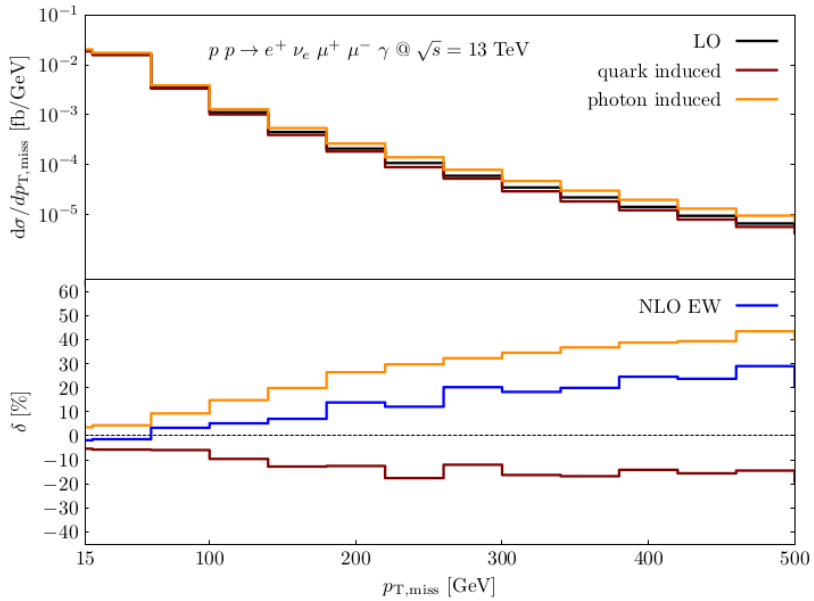
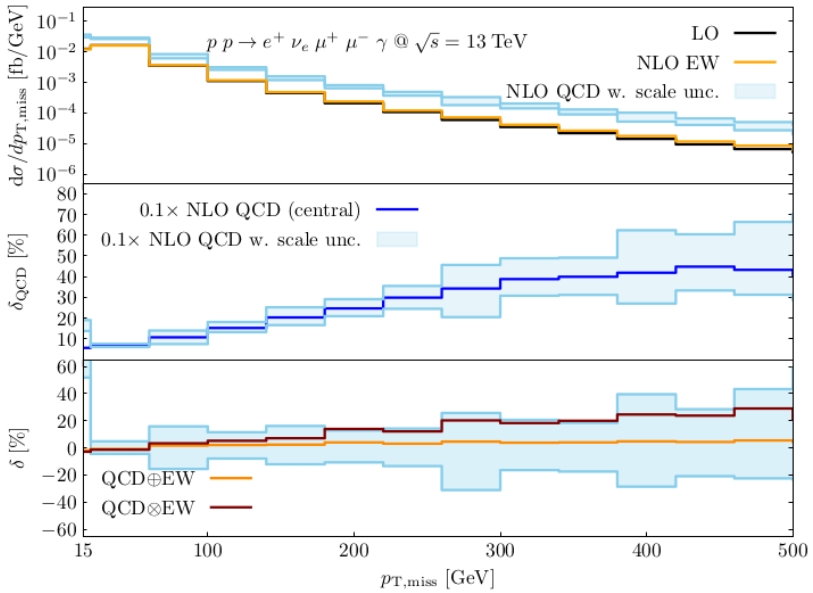


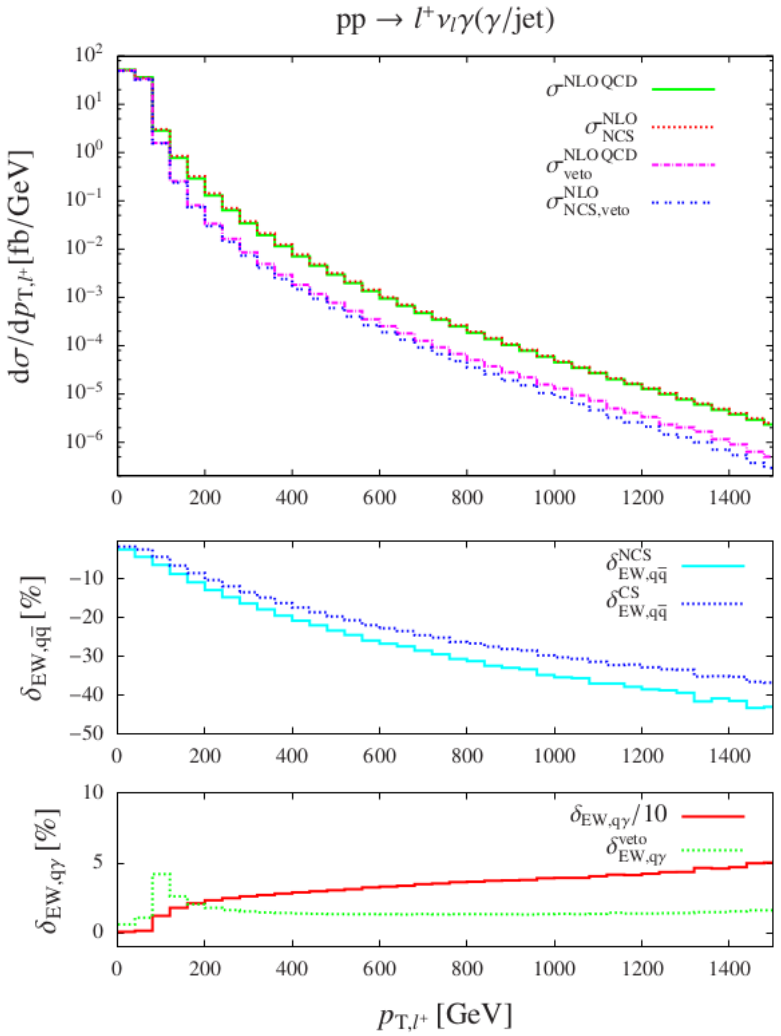


Sudakov logarithms vs. photon-induced

→ Large effect of photon-induced contributions also in pp → Wγ

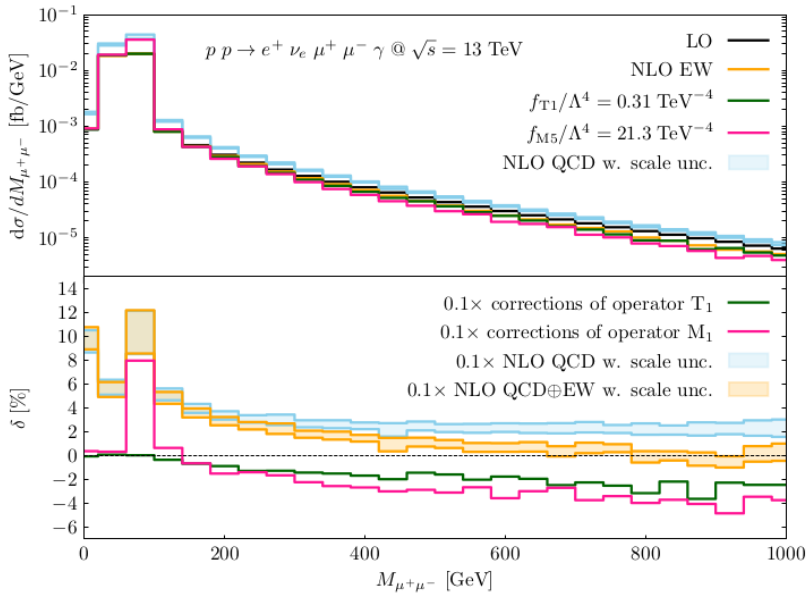
[Denner, Dittmaier, Hecht, Pasold; 1412.7421]

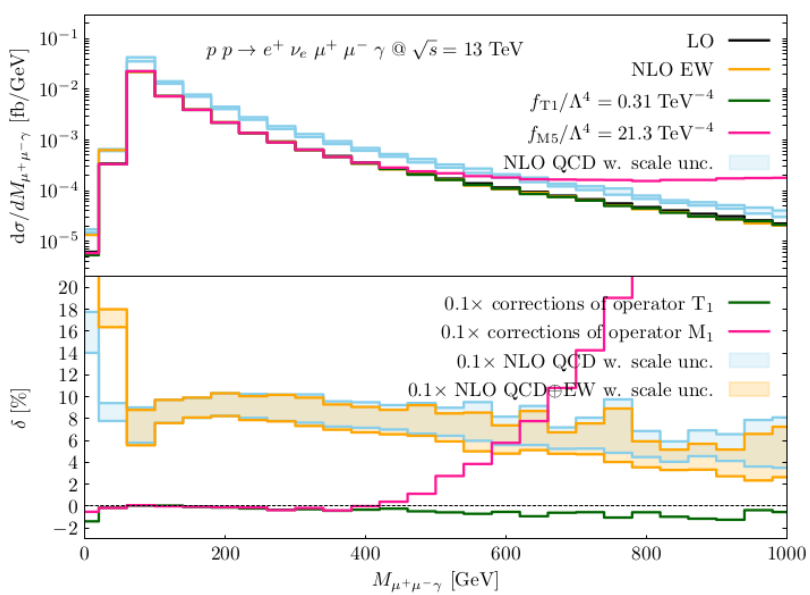
→ Effect due to hard-jet configurations
→ significantly reduced with jet veto
⚠ Important to be considered in experimental analysis



- Dim-8 operator in SMEFT:

$$\mathcal{O}_{\mathrm{M},5} = \left[(D_\mu \Phi)^\dagger \hat{W}_{\beta\nu} D^\nu \Phi\right] \times B^{\beta\mu}, \quad \mathcal{O}_{\mathrm{T},1} = \mathrm{Tr}\left[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\hat{W}_{\mu\beta}\hat{W}^{\alpha\nu}\right]$$

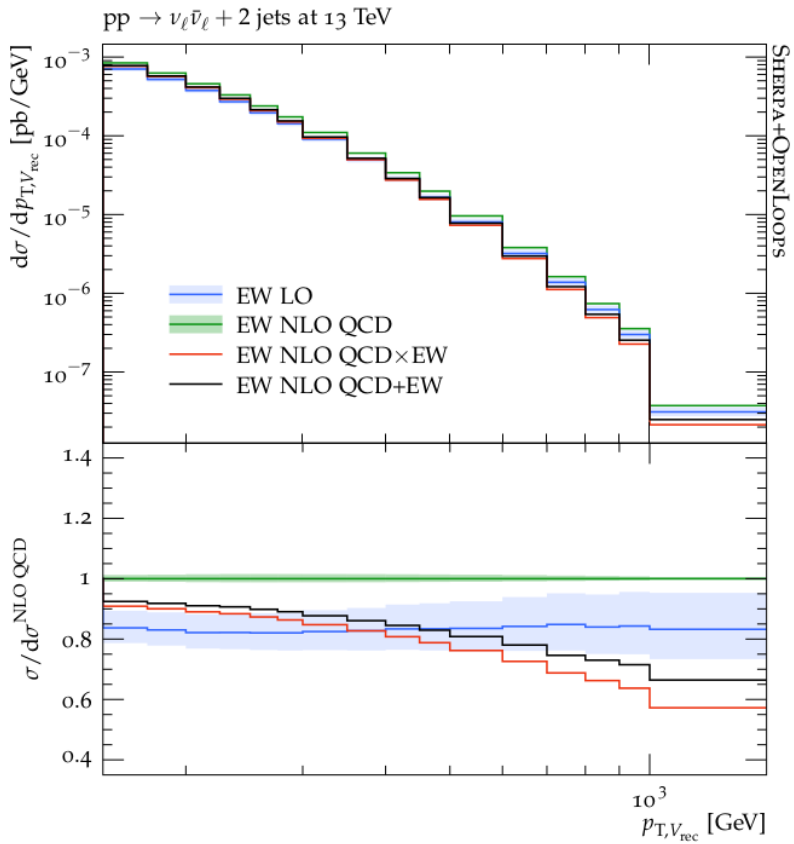


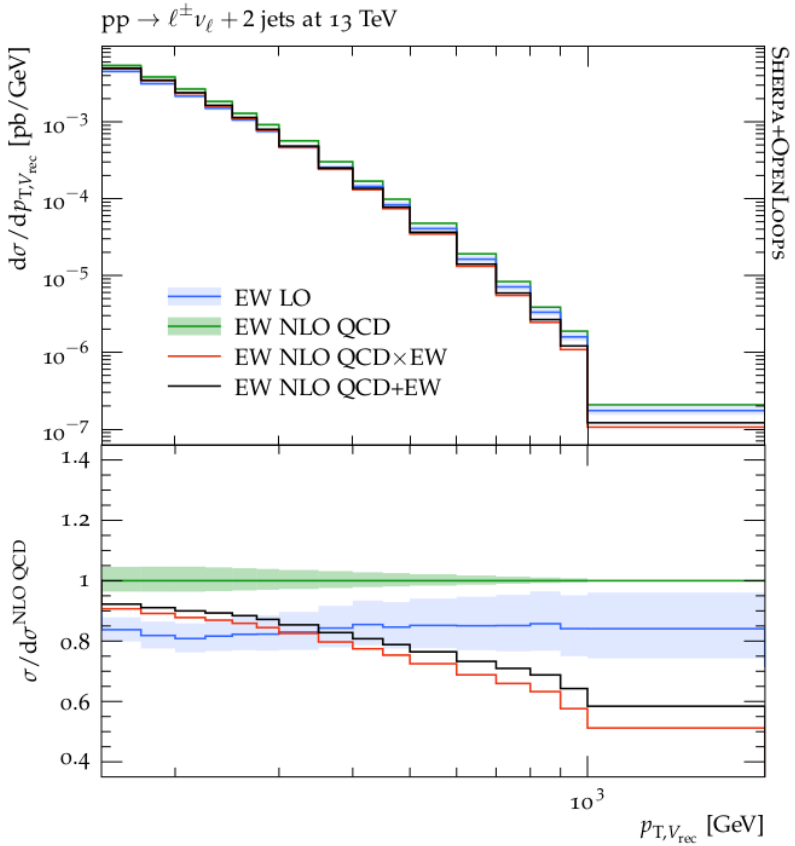


→ Missing EW corrections can mimic dim-8 operator ...
... if looking at single distributions

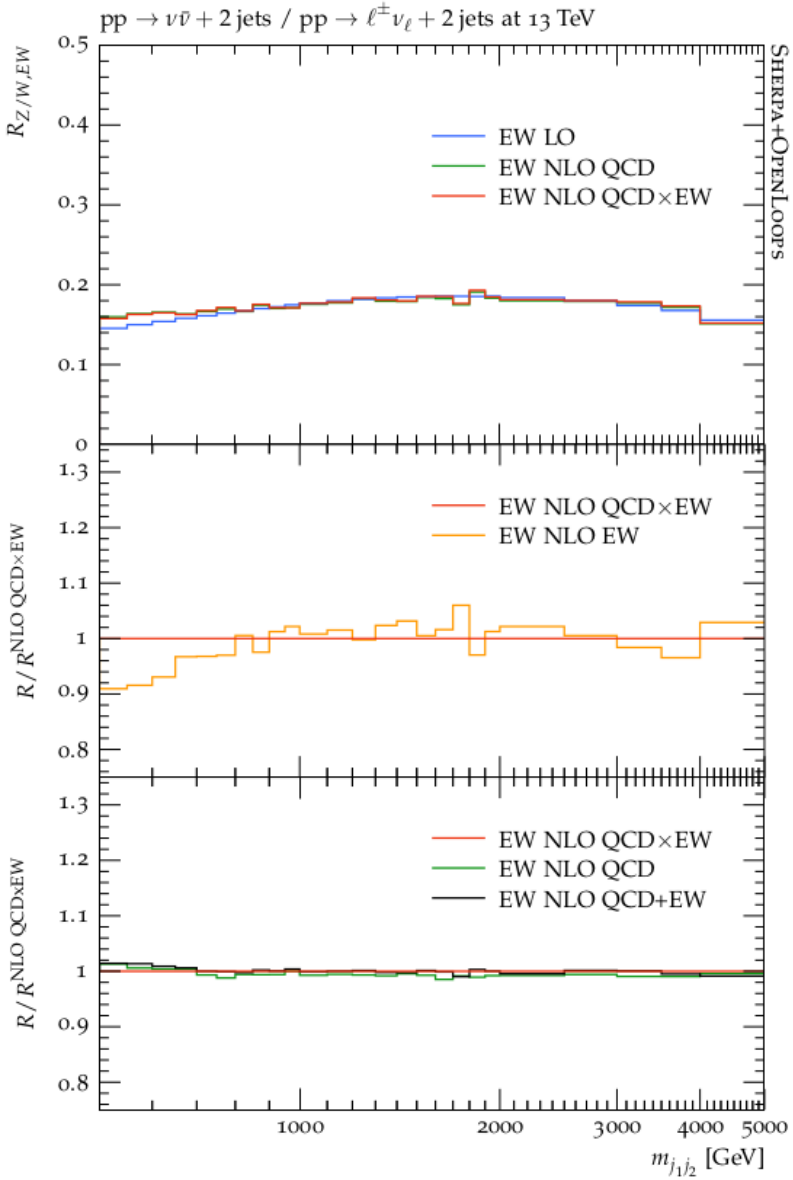
NLO QCD + EW to $V + 2j$ [Lindert, Pozzorini, Schönherr; 2204.07652]

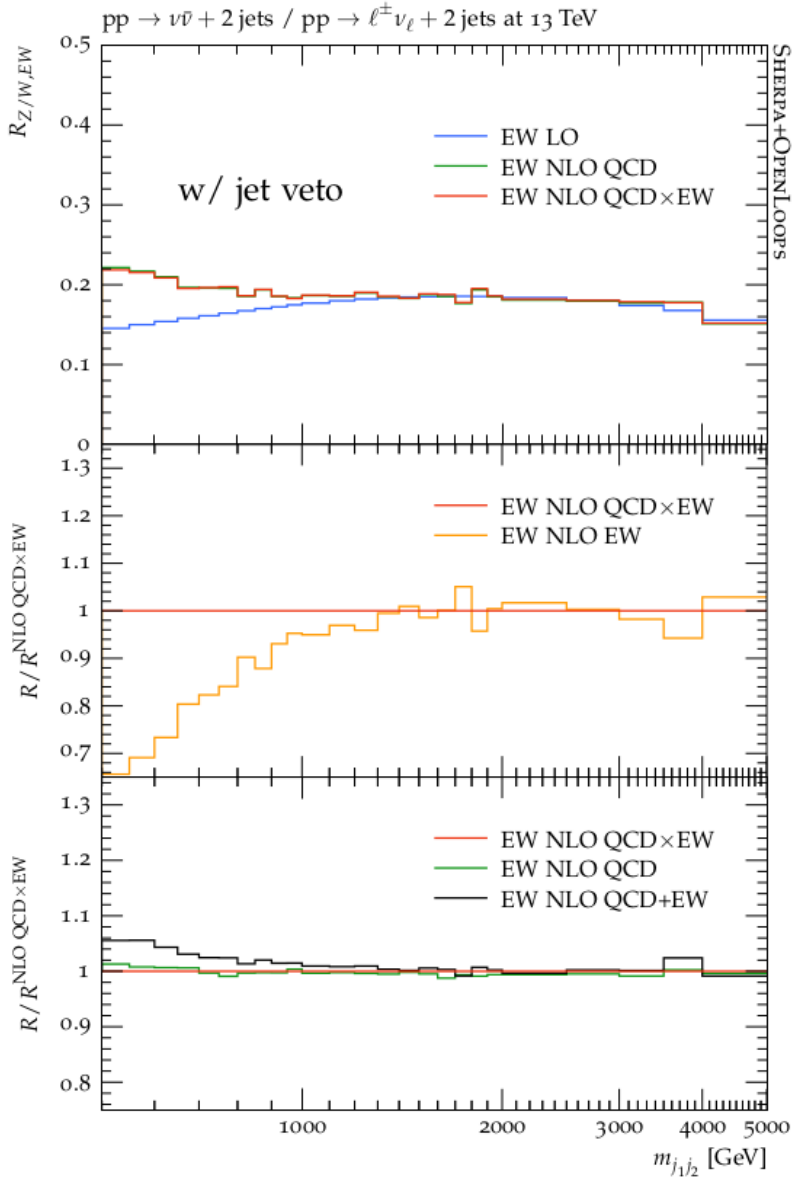
⚠ Not a multi-boson process! ... but still relevant





- backgrounds in searches for invisible Higgs decays
- pp $\to \nu_\ell \bar{\nu} \ell + 2j$ and pp $\to \nu_\ell \ell^\pm + 2j$
- QCD and EW production





→ Ratio of Z/W with and without jet-veto:
very relevant at high mjj for NP searches

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Thank you

BACK-UP