Vector boson scattering at next-to-leading order

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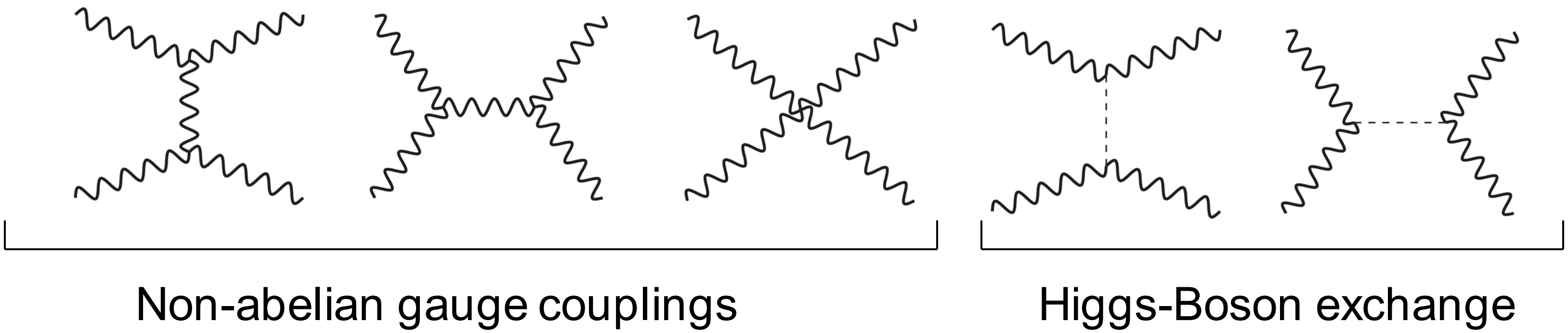
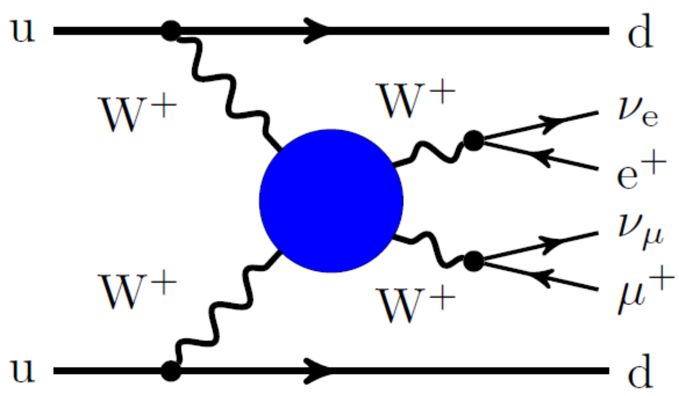
Vector boson scattering

$$VV \to VV, \qquad V = \{\mathrm{W}, \mathrm{Z}\}$$



- Tests the electroweak (EW) symmetry breaking mechanism
- Sensitivity to anomalous gauge couplings
- Crucial role of the Higgs boson as it guarantees unitarity

Vector boson scattering at the LHC



- Theoretical description:
  Two incoming quarks radiate vector bosons that scatter off each other (and decay)

- Experimental signature:
  Two jets in forward direction with large invariant mass and large rapidity separation plus two vector bosons (resp. their decay products)

Vector boson scattering at the LHC

Scattering channels with decays into (maximal number of) charged leptons:

$$pp \to ZZ + 2\text{jets} \to \ell^+\ell^-\ell'^+\ell'^- + 2\text{jets}$$

$$pp \to ZW + 2\text{jets} \to \ell^+\ell^-\ell'^\pm\nu + 2\text{jets}$$

$$pp \to WW + 2\text{jets} \to \ell^\pm\ell'^\mp\nu\nu' + 2\text{jets}$$ "opposite-sign WW"

$$\to \ell^\pm\ell'^\pm\nu\nu' + 2\text{jets}$$ "same-sign WW"

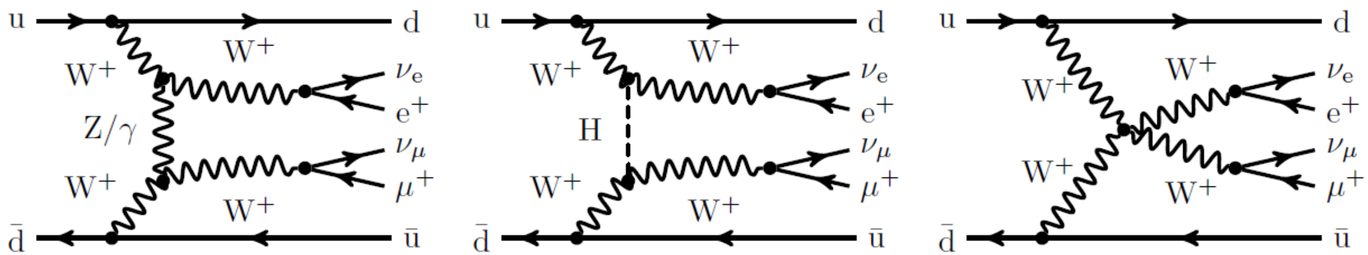
Outstanding role of "same sign WW" (ssWW) channel due to smallest irreducible QCD background.

$\longrightarrow$ Evidence for ssWW by ATLAS and CMS for Run-I
[1405.6241, 1611.02428,1410.6315]
Measurement of ssWW by CMS for run-II
[CMS-PAS-SMP-17-004]

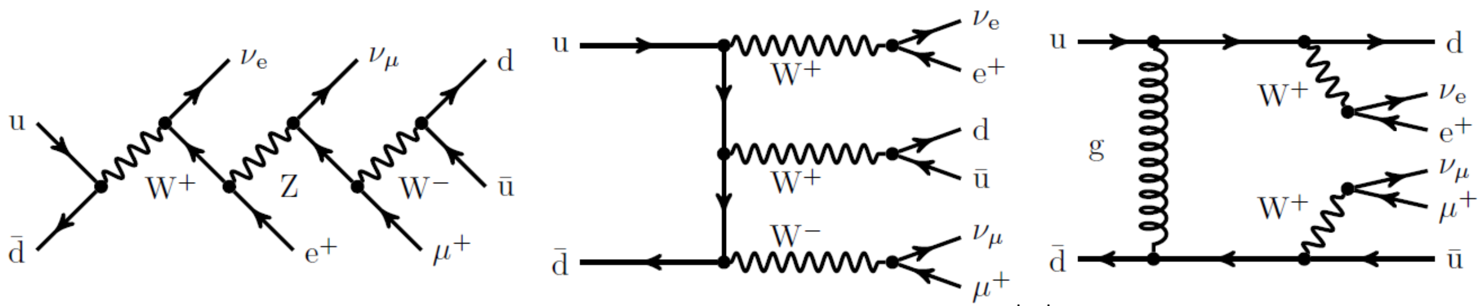
In this talk: Theoretical predictions for vector boson scattering in the same-sign WW channel at next-to-leading order.

$pp \to \mu^+ e^+ \nu_\mu \nu_e jj$ at leading order

Vector boson scattering (VBS) topologies: $\mathcal{O}\left(g^6\right)$



Irreducible background to VBS:



EW background to VBS $\mathcal{O}\left(g^6\right)$

QCD background $\mathcal{O}\left({g_s}^2 g^4\right)$

VBS-approximation in literature:

- discard t/u-channel interferences
- discard s-channel quark configuration

Our approach:

- Include all contributions

pp → $\mu^+e^+\nu_\mu\nu_e$ jj at leading order

Three gauge invariant contributions at squared-amplitude level:

$$\left(\mathcal{O}(g^6)+\mathcal{O}(g^4 g_s^2)\right)^2 \to \mathcal{O}(\alpha^6)+\mathcal{O}(\alpha^5\alpha_s^1)+\mathcal{O}(\alpha^4\alpha_s^2)$$

Purely EW
VBS + irreducible background

Interference, VBS suppressed
+ irreducible background

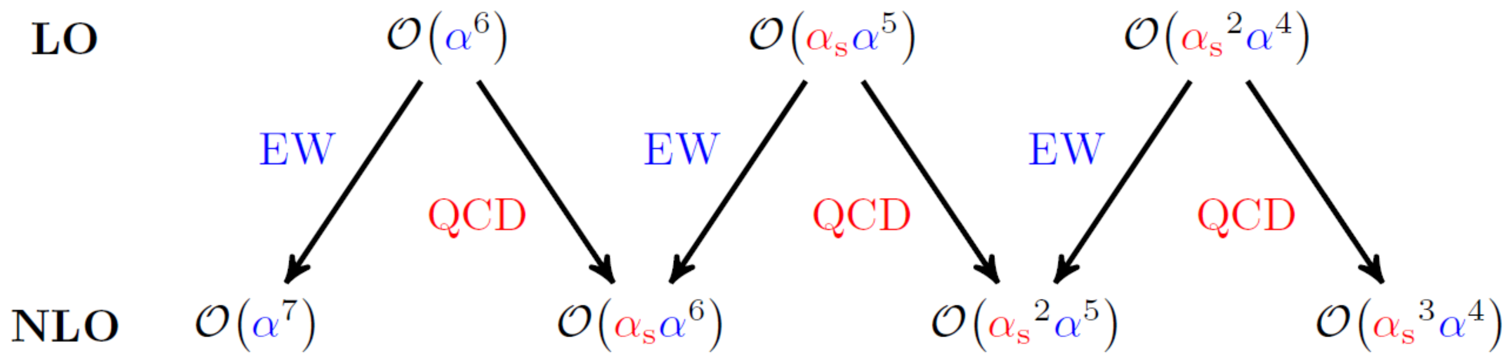
QCD irreducible background
no VBS

No interferences in VBS approximation

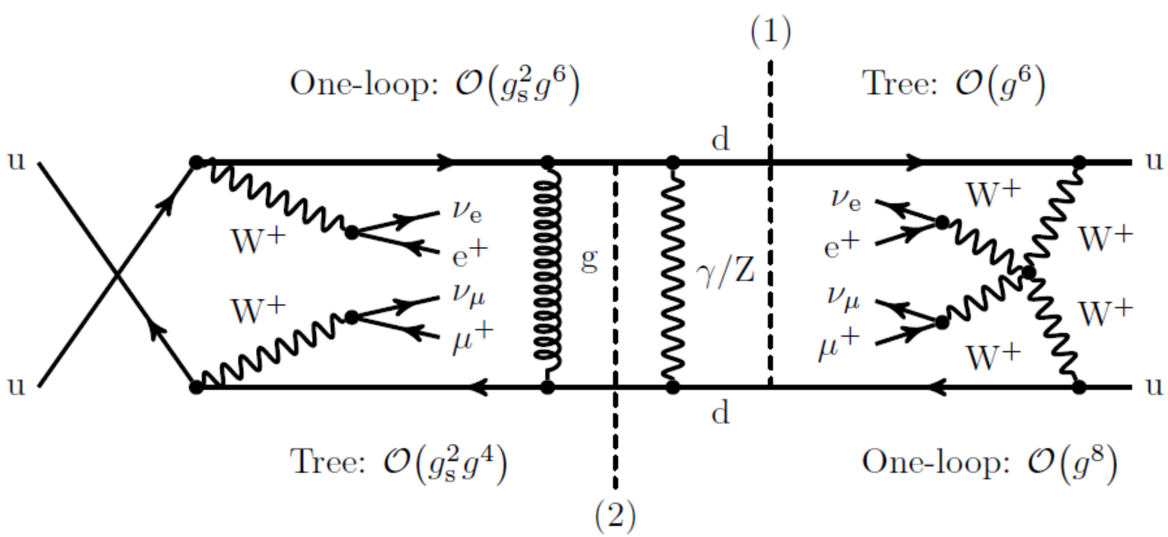
The experimental side:
- "EW" measurements separated from "QCD" measurement due to VBS cuts

Our approach: Keep all contributions, i.e. **NO approximation,** since different orders in the couplings mix at NLO.

$pp \to \mu^+ e^+ \nu_\mu \nu_e jj$ at NLO



Mixed QCD and EW corrections at $\mathcal{O}\left(\alpha_s \alpha^6\right)$ and $\mathcal{O}\left(\alpha_s{}^2 \alpha^5\right)$



Separation into EW and QCD part is not well defined at NLO.

Theory status pp $\rightarrow \mu^+e^+\nu_\mu\nu_e$jj at NLO

- NLO QCD to VBS in the VBS approximation
  [Jäger, Oleari, Zeppenfeld; 0907.0580], [Denner, Hošeková, Kallweit; 1209.2389]
- NLO QCD to QCD-induced process
  [Melia et al.; 1007.5313, 1104.2327]
- Matching to parton shower
  [Jäger, Zanderighi; 1108.0864]

New results (this talk):

- NLO EW corrections to purely EW part
  [BB, Denner, Pellen 1611.02951]
- Complete NLO EW and QCD corrections to pp $\rightarrow \mu^+e^+\nu_\mu\nu_e$jj
  [BB, Denner, Pellen 1708.00268]

Partonic channels

Include ALL partonic channels leading to the final state

$$pp \to \mu^+\nu_\mu e^+\nu_e \mathrm{jj}(+X)$$

⟶ Comprises all off-shell and non-resonant contributions

Born/virtual partonic channels		$\mathcal{O}(\alpha_s\alpha^5)$
uu	$\to \mu^+\nu_\mu e^+\nu_e dd$	yes
uc/cu	$\to \mu^+\nu_\mu e^+\nu_e ds$	no
cc	$\to \mu^+\nu_\mu e^+\nu_e ss$	yes
$u\bar{d}/\bar{d}u$	$\to \mu^+\nu_\mu e^+\nu_e d\bar{u}$	yes
$u\bar{d}/\bar{d}u$	$\to \mu^+\nu_\mu e^+\nu_e s\bar{c}$	no
$u\bar{s}/\bar{s}u$	$\to \mu^+\nu_\mu e^+\nu_e d\bar{c}$	no
$c\bar{d}/\bar{d}c$	$\to \mu^+\nu_\mu e^+\nu_e s\bar{u}$	no
$c\bar{s}/\bar{s}c$	$\to \mu^+\nu_\mu e^+\nu_e d\bar{u}$	no
$c\bar{s}/\bar{s}c$	$\to \mu^+\nu_\mu e^+\nu_e s\bar{c}$	yes
$\bar{d}\bar{d}$	$\to \mu^+\nu_\mu e^+\nu_e \bar{u}\bar{u}$	yes
$\bar{d}\bar{s}/\bar{s}\bar{d}$	$\to \mu^+\nu_\mu e^+\nu_e \bar{u}\bar{c}$	no
$\bar{s}\bar{s}$	$\to \mu^+\nu_\mu e^+\nu_e \bar{c}\bar{c}$	yes

Real partonic channels:

- Additional photon (gluon) in the final state for EW (QCD) radiation
- Cross final-state photon (gluon) with initial-state quarks to get photon-induced (gluon-induced) contributions

Details of the calculation

- Complex-mass scheme for resonances due to massive internal particles [Denner et al. 1999, 2005]
- RECOLA as matrix-element generator for all tree-level and one-loop amplitudes [Actis et al. 2013, 2017]
- COLLIER library for one-loop scalar and tensor integrals, two independent branches of the library used as cross-check [Denner et al. 2017]
- Matrix elements $\mathcal{O}(\alpha_s^3\alpha^4)$ checked against MadLoop [Hirschi et al. 2011]
- Various approximations as consistency checks (VBS approximation, pole approximation, effective vector boson approximation)
- Two different, private Monte Carlo implementations for the phase-space integration as cross-check

Some technical challenges:

complicated virtual EW corrections (8-point functions), large phase space, automated generation of partonic processes and dipoles, huge data sets,…

Numerical setup

- 13 TeV centre of mass energy
- NNPDF3.0 PDF set
- Dynamical factorisation and renormalisation scale with 7-pt scale variation

$$\mu_{\rm ren} = \mu_{\rm fac} = \sqrt{p_{\rm T,j_1}\, p_{\rm T,j_2}}$$

$$(\xi_{\rm fac}, \xi_{\rm ren}) \in \{\, (1/2, 1/2)\,,\ (1/2, 1)\,,\ (1, 1/2)\,,\ (1, 1)\,,\ (1, 2)\,,\ (2, 1)\,,\ (2, 2)\,\}$$

- G-Fermi scheme for the electromagnetic coupling
- Anti-k_T jet algorithm with R=0.4 for jet recombination and R=0.1 for photon recombination

VBS cuts:

charged lepton: $p_{\rm T,\ell} > 20$ GeV, $|y_\ell| < 2.5$, $\Delta R_{\ell\ell} > 0.3$

jets: $p_{\rm T,j} > 30$ GeV, $|y_{\rm j}| < 4.5$, $\Delta R_{\rm j\ell} > 0.3$

missing energy: $p_{\rm T,miss} > 40$ GeV,

jet-jet: $m_{\rm jj} > 500$ GeV, $|\Delta y_{\rm jj}| > 2.5$.

at least two jets required

Results for the fiducial LO cross section

$$\sigma_{\mathrm{LO}} = 1.6383(2)^{+11.66(2)\%}_{-9.44(2)\%}\ \mathrm{fb}$$

Central value

Scale uncertainty

Order	$\mathcal{O}(\alpha^6)$	$\mathcal{O}(\alpha_s\alpha^5)$	$\mathcal{O}(\alpha_s^2\alpha^4)$	Sum
σ_{LO} [fb]	1.4178(2)	0.04815(2)	0.17229(5)	1.6383(2)

- Dominant LO EW contribution (87%) thanks to VBS cuts
- Pure QCD contribution 10%
- Interference 3%

Results for the fiducial NLO cross section

$$\sigma_{\mathrm{LO}} = 1.6383(2)^{+11.66(2)\%}_{-9.44(2)\%}\ \mathrm{fb} \qquad \sigma_{\mathrm{NLO}} = 1.3577(7)^{+1.2(1)\%}_{-2.7(1)\%}\ \mathrm{fb}$$

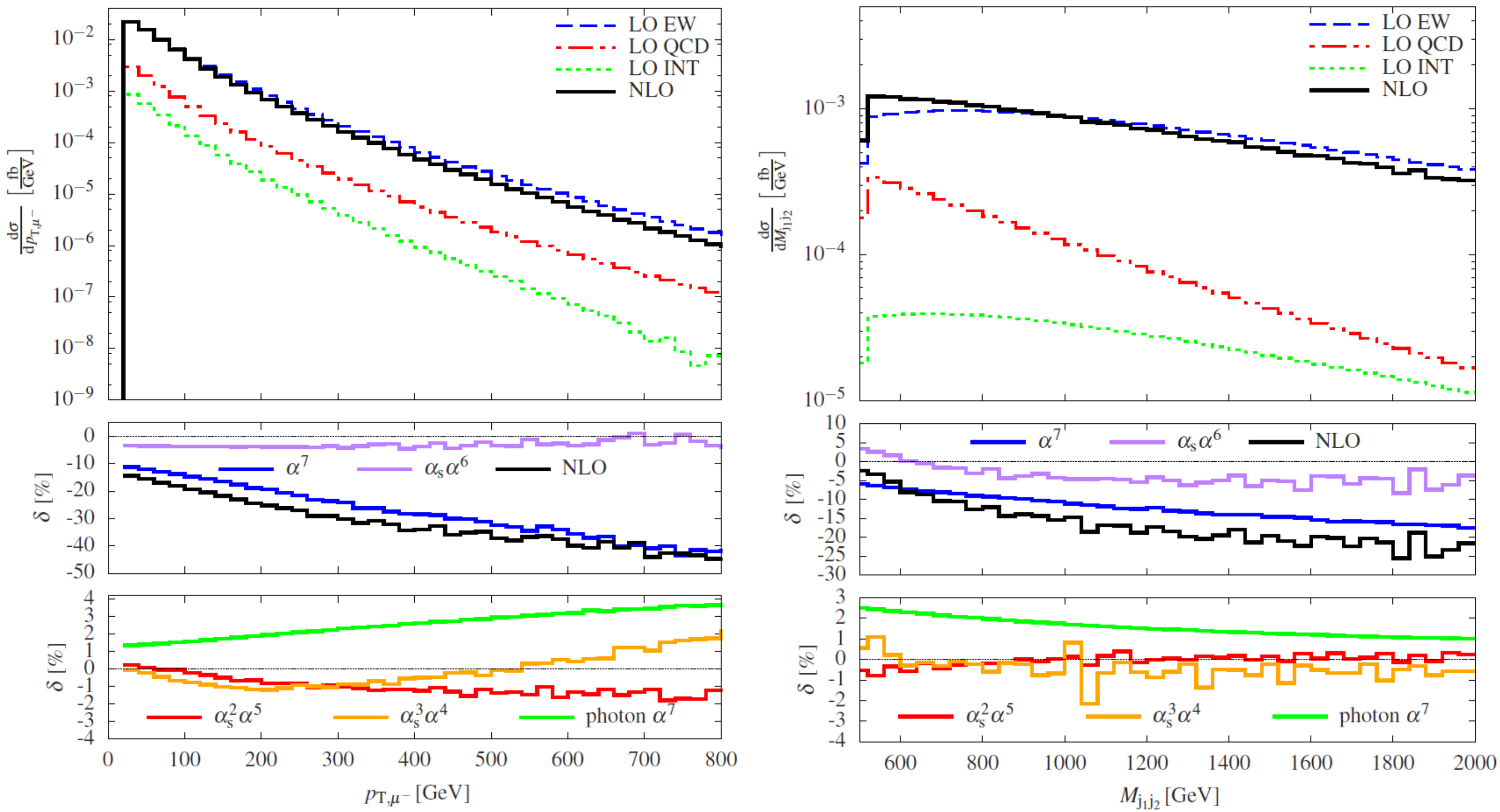
Reduced scale uncertainty, bands do NOT overlap, as dominant correction results from EW correction without α_s dependence.

Order	$\mathcal{O}(\alpha^6)$	$\mathcal{O}(\alpha_s\alpha^5)$	$\mathcal{O}(\alpha_s^2\alpha^4)$	Sum
σ_{LO} [fb]	1.4178(2)	0.04815(2)	0.17229(5)	1.6383(2)

Order	$\mathcal{O}(\alpha^7)$	$\mathcal{O}(\alpha_s\alpha^6)$	$\mathcal{O}(\alpha_s^2\alpha^5)$	$\mathcal{O}(\alpha_s^3\alpha^4)$	Sum
$\delta\sigma_{\mathrm{NLO}}$ [fb]	$-0.2169(3)$	$-0.0568(5)$	$-0.00032(13)$	$-0.0063(4)$	$-0.2804(7)$
$\delta\sigma_{\mathrm{NLO}}/\sigma_{\mathrm{LO}}$ [%]	-13.2	-3.5	0.0	-0.4	-17.1

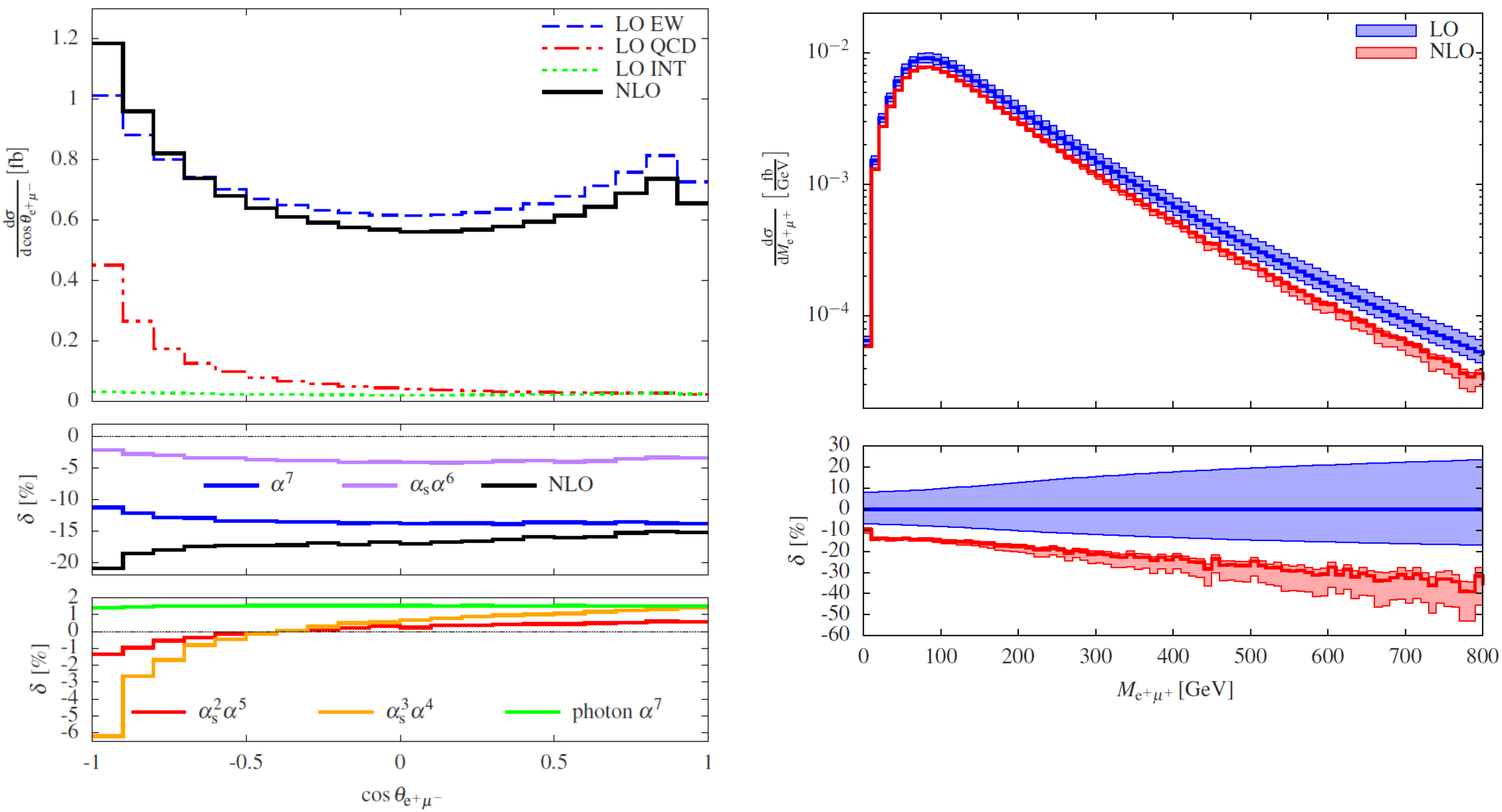
- Surprisingly large NLO corrections at $O(\alpha^7)$
- $O(\alpha_s\alpha^6)$ four times smaller
  $O(\alpha_s^2\alpha^5)$ and $O(\alpha_s^3\alpha^4)$ very small
- Photon-induced contribution at $O(\alpha^7)$ with LUXQED give +1.5% corrections, not included in our NLO definition, (other orders negligible)
- Comparison of full $O(\alpha_s\alpha^6)$ with VBS approximation shows difference of about half a percent -> VBS approximation in general sufficient

Differential distributions



- Sudakov enhancement in high-energy regions
- NLO corrections dominated by purely weak corrctions
- Remaining corrections at percent level or below

Differential distributions



- Lepton separation as example for observable that is not entirely dominated by EW production mode
- Invariant lepton mass as example for non-overlapping scale bands

Large NLO EW corrections to VBS

For “ordinary” LHC processes, EW corrections are usually…

… smaller than QCD corrections at fiducial cross section level
(usually they stay between 2% and 5%)
… only become large in tails of distribution where Sudakov Logarithms are enhanced

We could show that the large EW corrections of -13% to VBS are…

… an intrinsic feature of the VBS subprocess.

Steps towards understanding the large NLO EW corrections

1) Large corrections not due to VBS event selection

   - Remove $m_{jj} > 500\mathrm{GeV}; \quad |\Delta y_{j_1 j_2}| > 2.5$
   - Relax transverse-momentum cuts

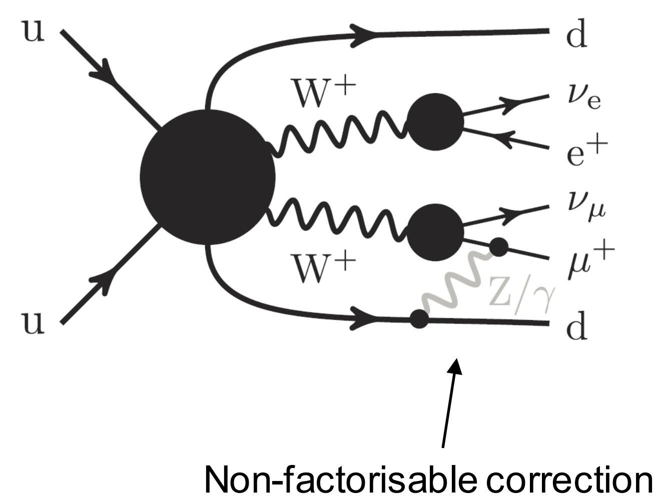
   Corrections stay at the same level

2) Numerical verification that the largest contribution stems from the bosonic part of the virtual corrections

Steps towards understanding the large NLO EW corrections

3) Virtual corrections in doube pole approximation (expansion about the two resonant W bosons)

- Two on-shell W bosons required
- Matrix elements split into those for production and decay
- approximation within 1% of full result
- 95% of subtracted virtual corrections stem from factorisable contributions



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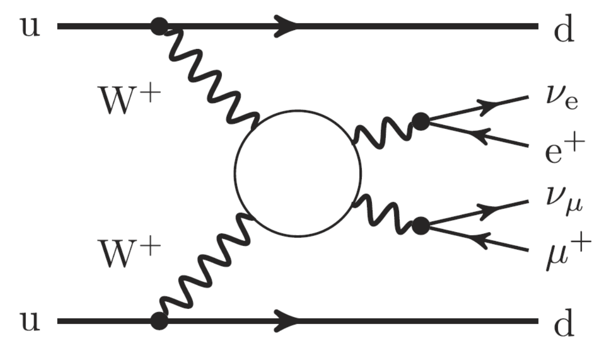
Large corrections driven by the WW scattering process

Steps towards understanding the large NLO EW corrections

4) Effective vector boson approximation (EVBA) combined with leading logarithmic expansion

EVBA reduces the logarithmic expansion to:

$$W^+W^+ \to W^+W^+$$



Leading logarithmic expansion:

[Accomando, Denner, Pozzorini 2007]

$$\sigma_{\rm LL} = \sigma_{\rm LO}\left[1 - \frac{\alpha}{4\pi} 4 C_W^{\rm EW} \log^2\left(\frac{Q^2}{W^2}\right) + \frac{\alpha}{4\pi} 2 b_W^{\rm EW} \log\left(\frac{Q^2}{W^2}\right)\right]$$

$$C_W^{\rm EW} = \frac{2}{s_w^2}$$

$$b_W^{\rm EW} = \frac{19}{6 s_w^2}$$

includes double EW logs, collinear single EW logs, and single logs from parameter renormalisation (angular-dependent logarithms omitted)

Understanding the large EW corrections

$$\sigma_{\mathrm{LL}} = \sigma_{\mathrm{LO}} \left[1 - \frac{\alpha}{4\pi} 4 C_W^{\mathrm{EW}} \log^2\left(\frac{Q^2}{W^2}\right) + \frac{\alpha}{4\pi} 2 b_W^{\mathrm{EW}} \log\left(\frac{Q^2}{W^2}\right) \right]$$

Average four-lepton invariant mass as natural scale for VBS subprocess :

$$Q = \langle m_{4\ell} \rangle \sim 390\,\mathrm{GeV}$$

$\longrightarrow$ Approximation recovers NLO EW corrections at percent level!

Putting all together:

1) $\langle m_{4\ell} \rangle$ larger for VBS than for WW production where $\langle m_{4\ell} \rangle \sim 250\,\mathrm{GeV}$

2) Casimir C^{EW} is larger for vector bosons than for fermions

3) Cancellation between single and double logs weaker for external fermions than for external fermions

$\longrightarrow$ Large NLO EW corrections to VBS

Conclusion

- First full NLO EW and QCD corrections to $pp \to \mu^+ e^+ \nu_\mu \nu_e jj$ presented.
- Complete matrix elements from RECOLA with all off-shell effects and non-resonant contributions included.
- Separate analysis for contributions of $\mathcal{O}(\alpha^7), \mathcal{O}(\alpha_s \alpha), \mathcal{O}(\alpha_s^2 \alpha^5), \mathcal{O}(\alpha_s^3 \alpha^4)$
- Large NLO EW corrections of -13% to VBS process for the fiducial cross section, reaching more than -40% at differential cross sections.
- Large NLO EW corrections as intrinsic feature of VBS process.
- First complete NLO computation of $\mathcal{O}(\alpha_s \alpha)$ confirms validity of VBS approximation.
- Subleading orders in the strong coupling are strongly suppressed with VBS cuts at fiducial cross section level, stay at percent level in distributions.
- Photon-induced corrections at the percent level for purely EW contribution, other orders negligible.
- Predictions available in terms of flexible MC programs, useful for experimental analysis.

Backup slides