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NLO EW and QCD corrections to polarised $W^+ W^+$ scattering at the LHC

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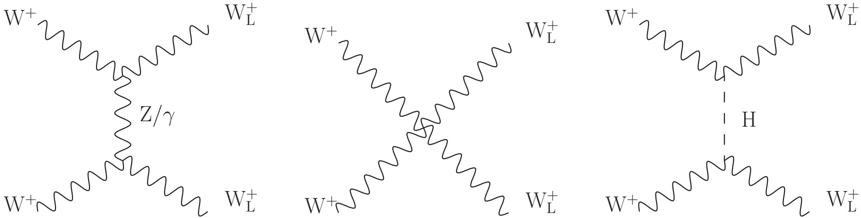
Multi-Boson Interactions, 25.–27. Sept. 2024

based on arXiv:2409.03620 (submitted to JHEP)

Table of contents

Motivation

- Polarised multi boson processes are sensitive spontaneous symmetry breaking
  - In particular polarised VBS processes are very sensitive to the unitarity cancellations
- Polarised cross-sections are very sensitive to beyond-Standard Model effects



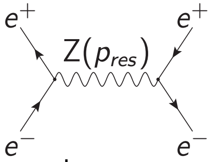
(t+u) $\mathcal{O}(s^2)$ $\mathcal{O}(s^2)$ (t+u) $\mathcal{O}(s)$

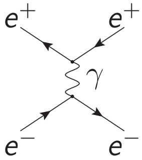
Prior work on vector-boson scattering

- For off-shell VBS experimental measurements and theoretical calculations exist
  - NLO QCD and NLO EW corrections are known
- Theoretical studies of polarised VBS are only LO accurate
  - NLO QCD and NLO EW corrections are needed

- Polarised same-sign WW scattering is the first VBS process for which a NLO polarisation study exists
  - CMS measurement [CMS 2009.09429]
  - LO accurate polarisation calculation [Ballestrero, Maina, Pelliccioli 2007.07133]
  - NLO accurate polarisation calculation [Denner, Haitz, Pelliccioli 2409.03620] $\Rightarrow$ todays topic

Amplitude in the pole approximation





- Diagrams with and without the wanted (s-channel) resonances contribute to a given process
- Remove non-resonant diagrams in a gauge-independent way
  - By using a pole approximation
    - Set resonant particles on-shell $\{p\} \Rightarrow \{\tilde{p}\}$: $\tilde{p}^2_{res} = M^2_{res}$
    - Conserve some off-shell effects by using the off-shell denominators of the propagators and applying the phase-space cuts to the off-shell momenta

$$\mathcal{M}\left(\{\tilde{p}\}, p^2_{res}\right) = \mathcal{M}_{\mu,\text{production}}\left(\{\tilde{p}\}\right) \frac{\mathcal{N}^{\mu\nu}\left(\{\tilde{p}\}\right)}{p^2_{res} - M^2_{res} + iM_{res}\Gamma_{res}} \mathcal{M}_{\nu,\text{decay}}\left(\{\tilde{p}\}\right)$$

Polarised amplitude in the pole approximation

- All Numerators of the resonant propagators contain a sum over all polarisation states

$$\sum_{\text{polarisations}} \epsilon^*_\mu \epsilon_\nu = -g_{\mu\nu}$$

$$\mathcal{M}\left(\{\tilde{p}\}, p^2_{res}\right) = \sum_\lambda \mathcal{M}_{\mu,\text{production}}\left(\{\tilde{p}\}\right) \frac{\epsilon^{\mu *}_\lambda\left(\{\tilde{p}\}\right)\epsilon^\nu_\lambda\left(\{\tilde{p}\}\right)}{p^2_{res} - M^2_{res} + iM_{res}\Gamma_{res}} \mathcal{M}_{\nu,\text{decay}}\left(\{\tilde{p}\}\right)$$

$$\mathcal{M}\left(\{\tilde{p}\}, p^2_{res}\right) = \sum_\lambda \mathcal{M}_\lambda\left(\{\tilde{p}\}, p^2_{res}\right)$$

Polarised cross-section in the pole approximation

- Take the square of the matrix element to calculate the cross-section

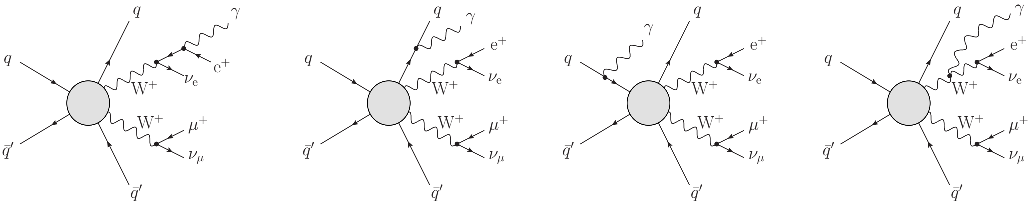
$$\underbrace{\left|\mathcal{M}\left(\{\tilde{p}\}, p_{res}^2\right)\right|^2}_{\text{unpolarised}} = \sum_{\lambda} \underbrace{\left|\mathcal{M}_\lambda\left(\{\tilde{p}\}, p_{res}^2\right)\right|^2}_{\text{polarisation }\lambda} + \underbrace{\sum_{\lambda \neq \lambda'} \mathcal{M}_\lambda^*\left(\{\tilde{p}\}, p_{res}^2\right) \mathcal{M}_{\lambda'}\left(\{\tilde{p}\}, p_{res}^2\right)}_{\text{interferences}}$$

Definition of polarised cross-sections

- Only the off-shell process can be accessed experimentally
  - Non-resonant background has to be subtracted
  - Template fits to extract polarisation fractions
- The polarisation vectors of the resonant particles are frame dependent
  - Polarised cross-section is frame dependent $\Rightarrow$ frame dependent polarisation fractions
  - Commonly used frame choices are
    - Lab frame
    - Centre-of-mass frame of the resonant particles (maximal unitarity cancellations)

NLO EW corrections

- There are IR singularities only present in the DPA
- Local counterterms (massive dipoles) are needed to cancel the divergences for the production and decay subprocess
- Resonant bosons take the role of emitter and/or spectator



Setup

$$p\,p \to W^+(\to e^+\,\nu_e)\,W^+(\to \mu^+\nu_\mu)\,jj + X \qquad @ \quad \sqrt{s} = 13.6\mathrm{TeV}$$

- The W bosons decay into different flavour leptons
- Polarisation is defined in the centre-of-mass frame of the two bosons
- Based on the CMS polarisation analysis [CMS 2009.09429]

NLO Integrated Results

state	σ_{LO} [fb]	δ_{EW} [%]	δ_{QCD} [%]	$\delta_{\mathrm{EW+QCD}}$ [%]	$\sigma_{\mathrm{NLO\,EW+QCD}}$ [fb]
full	$1.4863(1)^{+9.2\%}_{-7.8\%}$	-14.0	-4.7	-18.8	$1.208(1)^{+1.6\%}_{-3.1\%}$
unp	$1.46455(9)^{+9.2\%}_{-7.8\%}$	-14.2	-5.0	-19.2	$1.1836(5)^{+1.7\%}_{-3.3\%}$
LL	$0.14879(1)^{+8.3\%}_{-7.2\%}$	-10.1	-4.4	-14.5	$0.12715(8)^{+1.0\%}_{-2.1\%}$
LT	$0.23209(2)^{+9.1\%}_{-7.8\%}$	-13.1	-4.2	-17.3	$0.1919(1)^{+1.4\%}_{-2.8\%}$
TL	$0.23208(2)^{+9.1\%}_{-7.8\%}$	-13.1	-4.2	-17.3	$0.1918(1)^{+1.4\%}_{-2.8\%}$
TT	$0.87702(7)^{+9.4\%}_{-8.0\%}$	-15.4	-5.4	-20.8	$0.6944(4)^{+1.9\%}_{-3.7\%}$
int.	$-0.0254(1)^{-8.9\%}_{+10.6\%}$	-13.9	-0.7	-14.7	$-0.0217(7)^{-1.6\%}_{+0.7\%}$

(...) Integration uncertainty

$\pm$...% Relative QCD scale uncertainty

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- Large negative NLO EW corrections caused by Sudakov logarithms

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- Size of the EW corrections depends on the polarisation
- EW Casimir operators for a longitudinal vector boson are smaller than for a transverse vector boson that multiply the leading double logarithms

NLO Integrated Results

state	$\sigma_{\rm LO}$ [fb]	$\delta_{\rm EW}$ [%]	$\delta_{\rm QCD}$ [%]	$\delta_{\rm EW+QCD}$ [%]	$\sigma_{\rm NLO\,EW+QCD}$ [fb]
full	$1.4863(1)^{+9.2\%}_{-7.8\%}$	-14.0	-4.7	-18.8	$1.208(1)^{+1.6\%}_{-3.1\%}$
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- Small NLO QCD corrections
- Very similar for all polarised signals

NLO polarisation fractions

state	$f_{\mathrm{LO}}[\%]$	$f_{\mathrm{NLO\,EW}}[\%]$	$f_{\mathrm{NLO\,QCD}}[\%]$	$f_{\mathrm{NLO\,EW+QCD}}[\%]$
full	101.5	101.7	101.8	102.0
unp	100.0	100.0	100.0	100.0
LL	10.2	10.6	10.2	10.7
LT	15.8	16.0	16.0	16.2
TL	15.8	16.0	16.0	16.2
TT	59.9	59.0	59.6	58.7
int.	−1.7	−1.7	−1.8	−1.8

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TL	15.8	16.0	16.0	16.2
TT	59.9	59.0	59.6	58.7
int.	−1.7	−1.7	−1.8	−1.8

- Nonresonant/off-shell effects at the level of 1.5% to 2.0%
- Within the accuracy of the DPA Γ_W/M_W

NLO polarisation fractions

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- TT polarisation state dominates with $\approx 60\%$

NLO polarisation fractions

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TT	59.9	59.0	59.6	58.7
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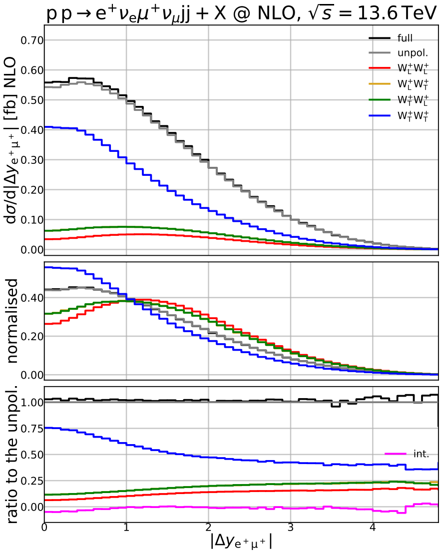
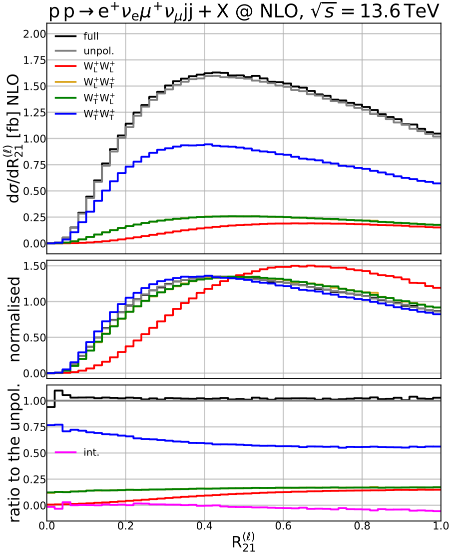
- Very small changes of the polarisation fractions
- Slight enhancement of the LL contribution from less negative NLO EW corrections

Rapidity difference of the positron and the anti-muon



- Different shape of the TT polarisation state
- TT polarisation state prefers smaller rapidity differences
- Polarisation fractions change

Transverse momentum ratio leptons $R_{21}^{(\ell)} = \frac{p_{\mathrm{T},\ell_2}}{p_{\mathrm{T},\ell_1}}$



- Different shape of the LL polarisation state
- LL polarisation state prefers more similar transverse momenta
- Polarisation fractions change

Summary

- First calculation of polarised W^+W^+ scattering at NLO EW and QCD
  - Used the double-pole approximation to define polarised signal
  - Used methods are general and applicable to any multi boson process
    - Polarisation studies of other VBS processes
    - Triple vector-boson production
- There are LHC observables that are well suited for polarisation discrimination
- NLO corrections only give small changes to the polarisation fractions

Backup Slides

On-shell projection (OSP) for two resonances

- Gauge invariance requires on-shell resonances
- Properties to ensure a physically meaningful result
  - Four-momentum conservation
  - Masses of the external particles are conserved
  - Smoothly approach the limit of on-shell resonances
- Additionally conserved in our implementation of the DPA
  - Momenta of other external particles that are not decay particles of the resonances
  - Direction of the resonant particles in the centre-of-mass frame of the two resonant particles
  - Direction of the decay particles in the rest frame of the corresponding resonance.
- When $(p_{res,1} + p_{res,2})^2 < (M_{res,1} + M_{res,2})^2$ the momenta cannot be projected on-shell and the amplitude is set to zero
- Generalisable to more resonances

On-shell projection for two resonances (explicit form)

- Threshold for the on-shell projection

$$(M_{res,1} + M_{res,2})^2 \leq (p_{res,1} + p_{res,2})^2$$

- Begin with the construction of the on-shell momenta of the resonances
- Boost to centre-of-mass frame of the two resonances
- Set absolute value of the three momentum of the resonance

$$\left|\tilde{p}'_{1,res}\right| = \frac{\left(p_{tot}^2\right)^2 - 2p_{tot}^2\left(M_{res,1}^2 + M_{res,2}^2\right) + \left(M_{res,1}^2 - M_{res,2}^2\right)^2}{4p_{tot}^2}$$

- Set energy to full fill the on-shell condition
- Boost back to lab frame

On-shell projection for two resonances (explicit form)

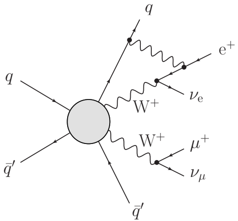
- Apply momentum rescaling to the decay momenta
  - Boost decay momentum into the rest frame of the off-shell resonance
  - Rescale decay momentum

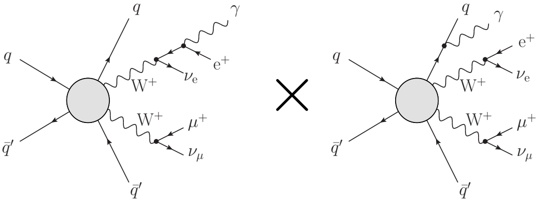
$$\tilde{p}''_{decay} = \frac{M_{res}}{\sqrt{p^2_{res}}} p''_{decay} \qquad \text{(massless decay particles)}$$

  - Boost back from the decay frame of the on-shell resonance to the lab frame

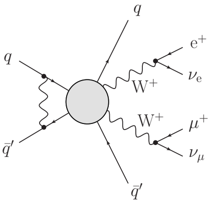
Calculation of NLO corrections in the DPA

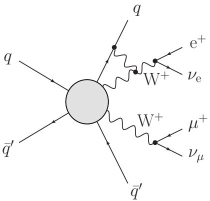
- Nonfactorisable contributions are background
  - Small when real and virtual treated in the DPA





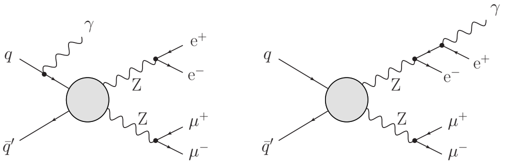
- Virtual and integrated dipole contributions are evaluated with the same methods as at LO





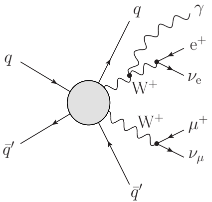
Real NLO EW corrections to neutral resonances

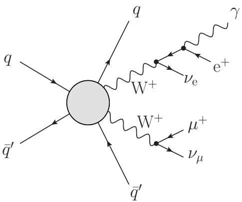
- Clear split between emission from production and the decay subprocess
- IR divergences can be canceled with the same type of dipole structures as in the full off-shell calculation
- For real emission from the decay the on-shell projection is done with one additional decay particle

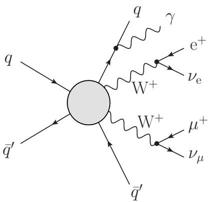


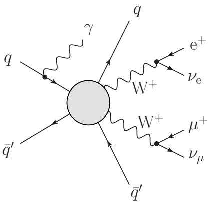
Real NLO EW corrections to charged resonances

- Diagrams with real radiation from the resonant propagators contribute
  - Split between production and decay part
- Additional divergent structures only present for on-shell resonances
  - Additional local counterterms (massive dipoles) are needed
  - Charged resonances take role of emitter and/or spectator in dipoles

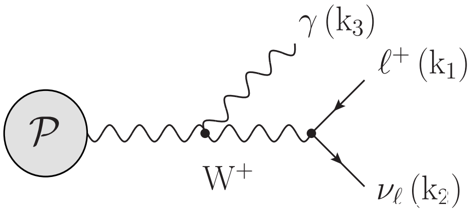








Partial-fraction decomposition



$$\mathcal{A} = \mathcal{N}(k_1, k_2, k_3)\,\frac{1}{s_{123} - M_W^2 + iM_W\Gamma_W} \cdot \frac{1}{s_{12} - M_W^2 + iM_W\Gamma_W}$$
$$= -\frac{\mathcal{N}(k_1, k_2, k_3)}{s_{13} + s_{23}}\left(\frac{1}{s_{123} - M_W^2 + iM_W\Gamma_W} - \frac{1}{s_{12} - M_W^2 + iM_W\Gamma_W}\right)$$

- Use a partial fraction decomposition to split the divergence between the process where the photon is emitted from the production and from the decay amplitude

Partial-fraction decomposition

- Split resonances s_{12} and s_{123}
- Project s_{12} on-shell $\rightarrow$ divergence is only in the production amplitude

$$\tilde{\mathcal{A}}^{(2)} = \frac{1}{s_{12} - M_W^2 + iM_W\Gamma_W} \left[\frac{\mathcal{N}(\tilde{k}_1^{(12)}, \tilde{k}_2^{(12)}, \tilde{k}_3^{(12)})}{\tilde{s}_{13}^{(12)} + \tilde{s}_{23}^{(12)}} \right]$$

- Project s_{123} on-shell $\rightarrow$ divergence is only in the decay amplitude

$$\tilde{\mathcal{A}}^{(3)} = \frac{1}{s_{123} - M_W^2 + iM_W\Gamma_W} \left[-\frac{\mathcal{N}(\tilde{k}_1^{(123)}, \tilde{k}_2^{(123)}, \tilde{k}_3^{(123)})}{\tilde{s}_{13}^{(123)} + \tilde{s}_{23}^{(123)}} \right]$$

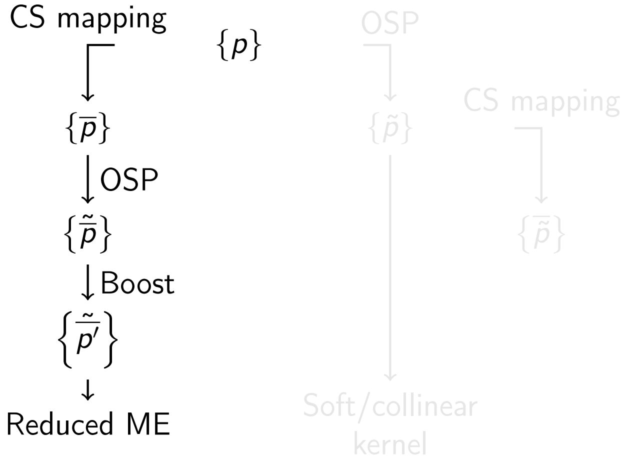
- Massive particle counterterms can be used to cancel the divergences in the production and decay amplitude

Resonance dipoles

- Decay dipoles
  - Newly derived dipole tailored to the W-boson decay reproducing its radiative decay
  - The other decay momenta (here the neutrino momentum) is used as the spectator for the subtraction mapping
- Production dipoles
  - Use the kernel structure for photon emission from a massive fermion [Catani, Dittmaier, Seymour, Trócsányi 0201036], [Dittmaier 9904440]
    - ⋆ Same singular behaviour as W-bosons

Evaluation of the local counterterms

- Off-shell real momenta $\{p\}$
- Reduced ME
  1. Catani-Seymour subtraction mapping
  2. Project on-shell (reduced)
  3. For polarised processes boost to the reference frame
- Soft/collinear kernel
  1. Project on-shell (real)
- The on-shell mapping and the subtraction mapping do not necessarily commute



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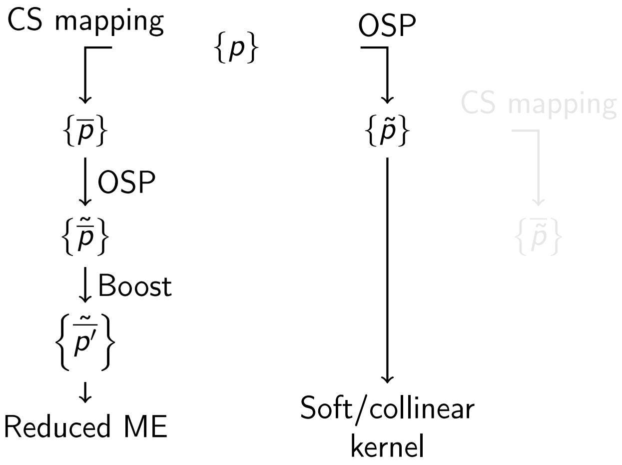

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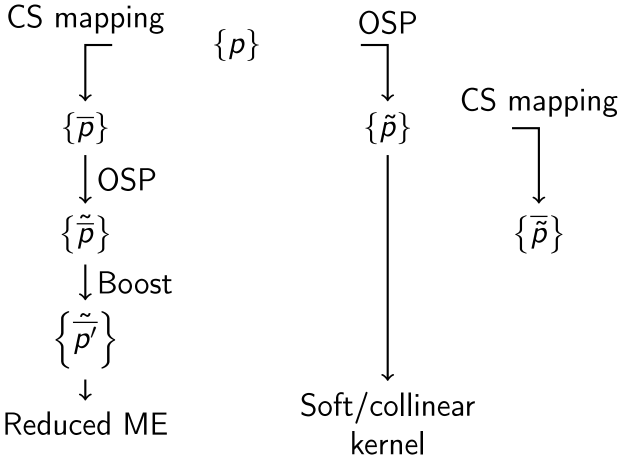
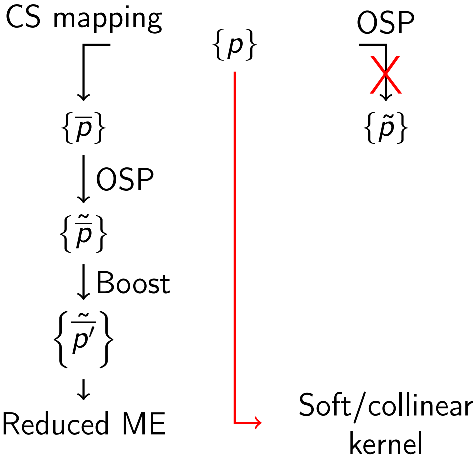


Evaluation of the local counterterms

- The subtraction mapping is applied to the off-shell phase-space point
- There are phase-space points where
  - Reduced momenta can be projected on-shell
  - Real momenta cannot be projected on-shell
- Far from the singular regions
  - Local subtraction is not effected by the treatment of these events
- Evaluate counterterm kernels with off-shell real momenta



Correspondence between local and integrated counterterms

- Finite parts of the local and integrated counterterms need to cancel
- Analytic integration in d-dimensions to compute the integrated counterterms is done over the on-shell radiation phase space
- Numerical integration of the local counterterms is done over the off-shell radiation phase space
- This introduces a mismatch between the local and integrated counterterms
  - For our method this is an effect beyond the accuracy of the DPA
  - Reverse order (On-shell projection first, CS mapping second) gives potentially larger discrepancies

NLO QCD corrections

- Colour neutral resonances (Z bosons, W bosons)
  - Analogous to NLO EW with uncharged resonances
- Colour charged resonances (top quarks)
  - Similar to charged resonances in the EW case
  - Additional local counterterms are needed
  - Resonance is the emitter and/or spectator
  - Massive recoiler in the mapping of the decay counterterms
  - Need dipole for gluon entering the reduced process and the resonance as spectator

Phase-space cuts

- Based on the CMS polarisation analysis [CMS 2009.09429]
- Charged leptons are dressed with the anti-k_T algorithm ($R = 0.1$)
- Cannot apply a cut on the W invariant mass to reduce the nonresonant background

Single lepton cuts	min p_{T,ℓ_1}	25 GeV
	min p_{T,ℓ_2}	20 GeV
	max $\lvert y_{\ell_{1,2}}\rvert$	2.5
Charged lepton pair cuts	min $M_{e^+\mu^-}$	20 GeV
Missing momentum cut	min $p_{T,mis}$	30 GeV
Single jet cuts	min $p_{T,j_{1,2}}$	50 GeV
	max $\lvert y_{j_{1,2}}\rvert$	4.7
	min $\Delta R_{\ell,j_{1,2}}$	0.4
Jet pair cuts	min $M_{j_1 j_2}$	500 GeV
	min $\lvert\Delta y_{j_1 j_2}\rvert$	2.5
Zeppenfeld cut	max $\dfrac{\max_{\ell=e^+,\mu^+}\left\lvert y_\ell - \frac{y_{j_1}+y_{j_2}}{2}\right\rvert}{\lvert\Delta y_{j_1 j_2}\rvert}$	0.75

LO Integrated Results

state	$\sigma_{\mathrm{LO}\alpha^6}$ [fb]	$\delta_{\alpha_s^1\alpha^5}$	$\delta_{\alpha_s^2\alpha^4}$	$\delta_{\alpha_s^1\alpha^5+\alpha_s^2\alpha^4}$	σ_{LO} [fb]
full	1.4863(1)	0.03	0.10	0.13	1.6780(1)
unp	1.46455(9)	0.03	0.10	0.13	1.65558(9)
LL	0.14879(1)	0.04	0.08	0.12	0.16721(1)
LT	0.23209(2)	0.03	0.13	0.16	0.26884(2)
TL	0.23208(2)	0.03	0.13	0.16	0.26884(2)
TT	0.87702(7)	0.03	0.09	0.12	0.98281(7)
int.	−0.0254(1)	0.11	0.16	0.26	−0.0321(1)

(...) Integration uncertainty

LO Integrated Results

state	$\sigma_{\mathrm{LO}\alpha^6}$ [fb]	$\delta_{\alpha_s^1\alpha^5}$	$\delta_{\alpha_s^2\alpha^4}$	$\delta_{\alpha_s^1\alpha^5+\alpha_s^2\alpha^4}$	σ_{LO} [fb]
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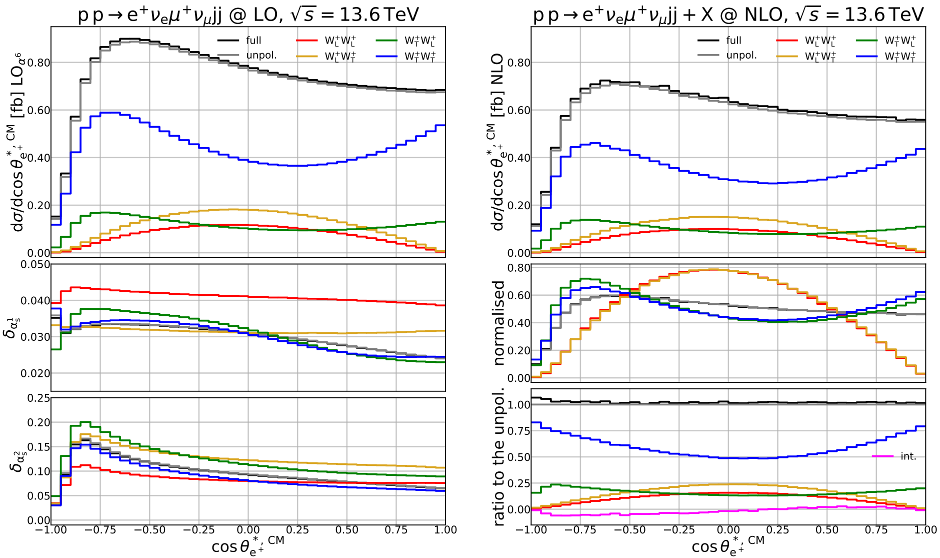
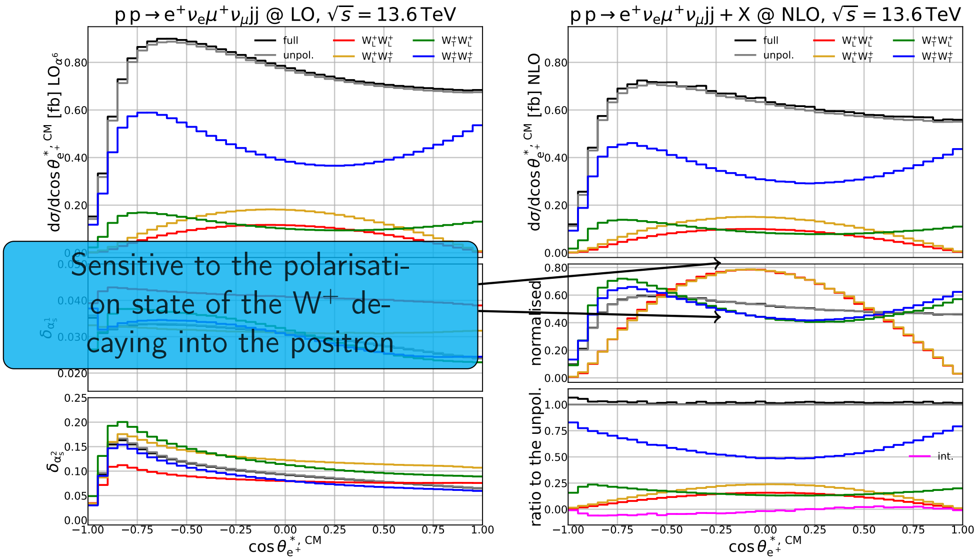
- Small background ($\mathcal{O}(\alpha_s^1\alpha^5) \approx 3\%$; $\mathcal{O}(\alpha_s^2\alpha^4) \approx 10\%$)
- Phase space cuts suppress the background well

Decay angle of the positron

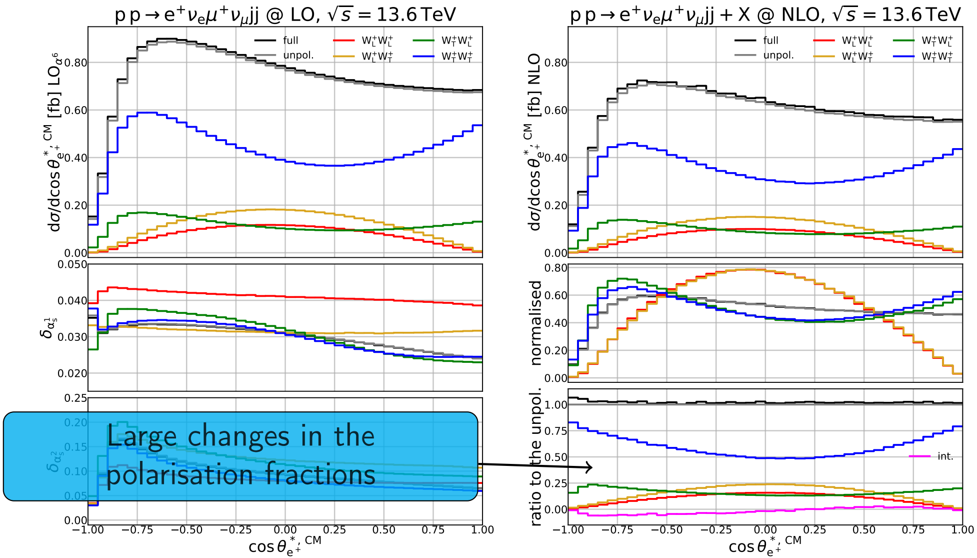


Decay angle of the positron



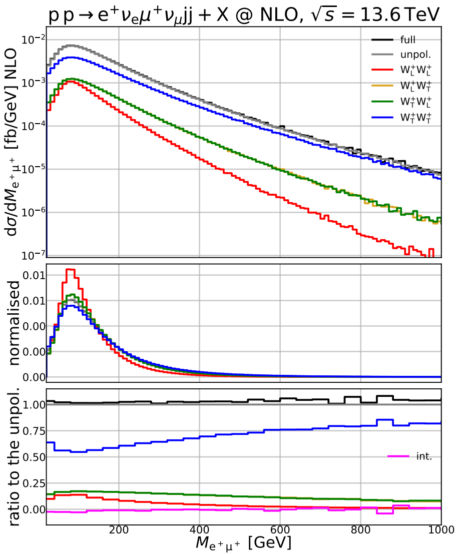
Sensitive to the polarisation state of the W^+ decaying into the positron

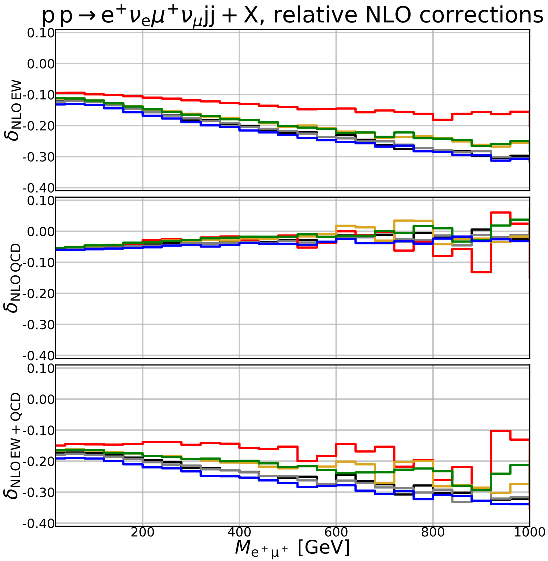
Decay angle of the positron



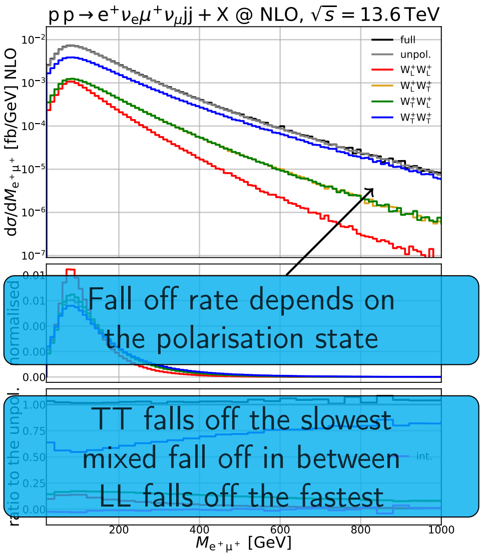
Large changes in the polarisation fractions

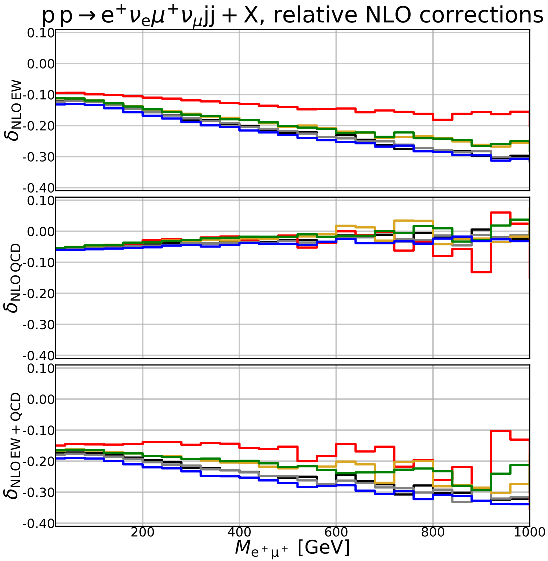
Invariant mass positron and anti muon



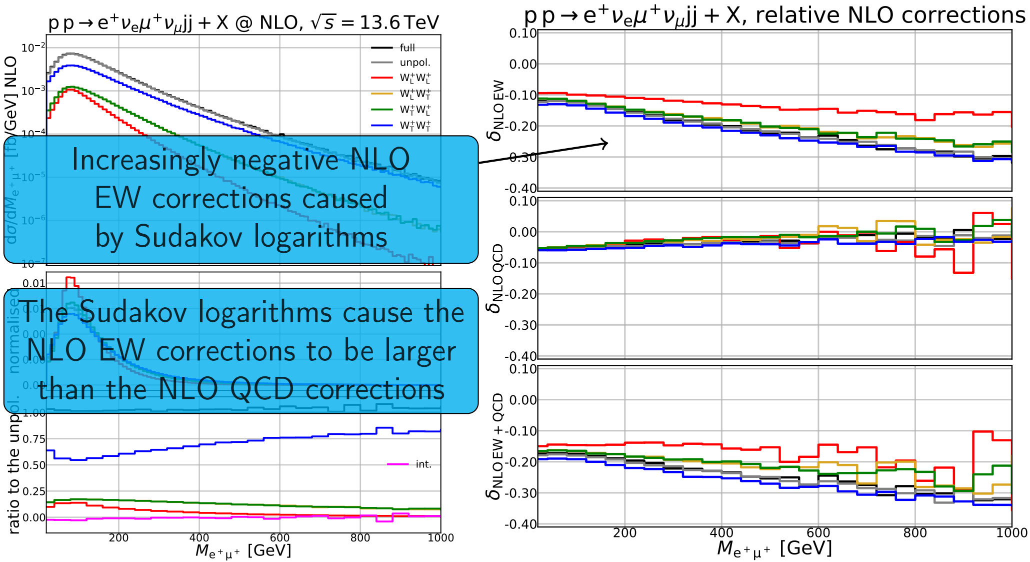


Invariant mass positron and anti muon





Invariant mass positron and anti muon



Increasingly negative NLO EW corrections caused by Sudakov logarithms

The Sudakov logarithms cause the NLO EW corrections to be larger than the NLO QCD corrections