Theory predictions for polarized di-boson and vector boson scattering at the LHC

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Based on arXiv:2006.14867 (with A. Denner)
and on arXiv:2007.07133 (with A. Ballestrero and E. Maina).

Motivations

LHC physics and polarizations

- LHC luminosities accumulated in Run 2 ($\approx 150\,\mathrm{fb}^{-1}$) at 13 TeV CoM energy and foreseen in next runs ($300\,\mathrm{fb}^{-1}$ in Run 3, and $3000\,\mathrm{fb}^{-1}$ in High-Lumi) allow for precise measurements of electroweak boson production processes.

- Polarization observables for W/Z non trivial to disentangle (unstable), but:
  1. are important probes of Standard Model (SM) gauge and Higgs sectors;
  2. may provide discrimination power between SM and beyond-SM physics.

- Longitudinal mode is consequence of the Electroweak Symmetry Breaking mechanism (EWSB): any deviation from the SM in longitudinal boson production could mean evidence for modified EWSB/BSM effects.

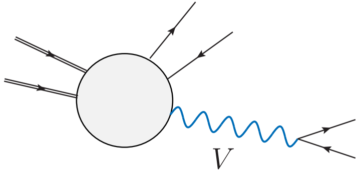
- Main interest in di-boson, vector boson scattering and top-quark decays.

- This talk: phenomenological results in the SM, but methods used for the calculations can be applied in presence of BSM physics.

Theory & Monte Carlo

Separating polarizations: basics

A natural definition for resonant diagrams, in the 't Hooft-Feynman gauge:



$$\mathcal{A}^{\text{unpol}} = \mathcal{P}_\mu \frac{-g^{\mu\nu}}{k^2 - M_V^2 + iM_V\Gamma_V} \mathcal{D}_\nu$$

$$= \mathcal{P}_\mu \frac{\sum_{\lambda'} \varepsilon^\mu_{\lambda'} \varepsilon^{*\nu}_{\lambda'}}{k^2 - M_V^2 + iM_V\Gamma_V} \mathcal{D}_\nu$$

$$\longrightarrow \mathcal{P}_\mu \frac{\varepsilon^\mu_{\lambda} \varepsilon^{*\nu}_{\lambda}}{k^2 - M_V^2 + iM_V\Gamma_V} \mathcal{D}_\nu = \mathcal{A}_\lambda$$

At the cross section level,

$$|\mathcal{A}^{\text{unpol}}|^2 = \underbrace{\sum_\lambda |\mathcal{A}_\lambda|^2}_{\text{incoherent sum}} + \underbrace{\sum_{\lambda \neq \lambda'} \mathcal{A}^*_\lambda \mathcal{A}_{\lambda'}}_{\text{interference terms}} \longrightarrow |\mathcal{A}_\lambda|^2 \propto \text{polarized cross section}$$

Polarization vectors are defined in a specific frame: natural choices are the laboratory or the di-boson system (when two weak bosons present).

Decay leptons angular distributions reflect polarization state of the decayed V boson.

Separating polarizations: analytic formulae

- At tree-level, for a resonant process: the following master equation holds (θ^*, ϕ^* are ℓ^+ angles in V rest frame, w.r.t. V direction in the lab) [Bern et al. 1103.5445],

$$\frac{d\sigma}{d\cos\theta^* d\phi^* dX} = \frac{d\sigma}{dX}\frac{3}{16\pi}\Big[(1+\cos^2\theta^*) + (A_0/2)(1-3\cos^2\theta^*) + A_1 \sin 2\theta^* \cos\phi^* + (A_2/2)\sin^2\theta^* \cos 2\phi^* + A_3 \sin\theta^* \cos\phi^* + A_4 \cos\theta^* + A_5 \sin^2\theta^* \sin 2\phi^* + A_6 \sin 2\theta^* \sin\phi^* + A_7 \sin\theta^* \sin\phi^*\Big]$$

where X are kin. variable independent of lepton angles (*e.g.* p_T^V, η_V). $A_i = A_i(X)$.

- If no lepton cuts applied, interferences vanish upon integration over full azimuth ϕ^*:

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta^*} = \frac{3}{8}f_-\left(1+\cos^2\theta^* - \frac{2(c_L^2-c_R^2)}{(c_L^2+c_R^2)}\cos\theta^*\right) + \frac{3}{8}f_+\left(1+\cos^2\theta^* + \frac{2(c_L^2-c_R^2)}{(c_L^2-c_R^2)}\cos\theta^*\right) + \frac{3}{4}f_L \sin^2\theta^*,$$

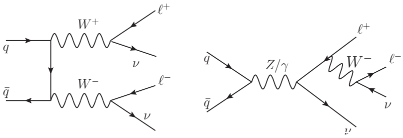
f_L, f_-, f_+ polarization fractions of the decayed V boson ($f_L + f_- + f_+ = 1$).

- If lepton cuts applied, analytic expression for $d\sigma/d\cos\theta^*$ does not hold anymore: interferences do not vanish (cannot integrate over the full ϕ^* range).

Selecting resonant diagrams

- Bottleneck: not all diagrams that contribute to multiboson processes are resonant!

To define polarizations in multiboson, we need a factorized amplitude (production $\otimes$ propagator $\otimes$ decay): not possible for all contributions. *E.g.* diboson (fully leptonic):



Double-resonant and non-double-resonant diagrams at LO. For the latter polarizations cannot be defined: drop them, providing a recipe to recover gauge invariance.

Separating resonant contributions is delicate: the only "truth" is the full computation.

- Consider non-double-resonant diagrams as non-resonant background.

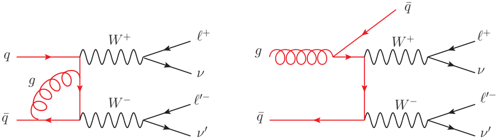
- Treat double-resonant diagrams with Double Pole Approximation (DPA) [Denner et al. 0006307]: project weak bosons on-shell, mantaining off-shell kinematics in Breit-Wigner modulation.

- Then separating polarizations is straightforward.

Going beyond leading-order

NLO QCD is in principle easy (no coupling to EW boson leptonic decays), but

- Born (B), virtuals (V) and reals (R) contribute: V+R is free of IR singularities;



- subtraction counterterms needed, *e.g.* dipoles D in Catani-Seymour formalism [Catani, Seymour 9605323]:

$$d\sigma_{\text{nlo}}/d\xi = \int d\phi_n (B + V + \int d\phi_{\text{rad}}\, D)_{d=4}\, \delta_\xi^{(n)} + \int d\phi_{n+1} (R\, \delta_\xi^{(n+1)} - D\, \delta_\xi^{(n)})_{d=4}\,; \quad (1)$$

- DPA usually used for LO kinematics (B,V), need for analogous prescription for R and subtraction counterterms (most involved part of the computation);
- separation of polarizations required for all contributions in Eq. 1.

Implemented in MoCaNLO MC interfaced with Recola [Actis et al. 1211.6316, 1605.01090] completely for processes without final state jets, *e.g.* diboson, close to completion for processes with final state jets, *e.g.* VBS.

NLO EW more involved (production and decay sub-amplitudes mixed in V and R).

Di-boson: W^+W^-

Setup(s) of the calculation

Process: $pp \to e^+\nu_e\mu^-\overline{\nu}_\mu + X$.
Accuracy: NLO QCD for $q\overline{q}$, combined with LO for the gg (loop-induced).
Code: MoCaNLO Monte Carlo integrator, interfaced with Recola+Collier.
Details: $N_F = 5$, G_μ-scheme for α, Complex-Mass-Scheme for weak bosons.
PDFs.: NNPDF3.1 at (N)LO with $\alpha_s(M_Z) = 0.118$, LHAPDF interface.
Ren. and fact. scale: $\mu_R = \mu_F = M_W$.

Two sets of selection cuts:

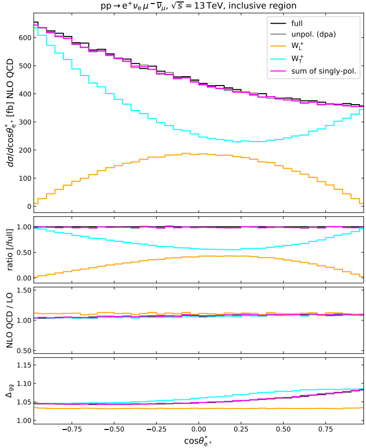
- inclusive: $p_{T,\ell} > 0.01\,\text{GeV}$ (technical),
  no jets with $|\eta_j| < 4.5$ and $p_{T,j} > 35\,\text{GeV}$.
- fiducial: $p_{T,\ell} > 27\,\text{GeV}$, $|y_\ell| < 2.5$, $p_T^{\text{miss}} > 20\,\text{GeV}$, $M_{e\mu} > 55\,\text{GeV}$,
  no jets with $|\eta_j| < 4.5$ and $p_{T,j} > 35\,\text{GeV}$.

We have simulated: full off-shell (σ_{full}), DPA unpolarized (σ_{unpol}),DPA singly-polarized (σ_λ, $\lambda = \text{L,T}$) for W^+, DPA doubly-polarized signals (σ_λ $\lambda = \text{LL, LT, TL, TT}$).

Non-resonant background: $\sigma_{\text{full}} - \sigma_{\text{unpol}}$. Interferences among pol. states: $\sigma_{\text{unpol}} - \sum_\lambda \sigma_\lambda$ (sum over singly- or doubly-pol.).

- Polarizations defined in the laboratory frame.

Inclusive setup: validation



- Total cross-sections:

non-res. bkg 1.4(1.1)% at LO(NLO QCD);

interferences are zero ($< 10^{-4}$).

- Distributions in $\cos\theta^*_\ell$:

very good agreement between analytic extraction of pol. fractions (and distributions) and the Monte Carlo results;

both singly- and doubly-polarized signals;

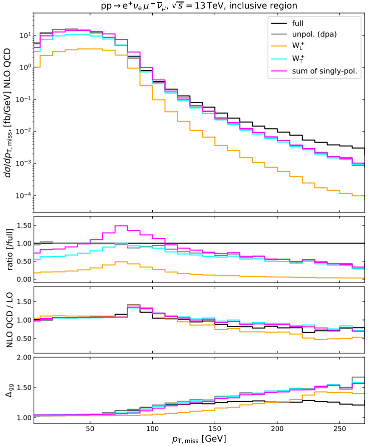
for singly-polarized signals similar K-factor to the unpol.;

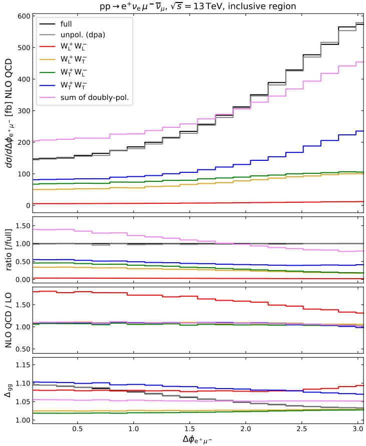
gg-channel reflects the different initial-st. spin-structure (*e.g.* left-right symmetry).

mode	MC (LO)	analytic (LO)	MC (NLO)	analytic (NLO)
W^+_{L}	$0.261(1)^{+0.002}_{-0.002}$	$0.260(3)^{+0.002}_{-0.003}$	$0.271(1)^{+0.001}_{-0.001}$	$0.272(3)^{+0.001}_{-0.001}$
W^+_{T}	$0.739(3)^{+0.003}_{-0.002}$	$0.740(5)^{+0.002}_{-0.002}$	$0.729(3)^{+0.002}_{-0.001}$	$0.728(6)^{+0.001}_{-0.001}$

Inclusive setup: correlation and surprises

For some observables, large interference effects and/or large non-resonant bkg.





Missing p_T: single-res. diagrams dominate, DPA does not decribe the full result (large non-res. bkg).

$\Delta\phi_{e\mu}$: large interferences (similarly to Higgs decay). Strong correl. between the W's, pure left-handed $W\ell\nu_\ell$ coupling.

Fiducial setup: integrated cross-sections

	LO	NLO QCD	K-factor	Δ_{gg}
full	$202.02(3)^{+4.6\%}_{-5.5\%}$	$220.16(8)^{+1.8\%}_{-2.2\%}$	1.09	1.06
unpolarized (DPA)	$195.91(3)^{+4.7\%}_{-5.5\%}$	$214.48(9)^{+1.8\%}_{-2.2\%}$	1.09	1.06
$W^+_L W^-_{\text{unpol}}$ (DPA)	$50.94(1)^{+5.5\%}_{-6.5\%}$	$57.42(4)^{+1.9\%}_{-2.6\%}$	1.13	1.04
$W^+_T W^-_{\text{unpol}}$ (DPA)	$141.72(2)^{+4.3\%}_{-5.1\%}$	$152.84(9)^{+1.7\%}_{-2.1\%}$	1.08	1.07
$W^+_L W^-_L$ (DPA)	$6.653(1)^{+4.9\%}_{-5.8\%}$	$9.057(5)^{+2.9\%}_{-3.0\%}$	1.36	1.08
$W^+_L W^-_T$ (DPA)	$44.08(1)^{+5.6\%}_{-6.5\%}$	$48.24(4)^{+1.9\%}_{-2.5\%}$	1.09	1.04
$W^+_T W^-_L$ (DPA)	$50.19(1)^{+5.5\%}_{-6.4\%}$	$54.02(4)^{+1.9\%}_{-2.5\%}$	1.08	1.03
$W^+_T W^-_T$ (DPA)	$99.61(2)^{+3.7\%}_{-4.6\%}$	$106.20(7)^{+1.6\%}_{-1.9\%}$	1.07	1.09

Tab. Total cross-sections (fiducial setup) in fb.

Non-res. bkg enhanced: 3.0(2.6%) at LO (NLO QCD). Small interferences (2%).

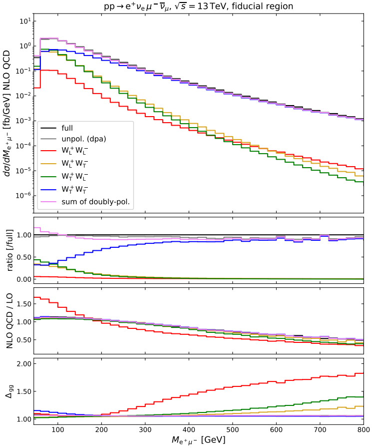
Transverse config.'s dominate (W^+_T >70%, $W^+_T W^+_T \approx$ 50%).

Large K-factor for $W^+_L W^-_L$ ($\approx$ 40%), similar to unpol. in other cases ($\approx$ 10%).

MC pol. fractions: stable against NLO QCD corr. ($\pm$1%, for singly-pol.),
very stable against scale var. (both at LO and NLO QCD).

gg-channel enhances spin-matrix diagonal entries ($\approx$ 10%).

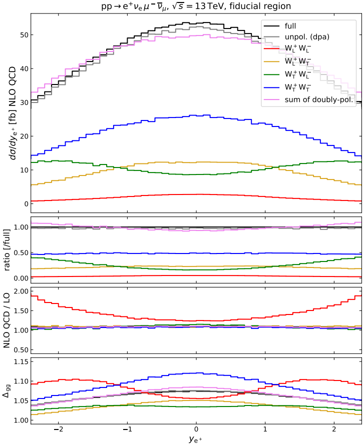
Fiducial setup: differential results

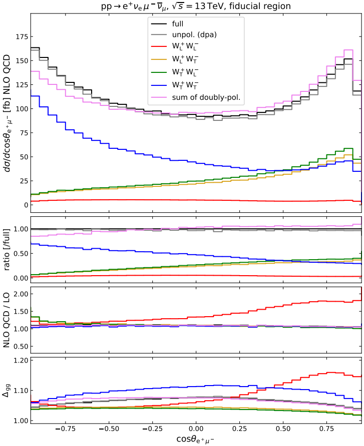


Distribution in $M_{e\mu}$:

- configurations with one longit. boson suppressed already at moderate masses (1% of $W_T^+W_T^-$ at 800 GeV);
- moderate interferences in the low mass spectrum (15-20%, with change of sign), relatively small non-res. bkg;
- $W_L^+W_L^-$ crosses the mixed config.'s at 500 GeV;
- NLO QCD corr. large (+50%) at low mass, positive for $M_{e\mu} < 200$ GeV, negative otherwise;
- gg-channel enhances $W_L^+W_L^-$ by $> 50\%$ for $M_{e\mu} > 450$ GeV

Fiducial setup: more differential results





Rapidity of e^+: shape differences in doubly-pol. signals, small interferences and non-res. bkg. (a few %) over the whole accessible range.

$\cos\theta_{e\mu}$: moderate interferences and small non-res. bkg. Discrimination power among pol. states. Mixed contributions relevant close to collinear regime.

Vector boson scattering: W^+W^+

Setup(s) of the calculation

Process: $pp \to e^+\nu_e\mu^+\nu_\mu jj$.
Accuracy: LO EW, $\mathcal{O}(\alpha^6)$.
Code: PHANTOM Monte Carlo.
Details: $N_F = 5$, G_μ-scheme for α, Complex-Mass-Scheme for weak bosons.
PDFs.: NNPDF3.0 at LO with $\alpha_s(M_Z) = 0.118$, LHAPDF interface.
Ren. and fact. scale: $\mu_R = \mu_F = \sqrt{p_{\mathrm{T,j1}}\,p_{\mathrm{T,j2}}}$.

Two sets of selection cuts:

- inclusive: $M_{jj} > 500\,\mathrm{GeV}$, $|\Delta\eta_{jj}| > 2.5$, $|\eta_j| < 5$, $p_{\mathrm{T,j}} > 20\,\mathrm{GeV}$.
- fiducial: $M_{jj} > 500\,\mathrm{GeV}$, $|\Delta\eta_{jj}| > 2.5$, $|\eta_j| < 5$, $p_{\mathrm{T,j}} > 20\,\mathrm{GeV}$,
  $p_{\mathrm{T},\ell} > 20\,\mathrm{GeV}$, $|y_\ell| < 2.5$, $p_{\mathrm{T}}^{\mathrm{miss}} > 40\,\mathrm{GeV}$.

- Singly- and doubly-polarized signals defined both in the laboratory frame (helicity coord. sys.) and in the WW-CM frame (modified coord. sys.).

- Strong validation performed in the inclusive setup: perfect agreement with the resuts extracted by projections of $\cos\theta^*_\ell$ unpolarized distributions.

Fiducial setup: integrated cross-sections

	LAB	WW-CM	ratio
full	1.593(2)		-
unpol	1.572(2)		-
0-unpol	0.4226(4)	0.4036(5)	0.96
T-unpol	1.165(1)	1.182(2)	1.01
0-0	0.1185(1)	0.1552(2)	1.31
0-T,T-0	0.3062(3)	0.2519(3)	0.82
T-T	0.8690(9)	0.9350(9)	1.08

Tab. Total cross-sections (fiducial setup) in fb.

Small non-resonant background (missing off-shell effects): 1.5%.

Small interferences among polarization (negative, $\approx 1\%$): the sum of polarized signals approximates to 0.5% the full result.

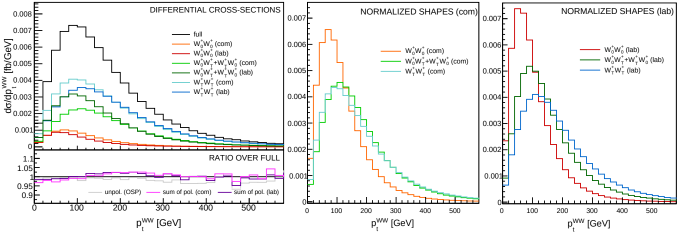
Singly-polarized signals rather insensitive to the polarization definition.

LL and TT signals are enhanced in the WW-CM definition (+31% and +8% respectively). Mixed enhanced in the LAB.

Stronger correlations in the WW-CM (most natural frame in the scattering of bosons).

Fiducial setup: differential results

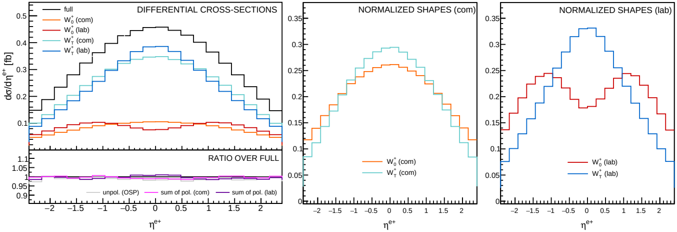
Interferences and non-resonant background are small even at the differential level: at most 5% effect in the full p_T^{WW} spectrum.



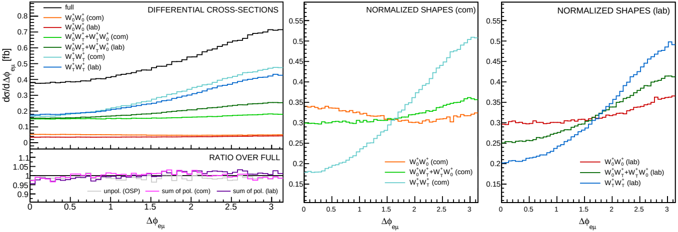
p_T^{WW}: sizeable shape differences between WW-CM and LAB definitions, more discrimination power in the LAB definition.

Measurable at the LHC, coincides with two-jet system p_T at LO: sensitive to additional QCD jets.

Fiducial setup: more differential results



η_{e^+}: strong shape differences in the transverse mode between two definitions: more discrimination power in the LAB.



$\Delta\phi_{\ell\ell'}$: noticeable shape differences among polarized modes, mostly in the CM.

Our results do not clearly favor either of the two polarization vector definitions.

Conclusions

Some final comments

Weak boson polarization gaining interest in experimental and theoretical communities.

We define polarized signals at the amplitude level and use double-pole approx.:

- di-boson: complete study at NLO QCD for W^+W^- [Denner, GP, 2006.14867], can be easily extended to $W^\pm Z$ and ZZ;
- VBS: complete study at LO EW for W^+W^- [Ballestrero, Maina, GP, 1710.09339], W^+Z and ZZ [Ballestrero, Maina, GP, 1907.04722] and W^+W^+ [Ballestrero, Maina, GP, 2007.07133].

A theory view point.

1. Defining polarized signals is delicate, several strategies (approximated).
2. Different polarization definition lead to sizeable differences in results.
3. Interferences usually small but definitely needed. Same for non-resonant bkg.
4. NLO accuracy needed: QCD available, EW more involved but feasible.
5. Polarized signals at the amplitude level more physically motivated and better behaved than other approaches.

Outlook: what's next

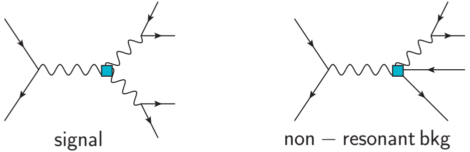
Possible future directions:

1. more processes (single top, $t\bar{t}$, QCD backgrounds, ...);
2. more decay channels (same-flavor, semi-leptonic);
3. beyond SM (UV-finite models, Effective Field Theory).

Two comments on EFT.

• Polarization observables in di-boson have been studied in SMEFT at NLO QCD *e.g.* in Ref. [Baglio, Dawson, Lewis 1812.00214] for on-shell bosons. Including decays and off-shell effects could play a relevant role in the results.

• Our approach just relies on the separation between a resonant signal (treated with DPA) and a non-resonant background (the missing off-shell effects). It can be applied with any underlying dynamics, for example SMEFT: some effective insertions will affect the non-resonant background, some will affect the signal.



Backup

Di-boson: total cross-sections in the inclusive setup

	LO	NLO QCD	K-factor	Δ_{gg}
full	$871.4(4)^{+4.2\%}_{-5.1\%}$	$932.0(9)^{+1.8\%}_{-2.3\%}$	1.07	1.05
unpolarized (DPA)	$859.1(2)^{+4.2\%}_{-5.1\%}$	$920.7(5)^{+1.9\%}_{-2.4\%}$	1.07	1.05
$W^+_L W^-_{\mathrm{unpol}}$ (DPA)	$224.0(1)^{+5.0\%}_{-6.3\%}$	$249.2(2)^{+2.0\%}_{-2.5\%}$	1.11	1.03
$W^+_T W^-_{\mathrm{unpol}}$ (DPA)	$635.0(1)^{+4.0\%}_{-4.8\%}$	$671.4(4)^{+1.8\%}_{-2.2\%}$	1.06	1.06
$W^+_L W^-_L$ (DPA)	$16.22(1)^{+5.2\%}_{-6.0\%}$	$25.19(2)^{+2.4\%}_{-3.3\%}$	1.55	1.08
$W^+_L W^-_T$ (DPA)	$207.8(1)^{+5.0\%}_{-6.0\%}$	$224.0(1)^{+2.0\%}_{-2.6\%}$	1.08	1.03
$W^+_T W^-_L$ (DPA)	$253.9(1)^{+4.8\%}_{-5.8\%}$	$266.3(2)^{+2.0\%}_{-2.5\%}$	1.05	1.02
$W^+_T W^-_T$ (DPA)	$381.1(1)^{+3.3\%}_{-4.1\%}$	$404.9(2)^{+1.6\%}_{-2.0\%}$	1.06	1.08

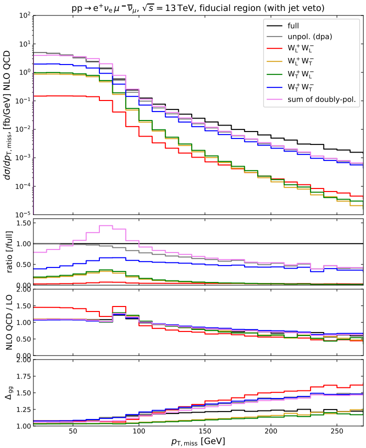
Tab. Total cross-sections (inclusive setup) in fb.

Di-boson: jet-veto in the fiducial setup

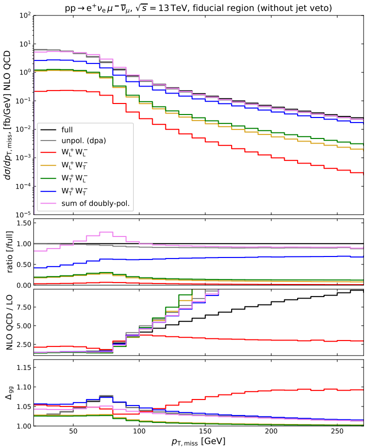
Jet-veto definition: zero jets with $p_{\mathrm{T,j}} > 35$ GeV and $|\eta_{\mathrm{j}}| < 4.5$.

Effects on the missing transverse momentum distributions:

applied

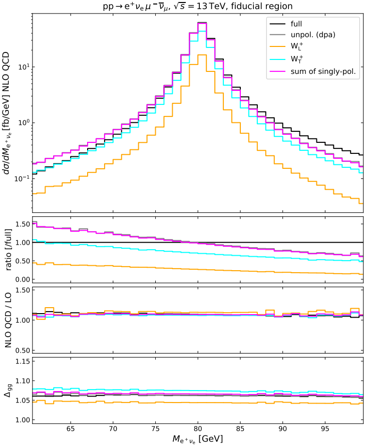


not applied



Di-boson: more distributions in the fiducial setup

$\ell\nu_\ell$ pair invariant mass.



Positron transverse momentum.