Istituto Nazionale di Fisica Nucleare
SEZIONE DI TORINO

UNIVERSITÀ
DEGLI STUDI
DI TORINO

POLARIZATIONS IN VBS AT THE LHC

WW, *ZZ* and *WZ* with PHANTOM

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in collaboration with Alessandro Ballestrero and Ezio Maina

W^+W^- channel

$p\ p \to j\ j\ e^-\mu^+\ \nu\ \nu$, LHC@13TeV, $\mathcal{O}(\alpha_{ew}^6)$

Recap of Ezio's talk in Split:

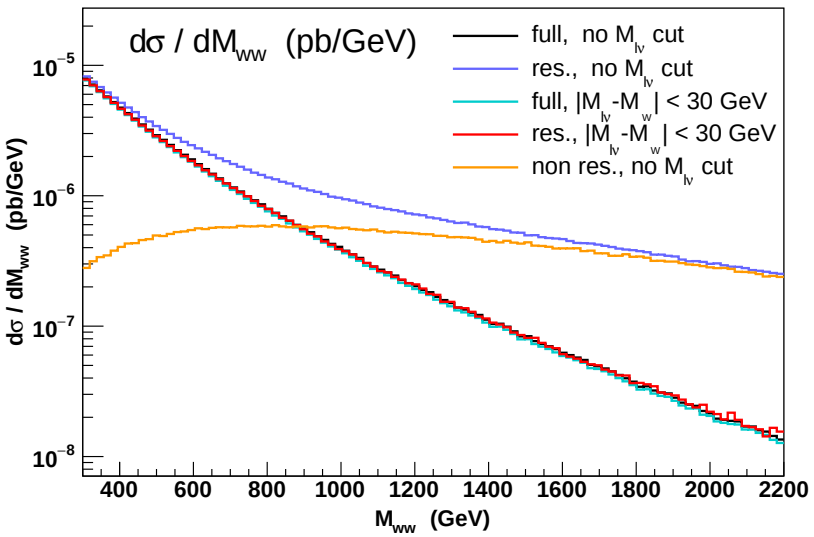
- ⋆ Proposed a way to isolate W bosons with definite polarization in W^+W^- scattering at the LHC, in the presence of minimal lepton cuts. Ballestrero, Maina, GP: JHEP03(2018)170

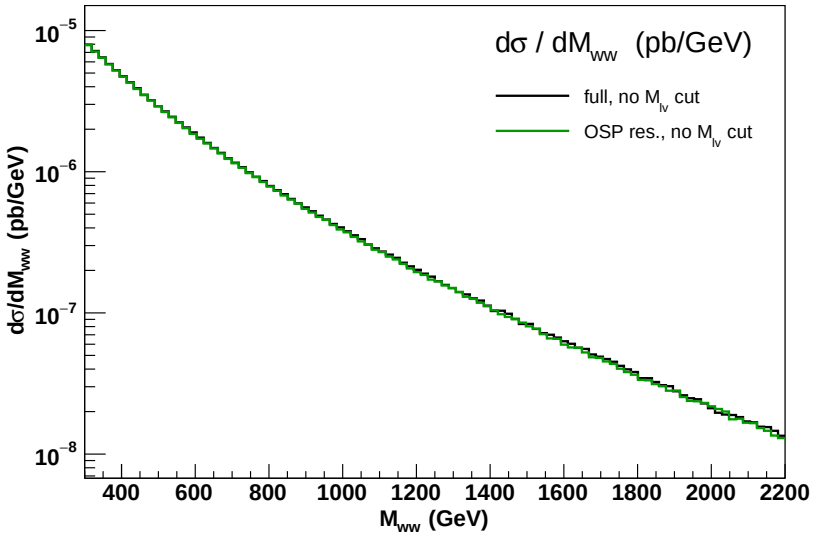
  Cuts: $p_t^j > 20$ GeV, $|\eta_j| < 5$, $M_{jj} > 600$ GeV, $|\Delta\eta_{jj}| > 3.6$, $\eta_{j_1} \cdot \eta_{j_2} < 0$
  $p_t^e > 20$ GeV, $|\eta_e| < 2.5$, $M_{4\ell} > 300$ GeV

- ⋆ Resonant diagrams only (necessary for polarizations definition) $\rightarrow$ On-Shell Projections required to restore gauge invariance ($M_{4\ell} > 2M_w$)

- ⋆ Possibility to extract polarization fractions for BSM models: fitting distributions with polarized SM shapes $\rightarrow$ model (in)dependence.

W^+W^-: resonant contributions and OSP





- Resonant and non-resonant diag. interfere strongly
- If no $M_{\ell\nu}$ cut, resonant diag. do not reproduce the full.
- In the presence of a $M_{\ell\nu}$ cut, at large M_{WW} and $p_t^W \rightarrow$ discrepancies.

On Shell Projections on WW doubly resonant contributions reproduce correctly the full,

with/without $M_{\ell\nu}$ cut.

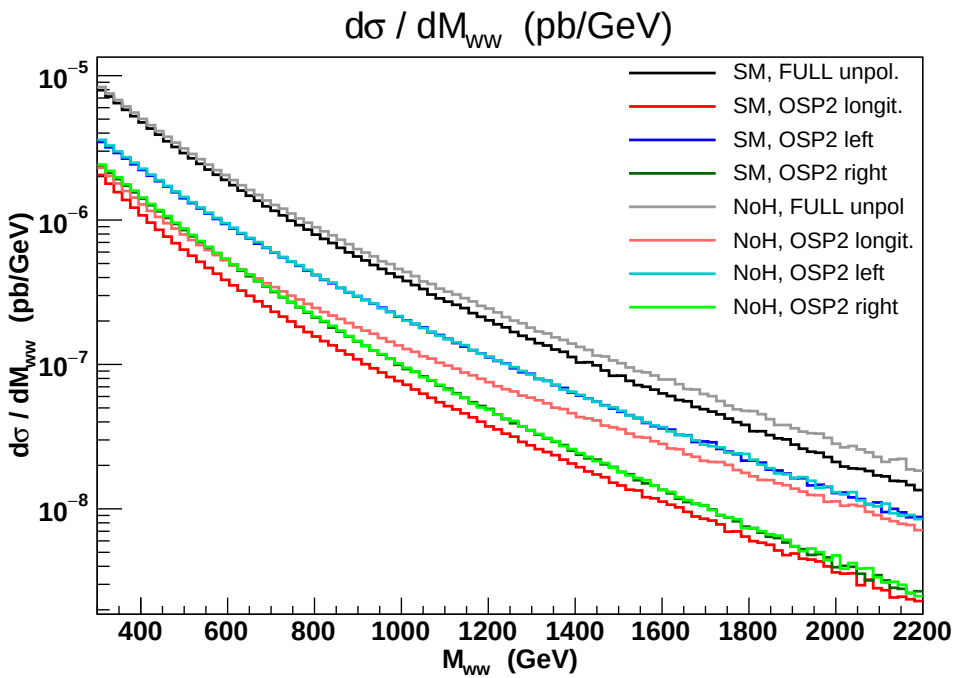
W^+W^-: SM vs NoH

REMARK: in our study W^+ is unpolarized, W^- has definite polarization.

Any Higgs sector realized in nature lies in between Standard Model (SM) and No Higgs (NoH) $\rightarrow$ most extreme BSM theory.

Distribution in $M_{4\ell}$: all the differences between SM and NOH resides in the longitudinal component

transverse component is not sensitive to the Higgs

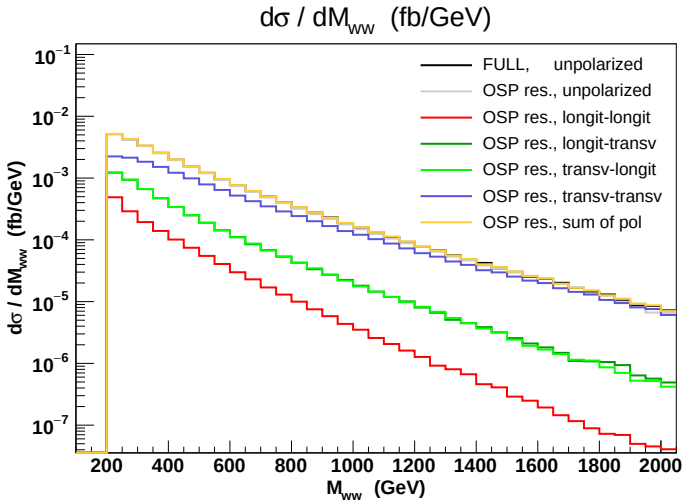


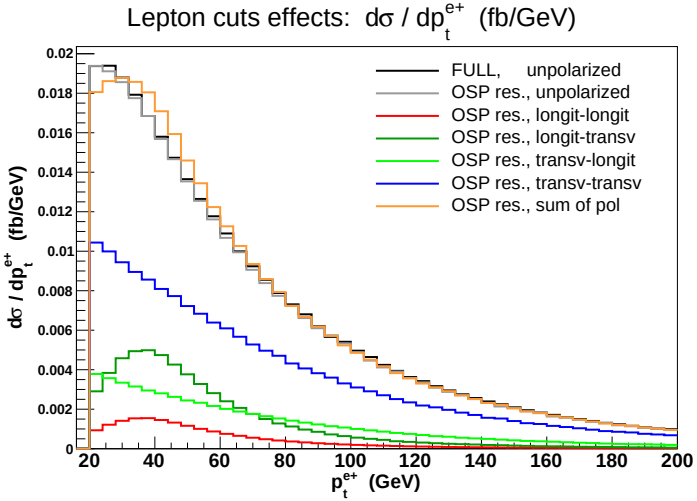
W^+W^+ channel

$pp \to jje^+\mu^+\nu\nu$ at $\mathcal{O}(\alpha_{ew}^6) \to$ more realistic set-up than W^+W^-

Set-up: $p_t^j > 30$ GeV, $|\eta_j| < 4.5$, $M_{jj} > 500$ GeV, $|\Delta\eta_{jj}| > 2.5$, $|\Delta R_{jj}| > 0.3$,
$p_t^{\rm miss} > 40$ GeV, $p_t^\ell > 20$ GeV, $|\eta_\ell| < 2.5$, $|\Delta R_{jj}| > 0.3$, $M_{4\ell} > 200$ GeV

- OSP works pretty well also with new set-up. Unpol. OSP: at most 2 % discrepancies w.r.t the full calc.
- PHANTOM simulations with both W^+ bosons polarized (longit. or transv.)





Leptonic cuts induce interferences among polarizations: sum of pol. distributions differs from the full $\sim 5-7\%$, mainly for leptonic variables

Fiducial cross-sec. within the cuts:

$\sigma_{\rm unpol} = 1.266(5)\,{\rm fb}$

$\sigma_{00} = 0.075(4)\,{\rm fb} \quad \sigma_{0T} = 0.238(2)\,{\rm fb}$

$\sigma_{T0} = 0.238(5)\,{\rm fb} \quad \sigma_{TT} = 0.726(6)\,{\rm fb}$

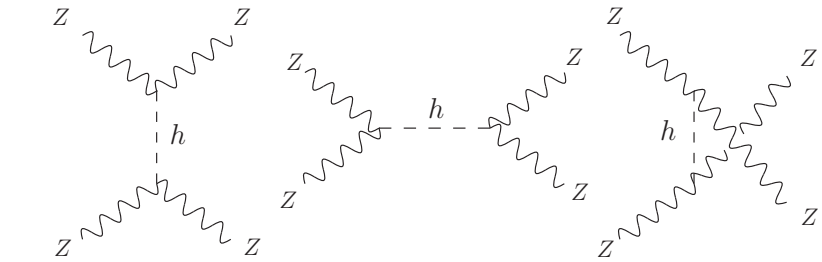
. . . but so far . . .

decay channels which are not realistic
from an experimental p.v.

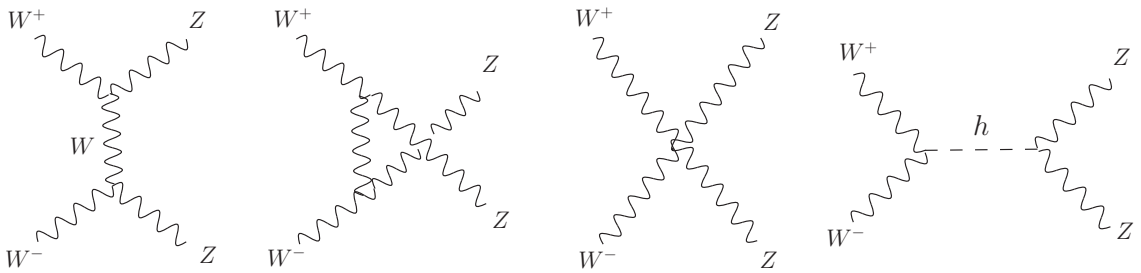
With the new (beta)version of PHANTOM it is possible to compute VBS processes with polarized Z bosons: access to polarized ZZ, $W^{\pm}Z$ scattering, both in leptonic and in semi-leptonic channel, at order $\mathcal{O}(\alpha_{ew}^6)$.

ZZ channel

ZZ production in VBF at the LHC $\rightarrow$ scattering diagrams include both $ZZ \rightarrow ZZ$ and $W^+W^- \rightarrow ZZ$.



No unitarity/gauge cancellations



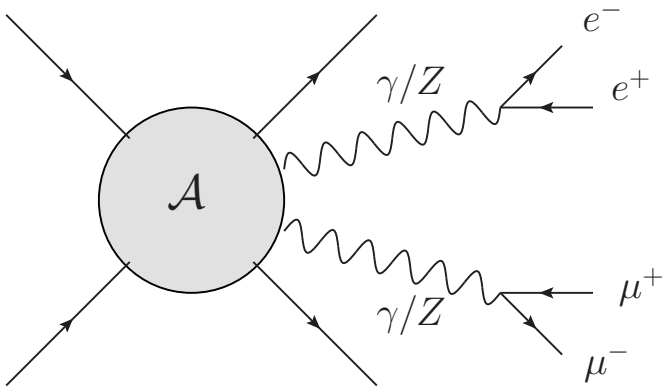
Unitarity/gauge cancellations in $V_L V_L \rightarrow V_L V_L$

REMARK

When selecting ZZ resonant diagrams, γ contributions are discarded.

Huge gauge violations $\Rightarrow$ do On Shell

Projections work also for ZZ scattering?



ZZ: gauge invariance - 1

No more agreement between OSP and full calc. (as obtained in *WW*): OSP doesn't restore gauge invariance.

$e^+e^-\mu^+\mu^-$ (4Z amplitude)

cut	FULL	OSP	RES
$u\ u \to u\ u\ e^-\ e^+\ \mu^-\ \mu^+$ (4Z)			
no cut	44.79	13.02 (-71%)	13.18 (-70%)
5 GeV	10.09	9.55 (-5%)	9.53 (-5%)

- both with and without $M_{\ell\ell}$ cut, non-negligible gauge violations $\to \gamma/Z$ mixing in SM
- switching off the γ decay contrib. ($Z \to \nu\bar{\nu}$): still gauge violations

$\nu_e\bar{\nu}_e\nu_\mu\bar{\nu}_\mu$ (4Z amplitude)

cut	FULL	OSP	RES
$u\ u \to u\ u\ \nu_e\ \bar{\nu}_e\ \nu_\mu\ \bar{\nu}_\mu$ (4Z)			
no cut	55.80	51.13 (-8%)	51.65 (-7%)

*tables results in 10^{-8} pb

ZZ: gauge invariance - 2

2W2Z amplitudes: if no $M_{\ell\ell}$ cut, smaller but non-negligible gauge violation. OSP doesn't restore gauge invariance.

$e^+e^-\mu^+\mu^-$ (2W2Z amplitude)

cut	FULL	OSP	RES
$u\ s \to d\ c\ e^-e^+\mu^-\mu+$ (2W2Z)			
no cut	267.30	248.60 (-7%)	324.38 (+21%)

- If no γ contributions $\Rightarrow$ OSP describes correctly the full calculation. Similar results as for WW.

$\nu_e\bar{\nu}_e\nu_\mu\bar{\nu}_\mu$ (2W2Z amplitude).

cut	FULL	OSP	RES
$u\ s \to d\ c\ \nu_e\ \bar{\nu}_e\ \nu_\mu\ \bar{\nu}_\mu$ (2W2Z)			
no cut	988.80	975.80 (-1%)	1266.3 (+28%)

Polarization studies for Z bosons: **sharp cut on $M_{\ell\ell}$ around M_Z required.**

No OSP. No exact gauge invariance with resonant diagrams only, even when considering all subprocesses.

*tables results in 10^{-8} pb

ZZ: no p_t^ℓ, η_ℓ lepton cuts

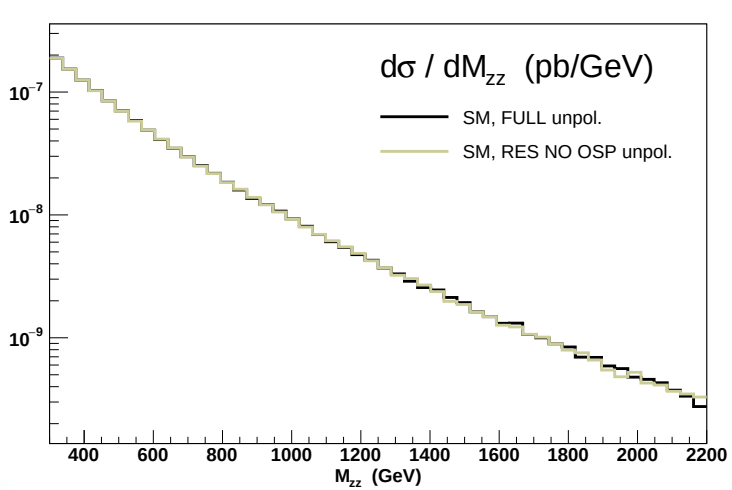
$p\ p \to j\ j\ e^-\ e^+\ \mu^-\ \mu^+$, LHC@13TeV, $\mathcal{O}(\alpha_{ew}^6)$

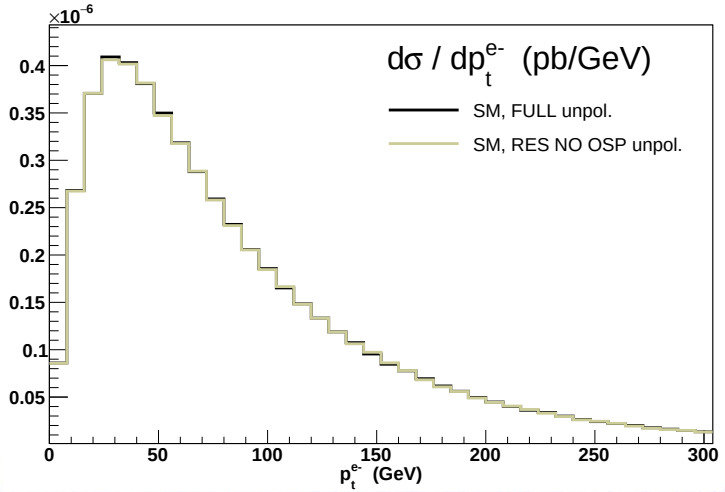
Cuts: $p_t^j > 20$ GeV, $|\eta_j| < 5$, $M_{jj} > 600$ GeV, $|\Delta\eta_{jj}| > 3.6$, $M_{4\ell} > 300$ GeV, $|M_{\ell^+\ell^-} - M_Z| < 5$ GeV

Full: $\sigma_{\rm unpol} = \mathbf{4.327(3)\cdot 10^{-5}}\,{\rm pb}$

- 4Z subprocesses are subdominant (0.5 %)
  $\Rightarrow$ expected small gauge violation effects ($M_{\ell\ell}$-cut and region dependent) when considering all subprocesses
- b-quarks contributions account for the 0.04 % $\Rightarrow$ negligible

Resonant (NO OSP) : $\sigma^{\rm res}_{\rm unpol} = \mathbf{4.316(7)\cdot 10^{-5}}{\rm pb}$





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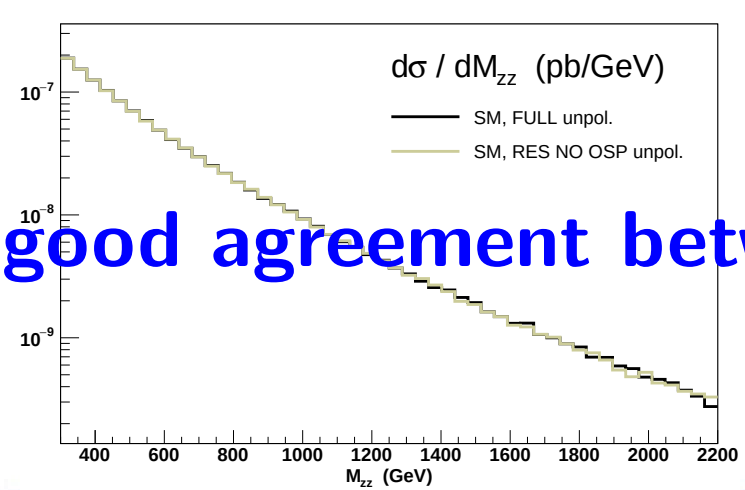
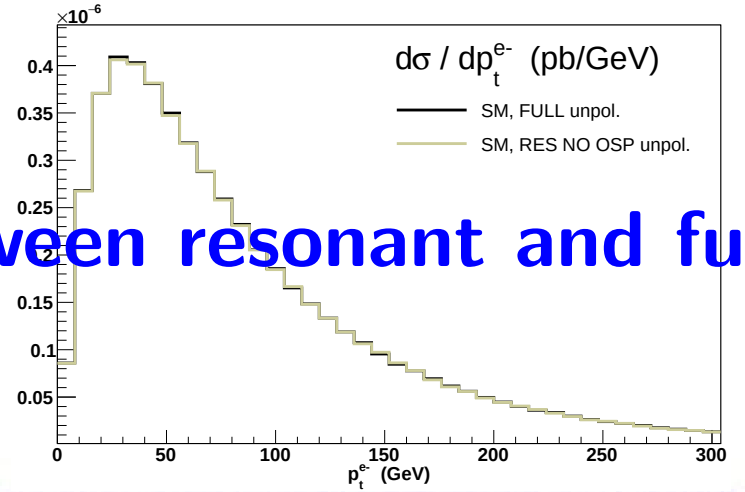




good agreement between resonant and full !

ZZ: no p_t^ℓ, η_ℓ lepton cuts

Polarized cross-sections with PHANTOM ($Z(\to \mu^+\mu^-)$ unpolarized):

$\sigma_{\rm long} = 0.995(3)\cdot 10^{-5}\,{\rm pb}$, $\sigma_{\rm L} = 2.153(1)\cdot 10^{-5}\,{\rm pb}$, $\sigma_{\rm R} = 1.170(1)\cdot 10^{-5}\,{\rm pb}$

$\cos\theta_{e^-}$ distribution: analytically known without lepton cuts:

$$\frac{d\sigma_{Z\,\to\,\ell^+\ell^-}}{d\cos\theta} \approx \frac{3}{4}\left(\sin\theta^2\right)\, f_{\rm long} + \frac{3}{8}\left(1+\cos\theta^2 - 2\,A_{Z\ell\ell}\,\cos\theta\right)\, f_{\rm L} + \frac{3}{8}\left(1+\cos\theta^2 + 2\,A_{Z\ell\ell}\,\cos\theta\right)\, f_{\rm R}\ , \quad A_{Z\ell\ell} = \frac{|c_L|^2 - |c_R|^2}{|c_L|^2 + |c_R|^2} \qquad (1)$$

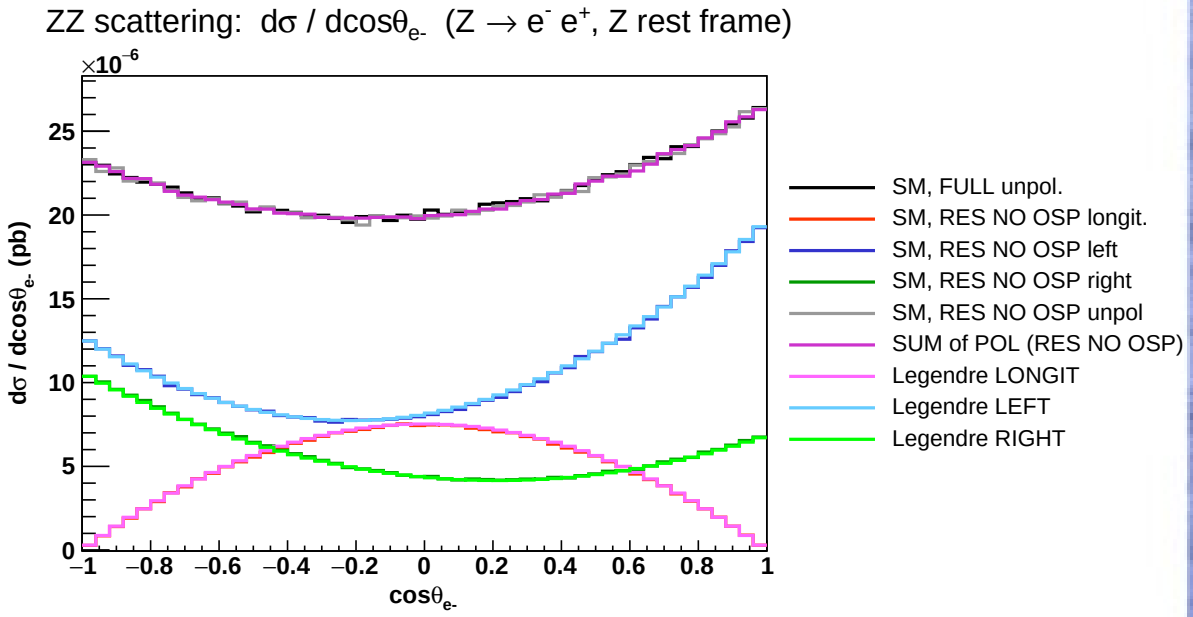
Polarized cross-sections (Legendre analysis of full):

$\sigma_{\rm long} = 1.003(9)\cdot 10^{-5}\,{\rm pb}$

$\sigma_{\rm L} = 2.161(9)\cdot 10^{-5}\,{\rm pb}$

$\sigma_{\rm R} = 1.161(5)\cdot 10^{-5}\,{\rm pb}$

pol. fractions and the distribution shapes obtained via Legendre analysis (Eq. 1) agree with the polarized MC distributions ($< 1\%$ discrep.)



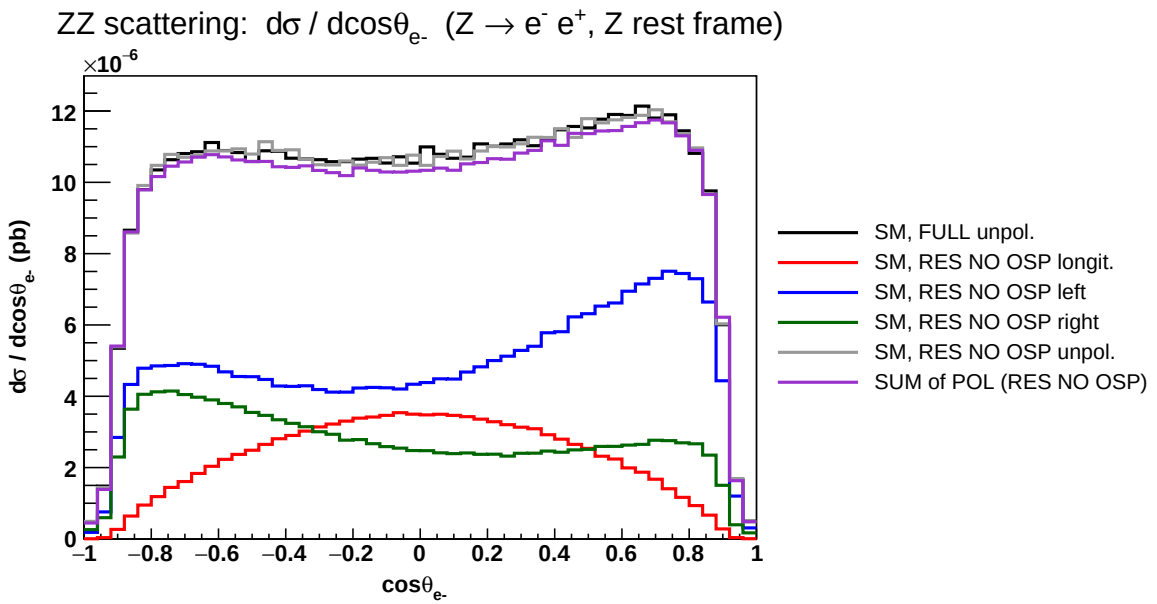
ZZ: lepton cuts

Additional cuts: $p_t^\ell > 20$ GeV, $|\eta_\ell| < 2.5$. $\cos\theta_{e^-}$ experimentally accessible!

Unpolarized: $\sigma_{\rm full} = \mathbf{1.982(8)\cdot 10^{-5}}\,{\rm pb}, \quad \sigma^{\rm res}_{\rm unpol} = \mathbf{1.979(9)\cdot 10^{-5}}\,{\rm pb}$

Polarized MC cross-sections:

$$\sigma_{\rm long} = 0.443(5)\cdot 10^{-5}\,{\rm pb}$$
$$\sigma_{\rm L} = 0.957(0)\cdot 10^{-5}\,{\rm pb}$$
$$\sigma_{\rm R} = 0.537(1)\cdot 10^{-5}\,{\rm pb}$$
$$\sigma_{\rm long+T} = 1.976(6)\cdot 10^{-5}\,{\rm pb}$$
$$\sigma_{\rm long+L+R} = 1.937(6)\cdot 10^{-5}\,{\rm pb}$$



- Good agreement between full and sum of polarized distributions.
- Small interferences between polarizations: reduced if considered coherent sum of L+R (T = transverse)

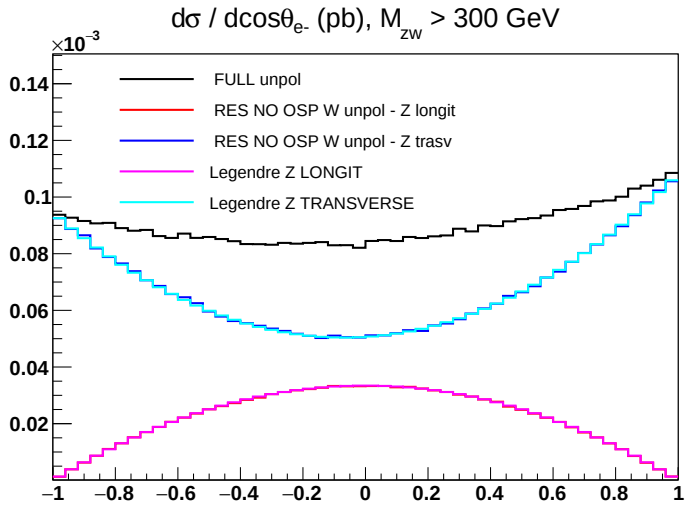
W^+Z channel

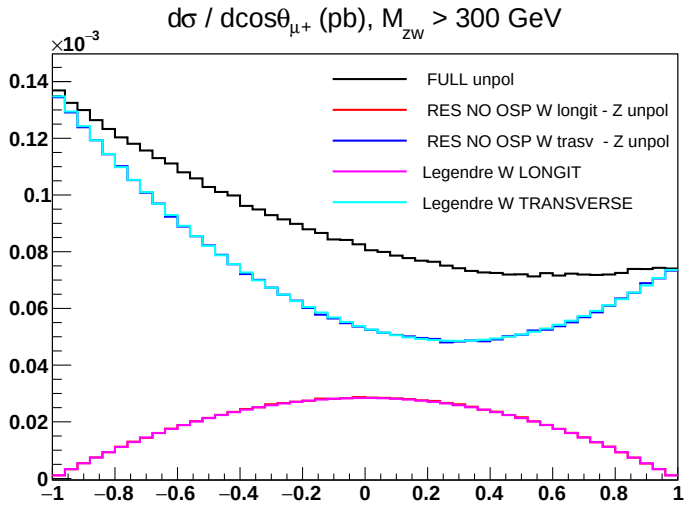
$p\ p \to j\ j\ e^-\ e^+\ \mu^+\ \nu_\mu$, LHC@13TeV, $\mathcal{O}(\alpha_{ew}^6)$ (no b contributions)

Cuts: $p_t^j > 20$ GeV, $|\eta_j| < 5$, $M_{jj} > 600$ GeV, $|\Delta\eta_{jj}| > 3.6$, $M_{4\ell} > 300$ GeV, $|M_{e^+e^-} - M_Z| < 5$ GeV, $|M_{\mu^+\nu_\mu} - M_W| < 5$ GeV

Additional lepton cuts: $p_t^\ell > 20$ GeV, $|\eta_\ell| < 2.5$, $p_t^{\rm miss} > 20$ GeV.

Simulated doubly-polarized processes

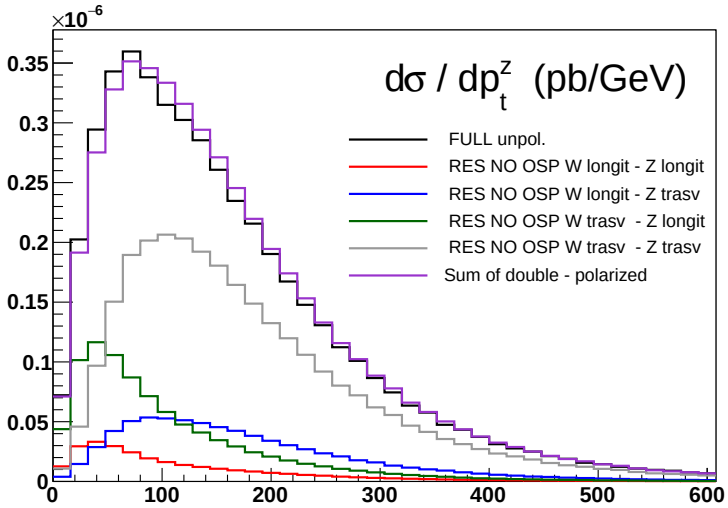


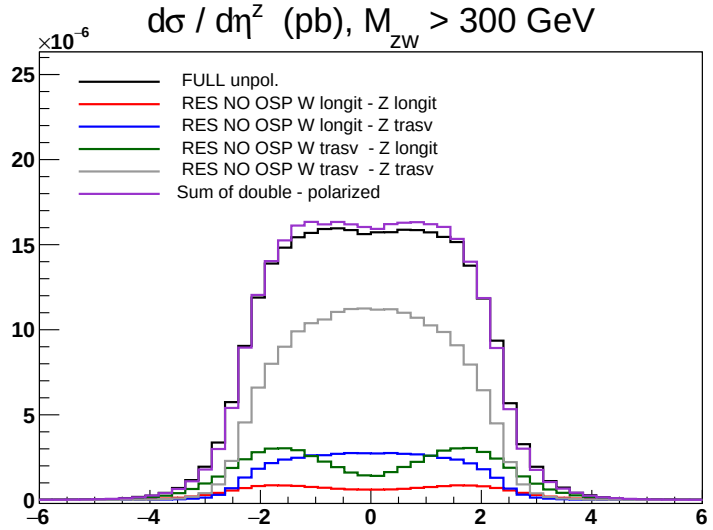


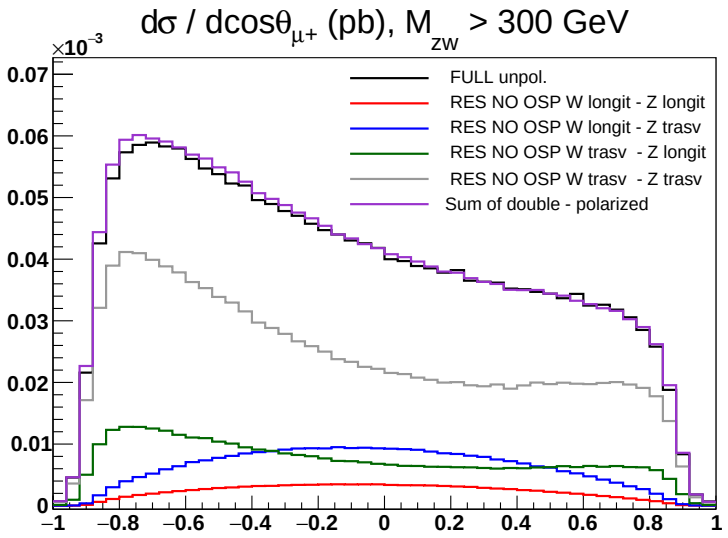
Legendre projections both for Z and W:
very good agreement with Monte Carlo predictions.

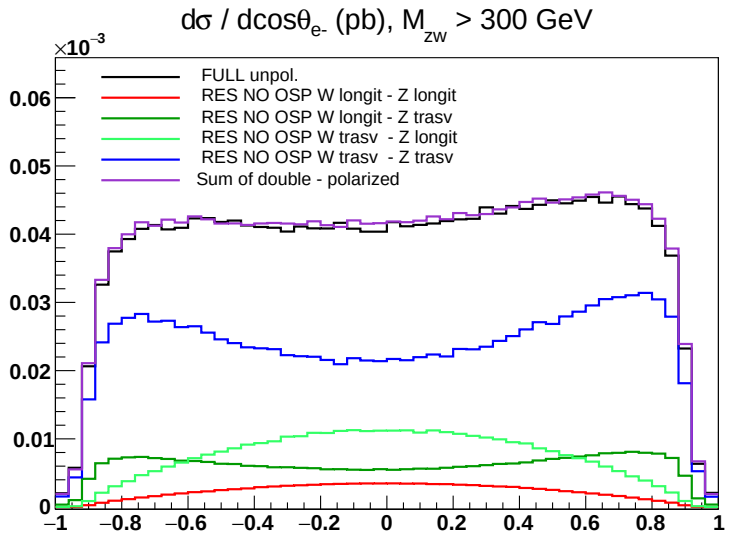
W^+Z: lepton cuts

Non negligible interferences. Sum of polarized vs Full calculation: $\sim 1\%$ discrepancy for total σ, $1-5\,\%$ in some phase space regions (*e.g.* central η and small p_t of the W/Z).









Conclusions and outlook

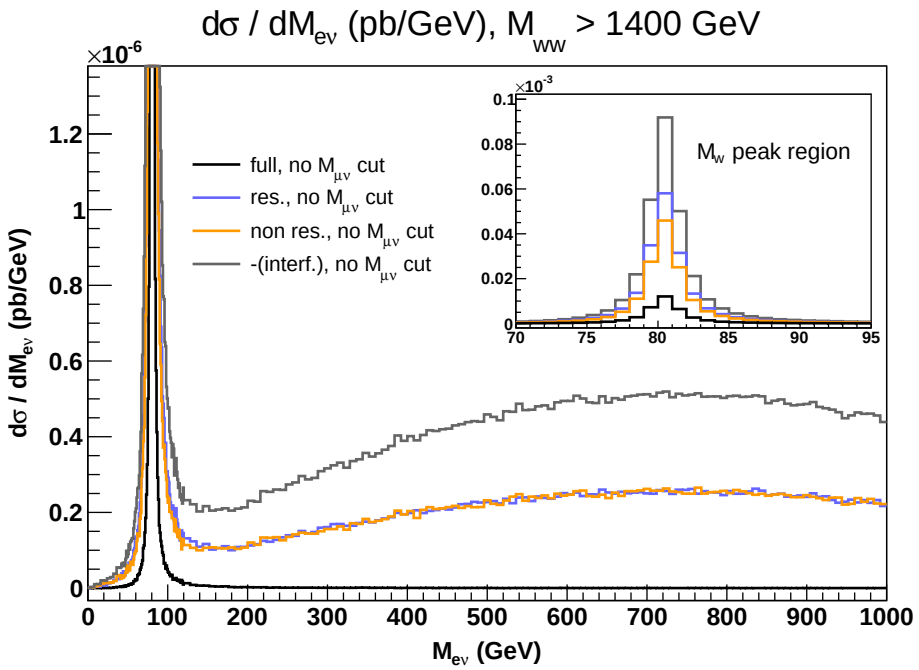
- We are able to compute with PHANTOM processes with polarized W/Z bosons (also in the massive case) at $\mathcal{O}(\alpha_{ew}^6)$.
- We performed studies on vector boson polarizations in WW, ZZ and WZ scattering.
  1. Impressive agreement between OSP and full description of WW scattering.
  2. OSP not enough for ZZ.
     Sharp $M_{\ell\ell}$ cut required to avoid large gauge violations.
  3. Good description of polarized process, both for WW and ZZ.
  4. Preliminary study of WZ channel: good description of double-polarized processes.
- Importance of collaboration between theoretical and experimental communities. Feedback and comments are welcome.

For more results on ZZ polarized scattering, see next talk by Ang.

BACKUP SLIDES

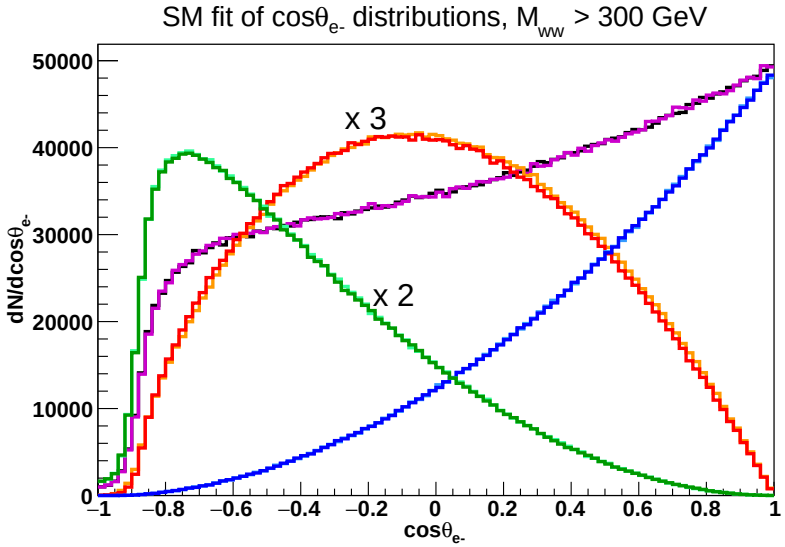
W^+W^-: resonant contributions, $M_{\ell\nu}$ distribution

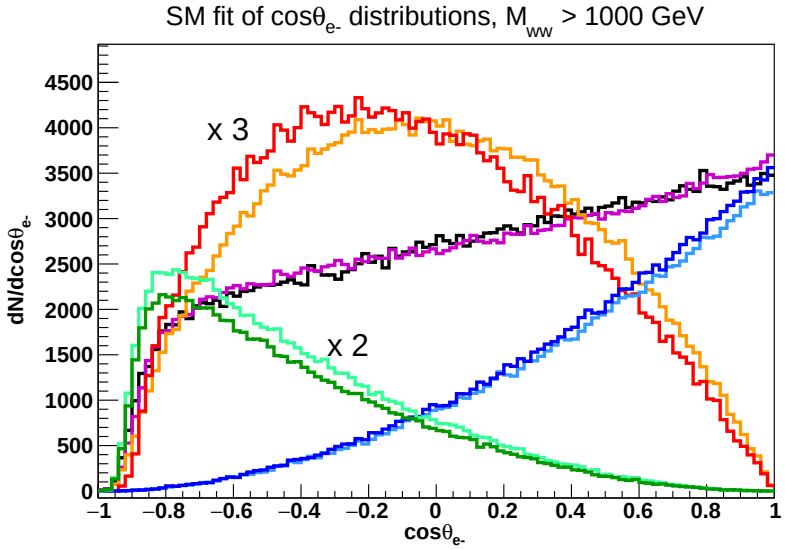
Distribution in $M_{\ell\nu}$ at very large M_{WW}: large interference between res. and non-res., even near M_W, huge enhancement at large masses.

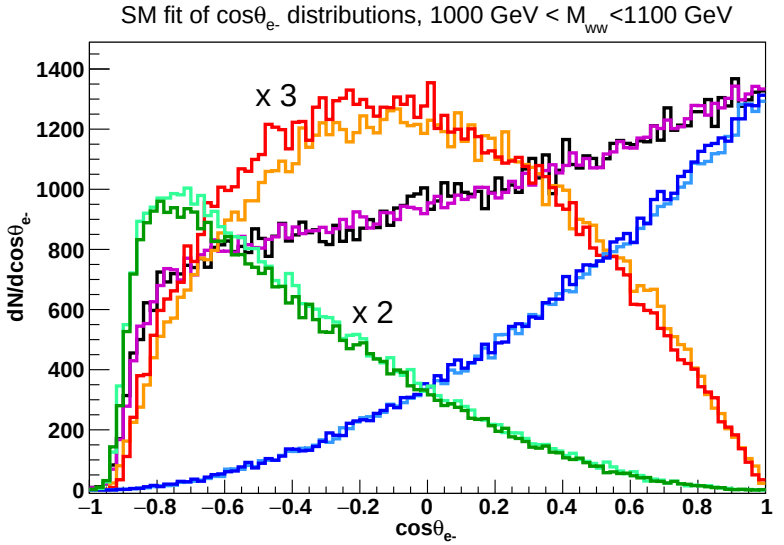


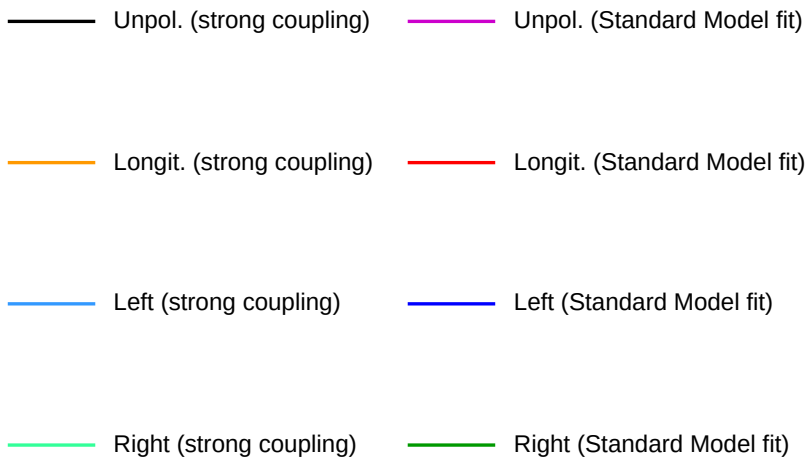
- Very sharp cancellation between res. and non-res, both near the peak (1%) and for off-shell W bosons ($< 0.1\%$)
  $\rightarrow$ Breit-Wigner distribution
- Enhancement at large masses due to large $W^+_{long}\,W^-_{long}$ scattering contributions ($s + t + u \gg$ on-shell masses)

W^+W^-: fit and model (in)dependence









ZZ: all subprocesses, cross-sections with no p_t^ℓ, η_ℓ cuts

cut	FULL	RES OSP	RES NO OSP
$p\ p \to j\ j\ e^-\ e^+\ \mu^-\ \mu^+$ (4Z)			
no cut	6.399	5.895	7.543
30 GeV	5.844	5.714	5.764
5 GeV	4.321	4.305	4.315

Table 1: Cross sections in pb^{-5} with different cuts around the Z pole ($\pm$ the cut), for the full calculation (FULL), resonant diagrams only with On Shell Projection (RES OSP) and resonant diagrams only without Projection (RES NO OSP). Cuts as in the r.in file in the distribution. No b. $\mathcal{O}(\alpha_{EM}^6)$

ZZ: distributions with lepton cuts