Recent developments of vector boson polarization modeling with SHERPA

Mareen Hoppe
(Technische Universität Dresden)

DIS Workshop 2026, Bologna, 5th May 2026

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Vector boson polarization...

- **strong independent probe of the electroweak gauge sector & EWSB**

→ due to direct connection to Higgs mechanism via longitudinal polarization

→ BSM effects might influence only certain polarization components

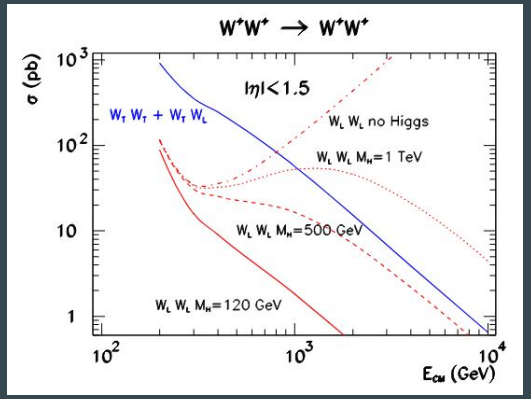
→ delicate cancellation in longitudinal VBS to rescue unitarity

- **non-trivial to measure**

→ template-fits based on polarized templates from MC

$$\frac{\mathrm{d}\sigma}{\mathrm{d}X} = f_L \frac{\mathrm{d}\sigma_L}{\mathrm{d}X} + f_R \frac{\mathrm{d}\sigma_R}{\mathrm{d}X} + f_0 \frac{\mathrm{d}\sigma_0}{\mathrm{d}X} \left(+ f_{int.} \frac{\mathrm{d}\sigma_{int.}}{\mathrm{d}X} \right)$$

M.Szleper 2015



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ATLAS 2022

inclusive WZ

	Data	POWHEG+PYTHIA	NLO QCD	
	$W^{\pm}Z$			
f_{00}	0.067 ± 0.010	0.0590 ± 0.0009	0.058 ± 0.002	7.1 σ
f_{0T}	0.110 ± 0.029	0.1515 ± 0.0017	0.159 ± 0.003	3.4 σ
f_{T0}	0.179 ± 0.023	0.1465 ± 0.0017	0.149 ± 0.003	7.1 σ
f_{TT}	0.644 ± 0.032	0.6431 ± 0.0021	0.628 ± 0.004	11 σ

ATLAS 2025

same-sign WW jj

Process	Predicted $\sigma\mathcal{B}$ (fb)	Measured $\sigma\mathcal{B}$ (fb)
$W^{\pm}_{L}W^{\pm}_{L}jj$	0.29 ± 0.07	0.01 ± 0.21 (tot.)
$W^{\pm}_{T}W^{\pm}jj$	2.56 ± 0.64	3.39 ± 0.35 (tot.)
$W^{\pm}_{L}W^{\pm}jj$	1.18 ± 0.29	0.88 ± 0.30 (tot.)
$W^{\pm}_{T}W^{\pm}_{T}jj$	1.67 ± 0.40	2.49 ± 0.32 (tot.)

Polarization of intermediate particles

- **Definition:**
  1. completeness relation $\left(-g^{\mu\nu} + \frac{q^\mu q^\nu}{m_V^2}\right) = \sum_{\lambda=1}^{4} \varepsilon^\mu(q,\lambda)\varepsilon^{*\nu}(q,\lambda)$
  2. spin basis choice: frame dependence $\Lambda^\mu{}_\nu \varepsilon^\nu(q) \neq \varepsilon^\mu(\Lambda q)$
  3. only resonant diagrams & physical polarizations: on-shell approximations

Narrow-Width Approximation (NWA)

$$\frac{1}{\left(q^2 - m_V^2\right)^2 + \Gamma_V^2 m_V^2} \to \frac{\pi\delta(q^2 - m_V^2)}{\Gamma_V m_V}$$

Pole Approximation ((D)PA) $Q^2 = m_V^2$

$$\frac{(-g^{\mu\nu} + q^\mu q^\nu/q^2)}{(q^2 - m_V^2)^2 + i\Gamma_V m_V} \to \frac{\sum_\lambda \varepsilon_\lambda^\mu(Q)\varepsilon_\lambda^{*\nu}(Q)}{(q^2 - m_V^2)^2 + i\Gamma_V m_V}$$

- **Additional contribution:**

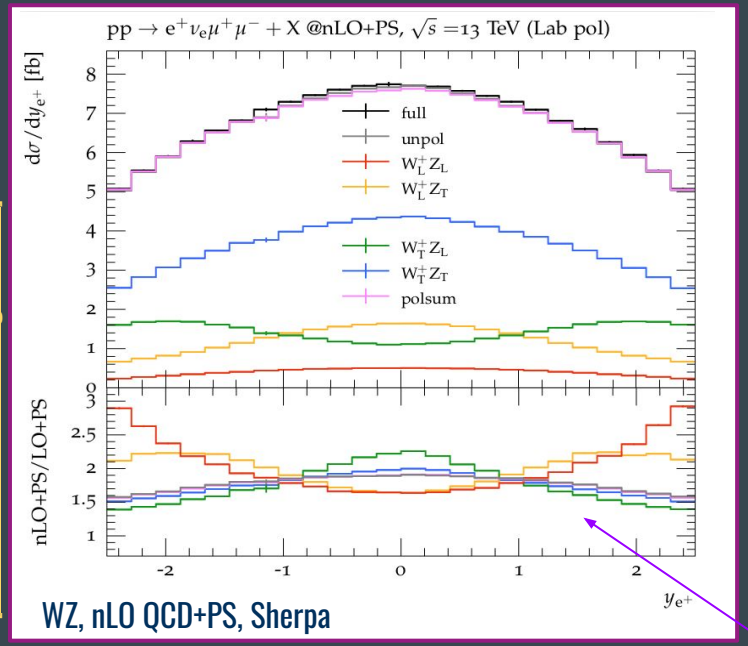
$$\sigma \propto |\mathcal{M}|^2 = \sum_\lambda \left|\mathcal{M}_\lambda^{\mathcal{F}}\right|^2 + \sum_{\lambda,\lambda'} \mathcal{M}_\lambda^{\mathcal{F}*} \mathcal{M}_{\lambda'}^{\mathcal{F}}$$

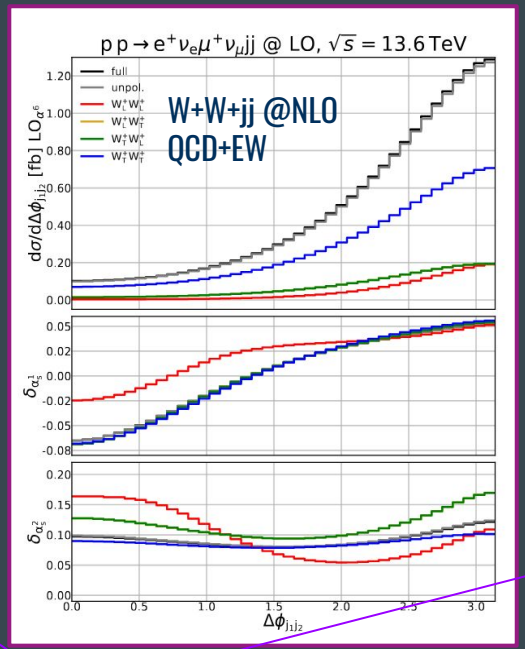
Polarized cross section for VB with polarization λ

interference terms

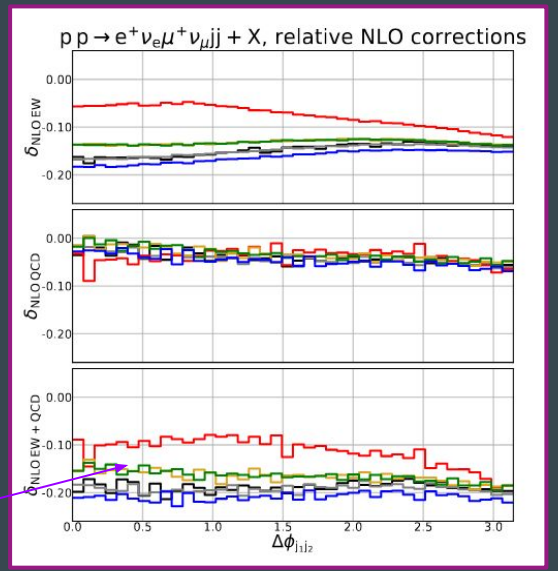
What's needed from the theory side? Precision!

[MH, M. Schönherr, F. Siegert 2023]





[A. Denner, C. Haitz, G. Pelliccioli 2024]



Higher order effects can change polarization fractions substantially!

Generator landscape

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MoCaNLO

DPA

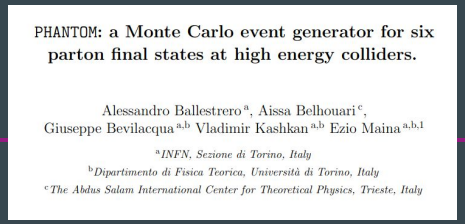
truncated propagator

NWA

- *(**MOCANLO+RECOLA:** arbitrary processes @ NLO QCD+EW)*
  [A. Denner et al. 2026]

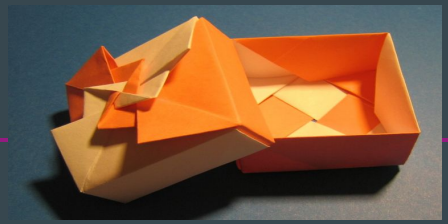
- **PHANTOM:** 2->6 processes @ LO+PS [A. Ballestrero et al. 2008, 2017]
- **MG5_aMC@NLO:** arbitrary processes @ LO+ PS, multi-jet merging
  [D. Buarque Franzosi et al. 2020, M. Javurkova et al. 2024]

- **SHERPA:** arbitrary processes @nLO QCD+PS, multi-jet merging [MH, M. Schönherr, F. Siegert 2023]
- **POWHEG-BOX-RES+PYTHIA:** inclusive diboson processes @NLO QCD+PS
  [G. Pelliccioli, G. Zanderighi 2023]


PHANTOM: a Monte Carlo event generator for six parton final states at high energy colliders.

Alessandro Ballestrero [a], Aissa Belhouari [c], Giuseppe Bevilacqua [a,b] Vladimir Kashkan [a,b] Ezio Maina [a,b,1]

[a] INFN, Sezione di Torino, Italy
[b] Dipartimento di Fisica Teorica, Università di Torino, Italy
[c] The Abdus Salam International Center for Theoretical Physics, Trieste, Italy



SHERPA

[MH, M. Schönherr, F. Siegert 2023]

Polarized vector bosons in Sherpa

- **on-shell approximation:** spin-correlated narrow-width approximation + a priori mass smearing
- **methodology:** polarized XS as event-weights in unpolarized calculation, based on entire spin density

  → ***fully differential polarization fractions*** incl. interference

$$\begin{pmatrix} ++ & +- & +0 \\ -+ & -- & -0 \\ 0+ & 0- & 00 \end{pmatrix}$$

interference

pure polarization states

- **processes:** arbitrary LO-tree-level processes
- **order:** approximate MC@NLO matching (+merging)

polarization fractions from

→ Real matrix elements: H - & resolved S - events
→ Born matrix elements: unresolved S - events

→ unpolarized XS full NLO QCD

virtual, ultra-soft, ultra-collinear effects on pol fractions neglected

Modeling still not satisfactory ...

This talk: essential steps towards (almost) all these goals ...

- matching of arbitrary loop-induced processes to PS
- NLO QCD+PS & NLO multi-jet merging for arbitrary processes
- NLO EW+PS
- *NNLO QCD+PS*

W^+W^+jj

state	σ_{LO} [fb]	δ_{EW}	δ_{QCD}	$\delta_{\text{EW+QCD}}$	$\sigma_{\text{NLO EW+QCD}}$ [fb]
full	$1.4863(1)^{+9.2\%}_{-7.8\%}$	−0.140	−0.047	−0.188	$1.208(1)^{+1.6\%}_{-3.1\%}$
unp.	$1.46455(9)^{+9.2\%}_{-7.8\%}$	−0.142	−0.050	−0.192	$1.1836(5)^{+1.7\%}_{-3.3\%}$
LL	$0.14879(1)^{+8.3\%}_{-7.2\%}$	−0.101	−0.044	−0.145	$0.12715(8)^{+1.0\%}_{-2.1\%}$
LT	$0.23209(2)^{+9.1\%}_{-7.8\%}$	−0.131	−0.042	−0.173	$0.1919(1)^{+1.4\%}_{-2.8\%}$
TL	$0.23208(2)^{+9.1\%}_{-7.8\%}$	−0.131	−0.042	−0.173	$0.1918(1)^{+1.4\%}_{-2.8\%}$
TT	$0.87702(7)^{+9.4\%}_{-8.0\%}$	−0.154	−0.054	−0.208	$0.6944(4)^{+1.9\%}_{-3.7\%}$
int.	$-0.0254(1)^{-8.9\%}_{+10.6\%}$	−0.139	−0.007	−0.147	$-0.0217(7)^{-1.6\%}_{+0.7\%}$

[A. Denner, C. Haitz, G. Pelliccioli 2024]

ZZ production

CERN-EP-2023-199

Contribution	Relative uncertainty [%]
Total	24
Data statistical uncertainty	23
Total systematic uncertainty	8.8
MC statistical uncertainty	1.7
Theoretical systematic uncertainties	
$q\bar{q} \to ZZ$ interference modelling	6.9
NLO reweighting observable choice for $q\bar{q} \to ZZ$	3.7
PDF, α_s and parton shower for $q\bar{q} \to ZZ$	2.2
NLO reweighting non-closure	1.0
QCD scale for $q\bar{q} \to ZZ$	0.2
NLO EW corrections for $q\bar{q} \to ZZ$	0.2
$gg \to ZZ$ modelling	1.4
Experimental systematic uncertainties	
Luminosity	0.8
Muons	0.6
Electrons	0.4
Non-prompt background	0.3
Pile-up reweighting	0.3
Triboson and $t\bar{t}Z$ normalisations	0.1

[MH, M. Schönherr, F. Siegert, in preparation]

Loop-induced processes with SHERPA

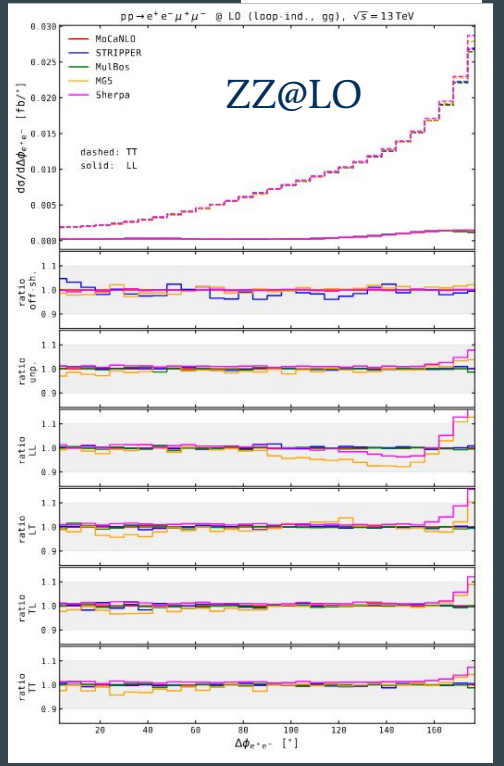
- production matrix elements from RECOLA
  - (color-summed) amplitude tensor of the production process

$$\mathcal{A}^{\binom{i_1}{j_1}\dots\binom{i_m}{j_m}}_{h_1\ \dots\ h_m} = \sum_{\pi} \delta^{i_1}_{j_{\pi(1)}} \delta^{i_m}_{j_{\pi(m)}} \mathcal{A}^{\pi(1)\dots\pi(m)}_{h_1\ \dots\ h_m}$$

$$|\mathcal{M}^{\text{prod}}|^2_{h_1 h'_1 \dots h_m h'_m} = \overline{\sum_{\binom{i_1}{j_1},\dots,\binom{i_m}{j_m}}} \mathcal{A}^{\binom{i_1}{j_1}\dots\binom{i_m}{j_m}}_{h_1\ \dots\ h_m} \mathcal{A}^{*\binom{i_1}{j_1}\dots\binom{i_m}{j_m}}_{h'_1\ \dots\ h'_m}$$

$$|\mathcal{M}^{\text{prod}}|^2_{\lambda_{\beta_1}\lambda'_{\beta_1}\dots\lambda_{\beta_n}\lambda'_{\beta_n}} = \frac{1}{\bar{N}} |\mathcal{M}^{\text{prod}}|^2_{h_1 h'_1 \dots h_m h'_m} \prod_{i\notin\{\beta_1\dots,\beta_n\}} \delta_{h_i h'_i}$$

- transformation to SHERPA's spin basis
- input for polarization framework: spin-correlations + decay matrix elements in SHERPA
- fixed LO & LO+PS
  - LO-multi-jet merging conceptually possible, but missing provider of loop amplitudes



C. Carrivale et al. 2025

W+W- @LO		full	unpol.	LL	LT	TL	TT	int
SHERPA	XS [fb]	13.892(8)	13.543(5)	0.718(1)	1.833(1)	1.833(1)	9.758(4)	−0.599(1)
(NWA)	%		100	5.3	13.5	13.5	72.1	−4.4
STRIPPER	XS [fb]	13.8(2)	13.28(3)	0.695(2)	1.790(5)	1.774(5)	9.58(2)	n.a.
(DPA)	%		100	5.2	13.5	13.4	72.1	

[R. Poncelet & A. Popescu 2021]

[MH, M. Schönherr, F. Siegert, in preparation]

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Loop-induced processes with SHERPA - total XS in diboson-COM

Process	ZZ	W+W-	ZZg	W+W-g	Zγ	ZH
unpol [fb]	1.8736(5)	14.442(4)	1.1089(17)	5.233(12)	7.7789(17)	0.80610(15)
pure L [%]	5.40	4.28	6.03	6.51	12.5	99.7
LT [%]	2.12	3.01	4.55	6.98		
TL [%]	2.10	3.00	4.57	6.98		
pure T [%]	90.5	92.3	85.2	80.7	88.4	0.14
int [%]	-0.08	-2.56	-0.22	-1.2	-0.94	-0.10

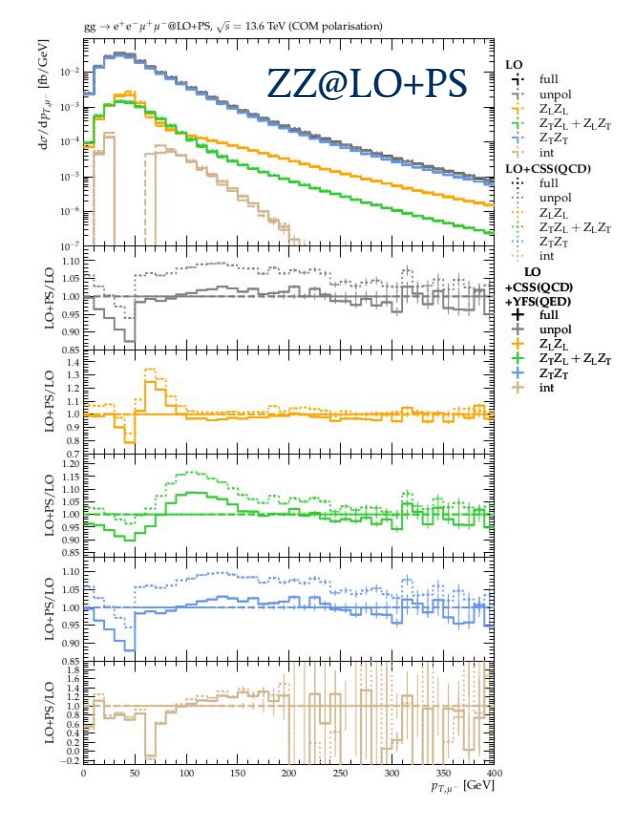
Mixed components suppressed @LO

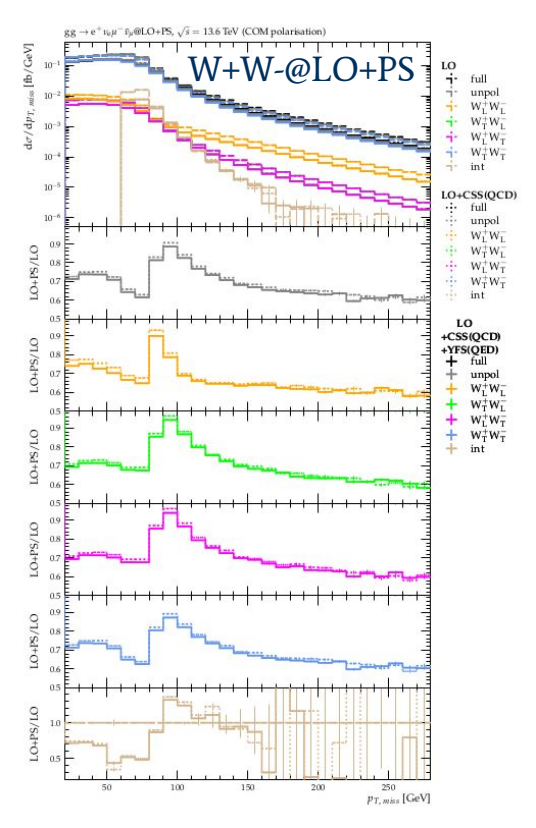
Higher-order effects prefer L states

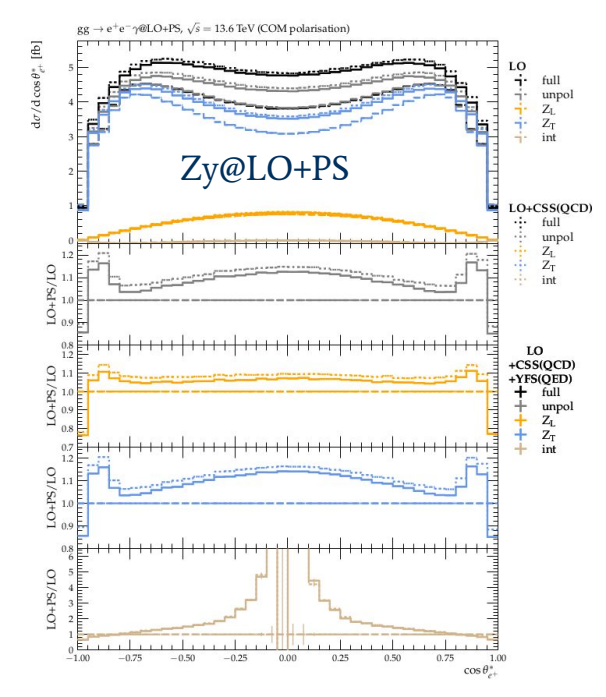
Processes not studied before

[MH, M. Schönherr, F. Siegert, in preparation]

Loop-induced processes with SHERPA - PS effects







Distortions by PS effects small, mainly QCD nature, LL state mostly affected

[S. Höche, MH, M. Schönherr]

Towards full polarized NLO+PS calculation in SHERPA

polarized in Sherpa 3.0 | new from Recola | new from Sherpa

$$\hat{\sigma}^{\mathrm{NLO}}_{ab\to n} = \int \mathrm{d}\Phi_n \left[\mathcal{B}_n(\Phi_n;\mu_F,\mu_R) + \tilde{\mathcal{V}}_n(\Phi_n;\mu_F,\mu_R) + \mathcal{I}^{\mathcal{S}}_n(\Phi_n;\mu_F,\mu_R)\right] + \int \mathrm{d}\Phi_{n+1}\left[\mathcal{R}_n(\Phi_{n+1};\mu_F,\mu_R) - \mathcal{D}^{\mathcal{S}}_n(\Phi_n;\mu_F,\mu_R)\right],$$

polarized in Sherpa 3.0 | new from Sherpa

- Catani-Seymour dipole subtraction
- all NLO terms in production process polarized
- V: procedure similar to loop-induced processes
- RS: decay kinematics from R production subevent
- initial-initial dipoles: additional transformation required

ME frame: IS off z-axis
measurement frame
(+start point pol
definition): FS takes recoil

[S. Höche, MH, M. Schönherr]

Towards full polarized NLO+PS calculation in SHERPA

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PRELIMINARY

WZ@ NLOQCD	Born	V	I/KP	RS	NLO (NWA)	literature DPA [A. Denner & G. Pelliccioli 2020]
unpol [fb]	19.594(6)	4.7751(18)	3.8055(19)	5.233(12)	35.378(30)	34.63(1)
LL [%]	7.89	6.81	7.54	-2.00	5.71	5.68
LT [%]	10.68	10.64	9.67	35	15.5	15.5
TL [%]	10.10	9.94	9.17	34	14.7	14.7
TT [%]	70.6	71.8	72.8	34	63.5	63.5
int [%]	0.7	0.7	0.8	0.0	0.6	—

RS dominates NLO effects!

Perfect agreement with literature + NWA/DPA fractions!

[S. Höche, MH, M. Schönherr]

Towards full polarized NLO+PS calculation in SHERPA

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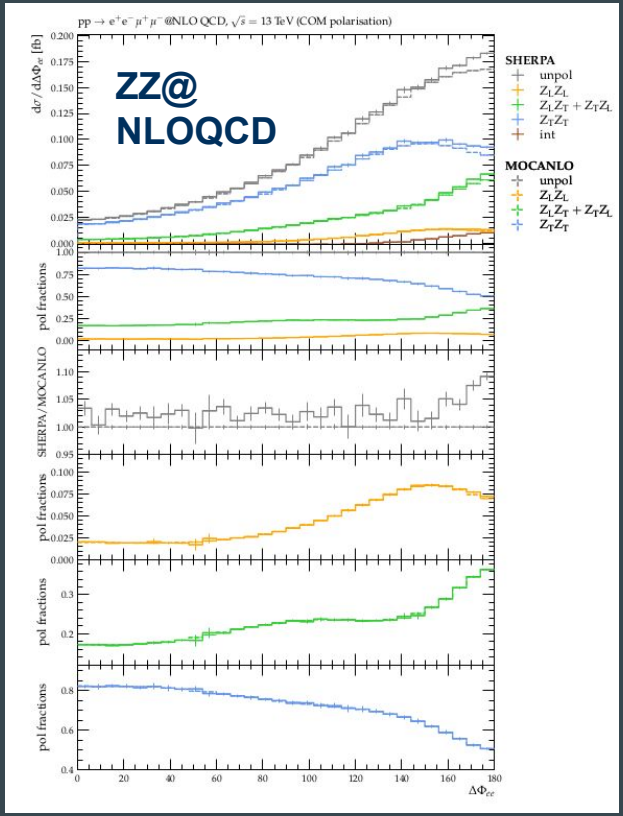
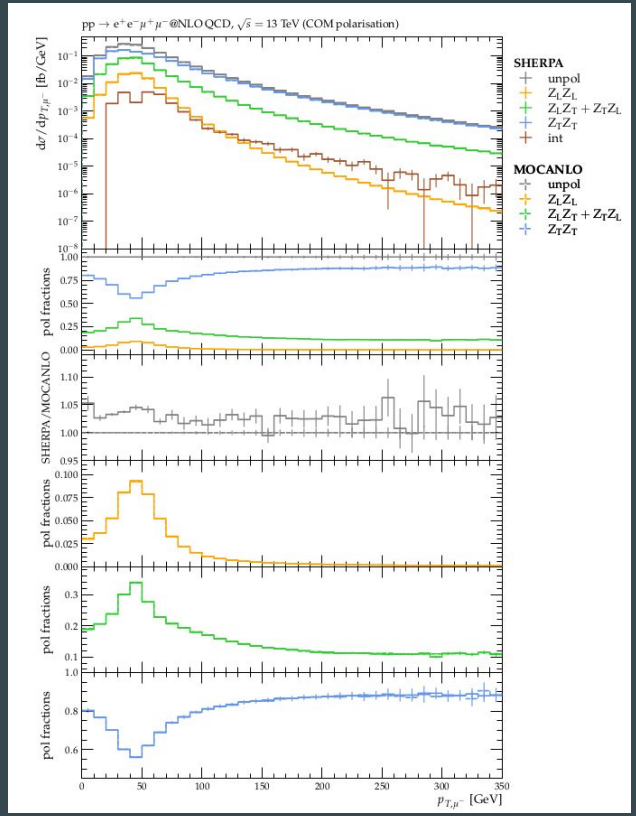
PRELIMINARY





Perfect agreement of differential polarization fractions, too!

Lays foundation for NLO EW (currently under validation) & NLO+PS calculations!

reference data: [C. Carrivale et al 2025]

[L. Alshut, E. Bachmann, MH, in preparation]

Is that all we can do? – Improving measurement strategies

Amplitude-assisted polarization tagging [M. Grossi et al. 2023]

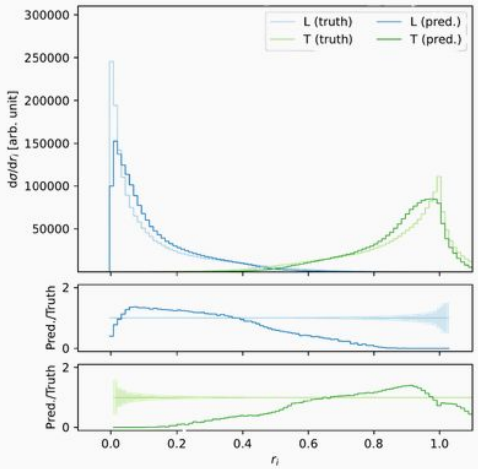
SHERPA+OPTIMA

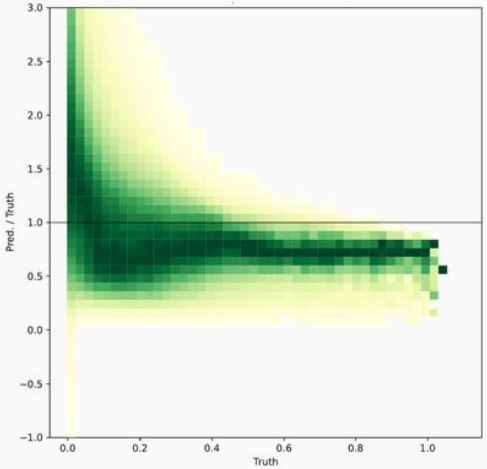
classification:
Does this event belong to the signal category ("Y=L") or not ("Y=T")?

regression:
Learn probability distribution of event being L directly

- In contrast to classification, **we know what the optimal result is!**
- Allows studying where deviations are coming from

pp → Zj @ LOPS





Ambiguities:
- partonic channel
- hard process IS & FS momenta (PS & PDF)

Are deviations caused by limited information or model capacity?

[E. Bachmann, FNAL 2025]

[L. Alshut, E. Bachmann, MH, in preparation]

SHERPA+OPTIMA

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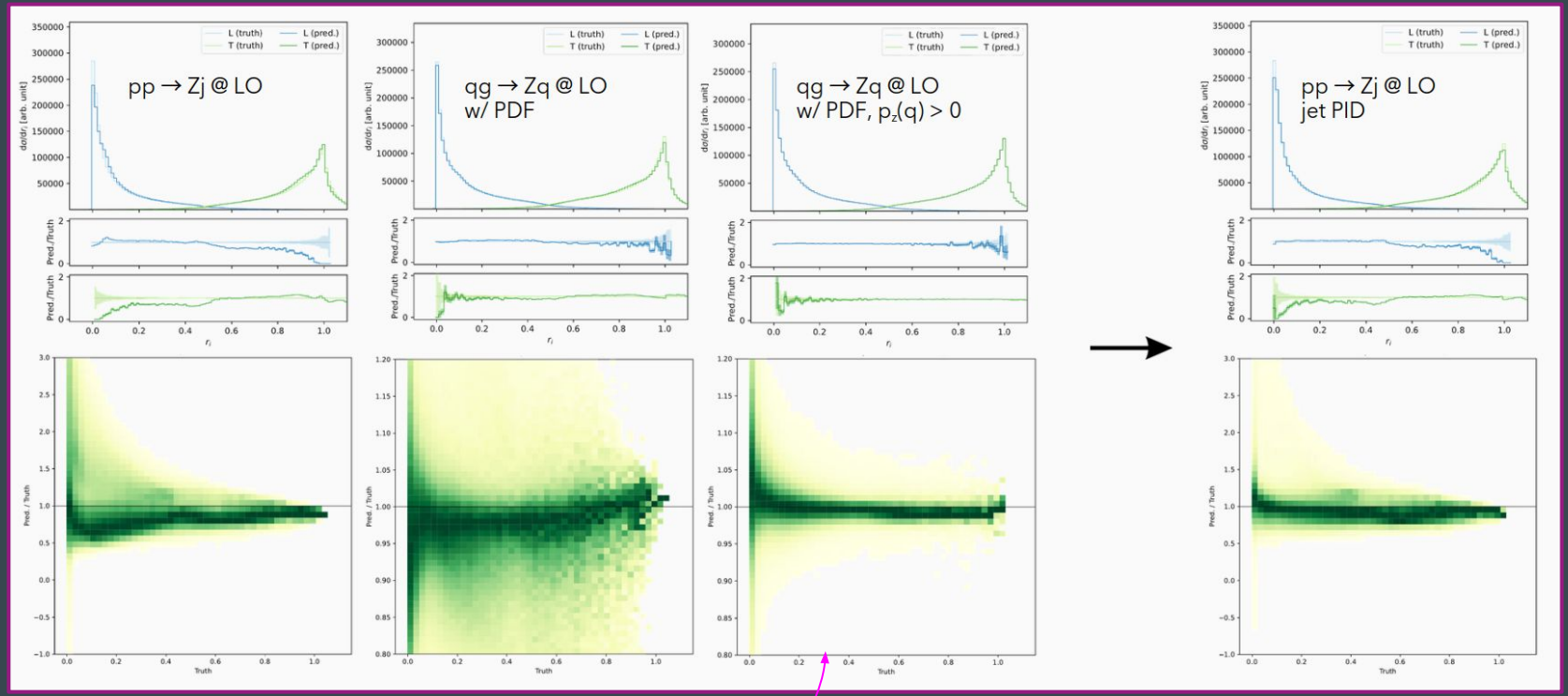
Is that all we can do? – Improving measurement strategies



Performance loss due to missing information!

Combination with qg-tagger might be helpful!

[L. Alshut, E. Bachmann, MH, in preparation]

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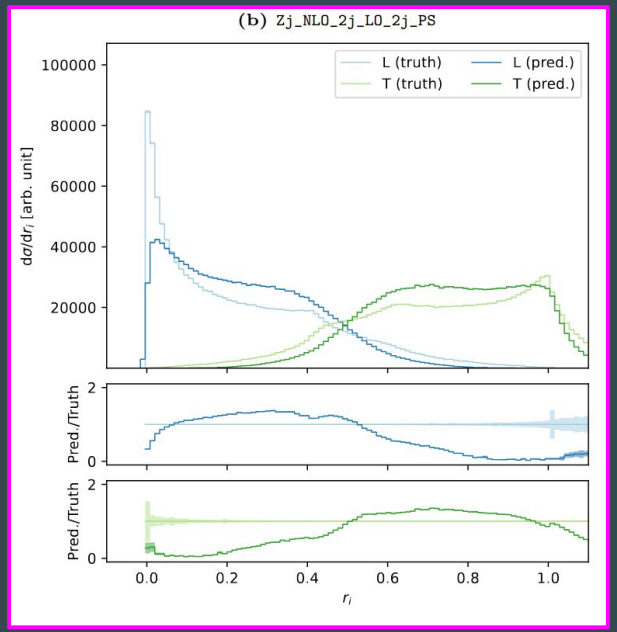
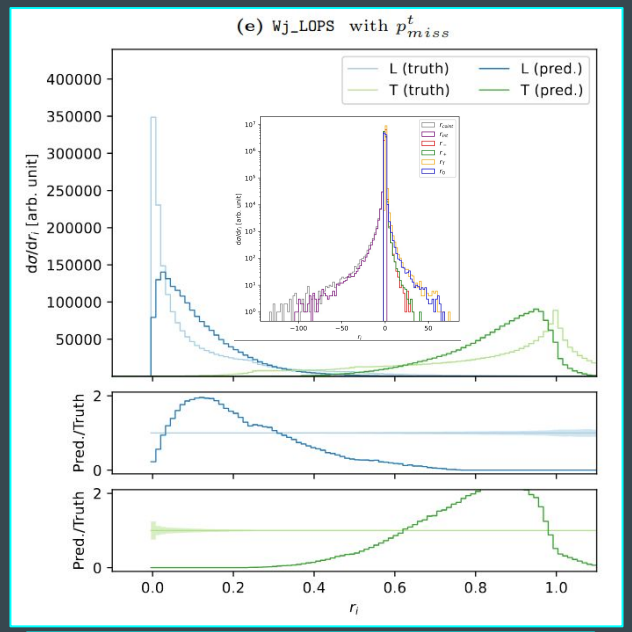
Polarization tagging: more aspects to study...

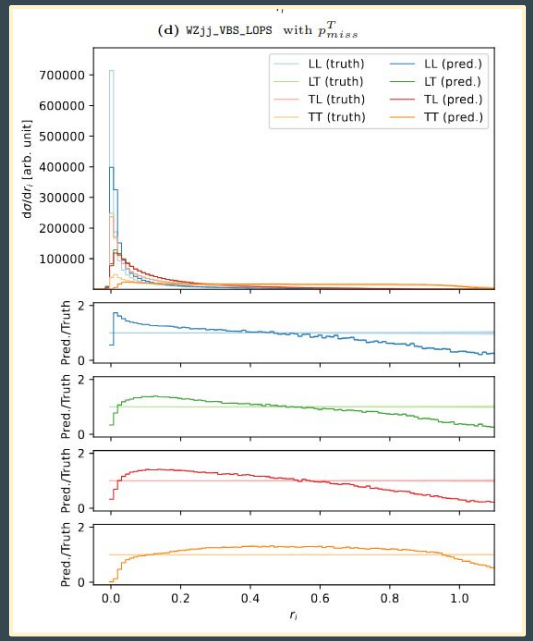
SHERPA+OPTIMA



Can we improve result for NLO?



W bosons – missing decay information + large interference



Multi-boson processes

Summary/Outlook

- Polarization measurements important part of LHC's physics program to explore EW sector
- Modeling still insufficient
- Improvements in Sherpa generator
  - loop-induced processes @LO+PS
  - all NLO terms polarized
- New physics-motivated ML-observable for polarization measurements

Outlook

- NLO EW+PS
- Parton shower matching / NLO merging
- LO-merging for loop-induced processes
- Investigate further aspects of polarization tagging

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Thank you for your attention!

Polarization of intermediate particles

- **Polarization dependence** of **intermediate particles** via **completeness relation**:

$$\left(-g^{\mu\nu} + \frac{q^\mu q^\nu}{m_V^2}\right) = \sum_{\lambda=1}^{4} \varepsilon^\mu(q,\lambda)\varepsilon^{*\nu}(q,\lambda)$$

$$\sigma \propto |\mathcal{M}|^2 = \sum_{\lambda} \left|\mathcal{M}_\lambda^{\mathcal{F}}\right|^2 + \sum_{\lambda,\lambda'} \mathcal{M}_\lambda^{\mathcal{F}*} \mathcal{M}_{\lambda'}^{\mathcal{F}}$$

Polarized cross section for VB with polarization λ

interference terms

→ omitting polarization sum defines polarized cross sections

→ interference contribution

- **Choice of polarization basis:**

$$\varepsilon_\pm^\mu(q) = \frac{e^{\mp i\phi}}{\sqrt{2}}(0, -\cos\theta\cos\phi \pm i\sin\phi, -\cos\theta\sin\phi \mp i\cos\phi, \sin\theta)$$

$$\varepsilon_0^\mu(q) = \frac{q^0}{m}\left(\frac{|\vec{q}|}{q^0}, \cos\phi\sin\theta, \sin\phi\sin\theta, \cos\theta\right)$$

Helicity basis

→ not Lorentz covariant

$$\Lambda^\mu{}_\nu \varepsilon^\nu(q) \neq \varepsilon^\mu(\Lambda q)$$

Frame dependence!

Separating polarized contribution in amplitudes

Not fully resonant contributions

polarization definition requires amplitudes with structure

production x propagator x decay

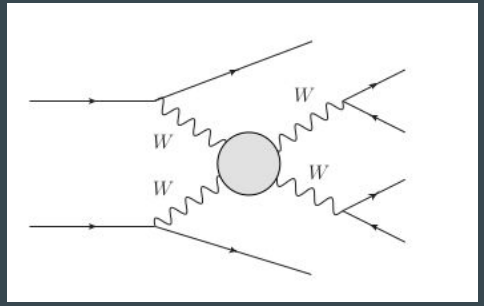
(= resonant diagrams)

Problem: not all amplitudes factorisable

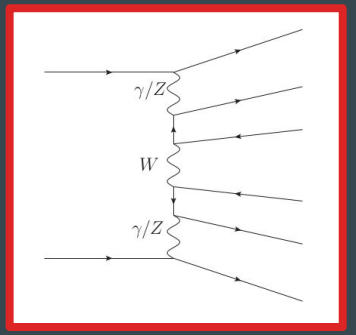
→ necessary for gauge invariance

Solution: suitable approximations

Example: ssWW scattering



double resonant



non resonant

Narrow-Width Approximation (NWA)

$$\frac{1}{\left(q^2 - m_V^2\right)^2 + \Gamma_V^2 m_V^2} \to \frac{\pi\delta\left(q^2 - m_V^2\right)}{\Gamma_V m_V}$$

Pole Approximation ((D)PA)

$$Q^2 = m_V^2$$

$$\frac{(-g^{\mu\nu} + q^\mu q^\nu / q^2)}{(q^2 - m_V^2)^2 + i\Gamma_V m_V} \to \frac{\sum_\lambda \varepsilon_\lambda^\mu(Q)\varepsilon_\lambda^{*\nu}(Q)}{(q^2 - m_V^2)^2 + i\Gamma_V m_V}$$

LHC - Measurements

Run 1 & early Run 2

- single W+j production: [CMS 2011], [ATLAS 2012]
- inclusive WZ production: [ATLAS 2019], [CMS 2021]
- W pol in ttbar events: [CMS 2016], [ATLAS 2017]

Recent Run 2 measurements

- inclusive WZ production: [ATLAS 2022, 2024]
- inclusive ZZ production: [ATLAS 2023]
- same-sign WW production: [CMS 2020, ATLAS 2025]

Measurement of joint polarization states

	Data	POWHEG+PYTHIA	NLO QCD	
		$W^{\pm}Z$		
f_{00}	0.067 ± 0.010	0.0590 ± 0.0009	0.058 ± 0.002	7.1 σ
f_{0T}	0.110 ± 0.029	0.1515 ± 0.0017	0.159 ± 0.003	3.4 σ
f_{T0}	0.179 ± 0.023	0.1465 ± 0.0017	0.149 ± 0.003	7.1 σ
f_{TT}	0.644 ± 0.032	0.6431 ± 0.0021	0.628 ± 0.004	11 σ

Measurement of LL polarization state

		Pre-fit	Post-fit
ZZ	$Z_L Z_L$	189.3 ± 8.7	220 ± 54
	$Z_T Z_L$	710 ± 29	711 ± 29
	$Z_T Z_T$	2170 ± 120	2147 ± 60
	Interference	33.7 ± 2.8	33.4 ± 2.7
Non-prompt		18.7 ± 7.1	18.5 ± 7.0
Others		20.0 ± 3.7	19.9 ± 3.7
Total		3140 ± 150	3149 ± 57
Data		3149	3149

$Z_L Z_L$ **4.3 σ**

3.3 σ

$W_L^{\pm} W_X^{\pm}$

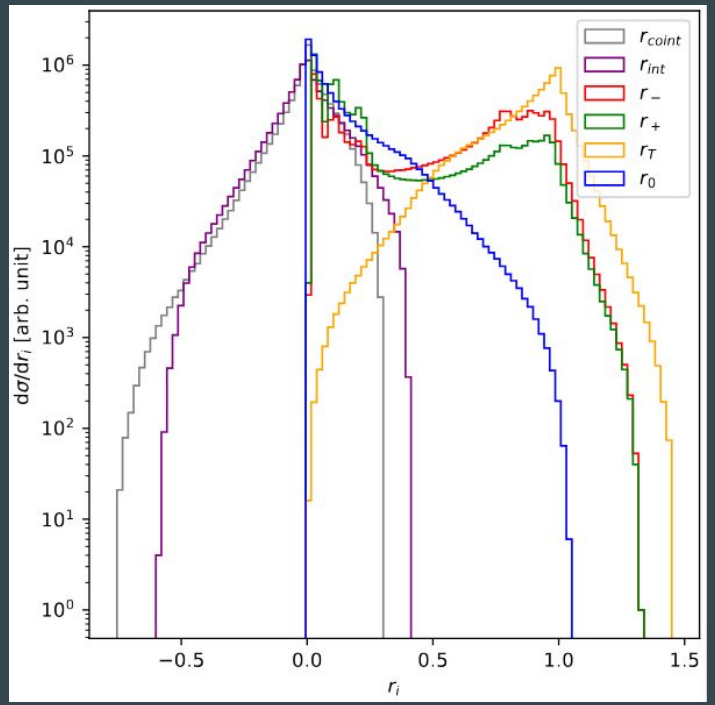
Process	Predicted $\sigma\mathcal{B}$ (fb)	Measured $\sigma\mathcal{B}$ (fb)
$W_L^{\pm} W_L^{\pm} jj$	0.29 ± 0.07	0.01 ± 0.21 (tot.)
$W_T^{\pm} W^{\pm} jj$	2.56 ± 0.64	3.39 ± 0.35 (tot.)
$W_L^{\pm} W^{\pm} jj$	1.18 ± 0.29	0.88 ± 0.30 (tot.)
$W_T^{\pm} W_T^{\pm} jj$	1.67 ± 0.40	2.49 ± 0.32 (tot.)

LHC Run 2 strategy

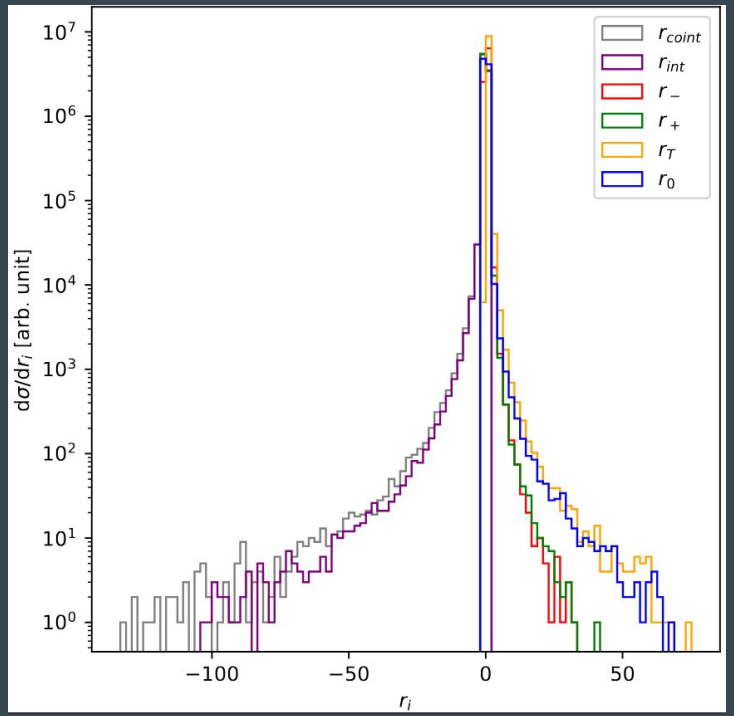
fit with polarized templates from MC simulation

$$\frac{d\sigma}{dX} = f_L \frac{d\sigma_L}{dX} + f_R \frac{d\sigma_R}{dX} + f_0 \frac{d\sigma_0}{dX} \left(+ f_{int.} \frac{d\sigma_{int.}}{dX} \right)$$

Pol probability distributions Z vs. W bosons



Z+j@LO+PS



W+j@LO+PS