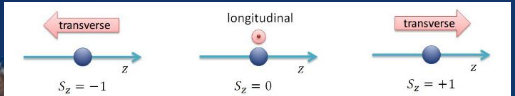
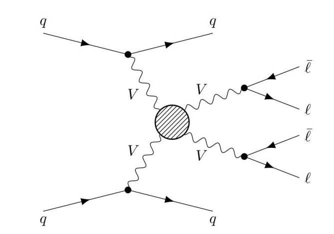
Mareen Hoppe[1], Marek Schönherr[2], Frank Siegert[1]

[1] *Institute of Nuclear and Particle Physics, Technische Universität Dresden*
[2] *Institute for Particle Physics Phenomenology, Durham University*



Dr. Z. Zinonos: Tests of the Standard Model of Particles. https://www.mpp.mpg.de/~zinonos/material/lecture10.pdf



Polarized cross sections for vector boson production with Sherpa

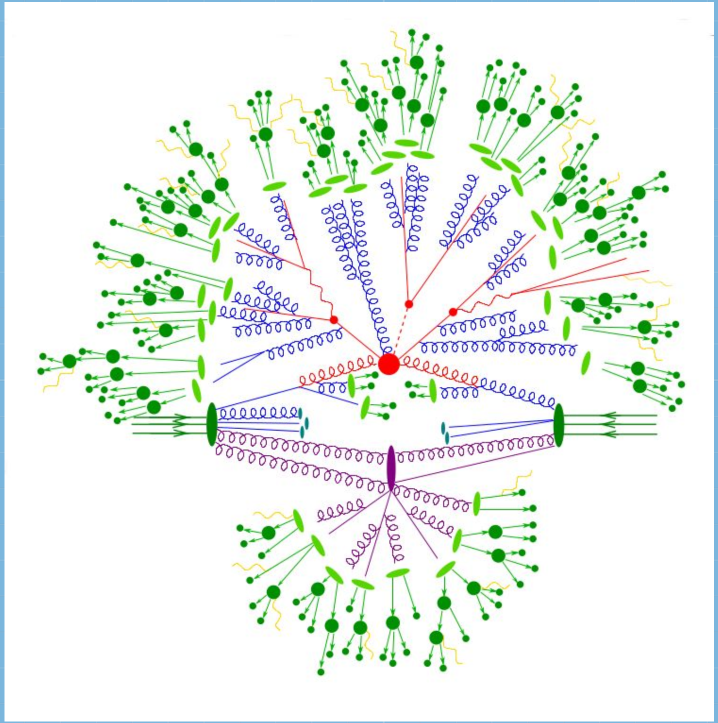
COMETA polarisation workshop Toulouse, September 23, 2024

The SHERPA event generator

New major release SHERPA 3.0.0 since July!

[E. Bothmann et al. 2019]

- two tree-level built-in matrix element generators: COMIX, AMEGIC
- higher order QCD effects: matching via S-MC@NLO, multi-jet merging via CKKW-L algorithm
- approximate NLO EW effects: EWvirt & EW Sudakov
- two parton showers: CSS, DIRE
- cluster fragmentation model
- hadron- and tau-decay module
- multiple interaction simulation á la PYTHIA
- higher-order QED effects via YFS resummation
- interfaces to
  - OpenLoops
  - Recola
  - GoSam
  - MCFM
  - BlackHat
  - MadLoop
  - RIVET 3 & 4
  - UFO
  - PYTHIA 8



Hard process
Parton shower
QED radiation
Hadronization
Hadron decays
Multiple interactions

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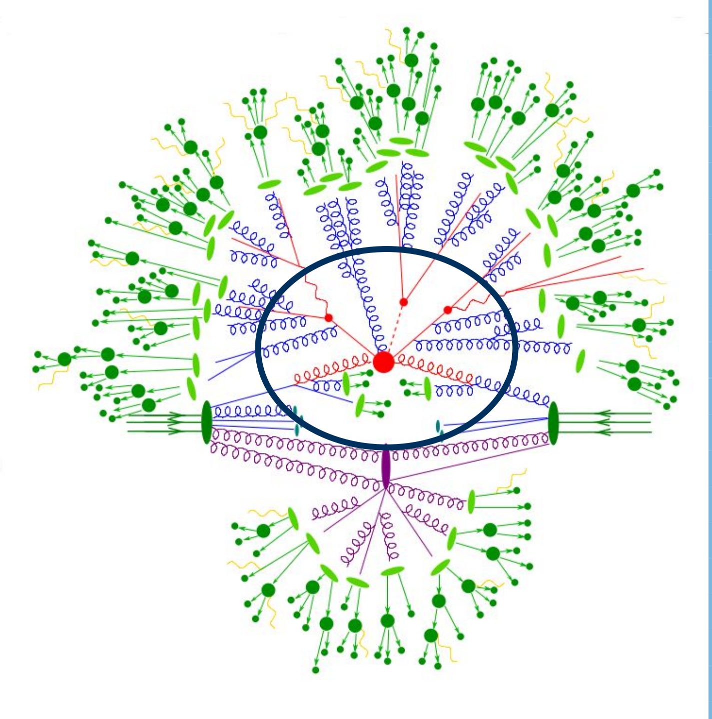

Hard process
Parton shower
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SHERPA's polarization framework

Design principles & features

Polarized cross sections for intermediate particles

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

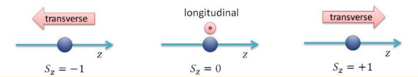
Polarization for intermediate particles

- completeness relation

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

- lead to interferences between different polarisations

Polarization basis



Dr. Z. Zinonos: Tests of the Standard Model of Particles. https://www.mpp.mpg.de/~zinonos/material/lecture10.pdf

- helicity basis

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

$$\varepsilon^\mu_0(q) = \frac{q^0}{m}\left(\frac{|\vec{q}\,|}{q^0}, \cos\phi\sin\theta, \sin\phi\sin\theta, \cos\theta\right)$$

- frame dependent!

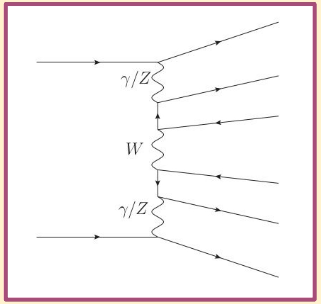
Separation of polarization

- amplitude needs to factorize: production ⊗ propagator ⊗ decay
- problem: non-resonant diagrams
  → no polarisation definition, but necessary for gauge invariance

- *solution:* appropriate approximations - gauge invariant options:

  - Pole Approximation ((D)PA)
  - Narrow-Width Approximation (NWA)

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



The narrow-width approximation

$$\mathcal{M} = \mathcal{M}_\mu^{\text{prod}} \left(\frac{i(-g^{\mu\nu} + \frac{q^\mu q^\nu}{m_V^2})}{q^2 - m_V^2 + i\Gamma_V m_V} \right) \mathcal{M}_\nu^{\text{decay}}$$

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

Completeness relation

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

Narrow width approximation

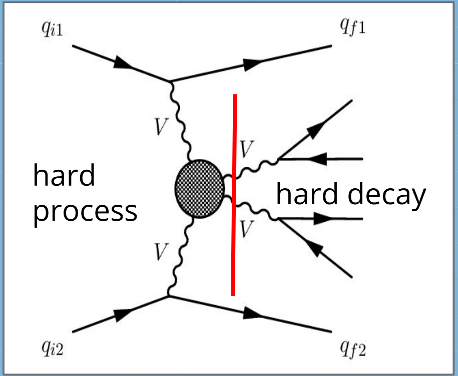
$$|\mathcal{M}|^2 \propto \sum_{\lambda_1\ldots\lambda_n;\,\lambda'_1\ldots\lambda'_n} \mathcal{M}^{\mathcal{P}}_{\lambda_1\ldots\lambda_n} \mathcal{M}^{*\mathcal{P}}_{\lambda'_1\ldots\lambda'_n} \mathcal{M}^{\mathcal{D}}_{\lambda_1\ldots\lambda_n} \mathcal{M}^{*\mathcal{D}}_{\lambda'_1\ldots\lambda'_n}$$

hard process

$$\left|\mathcal{M}^{\mathcal{P}}\right|^2 = \sum_{\lambda_1\ldots\lambda_n} \mathcal{M}^{\mathcal{P}}_{\lambda_1\ldots\lambda_n} \mathcal{M}^{*\mathcal{P}}_{\lambda_1\ldots\lambda_n}$$

hard decay

$$\left|\mathcal{M}^{\mathcal{D}}\right|^2 = \sum_{\lambda_1\ldots\lambda_n} \mathcal{M}^{\mathcal{D}}_{\lambda_1\ldots\lambda_n} \mathcal{M}^{*\mathcal{D}}_{\lambda_1\ldots\lambda_n}$$

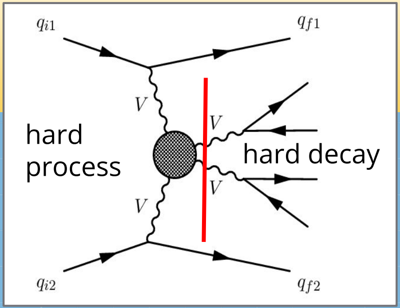


- **PROBLEM: spin correlations**

➔ **solution: spin-correlation algorithm** [P. Richardson 2001]

On-shell Approximation in SHERPA

[S. Höche et al. 2014]



- **extended narrow-width approximation:**
  - spin correlations preserved
  - off-shell effects via mass smearing of on-shell vector boson states

01	Simulation of unpolarized production process	$$\lvert\mathcal{M}^{\mathcal{P}}\rvert^2 = \sum_{\lambda_1\ldots\lambda_n} \mathcal{M}^{\mathcal{P}}_{\lambda_1\ldots\lambda_n}\mathcal{M}^{*\mathcal{P}}_{\lambda_1\ldots\lambda_n}$$
02	Recalculation of the production amplitude tensor	$$\lvert\mathcal{M}^{\mathcal{P}}\rvert^2_{\lambda_1\ldots\lambda_n;\lambda'_1\ldots\lambda'_n} = \mathcal{M}^{\mathcal{P}}_{\lambda_1\ldots\lambda_n}\mathcal{M}^{*\mathcal{P}}_{\lambda'_1\ldots\lambda'_n}$$
03	Spin correlation algorithm generates decay chain, LO decay matrices [P. Richardson 2001]	$$\mathcal{D}_{\lambda_A\lambda'_A} = \frac{1}{\mathcal{N}_{\mathcal{D}}}\mathcal{M}^{\mathcal{D}}_{\lambda_A}\mathcal{M}^{\mathcal{D}*}_{\lambda'_A}$$
04	Mass Smearing of the intermediate vector bosons according to Breit-Wigner distribution	$$\mathrm{BW} \sim \frac{1}{(p^2 - M^2)^2 + \Gamma^2 M^2}$$ E, |p| adjusted while preserving direction of flight in FS COM to account for new virtuality
05	Reweighting of production cross section with decay branching ratio	$$\lvert\mathcal{M}^{\mathrm{NWA}}\rvert^2 = \lvert\mathcal{M}^{\mathcal{P}}\rvert^2 \times \mathrm{BR}$$

Calculation of polarized cross sections

[MH, M. Schönherr, F. Siegert 2023]

- **algorithm for polarized cross sections:**
  - simulation essentially unpolarized
  - polarization fractions calculated on top
  - starting point: production amplitude tensor & decay matrices from spin correlation algorithm

1. Separated amplitudes from unpolarized simulation

$$\tilde{\mathcal{M}}^{\mathcal{P}}_{\kappa_1 \dots \kappa_n} \tilde{\mathcal{M}}^{*\mathcal{P}}_{\kappa'_1 \dots \kappa'_n}$$

$$\tilde{\mathcal{M}}^{\mathcal{D}}_{\kappa_1 \dots \kappa_n} \tilde{\mathcal{M}}^{*\mathcal{D}}_{\kappa'_1 \dots \kappa'_n}$$

2. Transformation to desired spin basis

$$|\mathcal{M}|^2_{\lambda_1 .. \lambda_n; \lambda'_1 \dots \lambda'_n} = \sum_{\kappa_1 \kappa'_1 \dots \kappa_n \kappa'_n} a^{\mathrm{part}1}_{\lambda_1 \kappa_1} a^{\mathrm{part}1*}_{\lambda'_1 \kappa'_1} \cdots \cdots a^{\mathrm{part}n}_{\lambda_n \kappa_n} a^{\mathrm{part}n*}_{\lambda'_n \kappa'_n} \left|\tilde{\mathcal{M}}\right|^2_{\kappa_1 \dots \kappa_n; \kappa'_1 \dots \kappa'_n}$$

3. Multiplication of production & decay

$$\left|\mathcal{M}^{pol}\right|^2_{\lambda_1 \dots \lambda_n;\, \lambda'_1 \dots \lambda'_n} \propto \mathcal{M}^{\mathcal{P}}_{\lambda_1 \dots \lambda_n} \mathcal{M}^{*\mathcal{P}}_{\lambda'_1 \dots \lambda'_n} \mathcal{M}^{\mathcal{D}}_{\lambda_1 \dots \lambda_n} \mathcal{M}^{*\mathcal{D}}_{\lambda'_1 \dots \lambda'_n}$$

4. Calculation of polarization fractions & labeling

$$\mathrm{Frac}_{\lambda_1 \dots \lambda_n; \lambda'_1 \dots \lambda'_n} = \frac{|\mathcal{M}^{pol}|^2_{\lambda_1 \dots \lambda_n; \lambda'_1 \dots \lambda'_n}}{\sum_{\lambda_1 \dots \lambda_n; \lambda'_1 \dots \lambda'_n} |\mathcal{M}^{pol}|^2_{\lambda_1 \dots \lambda_n; \lambda'_1 \dots \lambda'_n}}$$

5. Multiplication with event XS & output as event weights

Nominal or variation name	XS [pb]
Nominal	0.00636840738801
PolWeight_COM.W+.+_W+.+	0.00060858451764
PolWeight_COM.W+.+_W+.-	0.00078445056672
PolWeight_COM.W+.+_W+.0	0.00037696877407
PolWeight_COM.W+.-_W+.+	0.00077432059972
PolWeight_COM.W+.-_W+.-	0.00148317472445
PolWeight_COM.W+.-_W+.0	0.00063413615306
PolWeight_COM.W+.0_W+.+	0.00037938319197
PolWeight_COM.W+.0_W+.-	0.00063363366425
PolWeight_COM.W+.0_W+.0	0.00065521961374
PolWeight_COM.W+.0_W+.T	0.00101508799740
PolWeight_COM.W+.0_W+.t	0.00101301685622
PolWeight_COM.W+.T_W+.0	0.00101857271726
PolWeight_COM.W+.T_W+.T	0.00364953844553
PolWeight_COM.W+.t_W+.0	0.00101110492712
PolWeight_COM.W+.t_W+.t	0.00365053040852

Key part of the polarization framework: Transformation of the matrix elements

- two ways to change polarization definition in matrix elements:
  - a priori: change polarization definition directly in matrix element generator
  - **a posteriori: transformation of calculated production tensor, decay matrices**
- change of basis = basis transformation of polarization vectors

$$\begin{pmatrix} \tilde{\varepsilon}^0_+ & \tilde{\varepsilon}^0_- & \tilde{\varepsilon}^0_0 \\ \tilde{\varepsilon}^1_+ & \tilde{\varepsilon}^1_- & \tilde{\varepsilon}^1_0 \\ \tilde{\varepsilon}^2_+ & \tilde{\varepsilon}^2_- & \tilde{\varepsilon}^2_0 \\ \tilde{\varepsilon}^3_+ & \tilde{\varepsilon}^3_- & \tilde{\varepsilon}^3_0 \end{pmatrix} = \begin{pmatrix} \varepsilon^0_+ & \varepsilon^0_- & \varepsilon^0_0 \\ \varepsilon^1_+ & \varepsilon^1_- & \varepsilon^1_0 \\ \varepsilon^2_+ & \varepsilon^2_- & \varepsilon^2_0 \\ \varepsilon^3_+ & \varepsilon^3_- & \varepsilon^3_0 \end{pmatrix} \begin{pmatrix} a_{++} & a_{-+} & a_{0+} \\ a_{+-} & a_{--} & a_{0-} \\ a_{+0} & a_{-0} & a_{00} \end{pmatrix}$$

transformation coefficients

matrix of new polarization vectors

matrix of default polarization vectors

- transformation of matrix elements

$$|\mathcal{M}|^2_{\lambda_1\lambda_1'\ldots\lambda_n\lambda_n'} = \sum_{\kappa_1\kappa_1'\ldots\kappa_n\kappa_n'} a^{\mathrm{part}1}_{\lambda_1\kappa_1} a^{\mathrm{part}1*}_{\lambda_1'\kappa_1'} \cdots a^{\mathrm{part}n}_{\lambda_n\kappa_n} a^{\mathrm{part}n*}_{\lambda_n'\kappa_n'} |\mathcal{M}|^2_{\kappa_1\kappa_1'\ldots\kappa_n\kappa_n'}$$

matrix element in new basis

linear combination coefficients

matrix element in default basis

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```
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PolWeight_COM.W+.-_W+.+                  0.00077432059972
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PolWeight_COM.W+.-_W+.0                  0.00063413615306
PolWeight_COM.W+.0_W+.+                  0.00037938319197
PolWeight_COM.W+.0_W+.-                  0.00063363366425
PolWeight_COM.W+.0_W+.0                  0.00065521961374
PolWeight_COM.W+.0_W+.T                  0.00101508799740
PolWeight_COM.W+.0_W+.t                  0.00101301685622
PolWeight_COM.W+.T_W+.0                  0.00101857271726
PolWeight_COM.W+.T_W+.T                  0.00364953844553
PolWeight_COM.W+.t_W+.0                  0.00101110492712
PolWeight_COM.W+.t_W+.t                  0.00365053040852
```

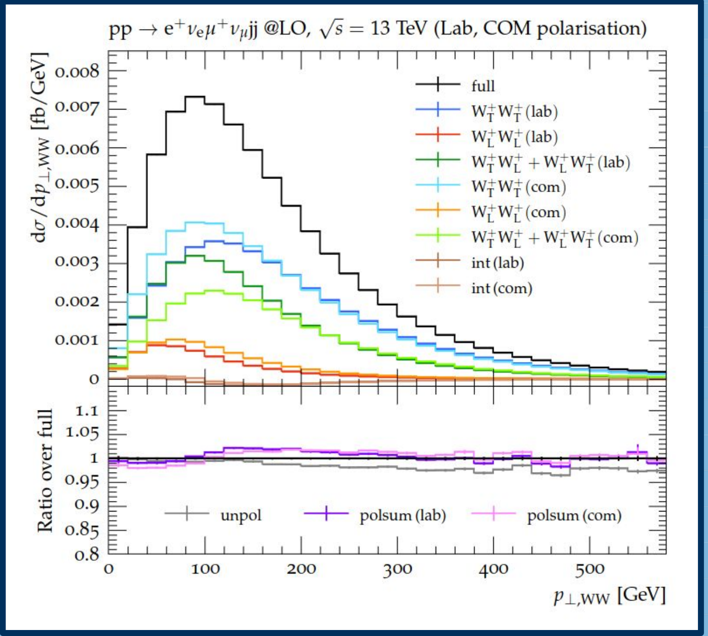
Advantages

- fully differential (per event) polarization fractions for all polarization combinations & interference

$$\underbrace{|\mathcal{M}|^2}_{\text{coherent sum}} = \underbrace{\sum_{\lambda} |\mathcal{M}_{\lambda}^{\mathcal{F}}|^2}_{\text{polarised contributions, incoherent sum}} + \underbrace{\sum_{\lambda\neq\lambda'} \mathcal{M}_{\lambda}^{\mathcal{F}} \mathcal{M}_{\lambda'}^{*\mathcal{F}}}_{\text{interference}} ,$$

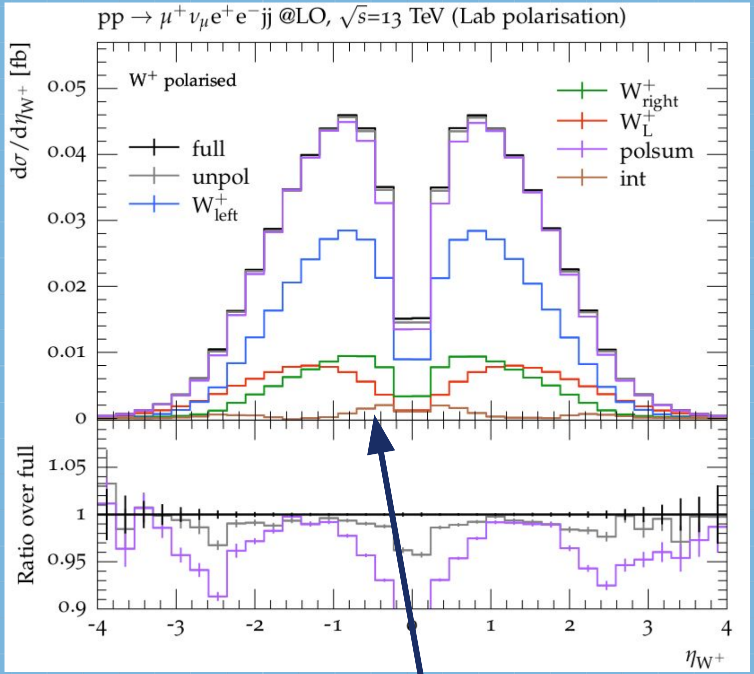
- different polarization definitions in one simulation run
  - ✓ laboratory frame
  - ✓ center of mass frame of arbitrary combination of initial- / final state particles
  - ✓ parton-parton frame
  - ✓ easily extendable, if necessary

W^+W^+-scattering

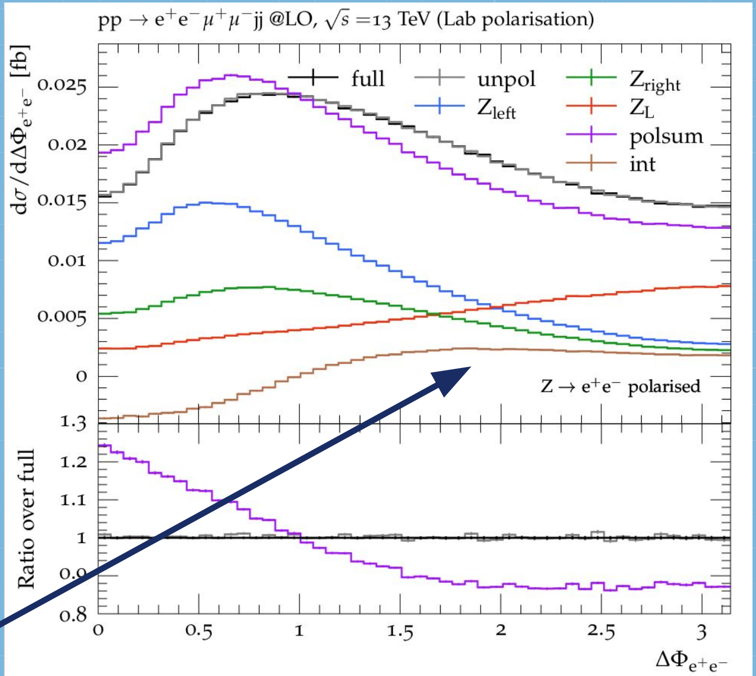


Interference templates

W^+Z-scattering



ZZ-scattering



➢ interference not always negligible

SHERPA's polarization framework

Higher order effects & BSM

Polarized cross sections matched to PS - MC@NLO

[S. Höche et al. 2012]

idea MC@NLO : double counting eliminated by subtraction of the shower contribution at fixed order from contributions of the hard process at higher orders

$$\sigma^{\mathrm{NLO}}_{\mathrm{MC@NLO}} = \underbrace{\int \mathrm{d}\tilde{\Phi}_n \bar{B}_n^{\mathcal{A}}(\tilde{\Phi}_n)\left[\bar{\Delta}^{\mathcal{A}}(t_0) + \int_{t_0} \mathrm{d}\tilde{\Phi}_1 \frac{D_n^{\mathcal{A}}(\tilde{\Phi}_{n+1})}{B_n(\tilde{\Phi}_n)} \bar{\Delta}^{\mathcal{A}}(t)\right]}_{=:\sigma_{\mathbb{S}}} + \underbrace{\int \mathrm{d}\tilde{\Phi}_{n+1} H_n^{\mathcal{A}}(\tilde{\Phi}_{n+1})}_{=:\sigma_{\mathbb{H}}}$$

Recalculation of the amplitude tensor in dependency of event type

Resolved S-events

- universal-soft-collinear radiation pattern in PS approximation above PS IR cutoff

- **construction from complete real emission amplitude**

virtual, ultra-soft & ultra-collinear emission effects neglected for polarization fractions

Unresolved S-events

- emissions below PS IR cutoff
- virtual corrections

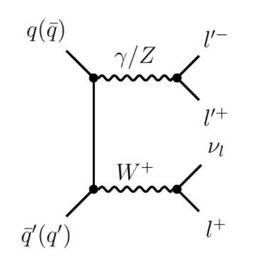
- **construction from Born amplitude**

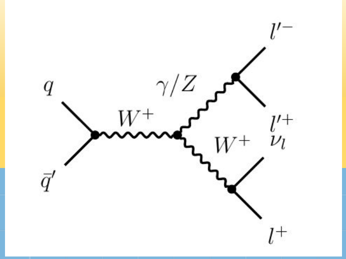
H-events

- hard, well-separated emissions beyond PS starting scale
- process-specific corrections to universal soft-collinear emission pattern

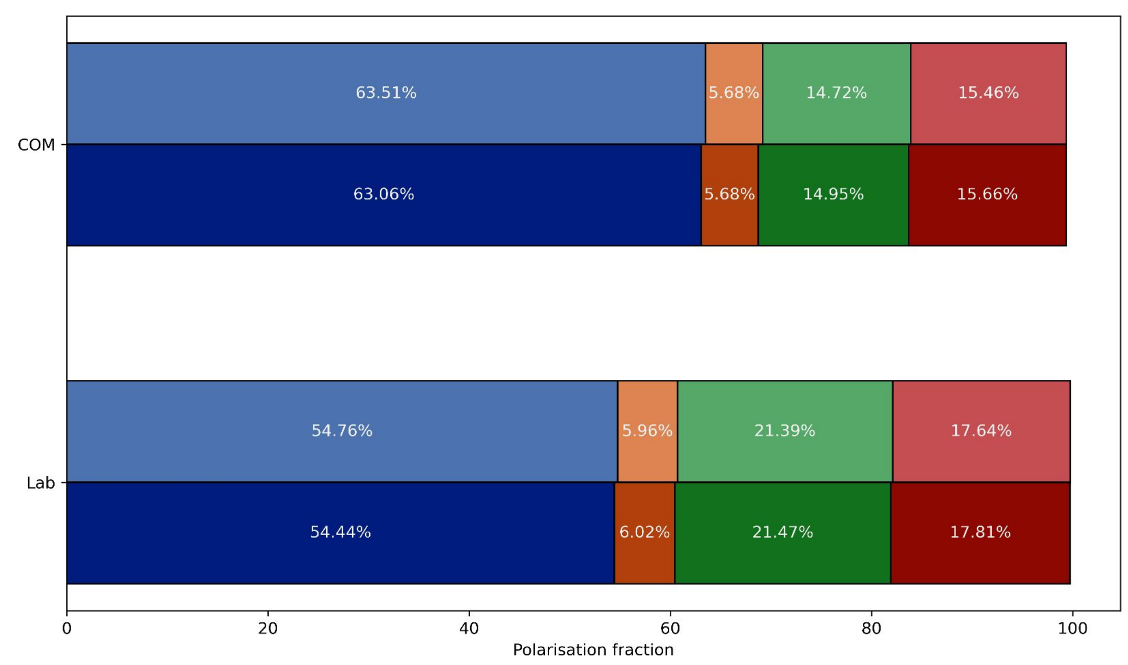
- **construction from complete real emission amplitude**

nLO+PS vs. full fixed NLO - WZ-Diboson production





Comparison with NLO QCD fixed order calculation [A. Denner & G. Pelliccioli 2021]



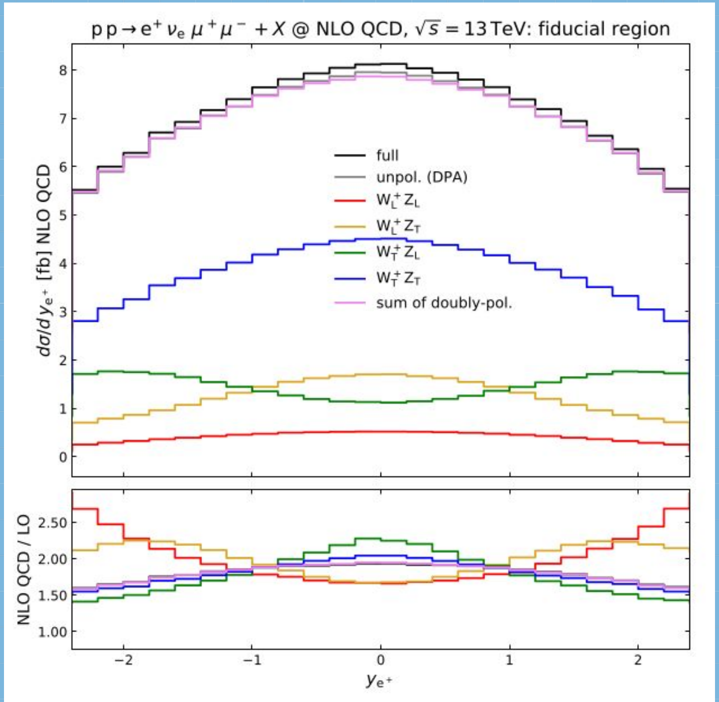
agreement of

Lab: < 1%

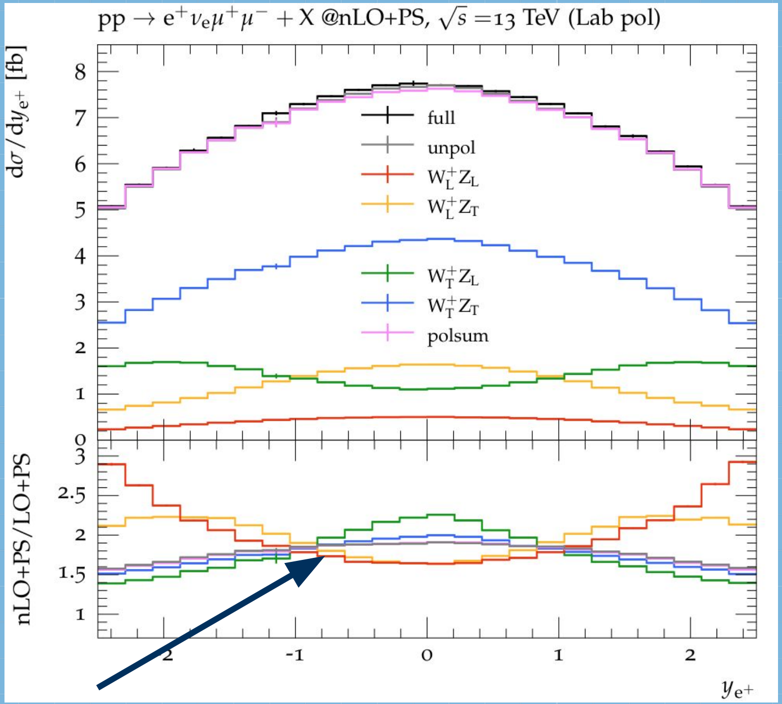
COM: ≤ 1.5%

WZ Diboson production - Rapidity of the W-lepton (lab)

NLO QCD calculation fixed order
[A. Denner & G. Pelliccioli 2021]



Sherpa nLO+PS



Reproduces even non-trivial NLO effects!

nLO+PS (Sherpa) vs. full NLO+PS (POWHEG+PYTHIA)

Literature: [G. Pellicciolo, G. Zanderighi 2023]

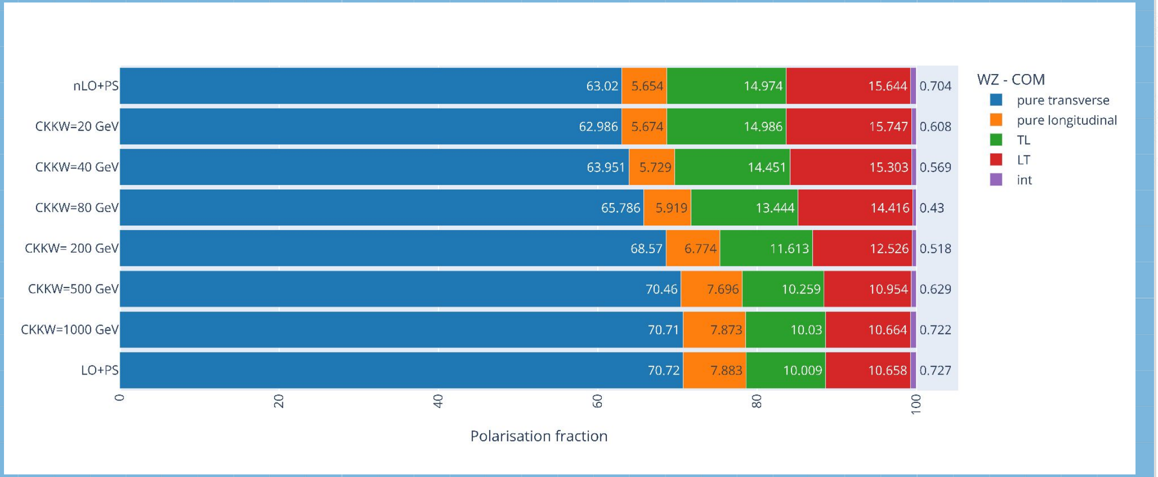
WZ production [G. Pellicciolo, G. Zanderighi 2023]: similar agreement compared to NLO QCD+PS

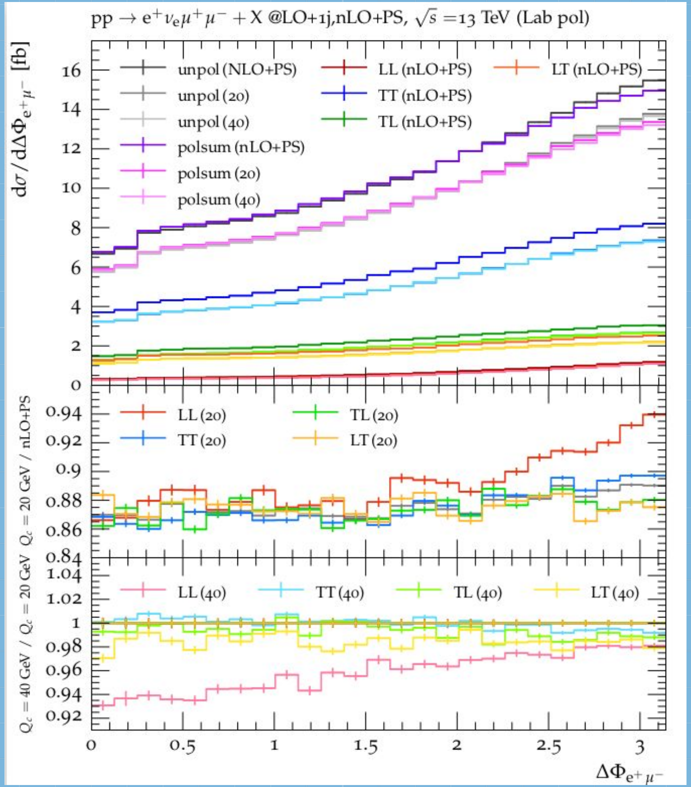
ZZ-Production

	$\sigma_{\mathrm{NLO+PS}}$ [fb]	Fraction [%]	$\sigma_{\mathrm{nLO+PS}}$ [fb]	Fraction [%]	$\frac{\mathrm{nLOPS}}{\mathrm{NLOPS}} - 1$ [%]	
					XS	Frac
unpol	14.02(1)	100	14.017(17)	100	-0.0	
LL	0.819(1)	5.84	0.8404(12)	5.996(11)	+2.6	+2.7
LT + TL	3.565(3)	25.43	3.6177(39)	25.81(4)	+1.5	+1.5
TT	9.47(1)	67.52	9.370(14)	66.85(13)	-1.1	-1.0
int	0.171	1.28	0.1886(24)	1.345(17)	+10.3	+5.1

Multi-leg merging

WZ-Diboson production



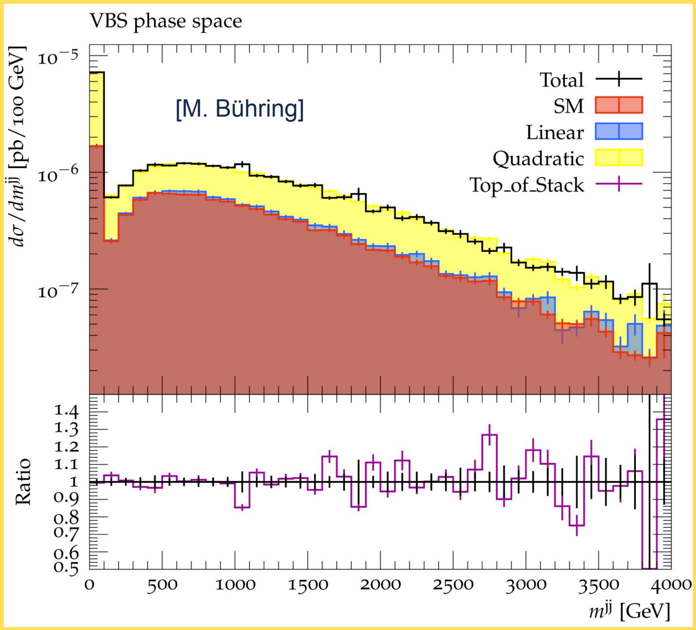


- based on CKKW merging
- LO & N(n)LO QCD accuracy
- small merging scale crucial
- no limitation in combination with polarization framework

VB polarization beyond the Standard Model

- **UFO format: standardized format for BSM models for simple import in event generators**
- **SHERPA UFO interface:** [S. Höche et al. 2014]
  - Lorentz & color structures built automatically
  - automatic decay tables / chains
  - handling of intermediate resonances
  - spin correlations
  - effective field theories
  - form factors
- **combination with polarization framework via intermediate resonances suite**

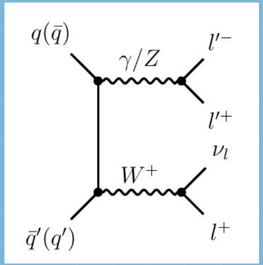
W+W+jj SMEFT dim-6

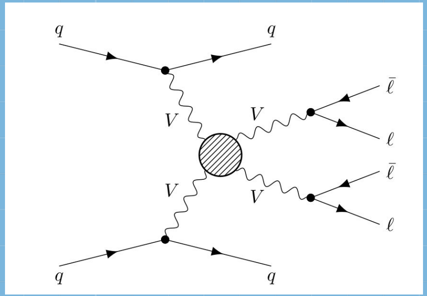


Polarization framework in real life

Available processes & current limitations

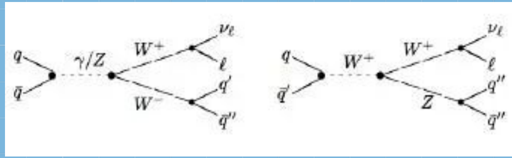
- all processes with intermediate vector bosons that are possible with SHERPA's tree-level matrix element generators
- up to nLO QCD in production process
- leptonic- as well as hadronic decays
- extension to spin-½ particles easily possible

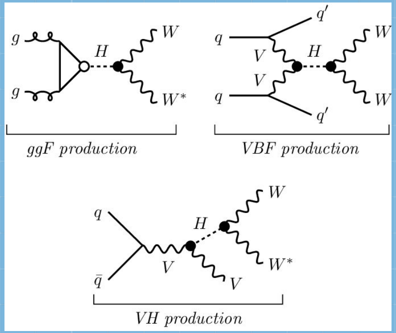


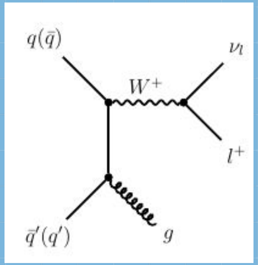


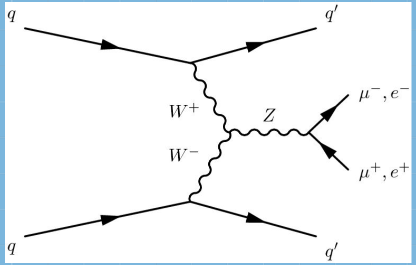
Limitations

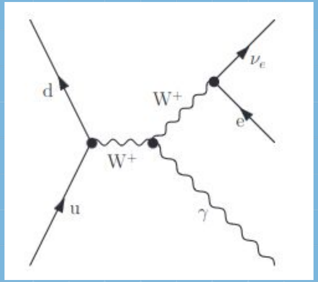
- no loop-induced processes
- no higher order effects on decays





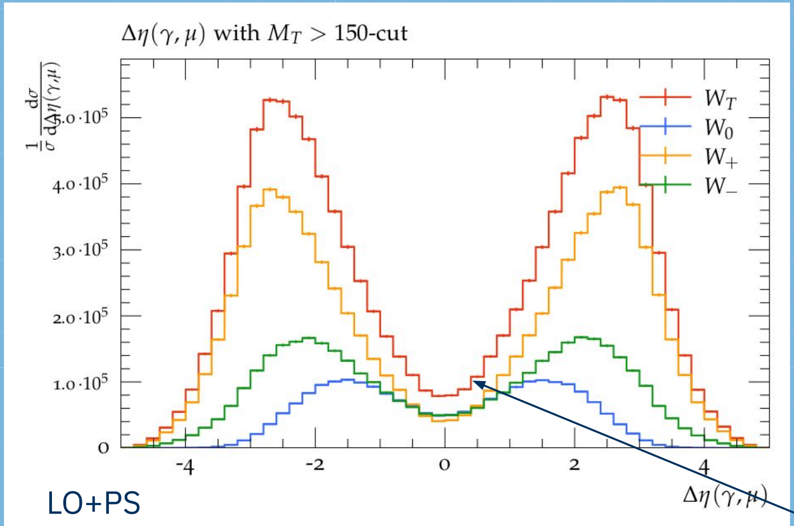


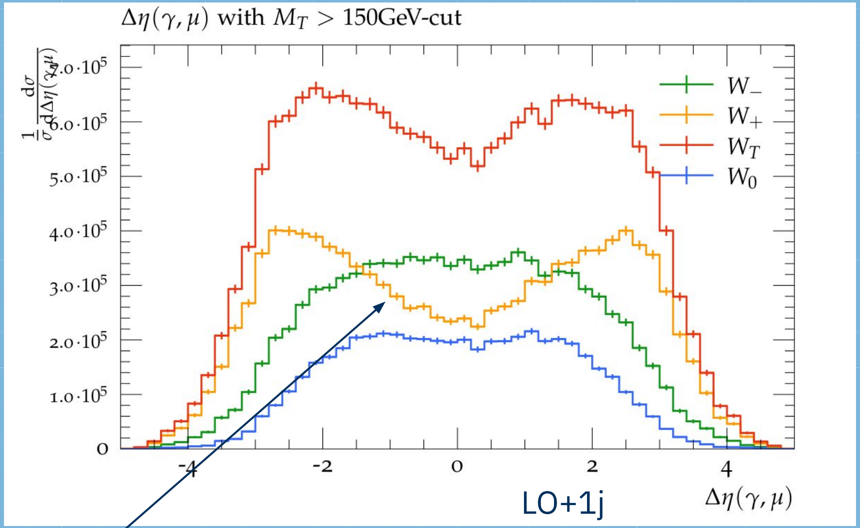




Polarized Wy production

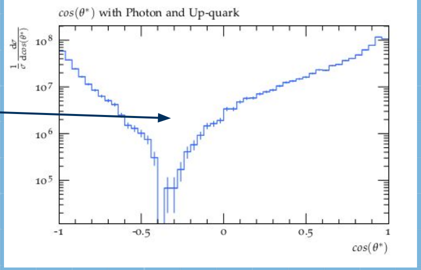
[R. Seip CERN-THESIS-2024-086]





	LO+PS	LO+1j
f_0	0.1556	0.2196
f_+	0.4277	0.3454
f_-	0.4166	0.4349

sums up to dip in unpolarized result due to radiation amplitude zero effect in cosΘ with Θ = ∡ between ɣ & u in Wɣ rest frame



Huge impact from higher order QCD corrections!

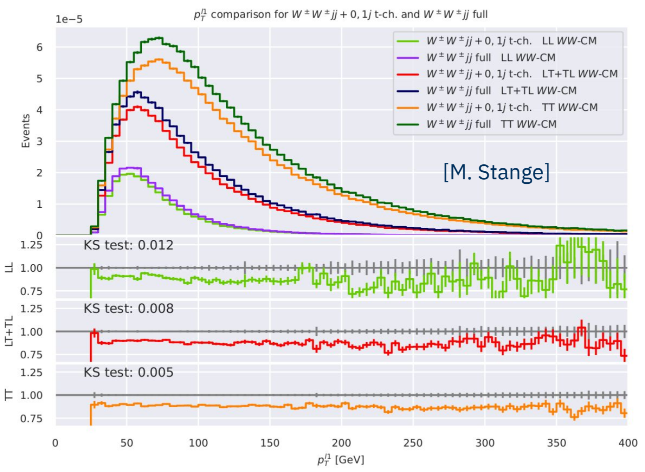
First higher order QCD predictions for VBS W^+W^+jj matched to PS

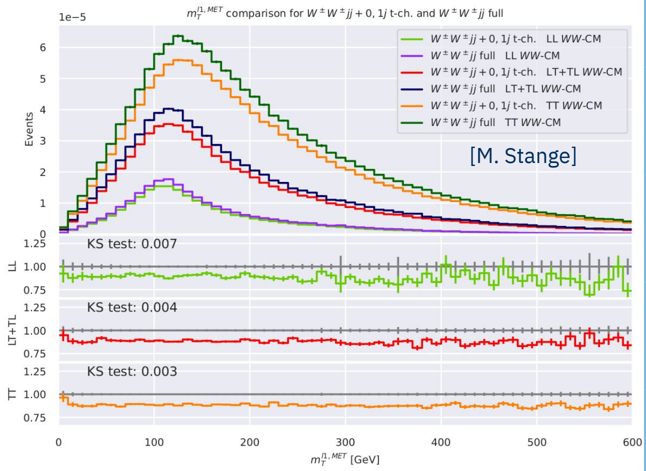
[E. Bachmann, MH, M. Stange]

	LO+PS	LO+1j VBS approx
unpol [fb]	2.459	2.302
LL [fb]	0.237	0.224
Fraction [%]	9.63	9.73
LT+TL [fb]	0.765	0.716
Fraction [%]	31.12	31.10
TT [fb]	1.497	1.399
Fraction [%]	60.88	60.77

Only sub-percent level effect on integrated…

… and differential polarization fractions!





Recently:
First NLO QCD + NLO EW fixed order results available [A. Denner, C. Haitz, G. Pelliccioli 2024]

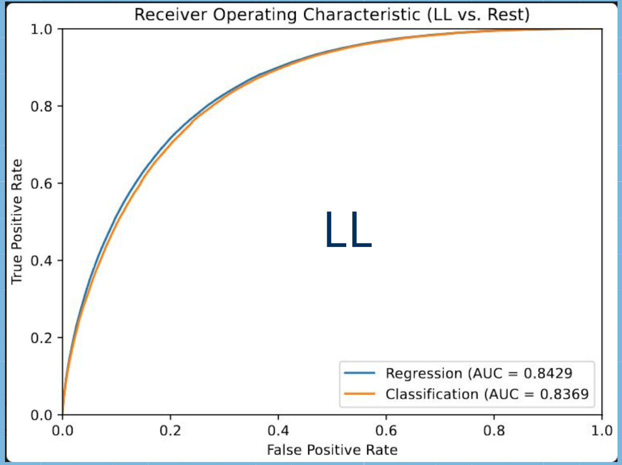
Current projects

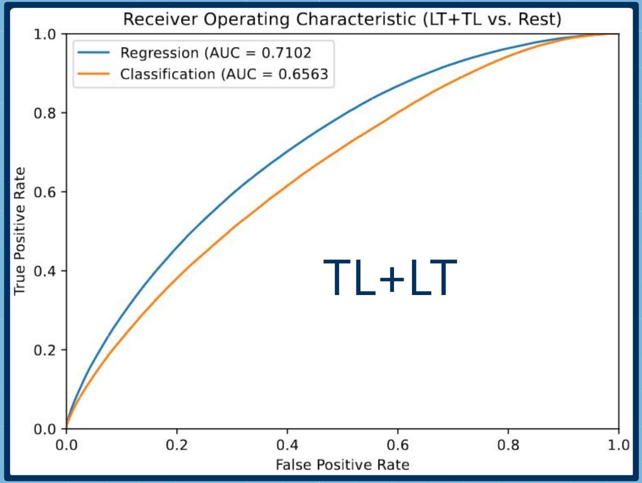
Ongoing: Extension to complete NLO QCD / NLO EW

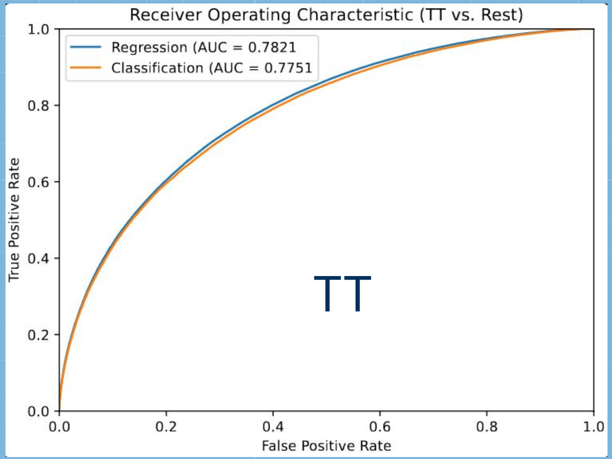
- **first step: Extension of SHERPA's Recola interface to get polarized loop-amplitudes**
  - transformation to SHERPA's spin basis to use it together with COMIX decay amplitudes
  - implemented spin trafo used
- **currently testing first implementation**
- **first application: loop-induced processes**

Ongoing: Usage as polarization tagger

- **first proof of concept study: recursion NN trained on polarization fractions in VBS W^+W^+jj @LO outperforms classification net [J. A. Neumann CERN-THESIS-2023-346]**



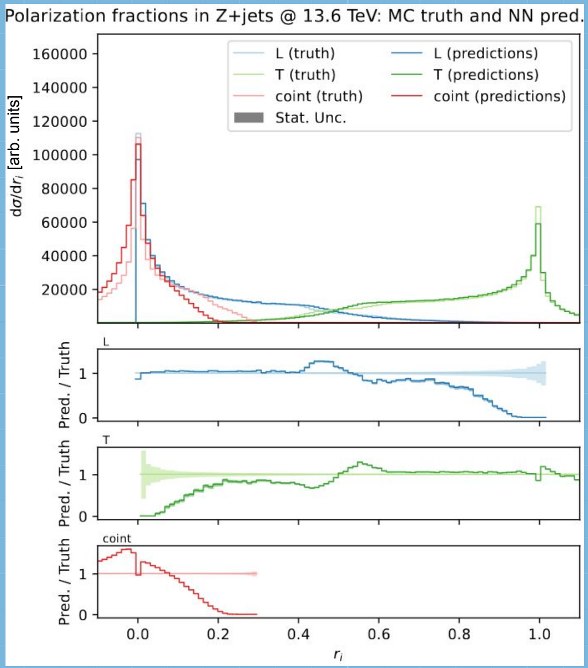




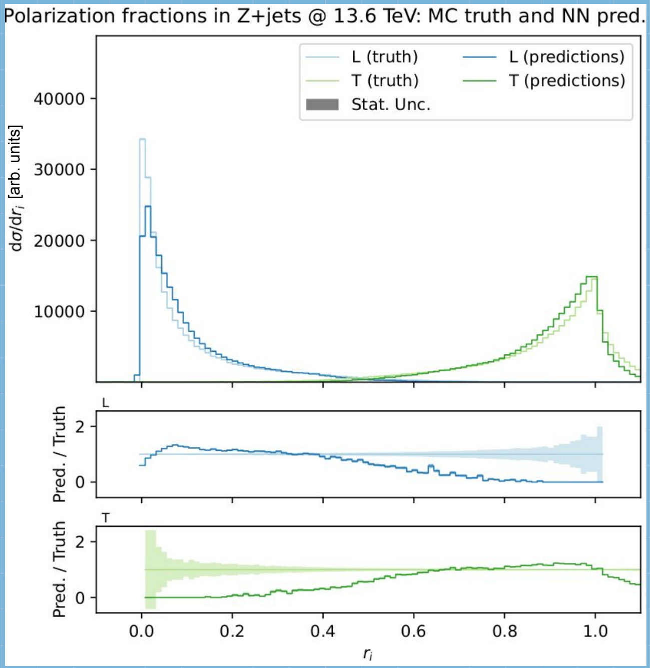
Ongoing: Usage as polarization tagger

[E. Bachmann, MH]

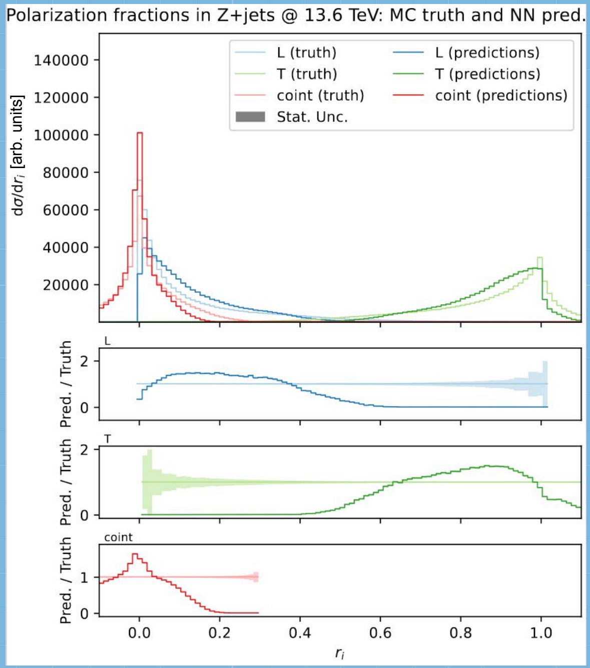
- **now: working on proper polarization tagger trained on polarization weights:**
  - starting with Z+jets example like in [[M. Grossi et al. 2023](#)] & multi-layer perceptrons in LAB



1. fixed order LO

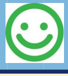


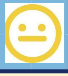
2. LO+PS restricted on events with 1 jet



3. LO+PS all jets

agreement true vs. NN:

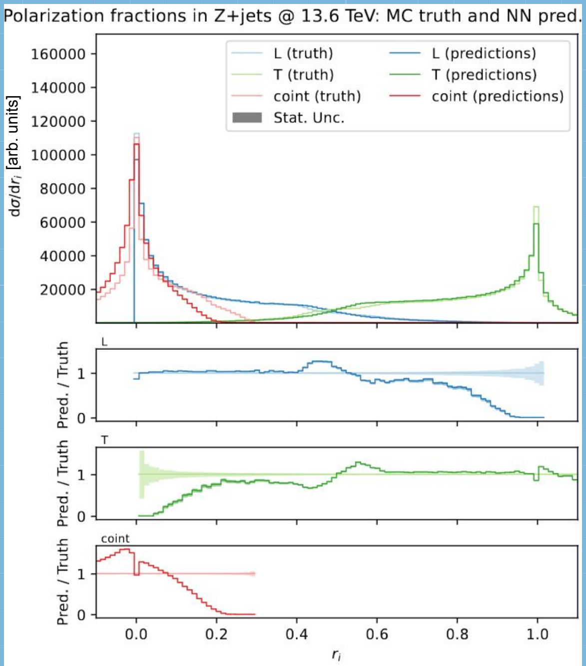


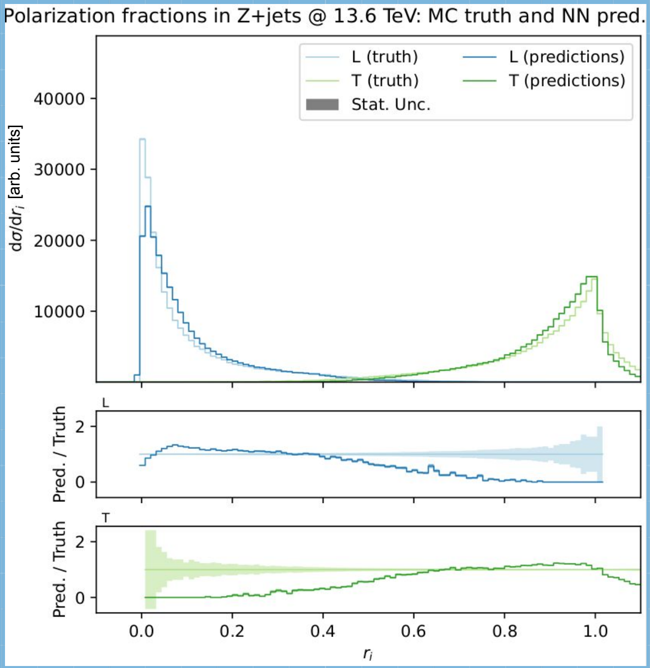


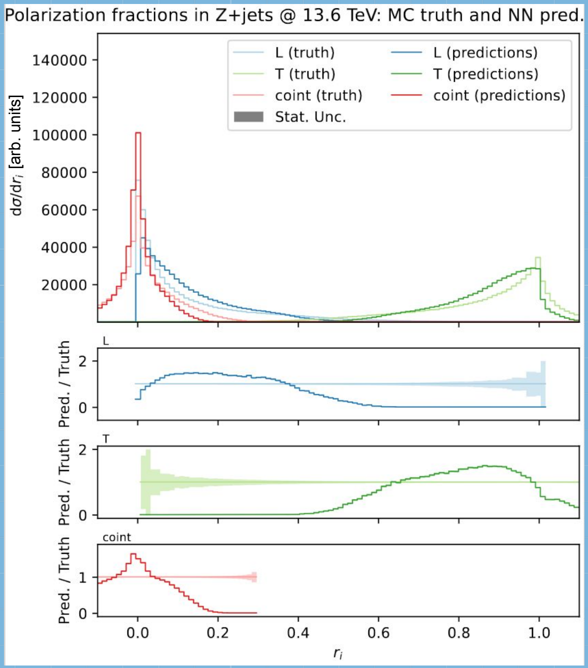
Ongoing: Usage as polarization tagger

Next step:
Trying different network architecture (GNNs) in order to include all jets as training inputs

- **now: working on proper polarization tagger trained on polarization weights:**
  - starting with Z+jets example like in [M. Grossi et al. 2023] & multi-layer percep







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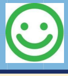
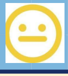
2. LO+PS restricted on events with 1 jet

3. LO+PS all jets

agreement true vs. NN:





Summary and Outlook

SHERPA

✓ **Overview over SHERPA's polarization framework**
  - publicly available since SHERPA 3.0.0beta

✓ **Key features:**
  - all polarized cross sections in one simulation run
  - direct calculation of interference between different polarizations
  - provide several reference frames
  - accuracy up to nLO+PS, multi-leg merging
  - no process limitation (for intermediate VBs) beside loop-induced processes
  - usable for SM and BSM physics

https://www.zeppelinschule-speyer.de/ausblick-auf-die-zeit-nach-pfingsten/

What comes next ...

- ❑ Extension to loop-induced processes
- ❑ Extension to NLO QCD and approximate NLO EW
- ❑ Application for polarization tagging
- ❑ Applications in phenomenological studies: NLO effects to VBS processes, BSM studies, hadronic decays

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- ❏ Application for polarization tagging
- ❏ NLO effects to VBS processes, BSM studies, hadronic decays

Thank you for your attention!

Backup

Spin-Correlation Algorithm

[P. Richardson 2001]

- **here only for VB decaying into stable leptons**

hard process final state particles & production (2→n) matrix element tensor $\left|\mathcal{M}^{\mathcal{P}}\right|^2_{\lambda_1\ldots\lambda_n\lambda'_1\ldots\lambda'_n}$

choose one outgoing particle A randomly

Spin density matrix $\rho_{\lambda_j\lambda'_j}(A) = \frac{1}{N_\rho}\mathcal{M}^{\mathcal{P}}{}_{\kappa_1\kappa_2;\lambda_1\ldots\lambda_j\ldots\lambda_n}\mathcal{M}^{\mathcal{P}*}_{\kappa_1\kappa_2;\,\lambda'_1\ldots\lambda'_j\,\ldots\lambda'_n}\prod_{i\neq j}\mathcal{D}^i_{\lambda_i\lambda'_i}$

with $\mathcal{D}^i_{\lambda_i\lambda'_i} = \dfrac{1}{n_{hel}}\delta_{\lambda_i\lambda'_i}$ if particle not chosen yet

choose decay channel of A according to branching ratios

Generate momenta of A's decay products according to $\rho_{\lambda_A\lambda'_A}\mathcal{M}^{\mathcal{D}}_{\lambda_A;\lambda_1\ldots\lambda_n}\mathcal{M}^{\mathcal{D}*}_{\lambda'_A;\,\lambda_1\ldots\lambda_n}$

all decay products stable

Calculate A's decay matrix $\mathcal{D}_{\lambda_A\lambda'_A} = \dfrac{1}{N_{\mathcal{D}}}\mathcal{M}^{\mathcal{D}}_{\lambda_A;\lambda_1\ldots\lambda_n}\mathcal{M}^{\mathcal{D}*}_{\lambda'_A;\lambda_1\ldots\lambda_n}$

Mass Smearing Algorithm

- **spin correlation algorithm runs on on-shell momenta**
- **mass smearing performed afterwards**

1. **Generate off-shell masses for VBs**
   a. determine max. available mass = invariant mass of total mom of VB production FS
   b. starting with VB with smallest decay width
   c. dice mass according to Breit-Wigner distribution from [0, totmass]
2. **Boost final state momenta of production process accordingly**
3. **Boost final state momenta of decay particles accordingly**

Guiding principles for 2.+3.

- **redistribute E, |p| of the particles while preserving direction of flight in CMS of the FS particles**

Basic Usage - ZZ production example

```
BEAMS: 2212
BEAM_ENERGIES: 6500

WIDTH_SCHEME: Fixed

COMIX_DEFAULT_GAUGE: 0

PARTICLE_DATA:
  24: {Width: 0}
  23: {Width: 0}
```

Real masses, couplings
→ no complex mass scheme

Spinor gauge such that polarization vectors have the typical form

VB width zero to fulfill SU(2) Ward identities

VB decay process

Polarised cross sections with ZZ COM reference frame enabled

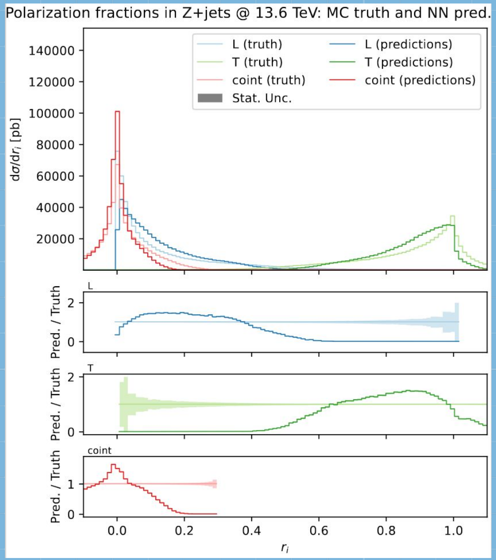
VB production process @nLO + PS

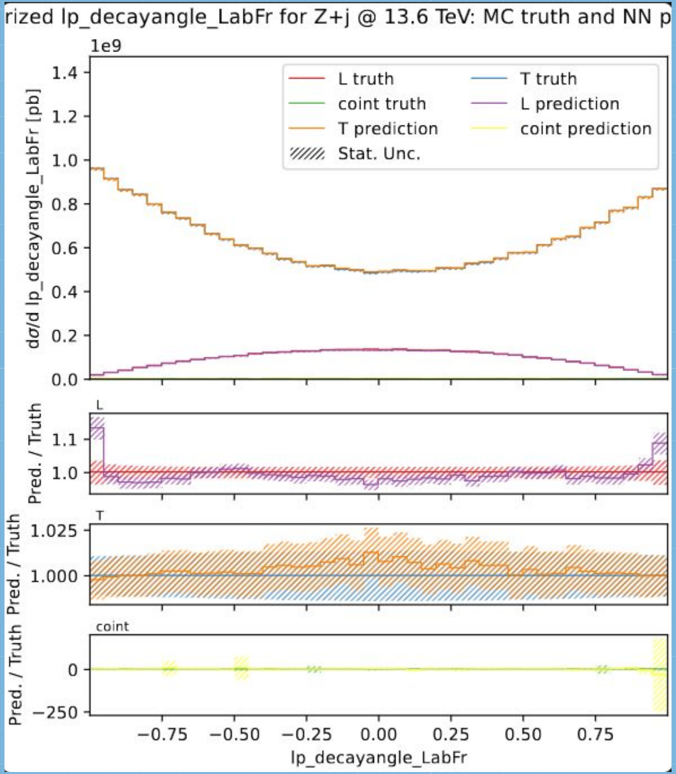
```
HARD_DECAYS:
  Enabled: true
  Channels:
    23,11,-11: {Status: 2}
    23,13,-13: {Status: 2}
  Pol_Cross_Section:
    Enabled: true
    Reference_System: COM

# production process: (jj -> ZZ)
PROCESSES:
- 93 93 -> 23 23:
    Order: {QCD: 0, EW: 2}
    NLO_Mode: MC@NLO
    NLO_Order: {QCD: 1, EW: 0}
    ME_Generator: Amegic
    RS_ME_Generator: Comix
    Loop_Generator: OpenLoops

ANALYSIS: Rivet
RIVET:
  --analyses:
      - COMETA_ZZ_production_analysis
```

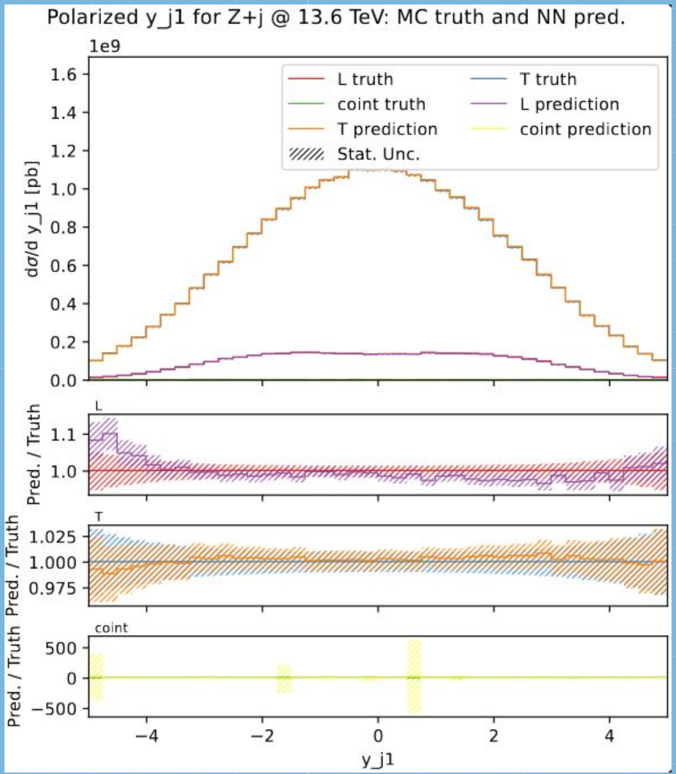
VB production process multi-leg merging (LO+1j)

```
# production process: (jj -> ZZ)
PROCESSES:
- 93 93 -> 23 23 93{1}:
    Order: {QCD: 0, EW: 2}
    CKKW: 20
```

Ongoing: Usage as polarization tagger







Z+jets @ LOPS,
Laboratory frame