New calculations & techniques for NLO EW

Facilitating Precision Physics at the LHC

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GEFÖRDERT VOM

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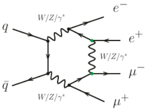
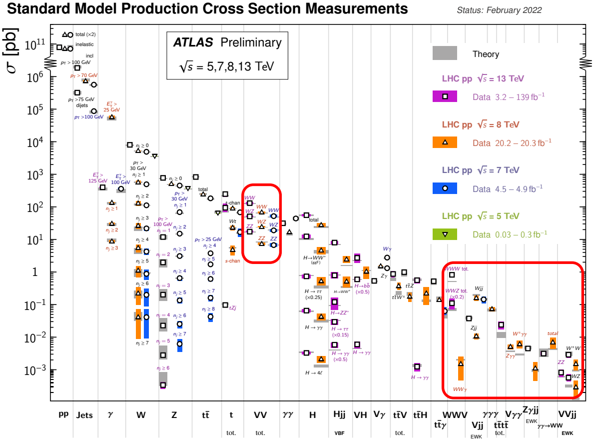
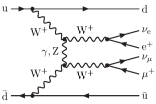
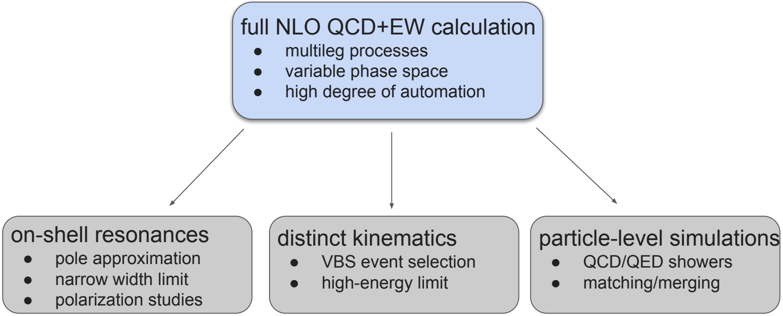






- rare & subtle electroweak signal processes probing EWSB
- triple-, quartic gauge-boson couplings
- longitudinal polarisation modes of massive gauge bosons

Accounting for (dominant) electroweak corrections



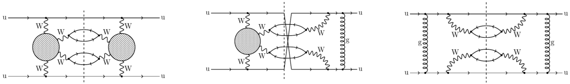
- EW one-loop and QED real emission amplitudes needed, e.g. RECOLA [Denner *et al.*], OPENLOOPS [Pozzorini *et al.*]
- QED infrared subtraction terms (dipole/FKS)
  $\rightsquigarrow$ real weak-boson radiation excluded
- frameworks to accomplish full calculations, e.g. MG5_aMC [Frederix *et al.*], POWHEG [Nason *et al.*], SHERPA [Bothmann *et al.*]
- invoke QCD/QED showers for particle-level predictions HERWIG [Bellm *et al.*], PYTHIA [Bierlich *et al.*], SHERPA

Pushing the limits: multileg NLO calculations

state-of-the-art: full NLO calculation for $2 \to 6$ processes

- full NLO QCD & EW corrections and QCD–EW interferences
  $\rightsquigarrow$ crucial benchmark for approximation schemes
- consider **like-sign W-boson scattering**: $pp \to e^+\nu_e\mu^+\nu_\mu jj$

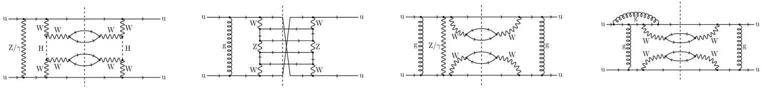
[Dittmaier et al. JHEP 11 (2023) 22] [Biedermann et al. JHEP 10 (2017) 124]



LO $\mathcal{O}(\alpha^6)$ $\mathcal{O}(\alpha_s\alpha^5)$ $\mathcal{O}(\alpha_s{}^2\alpha^4)$

EW QCD EW QCD EW QCD

NLO $\mathcal{O}(\alpha^7)$ $\mathcal{O}(\alpha_s\alpha^6)$ $\mathcal{O}(\alpha_s{}^2\alpha^5)$ $\mathcal{O}(\alpha_s{}^3\alpha^4)$



Pushing the limits: multileg NLO calculations

state-of-the-art: $pp \to e^+\nu_e\mu^+\nu_\mu jj$ at full NLO

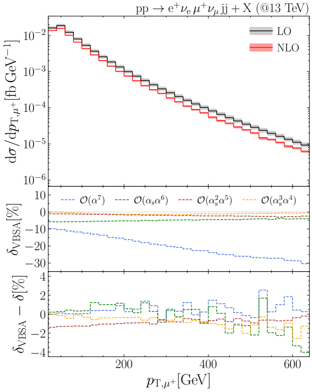
[Dittmaier et al. JHEP 11 (2023) 22] [Biedermann et al. JHEP 10 (2017) 124]

- consider **VBS event selection cuts**, in particular

$$M_{j_1 j_2} > 500\,\text{GeV}\,,\ |y_{j_1} - y_{j_2}| > 2$$

- full off-shell calculation vs. VBS/DPA approximations

	Order	Result [fb]	δ[%]	Scale uncertainty	
LO	$\mathcal{O}(\alpha^6\alpha_s^0)$	1.24597(5)		−7.7%	9.9%
	$\mathcal{O}(\alpha^5\alpha_s^1)$	0.051133(3)		−14.0%	17.7%
	$\mathcal{O}(\alpha^4\alpha_s^2)$	0.18649(2)		−22.2%	31.6%
	sum	1.48359(5)		−9.8%	12.1%
NLO	$\mathcal{O}(\alpha^7\alpha_s^0)$	−0.1747(5)	−11.8%		
	$\mathcal{O}(\alpha^6\alpha_s^1)$	−0.0902(8)	−6.1%		
	$\mathcal{O}(\alpha^5\alpha_s^2)$	−0.00017(19)	0.0%		
	$\mathcal{O}(\alpha^4\alpha_s^3)$	−0.0033(7)	−0.2%		
	sum	−0.268(1)	−18.1%		
LO+NLO	sum	1.215(1)		−4.0%	1.5%



- sizeable NLO corrections
- VBS/DPA within few %
- $\mathcal{O}(\alpha^7)$ dominate tails
  $\rightsquigarrow$ Sudakov logarithms

Pushing the limits: multileg NLO calculations

state-of-the-art: $pp \to e^+\nu_e\mu^+\nu_\mu jj$ at full NLO

[Denner, Pellen, Schönherr, S. to appear]

- consider **inclusive triple-W phase space**, in particular

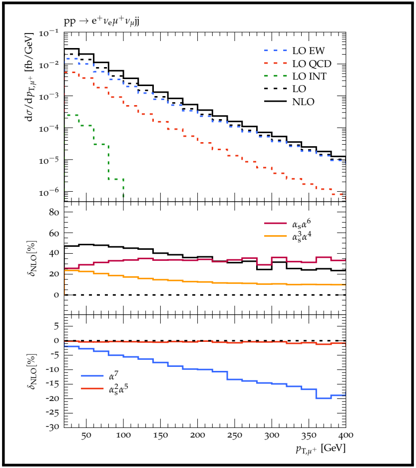
$$M_{j_1 j_2} < 160\,\text{GeV}\,,\ |y_{j_1} - y_{j_2}| < 1.5$$

[inspired by ATLAS 2201.13045]

orders	$\mathcal{O}(\alpha^6)$	$\mathcal{O}(\alpha_s\alpha^5)$	$\mathcal{O}(\alpha_s^2\alpha^4)$	sum
σ_{LO}[fb]	0.78549(9)	0.00732(1)	0.25925(3)	1.05206(9)
$\sigma/\sigma_{\text{LO}}^{\text{sum}}$[%]	74.7	0.7	24.6	100

orders	$\mathcal{O}(\alpha^7)$	$\mathcal{O}(\alpha_s\alpha^6)$	$\mathcal{O}(\alpha_s^2\alpha^5)$	$\mathcal{O}(\alpha_s^3\alpha^4)$	sum
$\delta\sigma$[fb]	$-0.035(1)$	0.305(1)	$-0.0032(3)$	0.2260(3)	0.493(2)
$\delta\sigma/\sigma_{\text{LO}}^{\text{sum}}$[%]	-3.4	29.0	-0.30	21.5	46.9

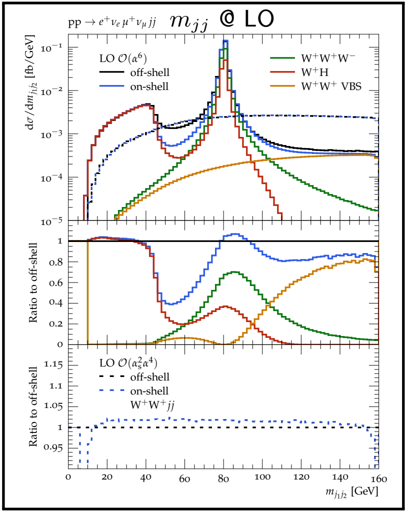
- many $\mathcal{O}(\alpha^6)$ contributions WWW, WH, WZ, VBS
- $\delta_{\text{NLO}} = +47\%$, largest $\mathcal{O}(\alpha_s\alpha^6)$ & $\mathcal{O}(\alpha_s^3\alpha^4)$
- $\mathcal{O}(\alpha^7)$ sizeable in tails $\rightsquigarrow$ Sudakov logarithms

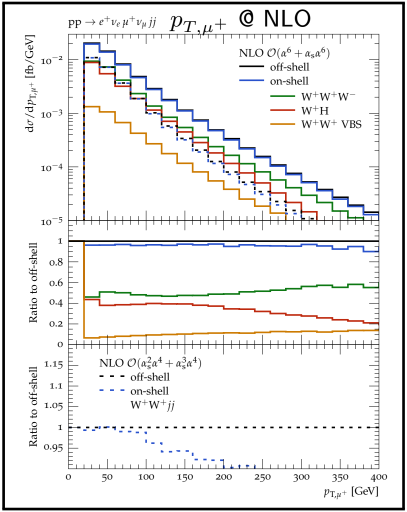


state-of-the-art: $pp \to e^+\nu_e\mu^+\nu_\mu jj$ at full NLO

[Denner, Pellen, Schönherr, S. to appear]

- full off-shell calc vs. incoherent sum of on-shell channels

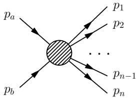




universal high-energy enhancements

- consider EW one-loop amplitudes in high-energy limit, where

$$s_{ij} \equiv (p_i + p_j)^2 \sim s \gg M_W^2 \quad \forall\, i,j$$



- amplitude factorization, dominance of scale-ratio logarithms

$$\mathcal{M}_1 \quad \propto \quad \mathcal{M}_0 \times \left(\delta^{\mathsf{DL}} + \delta^{\mathsf{SL}}\right)$$

$$\delta^{\mathsf{DL}} \sim \frac{\alpha}{4\pi} \log^2\left(\frac{|s_{ij}|}{M_W^2}\right) \qquad \delta^{\mathsf{SL}} \sim \frac{\alpha}{4\pi} \log\left(\frac{|s_{ij}|}{M_W^2}\right)$$

- algorithm to construct NLL EW corrections [Denner, Pozzorini '01]
- recent revisitations, refinements and new implementations

  Sherpa, MG5_aMC & OpenLoops

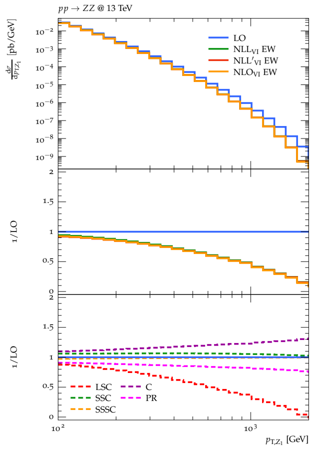
  [Bothmann, Napoletano '20, Bothmann et al. '22] [Pagani, Zaro '22, Pagani et al. '23] [Lindert, Mai '23]

Taming the tails: EW Sudakov logarithms

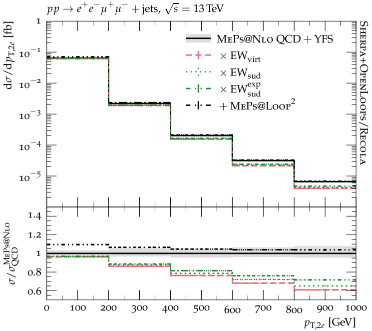
- extensive validation for OpenLoops [Lindert, Mai 2312.07927]
- comparison to $\mathrm{NLO_{VI}}$ EW approximation [Kallweit et al. '15]

⇝ used in Sherpa MEPS@NLO approach [Bothmann et al. JHEP 06 (2022) 131]

leading boson p_T in ZZ (OpenLoops)



MEPS@NLO $ZZ(\to 2e2\mu) + 0, 1j$ (Sherpa)



⇝ MG5_aMC Timea Vitos (Thu)

- NLL resummation in $\mathrm{SCET_{EW}}$

[Denner, Rode 2402.10503]

predicting vector-boson polarization fractions f_{pol}

- consider decay of on-shell massive gauge boson ($m_{q/l} = 0$)
  $\rightsquigarrow$ use pole approximation, i.e. on-shell projections, or NWA

$$\mathcal{M}^{\text{tot}} \approx \sum_{\lambda=L,\pm} \mathcal{M}_\lambda^{\text{fac}} = \frac{i}{p^2 - M_V^2 + i\Gamma_V M_V} \sum_{\lambda=L,\pm} \mathcal{M}_\lambda^{\text{prod}}(\tilde{p})\mathcal{M}_\lambda^{\text{dec}}(\tilde{p})$$

- consider inclusive & fiducial phase spaces
  $\rightsquigarrow$ residual interference contribution when fiducial cuts

$$|\mathcal{M}_{\text{res}}^{\text{tot}}|^2 = \sum_{\lambda=L,\pm} |\mathcal{M}_\lambda^{\text{fac}}|^2 + \sum_{\lambda\neq\lambda'} \mathcal{M}_\lambda^{\text{fac}}\mathcal{M}_{\lambda'}^{*\text{fac}}$$

- seek for differential distributions with $\lambda = L$ enhancements
  $\rightsquigarrow$ for use in experimental template fits
  $\rightsquigarrow$ note, f_{pol} frame dependent, e.g. lab or diboson rest frame

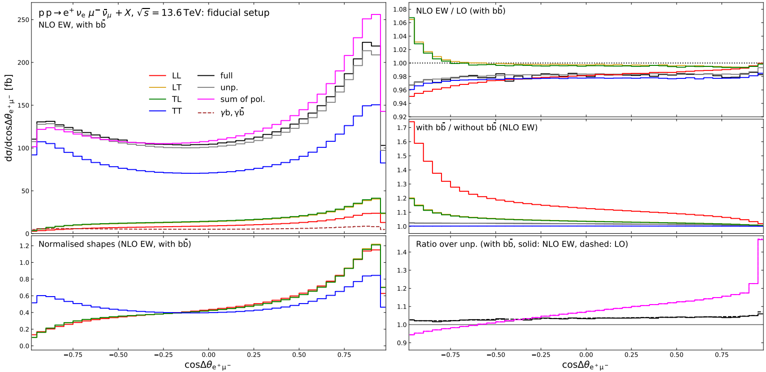
$\rightsquigarrow$ more on polarizations in Rene Poncelet's talk (Thu)

Probing EWSB: vector-boson polarizations

NLO EW for polarized $pp \to W^+(\to e^+\nu_e)W^-(\to \mu^-\bar{\nu}_\mu)$

[Denner et al. PLB 850 (2024) 138539] [Dao, Le EPJC 84 (2024) 3]

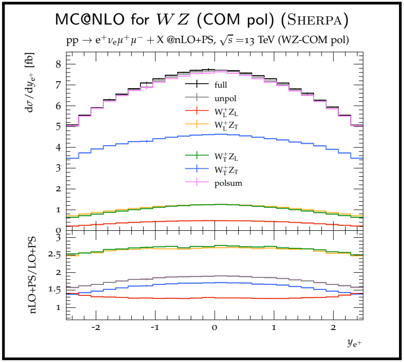
- full calc & DPA on-shell projection (valid for $\sqrt{\hat{s}} > 2M_W$)
- polarization states at amplitude level, fiducial cuts
  $\rightsquigarrow$ non-vanishing interference contributions
- allow for $\gamma\gamma$, $b\bar{b}$ & γb (full calc only) initial states
  $\rightsquigarrow$ contributing differently for LL, TT, LT/TL

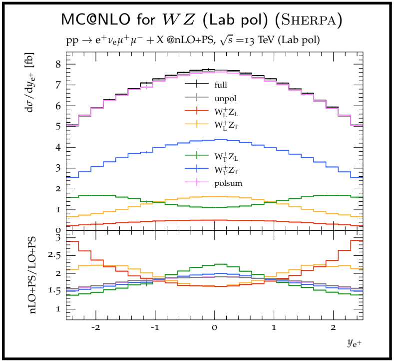


particle-level predictions for polarized bosons

[Hoppe, Schönherr, Siegert JHEP 04 (2024), 001] [Pellicciolі, Zanderighi EPJC 84 (2024) 1]

- implementations in SHERPA (NWA) & POWHEG (DPA)
- restrict to QCD corrections at (N)LO and QCD parton shower
- SHERPA utilizes its spin-correlated decay model [Höche et al. '15]
  - ⇝ event weights for different polarizations/frames on-the-fly
  - ⇝ (currently) assume virtual QCD amplitude as unpolarized





acounting for (dominant) NLO EW corrections

- full NLO SM calculations for $2 \to 6/7$ processes
  - $\rightsquigarrow$ numerous contributing (non-)resonant channels
  - $\rightsquigarrow$ corrections strongly dependent on phase-space selections
  - $\rightsquigarrow$ validity tests for approximation schemes
- automation of NLL EW Sudakov corrections in generators
  - $\rightsquigarrow$ SHERPA, MG5_aMC, OPENLOOPS
- predictions for polarised resonant vector bosons
  - $\rightsquigarrow$ NLO QCD EW corrections for diboson channels
  - $\rightsquigarrow$ NLO QCD+PS in POWHEG and SHERPA