The Electroweak Standard Model

facilitating precision physics at LHC and beyond

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Bad Honnef

Lecture 4

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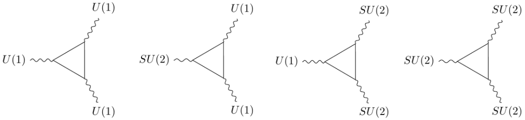
MCnet

The Electroweak Standard Model at the quantum level

- Standard Model is renormalizable QFT, free of gauge anomalies



- NLO EW corrections to LHC scattering processes

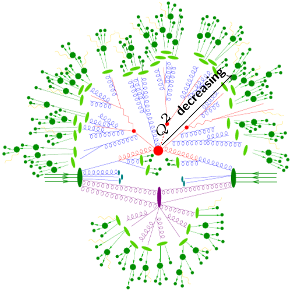
$$\sigma_{\text{tot}}^{\text{NLO}} = \sigma^{\text{Born}} \left(\underbrace{1}_{\text{LO}} + \underbrace{C_1 \frac{\alpha}{\pi}}_{\text{NLO EW}} + \underbrace{\ldots}_{\text{higher orders}} \right)$$

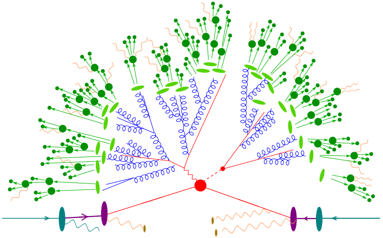
the road ahead

- the cutting edge of doing NLO QCD & EW calculations
- inclusion in full particle-level MC simulations
- longitudinal gauge-boson production, from theory to experiment

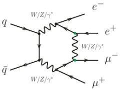
Predicting the Standard Model: Monte Carlo generators

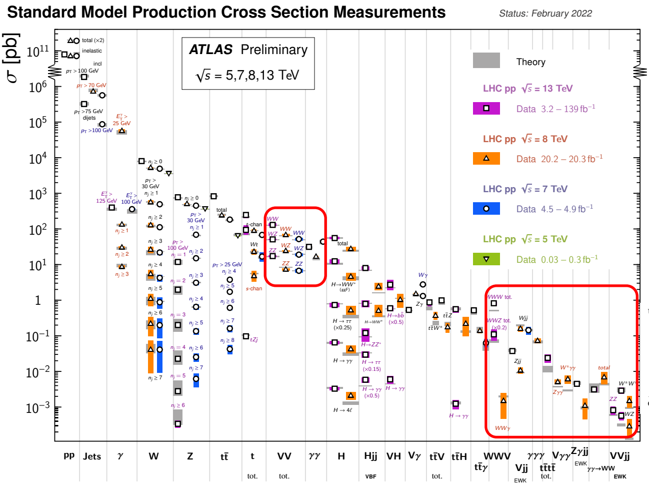
- stochastic simulation of exclusive particle level events
  - ⇝ factorized approach to model event evolution (modularity/automation)
  - ⇝ hard process, QCD/QED radiation, underlying event, hadronization
- vital for realistic phenomenological and experimental analyses
  - ⇝ facilitate experiment planning, physics feasibility studies
- address breadth & depth of community needs & challenges
  - ⇝ ongoing experiments (pp/ee/HI) & future ee/pp/ep colliders
  - ⇝ from per-mil level EW physics to QCD at the 10 TeV scale

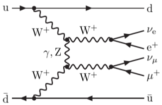




Predicting the Standard Model: multi-boson production

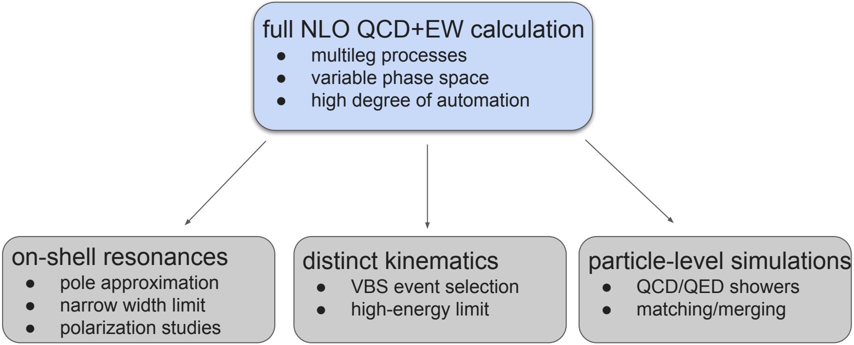






- rare & subtle electroweak signal processes probing EWSB
- triple-, quartic gauge-boson couplings, Higgs production & decay
- longitudinal polarisation modes of massive gauge bosons

Predicting the Standard Model: including EW corrections

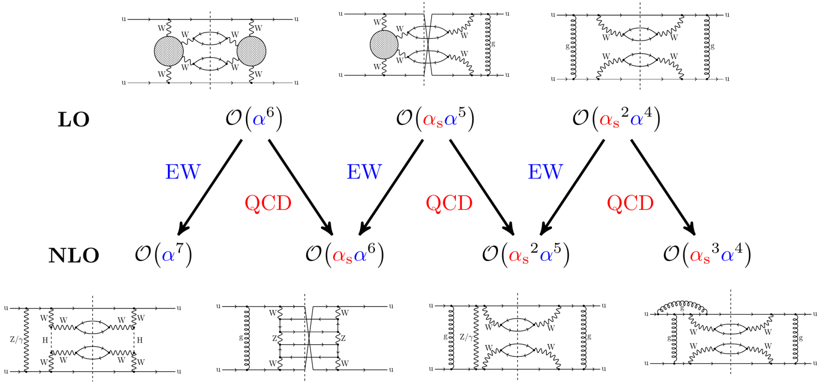


- EW one-loop and QED real emission amplitudes needed, e.g.
  RECOLA [Denner *et al.*], OPENLOOPS [Pozzorini *et al.*]
- QED infrared subtraction terms (dipole/FKS)
  $\rightsquigarrow$ real weak-boson radiation excluded
- frameworks to accomplish full calculations, e.g.
  MG5_aMC [Frederix *et al.*],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

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]



Pushing the limits: multileg NLO calculations

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

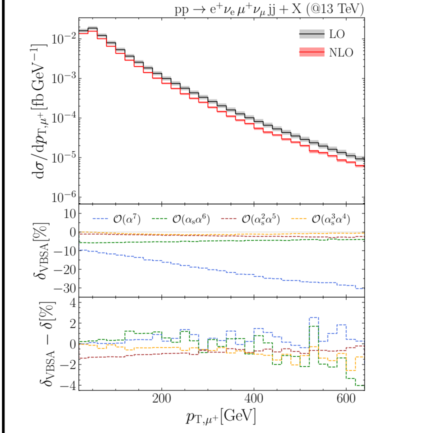
[Dittmaier et al. JHEP 11 (2023) 22] [Biedermann et al. JHEP 10 (2017) 124] [Denner et al. JHEP 08 (2024) 043]

- 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. Vector Boson Scattering (VBS) Approximation

	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
  $\rightsquigarrow$ EW Sudakov logarithms

Pushing the limits: multileg NLO calculations

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

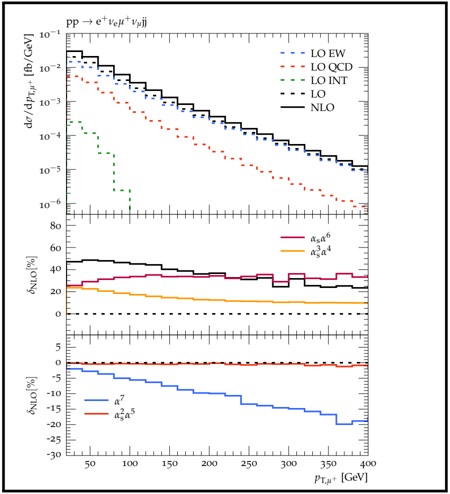
[Denner et al. JHEP 08 (2024) 043]

- 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



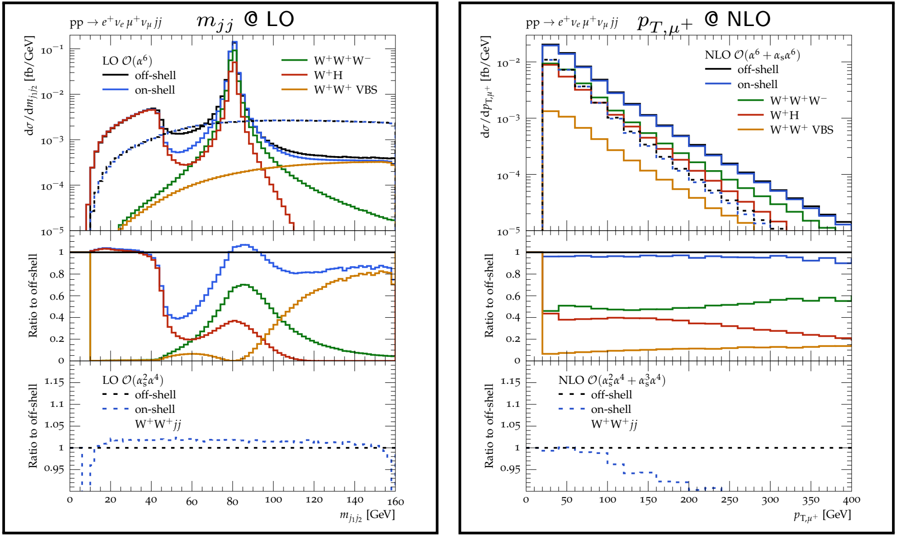
- many $\mathcal{O}(\alpha^6)$ contributions
  WWW, WH, WZ, VBS
- $\delta_{\text{NLO}} = +47\%$, largest
  $\mathcal{O}(\alpha_s\alpha^6)$ & $\mathcal{O}(\alpha_s^3\alpha^4)$
- $\mathcal{O}(\alpha^7)$ sizeable in tails
  $\rightsquigarrow$ EW Sudakov logarithms

Pushing the limits: multileg NLO calculations

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

[Denner et al. JHEP 08 (2024) 043]

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



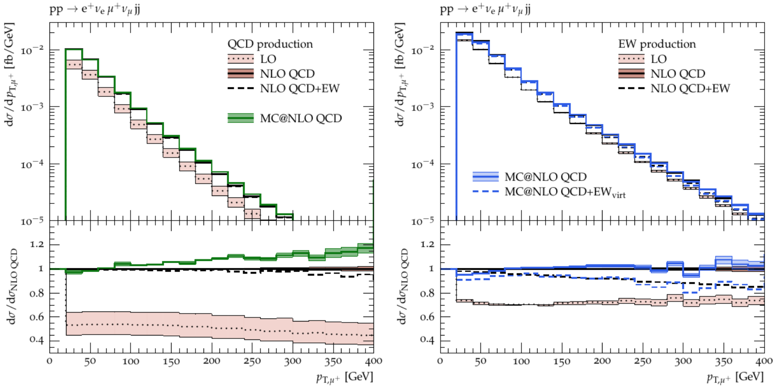
Pushing the limits: multileg NLO calculations

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

[Denner et al. JHEP 08 (2024) 043]

- inclusion of QCD parton showers, accounting for multiple QCD emissions
- separate into QCD $\mathcal{O}(\alpha_s^2\alpha^4)$ & EW $\mathcal{O}(\alpha^6)$ production modes

  $\rightsquigarrow$ NLO QCD via MC@NLO method, NLO EW approx by virtual corrections

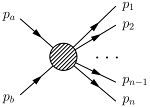


- consistent inclusion/combination of dominant QCD & EW corrections

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]
- approximation to full NLO EW calculation, possibly resummation of logs
- recent revisitations, refinements and new implementations

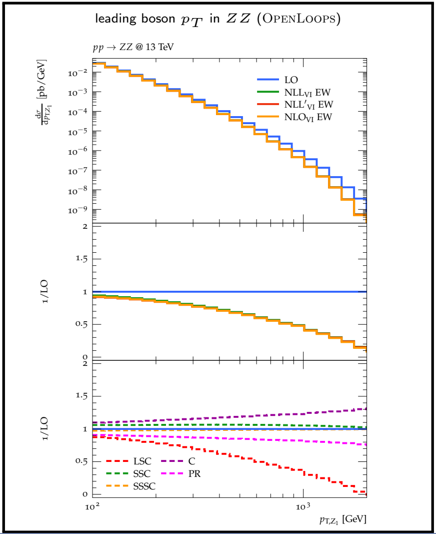
  SHERPA, MG5_aMC & OPENLOOPS

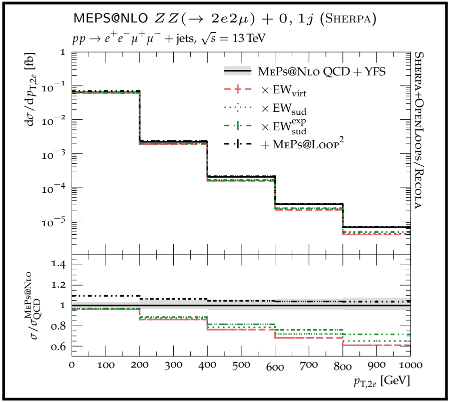
  [Bothmann, Napoletano '20, Bothmann et al. '22] [Pagani, Zaro '22, Pagani et al. '23] [Lindert, Mai '23]
- rather straight-forward combination with QCD parton showers

Taming the tails: EW Sudakov logarithms

- extensive validation for OpenLoops [Lindert, Mai EPJC 84 (2024) 10]
- comparison to NLO_{VI} EW (virtual only) approximation [Kallweit et al. '15]

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



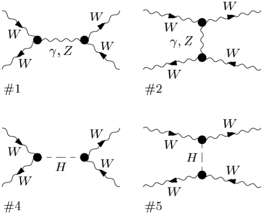


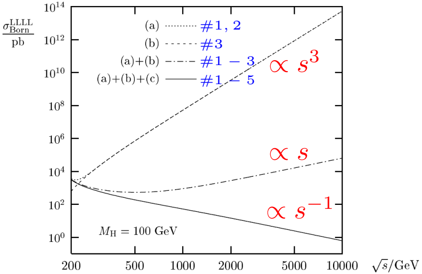
- NLL resummation in SCET_{EW}

[Denner, Rode EPJC 84 (2024) 5]

the case for polarized weak bosons

- SM $W^{\pm}$ and Z^{0} receive mass through Higgs mechanism
  $\rightsquigarrow$ absorb Goldstone bosons $G^{\pm}$, G^{0}, fields $W^{\pm}_{\mu}$, Z_{μ} have 3 polarizations
  $\rightsquigarrow$ transverse (T) $(\lambda = \pm)$ and longitudinal (L) $(\lambda = 0)$
- longitudinal states $W^{\pm}_{L}$, Z^{0}_{L} important probe of SM gauge & Higgs sector
- study polarized vector-boson production and scattering (VBS), e.g $VV(jj)$





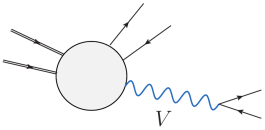
[Denner, Hahn Nucl Phys B 525 (1998) 27]

- $W_L W_L \to W_L W_L$ unitarized by intriguing gauge/Higgs cancellations

Probing EWSB: vector-boson polarizations

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

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

$$\frac{d\sigma_{\text{res}}^{\text{tot}}}{dO} = f_L \frac{d\sigma_L}{dO} + f_T \frac{d\sigma_T}{dO} + f_{\text{int}} \frac{d\sigma_{\text{int}}}{dO}$$

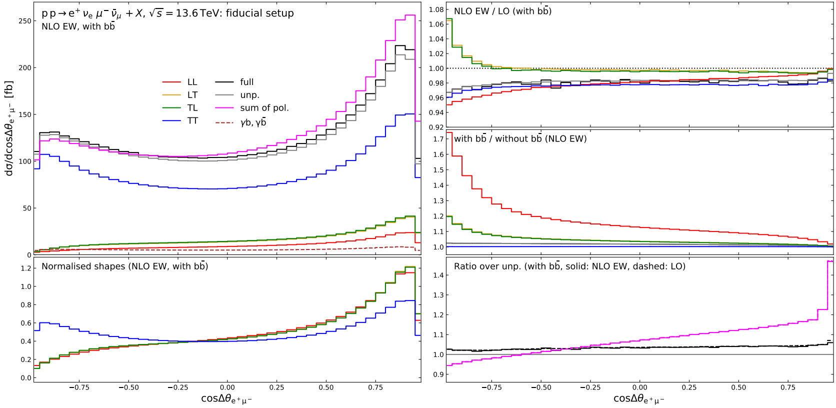
- seek for observables O with $\lambda = L$ enhancements
  $\rightsquigarrow$ separate $d\sigma_{L,T,\text{int}}$ predictions for use in experimental template fits
  $\rightsquigarrow$ note, f_{pol} frame dependent, e.g. lab or diboson rest frame

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]

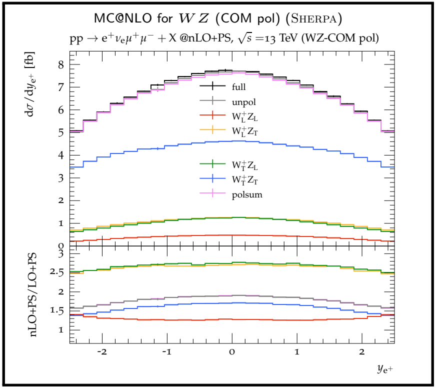
- full calc & DPA on-shell projection (valid for $\sqrt{\hat{s}} > 2M_W$)
- polarization states at amplitude level, fiducial cuts
  $\rightsquigarrow$ non-vanishing interference contributions
- allow for $\gamma\gamma$, $b\bar{b}$ & γb (full calc only) initial states
  $\rightsquigarrow$ contributing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

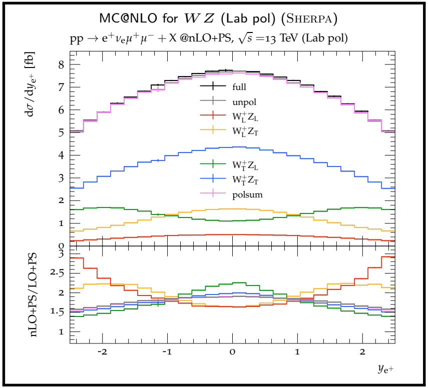


particle-level predictions for polarized bosons

[Hoppe, Schönherr, Siegert JHEP 04 (2024), 001] [Pellicciolì, 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





A real-life application: first evidence for $W_L^\pm W^\pm jj$ from ATLAS

EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

ATLAS EXPERIMENT

CERN

Submitted to: Phys. Rev. Lett.

CERN-EP-2025-048
March 17, 2025

Evidence for longitudinally polarized *W* bosons in the electroweak production of same-sign *W* boson pairs in association with two jets in pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector

[2503.11317]

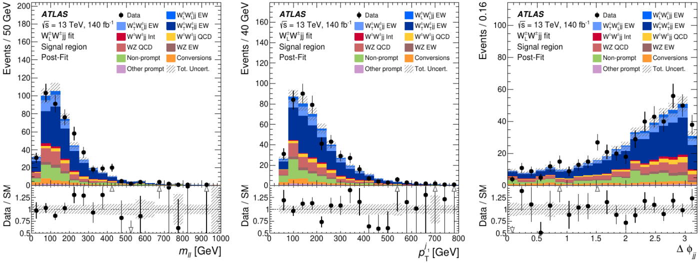
The ATLAS Collaboration

This Letter reports the first evidence of production of same-sign *W* boson pairs where at least one of the *W* bosons is longitudinally polarized and the most stringent constraint to date for the production of two longitudinally polarized same-sign *W* bosons. The data set used corresponds to an integrated luminosity of 140 fb^{-1} of proton–proton collisions at a center-of-mass energy of 13 TeV, collected with the ATLAS detector during Run 2 of the Large Hadron Collider. The study is performed in final states including two same-sign leptons (electrons or muons), missing transverse momentum, and at least two jets with a large invariant mass and a large rapidity difference. Two independent fits are performed targeting the production of same-sign *W* bosons with at least one, or two longitudinally polarized *W* bosons. The observed (expected) significance of the production with at least one longitudinally polarized *W* boson is 3.3 (4.0) standard deviations. An observed (expected) 95% confidence level upper limit of 0.45 (0.70) fb is reported on the fiducial production cross section of two longitudinally polarized same-sign *W* bosons.

- DNN to separate $W_L W_L jj$, $W_L W_T jj$, $W_T W_T jj$ contributions
- based on set of polarization sensitive observables (pols in WW COM)
- using particle level predictions for the signals from Sherpa
- account for recently evaluated NLO EW corrections [Denner et al. JHEP 11 (2024) 115]
  $\rightsquigarrow$ reweighting in m_{jj} individually for polarization subsamples
- see also corresponding CMS analysis: $W_L W jj$ at 2.3σ [Phys Lett B 812 (2021) 136018]

Probing EWSB: vector-boson polarizations

A real-life application: first evidence for $W_L^\pm W^\pm jj$ from ATLAS [2503.11317]

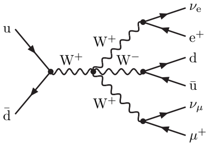


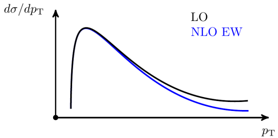
Process	Predicted $\sigma\mathcal{B}$ (fb)	Measured $\sigma\mathcal{B}$ (fb)	Uncertainty breakdown (fb)
$W_L^\pm W_L^\pm jj$	0.29 ± 0.07	0.01 ± 0.21 (tot.)	±0.20 (stat.) $\pm$ 0.02 (mod. syst.) $\pm$ 0.05 (exp. syst.)
$W_T^\pm W^\pm jj$	2.56 ± 0.64	3.39 ± 0.35 (tot.)	±0.30 (stat.) $\pm$ 0.08 (mod. syst.) $\pm$ 0.16 (exp. syst.)
$W_L^\pm W^\pm jj$	1.18 ± 0.29	0.88 ± 0.30 (tot.)	±0.28 (stat.) $\pm$ 0.05 (mod. syst.) $\pm$ 0.08 (exp. syst.)
$W_T^\pm W_T^\pm jj$	1.67 ± 0.40	2.49 ± 0.32 (tot.)	±0.30 (stat.) $\pm$ 0.05 (mod. syst.) $\pm$ 0.12 (exp. syst.)

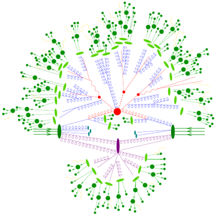
- stringent test of the SM EWSB mechanism
- theory calculations facilitating precision physics
  $\rightsquigarrow$ close and fruitful theory/experiment collaborations

accounting for (dominant) 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 MC generators
  - $\rightsquigarrow$ SHERPA, MG5_aMC, OPENLOOPS
- predictions for polarised resonant vector bosons
  - $\rightsquigarrow$ NLO QCD+EW corrections for $VV(jj)$ channels
  - $\rightsquigarrow$ NLO QCD+PS in POWHEG and SHERPA

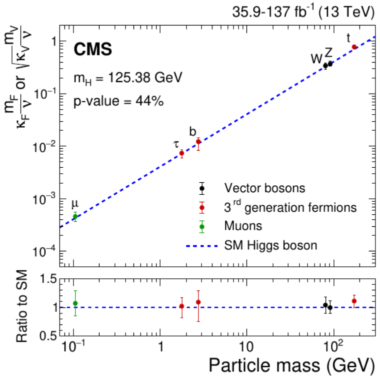




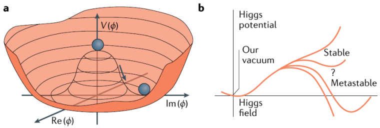


Closing remarks

- We have just entered the SM precision era ...
- Do the light fermions (u, d, s, e) acquire mass through Higgs Yukawas?
  $\rightsquigarrow$ besides electron, dominated by hadronic decays
- Is our vacuum configuration stable?
  $\rightsquigarrow$ determine Higgs self coupling, e.g. from Di-Higgs production
- Can we find any hints for BSM physics, i.e. deviations from SM?



[CMS JHEP 01 (2021) 148]



[Bass et al. Nature Rev Phys 3 (2021) 9]