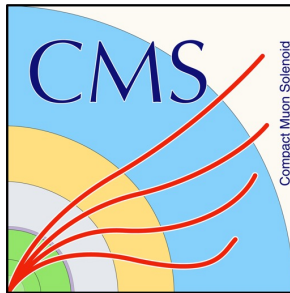


VV and $H \rightarrow VV$ polarization and QE overview at the LHC



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TeV mini-workshop 2026
2026.9.18-20, Beijing

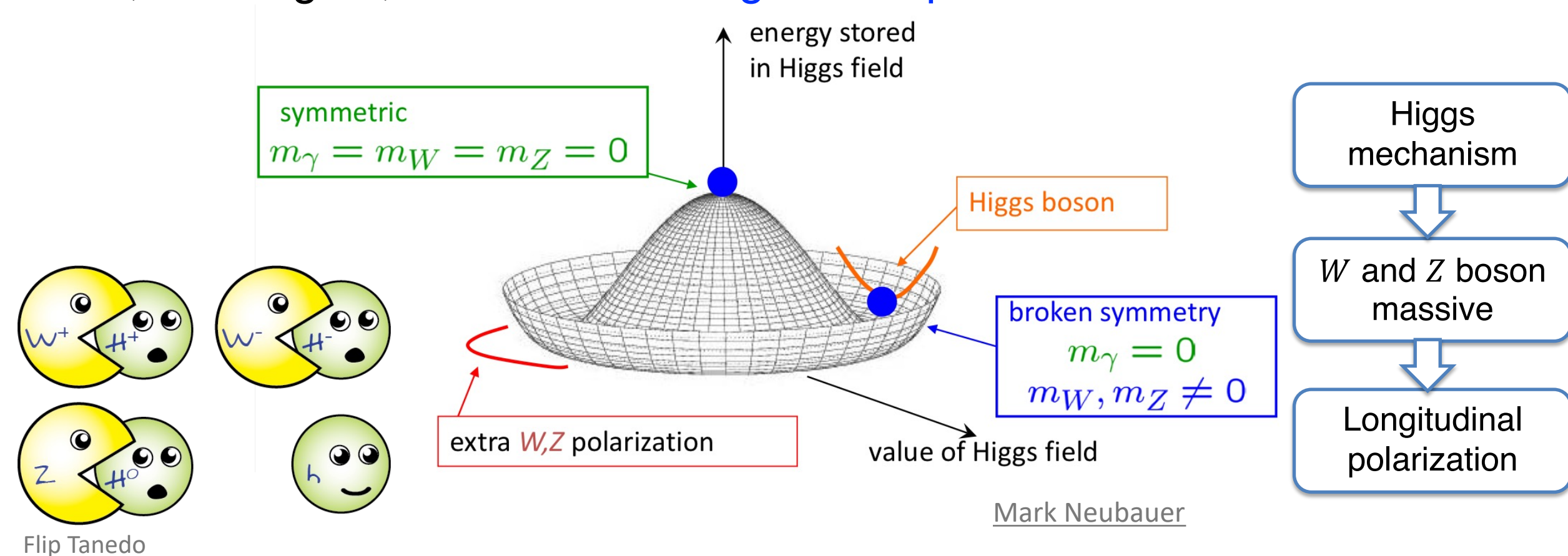


Diboson polarization:

probe the dynamics of EWSB

Weak boson polarization

- The Electroweak Symmetry Breaking mechanism: a cornerstone of Nature
- EWSB is responsible for generating the **masses** of the W and Z bosons and, in doing so, creates their **longitudinal polarization states**

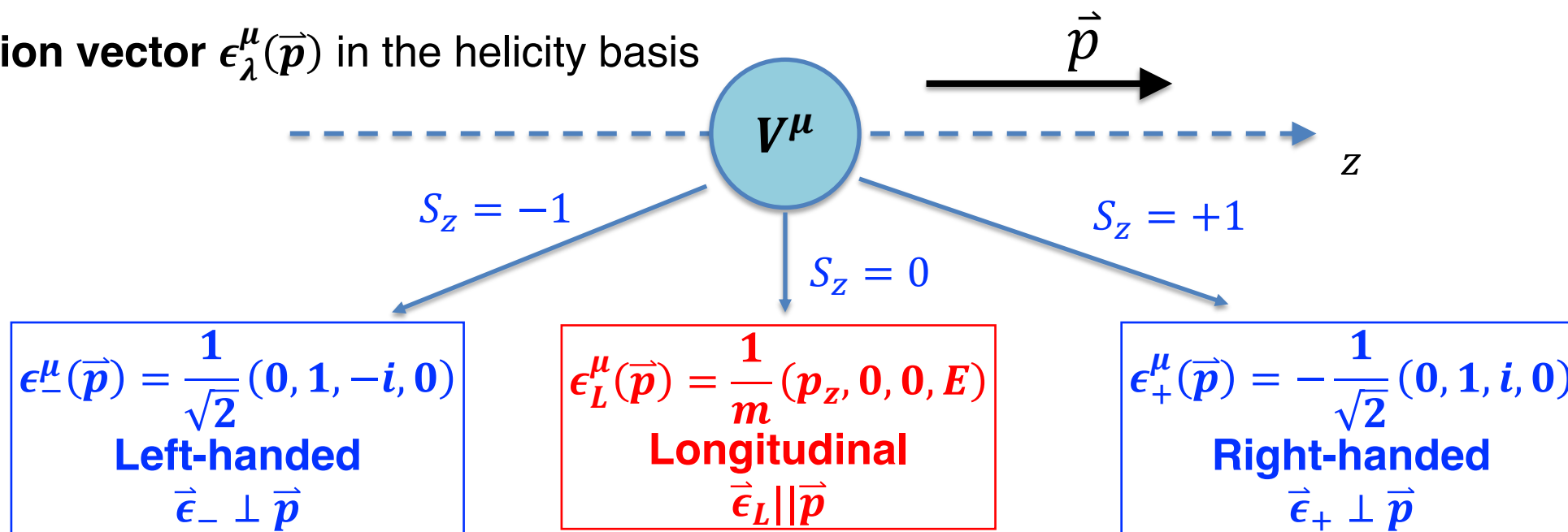


Weak boson polarization

- Helicity of spin-1 particles: $h = \frac{\vec{S} \cdot \vec{p}}{|\vec{p}|} = S_z$ (spin $\vec{S}$, momentum $\vec{p}$)
 - Transversal (“T”): right-handed ($h = +1$), left-handed ($h = -1$)
 - Longitudinal (“L” or “0”): $h = 0$

$$S_z |m\rangle = m |m\rangle, \\ m = +1, 0, -1$$

Polarization vector $\epsilon_\lambda^\mu(\vec{p})$ in the helicity basis



Massless photons forbid the longitudinal mode, only $\epsilon_\pm^\mu$ exist

Longitudinal: additional degree of freedom for massive weak bosons

Why longitudinal?

- The *transverse polarizations* already existed before the EWSB
- The *longitudinal polarization* is the physical remnant of the **Goldstone bosons**
- The LHC continues to push our understanding of the EWSB to ever higher energies
- At high energies, longitudinal vector bosons behave like the corresponding Goldstone bosons (**Goldstone Boson Equivalence Theorem**) → the unbroken EW regime

$$\text{For } E \gg m_W, m_Z \quad \mathcal{M}(\dots W_L^\pm, Z_L, \dots) = \mathcal{M}(\dots \phi^\pm, \phi^0, \dots) + \mathcal{O}\left(\frac{m_W}{E}\right)$$

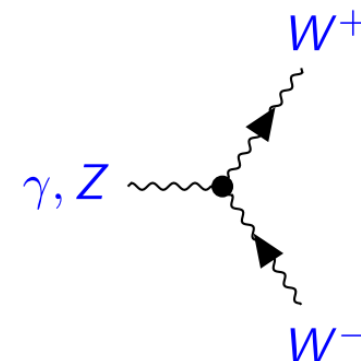
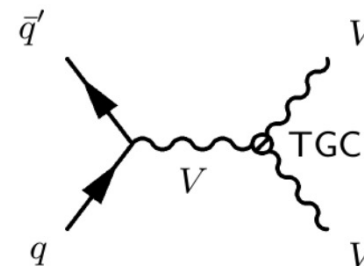
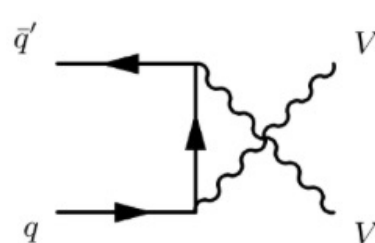
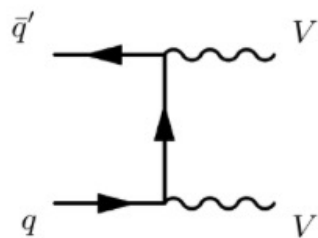
$$\begin{aligned} W_L^\pm &\rightarrow \phi^\pm, \text{ charged Goldstone bosons} \\ Z_L &\rightarrow \phi^0, \text{ neutral Goldstone bosons} \end{aligned}$$

- **Longitudinal vector bosons are the experimental gateway to the EWSB sector**
 - $V_L V_L$ production **reveals how they are created**
 - $V_L V_L \rightarrow V_L V_L$ scattering **reveals how the EWSB sector interacts**

$V_L V_L$ production

- Diboson production: direct test the **gauge structure** after the EWSB

Tree-level diagrams for $q\bar{q} \rightarrow VV$



- In diboson events, the polarizations of both bosons are **quantum correlated**
 - Joint polarization described by the Spin Density Matrix $\rightarrow$ test Quantum Entanglement and Bell non-locality for qutrit systems
- Novel sensitivity to BSM**

	SM	BSM
$q_{L,R} \bar{q}_{L,R} \rightarrow V_L V_L / V_L h$	~ 1	$\sim E^2 / M^2$
$q_{L,R} \bar{q}_{L,R} \rightarrow V_{\pm} V_L / V_{\pm} h$	$\sim m_W / E$	$\sim m_W E / M^2$
$q_{L,R} \bar{q}_{L,R} \rightarrow V_{\pm} V_{\pm}$	$\sim m_W^2 / E^2$	$\sim E^2 / M^2$
$q_{L,R} \bar{q}_{L,R} \rightarrow V_{\pm} V_{\mp}$	~ 1	~ 1

High-energy behavior of amplitudes with different diboson helicity configurations

F. Riva et al, [JHEP02\(2018\)111](#)

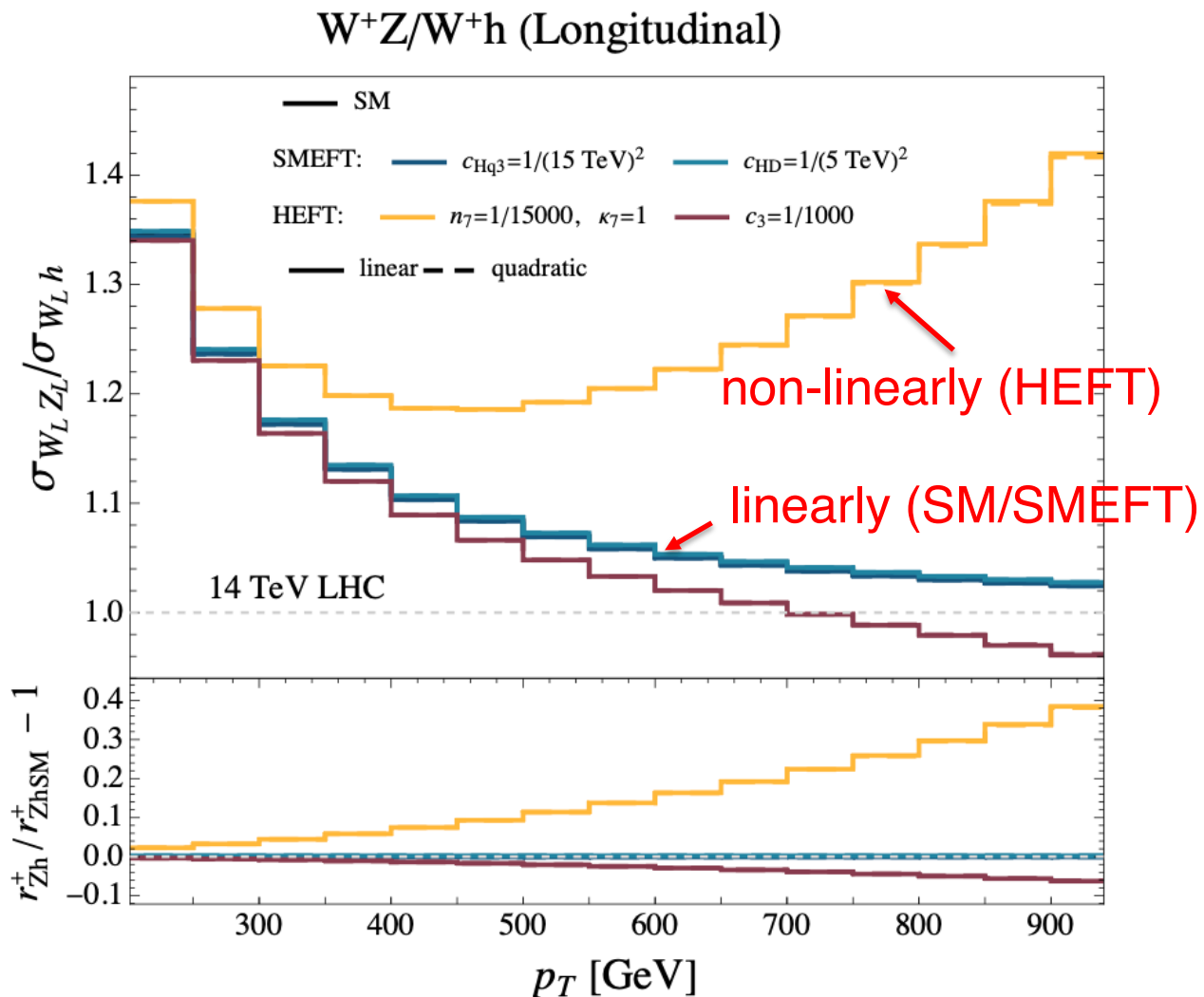
$V_L V_L$ production

- Probe EWSB dynamics

$$r_{Zh}^{\pm} \equiv \frac{d\sigma(pp \rightarrow W_L^{\pm} Z_L)/dp_T^W}{d\sigma(pp \rightarrow W_L^{\pm} h)/dp_T^W}$$

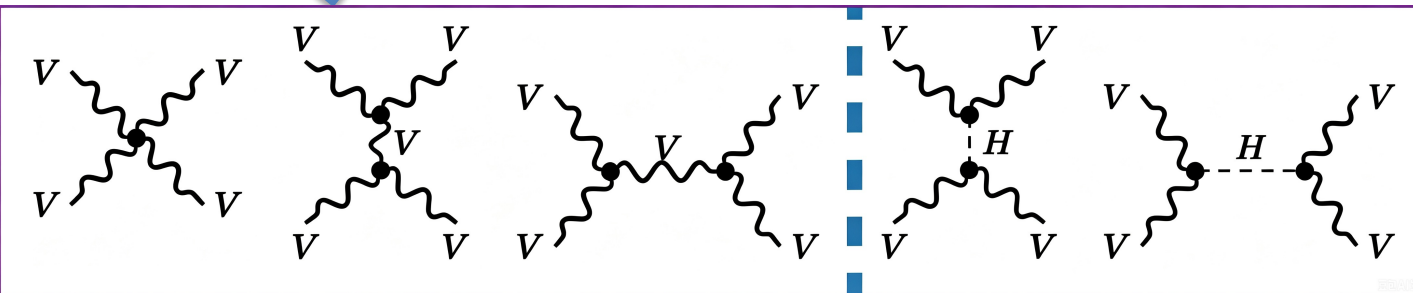
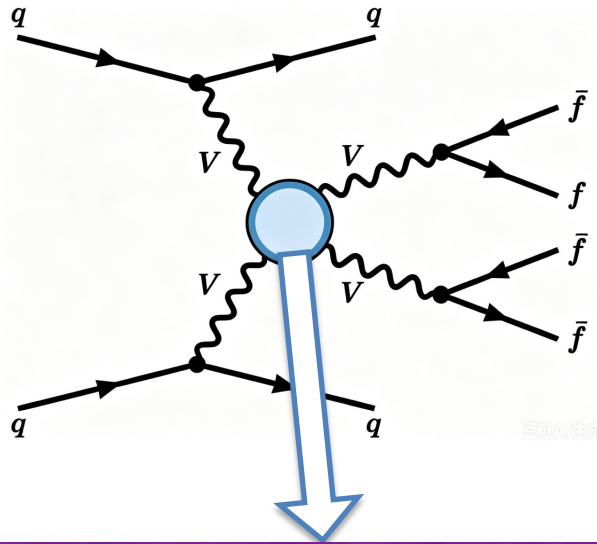
sensitive to whether EW symmetry is realized
linearly (SMEFT) or non-linearly (HEFT)

Z. Liu et al, [arXiv:2605.08433](https://arxiv.org/abs/2605.08433)



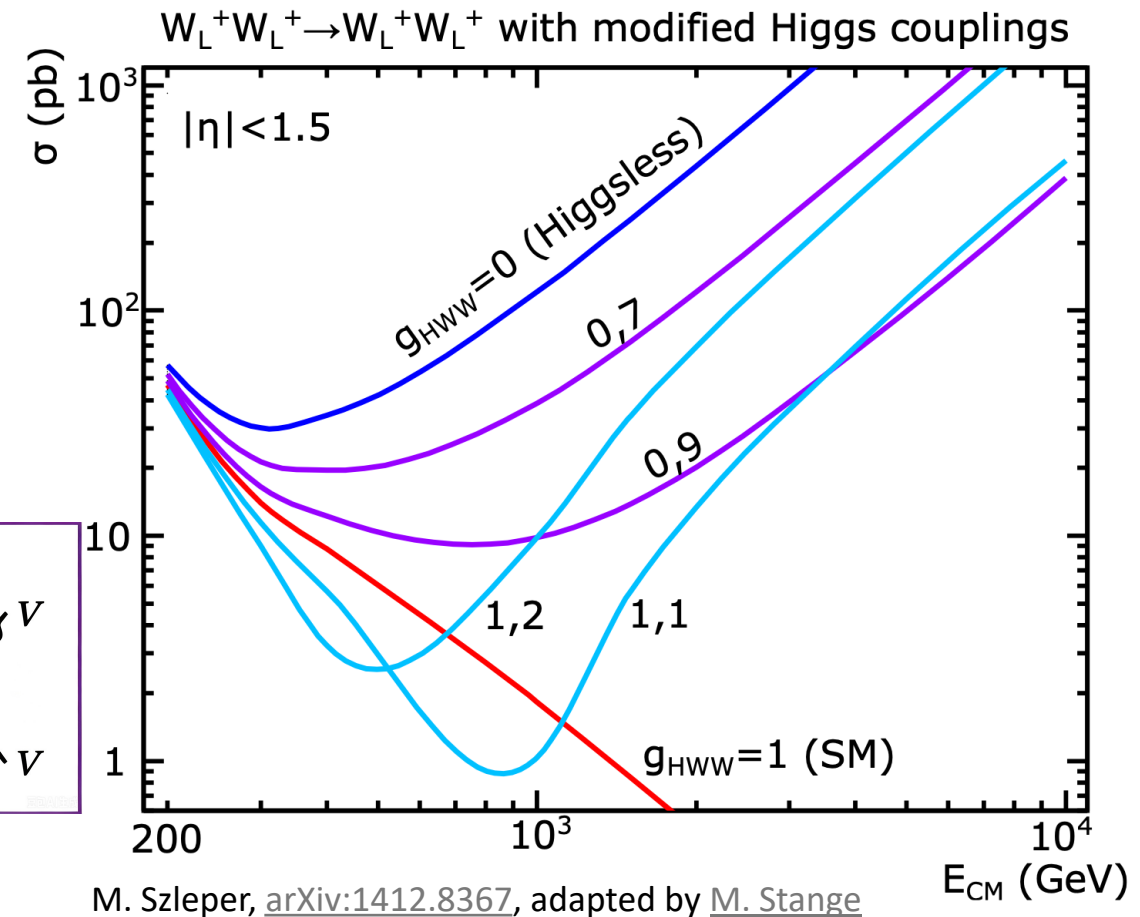
$V_L V_L \rightarrow V_L V_L$ scattering

- Vector boson scattering (VBS) $V_L V_L \rightarrow V_L V_L$: the cleanest probe
 - Strict cancellation required to unitarize the high energy behavior



Gauge structure of the SM

Electroweak symmetry breaking

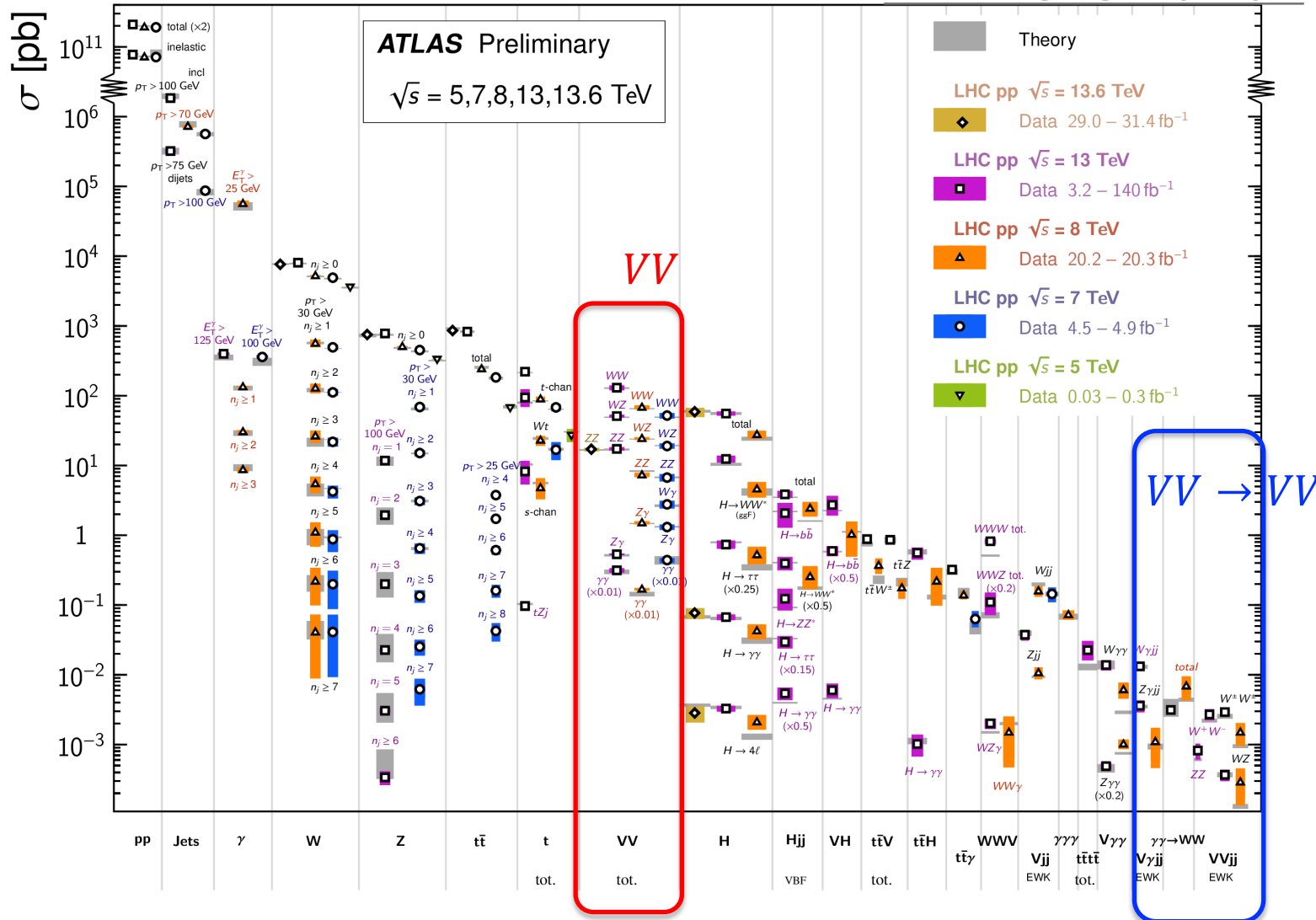


The experimental challenge

Standard Model Production Cross Section Measurements

Status: June 2024

ATL-PHYS-PUB-2024-011



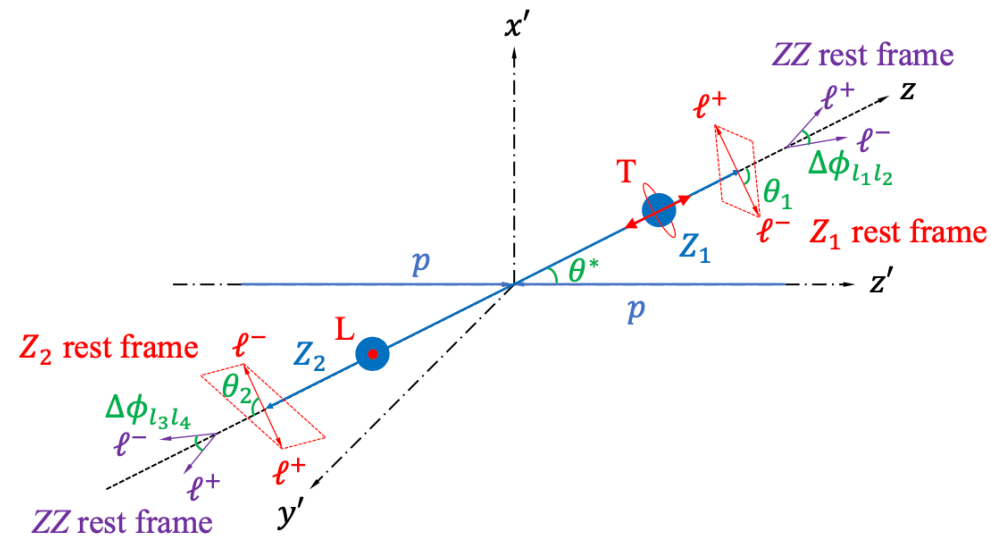
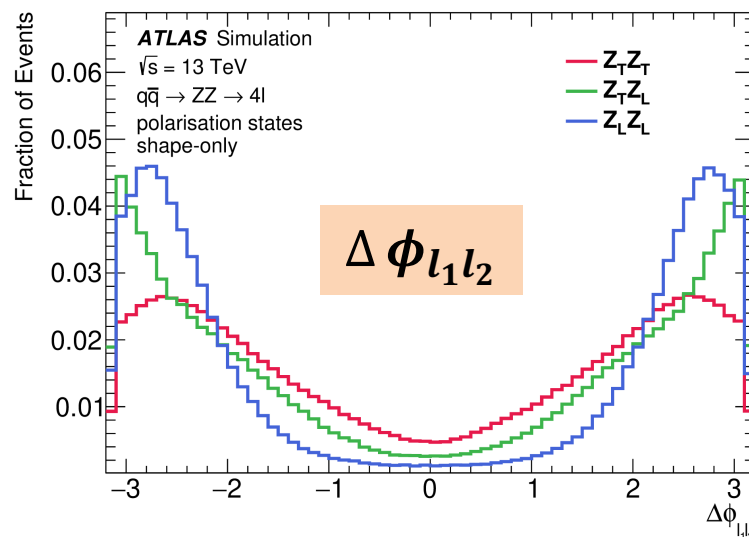
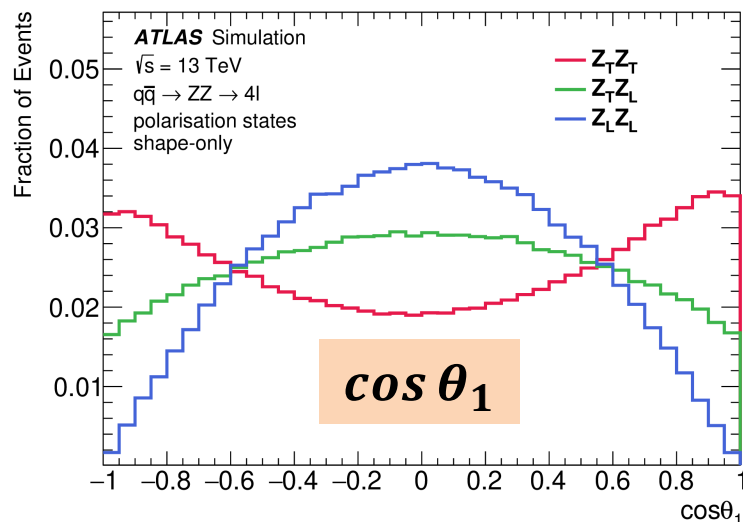
- We have entered the precision era for VV and $VV \rightarrow VV$ production
- But $V_L V_L$ is still very challenging due to its low rate $\rightarrow$ larger datasets needed

Diboson polarization: experimental overview

Process	Features			Experimental status
	Signal rate	S/B	Spin information	
$ZZ \rightarrow 4l$	X	✓	✓✓	ATLAS JHEP12(2023)107 ($Z_L Z_L$ measured with 4.3σ) ATLAS arXiv:2607.12879 ($Z_L Z_L$ observed with 6.5σ)
$WZ \rightarrow lvll$	✓	✓	✓	ATLAS PLB843(2023)137895 ($W_L Z_L$ observed with 7.1σ) ATLAS PRL133(2024)101802 (Radiation Amplitude Zero effect)
$WW \rightarrow lvlv$	✓	X	X	None
$WW \rightarrow lvqq$	✓	X	✓	None

$Z_L Z_L$ observation

- Polarization fraction measurements in $ZZ \rightarrow 4l$ process, using partial Run-3 data (164 fb⁻¹, 2022-24)
 - Data recorded with single-lepton triggers
 - Two Z boson candidates with two same-flavor-opposite-sign e/μ
 - On-shell requirements: $|m_{ll} - m_Z| < 10$ GeV, $m_{4l} > 180$ GeV
 - Statistical combination with the previous Run-2 analysis (140 fb⁻¹, [JHEP12\(2023\)107](#))
- Polarization separation: Boosted Decision Trees to distinguish LL from TT/TL



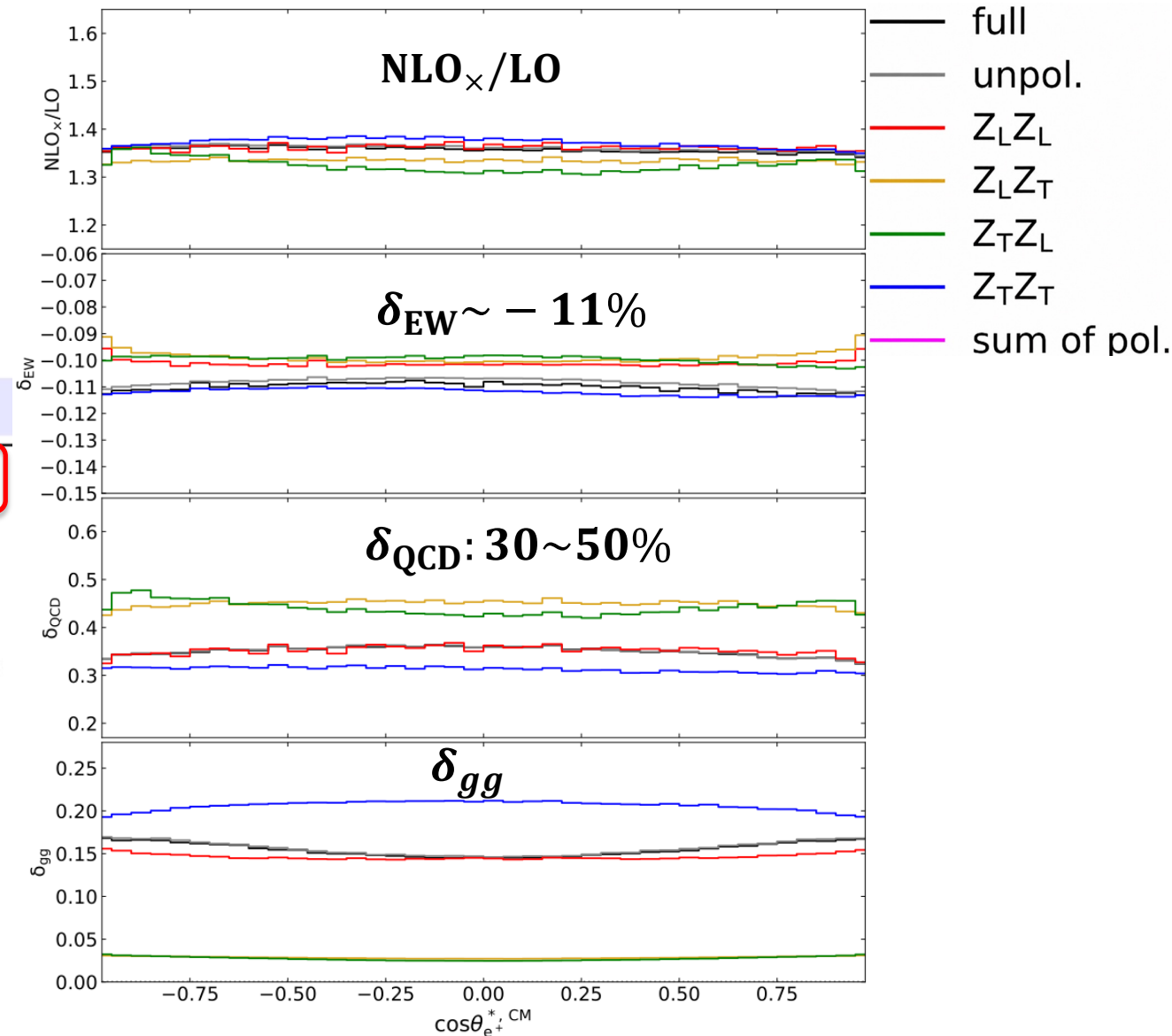
Polarized ZZ predictions

Fixed-order NLO QCD + NLO EW
predictions for $qq \rightarrow ZZ$ and LO for $gg \rightarrow ZZ$

A. Denner, G. Pelliccioli, [JHEP10\(2021\)097](#)

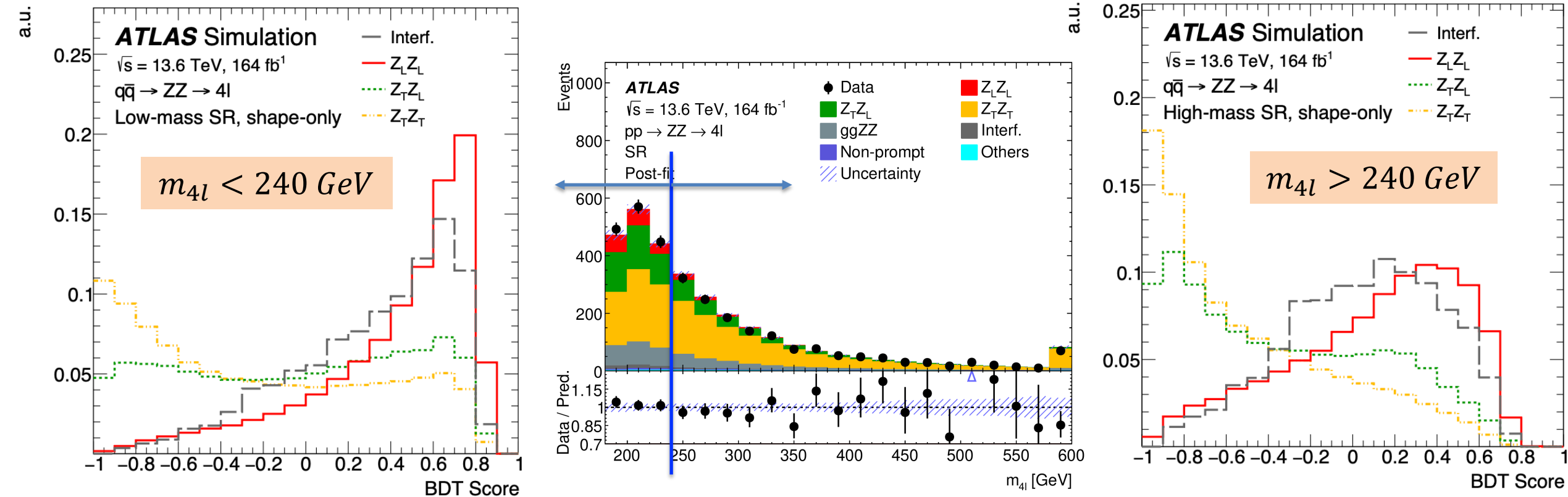
mode	f_{LO}	$f_{\text{NLO EW}}$	$f_{\text{NLO QCD}}$	f_{gg}
$Z_L Z_L$	5.8%	5.9%	5.9%	5.4%
$Z_T Z_L$	23.7%	23.9%	25.3%	4.2%
$Z_T Z_T$	69.3%	69.1%	67.4%	90.4%
interf.	1.1%	1.1%	1.3%	-0.02%

- $Z_L Z_L$ fraction only $\sim 6\%$
- Higher-order corrections significantly dependent on the polarization state



LL separation with BDT

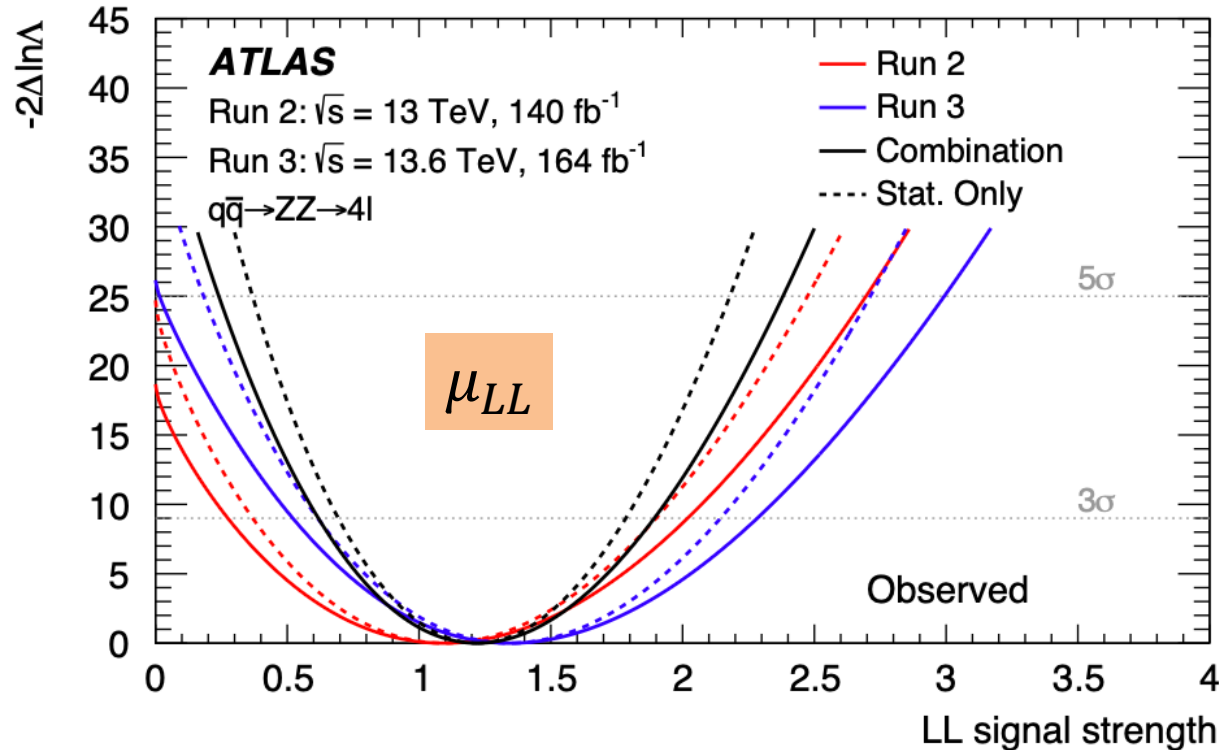
- Distributions of the BDT score in the signal regions



Events are further split into two m_{4l} regions, to explore the mass dependence effect of polarization fractions

Fit results

- Simultaneous fit of (μ_{LL}, μ_{TX})
 - Significance of μ_{LL} : obs, 6.5σ ; exp: 5.6σ

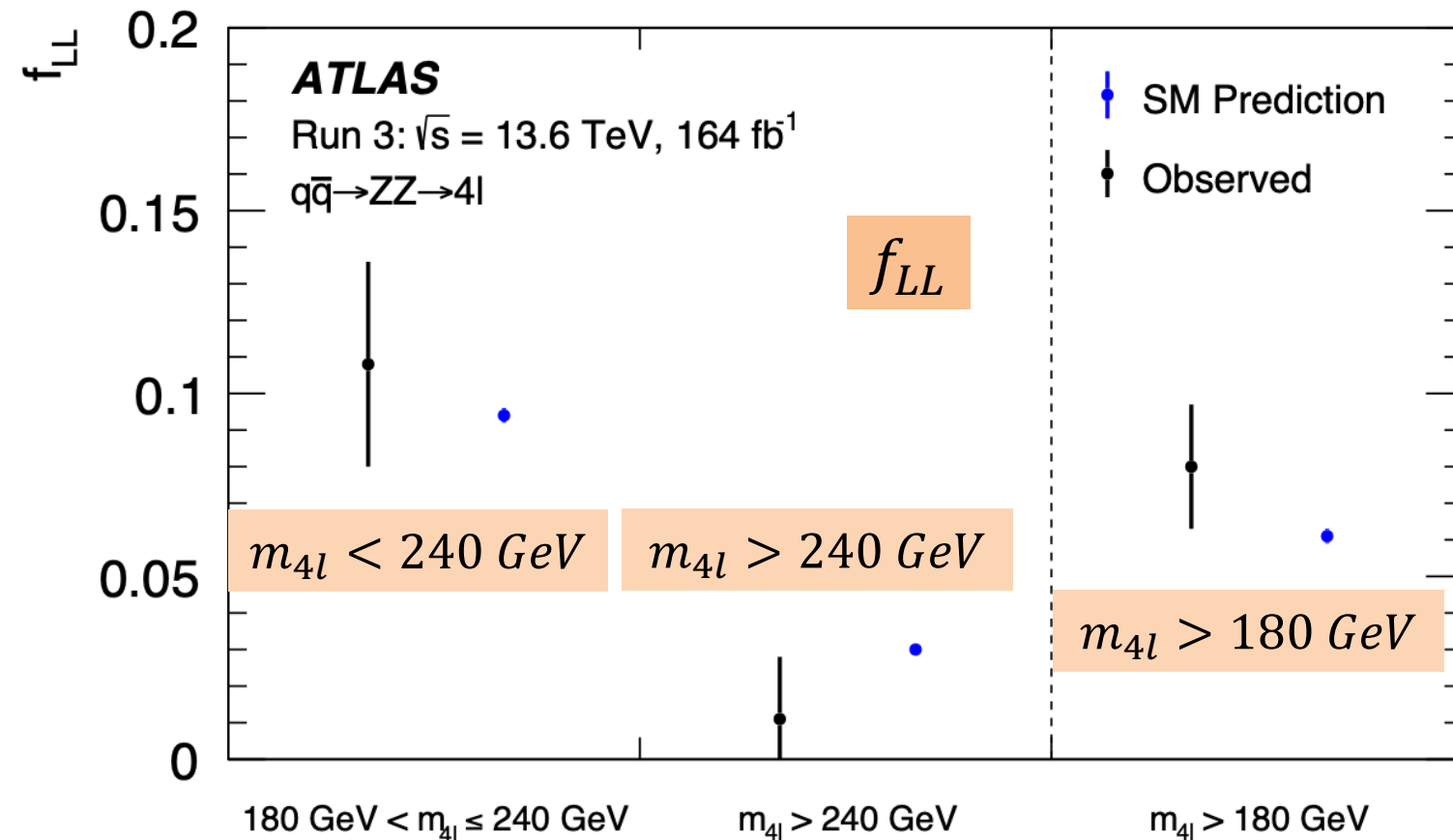


$$\mu_{LL}^{obs} = 1.22 \pm 0.21$$

Contribution	Relative uncertainty [%]
Total	17
Data statistical uncertainty	15
Total systematic uncertainty	8.1
MC statistical uncertainty	1.6
Theoretical systematic uncertainties	
$q\bar{q} \rightarrow ZZ$ interference modeling	0.9
SHERPA 3 shape difference for $q\bar{q} \rightarrow ZZ$	4.4
QCD scale for $q\bar{q} \rightarrow ZZ$	0.5
PDF and α_s for $q\bar{q} \rightarrow ZZ$	1.9
Parton shower for $q\bar{q} \rightarrow ZZ$	1.6
NLO EW corrections for $q\bar{q} \rightarrow ZZ$	2.9
QCD scale for $gg \rightarrow ZZ$	3.4
PDF and α_s for $gg \rightarrow ZZ$	0.2
Experimental systematic uncertainties	
Luminosity	1.3
Muons	0.5
Electrons	3.7
Non-prompt background	0.3
Pileup modeling	0.5
Triboson and $t\bar{t}Z$ normalizations	0.2

$Z_L Z_L$ fraction

- Simultaneous fit of (f_{LL}, μ_{ZZ}) : Run-3 only



	Measured	SM prediction
$f_{LL}^{low-m_{4l}}$	0.108 ± 0.028	0.094 ± 0.002
$f_{LL}^{high-m_{4l}}$	0.011 ± 0.017	0.030 ± 0.001
f_{LL}	0.080 ± 0.017	0.061 ± 0.002

- First attempt to measure the mass dependence of the f_{LL} , to probe the high-energy behavior
- Measured fractions consistent with SM predictions

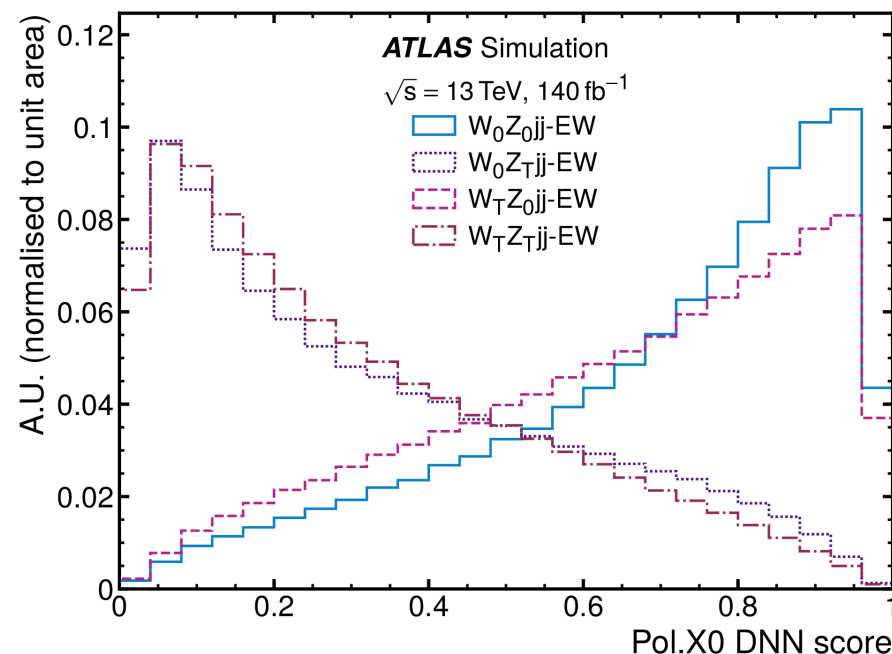
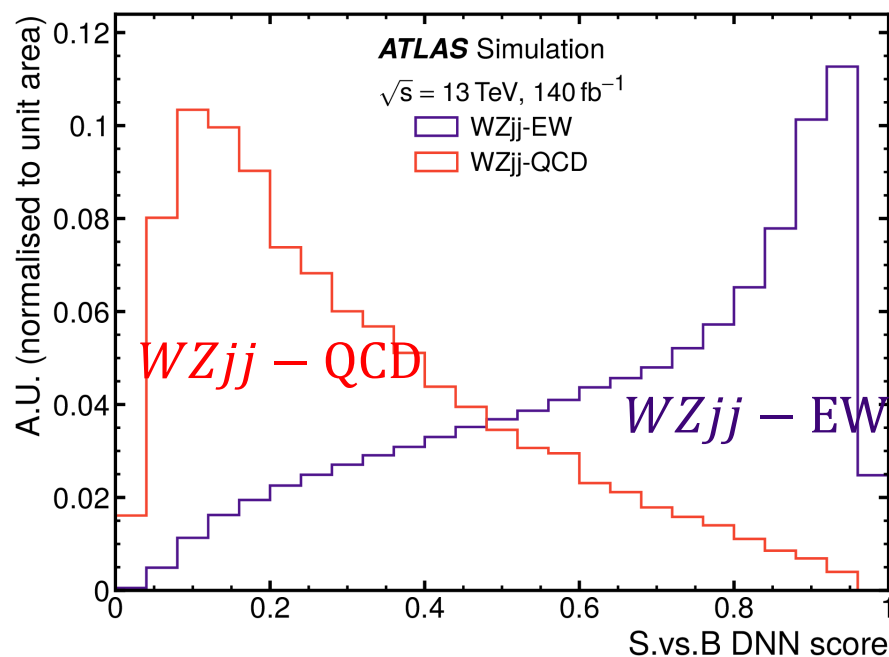
Polarization measurements in VBS

- Polarization measurements in VBS processes are even more challenging
 - Irreducible background from $VVjj$ – QCD

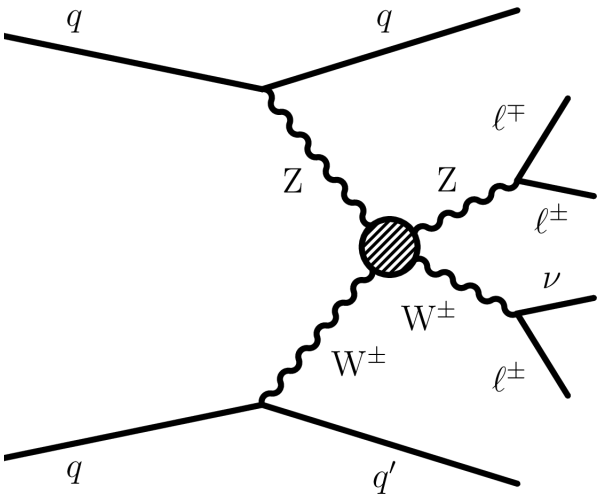
VBS Process	Experimental status	
$W^{\pm}W^{\pm}jj$	CMS PLB812(2020) 136018	$W_L W_X$ measured with 2.3σ
	ATLAS PRL135(2025) 111802	$W_L W_X$ measured with 3.3σ
$WZ(\rightarrow l\nu ll)jj$	ATLAS arXiv:2607.20246	$W_X Z_L jj$ measured with 4.0σ

Polarization in EW $WZ(\rightarrow lvll)jj$ process

- Using Run-2 (140 fb^{-1}) and partial Run-3 data (164 fb^{-1} , 2022-24), with fully leptonic final states
- Machine Learning techniques (DNN) to maximize the sensitivity
 - Two sets of deep neural network (DNN) classifiers
 - “S.vs.B” DNN: to separate $WZjj$ –EW from other backgrounds
 - Polarization DNN’s: to separate a given polarization state (eg $W_X Z_0 jj$ – EW) from $WZjj$ – EW



Modeling of polarized $WZjj$ – EW



Polarized $WZjj$ – EW predictions

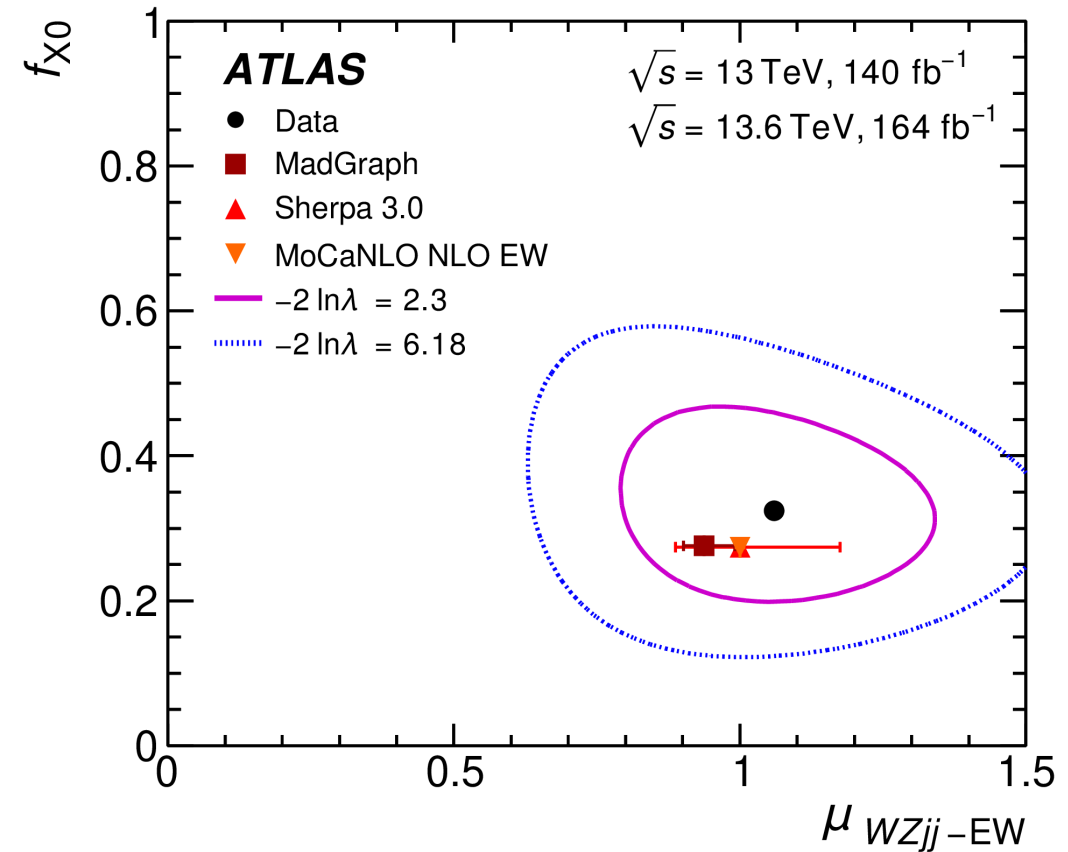
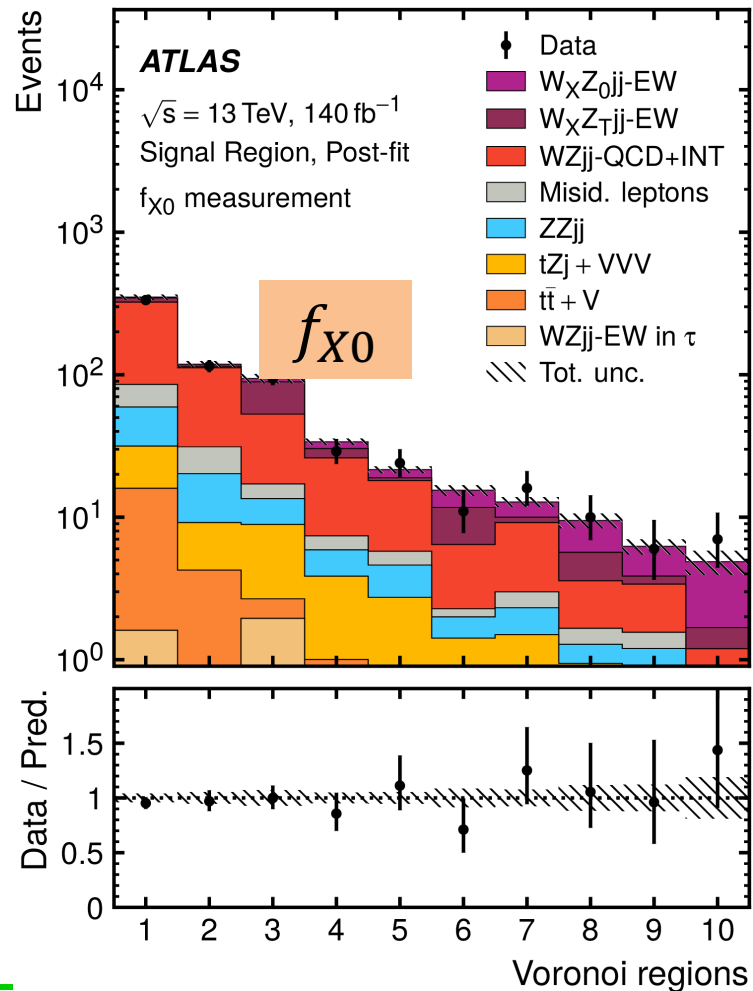
- Sherpa 3 MC, 0,1j@LO merged and matched to PS (M. Hoppe et al, [JHEP04\(2024\)001](#))
- MadGraph5+Pythia, LO+PS
- Fixed-order NLO EW, MoCaNLO (A. Denner et al, [JHEP02\(2026\)120](#))

mode	σ_{LO} [fb]	δ_{EW} [%]	σ_{NLOEW} [fb]	f_{LO} [%]	f_{NLOEW} [%]
$W_L Z_L$	0.023045(2)	-14.5	0.019701(4)	8.6	9.0
$W_L Z_T$	0.049365(3)	-17.9	0.040516(8)	18.4	18.6
$W_T Z_L$	0.049023(3)	-17.9	0.040233(8)	18.3	18.4
$W_T Z_T$	0.141725(8)	-19.6	0.11395(2)	52.9	52.2
int.	0.00462(2)	-15.0	0.00393(4)	1.7	1.8

Predicted polarization fractions (with NLO EW corrections) in the fiducial region:

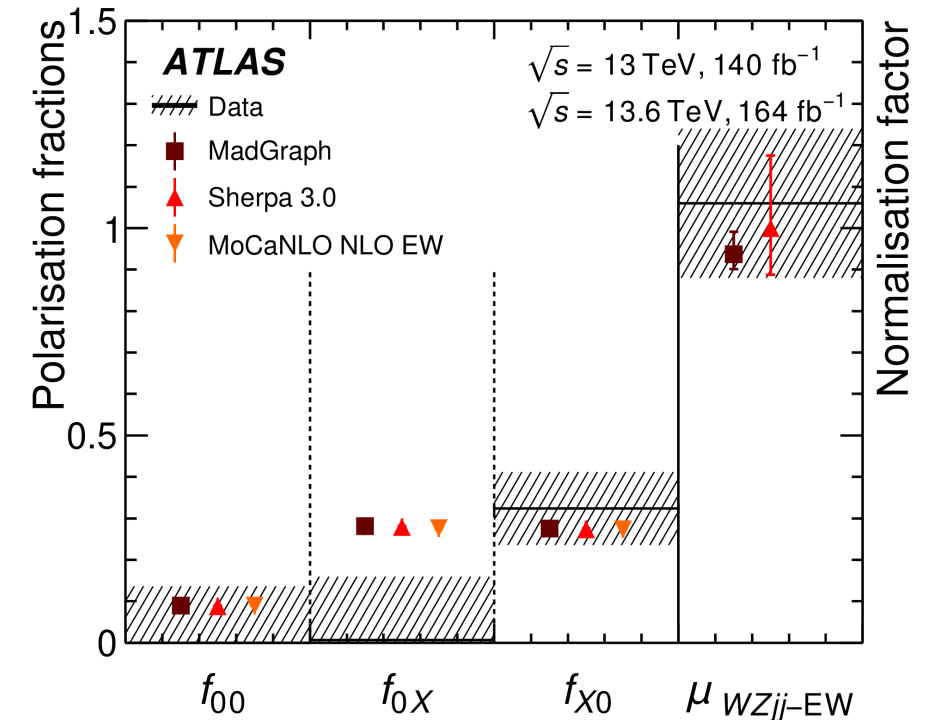
f_{00} for $W_0 Z_0 jj$ – EW: 9%
 f_{x0} for $W_x Z_0 jj$ – EW: 27%
 f_{0x} for $W_0 Z_x jj$ – EW: 28%

- First evidence of $W_X Z_0 jj$ – EW:
 - Significance: observed, 4.0σ ; expected: 2.9σ



	Data $\pm$ total ($\pm$ stat., $\pm$ syst., $\pm$ lumi.)	MADGRAPH	SHERPA 3.0	MoCANLO NLO EW
f_{00}	0.000 ± 0.134 (± 0.134 , ± 0.000 , ± 0.000)	0.0902 ± 0.0005	0.087 ± 0.001	0.0902 ± 0.0005
f_{0X}	0.007 ± 0.151 (± 0.150 , ± 0.018 , ± 0.001)	0.2808 ± 0.0002	0.2793 ± 0.0009	0.2758 ± 0.0008
f_{X0}	0.324 ± 0.088 (± 0.086 , ± 0.017 , ± 0.001)	0.2758 ± 0.0003	0.274 ± 0.001	0.2745 ± 0.0008
$\mu_{WZjj-EW}$	1.06 ± 0.18 (± 0.15 , ± 0.11 , ± 0.01)	$0.94^{+0.05}_{-0.04}$	$1.00^{+0.2}_{-0.1}$	—

- No evidence for $W_0Z_Xjj - EW$ or $W_0Z_0jj - EW$
 - Expected: 1.3σ for f_{00} and 2.6σ for f_{0X}
 - The probability to observe a value of $f_{0X} < 0.007$, under the SM hypothesis is 0.60%, corresponding to 2.5σ
 - The measured low f_{0X} is consistent with the slight increase of the measured f_{X0}
- 95% CL upper limits set on f_{0X}, f_{00}



Quantum Entanglement:

*from measuring event rates
to
measuring quantum state itself*

Quantum entanglement

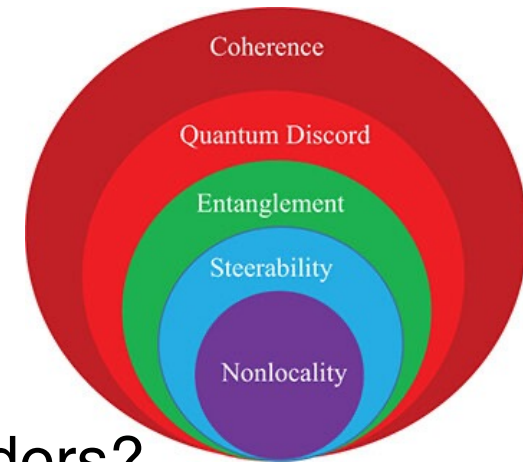
- Entanglement is a **fundamental property** of quantum mechanics
- Quantum entanglement is the non-separability of the joint quantum state of a composite system

$$|\psi\rangle = \frac{1}{\sqrt{2}}(|00\rangle \pm |11\rangle)$$

Entangled

$$|\psi\rangle = (a_1|0\rangle + a_2|1\rangle) \otimes (b_1|0\rangle + b_2|1\rangle)$$

Separable



- Has been well tested at the low-energy regime. Why study it at colliders?
 - **New regime**: test entanglement at the highest energies and shortest timescales
 - **Natural laboratory**: particle production and decay naturally create entangled spin states
 - **Probe quantum structure**: access *coherence* and *correlations* beyond conventional cross-section measurements
 - **New physics sensitivity**: provides new observables sensitive to the Lorentz/helicity/CP structure of interactions

QE in VV

- Unique qutrit system made up by spin states
- Density matrix for a $V_1 V_2$ pair

64 spin correlation coefficients

$$\rho = \frac{1}{9} \left[\mathbb{1}_3 \otimes \mathbb{1}_3 + \boxed{A_{LM}^1} T_M^L \otimes \mathbb{1}_3 + \boxed{A_{LM}^2} \mathbb{1}_3 \otimes T_M^L + \boxed{C_{L_1 M_1 L_2 M_2}} T_{M_1}^{L_1} \otimes T_{M_2}^{L_2} \right]$$

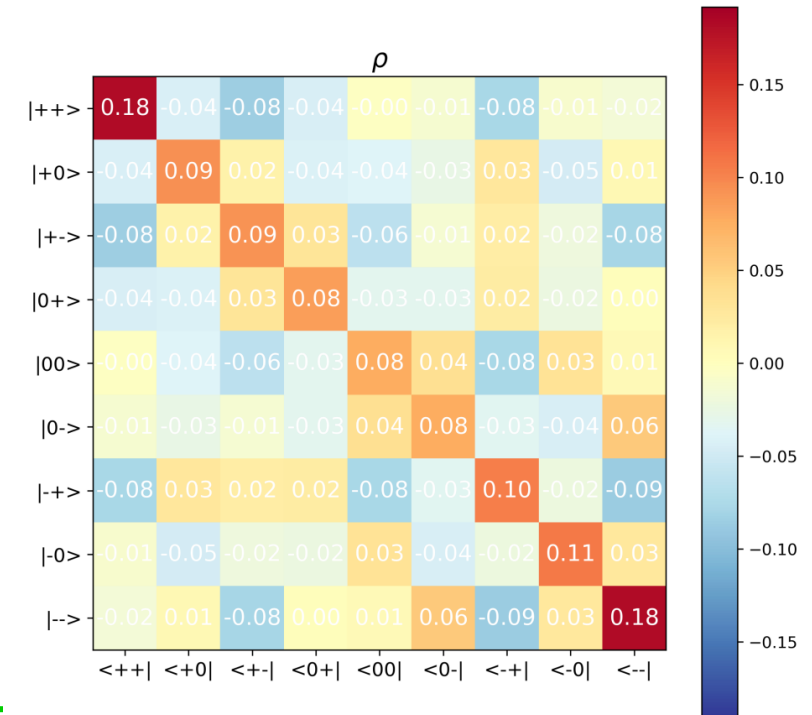
8 coefficients
corresponding to
 V_1 polarization

8 coefficients
corresponding to
 V_2 polarization

$$\begin{aligned} f_{00} &= \rho_{0000}, \\ f_{TT} &= \rho_{++--} + \rho_{--++} + \rho_{----} + \rho_{++++}, \\ f_{0T} &= \rho_{00--} + \rho_{00++}, \\ f_{T0} &= \rho_{--00} + \rho_{++00}. \end{aligned}$$

- ❖ Polarization merely contains reduced information of the SDM
- ❖ Ideally we want to measure the full SDM $\rightarrow$ quantum tomograph

An example of SDM for $qq \rightarrow ZZ$



QE in VV

- Unique qutrit system made up by spin states
- Density matrix for a $V_1 V_2$ pair

$$\rho = \frac{1}{9} \left[\mathbb{1}_3 \otimes \mathbb{1}_3 + \boxed{A_{LM}^1} T_M^L \otimes \mathbb{1}_3 + \boxed{A_{LM}^2} \mathbb{1}_3 \otimes T_M^L + \boxed{C_{L_1 M_1 L_2 M_2}} T_{M_1}^{L_1} \otimes T_{M_2}^{L_2} \right]$$

8 coefficients
corresponding to
 V_1 polarization
8 coefficients
corresponding to
 V_2 polarization

64 spin correlation
coefficients

- Fully predicts the angular distribution of the $V_1 V_2$ decay products

$$\frac{1}{\sigma} \frac{d\sigma}{d\Omega_1 d\Omega_2} = \frac{1}{(4\pi)^2} \left[1 + \color{red}{B_{L_1}^1} \color{blue}{A_{L_1 M_1}^1} Y_{L_1}^{M_1}(\Omega_1) + \color{red}{B_{L_2}^2} \color{blue}{A_{L_2 M_2}^2} Y_{L_2}^{M_2}(\Omega_2) \right. \\ \left. + \color{red}{B_{L_1}^1} \color{red}{B_{L_2}^2} \color{blue}{C_{L_1 M_1 L_2 M_2}} Y_{L_1}^{M_1}(\Omega_1) Y_{L_2}^{M_2}(\Omega_2) \right]$$

$\color{red}{B_1} = -\sqrt{2\pi} \eta_\ell, \quad \color{red}{B_2} = \sqrt{\frac{2\pi}{5}}$

$$\Omega_1 = (\theta_1, \varphi_1)$$

$$\Omega_2 = (\theta_2, \varphi_2)$$

$$\eta_\ell = \begin{cases} \frac{g_L^2 - g_R^2}{g_L^2 + g_R^2} & Z \\ 1 & W^- \\ -1 & W^+ \end{cases}$$

Entanglement criteria

- For a general quantum state ρ : $\text{Tr}(\rho) = 1$, $\rho^\dagger = \rho$, positive definite
- Peres-Horodecki criterion

Given a state ρ , it is entangled if and only if the partially transposed matrix, ρ^{T_A}, ρ^{T_B} , has **at least one negative eigenvalue**

- Other criteria:
 - CGLMP inequality (Bell-inequality for qutrits)

$$I_3 = \langle \mathcal{O}_{\text{Bell}} \rangle = \text{Tr}(\rho \mathcal{O}_{\text{Bell}}) \leq 2.$$

- Concurrence

$$(\mathcal{C}(\rho))^2 \geq 2 \max \left\{ 0, \text{Tr}[\rho^2] - \text{Tr}[(\rho_A)^2], \text{Tr}[\rho^2] - \text{Tr}[(\rho_B)^2] \right\} \equiv \mathcal{C}_{\text{LB}}^2,$$

$$(\mathcal{C}(\rho))^2 \leq 2 \min \left\{ 1 - \text{Tr}[(\rho_A)^2], 1 - \text{Tr}[(\rho_B)^2] \right\} \equiv \mathcal{C}_{\text{UB}}^2.$$

QE in HVV

- Scalar nature of the Higgs boson: entangled **pure state**

$$|\psi\rangle = \frac{1}{\sqrt{2 + \beta^2}} (|+ -\rangle - \beta|00\rangle + |- +\rangle)$$

- Simplify the 9×9 density matrix to **9 non-zero** elements

$$\rho = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \frac{1}{6}(\sqrt{2}A_{2,0}^1 + 2) & 0 & \frac{1}{3}C_{2,1,2,-1} & 0 & \frac{1}{3}C_{2,2,2,-2} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \frac{1}{3}C_{2,1,2,-1} & 0 & \frac{1}{3}(1 - \sqrt{2}A_{2,0}^1) & 0 & \frac{1}{3}C_{2,1,2,-1} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \frac{1}{3}C_{2,2,2,-2} & 0 & \frac{1}{3}C_{2,1,2,-1} & 0 & \frac{1}{6}(\sqrt{2}A_{2,0}^1 + 2) & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix}$$

QE witness: according to the PH criterion

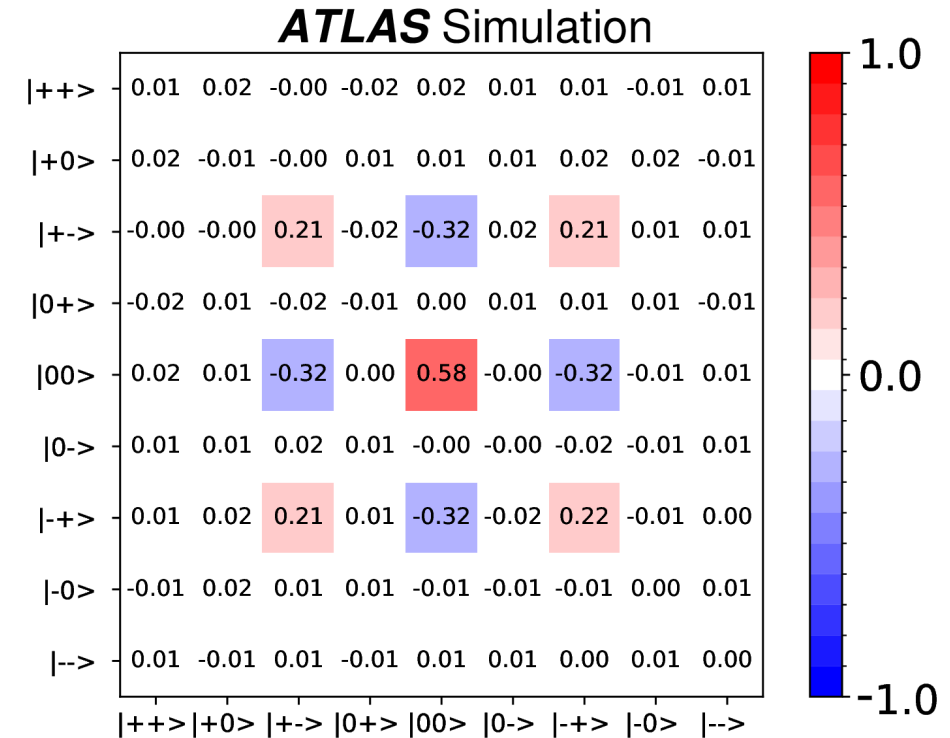
$$C_{212-1} \neq 0 \text{ or } C_{222-2} \neq 0$$



ZZ* Entangled

CGLMP inequality:

$$I_3 = \frac{1}{36} \left(18 + 16\sqrt{3} - \sqrt{2} \left(9 - 8\sqrt{3} \right) A_{2,0}^1 - 8 \left(3 + 2\sqrt{3} \right) C_{2,1,2,-1} + 6 C_{2,2,2,-2} \right)$$



QE measurements at the LHC

Quantum states	Process	Results	
Qubits $2 \otimes 2$	$t\bar{t}$	ATLAS (leptonic): Nature 633 (2024) 542	First observation of QE
		CMS (leptonic): ROPP 87 (2024) 117801 CMS (semi-leptonic): PRD 110 (2024) 112016	
Qutrits $3 \otimes 3$	$H \rightarrow ZZ^*$	ATLAS: PRL 137 (2026) 111804	Separable-state hypothesis disfavored at 4.7σ obs. / 4.9σ exp.
		CMS: CMS-PAS-HIG-25-011	

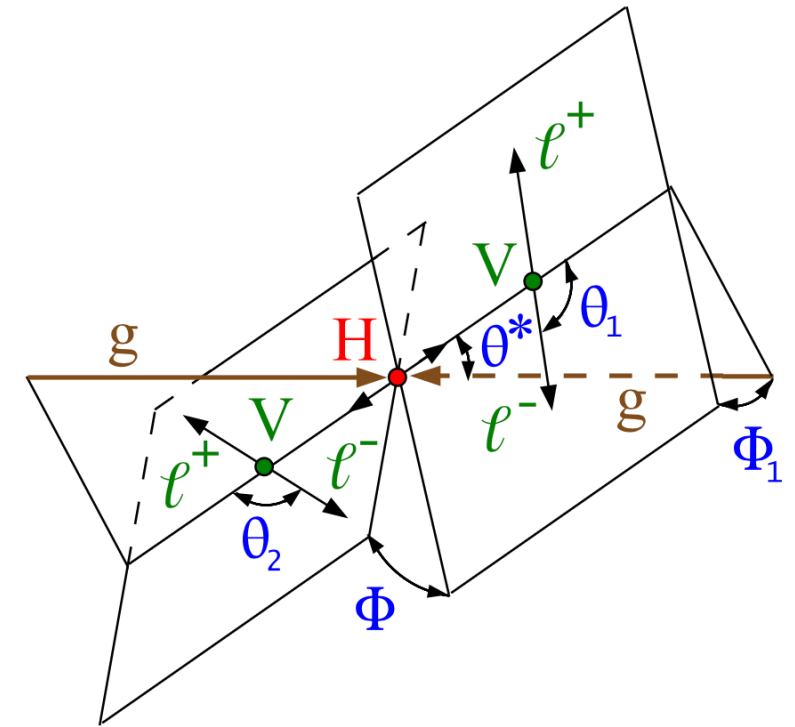
- The $H \rightarrow ZZ^* \rightarrow 4l$ is clean and capable of fully reconstructing spin states
- Using 300 fb^{-1} of Run 2 + partial Run 3 data
- Two complementary methods

Quantum tomography

- Directly measure C_{212-1} and C_{222-2} from angular observables
- Less model dependent
- Lower sensitivity due to limited statistics (event-by-event average)

Hypothesis test

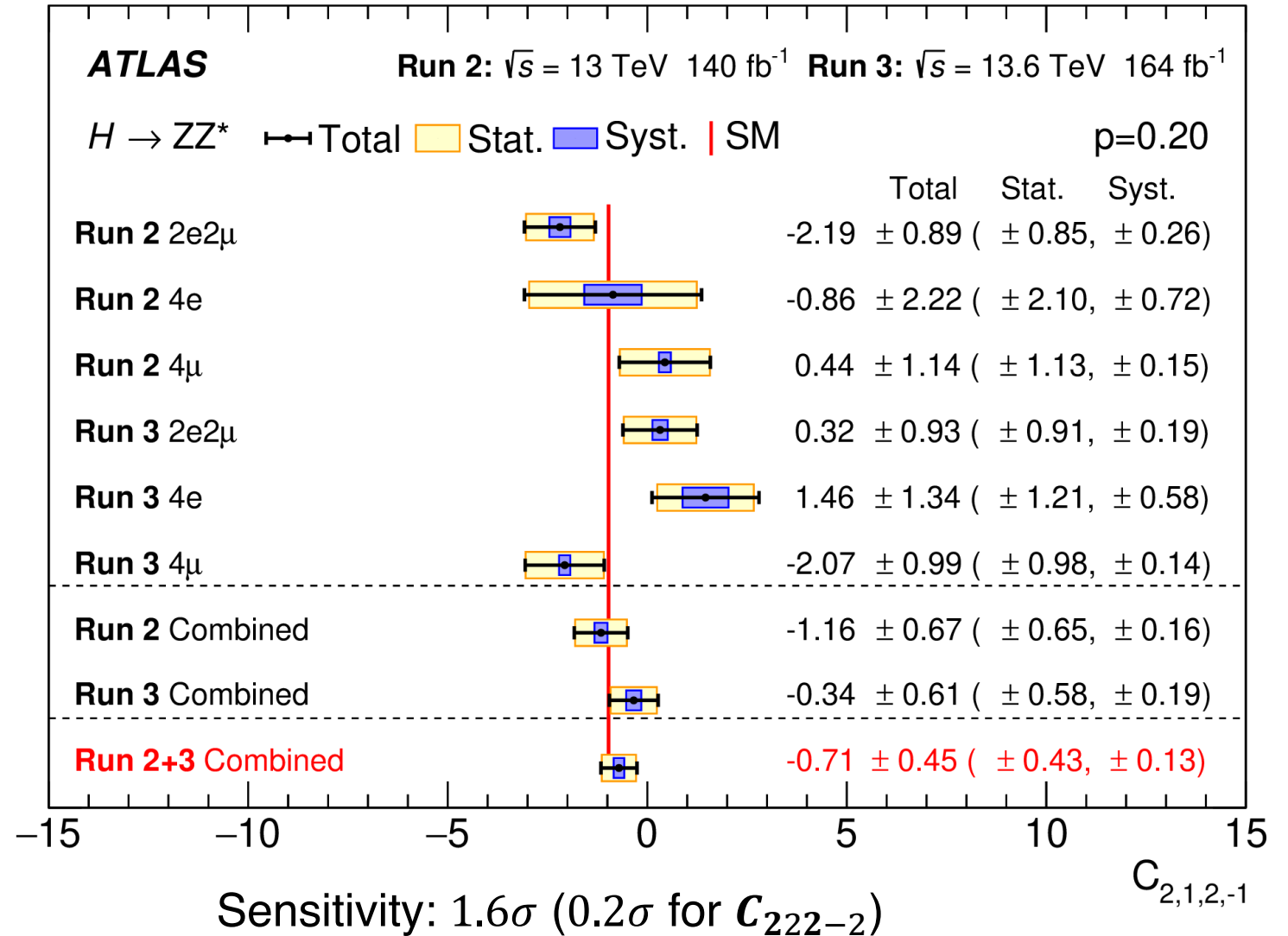
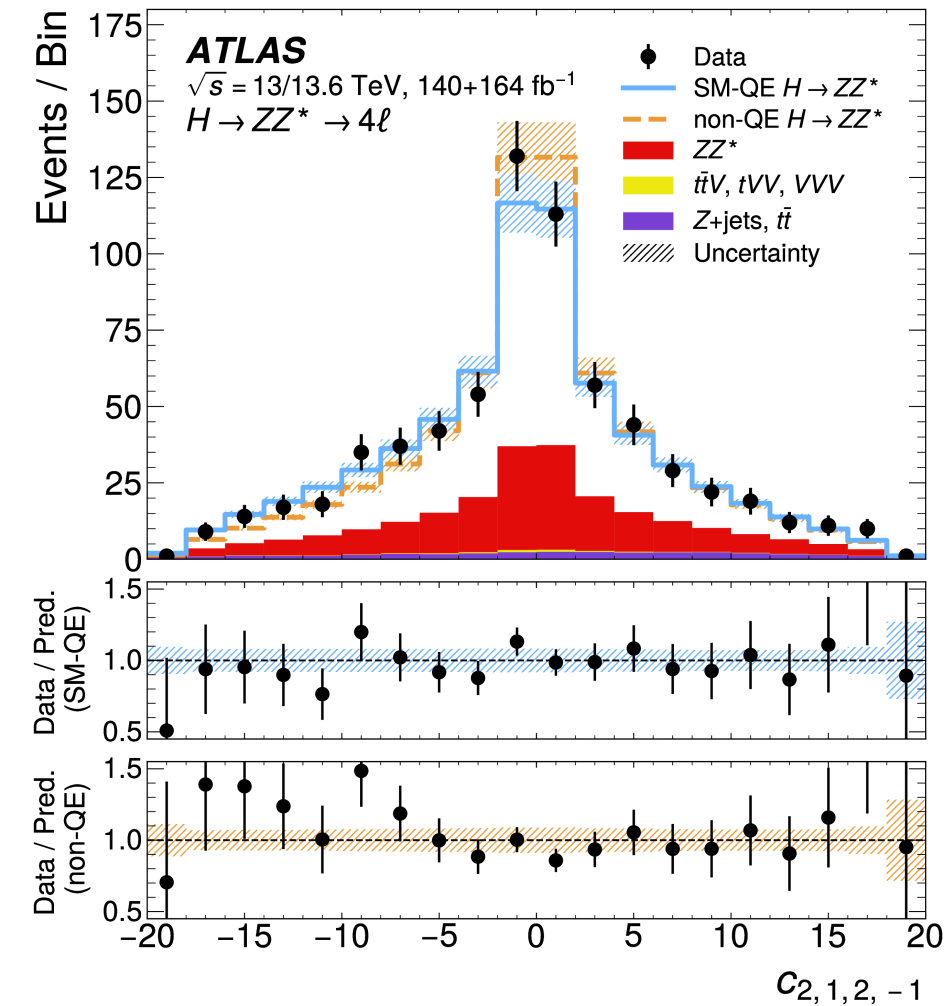
- QE and non-QE test
- HVV system not in pure $|00\rangle$ state $\longleftrightarrow$ Non-separable (Entangled)
- Higher sensitivity (using also the shape information)
- Increased model dependence



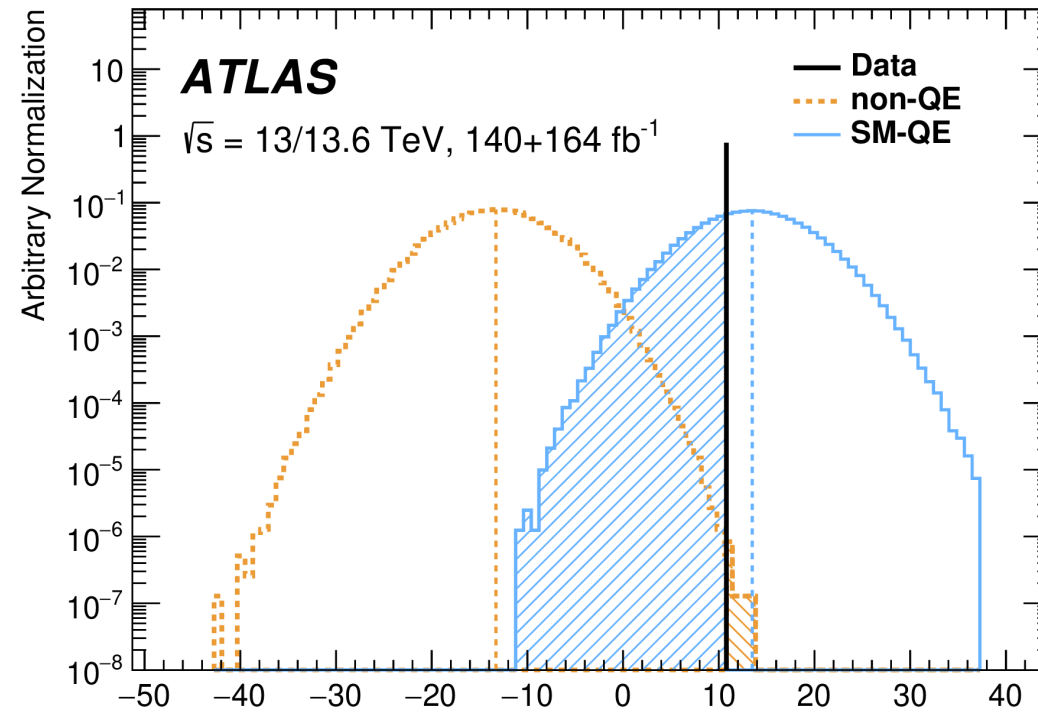
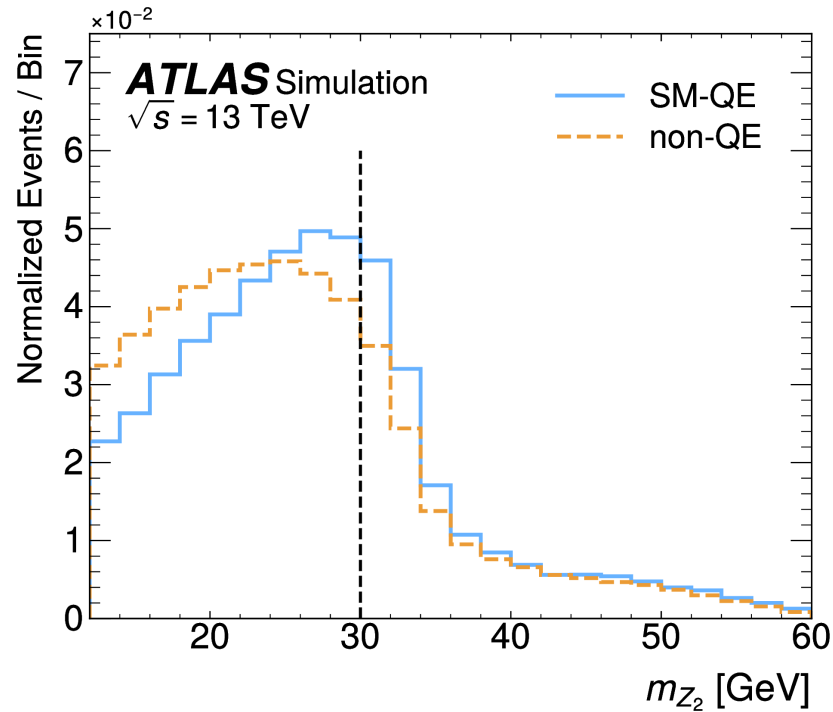
C_{212-1} measurements

PRL 137 (2026) 111804

Editors' suggestion



- Based on the C_{212-1} distribution
- Make full use of the line shape, instead of merely the mean value
- The SR further split into $m_{Z_2} < 30\text{GeV}$ and $m_{Z_2} > 30\text{GeV}$



Non-QE rejected with 4.7σ obs. (4.9σ exp)

- Using 200 fb⁻¹ of Run 2 + partial Run 3 data
- CMS emphasizes a global $H \rightarrow 4l$ spin/coupling framework
- Entanglement is one interpretation of fitted polarization-density-matrix parameters.

f_L : fraction of the pure $|00\rangle$ state

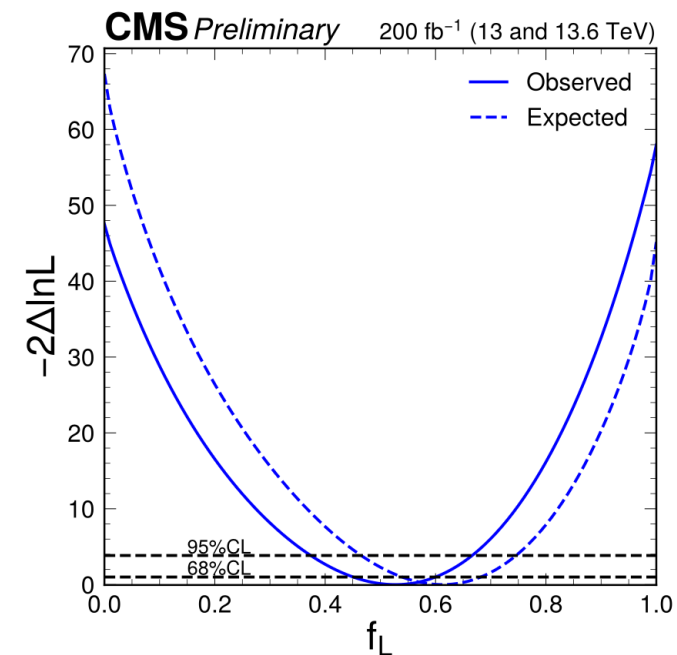
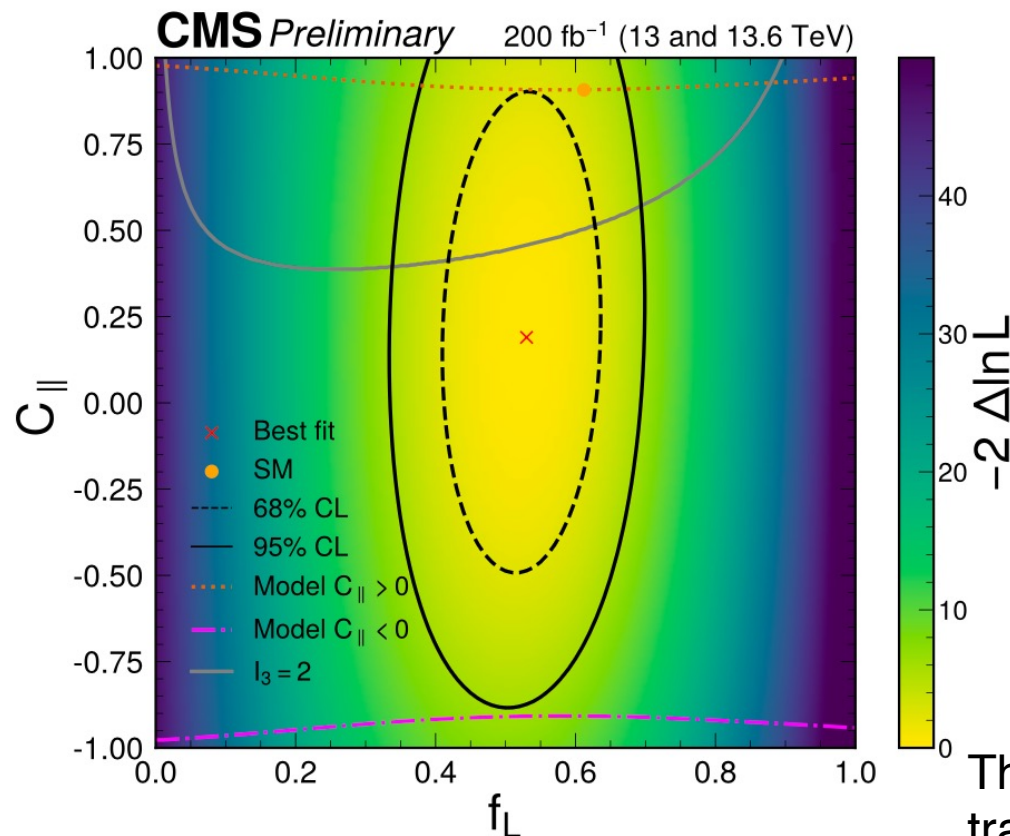
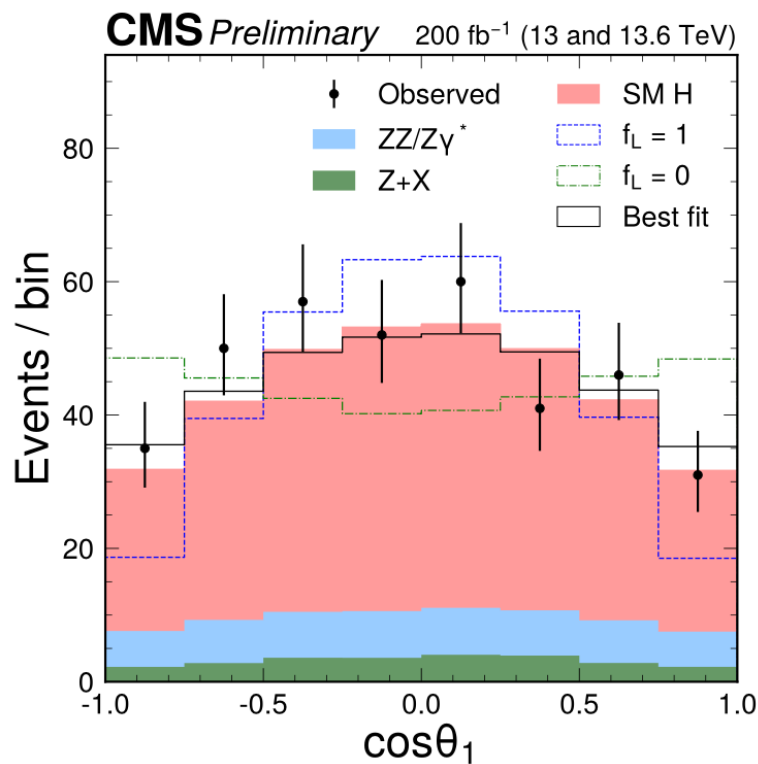
$C_{\parallel}$: quantify the interference between the longitudinal and CP-even transverse polarization states

$$\rho = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & (1-f_L)/2 & 0 & -C_{\parallel}\sqrt{f_L(1-f_L)}/2 & 0 & (1-f_L)/2 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & -C_{\parallel}\sqrt{f_L(1-f_L)}/2 & 0 & f_L & 0 & -C_{\parallel}\sqrt{f_L(1-f_L)}/2 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & (1-f_L)/2 & 0 & -C_{\parallel}\sqrt{f_L(1-f_L)}/2 & 0 & (1-f_L)/2 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix}$$

$$C_{2,2,2,-2} = \frac{3}{2}(1-f_L),$$

$$C_{2,1,2,-1} = -3C_{\parallel}\sqrt{f_L(1-f_L)}/2.$$

- Extract from a 4D fit (D_{bkg} , $\cos \theta_1$, $\cos \theta_2$, ϕ)
 - D_{bkg} : a matrix-element discriminant between $H4l$ signal and bkg (MELA)



The fully longitudinal and fully transverse polarization of the Z bosons are excluded at more than 6 σ

$$C_{2,2,2,-2} = \frac{3}{2}(1 - f_L),$$

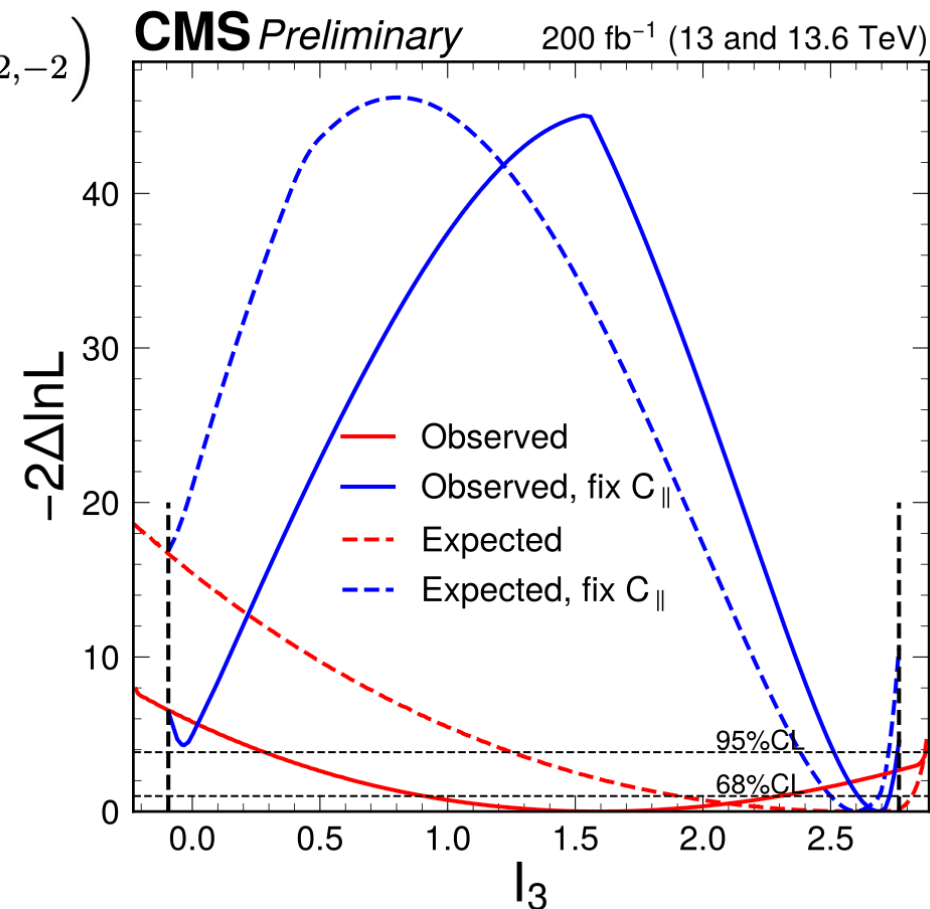
$$C_{2,1,2,-1} = -3C_{\parallel} \sqrt{f_L(1 - f_L)/2}.$$

- CMS also measured the CGLMP inequality I_3
 - $I_3 > 2$: violation of Bell-type inequality

$$I_3 = \frac{1}{36} \left(18 + 16\sqrt{3} - \sqrt{2} \left(9 - 8\sqrt{3} \right) A_{2,0}^1 - 8 \left(3 + 2\sqrt{3} \right) C_{2,1,2,-1} + 6 C_{2,2,2,-2} \right)$$

$$\rho = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \frac{1}{6} (\sqrt{2} A_{2,0}^1 + 2) & 0 & \frac{1}{3} C_{2,1,2,-1} & 0 & \frac{1}{3} C_{2,2,2,-2} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \frac{1}{3} C_{2,1,2,-1} & 0 & \frac{1}{3} (1 - \sqrt{2} A_{2,0}^1) & 0 & \frac{1}{3} C_{2,1,2,-1} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \frac{1}{3} C_{2,2,2,-2} & 0 & \frac{1}{3} C_{2,1,2,-1} & 0 & \frac{1}{6} (\sqrt{2} A_{2,0}^1 + 2) & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix}$$

Parameter	Scenario	Observed		Expected	
		68% CL	95% CL	68% CL	95% CL
I_3	fix $C_{\parallel}$	$2.69^{+0.03}_{-0.08}$	[2.52, 2.75]	2.60 ± 0.08	[2.39, 2.71]
I_3	float all	$1.60^{+0.70}_{-0.68}$	[0.28, 2.87]	$2.60^{+0.21}_{-0.68}$	[1.26, 2.87]



Summary

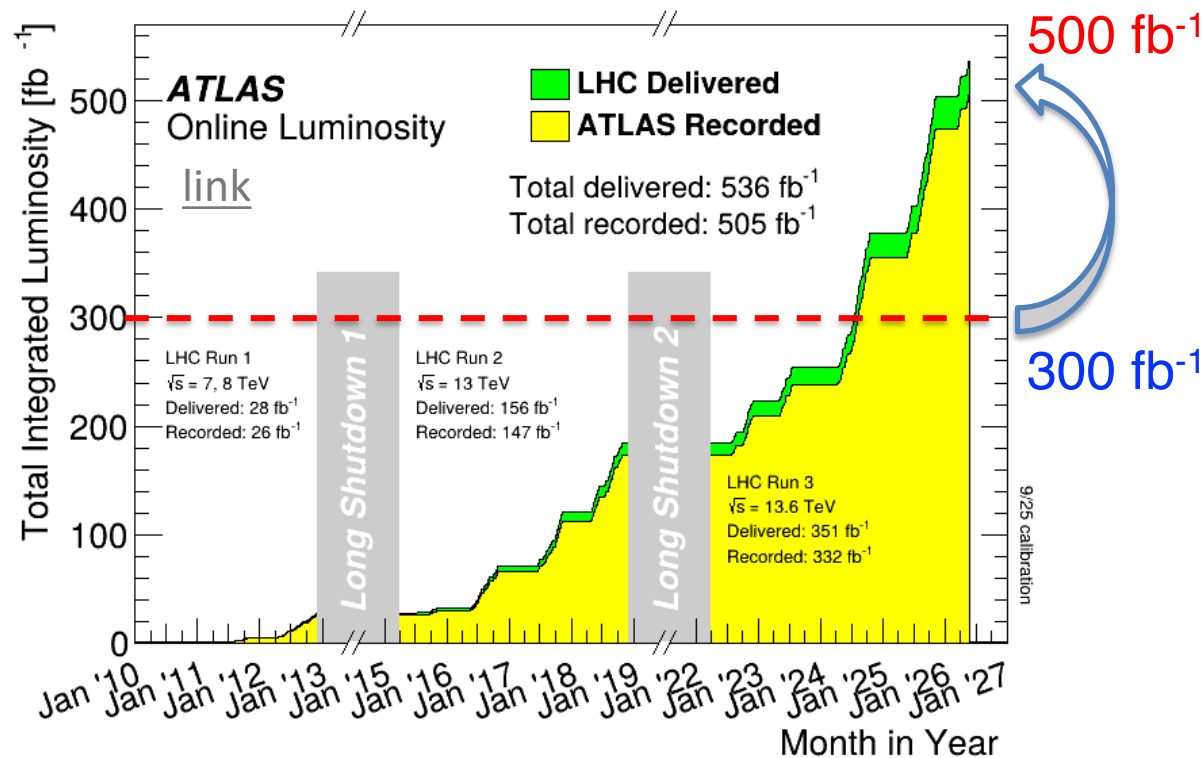
Future prospects: VV polarization

Near term:

- More Run-3 data
- More channels

HL-LHC and ultimate goals:

- Probe the EW Restoration regime or the Goldstone sector



$$pp \rightarrow V_L V_L$$

Already achieved:

- ✓ $pp \rightarrow Z_L Z_L$
- ✓ $pp \rightarrow W_L Z_L$

Next:

- $pp \rightarrow W_L W_L$?
- Hadronic V_L tagger?
- $pp \rightarrow V_L h$?

$$V_L V_L \rightarrow V_L V_L$$

Already achieved:

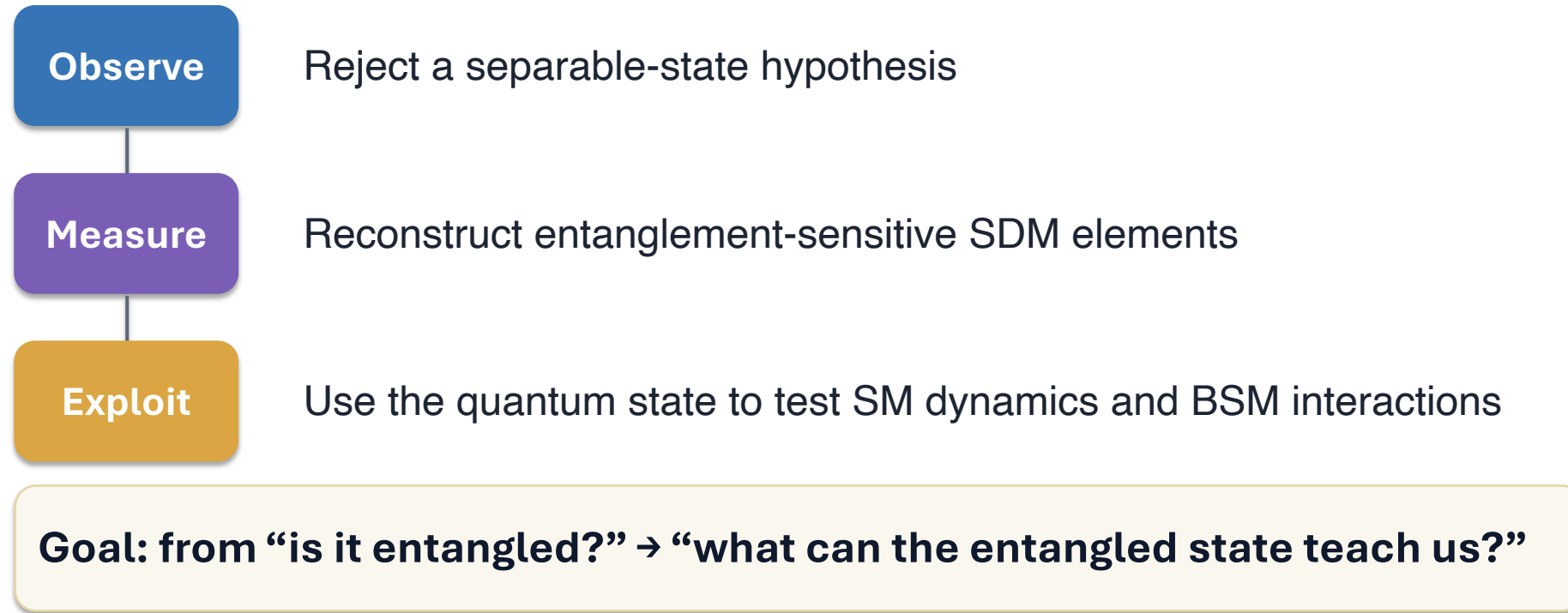
- ✓ $W_L^\pm W_X^\pm jj$ – EW evidence
- ✓ $W_X^\pm Z_L^\pm jj$ – EW evidence

Next:

- Evidence or observation of $V_L V_L jj$ – EW?

Future prospects: VV quantum observables

- Go beyond simple polarization fraction measurements → probe the full spin density matrix: quantum tomograph



- Quantum observables provide complementary probes of BSM interactions by accessing the spin correlations and coherence of the produced state

Conclusion

- Vector-boson polarization is emerging as a new precision frontier for exploring EWSB
- Recent highlights:
 - Observation of $Z_L Z_L$ production in 4ℓ final states [arXiv:2607.12879](#)
 - First evidence of a single longitudinally polarized Z boson in $WZjj$ – EW events [arXiv:2607.20246](#)
- More data opens the door to Quantum Entanglement and quantum-state tomography
 - ATLAS: strong evidence for entanglement of two massive spin-1 bosons [PRL 137 \(2026\) 111804](#)
 - CMS: complementary spin-density-matrix / Bell-type studies [CMS-PAS-HIG-25-011](#)
- Continuous development in theoretical calculations also essential

Backup

Diboson polarization

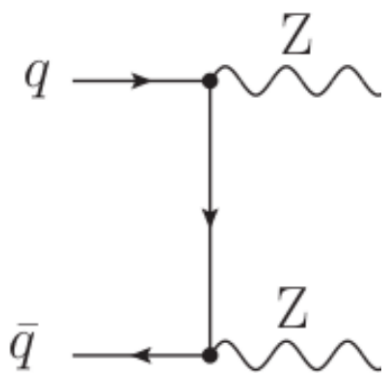
Why the LL fraction is smallest ?

Stable-Z approximation:

$$\varepsilon_-^\mu = \frac{1}{\sqrt{2}}(0, \cos \theta, -i, -\sin \theta),$$

$$\varepsilon_+^\mu = \frac{1}{\sqrt{2}}(0, -\cos \theta, -i, \sin \theta),$$

$$\varepsilon_L^\mu = \frac{1}{M}(p, E \sin \theta, 0, E \cos \theta) \xrightarrow{E \gg M} \frac{p^\mu}{M}$$



$$\frac{d\sigma_{LL}}{d\cos\theta} = \frac{a}{96} \frac{M_Z^4}{s^3} \frac{\cos^2\theta}{\sin^2\theta} + \mathcal{O}\left(\frac{1}{s^4}\right),$$

$$\frac{d\sigma_{LT}}{d\cos\theta} = \frac{a}{12} \frac{M_Z^2}{s^2} + \mathcal{O}\left(\frac{1}{s^3}\right),$$

$$\frac{d\sigma_{TT}}{d\cos\theta} = \frac{a}{48} \frac{1 + \cos^2\theta}{s} + \mathcal{O}\left(\frac{1}{s^2}\right)$$

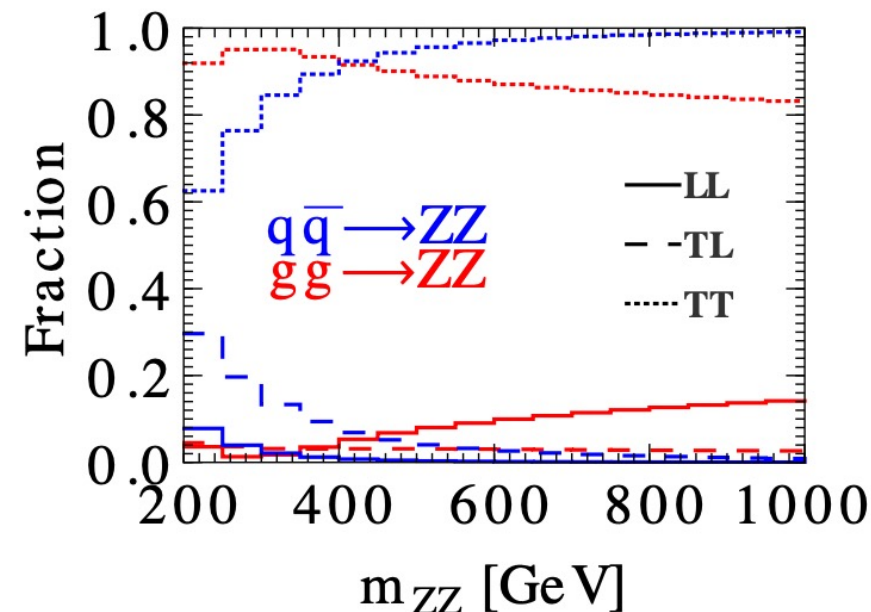
with $a = \pi\alpha^2(c_L^4 + c_R^4)/(s_W^4 c_W^4)$, $\sqrt{s} \in [2M_Z, 13 \text{ TeV}]$

► LL is most sensitive to the mass, but kinematically suppressed !

► Dominant contribution to σ_{LL} comes from the threshold region.

Duc Ninh LE, Phenikaa University, Vietnam

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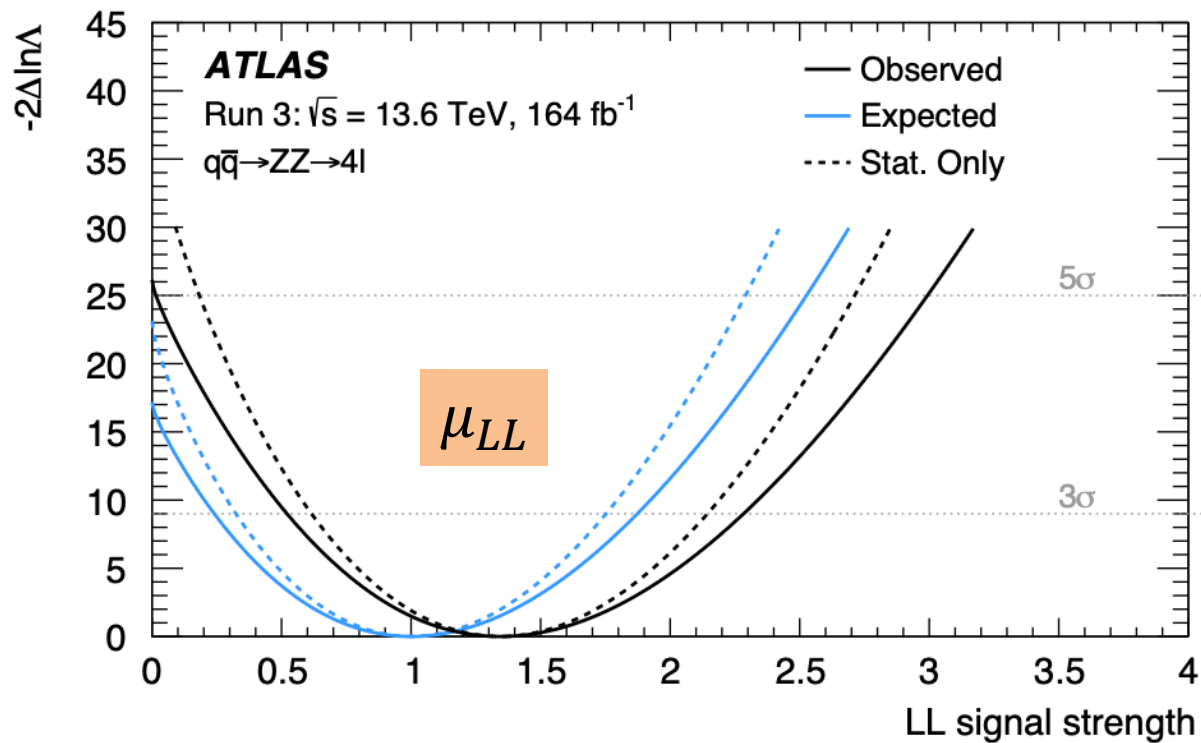


Q-H Cao, B. Yan et al, [arXiv:2004.02031](https://arxiv.org/abs/2004.02031)

Duc Ninh LE, LHCP 2025

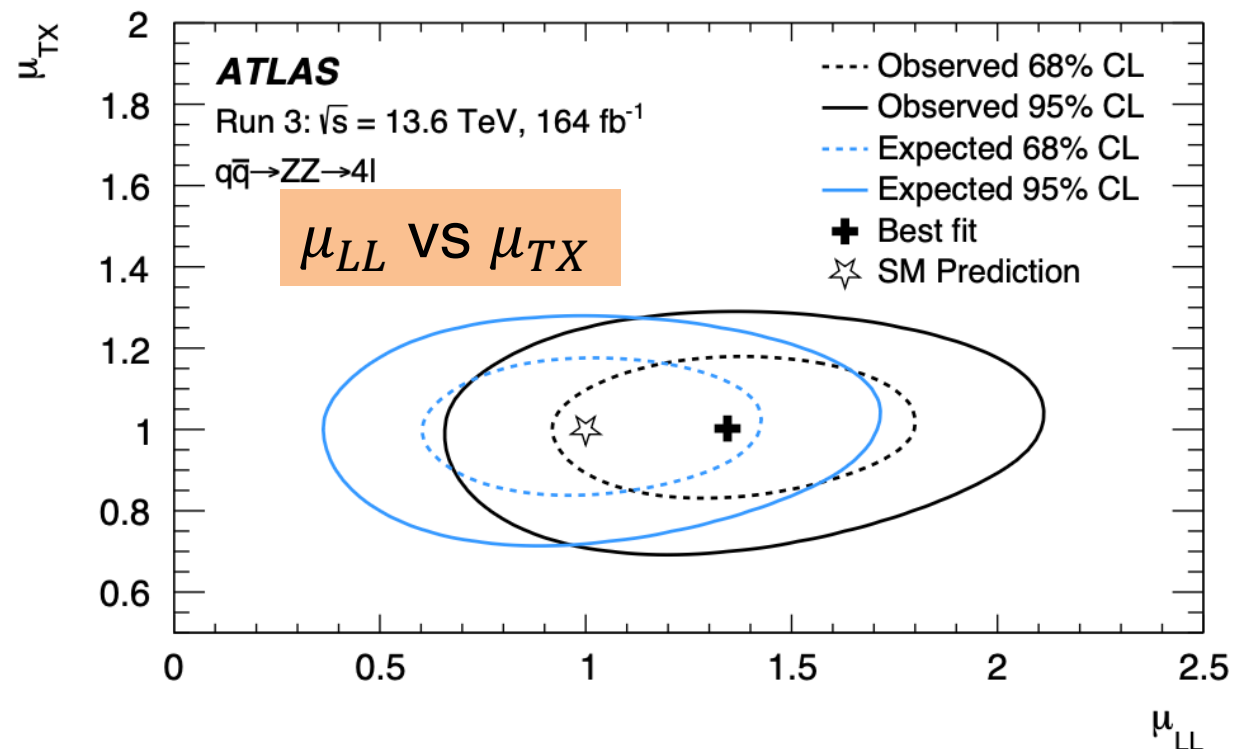
$Z_L Z_L$ signal strength (Run-3)

- Simultaneous fit of (μ_{LL}, μ_{TX})
 - Significance of μ_{LL} : obs, **5.1 σ** ; exp: 4.1 σ



$$\mu_{LL}^{obs} = 1.34 \pm 0.29$$

$$\mu_{LL}^{exp} = 1.00 \pm 0.27$$



$$\mu_{TX}^{obs} = 1.00 \pm 0.10$$

Polarization and Spin Density Matrix

- The density matrix of $Z \rightarrow ll$ decay

R. Rahaman, R. Singh, [arXiv:2109.09345](https://arxiv.org/abs/2109.09345)

$$\Gamma = \frac{1}{4} \begin{pmatrix} \boxed{1 + \cos^2 \theta - 2\eta_\ell \cos \theta}^{f_L} & \frac{1}{\sqrt{2}} (\sin 2\theta - 2\eta_\ell \sin \theta) e^{i\varphi} & (1 - \cos^2 \theta) e^{i2\varphi} \\ \frac{1}{\sqrt{2}} (\sin 2\theta - 2\eta_\ell \sin \theta) e^{-i\varphi} & \boxed{2 \sin^2 \theta}^{f_0} & -\frac{1}{\sqrt{2}} (\sin 2\theta + 2\eta_\ell \sin \theta) e^{i\varphi} \\ (1 - \cos^2 \theta) e^{-i2\varphi} & -\frac{1}{\sqrt{2}} (\sin 2\theta + 2\eta_\ell \sin \theta) e^{-i\varphi} & \boxed{1 + \cos^2 \theta + 2\eta_\ell \cos \theta}^{f_R} \end{pmatrix}$$

E. Gabrielli et al,
[arXiv:2302.00683](https://arxiv.org/abs/2302.00683)

- The differential cross section is simply given by the SDM

$$\frac{1}{\sigma} \frac{d\sigma}{d\Omega_1 d\Omega_2} = \left(\frac{3}{4\pi} \right)^2 \text{Tr} \{ \boxed{\rho} (\Gamma_1 \otimes \Gamma_2)^T \}$$

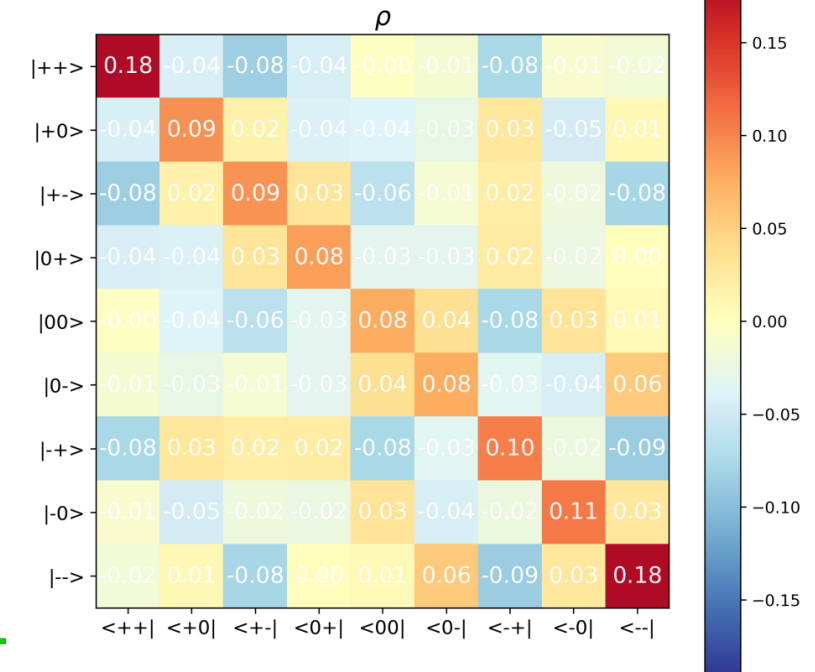
SDM for the V decay

SDM for the $pp \rightarrow VV$

$$\begin{aligned} f_{00} &= \rho_{0000}, \\ f_{\text{TT}} &= \rho_{++--} + \rho_{--++} + \rho_{----} + \rho_{++++}, \\ f_{0\text{T}} &= \rho_{00--} + \rho_{00++}, \\ f_{\text{T}0} &= \rho_{--00} + \rho_{++00}. \end{aligned}$$

- ❖ Polarization merely contains reduced information of the SDM
- ❖ Ideally we want to measure the full SDM $\rightarrow$ quantum tomograph

An example of SDM for $qq \rightarrow ZZ$



Quantum entanglement

- Entanglement is a fundamental property of quantum mechanics
- Spin density matrix for a bipartite quantum system

$$\rho = \sum_{i=1}^n p_i |\psi_i\rangle\langle\psi_i|, \text{ with } p_i \geq 0, \sum_{i=1}^n p_i = 1$$

A state (density matrix) ρ is called **separable** if and only if it can be written as a linear convex combination of tensor products of density matrices:

$$\rho = \sum_{ij} p_{ij} \rho_i^{(A)} \rho_j^{(B)}, \text{ with } p_{ij} > 0, \sum_{ij} p_{ij} = 1$$

