Observation of pair production of longitudinally polarized Z bosons in four-lepton final state with the ATLAS detector

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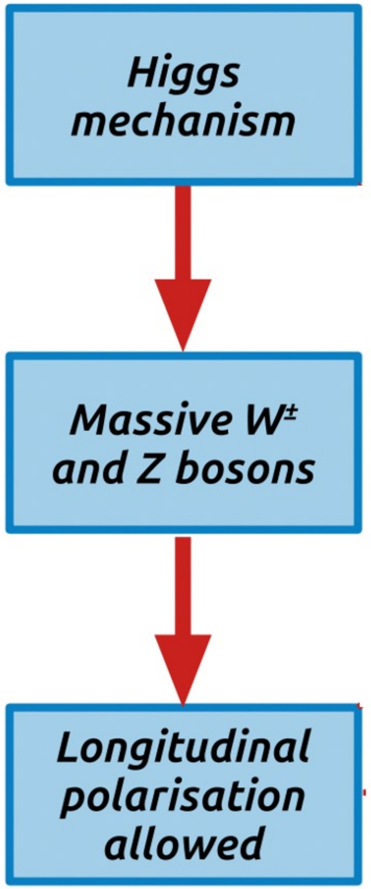
中国物理学会高能物理分会第十二届全国会员代表大会暨学术年会

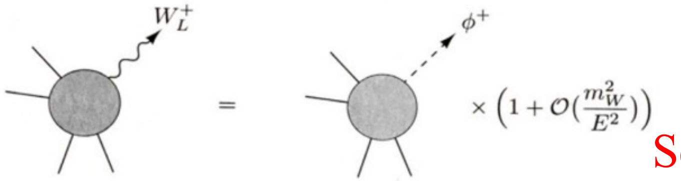
2026.7.13-19, Guangzhou

Motivation

- The polarization measurement of massive weak bosons provides a sensitive probe of the EWSB mechanism.

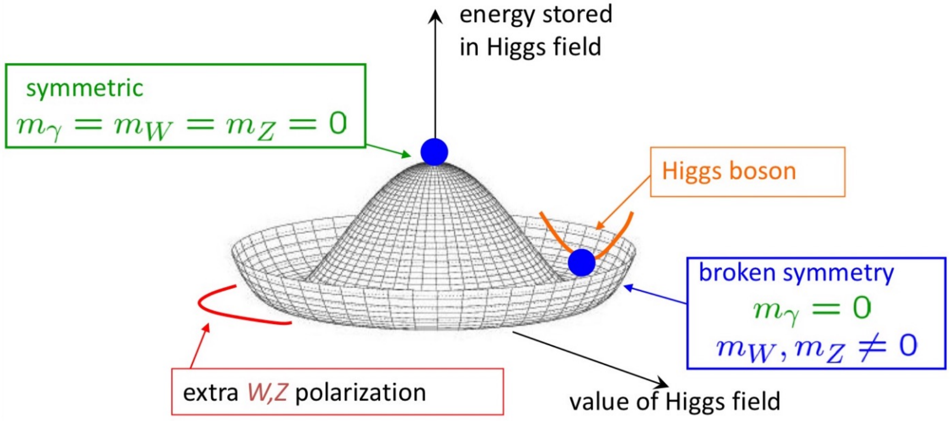


Goldstone equivalence theorem:
"At high energy, longitudinal vector bosons are analogous to goldstone bosons"

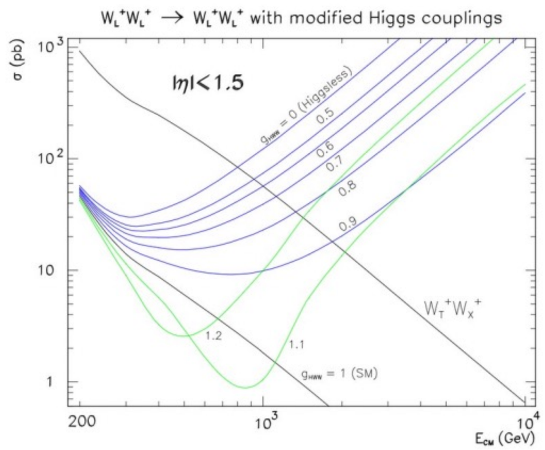


$$V_L V_L \approx \phi\phi$$

Sensitive to Higgs sector



- Direct polarization measurements through VBS remain statistically challenging.
  - Very rare (~5% of VBS events)
  - O(100) events at the end of HL-LHC



[arXiv:1412.8367]

- First step towards longitudinal VBS measurements
  - Inclusive ZZ joint-polarization

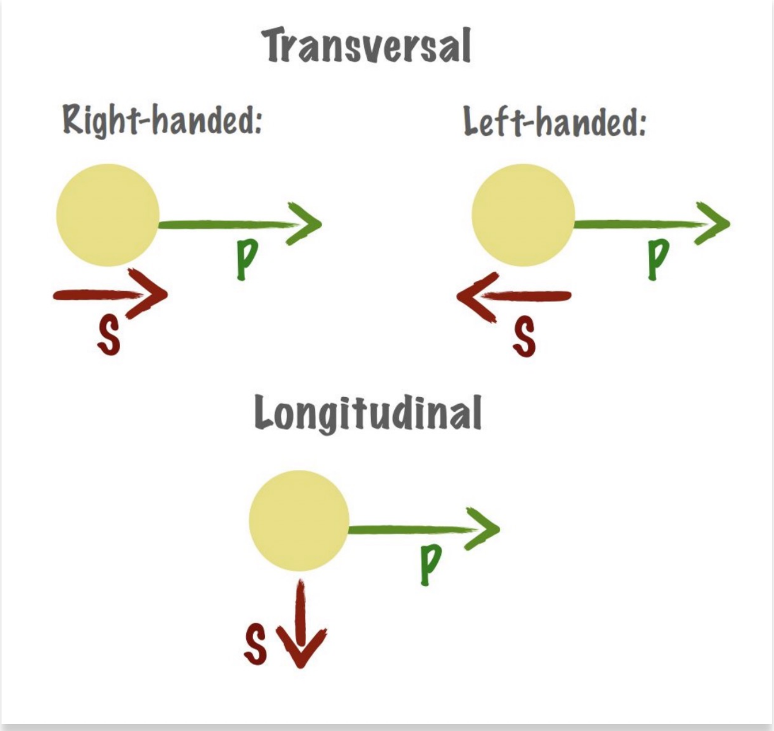
Polarization of weak bosons

- Polarization describes the alignment of a particle's spin with its momentum.

- Quantified using the helicity:

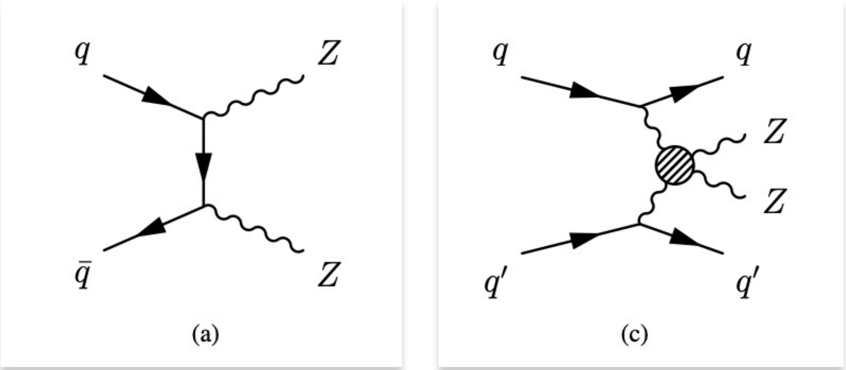
$$h = \vec{S} \cdot \frac{\vec{p}}{|p|}$$

- Thus results in 2 polarized states.
  - Transversal polarization (T)
    - Spin and momenta are (anti-)aligned. ($h = \pm 1$)
  - Longitudinal polarization (L)
    - Spin orthogonal to the momenta. ($h = 0$)
    - Originate from Goldstone modes → Direct link to EWSB

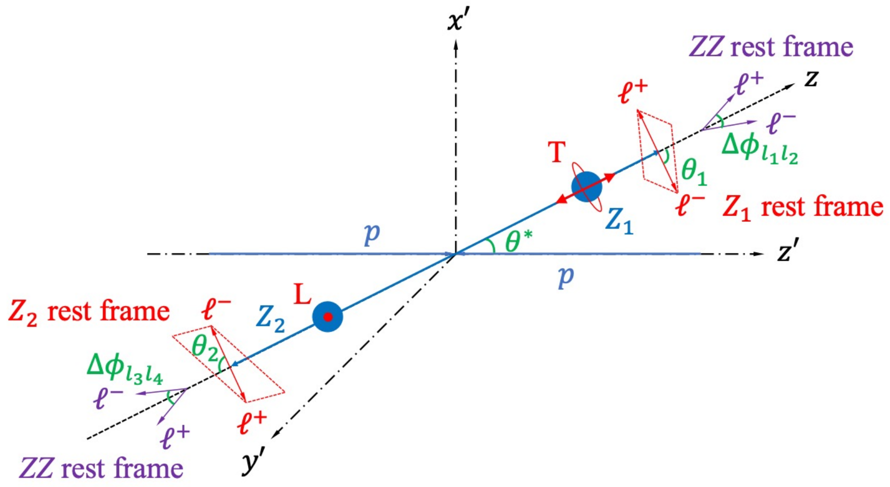


Introduction

- Joint polarization measurement of ZZ process in the four-lepton final state.
  - Partial Run-3 data (2022-2024), $L = 164\ \mathrm{fb}^{-1}$
  - Statistical combination with the full Run-2 analysis, $L = 140\ \mathrm{fb}^{-1}$ [JHEP 12 (2023) 107]
- Fiducial cross section measurement of $Z_L Z_L$ process.
- Measurement of the dependence of the LL component as a function of the di-boson invariant mass
  - Provide a crucial test of the EWSB mechanism and a sensitive probe of possible deviations from the SM.
- Polarization measured with angular variables ([1]$cos\theta$, [2]$cos\theta^*$,[3]$\Delta\phi$) in ZZ rest frame.
- Machine learning (BDT) was introduced to enhance the separation between LL and TX (TL, TT)



Signal processes



[1]Decay angles, [2]production angles, [3]azimuthal angle difference between leptons

Phase space definition

- Phase space formed with electrons and muons.
- Requires two same flavor opposite charge (SFOC) lepton pairs

Table 1: Summary of the event selection requirements.

Leptons	
Muons	$p_{\mathrm{T}} > 5$ GeV, $\lvert\eta\rvert < 2.5$
Electrons	$E_{\mathrm{T}} > 7$ GeV, $\lvert\eta\rvert < 2.47$
Lepton selection and quadruplet formation	
Lepton kinematics	$p_{\mathrm{T}} > 27/20$ GeV for the leading and sub-leading leptons
Lepton separation	$\Delta R_{ij} > 0.05$ for any two leptons
Low-mass $\ell^+\ell^-$ veto	$m_{ij} > 5$ GeV for all Same-Flavor, Opposite-Charge (SFOC) pairs
Quadruplet formation	Quadruplet with the smallest $\lvert m_{Z_1} - m_Z\rvert + \lvert m_{Z_2} - m_Z\rvert$
On-shell requirements	
On-shell Z boson	$\lvert m_{ij} - m_Z\rvert < 10$ GeV
On-shell ZZ pair	$m_{4l} > 180$ GeV
Signal region definition	
Signal region	The selected quadruplet contains 4 *signal* leptons
Low-mass signal region	$180 < m_{4l} < 240$ GeV
High-mass signal region	$m_{4l} \geq 240$ GeV

Event selections at detector level.
For the fiducial phase space, dressed muons and dressed electrons are used.

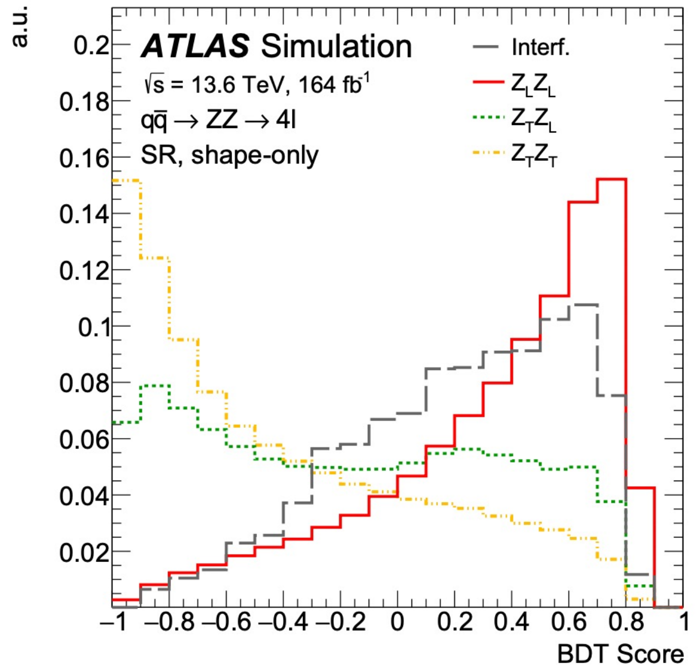
Signal modeling and backgrounds

- Polarized templates
  - qqZZ
    - MG LO polarized samples with NLO QCD + NLO EW corrections from MoCaNLO applied. baseline
    - Sherpa3 polarized qqZZ: Approximate NLO (nLO) QCD+PS, multi-jet merging. shape-only syst.
    - $\Longrightarrow$ Reweighted MG (baseline) + Sherpa3 (shape-only syst.)

    - Interference: reweighting the inclusive Sherpa 2 qqZZ using the fraction derived from Sherpa3 truth.

  - EW ZZjj
    - MG LO polarized samples

- Backgrounds
  - ggZZ, ttZ and triboson from MC
  - Fake background from the fake factor method.



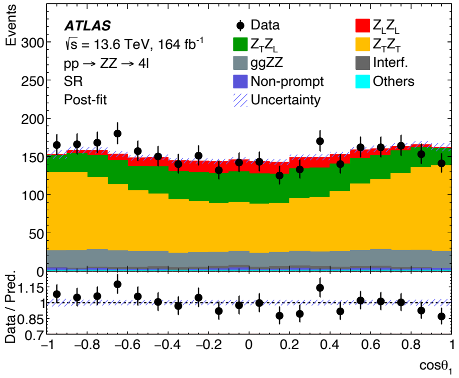
Comparison of BDT shape-only plots

Systematics

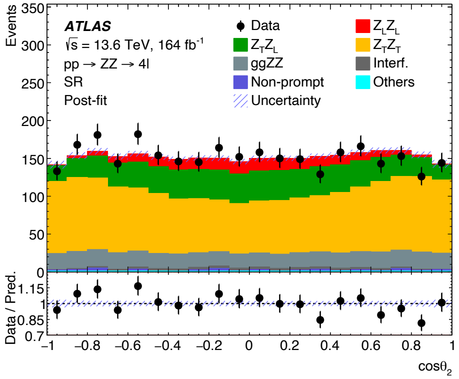
- $qq \to ZZ$
  - NLO EW, difference between multiplicative & additive.
  - NLO QCD, 7-point variation from MoCaNLO.
  - Parton shower, PDF + α_s
  - Shape difference between reweighted MG and Sherpa 3.
- $gg \to ZZ$
  - 60% flat uncertainty for missing high orders.
  - PDF + α_s.
- EW ZZjj
  - 7-point QCD scale uncertainty
  - PDF + α_s.
- Interference
  - 7-point QCD scale uncertainty
  - PDF + α_s.
  - the statistical uncertainties resulting from the subtraction of Sherpa 3 event weights
- Experimental systematics
  - Lepton momentum resolution and energy scale.
  - Lepton identification, isolation, reconstruction and trigger efficiency.
  - Pileup reweighting.
  - Luminosity, flat variation of 1.9%.
  - Trigger stat. and trigger sys.
- Background uncertainties.
  - Conservative variations of $\pm 40\%(15\%)$ on the cross section for triboson (ttZ).
  - Fake background
    - Statistic, FF systematic, MC systematic, fake composition uncertainty

Data/MC comparison

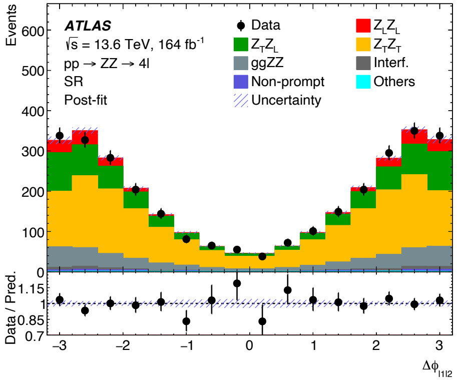
- Comparison



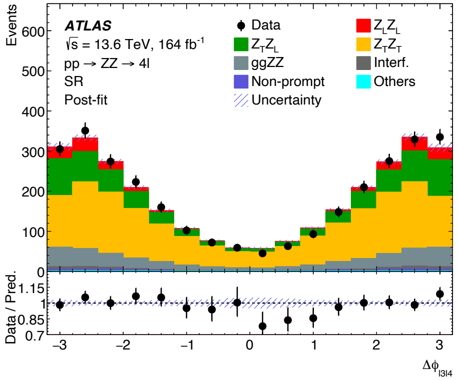
$cos\theta_1$



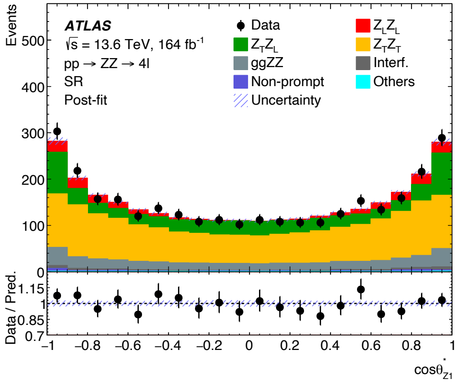
$cos\theta_2$



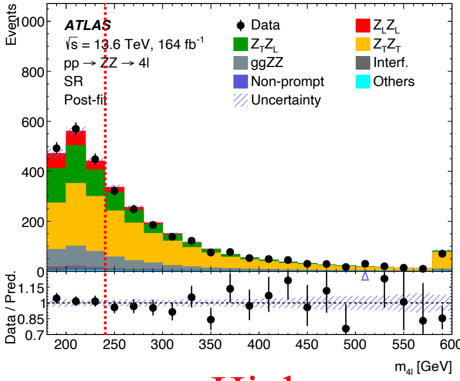
$\Delta\phi_{l1l2}$



$\Delta\phi_{l3l4}$

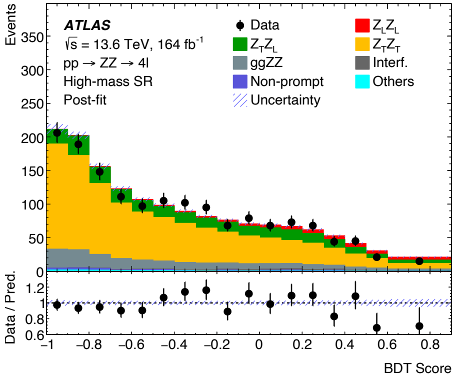


$cos\theta^*$

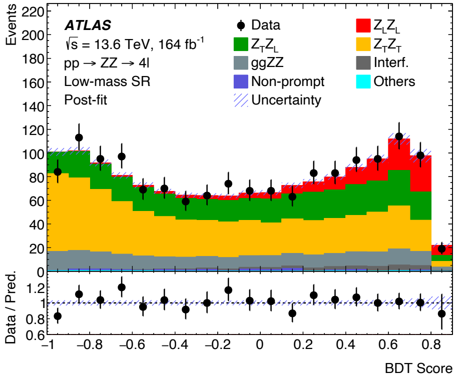


Low-mass High-mass

m_{4l}



BDT score in high-mass SR



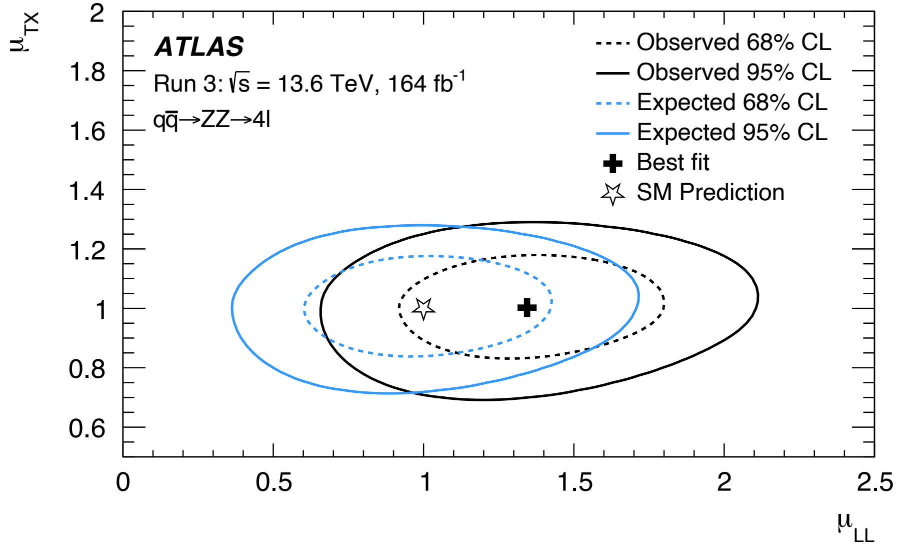
BDT score in low-mass SR

Process	Low-mass SR	High-mass SR
Z_LZ_L	154 ± 32	56 ± 12
Z_TZ_L	395 ± 32	268 ± 21
Z_TZ_T	665 ± 54	989 ± 77
Interference	31.1 ± 4.3	18.8 ± 2.8
$gg \to ZZ$	220 ± 110	196 ± 98
Non-prompt	15.3 ± 5.6	19.2 ± 6.5
Others	7.2 ± 1.3	14.1 ± 2.7
Total	1483 ± 36	1561 ± 32
Data	1510	1534

Observed and post-fit yields in SR.

LL signal strength and fiducial cross-section measurement

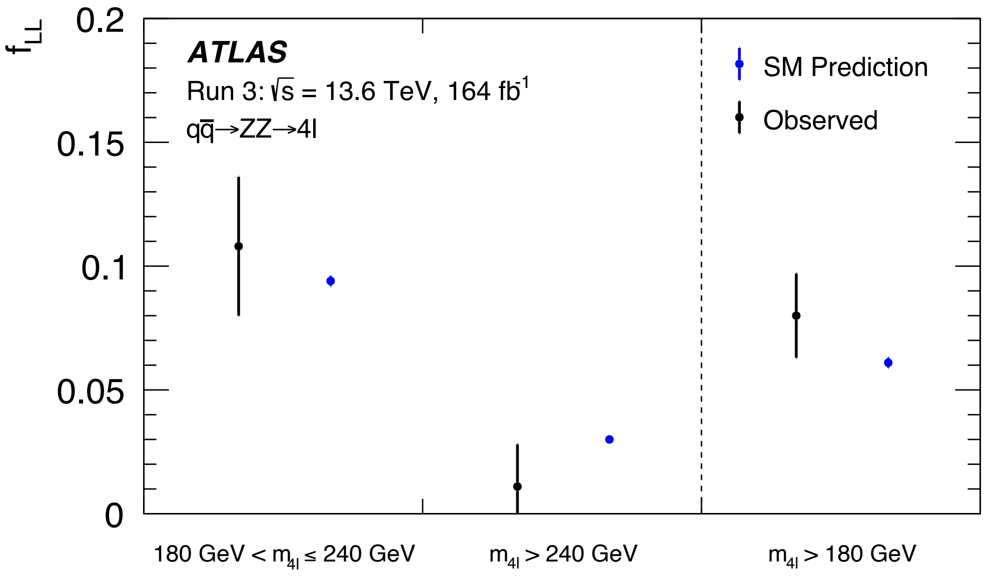
- Fit model — Floating parameters in the fit
  - $N_{data} = \mu_{LL} \cdot H_{LL} + \mu_{TX} \cdot H_{TX} + \sqrt{\mu_{LL} \cdot \mu_{TX}} \cdot H_{int} + H_{bkg}$
  - Input histogram templates (N is integral, h is the shape or normalized histogram)
    - $H_{LL} = N_{LL}^{SM} \cdot h_{LL};\ H_{TX} = N_{TX}^{SM} \cdot h_{TX};\ H_{int} = N_{int}^{SM} \cdot h_{int}$
- Fit results (exp.)
  - $\mu_{LL} = 1.00 \pm 0.27 = 1.00 \pm 0.24(stat.) \pm 0.12(syst.)$
  - $\mu_{TX} = 1.00 \pm 0.11$
- Fit results (obs.)
  - $\mu_{LL} = 1.34 \pm 0.29 = 1.34 \pm 0.26(stat.) \pm 0.13(syst.)$
  - $\mu_{TX} = 1.00 \pm 0.10$
- LL significance obs.(exp.): 5.1 (4.1) — First $Z_L Z_L$ observation
- Fiducial cross section measurement
  - $\sigma_{LL}^{Obs.} = 2.30 \pm 0.49\ \text{fb} = 2.30 \pm 0.45\ (\text{stat.}) \pm 0.19(\text{syst.})\ \text{fb}$
  - $\sigma_{LL}^{Pred.} = 1.71 \pm 0.11\ \text{fb}$
  - Limited by data statistical uncertainty.
  - The leading systematic uncertainty is from the theoretical modeling of the polarization templates.



The 2D contour for μ_{LL} versus μ_{TX}

LL fraction measurement

- Fit model   Floating parameters in the fit
  - $N_{data} = \mu_{ZZ} \cdot N_{incl}^{SM} \cdot \left[f_{LL} \cdot h_{LL} + f_{TX} \cdot h_{TX} + \kappa \cdot \sqrt{f_{LL} \cdot f_{TX}} \cdot h_{int}\right] + H_{bkg}$
    - $f_{LL} + f_{TX} + \kappa\sqrt{f_{LL} \cdot f_{TX}} = 1$
    - $\kappa = \frac{N_{int}^{SM}}{\sqrt{N_{LL}^{SM} \cdot N_{TX}^{SM}}}$
- Prediction.
  - $f_{LL} = 0.061 \pm 0.002$
  - $f_{LL.LM} = 0.094 \pm 0.002$
  - $f_{LL,HM} = 0.030 \pm 0.001$
- Obs.
  - $f_{LL} = 0.080 \pm 0.017$
  - $f_{LL.LM} = 0.108 \pm 0.028$
  - $f_{LL,HM} = 0.011 \pm 0.017$



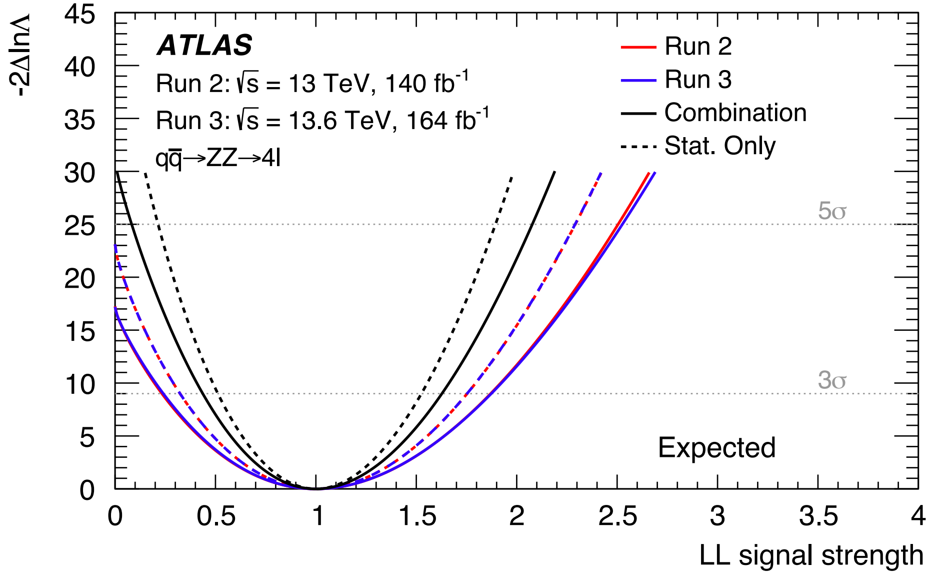
Comparison of the measured polarization fraction f_{LL} with the SM prediction in the low-mass, high-mass and inclusive m_{4l} range.

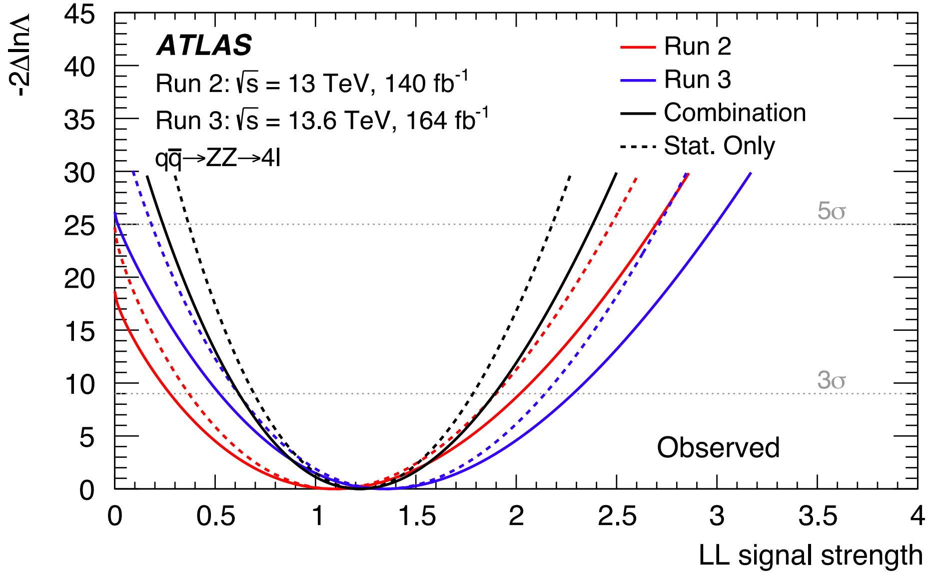
Combination

- Run-2 has been updated.
- LL significance
    - Run2 LL significance obs.(exp.): 4.3 (4.2)
    - Run3 LL significance obs.(exp.): 5.1 (4.1)
    - Combined LL significance obs. (exp.): 6.5 (5.6)

Table 6: Comparison of the original and updated Run 2 results used in the statistical combination.

	Original Run 2 [15]	Updated Run 2
Changes of the polarization modeling		
$gg \to ZZ$ treatment	Signal	Background
Interference modeling	Prediction from MoCaNLO	Prediction from Sherpa 3
$q\bar{q} \to ZZ$ modeling uncertainties	NLO reweighting observable choice and residual non-closure	Sherpa 3 shape difference
Change of results		
Expected LL signal strength	1.00 ± 0.27	1.00 ± 0.27
Observed LL signal strength	1.15 ± 0.29	1.09 ± 0.29
Expected LL significance	3.8	4.2
Observed LL significance	4.3	4.3





Summary

- The production of two simultaneously longitudinally polarized Z bosons has been measured.
  - Partial Run-3 data (2022-2024), $L = 164\ \text{fb}^{-1}$
  - Run-3 LL significance obs.(exp.): 5.1 (4.1)
- The inclusive $Z_L Z_L$ fraction is measured for the first time.
  - Obs. (exp.): $f_{LL} = 0.080 \pm 0.017\ (0.061 \pm 0.002)$
- The production cross-section of $Z_L Z_L$ events is measured in a fiducial phase space.
  - $\sigma_{LL}^{Obs.} = 2.30 \pm 0.49\ \text{fb} = 2.30 \pm 0.45\ (\text{stat.}) \pm 0.19 (\text{syst.})\ \text{fb}$
  - $\sigma_{LL}^{Pred.} = 1.71 \pm 0.11\ \text{fb}$
- With a statistical combination of the previous study using Run-2 data ($L = 140\ \text{fb}^{-1}$)
  - The first observation of two longitudinally polarized Z bosons is achieved
  - Combined LL significance obs. (exp.): 6.5 (5.6)
- Submitted to Phys. Rev. Lett.
  - arxiv: 2607.12879

Backup