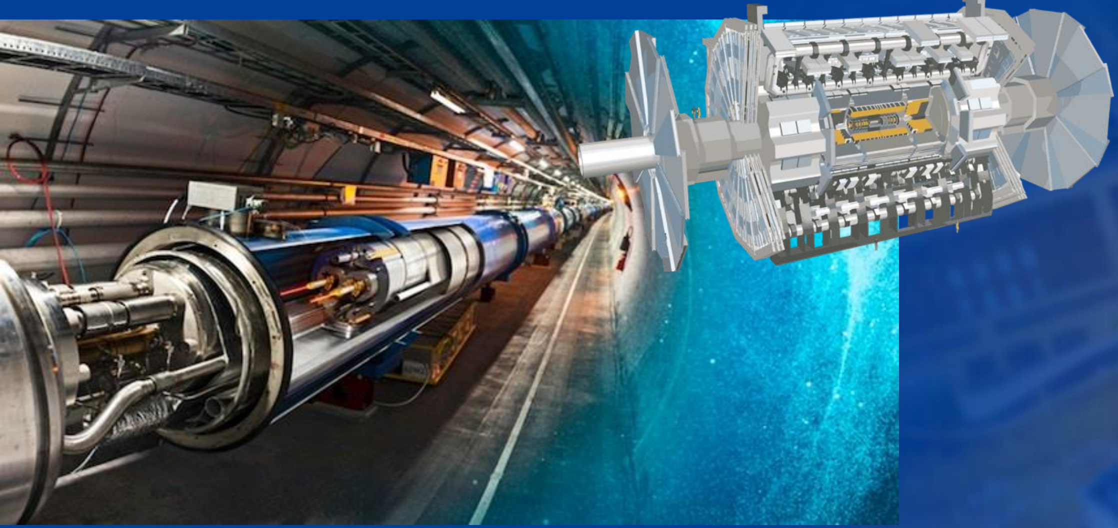
Recent Multi-Boson and Multi-Higgs Results from ATLAS



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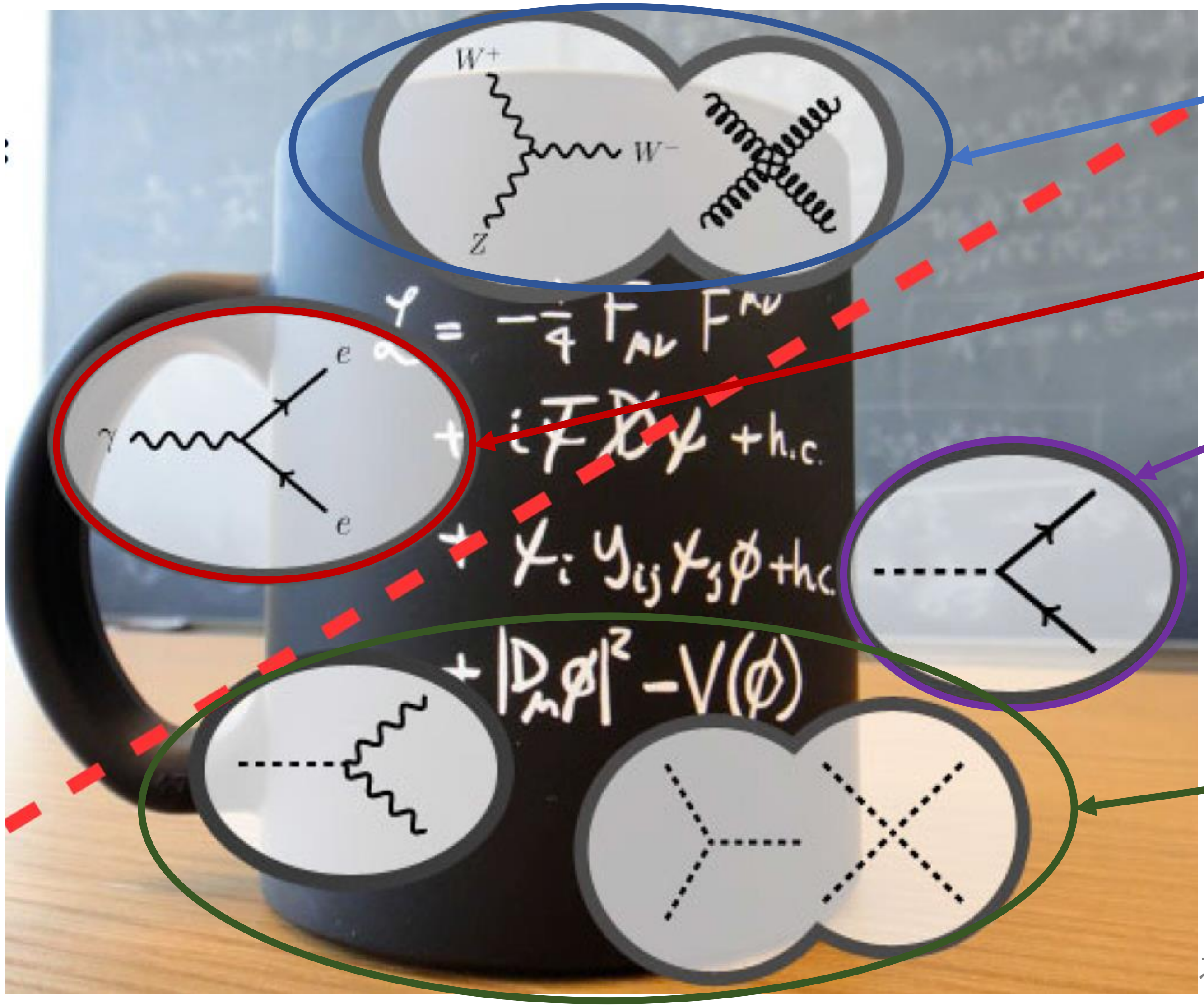
新物理前沿与交叉科学研讨会 (NPhiS2026)

2026.05.17

Keys to deepen the understanding of Standard Model

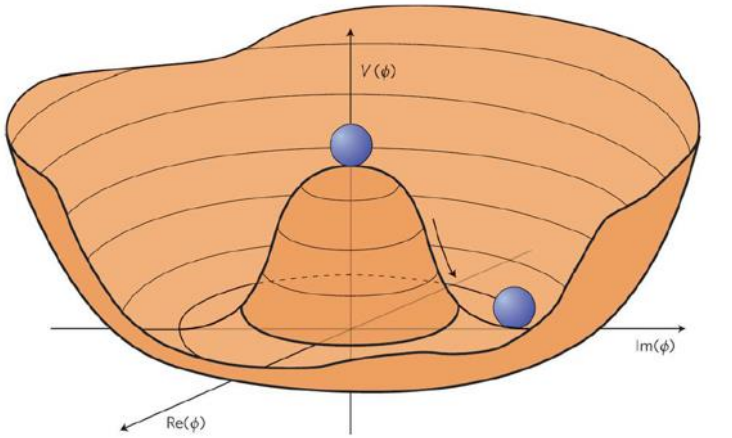


Electroweak/Strong (Gauge Boson Self-Interactions)

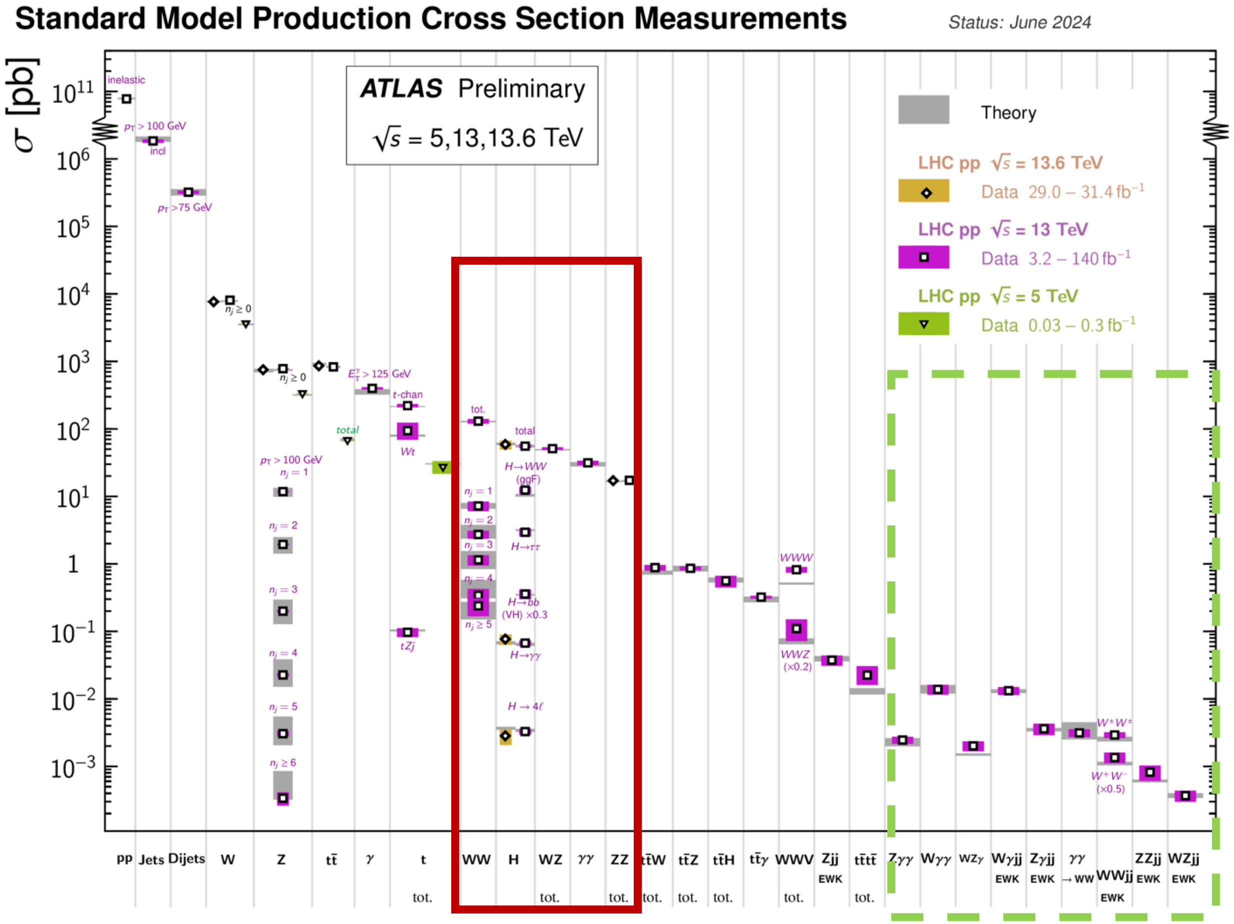
Gauge Bosons Interact with Fermions (Leptons & Quarks)

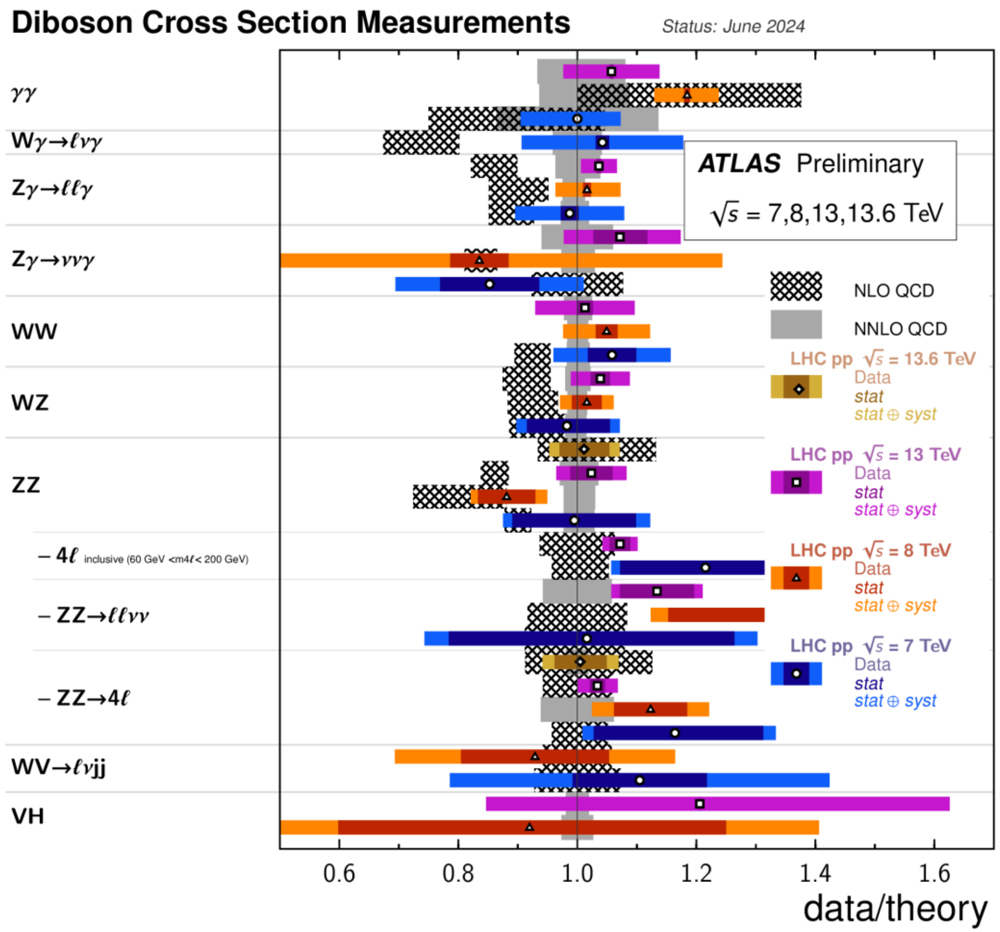
Higgs Yukawa Couplings (Origin of Masses for Leptons and Quarks)

EWSB (Origin of Weak Boson Mass), Higgs Potential (Higgs Self-Interactions)



Summary of ATLAS Diboson measurements

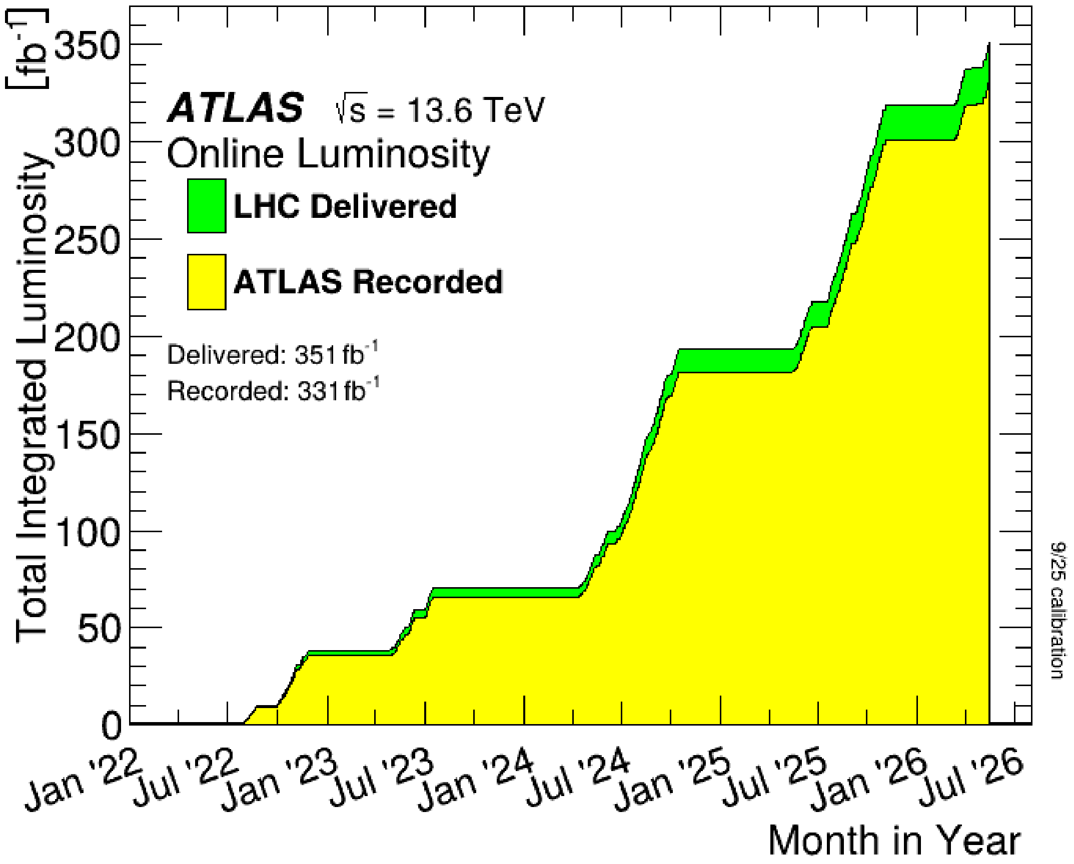


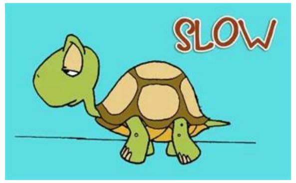


Diboson Physics at ATLAS:

Test of SM EWK Sector w/ high precision and as solid foundation for VBS and triboson measurements; examine perturbative QCD and EW high order effects; irreducible backgrounds for H→VV decays and other related BSM searches; sensitive to anomalous Triple Gauge Couplings (aTGCs) with SMEFT; ...

ATLAS Run-3 data-taking in-action!





Standard Model Measurements are slow but precise!
Stay tuned ☺
(check out 1st Run3 ZZ results by ATLAS: *Phys. Lett. B 855 (2024) 138764*)

PART 01

Inclusive Di-Boson (precision)

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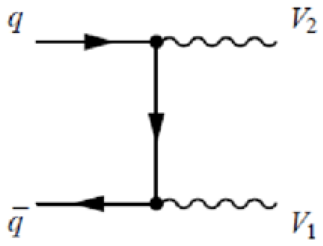
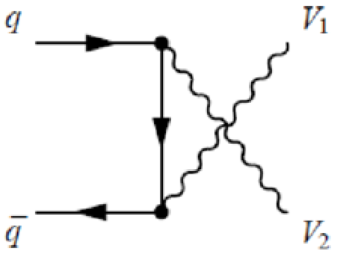
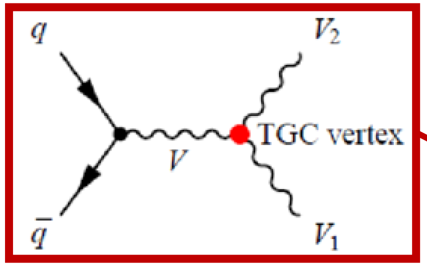
Diboson as main course starter



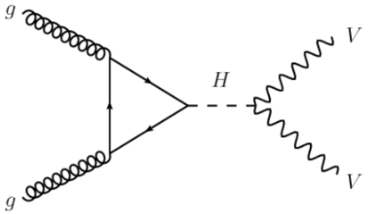
t-channel

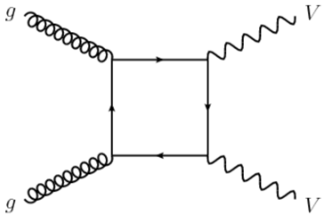


u-channel



s-channel





Wilson coefficient
(coupling strength)

Higher-dimensional Operator
(new/altered interaction)

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{c_i^{(5)}}{\Lambda} O_i^{(5)} + \sum_i \frac{c_i^{(6)}}{\Lambda^2} O_i^{(6)} + \dots$$

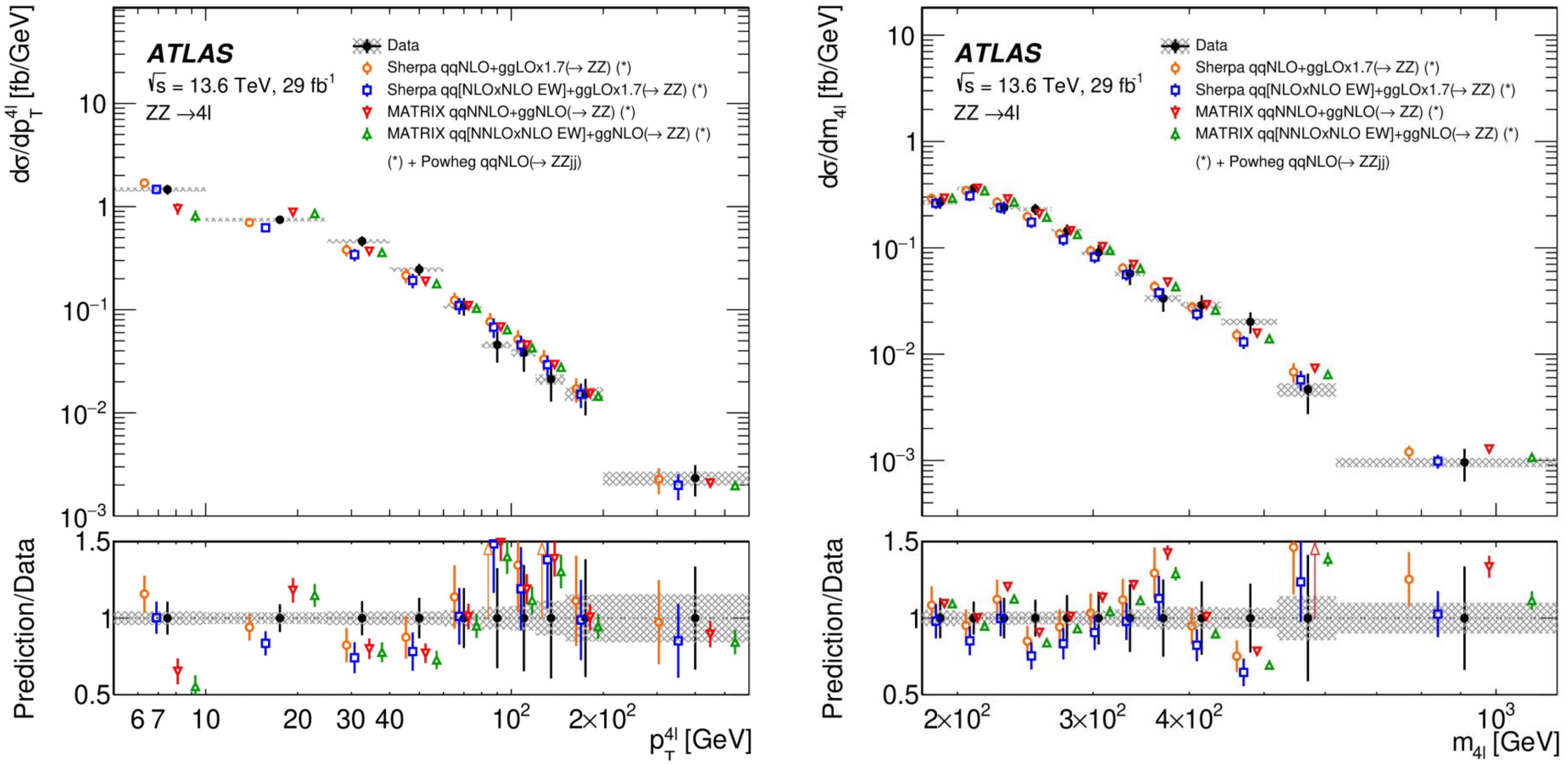
SM Lagrangian
(dimension four)

Mass scale of new physics

Phys. Lett. B 855 (2024) 138764

1st ZZ→4l total and differential measurements at 13.6TeV w/ ATLAS Run3

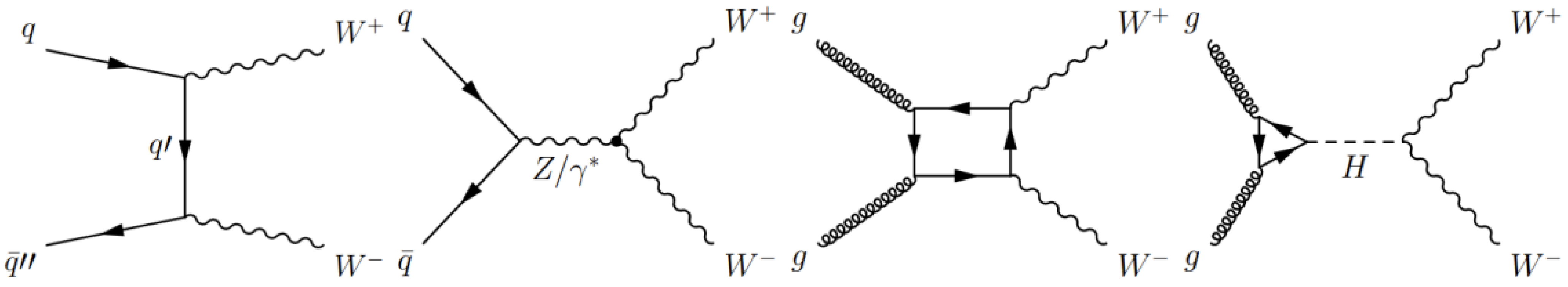
- ATLAS 1st diboson results in Run3 w/ 29 fb^{-1} DATA at 13.6 TeV: a milestone for LHC Run3 EWK physics
- $m_{4\ell}$ and $p_{\mathrm{T}}^{4\ell}$ differential cross sections measured in comparison with Sherpa and MATRIX prediction with both state-of-art MC simulations and fixed order calculations up to NNLO QCD+NLO EW
- Fid. & Tot. cross sections also measured w/ comparable stat. vs syst. unc. driving future full Run3 measurements into higher precision



	Measurement	MC prediction	MATRIX + EW $ZZjj$
Fiducial	36.7 ± 1.6(stat) ± 1.5(syst) ± 0.8(lumi) fb	$36.8\,^{+4.3}_{-3.5}$ fb	36.5 ± 0.7 fb
Total	16.8 ± 0.7(stat) ± 0.7(syst) ± 0.4(lumi) pb	$17.0\,^{+1.9}_{-1.4}$ pb	16.7 ± 0.5 pb

WW with ATLAS Full Run-2 13TeV

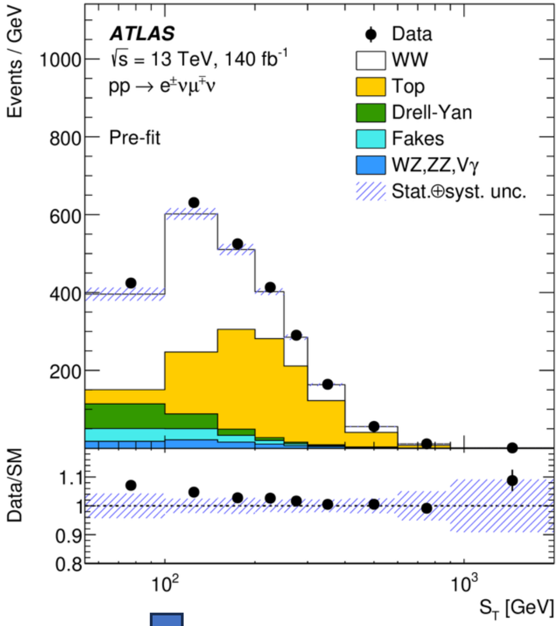
- WW total, fiducial and differential cross section measurements w/ ATLAS Full Run2 DATA (140 fb^{-1}) in fully leptonic final states (diff. flavor & oppo. charge to suppress Drell-Yan bgds)
- **Highlights:**
  - 12 measured observables: $p_T^{\text{lead lep.}}$, $p_T^{\text{sub-lead lep.}}$, $p_T^{e\mu}$, $y_T^{e\mu}$, $m_{e\mu}$, $\Delta\varphi_{e\mu}$, $\cos\theta^* = |\tanh(\Delta\eta(e,\mu)/2)|$, E_T^{miss}, $m_{T,e\mu}$, $H_T^{\text{lep.+MET}}$, S_T, N_{jet}
  - Jet incl. phase space measured w/ high precision (~3.1% unc.)
  - **Evidence of central-forward charge asymmetry**
  - Comparison w/ State-of-Art theory predictions w/ NNLO QCD and NLO EWK (along w/ NLO-QCD gg and γ-induced corrections) and new PDF



WW with ATLAS Full Run-2 13TeV

	Requirement	Criteria
Electron	p_T	> 27 GeV
	$\lvert\eta\rvert$	$\in [0\,, 1.37) \cup (1.52\,, 2.47)$
	Identification	`TightLH` working point
	Isolation	`Gradient`
	Impact parameters	$\lvert d_0/\sigma_{d_0}\rvert < 5$; $\lvert z_0 \cdot \sin\theta\rvert < 0.5$ mm
Muon	p_T	> 27 GeV
	$\lvert\eta\rvert$	< 2.5
	Identification	`Medium` working point
	Isolation	`Tight_FixedRad`
	Impact parameters	$\lvert d_0/\sigma_{d_0}\rvert < 3$; $\lvert z_0 \cdot \sin\theta\rvert < 0.5$ mm
b-jets	p_T	> 20 GeV
	$\lvert\eta\rvert$	< 2.5
	Pile-up suppression	jet-vertex tagger for $p_\mathrm{T} < 60$ GeV and $\lvert\eta\rvert < 2.4$
	b-tagging	DL1r, 85% efficiency working point
Jets	p_T	> 30 GeV
	$\lvert\eta\rvert$	< 4.5
	Pile-up suppression	jet-vertex tagger for $p_\mathrm{T} < 60$ GeV and $\lvert\eta\rvert < 2.4$
Event	Leptons	1 electron and 1 muon of opposite electric charge; no additional lepton with $p_\mathrm{T} > 10$ GeV, `Loose` isolation, and `LooseLH` (electron) / `Loose` (muon) identification
	Number of b-jets	0
	$m_{e\mu}$	> 85 GeV

Major phase space cuts, veto b-jet but no further jet veto

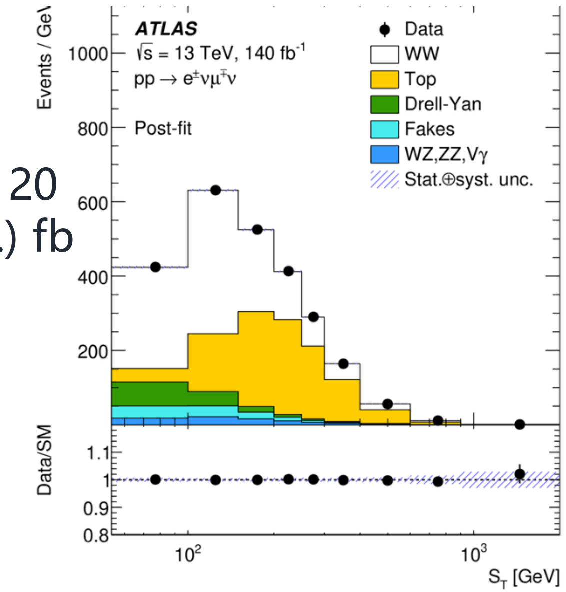


- Int. fid. cross-section determined using profile likelihood fit of S_T distribution
- Fid. Phase space:

Object	Requirement	Criteria
Prompt lepton	p_T	> 27 GeV
	$\lvert\eta\rvert$	< 2.5
Loose lepton	p_T	> 10 GeV
	$\lvert\eta\rvert$	< 2.5
b-jets	p_T	> 20 GeV
	$\lvert\eta\rvert$	< 2.5
Jets	p_T	> 30 GeV
	$\lvert\eta\rvert$	< 4.5
Event	Leptons	1 prompt electron and 1 prompt muon of opposite electric charge. No additional loose leptons
	Number of b-jets	0
	$m_{e\mu}$	> 85 GeV

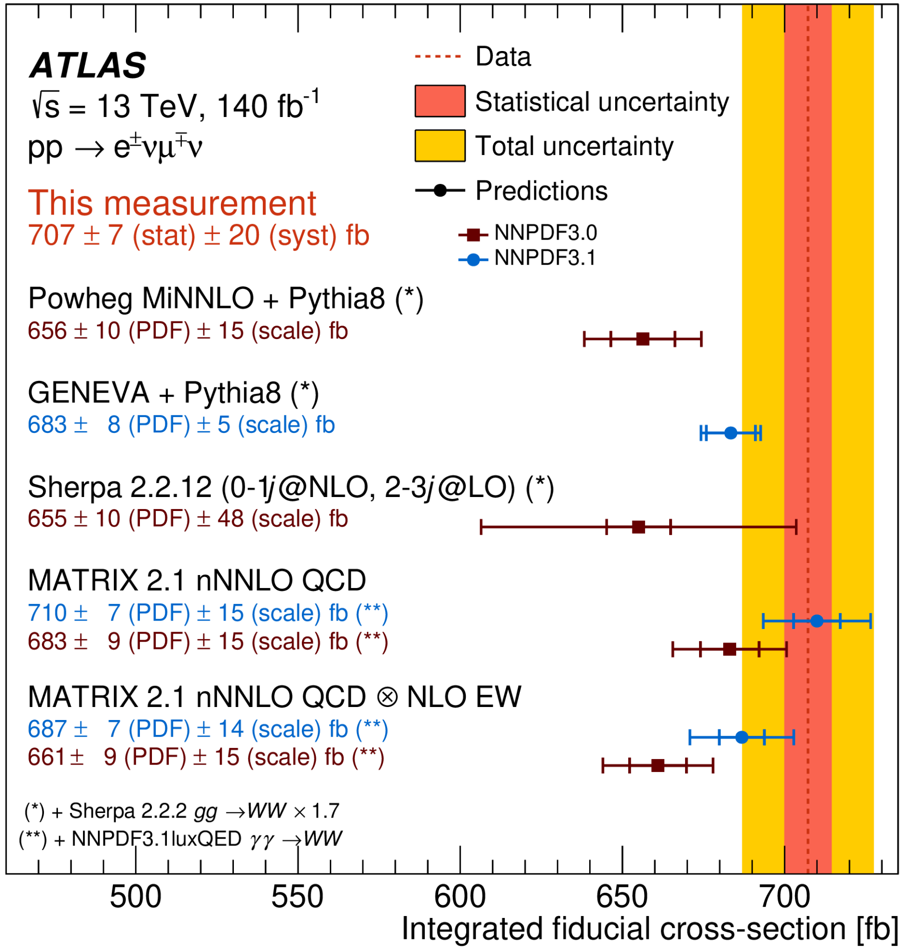
$\sigma_{\text{fid.}}$ = 707 ± 7 (stat.) ± 20 (syst.) ± 6 (lumi.) fb

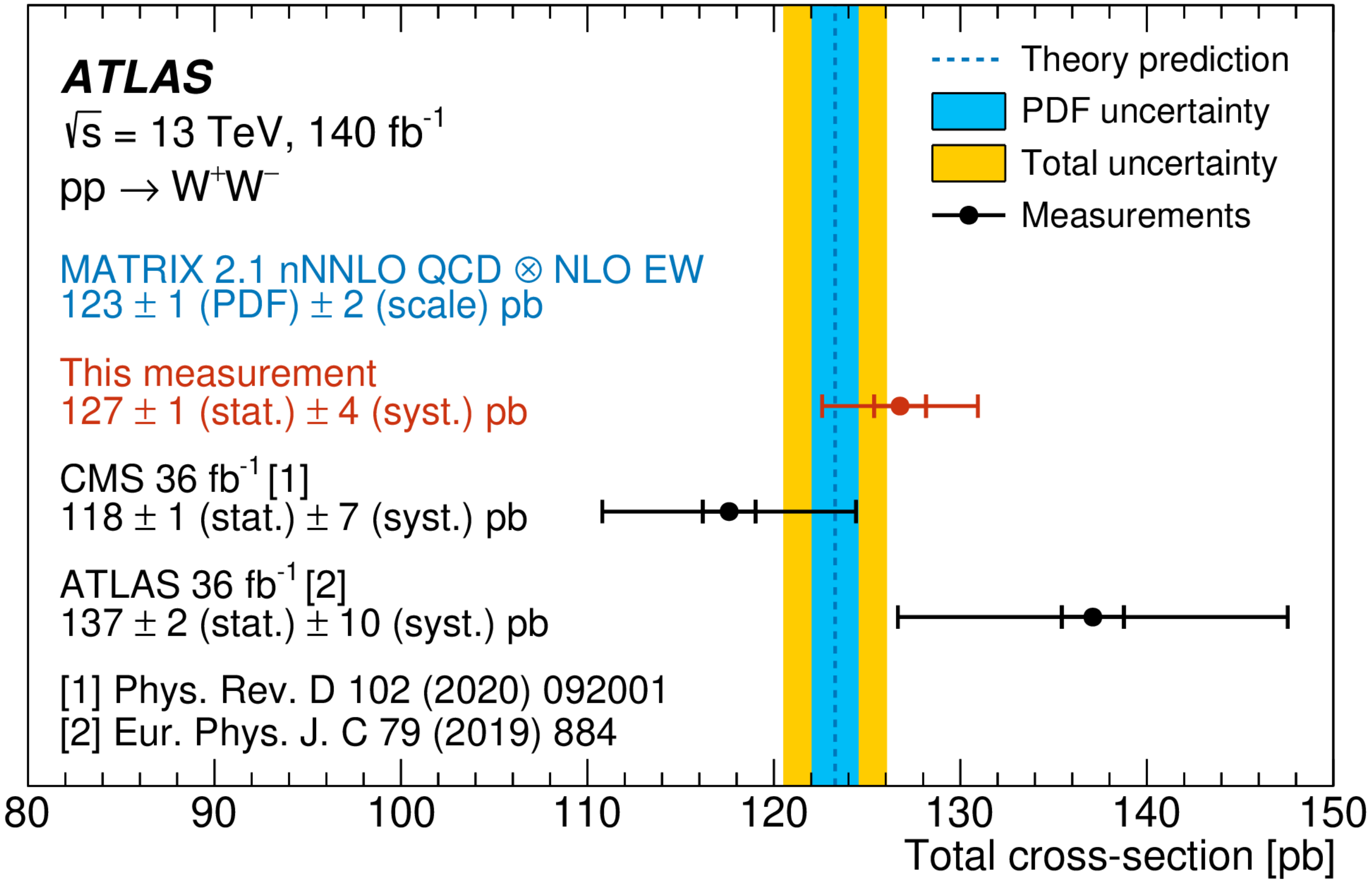
Post-fit



WW with ATLAS Full Run-2 13TeV

- Measured fid./tot. cross sections consistent w/ MOST precise theo. predictions: nNNLO QCD ⊗ NLO EW using NNPDF3.1 luxQED (better agreement compared w/ NNPDF3.0 PDF)





JHEP 08 (2025) 142

WW with ATLAS Full Run-2 13TeV

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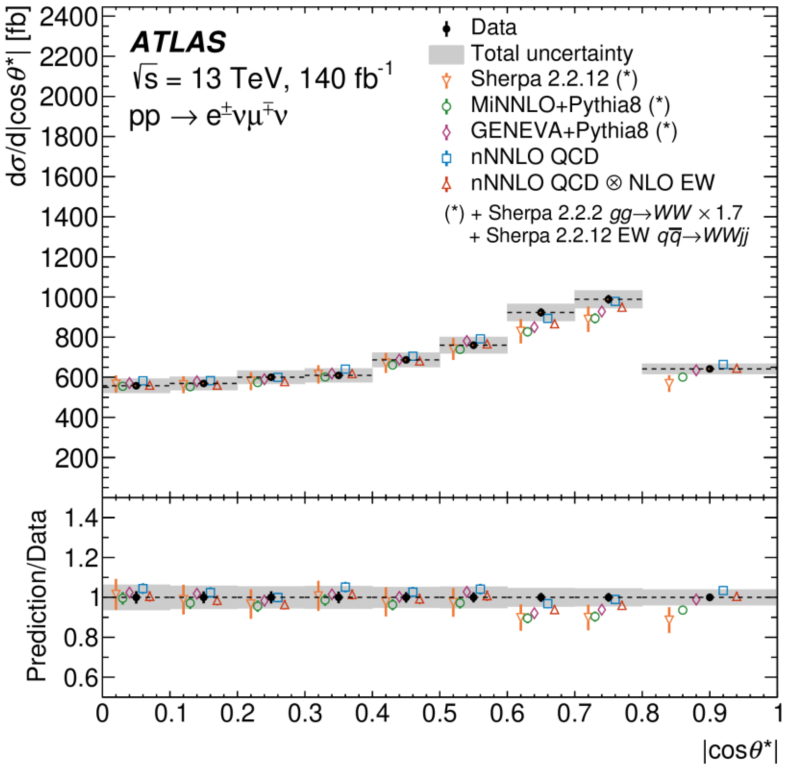
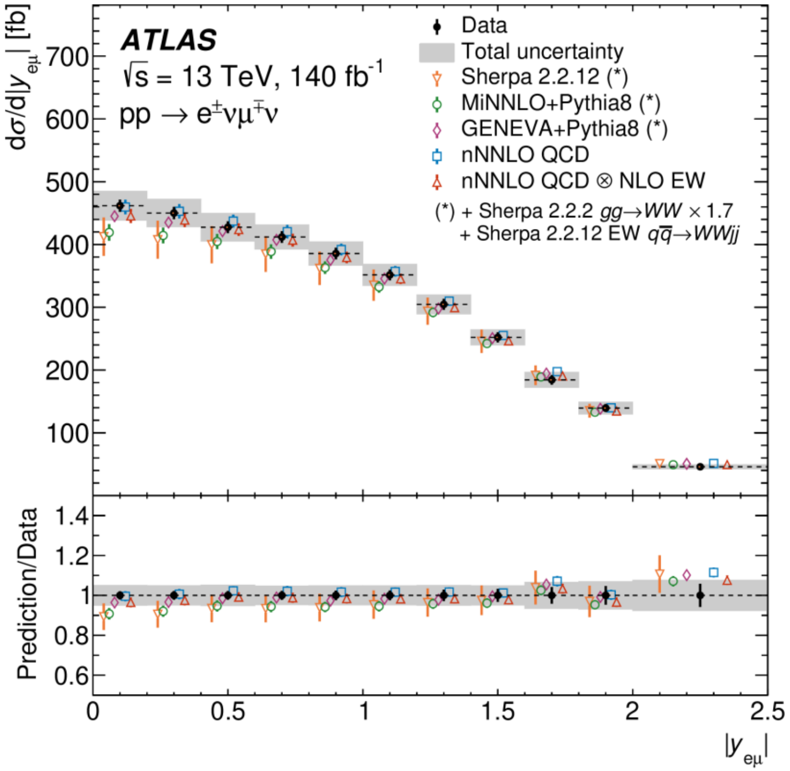
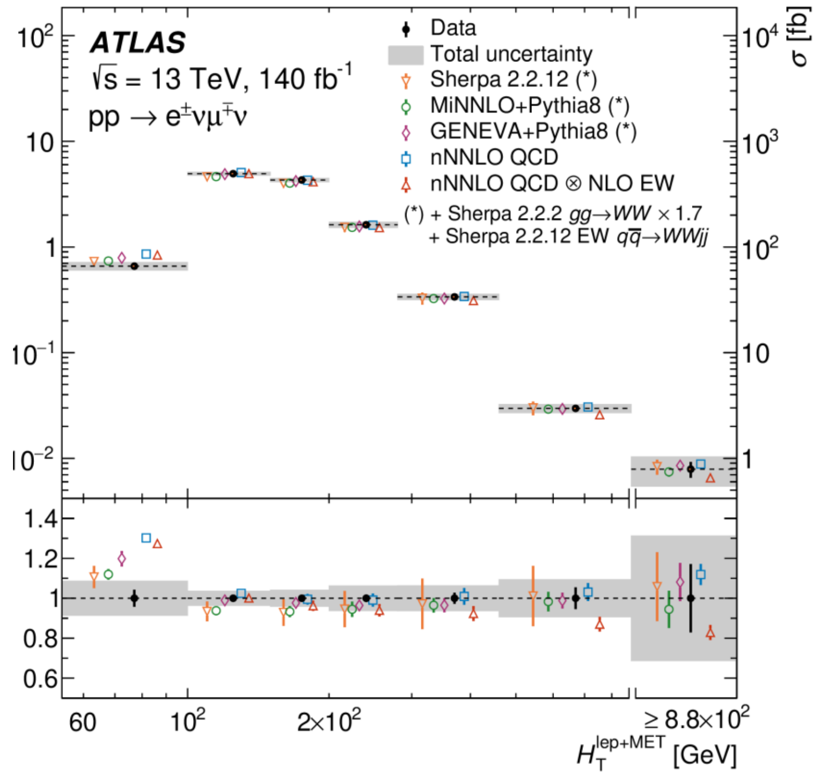
$|\cos\theta^*| = |\tanh(\Delta\eta_{e\mu}/2)|$
Sensitive to WW spin structure

$|y_{e\mu}|$
Absolute rapidity of the dilepton system

$H_T^{\text{lep.+MET}}$
scalar sum of E_T^{miss} and the lepton transverse momenta

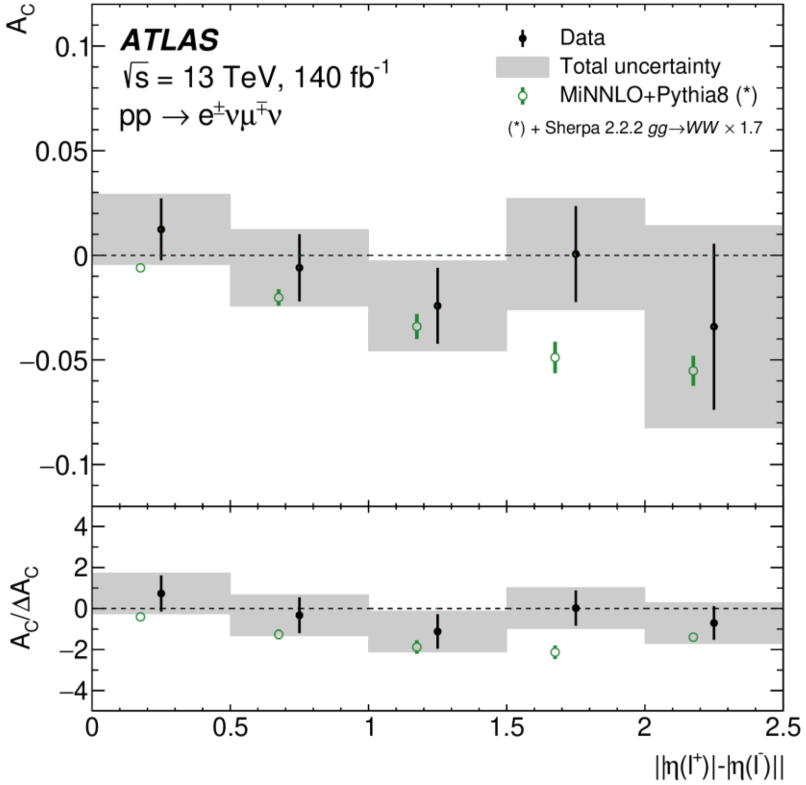


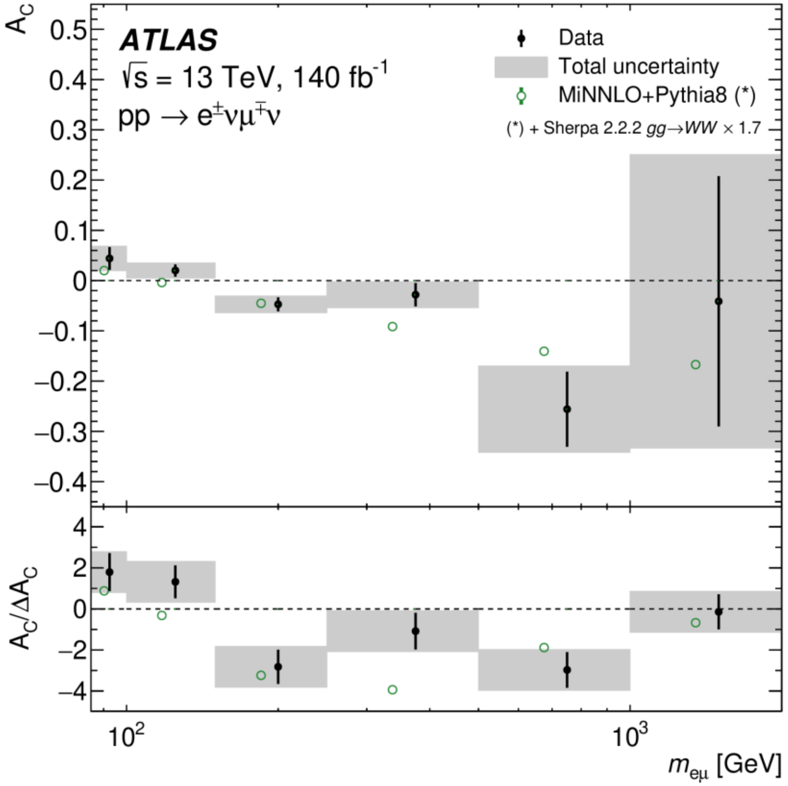




- Differential cross sections measured in general w/ excellent agreement at fixed-order, compared w/ MATRIX prediction jet-inclusively
- Most notable discrepancy is a local 3σ difference in the lowest bin of the H_T distribution

WW with ATLAS Full Run-2 13TeV





$$A = \frac{\sigma_{\rm fid}^{x>0} - \sigma_{\rm fid}^{x<0}}{\sigma_{\rm fid}}$$

$$A_C = -0.004 \pm 0.008\ (\text{stat.}) \pm 0.006\ (\text{syst.})$$

A_C: non-zero due to charge asymmetry of the partonic initial state

$$A_{CP} = 0.014 \pm 0.008\ (\text{stat.}) \pm 0.008\ (\text{syst.})$$

A_{CP}: asymmetry in CP-odd observable

$$O_z = \left((\vec{p}_{\ell^-} \times \vec{p}_{\ell^+})_z \,\text{sign}\left(p_{\ell^-,z} - p_{\ell^+,z}\right) \right)$$

consistent w/ SM prediction (zero) within ~1σ

- Charge asymmetry A_C measured as a function of absolute difference of leptons absolute rapidities $||\eta_{\ell+}| - |\eta_{\ell-}||$, and invariant mass of the dilepton system
- Compared w/ the NNLO+PS predictions from Powheg MiNNLO+Pythia8
- **Significant asymmetry seen for 1st time!** (due to 2:1 ratio of up:down valence quarks)

WZ with ATLAS Full Run-2 13TeV

- Follow up previous partial Run-2 WZ measurements (*Eur. Phys. J. C 79 (2019) 535*) and Full Run-2 WZ joint polarization (*Phys. Lett. B 843 (2023) 137895*) & high PT polarization measurements (*Phys. Rev. Lett. 133 (2024) 101802*)
- More precise measurements of incl. and differential cross sections w/ ATLAS Full Run-2 dataset (140 fb^{-1}), in comparison w/ NNLO QCD and NLO EWK state-of-art SM predictions
- Probing CP-conserving and CP-violating dimension-6 operators with m_T^{WZ} (low/high categorized)

Variable	Fiducial inclusive
Lepton $\lvert\eta\rvert$	< 2.5
p_T of ℓ_Z, p_T of ℓ_W [GeV]	> 15, > 20
m_Z range [GeV]	$\lvert m_Z - m_Z^{PDG}\rvert < 10$
m_T^W [GeV]	> 30
$\Delta R(\ell_Z^-, \ell_Z^+)$, $\Delta R(\ell_Z, \ell_W)$	> 0.2, > 0.3

Inclusive event selection	
ZZ veto	Less than 4 loose leptons
N leptons	Exactly three leptons passing the medium lepton selection
Leading lepton p_T	$p_T^{lead} > 25$ GeV (in 2015) or $p_T^{lead} > 27$ GeV (2016–2018)
Z leptons	Two same flavor oppositely charged leptons passing the medium lepton selection
Mass window	$\lvert M_{\ell\ell} - M_Z\rvert < 10$ GeV
W lepton	Remaining lepton passes the tight lepton selection
W transverse mass	$m_T^W > 30$ GeV

JHEP 11 (2025) 006

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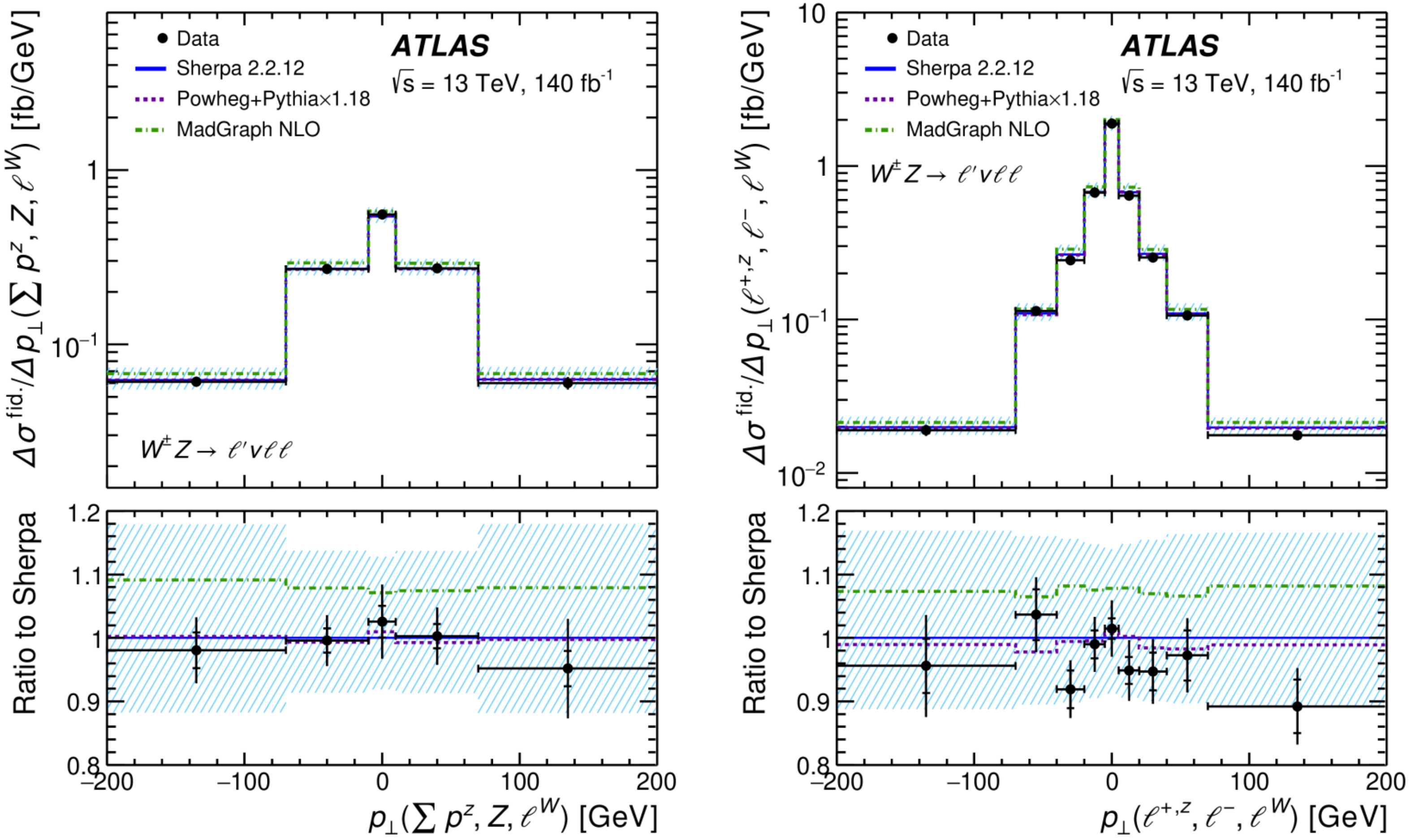
WZ with ATLAS Full Run-2 13TeV

New variables added for diff. measurements w.r.t. former results

- p_T^Z
- p_T^W
- $m_T^{WZ} \rightarrow$ thinner binning
- p_T^{ν}
- $|y_Z - y_{\ell,W}|$
- $\Delta\phi(W,Z)$
- $\Delta\phi(\ell^W, Z)$
- $p_T^{V_1}$
- $p_T^{V_2}$
- ϕ_W^*
- ϕ_Z^*
- $p_\perp(\sum \hat{p}^z, Z, \ell^W)$
- $p_\perp(\ell^{+,z}, \ell^-, \ell^W)$
- N_{jets}
- m_{jj}

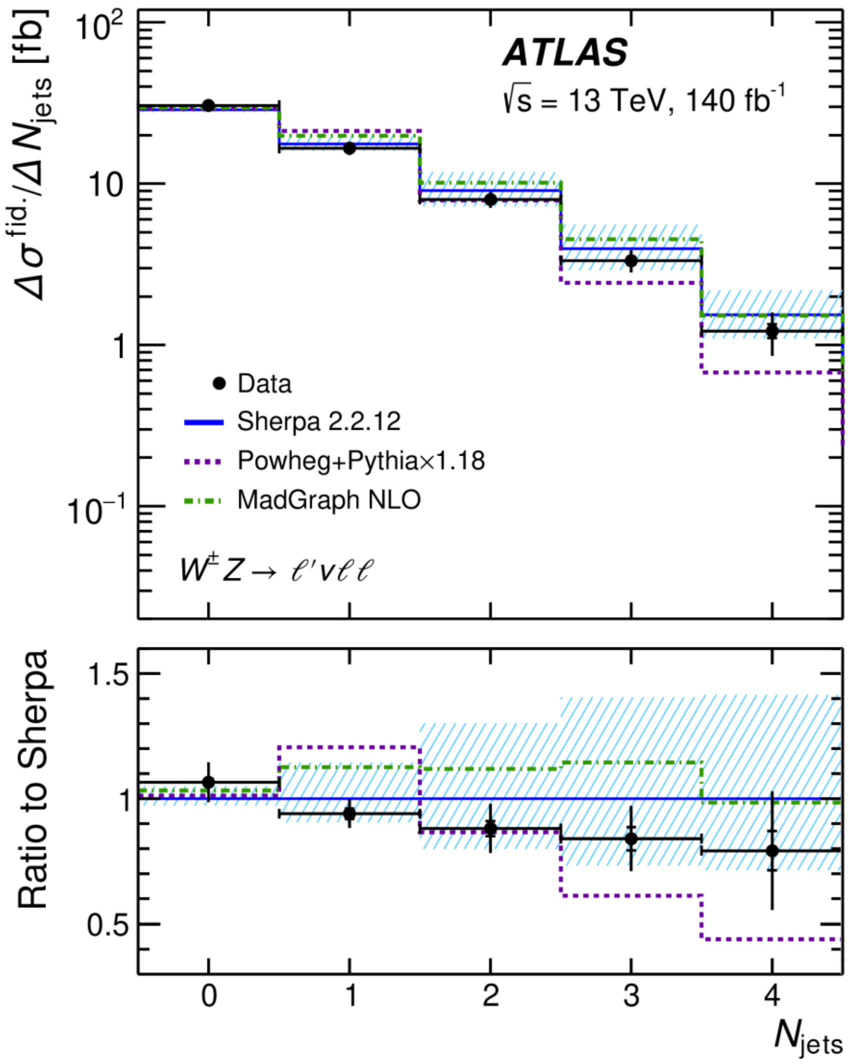


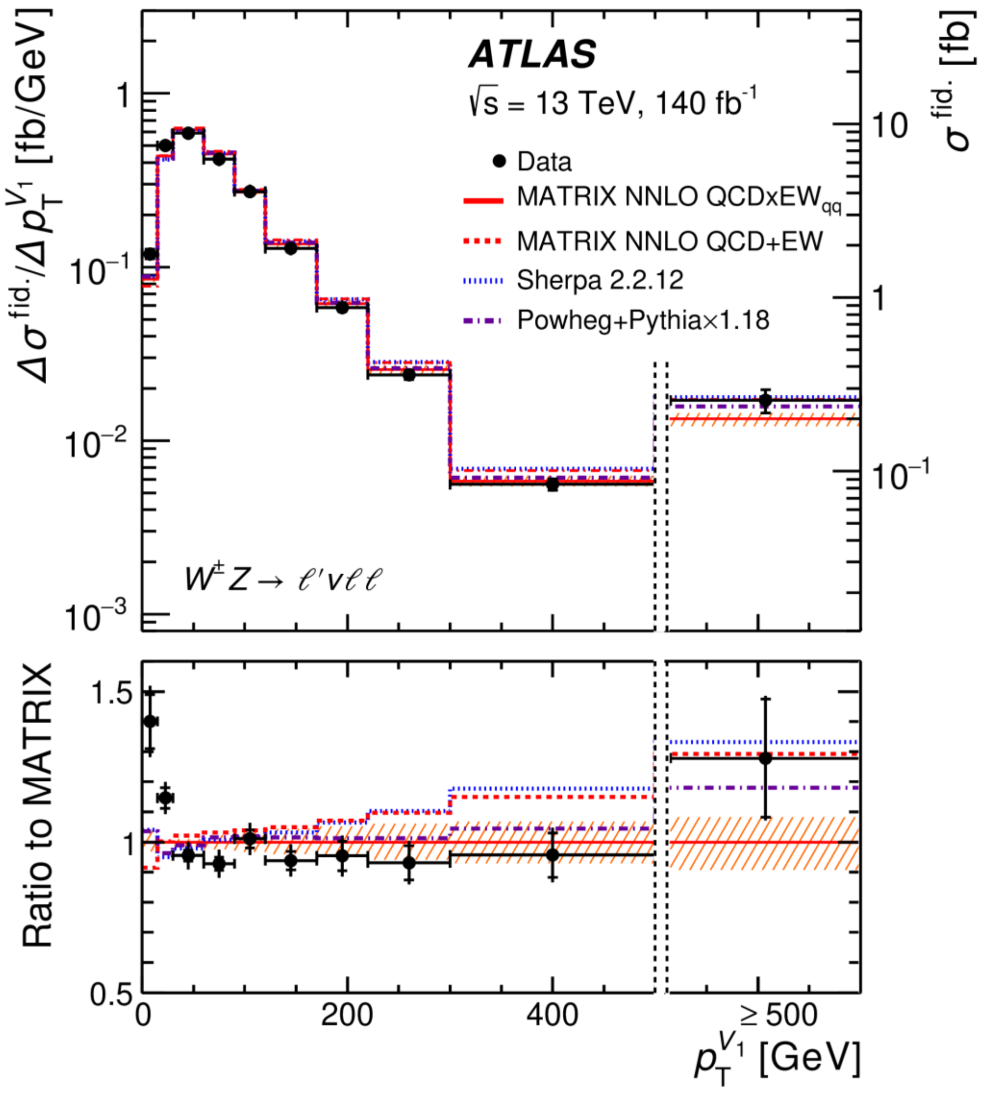
NEW!

Triple products are sensitive to CP-Violating SMEFT operators!

JHEP 11 (2025) 006

WZ with ATLAS Full Run-2 13TeV





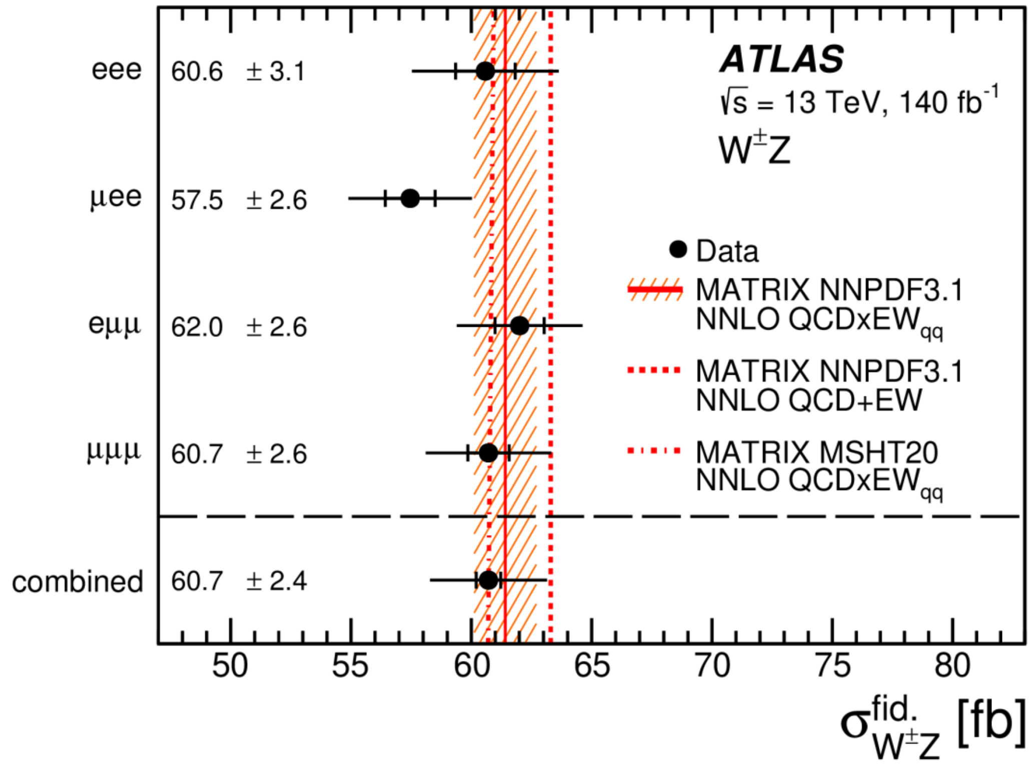
- MATRIX ⊕ vs ⊗ schemes differ at high p_T^{V1}
- Sherpa has a more complete description in high N_{jets} differing from PowHeg+Pythia
- Very low p_T discrepancies possibly explained by large logarithms in p_T/m_{VV}

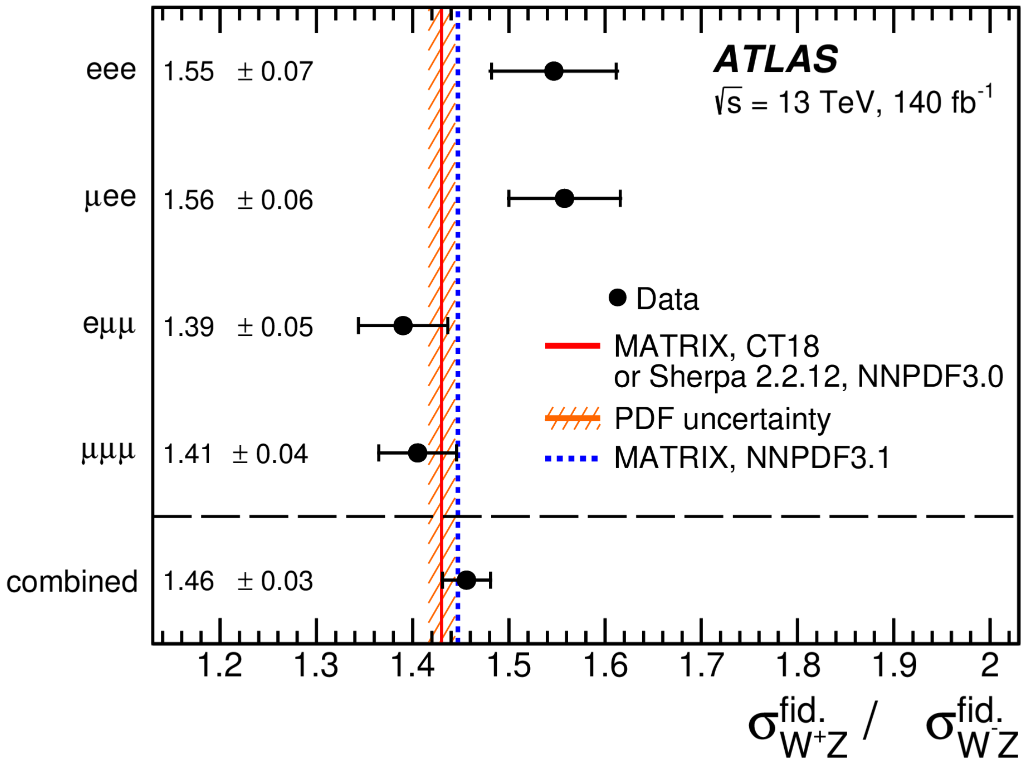
JHEP 11 (2025) 006

WZ with ATLAS Full Run-2 13TeV

$$\sigma^{\text{fid.}}_{W^\pm Z\to\ell'\nu\ell\ell} = 60.7 \pm 0.5\,(\text{stat.}) \pm 1.4\,(\text{exp. syst.}) \pm 1.8\,(\text{mod. syst.}) \pm 0.6\,(\text{lumi.})\ \text{fb}$$

$$\frac{\sigma^{\text{fid.}}_{W^+Z\to\ell'\nu\ell\ell}}{\sigma^{\text{fid.}}_{W^-Z\to\ell'\nu\ell\ell}} = 1.456 \pm 0.025\,(\text{stat.}) \pm 0.010\,(\text{syst.})$$





- Measured WZ fid. cross sections in agreement w/ NNLO QCD⊗EW_{qq} SM prediction from MATRIX using the NNPDF3.1nnlo_as_118_luxqed PDF and MSHT20nnlo PDF
- Measurement of charge ratio w/ ~2% precision (stat. limited)

JHEP 11 (2025) 006

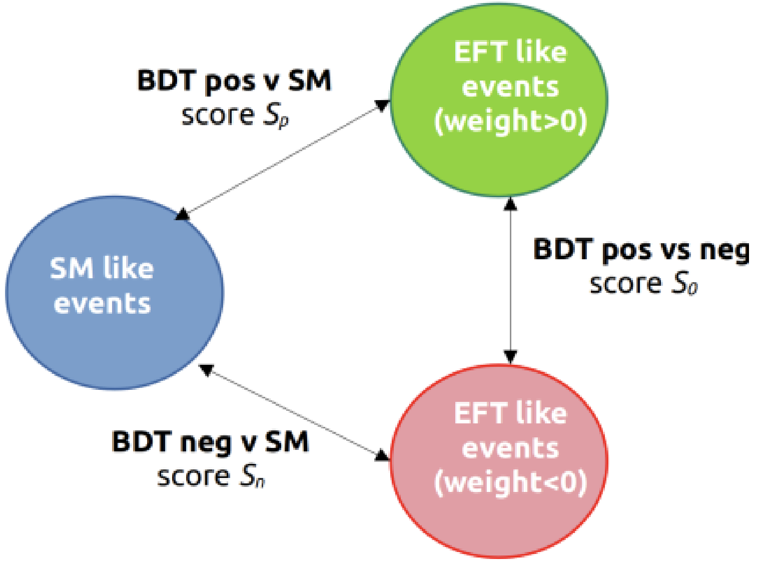
WZ with ATLAS Full Run-2 13TeV

CP-conserving EFT limits extracted with m_T^{WZ} distribution

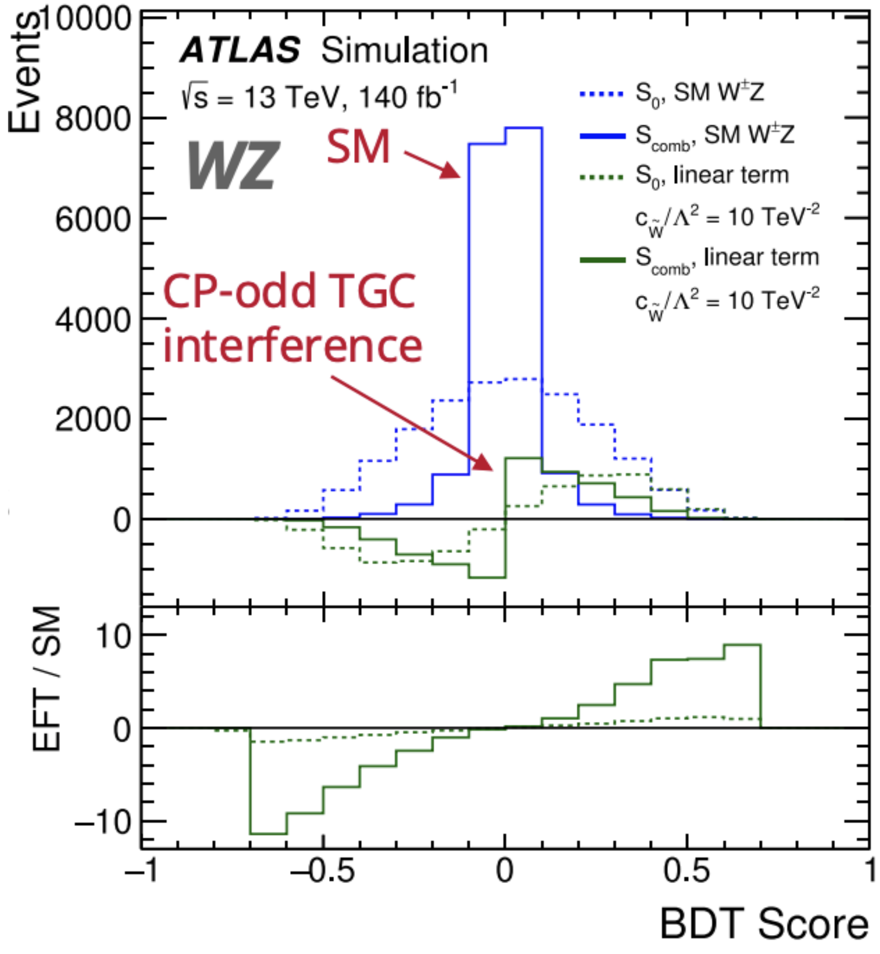
- c_W, c_{HWB}, c_{HD}, $c^{(1)}_{Hq}$, $c^{(3)}_{Hq}$

CP-violating EFT (**Strong!**) limits: BDTs for each operator to enhance sensitivity to CP-violation

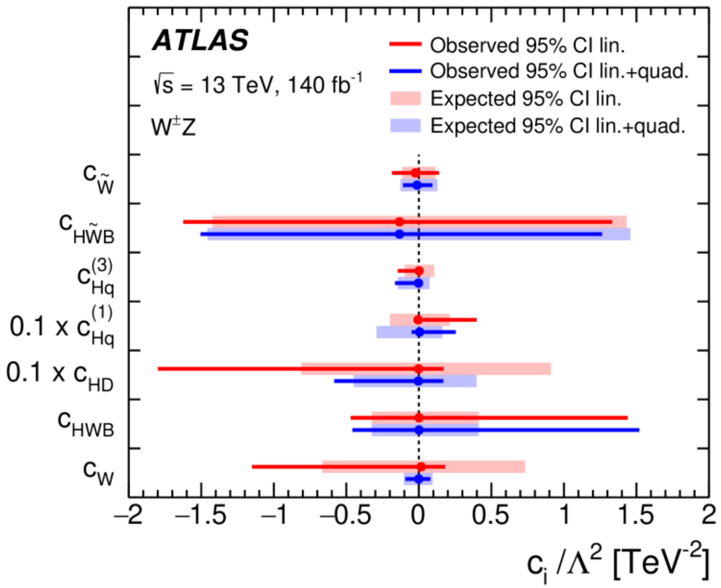
- c_{Wtild}, $c_{HWtildB}$

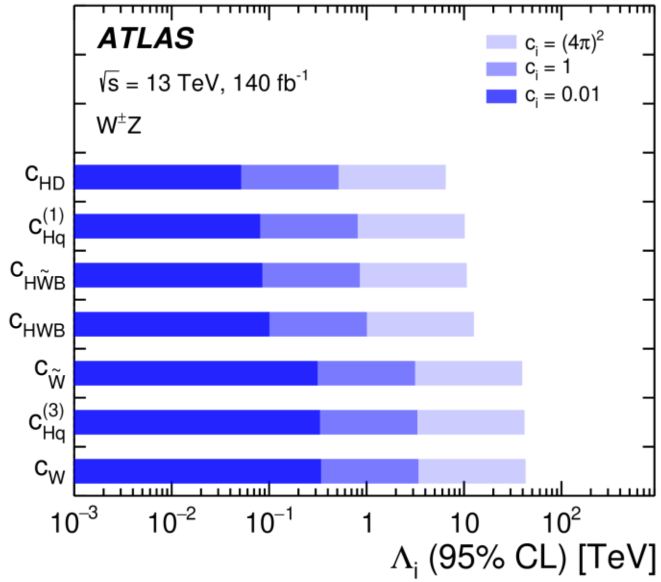


$$S_{comb} = S_o \times \frac{1+S_p}{2} \times \frac{1+S_n}{2}$$

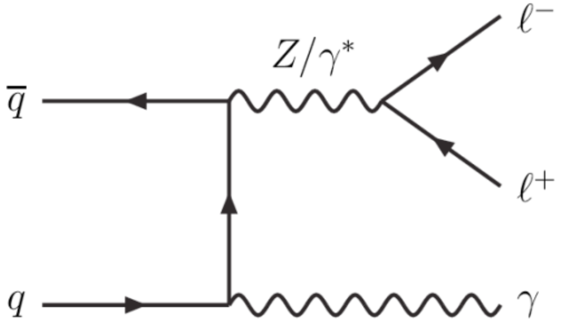


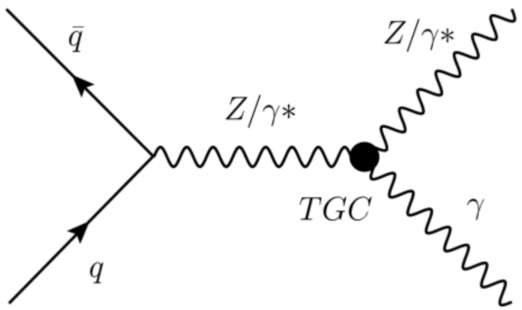
Strongest positive (negative) interf. for large S_{comb} ($-S_{comb}$)





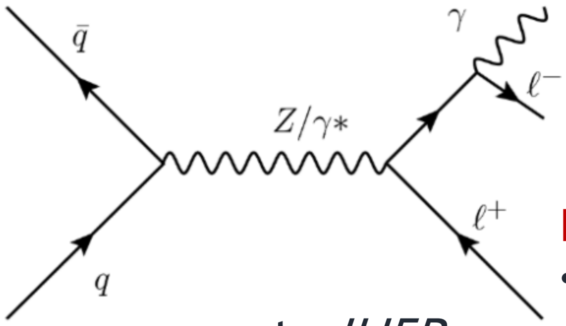
Zγ high p_T differential measurements and NEW nTGC at 13TeV





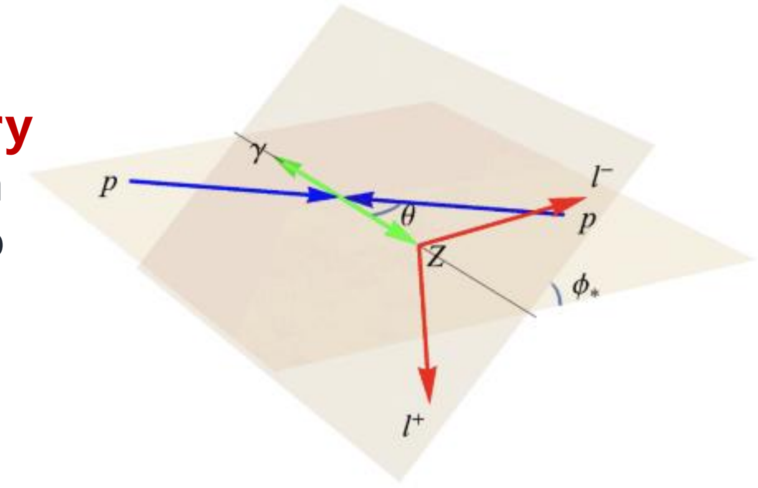
Suppressed w/ FSR rejection Cut

$m_{ll} + m_{ll\gamma} > 182$ GeV ~ 2 m_Z



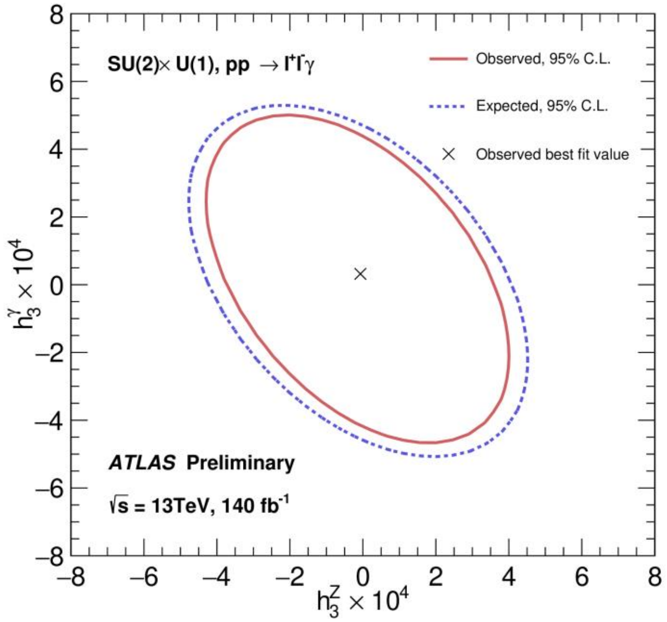
- Analysis designed on top of previous Zγ+jets differential measurements *JHEP 07 (2023) 072*
- Focus on **high $p_T(\gamma)$>200GeV with on-shell Z**: sensitive to neutral aTGCs (nTGCs): prohibited at SM tree level, but 1st arise from dimension-8 SMEFT
- Two approaches adopted to probe nTGCs
  - Dimension-8 operators in SMEFT approach
  - Form Factor (FF) in effective vertex approach
- Incorporating for **1st time $SU(2)_L \otimes U(1)_Y$ fully gauge invariant symmetry** [*PRD 107 (2023) 035005*] and cancelling spurious energy dependent term
- Conventional FF formulation only incorporated $U(1)$ symmetry, leading to limits overestimation by two orders of magnitude (**now corrected** ☺)

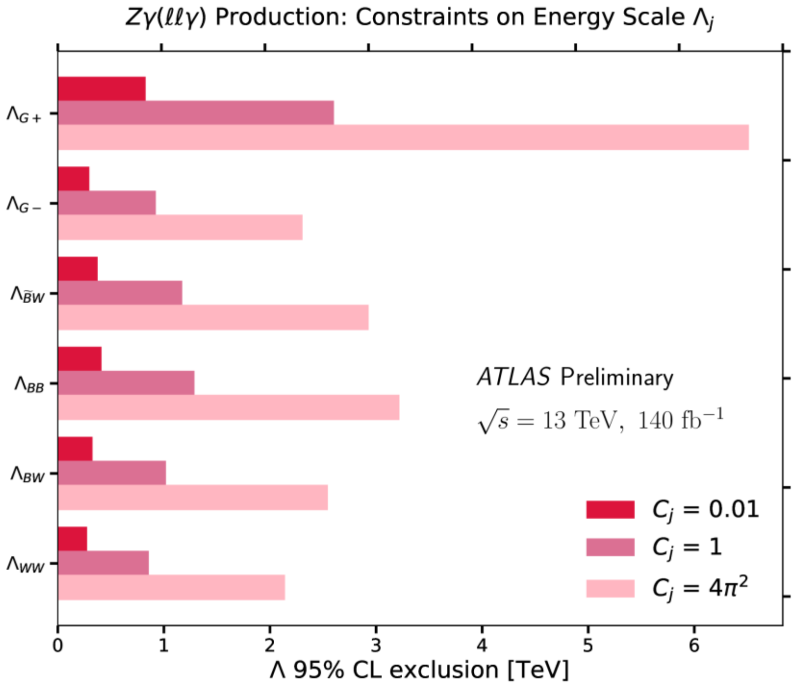
NEW diff. meas. of ϕ^*
- Angle b/w scattering plane and decay plane of Z in the ℓ+ℓ− frame
- Sensitive to interference b/w SM and pure BSM terms



Zγ high p_T differential measurements and NEW nTGC at 13TeV

- Limits extracted from high $p_T(\gamma)$ region differential cross section
- **NEW**! 1D and 2D limits w/ dimension-8 Wilson coefficients using fully gauge invariant theory treatment (**for 1st time at LHC**) and conversion FF limits
- Significantly relax the previous h_4 limits w/ only U(1) symmetry treatment





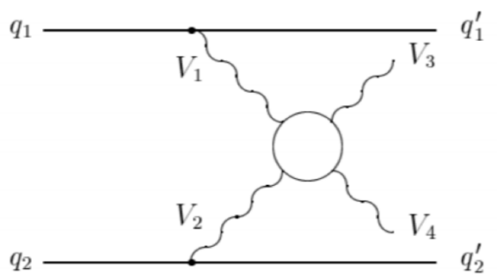
Parameters	Current limits at 95% C.L. (140 fb^{-1}) using new formalism		Limits at 95% C.L. from Reference [61] (36.1 fb^{-1}) using old formalism	
	Observed 95% C.L.	Expected 95 % C.L.	Observed 95% C.L.	Expected 95 % C.L.
h_4^γ	$[-1.3\times10^{-5}, 1.4\times10^{-5}]$	$[-1.5\times10^{-5}, 1.6\times10^{-5}]$	~~$[-4.4\times10^{-7}, 4.3\times10^{-7}]$~~	~~$[-5.1\times10^{-7}, 5.0\times10^{-7}]$~~
h_4^Z	$[-2.4\times10^{-5}, 2.6\times10^{-5}]$	$[-2.8\times10^{-5}, 3.0\times10^{-5}]$	~~$[-4.5\times10^{-7}, 4.4\times10^{-7}]$~~	~~$[-5.3\times10^{-7}, 5.1\times10^{-7}]$~~
h_3^γ	$[-3.5\times10^{-4}, 4.6\times10^{-4}]$	$[-4.0\times10^{-4}, 4.9\times10^{-4}]$	$[-3.7\times10^{-4}, 3.7\times10^{-4}]$	$[-4.2\times10^{-4}, 4.3\times10^{-4}]$
h_3^Z	$[-3.2\times10^{-4}, 3.2\times10^{-4}]$	$[-3.7\times10^{-4}, 3.6\times10^{-4}]$	$[-3.2\times10^{-4}, 3.3\times10^{-4}]$	$[-3.8\times10^{-4}, 3.8\times10^{-4}]$

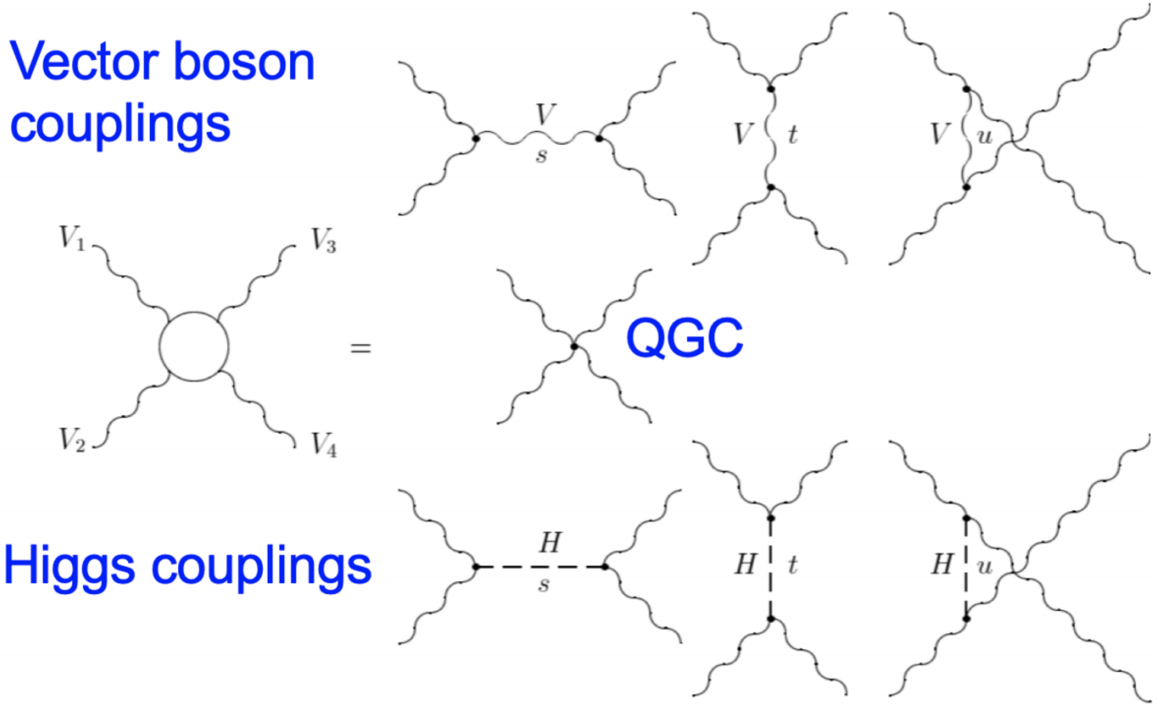
PART 02

Vector Boson Scattering Polarization

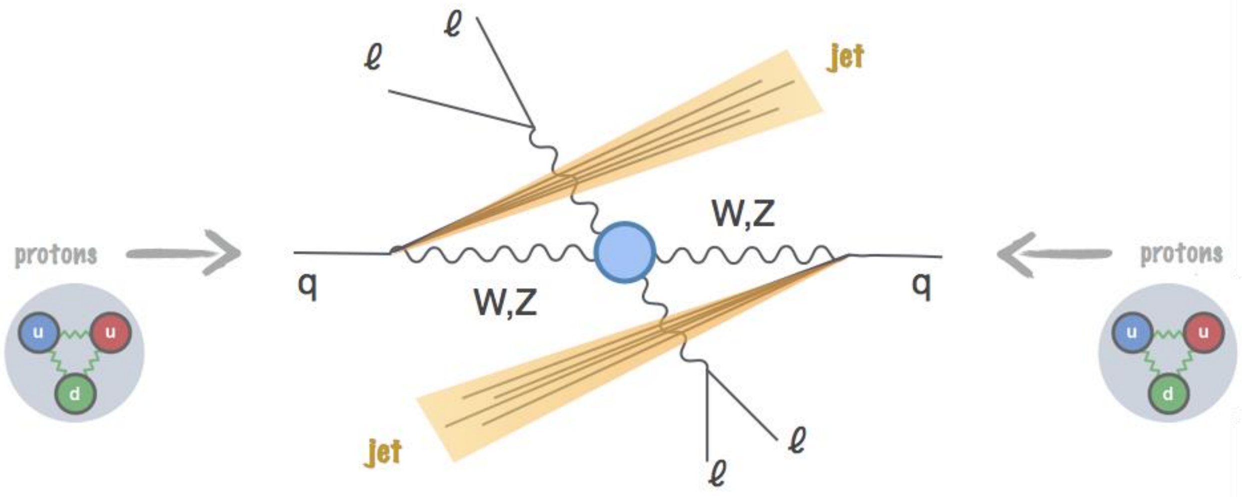
Tsung-Dao Lee Institute

Vector Boson Scattering topology in a nutshell





Protons in LHC serve as source of vector boson beams.

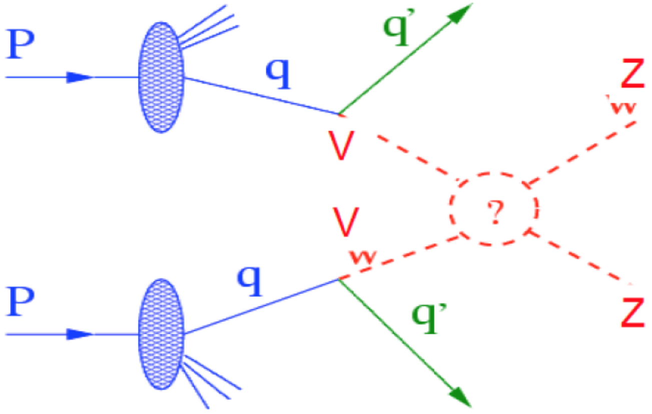


- Vector Boson Scattering (VBS) is a key process to probe the mechanism of EWSB
- Experimentally measured in a VBS enriched phasespace along with the other non-VBS EWK VVjj contributions suppressed

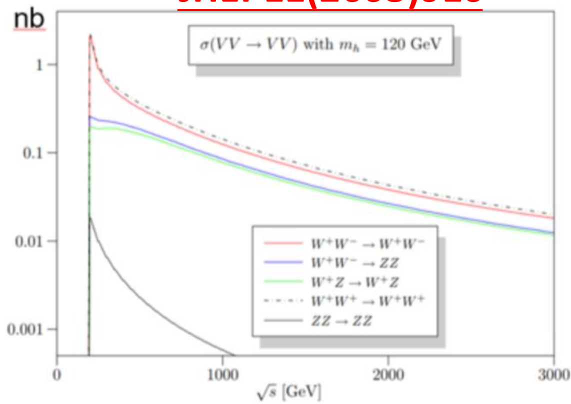
Physical interest of VV scattering

Unitarity violation of Vector Boson Scattering

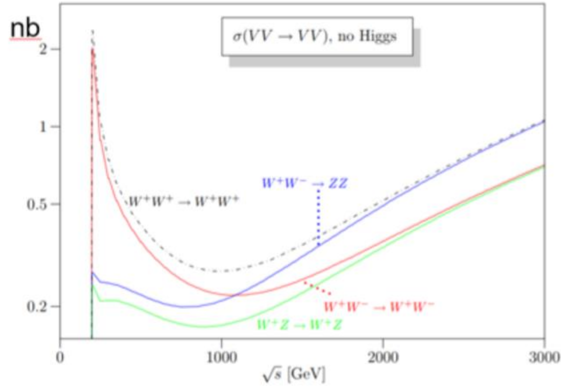
$$\mathcal{M}(W_L^+ W_L^- \rightarrow Z_L Z_L) \sim \frac{s}{M_W^2}$$



JHEP11(2008)010



w/ Higgs



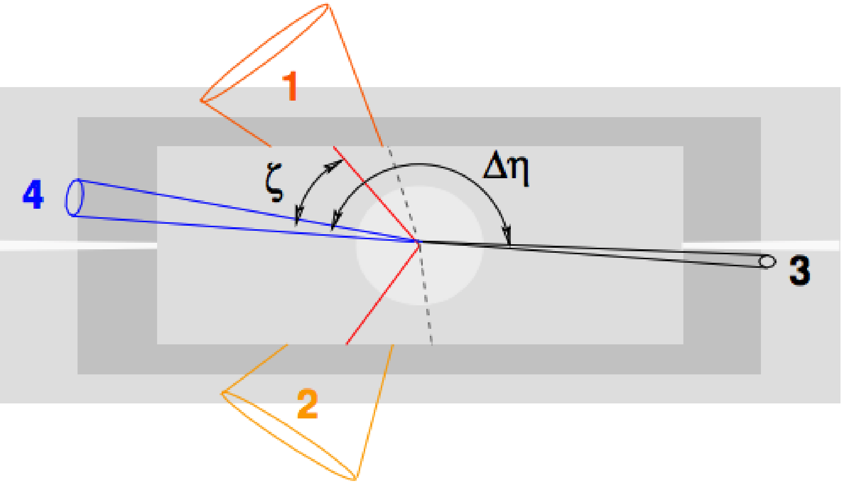
w/o Higgs

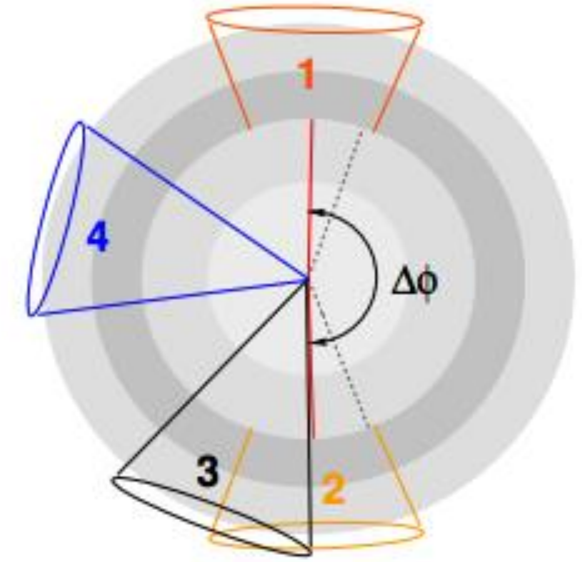
The m_h = 125 GeV Higgs will unitarize VV→VV scattering provided it has SM hVV couplings.
This can be carefully examined by either

- Precise measurements of the hVV couplings at the light Higgs resonance
- Measurement of VV→VV differential cross sections at high p_T and invariant mass

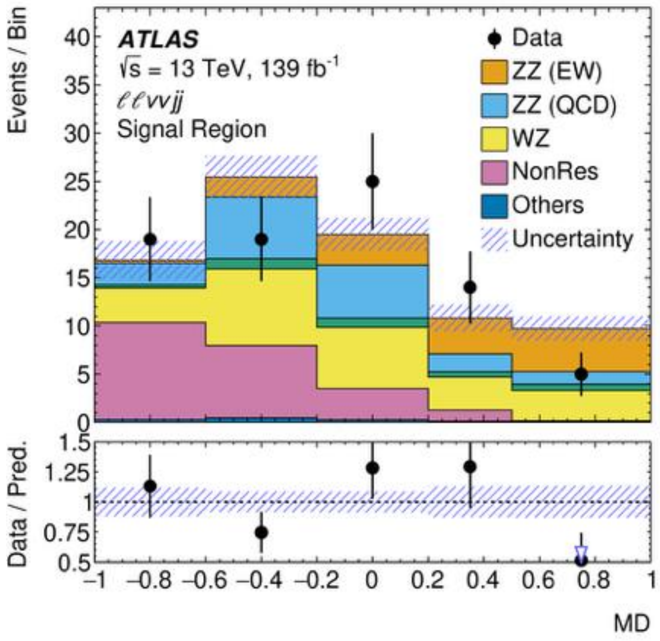
VBS signature in short

- Typical VBS topology
  - tagging jets:
    - transverse momenta: $p_T(j1)$, $p_T(j2)$
    - invariant mass: M(jj)
    - Pseudo-rapidity difference: $\Delta\eta$(jj)
  - central jet veto
  - centrality: $\max\left(\left|\frac{y_i - 0.5(y(j_1)+y(j_2))}{y(j_1)-y(j_2)}\right|\right)$
  - p_T balance: $\frac{\sum_i \vec{p_T}_i}{\sum_i |\vec{p_T}_i|}$
    - All hard process decay products and jets



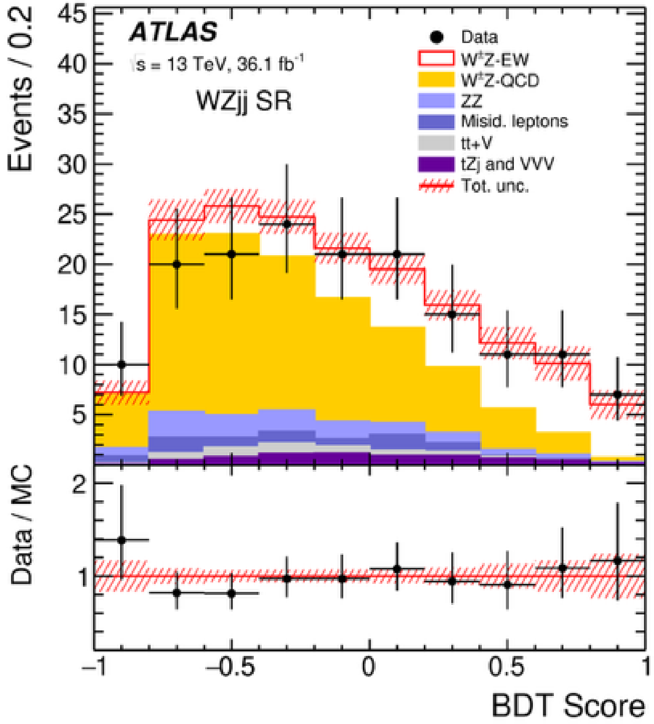


Vector Boson Scattering Measurements and Polarizations



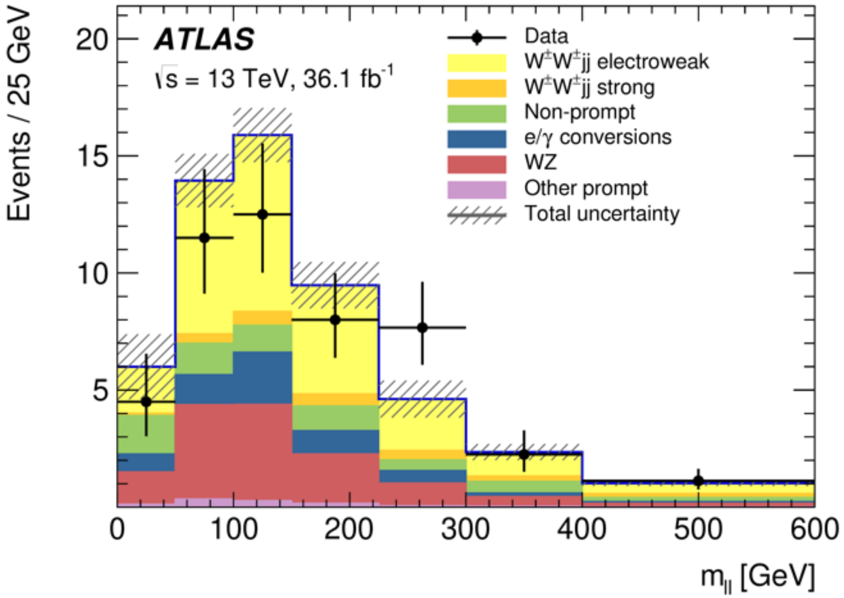
ZZ VBS (1st observation at LHC)

- **Nature Physics** 19 (2023) 237
- **PRD** 100 (2019) 032007
- arxiv:2511.15569 [**EPJC**]



WZ VBS (1st observation at LHC)

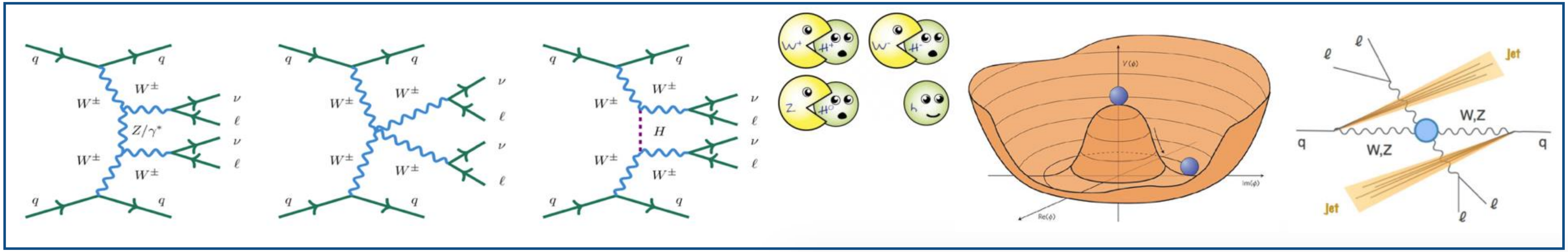
- **PLB** 793 (2019) 469 [AC]

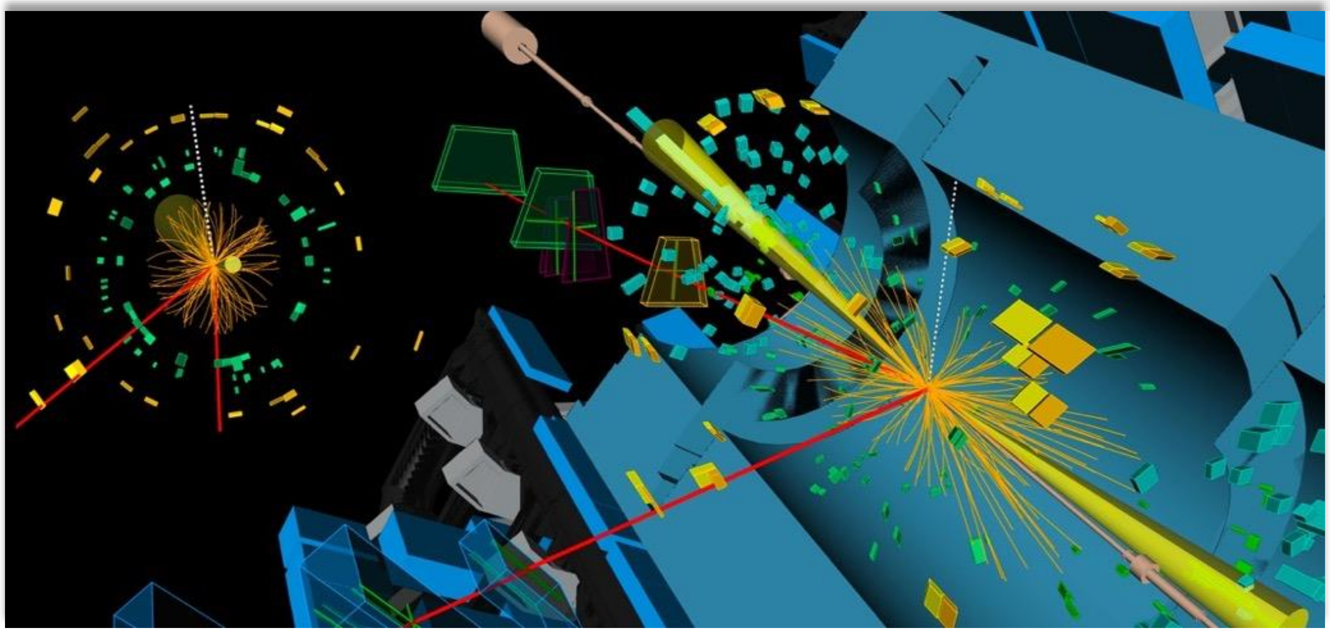


ssWW VBS ATLAS observation

- **PRL** 123 (2019) 161801

Same-sign WW VBS polarization w/ ATLAS Full Run2



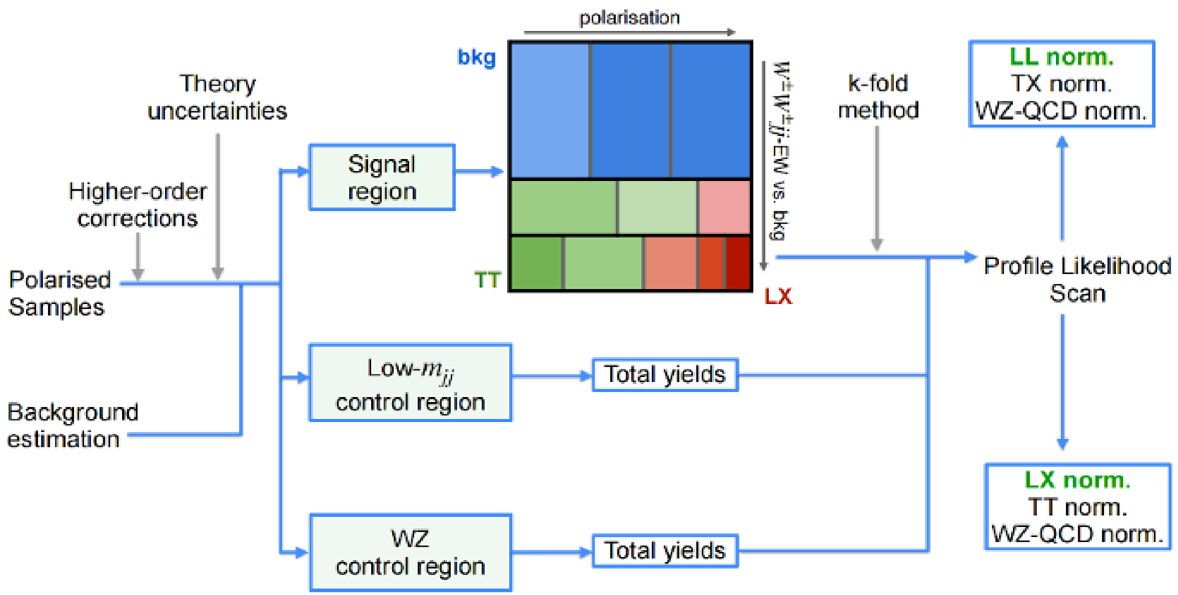


- Measure VBS ssWW in fully leptonic decays w/ ATLAS Run3(+Run2)
- Extract longitudinal polarization of $W_L W$ (3.3σ in Run2) & doubly $W_L W_L$, **further the sensitivity w/ larger statistics**
- **Physics Motivations:** test EWSB, unitarity preservation w/ Higgs (Symmetry Restoration!), unveil goldstone nature, probe BSM via VBF and more

PRL *135 (2025) 111802*

1st evidence of $W_L W$ → moving towards observation in Run3

ssWW VBS polarization methodologies



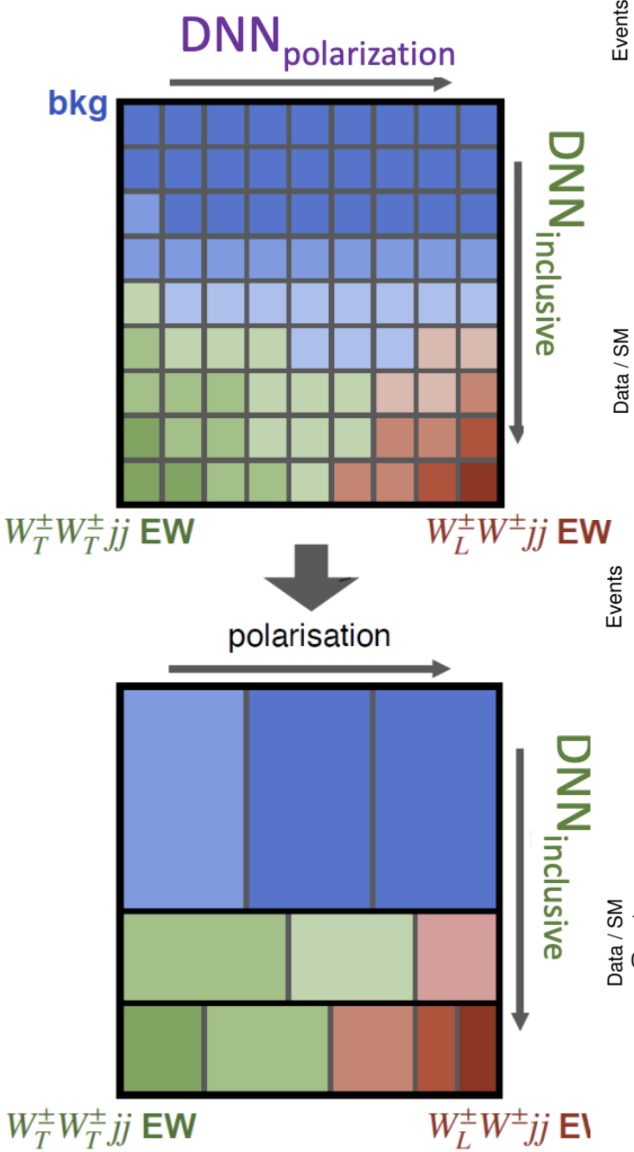
Run2 two-stage DNN (→GNN/Transformer in Run3)

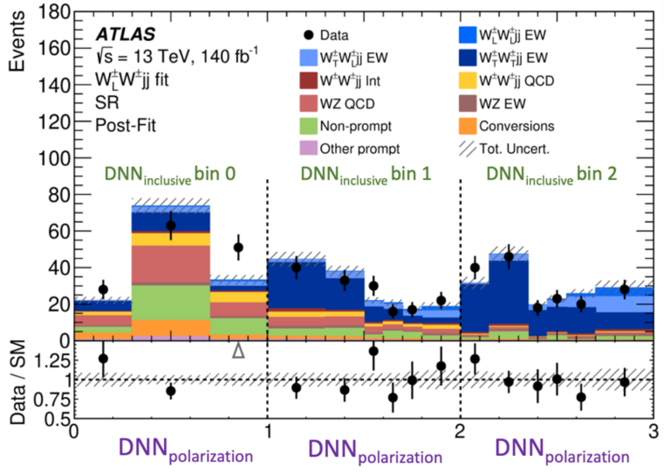
- EWK vs QCD
- W_LW_L vs W_TW & W_LW vs W_TW_T

Regions:

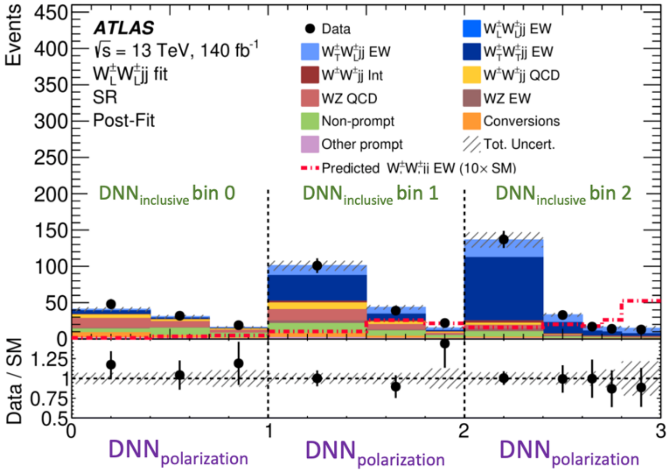
- Three regions for DNN inclusive: (0, 0.2, 0.6, 1.0) , (0, 0.3, 0.7, 1.0)
- Each DNN inclusive region contains 3-6 DNN polarization bins
- 1-bin for Low-m_{jj} and 1-bin for WZ control region

Binning optimization for $\mathrm{DNN}_{\mathrm{polarization}}$ and $\mathrm{DNN}_{\mathrm{inclusive}}$



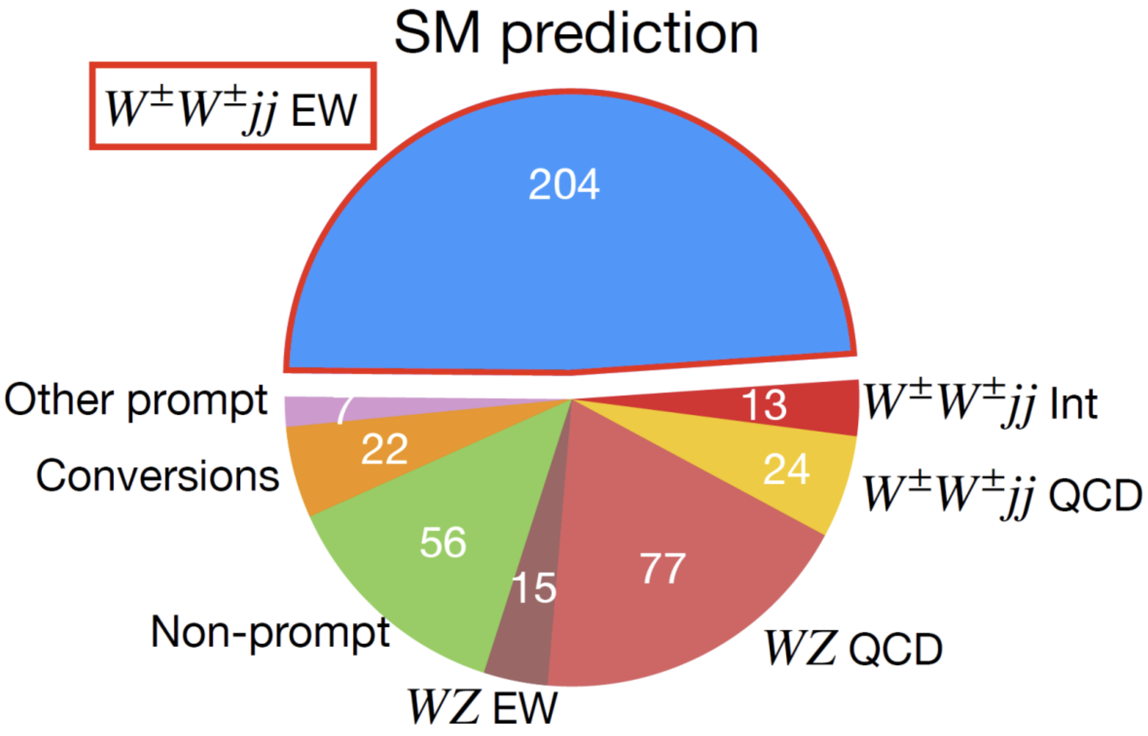


Obs. (Exp.) significance: 3.3 σ (4.0 σ)



Fiducial cross-section: 0.01 ± 0.21 fb
Obs. (Exp.) 95% CL upper limit of 0.45 (0.43) fb

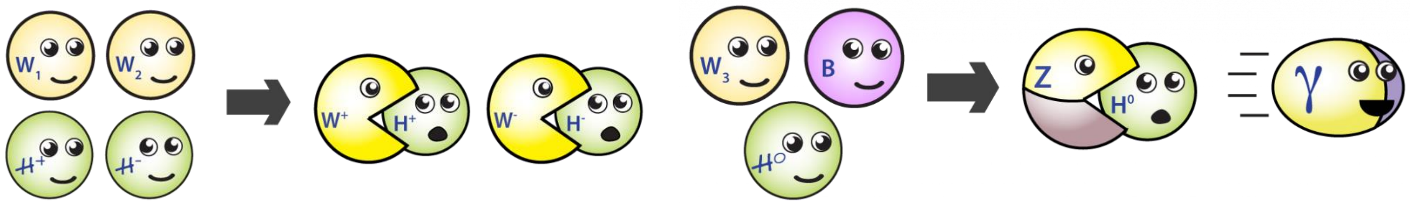
ssWW VBS signal region and signal polarization compositions



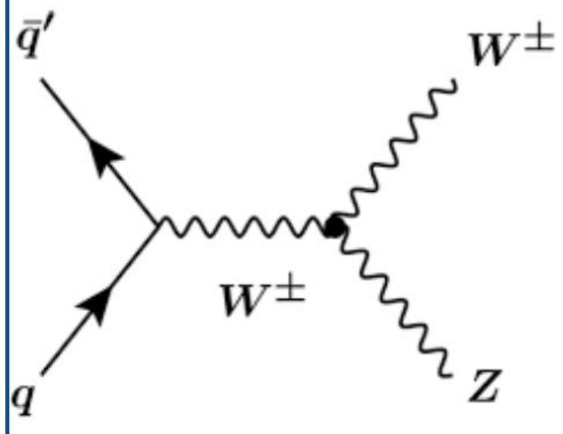
~ 200 signal events in full-run2 data:

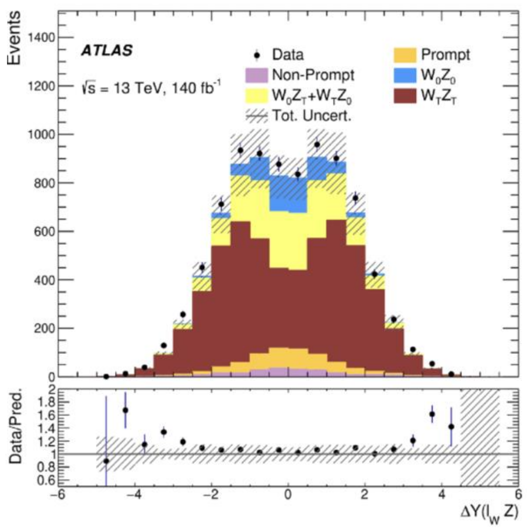
- LL: 10%
- LT: 21%
- TT: 69%

- Shape of Higgs potential → EWSB
- W/Z longitudinal polarization and Goldstone
- Constrain Higgs self-coupling through VBS V_LV_L scattering, making use of the EWSB and goldstone nature of W/Z boson!



Incl. diboson polarizations

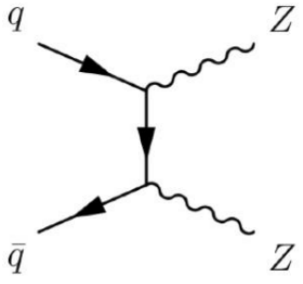


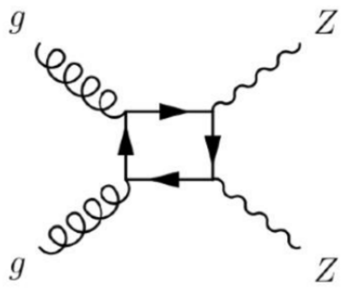


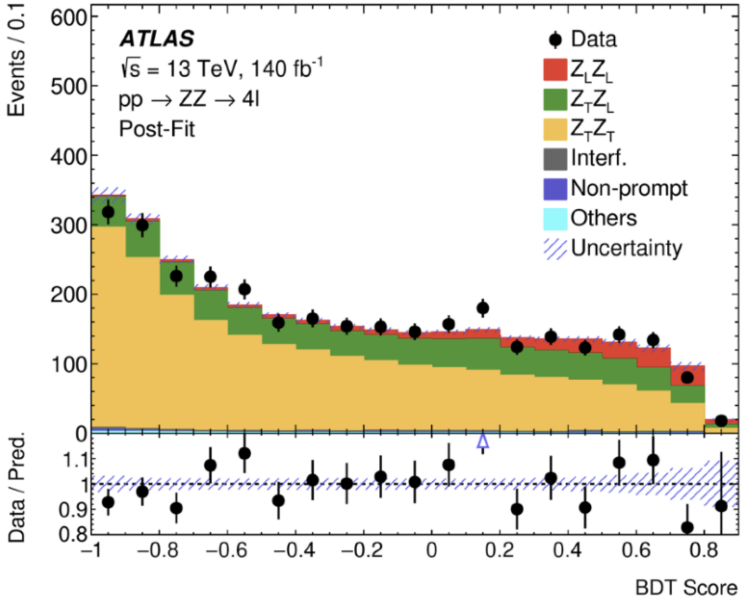
	Measurement	
	$100 < p_T^Z \leq 200$ GeV	$p_T^Z > 200$ GeV
f_{00}	$0.19 \pm^{0.03}_{0.03}$ (stat) $\pm^{0.02}_{0.02}$ (syst)	$0.13 \pm^{0.09}_{0.08}$ (stat) $\pm^{0.02}_{0.02}$ (syst)
f_{0T+T0}	$0.18 \pm^{0.07}_{0.08}$ (stat) $\pm^{0.05}_{0.06}$ (syst)	$0.23 \pm^{0.17}_{0.18}$ (stat) $\pm^{0.06}_{0.10}$ (syst)
f_{TT}	$0.63 \pm^{0.05}_{0.05}$ (stat) $\pm^{0.04}_{0.04}$ (syst)	$0.64 \pm^{0.12}_{0.12}$ (stat) $\pm^{0.06}_{0.06}$ (syst)
f_{00} obs (exp) sig.	5.2 (4.3) σ	1.6 (2.5) σ

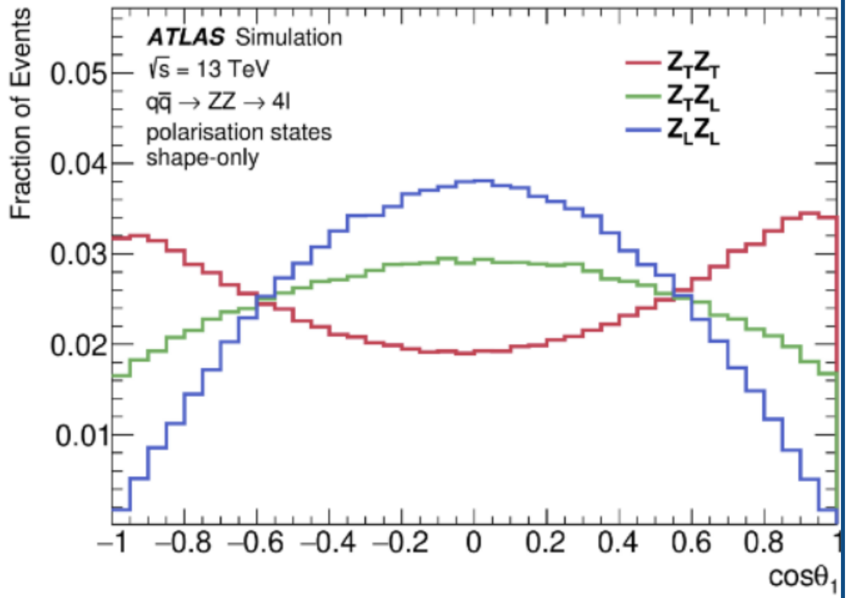
1st observation of joint longitudinally polarized WZ at high energy approaching regime of vector bosons' goldstone natures

- 1st evidence of $Z_L Z_L$ obs. 4.3 σ (3.8σ exp.)
- Five decay angle variables driving BDT separation of LL, LT, TT









PART 03

VBS and Composite Higgs

Tsung-Dao Lee Institute

From VBS VV to Di-Higgs, Goldstone Bosons and Compositeness

More on Higgs→BSM Portal: the Higgs Puzzle

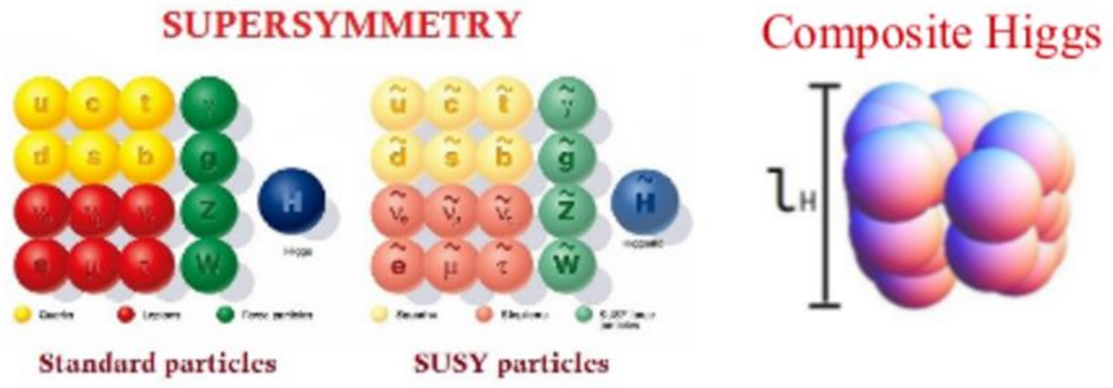
- First fundamental (?) scalar field to be discovered
- Spontaneous symmetry breaking by development of a VeV
  - But VeV is induced parametrically by ad-hoc Higgs potential, no dynamics
- Parameters of Higgs potential are not stable under radiative corrections
  - First time that the radiative correction to a particle mass is additive and quadratically divergent
  - Gauge boson masses are protected by gauge invariance
  - Fermion masses are protected by chiral symmetry of massless fermions
- Single scalar Higgs field is a strange beast, compared to fermions and gauge bosons
- Additional symmetries and/or dynamics strongly motivated by Higgs discovery

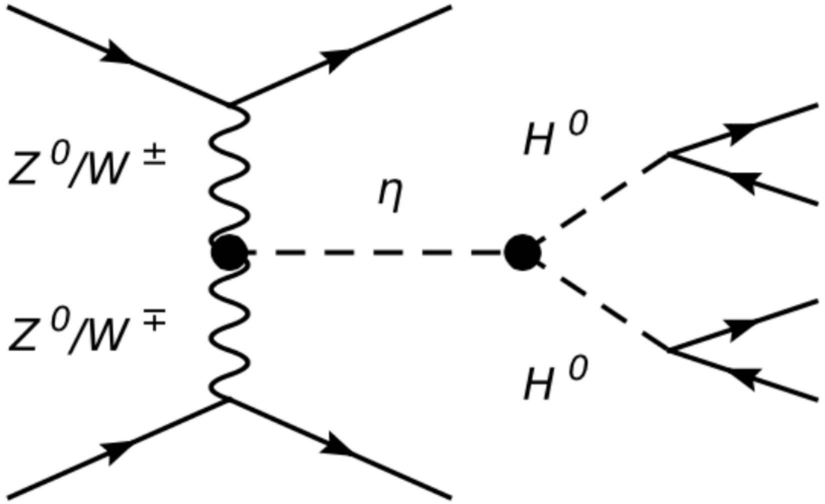
$$V(h) = \frac{1}{2}\mu^2 h^2 + \frac{\lambda}{4} h^4 \quad \text{or} \quad V(h) = \frac{1}{2}\mu^2 h^2 + \frac{\lambda}{4} h^4 + \frac{1}{\Lambda^2} h^6$$

- Ad-hoc potential, similar to and motivated by Landau-Ginzburg theory of superconductivity
- Higgs potential in SM can be extrapolated to Planck scale without additional parameters
  - but no a-priori reason for a parameterization to respect this condition

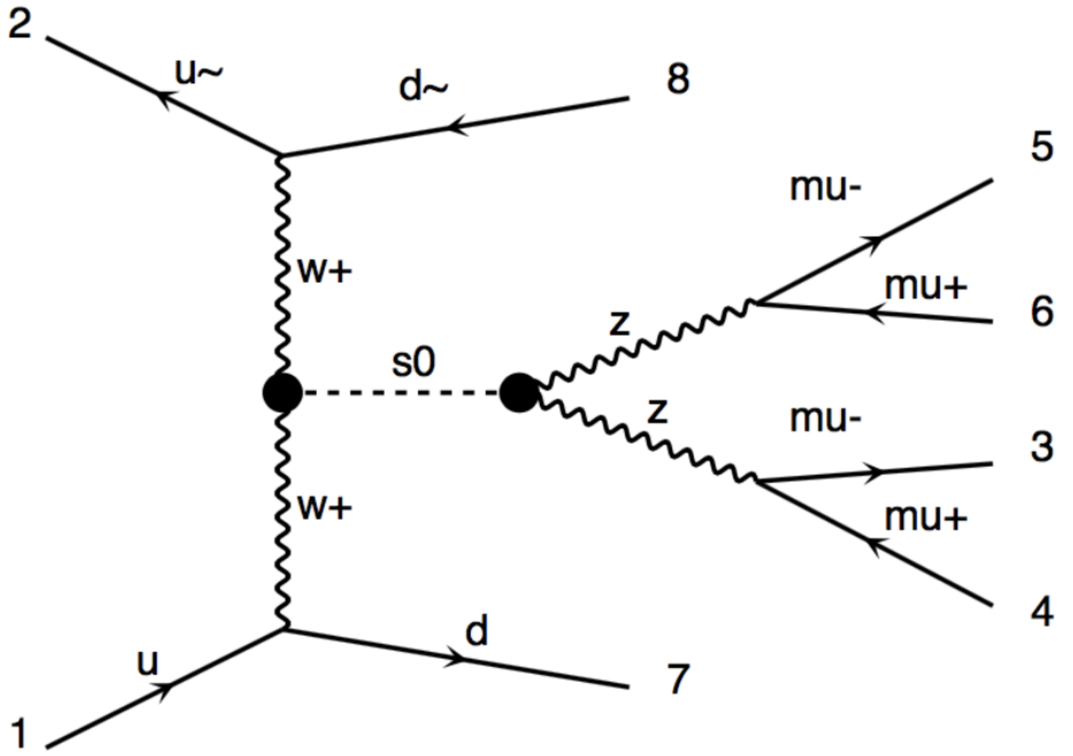
Composite Higgs, VBS-VV and VBF Di-Higgs

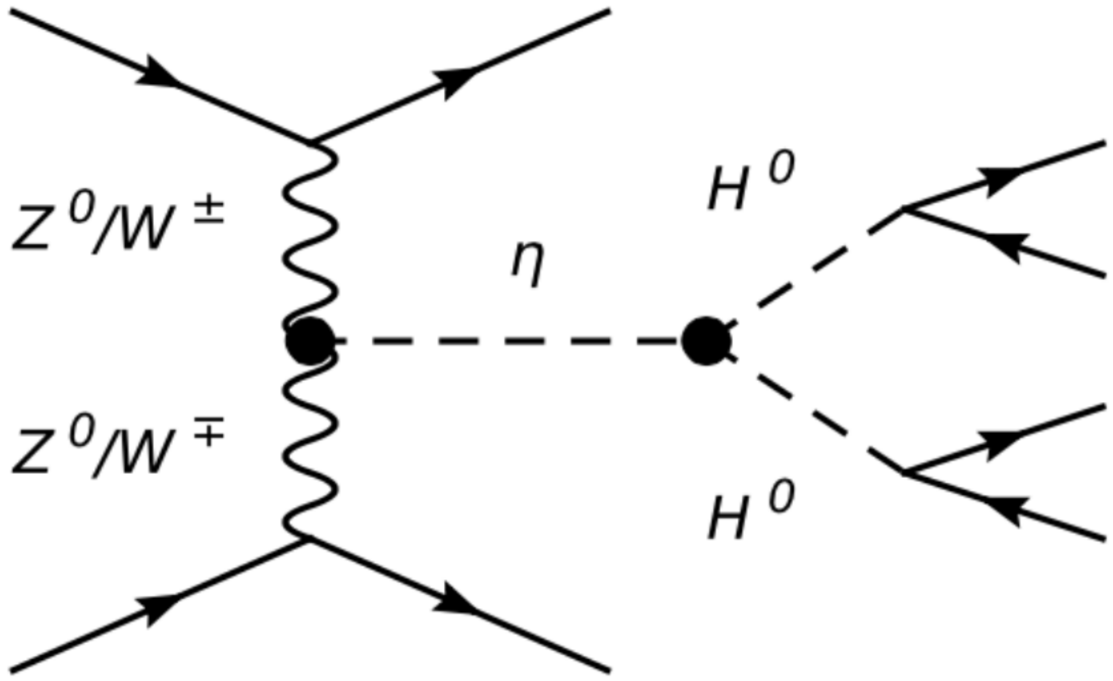
- Old idea: Higgs doublet (4 fields) is a Goldstone mode generated from the spontaneous breaking of a larger global symmetry
- But assuming there is a strong dynamics at the energy scale "f" which causes a condensate to form and break the SO(5) symmetry
- Resonances will be associated with this strong dynamics
- Lightest resonance will decay to the "pseudo-Goldstones" which are much lighter, i.e. longitudinal gauge bosons and Higgs bosons
  - Similar to QCD $\rho \rightarrow \pi\pi$
- Simplified model: arXiv:1109.1570 (Contino et al.) "On the effect of resonances in composite Higgs phenomenology"
  - Scalar resonance: $\eta \rightarrow hh, V_L V_L$





VBS-VV vs VBF HH



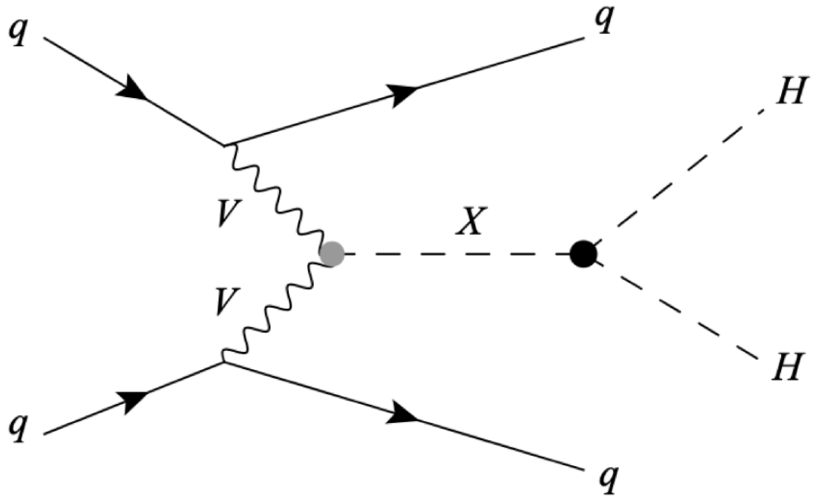


- Branching ratio to hh, $W_L W_L$ and $Z_L Z_L$ in the 1:2:1 ratio is a definitive prediction
- Resonance decaying to two Z_L bosons is a distinctive signature of the Goldstone nature of the Higgs boson
- Vector boson scattering topology
  - Quarks emit longitudinal vector bosons which interact with new (presumably strong) dynamics
  - Quarks scatter by small angle in the forward direction

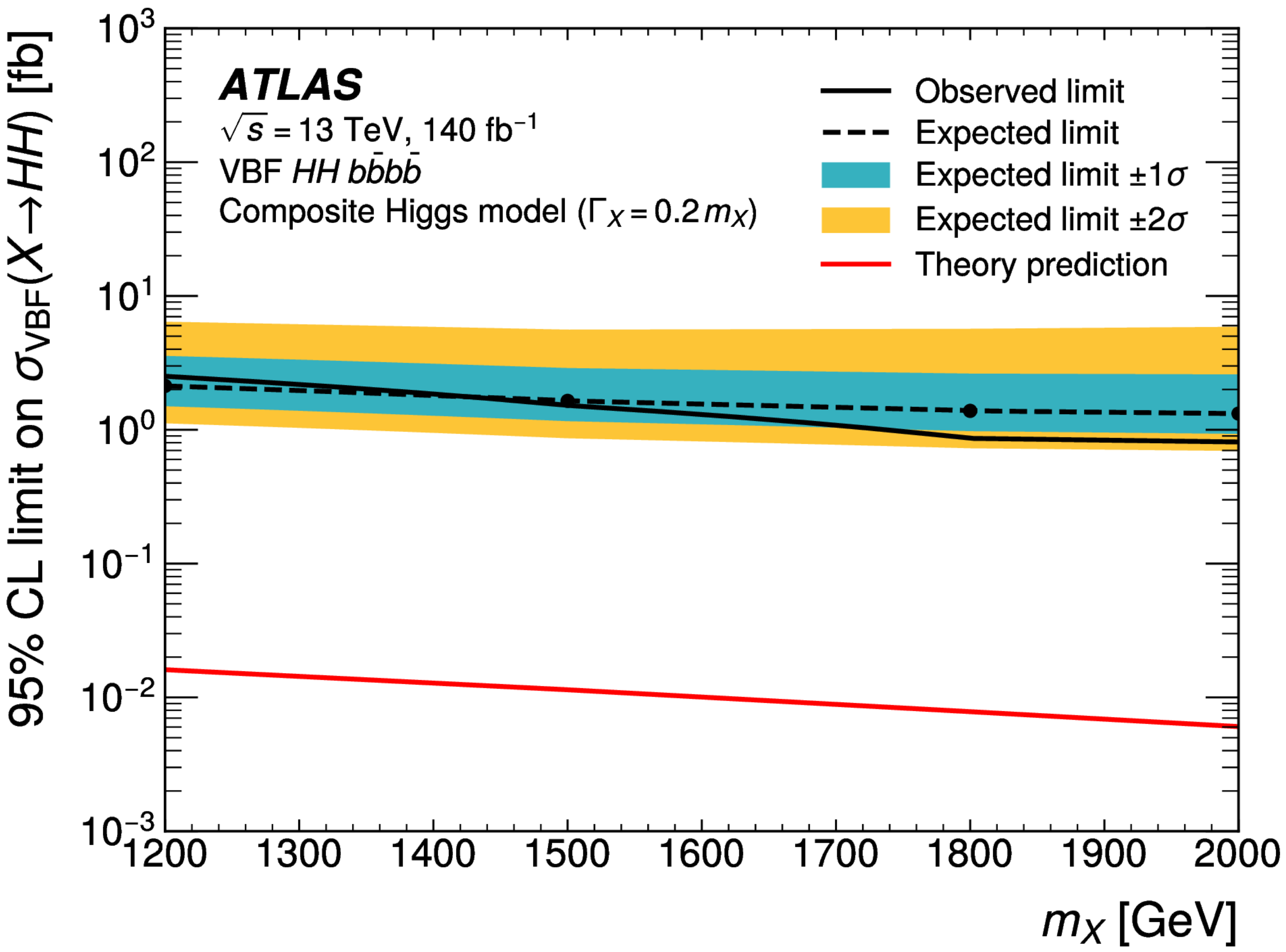
Phys. Lett. B 858 (2024) 139007

Where we stand…

李政道研究所 Tsung-Dao Lee Institute



- 1st LWA resonance search motivated by composite Higgs strong dynamics scenario
- Sensitivity is far from interesting conclusion
- Motivating VBF VV and HH more coherent and combined searches

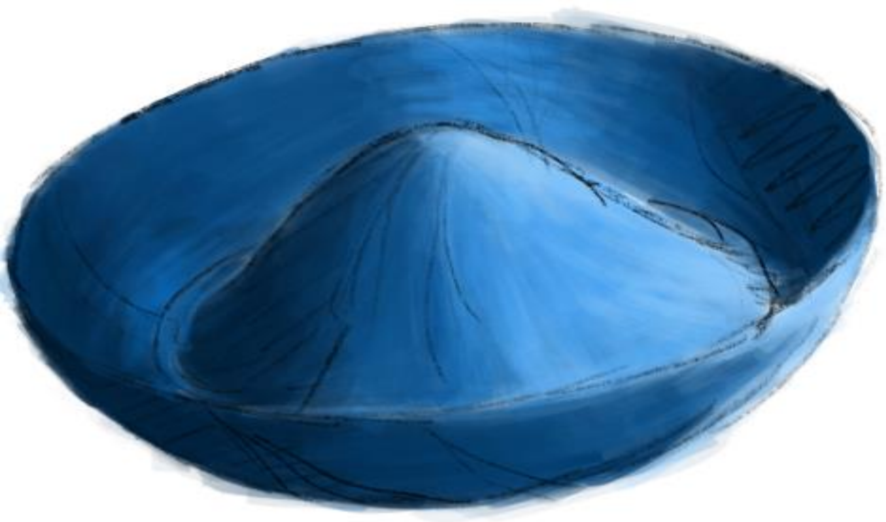


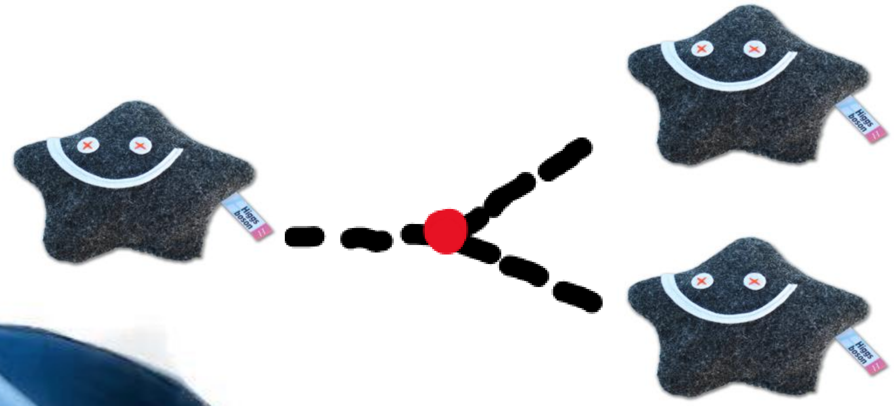
PART 04

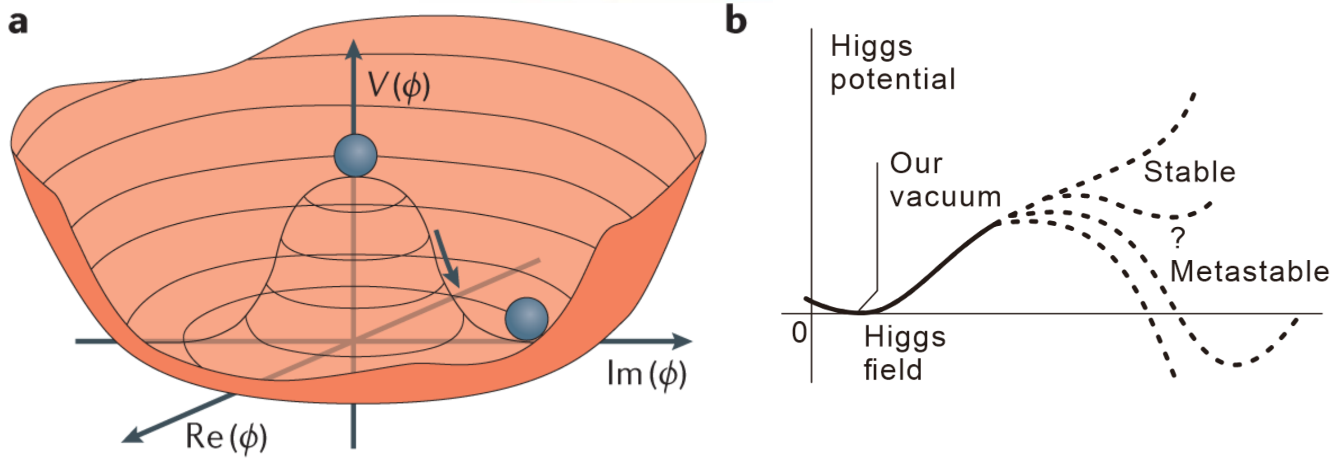
From Di-Higgs to Triple Higgs

TSUNG-DAO LEE INSTITUTE

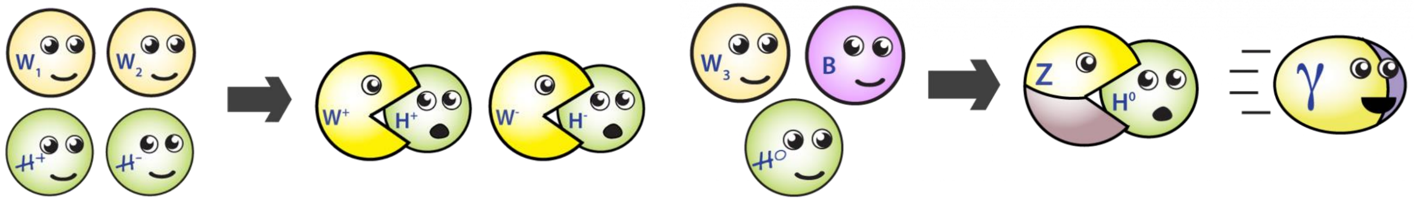
How the Higgs Boson self-interacts?
→ How stable is our universe?





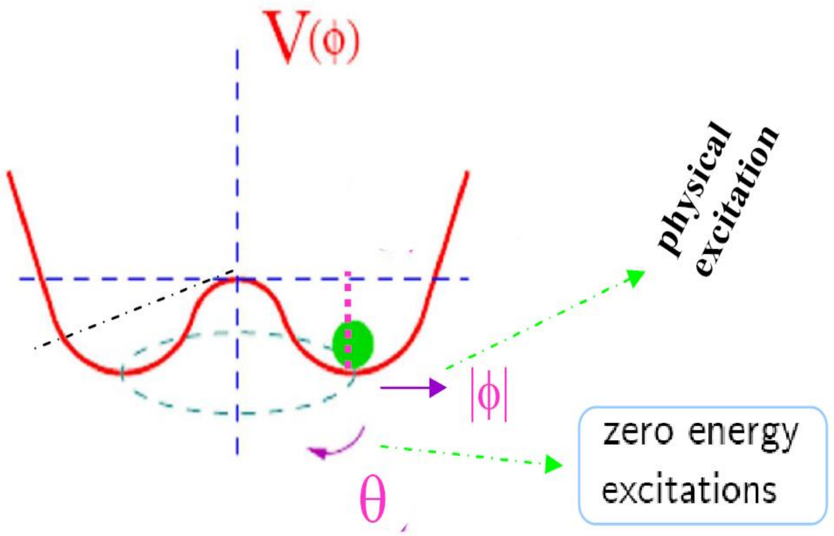


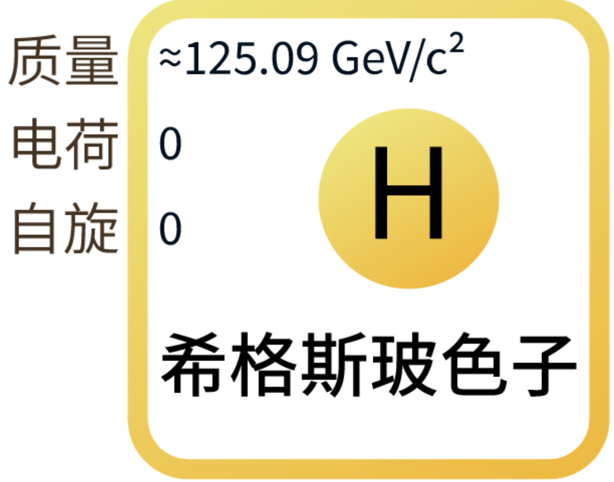
EWSB & Higgs



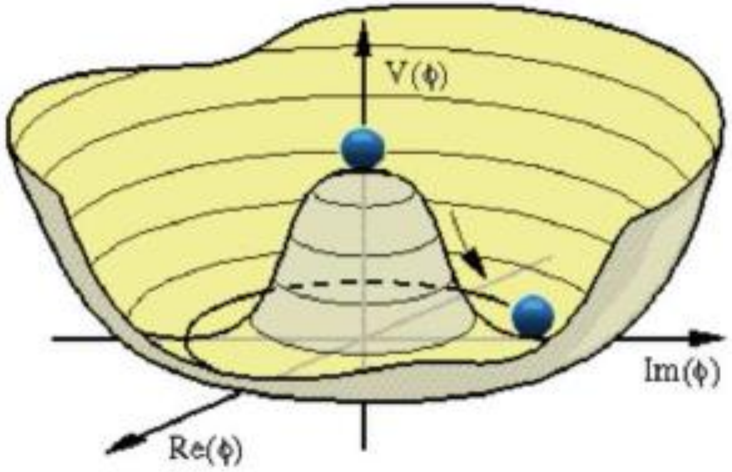
$$V(\phi) = -\mu^2\phi^\dagger\phi + \lambda\left(\phi^\dagger\phi\right)^2$$

$$\phi = \begin{pmatrix} iG^+ \\ \frac{v+h-iG^0}{\sqrt{2}} \end{pmatrix}$$





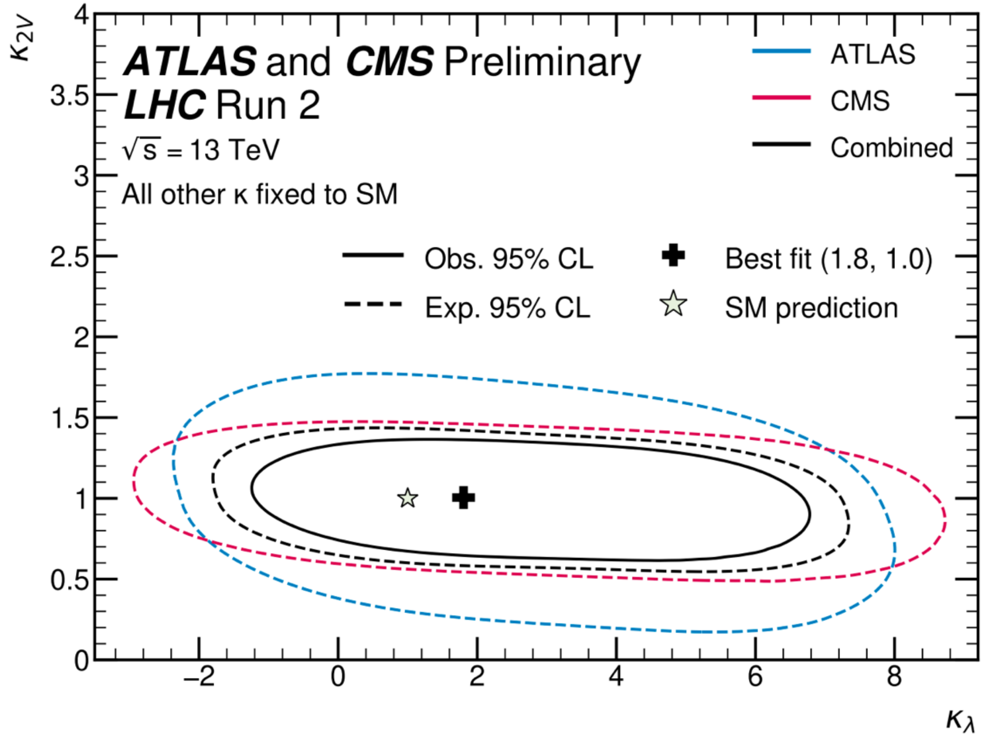
- Shape of Higgs potential → EWSB
- W/Z longitudinal polarization and Goldstone
- Interplay and joint interest of Higgs self-coupling through VBS V_LV_L scattering, making use of the EWSB and goldstone nature of W/Z boson!

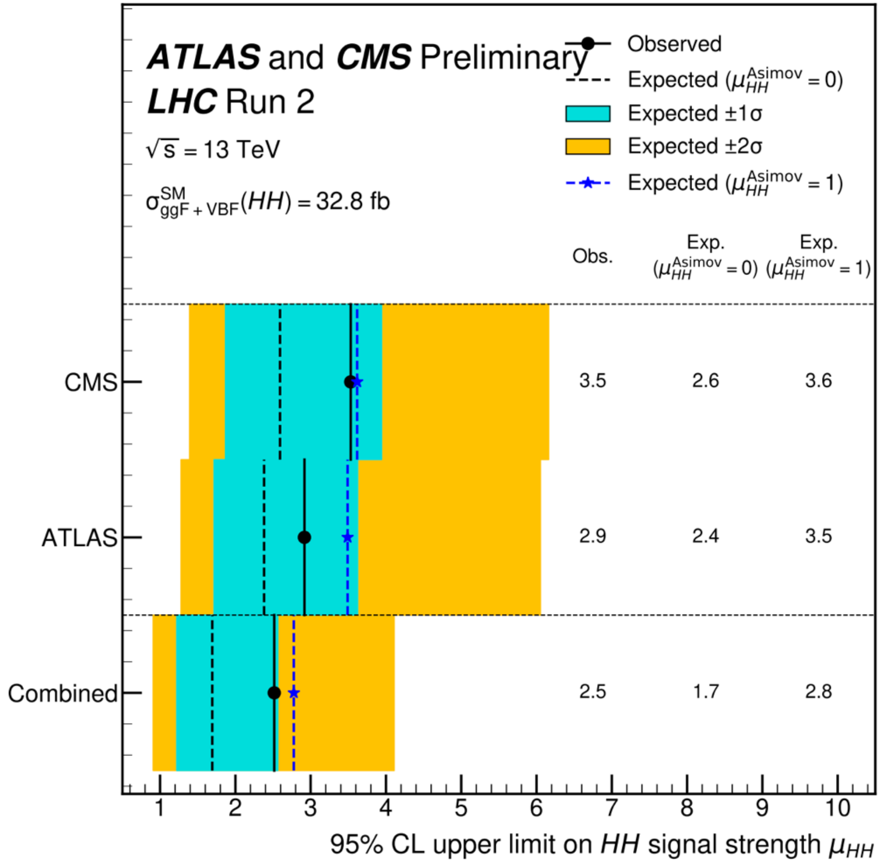


Higgs

ATLAS+CMS HH combination (Latest!)

ATLAS-CONF-2025-012
arXiv:2602.23991 (submitted to PRL)



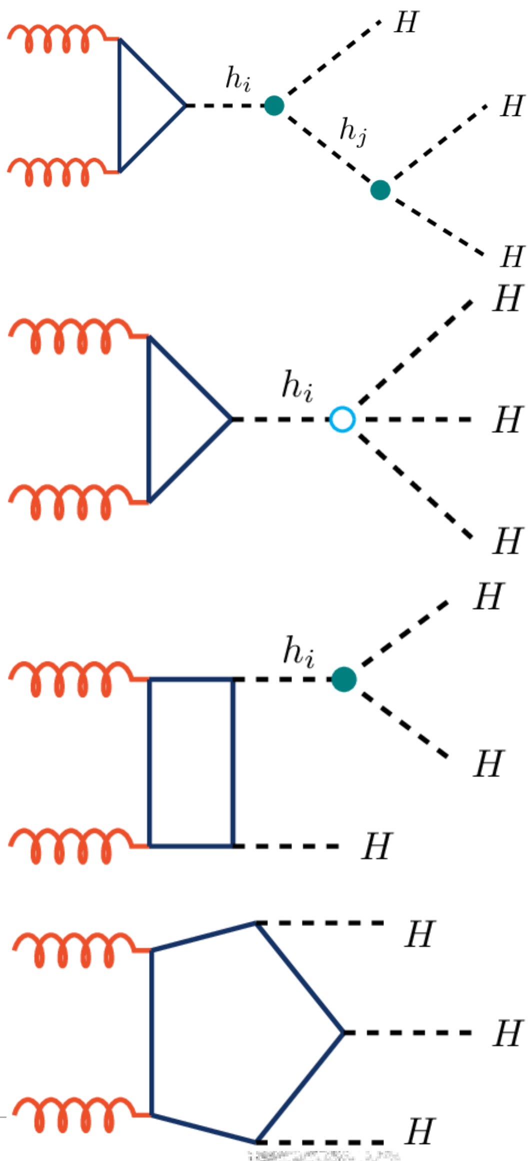


- ATLAS+CMS Run2 Full Dataset (126+140 fb^{-1}) Di-Higgs Combination!
- $\mu_{HH} = 0.8\,^{+0.9}_{-0.7}$ w.r.t. SM , Significance~1.1σ
- $-0.71 < \kappa_\lambda < 6.1$, $0.73 < \kappa_{2V} < 1.3$ (Best by far!!!)

Higgs Triple itself as a probe to quartic

$$V(H) = \frac{1}{2} m_H^2 H^2 + \lambda_3 v H^3 + \lambda_4 H^4 + O(H^5)$$

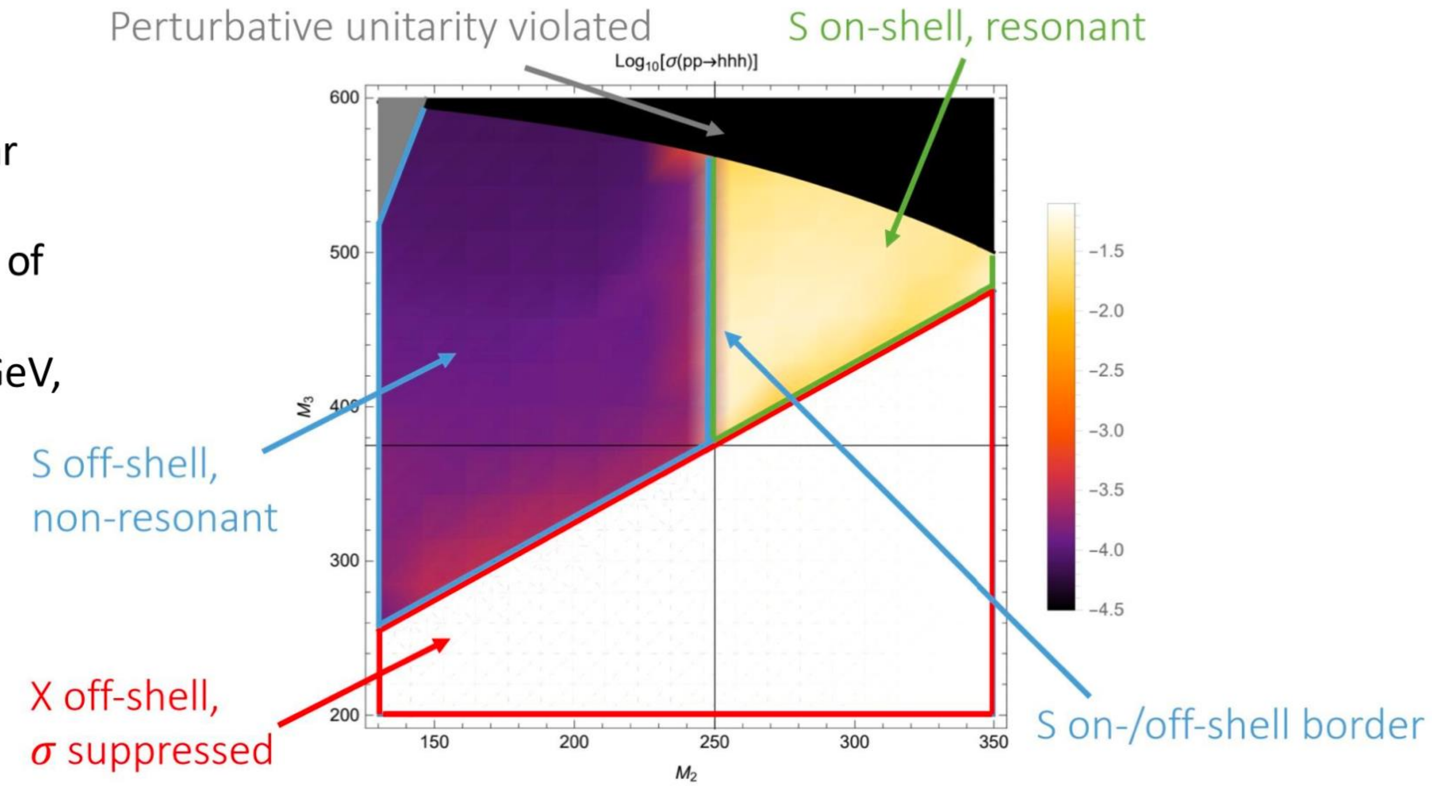
- SM tri-Higgs production is sensitive to tri-linear and quartic Higgs self-couplings (λ_3 & λ_4).
- Constrain modifications to SM coupling values (κ_3 & κ_4- no experimental bounds before).
- Quartic couplings can only be accessed directly this way.



- Small SM tri-Higgs ggF production cross-section at $\sqrt{s}$=13TeV : $\sim$ 0.079fb at NNLO.
- Some BSM theories predict nontrivial tri-Higgs production.
- Rare process → 6b final state (large branching ratio: $H \rightarrow b\bar{b}$ ~58%).

HHH as a probe to BSM

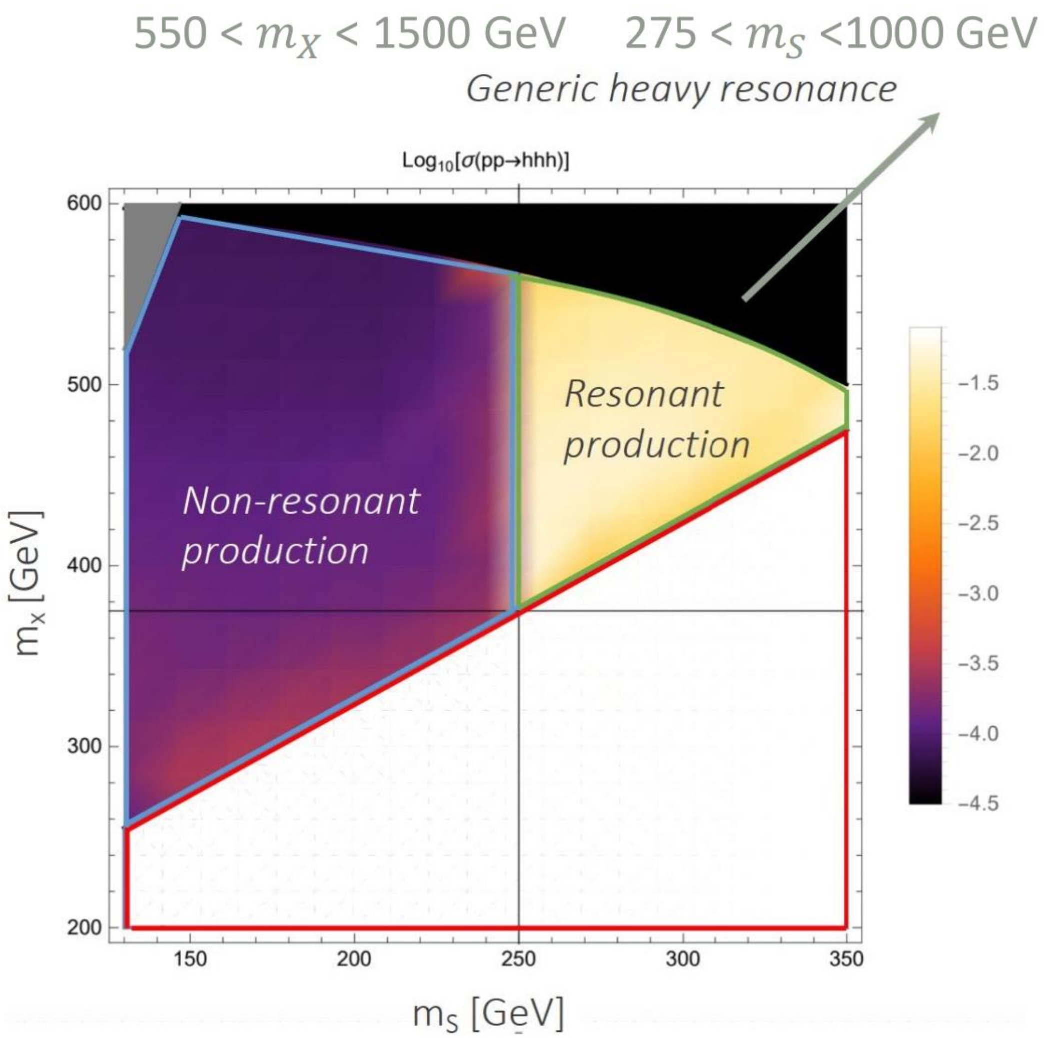
- Two Real Singlet Model (TRSM)
  - Extending the SM by adding two real scalar bosons ***X*** and ***S***.
  - LO productions reach cross-section values of ***up to ~ 50fb***.
  - Mass ranges: $m_X > m_S$, 325 < m_X <575 GeV, 200 < m_S <350 GeV (fulfill perturbative unitarity bounds).
  - Resonant + non-resonant, all LO ggF production modes (BSM + SM).
- Simple model for dark matter and CP violation (DM-CPV)
  - Dark matter is vector-like dark fermion.
  - Interacting with SM through scalars similar as the scalars in TRSM.
  - **Negligible differences** are found in the HHH event **kinematics between the TRSM and DM-CPV models**.



- Simplified TRSM model
  - TRSM breaks unitarity at high masses, and becomes dominated by the non-resonant diagrams. Simplify model to avoid TRSM problems.
  - Only consider **resonant ggF production** ($X \to SH \to HHH$).
  - $m_X > m_S$, 550 < m_X < 1500 GeV, 275 < m_S <1000 GeV.

Analysis overview in a nutshel

- Datasets: 126 fb^{-1}.
- **Three interpretations** based on the **kinematics** of the signal models.
  - **Non-resonant**: $m_S < 2m_H$ (250 GeV).
  - **Resonant**: $m_S > 2m_H$ (250 GeV).
  - **Heavy resonant**: generic heavy resonances (narrow & wide decay widths), m_S>275GeV, m_X > 550 GeV.
- Each search **follows the same general analysis strategy**.
- Dominant background: QCD multi-jet production. Estimate by **data-driven** method.
- A profile likelihood is performed on **Deep Neural Network (DNN) score** to obtain the final results.



Multiplexing the Higgs reco pairing

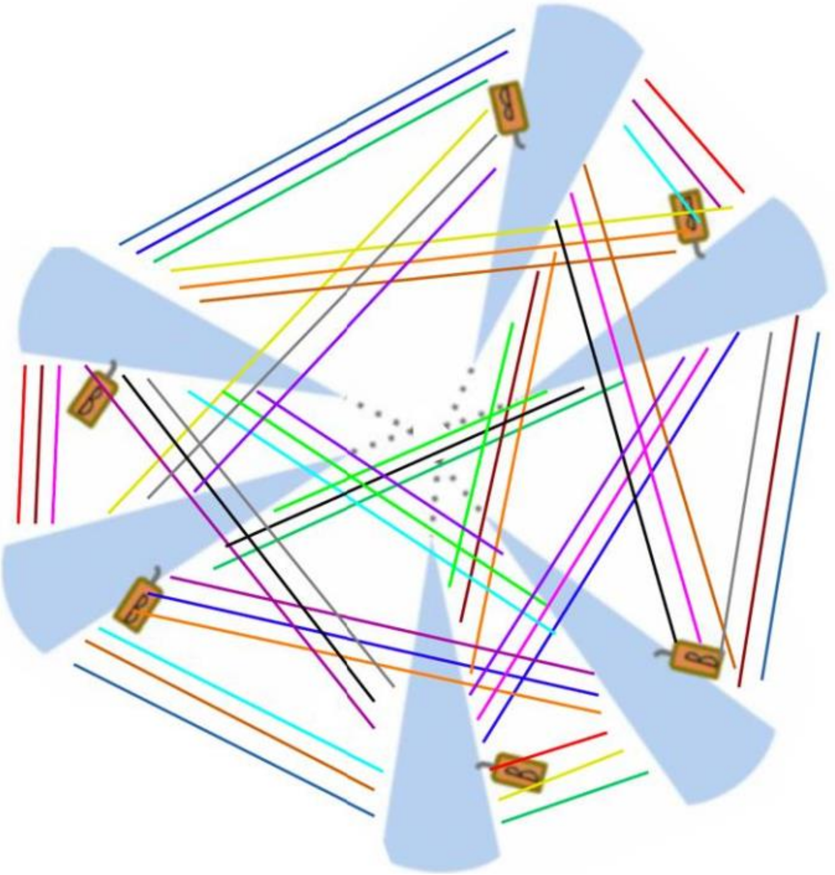
ATLAS Run2 data selected by triggers →

$\geq$ 6 jets
$\geq$ 4 jets with $p_T > 40$ GeV
$\geq$ 4 b-tagged jets

→ $\geq$ **6** b-tagged jets
Signal Region (SR)

→ = **5** b-tagged jets
Control Region (CR)
Background estimation & validation

→ = **4** b-tagged jets
Control Region
Background estimation & validation



Pairing efficiencies:

SM-like ~ **60%**

Resonant TRSM ~ **50%**

Heavy resonant ~ **80%**

For 5b (4b) events:

For 6b events:

Phys. Rev. D 111 (2025) 032006

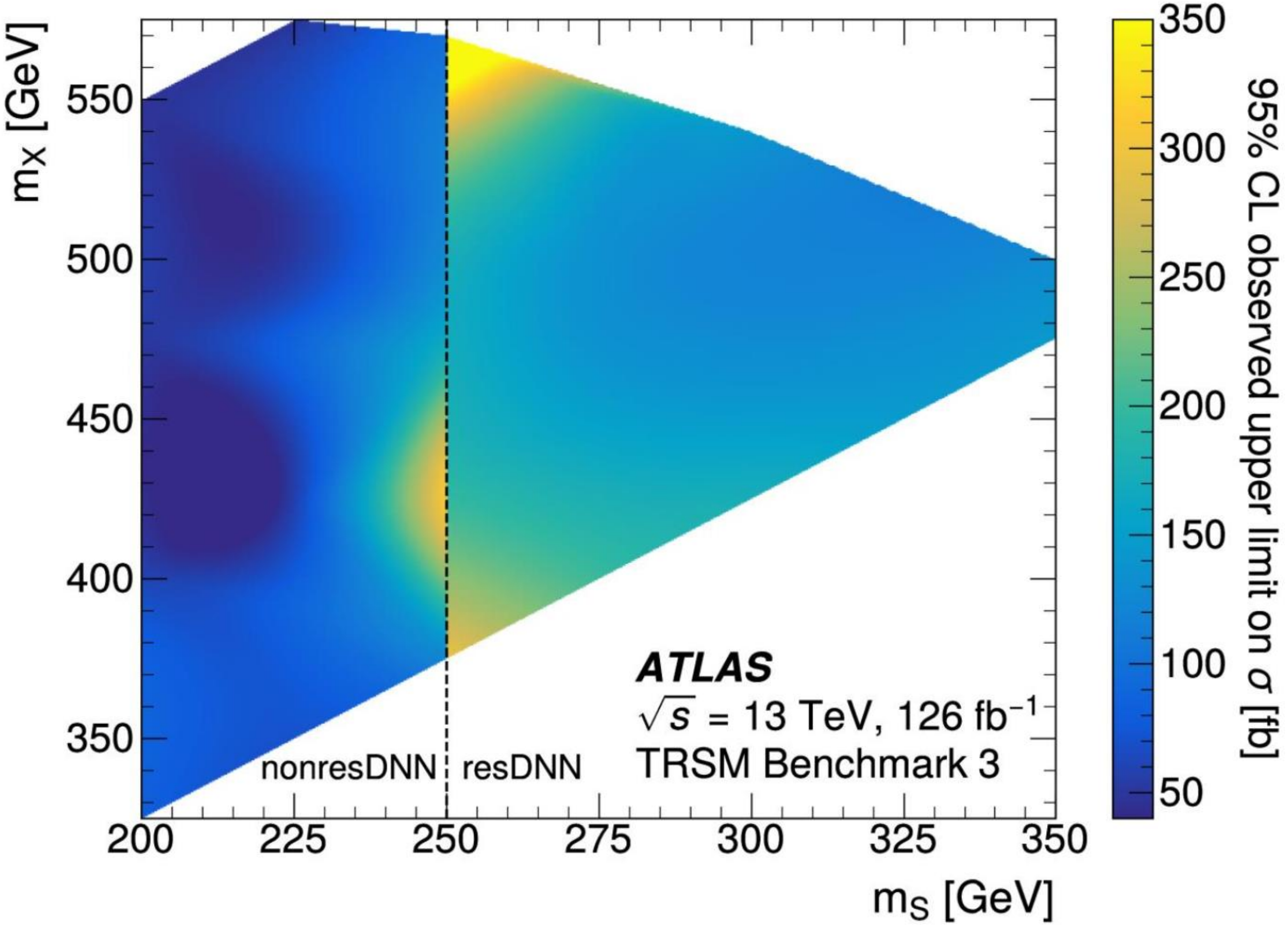
Non-resonant & resonant interpretations

- Cross-section upper limits in the (m_X, m_S) plane of non-resonant interpretation and resonant interpretation. (Observed: $48{\sim}310\ fb$.)

- SM HHH production:

$$\mu = \frac{\sigma_{HHH}}{\sigma_{HHH}^{SM}} \sim 750$$

Observed cross-section upper limit: $59 fb$



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Higgs Quartic Coupling for 1st time at LHC

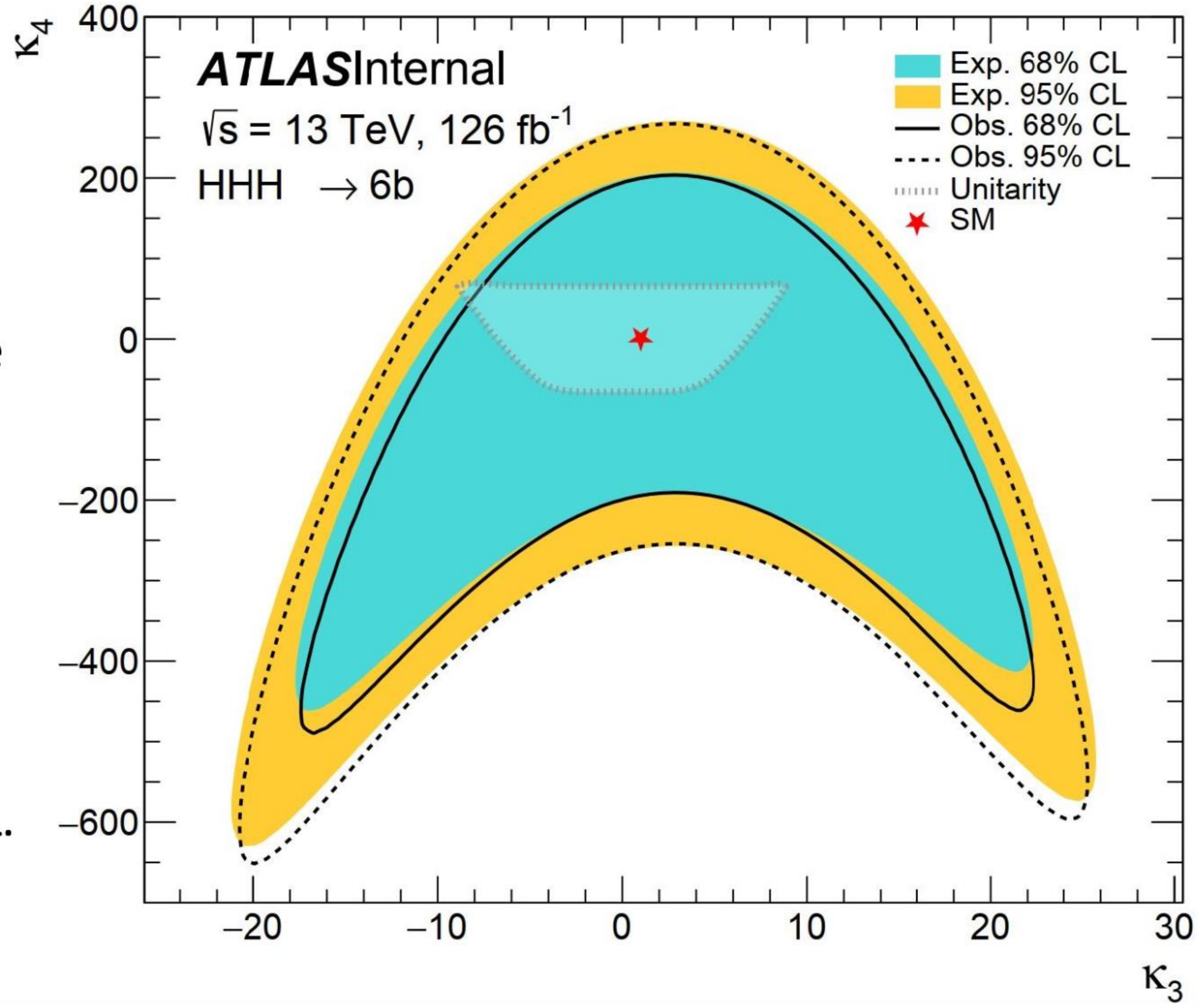
李政道研究所 Tsung-Dao Lee Institute

- **Constraints on quartic coupling** set for the first time.
- Degeneracy of $\sigma_{HHH}(\kappa_3, \kappa_4)$.
- At the 95% CL none of the phase space inside the unitarity bounds is excluded.

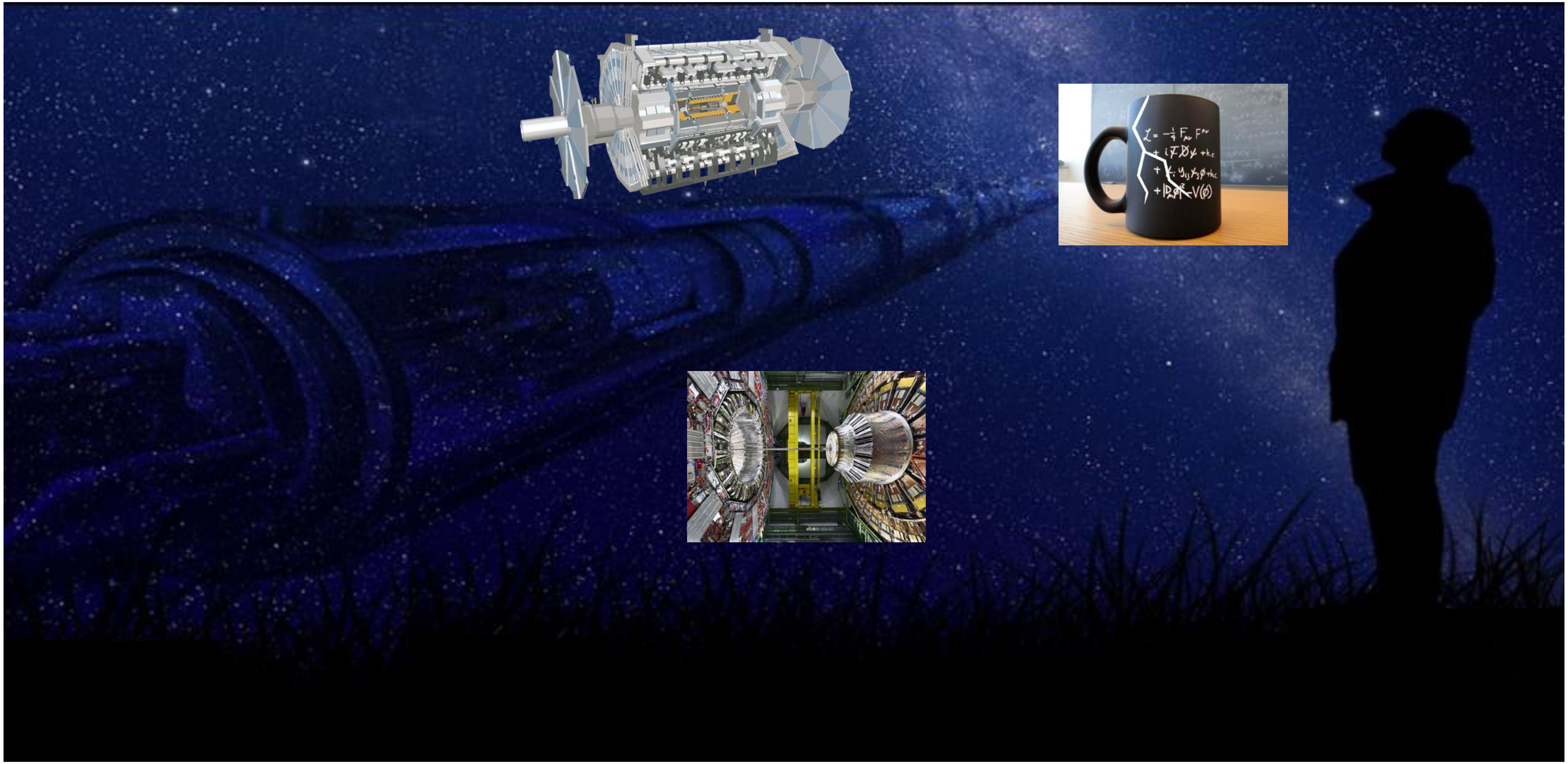
In the SM: $\kappa_3 = \kappa_4 = 1$

Assuming $\kappa_4 = 1$, κ_3: $-11\sim17$ at 95% CL.

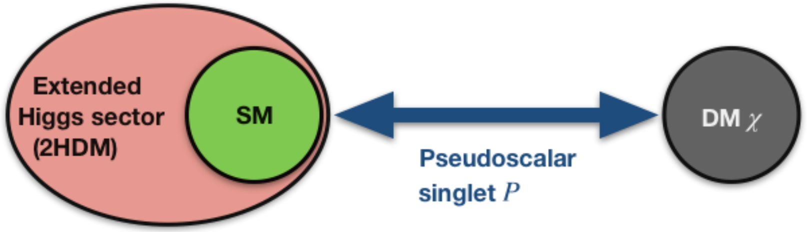
Assuming $\kappa_3 = 1$, κ_4: $-230\sim240$ at 95% CL.



Recap of LHC primary goals: looking into the “unknowns”



Science Bulletin: Welcome Submission



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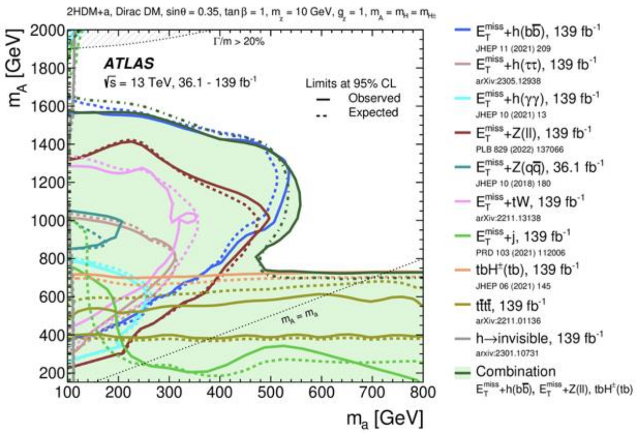

1st ATLAS Paper @ Science Bulletin

DOI:10.1016/j.scib.2024.06.003

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