Multiboson Physics to Explore

Qiang Li (Peking University)

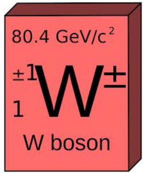
2025/4

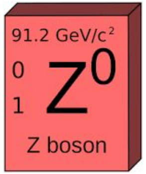
第5届LHCb前沿物理研讨会

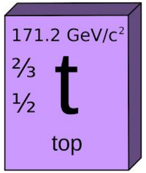
2023/11

2024/7

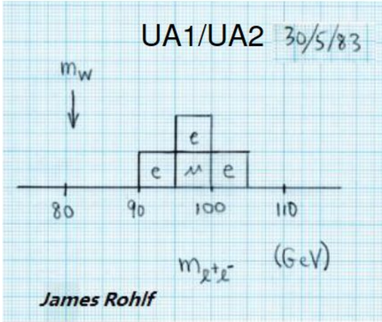
Electroweak milestones: From infancy to adolescence

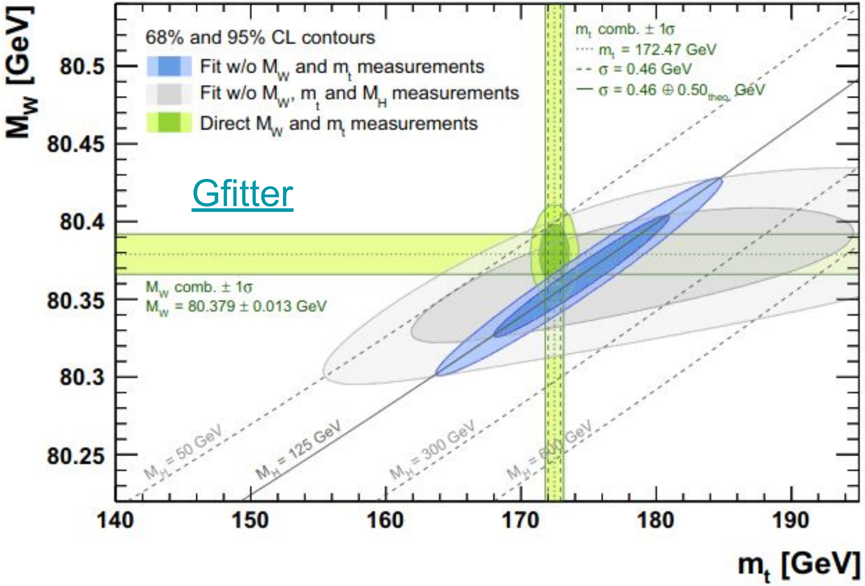




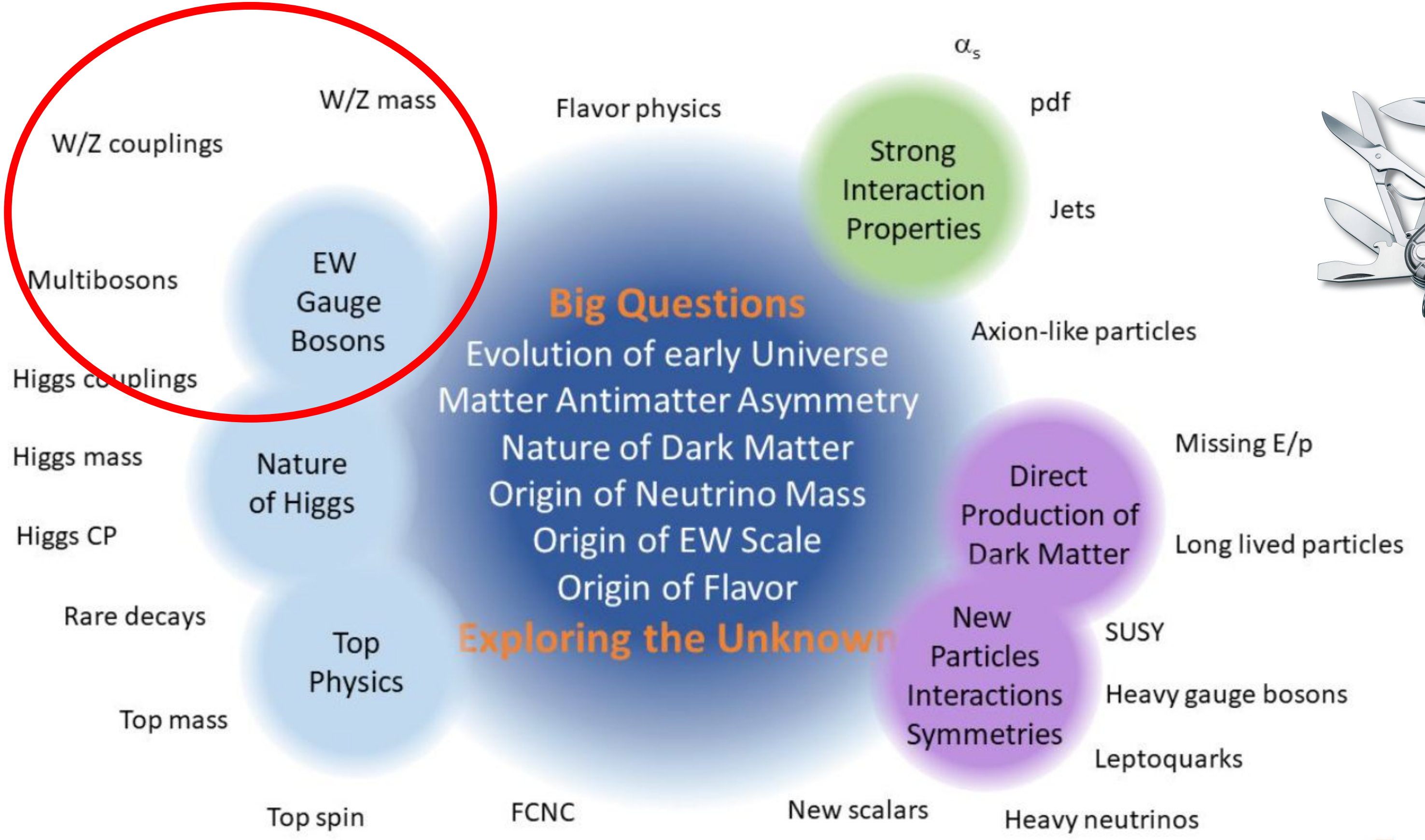


Neutral currents 52;
W/Z boson turns 42;
Top quark now 30;
Higgs turns 13.

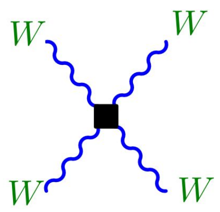


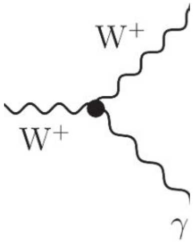


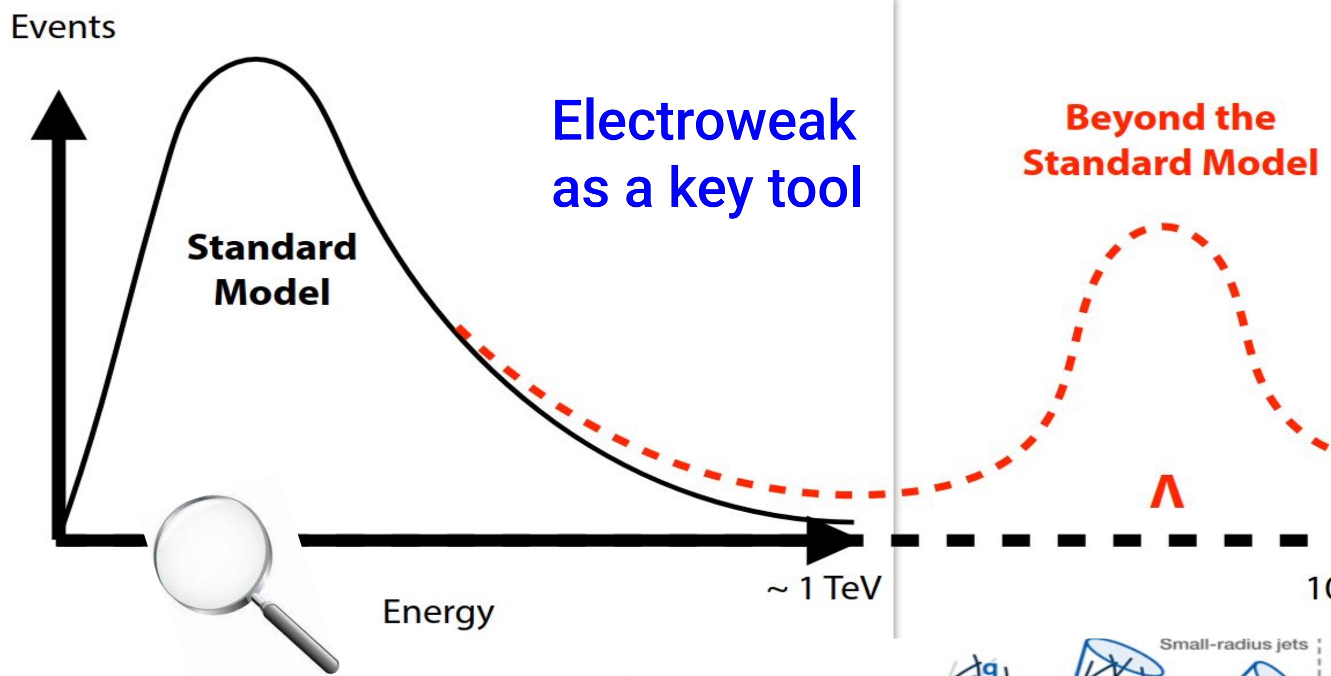
Seattle snowmass summer meeting 2022

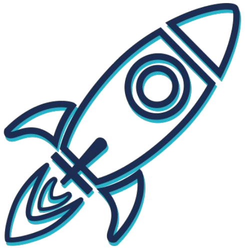


Direct and indirect searches for BSM



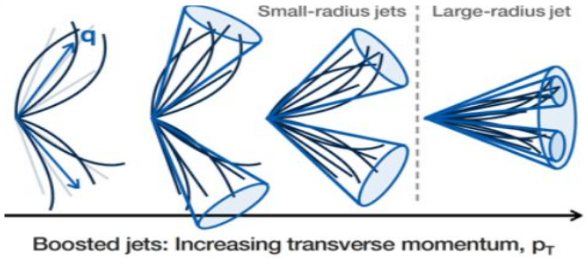




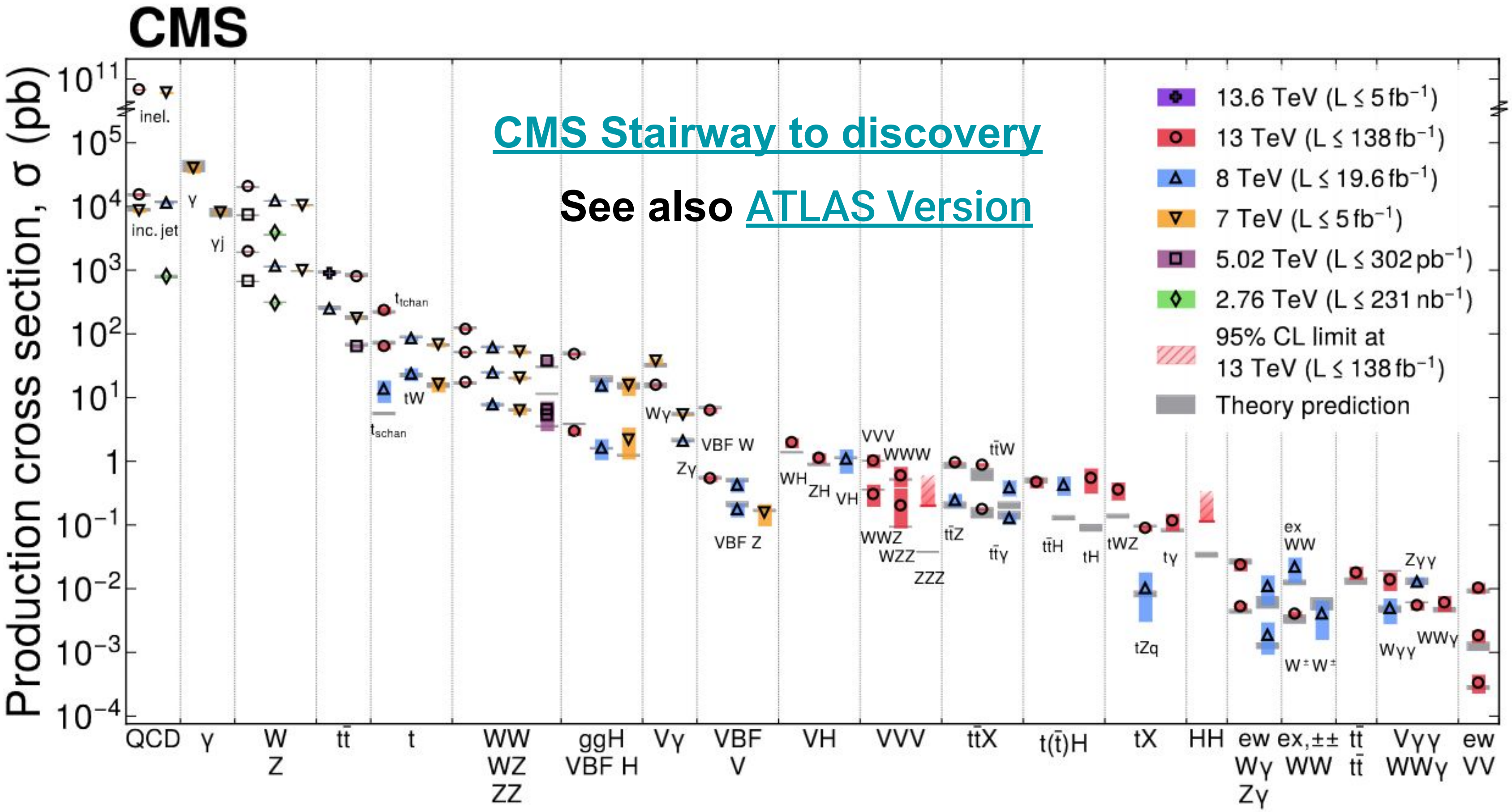


Anomalous couplings, EFT (CP even or odd)

$$L_{\mathrm{EFT}} = L_{\mathrm{SM}} + \sum_i \frac{C_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)} + \sum_i \frac{C_i^{(8)}}{\Lambda^4}\mathcal{O}_i^{(8)} + \dots$$

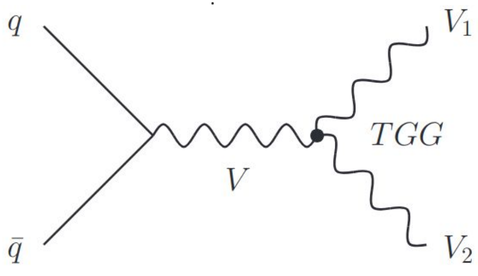


Rich results at the LHC (ATLAS, CMS)



Selected Topics with bias

- **Di-boson**
  - Wγ
- Polarized Di-boson
  - WZ
- Polarized VBS
  - Same-Sign WW scattering
- Tri-boson
  - WZγ, WWγ
- More VBS:
  - H scattering; 2 to 3 scattering
- Quantum tomography
  - H to VV and more



s − channel

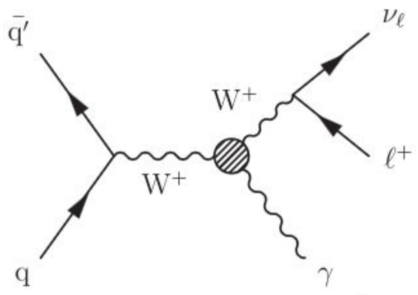
Phys. Rev. Lett. 126, 252002 (2021)

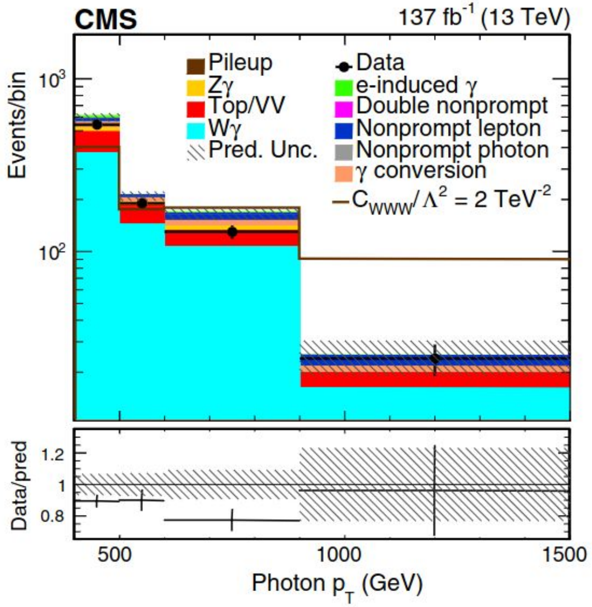
Wγ

- Wγ fiducial cross section measurement based on fit to $m_{l\gamma}$ distribution:
  - σ = 15.44 ± 0.05 (stat) ± 0.84 (exp) ± 0.12 (theory) pb
- Theoretical cross sections:
  - MadGraph5_aMC@NLO 0+1 jets at NLO: 15.44 ± 1.24 pb
  - POWHEG with "NLO competition" scheme: 22.45 ± 3.21 pb
- Limits on dimension 6 EFT operators based on photon p_T distribution

Coefficient	Exp. lower	Exp. upper	Obs. lower	Obs. upper
c_{WWW}/Λ^2	−0.85	0.87	−0.90	0.91
c_B/Λ^2	−46	45	−40	41
$c_{\bar{W}WW}/\Lambda^2$	−0.43	0.43	−0.45	0.45
$c_{\bar{W}}/\Lambda^2$	−23	22	−20	20

EWDim6/HISZ

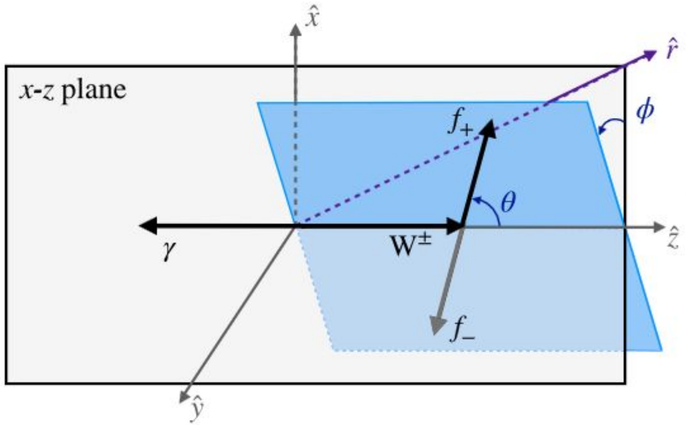




Phys. Rev. Lett. 126, 252002 (2021)
Phys. Rev. D 105 (2022) 052003

Wγ

- Technique called interference resurrection used to enhance anomalous coupling sensitivity
- Phenomenon called radiation amplitude zero: a 0 in the LO cross section at Δη(l,γ) = 0



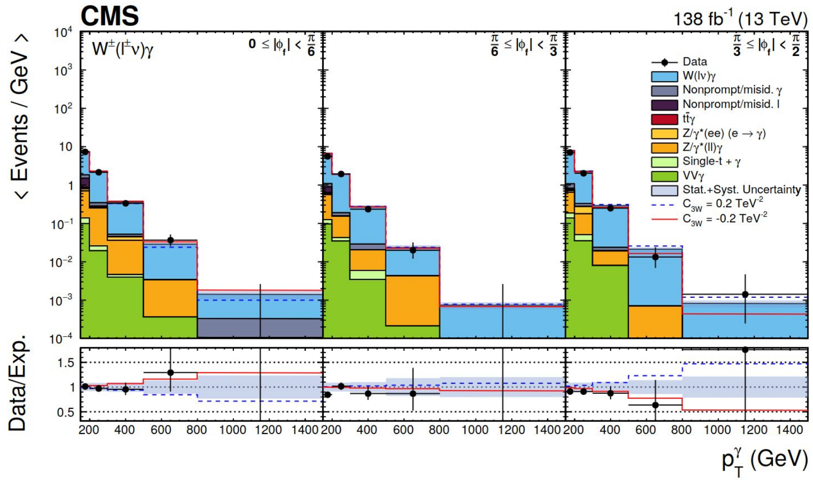
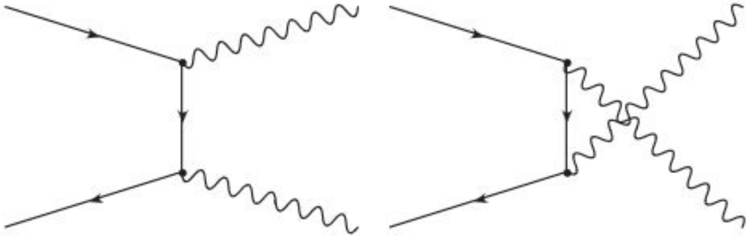


Table 4: Best fit values of C_{3W} and corresponding 95% CL confidence intervals as a function of the maximum p_T^γ bin included in the fit.

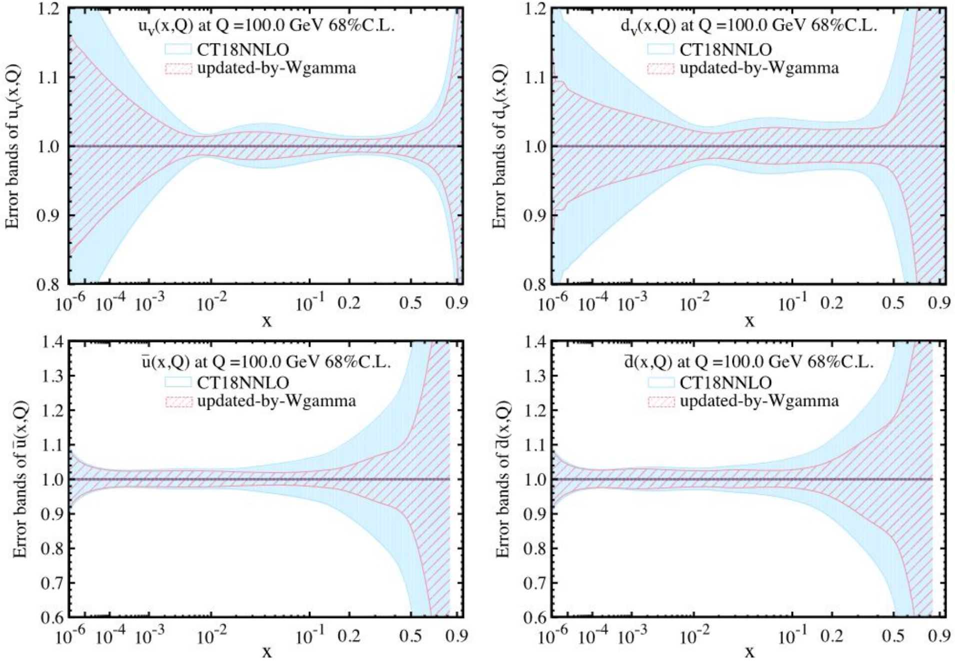
p_T^γ cutoff (GeV)	Best fit C_{3W} (TeV^{-2})		Observed 95% CL (TeV^{-2})		Expected 95% CL (TeV^{-2})	
	SM+int. only	SM+int.+BSM	SM+int. only	SM+int.+BSM	SM+int. only	SM+int.+BSM
200	−0.86	−0.24	[−2.01, 0.38]	[−0.76, 0.40]	[−1.16, 1.27]	[−0.81, 0.71]
300	−0.25	−0.17	[−0.81, 0.34]	[−0.39, 0.28]	[−0.56, 0.60]	[−0.33, 0.33]
500	−0.13	−0.025	[−0.50, 0.25]	[−0.15, 0.12]	[−0.35, 0.38]	[−0.17, 0.16]
800	−0.20	−0.033	[−0.49, 0.11]	[−0.10, 0.08]	[−0.29, 0.31]	[−0.097, 0.095]
1500	−0.13	−0.009	[−0.38, 0.17]	[−0.062, 0.052]	[−0.27, 0.29]	[−0.066, 0.065]

The technique will also be valuable in the future when sufficiently small values of aGCs are probed such that the interference contribution will be dominant

Boosted Assymetry of di-boson productions



$$A_{\text{boost}}^{W\gamma} = \frac{N(|Y_\gamma| > |Y_\ell|) - N(|Y_\gamma| < |Y_\ell|)}{N(|Y_\gamma| > |Y_\ell|) + N(|Y_\gamma| < |Y_\ell|)}$$



PHYSICAL REVIEW D **106,** L051301 (2022)

Letter

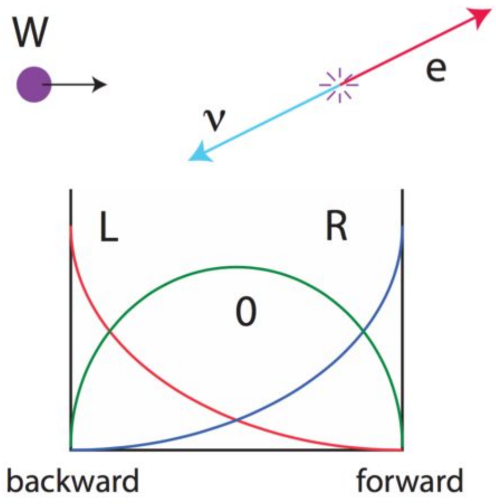
Boost asymmetry of the diboson productions in *pp* collisions

Siqi Yang,[1] Mingzhe Xie,[1] Yao Fu,[1] Zihan Zhao,[1] Minghui Liu,[1] Liang Han,[1] Tie-Jiun Hou,[2] and C.-P. Yuan[3]

[PHYSICAL REVIEW D 106, L051301 (2022)]

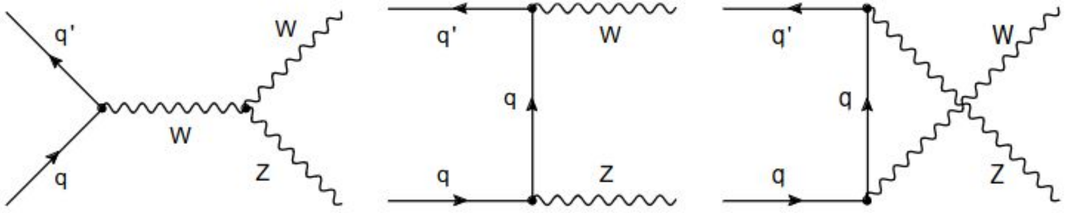
Selected Topics with bias

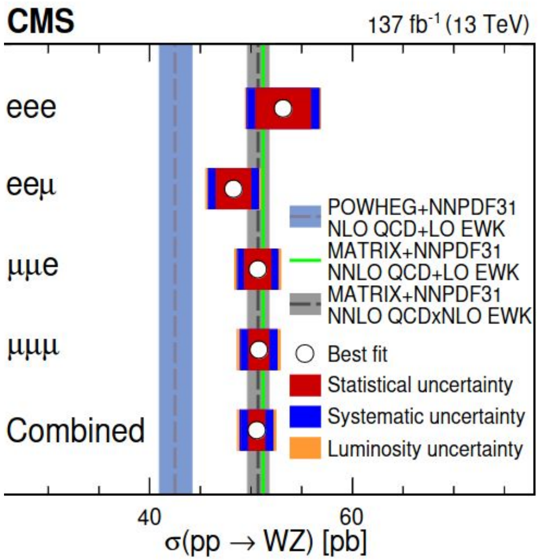
- Di-boson
  - Wγ
- **Polarized Di-boson**
  - WZ
- Polarized VBS
  - Same-Sign WW scattering
- Tri-boson
  - WZγ, WWγ
- More VBS:
  - H scattering; 2 to 3 scattering
- Quantum tomography
  - H to VV and more

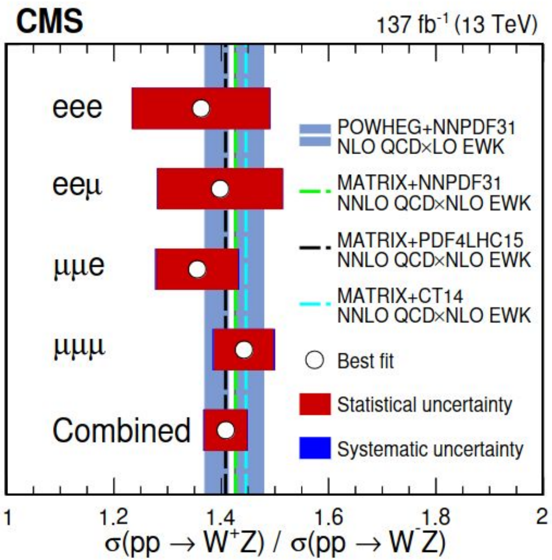


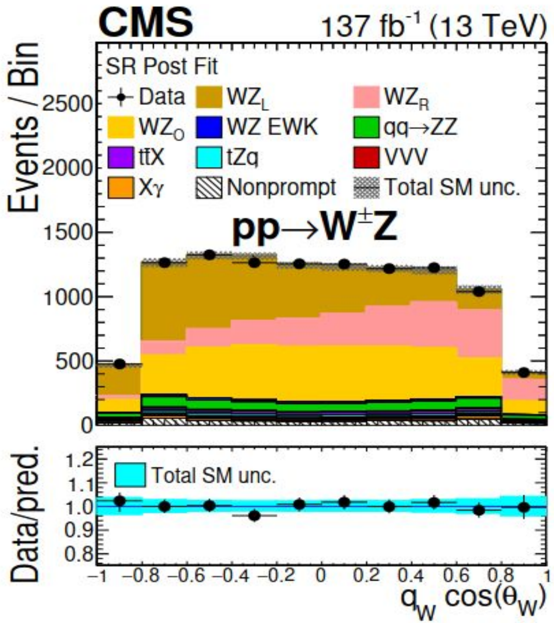
WZ (polarization)

JHEP 07 (2022) 032





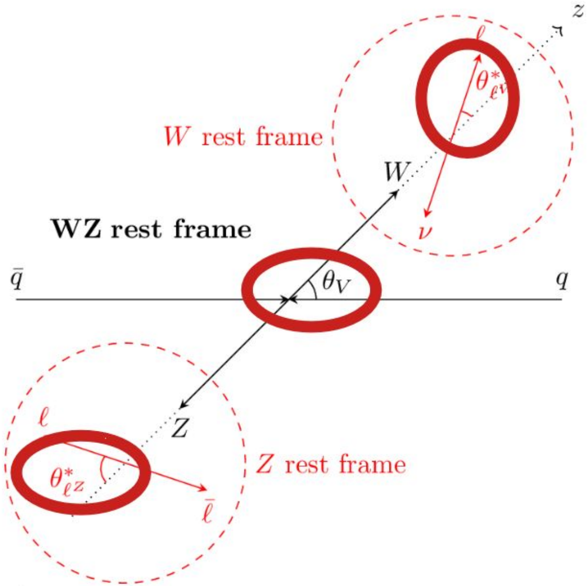


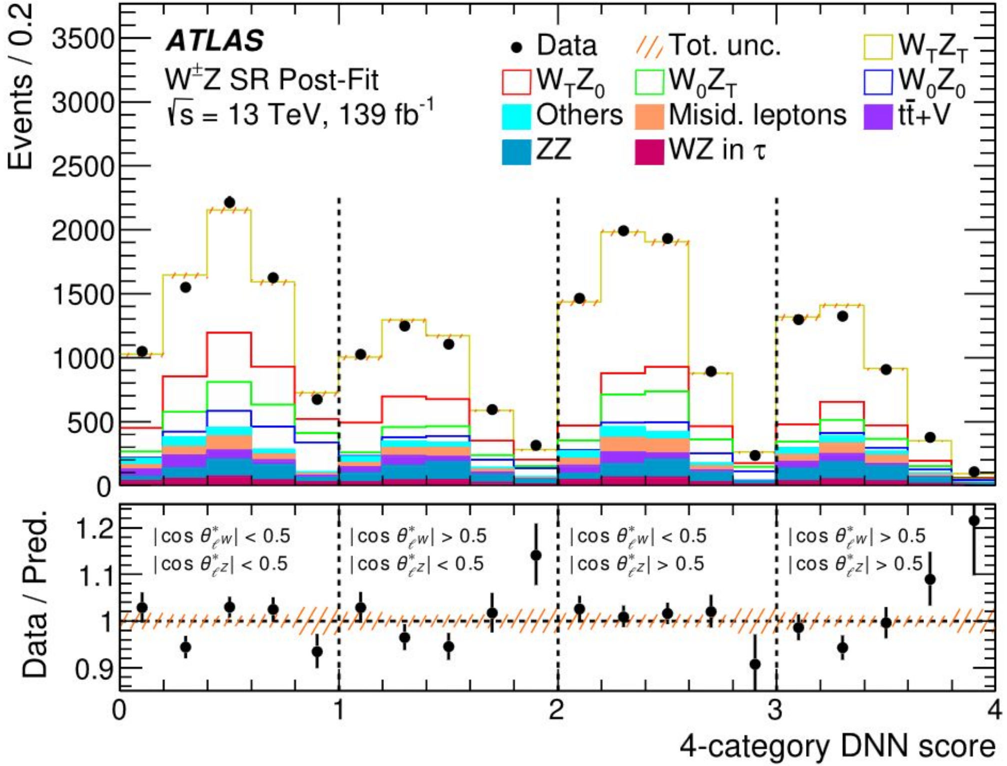


First observation of single longitudinally polarized W bosons in WZ production! 5.6σ (4.3σ) obs (exp).

Phys. Lett. B 843 (2023) 137895

WZ (joint polarization)





Measurement performed as well separating by the W charge

– Significance on f_{00} at 6.9σ in W+Z

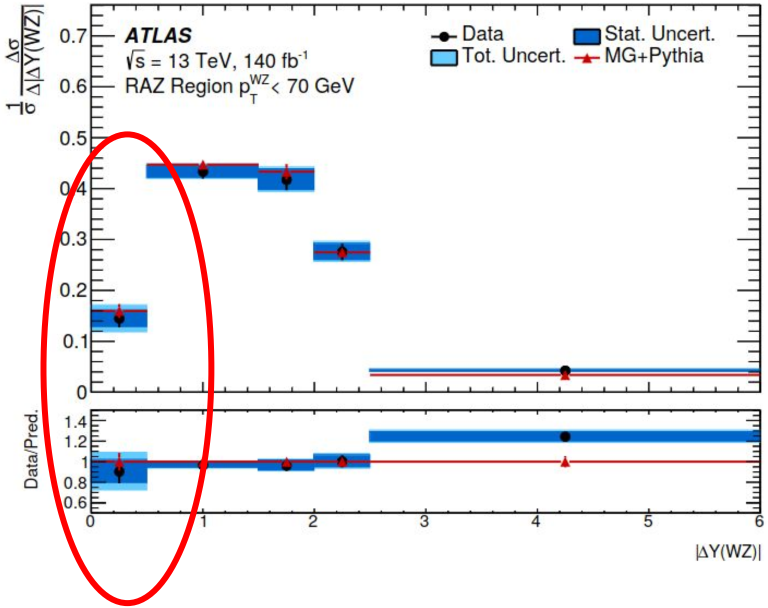
– Significance on f_{00} at 4.1σ in W-Z

PRL 133 (2024) 101802

WZ high PT polarization and RAZ

- This analysis focuses on WZ events with Z bosons required to have high transverse momenta
- Two fiducial regions featuring two longitudinally polarized bosons are defined.
- The first study of the Radiation Amplitude Zero effect
  - Events with two transversely polarized bosons are analyzed

	Signal regions		
	Radiation Amplitude Zero	00-enhanced region 1	00-enriched region 2
Pass inclusive WZ event selection	✓	✓	✓
Transverse momentum of the Z boson (p_T^Z)	-	[100, 200] GeV	> 200 GeV
Transverse momentum of the WZ system (p_T^{WZ})	< 20, 40, 70 GeV	< 70 GeV	



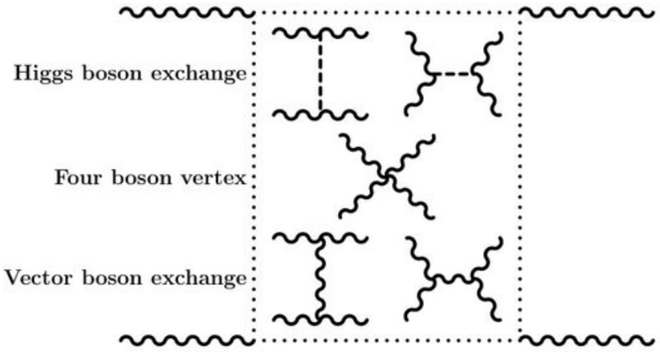
dominated by TT events with low momentum W and Z bosons [1, 2, 13]. This analysis focuses on WZ events with Z bosons required to have high transverse momenta (p_T^Z). The combination of high p_T^Z and low p_T^{WZ} significantly reduces the TT contribution and increases f_{00}. As a result, f_{00} increases from 5 – 7% in the inclusive region to 20 – 30% in the region with high p_T^Z and low p_T^{WZ} [14].

	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

5 sigma observation in $100 < p_{T,Z} < 200$ **GeV for** f_{00}

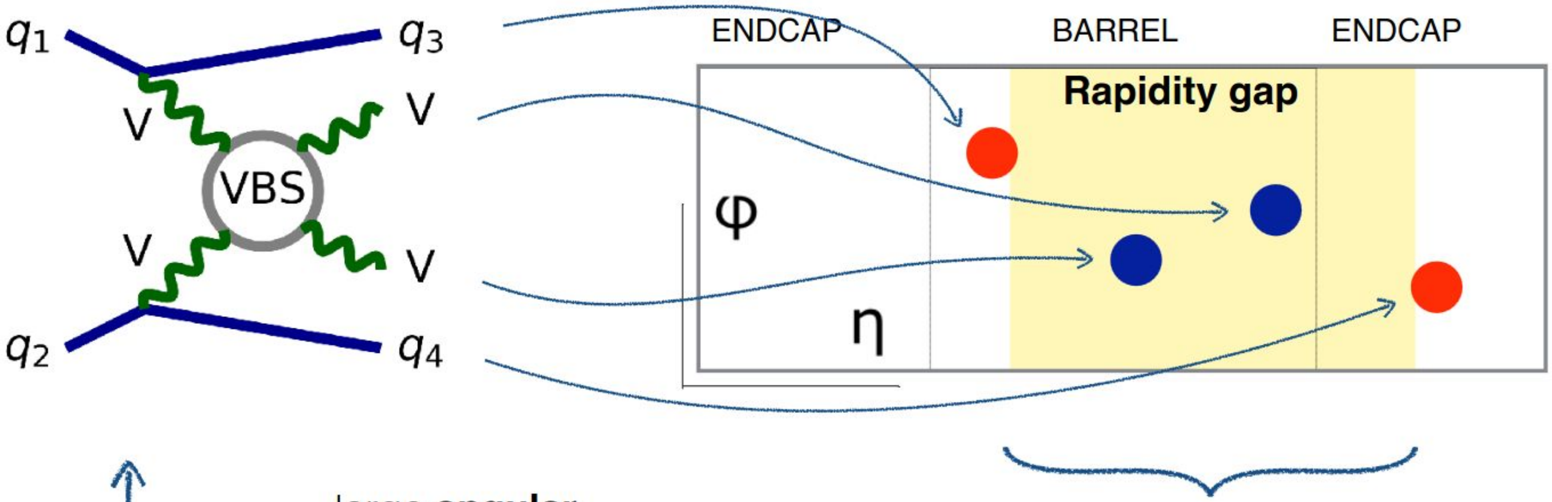
Selected Topics with bias

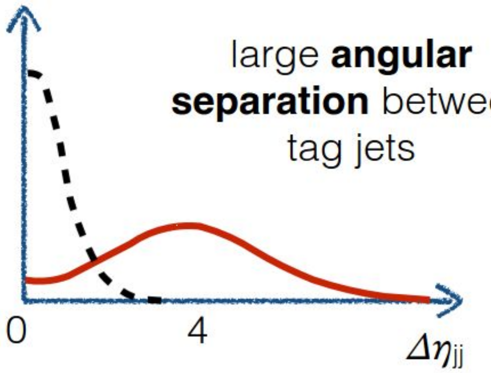
- Di-boson
  - Wγ
- Polarized Di-boson
  - WZ
- **Polarized VBS**
  - Same-Sign WW scattering
- Tri-boson
  - WZγ, WWγ
- More VBS:
  - H scattering; 2 to 3 scattering
- Quantum tomography
  - H to VV and more



PLB 841(2023)137495
JHEP 07 (2024) 254
JHEP 06 (2024) 192

Vector Boson Scattering: W+W- and WZ



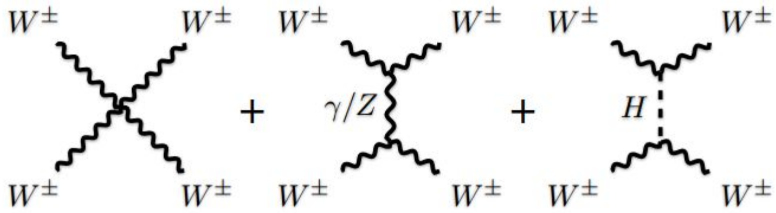


low QCD activity between tag jets, since there's no color flow between the two protons

https://indico.cern.ch/event/1253590/contributions/5843984/attachments/2872663/5031146/2024-06-07-govoni.pdf

Longitudinal Polarized VBS

Importance of $W_L^\pm W_L^\pm \rightarrow W_L^\pm W_L^\pm$

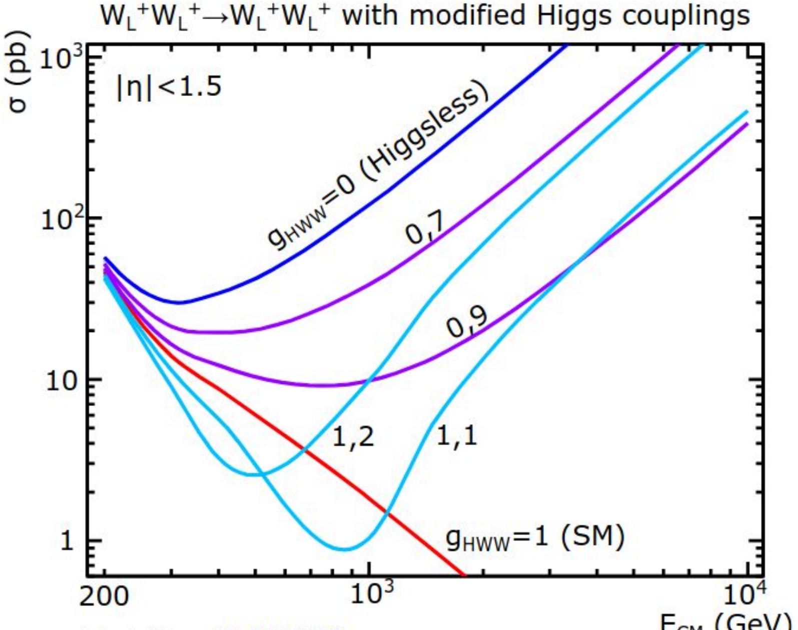


- Higgs Goldstone bosons result in longitudinal polarized vector bosons:

Higgs field Φ
- $H^+ \longrightarrow W_L^+$
- $H^- \longrightarrow W_L^-$
- $H^0 \longrightarrow Z_L$
- SM Higgs h

- Longitudinal $W_L^\pm W_L^\pm \rightarrow W_L^\pm W_L^\pm$ would **violate unitarity if Higgs coupling deviates from SM prediction**

➡ $W_L^\pm W_L^\pm \rightarrow W_L^\pm W_L^\pm$ is a **unique opportunity to probe electroweak symmetry-breaking**



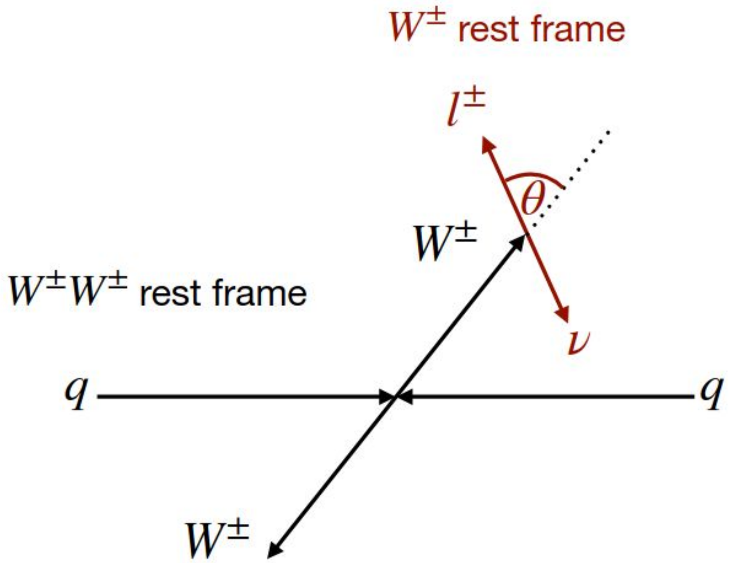
[adapted from arXiv:1412.8367]

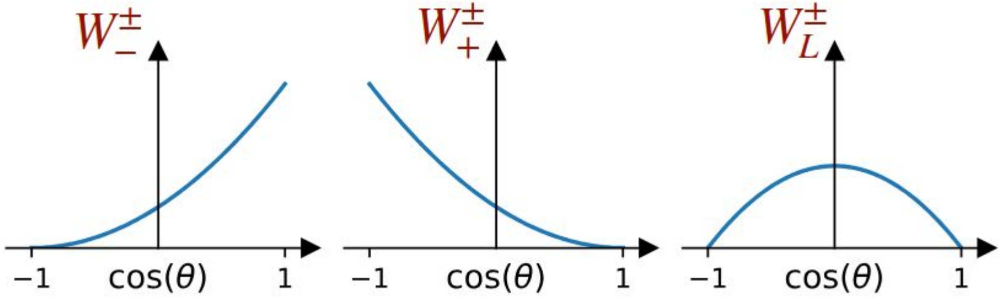
Access Polarization Information

- $W^{\pm}$ polarization determines decay angle

➡ BUT: Cannot access $W^{\pm}$ rest frame since the **two neutrinos are not reconstructable**

➡ **Simulate full event kinematic** of polarization states predicted by SM





[PLB 812 (2020) 136018](#)

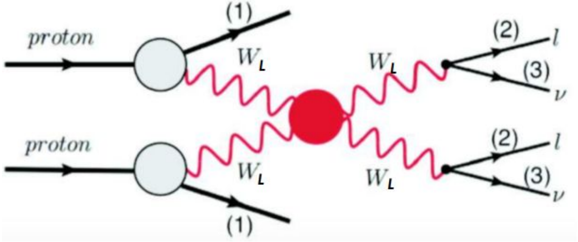
Polarized VBS from CMS

- Signal sample simulated in **WW/pp center-of-mass frame**
- Simultaneous fit on **two BDT discriminant variables**:

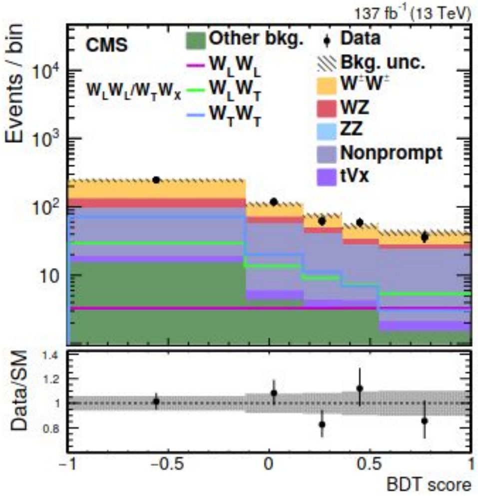
☑ $W_L^\pm W_L^\pm$: signal BDT ($W_L^\pm W_L^\pm$ vs $W_T^\pm W_X^\pm$) and inclusive BDT (VBS vs Bkg.)

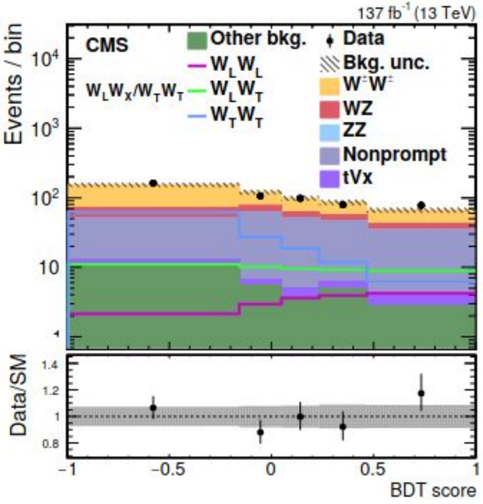
☑ $W_L^\pm W_X^\pm$: signal BDT ($W_L^\pm W_X^\pm$ vs $W_T^\pm W_T^\pm$) and inclusive BDT (VBS vs Bkg.)

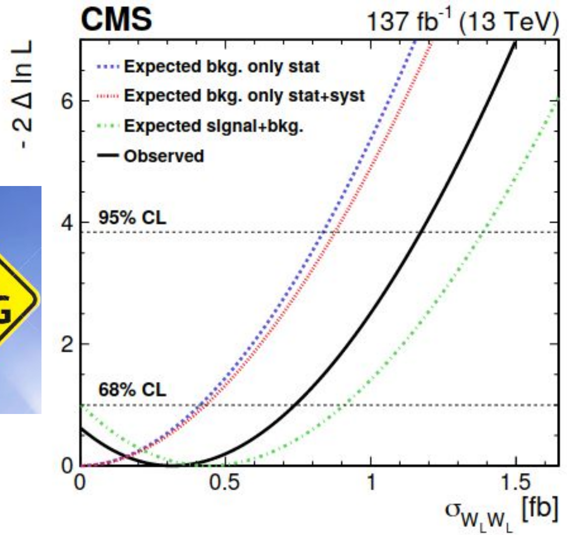
☑ Selection and CRs are same as EW $W^\pm W^\pm$ production



Observed (expected) significance for LL and LT+LL: 0.88 (1.17)σ; 2.3 (3.1)σ

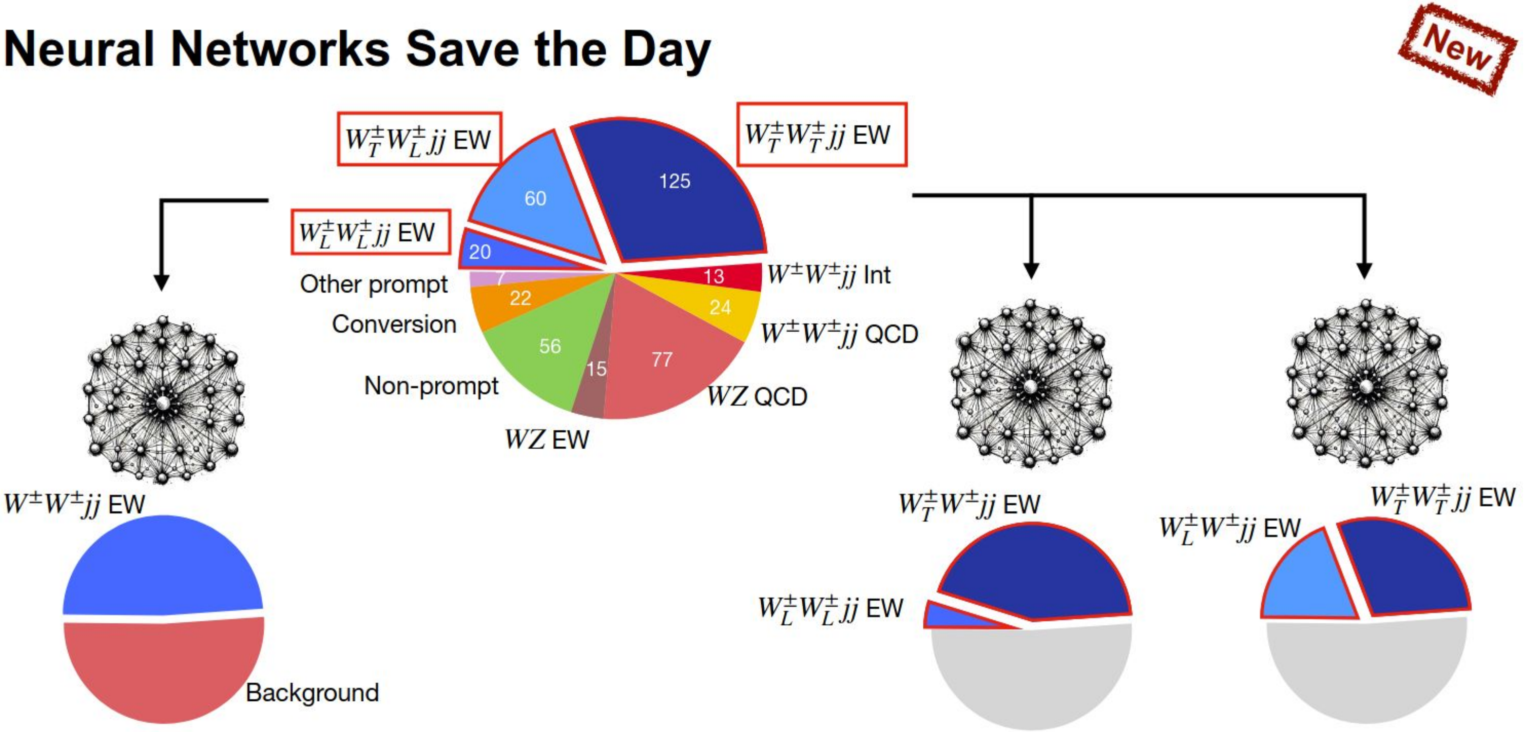






Polarized VBS from ATLAS

Neural Networks Save the Day



DNN trained to **split signal region in 3 regions** with **increasing $W^\pm W^\pm jj$ EW purity**

DNN trained as **discriminant variable to measure $W_L^\pm W_L^\pm jj$ EW / $W_L^\pm W^\pm jj$ EW**

10

Polarized VBS from ATLAS

Single Boson Polarization $W^\pm_L W^\pm$

New

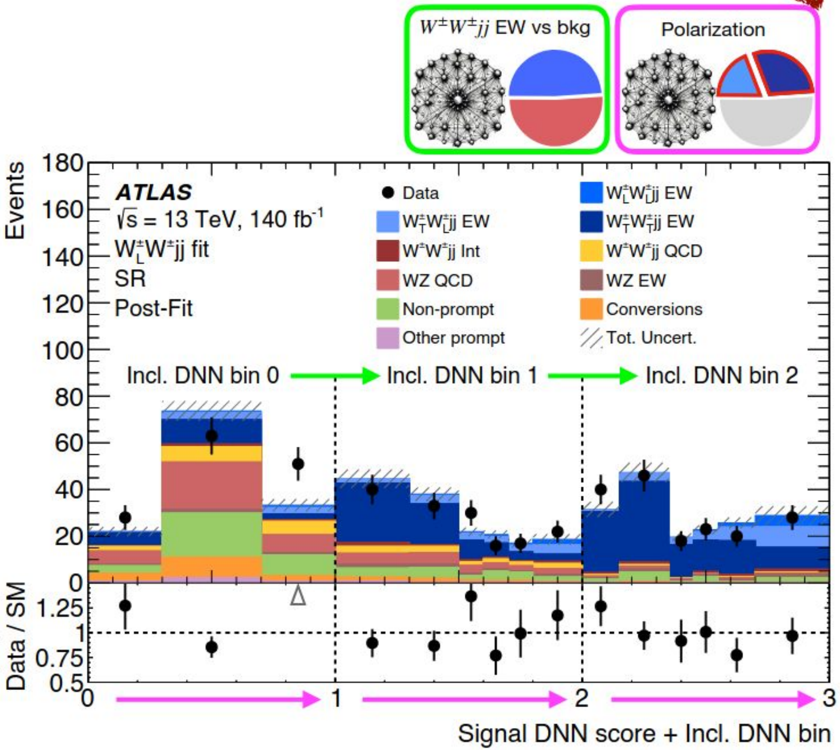
- **Significance of 3.3 σ** for $W^\pm_L W^\pm jj$ (expected 4.0 σ)

➡ **First evidence for longitudinal polarization in vector boson scattering**

- Measured cross-section **in agreement with the Standard Model**

- Dominated by **statistical uncertainty**

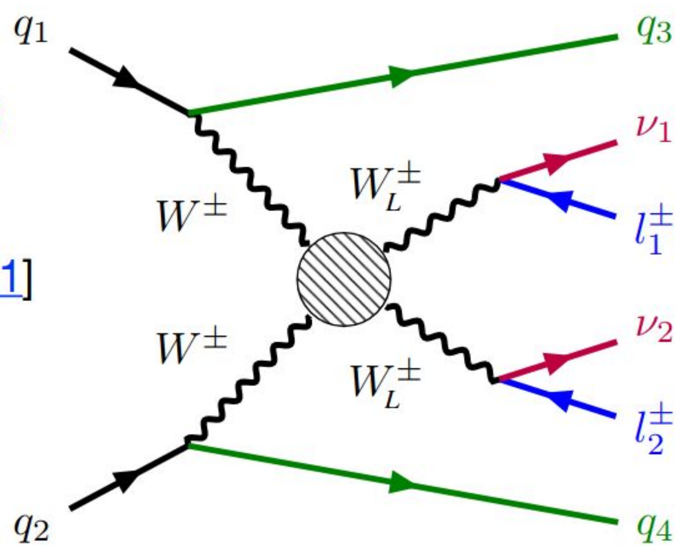
Prediction	Measured $\sigma\mathcal{B}$ (fb)	Uncertainty breakdown (fb)
1.18 ± 0.29	0.88 ± 0.30 (tot.)	± 0.28 (stat.) $\pm$ 0.08 (mod. syst.) $\pm$ 0.05 (exp. syst.)



Polarized VBS from ATLAS

[arXiv:2503.11317]

- $W_L^\pm W_L^\pm \to W_L^\pm W_L^\pm$ is unique opportunity to **probe EWS**
- **State-of-the-art polarization prediction**:
  - Multi-jet merging in matrix element [JHEP04(2024) 001]
  - NLO EW correction [JHEP11(2024) 115]
- **First evidence** for longitudinal polarization in vector boson scattering
- **Most stringent limits** for $W_L^\pm W_L^\pm jj$ EW (1.5 x SM)
- Dominated by **statistical uncertainty**

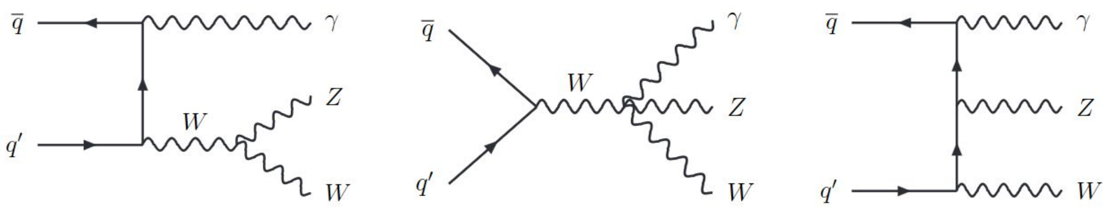


Selected Topics with bias

- Di-boson
  - $W\gamma$
- Polarized Di-boson
  - WZ
- Polarized VBS
  - Same-Sign WW scattering
- **Tri-boson**
  - $WZ\gamma$, $WW\gamma$
- More VBS:
  - H scattering; 2 to 3 scattering
- Quantum tomography
  - H to VV and more

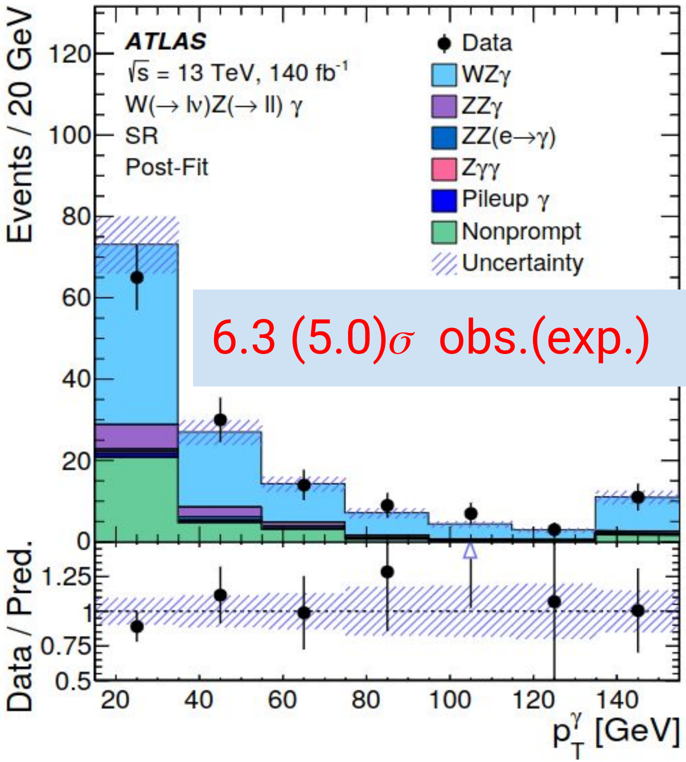
PRL132 (2024) 021802
arXiv:2503.21977

WZγ observation



($e\mu\mu$, μee, eee, $\mu\mu\mu$) channels combined profile-likelihood fit in SR+2CRs

Process	SR	$ZZ\gamma$ CR	$ZZ(e\to\gamma)$ CR
$WZ\gamma$	92 ± 15	0.21 ± 0.07	0.56 ± 0.14
$ZZ\gamma$	10.7 ± 2.3	23 ± 5	1.8 ± 0.4
$ZZ(e\to\gamma)$	3.0 ± 0.6	0.028 ± 0.020	30 ± 6
$Z\gamma\gamma$	1.05 ± 0.32	0.15 ± 0.06	0.29 ± 0.10
Nonprompt background	30 ± 6	-	-
Pileup γ	1.9 ± 0.7	-	-
Total yield	139 ± 12	23 ± 5	33 ± 6
Data	139	23	33



6.3 (5.0)σ obs.(exp.)

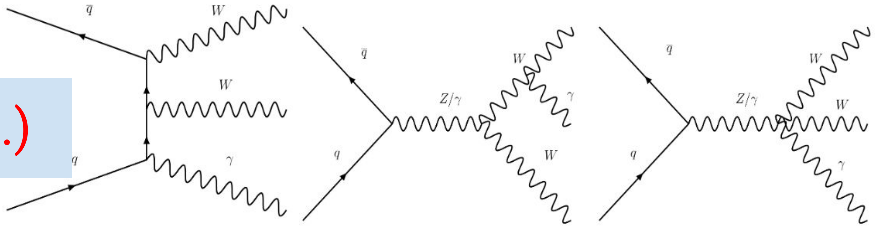
$$\sigma_{WZ\gamma} = 2.01 \pm 0.30\,(\text{stat.}) \pm 0.16\,(\text{syst.})\ \text{fb}$$

WWγ Observation

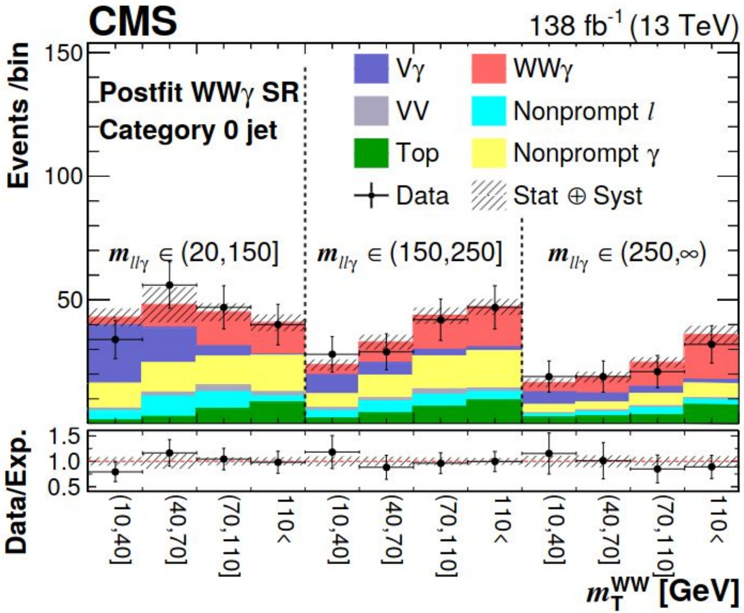
PRL132 (2024) 121901

- Signal region categorized with 0 and >0 jet,
- only $e\mu$ channel
- SSWWγ and TOPγ CRs,
- data-driven non-prompt backgrounds
- maximum likelihood fit of 2D binned distributions.

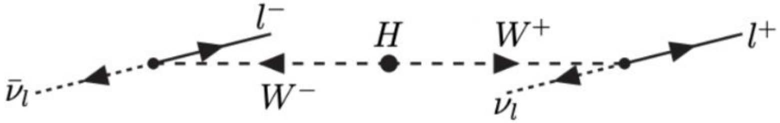
5.6 (4.7)σ obs.(exp.)



$$\mu^{\text{obs.}}_{\text{combined}} = 1.31 \pm 0.17\,(\text{stat}) \pm 0.21\,(\text{syst})$$



- Also sensitive to Higgs couplings with light quarks
  - no gluon fusion contribution due to Furry's theorem
- Further optimization targeting the Higgs characteristics



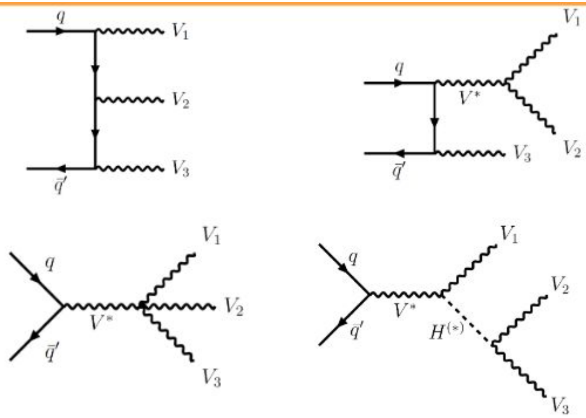
σ upper limits obs. (exp.) [fb]	κ_q limits obs. (exp.) at 95% CL
85 (67)	$\lvert\kappa_u\rvert \leq 16000$ (13000)
72 (58)	$\lvert\kappa_d\rvert \leq 17000$ (14000)
68 (49)	$\lvert\kappa_s\rvert \leq 1700$ (1300)
87 (67)	$\lvert\kappa_c\rvert \leq 200$ (110)

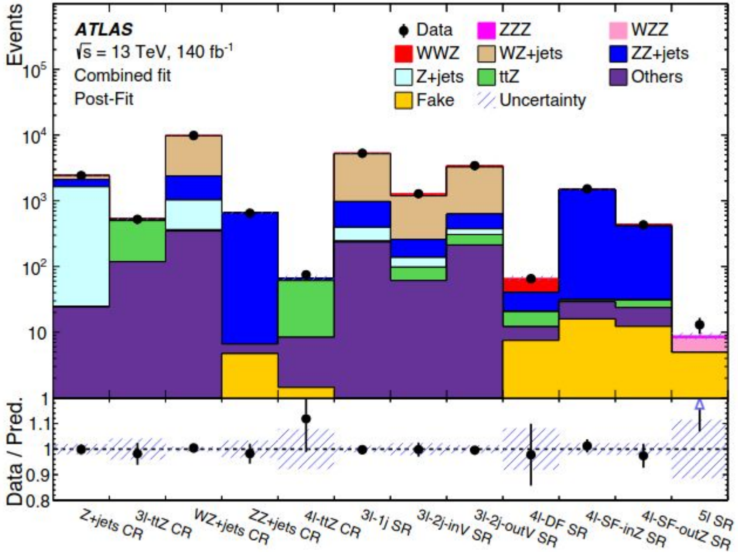
arXiv:2412.15123

VVZ Observation

- Among the **rarest processes** at the LHC
- measurement at 13 TeV with 140 fb^{-1}
- **VVZ (V= W, or Z): WWZ +WZZ+ZZZ**
- **3ℓ: WWZ and WZZ , 4ℓ WWZ, >5ℓ WZZ and ZZZ**
- BDT discriminant for each channel

Dominant background from **Diboson processes**: estimated from the data





Simultaneous fit across final states and CRs

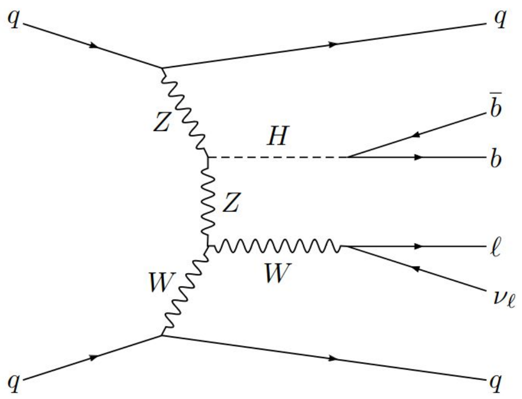
combined signal strength parameter μ for VVZ production

Significance: observed 6.4σ

Process	Signal strength	Cross section (fb)	Observed (expected) sensitivity
VVZ	$1.43 \pm 0.20(\text{stat.})^{+0.21}_{-0.19}(\text{syst.})$	$660^{+93}_{-90}(\text{stat.})^{+88}_{-81}(\text{syst.})$	$\boxed{6.4\ (4.7)\ \sigma}$
WWZ	$1.33 \pm 0.28(\text{stat.})^{+0.21}_{-0.17}(\text{syst.})$	$442 \pm 94(\text{stat.})^{+60}_{-52}(\text{syst.})$	$4.4\ (3.6)\ \sigma$
WZZ	$2.13^{+1.18}_{-0.96}(\text{stat.})^{+0.76}_{-0.41}(\text{syst.})$	$200^{+111}_{-91}(\text{stat.})^{+65}_{-37}(\text{syst.})$	$2.8\ (1.6)\ \sigma$

Selected Topics with bias

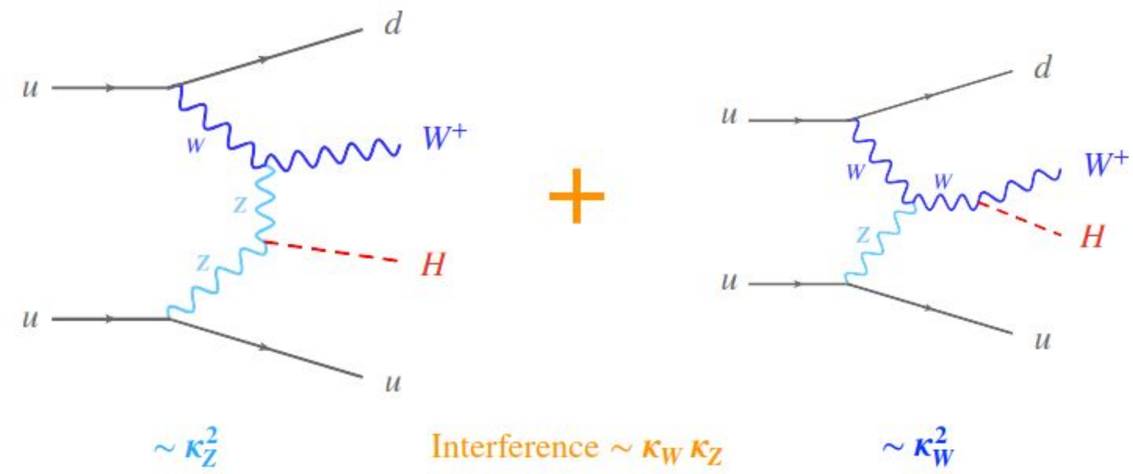
- Di-boson
  - Wγ
- Polarized Di-boson
  - WZ
- Polarized VBS
  - Same-Sign WW scattering
- Tri-boson
  - WZγ, WWγ
- **More VBS:**
  - H scattering; 2 to 3 scattering
- Quantum tomography
  - H to VV and more



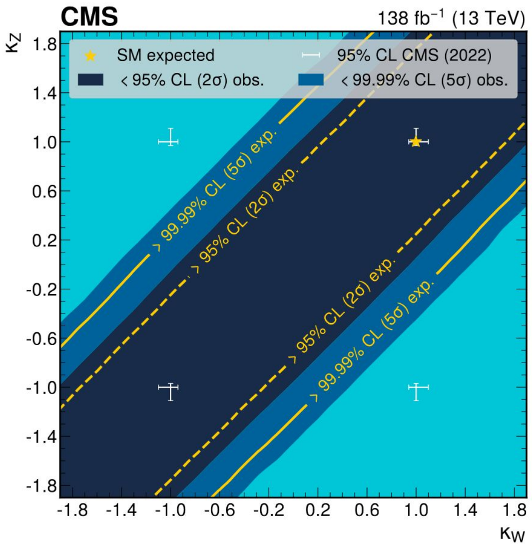
PRL 133 (2024) 141801
PLB 860 (2025) 139202

W and Higgs scattering

- A novel type of Vector Boson Scattering process
- Can be sensitive to the relative sign of HWW and HZZ
- ATLAS and CMS both exclude $\kappa_W/\kappa_Z<0$ beyond 5σ in H→bb final states



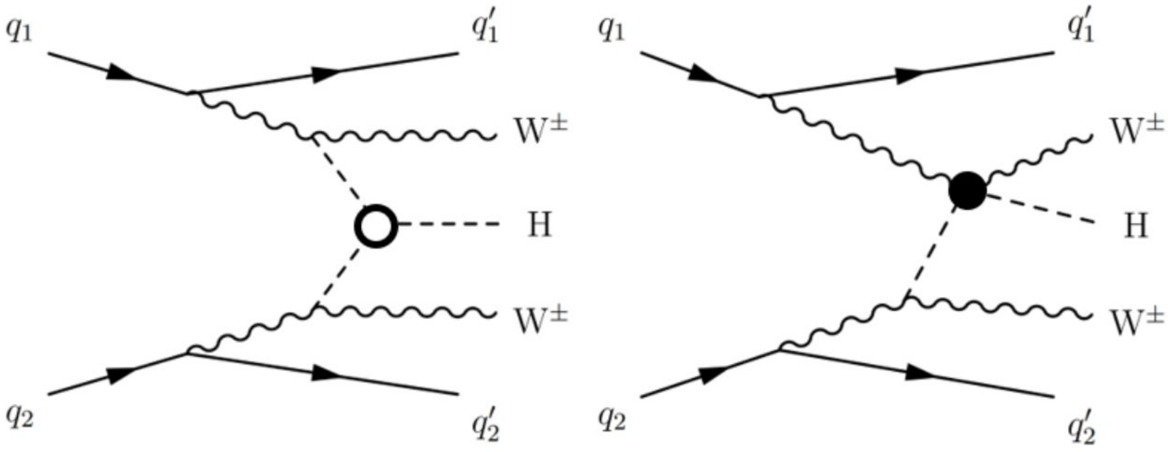
$$\sigma_{\mathrm{VBF},WH} \propto \kappa_Z^2 |\mathcal{M}_Z|^2 + \kappa_W^2 |\mathcal{M}_W|^2 - 2\,\kappa_Z \kappa_W\, \Re[\mathcal{M}_Z^\dagger \mathcal{M}_W]$$
$$= \kappa_Z^2 |\mathcal{M}_Z|^2 + \kappa_W^2 |\mathcal{M}_W|^2 - 2\,\kappa_Z^2 \boxed{\lambda_{WZ}}\, \Re[\mathcal{M}_Z^\dagger \mathcal{M}_W]$$

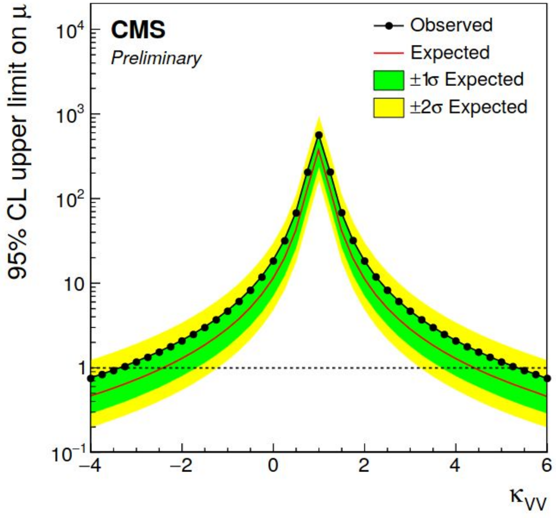


CMS-PAS-HIG-24-001

2→3 VBS Process

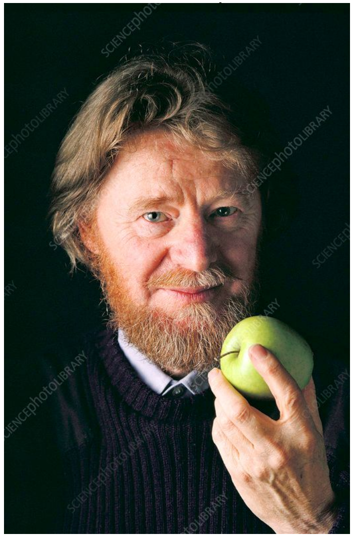
- Another novel type of Vector Boson Scattering
- Can be sensitive to HHVV coupling
- Open new doors to probe most rare process





Selected Topics with bias

- Di-boson
  - Wγ
- Polarized Di-boson
  - WZ
- Polarized VBS
  - Same-Sign WW scattering
- Tri-boson
  - WZγ, WWγ
- More VBS:
  - H scattering; 2 to 3 scattering
- **Quantum tomography**
  - H to VV and more



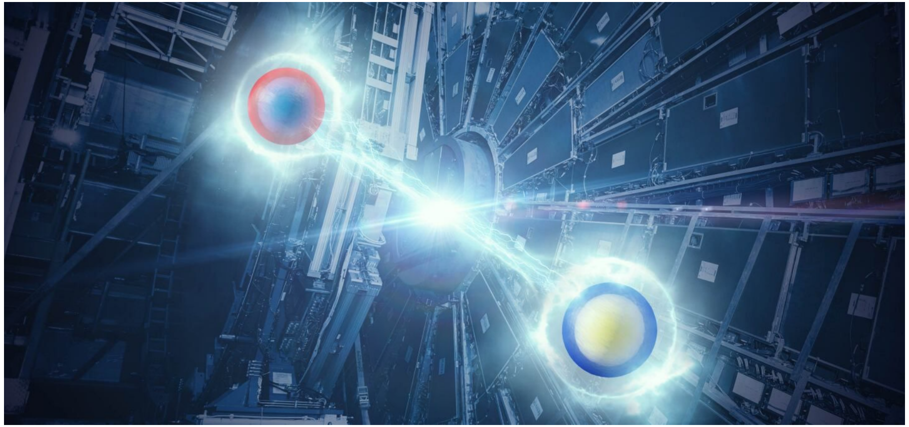
Quantum entanglement at high energy

Nature volume 633, pages 542–547 (2024)

LHC experiments at CERN observe quantum entanglement at the highest energy yet

The results open up a new perspective on the complex world of quantum physics

18 SEPTEMBER, 2024



Article

Observation of quantum entanglement with top quarks at the ATLAS detector

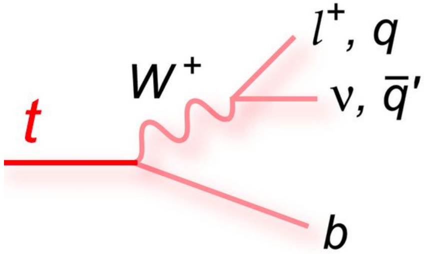
https://doi.org/10.1038/s41586-024-07824-z
Received: 14 November 2023
Accepted: 12 July 2024
Published online: 18 September 2024
Open access
Check for updates

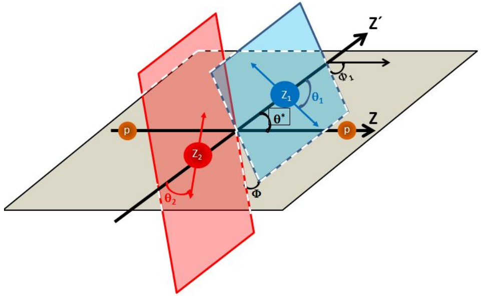
The ATLAS Collaboration*✉

Entanglement is a key feature of quantum mechanics[1–3], with applications in fields such as metrology, cryptography, quantum information and quantum computation[4–8]. It has been observed in a wide variety of systems and length scales, ranging from the microscopic[9–13] to the macroscopic[14–16]. However, entanglement remains largely unexplored at the highest accessible energy scales. Here we report the highest-energy observation of entanglement, in top–antitop quark events produced at the Large Hadron Collider, using a proton–proton collision dataset with a centre-of-mass energy of $\sqrt{s} = 13$ TeV and an integrated luminosity of 140 inverse femtobarns (fb)$^{-1}$ recorded with the ATLAS experiment. Spin entanglement is detected from the measurement of a single observable D, inferred from the angle between the charged leptons in their parent top- and antitop-quark rest frames. The observable is measured in a narrow interval around the top–antitop quark production threshold, at which the entanglement detection is expected to be significant. It is reported in a fiducial phase space defined with stable particles to minimize the uncertainties that stem from the limitations of the Monte Carlo event generators and the parton shower model in modelling top-quark pair production. The entanglement marker is measured to be $D = -0.537 \pm 0.002$ (stat.) ± 0.019 (syst.) for $340\ \text{GeV} < m_{t\bar{t}} < 380\ \text{GeV}$. The observed result is more than five standard deviations from a scenario without entanglement and hence constitutes the first observation of entanglement in a pair of quarks and the highest-energy observation of entanglement so far.

Why QE at high energy? (ref)

- **Understand quantum nature & seek for BSM effects.**
- Particle scattering/decay of unstable particles provide **a natural laboratory**
  - the momenta of observed particles are essentially commuting observables. Therefore, there is always some hidden variable theory that can explain the observed momentum data
  - However, one can focus on **spin correlation** emerges in different phase-space region
- It is plausible that **quantum mechanics undergoes modifications** (ref) **at some short distance scales** to achieve compatibility with gravity. Such modifications could, in principle, **be (only) detected by measuring Bell-type observables** or through quantum process tomography (ref)
- offers the potential to uncover **new insights into quantum field theory**.





https://scipost.org/10.21468/SciPostPhys.3.5.036


SciPost SciPost Phys. 3, 036 (2017)

Maximal entanglement in high energy physics

Alba Cervera-Lierta[1], José I. Latorre[1,2], Juan Rojo[3] and Luca Rottoli[4]

Quantum Entanglement among gauge bosons

A broad new programme for collider physics

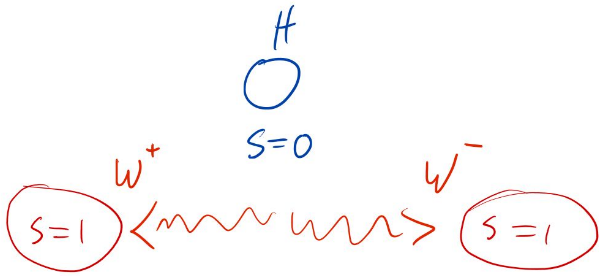
Testing the foundations of quantum theory (and beyond?)

- 12 orders of magnitude higher energy that existing tests (shorter time scale, shorter length scale. . .)
- In 'self-measuring' quantum system
- Deep in the realm of quantum field theory (virtual particles)
- in qubit and qutrit systems
- in bipartite and tripartite systems
- in systems with orbital angular momentum

$pp \to WW \,/\, ZZ$

$h \to WW^* \,/\, ZZ^*$

ttps://indico.cern.ch/event/1354279/contributions/5714378/attachments/2873703/5032375/SUSY24_Barr_



It's also a good way to find new fields

Many clever techniques and ideas being developed
Many measurements within reach (soon)

Review: AJB, M.Fabbrichesi, R.Floreanini, E.Gabrielli, L.Marzola: 2402.07972

QE Workshop@PKU

Workshop on Quantum Entanglement at the Energy Frontier

Apr 25, 2025, 4:00 PM → Apr 27, 2025, 12:00 PM Asia/Shanghai

W202 (School of Physics, Peking University)

Alim Ruzi (school of physics Peking Uniersity), Chen Zhou (Peking University （北京大学）), Hao Zhang (中国科学院高能物理研究所理论室), Qiang Li (School of physics, Peking University), Qing-Hong Cao (Peking University)

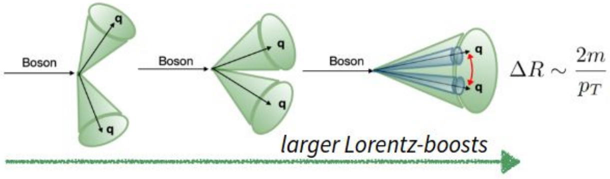
Description 研究量子纠缠和验证贝尔不等式的破坏是近期在高能量前沿特别是高能对撞机上的热点领域之一。虽然高能对撞机的探测器并非特别优化来探测量子纠缠，高能对撞的高亮度高能量对量子纠缠的研究提供了新的研究途径。反之，量子纠缠也可能对超出标准模型的新物理提供了新的观测量和寻找方案。

兹定于2025年4月25日至4月27日（4月25日周五注册、4月26日学术报告及海报，4月27日自由讨论）在北京大学物理学院召开“高能量前沿的量子纠缠研讨会”：https://indico.ihep.ac.cn/event/24387/。 诚邀各位同行踊跃参加此次学术交流。会议由北京大学物理学院、北京大学高能物理研究中心主办。

The study of the quantum entanglement and testing Bell inequality violation can be another new subject for the high energy physics community. While detectors at high-energy colliders are not specifically designed to probe quantum entanglement, they have demonstrated surprising effectiveness in this task. This opens up exciting opportunities for novel measurements in quantum information science, as well as potential discoveries that could extend beyond the Standard Model.

The ***workshop on Quantum Entanglement at the Energy Frontier*** (Registration on April 25, talks and posters on April 26, and free discussions on April 27) offers a welcoming environment for physicists interested in Quantum Entanglement at the energy frontiers, inviting both experimental and theoretical communities to come together and share their latest findings. This workshop aims to facilitate discussions on ongoing and proposed experiments, as well as to encourage participants to consider future possibilities.

AI for boosted boson



https://arxiv.org/abs/2503.00118

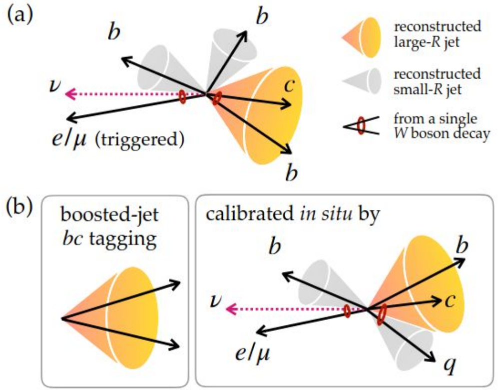
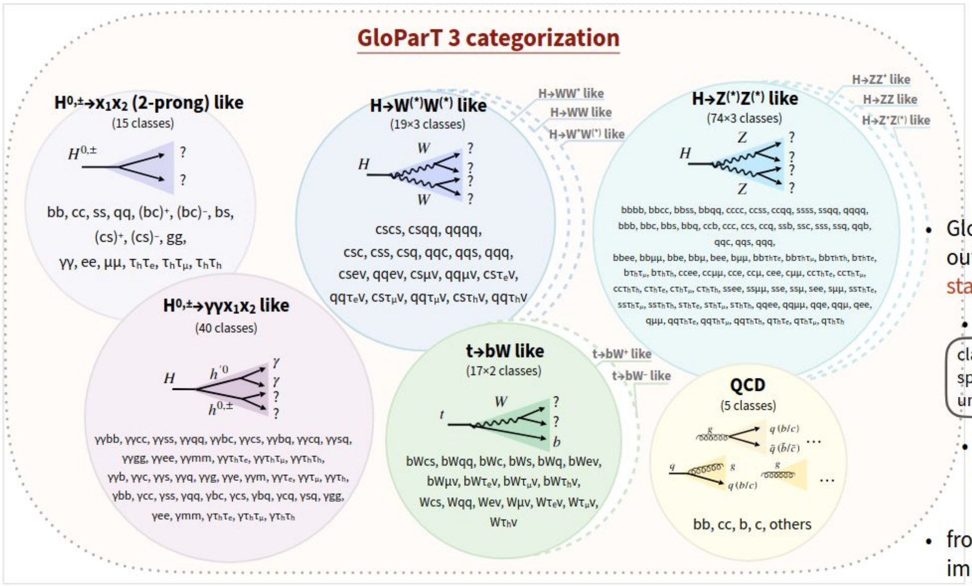


FIG. 1. Illustration of (a) the boosted event topology of semi-leptonic $t\bar{t}$ channel including a $W \to bc$ decay, and (b) techniques of boosted-jet bc tagging and *in-situ* calibration introduced in this work.

Global Particle Transformer (GloParT)

✅ A universal model that outperforms existing models across existing tasks

✅ Exhibits strong fine-tuning capability in various downstream tasks



- GloParTv3 has 750 raw output nodes (374 final states!) [review]
  - trained with
    - classification (374)
    - split-class mass regression (374)
    - unified-class mass regression (2)
  - trained as a mass-decorrelated model
- from v1-v3: complexity improves significantly

More funs to explore and enjoy:)

Summary and Prospects

- **Rich progress and potential from the electroweak physics**
  - Precise measurements, rare process discovery
    - NNNLO/polarization/interference/global…
  - Tools to explore unknown: QE, 0νμμ…
- **High energy, High Luminosity, High multiplicity**
  - **High opportunities although with challenges!**

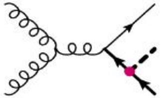
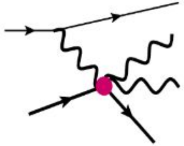
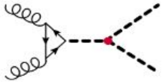
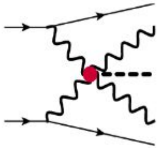
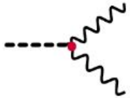
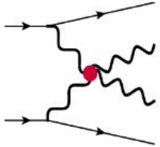
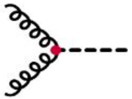
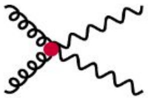
Quantity	Current precision	FCC-ee stat. (syst.) precision	Required theory input	Available calc. in 2019	Needed theory improvement†
m_Z Γ_Z $\sin^2\theta^\ell_{\rm eff}$	2.1 MeV 2.3 MeV 1.6×10^{-4}	0.004 (0.1) MeV 0.004 (0.025) MeV $2(2.4)\times10^{-6}$	non-resonant $e^+e^-\to f\bar{f}$, initial-state radiation (ISR)	NLO, ISR logarithms up to 6th order	NNLO for $e^+e^-\to f\bar{f}$
m_W	12 MeV	0.25 (0.3) MeV **sub-MeV precision**	lineshape of $e^+e^-\to WW$ near threshold	NLO ($ee\to 4f$ or EFT frame-work)	NNLO for $ee\to WW$, $W\to f\bar{f}$ in EFT setup
HZZ coupling	—	0.2%	cross-sect. for $e^+e^-\to ZH$	NLO + NNLO QCD	NNLO electroweak

FCC feasibility Mid-term report - Deliverable #8, physics and Experiment

Backup

Higgs without Higgs

TABLE I. Each effect (left-hand column) can be measured as an on-shell Higgs coupling (diagram in the HC column) or in a high-energy process (diagram in the HwH column), where it grows with energy as indicated in the last column.

		HC	HwH	Growth
κ_t	$\mathcal{O}_{y_t}$			$\sim(E^2/\Lambda^2)$
κ_λ	$\mathcal{O}_6$			$\sim(vE/\Lambda^2)$
$\kappa_{Z\gamma}$ $\kappa_{\gamma\gamma}$ κ_V	$\mathcal{O}_{WW}$ $\mathcal{O}_{BB}$ $\mathcal{O}_r$			$\sim(E^2/\Lambda^2)$
κ_g	$\mathcal{O}_{gg}$			$\sim(E^2/\Lambda^2)$

HCs are associated with an EFT Lagrangian $\mathcal{L} = \sum_i c_i \mathcal{O}_i/\Lambda^2$, consisting in particular of the dimension-six operators [12,13],

$$\begin{aligned} \mathcal{O}_r &= |H|^2 \partial_\mu H^\dagger \partial^\mu H, & \mathcal{O}_{y_\psi} &= Y_\psi |H|^2 \psi_L H \psi_R, \\ \mathcal{O}_{BB} &= g'^2 |H|^2 B_{\mu\nu} B^{\mu\nu}, & \mathcal{O}_{WW} &= g^2 |H|^2 W^a_{\mu\nu} W^{a\mu\nu}, \\ \mathcal{O}_{GG} &= g_s^2 |H|^2 G^a_{\mu\nu} G^{a\mu\nu}, & \mathcal{O}_6 &= |H|^6, \end{aligned} \tag{1}$$

with Y_ψ the Yukawa coupling for the fermion ψ. [Note that the parameters in Eq. (3) can be put in correspondence with other parametrizations of HCs: via partial widths $\kappa_i^2 = \Gamma_{h\to ii}/\Gamma^{\rm SM}_{h\to ii}$ [14], via Lagrangian couplings in the unitary gauge g_{hii} [13,15], or via pseudo-observables [16].]

The operators of Eq. (1) have the form $|H|^2 \times \mathcal{O}^{\rm SM}$, with $\mathcal{O}^{\rm SM}$ a dimension-four SM operator (i.e., kinetic terms, Higgs potential, and Yukawa couplings) times

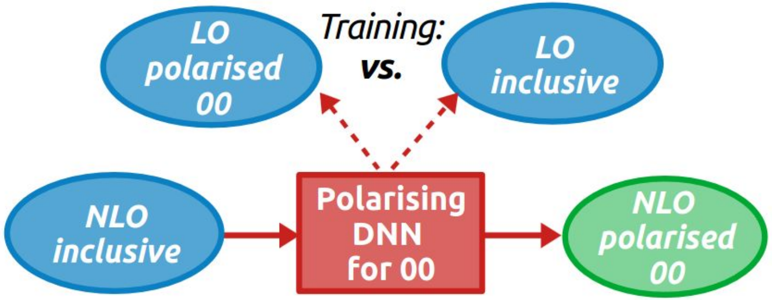
ATLAS WZ

DNN reweighting

Possible to reweight a distribution using a DNN [arXiv:1907.08209]

➔Acts as a **multi-dimensionnal reweighting** of the input MC sample

4 DNN **trained on polarised Madgraph samples** to discriminate one joint-polarisation states against the inclusive : event-by-event output used in **reweighting**



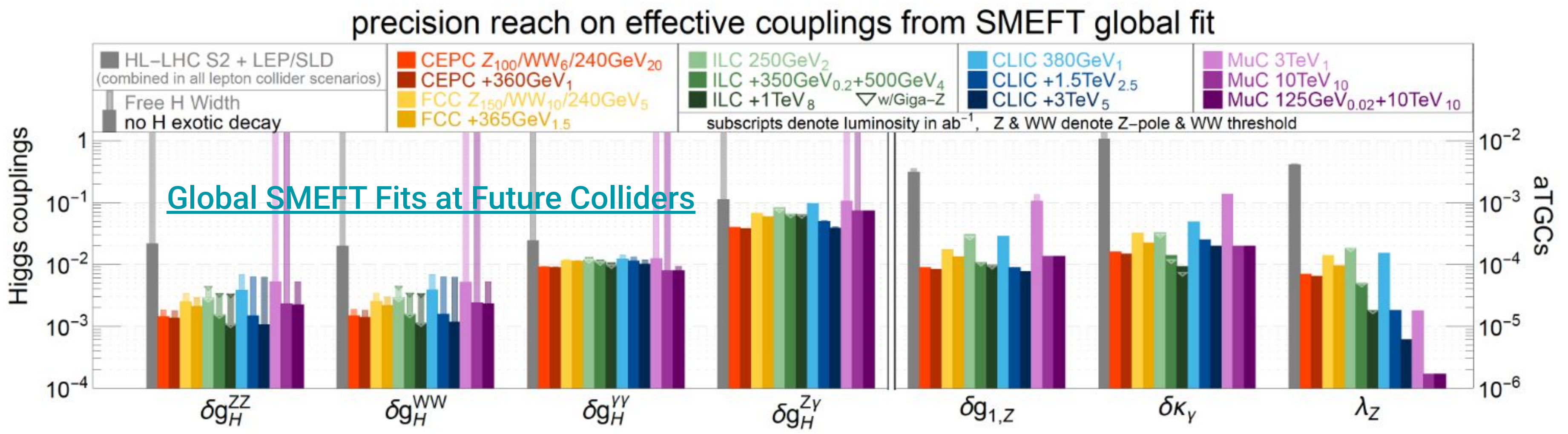
w(x)~ DNN(x) / (1 – DNN(x))

$|y_{\ell,W} - y_Z|$
$p_{\mathrm{T}}^{\ell,W}$
$E_{\mathrm{T}}^{\mathrm{miss}}$
$\Delta\phi(\ell^W, \ell^\nu)$
p_{T}^{WZ}
$p_{\mathrm{T}}^{\ell 1,Z}$
$p_{\mathrm{T}}^{\ell 2,Z}$
$\Delta\phi(\ell 1^Z, \ell 2^Z)$
m_{WZ}
$\cos(\theta^*_{\ell W})$
$\cos(\theta^*_{\ell^Z_{ss}})$
$\cos(\theta_V)$

Reweighting DNNs input variables

14

Future



[Global SMEFT Fits at Future Colliders]

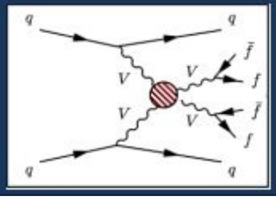
With 20 ab^{-1} at $\sqrt{s}$=100 TeV expect:

~ 10^{13} W
~ 10^{12} Z
~ 10^{11} tt
~ 10^{10} H
~ 10^{9} ttH
~ 10^{7} HH
~ 10^{5} gluino pairs m=8 TeV

Conclusive elucidation of EWSB by probing SM in regime where EW symmetry is restored ($\sqrt{\hat{s}}$ >> v=246 GeV)

Without H: $V_L V_L$ scattering violates unitarity at m_{VV} ~TeV
- H regularizes the theory fully → a crucial "closure test" of the SM
- Else: new physics: anomalous quartic couplings (VVVV, VVhh) and/or new heavy resonances

FCC-hh: direct discovery potential of new resonances in the O(10 TeV) range



Fabiola Gianotti at "The 50th Anniversary of Hadron Colliders at CERN"