Various Sides of Bosons

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Qiang Li (Peking University)

2025/6/13

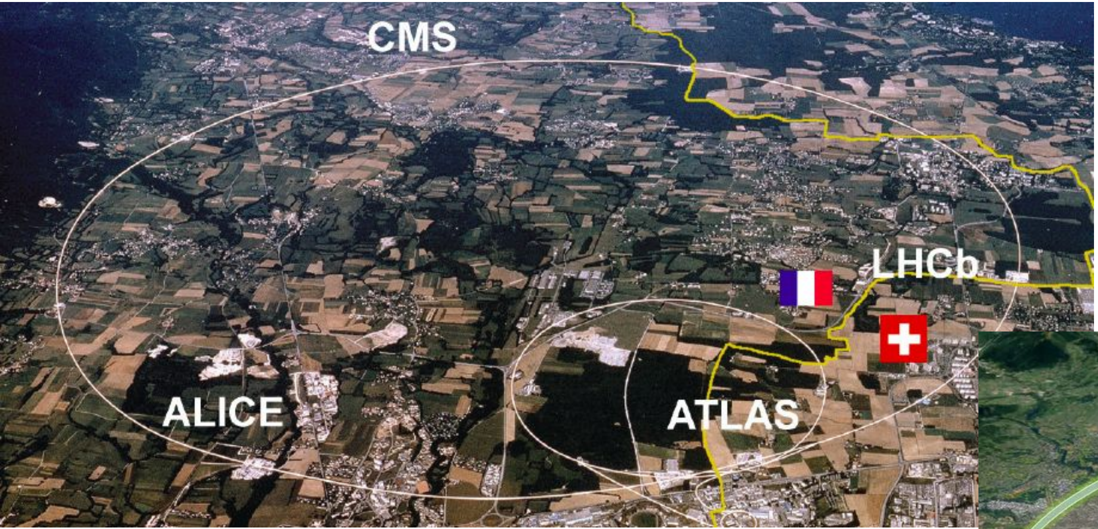
2023/11

2024/7

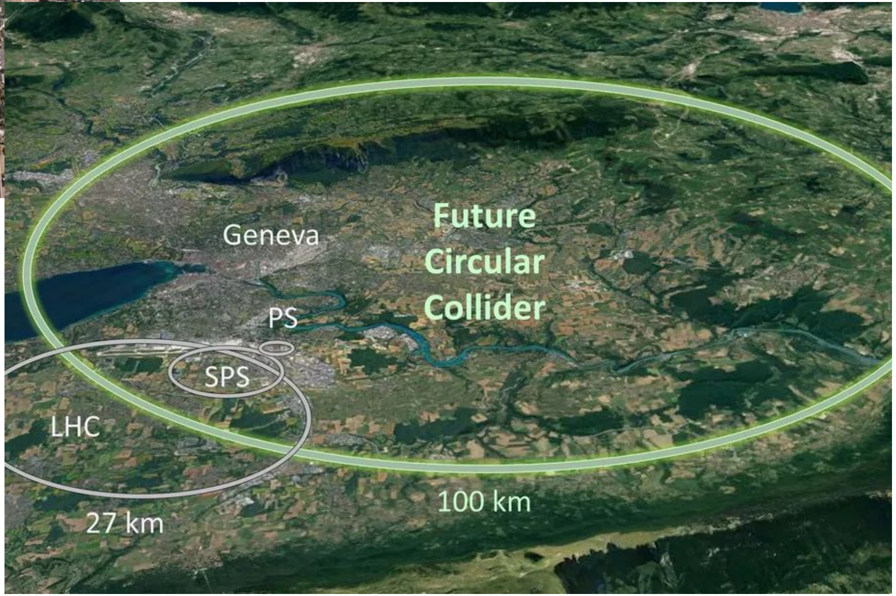
To introduce works done by many people together, CMS +ATLAS, not meant to be exhaustive.

Cares are put more on future prospects i.e. how/what we can achieve more?

世界微尘里，吾宁对与撞



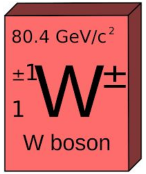
Large Hadron Collider:
欧洲核子中心；环长27公里，地下100米；质子-质子 13TeV对撞；其上有4个大型实验：
ALICE、ATLAS、CMS、LHCb



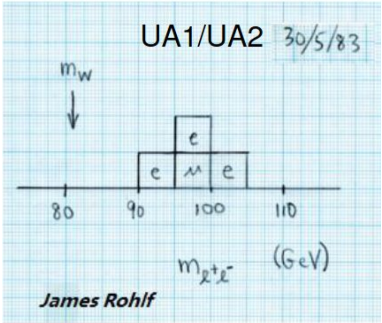
2012年Higgs发现之后，国际高能物理学界提出了**下一代对撞机方案**，包括：
欧洲的FCC-ee, FCC-hh；
中国的CEPC，SPPC。
以及国际直线加速器ILC等等。

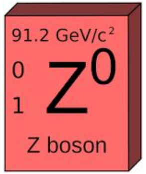

ELECTROWEAK
FORCE
PBS
GRAVITY
ELECTROMAGNETISM
WEAK FORCE
STRONG FORCE

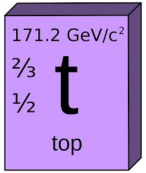
Electroweak milestones: From infancy to adolescence

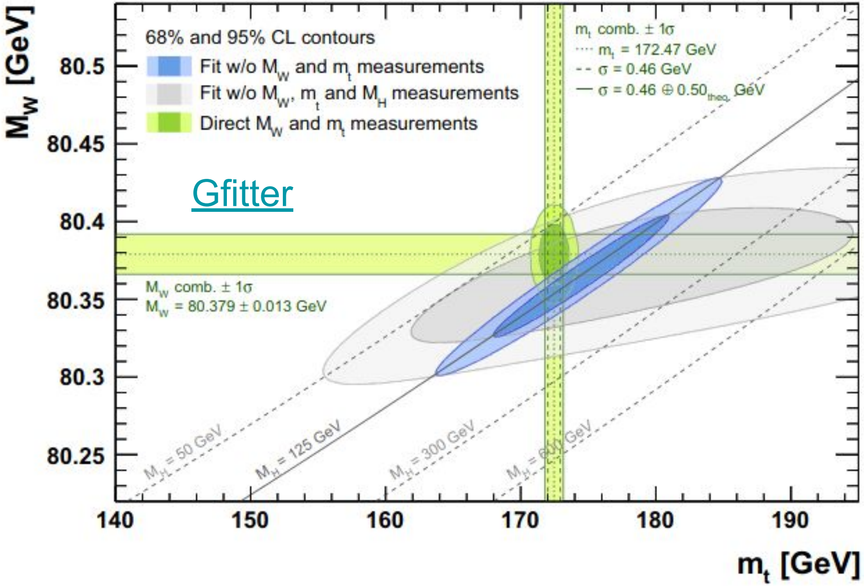


Neutral currents 52;
W/Z boson turns 42;
Top quark now 30;
Higgs turns 13.









https://cerncourier.com/a/electroweak-milestones-at-cern/

The Nobel Prize in Physics 1984

W，Z玻色子

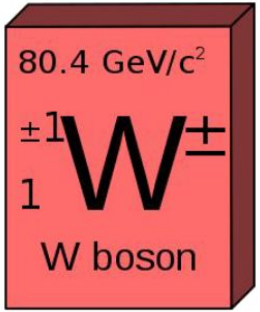
Carlo Rubbia

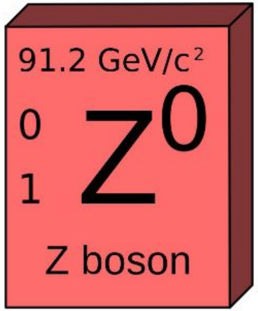
Prize share: 1/2

Simon van der Meer

Prize share: 1/2

The Nobel Prize in Physics 1984 was awarded jointly to Carlo Rubbia and Simon van der Meer *"for their decisive contributions to the large project, which led to the discovery of the field particles W and Z, communicators of weak interaction"*





The Nobel Prize in Physics 2013

Higgs Boson

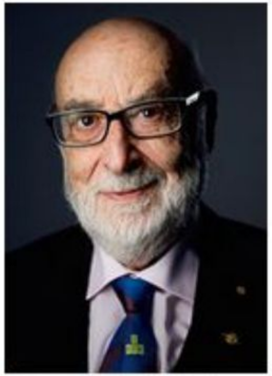


Photo: A. Mahmoud

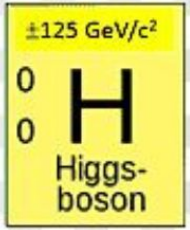
François Englert

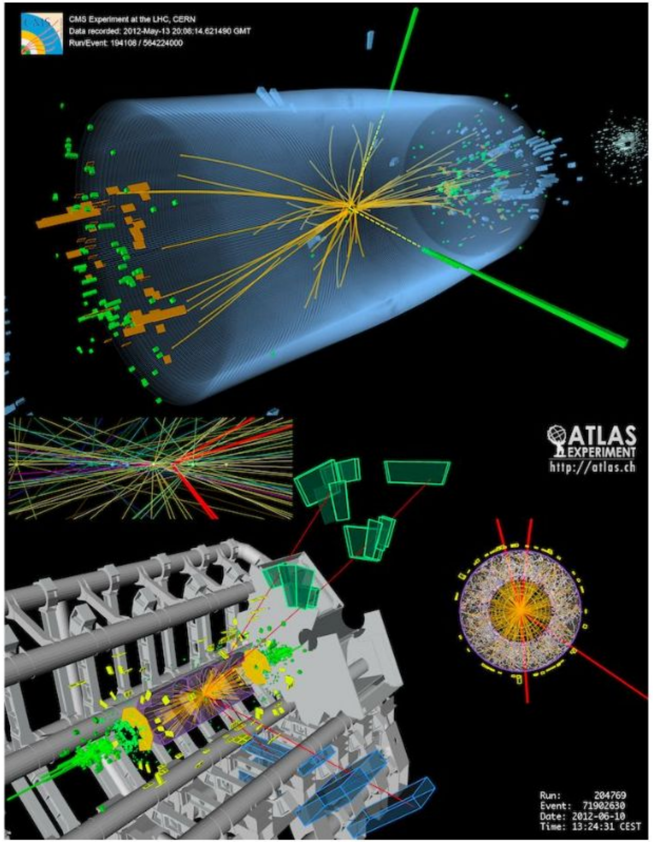
Prize share: 1/2

Photo: A. Mahmoud

Peter W. Higgs

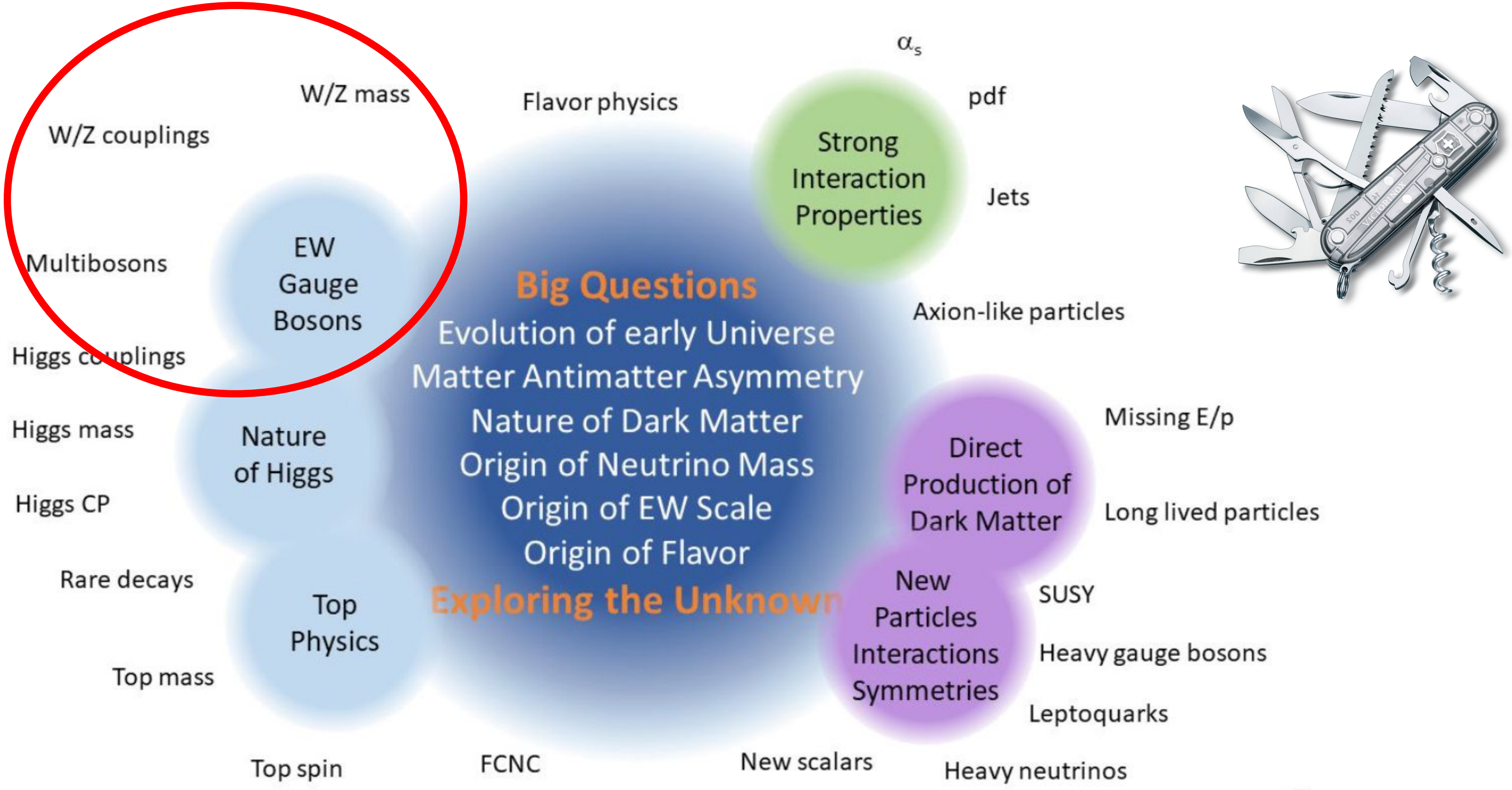
Prize share: 1/2



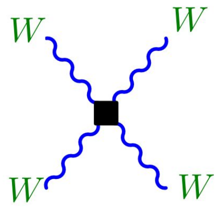


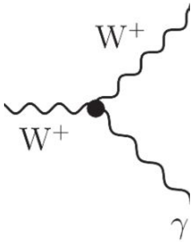
The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs *"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"*

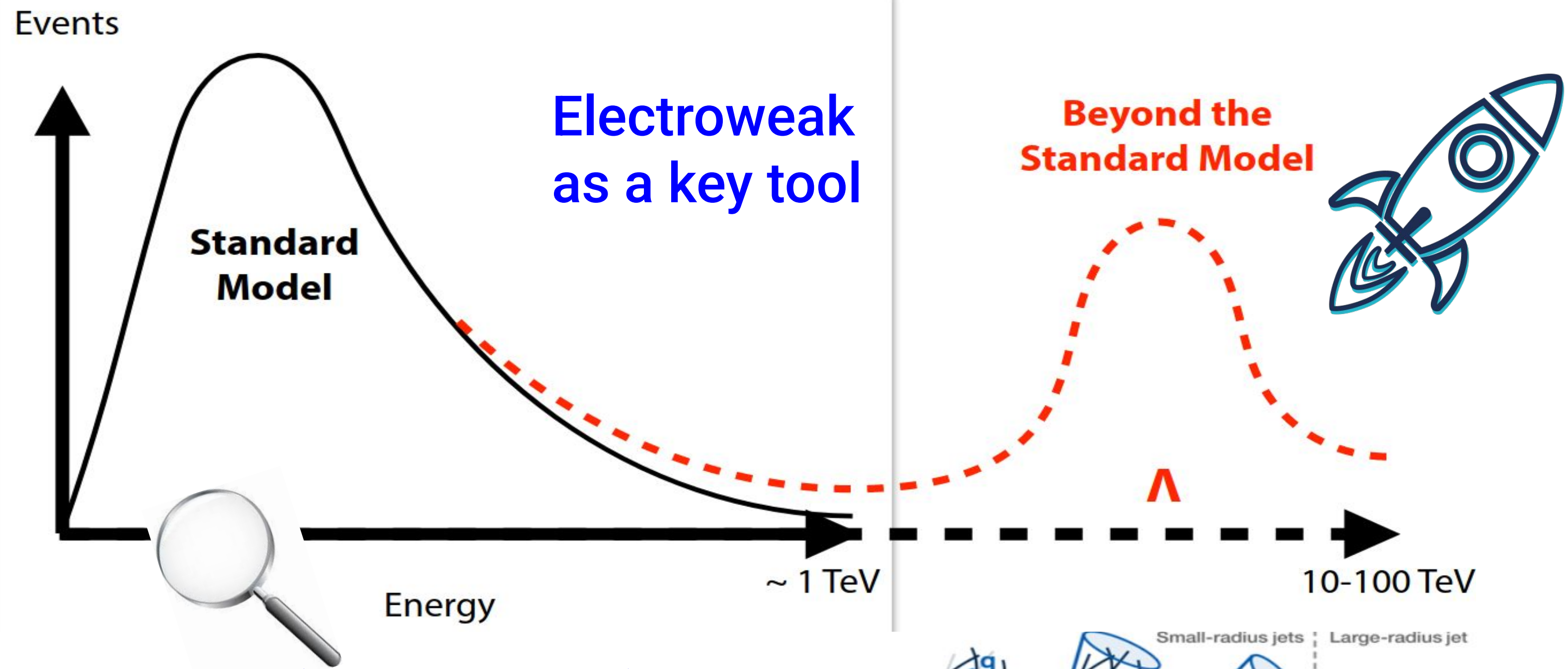
Seattle snowmass summer meeting 2022



Direct and indirect searches for BSM

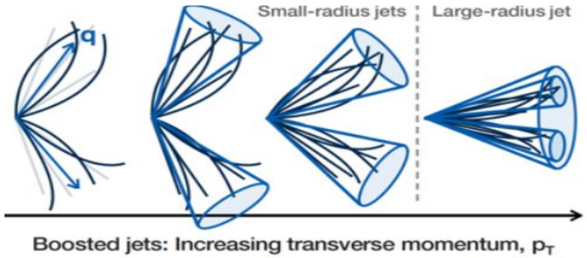




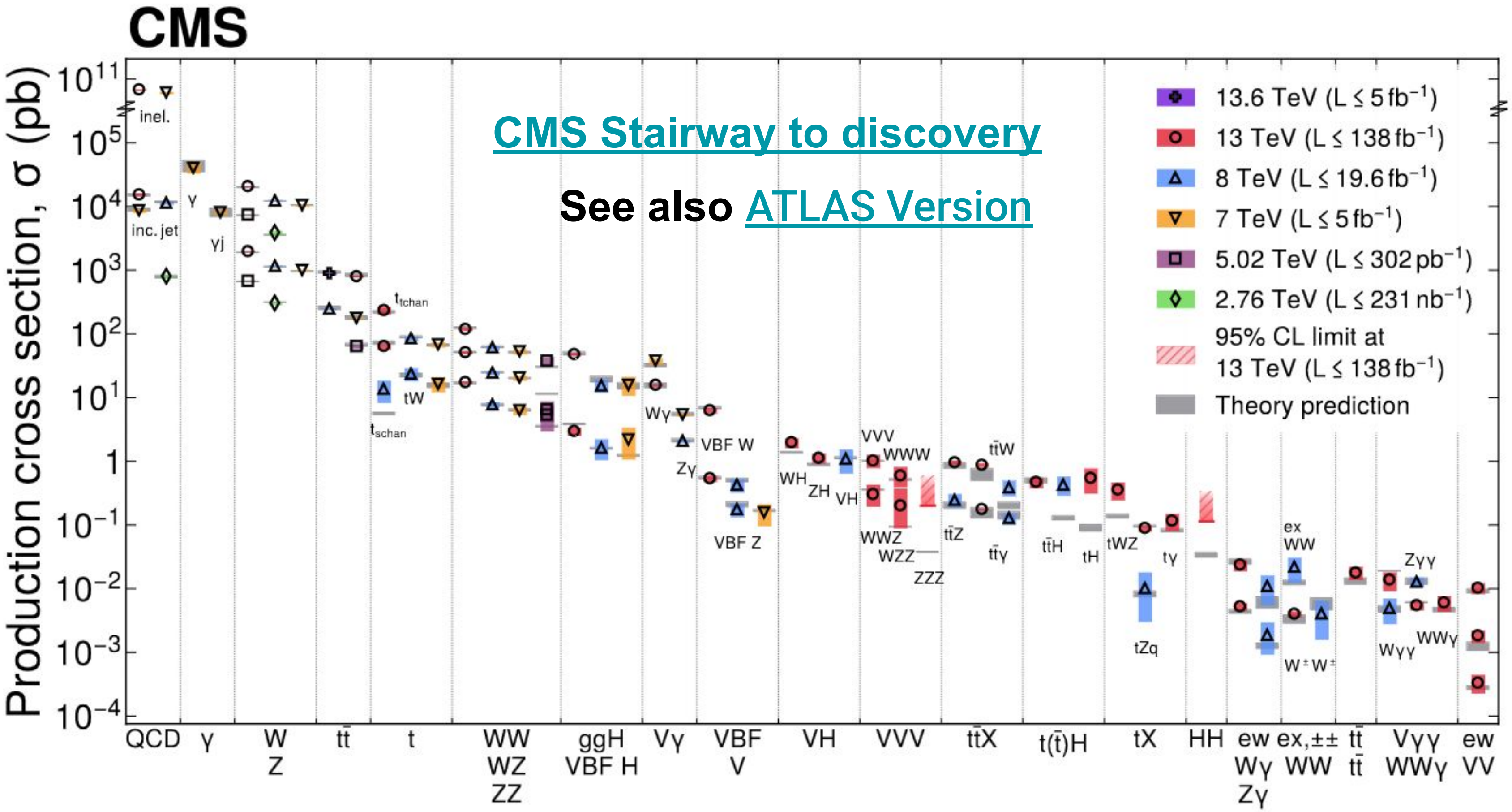


Anomalous couplings, EFT (CP even or odd)

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



Rich results at the LHC (ATLAS, CMS)

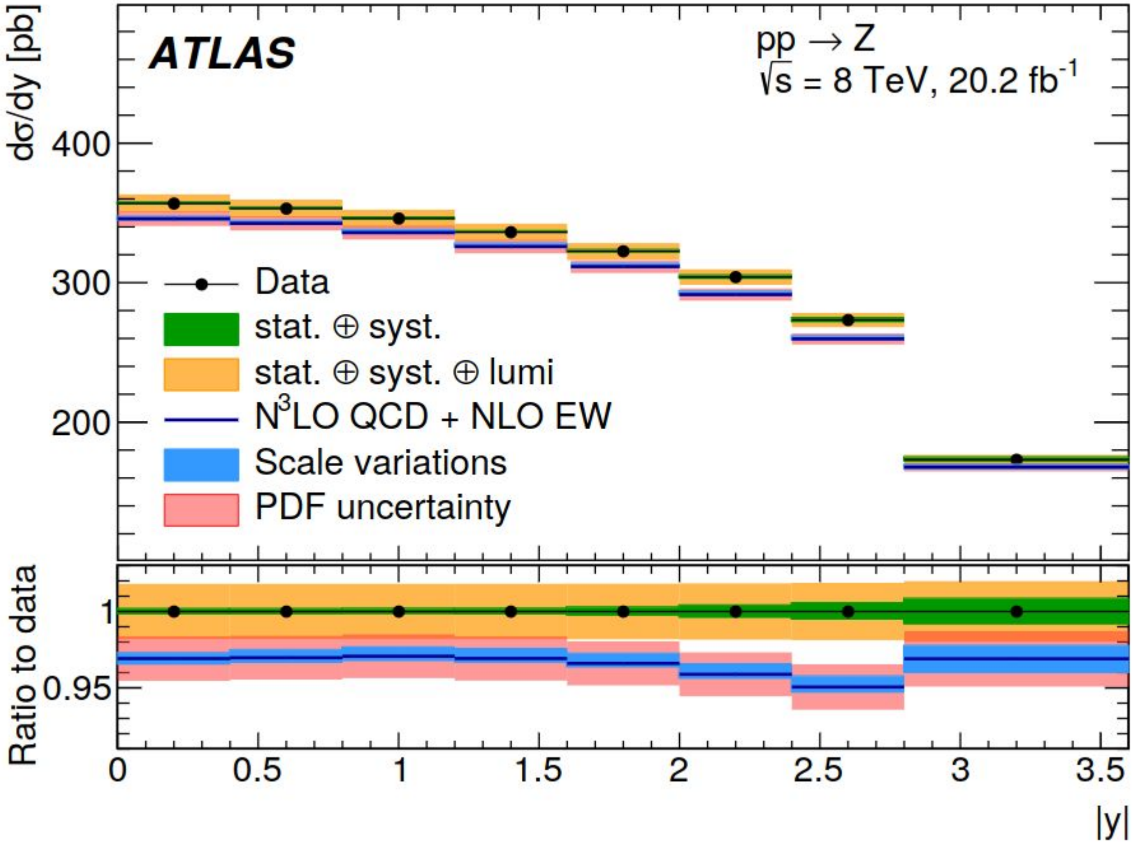


CMS Stairway to discovery

See also ATLAS Version

Eur. Phys. J. C 84 (2024) 315
Eur. Phys. J. C 83 (2023) 628

Drell-Yan precision



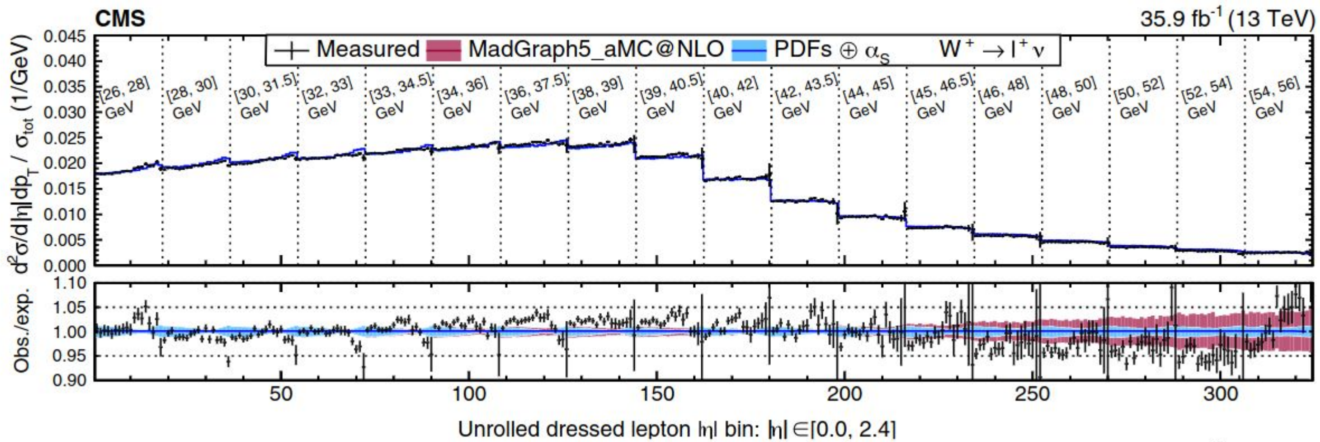
- N3LO QCD predictions obtained from DYTurbo

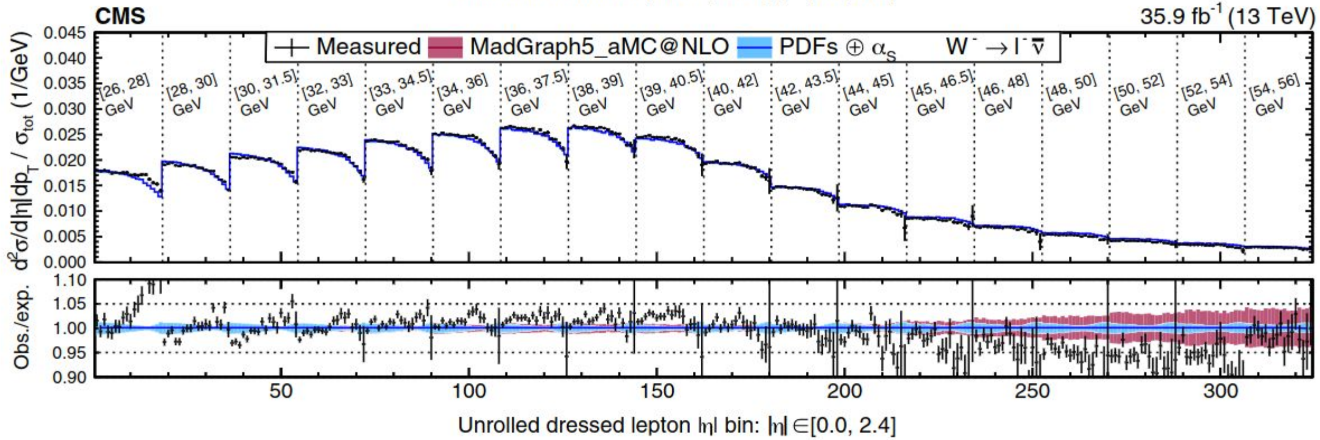
  aN^{3}LO MSHT PDF set.

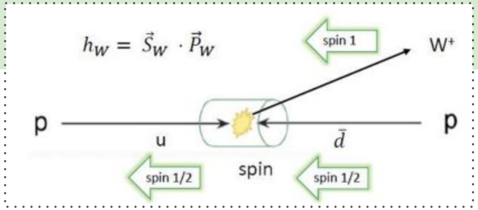
- A negative correction of 0.4% from NLO EW included
- a p-value of 11% if one only includes the uncertainties in the PDFs for the predictions
- 2D differential distributions measured in both papers

PRD 102 (2020) 092012

Single W precision



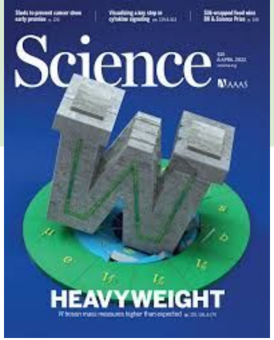




- lepton eta-pT depends on W helicity, which is largely determined by parton distribution function.
- Can be used to constrain parton distribution function, modelling, etc.
- Precursor to CMS W Mass measurement.

W Mass

Submitted to Nature



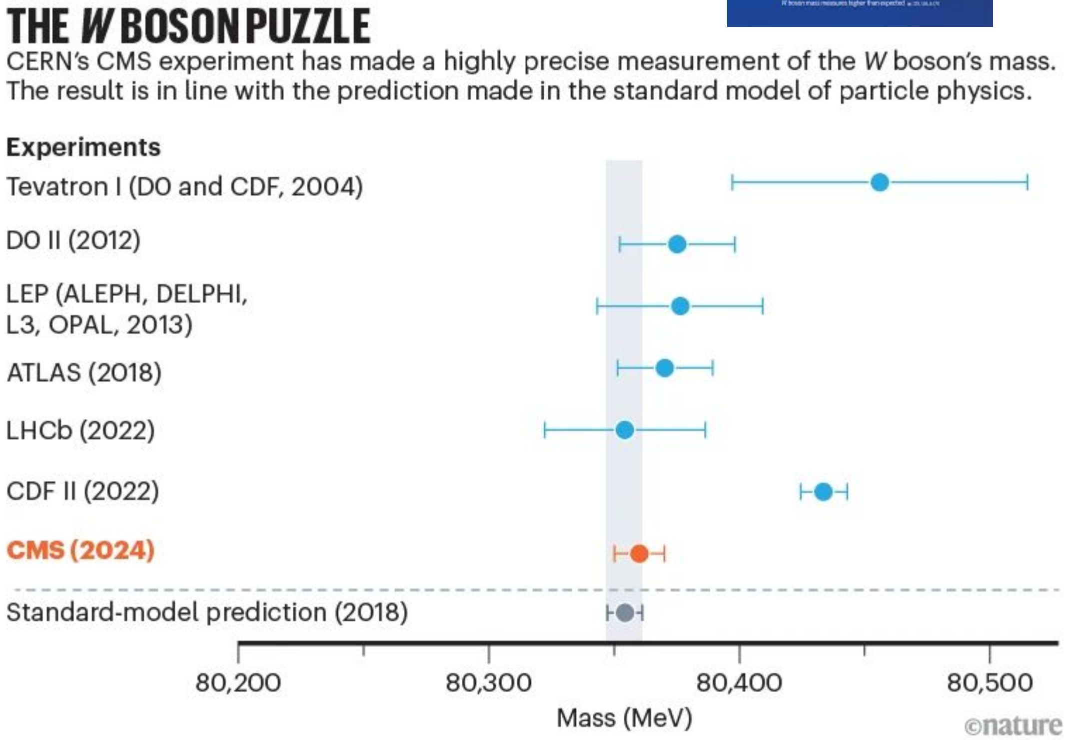
NEWS | 17 September 2024

'The standard model is not dead': ultra-precise particle measurement thrills physicists

CERN's calculation of the *W* boson's mass agrees with theory, contradicting a previous anomaly that had raised the possibility of new physics.

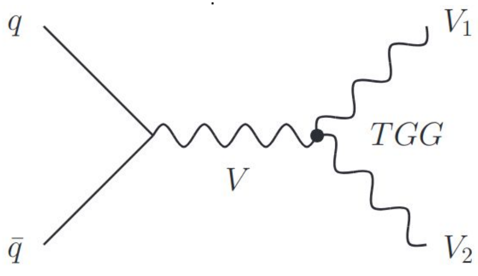
https://cms.cern/news/working-w-mass-no-sprint-it-marathon

This result is not a sprint, it is a marathon. How the teams behind the measurement of the W-boson mass at the CMS experiment found working on this result, almost a decade in the making.



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

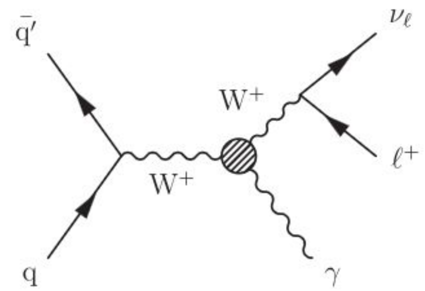
Wγ

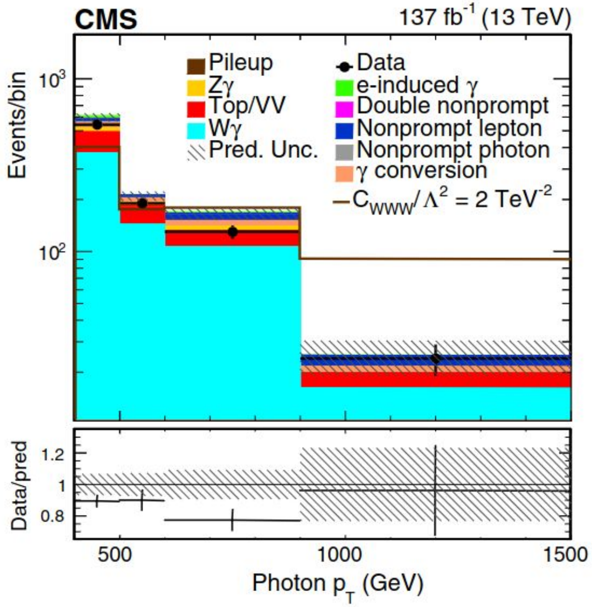
[Phys. Rev. Lett. 126, 252002 (2021)]

- 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

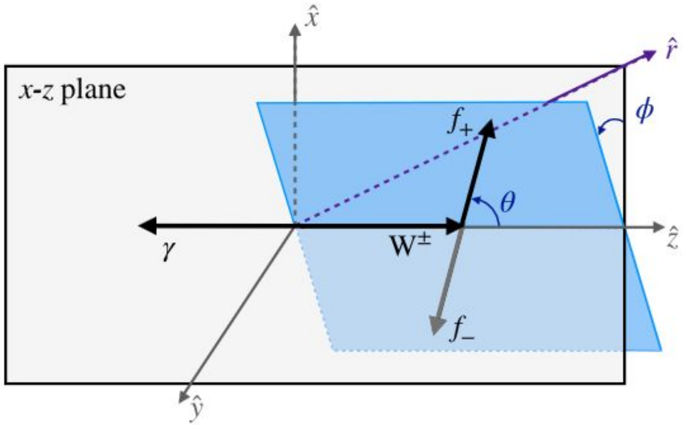




Phys. Rev. Lett. 126, 252002 (2021)
Phys. Rev. D 105 (2022) 052003

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



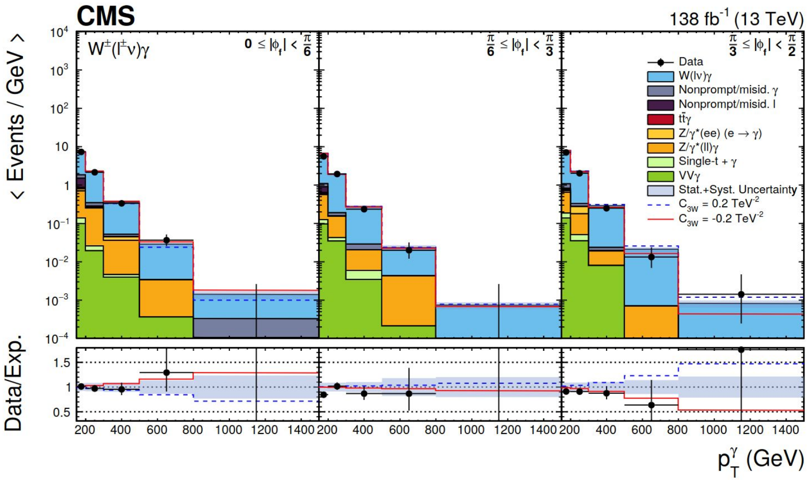
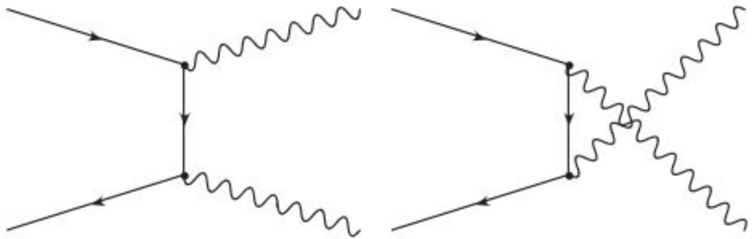


Table 4: Best fit values of C_{3W} and corresponding 95% CL confidence intervals as a function of the maximum p_T^γ bin included in the fit.

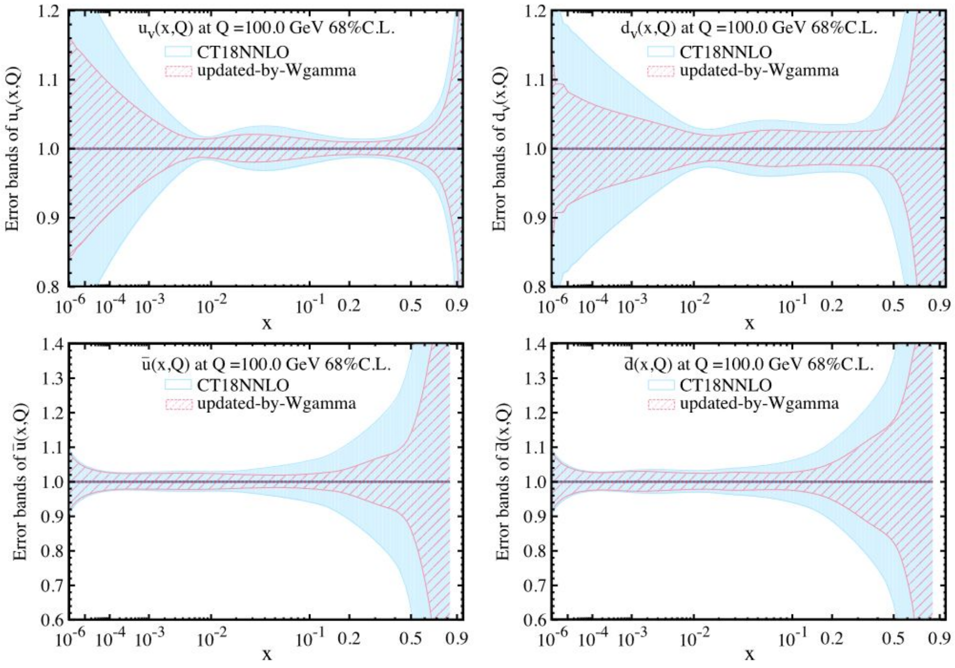
p_T^γ cutoff (GeV)	Best fit C_{3W} (TeV^{-2})		Observed 95% CL (TeV^{-2})		Expected 95% CL (TeV^{-2})	
	SM+int. only	SM+int.+BSM	SM+int. only	SM+int.+BSM	SM+int. only	SM+int.+BSM
200	−0.86	−0.24	[−2.01, 0.38]	[−0.76, 0.40]	[−1.16, 1.27]	[−0.81, 0.71]
300	−0.25	−0.17	[−0.81, 0.34]	[−0.39, 0.28]	[−0.56, 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



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



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)]

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- **Polarized Di-boson**
  - WZ
- Polarized VBS
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- Tri-boson
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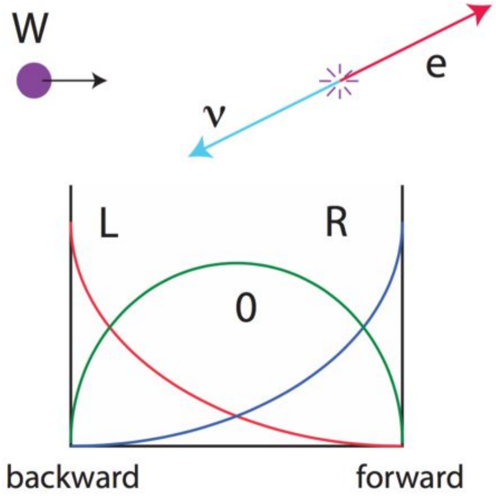
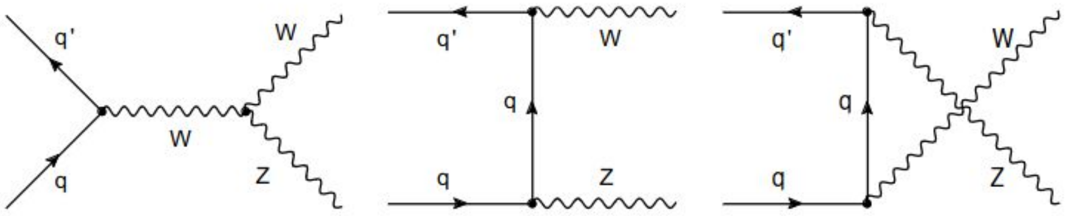
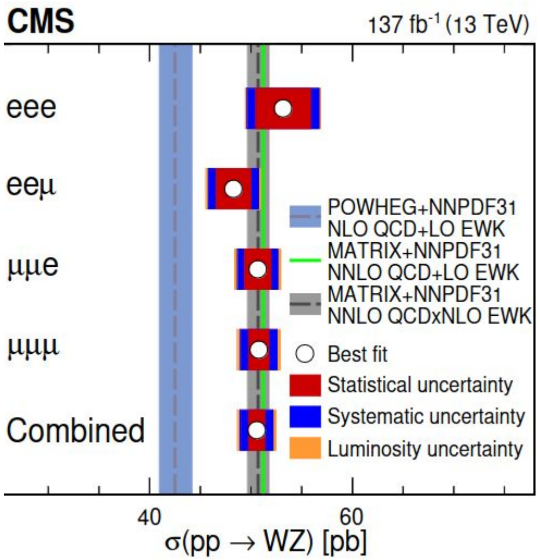
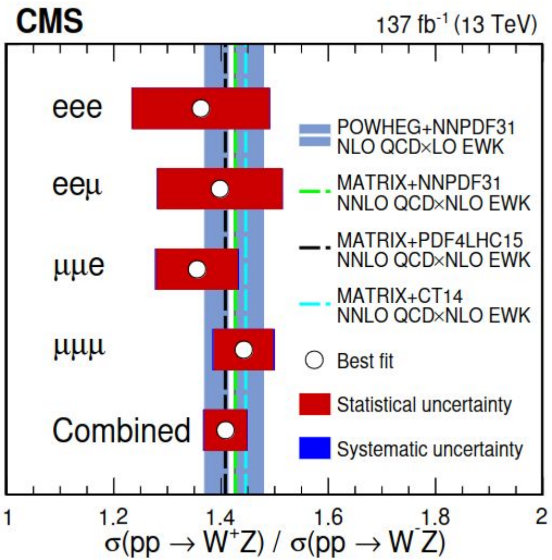


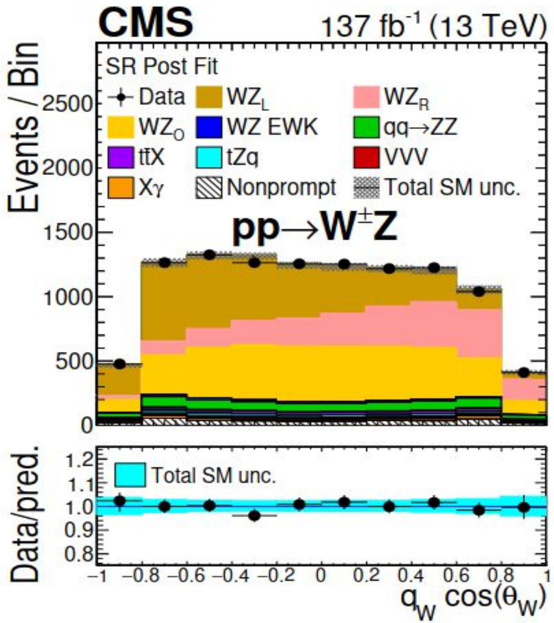
JHEP 07 (2022) 032

WZ (polarization)





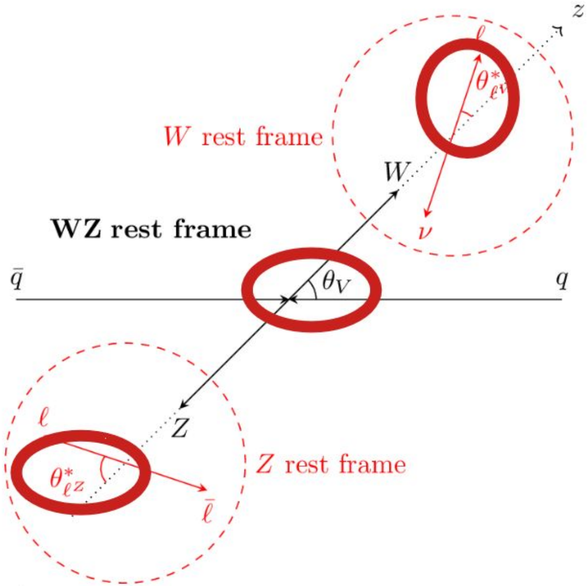


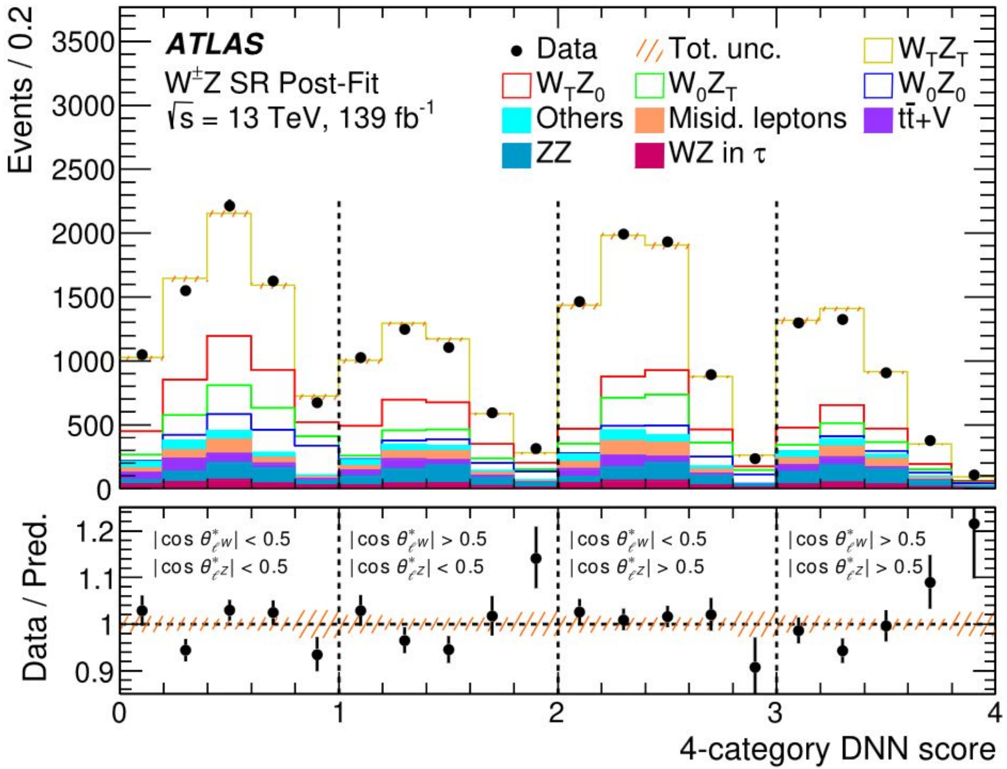


First observation of single longitudinally polarized W bosons in WZ production! 5.6σ (4.3σ) obs (exp).

Phys. Lett. B 843 (2023) 137895

WZ (joint polarization)





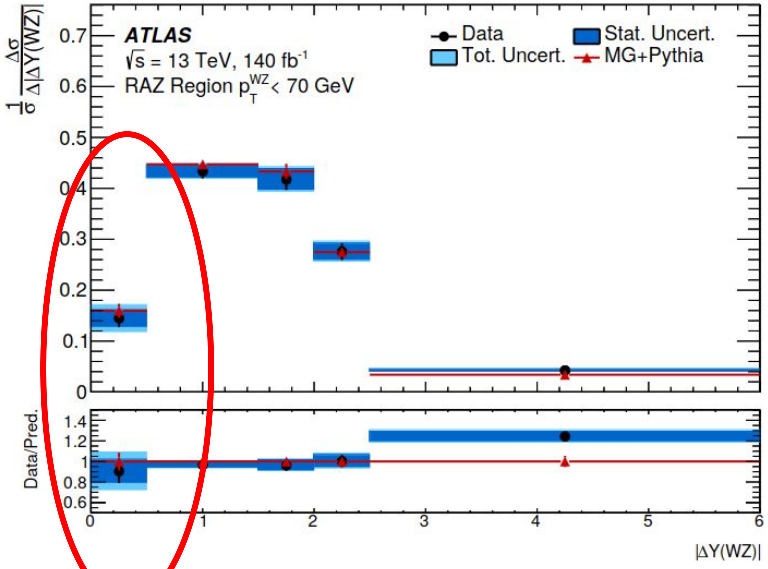
Measurement performed as well separating by the W charge
- Significance on f_{00} at 6.9σ in W+Z
- Significance on f_{00} at 4.1σ in W-Z

WZ high PT polarization and RAZ

PRL 133 (2024) 101802

- 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	Measurement $p_T^Z > 200$ 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}

arXiv:2505.09686

Precise Standard-Model predictions for polarised Z-boson pair production and decay at the LHC

Costanza Carrivale,[a] Roberto Covarelli,[b] Ansgar Denner,[c] Dongshuo Du,[d] Christoph Haitz,[c] Mareen Hoppe,[e] Martina Javurkova,[f] Duc Ninh Le,[g] Jakob Linder,[h] Rafael Coelho Lopes de Sa,[f] Olivier Mattelaer,[i] Susmita Mondal,[j] Giacomo Ortona,[k] Giovanni Pelliccioli,[k,1] Rene Poncelet,[l,1] Karolos Potamianos,[m] Richard Ruiz,[l] Marek Schönherr,[n] Frank Siegert,[e] Lailin Xu,[d] Xingyu Wu,[d] Giulia Zanderighi[h]

"For the first time, we accomplish the combination of NNLO QCD and NLO EW corrections, setting the new state-of-the-art perturbative accuracy for polarised Z-boson pairs at the LHC."

Selected Topics with bias

- Di-boson
  - Wγ
- Polarized Di-boson
  - WZ
- **Polarized VBS**
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- Tri-boson
  - WZγ, WWγ
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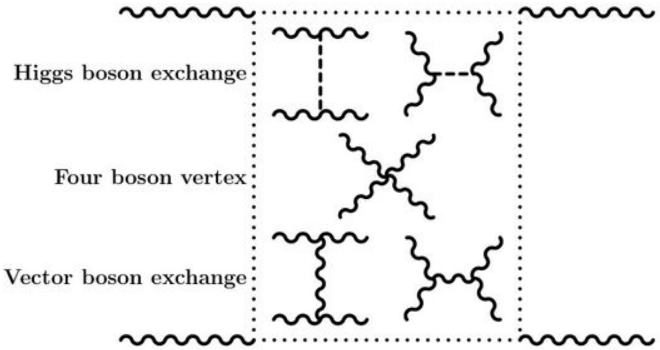
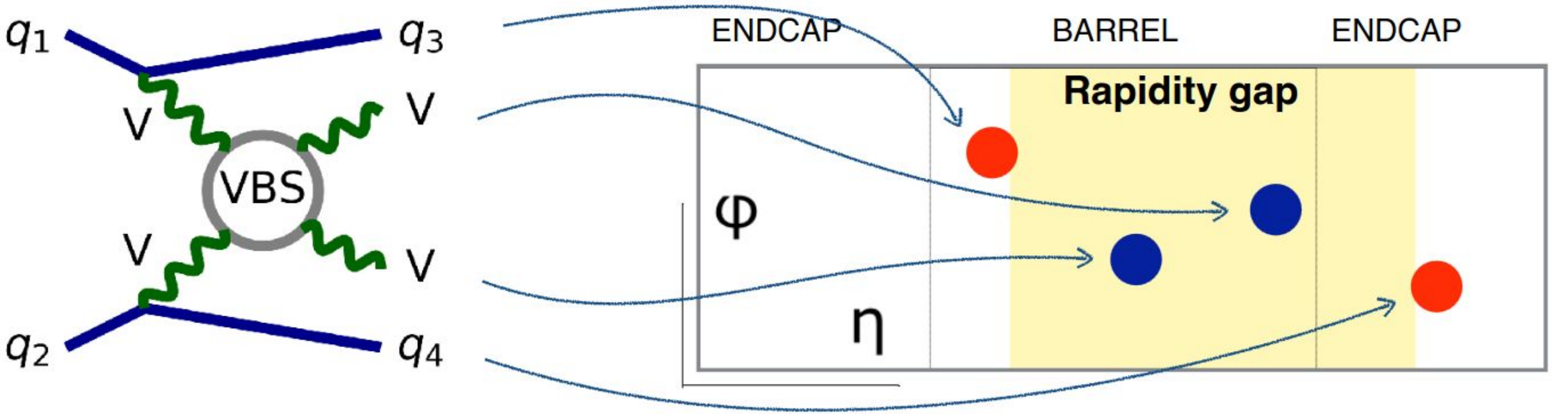
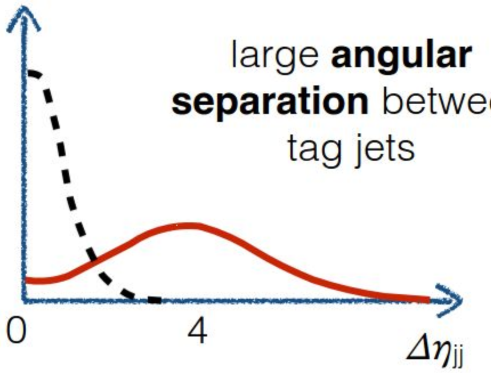


PLB 841(2023)137495
JHEP 07 (2024) 254
JHEP 06 (2024) 192

Vector Boson Scattering: W+W- and WZ





large **angular separation** between tag jets

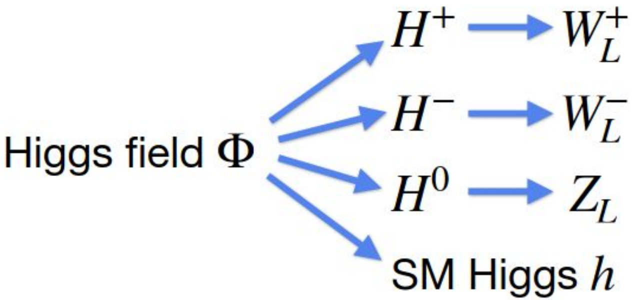
low QCD activity between tag jets, since there's no color flow between the two protons

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

Longitudinal Polarized VBS

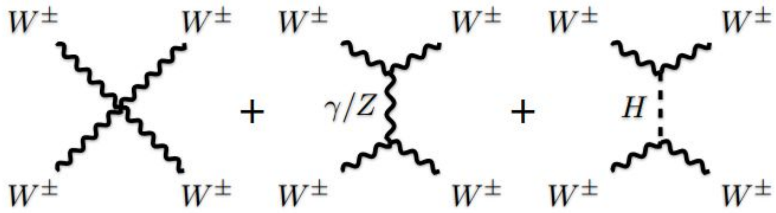
Importance of $W_L^{\pm}W_L^{\pm} \rightarrow W_L^{\pm}W_L^{\pm}$

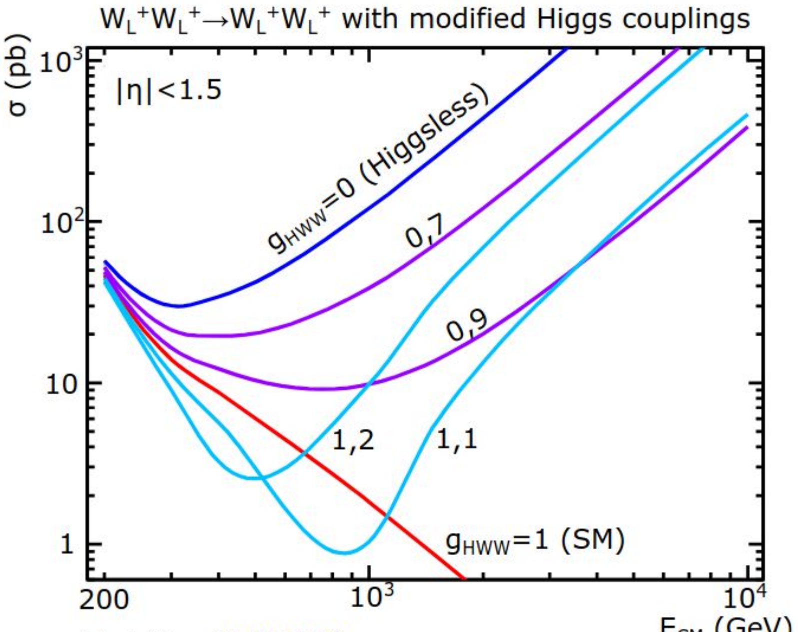
- Higgs Goldstone bosons result in longitudinal polarized vector bosons:



- 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**



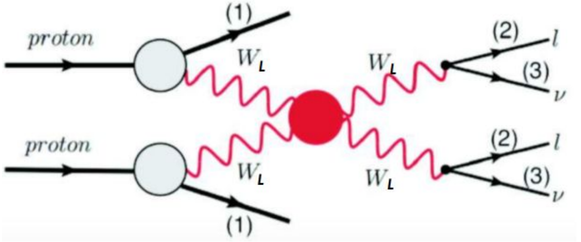


[adapted from arXiv:1412.8367]

Polarized VBS from CMS

PLB 812 (2020) 136018

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

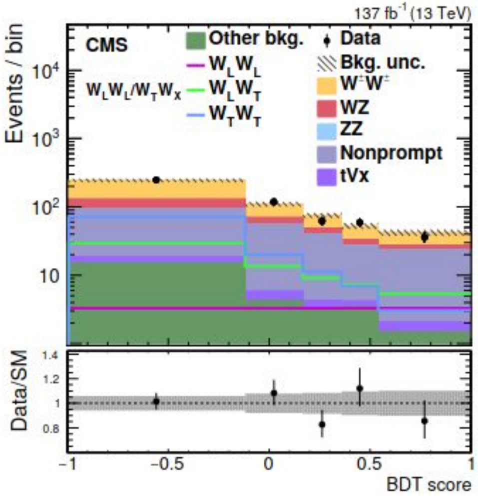


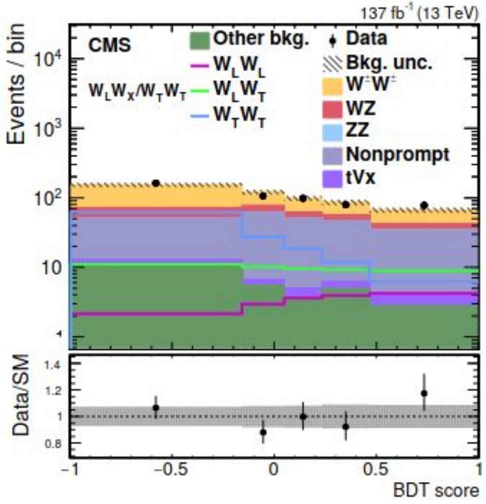
☑ $W_L^\pm W_L^\pm$: signal BDT ($W_L^\pm W_L^\pm$ vs $W_T^\pm W_X^\pm$) and inclusive BDT (VBS vs Bkg.)

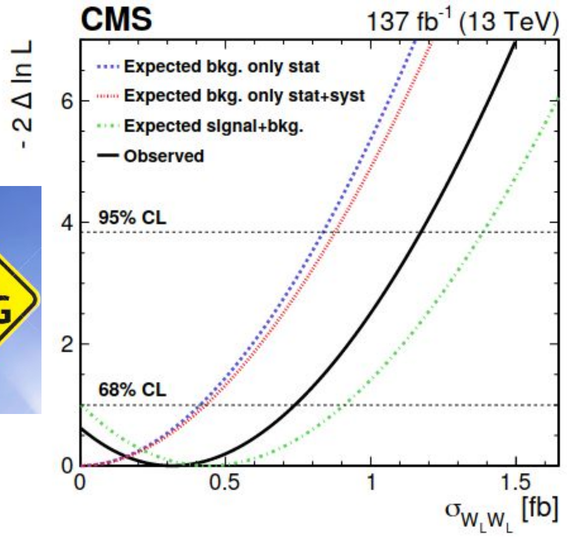
☑ $W_L^\pm W_X^\pm$: signal BDT ($W_L^\pm W_X^\pm$ vs $W_T^\pm W_T^\pm$) and inclusive BDT (VBS vs Bkg.)

☑ 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







Moriond 2025

Polarized VBS from ATLAS

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

New

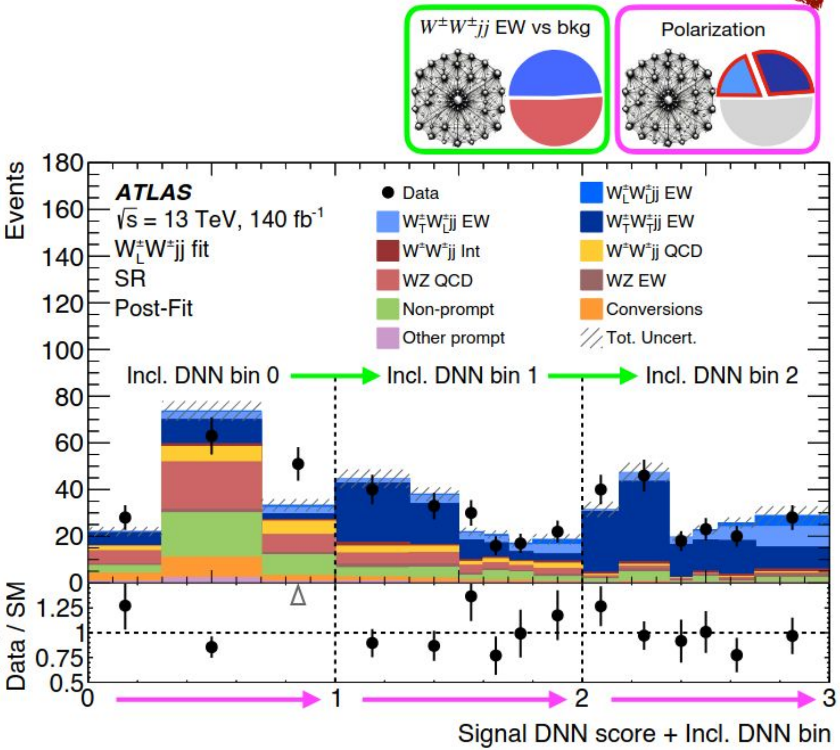
- **Significance of 3.3 σ** for $W_L^\pm W^\pm jj$ (expected 4.0 σ)

➡ **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.) ± 0.08 (mod. syst.) ± 0.05 (exp. syst.)

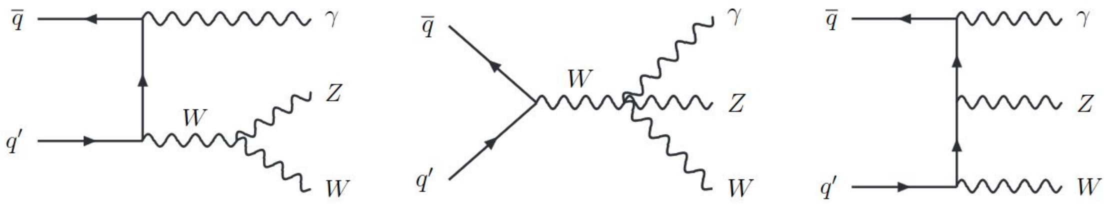


Selected Topics with bias

- 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

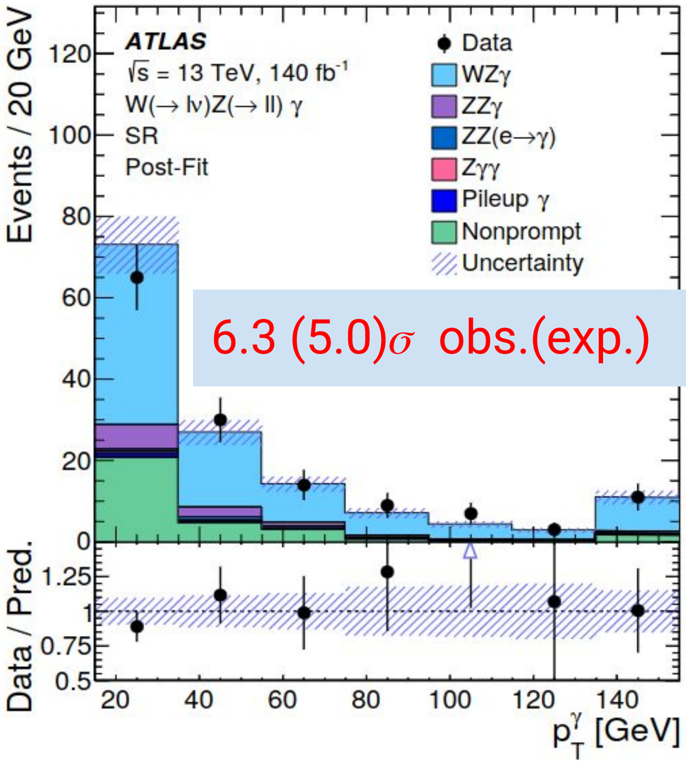
PRL132 (2024) 021802
arXiv:2503.21977

WZγ observation



$(e\mu\mu, \mu ee, eee, \mu\mu\mu)$ 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.)

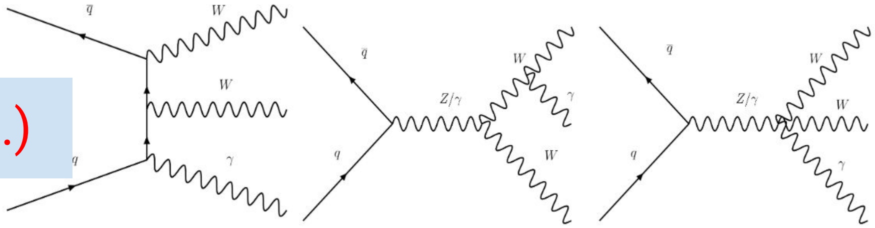
$$\sigma_{WZ\gamma} = 2.01 \pm 0.30\,(\text{stat.}) \pm 0.16\,(\text{syst.})\ \text{fb}.$$

WWγ Observation

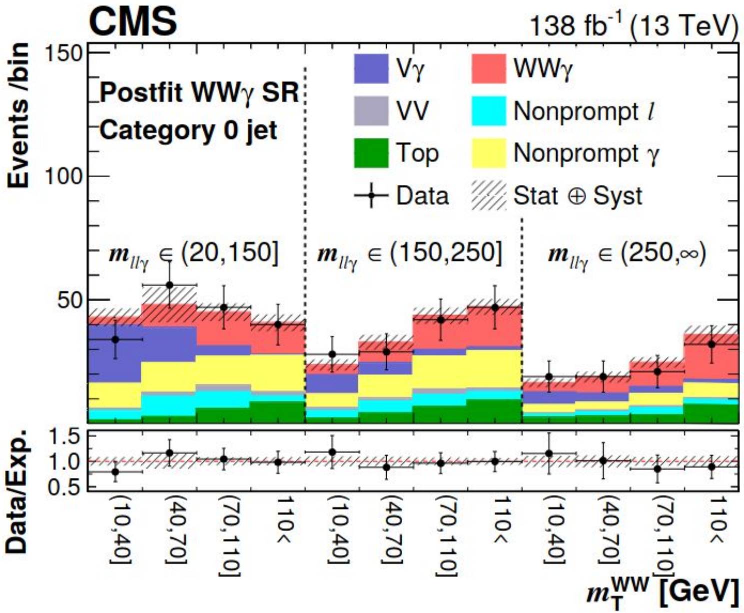
PRL132 (2024) 121901

- 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.

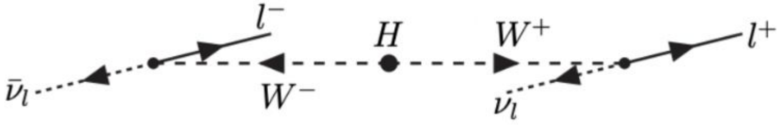
5.6 (4.7)σ obs.(exp.)



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



- 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)

Selected Topics with bias

- Di-boson
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- Polarized Di-boson
  - WZ
- Polarized VBS
  - Same-Sign WW scattering
- Tri-boson
  - WZγ, WWγ
- **More VBS:**
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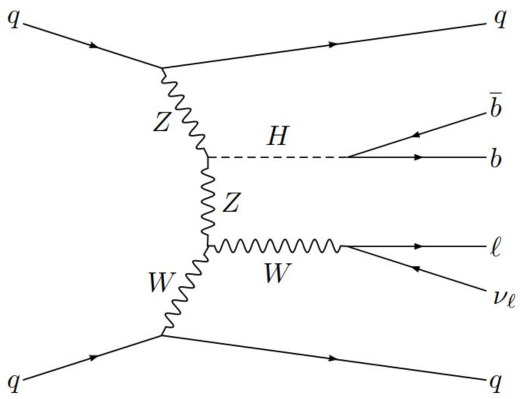
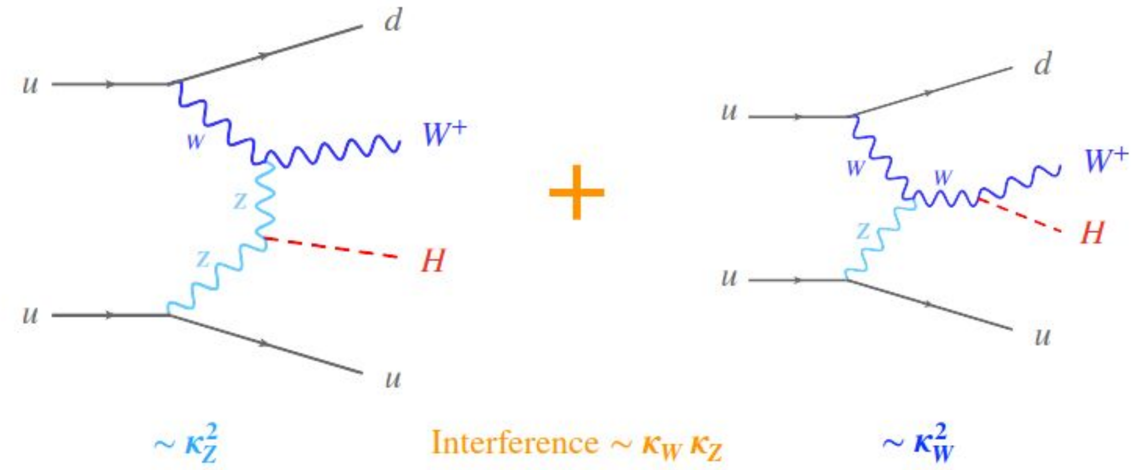
  - H to VV and more



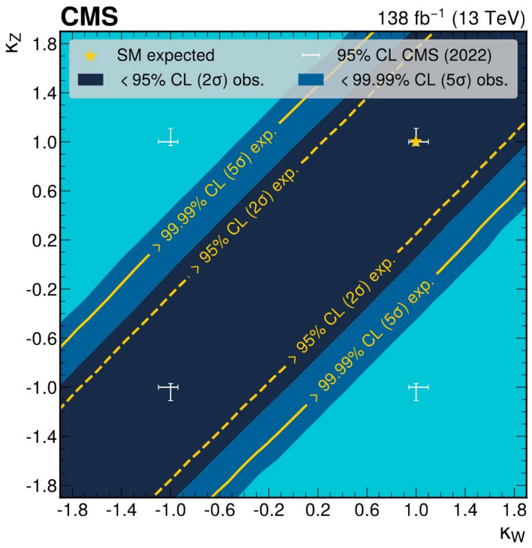
PRL 133 (2024) 141801
PLB 860 (2025) 139202

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 $k_W/k_Z<0$ beyond 5σ in H→bb final states



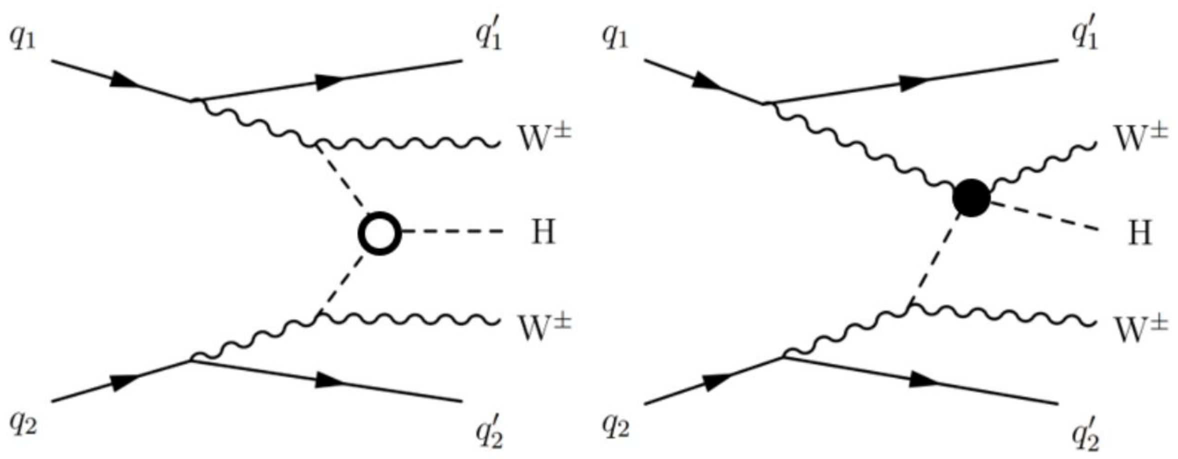
$$\sigma_{\mathrm{VBF},WH} \propto \kappa_Z^2|\mathcal{M}_Z|^2 + \kappa_W^2|\mathcal{M}_W|^2 - 2\,\kappa_Z\kappa_W\,\Re[\mathcal{M}_Z^\dagger\mathcal{M}_W]$$
$$= \kappa_Z^2|\mathcal{M}_Z|^2 + \kappa_W^2|\mathcal{M}_W|^2 - 2\,\kappa_Z^2\boxed{\lambda_{WZ}}\,\Re[\mathcal{M}_Z^\dagger\mathcal{M}_W]$$

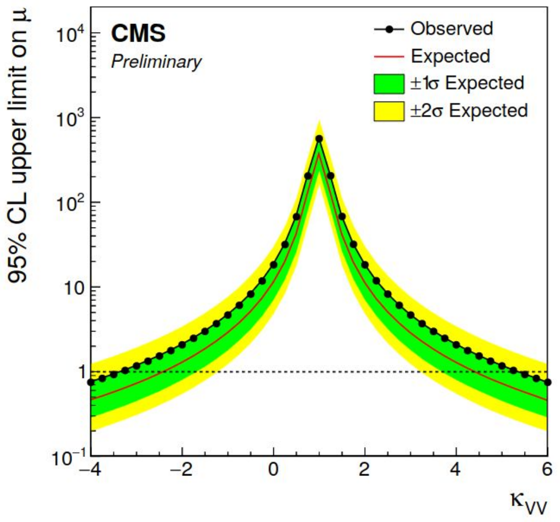


CMS-PAS-HIG-24-001

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





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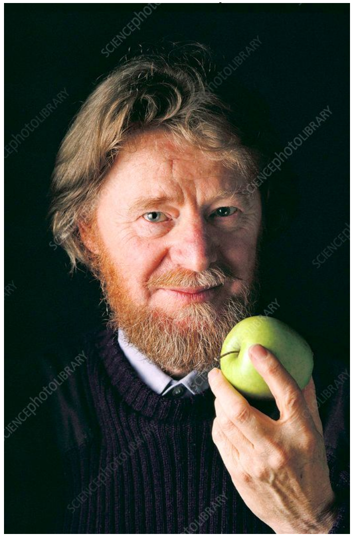


Spooky action at a distance!

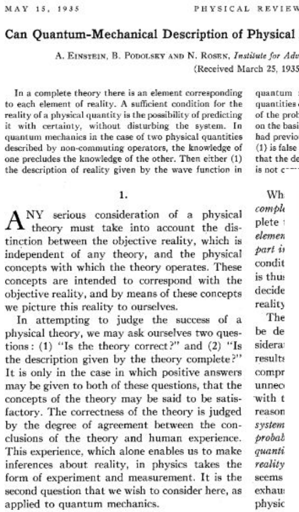
ref

"Can Quantum Mechanical Description of Physical Reality Be Considered Complete?"

A. Einstein B. Podolski N. Rosen

Physical reality must be local! - Podolsky

EPR Paradox



MAY 15, 1935 PHYSICAL REVIEW VOLUME 47

Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?

A. Einstein, B. Podolsky and N. Rosen, *Institute for Advanced Study, Princeton, New Jersey*

(Received March 25, 1935)

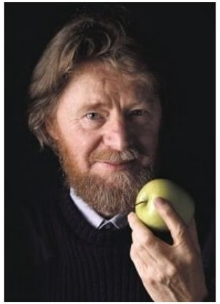
In a complete theory there is an element corresponding to each element of reality. A sufficient condition for the reality of a physical quantity is the possibility of predicting it with certainty, without disturbing the system. In quantum mechanics in the case of two physical quantities described by non-commuting operators, the knowledge of one precludes the knowledge of the other. Then either (1) the description of reality given by the wave function in quantum mechanics is not complete or (2) these two quantities cannot have simultaneous reality. Consideration of the problem of making predictions concerning a system on the basis of measurements made on another system that had previously interacted with it leads to the result that if (1) is false then (2) is also false. One is thus led to conclude that the description of reality as given by a wave function is not c…

1.

ANY serious consideration of a physical theory must take into account the distinction between the objective reality, which is independent of any theory, and the physical concepts with which the theory operates. These concepts are intended to correspond with the objective reality, and by means of these concepts we picture this reality to ourselves.

In attempting to judge the success of a physical theory, we may ask ourselves two questions: (1) "Is the theory correct?" and (2) "Is the description given by the theory complete?" It is only in the case in which positive answers may be given to both of these questions, that the concepts of the theory may be said to be satisfactory. The correctness of the theory is judged by the degree of agreement between the conclusions of the theory and human experience. This experience, which alone enables us to make inferences about reality, in physics takes the form of experiment and measurement. It is the second question that we wish to consider here, as applied to quantum mechanics.

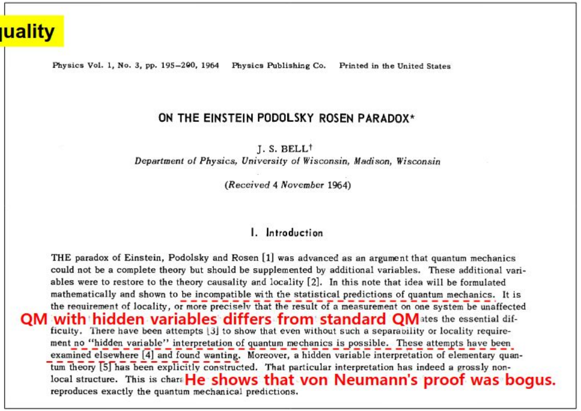
1964 QM with hidden variables differs from QM



1928~1990
John Stewart Bell

In the 1980s, he was always mentioned as a candidate for the Nobel Prize.

Bell's Inequality



Physics Vol. 1, No. 3, pp. 195–200, 1964 Physics Publishing Co. Printed in the United States

ON THE EINSTEIN PODOLSKY ROSEN PARADOX*

J. S. BELL†
Department of Physics, University of Wisconsin, Madison, Wisconsin

(*Received* 4 *November* 1964)

I. Introduction

THE paradox of Einstein, Podolsky and Rosen [1] was advanced as an argument that quantum mechanics could not be a complete theory but should be supplemented by additional variables. These additional variables were to restore to the theory causality and locality [2]. In this note that idea will be formulated mathematically and shown to be incompatible with the statistical predictions of quantum mechanics. It is the requirement of locality, or more precisely that the result of a measurement on one system be unaffected …ates the essential difficulty. There have been attempts [3] to show that even without such a separability or locality requirement no "hidden variable" interpretation of quantum mechanics is possible. These attempts have been examined elsewhere [4] and found wanting. Moreover, a hidden variable interpretation of elementary quantum theory [5] has been explicitly constructed. That particular interpretation has indeed a grossly nonlocal structure. This is char… reproduces exactly the quantum mechanical predictions.

QM with hidden variables differs from standard QM

He shows that von Neumann's proof was bogus.

Upon observation, the cat was found to be alive.

Huh? The cat suddenly died.

1 Light Year

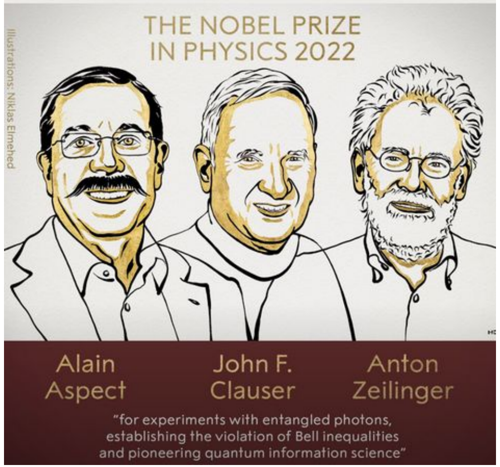
Planet A Planet B

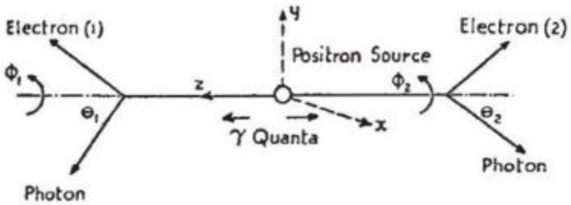
However, it still takes 1 light year for A and B to exchange answers.

Quantum mechanics is nonlocal

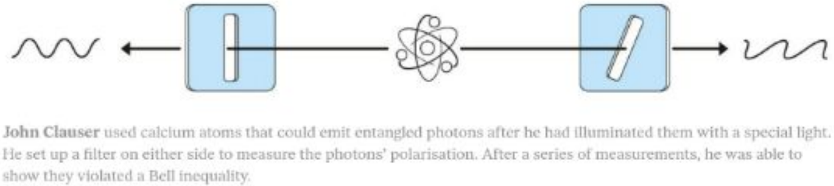
Quantum entanglement tests

- As reviewed by C. N. Yang, the first experiment on quantum entanglement is the Wu-Shaknov Experiment published in 1950 in which the angular correlation of two Compton scattered photons arising from $e+e-$ annihilation are measured.
- The violation of Bell inequality was demonstrated in 1970s using entangled photons, confirming the non-locality of our universe.
- Alain Aspect, John Clauser and Anton Zeilinger won Nobel Prize in Physics in 2022 for demonstrating the potential to investigate and control particles (photons) that are in entangled states





Wu-Shaknov Experiment



Clauser's photon entanglement experiment https://pubs.aip.org/physicstoday/article/77/12/28/3321126/Chien-Shiung-Wu-s-trailblazing-experiments-in

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Volume 77, Issue 12
1 December 2024

Chien-Shiung Wu's trailblazing experiments in particle physics

The Chinese American physicist led groundbreaking experiments that demonstrated parity violation and photon entanglement. Many in the physics community say Wu deserved more accolades in her lifetime.

Chon-Fai Kam; Cheng-Ning Zhang; Da Hsuan Feng

Check for updates

\+ Author & Article Information

Physics Today **77** (12), 28–35 (2024);
https://doi.org/10.1063/pt.oufp.zwkj

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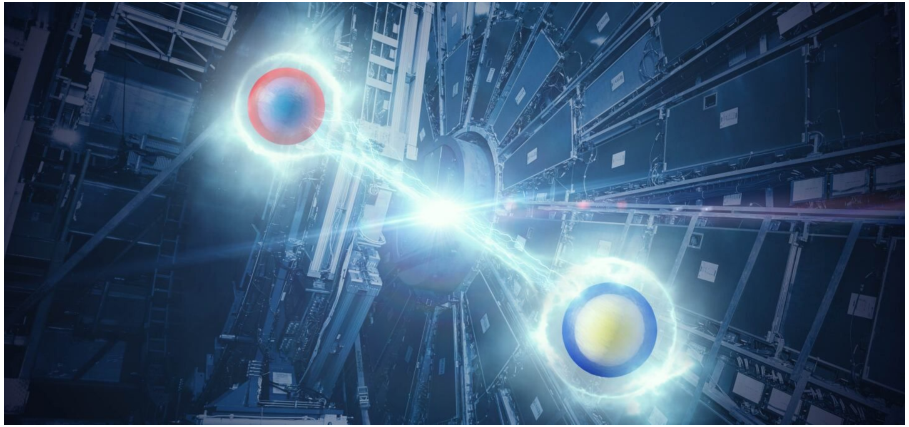
Quantum entanglement at high energy

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

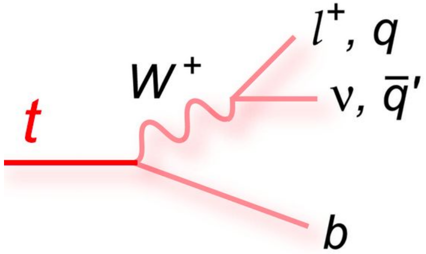
https://doi.org/10.1038/s41586-024-07824-z
Received: 14 November 2023
Accepted: 12 July 2024
Published online: 18 September 2024
Open access
Check for updates

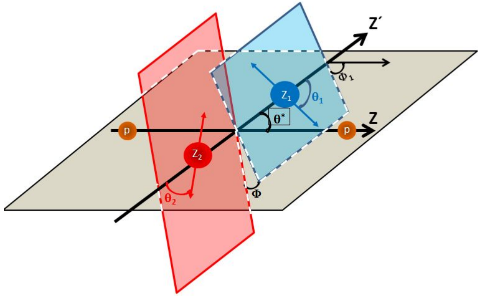
The ATLAS Collaboration*✉

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 $(\mathrm{fb})^{-1}$ 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 $D = -0.537 \pm 0.002\,(\mathrm{stat.}) \pm 0.019\,(\mathrm{syst.})$ for $340\ \mathrm{GeV} < m_{t\bar{t}} < 380\ \mathrm{GeV}$. 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 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]

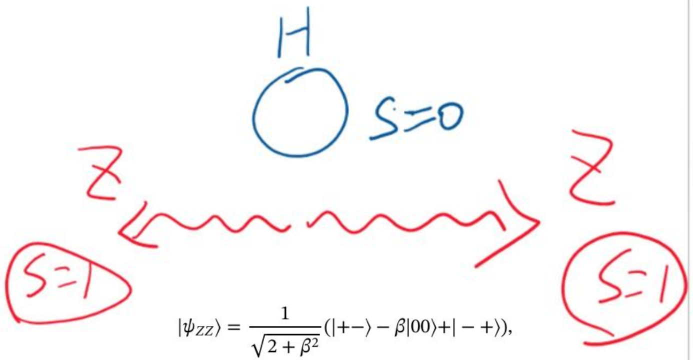
QE between qutrits: H→ VV

- The polarization density matrix(PDM) can be reconstructed from the angular distributions of the decay products:

$$\rho = |\Psi_{ZZ}\rangle\langle\Psi_{ZZ}| = |\Phi\rangle\langle\Phi|$$

$$|\Phi\rangle = \sum c_{ij}|ij\rangle \to \sum \mathcal{M}(\lambda_1,\lambda_2)|\lambda_1,\lambda_2\rangle$$

Ψ_Z has three polarization states: +1, 0, -1



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

For two-triplet system, we can expand the density matrix as

$$\rho = \frac{1}{9}\left[\mathbb{1}\otimes\mathbb{1}\right] + \sum_{a=1}^{8} f_a\left[T^a\otimes\mathbb{1}\right] + \sum_{a=1}^{8} g_a\left[\mathbb{1}\otimes T^a\right] + \sum_{a,b=1}^{8} h_{ab}\left[T^a\otimes T^b\right]$$

$$\frac{1}{\sigma}\frac{d\sigma}{d\Omega_+\,d\Omega_-} = \left(\frac{3}{4\pi}\right)^2 \mathrm{Tr}\left[\rho_{V_1V_2}\left(\Gamma_1\otimes\Gamma_2\right)\right]$$

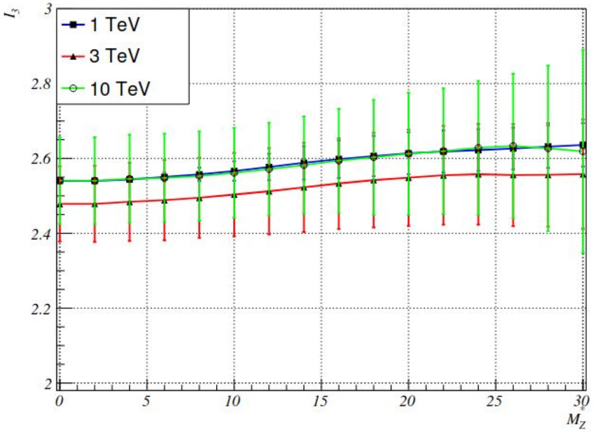
Production **Decay**

All coefficients → Quantum Tomography

- No direct spin measurements: inferred by angular distributions.
- Both the state before decay & the final state decay products inherit the SAME quantum information.

Prospects@LHC, MuC, CEPC

- The numerical analysis shows that with a luminosity of L =300 fb−1 entanglement can be probed at >3σ level. For **L=3 ab−1 (HL-LHC) entanglement** can be probed beyond the **5σ** level, while the sensitivity to **Bell inequalities** violation is at the **4.5σ** level.
- At Muon Collider, **Quantum entanglement** can be probed up to **4σ** of significance with lower MZ2 cut or 2σ ~ 3σ with higher MZ2 cut, using either one of the correlation coefficients C2,1,2,−1 and C2,2,2,−2. The significance of the **violation of Bell inequality** can be obtained up to **2σ**.



$\sqrt{s} = 1\,\text{TeV}$			
M_{Z_2} (GeV)	I_3	$C_{2,1,2,-1}$	$C_{2,2,2,-2}$
0.000	2.563 ± 0.325	-0.928 ± 0.216	0.527 ± 0.164
10.000	2.596 ± 0.335	-0.943 ± 0.220	0.553 ± 0.179
20.000	2.654 ± 0.373	-0.977 ± 0.248	0.574 ± 0.192
30.000	2.663 ± 0.508	-0.979 ± 0.334	0.589 ± 0.248

Table 2. Values of the correlation coefficients $C_{2,1,2,-1}$ and $C_{2,2,2,-2}$ as the signal for quantum entanglement and also the expectation value of the Bell operator I_3. The expected target luminosity is 30ab^{-1} and $\sqrt{s} = 1\,\text{TeV}$.

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.

QE Workshop@PKU

More funs-1 : AI for Boson Jets

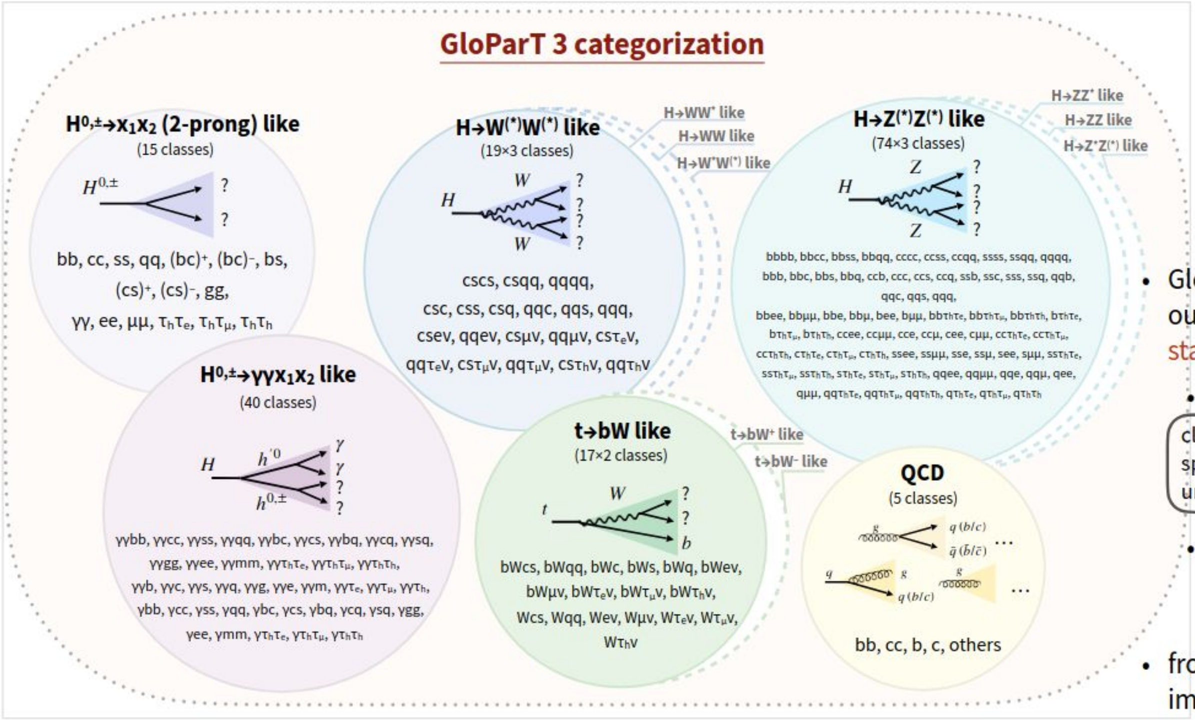
Congqiao Li's talk

AI for boosted boson

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

W→cb

A novel method for measuring |Vcb| at the LHC using an advanced boosted-jet tagger to identify “bc signatures”. By associating boosted **W → bc** signals with bc-matched jets from top-quark decays, we enable an in-situ calibration of the tagger.

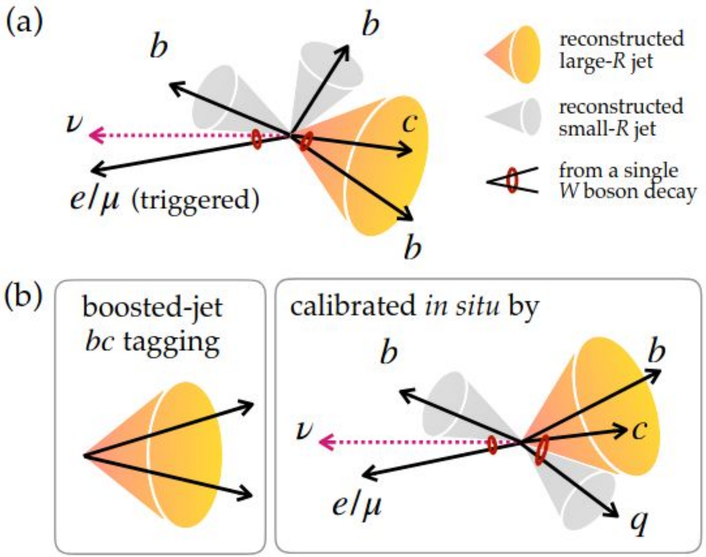
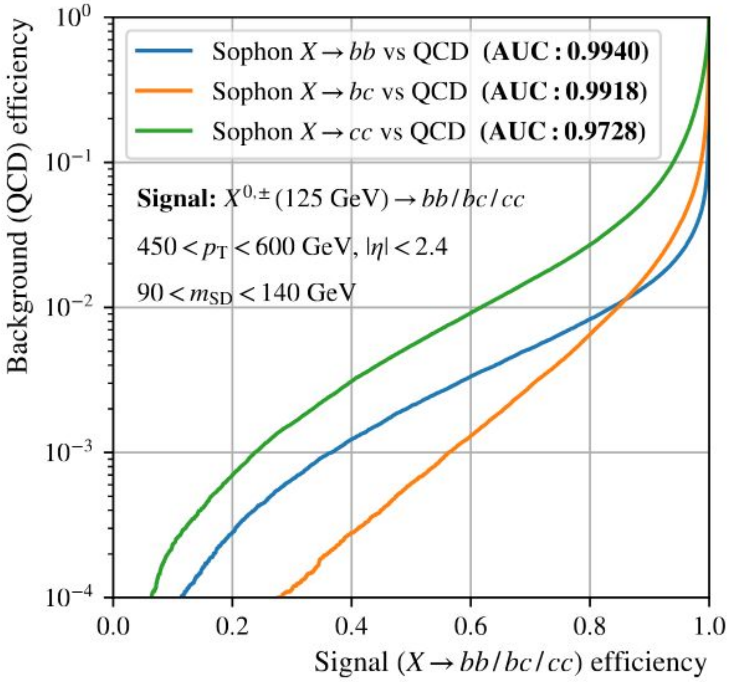
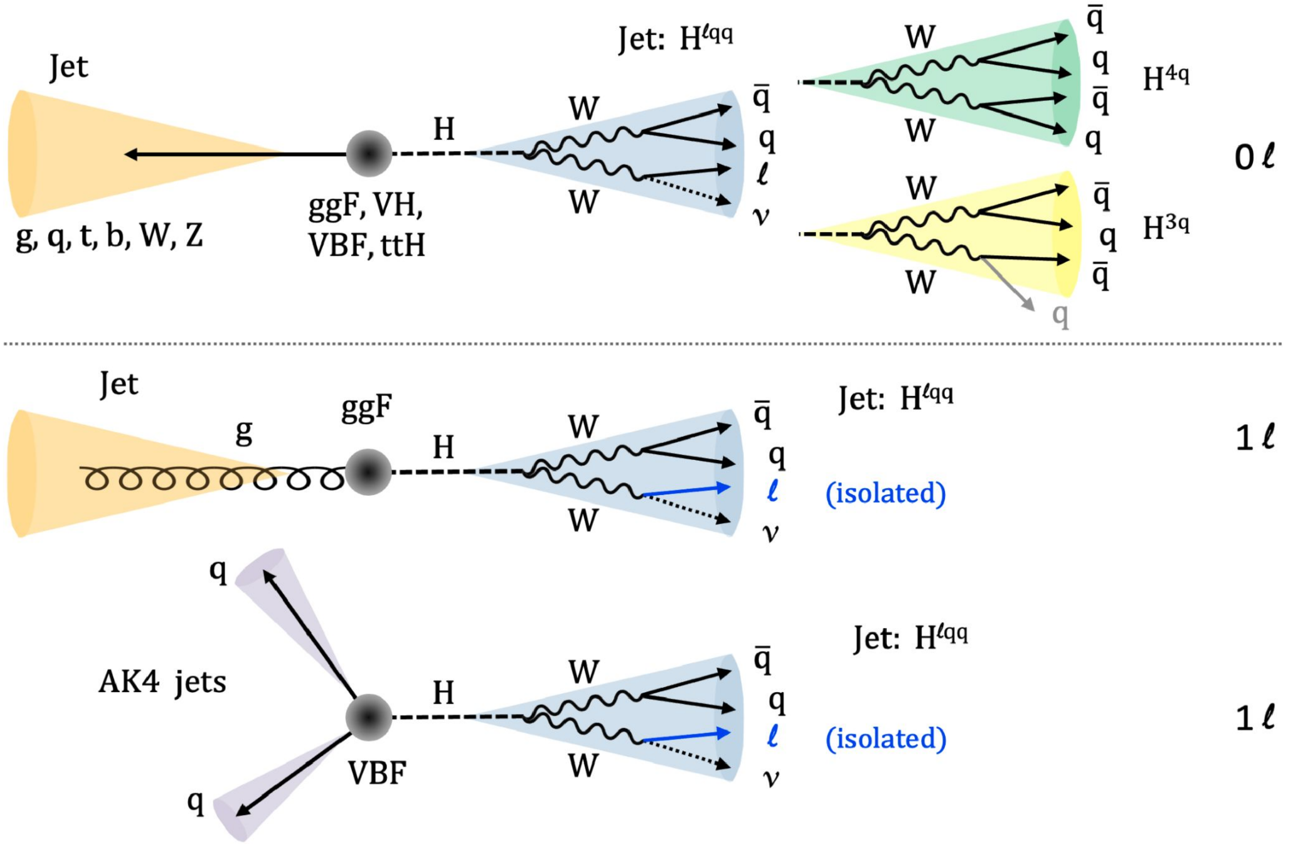


FIG. 1. Illustration of (a) the boosted event topology of semi-leptonic $t\bar{t}$ channel including a $W \to bc$ decay, and (b) techniques of boosted-jet bc tagging and *in-situ* calibration introduced in this work.

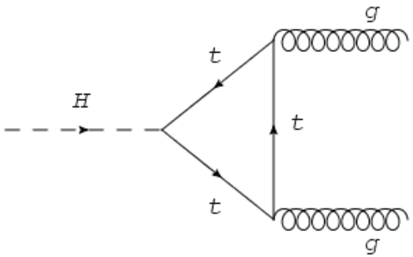


CMS-PAS-HIG-24-008

Boosted Higgs to WW*



H→ss?
H→gg?

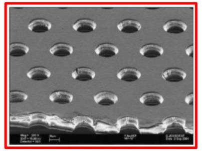


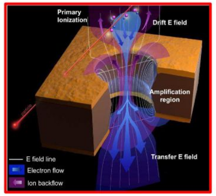
More funs-2：
Probing and Knocking with Muon
dark boson

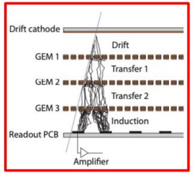
PKU Muon Detector Development

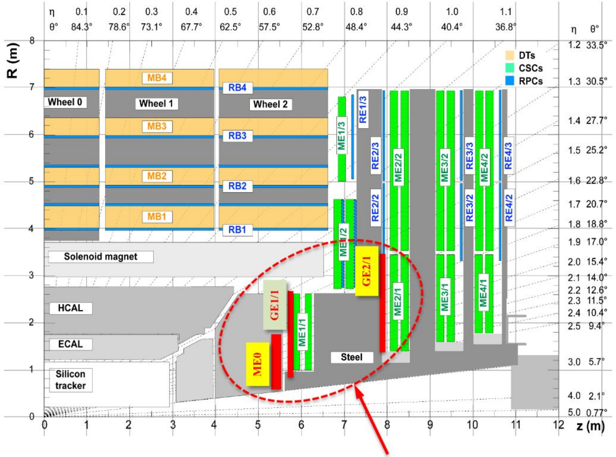
- ➔ CMS Muon Trigger RPC: assembled and tested at PKU at around 2002
- ➔ RPC R&D for nuclear physics
- ➔ CMS GEM upgrade program

北大基地生产的第一个CMS GEM模块









CMS端盖缪子探测器 GEM升级

北京大学、清华大学、中山大学、北京航空航天大学

Combination of glass RPC & Delay-line Readout


Contents lists available at SciVerse ScienceDirect

Nuclear Instruments and Methods in Physics Research A

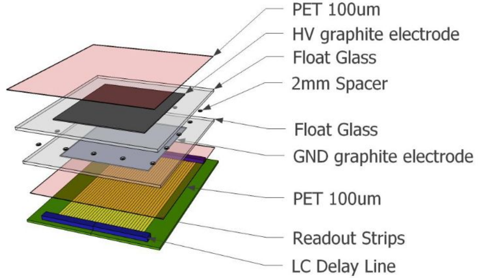
journal homepage: www.elsevier.com/locate/nima

ELSEVIER

Study of spatial resolution properties of a glass RPC

Qite Li, Yanlin Ye *, Chao Wen, Wei Ji, Yushou Song, Rongrong Ma, Chen Zhou, Yucheng Ge, Hongtao Liu

School of Physics and State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing 100871, China



Reference:

- 许金艳,**李奇特***, 等, ***物理实验*** 41(2021)23
- **Qi-Te, Li,** et al. ***Chinese Physics C*** 37 (2013)016002.
- S. Chen, **Q. Li***, et al, ***JINST***: 10 (2014)10022.

90% R134a+9% i-C_4H_{10}+1% SF_6 50ml/Min

Workshop on Muon Physics at the Intensity and Precision Frontiers (MIP 2024)

19 Apr 2024, 02:00 → 22 Apr 2024, 12:20 Asia/Shanghai

Peking University

Chen Zhou (Peking University (CN)), Qiang Li (Peking University (CN)), Qite Li (Peking University)

MIP2024

Several possible Chinese Muon beams in the near future:

Melody,

CIADS, HIAF

世界范围内的缪子散射、打靶实验

- 缪子作为第二代轻子，对其研究及应用相对较少，其科学和应用潜力巨大。

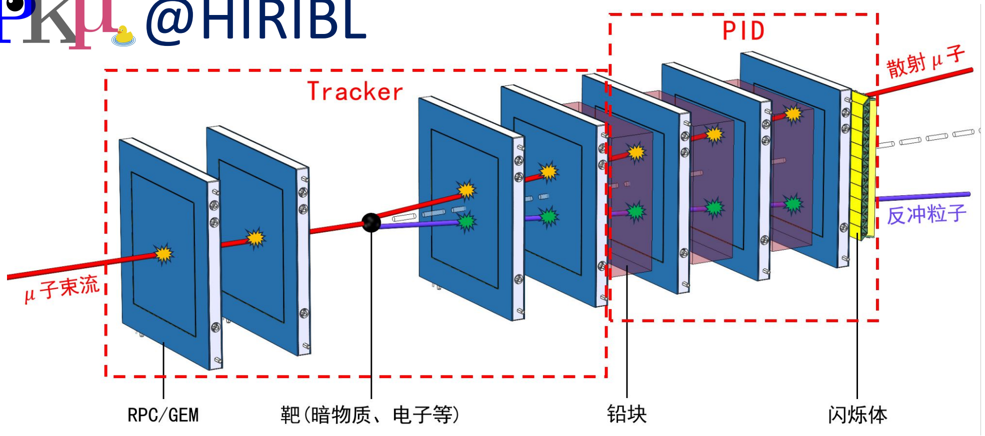
- NA64 和MUonE等实验利用高能缪子(150～160GeV)与靶散射
- 缪子散射蕴含大量的物理课题有待挖掘
  - **不同能量的缪子束流可以对不同的新物理空 间具有敏感性。**

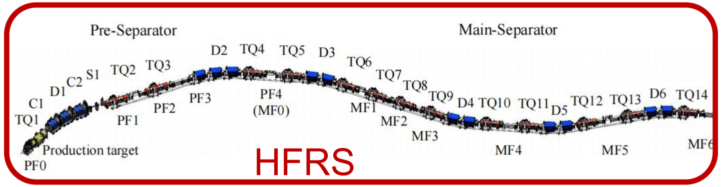
- 中国之前没有开展的缪子物理实验。<u>近年来条件有了很大变化</u>:
  - 中国散裂中子源的100kW，1.6GeV质子加速器已经建成，升级启动中；
  - 国家“十二五”重大科学工程项目“强流加速器装置(HIAF)”正在建设重离子加速器；
    - **2025年验收，第一条中国高能 (GeV)缪子束流？ 机遇！**
  - “十四五”启动建设的“加速器驱动嬗变系统(CiADS)” 拟建设连续流直线质子加速器；
  - 中国原子能科学研究院正在大力推动高功率质子回旋加速器的建设

Muon Scattering Experiment at HIAF-HIRIBL

PKMu(Probing and Knocking with Muons) Proposed by Peking University together with HIAF-HFRS from Institute of Modern Physics, Chinese Academy of Sciences, China: **using 1-10 GeV Muon to probe new physics beyond the Standard Model**

PKμ @HIRIBL



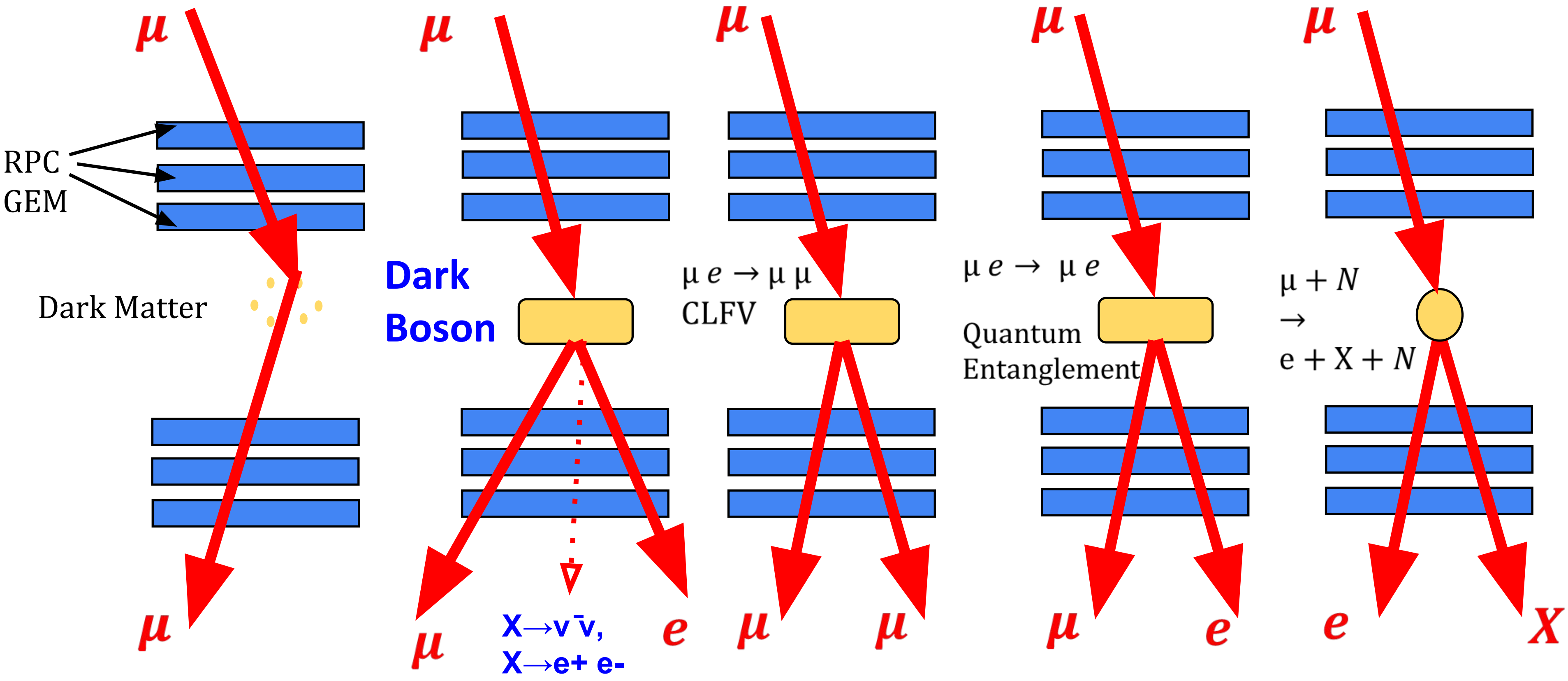


参考文献:[1] Phys. Rev. D 110, 016017 [2] arxiv:2410.20323 [3] arXiv:2411.12518 [4] Nucl. Instrum. Methods. Phys. Res. A 663 (2012) 22-25

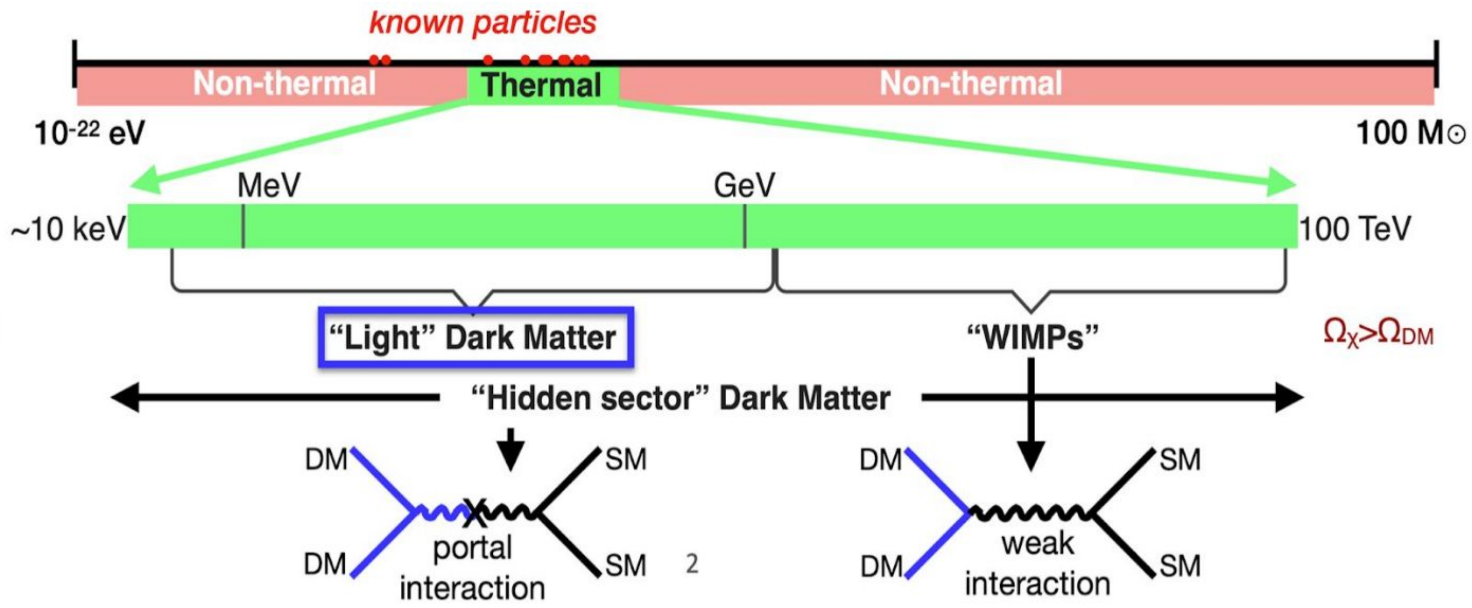
丰富的物理图景

→Cosmic μ or μ beam

Modern Physics Letters A (2025) 2530008



Light Dark Matter → Dark Sector

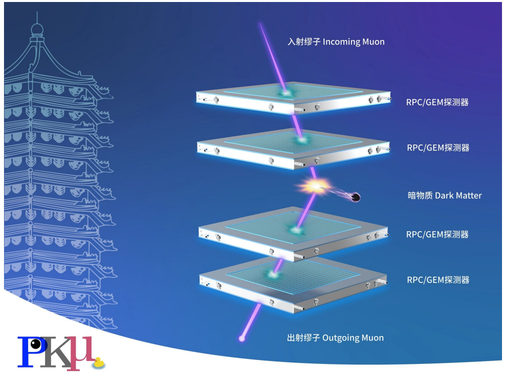


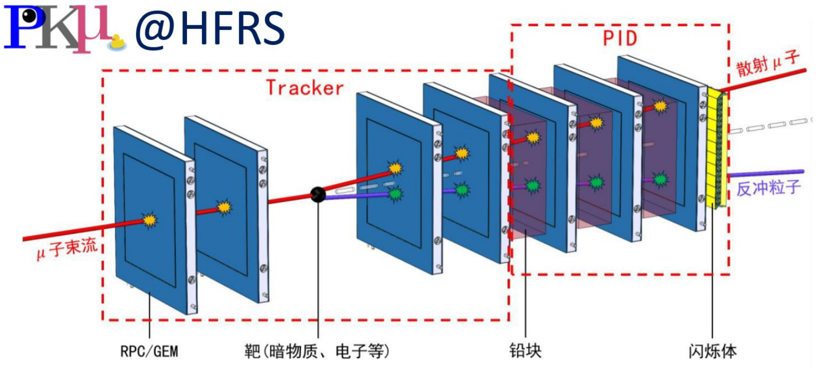
Minimal scenarios with light (sub-GeV) dark matter whose relic density is obtained from thermal freeze-out must include new light mediators. In particular, a very well-motivated case is that of a new "dark" massive vector gauge boson mediator. JHEP03(2018)084 Granada19 LDMX2024

(获得热遗留下来的轻(次GeV)暗物质的最低限度情景必须包含新的轻媒介粒子。特别是，一个非常有动机的情况是存在一种新的"暗"质量矢量规范玻色子作为媒介粒子。)

Muon Philic Dark Sector

- Muon Philic Dark Matter may be possible or even necessary!
  - $L_\mu - L_\tau$ gauged model (Z', χ) quite popular recently
  - 1) Direct searches for DM
    - See the PKMu proposal: *Phys.Rev.D* 110 (2024) 1, 016017
  - 2) On target experiments for Dark Boson: (see also cosmology constraints)
    - LDMX,DarkShine; eN → eNZ', Z'→$\nu\bar{\nu}$ or Z'→χχ (dark matter)
    - NA64μ, MMM μN → μNZ', Z'→$\nu\bar{\nu}$ or Z'→χχ (dark matter)
    - MuonE(pheno.) μe → μeZ', Z'→$\nu\bar{\nu}$ or Z'→χχ (dark matter)





参考文献: [1] Phys. Rev. D 110, 016017 [2] arxiv:2410.20323 [3] arXiv:2411.12518 [4] Nucl. Instrum. Methods. Phys. Res. A 663 (2012) 22-25

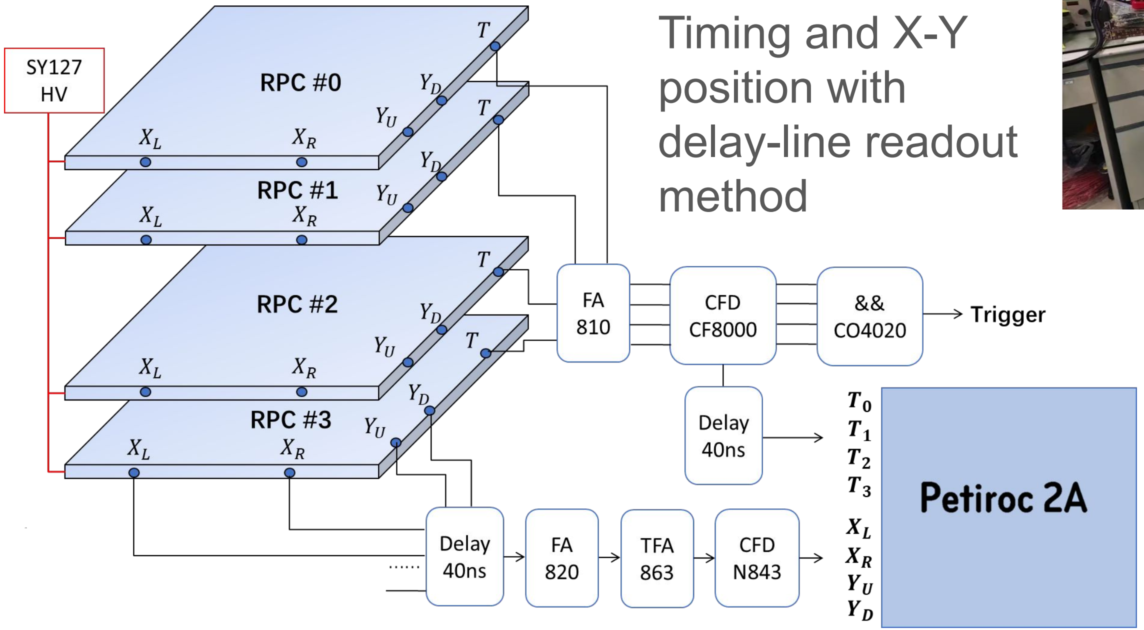
Current Box Exp. Status

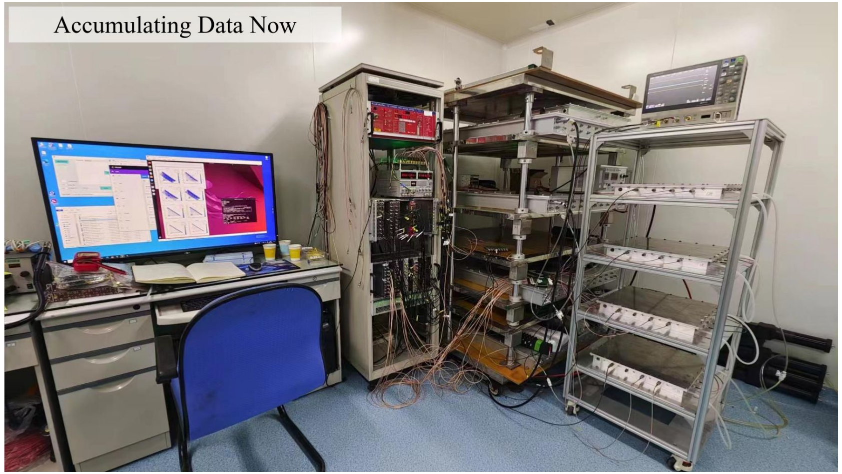
recent report from Cheng-en Liu and Qite Li

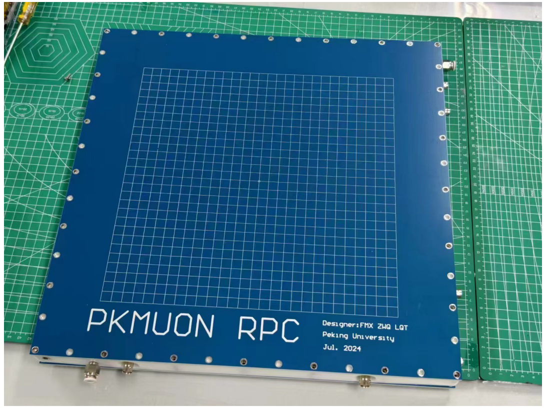
4-station 20cm*20cm RPC for the moment

Petiroc 2A is a 32-channel front-end ASIC

Timing and X-Y position with delay-line readout method





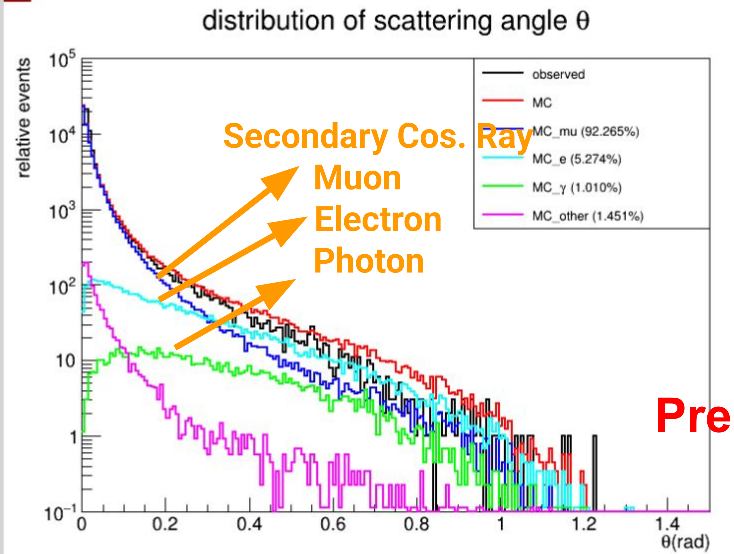


Byproduct: cosmic ray measurements

<u>缪子、电子、光子</u> 在大散射角度区域 有很好的区分度

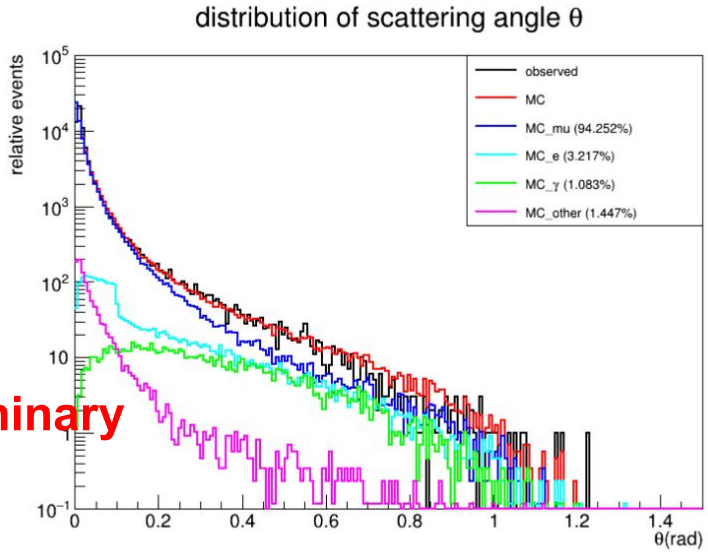
⇨ 地面宇宙次级射线新型测量手段

铅块数据对比



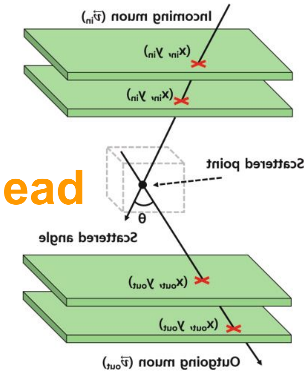
无调整

Preliminary



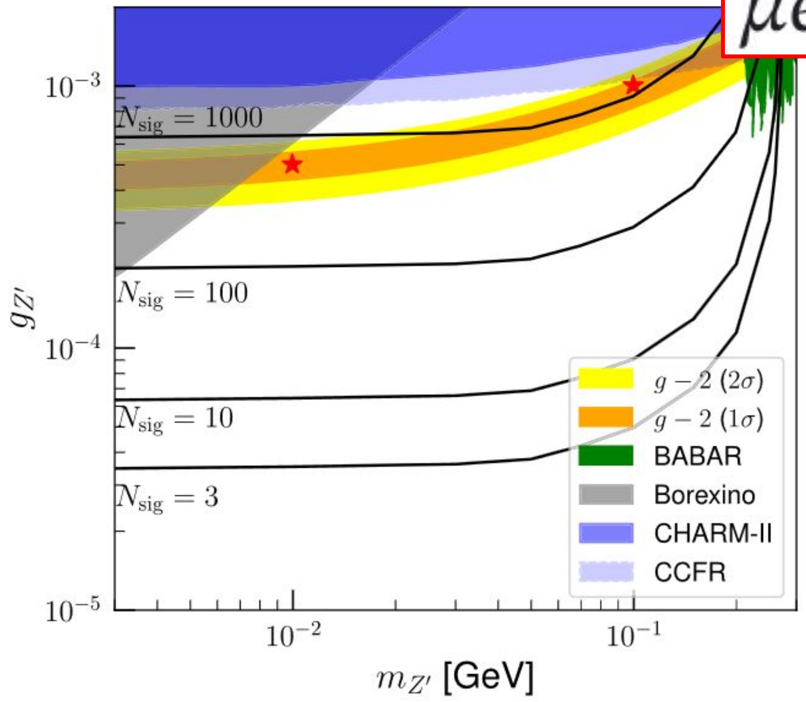
联合拟合后

lead

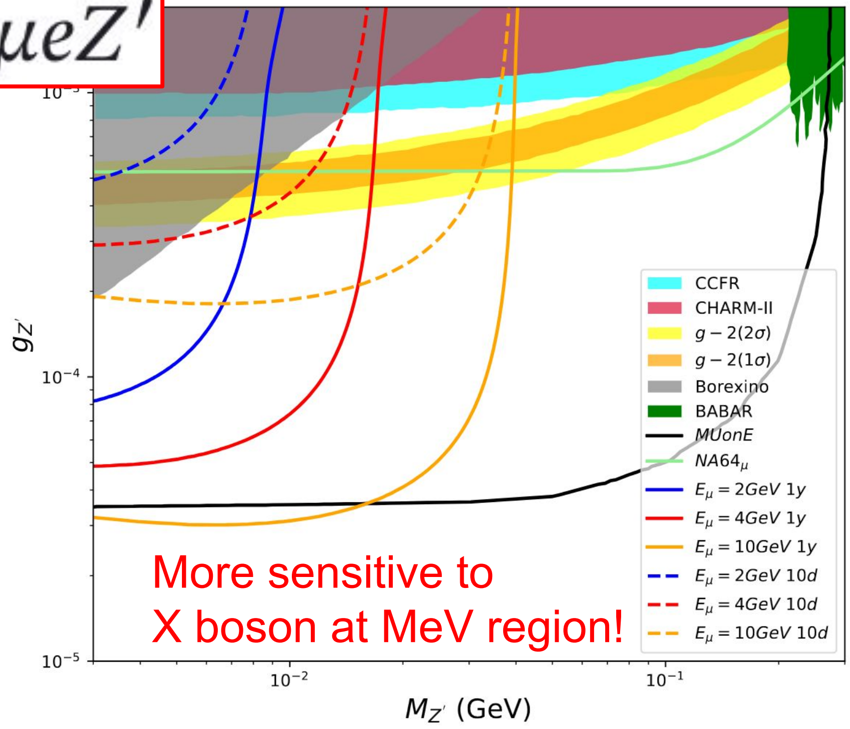


PKMu@HIRIBL vs. MuonE

$\mu e \to \mu e Z'$



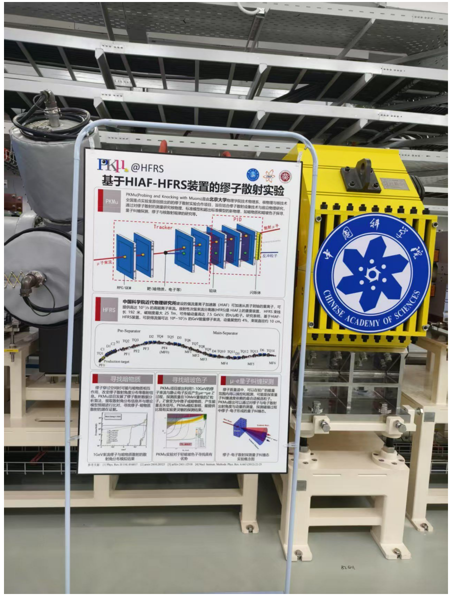
Phys.Rev.D 106 (2022) 5, L051702

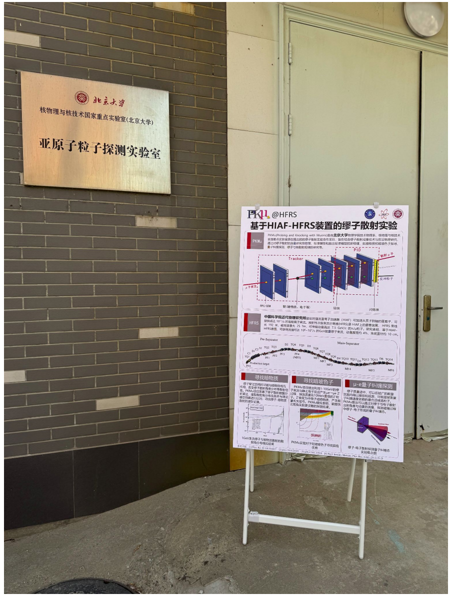


More sensitive to
X boson at MeV region!

Preliminary results

PKMu@HIRIBL Lab/Collaboration





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!**

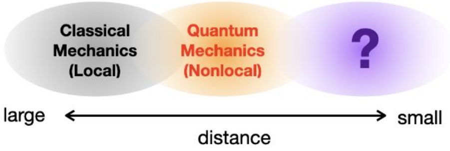
Quantity	Current precision	FCC-ee stat. (syst.) precision	Required theory input	Available calc. in 2019	Needed theory improvement†
m_Z	2.1 MeV	0.004 (0.1) MeV	non-resonant $e^+e^- \to f\bar{f}$, initial-state radiation (ISR)	NLO, ISR logarithms up to 6th order	NNLO for $e^+e^- \to f\bar{f}$
Γ_Z	2.3 MeV	0.004 (0.025) MeV			
$\sin^2\theta^{\ell}_{\rm eff}$	1.6×10^{-4}	$2(2.4)\times10^{-6}$			
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 framework)	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

Why QE at high energy?

https://conference-indico.kek.jp/event/278/contributions/6412/attachments/4329/6925/2025_02_19_K_Sakurai_KEKPH%20Kazuki%20Sakurai.pdf



Gravity

- QM might be an effective theory of more fundamental theory applicable only from some larger distances (lower energies)

- QM might be modified at shorter distances to be married with gravitation Gravity

- Currently, no LHC analysis can distinguish anomalies from QFT-based BSM and those from beyond-QFT

Possible Modifications of QM

Static:

Particles may exhibit a strong correlation that cannot be explained within QM

$$\mathcal{B} \equiv (A + A')B + (A - A')B'$$

$$\boxed{\langle \mathcal{B} \rangle_{\rm QM} \leq 2\sqrt{2}}$$ [Tsirelson '87]

$$\hat{\mathcal{B}}^2 = 4 - [\hat{A}, \hat{A}'][\hat{B}, \hat{B}']$$

$$|[\hat{A}, \hat{A}']|, |[\hat{B}, \hat{B}']| \leq 2 \leftarrow [\sigma_x, \sigma_y] = 2i\sigma_z$$

$$\Rightarrow \langle \mathcal{B}^2 \rangle_{\rm QM} \leq 8 \Rightarrow \langle \mathcal{B} \rangle_{\rm QM} \leq 2\sqrt{2}$$

QM will be excluded if this bound is violated!

No-signalling theory: [Popescu, Rohrlich(1994)]

$$\langle \mathcal{B} \rangle_{\rm NS}^{\rm max} = 4$$

Dynamical:

Quantum dynamics may be modified.

- Schrodinger evolution
- Wave function collapse

$$\rho_{\rm in} \longrightarrow \boxed{?} \longrightarrow \rho_{\rm out}$$

- Non-linear extensions of QM:

[Weinberg (1989), Polchinski (1991), D.E.Kaplan, Rajendran (2021)]

$$i\partial_t |\chi\rangle = \int d^3x \left[\hat{\mathcal{H}}(x) + \langle \chi | \hat{\mathcal{O}}_1(x) | \chi \rangle \hat{\mathcal{O}}_2(x) \right] |\chi\rangle$$

non-linear state-dependent term

Bell test cannot detect such modifications

We propose a method which detects modifications of quantum dynamics

A first electron-positron beam correlation measurement proposal

Leyun Gao@Muon4Future 2025
arXiv:2502.07597 (accepted by PRD)

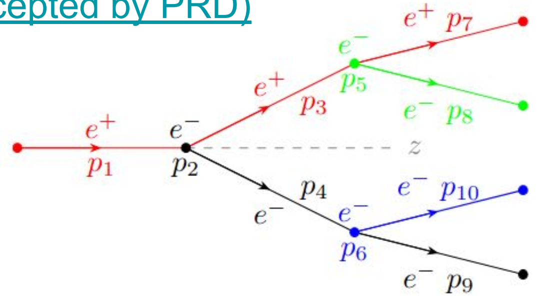


FIG. Proposed cascade experiment for measuring polarization correlations of the primary products

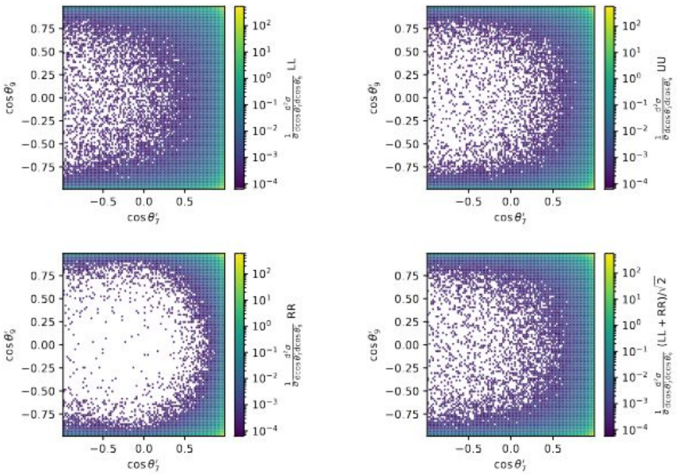


FIG. Joint angular distribution densities of the two secondary scattering processes

Simulation setup:

- $0.05\ \mathrm{rad} \leq \theta_3 \leq 0.1\ \mathrm{rad}$ in a 1 GeV positron on-target experiment
- The spins of target electrons 5 and 6 are aligned with the beam direction
- Consider the main component of the primary state, $(LL + RR)/\sqrt{2}$

Assuming the two secondary targets are $10\ \mathrm{cm}$ thick iron, the event rate in $\cos\theta_7' \leq 0.5 \wedge -0.75 \leq \theta_9' \leq 0.75$ is $\mathbf{1.4 \times 10^2}$/s for the state $(LL + RR)/\sqrt{2}$.

Future prospects: Scattering-based simplified state tomography

Take $0.05 \text{ rad} \leq \theta_3 \leq 0.1 \text{ rad}$ in a 1 GeV positron on-target experiment as an example:

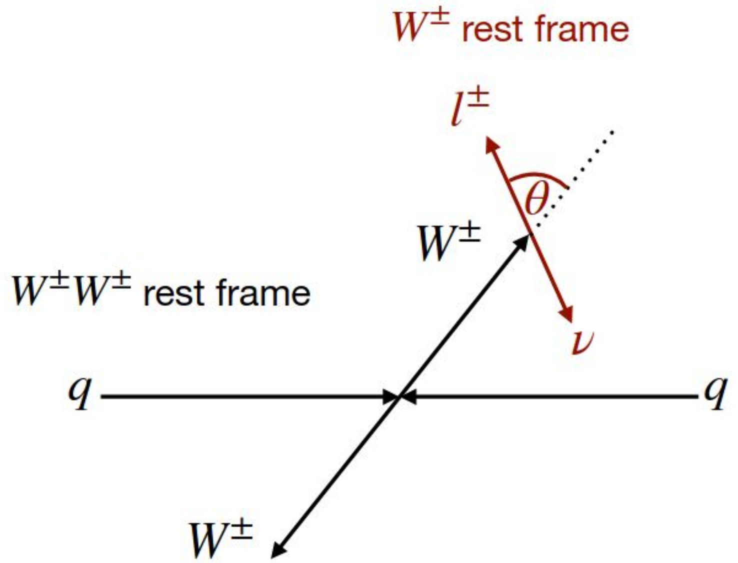
- The state of the primary products is approximately 1% $(RL + LR)/\sqrt{2}$, 1% $(RL - LR)/\sqrt{2}$, 7% $(RR - LL)/\sqrt{2}$, and 90% $(RR + LL)/\sqrt{2}$ in the lab frame
- The optimized ratio of the yields of $(LL + RR)/\sqrt{2}$ to UU is $1.29 \pm 0.03(\mathrm{MC})$, corresponding to 4.4×10^3 post-optimization efficient signal event counts and an expected signal yield over a **27-second** run; the result for $(LR + RL)/\sqrt{2}$ is $0.78 \pm 0.02(\mathrm{MC})$ in comparison
- Other uncertainties, such as those from process modeling and background suppression, may dominate the real experimental analysis
- For the 20% polarized targets, the ratios are 1.010 ± 0.009 and 0.986 ± 0.009 generated from 25 times the number of Monte Carlo events, corresponding to 2.5×10^4 efficient event counts accumulated in **680 seconds**
- The high event rate can help mitigate the decline in resolving power associated with low target polarization purities in real-world applications
- **A simplified state tomography can be performed assuming prior knowledge from the primary scattering**

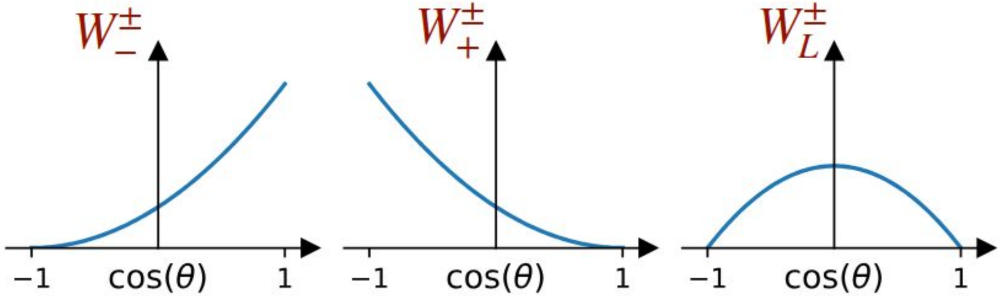
Access Polarization Information

- $W^{\pm}$ 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



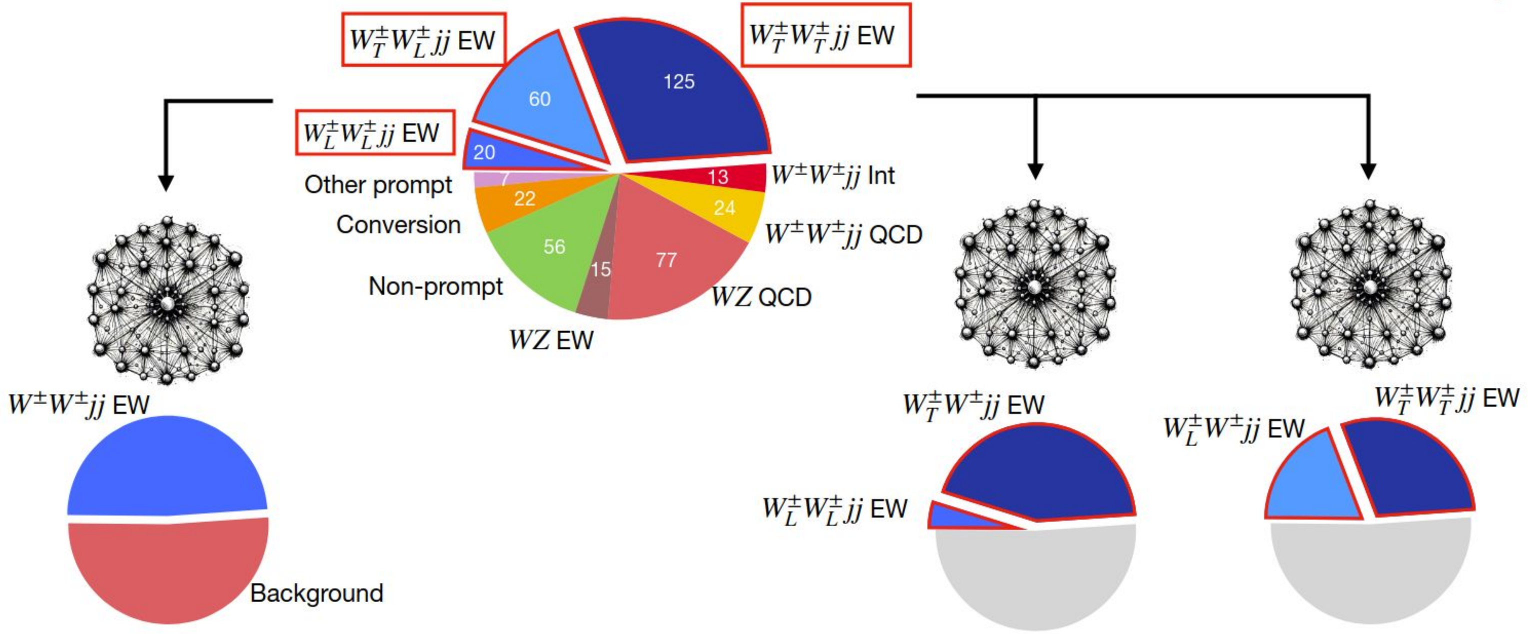


[Moriond 2025](#)

Polarized VBS from ATLAS

Neural Networks Save the Day

New

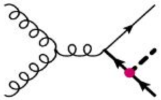
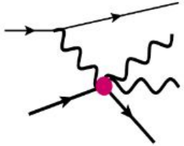
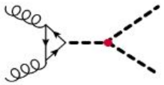
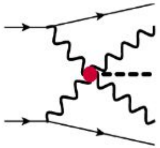
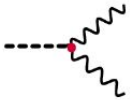
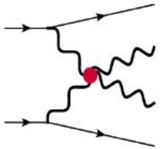
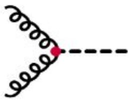
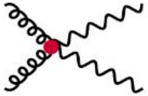


DNN trained to **split signal region in 3 regions** with **increasing $W^{\pm}W^{\pm}jj$ EW purity**

DNN trained as **discriminant variable to measure $W^{\pm}_{L}W^{\pm}_{L}jj$ EW / $W^{\pm}_{L}W^{\pm}jj$ EW**

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],

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

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

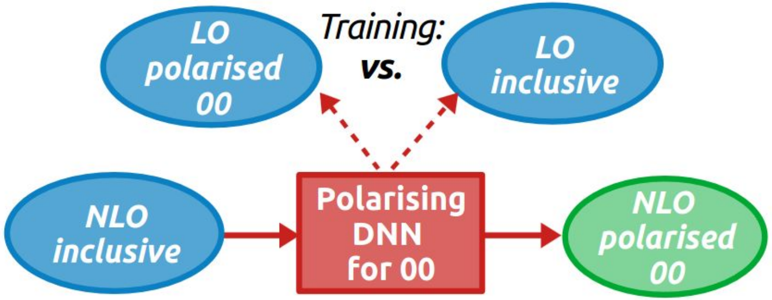
ATLAS WZ

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**

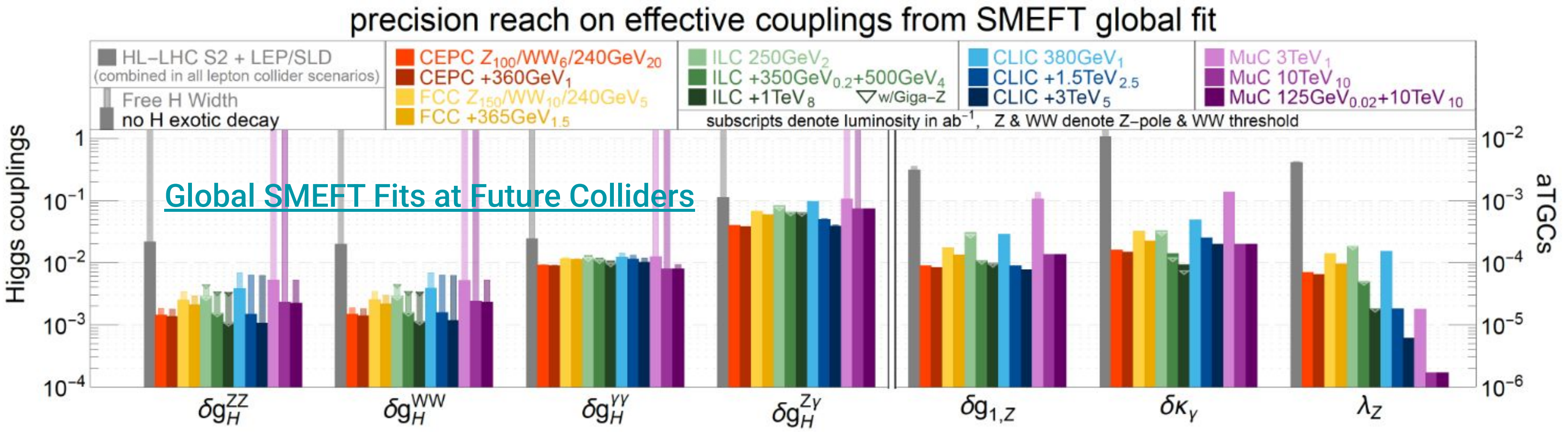


w(x)~ DNN(x) / (1 – DNN(x))

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

Reweighting DNNs input variables

Future



[Global SMEFT Fits at Future Colliders]

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

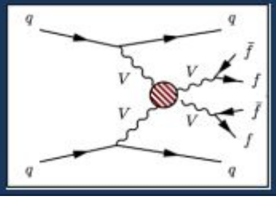
- ~ 10^{13} W
- ~ 10^{12} Z
- ~ 10^{11} tt
- ~ 10^{10} H
- ~ 10^{9} ttH
- ~ 10^{7} HH
- ~ 10^{5} gluino pairs m=8 TeV

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”]