Experimental Overview: Electroweak

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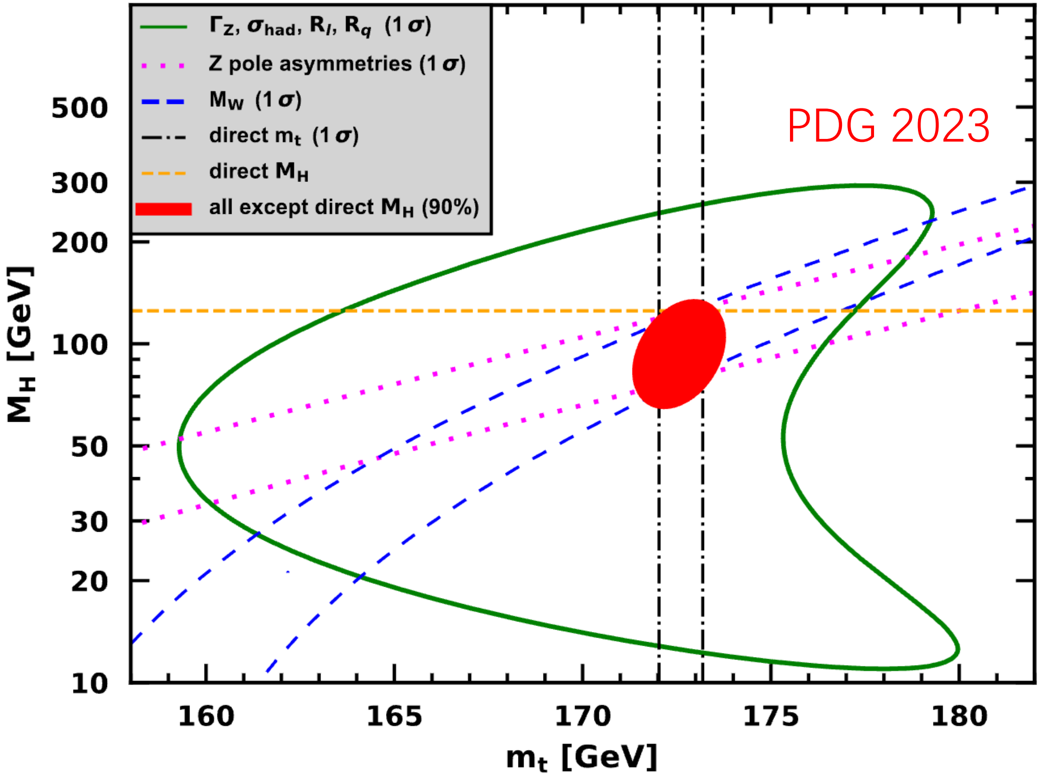
The status of electroweak global fit

❖7 key observables in electroweak global fit

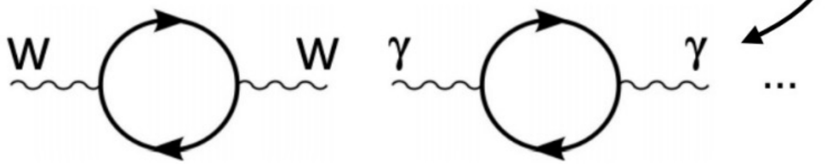
- ▶ Consistency study of the standard model electroweak section
- ▶ Need CEPC Z pole and WW runs : Precise measurements on EWK observables.



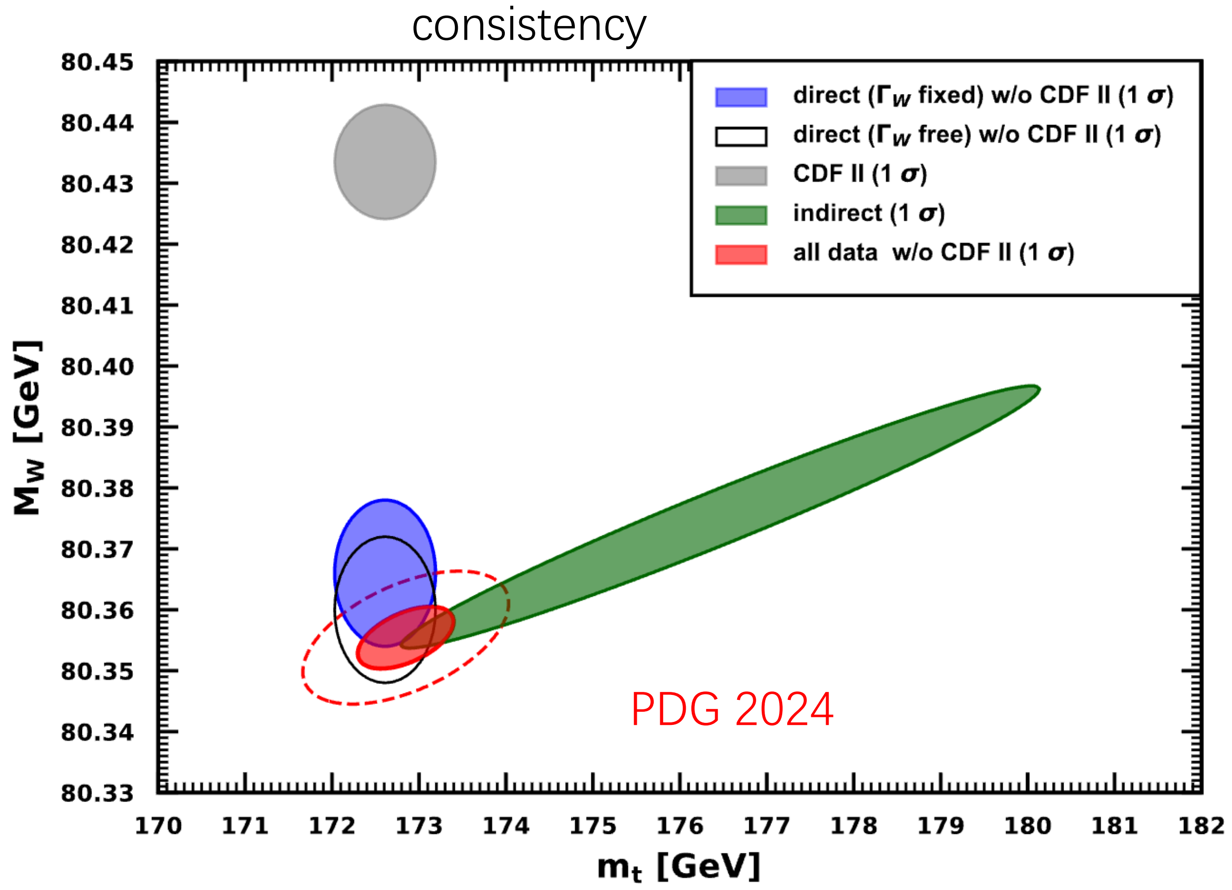
Fundamental constant	δx/x	measurements
$\alpha = 1/137.035999139\,(31)$	1×10^{-10}	$e^{\pm}$ g_2
$G_F = 1.1663787\,(6) \times 10^{-5}$ GeV^{-2}	1×10^{-6}	$\mu^{\pm}$ lifetime
$M_Z = 91.1876 \pm 0.0021$ GeV	1×10^{-5}	LEP
$M_W = 80.379 \pm 0.012$ GeV	1×10^{-4}	LEP/Tevatron/LHC
$\sin^2\theta_W = 0.23152 \pm 0.00014$	6×10^{-4}	LEP/SLD
$m_{top} = 172.74 \pm 0.46$ GeV	3×10^{-3}	Tevatron/LHC
$M_H = 125.14 \pm 0.15$ GeV	1×10^{-3}	LHC

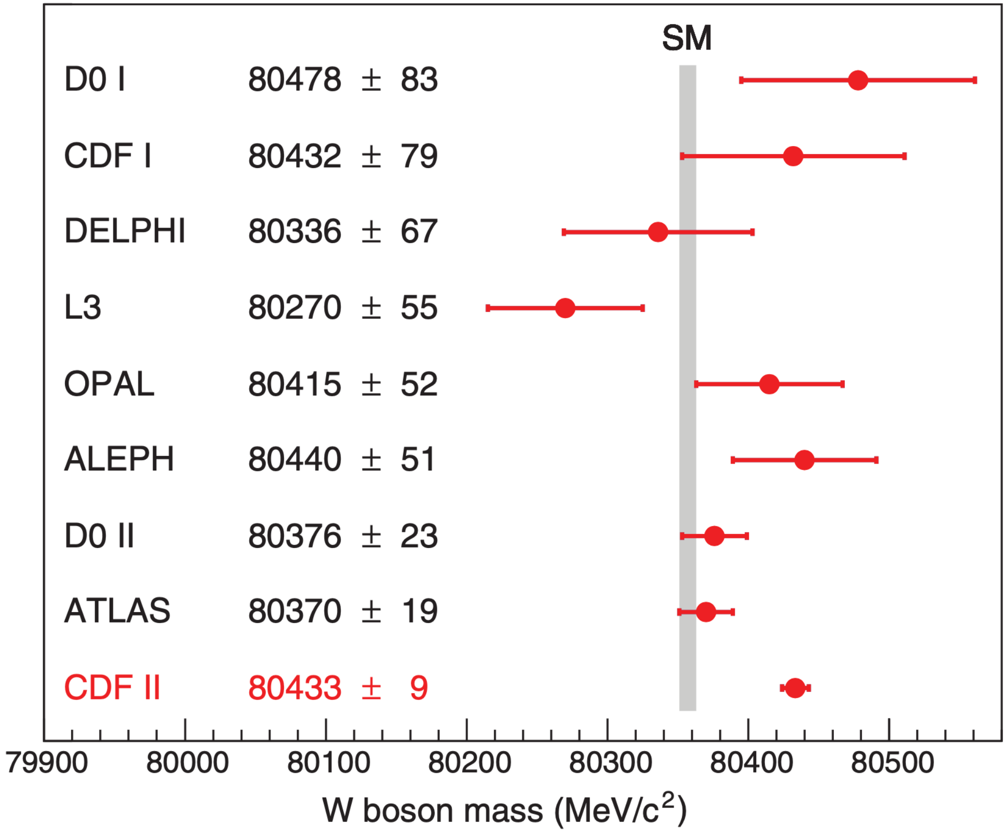
W mass measurement

$$m_W^2\left(1-\frac{m_W^2}{m_Z^2}\right)=\frac{\pi\alpha}{\sqrt{2}G_F}(1+\Delta)$$



- **m_W is a key observable to test SM consistency**
  - m_W Measurement at future collider is essential





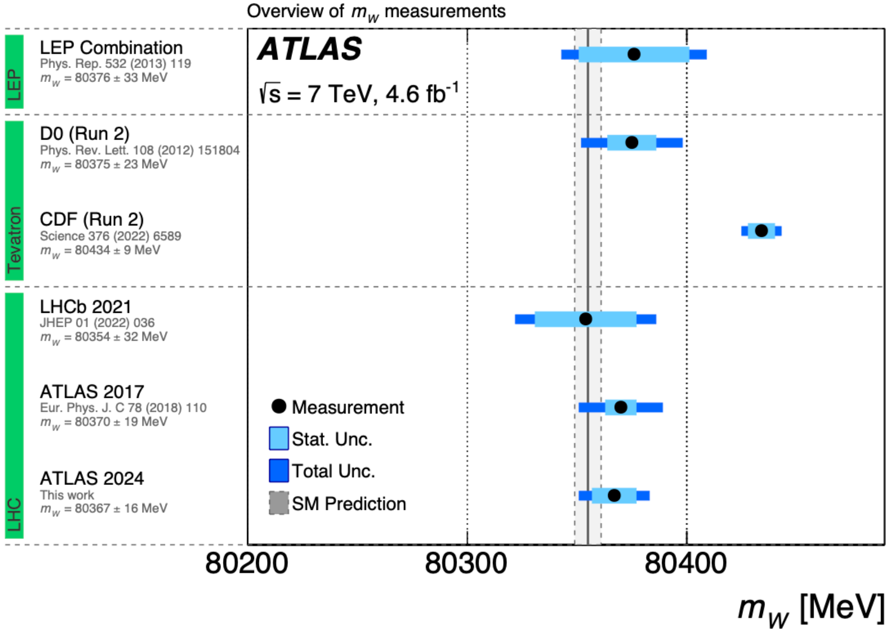
Science Vol 376, Issue 6589, pp. 170–176 (2022)

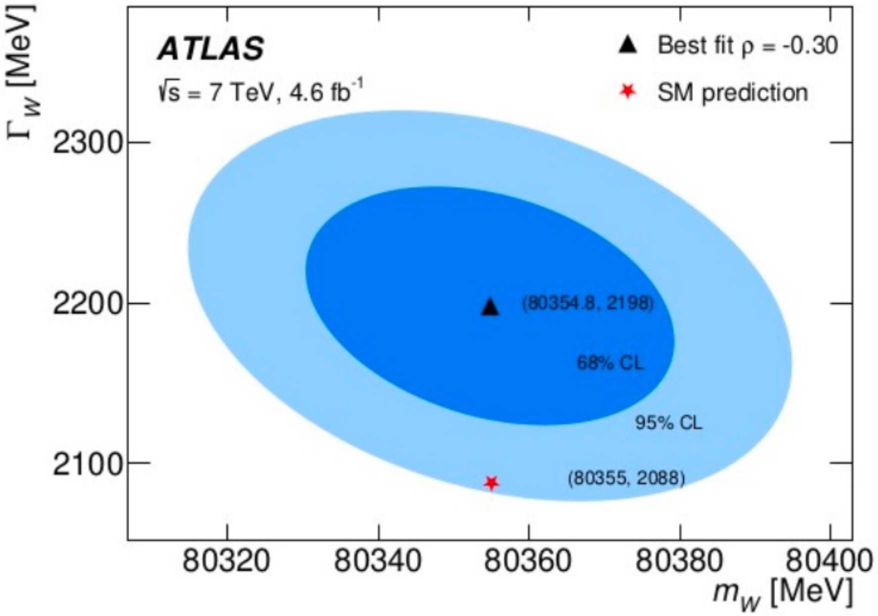
ATLAS W mass (run I data reanalysis)

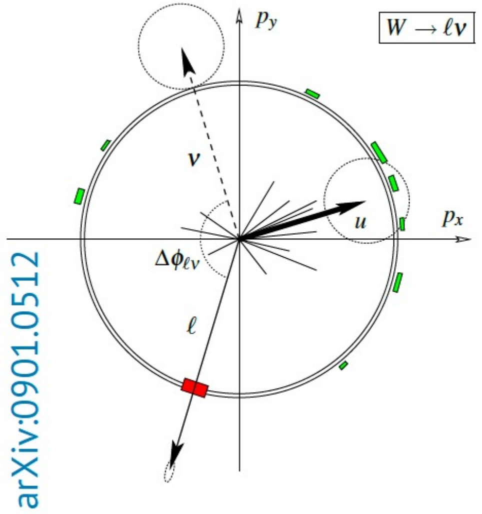
arXiv:2403.15085

- **New ATLAS result m_W = 80366.5 ± 15.9 MeV,** old result (2017, ATLAS) mW = 80370 ± 19 MeV

- **Γ_W = 2202 ± 47 MeV , Most precise single-experiment measurement of ΓW**



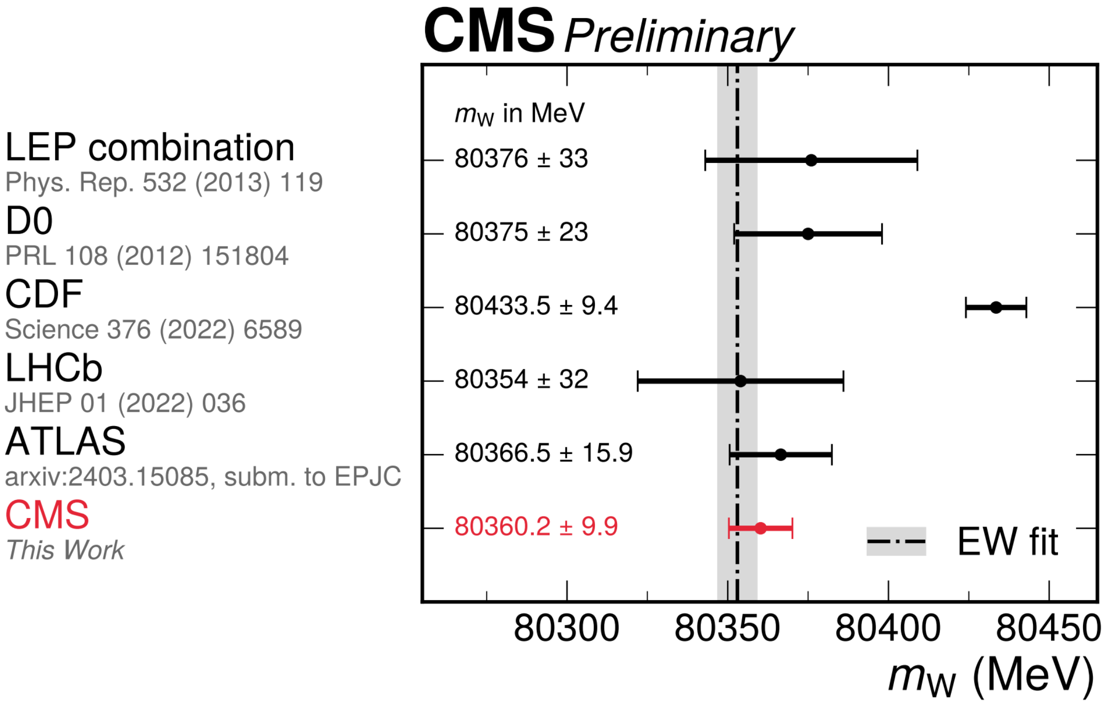


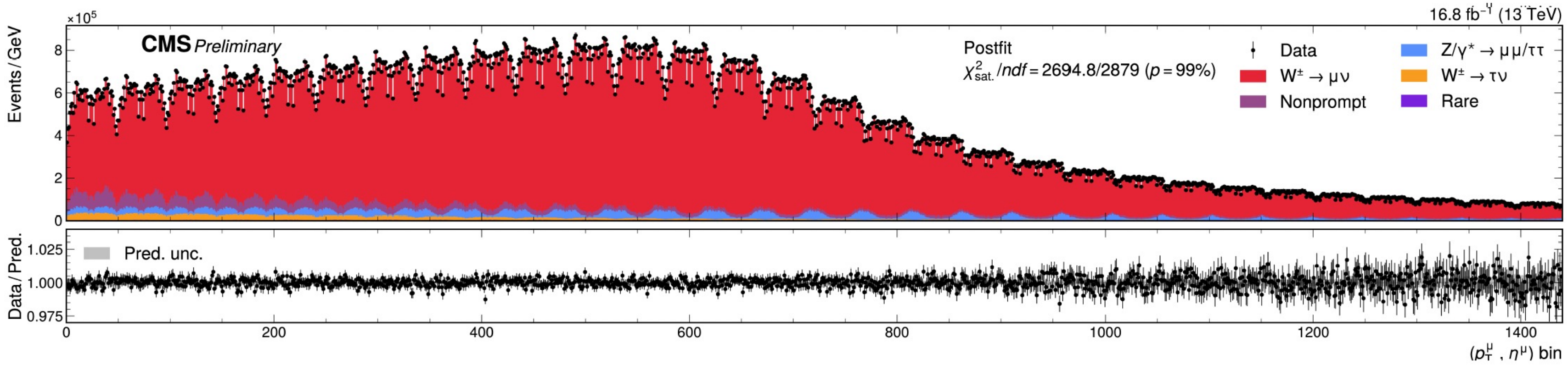


Unc. [MeV]	Total	Stat.	Syst.	PDF	A_i	Backg.	EW	e	μ	u_T	Lumi	Γ_W	PS
p_T^ℓ	16.2	11.1	11.8	4.9	3.5	1.7	5.6	5.9	5.4	0.9	1.1	0.1	1.5
m_T	24.4	11.4	21.6	11.7	4.7	4.1	4.9	6.7	6.0	11.4	2.5	0.2	7.0
Combined	15.9	9.8	12.5	5.7	3.7	2.0	5.4	6.0	5.4	2.3	1.3	0.1	2.3

New CMS W mass measurement

- Measured with uncertainty of 9.9 MeV
  - Precision comparable to CDF
  - 16.8 fb^{-1} from 2016 run (~ 30 pileup)
  - Large sample (>100M) of $W \to \mu\nu$
- Fit to granular distribution of pT_{μ} x η_{μ} x charge

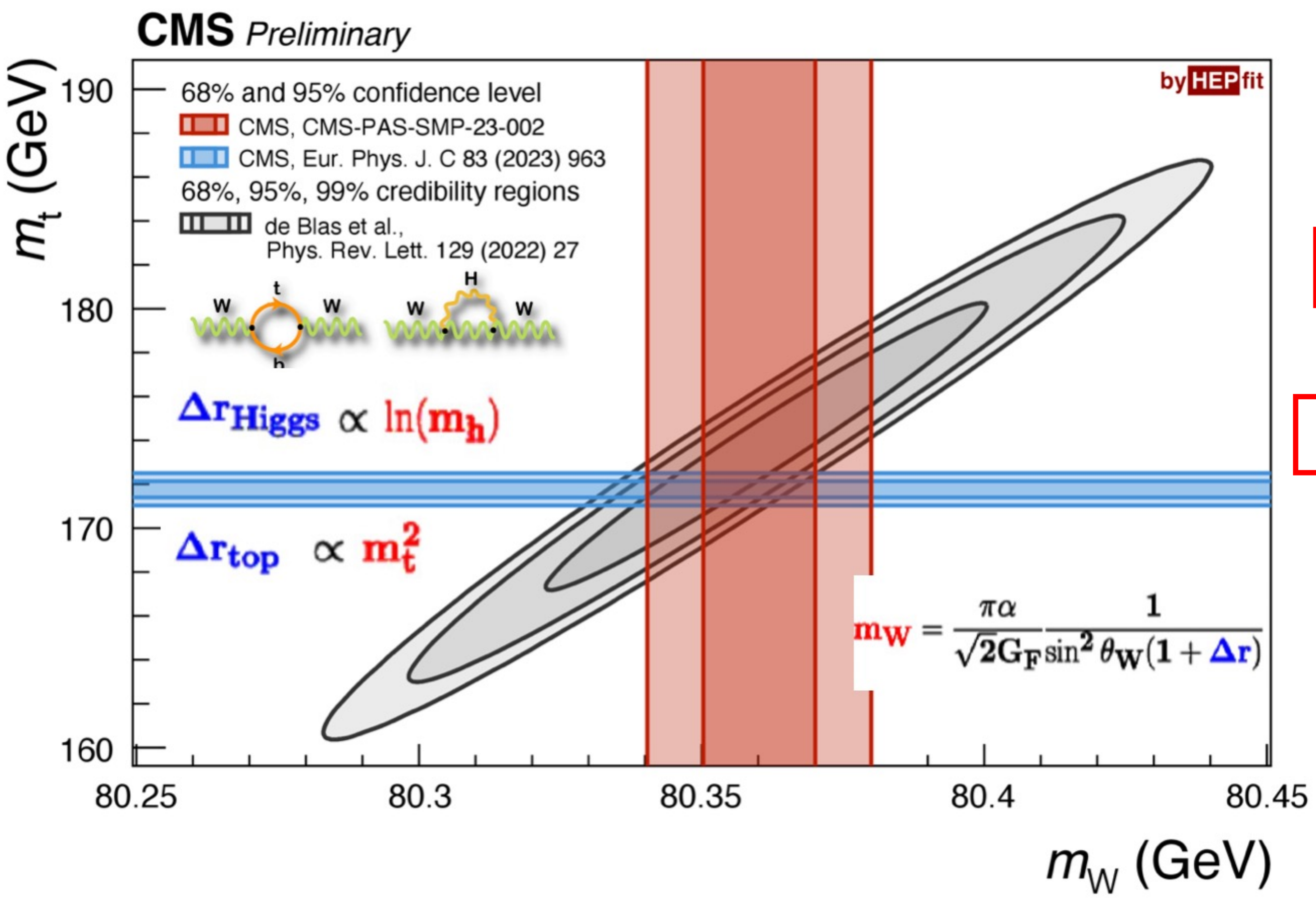




Source of uncertainty	Impact (MeV) Nominal	Impact (MeV) Global
Muon momentum scale	4.8	4.4
Muon reco. efficiency	3.0	2.3
W and Z angular coeffs.	3.3	3.0
Higher-order EW	2.0	1.9
p_T^V modeling	2.0	0.8
PDF	4.4	2.8
Nonprompt background	3.2	1.7
Integrated luminosity	0.1	0.1
MC sample size	1.5	3.8
Data sample size	2.4	6.0
Total uncertainty	9.9	9.9

CMS-PAS-SMP-23-002

W mass measurement (ATLAS and CMS comparison)



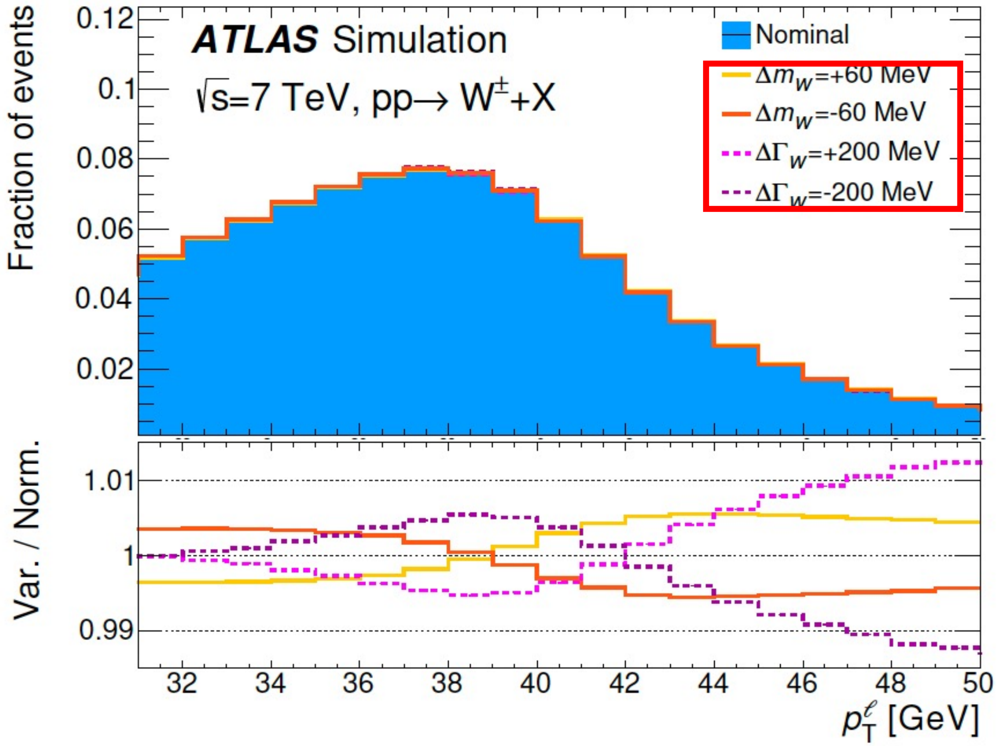
W mass uncertainty (MeV)		
	ATLAS, 7 TeV re-analysis	CMS
Stat	9.8	7.1
PDF	5.7	2.8
Bkg	2.0	1.7
EW	5.4	1.9
e	6.0	-
mu	5.4	5.0
recoil	2.3	-
QCD	4.4	3.1
Total	**16 MeV**	**9.9 MeV**

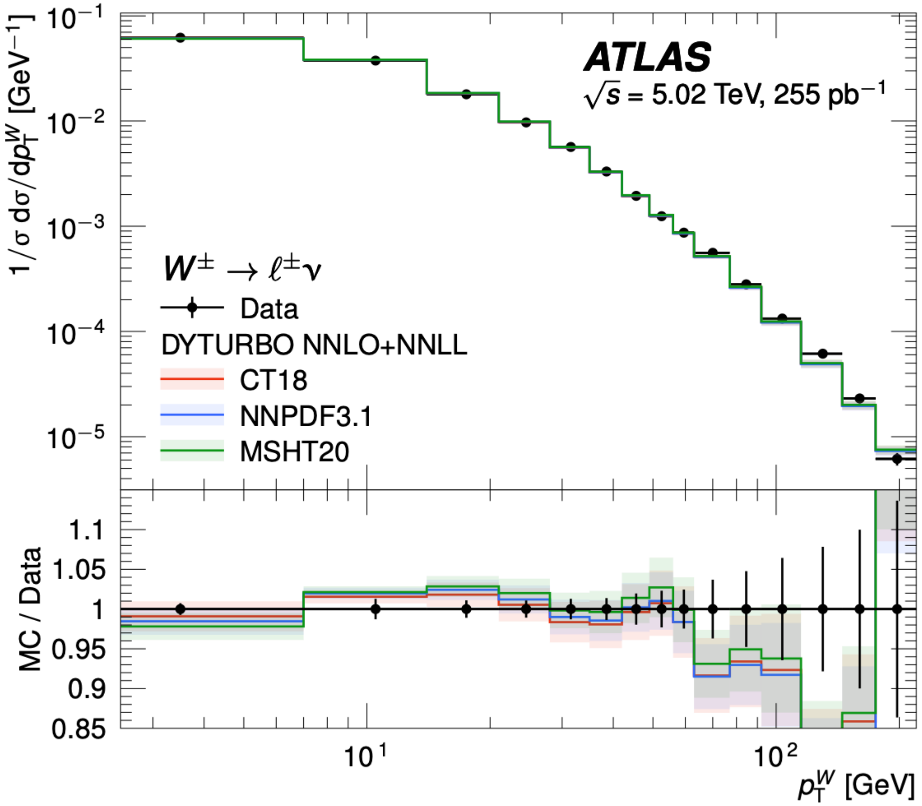
Next step in ATLAS W mass measurement

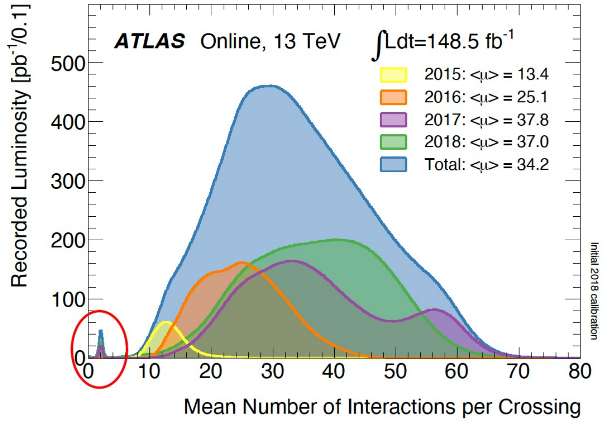
Eur. Phys. J. C 84 (2024) 1126

❖ **ATLAS is exploring low pileup run 2 data (5 TeV 255 pb^{-1}, 13 TeV: 338 pb^{-1})**

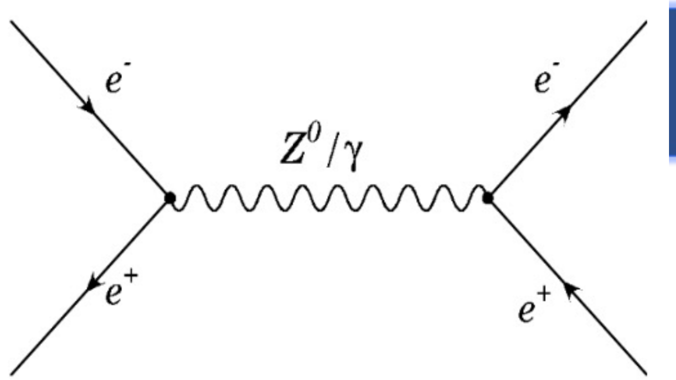
- ▶ First step to measure the W/Z pT (done)
- ▶ Expect to update W mass measurement with higher precision





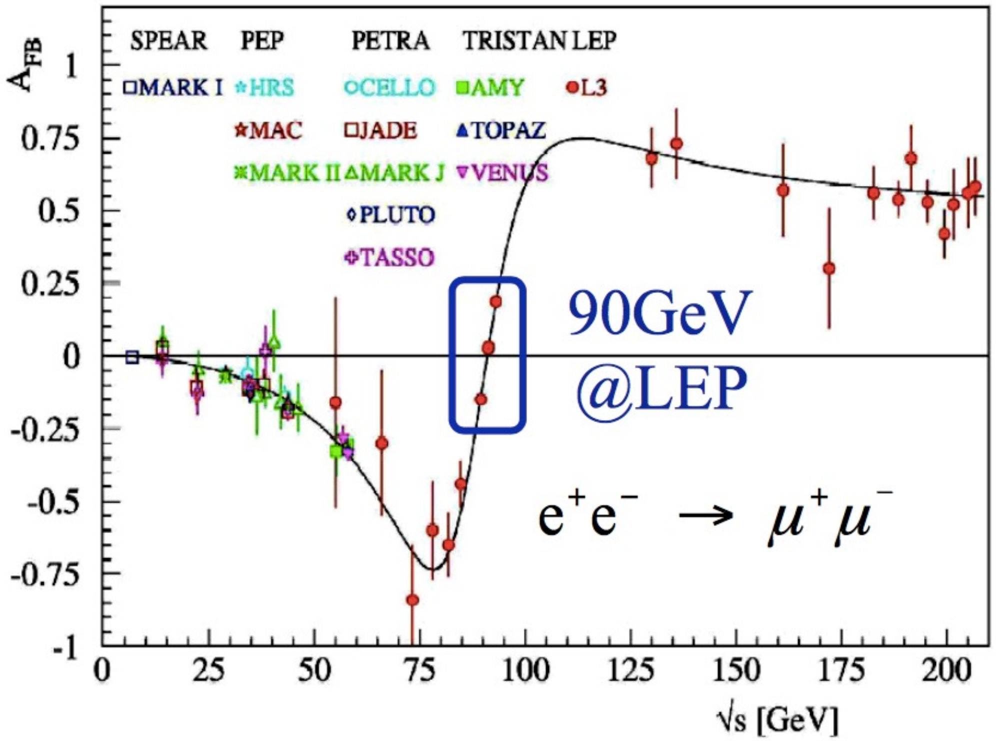


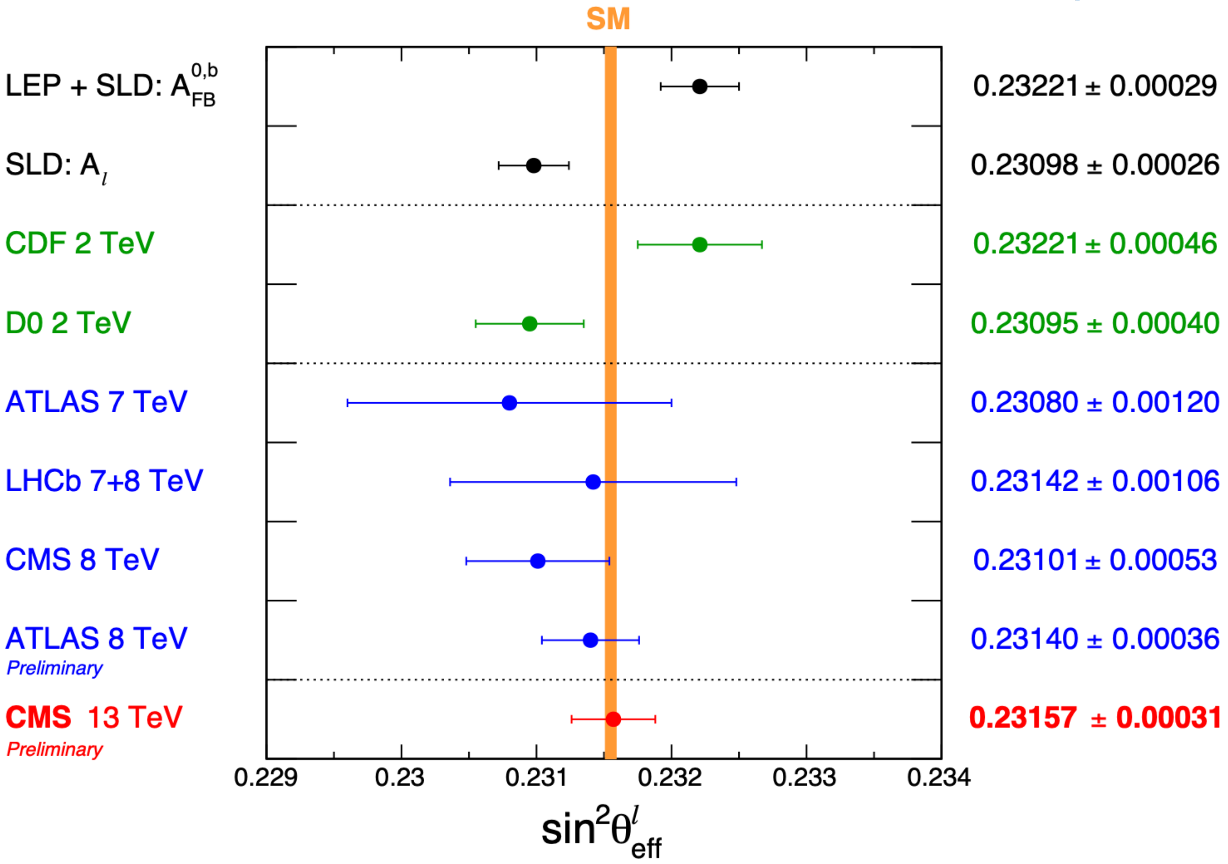
Weak mixing angle measurements ($Sin^2\theta_W$)



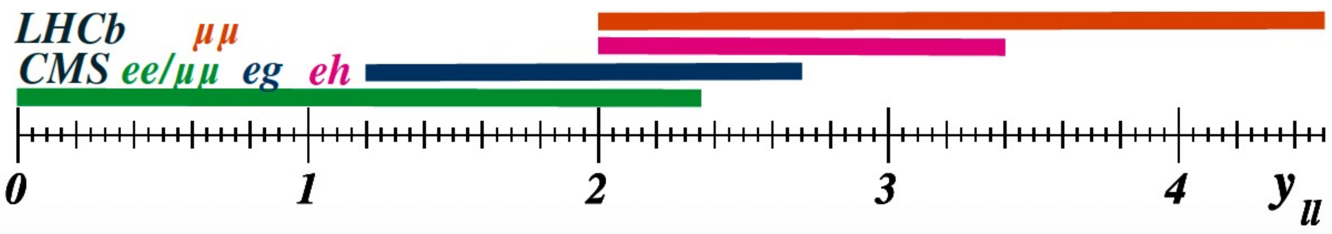
- **Weak mixing angle measurement is well motivated**
  - ▶ ~3σ tension between LEP and SLC measurements
  - ▶ LHC results can reach similar precision level now

CMS 2024 update
CMS PAS SMP-22-010



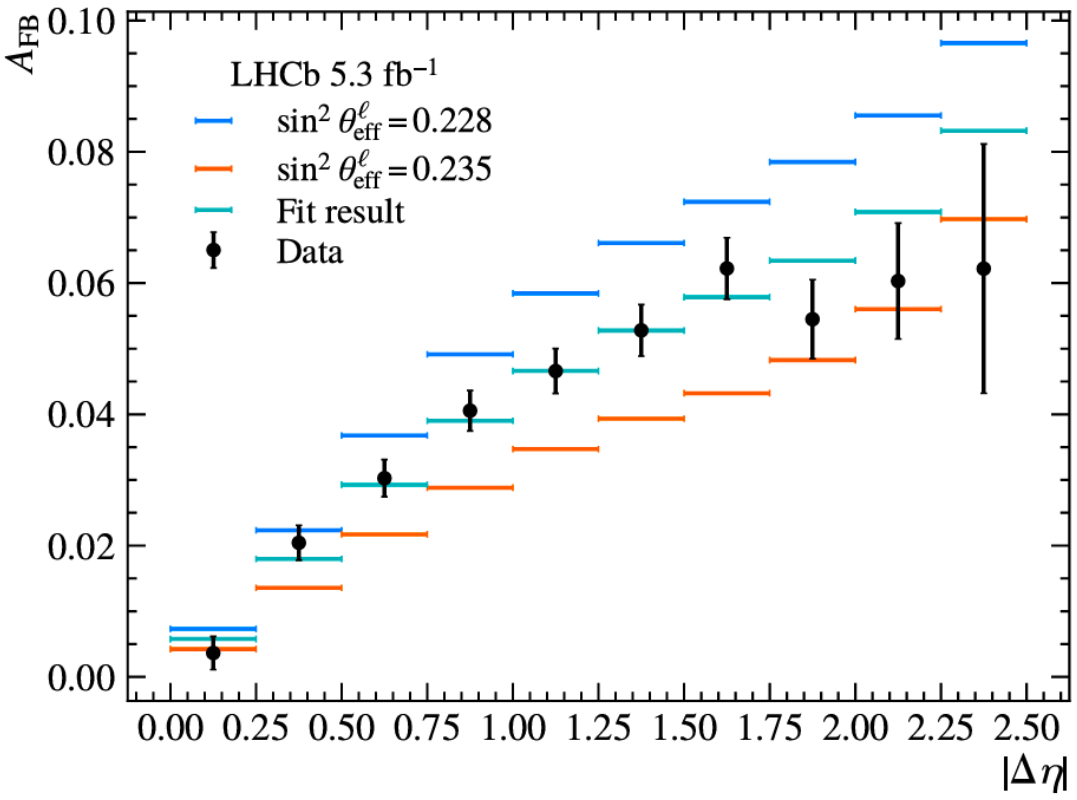


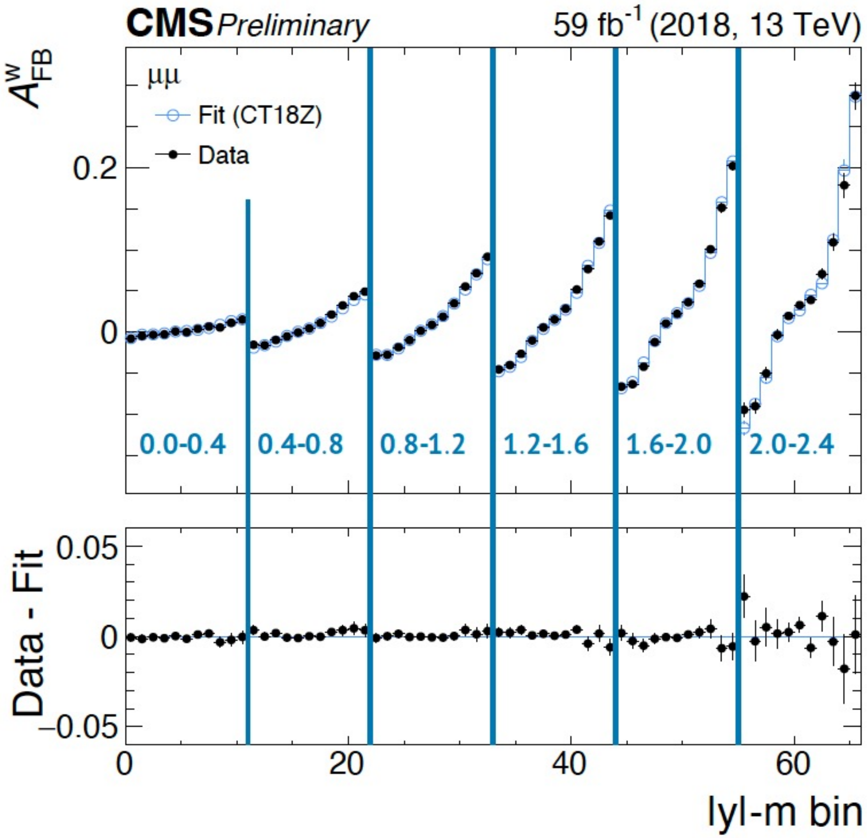
Weak mixing angle

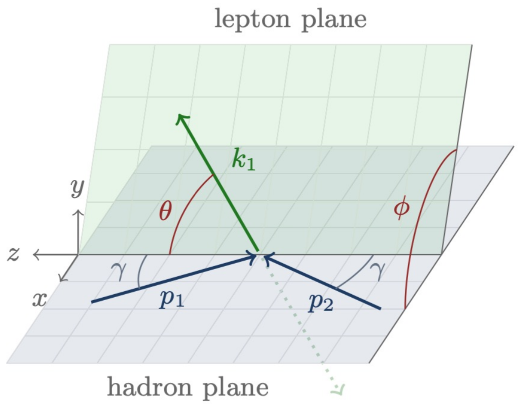


❖**High quality muon reconstruction in LHCb in 2.0 < |η| < 4.5**

❖**Reconstruction of electrons in CMS extended to |η| < 4.36**





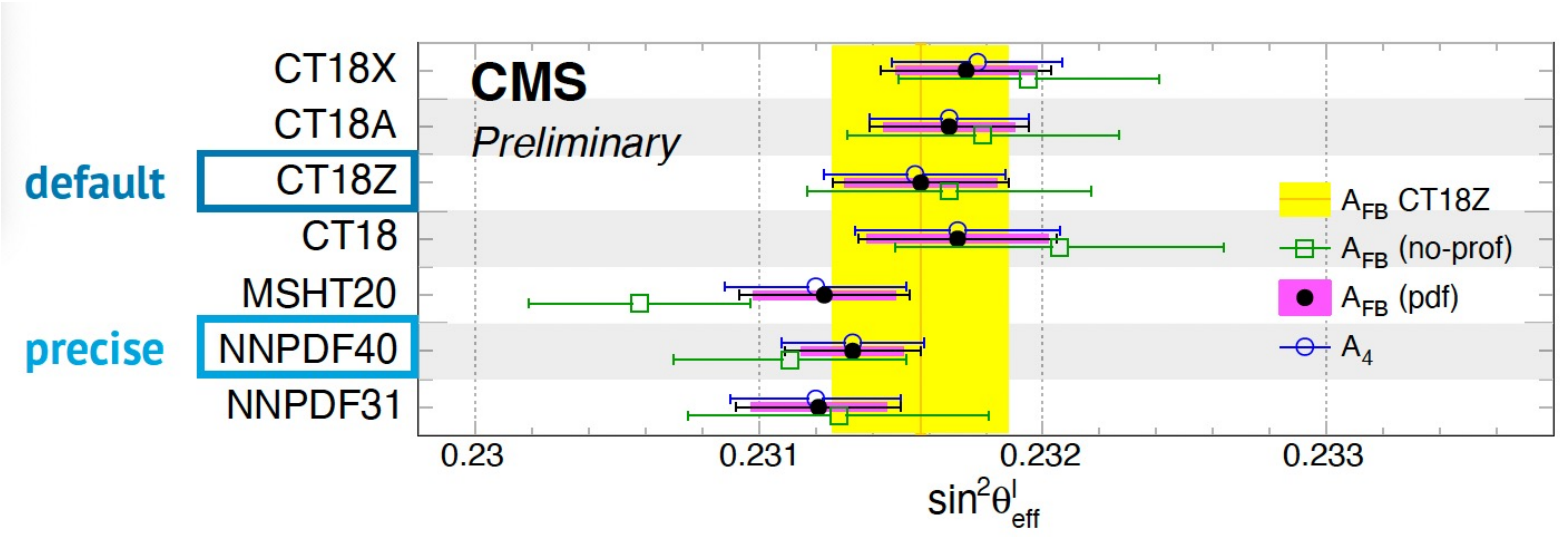


Weak mixing angle @LHC

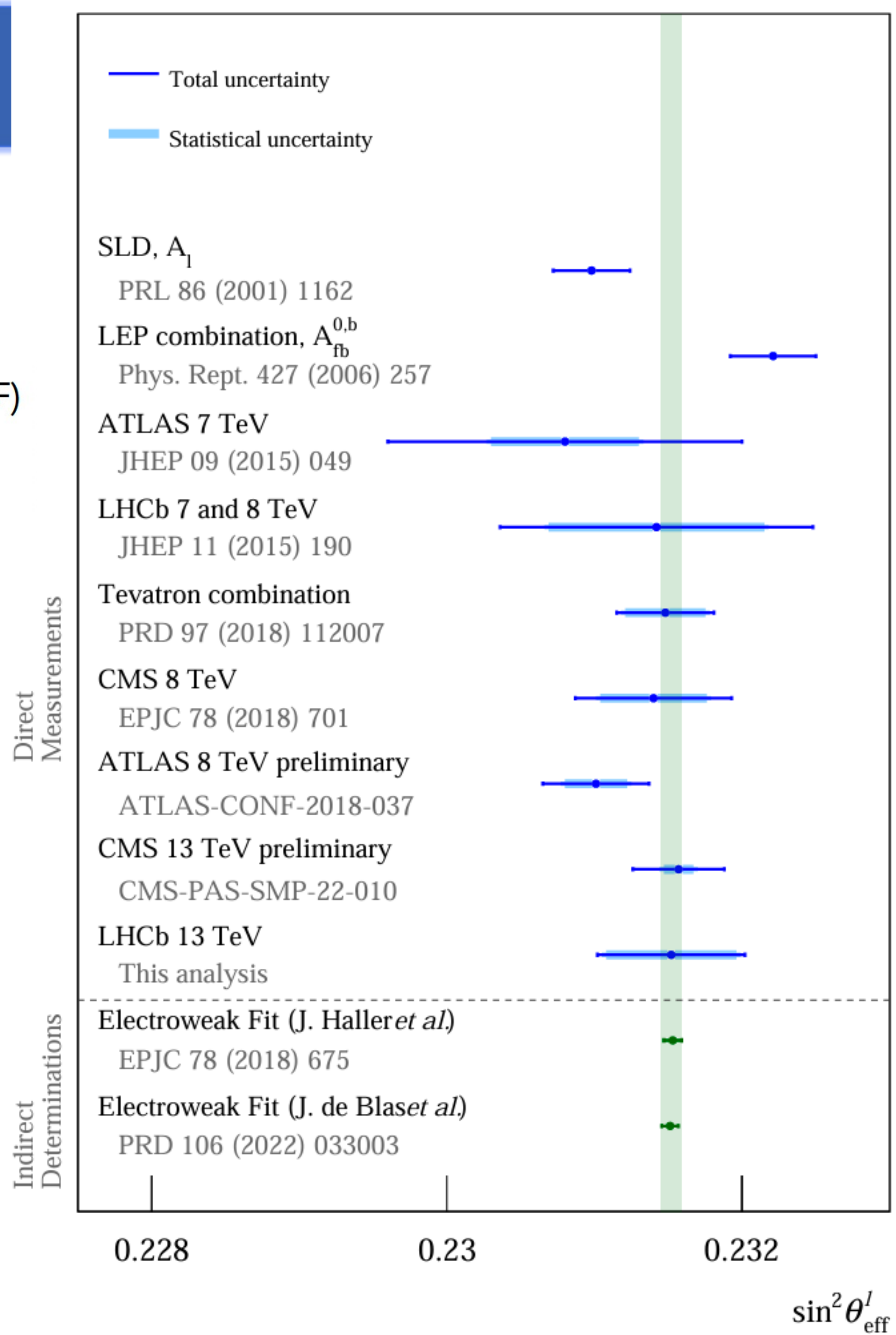
❖**PDF uncertainties is the key**

CMS: $\sin^2\theta^{\ell}_{\text{eff}} = 0.23157 \pm 0.00010\,(\text{stat}) \pm 0.00015\,(\text{syst}) \pm 0.00009\,(\text{theo}) \pm 0.00027(\text{PDF})$

LHCb: $\sin^2\theta^{\ell}_{\text{eff}} = 0.23152 \pm 0.00044\,(\text{stat}) \pm 0.00005\,(\text{syst}) \pm 0.00022\,(\text{theo/PDF})$

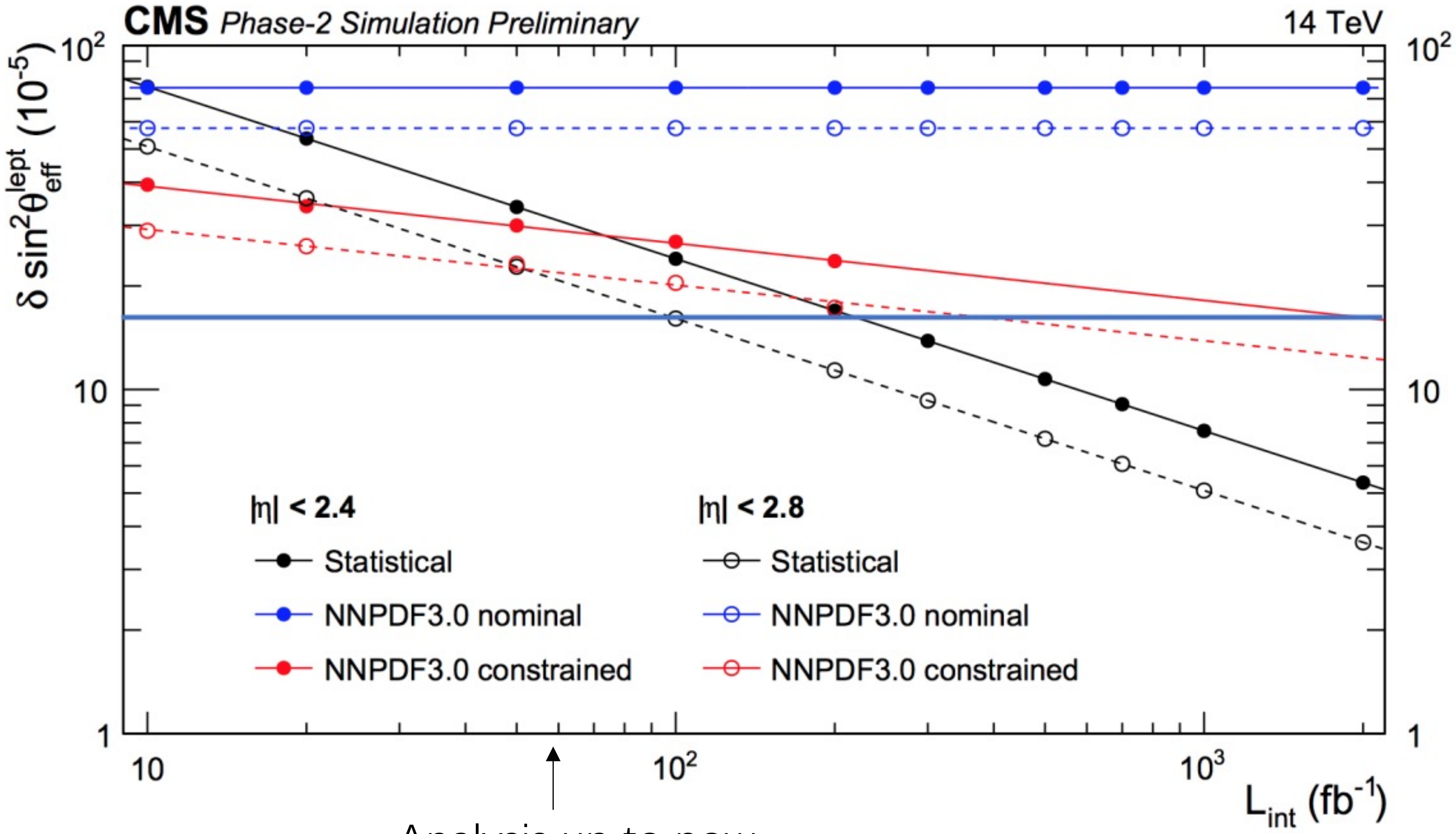


CMS-PAS-SMP-22-010



Weak mixing angle @ HL-LHC

❖**Extension of CMS/ATLAS acceptance forward during HL-LHC era increases the sensitivity to the Weinberg angle**



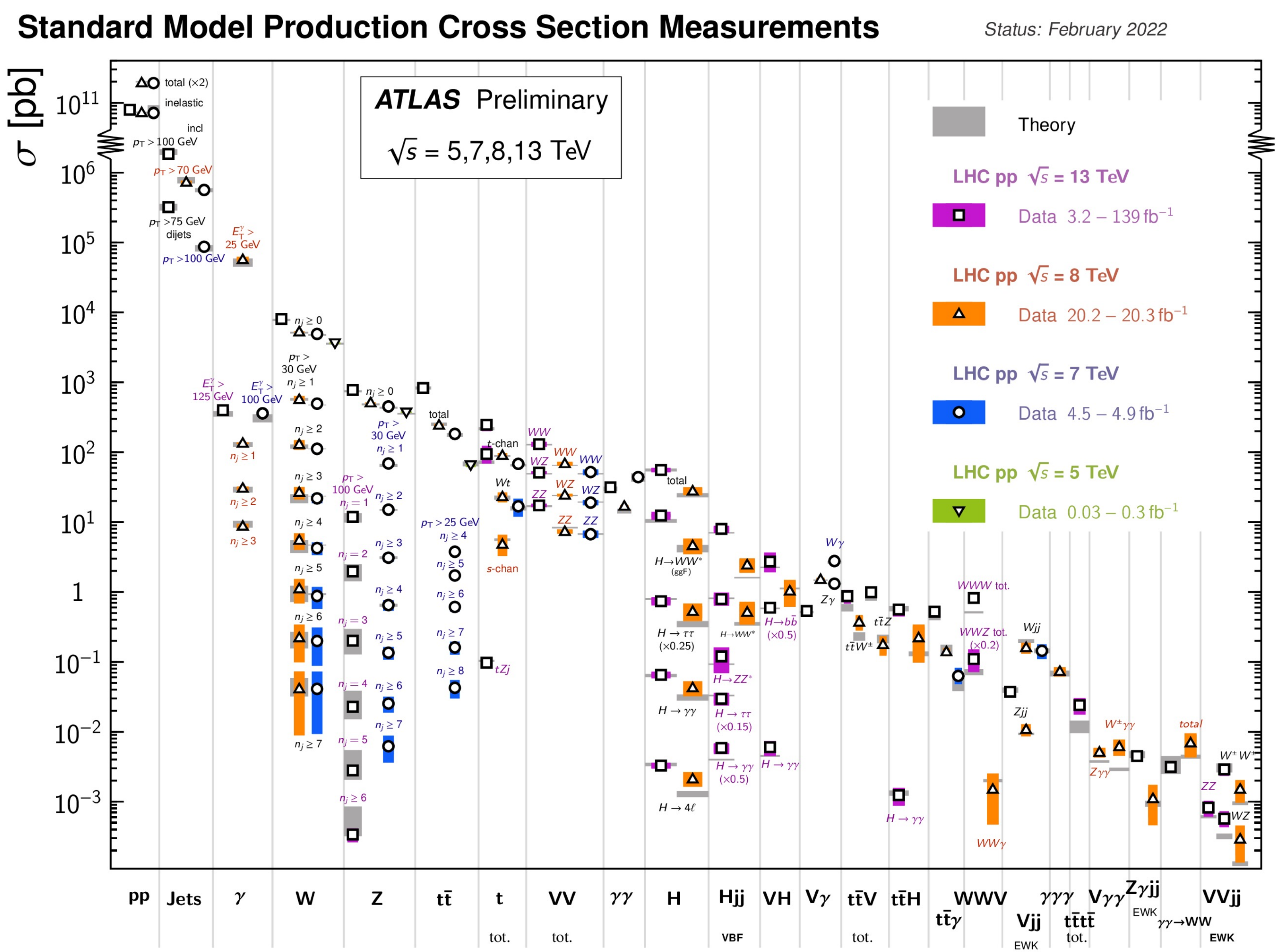
Analysis up to now

Studies here using muon channel.

CMS expect to have PDF uncertainties with precision of LEP+SLD average with L_{int} > O(300 fb^{-1}) using extended acceptance.

Overview of electroweak measurements at LHC

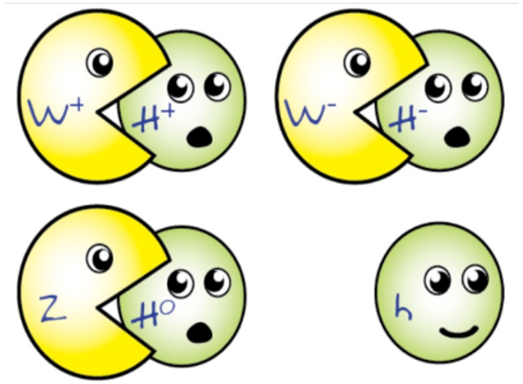
15 order of magnitude

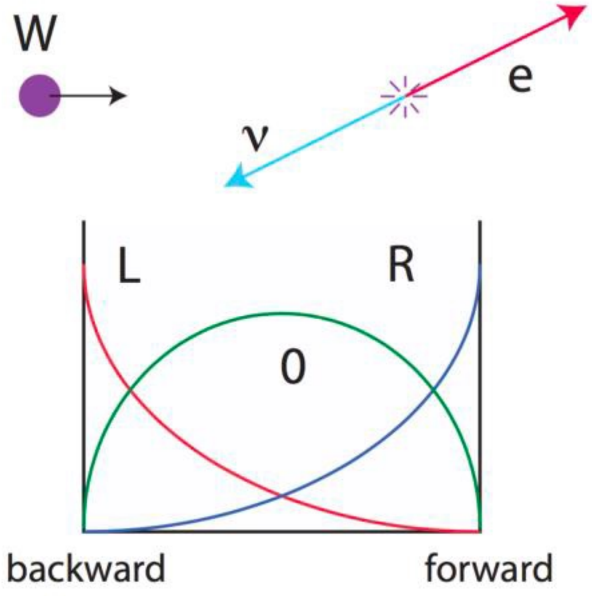


Diboson polarization

❖ **Diboson polarization measurements have gained increasing interest**

- in both the theory and experiment community in recent years
- Important probes of the EWK and Higgs sectors





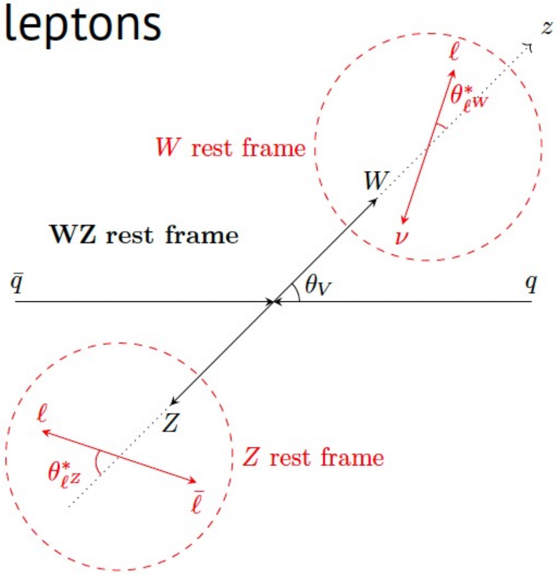
	SM	BSM
$q_{L,R}\bar{q}_{L,R} \to V_L V_L(h)$	~ 1	$\sim E^2/M^2$
$q_{L,R}\bar{q}_{L,R} \to V_\pm V_L(h)$	$\sim m_W/E$	$\sim m_W E/M^2$
$q_{L,R}\bar{q}_{L,R} \to V_\pm V_\pm$	$\sim m_W^2/E^2$	$\sim E^2/M^2$
$q_{L,R}\bar{q}_{L,R} \to V_\pm V_\mp$	~ 1	~ 1

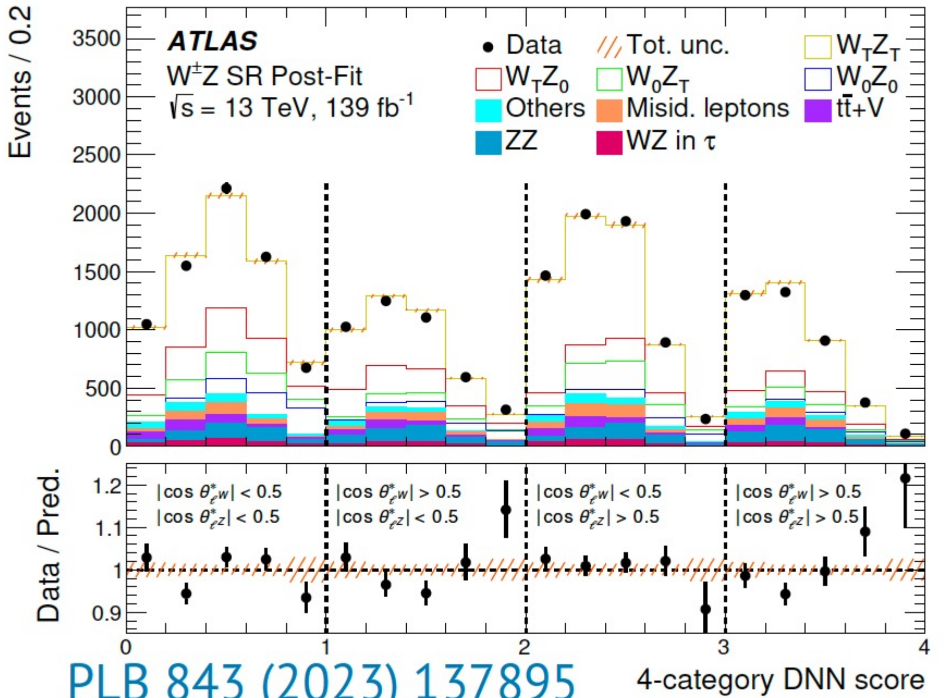
Diboson polarization

- Longitudinal polarisation generated by electroweak symmetry breaking

→ asymptotically behave like Goldstone bosons of electroweak symmetry

- Measured from decay angles of the decay leptons
- Individually in *WZ* events:
  - ATLAS: PLB 843 (2023) 137895
  - CMS: JHEP 07 (2022) 032

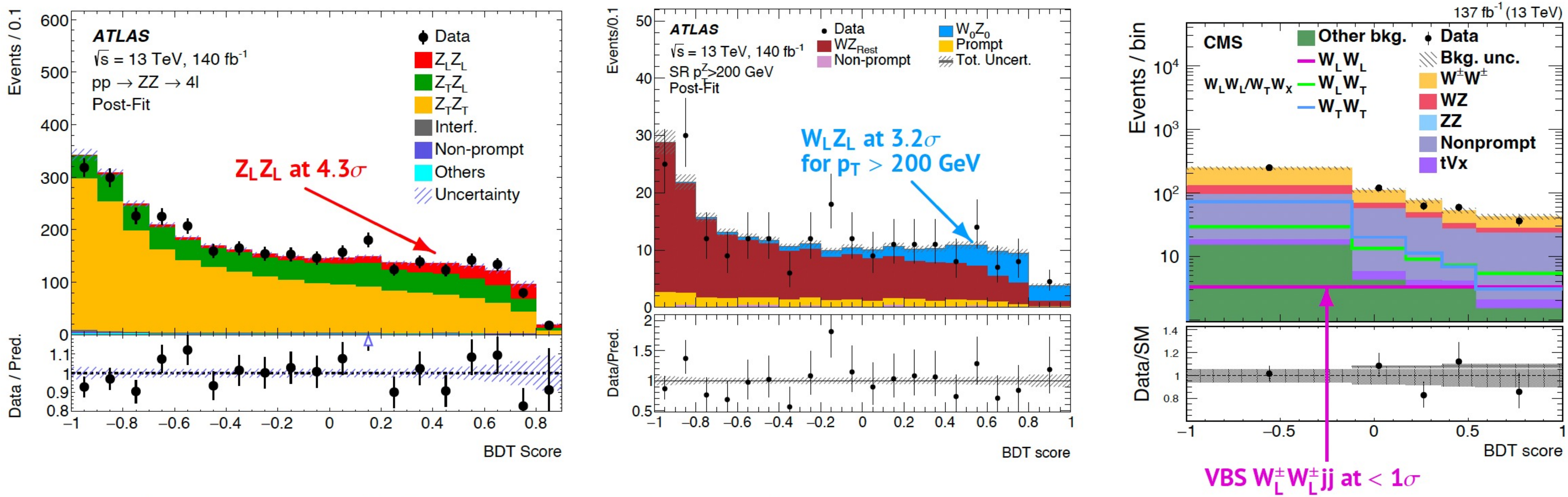




PLB 843 (2023) 137895

- Recent observation of joint polarisation
- Theoretical decomposition in individual components (LL, TL, LT, TT)
- Main challenge: incorporating higher-order corrections

Diboson polarization



- Experiments gain sensitivity to $V_L V_L$ production, starting to study energy dependence of cross section

Evidence for $Z_L Z_L$ production in JHEP 12 (2023) 107

Study of energy dependence of $W_L Z_L$ prod. in arXiv:2402.16365

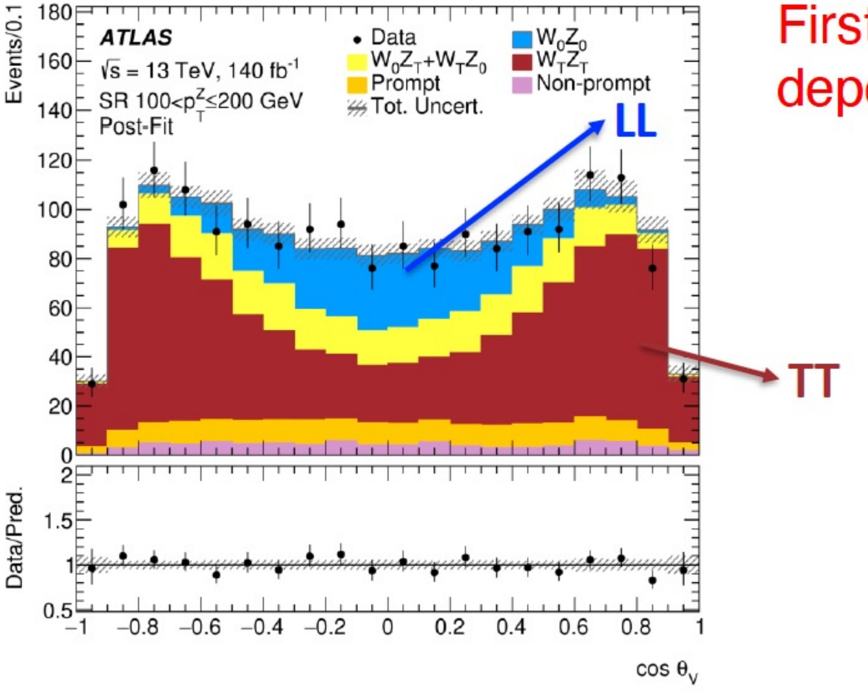
- Ultimate test of electroweak symmetry breaking is the study of $V_L V_L$ scattering at the HL-LHC

Analysis of $W^{\pm}_L W^{\pm}_X jj$ and $W^{\pm}_L W^{\pm}_L jj$ in PLB 812 (2020) 136018

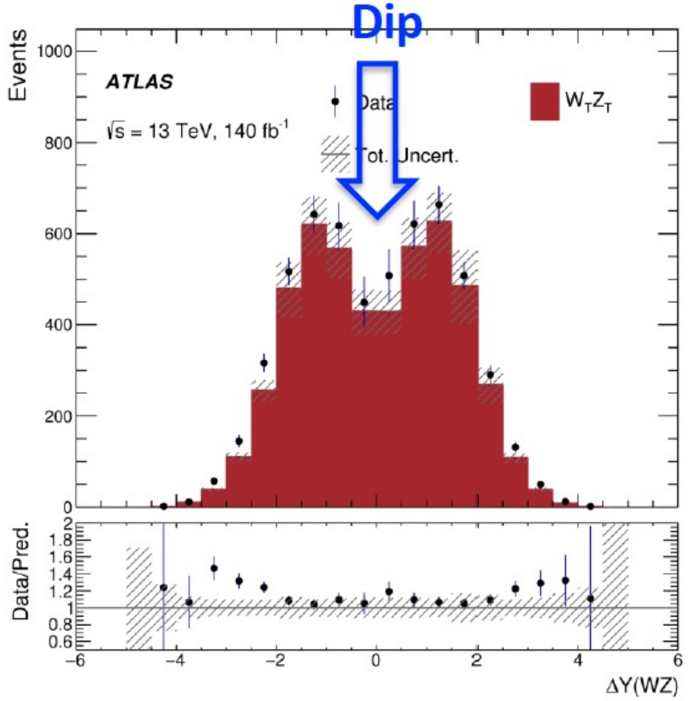
Diboson WZ polarization

ATLAS, PRL133 (2024) 101802

	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



First measurement of energy dependence of diboson polarization



- RAZ effect leads to a dip around 0 in the $\Delta Y(WZ)$ and $\Delta Y(l_W Z)$ distributions
- Significant dips are observed
- Unfolded distributions also measured

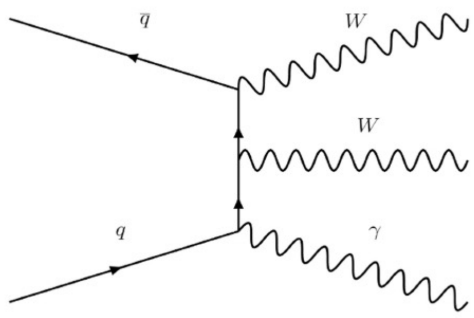
Triboson WWγ production

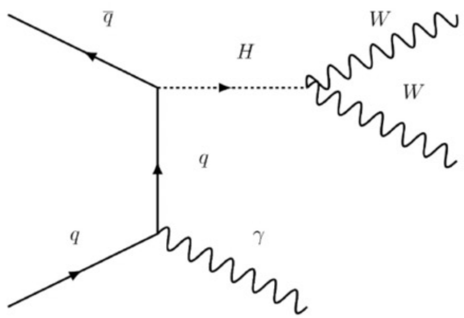
Phys. Rev. Lett. 132 (2024) 121901
编辑推荐

北大

❖CMS 发现新的三玻色子物理过程

- 并对希格斯与轻夸克耦合给出世界最灵敏探测





Process	σ_{up} pb exp.(obs.)	Yukawa couplings lim
$u\bar{u} \to H + \gamma \to e\mu\gamma$	0.067 (0.085)	$\lvert\kappa_u\rvert \leq 13000$ (16000)
$d\bar{d} \to H + \gamma \to e\mu\gamma$	0.058 (0.072)	$\lvert\kappa_d\rvert \leq 14000$ (17000)
$s\bar{s} \to H + \gamma \to e\mu\gamma$	0.049 (0.068)	$\lvert\kappa_s\rvert \leq 1300$ (1700)
$c\bar{c} \to H + \gamma \to e\mu\gamma$	0.067 (0.087)	$\lvert\kappa_c\rvert \leq 110(200)$

https://www.nature.com/articles/d41586-024-00764-8

nature > research highlights > article

RESEARCH HIGHLIGHT | 21 March 2024

A supercollider glimpses a gathering of three particles never seen together before

Data from billions of proton collisions reveal that subatomic particles called W^+ and W^- bosons keep company with a photon.

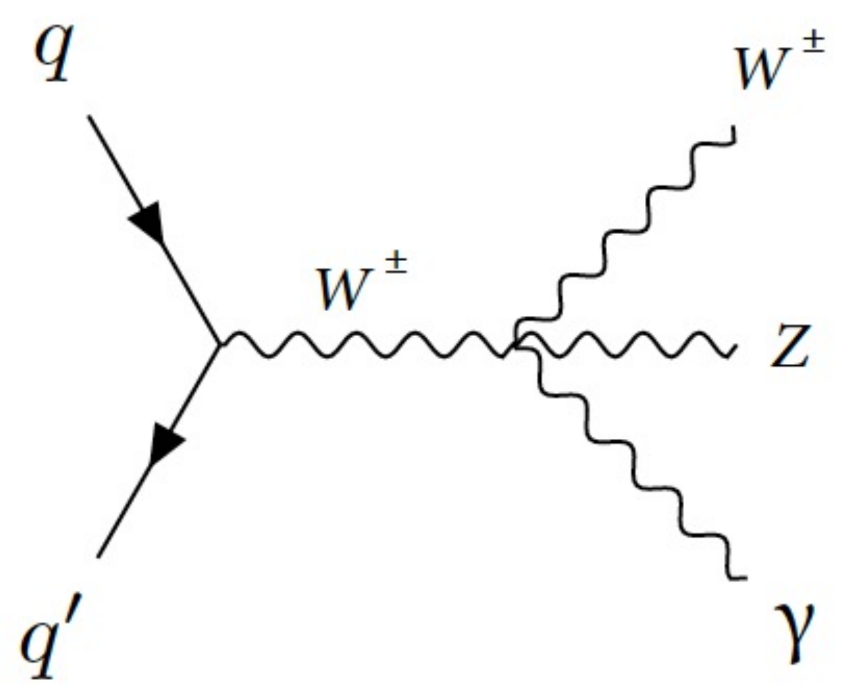
Triboson WZγ observation

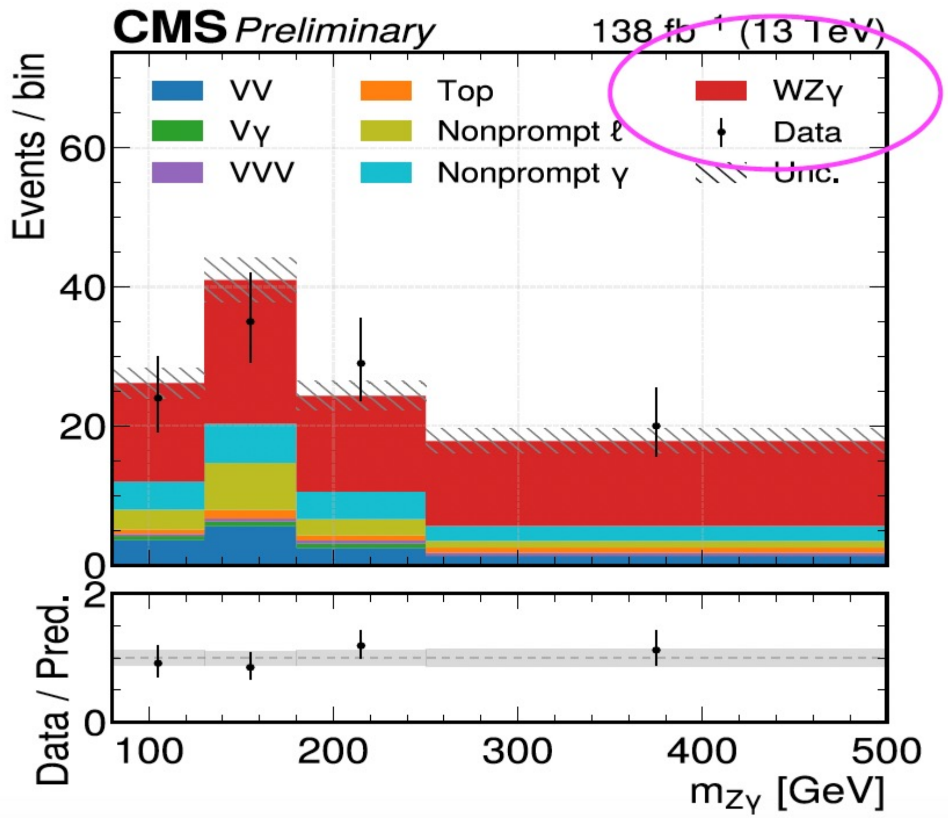
CMS-PAS-SMP-22-018

北大、中山

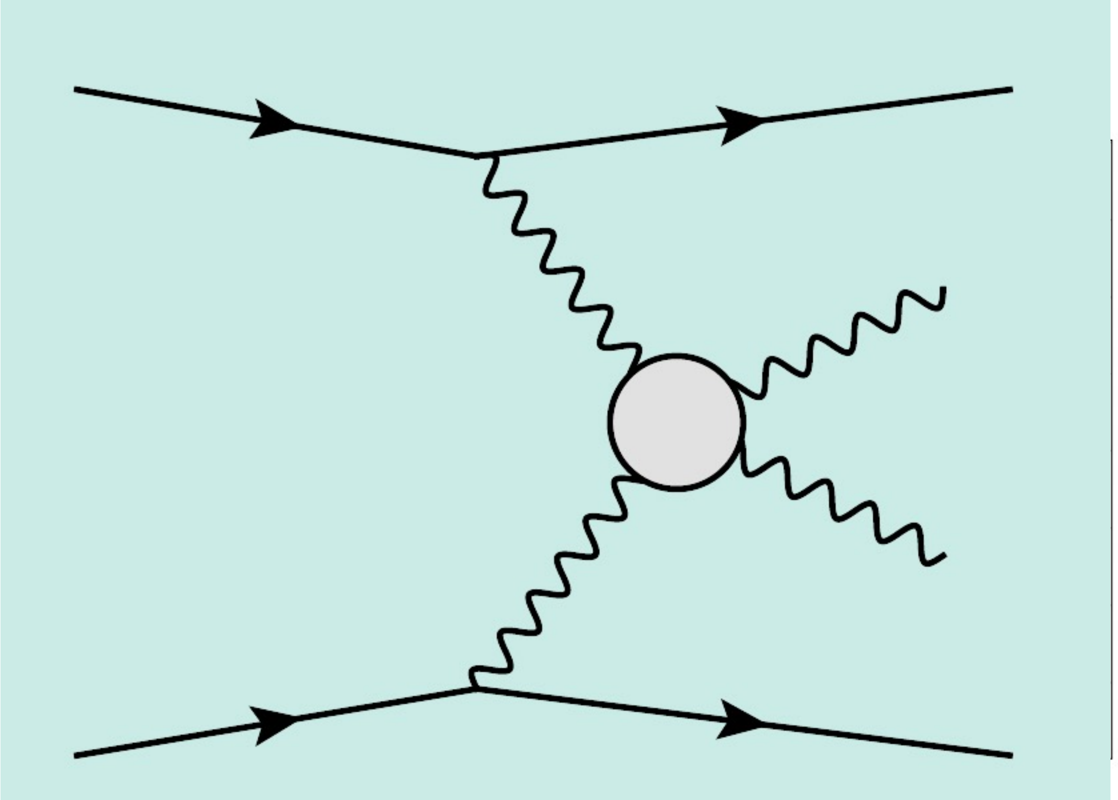
❖WZγ过程的观测显著度超过5s

▶ 对四规范玻色子耦合WWZγ灵敏





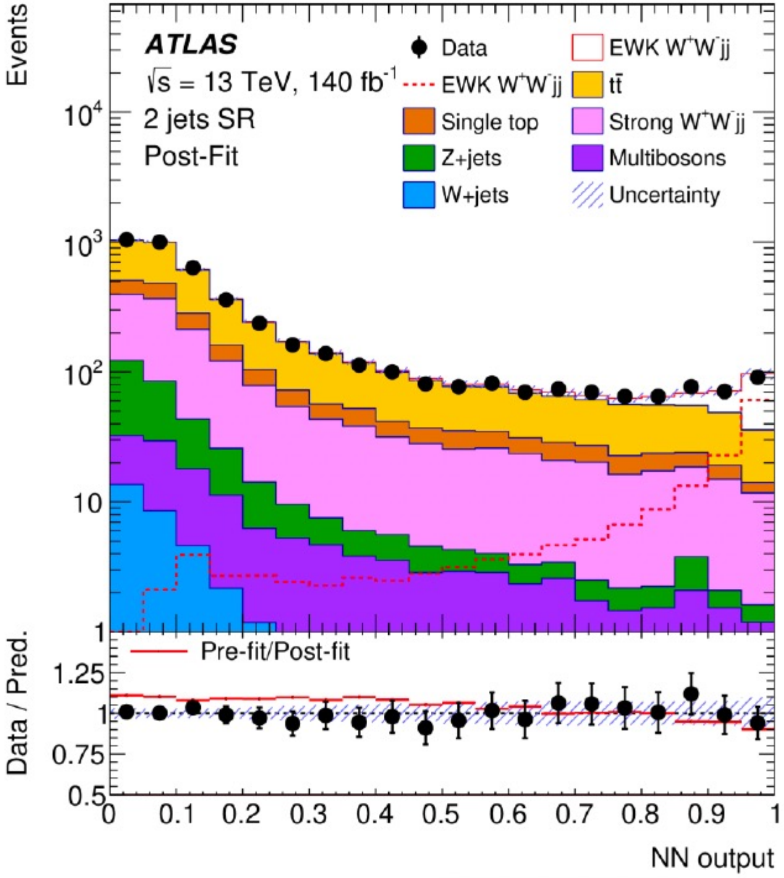
LHC as a Vector Boson Collider

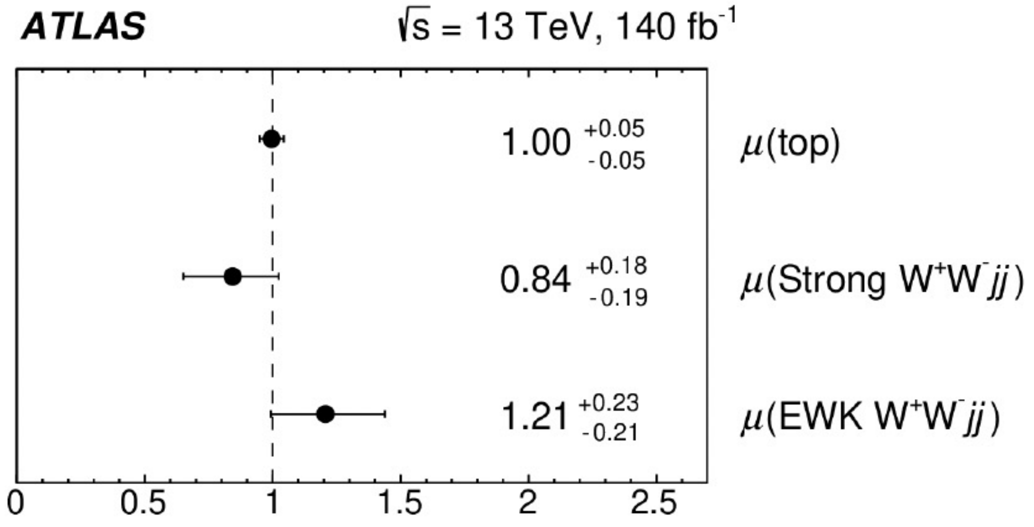


VBS observations	
$W^{\pm}W^{\pm}jj$ (same-sign)	CMS: PRL 120 (2018) 081801 ATLAS: PRL 123 (2019) 161801
$W^{\pm}W^{\mp}jj$ (opposite-sign)	CMS, PLB 841 (2023) 137495 ATLAS, JHEP 07 (2024) 254
$W^{\pm}Zjj$	ATLAS, PLB 793 (2019) 469 CMS, PLB 809 (2020) 135710
$W\gamma jj$	CMS, PLB 811 (2020) 135988 ATLAS, EPJC 84 (2024) 1064
$Z\gamma jj$	CMS, *PRD 104 (2021) 072001* ATLAS, PLB 846 (2023) 138222
$ZZjj$	ATLAS, Nature Phys. 19 (2023) 237

ATLAS $WWjj$ observation

- Observed by CMS(2023)
- Very challenging due to high background → a DNN discriminant used

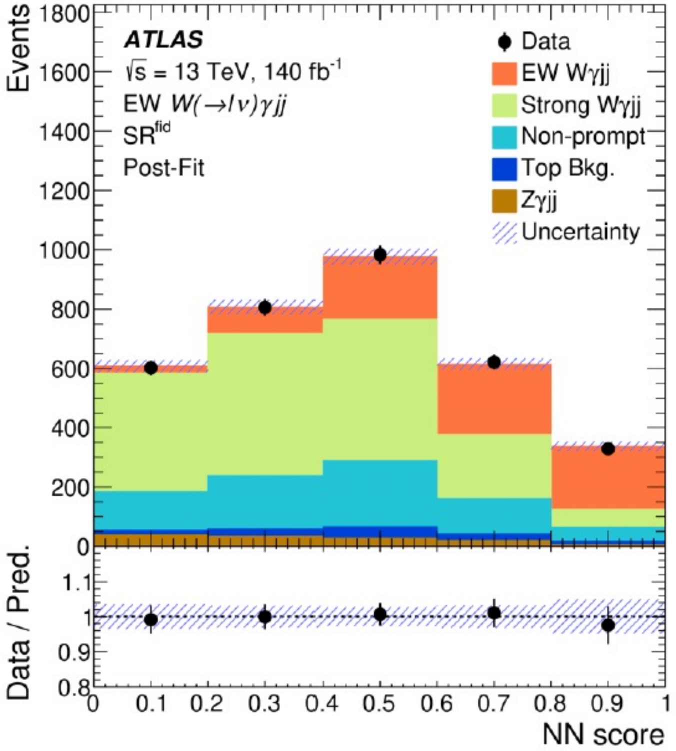




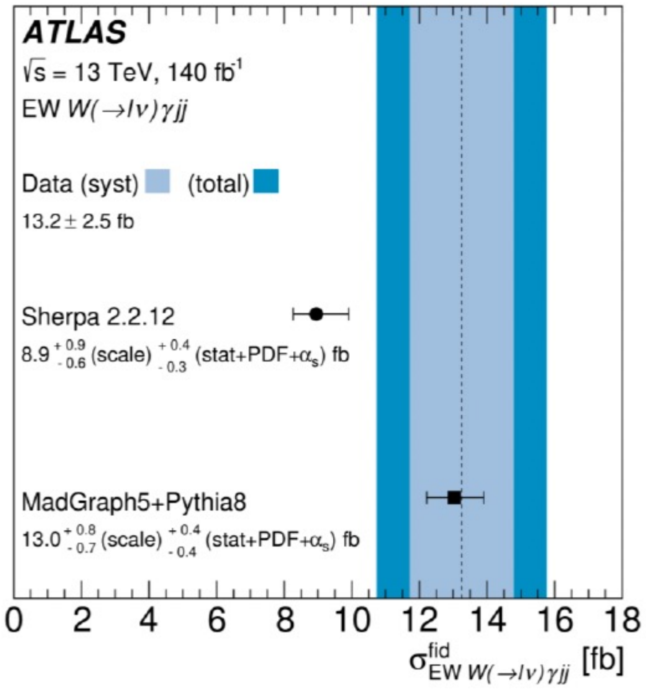
Observed (expected) significance: 7.1(6.2)σ

ATLAS $W\gamma jj$ observation

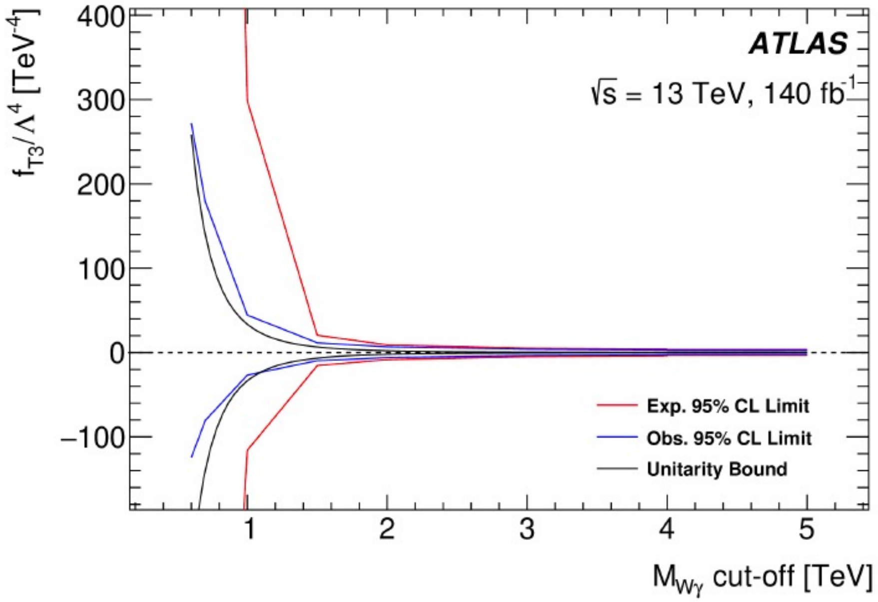
- Observed by CMS(2020)
- Very challenging due to high background → a DNN discriminant used



Observed significance well above 6σ (expected 6.3σ)



Fiducial and differential cross-sections measured



First LHC constraints on T_3, T_4 aQGC operators

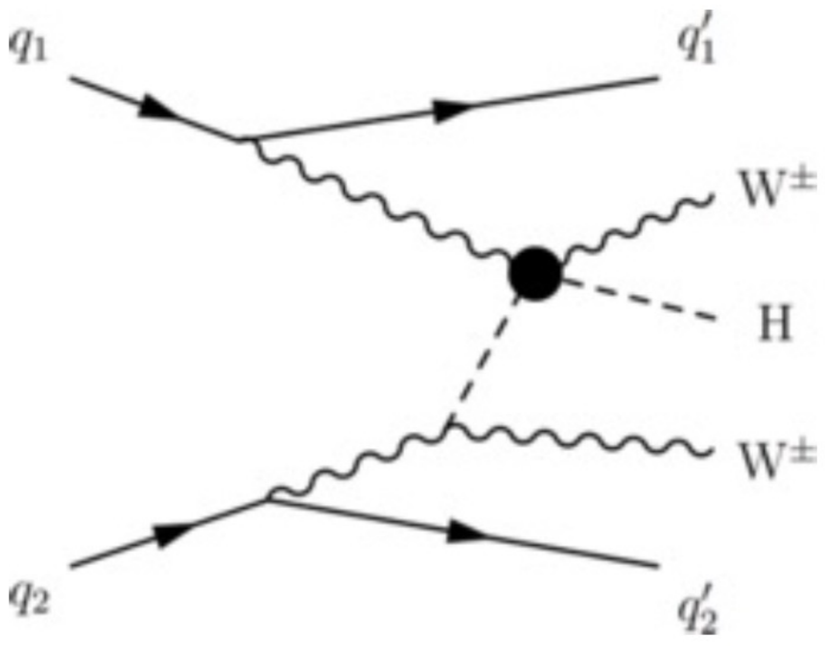
First search for VBS WWH

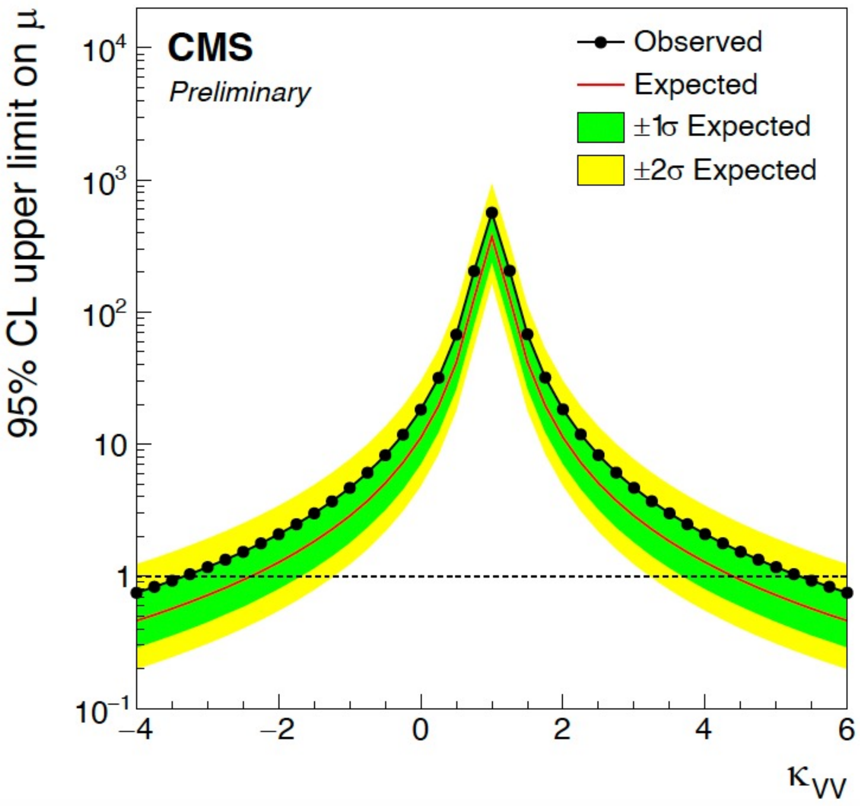
CMS-PAS-SMP-24-001

北大

❖2→3 玻色子散射过程的探测为多玻色子物理研究开辟新的疆域

▶ WWHH耦合强度被限制在[-3.33, 5.33]的范围中。



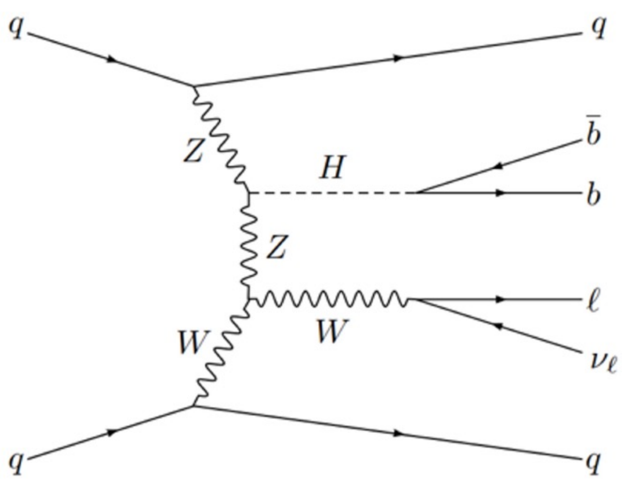


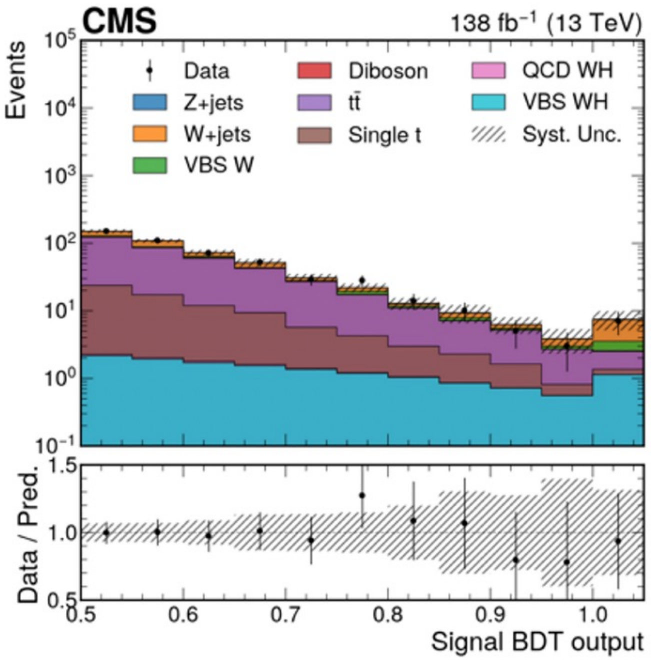
WH Vector boson scattering

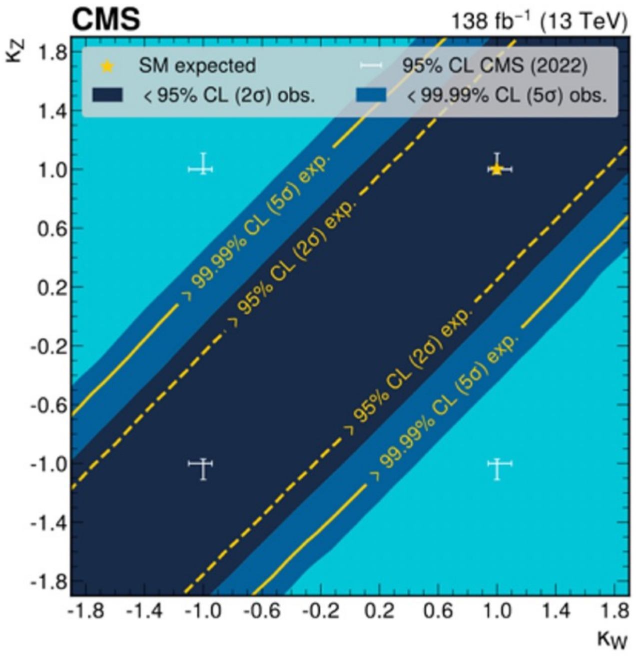
arXiv:2405.16566
投稿至 PLB

北大

- ❖新型VBS过程的首次探测，超过5s显著度
- ❖排除了HWW 和HZZ 耦合具有相反符号的新物理场景







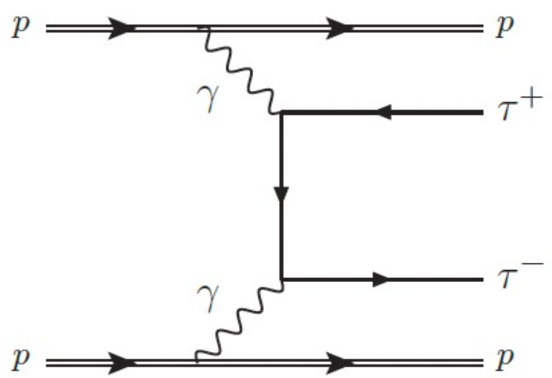
Production of τ-Leptons from Photons

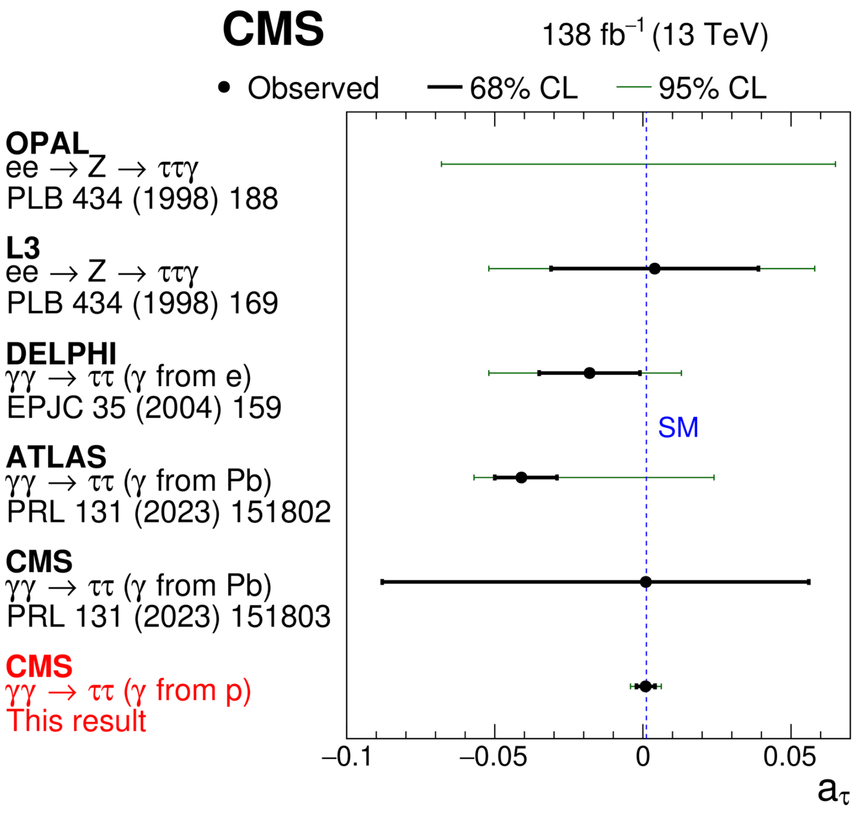
Rep. Prog. Phys. 87 (2024) 107801

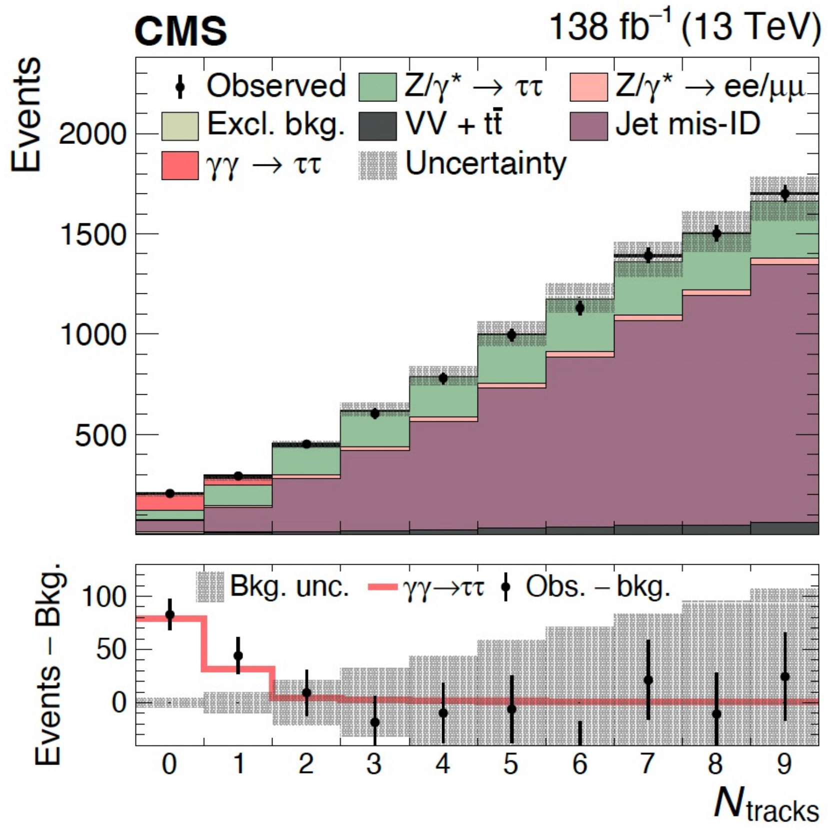
北大

❖首次观测pp对撞光生过程，对Tau轻子磁矩最佳测量，误差减小5倍

▶ $g\tau = 2.0018 \; {+0.0064} \; {-0.0062}$ (0.3%)



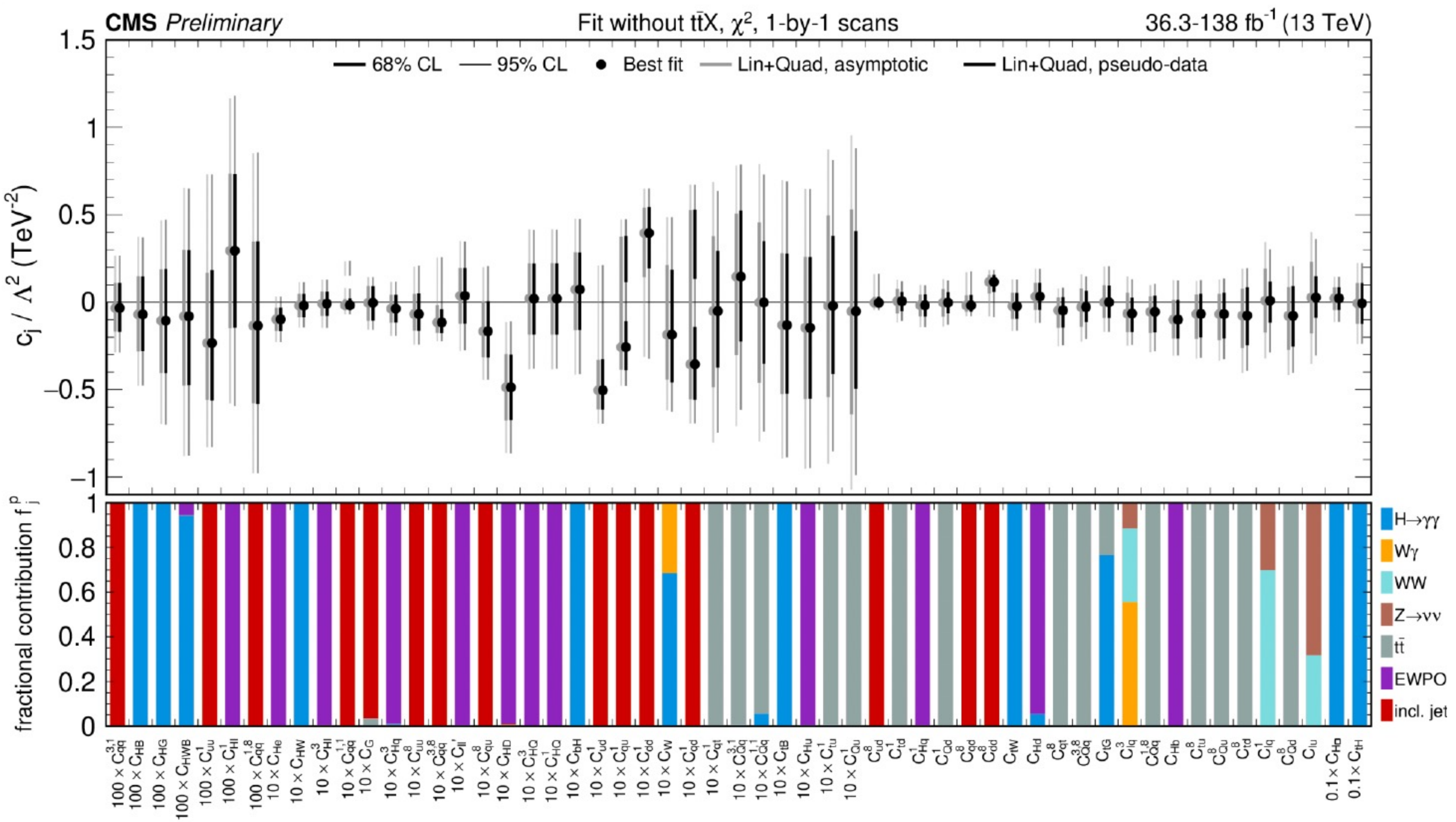




CMS EFT global fit

CMS-PAS-SMP-24-003

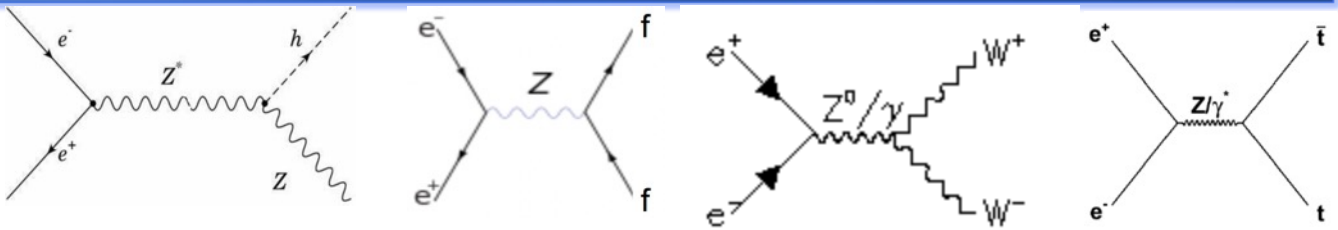
- SMEFT Warsaw basis
- Constraints on Wilson Coefficients
- Constraints also set on linear combinations of WCs (eigen-vectors from the Principal Component Analysis)



Future Electroweak measurement: CEPC physics program

An extremely versatile machine with a broad spectrum of physics opportunities

→ Far beyond a Higgs factory



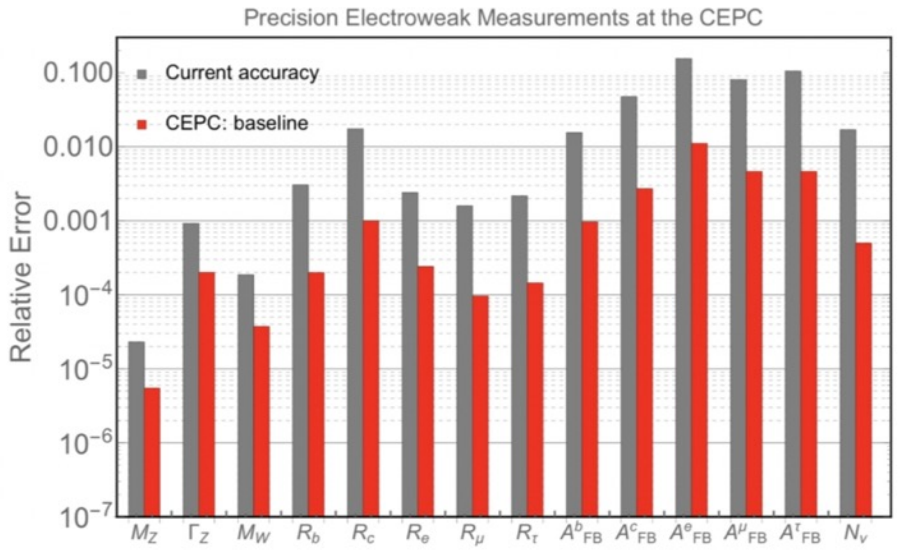
Operation mode			ZH	Z	W⁺W⁻	$t\bar{t}$
$\sqrt{s}$ [GeV]			~240	~91.2	~160	~360
Run time [years]			10	2	1	5
CDR (30 MW)		L / IP [$\times10^{34}$ cm^{-2}s^{-1}]	**3**	**32**	**10**	-
		$\int L\,dt$ [ab^{-1}, 2 IPs]	5.6	16	2.6	-
		Event yields [2 IPs]	1×10^{6}	7×10^{11}	2×10^{7}	-
Run Time [years]			10	2	1	~5
Latest	30 MW	L / IP [$\times10^{34}$ cm^{-2}s^{-1}]	**5.0**	**115**	**16**	**0.5**
	50 MW	L / IP [$\times10^{34}$ cm^{-2}s^{-1}]	**8.3**	**191.7**	**26.6**	**0.8**
		$\int L\,dt$ [ab^{-1}, 2 IPs]	20	96	7	1
		Event yields [2 IPs]	4×10^{6}	4×10^{12}	5×10^{7}	5×10^{5}

- ❖ **First 10 year operation**
  - ▶ **Higgs factory**
  - ▶ **low-lumi Z (20% of high-lumi Z)**
    - **Detector calibration and alignment**
    - **Physics with Giga-Z**
- ❖ **2 year of high-lumi Z factory operation**
- ❖ **1 year of WW threshold scan**
- ❖ **5 year of ttbar runs**

Both 50 MW and $t\bar{t}$ modes are currently considered as CEPC upgrades.

Future Electroweak measurement: CEPC physics program

Observable	current precision	CEPC precision (Stat. Unc.)	CEPC runs	main systematic
Δm_Z	2.1 MeV [37–41]	0.1 MeV (0.005 MeV)	Z threshold	E_{beam}
$\Delta\Gamma_Z$	2.3 MeV [37–41]	0.025 MeV (0.005 MeV)	Z threshold	E_{beam}
Δm_W	9 MeV [42–46]	0.5 MeV (0.35 MeV)	WW threshold	E_{beam}
$\Delta\Gamma_W$	49 MeV [46–49]	2.0 MeV (1.8 MeV)	WW threshold	E_{beam}
Δm_t	0.76 GeV [50]	$\mathcal{O}(10)$ MeV[a]	$t\bar{t}$ threshold	
ΔA_e	4.9×10^{-3} [37, 51–55]	1.5×10^{-5} (1.5×10^{-5})	Z pole ($Z \to \tau\tau$)	Stat. Unc.
ΔA_μ	0.015 [37, 53]	3.5×10^{-5} (3.0×10^{-5})	Z pole ($Z \to \mu\mu$)	point-to-point Unc.
ΔA_τ	4.3×10^{-3} [37, 51–55]	7.0×10^{-5} (1.2×10^{-5})	Z pole ($Z \to \tau\tau$)	tau decay model
ΔA_b	0.02 [37, 56]	20×10^{-5} (3×10^{-5})	Z pole	QCD effects
ΔA_c	0.027 [37, 56]	30×10^{-5} (6×10^{-5})	Z pole	QCD effects
$\Delta\sigma_{had}$	37 pb [37–41]	2 pb (0.05 pb)	Z pole	lumiosity
δR_b^0	0.003 [37, 57–61]	0.0002 (5×10^{-6})	Z pole	gluon splitting
δR_c^0	0.017 [37, 57, 62–65]	0.001 (2×10^{-5})	Z pole	gluon splitting
δR_e^0	0.0012 [37–41]	2×10^{-4} (3×10^{-6})	Z pole	E_{beam} and t channel
δR_μ^0	0.002 [37–41]	1×10^{-4} (3×10^{-6})	Z pole	E_{beam}
δR_τ^0	0.017 [37–41]	1×10^{-4} (3×10^{-6})	Z pole	E_{beam}
δN_ν	0.0025 [37, 66]	2×10^{-4} (3×10^{-5})	ZH run ($\nu\nu\gamma$)	Calo energy scale



CEPC is expected to improve the current precision by 1-2 orders of magnitude, offering a great opportunity to test the consistency of the SM.

CEPC snowmass input: https://arxiv.org/abs/2205.08553

Summary

❖ **Numerous results of precision electroweak physics released**

- *Active field on both theoretical and experimental side*

❖ **What may come next ?**

- Update of W mass and weak mixing angle measurements with better precision
- Diboson polarizations in high energy region
- More rare processes in triboson and Vector boson scattering
- ….