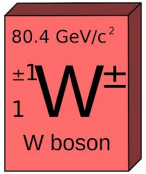
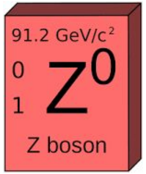
SM Physics "Electroweak Physics, W,Z,VBS.."

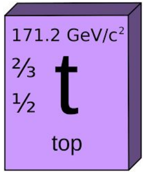
Qiang Li (Peking University)

2024/7

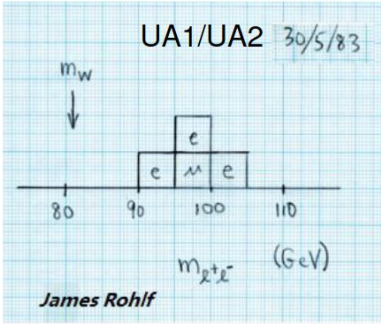
Electroweak milestones: From infancy to adolescence

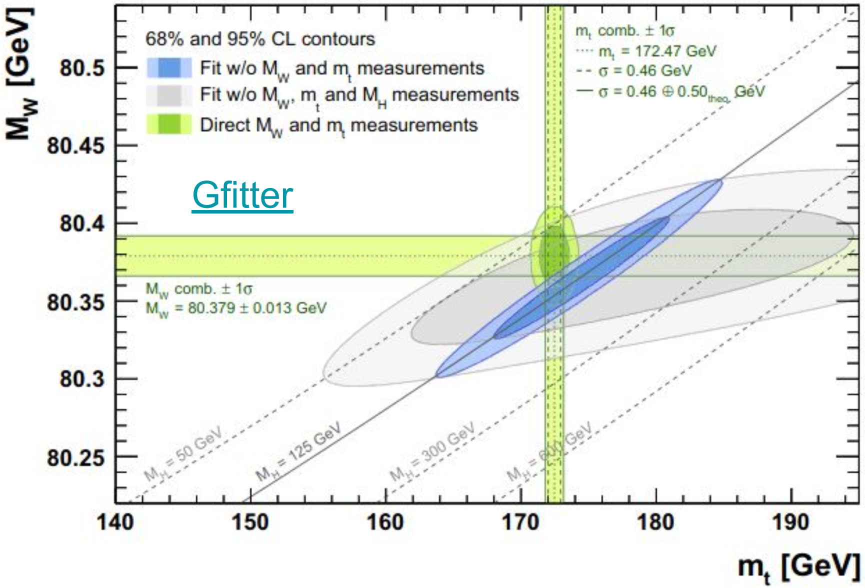




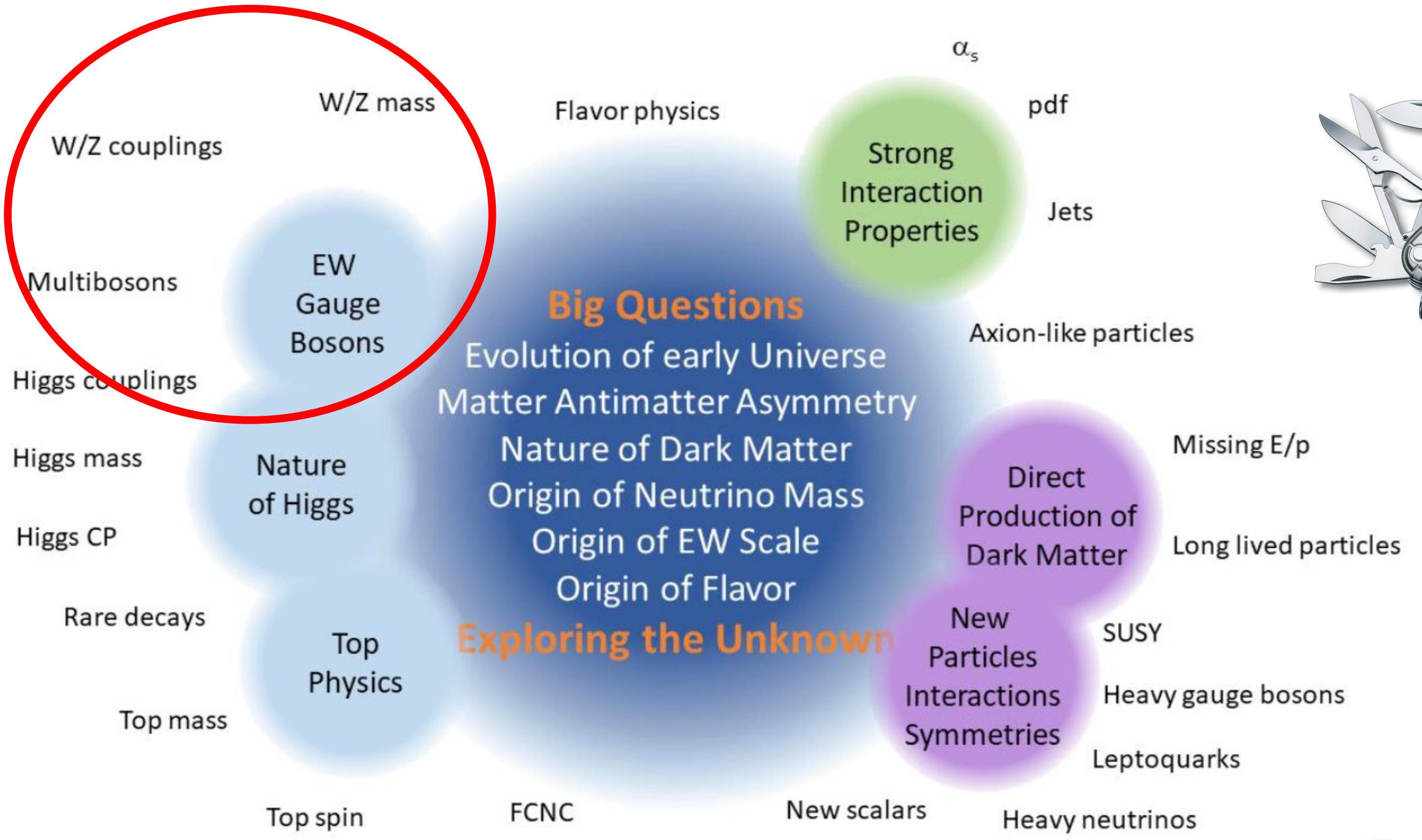


Neutral currents 51;
W/Z boson turns 41;
Top quark now 29;
Higgs turns 12.

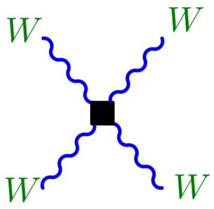


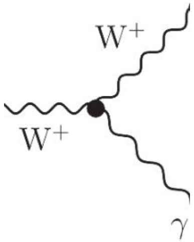


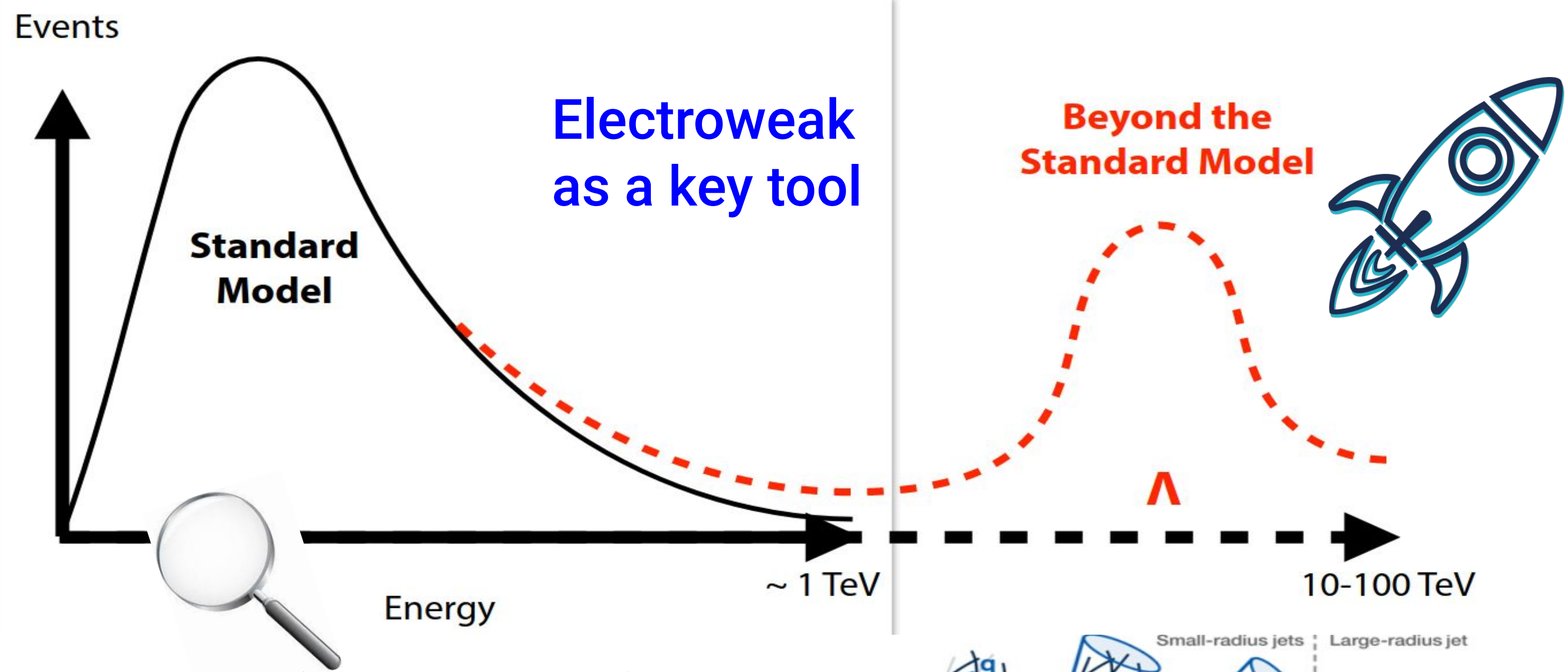
Seattle snowmass summer meeting 2022

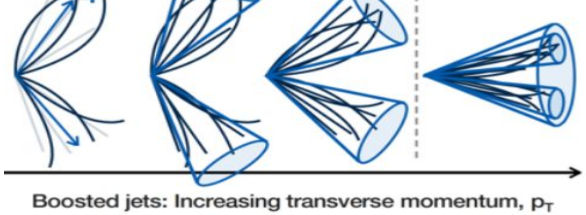


Direct and indirect searches for BSM





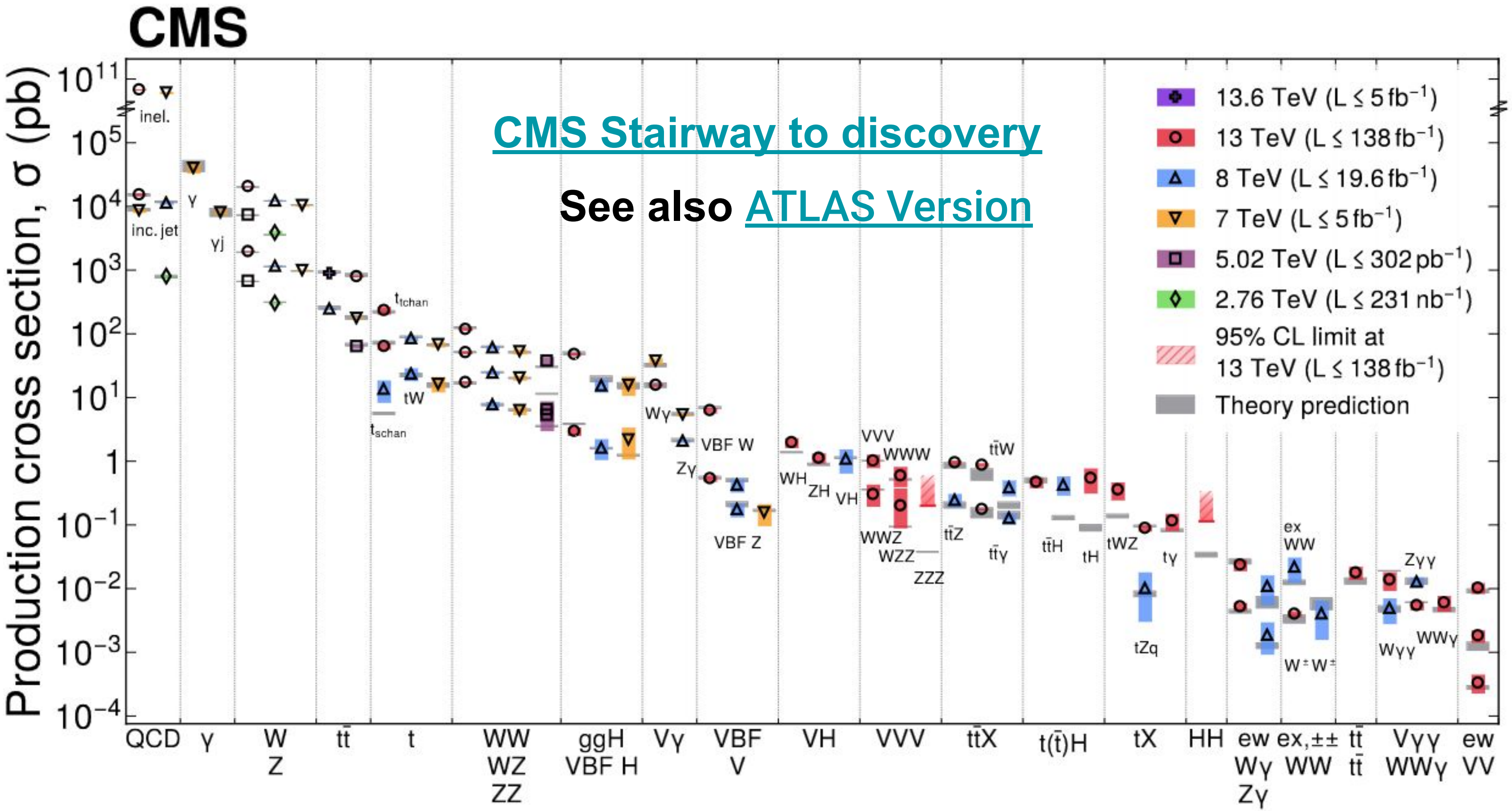




Anomalous couplings, EFT (CP even or odd)

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

Rich results at the LHC (ATLAS, CMS)



Selected Topics with bias

W Mass/Width
Single V
Effective leptonic weak mixing angle
V decay
Di-boson: W/Z+Photon, WZ
VBS: W+W-, WZ, polarization
Tri-boson: W+Z/W+photon,
EFT as the new SM
EWK as novel tools
Run 3: DY, W+W-
Future

See also:

Recent tau g-2 measurement from CMS
Zongsheng He (Peking University, Beijing)

VBF/VBS measurements in ATLAS
Zhen Wang (TD Lee Institute Shanghai Jiao Tong University)

Precision W physics in ATLAS (mass, width and pT)
Eram Syed Rizvi (Queen Mary University of London)

W Mass

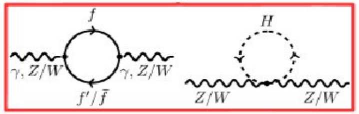
HIGGS AND ELECTROWEAK | FEATURE

The W boson's midlife crisis

24 August 2023

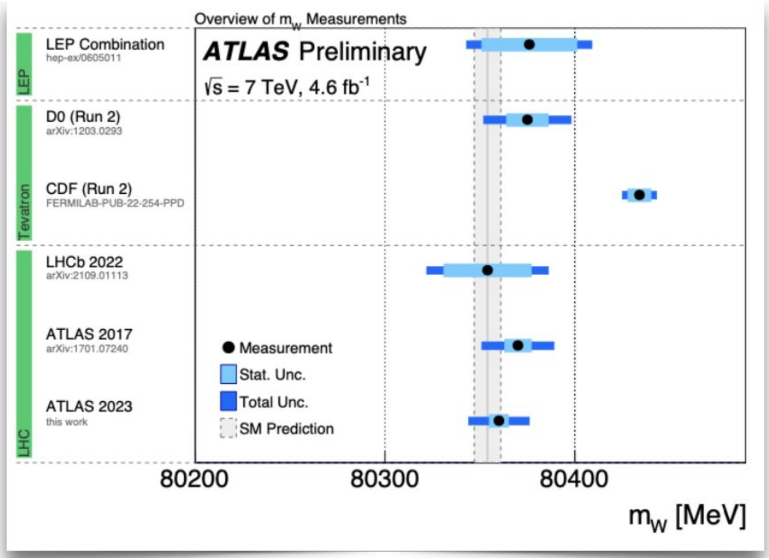
Forty years after its discovery, the W boson continues to intrigue. Chris Hays describes recent progress in understanding a surprisingly high measurement of its mass using data from the former CDF experiment.

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



Powerful tools for consistency test on over-constrained Standard Model

- CDF W-boson mass results: 80434 +- 9 MeV, differed significantly from the SM prediction and the other experimental results.
- Improved ATLAS result weighs in on the W boson: 80360 +- 16 MeV.
- LHCb W mass uncertainty as 32 MeV
- Future Colliders: ~ 0.3-0.4 MeV
- W-boson mass combination WG



arXiv:2403.15085

ATLAS W Mass and Width

Re-analysis of previous 7 TeV result

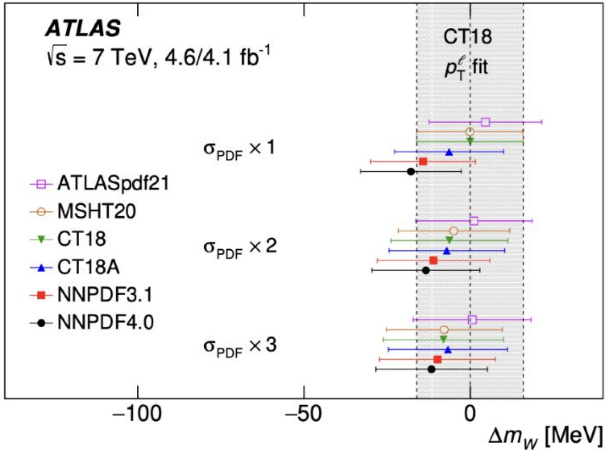
- Improved fit with likelihood minimization (PLH) and uncertainty profiling rather than chi2
- extended studies of PDFs, impact of profiling demonstrated by inflating pre-fit uncertainties
- mW and ΓW measured simultaneously or fixing one to SM

Updated m_W = 80366.5 ± 15.9 MeV (Γ_W fixed to SM)

- It was δm_W ~ 19 MeV in 2017, with 9.2 MeV from PDFs

Using CT18 PDFs

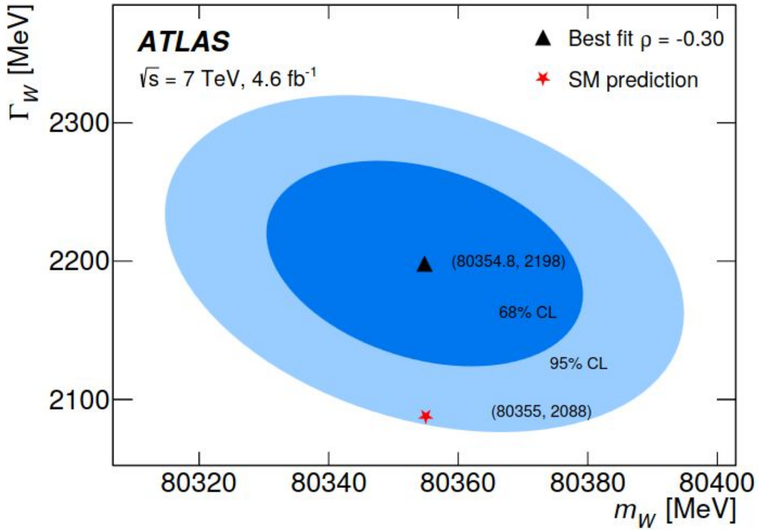
Unc. [MeV]	Total	Stat.	Syst.	PDF	A_i	Backg.	EW	e	μ	u_T	Lumi	Γ_W	PS
p_T^ℓ	16.2	11.1	11.8	4.9	3.5	1.7	5.6	5.9	5.4	0.9	1.1	0.1	1.5
m_T	24.4	11.4	21.6	11.7	4.7	4.1	4.9	6.7	6.0	11.4	2.5	0.2	7.0
Combined	15.9	9.8	12.5	5.7	3.7	2.0	5.4	6.0	5.4	2.3	1.3	0.1	2.3



Fixing m_W to SM, Γ_W = 2202 ± 47 MeV,

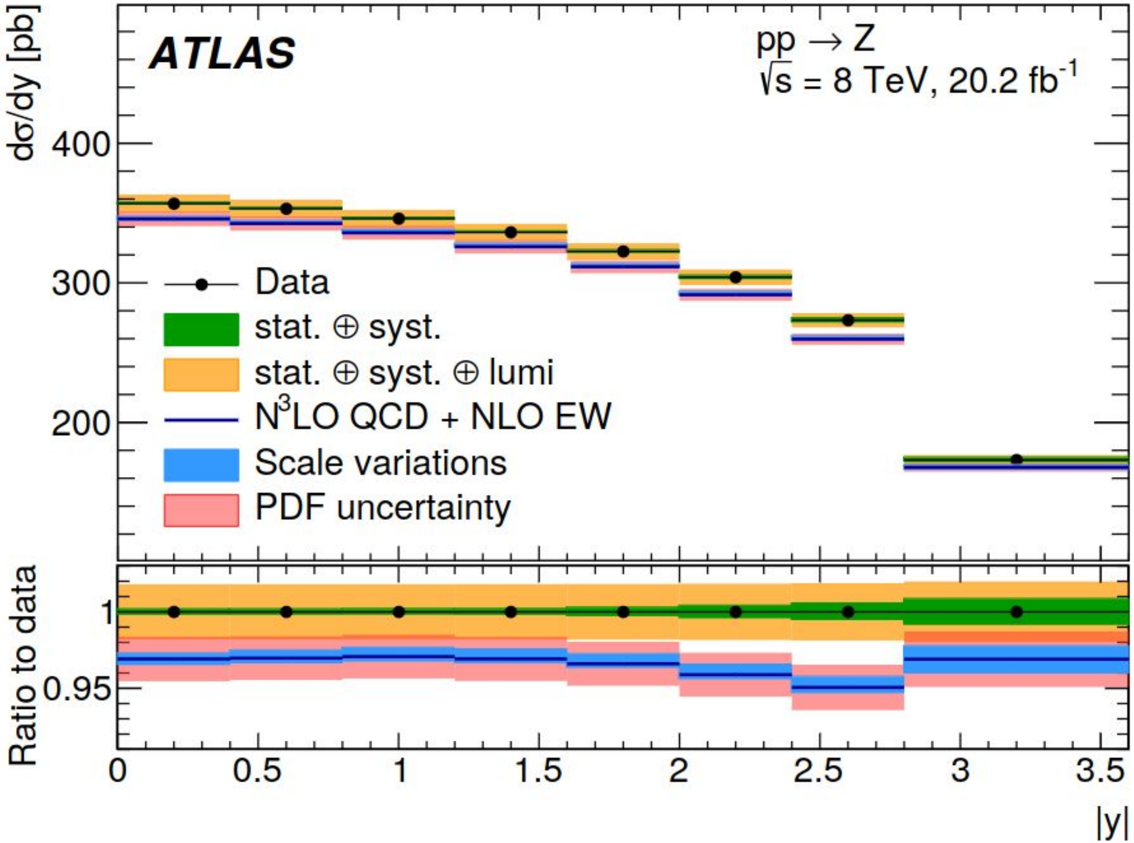
From simultaneous fit:

m_W = 80354.8 ± 16.1 MeV Γ_W =2198 ± 49 MeV



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

Drell-Yan precision



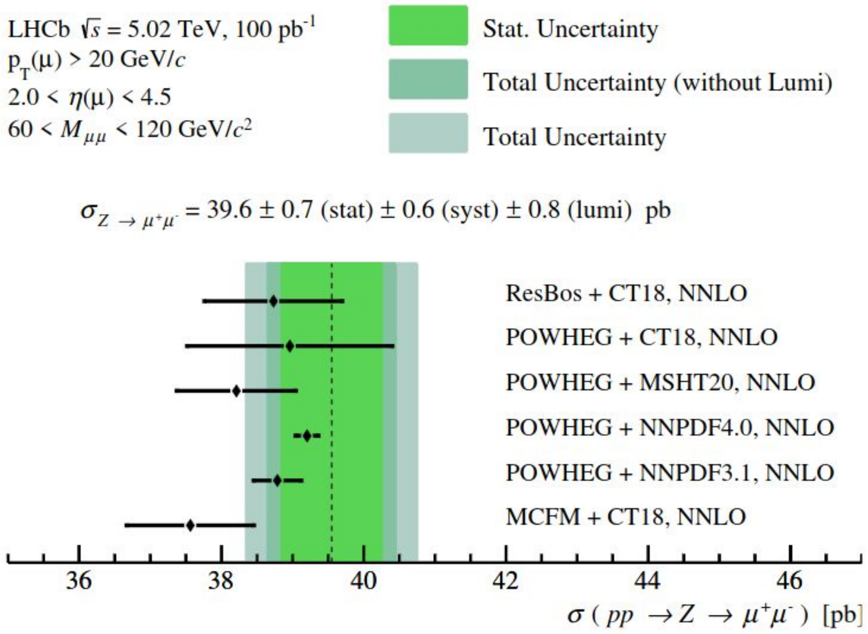
- N3LO QCD predictions obtained from DYTurbo

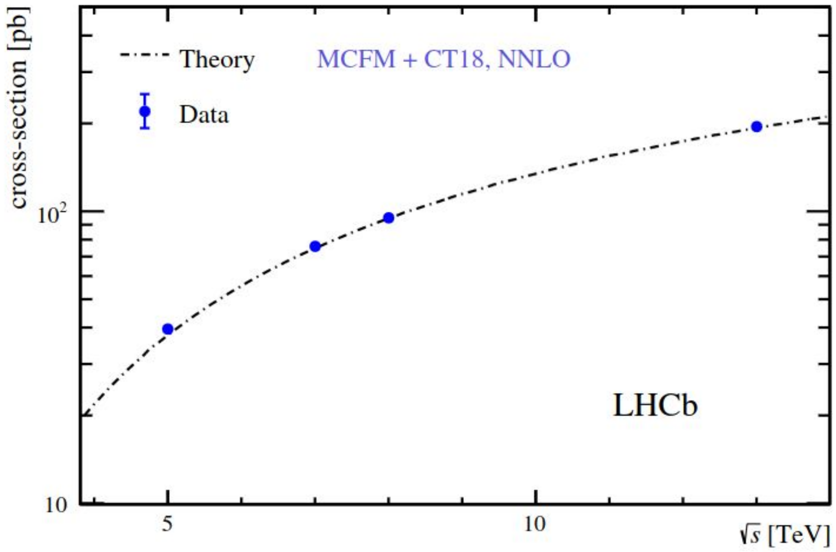
  aN^{3}LO MSHT PDF set.

- 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

JHEP 02 (2024) 070

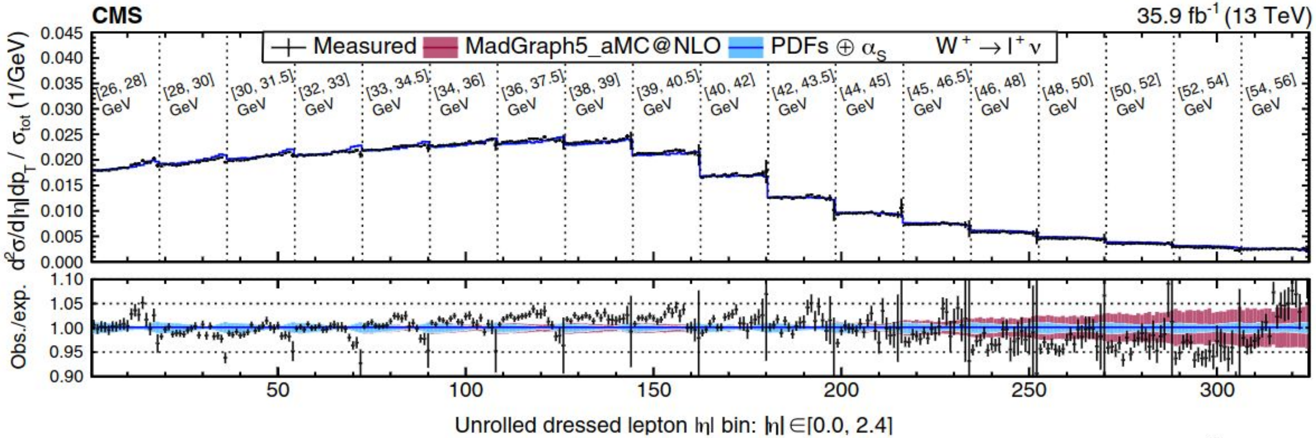
LHCb 5.02 TeV measurement of Z production
2017 pp reference run data-set: 100/pb

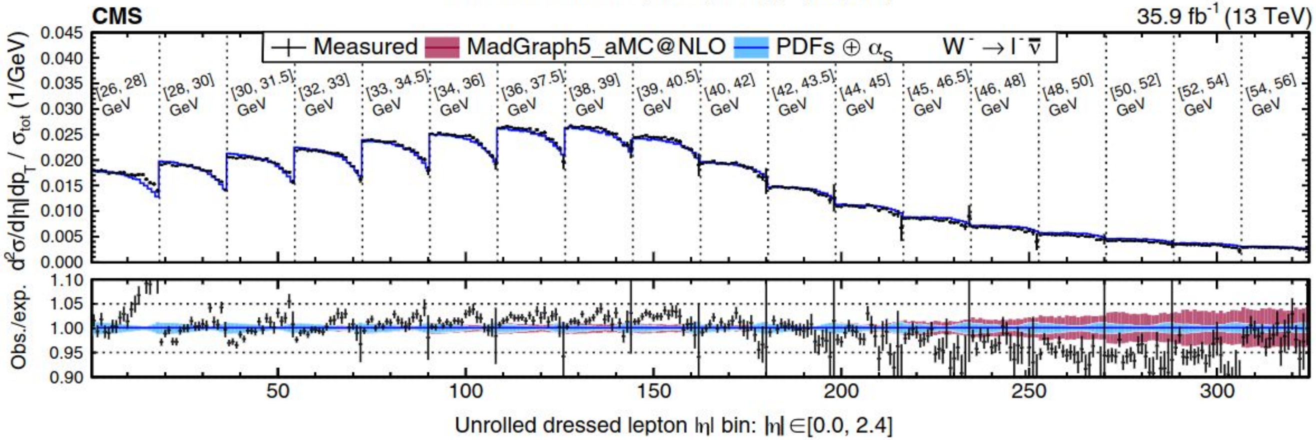


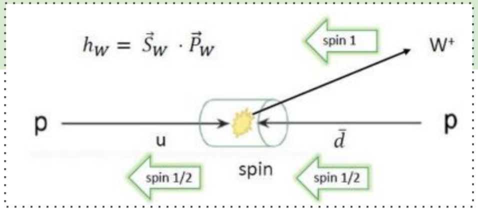


PRD 102 (2020) 092012

Single W precision







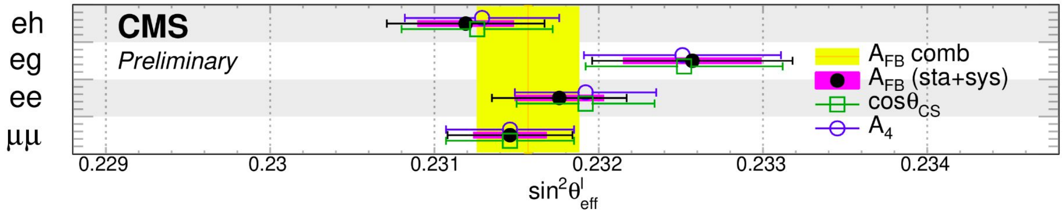
- lepton eta-pT depends on W helicity, which is largely determined by parton distribution function.
- Can be used to constrain parton distribution function, modelling, etc.
- Precursor to CMS W Mass measurement.

CMS-PAS-SMP-22-010

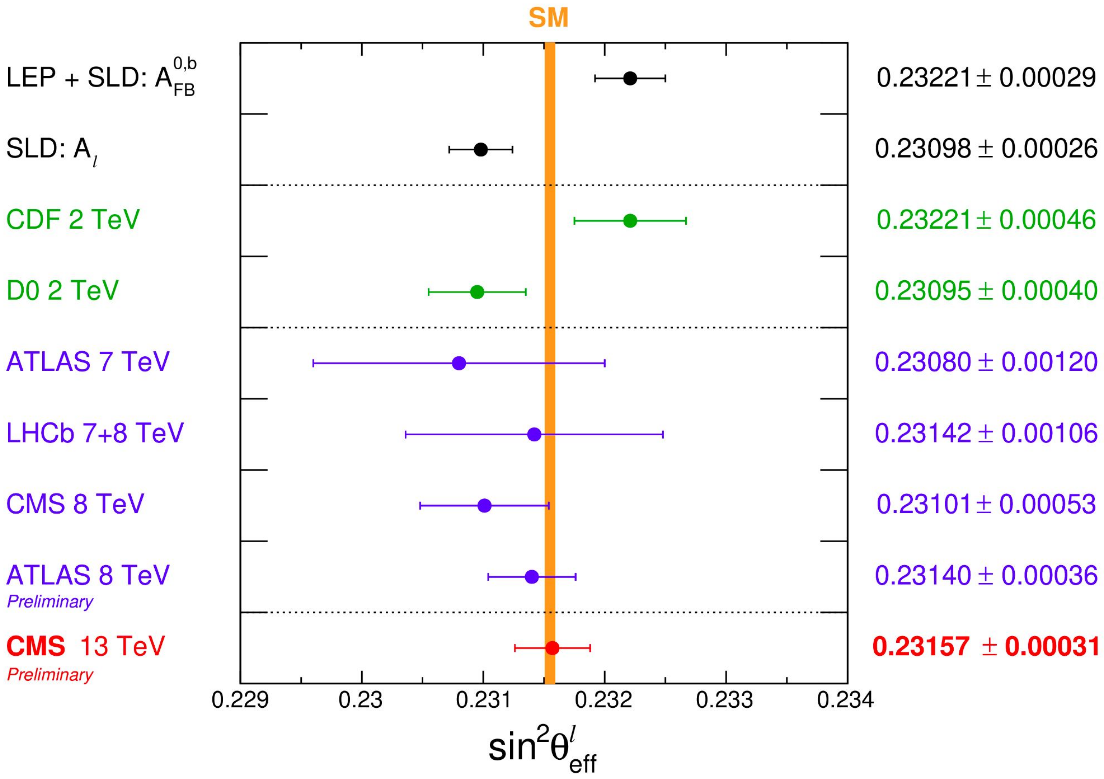
Effective leptonic weak mixing angle

- Fundamental EW parameter: $\sin^2\theta^\ell_{\rm eff} = (1 - m^2_{\rm W}/m^2_{\rm Z})\kappa^\ell$
  - Measured via Z/γ*→ll, asymmetry in lepton decay angle: $1+\cos^2\theta+0.5A_0(1-3\cos^2\theta)+A_4\cos\theta$
- Recent CMS measurement at 13 TeV $\rightarrow A_{\rm FB} = 3/8 A_4$
  - $\sin^2\theta^\ell_{\rm eff}$ measured via A_{FB} (similar to previous Run 1 approach)
  - New: unfolded A4 (for future reinterpretation)
- Strong dependence on PDFs
  - Profile in $\sin^2\theta^\ell_{\rm eff}$ fits
- Adds reconstruction of electrons outside tracker acceptance for increased A_{FB} sensitivity
  - e: |η| < 2.5
  - g: 2.5 < |η| < 2.87 (fwd. ECAL)
  - h: 3.14 < |η| < 4.36 (fwd. HCAL)

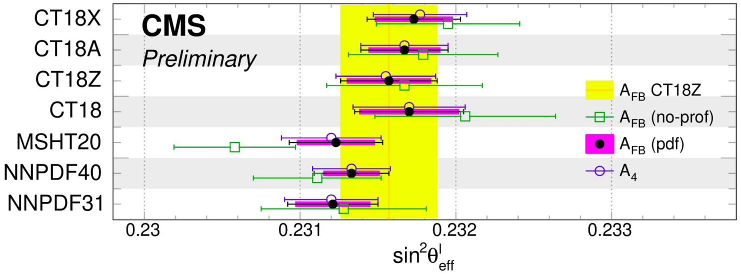
- Signal samples using POWHEG MiNNLO + Pythia8 + Photos; NLO weak + universal HO corrections
- Consistent results for AFB, A4 and direct cosθ fits
  - PDF profiling reduces differences between PDF sets
  - CT18Z chosen (pre-unblinding) as nominal: best coverage of other PDF central values



CMS-PAS-SMP-22-010 Effective leptonic weak mixing angle



Best hadron collider measurement, approaching LEP and SLD.



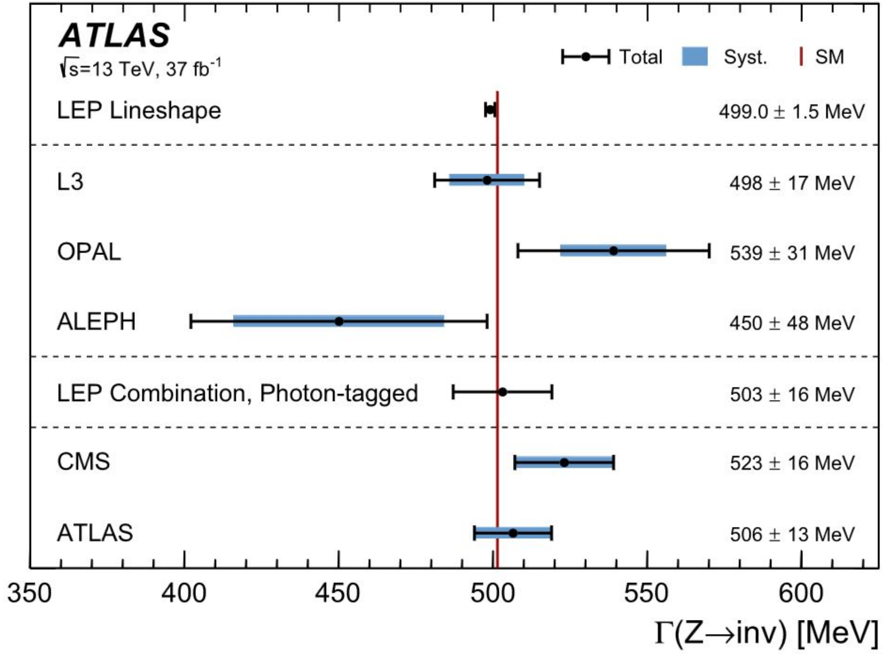
PRD 105 (2022) 072008
PLB 842 (2023) 137563
PLB 854 (2024) 138705

W/Z decay

JHEP 01 (2024) 101

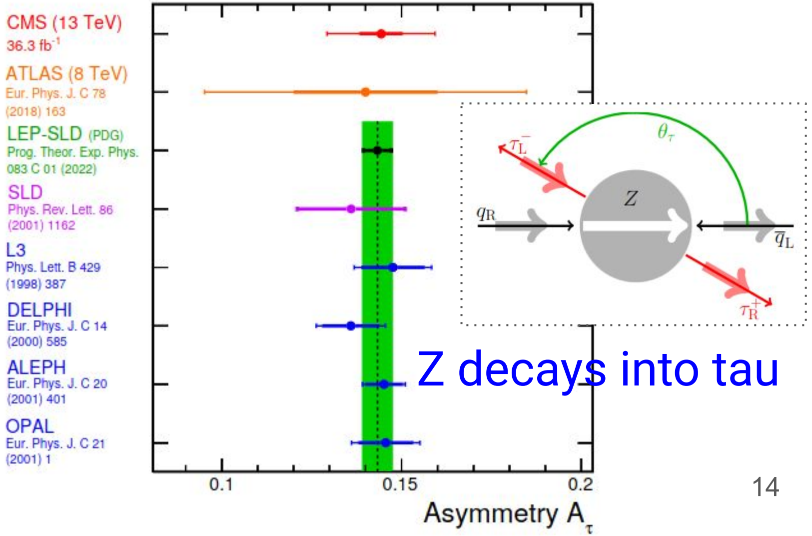
W decay branch ratio

	CMS	LEP
$\mathcal{B}(W \to e\overline{\nu}_e)$	$(10.83 \pm 0.01 \pm 0.10)\%$	$(10.71 \pm 0.14 \pm 0.07)\ \%$
$\mathcal{B}(W \to \mu\overline{\nu}_\mu)$	$(10.94 \pm 0.01 \pm 0.08)\%$	$(10.63 \pm 0.13 \pm 0.07)\ \%$
$\mathcal{B}(W \to \tau\overline{\nu}_\tau)$	$(10.77 \pm 0.05 \pm 0.21)\%$	$(11.38 \pm 0.17 \pm 0.11)\ \%$
$\mathcal{B}(W \to q\overline{q}')$	$(67.46 \pm 0.04 \pm 0.28)\%$	—
Assuming LFU		
$\mathcal{B}(W \to \ell\overline{\nu})$	$(10.89 \pm 0.01 \pm 0.08)\%$	$(10.86 \pm 0.06 \pm 0.09)\%$
$\mathcal{B}(W \to q\overline{q}')$	$(67.32 \pm 0.02 \pm 0.23)\%$	$(67.41 \pm 0.18 \pm 0.20)\%$



Z invisible decay width

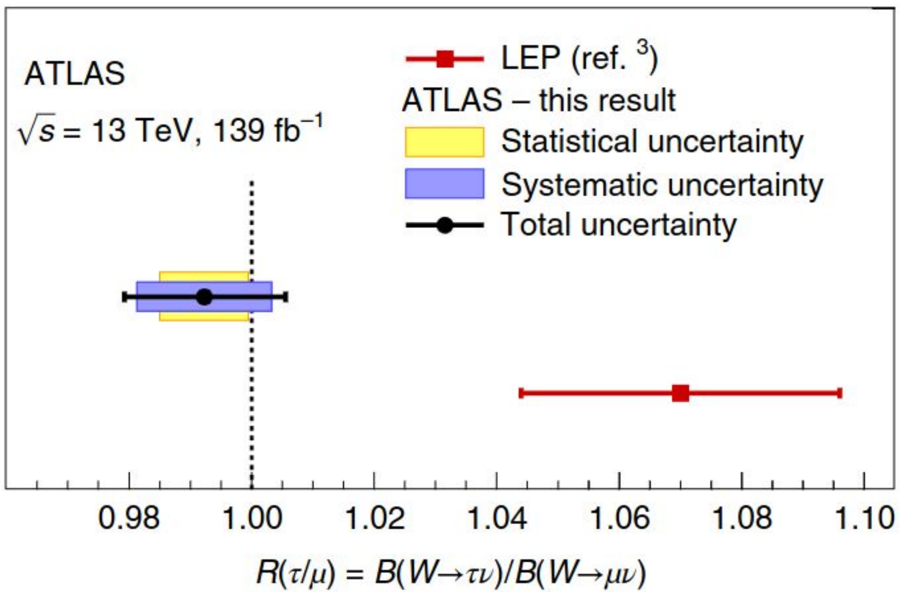
$$\Gamma(Z \to \nu\overline{\nu}) = \frac{\sigma(Z{+}\text{jets})\mathcal{B}(Z \to \nu\overline{\nu})}{\sigma(Z{+}\text{jets})\mathcal{B}(Z \to \ell\ell)}\Gamma(Z \to \ell\ell)$$

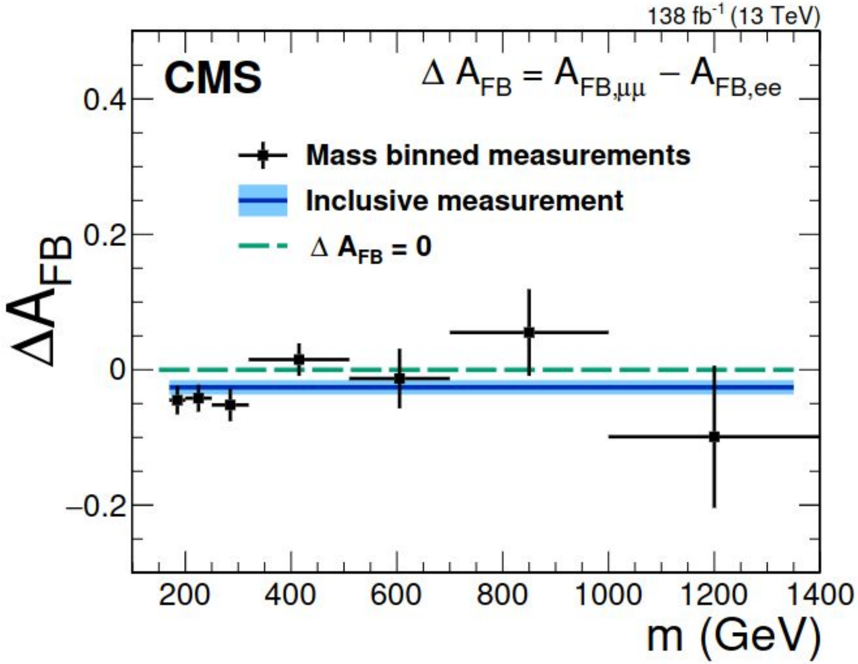


Z decays into tau

[JHEP 08 (2022) 063](#)
[Nature Physics 17, 813 (2021)](#)

LFUV





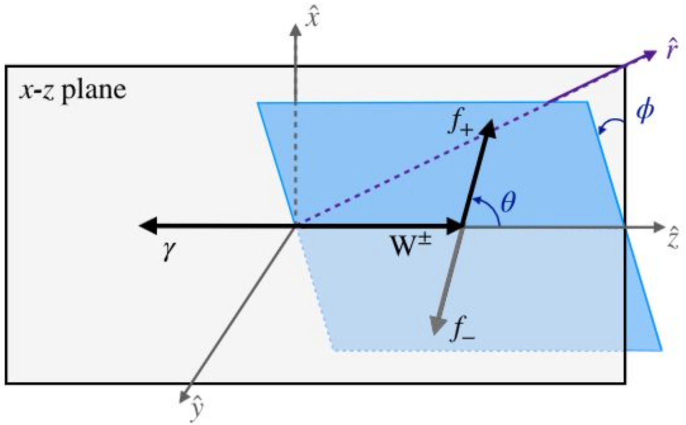
The tension LEP noticed is not visible in ATLAS data

The inclusive measurement ΔA_{FB} differs from zero at the level of 2.4 standard deviations

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



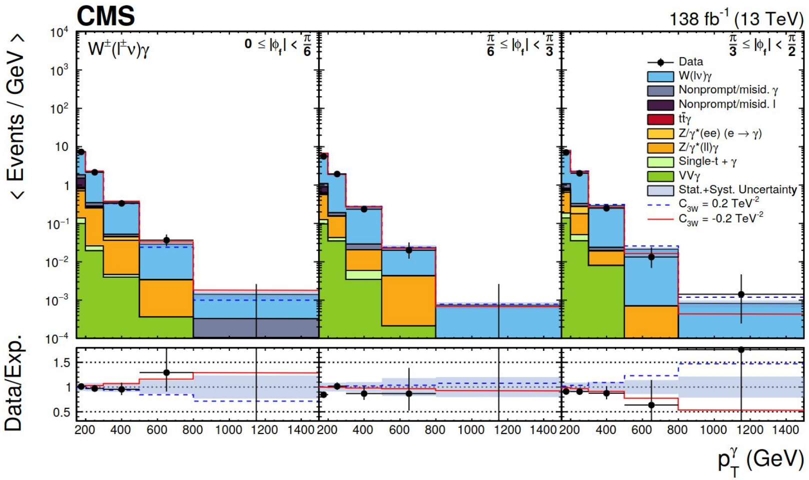


Table 4: Best fit values of C_{3W} and corresponding 95% CL confidence intervals as a function of the maximum p_T^γ bin included in the fit.

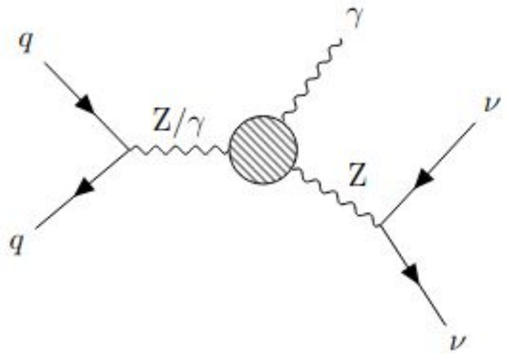
p_T^γ cutoff (GeV)	Best fit C_{3W} (TeV^{-2}) SM+int. only	Best fit C_{3W} (TeV^{-2}) SM+int.+BSM	Observed 95% CL (TeV^{-2}) SM+int. only	Observed 95% CL (TeV^{-2}) SM+int.+BSM	Expected 95% CL (TeV^{-2}) SM+int. only	Expected 95% CL (TeV^{-2}) SM+int.+BSM
200	−0.86	−0.24	[−2.01, 0.38]	[−0.76, 0.40]	[−1.16,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

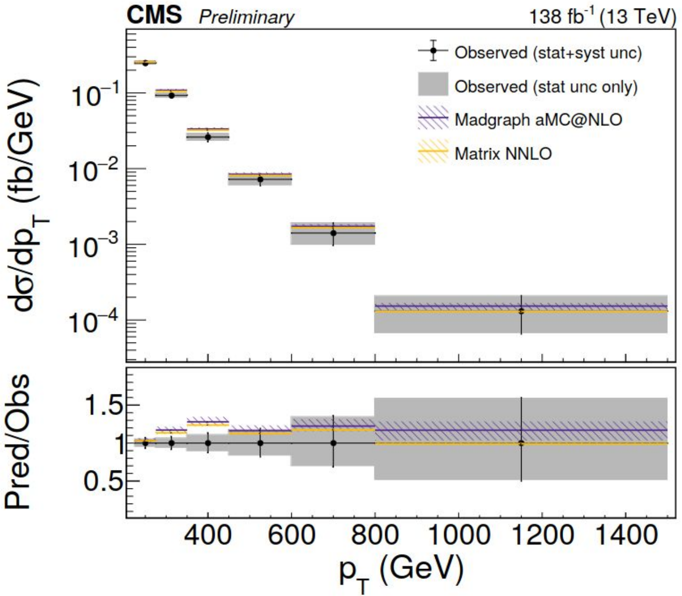
The technique will also be valuable in the future when sufficiently small values of aGCs are probed such that the interference contribution will be dominant

Zγ

CMS-PAS-SMP-22-009

- pp collisions@13 TeV, Full Run2 statistics (138 fb-1)
- Fiducial and differential xsec measurement
- Limits on aNTGCs h3Z,γ and h4Z,γ
- Exactly 1 high-pT (>225 GeV) photon + MET
- BDT algorithm to identify high-pT photons (92% efficiency)
- True and fake photons bkgs

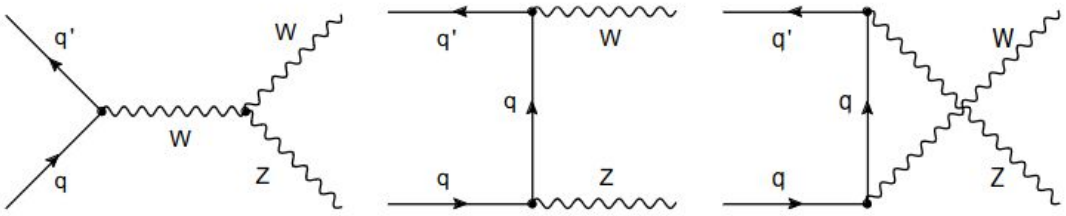


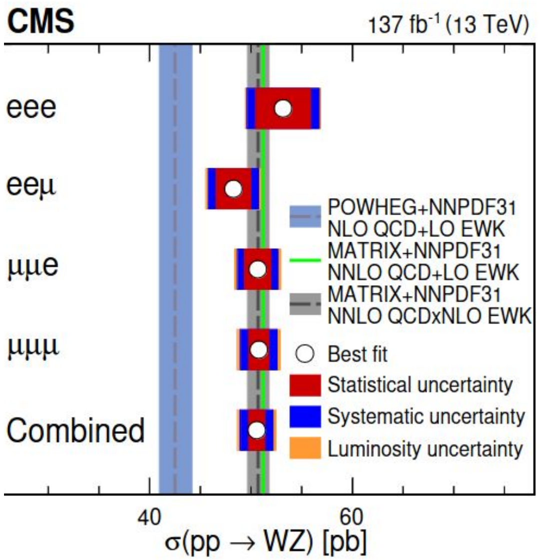


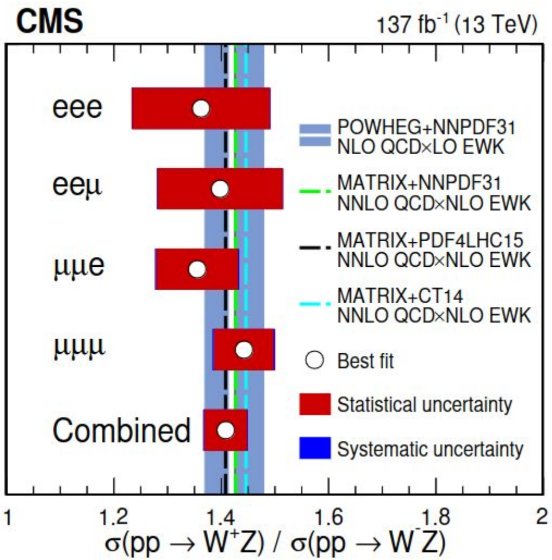
Parameter	Expected	Observed
$h_3^\gamma \times 10^4$	(-2.8, 2.9)	(-3.4, 3.5)
$h_4^\gamma \times 10^7$	(-5.9, 6.0)	(-6.8, 6.8)
$h_3^Z \times 10^4$	(-1.8,1.9)	(-2.2, 2.2)
$h_4^Z \times 10^7$	(-3.7, 3.7)	(-4.1, 4.2)

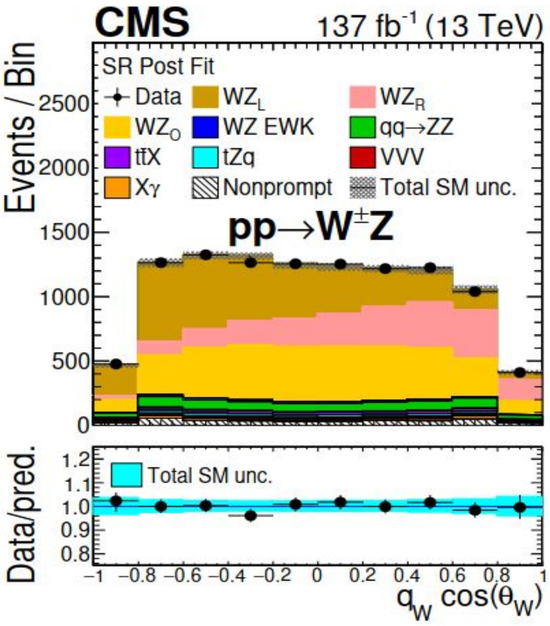
JHEP 07 (2022) 032

WZ (polarization)





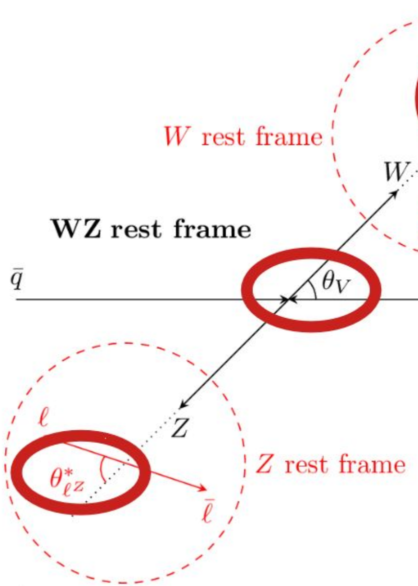


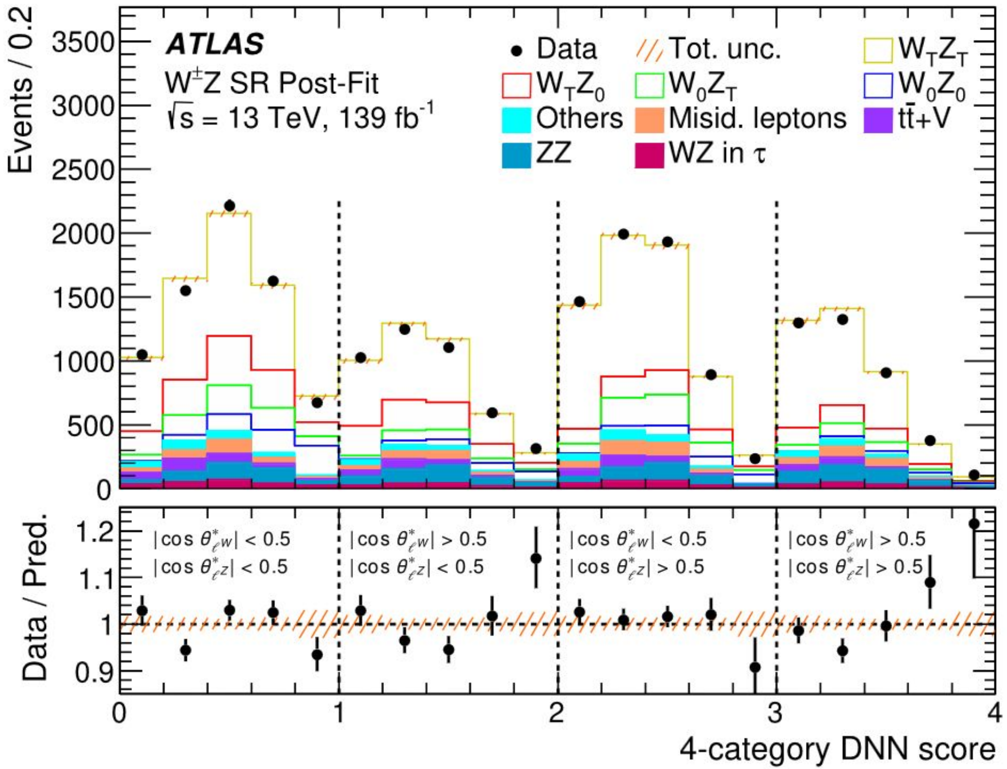


First observation of single longitudinally polarized W bosons in WZ production! 5.6σ (4.3σ) obs (exp).

WZ (joint polarization)

[Phys. Lett. B 843 (2023) 137895]





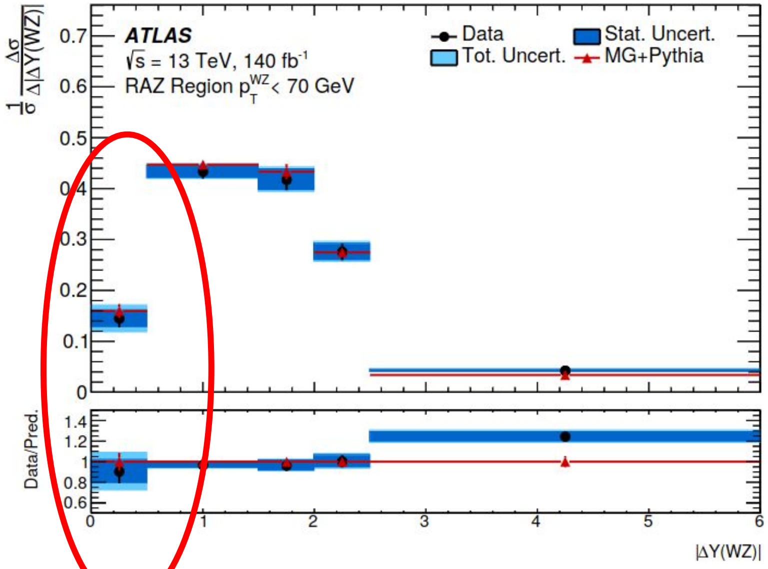
Measurement performed as well separating by the W charge

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

– Significance on f_{00} at 4.1σ in W-Z arXiv:2402.16365

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	

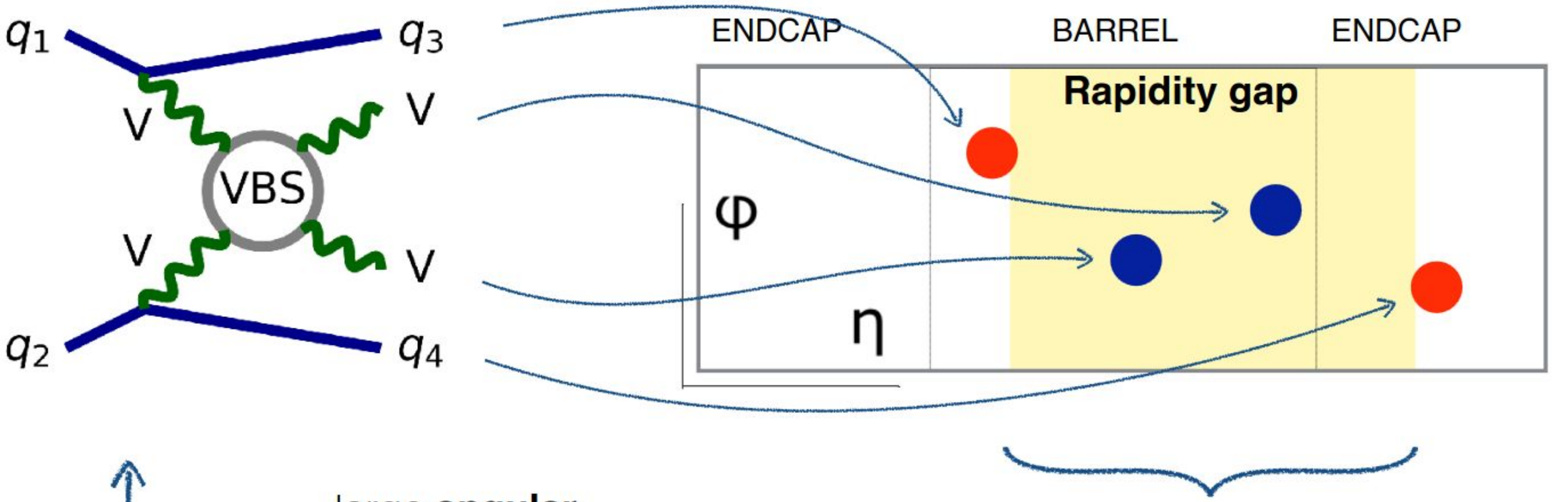
dominated by TT events with low momentum W and Z bosons [1, 2, 13]. This analysis focuses on WZ events with Z bosons required to have high transverse momenta (p_T^Z). The combination of high p_T^Z and low p_T^{WZ} significantly reduces the TT contribution and increases f_{00}. As a result, f_{00} increases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

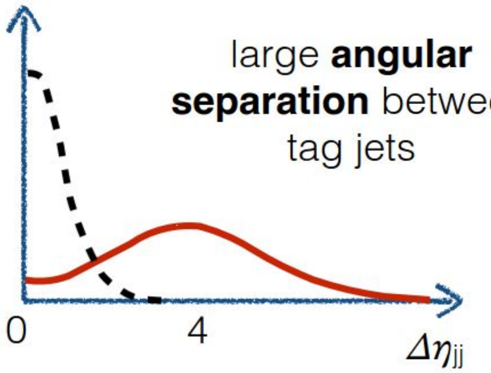
	Measurement $100 < p_T^Z \leq 200$ GeV	Measurement $p_T^Z > 200$ GeV
f_{00}	$0.19\ \pm^{0.03}_{0.03}$ (stat) $\pm^{0.02}_{0.02}$ (syst)	$0.13\ \pm^{0.09}_{0.08}$ (stat) $\pm^{0.02}_{0.02}$ (syst)
f_{0T+T0}	$0.18\ \pm^{0.07}_{0.08}$ (stat) $\pm^{0.05}_{0.06}$ (syst)	$0.23\ \pm^{0.17}_{0.18}$ (stat) $\pm^{0.06}_{0.10}$ (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}

PLB 841(2023)137495
arXiv:2403.04869
arXiv:2403.15296

Vector Boson Scattering: W+W- and WZ





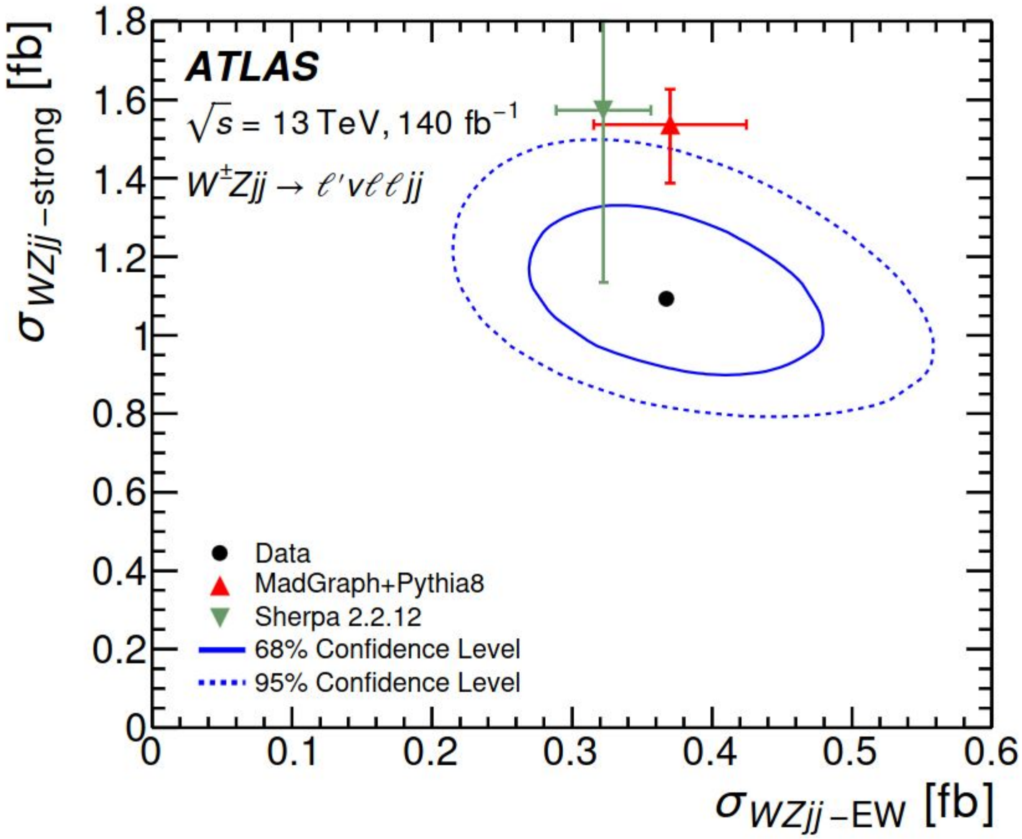
large **angular separation** between tag jets

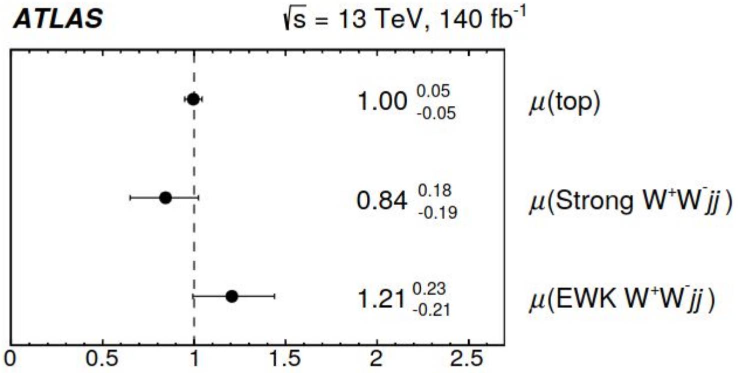
low QCD activity between tag jets, since there's no color flow between the two protons

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

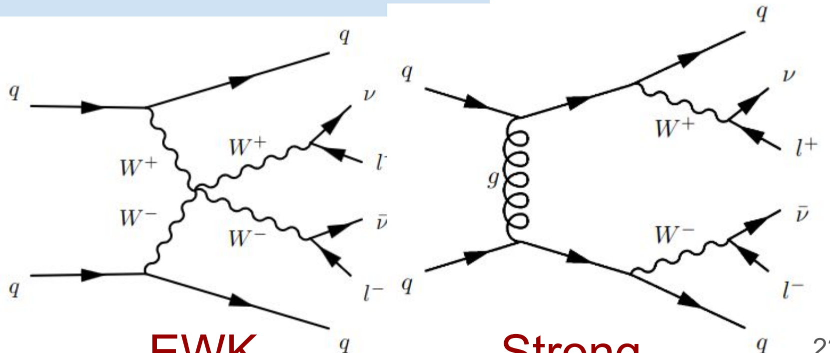
PLB 841(2023)137495
arXiv:2403.04869
arXiv:2403.15296

Vector Boson Scattering: W+W- and WZ





7.1 (6.2)σ obs.(exp.)

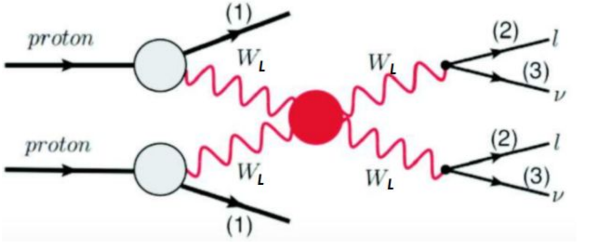


EWK Strong

[PLB 812 (2020) 136018](#)

Polarized VBS

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

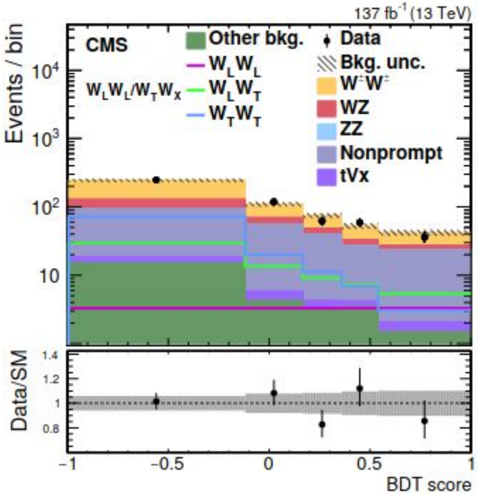


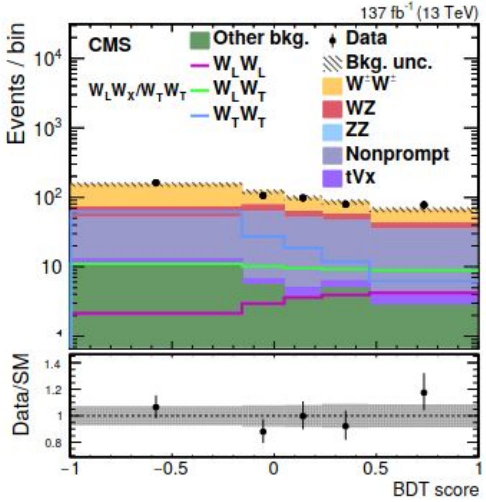
☑ $W_L^{\pm} W_L^{\pm}$: signal BDT ($W_L^{\pm} W_L^{\pm}$ vs $W_T^{\pm} W_X^{\pm}$) and inclusive BDT (VBS vs Bkg.)

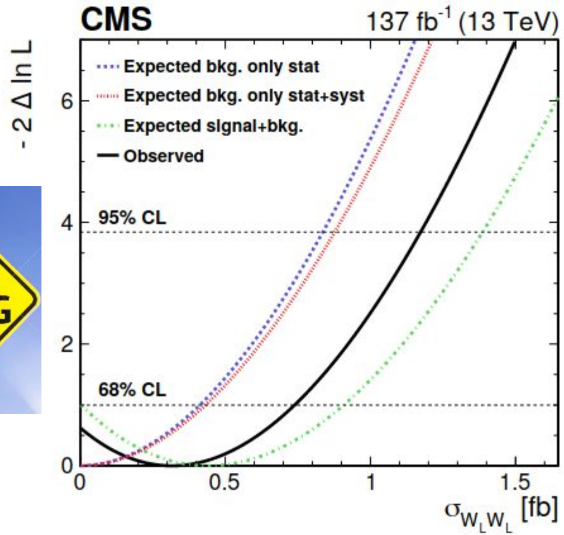
☑ $W_L^{\pm} W_X^{\pm}$: signal BDT ($W_L^{\pm} W_X^{\pm}$ vs $W_T^{\pm} W_T^{\pm}$) and inclusive BDT (VBS vs Bkg.)

☑ 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

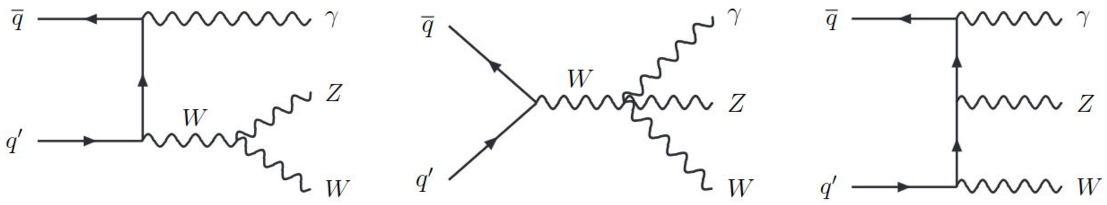






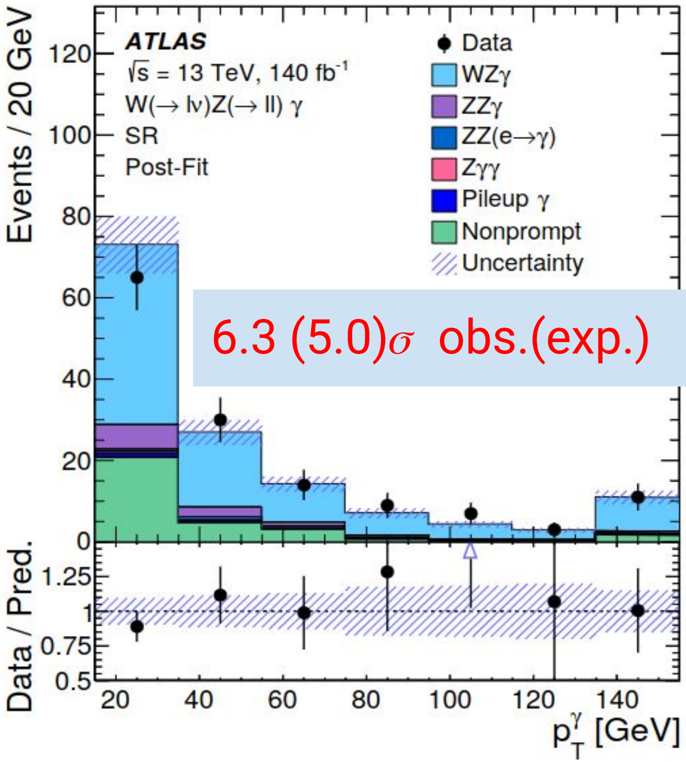
PRL132 (2024) 021802

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.)

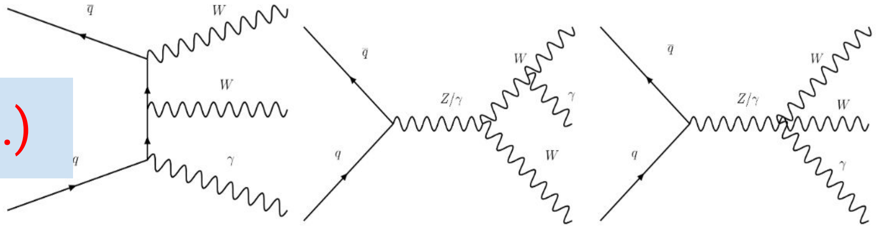
$$\sigma_{WZ\gamma} = 2.01 \pm 0.30\ (\text{stat.}) \pm 0.16\ (\text{syst.})\ \text{fb}$$

PRL132 (2024) 121901

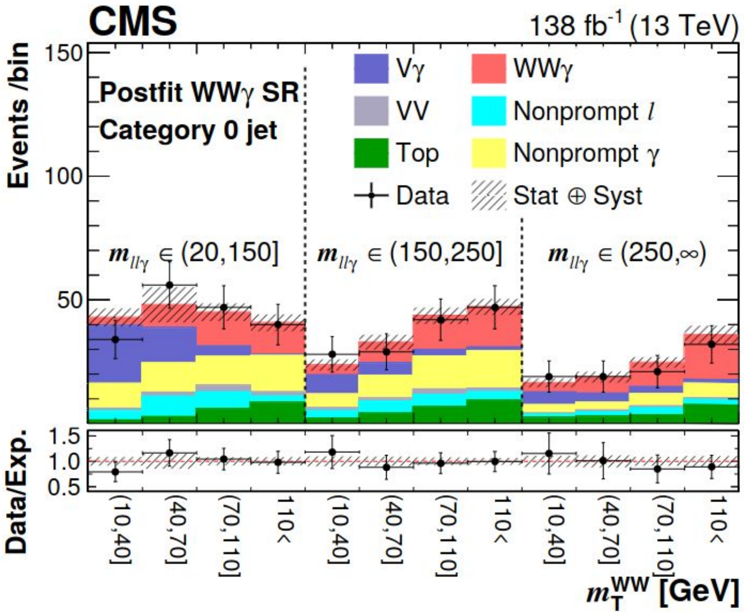
WWγ Observation

- 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.

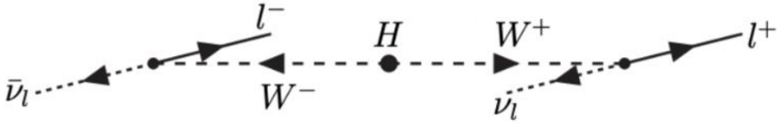
5.6 (4.7)σ obs.(exp.)



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



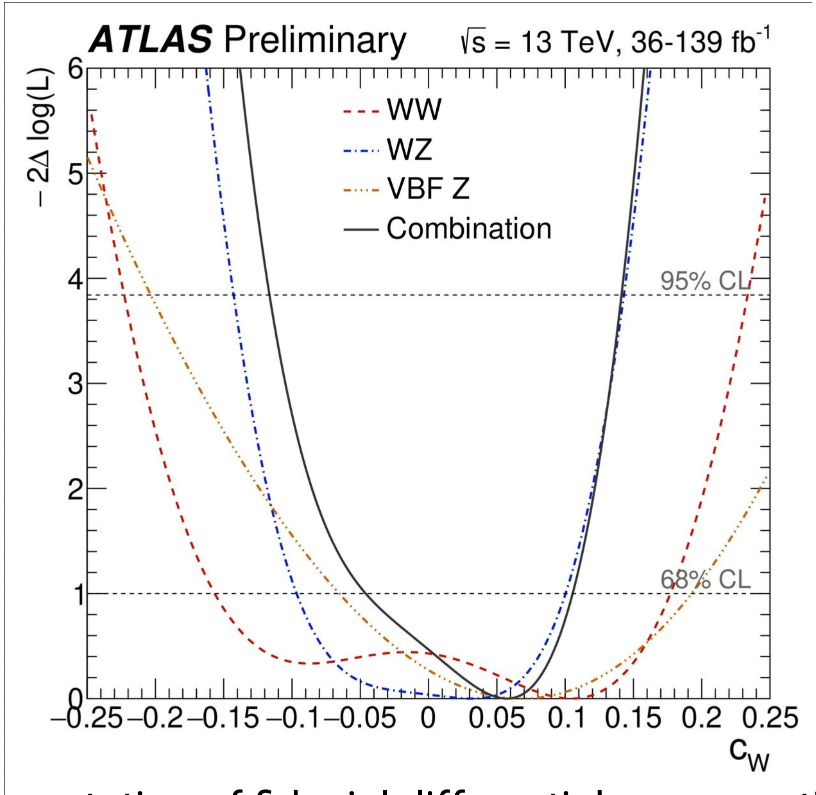
- Also sensitive to Higgs couplings with light quarks
  - no gluon fusion contribution due to Furry's theorem
- Further optimization targeting the Higgs characteristics



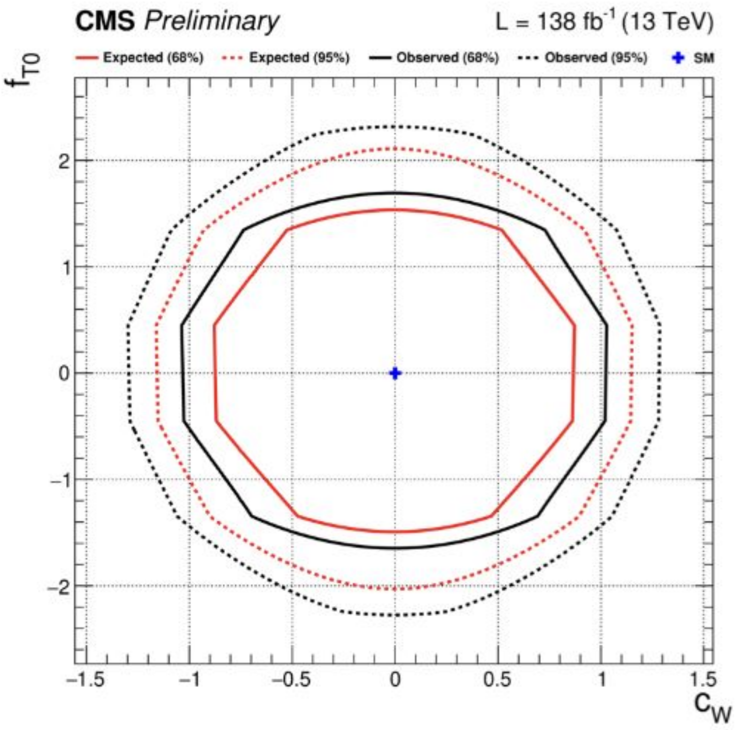
σ upper limits obs. (exp.) [fb]	κ_q limits obs. (exp.) at 95% CL
85 (67)	$\lvert\kappa_u\rvert \leq 16000$ (13000)
72 (58)	$\lvert\kappa_d\rvert \leq 17000$ (14000)
68 (49)	$\lvert\kappa_s\rvert \leq 1700$ (1300)
87 (67)	$\lvert\kappa_c\rvert \leq 200$ (110)

ATL-PHYS-PUB-2021-022 ATL-PHYS-PUB-2022-037
CMS-PAS-SMP-22-008 arXiv:2211.08353

SMEFT: The new Standard Model



Interpretation of fiducial differential cross-sections

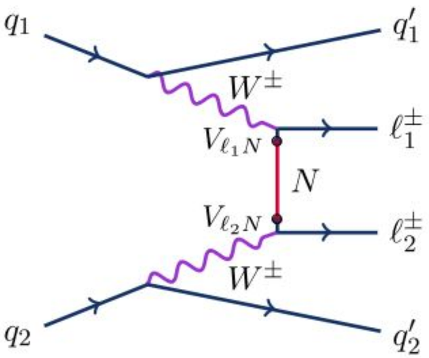


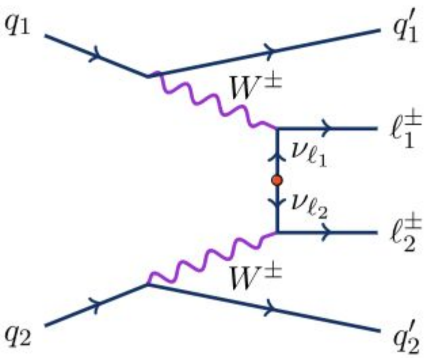
Interplay of dim-8 and dim-6 operators from VBS

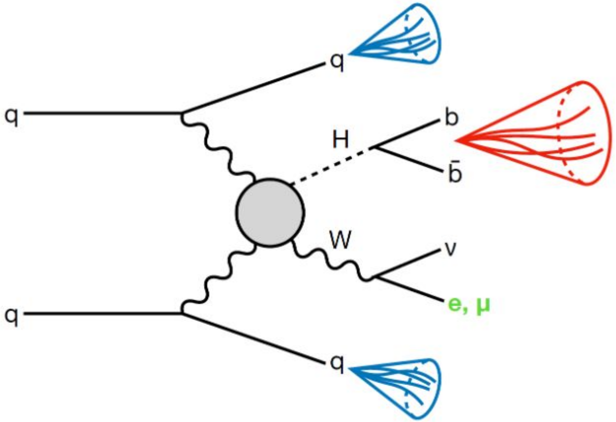
Phys. Rev. Lett. 131 (2023) 011803
Eur.Phys.J.C 83 (2023) 9, 824

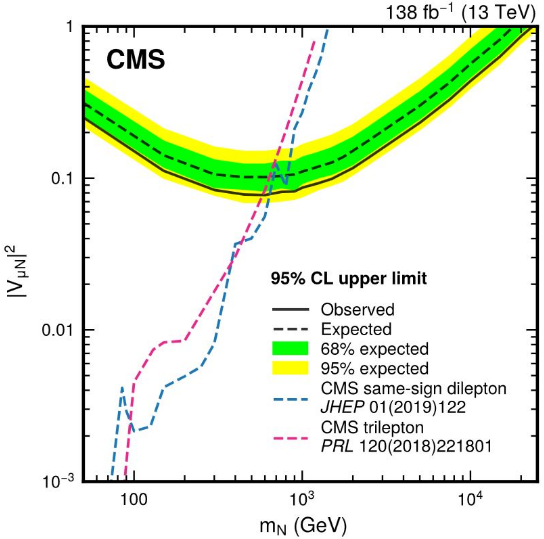
VBS as a novel tool

arXiv:2402.00426
arXiv:2405.16566









Heavy Majorana searched up to 23TeV!

0νμμ experiment and effective neutrino mass probe

- **Excluded λ_{WZ} = -1 at >8σ**
- Measure μ for +λ_{WZ} signal

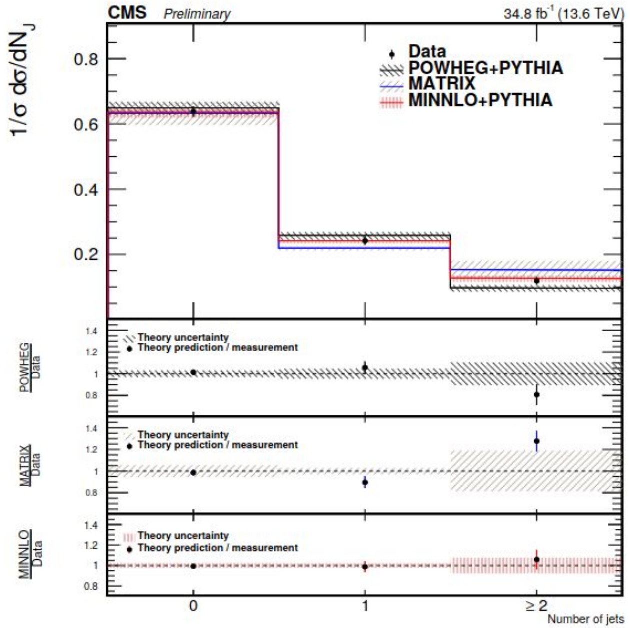
Fit: $\hat{\mu} = 2.6^{+4.6}_{-4.5}$

JHEP 08 (2023) 204 PLB 848 (2024) 138376
PLB 855 (2024) 138764 CMS-PAS-SMP-22-017
arXiv:2406.05101

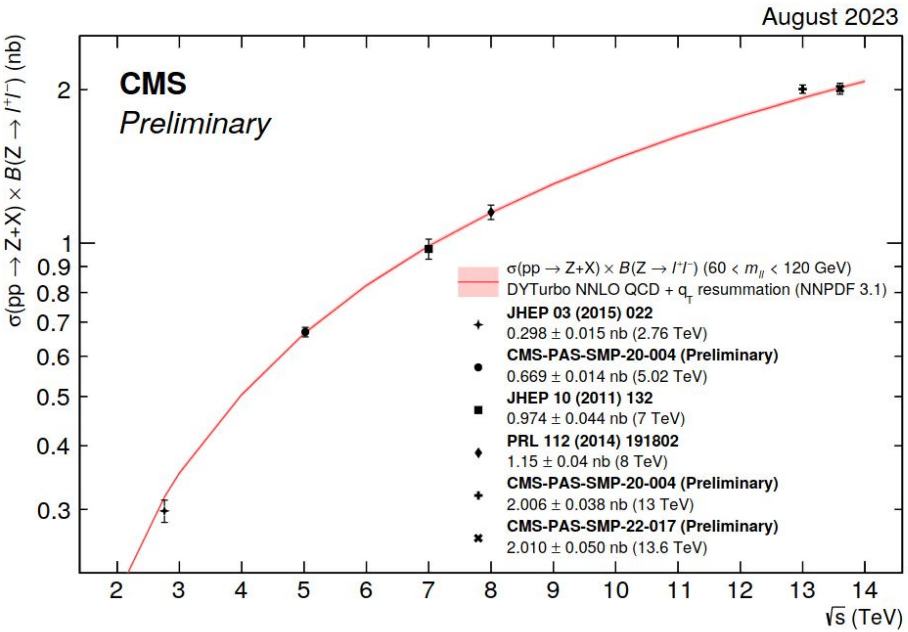
Run3

fast well to arrive at a new energy frontier
13.6 TeV

$$(\sigma_{tot}\mathcal{B})_{measured} = (2.010 \pm 0.001(\mathrm{stat}) \pm 0.018(\mathrm{syst}) \pm 0.046(\mathrm{lumi}) \pm 0.007(\mathrm{theo}))\,\mathrm{nb},$$
$$(\sigma_{tot}\mathcal{B})_{predicted} = (2.018 \pm 0.012(\mathrm{PDF})^{+0.018}_{-0.023}(\mathrm{scale}))\,\mathrm{nb},$$
NNLO QCD + qT resumm.



W+W− differential cross sections as a function of the jet multiplicity



DY cross section

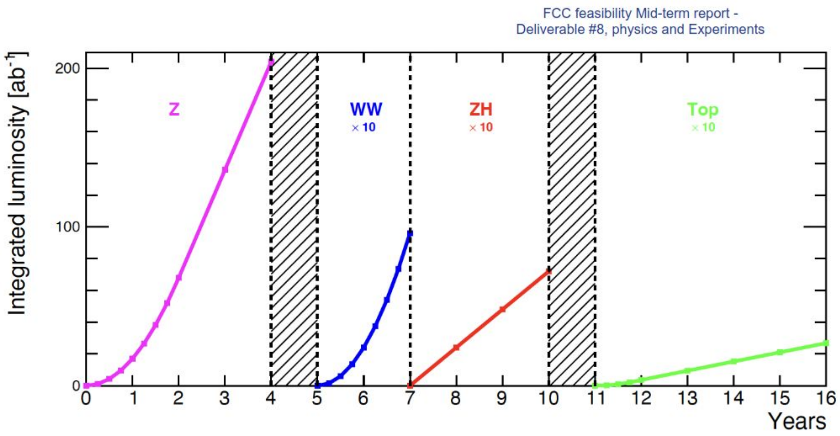
Future

2020 European Strategy Update

**“An electron-positron Higgs factory is the highest-priority next collider.
For the longer term, the European particle physics community has the ambition to operate a proton-proton collider at the highest achievable energy.”**
(European Strategy Update brochure)

Snowmass 2021

**“The intermediate future is an e+e- Higgs factory, either based on a linear (ILC, C3) or circular collider (FCC-ee, CepC).
In the long term EF envision a collider that probes the multi-TeV scale, up or above 10 TeV parton center-of-mass energy (FCC-hh, SppC, Muon Coll.)”**
(Energy Frontier Plenary by Alessandro Tricoli)



FCC-ee

CEPC

		Operation mode	ZH	Z	W^+W^-	$t\bar{t}$
		$\sqrt{s}$ [GeV]	240	91	160	360
		Run time [years]	7	2	1	-
CDR (30 MW)		L / IP [$\times 10^{34}$ 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	-
TDR (Latest)		Run Time [years]	10	2	1	5
	30 MW	L / IP [$\times 10^{34}$ cm^{-2}s^{-1}]	**5.0**	**115**	**16**	0.5
		$\int L\,dt$ [ab^{-1}, 2 IPs]	13	60	4.2	0.65
		Event yields [2 IPs]	2.6×10^6	2.5×10^{12}	1.3×10^8	4×10^5
	50 MW	L / IP [$\times 10^{34}$ cm^{-2}s^{-1}]	**8.3**	**192**	**26.7**	**0.8**
		$\int L\,dt$ [ab^{-1}, 2 IPs]	21.6	100	6.9	1.0
		Event yields [2 IPs]	4.3×10^6	4.1×10^{12}	2.1×10^8	6×10^5

Future

Observable	present value	±	error	FCC-ee Stat.	FCC-ee Syst.	Comment and leading error
m_Z (keV)	91186700	±	2200	**4**	100	From Z line shape scan Beam energy calibration
Γ_Z (keV)	2495200	±	2300	**4**	25	From Z line shape scan Beam energy calibration
$\sin^2\theta_W^{eff}(\times 10^6)$	231480	±	160	**2**	2.4	From $A_{FB}^{\mu\mu}$ at Z peak Beam energy calibration
$1/\alpha_{QED}(m_Z^2)(\times 10^3)$	128952	±	14	**3**	small	From $A_{FB}^{\mu\mu}$ off peak QED&EW errors dominate
R_ℓ^Z $(\times 10^3)$	20767	±	25	**0.06**	0.2-1	Ratio of hadrons to leptons Acceptance for leptons
$\alpha_s(m_Z^2)$ $(\times 10^4)$	1196	±	30	**0.1**	0.4-1.6	From R_ℓ^Z
σ_{had}^0 $(\times 10^3)$ (nb)	41541	±	37	**0.1**	4	Peak hadronic cross section Luminosity measurement
$N_\nu(\times 10^3)$	2996	±	7	**0.005**	1	Z peak cross sections Luminosity measurement
R_b $(\times 10^6)$	216290	±	660	**0.3**	<60	Ratio of $b\bar{b}$ to hadrons Stat. extrapol. from SLD
$A_{FB}^b, 0$ $(\times 10^4)$	992	±	16	**0.02**	1-3	b-quark asymmetry at Z pole From jet charge
$A_{FB}^{pol,\tau}$ $(\times 10^4)$	1498	±	49	**0.15**	<2	τ polarization asymmetry τ decay physics
τ lifetime (fs)	290.3	±	0.5	**0.001**	0.04	Radial alignment
τ mass (MeV)	1776.86	±	0.12	**0.004**	0.04	Momentum scale
τ leptonic $(\mu\nu_\mu\nu_\tau)$ B.R. (%)	17.38	±	0.04	**0.0001**	0.003	e/μ/hadron separation
m_W (MeV)	80350	±	15	**0.25**	0.3	From WW threshold scan Beam energy calibration
Γ_W (MeV)	2085	±	42	**1.2**	0.3	From WW threshold scan Beam energy calibration

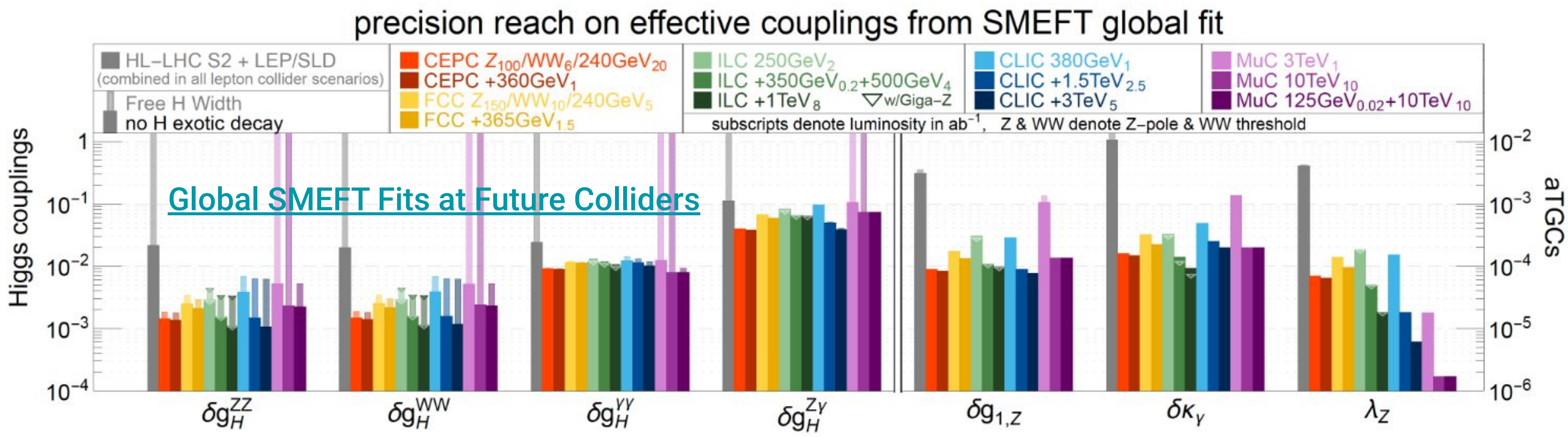
FCC feasibility Mid-term report -Deliverable #8, physics and Experiments

Comprehensive measurements of the Z lineshape and many Electroweak Precision Observables

- **50x improved precision**

W mass, width and more

Future



Global SMEFT Fits at Future Colliders

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

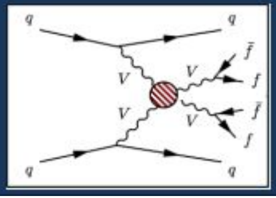
- ~ 10^{13} W
- ~ 10^{12} Z
- ~ 10^{11} tt
- ~ 10^{10} H
- ~ 10^{9} ttH
- ~ 10^{7} HH
- ~ 10^{5} gluino pairs m=8 TeV

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"

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 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