# Electroweak physics at the LHC
## (including top mass and top properties)

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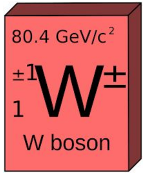
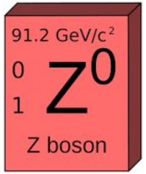
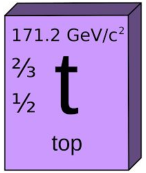
2023/11/28

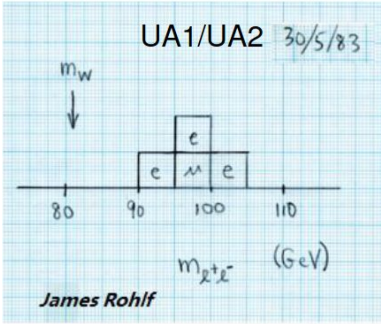
# Electroweak milestones: From infancy to adolescence

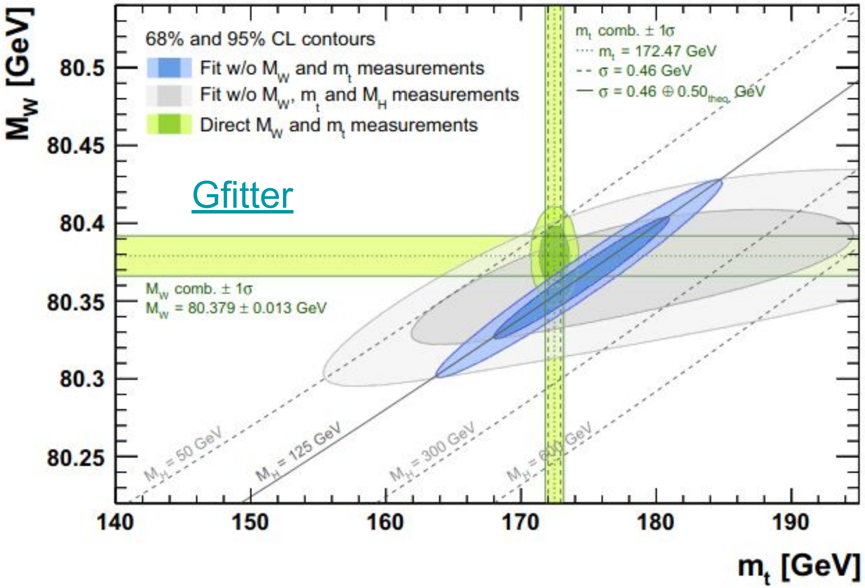


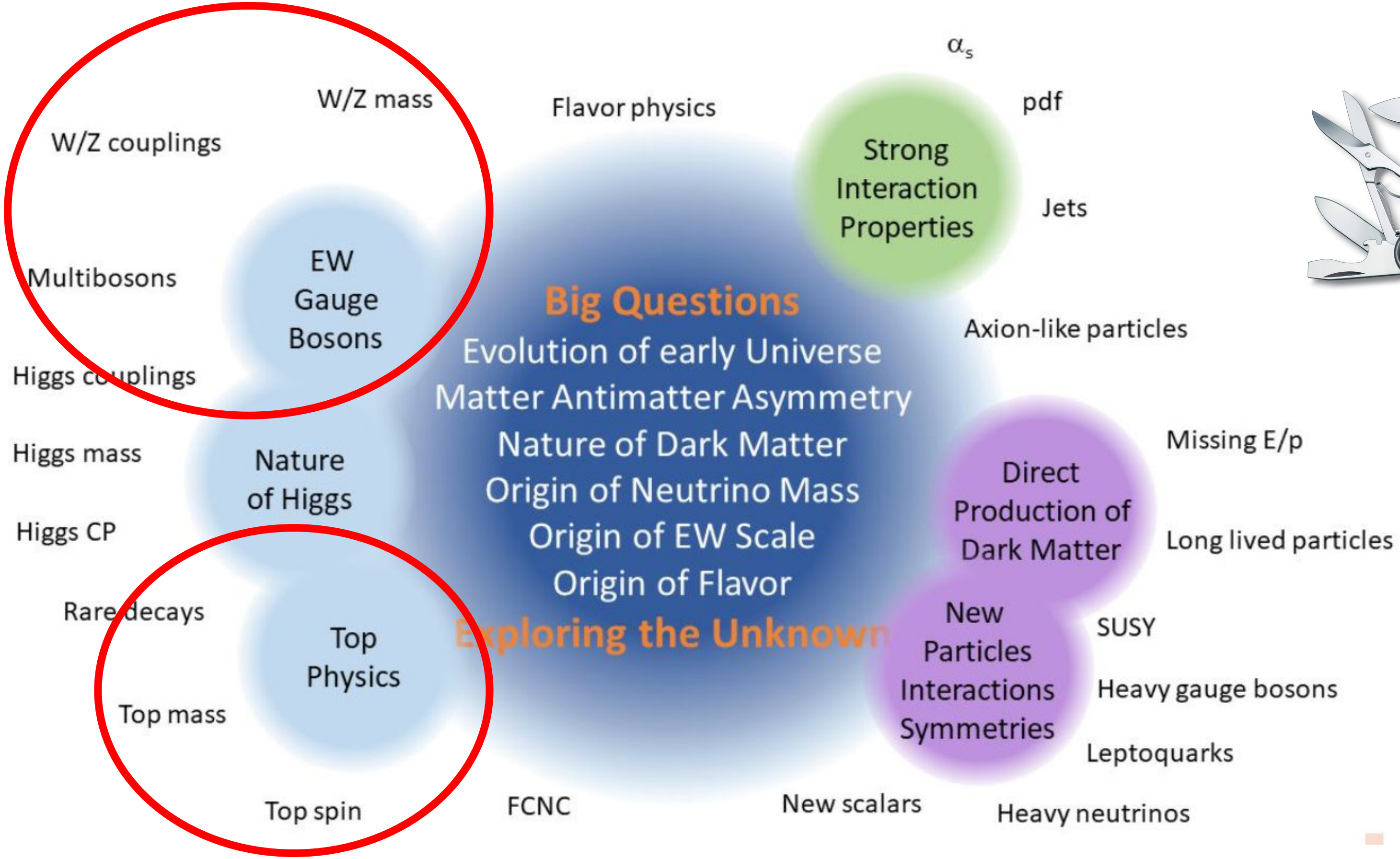




Neutral currents 50;
W/Z boson turns 40;
Top quark now 28;
Higgs turns 11.

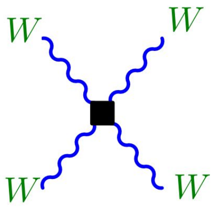


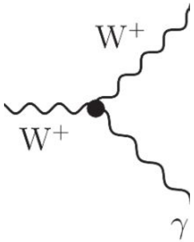



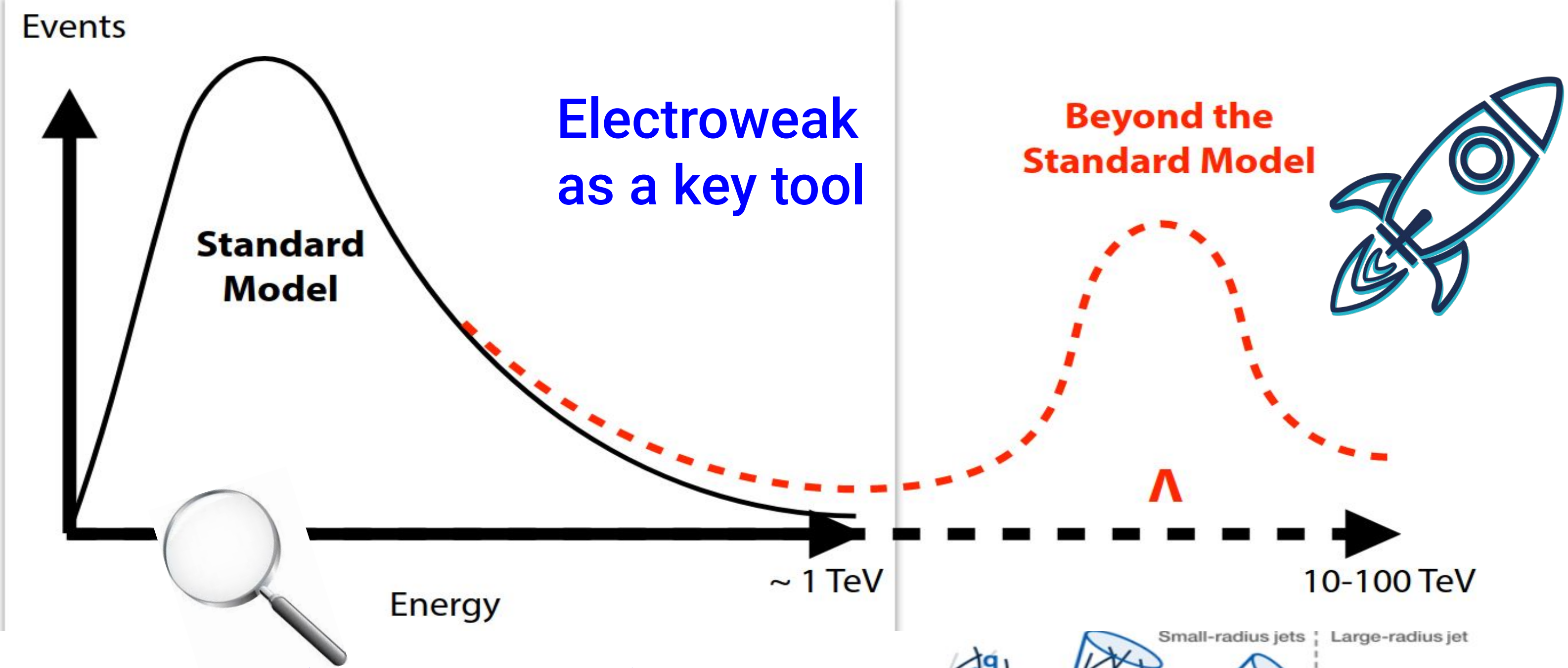
# Seattle snowmass summer meeting 2022




# Direct and indirect searches for BSM

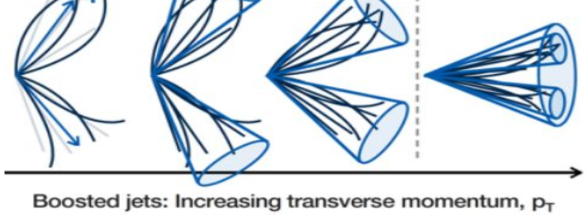


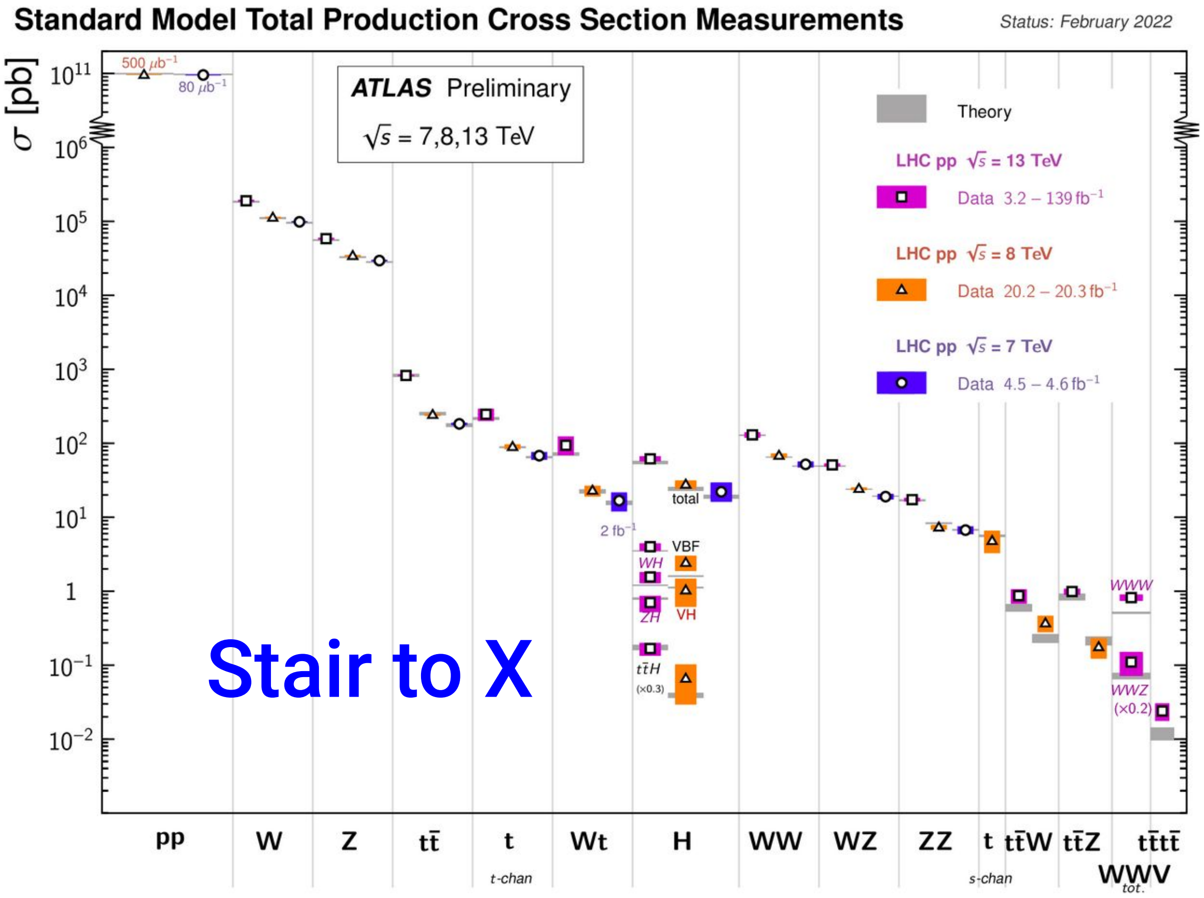




Anomalous couplings, EFT (CP even or odd)

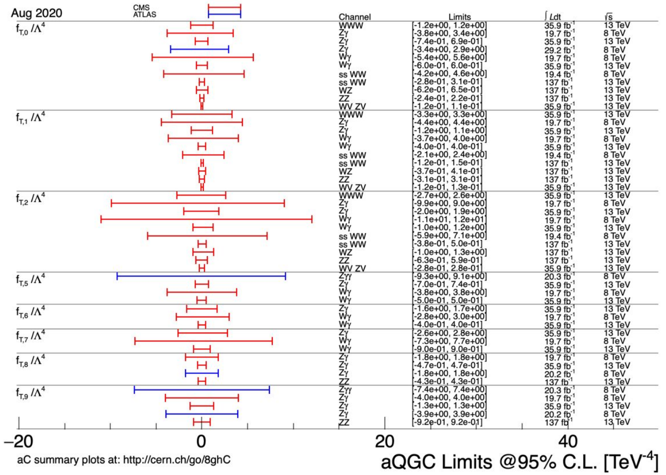
$$L_{\mathrm{EFT}} = L_{\mathrm{SM}} + \sum_i \frac{C_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)} + \sum_i \frac{C_i^{(8)}}{\Lambda^4}\mathcal{O}_i^{(8)} + \ldots$$

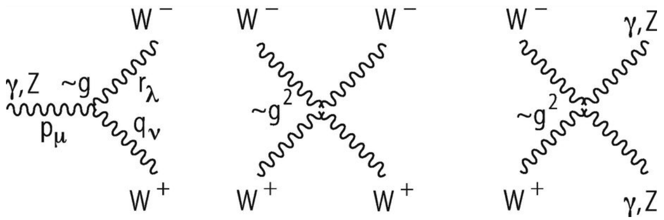


# Rich results at the LHC (ATLAS, CMS)



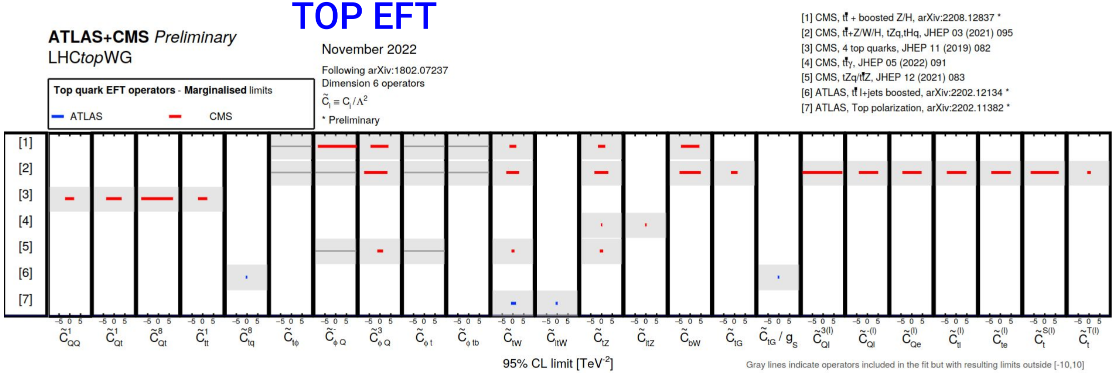

Stair to X



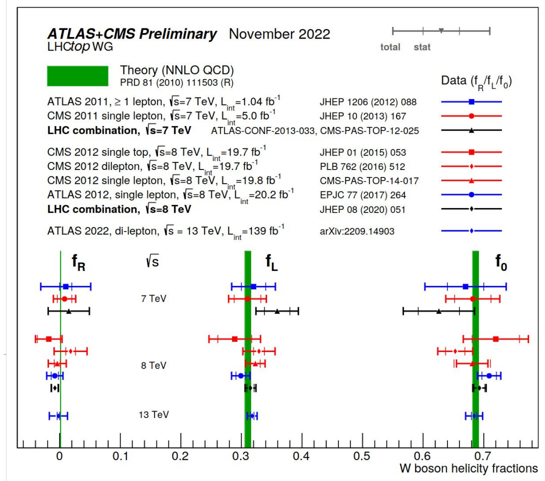



# Rich Results at the LHC (ATLAS, CMS)

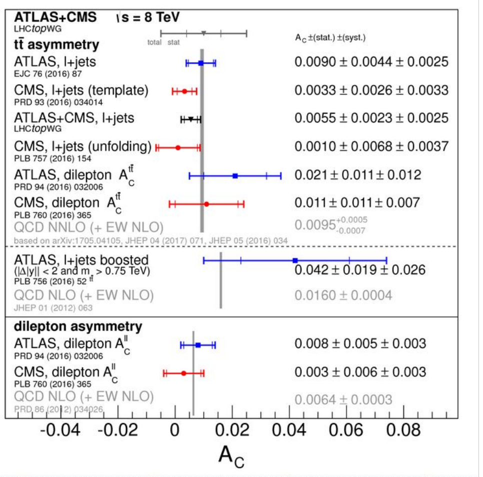
## TOP EFT



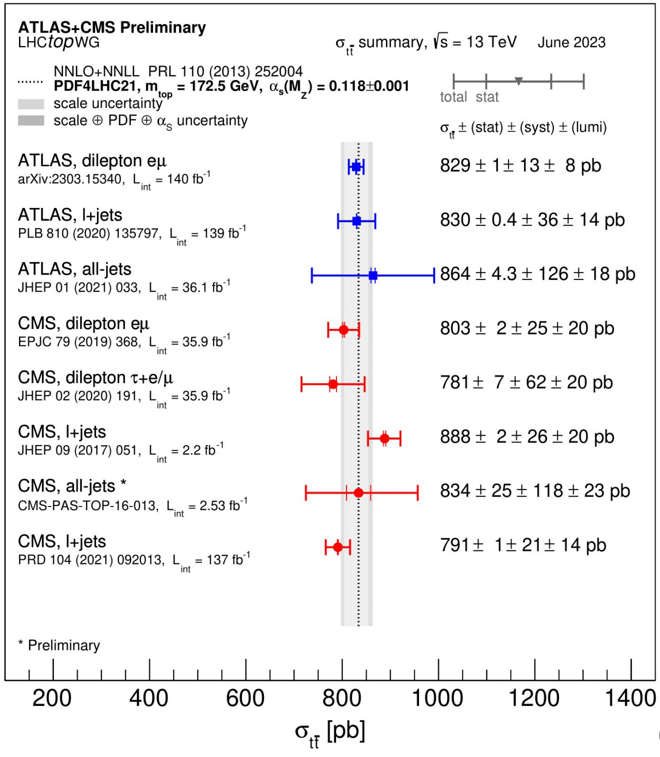

## W helicity fraction (also here)




## Charge Asymmetry




## Top-pair production cross-section



# **Selected Topics** with bias

W Mass
Top Mass
Single V, V decay
Di-boson
VBS
Tri-boson
Four Top
EFT as the new SM
Ewk/Top as novel tools
Run 3 & Future

# W Mass

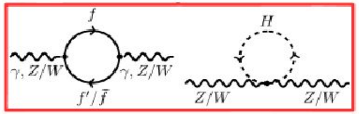
HIGGS AND ELECTROWEAK | FEATURE

**The W boson's midlife crisis**

24 August 2023

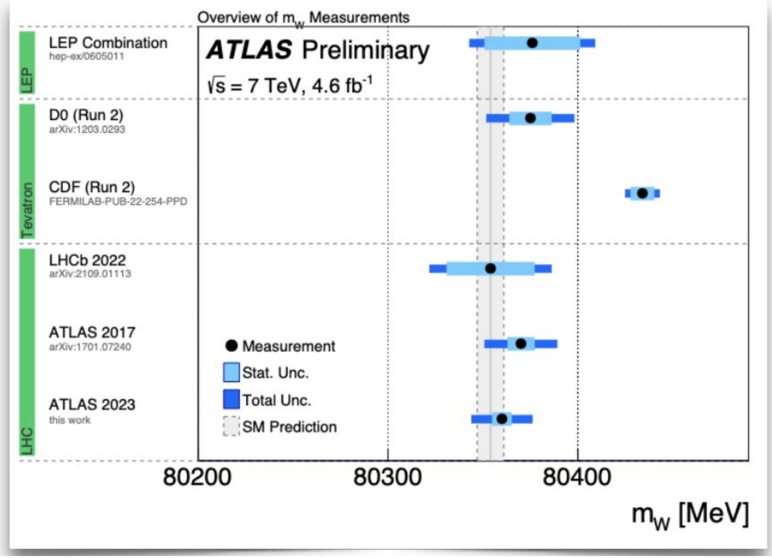
Forty years after its discovery, the W boson continues to intrigue. Chris Hays describes recent progress in understanding a surprisingly high measurement of its mass using data from the former CDF experiment.

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



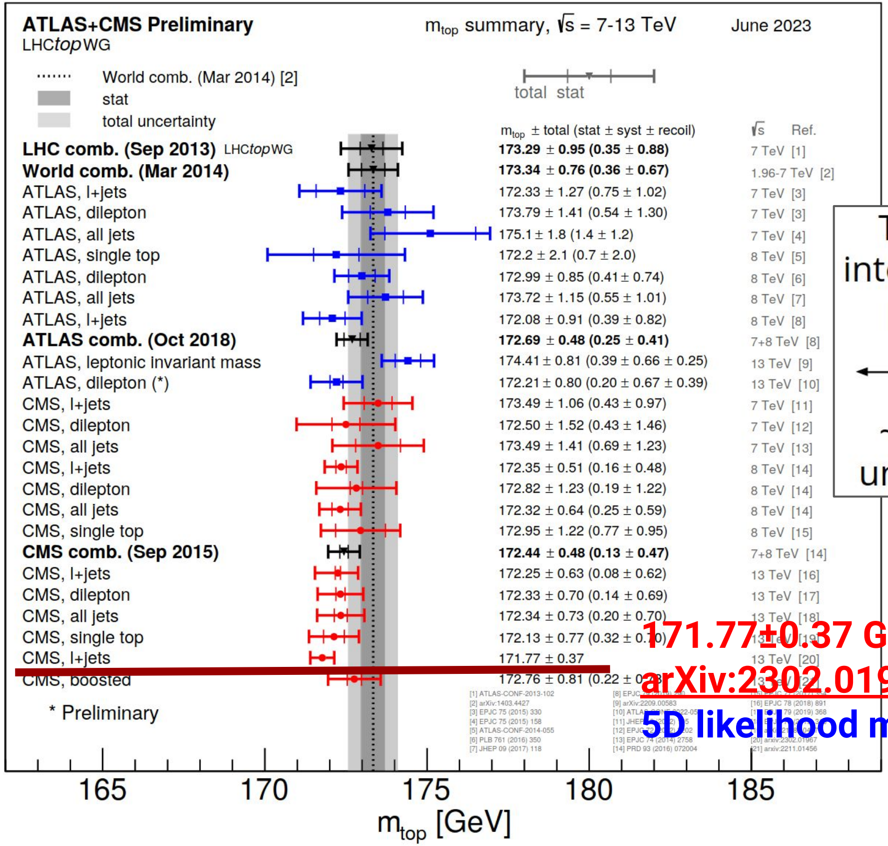

**Powerful tools for consistency test on over-constrained Standard Model**

- 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



# Top mass

## Direct measurements $m_t^{MC}$



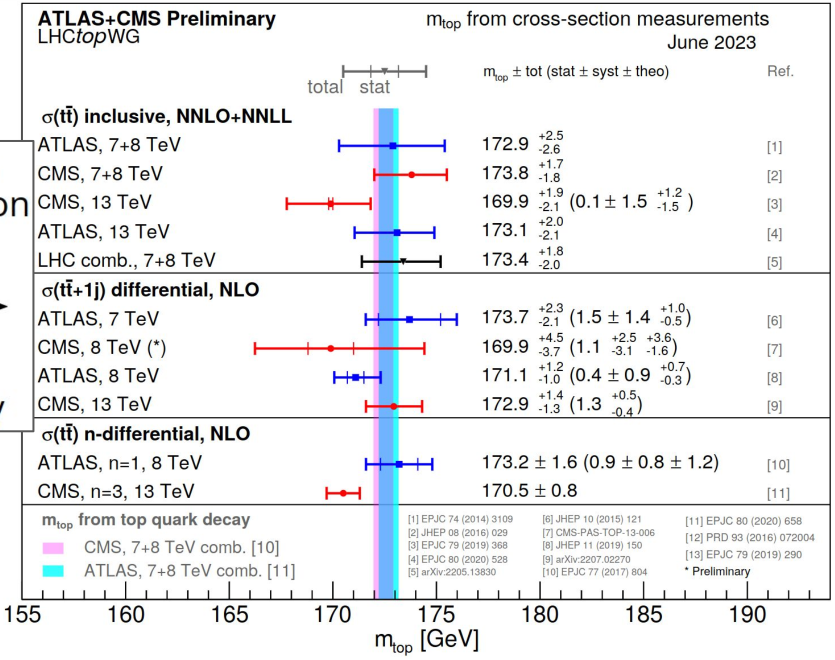

**171.77±0.37 GeV**
**arXiv:2302.01967**
**5D likelihood method**

Top mass interpretation problem

←→

~0.5 GeV uncertainty

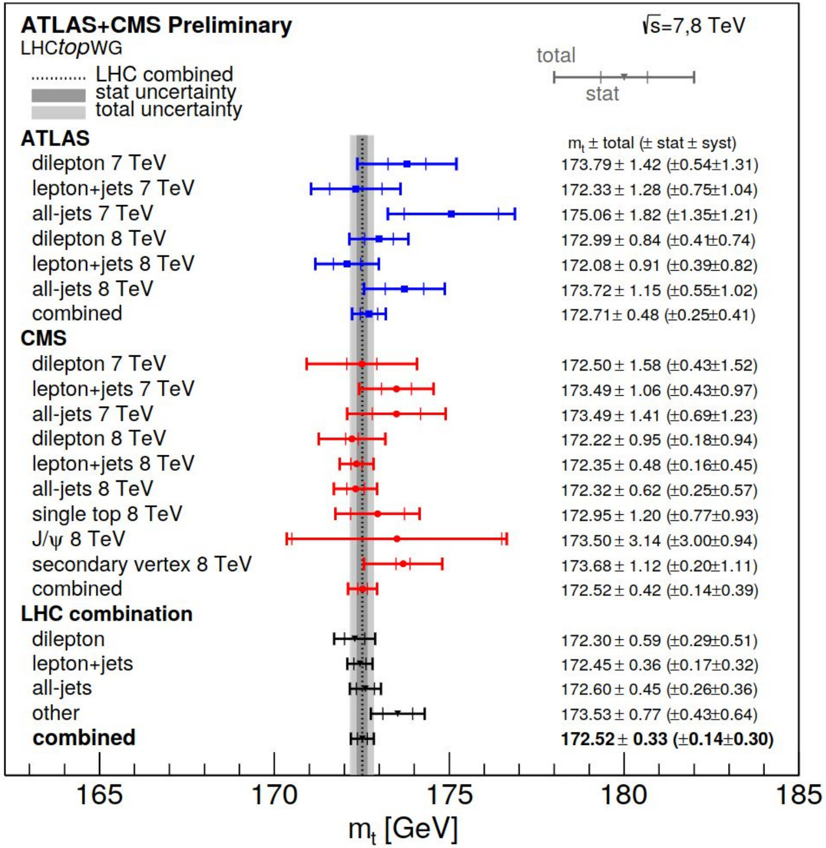
## Indirect measurements $m_t^{pole}$




arXiv:2004.12915, ATL-PHYS-PUB-2023-015

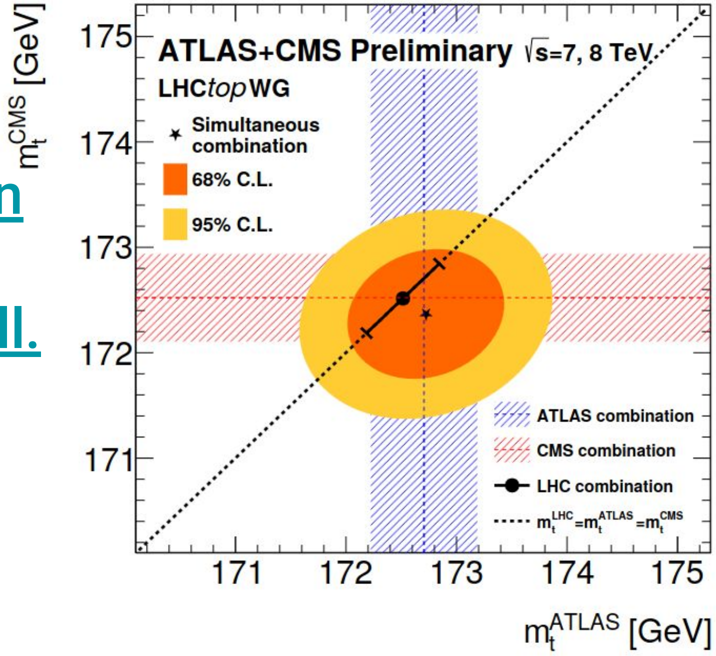
CERN-LPCC-2023-02

# Run I LHC top mass combination



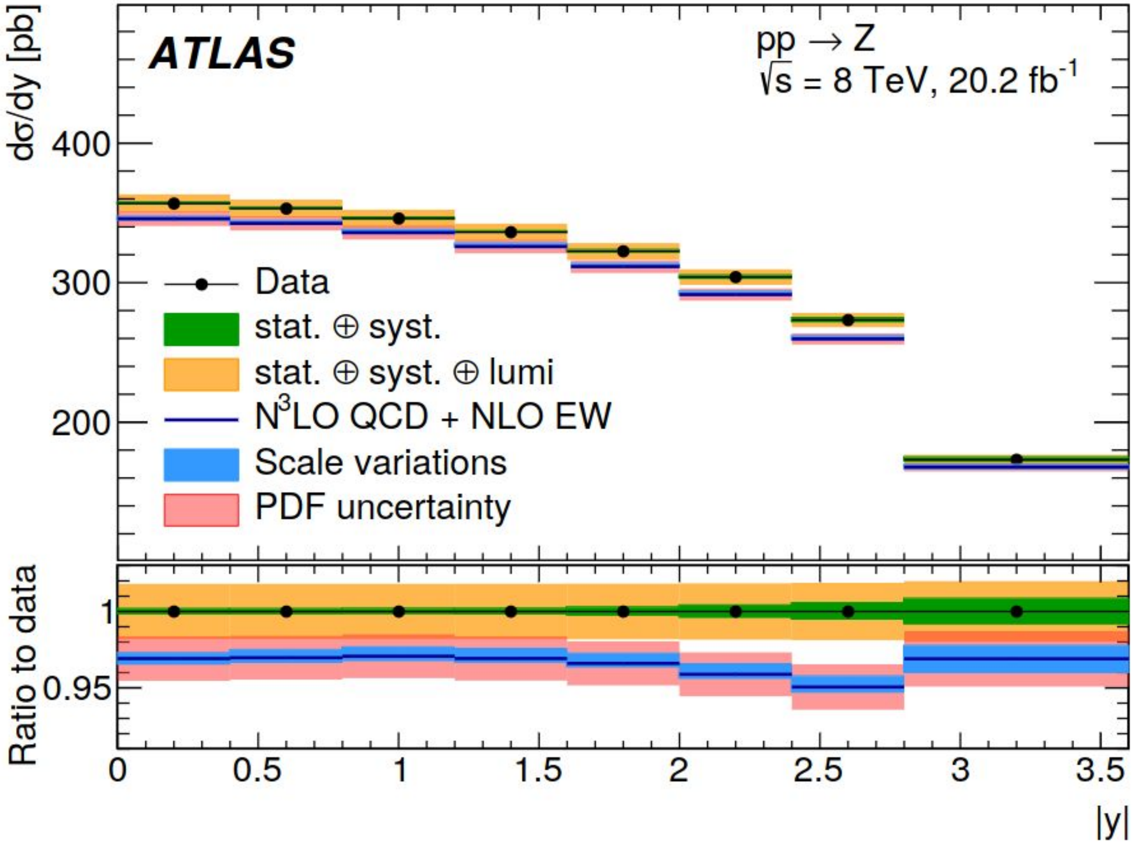

| Uncertainty category | Uncertainty impact [GeV] LHC | ATLAS | CMS |
|---|---|---|---|
| LHC b-JES | 0.18 | 0.17 | 0.25 |
| b tagging | 0.09 | 0.16 | 0.03 |
| ME generator | 0.08 | 0.13 | 0.14 |
| LHC JES 1 | 0.08 | 0.18 | 0.06 |
| LHC JES 2 | 0.08 | 0.11 | 0.10 |

**a precision of 2 per mill.**



arXiv:2309.09318
Eur. Phys. J. C 83 (2023) 628

# Drell-Yan precision



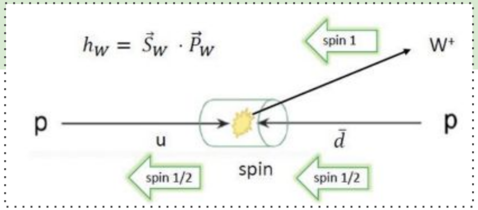

- N3LO QCD predictions obtained from DYTurbo

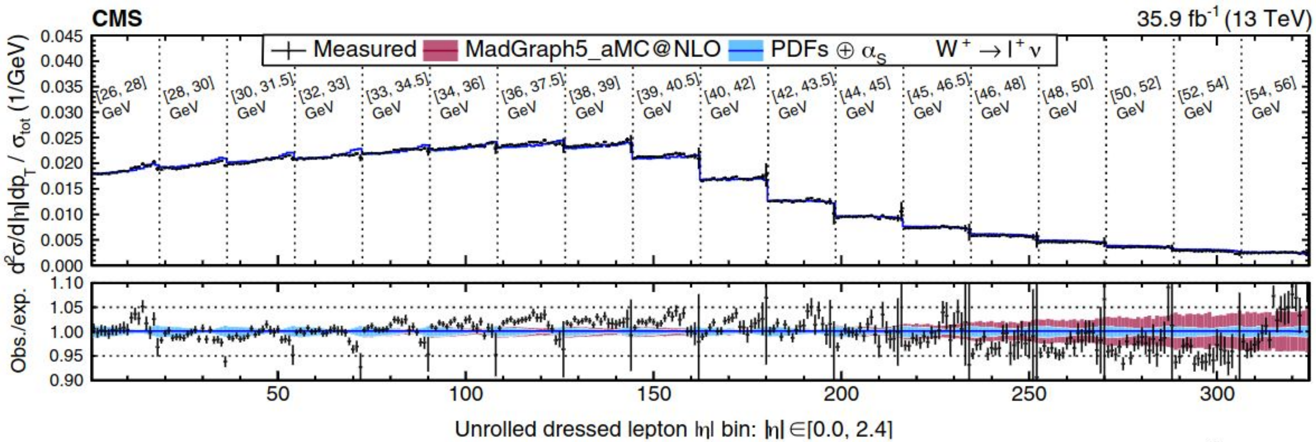
  aN$^3$LO MSHT PDF set.

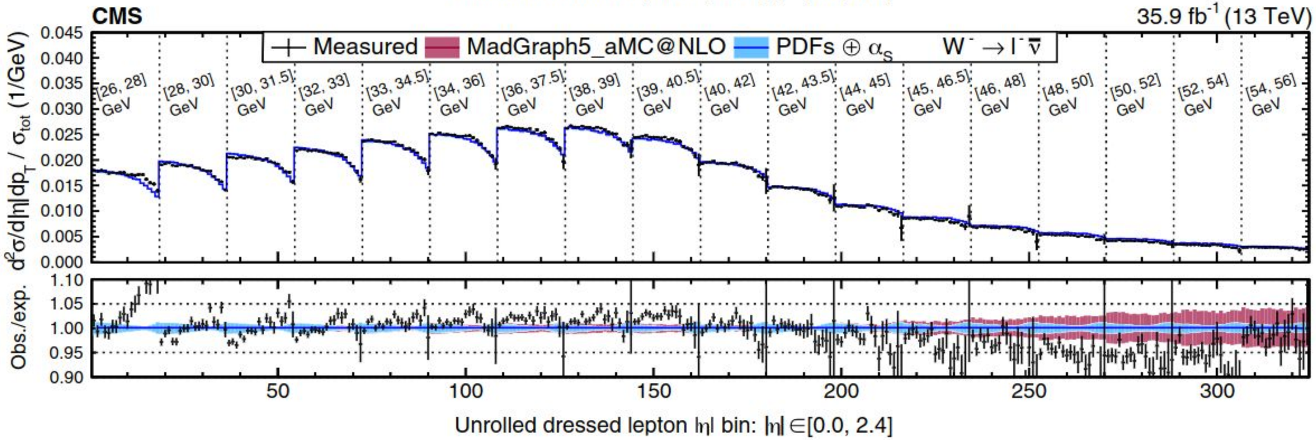
- A negative correction of 0.4% from NLO EW included
- a p-value of 11% if one only includes the uncertainties in the PDFs for the predictions
- 2D differential distributions measured in both papers

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.

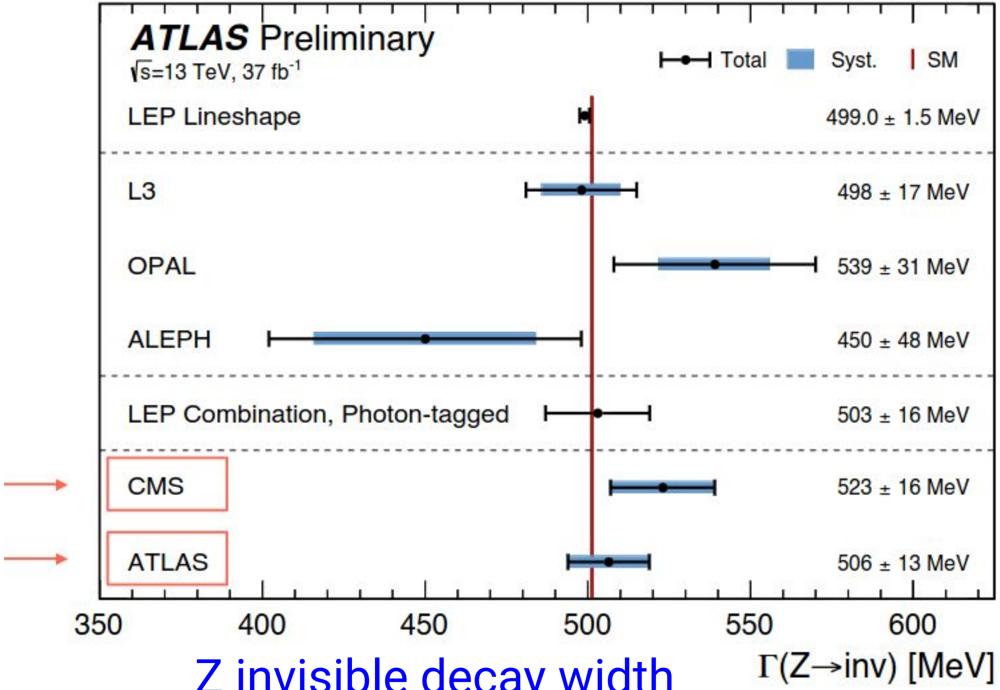
PRD 105 (2022) 072008
PLB 842 (2023) 137563
ATLAS-CONF-2023-053

# W/Z decay

arXiv:2309.12408

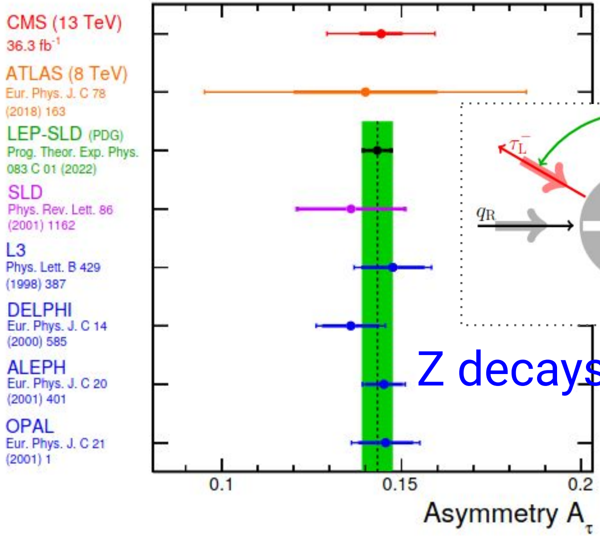
## W decay branch ratio

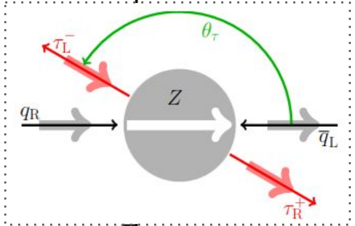
| | CMS | LEP |
|---|---|---|
| $\mathcal{B}(W \to e\overline{\nu}_e)$ | $(10.83 \pm 0.01 \pm 0.10)\%$ | $(10.71 \pm 0.14 \pm 0.07)\ \%$ |
| $\mathcal{B}(W \to \mu\overline{\nu}_\mu)$ | $(10.94 \pm 0.01 \pm 0.08)\%$ | $(10.63 \pm 0.13 \pm 0.07)\ \%$ |
| $\mathcal{B}(W \to \tau\overline{\nu}_\tau)$ | $(10.77 \pm 0.05 \pm 0.21)\%$ | $(11.38 \pm 0.17 \pm 0.11)\ \%$ |
| $\mathcal{B}(W \to q\overline{q}')$ | $(67.46 \pm 0.04 \pm 0.28)\%$ | — |
| 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

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

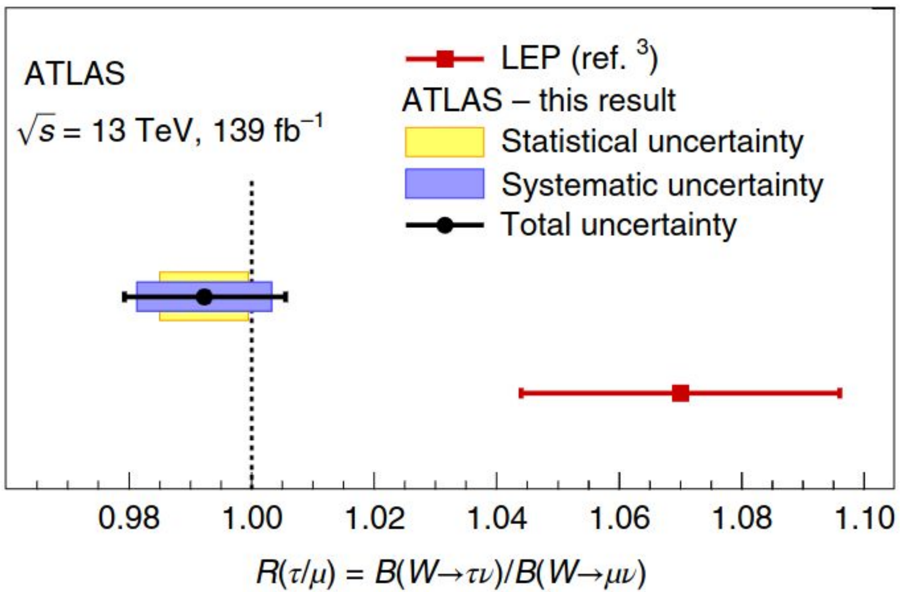


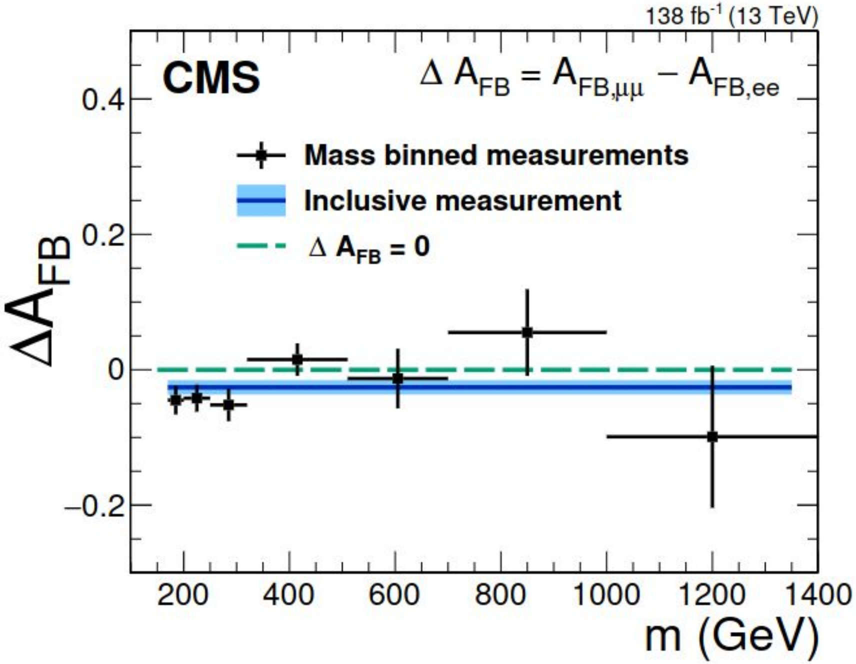

## Z decays into tau

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

# LFUV




The tension LEP noticed is not visible in ATLAS data

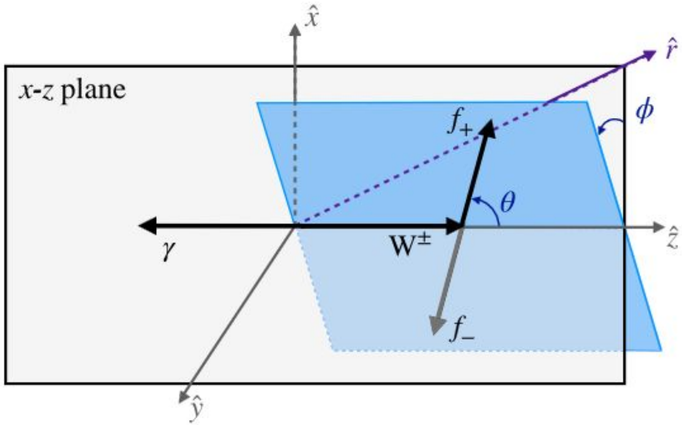



The inclusive measurement $\Delta A_{FB}$ differs from zero at the level of 2.4 standard deviations

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



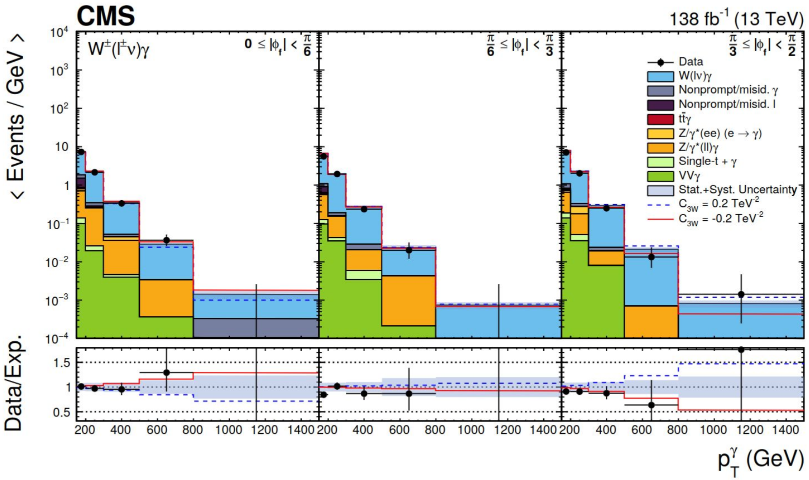



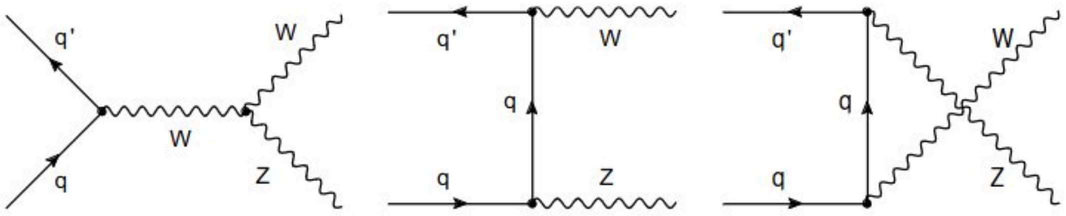

Table 4: Best fit values of $C_{3W}$ and corresponding 95% CL confidence intervals as a function of the maximum $p_T^\gamma$ bin included in the fit.

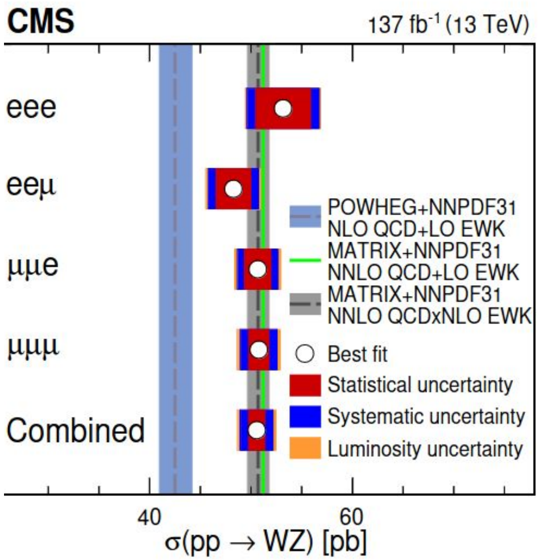
| $p_T^\gamma$ cutoff (GeV) | Best fit $C_{3W}$ (TeV$^{-2}$) | | Observed 95% CL (TeV$^{-2}$) | | Expected 95% CL (TeV$^{-2}$) | |
|---|---|---|---|---|---|---|
| | SM+int. only | SM+int.+BSM | SM+int. only | SM+int.+BSM | SM+int. only | SM+int.+BSM |
| 200 | −0.86 | −0.24 | [−2.01, 0.38] | [−0.76, 0.40]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

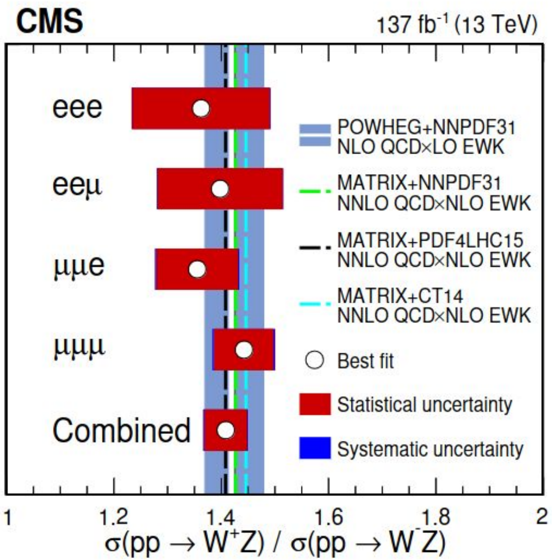
**The technique will also be valuable in the future when sufficiently small values of aGCs are probed such that the interference contribution will be dominant**

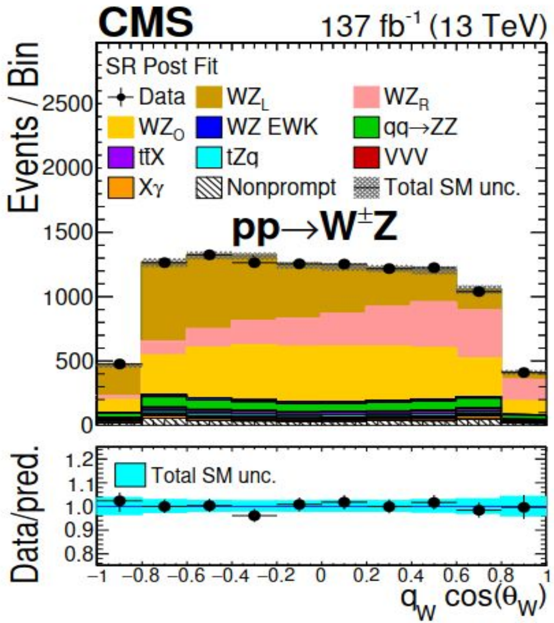
JHEP 07 (2022) 032

# WZ (polarization)



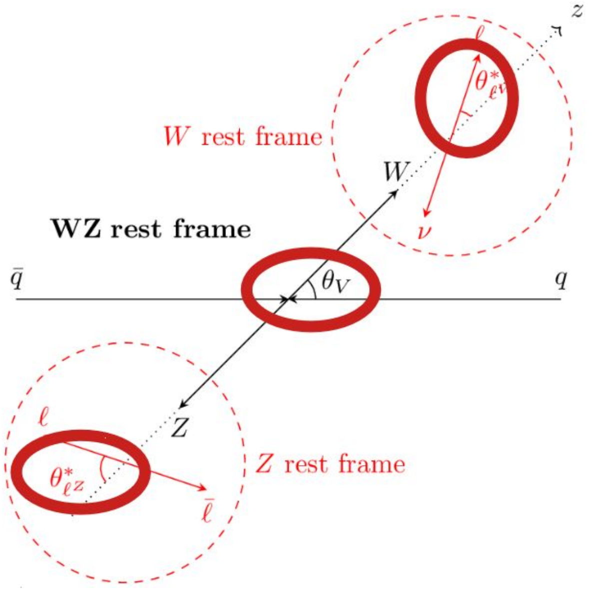



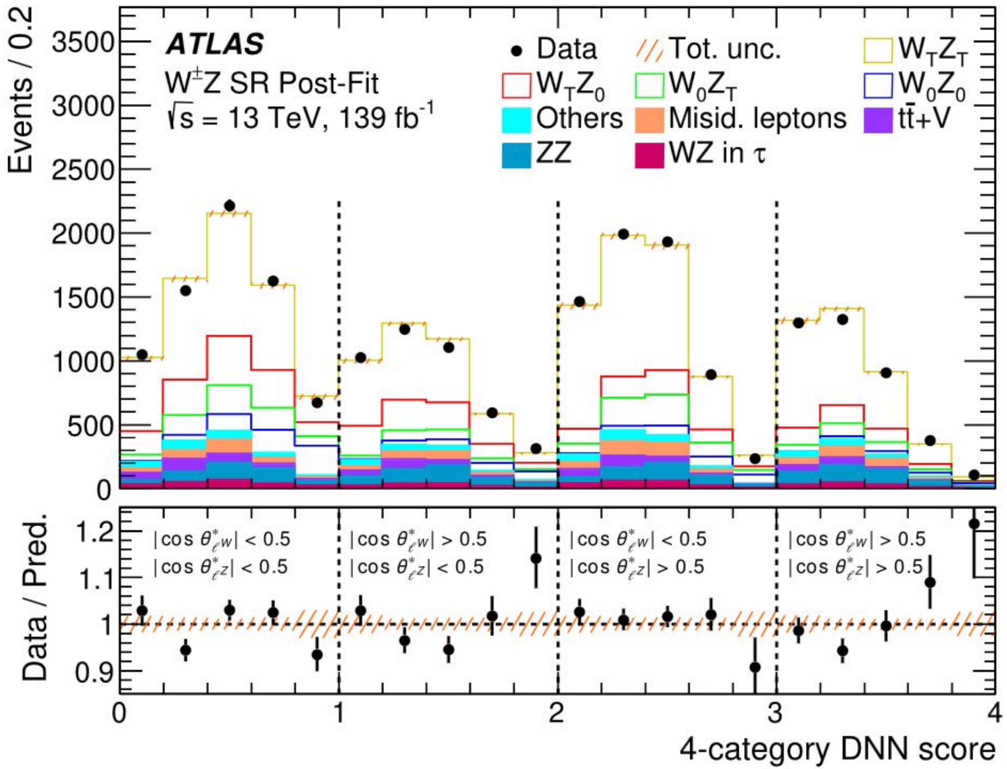

First observation of single longitudinally polarized W bosons in WZ production! 5.6σ (4.3σ) obs (exp).

# 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



Phys. Lett. B 812 (2020) 136018

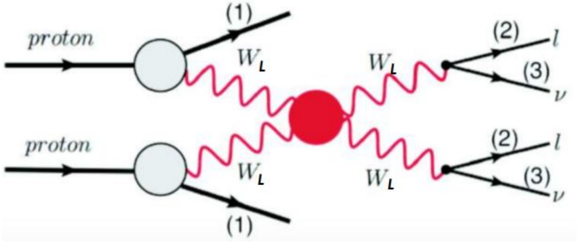
# Polarized VBS

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

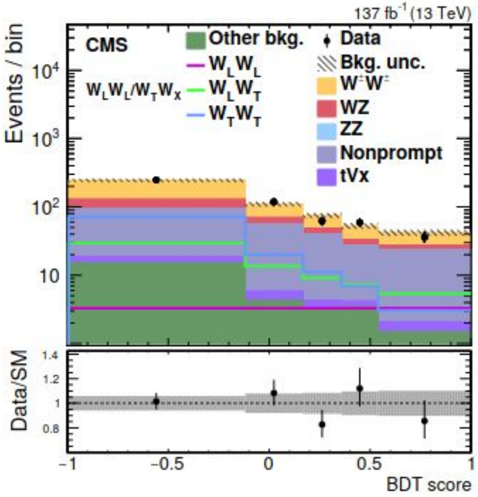
☑ $W_L^{\pm} W_L^{\pm}$: signal BDT ($W_L^{\pm} W_L^{\pm}$ vs $W_T^{\pm} W_X^{\pm}$) and inclusive BDT (VBS vs Bkg.)

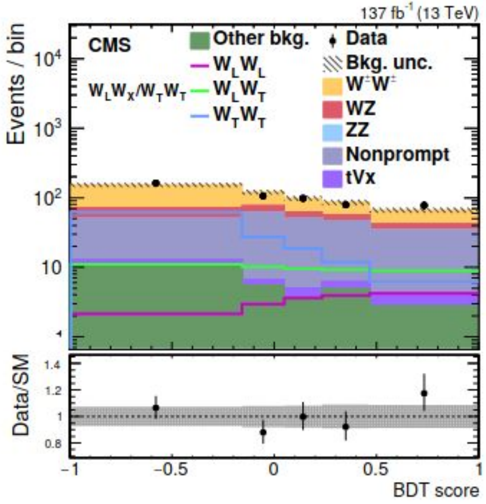
☑ $W_L^{\pm} W_X^{\pm}$: signal BDT ($W_L^{\pm} W_X^{\pm}$ vs $W_T^{\pm} W_T^{\pm}$) and inclusive BDT (VBS vs Bkg.)

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

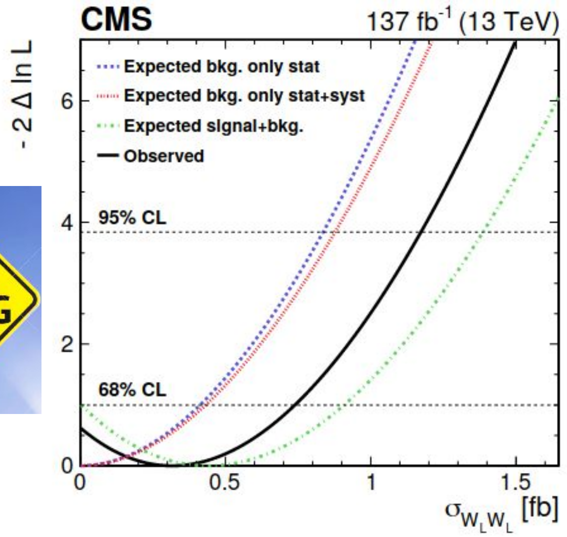



Observed (expected) significance for LL and LT+LL: 0.88 (1.17)σ; 2.3 (3.1)σ



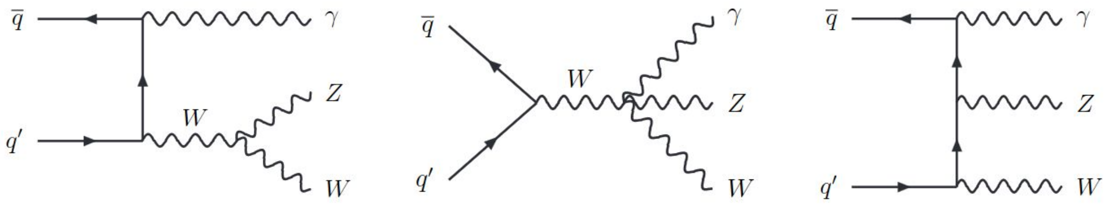







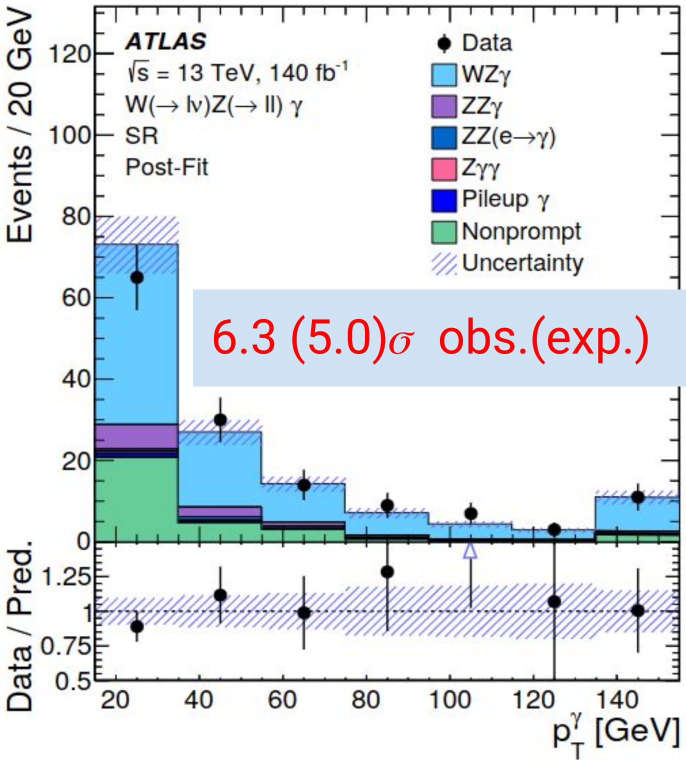
arXiv:2305.16994

# WZγ observation




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

| Process | SR | ZZγ CR | ZZ(e → γ) 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 $\gamma$ | 1.9 ± 0.7 | - | - |
| Total yield | 139 ± 12 | 23 ± 5 | 33 ± 6 |
| Data | 139 | 23 | 33 |




6.3 (5.0)$\sigma$ obs.(exp.)

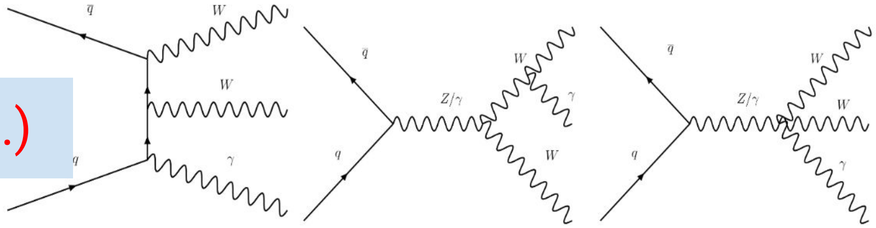
$\sigma_{WZ\gamma} = 2.01 \pm 0.30\,(\text{stat.}) \pm 0.16\,(\text{syst.})$ fb.

arXiv:2310.05164

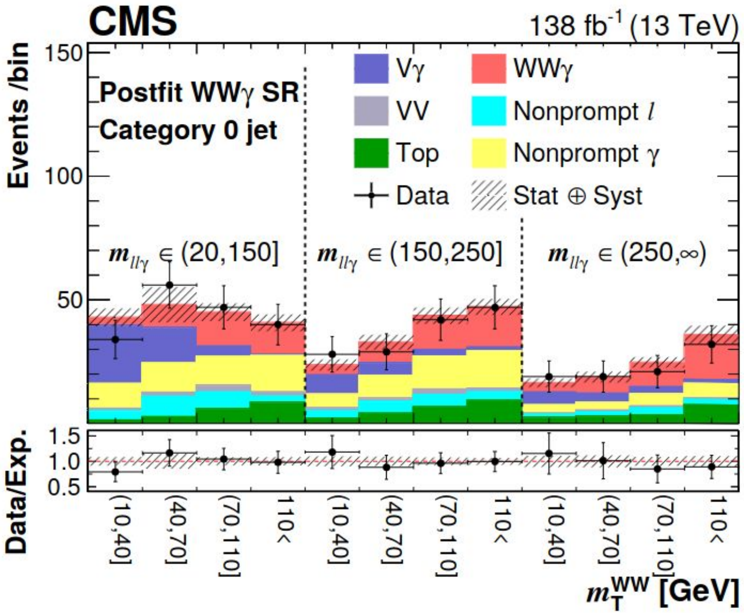
# WWγ Observation

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

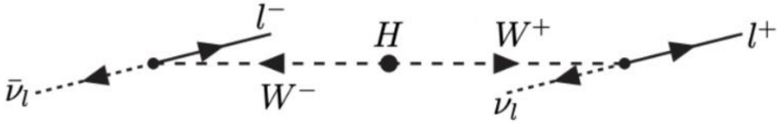
5.6 (4.7)$\sigma$ obs.(exp.)



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




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




| $\sigma$ upper limits obs. (exp.) [fb] | $\kappa_q$ 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) |

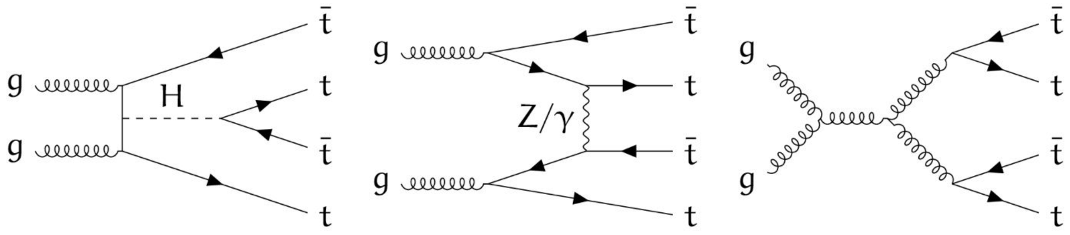
[EPJC 83 (2023) 496](#) [PL B 847 (2023) 138290](#)

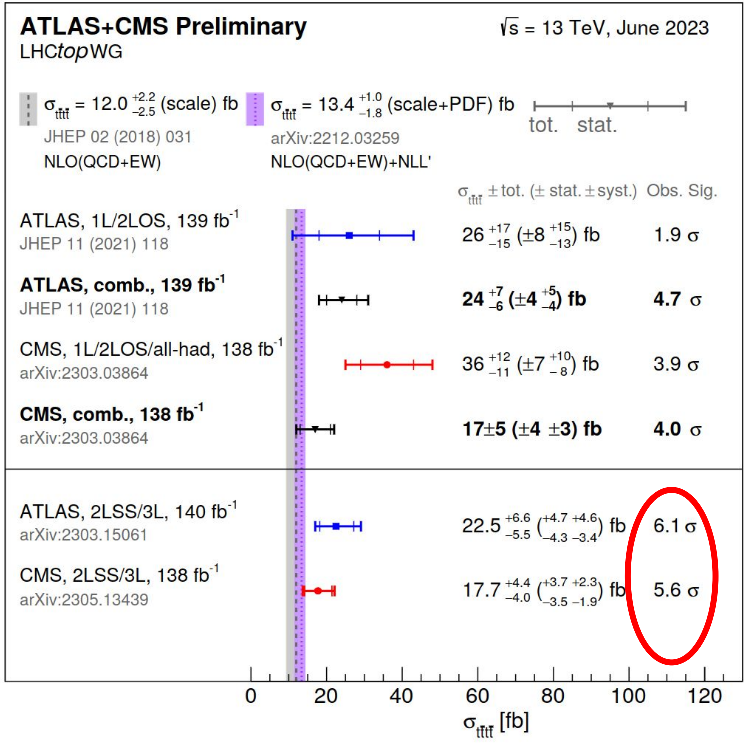
# Four Top

## Four top production (tttt): a very rare standard model (SM) process

- $\sigma(t\bar{t}t\bar{t})_{NLO(QCD+EW)}$ = 12.0 ± 2.4 fb [JHEP 02 (2018) 031]
- $\sigma(t\bar{t}t\bar{t})_{NLO(QCD+EW)+NLL'}$ = $13.4^{+1.0}_{-1.8}$ fb [arXiv:2212.03259]

➔ **Probe of top-Higgs Yukawa coupling**
➔ **Heaviest final state observed at LHC**
➔ **Sensitivity to wide range of new physics scenarios and effective field theory (EFT) operators**

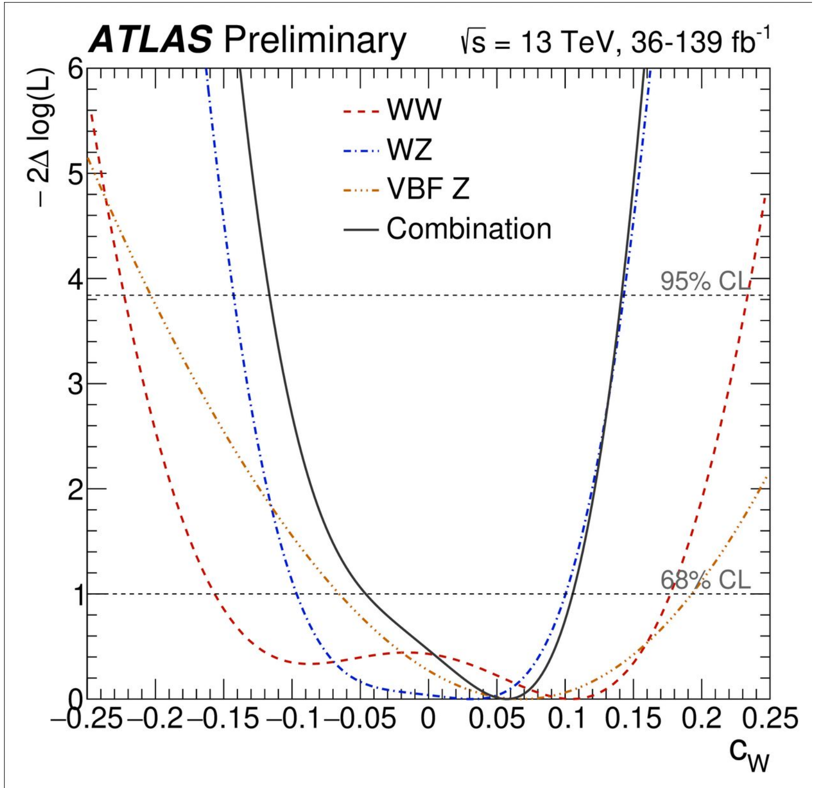


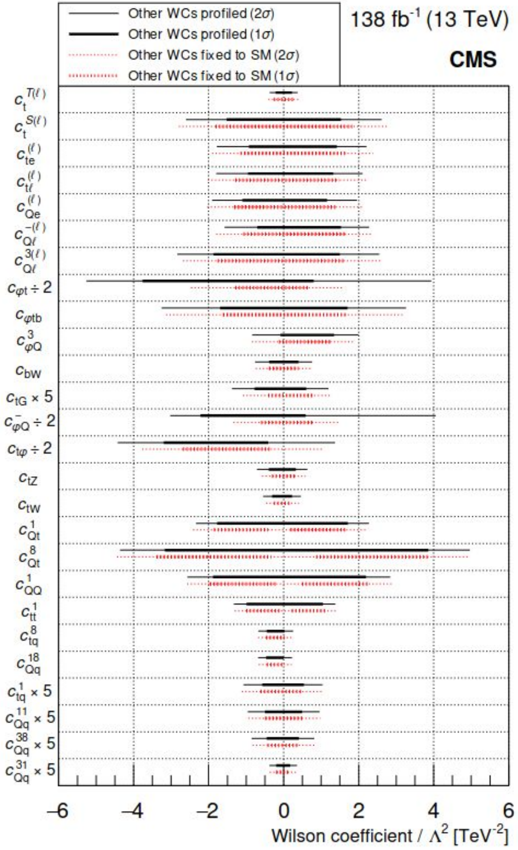

**Observations based on Re-analysis of Run 2 datasets.** **Systematically limited**

ATL-PHYS-PUB-2021-022 ATL-PHYS-PUB-2022-037
arXiv:2307.15761 arXiv:2211.08353

# SMEFT: The new Standard Model




Interpretation of fiducial differential cross-sections



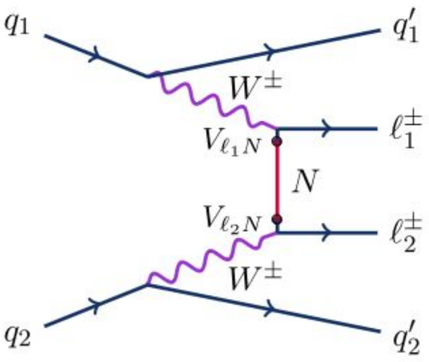

top quark production with additional leptons,

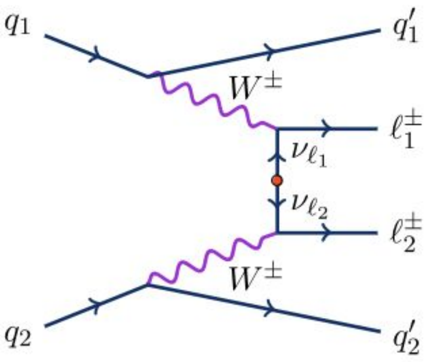
26 EFT operators simultaneously fit to the data

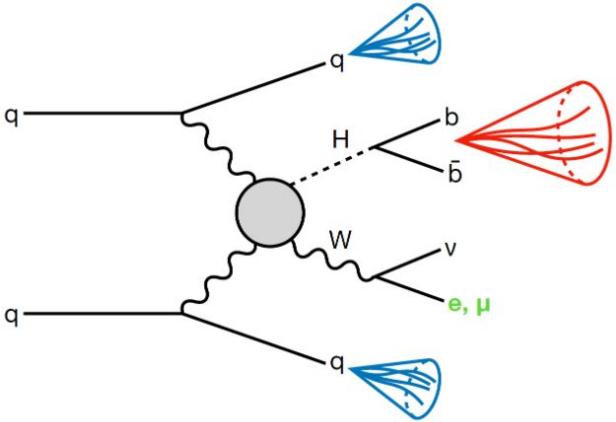
# VBS as a novel tool

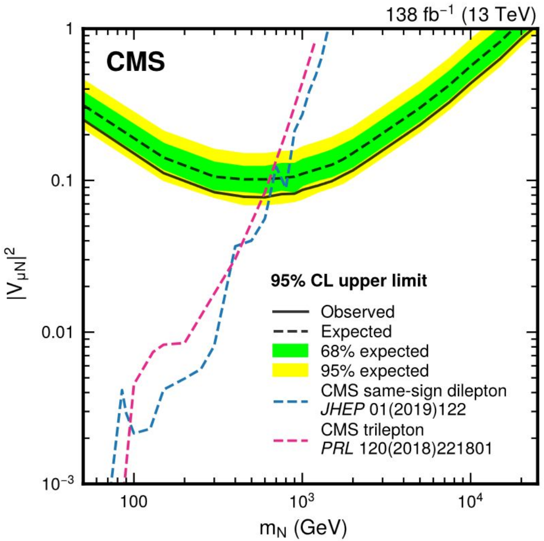
Phys. Rev. Lett. 131 (2023) 011803
Eur.Phys.J.C 83 (2023) 9, 824

ATLAS-CONF-2023-057
CMS-PAS-HIG-23-007




Heavy Majorana searched up to 23TeV!

0νμμ experiment and effective neutrino mass probe

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

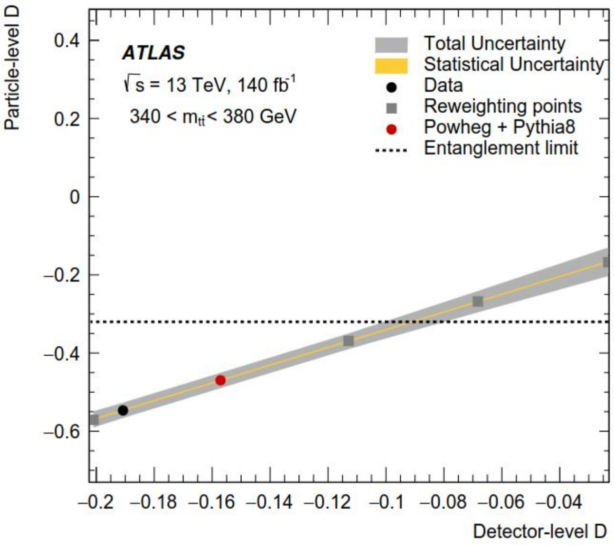
Fit: $\hat{\mu} = 2.6^{+4.6}_{-4.5}$

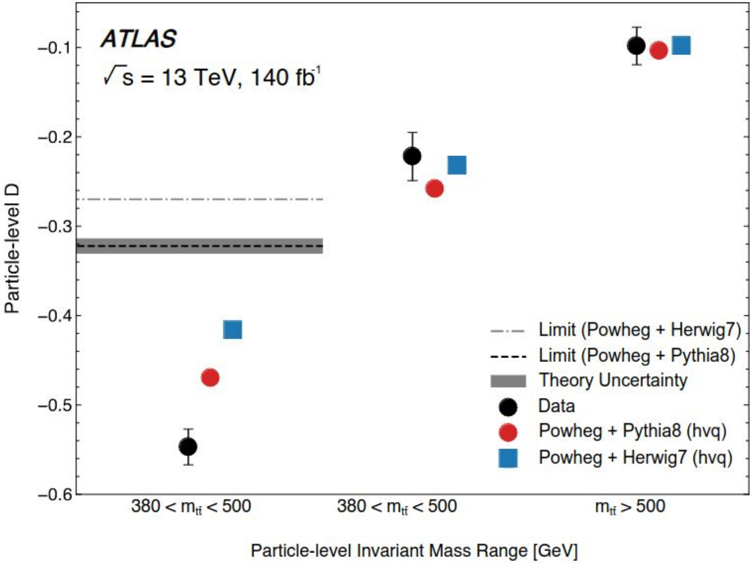
# arXiv:2311.07288 Top pair as a novel tool: Quantum Entanglement

- **Highest-energy observation of quantum entanglement** between a pair of qubits
- **Quantum Tomography:** reconstruction of the quantum state from measurement of a set of expectation values, see e.g., : EPJP (2021), Quantum (2022), EPJC (2022)
- **A single observable** can be used as an entanglement witness, with the QE criteria:

$$D = -3 \cdot \langle \cos\varphi \rangle\,, \quad D < -1/3$$

The shape of $\cos\varphi$/D is distorted by detector and event-selection effects for which it has to be corrected.



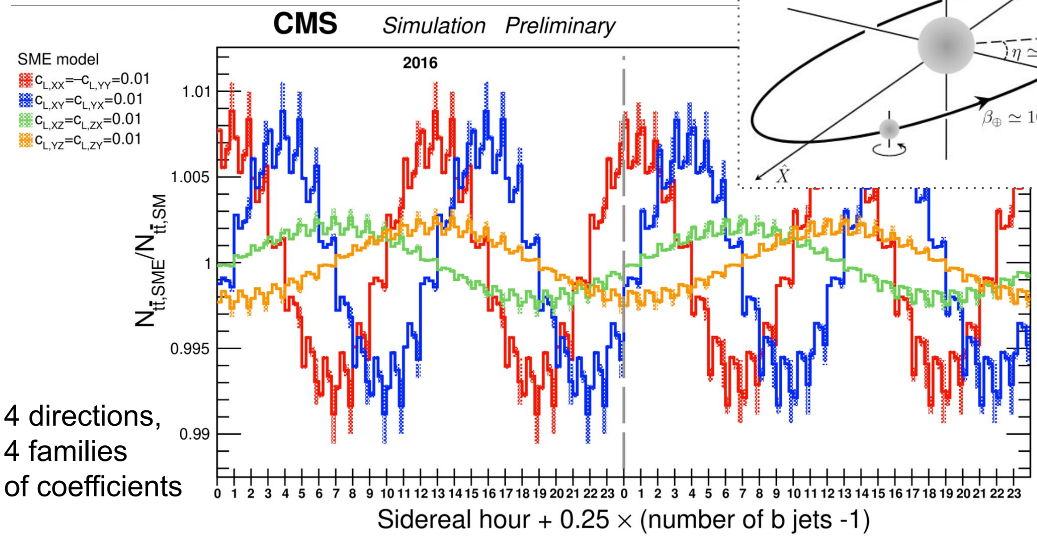



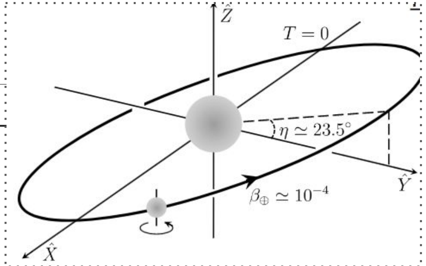

Non-relativistic QCD effects close to threshold, not included in MC generators

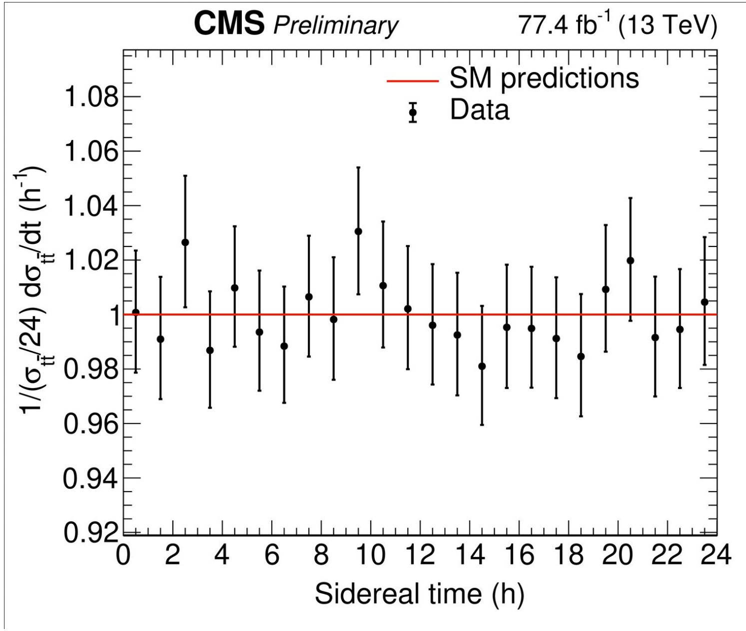
CMS-PAS-TOP-22-007

# Top pair as a novel tool: Lorentz Violation

- Dilepton eμ final state with 2016-2017 Run 2 dataset
- Number of b-jets in bins of sidereal time
  - Separate between $t\bar{t}$ and tW background
- Modulation of cross section with sidereal time




4 directions, 4 families of coefficients

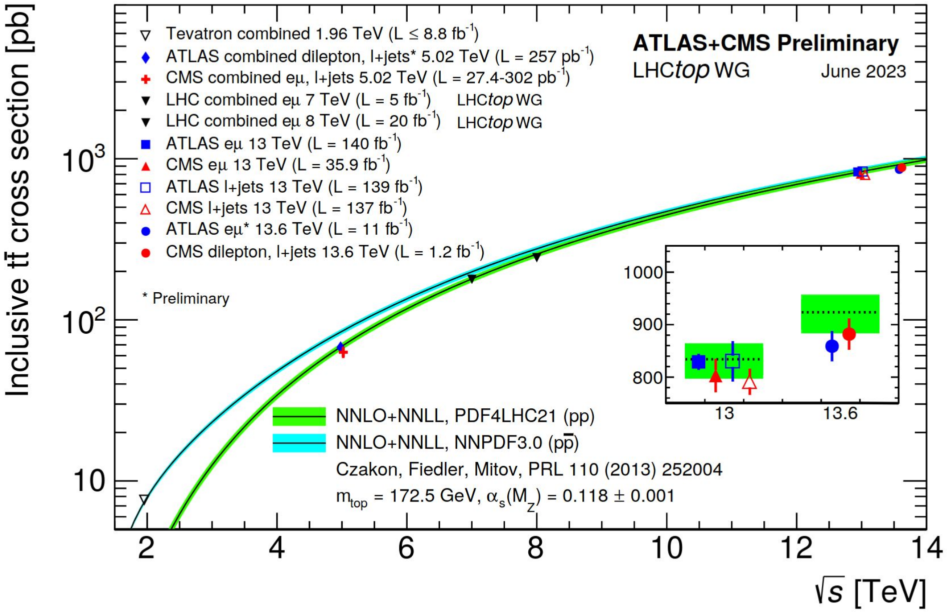
No significant deviation and significant improvement (~100) over D0 (PRL 108 (2012) 261603)

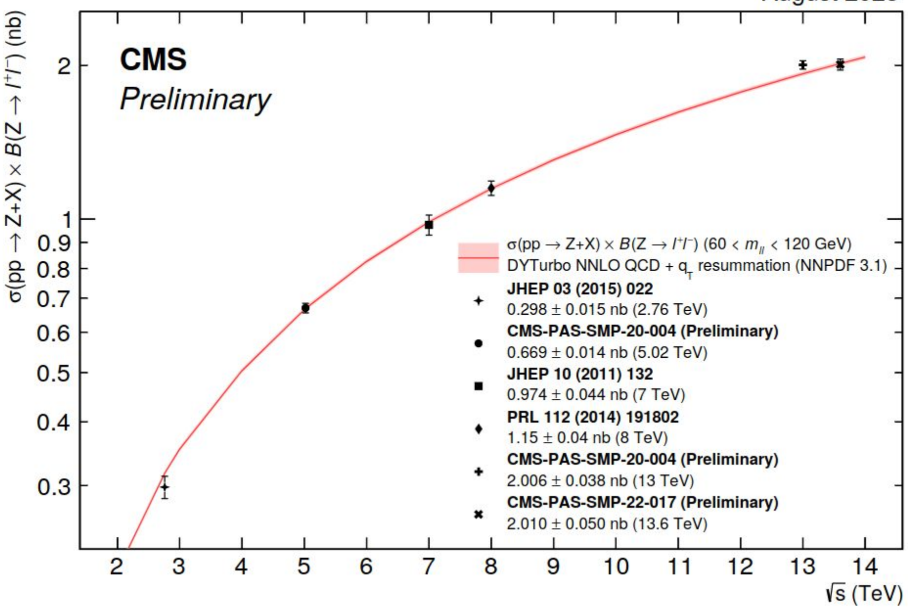
JHEP 08 (2023) 204 arXiv:2308.09529
arXiv:2311.09715 CMS-PAS-SMP-22-017

# Run3

fast well to arrive at a new energy frontier
13.6 TeV

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




$t\bar{t}$ cross section and $t\bar{t}$/Z ratio
relative uncertainty already small

DY cross section

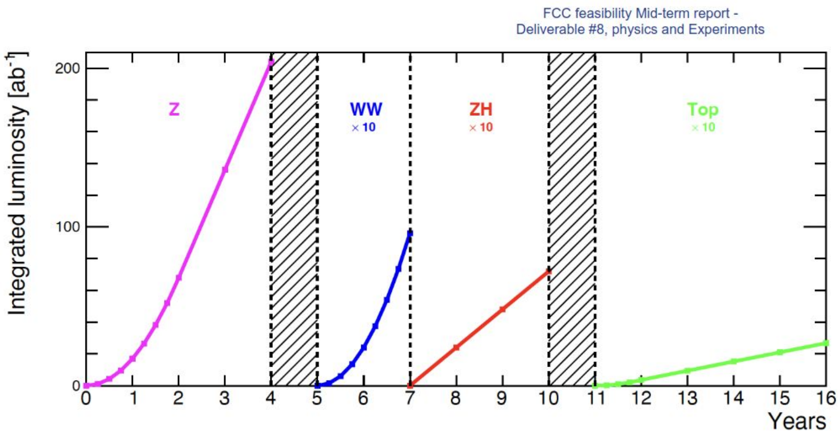
# Future

**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 [$\times10^{34}$ cm$^{-2}$s$^{-1}$] | **3** | **32** | **10** | - |
| | | $\int L\,dt$ [ab$^{-1}$, 2 IPs] | 5.6 | 16 | 2.6 | - |
| | | Event yields [2 IPs] | $1\times10^6$ | $7\times10^{11}$ | $2\times10^7$ | - |
| Run Time [years] | | | 10 | 2 | 1 | 5 |
| TDR (Latest) | 30 MW | $L$ / IP [$\times10^{34}$ 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] | $2.6\times10^6$ | $2.5\times10^{12}$ | $1.3\times10^8$ | $4\times10^5$ |
| | 50 MW | $L$ / IP [$\times10^{34}$ 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] | $4.3\times10^6$ | $4.1\times10^{12}$ | $2.1\times10^8$ | $6\times10^5$ |

# 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<br>Beam energy calibration |
| $\Gamma_Z$ (keV) | 2495200 | ± | 2300 | **4** | 25 | From Z line shape scan<br>Beam energy calibration |
| $\sin^2\theta_W^{eff}(\times 10^6)$ | 231480 | ± | 160 | **2** | 2.4 | From $A_{FB}^{\mu\mu}$ at Z peak<br>Beam energy calibration |
| $1/\alpha_{QED}(m_Z^2)(\times 10^3)$ | 128952 | ± | 14 | **3** | small | From $A_{FB}^{\mu\mu}$ off peak<br>QED&EW errors dominate |
| $R_\ell^Z$ $(\times 10^3)$ | 20767 | ± | 25 | **0.06** | 0.2-1 | Ratio of hadrons to leptons<br>Acceptance for leptons |
| $\alpha_s(m_Z^2)$ $(\times 10^4)$ | 1196 | ± | 30 | **0.1** | 0.4-1.6 | From $R_\ell^Z$ |
| $\sigma_{had}^0$ $(\times 10^3)$ (nb) | 41541 | ± | 37 | **0.1** | 4 | Peak hadronic cross section<br>Luminosity measurement |
| $N_\nu(\times 10^3)$ | 2996 | ± | 7 | **0.005** | 1 | Z peak cross sections<br>Luminosity measurement |
| $R_b$ $(\times 10^6)$ | 216290 | ± | 660 | **0.3** | $< 60$ | Ratio of $b\bar{b}$ to hadrons<br>Stat. extrapol. from SLD |
| $A_{FB}^b, 0$ $(\times 10^4)$ | 992 | ± | 16 | **0.02** | 1-3 | b-quark asymmetry at Z pole<br>From jet charge |
| $A_{FB}^{pol,\tau}$ $(\times 10^4)$ | 1498 | ± | 49 | **0.15** | $<2$ | $\tau$ polarization asymmetry<br>$\tau$ decay physics |
| $\tau$ lifetime (fs) | 290.3 | ± | 0.5 | **0.001** | 0.04 | Radial alignment |
| $\tau$ mass (MeV) | 1776.86 | ± | 0.12 | **0.004** | 0.04 | Momentum scale |
| $\tau$ 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<br>Beam energy calibration |
| $\Gamma_W$ (MeV) | 2085 | ± | 42 | **1.2** | 0.3 | From WW threshold scan<br>Beam energy calibration |

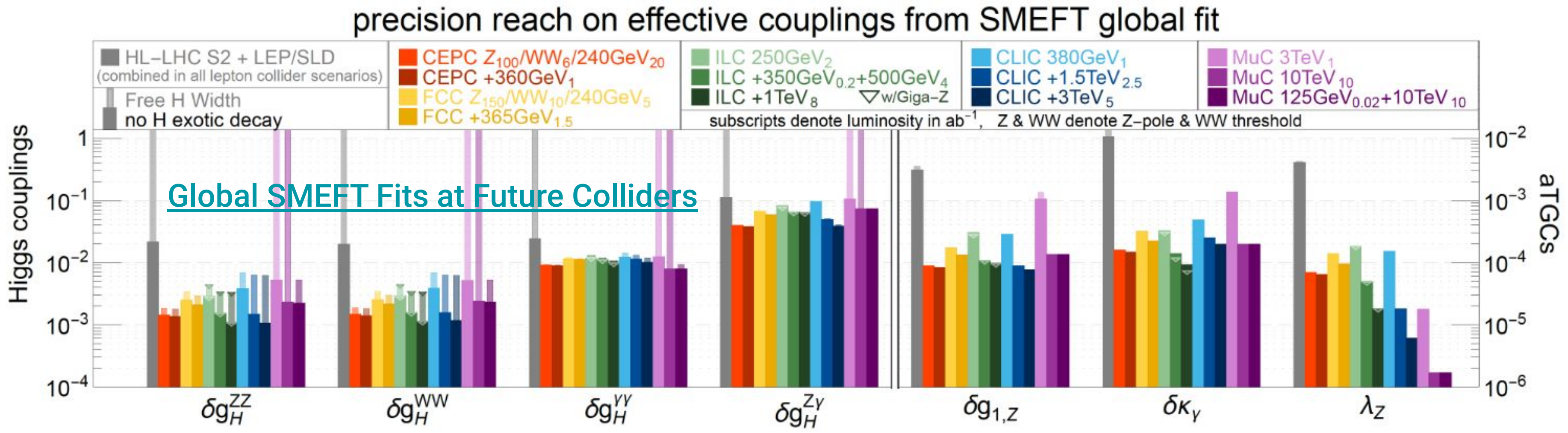
FCC feasibility Mid-term report -Deliverable #8, physics and Experiments

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:

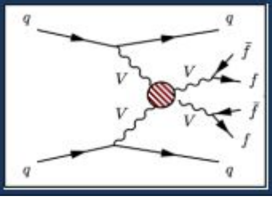
- ~ $10^{13}$ W
- ~ $10^{12}$ Z
- ~ $10^{11}$ tt
- ~ $10^{10}$ H
- ~ $10^{9}$ ttH
- ~ $10^{7}$ HH
- ~ $10^{5}$ gluino pairs m=8 TeV

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 and top physics**
  - Precise measurements, rare process discovery
    - NNNLO/polarization/interference/global…
  - Tools to explore unknown: QE, Lorentz Violation, 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† |
|---|---|---|---|---|---|
| $m_Z$<br>$\Gamma_Z$<br>$\sin^2\theta^{\ell}_{\mathrm{eff}}$ | 2.1 MeV<br>2.3 MeV<br>$1.6\times10^{-4}$ | 0.004 (0.1) MeV<br>0.004 (0.025) MeV<br>$2(2.4)\times10^{-6}$ | 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<br>**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

# EFT for multi-boson processes

## SMEFT

| Wilson Coefficient | Operator |
|---|---|
| $C_W$ ($C_{WWW}$) | $\epsilon^{abc} W_\mu^{a\nu} W_\nu^{b\rho} W_\rho^{a\mu}$ |
| $C_{HD}$ | $\lvert H^\dagger (D_\mu \Phi) \rvert^2$ |
| $C_{HWB}$ | $H^\dagger \sigma^a \Phi W^a_{\mu\nu} B^{\mu\nu}$ |
| $C_{Hl}^{(1)}$ | $(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{l}_p \gamma^\mu l_r)$ |
| $C_{Hl}^{(3)}$ | $(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{l}_p \tau^I \gamma^\mu l_r)$ |
| $C_{Hq}^{(1)}$ | $(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{q}_p \gamma^\mu q_r)$ |
| $C_{Hq}^{(3)}$ | $(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{q}_p \tau^I \gamma^\mu q_r)$ |
| $C_{Hud}$ | $i \left( \tilde{H}^\dagger D_\mu H \right) \bar{u}_R \gamma^\mu d_R$ |
| $C_{ll}$ | $(\bar{l}_p \gamma_\mu l_r)(\bar{l}_s \gamma^\mu l_t)$ |
| $C_{Hd}$ | $(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{d}_p \gamma^\mu d_r)$ |

Table 1: The various other dim-6 EFT operators.

## EWDim6/HISZ

The minimal set of dimension-6 operators explored in CMS in $WW$ and $WZ$ final states are the following:

$$\mathcal{O}_{WWW} = \mathrm{Tr}\,[W_{\mu\nu} W^{\nu\rho} W_\rho^\mu] \quad (1.1)$$

$$\mathcal{O}_W = (D_\mu \Phi)^\dagger W^{\mu\nu} (D_\nu \Phi) \quad (1.2)$$

$$\mathcal{O}_B = (D_\mu \Phi)^\dagger B^{\mu\nu} (D_\nu \Phi) \quad (1.3)$$

which are the three C and P conserving operators. In addition, there are two additional C and P violating operators are:

$$\mathcal{O}_{\tilde{W}WW} = \mathrm{Tr}\,[\tilde{W}_{\mu\nu} W^{\nu\rho} W_\rho^\mu] \quad (1.4)$$

$$\mathcal{O}_{\tilde{W}} = (D_\mu \Phi)^\dagger \tilde{W}^{\mu\nu} (D_\nu \Phi) \quad (1.5)$$

These operators seem to be defined in an *ad-hoc* basis first making their appearance in Ref. [1] and subsequently in Ref. [2].

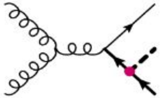
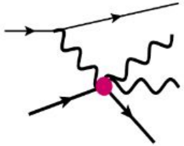
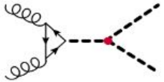
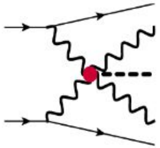
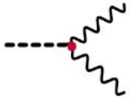
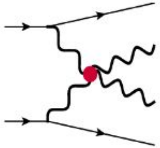
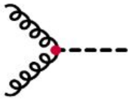
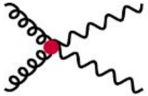

[1] K. Hagiwara et al. "Low energy effects of new interactions in the electroweak boson sector" Phy. Rev. D Vol 48 No. 5

[2] C. Degrande et al. "Effective Field Theory: A Modern Approach to Anomalous Couplings" arXiv:1205.4231


Ref $$\mathcal{O}_{WWW} = \frac{g^3}{4} Q_W \,,$$

# 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 |
|---|---|---|---|---|
| $\kappa_t$ | $\mathcal{O}_{y_t}$ |  |  | $\sim(E^2/\Lambda^2)$ |
| $\kappa_\lambda$ | $\mathcal{O}_6$ |  |  | $\sim(vE/\Lambda^2)$ |
| $\kappa_{Z\gamma}$<br>$\kappa_{\gamma\gamma}$<br>$\kappa_V$ | $\mathcal{O}_{WW}$<br>$\mathcal{O}_{BB}$<br>$\mathcal{O}_r$ |  |  | $\sim(E^2/\Lambda^2)$ |
| $\kappa_g$ | $\mathcal{O}_{gg}$ |  |  | $\sim(E^2/\Lambda^2)$ |

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],

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

with $Y_\psi$ the Yukawa coupling for the fermion $\psi$. [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].]

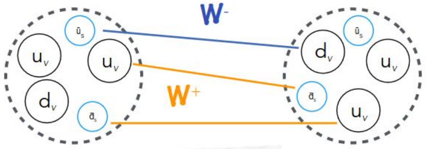
The operators of Eq. (1) have the form $|H|^2 \times \mathcal{O}^{\rm SM}$, with $\mathcal{O}^{\rm SM}$ a dimension-four SM operator (i.e., kinetic terms, Higgs potential, and Yukawa couplings) times https://indico.cern.ch/event/1281608/attachments/2682026/4652614/LAB_cern_seminar_WprecisionNEW.pdf

Revisit ATLAS measurement with profile likelihood (PLH) fitting

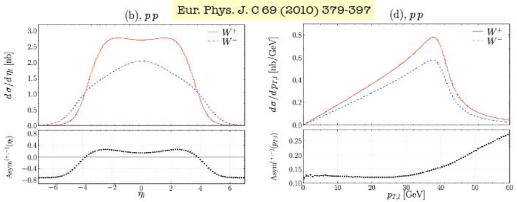
- Advantage:
  - (in situ) constrain experimental & modelling systematic uncertainties
  - + adding modern PDF sets
- Disadvantage:
  - Computational expensive
  - Several 1000 Nuisance Parameter (NP) → robust systematic model

- New data-driven multijet Background estimation
  - $\Delta m_W$ =1.9 MeV and reduction unc. by 2 MeV
- Better evaluation of EW uncertainties
  - Increase of 1-2 MeV unc.
- Recovering data in the electron channel
  - Increase statistics by 1.5%
- Add parametric uncertainty on Γ(W)

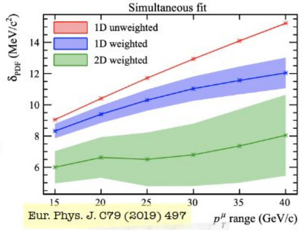
ATLAS New MW




*In pp collision: different cross section for W+ and W- and different dynamics.*




- Difference between u,d valence and the see distributions determine the W-boson rapidity distributions → affects acceptance and fiducial volume
  - kinematic distributions & signal yields in the different categories have additional constraining power on the PDFs unc. (in situ constraint)
- With profiling of PDF uncertainty it is expected :
  - **reduction** of **$\Delta m_W$ PDFs envelope**
  - **reduction** impact of PDF uncertainties
  (previous measurement $\delta^{(PDF)} m_W \pm$ 9-10 MeV)



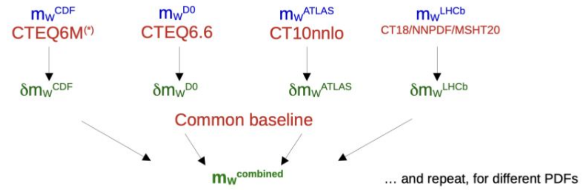

PDF in situ constraint the proof of principle with LHCb kinematics https://indico.fnal.gov/event/59091/contributions/271335/attachments/168905/226538/SMATLHC23-AMOROSO.pdf

## Uncertainties comparison

| | D0 | CDF (old/new) | ATLAS (old/new) | LHCb |
|---|---|---|---|---|
| **Momentum scale** | 15 | 7 / 3 | 8.4 / 6.8 | 7 |
| **Efficiency** | - | - / 0.4 | 5.0 / 4.0 | 2 |
| **Background** | 2 | 3 / 3.3 | 4.6 / 2.4 | 2 |
| **EW ho** | 7 | 4 / 2.7 | 5.7 / 6.0 | 9 |
| **$p_T$,Y modelling** | 2 | 5 / 2 | 5.9 / 3.5 | 11 |
| **Ai modeling** | - | - / - | 5.8 / 3.5 | 10 |
| **PDF** | 10 | 10 / 3.9 | 9.0 / 7.7 | 9 |
| **Total sys.** | 20 | 15 / 6.9 | 17.2 / 15.5 | 22 |
| **Statistical** | 11 | 12 / 6.4 | 7.2 / 4.9 | 23 |
| **Total** | 23 | 19 / 9.4 | 18.7 / 16.3 | 32 |

## Combination strategy

- Measurements performed at different times, using different PDFs and QCD models: need to translate them first to a common baseline
  - Correct all measurements to a ***common PDF and QCD model***
  - ***Combine*** them with correlations




- Procedure decomposed into generator/QCD and PDF effects

$$m_W^{new} = m_W^{ref} - \delta m_W^{QCD} - \delta m_W^{PDF}$$

published value — Improved predictions — PDF extrapolation

$\delta m_W^{PDF}$ correction to reference PDF

$\delta m_W^{QCD}$ correction to QCD modelling beyond quoted uncertainties

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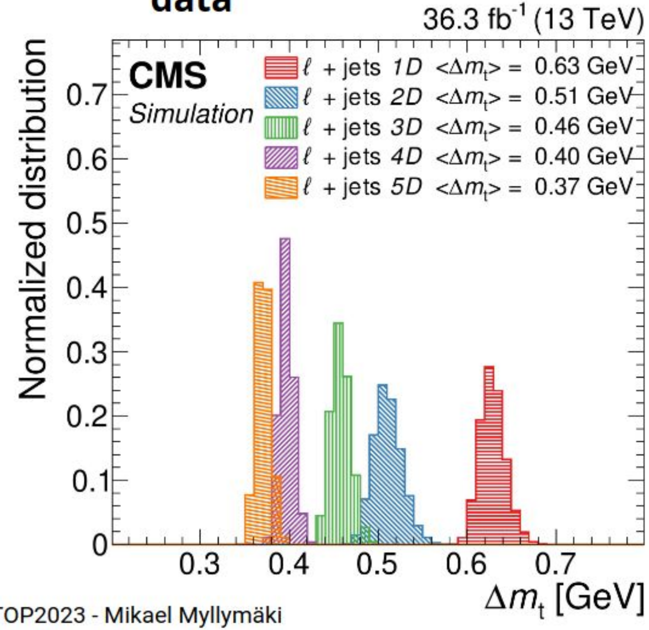
# W Mass Combination

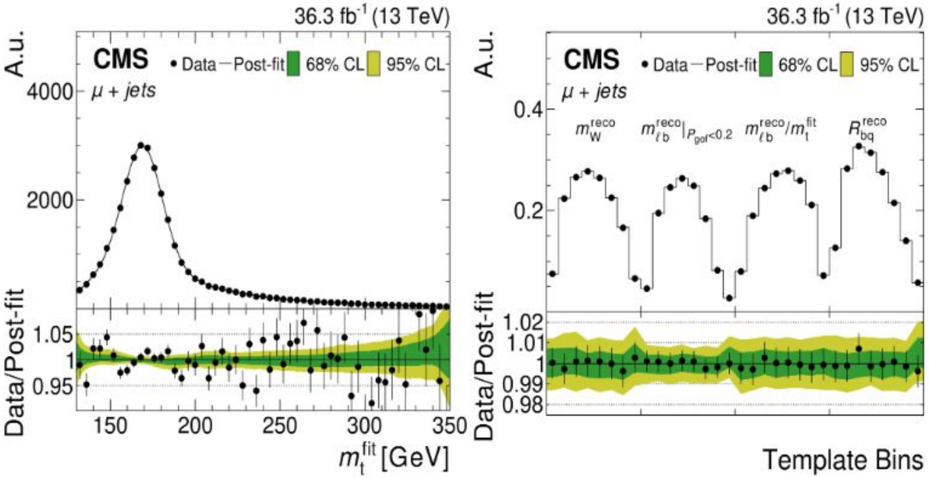
# Profiled maximum-likelihood fit

arXiv:2302.01967 (submitted to EPJC)
$t\bar{t}$ lepton+jets
$36.3 fb^{-1}$ 13 TeV

## CMS Top Mass

- $m_t^{MC}$ from profiled maximum-likelihood fit using 5 observables
- Nuisance parameters for syst. uncertainties
- **Possible to constrain systematics with data**




$m_t^{fit}$ → for $m_t$ } parametrized

$m_W^{reco}$ → light quark JES

$R_{bq}^{reco} = (p_T^{b1} + p_T^{b2})/(p_T^{q1} + p_T^{q2})$ → b-JES

$m_{lb}^{red} = m_{lb}^{reco} / m_t^{fit}$ → for lep syst.

$m_{lb}^{reco}$ $(P_{gof} < 0.2)$ → for full statistics } binned https://indico.fnal.gov/event/59091/contributions/270365/attachments/168772/226212/sm%40lhc.pdf

# ATLAS full phase space Z measurement

- First precise measurement at the LHC in the full phase space of the decay leptons (√s = 8 TeV, L=20.2fb-1)
  - Statistically dominated measurement
  - Negligible theoretical uncertainties as there is no direct extrapolation to full phase space
    - Cross sections are parameters of the fit. Fit parameters are $8A_i$ + 1 cross section in pT-Y 176 bins

$$\frac{d\sigma}{dpdq} = \frac{d^3\sigma^{U+L}}{dp_T dy dm}\left(1+\cos^2\theta + \sum_{i=0}^{7} A_i(y,p_T,m)P_i(\cos\theta,\phi)\right)$$

Expected Yield

22528 (cosθ,ϕ,$p_T$,y) bins

Reco ($p_T^Z$,$y^Z$,$m^Z$, cosθ, ϕ) bin

Cross section

Background template

$$N^n_{\rm exp}(A,\sigma,\theta) = \left\{\sum_{j=1}^{N^{ana}_{\rm bins}} \mathcal{L}\sigma_j\left[t^n_{8j}(\beta) + \sum_{i=0}^{7} A_{ij}t^n_{ij}(\beta)\right]\right\}\gamma^n + \sum_{B}^{\rm bkgs} T^n_B(\beta)$$

Likelihood

Truth ($p_T^Z$,$y^Z$,$m^Z$) bin

Angular coefficient

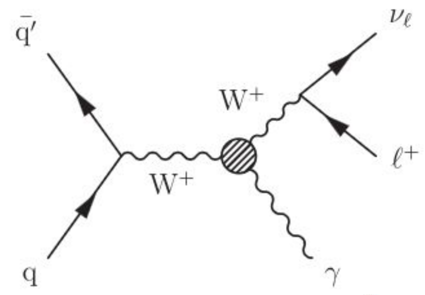
Templated polynomial

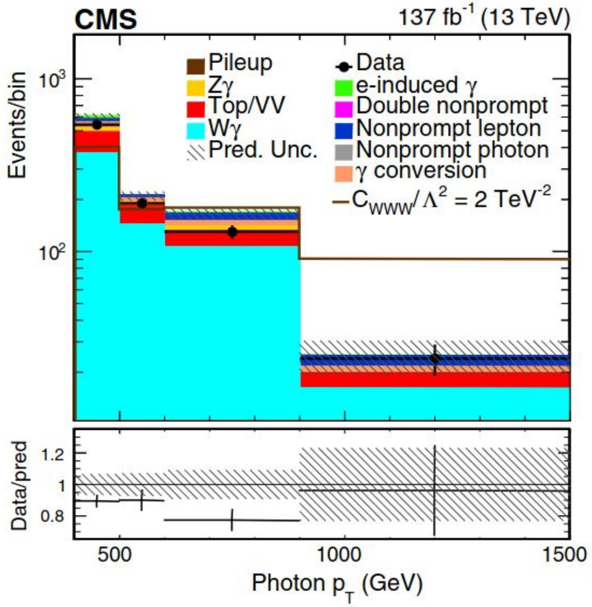
Phys. Rev. Lett. 126, 252002 (2021)

# Wγ

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

| Coefficient | Exp. lower | Exp. upper | Obs. lower | Obs. upper |
|---|---|---|---|---|
| $c_{WWW}/\Lambda^2$ | −0.85 | 0.87 | −0.90 | 0.91 |
| $c_B/\Lambda^2$ | −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

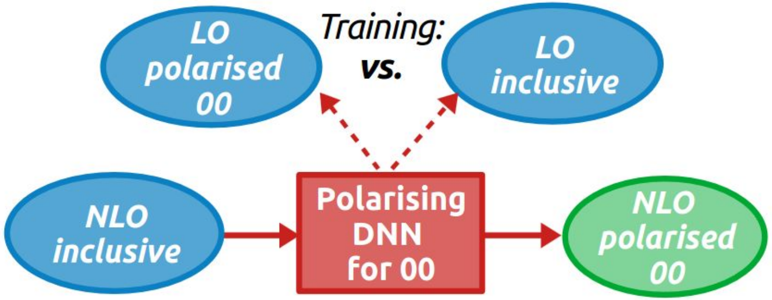
# ATLAS WZ

## 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***

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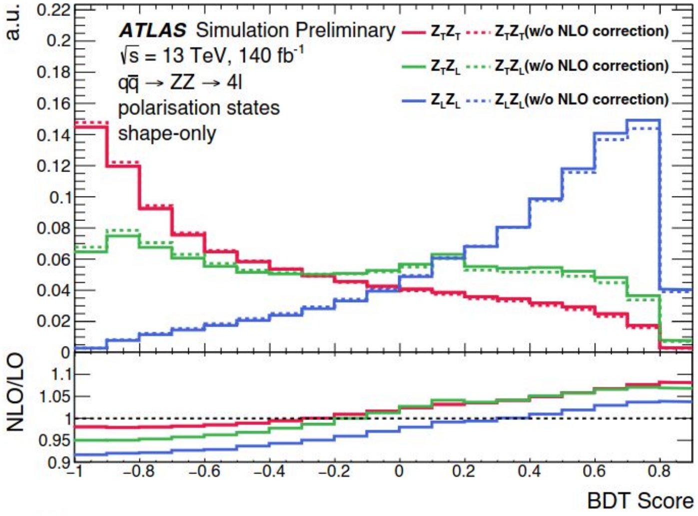
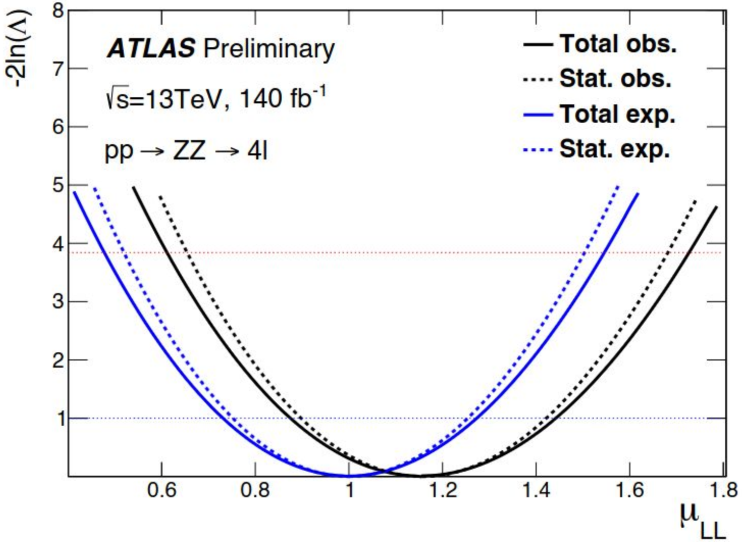
# ATLAS ZZ

## pp → ZZ polarisation

NEW!

07/2023 (public)
CONF-2023-038




**Measurement**

13 TeV full Run 2, 4 leptons

- BDT using only angular observables to distinguish TT, LT/TL, LL

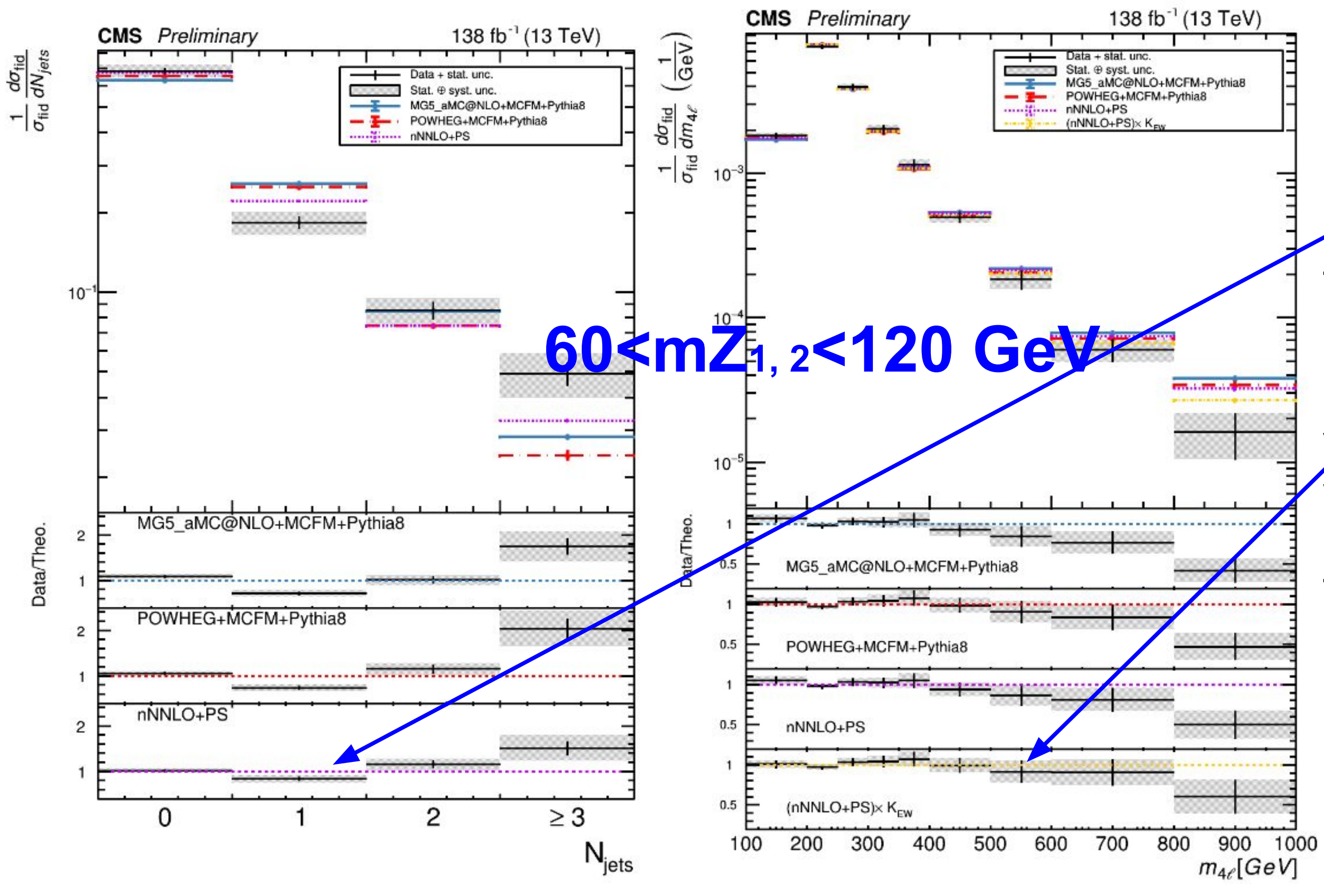
Fit yields 220 ± 50 $Z_L Z_L$ events

→ Evidence (4.3σ) for $Z_L Z_L$ pair-production

$\sigma_{fid} = 2.4 \pm 0.6$ fb

(SM NLO $\sigma_{fid} = 2.1 \pm 0.1$ fb)

# ZZ+jets [CMS-PAS-SMP-22-001]




In general, the nNNLO+PS prediction describes the Njet distribution better.

The EW corrected nNNLO+PS predictions describe the measured values better than those without the EW corrections

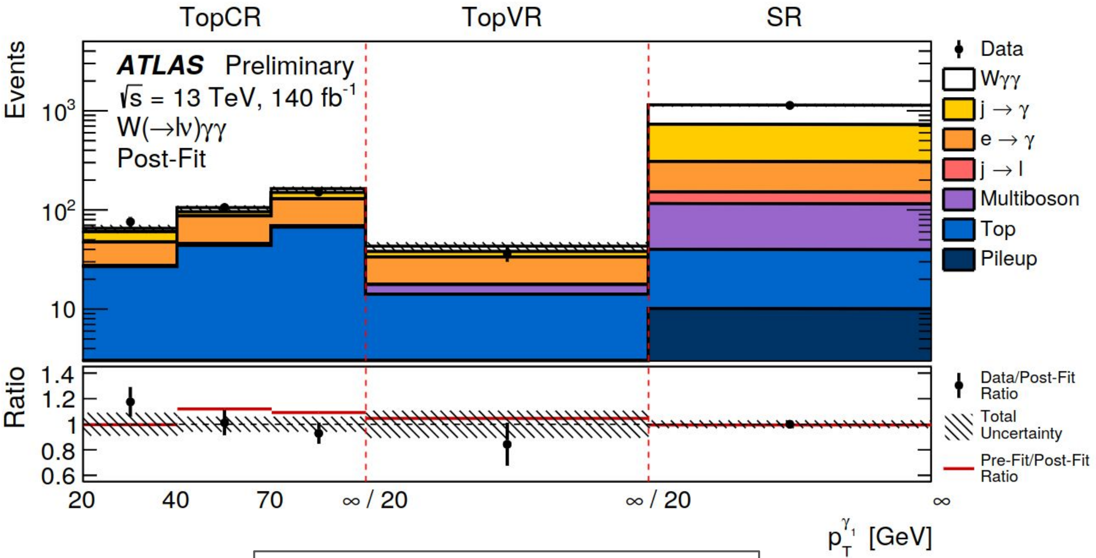
The EW corrections have negligible effect on any other normalized distributions than $m_{4l}$.

# Wγγ observation ATLAS-CONF-2023-005

- Dominant background from non-prompt leptons and photons
- Main source of systematics due to data-driven bkg estimates

**5.6 (5.6)$\sigma$ obs.(exp.)**

| Source of uncertainty | Impact [%] |
|---|---|
| Data-driven background estimates | 13 |
| Photon efficiency | 4.5 |
| Signal MC theoretical modeling | 3.5 |
| Background MC theoretical modeling | 3.0 |
| Monte Carlo statistics | 2.8 |
| Jet efficiency and calibration | 2.4 |
| Top normalization | 2.4 |
| Pileup reweighting | 1.6 |
| $E_{\mathrm{T}}^{\mathrm{miss}}$ calibration | 1.4 |
| Muon efficiency and calibration | 1.4 |
| Luminosity | 1.0 |
| Electron and photon calibration | 0.7 |
| Flavor tagging efficiency | 0.6 |
| Systematic | 15 |
| Statistical | 8.3 |
| Total | 17 |




$$\mu_{\mathrm{obs}} = 1.01^{+0.17}_{-0.16}$$

$$\sigma^{\mathrm{fid}}_{\mathrm{obs}} = 12.2^{+2.1}_{-2.0}\ \mathrm{fb}$$

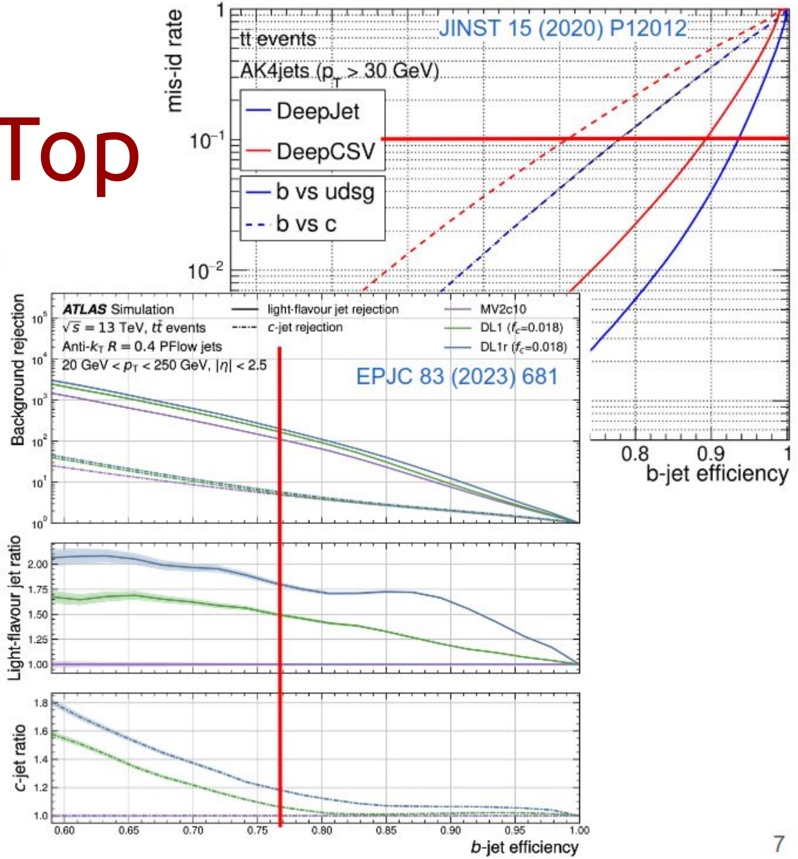
# Observation in SSDL and ML channels

ATLAS: EPJC 83 (2023) 496
CMS: arXiv:2305.13439 (submitted to PLB)

First observation of four top production at both ATLAS and CMS

- Re-analysis of Run 2 datasets
  - Supersede previous results
- Profit significantly from general improvements in lepton and jet selection:
  - Better reconstruction methods
  - **Improved b-tagging**
  - Better lepton identification methods
- Major improvements in analysis methods
  - Stronger machine learning discriminants: GNNs (ATLAS) or multiclass BDTs (CMS)
  - Better handles on tt̄X backgrounds

Four Top




https://indico.cern.ch/event/1233341/timetable/?view=standard#15-4-top-measurements-atlascms

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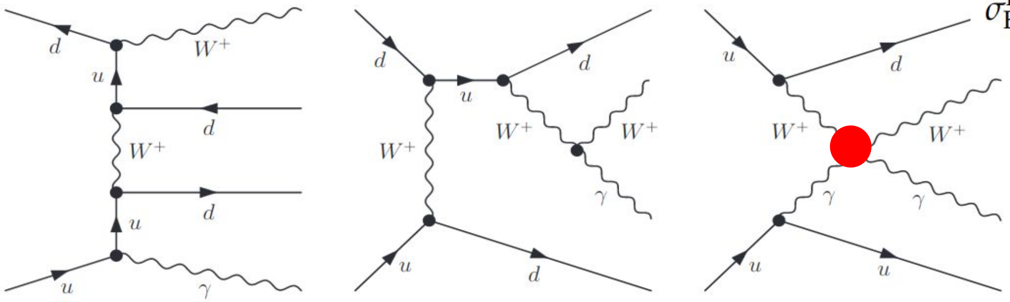
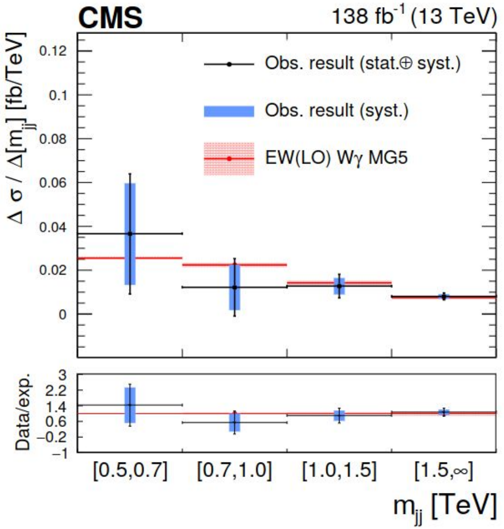
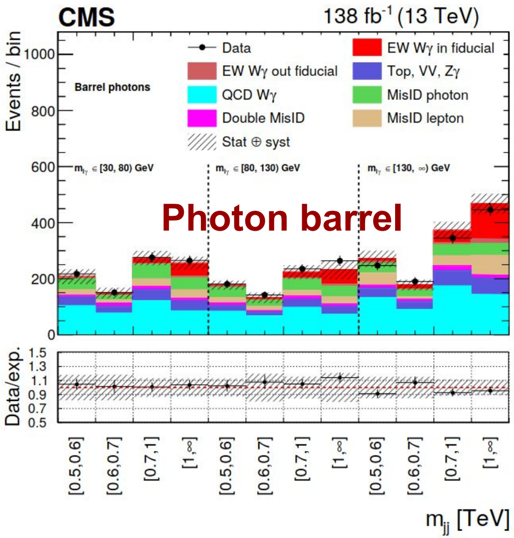
# VBS Wγ [Phys. Rev. D 108 (2023) 032017]

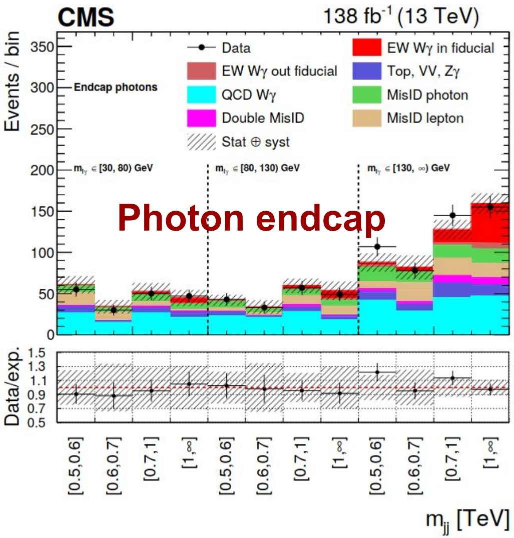



$$\sigma_{\mathrm{EW}}^{\mathrm{fid}} = 23.5 \pm 2.8\,(\mathrm{stat})^{+1.9}_{-1.7}\,(\mathrm{theo})^{+3.5}_{-3.4}\,(\mathrm{syst})\,\mathrm{fb} = 23.5^{+4.9}_{-4.7}\,\mathrm{fb}.$$

**6.0 (6.8)σ observed (expected)**




- **Fiducial and differential** cross sections;
- **Stringent limits on aQGCs:** fM,2-4 and fT6-7

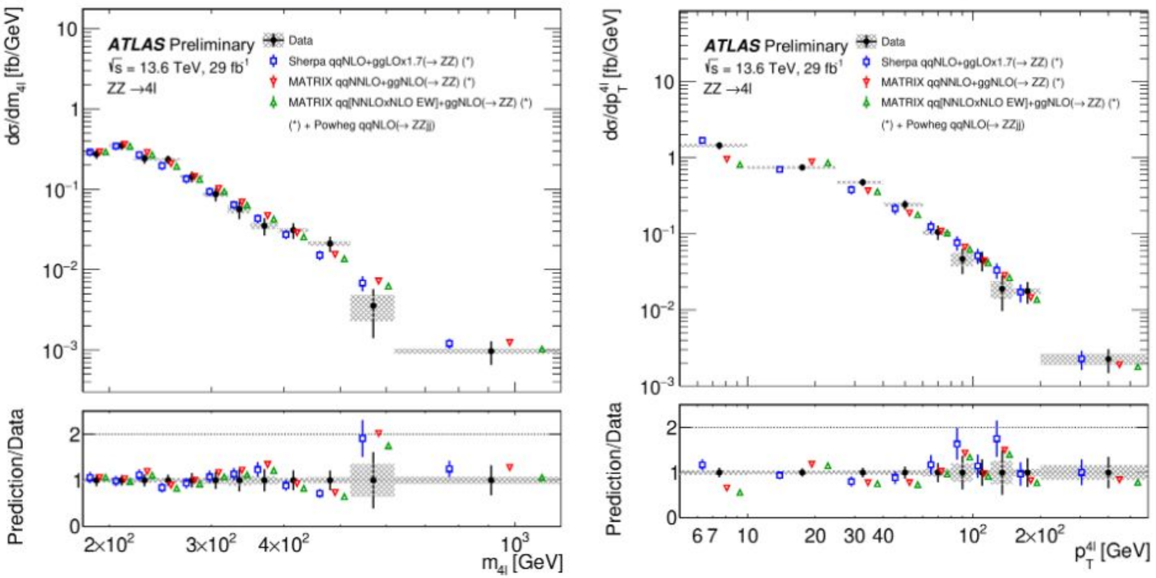
ATLAS-CONF-2023-062

# Run3 ZZ

| | Measurement | MC prediction | MATRIX prediction |
|---|---|---|---|
| Fiducial | $36.7 \pm 1.6(\text{stat}) \pm 1.5(\text{syst}) \pm 0.8(\text{lumi})$ fb | $36.8\ ^{+4.3}_{-3.5}$ fb | $36.5 \pm 0.6$ fb |
| Total | $16.9 \pm 0.7(\text{stat}) \pm 0.7(\text{syst}) \pm 0.4(\text{lumi})$ pb | $17.0\ ^{+1.9}_{-1.4}$ pb | $16.7 \pm 0.4$ pb |

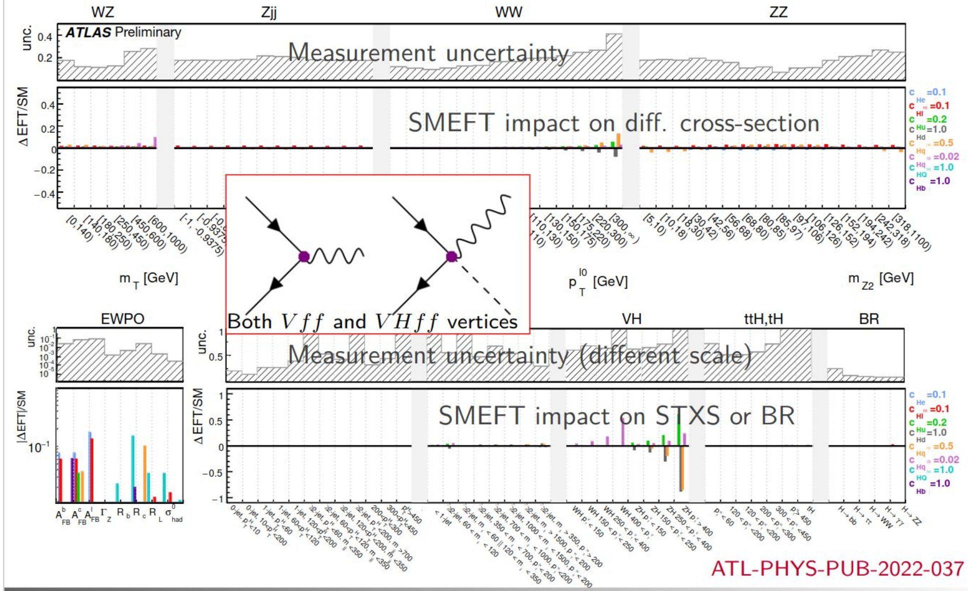
$q\bar{q} \to ZZ$, $gg \to ZZ$, and EW $qq \to ZZ + 2j$

- Inclusive & differential measurements
- Compares to state-of-art MC
- Well in agreement with SM predictions
- Done using a new light data format developed for Run 4



https://indico.fnal.gov/event/59091/contributions/270411/attachments/168822/226374/hmilder_smatlhc2023.pdf

## SMEFT impact example




ATL-PHYS-PUB-2022-037



## Conclusion

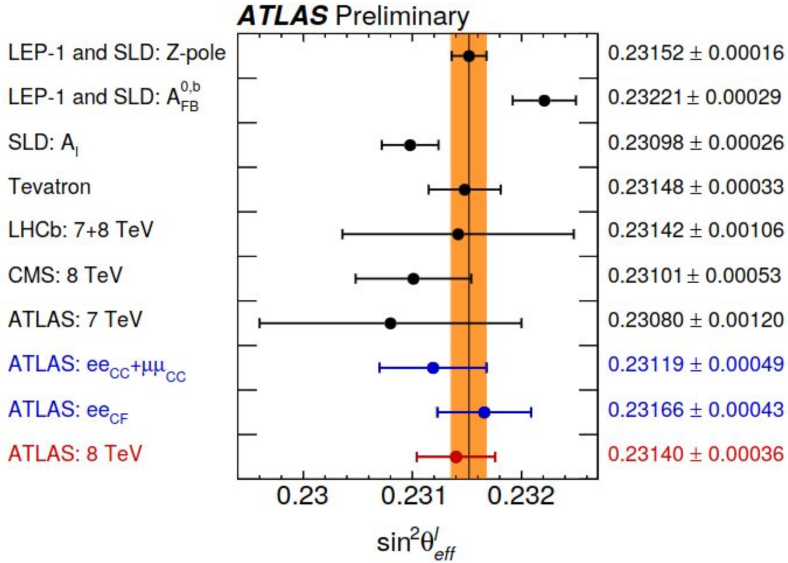
- Presented EFT combination programme of ATLAS, CMS, and LHC EFT WG
- Mainly discussed first ATLAS global (EWPO+EW+Higgs) combination
- Highlighted six main challenges
  1. Number of degrees of freedom → requires effort but (surprisingly) manageable
  2. Precise predictions → needed for SM and SMEFT
  3. SM assumption of interpreted measurements → requires ad-hoc fixes or dedicated SMEFT measurements
  4. Overlap and correlations → so far moderate impact but sometimes difficult to assess even within collaboration
  5. Validity → possibly most serious challenge, competing proposals, difficult to implement for large combination
  6. ATLAS+CMS combination → still in infancy, requires coordination and harmonization

https://cds.cern.ch/record/2766293/files/ATL-PHYS-SLIDE-2021-150.pdf

# ATLAS and CMS Results [3, 4]

**ATLAS:** $\sin^2\theta^\ell_{\mathrm{eff}} = 0.23140 \pm 0.00021\,(\mathrm{stat.}) \pm 0.00024\,(\mathrm{PDF}) \pm 0.00016\,(\mathrm{syst.})$

**CMS:** $\sin^2\theta^\ell_{\mathrm{eff}} = 0.23101 \pm 0.00036\,(\mathrm{stat.}) \pm 0.00031\,(\mathrm{PDF}) \pm 0.00018\,(\mathrm{syst.}) \pm 0.00016\,(\mathrm{theo.})$




| | ATLAS $\sqrt{s} = 8$ TeV | ATLAS $\sqrt{s} = 14$ TeV | ATLAS $\sqrt{s} = 14$ TeV |
|---|---|---|---|
| $\mathcal{L}$ [fb$^{-1}$] | 20 | 3000 | 3000 |
| PDF set | MMHT14 | CT14 | PDF4LHC15$_{HL-LHC}$ |
| $\sin^2\theta^{\mathrm{lept}}_{\mathrm{eff}}$ [$\times 10^{-5}$] | 23140 | 23153 | 23153 |
| Stat. | ± 21 | ± 4 | ± 4 |
| PDFs | ± 24 | ± 16 | ± 13 |
| Experimental Syst. | ± 9 | ± 8 | ± 6 |
| Other Syst. | ± 13 | - | - |
| Total | ± 36 | ± 18 | ± 15 |

- Uncertainties are significantly reduced relative to previous measurements, now approaching Tevatron precision:
  - **ATLAS:** $0.23080 \pm 0.0012$ (ATLAS 7 TeV) $\rightarrow$ $0.23140 \pm 0.00036$ (ATLAS 8 TeV)
  - **CMS:** $0.22870 \pm 0.0032$ (CMS 7 TeV) $\rightarrow$ $0.23101 \pm 0.00053$ (CMS 8 TeV)
- Not including $ee_{\mathrm{CF}}$, ATLAS $ee_{\mathrm{CC}}+\mu\mu_{\mathrm{CC}}$ comparable to CMS result.

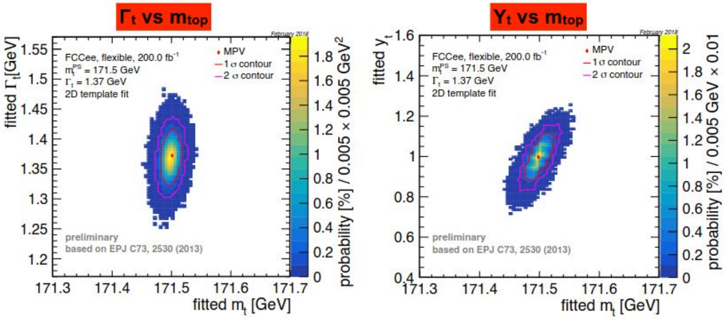
Eur.Phys.J.C 83 (2023) 4, 269,
Eur.Phys.J.C 83 (2023) 6, 501 (erratum)

# TOP Mass

| Source | $m_{top}$ precision (MeV) | |
|---|---|---|
| | Optimistic | Conservative |
| Statistics | 9 | 9 |
| Theory | 9 | 26 |
| Quick scan | 3 | 3 |
| $\alpha_S$ | 17 | 17 |
| Top width | 10 | 10 |
| Experimental efficiency | 5 | 45 |
| Background | 4 | 18 |
| Beam energy | 2 | 2 |
| Luminosity spectrum | 3 | 5 |
| Total | 25 | 59 |

CEPC

TOP MEASUREMENTS FROM THRESHOLD SCAN @FCC-ee

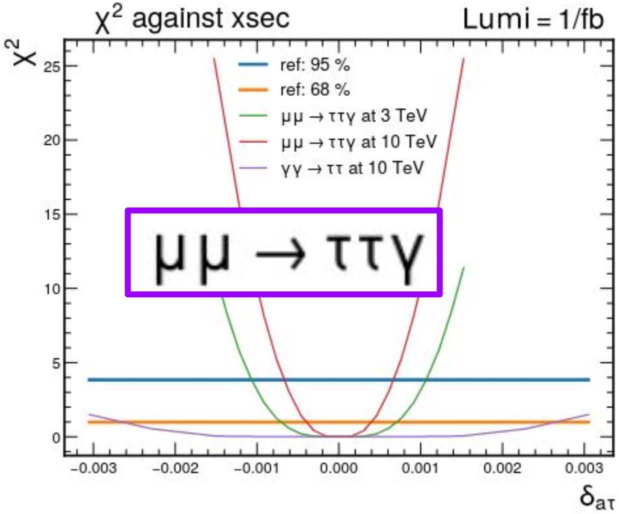



$Y_{top}$ can be extracted with a10% uncertainty

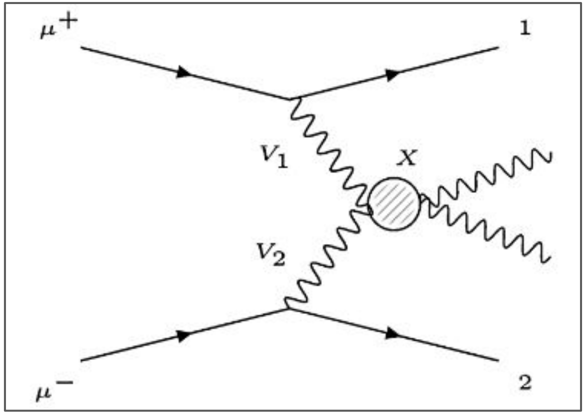
FCC-ee

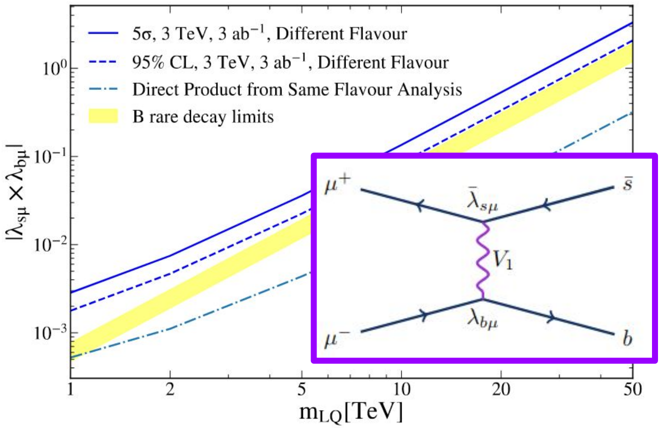
With 200 fb$^{-1}$ FCC-ee can measure $m_{top}(\Gamma_{top})$ with ~17(45) MeV statistical accuracy.
*Systematics*: 3MeV from center of mass energy, 5MeV from $\alpha_s$ ($2\times10^{-4}$ as measured at lower energy) and ~40MeV from theory uncertainties (NNNLO)

# Rich Physics at Muon Collider




Longitudinally polarized $ZZ$ scattering




arXiv:2201.07808
Tau at TeV scale, flying several cms, sensitive to tau g-2

Displaced Tau reconstruction: tracker

arXiv:2107.13581
LL Polarized ZZ scattering
>5σ with 3/ab at 14 TeV MC

Closer Z decay products: finer calorimeter

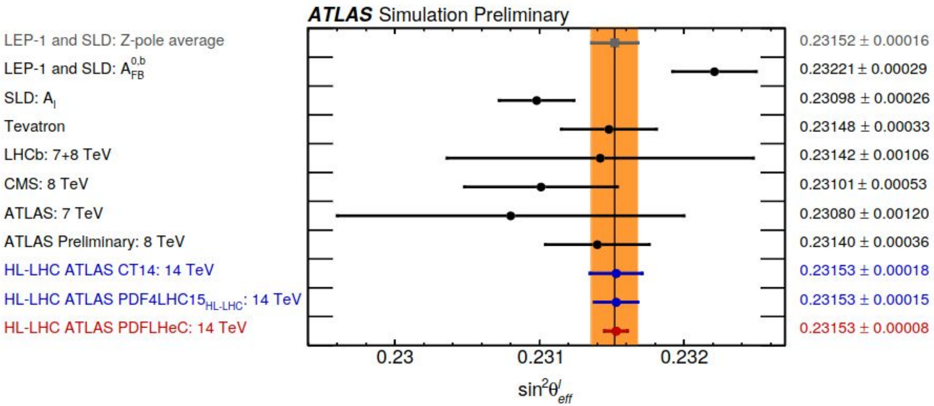
arXiv:2109.01265
Leptoquark searches
B anomaly

Flavor tagging: Tracker, vertex

CMS-PAS-FTR-22-001

# HL-LHC, FCChh/SPPC

6th FCC Physics Workshop




(a)