Highlights and prospects on electroweak and top physics at the (HL)-LHC

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on behalf of

ATLAS, CMS & LHCb Collaborations, CERN-LHC

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Physics performance at the LHC

pp collision data collected by each of the ATLAS and CMS experiments:

- Run-1 at $\sqrt{s}$ = 7, 8 TeV (2010 - 2012) : $\mathcal{L} \sim 20\ \text{fb}^{-1}$
- Run-2 at $\sqrt{s}$ = 13 TeV (2015 - 2018): $\mathcal{L} \sim 140\ \text{fb}^{-1}$
- Run-3 at $\sqrt{s}$ = 13.6 TeV (2022+2023): $\mathcal{L} \sim 70\ \text{fb}^{-1}$

Low lumi datasets in 2017
$\mathcal{L}$ = 298 pb^{-1} @ $\sqrt{s}$ =5.02 TeV
$\mathcal{L}$ = 201 pb^{-1} @ $\sqrt{s}$ =13 TeV

\+ Heavy ion runs

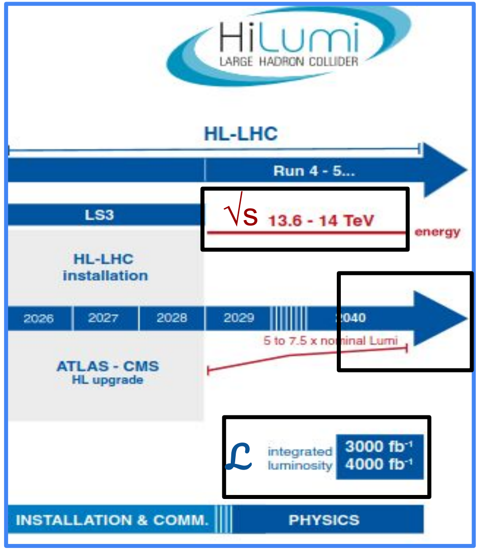
Run-3 continues till 2025, expect at 13.6 TeV total $\mathcal{L} \sim 250\ \text{fb}^{-1}$

- No direct evidence for physics beyond standard model (SM)
  → can access higher mass scale physics in terms of virtual contribution.
- Compare measurements of the observables with precise SM predictions and look for deviations.
- New physics at high scale ⇒ effectively modify couplings in various processes observed.
- Study the impact of higher dimension operators as a function of energy.
- Effective Field Theory (EFT) describes possible pattern of deviations introduced by new physics

$$\mathcal{L}_{\text{Eff}} = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \frac{1}{\Lambda^3}\mathcal{L}_7 + \frac{1}{\Lambda^4}\mathcal{L}_8 + \cdots, \qquad \mathcal{L}_d = \sum_i c_i^{(d)} \mathcal{O}_i^{(d)}$$

EFT formalism does not assume the SM structure of the couplings,but respects the gauge symmetries of the SM.

Prospects at the HL-LHC



Start of the HL-LHC is ~ 5 years away, will continue till mid-2040s at least ⇒ **20 times more data** compared to current volume in about **20 years time** to be collected with **new avatars of the ATLAS and CMS detectors.**

With more data :

- Rare processes
- (Multi-) differential measurements
- Explore corners of phase space

With more time:

- More powerful analysis techniques
- More accurate theoretical tools
- Other "technological" breakthroughs (computing, AI, …)
- New ideas!

Results from studies for Snowmass Workshop, 2021-22 and CERN Yellow Report
Assuming ultimate performance of experiments comparable to that achieved during the LHC Run 2.

Uncertainties considered in the projections studies:

- 1% in luminosity.
- Experimental uncertainties: scaled down with $\sqrt{\mathcal{L}}$.
- Theoretical uncertainties: halved with respect to current value.

This presentation is NOT an exhaustive discussion of the full electroweak and top physics projections at the HL-LHC.

More details in "Future physics with CMS detector at HL-LHC " by Jyothsna Rani Komaragiri

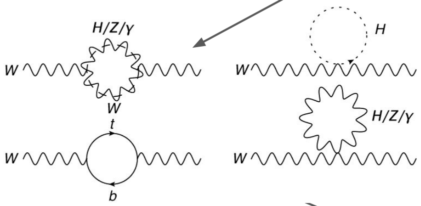
Electroweak physics

Milestones by 2023:

- Neutral currents: 50 yrs
- QCD: 50 yrs

- W, Z turns 40
- Top: 28
- Higgs: 11

$$M_W^2\left(1-\frac{M_W^2}{M_Z^2}\right)=\frac{\pi\,\alpha_{EM}(M_Z)}{\sqrt{2}G_F(1-\Delta r)}$$



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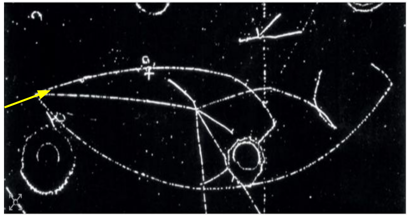
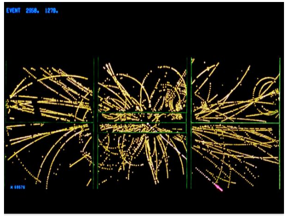
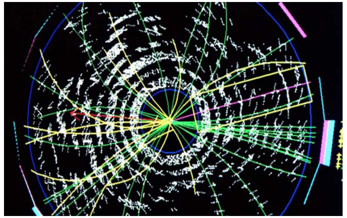
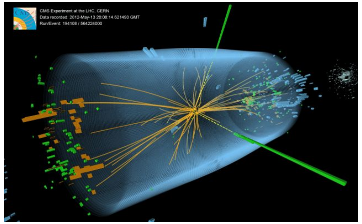






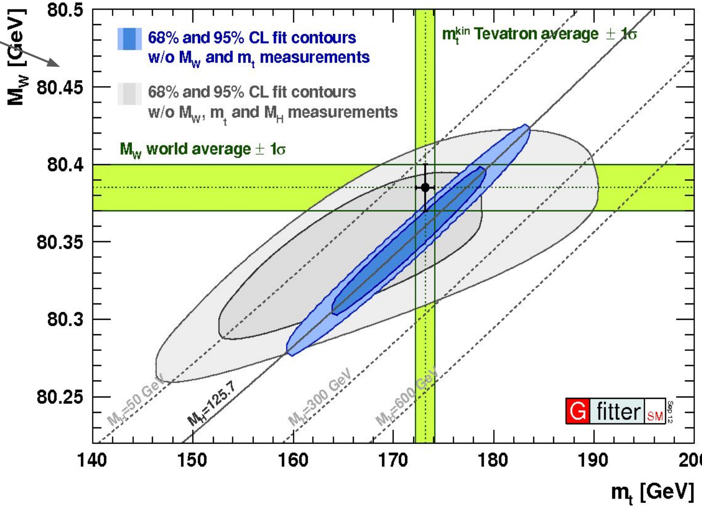


SM input parameters for predictions

- W Mass
- Top Mass
- Higgs Mass
- …

⇒ Precision measurements at the LHC crucial

Eg. theoretical uncertainty of
ΔM_{top} = 2.1 GeV ⇒
ΔM_W = 1.9 GeV



W,Z measurements are the experimental candles always.

LHC unraveling in productions of

- Multiple bosons
- Multiple top quarks

LHC achieving much more than anticipated → able to mention only few.

More in the talk by Mario Pellicccioni: Physics of the Electroweak sector in CMS

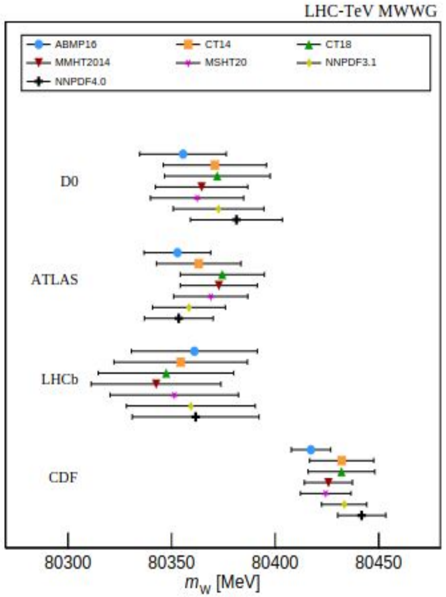
Measurement of W mass

Precise M_W value provides sensitive test for the consistency of the model.

- W/Z production described by differential xsec + angular coefficients (say, A_i's) driven by polarization.
- Unpolarized cross-section & A_i 's can be determined in pQCD calculations
  → depends on paton density function (PDF)
  → Known at NNLO QCD + NLO EWK,
  Resummation-improved calculations available at N3LL+NNLO. arXiv:2207.07056
- M_W extracted from fit of data to MC-based templates.

Current uncertainty of m_H (~0.1%) →ΔM_W~8 MeV

- Measurements limited by model-uncertainties: PDFs, p_T^{ℓ} and A_i



CDF-II : 80.4335 ± 0.0094 GeV Science 376 (2022)

ATLAS : 80.3665 ± 0.0159 GeV [9.8 (stat.) ± 12.5 (syst.) MeV] arXiv:2403.15085

LHC EW WG: 80.377 ± 0.012 GeV arXiv:2308.09417

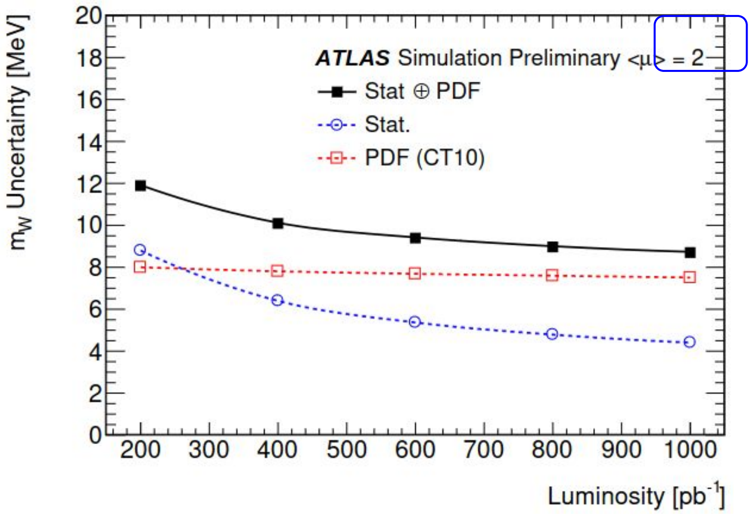
Note: CDF and LHC experiments performed at different times, with different baseline PDFs and QCD tools, different experimental conditions,..

- LHC EW WG average and the **published CDF result** , when considered on equal footing but **statistically incompatible** (difference ~3.6 s.d.).
- Latest reanalysis of 7 TeV ATLAS data
  Γ_W = 2202 ± 32 (stat.) ± 34 (syst.) MeV = **2.202 ± 0.047 GeV.**

New, independent measurements required.

W mass measurement at the HL-LHC

ATL-PHYS-PUB-2018-026,



Requirements for future improvements:

- May be a low instantaneous luminosity ? Likely to enable reconstruction of the missing transverse momentum with sufficient precision.
- Enhanced detector coverage in higher rapidity regions → forward lepton reconstruction.
- Since M_W determined from template fit ⇒ huge amount of simulation ~ $\mathcal{O}(10^{10})$ W events.

arXiv:2308.09417

Expected ΔM_W (stat.): 10 MeV with 200 pb^{-1}
3 MeV with 1 fb^{-1}.

LHCb data at the HL-LHC potentially would provide comprehensive information to reduce the PDF uncertainty for the LHC-wide combination of W mass and weak mixing angle.

Measurement of effective weak mixing angle $\sin^2\theta^\ell_{eff}$

Leptonic effective mixing angle: key SM parameter $\sin^2\theta^\ell_{eff} = (1 - m^2_W/m^2_Z)\kappa$ (k~1.037)

CMS-PAS -SMP-22-010

Two most precise measurements of $\sin^2\theta^\ell_{eff}$, from LEP & SLC, differ by ~ 3σ . CDF II estimation of m_W prefers lower value.

LHC: use pp→Z/ +X →ℓ+ℓ- +X: angular distribution of leptons in Collin-Soper frame

$$\cos\theta_{CS} = \frac{2\,(P_1^+ P_2^- - P_1^- P_2^+)}{\sqrt{m^2_{\ell\ell}(m^2_{\ell\ell} + p^2_{T,\ell\ell})}} \frac{y_{\ell\ell}}{|y_{\ell\ell}|},$$

$$\frac{16\pi}{3\sigma}\frac{d\sigma}{d\cos\theta\, d\phi} = 1 + \cos^2\theta + \sum_{i=0}^{7} A_i f_i(\theta,\phi)$$

2 methods for measurements using large # of bins and 7 PDF sets

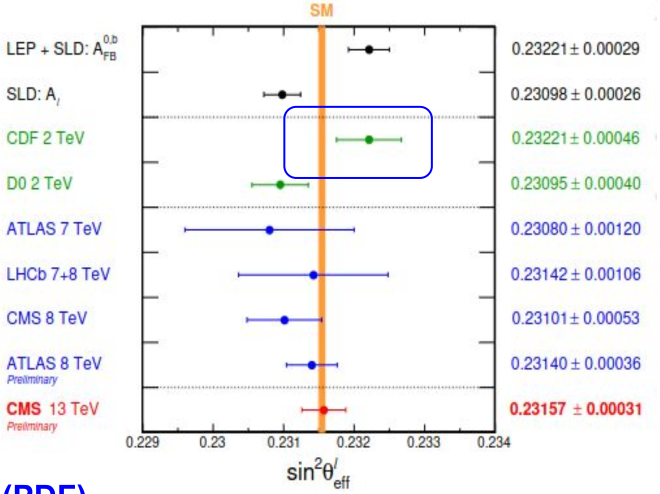
i) $A_{FB} = (\sigma_F - \sigma_B)/(\sigma_F + \sigma_F)$ where $\sigma_{F,B}$: $\cos\theta_{CS} > 0$, < 0

→ detector effects cancel out

ii) $A_{FB} = \frac{3}{8} A_4(y,m)$ before final state radiation

→ fit A_4 coeff. using measured differential distributions after unfolding

→ small theory and PDF uncertainties



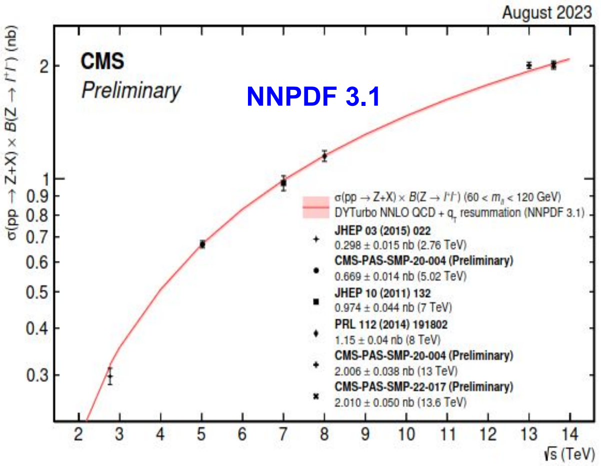
$\sin^2\theta^\ell_{eff}$ = 0.23157 ± 0.00010 (stat) ± 0.00015 (syst) ± 0.00009 (theo) ± 0.00027 (PDF)

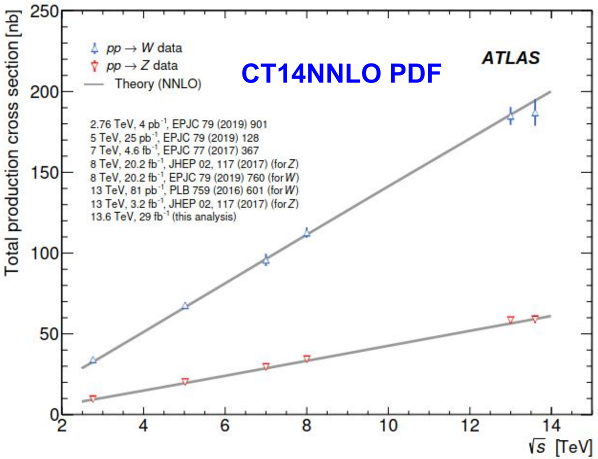
= 0.23157 ± 0.00031 using A_{FB} method

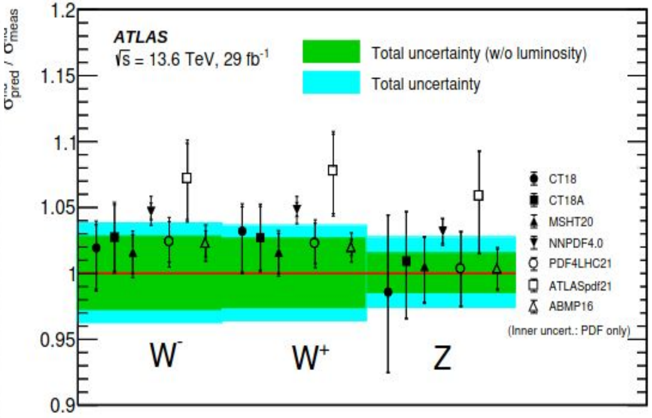
= .23155 ± 0.00032 using A_4 method

for CTZ18 PDF set

W/Z productions Run3 data, √s = 13.6 TeV







Ratio of fiducial cross sections:

$R_{W+/W-}$ = 1.286 ± 0.022

$R_{W\pm/Z}$ = 10.17 ± 0.25

$R_{tt/W\pm}$ = 0.112 ± 0.003

CMS-PAS-SMP-22-017 arXiv:2403.12902

Evolution with energy matches well with prediction.

arXiv:2403.12902

Fiducial cross sections

ATLAS: $\sigma(pp \to W^+ + X)^* \mathcal{B}(W^+ \to \ell^+ \nu)$ = 4250 ± 150 pb & $\sigma(pp \to W^- + X)\mathcal{B}(W^- \to \ell^- \nu)$ = 3310 ± 120 pb

$\sigma(pp \to Z + X)^* \mathcal{B}(Z \to \ell^+\ell^-)$ = 744 ± 20 pb , $m_{\ell\ell}$:[66,116] GeV

CMS: $\sigma(pp \to Z + X)^*\mathcal{B}(Z \to \mu^+\mu^-)$ = 763.5 ± 4(stat) ± 6.9(syst) ± 17.6(lumi) pb $m_{\mu\mu}$:[60,120] GeV

$\sigma^*\mathcal{B}$ (pred.)$_{\mu\mu}$ = 766.6 ± 6.5 (PDF) $^{+2.1}_{-4.5}$(scale) pb @N2LO of QCD + NLO of EW

CMS-PAS-SMP-22-017

Z production at $\sqrt{s}$ = 5.02 TeV

$\mathcal{L}$ = 100 ± 2 pb^{-1} , pp @ $\sqrt{s}$ =5.02 TeV

arXiv:2308.12940

LHCb measurement, complementary phase space to ATLAS and CMS

$\sigma(pp \rightarrow Z+X) * \mathcal{B}(Z \rightarrow \mu^+ \mu^-)$ = 39.6 ± 0.7 (stat) ± 0.6 (syst) ± 0.8 (lumi) pb

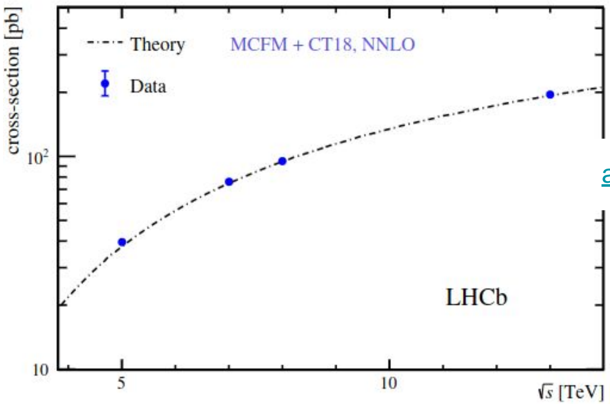
$2.0 < \eta < 4.5$

pT>20 GeV,

$m_{\mu\mu}$:[60,120] GeV

Measurements validates theoretical calculations accurate to $\mathcal{O}(\alpha_s^2)$.

Measurements probe nPDFs @Bjorken-x values of $10^{-4} < x < 10^{-3}$



arXiv:2308.12940

Extraction of **nuclear modification factor** using measurements from p-Pb collision dataset @ $\sqrt{s_{NN}}$ =5.02 TeV (208 binary NN collisions) for

forward [$1.53 < y^*_\mu < 4.03$] and backward regions [$-4.97 < y^*_\mu < -2.47$]

y^*_μ : μ rapidity in CM frame.

Acceptance correction

$$R^F_{pPb} = k^F_{pPb} \cdot \frac{\sigma_{(pPb,\ 1.53<y^*_\mu<4.03)}}{208 \cdot \sigma_{(pp,\ 2.0<\eta<4.5)}},$$

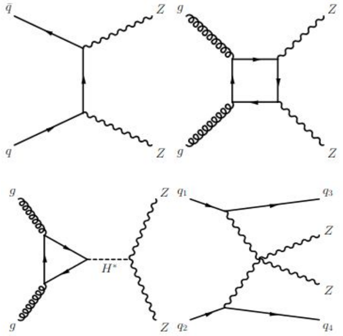
$R^F_{pPb} = 1.2^{+0.5}_{-0.3}$ (stat) ± 0.1 (syst)

$R^F_{pPb} = 3.6^{+1.6}_{-0.9}$ (stat) ± 0.2 (syst)

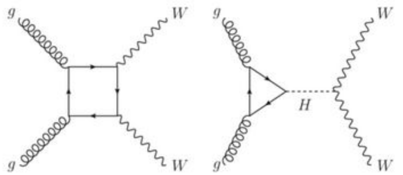
Inclusive ZZ, WW productions at $\sqrt{s}$ = 13.6 TeV

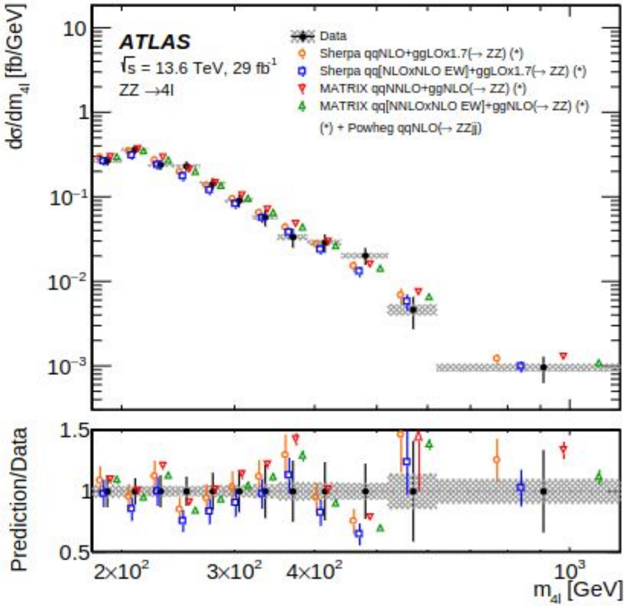
Important for Higgs and gauge coupling studies; also BSM searches.

ZZ



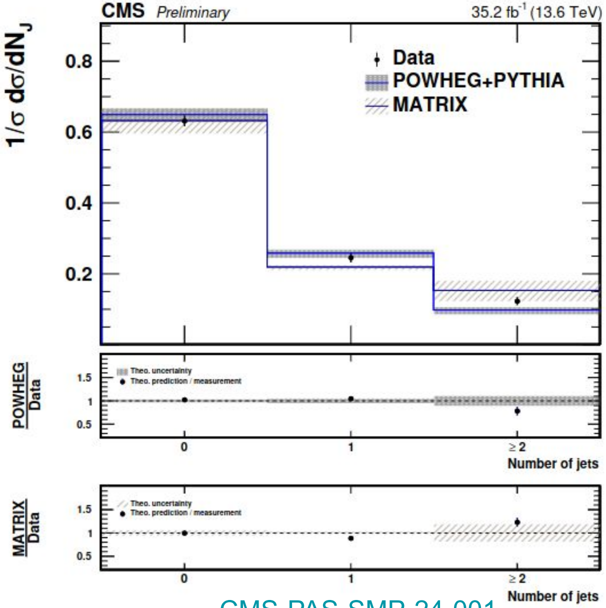
WW





arXiv:2311.09715

$\sigma(4\ell+X)_{fid}$ = 16.8 ± 1.1 pb
66 < m_Z < 116 GeV, ℓ =e, μ



CMS-PAS-SMP-24-001

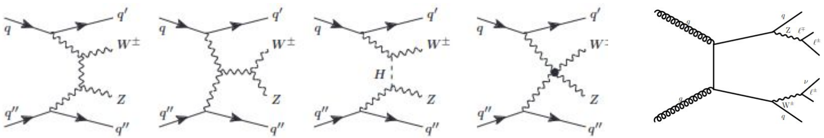
$\sigma(WW+X)_{fid}$
e, μ modes

Observable	Expected	Observed
Cross section (fb)	812 ± 35	808 ± 36
0-jet fraction	0.648 ± 0.014	0.633 ± 0.015
1-jet fraction	0.256 ± 0.012	0.245 ± 0.012
≥ 2-jet fraction	0.096 ± 0.010	0.122 ± 0.014

$\sigma(WW+X)_{tot}$ = 25.7 ± 5.6 pb

Detailed presentation of vector boson scattering results in parallel session: Costanza Carnvale

WZ productions at $\sqrt{s}$ = 13 TeV



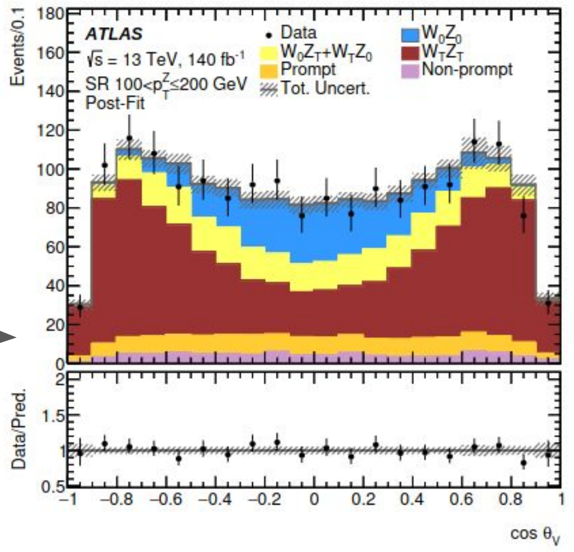
EW QCD

arXiv:2402.16365

- WZ polarisation measurements probe the nature of EW symmetry breaking. Polarization energy dependent.
- Analysis identifies 2 fiducial regions with different longitudinal (L) polarization.
- For low (high) p_T bosons polarization is mostly transverse (longitudinal) .

Study rapidity difference ΔY between
i) lepton from the W boson decay and the Z boson
ii) the W boson and the Z boson.

Significant suppression of events in both cases for ΔY =0



θ_V : scattering angle of the W boson in the WZ rest frame with respect to the z-axis.

⇒ TT amplitude vanishes for θ_V =0.

First observation of radiation amplitude zero region!

- **A non-zero fraction of events (e, μ modes) with diboson polarization**

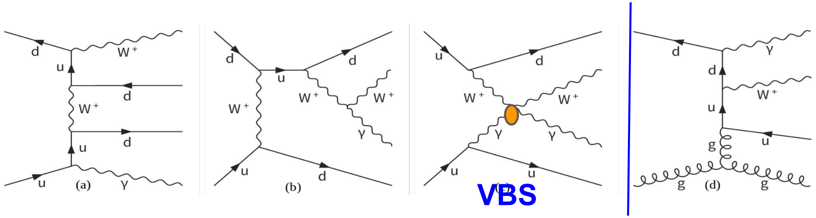
  →observed significance: 5.3 s.d, p^Z_T: [100, 200 GeV].

Fiducial $\sigma(WZjj \to \ell' \nu \ell\ell jj)_{EW}$ = 0.368 ± 0.037 (stat.) ± 0.059 (syst.) ± 0.003 (lumi.) fb

Constraint on dim-8 operators in EFT analysis of VBS production of WZ. arXiv: 2403.15296

$W\gamma$ + jj at $\sqrt{s}$ = 13 TeV

EW production probes quartic gauge coupling and related to CP nature $WW\gamma Z$ and $WW\gamma\gamma$ couplings ⇒ sensitive to the EWSB.



The interference term with QCD (~1 to 3% of EW signal depending on Mjj range)

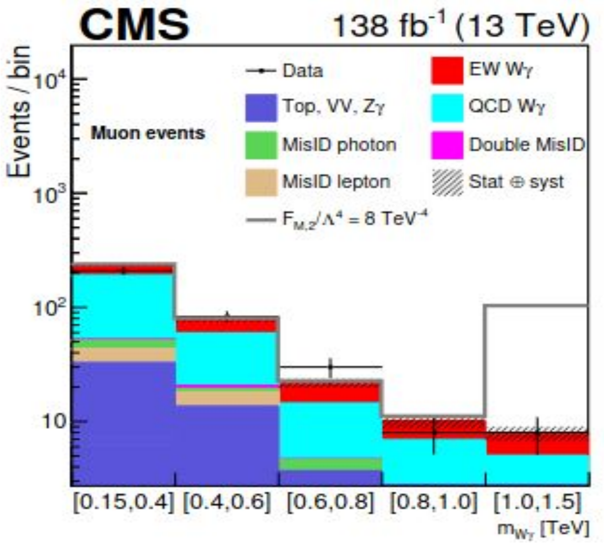
CMS measurements:

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

$$\sigma^{\text{fid}}_{\text{EW+QCD}} = 113 \pm 2.0\,(\text{stat})^{+2.5}_{-2.3}\,(\text{theo})^{+13}_{-13}\,(\text{syst})\text{ fb} = 113 \pm 13\text{ fb}$$

Effective field theory with dim-8 operators involving 2 types of operators: only field strengths (eg,$B_{\mu\nu}$) and both field strength & covariant derivative ($D_\mu\varphi$),

PRD 74 (2006) 073005



ATLAS: $W\gamma$ + jj process observed with 6.3 s.d.
→ studied various kinematic observables:
p_T^{jj} most sensitive to the **tensor-type operators**
→ **first LHC limits**

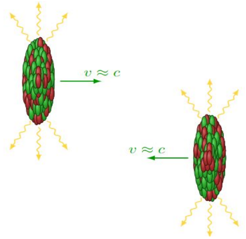
arXiv:2403.02809

p_T^{ℓ} most sensitive to the mixed scalar operators.

PRD 108 (2023) 032017

EW results in two-photon collisions

CMS-PAS-SMP-23-005



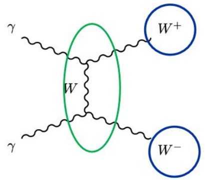
Photons can be simultaneously emitted by charged particles during p-p/ p-Pb/ Pb-Pb collisions

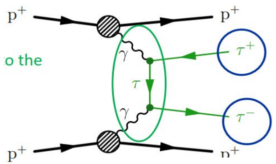
Cross section ~ Z^4 ⇒ large rate of diphoton production in heavy ion runs.

At very high masses of $m_{\gamma\gamma}$, diffracted protons can be tagged by the forward detectors ⇒ study diffractive production of WW / $\tau\tau$

Utilize excellent tracking capability of experiments

CMS: ~ 30% of the 1 mm window around the beamspot not contain any pileup track.





- 2 back-to-back objects
- No hadronic activity close to the di-W/τ vertex
- Ntracks = 0, pT > 0.5 GeV, $|\eta| < 2$

First observation of $\gamma\gamma \rightarrow \tau\tau$ in pp collisions by CMS

σ_{fid}(obs) = 11.2 + 3.1−2.4 (syst) +2.2−2.1 (stat) fb, Significance 5.3 s.d. (6.5 exp.)

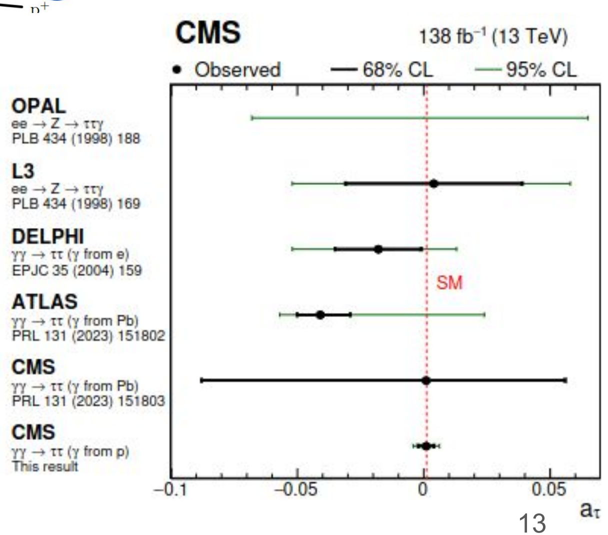
Constraints on the anomalous electromagnetic moments of τ:

$a_\tau = 0.0009^{+0.0032}_{-0.0031}$

Dirac a_τ: 0.0

Schwinger (SM) a_τ = 0.00116(9)

Dipole moment: $-1.7 < d_\tau < 1.7 \times 10^{-17}$ e cm.



Exclusive production of high mass diphoton at 13 TeV

Also called light-by-light (LbyL) scattering .

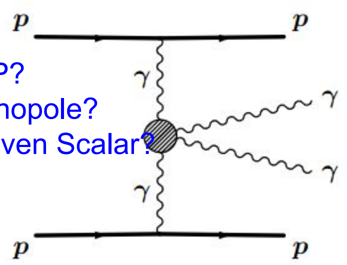
Protons tagged in TOTEM precision proton spectrometer

Anomalous 4γ interaction in dim-8 EFT:

$$\mathcal{L}_{4\gamma} = \zeta_1 F_{\mu\nu}F^{\mu\nu}F_{\rho\sigma}F^{\rho\sigma} + \zeta_2 F_{\mu\nu}F^{\nu\rho}F_{\rho\lambda}F^{\lambda\mu},$$

ζ_i =0 in SM

ALP?
Monopole?
C-even Scalar?
….

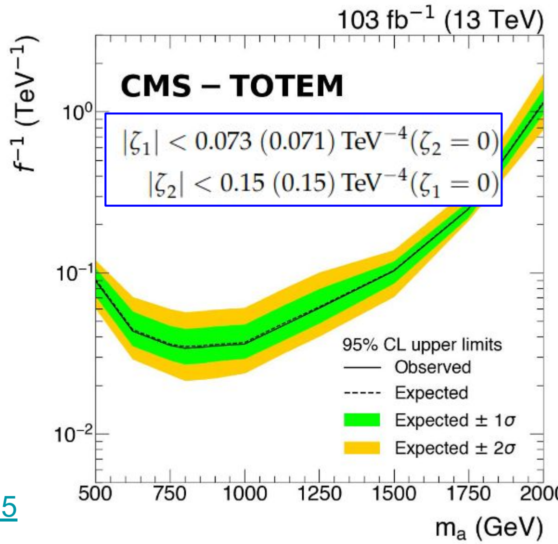


Study differential cross section:

$$\frac{d\sigma}{d\Omega} = \frac{1}{16\pi^2 s}\left(s^2+t^2+st\right)^2\left[48\zeta_1^2+40\zeta_1\zeta_2+11\zeta_2^2\right]$$

Only 1 event found in relevant phase-space, expected background: 1.1 event

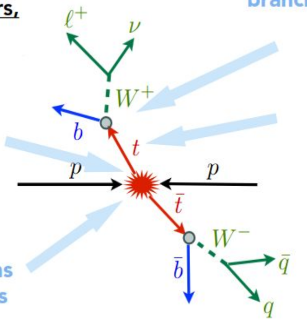
CMS σ(pp → pγγp) < 0.61 fb
for p_T^{γ}> 100 GeV, $|\eta^{\gamma}|$ < 2.5, $m_{\gamma\gamma}$ > 350 GeV
fractional proton energy loss of 0.035 < ξp < 0.150(0.180) for the +z (-z) arm of PPS.



Limits on axion-like particle (ALP) production in s-channel $\gamma\gamma \to a \to \gamma\gamma$
Coupling: $f^{-1} \geq 0.03$ to 1 TeV^{-1} for m_a = 500–2000 GeV

arXiv:2311.02725

Physics of the top quark



- Heaviest known elementary particle
- Abundant production at the LHC (in Run 2 ~10^8 per expt.)
- Extremely short-lived, decays before hadronizing → allows to observe properties of the bare quark
- Mass/ Yukawa coupling: free parameter in SM, to be measured in experiments: $y_f = \sqrt{2}\, m_f / v$. **Also** key factor in stability of SM Higgs potential
- Top mass must be measured with precision.

CERN-LPCC-2023-002
arXiv:2402.08713
CMS-PAS-TOP-022-001

ATLAS & CMS combination of 15 measurements using Run1 data ($\sqrt{s}$ =7 & 8 TeV) uses top pair and single top productions:

$\mathbf{m_t = 172.52 \pm 0.33\ [0.14\ (stat),\ 0.33(syst)]\ \ GeV}$ → impressive *precision of 0.18%*

Currently, best measurement in a single channel: m_t = 171.77 ± 0.37 GeV CMS-PAS-TOP-022-008

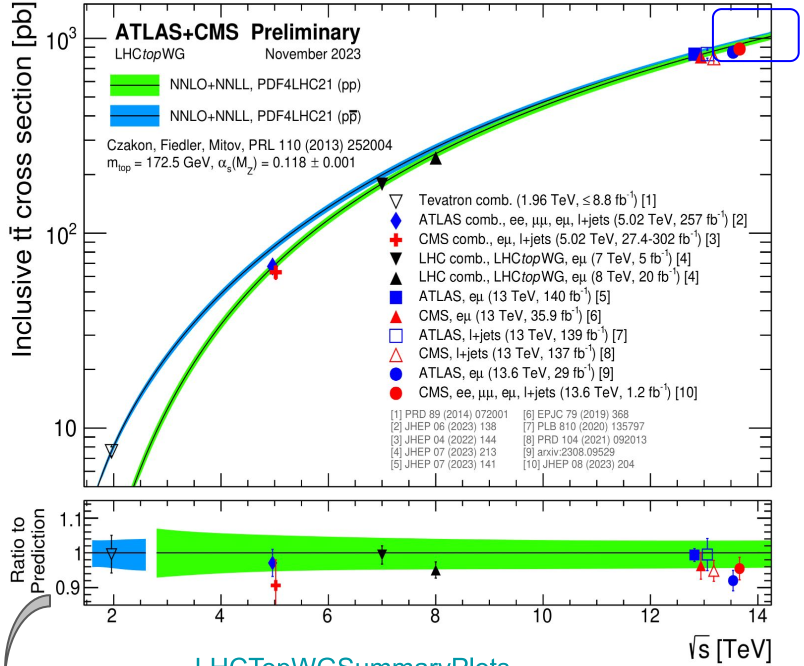
Issue: difference of ~ 0.5 GeV between direct measurement of m_t^{MC} (parameter in event generation tool), indirect measurement from cross section corr. m_t^{pole} (top-mass renormalization scheme in field-theory) A.Hoang: 2004.01915

HL-LHC projection for Δm_t ~200 MeV
Ultimate precision expected ~0.1%

CERN YR

More details in *Recent highlights of the top quark production from CMS* by Jeremy Andrea

Cross section for top quark pair production



LHCTopWGSummaryPlots

Compatibility with theory predictions at high order in perturbation theory

Measurement of tt roduction cross section:

→ Test QCD predictions & extract SM parameters

→Constrain top quarks as background process

Measurements at √s =13.6 TeV tests the scaling with energy & other experimental improvements

σ(theo) = 924^{+32}_{-40} pb

ATLAS: σ(tt+X) = 850 ± 3 (stat) ± 18 (syst) ± 20 (lumi) pb

Total uncertainty ~ 3.2% using 29 fb-[1]

PLB 848 (2024) 138376

CMS: σ(tt+X) = 881 ± 23 (stat ± syst) ± 20 (lumi) pb

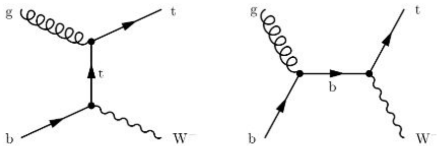
Total uncertainty ~ 3.5% _using 1.21 fb--[1]

JHEP 08(2023) 204

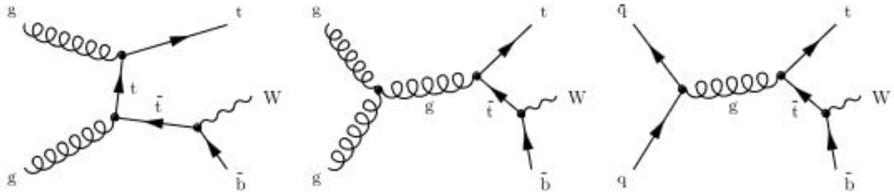
New ATLAS result at 13 TeV reaches precision of 1.8% !

JHEP 07 (2023) 141

Measurements of tW production



Removed processes of tW production at NLO in simulation →



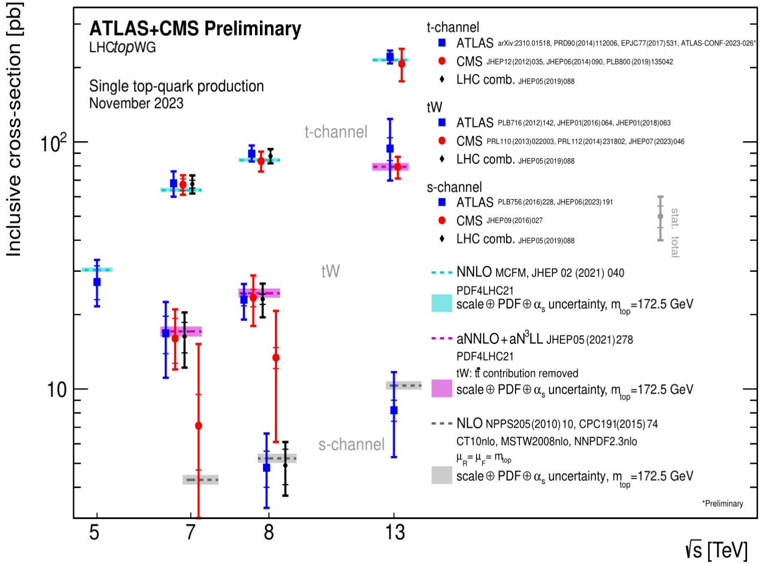
CMS: σ(tW) = 84.1 ± 2.1 (stat) $^{+9.8}_{-10.2}$ (syst) ± 3.3 (lumi) pb at 13.6 TeV

→ total relative uncertainty ~ 13%

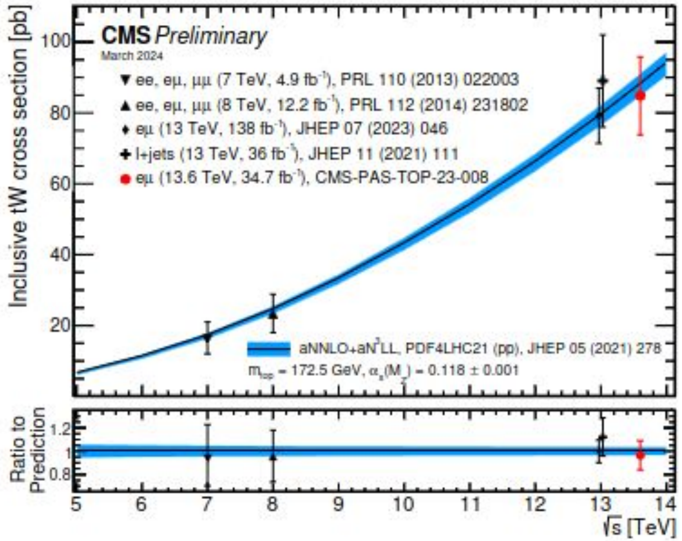
t-channel measurement with ~ 6% uncert. by ATLAS at 13 TeV

arXiv:2403.02126

HCTopWGSummaryPlots

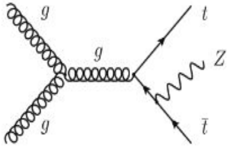


Ratio of tq to tbar-q productions can potentially differentiate between different PDF sets.



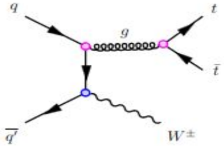
CMS-PAS-TOP-23-008

ttZ, ttW, tZq productions at 13 TeV



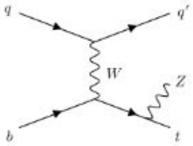
arXiv:2312.04450

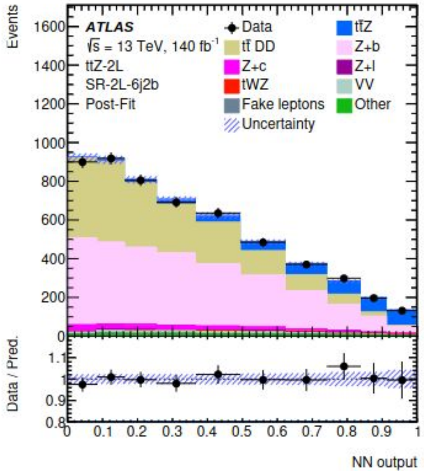
CMS-PAS-TOP-23-004



arXiv:2401.05299

JHEP 07 (2023) 219





ATLAS:

- Measured total cross section: **σ(ttZ) = 0.86 ± 0.04(stat) ± 0.04(syst) pb**
  SM: σ(ttZ) = 0.86 ± 0.09 pb at NLO(QCD+EW)+NNLL

EPJC 79 (2019) 249

- Spin correlations of the top quarks consistent with the SM
  1.8 s.d. difference from the hypothesis of no spin correlations

JHEP 03 (2020) 056

JHEP 07 (2023) 219

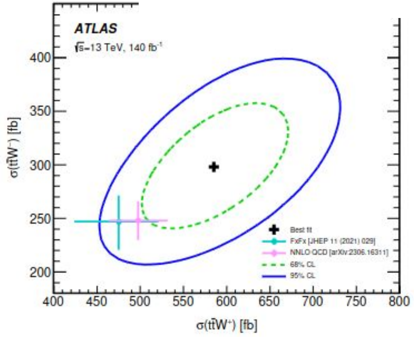
- **Recent measurement $\sigma(tt\gamma)_{fid}$ = 793 ± 38 fb = 793 ± 5 (stat) $^{+38}_{-37}$ (syst) fb.**
- Combined EFT analysis for ttZ and ttγ measurements

arXiv: 2403.09452

charge asymmetry between ttW⁺ and ttW⁻

- Measured total cross section: **σ(ttW) = 0.88 ± 0.08 pb**
  SM: σ(ttW) = 0.75 ± 0.05 pb at NNLO(QCD)+NLO(EW))

PRL 131 (2023) 231901

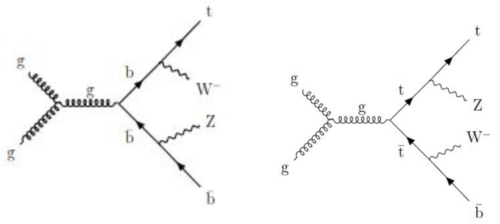


CMS:

σ(ttW) = 0.868 ± 0.040 (stat) ± 0.051 (syst) pb.

σ(tZq) = 0.81 ± 0.10 pb

Evidence of tWZ production

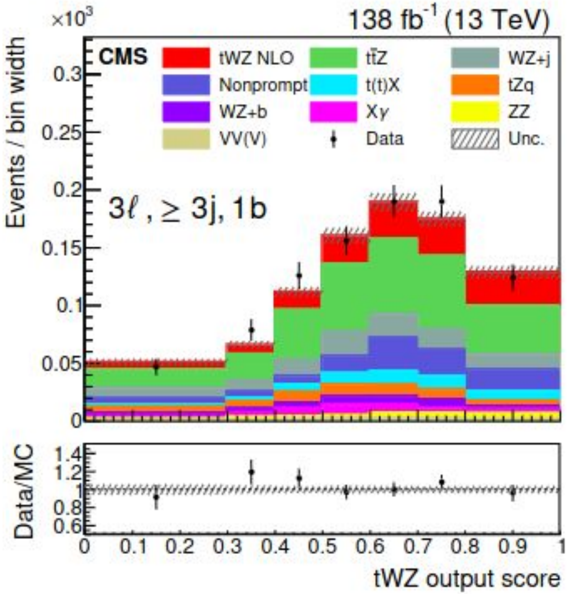


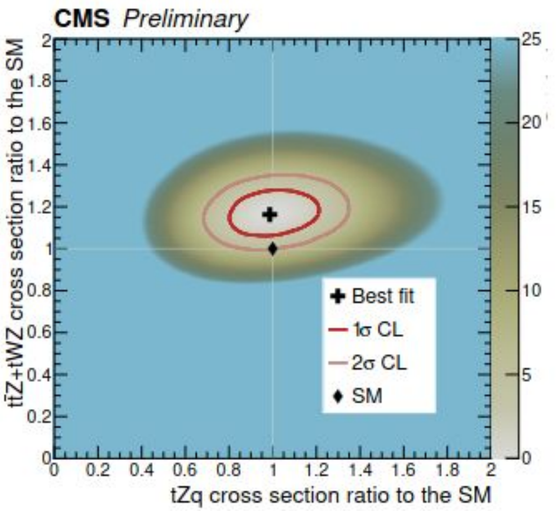
Measured $\boldsymbol{\sigma}$**(tWZ) = 354 ± 54 (stat) ± 95 (syst) fb**
statistical significance 3.4 s.d. (expected: 1.4 s.d.)

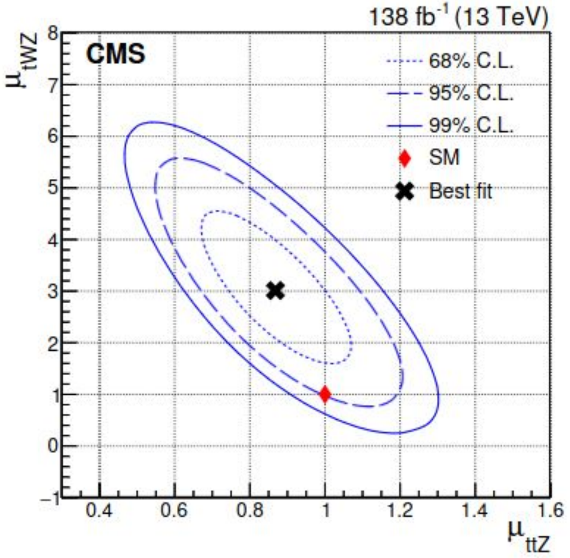
2σ above the SM prediction of 136 ± 9 fb at NLO(QCD)

Main background ttZ process

σ(ttZ + tWZ) = 1.14 ± 0.07 pb



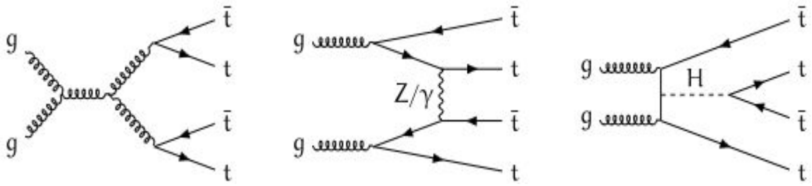




Likelihood scan of signal strengths
$\boldsymbol{\mu}$(ttZ + tWZ) vs.$\boldsymbol{\mu}$(tZq)

arXiv:2312.11668

Observation of 4t production



- Heaviest final state ⇒ expect about 2k events @13 TeV

  Observed (expected) significance
  6.1(4.7) s.d. : ATLAS
  5.6 (4.9) s.d.: CMS

EPJC 83 (2023) 496
PLB 847 (2023) 138290

- Possible enhancement in BSM: ⇒ Several constraints on new physics.

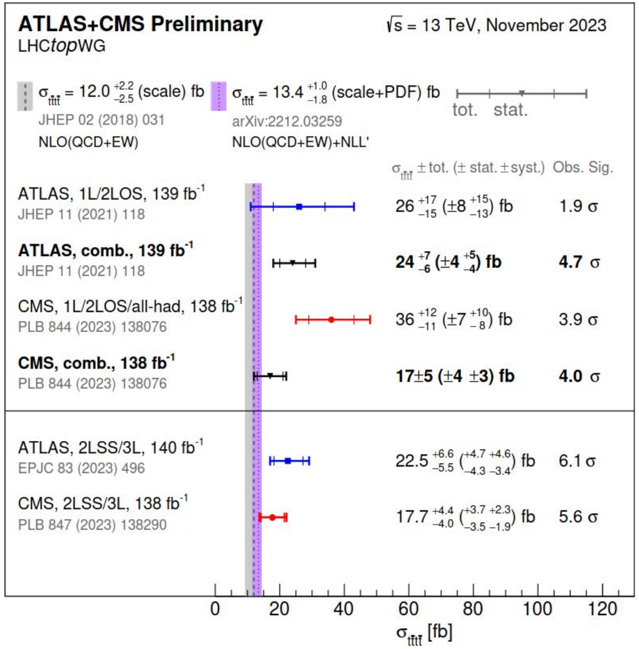
- Cross section sensitive to top Yukawa coupling, its CP properties.
  Derive limits in 2d parameter space of $|\kappa t \cos(\alpha)|, |\kappa_t \sin(\alpha)|), \kappa_t = y_t / y^{SM}$

Assuming a pure CP-even coupling ($\alpha = 0$), **observed upper limit on**

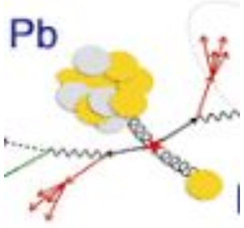
$|\kappa_t|$ = 1.9 at 95% CL EPJC 84 (2024) 156

- EFT: constrain 4-fermion interactions of dim-6

- Observed constraint on Higgs boson oblique parameter <0.2 at 95% CL → coincides with the maximum allowed value compatible with perturbation theory



Top quark production in heavy ion collisions



First observation of tops in p-Pb collisions at $\sqrt{s_{NN}}$= 8.16 TeV by **CMS 45 ± 8 nb** PRL 119 (2017) 242001

New measurement by **ATLAS : = 57.9 ± 2.0(stat) $^{+4.9}_{-4.5}$(syst) nb at $\sqrt{s_{NN}}$= 8.16 TeV** ATLAS-CONF-2023-063

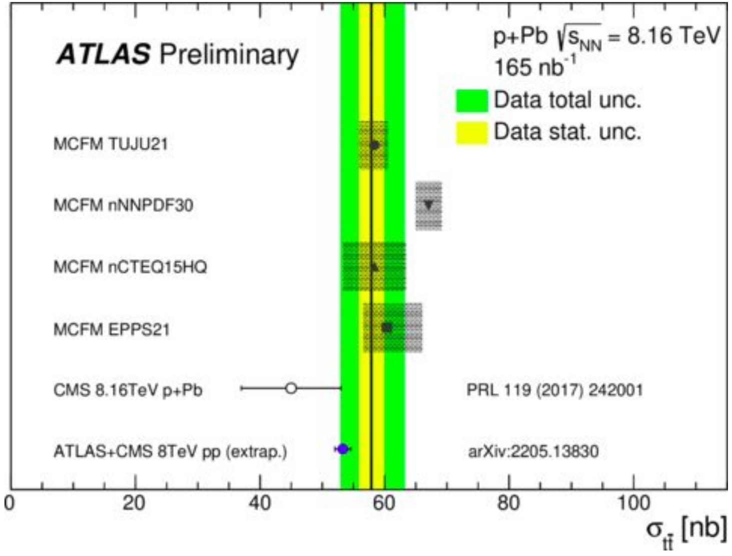
Total uncertainty in integrated cross section: ~9%

Measurement paves a new way to constraint nPDFs in the high-x region

Evidence for top quark production in Pb-Pb collisions (CMS)

→ Precise probe of nuclear gluon density PRL 125 (2020) 222001

Precision of the measurement in the individual $t\,t$ decay channel limited by systematic uncertainties in both channels fr ATLAS, but for CMS the ℓ+jets channel uncertainty is mainly due to systematics while the dilepton region is dominated by statistics.



Quantum entanglement (observed at the highest energy so far)

- Entanglement explored for the first time between a pair of quarks at relativistic energies.

$$|\mathcal{M}(q\bar{q}/gg \to t\bar{t} \to (\ell^+\nu b)(\ell^-\bar{\nu}\bar{b}))|^2 \sim tr[PR\bar{P}].$$

R: production spin density matrix
P: decay spin density matrix of top

$$\underbrace{\frac{1}{m_t}}_{\substack{\text{production}\\10^{-27}\text{ s}}} < \underbrace{\frac{1}{\Gamma_t}}_{\substack{\text{lifetime}\\10^{-25}\text{ s}}} < \underbrace{\frac{1}{\Lambda_{QCD}}}_{\substack{\text{hadronization}\\10^{-24}\text{ s}}} < \underbrace{\frac{m_t}{\Lambda^2}}_{\substack{\text{spin-flip}\\10^{-21}\text{ s}}}$$

EPJ+ 136 (2021) 907

- In pair production of tt spin information is correlated and transferred to decay products.
- Spin correlations at low m(tt) used as a proxy to estimate the entanglement.
- Study two-qubit states at tt production threshold (system is spin-singlet, rotationally invariant), with well-specified fiducial phase-space.

Degree of entanglement depends on tt kinematics

$$\frac{1}{\sigma}\frac{d\sigma}{d\Omega_+ d\Omega_-} = \frac{1 + \mathbf{B}^+ \cdot \hat{\mathbf{q}}_+ - \mathbf{B}^- \cdot \hat{\mathbf{q}}_- - \hat{\mathbf{q}}_+ \cdot \mathbf{C} \cdot \hat{\mathbf{q}}_-}{(4\pi)^2}$$

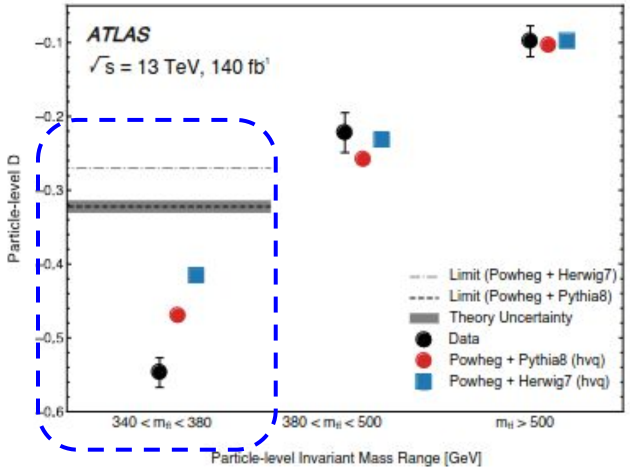
$$D = \frac{\mathrm{Tr}\,[\mathbb{C}]}{3} \Rightarrow D < -\frac{1}{3}$$

B : top polarization
C: spin correlation matrix
Tr.[**C**] < -1

Observable dependent on the angle between the charged leptons in the rest frame of their parents

arXiv:2311.07288

CMS PAS-TOP-23-001



ATLAS: D = -0.547 ± 0.002 (stat) ± 0.020 (syst)

CMS: $D = -0.478^{+0.025}_{-0.027}$

Significance more than 5 s.d. compared to null hypothesis of no-entanglement.

Measurement: first step towards quantum tomography and coherence in top quark events.

Conclusion

Presented a non-exhaustive (personal) selection of topics to highlight the breadth of the electroweak and top physics analyses being performed at the LHC. Accurate measurements supported by precision theoretical work and better simulations.

Looking forward eagerly for healthy data collection during 2024 and 2025 to improve results from Run 3. This is critical to resolve some of the disagreements between measurements and predictions; eg., cross sections for ttW, tWZ, tttt etc.

Technical advancements are hard to predict ⇒ Expectations are often exceeded.
Hence did not delve much into the projection studies for HL-LHC, performed few years back,

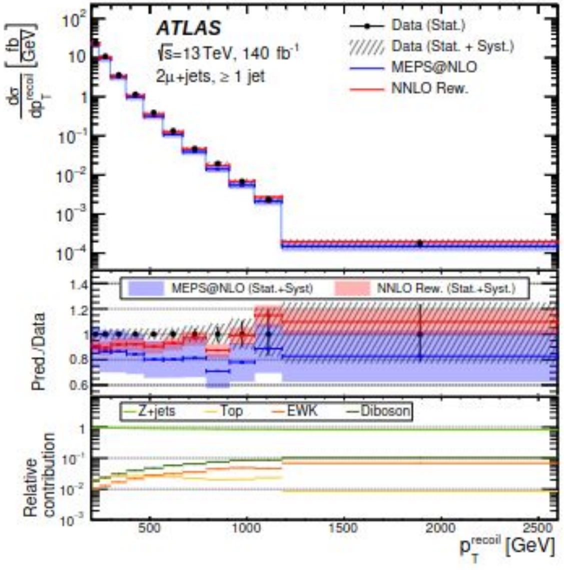
The diversity of analyses after more than a decade of the start of the LHC indicates that the mining of interesting physics will continue for next several decades.

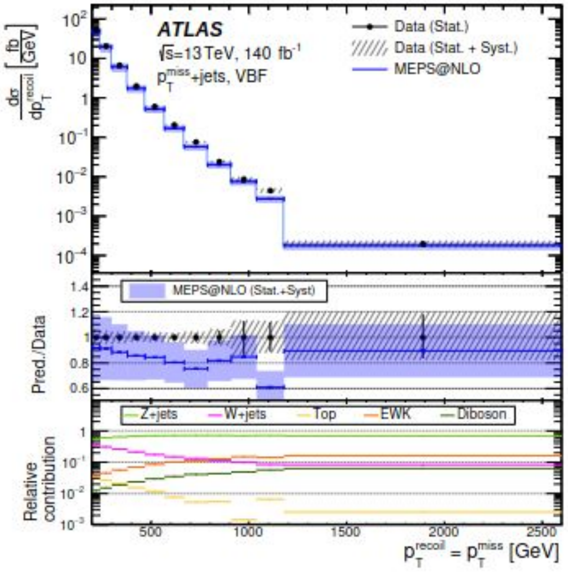
On behalf of the LHC experimental community we congratulate the CERN accelerator team and the WLCG.

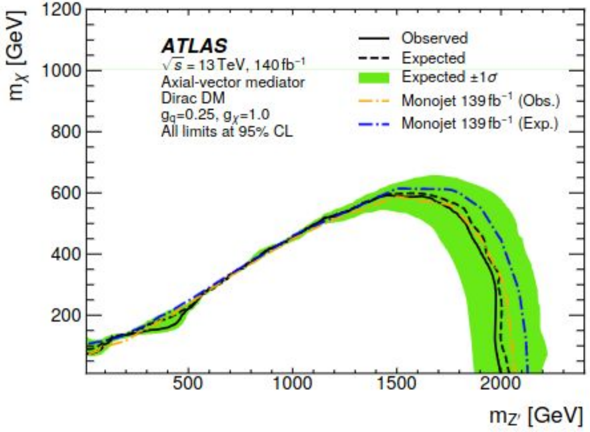
Thank you!

Backup

Differential measurement of p_T^{recoil} , p_T^{miss}







arXiv:2403.02793

$$R^{\text{miss}} = \frac{\sigma_{\text{fid}}\left(p_{\text{T}}^{\text{miss}} + \text{jets}\right)}{\sigma_{\text{fid}}\left(\ell^+\ell^- + \text{jets}\right)}$$

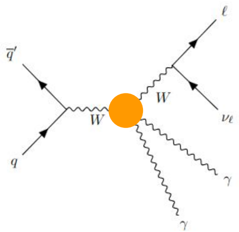
This ratio won't reveal contribution of DM

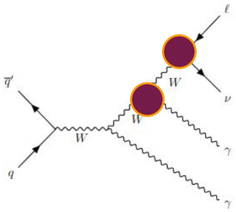
Search for dark matter (DM) in events with p_T^{miss} + jets or 1, 2 leptons + jets or 1 photon + jets

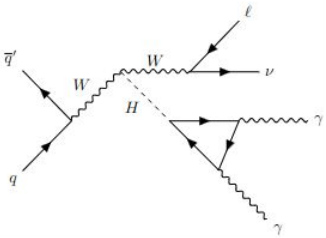
BSM interpretation possible with reasonably good sensitivity: DM production via Z' respecting additional U(1) symmetry.

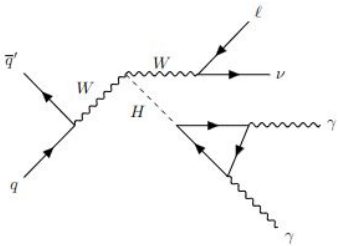
Electroweak production of tribosons W$\gamma\gamma$

ATLAS-CONF-2023-005









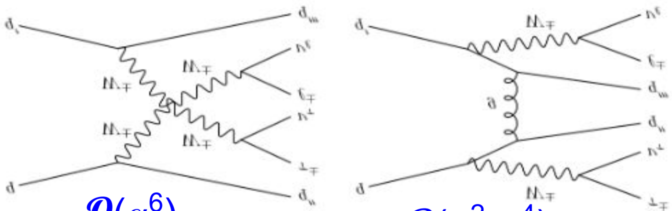
W$\gamma\gamma$ process: 5.6 s.d. observation
(e + μ channel) σ ~ 12.2 ± 2 fb

All measurements match with SM

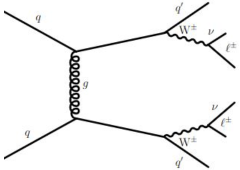
Source of uncertainty	Impact [%]
Data-driven background estimates	13
Photon efficiency	4.5
Signal MC theoretical modeling	3.5
Background MC theoretical modeling	3.0
Monte Carlo statistics	2.8
Jet efficiency and calibration	2.4
Top normalization	2.4
Pileup reweighting	1.6
$E_{\mathrm{T}}^{\mathrm{miss}}$ 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

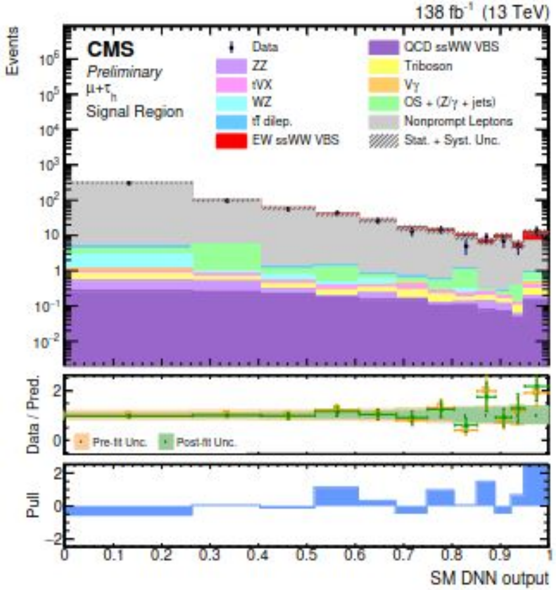
VBS: Same-sign W pair using one τ lepton at 13 TeV

CMS-PAS-SMP-22-008



$\mathcal{O}(\alpha^6)$ $\mathcal{O}(\alpha^2\alpha_s^4)$





- Measurement statistically limited.
- EFT interpretation of dim-6 and dim-8 coefficients

Total systematic uncertainty	+0.344	−0.302
Data statistical uncertainty	+0.522	−0.477
Total uncertainty	+0.625	−0.564

Observed (expected) EW signal strength (fixing QCD part to SM) : $1.44^{+0.63}_{-0.56}$

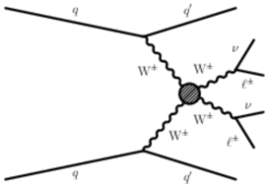
significance: 2.7 (1.9) s.d.

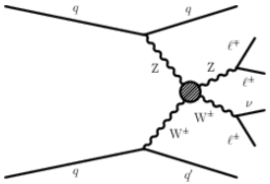
Vector boson scattering: WW, WZ at HL-LHC

CMS-PAS-FTR-21-001

VBS insight into EWSB of the SM

cross section can be modified via BSM contributions

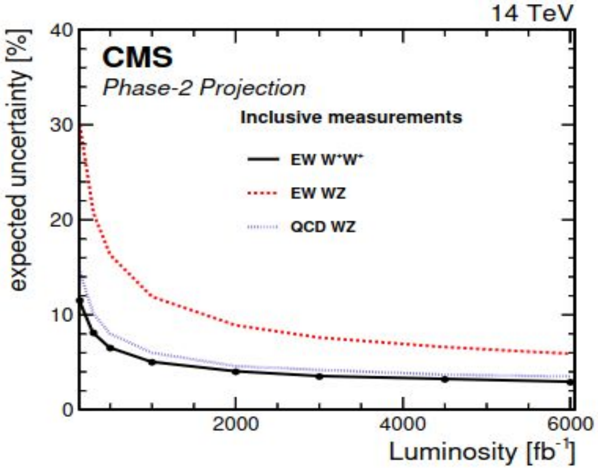


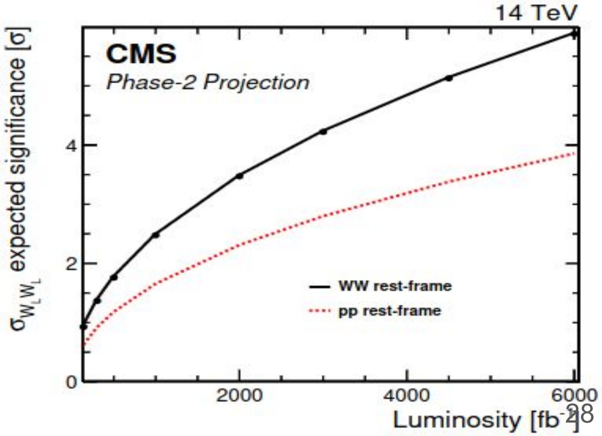


- Two gauge bosons + two jets w/ large mjj and large |Δηjj|
- Three (WL±WL±, WL±WT± and WT±WT±) polarization states
- Sensitivity to VBS & WL±WL± as a function of luminosity
- Based on 13 TeV measurements, projected with the similar S/B raeo

o uncertainty for inclusive measurements: $\mathcal{O}$(20-30%)

o estimated significance for observation of EW WL±WL±





Top Quark Spin Correlation at HL-LHC

CMS-PAS-FTR-18-034

Spin information can be used to search for new physics. eg.,: production of top squark pair ⇒ spin of daughter top quarks uncorrelated unlike the ttbar production in the Standard Model

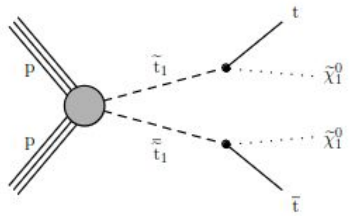
• HL-LHC projection at 14 TeV and 3000 fb^{-1} of angular distribution of leptons from the decay of top quark.

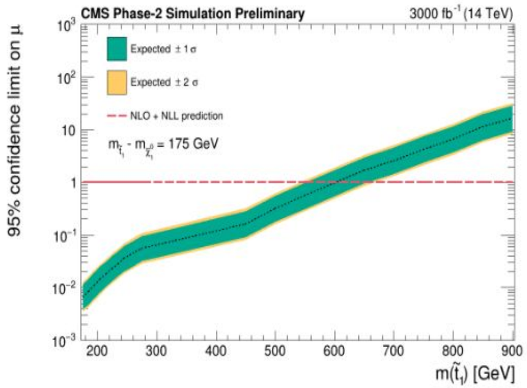
Spin correlation fraction f_{SM} :fraction of SM-like spin correlation events as opposed to events with no spin correlation ⇒ represents the strength of the given measure of spin correlation relative to the SM prediction.

f_{SM} =0 → no correlation

• **The most accurate laboratory-frame observable can be measured with a 3% total uncertainty**

• Can be utilised to **extend the ultimate LHC reach to discover top squarks or exclude a mass above 600 GeV.**





Invisible width of Z boson

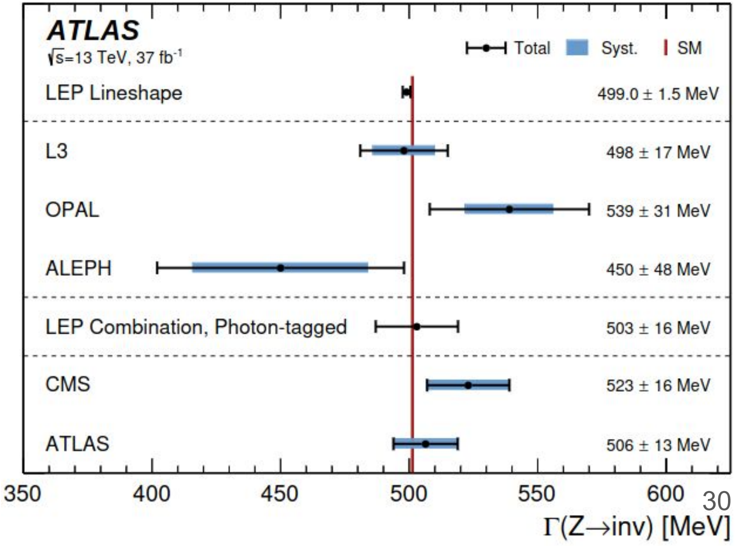
ATLAS arXiv:2312.02789
CMS: PLB 843 (2023) 137563

ATLAS, using 2015+2016 data $\mathcal{L}$ = 37 fb−1 @ √s =13 TeV

Use ratio of Z→$\nu\nu$ +X to Z→ $\ell\ell$ + X

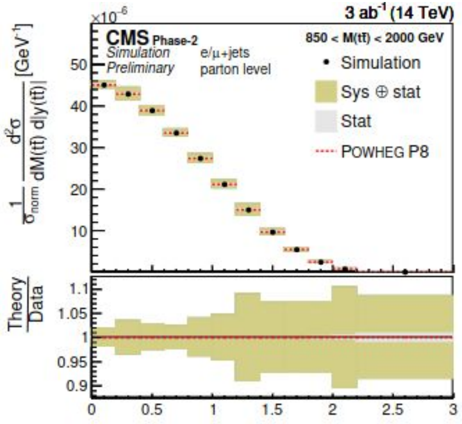
506 ± 2 (stat.) ± 12 (syst.) MeV

$$R^{\text{miss}}(p_{\text{T,Z}}) \equiv \frac{\frac{d\sigma(Z(\to\text{inv})+\text{jets})}{dp_{\text{T,Z}}}}{\frac{d\sigma(Z(\to\ell\ell)+\text{jets})}{dp_{\text{T,Z}}}} = \frac{\frac{d\sigma(Z+\text{jets})\times BR(Z\to\text{inv})}{dp_{\text{T,Z}}}}{\frac{d\sigma(Z+\text{jets})\times BR(Z\to\ell\ell)}{dp_{\text{T,Z}}}}$$



Top related measurements at the HL-LHC

CMS-PAS-FTR-18-015

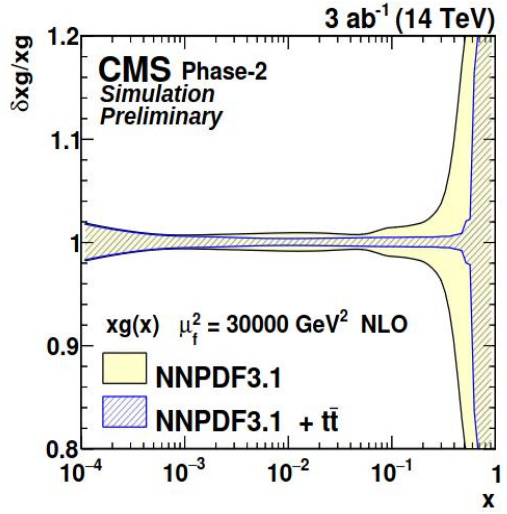


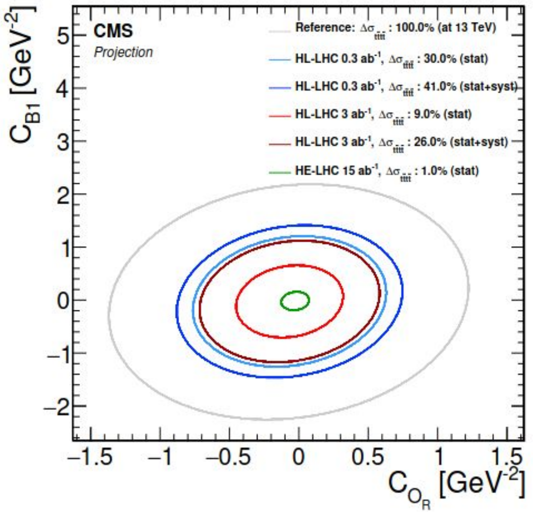
Measurements possible at higher rapidity with upgraded detectors

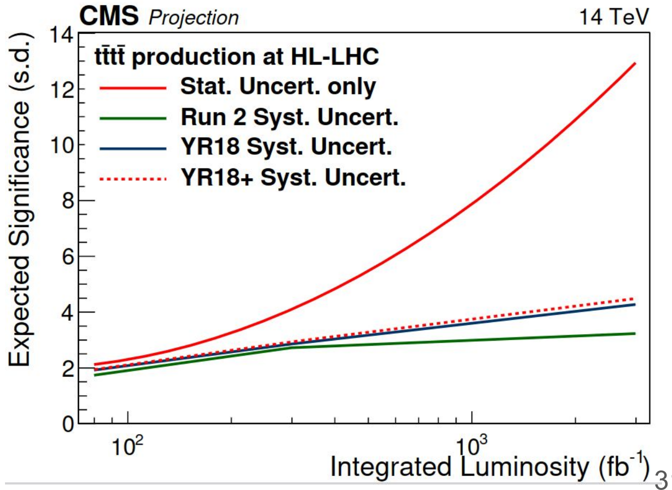
Huge pile up issue can be tackled efficiently.

Differential distributions: ultimate precision: ~ 5% due to improved jet energy calibration and a reduced uncertainty in the b-jet ident ⇒ Constrain PDFs

Measurement of 4 top production cross section constraints EFT parameter space CMS-PAS-FTR-18-031

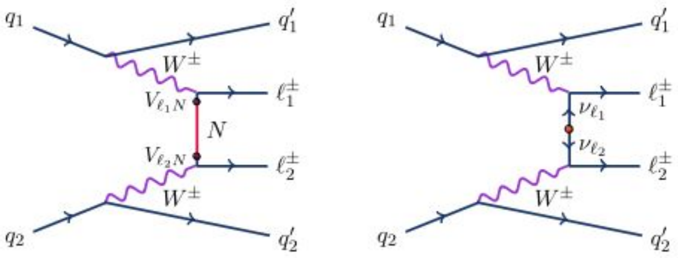


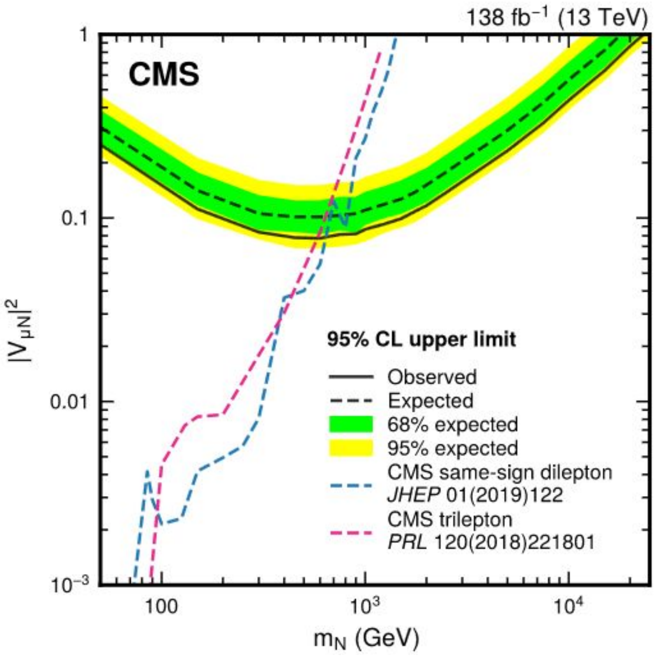




Vector boson fusion process: novel tool for BSM search

PRL 131 (2023) 011803





- Same sign dilepton in central region of detector in VBF-like event topology
  ==> lepton number violation

i) Heavy, Majorana neutrino (N) production

ii) Process mediated by Weinberg operator (dim-5) with flavour-dependent coefficients

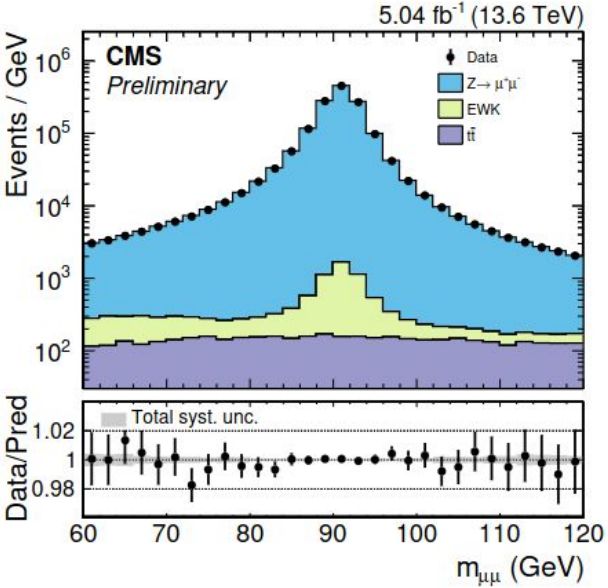
- Best limit on mixing element $|V_{mN}|^2$ puts the best constraint so far : m_N > 650 GeV
- Effective $\mu\mu$ Majorana neutrino mass associated with W-operator excluded : 10.8 GeV

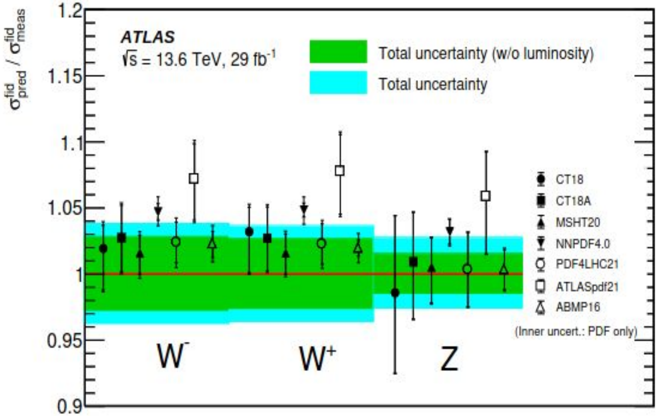
W/Z production in Run3 data, $\sqrt{s}$ = 13.6 TeV

W,Z processes marked by clear experimental signatures:

→ standard candles
→ ideal tools for QCD, EW studies
→ determination of SM parameters
→ extraction of PDFs
→ testbed for state-of-the-art predictions
→ important backgrounds to Higgs, BSM searches etc.

Precision EW measurements provide insight into BSM realm.





Ratio of fiducial cross sections:
$R_{W+/W-}$ = 1.286 ± 0.022
$R_{W\pm/Z}$ = 10.17 ± 0.25
$R_{tt/W\pm}$ = 0.112 ± 0.003

arXiv:2403.12902

Fiducial cross sections

ATLAS: $\sigma(pp \rightarrow W^+ + X)^* \mathcal{B}(W^+ \rightarrow \ell^+ \nu)$ = 4250 ± 150 pb $\sigma(pp \rightarrow W^- + X)\mathcal{B}(W^- \rightarrow \ell^- \nu)$ = 3310 ± 120 pb
$\sigma(pp \rightarrow Z + X)^* \mathcal{B}(Z \rightarrow \ell^+\ell^-)$ = 744 ± 20 pb , $m_{\ell\ell}$:[66,116] GeV

CMS: $\sigma(pp \rightarrow Z + X)^*\mathcal{B}(Z \rightarrow \mu^+\mu^-)$ = 763.5 ± 4(stat) ± 6.9(syst) ± 17.6(lumi) pb , $m_{\mu\mu}$:[60,120] GeV

$\sigma^*\mathcal{B}$ (pred.) = 766.6 ± 6.5 (PDF) $^{+2.1}_{-4.5}$(scale) nb @N2LO of QCD + NLO of EW

ZZ + jets at $\sqrt{s}$ = 13 TeV

Differential cross-section measurements of 4 charged leptons + 2 jets production in various kinematic variables:

i) VBS sensitive ⇒ m_{4l}, $p_T(4l)$, m_{jj}, Δy_{jj} , $p_T(jj)$.

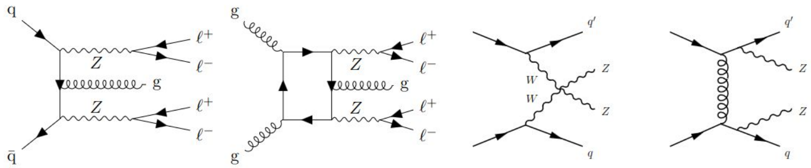
ii) Polarization and CP structure of WWZ & WWZZ self-interactions ⇒ $\cos\theta^*_{12}$, $\cos\theta^*_{34}$, m_{jj} , $\Delta\varphi_{jj}$, $p_T(jj)$.

Note-1: NNLO + PS prediction improves the data / prediction agreement in the 1-jet and high jet multiplicity regions,

Note-2: Jet multiplicity description better than NLO samples generated with the event generators MADGRAPH5 aMC@NLO and POWHEG.

Note-3: Electroweak corrections improves the description of the m_{4l} distribution.

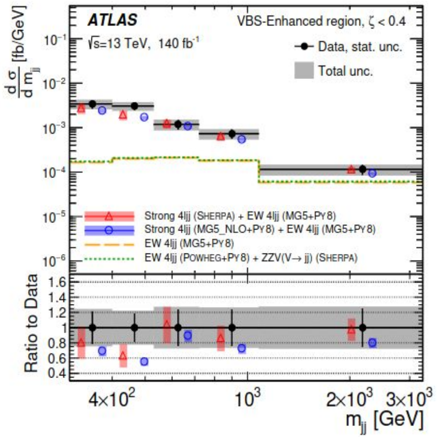
Required: better MC modeling for events with complex multiboson final states and extra jets.

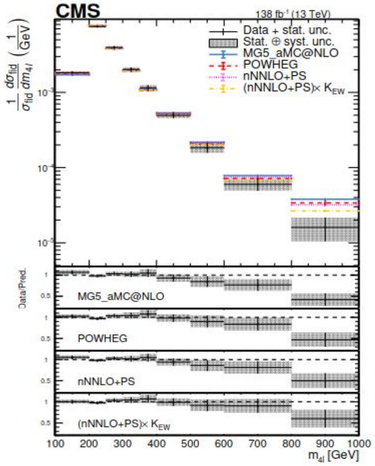


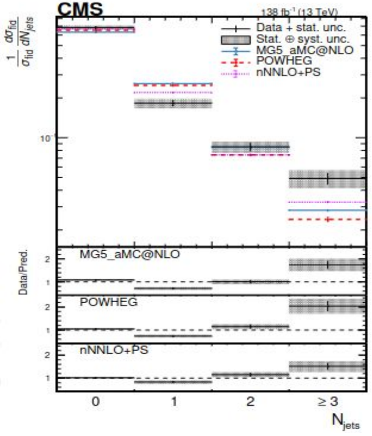
Test EFT dim-8 and dim-6 operators for aQGC.

$$|\mathcal{M}|^2 = |\mathcal{M}_{SM}|^2 + 2\,\mathrm{Re}(\mathcal{M}_{SM}{}^*\mathcal{M}_{d8}) + |\mathcal{M}_{d8}|^2,$$

Constraints on the dim-8 aQGC by including/ excluding the pure dim-8 contributions for cut-off scale (m_{4l} < E cutoff) using 2D (m_{jj} , m_{4l}) fit.





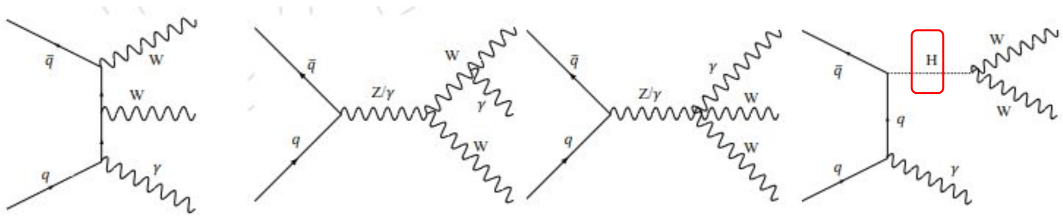


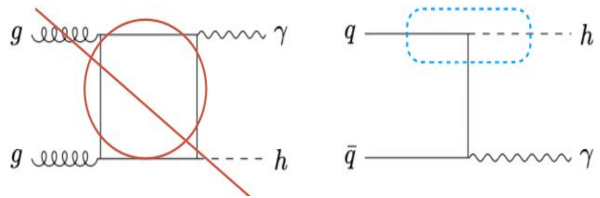
JHEP 01(2024) 04

CMS-PAS-SMP-22-001 , *in arXiv soon*

Observation of WWγ (and search for Hγ) process

arXiv:2310.05164





- Anomalous coupling between Higgs and quarks can disturb the balance and create large cross sections at high energies.
- **First observation by CMS with significance 5.6 s.d. (5.1 s.d. exp.)**

- Measured **fiducial cross section for WWγ process: 6.0 ± 1.2 fb.**
- **Upper limits f**or H production and derived limits on Yukawa couplings of light quarks.
  Note: recent constraint on anomalous Hcc coupling 1.1< $|\kappa_c|$ <5.5

PRL 131 (2023) 061801

Process	σ upper limits obs. (exp.) [fb]	κ_q limits obs. (exp.) at 95% CL	$\bar{\kappa}_q$ limits obs. (exp.) at 95% CL
$u\bar{u} \to H + \gamma \to e\mu\nu_e\nu_\mu\gamma$	85 (67)	$\|\kappa_u\| \leq 16000$ (13000)	$\|\bar{\kappa}_u\| \leq 7.5$ (6.1)
$d\bar{d} \to H + \gamma \to e\mu\nu_e\nu_\mu\gamma$	72 (58)	$\|\kappa_d\| \leq 17000$ (14000)	$\|\bar{\kappa}_d\| \leq 16.6$ (14.7)
$s\bar{s} \to H + \gamma \to e\mu\nu_e\nu_\mu\gamma$	68 (49)	$\|\kappa_s\| \leq 1700$ (1300)	$\|\bar{\kappa}_s\| \leq 32.8$ (25.2)
$c\bar{c} \to H + \gamma \to e\mu\nu_e\nu_\mu\gamma$	87 (67)	$\|\kappa_c\| \leq 200$ (110)	$\|\bar{\kappa}_c\| \leq 45.4$ (25.0)