Standard Model and Effective Field Theory measurements

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Outline

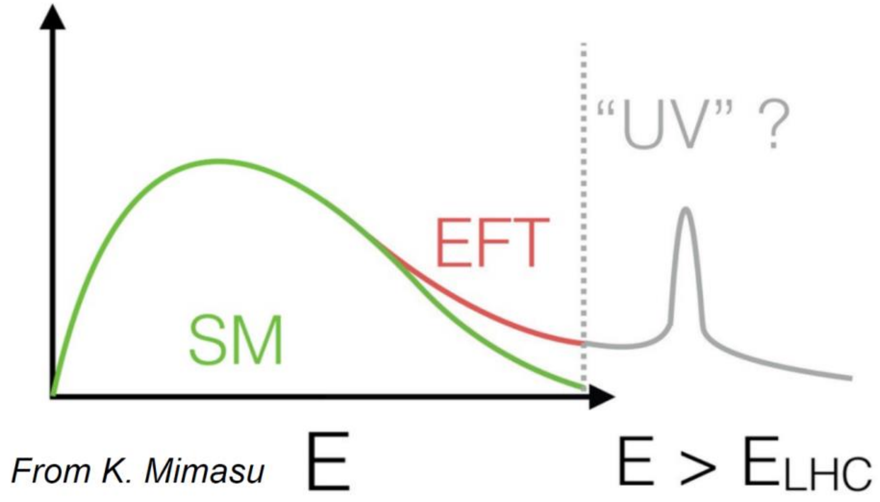
- Standard Model (SM) Electro-Weak measurements
  - Single boson $boson = W, Z, \gamma$
  - Di-boson (VBS)
  - Tri-boson
- Effective Field Theory (EFT) measurements
  - Electroweak
  - Higgs
  - Top related

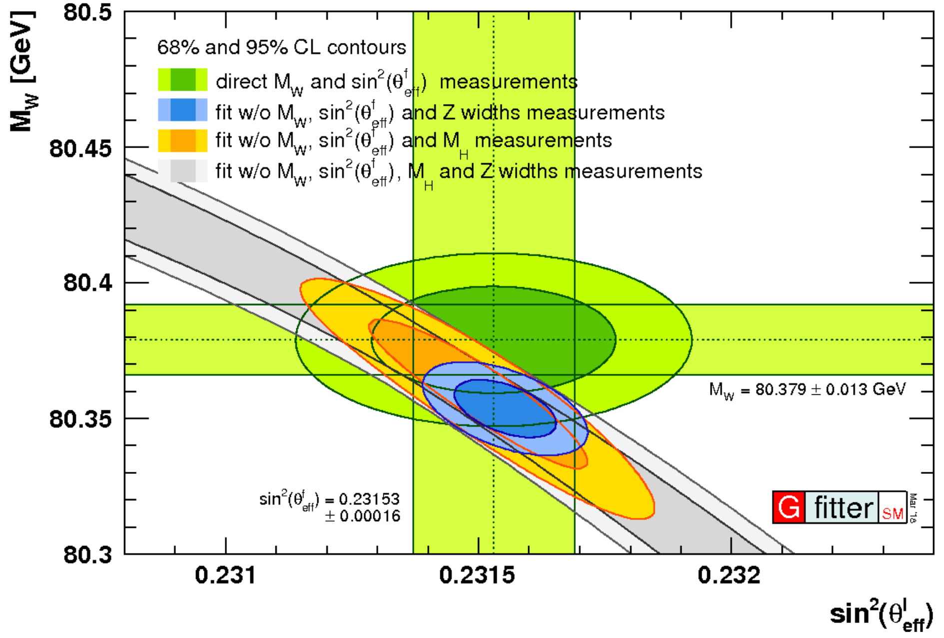
Introduction

- Electroweak theory has been proven to be successful
- Huge W/Z boson production at LHC to test SM self-consistency
- Test theoretical models with higher order QCD
- Search for New Physics with EFT formalism

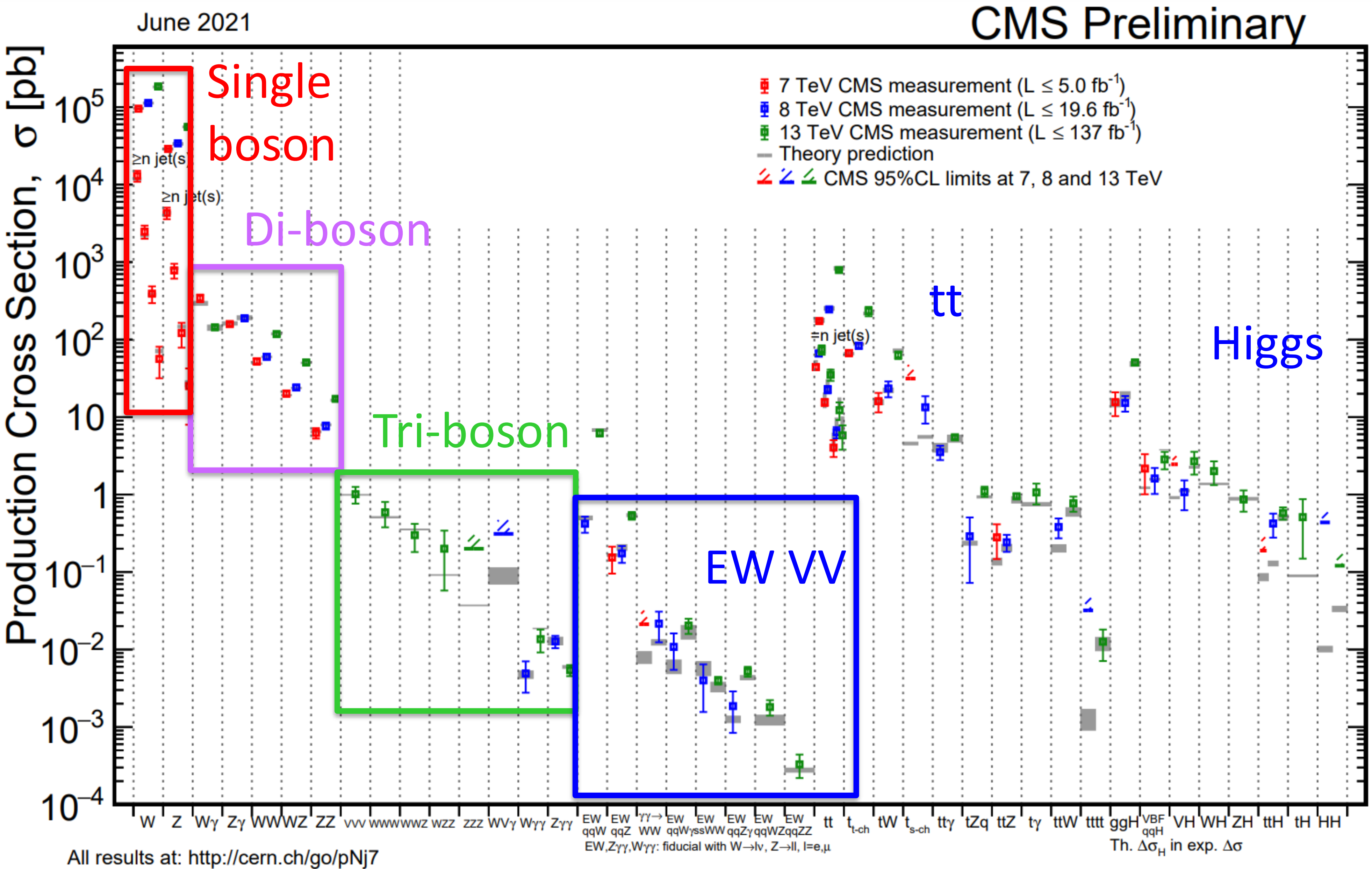
$$m_W^2\left(1-\frac{m_W^2}{m_Z^2}\right)=\frac{\pi\alpha}{\sqrt{2}G_\mu}(1+\Delta r)$$

Higher-order corrections





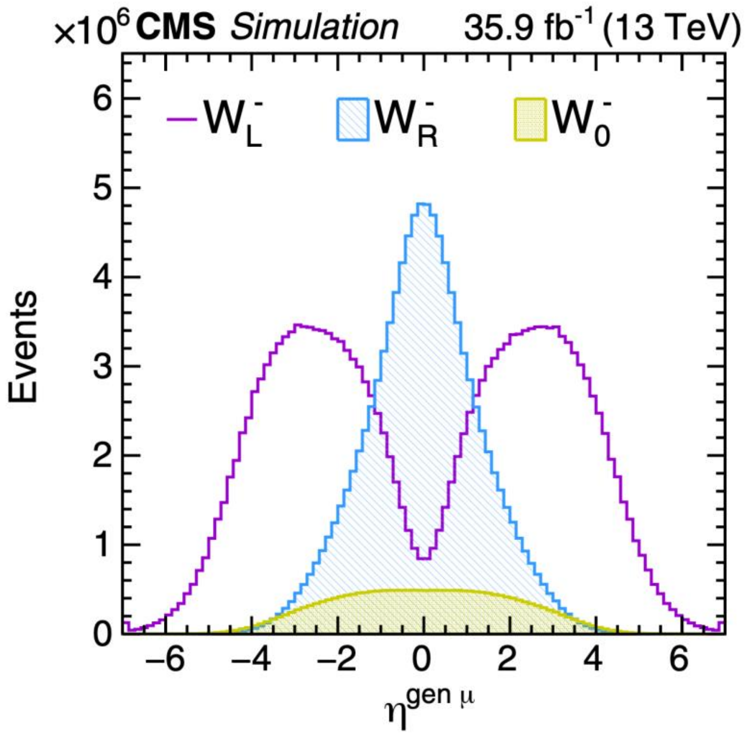
Cross Section measurements

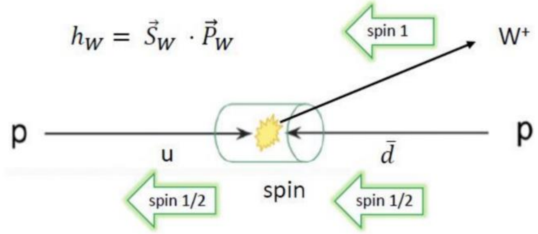


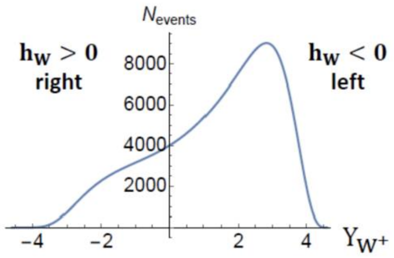
W production: rapidity, helicity & PDF

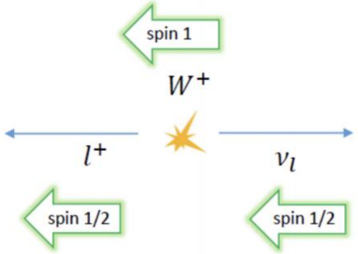
- W rapidity, lepton pseudo-rapidity, for PDF constraints
- 2D binning (p_T, η) distribution sensitive to helicity fractions

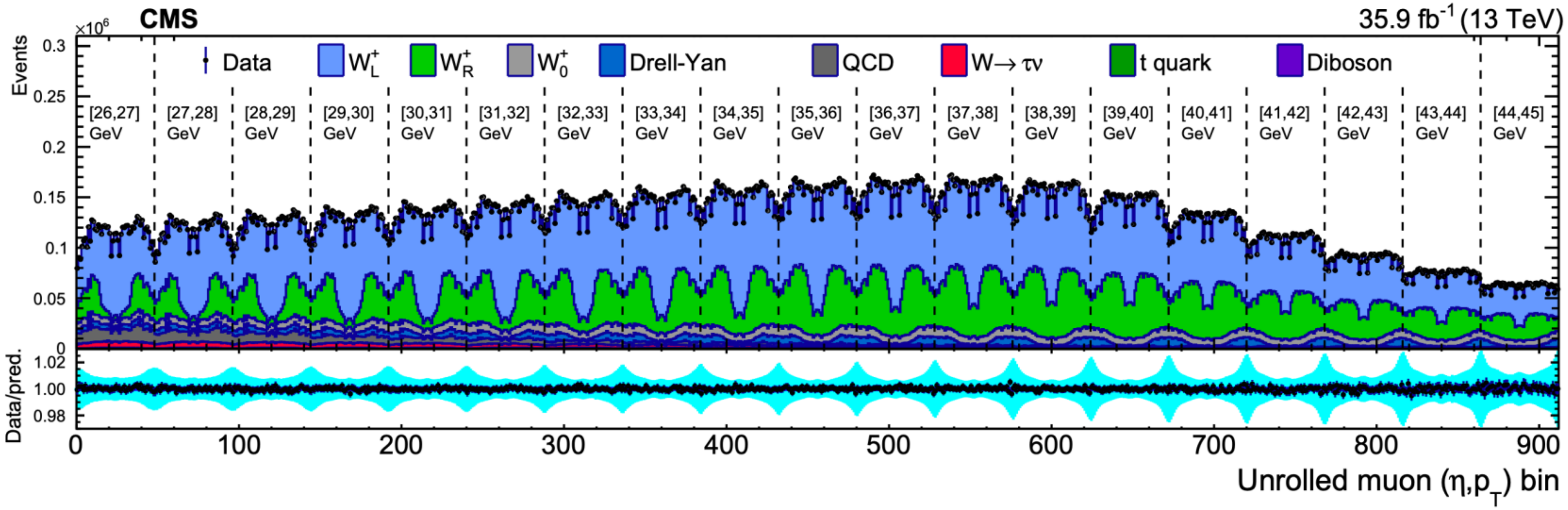
PRD 102 (2020) 092012









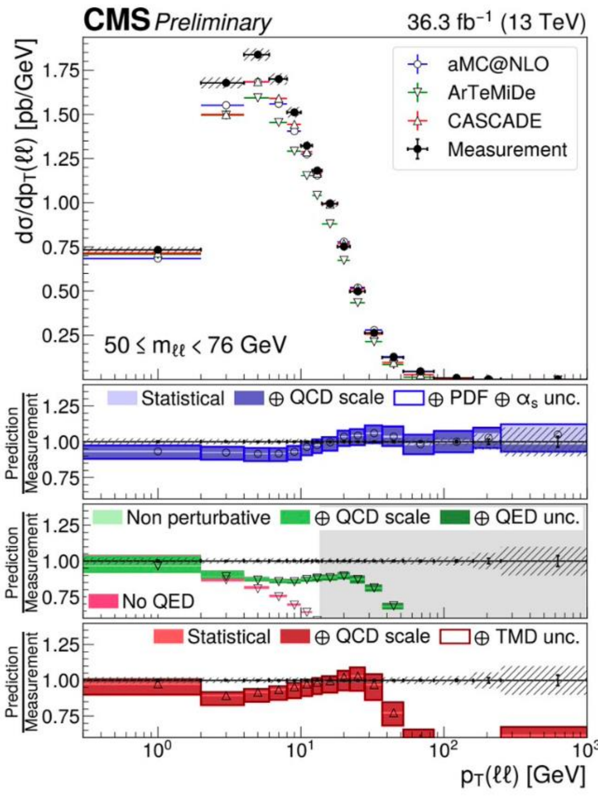


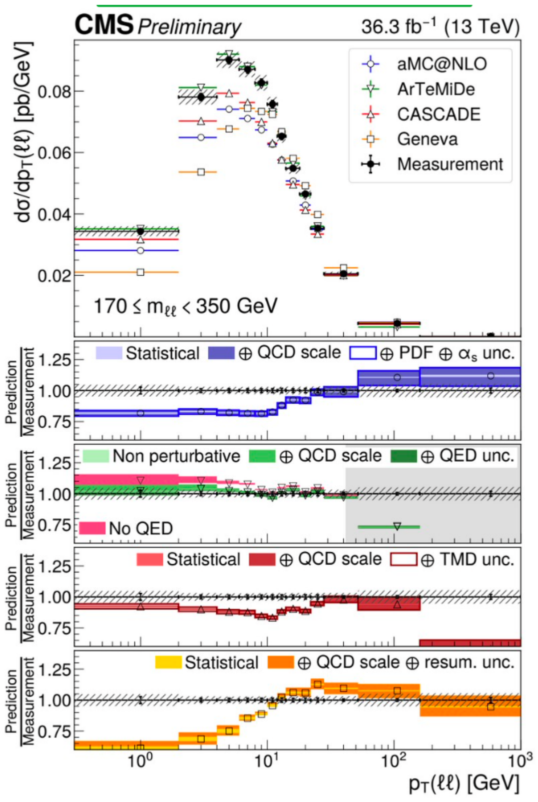
Z production: p_T distribution

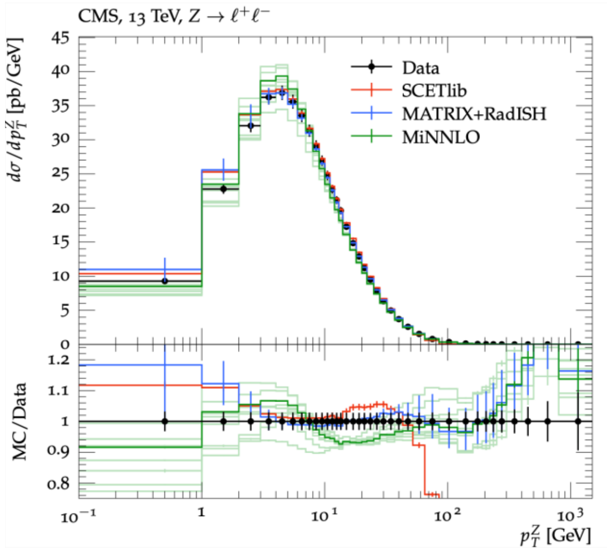
- $Z \to ll,\ Z \to \upsilon\upsilon$, multi-differential p_T distribution
- Excellent performance of theoretical tools, NLO EW corrections

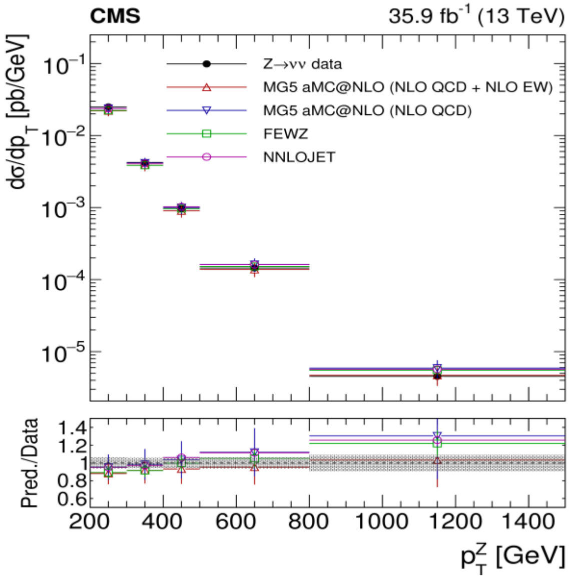
China CMS (PKU) team plays a leading role

JHEP 05(2021) 205
CMS-PAS-SMP-20-003
CMS-PAS-SMP-21-003





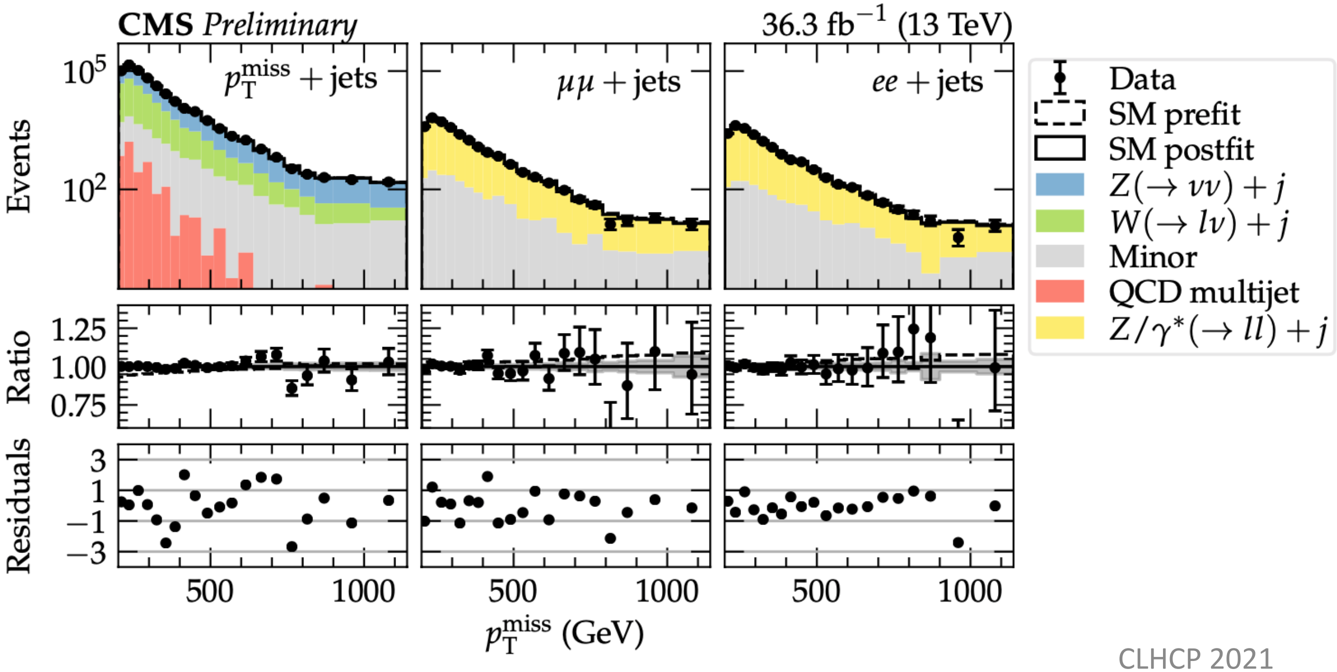


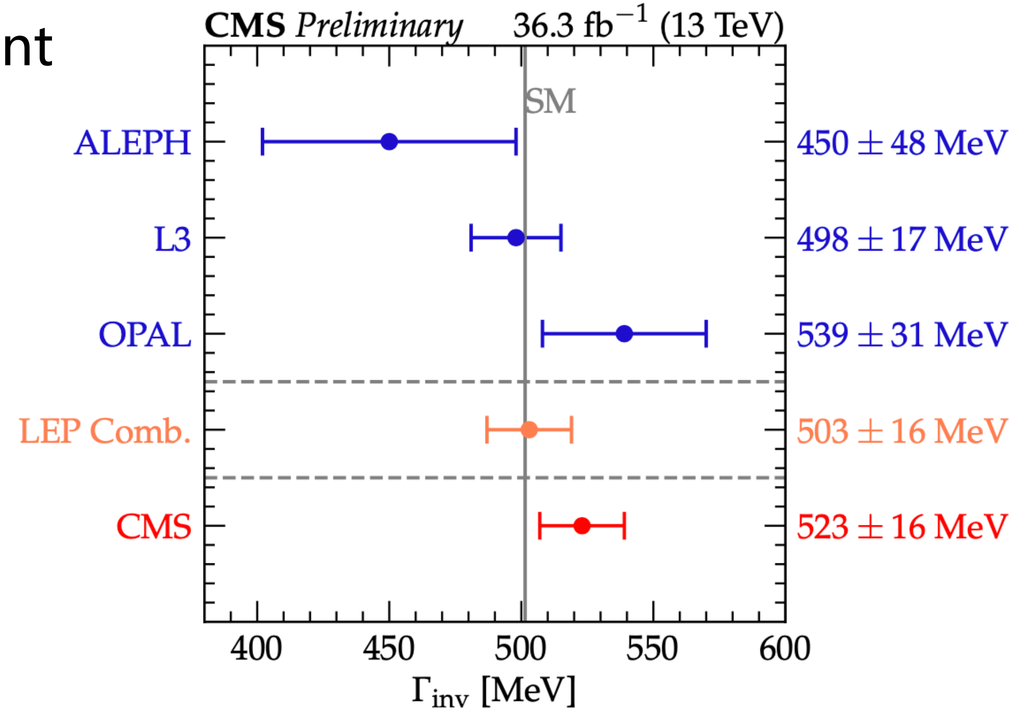


Invisible Z width

- $\Gamma(Z \to \nu\bar{\nu}) = \frac{\sigma(Z+\text{jets})\mathcal{B}(Z \to \nu\bar{\nu})}{\sigma(Z+\text{jets})\mathcal{B}(Z \to \ell\ell)}\Gamma(Z \to \ell\ell)$
- Using 36.3 fb^{-1} of 13 TeV data
- First direct measurement of invisible Z width at a hadron collider
- Precision competitive with LEP direct measurement

CMS-PAS-SMP-18-014



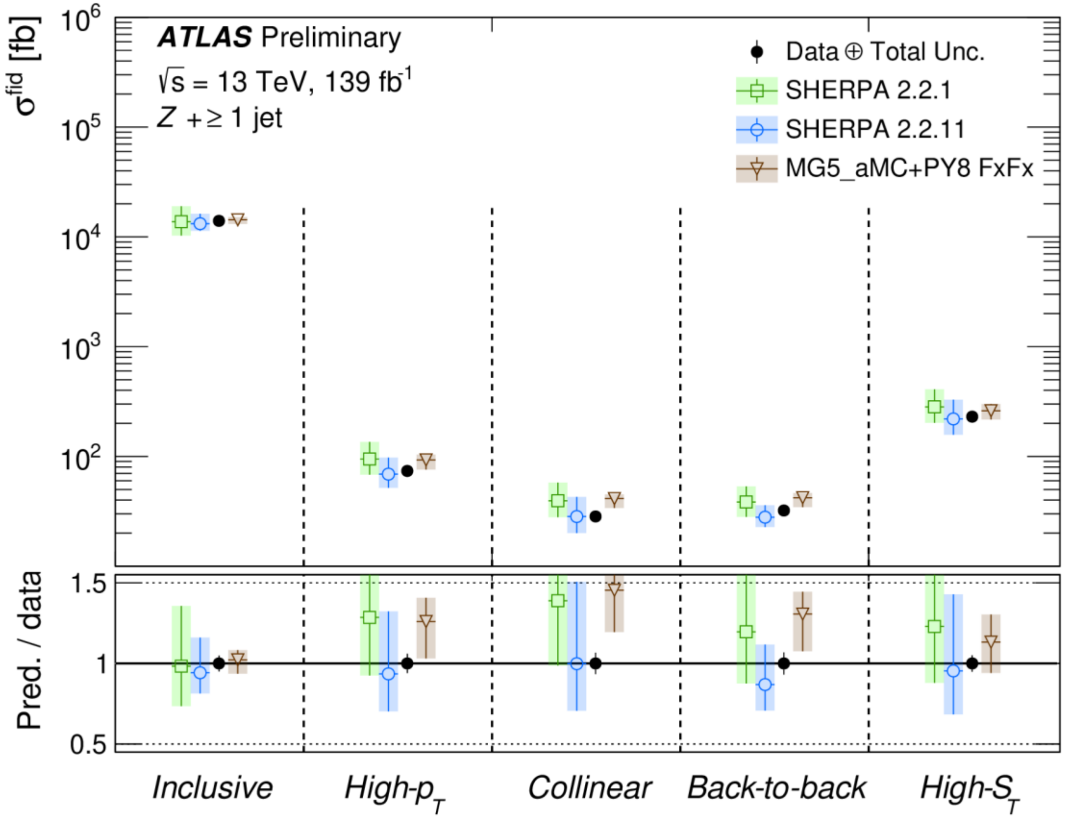


$$\Gamma_{inv} = 523 \pm 3\,(\text{stat}) \pm 16\,(\text{syst})\,\text{MeV}$$

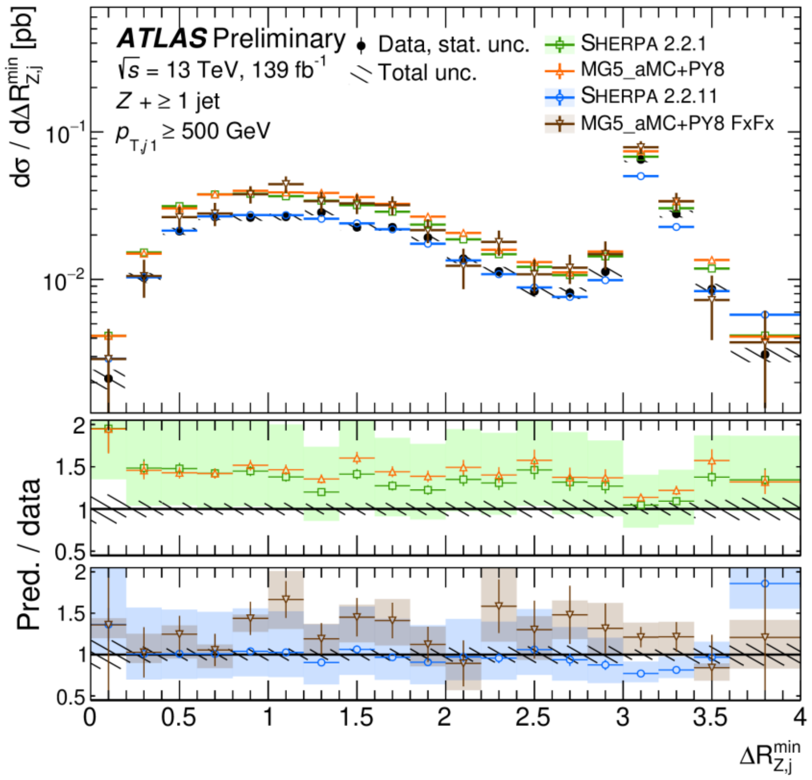
Z + high p_T jets

ATLAS-CONF-2021-033

- Full 13 TeV data ($139\ fb^{-1}$), ee and $\mu\mu$ channels combined
- Jet p_T > 500 GeV (High-p_T = collinear + back-to-back)
- Some overestimates of large p_T σ from MG5@LO and Sherpa v.2.2.1



High p_T

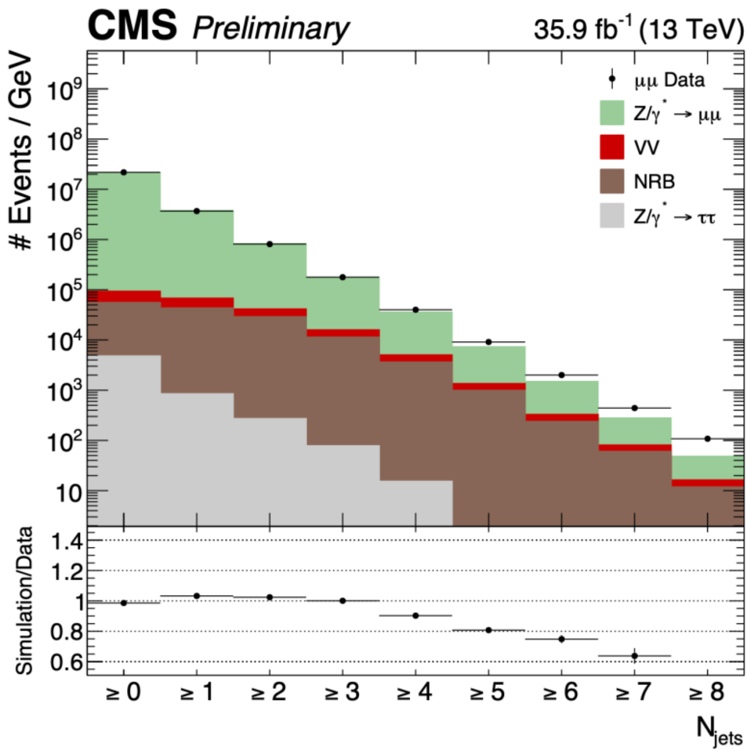


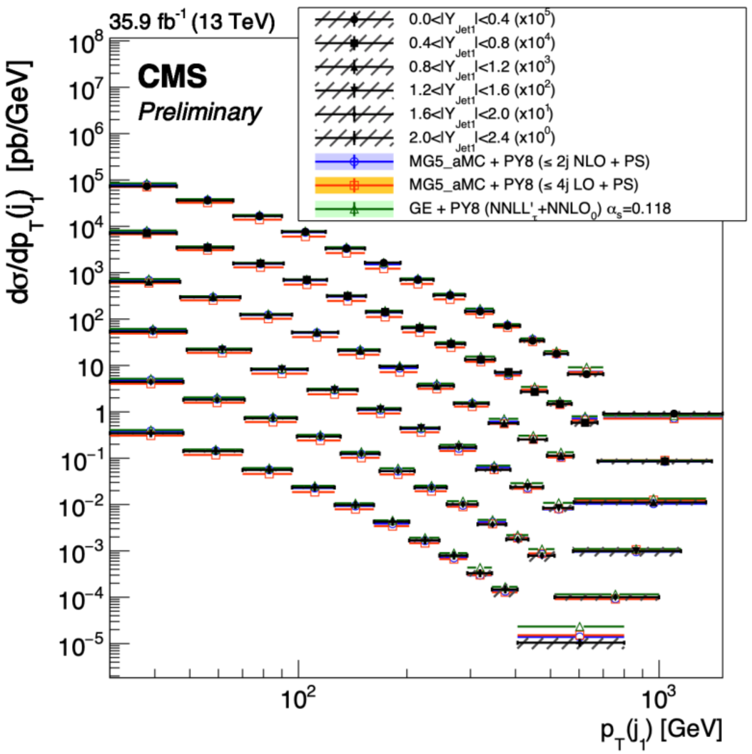
Z + jets

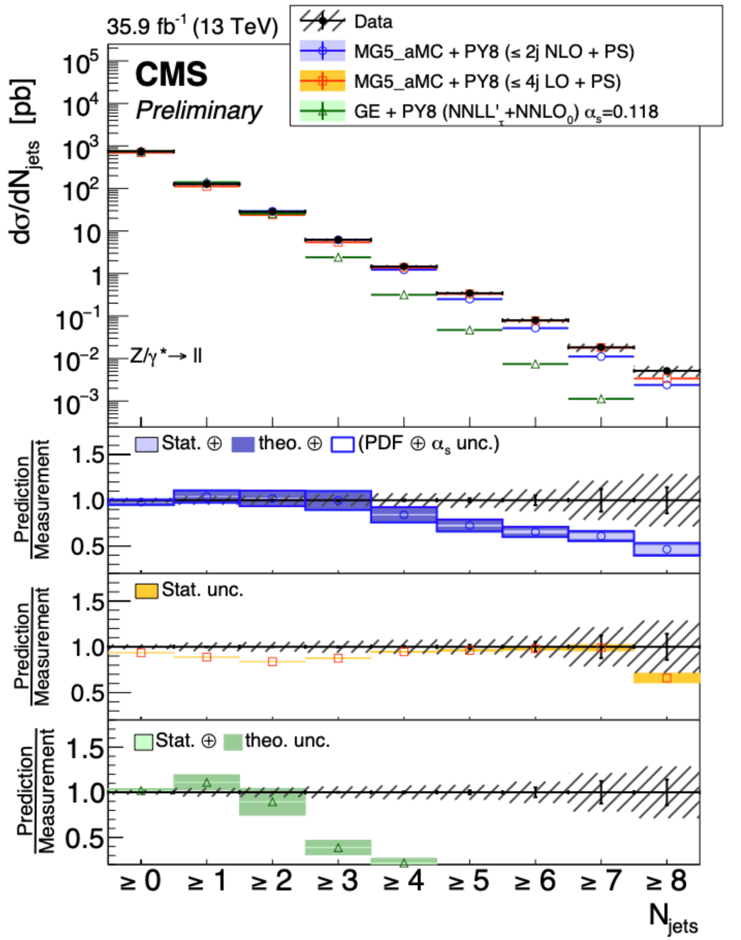
- Using $35.9\ fb^{-1}$ of 13 TeV data (2016), ee and $\mu\mu$ channels combined
- Provides a sensitive evaluation of the accuracy of QCD modeling

CMS-PAS-SMP-19-009
CMS-PAS-SMP-21-003

China CMS (PKU) team makes important contributions



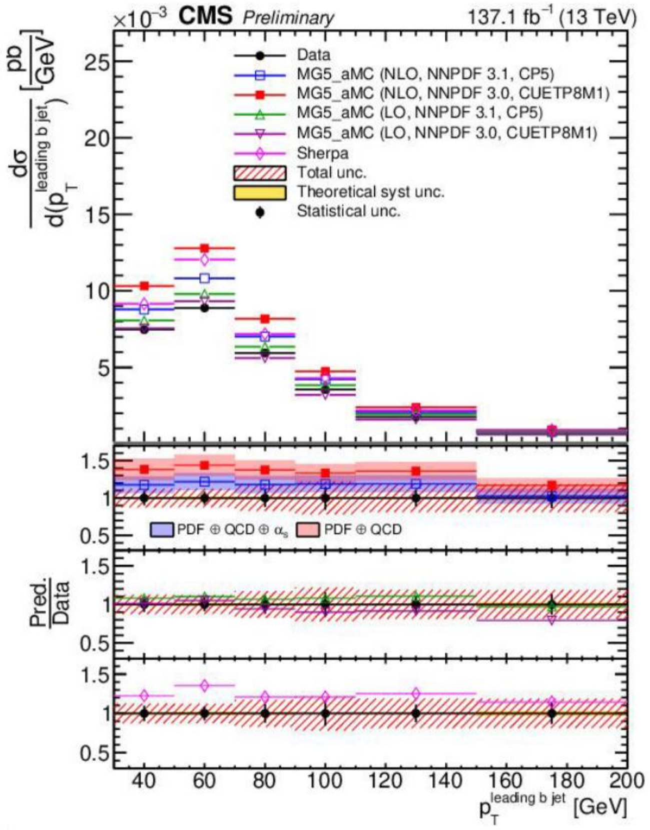


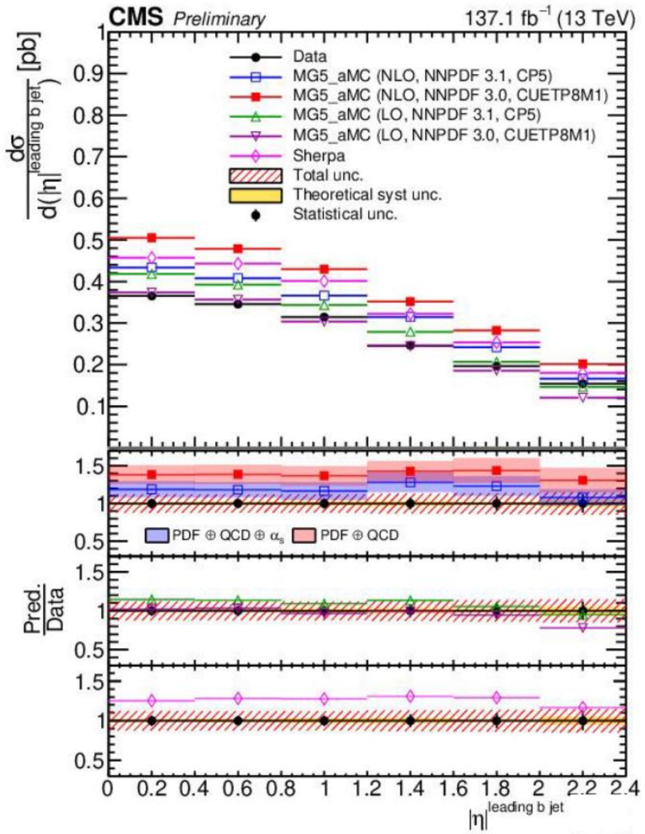


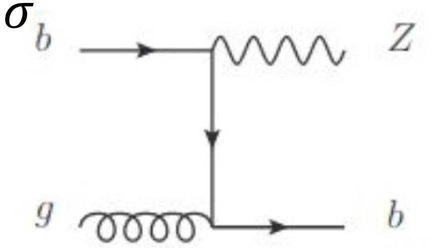
Z + b jets

CMS-PAS-SMP-20-015

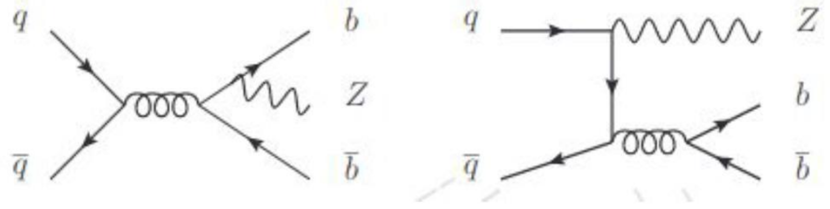
- Full 13 TeV data ($139\ fb^{-1}$), ee and $\mu\mu$ channels combined
- Differential cross section as function of p_T and |η| of leading b jet
- MG5@NLO Sherpa have good shape predictions but overestimate total σ







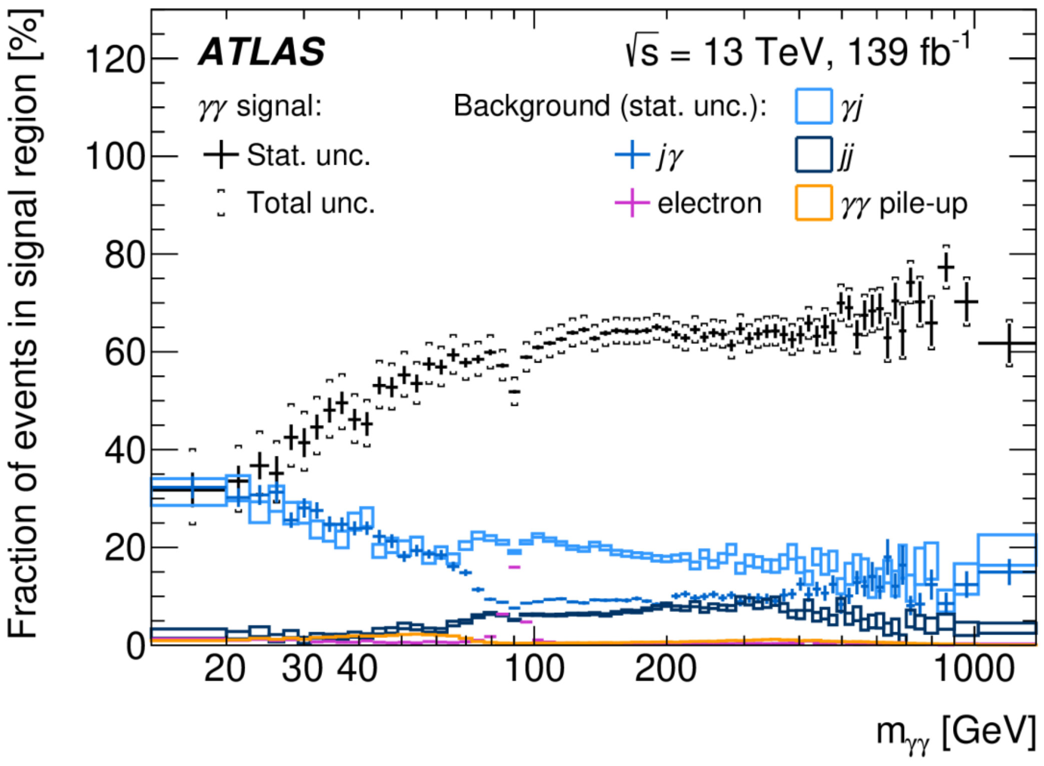
$Z + \geq 1\ b\ jet$



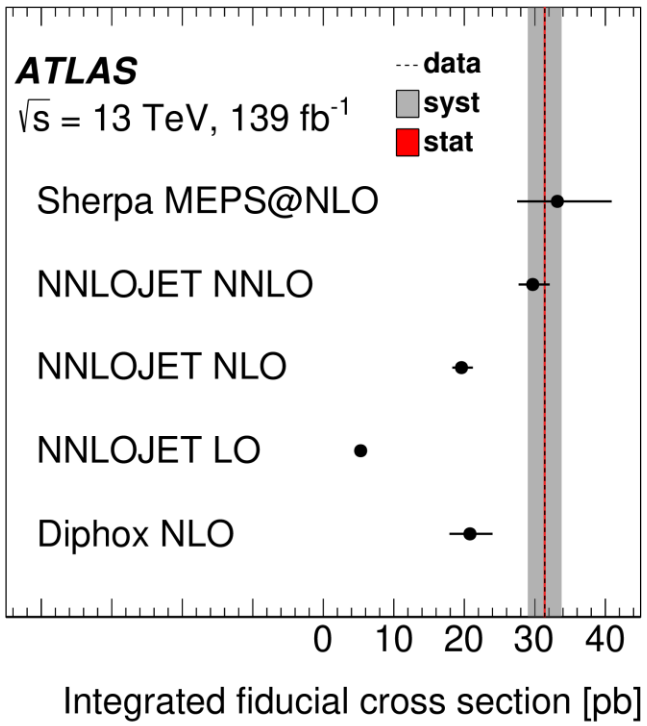
$Z + \geq 2\ b\ jets$

Photon pairs

- Full 13 TeV data ($139\ fb^{-1}$), direct and fragmentation prompt γ [arXiv:2107.09330](https://arxiv.org/abs/2107.09330)
- Main challenge and uncertainty from non-prompt γ
- Differential distributions in good agreement with Sherpa MEPS and FO NNLO

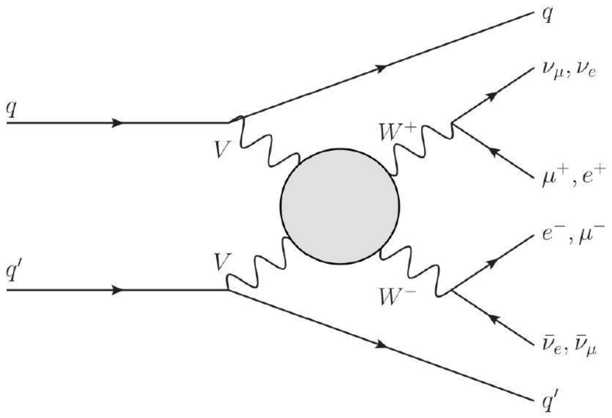


$$\sigma_{\gamma\gamma} = 31.4 \pm 0.1(stat.) \pm 0.1(syst.)\ pb$$

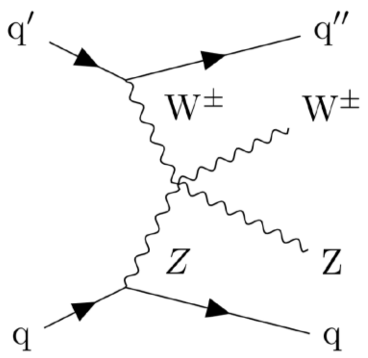


Di-boson

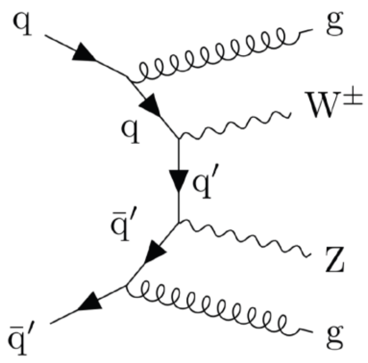
- The Vector Boson Scattering and Vector Boson Fusion
- Allow precision measurements of EW
- Rare process $\sim\alpha_{EW}^{6}$ $@LO$
- Important component of $VVjj$ production via EW
- Vector boson self-coupling and coupling to Higgs boson
- Very sensitive to New Physics effects
- Sensitive to aTGCs/aQGCs

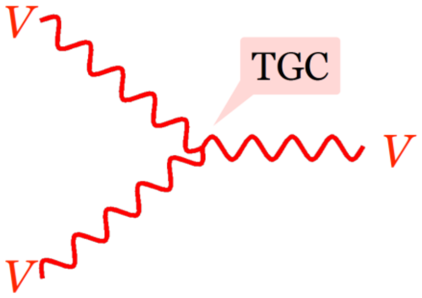


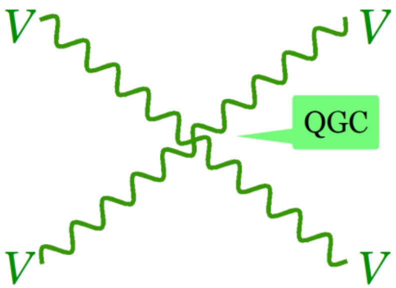
$VBS\ WZjj$



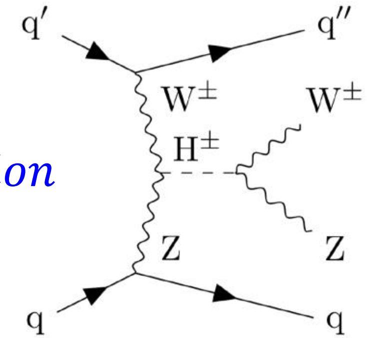
$Non-VBS\ WZjj$



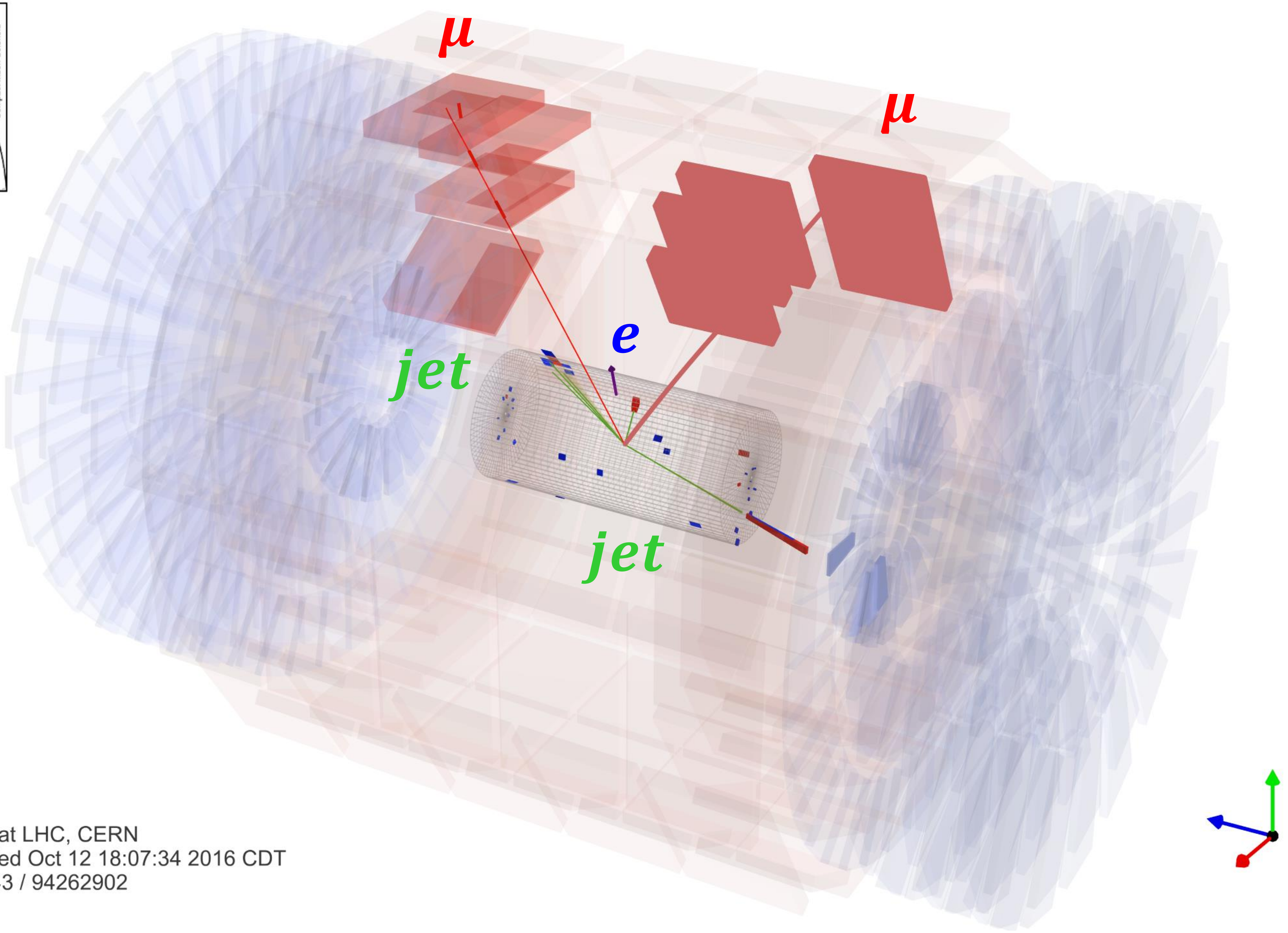


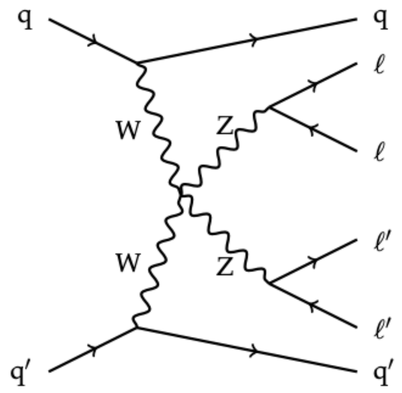


$BSM\ H^{\pm}\ production$



VBS





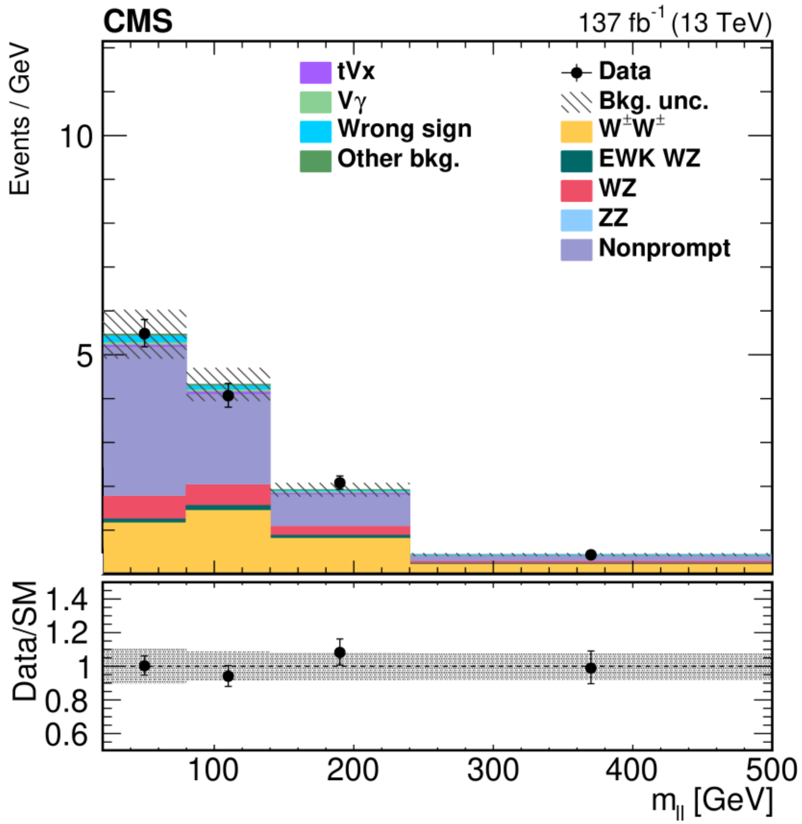
CMS Experiment at LHC, CERN
Data recorded: Wed Oct 12 18:07:34 2016 CDT
Run/Event: 283043 / 94262902

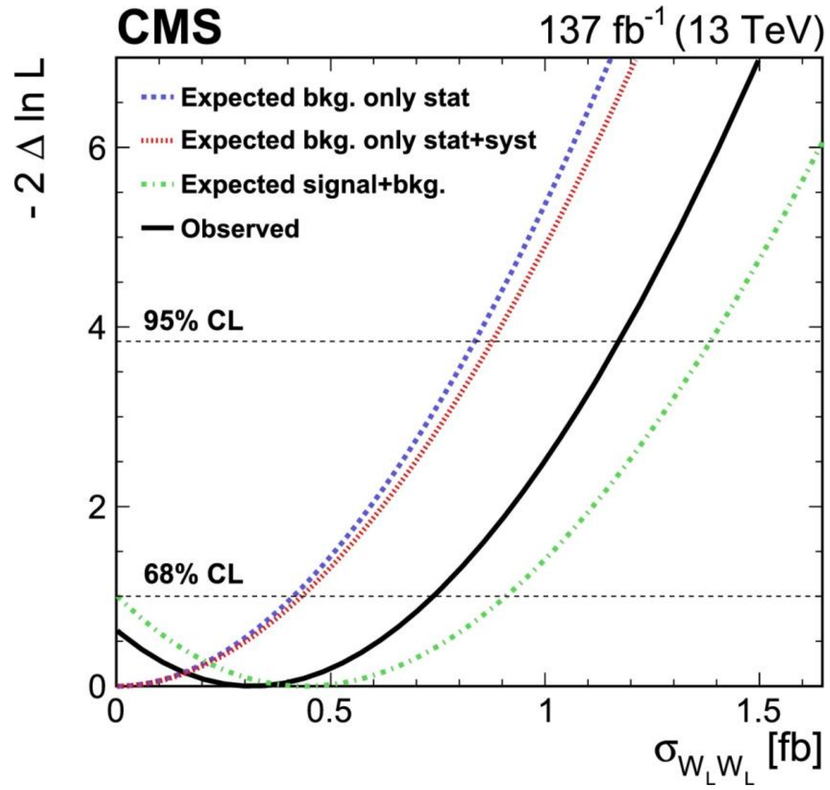
Longitudinal polarized $W^{\pm}W^{\pm}$ VBS

- First measurement of production cross sections for polarized $W^{\pm}W^{\pm}$ [PLB 812 (2020) 136018]

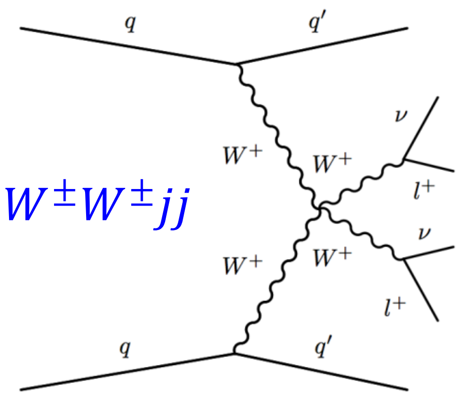
  China CMS (PKU) team makes important contributions

- Golden channel for VBS, EW production dominant over QCD

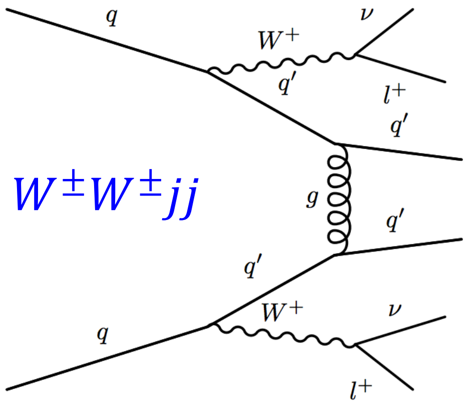




$VBS\ W^{\pm}W^{\pm}jj$



$QCD\ W^{\pm}W^{\pm}jj$

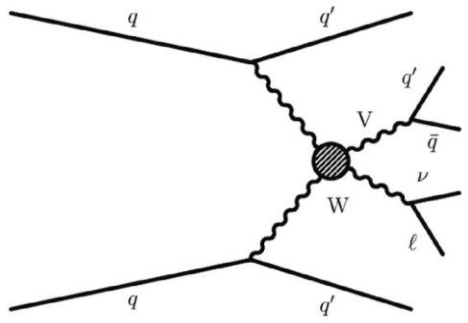


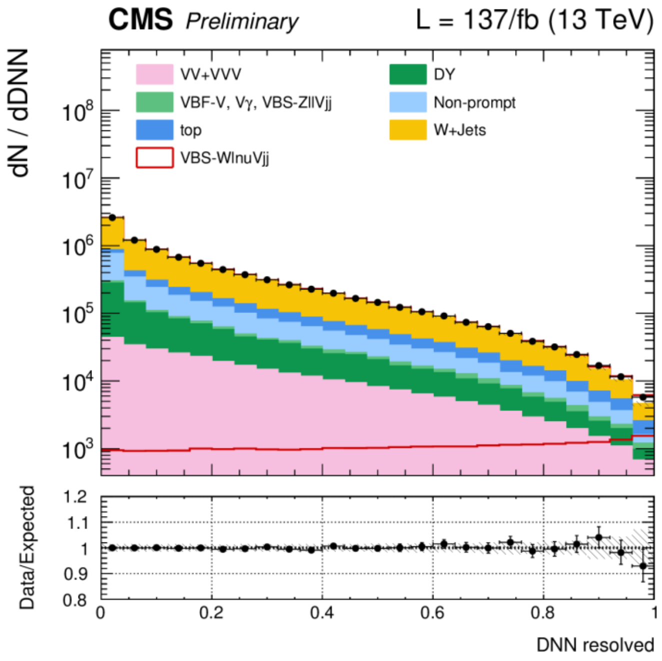
Semi-leptonic WV VBS

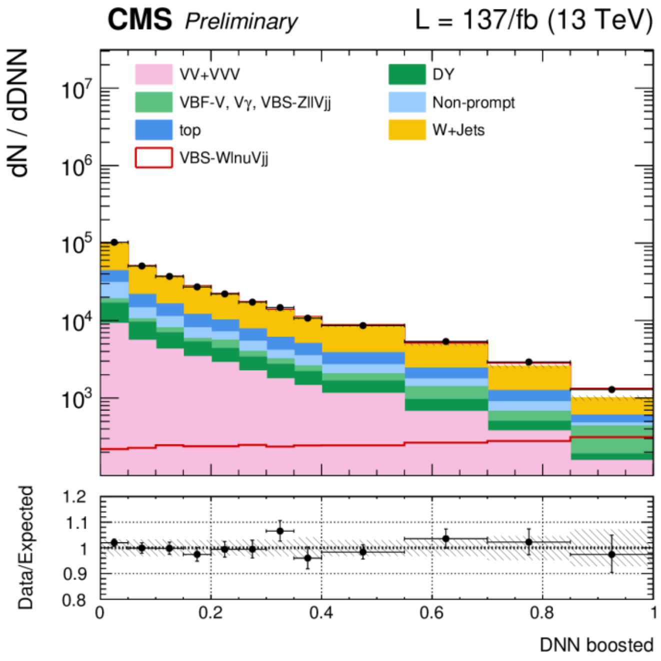
CMS-PAS-SMP-20-013

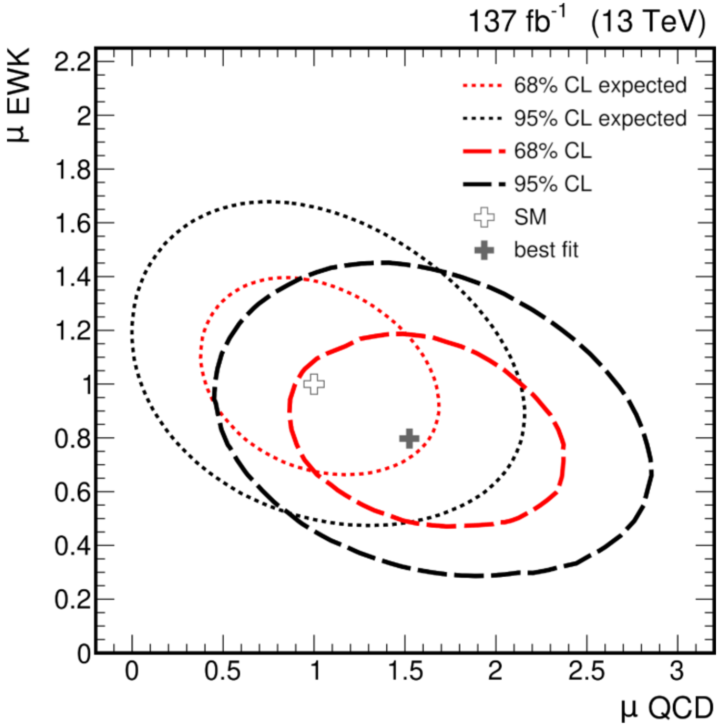
- Full 13 TeV data ($137\ fb^{-1}$), e and μ channels combined
- Good agreements between data and MC prediction
- First evidence for EW WV plus two jets in the semi-leptonic channel

China CMS (IHEP) team makes important contributions









EW ZZ + 2 jets

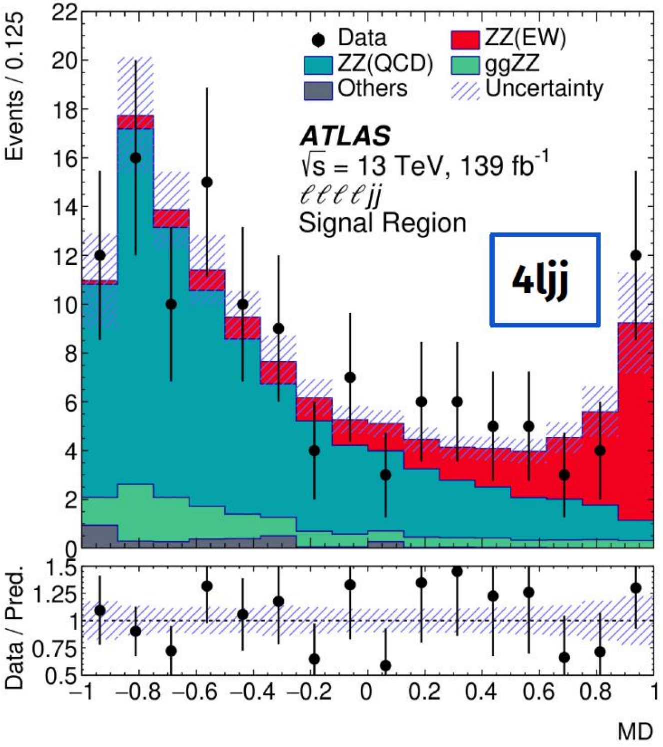
[arXiv:2004.10612](#)
[PLB 812 (2021) 135992](#)

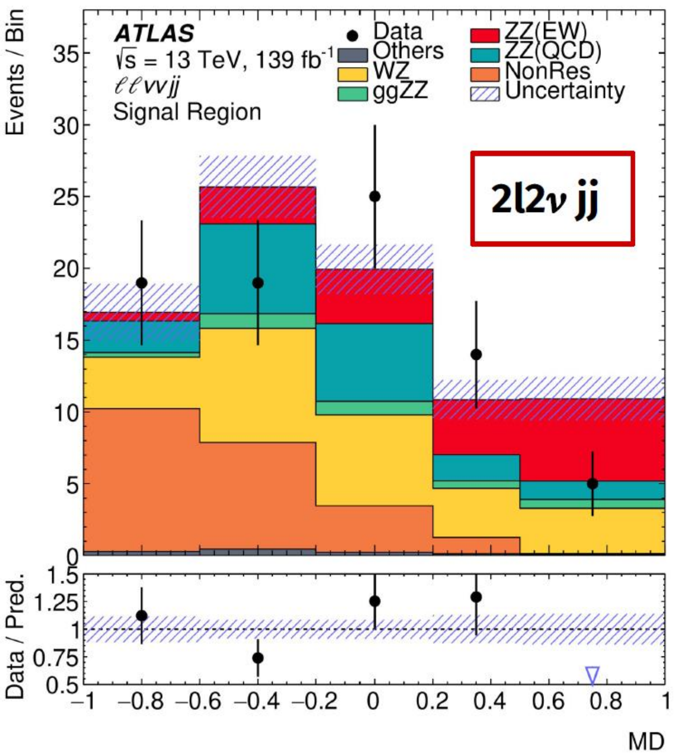
- ATLAS: combined fit in $4l\ jj$ and $2l2l\nu\ jj$ 5.5σ (4.3σ)

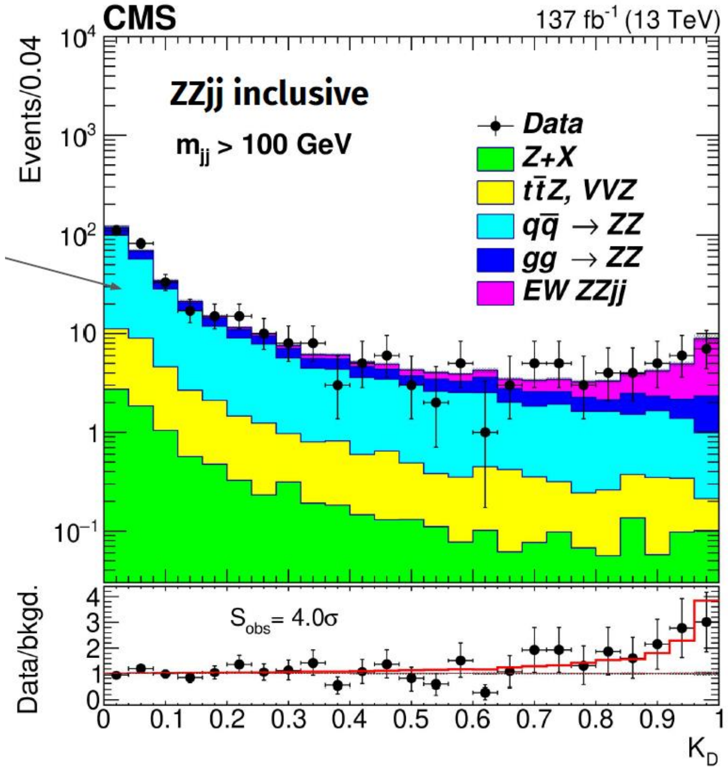
  China ATLAS (USTC, TDLI/SJTU) team plays a leading role

- CMS: full 13 TeV data $(137\ fb^{-1})$, evidence of $EW\ ZZjj$ production at 4σ

  China CMS (PKU) team plays an important role



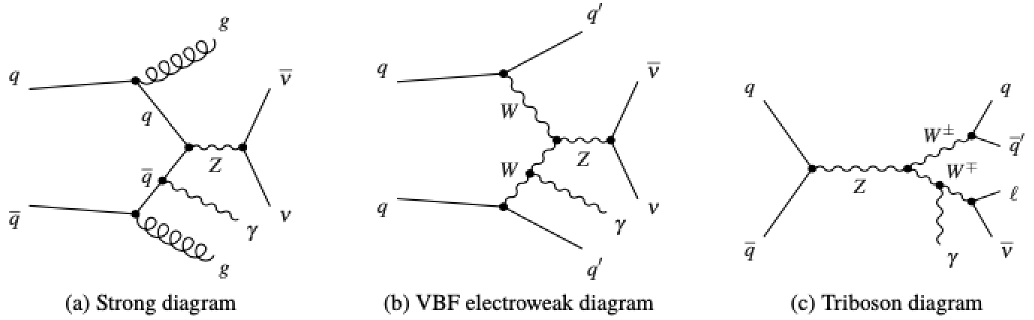


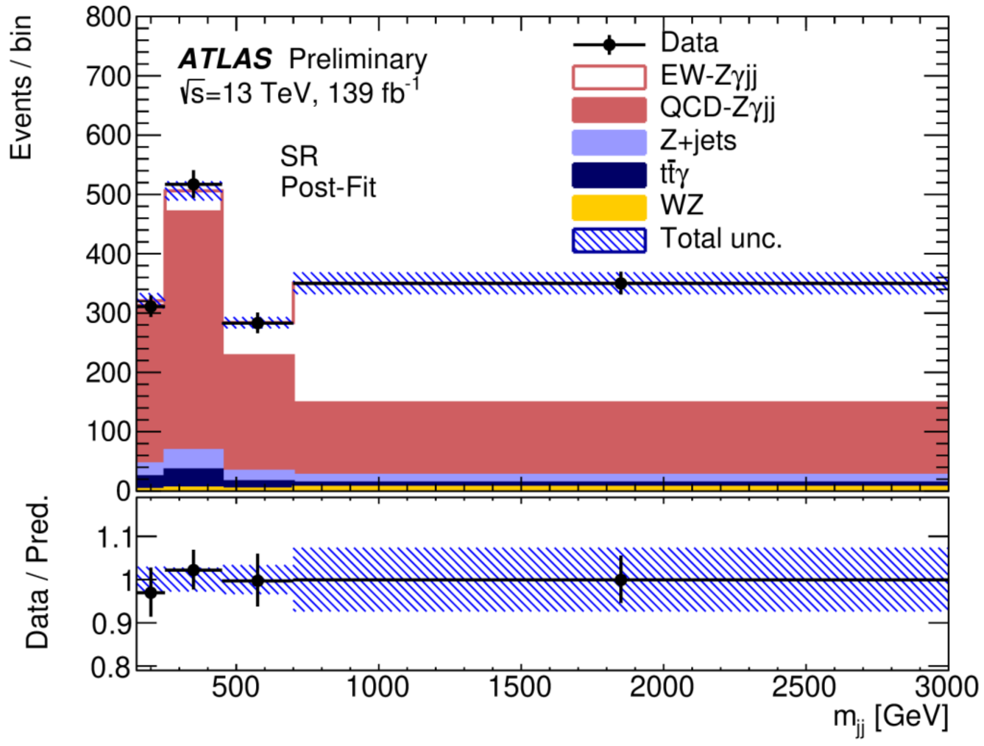


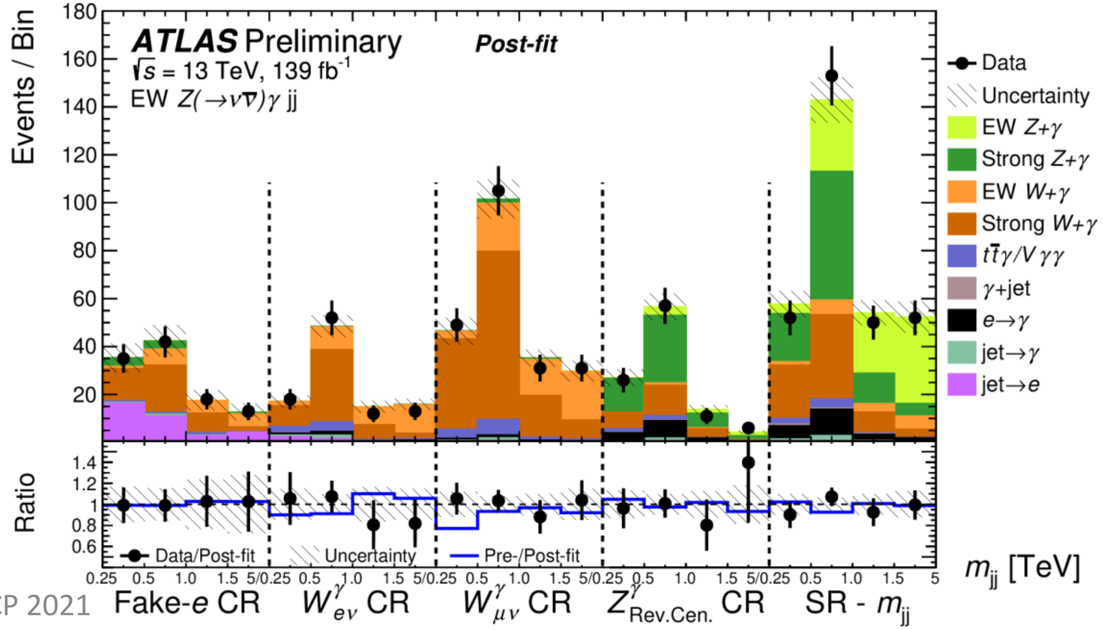
EW $Z\gamma + jj$

ATLAS-CONF-2021-038
CERN-EP-2021-137

- Observation of EW $Z(ll)\gamma jj$, e and μ channels combined
- EW $Z(ll)\gamma jj$ signal observed with 10σ
- EW $Z(\nu\nu)\gamma jj$ signal with 5.2σ (5.1σ)







EW di-boson production cross-section

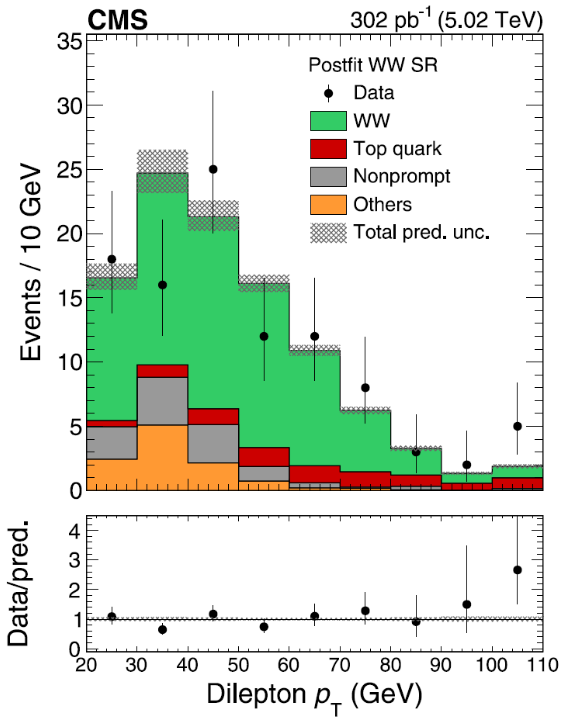
- The first measurements of di-boson cross sections in pp @ 5 TeV

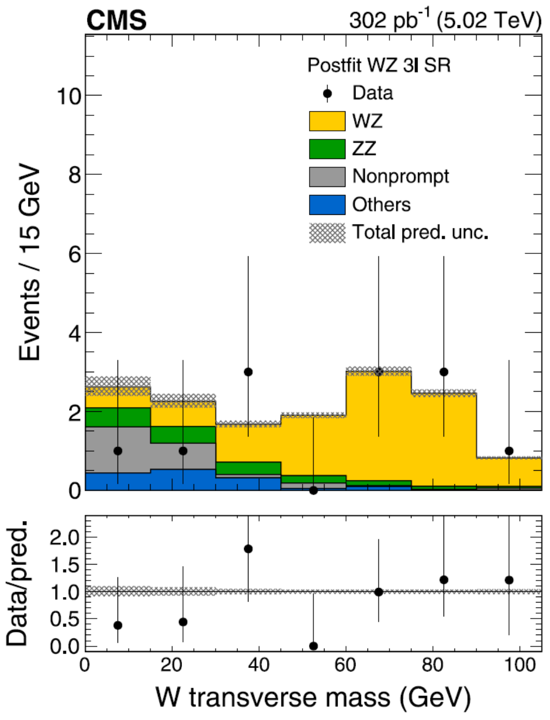
[PRL 127 (2021) 191801]

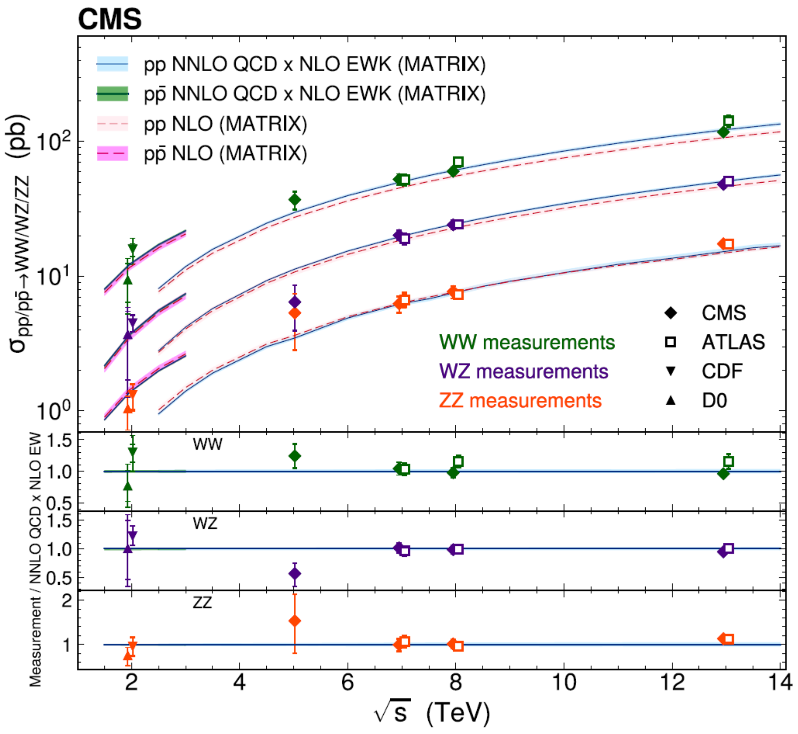
- All measurements are in good agreements with NNLO-QCD and NL EW

$$\sigma_{WW} = 37.0^{+5.5}_{-5.2}\,(stat.)\,^{+2.7}_{-2.6}(syst.)\,pb \qquad \sigma_{WZ} = 6.4^{+2.5}_{-2.1}\,(stat.)\,^{+0.5}_{-0.3}(syst.)\,pb$$

$$\sigma_{ZZ} = 5.3^{+2.5}_{-2.1}\,(stat.)\,^{+0.5}_{-0.4}(syst.)\,pb$$



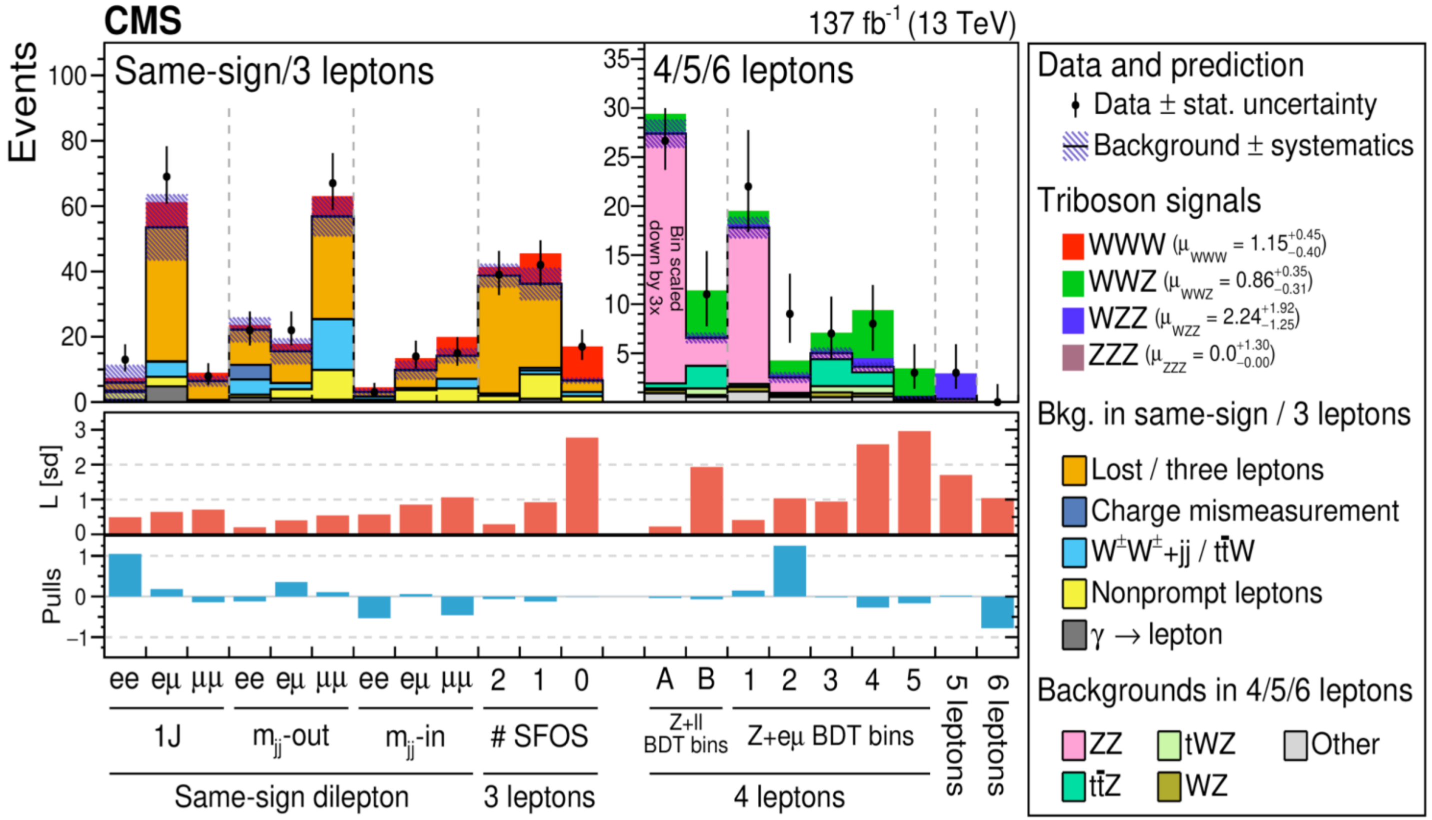


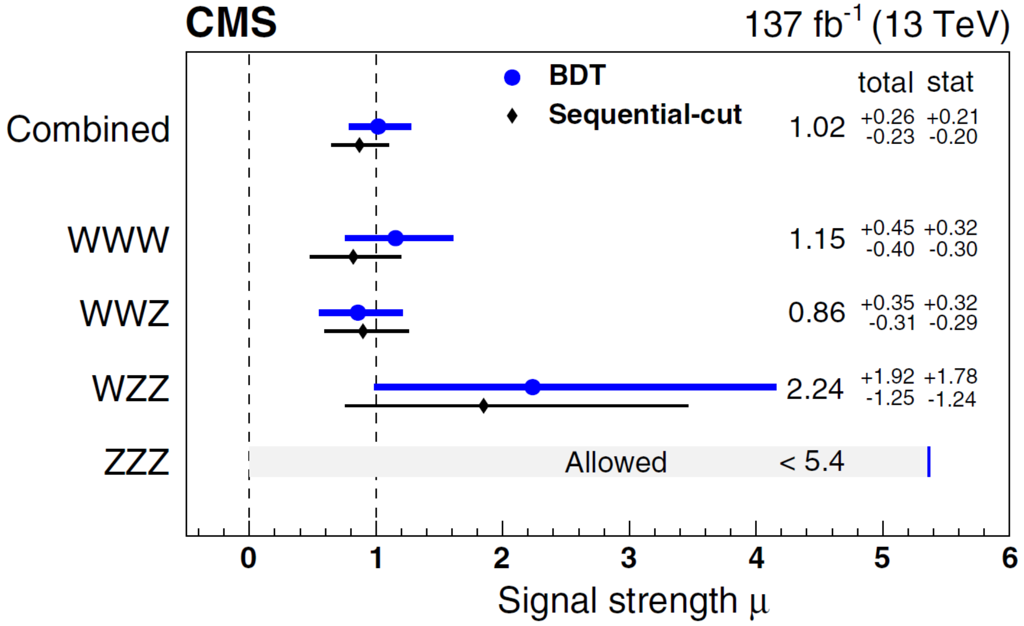


Tri-boson

[PRL 125 (2020) 151802]

- Tri-boson measurements are statistical limited
- First observation of VVV production, $VVV = WWW, WWZ, WZZ, ZZZ$, including VH

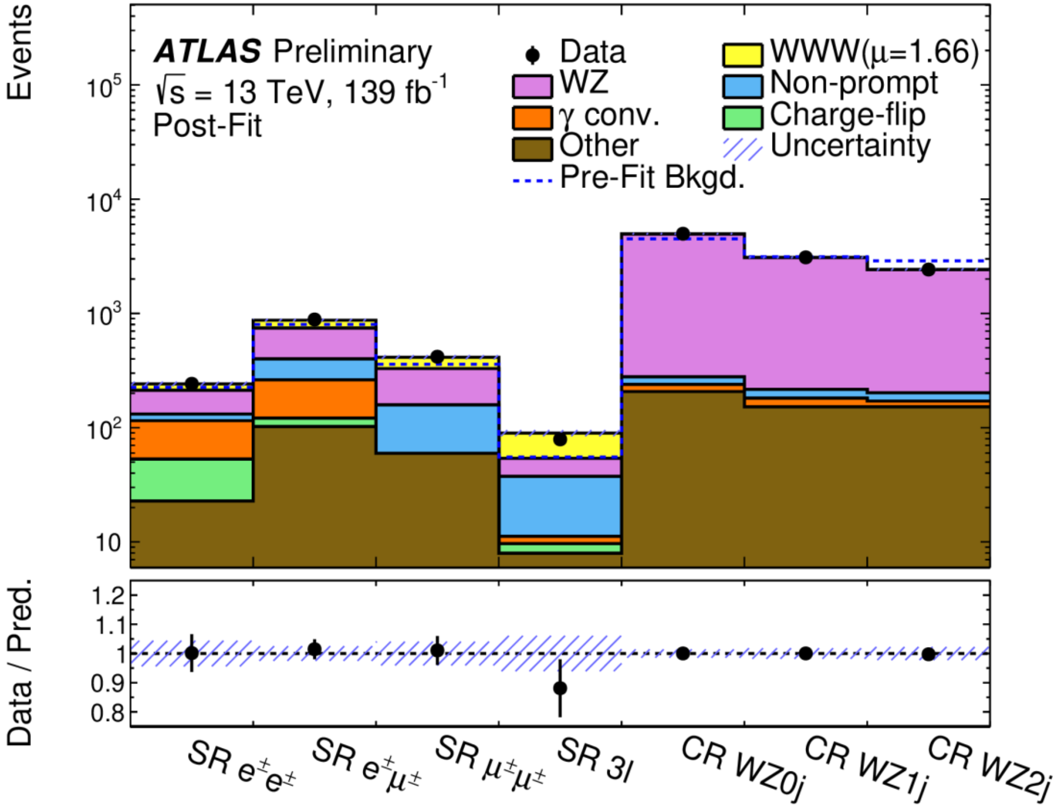


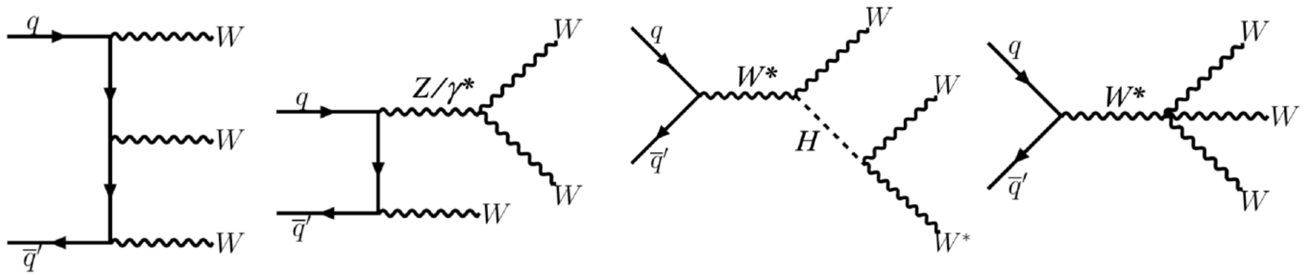


WWW

ATLAS-CONF-2021-039

- Full 13 TeV data ($139\ fb^{-1}$), e and μ channels combined
- WWW production observed with 8.2σ (5.4σ)





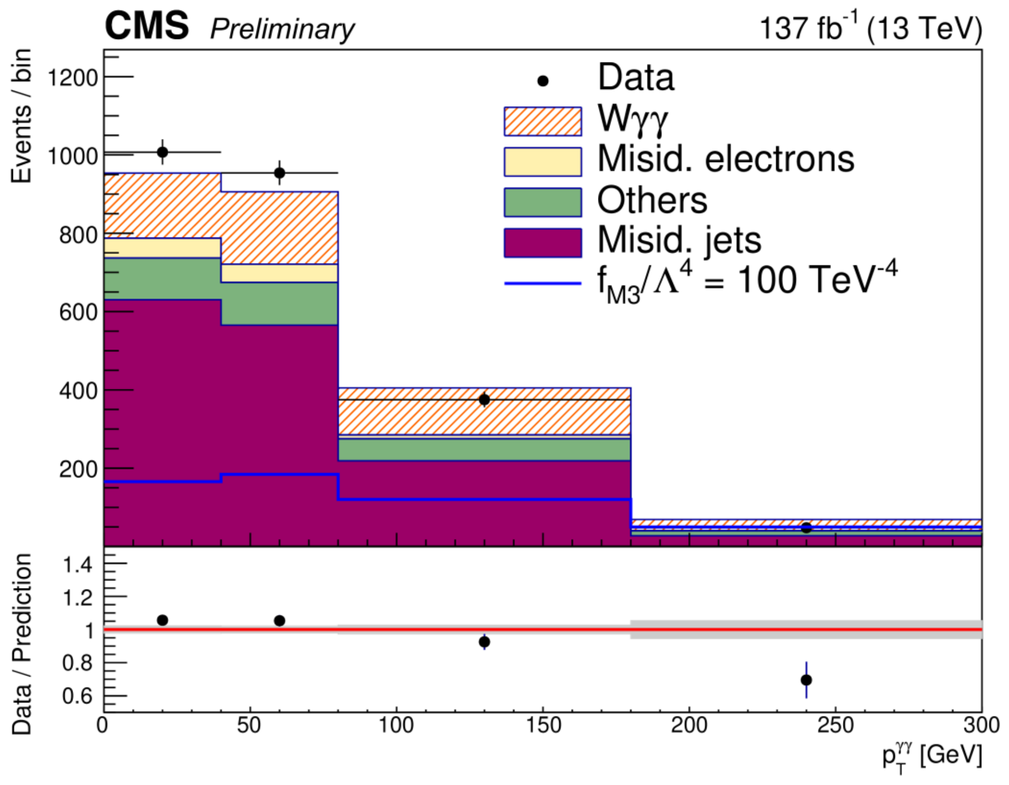
Fit	Observed (expected) significances $[\sigma]$	$\mu(WWW)$
$e^{\pm}e^{\pm}$	2.3 (1.4)	1.69 ± 0.79
$e^{\pm}\mu^{\pm}$	4.6 (3.1)	1.57 ± 0.40
$\mu^{\pm}\mu^{\pm}$	5.6 (2.8)	2.13 ± 0.47
2ℓ	6.9 (4.1)	1.80 ± 0.33
3ℓ	4.8 (3.7)	1.33 ± 0.39
Combined	**8.2 (5.4)**	$\mathbf{1.66 \pm 0.28}$

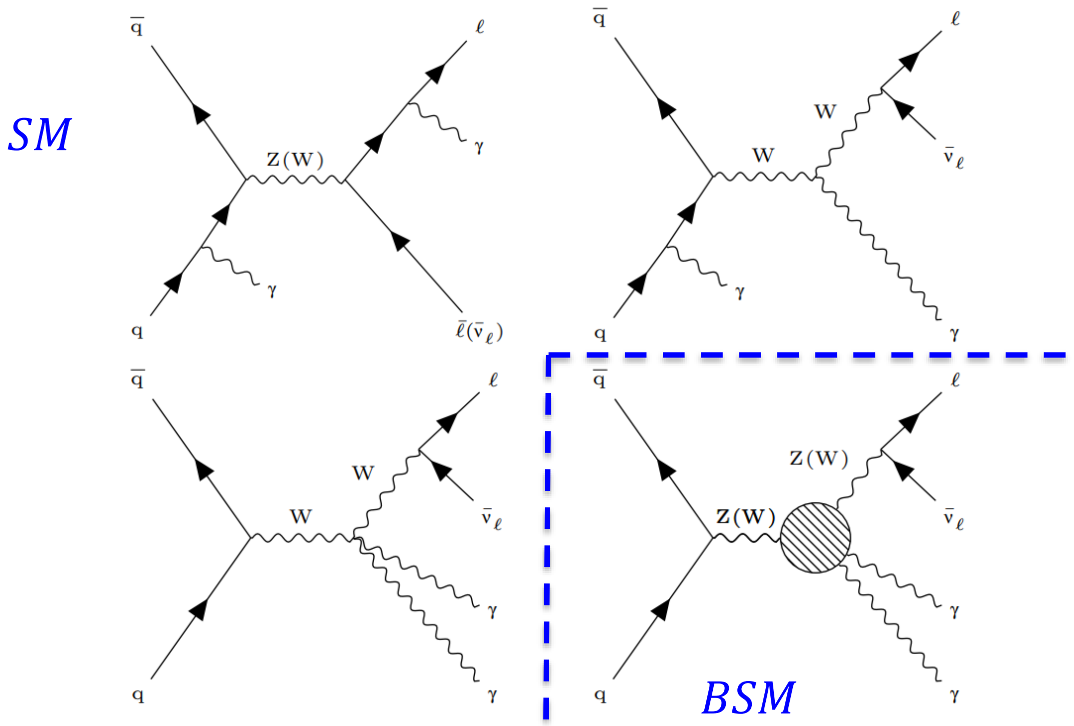
$$\sigma_{WWW} = 850 \pm 100(stat.) \pm 80(syst.)\ fb$$

$V\gamma\gamma$

JHEP 10 (2021) 174

- First measurement of $\mathbf{V\gamma\gamma}$ at 13 TeV
- First evidence of $\mathbf{W\gamma\gamma}$ and first observation of $\mathbf{Z\gamma\gamma}$ at 13 TeV
- $\mathbf{W\gamma\gamma}$ significance 3.1σ (4.5σ) , $\mathbf{Z\gamma\gamma}$ significance 4.8σ (5.8σ)



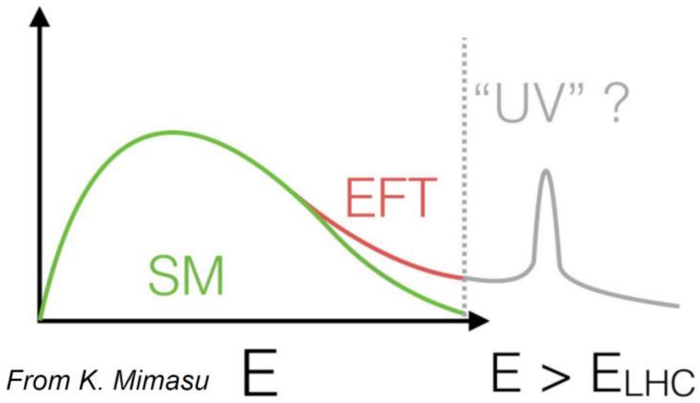


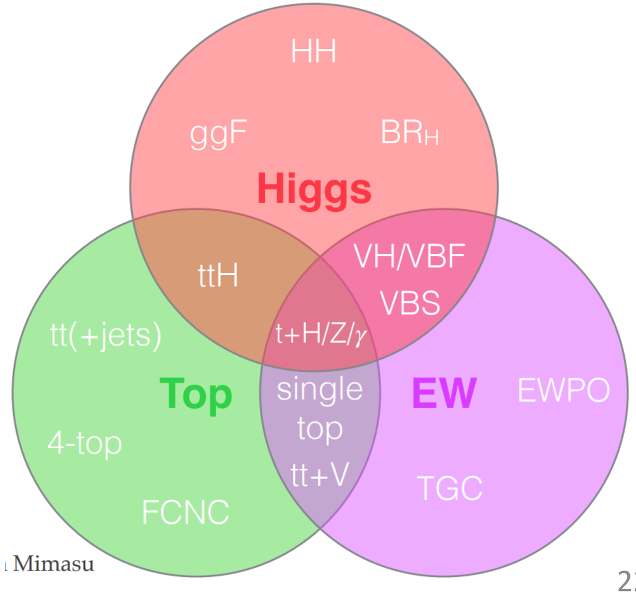
EFT introduction

- No direct evidence of new physics from resonance searches
- Indirect search for NP with precision measurements
- Standard Model Effective Field Theory
  - Parametrize deviations with higher dimensional operators

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)} + \sum_i \frac{c_i^{(8)}}{\Lambda^4}\mathcal{O}_i^{(8)}$$

- Measurements from ATLAS and CMS analyses
  - Dedicated measurements
  - EFT re-parametrization
  - EW, Higgs, Top and combinations



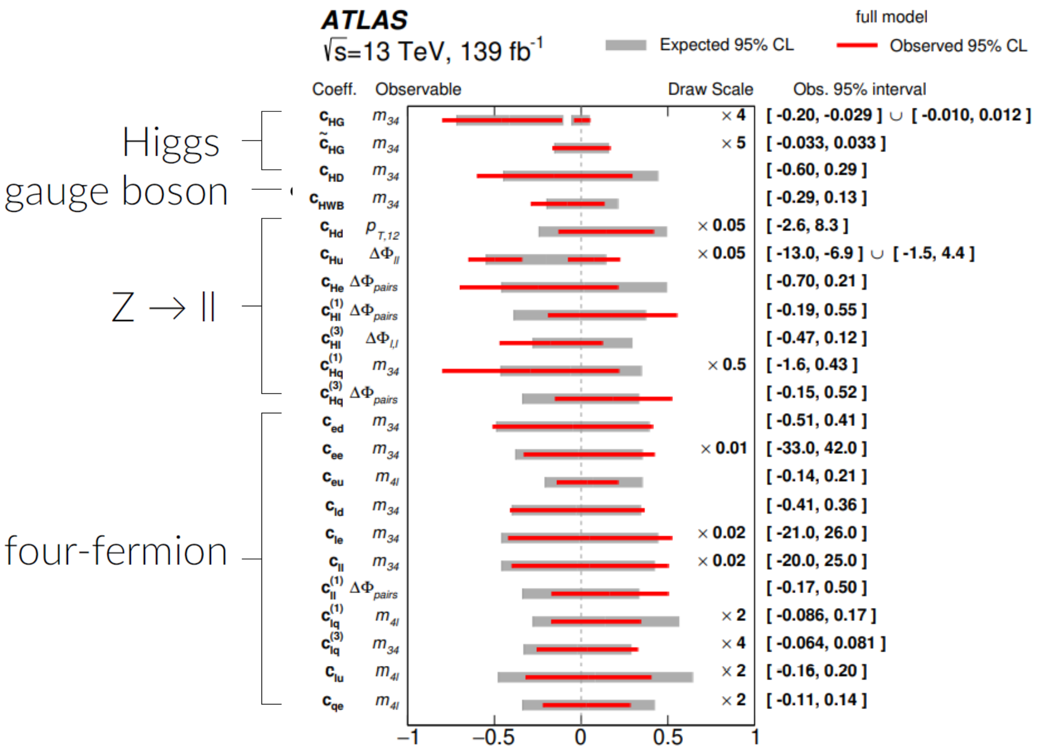


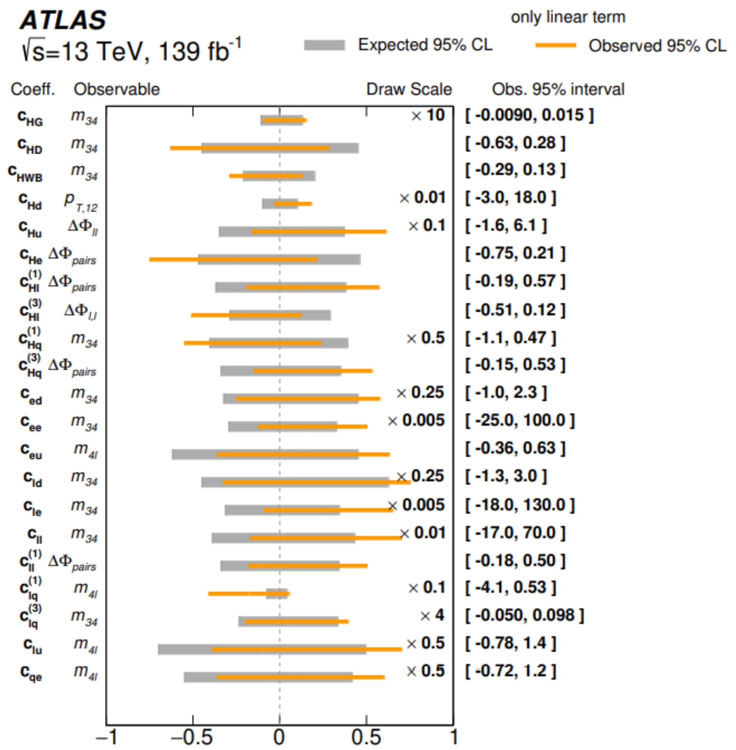
EW-EFT: $pp \to 4l$

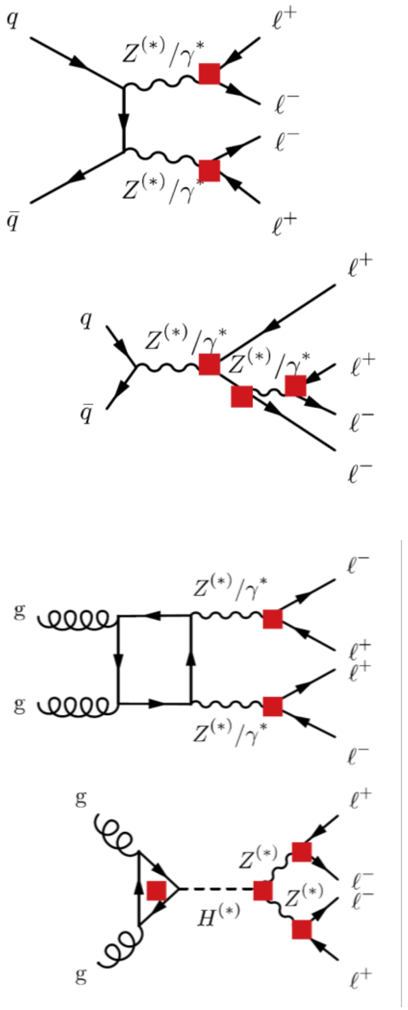
JHEP 07 (2021) 005

- $pp \to 4l$, quadratic terms significant for four-fermion operators
- 22 coefficients giving non-negligible contributions considered separately
- Linear and linear + quadratic fits performed

China ATLAS (USTC) team makes important contributions





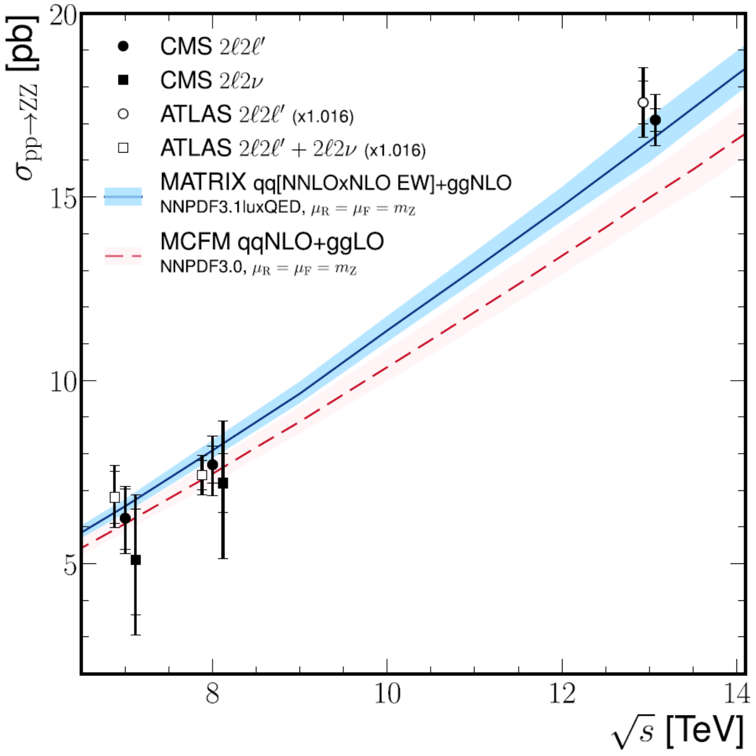


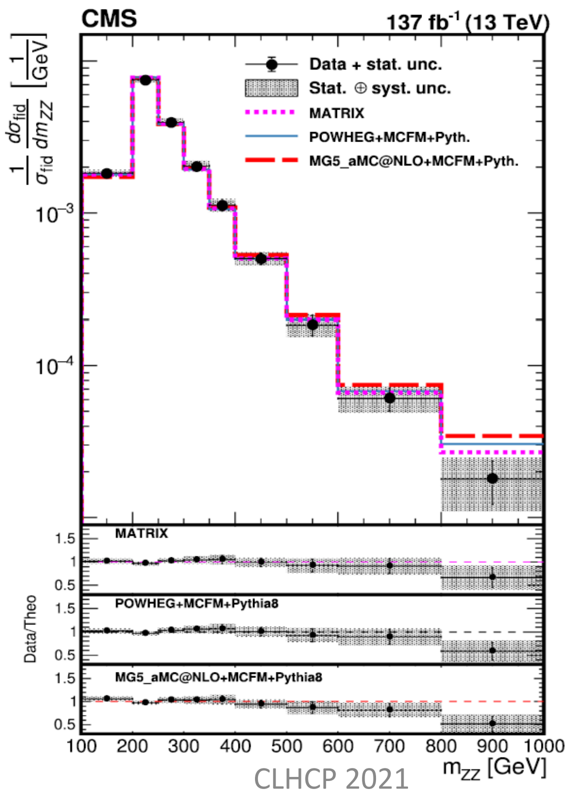
EW-EFT: $ZZ \to 4l$

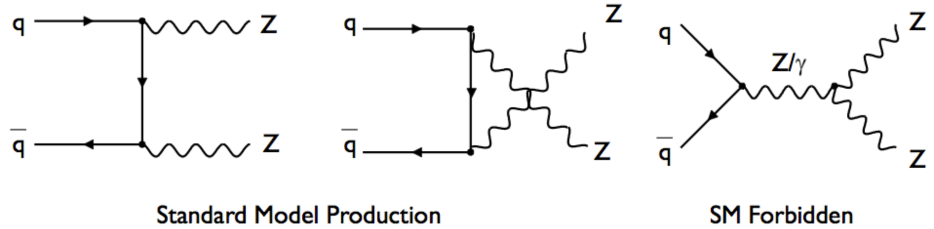
EPJC 81 (2021) 200

- Full Run2 data, measurement of SM ZZ cross-section
- Best limits on neutral aTGC ZZ and ZZZ couplings

China CMS (IHEP) team makes important contributions







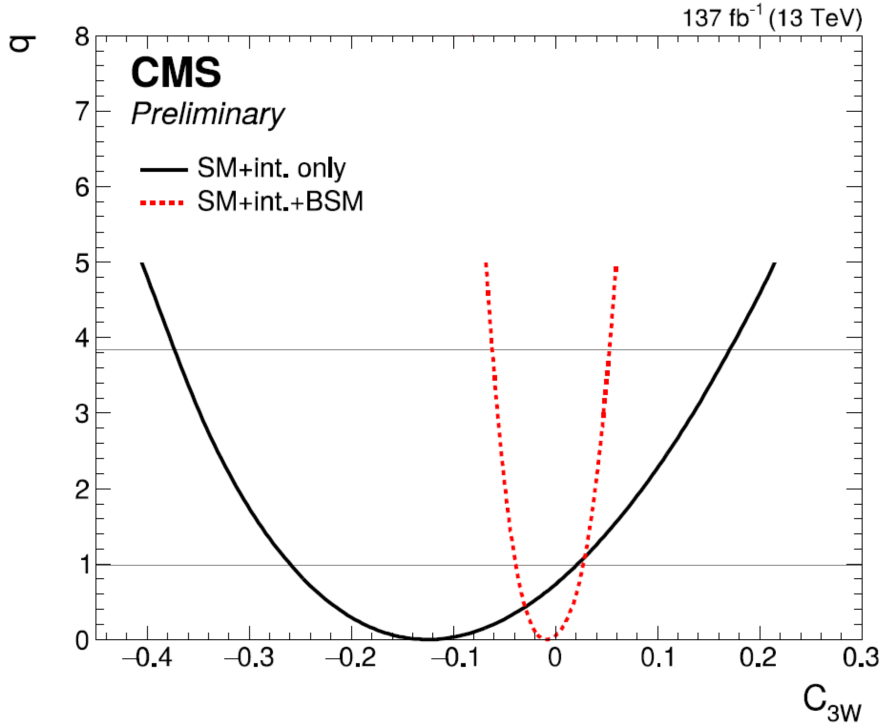
	Expected 95% CL	Observed 95% CL
aTGC parameter	$\times 10^{-4}$	$\times 10^{-4}$
f_4^Z	-8.8 ; 8.3	-6.6 ; 6.0
f_5^Z	-8.0 ; 9.9	-5.5 ; 7.5
f_4^γ	-9.9 ; 9.5	-7.8 ; 7.1
f_5^γ	-9.2 ; 9.8	-6.8 ; 7.5
EFT parameter	TeV^{-4}	TeV^{-4}
$C_{\tilde{B}W}/\Lambda^4$	-3.1 ; 3.3	-2.3 ; 2.5
C_{WW}/Λ^4	-1.7 ; 1.6	-1.4 ; 1.2
C_{BW}/Λ^4	-1.8 ; 1.9	-1.4 ; 1.3
C_{BB}/Λ^4	-1.6 ; 1.6	-1.2 ; 1.2

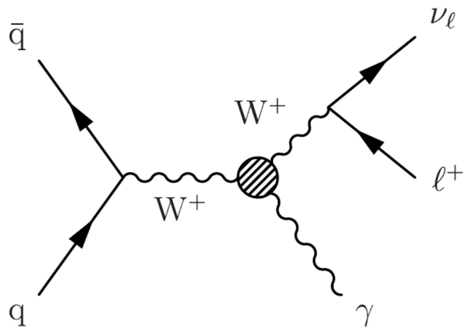
EW-EFT: $W\gamma$

[PRL 126, 252002 (2021)](#)
[CMS-PAS-SMP-20-005](#)

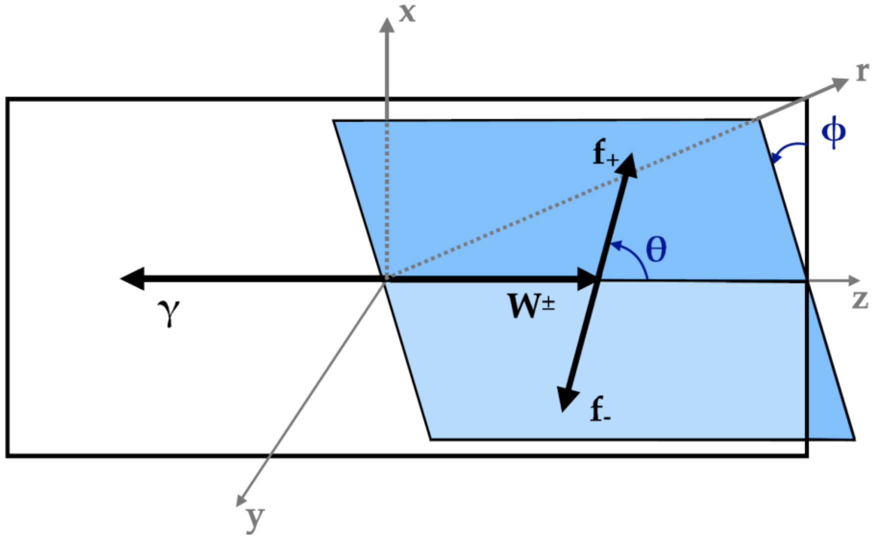
- Interference term suppressed, O_{3W} affects triple gauge boson vertex
- Quadratic terms dominant, higher dimension may be important
- Sensitivity to linear term improved by $\times\, 10$

China CMS (PKU) team plays a leading role





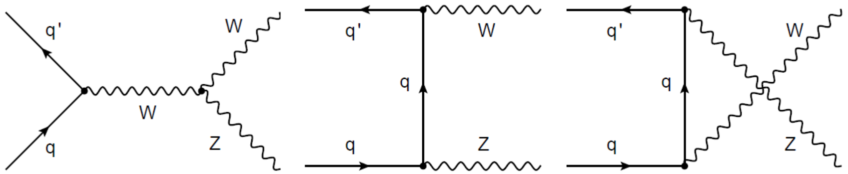
$$\sigma_j^{\text{tot}} = \sigma_j^{\text{SM}} + C_{3W}\sigma_j^{\text{int}} + C_{3W}^2\sigma_j^{\text{BSM}}$$

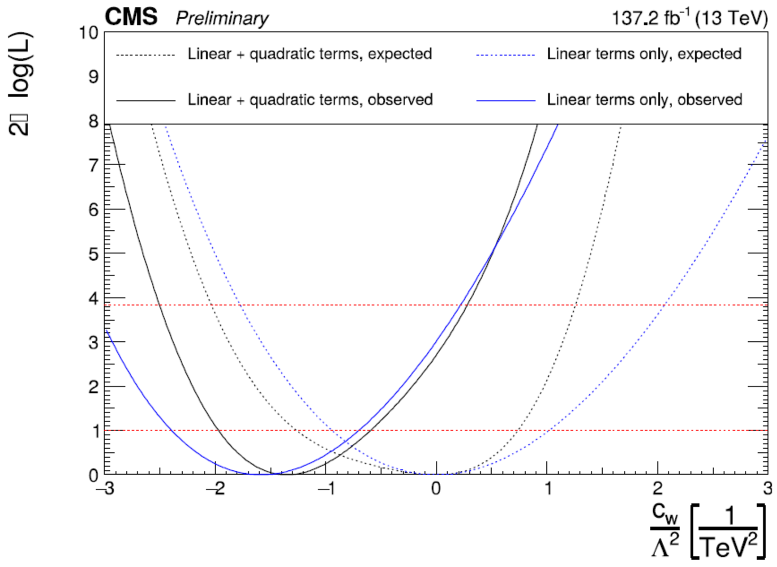


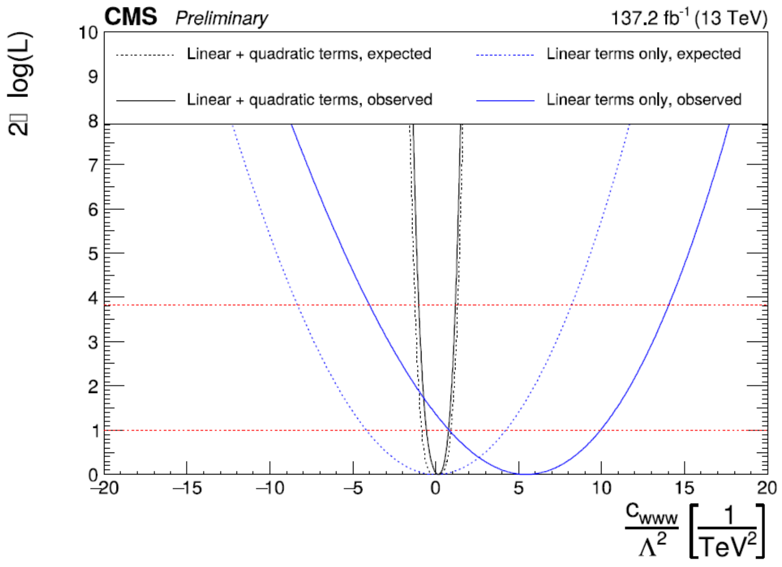
EW-EFT: WZ

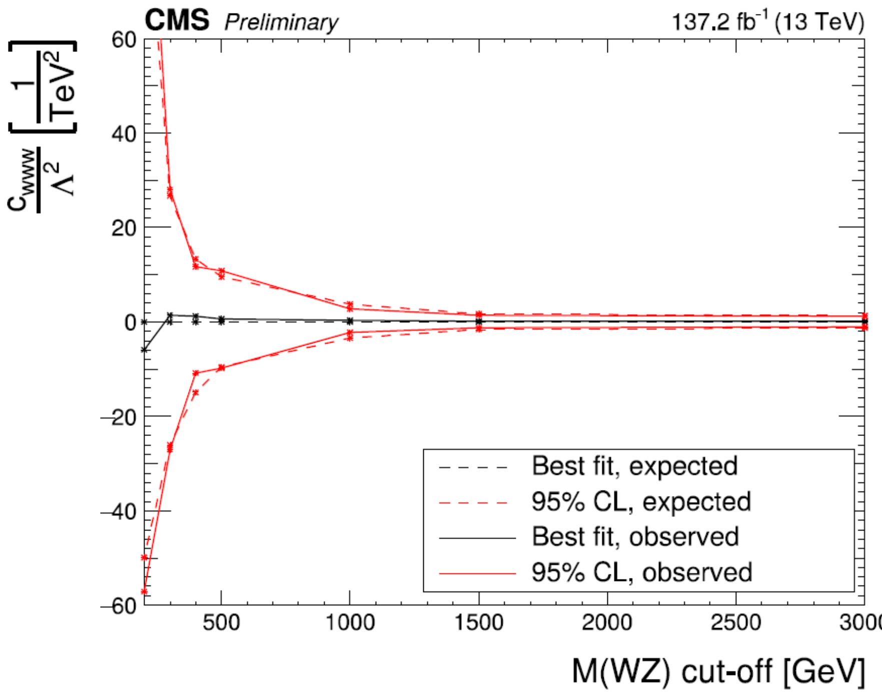
[CMS-SMP-20-014](#)
[arXiv:2110.11231](#)

- $pp \to WZ$, cross section measured in tri-lepton final states
- Sensitivity to 3 CP-conserving and 2 CP-violating terms
- Quadratic term has dominant impact on several coefficients
- Validity of EFT expansion investigated by varying m(WZ) cut-off





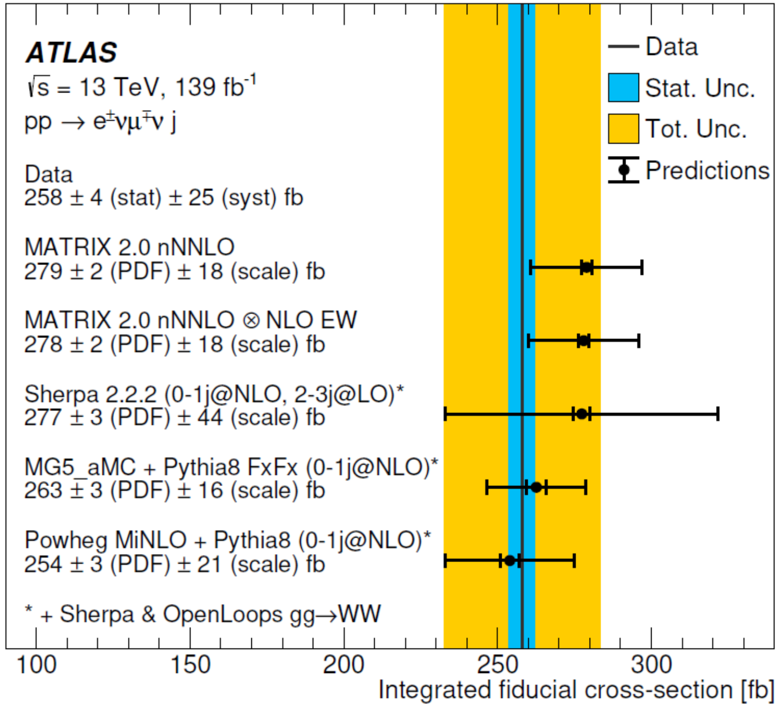


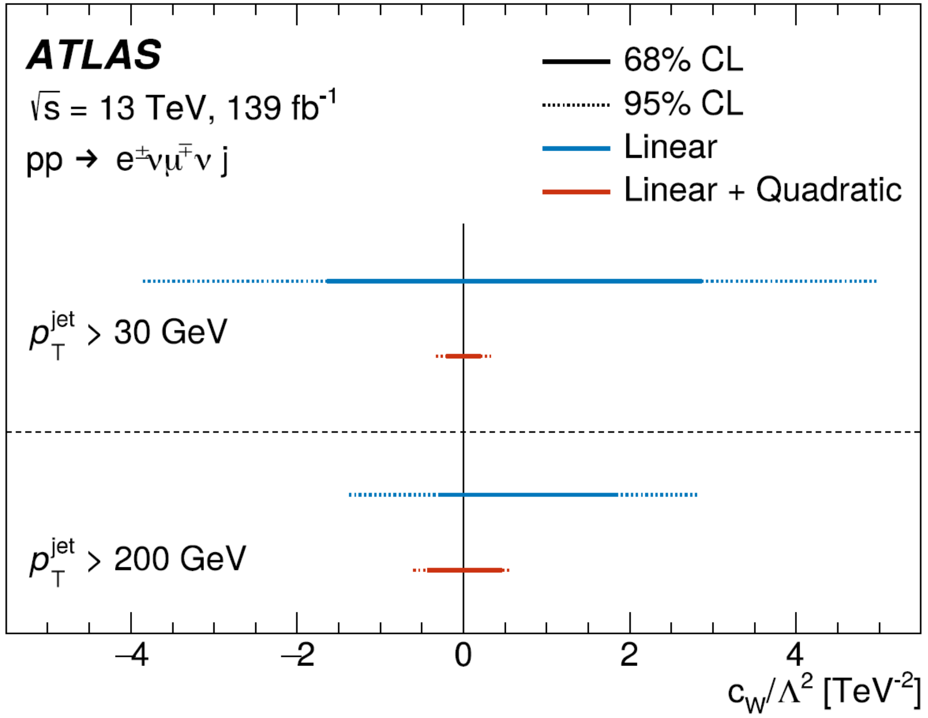


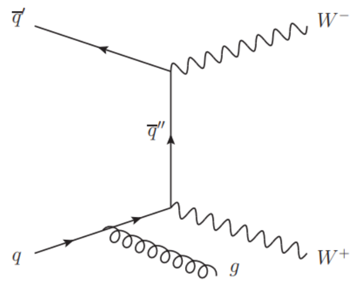
EW-EFT: $WW + \geq 1j$

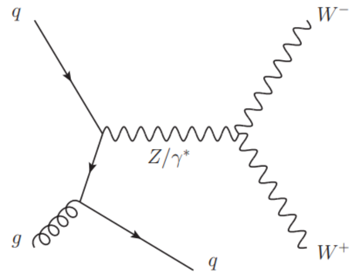
[JHEP 06 (2021) 003]

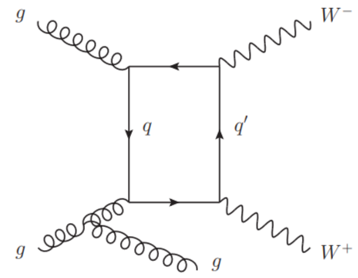
- $WW + \geq 1jet$, sensitive to c_W via gauge boson self-coupling
- First jet-inclusive differential WW measurements at LHC
- Quadratic term still dominant, but impact reduced at higher jet pT











EW-EFT: $Z\gamma jj$

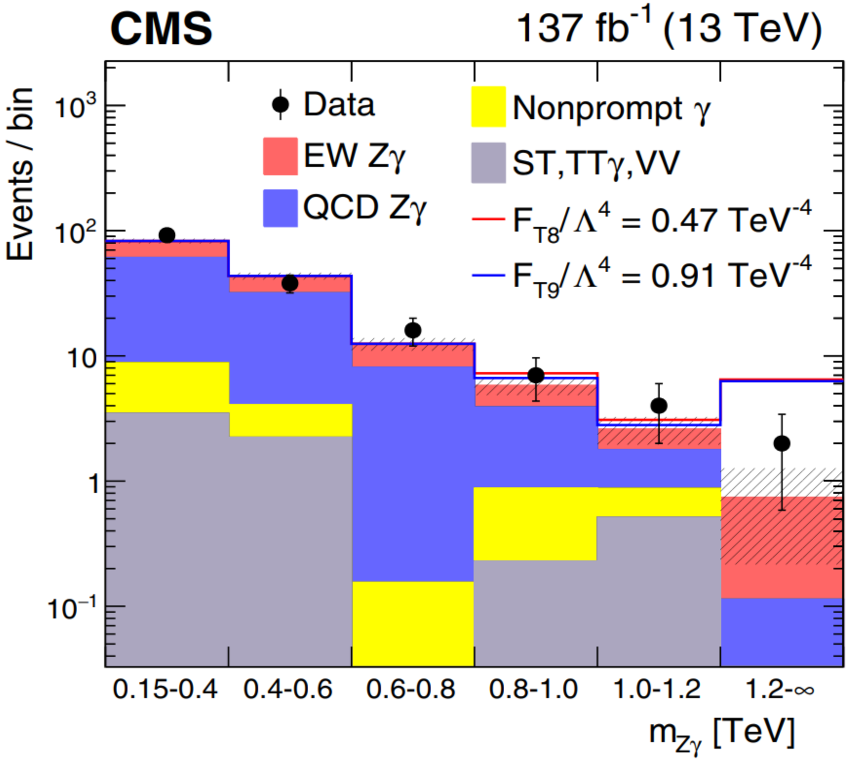
- $Z\gamma jj$, aQGC limits on dimension 8 operators

[PRD 104 (2021) 072001](#)

- Similar sensitivity on $T8$ and $T9$ between $VBS\ Z\gamma$ and $VBS\ ZZ$, limit for $T9$ most stringent

China CMS (PKU) team plays a leading role

China CMS (SYSU) team makes important contributions



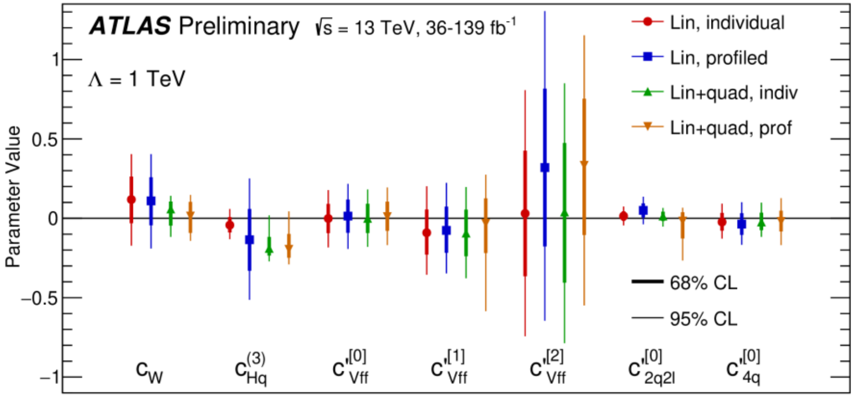
Coupling	Exp. lower	Exp. upper	Obs. lower	Obs. upper	Unitarity bound
F_{M0}/Λ^4	−12.5	12.8	−15.8	16.0	1.3
F_{M1}/Λ^4	−28.1	27.0	−35.0	34.7	1.5
F_{M2}/Λ^4	−5.21	5.12	−6.55	6.49	1.5
F_{M3}/Λ^4	−10.2	10.3	−13.0	13.0	1.8
F_{M4}/Λ^4	−10.2	10.2	−13.0	12.7	1.7
F_{M5}/Λ^4	−17.6	16.8	−22.2	21.3	1.7
F_{M7}/Λ^4	−44.7	45.0	−56.6	55.9	1.6
F_{T0}/Λ^4	−0.52	0.44	−0.64	0.57	1.9
F_{T1}/Λ^4	−0.65	0.63	−0.81	0.90	2.0
F_{T2}/Λ^4	−1.36	1.21	−1.68	1.54	1.9
F_{T5}/Λ^4	−0.45	0.52	−0.58	0.64	2.2
F_{T6}/Λ^4	−1.02	1.07	−1.30	1.33	2.0
F_{T7}/Λ^4	−1.67	1.97	−2.15	2.43	2.2
F_{T8}/Λ^4	−0.36	0.36	−0.47	0.47	1.8
F_{T9}/Λ^4	−0.72	0.72	−0.91	0.91	1.9

Combined EFT fit

ATLAS-PHYS-PUB-2021-022

- Combined fit of $WW, WZ, 4l, VBF\ Z$, 6 differential inputs
- Considering both linear-only and also quadratic effects
- Constrained individually or in combination (profiled)

China ATLAS (USTC & TDLI/SJTU) teams make important contributions



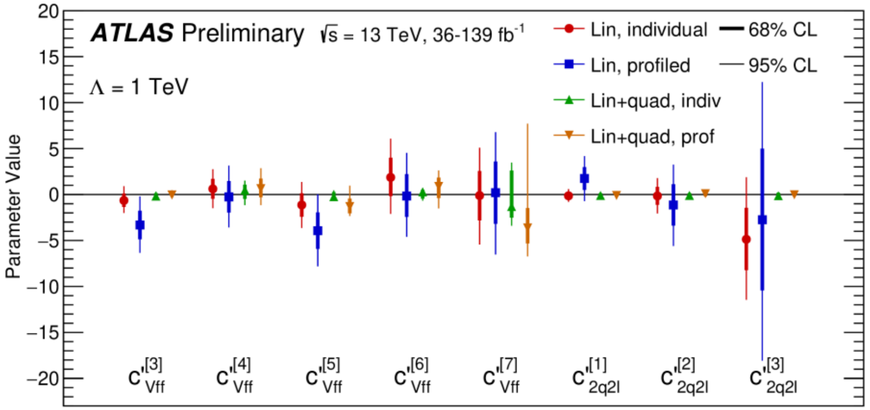
$c'^{[0]}_{Vff} \approx 0.81c_{HWB} + 0.38c_{HD} + 0.13c^{(1)}_{Hl} + 0.37c^{(3)}_{Hl} - 0.14c^{(1)}_{ll} + 0.12c^{(1)}_{Hq}$

$c'^{[1]}_{Vff} \approx 0.73c^{(1)}_{Hl} - 0.28c^{(3)}_{Hl} - 0.48c_{He} + 0.38c^{(1)}_{ll} + 0.13c^{(1)}_{Hq}$

$c'^{[2]}_{Vff} \approx 0.37c_{HWB} + 0.17c_{HD} - 0.31c^{(1)}_{Hl} - 0.53c^{(3)}_{Hl} + 0.25c_{He} + 0.59c^{(1)}_{ll} - 0.21c^{(1)}_{Hq}$

$c'^{[0]}_{2q2l} \approx -0.37c^{(1)}_{lq} + 0.89c^{(3)}_{lq} - 0.11c_{lu} - 0.21c_{eu} - 0.13c_{qe}$

$c'^{[0]}_{4q} \approx 0.11c^{(11)}_{qq} + 0.22c^{(18)}_{qq} + 0.95c^{(31)}_{qq} - 0.2c^{(38)}_{qq}$



$c'^{[3]}_{Vff} \approx -0.19c^{(1)}_{Hl} - 0.14c^{(3)}_{Hl} + 0.86c^{(1)}_{Hq} + 0.41c_{Hu} - 0.17c_{Hd}$

$c'^{[4]}_{Vff} \approx -0.35c_{HWB} + 0.49c_{HD} + 0.26c^{(1)}_{Hl} + 0.35c^{(3)}_{Hl} + 0.51c_{He} + 0.38c^{(1)}_{ll} + 0.18c^{(1)}_{Hq}$

$c'^{[5]}_{Vff} \approx 0.25c_{HD} + 0.33c^{(1)}_{Hl} - 0.22c^{(3)}_{Hl} + 0.18c_{He} - 0.35c^{(1)}_{ll} - 0.3c^{(1)}_{Hq} + 0.71c_{Hu} - 0.16c_{Hd}$

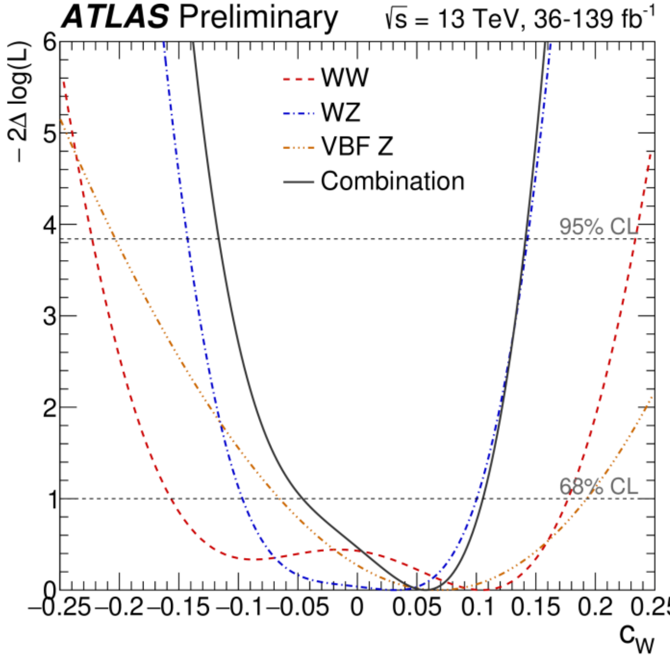
$c'^{[6]}_{Vff} \approx -0.22c^{(1)}_{Hl} + 0.52c^{(3)}_{Hl} - 0.39c_{He} + 0.44c^{(1)}_{ll} - 0.22c^{(1)}_{Hq} + 0.52c_{Hu}$

$c'^{[7]}_{Vff} \approx -0.28c_{HWB} + 0.71c_{HD} - 0.31c^{(1)}_{Hl} - 0.21c^{(3)}_{Hl} - 0.5c_{He} - 0.14c^{(1)}_{ll}$

$c'^{[1]}_{2q2l} \approx 0.56c^{(1)}_{lq} + 0.44c^{(3)}_{lq} + 0.61c_{eu} - 0.1c_{ed} + 0.34c_{qe}$

$c'^{[2]}_{2q2l} \approx 0.68c^{(1)}_{lq} + 0.15c^{(3)}_{lq} + 0.33c_{lu} - 0.51c_{eu} + 0.13c_{ed} - 0.37c_{qe}$

$c'^{[3]}_{2q2l} \approx -0.27c^{(1)}_{lq} + 0.79c_{lu} - 0.39c_{ld} + 0.26c_{eu} - 0.22c_{ed} - 0.16c_{qe}$

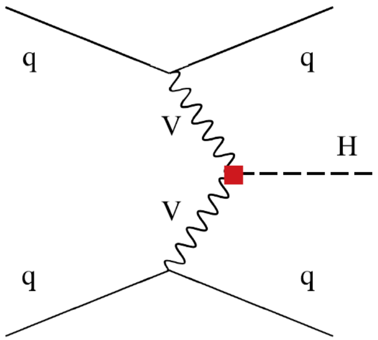


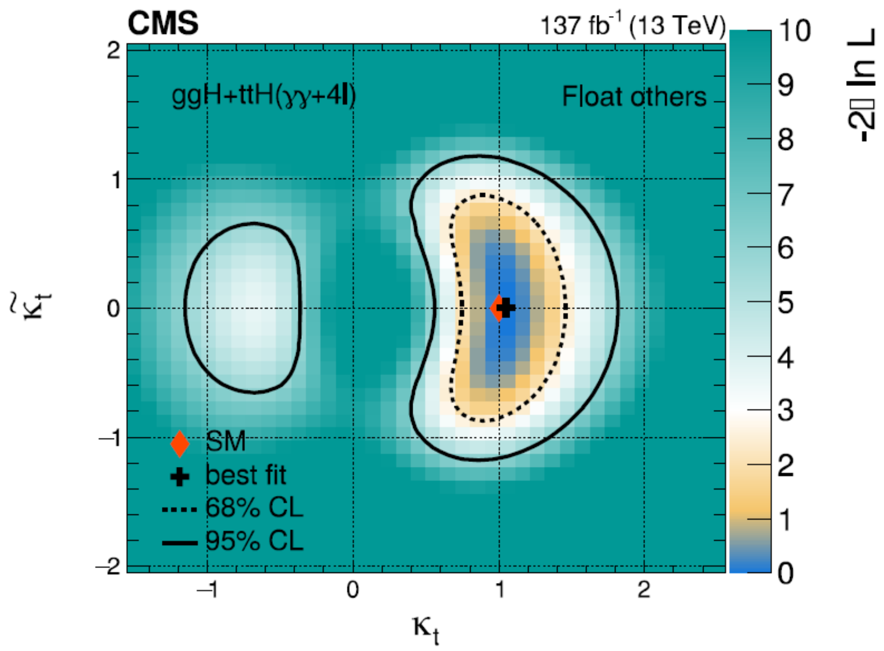
Higgs-EFT

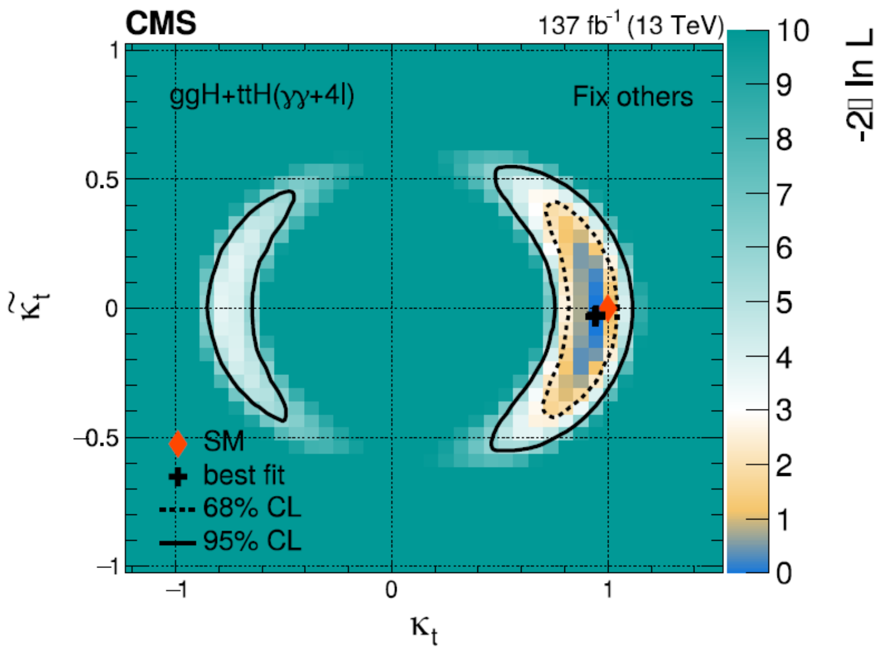
PRD 104, 052004 (2021)

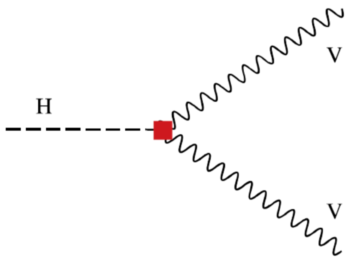
- $H \to 4l,\ tH + ttH + ggH$
- Study structure of HVV, ggH, ttH in SMEFT framework
- Results consistent with SM Higgs

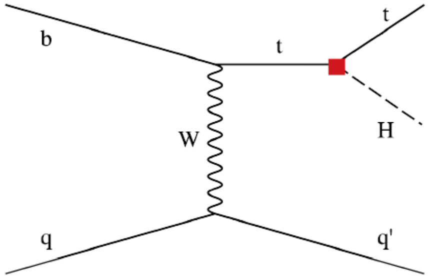
China CMS (Zhejiang Univ.) team plays a leading role







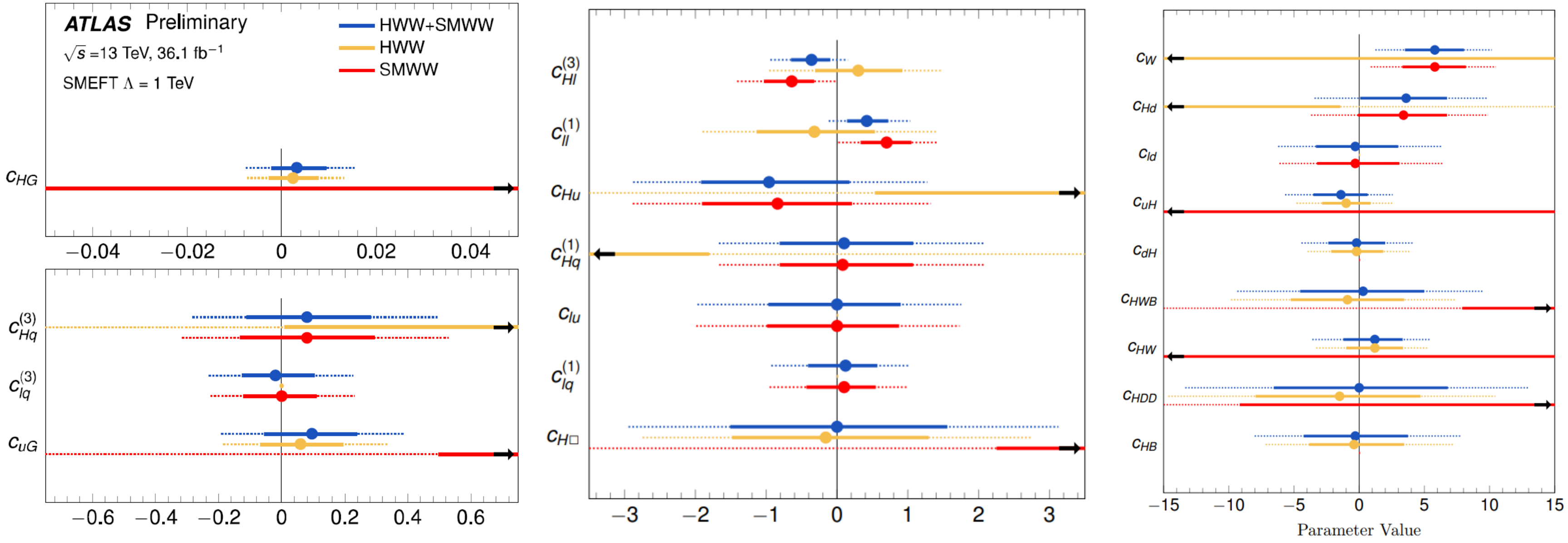


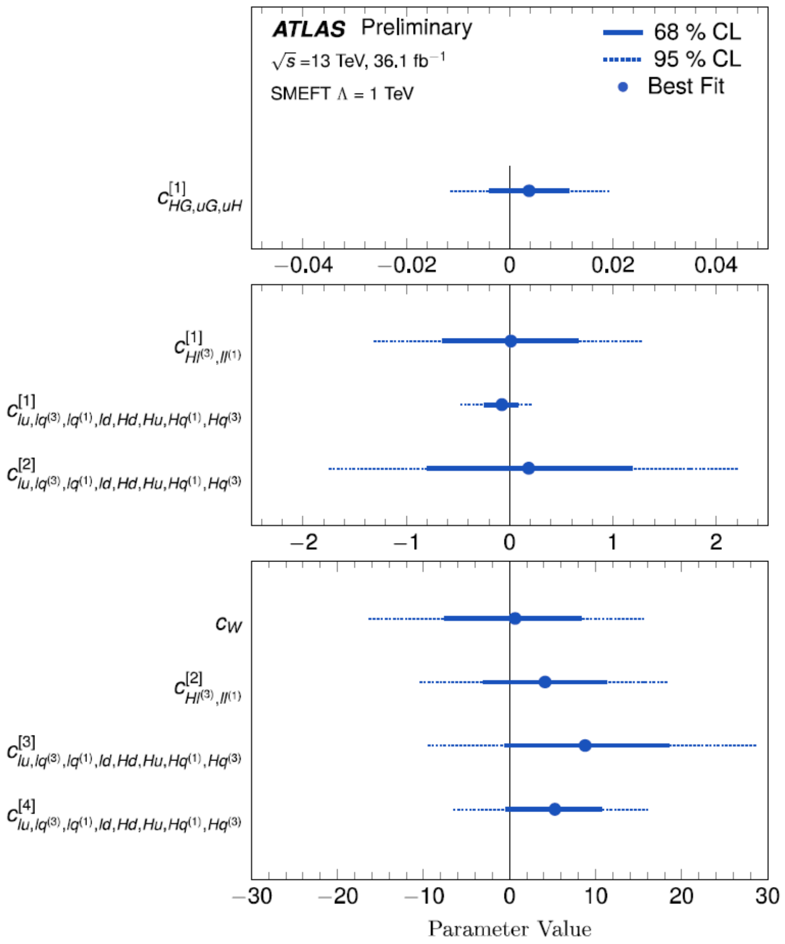


Higgs-EFT: $WW, H(WW^*)$

ATL-PHYS-PUB-2021-010

- Combination of a measurement $H \to WW^*$ in WW, $36.1\ fb^{-1}$
- Consider 20 CP-even Wilson coefficients
- Agreement with SM at the level of 1σ

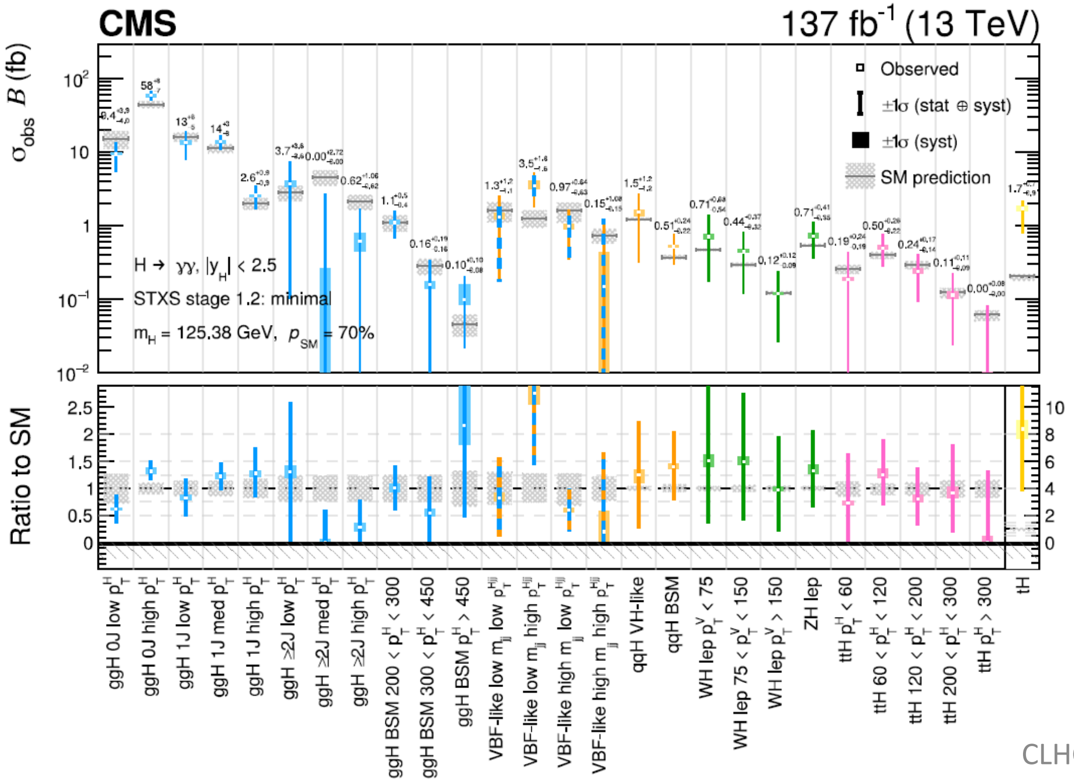


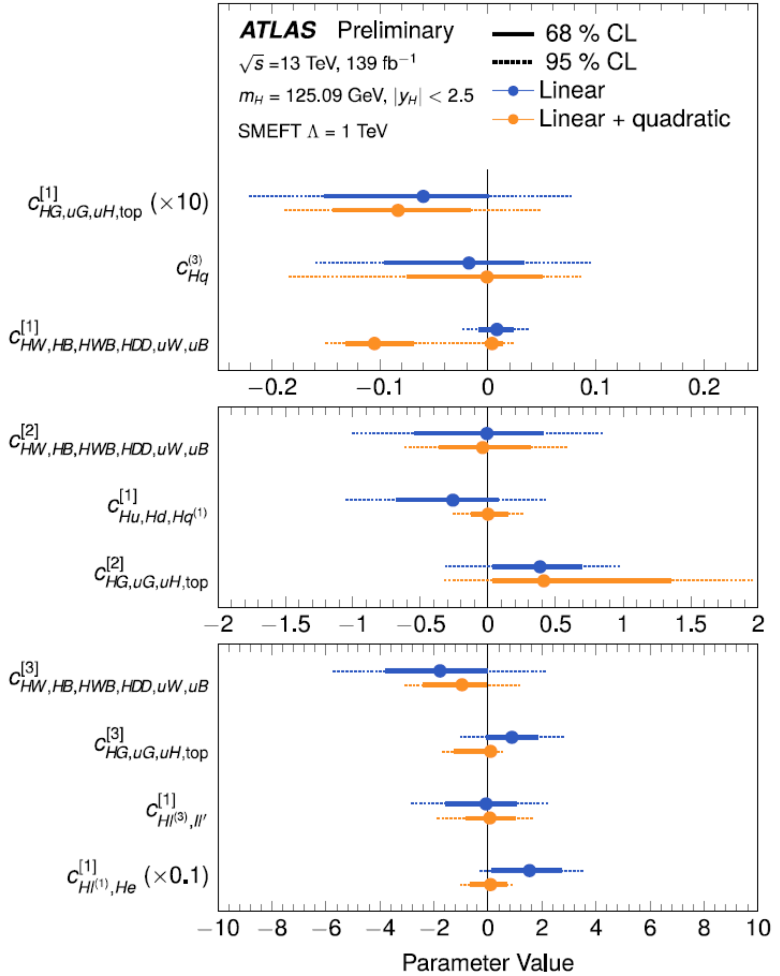


EFT: Higgs combination

- $H \to \gamma\gamma, H \to ZZ \to 4l, H \to b\bar{b}$, combined measurements
- Separate measurements using STXS framework
- The observations are consistent with SM

JHEP 07 (2021) 027
EPJC 81 (2021) 488
ATLAS-CONF-2020-053

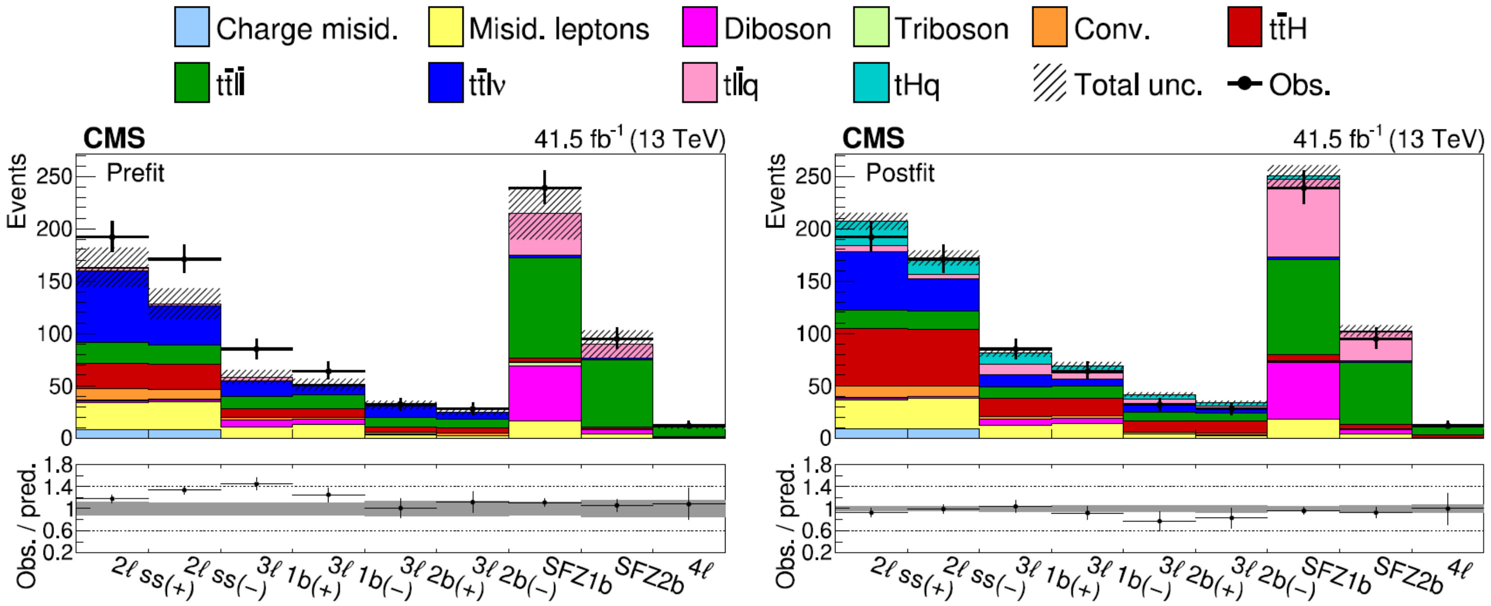


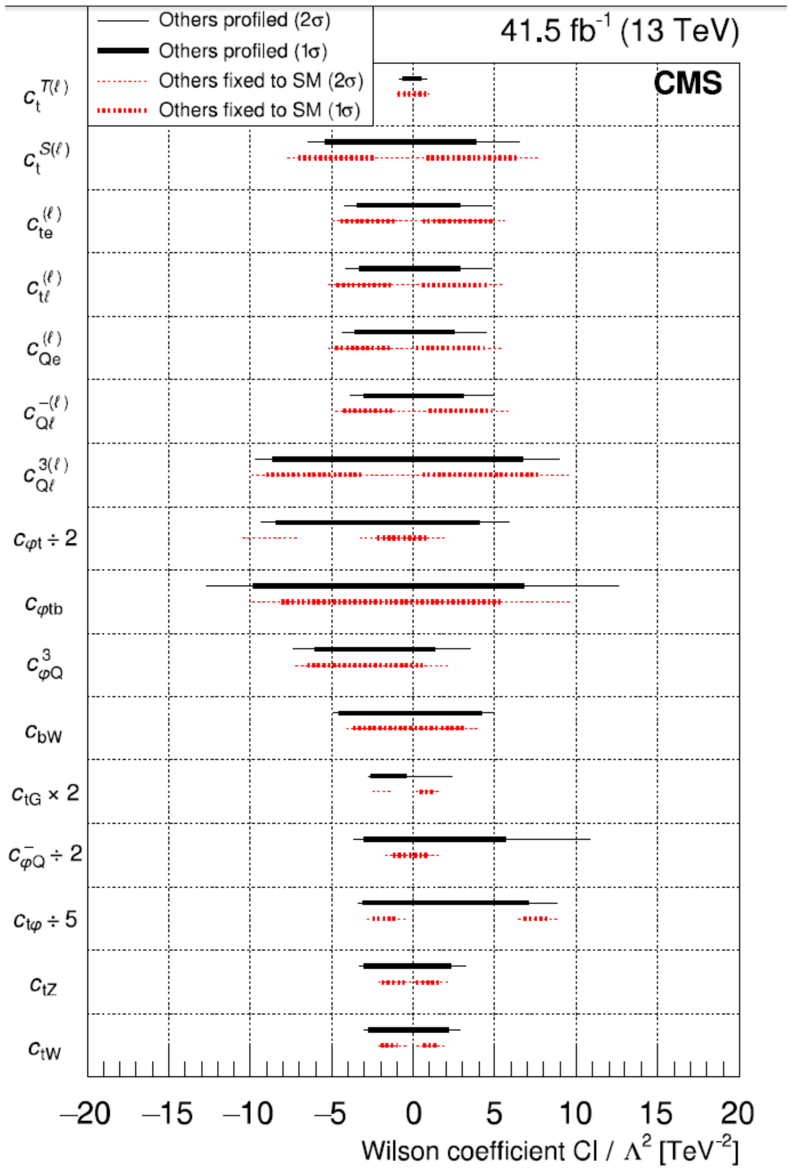


Top-EFT

JHEP 03 (2021) 095

- $t(t) + lepton$, combined measurements
- Five signal processes $ttH, ttll, ttlv, tllq, tHq$
- 16 operators considered
- Consistent with SM at 2σ





Summary & Outlook

- EW measurements
  - LHC has entered the era of precise measurements
  - In di-boson production (VBS), theoretical systematic at the same level of statistical
  - Statistical limited in tri-boson measurements
- EFT measurements
  - Two approaches, reparameterization or direct measurements
  - Both ATLAS and CMS have provided excellent results in EWK, Higgs, Top sectors
- The coming run3 data will increase the BSM sensitivity