BROOKHAVEN
NATIONAL LABORATORY

Probing SMEFT with diboson processes

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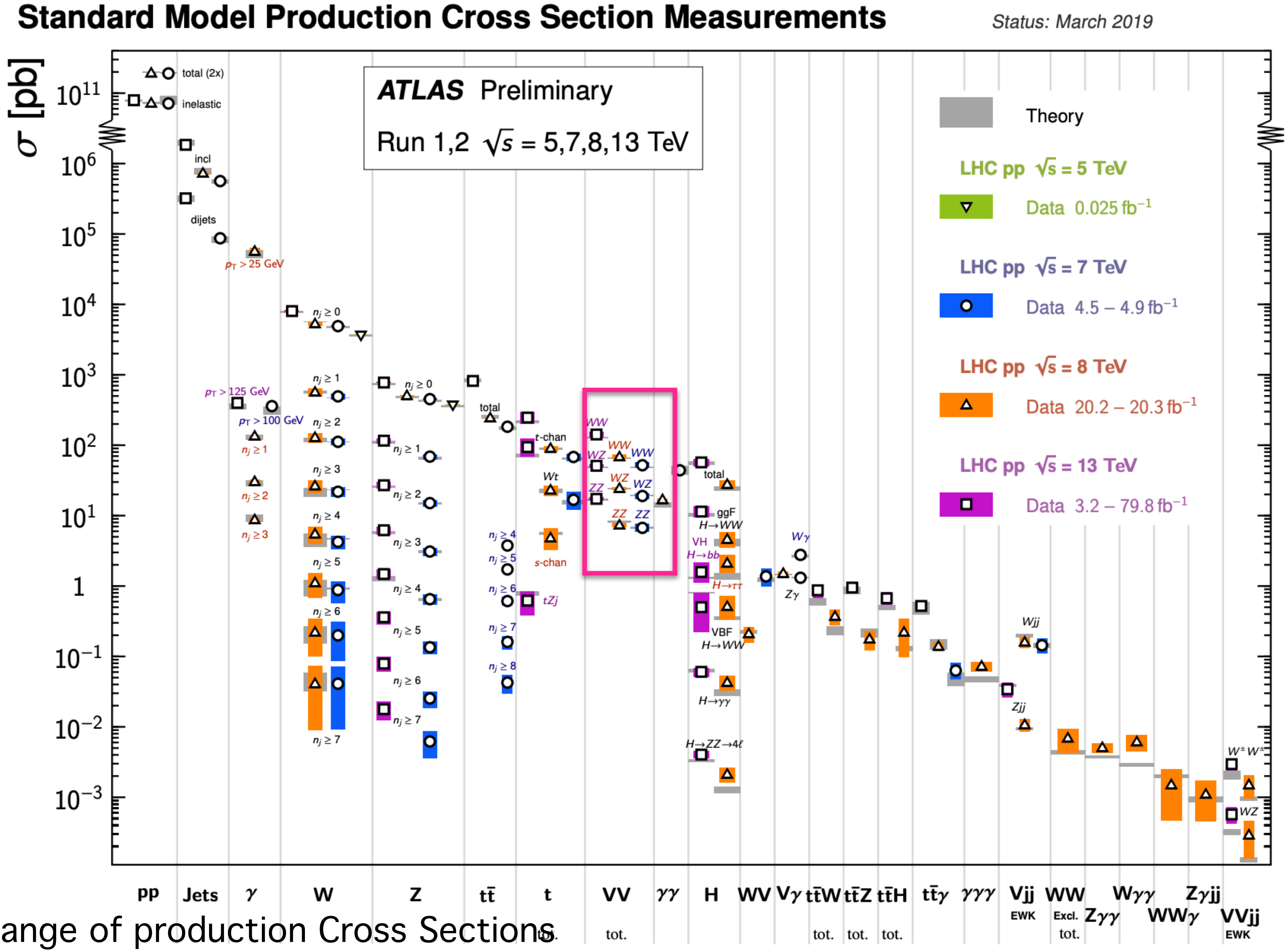
Why study diboson?

- One of the main goals of the LHC is to study the mechanism of Electroweak Spontaneous Symmetry Breaking.
- This process determines particle content of the Standard Model:

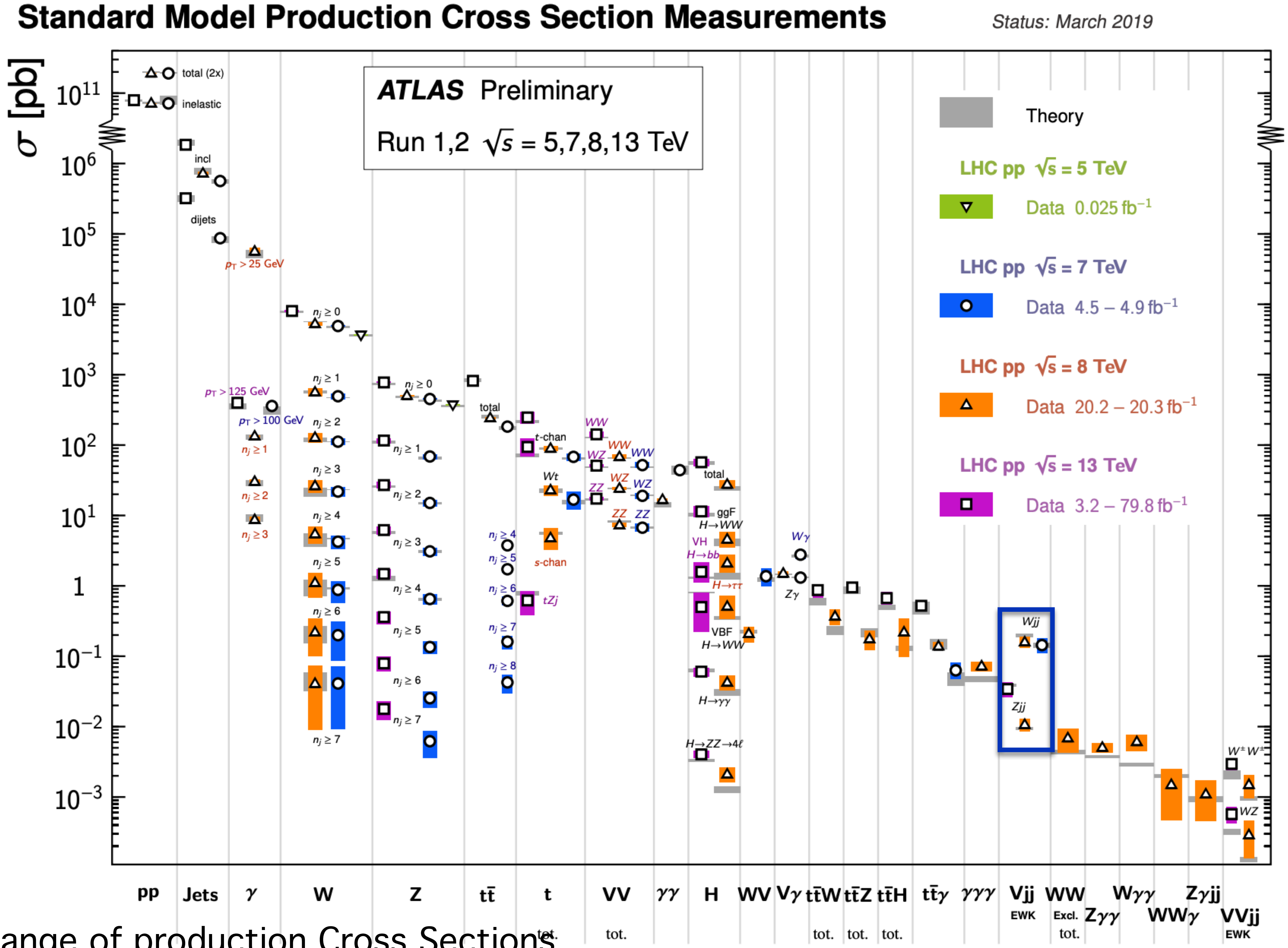
$$\begin{array}{l} (\text{massless vector})\ W^a_\mu, B_\mu \\ (\text{Higgs doublet})\ \sigma, \chi^a \end{array} \Longrightarrow \begin{array}{l} (\text{massive vector})\ W^+_\mu, W^-_\mu, Z_\mu \\ (\text{Higgs field})\ H \end{array}$$

- The dynamics of massive bosons is a window into the physics of spontaneous symmetry breaking.
- New Physics associated to Electroweak Symmetry Breaking could alter the dynamics of the Higgs, W and Z bosons
- No direct observation of new physics at the LHC after Higgs boson discovery
  - Precision measurements are more important than ever
- Several extensions of the SM predict additional processes with multiple bosons in the final state
  - Any observed deviation of multiboson production cross sections from their SM predictions could be an early sign of new physics



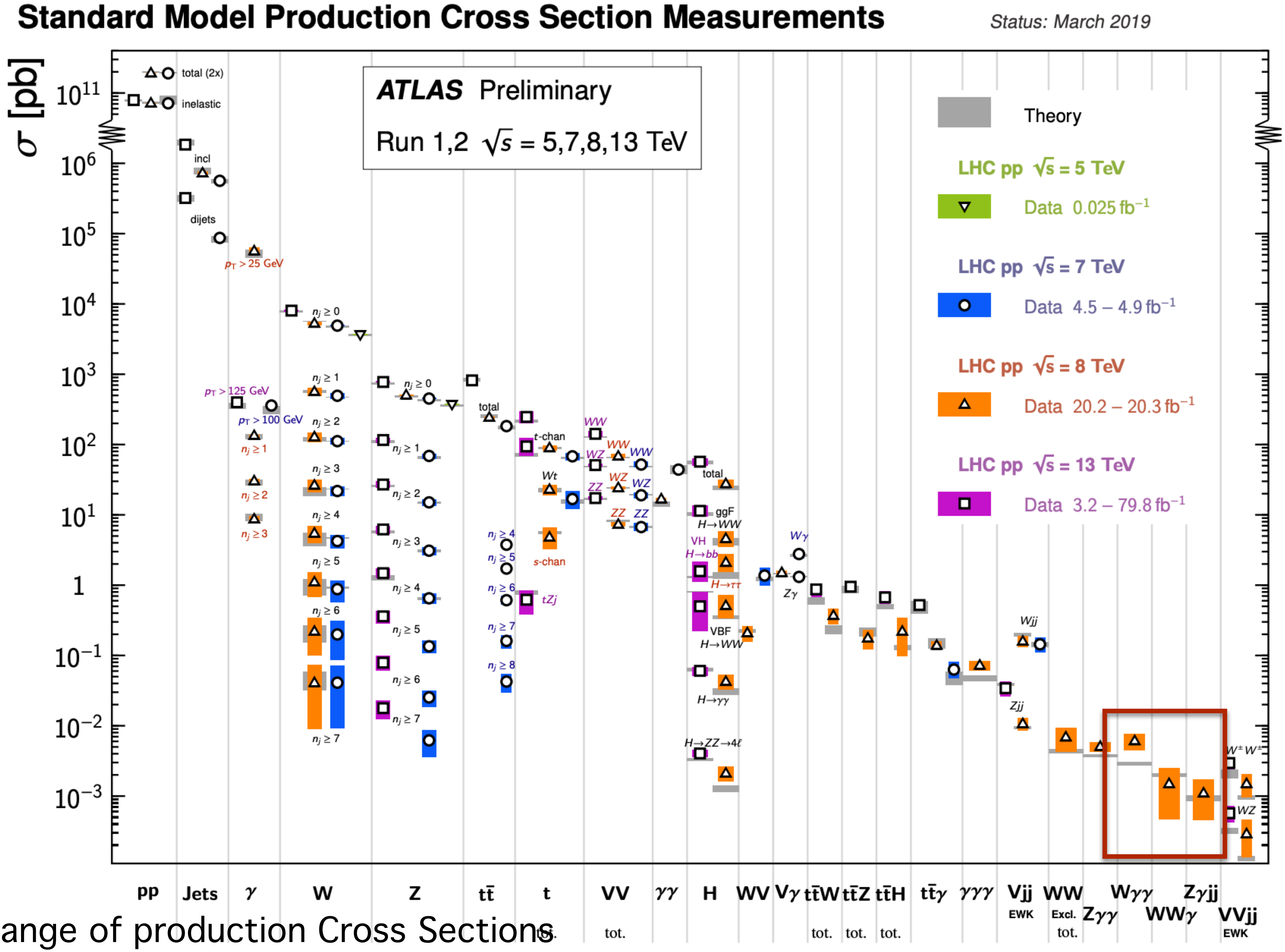
Huge range of production Cross Sections

- 5-300 pb: Inclusive (QCD) diboson production:
    - Sensitive to higher order QCD (and QED) perturbative corrections
    - SM gauge structure: Triple Gauge Couplings (TGC)



Huge range of production Cross Sections

- <0.01 pb: VBS/VBF (QED) diboson production
  - Sensitive to higher order QED perturbative corrections
  - The nature of EWSB SM gauge structure: Triple Gauge Couplings (TGC)

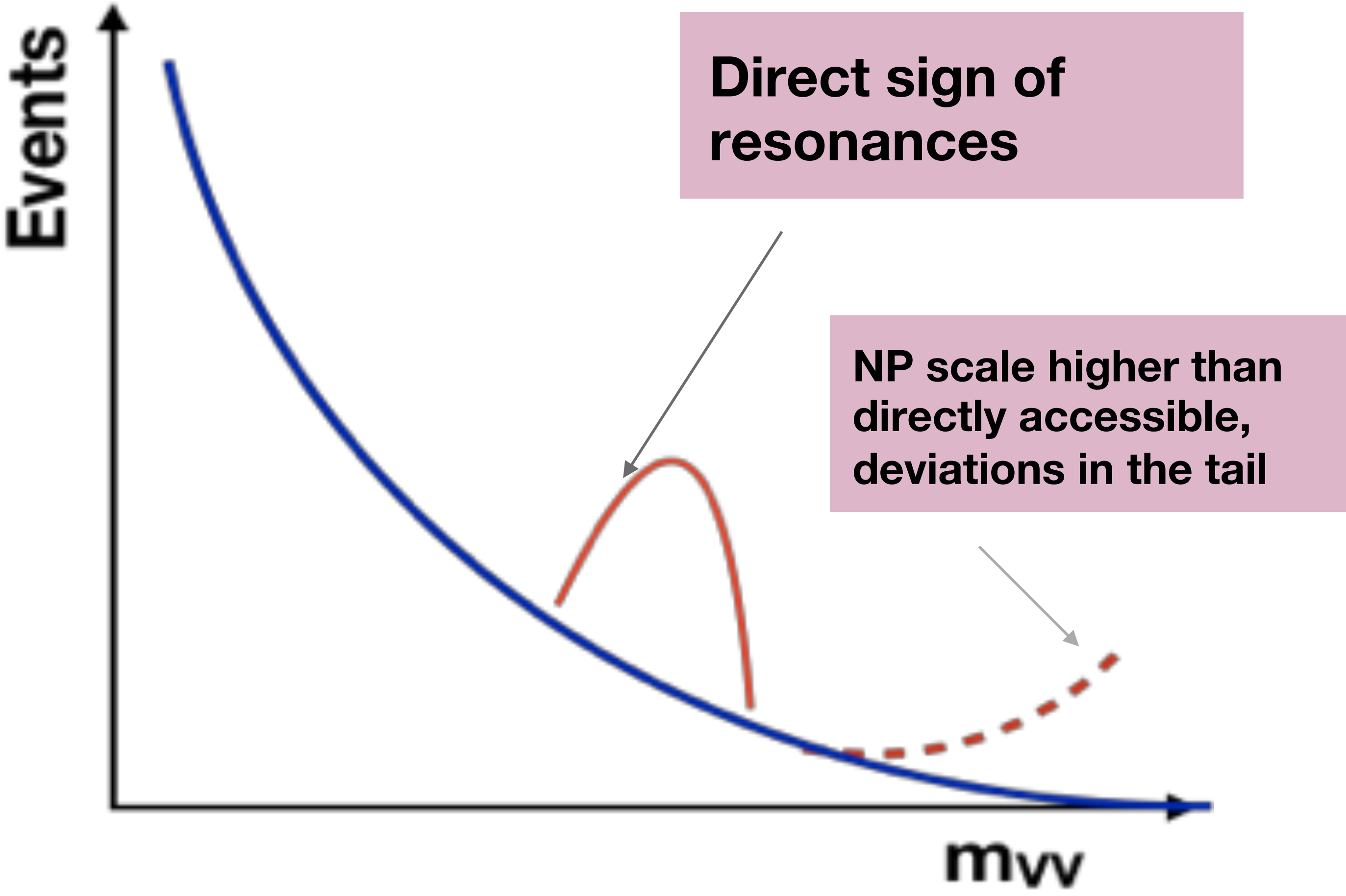


Huge range of production Cross Sections

- 10^{-3}-10^{-1}pb: Inclusive (QCD) triboson production
  - Sensitive to higher order QCD (and QED) perturbative corrections
  - SM gauge structure: Triple Gauge Couplings (TGC) and Quartic Gauge Couplings (QGC)

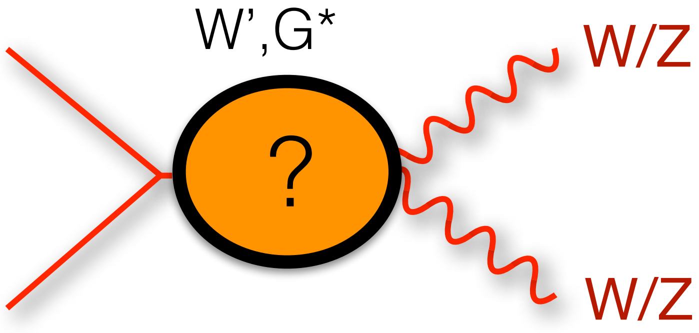
Two paths to BSM Physics

- Direct Searches
- Indirect searches

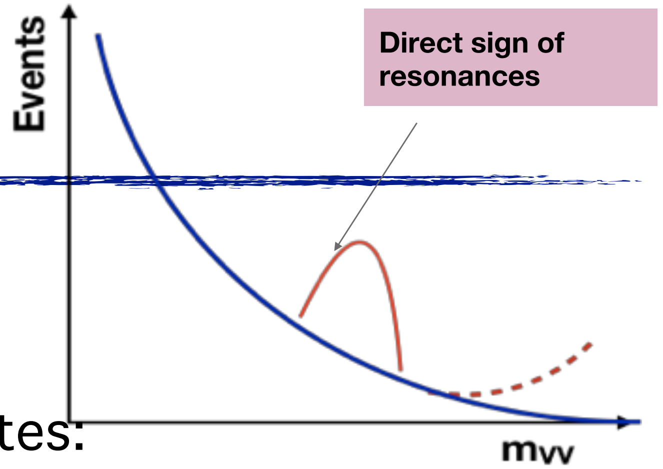


Direct sign of resonances

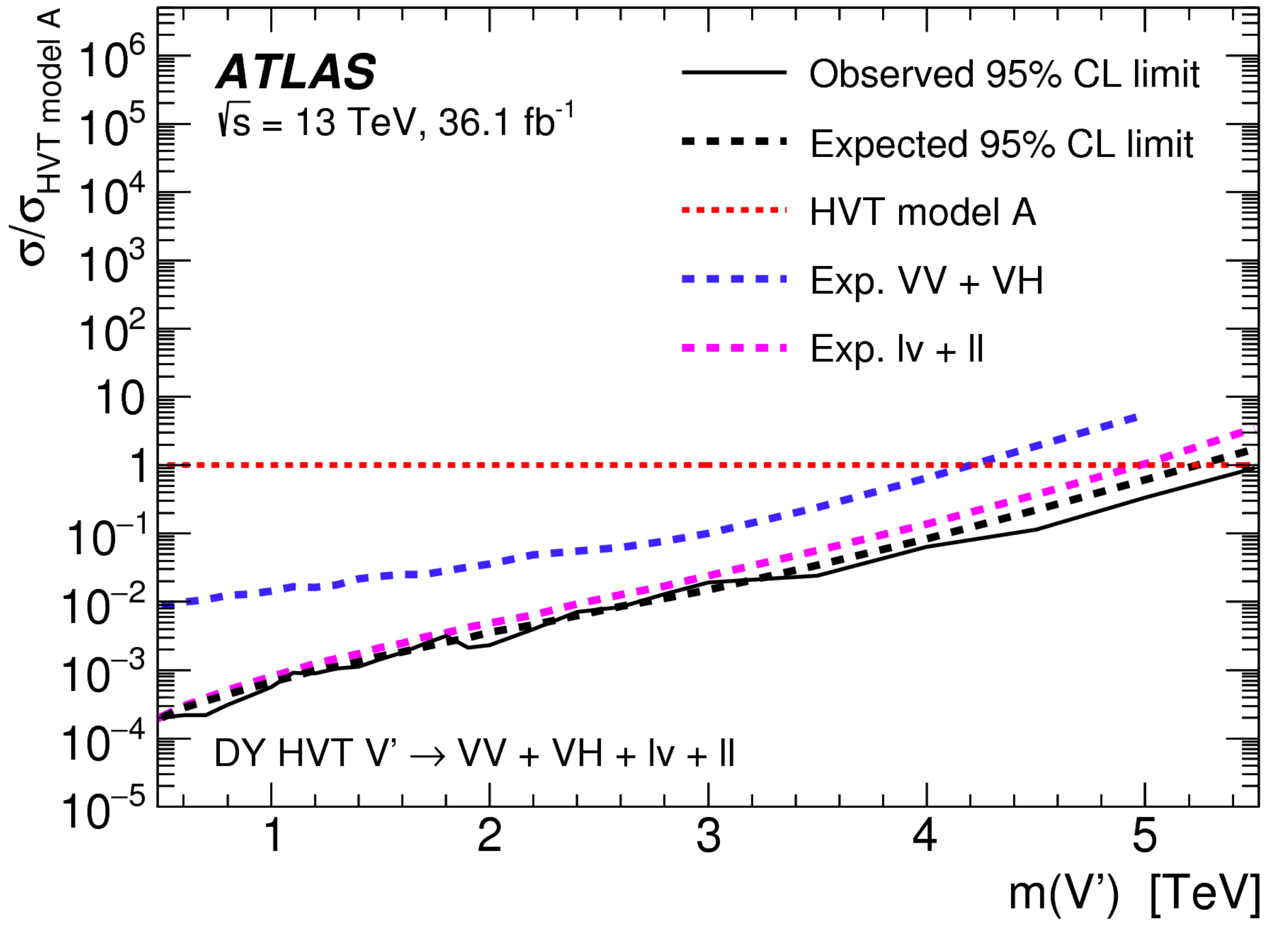
NP scale higher than directly accessible, deviations in the tail

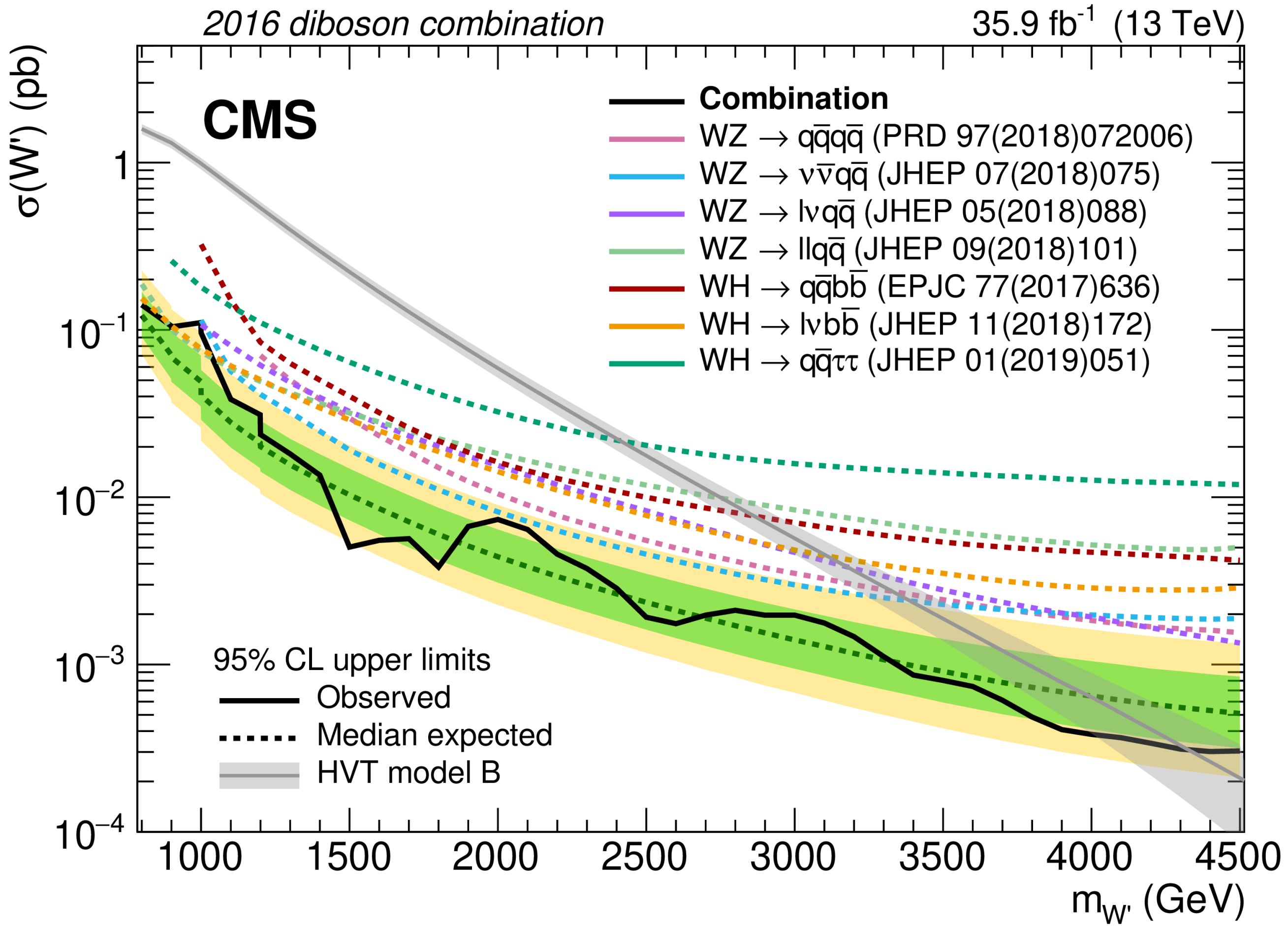


Direct Searches

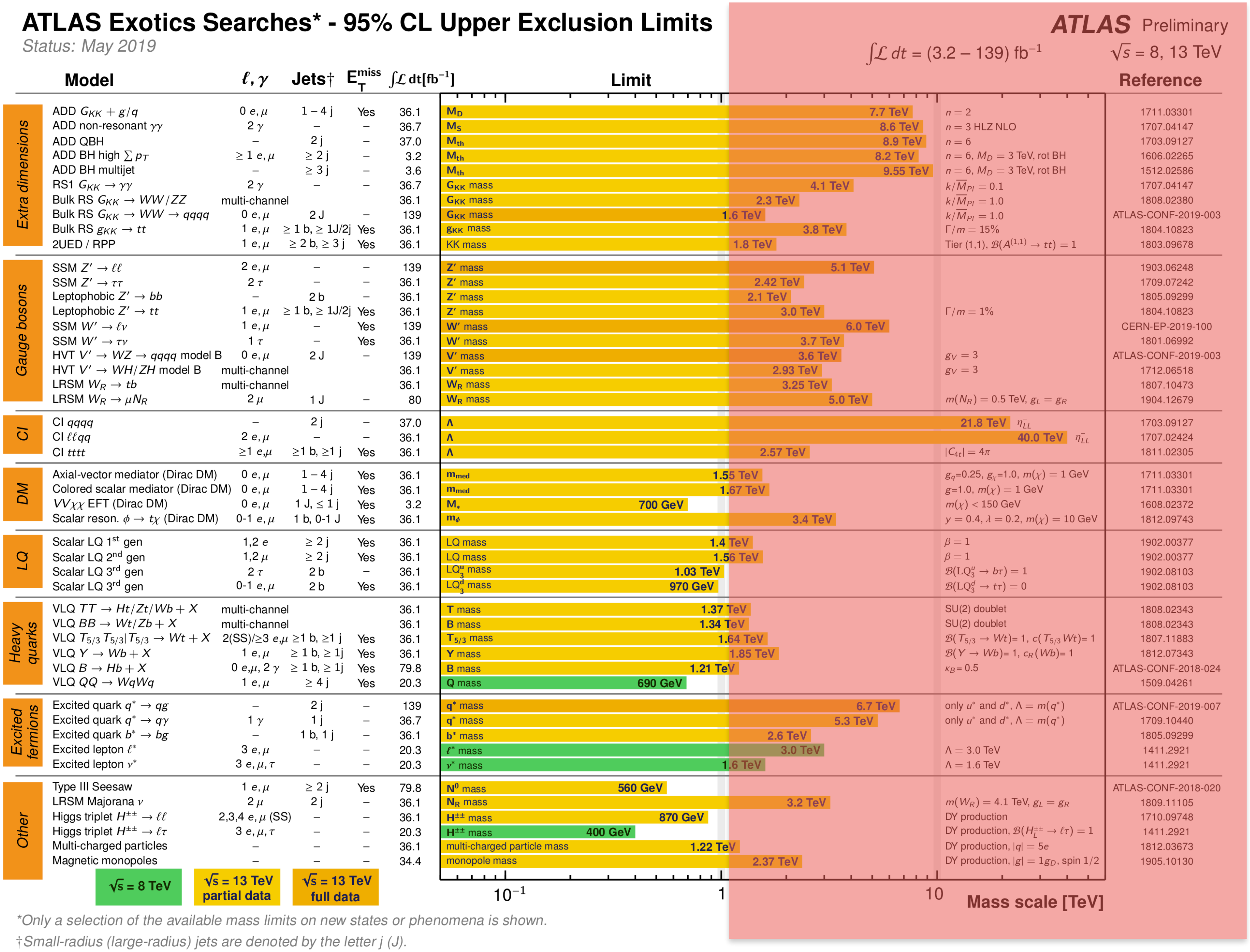


- CMS and ATLAS have been searching for direct resonances in several final states:
  - Diboson, VV, VH, HH
  - Dilepton
  - .....





Run2 and beyond: Resonance limits to local operators



ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

Status: May 2019

ATLAS Preliminary

$\int \mathcal{L}\, dt = (3.2 - 139)\ \mathrm{fb}^{-1}$

$\sqrt{s} = 8, 13$ TeV

	Model	ℓ, γ	Jets†	E_T^{miss}	$\int \mathcal{L}\, dt[\mathrm{fb}^{-1}]$	Limit		Reference
Extra dimensions	ADD $G_{KK} + g/q$	0 e, μ	1 – 4 j	Yes	36.1	M_D 7.7 TeV	$n = 2$	1711.03301
	ADD non-resonant $\gamma\gamma$	2 γ	–	–	36.7	M_S 8.6 TeV	$n = 3$ HLZ NLO	1707.04147
	ADD QBH	–	2 j	–	37.0	M_{th} 8.9 TeV	$n = 6$	1703.09127
	ADD BH high $\sum p_T$	≥ 1 e, μ	≥ 2 j	–	3.2	M_{th} 8.2 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1606.02265
	ADD BH multijet	–	≥ 3 j	–	3.6	M_{th} 9.55 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1512.02586
	RS1 $G_{KK} \to \gamma\gamma$	2 γ	–	–	36.7	G_{KK} mass 4.1 TeV	$k/\overline{M}_{Pl} = 0.1$	1707.04147
	Bulk RS $G_{KK} \to WW/ZZ$	multi-channel			36.1	G_{KK} mass 2.3 TeV	$k/\overline{M}_{Pl} = 1.0$	1808.02380
	Bulk RS $G_{KK} \to WW \to qqqq$	0 e, μ	2 J	–	139	G_{KK} mass 1.6 TeV	$k/\overline{M}_{Pl} = 1.0$	ATLAS-CONF-2019-003
	Bulk RS $g_{KK} \to tt$	1 e, μ	≥ 1 b, ≥ 1J/2j	Yes	36.1	g_{KK} mass 3.8 TeV	$\Gamma/m = 15\%$	1804.10823
	2UED / RPP	1 e, μ	≥ 2 b, ≥ 3 j	Yes	36.1	KK mass 1.8 TeV	Tier (1,1), $\mathcal{B}(A^{(1,1)} \to tt) = 1$	1803.09678
Gauge bosons	SSM $Z' \to \ell\ell$	2 e, μ	–	–	139	Z' mass 5.1 TeV		1903.06248
	SSM $Z' \to \tau\tau$	2 τ	–	–	36.1	Z' mass 2.42 TeV		1709.07242
	Leptophobic $Z' \to bb$	–	2 b	–	36.1	Z' mass 2.1 TeV		1805.09299
	Leptophobic $Z' \to tt$	1 e, μ	≥ 1 b, ≥ 1J/2j	Yes	36.1	Z' mass 3.0 TeV	$\Gamma/m = 1\%$	1804.10823
	SSM $W' \to \ell\nu$	1 e, μ	–	Yes	139	W' mass 6.0 TeV		CERN-EP-2019-100
	SSM $W' \to \tau\nu$	1 τ	–	Yes	36.1	W' mass 3.7 TeV		1801.06992
	HVT $V' \to WZ \to qqqq$ model B	0 e, μ	2 J	–	139	V' mass 3.6 TeV	$g_V = 3$	ATLAS-CONF-2019-003
	HVT $V' \to WH/ZH$ model B	multi-channel			36.1	V' mass 2.93 TeV	$g_V = 3$	1712.06518
	LRSM $W_R \to tb$	multi-channel			36.1	W_R mass 3.25 TeV		1807.10473
	LRSM $W_R \to \mu N_R$	2 μ	1 J	–	80	W_R mass 5.0 TeV	$m(N_R) = 0.5$ TeV, $g_L = g_R$	1904.12679
CI	CI $qqqq$	–	2 j	–	37.0	Λ 21.8 TeV	η_{LL}^{-}	1703.09127
	CI $\ell\ell qq$	2 e, μ	–	–	36.1	Λ 40.0 TeV	η_{LL}^{-}	1707.02424
	CI $tttt$	≥1 e,μ	≥1 b, ≥1 j	Yes	36.1	Λ 2.57 TeV	$\lvert C_{4t}\rvert = 4\pi$	1811.02305
DM	Axial-vector mediator (Dirac DM)	0 e, μ	1 – 4 j	Yes	36.1	m_{med} 1.55 TeV	g_q=0.25, g_χ=1.0, $m(\chi) = 1$ GeV	1711.03301
	Colored scalar mediator (Dirac DM)	0 e, μ	1 – 4 j	Yes	36.1	m_{med} 1.67 TeV	g=1.0, $m(\chi) = 1$ GeV	1711.03301
	$VV\chi\chi$ EFT (Dirac DM)	0 e, μ	1 J, ≤ 1 j	Yes	3.2	M_* 700 GeV	$m(\chi) < 150$ GeV	1608.02372
	Scalar reson. $\phi \to t\chi$ (Dirac DM)	0-1 e, μ	1 b, 0-1 J	Yes	36.1	m_ϕ 3.4 TeV	$y = 0.4$, $\lambda = 0.2$, $m(\chi) = 10$ GeV	1812.09743
LQ	Scalar LQ 1st gen	1,2 e	≥ 2 j	Yes	36.1	LQ mass 1.4 TeV	$\beta = 1$	1902.00377
	Scalar LQ 2nd gen	1,2 μ	≥ 2 j	Yes	36.1	LQ mass 1.56 TeV	$\beta = 1$	1902.00377
	Scalar LQ 3rd gen	2 τ	2 b	–	36.1	LQ_3^u mass 1.03 TeV	$\mathcal{B}(\mathrm{LQ}_3^u \to b\tau) = 1$	1902.08103
	Scalar LQ 3rd gen	0-1 e, μ	2 b	Yes	36.1	LQ_3^d mass 970 GeV	$\mathcal{B}(\mathrm{LQ}_3^d \to t\tau) = 0$	1902.08103
Heavy quarks	VLQ $TT \to Ht/Zt/Wb + X$	multi-channel			36.1	T mass 1.37 TeV	SU(2) doublet	1808.02343
	VLQ $BB \to Wt/Zb + X$	multi-channel			36.1	B mass 1.34 TeV	SU(2) doublet	1808.02343
	VLQ $T_{5/3} T_{5/3} \lvert T_{5/3} \to Wt + X$	2(SS)/≥3 e,μ	≥1 b, ≥1 j	Yes	36.1	$T_{5/3}$ mass 1.64 TeV	$\mathcal{B}(T_{5/3} \to Wt)$= 1, $c(T_{5/3}Wt)$= 1	1807.11883
	VLQ $Y \to Wb + X$	1 e, μ	≥ 1 b, ≥ 1j	Yes	36.1	Y mass 1.85 TeV	$\mathcal{B}(Y \to Wb)$= 1, $c_R(Wb)$= 1	1812.07343
	VLQ $B \to Hb + X$	0 e,μ, 2 γ	≥ 1 b, ≥ 1j	Yes	79.8	B mass 1.21 TeV	κ_B= 0.5	ATLAS-CONF-2018-024
	VLQ $QQ \to WqWq$	1 e, μ	≥ 4 j	Yes	20.3	Q mass 690 GeV		1509.04261
Excited fermions	Excited quark $q^* \to qg$	–	2 j	–	139	q^* mass 6.7 TeV	only u^* and d^*, $\Lambda = m(q^*)$	ATLAS-CONF-2019-007
	Excited quark $q^* \to q\gamma$	1 γ	1 j	–	36.7	q^* mass 5.3 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1709.10440
	Excited quark $b^* \to bg$	–	1 b, 1 j	–	36.1	b^* mass 2.6 TeV		1805.09299
	Excited lepton ℓ^*	3 e, μ	–	–	20.3	ℓ^* mass 3.0 TeV	$\Lambda = 3.0$ TeV	1411.2921
	Excited lepton ν^*	3 e, μ, τ	–	–	20.3	ν^* mass 1.6 TeV	$\Lambda = 1.6$ TeV	1411.2921
Other	Type III Seesaw	1 e, μ	≥ 2 j	Yes	79.8	N^0 mass 560 GeV		ATLAS-CONF-2018-020
	LRSM Majorana ν	2 μ	2 j	–	36.1	N_R mass 3.2 TeV	$m(W_R) = 4.1$ TeV, $g_L = g_R$	1809.11105
	Higgs triplet $H^{\pm\pm} \to \ell\ell$	2,3,4 e, μ (SS)	–	–	36.1	$H^{\pm\pm}$ mass 870 GeV	DY production	1710.09748
	Higgs triplet $H^{\pm\pm} \to \ell\tau$	3 e, μ, τ	–	–	20.3	$H^{\pm\pm}$ mass 400 GeV	DY production, $\mathcal{B}(H_L^{\pm\pm} \to \ell\tau) = 1$	1411.2921
	Multi-charged particles	–	–	–	36.1	multi-charged particle mass 1.22 TeV	DY production, $\lvert q\rvert = 5e$	1812.03673
	Magnetic monopoles	–	–	–	34.4	monopole mass 2.37 TeV	DY production, $\lvert g\rvert = 1g_D$, spin 1/2	1905.10130

🟩 $\sqrt{s}$ = 8 TeV

🟨 $\sqrt{s}$ = 13 TeV partial data

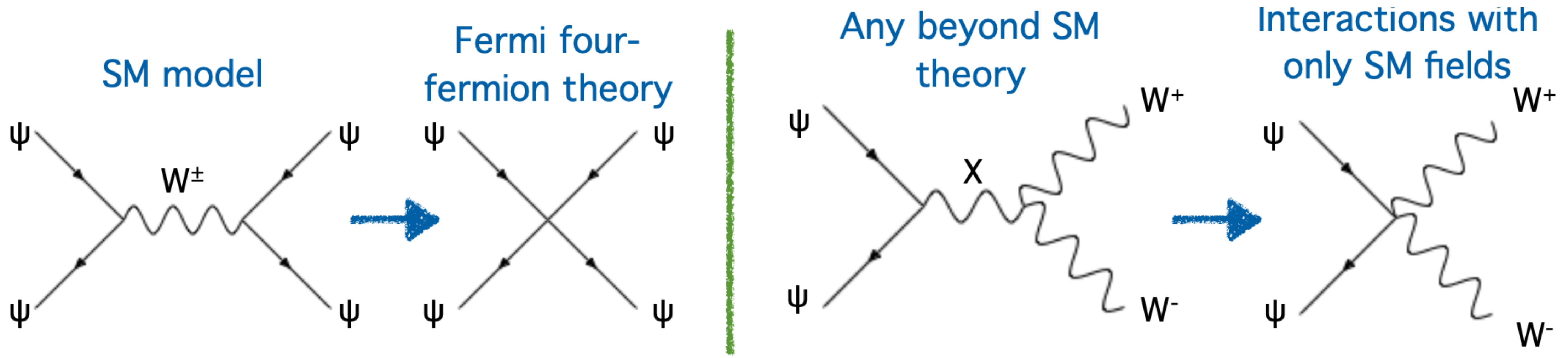
🟧 $\sqrt{s}$ = 13 TeV full data

*Only a selection of the available mass limits on new states or phenomena is shown.

†Small-radius (large-radius) jets are denoted by the letter j (J).

- Now that these bounds have been pushed away from v
- USE v/M < 1:
- bound many models at once
- bound multiple resonances at same time

The EFT approach to New Physics



- In absence of new particles, the SM can be considered as an effective low-energy theory.
- Any Beyond Standard Model physics can be thought of as modifications of the interactions containing only SM fields
- Assuming that the SM describes physics well in the energy range up to the scale Λ and new physics occurs only above that scale, the physics phenomena can be described by an effective Lagrangian

Classify the effect of any beyond SM model using operators with D > 4

$$\mathcal{L} = \mathcal{L}_4^{\mathrm{SM}} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \dots$$

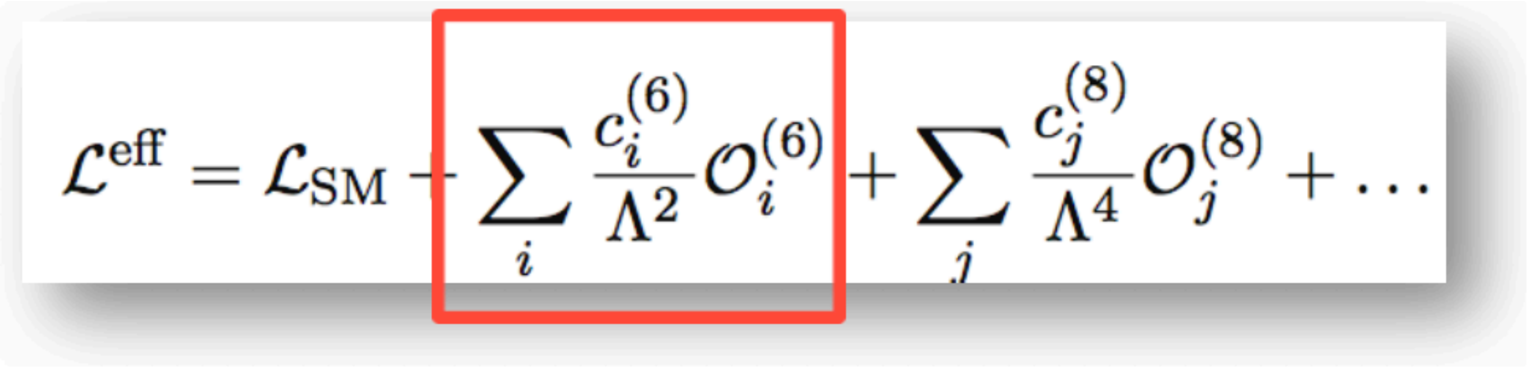
$$\frac{1}{\Lambda^2}\mathcal{L}_6 \to \left(\frac{E}{\Lambda}\right)^2 \qquad \frac{1}{\Lambda^4}\mathcal{L}_8 \to \left(\frac{E}{\Lambda}\right)^4$$

For large scales E/Λ « 1, only operators with lower mass dimension will matter.

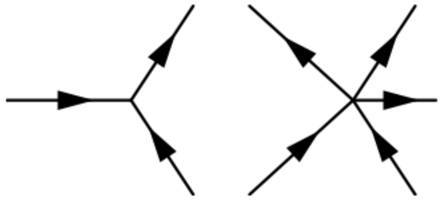
$$\mathcal{L}^{\mathrm{eff}} = \mathcal{L}_{\mathrm{SM}} + \boxed{\sum_i \frac{c_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)}} + \sum_j \frac{c_j^{(8)}}{\Lambda^4}\mathcal{O}_j^{(8)} + \dots$$

$$c_i^{(D)} \simeq \frac{(\text{coupling})^{n_i-2}}{(\text{high mass scale})^{D-4}}$$

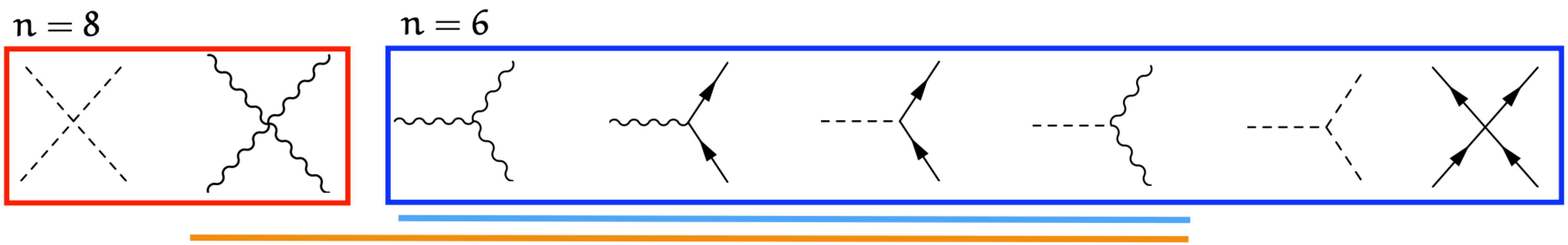
EFT on VV, VVjj



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

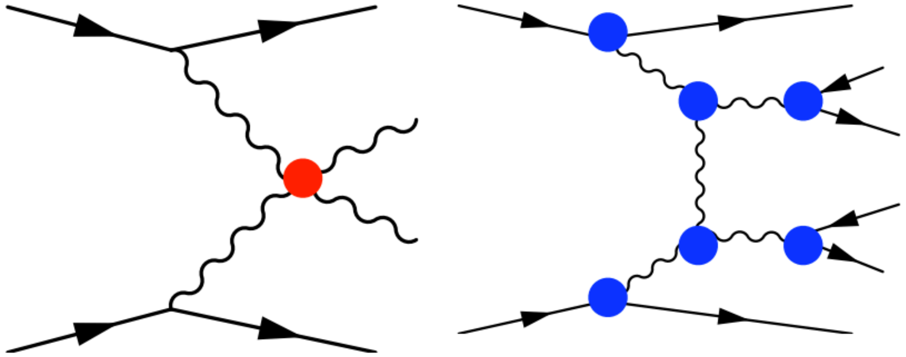


n=5,7 : violate
lepton number



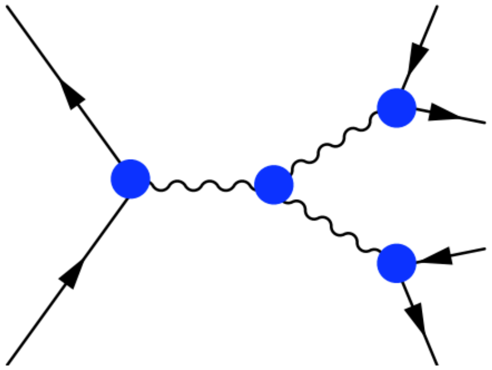
VVjj

- **Semi-lep**
- Full-lep
- (Full-had)

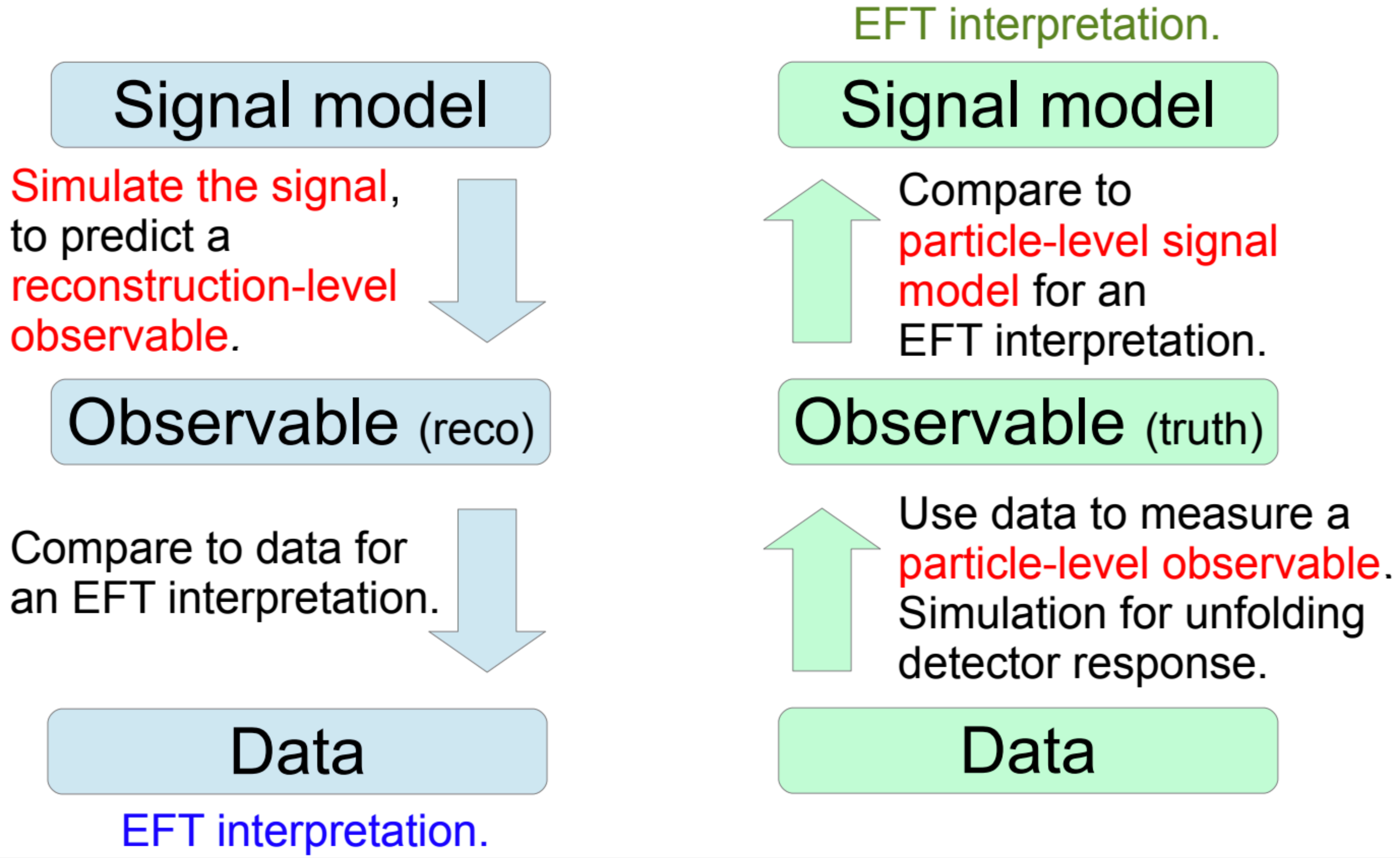


VV

- **Semi-lep**
- Full-lep
- Full-had



Two approaches for an EFT interpretation



Top-Down

(most common for individual channels)

Signal model

Simulate the signal, to predict a reconstruction-level observable.

Observable (reco)

Compare to data for an EFT interpretation.

Data

EFT interpretation.

Bottom-Up

(more convenient for combination)

EFT interpretation.

Signal model

Compare to particle-level signal model for an EFT interpretation.

Observable (truth)

Use data to measure a particle-level observable. Simulation for unfolding detector response.

Data

EFT models

- dim-6
  - SMEFT model
  - Adopted global EFT fit.
    - Simultaneous fit of top/SM/BSM analyses -
    - 50 operators.
    - (Development of dim-8 is on-going.)

- dim-8
  - Eboli model dim-8
  - Used by both CMS and ATLAS for aQGC interpretation for now.
  - 18 independent operators

Operators

Gauge Fields

$1 : X^3$

Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
$Q_{\widetilde{G}}$	$f^{ABC} \widetilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
$\boxed{Q_W}$	$\epsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$
$Q_{\widetilde{W}}$	$\epsilon^{IJK} \widetilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$

$2 : H^6$

Q_H	$(H^\dagger H)^3$

$3 : H^4 D^2$

$Q_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$
Q_{HD}	$\left(H^\dagger D^\mu H\right)^* \left(H^\dagger D_\mu H\right)$

Higgs Fields

$5 : \psi^2 H^3 + \text{h.c.}$

Q_{eH}	$(H^\dagger H)(\bar{l}_p e_r H)$
Q_{uH}	$(H^\dagger H)(\bar{q}_p u_r \widetilde{H})$
Q_{dH}	$(H^\dagger H)(\bar{q}_p d_r H)$

Gauge & Higgs Fields

$4 : X^2 H^2$

Q_{HG}	$H^\dagger H\, G_{\mu\nu}^A G^{A\mu\nu}$
$Q_{H\widetilde{G}}$	$H^\dagger H\, \widetilde{G}_{\mu\nu}^A G^{A\mu\nu}$
$\boxed{Q_{HW}}$	$H^\dagger H\, W_{\mu\nu}^I W^{I\mu\nu}$
$Q_{H\widetilde{W}}$	$H^\dagger H\, \widetilde{W}_{\mu\nu}^I W^{I\mu\nu}$
Q_{HB}	$H^\dagger H\, B_{\mu\nu} B^{\mu\nu}$
$Q_{H\widetilde{B}}$	$H^\dagger H\, \widetilde{B}_{\mu\nu} B^{\mu\nu}$
Q_{HWB}	$H^\dagger \tau^I H\, W_{\mu\nu}^I B^{\mu\nu}$
$Q_{H\widetilde{W}B}$	$H^\dagger \tau^I H\, \widetilde{W}_{\mu\nu}^I B^{\mu\nu}$

fermion

$6 : \psi^2 X H + \text{h.c.}$

Q_{eW}	$(\bar{l}_p \sigma^{\mu\nu} e_r)\tau^I H W_{\mu\nu}^I$
Q_{eB}	$(\bar{l}_p \sigma^{\mu\nu} e_r) H B_{\mu\nu}$
Q_{uG}	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r)\widetilde{H}\, G_{\mu\nu}^A$
Q_{uW}	$(\bar{q}_p \sigma^{\mu\nu} u_r)\tau^I \widetilde{H}\, W_{\mu\nu}^I$
Q_{uB}	$(\bar{q}_p \sigma^{\mu\nu} u_r)\widetilde{H}\, B_{\mu\nu}$
Q_{dG}	$(\bar{q}_p \sigma^{\mu\nu} T^A d_r) H\, G_{\mu\nu}^A$
Q_{dW}	$(\bar{q}_p \sigma^{\mu\nu} d_r)\tau^I H\, W_{\mu\nu}^I$
Q_{dB}	$(\bar{q}_p \sigma^{\mu\nu} d_r) H\, B_{\mu\nu}$

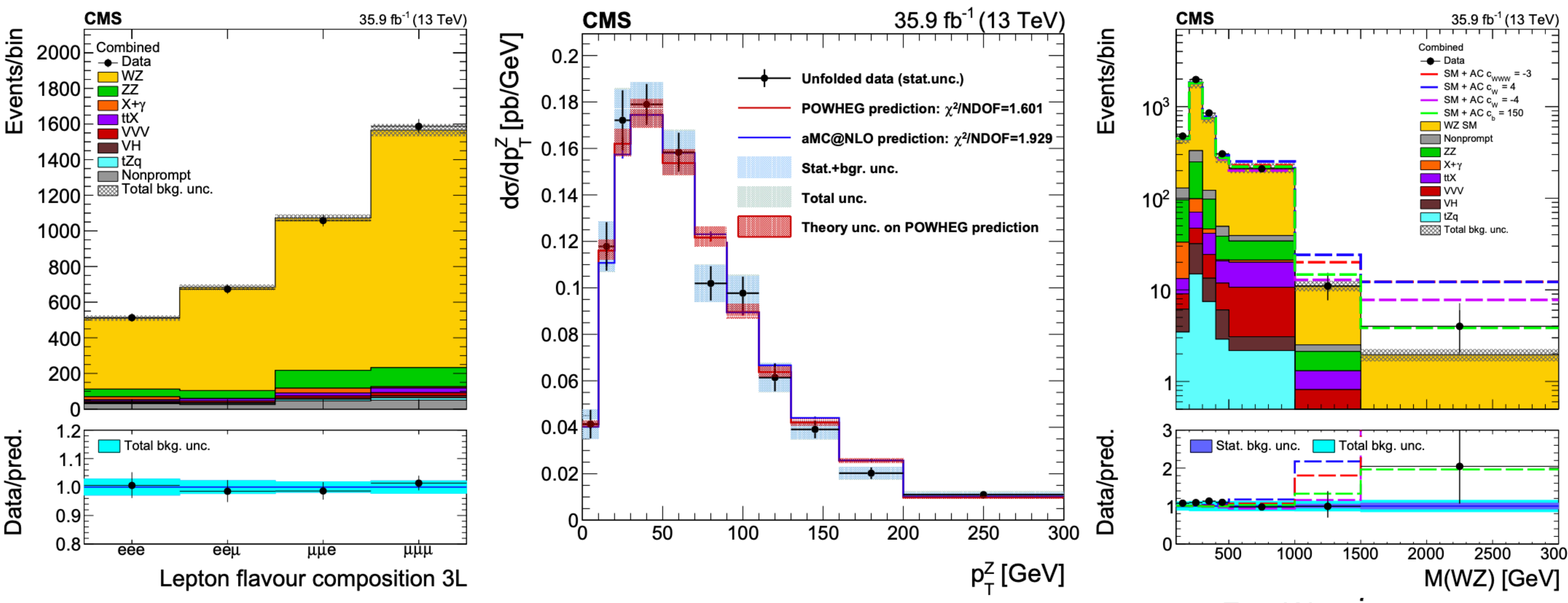
$7 : \psi^2 H^2 D$

$Q_{Hl}^{(1)}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{l}_p \gamma^\mu l_r)$
$Q_{Hl}^{(3)}$	$(H^\dagger i \overleftrightarrow{D}{}^I_\mu H)(\bar{l}_p \tau^I \gamma^\mu l_r)$
Q_{He}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{e}_p \gamma^\mu e_r)$
$\boxed{Q_{Hq}^{(1)}}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{q}_p \gamma^\mu q_r)$
$Q_{Hq}^{(3)}$	$(H^\dagger i \overleftrightarrow{D}{}^I_\mu H)(\bar{q}_p \tau^I \gamma^\mu q_r)$
Q_{Hu}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{u}_p \gamma^\mu u_r)$
Q_{Hd}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{d}_p \gamma^\mu d_r)$
Q_{Hud} + h.c.	$i(\widetilde{H}^\dagger D_\mu H)(\bar{u}_p \gamma^\mu d_r)$

WZ @ 13 TeV (CMS)

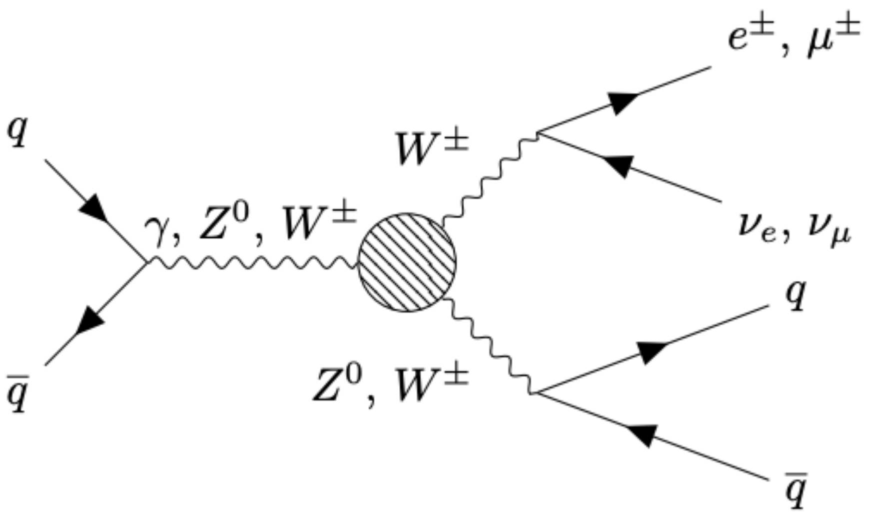
CMS SMP-18-002

- 3 leptons plus missing ET
- Dominant background: misidentified leptons
- Dominant uncertainties:
    - Misidentified lepton

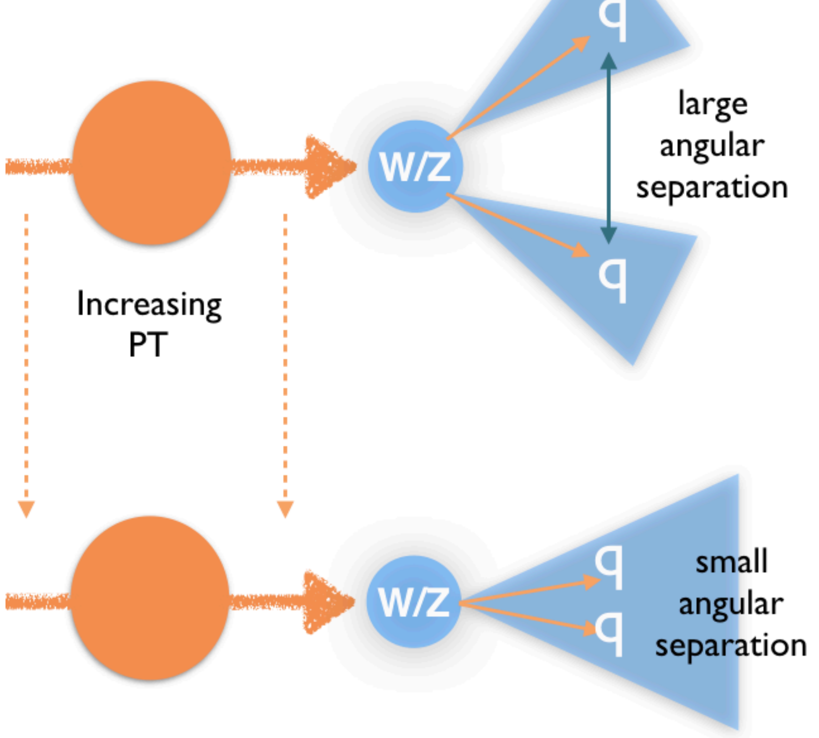


WW and WZ at 13 TeV (CMS)

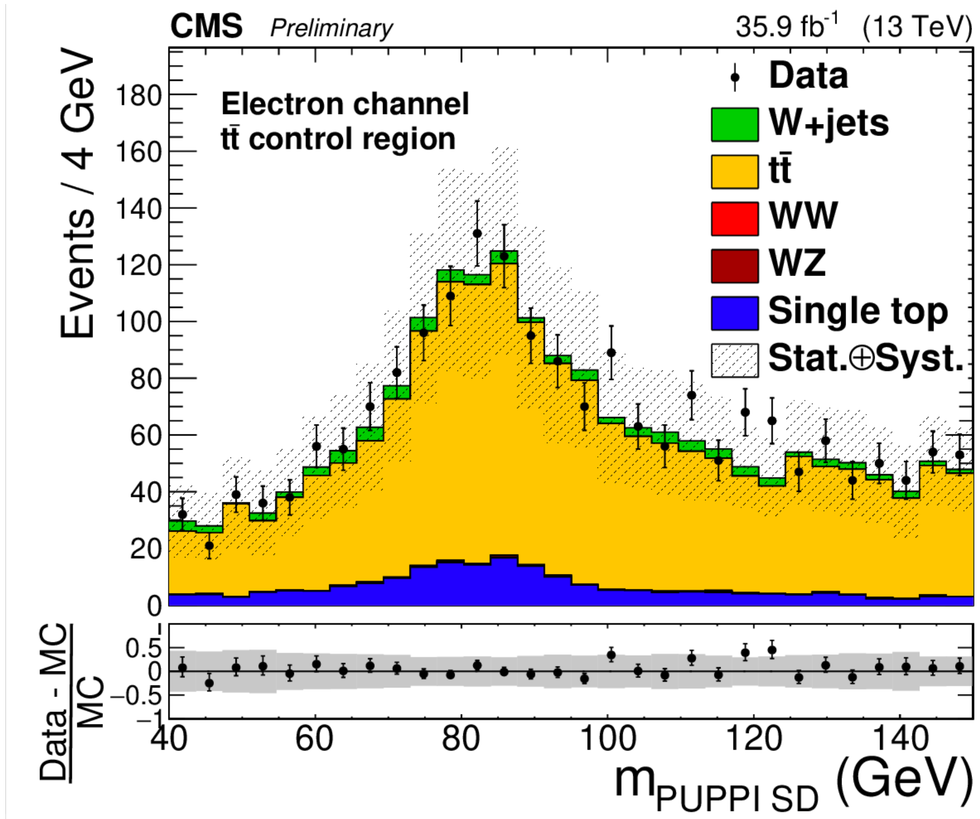
- Identify leptonically decaying W boson while other W or Z boson decays to jets
- Select dijet events and boosted events such that the decay jets merge into a single jet



CMS-PAS-SMP-18-008



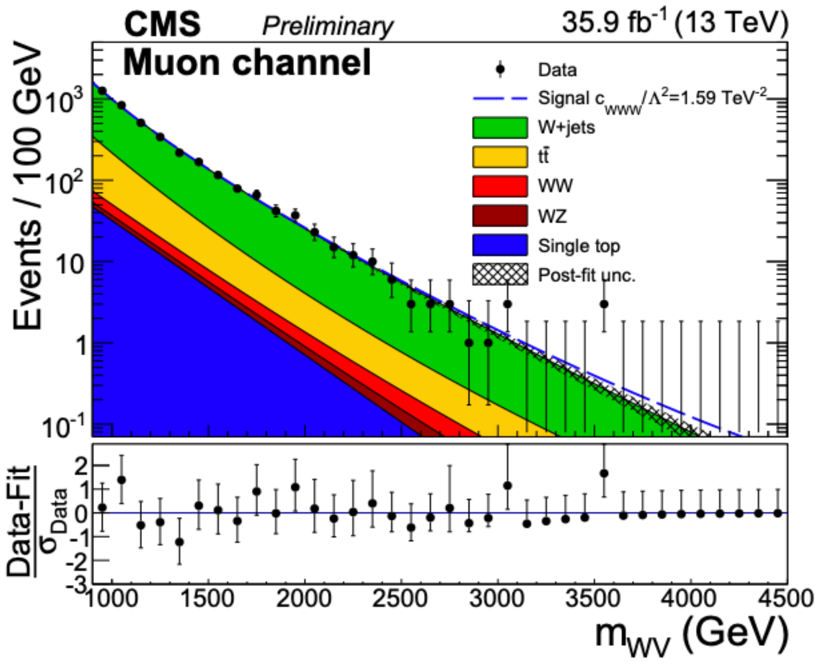
- AntiKt jet with 0.8 cone with pT > 200 GeV
- hadronic V candidate, mWV > 900 GeV
- Reject b jets ==> which reduces t tbar contribution
- apply PUPPI+SD on AK8, τ21 < 0.55, W+jets from sidebands

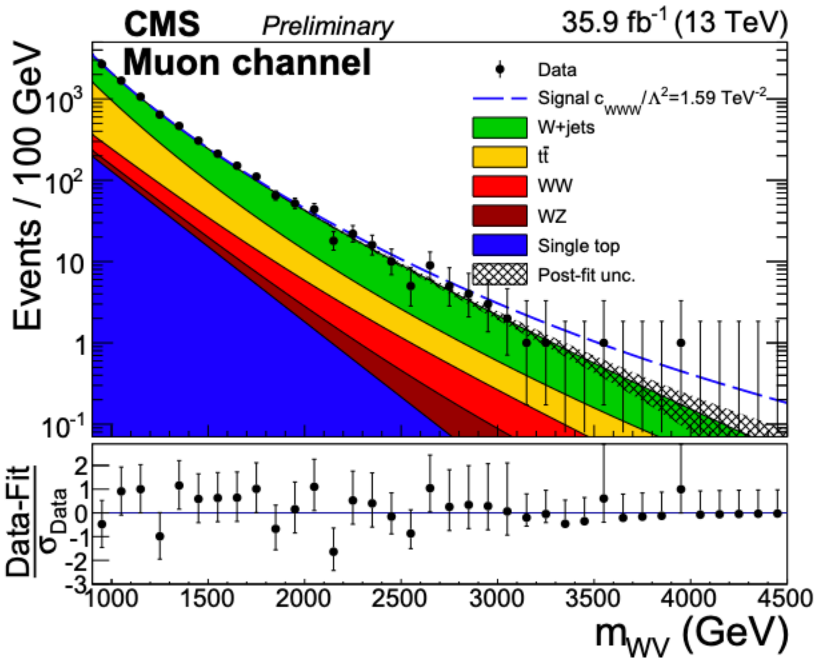


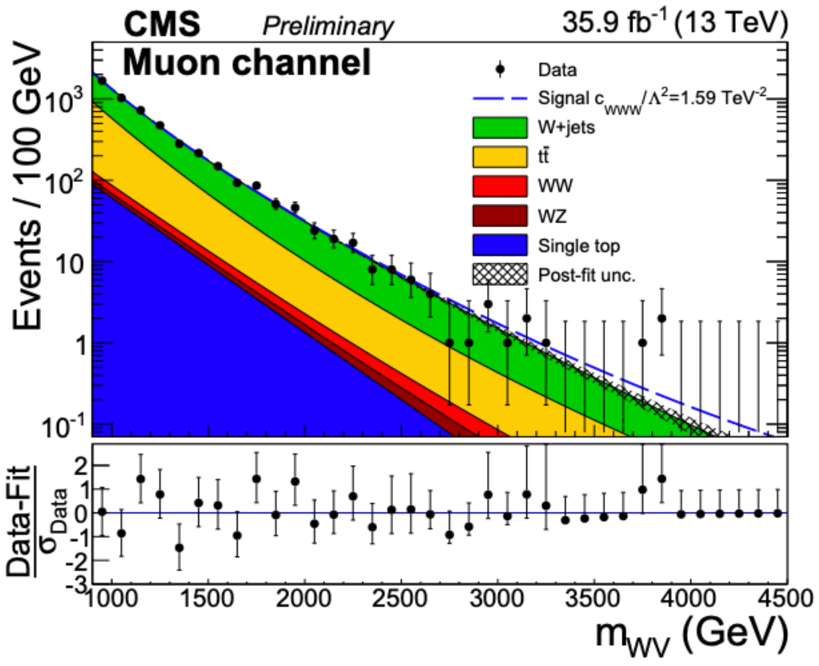
Maximizes sensitivity to aTGC ==> more events at high mass!

WW and WZ at 13 TeV (CMS)

- mWV used to extract limits on EFT







Parametrization	aTGC	Expected limit	Observed limit	Run I limit
EFT	c_{WWW}/Λ^2 (TeV^{-2})	[-1.44, 1.47]	[-1.58, 1.59]	[-2.7, 2.7]
	c_W/Λ^2 (TeV^{-2})	[-2.45, 2.08]	[-2.00, 2.65]	[-2.0, 5.7]
	c_B/Λ^2 (TeV^{-2})	[-8.38, 8.06]	[-8.78, 8.54]	[-14, 17]

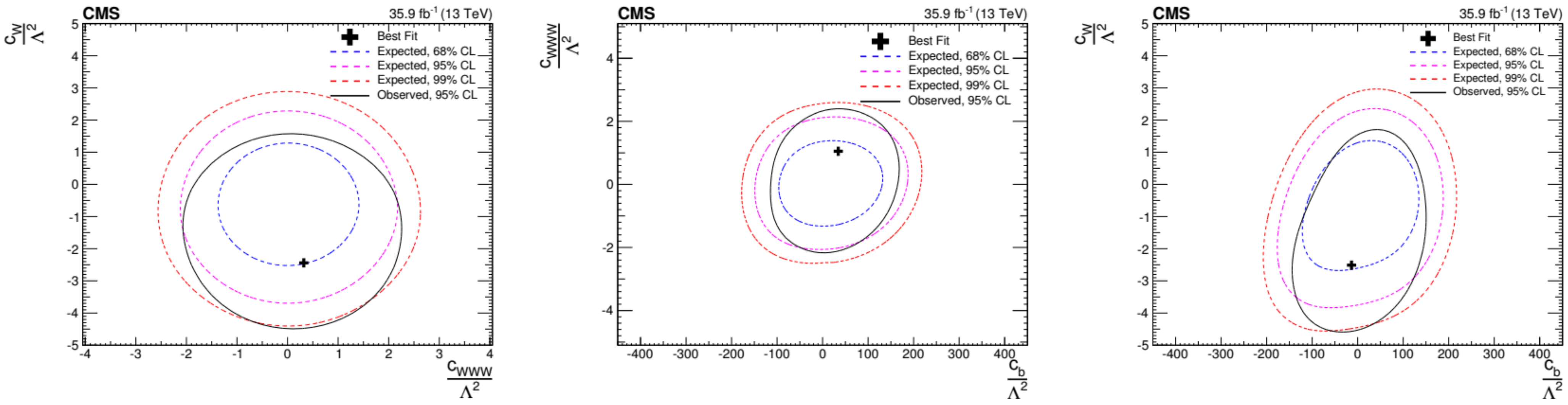
Comparison of limits

Limits on anomalous couplings

$$\delta\mathcal{L}_{\mathrm{AC}} = \frac{c_{WWW}}{\Lambda^2}\mathrm{Tr}[W_{\mu\nu}W^{\nu\rho}W_{\rho}^{\mu}] + \frac{c_W}{\Lambda^2}(D_\mu H)^\dagger W^{\mu\nu}(D_\nu H) + \frac{c_B}{\Lambda^2}(D_\mu H)^\dagger B^{\mu\nu}(D_\nu H)$$

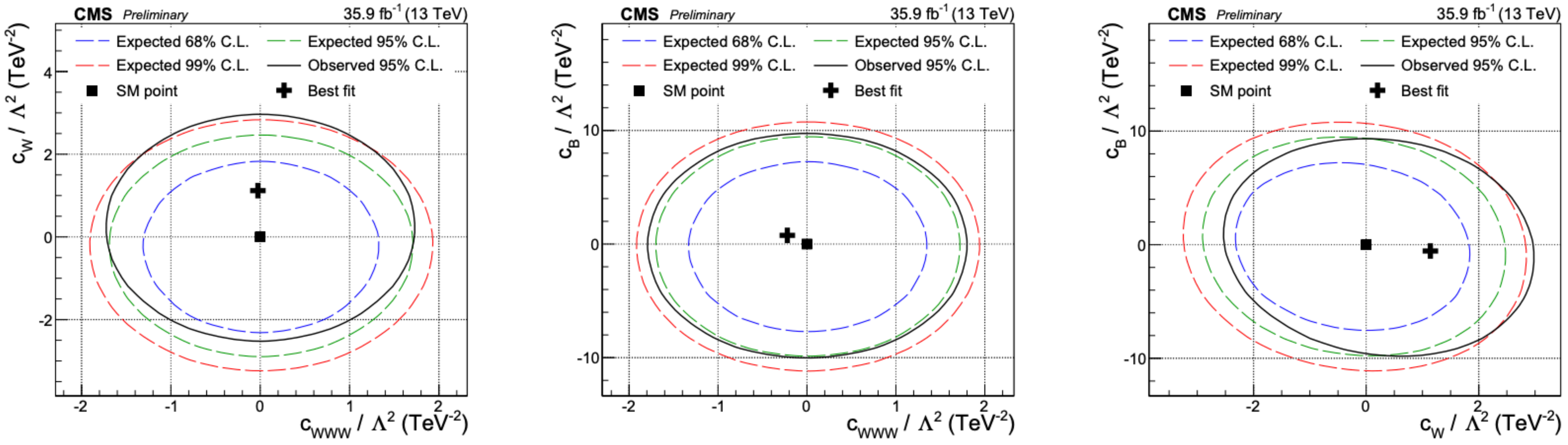
3-lepton analysis **CMS** **SMP-18-002**

- From M(WZ) up to 3 TeV
- No excess observed



Boosted analysis **CMS** **PAS-SMP-18-008**

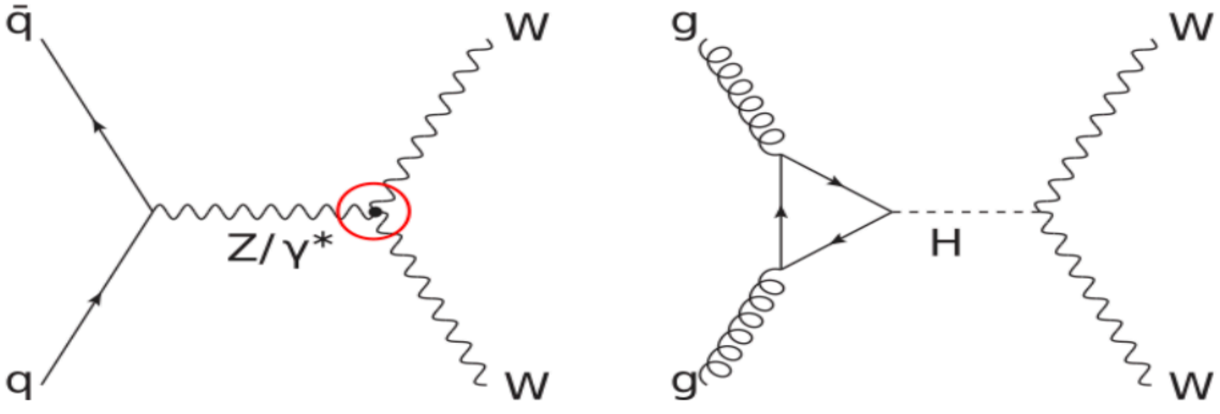
- From M(WV) up to 4.5 TeV
- Gained factor >10 in $\mathcal{C}_{\mathrm{B}}$ limit from WW component

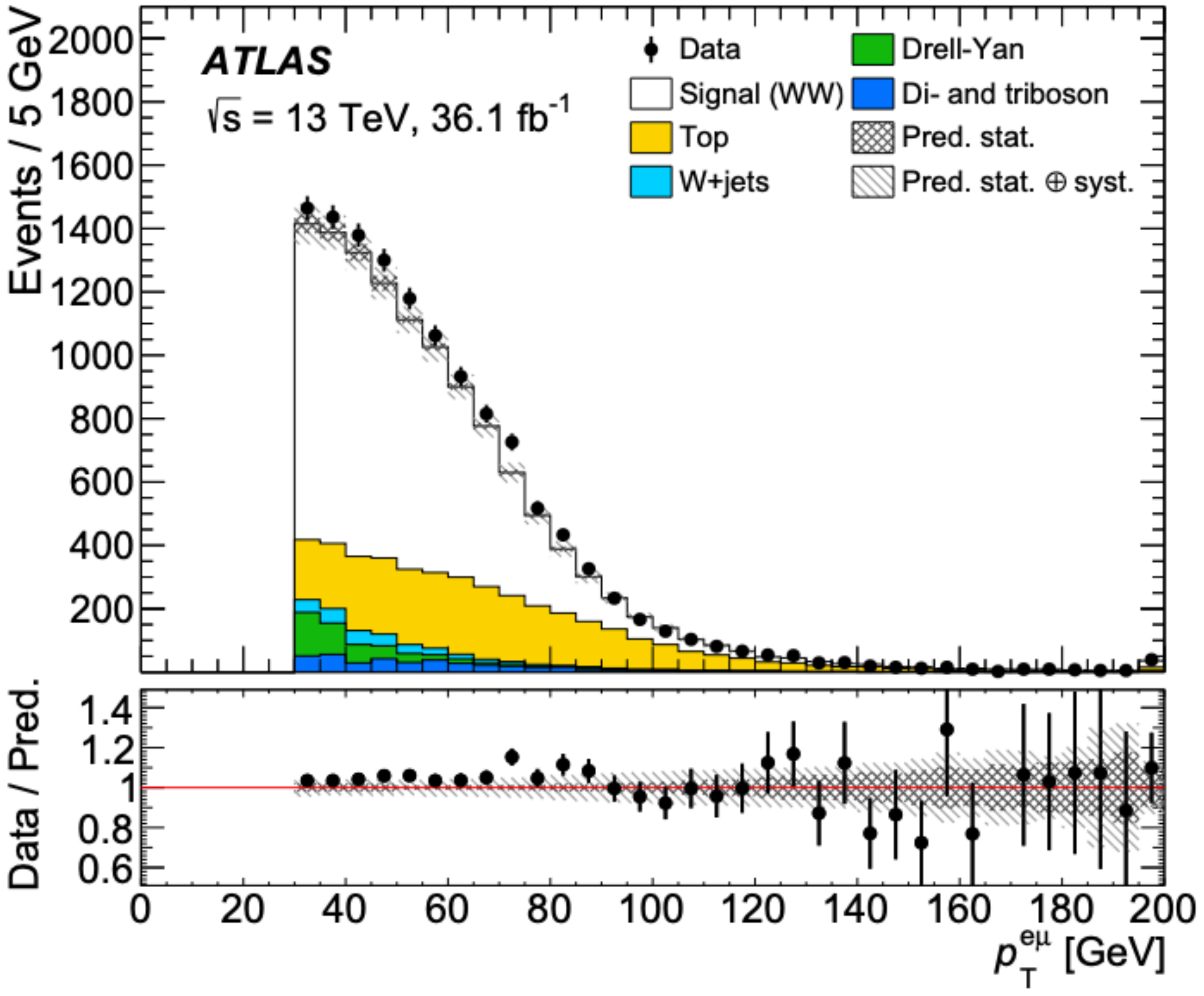


WW @13 TeV (ATLAS)

https://arxiv.org/abs/1905.04242

- WW (s-channel and H-induced)
- WW signal region (SR):
  - 1 $e\mu$ pair of isolated central leptons
  - No additional leptons ==> suppress VV
  - No jet with pT > 35 GeV & no central b-jets ==> reduce top
  - missing p_T > 20 GeV & $p^{e\mu}_T$ > 30 GeV ==>reduce DY
  - $m_{e\mu}$ > 55 GeV (orthogonal to HWW analysis)
- Backgrounds (% of SR):
  - $t\bar{t}$ and W t (~ 26%): from top-enriched Data CR
  - Non-prompt leptons, mostly W+jets (~ 3%): estimate relies on fake rate from Data
  - DY (~ 4%), Multi-bosons (~ 3%): using simulated samples



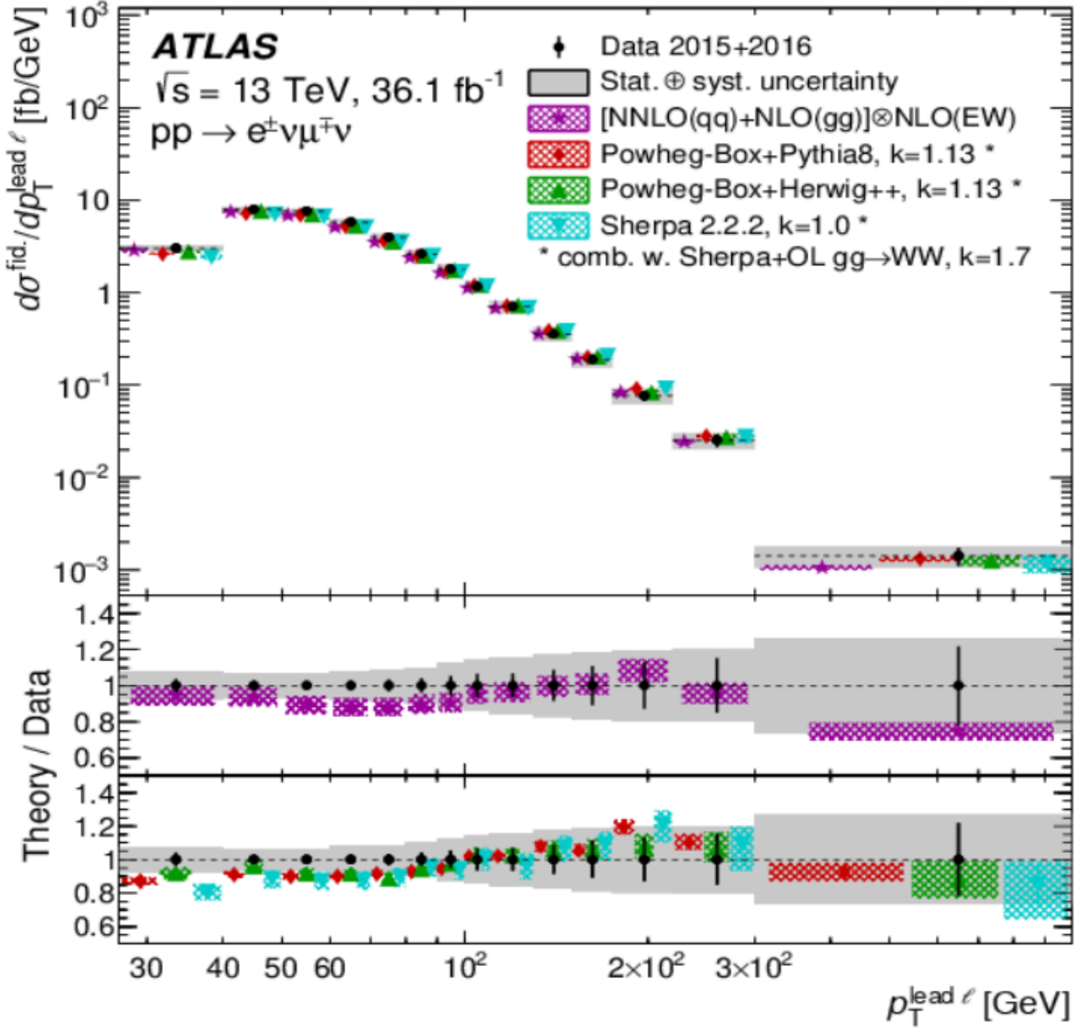


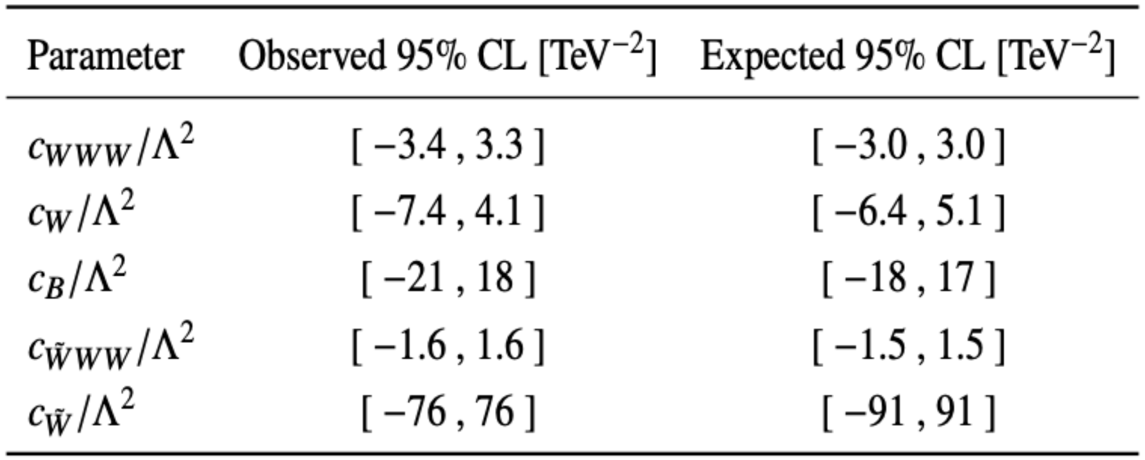
Fiducial cross section and unfolded cross section measurement

WW @13 TeV (ATLAS)

https://arxiv.org/abs/1905.04242

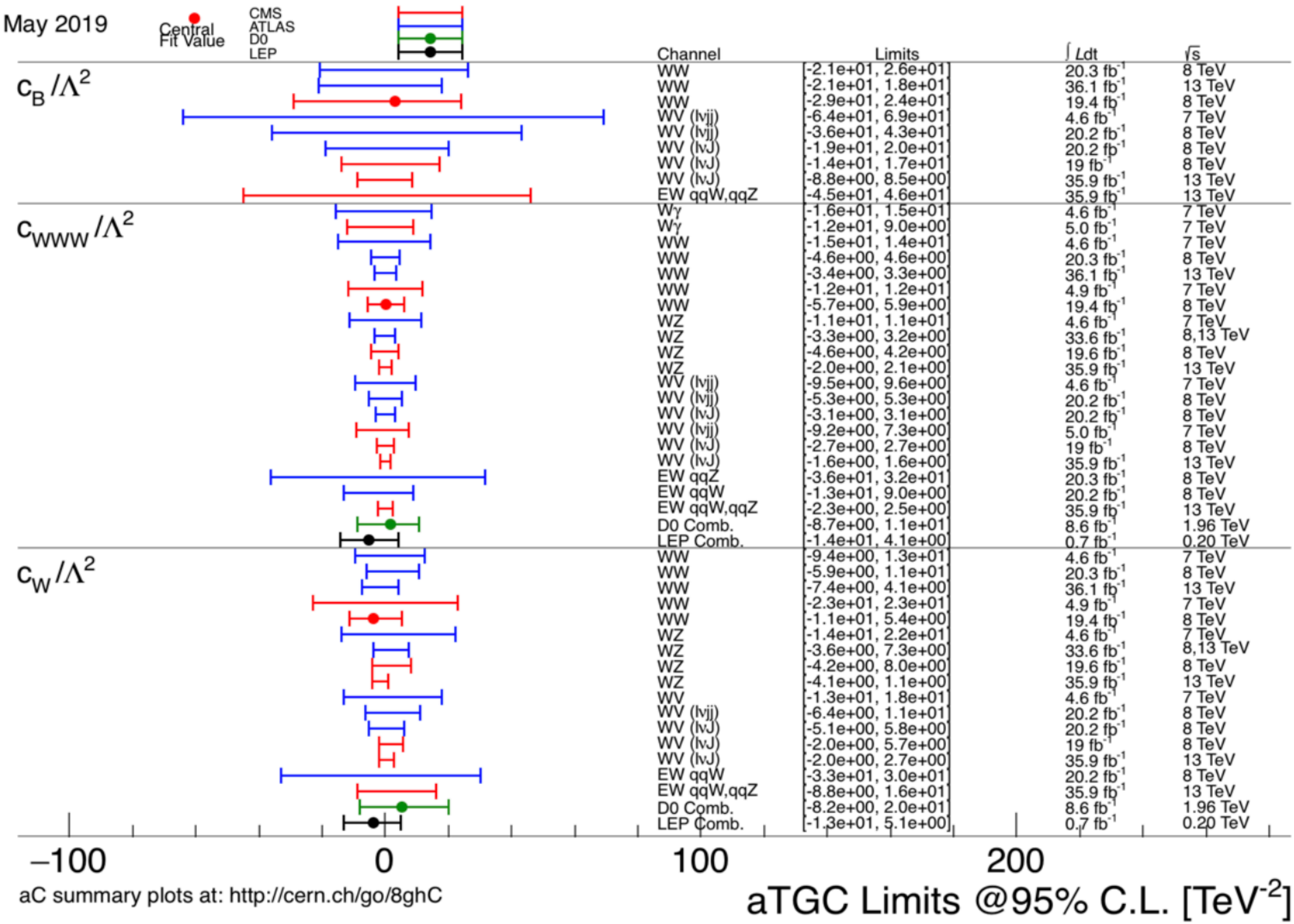
- Considering Effective Field Theory with five dimension-6 operators associated to the couplings: cWWW , cW , cB, cWWW , cW
- Unfolded p_T leading lepton distribution which is sensitive to anomalous couplings (especially last bin), and was used to constrain aTGC
- Signal including aTGC generated with madgraph5 amc@nlo+pythia8
- Competitive 95% CL intervals for aTGC are derived via a profile likelihood ratio test statistic, thanks to high center-of-mass energy





Parameter	Observed 95% CL [TeV^{-2}]	Expected 95% CL [TeV^{-2}]
c_{WWW}/Λ^2	[−3.4 , 3.3]	[−3.0 , 3.0]
c_W/Λ^2	[−7.4 , 4.1]	[−6.4 , 5.1]
c_B/Λ^2	[−21 , 18]	[−18 , 17]
$c_{\tilde{W}WW}/\Lambda^2$	[−1.6 , 1.6]	[−1.5 , 1.5]
$c_{\tilde{W}}/\Lambda^2$	[−76 , 76]	[−91 , 91]

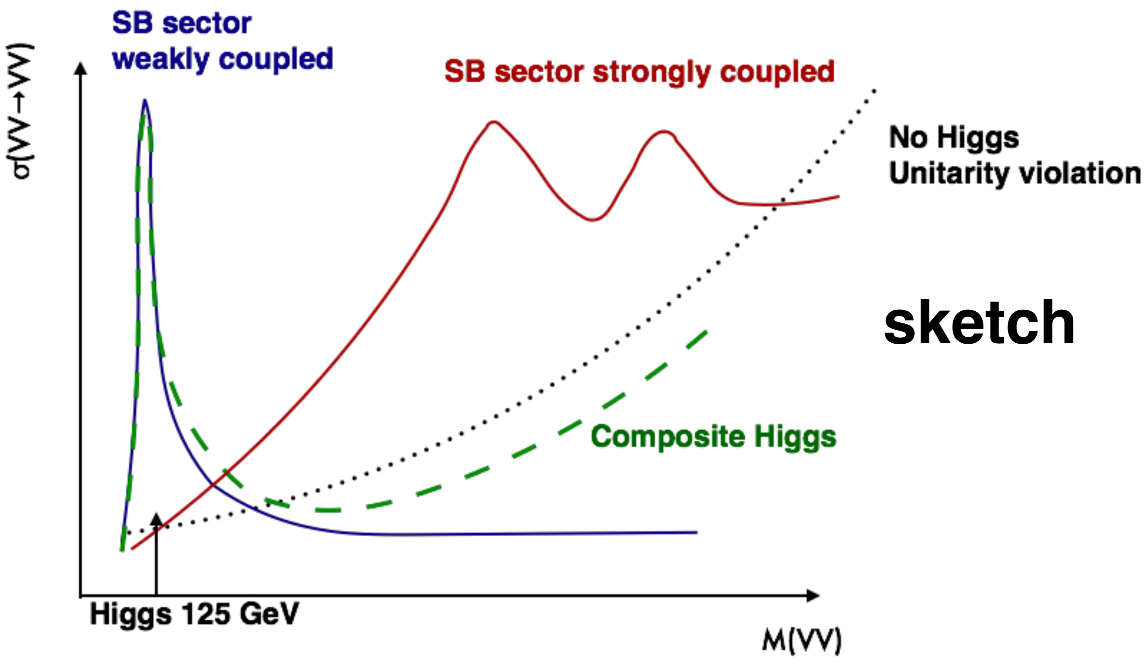
Comparison

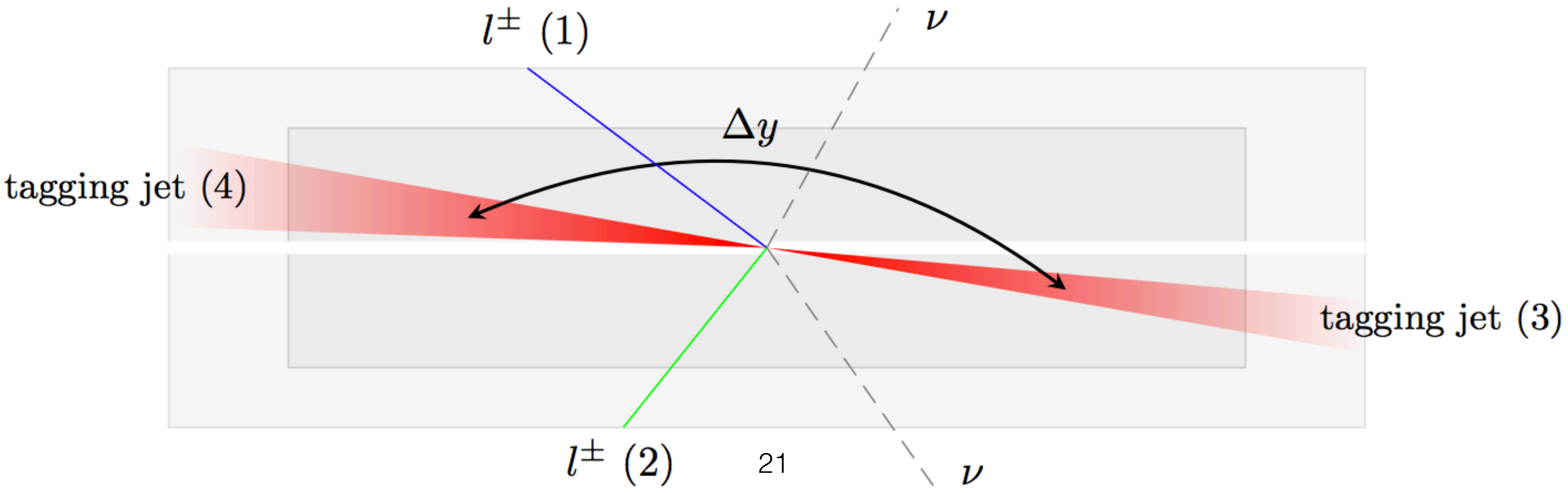


	Channel	Limits	$\int Ldt$	$\sqrt{s}$
c_B/Λ^2	WW	[-2.1e+01, 2.6e+01]	20.3 fb^{-1}	8 TeV
	WW	[-2.1e+01, 1.8e+01]	36.1 fb^{-1}	13 TeV
	WW	[-2.9e+01, 2.4e+01]	19.4 fb^{-1}	8 TeV
	WV (lνjj)	[-6.4e+01, 6.9e+01]	4.6 fb^{-1}	7 TeV
	WV (lνjj)	[-3.6e+01, 4.3e+01]	20.2 fb^{-1}	8 TeV
	WV (lνJ)	[-1.9e+01, 2.0e+01]	20.2 fb^{-1}	8 TeV
	WV (lνJ)	[-1.4e+01, 1.7e+01]	19 fb^{-1}	8 TeV
	WV (lνJ)	[-8.8e+00, 8.5e+00]	35.9 fb^{-1}	13 TeV
	EW qqW,qqZ	[-4.5e+01, 4.6e+01]	35.9 fb^{-1}	13 TeV
c_{WWW}/Λ^2	Wγ	[-1.6e+01, 1.5e+01]	4.6 fb^{-1}	7 TeV
	Wγ	[-1.2e+01, 9.0e+00]	5.0 fb^{-1}	7 TeV
	WW	[-1.5e+01, 1.4e+01]	4.6 fb^{-1}	7 TeV
	WW	[-4.6e+00, 4.6e+00]	20.3 fb^{-1}	8 TeV
	WW	[-3.4e+00, 3.3e+00]	36.1 fb^{-1}	13 TeV
	WW	[-1.2e+01, 1.2e+01]	4.9 fb^{-1}	7 TeV
	WW	[-5.7e+00, 5.9e+00]	19.4 fb^{-1}	8 TeV
	WZ	[-1.1e+01, 1.1e+01]	4.6 fb^{-1}	7 TeV
	WZ	[-3.3e+00, 3.2e+00]	33.6 fb^{-1}	8,13 TeV
	WZ	[-4.6e+00, 4.2e+00]	19.6 fb^{-1}	8 TeV
	WZ	[-2.0e+00, 2.1e+00]	35.9 fb^{-1}	13 TeV
	WV (lνjj)	[-9.5e+00, 9.6e+00]	4.6 fb^{-1}	7 TeV
	WV (lνjj)	[-5.3e+00, 5.3e+00]	20.2 fb^{-1}	8 TeV
	WV (lνJ)	[-3.1e+00, 3.1e+00]	20.2 fb^{-1}	8 TeV
	WV (lνjj)	[-9.2e+00, 7.3e+00]	5.0 fb^{-1}	7 TeV
	WV (lνJ)	[-2.7e+00, 2.7e+00]	19 fb^{-1}	8 TeV
	WV (lνJ)	[-1.6e+00, 1.6e+00]	35.9 fb^{-1}	13 TeV
	EW qqZ	[-3.6e+01, 3.2e+01]	20.3 fb^{-1}	8 TeV
	EW qqW	[-1.3e+01, 9.0e+00]	20.2 fb^{-1}	8 TeV
	EW qqW,qqZ	[-2.3e+00, 2.5e+00]	35.9 fb^{-1}	13 TeV
	D0 Comb.	[-8.7e+00, 1.1e+01]	8.6 fb^{-1}	1.96 TeV
	LEP Comb.	[-1.4e+01, 4.1e+00]	0.7 fb^{-1}	0.20 TeV
c_W/Λ^2	WW	[-9.4e+00, 1.3e+01]	4.6 fb^{-1}	7 TeV
	WW	[-5.9e+00, 1.1e+01]	20.3 fb^{-1}	8 TeV
	WW	[-7.4e+00, 4.1e+00]	36.1 fb^{-1}	13 TeV
	WW	[-2.3e+01, 2.3e+01]	4.9 fb^{-1}	7 TeV
	WW	[-1.1e+01, 5.4e+00]	19.4 fb^{-1}	8 TeV
	WZ	[-1.4e+01, 2.2e+01]	4.6 fb^{-1}	7 TeV
	WZ	[-3.6e+00, 7.3e+00]	33.6 fb^{-1}	8,13 TeV
	WZ	[-4.2e+00, 8.0e+00]	19.6 fb^{-1}	8 TeV
	WZ	[-4.1e+00, 1.1e+00]	35.9 fb^{-1}	13 TeV
	WV	[-1.3e+01, 1.8e+01]	4.6 fb^{-1}	7 TeV
	WV (lνjj)	[-6.4e+00, 1.1e+01]	20.2 fb^{-1}	8 TeV
	WV (lνJ)	[-5.1e+00, 5.8e+00]	20.2 fb^{-1}	8 TeV
	WV (lνJ)	[-2.0e+00, 5.7e+00]	19 fb^{-1}	8 TeV
	WV (lνJ)	[-2.0e+00, 2.7e+00]	35.9 fb^{-1}	13 TeV
	EW qqW	[-3.3e+01, 3.0e+01]	20.2 fb^{-1}	8 TeV
	EW qqW,qqZ	[-8.8e+00, 1.6e+01]	35.9 fb^{-1}	13 TeV
	D0 Comb.	[-8.2e+00, 2.0e+01]	8.6 fb^{-1}	1.96 TeV
	LEP Comb.	[-1.3e+01, 5.1e+00]	0.7 fb^{-1}	0.20 TeV

EWK production: Vector Boson Scattering

- VV+2jets production dominated by O(αs2) QCD processes
- V_LV_L scattering linked to the mechanism responsible for the EWSB
- Typical signature: two high pT jets in the forward-backward region with large rapidity separation and low hadronic activity elsewhere





Operators (Eboli model)

Higgs Fields

$$\mathcal{L}_{S,0} = \left[(D_\mu\Phi)^\dagger D_\nu\Phi\right] \times \left[(D^\mu\Phi)^\dagger D^\nu\Phi\right]$$

$$\mathcal{L}_{S,1} = \left[(D_\mu\Phi)^\dagger D^\mu\Phi\right] \times \left[(D_\nu\Phi)^\dagger D^\nu\Phi\right]$$

Gauge & Higgs Fields

$$\begin{aligned}
\mathcal{L}_{M,0} &= \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right] \\
\mathcal{L}_{M,1} &= \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right] \\
\mathcal{L}_{M,2} &= \left[B_{\mu\nu}B^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right] \\
\mathcal{L}_{M,3} &= \left[B_{\mu\nu}B^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right] \\
\mathcal{L}_{M,4} &= \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu} D^\mu\Phi\right] \times B^{\beta\nu} \\
\mathcal{L}_{M,5} &= \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu} D^\nu\Phi\right] \times B^{\beta\mu} \\
\mathcal{L}_{M,6} &= \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu}\hat{W}^{\beta\nu} D^\mu\Phi\right] \\
\mathcal{L}_{M,7} &= \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu}\hat{W}^{\beta\mu} D^\nu\Phi\right]
\end{aligned}$$

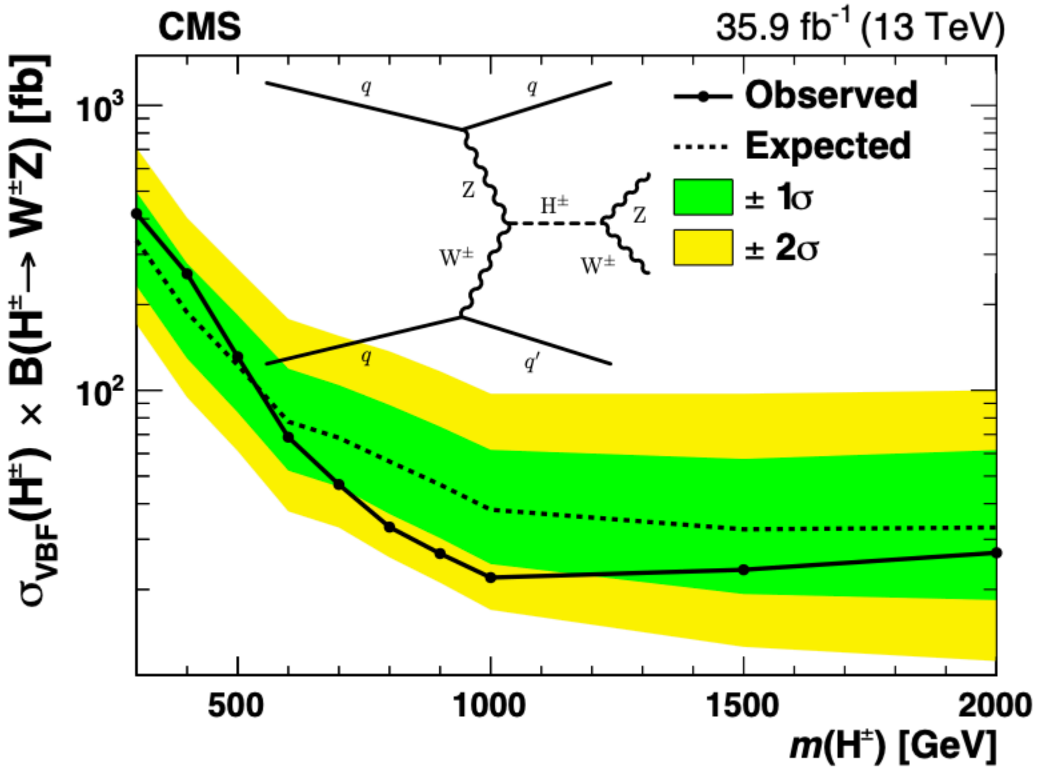
Gauge Fields

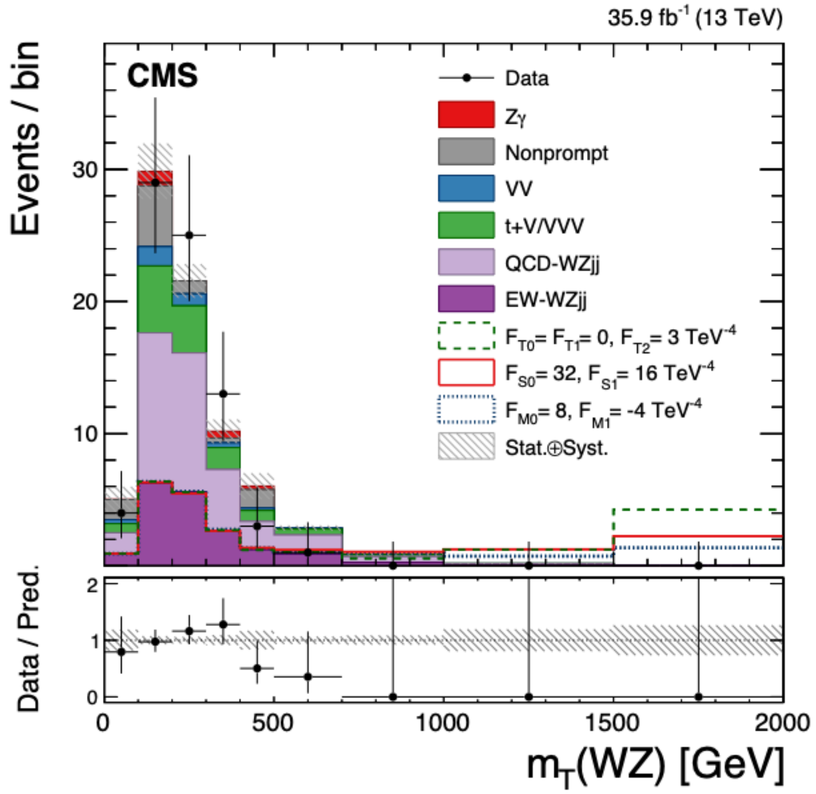
$$\begin{aligned}
\mathcal{L}_{T,0} &= \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times \mathrm{Tr}\left[\hat{W}_{\alpha\beta}\hat{W}^{\alpha\beta}\right] \\
\mathcal{L}_{T,1} &= \mathrm{Tr}\left[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\hat{W}_{\mu\beta}\hat{W}^{\alpha\nu}\right] \\
\mathcal{L}_{T,2} &= \mathrm{Tr}\left[\hat{W}_{\alpha\mu}\hat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\hat{W}_{\beta\nu}\hat{W}^{\nu\alpha}\right] \\
\mathcal{L}_{T,5} &= \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times B_{\alpha\beta}B^{\alpha\beta} \\
\mathcal{L}_{T,6} &= \mathrm{Tr}\left[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}\right] \times B_{\mu\beta}B^{\alpha\nu} \\
\mathcal{L}_{T,7} &= \mathrm{Tr}\left[\hat{W}_{\alpha\mu}\hat{W}^{\mu\beta}\right] \times B_{\beta\nu}B^{\nu\alpha} \\
\mathcal{L}_{T,8} &= B_{\mu\nu}B^{\mu\nu}B_{\alpha\beta}B^{\alpha\beta} \\
\mathcal{L}_{T,9} &= B_{\alpha\mu}B^{\mu\beta}B_{\beta\nu}B^{\nu\alpha}
\end{aligned}$$

WZ VBS: aQGC

CMS-SMP-18-001

- aQGCs are constrained with $m_T(WZ)$
- limits on $\sigma \times BF$ for VBF production of $H^{\pm}$





Parameters	Exp. limit	Obs. limit
f_{M0}/Λ^4	$[-11.2, 11.6]$	$[-9.15, 9.15]$
f_{M1}/Λ^4	$[-10.9, 11.6]$	$[-9.15, 9.45]$
f_{S0}/Λ^4	$[-32.5, 34.5]$	$[-26.5, 27.5]$
f_{S1}/Λ^4	$[-50.2, 53.2]$	$[-41.2, 42.8]$
f_{T0}/Λ^4	$[-0.87, 0.89]$	$[-0.75, 0.81]$
f_{T1}/Λ^4	$[-0.56, 0.60]$	$[-0.49, 0.55]$
f_{T2}/Λ^4	$[-1.78, 2.00]$	$[-1.49, 1.85]$

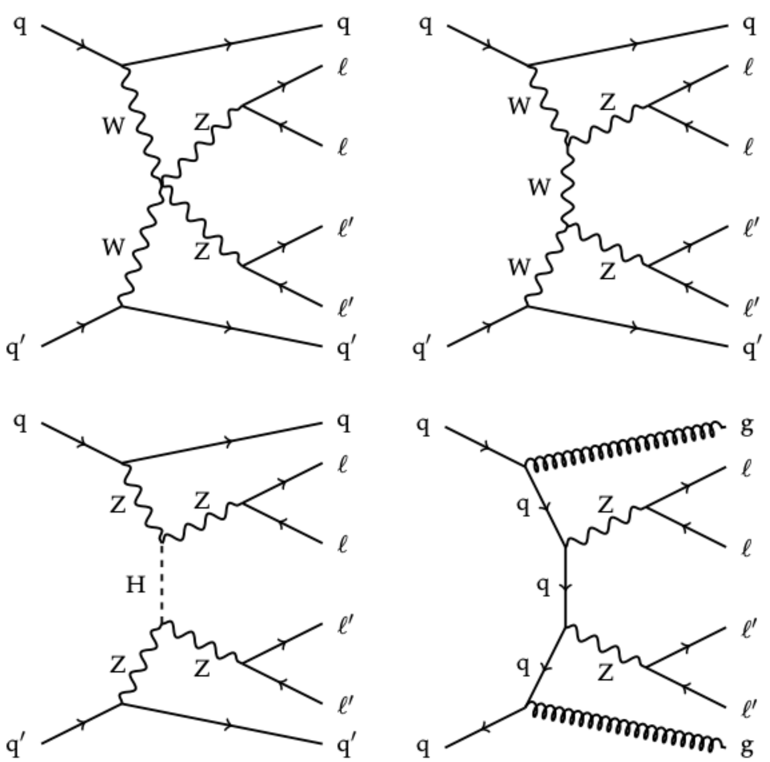
involve a mixture of gauge and Higgs field interactions

involve interactions with the Higgs field

purely from the SU(2) gauge fields

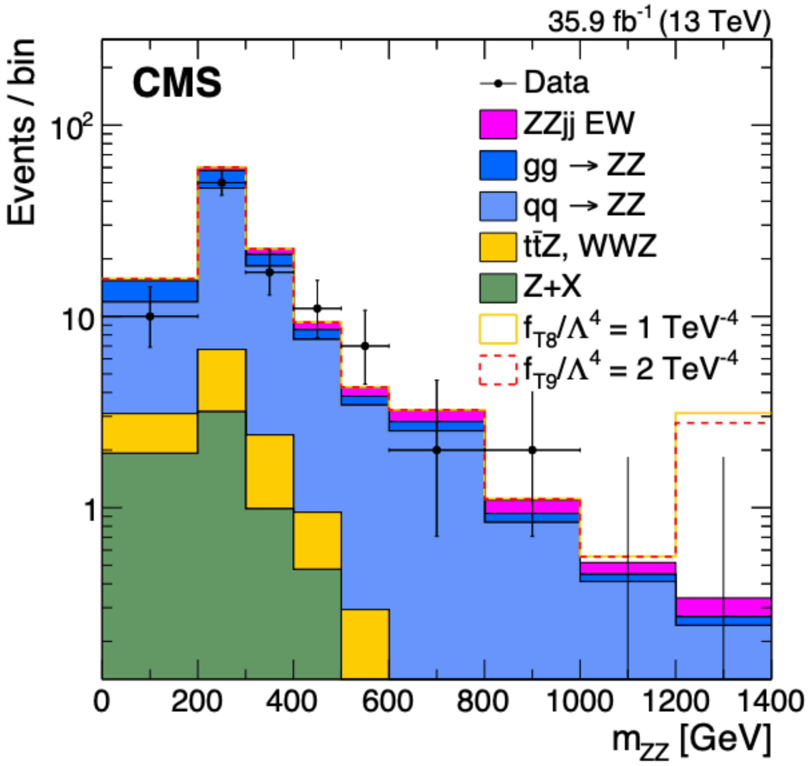
ZZ VBS (CMS)

Eur. Phys. J. C 78 (2018) 165



QCD-induced background

- fully leptonic final state ZZ→llll (l = e, μ)
  - low σ, small BR, large irreducible QCD background → all final state particles can be reconstructed → favorable for EWSB study
  - clean leptonic final state → small reducible background
- MZZ is used to constrain the aQGCs
  - the results are statistically limited so far



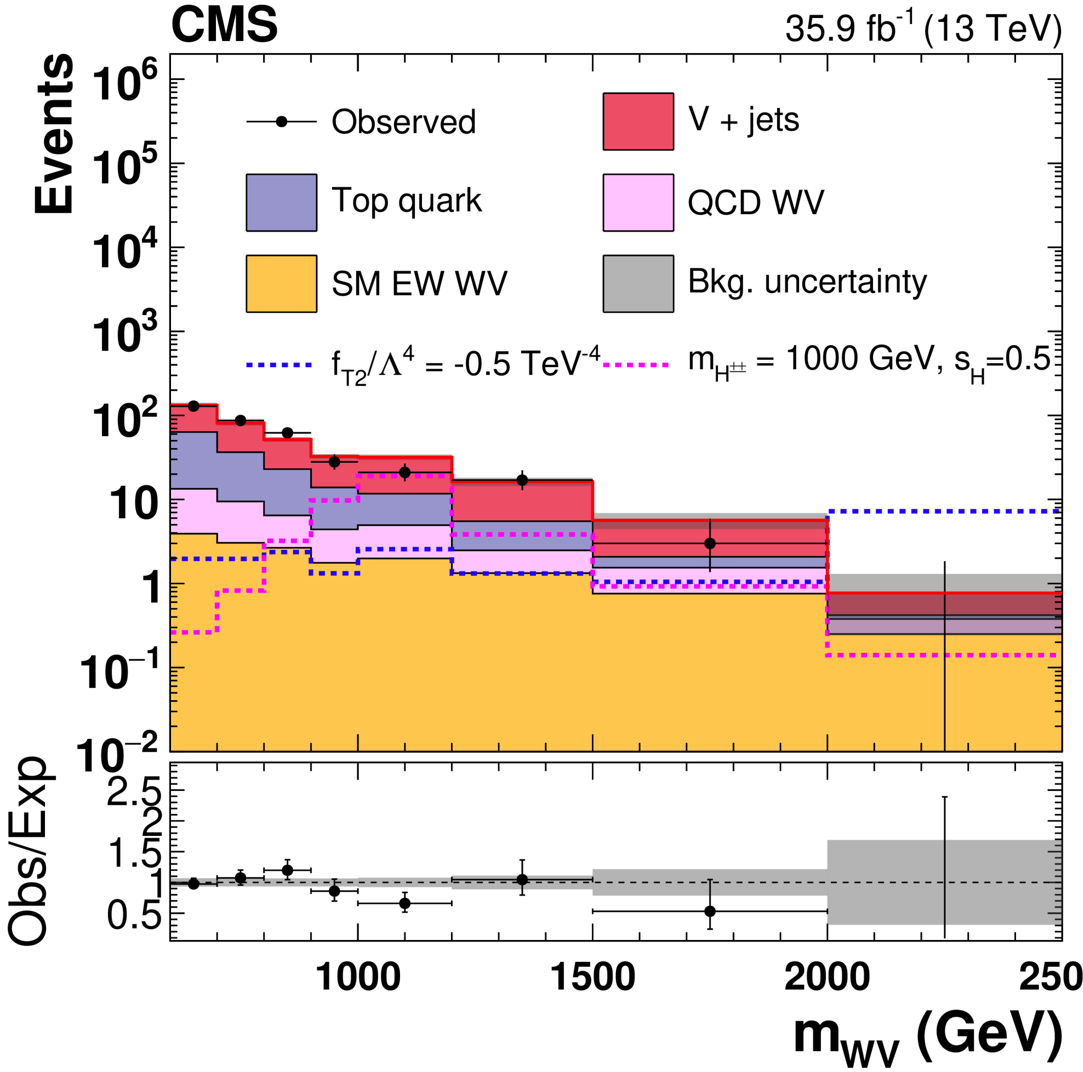
Coupling	Exp. lower	Exp. upper	Obs. lower	Obs. upper
f_{T0}/Λ^4	−0.53	0.51	−0.46	0.44
f_{T1}/Λ^4	−0.72	0.71	−0.61	0.61
f_{T2}/Λ^4	−1.4	1.4	−1.2	1.2
f_{T8}/Λ^4	−0.99	0.99	−0.84	0.84
f_{T9}/Λ^4	−2.1	2.1	−1.8	1.8

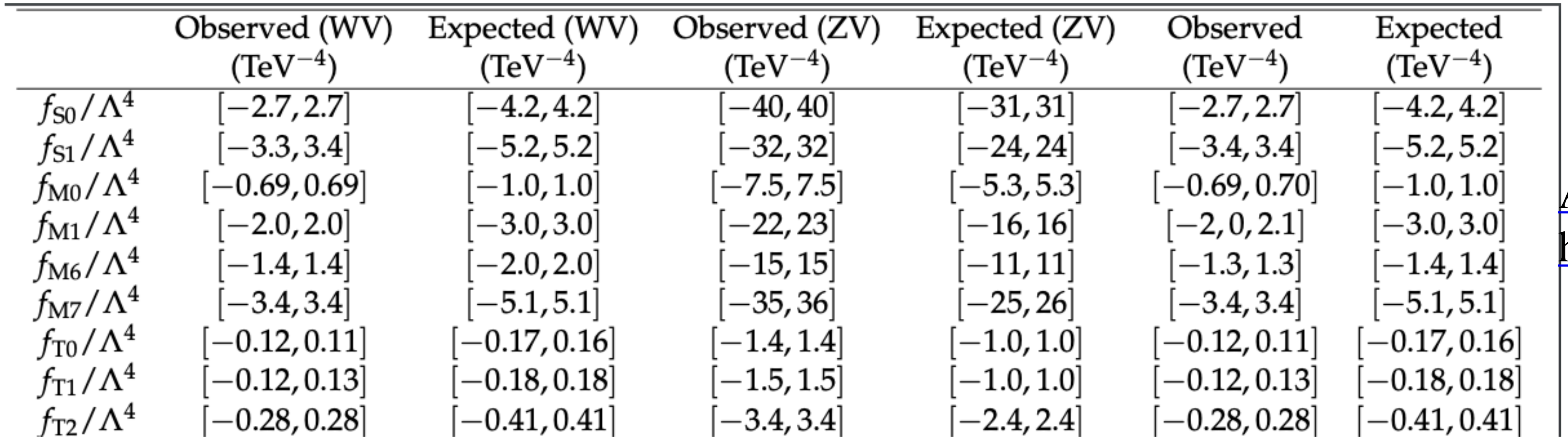
involve U(1) fields only accessible via the final state of neutral gauge bosons

WV, ZV VBS (V=W,Z): aQGC (CMS)

CMS-PAS-SMP-18-006

- WV→lv + a large radius jet , ZV→ll + a large radius jet
- sensitivity is enhanced by requiring tight dijet selections and centrality of leptonically decayed W
    - major backgrounds： V+jets and tt (for WV) • not sensitive to SM yet
- MWV and MZV are used to constrain aQGCs
- stringent limits are set and improve the results with fully leptonic final state by factors of up to seven

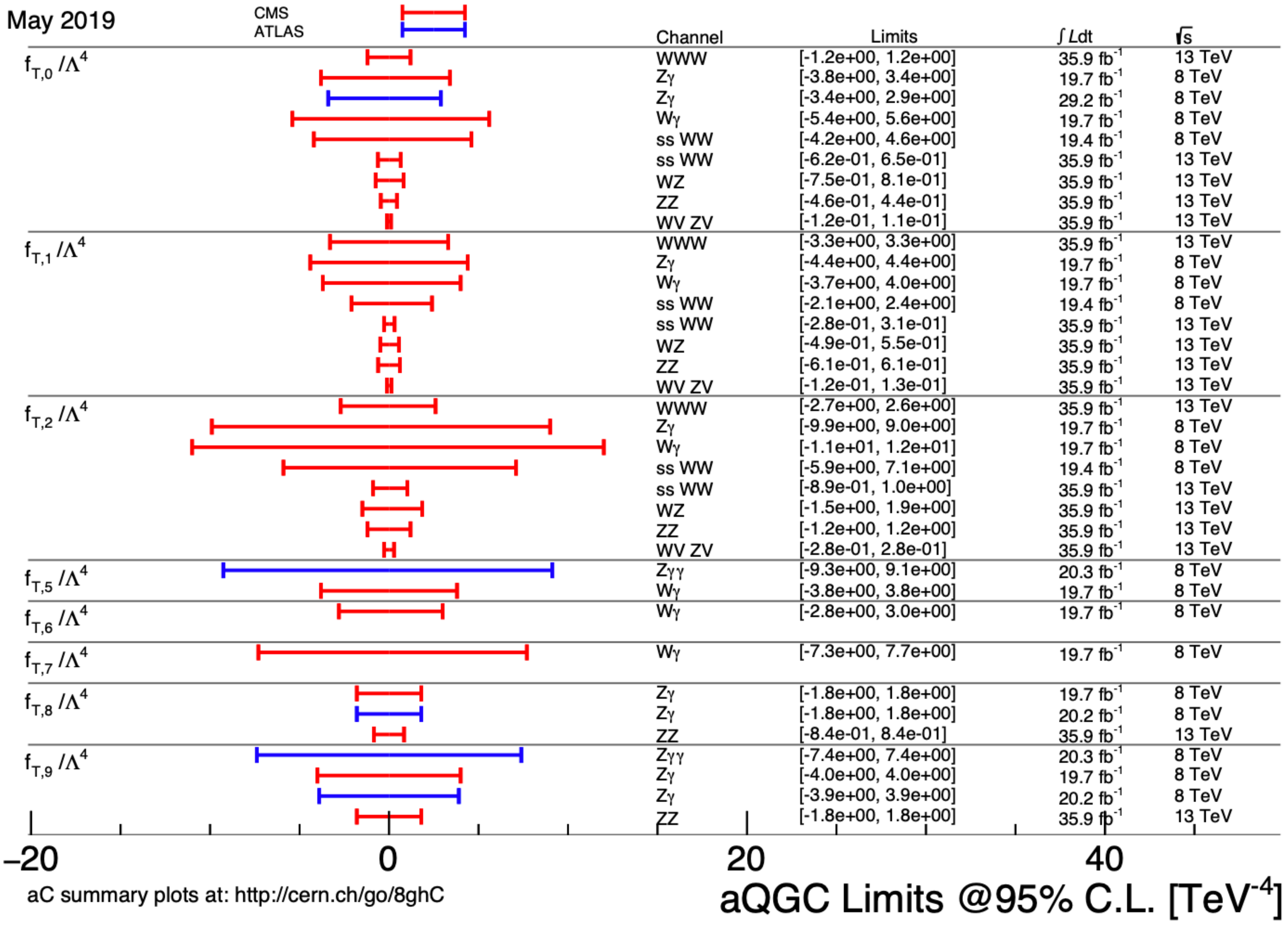




	Observed (WV) (TeV^{-4})	Expected (WV) (TeV^{-4})	Observed (ZV) (TeV^{-4})	Expected (ZV) (TeV^{-4})	Observed (TeV^{-4})	Expected (TeV^{-4})
f_{S0}/Λ^4	$[-2.7, 2.7]$	$[-4.2, 4.2]$	$[-40, 40]$	$[-31, 31]$	$[-2.7, 2.7]$	$[-4.2, 4.2]$
f_{S1}/Λ^4	$[-3.3, 3.4]$	$[-5.2, 5.2]$	$[-32, 32]$	$[-24, 24]$	$[-3.4, 3.4]$	$[-5.2, 5.2]$
f_{M0}/Λ^4	$[-0.69, 0.69]$	$[-1.0, 1.0]$	$[-7.5, 7.5]$	$[-5.3, 5.3]$	$[-0.69, 0.70]$	$[-1.0, 1.0]$
f_{M1}/Λ^4	$[-2.0, 2.0]$	$[-3.0, 3.0]$	$[-22, 23]$	$[-16, 16]$	$[-2, 0, 2.1]$	$[-3.0, 3.0]$
f_{M6}/Λ^4	$[-1.4, 1.4]$	$[-2.0, 2.0]$	$[-15, 15]$	$[-11, 11]$	$[-1.3, 1.3]$	$[-1.4, 1.4]$
f_{M7}/Λ^4	$[-3.4, 3.4]$	$[-5.1, 5.1]$	$[-35, 36]$	$[-25, 26]$	$[-3.4, 3.4]$	$[-5.1, 5.1]$
f_{T0}/Λ^4	$[-0.12, 0.11]$	$[-0.17, 0.16]$	$[-1.4, 1.4]$	$[-1.0, 1.0]$	$[-0.12, 0.11]$	$[-0.17, 0.16]$
f_{T1}/Λ^4	$[-0.12, 0.13]$	$[-0.18, 0.18]$	$[-1.5, 1.5]$	$[-1.0, 1.0]$	$[-0.12, 0.13]$	$[-0.18, 0.18]$
f_{T2}/Λ^4	$[-0.28, 0.28]$	$[-0.41, 0.41]$	$[-3.4, 3.4]$	$[-2.4, 2.4]$	$[-0.28, 0.28]$	$[-0.41, 0.41]$

ATLAS has a results with 2.7 sigma
https://arxiv.org/abs/1905.07714

Summary



	Channel	Limits	$\int L dt$	$\sqrt{s}$
$f_{T,0}/\Lambda^4$	WWW	[-1.2e+00, 1.2e+00]	35.9 fb^{-1}	13 TeV
	Zγ	[-3.8e+00, 3.4e+00]	19.7 fb^{-1}	8 TeV
	Zγ	[-3.4e+00, 2.9e+00]	29.2 fb^{-1}	8 TeV
	Wγ	[-5.4e+00, 5.6e+00]	19.7 fb^{-1}	8 TeV
	ss WW	[-4.2e+00, 4.6e+00]	19.4 fb^{-1}	8 TeV
	ss WW	[-6.2e-01, 6.5e-01]	35.9 fb^{-1}	13 TeV
	WZ	[-7.5e-01, 8.1e-01]	35.9 fb^{-1}	13 TeV
	ZZ	[-4.6e-01, 4.4e-01]	35.9 fb^{-1}	13 TeV
	WV ZV	[-1.2e-01, 1.1e-01]	35.9 fb^{-1}	13 TeV
$f_{T,1}/\Lambda^4$	WWW	[-3.3e+00, 3.3e+00]	35.9 fb^{-1}	13 TeV
	Zγ	[-4.4e+00, 4.4e+00]	19.7 fb^{-1}	8 TeV
	Wγ	[-3.7e+00, 4.0e+00]	19.7 fb^{-1}	8 TeV
	ss WW	[-2.1e+00, 2.4e+00]	19.4 fb^{-1}	8 TeV
	ss WW	[-2.8e-01, 3.1e-01]	35.9 fb^{-1}	13 TeV
	WZ	[-4.9e-01, 5.5e-01]	35.9 fb^{-1}	13 TeV
	ZZ	[-6.1e-01, 6.1e-01]	35.9 fb^{-1}	13 TeV
	WV ZV	[-1.2e-01, 1.3e-01]	35.9 fb^{-1}	13 TeV
$f_{T,2}/\Lambda^4$	WWW	[-2.7e+00, 2.6e+00]	35.9 fb^{-1}	13 TeV
	Zγ	[-9.9e+00, 9.0e+00]	19.7 fb^{-1}	8 TeV
	Wγ	[-1.1e+01, 1.2e+01]	19.7 fb^{-1}	8 TeV
	ss WW	[-5.9e+00, 7.1e+00]	19.4 fb^{-1}	8 TeV
	ss WW	[-8.9e-01, 1.0e+00]	35.9 fb^{-1}	13 TeV
	WZ	[-1.5e+00, 1.9e+00]	35.9 fb^{-1}	13 TeV
	ZZ	[-1.2e+00, 1.2e+00]	35.9 fb^{-1}	13 TeV
	WV ZV	[-2.8e-01, 2.8e-01]	35.9 fb^{-1}	13 TeV
$f_{T,5}/\Lambda^4$	Zγγ	[-9.3e+00, 9.1e+00]	20.3 fb^{-1}	8 TeV
	Wγ	[-3.8e+00, 3.8e+00]	19.7 fb^{-1}	8 TeV
$f_{T,6}/\Lambda^4$	Wγ	[-2.8e+00, 3.0e+00]	19.7 fb^{-1}	8 TeV
$f_{T,7}/\Lambda^4$	Wγ	[-7.3e+00, 7.7e+00]	19.7 fb^{-1}	8 TeV
$f_{T,8}/\Lambda^4$	Zγ	[-1.8e+00, 1.8e+00]	19.7 fb^{-1}	8 TeV
	Zγ	[-1.8e+00, 1.8e+00]	20.2 fb^{-1}	8 TeV
	ZZ	[-8.4e-01, 8.4e-01]	35.9 fb^{-1}	13 TeV
$f_{T,9}/\Lambda^4$	Zγγ	[-7.4e+00, 7.4e+00]	20.3 fb^{-1}	8 TeV
	Zγ	[-4.0e+00, 4.0e+00]	19.7 fb^{-1}	8 TeV
	Zγ	[-3.9e+00, 3.9e+00]	20.2 fb^{-1}	8 TeV
	ZZ	[-1.8e+00, 1.8e+00]	35.9 fb^{-1}	13 TeV

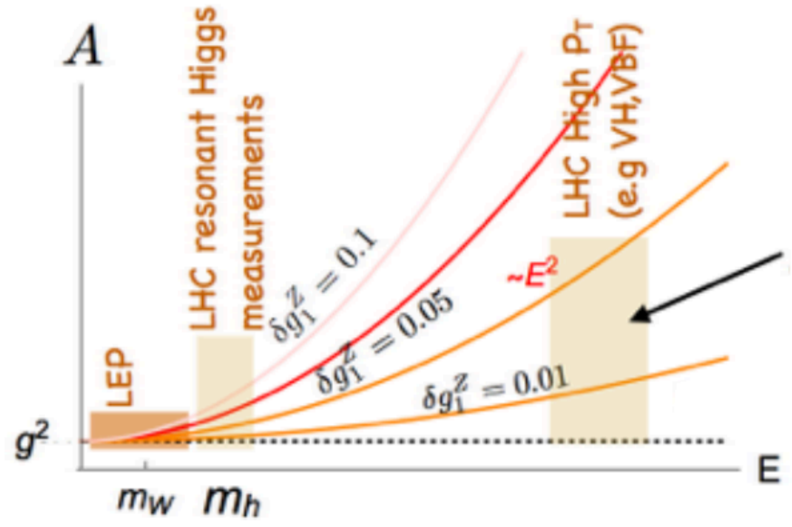
aC summary plots at: http://cern.ch/go/8ghC

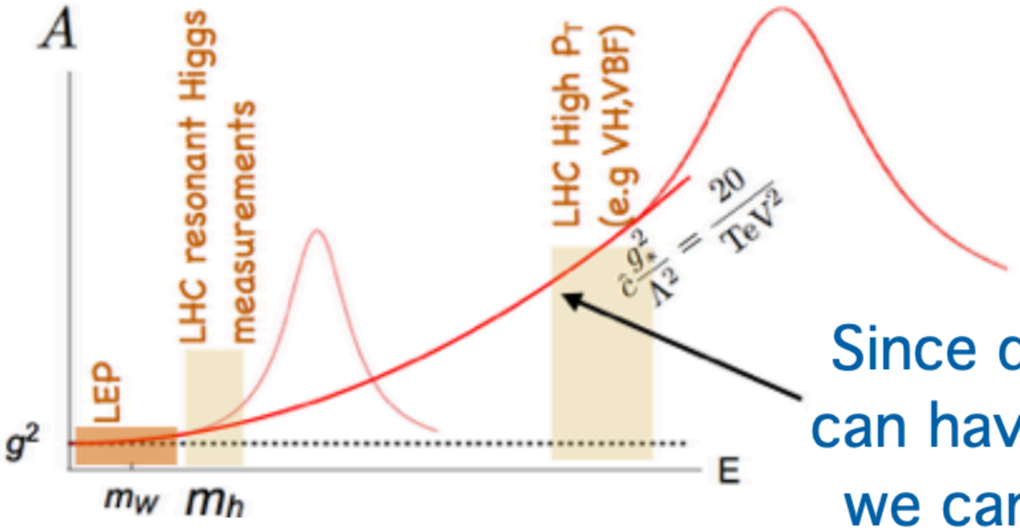
Discussion points

- Variables and binning:
  - What variables to measure (in case of unfolded distributions)
  - Which are the most sensitive to aGCs/EFT parameters?
  - Often only most obvious variables, correlated with the centre-of-mass energy are used
  - Useful to receive feedback on other interesting distributions (angular variables, 2 D distributions)

Discussion points

- Unitarization
  - Clipping? removing EFT signals above a certain threshold on truth level
  - easiest to implement but not well studied

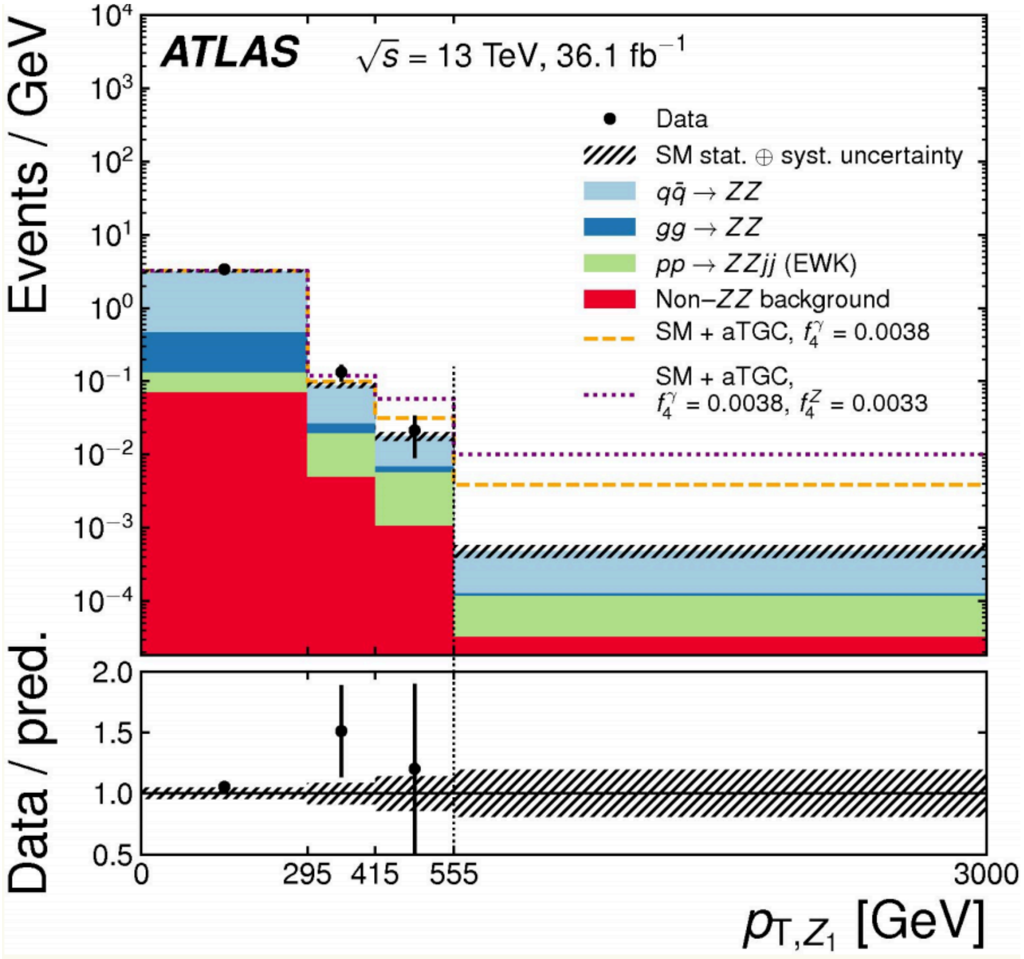


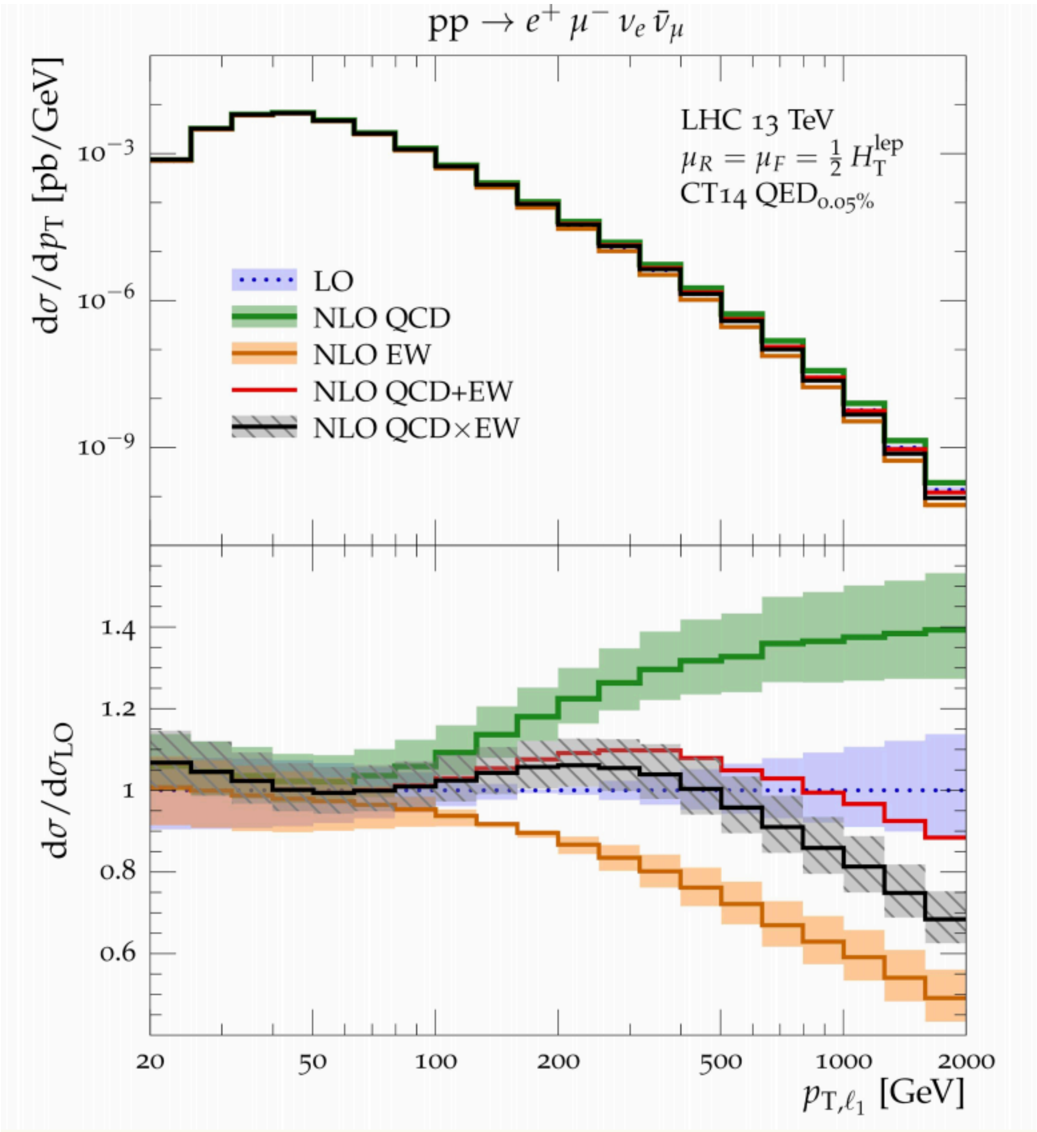


Since dibosons processes can have very high energy, we can easily go outside the validity region of the EFT approach.

Discussion points

- Tools? What is the best approach to interpolate between EFT !=0 points?
  - MC@NLO, aMC@NLO (reweighting, possibility to generate single terms), etc…
- Theory uncertainties on tails

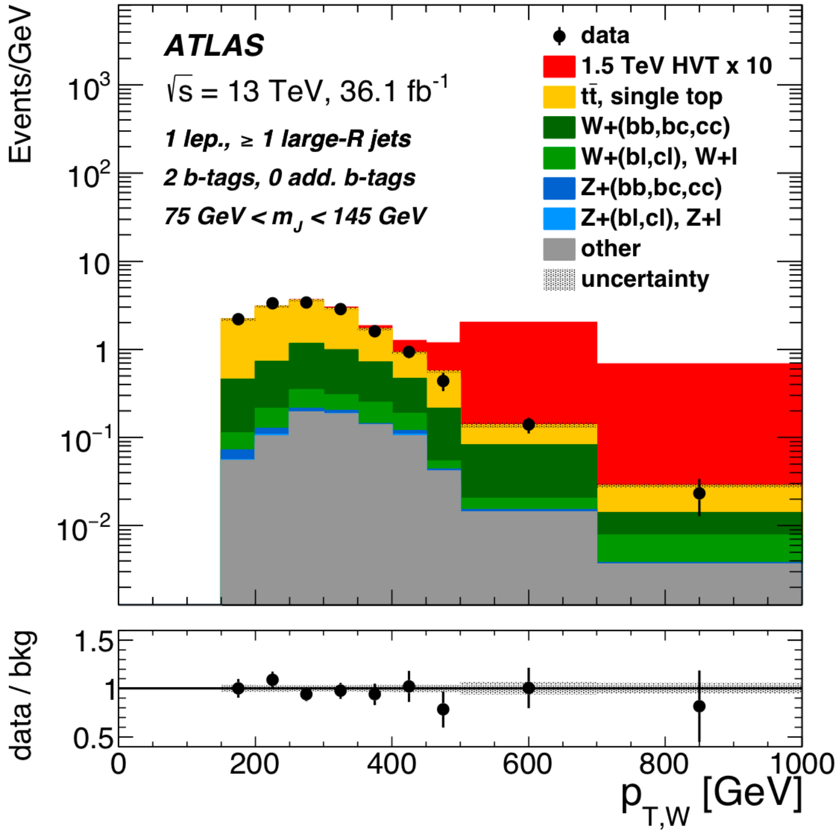


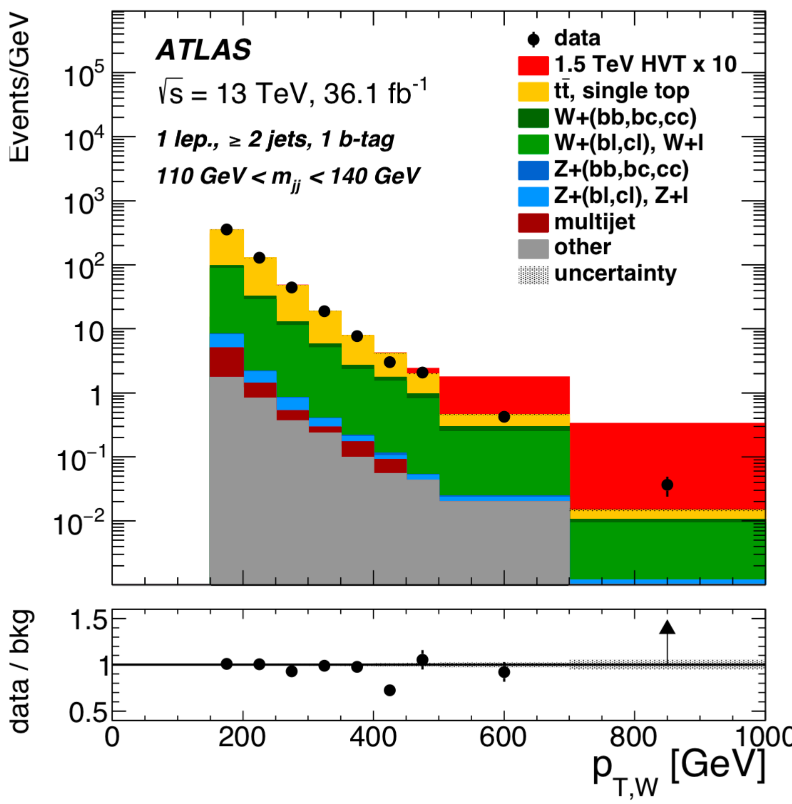


arXiv:1705.00598v1

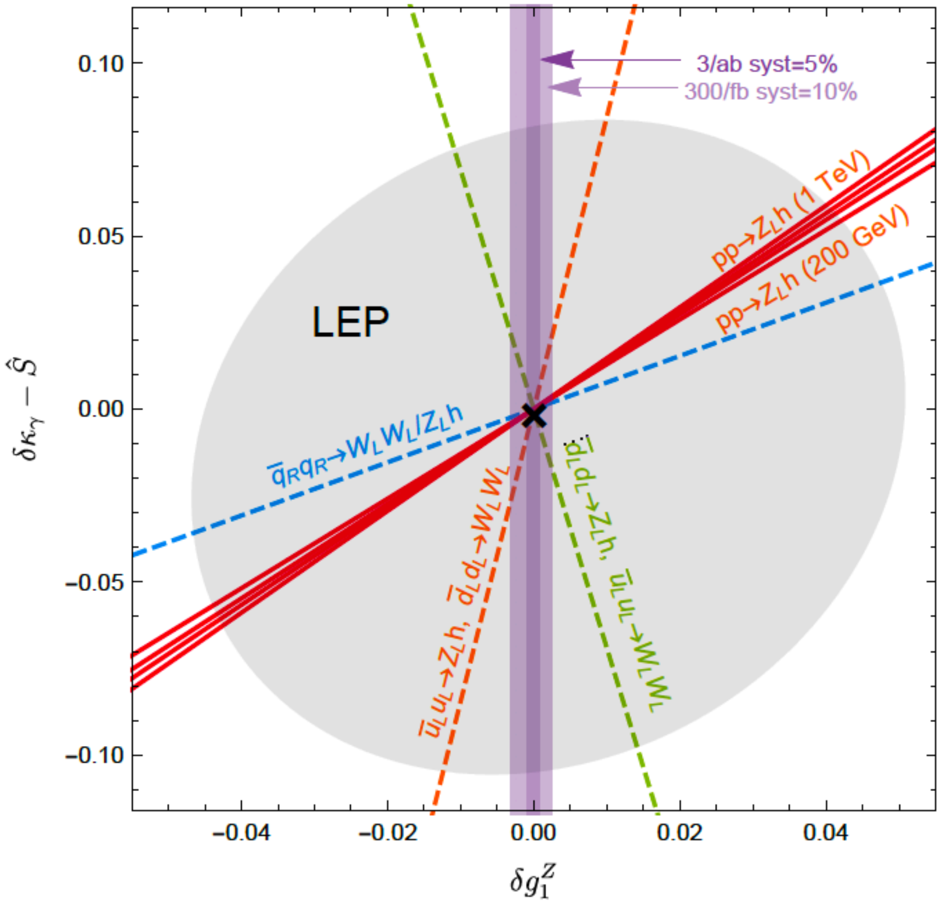
Other possibilities: VH boosted

- VH resonance analysis
  - Relies on V+Hf production modeling
  - Modeling systematics are dominant
  - V+bb is constrained with a specific control region but V+c is not



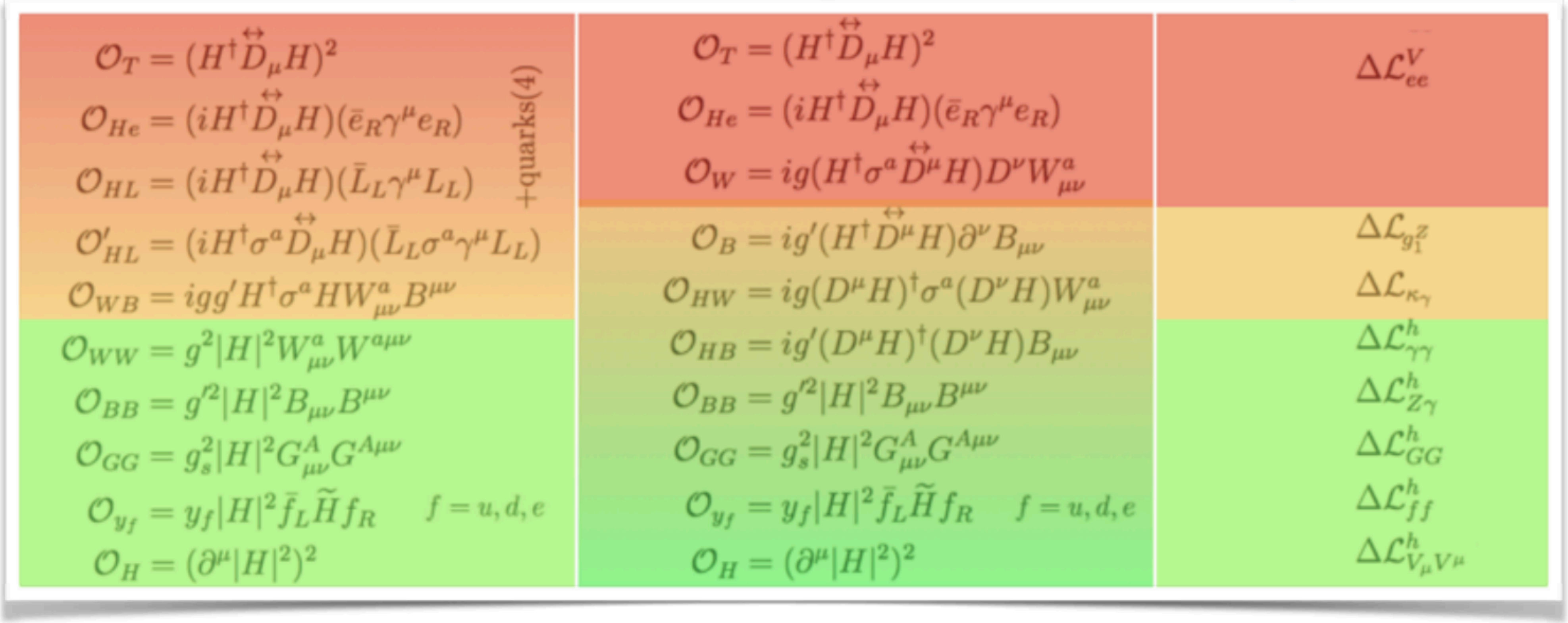


- Large systematics imposed ==> high mass is limited by statistics, we don't care?
- What if we want to looks for non -resonant new physics: Electroweak Precision Tests in High-Energy Diboson Processes
  - **arXiv:1712.01310v1**
  - Need precision!



Ideas for the future (end of Run2-Run3)

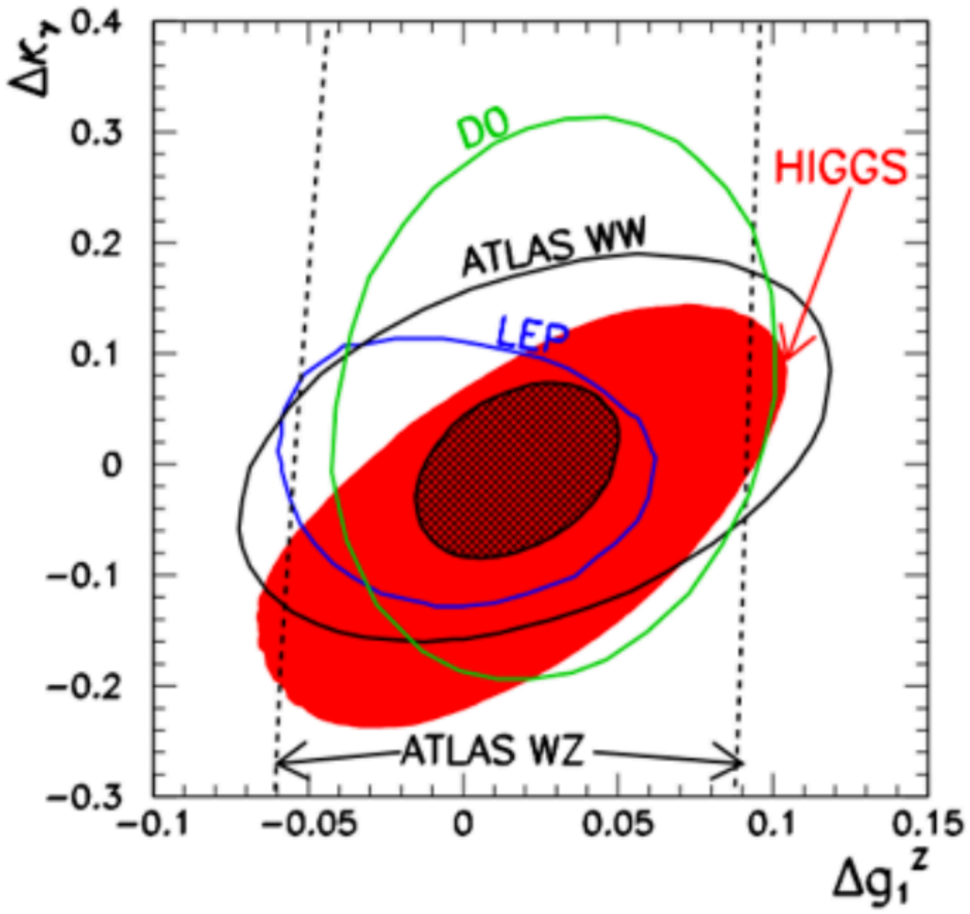
- The idea for the future is to perform a global analysis of Higgs and diboson measurements at the LHC.
- Even though the choice of basis for the D=6 operators should be equivalent (up to EOM), it is relevant for how these combinations will be performed in practice.



	Warsaw	SILH	BSM primaries
EWPO	$\mathcal{O}_T = (H^\dagger \overleftrightarrow{D}_\mu H)^2$ $\mathcal{O}_{He} = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{e}_R \gamma^\mu e_R)$ $\mathcal{O}_{HL} = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{L}_L \gamma^\mu L_L)$ $\mathcal{O}'_{HL} = (iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H)(\bar{L}_L \sigma^a \gamma^\mu L_L)$ $\mathcal{O}_{WB} = igg' H^\dagger \sigma^a H W^a_{\mu\nu} B^{\mu\nu}$ +quarks(4)	$\mathcal{O}_T = (H^\dagger \overleftrightarrow{D}_\mu H)^2$ $\mathcal{O}_{He} = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{e}_R \gamma^\mu e_R)$ $\mathcal{O}_W = ig(H^\dagger \sigma^a \overleftrightarrow{D}^\mu H) D^\nu W^a_{\mu\nu}$	$\Delta\mathcal{L}^V_{ee}$
diboson		$\mathcal{O}_B = ig'(H^\dagger \overleftrightarrow{D}^\mu H) \partial^\nu B_{\mu\nu}$ $\mathcal{O}_{HW} = ig(D^\mu H)^\dagger \sigma^a (D^\nu H) W^a_{\mu\nu}$	$\Delta\mathcal{L}_{g_1^Z}$ $\Delta\mathcal{L}_{\kappa_\gamma}$
Higgs	$\mathcal{O}_{WW} = g^2 \lvert H\rvert^2 W^a_{\mu\nu} W^{a\mu\nu}$ $\mathcal{O}_{BB} = g'^2 \lvert H\rvert^2 B_{\mu\nu} B^{\mu\nu}$ $\mathcal{O}_{GG} = g_s^2 \lvert H\rvert^2 G^A_{\mu\nu} G^{A\mu\nu}$ $\mathcal{O}_{y_f} = y_f \lvert H\rvert^2 \bar{f}_L \widetilde{H} f_R \quad f = u, d, e$ $\mathcal{O}_H = (\partial^\mu \lvert H\rvert^2)^2$	$\mathcal{O}_{HB} = ig'(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$ $\mathcal{O}_{BB} = g'^2 \lvert H\rvert^2 B_{\mu\nu} B^{\mu\nu}$ $\mathcal{O}_{GG} = g_s^2 \lvert H\rvert^2 G^A_{\mu\nu} G^{A\mu\nu}$ $\mathcal{O}_{y_f} = y_f \lvert H\rvert^2 \bar{f}_L \widetilde{H} f_R \quad f = u, d, e$ $\mathcal{O}_H = (\partial^\mu \lvert H\rvert^2)^2$	$\Delta\mathcal{L}^h_{\gamma\gamma}$ $\Delta\mathcal{L}^h_{Z\gamma}$ $\Delta\mathcal{L}^h_{GG}$ $\Delta\mathcal{L}^h_{ff}$ $\Delta\mathcal{L}^h_{V_\mu V^\mu}$
	Partially available at NLO	Easy UV matching (SUSY, Comp Higgs, ...)	Traditional param. Not easy UV matching

Interplay between diboson and Higgs

- The combined analysis will substantially increase the sensitivity to the coefficients of the D=6 operators in SMEFT.
- The idea is to provide combined limits in the (g^*, Λ) plane with different energy cuts. We are also working towards a robust determination of the uncertainties associated to D=8 operators and SMEFT NLO corrections



[plots from arXiv:1304.1151]

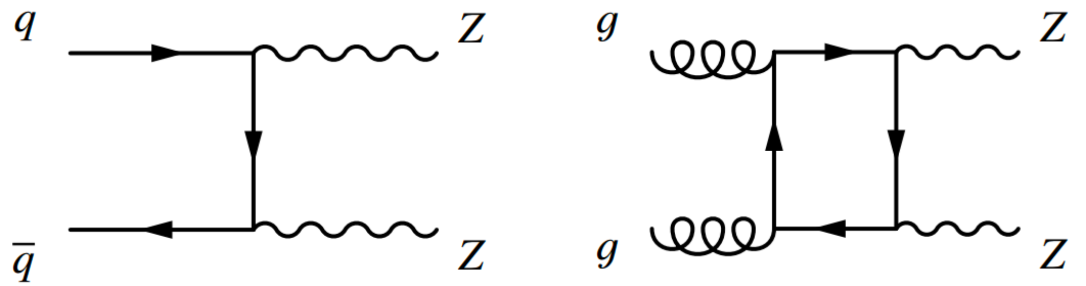
Summary

- Combined dim-6 EFT fit of aTGC measurements seems doable and worthwhile
  - Which measurements to include, which operator basis?
  - How to implement fit, treat correlation?
  - How can this be helpful in the greater scheme of things (global EFT fit)?
- For aQGC measurements situation less transparent
  - Different models and unitarizations schemes used in Run 1
  - Many measurements ongoing or planned
- Prospect show good potential for future runs/colliders

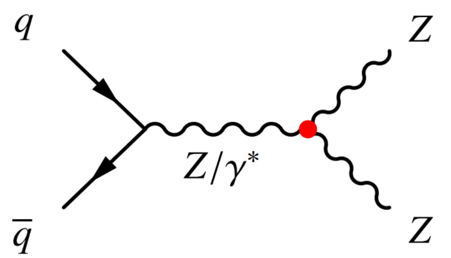
Backup

ZZ production

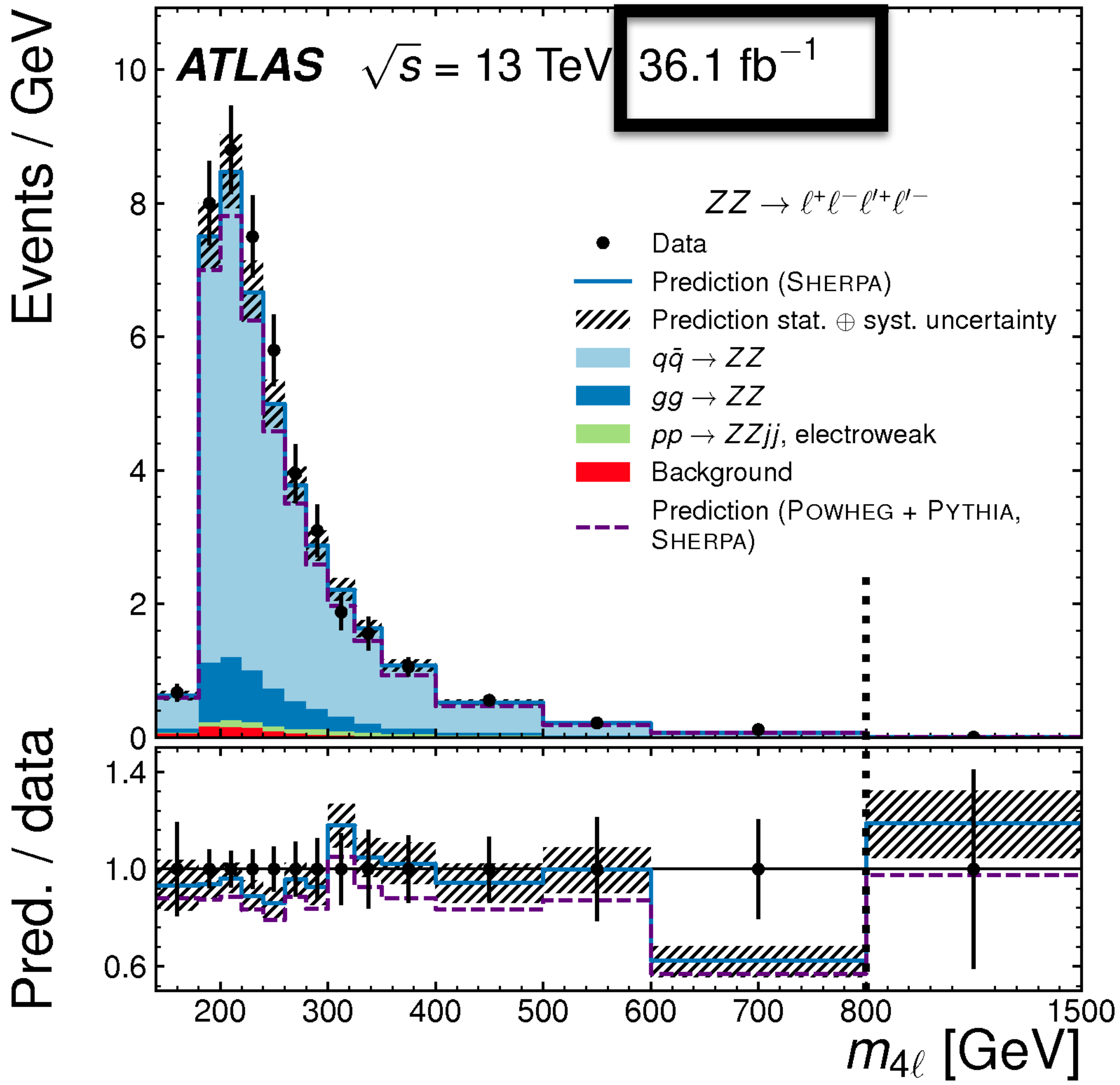
- Fully leptonic final state (electrons/muons)
  - Very clean experimental signature
- Only on-shell: 66 < m_Z < 116 GeV
- Main background from 'fake' leptons.
- Measurement uncertainty is dominated by statistics.
- Dominant experimental uncertainties:
  - lepton reconstruction and identification efficiencies.

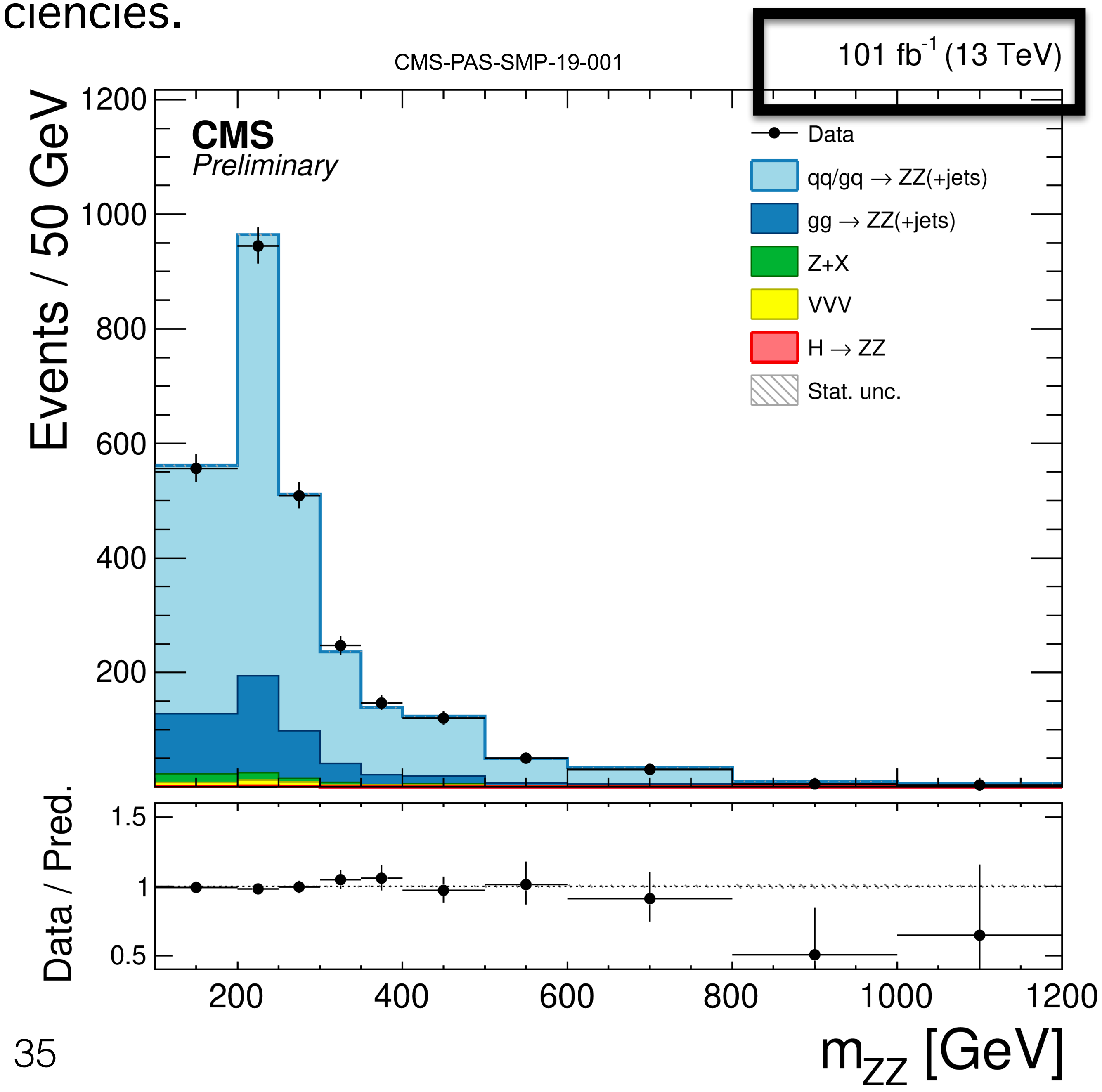


TGC vertex —> prohibited in SM



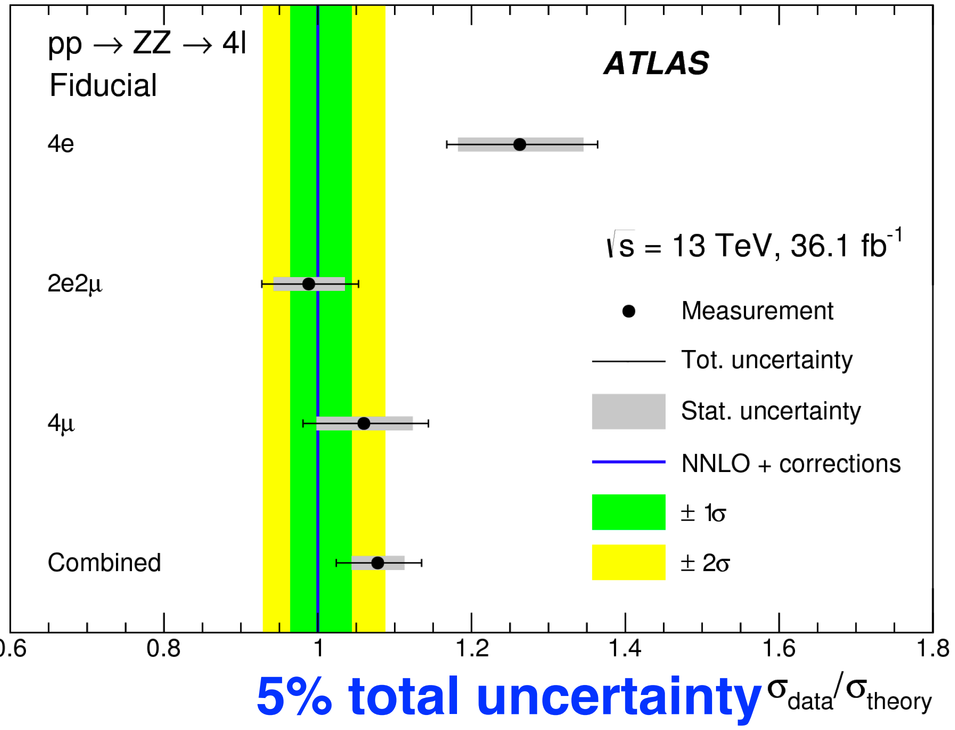
ATLAS: Phys. Rev. D 97 (2018) 032005





ZZ production

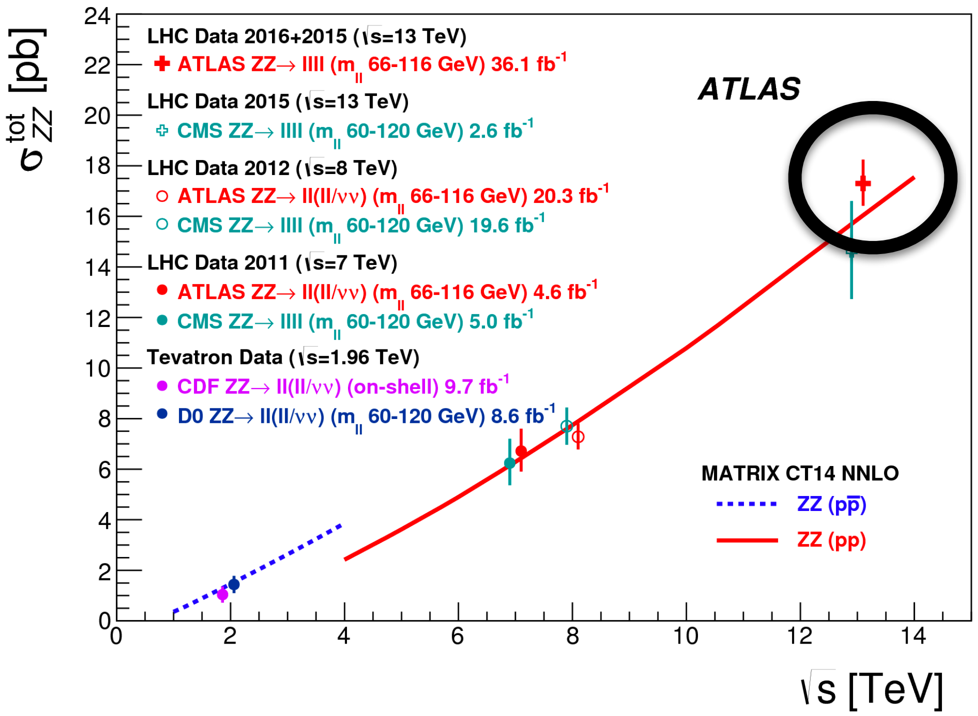
Fiducial cross section



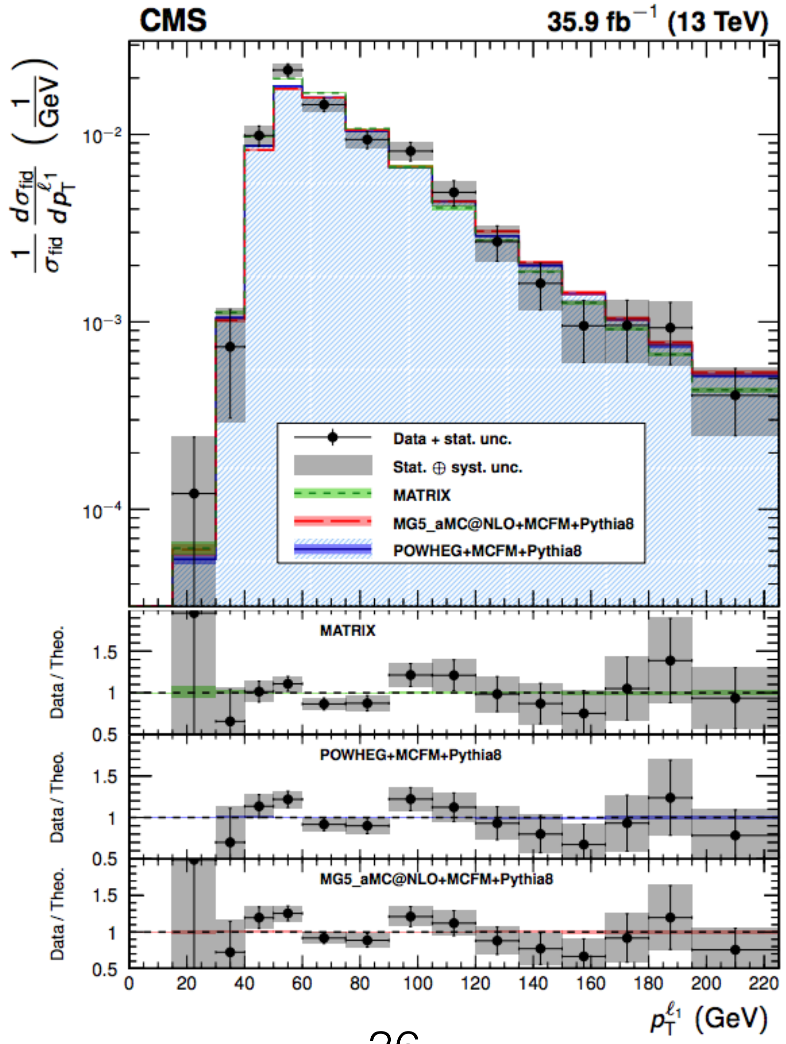
5% total uncertainty

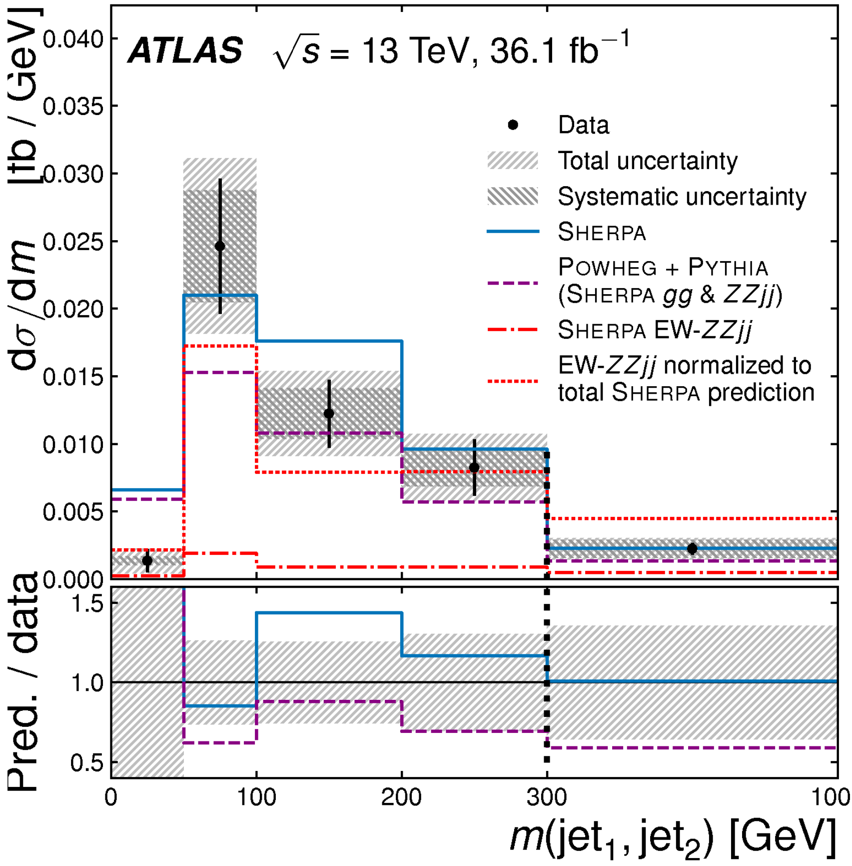
- **Best available SM predictions are based on fixed-order MATRIX NNLO QCD calculations:**
- **NNLO QCD + NLO QCD gg-initiated contribution + NLO EWK corrections + EWK-ZZjj**

Total cross section



- Differential cross sections measured as a function of 20 observables.
- Δy(j1-j2) and m(jet1, jet2) are particularly sensitive to the EWK-ZZjj process

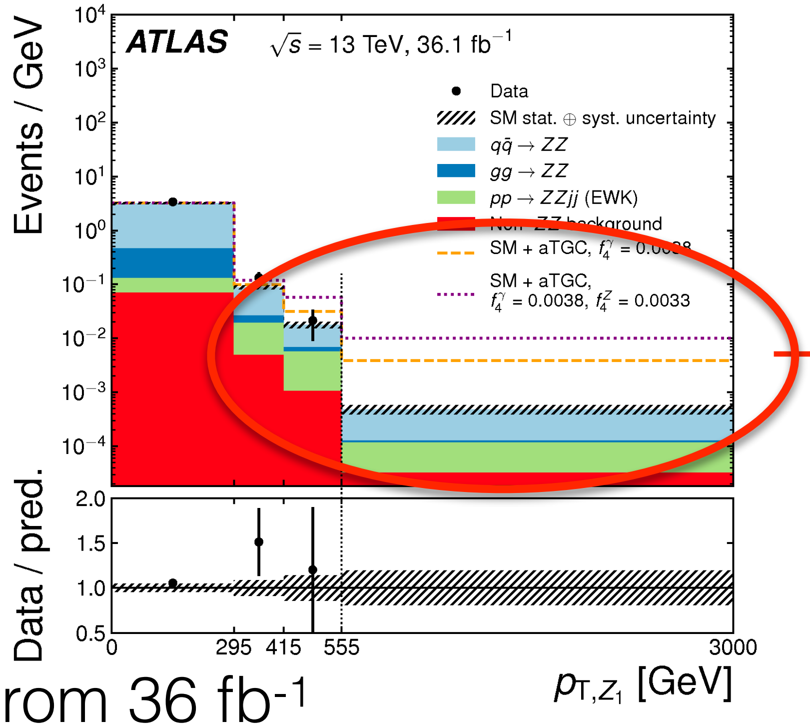


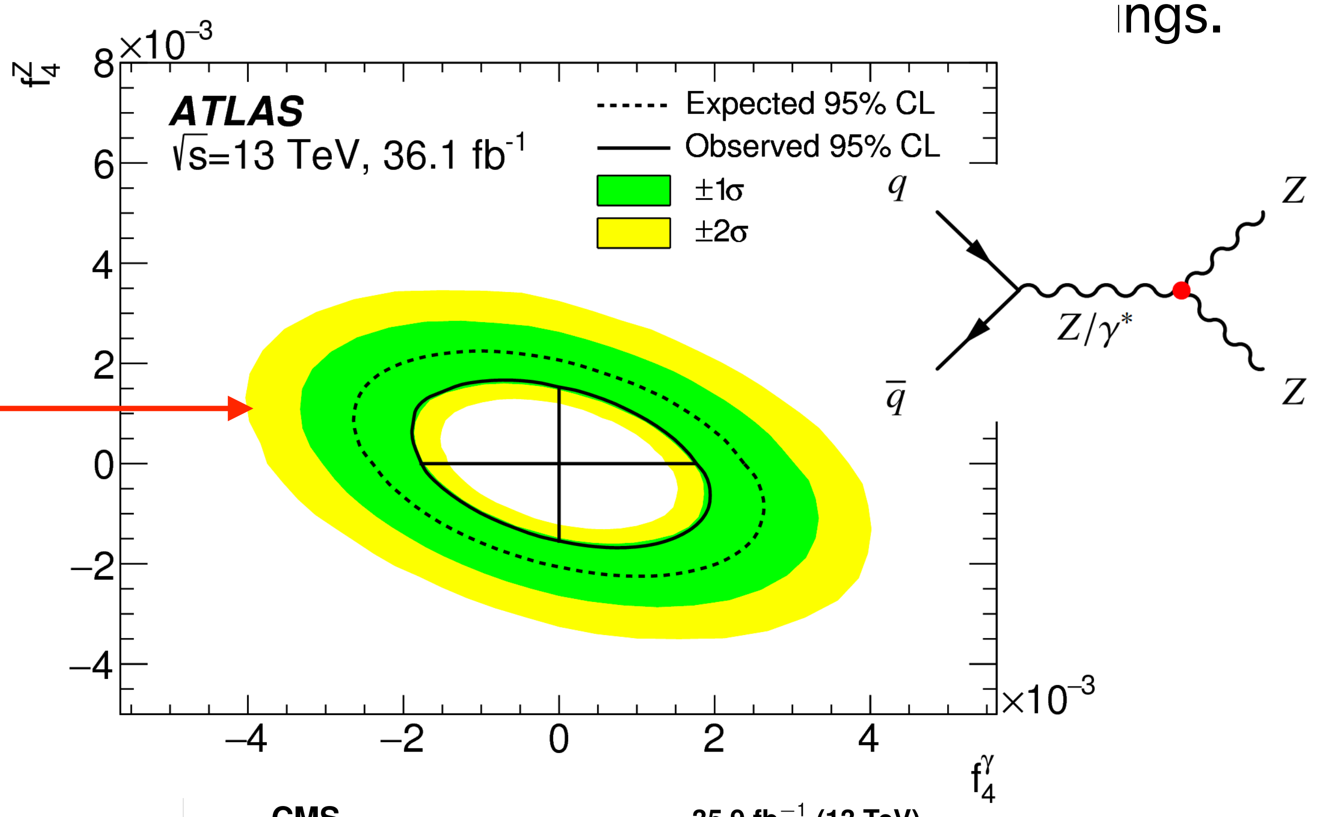


Search for neutral aTGCs

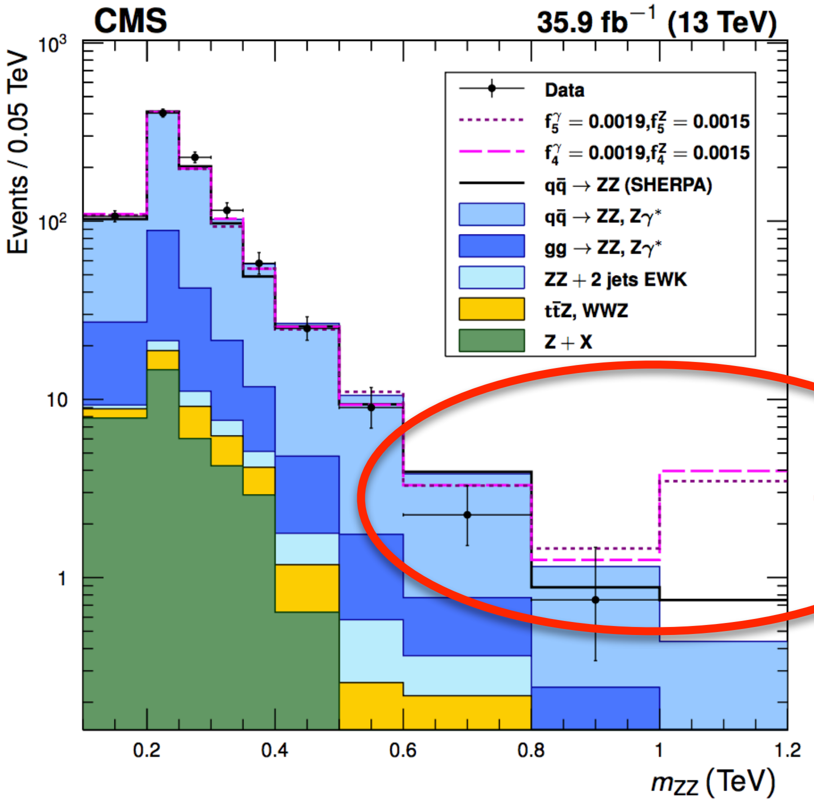
$$\mathcal{L}_{\mathrm{ZZV}} = -\frac{e}{M_Z^2}\left(f_4^V(\partial_\mu V^{\mu\beta})Z_\alpha(\partial^\alpha Z_\beta) + f_5^V(\partial^\sigma V_{\sigma\mu})\tilde{Z}^{\mu\beta}Z_\beta\right)$$

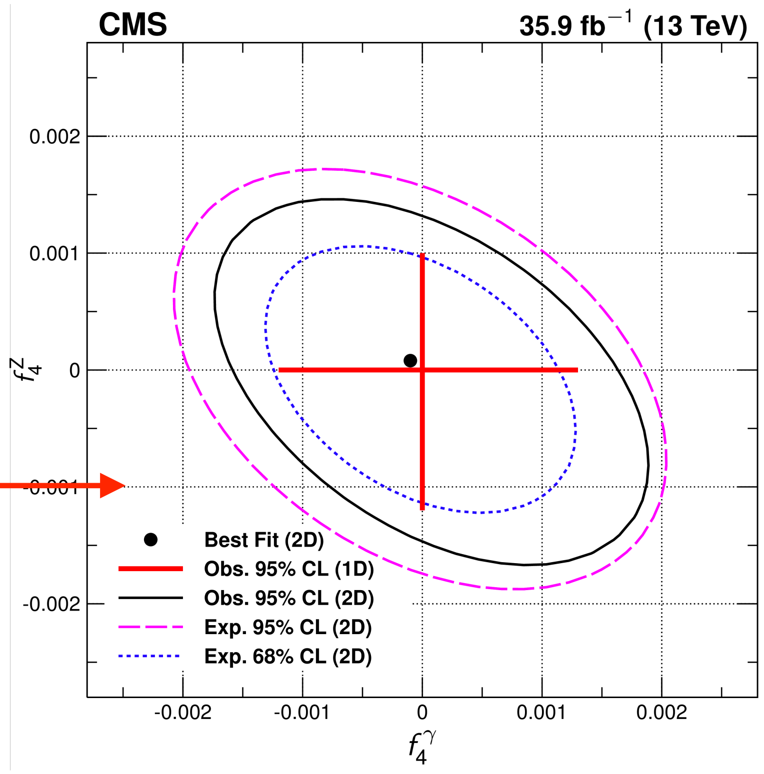
- Primary signature of non-0 nTGC is increase in ZZ cross-section at high ZZ invariant masses and high Z bosons pT.
- ATLAS: pT-distribution of leading Z boson is used ings.
- CMS use mZZ





CMS results from 36 fb^{-1}

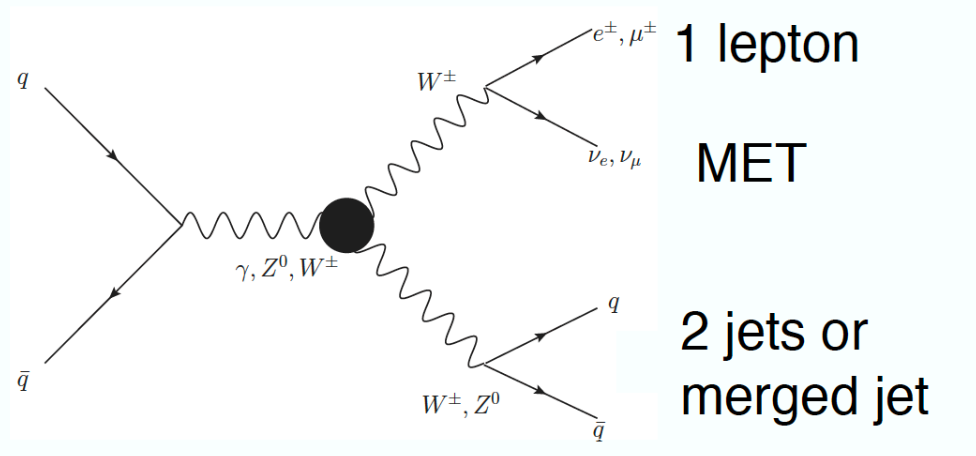




WW/WZ->lνjj

- Identify leptonically decaying W boson while other W or Z boson decays to jets
- Select dijet events and boosted events such that the decay jets merge into a single jet

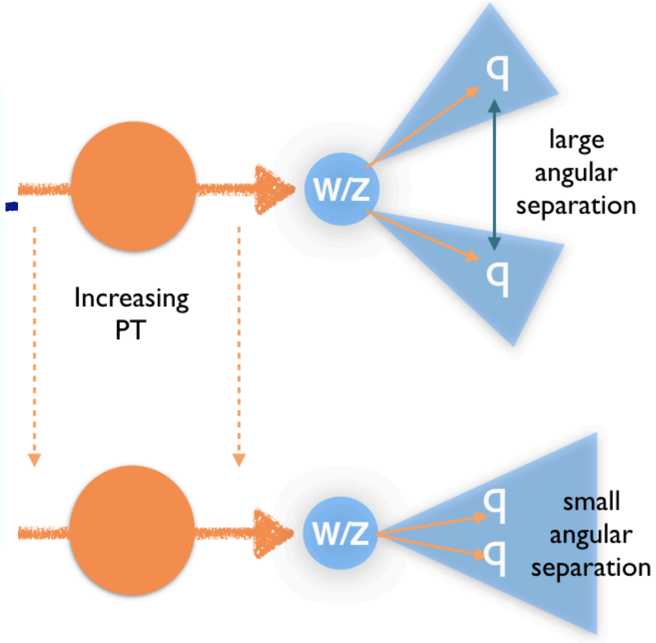
Maximizes sensitivity to aTGC

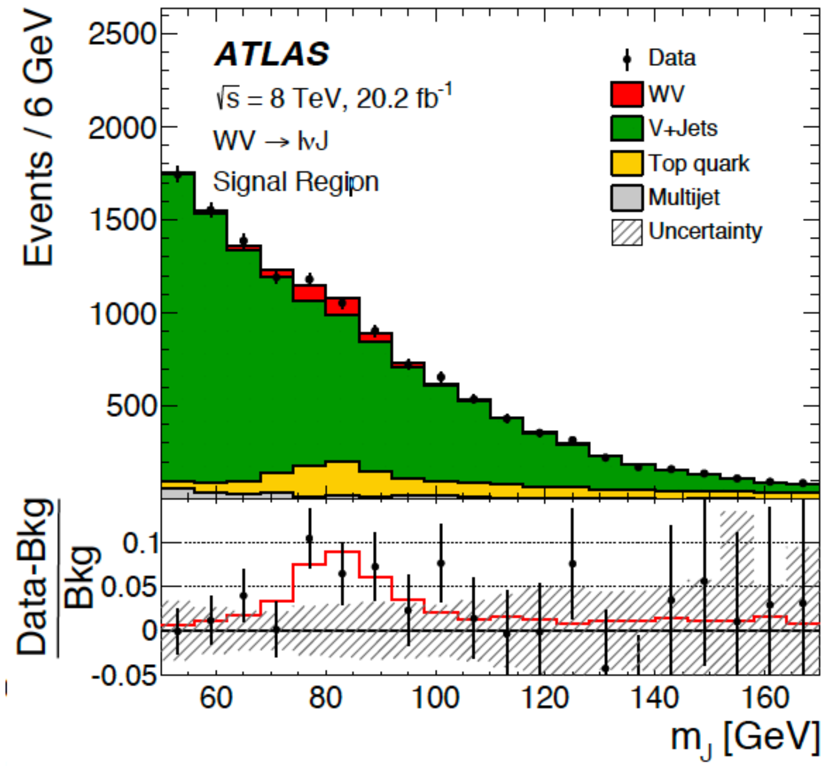


1 lepton

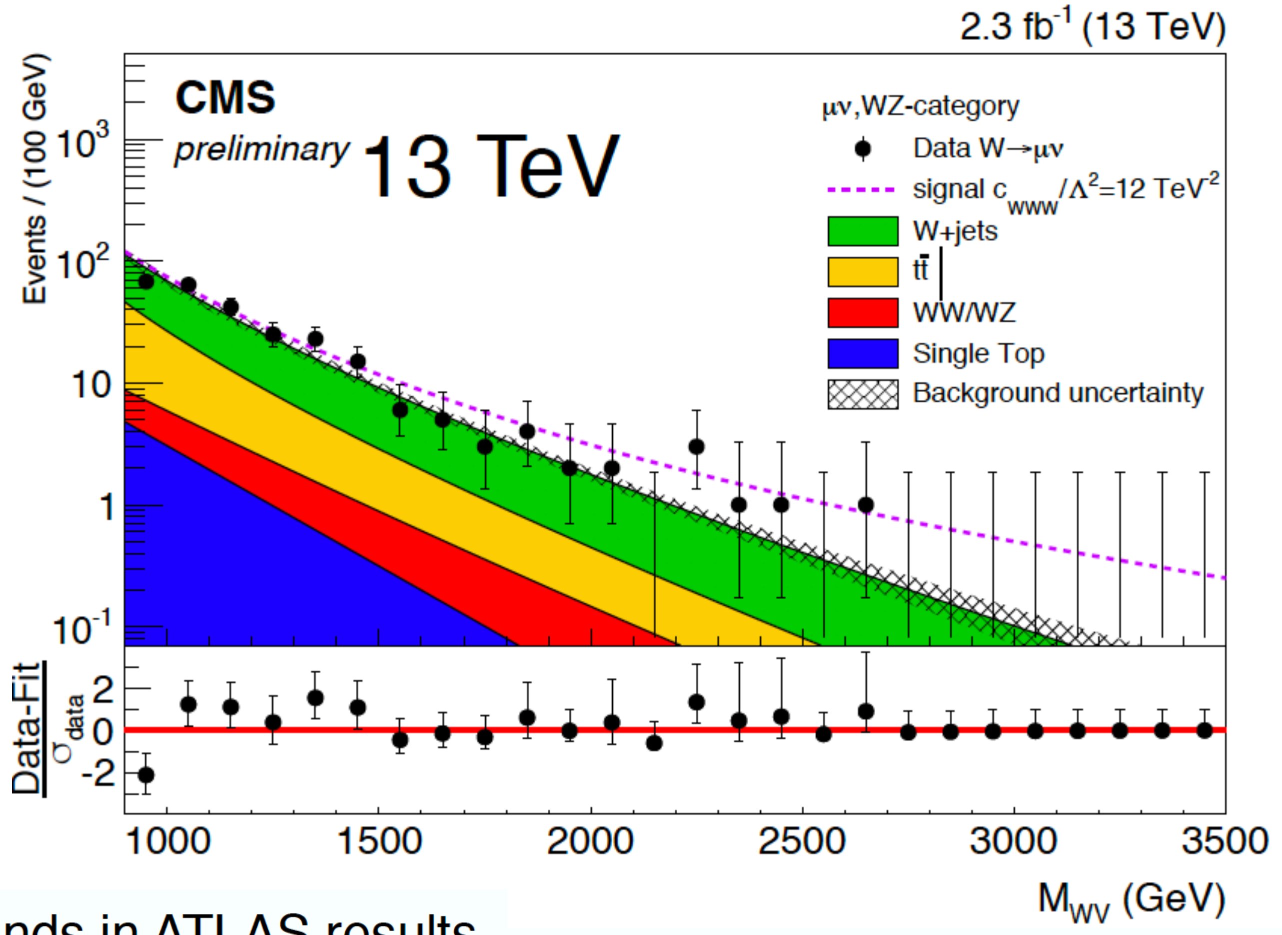
MET

2 jets or merged jet





Phys. Rev. D 95 (2017) 032001



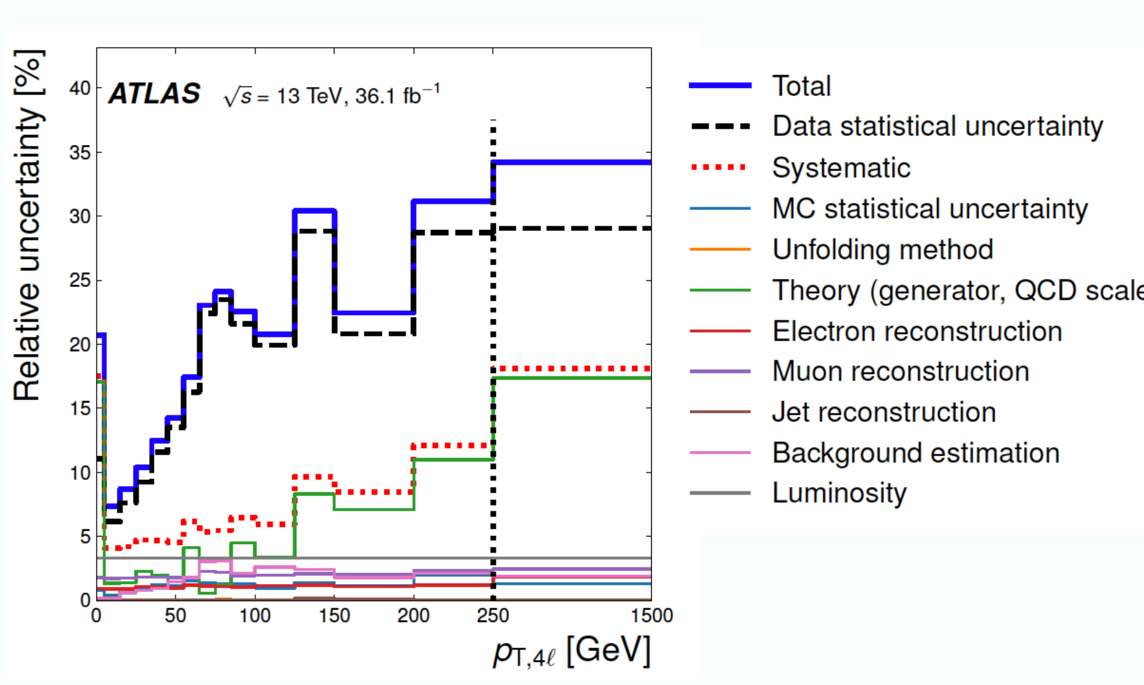
Comparison of CMS results — Similar trends in ATLAS results

8 TeV	**WW→ℓνℓν**	**WZ→ ℓνℓℓ**	**WV→ℓν jj**
c_{WWW}/Λ^2	[-5.7, 5.9]	[-4.6, 4.2]	[-2.7,2.7]
c_W/Λ^2	[-11.4,5.4]	[-4.2, 8.0]	[-2.0,5.7]
c_B/Λ^2	[-29.2, 23.9]	[-260, 210]	[-14,17]

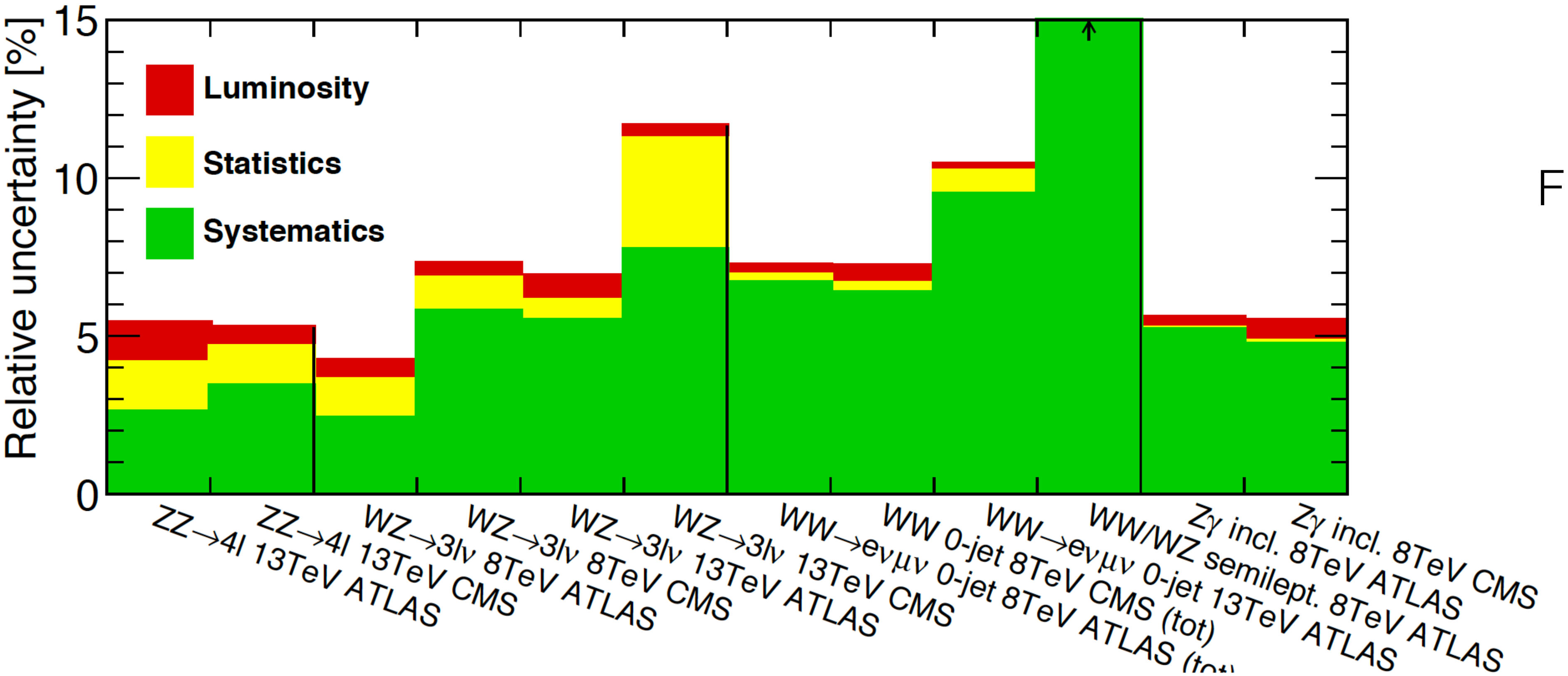
Limits already surpass LEP and will improve with Run2 Data

Diboson Summary

- A lot of work has gone into understanding the theory aspects
  - We can currently test up to NNLO!
- Uncertainties on total cross section measurements are approaching the luminosity uncertainty
- Uncertainties on differential measurements still dominated by statistics
- Theory uncertainties are important as well
- Can mitigate lumi, theory uncertainties with ratios



(a) Transverse momentum of the four-lepton system.



stack of uncertainties in quadrature: syst, $\sqrt{\text{syst}^2 + \text{stat}^2}$, ..

From Elena Yatsenko talk LHCEWWG-MB: https://indico.cern.ch/event/706190/

Diboson Summary

- A lot of work has gone into understanding the theory aspects
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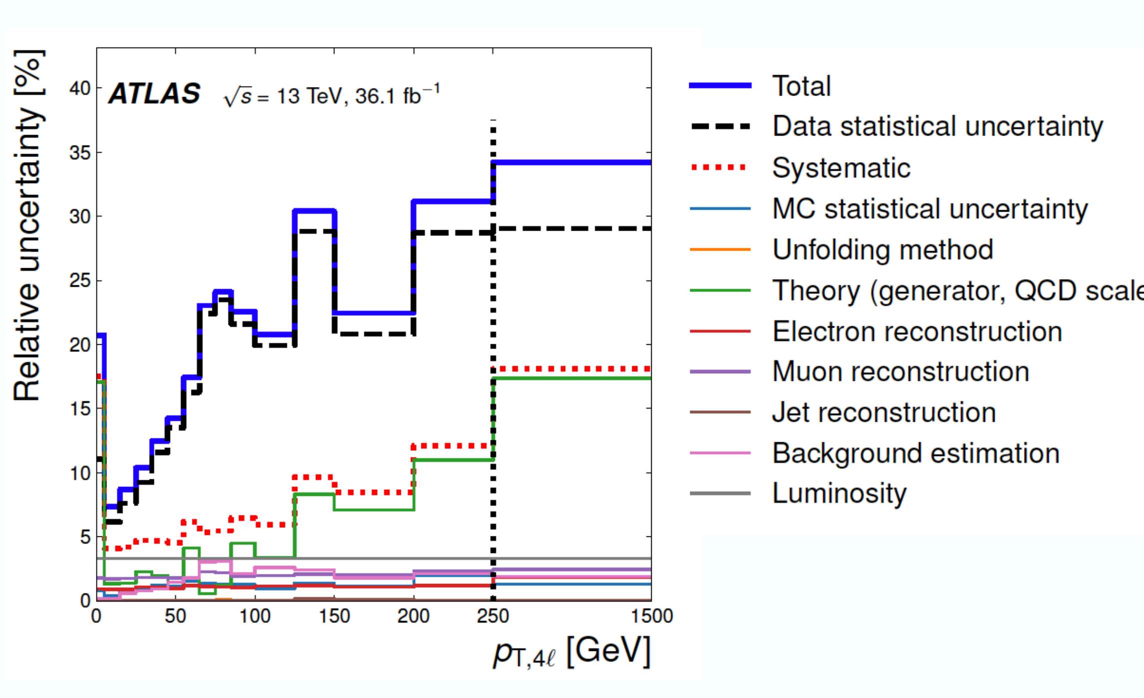

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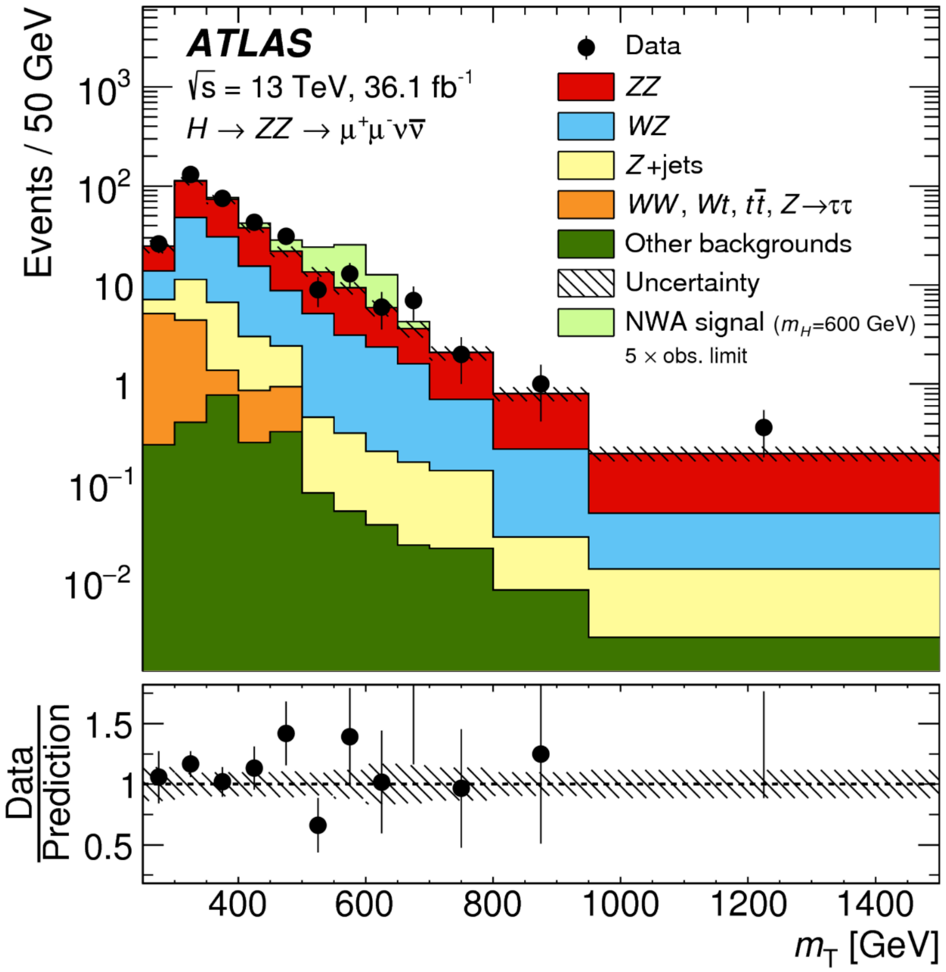


- Synergies with searches in the same final states
  - X→ WW → lvlv: Eur. Phys. J. C 78 (2018) 24
  - X→ ZZ→ llll arXiv:1712.06386
  - X→ ZZ→ llvv arXiv:1712.06386

ssWW and ZZ

- Two forward jets well separated in rapidity - highest pT jets considered as tag jets
- Two same-sign leptons & ET_{miss}
- Non-VBS EW processes with the same final state contribute to the signal → suppressed through kinematic cuts

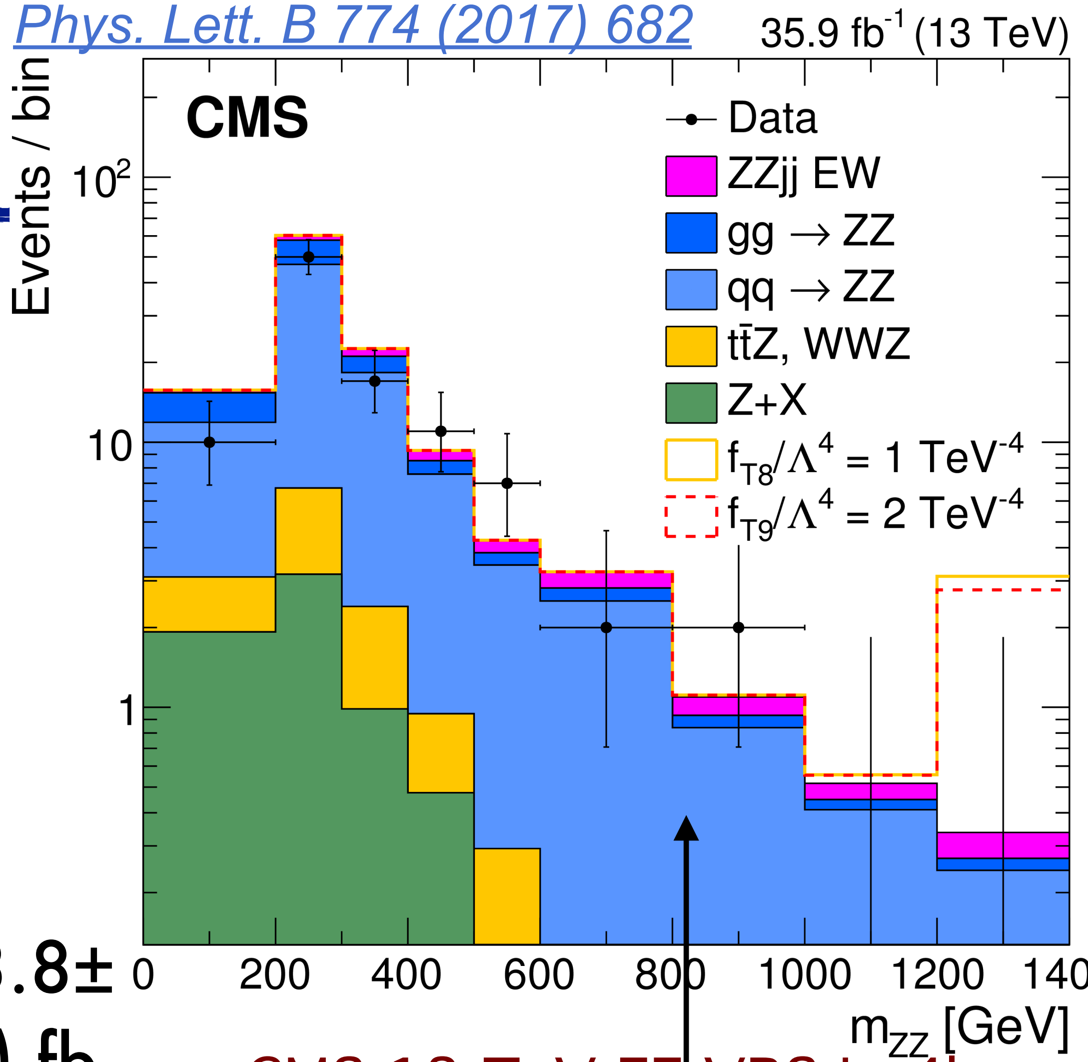
ATLAS 8 TeV

- 3.6 σ evidence
- measured sigma of 1.5± 0.5 fb

CMS 13 TeV

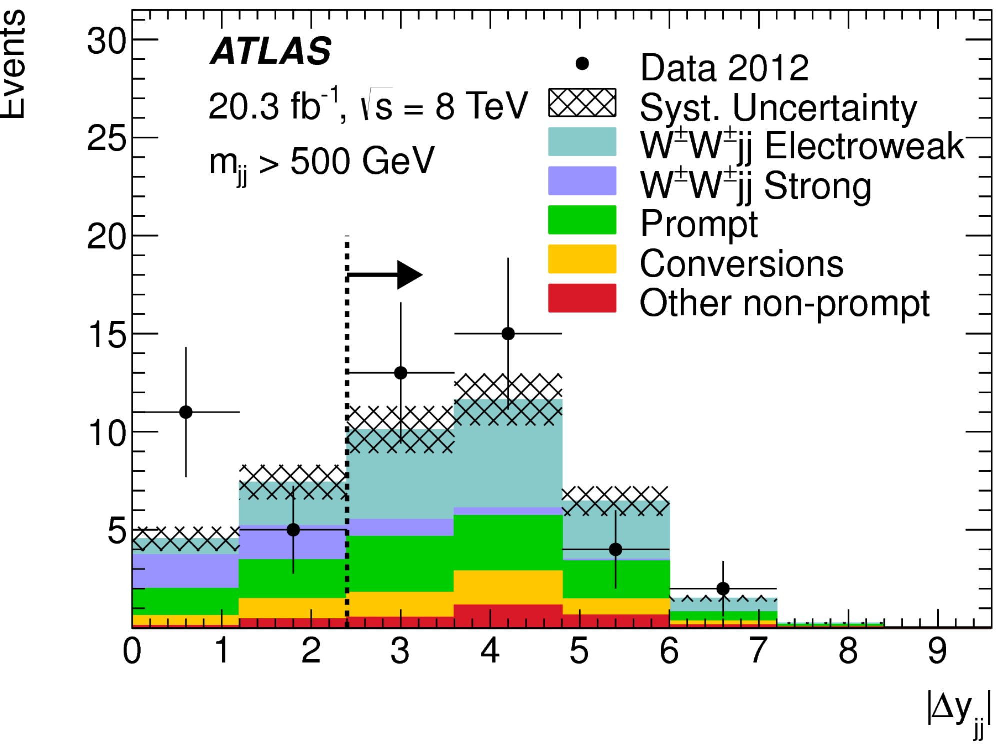
- 5.5 σ observation
- measured sigma of 3.8± 0.7 (stat) ± 0.4 (syst) fb

Phys. Lett. B 774 (2017) 682

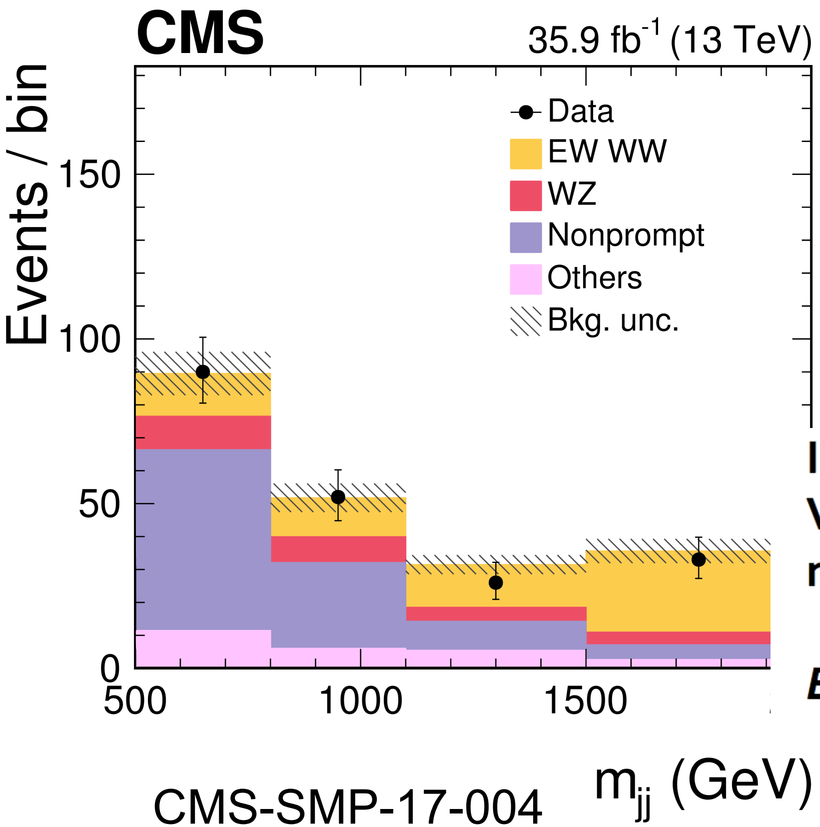


CMS 13 TeV ZZ VBS in 4l

- Start from inclusive ZZ measurement
  - Add 2 jets in VBS Topology



Phys. Rev. Lett. 113, 141803



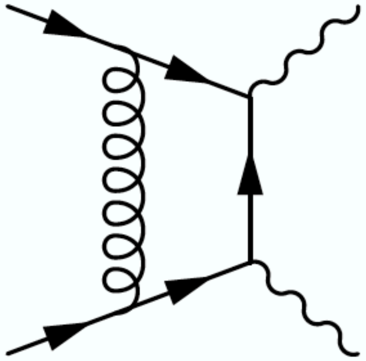
CMS-SMP-17-004

Inclusive region: m_{jj}>100GeV
VBS region: $|\Delta\eta_{jj}| > 2.4$ + $m_{jj} > 400$ GeV
non-VBS region: $|\Delta\eta_{jj}| < 2.4$ or $m_{jj} < 400$ GeV

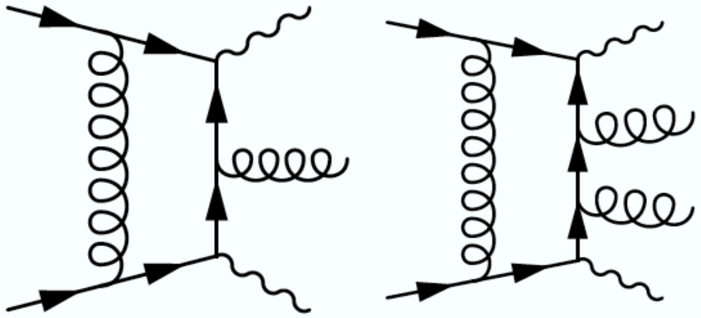
EWK signal significance 2.7σ (exp 1.6σ)

Simulation Tools

Full NLO simulation

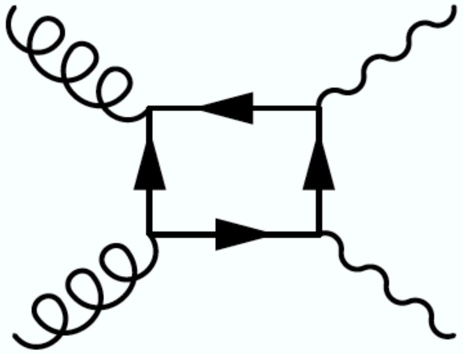


Madgraph_amc@NLO
Powheg (-Box)
Sherpa



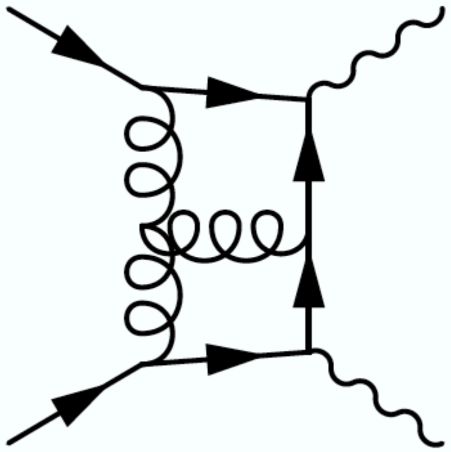
With FxFx merging of tree-level emission of additional jets

simulation of tree level gluon-gluon (NNLO)



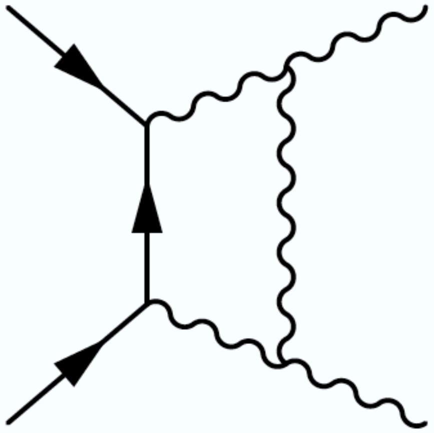
gg2VV
MCFM
Sherpa

Full NNLO calculations



MATRIX
2γNNlo
published calculations

EWK corrections



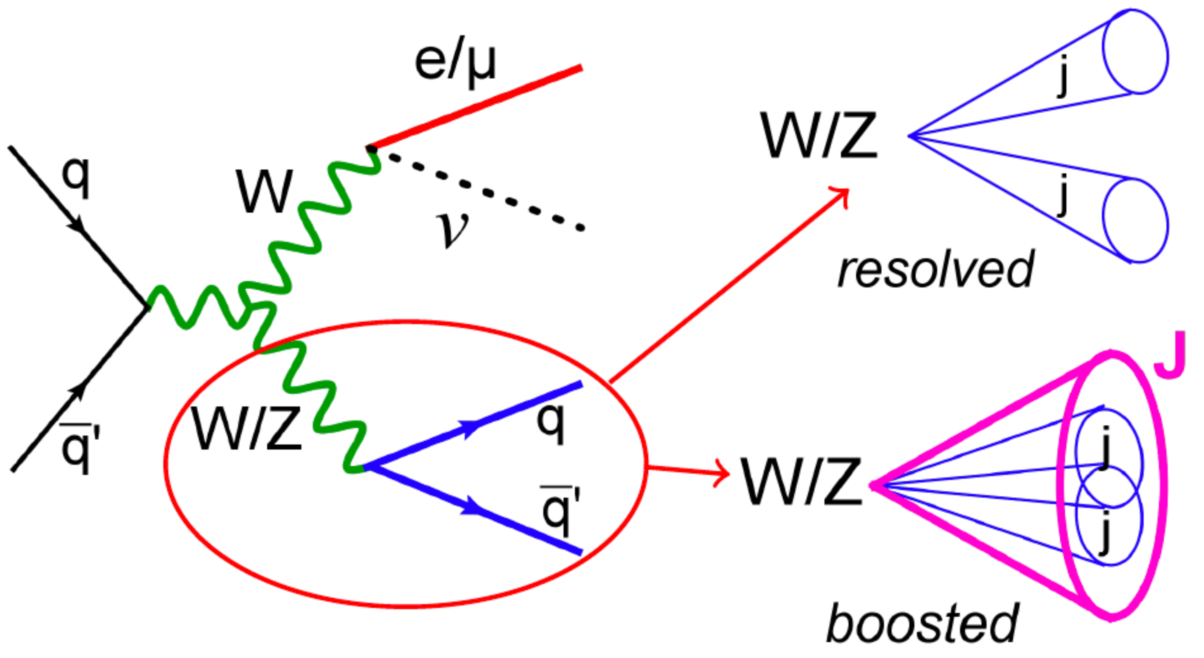
PHANTOM
Recola
published calculations

Pythia : Parton showering, hadronization, UE
PDFs : NNPDF commonly used now

WW/WZ ->lvjj

STDM-2015-23

- 20.2 fb^{-1} of 8 TeV data
- $\sim$ 6 times higher branching fraction than fully-leptonic channels.
- Two topologies:
  $WV \rightarrow \ell\nu jj$ (resolved)
  $WV \rightarrow \ell\nu J$ (boosted)
- Dominant background: W/Z+jets

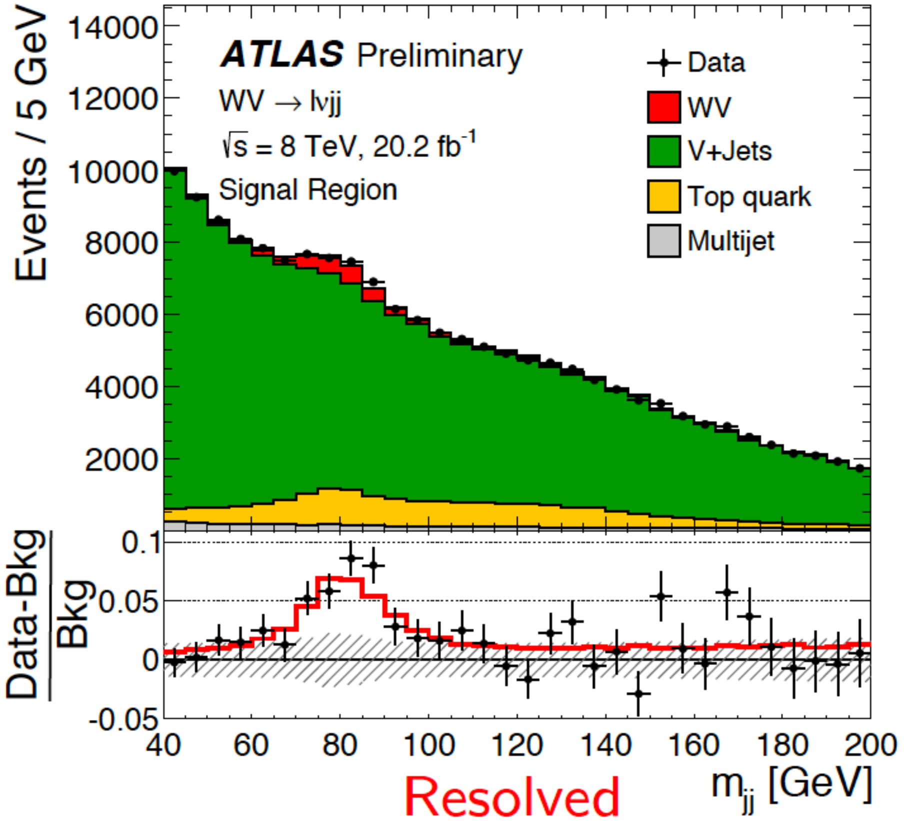


Resolved topology:

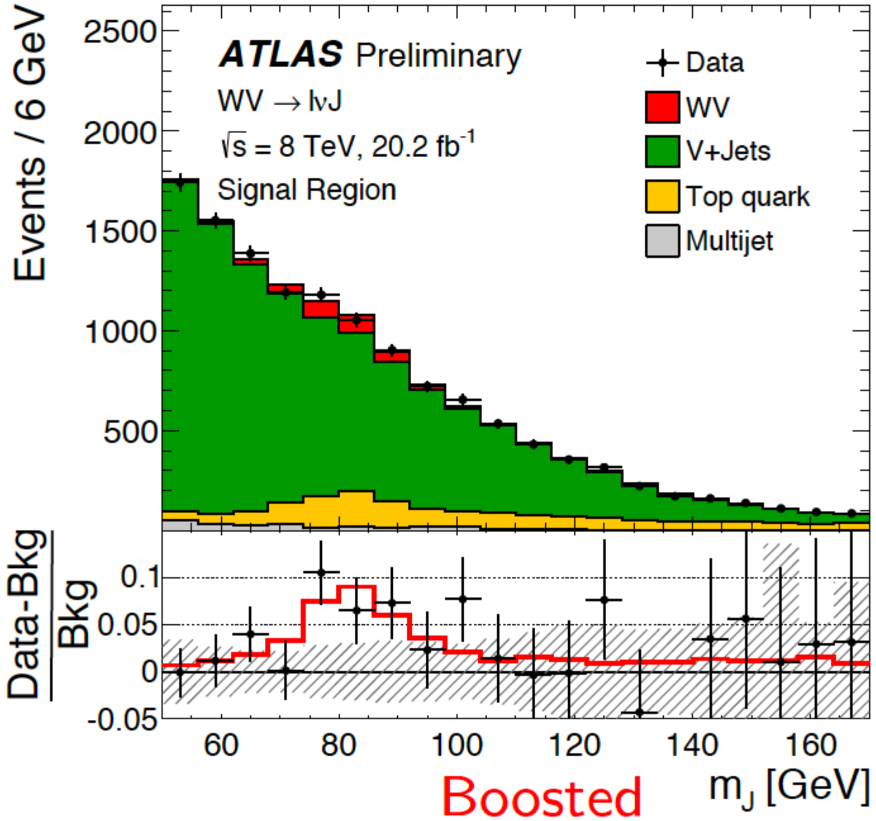
- Two anti-kt R=0.4 jets
- **Large statistics** and **lower systematic uncertainty**

Boosted topology:

- One anti-kt R=1 jet
- **High sensitivity to aTGCs** due to probing higt p_T range



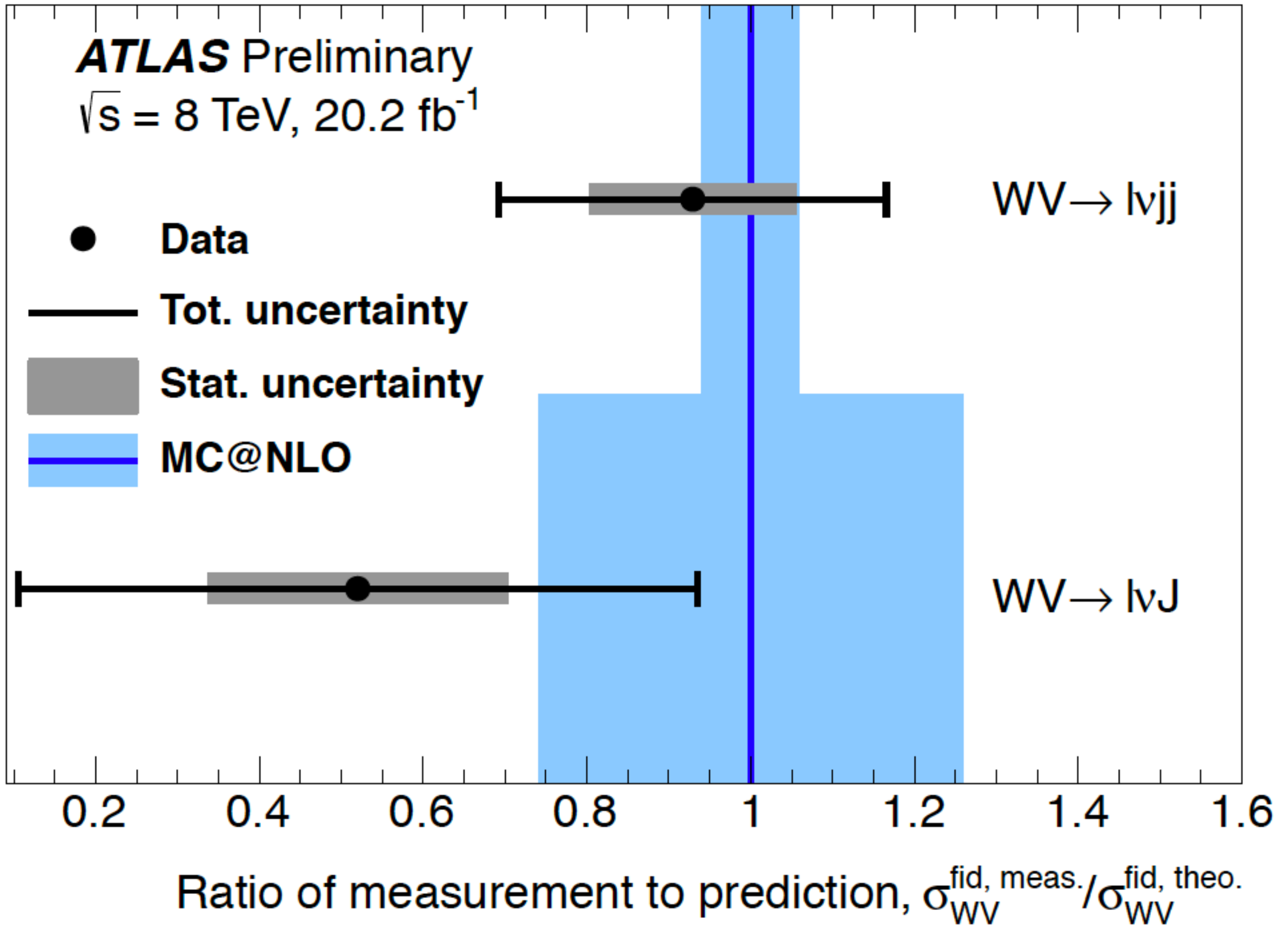
Resolved



Boosted

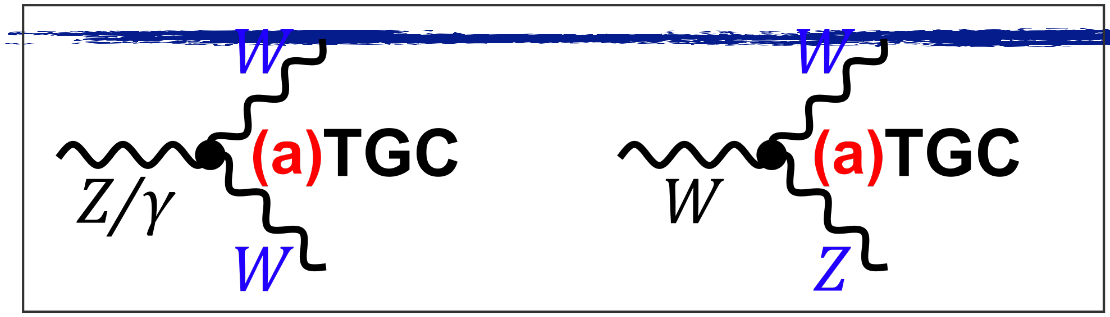
WW/WZ->lvjj

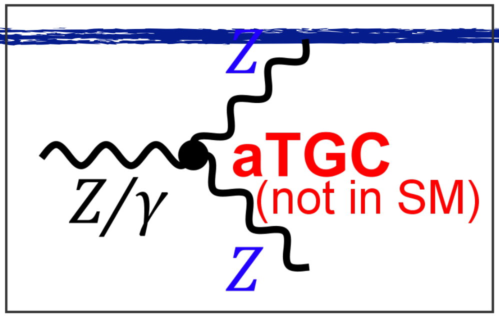
- Fiducial cross section is measured independently for the $WV \to \ell\nu jj$ and $WV \to \ell\nu J$ phase spaces.
- The two phase spaces are *partially overlapping*: some $V \to qq'$ events can be reconstructed both as 2 small-R jets and as one large-R jet => no combination of the two cross section measurements.
- The cross-section is extracted from a fit of the signal and background templates to m(jj)/m(J).



- Both measurements are compatible with Standard Model predictions at NLO QCD.

Anomalous gauge couplings and rare processes



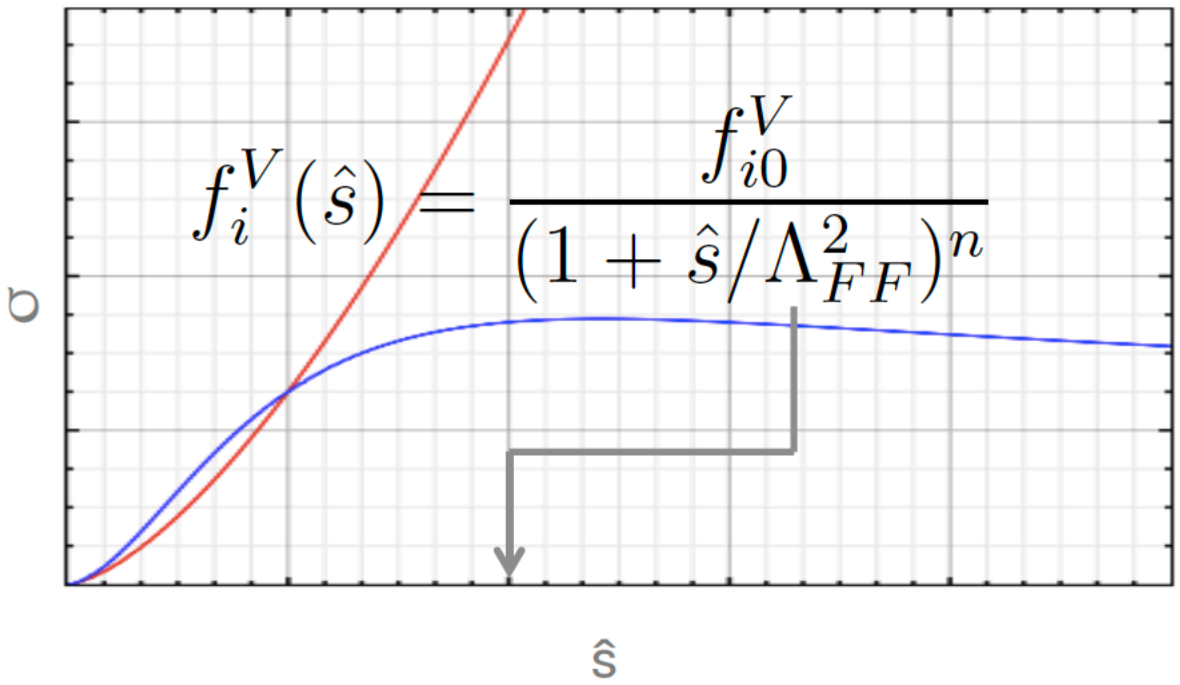


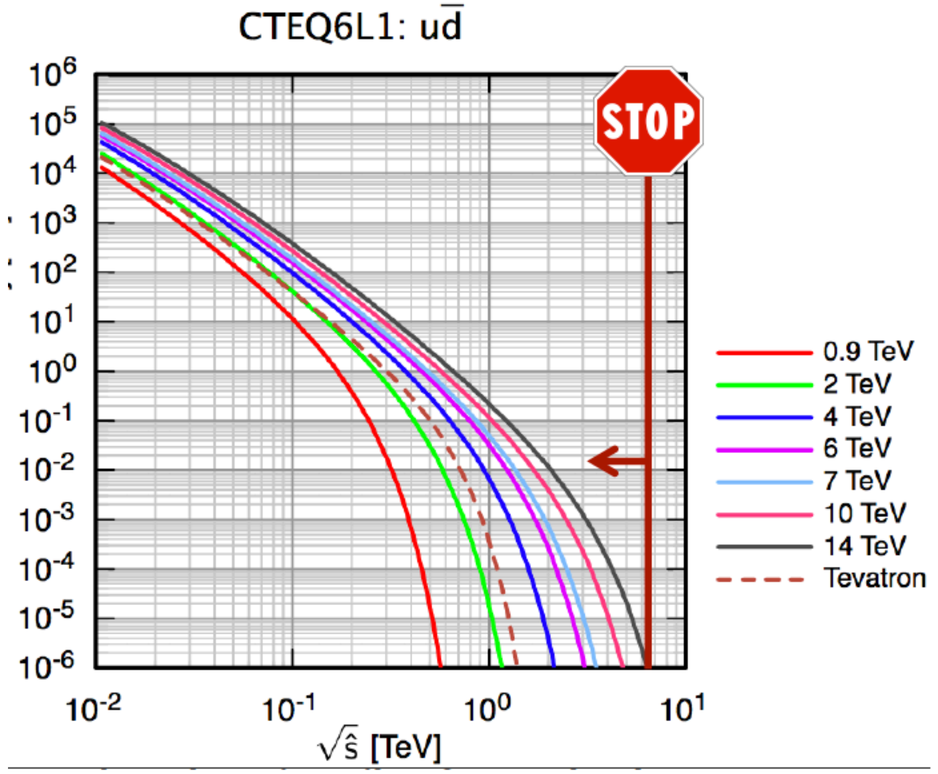
parameters in red zero in SM

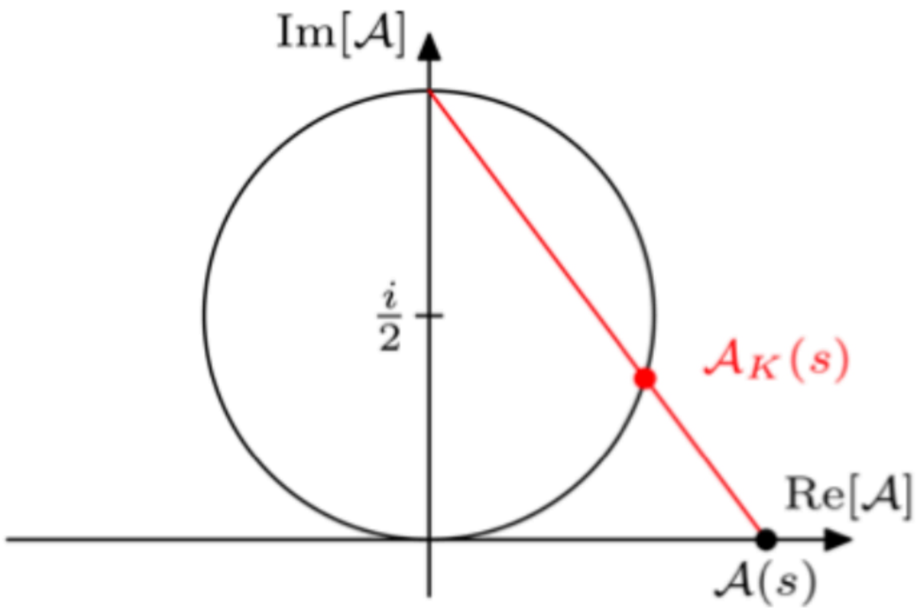
- WWV (V= Z/γ) couplings -> WW and WZ measurements (also Wγ)
  - Effective Lagrangian: new physics effects are parameterized as deviations from SM coupli $\frac{\mathcal{L}_{\rm WWV}}{g_{\rm WWV}} = ig_1^{\rm V}({\rm W}^+_{\mu\nu}{\rm W}^{\mu}{\rm V}^{\nu} - {\rm W}^+_{\mu}{\rm V}_{\nu}{\rm W}^{\mu\nu}) + i\kappa_{\rm V}{\rm W}^+_{\mu}{\rm W}_{\nu}{\rm V}^{\mu\nu} + \frac{i\lambda_{\rm V}}{m^2_{\rm W}}W^+_{\lambda\mu}W^{\mu}_{\nu}{\rm V}^{\nu\lambda}$
  - 5 parameters: Δg_1^Z (g_1^Z-1), $\Delta\kappa_1^Z$ (κ_1^Z -1), $\Delta\kappa_1^\gamma$ (κ_1^γ-1), λ_Z, λ_γ
- Effective field theory (EFT) approach: cWWW=Λ^2, cW =Λ^2, cB=Λ^2 (WWZ, WWγ)
- ZZV (V= Z/γ) couplings -> ZZ measurements (also Zγ)
  - Effective vertex function approach: $\mathcal{L}_{\rm ZZV} = -\frac{e}{M_{\rm Z}^2}\left(f_4^{\rm V}(\partial_\mu {\rm V}^{\mu\beta})Z_\alpha(\partial^\alpha Z_\beta) + f_5^{\rm V}(\partial^\sigma V_{\sigma\mu})\tilde{Z}^{\mu\beta}Z_\beta\right)$
- Tools: Start with SM prediction (usually NLO)
- Add weights to simulated sample corresponding to different aGC values, reweight from one point to the other
  - Commonly use Madgraph at LO, NLO becoming available
  - VBFNLO, MC@NLO also provide calculations for different point

Interpretation

- Fix this by
  - Introducing form factors.
    - LEP, TeVatron, LHC
  - Project scattering amplitude.
    - k-Matrix (ATLAS)
  - Limit range of validity.
    - SM EFT
      (ATLAS, CMS).





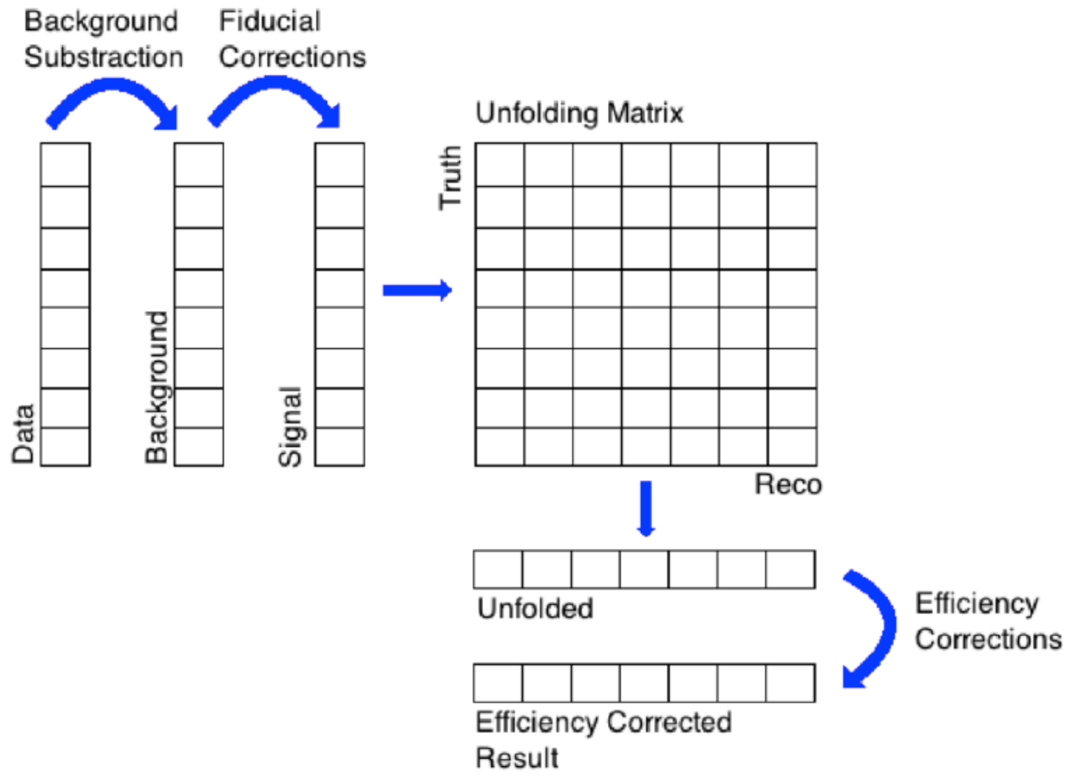


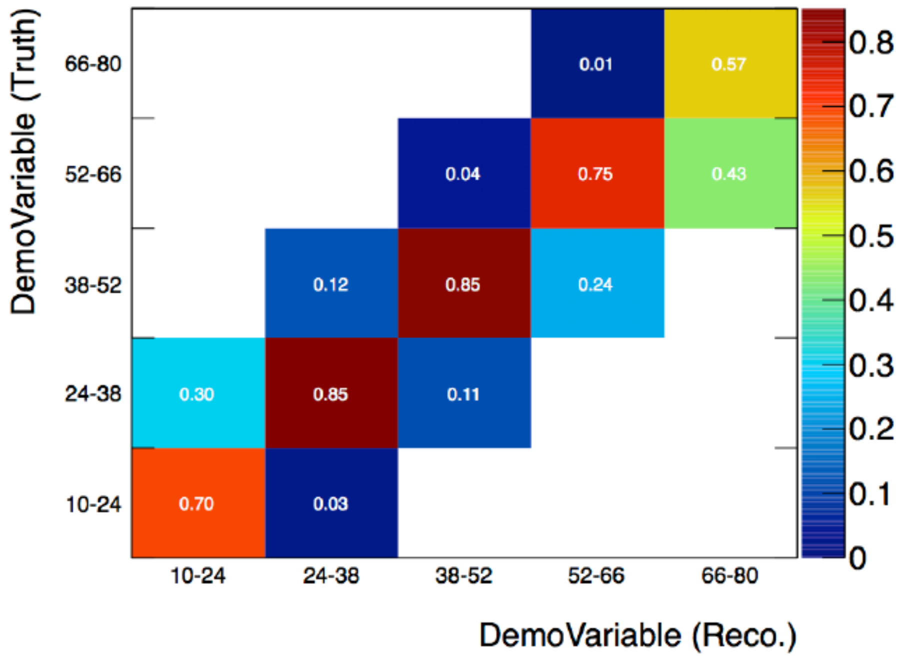
Interpretation

	Limits	**Unitarisation Scheme**	**Vertex**	**Process**
TGC	κ, λ, g_1	FF, none	WW(Z/γ)	pp - WZ,Wγ,WW,Wjj
	f_4, f_5	FF, none	ZZ(Z/γ)	pp - ZZ, Zjj
	h_3, h_4	FF, none	Zγ (Z/γ)	pp - Zγ
QGC	$a_{0,C}^{W}, f_{T,M}$	FF, none	WWγγ	pp - WW (excl), Wγγ
	$f_{T,M}$	FF, none	γγZ(Z/γ)	pp - Zγγ
	$f_{s,M}, \alpha_{4,5}$	FF, none, k-matrix	WWWW	pp - WWW,WWjj (ss)
	$\alpha_{4,5}$	k-matrix	WZW(Z/γ)	pp - WZjj

Unfolding

- Unfolded kinematic distributions:
  - Remove detector effects to allow independent interpretation of Data.
- Commonly used method
  - Bayesian iterative unfolding.
  - Unfolding within detector acceptance.
  - Normalised distributions.
- Published Results (HEPDATA):
  - Fractional, binned kinematic distributions.
  - Full correlation matrices.
  - Statistical and systematic uncertainties, background contributions.





The k-framework (1307.1347)

- modifications of the SM couplings involving h in the unitary gauge

$$\frac{\sigma_{\mathrm{WH}}}{\sigma_{\mathrm{WH}}^{\mathrm{SM}}} = \kappa_{\mathrm{W}}^2 \qquad \frac{\Gamma_{\mathrm{ZZ}^{(*)}}}{\Gamma_{\mathrm{ZZ}^{(*)}}^{\mathrm{SM}}} = \kappa_{\mathrm{Z}}^2$$

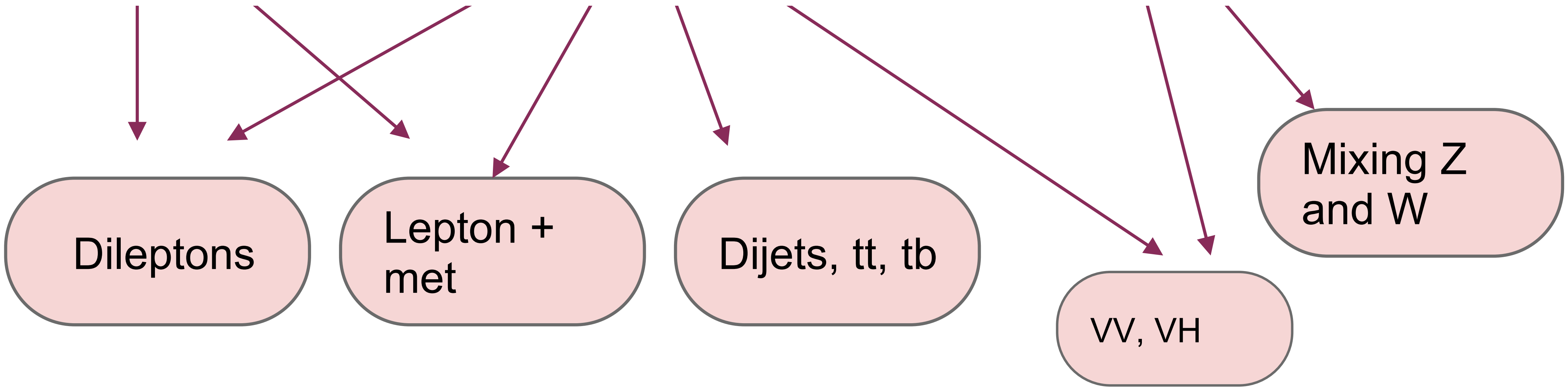
$$\frac{\sigma_{\mathrm{ZH}}}{\sigma_{\mathrm{ZH}}^{\mathrm{SM}}} = \kappa_{\mathrm{Z}}^2 \qquad \frac{\Gamma_{\mathrm{b\bar{b}}}}{\Gamma_{\mathrm{b\bar{b}}}^{\mathrm{SM}}} = \kappa_{\mathrm{b}}^2$$

- PROs:
  - Simple and intuitive (at first)
  - Good for exploratory analysis (of SM hypothesis)
- CONs:
  - Not so Simple and intuitive in more complex situations
  - Not supported by physical hypothesis
  - Not renormalizable

Why combine?

- **Diboson:** Several final states with same sensitivity, expect good improvement with combination
- **Diboson+Leptons:** allows to distinguish between models
- We use a model with a generalized interaction Lagrangian
- **Referred to as the Heavy Vector Triplet (HVT) model**
- Define HVT-A (weakly-coupled) and HVT-B (strongly-coupled) benchmarks

$$\mathcal{L}_{\mathcal{W}}^{\text{int}} = -g_q \mathcal{W}^a_\mu \bar{q}_k \gamma^\mu \frac{\sigma_a}{2} q_k - g_\ell \mathcal{W}^a_\mu \bar{\ell}_k \gamma^\mu \frac{\sigma_a}{2} \ell_k - g_H \left(\mathcal{W}^a_\mu H^\dagger \frac{\sigma_a}{2} i D^\mu H + \text{h.c.} \right)$$



Dileptons

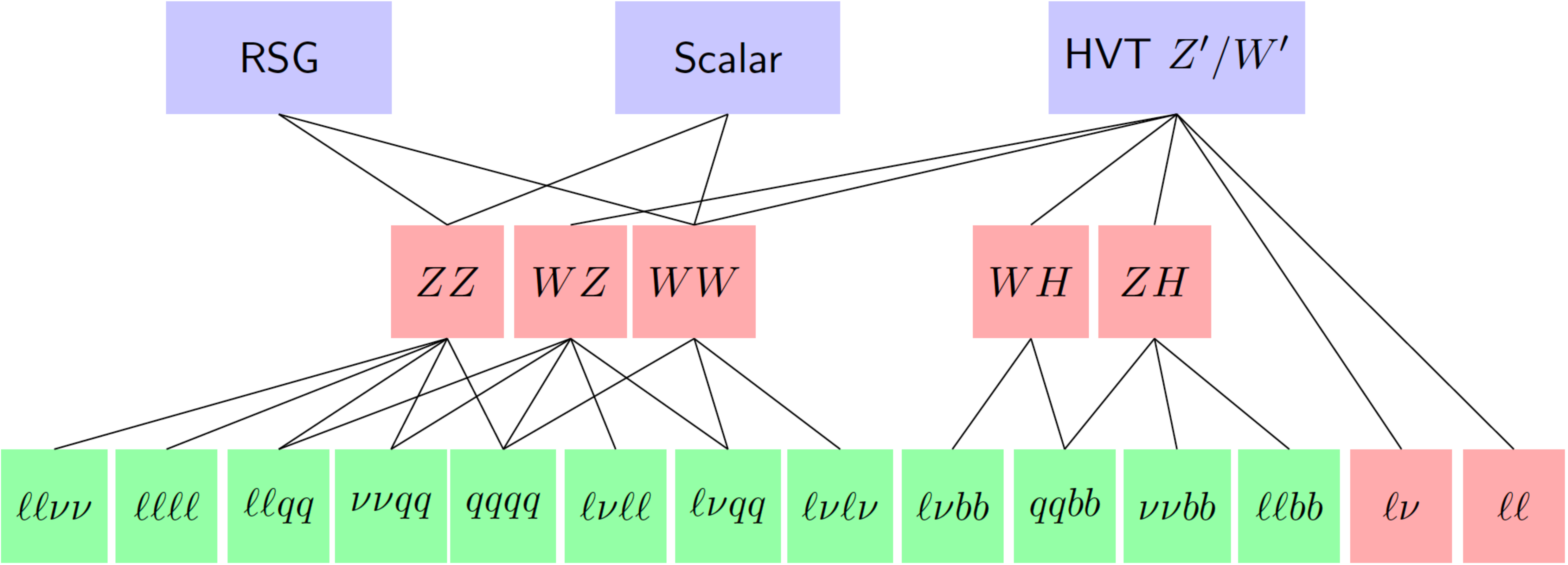
Lepton + met

Dijets, tt, tb

VV, VH

Mixing Z and W

Bosonic & leptonic channels: VV, VH, lv, ll


RSG
Scalar
HVT Z'/W'

ZZ
WZ
WW
WH
ZH

$\ell\ell\nu\nu$
$\ell\ell\ell\ell$
$\ell\ell qq$
$\nu\nu qq$
$qqqq$
$\ell\nu\ell\ell$
$\ell\nu qq$
$\ell\nu\ell\nu$
$\ell\nu bb$
$qqbb$
$\nu\nu bb$
$\ell\ell bb$
$\ell\nu$
$\ell\ell$

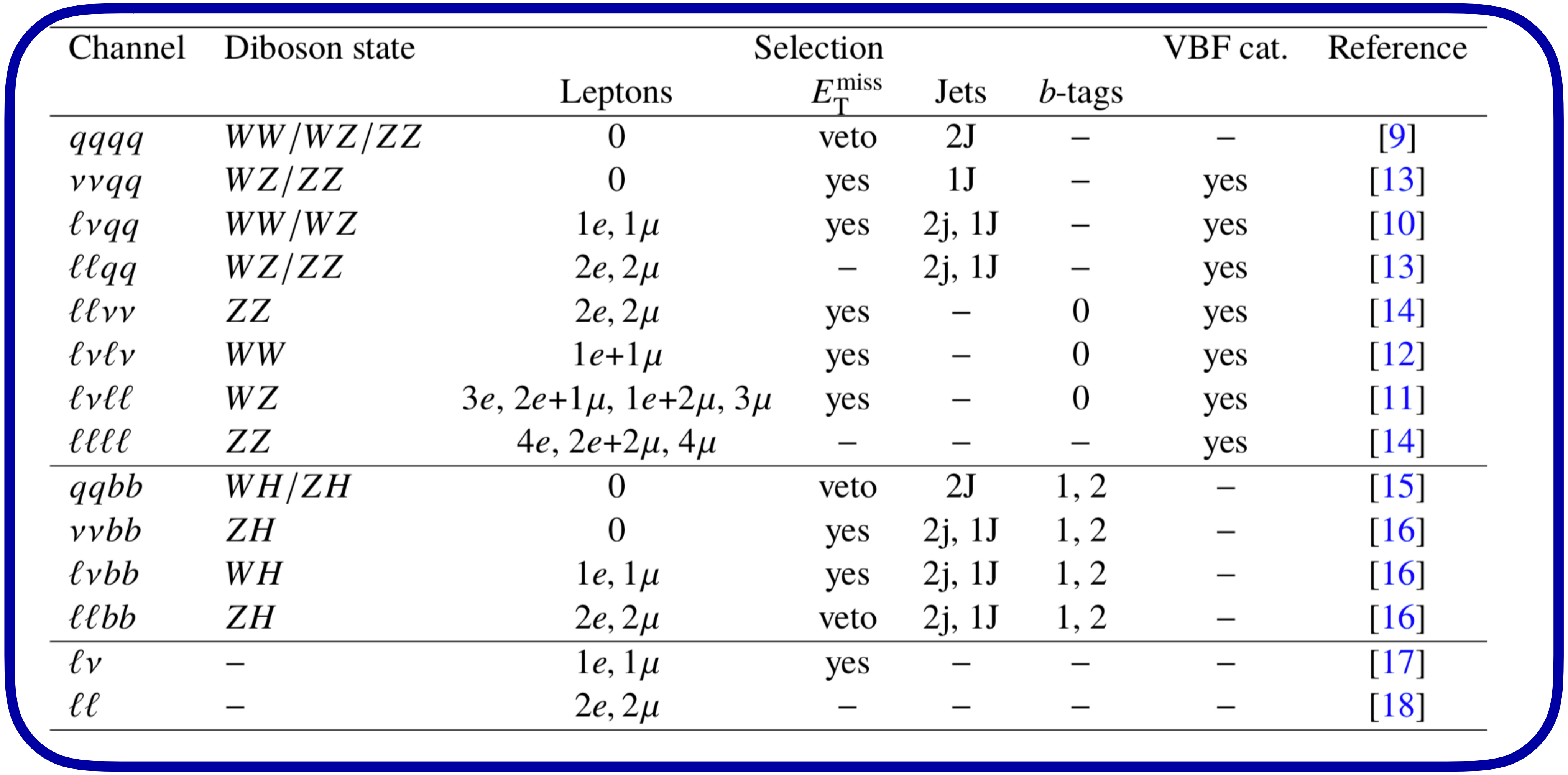
Step-by-step combination procedure:

1. Combine seperately VV, VH, and dilepton
2. Combine VV+VH
3. Combine VV+VH+dilepton **first time @ LHC**

Combination

- Orthogonality between channels guaranteed by selection on number of leptons, jets, b-tags, and selection on ETmiss
- Overlap between VV and VH analyses removed by vetoing Higgs boson candidates overlapping W or Z mass window

j=small-R jet, J=large-R jet

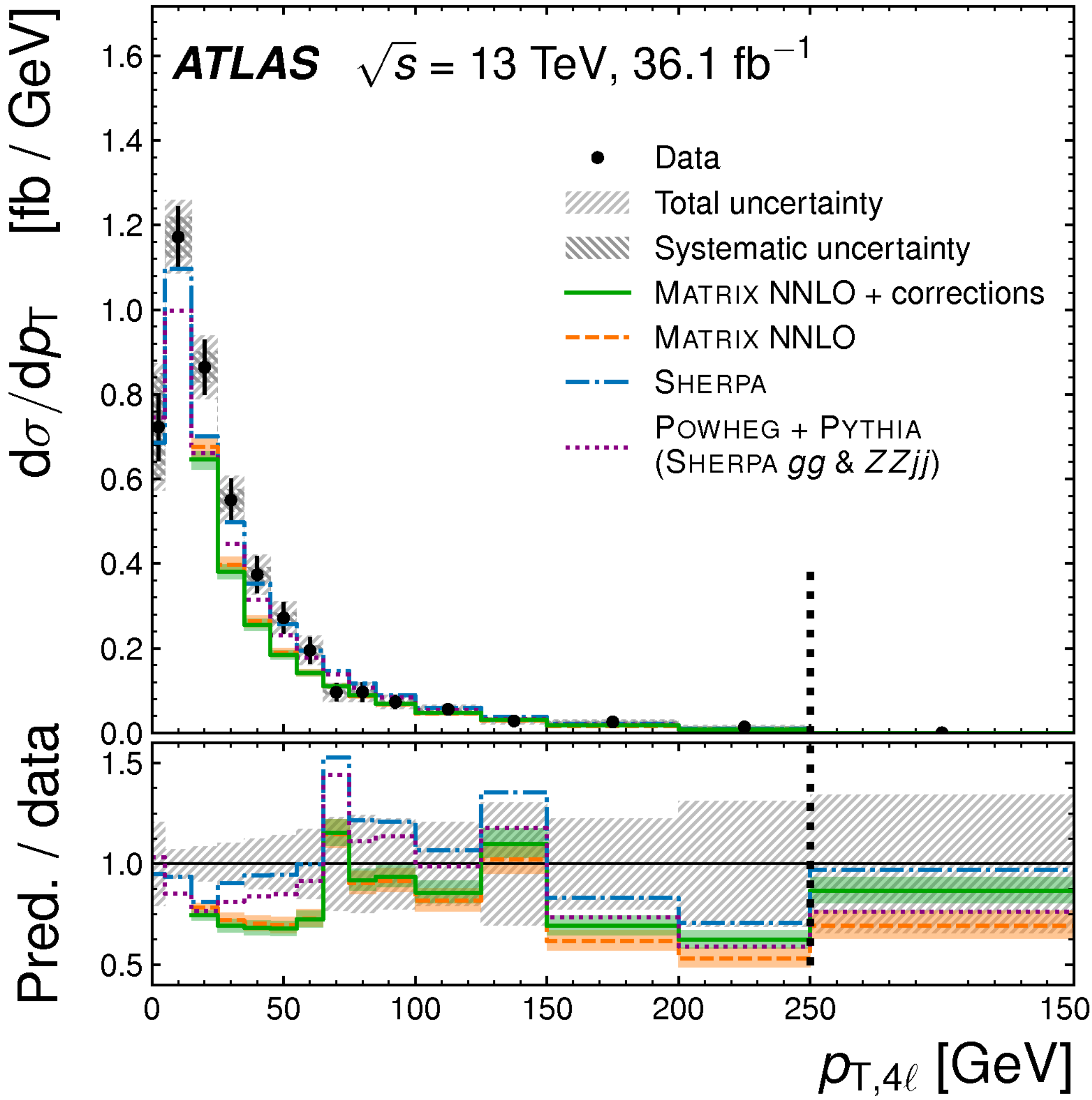


Channel	Diboson state	Selection				VBF cat.	Reference
		Leptons	E_T^{miss}	Jets	*b*-tags		
$qqqq$	$WW/WZ/ZZ$	0	veto	2J	–	–	[9]
$\nu\nu qq$	WZ/ZZ	0	yes	1J	–	yes	[13]
$\ell\nu qq$	WW/WZ	$1e$, 1μ	yes	2j, 1J	–	yes	[10]
$\ell\ell qq$	WZ/ZZ	$2e$, 2μ	–	2j, 1J	–	yes	[13]
$\ell\ell\nu\nu$	ZZ	$2e$, 2μ	yes	–	0	yes	[14]
$\ell\nu\ell\nu$	WW	$1e$+1μ	yes	–	0	yes	[12]
$\ell\nu\ell\ell$	WZ	$3e$, $2e$+1μ, $1e$+2μ, 3μ	yes	–	0	yes	[11]
$\ell\ell\ell\ell$	ZZ	$4e$, $2e$+2μ, 4μ	–	–	–	yes	[14]
$qqbb$	WH/ZH	0	veto	2J	1, 2	–	[15]
$\nu\nu bb$	ZH	0	yes	2j, 1J	1, 2	–	[16]
$\ell\nu bb$	WH	$1e$, 1μ	yes	2j, 1J	1, 2	–	[16]
$\ell\ell bb$	ZH	$2e$, 2μ	veto	2j, 1J	1, 2	–	[16]
$\ell\nu$	–	$1e$, 1μ	yes	–	–	–	[17]
$\ell\ell$	–	$2e$, 2μ	–	–	–	–	[18]

- HVT model for lv+ll: Require generator-level mass to be within mass window of W'/Z' pole to minimize effects of interference btw signal and dominant DY bkg

Cross section definitions

- Why fiducial cross-sections?
- Correction for detector effects
  - easy interpretation for theorists
  - preserve measurements for posterity
- No acceptance correction
  - less model dependence



Number of measured signal events

Cross section

Branching fraction

bin i

$$\sigma_i = \frac{N_{reco,i}}{c_i * A_i * L * B}$$

Integrated luminosity

Correction for detector efficiency

Acceptance

Fiducial cross section = cross section in fiducial volume (cuts applied to generated events)

$$\sigma_{fid,i} * B = \frac{N_{reco,i}}{c_i * L}$$

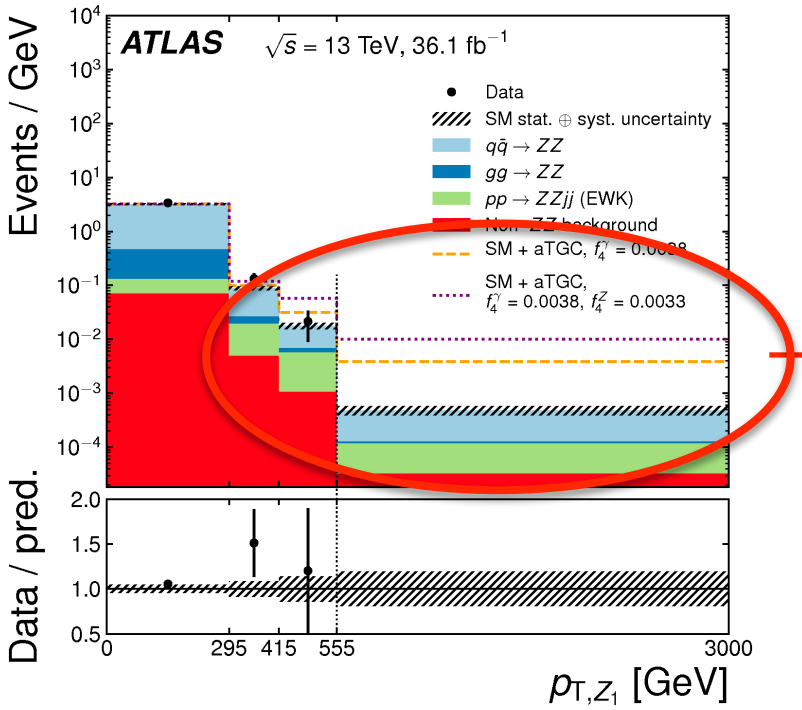
Fiducial volumes depend on event selection/decay channel

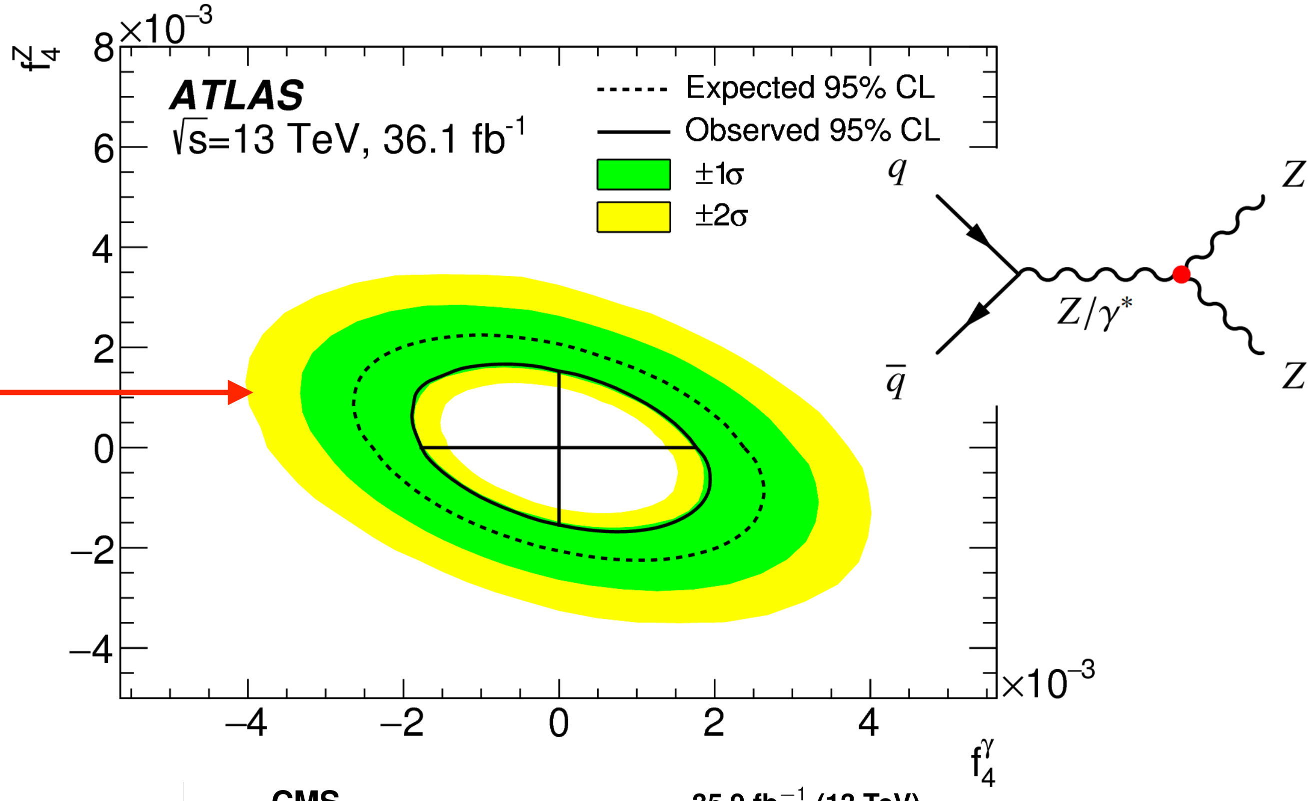
- Why differential cross section?
- 1. check of SM calculations, and MC generators used in the analyses → feedback to theory groups
- 2. deviations from the Standard Model predictions could be due to new physics → high energy bins are sensitive to aGCs

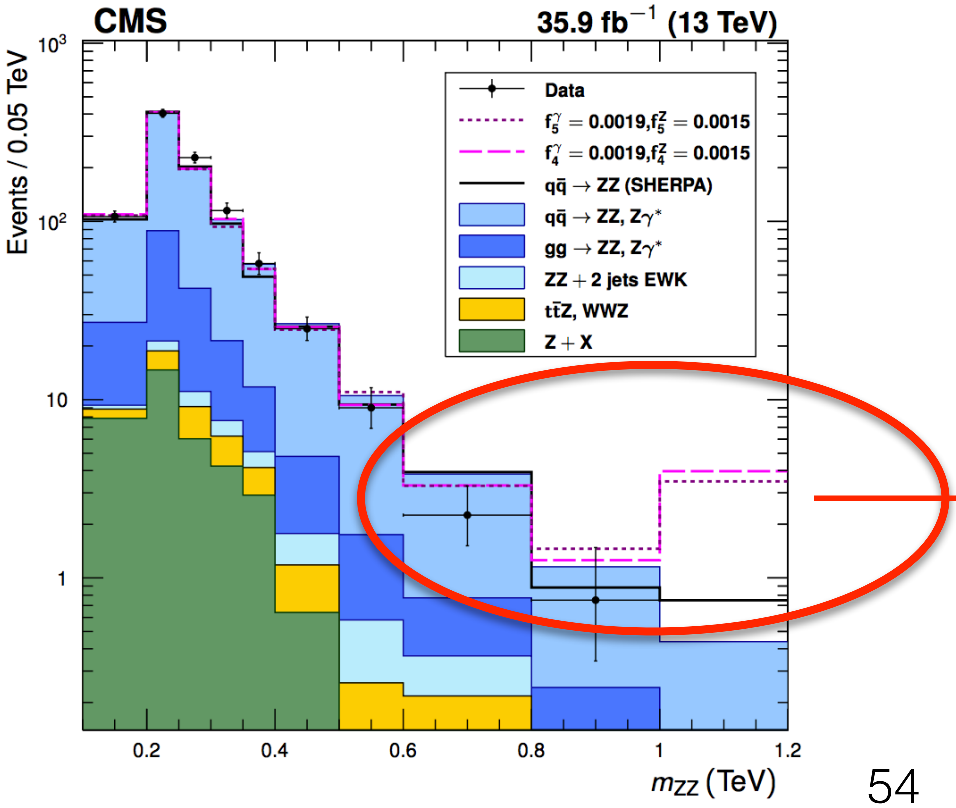
Search for neutral aTGCs

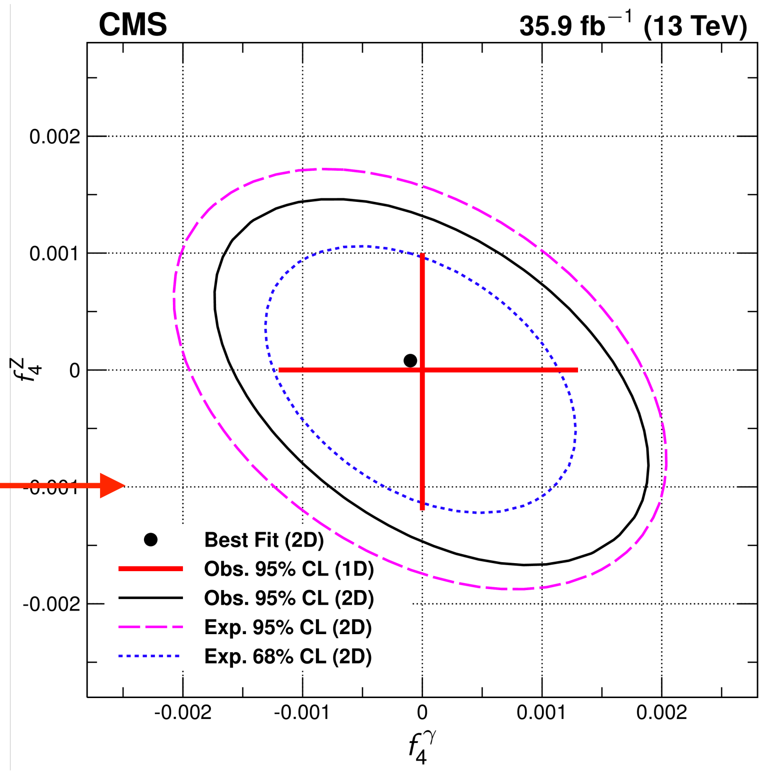
$$\mathcal{L}_{\mathrm{ZZV}} = -\frac{e}{M_Z^2}\left(f_4^V(\partial_\mu V^{\mu\beta})Z_\alpha(\partial^\alpha Z_\beta) + f_5^V(\partial^\sigma V_{\sigma\mu})\tilde{Z}^{\mu\beta}Z_\beta\right)$$

- Primary signature of non-0 nTGC is increase in ZZ cross-section at high ZZ invariant masses and high Z bosons pT.
- ATLAS: pT-distribution of leading Z boson is used to derive limits on anomalous triple gauge couplings.
- CMS use mZZ



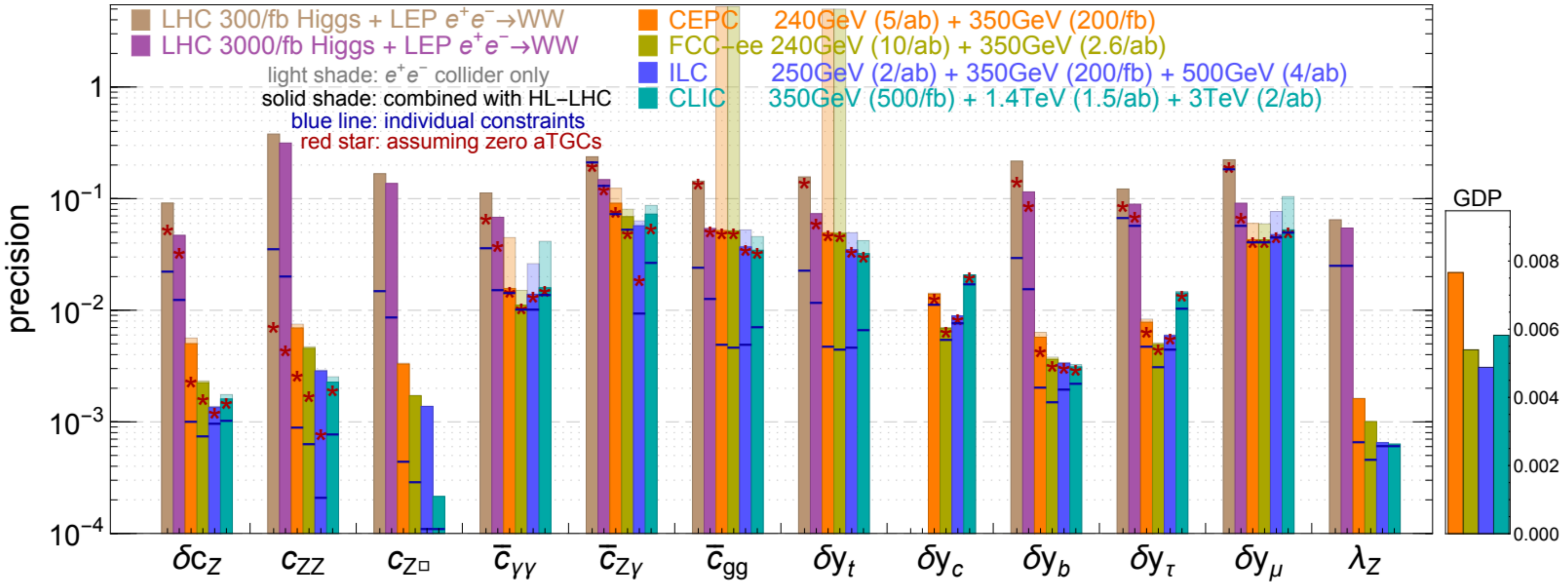






Global Higgs and diboson constraints

[Duriex, Grojean, Gu, Wang, '17]



- importance of complementary measurements
  (different c.o.m. energies, polarizations, distributions)
- importance of diboson measurement precision
  (not studied much by exp. collaborations)
- order of magnitude improvement wrt LHC, and δy_c constraint
  (especially on δc_Z, δc_{ZZ}, $\delta c_{Z\Box}$, δy_b, δy_τ, λ_Z)
- LHC helps for $\bar{c}_{\gamma\gamma}$, δy_μ, and δy_t (below 500 GeV!)