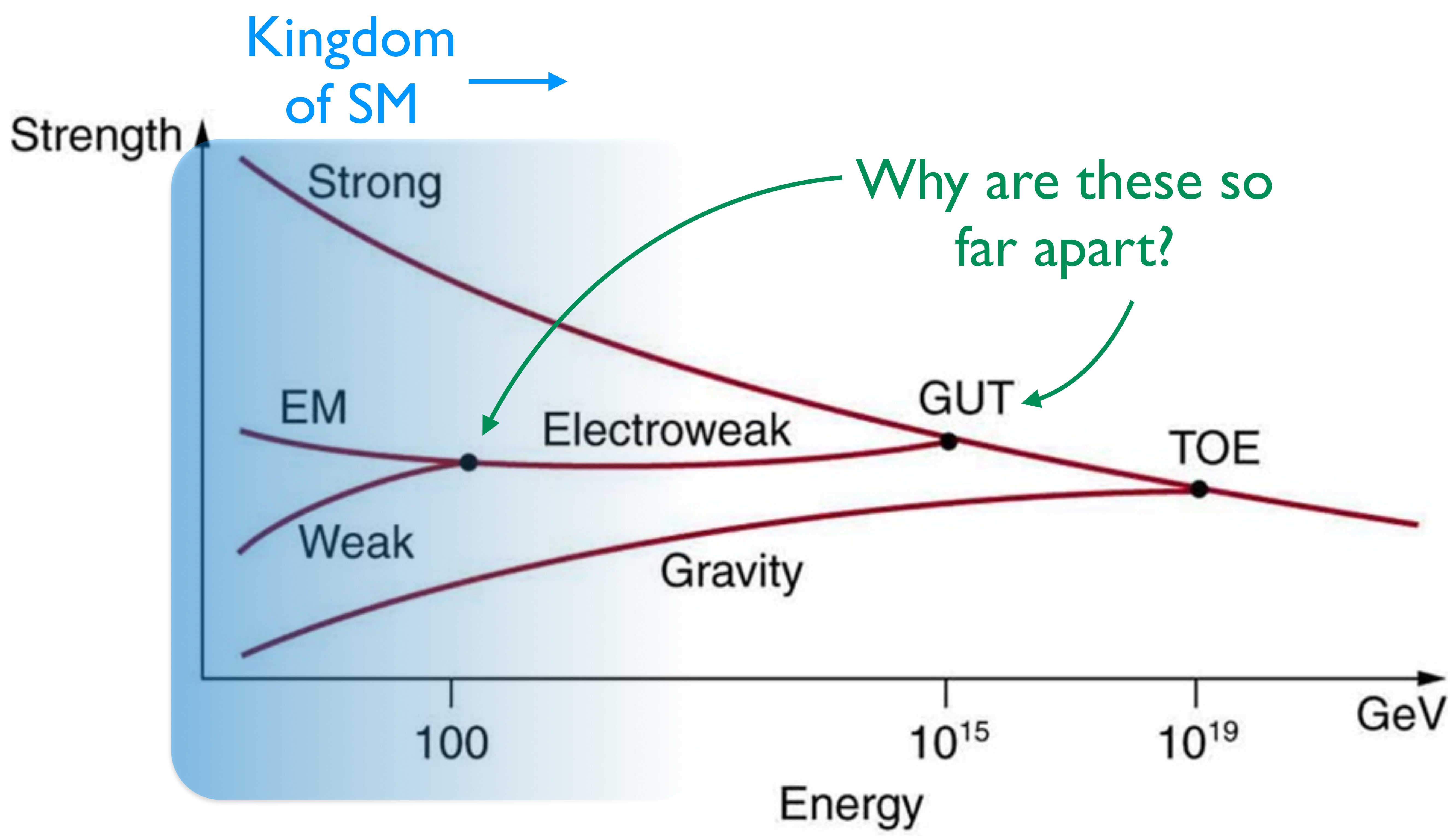
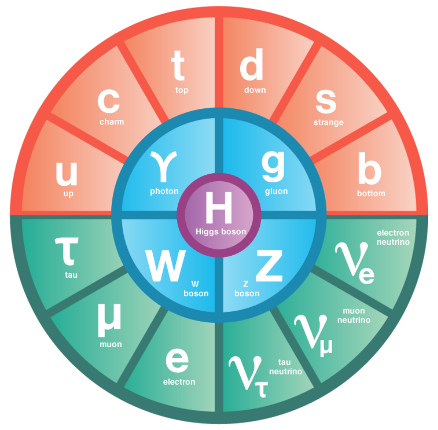
New Physics Searches in SM Standard Candles

Claire Lee, BNL
on behalf of the ATLAS and CMS Collaborations
SM@LHC, Zurich, 23-26 April 2019

“In the beginning there was symmetry.”

- Werner Heisenberg





Here be dragons (new physics)

- …and then it broke. Now all we’ve got are particles.
- Despite the (ongoing) success of the Standard Model, we know there needs to be something more.
- Investigating the nature of the EWSB mechanism is one of the primary targets for LHC physics in the upcoming years.
- The study of triple and quartic (and Higgs) couplings at high precision will be an important test of the SM
    - QGCs are connected to the EWSB sector, with the Higgs, to ensure unitarity at high energies for longitudinally-polarised scattering processes

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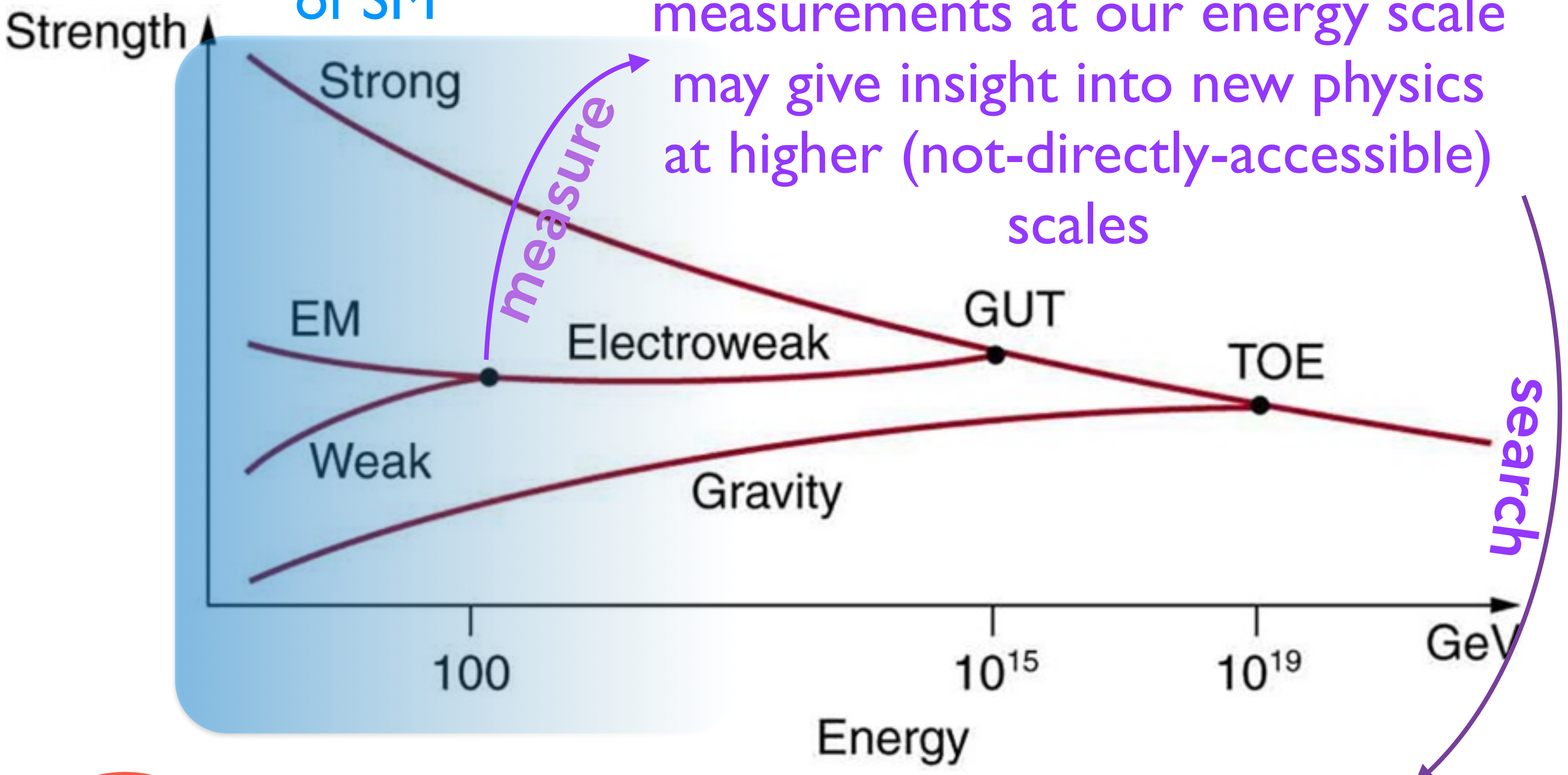
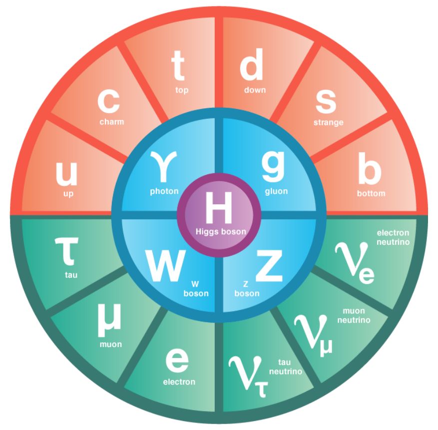
Kingdom of SM

Precision electroweak sector measurements at our energy scale may give insight into new physics at higher (not-directly-accessible) scales





Here be dragons (new physics) … somewhere

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Dibosons & VBF:	aTGC
Tribosons & VBS:	aQGC

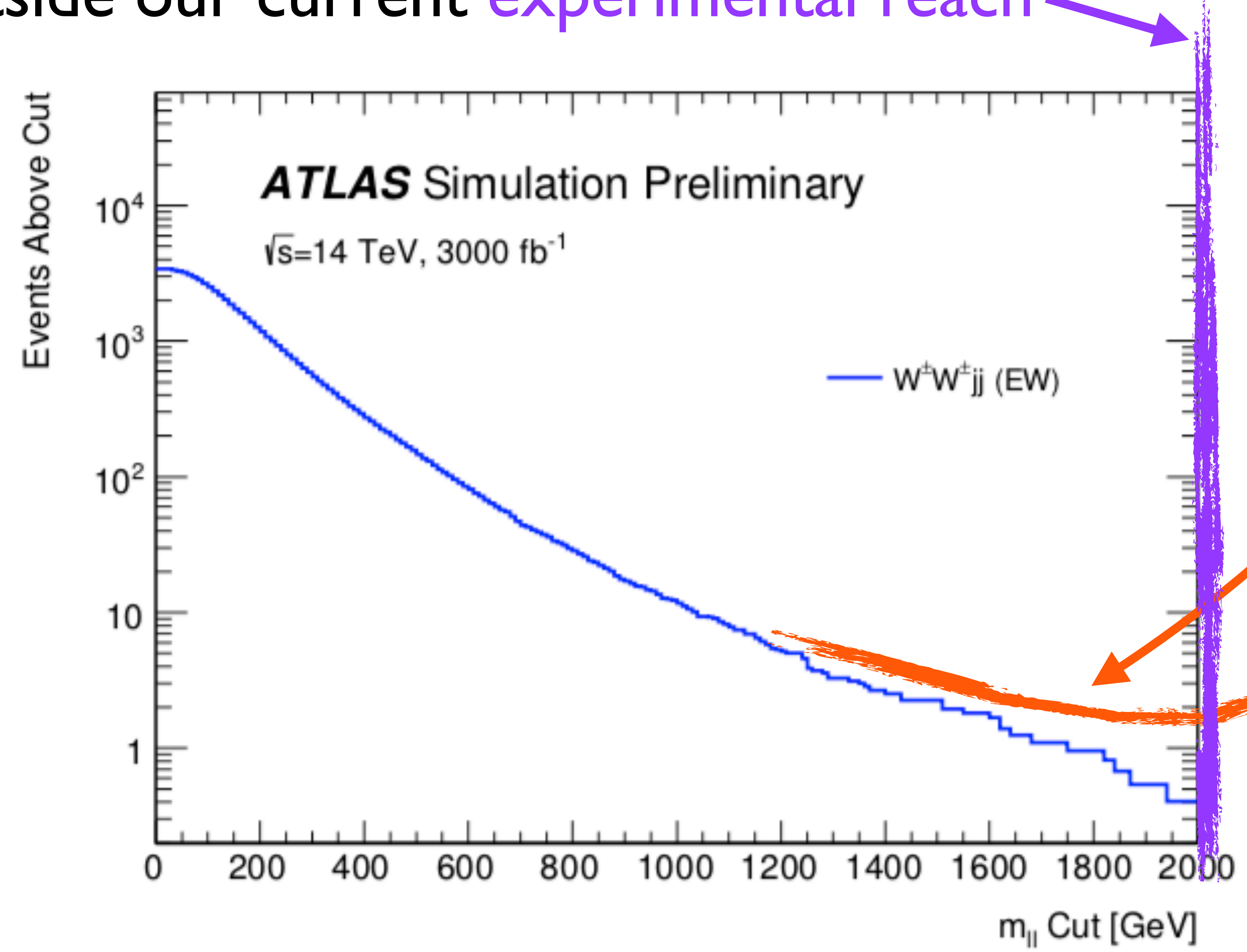
Signatures of Anomalous Couplings

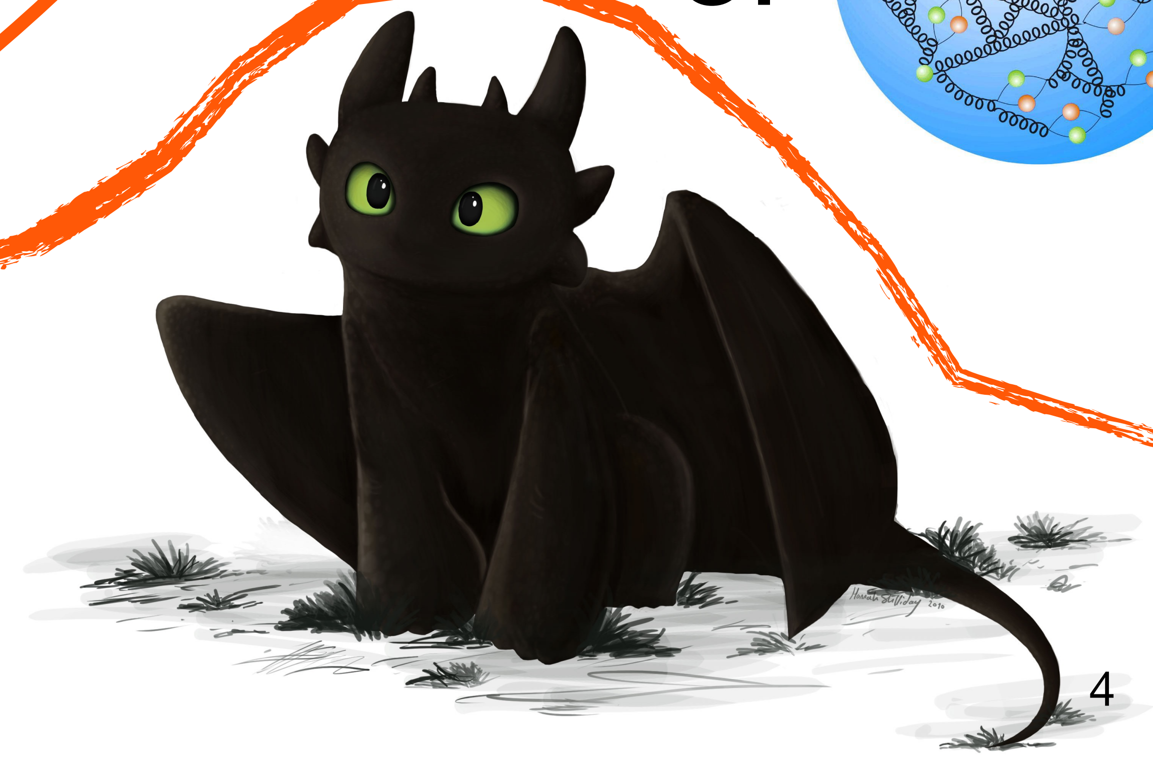
- Trilinear and Quartic Gauge boson couplings are precisely determined by the non-Abelian nature of the SU(2) x U(1) gauge symmetry group that governs Electroweak theory

- Anomalous couplings would result in an enhancement of vector boson cross sections at high energy scales and would be a signature of new physics outside our current experimental reach

- The best observables are those related to the energy of the system, with the highest sensitivity in the highest bins

  - The sensitivity of the result depends on backgrounds, size of the anomalous coupling signal, and uncertainties





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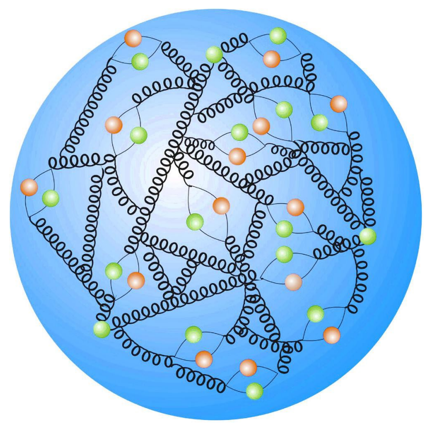

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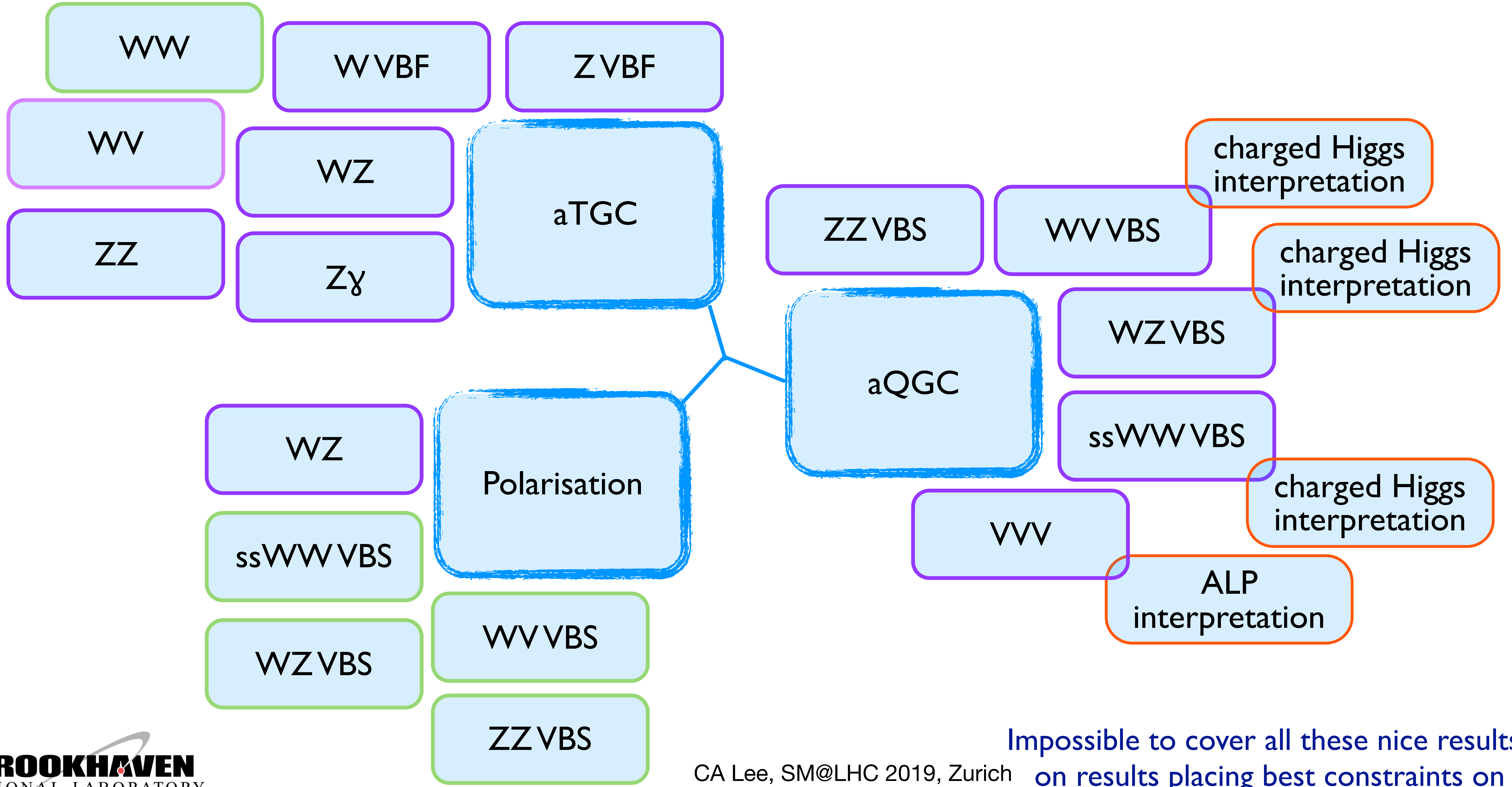
13TeV HL/HE-LHC

New Physics Results using SM Standard Candles



Impossible to cover all these nice results today - focus on results placing best constraints on new physics

The EFT Approach

- A useful way to quantify the effects of new physics in a model-independent framework is to use an EFT description of the SM

- Define a scale of new physics Λ, and add higher-dimension operators to the SM Lagrangian:

$$\mathscr{L} = \mathscr{L}_{SM} + \sum_i \frac{c_i}{\Lambda^2}\mathscr{O}_i + \sum_j \frac{f_j}{\Lambda^4}\mathscr{O}_j + \ldots$$

The EFT Approach: TGCs

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- There are three CP-conserving dimension-6 operators, with coefficients that are zero in the SM (and are related to the LEP-constrained aTGC parameters):

$$\begin{aligned} O_W &= (D_\mu\Phi)^\dagger W^{\mu\nu}(D_\nu\Phi)\,, \\ O_B &= (D_\mu\Phi)^\dagger B^{\mu\nu}(D_\nu\Phi)\,, \\ O_{WWW} &= Tr[W_{\mu\nu}W^{\nu\rho}W^{\mu}_{\rho}]\,. \end{aligned}$$

$$\begin{aligned} \frac{c_W}{\Lambda^2} &= \frac{2}{m_Z^2}\Delta g_1^Z\,, \\ \frac{c_B}{\Lambda^2} &= \frac{2}{m_W^2}\Delta\kappa_\gamma - \frac{2}{m_Z^2}\Delta g_1^Z\,, \\ \frac{c_{WWW}}{\Lambda^2} &= \frac{2}{3g^2 m_W^2}\lambda\,. \end{aligned}$$

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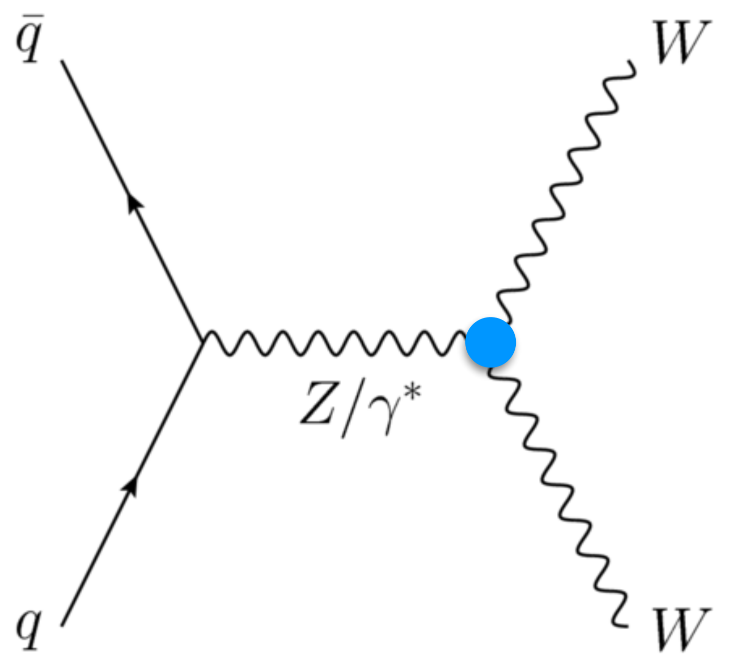
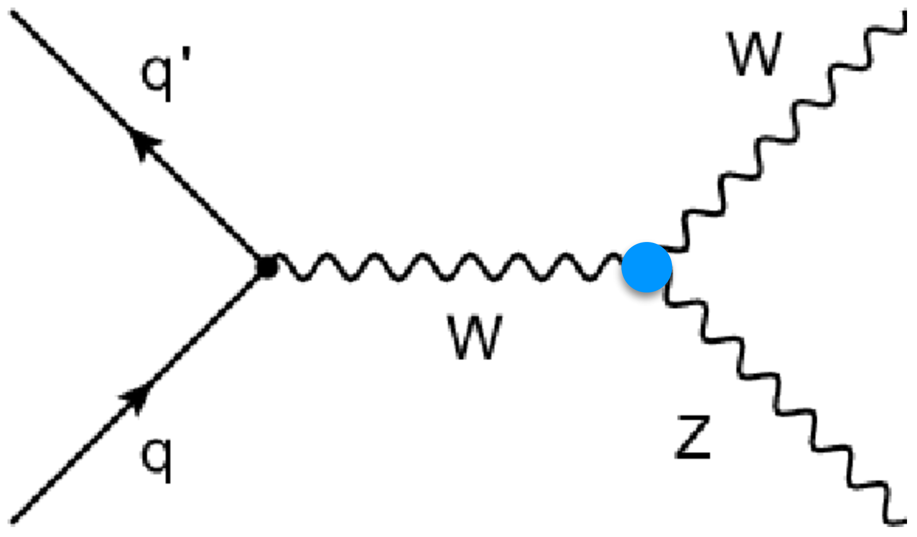
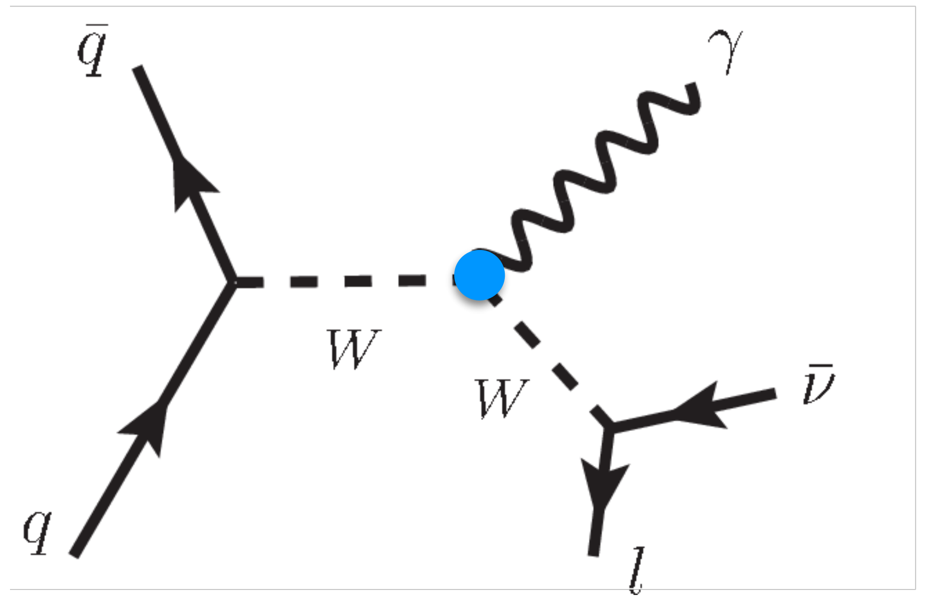
also see Pietro's talk (Wed)

WZ ATLAS CMS

Dibosons and aTGCs: charged vertices





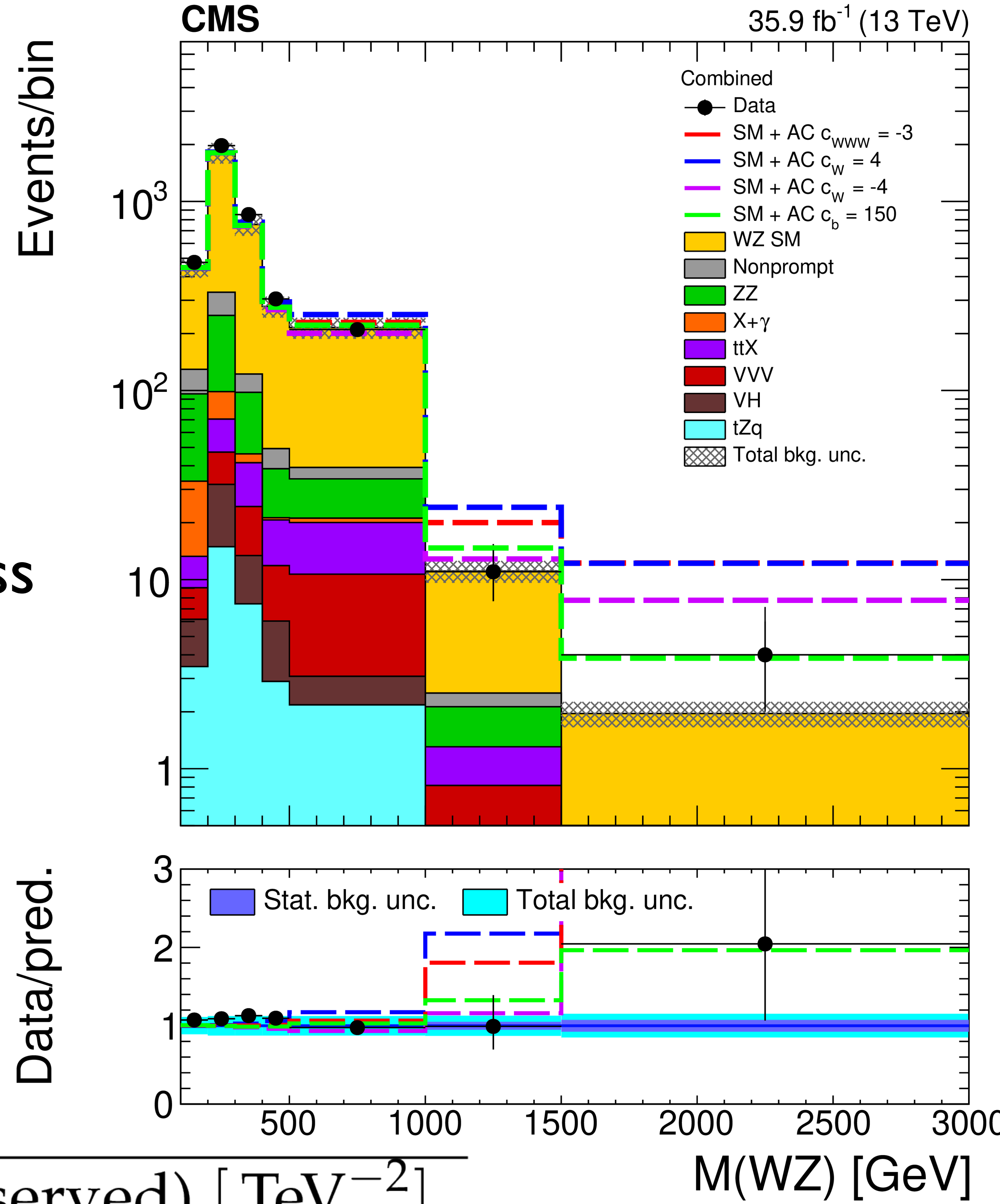


only WWɣ and WWZ allowed in SM

- Measurement of WZ events in 3 lepton final state, with dominant systematic uncertainties from btagging and lepton efficiencies
- 3-dimensional quadratic fit to yields in WZ invariant mass distribution to determine 95% confidence intervals for EFT parameter limits, where

$$M(WZ)^2 = [p(\ell_1) + p(\ell_2) + p(\ell_3) + p(\nu)]^2$$

$$p(\nu) = (0, p_{\mathrm{T}}(p_{\mathrm{T}}^{\mathrm{miss}}), 0, \phi(p_{\mathrm{T}}^{\mathrm{miss}}))$$



Parameter	95% CI (expected) $[\mathrm{TeV}^{-2}]$	95% CI (observed) $[\mathrm{TeV}^{-2}]$
c_W/Λ^2	$[-3.3, 2.0]$	$[-4.1, 1.1]$
c_{WWW}/Λ^2	$[-1.8, 1.9]$	$[-2.0, 2.1]$
c_b/Λ^2	$[-130, 170]$	$[-100, 160]$

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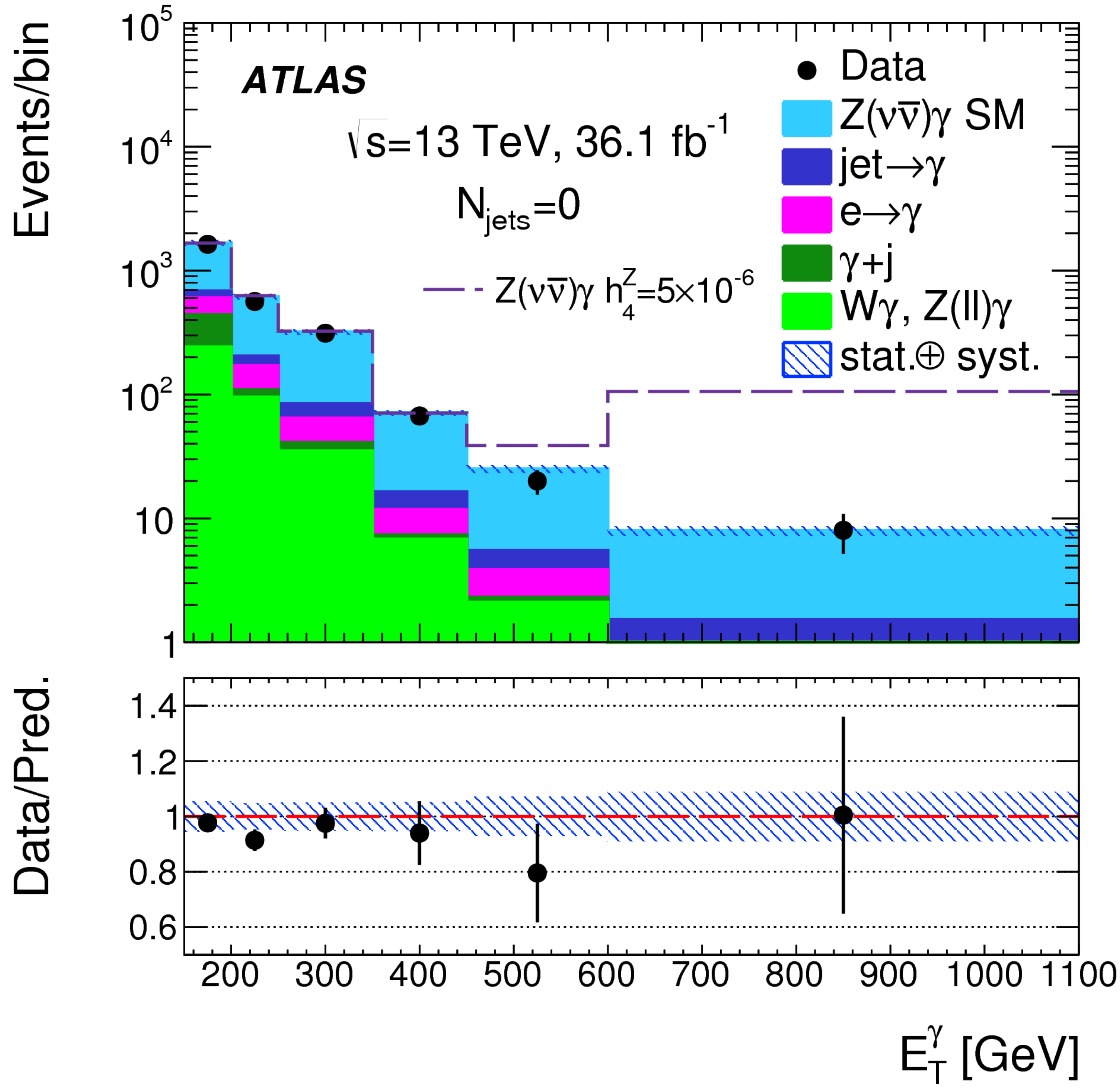
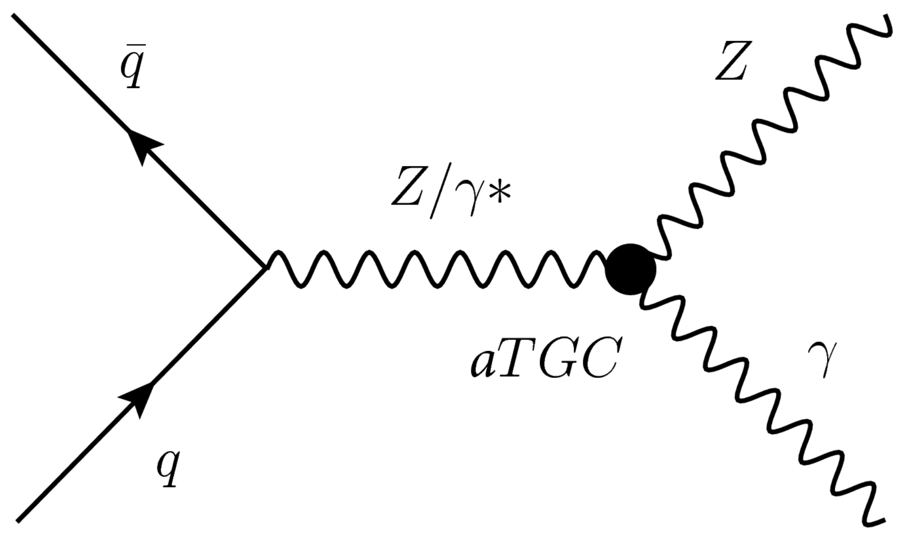
also see Evgenii's talk (Wed)

Zɣ | ZZ

Dibosons and aTGCs: neutral vertices

- Evidence of anomalous triple gauge-boson couplings is sought in Zγ production with photon ET greater than 600 GeV and the Z boson decaying to neutrinos
- Dominant systematic uncertainty comes from photon energy scale and ID efficiency
- Limits are derived for four dimension-8 operators describing aTGC interactions of neutral gauge bosons - up to 7 times more stringent than those available prior to this study.





Category	Requirement
Photons	$E_T^\gamma > 150$ GeV $\lvert\eta\rvert < 2.37$
Jets	$\lvert\eta\rvert < 4.5$ $p_T > 50$ GeV $\Delta R(\text{jet}, \gamma) > 0.3$ Inclusive : $N_{\text{jet}} \geq 0$, Exclusive : $N_{\text{jet}} = 0$
Neutrino	$p_T^{\nu\nu} > 150$ GeV

Parameter	Limit 95% CL	
	Measured [TeV^{-4}]	Expected [TeV^{-4}]
$C_{\tilde{B}W}/\Lambda^4$	$(-1.1, 1.1)$	$(-1.3, 1.3)$
C_{BW}/Λ^4	$(-0.65, 0.64)$	$(-0.74, 0.74)$
C_{WW}/Λ^4	$(-2.3, 2.3)$	$(-2.7, 2.7)$
C_{BB}/Λ^4	$(-0.24, 0.24)$	$(-0.28, 0.27)$

Yellow Report

Dibosons and aTGCs (for fun) $p_T^l > 30$ GeV, $|\eta^l| < 2.5$, $m_{ll} > 10$ GeV, $E_T^{miss} > 20$ GeV

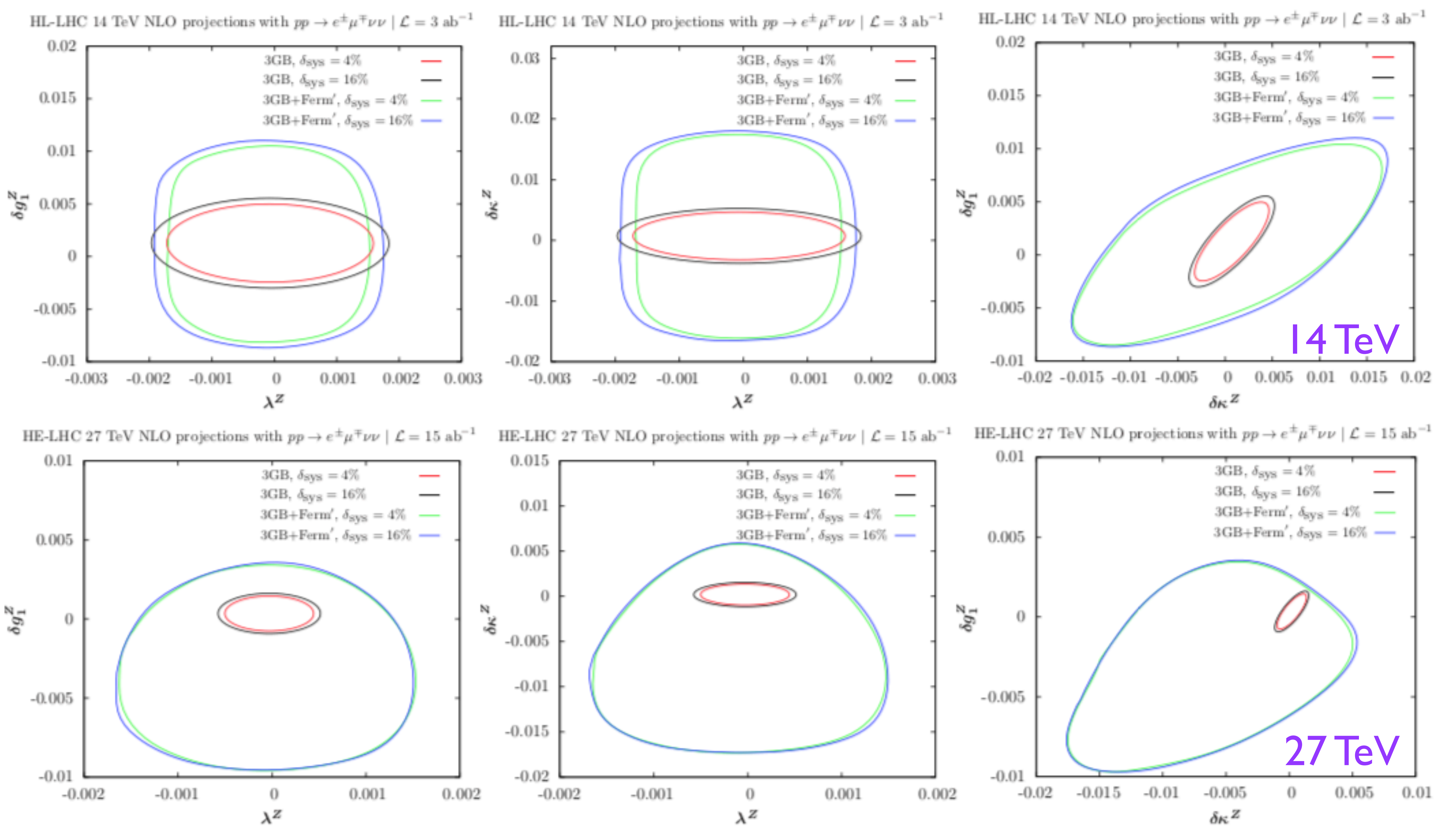
- Sensitivity of the production of WW pairs to anomalous couplings using POWHEG BOX has been calculated using a general systematic uncertainty of 16%

- Significant improvement in sensitivity going from 14 TeV (top) to 27 TeV (bottom)

- Improvement from reducing the systematic error from 16 to 4%, is marginal (red vs black, green vs blue)

- Including anomalous fermion couplings (green&blue) reduces the sensitivity significantly

  - Global fits to both anomalous fermion and 3 gauge boson couplings will be necessary.



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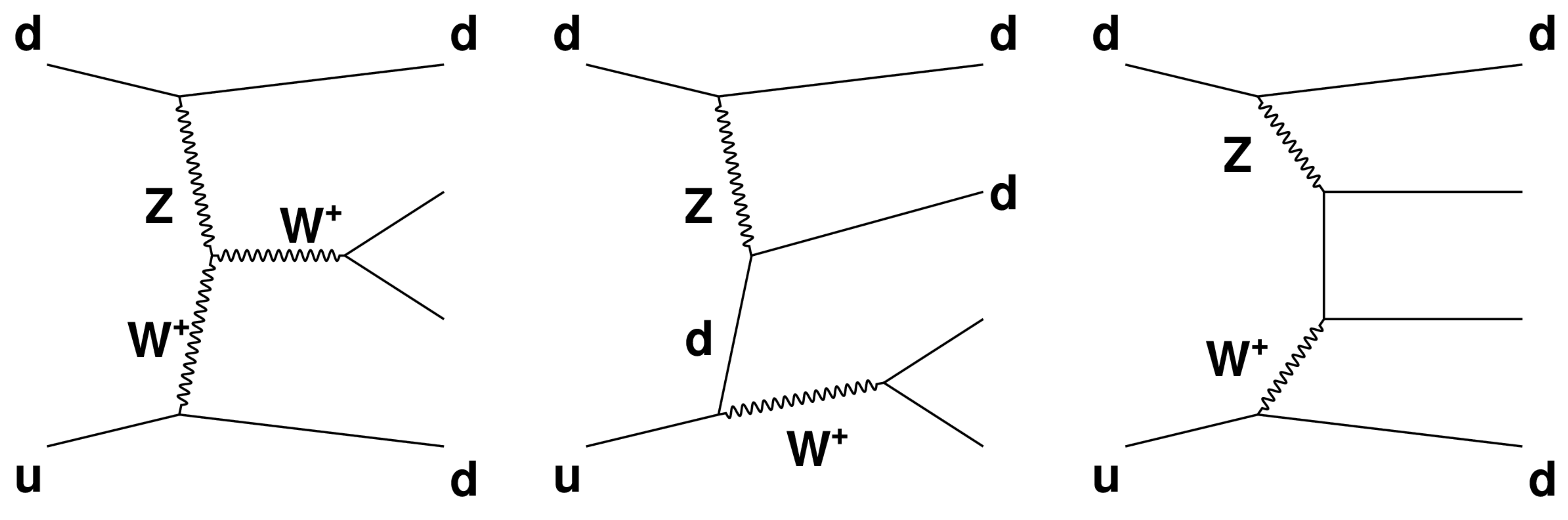
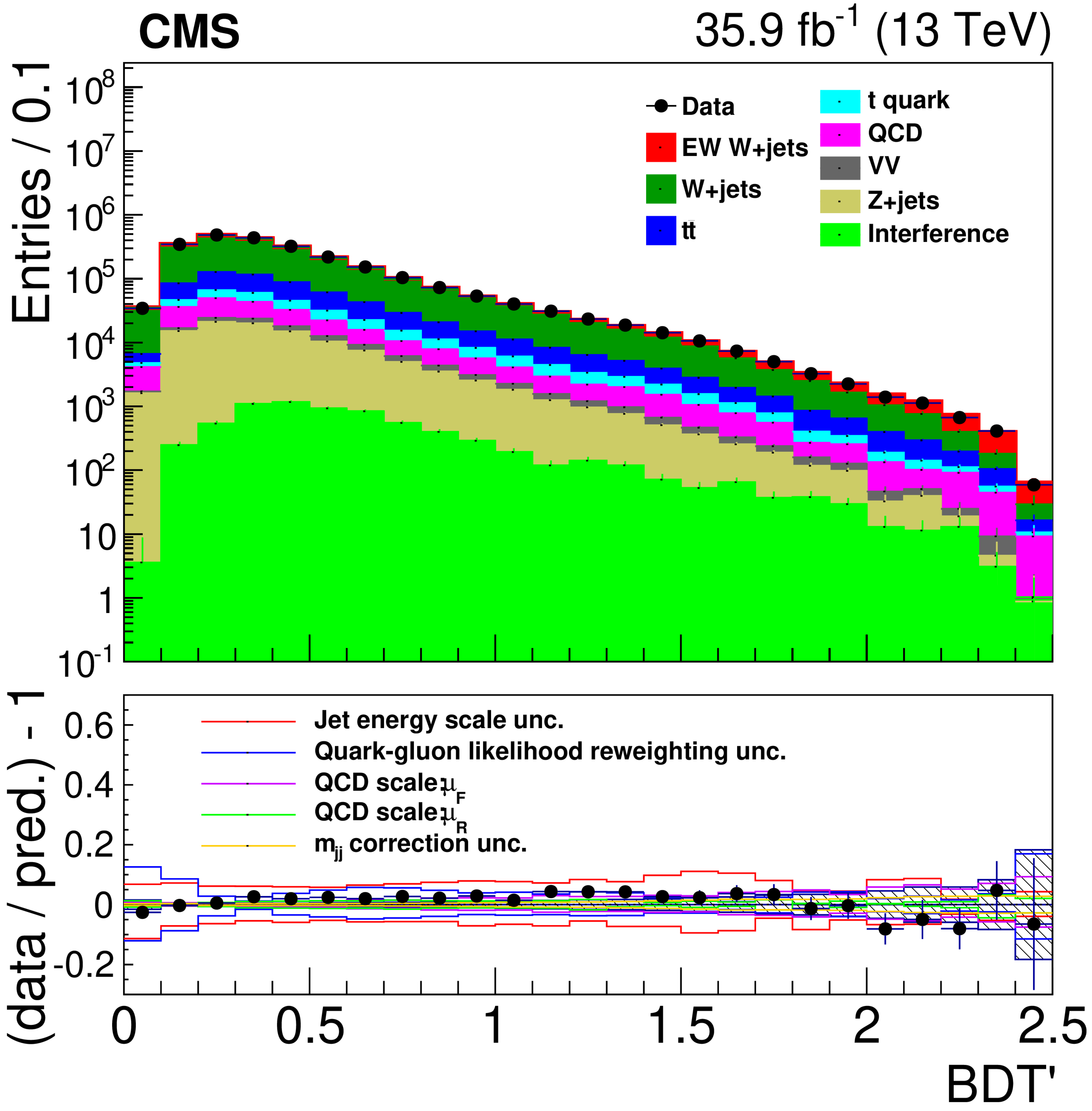
also see Kenneth's talk (Fri)

W VBF

Z VBF

VBF and aTGCs



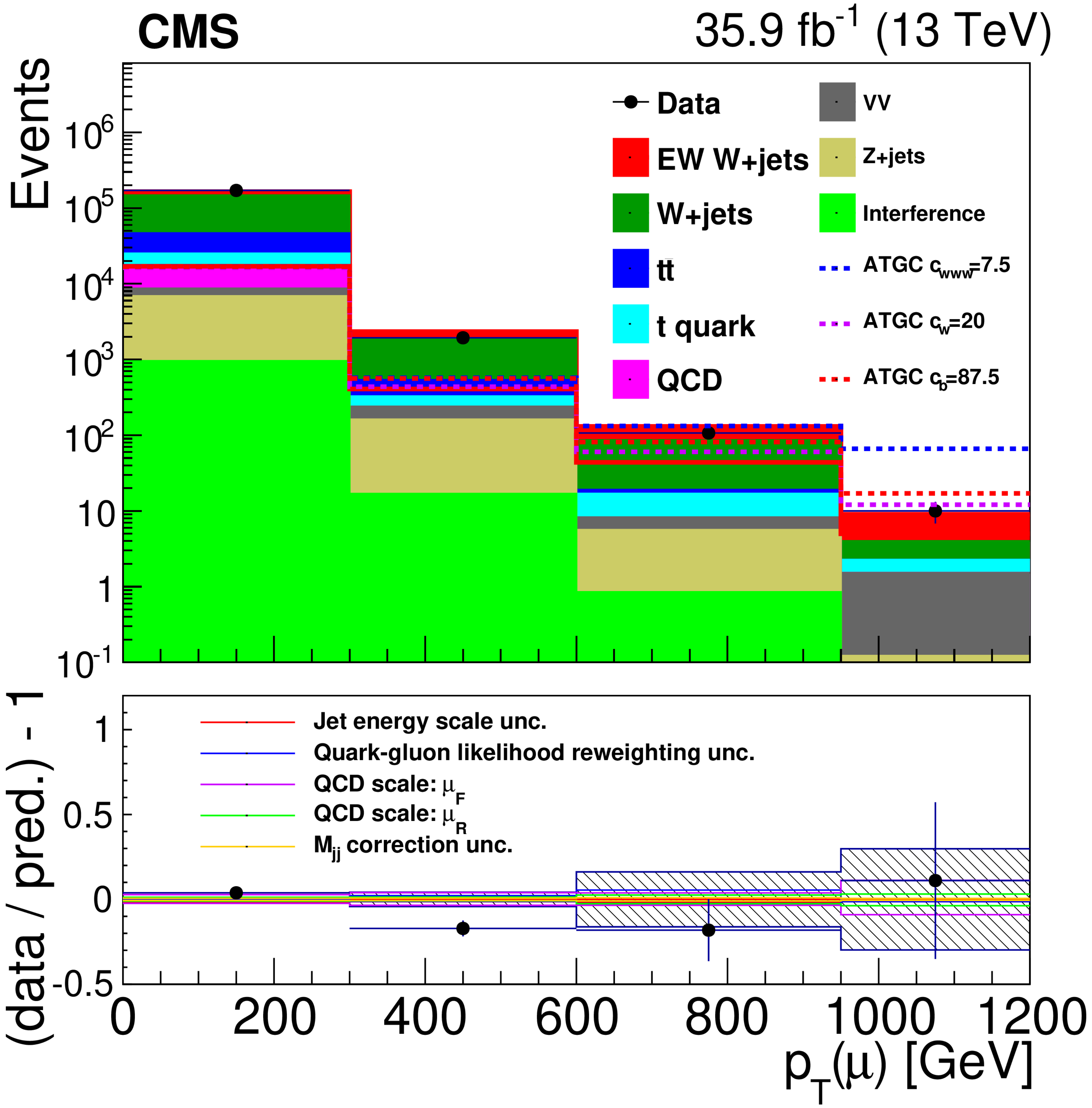


- VBF production of W bosons is measured in the lvjj final state with mjj > 120 GeV and pTj > 25 GeV
- BDT used to separate signal from DY background
- Dominant theoretical uncertainties are signal yield and scale uncertainties

also see Kenneth's talk (Fri)

VBF and aTGCs

- Templates in bins of lepton pT are used to extract limits on aTGCs
- Results are combined with those from the VBF Z analysis since both analyses are sensitive to couplings related to the WWZ vertex.
- Simultaneous binned likelihood fit performed for e and mu channels with the primary uncertainties (such as JES and JER) correlated, provides most stringent limit on cwww/Λ^2 to date *



Coupling constant	Expected 95% CL interval (TeV^{-2})	Observed 95% CL interval (TeV^{-2})
c_{WWW}/Λ^2	$[-2.3, 2.4]$	$[-1.8, 2.0]$
c_W/Λ^2	$[-11, 14]$	$[-5.8, 10.0]$
c_B/Λ^2	$[-61, 61]$	$[-43, 45]$

The EFT Approach: QGCs

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- Define a scale of new physics Λ, and add higher-dimension operators to the SM Lagrangian:

$$\mathscr{L} = \mathscr{L}_{SM} + \sum_i \frac{c_i}{\Lambda^2}\mathscr{O}_i + \sum_j \frac{f_j}{\Lambda^4}\mathscr{O}_j + \dots$$

- Dimension-8 operators are the lowest-dimension operators inducing only QGCs without TGC vertices: 18 independent C,P conserving aQGC (dim 8) operators O:

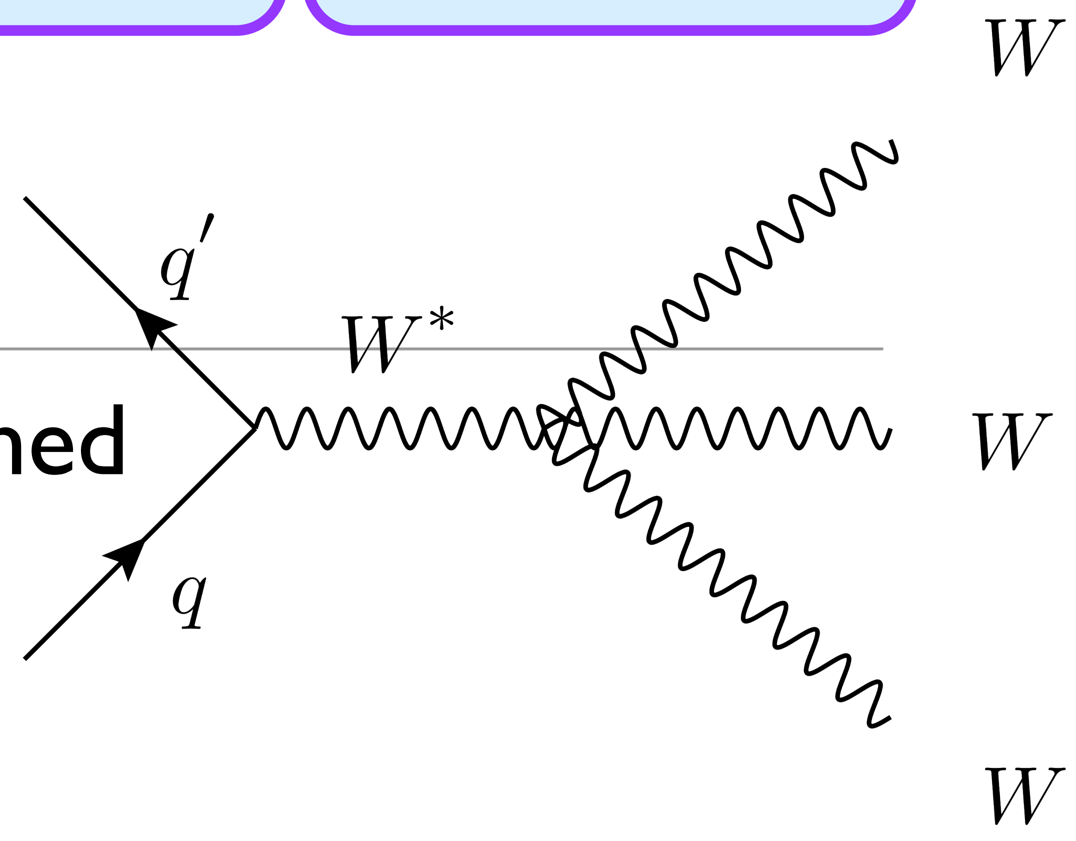
S: Pure Higgs field, pure longitudinal
M: Mixed Higgs-field-strength, mixed long-transverse
T: Pure field-strength tensor, pure transverse

	$WWWW$	$WWZZ$	$WW\gamma Z$	$WW\gamma\gamma$	$ZZZZ$	$ZZZ\gamma$	$ZZ\gamma\gamma$	$Z\gamma\gamma\gamma$	$\gamma\gamma\gamma\gamma$
$\mathcal{O}_{S,0}$, $\mathcal{O}_{S,1}$	✓	✓			✓				
$\mathcal{O}_{M,0}$, $\mathcal{O}_{M,1}$, $\mathcal{O}_{M,6}$, $\mathcal{O}_{M,7}$	✓	✓	✓	✓	✓	✓	✓		
$\mathcal{O}_{M,2}$, $\mathcal{O}_{M,3}$, $\mathcal{O}_{M,4}$, $\mathcal{O}_{M,5}$		✓	✓	✓	✓	✓	✓		
$\mathcal{O}_{T,0}$, $\mathcal{O}_{T,1}$, $\mathcal{O}_{T,2}$	✓	✓	✓	✓	✓	✓	✓	✓	✓
$\mathcal{O}_{T,5}$, $\mathcal{O}_{T,6}$, $\mathcal{O}_{T,7}$		✓	✓	✓	✓	✓	✓	✓	✓
$\mathcal{O}_{T,8}$, $\mathcal{O}_{T,9}$					✓	✓	✓	✓	✓

Allowed by SM

WWW WVV

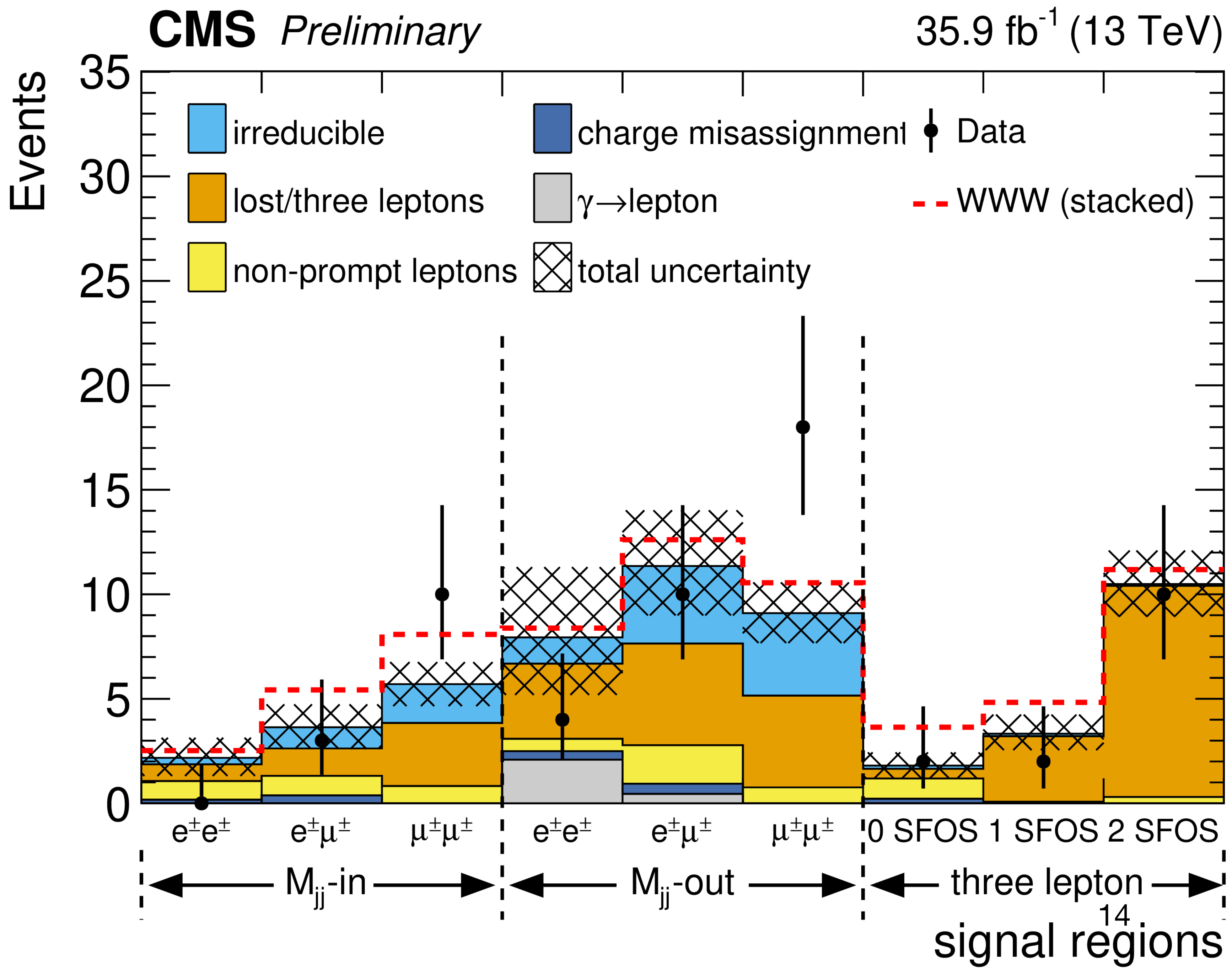
Tribosons and aQGCs (and axion-like particles)



- New ATLAS result quotes 4.0σ evidence (3.1σ expected) for WWW+WWZ+WZZ combined
- The latest CMS result focuses on WWW in the 2ss- and 3-lepton channels
  - Dominant uncertainties from MC statistics and theory (renormalisation & factorisation scale, and cross section)
  - Limits on aQGCs for ST > 2.0 (1.5) TeV for the 2 (3) lepton channel, where ST=sum (leptons, jets, pTmiss)

Anomalous coupling	Allowed range (TeV^{-4}) Expected	Observed
$f_{T,0}/\Lambda^4$	[-1.3, 1.3]	[-1.2, 1.2]
$f_{T,1}/\Lambda^4$	[-3.7, 3.7]	[-3.3, 3.3]
$f_{T,2}/\Lambda^4$	[-3.0, 2.9]	[-2.7, 2.6]

  - Additionally, photophobic axion-like particles that decay to WW with masses between 200 and 480 GeV are excluded for $1/f_a$=5TeV-1



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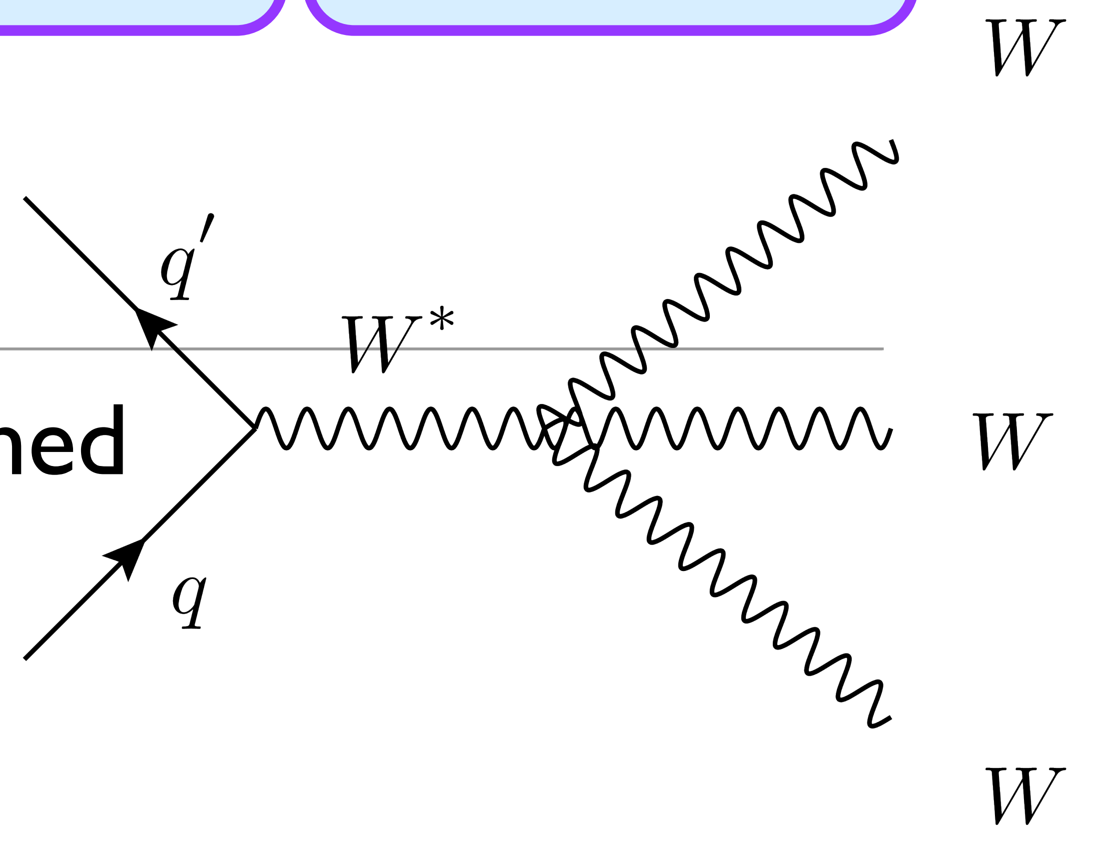
also see Pietro's talk (Wed)

WWW

WVV



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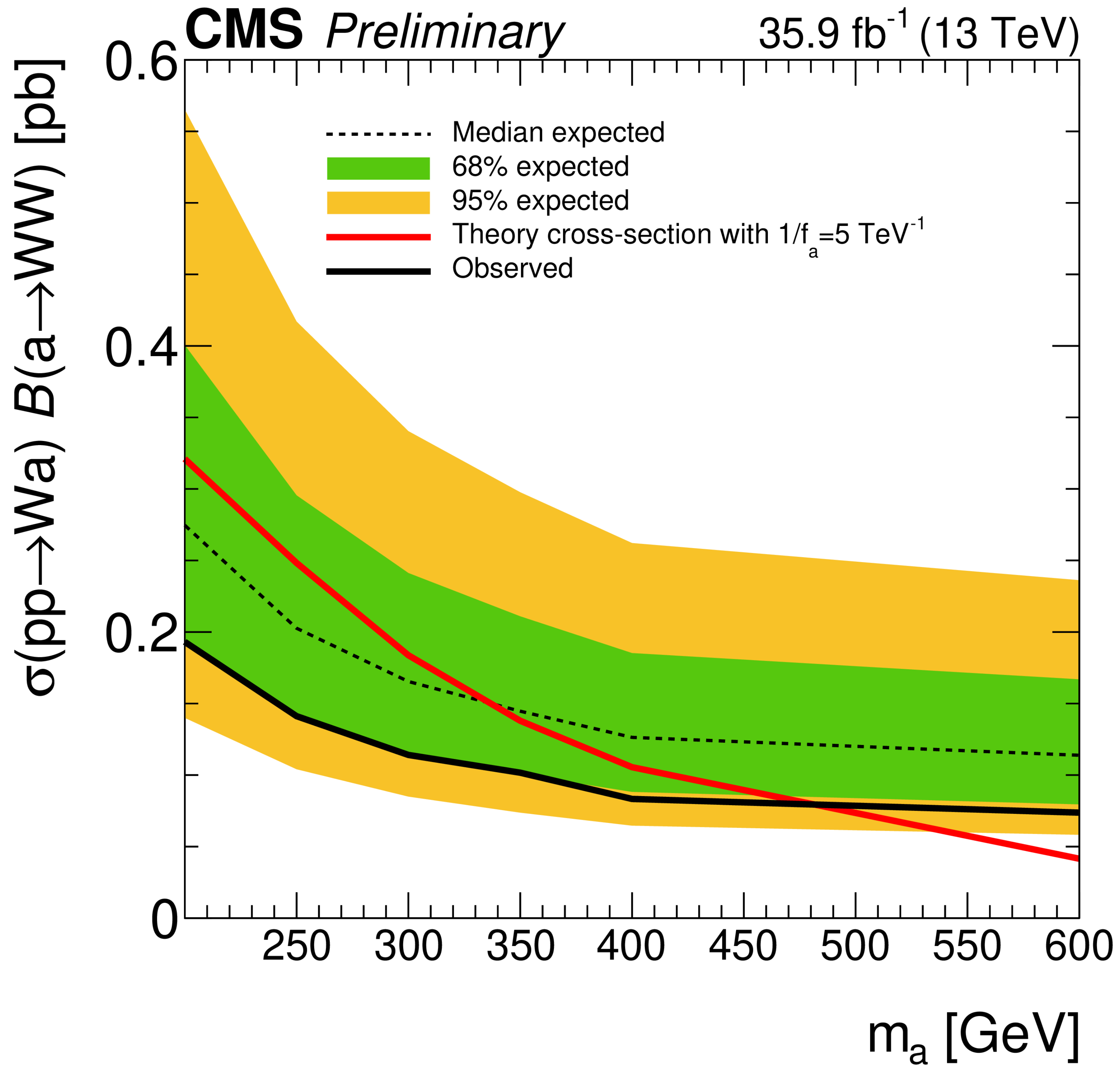

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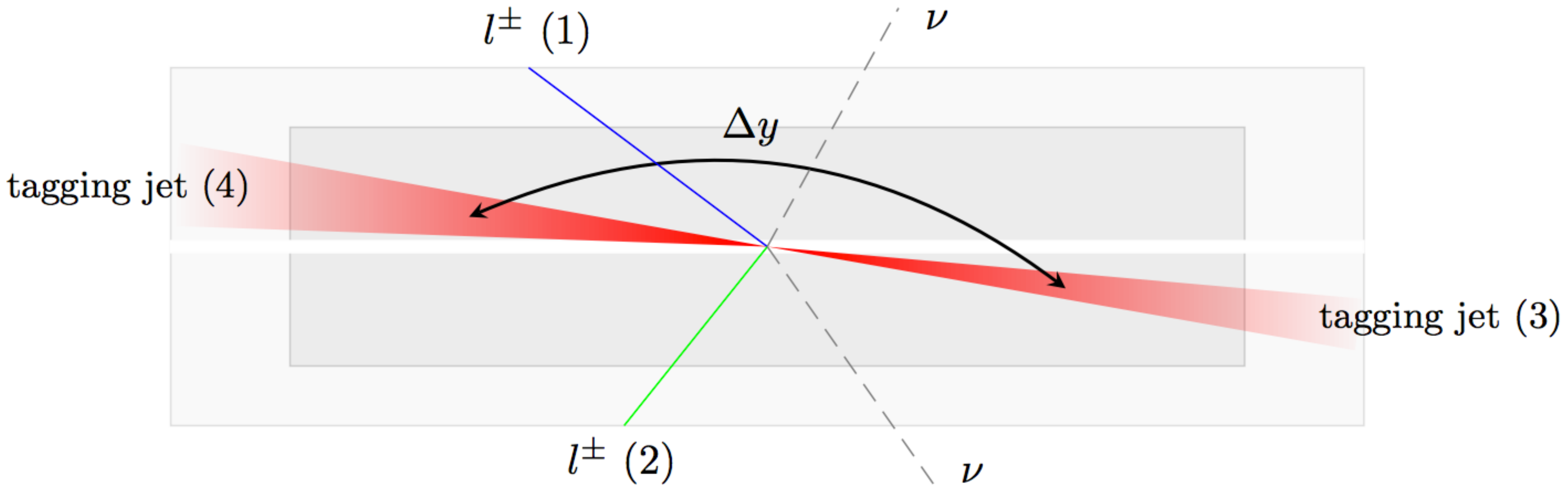
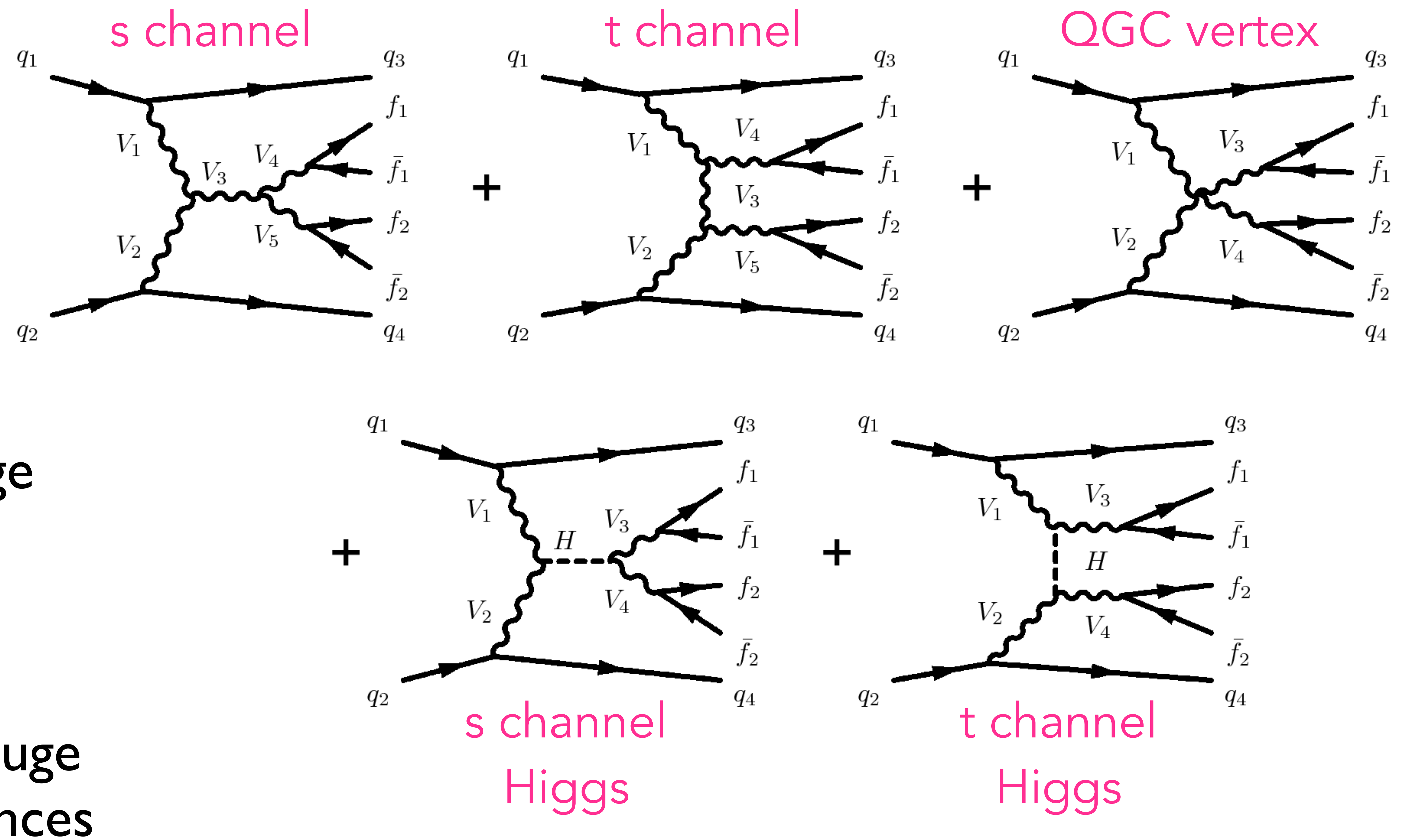
VBS and aQGCs

- In the VBS topology, two incoming quarks radiate bosons which interact giving a final state of two jets and two massive bosons
- This final state can be the result of EW production with and without a scattering topology, or of processes involving the strong interaction.
- Two "tag" jets with large rapidity separation and large invariant mass give a good experimental signature
- An excess of events with respect to SM predictions could indicate the presence of anomalous quartic gauge couplings (AQGCs) or the existence of new resonances

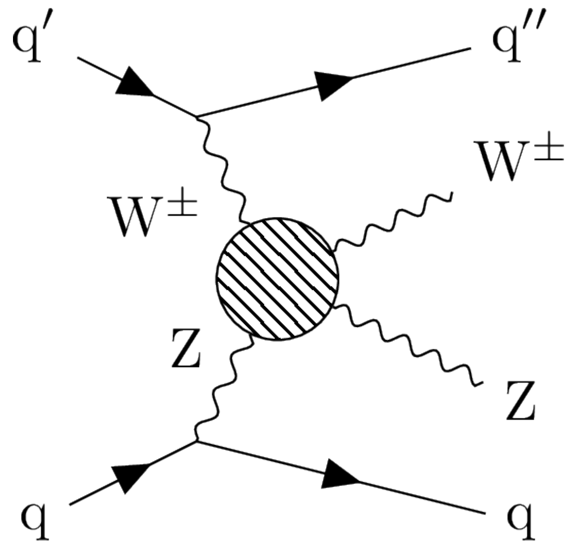




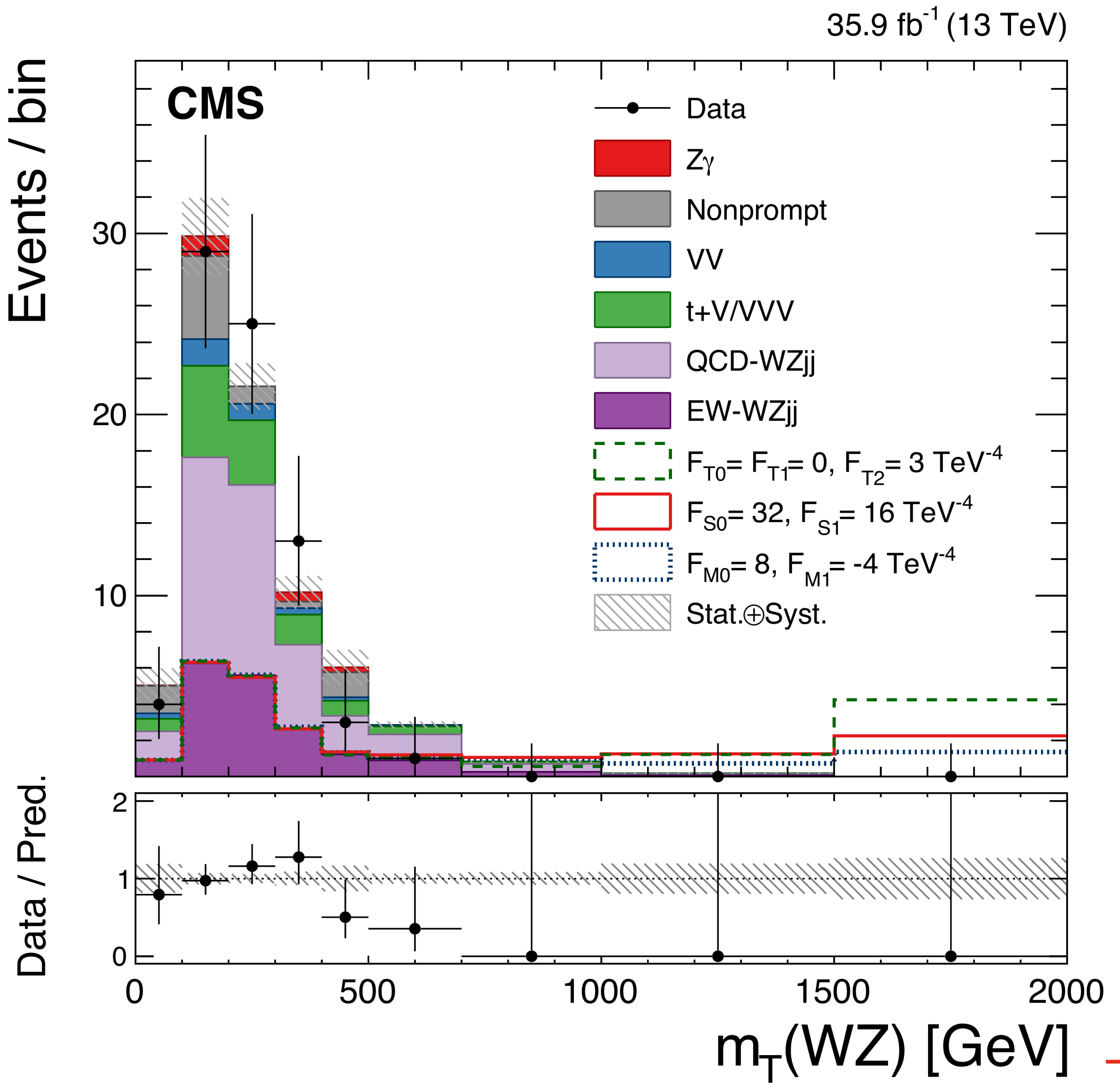
also see Kenneth's talk (Fri)

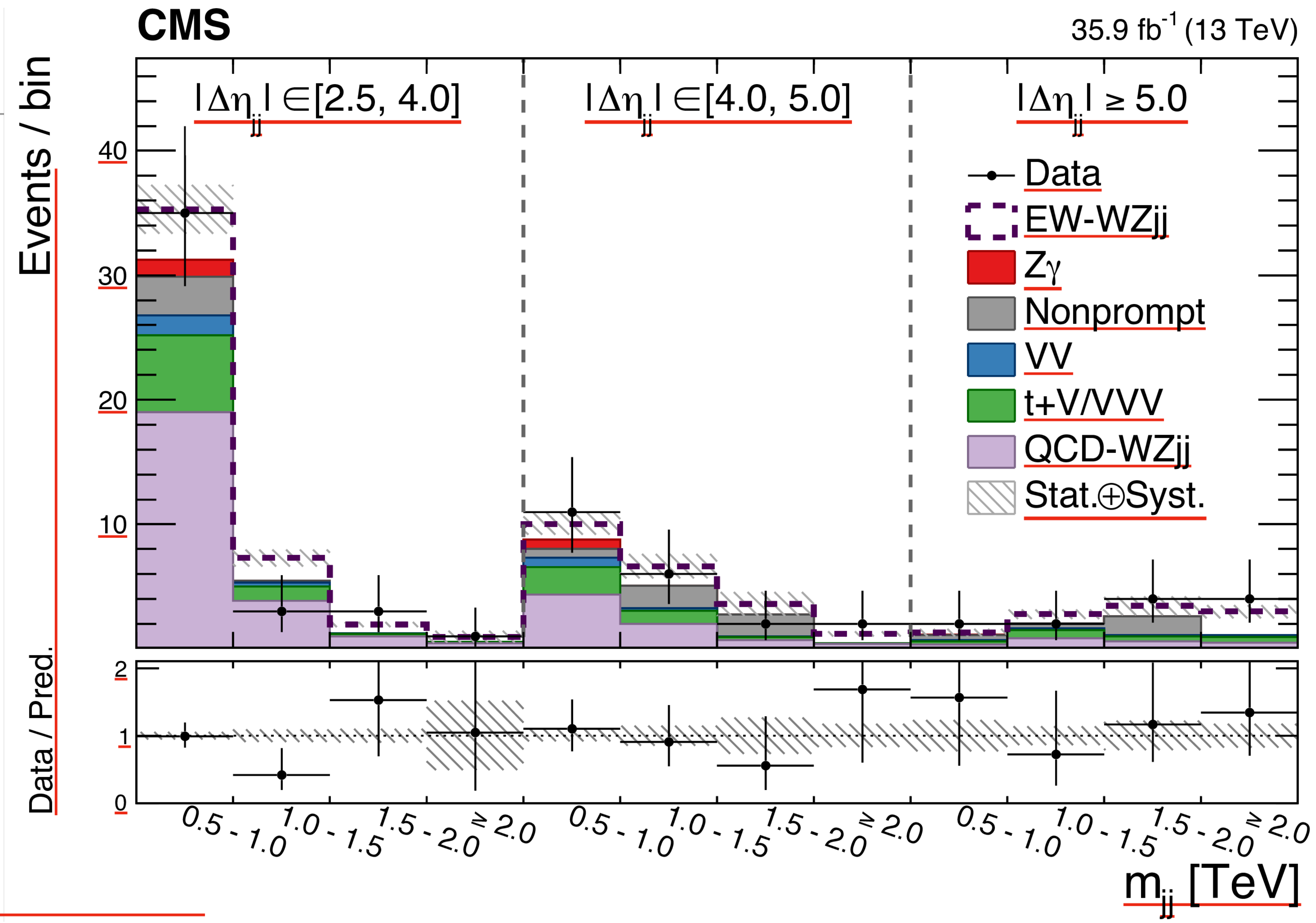
WZ VBS ATLAS CMS | semileptonic VBS CMS | ssWW VBS ATLAS CMS | ZZ VBS CMS

VBS and aQGCs: WZ



- Search for new physics modifying the WWZZ coupling in 3 lepton final state
- Binned likelihood fit to 2D distribution of mjj vs detajj, and the yield in the QCD WZ sideband
- Dominant uncertainties from JES, QCD background modelling, and nonprompt background yield





- mT of WZ system used to extract constraints on the anomalous coupling parameters

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	$[-1.78, 2.00]$	$[-1.49, 1.85]$

WZ VBS
ATLAS CMS

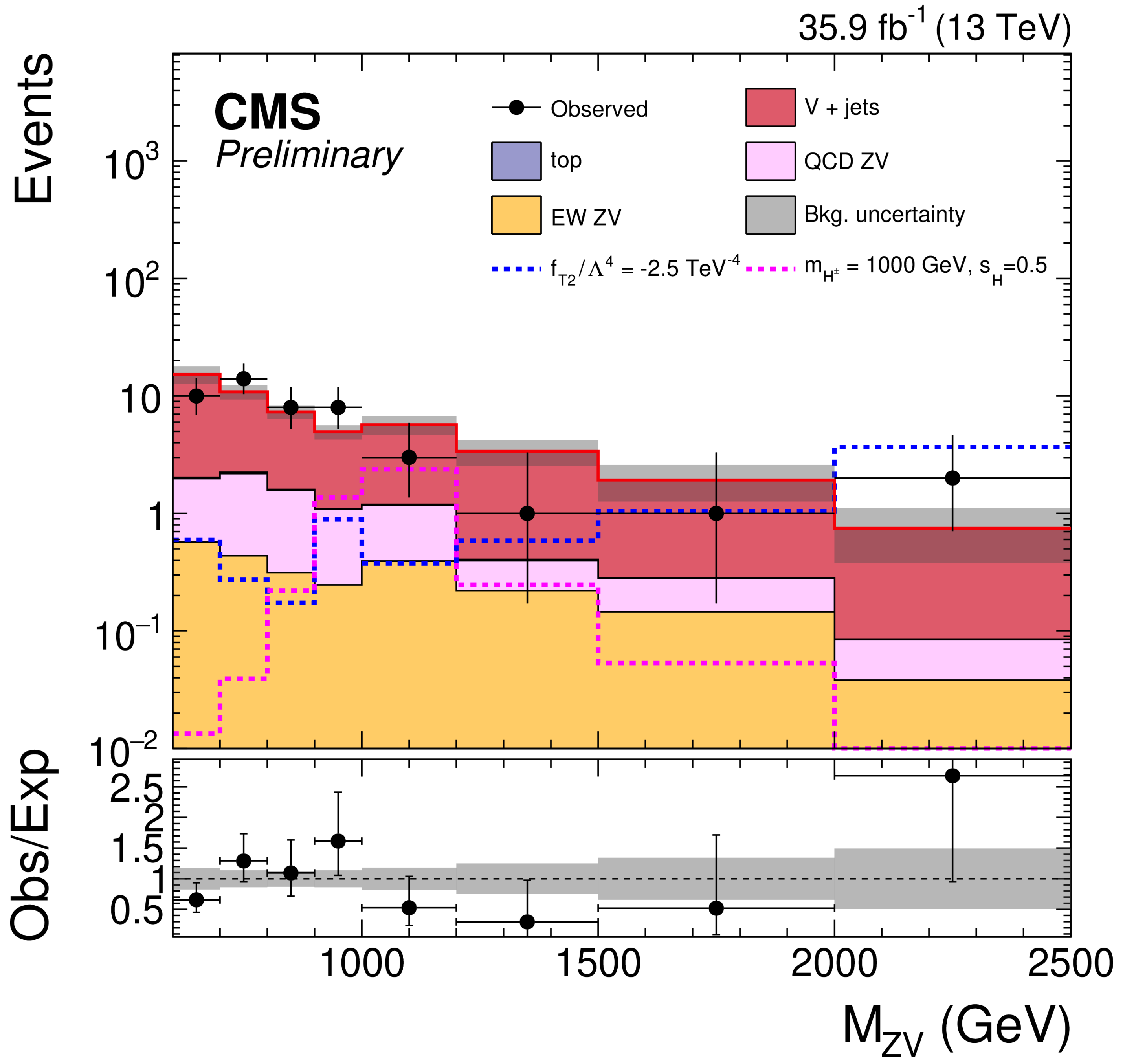
semileptonic
VBS CMS

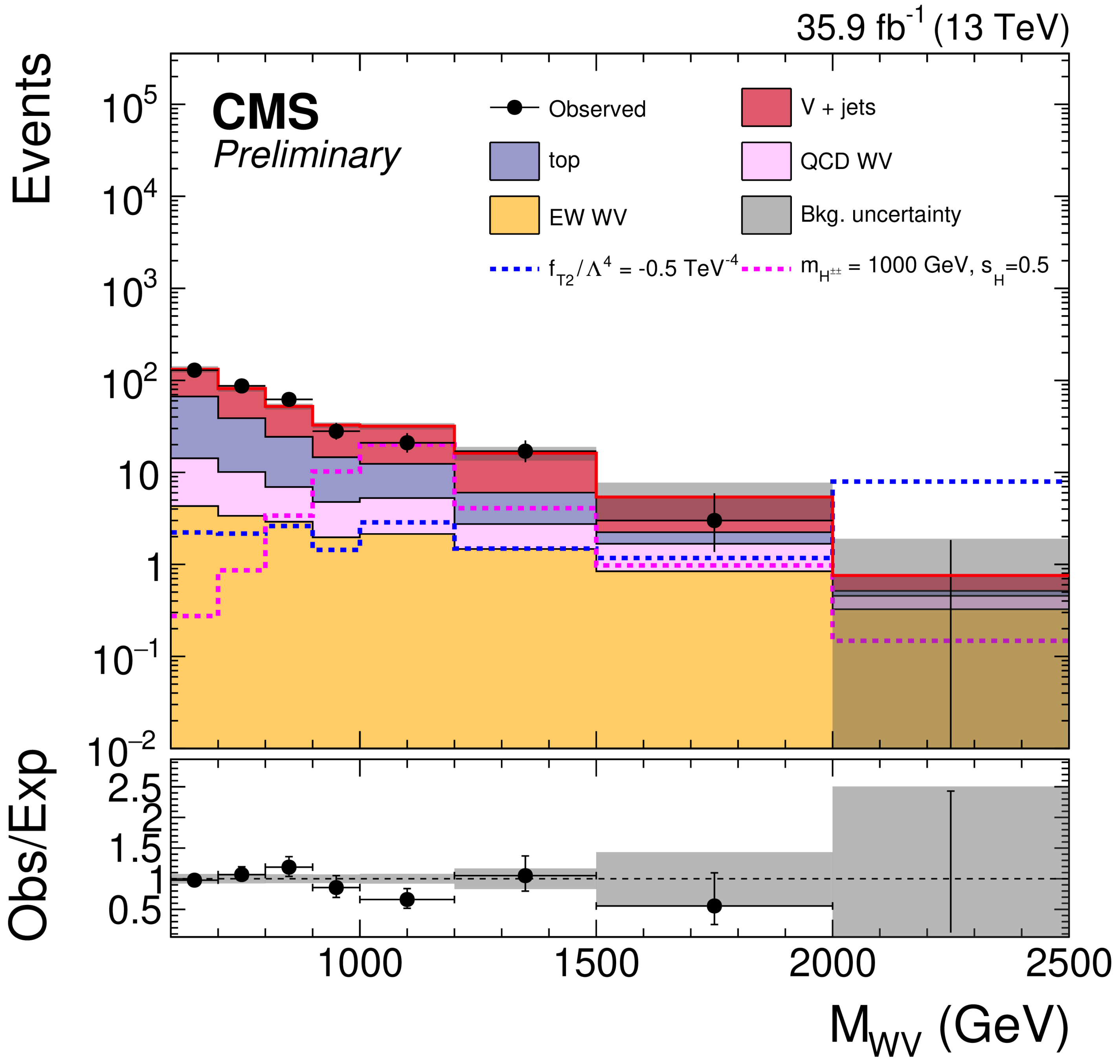
ssWW VBS
ATLAS CMS

ZZ VBS
CMS

VBS and aQGCs: WV & ZV

- Search for presence of aQGCs in WV and ZV channels with boosted V decaying hadronically
- Dominated by PDF and QCD scale uncertainties, as well as statistics in the V+jets background
- Fit to mass distribution provides most stringent constraints on parameters for dimension 8 operators to date





mjj > 800 GeV
|Δηjj| > 4.0

	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	$[-2.6, 2.7]$	$[-4.0, 4.0]$	$[-37, 37]$	$[-29, 29]$	$[-2.6, 2.7]$	$[-4.0, 4.0]$
f_{S1}/Λ^4	$[-3.2, 3.3]$	$[-4.9, 4.9]$	$[-30, 30]$	$[-23, 23]$	$[-3.3, 3.3]$	$[-4.9, 4.9]$
f_{M0}/Λ^4	$[-0.66, 0.66]$	$[-0.95, 0.95]$	$[-6.9, 6.9]$	$[-5.1, 5.1]$	$[-0.66, 0.66]$	$[-0.95, 0.95]$
f_{M1}/Λ^4	$[-1.9, 2.0]$	$[-2.8, 2.8]$	$[-21, 21]$	$[-15, 15]$	$[-1.9, 2.0]$	$[-2.8, 2.8]$
f_{M6}/Λ^4	$[-1.3, 1.3]$	$[-1.9, 1.9]$	$[-14, 14]$	$[-10, 10]$	$[-1.3, 1.3]$	$[-1.9, 1.9]$
f_{M7}/Λ^4	$[-3.3, 3.2]$	$[-4.8, 4.8]$	$[-33, 33]$	$[-24, 24]$	$[-3.3, 3.3]$	$[-4.8, 4.8]$
f_{T0}/Λ^4	$[-0.11, 0.10]$	$[-0.16, 0.15]$	$[-1.3, 1.3]$	$[-0.95, 0.95]$	$[-0.12, 0.10]$	$[-0.16, 0.15]$
f_{T1}/Λ^4	$[-0.11, 0.12]$	$[-0.17, 0.17]$	$[-1.4, 1.4]$	$[-0.98, 0.99]$	$[-0.11, 0.12]$	$[-0.17, 0.17]$
f_{T2}/Λ^4	$[-0.27, 0.27]$	$[-0.38, 0.38]$	$[-3.1, 3.2]$	$[-2.3, 2.3]$	$[-0.27, 0.27]$	$[-0.38, 0.38]$

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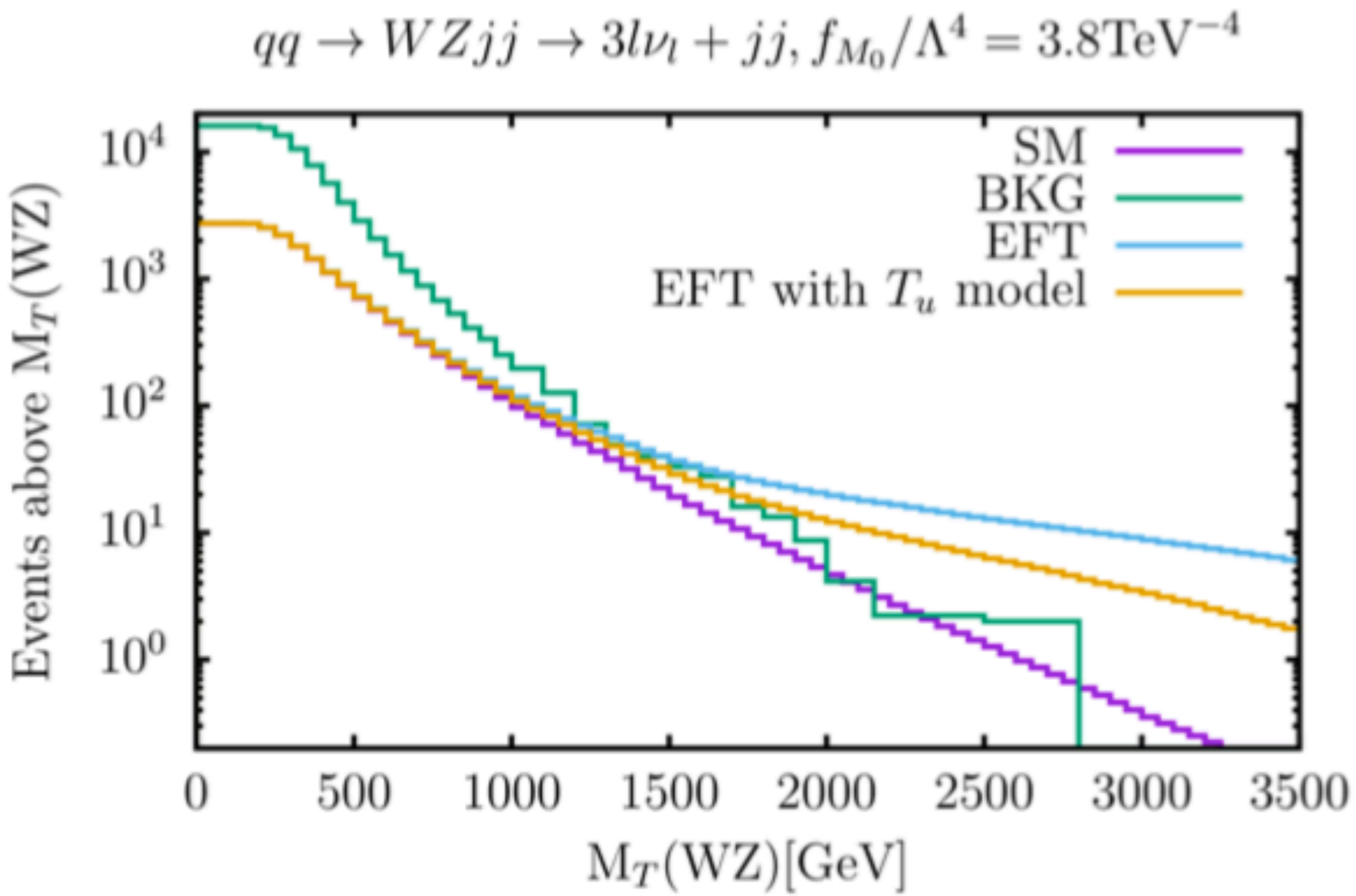
Yellow Report

VBS and aQGCs (for fun)

- Due to the strong gauge theory cancellations between the different Feynman graphs present in VBS ,VBS processes provide excellent probes for QGCs
- 95% CL bounds on aQGC calculated for VBS $W^{\pm}W^{\pm}$ and WZ production using the distributions of expected number of events as a function of mass
- Expect that these results would improve with analysis optimisation for aQGC sensitivity



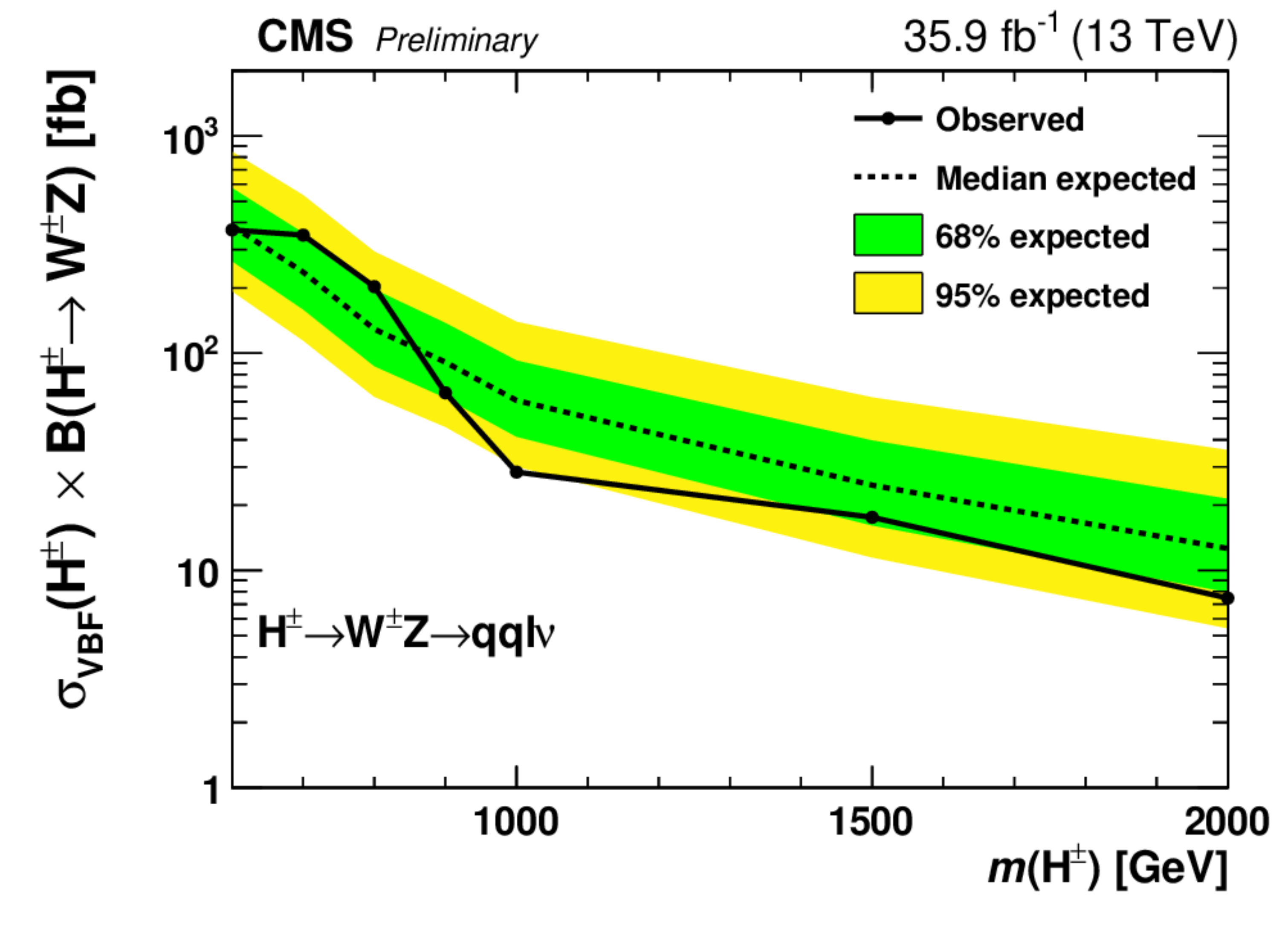
	14 TeV		27 TeV	
	$WZjj$	$W^{\pm}W^{\pm}jj$	$WZjj$	$W^{\pm}W^{\pm}jj$
f_{S_0}/Λ^4	[-8,8]	[-6,6]	[-1.5,1.5]	[-1.5,1.5]
f_{S_1}/Λ^4	[-18,18]	[-16,16]	[-3,3]	[-2.5,2.5]
f_{T_0}/Λ^4	[-0.76,0.76]	[-0.6,0.6]	[-0.04,0.04]	[-0.027,0.027]
f_{T_1}/Λ^4	[-0.50,0.50]	[-0.4,0.4]	[-0.03,0.03]	[-0.016,0.016]
f_{M_0}/Λ^4	[-3.8,3.8]	[-4.0,4.0]	[-0.5,0.5]	[-0.28,0.28]
f_{M_1}/Λ^4	[-5.0,5.0]	[-12,12]	[-0.8,0.8]	[-0.90,0.90]

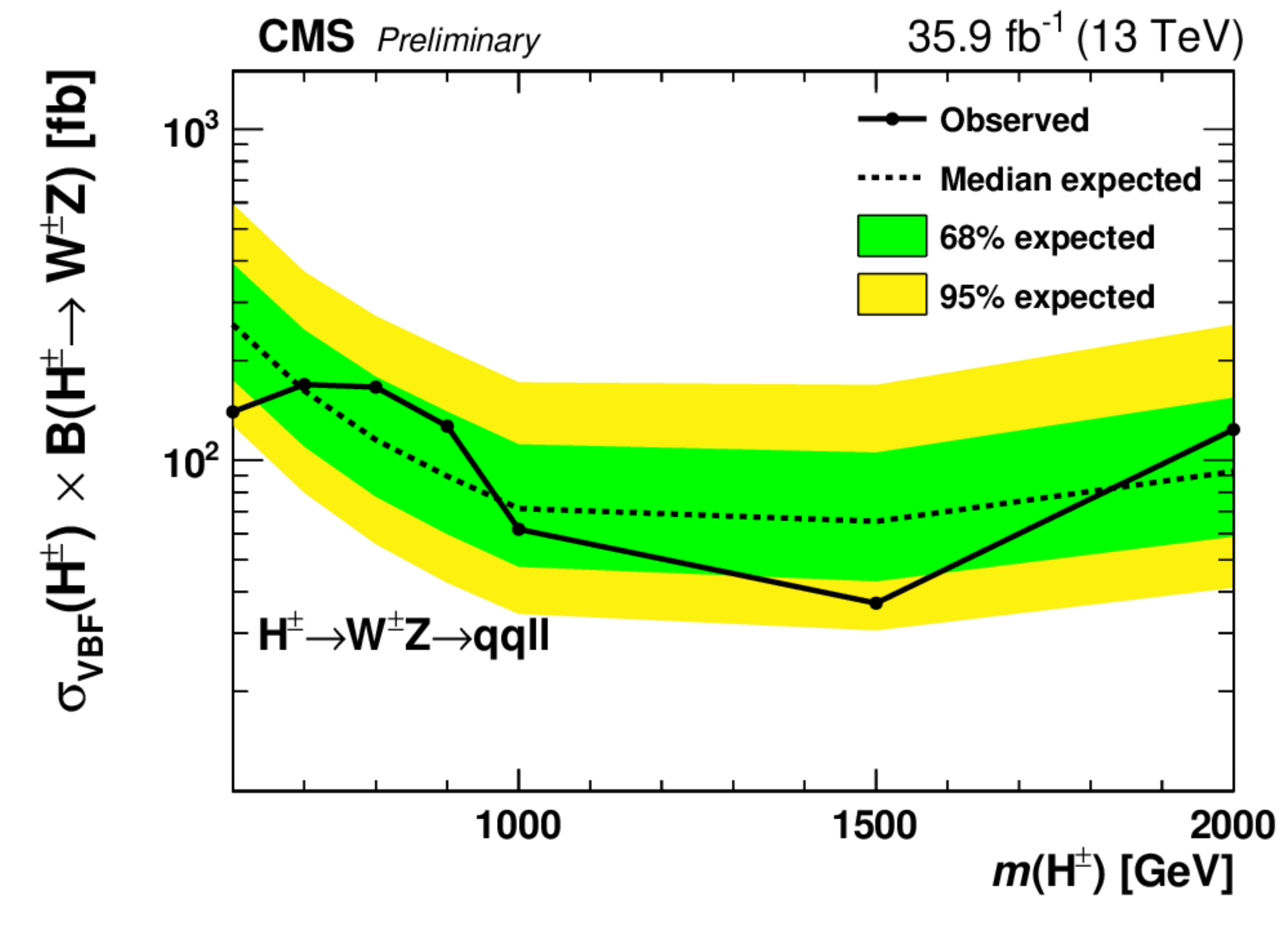
also see WZ VBS (CMS), ssWW (CMS) and WZ resonances (ATLAS)

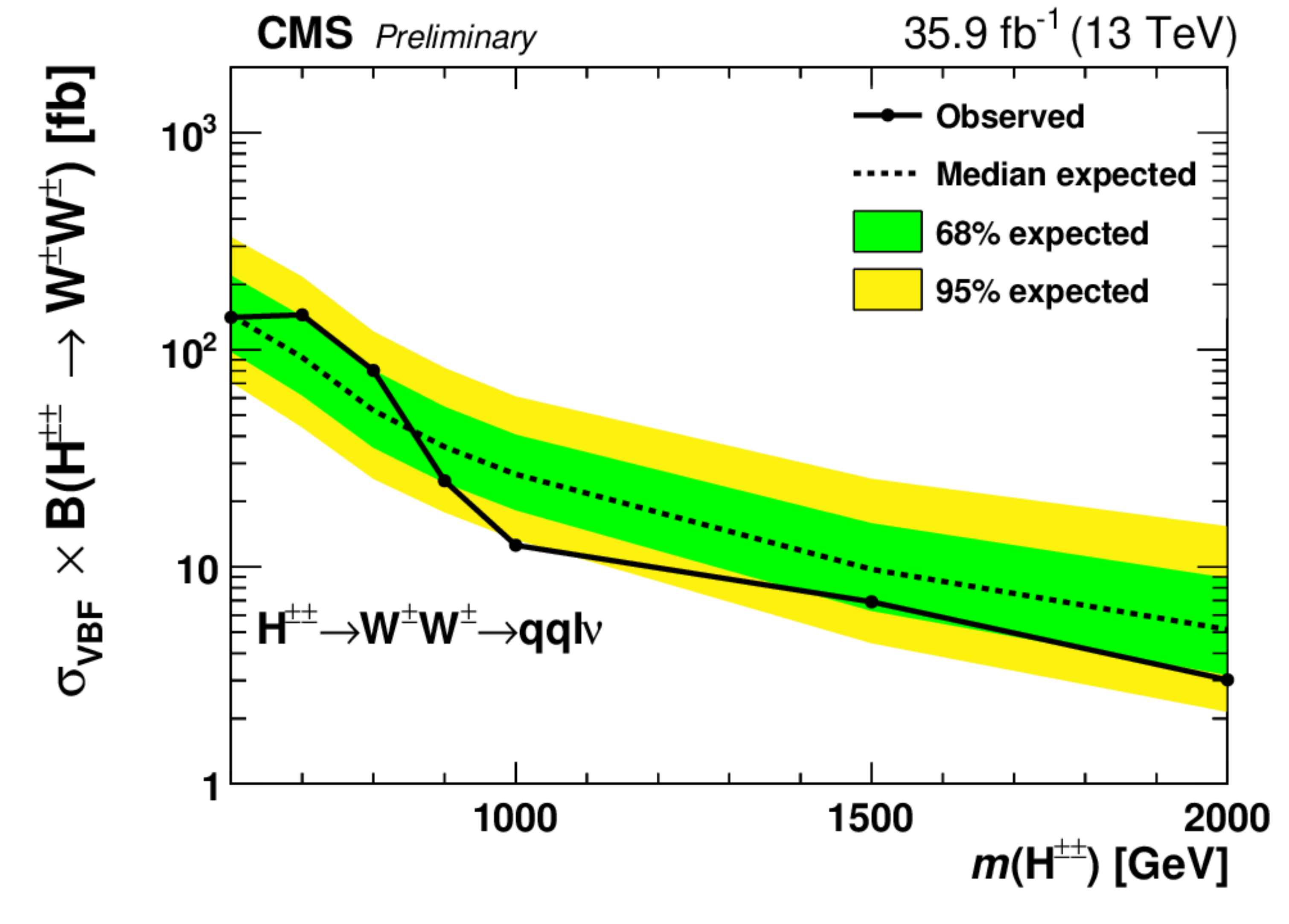
semileptonic VBS CMS

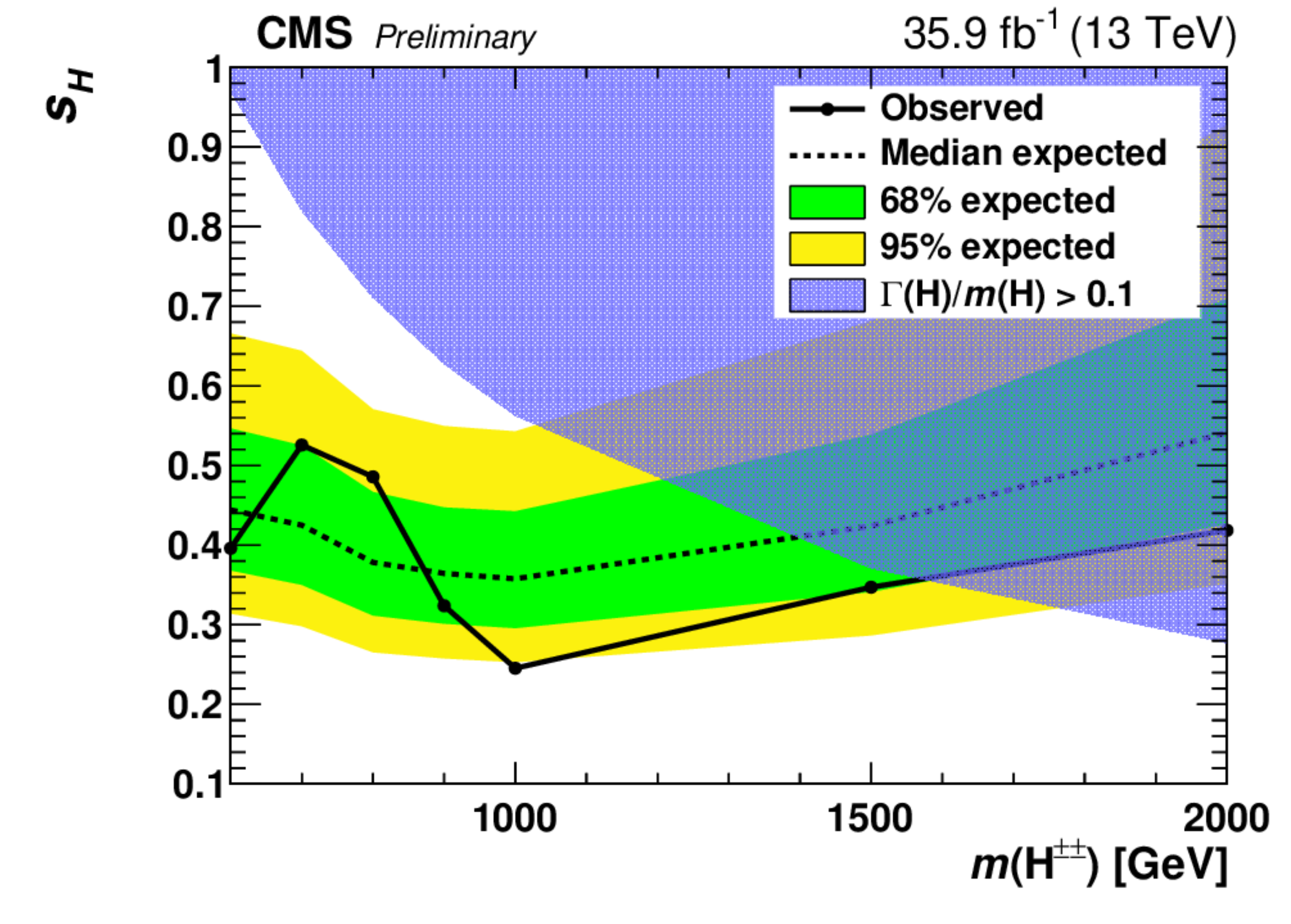
Charged Higgs Interpretations

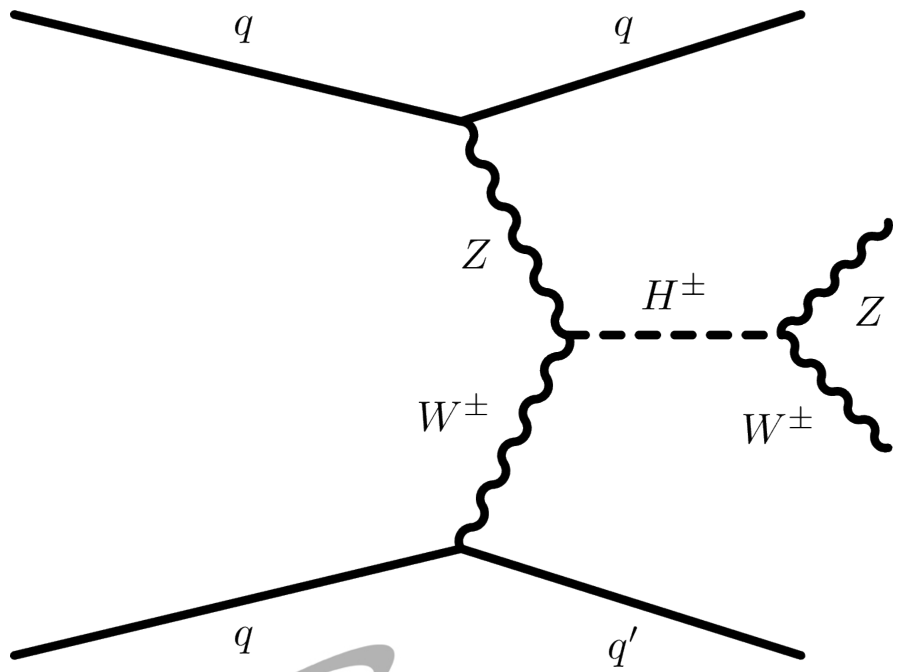
- Extended Higgs sectors with additional SU(2) isotriplet scalars give rise to charged Higgs bosons with couplings to W and Z bosons at the tree level.
- In the Georgi- Machacek (GM) model, singly and doubly charged Higgs bosons are produced via vector boson fusion (VBF) and decay to WZ or ssWW
- mWV and mZV on previous slide also used to derive limits on single- and doubly-charged Higgs production

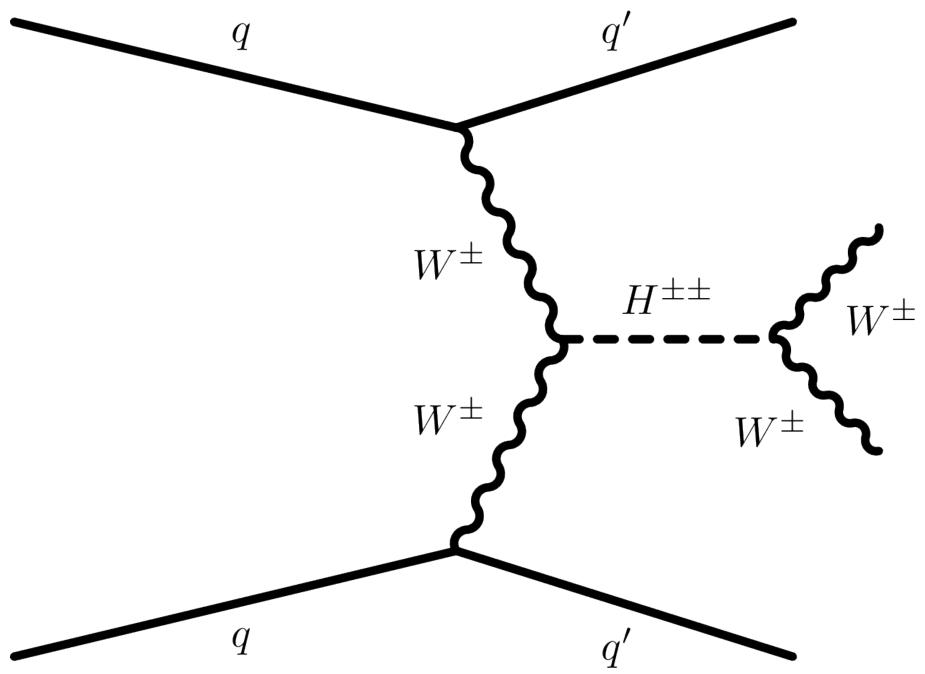












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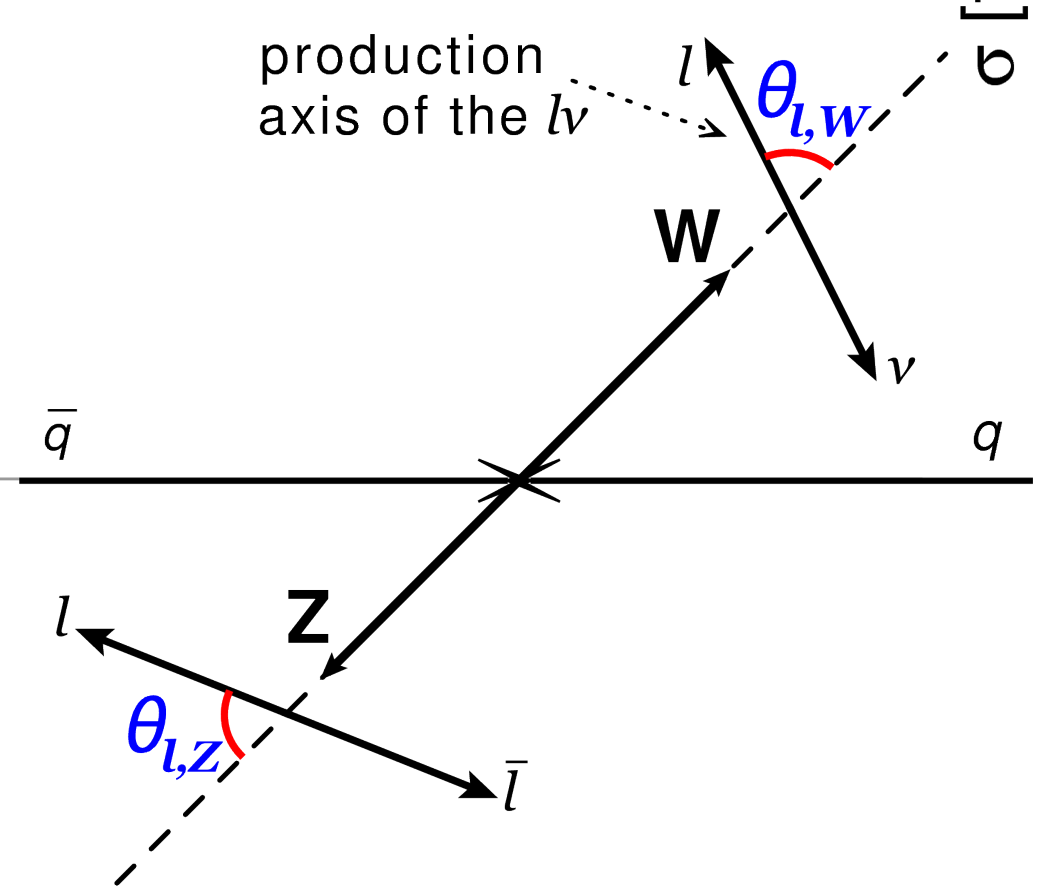
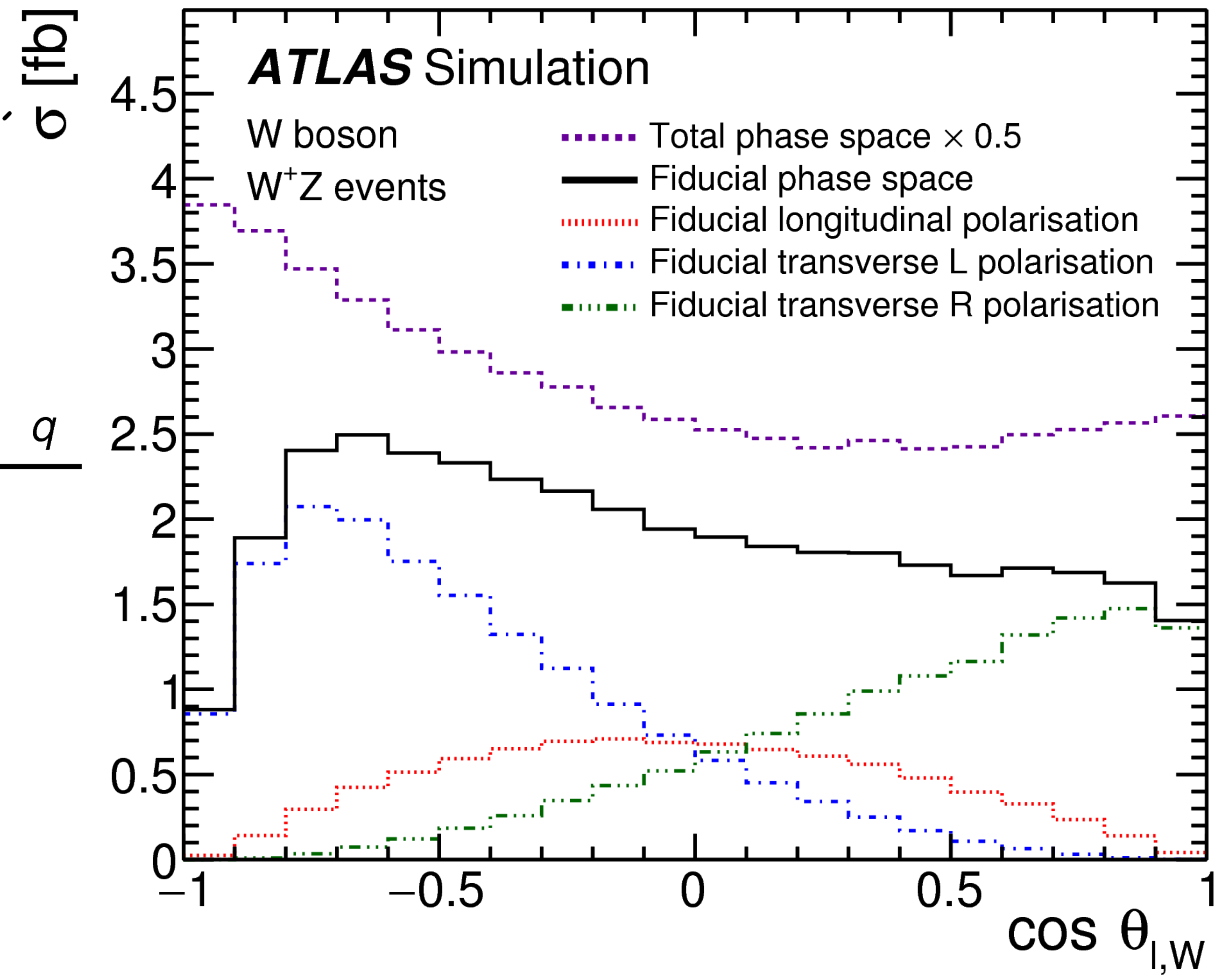
also see Pietro's talk (Wed)

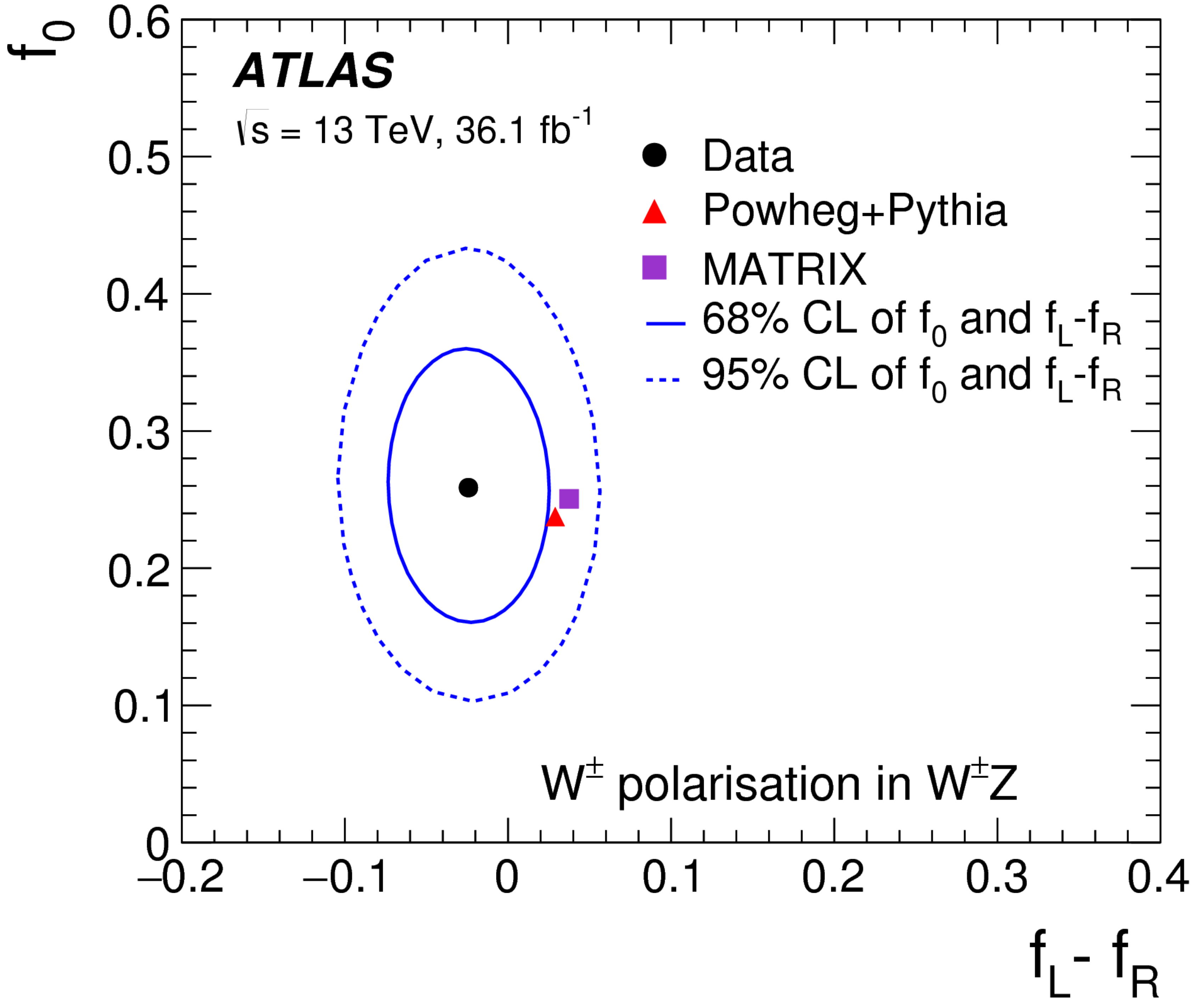
WZ

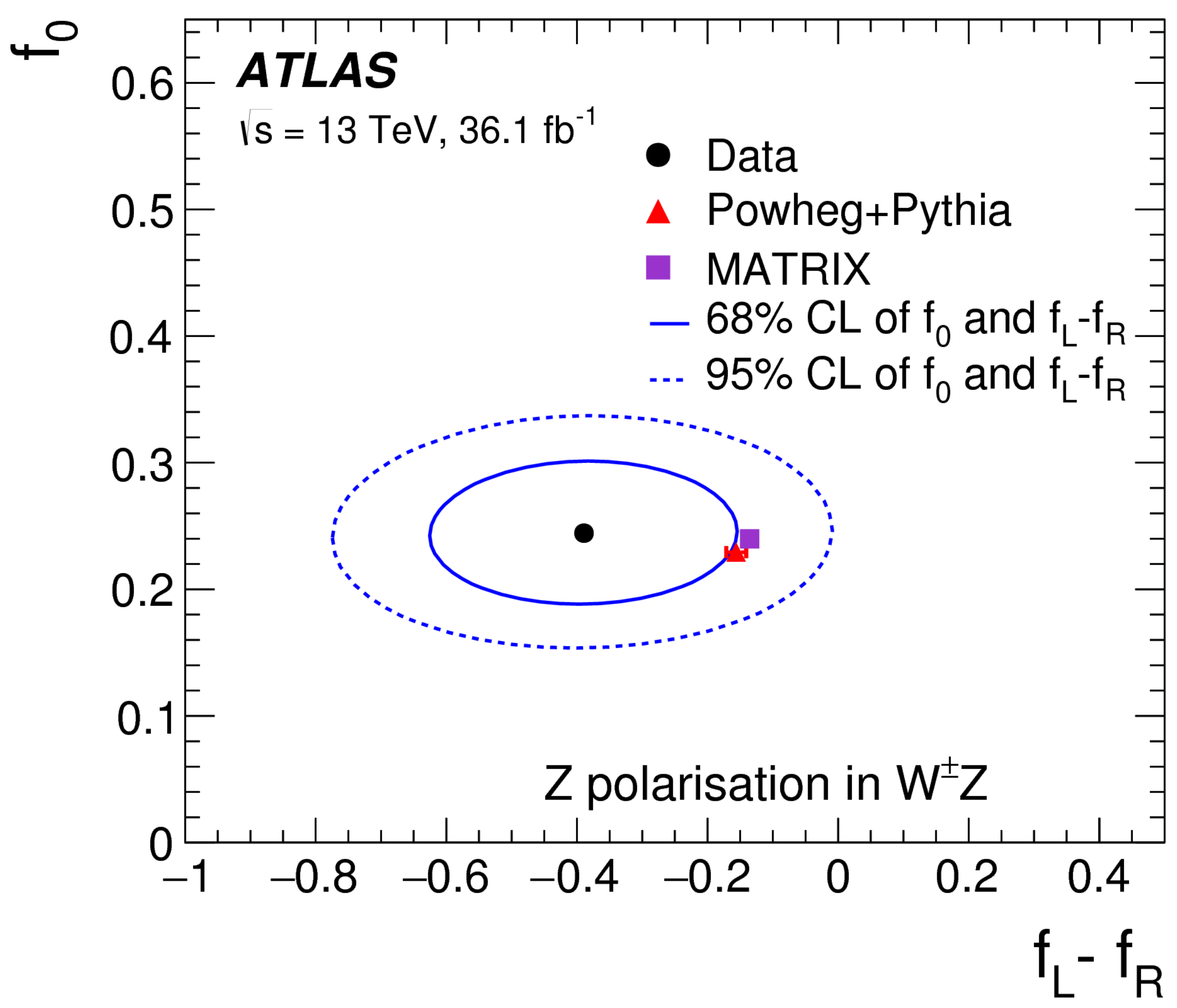
Polarisation

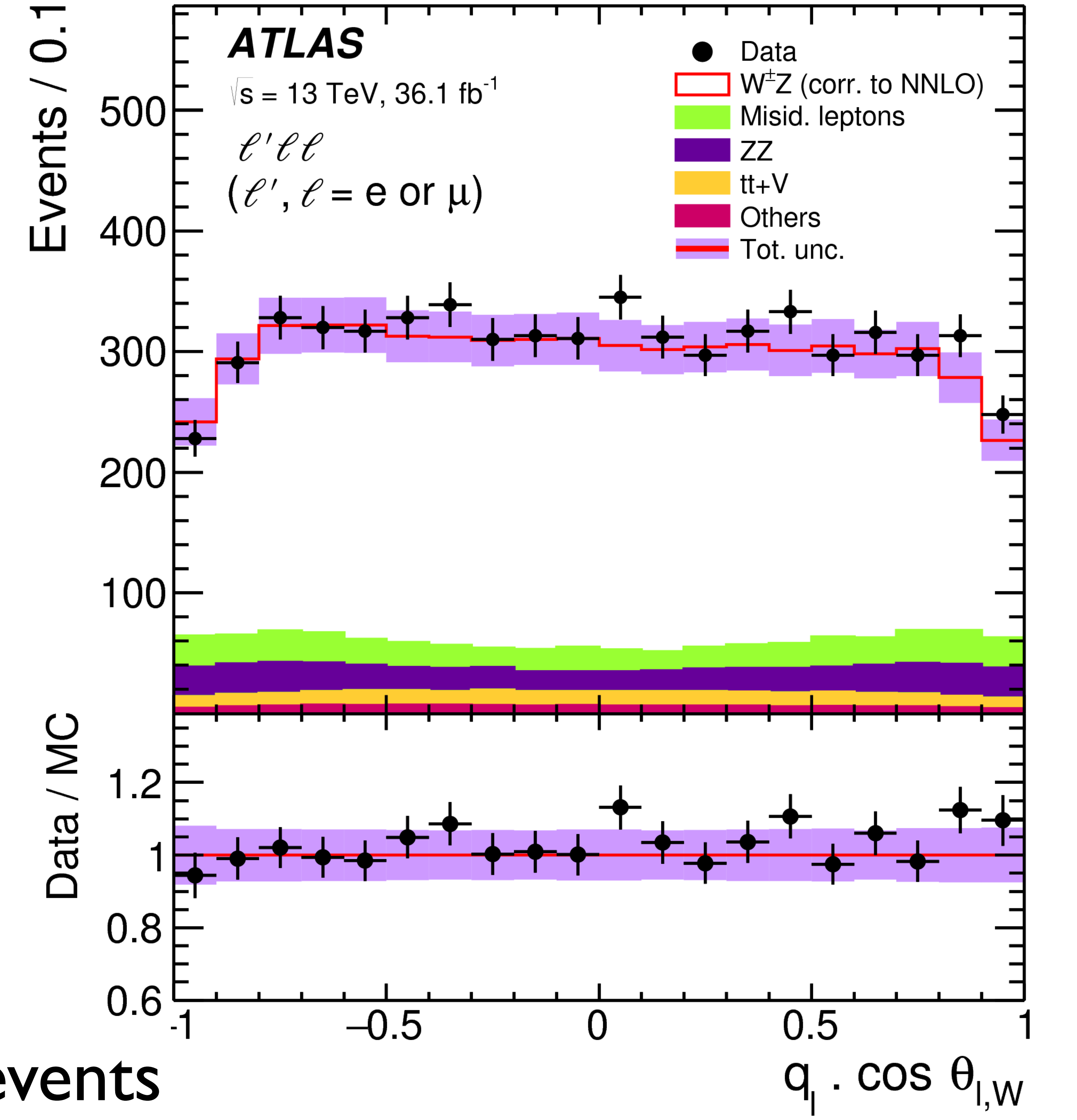




- The existence of the longitudinally polarised state is a consequence of the non-vanishing mass of the bosons generated by the EWSB mechanism. Angular observables can be used to look for new interactions that can lead to different polarisation behaviour than predicted by the SM







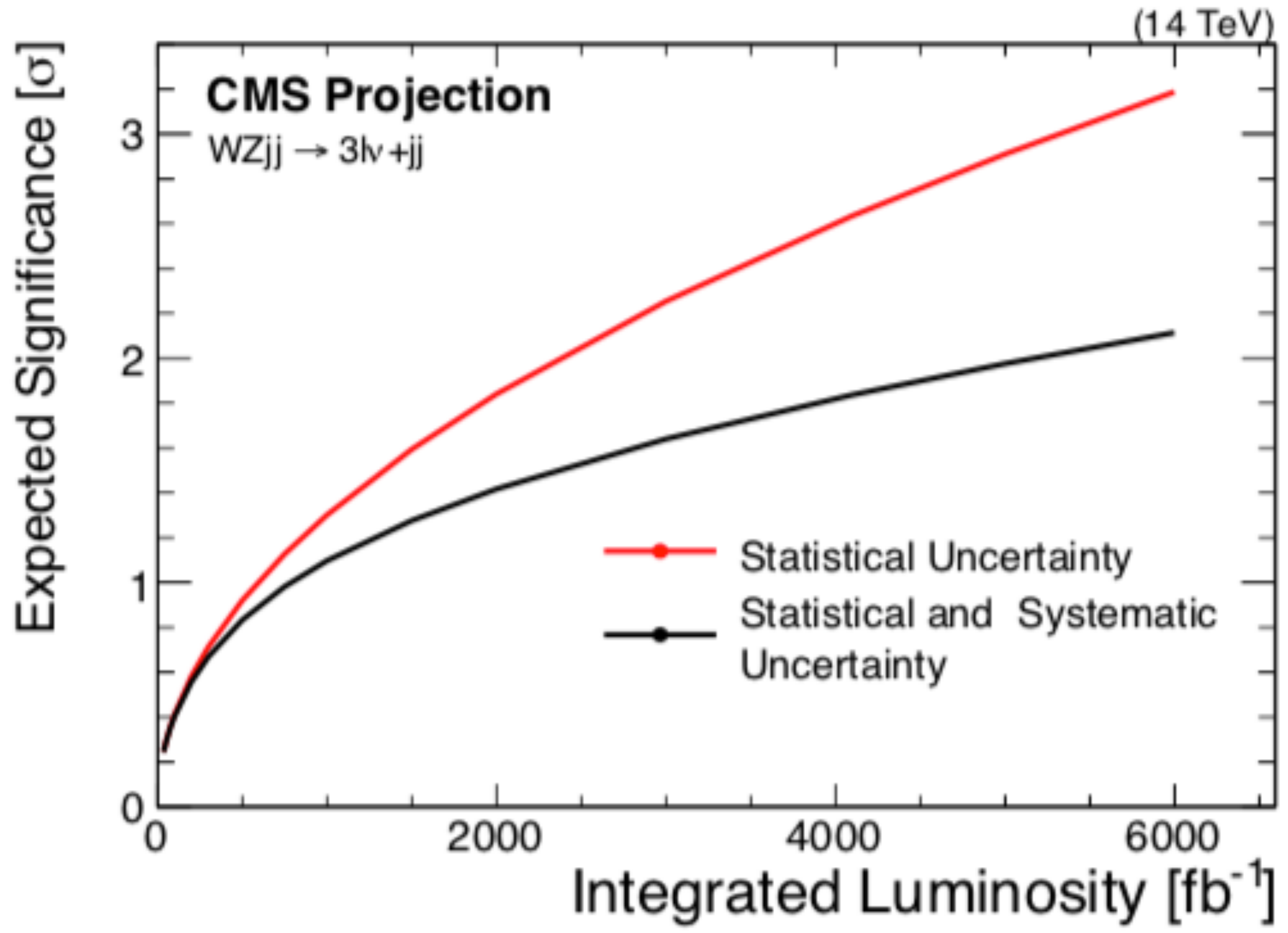
Longitudinal helicity fraction of pair-produced vector bosons is measured in WZ events

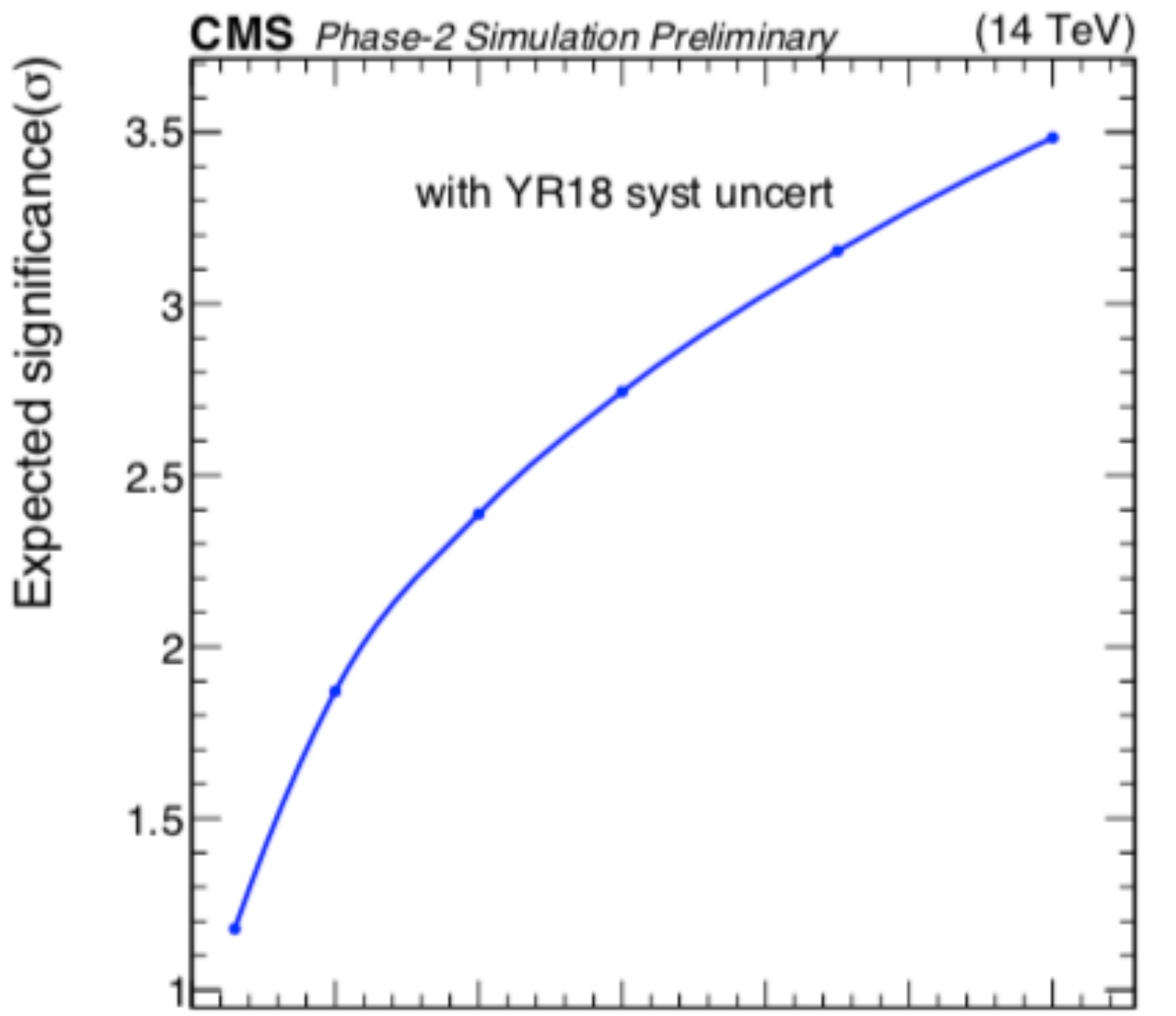
Longitudinal Scattering Projections (for fun)

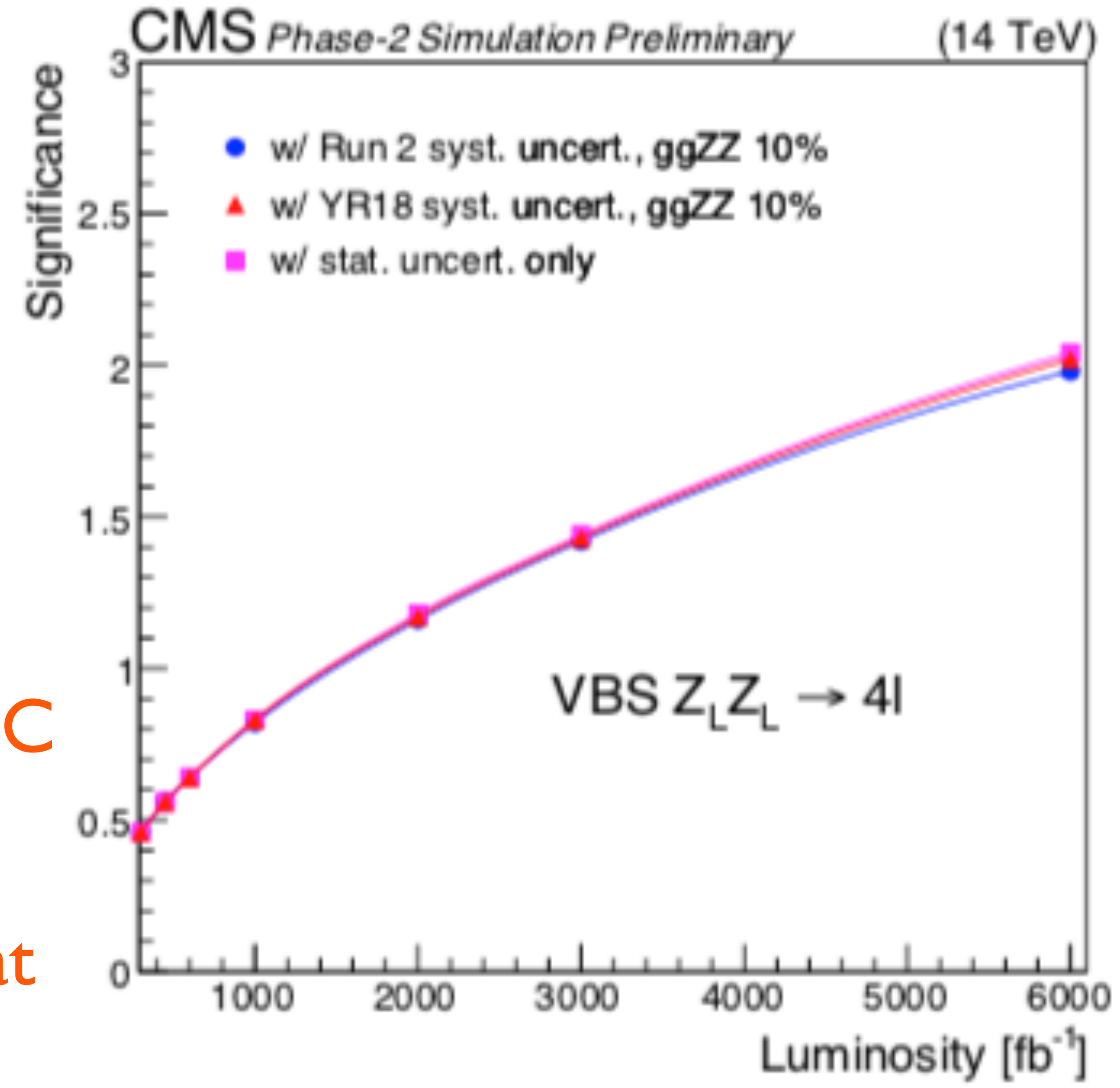
Yellow Report

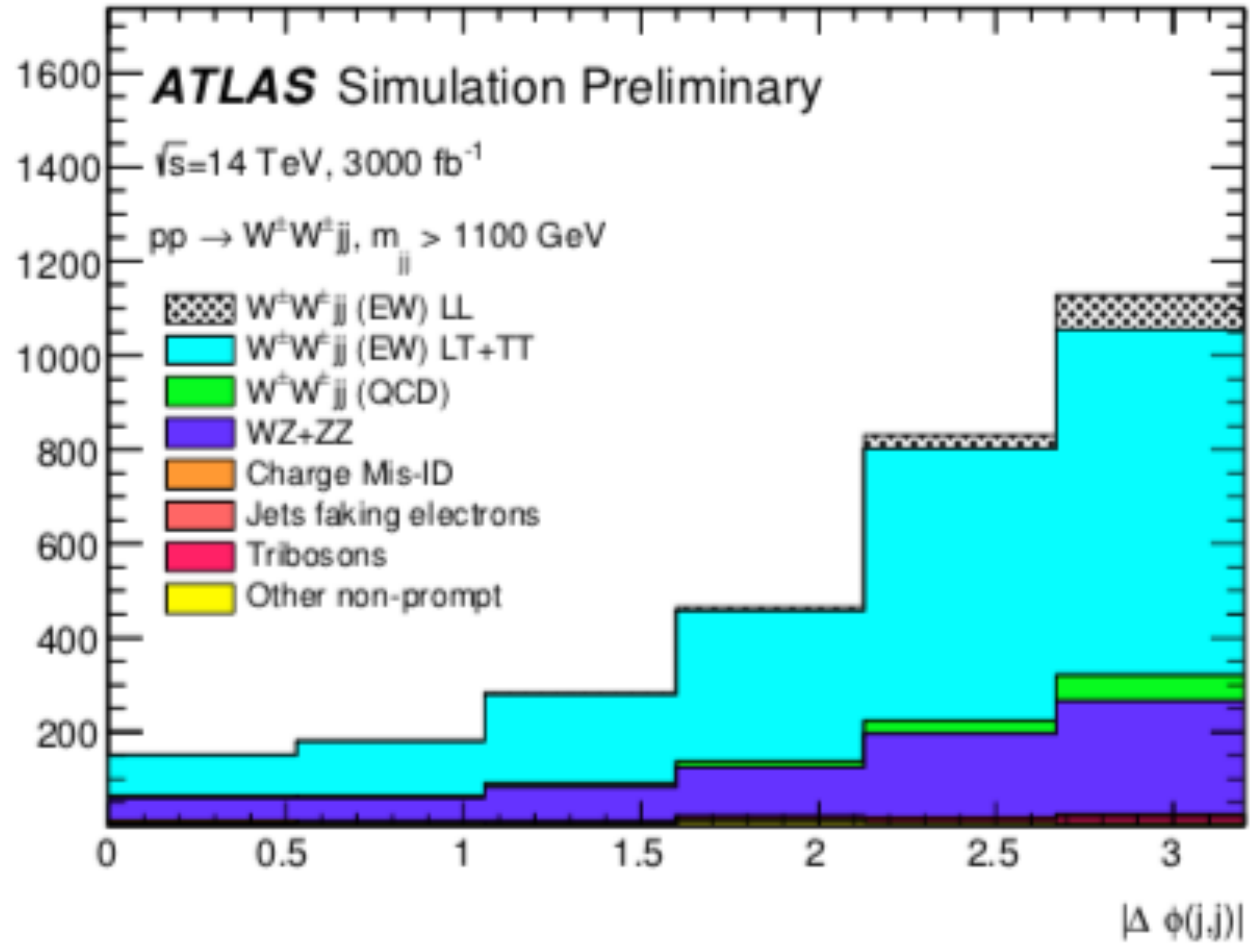
- The total vector boson scattering is composed of three components, depending on the polarisation of the final-state vector bosons

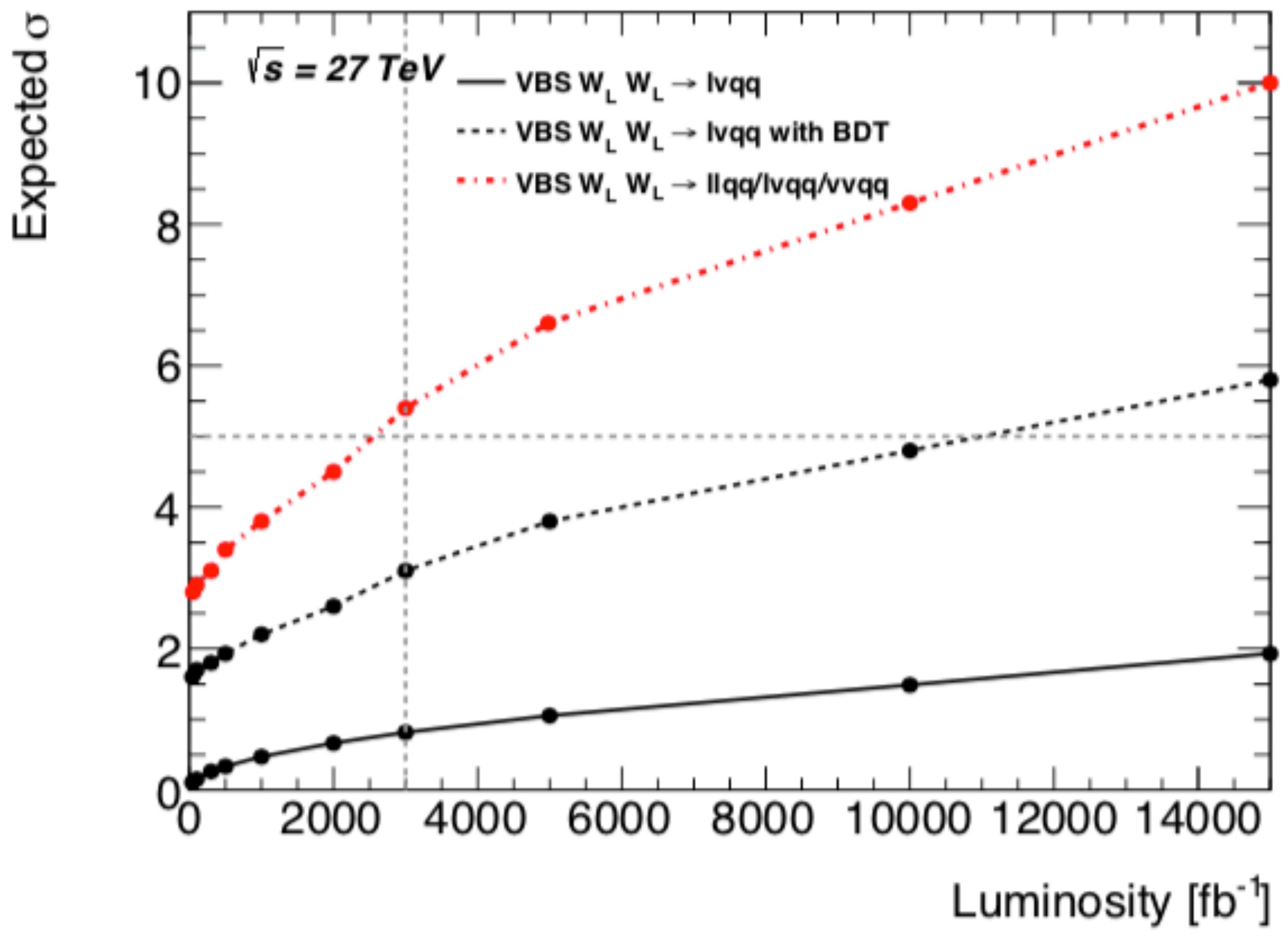
- In the SM, the Higgs boson unitarises the longitudinal V V scattering amplitude completely, so measuring this process will give important information on the nature of the EWSB mechanism











>3σ expected for ssWW with ATLAS+CMS at HL-LHC

5σ for ZLZL fraction at HE-LHC

	significance		precision (%)	
	w/ syst. uncert.	w/o syst. uncert.	w/ syst. uncert.	w/o syst. uncert.)
HL-LHC	1.4σ	1.4σ	75%	75%
HE-LHC	5.2σ	5.7σ	20%	19%

Summary 1

- The determination of the true nature of the EWSB mechanism is the primary goal of the LHC programme, and the study of triple, quartic, and Higgs couplings at high precision will be an important test of the SM in the coming years

- Whatever new physics there is, it seems (for the moment) to be lurking out of our grasp, but new physics may introduce deviations in couplings at high energy scales, leading to an enhancement of vector boson cross sections in ranges we can measure today.

- Results from the LHC on the 7 and 8 TeV datasets surpassed LEP/Tevatron limits for essentially all parameters

- With the excellent performance of the LHC in run 2 at 13 TeV, we now have the opportunity to complete the set of measurements, placing the tightest restrictions on aTGC parameters and EFT coefficients yet.

Summary 2

Improved lepton efficiencies

Additional pileup rejection

Forward lepton tagging

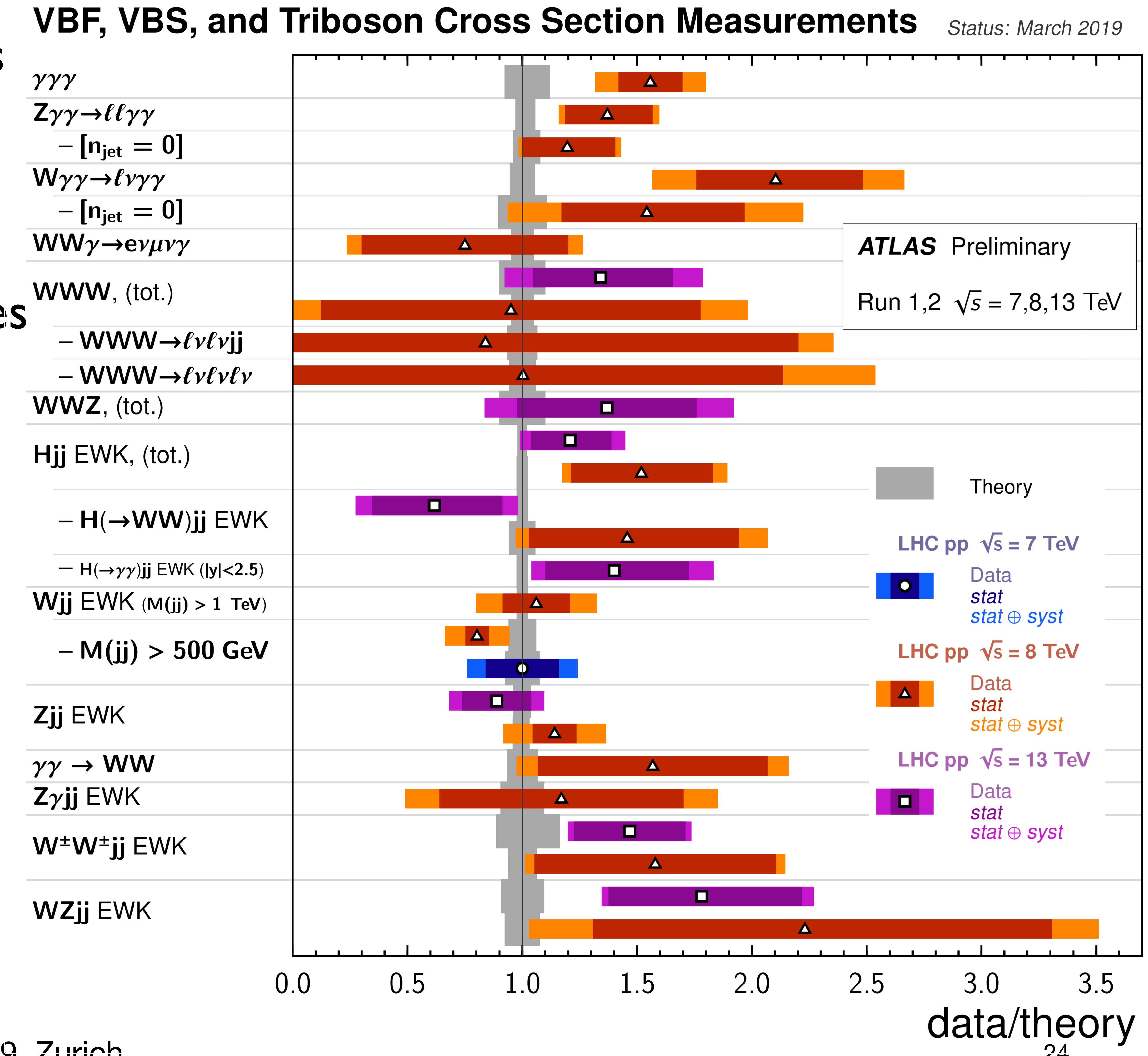
Topological triggers

Jet tagging (q/g)

Forward tracking

Boosted boson tagging

- VBF, VBS, and multiboson signatures allow us to probe aGCs but face a number of experimental challenges
- Currently our results are mostly dominated by stat uncertainties, but we will soon reach the point (in some cases we have already) where PDF and theory uncertainties dominate
    - What can we do now to improve models in the future?
- Semileptonic channels are currently giving us best sensitivity
- Where should we focus our attention for Run 3?



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Backup

aTGC Results Overview

WZ fully leptonic

Parameter	95% CI (expected) $[\mathrm{TeV}^{-2}]$	95% CI (observed) $[\mathrm{TeV}^{-2}]$
c_W/Λ^2	$[-3.3, 2.0]$	$[-4.1, 1.1]$
c_{WWW}/Λ^2	$[-1.8, 1.9]$	$[-2.0, 2.1]$
c_b/Λ^2	$[-130, 170]$	$[-100, 160]$

W+Z VBF

Coupling constant	Expected 95% CL interval (TeV^{-2})	Observed 95% CL interval (TeV^{-2})
c_{WWW}/Λ^2	$[-2.3, 2.4]$	$[-1.8, 2.0]$
c_W/Λ^2	$[-11, 14]$	$[-5.8, 10.0]$
c_B/Λ^2	$[-61, 61]$	$[-43, 45]$

WV semileptonic (new)

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]

aQGC Results Overview

Triboson

Anomalous coupling	Allowed range (TeV^{-4})	
	Expected	Observed
$f_{T,0}/\Lambda^4$	[-1.3, 1.3]	[-1.2, 1.2]
$f_{T,1}/\Lambda^4$	[-3.7, 3.7]	[-3.3, 3.3]
$f_{T,2}/\Lambda^4$	[-3.0, 2.9]	[-2.7, 2.6]

WZ fully leptonic

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	$[-1.78, 2.00]$	$[-1.49, 1.85]$

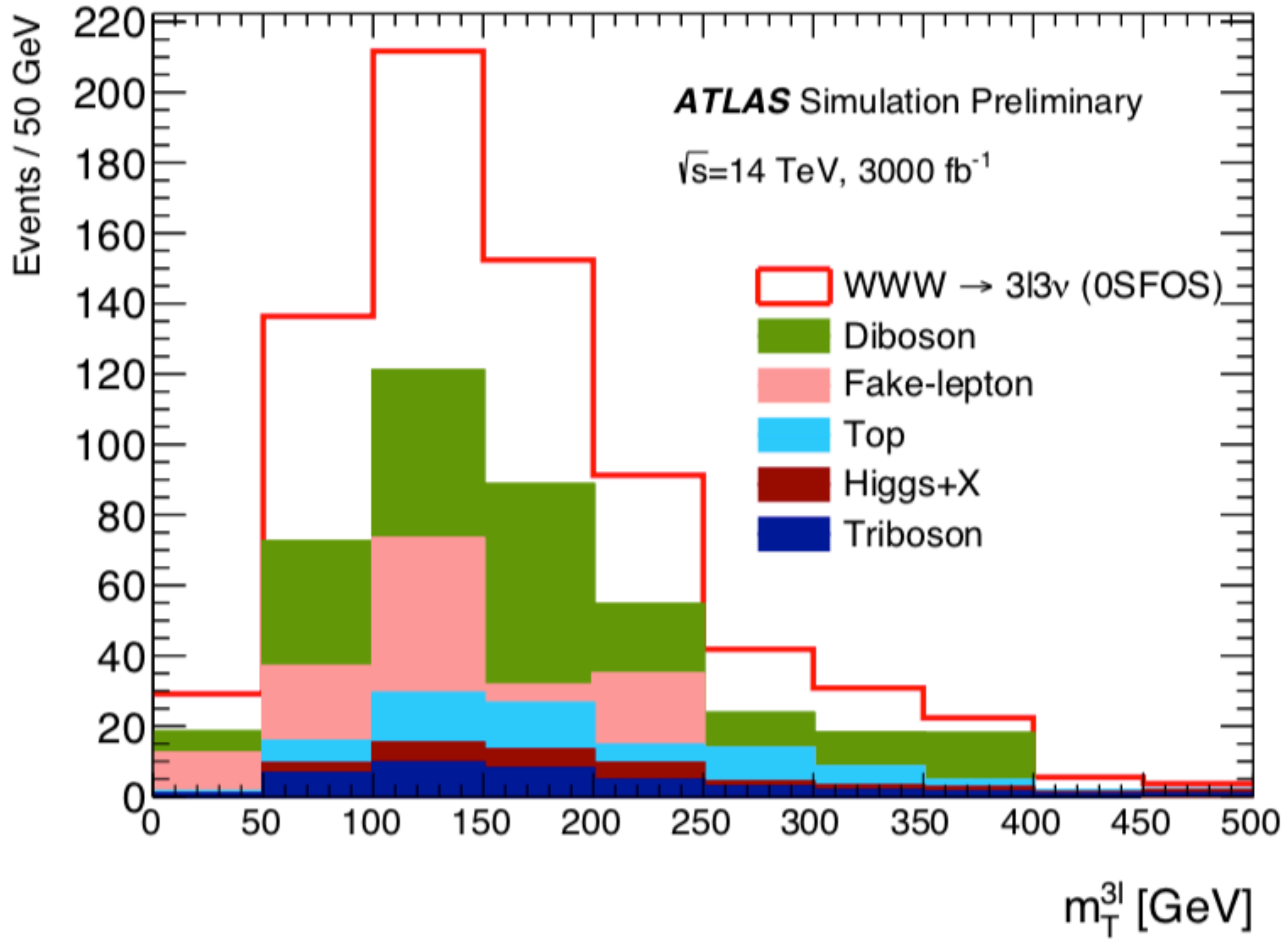
WV semileptonic

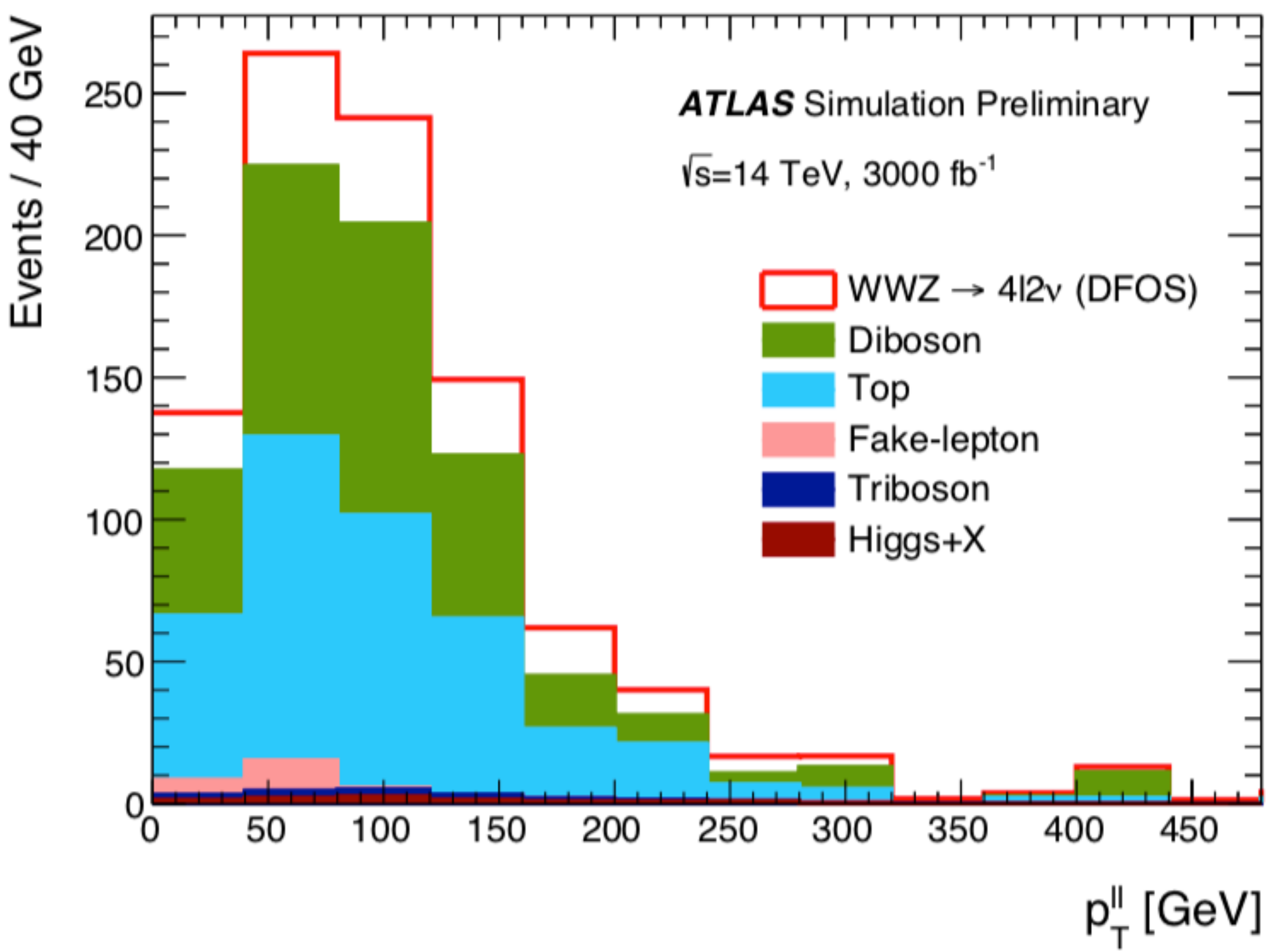
	Observed (WV) (TeV^{-4})	Expected (WV) (TeV^{-4})	Observed (ZV) (TeV^{-4})	Expected (ZV) (TeV^{-4})	Observed (TeV^{-4})	Expected (TeV^{-4})
f_{S0}/Λ^4	$[-2.6, 2.7]$	$[-4.0, 4.0]$	$[-37, 37]$	$[-29, 29]$	$[-2.6, 2.7]$	$[-4.0, 4.0]$
f_{S1}/Λ^4	$[-3.2, 3.3]$	$[-4.9, 4.9]$	$[-30, 30]$	$[-23, 23]$	$[-3.3, 3.3]$	$[-4.9, 4.9]$
f_{M0}/Λ^4	$[-0.66, 0.66]$	$[-0.95, 0.95]$	$[-6.9, 6.9]$	$[-5.1, 5.1]$	$[-0.66, 0.66]$	$[-0.95, 0.95]$
f_{M1}/Λ^4	$[-1.9, 2.0]$	$[-2.8, 2.8]$	$[-21, 21]$	$[-15, 15]$	$[-1.9, 2.0]$	$[-2.8, 2.8]$
f_{M6}/Λ^4	$[-1.3, 1.3]$	$[-1.9, 1.9]$	$[-14, 14]$	$[-10, 10]$	$[-1.3, 1.3]$	$[-1.9, 1.9]$
f_{M7}/Λ^4	$[-3.3, 3.2]$	$[-4.8, 4.8]$	$[-33, 33]$	$[-24, 24]$	$[-3.3, 3.3]$	$[-4.8, 4.8]$
f_{T0}/Λ^4	$[-0.11, 0.10]$	$[-0.16, 0.15]$	$[-1.3, 1.3]$	$[-0.95, 0.95]$	$[-0.12, 0.10]$	$[-0.16, 0.15]$
f_{T1}/Λ^4	$[-0.11, 0.12]$	$[-0.17, 0.17]$	$[-1.4, 1.4]$	$[-0.98, 0.99]$	$[-0.11, 0.12]$	$[-0.17, 0.17]$
f_{T2}/Λ^4	$[-0.27, 0.27]$	$[-0.38, 0.38]$	$[-3.1, 3.2]$	$[-2.3, 2.3]$	$[-0.27, 0.27]$	$[-0.38, 0.38]$

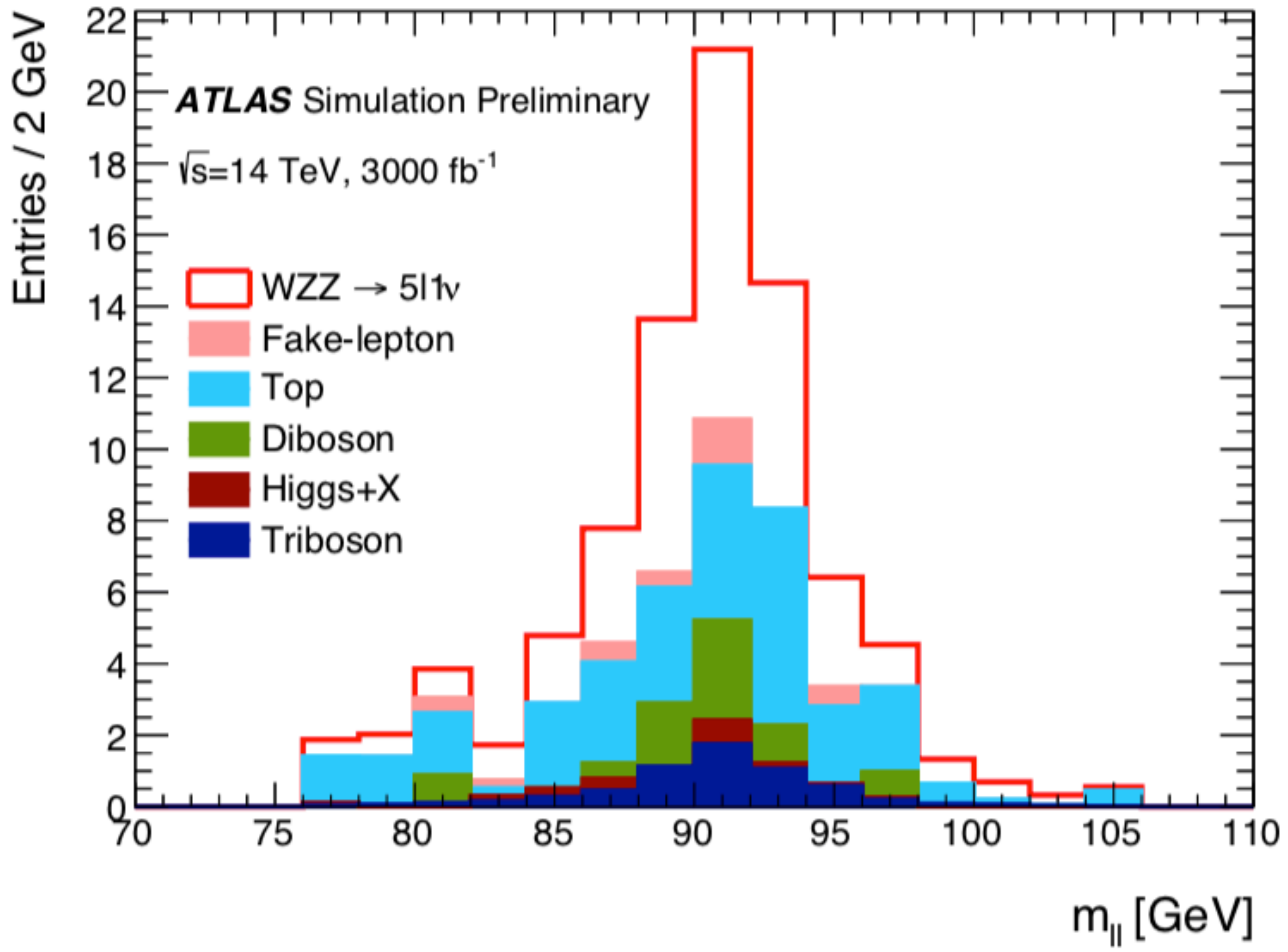
Triboson Expectations

- The HL-LHC will offer a large improvement to triboson production, with 5σ observation expected for the WWW channel
  - Important to constrain these processes as they form the background to many direct new physics searches
  - Fully leptonic channels provide the best sensitivity, though again lepton efficiencies will be important

Process	WWW	WWZ	WZZ
Final state	$3\ell 3\nu$	$4\ell 2\nu$	$5\ell\nu$
Precision	11%	27%	36%
Significance	$>5\sigma$	3.0σ	3.0σ







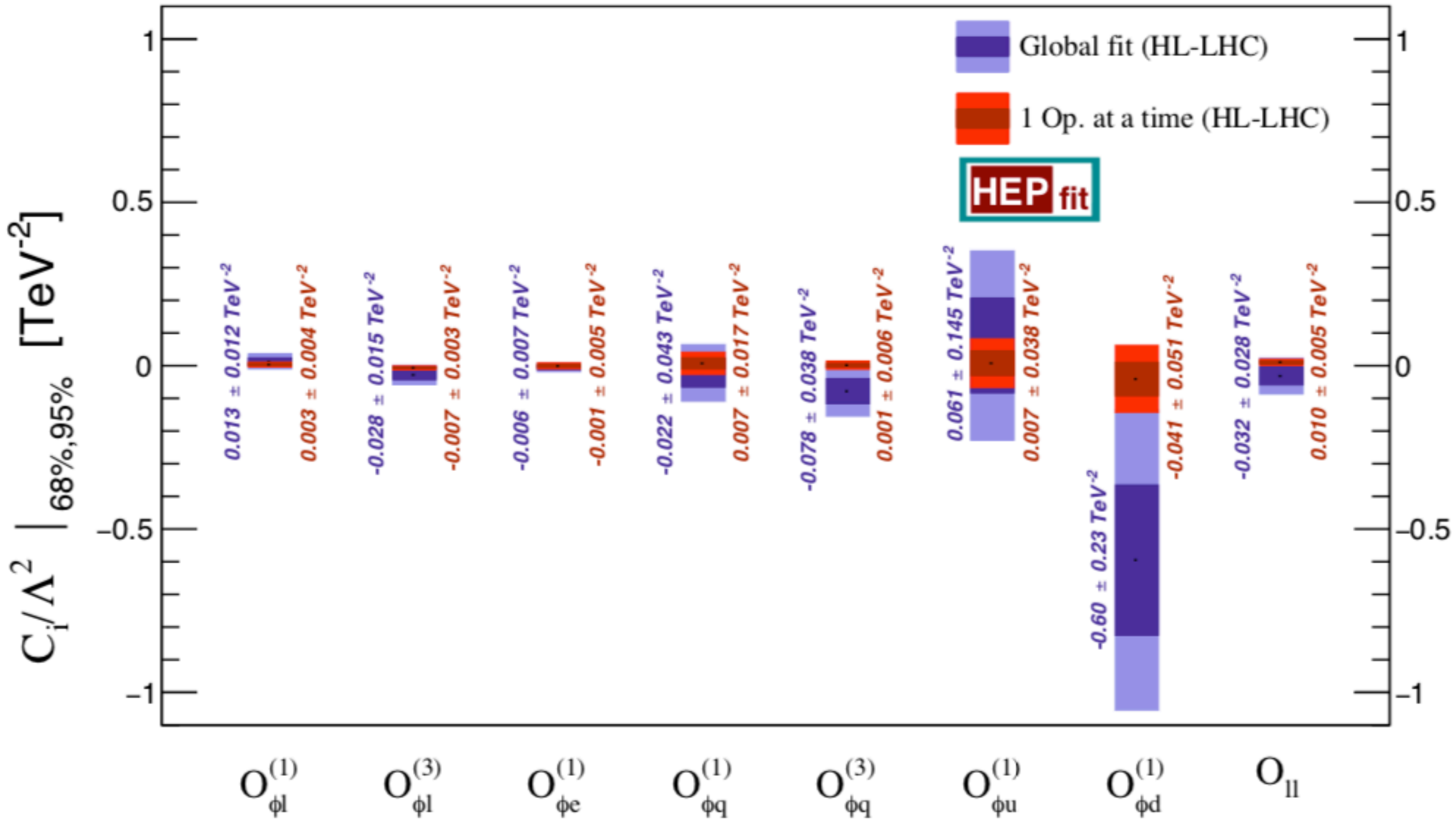
see Raquel's talk next!

Yellow Report

Putting it all together: Global Electroweak Fit at HL-LHC

- The HL-LHC could also improve the current bounds on some of the considered Wilson coefficients by up to 10-30%

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_{d>4} \frac{1}{\Lambda^{d-4}} \mathcal{L}_d \qquad \mathcal{L}_d = \sum_i C_i \mathcal{O}_i^{(d)}, \quad \left[\mathcal{O}_i^{(d)}\right] = d$$



Operator Coefficient	Current uncertainty [TeV^{-2}] 1 op. at a time	Current uncertainty [TeV^{-2}] Global fit	Precision at HL-LHC [TeV^{-2}] 1 op. at a time	Precision at HL-LHC [TeV^{-2}] Global fit
$\overline{C}_{\phi l}^{(1)}$	0.004	0.012	0.004	0.012
$\overline{C}_{\phi q}^{(1)}$	0.018	0.044	0.017	0.043
$\overline{C}_{\phi e}$	0.005	0.009	0.005	0.007
$\overline{C}_{\phi u}$	0.040	0.146	0.038	0.145
$\overline{C}_{\phi d}$	0.054	0.237	0.051	0.230
$\overline{C}_{\phi l}^{(3)}$	0.004	0.017	0.003	0.015
$\overline{C}_{\phi q}^{(3)}$	0.007	0.040	0.006	0.038
$\overline{C}_{ll}$	0.007	0.028	0.005	0.028
$\overline{C}_{\phi WB}$	0.003	–	0.002	–
$\overline{C}_{\phi D}$	0.007	–	0.005	–