Vector boson scattering and triboson studies at ATLAS

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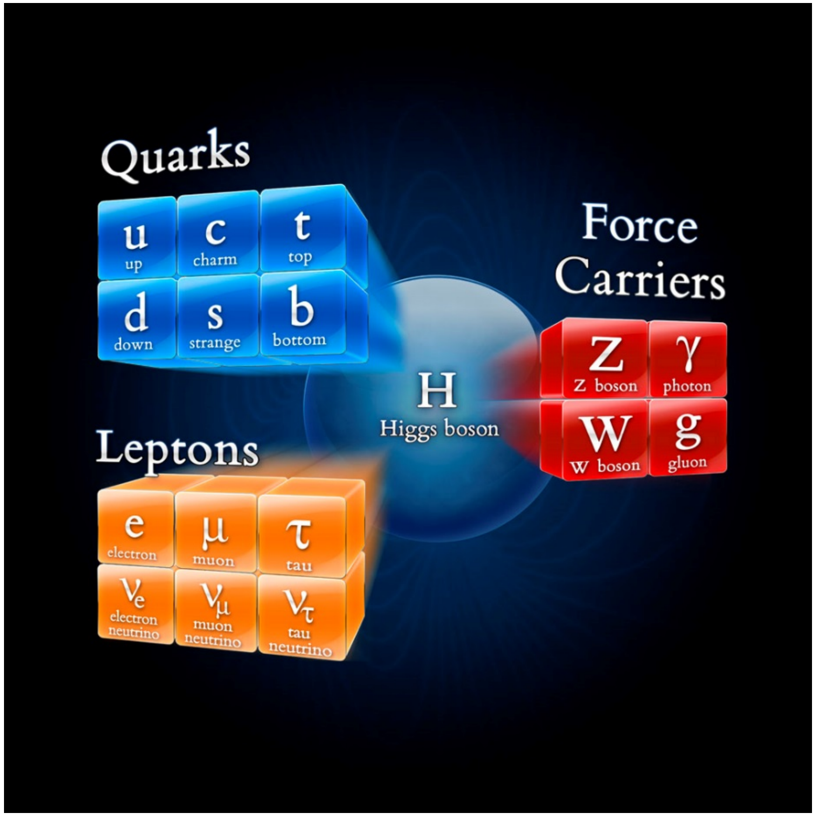
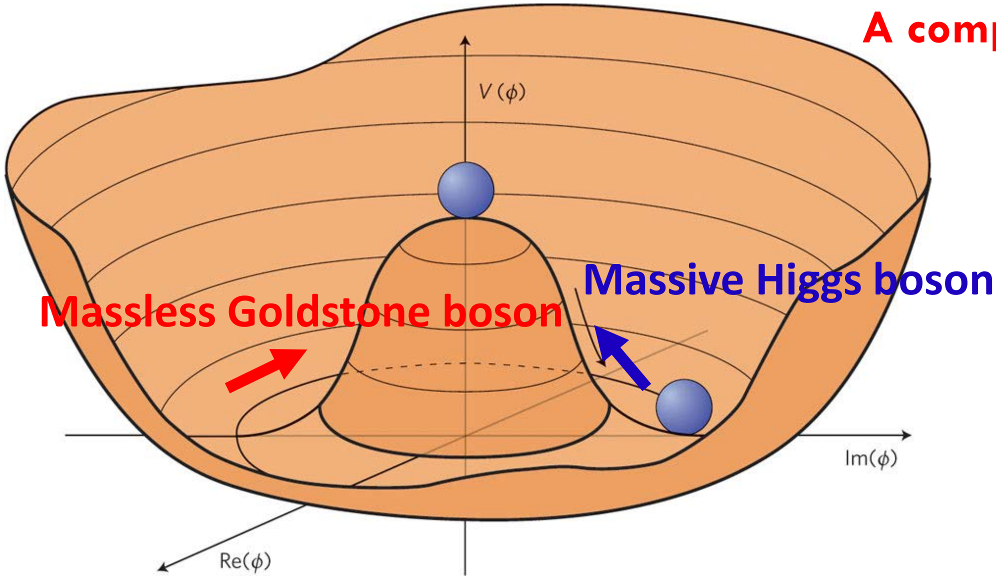
Periodic Table of SM Particles



- Particle physics: study fundamental particles and their interactions
- Particles in the SM:
  - 12 matter particles – spin-½ fermions
  - 4 force carrier particles – spin-1 bosons (vector bosons)
    - Electromagnetic (γ), weak (W^+/W^-, Z) and strong (g)
    - Eletromagnetic and weak forces unified to electroweak force
  - 1 Higgs particle – spin-0 boson (scalar boson)

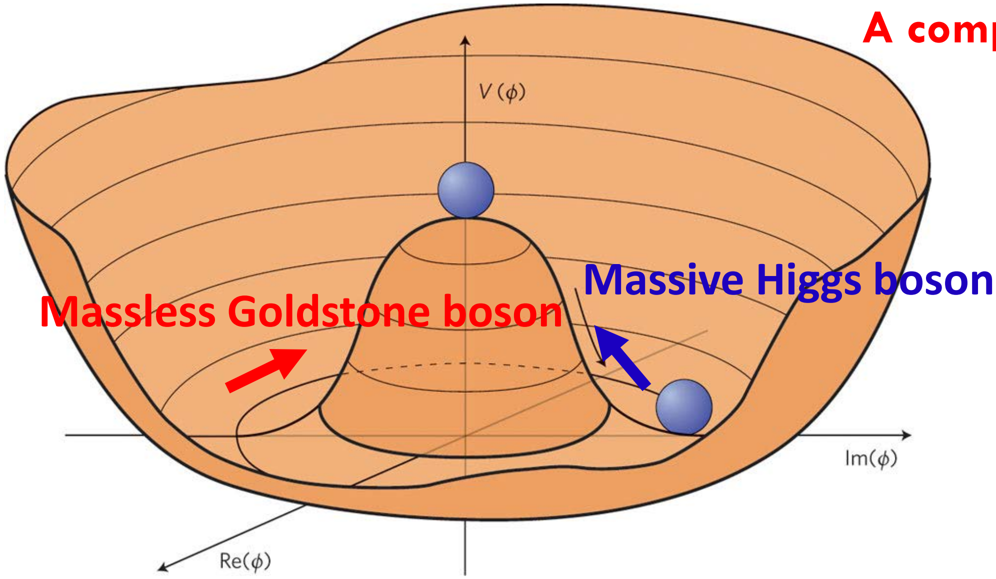
Spontaneous Symmetry Breaking in SM

A complex Higgs field (2 DOFs)

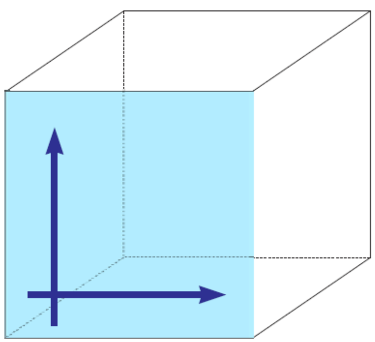


Spontaneous Symmetry Breaking in SM

A complex Higgs field (2 DOFs)

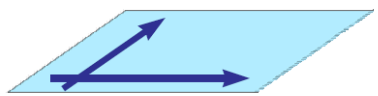


Two transverse modes of massless vector field:



Massless vector boson

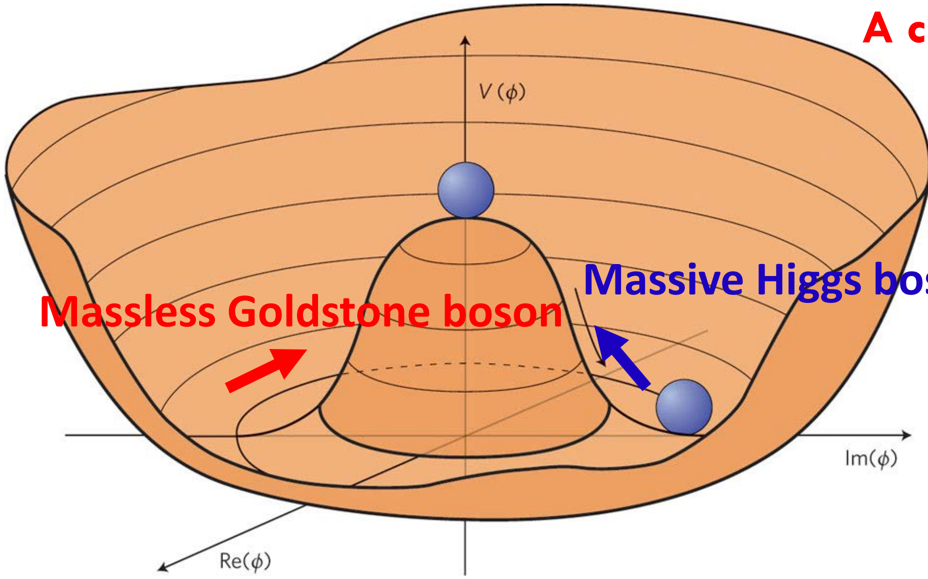
Complex scalar field (2 degrees of freedom):

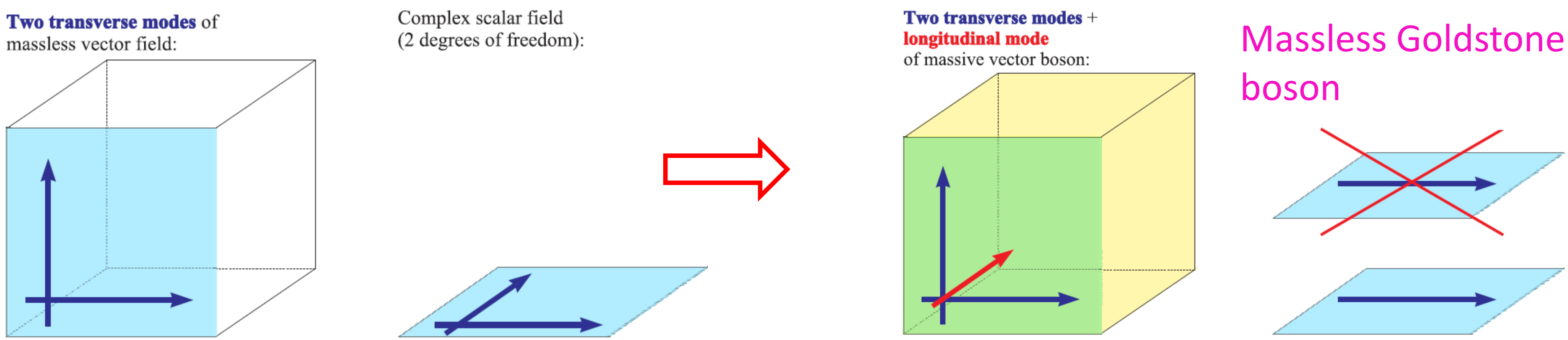


Higgs field

Spontaneous Symmetry Breaking in SM

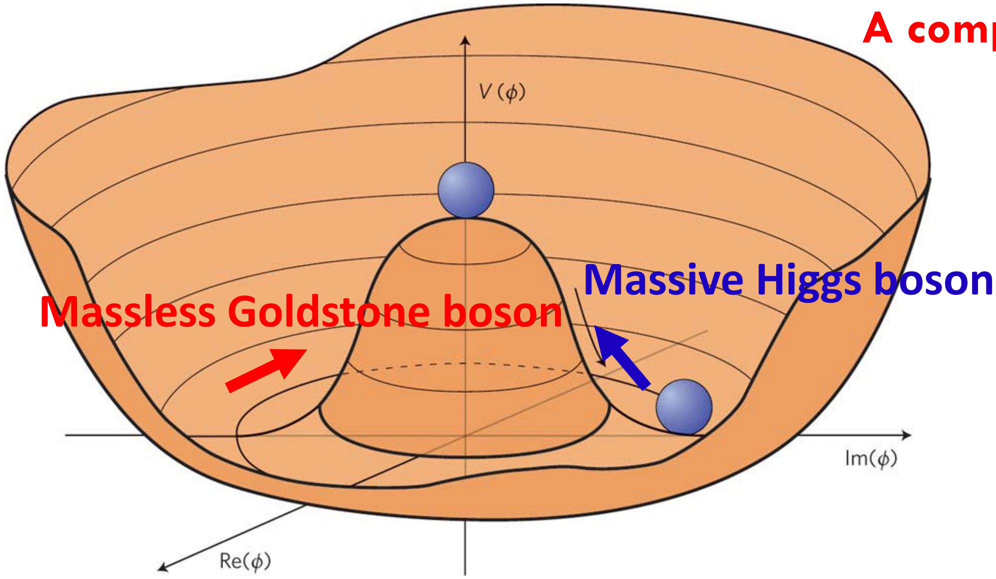
A complex Higgs field (2 DOFs)

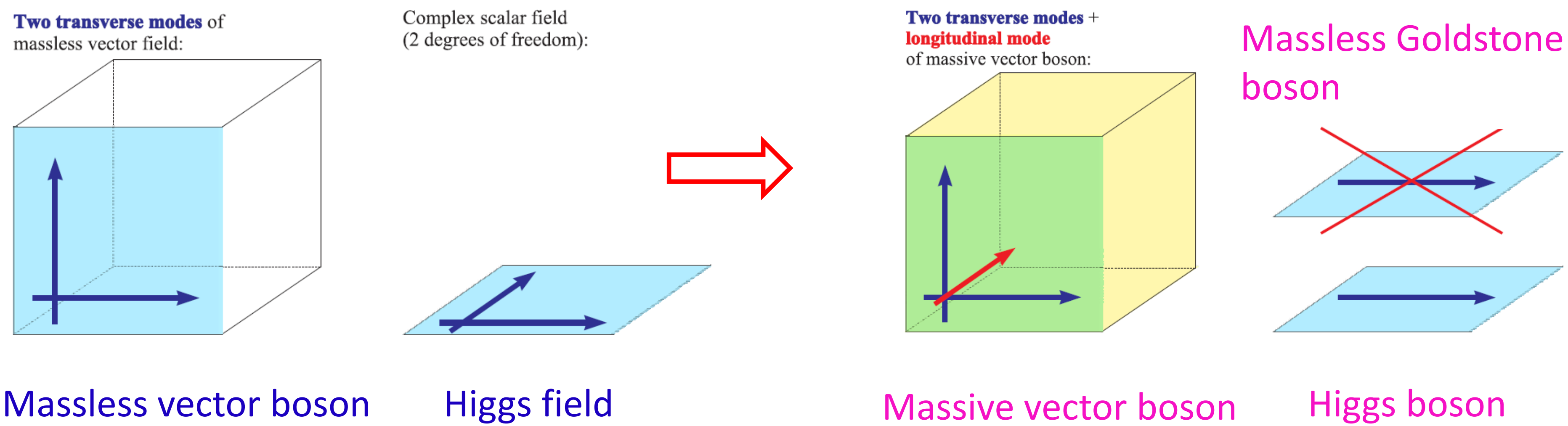




Massless vector boson   Higgs field   Massive vector boson   Higgs boson

Spontaneous Symmetry Breaking in SM





Massless Goldstone boson is "eaten" by massless vector boson and becomes its longitudinal mode -- the Higgs mechanism

EWSB (Higgs) mechanism

4 massless vector bosons (W^+, W^-, Z, γ)

$$4 \times 2 + 4$$

2 transverse modes

4 DOFs for the Higgs sector
(Higgs field is a weak isospin doublet)

1 Higgs boson and 3 massless Goldstone bosons

EWSB (Higgs) mechanism

4 massless vector bosons (W^+, W^-, Z, γ)

$$4 \times 2 + 4$$

2 transverse modes

4 DOFs for the Higgs sector
(Higgs field is a weak isospin doublet)

1 Higgs boson and 3 massless
Goldstone bosons

the Higgs mechanism

3 massive bosons (W^+, W^-, Z)

Massless γ

the Higgs boson

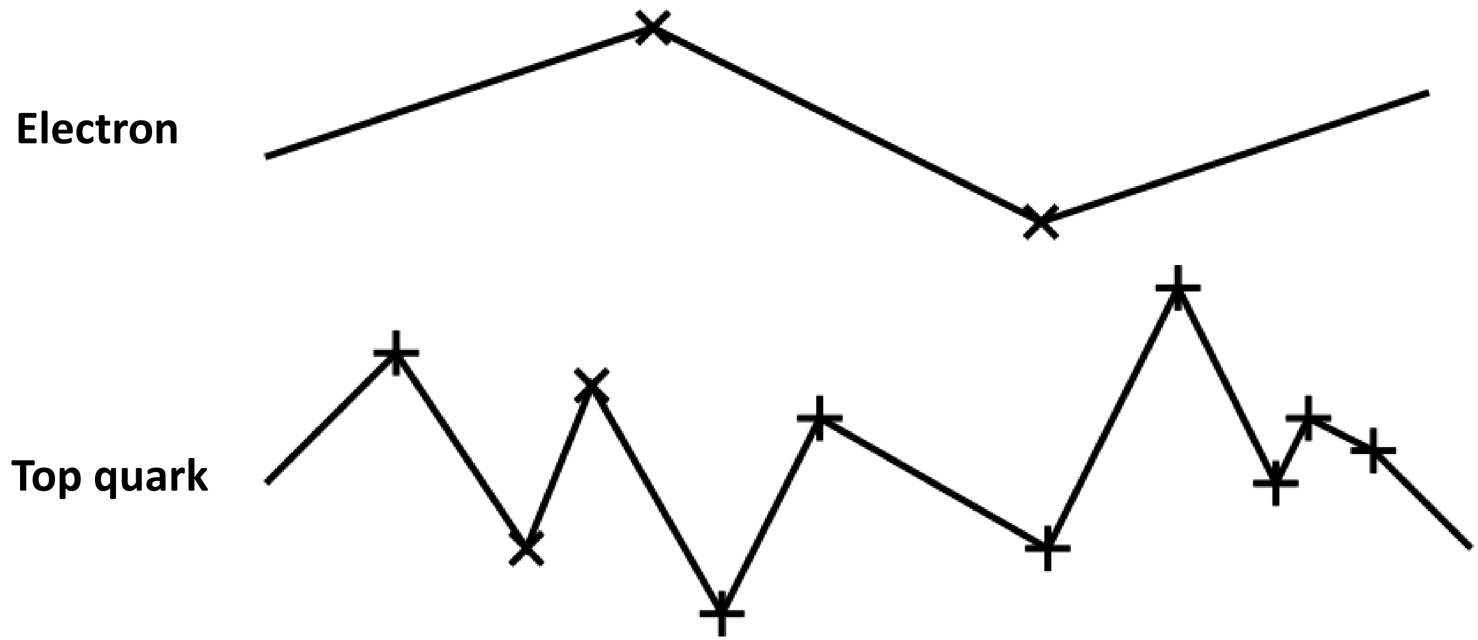
$$3 \times 3 + 2 + 1$$

2 transverse modes +
1 longitudinal mode

- Important to test EWSB by studying the scattering of longitudinal modes of massive vector bosons (longitudinal vector boson scattering): $V_L V_L \rightarrow V_L V_L$

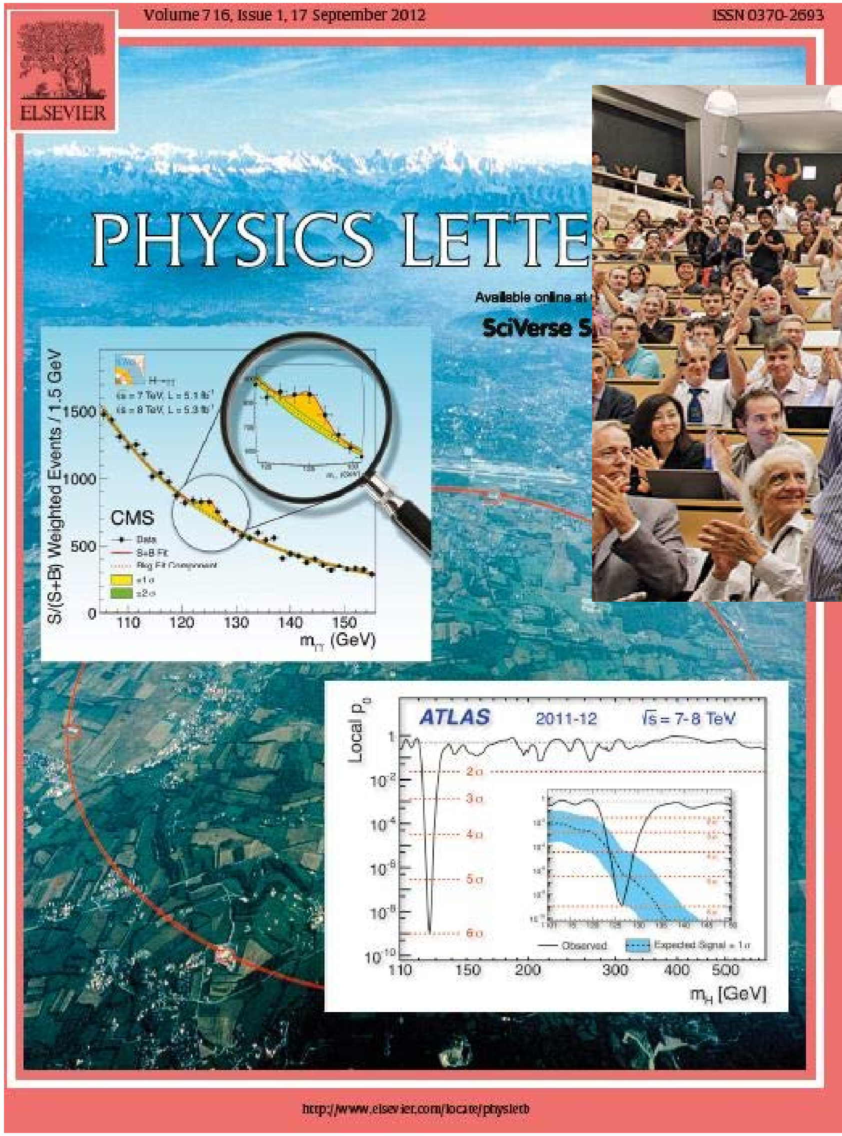
Fermion masses

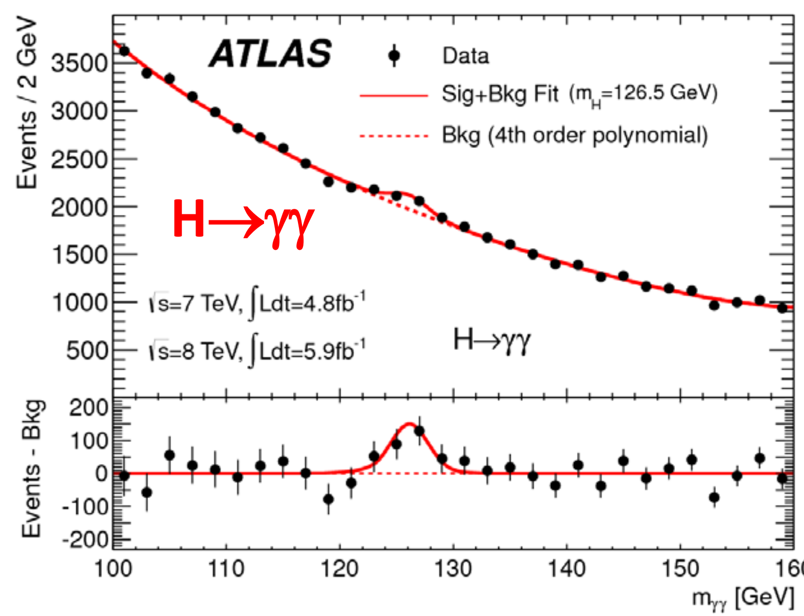
- Masses of other matter particles (Fermions) come from the Yukawa coupling between the particle and the Higgs field
- The coupling depends on the mass of the particle, Higgs likes to couple to heavy particles ($\kappa_{Htt} >> \kappa_{Hee}$)



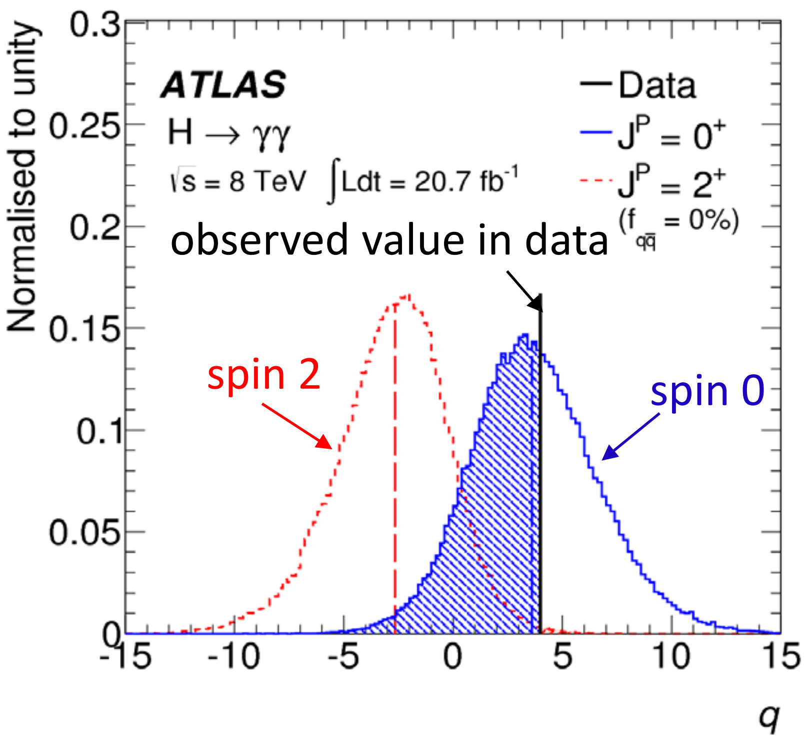
- Empty space is not really empty but filled with the Higgs field
- Matter particles interact with the Higgs field, “slow down” and appear to be massive

Higgs boson discovery in 2012





Seems to be the first fundamental scalar particle

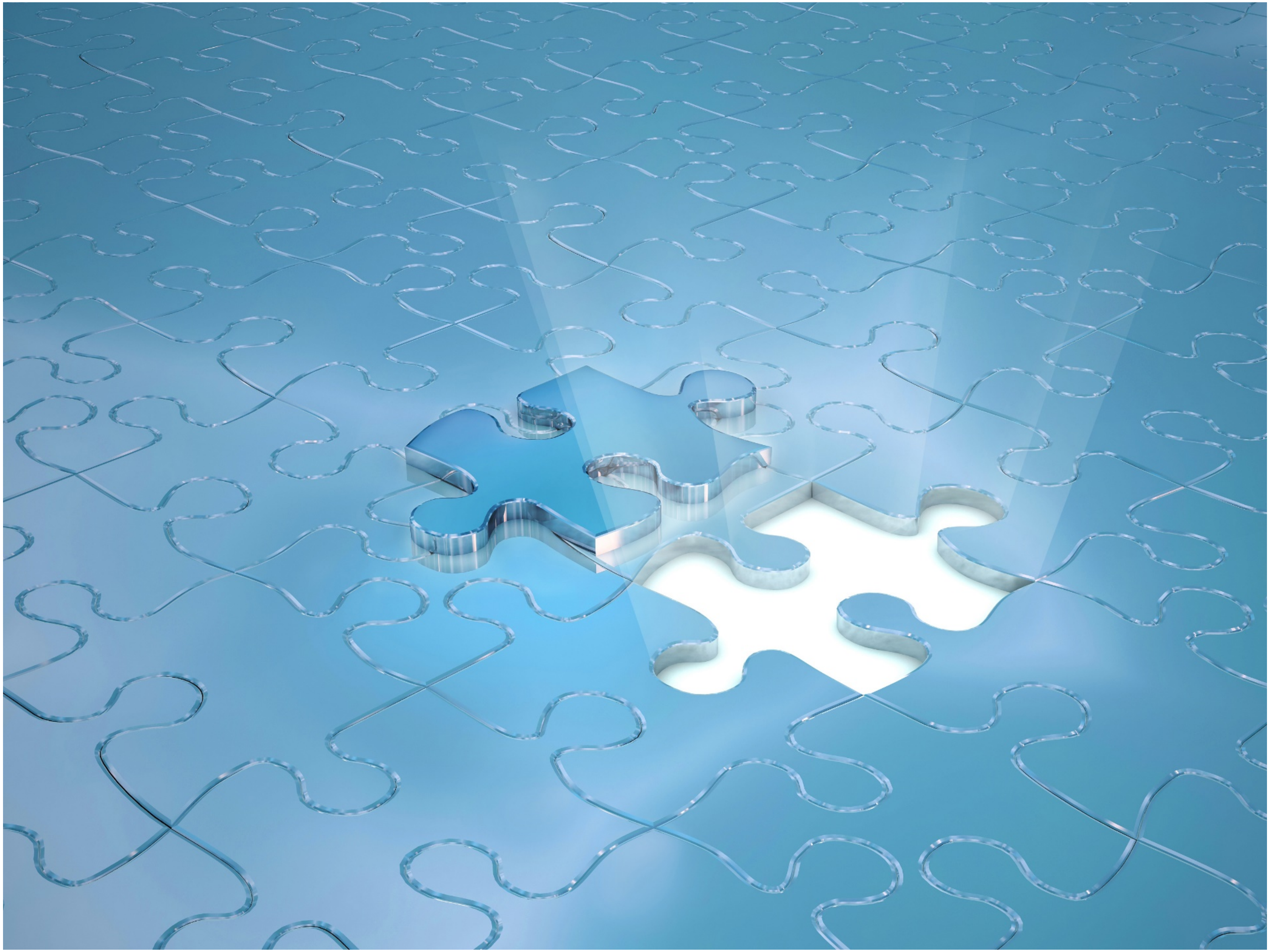


- A very profound discovery, not just a discovery of another particle
- The Higgs discovery to particle physics is like the DNA discovery to biology
- A scalar particle lacks of internal structure and is thus easier to deal with, however many people argue about its actual existence in nature
- Non-zero spin particles remain massless or light due to symmetries on their extra structure
- Spin-0 particle masses are unprotected against large quantum corrections

$$\Delta m_H^2 \propto \Lambda^2 \text{ with } \Lambda \sim 10^{19}\text{ GeV}$$

- Fine tuning problem (measured m_H = 125 GeV) → SUSY or other theories

Higgsaw puzzle



Higgsaw puzzle

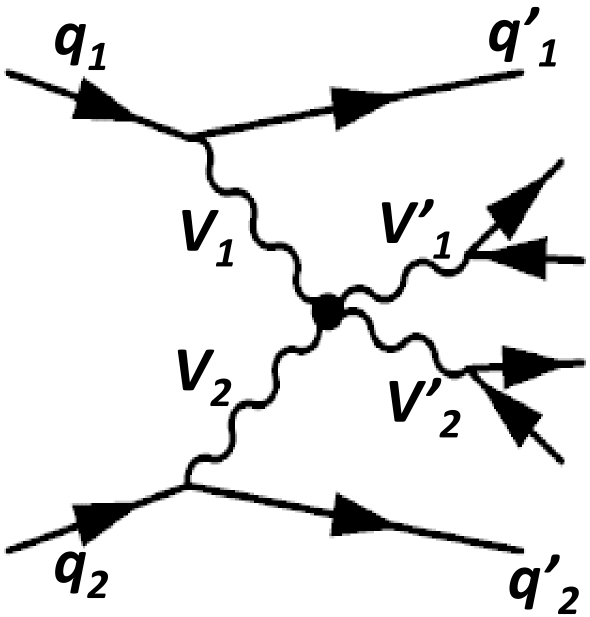
- Does it couple to particle masses ?
- Will it decay to other final states not predicted by the SM ?
- Does it have other neutral or charged siblings ?
- What is its spin ?
- Is it a scalar particle ?
- Is it an elementary or composite particle ?
- Why its mass is around 125 GeV ?
- Is it the first SUSY particle ever observed ?
- …

Longitudinal Vector Boson Scattering ($V_L V_L \rightarrow V_L V_L$)

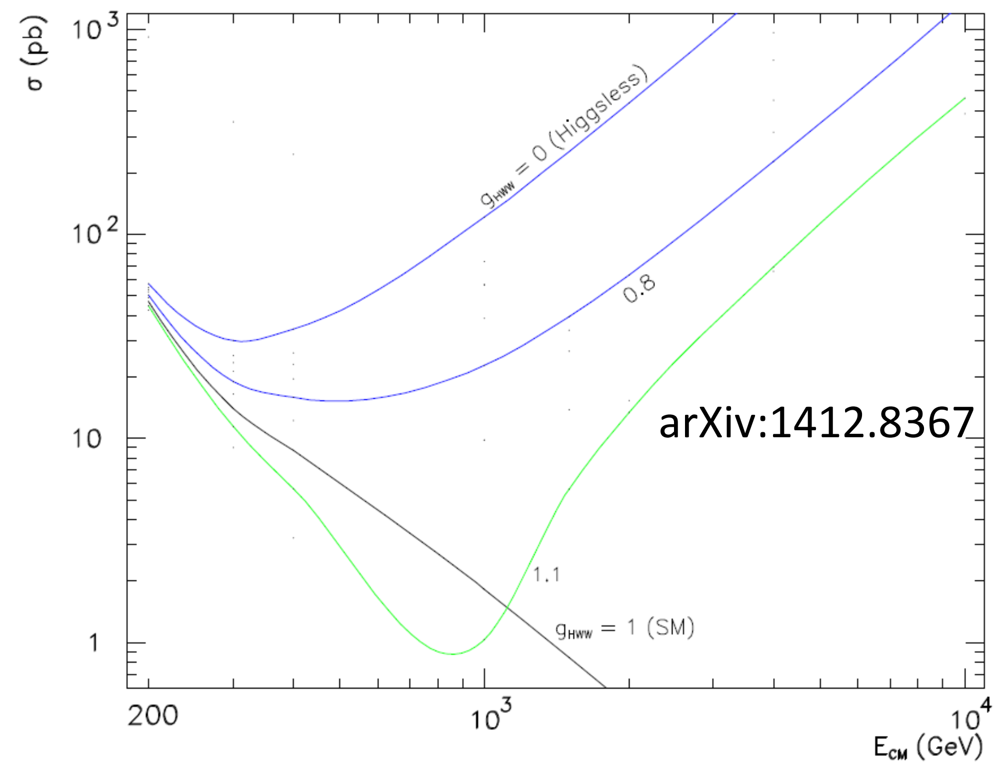
The discovery of a Higgs boson does not totally validate the Higgs mechanism, a few other theories also predict the existence of a Higgs boson

Higgs mechanism: the Goldstone bosons after the EWSB are "eaten" by masselsss W/Z bosons and become their longitudinal modes

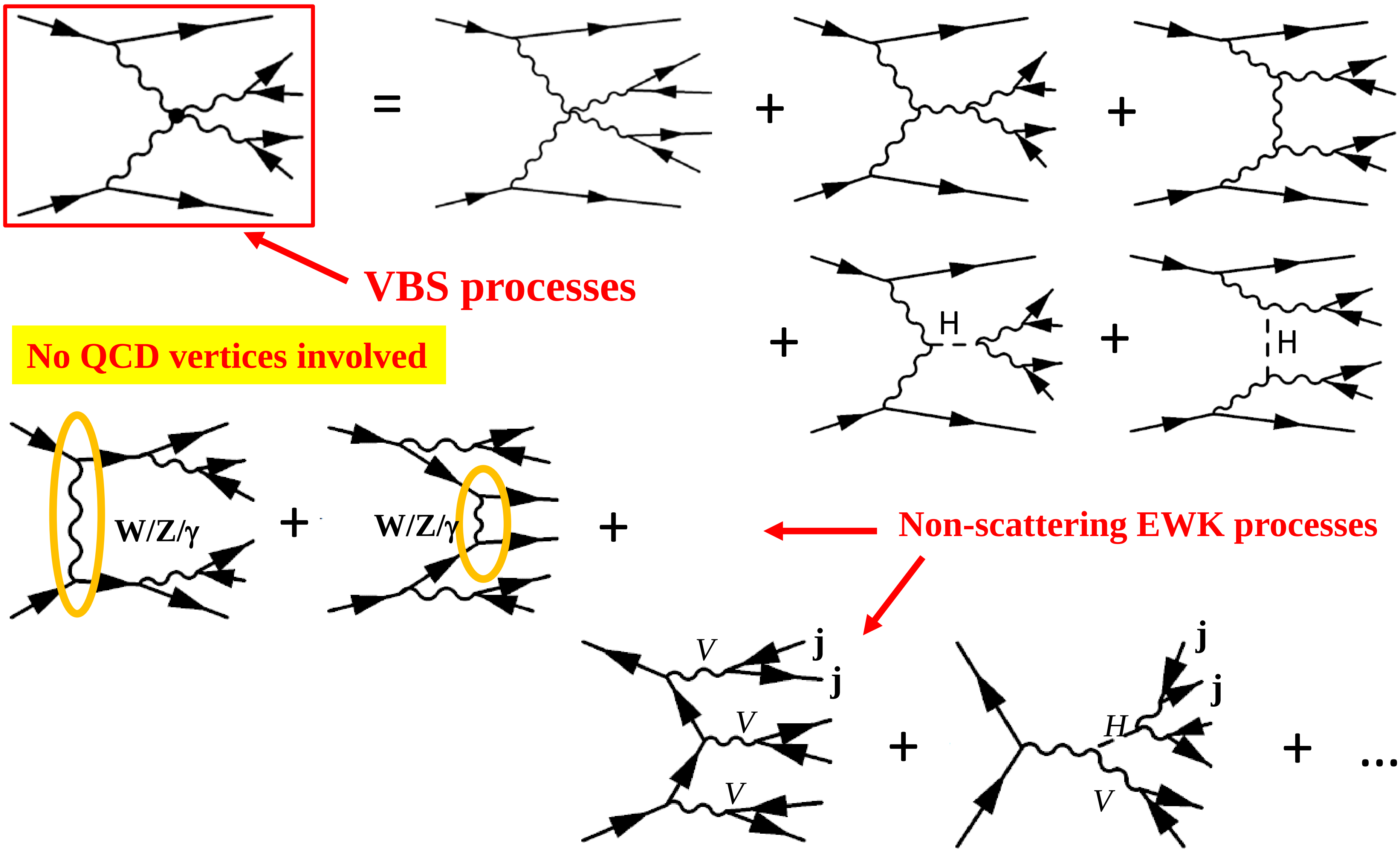
Need to observe VV→VV first and then study $V_L V_L \rightarrow V_L V_L$



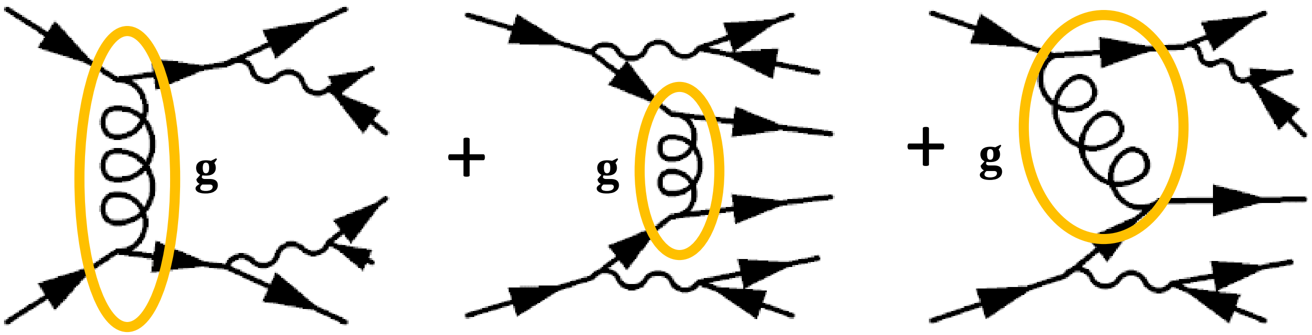
$V_1 V_2 \rightarrow V_1 V_2$ (V_1, V_2 = W, Z) scattering



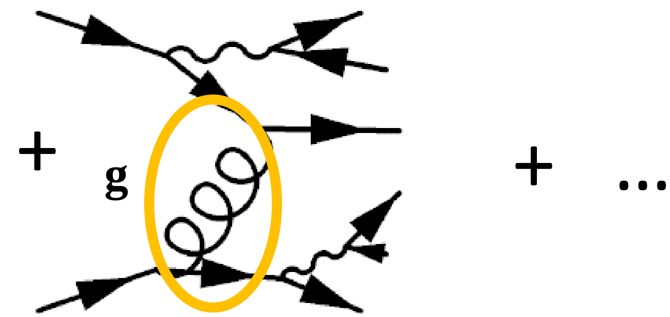
VBS-EWK processes



VBS-QCD processes



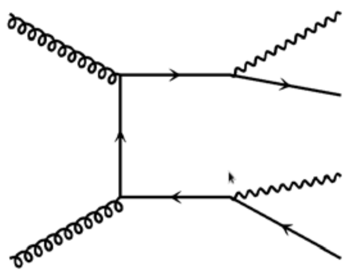
QCD vertices involved

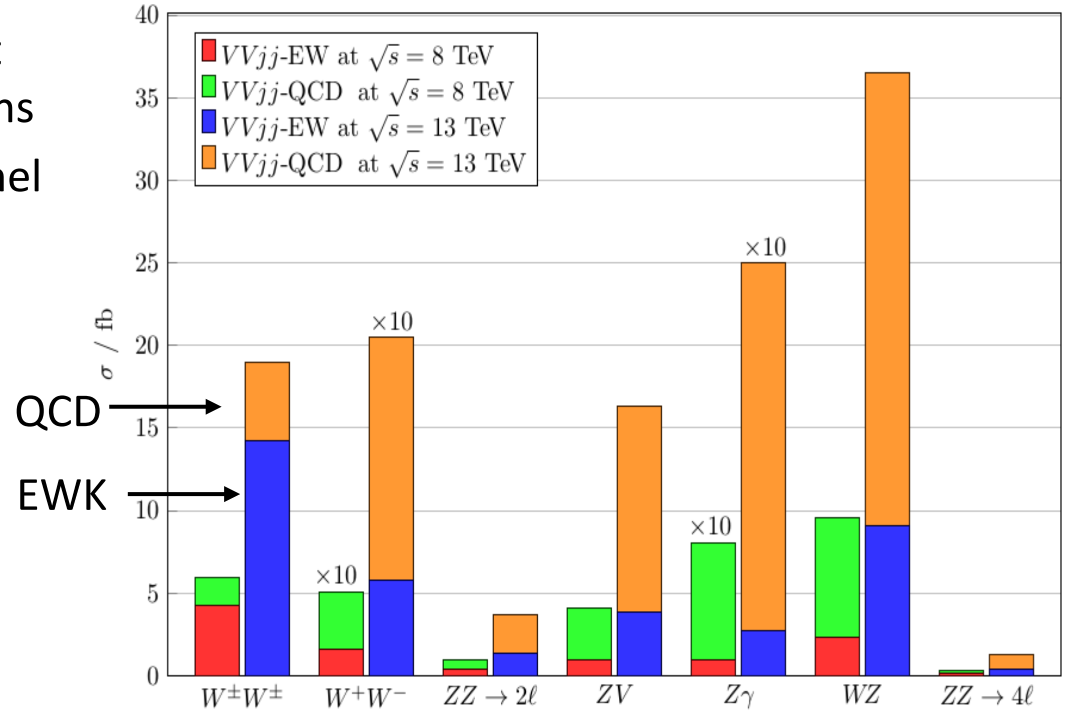


- VBS processes are interesting processes to study
- Investigate different selection criteria (forward jets, large m_{jj}, Δy_{jj}, central-jet veto etc) to reduce the contributions from QCD production and non-scattering EWK production

EWK vs QCD cross sections

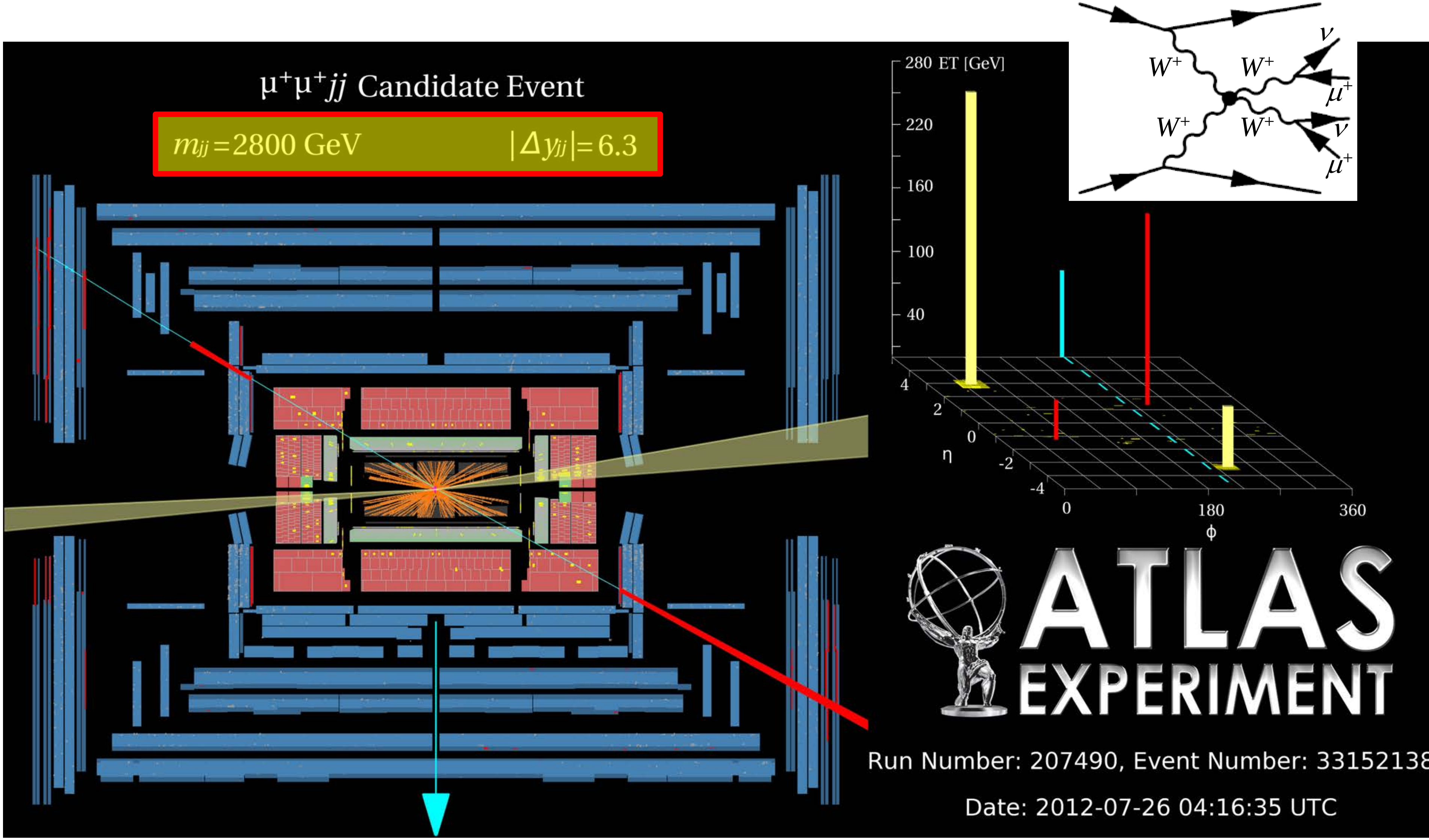
- Not an easy task to observe VBS:
  - We do not have W/Z beams
  - Large reducible and irreducible SM backgrounds
  - Often could not fully reconstruct the final states W and/or Z bosons
- EWK and QCD production by channel
  - **After some analysis cuts to reduce QCD production**
- $W^{\pm}W^{\pm}$ has no gluon initial states





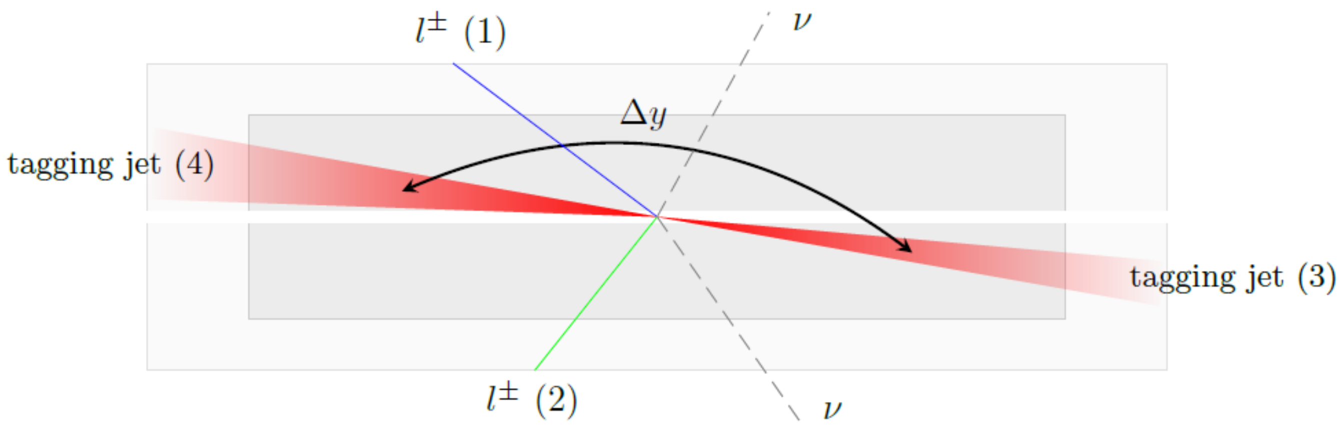
- Others experimentally challenging

First study of $W^{\pm}W^{\pm} \rightarrow W^{\pm}W^{\pm}$

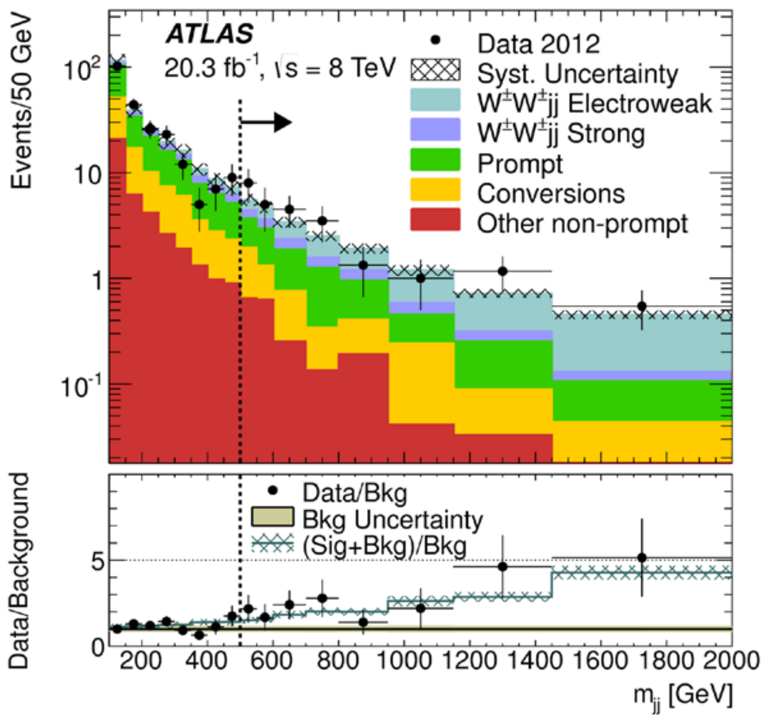


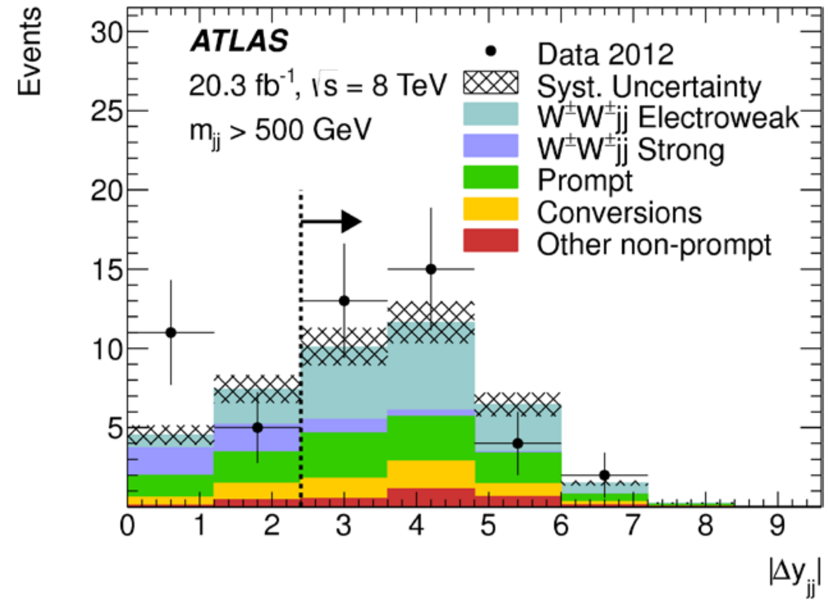
Event selection

- Exactly two SS isolated leptons with p_T>25 GeV and $|\eta|$<2.5
- MET > 40 GeV
- At least two jets with p_T>30 GeV and $|\eta|$<4.5
- WZ veto: veto a third lepton with lower p_T and looser quality requirements
- Z veto: $|m_{ee} - m_Z|$ > 10 GeV to suppress the Z→ee contribution with the charge of one electron misidentified
- ttbar veto: no b-tagged jets in each event
- Inclusive region: m_{jj} > 500 GeV
- VBS region: m_{jj} > 500 GeV and $|\Delta y_{jj}|$ > 2.4 → enhance the contribution from electroweak production

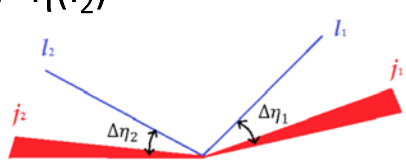


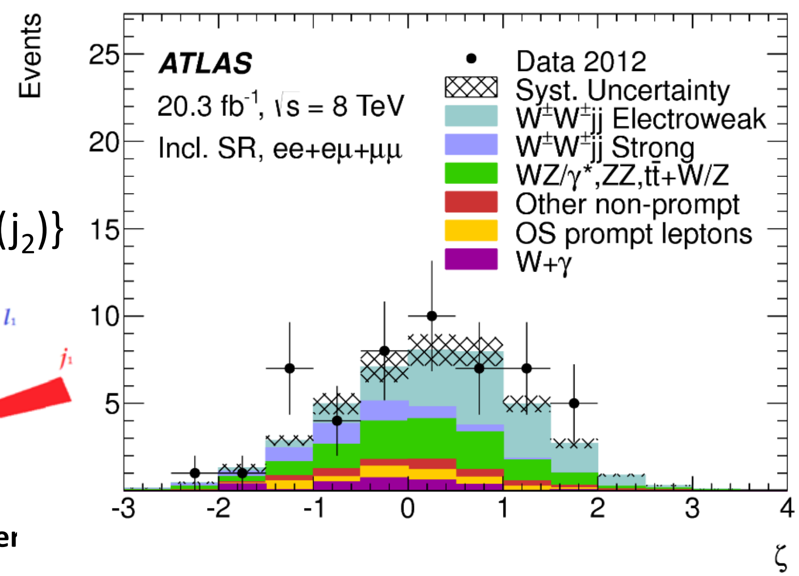
Inclusive and VBS signal regions





Lepton centrality: $\zeta = \min\{\eta(j_1)-\eta(l_1), \eta(l_2)-\eta(j_2)\}$
where $\eta(j_1)>\eta(j_2)$ and $\eta(l_1)>\eta(l_2)$





Signal region numbers

Inclusive Signal Region				
	$e^\pm e^\pm$	$e^\pm \mu^\pm$	$\mu^\pm \mu^\pm$	Total
$W^\pm W^\pm$jj Electroweak	3.07 ± 0.30	9.0 ± 0.8	4.9 ± 0.5	16.9 ± 1.5
$W^\pm W^\pm$jj Strong	0.89 ± 0.15	2.5 ± 0.4	1.42 ± 0.23	4.8 ± 0.8
$WZ/\gamma^*, ZZ, t\bar{t} + W/Z$	3.0 ± 0.7	6.1 ± 1.3	2.6 ± 0.6	11.6 ± 2.5
$W+\gamma$	1.1 ± 0.6	1.6 ± 0.8	–	2.7 ± 1.2
OS prompt leptons	2.1 ± 0.4	0.77 ± 0.27	–	2.8 ± 0.6
Other non-prompt	0.61 ± 0.30	1.9 ± 0.8	0.41 ± 0.22	2.9 ± 0.8
Total Predicted	10.7 ± 1.4	21.7 ± 2.6	9.3 ± 1.0	42 ± 5
Data	12	26	12	50

VBS Signal Region				
	$e^\pm e^\pm$	$e^\pm \mu^\pm$	$\mu^\pm \mu^\pm$	Total
$W^\pm W^\pm$jj Electroweak	2.55 ± 0.25	7.3 ± 0.6	4.0 ± 0.4	13.9 ± 1.2
$W^\pm W^\pm$jj Strong	0.25 ± 0.06	0.71 ± 0.14	0.38 ± 0.08	1.34 ± 0.26
$WZ/\gamma^*, ZZ, t\bar{t} + W/Z$	2.2 ± 0.5	4.2 ± 1.0	1.9 ± 0.5	8.2 ± 1.9
$W + \gamma$	0.7 ± 0.4	1.3 ± 0.7	–	2.0 ± 1.0
OS prompt leptons	1.39 ± 0.27	0.64 ± 0.24	–	2.0 ± 0.5
Other non-prompt	0.50 ± 0.26	1.5 ± 0.6	0.34 ± 0.19	2.3 ± 0.7
Total Predicted	7.6 ± 1.0	15.6 ± 2.0	6.6 ± 0.8	29.8 ± 3.5
Data	6	18	10	34

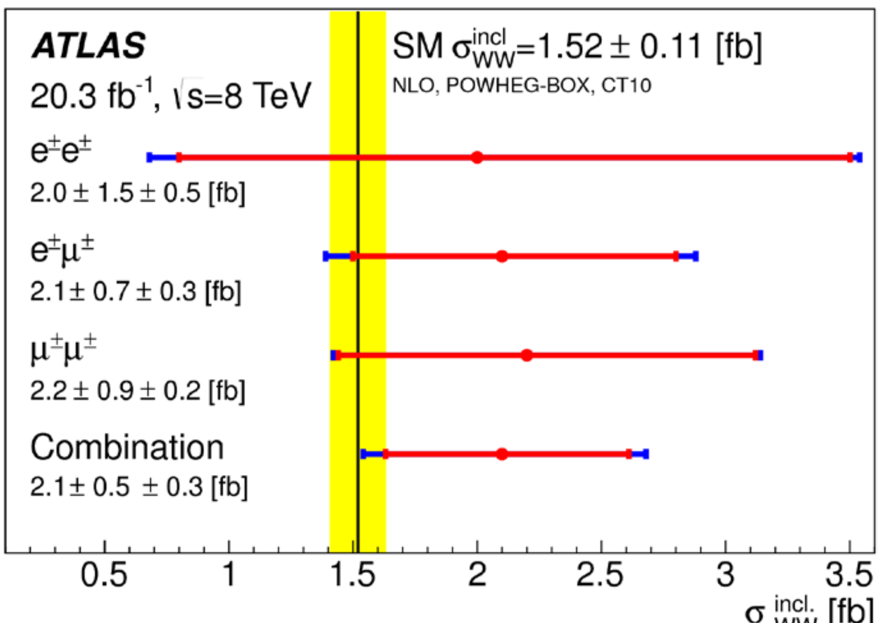
Cross section extraction

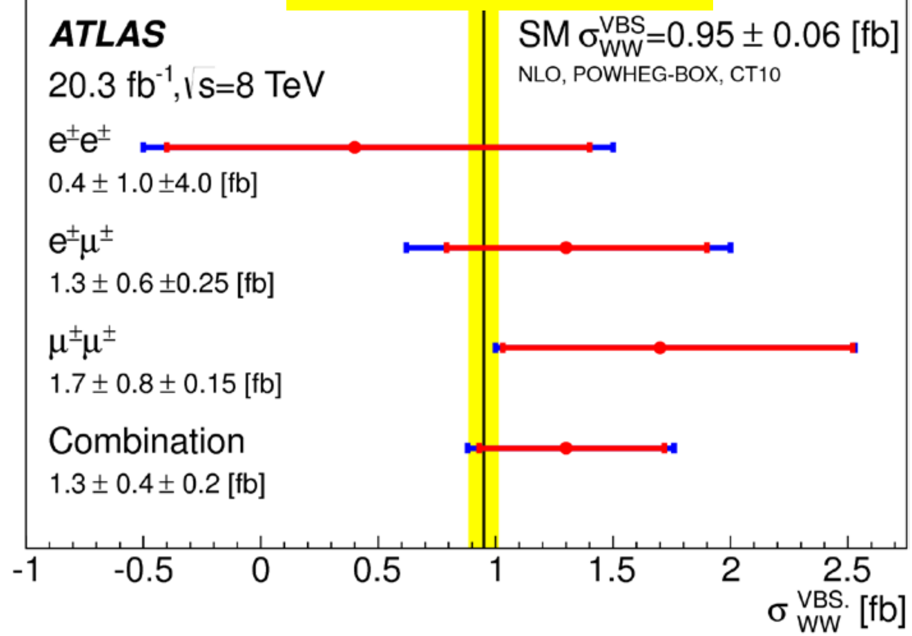
- Profile likelihood ratio method used to extract the final cross sections from all three channels taken into account correlated systematics

$$L(\sigma_{W^\pm W^\pm jj}, \mathcal{L}, \alpha_j) = \text{Gaus}(\mathcal{L}_0|\mathcal{L}, \sigma_{\mathcal{L}}) \prod_{i\in\{ee,\mu\mu,e\mu\}} \text{Pois}(N_i^{\text{obs}}|N_{i,\text{tot}}^{\text{exp}}) \prod_{j\in \text{syst}} \text{Gaus}(\alpha_j^0|\alpha_j, 1)$$

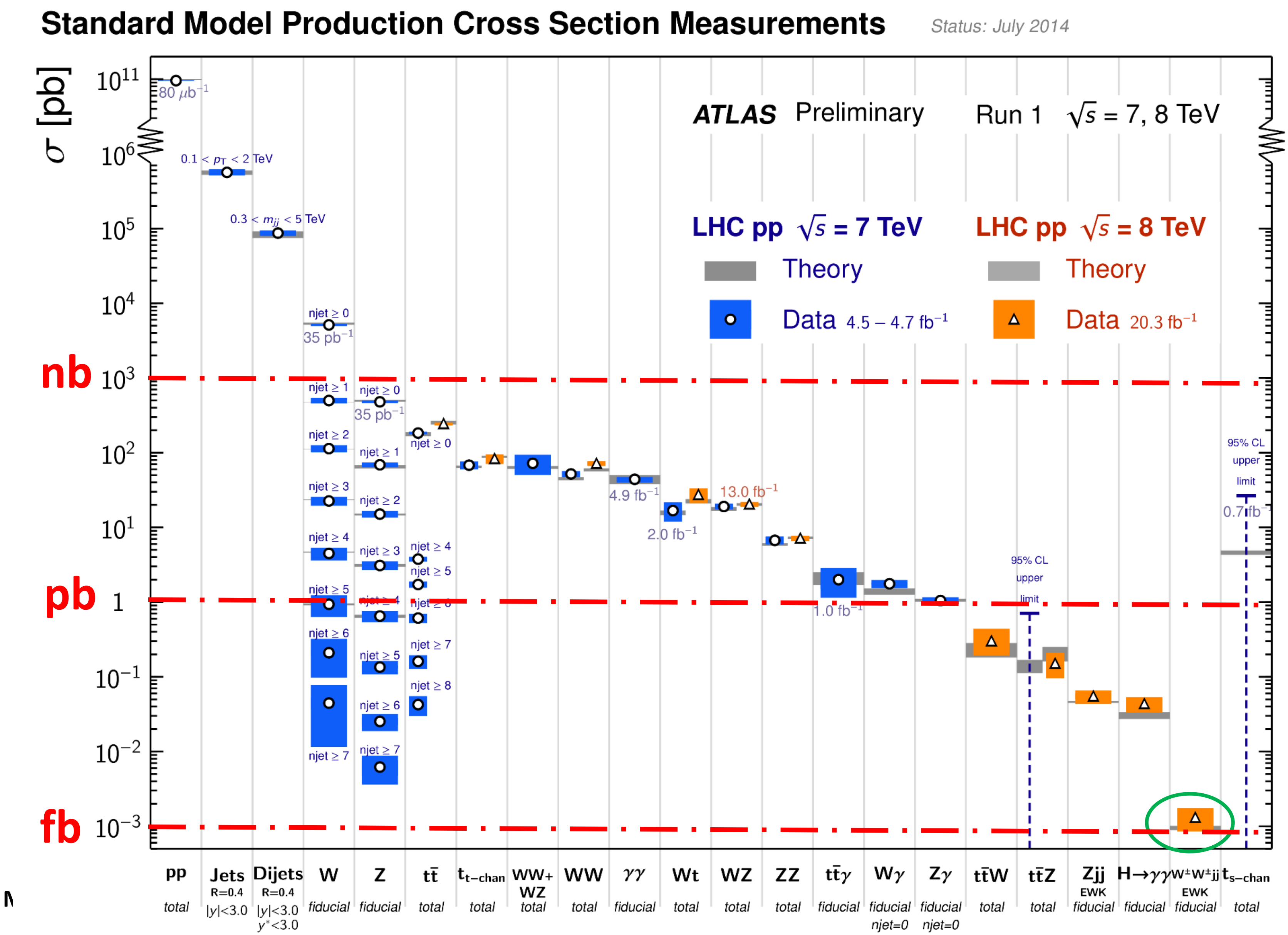
  - Inclusive SR: σ = 2.1 ± 0.5 (stat) ± 0.3 (syst) fb, 4.5σ obs. (3.4σ exp.)
  - VBS SR: σ = 1.3 ± 0.4 (stat) ± 0.2 (syst) fb, 3.6σ obs. (2.8σ exp.)
- First evidence for EWK VV → VV scattering at the LHC

PRL 113, 141803 (2014)
PRL Editor's Suggestion

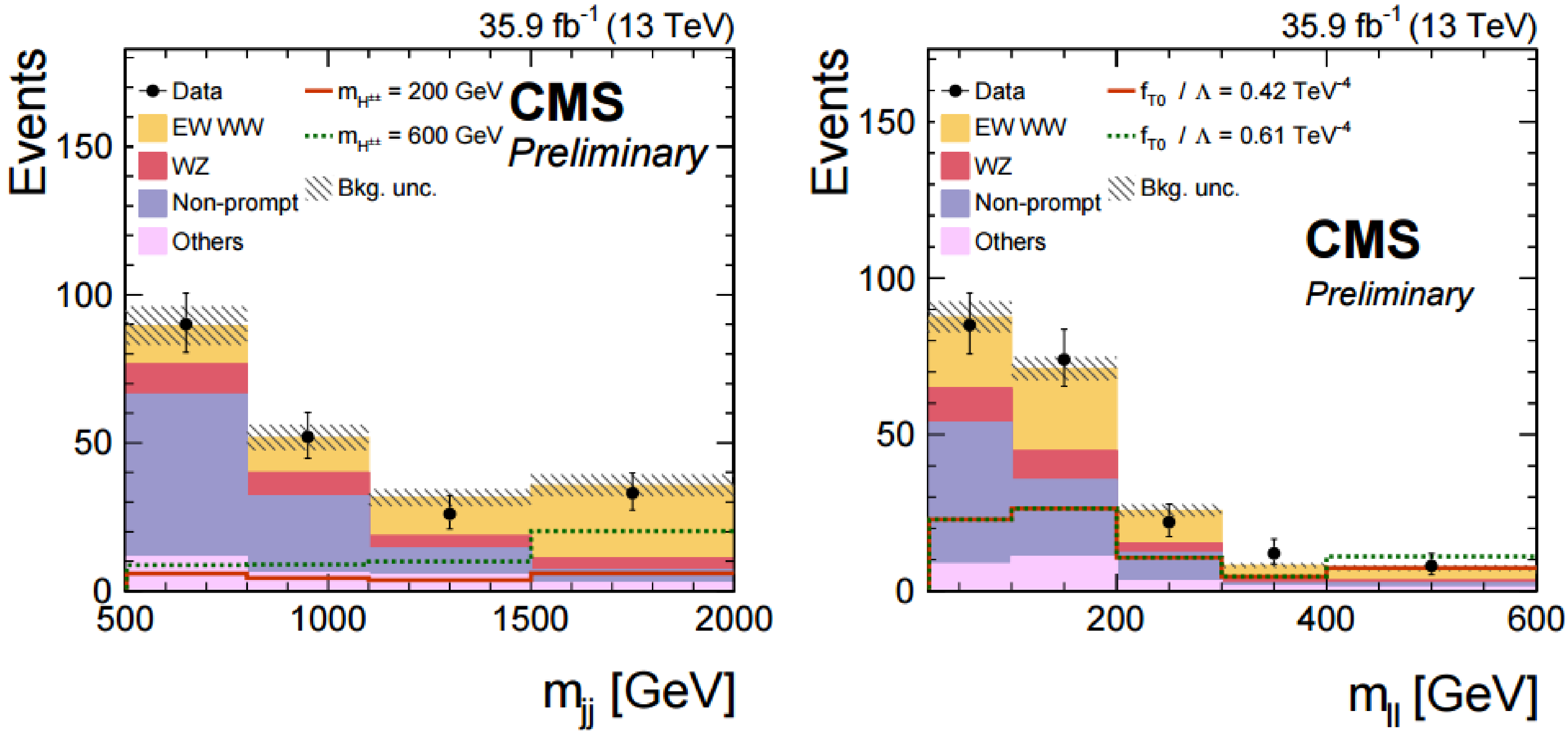




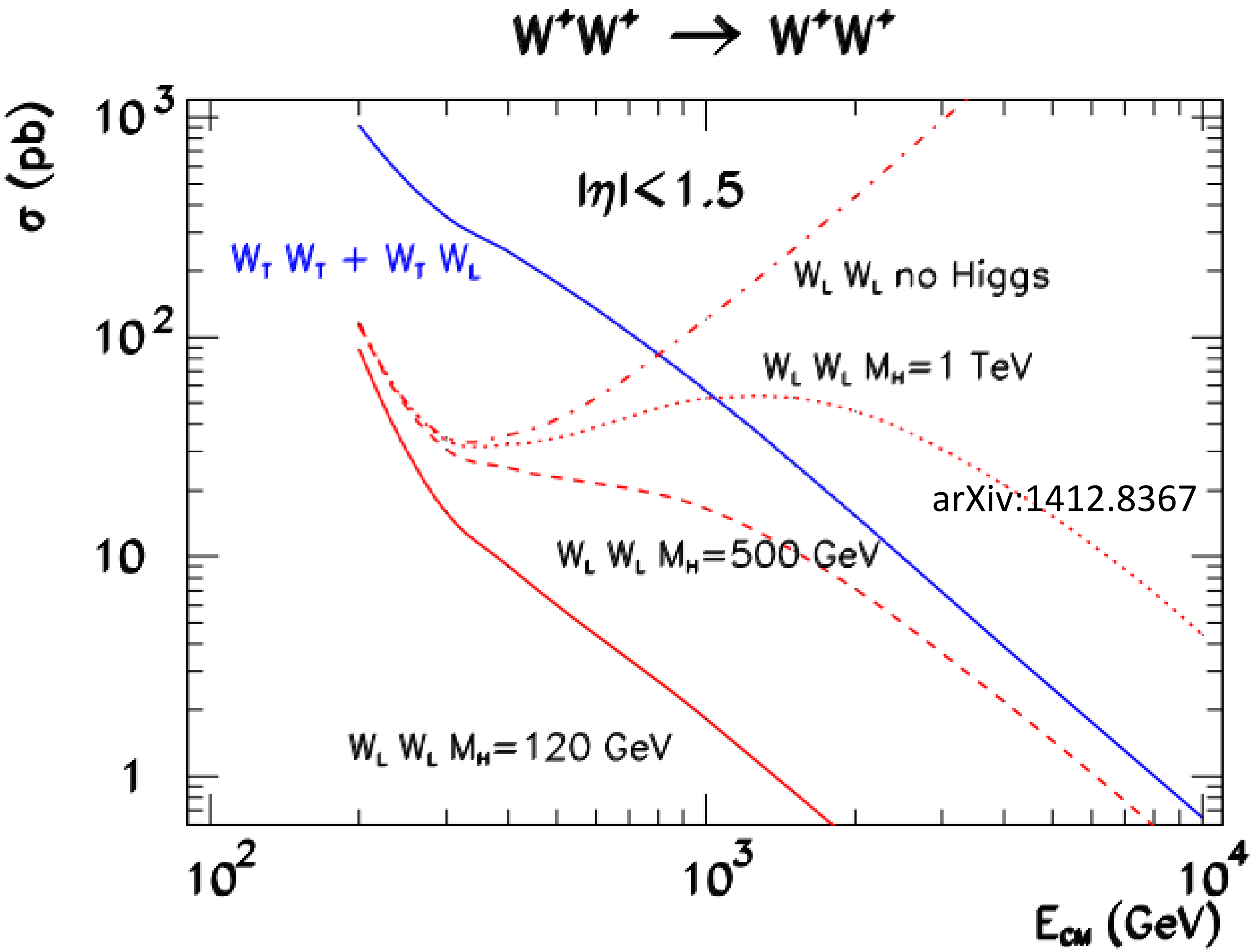
ATLAS SM cross section measurements



CMS 13 TeV results

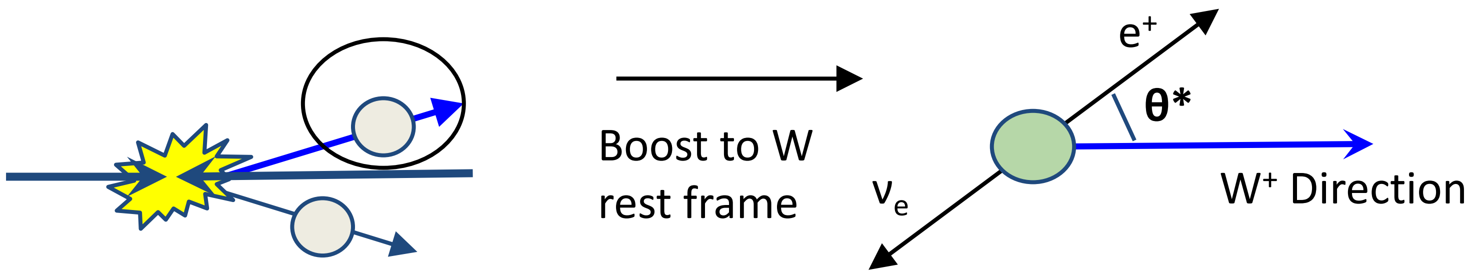


Transversal vs longitudinal scattering

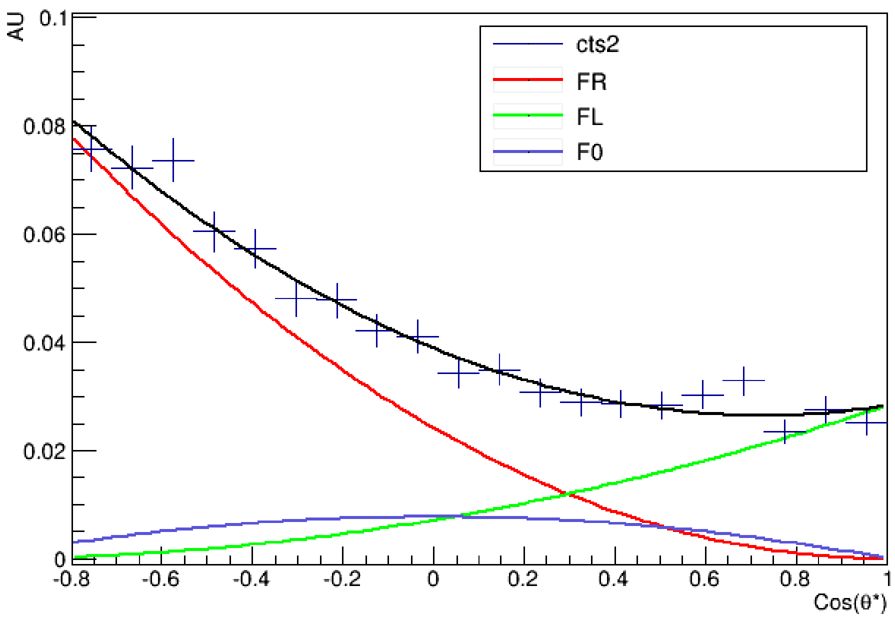


arXiv:1412.8367

Angular distribution



$$\frac{1}{\sigma}\frac{d\sigma}{dcos\theta^*} = \frac{3}{8}f_L(1\mp cos\theta^*)^2 + \frac{3}{8}f_R(1 \pm cos\theta^*)^2 + \frac{3}{4}f_0 sin^2\theta^*$$

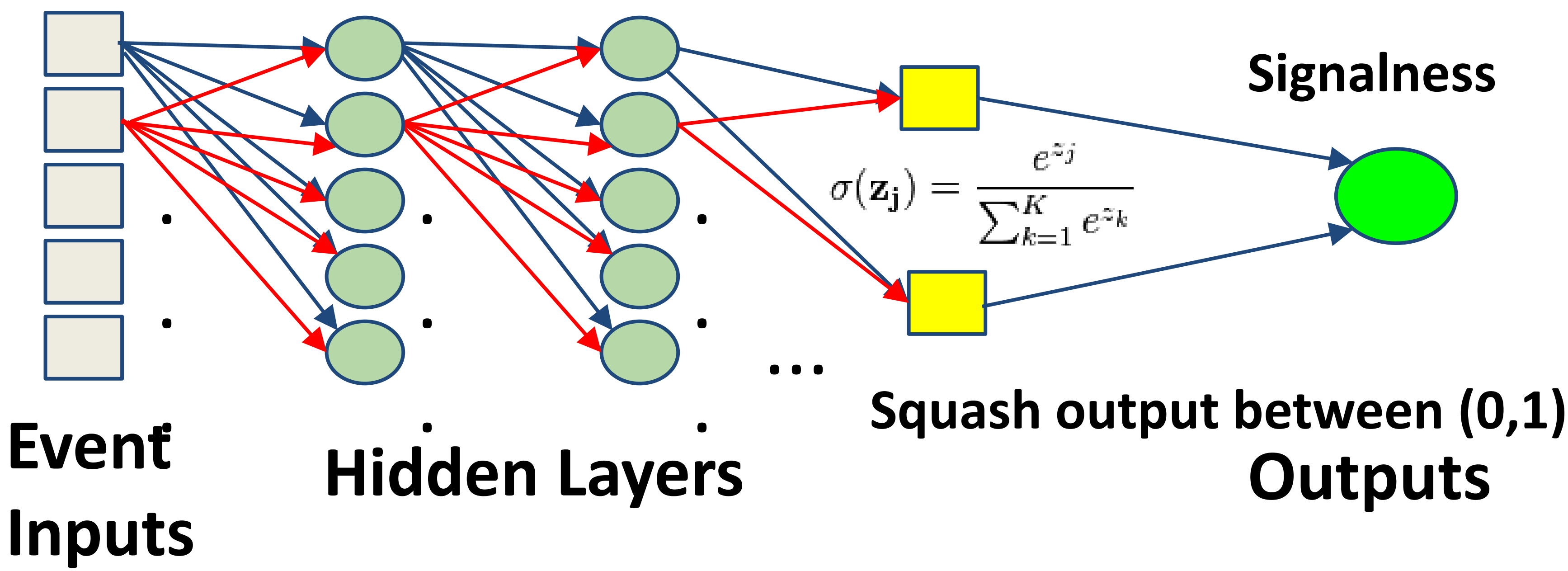


Cannot directly measure θ^* in the dileptonic channel due to the presence of missing transverse energy

People developed some non- θ^* variables such as $\Delta\phi_{ll}$ or $pT_{l1}/pT_{j1}\times pT_{l2}/pT_{j2}$ to extract the longitudinal fractions, no golden variables found yet

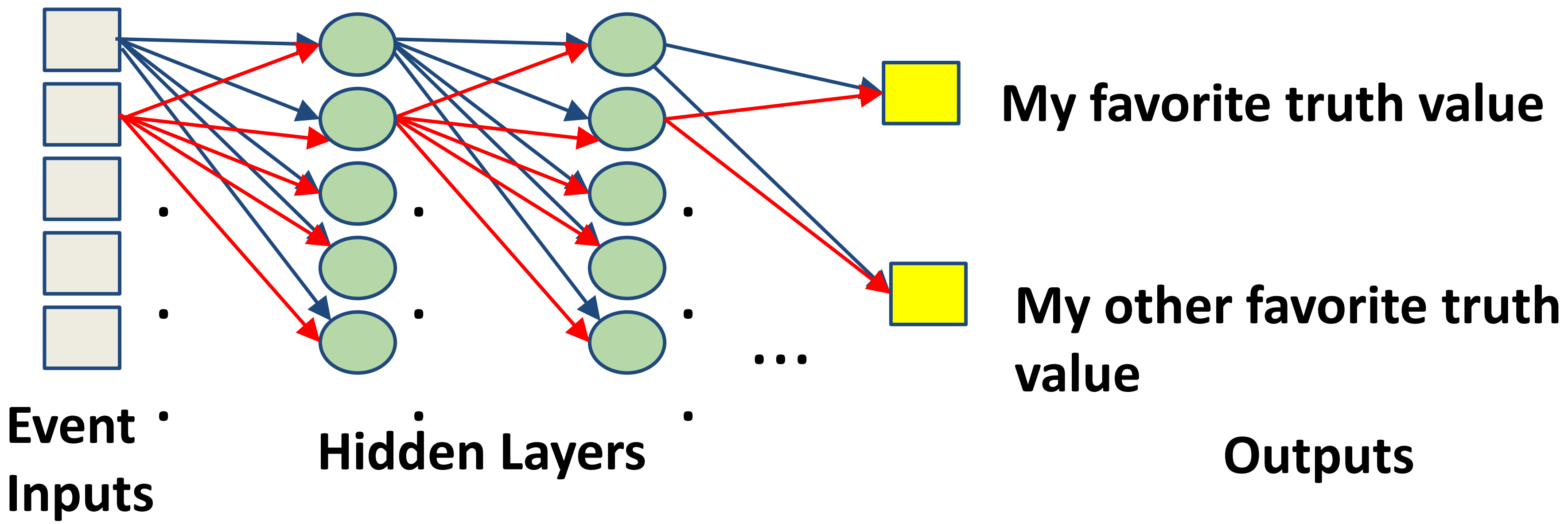
Machine learning neural network

- Really common in HEP to use multivariate techniques classification (discret estimation)
- **Just a simple $f(x_i) \rightarrow$ Output**
- **Train weights so this mapping gives you the best discriminate between signal and background**



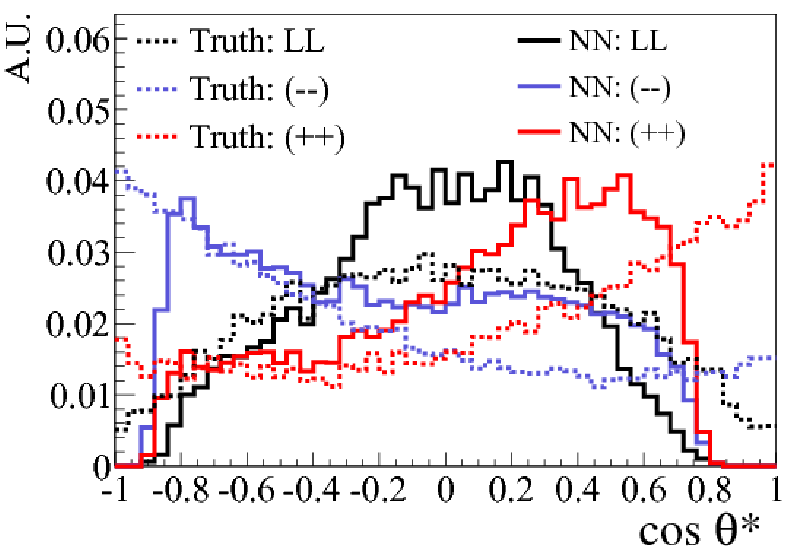
Machine learning neural network

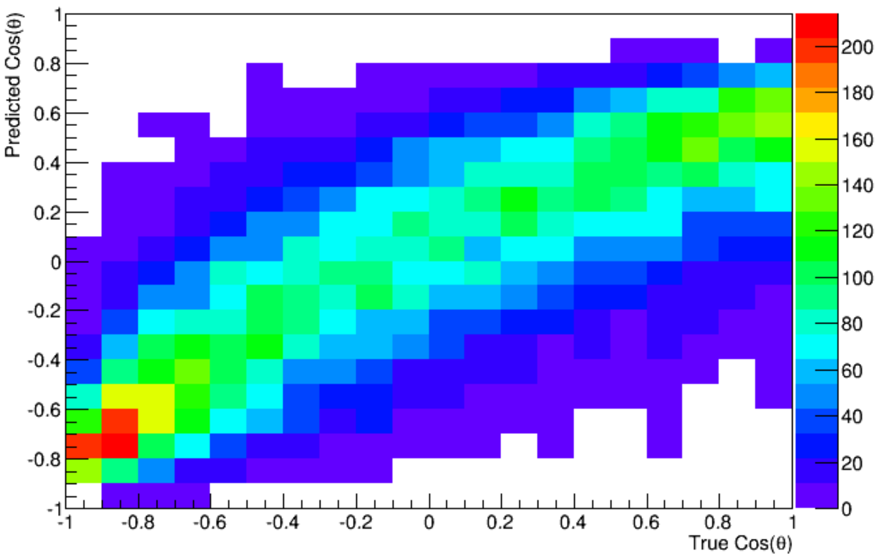
- You can also train NN to approximate continuous functions (Regression)
- Not squash the outputs



Training the neural network

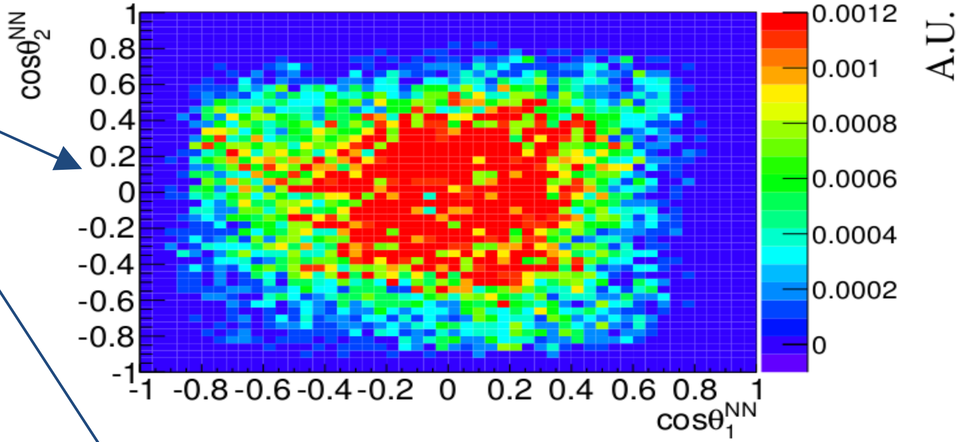
- Deep learning is simply extending a simple neural network with many layers
  - Conceptually simple, computationally difficult
- Use Deep Learning to get a good approximate of the true cos(θ*)
  - Network with 20 layers and 200 nodes
  - Validated on independent data

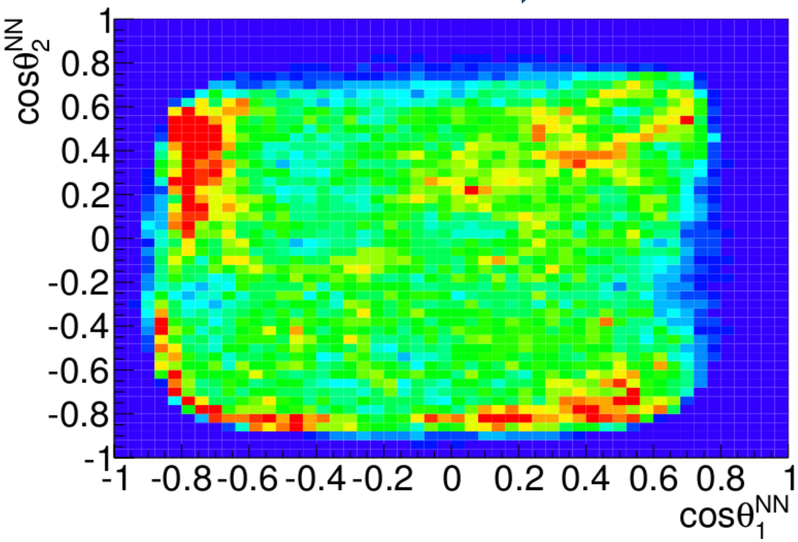


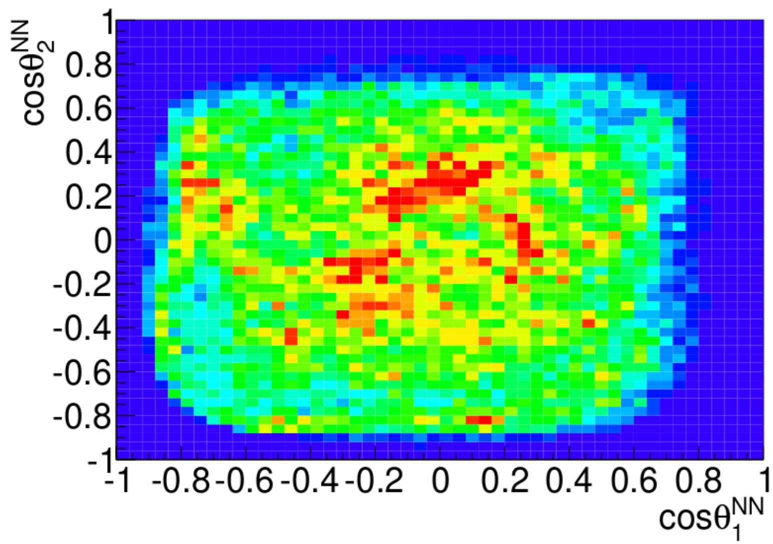


2D neural network

- Each event has two W bosons so we make templates based on the Neural Network output
  - Events with 2 Longitudinal bosons
  - Events with 1 Longitudinal bosons
  - Events with 0 Longitudinal bosons

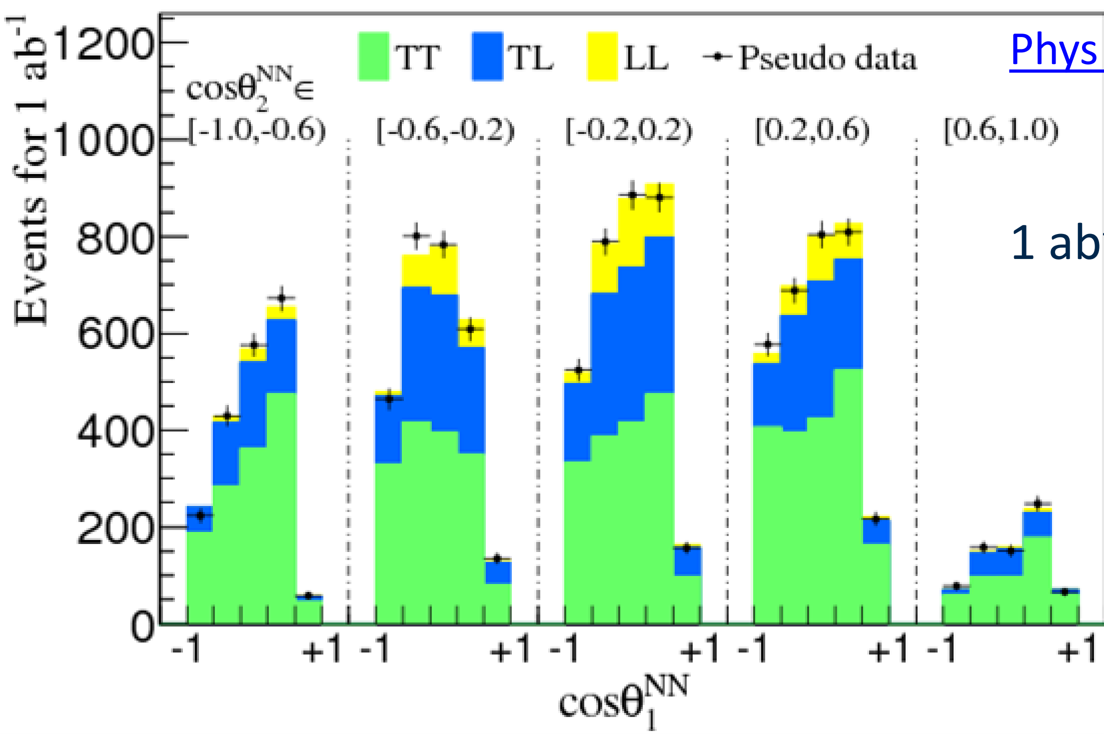






Neural network fit

- 6 templates
  - ++,--,+-,LL,+L,-L
- Combined into three templates: TT, TL and LL
- **This plot is made assuming a perfect detector**
  - In the least optimistic case with non-optimized cuts, and no detector upgrades we expect a measurement of the LL fraction of about 7^{+6}_{-5}%



Phys Rev D 93 094033 (2016)

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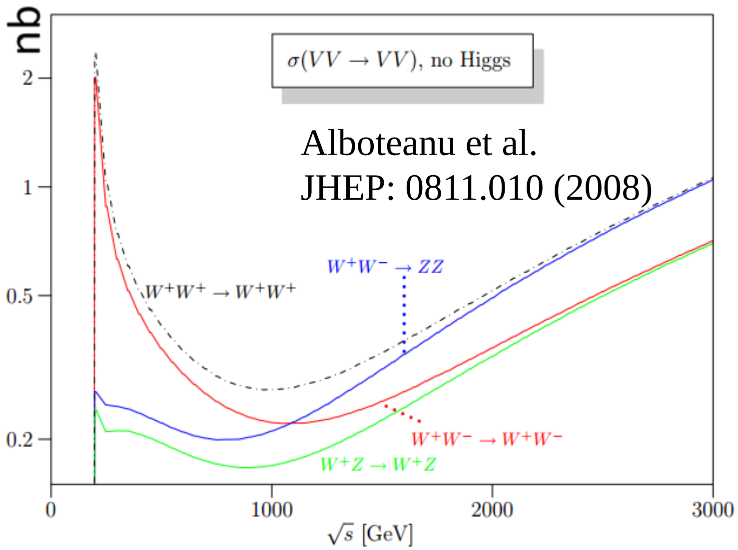
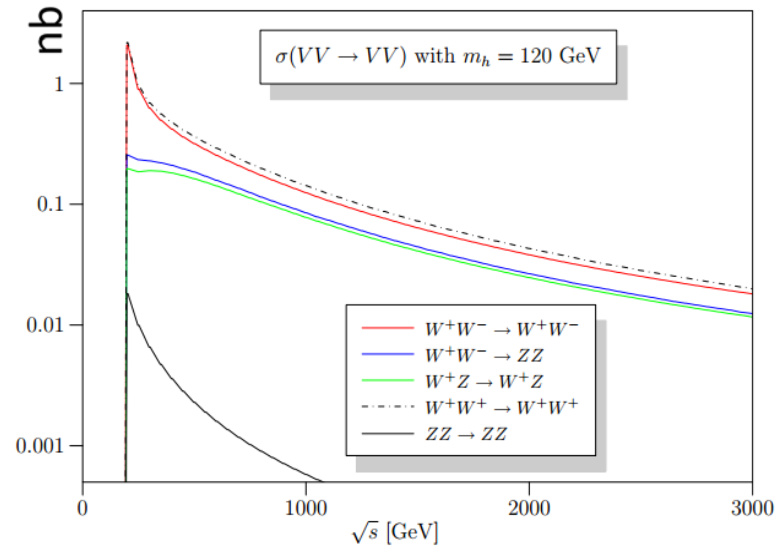
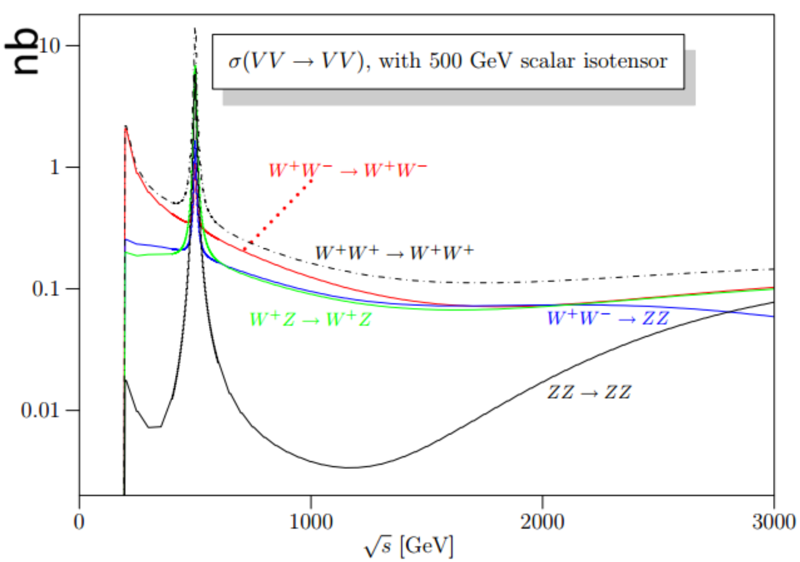
New resonances in $V_L V_L \rightarrow V_L V_L$



Without a SM Higgs boson,
Unitarity violation



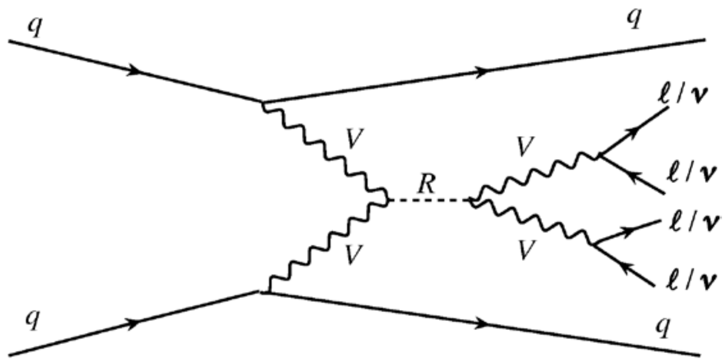
With a SM Higgs boson,
Unitarity is restored



- The Higgs boson is the most economical solution to restore the unitarity, but it is not the only choice (new particle + (non)-SM Higgs)

W^+W^-jj resonance search

- Search for neutral heavy resonances in the W^+W^-jj channel



- Whizard is used to generate new resonances
  - Assume that new resonances only couples to the longitudinal component of the W boson
  - K-matrix unitarization is used
  - Coupling constant g=2.5 is used

	Type	Spin J	Isospin I	Electric Charge	Γ/Γ_0
Scalar isoscalar	σ	0	0	0	6
Scalar isotensor	ϕ	0	2	$--,-,0,+,++$	1
Vector isovector	ρ	1	1	$-,0,+$	$\frac{4}{3}(\frac{v^2}{m^2})$
Tensor isoscalar	f	2	0	0	$\frac{1}{5}$
Tensor isotensor	t	2	2	$--,-,0,+,++$	$\frac{1}{30}$

Selection criteria

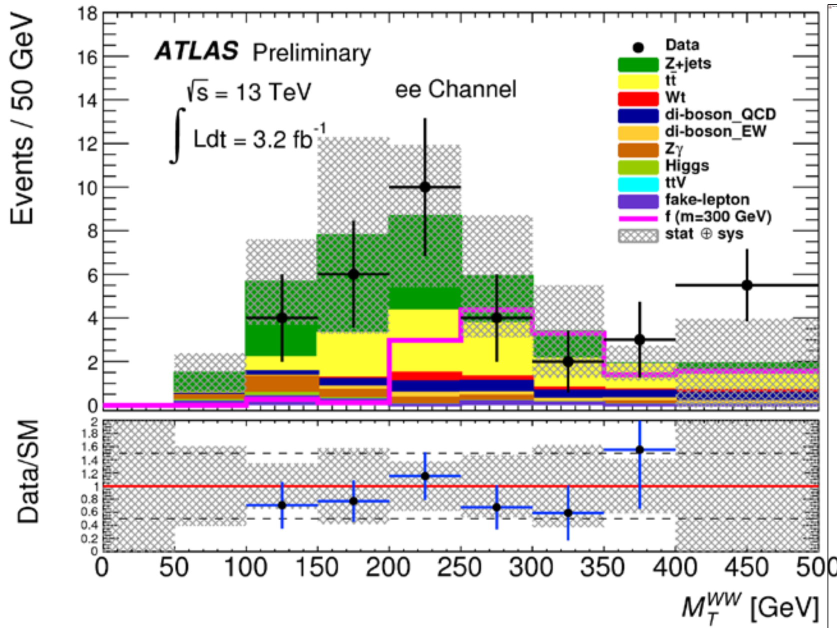
#	Selection criteria
1	event preselection requirements, see text
2	exactly two leptons with $p_{\mathrm{T}} > 25$ GeV
3	pass single lepton trigger and trigger matching
4	third lepton veto
5	dilepton mass $m_{\ell\ell} > 40$ GeV
6	$q_{\ell_1} \times q_{\ell_2} < 0$
7	$\|m_{\ell\ell} - m_Z\| > 25$ GeV in the ee and $\mu\mu$ channels
8	at least two selected jets with $p_T > 30$ (50) GeV and $\|\eta\| < 2.5$ ($2.5 < \|\eta\| < 4.5$)
9	b-jet veto
10	$E_{\mathrm{T}}^{\mathrm{miss}} > 35$ GeV
11	$m_{jj} > 500$ GeV
12	$\|\Delta\eta_{jj}\| > 2.4$
13	$\eta_{j_1} \times \eta_{j_2} < 0$
14	lepton centrality $\zeta > -0.5$
15	$f_{\mathrm{recoil}} < 2.0$

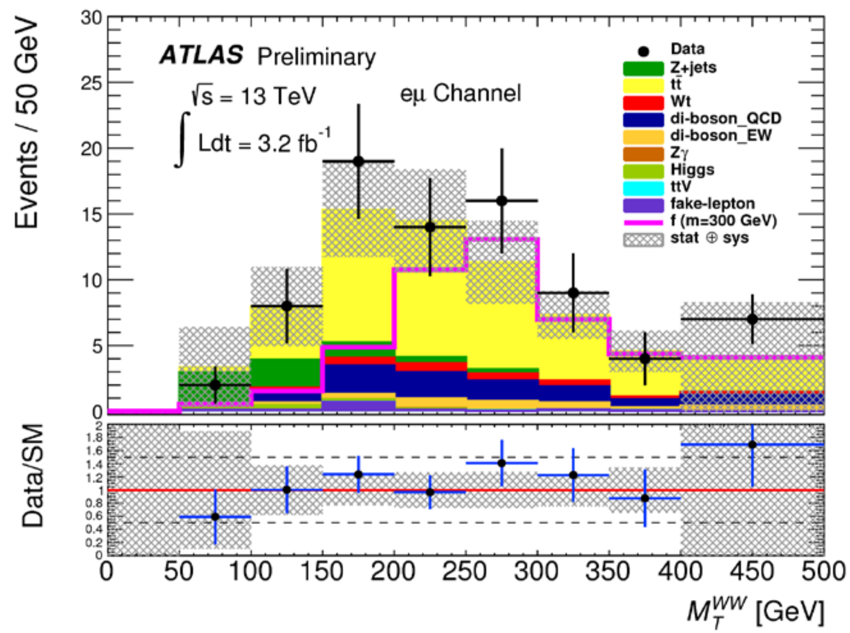
Signal and background contributions in the SR

- Dominant backgrounds from Z+jets (for ee and μμ channels) and ttbar (eμ channel)
- Various control regions defined to validate various background estimates

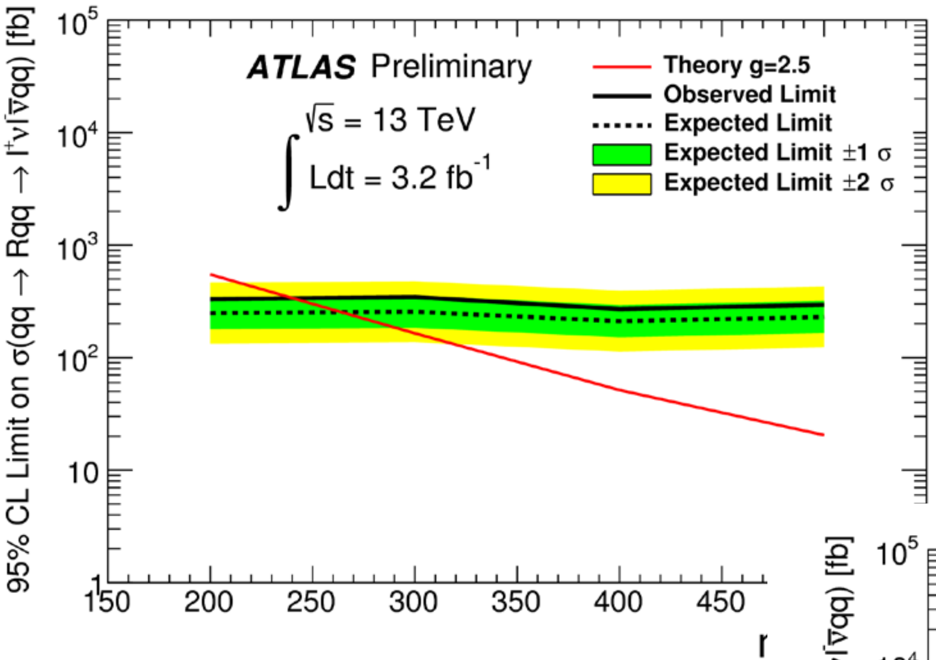
	ee	$\mu\mu$	$e\mu$
Z+jets	$17.6 \pm 1.2 \pm 11.6$	$36.6 \pm 2.3 \pm 19.0$	$6.7 \pm 1.2 \pm 1.7$
$t\bar{t}$	$12.1 \pm 0.6 \pm 3.2$	$18.2 \pm 0.7 \pm 4.6$	$46.9 \pm 1.2 \pm 12.1$
Wt	$1.2 \pm 0.2 \pm 0.3$	$1.5 \pm 0.2 \pm 0.5$	$3.1 \pm 0.3 \pm 0.8$
diboson_QCD	$3.1 \pm 0.3 \pm 0.5$	$4.2 \pm 0.3 \pm 0.7$	$10.2 \pm 0.3 \pm 1.6$
diboson_EW	$1.2 \pm 0.1 \pm 0.1$	$1.7 \pm 0.1 \pm 0.2$	$3.6 \pm 0.1 \pm 0.4$
$Z\gamma$	$2.1 \pm 0.3 \pm 0.6$	$3.8 \pm 0.3 \pm 0.7$	$0.1 \pm 0.0 \pm 0.1$
Higgs	$0.3 \pm 0.0 \pm 0.1$	$0.4 \pm 0.0 \pm 0.1$	$0.8 \pm 0.0 \pm 0.1$
ttV	$0.0 \pm 0.0 \pm 0.0$	$0.0 \pm 0.0 \pm 0.0$	$0.1 \pm 0.0 \pm 0.0$
fake-lepton	$0.6 \pm 0.6 \pm 0.1$	$0.0 \pm 0.0 \pm 0.0$	$1.3 \pm 0.7 \pm 0.1$
σ ($m = 300$ GeV)	$5.1 \pm 0.3 \pm 0.6$	$7.5 \pm 0.3 \pm 0.9$	$14.4 \pm 0.4 \pm 1.9$
ϕ ($m = 300$ GeV)	$0.3 \pm 0.1 \pm 0.2$	$1.0 \pm 0.1 \pm 0.4$	$1.6 \pm 0.2 \pm 0.4$
ρ ($m = 300$ GeV)	$8.0 \pm 0.4 \pm 1.6$	$11.7 \pm 0.4 \pm 1.4$	$24.1 \pm 0.6 \pm 3.1$
f ($m = 300$ GeV)	$15.6 \pm 0.6 \pm 1.9$	$22.6 \pm 0.8 \pm 1.9$	$50.4 \pm 1.2 \pm 3.8$
t ($m = 300$ GeV)	$3.3 \pm 0.2 \pm 0.4$	$4.7 \pm 0.2 \pm 0.6$	$6.9 \pm 0.3 \pm 1.1$
Total background	$38.2 \pm 1.6 \pm 13.9$	$66.4 \pm 2.5 \pm 21.6$	$72.6 \pm 1.9 \pm 14.8$
Data	40	74	86

VV resonance search





First sets of limits on new resonances



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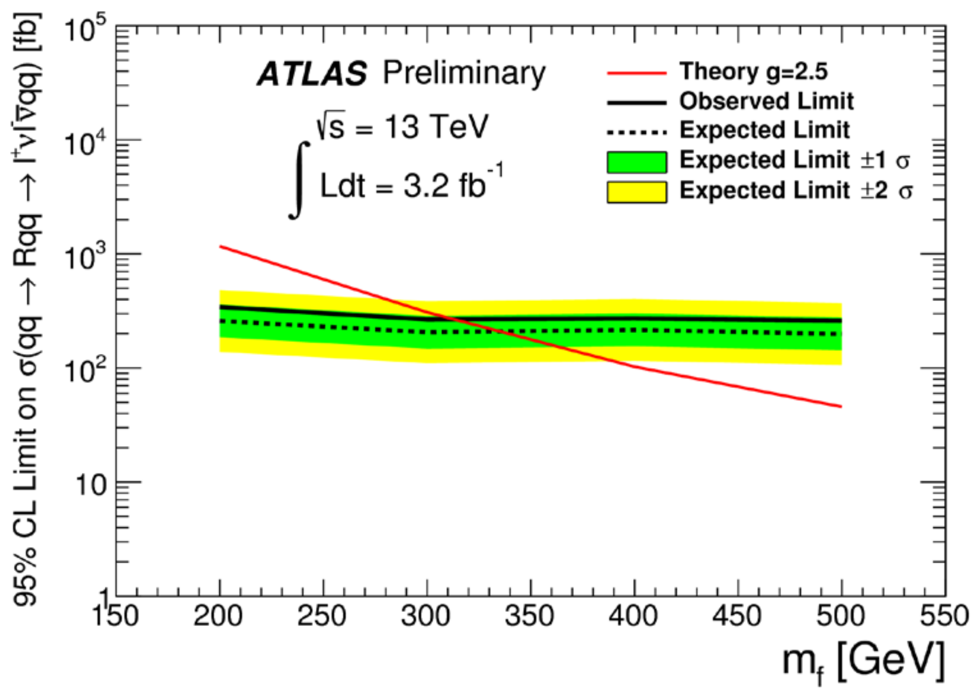
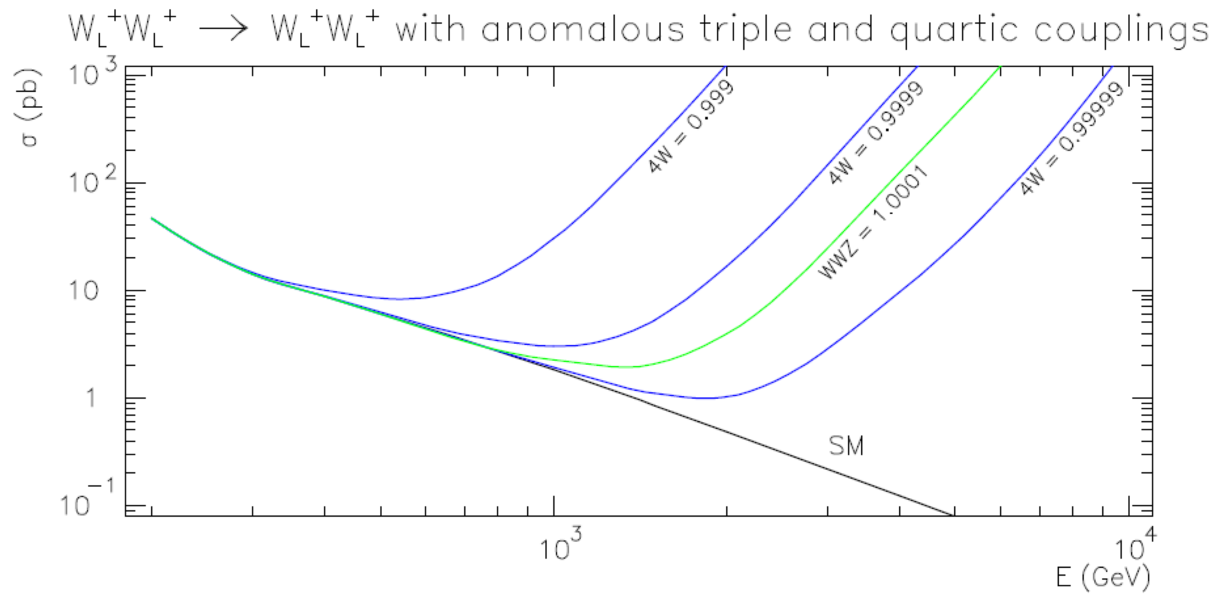
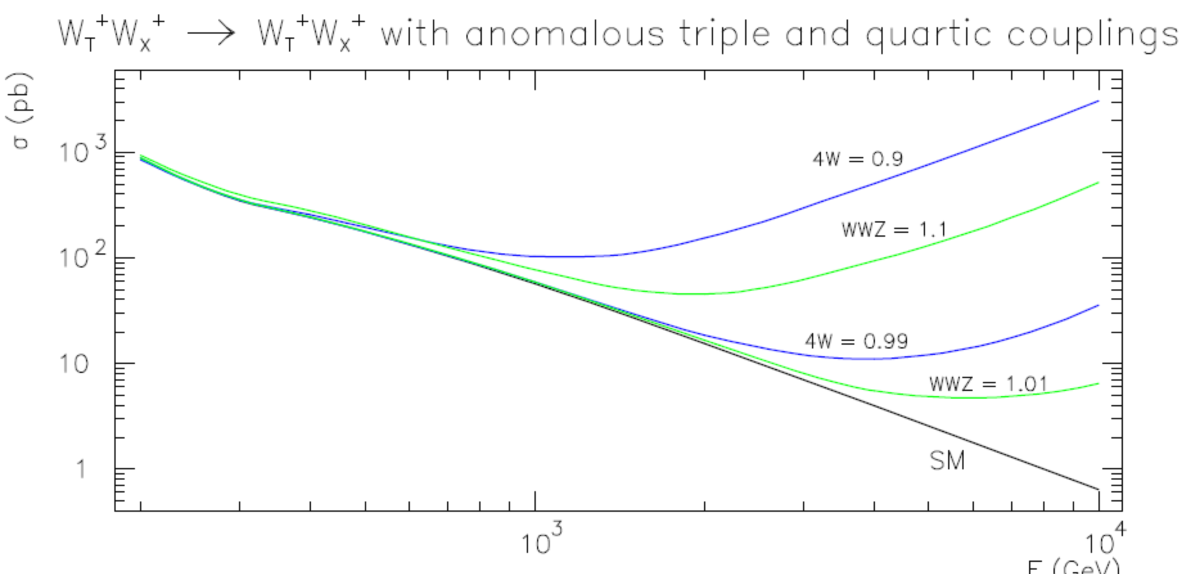


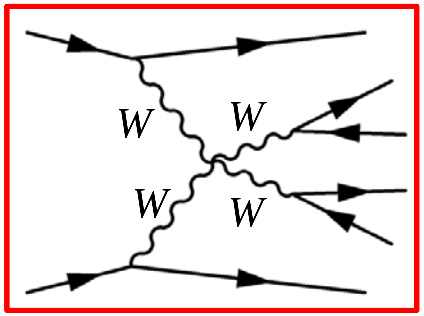
Anomalous TGCs and QGCs



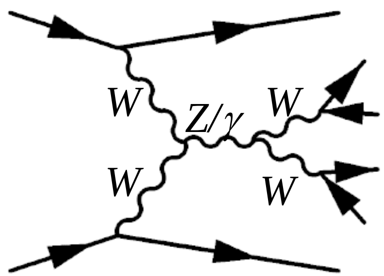


QGC processes

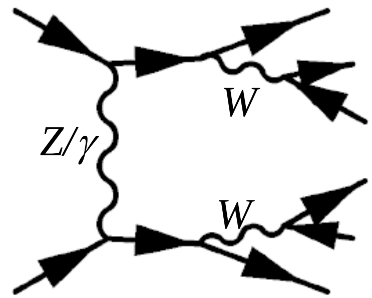
- QGC process: process where a QGC vertex contributes
  - No reaction is ever mediated by a QGC vertex alone
- Two classes of QGC processes are measurable:
  - Vector boson scattering/fusion (VBS/VBF)



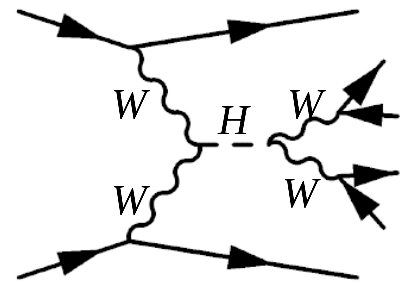
QGC



TGC

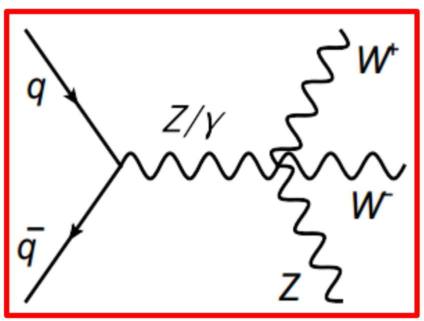


Fermion-mediated

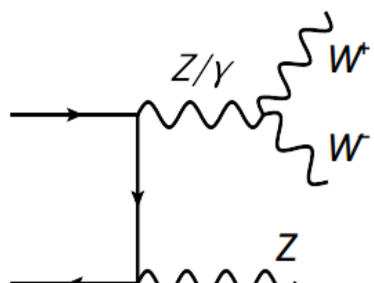


Higgs-mediated

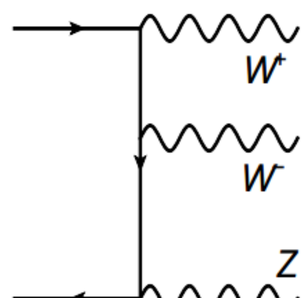
  - Triboson production (WWZ as one example)



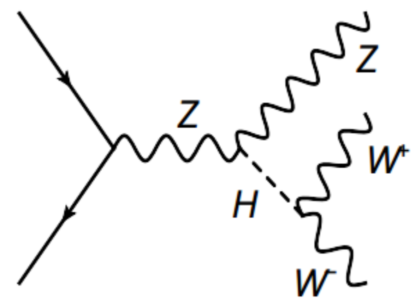
QGC



TGC



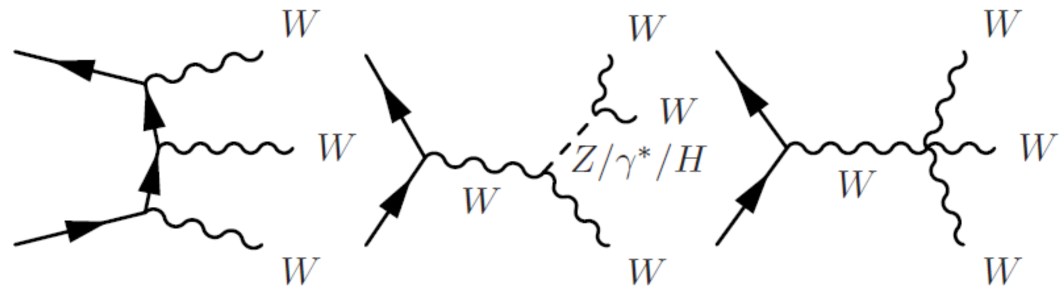
Fermion-mediated



Higgs-mediated

WWW selection criteria

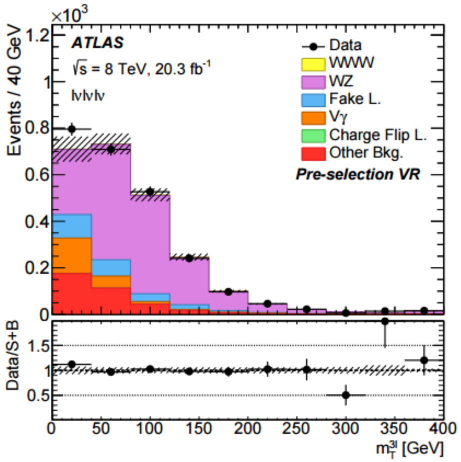
- Reuse the $l^{\pm}\nu l^{\pm}\nu jj$ framework we developed for the ssWW analysis
- Later joined by the lvlvlv group

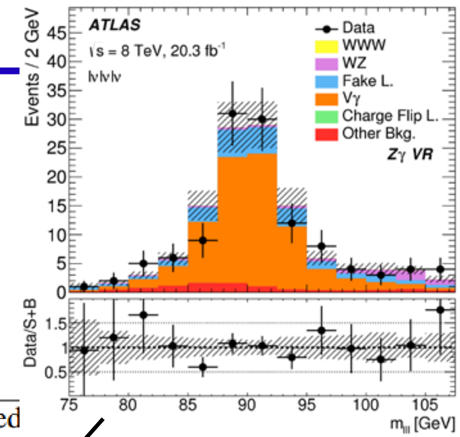


$\ell\nu\ell\nu jj$	$e^{\pm}e^{\pm}$	$e^{\pm}\mu^{\pm}$	$\mu^{\pm}\mu^{\pm}$
Lepton	Exactly two same-charge leptons with $p_{\mathrm{T}} > 30$ GeV		
Jets	At least two jets with $p_{\mathrm{T}}(1) > 30$ GeV, $p_{\mathrm{T}}(2) > 20$ GeV and $\lvert\eta\rvert < 2.5$		
$m_{\ell\ell}$	$m_{\ell\ell} > 40$ GeV		
$E_{\mathrm{T}}^{\mathrm{miss}}$	$E_{\mathrm{T}}^{\mathrm{miss}} > 55$ GeV		-
m_{jj}	65 GeV $< m_{jj} <$ 105 GeV		
$\Delta\eta_{jj}$	$\lvert\Delta\eta_{jj}\rvert < 1.5$		
Z boson veto	$m_{ee} < 80$ GeV or $m_{ee} > 100$ GeV	-	
Third-lepton veto	No third lepton with $p_{\mathrm{T}} > 6$ GeV and $\lvert\eta\rvert < 2.5$ passing looser identification requirements		
b-jet veto	No identified b–jets with $p_{\mathrm{T}} > 25$ GeV and $\lvert\eta\rvert < 2.5$		

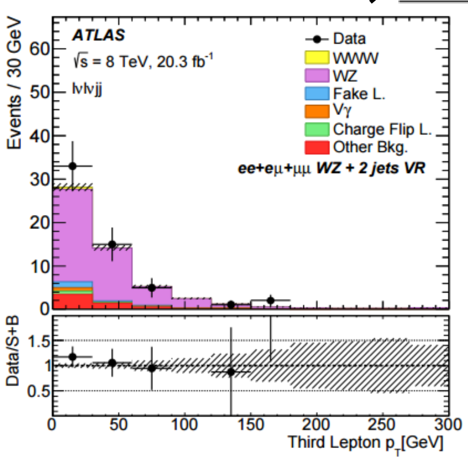
$\ell\nu\ell\nu\ell\nu$	0 SFOS	1 SFOS	2 SFOS
Preselection	Exactly three charged leptons with $p_{\mathrm{T}} > 20$ GeV		
$E_{\mathrm{T}}^{\mathrm{miss}}$	-	$E_{\mathrm{T}}^{\mathrm{miss}} > 45$ GeV	$E_{\mathrm{T}}^{\mathrm{miss}} > 55$ GeV
Same-flavour dilepton mass	$m_{\ell\ell} > 20$ GeV	-	
Angle between trilepton and $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$	$\lvert\phi^{3\ell} - \phi^{\vec{p}_{\mathrm{T}}^{\mathrm{miss}}}\rvert > 2.5$		
Z boson veto	$\lvert m_{ee} - m_Z\rvert > 15$ GeV	$m_Z - m_{\mathrm{SFOS}} > 35$ GeV or $m_{\mathrm{SFOS}} - m_Z > 20$ GeV	$\lvert m_{\mathrm{SFOS}} - m_Z\rvert > 20$ GeV
Jet veto	At most one jet with $p_{\mathrm{T}} > 25$ GeV and $\lvert\eta\rvert < 4.5$		
b-jet veto	No identified b–jets with $p_{\mathrm{T}} > 25$ GeV and $\lvert\eta\rvert < 2.5$		

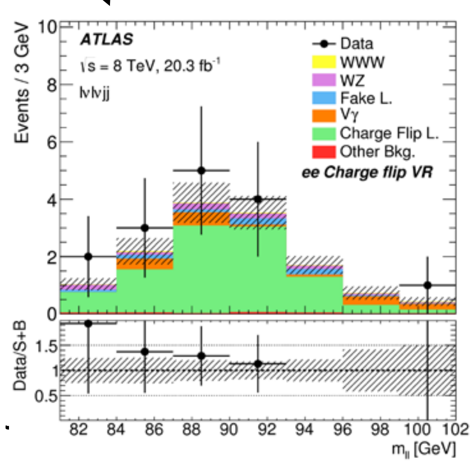
Validation regions

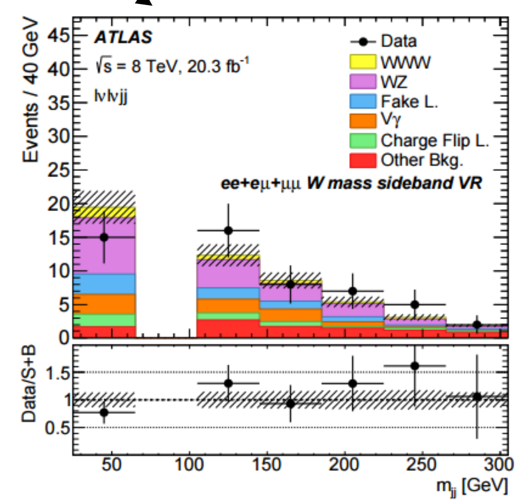




	Validation Region	Signal	Background	Observed
	Preselection	$9.78 \pm 0.04 \pm 0.45$	$2392 \pm 7 \pm 298$	2472
$\ell\nu\ell\nu\ell\nu$	Fake-lepton	$0.15 \pm 0.01 \pm 0.02$	$15 \pm 1 \pm 10$	18
	$Z\gamma$	$0.32 \pm 0.01 \pm 0.02$	$119 \pm 3 \pm 20$	119
	Charge-flip	$0.98 \pm 0.04 \pm 0.06$	$21 \pm 1 \pm 2$	22
	WZ + 2-jets	$0.55 \pm 0.03 \pm 0.04$	$52 \pm 1 \pm 10$	56
$\ell\nu\ell\nu jj$	b-tagged	$1.00 \pm 0.05 \pm 0.07$	$69 \pm 1 \pm 23$	78
	W mass sideband	$3.35 \pm 0.08 \pm 0.43$	$48 \pm 2 \pm 6$	53
	≤ 1 jet	$1.62 \pm 0.06 \pm 0.40$	$139 \pm 3 \pm 18$	145

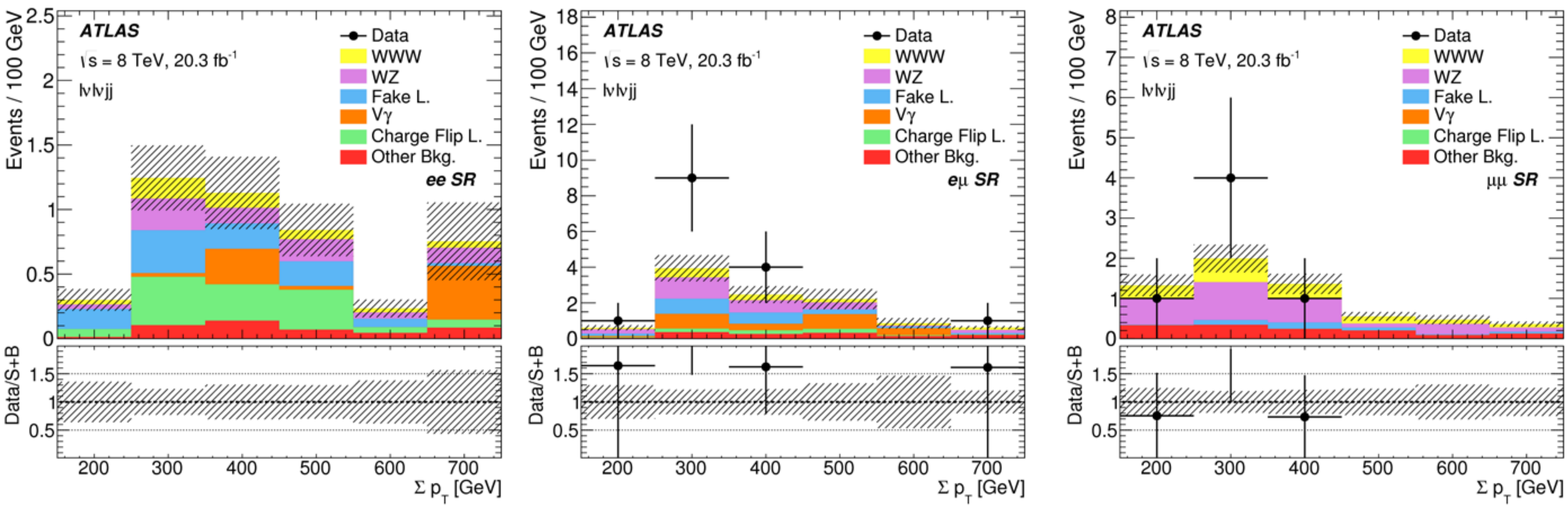






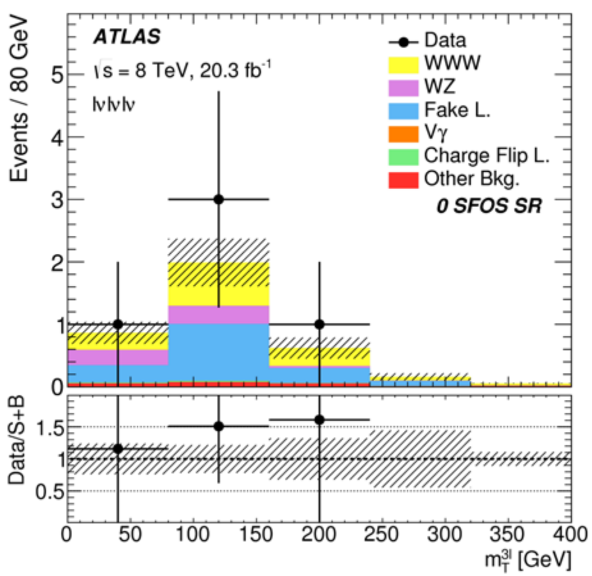
Signal regions (lvlvjj)

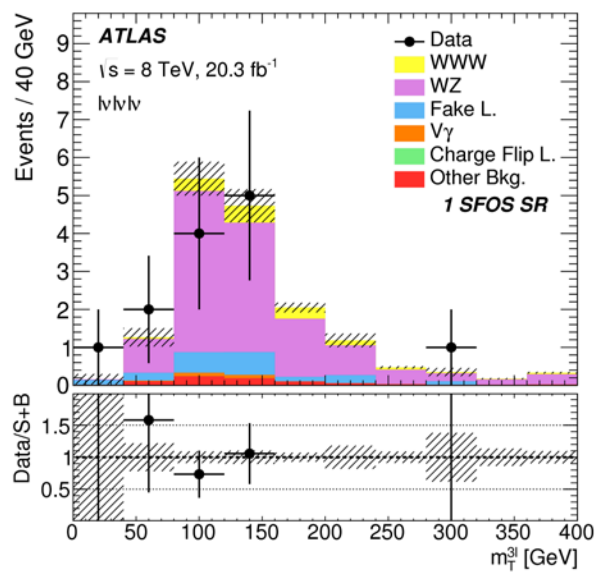
$\ell\nu\ell\nu jj$	$e^{\pm}e^{\pm}$	$e^{\pm}\mu^{\pm}$	$\mu^{\pm}\mu^{\pm}$
$W^{\pm}W^{\pm}W^{\mp}$ signal	0.46 ± 0.03 ± 0.07	1.35 ± 0.05 ± 0.19	1.65 ± 0.06 ± 0.30
WZ	0.74 ± 0.13 ± 0.44	2.77 ± 0.27 ± 0.66	3.28 ± 0.29 ± 0.71
Other prompt background	0.46 ± 0.05 ± 0.16	1.33 ± 0.10 ± 0.38	1.33 ± 0.15 ± 0.38
Charge-flip background	1.13 ± 0.13 ± 0.24	0.74 ± 0.08 ± 0.16	-
$V\gamma$	0.75 ± 0.35 ± 0.21	2.5 ± 0.7 ± 0.7	-
Fake-lepton background	0.96 ± 0.15 ± 0.39	2.04 ± 0.22 ± 0.89	0.43 ± 0.06 ± 0.25
Total background	4.0 ± 0.4 ± 0.7	9.4 ± 0.8 ± 1.4	5.0 ± 0.3 ± 0.8
Signal + background	4.5 ± 0.4 ± 0.7	10.7 ± 0.8 ± 1.4	6.7 ± 0.3 ± 0.9
Data	0	15	6

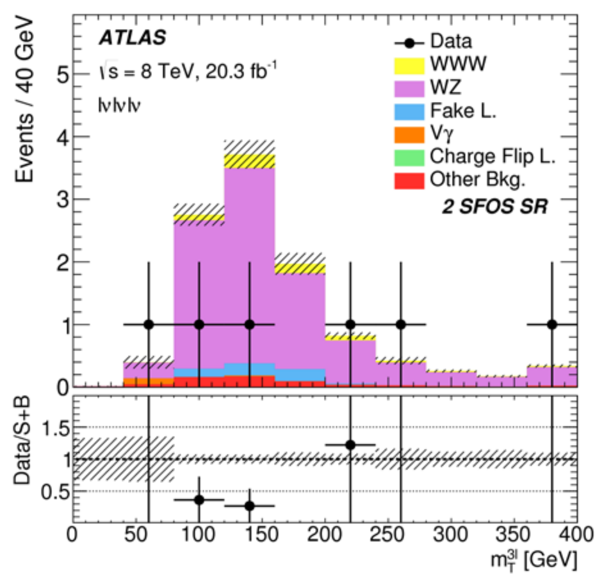


Signal regions (lvlvlv)

$\ell\nu\ell\nu\ell\nu$	0 SFOS	1 SFOS	2 SFOS
$W^{\pm}W^{\pm}W^{\mp}$ signal	1.34 ± 0.02 ± 0.07	1.39 ± 0.02 ± 0.08	0.61 ± 0.01 ± 0.03
WZ	0.59 ± 0.00 ± 0.07	11.9 ± 0.1 ± 1.3	9.1 ± 0.1 ± 1.0
Other prompt background	0.21 ± 0.01 ± 0.02	0.78 ± 0.02 ± 0.11	0.60 ± 0.02 ± 0.10
Charge-flip background	0.04 ± 0.00 ± 0.01	-	-
$V\gamma$	-	0.20 ± 0.13 ± 0.29	0.11 ± 0.10 ± 0.29
Fake-lepton background	1.5 ± 0.3 ± 1.4	1.9 ± 0.3 ± 1.9	0.49 ± 0.16 ± 0.47
Total background	2.4 ± 0.3 ± 1.4	14.8 ± 0.4 ± 2.3	10.3 ± 0.2 ± 1.2
Signal + background	3.7 ± 0.3 ± 1.4	16.2 ± 0.4 ± 2.3	10.9 ± 0.2 ± 1.2
Data	5	13	6



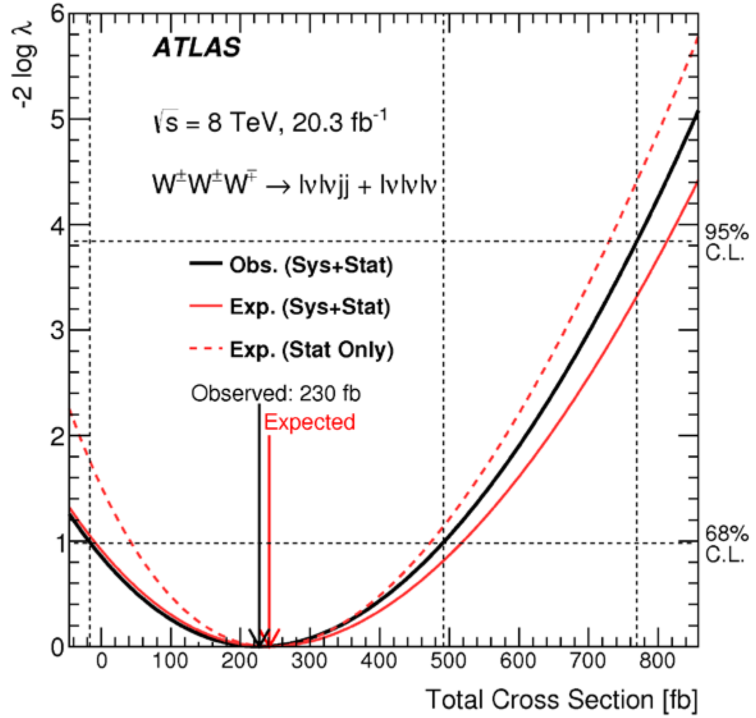




Cross section results

- Cross sections determined using events from all six channels
- Cross sections for both fiducial and common regions are determined

		Cross section [fb]	
		Theory	Observed
Fiducial	$\ell\nu\ell\nu\ell\nu$	0.309 ± 0.007 (stat.) ± 0.015 (PDF) ± 0.008 (scale)	$0.31\ ^{+0.35}_{-0.33}$ (stat.) $^{+0.32}_{-0.35}$ (syst.)
	$\ell\nu\ell\nu jj$	0.286 ± 0.006 (stat.) ± 0.015 (PDF) ± 0.010 (scale)	$0.24\ ^{+0.39}_{-0.33}$ (stat.) $^{+0.19}_{-0.19}$ (syst.)
Total		241.5 ± 0.1 (stat.) $\pm$ 10.3 (PDF) $\pm$ 6.3 (scale)	230 $\pm$200 (stat.) $^{+150}_{-160}$ (syst.)



EPJC (2017) 77, 141

The European Physical Journal

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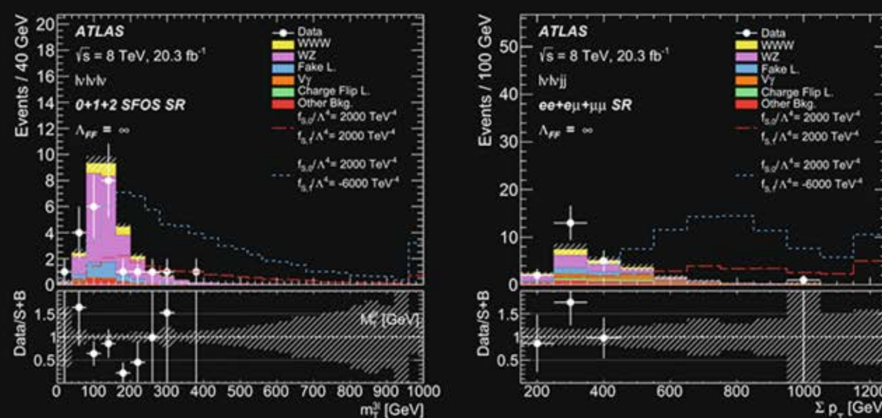
Particles and Fields



The distribution of m_T^{lll} for the *lνlνlν* channel (*left*) and the distribution of $\sum p_T$ for the *lνlνjj* channel (*right*) as observed in the data (*dots with error bars* indicating the statistical uncertainties) and as expected from SM signal and background processes. The ratios between the observed numbers of events in data and the expected SM signal plus background contributions are shown in the lower panels. The *hashed bands* result from the systematic uncertainties on the sum of the signal plus background contributions. The "other backgrounds" contain prompt leptons and are estimated from MC. Possible contributions from various anomalous Quartic Gauge Couplings are also shown.
From the ATLAS Collaboration: Search for triboson $W^\pm W^\pm W^\mp$ production in *pp* collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector.

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Anomalous QGCs

- **Often how we describe sensitivity to new physics**
  - Allow for new operators in the Lagrangian typically dimension 8 for aQGC
  - Generally produces production enhancements at high boson p_T
- **ATLAS has been using the α_4,α_5 parameterization**
  - A. Alboteanu et al, J. High Energy Phys. 11 (2008)
  - T. Appelquist and C. Bernard,Phys. Rev. D 22, 200 (1980)
  - A. C. Longhitano, Phys. Rev. D22, 1166 (1980); Nucl. Phys. B188, 118 (1981)

$$\mathcal{L}_4 = \alpha_4(\mathrm{tr}\,[\mathbf{V}_\mu \mathbf{V}_\nu])^2$$
$$\mathcal{L}_5 = \alpha_5(\mathrm{tr}\,[\mathbf{V}_\mu \mathbf{V}^\mu])^2$$

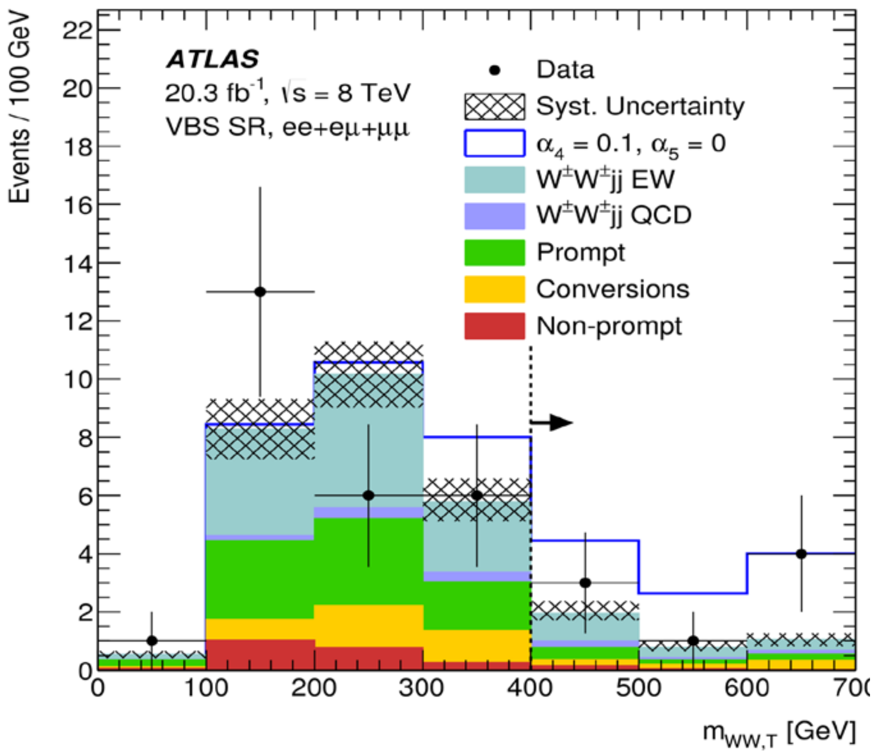
- **Moving toward f_{so},f_{s1} parameterization**
  - O. J. P. Eboli et al., Phys. Rev. D74 (2006)
  - G. Belanger et al., Eur. Phys. J. C 13 (2000) 283

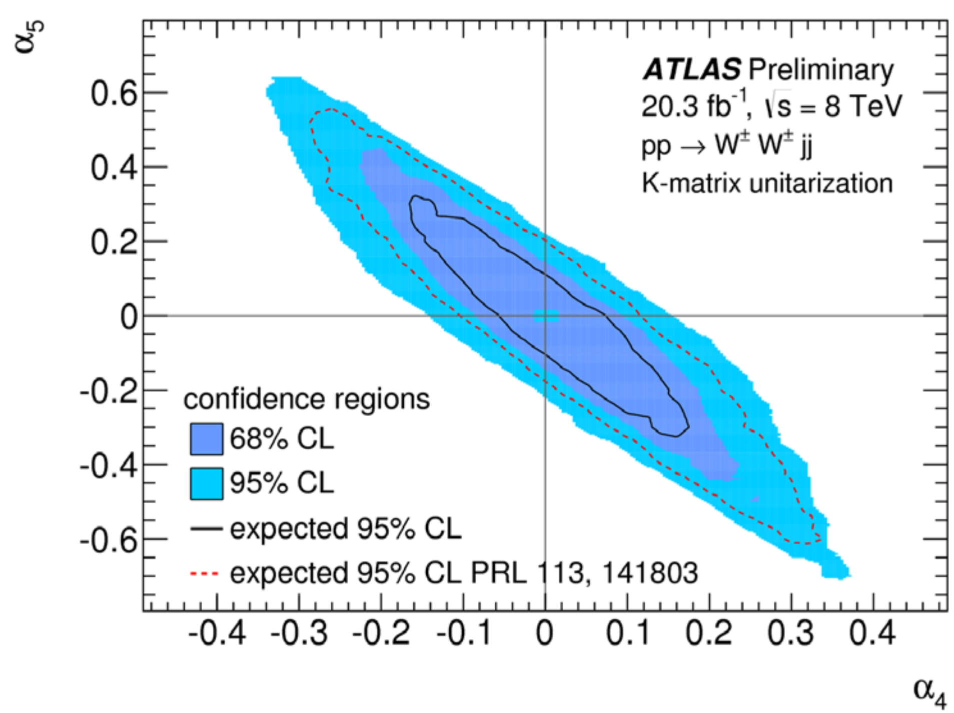
$$\mathcal{L}_{S,0} = \frac{f_{S,0}}{\Lambda^4}[(D_\mu\Phi)^\dagger D_\nu\Phi] \times [(D^\mu\Phi)^\dagger D^\nu\Phi] \qquad \mathcal{L}_{S,1} = \frac{f_{S,1}}{\Lambda^4}[(D_\mu\Phi)^\dagger D^\mu\Phi] \times [(D_\nu\Phi)^\dagger D^\nu\Phi]$$

- **If parameters become large these models become unphysical (are un-unitarized)**
  - ATLAS addresses this with a **K-Matrix** of **form factor**
    - A. Alboteanu, W. Kilian, and J. Reuter, J. High Energy Phys. 11 (2008) 010
    - O. J. P. Eboli, M. C. Gonzalez-Garcia and S. M. Lietti, Phys. Rev. D (2004)

aQGCs from $W^\pm W^\pm jj$ scattering

- Cuts on the transverse mass of the WW system can enhance aQGC sensitivity

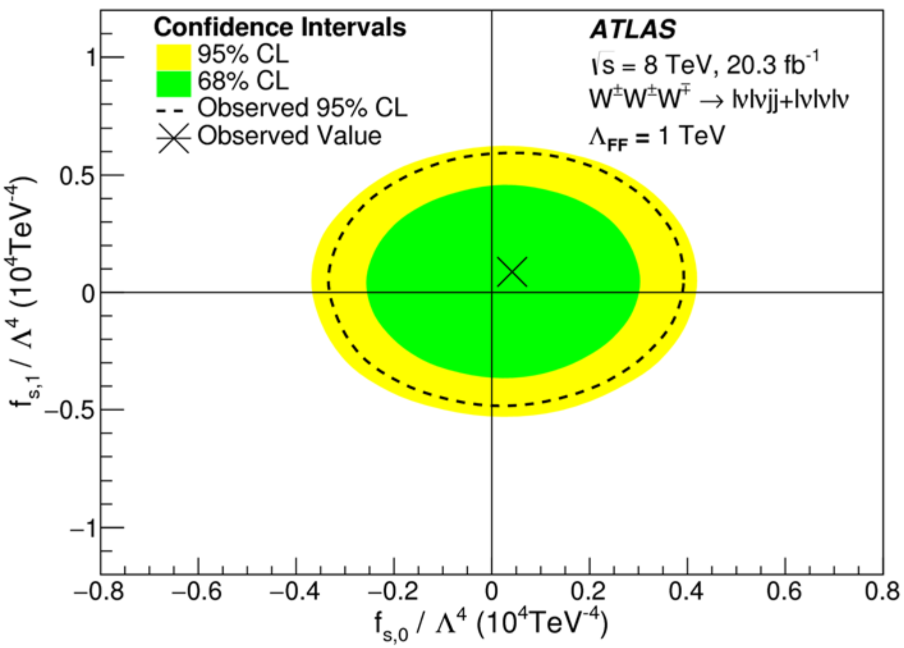




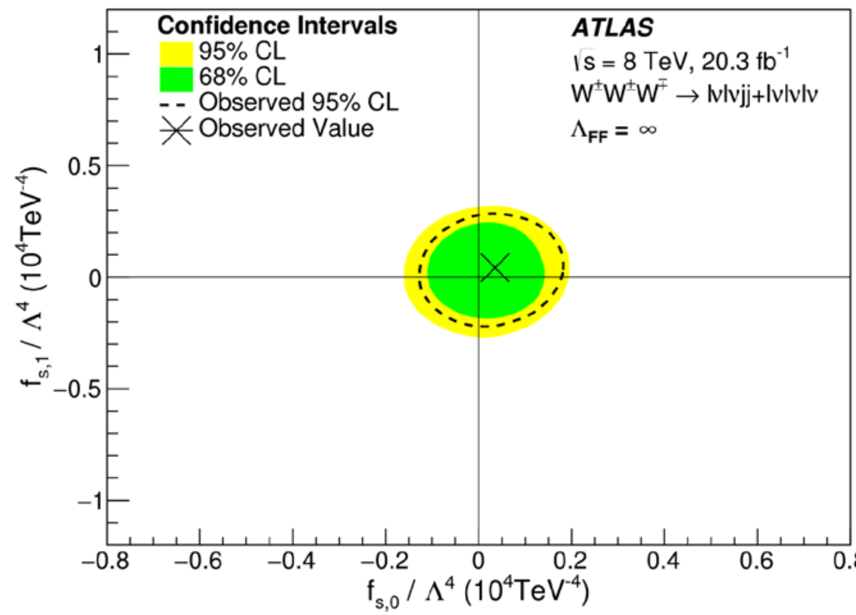
arXiv: 1611.02428
Submitted to Phys. Rev. D

aQGCs from WWW

- Use the observed cross sections to set limits on $f_{s,0}$ $f_{s,1}$



Unitarized



Un-unitarized

EPJC (2017) 77, 141

Conclusions

- The Higgs mechanism was introduced to explain the EWSB and origin of mass for elementary particles
- Important to study VBS processes to obtain a better understanding of the EWSB (need to know if this boson is fully or only partially responsible for the EWSB in the whole energy regime, determine the dynamics of EWSB)
- A few topics shown with significant contributions from my group:
  - First evidence for $W^{\pm}W^{\pm}jj$ VBS process
  - Use deep machine learning technique to extract longitudinal fractions
  - First search for neutral resonances in the $W^{+}W^{-}jj$ channel
  - First search for the WWW process
  - Limits on aQGCs from both $W^{\pm}W^{\pm}jj$ and WWW processes
- More studies with 13/14 TeV data ongoing