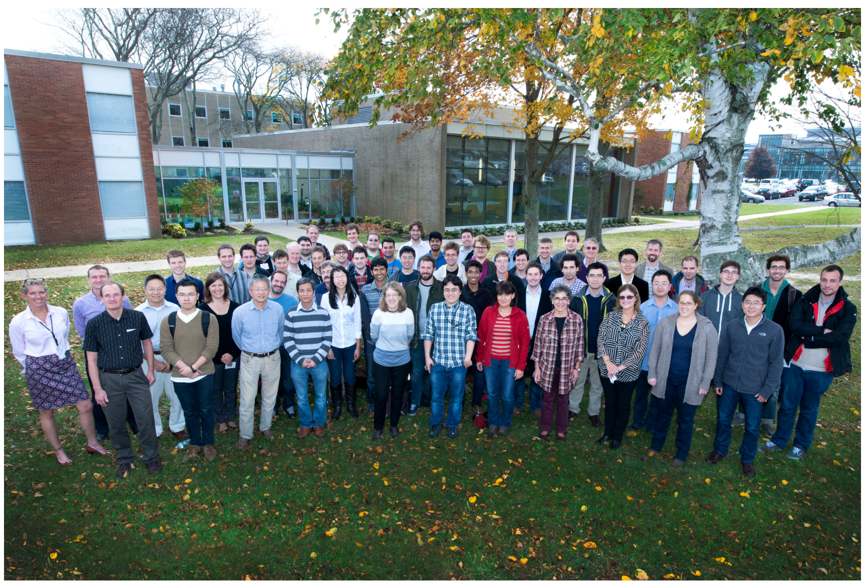
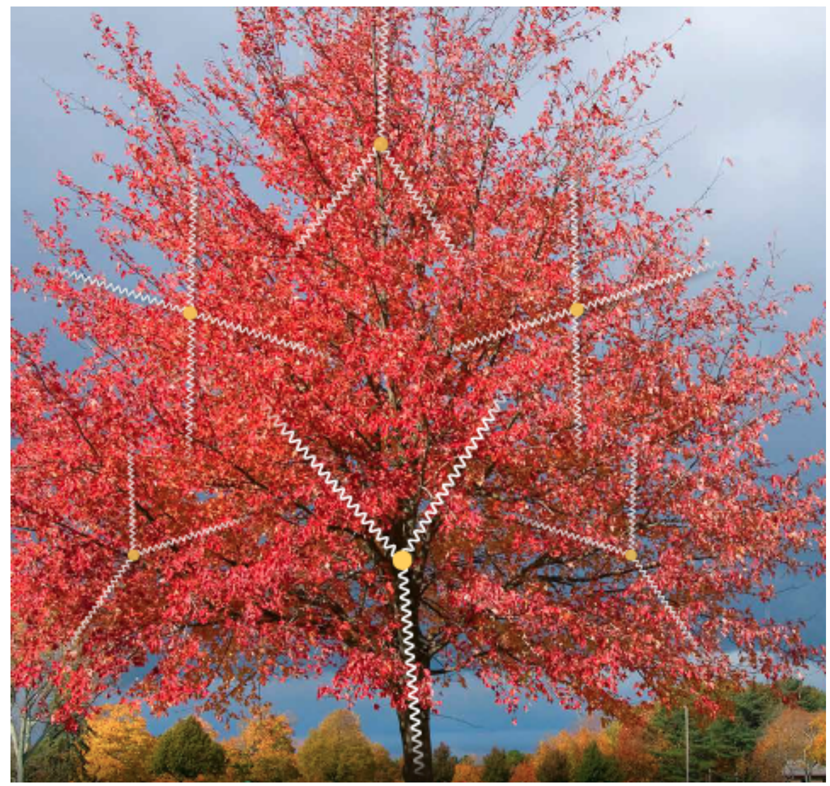
The Search for New Physics

What can VV interactions tell us?

S. Dawson, BNL
October 30, 2014



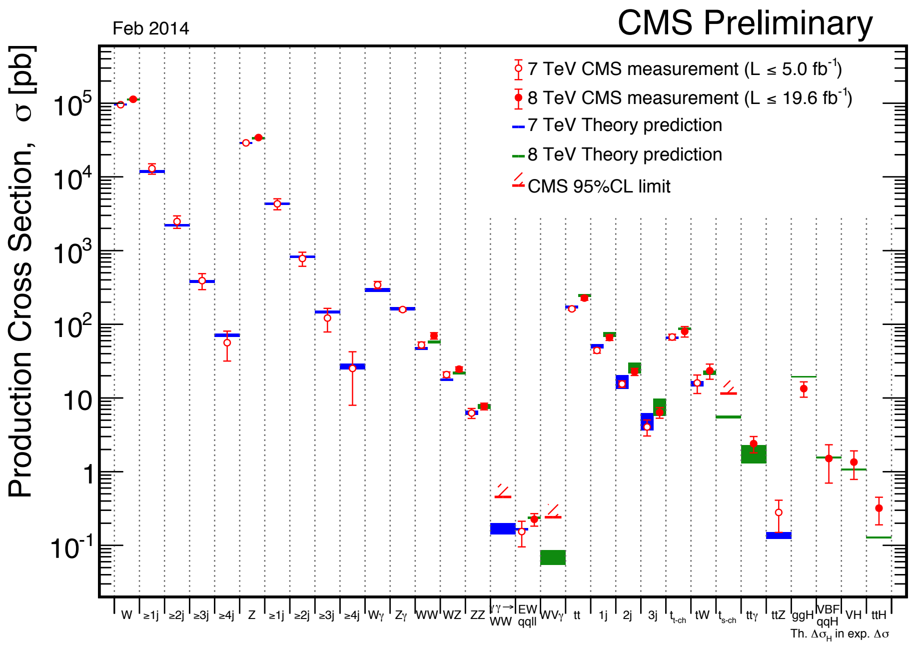


Thanks

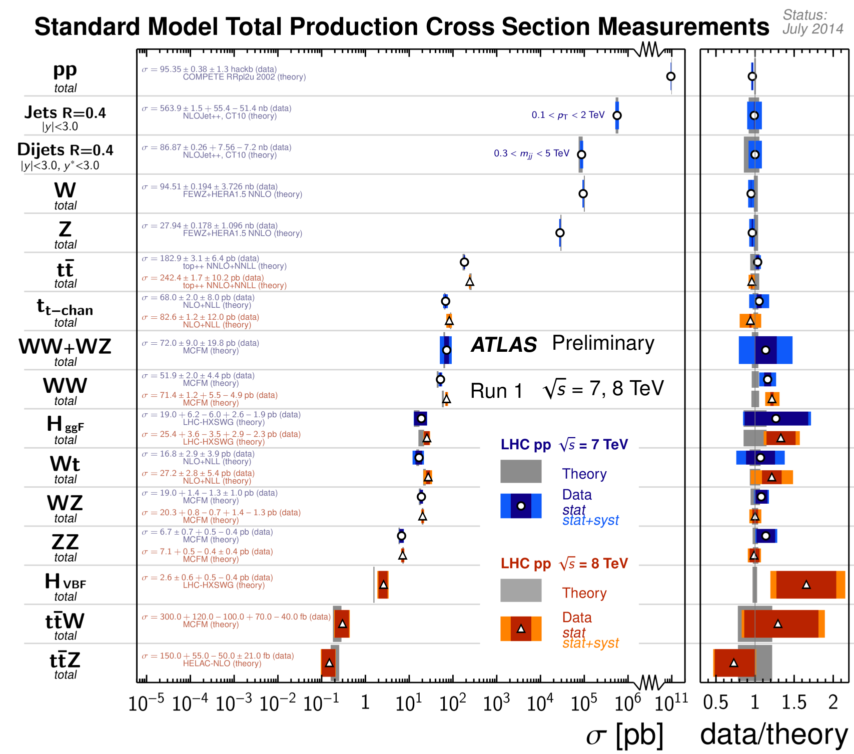
- *Thanks to Linda Feierabend for the superb organization*
- Thanks to all the speakers for such interesting talks
- Thanks to Marc-Andre Pleier for the great program

Apologies.....this is a selection of results which caught my fancy....no priorities implied

LHC Cross sections are close to SM

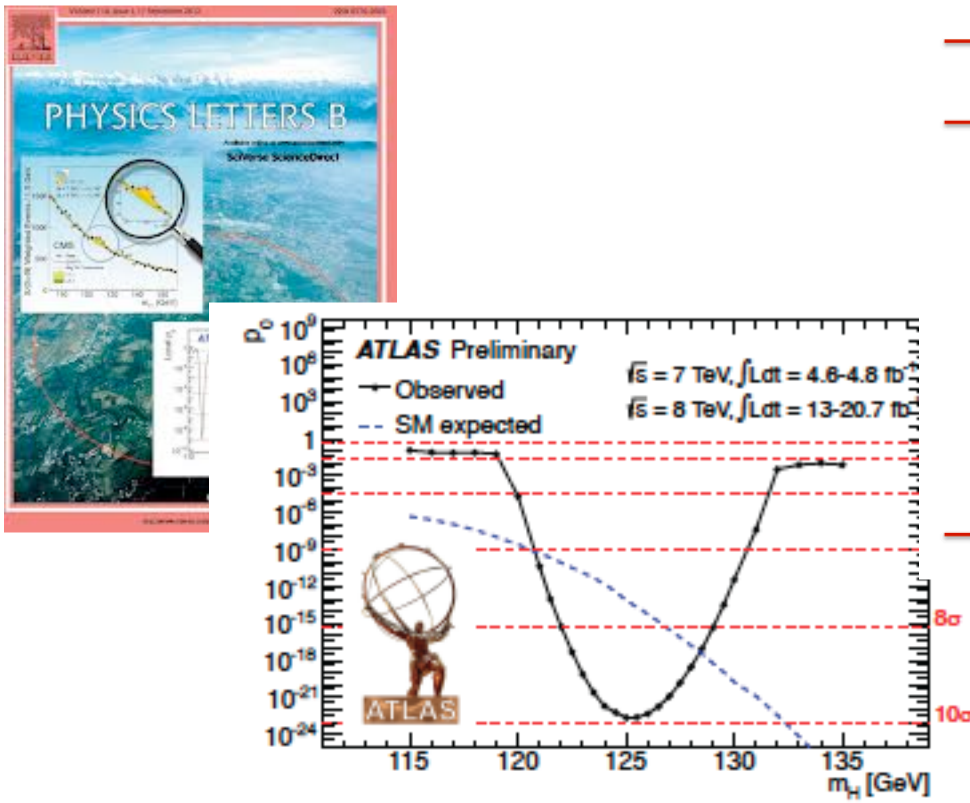


At a generic level, data and theory in excellent agreement for many different processes



We discovered a Higgs boson!

- The minimal Higgs model is very predictive
- Only free parameter is M_H



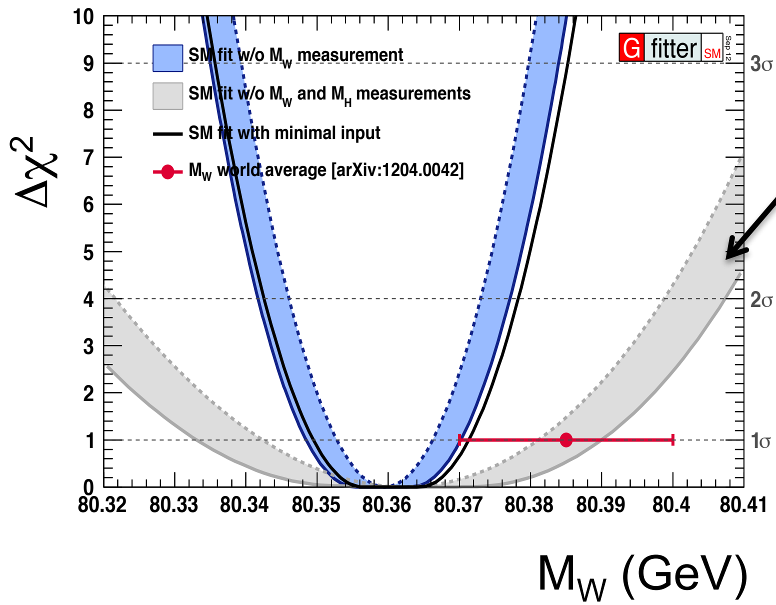
CMS

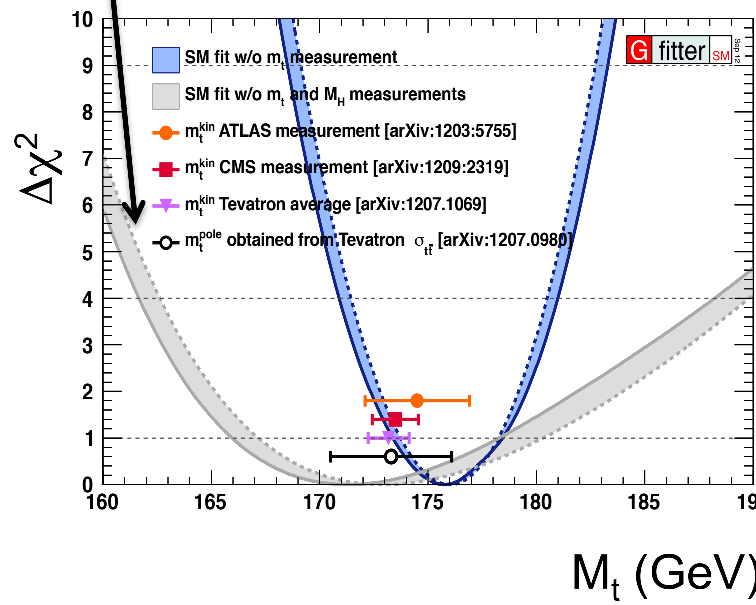
Decay	Expected	Observed
ZZ	7.1 σ	6.7 σ
γγ	3.9 σ	3.2 σ
WW	5.3 σ	3.9 σ
bb	2.2 σ	2.1 σ
ττ	2.6 σ	2.8 σ

Both ATLAS and CMS have close to 10σ significance

Precision Physics After Higgs Discovery

Fit without Higgs





The SM as an effective low energy theory is an extremely good approximation

But the SM can’t be complete

- It doesn’t explain:
  - Neutrino masses
  - Dark matter
  - Baryon asymmetry
  - The pattern of fermion masses

If new physics explains any of this, how do we get a handle on the relevant energy scale?

Vector boson self interactions are a good place to test our understanding of QCD and look for BSM physics

Inspires theorists to do the really hard calculations!

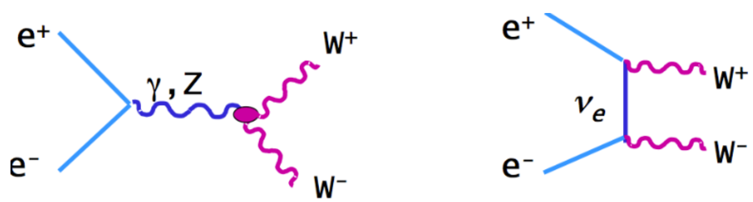
Deviations from SM

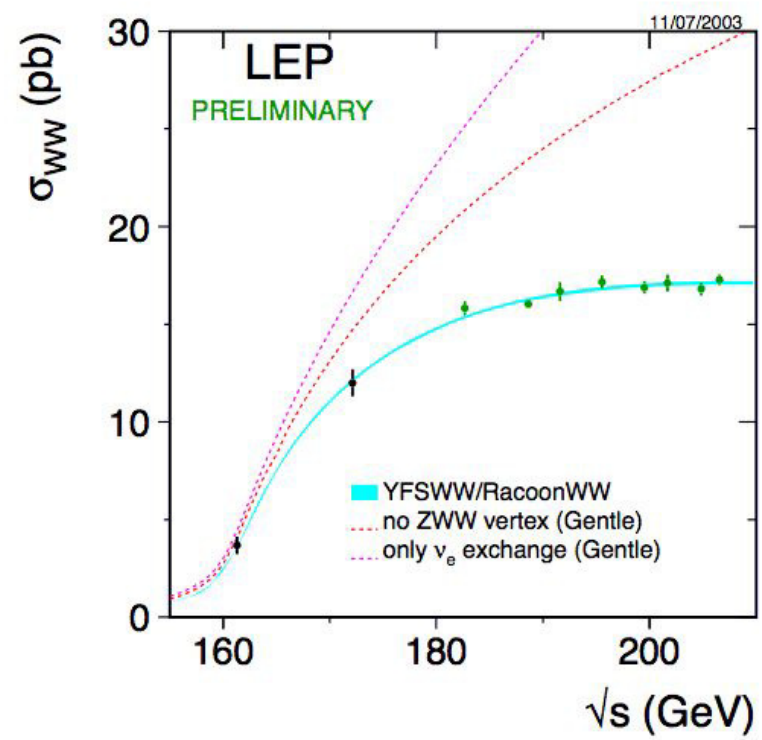
- We already know they must be small!
  - But we expect deviations ~ $v^2/(\text{TeV})^2$
  - Just starting to explore interesting region
- Need to hone our tools for precise predictions and measurements

Gauge boson self interactions play a special role

VV Pair Production

- Cancellations between contributions

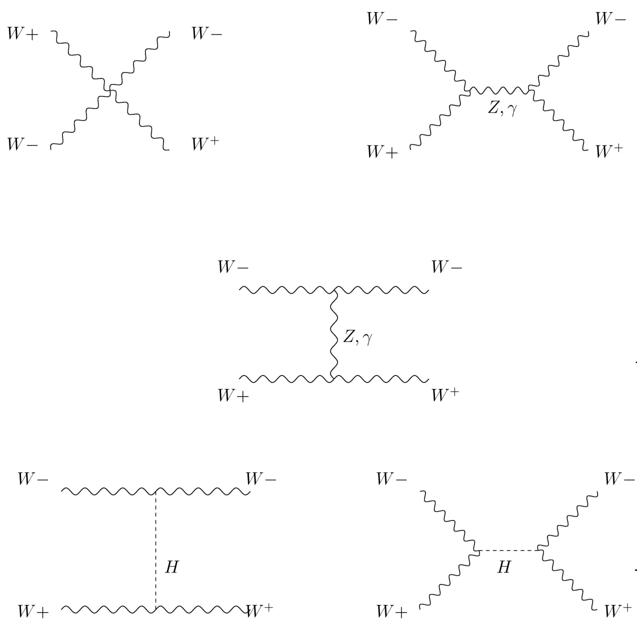




Large cancellations spoiled if γWW and ZWW vertices not *exactly* SM

* Exactly the same physics in pp $\rightarrow W^+W^-$, but PDFs come in

VV Scattering



$$A \approx g^2 \frac{E^2}{M_W^2}$$

$$A \approx -g^2 \frac{E^2}{M_W^2}$$

E^4 terms cancel between TGC and QGC

Terms which grow with energy cancel for $E >> M_H$

This cancellation requires $M_H < 800$ GeV

SM particles have just the right couplings so amplitudes don't grow with energy

BSM Physics with EFT

- Add higher order contributions

$$L \sim L_{SM} + \Sigma_i \frac{C_i}{\Lambda^{n-4}} O_n$$

  - O_n constructed to obey all symmetries of theory
  - Weakly interacting theories, SM loops same size as leading EFT operators
- No unique operator parameterization
- Equations of motion relate operators
  - Most useful basis depends on process
  - Generically EFT operators give effects $O(s/\Lambda^2)$

[Reuter, Sekkula]

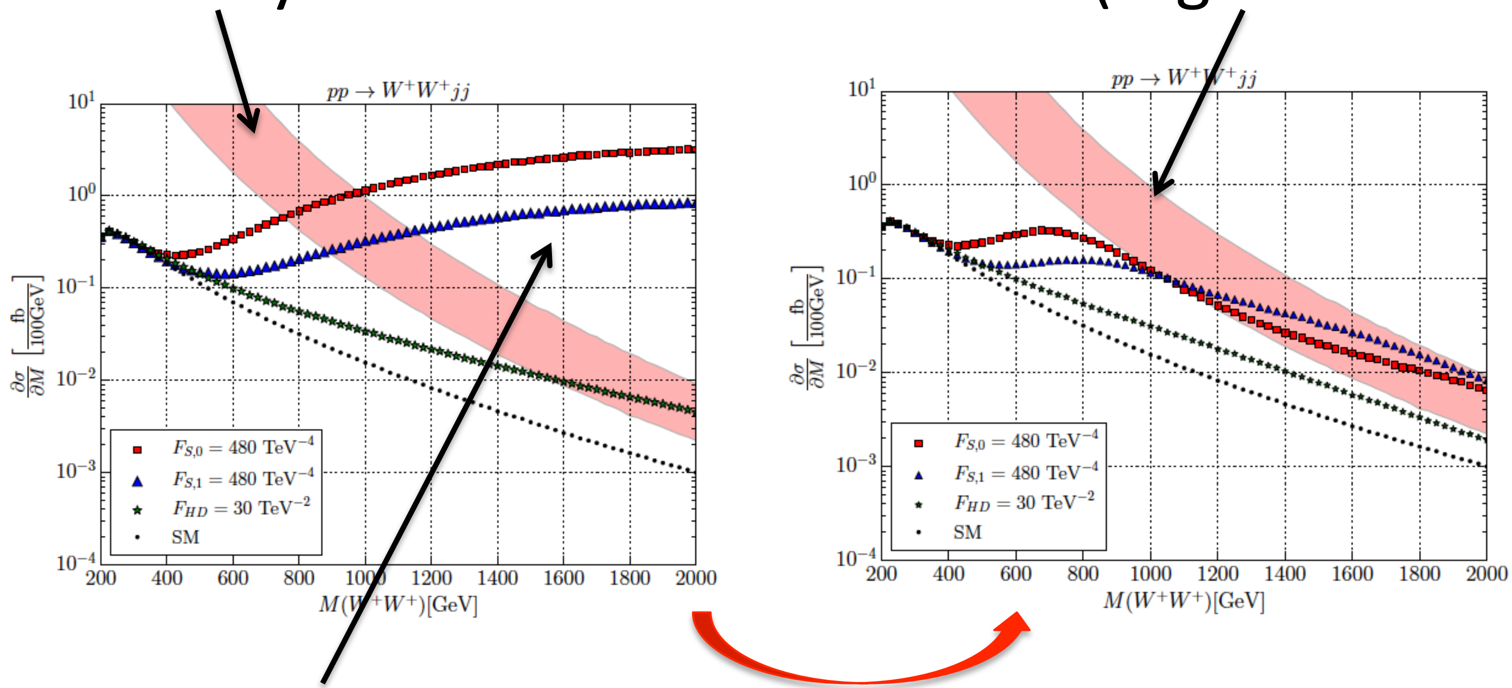
Where is EFT Valid?

- Specific models for BSM physics theoretically well behaved
  - But have to do analysis for each model
- If no new light particles, an effective Lagrangian can be used
  - Approach fails if kinematic variables are near resonances
    - *Valid at scales much below all new physics, $E \ll \Lambda$*
  - Approach violates unitarity at some scale
  - Form factors can cure unitarity violation, but violate gauge invariance

Kilian: EFTs tend to have larger region of validity for TGCs than for QGCs

BSM VB Scattering: W^+W^+jj

- New physics effects grow like s/Λ^2, spoil cancellations
- Unitarity violation above red band (region of validity)



Note growth of EFT effects with M_{WW}

Unitarization

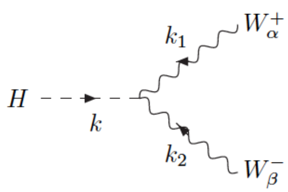
Kilian, Ohl, Reuter, Sekulla, arXiv:1408.6207

[Kilian]

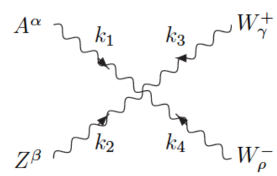
Higgs ⟺ VV interactions

- Higgs and VV interactions related in EFTs

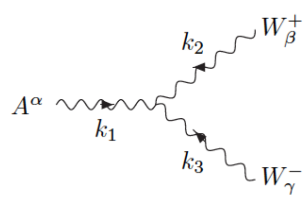
$$
\begin{aligned}
O_W &= (D_\mu \Phi)^\dagger W^{\mu\nu} D_\nu \phi \\
O_B &= (D_\mu \phi)^\dagger B^{\mu\nu} D_\nu \phi
\end{aligned}
$$



$$
i\,\frac{g m_W}{\Lambda^2}\Big\{\frac{f_W}{2}\big[(k_1^\alpha k_1^\beta + k_2^\alpha k_2^\beta) - g^{\alpha\beta}(k_1^2 + k_2^2)\big] + (f_W - 2 f_{WW})\big[k_2^\alpha k_1^\beta - g^{\alpha\beta}(k_1 \cdot k_2)\big]\Big\}
$$



$$
i\,\frac{g^2 m_W^2 s}{\Lambda^2 c} f_W \left[g^{\alpha\gamma} g^{\beta\rho} + g^{\alpha\rho} g^{\beta\gamma} - 2 g^{\alpha\beta} g^{\gamma\rho}\right]
$$

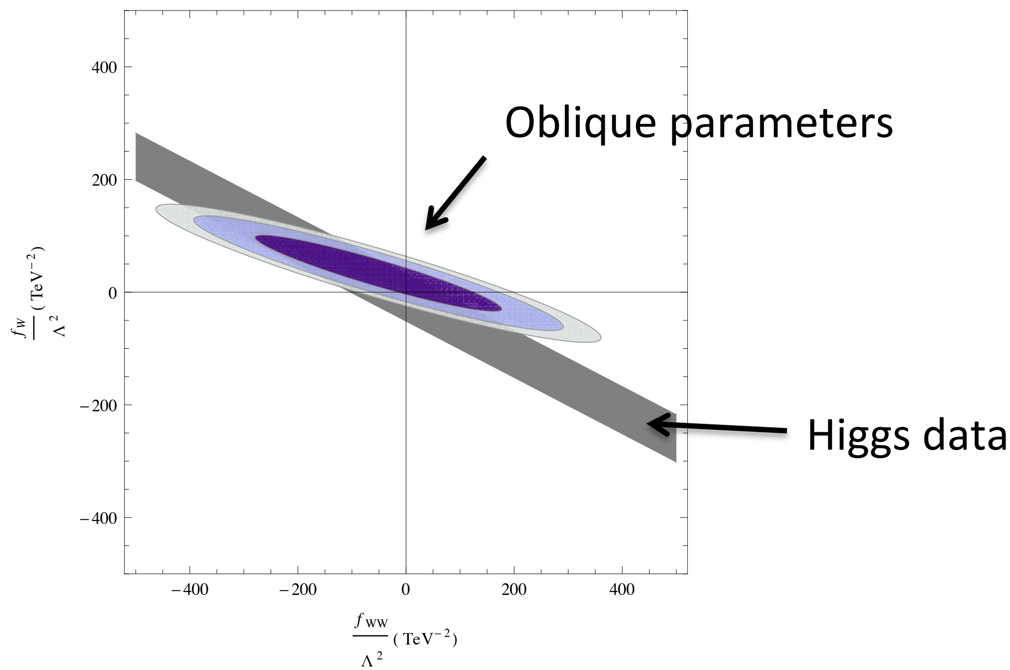


$$
\begin{aligned}
&i\,\frac{g s}{2\Lambda^2}\Big\{m_W^2 (f_B + f_W)\,[g^{\alpha\beta} k_1^\gamma - g^{\alpha\gamma} k_1^\beta] + \\
&-3 g^2 f_{WWW}\Big[k_1^\beta k_2^\gamma k_3^\alpha - k_1^\gamma k_2^\alpha k_3^\beta + (k_1 \cdot k_2)\left(g^{\alpha\gamma} k_3^\beta - g^{\beta\gamma} k_3^\alpha\right) + \\
&(k_1 \cdot k_3)\left(g^{\beta\gamma} k_2^\alpha - g^{\alpha\beta} k_2^\gamma\right) + (k_2 \cdot k_3)\left(g^{\alpha\beta} k_1^\gamma - g^{\alpha\gamma} k_1^\beta\right)\Big]\Big\}
\end{aligned}
$$

[Reuter]

Example

$$\frac{\Gamma(H\to W^+W^-)}{\Gamma(H\to W^+W^-)_{SM}}\sim 1+\left[.0086 f_{WW}(m_Z)+.017 f_W(m_Z)\right]\left(\frac{1\ TeV}{\Lambda}\right)^2$$



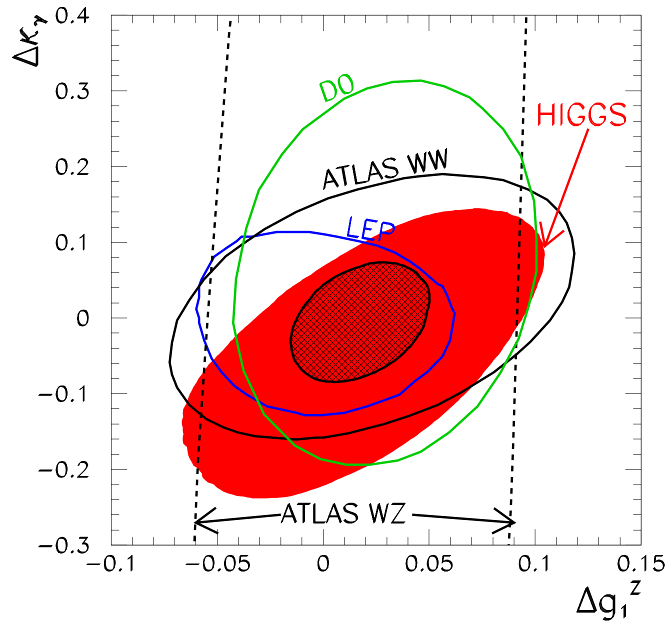
In principle, complementary data from oblique parameters and Higgs data

Interconnections

- Important to do global fits
- W^+W^- production probes complementary coupling space to Higgs coupling limits

$$\Delta\kappa_\gamma = \frac{M_W^2}{2\Lambda^2}(f_W + f_B)$$

$$\Delta g_1^Z = \frac{M_Z^2}{2\Lambda^2} f_W$$

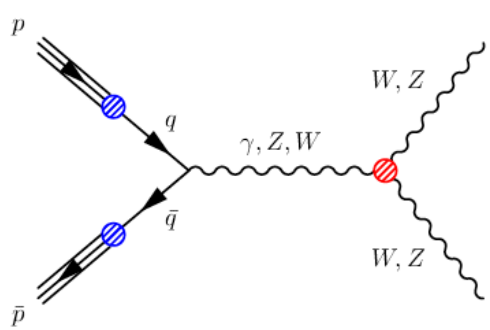


Limits on a single operator from a single process can be misleading

Corbett et al, arXiv:1304.1151

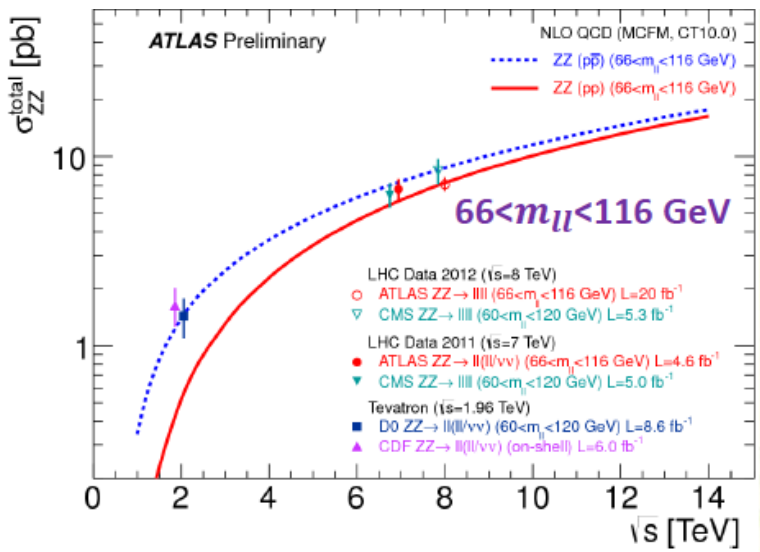
Dibosons

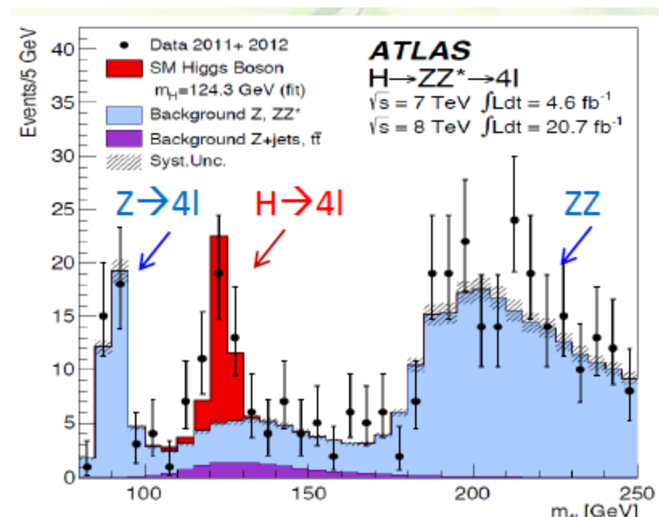
- $W\gamma$, $Z\gamma$, WW, WZ, ZZ
  - QCD effects are large
    - Often requires NNLO, resummation
    - *Tools provided by theorists not complete!*
  - Sensitive to new physics
  - Backgrounds to Higgs measurements



ZZ Production

- Rates in good agreement with NLO





Phys. Lett. B 726 (2013) 88

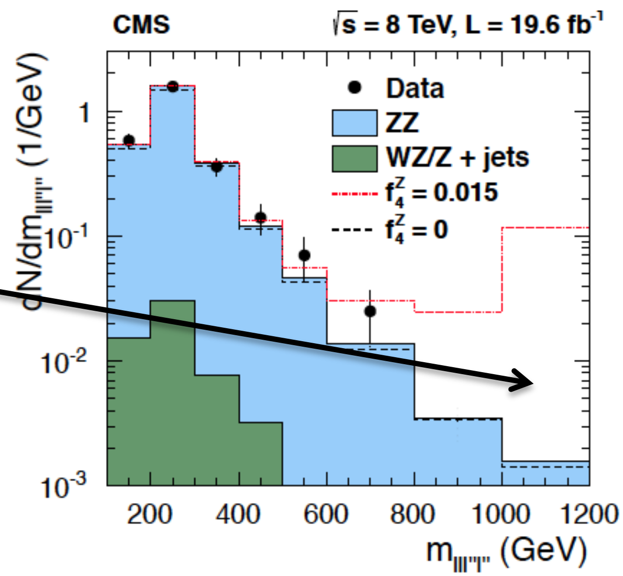
[Wu (ATLAS)]

ZZ looks SM-like

$\sqrt{s}$ [TeV]	σ_{LO} [pb]	σ_{NLO} [pb]	σ_{NNLO} [pb]
7	$4.172^{+0.7\%}_{-1.6\%}$	$6.049^{+2.8\%}_{-2.2\%}$	$6.747^{+2.9\%}_{-2.3\%}$
8	$5.066^{+2.7\%}_{-1.6\%}$	$7.376^{+2.8\%}_{-2.3\%}$	$8.294^{+3.0\%}_{-2.3\%}$

NNLO becoming standard candle

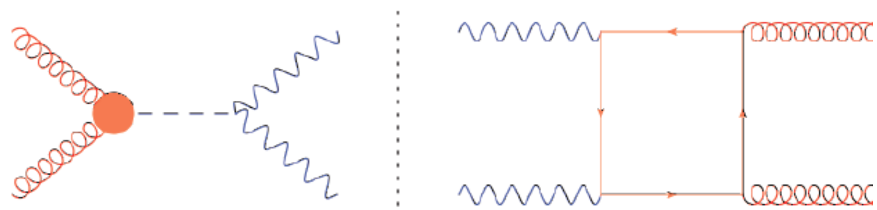
Always the last bins for anomalous couplings

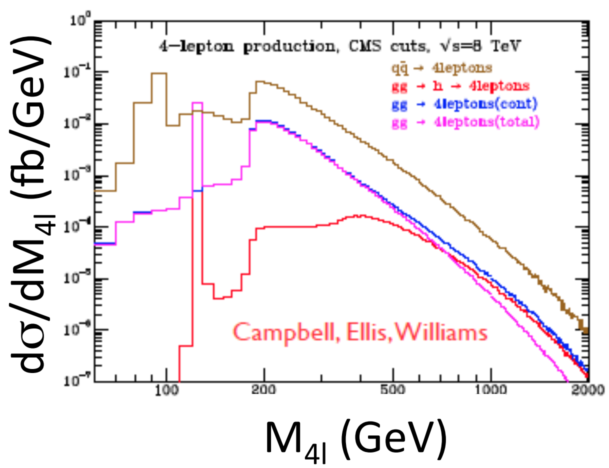


[Channon (CMS), Kallweit]

ZZ and Higgs Width

- gg → ZZ receives contributions from gg → H
  - Amplitude behaves differently on peak and above peak



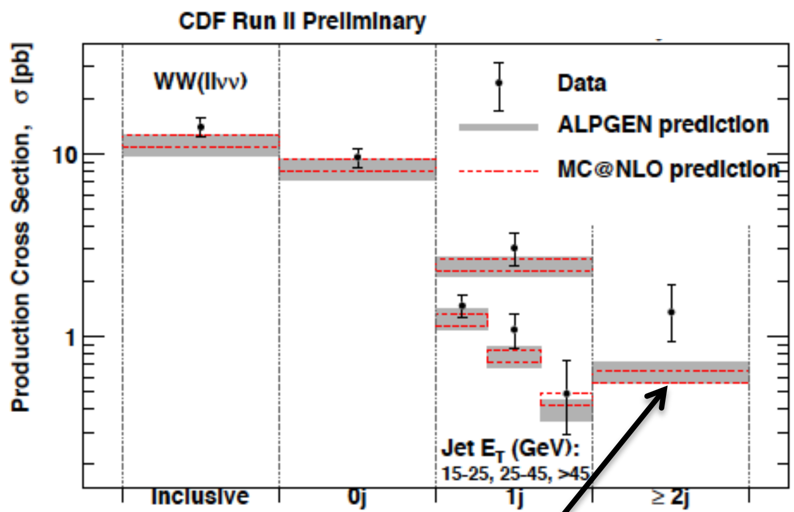


CMS: $\Gamma_H < 5.4\ \Gamma_{H,SM}$
ATLAS: $\Gamma_H < 4.8\text{-}7.7\ \Gamma_{H,SM}$

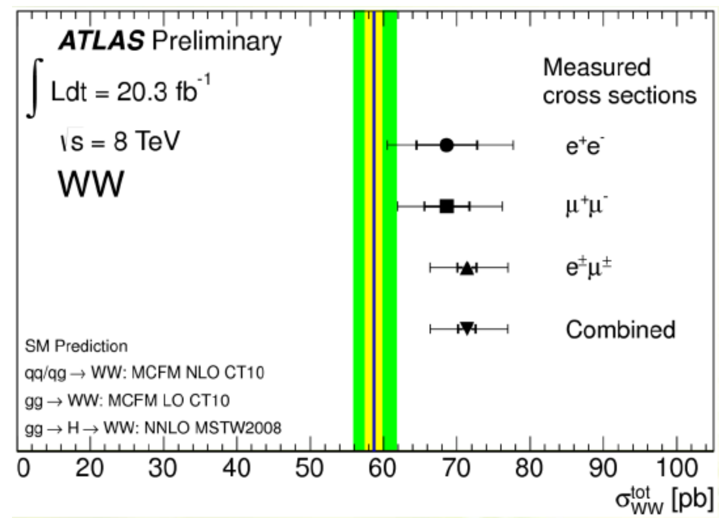
Campbell, Ellis, Williams, arXiv: 1311.3589

[Ellis]

WW Production



Last bin effect



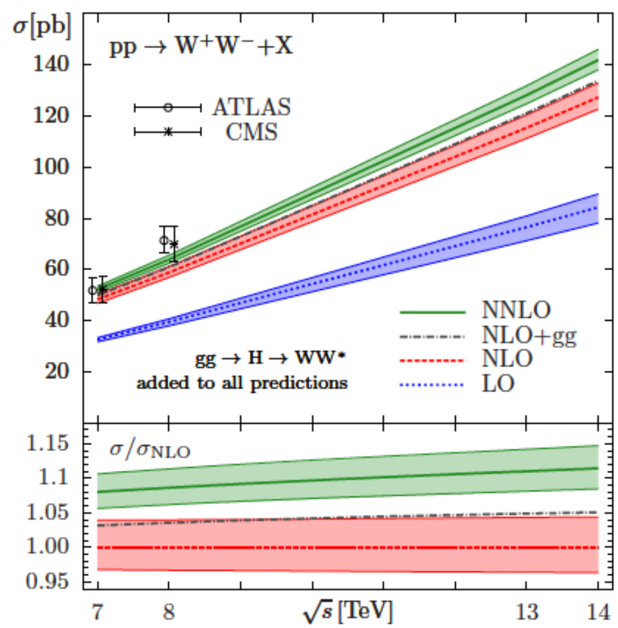
2σ higher than NLO SM prediction

[Wu (ATLAS), Parker (Tevatron)]

NNLO WW Production

$\sqrt{s}$ [TeV]	σ_{LO} [pb]	σ_{NLO} [pb]	σ_{NNLO} [pb]	$\sigma_{gg\to H\to WW^*}$ [pb]
7	$29.52^{+1.6\%}_{-2.5\%}$	$45.16^{+3.7\%}_{-2.9\%}$	$49.04^{+2.1\%}_{-1.8\%}$	$3.25^{+7.1\%}_{-7.8\%}$
8	$35.50^{+2.4\%}_{-3.5\%}$	$54.77^{+3.7\%}_{-2.9\%}$	$59.84^{+2.2\%}_{-1.9\%}$	$4.14^{+7.2\%}_{-7.8\%}$

ATLAS 2σ excess reduced by NNLO contributions

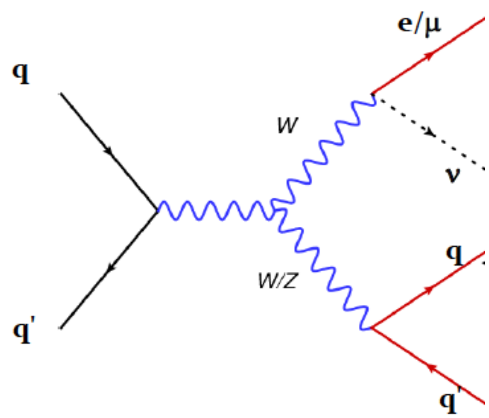


Gehrmann *et al* arXiv:1408.5243

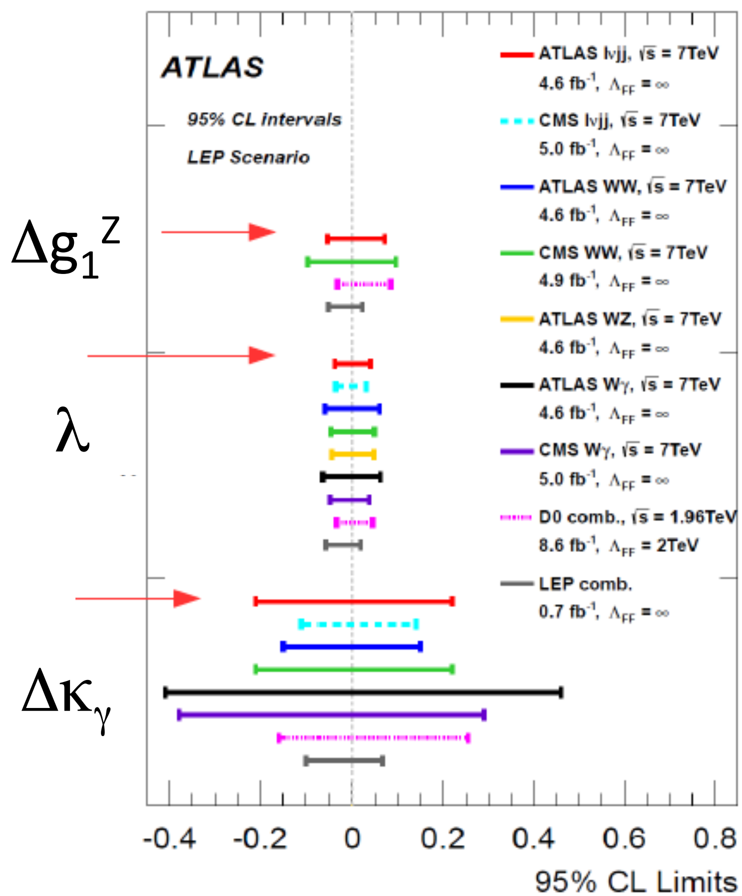
[Kallweit]

Semi-Leptonic WW+WZ

- Large backgrounds
  - 3.4σ observation
  - σ_{tot}=68±7(stat)±19 (syst) pb
  - σ_{NLO}=61.1±2.2 pb



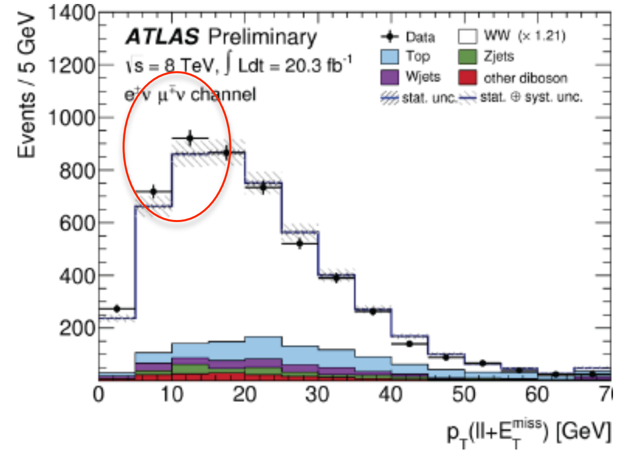
No form factors



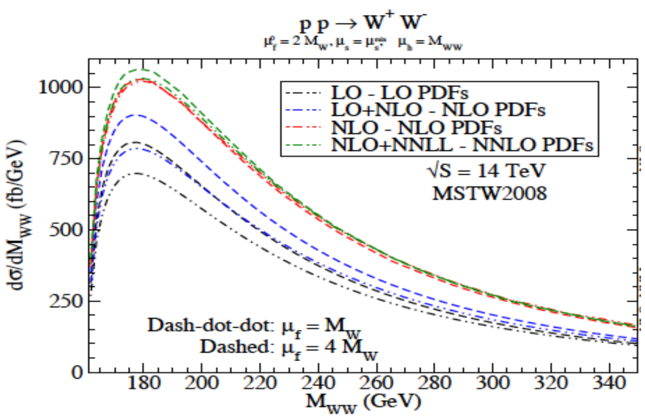
[Lindquist]

WW Production

- Information in distributions
- Is slight excess at peak BSM or QCD?

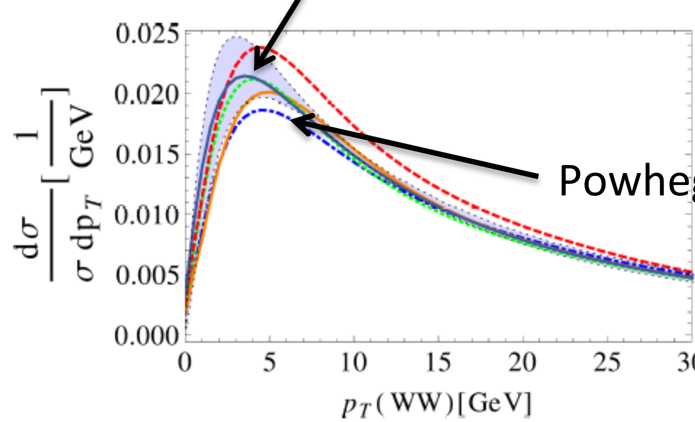


Threshold resummation



Dawson, Lewis, Zeng, arXIv:1307.3249

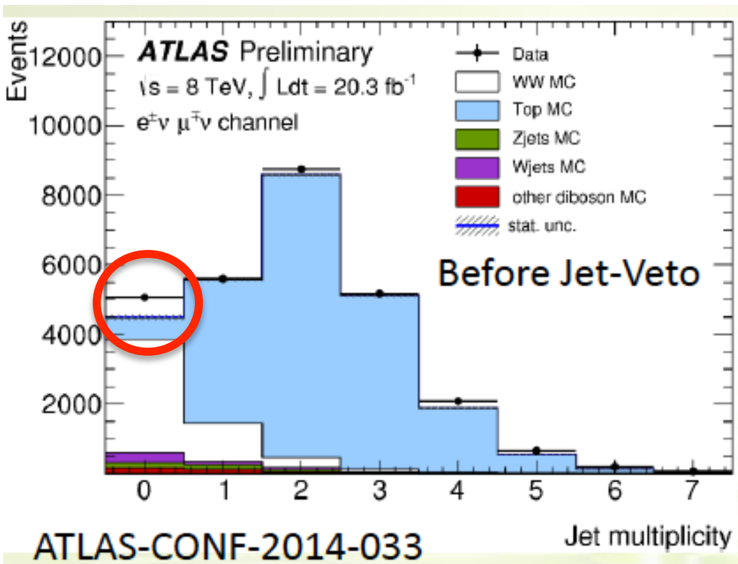
p_T logs resummed

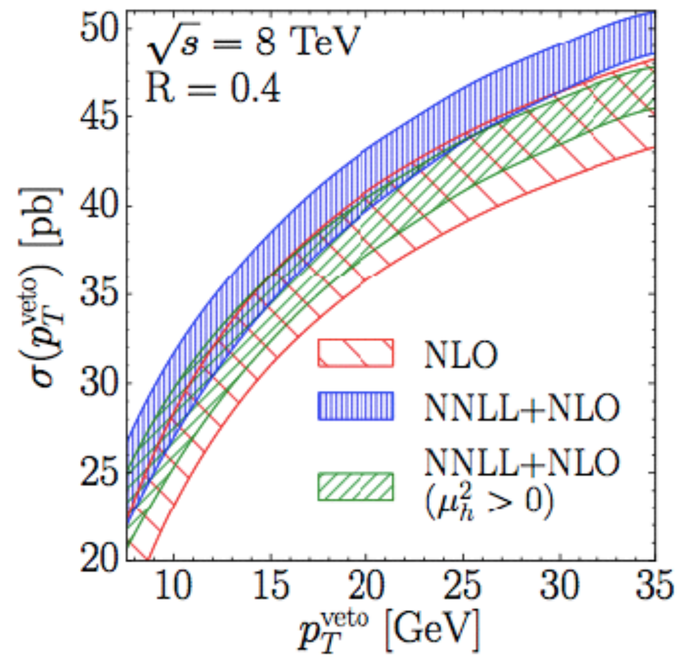


Meade, Ramani, Zeng, arXiv:1407.4481

[Lewis, Meade]

Jet Veto and WW Production

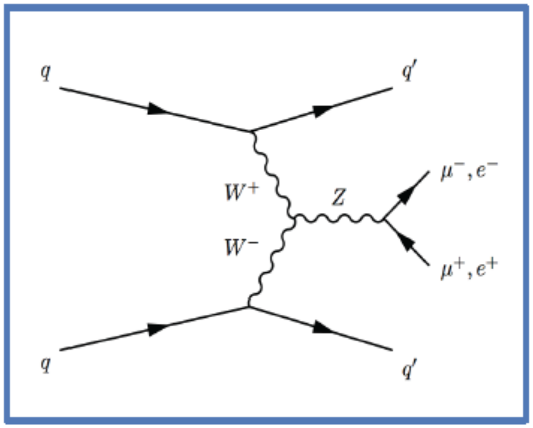


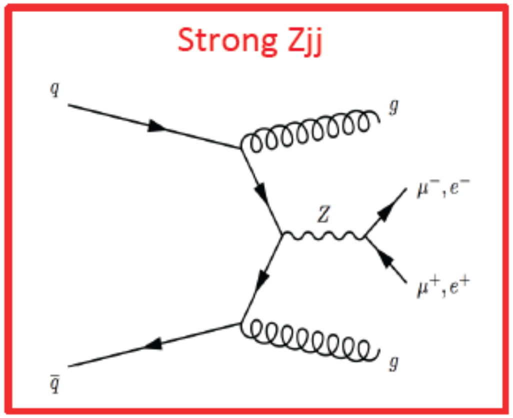


VV production pushes theory

[Jaiswal, Wu (ATLAS)]

VBS Zjj Production





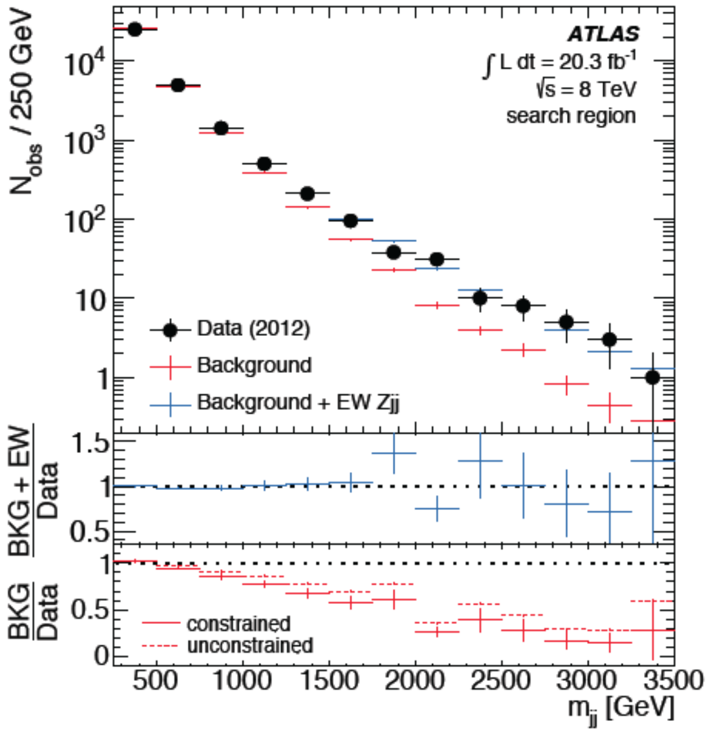
Important for modeling VBF Higgs production; understanding of VBF cuts

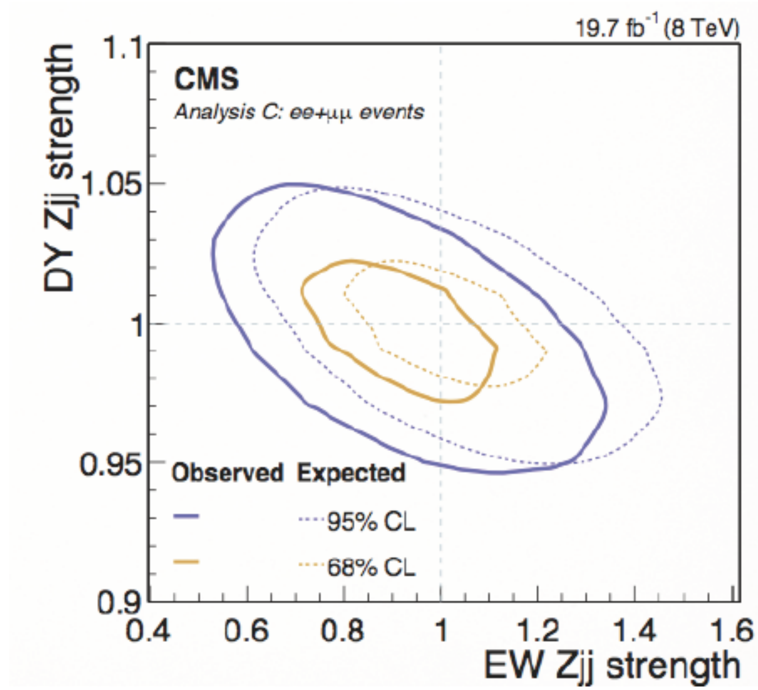
- 1% of strong Zjj rate
- Large rapidity gap, large M_{jj}

- Experiment: Complicated MC modeling of Zjj events
- Theory: need better understanding of interference effects

[Pilkington (ATLAS), Wen (CMS)]

Zjj at 8 TeV

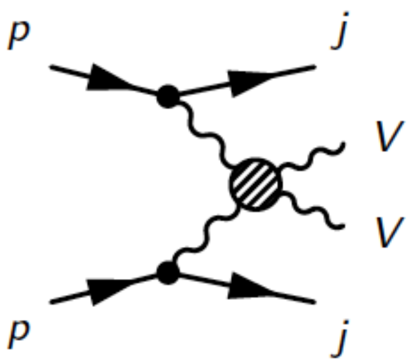




ATLAS & CMS both have 5σ observation of EW Zjj signal

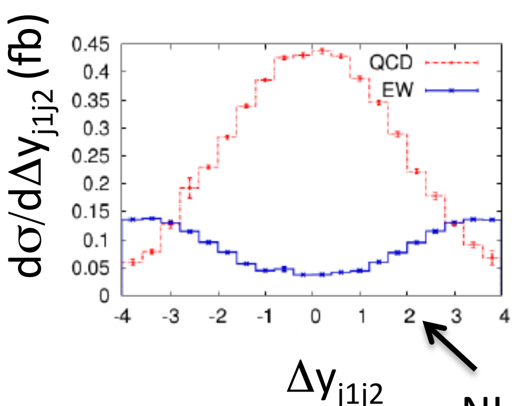
[Pilkington (ATLAS), Wen (CMS)]

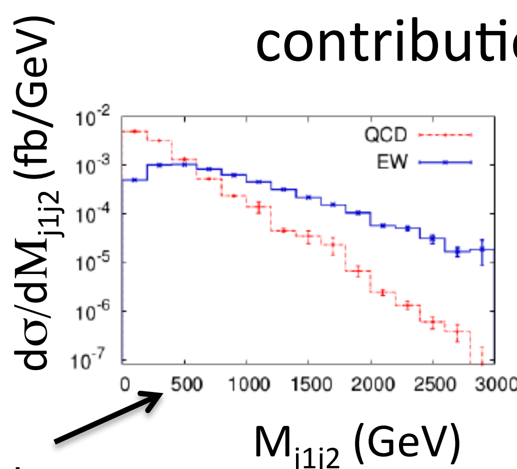
VVjj Production

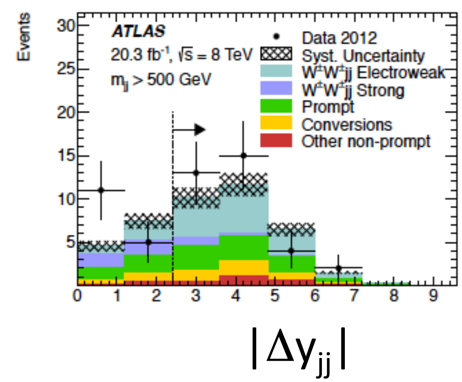


Theory: VBFNLO (fixed order QCD) for ZZjj, WWjj, WZjj

VBF cuts separate QCD and EW contributions very efficiently





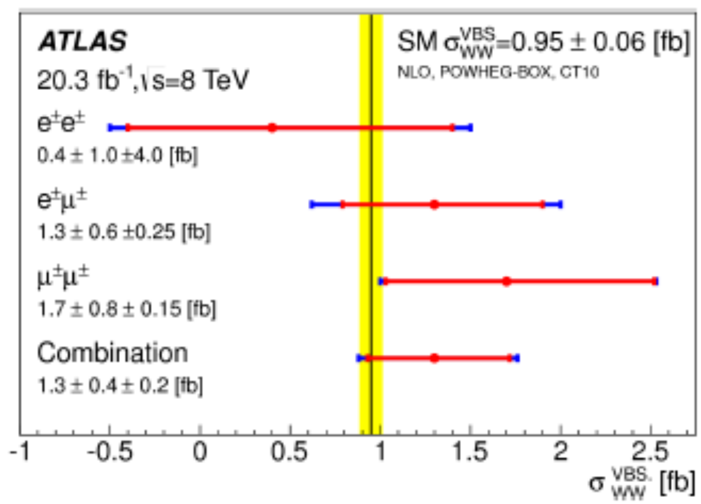


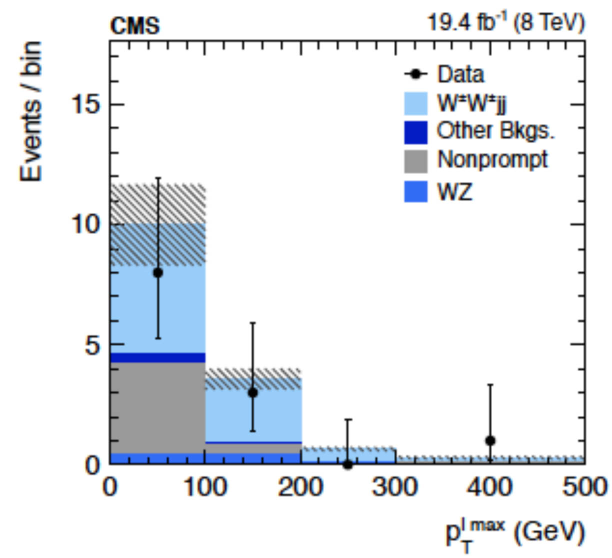
NLO Theory

[Karlberg, Liu (ATLAS)]

W^+W^+jj Production

- W^+W^+ production suppresses QCD contributions
  - Sensitivity to quartic gauge interactions

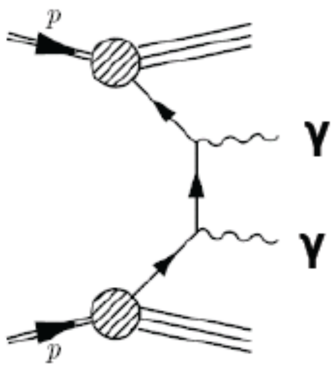


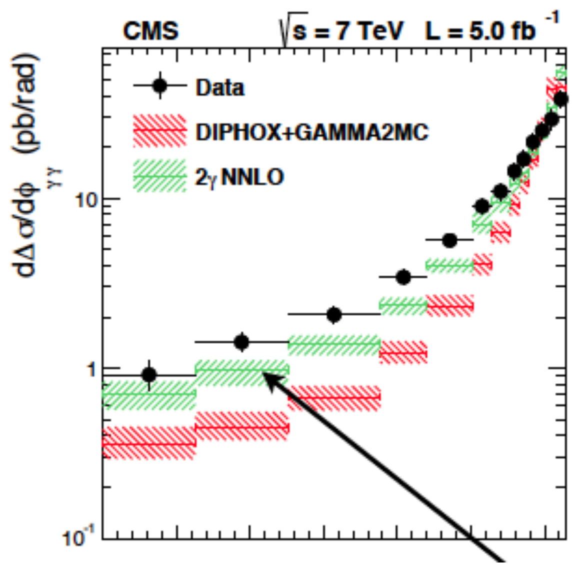


2σ observation of EW WWjj in both experiments

[Lopes de Sal (CMS), Liu (ATLAS)]

γγ production



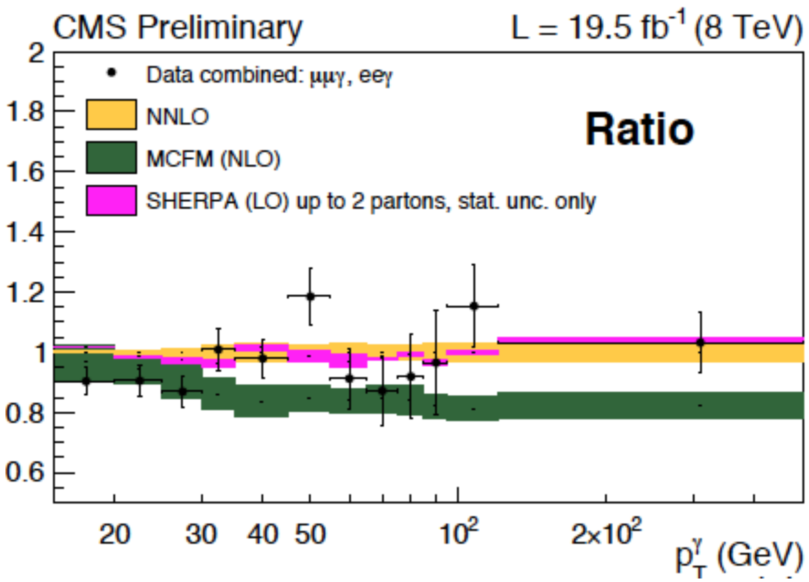


Even at NNLO still an excess in data at low $\Delta\phi$

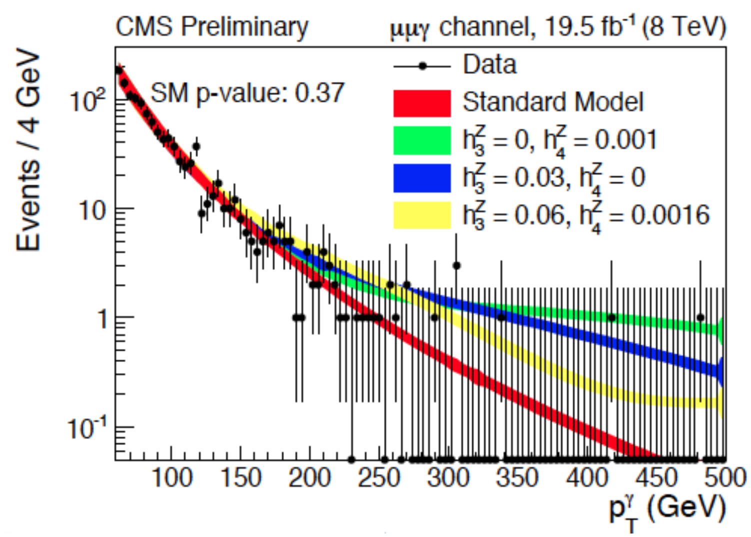
[Channon(CMS)]

Zγ

	LO	NLO	NNLO	experiment
ATLAS setup $p_T^\gamma > 15\,\mathrm{GeV}$	$0.8507[2]^{+7\%}_{-9\%}\,\mathrm{pb}$	$1.2262[4]^{+4\%}_{-5\%}\,\mathrm{pb}$	$1.305[3]^{+1\%}_{-2\%}\,\mathrm{pb}$	$1.310 \begin{array}{l}\pm.020(\mathrm{stat})\\ \pm.110(\mathrm{syst})\\ \pm.050(\mathrm{lumi})\end{array}\,\mathrm{pb}$



Agrees with NNLO even at large p_T^γ

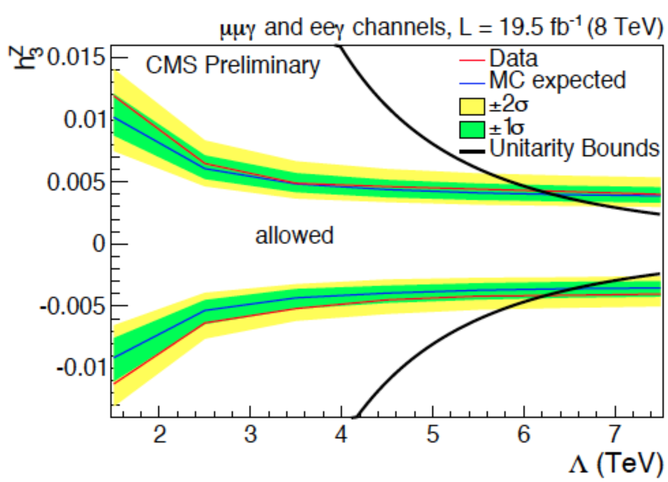


[Channon(CMS), Kallweit]

To unitarize or not to unitarize?

- As a theorist, I want results which I can interpret in terms of my favorite BSM model and use to test QCD calculations
- As soon as you find a signal and measure an anomalous coupling, theorists will build models to explain it

CMS Zγ anomalous coupling



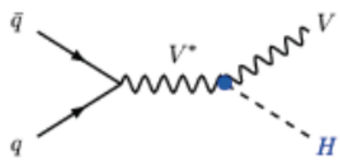
Dipole unitarization: $\left(\frac{1}{1+\frac{s}{\Lambda^2}}\right)^2$

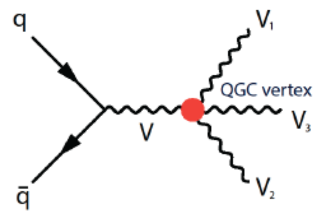
$\Lambda \rightarrow \infty$ is un-unitarized bound

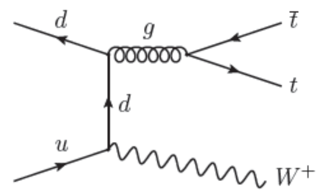
[Channon (CMS)]

Tribosons

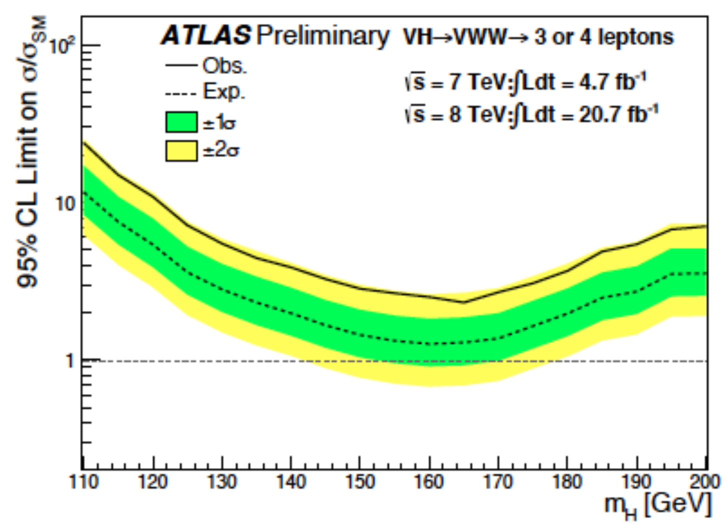
- Tribosons are background to HV, ttV, SUSY searches







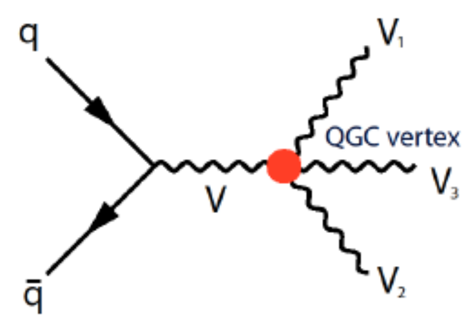
Signal strength
$3.7^{+1.9}_{-2.1}$ times SM



[Neugen(ATLAS)]

Triboson Results

- Limits on $W V\gamma$ production
  - Sensitive to $WW\gamma$, ZWW, $WWV\gamma$ vertices
  - Really small SM rate!
  - Look for enhancement at high p_T (just where EFT is breaking down, and problems with unitarity)
  - $WW\gamma\gamma$ dimension-8 operator limits
    - $|a_0^W/\Lambda^2| < 20$ TeV^{-2} (CMS)
    - $|a_0^w/\Lambda^2| < 5$ TeV^{-2} (D0)

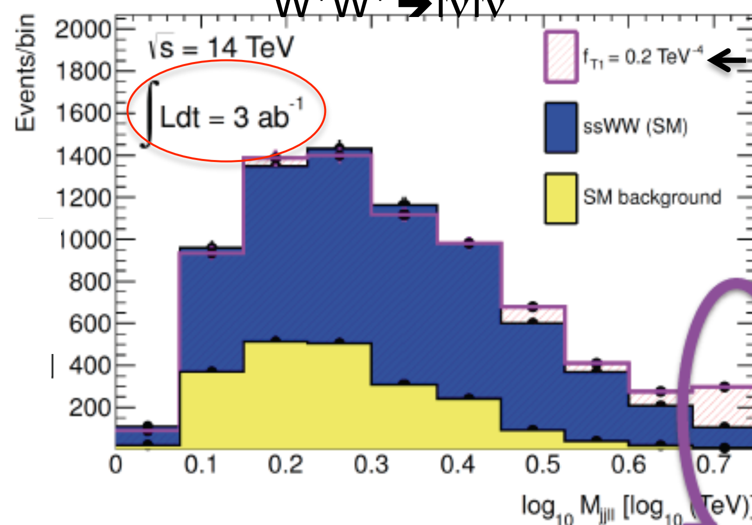


[Faulkner(CMS), Parker(Tevatron)]

Large increase in Rates at 14 TeV

8 TeV	ZZ	WZ	WW	$Z(\to \ell\ell)\gamma$	$W(\to \ell\nu)\gamma$	$\gamma\gamma$
σ_{LO} (pb)	5.06	12.94	35.56	9.23	45.39	43.01
σ_{NLO} (pb)	$7.92^{+4.7\%}_{-3.0\%}$	$22.88^{+7.5\%}_{-5.7\%}$	$57.25^{+4.1\%}_{-2.8\%}$	$11.48^{+3.5\%}_{-5.1\%}$	$59.7^{+6\%}_{-9\%}$	$55.8^{+4\%}_{-6\%}$
14 TeV	ZZ	WZ	WW	$Z(\to \ell\ell)\gamma$	$W(\to \ell\nu)\gamma$	$\gamma\gamma$
σ_{LO} (pb)	10.92	27.55	74.48	17.97	85.8	88.76
σ_{NLO} (pb)	$17.72^{+3.5\%}_{-2.5\%}$	$51.82^{+5.5\%}_{-4.3\%}$	$124.31^{+2.8\%}_{-2.0\%}$	$21.20^{+3.7\%}_{-6.6\%}$	$110.2^{+6\%}_{-12\%}$	$108.1^{+3\%}_{-5\%}$

$W^+W^+ \to l\nu l\nu$



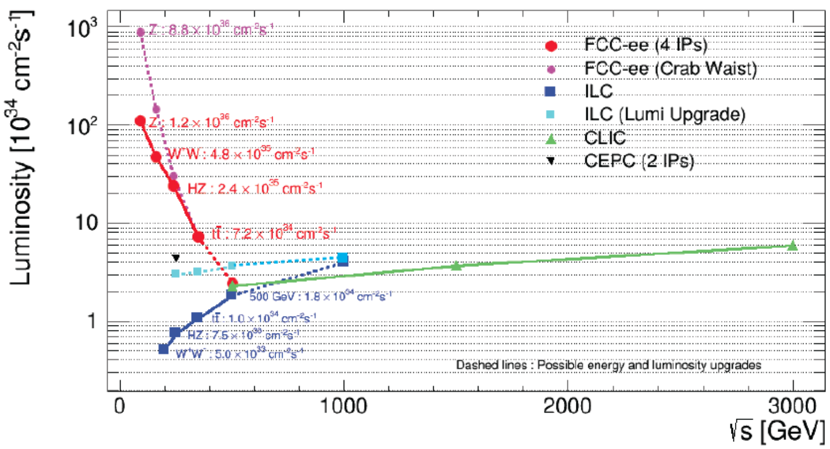
Dimension-8 operator

Significance = 17σ

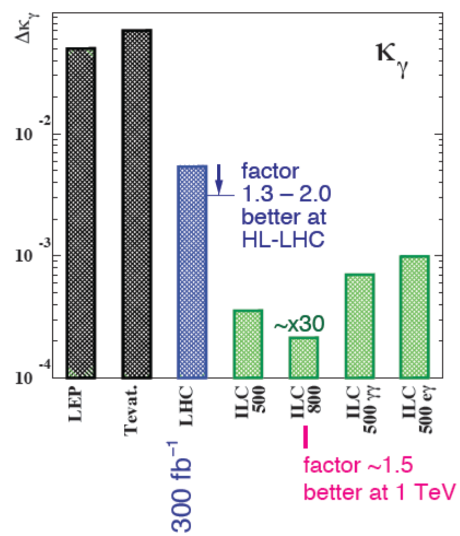
[Metcalfe]

Anomalous couplings at e^+e^-

- Precise measurements aided by knowledge of beam energy, polarization



$e^+e^- \rightarrow W^+W^-$



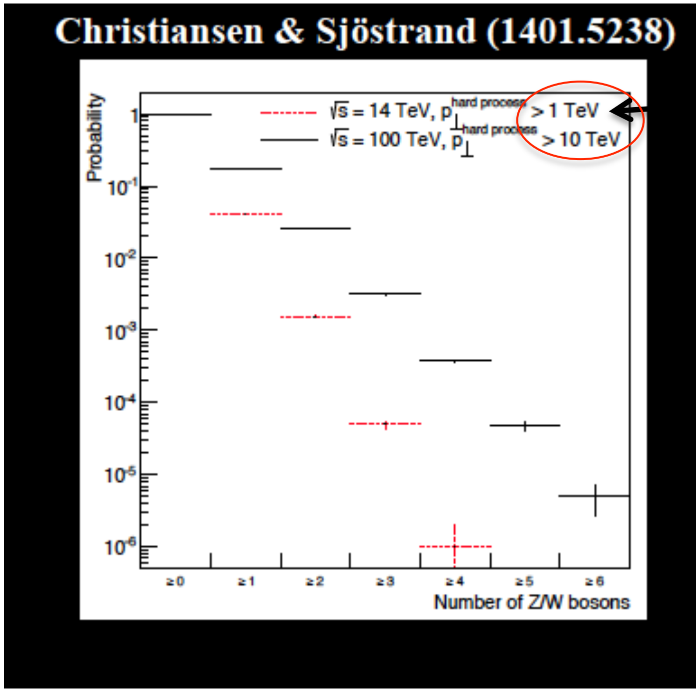
- Measurement of VVVV couplings require high energy
- Typically LHC does better

[Van Kooten]

The Far Future

- Large rates for gauge boson production at 100 TeV
  - New physics: W/Z as showers
  - Splittings to real W/Z's enhanced by $\log(s/M_V^2)$

Probability of q→ qV



Very high p_T W/Z's!

[Tweedie]

Conclusions

- The study of gauge boson interactions at the LHC is n[redacted]
  - [redacted] observations of VV, Vjj, VVjj, V[redacted]
  - C[redacted] theory (NLO/N[redacted]
  - Theorists [redacted]sults into tools for experi[redacted]
  - Rates incre[redacted]
- Limi[redacted]eld theorie[redacted]ysics
  - [redacted]eory issues in interpreting i[redacted]

IT LOOKS [redacted] THE SM!

BUT LET's HOPE NOT!