Same-sign WW Scattering

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Higgs and BSM at 100 TeV, CERN
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Vector boson scattering

- VBS studies have a long and rich history

Lee, Quigg, Thacker (1977)

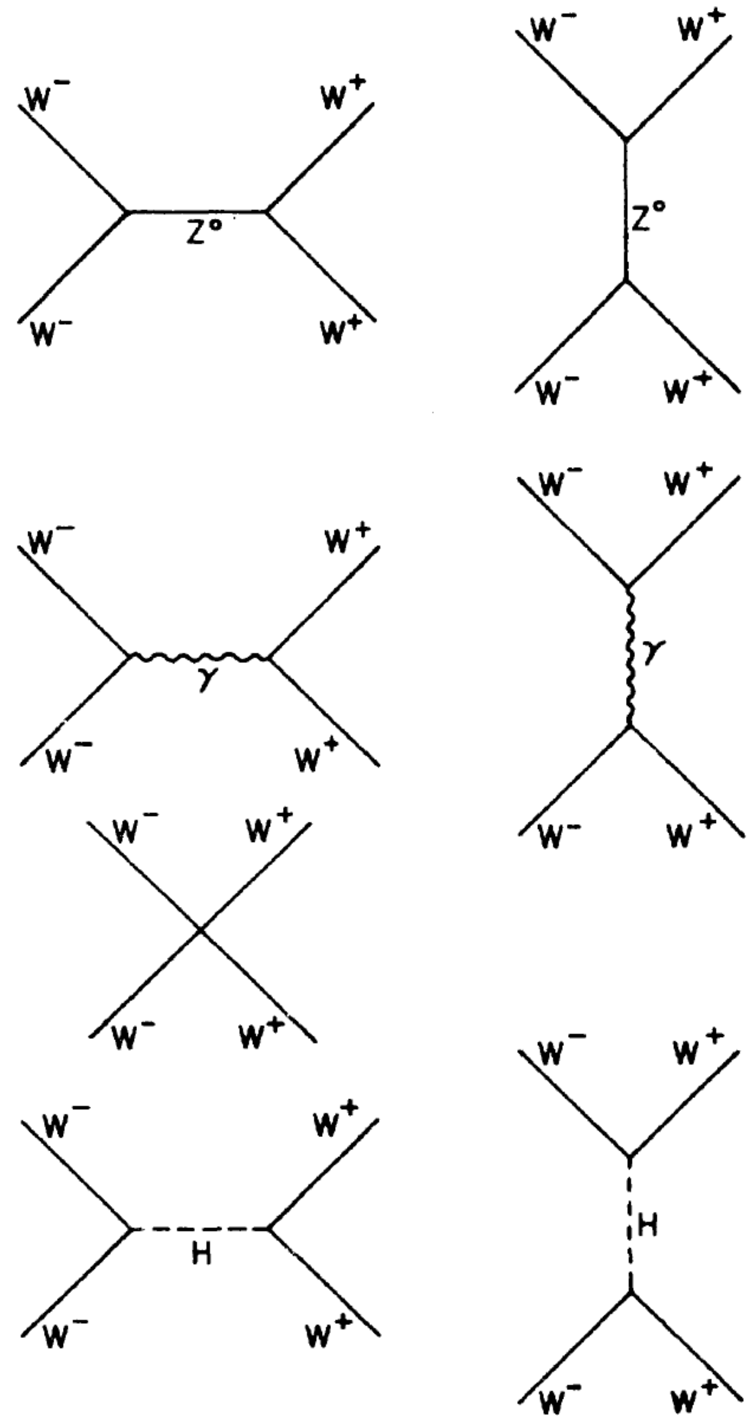
- The Higgs is the centerpiece of the SM
  - Gives W and Z masses
  - Gives fermion masses
  - Can be leading window to New Physics
- Measuring VBS is fundamental
  - Test of Higgs mechanism for EW symmetry breaking
  - Complementary to on-shell Higgs coupling measurements

M_H from perturbative unitarity

- SM calculation of longitudinal gauge boson scattering
- Partial wave expansion of scattering amplitude
- Unitarity on partial wave coefficients dictates M_H bound

$$M_H \le M_c = (8\pi\sqrt{2}/3G_F)^{1/2} \simeq 1\ \mathrm{TeV}/c^2$$

Lee, Quigg, Thacker (1977)



New Physics scale from c_V

- Can reinterpret calculation of W^+W^- for non-SM c_V

s-channel, Z+gamma

$$i\mathcal{M}_{s,\ Z+\gamma} = \frac{ig^2}{m_W^4}\frac{u-t}{4}\left(s+5m_W^2+\ldots\right)$$

t-channel, Z+gamma

$$i\mathcal{M}_{t,\ Z+\gamma} = \frac{ig^2}{m_W^4}\frac{t-3m_W^2}{4}\left(-s+u+8m_W^2+\ldots\right)$$

quartic

$$i\mathcal{M}_4 = \frac{ig^2}{4m_W^4}\left(s^2+4st+t^2-4m_W^2(s+t)-\frac{8m_W^2}{s}ut+\ldots\right)$$

s-channel, Higgs

$$i\mathcal{M}_{s,h} = \frac{ig^2}{m_W^2}\left(1+\frac{m_h^2}{s}\right)\left(-\frac{s}{4}+m_W^2+\frac{3m_W^4}{s}+\ldots\right)$$

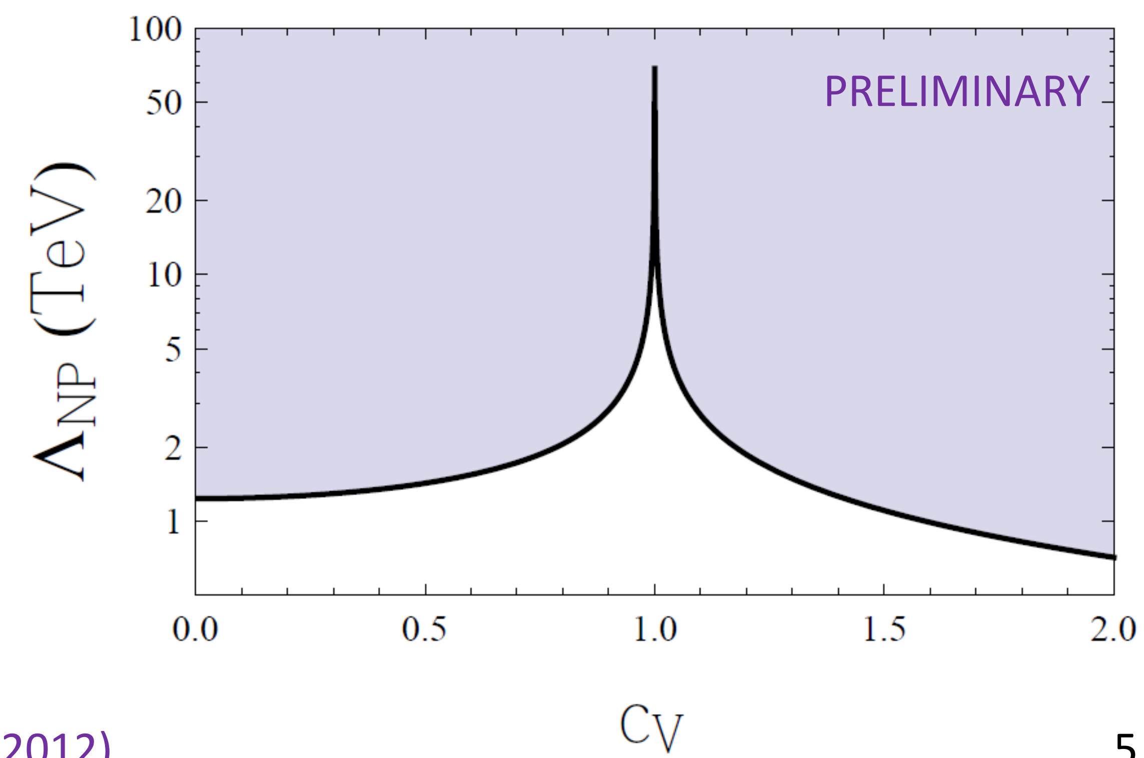
t-channel, Higgs

$$i\mathcal{M}_{t,h} = \frac{ig^2}{m_W^2}\left(1+\frac{m_h^2}{t}\right)\left(-\frac{t}{4}+m_W^2+\frac{3m_W^4}{t}+\frac{2m_W^2 u}{s}+\ldots\right)$$

New Physics scale from c_V

- Artificially modifying Higgs amplitudes by c_V^2 reintroduces unitarity violation

$$i\mathcal{M}_{\text{tot}} = \frac{ig^2}{m_W^2}\left(\frac{u}{4}(1-c_V^2) - m_W^2(3+c_V^2) - \frac{um_W^2}{s}(6-2c_V^2)\right)$$



Also see, e.g. Bhattacharyya, Das, Pal (2012)

New Physics scale from c_V

- Artificially modifying Higgs amplitudes by c_V^2 reintroduces unitarity violation

Table 1-20. *Expected precisions on the Higgs couplings and total width from a constrained 7-parameter fit assuming no non-SM production or decay modes. The fit assumes generation universality ($\kappa_u \equiv \kappa_t = \kappa_c$, $\kappa_d \equiv \kappa_b = \kappa_s$, and $\kappa_\ell \equiv \kappa_\tau = \kappa_\mu$). The ranges shown for LHC and HL-LHC represent the conservative and optimistic scenarios for systematic and theory uncertainties. ILC numbers assume (e^-, e^+) polarizations of $(-0.8, 0.3)$ at 250 and 500 GeV and $(-0.8, 0.2)$ at 1000 GeV, plus a 0.5% theory uncertainty. CLIC numbers assume polarizations of $(-0.8, 0)$ for energies above 1 TeV. TLEP numbers assume unpolarized beams.*

Facility	LHC	HL-LHC	ILC500	ILC500-up	ILC1000	ILC1000-up	CLIC	TLEP (4 IPs)
$\sqrt{s}$ (GeV)	14,000	14,000	250/500	250/500	250/500/1000	250/500/1000	350/1400/3000	240/350
$\int \mathcal{L}dt$ (fb^{-1})	300/expt	3000/expt	250+500	1150+1600	250+500+1000	1150+1600+2500	500+1500+2000	10,000+2600
κ_γ	5 – 7%	2 – 5%	8.3%	4.4%	3.8%	2.3%	–/5.5/<5.5%	1.45%
κ_g	6 – 8%	3 – 5%	2.0%	1.1%	1.1%	0.67%	3.6/0.79/0.56%	0.79%
κ_W	4 – 6%	2 – 5%	0.39%	0.21%	0.21%	0.2%	1.5/0.15/0.11%	0.10%
κ_Z	4 – 6%	2 – 4%	0.49%	0.24%	0.50%	0.3%	0.49/0.33/0.24%	0.05%
κ_ℓ	6 – 8%	2 – 5%	1.9%	0.98%	1.3%	0.72%	3.5/1.4/<1.3%	0.51%
$\kappa_d = \kappa_b$	10 – 13%	4 – 7%	0.93%	0.60%	0.51%	0.4%	1.7/0.32/0.19%	0.39%
$\kappa_u = \kappa_t$	14 – 15%	7 – 10%	2.5%	1.3%	1.3%	0.9%	3.1/1.0/0.7%	0.69%

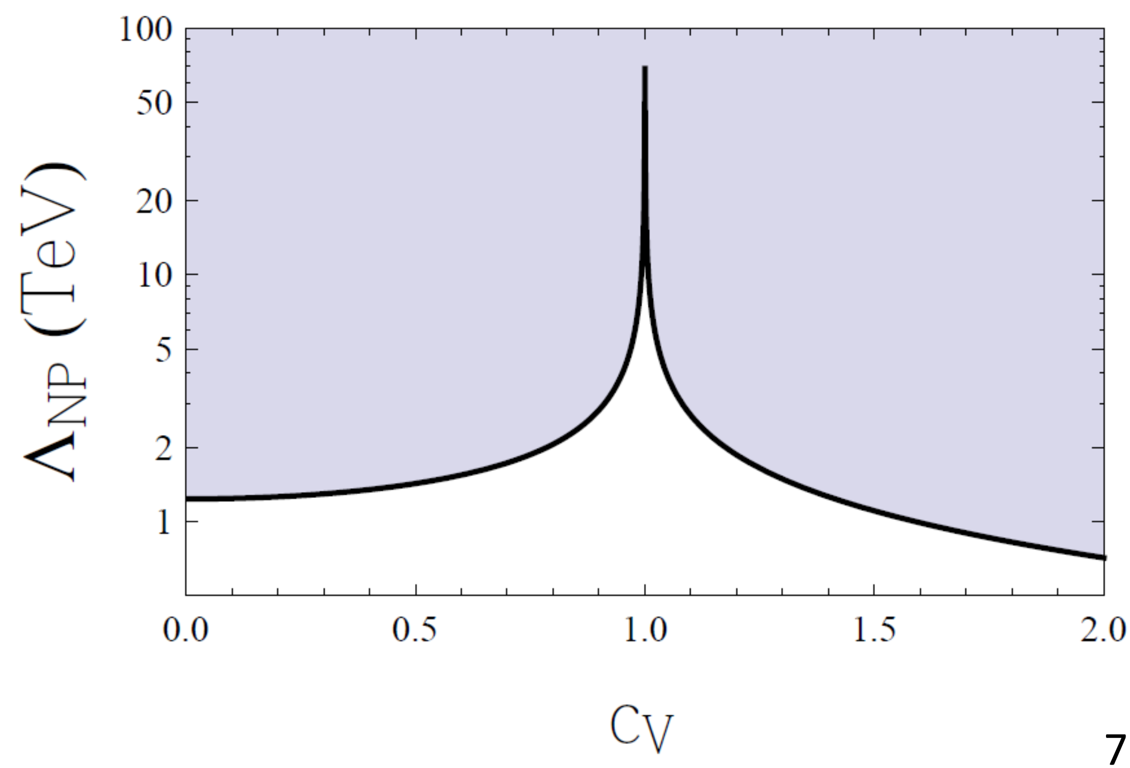
Snowmass Higgs Working Group Summary [1310.8361]

New Physics scale from c_V

- Artificially modifying Higgs amplitudes by c_V^2 reintroduces unitarity violation
  - Self-consistent NP model realizing a given c_V has scale of NP below Λ_{NP}

c_V	Λ_{NP} (TeV)
{0.8, 1.2}	{2.1, 1.9}
{0.9, 1.1}	{2.8, 2.7}
{0.95, 1.05}	{4.0, 3.9}
{0.98, 1.02}	{6.2, 6.1}
{0.99, 1.01}	{8.8, 8.7}
{0.995, 1.005}	{12.4, 12.3}
{0.999, 1.001}	{27.6, 27.6}

PRELIMINARY



Introducing NP

- Possible for Λ_{NP} from unitarity violation to be well above masses for new states
  - But no guarantee new states are observable
    - Can help dictate luminosity goals
- Will focus on Higgs role in unitarizing scattering
  - Can also consider testing anomalous quartics
- Akin to off-shell coupling measurement of Higgs
  - Higgs coupling deviations cannot be naïvely rescaled
  - Use 2HDM and Georgi-Machacek as concrete models of realizing c_V deviations
    - Needed to move beyond consistency test of SM

Georgi, Machacek (1985)

On-shell vs. off-shell measurements

- c_V rescaling inadequate for capturing NP effects for off-shell measurements
  - In 2HDM, leading SM Higgs contribution shared between light and heavy Higgs amplitudes
  - In G-M, have light and heavy Higgs as well as H_5^0 and H_5^{++} scalars
  - M_H-independent contributions cancel energy growth in amplitude from SM gauge bosons
- Event rate from light Higgs contribution is insensitive to Higgs width

VBS phenomenology

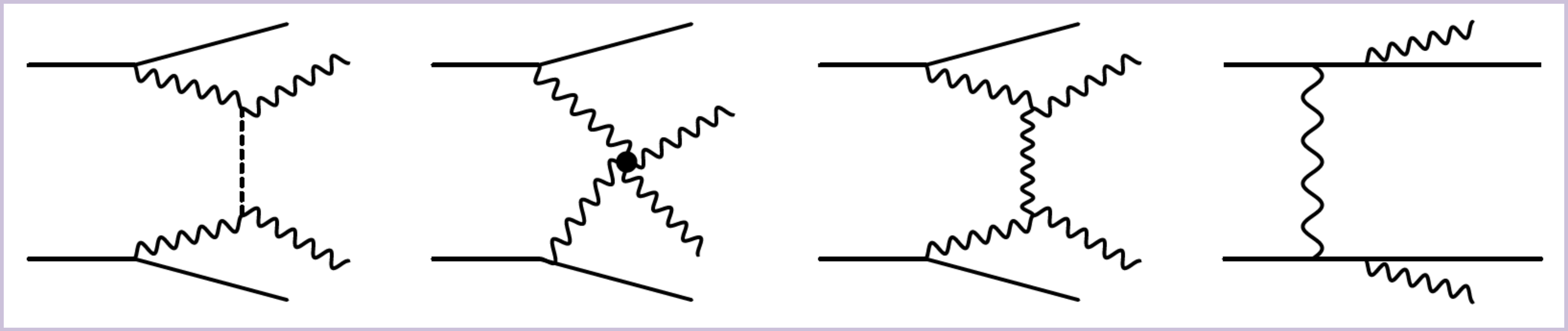
- W^+W^- final state is largest rate, but also large backgrounds
- $W^\pm W^\pm$ much cleaner (leptonic decays assumed)
- $W^\pm Z$ and ZZ also possible, but smaller rates

See, e.g. Campbell, Ellis [1502.02990]

- All VBS topologies inherently have forward jets
  - Possible area of improvement over LHC if η coverage is improved for 100 TeV detectors
  - Additional QCD diagrams for $W^\pm W^\pm$ can be suppressed with hard cuts on forward jets

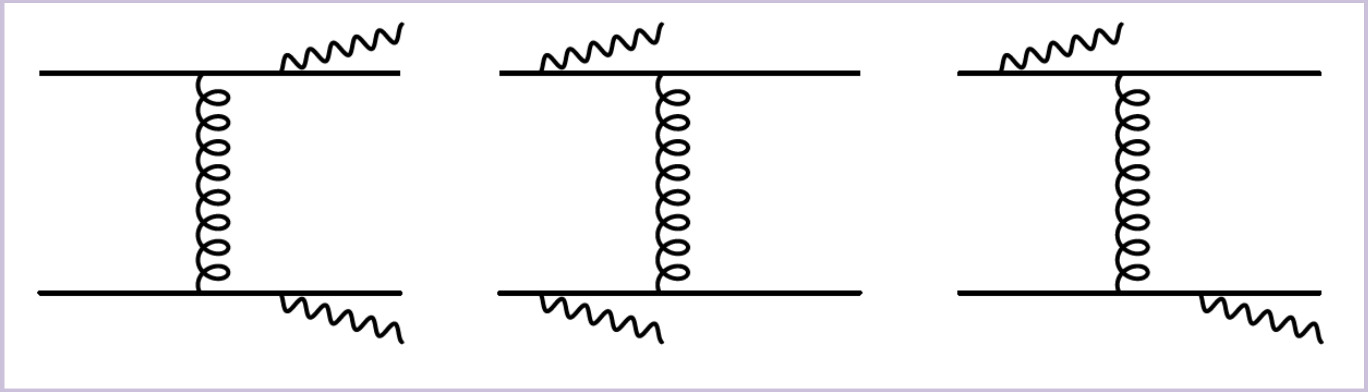
Same-sign WW scattering

QED and Higgs production diagrams



*G-M model also has s-channel doubly charged scalar

QCD production diagrams



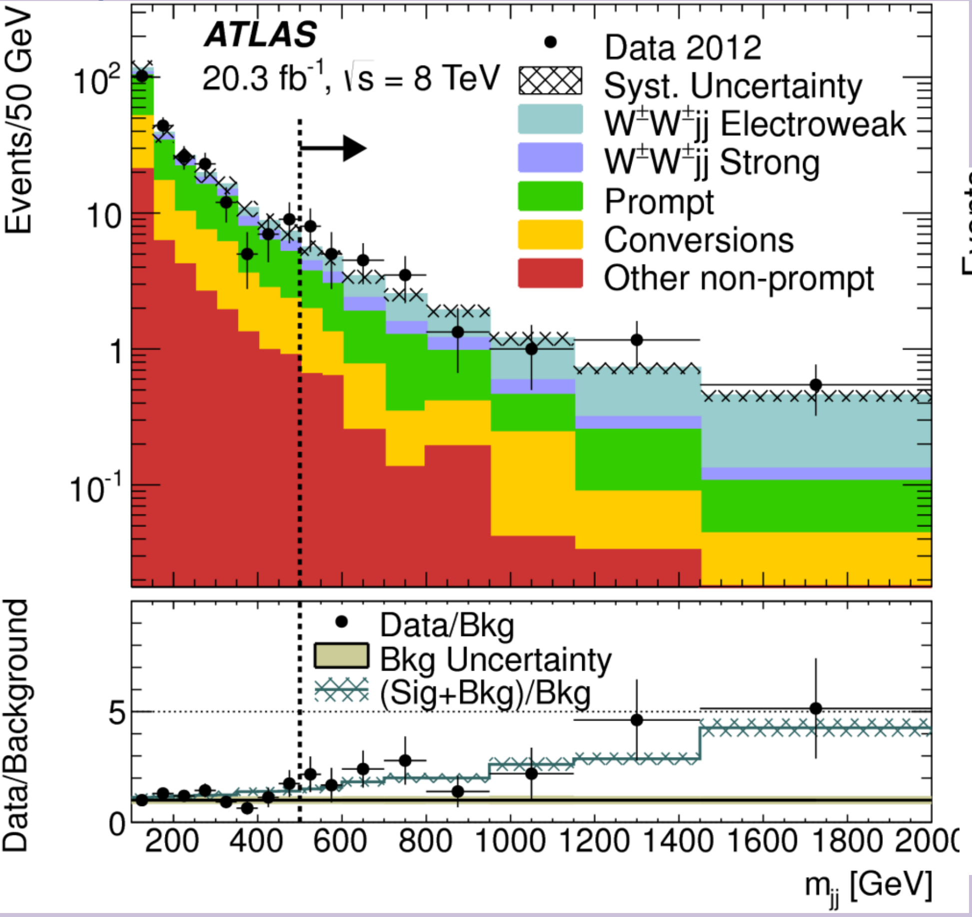
Basic rates at LO

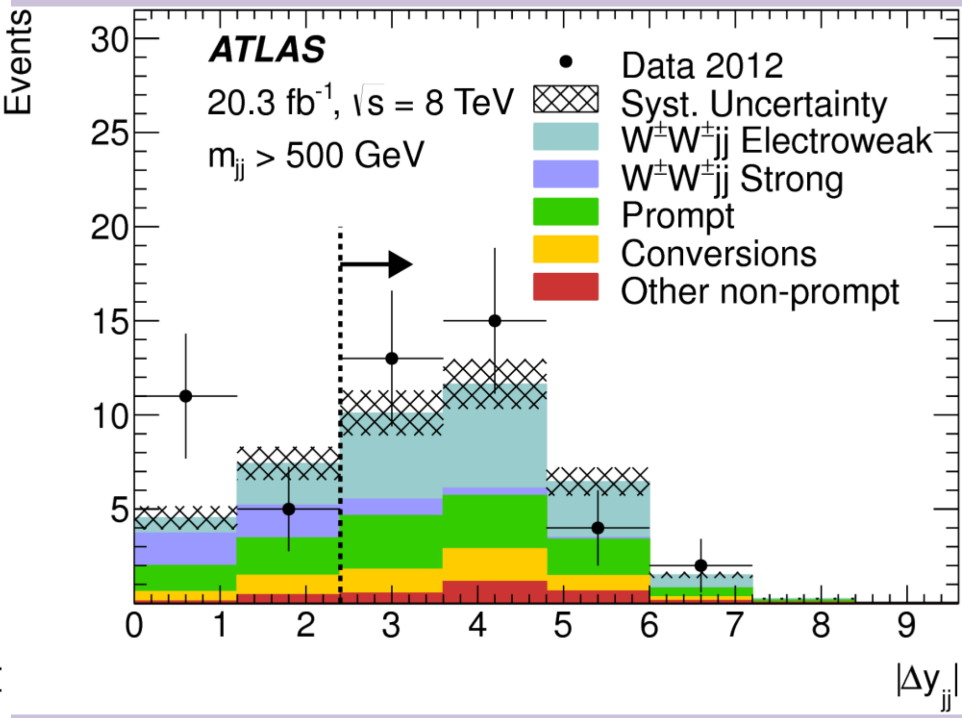
- MadGraph 5 + Pythia 6, MLM matching for $W^{\pm}W^{\pm}$ with 2 or 3 jets
  - Preselection: jet $p_T > 20$ GeV, $|\eta| < 5$, $m_{jj} > 250$ GeV
  - Leptonic branching fractions not included
- QED processes grow faster than QCD processes (ignoring QCD-QED interference)

xsec (pb)	W^+W^+ QCD	W^+W^+ QED	W^-W^- QCD	W^-W^- QED	Total
14 TeV	0.251	0.260	0.104	0.098	0.713
100 TeV	3.71	5.11	2.36	3.10	14.3
Ratio $\sigma_{100} / \sigma_{14}$	23×	31×	15×	20×	20×
N events with SS leptons @ 14 TeV, 3 ab^{-1} = 137k					
N events with SS leptons @ 100 TeV, 3 ab^{-1} = 2.74M					PRELIMINARY

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

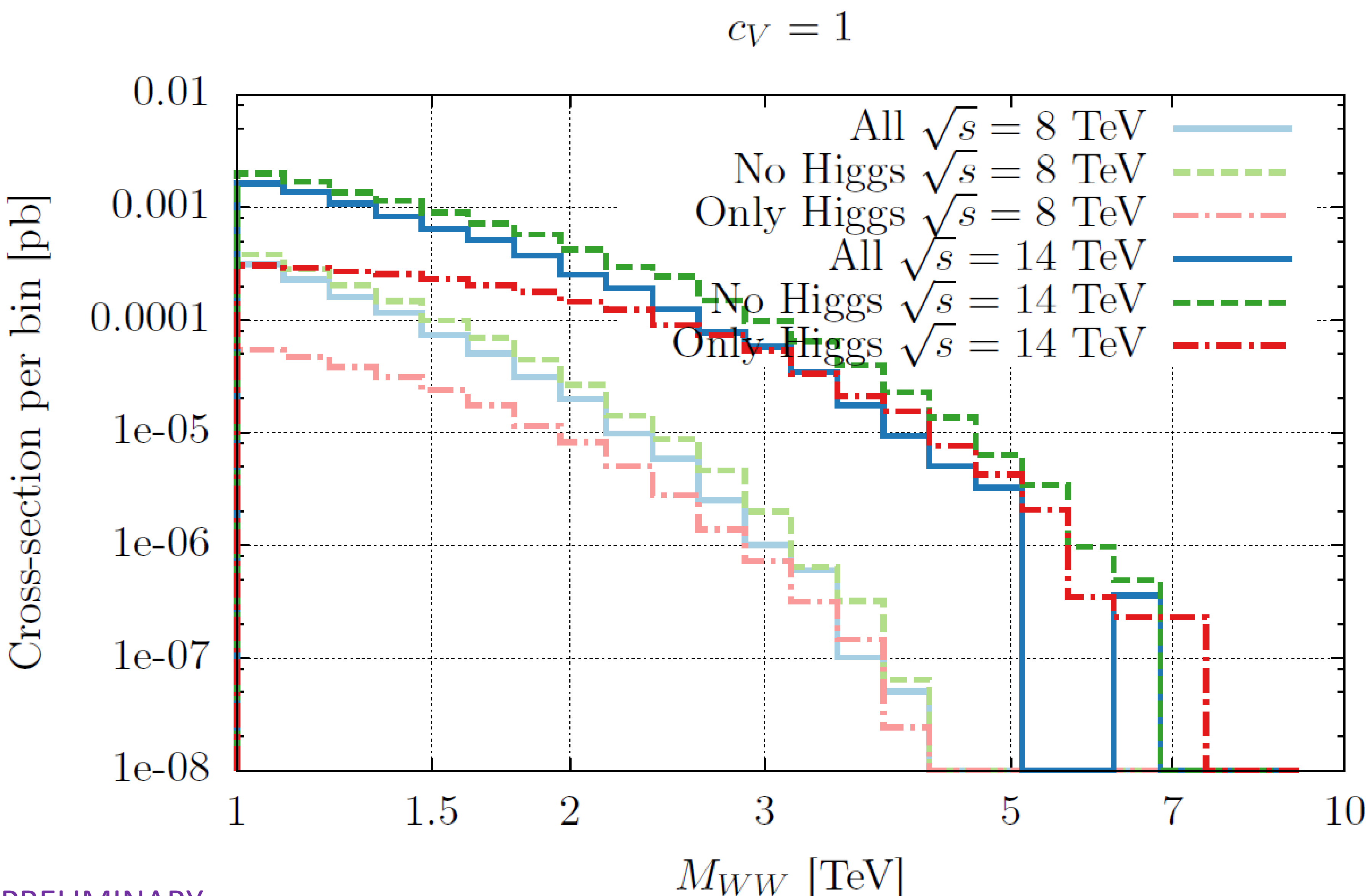
- Model after ATLAS 8 TeV result of evidence for EW production of $W^{\pm}W^{\pm}$





ATLAS PRL 113, 141083 [1405.6241]

Quantifying the Higgs contribution



PRELIMINARY

Work in progress

- Studying m_{jj} and $|\Delta\eta_{jj}|$ cuts to suppress QCD contributions
  - Want to understand impact of extended η coverage
- Then use SS dilepton and dijet kinematics to enhance sensitivity to longitudinal WW scatters
  - Use m_T(WW) or m_{T2}(WW) as proxy for m(WW)
  - Prospect for charge-2 scalar resonance in G-M model
  - Interplay with aTGC and aQGC effects

See, e.g. Doroba, Kalinowski, Kuczmarski, Pokorski, Rosiek, Szleper, Tkaczyk [1201.2768]
Freitas, Gainer [1212.3598]
Chang, Cheung, Lu, Yuan [1303.6335]

Summary

- Prospects for 100 TeV forthcoming
- Future 100 TeV machine will be critical to test Higgs role in taming perturbative unitarity violation
  - Extracting Higgs contribution for testing NP is challenging
  - Fundamental measurement for SM structure