Vector Boson Scattering and Quartic Gauge Couplings at the LHC

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Outline

1. Introduction & motivation
2. Vector boson scattering at the LHC
3. Anomalous quartic gauge couplings
4. Summary and outlook

The Standard Model of particle physics (SM)

- the SM is based on 3 fundamental symmetries being origin of interactions between matter particles & mediators of the interactions

$$SU(3)_C \times SU(2)_L \times U(1)_Y$$

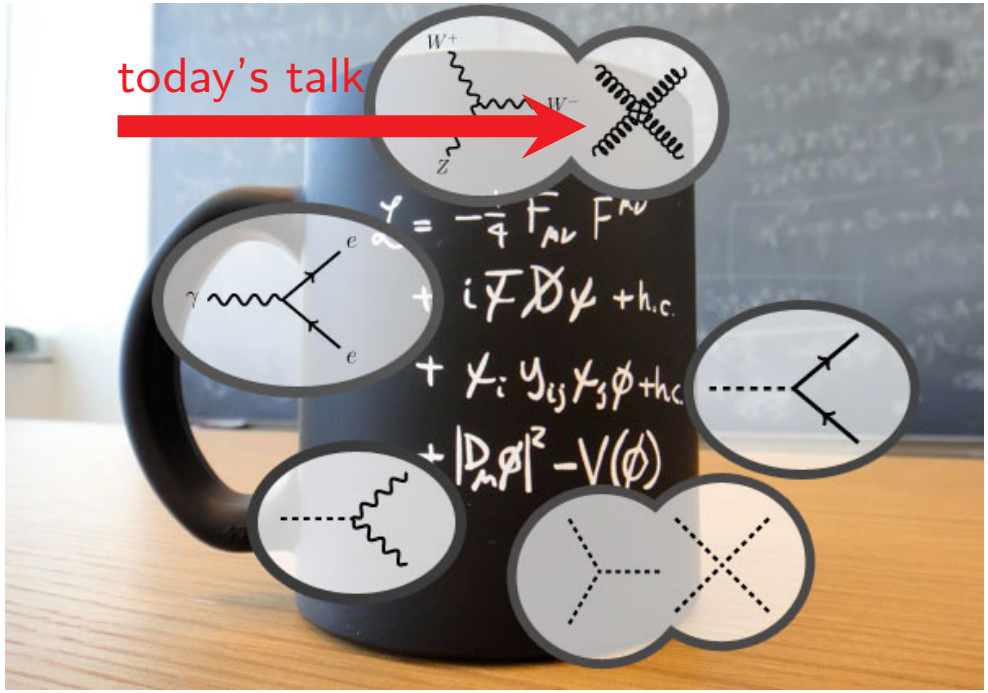
- the Lagrangian density $\mathscr{L}$ must be invariant under these symmetries, fundamental principle: local gauge invariance $\rightarrow$ conservation laws

- main ingredients of the SM:

forces: electromagnetism (γ)
weak interaction ($W^{\pm}, Z$)
strong interaction (g)

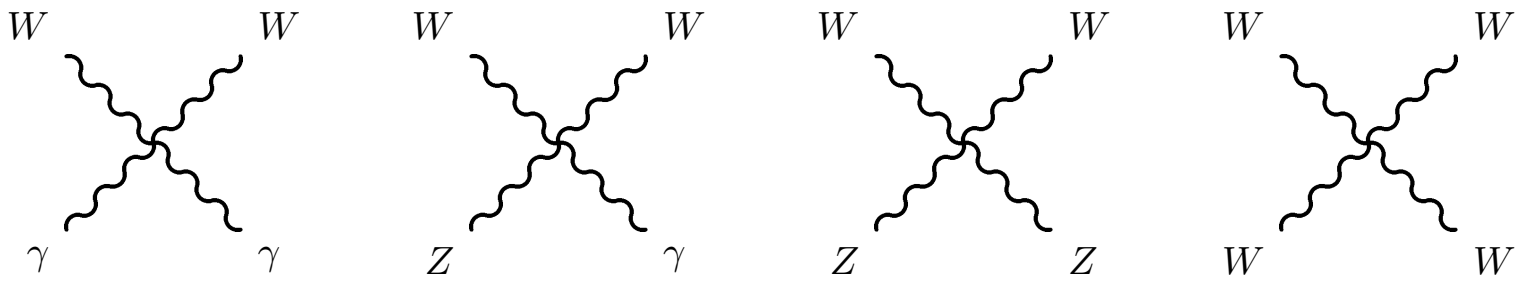
matter: 6 quarks and 6 leptons in 3 generations

EWSB: spontaneous electroweak symmetry breaking via Brout-Englert-Higgs mechanism



The Standard Model of particle physics (SM)

- EW theory is non-Abelian
  - $\Rightarrow$ EW gauge bosons carry weak charge
  - $\Rightarrow$ their self-interactions should exist
- $\mathscr{L}_{WWVV}$ contains the **quartic gauge self-couplings (QGC)**



$$\mathscr{L}_{WWVV} = -\frac{g^2}{4}\Big\{[2W_\mu^+ W^{-\mu} + (A_\mu \sin\theta_W - Z_\mu \cos\theta_W)^2]^2 \\ -[W_\mu^+ W_\nu^- + W_\nu^+ W_\mu^- + (A_\mu \sin\theta_W - Z_\mu \cos\theta_W)(A_\nu \sin\theta_W - Z_\nu \cos\theta_W)]^2\Big\}$$

- no neutral gauge boson self-couplings in the SM

Vector boson scattering and EWSB

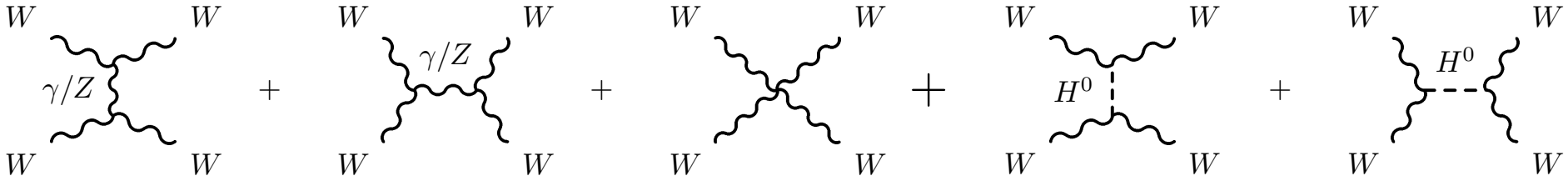
- the heavy vector bosons $W^{\pm}$ and Z acquire their mass and longitudinal polarization state through spontaneous EWSB

- the mechanism responsible for EWSB must regulate $\sigma(V_L V_L \to V_L V_L)$ to restore unitarity above $\sim 1 - 2$ TeV

  $\to$ cross section attenuated to a linear growth by the quartic gauge boson self-coupling

  $\to$ a light SM Higgs boson exactly cancels increase for large s (for HWW coupling)

$$\mathcal{A}(W_L W_L \to W_L W_L) \propto \frac{g_W^2}{v^2}\left[-s - t + \frac{s^2}{s - m_H^2} + \frac{t^2}{t - m_H^2}\right]$$

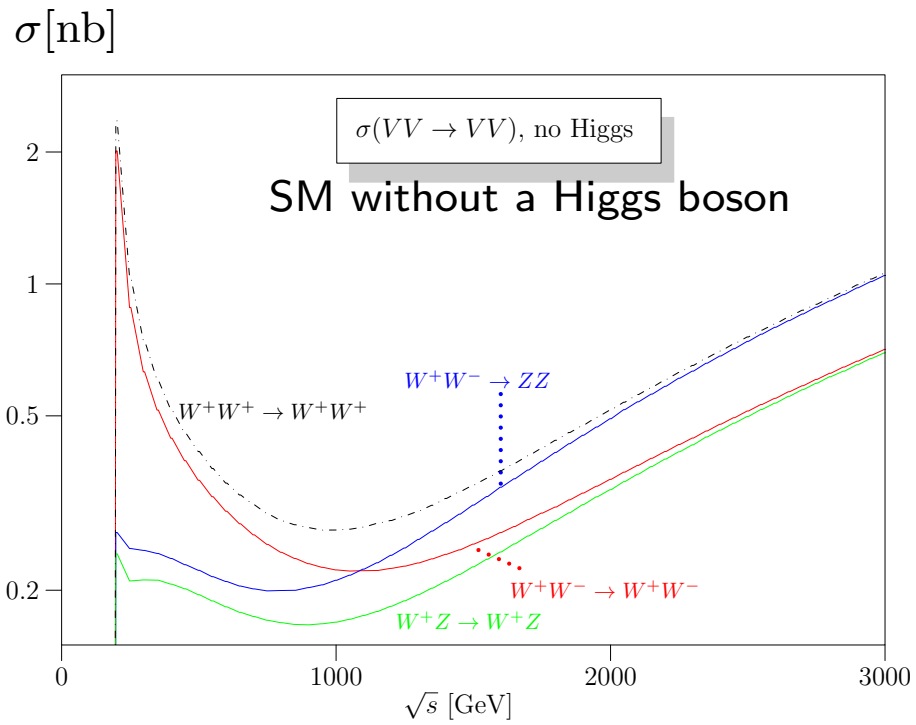


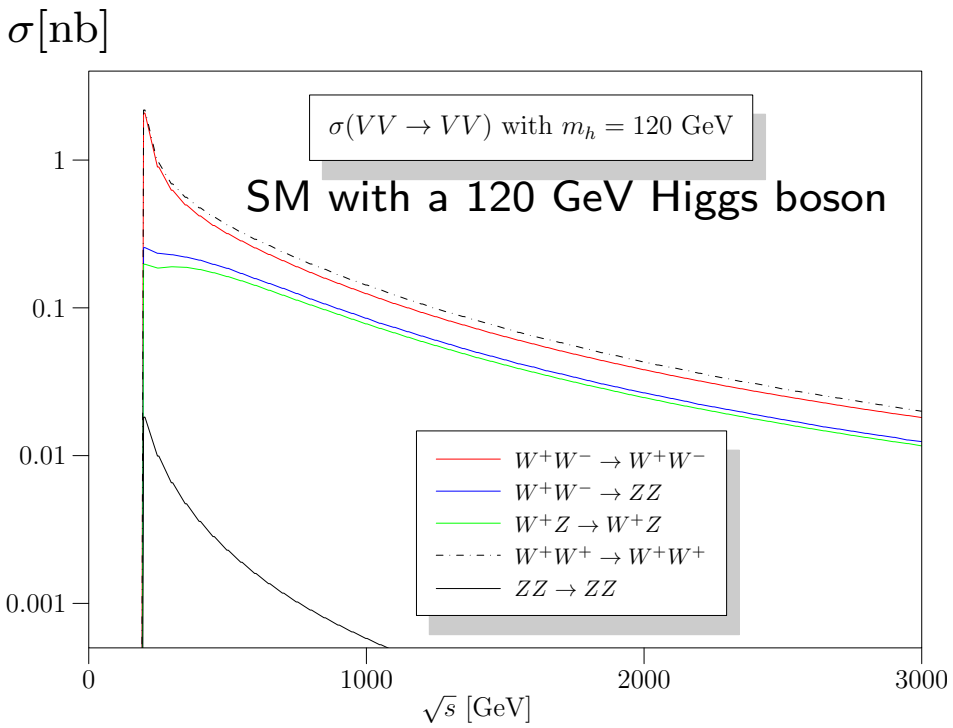
- unitarity preservation visible only in VV scattering

  $\Rightarrow$ VV scattering is the key process to experimentally probe the SM nature of EWSB!

Vector boson scattering and EWSB

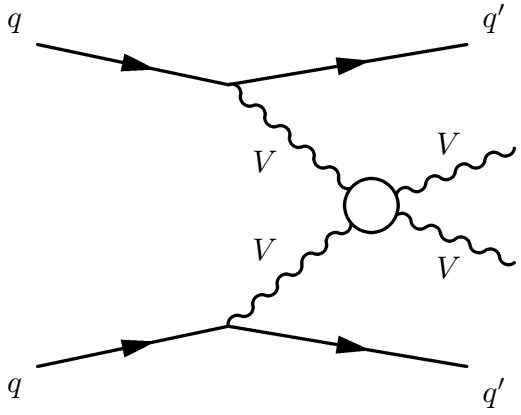
- total cross sections as a function of the m_{VV} center-of-mass energy:
  arXiv:0806.4145





Processes with quartic gauge boson couplings

- no reaction is ever mediated by a QGC vertex alone
  (even a gauge-invariant definition of the QGC contribution is not possible!)
- two measurable classes of processes where a QGC vertex **contributes**:
  - $\rightarrow$ triple gauge boson production, VVV
  - $\rightarrow$ vector boson scattering (VBS) as $VVjj$
    or exclusive $VV(pp)$ final states



- what can we learn from QGC vertices?
  - observe the SM processes with QGC vertices
    - $\rightarrow$ pre-LHC: attempted for $\gamma\gamma WW$ and γZWW
  - constrain anomalous quartic gauge couplings (aQGC)
    - $\rightarrow$ loose limits by LEP and Tevatron
  - test EWSB and Higgs properties
    - $\rightarrow$ access through $ZZWW$ and $WWWW$ at large $\sqrt{\hat{s}} = m_{VV} \gtrsim 1$ TeV
    - $\rightarrow$ one of the core reasons, why LHC has been built!

Experimental tests of the EW theory at LEP

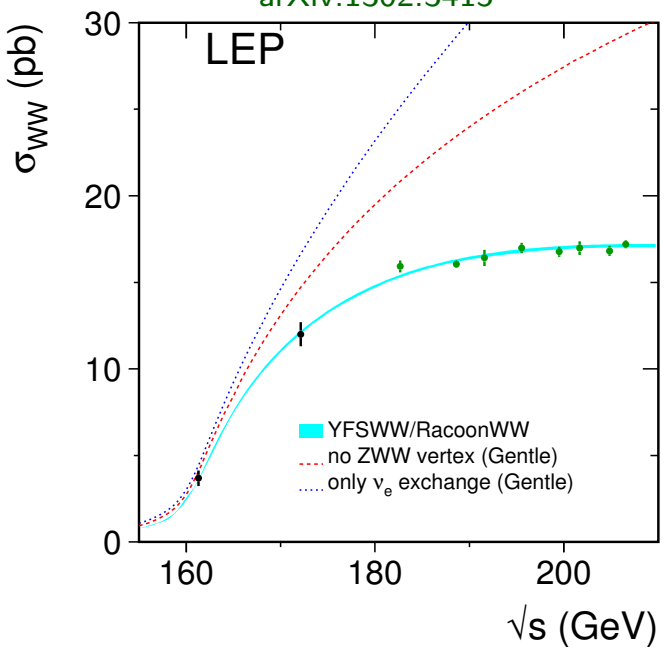
- SM confirmed at very high precision by the LEP experiments
- triple gauge boson couplings validated by $e^+e^- \to W^+W^-$ cross section measurements
- measured processes with QGC vertices at LEP:
  - e.g. $e^+e^- \to \nu\nu\gamma\gamma$ and $e^+e^- \to W^+W^-\gamma$
  - significant observation with small/negligible background

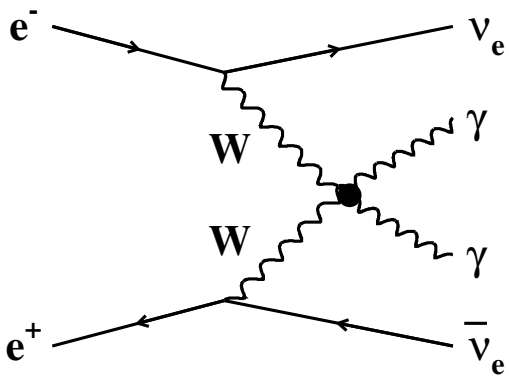
$\to$ **consistent with ISR/FSR processes**
(can be gauge-invariantly distinguished from processes containing QGC vertices)

- OPAL: http://arxiv.org/abs/hep-ex/0402021v1
- L3: http://arxiv.org/pdf/hep-ex/0111029v1
- OPAL: http://arxiv.org/abs/hep-ex/0309013
- DELPHI: http://arxiv.org/pdf/hep-ex/0311004v1

$\to$ no "real" observation of any process including QGC vertices at LEP (nor at Tevatron)

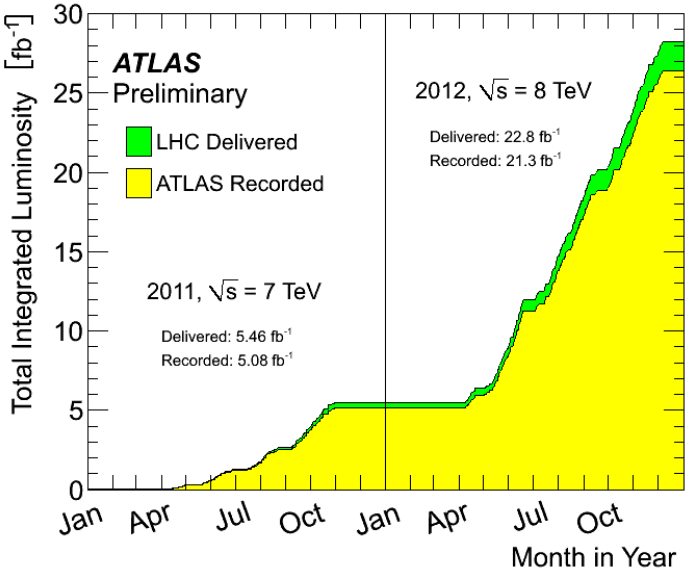
arXiv:1302.3415





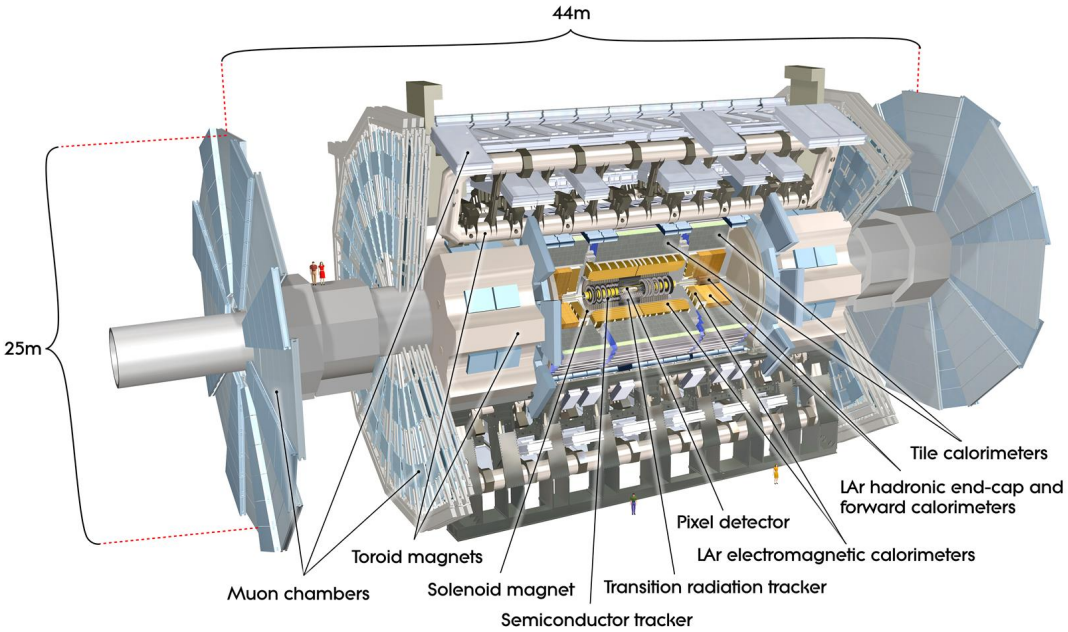
Large Hadron Collider (LHC) at CERN

- pp collisions at $\sqrt{s} = 7/8$ TeV in 2011/2012
- outstanding LHC performance:
  delivered $\sim$ 6 fb^{-1} @ 7 TeV and $\sim$ 23 fb^{-1} @ 8 TeV
- large rise in instantaneous luminosity
  from $2 \times 10^{32}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ to $7.7 \times 10^{33}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$
- 50 ns bunch spacing and up to almost
  40 interactions/bunch crossing

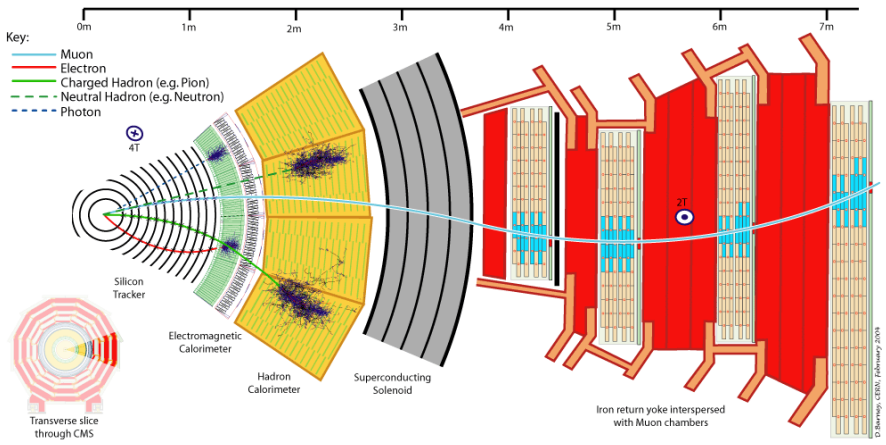


The multi-purpose detectors ATLAS & CMS

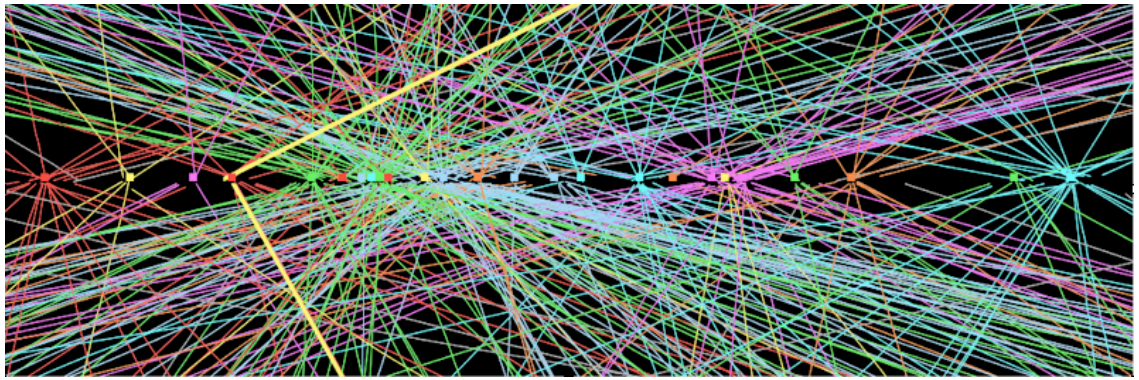
ATLAS



CMS



candidate $Z \to \mu\mu$ event with high pileup — length $\approx$ 25 cm



ATLAS Experiment © 2013 CERN

large luminosity comes at the cost of high pileup (many pp collisions overlaid)

Vector boson scattering at the LHC

$VV(pp)$ from "exclusive" $\gamma\gamma \to WW$

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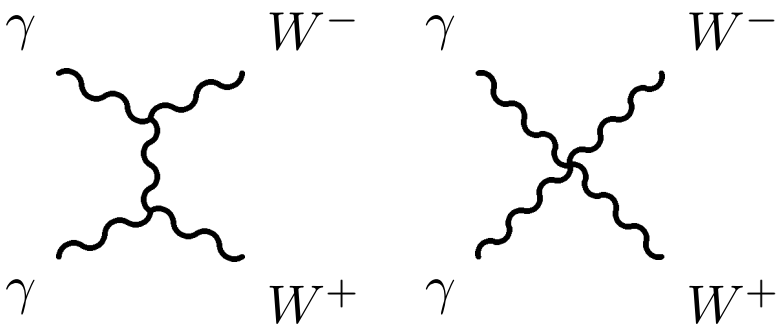
- **first $VV \to VV$ analysis at LHC: $\gamma\gamma \to WW$**
- CMS, $\sqrt{s} = 7$ TeV, $\mathcal{L} = 5$ fb^{-1}
- exclusive or quasi-exclusive W^+W^- production

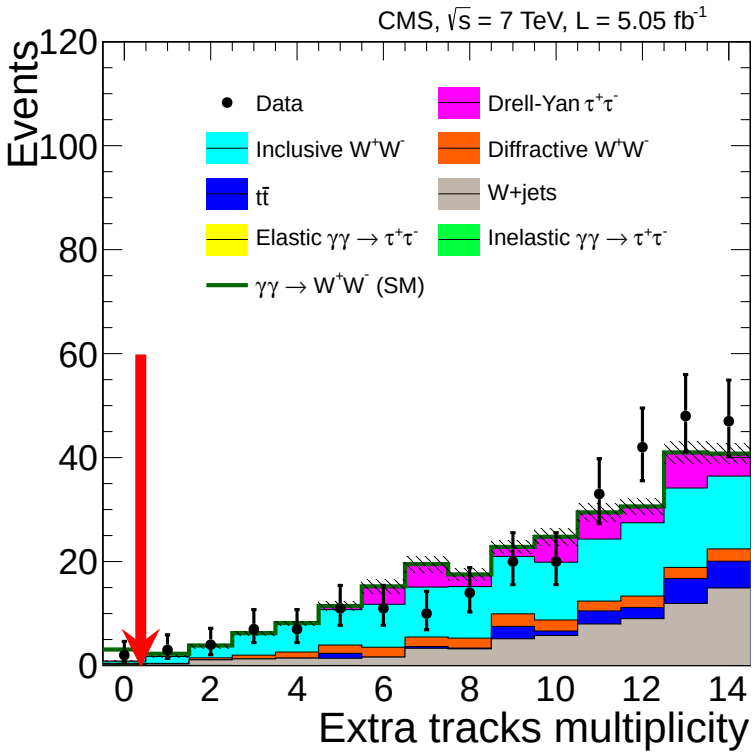
  $pp \to p^{(*)}W^+W^-p^{(*)} \to p^{(*)}e^+\bar{\nu}\mu^-\nu p^{(*)}$

  in mixed flavour $e\mu$ channel

  both very forward-scattered protons escape detection
- main event selection variables:
  - 2 high p_T isolated opposite charge μe
  - **0 extra tracks from primary vertex**
  - $m(\mu^\pm e^\mp) > 20$ GeV
  - $p_T(\mu^\pm e^\mp) > 30$ GeV

    $\to$ suppresses $\tau^+\tau^-$ background from Drell-Yan and $\gamma\gamma$
  - $(p_T(\mu^\pm e^\mp) > 100$ GeV (for aQGC analysis)$)$





$VV(pp)$ from "exclusive" $\gamma\gamma \to WW$

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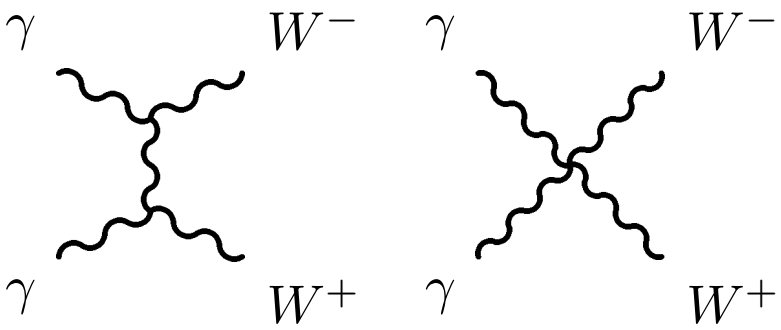
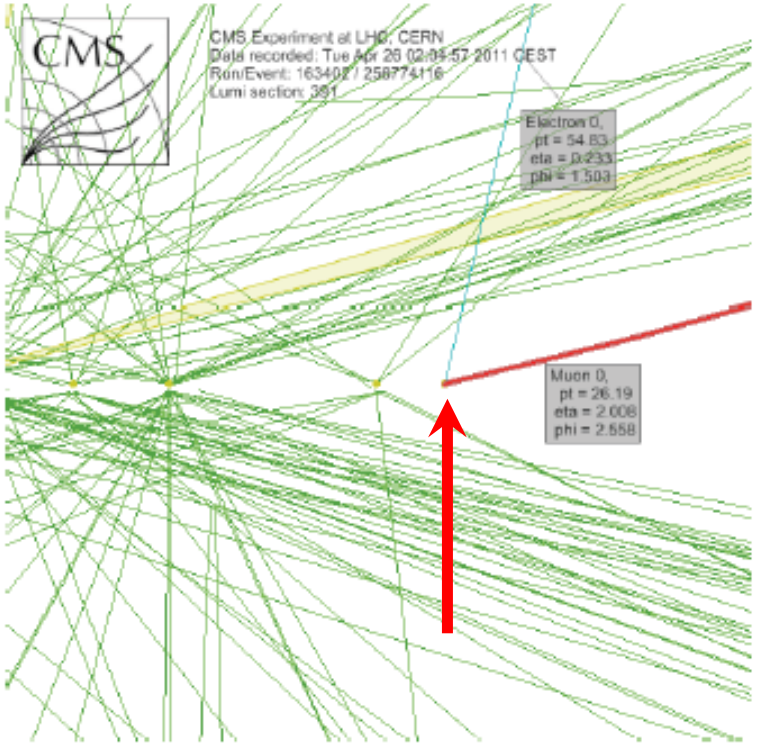
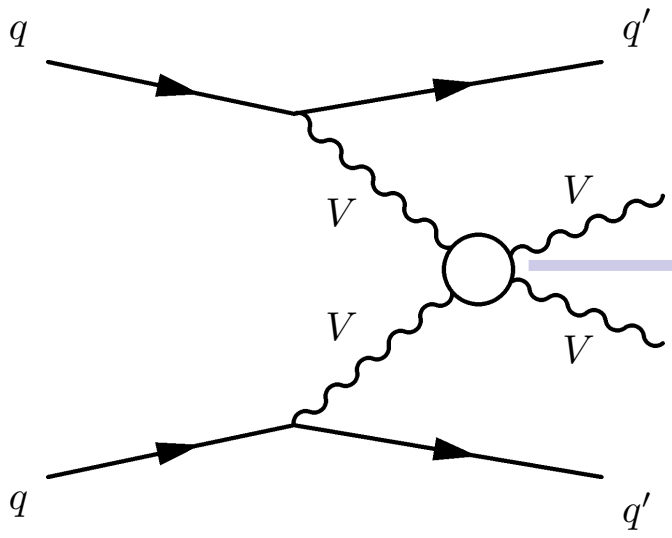


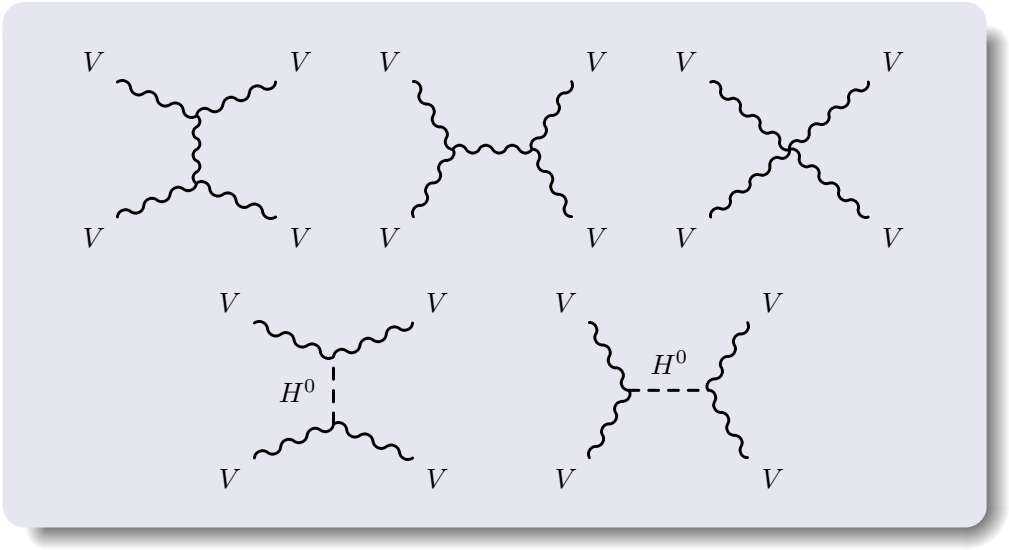
- remaining background very small
  - after $p_T(\mu^\pm e^\mp) > 30$ GeV: diffractive WW and W+jets production
- event yields:
  - expected background: 0.84 $\pm$ 0.15
  - expected signal: 2.2 $\pm$ 0.4
  - observed: 2 events
- cross sections:
  - predicted: $\sigma \times BR = 4.0 \pm 0.7$ fb
  - measured: $\sigma \times BR = 2.2^{+3.3}_{-2.0}$ fb ($\sim 1\sigma$)
  - upper limit: $\sigma < 10.6$ fb @ 95% C.L.



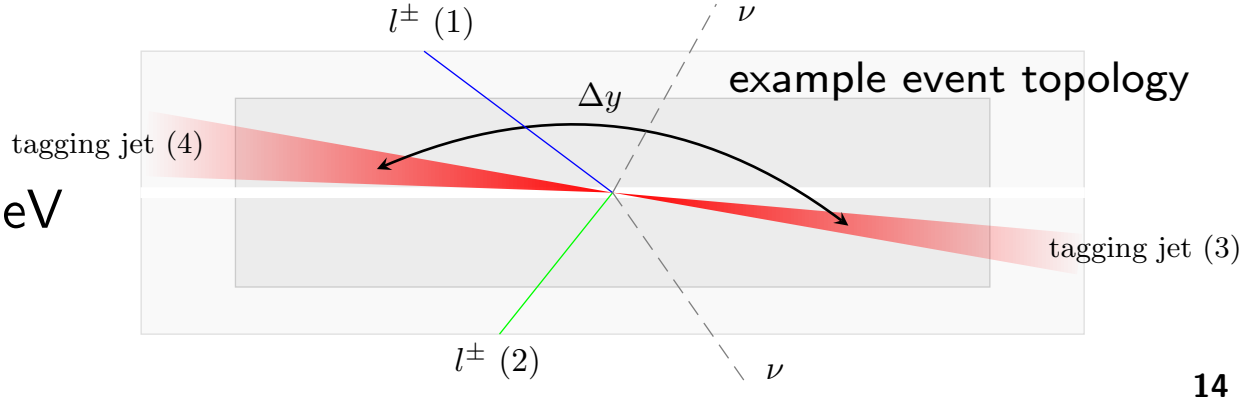
Vector boson scattering in $VVjj$ final states

- VBS: SM processes which have not been measured so far
- protons in LHC serve as source of vector boson beams





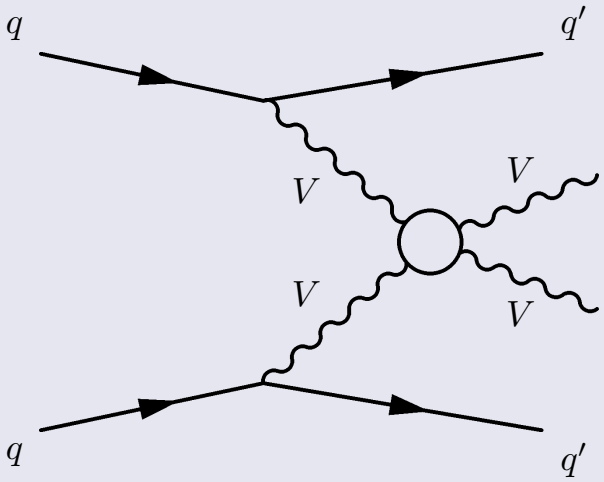
- signature: diboson + 2 jets ($VVjj$)
  - → typically large m_{jj}
  - → jets well separated in y
- $\sqrt{\hat{s}} = m_{VV} \approx 300 - 800$ GeV



$VVjj$ production process classification

pure electroweak $VVjj$ production: $\mathcal{O}(\alpha_{\mathrm{w}}^6)$

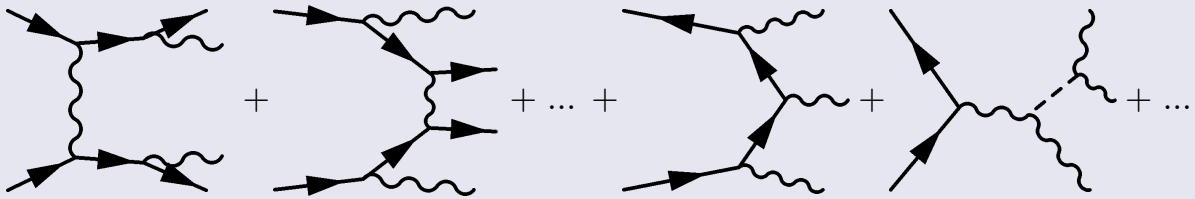
VBS diagrams



non-VBS EW diagrams, gauge invariantly

not separable:

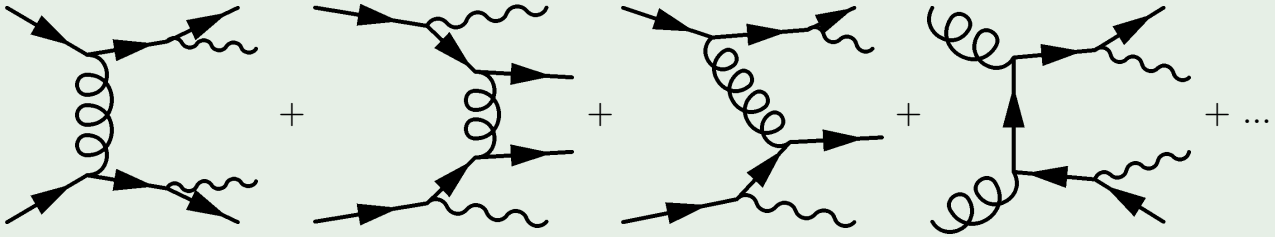
separable:



can be suppressed by VBS topology cuts

"strong" $VVjj$ production: $\mathcal{O}(\alpha_{\mathrm{w}}^4 \alpha_s^2)$

gauge invariantly separable: can be suppressed by VBS topology cuts



VBS processes (heavy vector bosons only)

- leading order cross sections (SHERPA) at $\sqrt{s} = 8$ TeV:

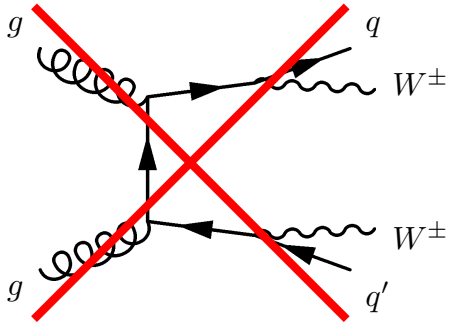
final state	$\sigma(VVjj$-EW)	σ(strong $VVjj$)	σ(EW)/σ(strong)
$W^\pm W^\pm jj$	19.5 fb	18.8 fb	$\sim$ **1:1**
$W^\pm W^\mp jj + ZZjj$	93.7 fb	3192 fb	$\sim$ 1:35
$WZjj$	30.2 fb	687 fb	$\sim$ 1:20
$ZZjj$	1.5 fb	106 fb	$\sim$ 1:70*

* includes γ^*, would be also 1:20 – 1:30 with higher m_{ll} cut

(generator cuts: $m_{\ell\ell} > 4$ GeV, $p_T^l > 5$ GeV, $p_T^j > 15$ GeV)

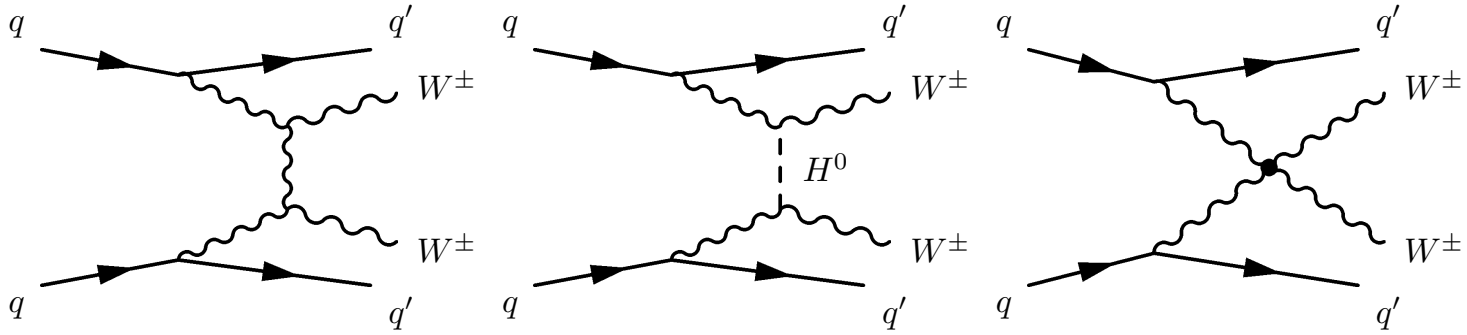
$\Rightarrow$ most promising measurable $VVjj$ final states in terms of VBS:

- same-sign $W^\pm W^\pm jj$
  - $\rightarrow$ strong $W^\pm W^\pm jj$ contributions very small (no LO gluon-gluon initial state)
- $W^\pm Zjj$
  - $\rightarrow$ clean channel due to 3-lepton final state



Same-sign $W^{\pm}W^{\pm}jj$ measurement

- $W^{\pm}W^{\pm}jj$-EW VBS (no s-channel diagrams):



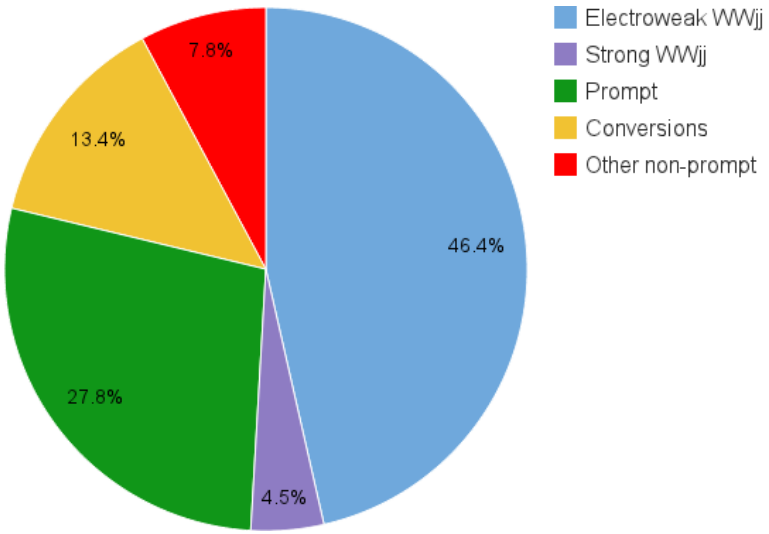
- lowest order: $W^{\pm}W^{\pm} + 2$ jets, there is no SM inclusive $W^{\pm}W^{\pm}$!
- **for EW+strong measurement** ("inclusive signal phase space")
  - look at $e^{\pm}e^{\pm}$, $e^{\pm}\mu^{\pm}$ and $\mu^{\pm}\mu^{\pm}$ channels
  - exactly 2 high p_T same-sign leptons with $p_T > 25$ GeV
  - $E_{\mathrm{T}}^{\mathrm{miss}} > 40$ GeV (from W decays)
  - veto events containing b-jets
  - 2 hard, forward tagging jets with $p_T > 30$, GeV and large m_{jj}
    $\rightarrow$ cut on $m_{jj} > 500$ GeV
- **for EW-only measurement** ("VBS signal phase space")
  - **additional** cut on $|\Delta y_{jj}| > 2.4$

$W^{\pm}W^{\pm}jj$ sample composition

arXiv:1405.6241

- $W^{\pm}W^{\pm}jj$ EW (46%)
  $W^{\pm}W^{\pm}jj$ strong (5%)
  (SHERPA, normalized with POWHEG)
- prompt background (28%):
  - → 3 or more prompt leptons
    - WZ/γ^*+jets (SHERPA)
    - ZZ+jets (SHERPA)
    - $t\bar{t} + W/Z$ (MADGRAPH+PYTHIA8)
    - tZj (SHERPA)
- conversions (13%):
  - → prompt photon conversion
    - $W\gamma$ (ALPGEN+HERWIG/JIMMY, SHERPA)
  - → charge mis-ID due to bremsstrahlung with conversion (data driven)
    - Z/γ^*+jets
    - di-leptonic $t\bar{t}$ decays
    - $W^{\pm}W^{\mp}$

VBS signal region



- other non-prompt background (8%): (data driven)
  - → leptons from hadron decays in jets
    - W+jets
    - semi-leptonic $t\bar{t}$ decays
    - di-jet events

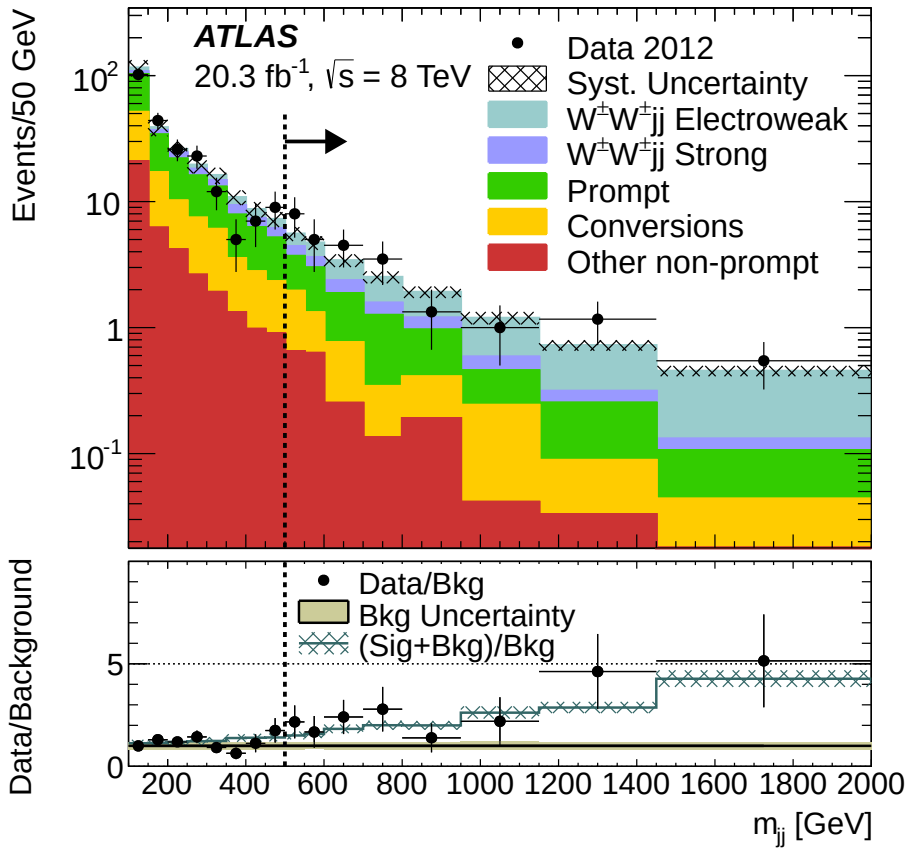
Electroweak $W^{\pm}W^{\pm}jj$ production

arXiv:1405.6241

inclusive region

(EW+strong measurement)

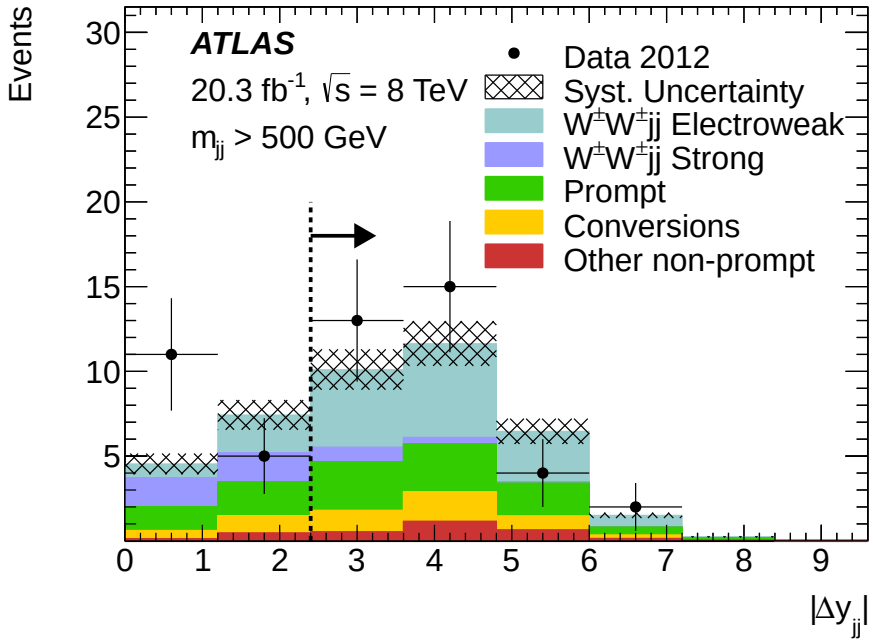
invariant mass of the 2 tagging jets
(before m_{jj} cut)



VBS signal region

(EW-only measurement)

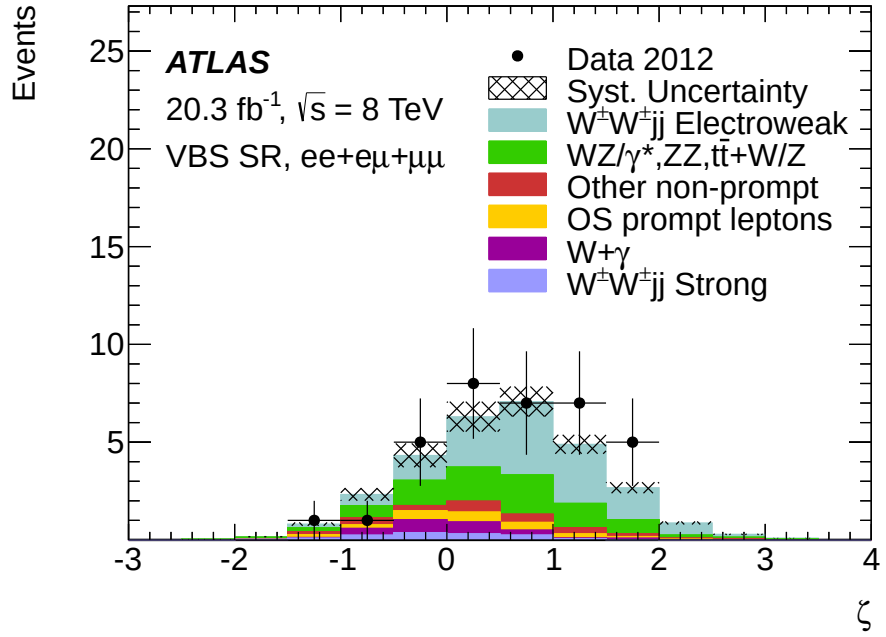
$|\Delta y_{jj}|$ between the 2 tagging jets
(before $|\Delta y_{jj}|$ cut)



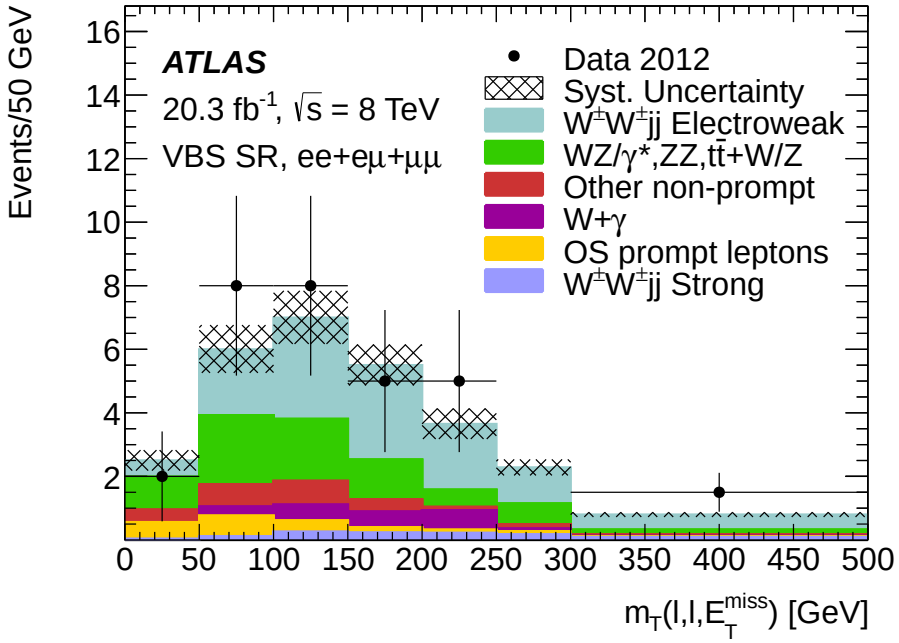
$W^{\pm}W^{\pm}$ system in the VBS signal region

arXiv:1405.6241

lepton centrality ζ



transverse mass of $W^{\pm}W^{\pm}$ system



lepton centrality:

$$\zeta = \min\left[\min(\eta_{\ell 1}, \eta_{\ell 2}) - \min(\eta_{j1}, \eta_{j2}), \max(\eta_{j1}, \eta_{j2}) - \max(\eta_{\ell 1}, \eta_{\ell 2})\right]$$

→ both leptons within tagging jets (in η): $\zeta > 0$

→ one or both leptons with larger η than closest jet: $\zeta < 0$

$W^{\pm}W^{\pm}jj$ event yields

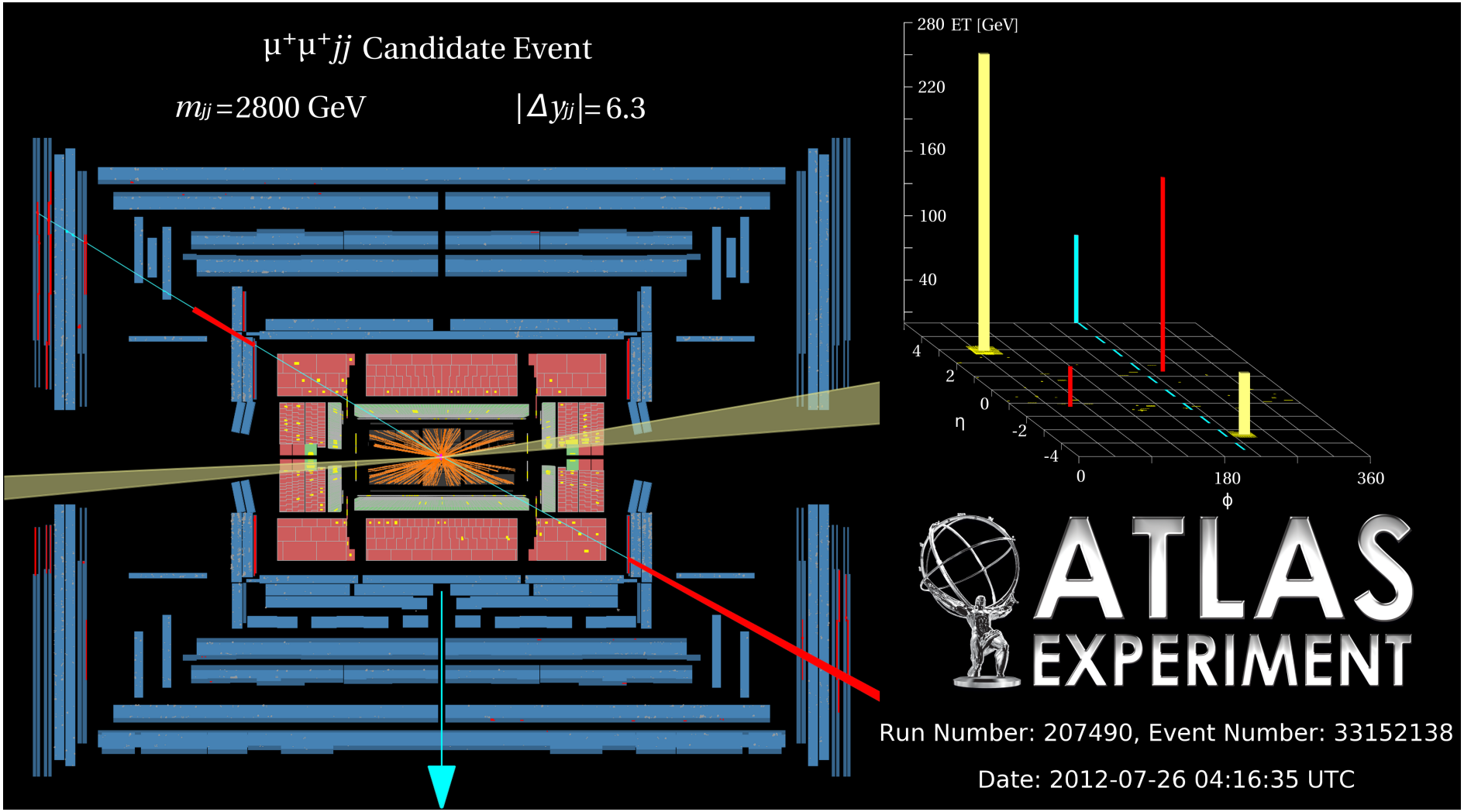
arXiv:1405.6241

	VBS Region		
	$e^{\pm}e^{\pm}$	$e^{\pm}\mu^{\pm}$	$\mu^{\pm}\mu^{\pm}$
Prompt	2.2 ± 0.5	4.2 ± 1.0	1.9 ± 0.5
Conversions	2.1 ± 0.5	1.9 ± 0.7	–
Other non-prompt	0.50 ± 0.26	1.5 ± 0.6	0.34 ± 0.19
$W^{\pm}W^{\pm}jj$ Strong	0.25 ± 0.06	0.71 ± 0.14	0.38 ± 0.08
$W^{\pm}W^{\pm}jj$ Electroweak	2.55 ± 0.25	7.3 ± 0.6	4.0 ± 0.4
Total background	5.0 ± 0.9	8.3 ± 1.6	2.6 ± 0.5
Total predicted	7.6 ± 1.0	15.6 ± 2.0	6.6 ± 0.8
Data	6	18	10

- interference between EW and strong $W^{\pm}W^{\pm}jj$ production: $\sim$ 7% evaluated with SHERPA, included in EW $W^{\pm}W^{\pm}jj$ prediction

$W^{\pm}W^{\pm}jj$ candidate event

arXiv:1405.6241



jets: $p_T^{j1} = 271$ GeV, $p_T^{j2} = 54$ GeV, $\eta^{j1} = 2.9$, $\eta^{j2} = -3.4$

muons: $p_T^{\mu 1} = 180$ GeV, $p_T^{\mu 2} = 38$ GeV, $\eta^{\mu 1} = 1.4$, $\eta^{\mu 2} = -1.3$

$E_{\mathrm{T}}^{\mathrm{miss}} = 75$ GeV

$W^{\pm}W^{\pm}jj$ production cross sections

arXiv:1405.6241

- cross sections measured in two fiducial regions with different sensitivities to EW and strong $W^{\pm}W^{\pm}jj$ production mechanisms
  - → extracted by fitting a likelihood function to the observed data

	measurement	theory prediction PowhegBox+Pythia8
inclusive signal region (EW+strong $W^{\pm}W^{\pm}jj$ production)		
cross section [fb]	2.1 ± 0.5(stat) ± 0.3(syst)	1.52 ± 0.11
significance	4.5 σ	3.4 σ
VBS signal region (EW $W^{\pm}W^{\pm}jj$ production)		
cross section [fb]	1.3 ± 0.4(stat) ± 0.2(syst)	0.95 ± 0.06
significance	3.6 σ	2.8 σ

- **first evidence of a process containing a VVVV vertex!**

Anomalous quartic gauge couplings

Look at physics beyond the SM

- the SM is assumed to be a low energy effect of new physics at scales beyond the current kinematic reach
- model independent approach, complementary to direct searches for new physics:
  - → low energy effects from beyond SM physics can be parametrized by an effective Lagrangian (SM + higher-dimension operators):

$$\mathscr{L}_{\text{eff}} = \mathscr{L}_{\text{SM}} + \sum_{\text{dimension } d} \sum_{i} \frac{c_i^{(d)}}{\Lambda^{d-4}} \mathcal{O}_i^{(d)}$$

  (valid only, if new physics out of direct LHC reach, $s \ll \Lambda^2$)
- new physics in EW sector modify gauge boson self-interactions
  - → VBS could still be strong and differ from SM predictions
- genuine dimension 8 QGC operators with no effect on TGC:

	WWWW	WWZZ	ZZZZ	WWAZ	WWAA	ZZZA	ZZAA	ZAAA	AAAA
$\mathcal{O}_{S,0}$, $\mathcal{O}_{S,1}$	X	X	X						
$\mathcal{O}_{M,0}$, $\mathcal{O}_{M,1}$, $\mathcal{O}_{M,6}$, $\mathcal{O}_{M,7}$	X	X	X	X	X	X	X		
$\mathcal{O}_{M,2}$, $\mathcal{O}_{M,3}$, $\mathcal{O}_{M,4}$, $\mathcal{O}_{M,5}$		X	X	X	X	X	X		
$\mathcal{O}_{T,0}$, $\mathcal{O}_{T,1}$, $\mathcal{O}_{T,2}$	X	X	X	X	X	X	X	X	X
$\mathcal{O}_{T,5}$, $\mathcal{O}_{T,6}$, $\mathcal{O}_{T,7}$		X	X	X	X	X	X	X	X
$\mathcal{O}_{T,8}$, $\mathcal{O}_{T,9}$			X			X	X	X	X

Look at physics beyond the SM

- Effective Field Theory description can be translated in EW chiral Lagrangian approach and vice versa arXiv:hep-ph/0606118
  - $\rightarrow$ switch of operator basis, dependent on vertex
- relevant effective aQGC parametrizations (examples):

dimension 4	dimension 6	dimension 8
$WWWW$, $WWZZ$	$WWZ\gamma$,$WW\gamma\gamma$	all VVVV
EW chiral Lagrangian		effective operators
non-linear representation		linear representation
α_4, α_5	a_0/Λ^2, a_c/Λ^2	$f_{S,i}/\Lambda^4$, $f_{M,i}/\Lambda^4$, $f_{T,i}/\Lambda^4$
Appelquist et al. (1980)	Belanger et al. (1992)	Eboli et al. (2006)

- example: $\alpha_{4/5} \leftrightarrow \frac{f_{S,0/1}}{\Lambda^4}$ conversion arXiv:1309.7890, arXiv:1310.6708
  - $\rightarrow$ $WWWW$ vertex: $\alpha_4 = \frac{f_{S,0}}{\Lambda^4}\frac{v^4}{8}$ and $\alpha_4 + 2 \cdot \alpha_5 = \frac{f_{S,1}}{\Lambda^4}\frac{v^4}{8}$

Unitarization

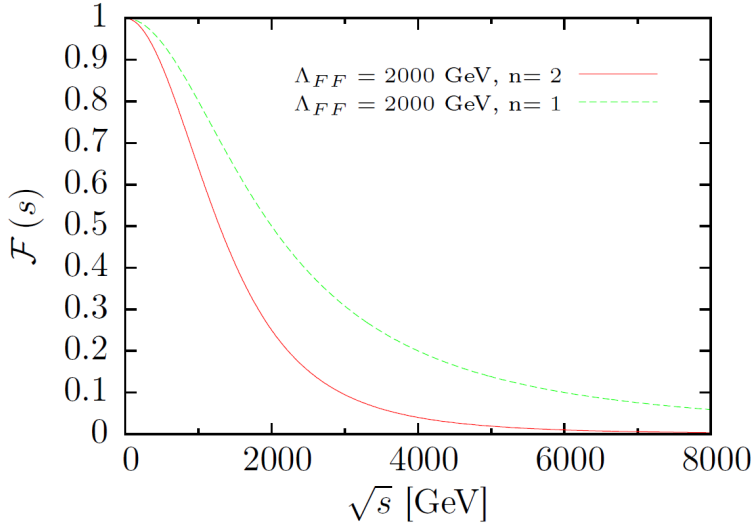
- with aQGCs unitarity may be violated even in the presence of a SM Higgs (effective parametrization always violates unitarity at some m_{VV})
  - $\Rightarrow$ unitarization scheme needed!
  - $\rightarrow$ **all unitarization schemes are arbitrary and introduce model dependence!**

- **form factors** (e.g. in VBFNLO arXiv:1205.4231)

$$\mathcal{F}(s) = (1 + \hat{s}/\Lambda_{\mathrm{FF}}^2)^{-n}$$

  - $\rightarrow$ suppression of amplitude
    - additional arbitrary parameters: exponent n and form factor scale Λ_{FF}
    - weakly motivated, but easy to implement
    - can be generally used for arbitrary anomalous operators
    - needs "fine tuning"

Feigl, Zeppenfeld, 2010



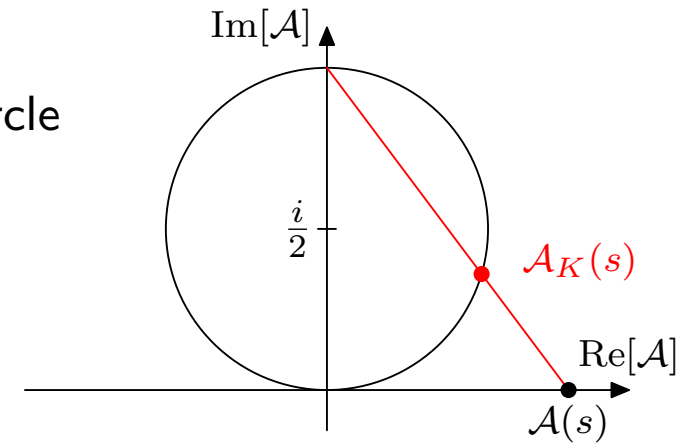
for $n = 2$ at $\Lambda_{\mathrm{FF}} = 2$ TeV:

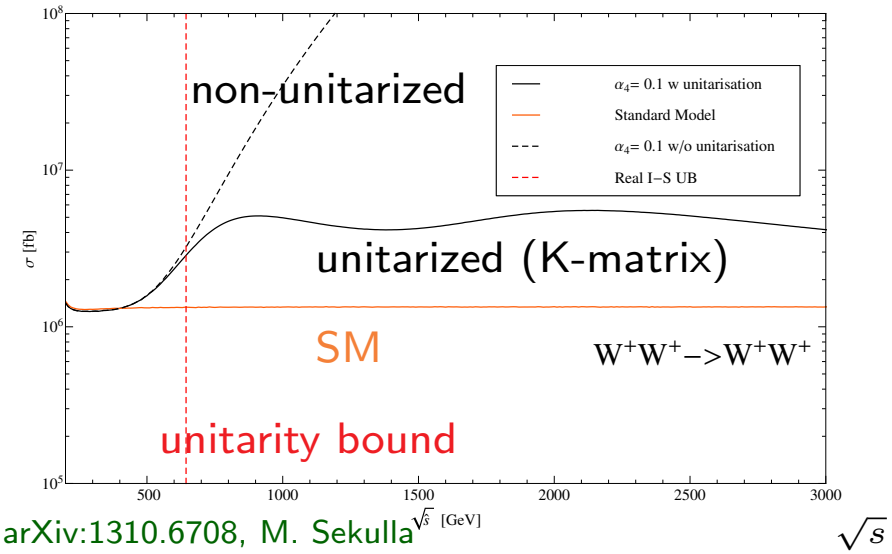
amplitude suppressed by a factor of 4

Unitarization

- with aQGCs unitarity may be violated even in the presence of a SM Higgs (effective parametrization always violates unitarity at some m_{VV})
  - $\Rightarrow$ unitarization scheme needed!
  - $\rightarrow$ **all unitarization schemes are arbitrary and introduce model dependence!**

- **K-matrix** method (WHIZARD arXiv:0806.4145)
  - scattering amplitude $\mathcal{A}(s)$ projected on Argand circle
    $\rightarrow$ saturation of the amplitude





arXiv:1310.6708, M. Sekulla

$\rightarrow$ allows for probing the entire kinematic phase space without being unphysical

Constraints on aQGCs from $\gamma\gamma \to WW$

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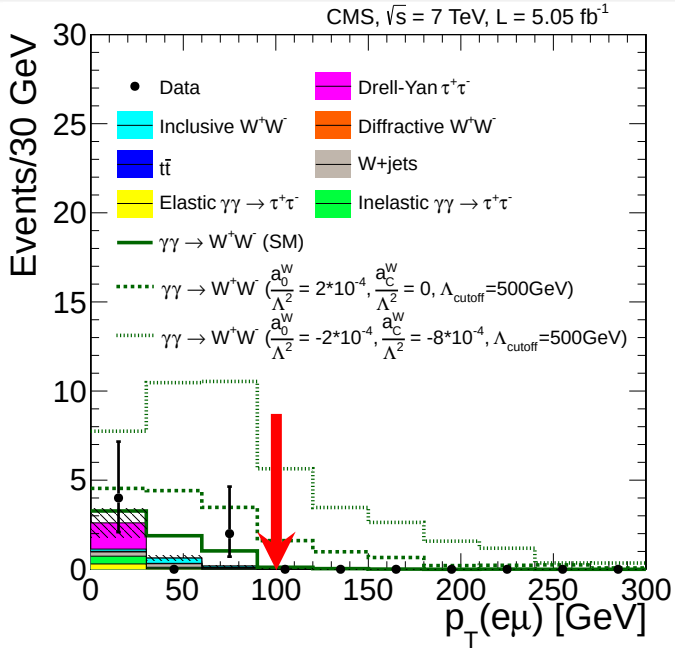
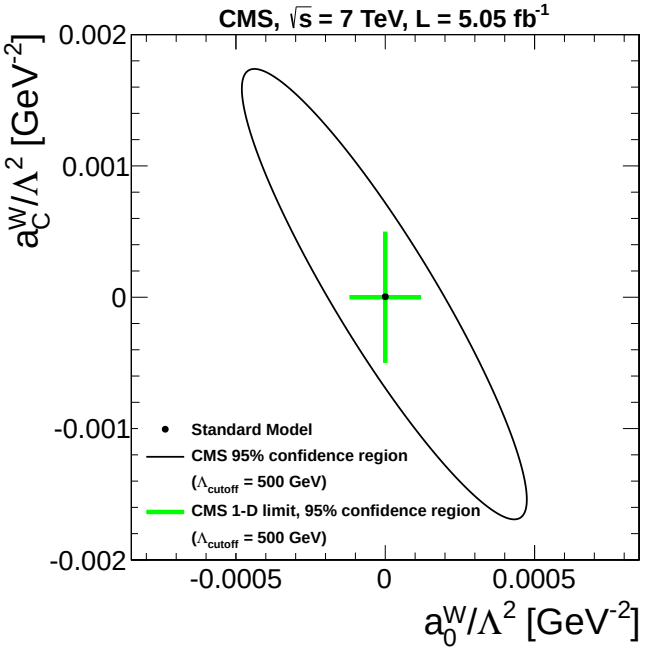
- sensitive to $WW\gamma\gamma$ vertex
- additional cut at $p_T(\mu^{\pm}e^{\mp}) > 100$ GeV:
  - $\rightarrow$ 0 events left
- 1D and 2D limits (95% CL) on aQGC parameters a_0^W/Λ^2 and a_c^W/Λ^2:
  - $|a_0^W/\Lambda^2| < 0.00015\ \mathrm{GeV}^{-2}$
  - $|a_c^W/\Lambda^2| < 0.0005\ \mathrm{GeV}^{-2}$
- unitarization with form factor with $\Lambda_{\mathrm{FF}} = 500\ \mathrm{GeV}$, $n = 2$
- un-unitarized limits (without form factor):
  - 30 – 40 times better, but dominated by $\sqrt{\hat{s}}$ above unitarity
  - $\times$100 improvement wrt. D0
  - $\times$3000 improvement wrt. LEP

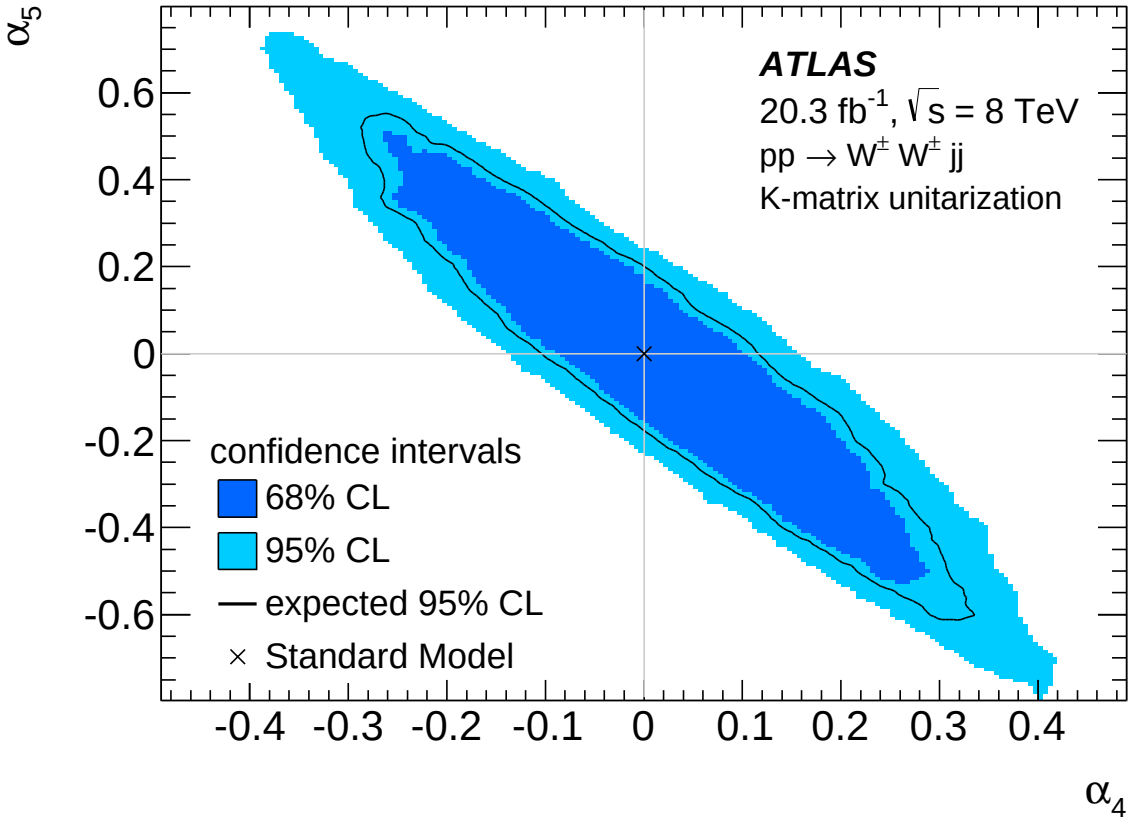


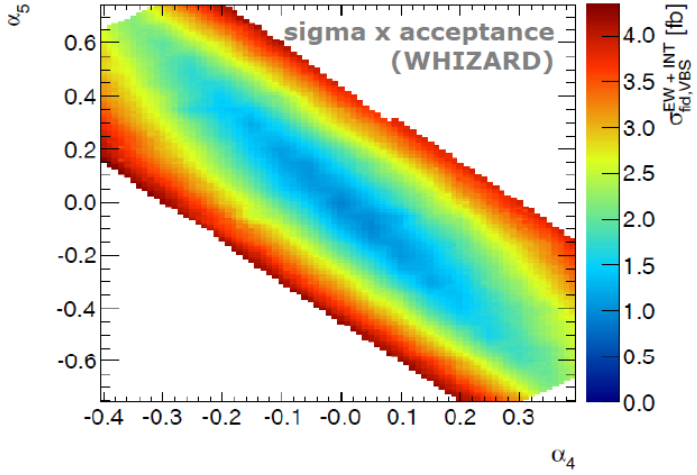


Constraints on aQGCs from $W^{\pm}W^{\pm}jj$

arXiv:1405.6241

- exclusion limits on α_4 and α_5 extracted from cross section in VBS phase space
  - aQGC samples from WHIZARD+PYTHIA8 with K-matrix unitarization
  - efficiency only weakly dependent on aQGC





1D 95% confidence intervals

expected:

$$-0.10 < \alpha_4 < 0.12$$
$$-0.18 < \alpha_5 < 0.20$$

observed:

$$\boldsymbol{-0.14 < \alpha_4 < 0.16}$$
$$\boldsymbol{-0.23 < \alpha_5 < 0.24}$$

(respective other $\alpha_i = 0$)

$\widehat{=}$ scale of new physics: $\Lambda > 500 - 650$ GeV

(rule of thumb: $\Lambda = v/\sqrt{\alpha_i}$ arXiv:1307.8170)

Summary

- exploring gauge boson self-interactions at the LHC in full swing
- first results on processes involving a VVVV vertex
- cross sections for vector boson scattering processes:

CMS	$\sigma(\gamma\gamma \to W^+W^-) \times BR$	$= 2.2^{+3.3}_{-2.0}$ fb	$\sim$ 1 s.d.
ATLAS	$\sigma(pp \to W^\pm W^\pm jj\text{-EW}) \times BR$	$= 1.3 \pm 0.4 \pm 0.2$ fb	3.6 s.d.

$\rightarrow$ **first evidence for a process containing vector boson scattering**
$\rightarrow$ **first evidence for a process containing a VVVV vertex!**

- rough sensitivity scales Λ from aQGC limits:

	CMS $\gamma\gamma \to W^+W^-$	ATLAS $W^\pm W^\pm \to W^\pm W^\pm$
un-unitarized	260 - 500 GeV	not given
unitarized	40 - 80 GeV	500 - 650 GeV

- further 8 TeV results expected

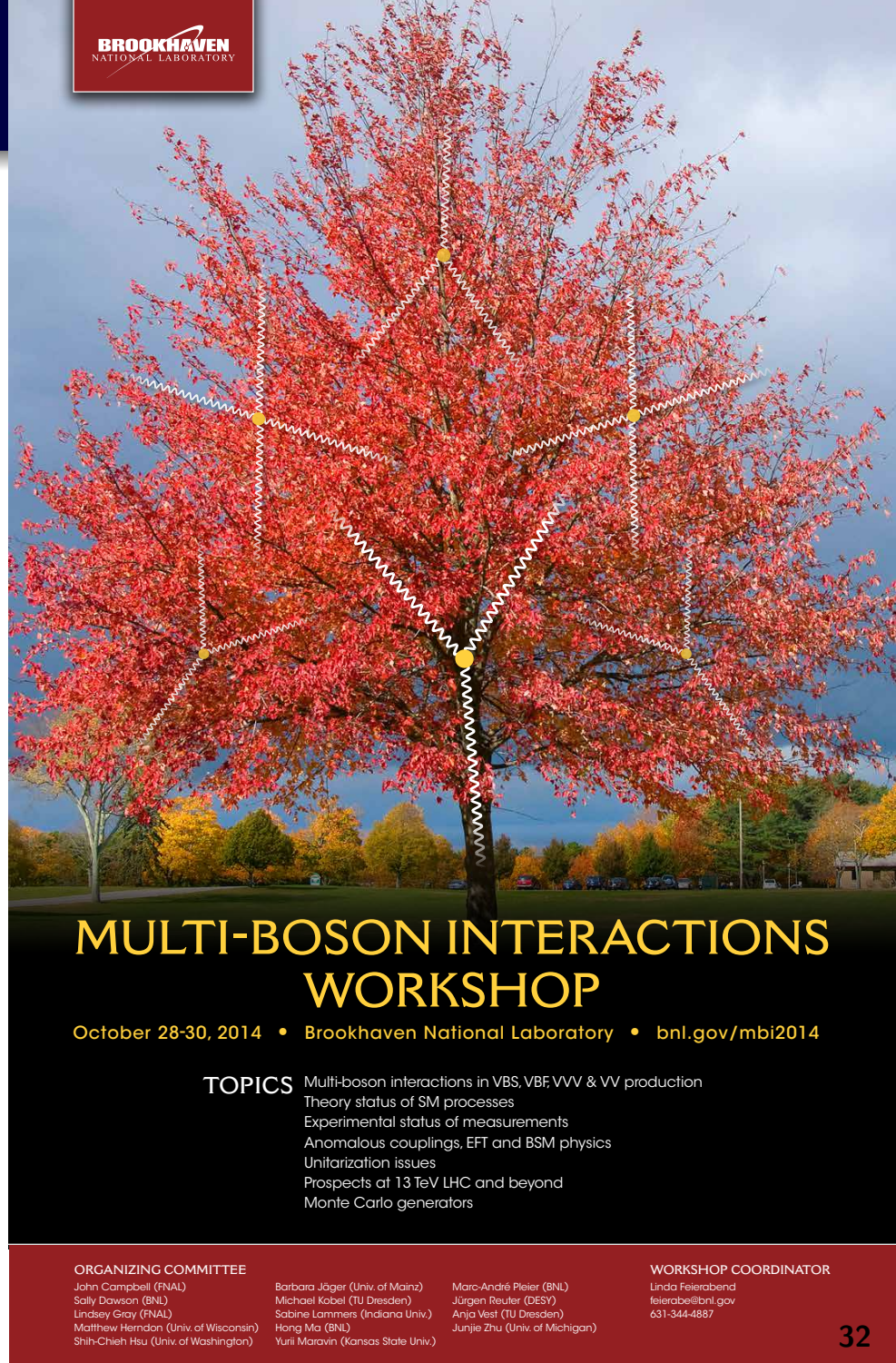
Outlook

- Higgs boson discovered, but still need to check whether this Higgs unitarizes the VBS process

  → need to explore VBS at higher energies, complementary to studying Higgs properties

- LHC @ 13/14 TeV:
  above $\sqrt{\hat{s}} = m_{VV} \approx 1 - 2$ TeV it will become possible to experimentally probe the SM nature of EWSB by VBS measurements

- beyond the LHC:
  fully explore EWSB, probing in particular unitarization of WW scattering at $m_{WW} \gg 1$ TeV, and explore dynamics well above EWSB

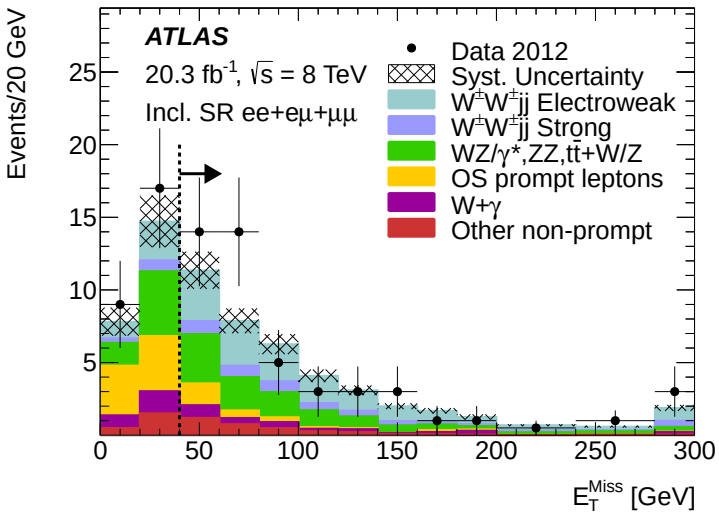


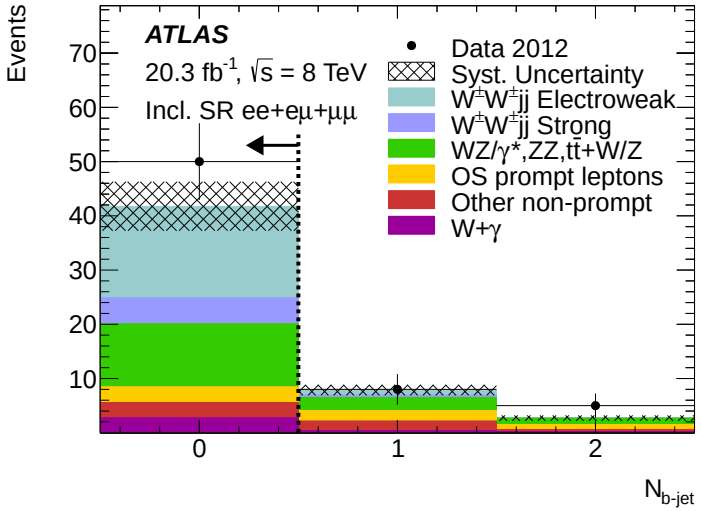
Backup

$W^{\pm}W^{\pm}jj$ production: event selection

arXiv:1405.6241

- exactly 2 same-sign leptons, $p_T^{\ell} > 25$ GeV, $|\eta^{\ell}| < 2.5$
  $e^{\pm}e^{\pm}$, $e^{\pm}\mu^{\pm}$ and $\mu^{\pm}\mu^{\pm}$ final states
- $m_{\ell\ell} > 20$ GeV
- veto events with any additional electron (muon) with $p_T > 7(6)$ GeV $\rightarrow$ reduces WZ and ZZ
- $E_{\mathrm{T}}^{\mathrm{miss}} > 40$ GeV
  $\rightarrow$ reduces Z+jets with charge mis-identification
- Z-veto in ee channel: $|m_{ee} - m_Z| > 10$ GeV
  $\rightarrow$ reduces Z+jets with charge mis-identification
- ≥ 2 jets, $p_T^{\mathrm{jet}} > 30$ GeV, $|\eta^{\mathrm{jet}}| < 4.5$
- veto events containing b-jets
  $\rightarrow$ reduces $t\bar{t}$ events (lepton from b-decays)
- $m_{jj} > 500$ GeV (jets with largest p_T)
- VBS signal region: $|\Delta\eta_{jj}| > 2.4$

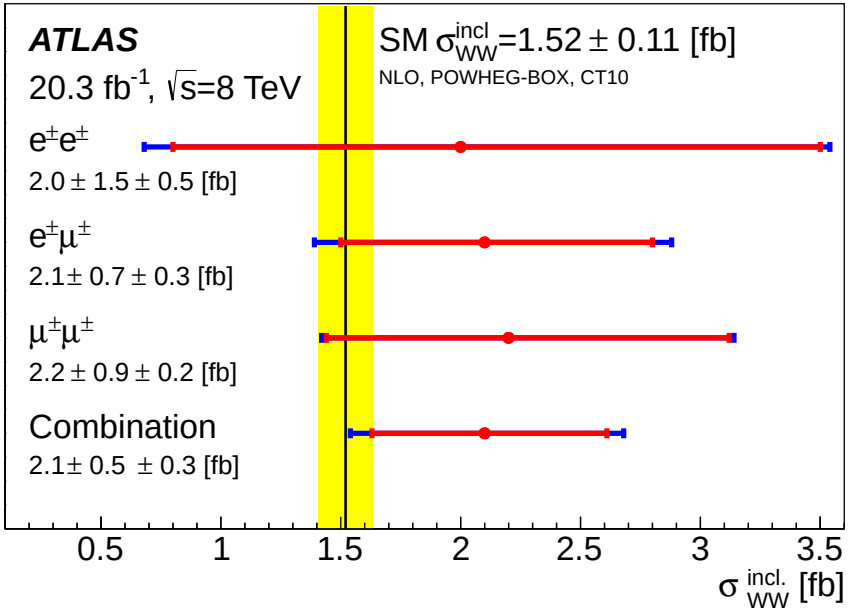




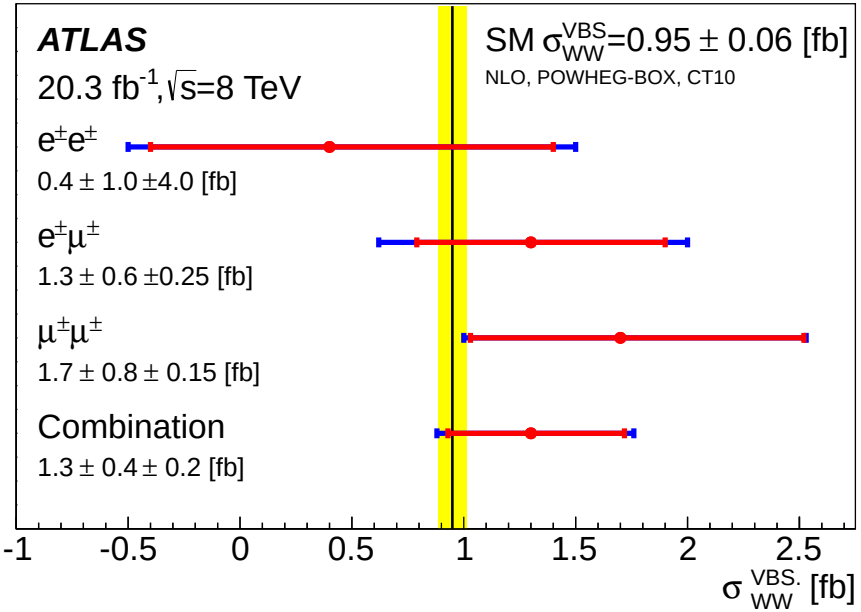
Electroweak $W^{\pm}W^{\pm}jj$ production

arXiv:1405.6241

inclusive phase space



VBS phase space



	Inclusive Signal Region				VBS Signal Region			
	$e^{\pm}e^{\pm}$	$e^{\pm}\mu^{\pm}$	$\mu^{\pm}\mu^{\pm}$	Total	$e^{\pm}e^{\pm}$	$e^{\pm}\mu^{\pm}$	$\mu^{\pm}\mu^{\pm}$	Total
$W^{\pm}W^{\pm}$jj Electroweak	3.07 ± 0.30	9.0 ± 0.8	4.9 ± 0.5	16.9 ± 1.5	2.55 ± 0.25	7.3 ± 0.6	4.0 ± 0.4	13.9 ± 1.2
$W^{\pm}W^{\pm}$jj Strong	0.89 ± 0.15	2.5 ± 0.4	1.42 ± 0.23	4.8 ± 0.8	0.25 ± 0.06	0.71 ± 0.14	0.38 ± 0.08	1.34 ± 0.26
$WZ/\gamma^{*}, ZZ, t\bar{t}+W/Z$	3.0 ± 0.7	6.1 ± 1.3	2.6 ± 0.6	11.6 ± 2.5	2.2 ± 0.5	4.2 ± 1.0	1.9 ± 0.5	8.2 ± 1.9
$W+\gamma$	1.1 ± 0.6	1.6 ± 0.8	–	2.7 ± 1.2	0.7 ± 0.4	1.3 ± 0.7	–	2.0 ± 1.0
OS prompt leptons	2.1 ± 0.4	0.77 ± 0.27	–	2.8 ± 0.6	1.39 ± 0.27	0.64 ± 0.24	–	2.0 ± 0.5
Other non-prompt	0.61 ± 0.30	1.9 ± 0.8	0.41 ± 0.22	2.9 ± 0.8	0.50 ± 0.26	1.5 ± 0.6	0.34 ± 0.19	2.3 ± 0.7
Total Predicted	10.7 ± 1.4	21.7 ± 2.6	9.3 ± 1.0	42 ± 5	7.6 ± 1.0	15.6 ± 2.0	6.6 ± 0.8	29.8 ± 3.5
Data	12	26	12	50	6	18	10	34

$W^{\pm}W^{\pm}jj$ event yields

arXiv:1405.6241

	Inclusive Region		
	$e^{\pm}e^{\pm}$	$e^{\pm}\mu^{\pm}$	$\mu^{\pm}\mu^{\pm}$
Prompt	3.0 ± 0.7	6.1 ± 1.3	2.6 ± 0.6
Conversions	3.2 ± 0.7	2.4 ± 0.8	–
Other non-prompt	0.61 ± 0.30	1.9 ± 0.8	0.41 ± 0.22
$W^{\pm}W^{\pm}jj$ Strong	0.89 ± 0.15	2.5 ± 0.4	1.42 ± 0.23
$W^{\pm}W^{\pm}jj$ Electroweak	3.07 ± 0.30	9.0 ± 0.8	4.9 ± 0.5
Total background	6.8 ± 1.2	10.3 ± 2.0	3.0 ± 0.6
Total predicted	10.7 ± 1.4	21.7 ± 2.6	9.3 ± 1.0
Data	12	26	12

- interference between EW and strong $W^{\pm}W^{\pm}jj$ production: $\sim$ 12% evaluated with SHERPA, included in EW $W^{\pm}W^{\pm}jj$ prediction

$W^{\pm}W^{\pm}jj$ production – systematic uncertainties

arXiv:1405.6241

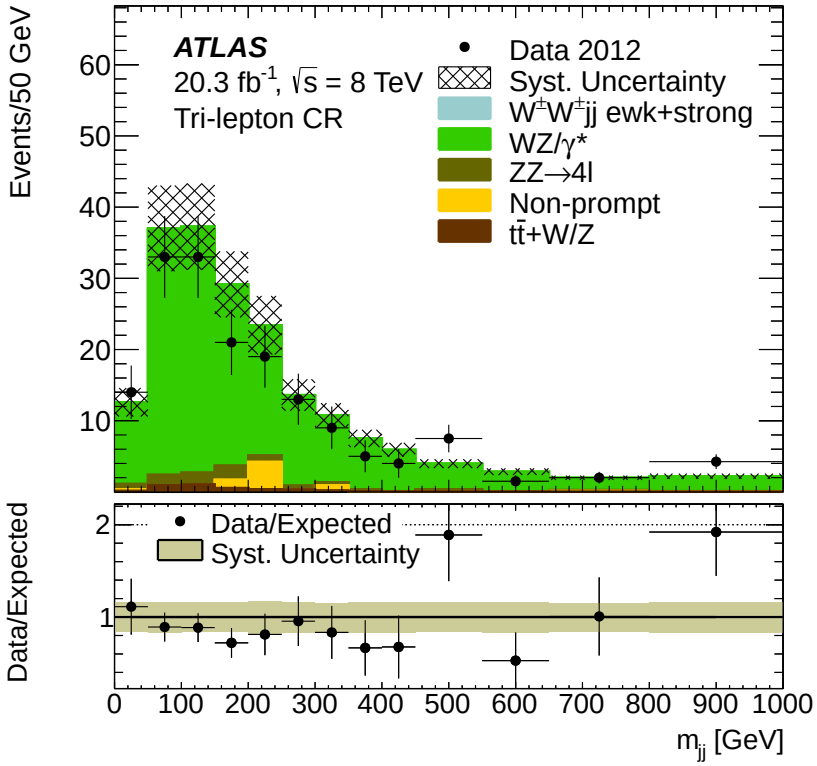
Systematic Uncertainties $ee/e\mu/\mu\mu$ (%) - VBS SR			
Background		Signal	
Jet uncertainties	13/15/15	Theory $W^{\pm}W^{\pm}jj$-ewk	6.0
Theory WZ/γ^*	4.5/5.4/7.8	Jet uncertainties	5.1
MC statistics	8.9/6.4/8.4	Luminosity	2.8
Fake rate	4.0/7.2/6.8	MC statistics	4.5/2.7/3.7
OS lepton bkg/ Conversion rate	5.5/4.4/–	E_T^{miss} reconstruction	1.1
E_T^{miss} reconstruction	2.9/3.2/1.4	Lepton reconstruction	1.9/1.0/0.7
Theory $W+\gamma$	3.1/2.6/–	b-tagging efficiency	0.6
Luminosity	1.7/2.1/2.4	trigger efficiency	0.1/0.3/0.5
Theory $W^{\pm}W^{\pm}jj$-strong	0.9/1.5/2.6		
Lepton reconstruction	1.7/1.1/1.1		
b-tagging efficiency	0.8/0.9/0.7		
Trigger efficiency	0.1/0.2/0.4		

$W^{\pm}W^{\pm}jj$ production – control regions

arXiv:1405.6241

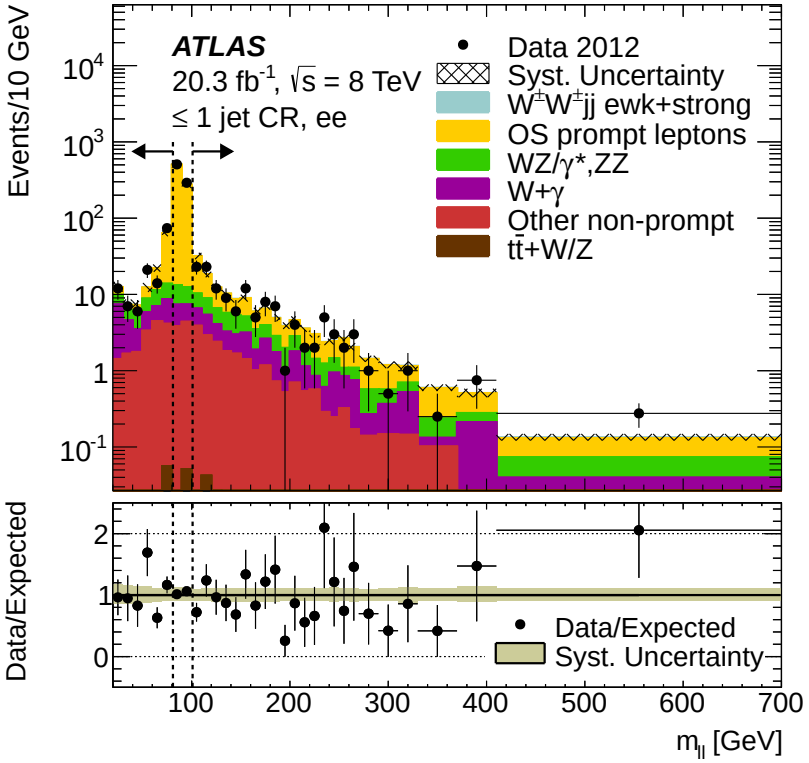
trilepton control region:

$\rightarrow$ prompt



$\leq$ 1 jet control region:

$\rightarrow$ conversions (ee), prompt ($\mu\mu$)



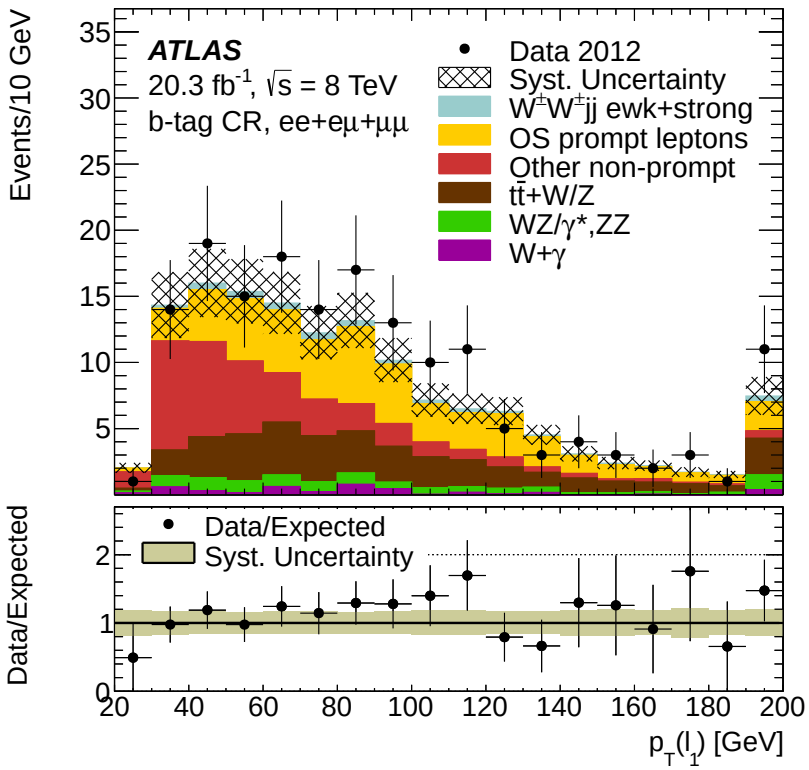
Control Region		Trilepton	$\leq$ 1 jet	b-tagged	Low m_{jj}
$e^{\pm}e^{\pm}$	exp.	36 $\pm$ 6	278 $\pm$ 28	40 $\pm$ 6	76 $\pm$ 9
	data	40	288	46	78
$e^{\pm}\mu^{\pm}$	exp.	110 $\pm$ 18	288 $\pm$ 42	75 $\pm$ 13	127 $\pm$ 16
	data	104	328	82	120
$\mu^{\pm}\mu^{\pm}$	exp.	60 $\pm$ 10	88 $\pm$ 14	25 $\pm$ 7	40 $\pm$ 6
	data	48	101	36	30

$W^{\pm}W^{\pm}jj$ production – control regions

arXiv:1405.6241

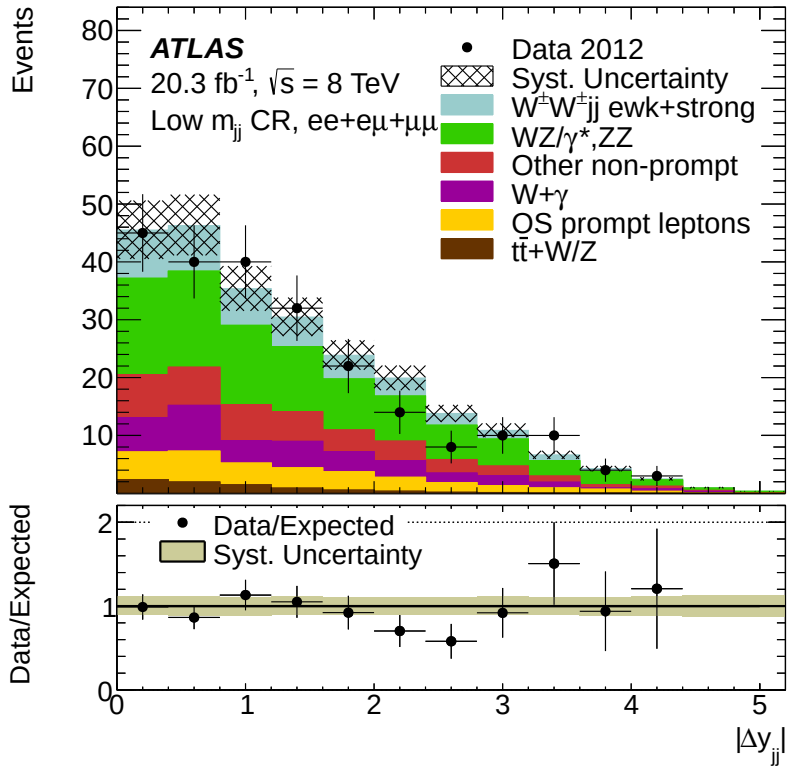
$t\bar{t}$/b-tag control region:

$\rightarrow$ other non-prompt (b-decays)



$m_{jj} < 500$ GeV control region:

$\rightarrow$ mix

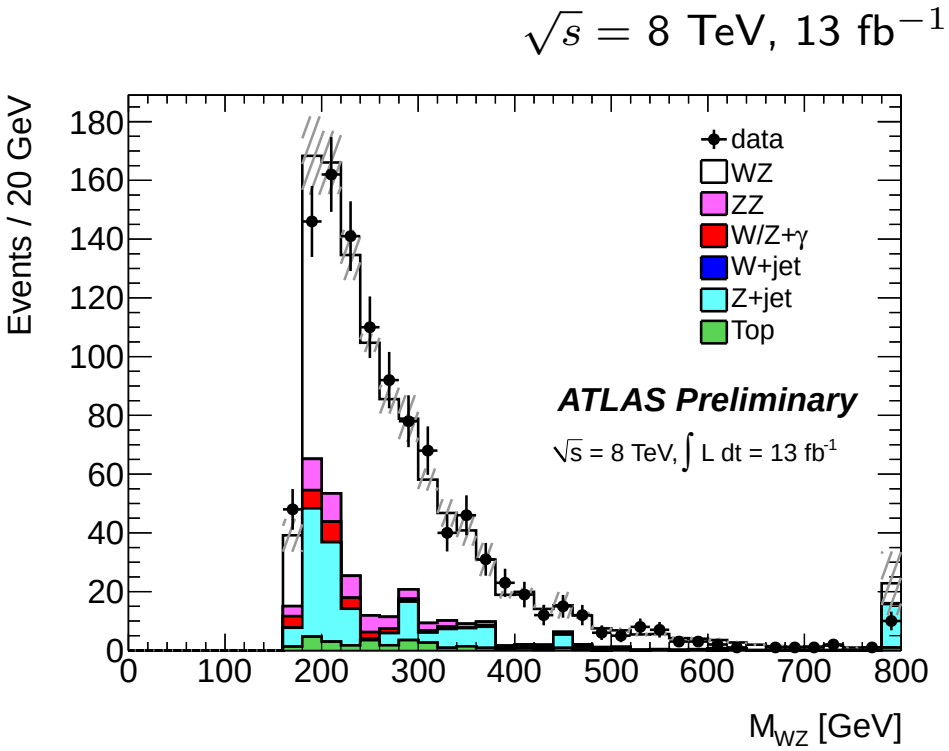


Control Region		Trilepton	≤ 1 jet	b-tagged	Low m_{jj}
$e^{\pm}e^{\pm}$	exp.	36 ± 6	278 ± 28	40 ± 6	76 ± 9
	data	40	288	46	78
$e^{\pm}\mu^{\pm}$	exp.	110 ± 18	288 ± 42	75 ± 13	127 ± 16
	data	104	328	82	120
$\mu^{\pm}\mu^{\pm}$	exp.	60 ± 10	88 ± 14	25 ± 7	40 ± 6
	data	48	101	36	30

$W^{\pm}Zjj$: experimental tasks

ATLAS-CONF-2013-021

- $W^{\pm}Z$ (+ n jets) can have **any** number of jets: $n = 0, 1, 2, 3, ...$
  - → lowest order: $W^{\pm}Z + 0$ jets
- 3 high p_T, isolated leptons
- 1 opposite-sign lepton pair forming Z within 81 GeV $< m_{\ell\ell} <$ 101 GeV
- residual lepton + $E_{\mathrm{T}}^{\mathrm{miss}}$ forming W
- results:
  - 1094 events observed
  - 277 background events expected (mainly Z+jets & fake leptons)
  - $\sigma_{\mathrm{total}} = 20.3^{+0.8}_{-0.7}(\mathrm{stat})^{+1.2}_{-1.1}(\mathrm{syst})^{+0.7}_{-0.6}(\mathrm{lumi})\,\mathrm{pb}$
  - $\sigma_{\mathrm{MCFM}} = 20.3 \pm 0.8\,\mathrm{pb}$



- for $W^{\pm}Z$ VBS measurement: require additional 2 jets

Modeling of anomalous quartic gauge couplings

EFT description can be translated in EW chiral Lagrangian approach for aTGC/aQGC and vice versa (switch of operator bases) arXiv:hep-ph/0606118

EW chiral Lagrangian approach (non-linear realization of the gauge symmetry)

- aQGC operators (dimension 4):

$$\mathscr{L}_4 = \alpha_4 (\mathrm{Tr}[\mathbf{V}_\mu \mathbf{V}_\nu])^2 \qquad \mathscr{L}_5 = \alpha_5 (\mathrm{Tr}[\mathbf{V}_\mu \mathbf{V}^\mu])^2$$

- $\mathbf{V}_\mu = \Sigma (D_\mu \Sigma)^\dagger$, $\Sigma = e^{-i\frac{\mathbf{w}}{v}}$, $\mathbf{w}$: goldstone scalar field triplett
- aQGC parametrizations: α_4 and α_5

EFT approach (linear realization of gauge symmetry)

- operators (dimension 8):

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

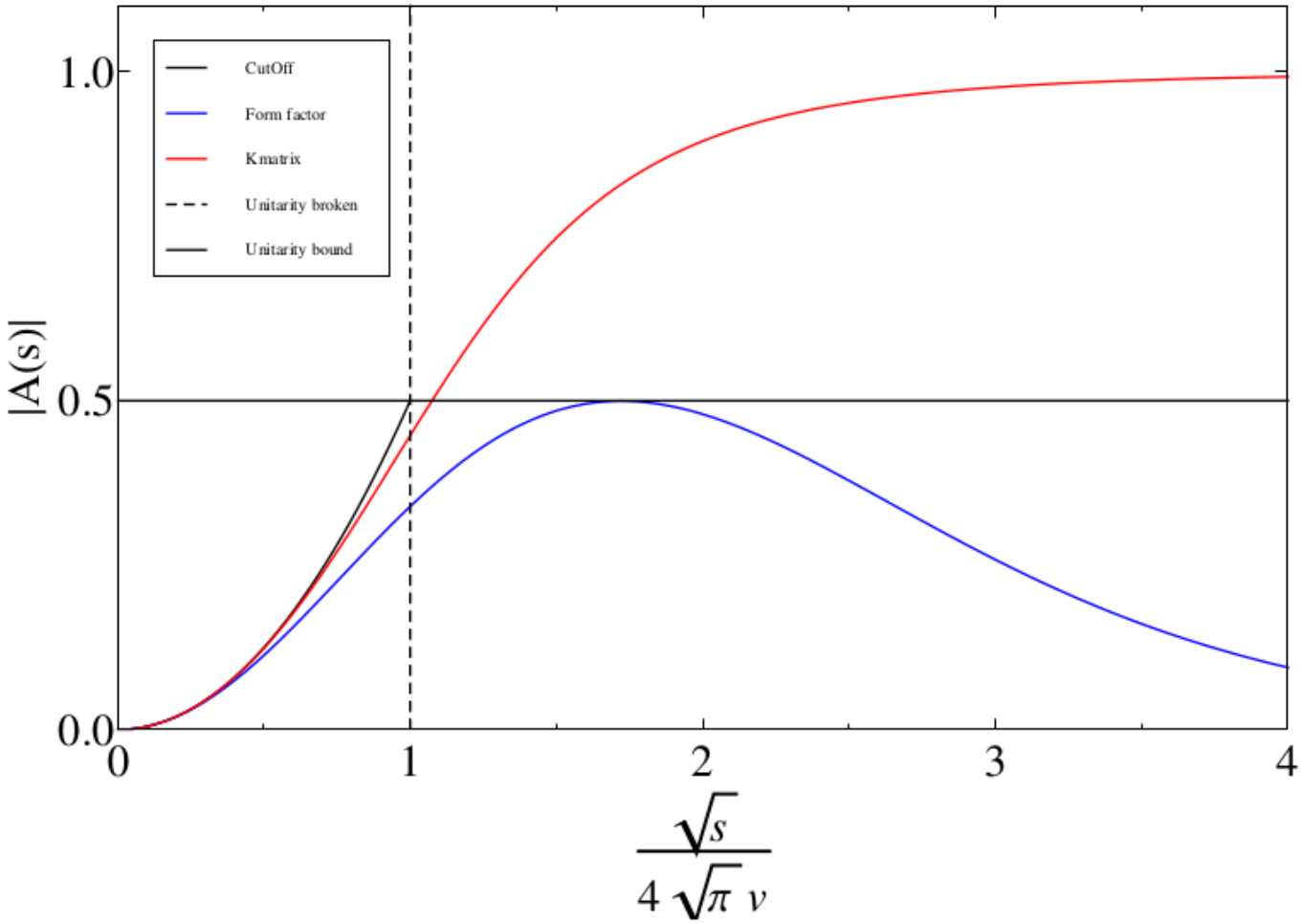
$$\mathscr{L}_{S,1} = \frac{f_{S,1}}{\Lambda^4} [(D_\mu \Phi)^\dagger D^\mu \Phi] \times [(D_\nu \Phi)^\dagger D^\nu \Phi]$$

- parametrizations: $\frac{f_{S,0}}{\Lambda^4}$ and $\frac{f_{S,1}}{\Lambda^4}$

Unitarization schemes

K-matrix: saturation of amplitude to achieve unitarity

form factor: suppression of amplitude to get below unitarity bound

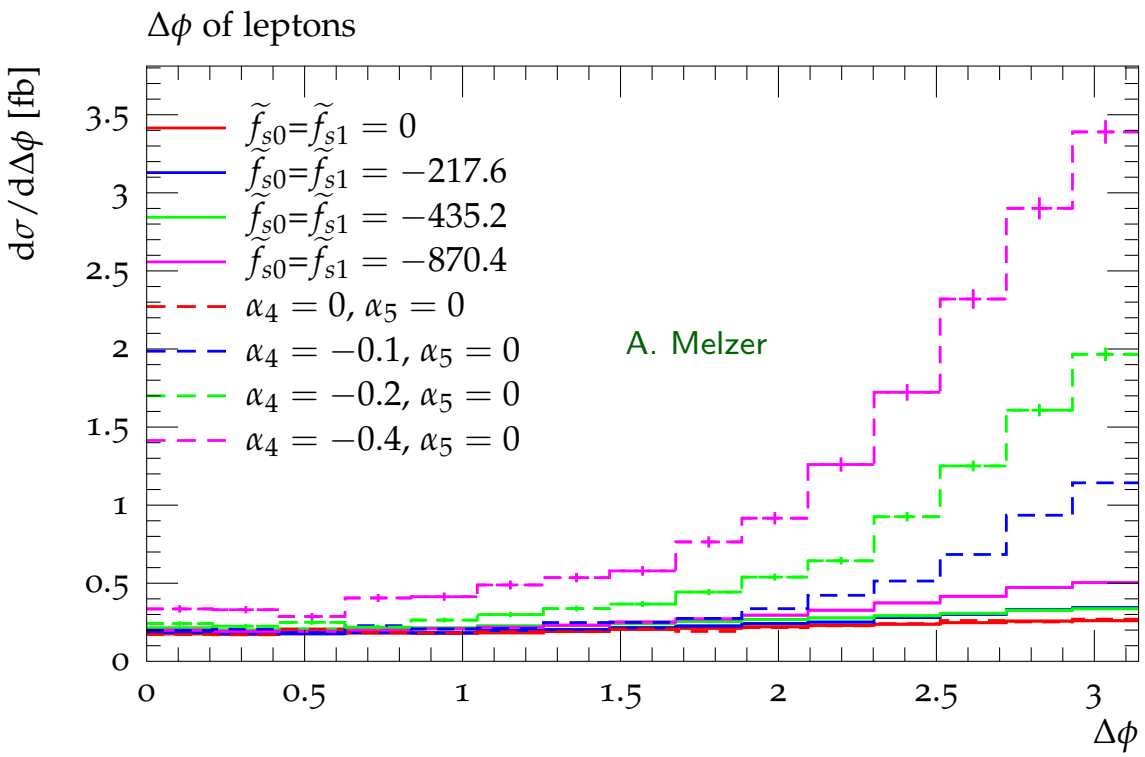


https://indico.desy.de/getFile.py/access?contribId=8&sessionId=2&resId=0&materialId=slides&confId=7512

Kinematic distributions, unitarized

- comparison of unitarization with K-matrix method (WHIZARD, $\alpha_{4/5}$) and form factors (VBFNLO, $f_{S,0/1}$) at generator level
- example process: $pp \to qqe^+\nu e^+\nu$

$\Delta\phi$(leptons) differential cross-section distribution:



generator cuts:

- $p_T^\ell > 10$ GeV, $|\eta_l| < 5$
- $p_T^j > 20$ GeV, $|\eta_j| < 5$
- $|\Delta R(jj)| > 0.4$
- $m_{jj} > 150$ GeV

aQGC parameter:

- $\tilde{f}_{S,0} = \tilde{f}_{S,1} \approx 2176 \cdot \alpha_4$ (with $\tilde{f}_{S,0/1} = \frac{f_{S,0/1}}{\Lambda^4}$ TeV^4)
- $\alpha_5 = 0$

Limits on aQGCs for $WW\gamma\gamma$

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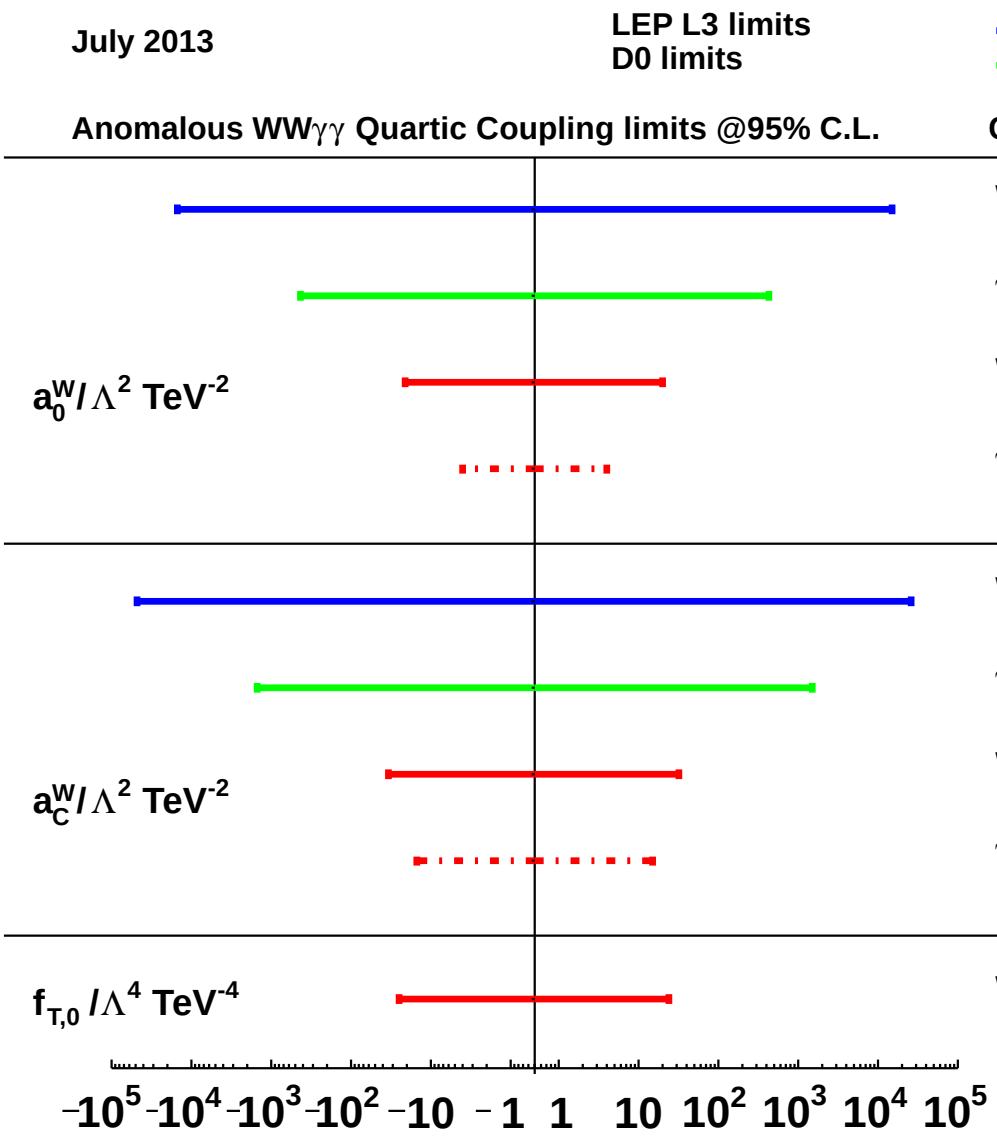


Channel	Limits	L	$\sqrt{s}$
WWγ	[- 15000, 15000]	0.43fb^{-1}	0.20 TeV
γγ → WW	[- 430, 430]	9.70fb^{-1}	1.96 TeV
WWγ	[- 21, 20]	19.30fb^{-1}	8.0 TeV
γγ → WW	[- 4, 4]	5.05fb^{-1}	7.0 TeV
WWγ	[- 48000, 26000]	0.43fb^{-1}	0.20 TeV
γγ → WW	[- 1500, 1500]	9.70fb^{-1}	1.96 TeV
WWγ	[- 34, 32]	19.30fb^{-1}	8.0 TeV
γγ→ WW	[- 15, 15]	5.05fb^{-1}	7.0 TeV
WWγ	[- 25, 24]	19.30fb^{-1}	8.0 TeV

Effective QGC in VBS

arXiv:0806.4145

- non-linear realization of the gauge symmetry → chiral EW Lagrangian:

$$\mathscr{L}_4 = \alpha_4 \frac{g^2}{2}\left\{[(W^+W^+)(W^-W^-) + (W^+W^-)^2] + \frac{2}{c_{\mathrm{w}}^2}(W^+Z)(W^-Z) + \frac{1}{2c_{\mathrm{w}}^4}(ZZ)^2\right\}$$

$$\mathscr{L}_5 = \alpha_4 \frac{g^2}{2}\left\{(W^+W^-)^2 + \frac{2}{c_{\mathrm{w}}^2}(W^+W^-)(ZZ) + \frac{1}{2c_{\mathrm{w}}^4}(ZZ)^2\right\}$$

- effective parametrization of physics beyond kinematic reach, e.g. resonances at new physics scale $\Lambda = v/\sqrt{\alpha_i}$
  - wide → continuum, narrow → particles
- α_i parametrize low-mass tail of these resonances, e.g. $\alpha_5 = g_\sigma^2\left(\frac{v^2}{8M_\sigma^2}\right)$

	$J=0$	$J=1$	$J=2$
$I=0$	σ^0 (Higgs)	ω^0 (γ'/Z')	f^0 (Graviton?)
$I=1$	$\pi^\pm, \pi^0$ (2HDM?)	$\rho^\pm, \rho^0$ (w'/Z')	$a^\pm, a^0$
$I=2$	$\phi^{\pm\pm}, \phi^\pm, \phi^0$ (Higgs triplett?)	–	$t^{\pm\pm}, t^\pm, t^0$

- unitarization only guaranteed for explicitly included resonance(s) at unique values of the coupling g
- effective parametrization always violates unitarity at some m_{VV}

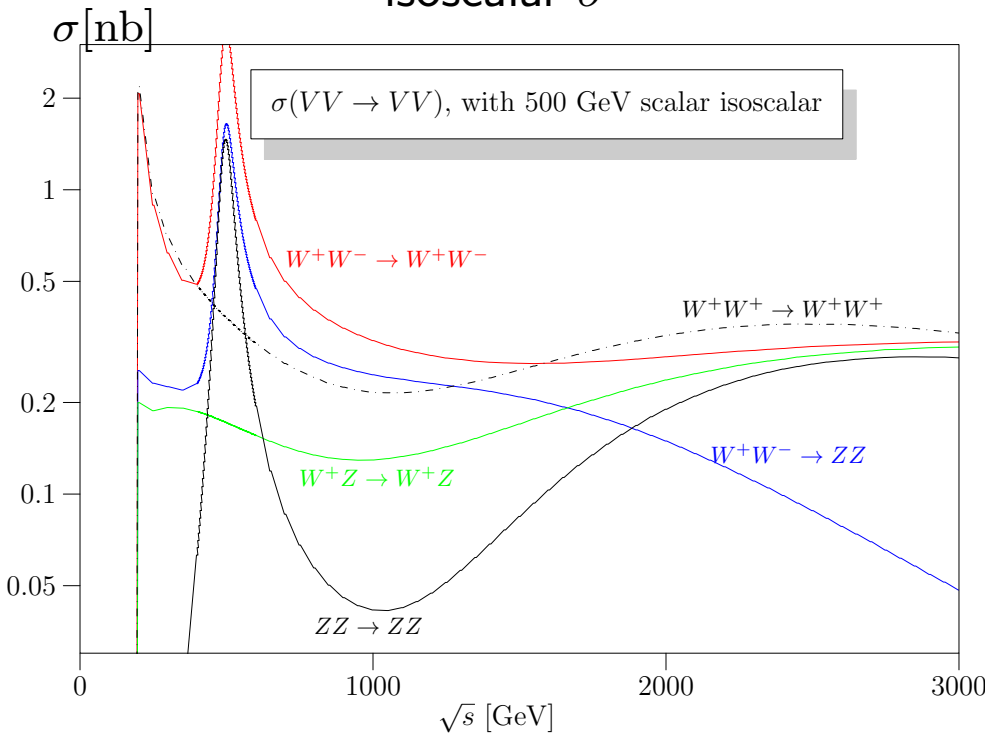
Resonances in VBS

arXiv:0806.4145

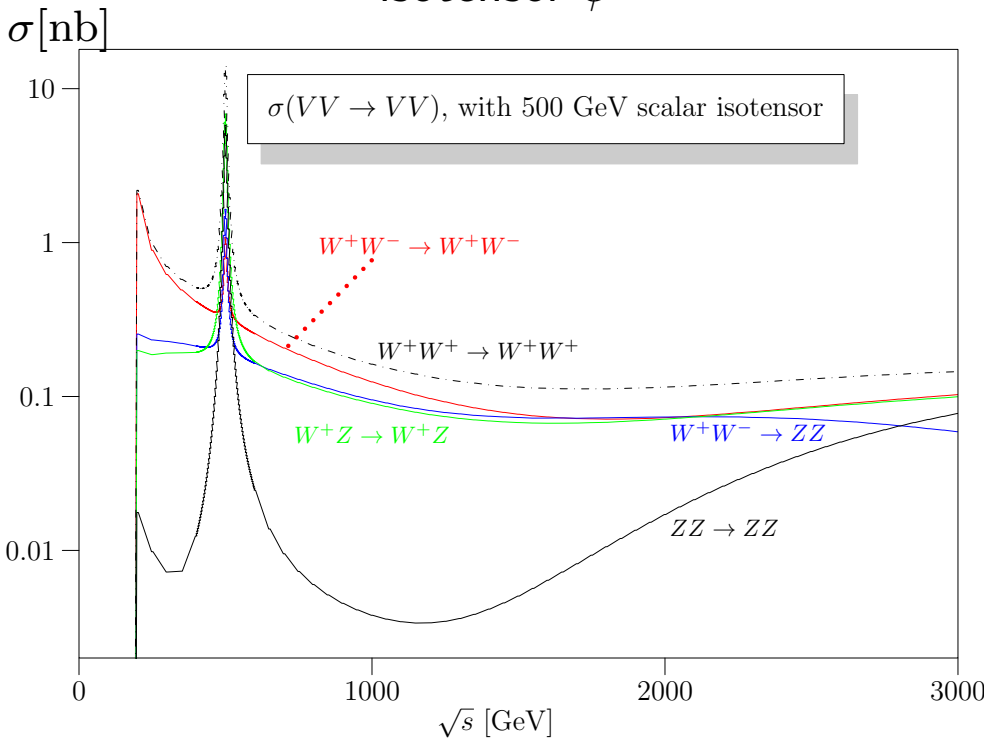
Example with resonances, scalars (α_4 and $\alpha_5 = 0$, no longer needed!)

$\rightarrow$ cross sections (in nb) for VV scattering in dependence of the centre-of-mass energy:

isoscalar σ

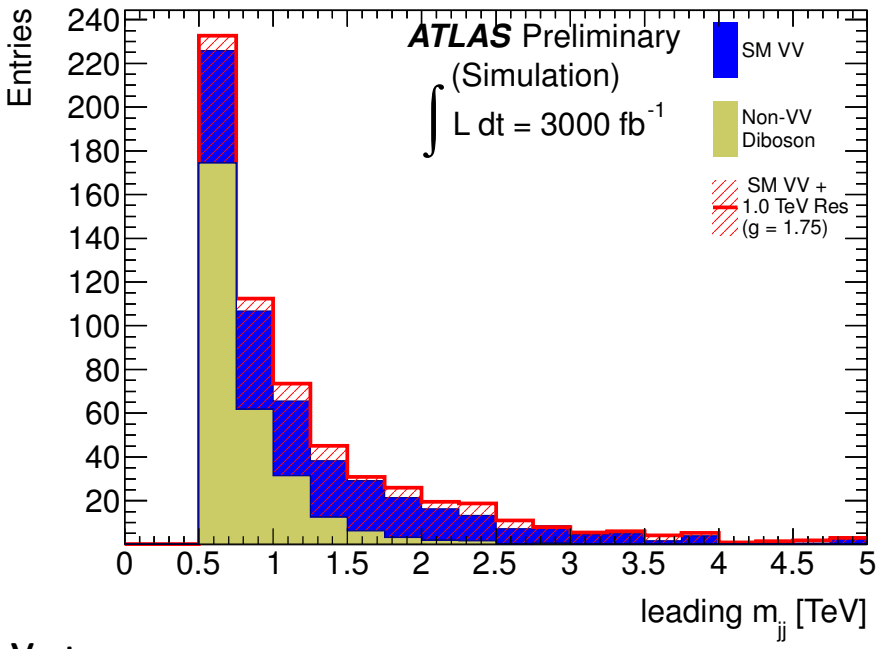
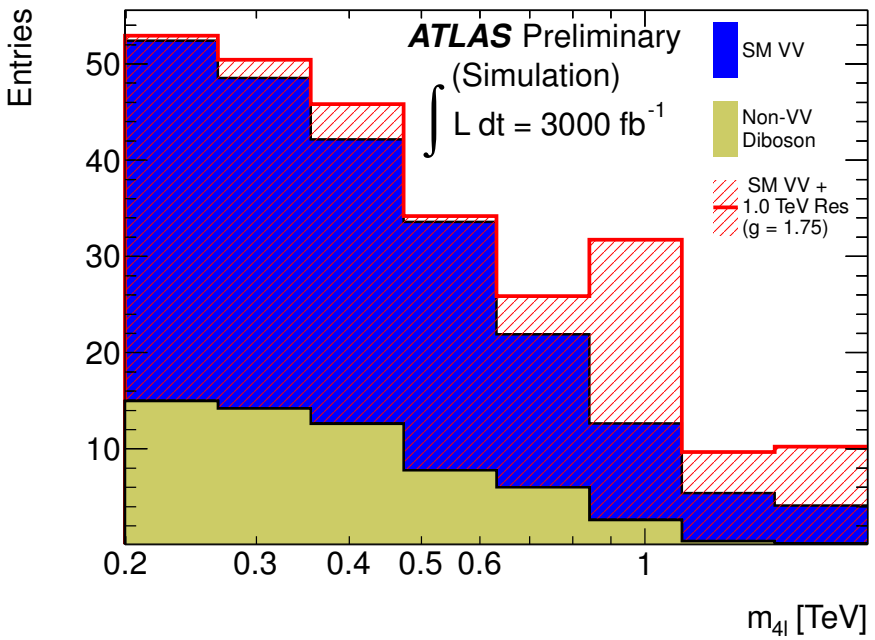


isotensor ϕ



Prospects for VBS at $\sqrt{s} = 14$ TeV

CERN-ESG-005, ATLAS-PHYS-PUB-2012-005

- LHC @ 14 TeV $\rightarrow \sqrt{\hat{s}} = m_{VV} \approx 1 - 2$ TeV
- signal chosen: anomalous VBS ZZ tensor singlet resonance f^0
  - $\rightarrow$ exactly four selected leptons: two opposite sign, same flavor pairs
  - $\rightarrow$ hard benchmark, sensitivity higher for other resonances

$m_{\text{resonance}}$	coupling	width	300 fb^{-1}	3000 fb^{-1}
500 GeV	$g = 1$	$\Gamma = 2$ GeV	2.4σ	7.5σ
1 TeV	$g = 1.75$	$\Gamma = 50$ GeV	1.7σ	5.5σ
1 TeV	$g = 2.5$	$\Gamma = 100$ GeV	3.0σ	9.4σ