TECHNISCHE UNIVERSITÄT DRESDEN

Fakultät Mathematik und Naturwissenschaften, Fachrichtung Physik

QGC in VVjj and VVV final states: Measurements and prospects at LHC

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on behalf of the ATLAS and CMS collaborations

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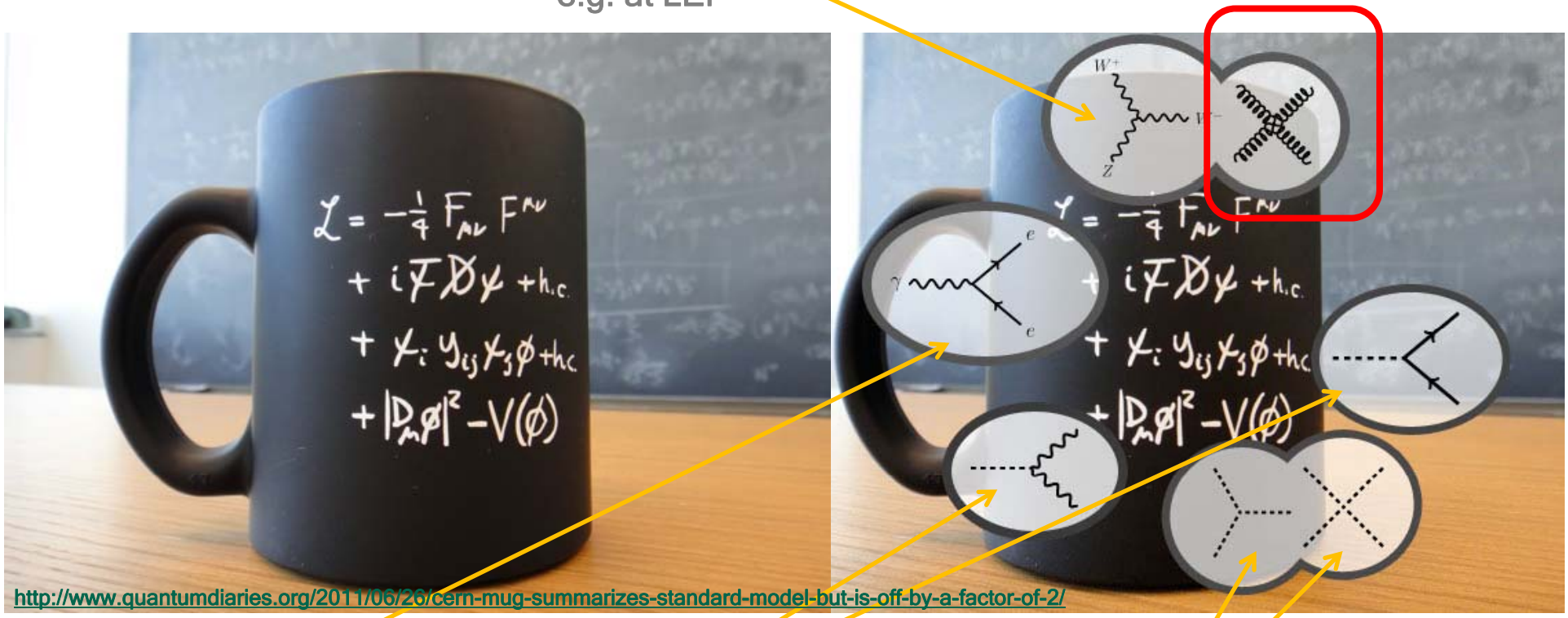
FSP 101 ATLAS
GRADUIERTEN KOLLEG Masse-Spektrum-Symmetrie
PHYSICS AT THE TERA SCALE Helmholtz Alliance
DRESDEN concept

The Standard Model Lagrangian

Precisely checked,
e.g. at LEP

Today's topic



http://www.quantumdiaries.org/2011/06/26/cern-mug-summarizes-standard-model-but-is-off-by-a-factor-of-2/

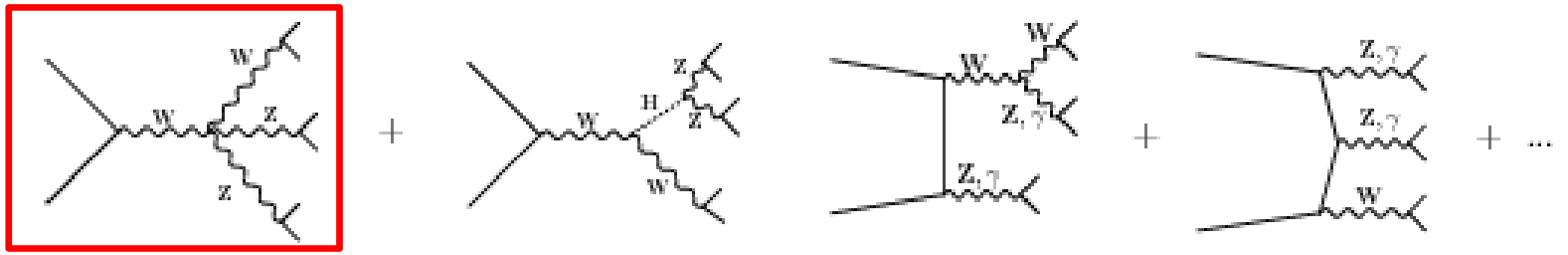
Most frequent
and best understood

Recently seen:
H→WW,ZZ and H→ ττ, (tt)

Not yet seen:
H→HH and H→ HHH

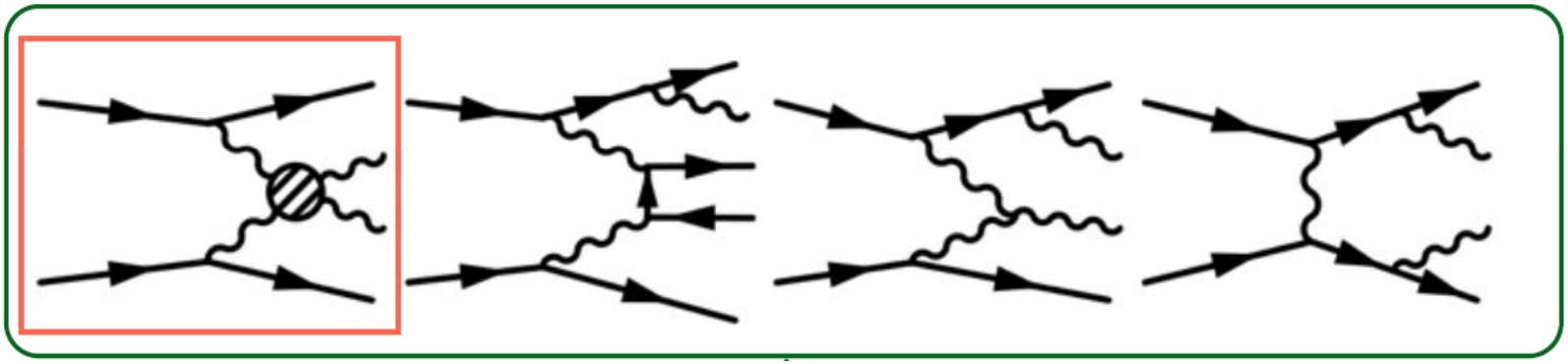
Processes with Quartic-Gauge-Couplings

- **QGC Process** := Process, where a QGC vertex *contributes*
  - No reaction is ever mediated by a QGC Vertex alone
  - Even a gauge-invariant definition of the QGC contribution is not possible!
- Two classes of QGC processes are measurable (example diagrams)
  - **Triple Boson production, VVV**



QGC H-mediated TGC Fermion-mediated

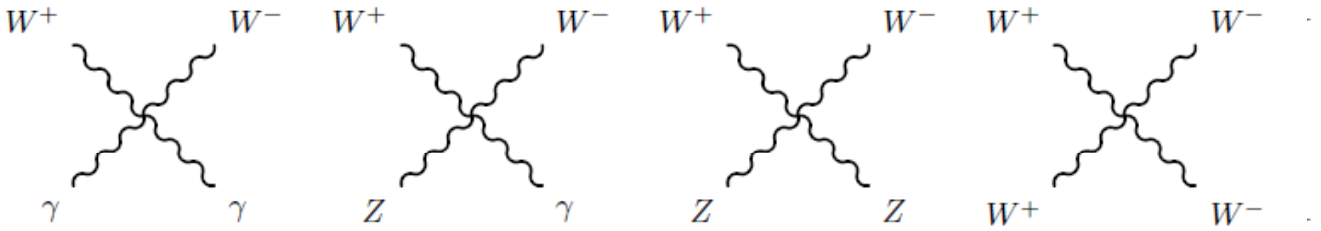
  - **Vector Boson Scattering (VBS), as VVjj or exclusive VV(pp)**



QGC+ H-mediated+ TGC virtual TGC Fermion-mediated

What can we learn from QGC Vertices?

- Standard model:
  - $\mathcal{L}_{WWVV}$ contains the quartic gauge self-couplings (QGC)



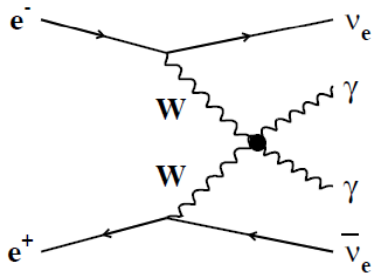
$$\mathcal{L}_{WWVV} = -\frac{g^2}{4}\Big\{[2W_\mu^+ W^{-\mu} + (A_\mu \sin\theta_W - Z_\mu \cos\theta_W)^2]^2 - [W_\mu^+ W_\nu^- + W_\nu^+ W_\mu^- + (A_\mu \sin\theta_W - Z_\mu \cos\theta_W)(A_\nu \sin\theta_W - Z_\nu \cos\theta_W)]^2\Big\}$$

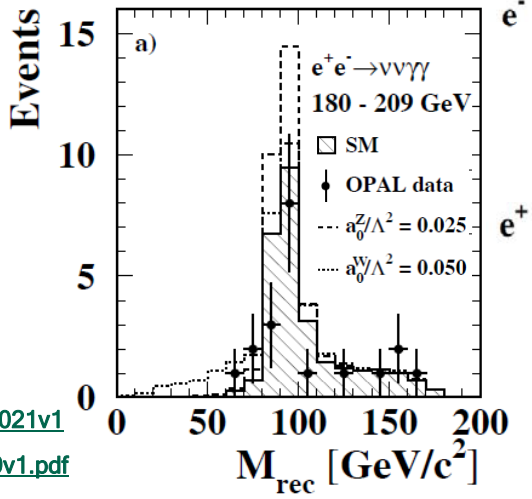
  - no neutral self-couplings in the SM

- **1. Observe the SM QGC Processes with these vertices**
  - Pre-LHC: attempted for γγWW and γZWW, but not „really" successful
- **2. Constrain anomalous Quartic Gauge Couplings (aQGC)**
  - Pre-LHC: loose limits by LEP and Tevatron for γγWW and γZWW
- **3. Test Eweak Symmetry breaking and Higgs properties**
  - Access through ZZWW and WWWW at large $\sqrt{\hat{s}} = M_{VV} >\sim 1$ TeV
  - **One of the core reasons, why LHC has been built!**

1. Have we seen SM QGC Processes before?

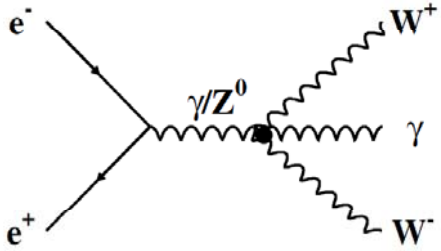
❖ „observed" QGC Processes at LEP: $e^+e^- \to \nu\nu\gamma\gamma$ and $W^+W^-\gamma$





OPAL: http://arxiv.org/abs/hep-ex/0402021v1

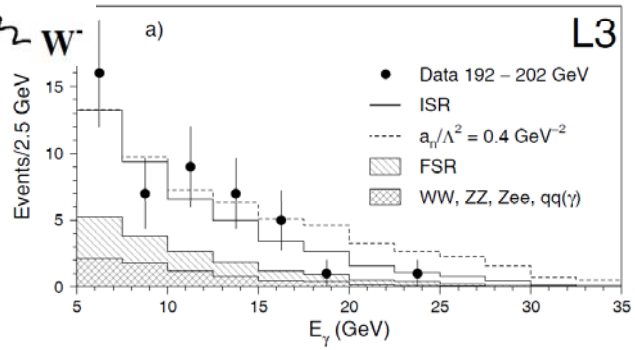
L3: http://arxiv.org/pdf/hep-ex/0111029v1.pdf



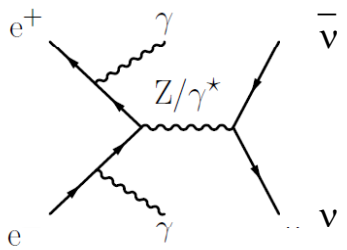
OPAL: http://arxiv.org/abs/hep-ex/0309013

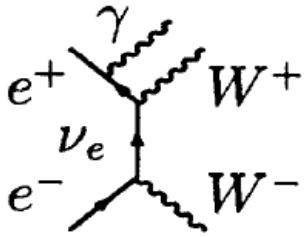
L3: http://arxiv.org/pdf/hep-ex/0111029v1.pdf

DELPHI: http://arxiv.org/pdf/hep-ex/0311004v1.pdf



- significant observation with small/negligble background
- But: consistent with ISR / FSR processes,
  which can be gauge-invariantly distinguished from QGC Processes





At $\sqrt{s}$= 200 GeV,
$\sigma_{WW\gamma}$ = 304 fb (QGCs included)
$\sigma_{WW\gamma}$ = 318 fb (QGCs excluded)
(M.Musy, Moriond 2001)

❖ → No „real" observation of any QGC process at LEP (nor at Tevatron)

2. Beyond the SM in this vertex: aQGC

❖ **Assume SM is effective theory of a more complex one**, as e.g.
- Low-E Fermi-Theorie with 4f Vertex → Weak Gauge Bosons in SU(2)
- Low-E Chiral QCD langrangian → Composite qq condensate, hadrons

❖ **Consider effective electroweak Langrangian**

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

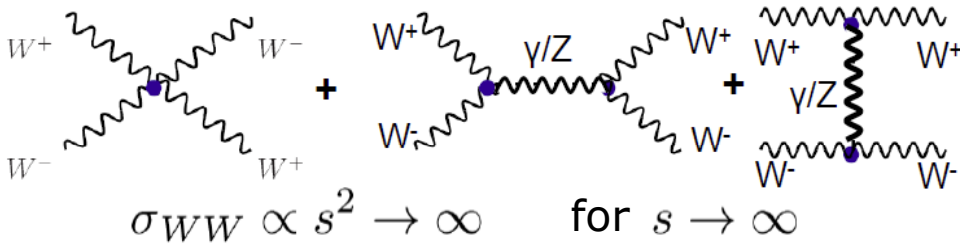
- valid only, if new physics beyond kinematic reach ($\Lambda \gg \sqrt{\hat{s}}$)
- model independent, complementary to direct searches
- generally requires additional unitarization (killing model independence)

❖ **Relevant parameters for aQGC contributions**
- Some d=8 parameters can be mapped to those for d=6 and d=4

d=4	d=6	d=8
WWWW, WWZZ	WWZγ, WWγγ	all VVVV
Chiral Lagrangian non-linear representation		Effective Operators 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)

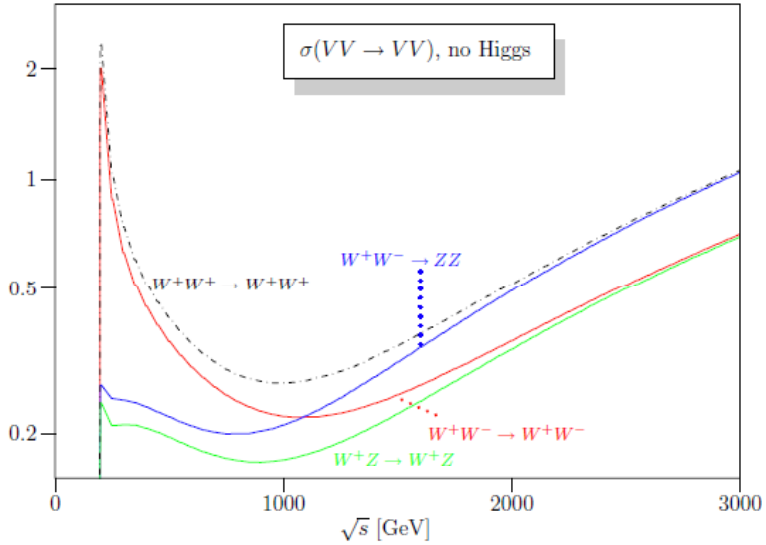
3. Special Role of the Higgs Boson

❖ VBS Without Higgs contribution:

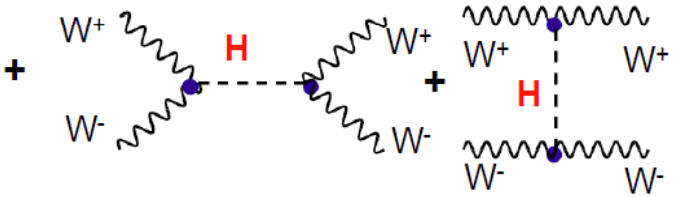


$\sigma_{WW} \propto s^2 \to \infty$ for $s \to \infty$

- Violates „unitarity"(probability>1) at ~2 TeV



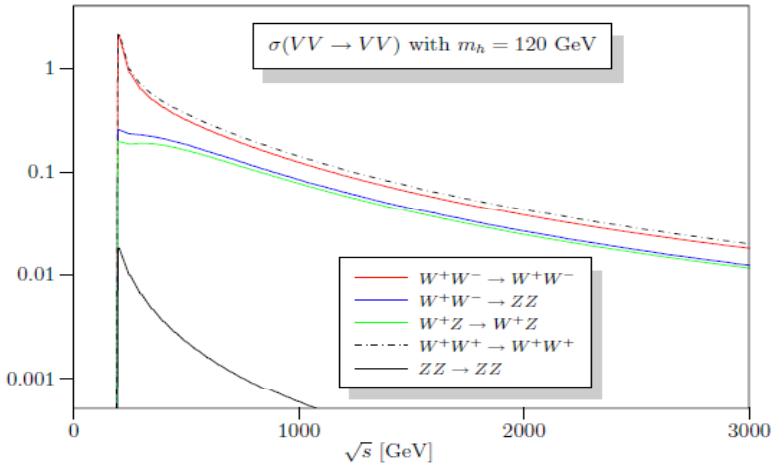
❖ Higgs contribution (or new physics, or both) needed



- Higgs exactly cancels increase for large s

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

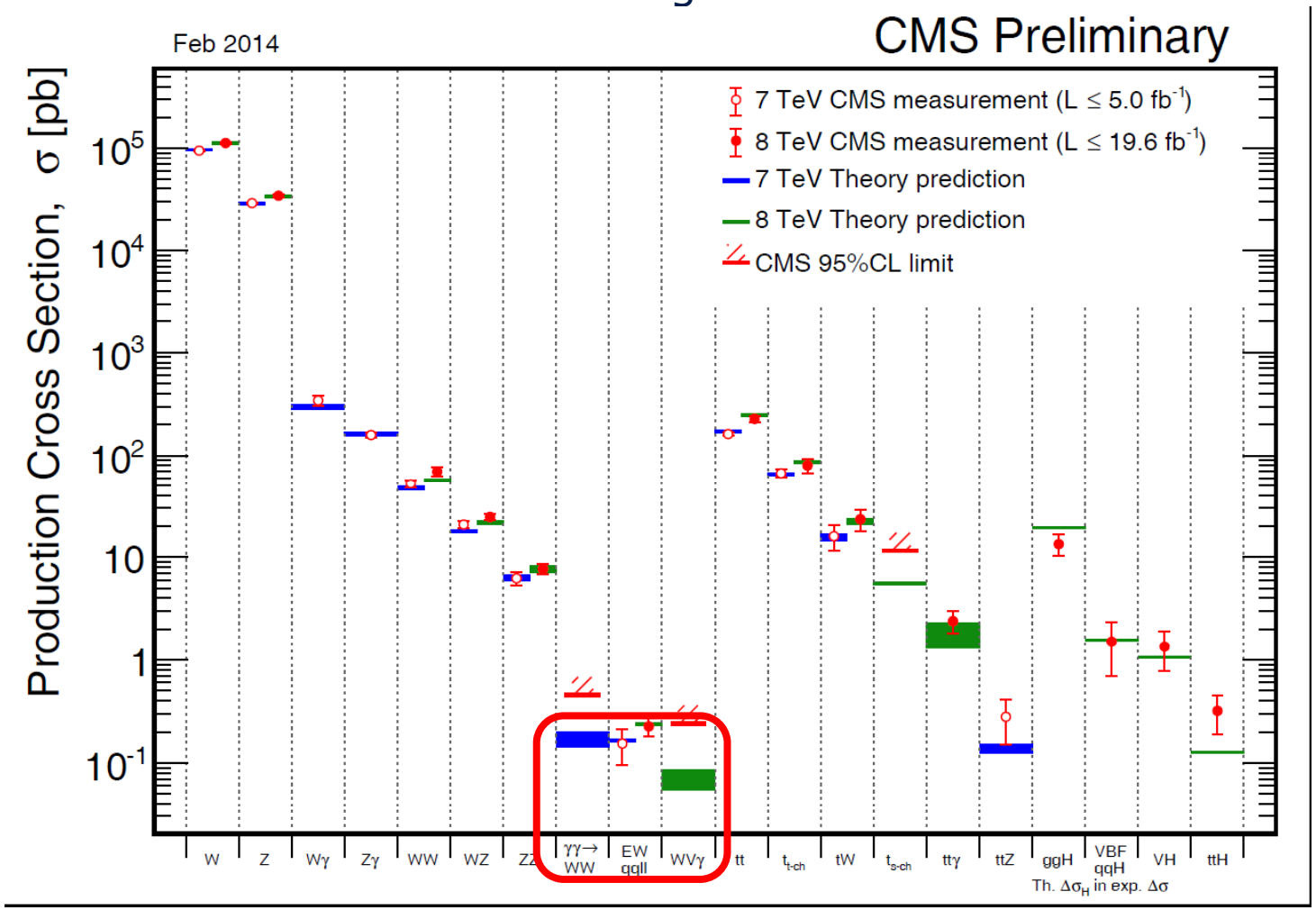
but *only* for SM H-WW coupling!



A. Alboteanu, W. Kilian, J. Reuter: http://arxiv.org/abs/0806.4145v1

LHC measurements

- Impressive range of measurements on V+Jets and VV
- VV->VV and VVV are a real challenge

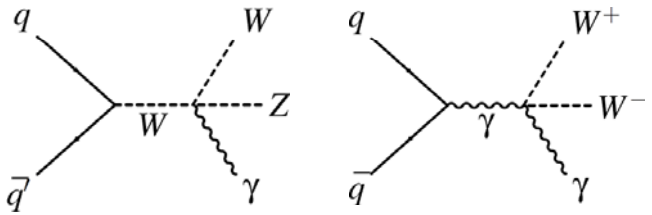


Triple Boson production at LHC

first accessible WWγ, WZγ, Wγγ, Zγγ …, later also WWW, WWZ, …

First VVV analysis at LHC: WVγ = WZγ + WWγ → ℓν jj γ

- CMS prel.: CMS-PAS-SMP-13-009
- 8 TeV data, 19.3 fb^{-1}
- Background dominated
- Limits on d=6 and d=8 aQGCs



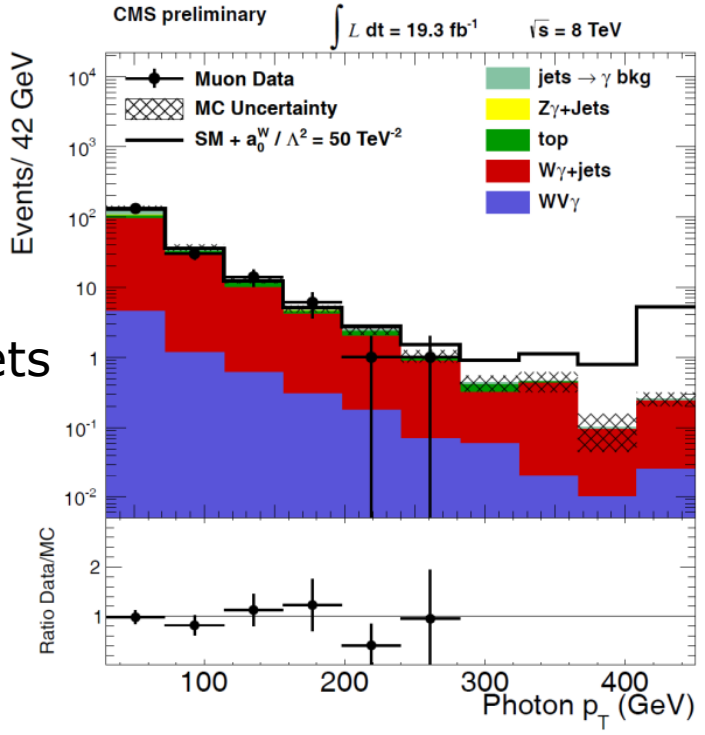
main selection cuts

- ℓν : E_T^{miss} > 35 GeV, p_T >25(μ)-30(e) GeV
- jj: p_T >30 GeV, 70 GeV < m_{jj} < 100 GeV
- γ: p_T >30 GeV

Main (75%) background and syst.: Wγ+jets

Expected SM signal: 7 (5) events in μ (e)

- Observed: 183 (139) in μ (e)
- Expected: 194±12 (148±11) in μ(e)
- Cross-section limit 241 fb@95% = 3.4xSM



aQGC limits from WVγ

- Sensitive to aQGC in WWγγ and WWZγ vertices
- Limits on d=6 and d=8 aQGCs, setting all others to Zero

$$\mathcal{L}_{AQGC} = \frac{a_0^W}{4g^2}\mathcal{W}_0^\gamma + \frac{a_c^W}{4g^2}\mathcal{W}_c^\gamma + \sum_i k_i^W \mathcal{W}_i^Z + \mathcal{L}_{T,0} + \mathcal{L}_{T,1} + \mathcal{L}_{T,2}$$

WWγγ WWZγ contributions

- Transformation between d=6 and d=8: $\frac{q_i}{\Lambda^4} = \frac{8a_i}{\Lambda^2 M_W^2}$

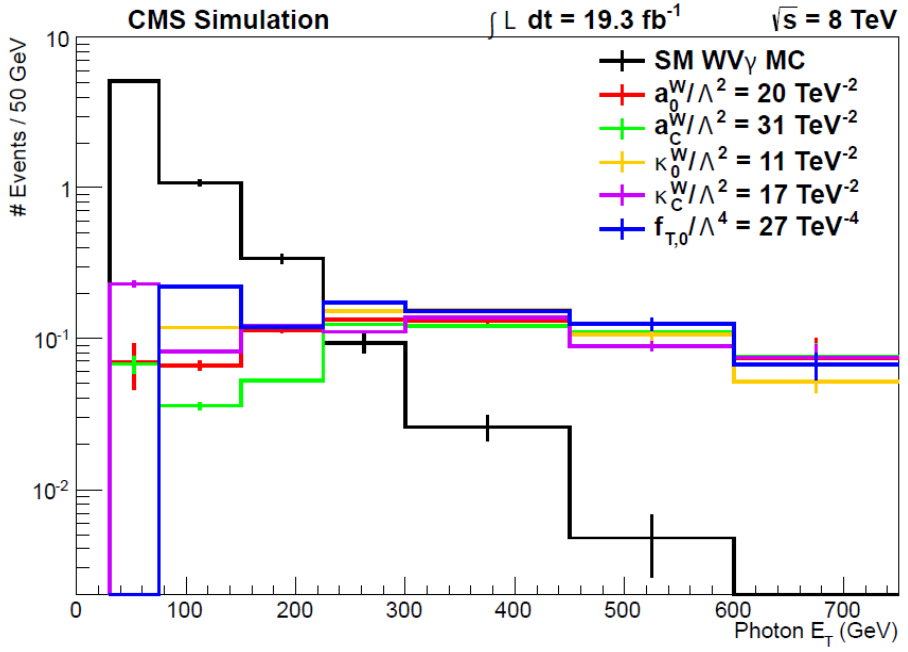
- Discriminating variable
  - high Photon E_T

- **Observed (~ expected) limits without unitarization**

$-21\ (\mathrm{TeV}^{-2}) < a_0^W/\Lambda^2 < 20\ (\mathrm{TeV}^{-2})$
$-34\ (\mathrm{TeV}^{-2}) < a_C^W/\Lambda^2 < 32\ (\mathrm{TeV}^{-2})$
$-25\ (\mathrm{TeV}^{-4}) < f_{T,0}/\Lambda^4 < 24\ (\mathrm{TeV}^{-4})$
$-12\ (\mathrm{TeV}^{-2}) < \kappa_0^W/\Lambda^2 < 10\ (\mathrm{TeV}^{-2})$
$-18\ (\mathrm{TeV}^{-2}) < \kappa_C^W/\Lambda^2 < 17\ (\mathrm{TeV}^{-2})$

  - Example: for $a_0^W = 1$

$$\Lambda_{WW\gamma\gamma} > \sqrt{\frac{a_0^W}{20}}\,TeV \approx 220GeV$$



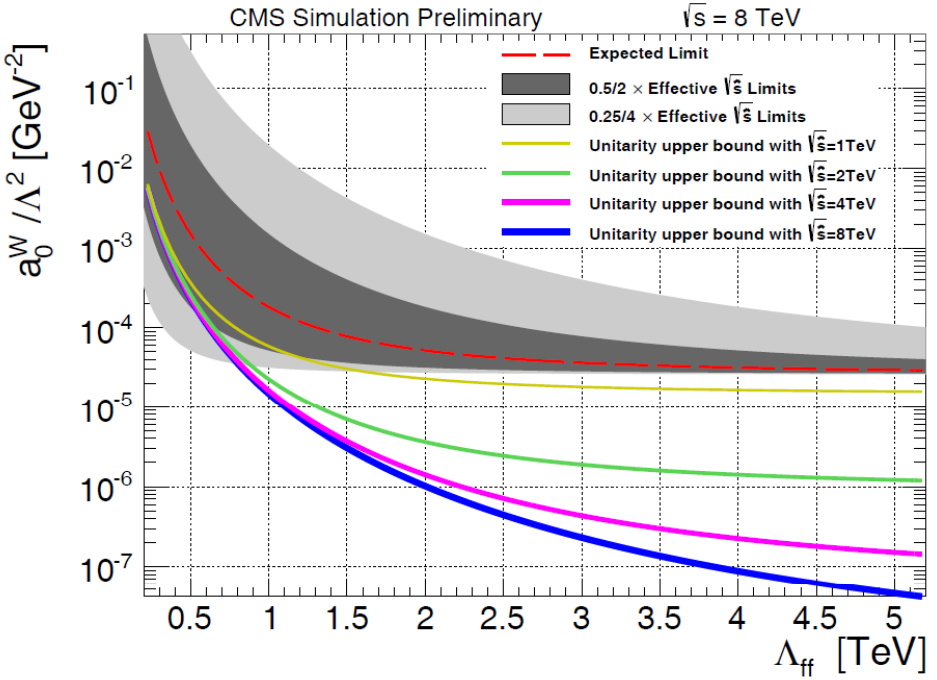
Unitarity issue

- But: any non-zero aQGC will violate unitarity
- Unitarization attempt: dipole form factor with n=2

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

  - Damps high-ŝ events to **zero**, little effect on low-ŝ events
  - Plot: approx 2→2 unitarity upper bounds .vs. Λ_{FF} for several √ŝ

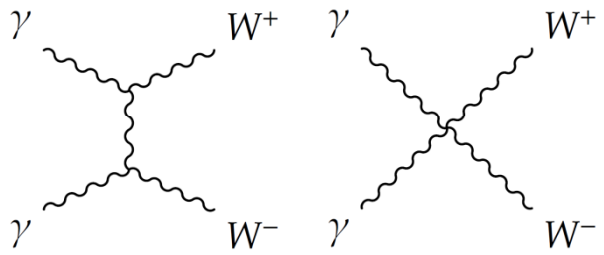
- Conclusion
  - typically √ŝ = 2 TeV for the values of aQGC parameters close to measured limit (green curve)
  - Expected ~ observed limit (dashed red line) always above this unitarity limit
  - **Limit is in non-unitary region, no matter which Λ_{FF} is chosen**

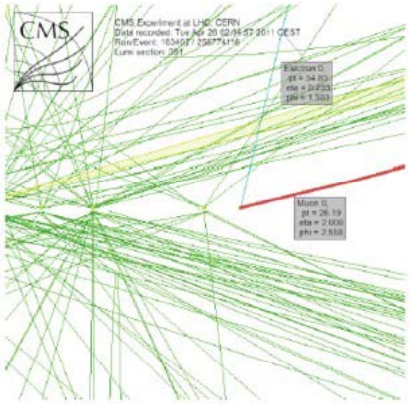


VV(pp) from „exclusive“ γγ→WW

First VV→VV analysis at LHC: γγ→WW

- CMS, 7 TeV, 5.2 fb^{-1}: JHEP 07 (2013) 216,
- Via exclusive or quasi-exclusive W^+W^- production
  $pp \rightarrow p^{(*)}\,\gamma\,\gamma\,p^{(*)} \rightarrow p^{(*)}\,W^+W^-\,p^{(*)} \rightarrow p^{(*)}\,e^+\nu\,\mu^-\nu\,p^{(*)}\,jj\,\gamma$
  in mixed flavor eμ channel
- Both very forward-scattered protons escape detection



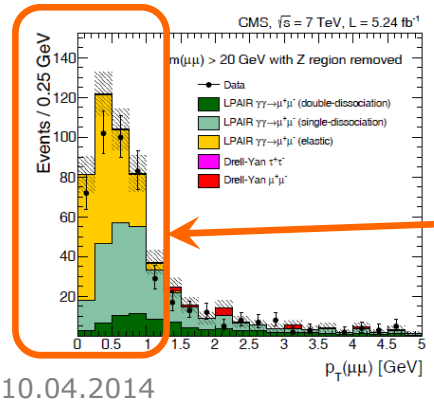


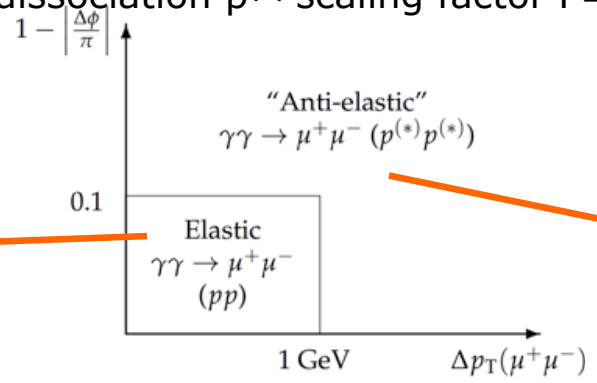
Two major selection variables

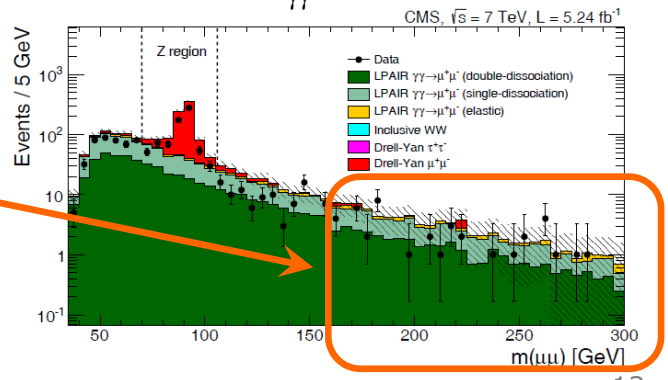
- 0 extra tracks from vertex
- p_T (eμ) > 30 GeV (γγ→WW)
- p_T (eμ) > 100 GeV for aQGC analysis

Important control sample: $\gamma\,\gamma \rightarrow \mu^+\mu^-$

- Exclusive-enriched → test 0-track cut (pileup)
- Quasi-exclusive → dissociation $p^{(*)}$ scaling factor F=3.2±0.5 for $m_{\gamma\gamma}$ > 160 GeV

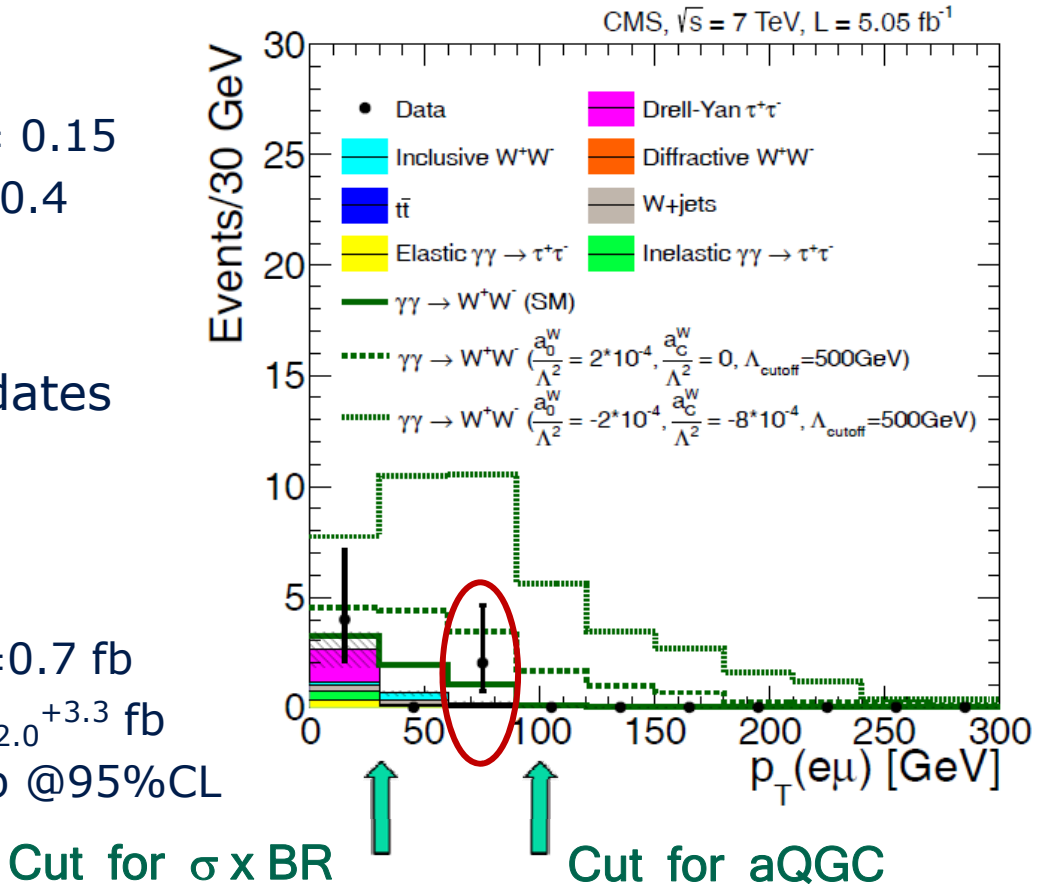






2 candidate events from „exclusive“ pp → ppγγ → ppW⁺W⁻ from CMS in 2013

- Remaining background very small (from control regions)
  - Before p_T (eμ) > 30 GeV : ττ (from Drell-Yan and γγ)
  - After p_T (eμ) > 30 GeV : diffractive WW and W+Jets
- Event yield:
  - Expected bckgr: 0.84 ± 0.15
  - Expected signal: 2.2 ± 0.4
  - Observed: 2
- 2 good γγ →W⁺W⁻ candidates
  - Significance ~ 1 s.d.
- Cross-sections
  - Predicted: σxBR = 4.0±0.7 fb
  - Measured: σxBR = $2.2_{-2.0}^{+3.3}$ fb
  - Upper limit: σ < 10.6fb @95%CL



Limit on aQGC for $\gamma\gamma W^+W^-$

- Cut at p_T (eμ) > 100 GeV : Zero events left
- 1D and 2D limits on a^W_0/Λ^2 and a^W_C/Λ^2
  - 1D Using form factor Λ_{FF} = 500 GeV

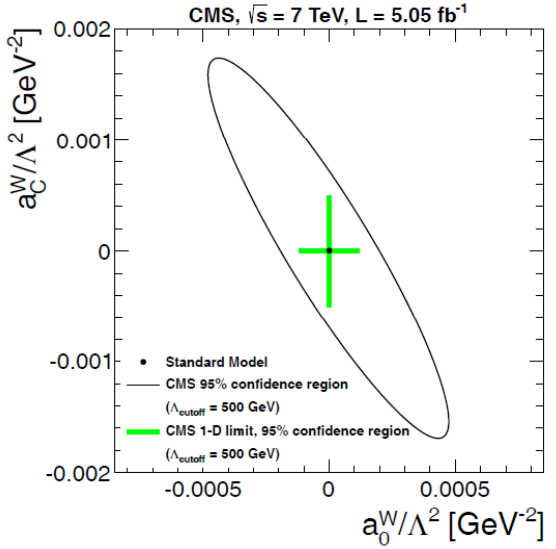
$$-0.00015 < a_0^W/\Lambda^2 < 0.00015\,\mathrm{GeV}^{-2}$$

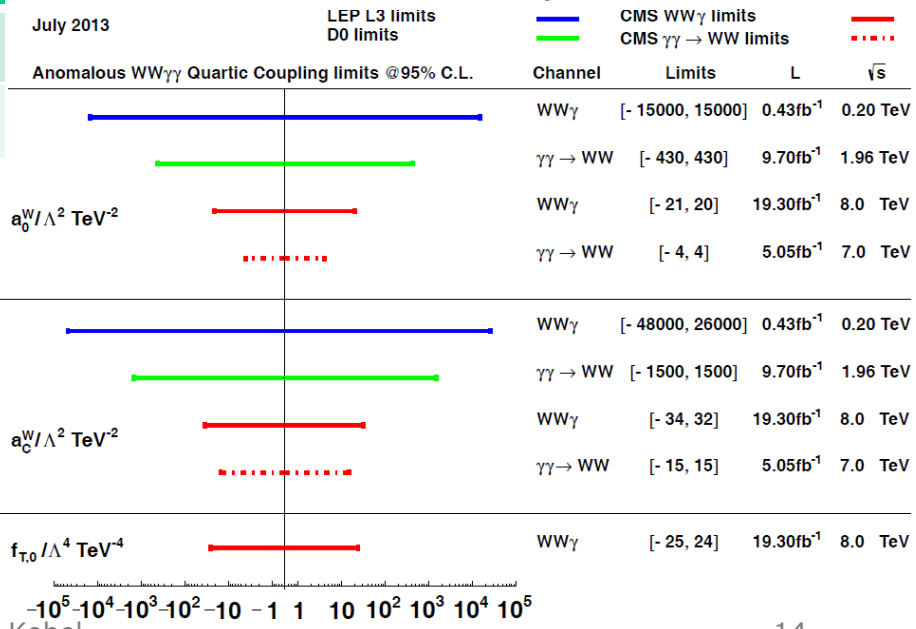
$$-0.0005 < a_C^W/\Lambda^2 < 0.0005\,\mathrm{GeV}^{-2}$$

  - w/o form factor: 30-40 times better, but dominated by $\sqrt{\hat{s}}$ above unitarity
- Comparison of scales Λ for $a^W = 1$

Λ (Λ_{FF})	LEP(0)	D0(500)	CMS(500)	CMS(0)
a^W_0/Λ^2	7 GeV	20 GeV	80 GeV	500 GeV
a^W_C/Λ^2	5 GeV	10 GeV	40 GeV	260 GeV

- Improved un-unitarized limits:
  - ÷100 w.r.t. D0, ÷3000 w.r.t. LEP
  - Same order as from $WW\gamma$
- Unitarized limits possible
  - ÷16 w.r.t. D0
  - Still rather weak

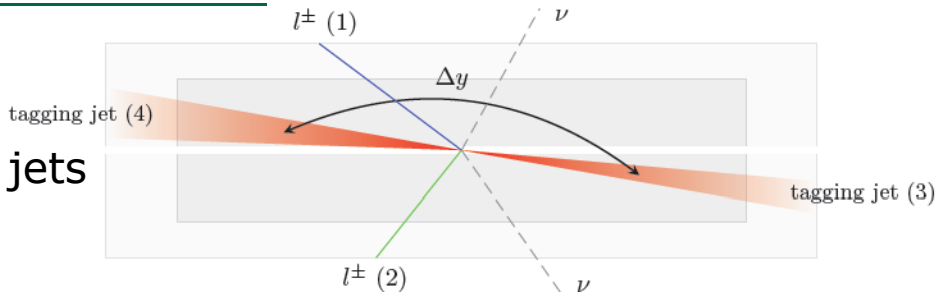




VVjj via Vector Boson Scattering

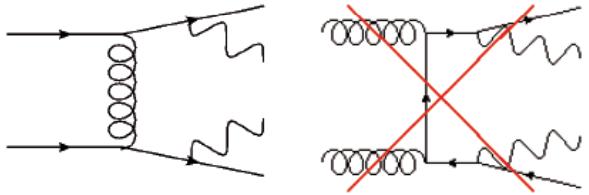
❖ NEW: First massive VV→VV analysis at LHC: $W^{\pm}W^{\pm} \rightarrow W^{\pm}W^{\pm}$

- ATLAS, 8 TeV, 20.3 fb^{-1} , ATLAS-CONF-2014-013
- Distinct qq → VVjj topology:
  - tagging Jets with large Δy
  - leptons from VV → $\ell\nu\ \ell\nu$ between jets

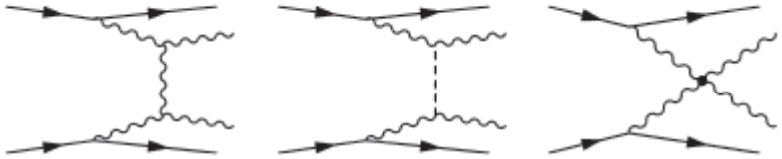


❖ VVjj has two process classes:

- $W^{\pm}W^{\pm}$jj-QCD:= $\mathcal{O}(\alpha_s^2 \times \alpha_W^4)$
  - Lowest order is pp→ $W^{\pm}W^{\pm}$+ **2j**,
  - no gg initial state (special for $W^{\pm}W^{\pm}$) → low background



- $W^{\pm}W^{\pm}$jj-EW:= $\mathcal{O}(\alpha_W^6)$
  - contains VBS part (t-channel +QGC)
  - interf(QCD-EW)~10% included



leading order cross sections (SHERPA) at $\sqrt{s} = 8$ TeV:
(generator cuts: $m_{ll} > 4$ GeV, $p_T^l > 5$ GeV, $p_T^j > 15$ GeV)

Final state	Process	VVjj-EW	VVjj-QCD	Ratio
$\ell^{\pm}\nu\ell'^{\pm}\nu' jj$	$W^{\pm}W^{\pm}$	19.5 fb	18.8 fb	1:1
$\ell^{\pm}\nu\ell^{\mp}\nu jj$	$W^{\pm}W^{\mp} + ZZ$	93.7 fb	3192 fb	1:30
$\ell^{\pm}\ell^{\mp}\ell'^{\pm}\nu' jj$	$W^{\pm}Z$	30.2 fb	687 fb	1:20
$\ell\ell\ell\ell jj$	ZZ	1.5 fb	106 fb	1:70

Two analysis phase spaces

❖ Inclusive Region (EW : QCD ~ 3.5 : 1)

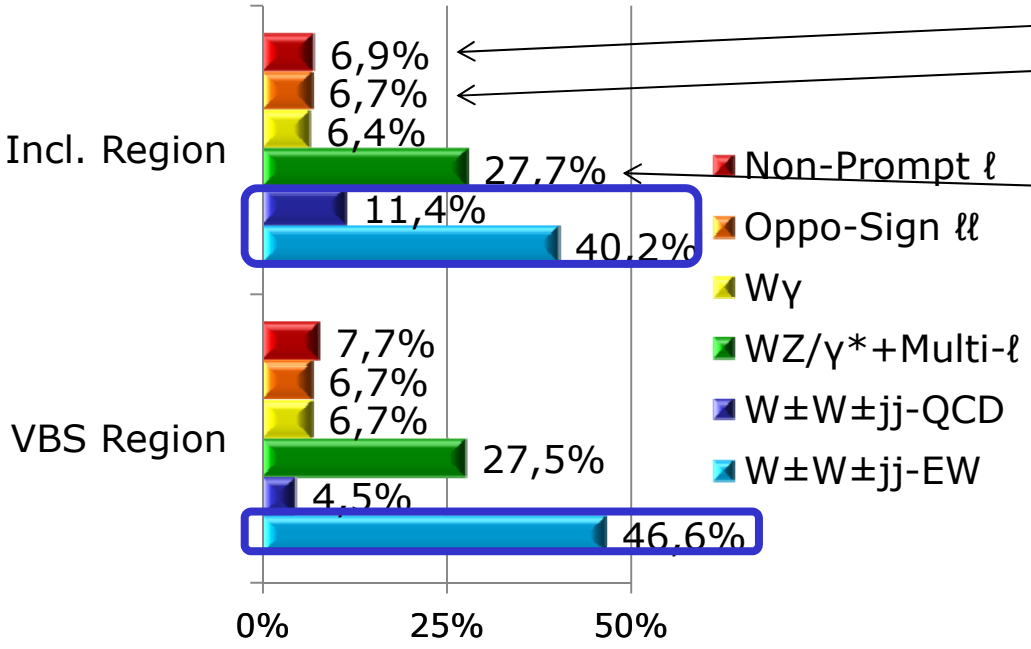
- **Exactly 2(e/μ):** p_T > 25 GeV
- **Neutrinos:** p_T^{miss} > 40 GeV
- **≥2 non-b Jets:** p_T > 30 GeV, m_{jj} > 500 GeV
- Other cuts: $m_{\ell\ell}$>20GeV, $\Delta R(\ell)$>0.3, Z→ee veto

Measure $W^{\pm}W^{\pm}jj$ (incl. EW, QCD)

❖ VBS Region (EW : QCD ~ 10 : 1)

- **Rapidity gap:** Δy_{jj} > 2.4

Measure $W^{\pm}W^{\pm}jj$ EW and set aQGC limits

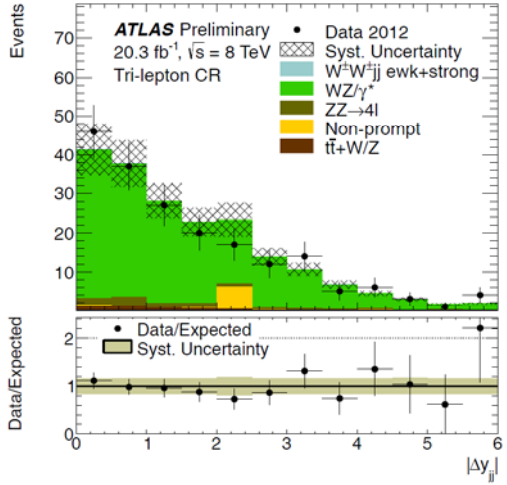


❖ Data driven background

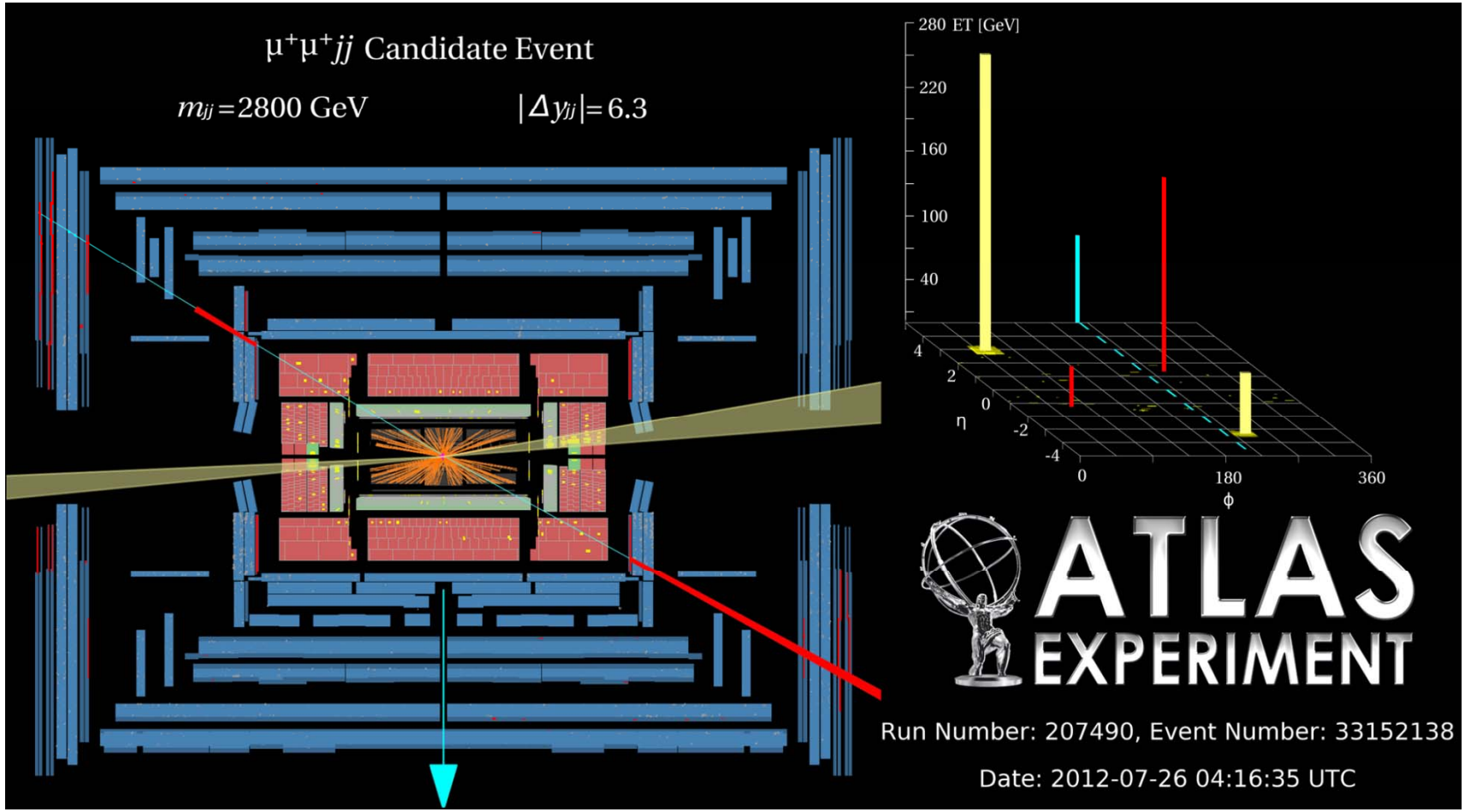
- Fake leptons (W+Jets, …)
- Charge mis-ID (Z+jets,…)

❖ Control regions

- Lost lepton (WZ/γ*+Jets, …)
- …



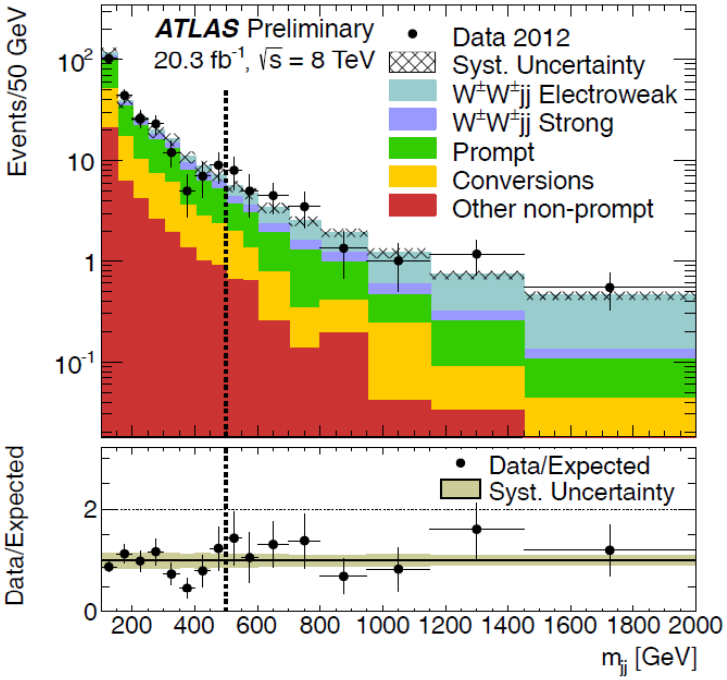
Candidate event



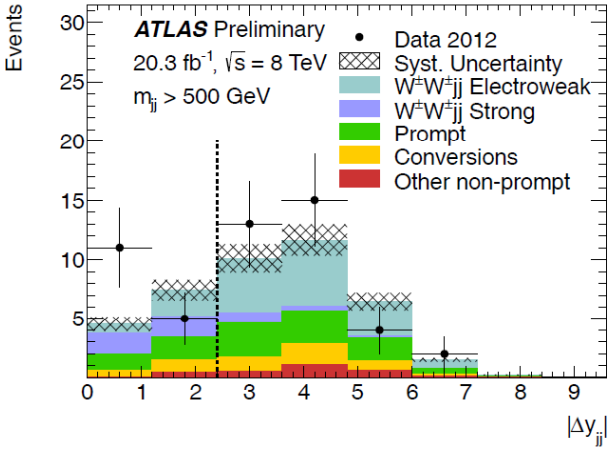
- $p_T(j_1)$ = 271 GeV, $p_T(j_2)$ =54 GeV

Result: Kinematics and cross-section

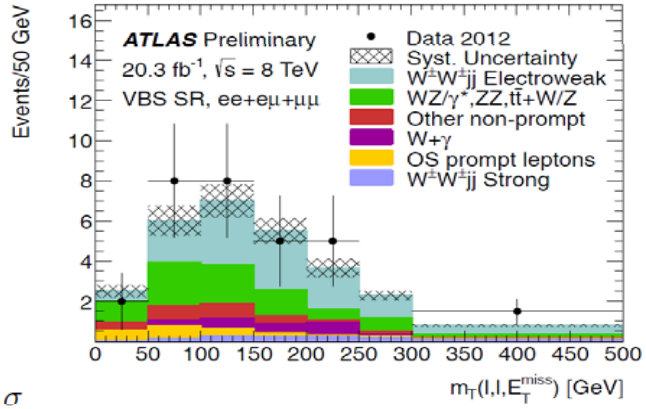
- Inclusive region: m_{jj} before cut



- VBS region: Δy_{jj} before cut



- VBS region: $m_T(\ell_1,\ell_2, p_T^{miss})$



- Cross-section from event counting

inclusive region (EW+QCD)	$\sigma_{fid} = 2.1 \pm 0.5(stat) \pm 0.3(syst)$ fb	4.5 σ
VBS signal region (EW)	$\sigma_{fid} = 1.3 \pm 0.4(stat) \pm 0.2(syst)$ fb	3.6 σ

theory prediction (PowhegBox + Pythia8):

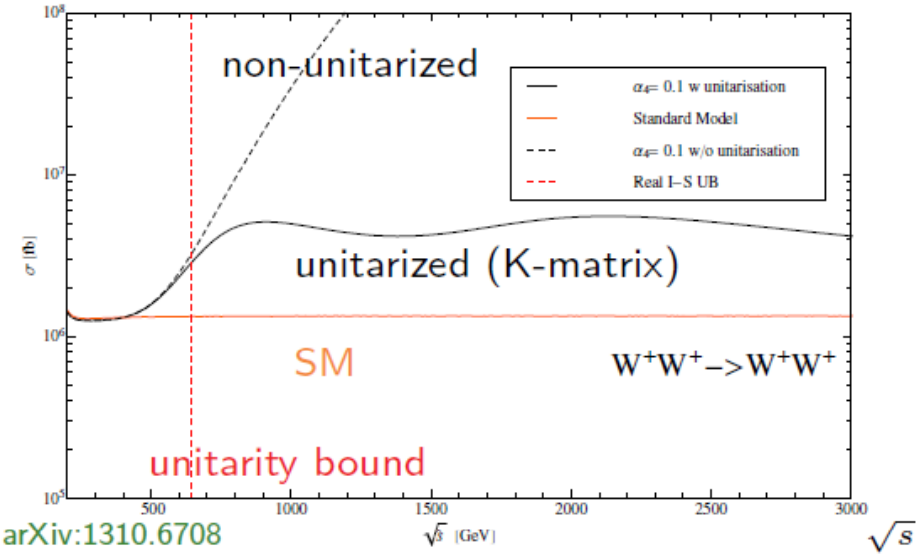
inclusive region (EW+QCD)	$\sigma_{SM} = 1.52 \pm 0.11$ fb	3.4 σ
VBS signal region (EW)	$\sigma_{SM} = 0.95 \pm 0.06$ fb	2.8 σ

- **$W^\pm W^\pm \rightarrow W^\pm W^\pm$ is first ever observation of electroweak VBS VV→VV**

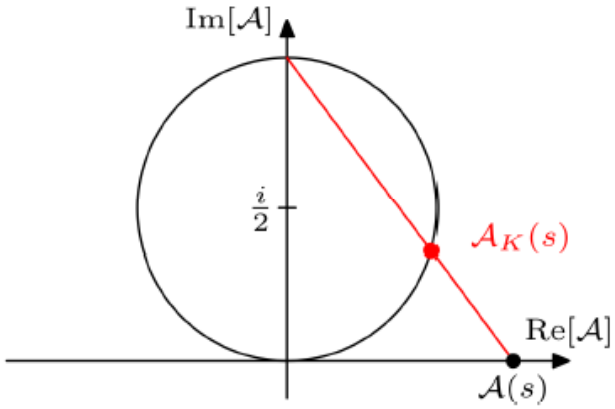
Limits on aQGCs in $W^{\pm}W^{\pm}W^{\pm}W^{\pm}$ vertex

❖ Unitarization:

- **K-matrix** method (WHIZARD arXiv:0806.4145)
  - projecting the scattering amplitude $\mathcal{A}(s)$ on the Argand circle → saturation of the amplitude
  - retains the property of probing the entire kinematic phase space without being unphysical
  - only available for $2 \to 2$ processes so far



arXiv:1310.6708

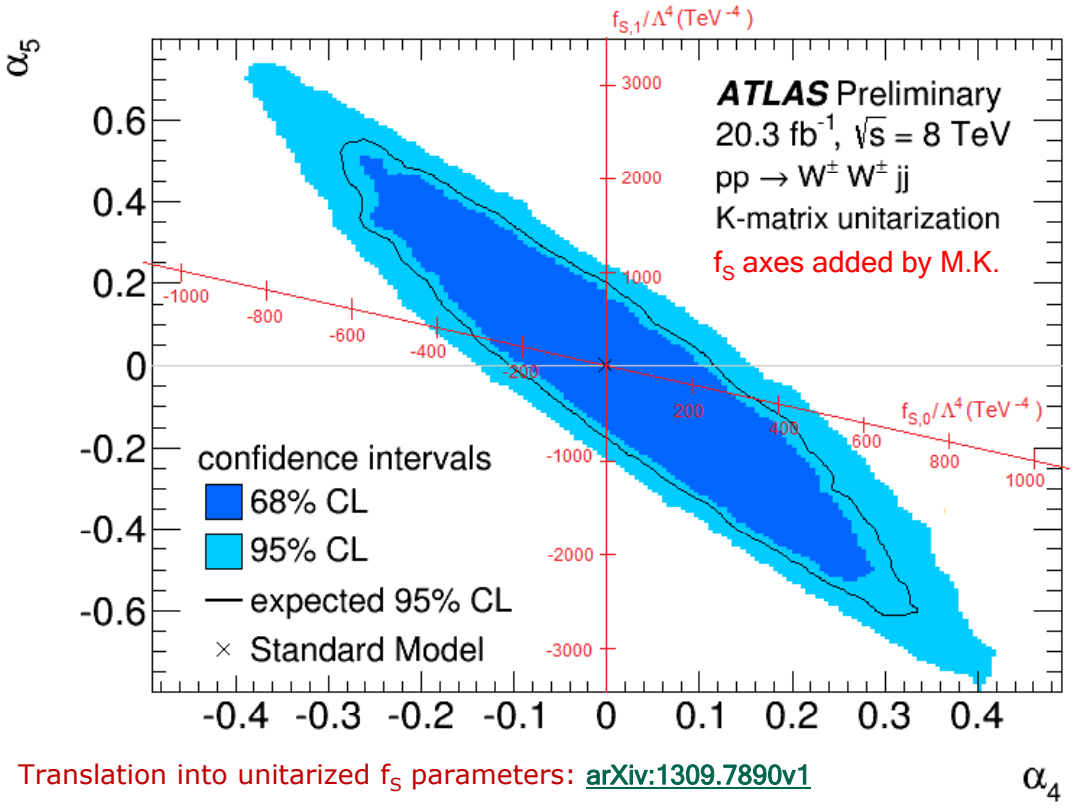


WHIZARD cross section for $W^+W^+ \to W^+W^+$ with anomalous quartic gauge coupling α_4

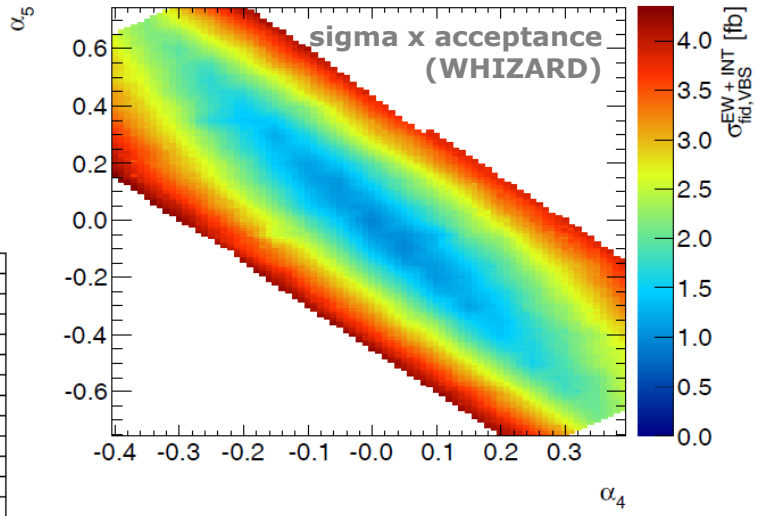
Slide by Anja Vest, TU Dresden

Limits on K-Matrix-unitarized aQGCs

- Extracted from **cross-section** in VBS phase space
  - Fine grid of sigma x acceptance from WHIZARD w/ K-matrix
  - Acceptance strongly, efficiency only weakly dependent on aQGC



Translation into unitarized f_S parameters: arXiv:1309.7890v1



- 1-d limits expected
  - $-0.10 < \alpha_4 < 0.12$
    $-0.18 < \alpha_5 < 0.20$
- **1-d limits observed**
  - **$-0.14 < \alpha_4 < 0.16$**
    $-0.23 < \alpha_5 < 0.24$
  - With $\Lambda \sim v/\sqrt{\alpha}$ (arxiv 1307.8170)
    $\Lambda > 500 - 650$ GeV

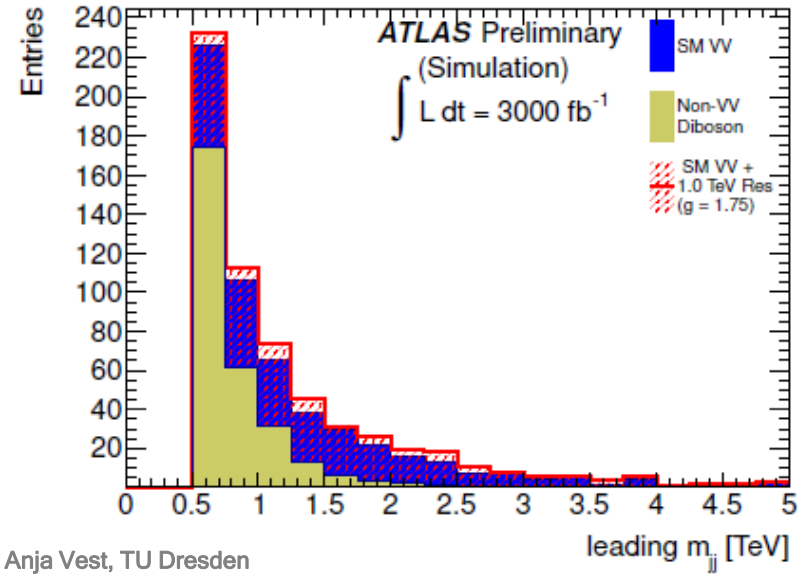
Outlook: LHC@14 TeV : resonances

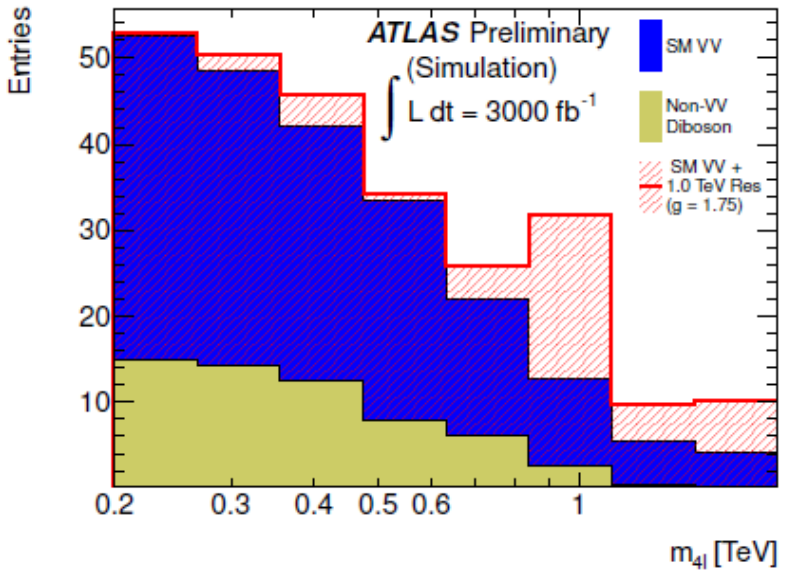
❖ European strategy CERN-ESG-005, ATLAS-PHYS-PUB-2012-005

- LHC @ 14 TeV $\rightarrow$ VBS centre-of-mass energy of $\sim 1-2$ TeV
- signal: anomalous VBS ZZ tensor singlet resonance f^0

  $\rightarrow$ signal chosen is a hard benchmark, sensitivity higher for other resonances

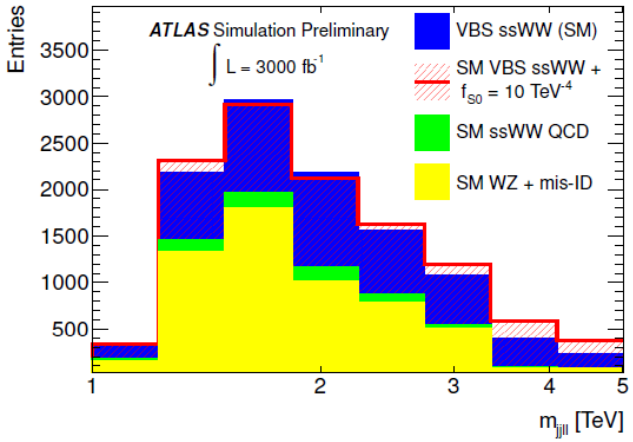
$m_{\text{resonance}}$	coupling	width	300 fb^{-1}	3000 fb^{-1}
500 GeV	$g = 1$	$\Gamma = 2$ GeV	2.4σ	7.5σ
1 TeV	$g = 1.75$	$\Gamma = 50$ GeV	1.7σ	5.5σ
1 TeV	$g = 2.5$	$\Gamma = 100$ GeV	3.0σ	9.4σ

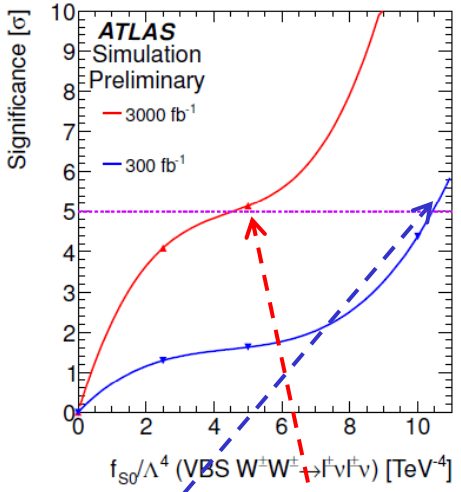




Outlook: LHC@14 TeV: aQGCs

- Snowmass Studies 2013: ATLAS-PHYS-PUB-2013-006
  - Example: Fully simulated $W^{\pm}W^{\pm}jj$ events under high pileup conditions





  - Sensitivity for studies in untarity conserving region $\sqrt{\hat{s}} < \Lambda_{UV}$

Parameter	dimension	channel	Λ_{UV} [TeV]	300 fb^{-1}		3000 fb^{-1}	
				5σ	95% CL	5σ	95% CL
$c_{\phi W}/\Lambda^2$	6	ZZ	1.9	34 TeV^{-2}	20 TeV^{-2}	16 TeV^{-2}	9.3 TeV^{-2}
f_{S0}/Λ^4	8	$W^{\pm}W^{\pm}$	2.0	10 TeV^{-4}	6.8 TeV^{-4}	4.5 TeV^{-4}	0.8 TeV^{-4}
f_{T1}/Λ^4	8	WZ	3.7	1.3 TeV^{-4}	0.7 TeV^{-4}	0.6 TeV^{-4}	0.3 TeV^{-4}
f_{T8}/Λ^4	8	$Z\gamma\gamma$	12	0.9 TeV^{-4}	0.5 TeV^{-4}	0.4 TeV^{-4}	0.2 TeV^{-4}
f_{T9}/Λ^4	8	$Z\gamma\gamma$	13	2.0 TeV^{-4}	0.9 TeV^{-4}	0.7 TeV^{-4}	0.3 TeV^{-4}

Table 5: 5σ-significance discovery values and 95% CL limits for coefficients of higher-dimension operators. Λ_{UV} is the unitarity violation bound corresponding to the sensitivity with 3000 fb^{-1} of integrated luminosity.

Summary

- First results from LHC on QGC processes
  = processes involving a VVVV vertex

- Cross-sections
  - CMS: $\sigma(WW\gamma + WZ\gamma) < 241$ fb (< 3.4 x SM)
  - CMS: $\sigma(\gamma\gamma \rightarrow W^+W^-) \times BR = 2.2^{+3.3}_{-2.0}$ fb ~ 1 s.d.
  - ATLAS: $\sigma(pp \rightarrow W^\pm W^\pm jj\text{-EW}) \times BR = 1.3 \pm 0.4 \pm 0.2$ fb 3.6. s.d.

    → **first observation of Vector Boson Scattering**

- Rough sensitivity scales Λ from aQGC limits

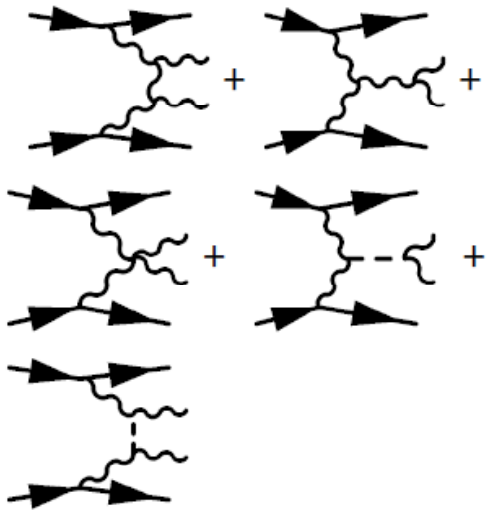
Λ	CMS $\gamma \rightarrow WW\gamma$, $W \rightarrow WZ\gamma$	CMS $\gamma\gamma \rightarrow W^+W^-$	ATLAS $W^\pm W^\pm \rightarrow W^\pm W^\pm$
Un- unitarized	220 GeV	260-500 GeV	not given
unitarized	-	40- 80 GeV	500-650 GeV

- Further 8 TeV results expected
- 13/14 TeV data will vastly increase the sensitivity range

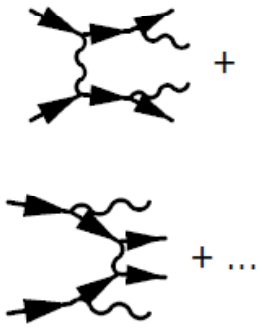
BACKUP

Event classification

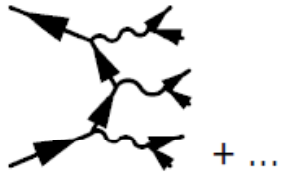
- VVjj-EW (V=W,Z)



VV scattering diagrams
(including triple and quartic gauge vertices, Higgs channels



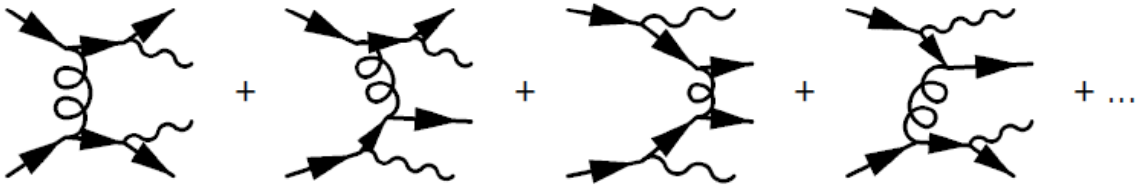
non-VBS EW diagrams
(not gauge invariantly separable)



VVV diagrams
(same $\mathcal{O}(EW)$, but can be gauge invariantly separated and suppressed by VBS topology cuts)

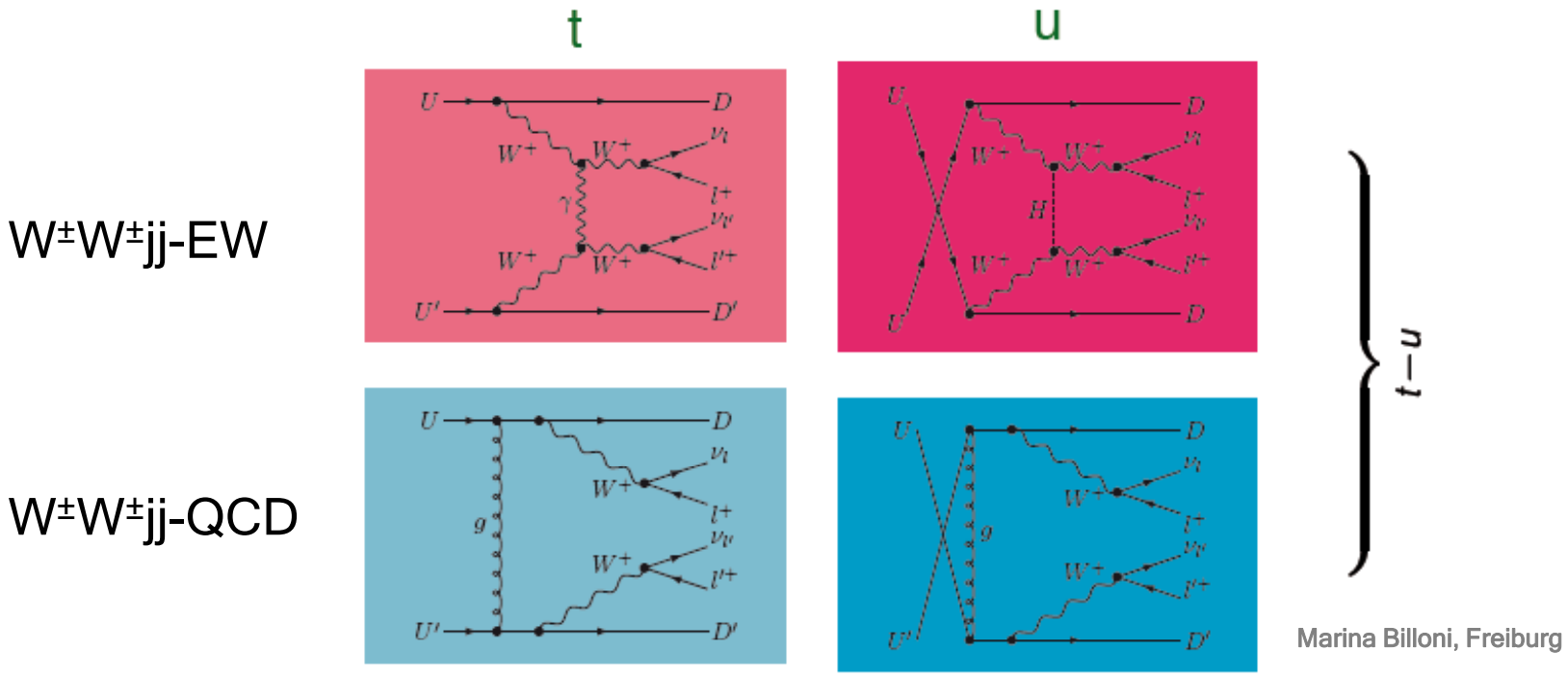
- VVjj-QCD

VVjj-QCD diagrams: $\mathcal{O}(EW) = 4 \bigoplus \mathcal{O}(QCD) = 2$



- Same final state, some kinematic suppression possible

Interference between EW and QCD



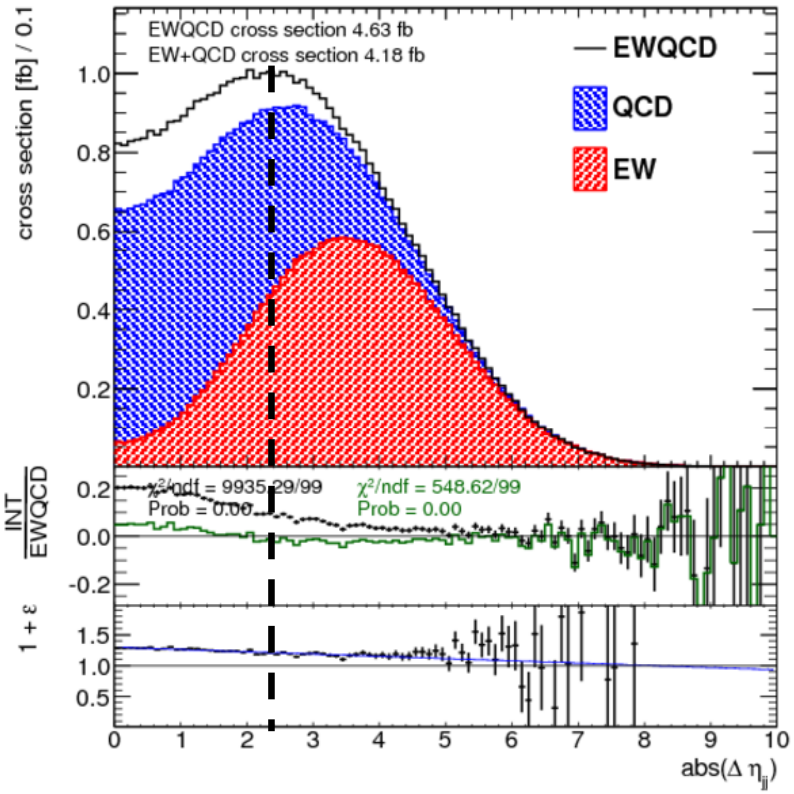
- Investigated using SHERPA

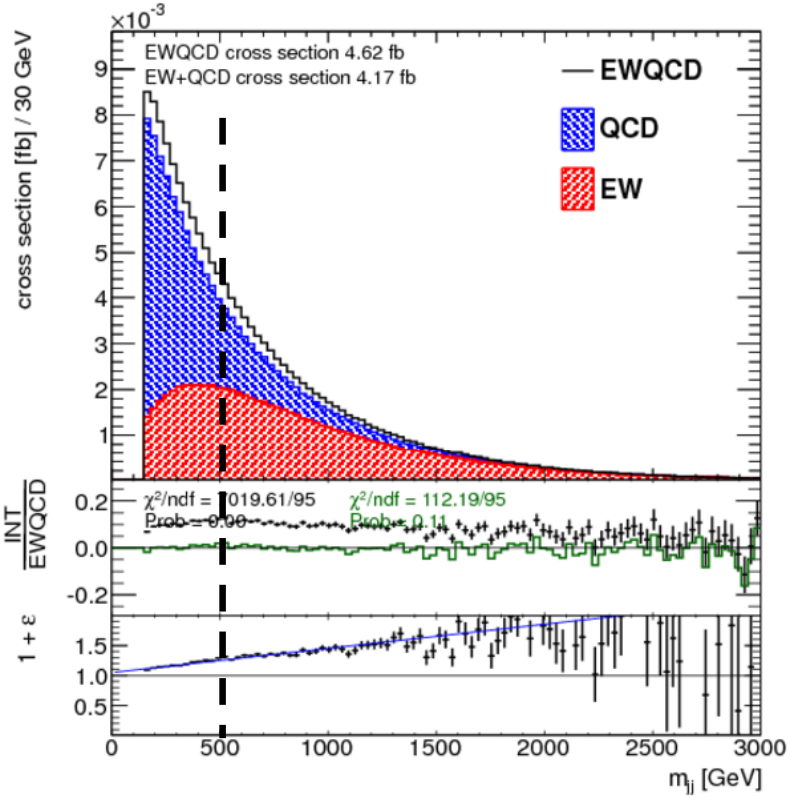
$$EWQCD := |EW + QCD|^2 =: |EW|^2 + INT + |QCD|^2$$

$$approximate\ finding: \ INT \approx +0.23 \sqrt{|EW|^2 |QCD|^2}$$

QCD-EW interf. in SHERPA, generator level

- Bachelor thesis, Nico Madysa, TU Dresden:





- in signal regions:

	QCD	int	EW	signal
incl	**0.35 fb**	**0.17 fb**	**1.00 fb**	**1.52 fb**
VBS	0.10 fb	**0.07 fb**	**0.88 fb**	**0.95 fb**

MC simulation

❖ Generators used for VVjj processes

LO

SHERPA

extensive sample production for VVjj-EW and VVjj-QCD (WW,WZ,ZZ) with ME+PS merging

WHIZARD

Validation of Sherpa; anomalous QGC

NLO

VBFNLO

EW contribution for $W^{\pm}W^{\pm}$ and $W^{\pm}Z$;
VVjj-QCD for $W^{\pm}Z$

POWHEGBOX

VVjj-QCD for $W^{\pm}W^{\pm}$

MADGRAPH

$t\bar{t}$ + $W^{\pm}Z$

U.Schnoor, DPG, Dresden 03/2013

Quartic gauge couplings beyond SM

Dimension 8 couplings

- operator assignment to vertices:

	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

measurements: VBS WW $WZ\gamma$ $WW\gamma$ + WWγγ

ATLAS-CONF-2014-013 CMS-PAS-SMP-13-009 JHEP 07 (2013) 216

$$\mathcal{O}_{S,0} = \left[(D_\mu\Phi)^\dagger D_\nu\Phi\right] \times \left[(D^\mu\Phi)^\dagger D^\nu\Phi\right] ,$$
$$\mathcal{O}_{S,1} = \left[(D_\mu\Phi)^\dagger D^\mu\Phi\right] \times \left[(D_\nu\Phi)^\dagger D^\nu\Phi\right] ,$$

$$\mathcal{O}_{M,0} = \mathrm{Tr}\left[W_{\mu\nu}W^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right]$$
$$\mathcal{O}_{M,1} = \mathrm{Tr}\left[W_{\mu\nu}W^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right]$$
$$\mathcal{O}_{M,2} = \left[B_{\mu\nu}B^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right] ,$$
$$\mathcal{O}_{M,3} = \left[B_{\mu\nu}B^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right] ,$$
$$\mathcal{O}_{M,4} = \left[(D_\mu\Phi)^\dagger W_{\beta\nu}D^\mu\Phi\right] \times B^{\beta\nu} ,$$
$$\mathcal{O}_{M,5} = \left[(D_\mu\Phi)^\dagger W_{\beta\nu}D^\nu\Phi\right] \times B^{\beta\mu} ,$$
$$\mathcal{O}_{M,6} = \left[(D_\mu\Phi)^\dagger W_{\beta\nu}W^{\beta\nu}D^\mu\Phi\right] ,$$
$$\mathcal{O}_{M,7} = \left[(D_\mu\Phi)^\dagger W_{\beta\nu}W^{\beta\mu}D^\nu\Phi\right] ,$$

$$\mathcal{O}_{T,0} = \mathrm{Tr}\left[W_{\mu\nu}W^{\mu\nu}\right] \times \mathrm{Tr}\left[W_{\alpha\beta}W^{\alpha\beta}\right] ,$$
$$\mathcal{O}_{T,1} = \mathrm{Tr}\left[W_{\alpha\nu}W^{\mu\beta}\right] \times \mathrm{Tr}\left[W_{\mu\beta}W^{\alpha\nu}\right] ,$$
$$\mathcal{O}_{T,2} = \mathrm{Tr}\left[W_{\alpha\mu}W^{\mu\beta}\right] \times \mathrm{Tr}\left[W_{\beta\nu}W^{\nu\alpha}\right] ,$$
$$\mathcal{O}_{T,5} = \mathrm{Tr}\left[W_{\mu\nu}W^{\mu\nu}\right] \times B_{\alpha\beta}B^{\alpha\beta} ,$$
$$\mathcal{O}_{T,6} = \mathrm{Tr}\left[W_{\alpha\nu}W^{\mu\beta}\right] \times B_{\mu\beta}B^{\alpha\nu} ,$$
$$\mathcal{O}_{T,7} = \mathrm{Tr}\left[W_{\alpha\mu}W^{\mu\beta}\right] \times B_{\beta\nu}B^{\nu\alpha} ,$$
$$\mathcal{O}_{T,8} = B_{\mu\nu}B^{\mu\nu}B_{\alpha\beta}B^{\alpha\beta}$$
$$\mathcal{O}_{T,9} = B_{\alpha\mu}B^{\mu\beta}B_{\beta\nu}B^{\nu\alpha} .$$

- Chiral Lagrangian and translation into resonances
  - e.g. J. Reuter, talk at Bonn and http://arxiv.org/abs/hep-ph/0604048

Electroweak Chiral Lagrangian

Complete Lagrangian contains infinitely many parameters

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{min}} - \sum_{\psi} \overline{\psi}_L \Sigma M \psi_R + \beta_1 \mathcal{L}_0' + \sum_i \alpha_i \mathcal{L}_i + \frac{1}{v} \sum_i \alpha_i^{(5)} \mathcal{L}^{(5)} + \frac{1}{v^2} \sum_i \alpha_i^{(6)} \mathcal{L}^{(6)} + \dots$$

$$\mathcal{L}_0' = \frac{v^2}{4} \text{tr}\left[\mathbf{T}\mathbf{V}_\mu\right] \text{tr}\left[\mathbf{T}\mathbf{V}^\mu\right]$$

$$\mathcal{L}_1 = \text{tr}\left[\mathbf{B}_{\mu\nu}\mathbf{W}^{\mu\nu}\right]$$
$$\mathcal{L}_2 = \text{itr}\left[\mathbf{B}_{\mu\nu}[\mathbf{V}^\mu, \mathbf{V}^\nu]\right]$$
$$\mathcal{L}_3 = \text{itr}\left[\mathbf{W}_{\mu\nu}[\mathbf{V}^\mu, \mathbf{V}^\nu]\right]$$
$$\mathcal{L}_4 = \text{tr}\left[\mathbf{V}_\mu\mathbf{V}_\nu\right] \text{tr}\left[\mathbf{V}^\mu\mathbf{V}^\nu\right]$$
$$\mathcal{L}_5 = \text{tr}\left[\mathbf{V}_\mu\mathbf{V}^\mu\right] \text{tr}\left[\mathbf{V}_\nu\mathbf{V}^\nu\right]$$

$$\mathcal{L}_6 = \text{tr}\left[\mathbf{V}_\mu\mathbf{V}_\nu\right] \text{tr}\left[\mathbf{T}\mathbf{V}^\mu\right] \text{tr}\left[\mathbf{T}\mathbf{V}^\nu\right]$$
$$\mathcal{L}_7 = \text{tr}\left[\mathbf{V}_\mu\mathbf{V}^\mu\right] \text{tr}\left[\mathbf{T}\mathbf{V}_\nu\right] \text{tr}\left[\mathbf{T}\mathbf{V}^\nu\right]$$
$$\mathcal{L}_8 = \tfrac{1}{4}\text{tr}\left[\mathbf{T}\mathbf{W}_{\mu\nu}\right] \text{tr}\left[\mathbf{T}\mathbf{W}^{\mu\nu}\right]$$
$$\mathcal{L}_9 = \tfrac{\text{i}}{2}\text{tr}\left[\mathbf{T}\mathbf{W}_{\mu\nu}\right] \text{tr}\left[\mathbf{T}[\mathbf{V}^\mu, \mathbf{V}^\nu]\right]$$
$$\mathcal{L}_{10} = \tfrac{1}{2}\left(\text{tr}\left[\mathbf{T}\mathbf{V}_\mu\right] \text{tr}\left[\mathbf{T}\mathbf{V}^\mu\right]\right)^2$$

Indirect info on new physics in $\beta_1, \alpha_i, \dots$ (Flavor physics only in M)

Effective QGC in VBS

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

$$\mathcal{L}_5 = \alpha_5 \frac{g^2}{2} \left\{ (W^+W^-)^2 + \frac{2}{c_W^2}(W^+W^-)(ZZ) + \frac{1}{2c_W^4}(ZZ)^2 \right\}$$

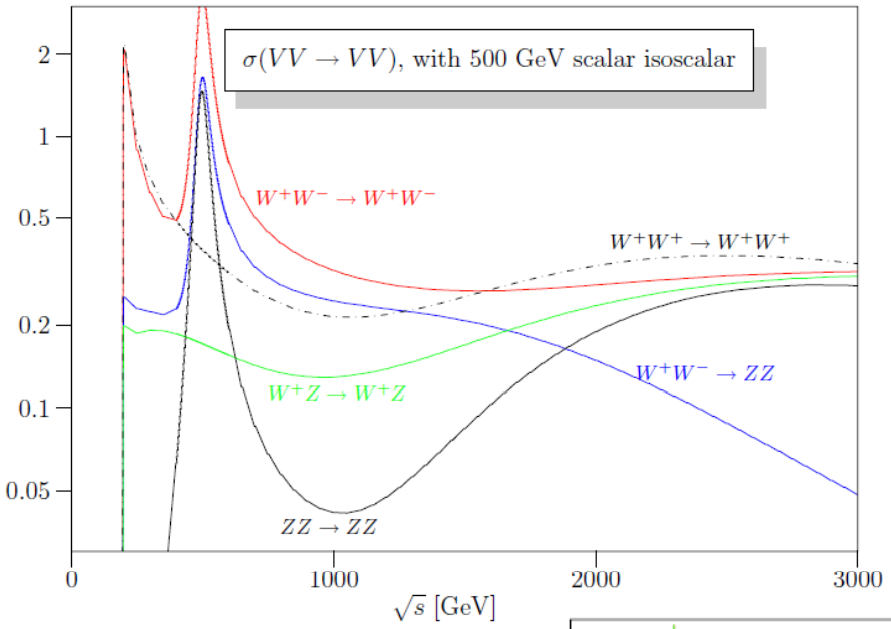
❖ = Effective parametrization of physics beyond kinematic reach

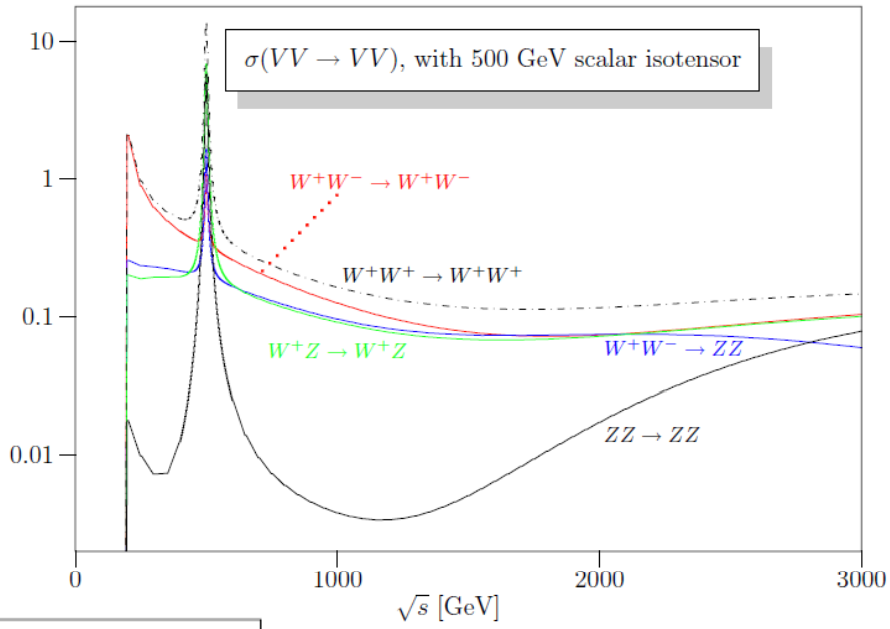
- e.g. resonances at new physics scale $\Lambda = \upsilon / \sqrt{\alpha_i}$
  - Wide: → continuum
  - Narrow: → particles
- α parametrize low-mass tail of these resonances, e.g. $\alpha_5 = g_\sigma^2 \left(\frac{v^2}{8M_\sigma^2} \right)$

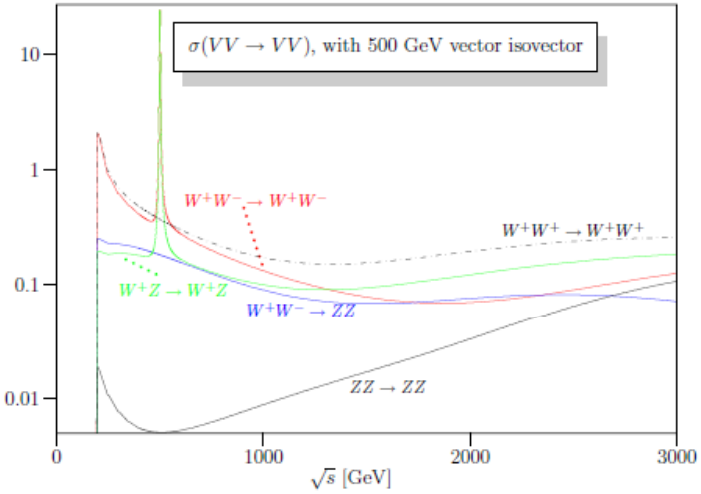
	$J=0$	$J=1$	$J=2$
$I=0$	σ^0 (Higgs ?)	ω^0 (γ'/Z' ?)	f^0 (Graviton ?)
$I=1$	$\pi^\pm, \pi^0$ (2HDM ?)	$\rho^\pm, \rho^0$ (W'/Z' ?)	$a^\pm, a^0$
$I=2$	$\phi^{\pm\pm}, \phi^\pm, \phi^0$ (Higgs triplet ?)	—	$t^{\pm\pm}, t^\pm, t^0$

- Unitarization only guaranteed for
  - Explicitly included resonance(s) at unique value(s) of *g*
  - effective parametrization always violates unitarity at some m_{VV}

Example with resonances (α_4 and α_5=0, no longer needed!)







Ununitarized comparisons WHIZARD - VBFNLO

- Alexander Melzer (bachelor thesis)
- channel: $W^{\pm}W^{\pm}jj$
  - w/o unitarisation

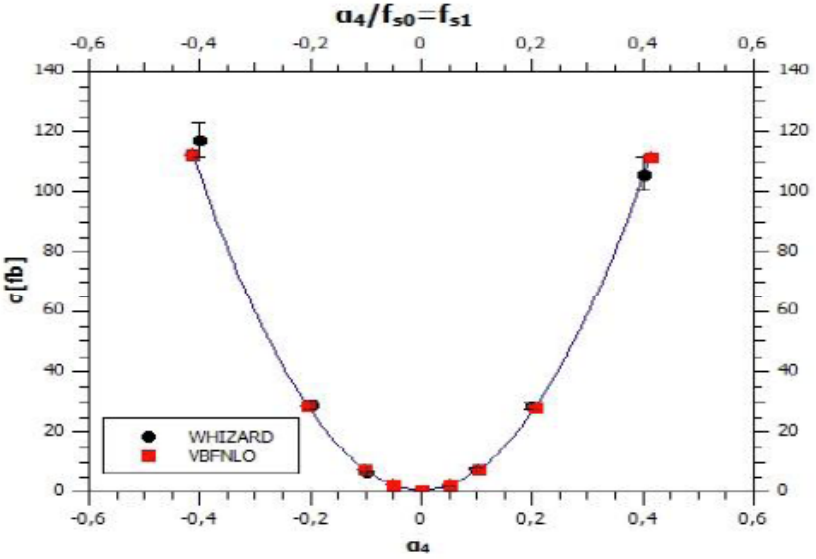
$$\alpha_4 = k\tilde{f}_{s0} \quad (2) \text{ and } \alpha_5 = k\frac{1}{2}\left(\tilde{f}_{s1} - \tilde{f}_{s0}\right)$$

$$\tilde{f} = \frac{f}{\Lambda^4}$$

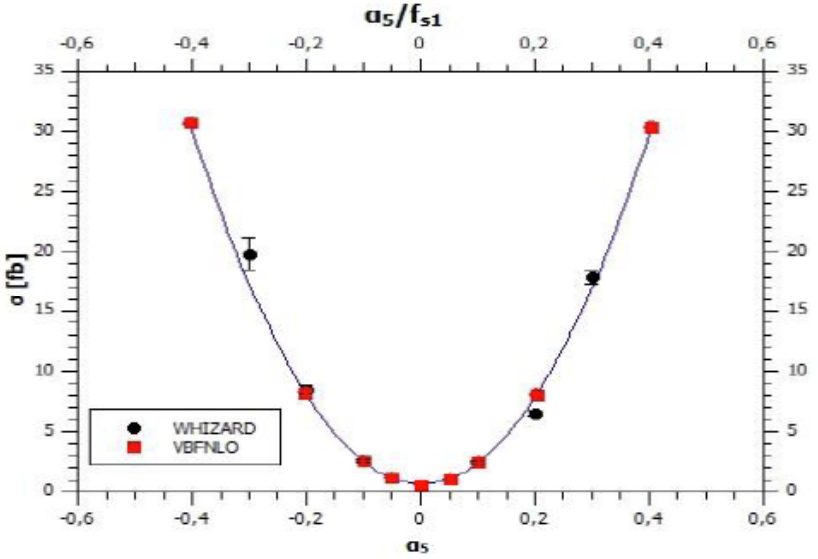
$$k \equiv \frac{v^4}{8\,TeV^4} = \frac{1}{2177}$$

Common Fit of WHIZARD and VBFNLO

scenario (i)

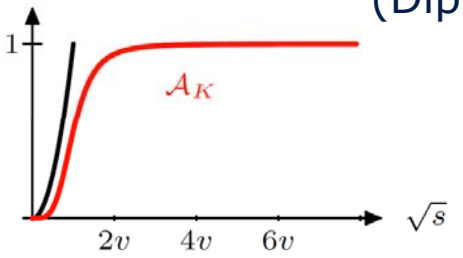


scenario (ii)

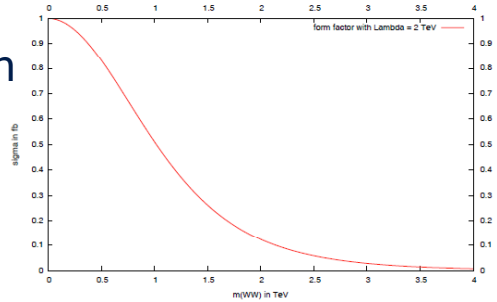


kinematics depending on unitarization model

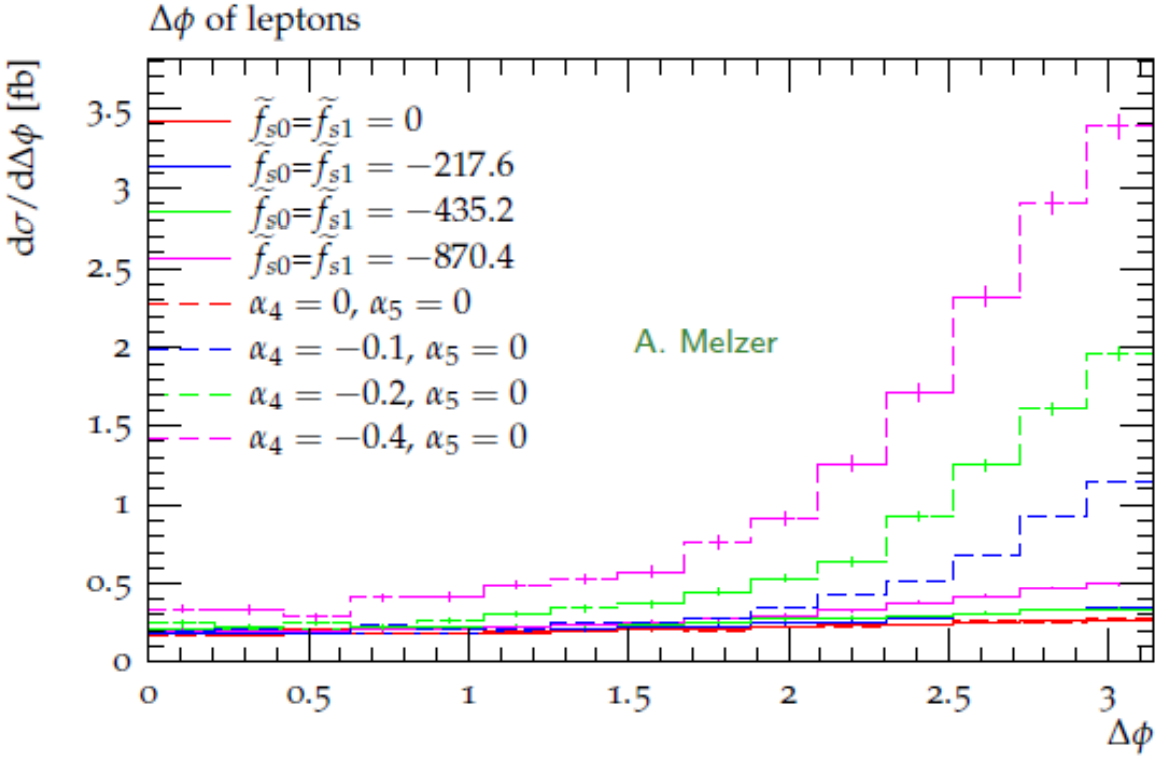
- Carsten Bittrich (CERN-THESIS-2012-259, Bachelor Thesis)
  $W^{\pm}W^{\pm}jj$ with unitarisation
  - WHIZARD unitarisation (K-Matrix)



VBFNLO unitarisation (Dipole Form factor)



Shape of implemented form factor using the parameters $\Lambda_{FF} =$



generator cuts:

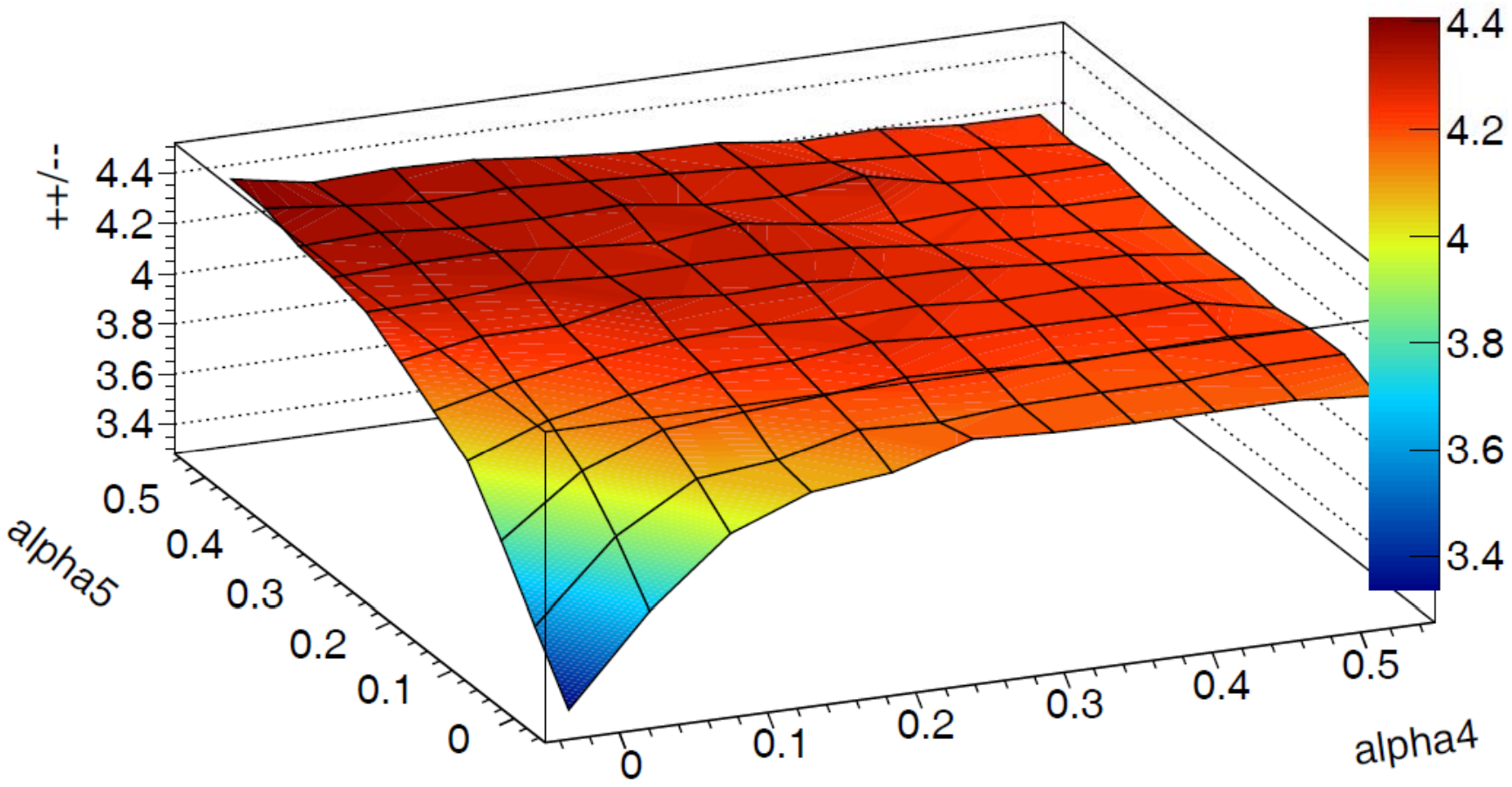
- $p_T^l > 10$ GeV, $|\eta_l| < 5$
- $p_T^j > 20$ GeV, $|\eta_j| < 5$
- $|\Delta R(jj)| > 0.4$
- $m_{jj} > 150$ GeV

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
- $\alpha_5 = 0$

Charge ratio vs aQGC

- WHIZARD Generator simulation (unitarized)

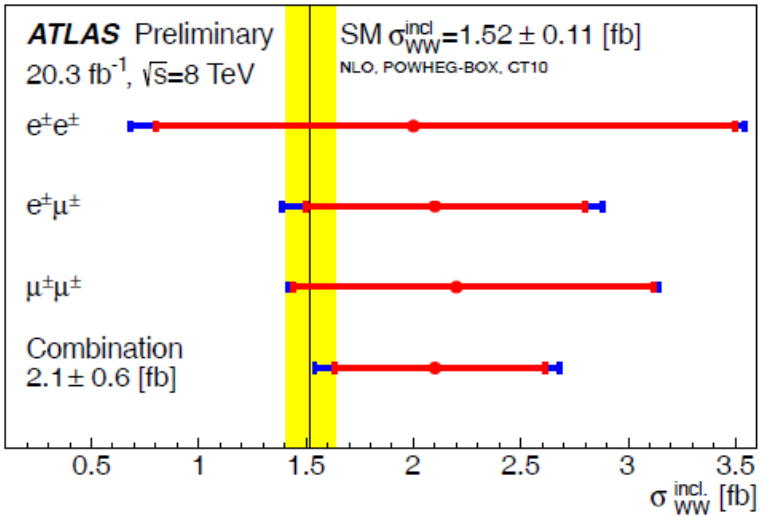


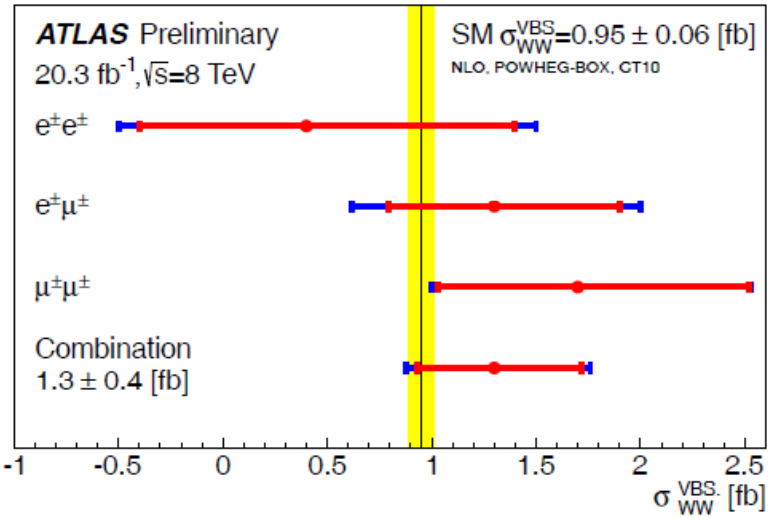
Backup info for: $W^{\pm}W^{\pm}jj$

Fiducial region for cross-section measurements

- Inclusive region:
  - No ME-level τ lepton
  - Two leptons (e or μ) with $p_{\mathrm{T}} > 25$ GeV and $|\eta| < 2.5$
  - Two leptons have same electric charge with $m_{\ell\ell'} > 20$ GeV
  - Two leptons are separated with $\Delta R(\ell\ell') > 0.3$
  - Truth $E_{\mathrm{T}}^{\mathrm{miss}} > 40$ GeV
  - At least two jets with $p_{\mathrm{T}} > 30$ GeV and $|\eta| < 4.5$, reconstructed with the anti-k_{T} algorithm with radius parameter $R = 0.4$
  - Selected leptons and jets are separated with $\min(\Delta R(\ell, jet)) > 0.3$
  - The two leading p_{T} jets have $m_{jj} > 500$ GeV
- VBS region:
  - On top of the inclusive region, reguire the two leading p_{T} jets separated with $|\Delta y_{jj}| > 2.4$

Result broken down in flavors

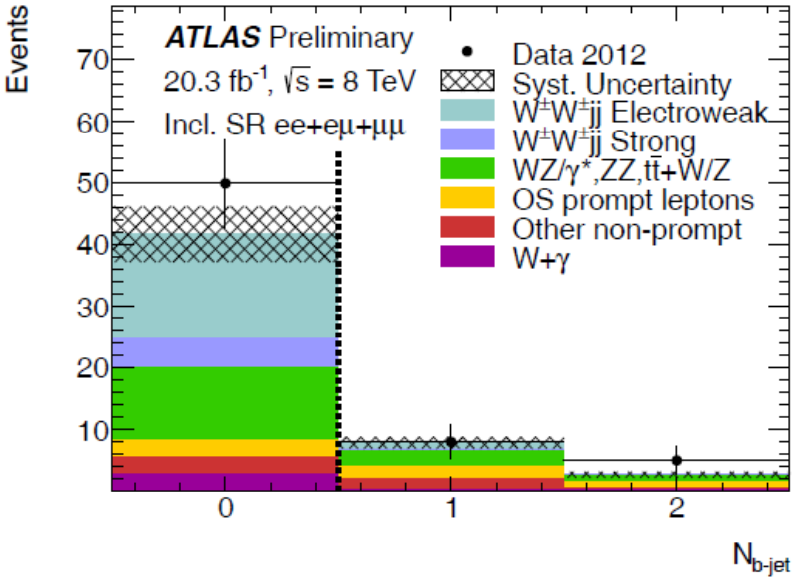


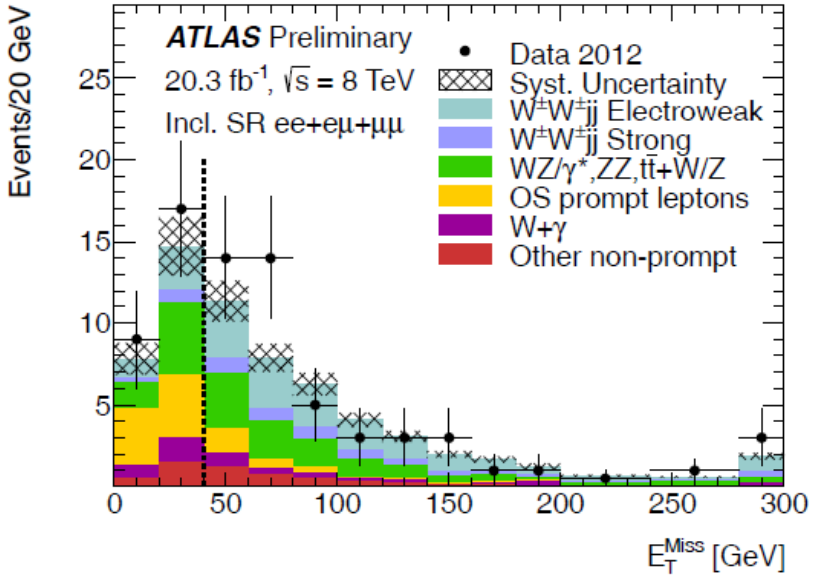


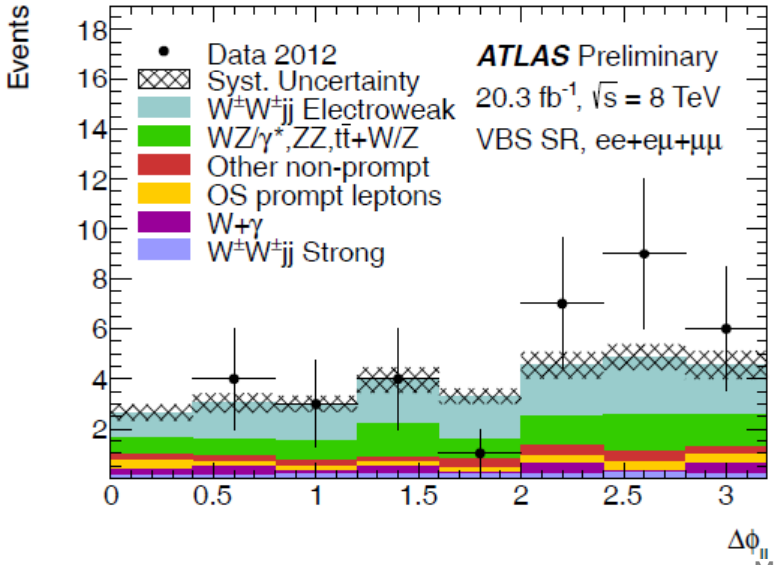
Inclusive Signal Region				
	$e^{\pm}e^{\pm}$	$e^{\pm}\mu^{\pm}$	$\mu^{\pm}\mu^{\pm}$	Total
$W^{\pm}W^{\pm}$jj Electroweak	3.07 ± 0.30	9.0 ± 0.8	4.9 ± 0.5	16.9 ± 1.5
$W^{\pm}W^{\pm}$jj Strong	0.89 ± 0.15	2.5 ± 0.4	1.42 ± 0.23	4.8 ± 0.8
WZ/γ^*,ZZ,$t\bar{t}$+W/Z	3.0 ± 0.7	6.1 ± 1.3	2.6 ± 0.6	11.6 ± 2.5
$W+\gamma$	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

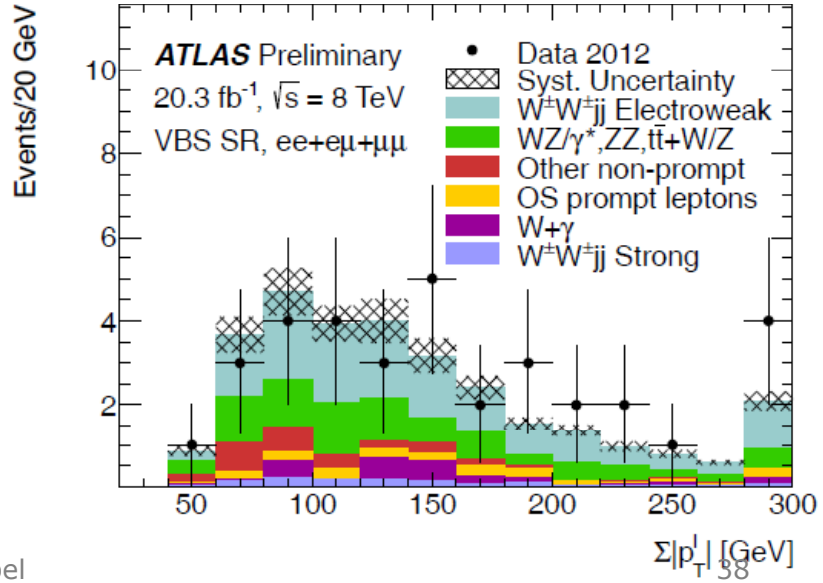
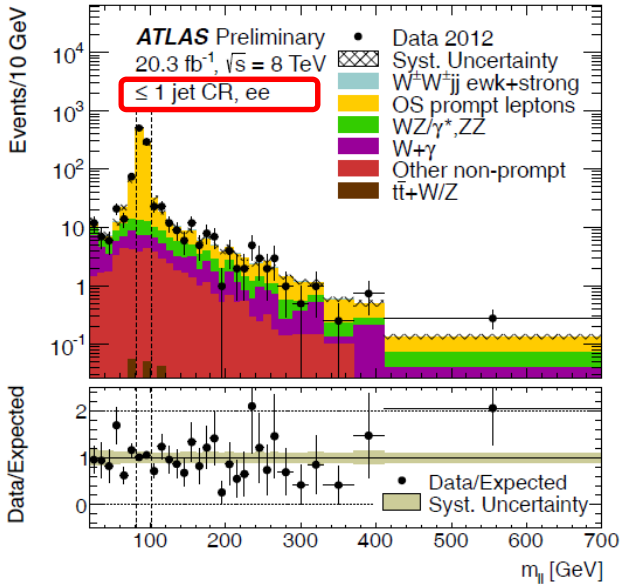
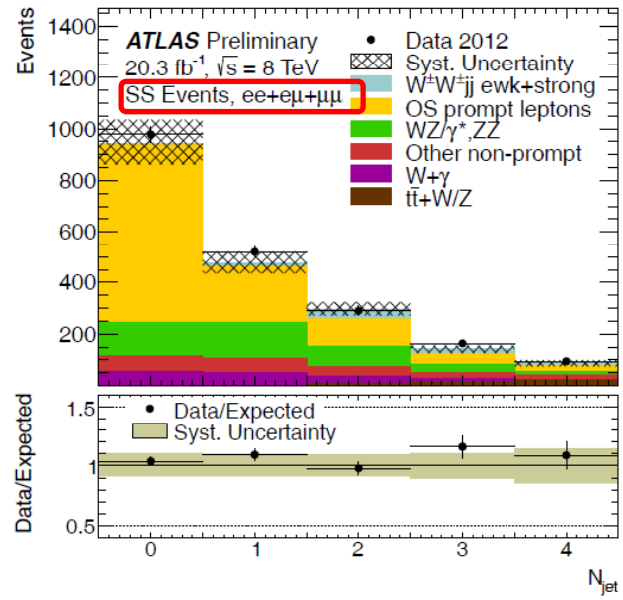
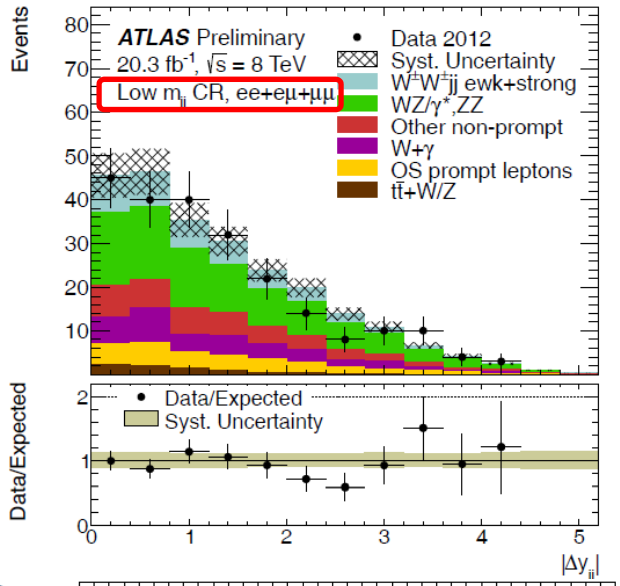
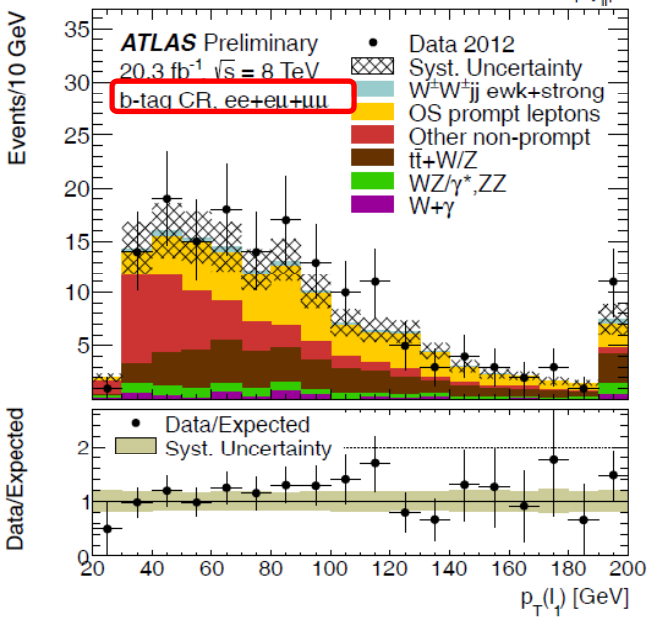
VBS Signal Region			
$e^{\pm}e^{\pm}$	$e^{\pm}\mu^{\pm}$	$\mu^{\pm}\mu^{\pm}$	Total
2.55 ± 0.25	7.3 ± 0.6	4.0 ± 0.4	13.9 ± 1.2
0.25 ± 0.06	0.71 ± 0.14	0.38 ± 0.08	1.34 ± 0.26
2.2 ± 0.5	4.2 ± 1.0	1.9 ± 0.5	8.2 ± 1.9
0.7 ± 0.4	1.3 ± 0.7	–	2.0 ± 1.0
1.39 ± 0.27	0.64 ± 0.24	–	2.0 ± 0.5
0.50 ± 0.26	1.5 ± 0.6	0.34 ± 0.19	2.3 ± 0.7
7.6 ± 1.0	15.6 ± 2.0	6.6 ± 0.8	29.8 ± 3.5
6	18	10	34

Kinematic distributions in signal regions









Control region distributions