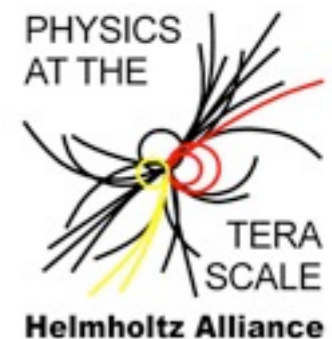


$VVjj$ ($V=W,Z$) final states at LHC

Philipp Anger

TU Dresden, Institut für Kern- und Teilchenphysik



aQGC Workshop - 30th of September 2013

Overview

This talk covers the **experimental** view on VVjj/VBS/aQGC

- ❖ no public results from LHC up to now
 - ❖ just MC studies are allowed to be presented here :-0
 - ❖ see Finn's talk about public results of exclusive $\gamma\gamma \rightarrow WW$
- ❖ focusing on questions to theorists
- ❖ skipping overview of LHC / experiments



Overview

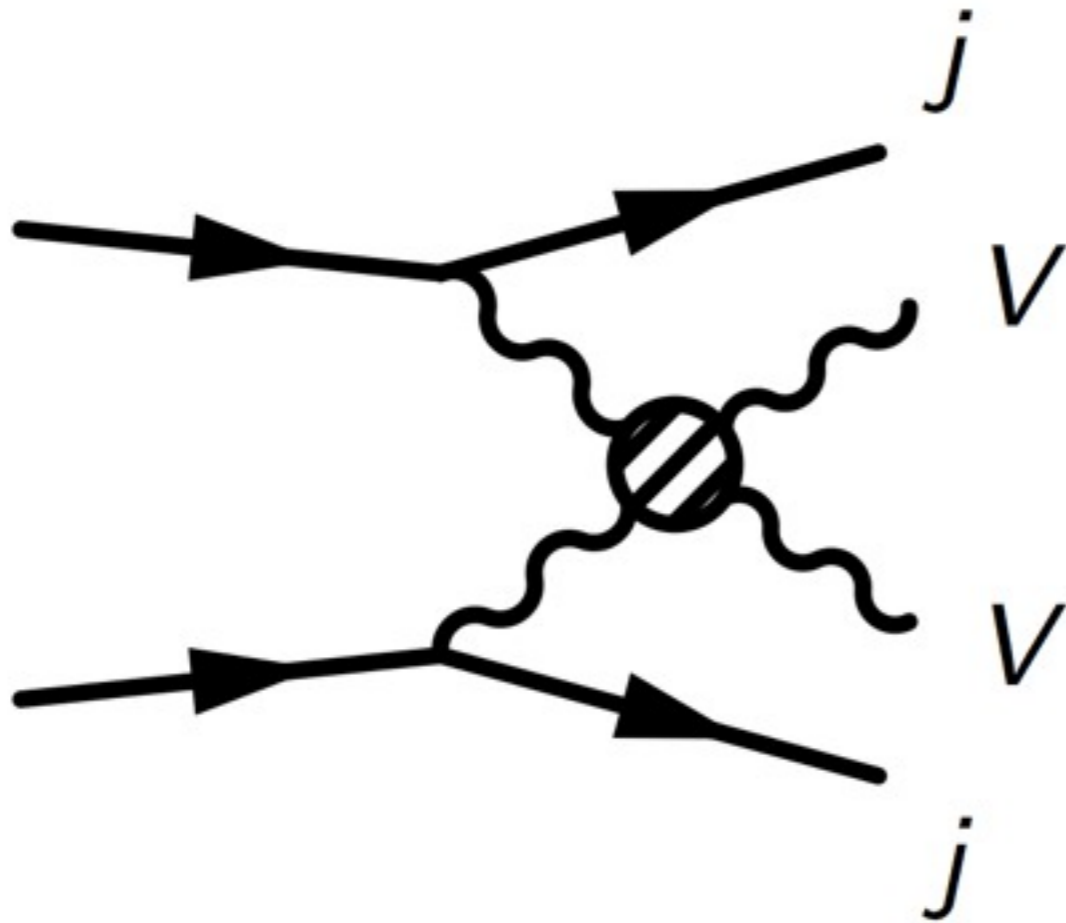
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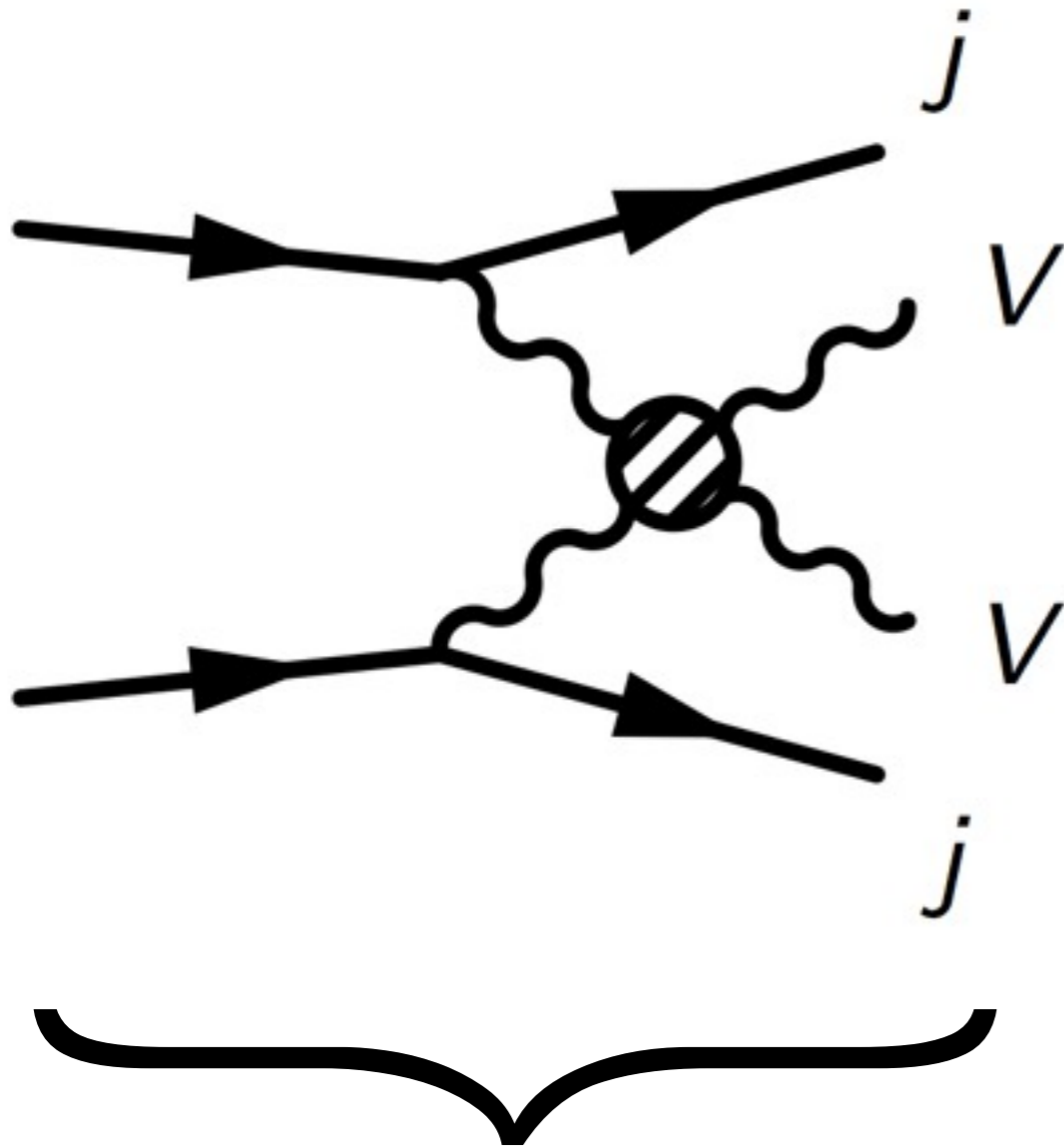
Many questions are included in the talk. Maybe some of them can be answered during the talk but I also summarize the questions at the end of this presentation.



Overview

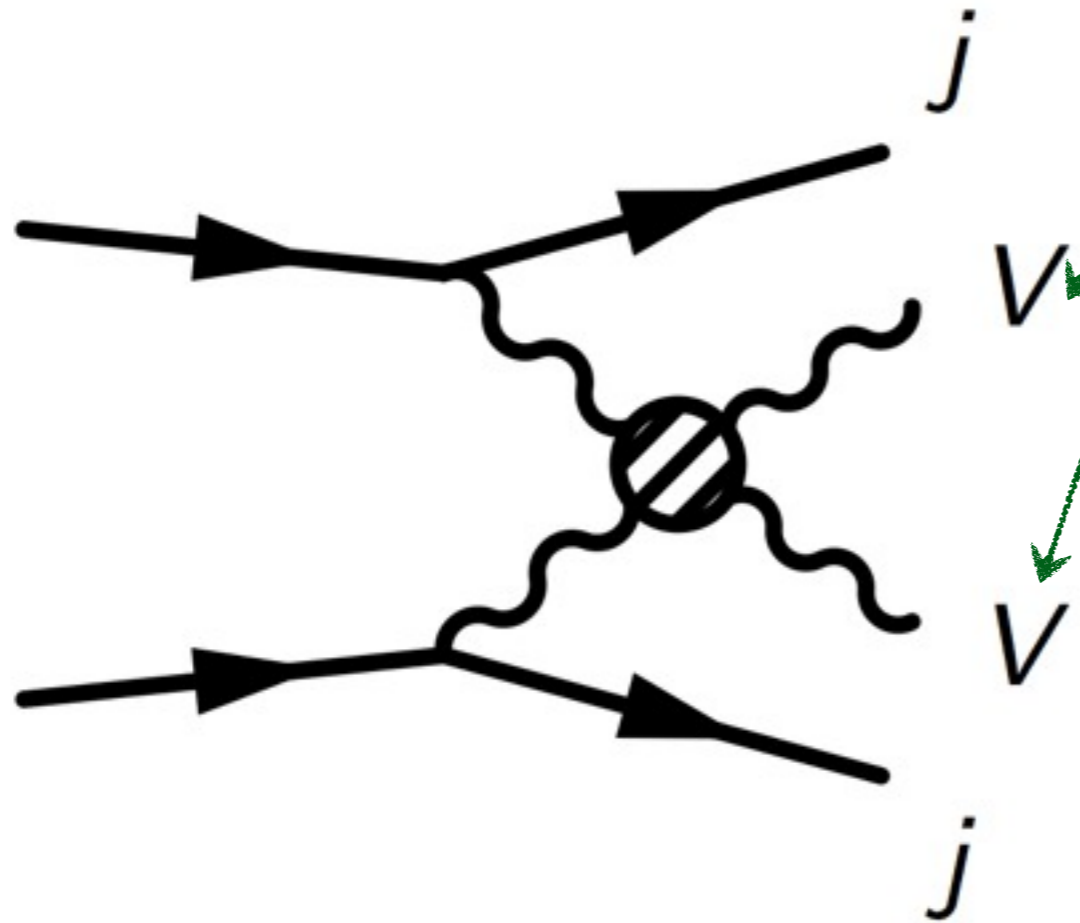


Overview



(1) Subsumption of this diagram
quite theoretical, 5 min

Overview

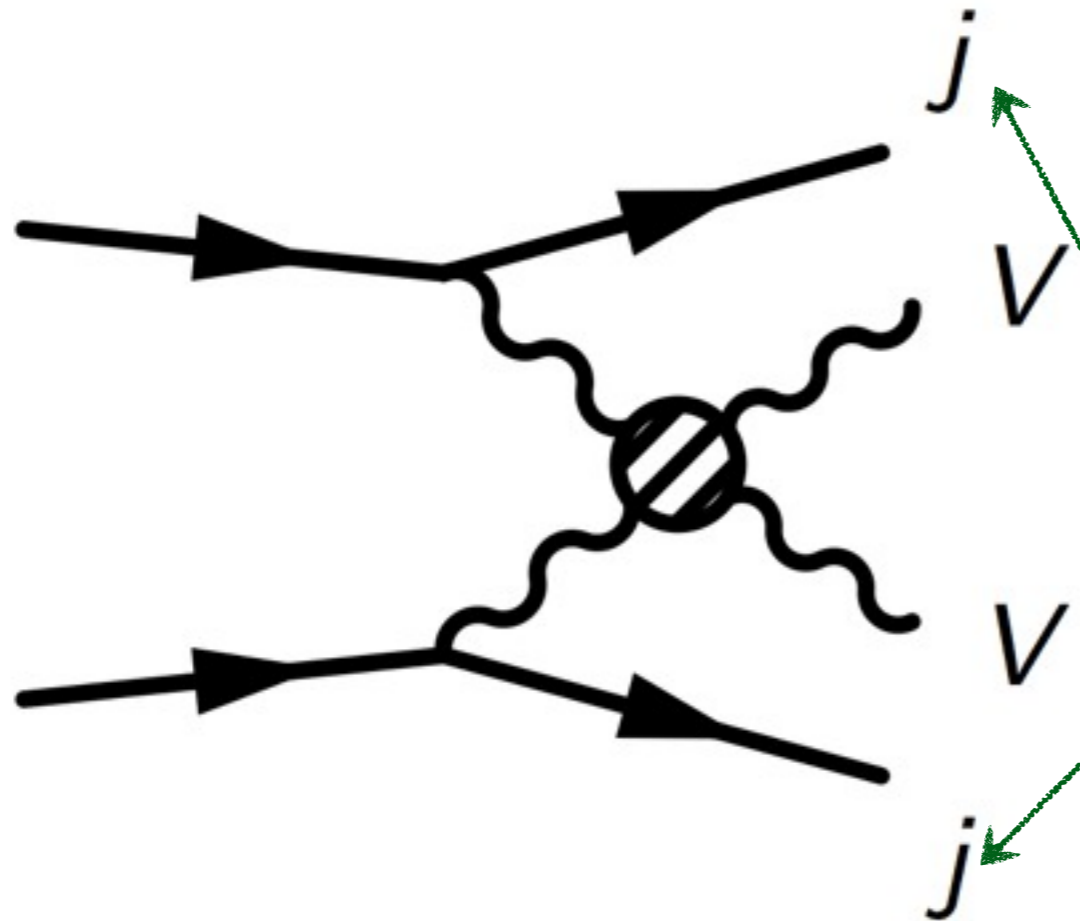


(2) Classification of final state electro-weak bosons and their decay products

5 min

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quite theoretical, 5 min

Overview



(2) Classification of final state electro-weak bosons and their decay products

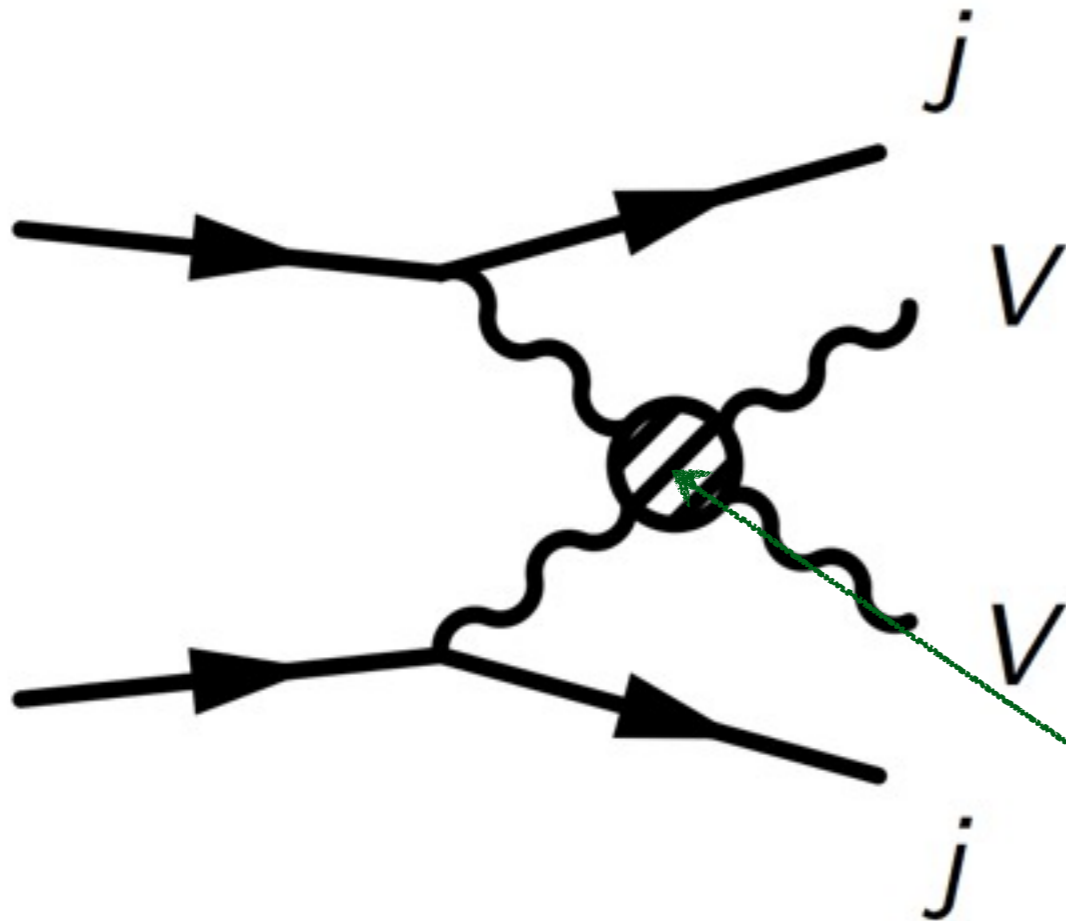
5 min

(3) Tagging Jets

5 min

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Overview



(2) Classification of final state electro-weak bosons and their decay products

5 min

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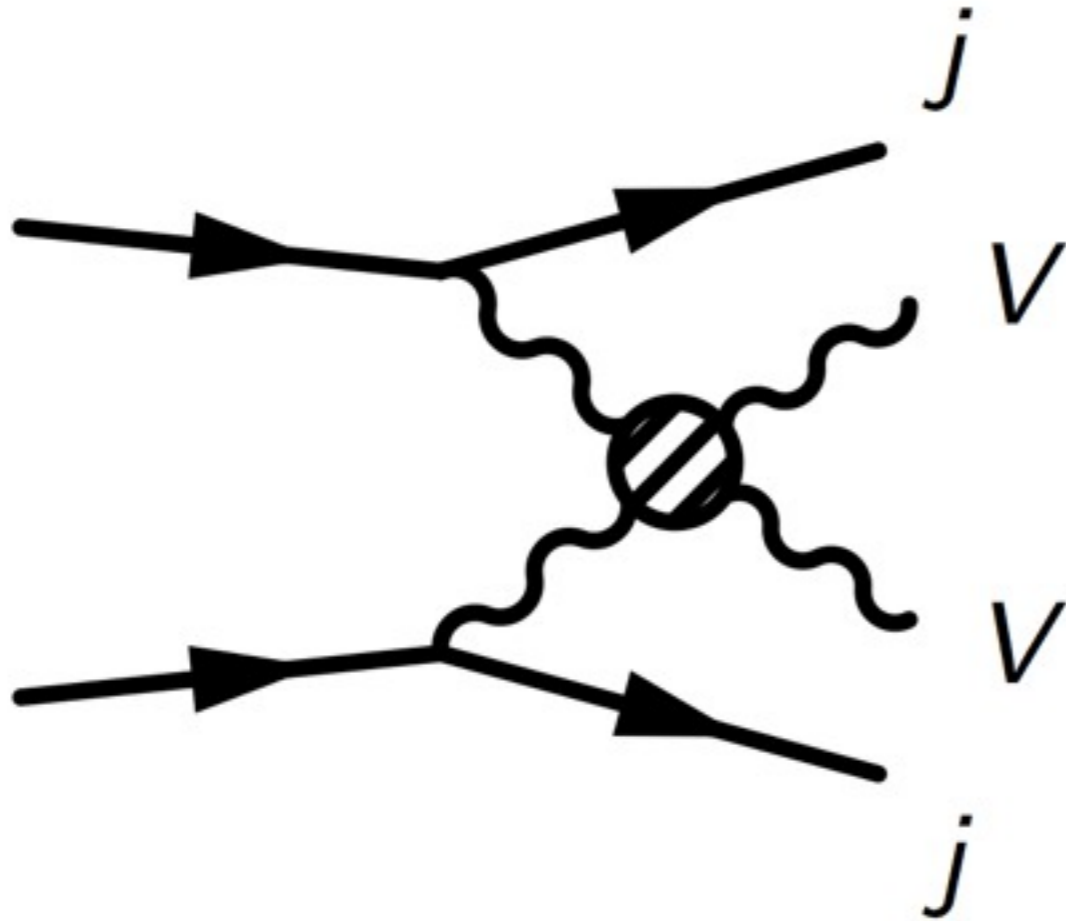
5 min

(4) aQGC

15 min

(1) Subsumption of this diagram
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Overview



(2) Classification of final state electro-weak bosons and their decay products

5 min

(3) Tagging Jets

5 min

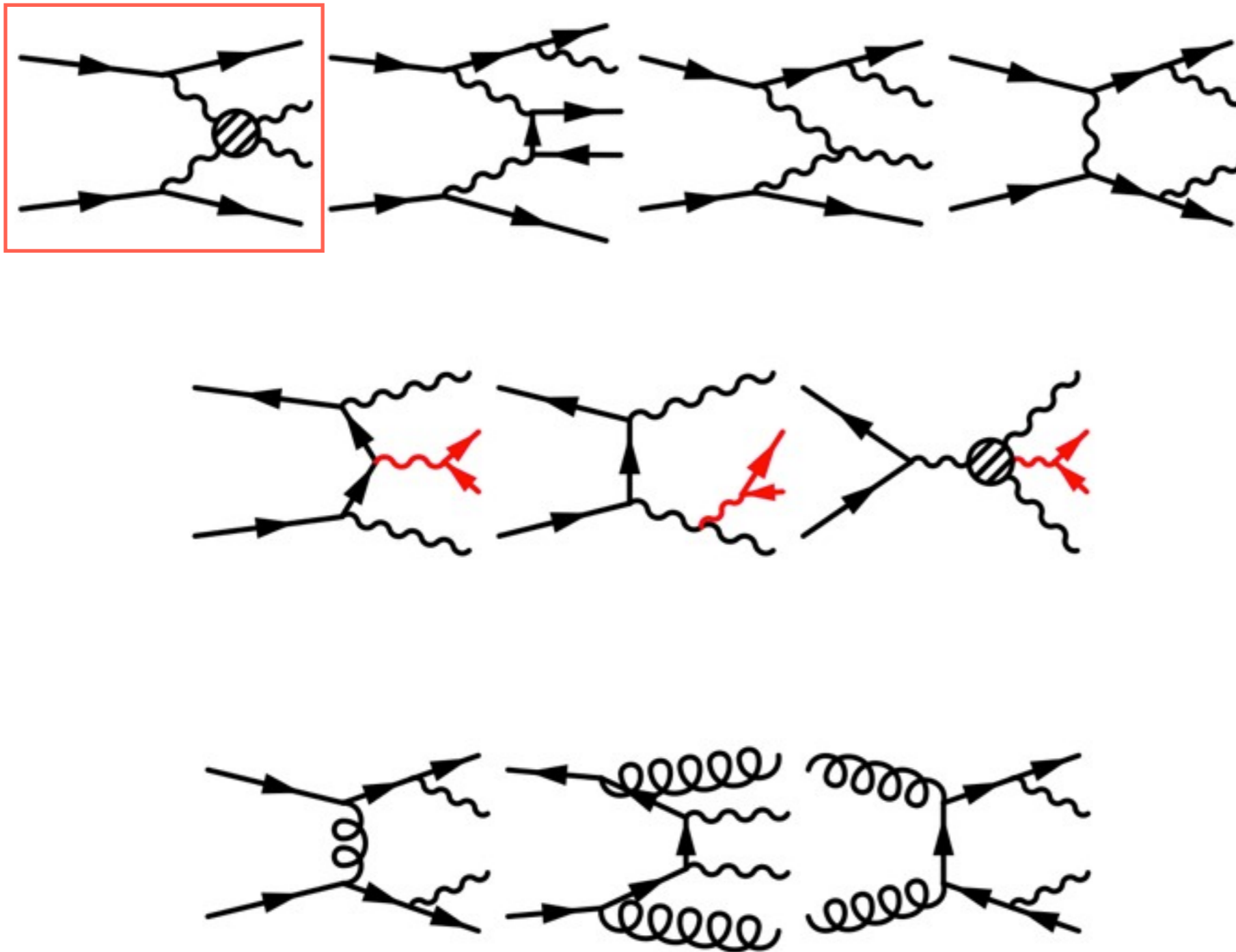
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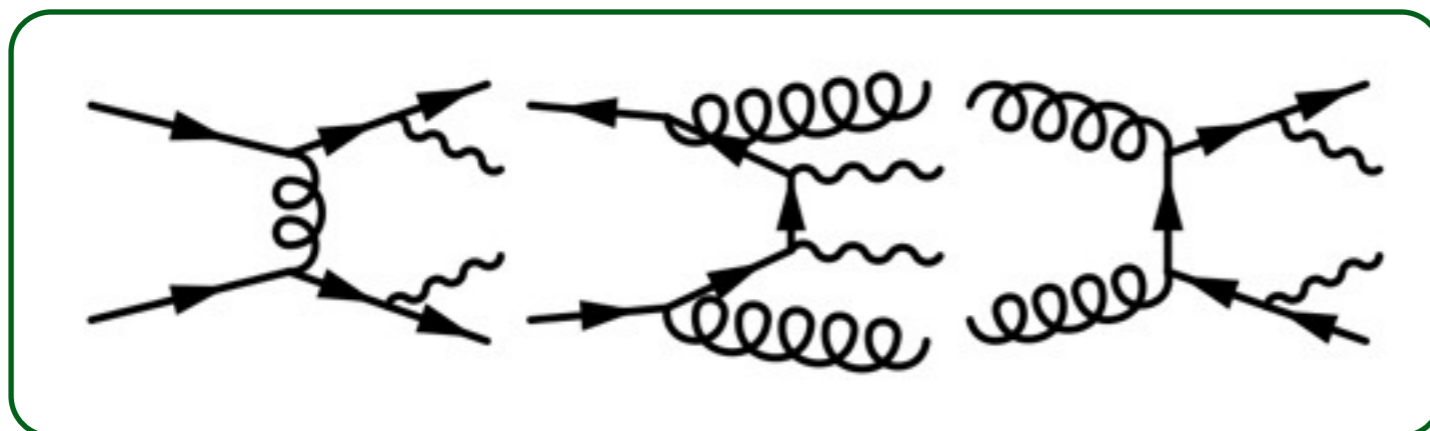
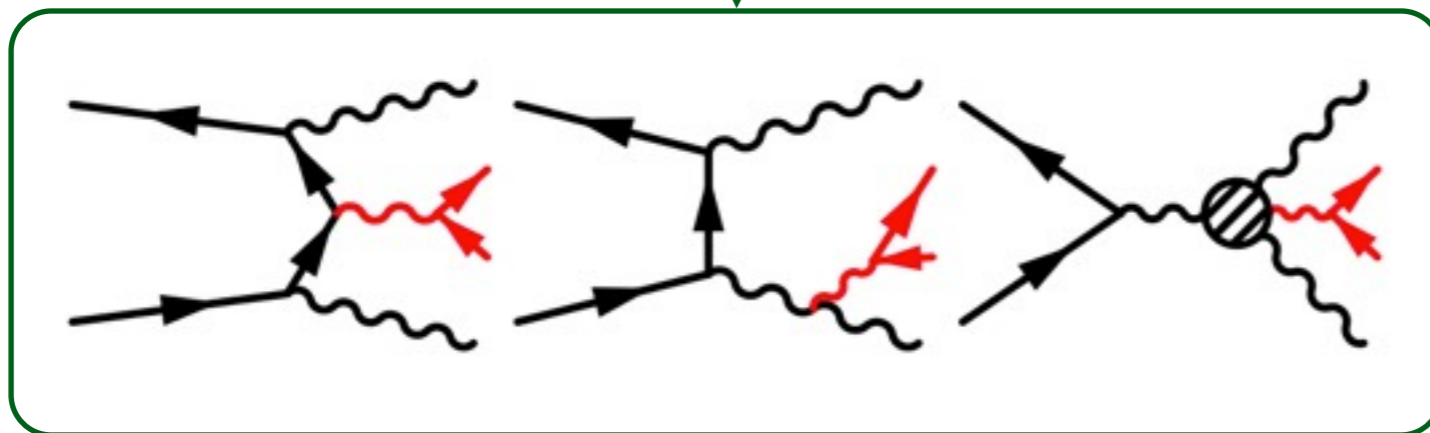
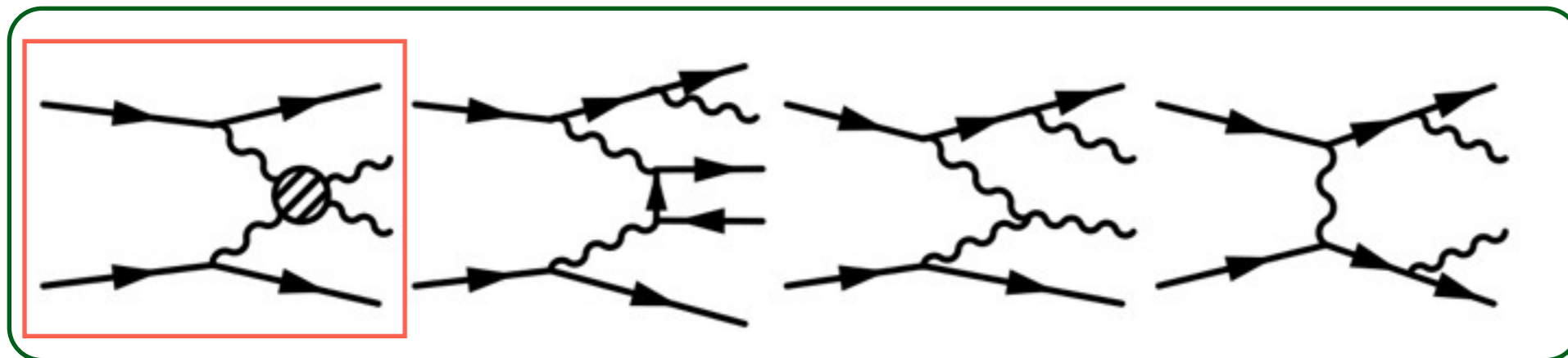
(1) Classification of processes

(1.1) Types of **leading-order EW/QCD** diagrams with VVjj final state



(1) Classification of processes

(1.1) Types of **leading-order EW/QCD** diagrams with VVjj final state



VVjj-EW

$$\sigma^{\text{LO}} \propto \alpha_w^6 \alpha_s^0$$

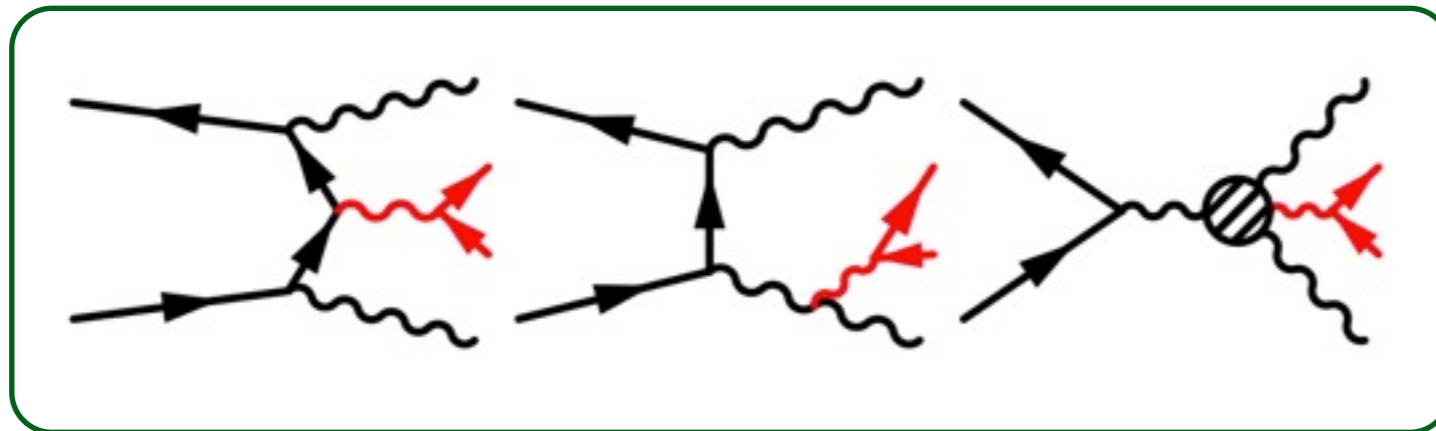
VVjj-QCD

$$\sigma^{\text{LO}} \propto \alpha_w^4 \alpha_s^2$$

(1) Classification of processes

(1.2) Diagrams with $V \rightarrow jj$ final state

- ♣ includes triple-V production (last graph)
- ♣ contribution less than 1% after $M(j,j) > 150$ GeV (checked with Sherpa)
- ♣ gauge invariantly separable from other VVjj-EW and VVjj-QCD diagrams



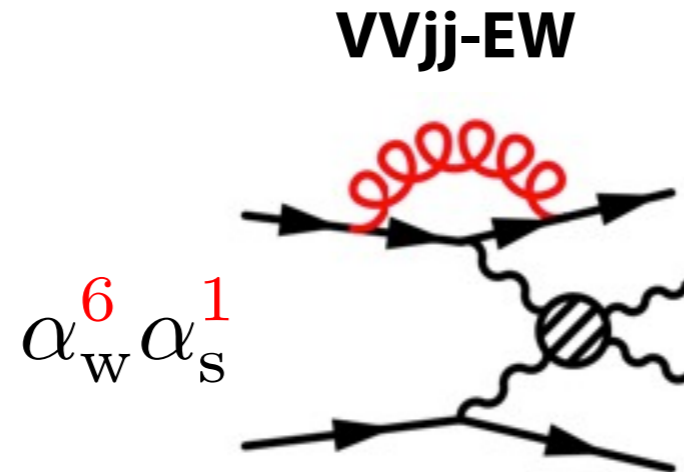
$$\text{VVjj-EW}$$
$$\sigma^{\text{LO}} \propto \alpha_w^6 \alpha_s^0$$

(1) Classification of processes

Stefan Dittmaier, seminar in Dresden, 4.7.2013

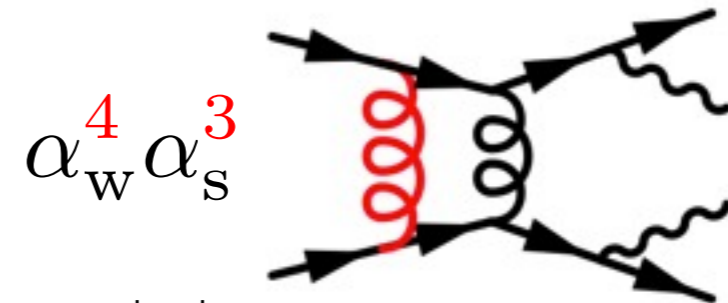
(1.3) Higher order EW and QCD to VVjj processes

**NLO QCD
corrections
(known)**



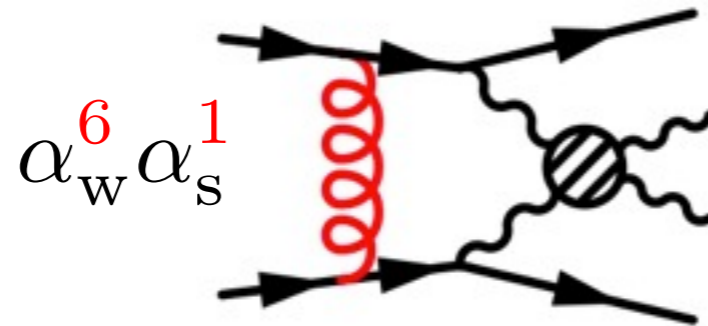
$W^+W^-/ZZ/WZ/W^\pm W^\pm$: Jäger et al. '06-'09
VBFNLO, PowhegBox

VVjj-QCD

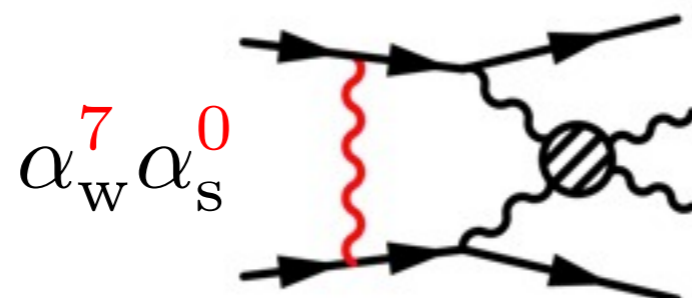


$W^+W^-/W^\pm W^\pm$: Melia, Melnikov, Rontsch, Zanderighi '10,'11
 WZ : Campanario, Kerner, Ninh, Zeppenfeld '13
VBFNLO, PowhegBox

**Mixed
QCD-EW
corrections
(unknown)**



**NLO EW
corrections
(unknown)**

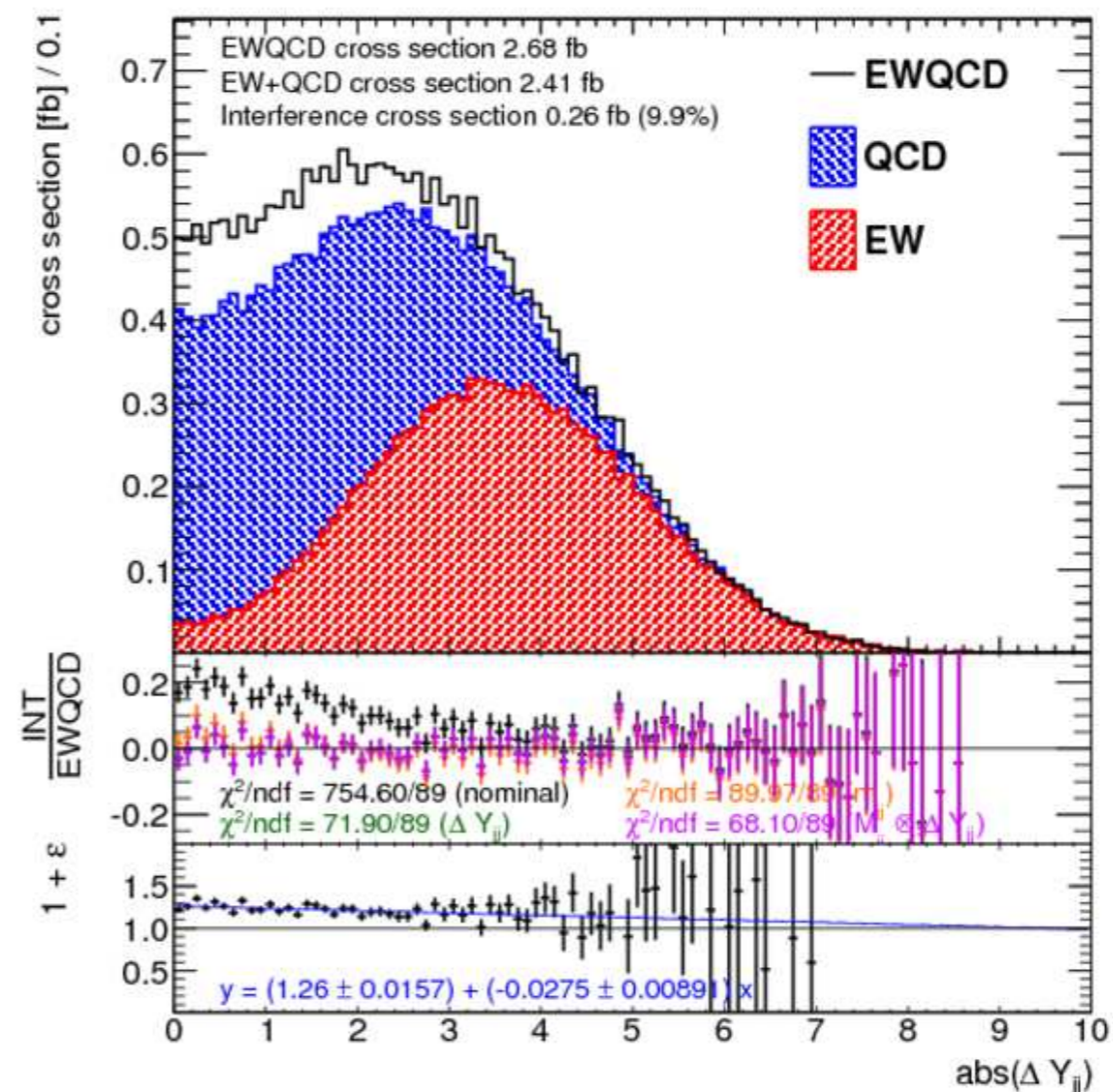
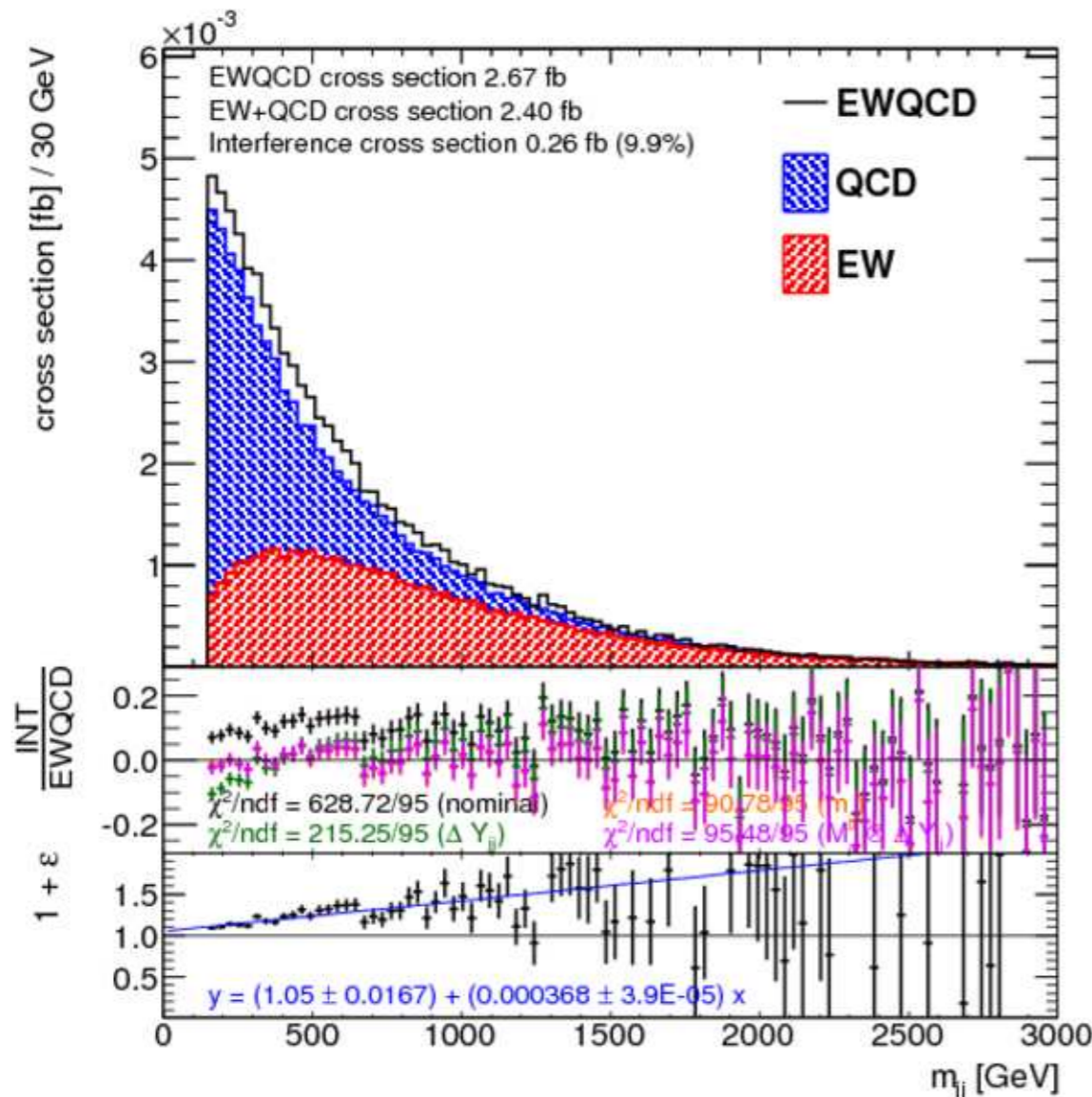


supposed to be relevant!

(1) Classification of processes

(1.5) Interference between VVjj-EW and VVjj-QCD

- ❖ expected to be small
- ❖ color suppressed
- ❖ order $\alpha_W^5 \alpha_S^1$
- ❖ not small for $W^\pm W^\pm$
- ❖ plots for
- ❖ using Sherpa MC $pp \rightarrow e^+ \nu_e \mu^+ \nu_\mu jj$
- ❖ phase-space: $M(j,j) > 150$ GeV, lepton, jet-pT cuts



(1) Classification of processes

(1.6) G_F scheme

At leading order, all parameters derived from G_F , m_Z , m_W :

$$\cos \theta_W = \frac{m_W}{m_Z} \qquad \sin \theta_W = \frac{e}{g_W}$$

$$\text{fixed } \alpha_W = \frac{e^2}{4\pi} \approx 132.5$$

$$\frac{G_F}{\sqrt{2}} = \left(\frac{g_W}{2\sqrt{2}} \right)^2 \frac{1}{m_W^2}$$

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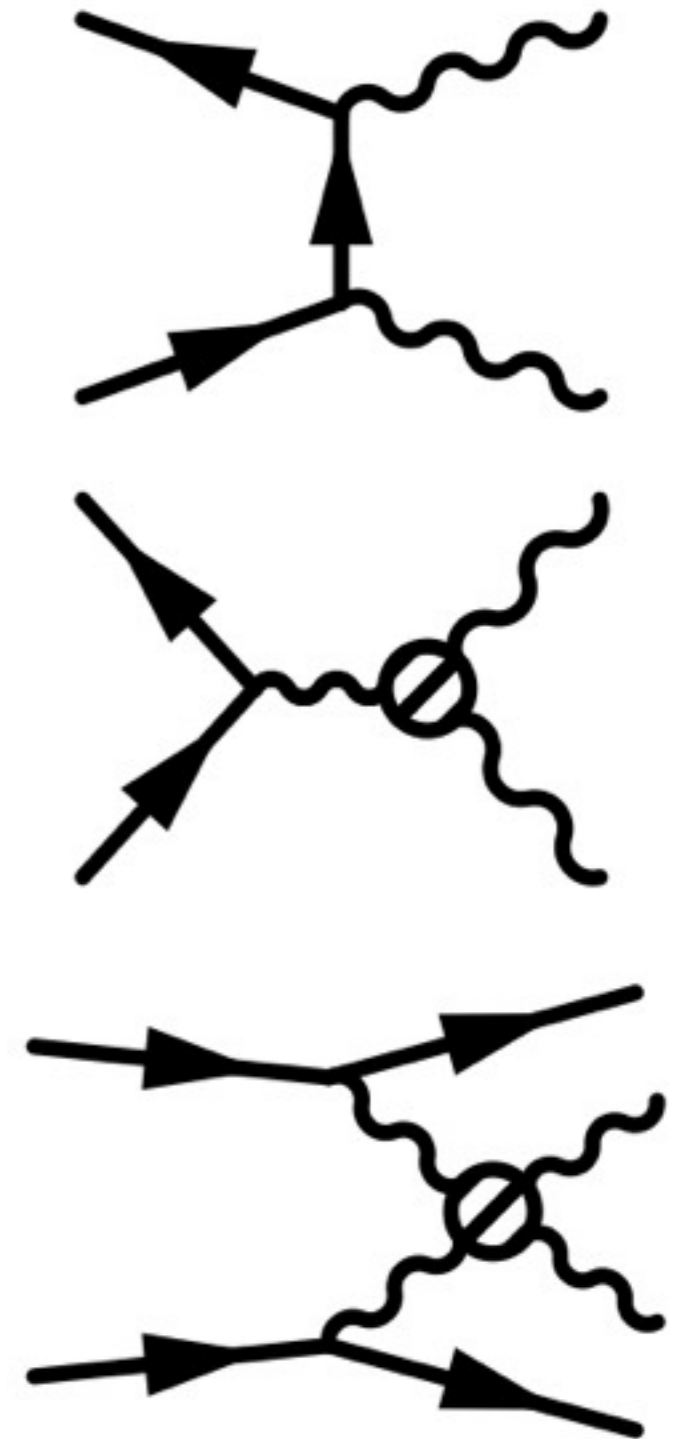
*Should this scheme be used for VVjj?
Combine VVjj-EW with GF scheme and
VVjj-QCD without?
Are other studies using it?
Why?*

- ♣ *small NLO corrections?* [arXiv: hep-ph/0109062](https://arxiv.org/abs/hep-ph/0109062)
- ♣ *to ensure unitarity restoration by light SM Higgs?*

(2) Final state electroweak bosons + decay products

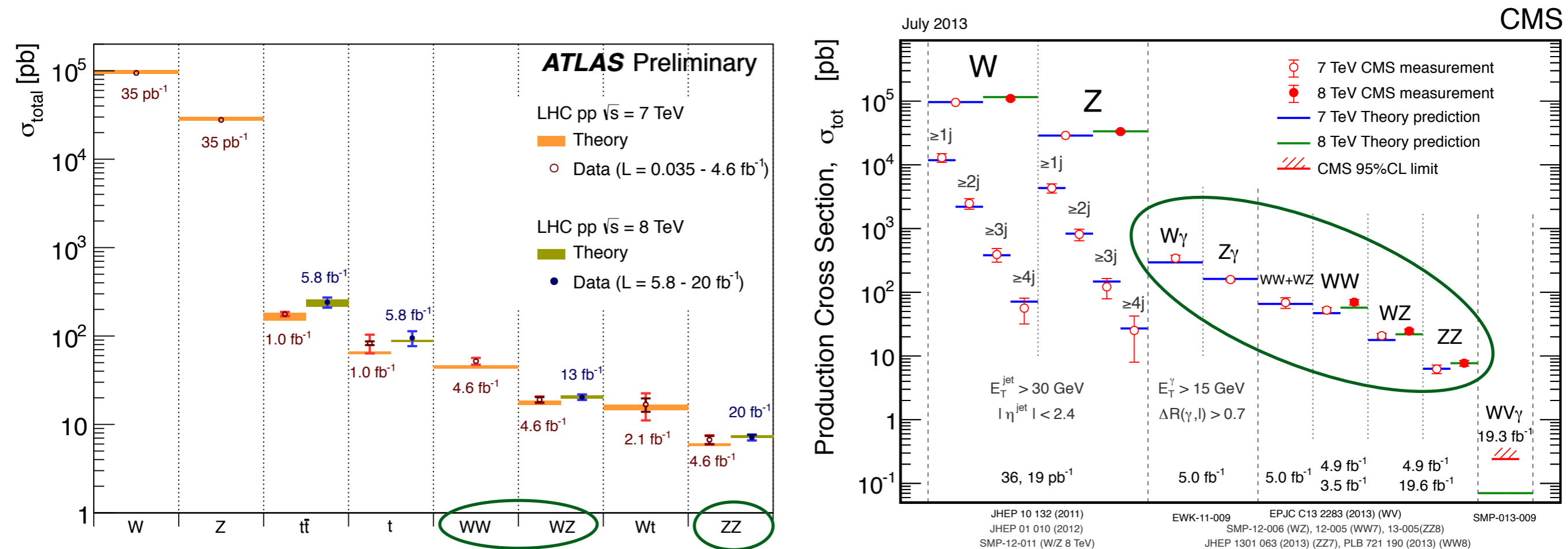
VVjj processes have two electroweak bosons in the final state

- ❖ diboson measurements as a first check are very important for VVjj studies
- ❖ also important test of the Standard Model and background for new physics and Higgs searches (aTGC)
- ❖ next slide: overview of diboson measurements at ATLAS / CMS



(2) Final state electroweak bosons + decay products

Standard Model total production cross-section corrected for leptonic branching fractions, compared to theoretical expectations



no significant deviations from the SM observed massive diboson measurements:

- ✦ unfolded differential cross-sections for most of the channels
- ✦ jet multiplicity bins not yet measured

(2) Final state electroweak bosons + decay products

			xsec [fb] VVjj-EW	xsec [fb] VVjj-QCD
fully leptonic final states	$W^\pm W^\pm jj \rightarrow l^\pm \nu l^\pm \nu jj$	best ratio between VVjj-EW and VVjj-QCD (due to no gluons in the initial state for VVjj-QCD)	20	19
	$W^+ W^- jj \rightarrow l^+ \nu l^- \nu jj$	huge ttbar background	91	3030
	$WZjj \rightarrow l \nu l^+ l^- jj$	clean channel due to three leptons in the final state	30	687
	$ZZjj \rightarrow l^+ l^- l^+ l^- jj$	clean channel due to four leptons in the final state	2	106
	$ZZjj \rightarrow l^+ l^- \nu \nu jj$	higher branching ratio but more difficult to measure	3	162

semileptonic final states	$WWjj, WZjj \rightarrow l \nu jjj_{\text{tag}} j_{\text{tag}}$	larger branching ratio, easier mass reconstruction, but harder to distinguish from hadronic background
	$WZjj, ZZjj \rightarrow lljjj_{\text{tag}} j_{\text{tag}}$	hadronic background, Z-mass window useful
photons in the final state	$W\gamma jj, Z\gamma jj, \gamma\gamma jj$	often not taken into account for VVjj VBS studies, since longitudinal degrees are interesting for VBS

(2) Final state electroweak bosons + decay products

process	main backgrounds
$W^\pm W^\pm jj \rightarrow l^\pm \nu l^\pm \nu jj$	leptonic WZ decay [missing one lepton] charge flip fake leptons [jet misidentified as a lepton]
$W^+ W^- jj \rightarrow l^+ \nu l^- \nu jj$	double-leptonic ttbar decay fake leptons [jet misidentified as a lepton]
$WZ jj \rightarrow l \nu l^+ l^- jj$	fake leptons [jet misidentified as a lepton] $ZZ \rightarrow llll$
$ZZ jj \rightarrow l^+ l^- l^+ l^- jj$	fake leptons [jet misidentified as a lepton]
$W \gamma jj \rightarrow l \nu \gamma jj$	fake photon [jet misidentified as a photon]
$Z \gamma jj \rightarrow \nu \nu \gamma jj$	fake photon [jet misidentified as photon, non-collision events]
$Z \gamma jj \rightarrow ll \gamma jj$	fake photon [jet misidentified as a photon]

Dominant backgrounds always derived from data, others with small contribution from simulation.

(2) Final state electroweak bosons + decay products

Fake factor method (used for fake leptons = jets misidentified as leptons)

- ❖ estimate fake factor from data (= probability for a jet-like/loose lepton object to pass the tight selection requirements)
- ❖ use fake factor to extrapolate the yield from a loose lepton sample (background enriched) to the fully selected leptons

Data/MC scale factor

- ❖ using data control sample dominated with background to rescale simulation

Efficiency measurement

- ❖ measurement of selection efficiency and applying to background dominated data control sample

Template fit method (fake photons = jets misidentified as photons)

- ❖ two component fit using signal and background templates in discriminating observable

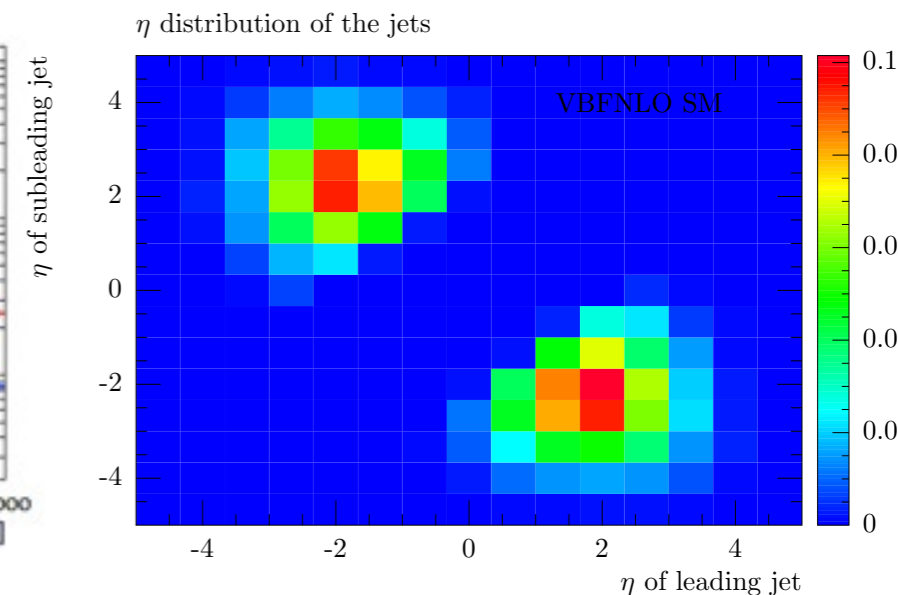
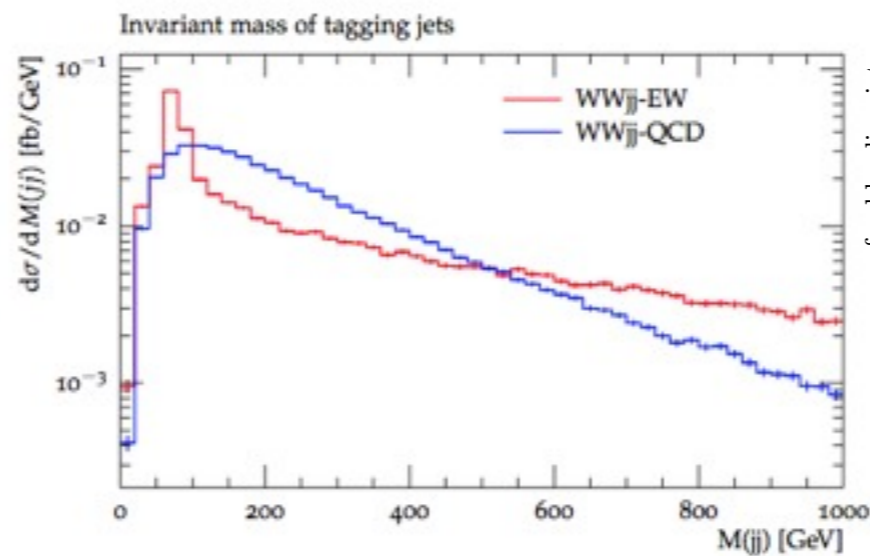
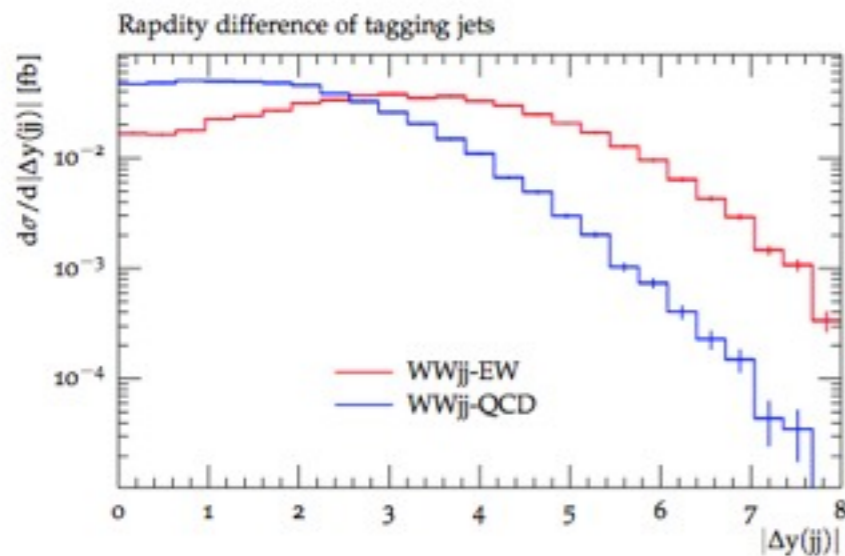
(3) Tagging Jets

several definitions possible and useful depending on the final state

- ❖ two jets with the largest p_T in the event (most common; useful cut at at least 25 GeV due to pileup)
- ❖ two jets with largest p_T and opposite sign rapidity outside the central region (semileptonic channels)
- ❖ two jets with largest separation in rapidity

properties for VVjj-EW

- ❖ large difference in rapidity and large invariant mass



rule of thumb for VVjj-EW

- ❖ jets not extremely forward (peak at $|\eta| \sim 1...3$)
- ❖ after reasonable cuts on $M(j,j)$, at least one jet very forward (peak $|\eta| \sim 2...4$; some $|\eta| \sim 4...5$), second tagging jet not very forward ($|\eta| \sim 1...3$)

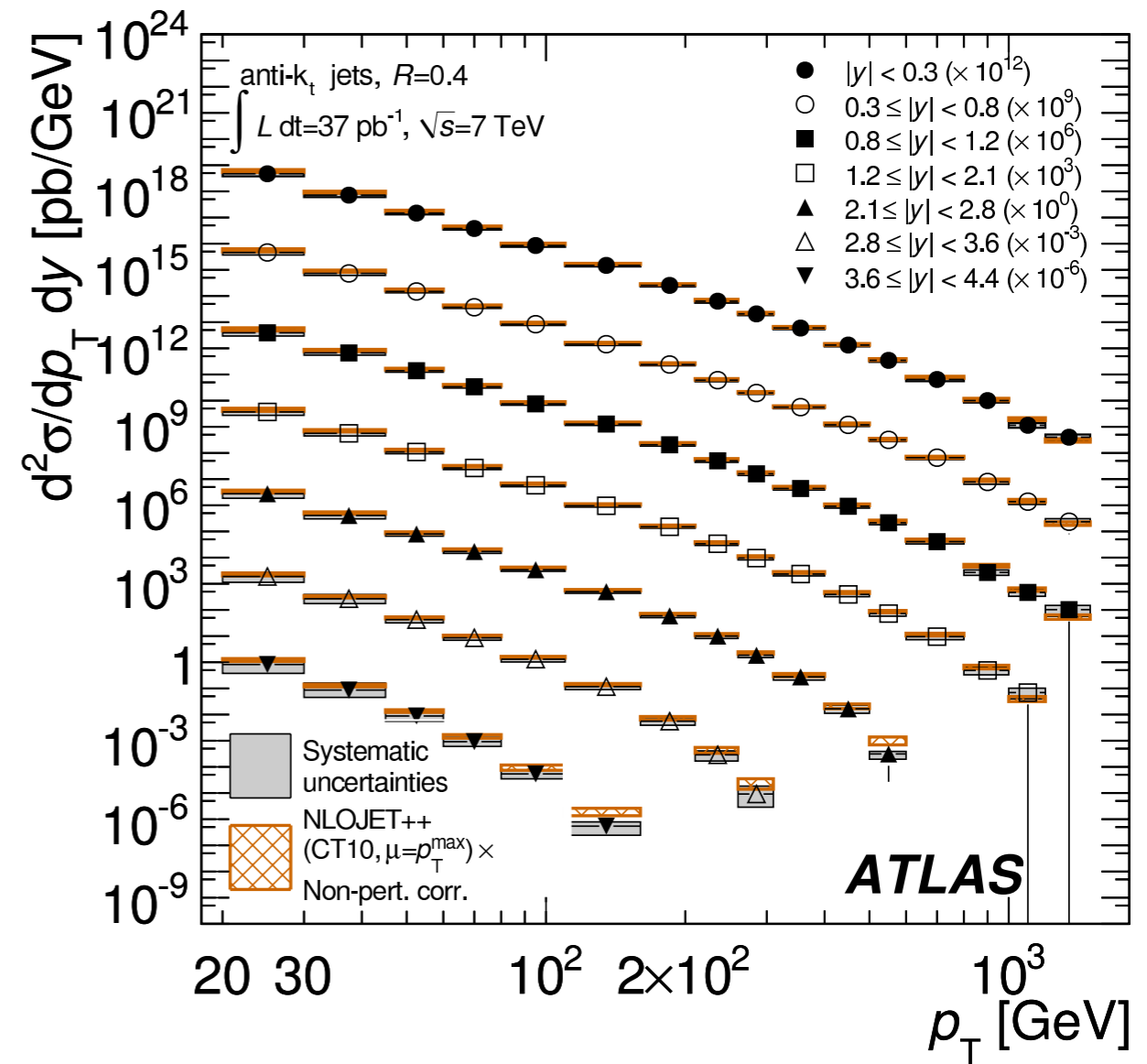
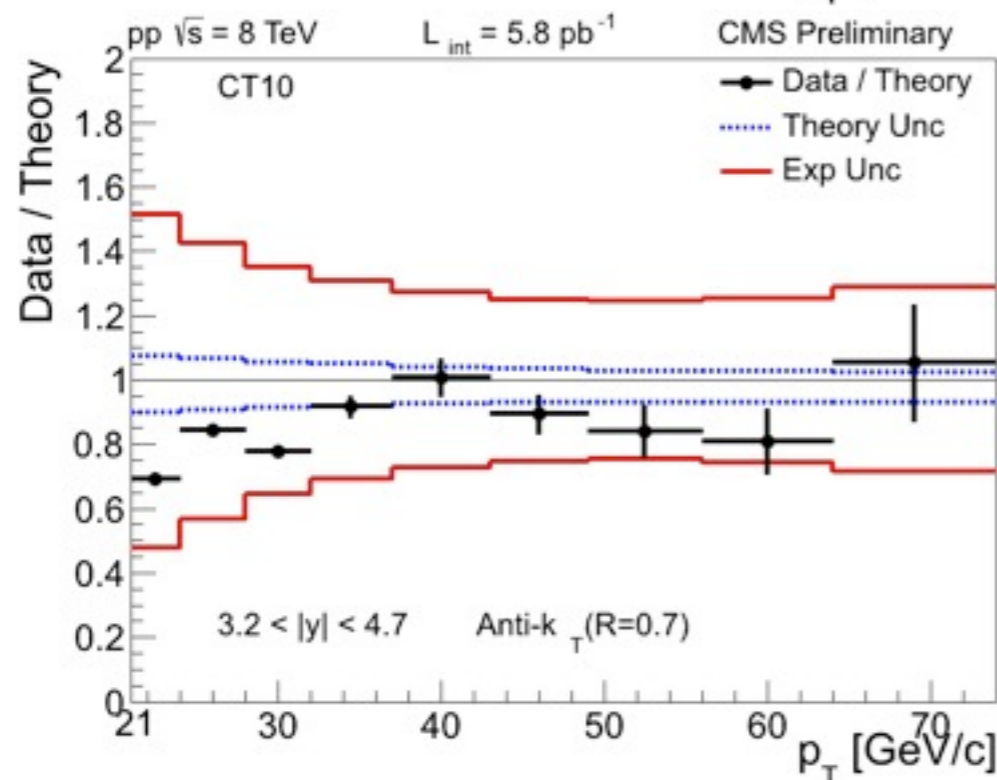
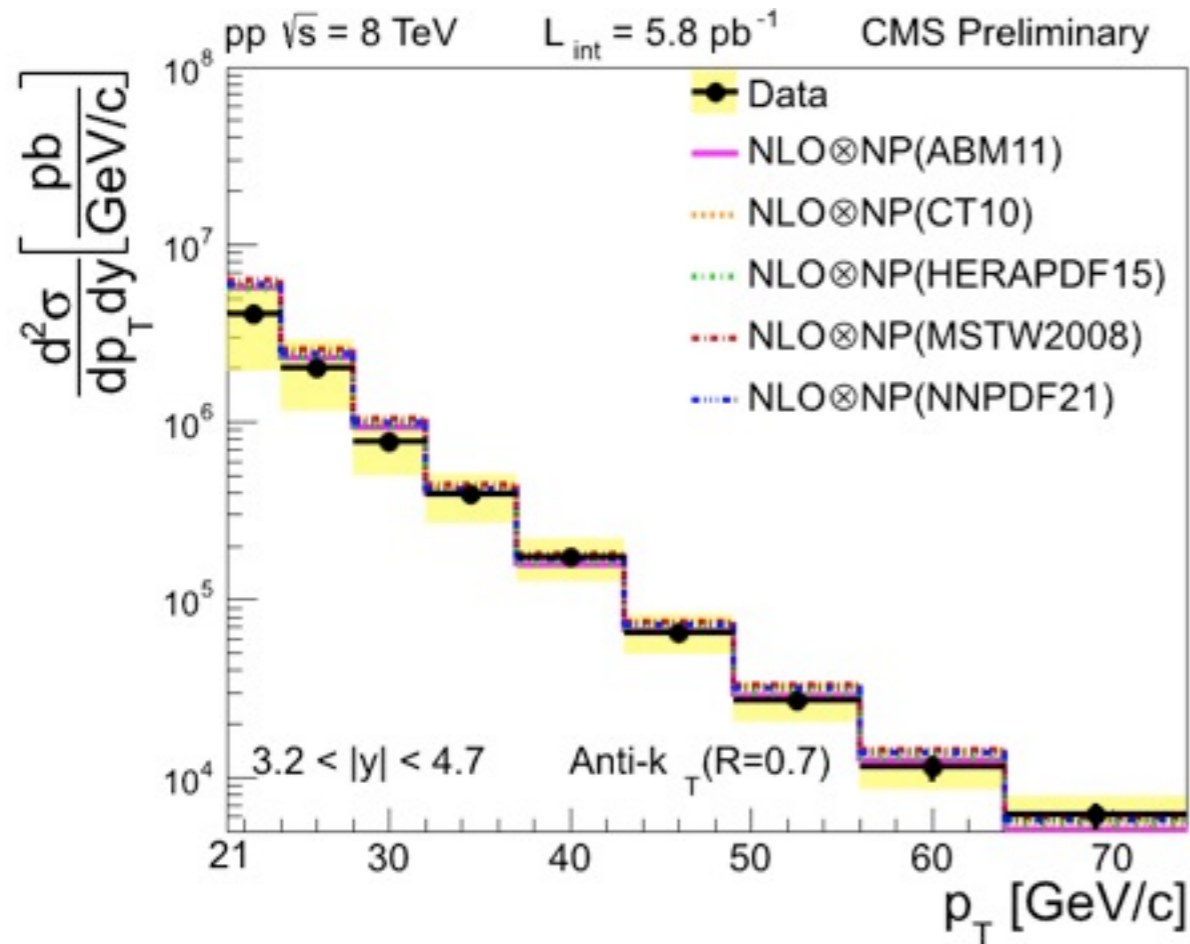
but keep in mind:

$ \eta $	1	2	3	4	5
$ \theta $	40°	15°	6°	2°	0.8°

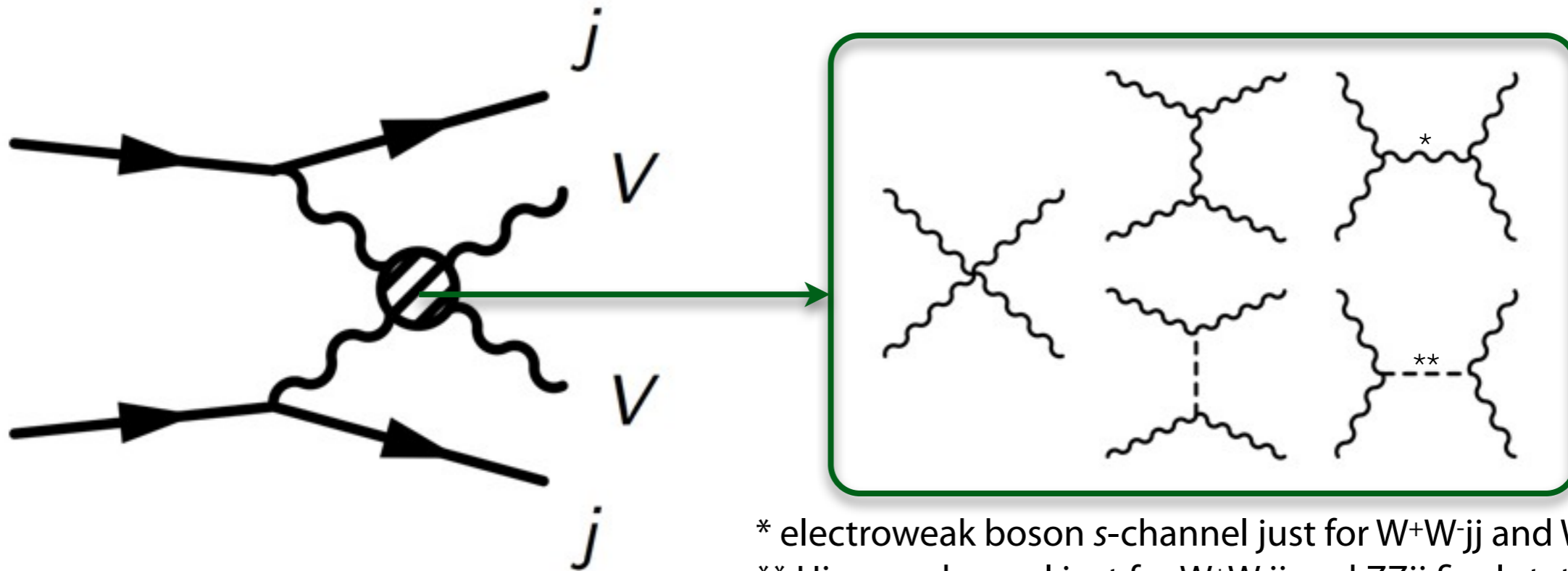
(3) Tagging Jets

CMS: CMS-PAS-FSQ-12-031
ATLAS: Phys.Rev. D86 (2012) 014022

examples of forward jet
measurements at CMS (left) and
ATLAS (right)
[a talk on its own]



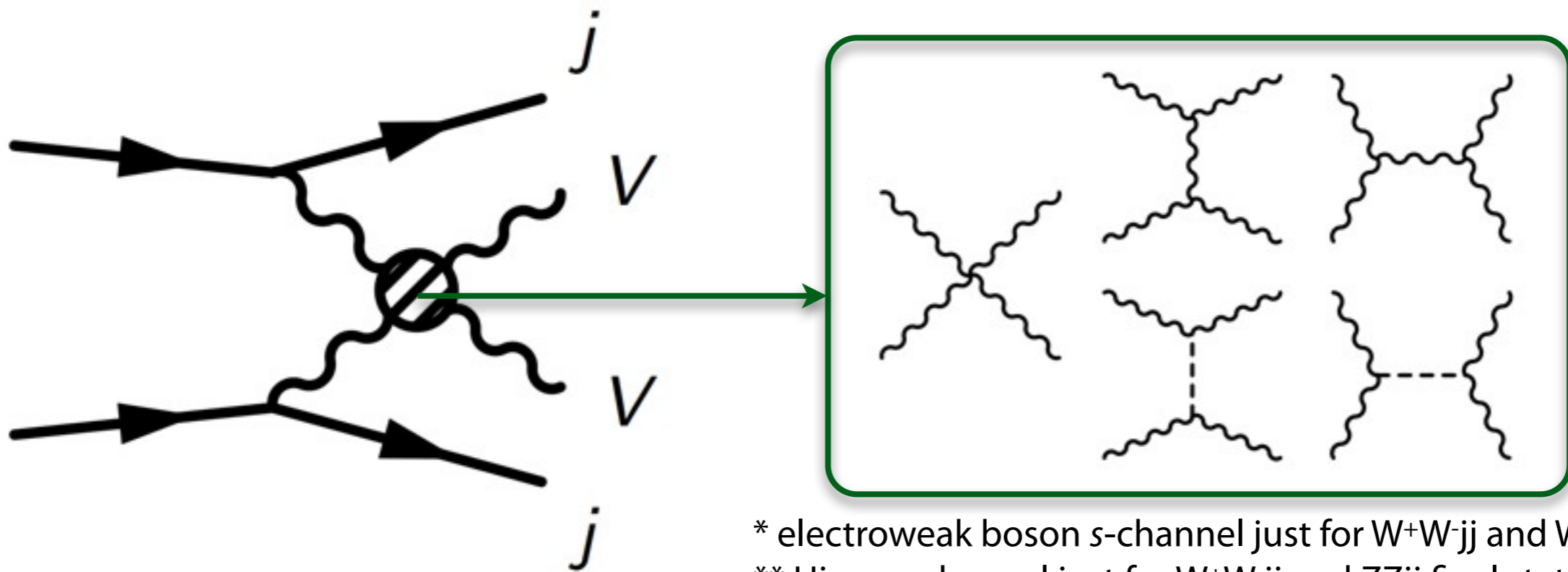
(4) aQGC



* electroweak boson s-channel just for W^+W^-jj and $WZjj$ final states
 ** Higgs s-channel just for W^+W^-jj and $ZZjj$ final state

- ❖ allowed in the Standard Model are just charged vertices at tree-level:
 - ❖ four-boson vertex: $WW\gamma\gamma$, $WWZ\gamma$, $WWWW$, $WWZZ$
 - ❖ tri-boson vertex: WWZ , $WW\gamma$
- ❖ neutral couplings are forbidden in the Standard Model:
 - ❖ $ZZZZ$, $ZZZ\gamma$, $ZZ\gamma\gamma$, $Z\gamma\gamma\gamma$, $\gamma\gamma\gamma\gamma$, ZZZ , $ZZ\gamma$, $Z\gamma\gamma$, $\gamma\gamma\gamma$
- ❖ ideally (see later), aQGC parametrization is chosen to just modify the four-boson interaction
- ❖ aQGC also accessible in triple weak boson production (see separate talk)

(4) aQGC Outline



* electroweak boson s-channel just for W^+W^-jj and $WZjj$ final states

** Higgs s-channel just for W^+W^-jj and $ZZjj$ final state

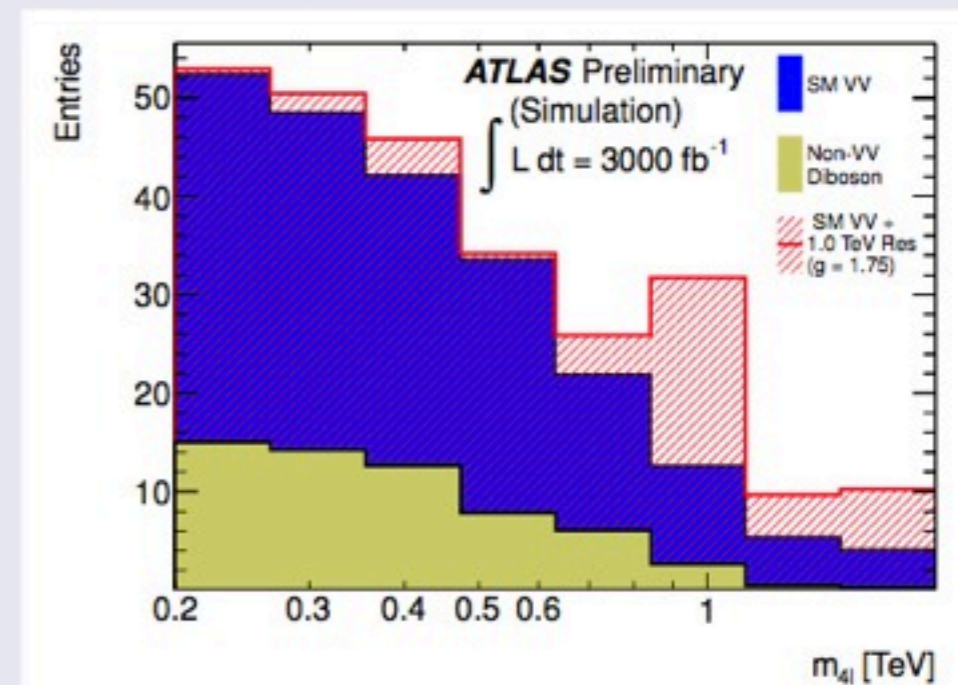
- ❖ direct searches for additional resonances
- ❖ indirect searches
- ❖ unitarization
- ❖ discriminating variables
- ❖ prospects for 14 TeV
- ❖ Monte Carlo generators

(4) aQGC direct search - adding new resonances (arXiv:0806.4145)

		isospin		
		$J = 0$	$J = 1$	$J = 2$
spin	$I = 0$	σ^0 (Higgs)	ω^0 (γ'/Z')	f^0 (Graviton)
	$I = 1$	π^0, π^\pm (2HDM)	ρ^0, ρ^\pm (W'/Z')	a^0, a^\pm
	$I = 2$	$\phi^0, \phi^\pm, \phi^{\pm\pm}$ (Higgs triplet)		$t^0, t^\pm, t^{\pm\pm}$

prospects for $\sqrt{s} = 14$ TeV (CERN-ESG-005, ATLAS-PHYS-PUB-2012-005)

- f_0 resonance
($m = 1$ TeV, $g = 1.75$, $\Gamma = 50$ GeV)
- VBS $ZZjj \rightarrow lllljj$
- $m_{jj} > 1$ TeV
- sensitivity for 300fb^{-1} : 1.7σ
- sensitivity for 3000fb^{-1} : 5.5σ
- plot: invariant four-lepton mass



(4) aQGC indirect search

LHC at 7/8 TeV ($m_{VV} \sim 0.5$ TeV) not in the range of very heavy resonances
--> study of traces of resonances at low energy (deviations from SM couplings, 'decoupling', arXiv: 1307.8170) is possible:

indirect search: parametrization of the low-mass tail of these resonances in an effective Low Energy Theory

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

- ❖ effective Lagrangian extended by additional operators
- ❖ lowest *independent* aQGC interactions at dimension 8 (dimension 6 also makes aQGC, but also aTGC)
- ❖ two different parametrization (see next slides)

(4) aQGC indirect search

linear realization of symmetry breaking arXiv:hep-ph/0606118v2, Eboli et. al

- ❖ three possibilities to get dimension-8 operators lead to 20 different parameters:
 - ❖ operators with just covariant derivative of Higgs doublet: parameter $f_{S,i}$ with $i \in \{0,1\}$
 - ❖ operators with covariant derivative of Higgs doublet and field strength: $f_{M,j}$ with $j \in \{0,...,7\}$
 - ❖ operators with just field strength tensor: $f_{T,k}$ with $k \in \{0,...,9\}$
- ❖ all of them implemented in VBFNLO arXiv:0811.4559

$$\begin{aligned}\mathcal{L}_{S,0} &= [(D_\mu \Phi)^\dagger D_\nu \Phi] \times [(D^\mu \Phi)^\dagger D^\nu \Phi] \\ \mathcal{L}_{S,1} &= [(D_\mu \Phi)^\dagger D^\mu \Phi] \times [(D_\nu \Phi)^\dagger D^\nu \Phi] \\ \mathcal{L}_{M,0} &= \text{Tr} [\hat{W}_{\mu\nu} \hat{W}^{\mu\nu}] \times [(D_\beta \Phi)^\dagger D^\beta \Phi] \\ \mathcal{L}_{M,1} &= \text{Tr} [\hat{W}_{\mu\nu} \hat{W}^{\nu\beta}] \times [(D_\beta \Phi)^\dagger D^\mu \Phi] \\ \mathcal{L}_{M,2} &= [B_{\mu\nu} B^{\mu\nu}] \times [(D_\beta \Phi)^\dagger D^\beta \Phi] \\ \mathcal{L}_{M,3} &= [B_{\mu\nu} B^{\nu\beta}] \times [(D_\beta \Phi)^\dagger D^\mu \Phi] \\ \mathcal{L}_{M,4} &= [(D_\mu \Phi)^\dagger \hat{W}_{\beta\nu} D^\mu \Phi] \times B^{\beta\nu} \\ \mathcal{L}_{M,5} &= [(D_\mu \Phi)^\dagger \hat{W}_{\beta\nu} D^\nu \Phi] \times B^{\beta\mu} \\ \mathcal{L}_{M,6} &= [(D_\mu \Phi)^\dagger \hat{W}_{\beta\nu} \hat{W}^{\beta\mu} D^\nu \Phi] \\ \mathcal{L}_{M,7} &= [(D_\mu \Phi)^\dagger \hat{W}_{\beta\nu} \hat{W}^{\beta\mu} D^\nu \Phi] \\ \mathcal{L}_{T,0} &= \text{Tr} [\hat{W}_{\mu\nu} \hat{W}^{\mu\nu}] \times \text{Tr} [\hat{W}_{\alpha\beta} \hat{W}^{\alpha\beta}] \\ \mathcal{L}_{T,1} &= \text{Tr} [\hat{W}_{\alpha\nu} \hat{W}^{\mu\beta}] \times \text{Tr} [\hat{W}_{\mu\beta} \hat{W}^{\alpha\nu}] \\ \mathcal{L}_{T,2} &= \text{Tr} [\hat{W}_{\alpha\mu} \hat{W}^{\mu\beta}] \times \text{Tr} [\hat{W}_{\beta\nu} \hat{W}^{\nu\alpha}] \\ \mathcal{L}_{T,3} &= \text{Tr} [\hat{W}_{\alpha\mu} \hat{W}^{\mu\beta} \hat{W}^{\nu\alpha}] \times B_{\beta\nu} \\ \mathcal{L}_{T,4} &= \text{Tr} [\hat{W}_{\alpha\mu} \hat{W}^{\alpha\mu} \hat{W}^{\beta\nu}] \times B_{\beta\nu} \\ \mathcal{L}_{T,5} &= \text{Tr} [\hat{W}_{\mu\nu} \hat{W}^{\mu\nu}] \times B_{\alpha\beta} B^{\alpha\beta} \\ \mathcal{L}_{T,6} &= \text{Tr} [\hat{W}_{\alpha\nu} \hat{W}^{\mu\beta}] \times B_{\mu\beta} B^{\alpha\nu} \\ \mathcal{L}_{T,7} &= \text{Tr} [\hat{W}_{\alpha\mu} \hat{W}^{\mu\beta}] \times B_{\beta\nu} B^{\nu\alpha} \\ \mathcal{L}_{T,8} &= B_{\mu\nu} B^{\mu\nu} B_{\alpha\beta} B^{\alpha\beta} \\ \mathcal{L}_{T,9} &= B_{\alpha\mu} B^{\mu\beta} B_{\beta\nu} B^{\nu\alpha}\end{aligned}$$

(4) aQGC indirect search

linear realization of symmetry breaking arXiv:hep-ph/0606118v2, Eboli et. al

- ❖ three possibilities to get dimension-8 operators lead to 20 different parameters:
 - ❖ operators with just covariant derivative of Higgs doublet: parameter $f_{S,i}$ with $i \in \{0,1\}$
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 - ❖ operators with just field strength tensor: $f_{T,k}$ with $k \in \{0,...,9\}$
- ❖ all of them implemented in VBFNLO arXiv:0811.4559

- ❖ $f_{M,j}$ parameters have D6 equivalents (a_0, a_c)? They effect TGC?
- ❖ $f_{S,i}$ and $f_{T,k}$ are unique to dimension eight?
- ❖ All parameters conserve CP and custodial symmetry?
- ❖ Do some of these parameters have advantages/disadvantages or real physical interpretations and are more useful than others?

$$\begin{aligned}
 \mathcal{L}_{S,0} &= [(D_\mu \Phi)^\dagger D_\nu \Phi] \times [(D^\mu \Phi)^\dagger D^\nu \Phi] \\
 \mathcal{L}_{S,1} &= [(D_\mu \Phi)^\dagger D^\mu \Phi] \times [(D_\nu \Phi)^\dagger D^\nu \Phi] \\
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 \mathcal{L}_{M,5} &= [(D_\mu \Phi)^\dagger \hat{W}_{\beta\nu} D^\nu \Phi] \times B^{\beta\mu} \\
 \mathcal{L}_{M,6} &= [(D_\mu \Phi)^\dagger \hat{W}_{\beta\nu} \hat{W}^{\beta\mu} D^\mu \Phi] \\
 \mathcal{L}_{M,7} &= [(D_\mu \Phi)^\dagger \hat{W}_{\beta\nu} \hat{W}^{\beta\mu} D^\nu \Phi] \\
 \mathcal{L}_{T,0} &= \text{Tr} [\hat{W}_{\mu\nu} \hat{W}^{\mu\nu}] \times \text{Tr} [\hat{W}_{\alpha\beta} \hat{W}^{\alpha\beta}] \\
 \mathcal{L}_{T,1} &= \text{Tr} [\hat{W}_{\alpha\nu} \hat{W}^{\mu\beta}] \times \text{Tr} [\hat{W}_{\mu\beta} \hat{W}^{\alpha\nu}] \\
 \mathcal{L}_{T,2} &= \text{Tr} [\hat{W}_{\alpha\mu} \hat{W}^{\mu\beta}] \times \text{Tr} [\hat{W}_{\beta\nu} \hat{W}^{\nu\alpha}] \\
 \mathcal{L}_{T,3} &= \text{Tr} [\hat{W}_{\alpha\mu} \hat{W}^{\mu\beta} \hat{W}^{\nu\alpha}] \times B_{\beta\nu} \\
 \mathcal{L}_{T,4} &= \text{Tr} [\hat{W}_{\alpha\mu} \hat{W}^{\alpha\mu} \hat{W}^{\beta\nu}] \times B_{\beta\nu} \\
 \mathcal{L}_{T,5} &= \text{Tr} [\hat{W}_{\mu\nu} \hat{W}^{\mu\nu}] \times B_{\alpha\beta} B^{\alpha\beta} \\
 \mathcal{L}_{T,6} &= \text{Tr} [\hat{W}_{\alpha\nu} \hat{W}^{\mu\beta}] \times B_{\mu\beta} B^{\alpha\nu} \\
 \mathcal{L}_{T,7} &= \text{Tr} [\hat{W}_{\alpha\mu} \hat{W}^{\mu\beta}] \times B_{\beta\nu} B^{\nu\alpha} \\
 \mathcal{L}_{T,8} &= B_{\mu\nu} B^{\mu\nu} B_{\alpha\beta} B^{\alpha\beta} \\
 \mathcal{L}_{T,9} &= B_{\alpha\mu} B^{\mu\beta} B_{\beta\nu} B^{\nu\alpha}
 \end{aligned}$$

(4) aQGC indirect search

linear realization of symmetry breaking arXiv:hep-ph/0606118v2, Eboli et. al

VVjj final state	ZZ	Z γ $\gamma\gamma$	W ⁺ W ⁻ WZ	W [±] W [±]	W γ	
VVV final state	ZZZ	ZZ γ Z $\gamma\gamma$	WWZ WZZ	WWW	WV γ	$\gamma\gamma\gamma$
f _{S,0} , f _{S,1}	X	O	X	X	O	O
f _{M,0} , f _{M,1} , f _{M,6} , f _{M,7}	X	X	X	X	X	O
f _{M,2} , f _{M,3} , f _{M,4} , f _{M,5}	X	X	X	O	X	O
f _{T,0} , f _{T,1} , f _{T,2}	X	X	X	X	X	X
f _{T,5} , f _{T,6} , f _{T,7}	X	X	X	O	X	X
f _{T,8} , f _{T,9}	X	X	O	O	O	X

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VVjj final state	ZZ	Z γ $\gamma\gamma$	W ⁺ W ⁻ WZ	W [±] W [±]	W γ	
VVV final state	ZZZ	ZZ γ Z $\gamma\gamma$	WWZ WZZ	WWW	WV γ	$\gamma\gamma\gamma$
f _{S,0} , f _{S,1}	X	O	X	X	O	O
f _{M,0} , f _{M,1} , f _{M,6} , f _{M,7}	X	X	X	X	X	O
f _{M,2} , f _{M,3} , f _{M,4} , f _{M,5}	X	X	X	O	X	O
f _{T,0} , f _{T,1} , f _{T,2}	X	X	X	X	X	X
f _{T,5} , f _{T,6} , f _{T,7}	X	X	X	O	X	X
f _{T,8} , f _{T,9}	X	X	O	O	O	X

What about f_{T,3}, f_{T,4}? Appear in first papers but started to 'disappear'.

(4) aQGC indirect search

non-linear realization of symmetry breaking [arXiv: hep-ph/9304240]

- ♣ chiral Lagrangian
- ♣ symmetries enforced without light Higgs
- ♣ add higher-order **dimension-4** operators (NLO in E/Λ): β_1, α_i with $i = \{1, \dots, 19\}$

	CP	custodial sym.		dimension	
α_1	conserving	conserving	aTGC	4	S parameter (LEP)
α_2, α_3	conserving	conserving	just aTGC	4	constrained at LEP / aTGC
α_4, α_5	conserving	conserving	just aQGC	4	
α_6, α_7	conserving	violating		4	
α_8	conserving	violating	aTGC	4	U parameter (LEP)
α_9	conserving	violating	aTGC	4	
α_{10}	conserving	violating		4	
α_{11}	conserving (violates C and P)		aTGC	4	
$\alpha_{12 \dots 19}$	violating			4	
β_1	conserving	violating	aTGC	2	T parameter (LEP)

(4) aQGC indirect search

non-linear realization of symmetry breaking [arXiv: hep-ph/9304240]

- ♣ chiral Lagrangian
- ♣ symmetries enforced without light Higgs
- ♣ add higher-order **dimension-4** operators (NLO in E/Λ): β_1, α_i with $i = \{1, \dots, 19\}$

*SM Higgs can be included [arXiv: hep-ph/1307.8170].
What will be the difference to the linear realization with the Higgs build in from the start?*

	CP	custodial sym.		dimension	
α_1	conserving	conserving	aTGC	4	S parameter (LEP)
α_2, α_3	conserving	conserving	just aTGC	4	constrained at LEP / aTGC
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α_{10}	conserving	violating		4	
α_{11}	conserving (violates C and P)		aTGC	4	
$\alpha_{12...19}$	violating			4	
β_1	conserving	violating	aTGC	2	T parameter (LEP)

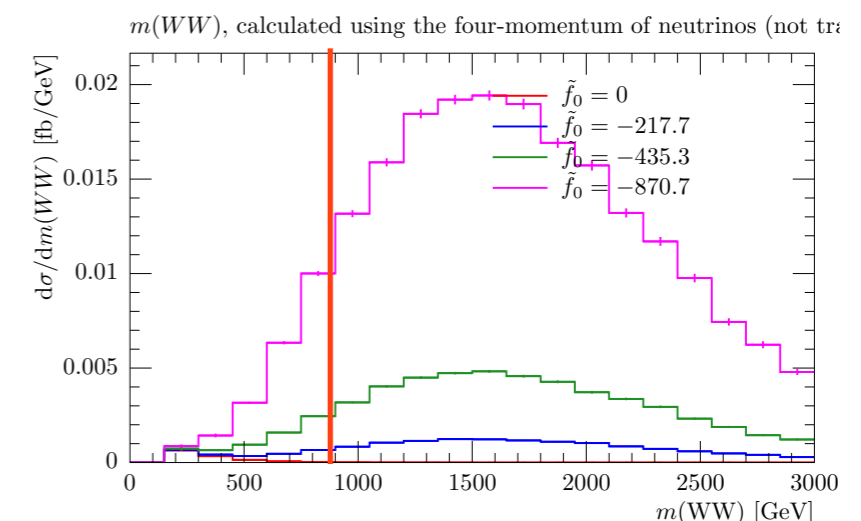
2 parameters effecting (just) aQGC: α_4, α_5 . How can this be compared to 20 parameters of the linear realization?

(4) aQGC unitarization

adding aQGC can lead to violation of unitarity → loss of physical meaning

I will not go into detail here → see theory talks tomorrow

K-matrix	<i>projection of (eigen)amplitudes at Argand circle (optical theorem ensures unitarity)</i> + physics interpretation (infinitely heavy and wide resonance) + experience from pion physics + includes other unitarization schemes - 'difficult' to implement - up to now just in Whizard
form-factor	$\alpha \rightarrow \alpha(\hat{s}) = \frac{\alpha}{(1 + \frac{\hat{s}}{\Lambda^2})^n}$ + heavily used in aTGC studies - kind of arbitrary scale and exponent - up to now just in VBFNLO
clipping cutoff	<i>cut in M_{VV}</i> + easy to implement in MC generator + can be applied on generated events - how to choose cutoff scale? - very unmotivated / unphysical



(4) aQGC unitarization

adding aQGC can lead to violation of unitarity → loss of physical meaning

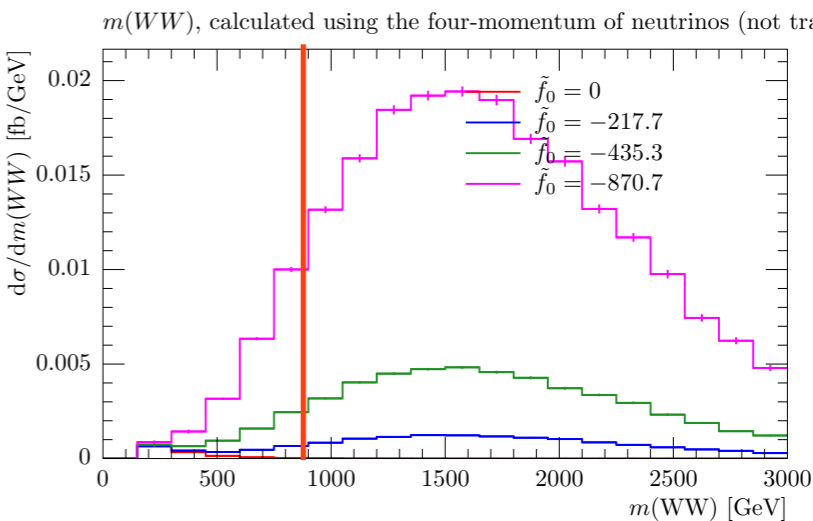
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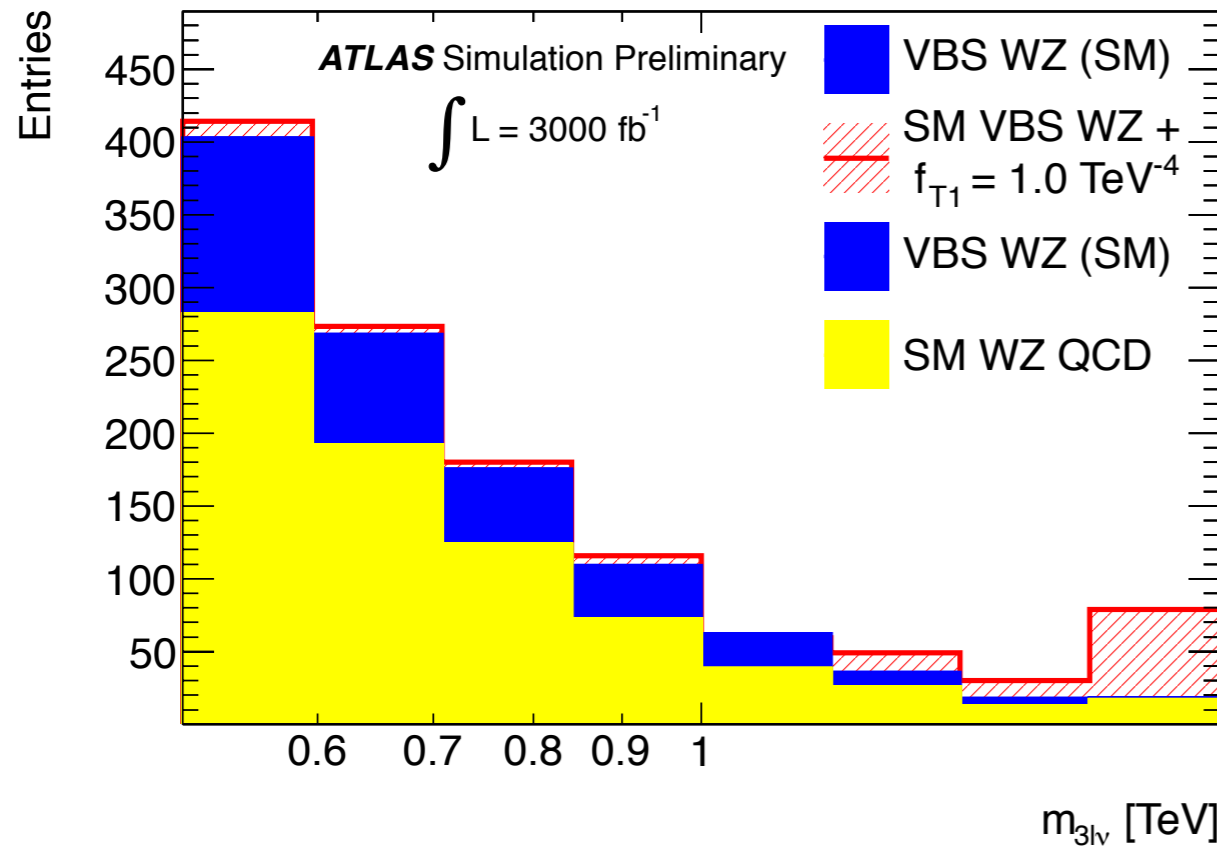
Limits / measurements

- ❖ *as function of form-factor scale (done for aTGC)?*
- ❖ *as function of form-factor scale AND exponent (how to motivate each exponent?)*
- ❖ *for FF-scale that gives best limits and still unitary results?*

*How to define clipping scale?
(done in the past: use largest scale that still gives unitary results)*



(4) aQGC ATLAS prospects for 14 TeV



VBS WZjj \rightarrow $\ell\nu\ell\ell jj$ analysis
 ATL-PHYS-PUB-2013-006

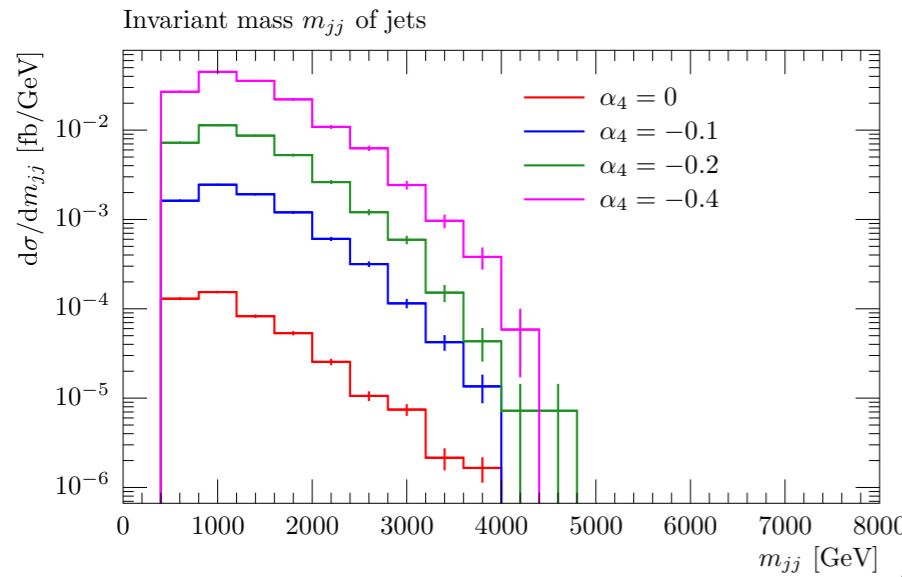
- ❖ MadGraph, linear realization, cutoff unitarization
- ❖ expected sensitivity for 14 TeV in terms of 5σ -discovery values:

analysis	parameter	300 fb^{-1}	3000 fb^{-1}
VBS $WZjj \rightarrow \ell\nu\ell\ell jj$	$f_{T,1}/\Lambda^4 \text{ TeV}^{-4}$	1.3	0.6
VBS $W^\pm W^\pm jj \rightarrow \ell^\pm \nu \ell^\pm \nu jj$	$f_{S,0}/\Lambda^4 \text{ TeV}^{-4}$	10	4.5
$Z\gamma\gamma$	$f_{T,8}/\Lambda^4 \text{ TeV}^{-4}$	0.9	0.4
$Z\gamma\gamma$	$f_{T,9}/\Lambda^4 \text{ TeV}^{-4}$	2.0	0.7

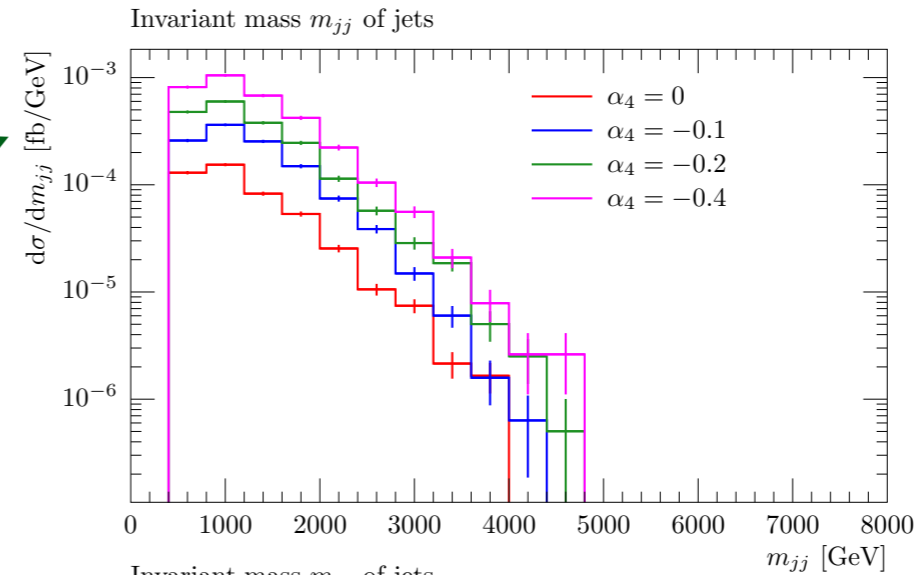
(4) aQGC discriminating variables

invariant mass of tagging jets

un-unitarized

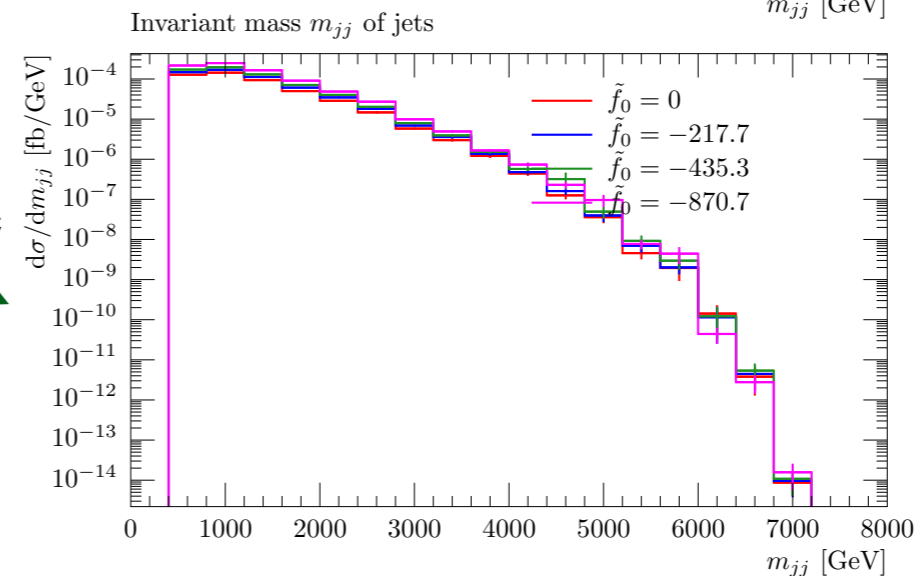


K-matrix



form-factor *

* form-factor scale:
lowest possible scale to
still ensure unitarity



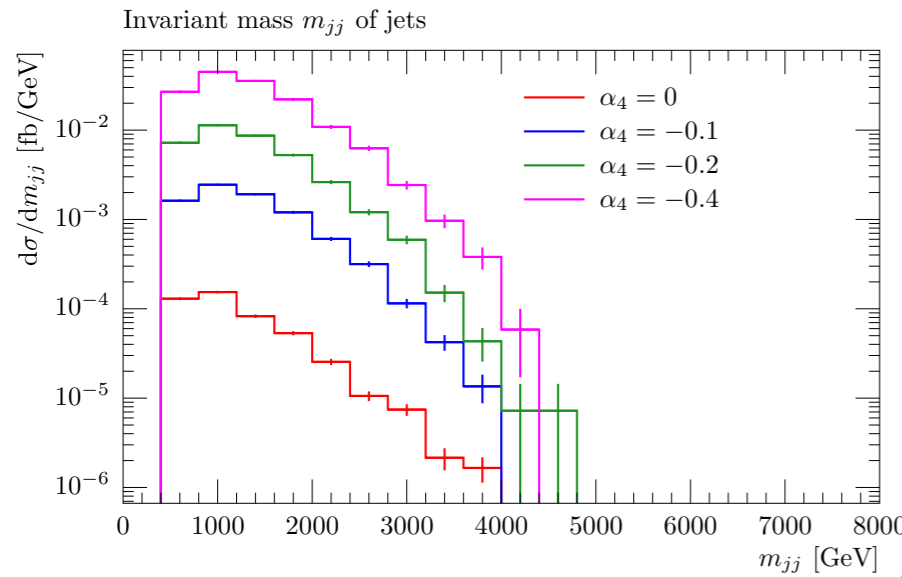
- ❖ huge impact of unitarization → large **model dependence**
- ❖ very low sensitivity after form-factor unitarization

Shown here: $W+W+jj$ final state, $p_T(\text{jet}) > 20$ GeV, $p_T(\text{leptons}) > 10$ GeV, $|\eta| < 5$, $\Delta R(j,j) > 0.4$, $M(j,j) > 150$ GeV

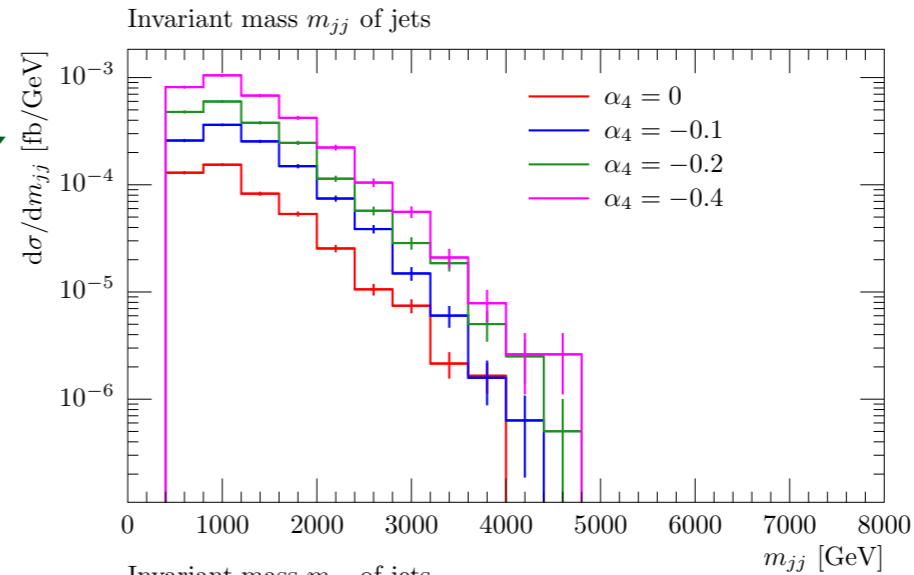
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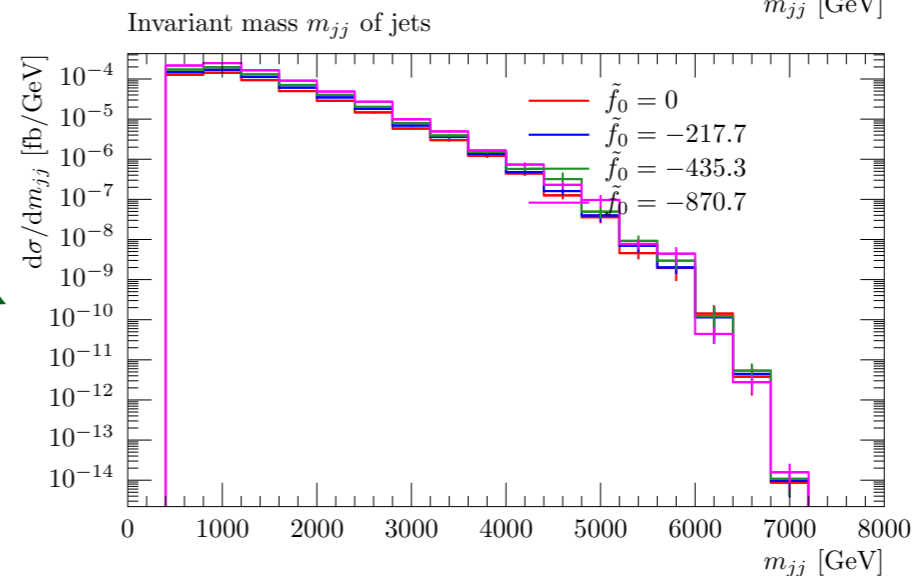


K-matrix



form-factor *

* form-factor scale:
lowest possible scale to
still ensure unitarity



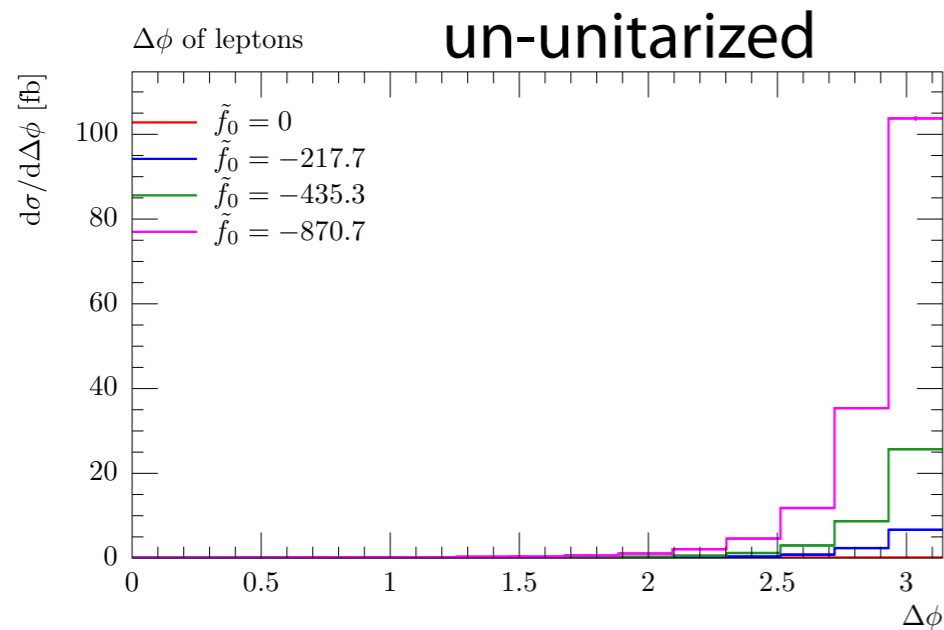
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Unique to $f_{S,i}$? Why?

Shown here: $W+W+jj$ final state, $p_T(\text{jet}) > 20$ GeV, $p_T(\text{leptons}) > 10$ GeV, $|\eta| < 5$, $\Delta R(j,j) > 0.4$, $M(j,j) > 150$ GeV

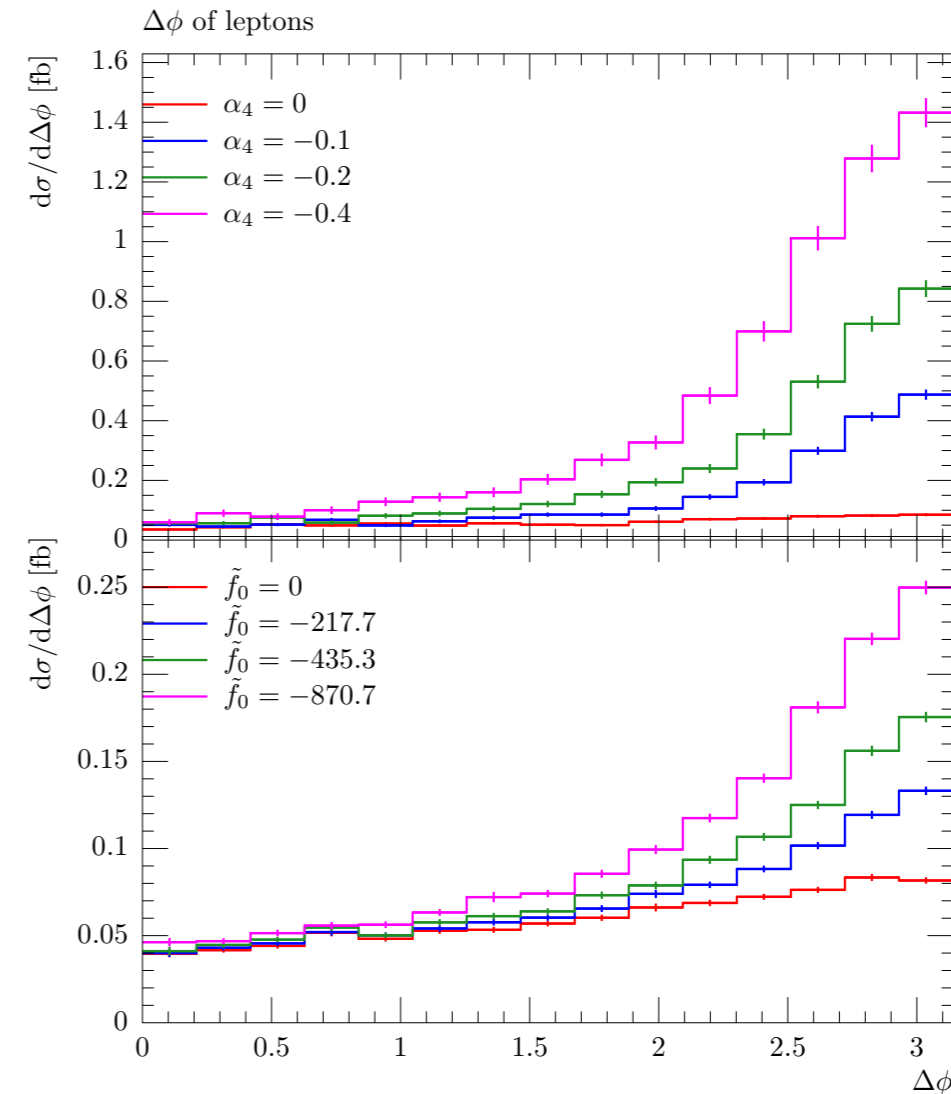
(4) aQGC discriminating variables

$\Delta\phi$ between leptons



K-matrix

form-factor *



Signature (view of an experimentalist):

- ❖ aQGC **don't** change kinematics, just the ratio of Feynman diagrams within VVjj-EW
- ❖ add aQGC → four-boson diagram enhanced → back-to-back bosons (and leptons)

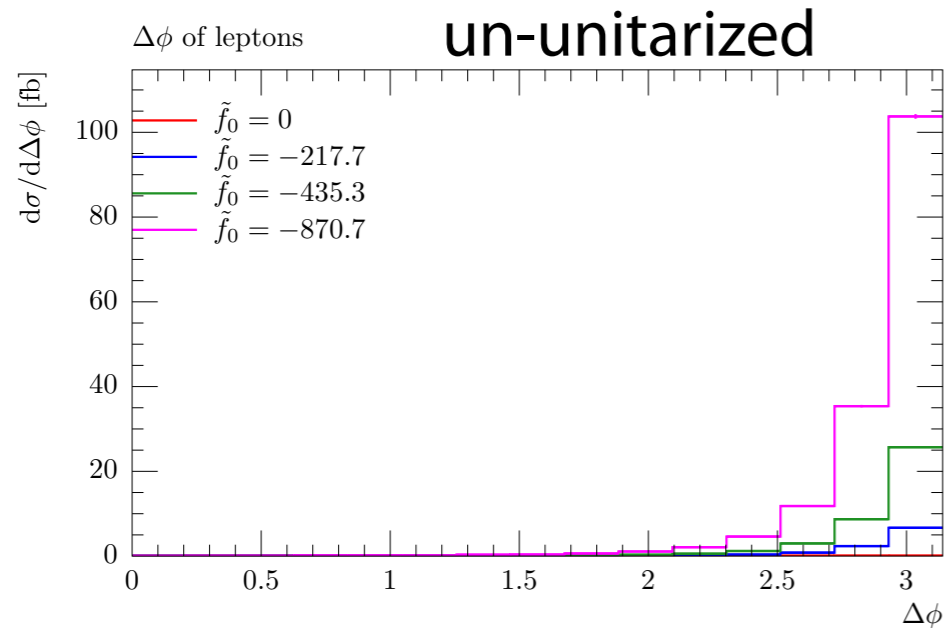
Shown here:

W^+W^+jj final state, $p_T(\text{jet}) > 20$ GeV, $p_T(\text{leptons}) > 10$ GeV,
 $|\eta| < 5$, $\Delta R(j,j) > 0.4$, $M(j,j) > 150$ GeV

* form-factor scale: lowest possible scale to still ensure unitarity

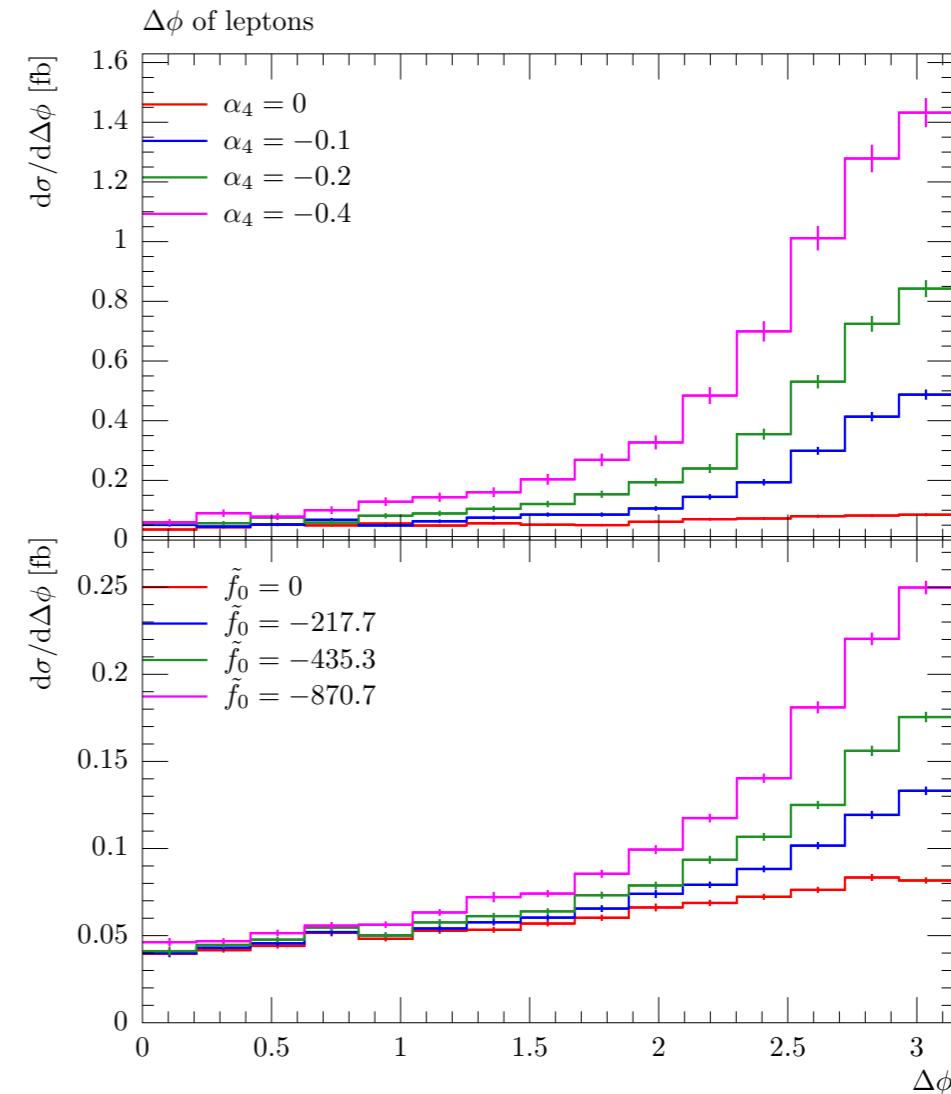
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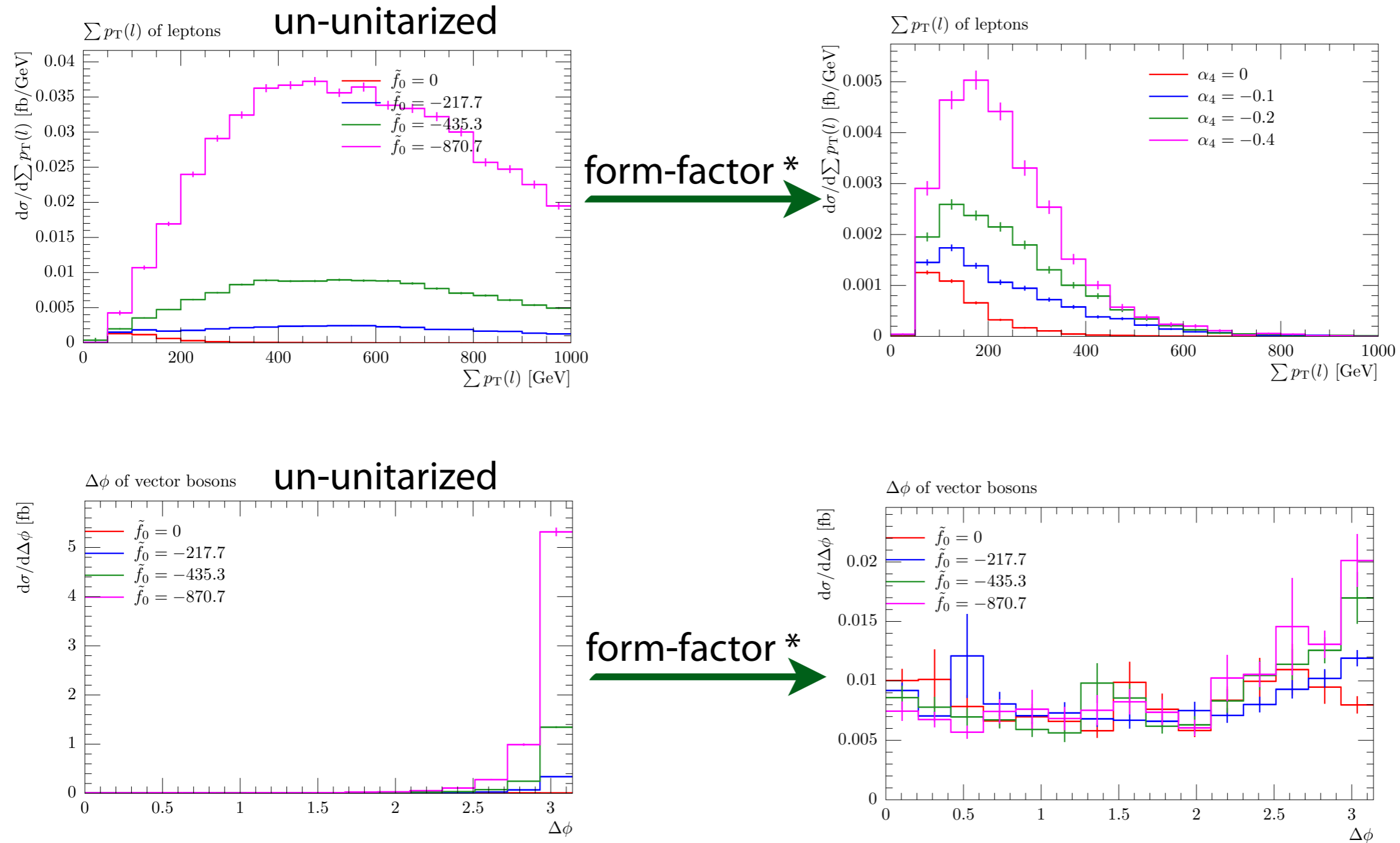
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* form-factor scale: lowest possible scale to still ensure unitarity

Since many people are asking and will ask this question:
Is it possible/meaningful to select/enhance a single diagrams within VVjj-EW?
E.g. is it defined to enhance the four-boson vertex alone to see the sensitivity to this single (most interesting) diagram?

(4) aQGC discriminating variables

scalar sum of lepton p_T
 $\Delta\phi$ between W and Z



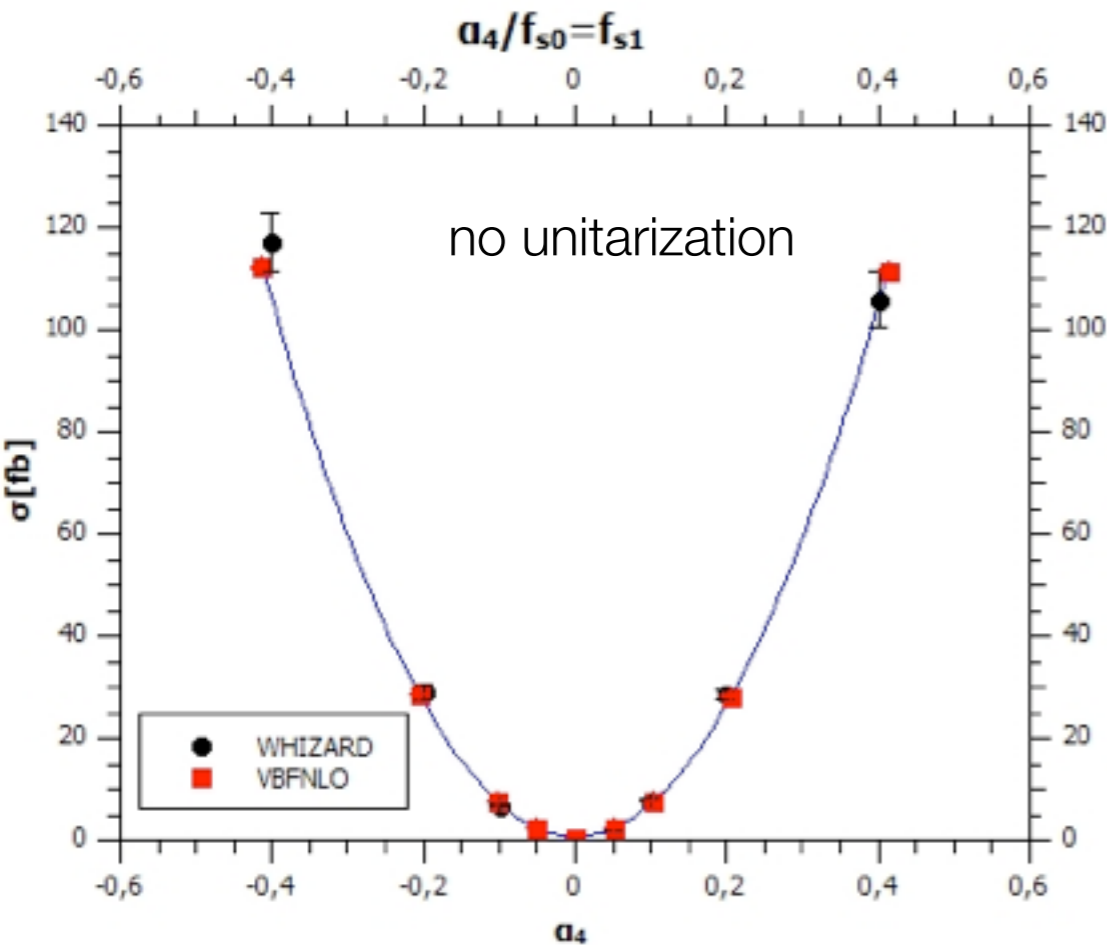
Shown here:

W^+W^+jj (top) / W^+Zjj (bottom) final state, $p_T(\text{jet}) > 20$ GeV, $p_T(\text{leptons}) > 10$ GeV, $|\eta| < 5$, $\Delta R(j,j) > 0.4$, $M(j,j) > 150$ GeV

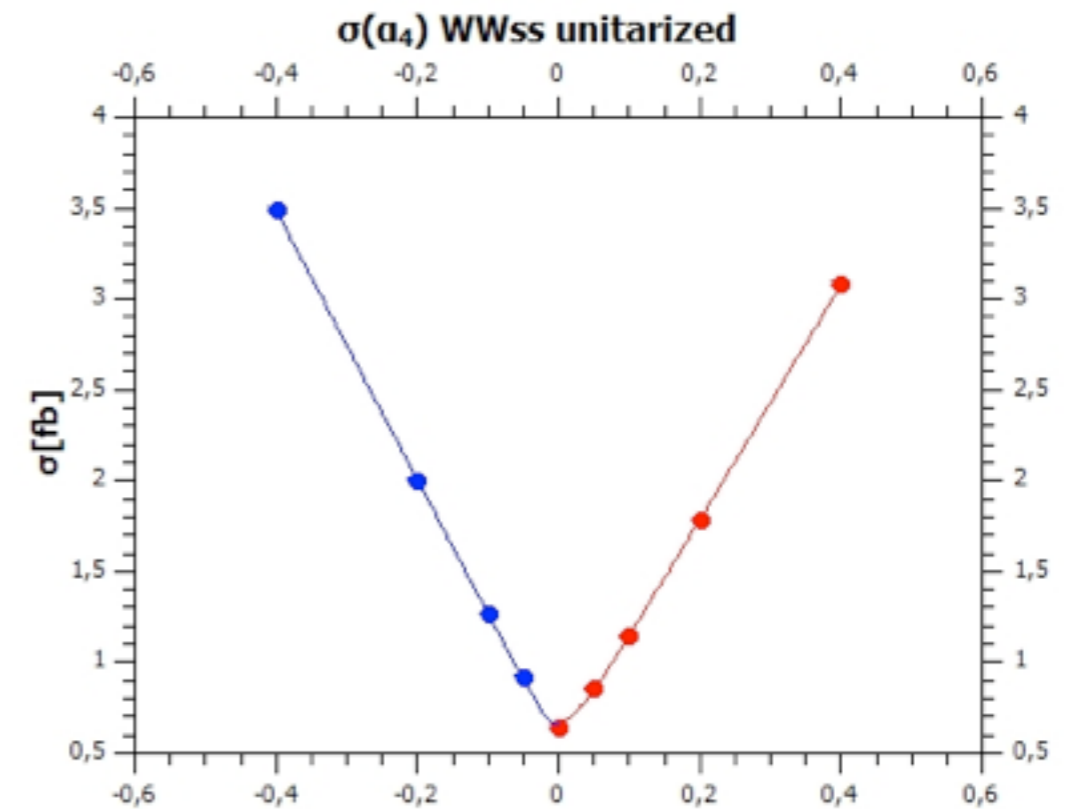
* form-factor scale: lowest possible scale to still ensure unitarity

(4) aQGC discriminating variables

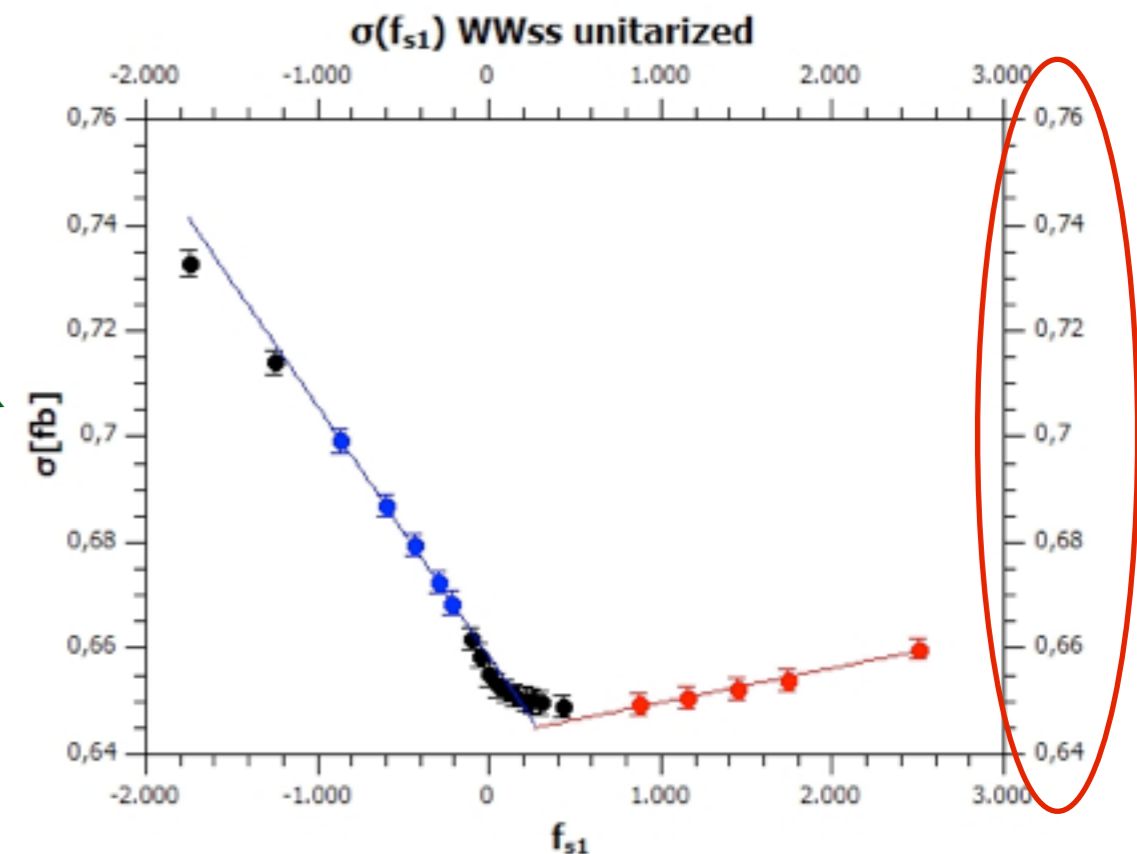
- ❖ conversion between $f_{s,i}$ and α_j possible (interesting topic, skipping here)
- ❖ quadratic \rightarrow linearish shape



K-matrix



form-factor *



Shown here:

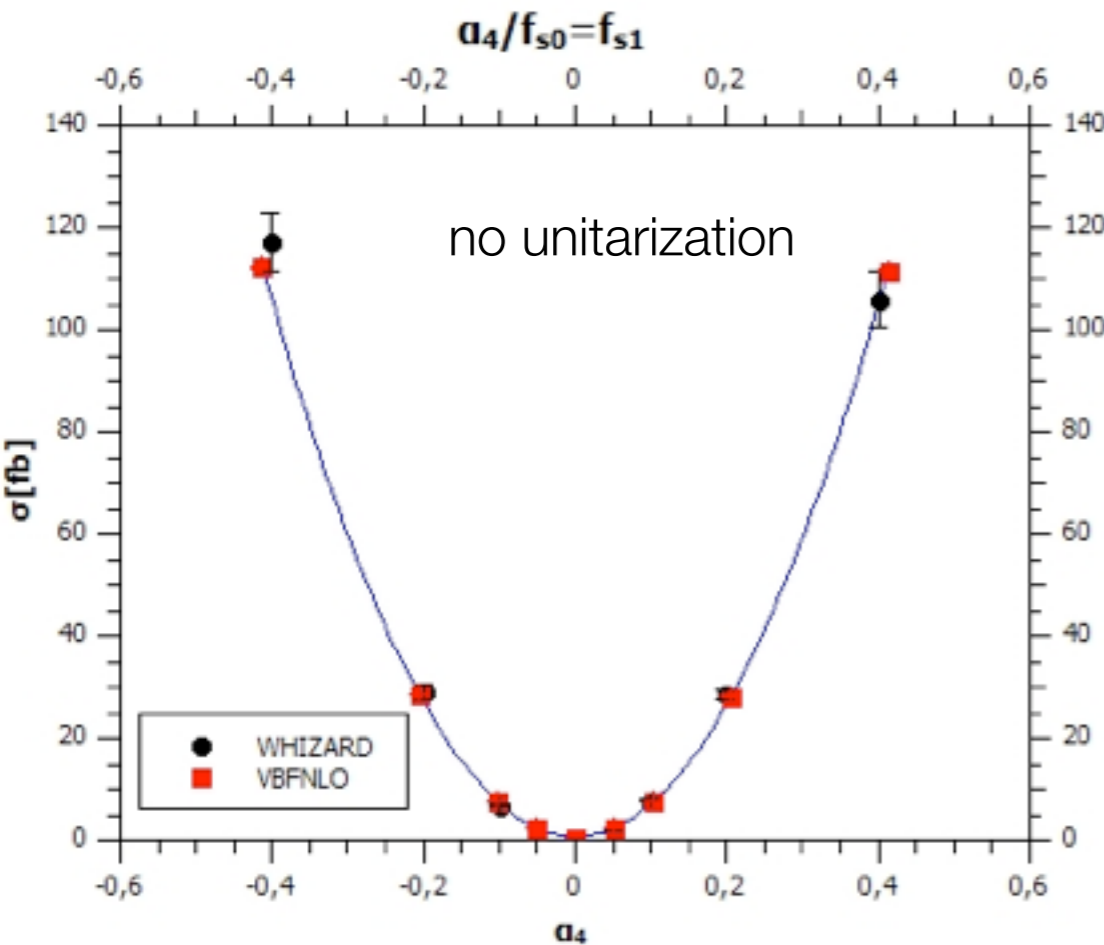
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* form-fajjctor scale: lowest possible scale to still ensure unitarity

(4) aQGC discriminating variables

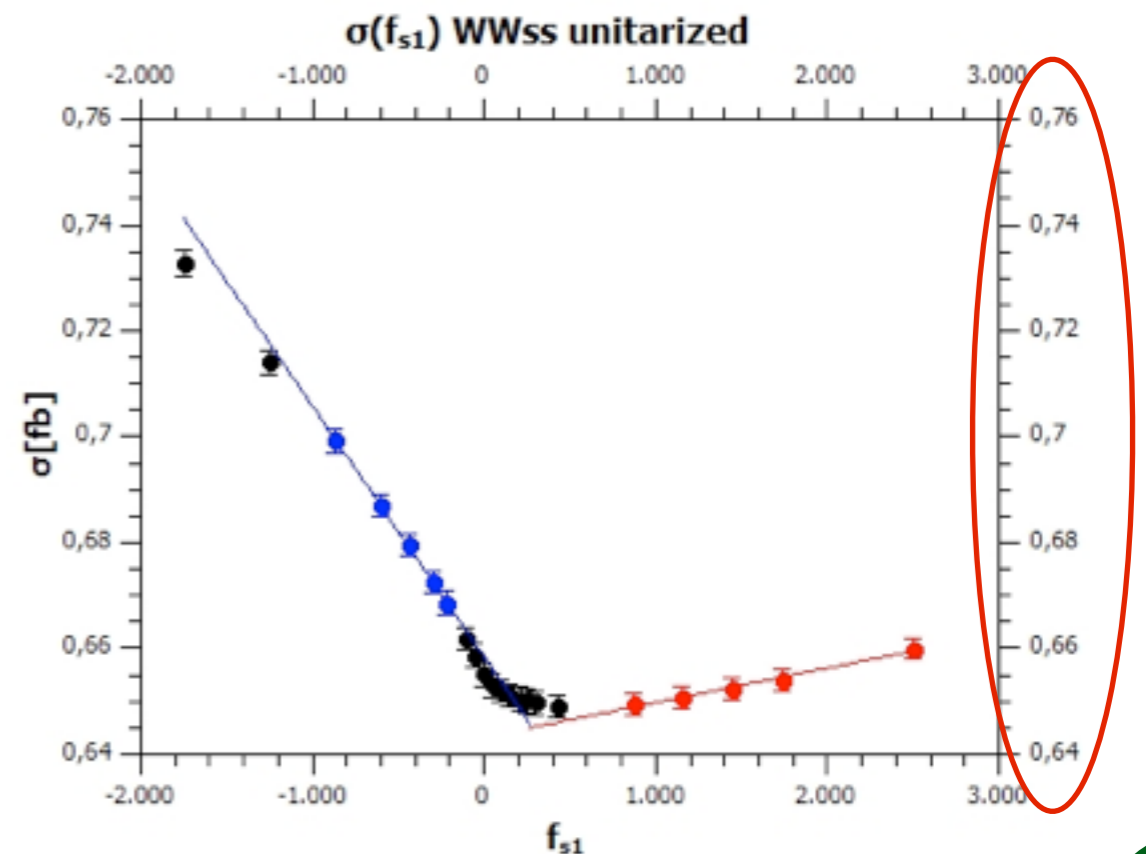
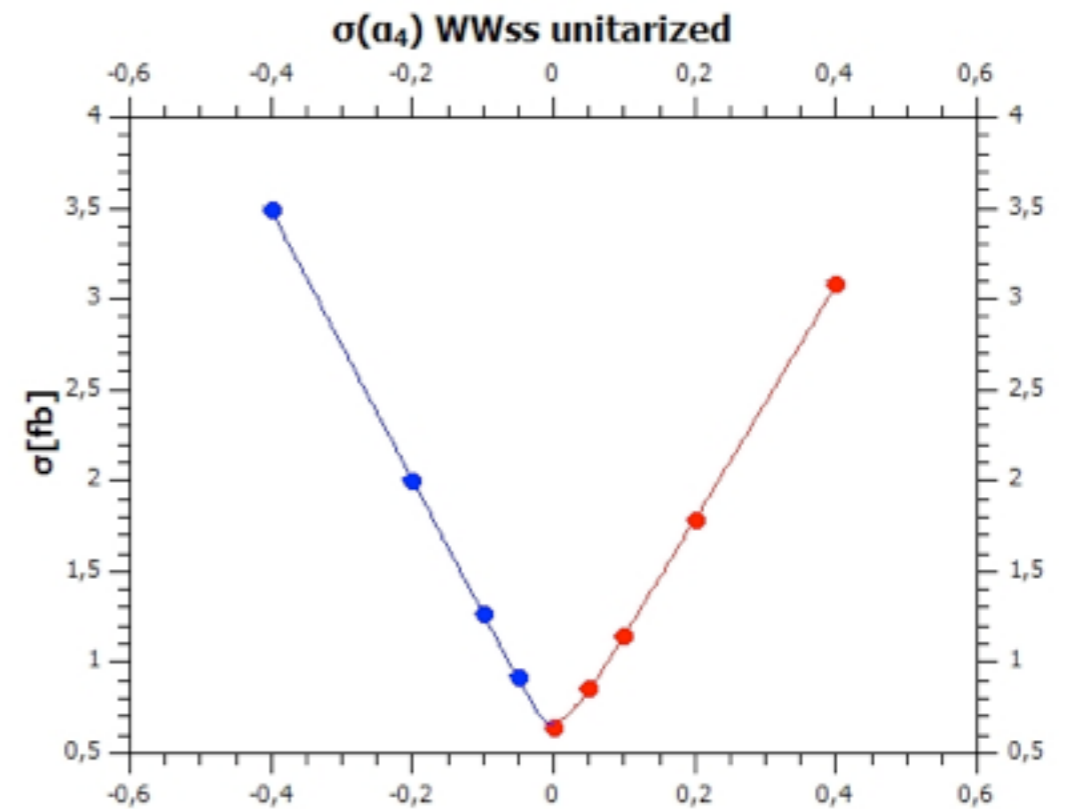
- ❖ conversion between $f_{s,i}$ and α_j possible (interesting topic, skipping here)
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Why?



K-matrix

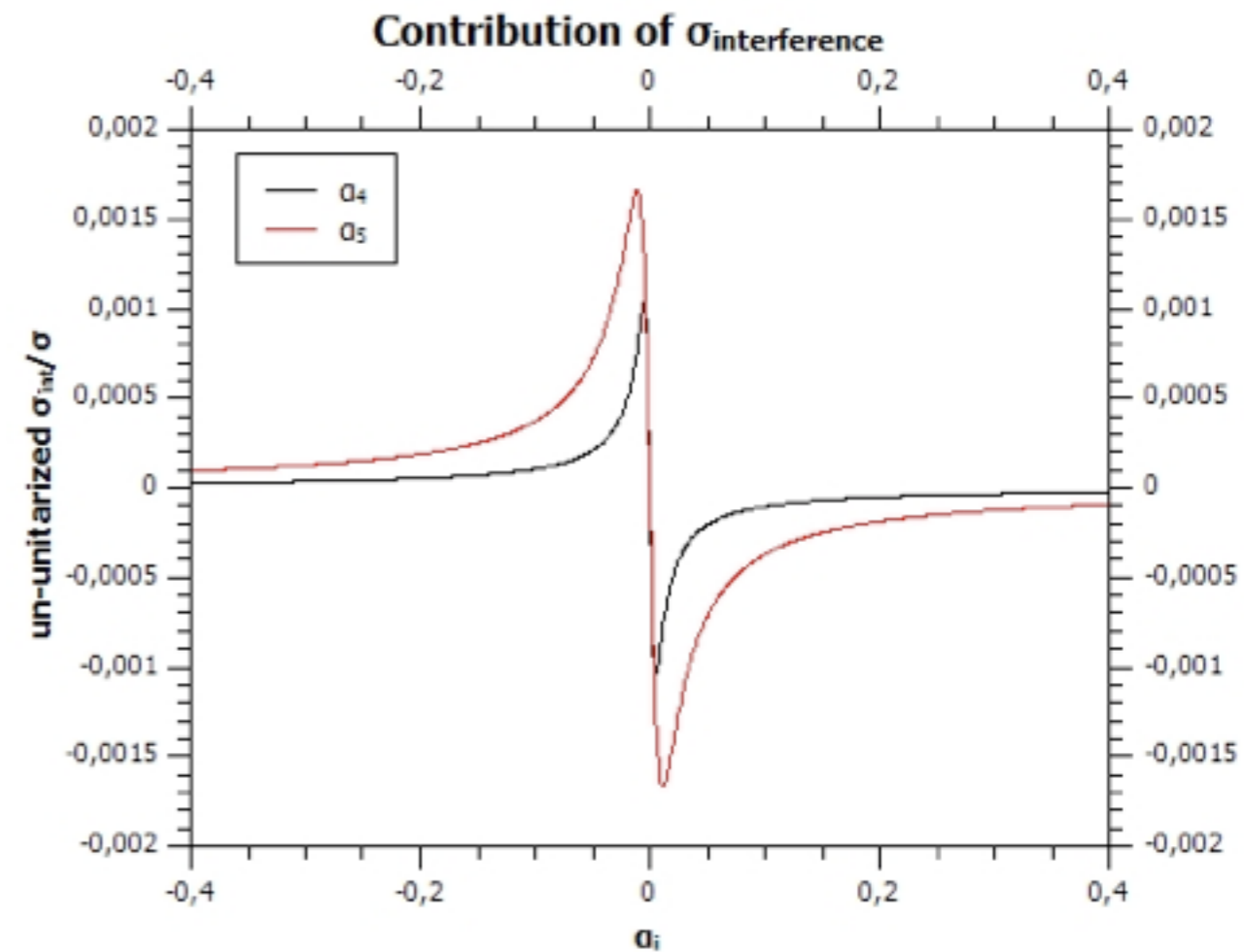
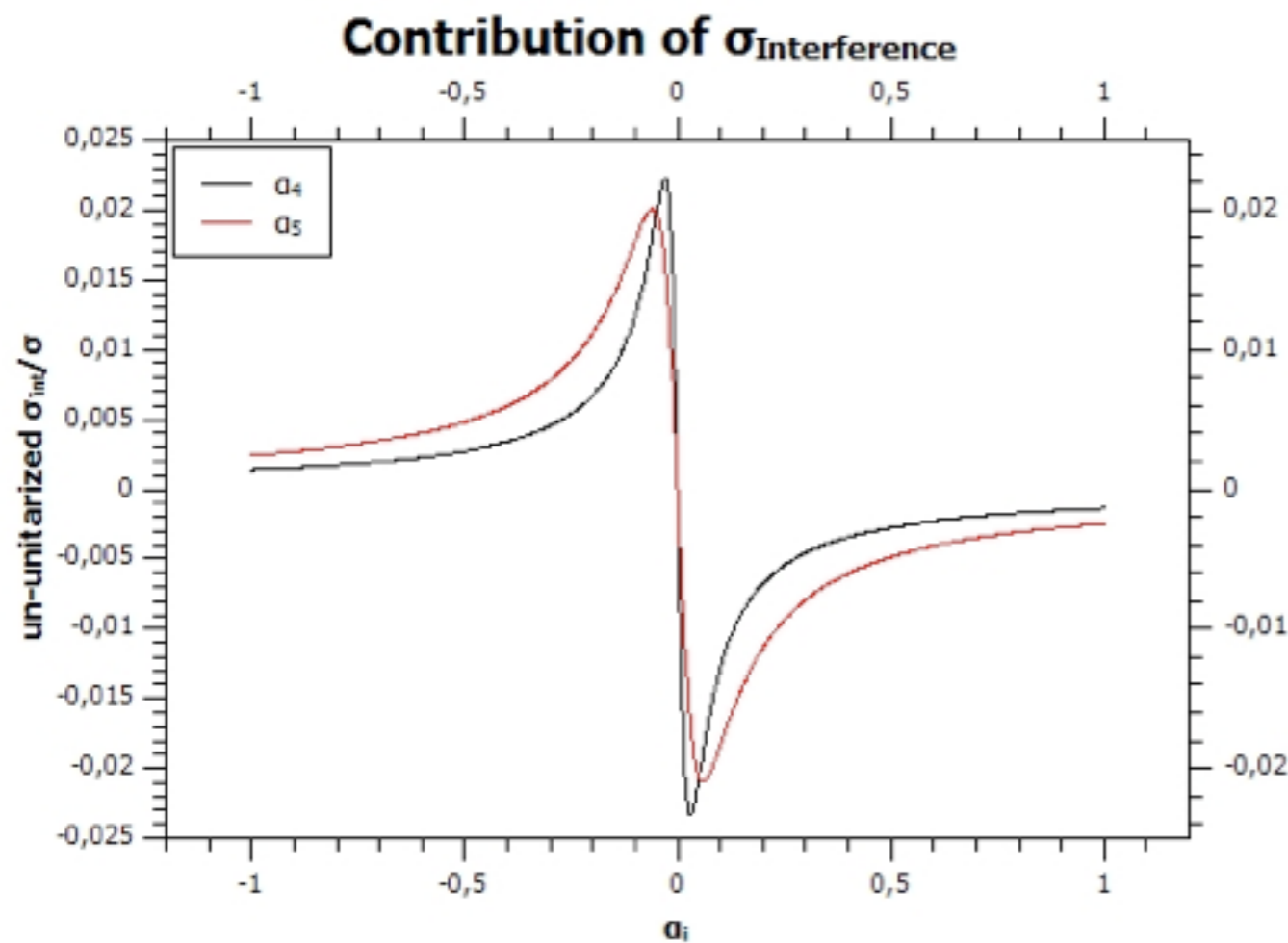
form-factor *



Shown here:
 W^+W^+jj final state, $p_T(\text{jet}) > 20 \text{ GeV}$, $p_T(\text{leptons}) > 10 \text{ GeV}$, $|\eta| < 5$,
 $\Delta R(j,j) > 0.4$, $M(j,j) > 150 \text{ GeV}$
 * form-fajjtor scale: lowest possible scale to still ensure unitarity

(4) aQGC interference

- ❖ normalized interference between aQGC and the Standard Model (the part of the cross-section linear in the aQGC parameter)
 - ❖ W^+W^+jj (left) and W^+Zjj (right) final state
 - ❖ not unitarized
- **interference small** for W^+W^+jj (up to 2%) and negligible for W^+Zjj ($\ll 1\%$)



(4) aQGC Monte Carlo generators for VVjj and aQGC

Generator	aQGC parametrization	unitarization	VVjj-EW channels	VVjj-QCD channels	order QCD
VBFNLO	non-linear	form-factor, clipping	all (not all diagrams)	WZjj work ongoing	NLO no events
Whizard	linear	K-matrix, clipping	all	all (via VVjj-EWQCD minus VVjj-EW)	LO
PowhegBox	linear	clipping	WWss (not all diagrams)	WWss	NLO
Sherpa	non-linear	clipping	all	all	LO
Madgraph (and any other generator reading FeynRules)	linear http://feynrules.irmp.ucl.ac.be/wiki/AnomalousGaugeCoupling (non-linear)	clipping	all	all	LO
Phantom					

Details and possible updates of this table see generator session on Wednesday.

Summary

Experimental:

- ❖ ATLAS / CMS sensitive to aQGC (better at 14 TeV)
- ❖ keep in mind: Even SM process of VVjj has not been measured up to now
- ❖ groundwork in terms of diboson measurements, but additional input useful
- ❖ crucial part: understanding forward jets and backgrounds at *low* statistics

Theory input needed for aQGC:

- ❖ useful parameters to measure? (many + different + overlapping parametrizations, some change TGC, some just QGC, some break symmetries)
- ❖ unitarization? (model dependence, which scale, combination)
- ❖ how to publish results?

Thank you for your attention!!!

Questions

Important decision between experimentalists at ATLAS and CMS:

- (1) should we decide for one parametrization (linear, non-linear)?
- (2) should we set limits on both?
- (3) use just operators effecting QGC (and not TGC)?
- (4) unitarization?

Important questions to theorists:

- (1) linear parameters: Which are unique to aQGC / dimension-8? Are some more useful than others (there are 20 - set limits on all of them)? [slide 20]
- (2) Are there non-linear parameters corresponding to the many linear ones? [slide 22]
- (3) Can the Higgs be added consistently to the non-linear approach and how does the result compare to the linear parametrization [slide 22]?
- (4) Which unitarization is useful for publishing results and combination of results? How to derive scales used for clipping and form factor? [slide 23]
- (5) Why is there no sensitivity to $\alpha_{\{4,5\}}$ / $f_{S,\{0,1\}}$ with form-factor unitarization? [slide 25]