New Physics / Resonances in Vector Boson Scattering at the LHC

Jürgen R. Reuter, DESY

HELMHOLTZ | GEMEINSCHAFT

based on work with A. Alboteanu, W. Kilian, T. Ohl, M. Sekulla

PRD93(16),3. 036004 [1511.00022], PRD91(15),096007 [1408.6207], US Snowmass Summer Study 1310.6708,1309.7890,1307.8180, JHEP 0811.010 [0806.4145], EPJC48(06)353 [hep-ph/0604048]

Seen signals, unseen signals, seen un-signals (?)

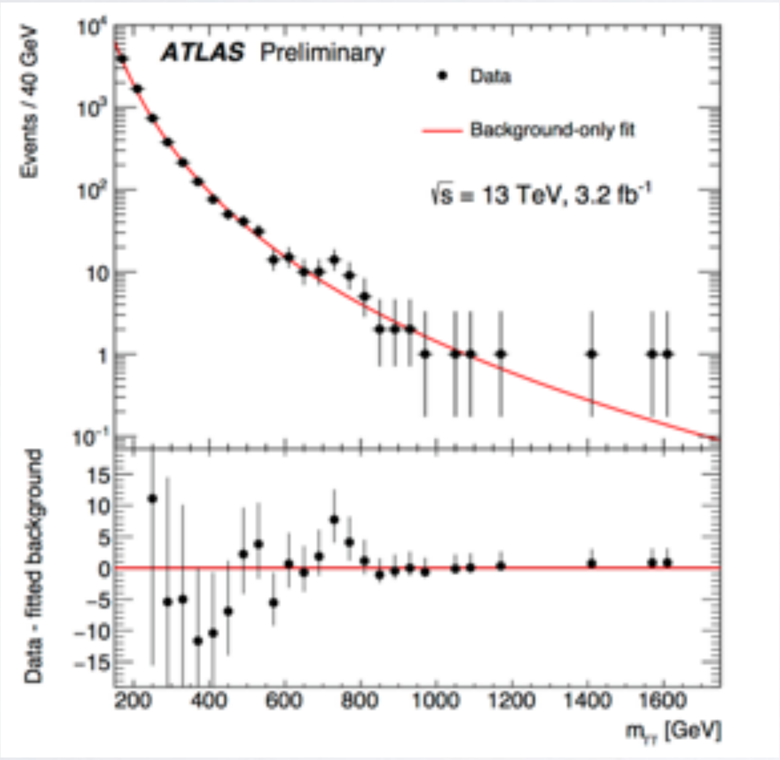
- Discovery of a light Higgs boson leaves still open questions:

1. Nature of Electroweak Symmetry Breaking
2. Higgs boson potential, all the way like the Standard Model!?
3. Does it fulfill the US-fermion/Europe-boson rule?
4. Is the 125 GeV state the only resonance in the system of EW vector bosons?
5. How do EW vector bosons scatter? (true heart of weak interactions)
6. Is there something related to the Little Hierarchy problem (strong or weak)

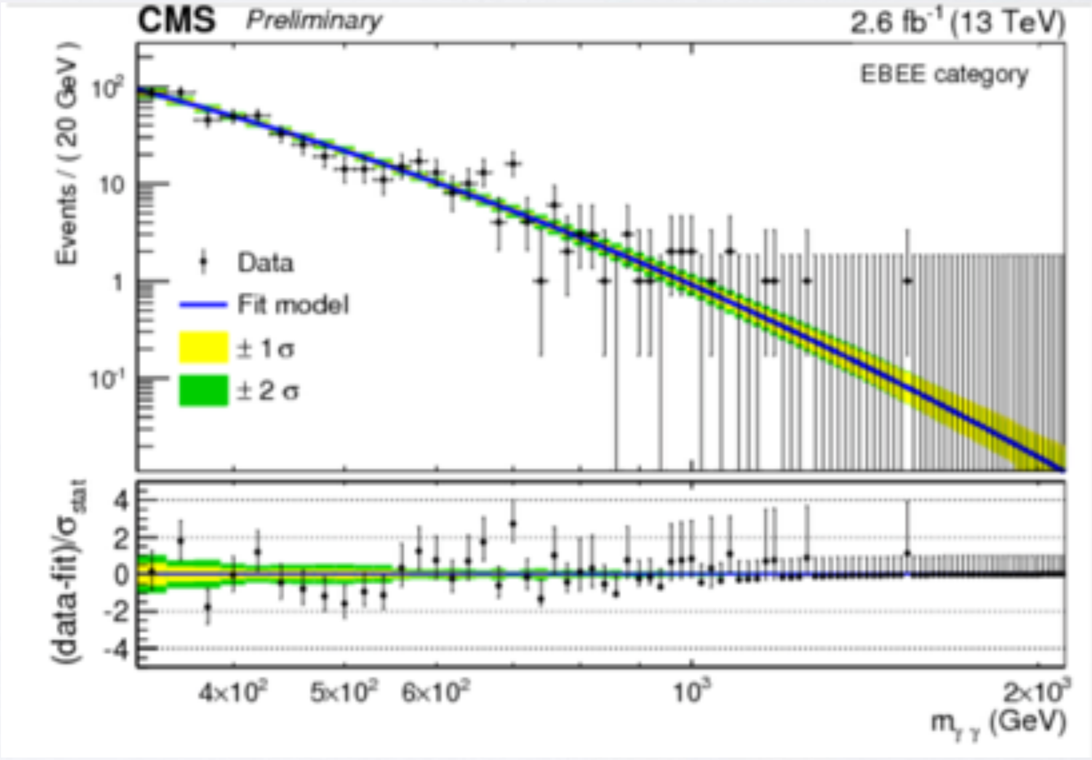
Seen signals, unseen signals, seen un-signals (?)

- Discovery of a light Higgs boson leaves still open questions:

1. Nature of Electroweak Symmetry Breaking
2. Higgs boson potential, all the way like the Standard Model!?
3. Does it fulfill the US-fermion/Europe-boson rule?
4. Is the 125 GeV state the only resonance in the system of EW vector bosons?
5. How do EW vector bosons scatter? (true heart of weak interactions)
6. Is there something related to the Little Hierarchy problem (strong or weak)



ATLAS-CONF-2015-081



CMS-PAS-EXO-15-004

Seen signals, unseen signals, seen un-signals (?)

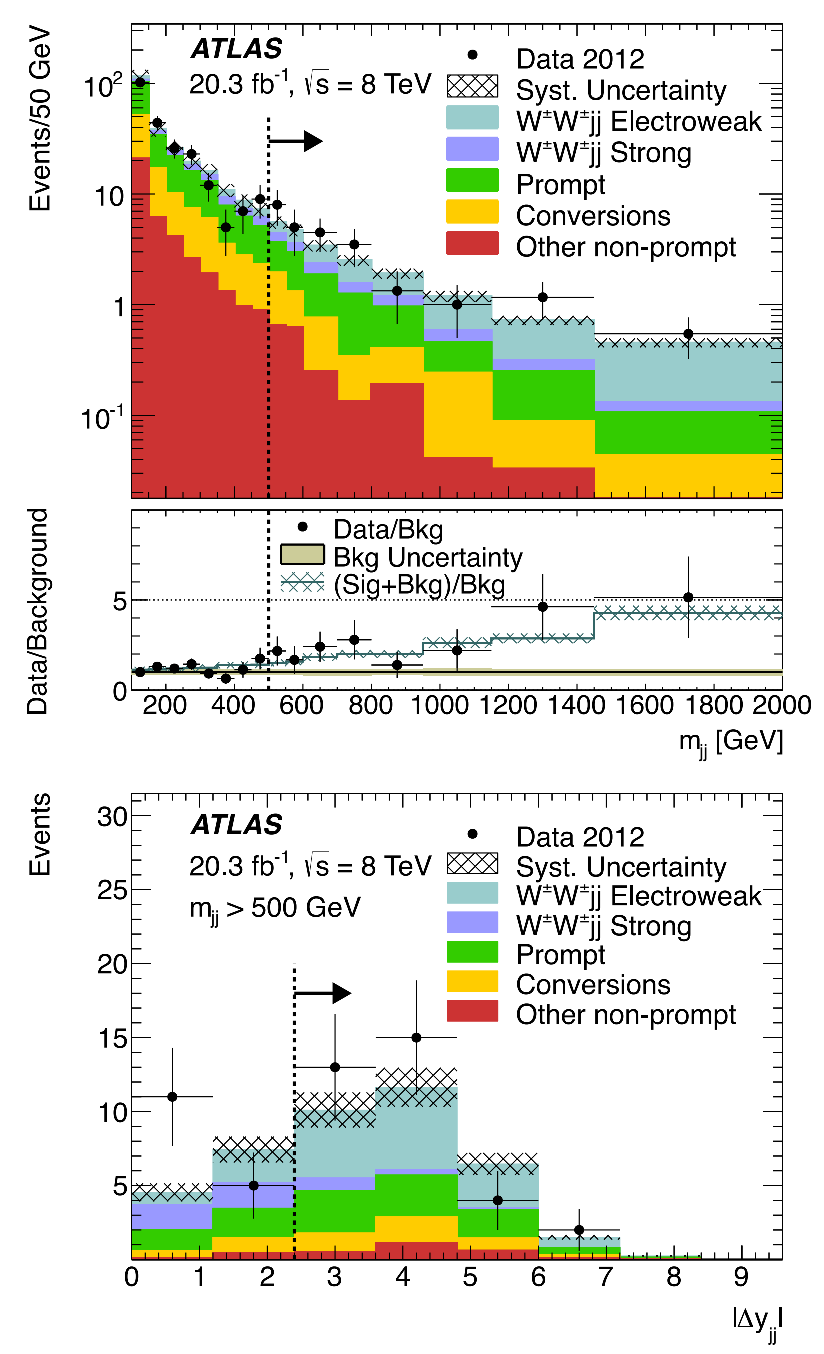
- Evidence for W^+W^+jj (electroweak production) Talk by Brigitte Vachon
  ATLAS PRL 113(2014)14, 141803 [1405.6241]; CMS PRL 114(2015), 051801 [1410.6315]
- First limits on New Physics in pure electroweak gauge/Goldstone sector

Seen signals, unseen signals, seen un-signals (?)

- Evidence for W^+W^+jj (electroweak production) Talk by Brigitte Vachon

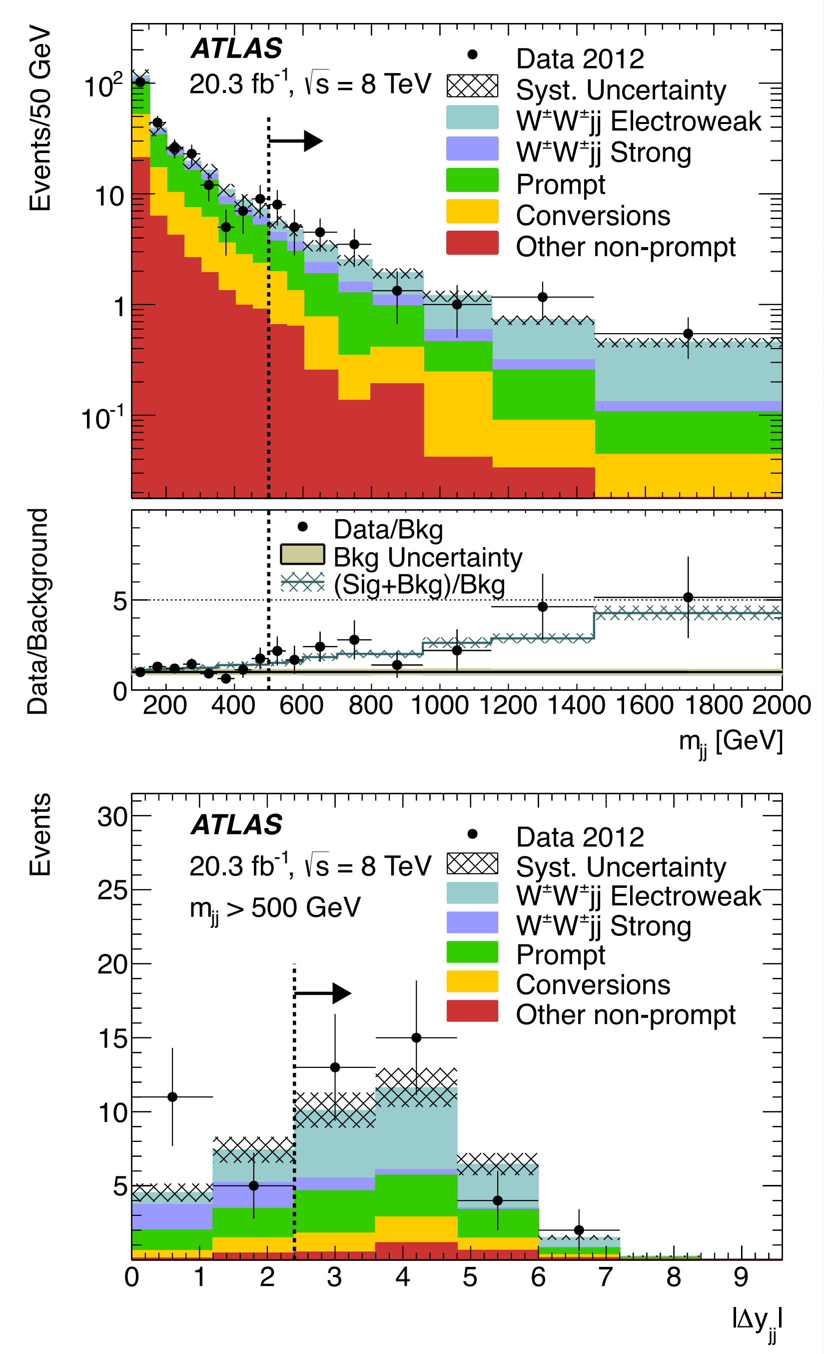
  ATLAS PRL 113(2014)14, 141803 [1405.6241]; CMS PRL 114(2015), 051801 [1410.6315]

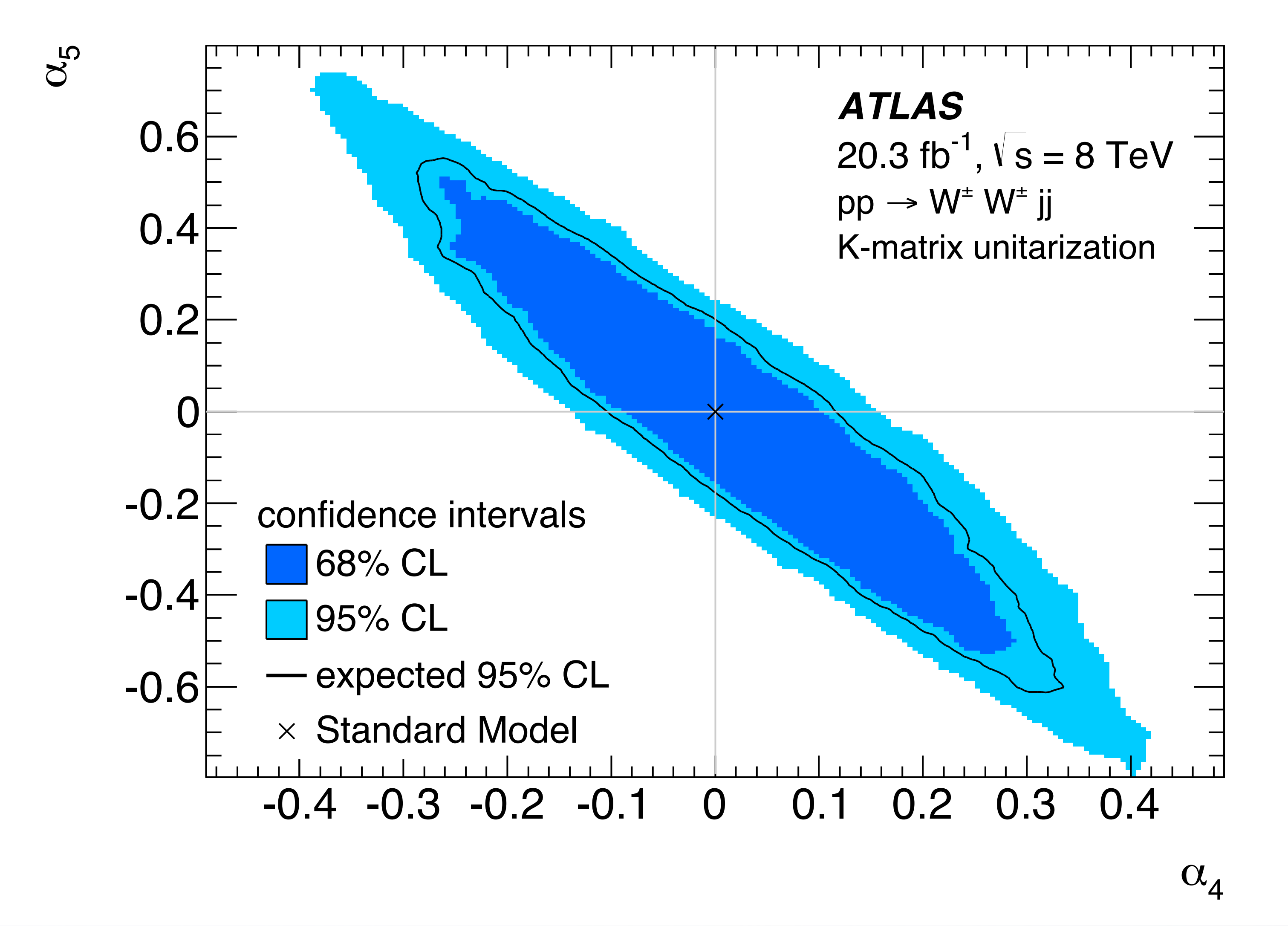
- First limits on New Physics in pure electroweak gauge/Goldstone sector



Seen signals, unseen signals, seen un-signals (?)

- Evidence for W^+W^+jj (electroweak production) Talk by Brigitte Vachon
  ATLAS PRL 113(2014)14, 141803 [1405.6241]; CMS PRL 114(2015), 051801 [1410.6315]
- First limits on New Physics in pure electroweak gauge/Goldstone sector



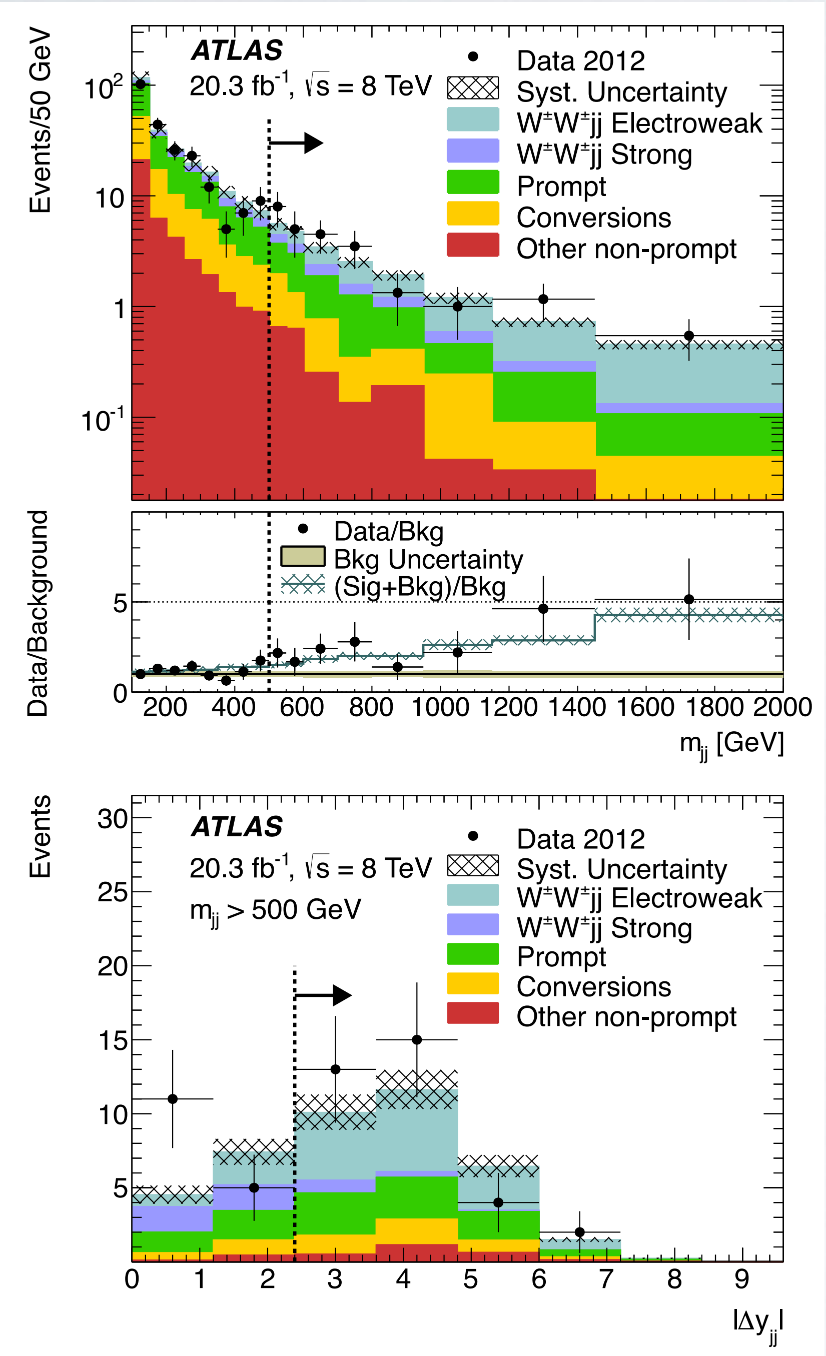


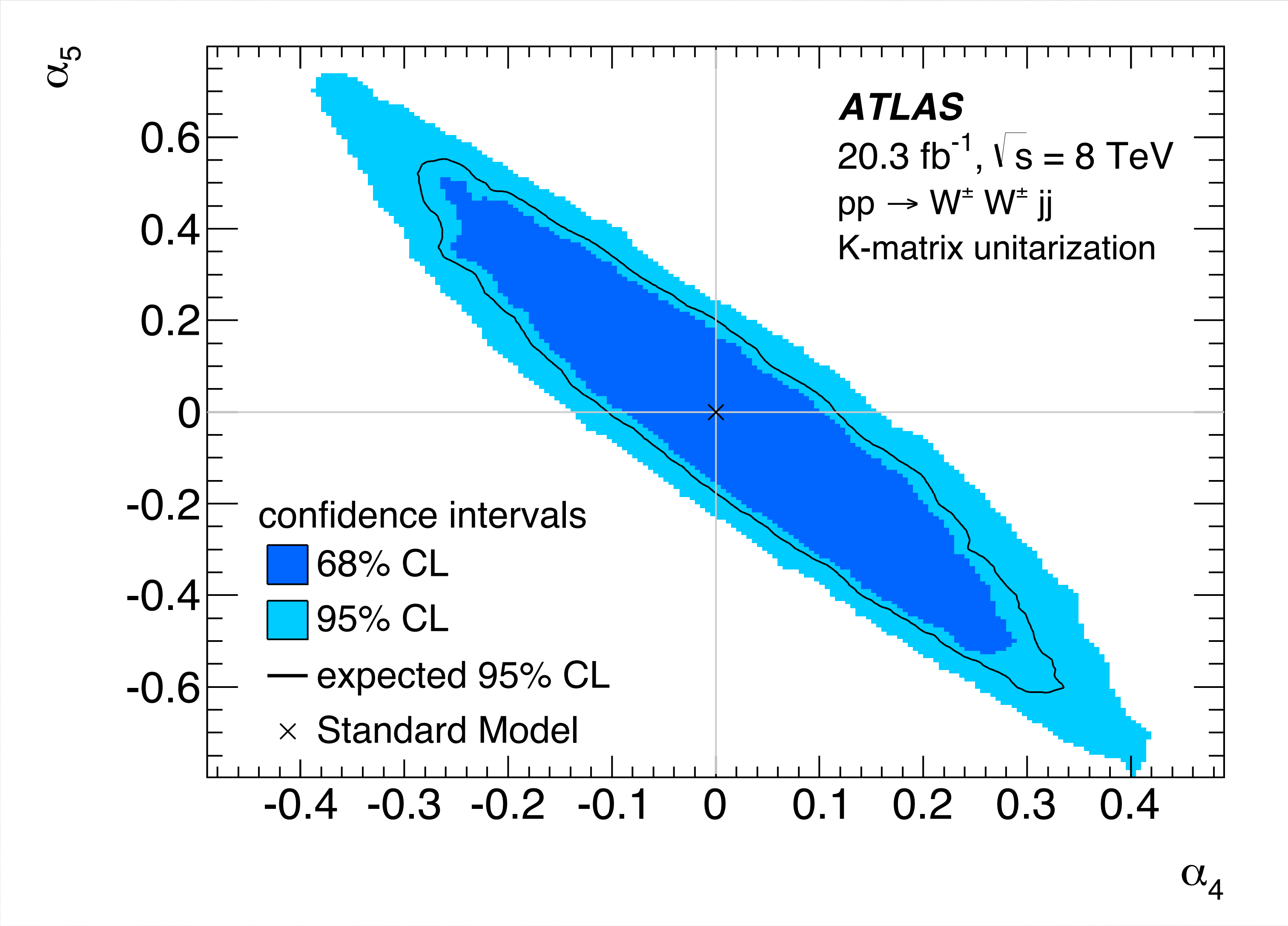
Seen signals, unseen signals, seen un-signals (?)

- Evidence for W^+W^+jj (electroweak production) Talk by Brigitte Vachon

  ATLAS PRL 113(2014)14, 141803 [1405.6241]; CMS PRL 114(2015), 051801 [1410.6315]

- First limits on New Physics in pure electroweak gauge/Goldstone sector



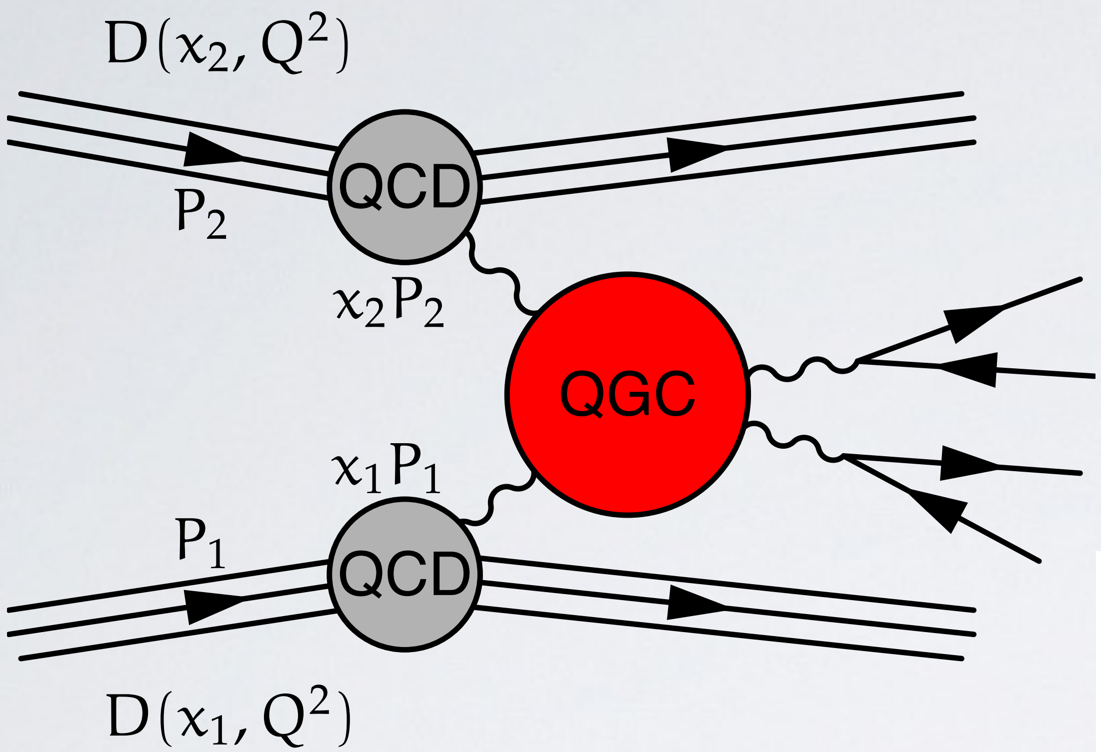


Exploration of E-frontier → look for heavy objects, including high-mass $V_L V_L$ scattering:
❑ requires as much integrated luminosity as possible (cross-section goes like 1/s)

F. Gianotti, 01/2014

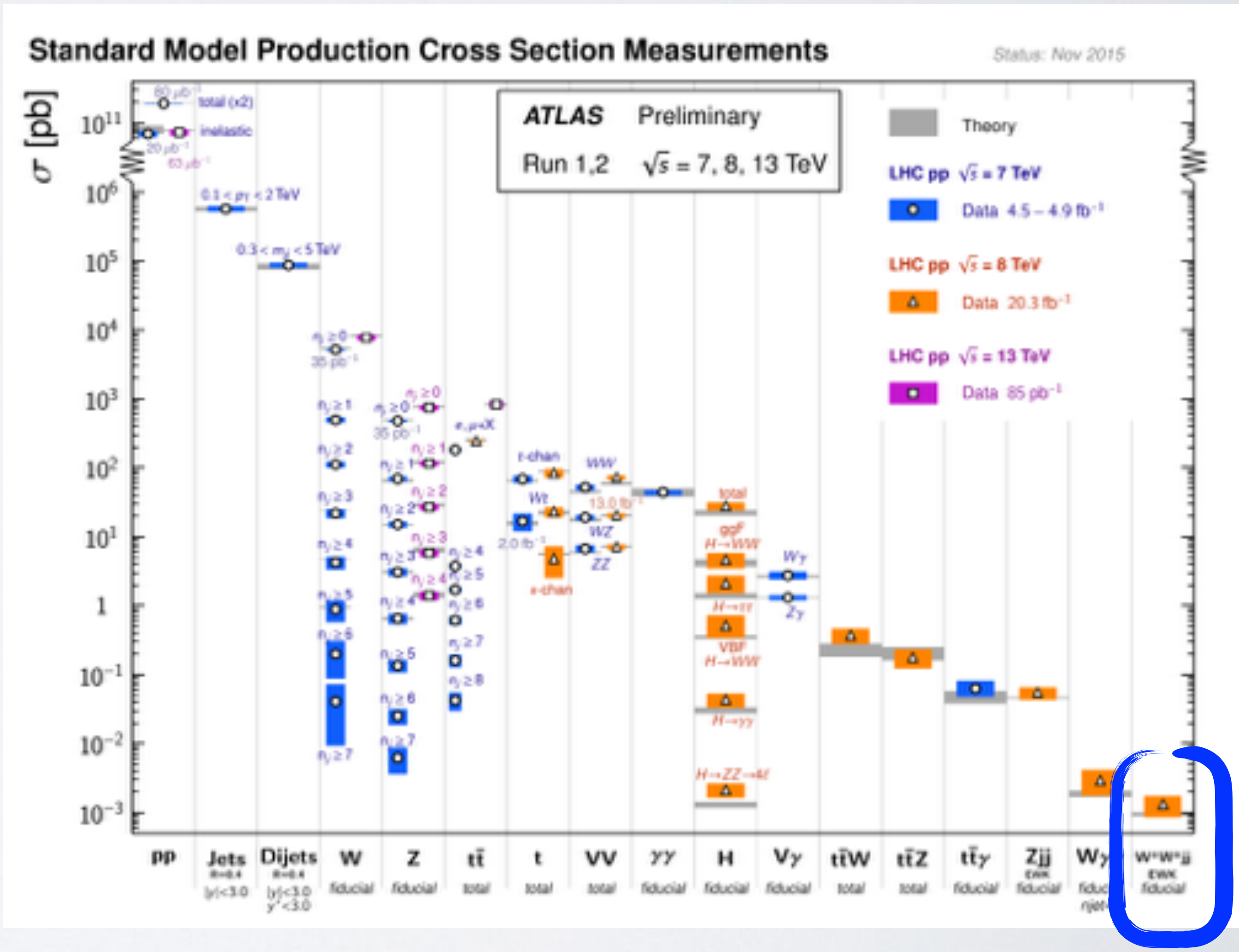
Anatomy of Vector Boson Scattering (VBS)

$$pp \to WWjj \to \ell\ell\nu\nu jj$$



Backgrounds [+ $V_T V_T$ bkgd.]:

- *tt* → *WbWb*
- *W + jets*
- single top, misreconstructed jet
- *WWjj* QCD production
- *ll* + X + Emiss ("prompt")



Fiducial phase space volume:

- *lljj* tag
- m_{jj} > 500 GeV ("jet recoil")
- $y_{j,1} \cdot y_{j,2} < 0$ ("collinear beams")
- $|\Delta y_{jj}| > 2.4$ ("rapidity distance")
- Cuts on E_j , p_T^j
- No mini jet vetoes

EFTs: Higher-dimensional operators

- Must include all dim 6 operators from SM fields — Buchmüller/Wyler, 1986
- Redundancy of operators $\Longrightarrow$ minimal set of operators (in principle)

  1. Equations of motion: $D_\mu \mathbf{W}^{\mu\nu} = \Phi^\dagger (D^\nu \Phi) - (D^\nu \Phi)^\dagger \Phi + \ldots$
  2. Gauge symmetry: $[D_\mu, D_\nu]\, \Phi \propto \mathbf{W}_{\mu\nu} \Phi$
  3. Integration by parts: $(\Phi^\dagger \Phi)\, \Box\, (\Phi^\dagger \Phi) \longrightarrow \partial_\mu \left(\Phi^\dagger \Phi\right) \partial^\mu \left(\Phi^\dagger \Phi\right)$

- Further reduction by use of discrete / horizontal symmetries

  1. *B* and *L* conservation (excludes 5 operators per generation)
  2. Flavor symmetries (assumption: Minimal Flavor Violation)
  3. *CP* symmetry

- Assuming *B* and *L* conservation: number of operators (without ν_R)

EFTs: Higher-dimensional operators

- Must include all dim 6 operators from SM fields Buchmüller/Wyler, 1986
- Redundancy of operators $\Longrightarrow$ minimal set of operators (in principle)
  1. Equations of motion: $D_\mu \mathbf{W}^{\mu\nu} = \Phi^\dagger (D^\nu \Phi) - (D^\nu \Phi)^\dagger \Phi + \ldots$
  2. Gauge symmetry: $[D_\mu, D_\nu]\, \Phi \propto \mathbf{W}_{\mu\nu} \Phi$
  3. Integration by parts: $\left(\Phi^\dagger \Phi\right) \Box \left(\Phi^\dagger \Phi\right) \longrightarrow \partial_\mu \left(\Phi^\dagger \Phi\right) \partial^\mu \left(\Phi^\dagger \Phi\right)$
- Further reduction by use of discrete / horizontal symmetries
  1. *B* and *L* conservation (excludes 5 operators per generation)
  2. Flavor symmetries (assumption: Minimal Flavor Violation)
  3. *CP* symmetry
- Assuming *B* and *L* conservation: number of operators (without ν_R)
  - 1 dim-2 operator + 15 dim-4 operators
  - 59 dim-6 operators for 1 generation
  - 2499 dim-6 operators for 3 generations Alonso/Jenkins/Manohar/Trott, 2013

EFTs: Higher-dimensional operators

- Must include all dim 6 operators from SM fields Buchmüller/Wyler, 1986
- Redundancy of operators $\Longrightarrow$ minimal set of operators (in principle)

  1. Equations of motion: $D_\mu \mathbf{W}^{\mu\nu} = \Phi^\dagger (D^\nu \Phi) - (D^\nu \Phi)^\dagger \Phi + \ldots$
  2. Gauge symmetry: $[D_\mu, D_\nu]\,\Phi \propto \mathbf{W}_{\mu\nu} \Phi$
  3. Integration by parts: $\left(\Phi^\dagger \Phi\right) \Box \left(\Phi^\dagger \Phi\right) \longrightarrow \partial_\mu \left(\Phi^\dagger \Phi\right) \partial^\mu \left(\Phi^\dagger \Phi\right)$

- Further reduction by use of discrete / horizontal symmetries

  1. *B* and *L* conservation (excludes 5 operators per generation)
  2. Flavor symmetries (assumption: Minimal Flavor Violation)
  3. *CP* symmetry

- Assuming *B* and *L* conservation: number of operators (without ν_R)

  - 1 dim-2 operator + 15 dim-4 operators
  - 59 dim-6 operators for 1 generation
  - 2499 dim-6 operators for 3 generations Alonso/Jenkins/Manohar/Trott, 2013

- No unique basis exists (more in a second)
- Well-known in *B* physics: different experimental measurements constrain different operators

Effective Field Theories: Operator Bases

No unique basis exists

- "HISZ" basis: no fermionic operators — Hagiwara/Ishihara/Szalapski/Zeppenfeld, 1993
- "GIMR" basis: first minimal complete basis — Grzadkowski/Iskrzyński/Misiak/Rosiek, 2010
- "SILH" basis: complete basis — Giudice/Grojean/Pomarol/Ratazzi, 2007; Elias-Miró et al, 2013
- Dim. 8 operators: — Eboli et al., 2006; Kilian/JRR/Ohl/Sekulla, 2014+2015

Effective Field Theories: Operator Bases

No unique basis exists

- "HISZ" basis: no fermionic operators — Hagiwara/Ishihara/Szalapski/Zeppenfeld, 1993
- "GIMR" basis: first minimal complete basis — Grzadkowski/Iskrzyński/Misiak/Rosiek, 2010
- "SILH" basis: complete basis — Giudice/Grojean/Pomarol/Ratazzi, 2007; Elias-Miró et al, 2013
- Dim. 8 operators: — Eboli et al., 2006; Kilian/JRR/Ohl/Sekulla, 2014+2015

Φ^6 and $\Phi^4 D^2$	$\psi^2\Phi^3$	X^3
$\mathcal{O}_\Phi = (\Phi^\dagger\Phi)^3$	$\mathcal{O}_{e\Phi} = (\Phi^\dagger\Phi)(\bar{l}\Gamma_e e\Phi)$	$\mathcal{O}_G = f^{ABC}G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$
$\mathcal{O}_{\Phi\Box} = (\Phi^\dagger\Phi)\Box(\Phi^\dagger\Phi)$	$\mathcal{O}_{u\Phi} = (\Phi^\dagger\Phi)(\bar{q}\Gamma_u u\widetilde{\Phi})$	$\mathcal{O}_{\widetilde{G}} = f^{ABC}\widetilde{G}_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$
$\mathcal{O}_{\Phi D} = (\Phi^\dagger D^\mu\Phi)^*(\Phi^\dagger D_\mu\Phi)$	$\mathcal{O}_{d\Phi} = (\Phi^\dagger\Phi)(\bar{q}\Gamma_d d\Phi)$	$\mathcal{O}_W = \varepsilon^{IJK}W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$
		$\mathcal{O}_{\widetilde{W}} = \varepsilon^{IJK}\widetilde{W}_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$
$X^2\Phi^2$	$\psi^2 X\Phi$	$\psi^2\Phi^2 D$
$\mathcal{O}_{\Phi G} = (\Phi^\dagger\Phi)G_{\mu\nu}^A G^{A\mu\nu}$	$\mathcal{O}_{uG} = (\bar{q}\sigma^{\mu\nu}\frac{\lambda^A}{2}\Gamma_u u\widetilde{\Phi})G_{\mu\nu}^A$	$\mathcal{O}_{\Phi l}^{(1)} = (\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi)(\bar{l}\gamma^\mu l)$
$\mathcal{O}_{\Phi\widetilde{G}} = (\Phi^\dagger\Phi)\widetilde{G}_{\mu\nu}^A G^{A\mu\nu}$	$\mathcal{O}_{dG} = (\bar{q}\sigma^{\mu\nu}\frac{\lambda^A}{2}\Gamma_d d\Phi)G_{\mu\nu}^A$	$\mathcal{O}_{\Phi l}^{(3)} = (\Phi^\dagger i\overleftrightarrow{D}_\mu^I\Phi)(\bar{l}\gamma^\mu\tau^I l)$
$\mathcal{O}_{\Phi W} = (\Phi^\dagger\Phi)W_{\mu\nu}^I W^{I\mu\nu}$	$\mathcal{O}_{eW} = (\bar{l}\sigma^{\mu\nu}\Gamma_e e\tau^I\Phi)W_{\mu\nu}^I$	$\mathcal{O}_{\Phi e} = (\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi)(\bar{e}\gamma^\mu e)$
$\mathcal{O}_{\Phi\widetilde{W}} = (\Phi^\dagger\Phi)\widetilde{W}_{\mu\nu}^I W^{I\mu\nu}$	$\mathcal{O}_{uW} = (\bar{q}\sigma^{\mu\nu}\Gamma_u u\tau^I\widetilde{\Phi})W_{\mu\nu}^I$	$\mathcal{O}_{\Phi q}^{(1)} = (\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi)(\bar{q}\gamma^\mu q)$
$\mathcal{O}_{\Phi B} = (\Phi^\dagger\Phi)B_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{dW} = (\bar{q}\sigma^{\mu\nu}\Gamma_d d\tau^I\Phi)W_{\mu\nu}^I$	$\mathcal{O}_{\Phi q}^{(3)} = (\Phi^\dagger i\overleftrightarrow{D}_\mu^I\Phi)(\bar{q}\gamma^\mu\tau^I q)$
$\mathcal{O}_{\Phi\widetilde{B}} = (\Phi^\dagger\Phi)\widetilde{B}_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{eB} = (\bar{l}\sigma^{\mu\nu}\Gamma_e e\Phi)B_{\mu\nu}$	$\mathcal{O}_{\Phi u} = (\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi)(\bar{u}\gamma^\mu u)$
$\mathcal{O}_{\Phi WB} = (\Phi^\dagger\tau^I\Phi)W_{\mu\nu}^I B^{\mu\nu}$	$\mathcal{O}_{uB} = (\bar{q}\sigma^{\mu\nu}\Gamma_u u\widetilde{\Phi})B_{\mu\nu}$	$\mathcal{O}_{\Phi d} = (\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi)(\bar{d}\gamma^\mu d)$
$\mathcal{O}_{\Phi\widetilde{W}B} = (\Phi^\dagger\tau^I\Phi)\widetilde{W}_{\mu\nu}^I B^{\mu\nu}$	$\mathcal{O}_{dB} = (\bar{q}\sigma^{\mu\nu}\Gamma_d d\Phi)B_{\mu\nu}$	$\mathcal{O}_{\Phi ud} = i(\widetilde{\Phi}^\dagger D_\mu\Phi)(\bar{u}\gamma^\mu\Gamma_{ud}d)$

+ 25 four-fermion operators

Grzadkowski et al.

Effective Field Theories: Operator Bases

No unique basis exists

- "HISZ" basis: no fermionic operators — Hagiwara/Ishihara/Szalapski/Zeppenfeld, 1993
- "GIMR" basis: first minimal complete basis — Grzadkowski/Iskrzyński/Misiak/Rosiek, 2010
- "SILH" basis: complete basis — Giudice/Grojean/Pomarol/Ratazzi, 2007; Elias-Miró et al, 2013
- Dim. 8 operators: — Eboli et al., 2006; Kilian/JRR/Ohl/Sekulla, 2014+2015

Φ^6 and $\Phi^4 D^2$	$\psi^2\Phi^3$	X^3
$\mathcal{O}'_6 = (\Phi^\dagger\Phi)^3$	$\mathcal{O}'_{e\Phi} = (\Phi^\dagger\Phi)(\bar{l}\,\Gamma_e e\Phi)$	$\mathcal{O}'_G = f^{ABC}G^{A\nu}_\mu G^{B\rho}_\nu G^{C\mu}_\rho$
$\mathcal{O}'_\Phi = \partial_\mu(\Phi^\dagger\Phi)\partial^\mu(\Phi^\dagger\Phi)$	$\mathcal{O}'_{u\Phi} = (\Phi^\dagger\Phi)(\bar{q}\,\Gamma_u u\widetilde{\Phi})$	$\mathcal{O}'_{\widetilde{G}} = f^{ABC}\widetilde{G}^{A\nu}_\mu G^{B\rho}_\nu G^{C\mu}_\rho$
$\mathcal{O}'_T = (\Phi^\dagger \overleftrightarrow{D}_\mu\Phi)(\Phi^\dagger \overleftrightarrow{D}^\mu\Phi)$	$\mathcal{O}'_{d\Phi} = (\Phi^\dagger\Phi)(\bar{q}\,\Gamma_d d\Phi)$	$\mathcal{O}'_W = \varepsilon^{IJK}W^{I\nu}_\mu W^{J\rho}_\nu W^{K\mu}_\rho$
		$\mathcal{O}'_{\widetilde{W}} = \varepsilon^{IJK}\widetilde{W}^{I\nu}_\mu W^{J\rho}_\nu W^{K\mu}_\rho$
$X^2\Phi^2$	$\psi^2 X\Phi$	$\psi^2\Phi^2 D$
$\mathcal{O}'_{DW} = \left(\Phi^\dagger\tau^I i\overleftrightarrow{D}^\mu\Phi\right)(D^\nu W_{\mu\nu})^I$	$\mathcal{O}'_{uG} = (\bar{q}\sigma^{\mu\nu}\frac{\lambda^A}{2}\Gamma_u u\widetilde{\Phi})G^A_{\mu\nu}$	$\mathcal{O}'^{(1)}_{\Phi l} = (\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi)(\bar{l}\gamma^\mu l)$
$\mathcal{O}'_{DB} = \left(\Phi^\dagger i\overleftrightarrow{D}^\mu\Phi\right)(\partial^\nu B_{\mu\nu})$	$\mathcal{O}'_{dG} = (\bar{q}\sigma^{\mu\nu}\frac{\lambda^A}{2}\Gamma_d d\Phi)G^A_{\mu\nu}$	$\mathcal{O}'^{(3)}_{\Phi l} = (\Phi^\dagger i\overleftrightarrow{D}^I_\mu\Phi)(\bar{l}\gamma^\mu\tau^I l)$
$\mathcal{O}'_{D\Phi W} = i(D^\mu\Phi)^\dagger\tau^I(D^\nu\Phi)W^I_{\mu\nu}$	$\mathcal{O}'_{eW} = (\bar{l}\sigma^{\mu\nu}\Gamma_e e\tau^I\Phi)W^I_{\mu\nu}$	$\mathcal{O}'_{\Phi e} = (\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi)(\bar{e}\gamma^\mu e)$
$\mathcal{O}'_{D\Phi\widetilde{W}} = i(D^\mu\Phi)^\dagger\tau^I(D^\nu\Phi)\widetilde{W}^I_{\mu\nu}$	$\mathcal{O}'_{uW} = (\bar{q}\sigma^{\mu\nu}\Gamma_u u\tau^I\widetilde{\Phi})W^I_{\mu\nu}$	$\mathcal{O}'^{(1)}_{\Phi q} = (\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi)(\bar{q}\gamma^\mu q)$
$\mathcal{O}'_{D\Phi B} = i(D^\mu\Phi)^\dagger(D^\nu\Phi)B_{\mu\nu}$	$\mathcal{O}'_{dW} = (\bar{q}\sigma^{\mu\nu}\Gamma_d d\tau^I\Phi)W^I_{\mu\nu}$	$\mathcal{O}'^{(3)}_{\Phi q} = (\Phi^\dagger i\overleftrightarrow{D}^I_\mu\Phi)(\bar{q}\gamma^\mu\tau^I q)$
$\mathcal{O}'_{D\Phi\widetilde{B}} = i(D^\mu\Phi)^\dagger(D^\nu\Phi)\widetilde{B}_{\mu\nu}$	$\mathcal{O}'_{eB} = (\bar{l}\sigma^{\mu\nu}\Gamma_e e\Phi)B_{\mu\nu}$	$\mathcal{O}'_{\Phi u} = (\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi)(\bar{u}\gamma^\mu u)$
$\mathcal{O}'_{\Phi B} = (\Phi^\dagger\Phi)B_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}'_{uB} = (\bar{q}\sigma^{\mu\nu}\Gamma_u u\widetilde{\Phi})B_{\mu\nu}$	$\mathcal{O}'_{\Phi d} = (\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi)(\bar{d}\gamma^\mu d)$
$\mathcal{O}'_{\Phi\widetilde{B}} = (\Phi^\dagger\Phi)B_{\mu\nu}\widetilde{B}^{\mu\nu}$	$\mathcal{O}'_{dB} = (\bar{q}\sigma^{\mu\nu}\Gamma_d d\Phi)B_{\mu\nu}$	$\mathcal{O}'_{\Phi ud} = i(\widetilde{\Phi}^\dagger D_\mu\Phi)(\bar{u}\gamma^\mu\Gamma_{ud}d)$
$\mathcal{O}'_{\Phi G} = \Phi^\dagger\Phi G^A_{\mu\nu}G^{A\mu\nu}$		
$\mathcal{O}'_{\Phi\widetilde{G}} = \Phi^\dagger\Phi G^A_{\mu\nu}\widetilde{G}^{A\mu\nu}$	Giudice et al. / Contino at al.	+(25-2) four-fermion operators

Operators and Multi(EW)-boson Physics (I)

Operators and Multi(EW)-boson Physics (I)

Dimension-6 operators for Multiboson physics (CP-conserving)

$$\begin{aligned}
\mathcal{O}_{WWW} &= \mathrm{Tr}[W_{\mu\nu}W^{\nu\rho}W^{\mu}_{\rho}] \\
\mathcal{O}_{W} &= (D_\mu\Phi)^\dagger W^{\mu\nu}(D_\nu\Phi) \\
\mathcal{O}_{B} &= (D_\mu\Phi)^\dagger B^{\mu\nu}(D_\nu\Phi)
\end{aligned}$$

$$\begin{aligned}
\mathcal{O}_{\partial\Phi} &= \partial_\mu\left(\Phi^\dagger\Phi\right)\partial^\mu\left(\Phi^\dagger\Phi\right) \\
\mathcal{O}_{\Phi W} &= \left(\Phi^\dagger\Phi\right)\mathrm{Tr}[W^{\mu\nu}W_{\mu\nu}] \\
\mathcal{O}_{\Phi B} &= \left(\Phi^\dagger\Phi\right)B^{\mu\nu}B_{\mu\nu}
\end{aligned}$$

Operators and Multi(EW)-boson Physics (I)

Dimension-6 operators for Multiboson physics (CP-conserving)

$$\mathcal{O}_{WWW} = \mathrm{Tr}[W_{\mu\nu} W^{\nu\rho} W^{\mu}_{\rho}]$$
$$\mathcal{O}_{W} = (D_\mu \Phi)^\dagger W^{\mu\nu} (D_\nu \Phi)$$
$$\mathcal{O}_{B} = (D_\mu \Phi)^\dagger B^{\mu\nu} (D_\nu \Phi)$$

$$\mathcal{O}_{\partial\Phi} = \partial_\mu \left(\Phi^\dagger \Phi\right) \partial^\mu \left(\Phi^\dagger \Phi\right)$$
$$\mathcal{O}_{\Phi W} = \left(\Phi^\dagger \Phi\right) \mathrm{Tr}[W^{\mu\nu} W_{\mu\nu}]$$
$$\mathcal{O}_{\Phi B} = \left(\Phi^\dagger \Phi\right) B^{\mu\nu} B_{\mu\nu}$$

Dimension-6 operators for Multiboson physics (CP-violating)

$$\mathcal{O}_{\widetilde{W}W} = \Phi^\dagger \widetilde{W}_{\mu\nu} W^{\mu\nu} \Phi$$
$$\mathcal{O}_{\widetilde{B}B} = \Phi^\dagger \widetilde{B}_{\mu\nu} B^{\mu\nu} \Phi$$

$$\mathcal{O}_{\widetilde{W}WW} = \mathrm{Tr}[\widetilde{W}_{\mu\nu} W^{\nu\rho} W^{\mu}_{\rho}]$$
$$\mathcal{O}_{\widetilde{W}} = (D_\mu \Phi)^\dagger \widetilde{W}^{\mu\nu} (D_\nu \Phi)$$

Operators and Multi(EW)-boson Physics (I)

Dimension-6 operators for Multiboson physics (CP-conserving)

$$\begin{aligned} \mathcal{O}_{WWW} &= \mathrm{Tr}[W_{\mu\nu} W^{\nu\rho} W_{\rho}^{\mu}] \\ \mathcal{O}_{W} &= (D_\mu \Phi)^\dagger W^{\mu\nu} (D_\nu \Phi) \\ \mathcal{O}_{B} &= (D_\mu \Phi)^\dagger B^{\mu\nu} (D_\nu \Phi) \end{aligned}$$

$$\begin{aligned} \mathcal{O}_{\partial\Phi} &= \partial_\mu \left(\Phi^\dagger \Phi\right) \partial^\mu \left(\Phi^\dagger \Phi\right) \\ \mathcal{O}_{\Phi W} &= \left(\Phi^\dagger \Phi\right) \mathrm{Tr}[W^{\mu\nu} W_{\mu\nu}] \\ \mathcal{O}_{\Phi B} &= \left(\Phi^\dagger \Phi\right) B^{\mu\nu} B_{\mu\nu} \end{aligned}$$

Dimension-6 operators for Multiboson physics (CP-violating)

$$\begin{aligned} \mathcal{O}_{\widetilde{W}W} &= \Phi^\dagger \widetilde{W}_{\mu\nu} W^{\mu\nu} \Phi \\ \mathcal{O}_{\tilde{B}B} &= \Phi^\dagger \widetilde{B}_{\mu\nu} B^{\mu\nu} \Phi \end{aligned}$$

$$\begin{aligned} \mathcal{O}_{\widetilde{W}WW} &= \mathrm{Tr}[\widetilde{W}_{\mu\nu} W^{\nu\rho} W_{\rho}^{\mu}] \\ \mathcal{O}_{\widetilde{W}} &= (D_\mu \Phi)^\dagger \widetilde{W}^{\mu\nu} (D_\nu \Phi) \end{aligned}$$

Affect the following electroweak couplings:

	ZWW	AWW	HWW	HZZ	HZA	HAA	WWWW	ZZWW	ZAWW	AAWW
$\mathcal{O}_{WWW}$	✓	✓					✓	✓	✓	✓
$\mathcal{O}_{W}$	✓	✓	✓	✓	✓		✓	✓	✓	
$\mathcal{O}_{B}$	✓	✓		✓	✓					
$\mathcal{O}_{\Phi d}$			✓	✓						
$\mathcal{O}_{\Phi W}$			✓	✓	✓	✓				
$\mathcal{O}_{\Phi B}$				✓	✓	✓				
$\mathcal{O}_{\tilde{W}WW}$	✓	✓					✓	✓	✓	✓
$\mathcal{O}_{\tilde{W}}$	✓	✓	✓	✓	✓					
$\mathcal{O}_{\tilde{W}W}$			✓	✓	✓	✓				
$\mathcal{O}_{\tilde{B}B}$				✓	✓	✓				

Operators and Multi(EW)-boson Physics (I)

Dimension-6 operators for Multiboson physics (CP-conserving)

$$\mathcal{O}_{WWW} = \mathrm{Tr}[W_{\mu\nu}W^{\nu\rho}W_\rho^{\mu}]$$

$$\mathcal{O}_{W} = (D_\mu\Phi)^\dagger W^{\mu\nu}(D_\nu\Phi)$$

$$\mathcal{O}_{B} = (D_\mu\Phi)^\dagger B^{\mu\nu}(D_\nu\Phi)$$

$$\mathcal{O}_{\partial\Phi} = \partial_\mu\left(\Phi^\dagger\Phi\right)\partial^\mu\left(\Phi^\dagger\Phi\right)$$

$$\mathcal{O}_{\Phi W} = \left(\Phi^\dagger\Phi\right)\mathrm{Tr}[W^{\mu\nu}W_{\mu\nu}]$$

$$\mathcal{O}_{\Phi B} = \left(\Phi^\dagger\Phi\right)B^{\mu\nu}B_{\mu\nu}$$

Dimension-6 operators for Multiboson physics (CP-violating)

$$\mathcal{O}_{\widetilde{W}W} = \Phi^\dagger\widetilde{W}_{\mu\nu}W^{\mu\nu}\Phi$$

$$\mathcal{O}_{\tilde{B}B} = \Phi^\dagger\tilde{B}_{\mu\nu}B^{\mu\nu}\Phi$$

$$\mathcal{O}_{\widetilde{W}WW} = \mathrm{Tr}[\widetilde{W}_{\mu\nu}W^{\nu\rho}W_\rho^{\mu}]$$

$$\mathcal{O}_{\widetilde{W}} = (D_\mu\Phi)^\dagger\widetilde{W}^{\mu\nu}(D_\nu\Phi)$$

Affect the following electroweak couplings:

	ZWW	AWW	HWW	HZZ	HZA	HAA	WWWW	ZZWW	ZAWW	AAWW
$\mathcal{O}_{WWW}$	✓	✓					✓	✓	✓	✓
$\mathcal{O}_{W}$	✓	✓	✓	✓	✓		✓	✓	✓	
$\mathcal{O}_{B}$	✓	✓		✓	✓					
$\mathcal{O}_{\Phi d}$			✓	✓						
$\mathcal{O}_{\Phi W}$			✓	✓	✓	✓				
$\mathcal{O}_{\Phi B}$				✓	✓	✓				
$\mathcal{O}_{\tilde{W}WW}$	✓	✓					✓	✓	✓	✓
$\mathcal{O}_{\tilde{W}}$	✓	✓	✓	✓	✓					
$\mathcal{O}_{\tilde{W}W}$			✓	✓	✓	✓				
$\mathcal{O}_{\tilde{B}B}$				✓	✓	✓				

connected to Higgs physics

Operators and Multi(EW)-boson Physics (II)

Dimension-8 operators for Multiboson physics

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

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

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

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

Operators and Multi(EW)-boson Physics (II)

Dimension-8 operators for Multiboson physics

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

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

$$\mathcal{O}_{M,0} = \mathrm{Tr}\left[W_{\mu\nu} W^{\mu\nu} \right] \cdot \left[(D_\beta \Phi)^\dagger D^\beta \Phi \right]$$

$$\mathcal{O}_{M,1} = \mathrm{Tr}\left[W_{\mu\nu} W^{\nu\beta} \right] \cdot \left[(D_\beta \Phi)^\dagger D^\mu \Phi \right]$$

$$\mathcal{O}_{M,2} = \left[B_{\mu\nu} B^{\mu\nu} \right] \cdot \left[(D_\beta \Phi)^\dagger D^\beta \Phi \right]$$

$$\mathcal{O}_{M,3} = \left[B_{\mu\nu} B^{\nu\beta} \right] \cdot \left[(D_\beta \Phi)^\dagger D^\mu \Phi \right]$$

$$\mathcal{O}_{M,4} = \left[(D_\mu \Phi)^\dagger W_{\beta\nu} D^\mu \Phi \right] \cdot B^{\beta\nu}$$

$$\mathcal{O}_{M,5} = \left[(D_\mu \Phi)^\dagger W_{\beta\nu} D^\nu \Phi \right] \cdot B^{\beta\mu}$$

$$\mathcal{O}_{M,6} = \left[(D_\mu \Phi)^\dagger W_{\beta\nu} W^{\beta\nu} D^\mu \Phi \right]$$

$$\mathcal{O}_{M,7} = \left[(D_\mu \Phi)^\dagger W_{\beta\nu} W^{\beta\mu} D^\nu \Phi \right]$$

$$\mathcal{O}_{T,0} = \mathrm{Tr}\left[W_{\mu\nu} W^{\mu\nu} \right] \cdot \mathrm{Tr}\left[W_{\alpha\beta} W^{\alpha\beta} \right]$$

$$\mathcal{O}_{T,1} = \mathrm{Tr}\left[W_{\alpha\nu} W^{\mu\beta} \right] \cdot \mathrm{Tr}\left[W_{\mu\beta} W^{\alpha\nu} \right]$$

$$\mathcal{O}_{T,2} = \mathrm{Tr}\left[W_{\alpha\mu} W^{\mu\beta} \right] \cdot \mathrm{Tr}\left[W_{\beta\nu} W^{\nu\alpha} \right]$$

$$\mathcal{O}_{T,5} = \mathrm{Tr}\left[W_{\mu\nu} W^{\mu\nu} \right] \cdot B_{\alpha\beta} B^{\alpha\beta}$$

$$\mathcal{O}_{T,6} = \mathrm{Tr}\left[W_{\alpha\nu} W^{\mu\beta} \right] \cdot B_{\mu\beta} B^{\alpha\nu}$$

$$\mathcal{O}_{T,7} = \mathrm{Tr}\left[W_{\alpha\mu} W^{\mu\beta} \right] \cdot B_{\beta\nu} B^{\nu\alpha}$$

$$\mathcal{O}_{T,8} = B_{\mu\nu} B^{\mu\nu} B_{\alpha\beta} B^{\alpha\beta}$$

$$\mathcal{O}_{T,9} = B_{\alpha\mu} B^{\mu\beta} B_{\beta\nu} B^{\nu\alpha}$$

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

Operators and Multi(EW)-boson Physics (II)

Dimension-8 operators for Multiboson physics

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

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

$$\mathcal{O}_{T,0} = \mathrm{Tr}\left[W_{\mu\nu}W^{\mu\nu}\right] \cdot \mathrm{Tr}\left[W_{\alpha\beta}W^{\alpha\beta}\right]$$

$$\mathcal{O}_{T,1} = \mathrm{Tr}\left[W_{\alpha\nu}W^{\mu\beta}\right] \cdot \mathrm{Tr}\left[W_{\mu\beta}W^{\alpha\nu}\right]$$

$$\mathcal{O}_{T,2} = \mathrm{Tr}\left[W_{\alpha\mu}W^{\mu\beta}\right] \cdot \mathrm{Tr}\left[W_{\beta\nu}W^{\nu\alpha}\right]$$

$$\mathcal{O}_{T,5} = \mathrm{Tr}\left[W_{\mu\nu}W^{\mu\nu}\right] \cdot B_{\alpha\beta}B^{\alpha\beta}$$

$$\mathcal{O}_{T,6} = \mathrm{Tr}\left[W_{\alpha\nu}W^{\mu\beta}\right] \cdot B_{\mu\beta}B^{\alpha\nu}$$

$$\mathcal{O}_{T,7} = \mathrm{Tr}\left[W_{\alpha\mu}W^{\mu\beta}\right] \cdot B_{\beta\nu}B^{\nu\alpha}$$

$$\mathcal{O}_{T,8} = B_{\mu\nu}B^{\mu\nu}B_{\alpha\beta}B^{\alpha\beta}$$

$$\mathcal{O}_{T,9} = B_{\alpha\mu}B^{\mu\beta}B_{\beta\nu}B^{\nu\alpha}$$

$$\mathcal{O}_{M,0} = \mathrm{Tr}\left[W_{\mu\nu}W^{\mu\nu}\right] \cdot \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right]$$

$$\mathcal{O}_{M,1} = \mathrm{Tr}\left[W_{\mu\nu}W^{\nu\beta}\right] \cdot \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right]$$

$$\mathcal{O}_{M,2} = \left[B_{\mu\nu}B^{\mu\nu}\right] \cdot \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right]$$

$$\mathcal{O}_{M,3} = \left[B_{\mu\nu}B^{\nu\beta}\right] \cdot \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right]$$

$$\mathcal{O}_{M,4} = \left[(D_\mu\Phi)^\dagger W_{\beta\nu}D^\mu\Phi\right] \cdot B^{\beta\nu}$$

$$\mathcal{O}_{M,5} = \left[(D_\mu\Phi)^\dagger W_{\beta\nu}D^\nu\Phi\right] \cdot B^{\beta\mu}$$

$$\mathcal{O}_{M,6} = \left[(D_\mu\Phi)^\dagger W_{\beta\nu}W^{\beta\nu}D^\mu\Phi\right]$$

$$\mathcal{O}_{M,7} = \left[(D_\mu\Phi)^\dagger W_{\beta\nu}W^{\beta\mu}D^\nu\Phi\right]$$

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

- Dim. 8 generate aQGCs independently
- generate neutral quartic couplings

Unitarity in vector boson scattering

Optical Theorem (Unitarity of the S(cattering) Matrix):

$$\sigma_{\text{tot}} = \text{Im}\left[\mathcal{M}_{ii}(t=0)\right]/s \qquad t = -s(1-\cos\theta)/2$$

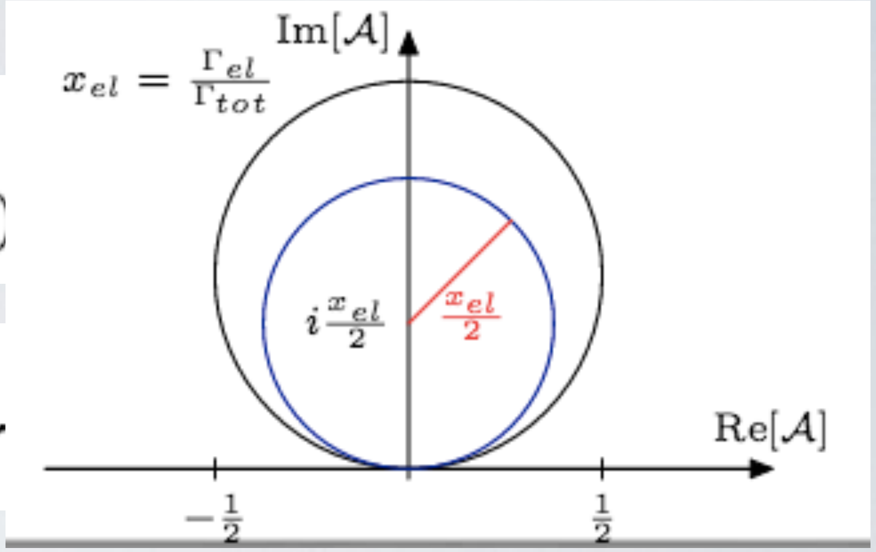
Partial wave amplitudes:

$$\mathcal{M}(s,t,u) = 32\pi \sum_\ell (2\ell+1)\mathcal{A}_\ell(s) P_\ell(\cos\theta)$$ ("Power spectrum")

Unitarity in vector boson scattering

Optical Theorem (Unitarity of the S(cattering) Matrix):

$$\sigma_{\text{tot}} = \text{Im}\left[\mathcal{M}_{ii}(t=0)\right]/s \qquad t = -s(1-\cos\theta)$$



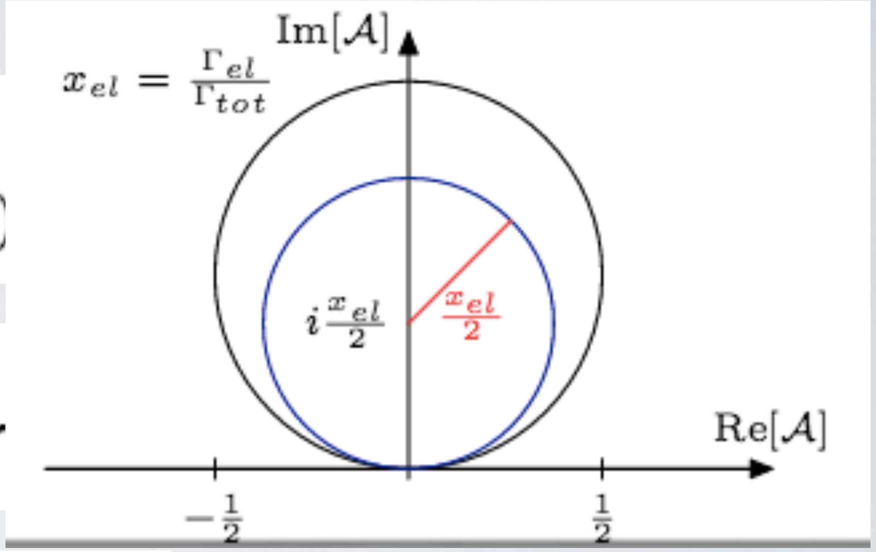
Partial wave amplitudes:

$$\mathcal{M}(s,t,u) = 32\pi \sum_\ell (2\ell+1)\mathcal{A}_\ell(s) P_\ell(\cos\theta) \qquad \text{("Power spectr}$$

Unitarity in vector boson scattering

Optical Theorem (Unitarity of the S(cattering) Matrix):

$$\sigma_{\text{tot}} = \text{Im}\left[\mathcal{M}_{ii}(t=0)\right]/s \qquad t = -s(1-\cos\theta)$$



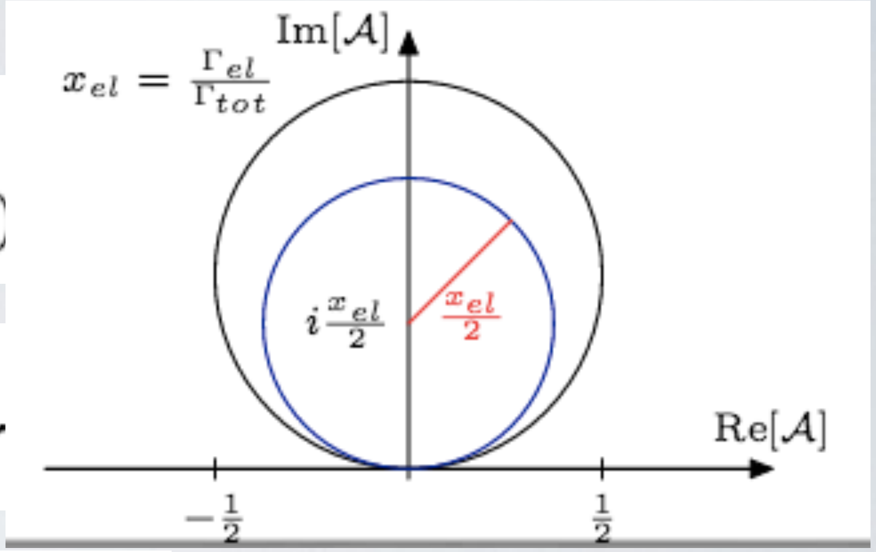
Partial wave amplitudes:

$$\mathcal{M}(s,t,u) = 32\pi \sum_\ell (2\ell+1)\mathcal{A}_\ell(s) P_\ell(\cos\theta)$$ ("Power spectr

Assuming only elastic scattering:

$$\sigma_{\text{tot}} = \sum_\ell \frac{32\pi(2\ell+1)}{s}|\mathcal{A}_\ell|^2 \stackrel{!}{=} \sum_\ell \frac{32\pi(2\ell+1)}{s}\text{Im}\left[\mathcal{A}_\ell\right] \quad \Rightarrow \quad \boxed{|\mathcal{A}_\ell|^2 = \text{Im}\left[\mathcal{A}_\ell\right]}$$

Unitarity in vector boson scattering



Optical Theorem (Unitarity of the S(cattering) Matrix):

$$\sigma_{\text{tot}} = \text{Im}\left[\mathcal{M}_{ii}(t=0)\right]/s \qquad t = -s(1-\cos\theta)$$

Partial wave amplitudes:

$$\mathcal{M}(s,t,u) = 32\pi \sum_\ell (2\ell+1)\mathcal{A}_\ell(s) P_\ell(\cos\theta)$$ ("Power spectr

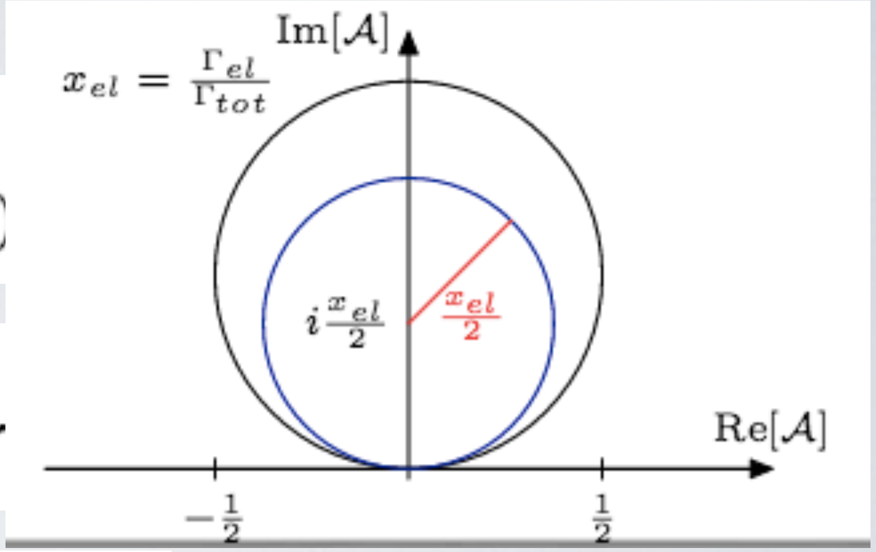
Assuming only elastic scattering:

$$\sigma_{\text{tot}} = \sum_\ell \frac{32\pi(2\ell+1)}{s}|\mathcal{A}_\ell|^2 \stackrel{!}{=} \sum_\ell \frac{32\pi(2\ell+1)}{s}\text{Im}\left[\mathcal{A}_\ell\right] \quad \Rightarrow \quad \boxed{|\mathcal{A}_\ell|^2 = \text{Im}\left[\mathcal{A}_\ell\right]}$$

SM longitudinal isospin eigenamplitudes ($\mathcal{A}_{I,\text{spin}=J}$):

$$\mathcal{A}_{I=0} = 2\frac{s}{v^2}P_0(s) \qquad \mathcal{A}_{I=1} = \frac{t-u}{v^2} = \frac{s}{v^2}P_1(s) \qquad \mathcal{A}_{I=2} = -\frac{s}{v^2}P_0(s)$$

Unitarity in vector boson scattering



Optical Theorem (Unitarity of the S(cattering) Matrix):

$$\sigma_{\text{tot}} = \text{Im}\left[\mathcal{M}_{ii}(t=0)\right]/s \qquad t = -s(1-\cos\theta$$

Partial wave amplitudes:

$$\mathcal{M}(s,t,u) = 32\pi \sum_\ell (2\ell+1)\mathcal{A}_\ell(s) P_\ell(\cos\theta)$$ ("Power spectr

Assuming only elastic scattering:

$$\sigma_{\text{tot}} = \sum_\ell \frac{32\pi(2\ell+1)}{s}|\mathcal{A}_\ell|^2 \stackrel{!}{=} \sum_\ell \frac{32\pi(2\ell+1)}{s}\text{Im}\left[\mathcal{A}_\ell\right] \quad \Rightarrow \quad \boxed{|\mathcal{A}_\ell|^2 = \text{Im}\left[\mathcal{A}_\ell\right]}$$

SM longitudinal isospin eigenamplitudes ($\mathcal{A}_{I,\text{spin}=J}$):

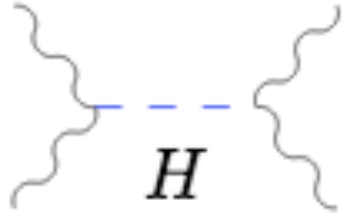
$$\mathcal{A}_{I=0} = 2\frac{s}{v^2}P_0(s) \qquad \mathcal{A}_{I=1} = \frac{t-u}{v^2} = \frac{s}{v^2}P_1(s) \qquad \mathcal{A}_{I=2} = -\frac{s}{v^2}P_0(s)$$

Lee/Quigg/Thacker, 1973

exceeds unitarity bound $|\mathcal{A}_{IJ}| \lesssim \frac{1}{2}$ at:

$$I = 0: \qquad E \sim \sqrt{8\pi}v = 1.2\,\text{TeV}$$
$$I = 1: \qquad E \sim \sqrt{48\pi}v = 3.5\,\text{TeV}$$
$$I = 2: \qquad E \sim \sqrt{16\pi}v = 1.7\,\text{TeV}$$

Higgs exchange:

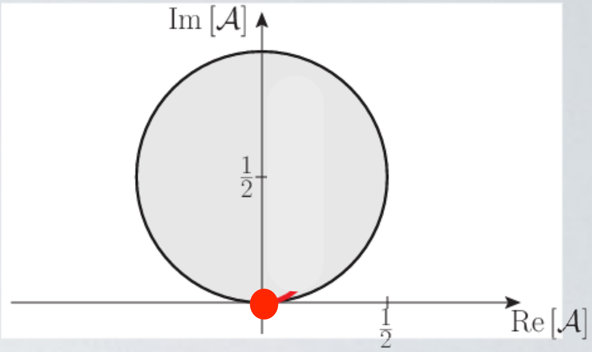


$$\mathcal{A}(s,t,u) = -\frac{M_H^2}{v^2}\frac{s}{s-M_H^2}$$

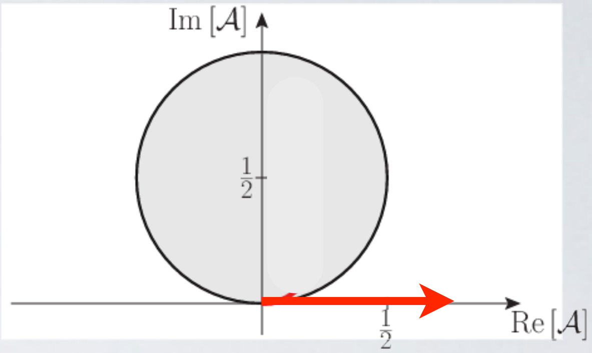
Unitarity: $M_H \lesssim \sqrt{8\pi}v \sim 1.2\,\text{TeV}$

Scenarios for New Physics in VBS

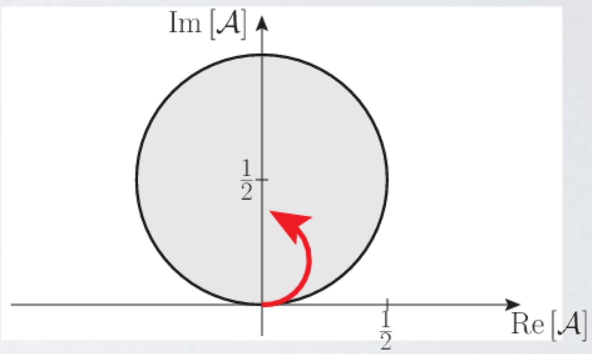
1. SM or weakly coupled physics (e.g. 2HDM):
   amplitude remains close to origin



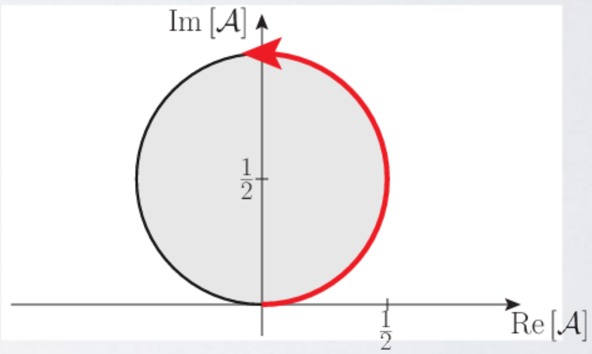
2. Rising amplitude (at least one dim-8 operator): rise beyond unitarity circle [unphys.], strongly interacting regime



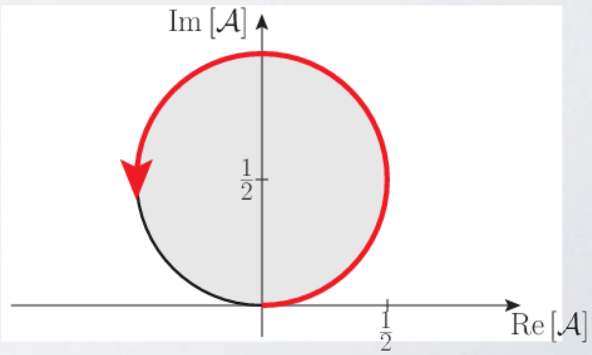
3. Inelastic channel opens (form-factor description): new channels open out, multi-boson final states



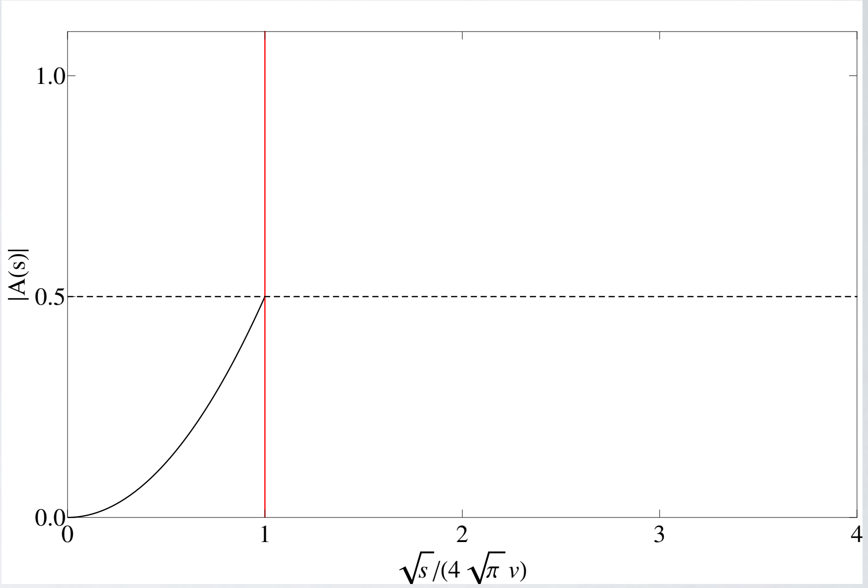
4. Saturation of amplitude: maximal amplitude, strongly interacting continuum, K-/T-matrix unitarization



5. New resonance: amplitude turns over



Procedures to treat unitarity violations

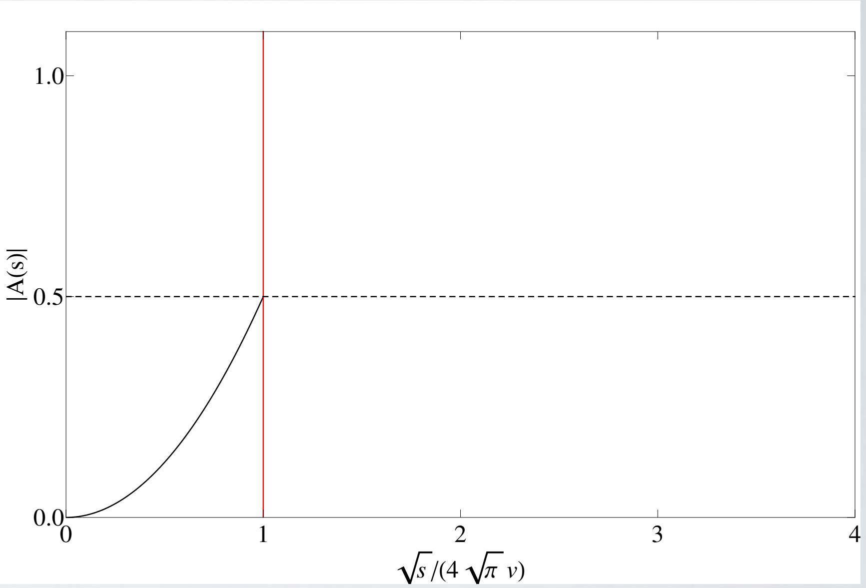


Cut-off (a.k.a. "Event clipping") $\theta(\Lambda_C^2 - s)$

unitarity bound (0th partial wave) at Λ_C
no continuous transition beyond

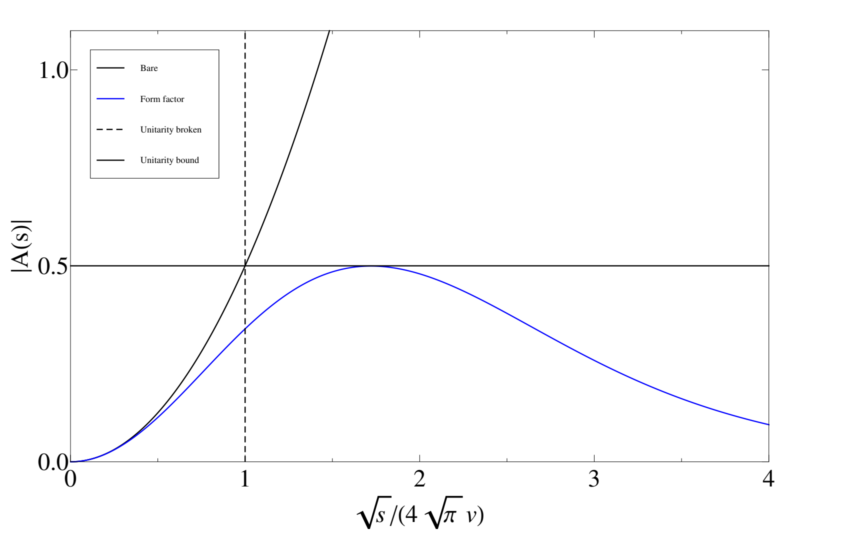
Procedures to treat unitarity violations

Cut-off (a.k.a. “Event clipping”) $\theta(\Lambda_C^2 - s)$



unitarity bound (0th partial wave) at Λ_C
no continuous transition beyond

Form factor $\frac{1}{\left(1+\frac{s}{\Lambda_{FF}}\right)^n}$

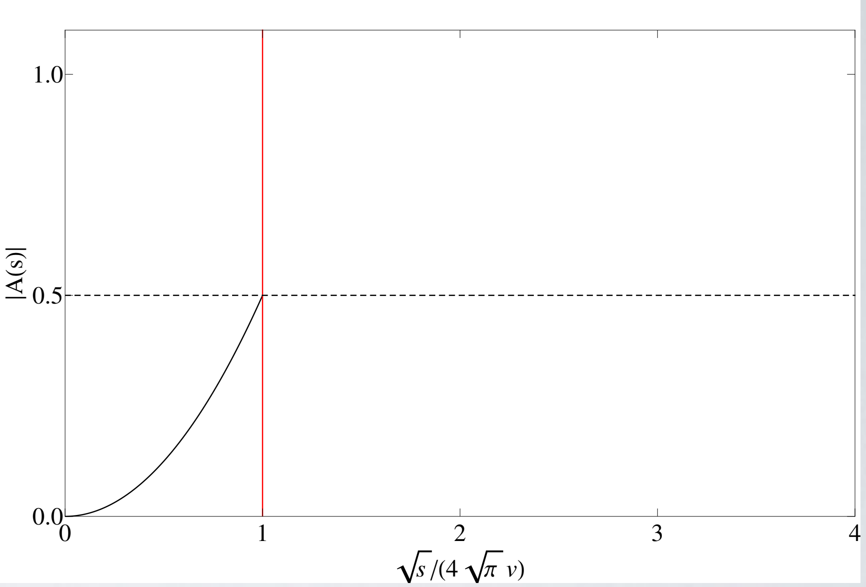


Applicable for arbitrary operators, tuning in 2 parameters: *n* damps unitarity violation, Λ_{FF} highest value to satisfy 0th partial wave

Procedures to treat unitarity violations

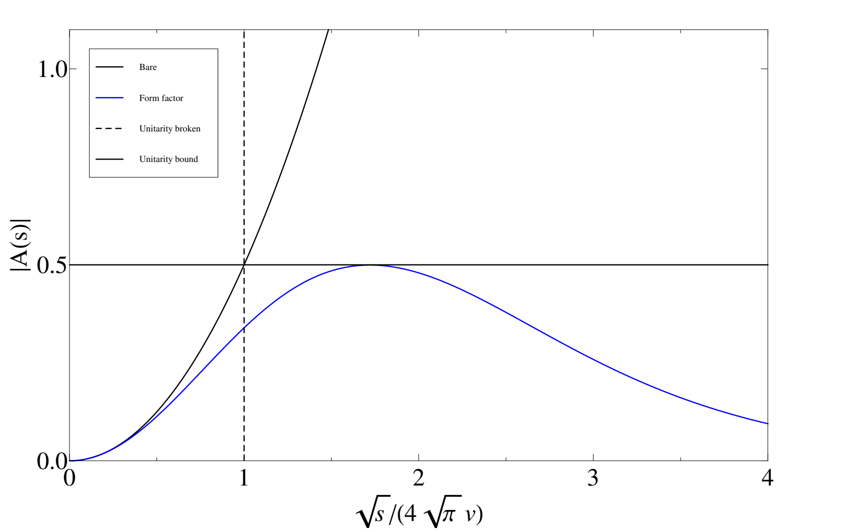
Cut-off (a.k.a. "Event clipping") $\theta(\Lambda_C^2 - s)$

unitarity bound (0th partial wave) at Λ_C
no continuous transition beyond



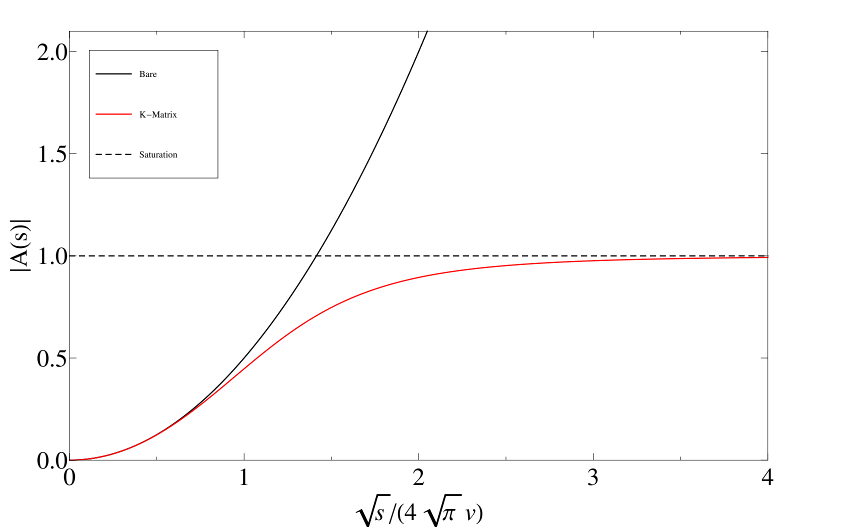
Form factor $\frac{1}{\left(1+\frac{s}{\Lambda_{FF}}\right)^n}$

Applicable for arbitrary operators, tuning in 2 parameters: *n* damps unitarity violation, Λ_{FF} highest value to satisfy 0th partial wave



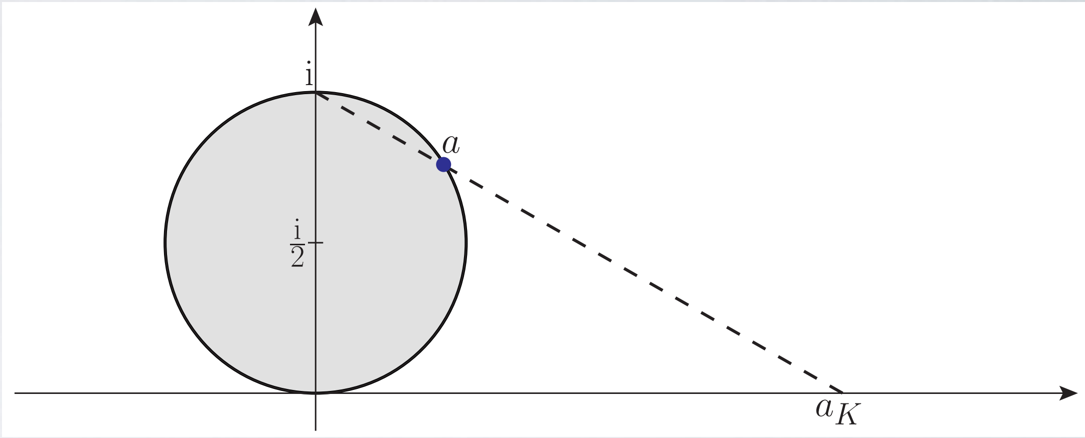
K-/T-matrix saturation

saturates the amplitude, usable for complex amplitudes, no additional parameters



Different unitarity projections

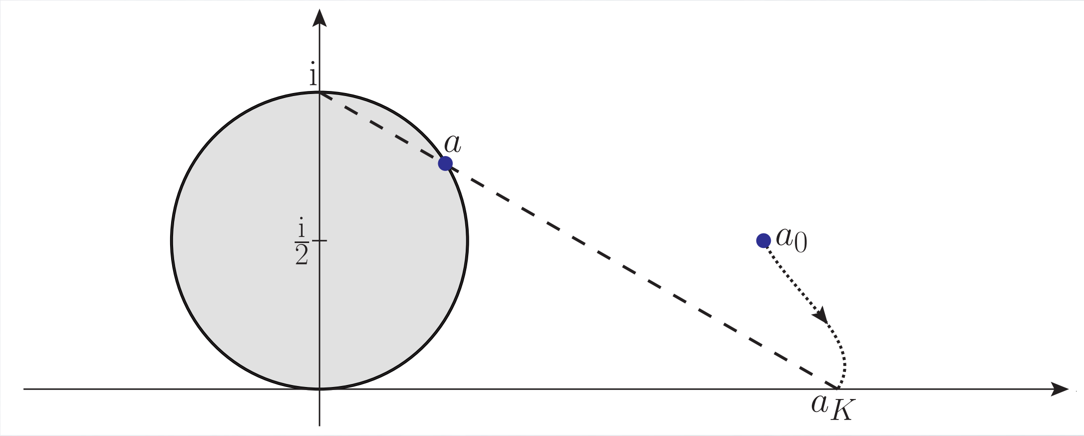
- *K*-matrix: Cayley transform of *S*-matrix   Heitler, 1941; Schwinger, 1949; Gupta, 1950
- Stereographic projection to Argand circle



$$S = \frac{1+iK/2}{1-iK/2} \qquad a_K(s) = \frac{a(s)}{1-\mathrm{i}a(s)}$$

Different unitarity projections

- *K*-matrix: Cayley transform of *S*-matrix   Heitler, 1941; Schwinger, 1949; Gupta, 1950
- Stereographic projection to Argand circle

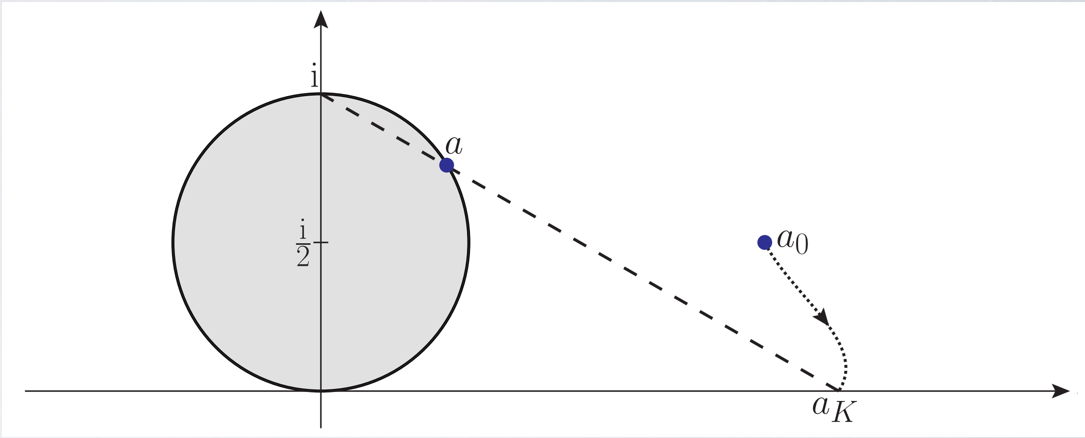


$$S = \frac{1+iK/2}{1-iK/2} \qquad a_K(s) = \frac{a(s)}{1-\mathrm{i}a(s)}$$

- Stereographic projection to Argand circle
- Formalism does a partial resummation of perturbative series
- need to construct (orig.) *K*-matrix as self-adjoint intermediate operator
  Problems, if *S*-matrix non-diagonal, presence of non-perturbative contrib.

Different unitarity projections

- *K*-matrix: Cayley transform of *S*-matrix   Heitler, 1941; Schwinger, 1949; Gupta, 1950
- Stereographic projection to Argand circle

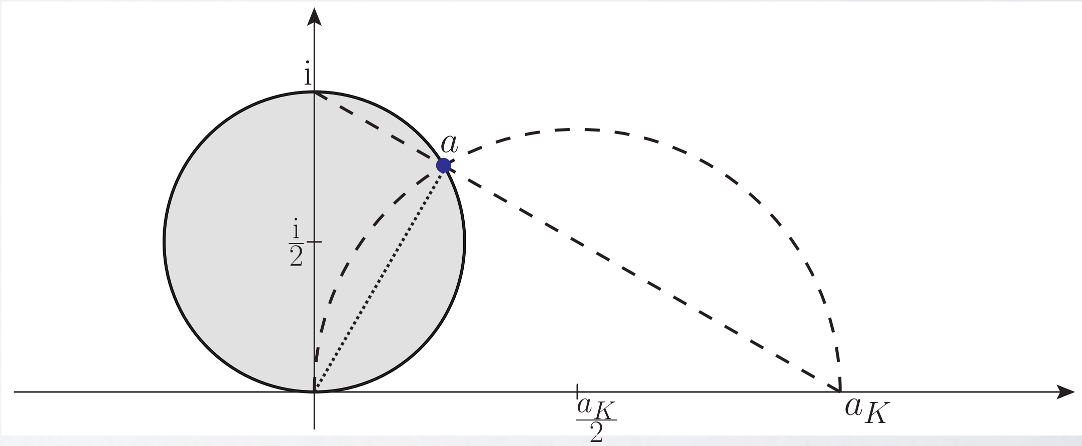


$$S = \frac{1+iK/2}{1-iK/2} \qquad a_K(s) = \frac{a(s)}{1-\mathrm{i}a(s)}$$

- Stereographic projection to Argand circle
- Formalism does a partial resummation of perturbative series
- need to construct (orig.) *K*-matrix as self-adjoint intermediate operator

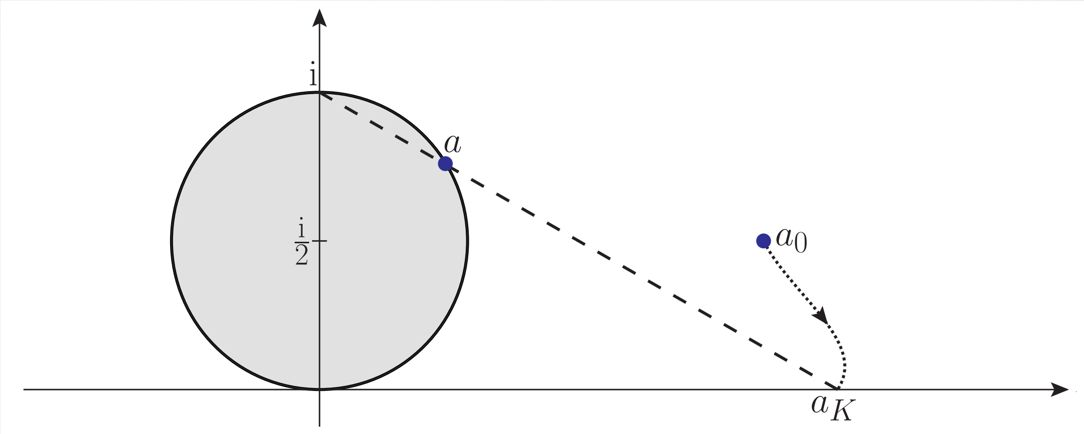
  Problems, if *S*-matrix non-diagonal, presence of non-perturbative contrib.

- *T*-matrix: Thales circle construction   Kilian/Ohl/JRR/Sekulla, 2014
- Defined via $\left|a - \frac{a_K}{2}\right| = \frac{a_K}{2} \quad \Rightarrow \quad a = \frac{1}{\mathrm{Re}\left(\frac{1}{a_0}\right) - \mathrm{i}}$



Different unitarity projections

- *K*-matrix: Cayley transform of *S*-matrix — Heitler, 1941; Schwinger, 1949; Gupta, 1950
- Stereographic projection to Argand circle

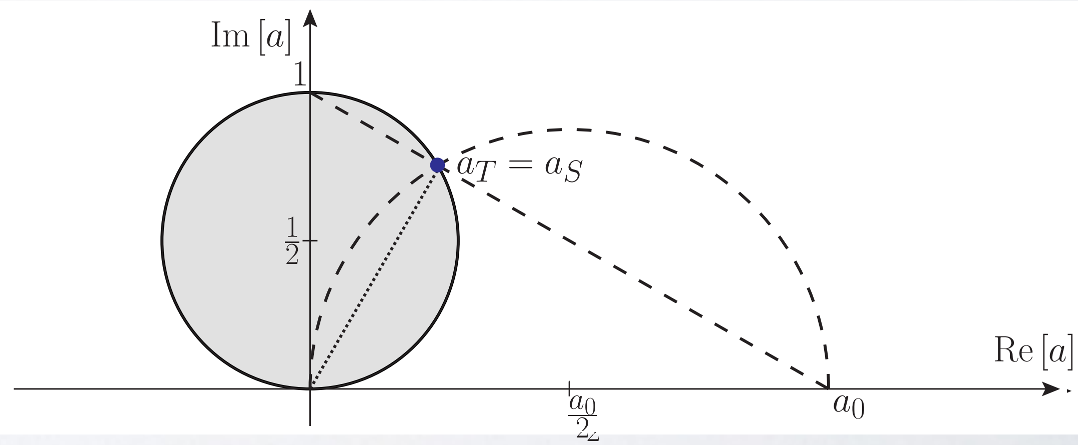


$$S = \frac{1+iK/2}{1-iK/2} \qquad a_K(s) = \frac{a(s)}{1-\mathrm{i}a(s)}$$

- Stereographic projection to Argand circle
- Formalism does a partial resummation of perturbative series
- need to construct (orig.) *K*-matrix as self-adjoint intermediate operator

  Problems, if *S*-matrix non-diagonal, presence of non-perturbative contrib.

- *T*-matrix: Thales circle construction — Kilian/Ohl/JRR/Sekulla, 2014
- Defined via $\left|a - \frac{a_K}{2}\right| = \frac{a_K}{2} \quad \Rightarrow \quad a = \frac{1}{\mathrm{Re}\left(\frac{1}{a_0}\right) - \mathrm{i}}$

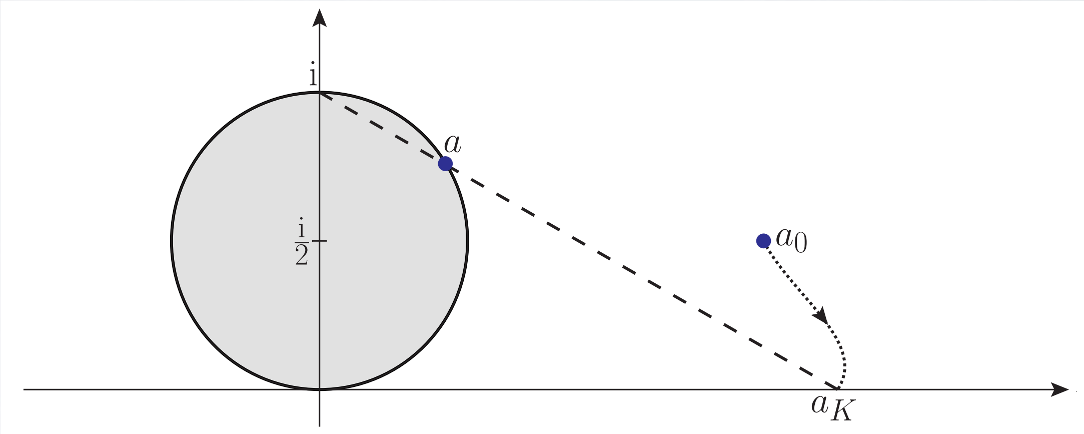


- Identical to *K* matrix for real amplitudes
- Points on Argand circle left invariant
- Does not rely on perturbation theory
- Applicable for amplitudes with imaginary parts (models with resonances)

Different unitarity projections

- *K*-matrix: Cayley transform of *S*-matrix   Heitler, 1941; Schwinger, 1949; Gupta, 1950
- Stereographic projection to Argand circle

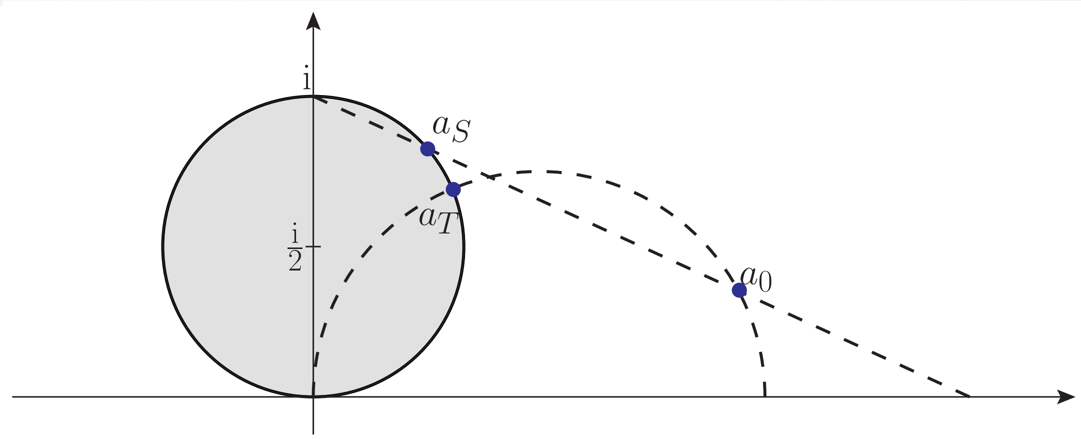
$$S = \frac{1+iK/2}{1-iK/2} \qquad a_K(s) = \frac{a(s)}{1-\mathrm{i}a(s)}$$



- Stereographic projection to Argand circle
- Formalism does a partial resummation of perturbative series
- need to construct (orig.) *K*-matrix as self-adjoint intermediate operator

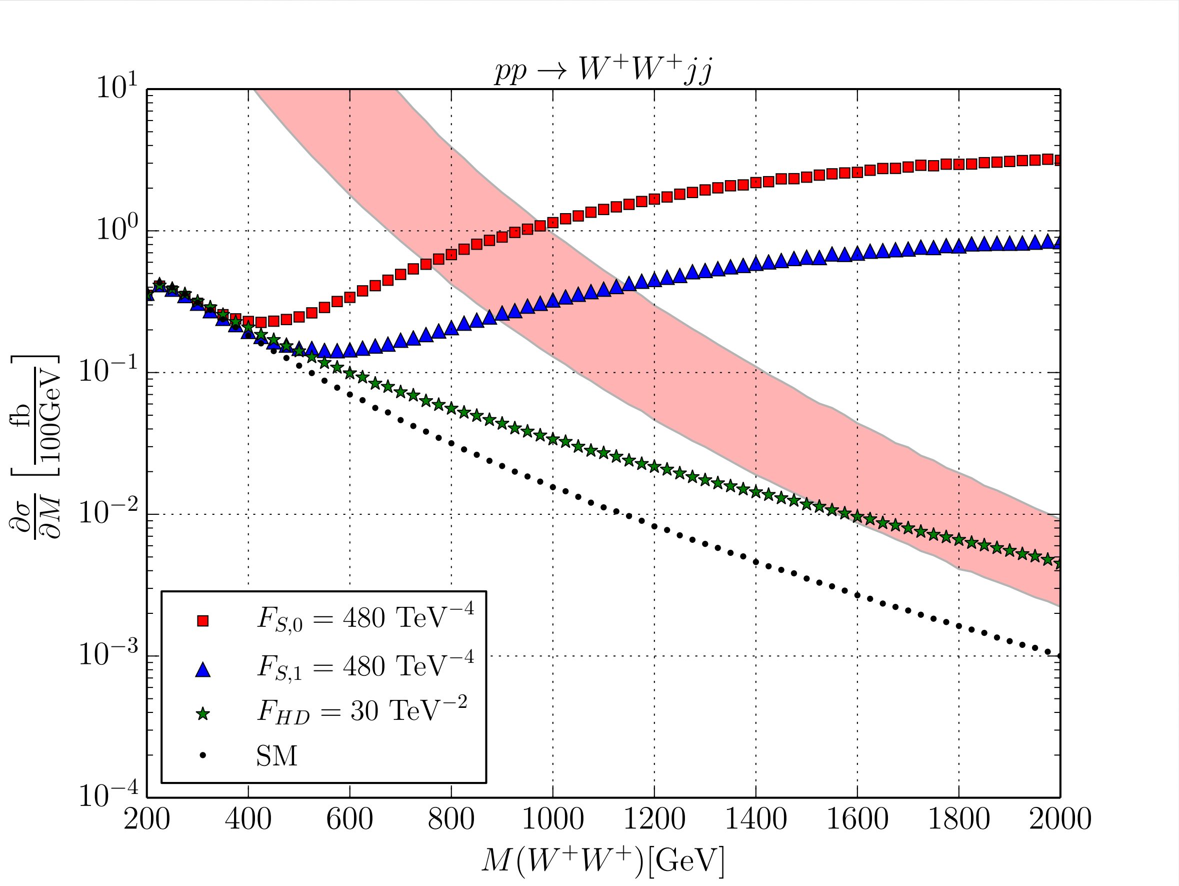
  Problems, if *S*-matrix non-diagonal, presence of non-perturbative contrib.

- *T*-matrix: Thales circle construction   Kilian/Ohl/JRR/Sekulla, 2014
- Defined via $\left|a - \frac{a_K}{2}\right| = \frac{a_K}{2} \quad \Rightarrow \quad a = \frac{1}{\mathrm{Re}\left(\frac{1}{a_0}\right) - \mathrm{i}}$



- Identical to *K* matrix for real amplitudes
- Points on Argand circle left invariant
- Does not rely on perturbation theory
- Applicable for amplitudes with imaginary parts (models with resonances)

VBS diboson spectra



WWWW-Vertex:

$$\alpha_4 = \frac{f_{S,0}}{\Lambda^4}\frac{v^4}{8}$$

$$\alpha_4 + 2\cdot\alpha_5 = \frac{f_{S,1}}{\Lambda^4}\frac{v^4}{8}$$

WWZZ-Vertex:

$$\alpha_4 = \frac{f_{S,0}}{\Lambda^4}\frac{v^4}{16}$$

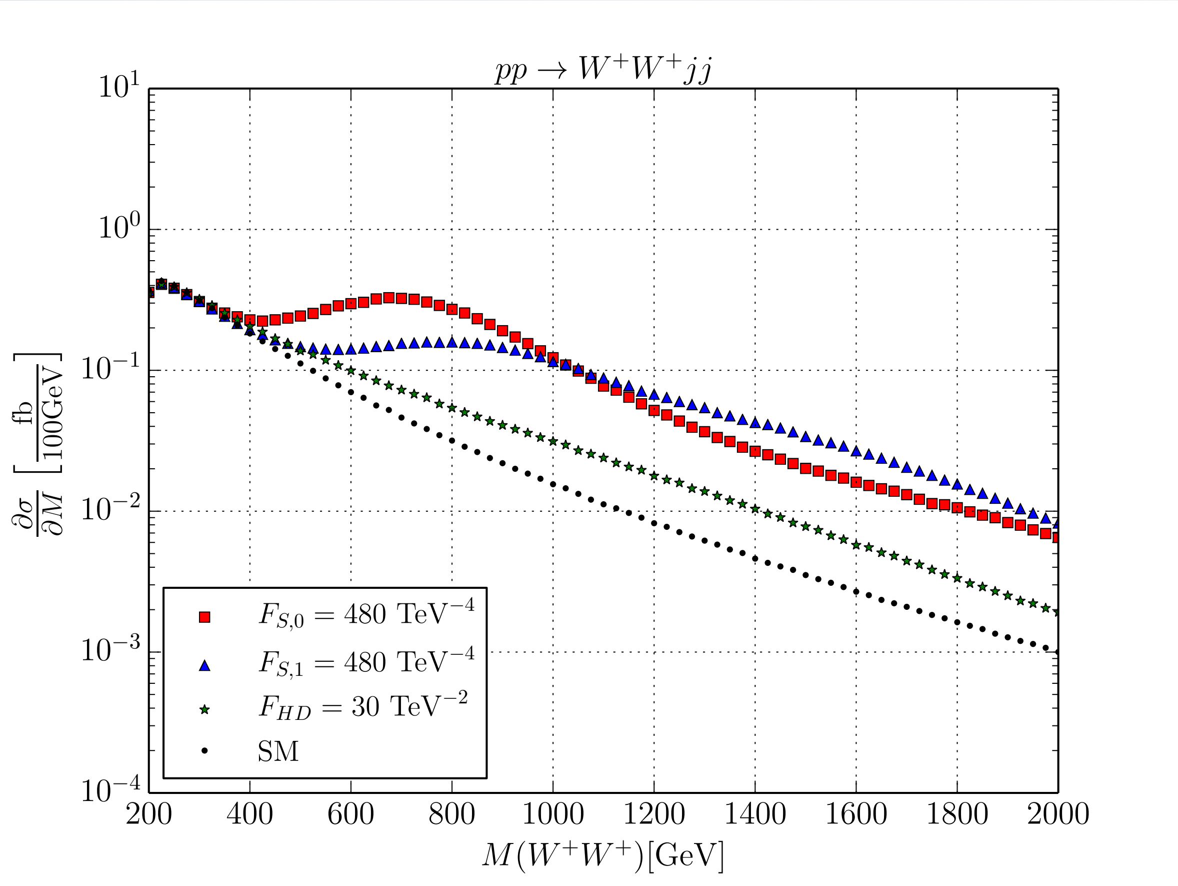
$$\alpha_5 = \frac{f_{S,1}}{\Lambda^4}\frac{v^4}{16}$$

ZZZZ-Vertex:

$$\alpha_4 + \alpha_5 = \left(\frac{f_{S,0}}{\Lambda^4} + \frac{f_{S,1}}{\Lambda^4}\right)\frac{v^4}{16}$$

General cuts: $M_{jj} > 500\,\text{GeV};\ \Delta\eta_{jj} > 2.4;\ p_T^j > 20\,\text{GeV};\ |\Delta\eta_j| < 4.5$

VBS diboson spectra



WWWW-Vertex:

$$\alpha_4 = \frac{f_{S,0}}{\Lambda^4}\frac{v^4}{8}$$

$$\alpha_4 + 2\cdot\alpha_5 = \frac{f_{S,1}}{\Lambda^4}\frac{v^4}{8}$$

WWZZ-Vertex:

$$\alpha_4 = \frac{f_{S,0}}{\Lambda^4}\frac{v^4}{16}$$

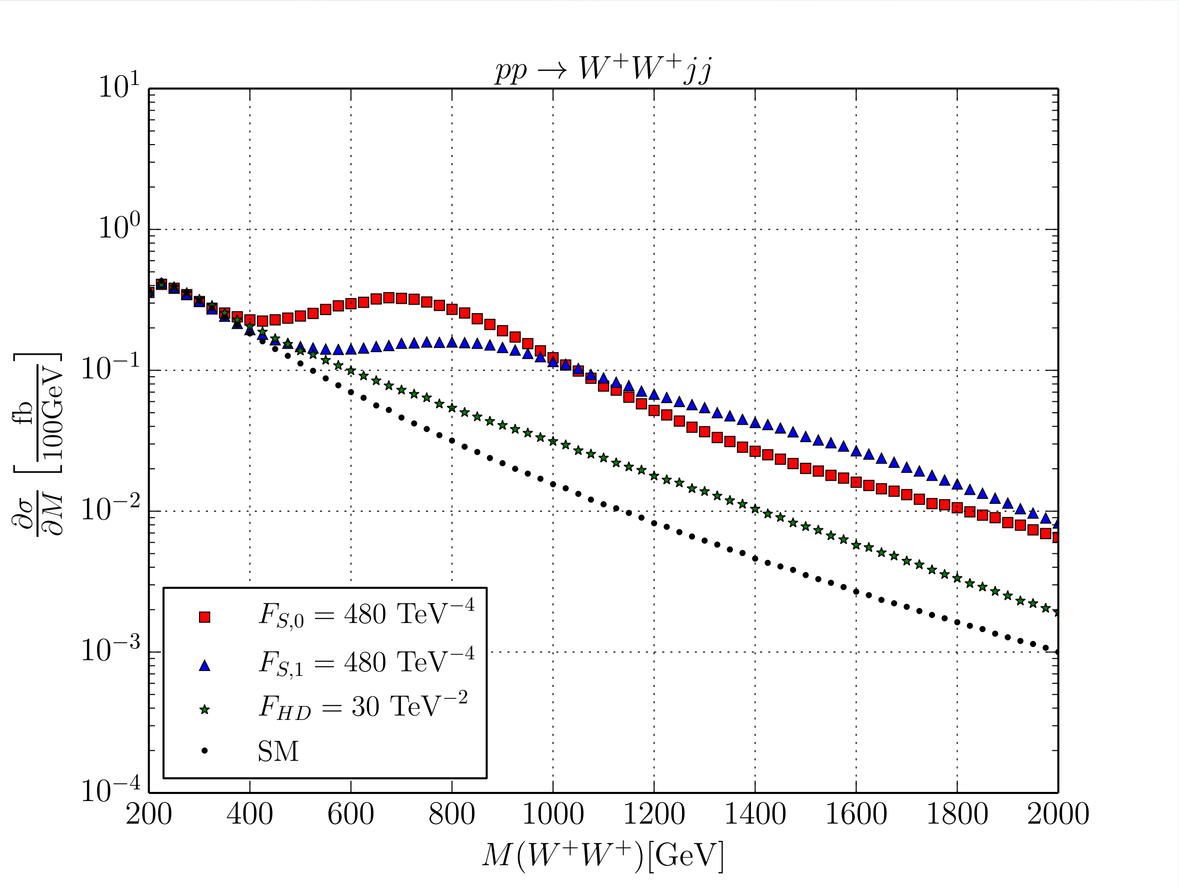
$$\alpha_5 = \frac{f_{S,1}}{\Lambda^4}\frac{v^4}{16}$$

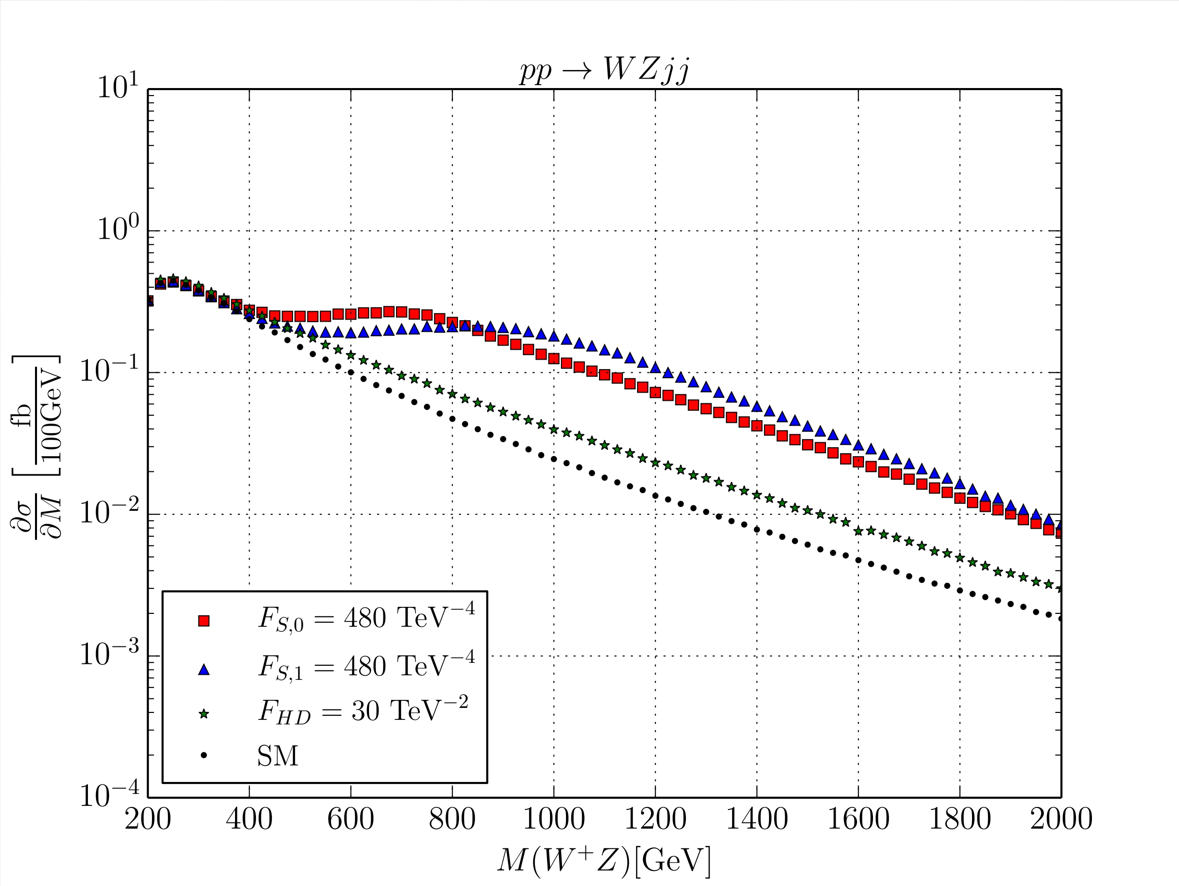
ZZZZ-Vertex:

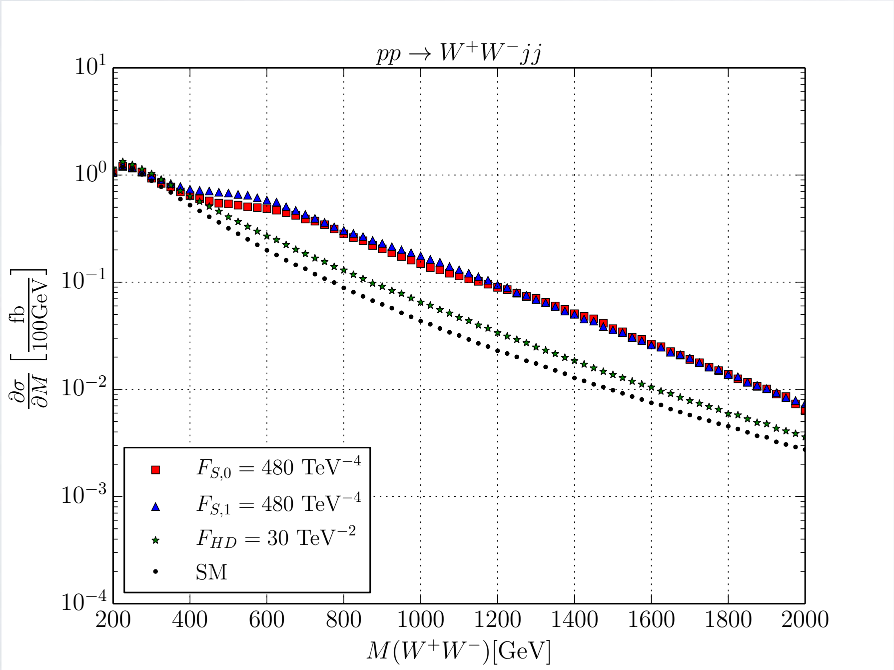
$$\alpha_4 + \alpha_5 = \left(\frac{f_{S,0}}{\Lambda^4} + \frac{f_{S,1}}{\Lambda^4}\right)\frac{v^4}{16}$$

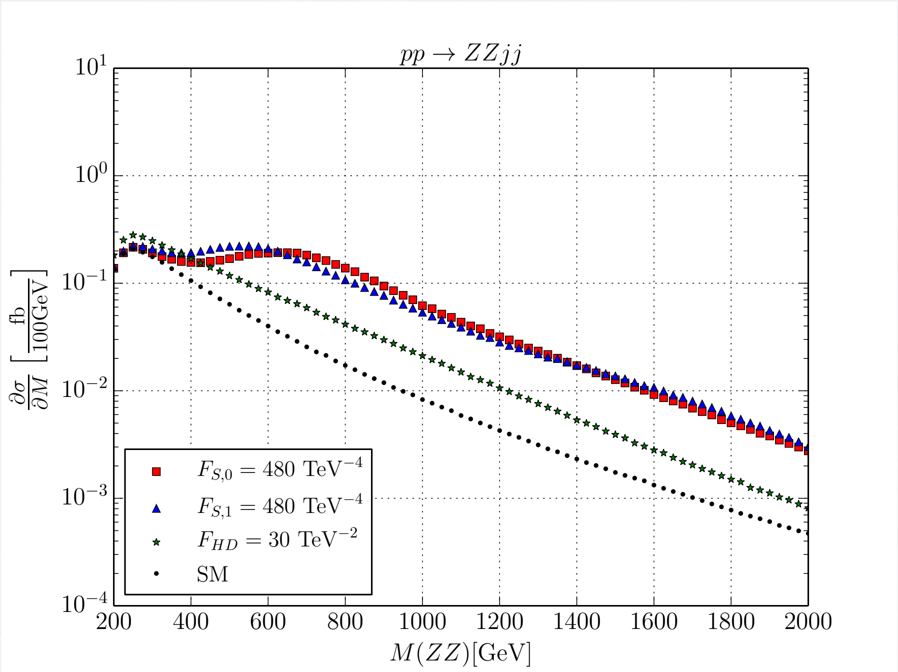
General cuts: $M_{jj} > 500\,\text{GeV};\ \Delta\eta_{jj} > 2.4;\ p_T^j > 20\,\text{GeV};\ |\Delta\eta_j| < 4.5$

VBS diboson spectra









WWWW-Vertex:

$$\alpha_4 = \frac{f_{S,0}}{\Lambda^4}\frac{v^4}{8}$$

$$\alpha_4 + 2\cdot\alpha_5 = \frac{f_{S,1}}{\Lambda^4}\frac{v^4}{8}$$

WWZZ-Vertex:

$$\alpha_4 = \frac{f_{S,0}}{\Lambda^4}\frac{v^4}{16}$$

$$\alpha_5 = \frac{f_{S,1}}{\Lambda^4}\frac{v^4}{16}$$

ZZZZ-Vertex:

$$\alpha_4 + \alpha_5 = \left(\frac{f_{S,0}}{\Lambda^4} + \frac{f_{S,1}}{\Lambda^4}\right)\frac{v^4}{16}$$

General cuts: $M_{jj} > 500\,\text{GeV};\ \Delta\eta_{jj} > 2.4;\ p_T^j > 20\,\text{GeV};\ |\Delta\eta_j| < 4.5$

Differential spectra in VBS

$$pp \to e^+\mu^+\nu_e\nu_\mu jj \qquad \sqrt{s} = 14\,\mathrm{TeV} \qquad \mathcal{L} = 1\,\mathrm{ab}^{-1}$$

Simulations with `WHIZARD` [http://whizard.hepforge.org, Kilian/Ohl/JRR]

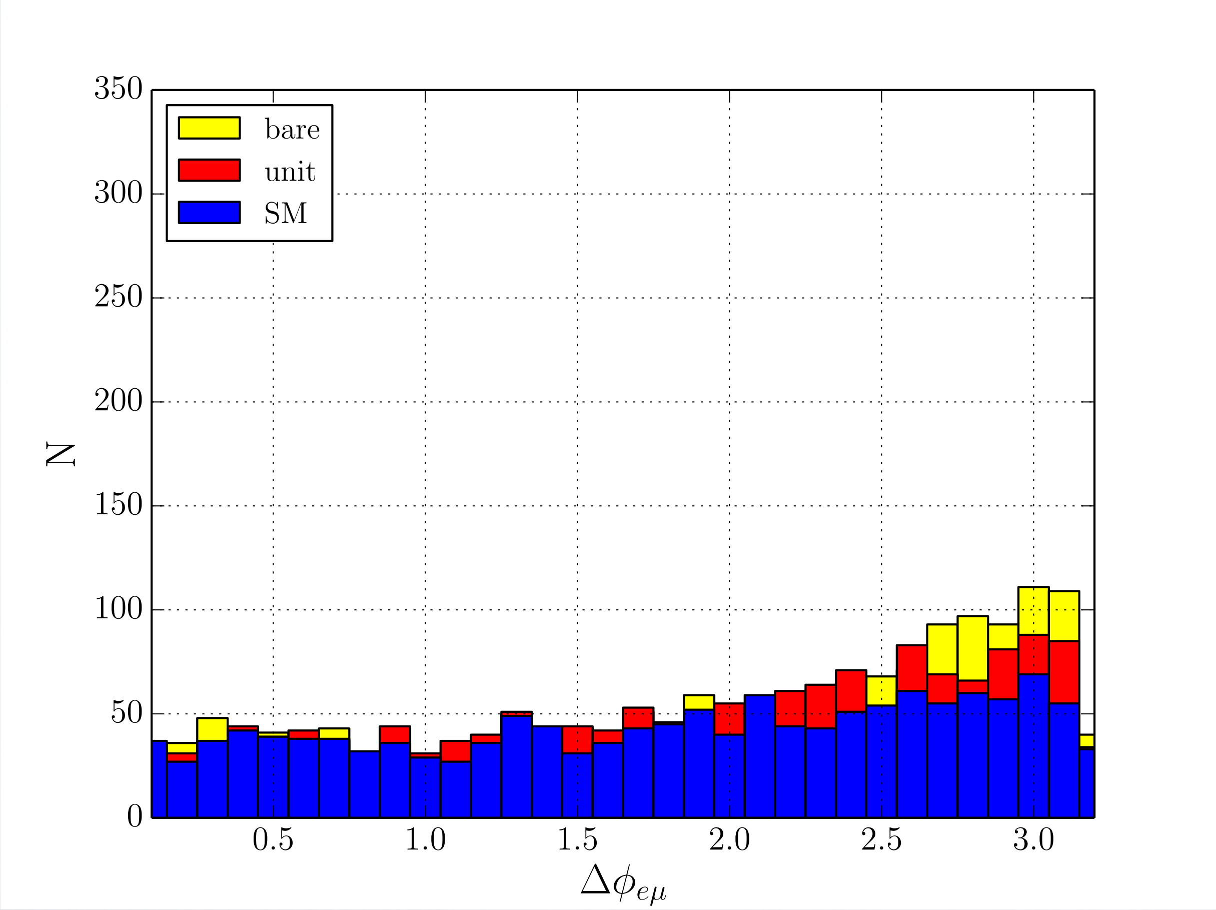
$$M_{jj} > 500\,\mathrm{GeV}; \quad \Delta\eta_{jj} > 2.4; \quad p_T^j > 20\,\mathrm{GeV}; \quad |\Delta\eta_j| < 4.5; \quad p_T^\ell > 20\,\mathrm{GeV}$$

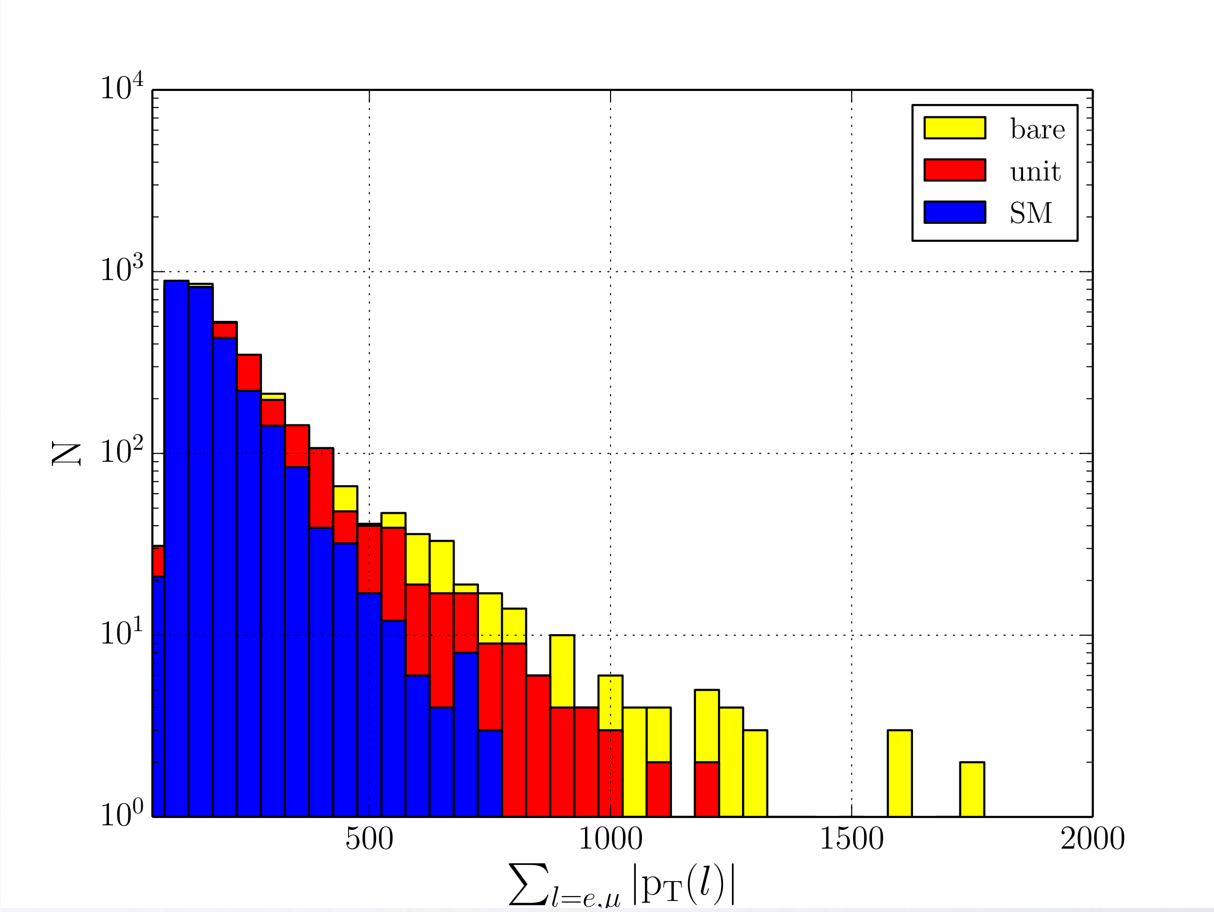
Differential spectra in VBS

$$pp \to e^+\mu^+\nu_e\nu_\mu jj \qquad \sqrt{s} = 14\,\mathrm{TeV} \qquad \mathcal{L} = 1\,\mathrm{ab}^{-1}$$

Simulations with `WHIZARD` [http://whizard.hepforge.org , Kilian/Ohl/JRR]

$$F_{HD} = 30\ \mathrm{TeV}^{-2}$$





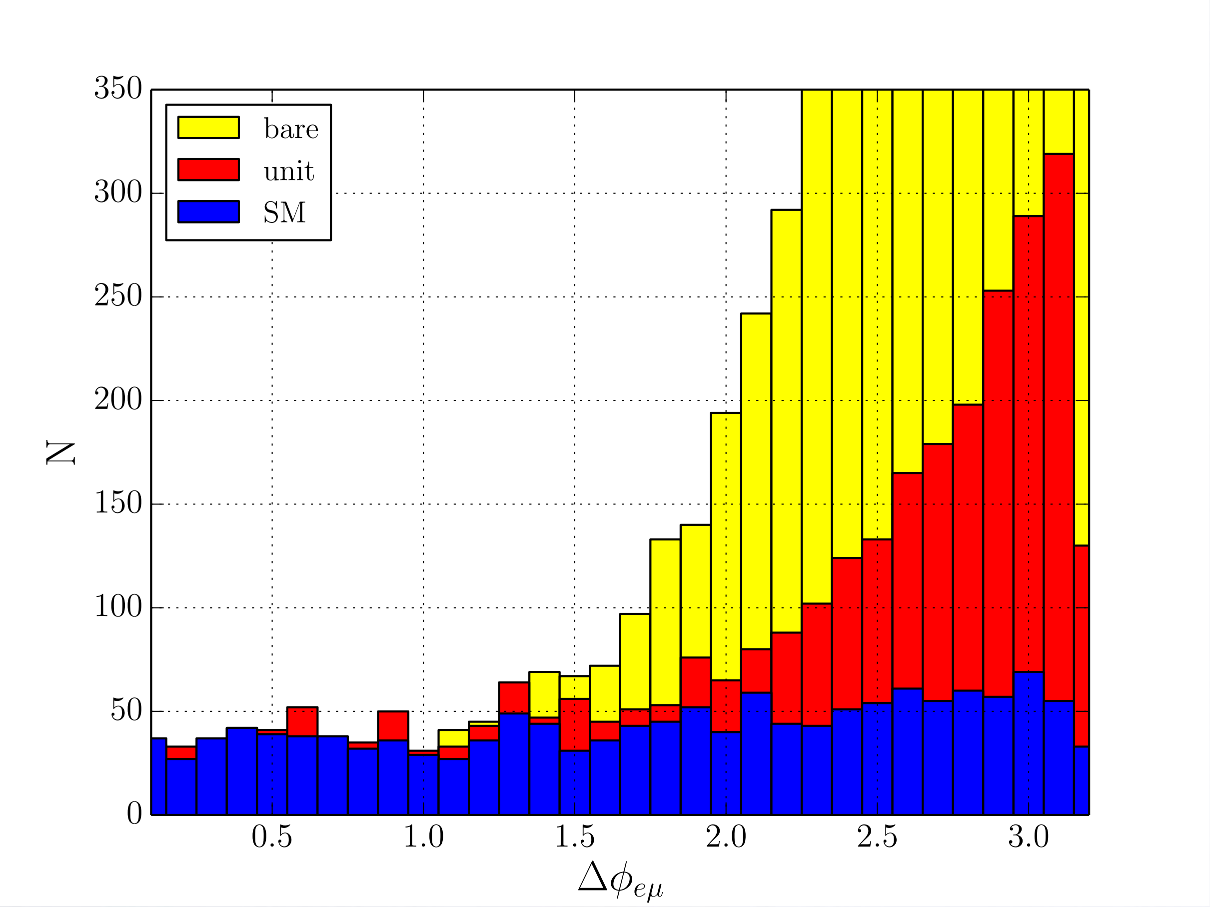
$$M_{jj} > 500\,\mathrm{GeV}; \quad \Delta\eta_{jj} > 2.4; \quad p_T^j > 20\,\mathrm{GeV}; \quad |\Delta\eta_j| < 4.5; \quad p_T^\ell > 20\,\mathrm{GeV}$$

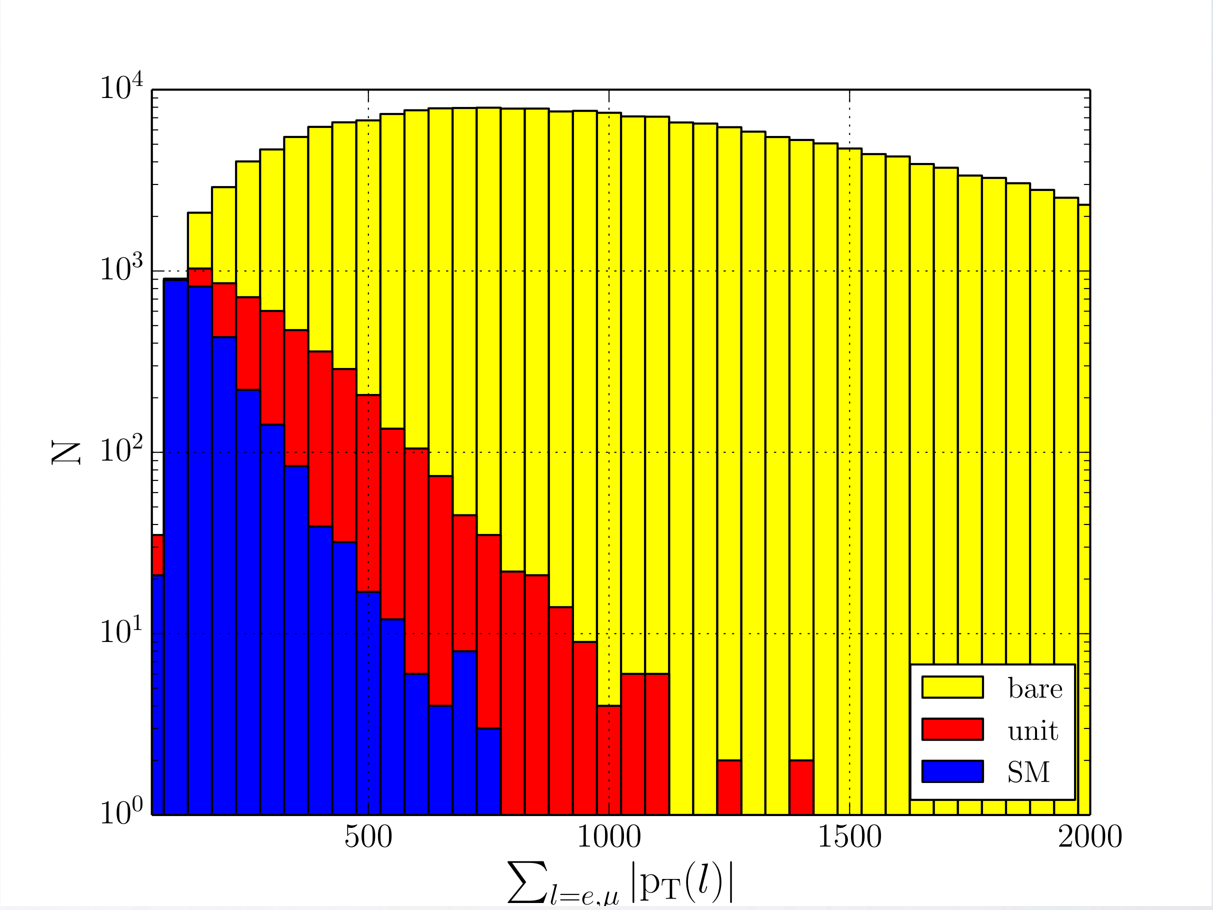
Differential spectra in VBS

$$pp \to e^+\mu^+\nu_e\nu_\mu jj \qquad \sqrt{s} = 14\,\text{TeV} \qquad \mathcal{L} = 1\,\text{ab}^{-1}$$

Simulations with WHIZARD [http://whizard.hepforge.org, Kilian/Ohl/JRR]

$$F_{S,0} = 480\ \text{TeV}^{-4}$$





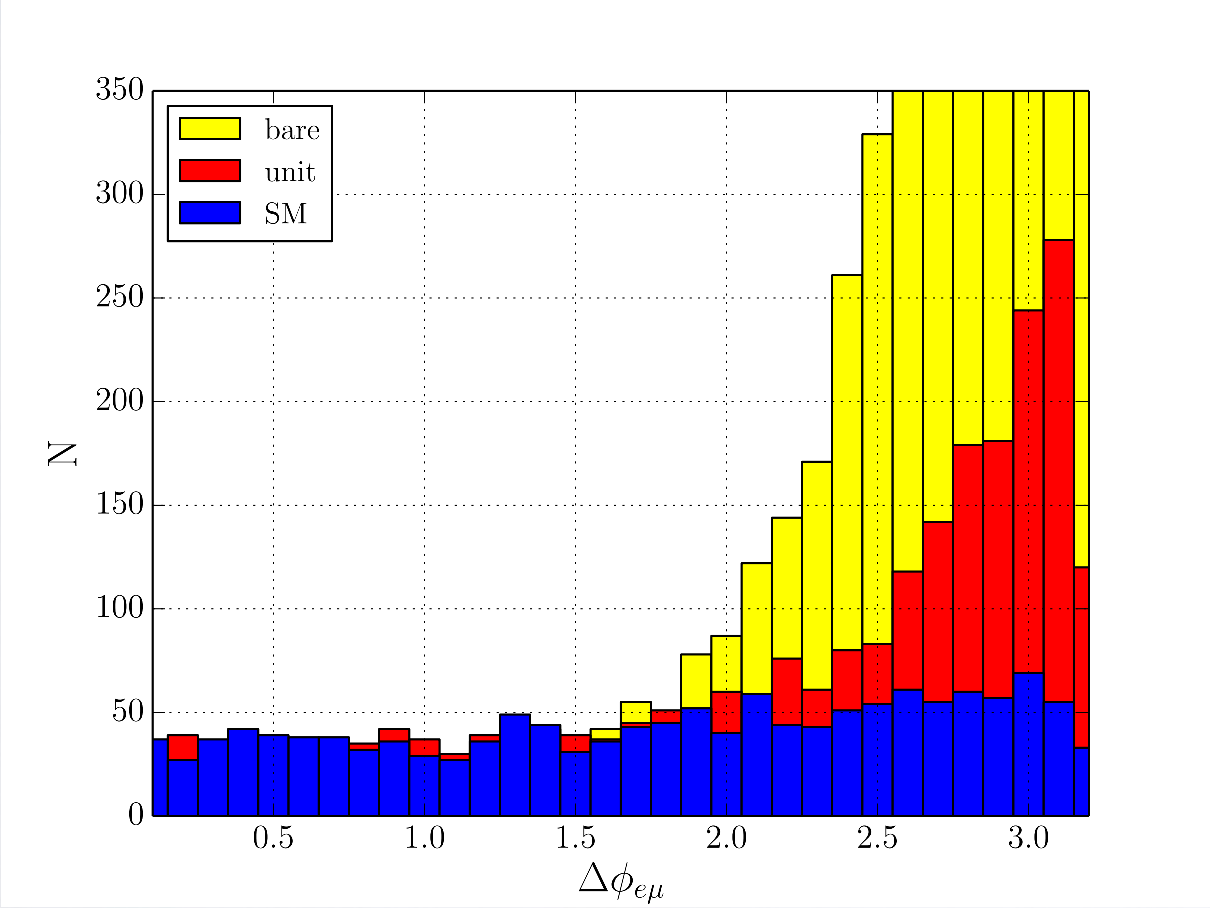
$$M_{jj} > 500\,\text{GeV}; \quad \Delta\eta_{jj} > 2.4; \quad p_T^j > 20\,\text{GeV}; \quad |\Delta\eta_j| < 4.5; \quad p_T^\ell > 20\,\text{GeV}$$

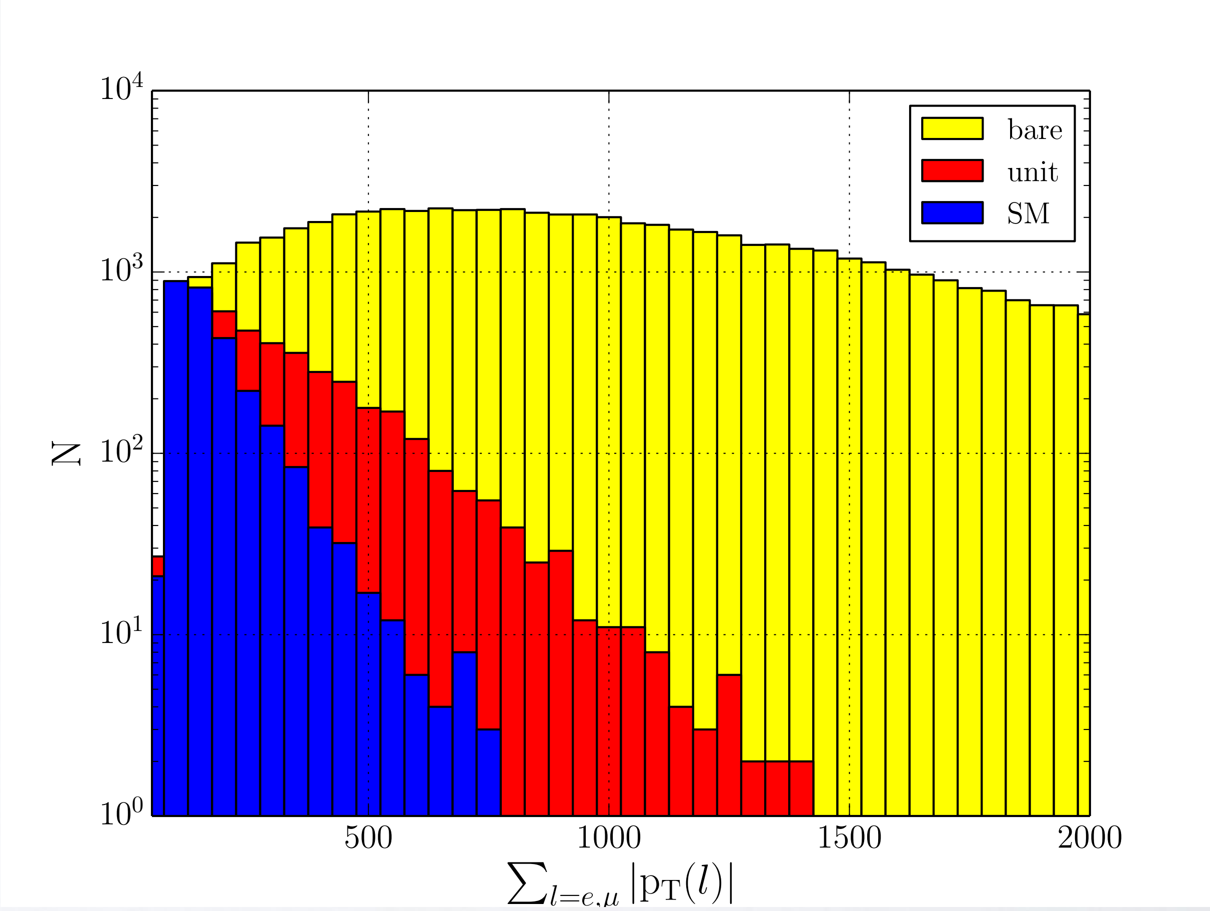
Differential spectra in VBS

$$pp \to e^+\mu^+\nu_e\nu_\mu jj \qquad \sqrt{s} = 14\,\mathrm{TeV} \qquad \mathcal{L} = 1\,\mathrm{ab}^{-1}$$

Simulations with `WHIZARD` [http://whizard.hepforge.org , Kilian/Ohl/JRR]

$$F_{S,1} = 480\ \mathrm{TeV}^{-4}$$





$$M_{jj} > 500\,\mathrm{GeV}; \quad \Delta\eta_{jj} > 2.4; \quad p_T^j > 20\,\mathrm{GeV}; \quad |\Delta\eta_j| < 4.5; \quad p_T^\ell > 20\,\mathrm{GeV}$$

Resonances: Quantum numbers & simplified models

- Rise of amplitude / anomalous coupling: Taylor expansion below a resonance
- Resonances might be in direct reach of LHC
- EFT framework EW-restored regime: $SU(2)_L \times SU(2)_R$, $SU(2)_L \times U(1)_Y$ gauged
- Include EFT operators in addition (more resonances, continuum contribution)
- Apply T-matrix unitarization beyond resonance ("UV-incomplete" model)

Resonances: Quantum numbers & simplified models

- Rise of amplitude / anomalous coupling: Taylor expansion below a resonance
- Resonances might be in direct reach of LHC
- EFT framework EW-restored regime: $SU(2)_L \times SU(2)_R$, $SU(2)_L \times U(1)_Y$ gauged
- Include EFT operators in addition (more resonances, continuum contribution)
- Apply *T*-matrix unitarization beyond resonance ("UV-incomplete" model)

Spins 0, 2 considered, Spin 1 has different physics (mixing with *W*/*Z*)

Resonances: Quantum numbers & simplified models

- Rise of amplitude / anomalous coupling: Taylor expansion below a resonance
- Resonances might be in direct reach of LHC
- EFT framework EW-restored regime: $SU(2)_L \times SU(2)_R$, $SU(2)_L \times U(1)_Y$ gauged
- Include EFT operators in addition (more resonances, continuum contribution)
- Apply *T*-matrix unitarization beyond resonance ("UV-incomplete" model)

Spins 0, 2 considered, Spin 1 has different physics (mixing with *W*/*Z*)

$SU(2)_L \times SU(2)_R$	$\to$	$SU(2)_C$
$(0,0)$	$\to$	0
$(1,1)$	$\to$	$2+1+0$

Resonances: Quantum numbers & simplified models

- Rise of amplitude / anomalous coupling: Taylor expansion below a resonance
- Resonances might be in direct reach of LHC
- EFT framework EW-restored regime: $SU(2)_L \times SU(2)_R$, $SU(2)_L \times U(1)_Y$ gauged
- Include EFT operators in addition (more resonances, continuum contribution)
- Apply *T*-matrix unitarization beyond resonance ("UV-incomplete" model)

Spins 0, 2 considered, Spin 1 has different physics (mixing with *W*/*Z*)

$SU(2)_L \times SU(2)_R$	$\to$	$SU(2)_C$
$(0,0)$	$\to$	0
$(1,1)$	$\to$	$2+1+0$

	isoscalar	isotensor
scalar	σ^0	$\phi_t^{--}, \phi_t^{-}, \phi_t^{0}, \phi_t^{+}, \phi_t^{++}$ $\phi_v^{-}, \phi_v^{0}, \phi_v^{+}$ ϕ_s^{0}
tensor	f^0	$\begin{pmatrix} X_t^{--}, X_t^{-}, X_t^{0}, X_t^{+}, X_t^{++} \\ X_v^{-}, X_v^{0}, X_v^{+} \\ X_s^{0} \end{pmatrix}$
...	...	...

Resonances: Quantum numbers & simplified models

- Rise of amplitude / anomalous coupling: Taylor expansion below a resonance
- Resonances might be in direct reach of LHC
- EFT framework EW-restored regime: $SU(2)_L \times SU(2)_R$, $SU(2)_L \times U(1)_Y$ gauged
- Include EFT operators in addition (more resonances, continuum contribution)
- Apply *T*-matrix unitarization beyond resonance ("UV-incomplete" model)

Spins 0, 2 considered, Spin 1 has different physics (mixing with *W*/*Z*)

$SU(2)_L \times SU(2)_R$	$\to$	$SU(2)_C$
$(0,0)$	$\to$	0
$(1,1)$	$\to$	$2+1+0$

	isoscalar	isotensor
scalar	σ^0	$\phi_t^{--}, \phi_t^{-}, \phi_t^{0}, \phi_t^{+}, \phi_t^{++}$ $\phi_v^{-}, \phi_v^{0}, \phi_v^{+}$ ϕ_s^{0}
tensor	f^0	$\begin{pmatrix} X_t^{--}, X_t^{-}, X_t^{0}, X_t^{+}, X_t^{++} \\ X_v^{-}, X_v^{0}, X_v^{+} \\ X_s^{0} \end{pmatrix}$
...	...	...

Tensor resonances

- Symmetric tensor $f_{\mu\nu}$
- On-shell conditions: 10 → 5 components
- Tracelessness: $f_\mu{}^\mu = 0$
- Transversality: $\partial_\mu f^{\mu\nu} = 0$

How to deal with *off-shell* tensor in realistic processes?

Tensor resonances: Fierz-Pauli vs. Stückelberg

- Start with Fierz-Pauli Lagrangian for symmetric tensor

$$\mathcal{L}_{\rm FP} = \frac{1}{2}\partial_\alpha f_{\mu\nu}\partial^\alpha f^{\mu\nu} - \frac{1}{2}m^2 f_{\mu\nu}f^{\mu\nu} - \frac{1}{2}\partial_\alpha f^\mu_\mu \partial^\alpha f^\nu_\nu + \frac{1}{2}m^2 f^\mu_\mu f^\nu_\nu$$
$$- \partial^\alpha f_{\alpha\mu}\partial_\beta f^{\beta\mu} - f^\alpha_\alpha \partial^\mu\partial^\nu f_{\mu\nu} + f_{\mu\nu}J^{\mu\nu}_f$$

Tensor resonances: Fierz-Pauli vs. Stückelberg

- Start with Fierz-Pauli Lagrangian for symmetric tensor

$$\mathcal{L}_{\text{FP}} = \frac{1}{2}\partial_\alpha f_{\mu\nu}\partial^\alpha f^{\mu\nu} - \frac{1}{2}m^2 f_{\mu\nu}f^{\mu\nu} - \frac{1}{2}\partial_\alpha f^\mu_{\ \mu}\partial^\alpha f^\nu_{\ \nu} + \frac{1}{2}m^2 f^\mu_{\ \mu} f^\nu_{\ \nu} - \partial^\alpha f_{\alpha\mu}\partial_\beta f^{\beta\mu} - f^\alpha_{\ \alpha}\partial^\mu\partial^\nu f_{\mu\nu} + f_{\mu\nu}J_f^{\mu\nu}$$

- Fierz-Pauli conditions not valid off-shell
- Fierz-Pauli propagator has bad high-energy behavior
- Use Stückelberg formalism to make off-shell high-energy behavior explicit
- Introduce compensator fields $\Rightarrow$ no propagators with momentum factors
- Crucial for MCs

Tensor resonances: Fierz-Pauli vs. Stückelberg

- Start with Fierz-Pauli Lagrangian for symmetric tensor

$$\mathcal{L}_{\rm FP} = \frac{1}{2}\partial_\alpha f_{\mu\nu}\partial^\alpha f^{\mu\nu} - \frac{1}{2}m^2 f_{\mu\nu}f^{\mu\nu} - \frac{1}{2}\partial_\alpha f^\mu_{\ \mu}\partial^\alpha f^\nu_{\ \nu} + \frac{1}{2}m^2 f^\mu_{\ \mu} f^\nu_{\ \nu} \\ - \partial^\alpha f_{\alpha\mu}\partial_\beta f^{\beta\mu} - f^\alpha_{\ \alpha}\partial^\mu\partial^\nu f_{\mu\nu} + f_{\mu\nu}J^{\mu\nu}_f$$

- Fierz-Pauli conditions not valid off-shell
- Fierz-Pauli propagator has bad high-energy behavior
- Use Stückelberg formalism to make off-shell high-energy behavior explicit
- Introduce compensator fields $\Rightarrow$ no propagators with momentum factors
- Crucial for MCs
  - $f^{\mu\nu}$: on-shell $f^{\mu\nu}$
  - ϕ: $\partial_\mu\partial_\nu f^{\mu\nu}$
  - A^μ: $\partial_\nu f^{\mu\nu}$
  - σ: $f^\mu_{\ \mu}$

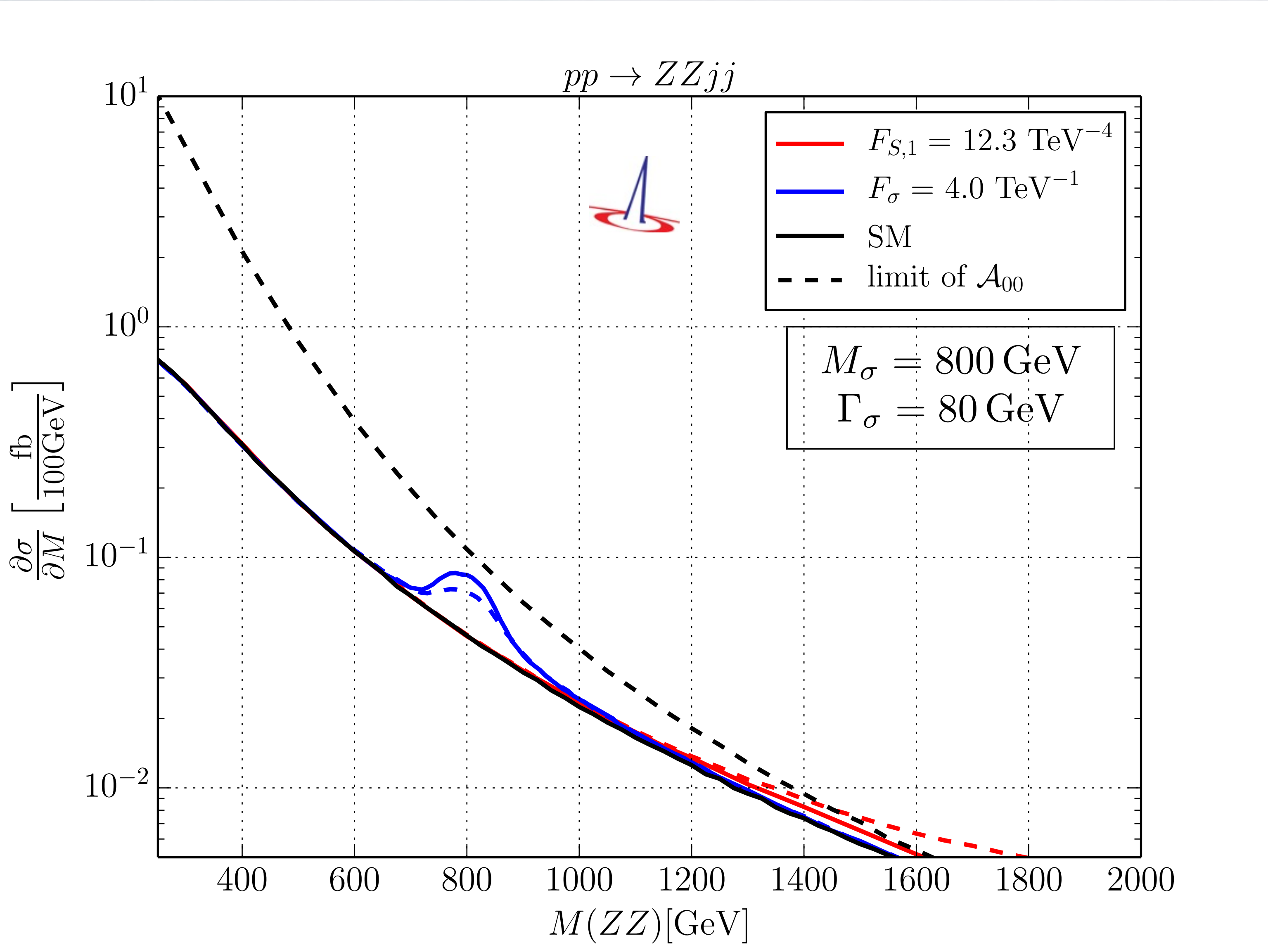
  Gauge fixing: $\sigma = -\phi$

$$\mathcal{L} = \frac{1}{2} f_{f\mu\nu}\left(-\partial^2 - m_f^2\right) f_f^{\mu\nu} + \frac{1}{2} f^\mu_{f\ \mu}\left(-\frac{1}{2}\left(-\partial^2 - m_f^2\right)\right) f^\nu_{f\ \nu} \\ + \frac{1}{2} A_{f\mu}\left(\partial^2 + m_f^2\right) A_f^\mu + \frac{1}{2}\sigma_f\left(-\partial^2 - m_f^2\right)\sigma_f \\ + \left(f_{\mu\nu} - \frac{1}{\sqrt{6}}\sigma_f g_{\mu\nu}\right) J_f^{\mu\nu} \\ - \left(\frac{1}{\sqrt{2}m_f}\left(A_{f\mu}\partial_\nu + A_{f\nu}\partial_\mu\right) - \frac{\sqrt{2}}{\sqrt{3}m_f^2}\sigma_f\partial_\mu\partial_\nu\right) J_f^{\mu\nu}$$

Comparison: Simplified Models & EFT

Kilian/Ohl/JRR/Sekulla: PRD93(16),3. 036004 [1511.00022]

Black dashed line:
saturation of $\mathcal{A}_{22}(W^+W^+)/\mathcal{A}_{00}(ZZ)$



- EFT fails at resonance
- aQGC describe rise of resonance
- Unitarization applied
- Tensor resonances better visible than scalars

$32\pi\Gamma/M^5$

	σ	ϕ	f	X
$F_{S,0}$	$\frac{1}{2}$	2	15	5
$F_{S,1}$	–	$-\frac{1}{2}$	-5	-35

$M_{jj} > 500\,\text{GeV};\ \Delta\eta_{jj} > 2.4;\ \ p_T^j > 20\,\text{GeV};\ \ |\Delta\eta_j| < 4.5$

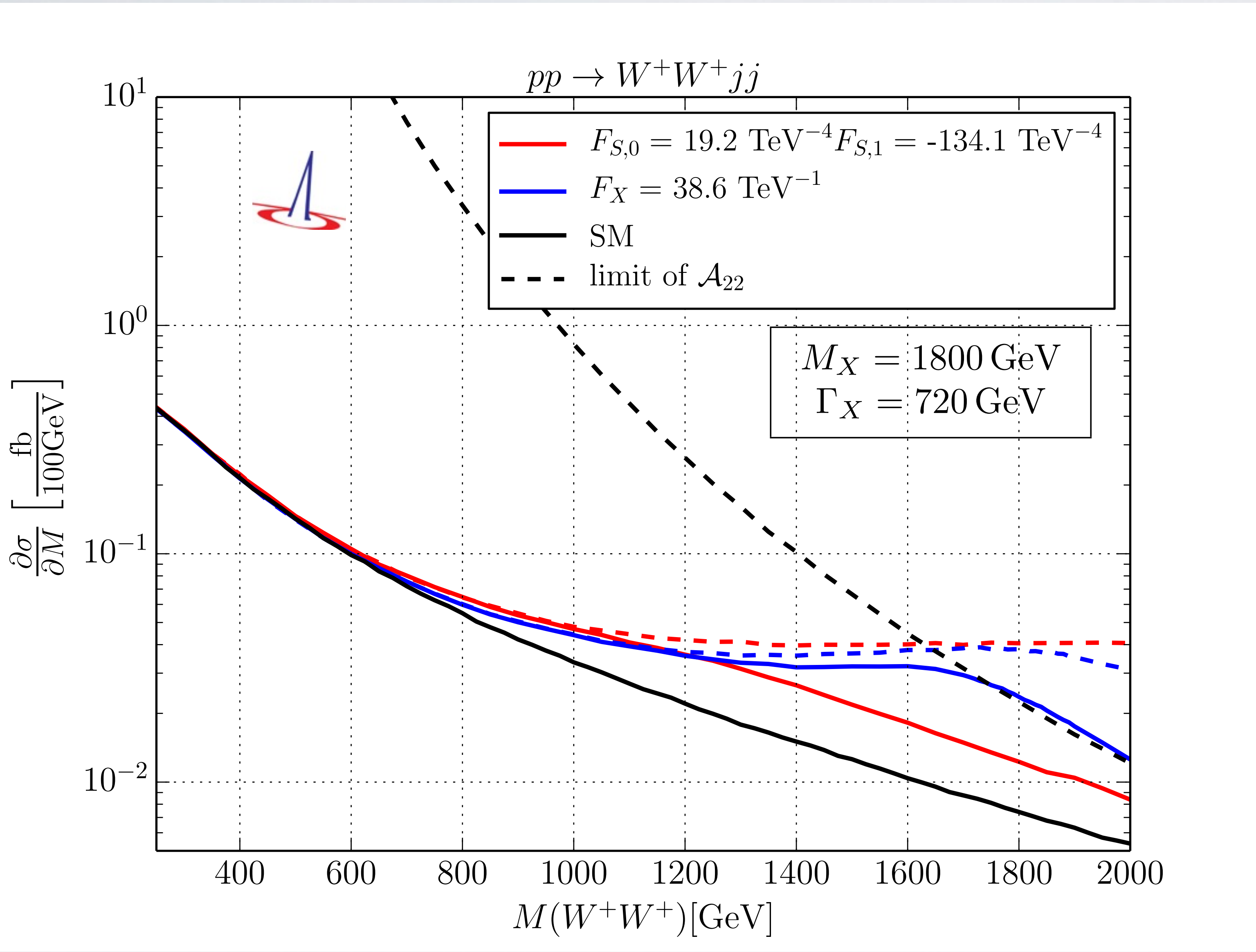
$|F_{S,0}| < 480\ \text{TeV}^{-4} \qquad |F_{S,1}| < 480\ \text{TeV}^{-4}$

ATLAS PRL 113(2014)14, 141803 [1405.6241]

Comparison: Simplified Models & EFT

Kilian/Ohl/JRR/Sekulla: PRD93(16),3. 036004 [1511.00022]

Black dashed line:
saturation of $\mathcal{A}_{22}(W^+W^+)/\mathcal{A}_{00}(ZZ)$



- EFT fails at resonance
- aQGC describe rise of resonance
- Unitarization applied
- Tensor resonances better visible than scalars

$$32\pi\Gamma/M^5$$

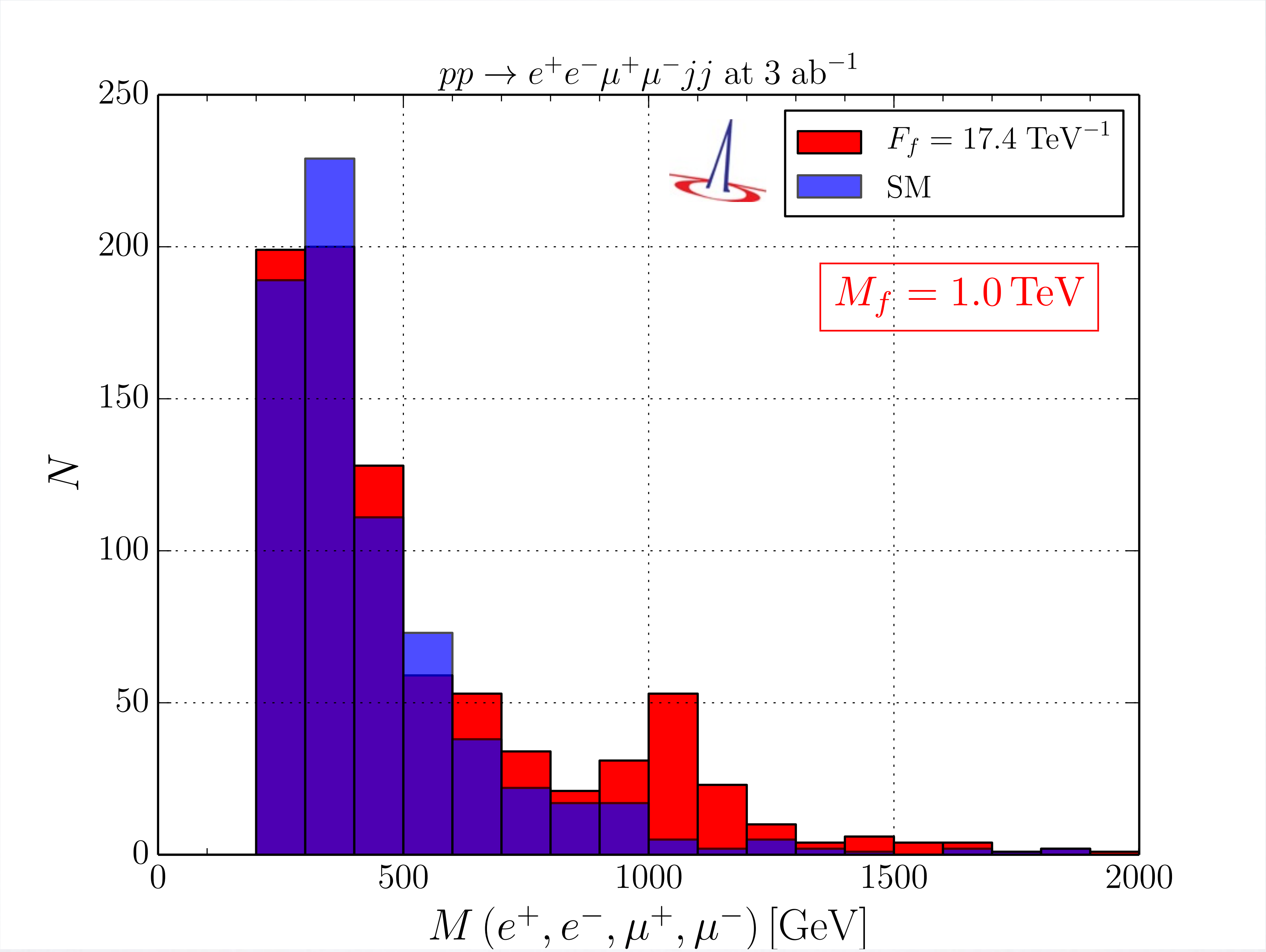
	σ	ϕ	f	X
$F_{S,0}$	$\frac{1}{2}$	2	15	5
$F_{S,1}$	–	-$\frac{1}{2}$	-5	-35

$$M_{jj} > 500\,\text{GeV};\ \ \Delta\eta_{jj} > 2.4;\ \ p_T^j > 20\,\text{GeV};\ \ |\Delta\eta_j| < 4.5$$

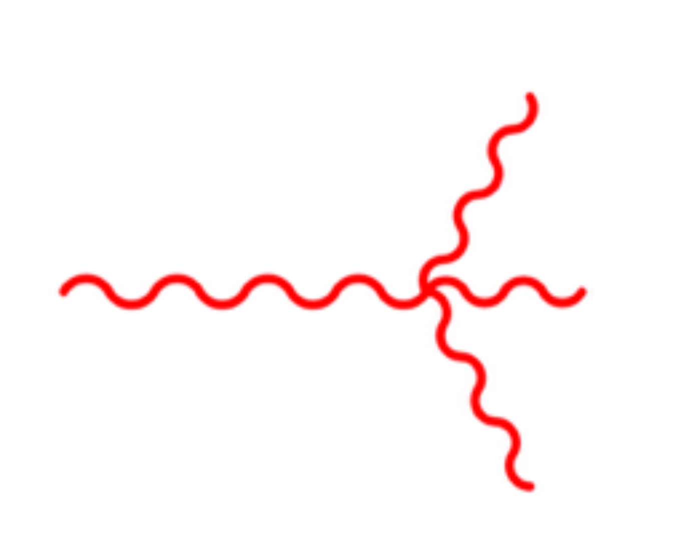
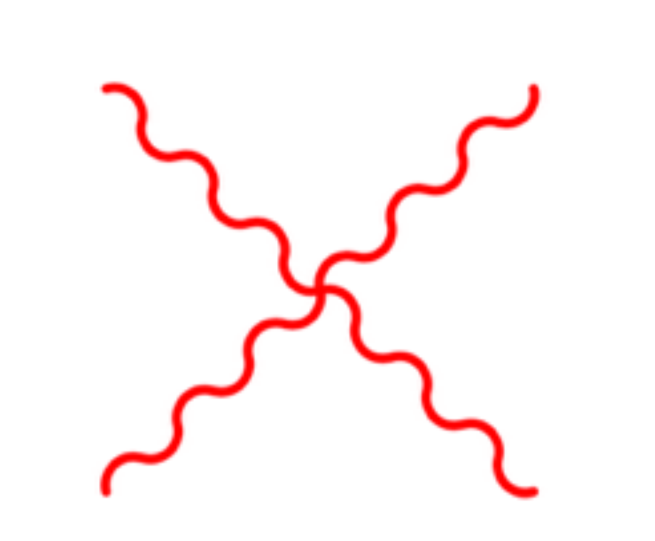
$$|F_{S,0}| < 480\ \text{TeV}^{-4} \qquad |F_{S,1}| < 480\ \text{TeV}^{-4}$$

ATLAS PRL 113(2014)14, 141803 [1405.6241]

Complete LHC process at 14 TeV



Triple [multiple] Vector Boson Production ?

Relate  to  ?

- Yes, same Feynman rule as in VBS, but …
- one external $W/Z/\gamma$ always far off-shell
- Unitarization formalism not available (would need $2 \to 3$ unitarizations)
- Different Wilson coefficients dominate (particularly for resonances)
- Important physics (partially) independent from VBS

Conclusions / Summary

- Vector boson scattering one of flagship measurements of Runs II/III
- EFT provides *a* (!) [not *the*] consistent framework for SM deviations
- Very well-defined (and limited) range of applicability
- Accounts for access to New Physics in VBS and Di-/Triboson channels
- Unitarization for theoretically sane description (allows to calculate 'best limit')
- *T*-matrix unitarization universal scheme for EFT and resonances
- Simplified models: generic electroweak resonances
- Limits from LHC still incredibly limited: $M \sim$ 200-300 GeV
- Make sure that actual limits are meaningful and comparable

Conclusions / Summary

- Vector boson scattering one of flagship measurements of Runs II/III
- EFT provides *a* (!) [not *the*] consistent framework for SM deviations
- Very well-defined (and limited) range of applicability
- Accounts for access to New Physics in VBS and Di-/Triboson channels
- Unitarization for theoretically sane description (allows to calculate 'best limit')
- *T*-matrix unitarization universal scheme for EFT and resonances
- Simplified models: generic electroweak resonances
- Limits from LHC still incredibly limited: $M \sim$ 200-300 GeV
- Make sure that actual limits are meaningful and comparable

ILC 1 TeV, 1/ab expectations:

Spin	$I=0$	$I=1$	$I=2$
0	1.55	–	1.95
1	–	2.49	–
2	3.29	–	4.30

LHC 13/14 TeV, 0.3-3/ab

Spin	$I=0$	$I=1$	$I=2$
0	1.39	1.55	1.95
1	1.74	2.67	–
2	3.00	3.01	5.84

Conclusions / Summary

- Vector boson scattering one of flagship measurements of Runs II/III
- EFT provides *a* (!) [not *the*] consistent framework for SM deviations
- Very well-defined (and limited) range of applicability
- Accounts for access to New Physics in VBS and Di-/Triboson channels
- Unitarization for theoretically sane description (allows to calculate 'best limit')
- *T*-matrix unitarization universal scheme for EFT and resonances
- Simplified models: generic electroweak resonances
- Limits from LHC still incredibly limited: $M \sim$ 200-300 GeV
- Make sure that actual limits are meaningful and comparable

ILC 1 TeV, 1/ab expectations:

Spin	$I=0$	$I=1$	$I=2$
0	1.55	–	[illegible]
1	–	2.49	[illegible]
2	3.29	[illegible]	[illegible]

LHC 13/14 TeV, 0.3-3/ab

[illegible]	[illegible]	$I=1$	$I=2$
[illegible]	1.39	1.55	1.95
1	1.74	2.67	–
2	3.00	3.01	5.84

ca. 1-3 TeV
[very preliminary]

light Higgs: also needs to be updated

whatever approach ....

whatever approach .... always get the correct ellipses

BACKUP SLIDES

Effective Field Theory (EFT) for Weak Interactions

- SppS: discovery of W, Z (on-shell)
- SLC/LEP: proof of non-Abelian weak structure, failure to find (very) light Higgs
- Measurement of longitudinal Ws: $ee \to WW$ (LEP), $t \to Wb$ (Tevatron)
- Using all known d.o.f., parameterizing all possible interactions

Building blocks for EFT:

$$\psi \quad , \qquad \mathbf{W}_\mu \quad , \qquad \mathbf{B}_\mu \quad , \qquad \Sigma = \exp\left[\frac{-i}{v}\mathbf{w}\boldsymbol{\tau}\right]$$

SM fermions | weak bosons | hypercharge boson | longitudinal d.o.f.

Effective Field Theory (EFT) for Weak Interactions

- SppS: discovery of W, Z (on-shell)
- SLC/LEP: proof of non-Abelian weak structure, failure to find (very) light Higgs
- Measurement of longitudinal Ws: $ee \to WW$ (LEP), $t \to Wb$ (Tevatron)
- Using all known d.o.f., parameterizing all possible interactions

Building blocks for EFT:

$$\psi \quad , \quad \mathbf{W}_\mu \quad , \quad \mathbf{B}_\mu \quad , \quad \Sigma = \exp\left[\frac{-i}{v}\mathbf{w}\boldsymbol{\tau}\right]$$

SM fermions | weak bosons | hypercharge boson | longitudinal d.o.f.

Minimal Lagrangian describing measurements at SLC / LEP [II] / Tevatron

$$\mathcal{L}_{\text{pre-LHC}} = \sum_\psi \overline{\psi}(i\not{D})\psi - \frac{1}{2g^2}\text{tr}\left[\mathbf{W}_{\mu\nu}\mathbf{W}^{\mu\nu}\right] - \frac{1}{2g'^2}\text{tr}\left[\mathbf{B}_{\mu\nu}\mathbf{B}^{\mu\nu}\right] + \frac{v^2}{4}\text{tr}\left[(\mathbf{D}_\mu\Sigma)(\mathbf{D}^\mu\Sigma)\right]$$

with the following useful definitions:

$$\mathbf{D}_\mu = \partial_\mu + \frac{i}{2}g\boldsymbol{\tau}^I W^I_\mu + \frac{i}{2}g' B_\mu \boldsymbol{\tau}^3$$

$$\mathbf{W}_{\mu\nu} = \frac{i}{2}g\boldsymbol{\tau}^I(\partial_\mu W^I_\nu - \partial_\nu W^I_\mu + g\epsilon_{IJK}W^J_\mu W^K_\nu)$$

$$\mathbf{B}_{\mu\nu} = \frac{i}{2}g'(\partial_\mu B_\nu - \partial_\nu B_\mu)\boldsymbol{\tau}^3$$

Effective Field Theory (EFT) for Weak Interactions

- SppS: discovery of W, Z (on-shell)
- SLC/LEP: proof of non-Abelian weak structure, failure to find (very) light Higgs
- Measurement of longitudinal Ws: $ee \to WW$ (LEP), $t \to Wb$ (Tevatron)
- Using all known d.o.f., parameterizing all possible interactions

Building blocks for EFT:

$$\psi \quad , \quad \mathbf{W}_\mu \quad , \quad \mathbf{B}_\mu \quad , \quad \Sigma = \exp\left[\frac{-i}{v}\mathbf{w}\boldsymbol{\tau}\right]$$

SM fermions — weak bosons — hypercharge boson — longitudinal d.o.f.

Minimal Lagrangian describing measurements at SLC / LEP [II] / Tevatron

$$\mathcal{L}_{\text{pre-LHC}} = \sum_\psi \overline{\psi}(i\not{D})\psi - \frac{1}{2g^2}\text{tr}\left[\mathbf{W}_{\mu\nu}\mathbf{W}^{\mu\nu}\right] - \frac{1}{2g'^2}\text{tr}\left[\mathbf{B}_{\mu\nu}\mathbf{B}^{\mu\nu}\right] + \frac{v^2}{4}\text{tr}\left[(\mathbf{D}_\mu\Sigma)(\mathbf{D}^\mu\Sigma)\right]$$

with the following useful definitions:

$$\mathbf{D}_\mu = \partial_\mu + \frac{i}{2}g\boldsymbol{\tau}^I W^I_\mu + \frac{i}{2}g' B_\mu \boldsymbol{\tau}^3$$

$$\mathbf{W}_{\mu\nu} = \frac{i}{2}g\boldsymbol{\tau}^I(\partial_\mu W^I_\nu - \partial_\nu W^I_\mu + g\epsilon_{IJK}W^J_\mu W^K_\nu)$$

$$\mathbf{B}_{\mu\nu} = \frac{i}{2}g'(\partial_\mu B_\nu - \partial_\nu B_\mu)\boldsymbol{\tau}^3$$

Electroweak Chiral Lagrangian

Effective Field Theory (EFT) for Weak Interactions

- SppS: discovery of W, Z (on-shell)
- SLC/LEP: proof of non-Abelian weak structure, failure to find (very) light Higgs
- Measurement of longitudinal Ws: $ee \to WW$ (LEP), $t \to Wb$ (Tevatron)
- Using all known d.o.f., parameterizing all possible interactions

Building blocks for EFT:

$$\psi \quad , \quad \mathbf{W}_\mu \quad , \quad \mathbf{B}_\mu \quad , \quad \Sigma = \exp\left[\frac{-i}{v}\mathbf{w}\boldsymbol{\tau}\right]$$

SM fermions | weak bosons | hypercharge boson | longitudinal d.o.f.

Minimal Lagrangian describing measurements at SLC / LEP [II] / Tevatron

$$\mathcal{L}_{\text{pre-LHC}} = \sum_\psi \overline{\psi}(i\not{D})\psi - \frac{1}{2g^2}\mathrm{tr}\left[\mathbf{W}_{\mu\nu}\mathbf{W}^{\mu\nu}\right] - \frac{1}{2g'^2}\mathrm{tr}\left[\mathbf{B}_{\mu\nu}\mathbf{B}^{\mu\nu}\right] + \frac{v^2}{4}\mathrm{tr}\left[(\mathbf{D}_\mu\Sigma)(\mathbf{D}^\mu\Sigma)\right]$$

with the following useful definitions:

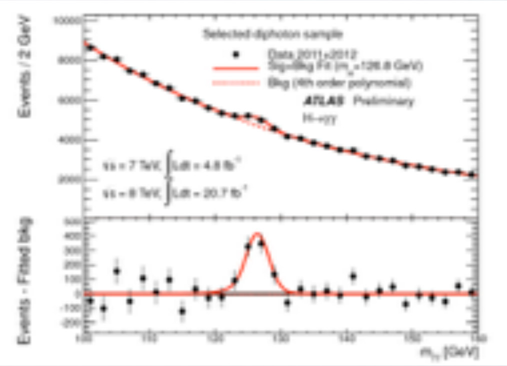
Electroweak Chiral Lagrangian

$$\mathbf{D}_\mu = \partial_\mu + \frac{i}{2} g \boldsymbol{\tau}^I W^I_\mu + \frac{i}{2} g' B_\mu \boldsymbol{\tau}^3$$

$$\mathbf{W}_{\mu\nu} = \frac{i}{2} g \boldsymbol{\tau}^I (\partial_\mu W^I_\nu - \partial_\nu W^I_\mu + g \epsilon_{IJK} W^J_\mu W^K_\nu)$$

$$\mathbf{B}_{\mu\nu} = \frac{i}{2} g' (\partial_\mu B_\nu - \partial_\nu B_\mu) \boldsymbol{\tau}^3$$

Ruled out by LHC data (Higgs discovery)



Parameterizing SM deviations

★ Specific models (SUSY, Compositeness, Little Higgses, 2HDM, Modified Higgses, Xdim, ...)

- Could give strong signals in VBS (presumably Little Higgses, Compositeness, Xdim ....)
- Could give faint signals in VBS (presumably SUSY, 2HDM [Higgs data!], ...)
- Up to parametric uncertainties precise predictions from the models (new independent couplings)
- Mostly even beyond tree level predictable
- Analysis has to be repeated for each and every model, introduces new parameters

Parameterizing SM deviations

★ Specific models (SUSY, Compositeness, Little Higgses, 2HDM, Modified Higgses, Xdim, ...)

- Could give strong signals in VBS (presumably Little Higgses, Compositeness, Xdim ....)
- Could give faint signals in VBS (presumably SUSY, 2HDM [Higgs data!], ...)
- Up to parametric uncertainties precise predictions from the models (new independent couplings)
- Mostly even beyond tree level predictable
- Analysis has to be repeated for each and every model, introduces new parameters

★ Anomalous Couplings

- Usually first "model-independent" proposal
- At the moment applied by HXSWG (but under debate)
- Only modifications of SM couplings or introduction of new (Lorentz) structures ?
- Allows fits of coupling strengths
- Possible deviations difficult to interpret in terms of quantum field theory, unitarity!!

Parameterizing SM deviations

★ Specific models (SUSY, Compositeness, Little Higgses, 2HDM, Modified Higgses, Xdim, ...)

- Could give strong signals in VBS (presumably Little Higgses, Compositeness, Xdim ....)
- Could give faint signals in VBS (presumably SUSY, 2HDM [Higgs data!], ...)
- Up to parametric uncertainties precise predictions from the models (new independent couplings)
- Mostly even beyond tree level predictable
- Analysis has to be repeated for each and every model, introduces new parameters

★ Anomalous Couplings

- Usually first "model-independent" proposal
- At the moment applied by HXSWG (but under debate)
- Only modifications of SM couplings or introduction of new (Lorentz) structures ?
- Allows fits of coupling strengths
- Possible deviations difficult to interpret in terms of quantum field theory, unitarity!!

★ Form factors

- Similar approach to anomalous couplings, partially resums perturbative series
- (Almost) completely general and model-independent
- Needs parameterizations, violates gauge invariance, unitarity ad-hoc curable (new parameters)

Parameterizing SM deviations

★ Specific models (SUSY, Compositeness, Little Higgses, 2HDM, Modified Higgses, Xdim, ...)

- Could give strong signals in VBS (presumably Little Higgses, Compositeness, Xdim ....)
- Could give faint signals in VBS (presumably SUSY, 2HDM [Higgs data!], ...)
- Up to parametric uncertainties precise predictions from the models (new independent couplings)
- Mostly even beyond tree level predictable
- Analysis has to be repeated for each and every model, introduces new parameters

★ Anomalous Couplings

- Usually first "model-independent" proposal
- At the moment applied by HXSWG (but under debate)
- Only modifications of SM couplings or introduction of new (Lorentz) structures ?
- Allows fits of coupling strengths
- Possible deviations difficult to interpret in terms of quantum field theory, unitarity!!

★ Form factors

- Similar approach to anomalous couplings, partially resums perturbative series
- (Almost) completely general and model-independent
- Needs parameterizations, violates gauge invariance, unitarity ad-hoc curable (new parameters)

★ Effective Field Theory

- (Almost) model-independent, consistent calculation of perturbative corrections (power counting !?)
- Depends on (possibly) many free parameters
- Requires decoupling of New Physics
- Range of applicability strongly depends on couplings and scales (unitarity issue)

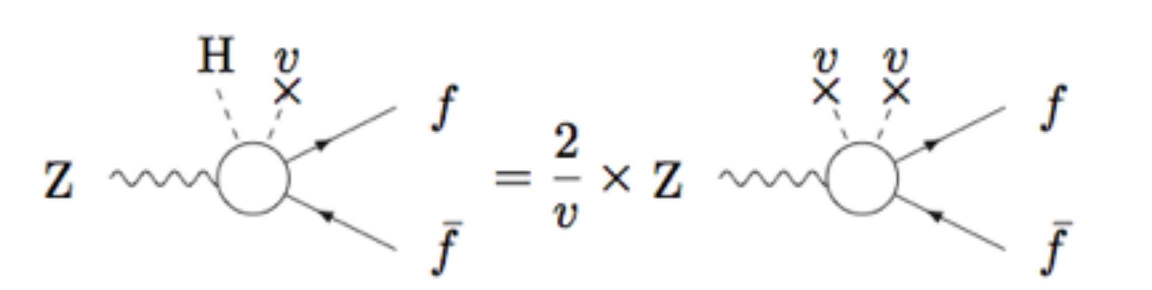
General Procedure using EFTs

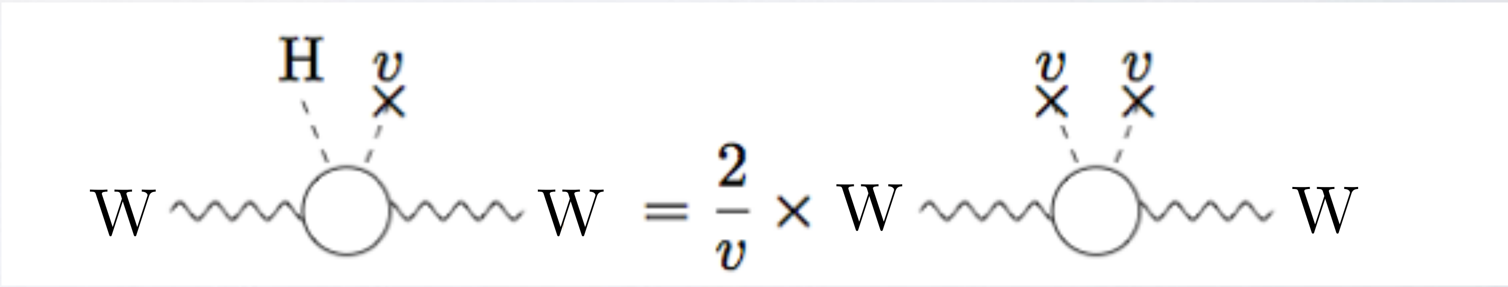
- Use all experimental observables $\Longrightarrow$ global fit to all Wilson coefficients
- Would-be optimal approach
- Too many independent variables $\Longrightarrow$ needs staged fitting
- Need for simplifying assumptions
- Try to find minimal "physically well motivated" operator basis
- Experimental bias: consider only LHC-accessible operators
- Cross check from low-energy physics (flavor / EDMs / EWPO etc. / Higgs!)
- Explore full structure of EW Higgs doublet:

General Procedure using EFTs

- Use all experimental observables $\Longrightarrow$ global fit to all Wilson coefficients
- Would-be optimal approach
- Too many independent variables $\Longrightarrow$ needs staged fitting
- Need for simplifying assumptions
- Try to find minimal "physically well motivated" operator basis
- Experimental bias: consider only LHC-accessible operators
- Cross check from low-energy physics (flavor / EDMs / EWPO etc. / Higgs!)
- Explore full structure of EW Higgs doublet:

$$\mathcal{O}_{\Phi f} = (\Phi^\dagger \overleftrightarrow{D}_\mu \Phi)\,(\overline{f}\gamma^\mu f) \qquad\qquad \mathcal{O}_{\Phi W} = (\Phi^\dagger \Phi) W_{\mu\nu} W^{\mu\nu}$$





Effects in $H \to Zff$ related to $Z \to ff$ $\Longrightarrow$ constrained by SLC/LEP

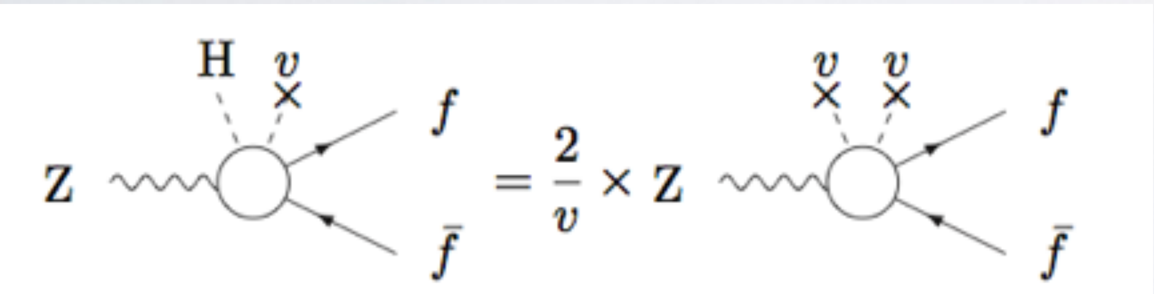
visible in Higgs physics: $H \to WW$

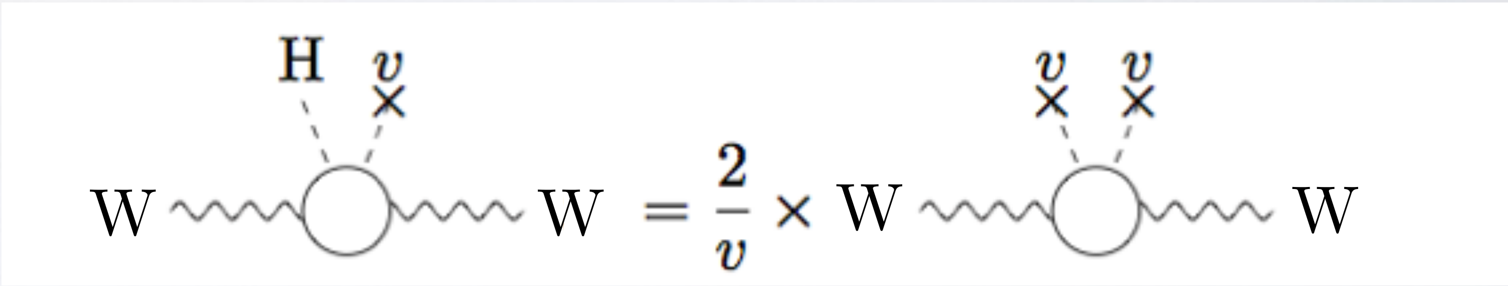
redefines only SM parameters $\Longrightarrow$ no experimental constraints

General Procedure using EFTs

- Use all experimental observables $\Longrightarrow$ global fit to all Wilson coefficients
- Would-be optimal approach
- Too many independent variables $\Longrightarrow$ needs staged fitting
- Need for simplifying assumptions
- Try to find minimal "physically well motivated" operator basis
- Experimental bias: consider only LHC-accessible operators
- Cross check from low-energy physics (flavor / EDMs / EWPO etc. / Higgs!)
- Explore full structure of EW Higgs doublet:

$$\mathcal{O}_{\Phi f} = (\Phi^\dagger \overleftrightarrow{D}_\mu \Phi)\,(\overline{f}\gamma^\mu f) \qquad\qquad \mathcal{O}_{\Phi W} = (\Phi^\dagger \Phi) W_{\mu\nu} W^{\mu\nu}$$





Effects in $H \to Zff$ related to $Z \to ff$ $\Longrightarrow$ constrained by SLC/LEP

visible in Higgs physics: $H \to WW$

redefines only SM parameters $\Longrightarrow$ no experimental constraints

- Often use *vev*-subtracted operators: $\mathcal{O}(\Phi^\dagger\Phi) \longrightarrow \mathcal{O}'(\Phi^\dagger\Phi - v^2)$
- EFT allows to systemically calculate higher-order corrections

How to get EFTs from New Physics

- Consider effects from heavy states by using (known) low-energy d.o.f.s

> In addition to being a great convenience, effective field theory allows us to ask all the really scientific questions that we want to ask without committing ourselves to a picture of what happens at arbitrarily high energy.

H. Georgi, 1993

How to get EFTs from New Physics

- Consider effects from heavy states by using (known) low-energy d.o.f.s

> In addition to being a great convenience, effective field theory allows us to ask all the really scientific questions that we want to ask without committing ourselves to a picture of what happens at arbitrarily high energy.

H. Georgi, 1993

- Integrating out heavy d.o.f.s marginalizes over details of short-distance interactions
- Toy Example: two interacting scalar fields φ, Φ

Path integral

$$\mathcal{Z}[j,J] = \int \mathcal{D}[\Phi]\,\mathcal{D}[\varphi]\ \exp\Big[i\int dx\Big(\tfrac{1}{2}(\partial\varphi)^2 - \tfrac{1}{2}\Phi(\Box + M^2)\Phi - \lambda\varphi^2\Phi - \ldots + J\Phi + j\varphi\Big)\Big]$$

How to get EFTs from New Physics

- Consider effects from heavy states by using (known) low-energy d.o.f.s

> In addition to being a great convenience, effective field theory allows us to ask all the really scientific questions that we want to ask without committing ourselves to a picture of what happens at arbitrarily high energy.

H. Georgi, 1993

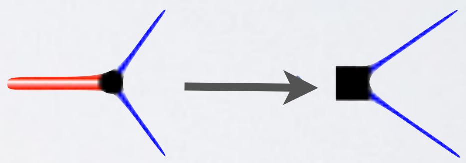
- Integrating out heavy d.o.f.s marginalizes over details of short-distance interactions
- Toy Example: two interacting scalar fields φ, Φ

Path integral

$$\mathcal{Z}[j,J] = \int \mathcal{D}[\Phi]\,\mathcal{D}[\varphi]\;\exp\left[i\int dx\left(\tfrac{1}{2}(\partial\varphi)^2 - \tfrac{1}{2}\Phi(\Box + M^2)\Phi - \lambda\varphi^2\Phi - \ldots + J\Phi + j\varphi\right)\right]$$

Completing the square (Gaussian integration)

$$\Phi' = \Phi + \frac{\lambda}{M^2}\left(1 + \frac{\partial^2}{M^2}\right)^{-1}\varphi^2 \qquad \Longrightarrow$$



How to get EFTs from New Physics

- Consider effects from heavy states by using (known) low-energy d.o.f.s

> In addition to being a great convenience, effective field theory allows us to ask all the really scientific questions that we want to ask without committing ourselves to a picture of what happens at arbitrarily high energy.

H. Georgi, 1993

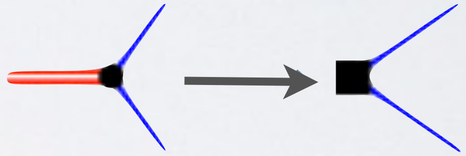
- Integrating out heavy d.o.f.s marginalizes over details of short-distance interactions
- Toy Example: two interacting scalar fields φ, Φ

Path integral

$$\mathcal{Z}[j,J] = \int \mathcal{D}[\Phi]\,\mathcal{D}[\varphi]\;\exp\left[i\int dx\left(\tfrac{1}{2}(\partial\varphi)^2 - \tfrac{1}{2}\Phi(\Box + M^2)\Phi - \lambda\varphi^2\Phi - \ldots + J\Phi + j\varphi\right)\right]$$

Completing the square (Gaussian integration)

$$\Phi' = \Phi + \frac{\lambda}{M^2}\left(1 + \frac{\partial^2}{M^2}\right)^{-1}\varphi^2 \qquad \Longrightarrow$$



In the Lagrangian remove the high-scale d.o.f.s:

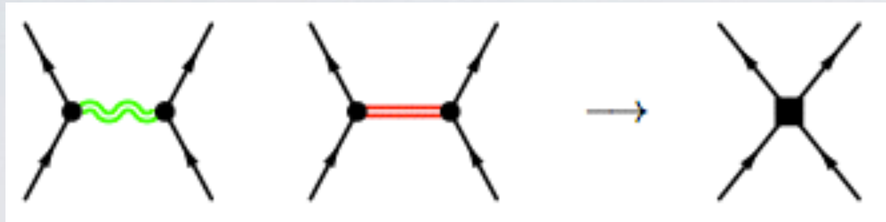
$$\frac{1}{2}(\partial\Phi)^2 - \frac{1}{2}M^2\Phi^2 - \lambda\varphi^2\Phi \quad = \quad \underbrace{-\frac{1}{2}\Phi'(M^2 + \partial^2)\Phi'}_{\text{Irrelevant normalization of the path integral}} + \underbrace{\frac{\lambda^2}{2M^2}\varphi^2\left(1 + \frac{\partial^2}{M^2}\right)^{-1}\varphi^2}_{\text{Tower of higher and higher-dim. operators of light fields}}$$

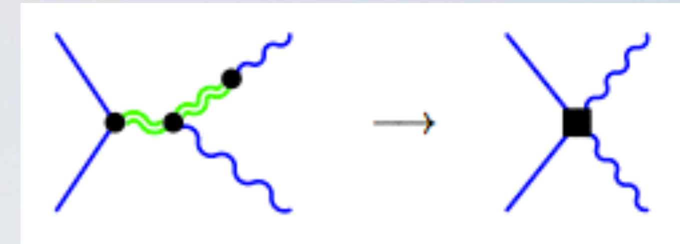
Irrelevant normalization of the path integral

Tower of higher and higher-dim. operators of light fields

Generation of Higher-dimensional Operators

$$\mathcal{O}^{(I)}_{JJ} = \frac{1}{\Lambda^2}\mathrm{tr}\left[J^{(I)}\cdot J^{(I)}\right]$$





$$\mathcal{O}'_{\Phi,1} = \tfrac{1}{\Lambda^2}\left((D\Phi)^\dagger\Phi\right)\cdot\left(\Phi^\dagger(D\Phi)\right) - \tfrac{v^2}{2}|D\Phi|^2$$

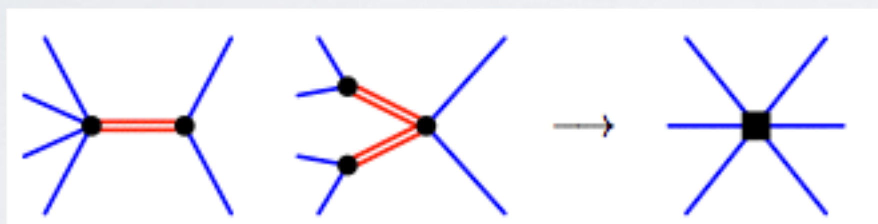
$$\mathcal{O}'_{\Phi\Phi} = \tfrac{1}{\Lambda^2}(\Phi^\dagger\Phi - v^2/2)\,(D\Phi)^\dagger\cdot(D\Phi)$$

$$\mathcal{O}'_{WW} = -\frac{1}{\Lambda^2}\frac{1}{2}(\Phi^\dagger\Phi - v^2/2)\mathrm{tr}\left[W_{\mu\nu}W^{\mu\nu}\right]$$

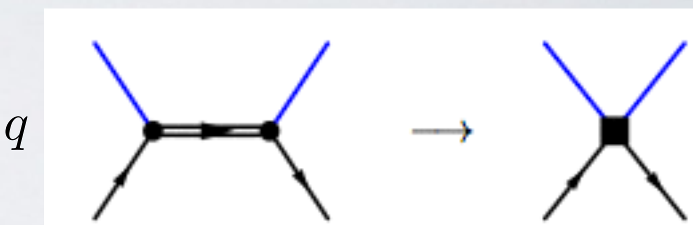
$$\mathcal{O}_B = \frac{1}{\Lambda^2}\frac{i}{2}(D_\mu\Phi)^\dagger(D_\nu\Phi)B^{\mu\nu}$$

$$\mathcal{O}'_{BB} = -\frac{1}{F^2}\frac{1}{4}(\Phi^\dagger\Phi - v^2/2)B_{\mu\nu}B^{\mu\nu}$$

$$\mathcal{O}'_{\Phi,3} = \frac{1}{\Lambda^2}\frac{1}{3}(\Phi^\dagger\Phi - v^2/2)^3$$



$$\mathcal{O}_{Vq} = \frac{1}{\Lambda^2}\overline{q}\Phi(\not{D}\Phi)q$$

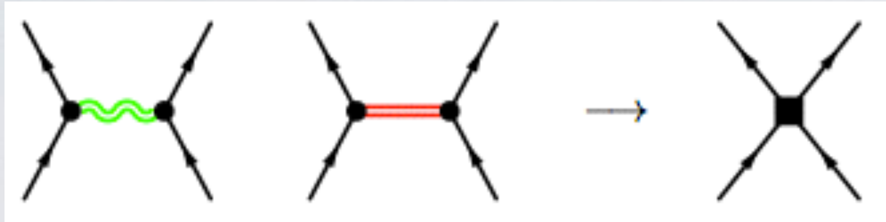


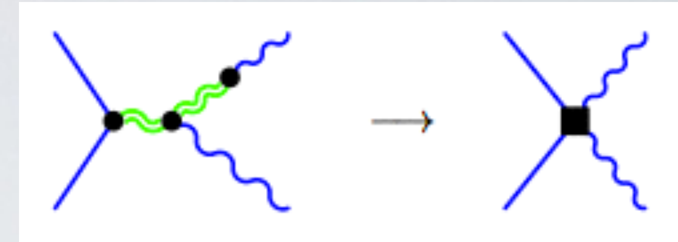
Couplings of new states to the longitudinal / transversal diboson system

	$J=0$	$J=1$	$J=2$
$I=0$	σ^0 (Higgs singlet?)	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 ?)	—	$t^{\pm\pm}, t^\pm, t^0$

Generation of Higher-dimensional Operators

$$\mathcal{O}_{JJ}^{(I)} = \frac{1}{\Lambda^2}\mathrm{tr}\left[J^{(I)}\cdot J^{(I)}\right]$$





$$\mathcal{O}'_{\Phi,1} = \tfrac{1}{\Lambda^2}\left((D\Phi)^\dagger\Phi\right)\cdot\left(\Phi^\dagger(D\Phi)\right) - \tfrac{v^2}{2}|D\Phi|^2$$

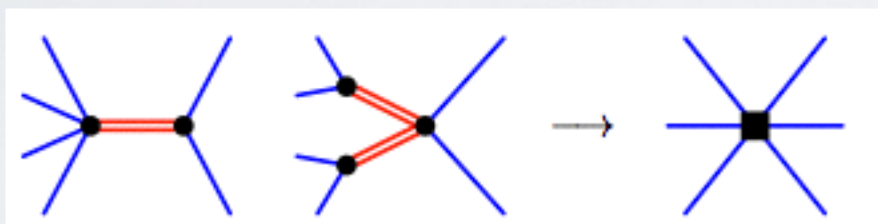
$$\mathcal{O}'_{\Phi\Phi} = \tfrac{1}{\Lambda^2}(\Phi^\dagger\Phi - v^2/2)\,(D\Phi)^\dagger\cdot(D\Phi)$$

$$\mathcal{O}'_{WW} = -\frac{1}{\Lambda^2}\frac{1}{2}(\Phi^\dagger\Phi - v^2/2)\mathrm{tr}\left[W_{\mu\nu}W^{\mu\nu}\right]$$

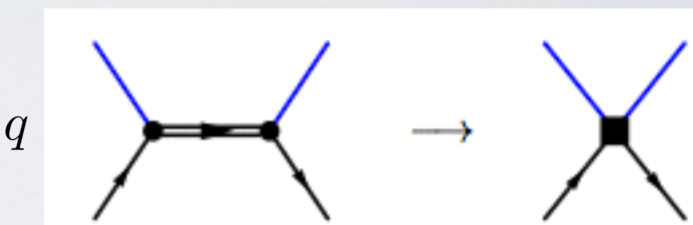
$$\mathcal{O}_B = \frac{1}{\Lambda^2}\frac{i}{2}(D_\mu\Phi)^\dagger(D_\nu\Phi)B^{\mu\nu}$$

$$\mathcal{O}'_{BB} = -\frac{1}{F^2}\frac{1}{4}(\Phi^\dagger\Phi - v^2/2)B_{\mu\nu}B^{\mu\nu}$$

$$\mathcal{O}'_{\Phi,3} = \frac{1}{\Lambda^2}\frac{1}{3}(\Phi^\dagger\Phi - v^2/2)^3$$



$$\mathcal{O}_{Vq} = \frac{1}{\Lambda^2}\bar{q}\Phi(\not{D}\Phi)q$$



Couplings of new states to the longitudinal / transversal diboson system

	$J=0$	$J=1$	$J=2$
$I=0$	σ^0 (Higgs singlet?)	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 ?)	—	$t^{\pm\pm}, t^\pm, t^0$

Different power counting for weakly and strongly interacting theories

$$\frac{c_i}{\Lambda} \sim \frac{g}{4\pi\Lambda} \quad \text{vs.} \quad \frac{c_i}{\Lambda} \sim \frac{g}{\Lambda}$$