(Mostly) Model-Independent Searches for New Physics in Vector Boson Scattering

Jürgen R. Reuter, DESY

work with A. Alboteanu, C. Fleper, W. Kilian, T. Ohl, M. Sekulla

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US Snowmass Summer Study 1310.6708,1309.7890,1307.8180,
JHEP 0811.010 [0806.4145], EPJC48(06)353 [hep-ph/0604048], 1607.03030 [tbp in EPJC]

Why [EW] vector boson scattering ?

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

1. Nature of Electroweak Symmetry Breaking
2. Does the H(125) fulfill the US-fermion/Europe-boson rule?
3. Is the *H*(125) the only resonance in the system of EW vector bosons?
4. How do EW vector bosons scatter? (true heart of weak interactions)
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- Specific models: Compositeness / Little Higgs / Twin Higgs / [(N)MSSM]
- Flavor: small mixing with SM fermions $\Longrightarrow$ Drell-Yan might be suppressed
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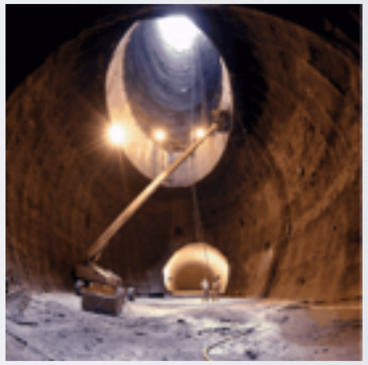

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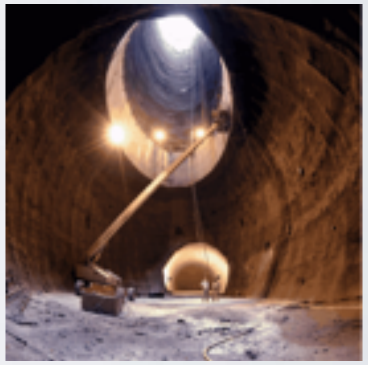

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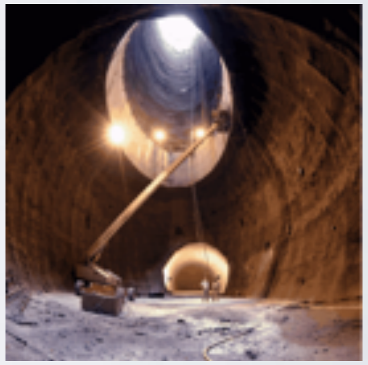

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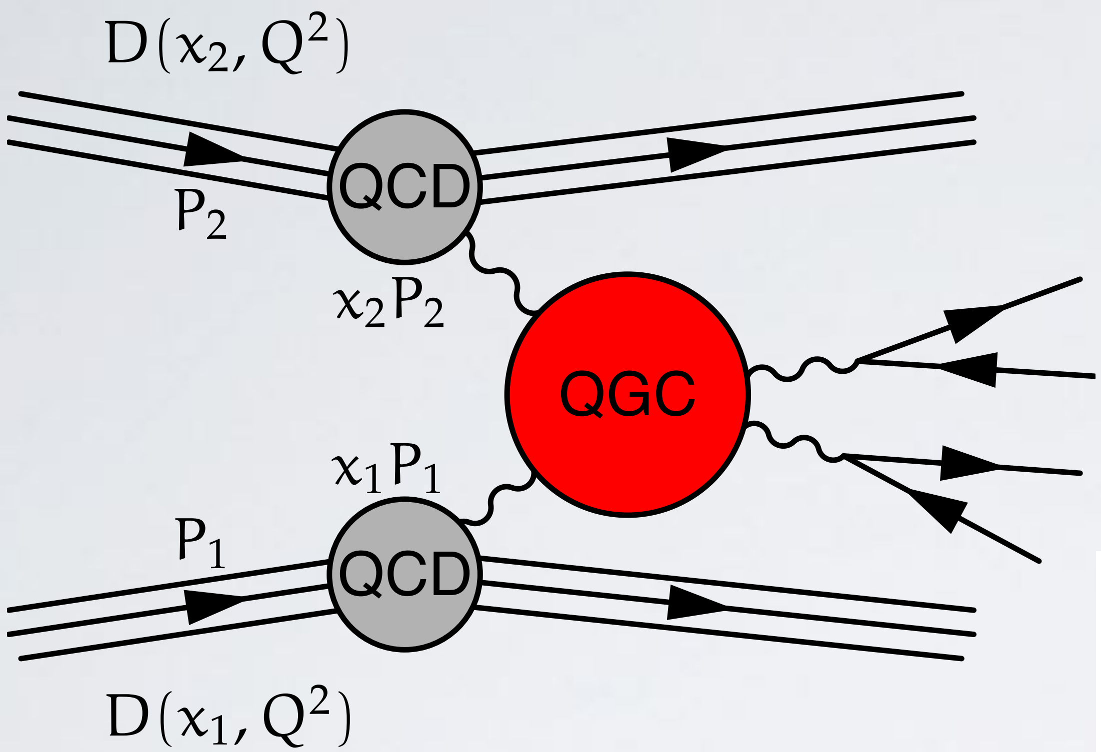
Exploration of E-frontier → look for heavy objects, including high-mass $V_L V_L$ scattering:
❑ requires as much integrated luminosity as possible (cross-section goes like 1/s)

F. Gianotti, 01/2014

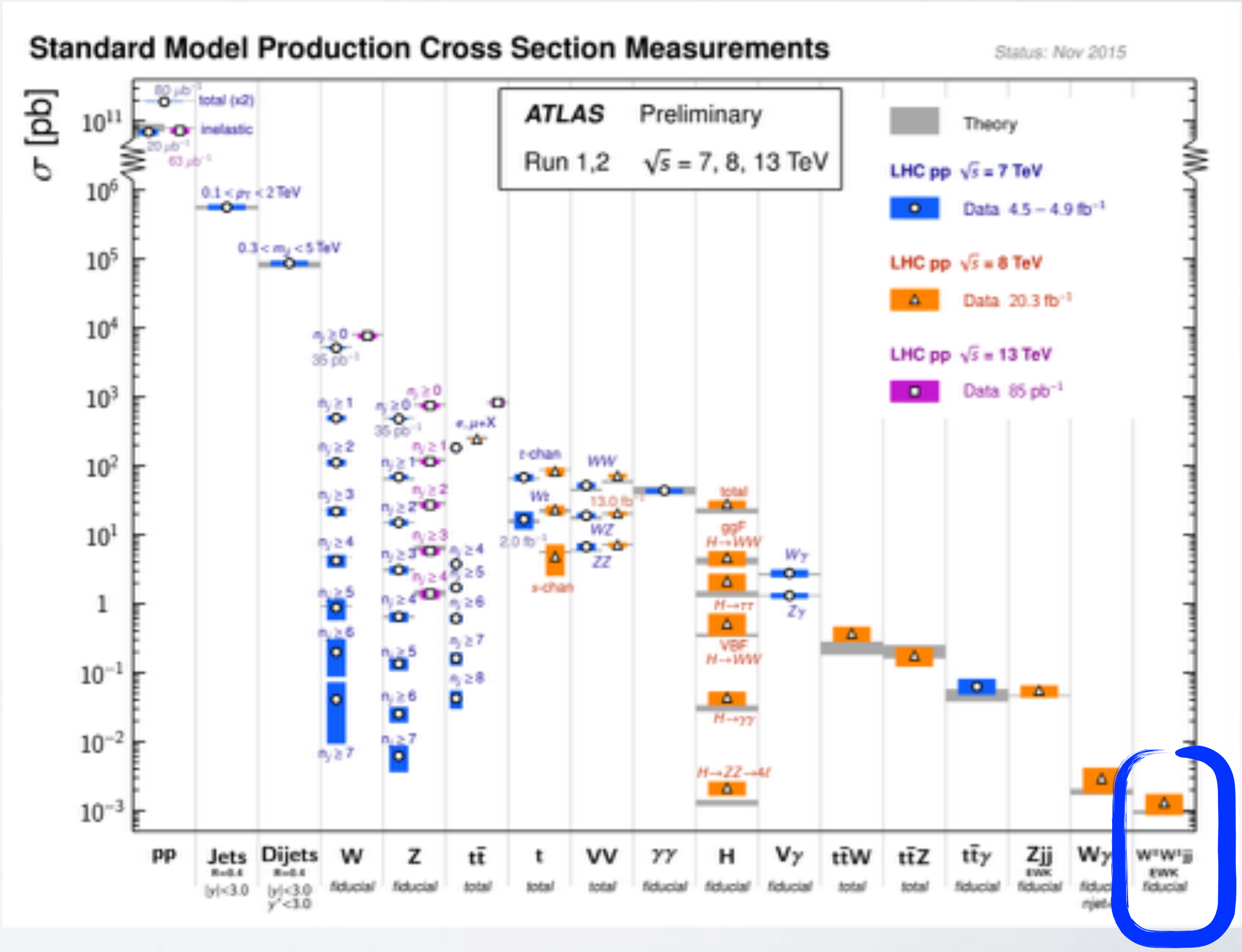
Anatomy of Vector Boson Scattering (VBS)

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



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

LHC Run I: First time evidence for VBS

- Evidence for W^+W^+jj (electroweak production)
  ATLAS PRL 113(2014)14, 141803 [1405.6241], 1611.02428 (PRD); CMS PRL 114(2015), 051801 [1410.6315]
- First limits on New Physics in pure electroweak gauge/Goldstone sector

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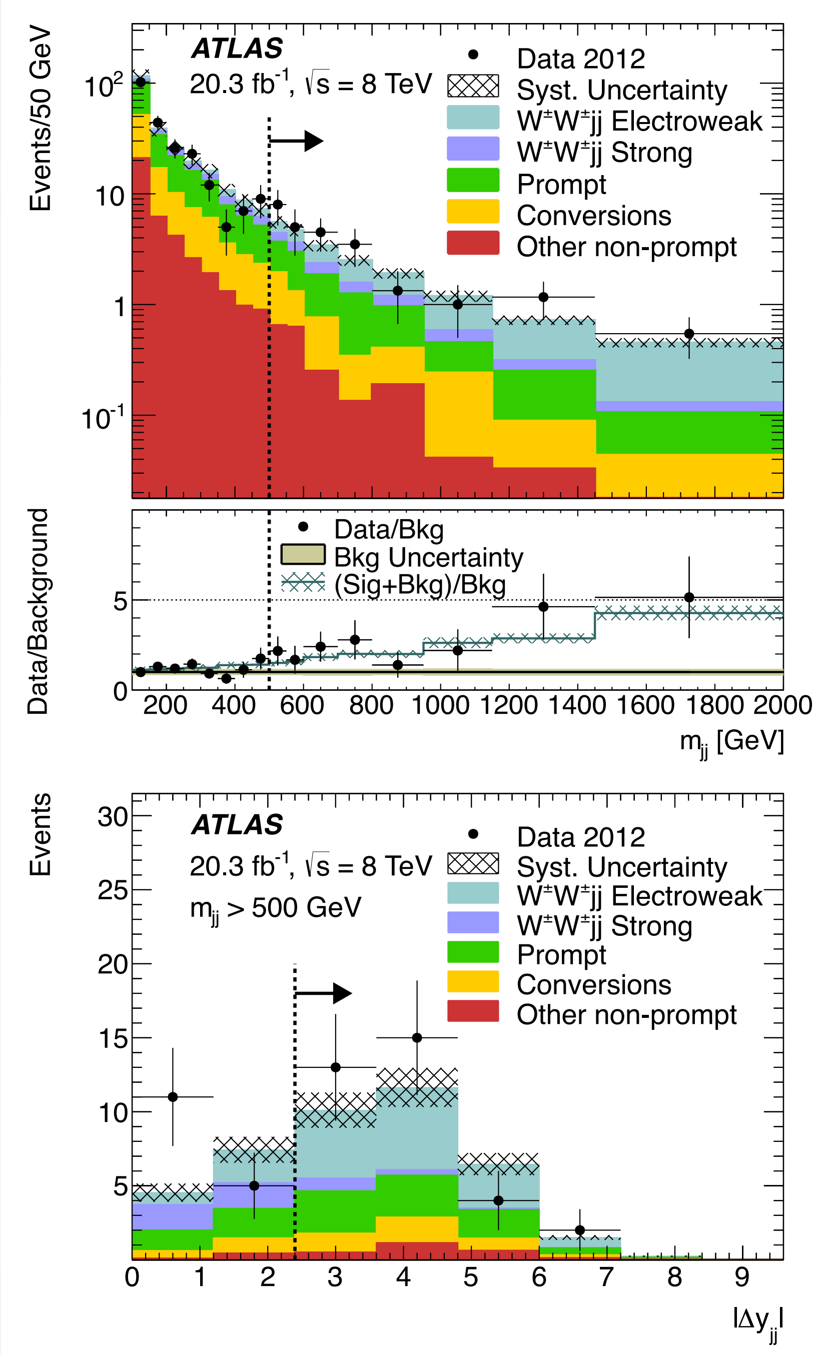

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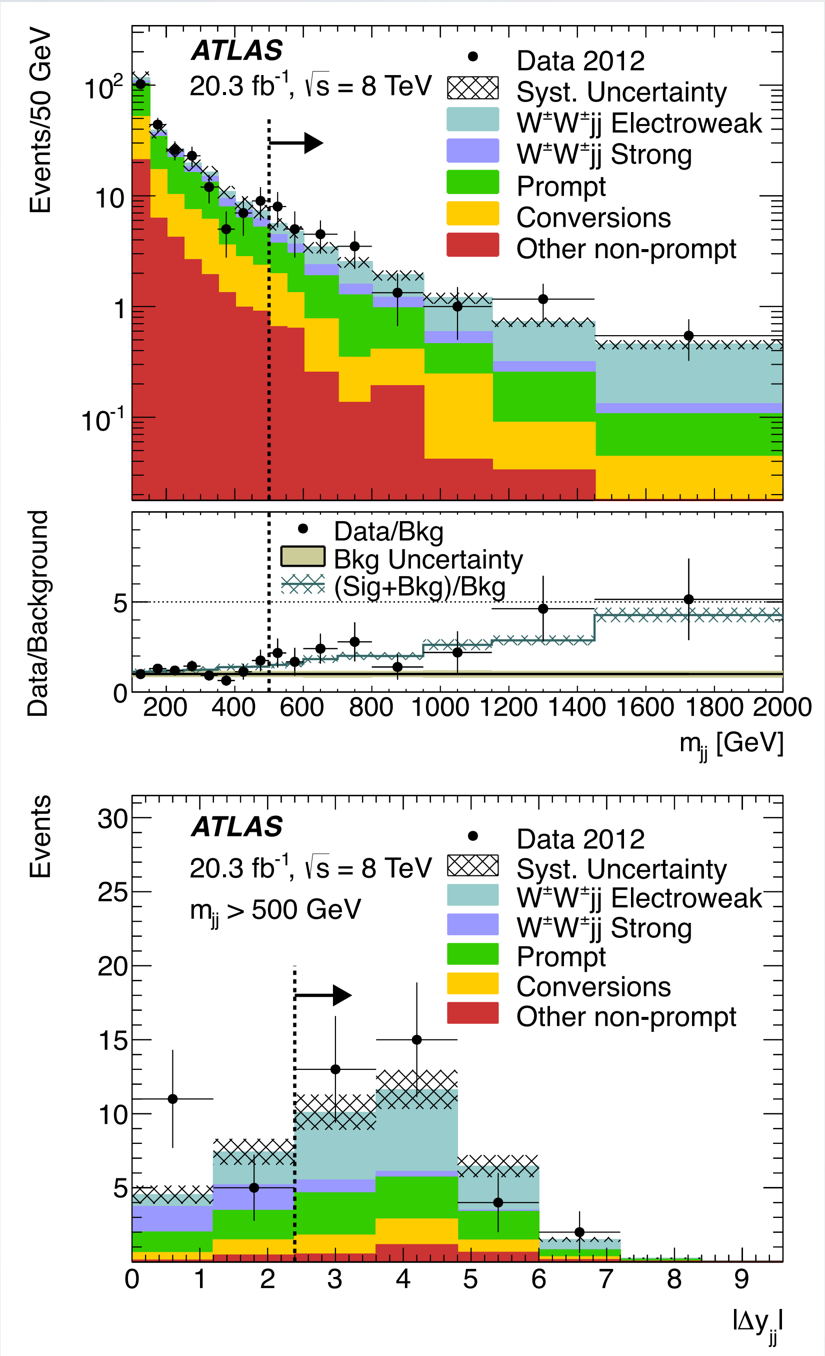

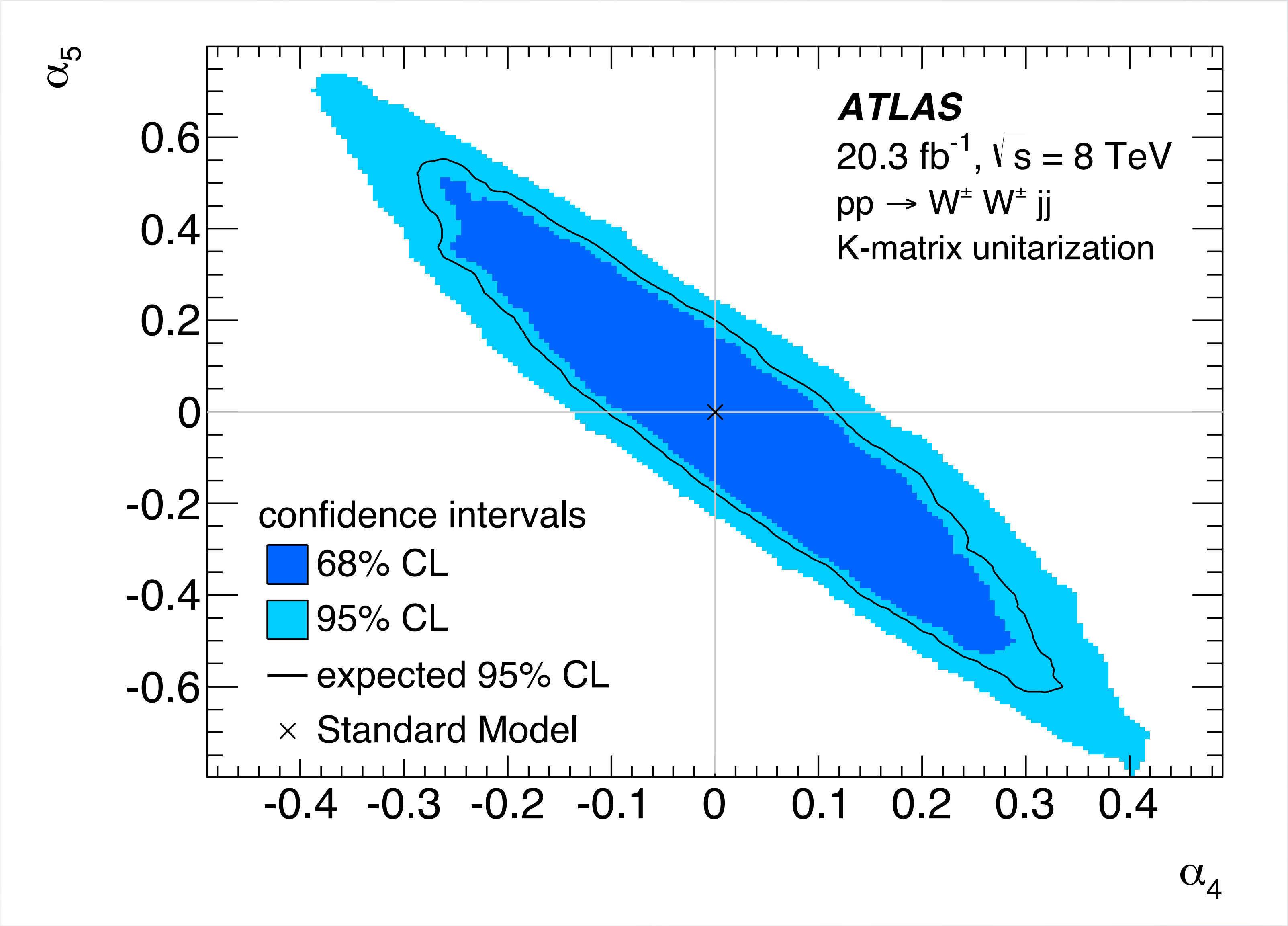

EFTs: Higher-dimensional operators

- 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
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  - 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

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

+ 25 four-fermion operators

Grzadkowski et al.

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

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

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

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

Affect the following electroweak couplings:

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

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

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

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

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

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

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	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)

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

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

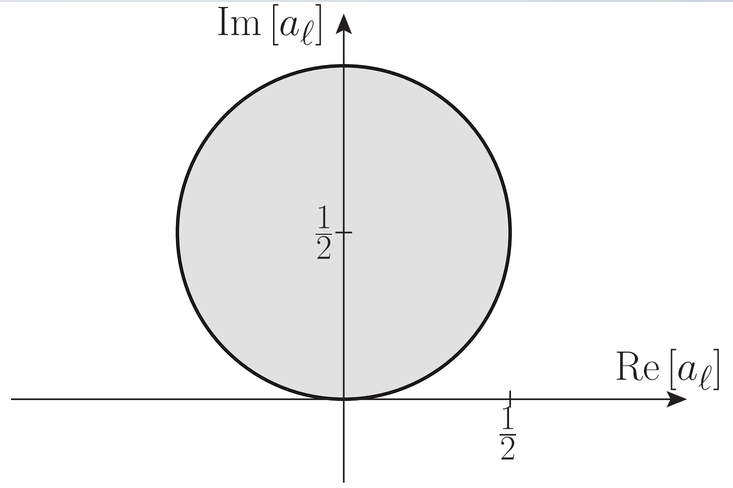
Unitarity in vector boson scattering

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

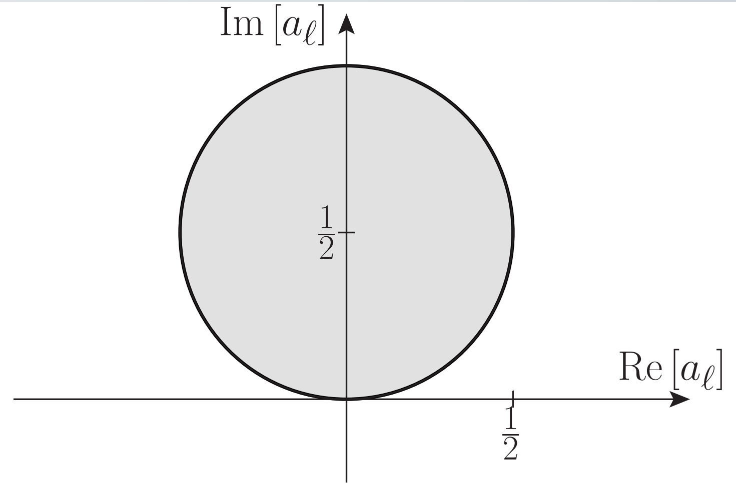
$$\sigma_{\text{tot}} = \text{Im}\left[\mathcal{M}_{ii}(t=0)\right]/s \qquad t = -s(1-\cos\theta)/2$$

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



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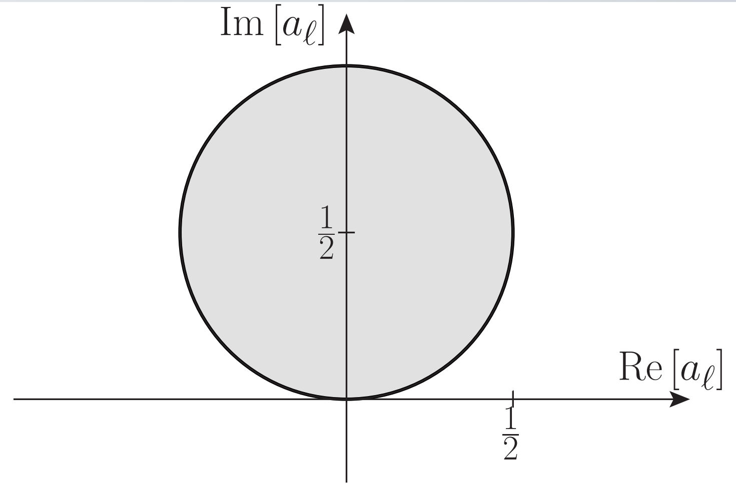
Unitarity in vector boson scattering



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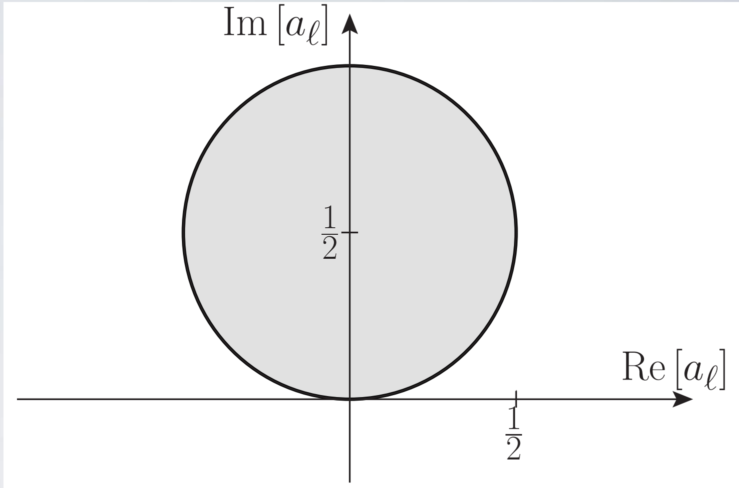
SM longitudinal isospin eigenamplitudes ($\mathcal{A}_{I,\text{spin}=J}$):

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

Unitarity in vector boson scattering



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Lee/Quigg/Thacker, 1973

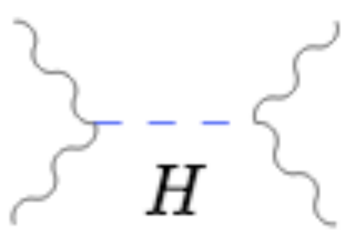
exceeds unitarity bound $|\mathcal{A}_{IJ}| \lesssim \frac{1}{2}$ at:

$$I = 0: \qquad E \sim \sqrt{8\pi}v = 1.2\,\text{TeV}$$

$$I = 1: \qquad E \sim \sqrt{48\pi}v = 3.5\,\text{TeV}$$

$$I = 2: \qquad E \sim \sqrt{16\pi}v = 1.7\,\text{TeV}$$

Higgs exchange:

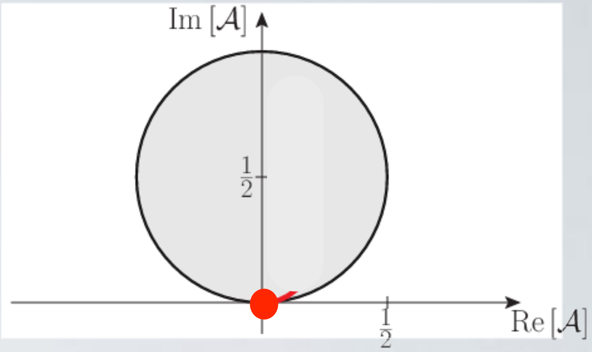


$$\mathcal{A}(s,t,u) = -\frac{M_H^2}{v^2}\frac{s}{s-M_H^2}$$

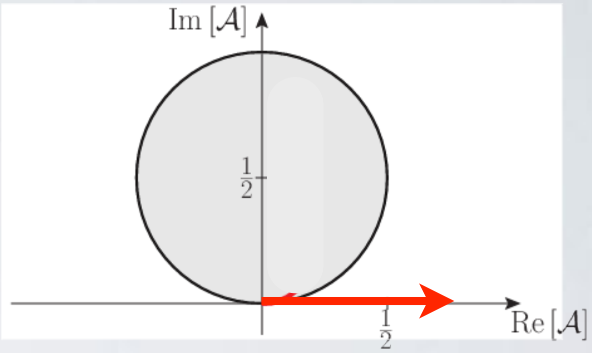
Unitarity: $M_H \lesssim \sqrt{8\pi}v \sim 1.2\,\text{TeV}$

Scenarios for New Physics in VBS

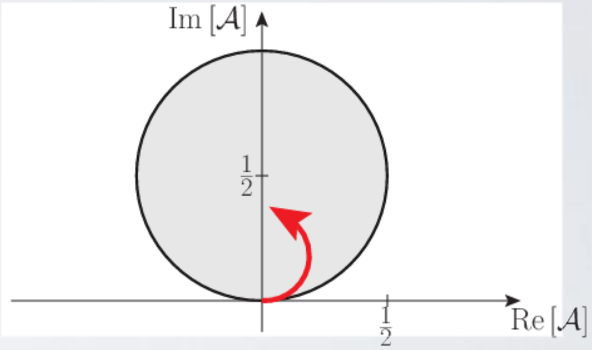
1. SM or weakly coupled physics (e.g. 2HDM): amplitude remains close to origin



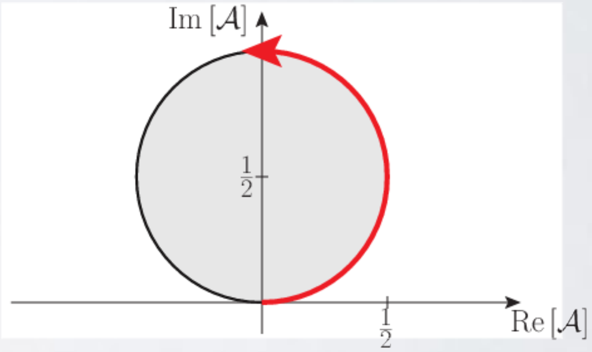
2. Rising amplitude (at least one dim-8 operator): rise beyond unitarity circle [unphys.], strongly interacting regime



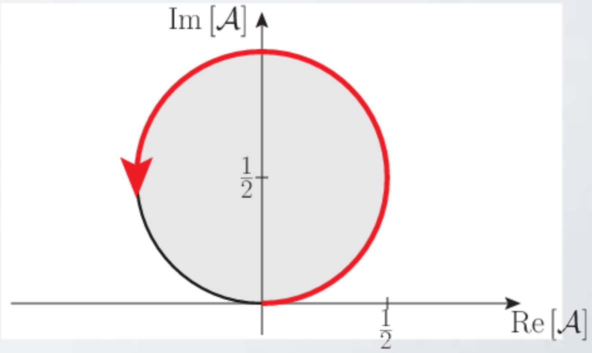
3. Inelastic channel opens (form-factor description): new channels open out, multi-boson final states



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



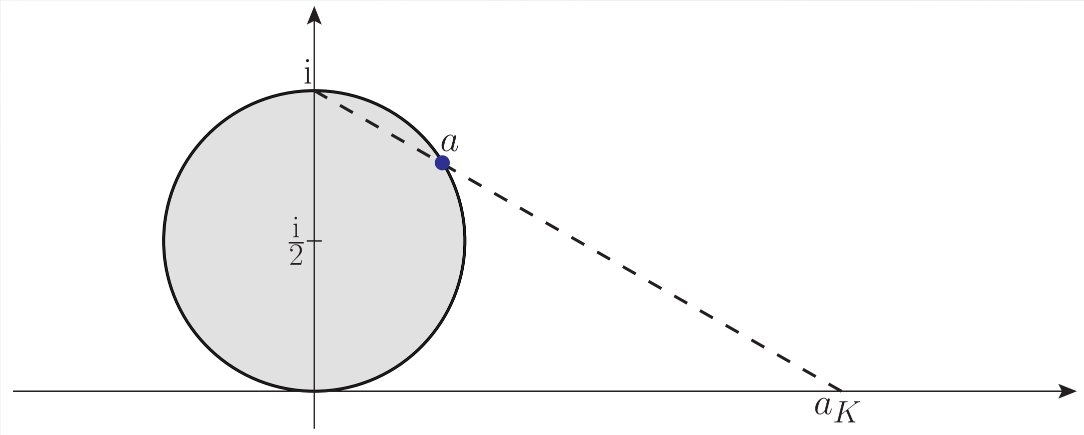
5. New resonance: amplitude turns over



Different unitarity projections

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

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



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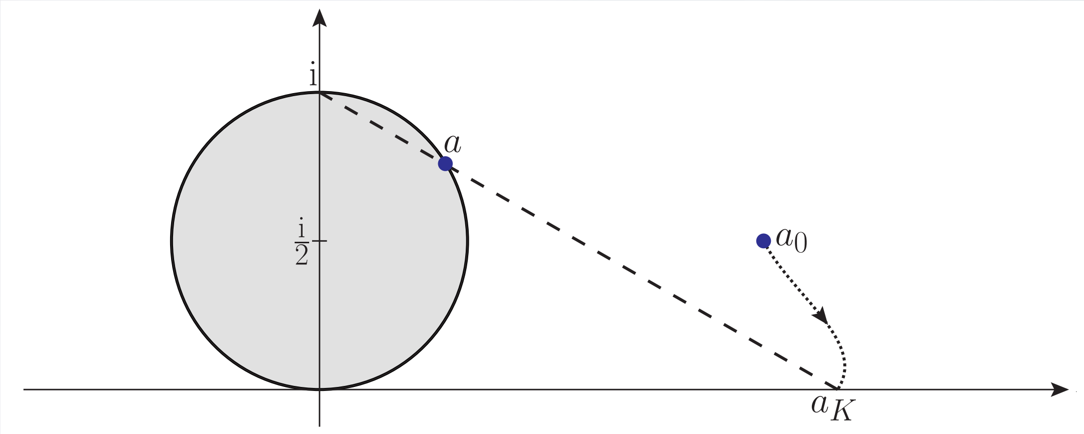

- Stereographic projection to Argand circle
- Formalism does a partial resummation of perturbative series
- need to construct (orig.) *K*-matrix as self-adjoint intermediate operator

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

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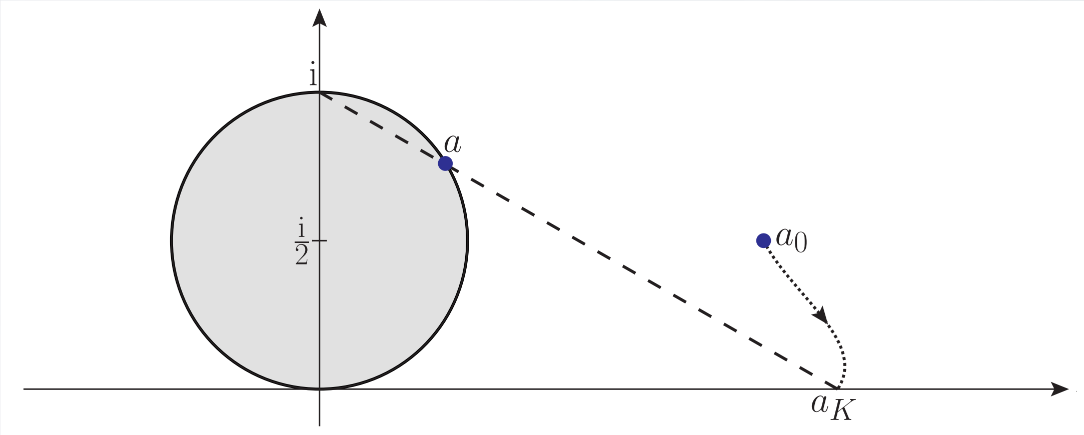

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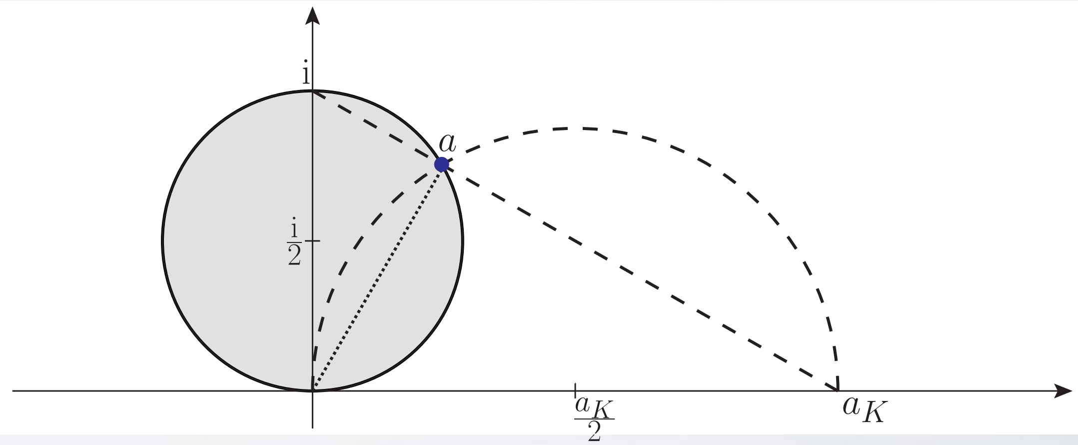
- Defined via $\left|a - \frac{a_K}{2}\right| = \frac{a_K}{2} \quad \Rightarrow \quad a = \frac{1}{\mathrm{Re}\left(\frac{1}{a_0}\right) - \mathrm{i}}$



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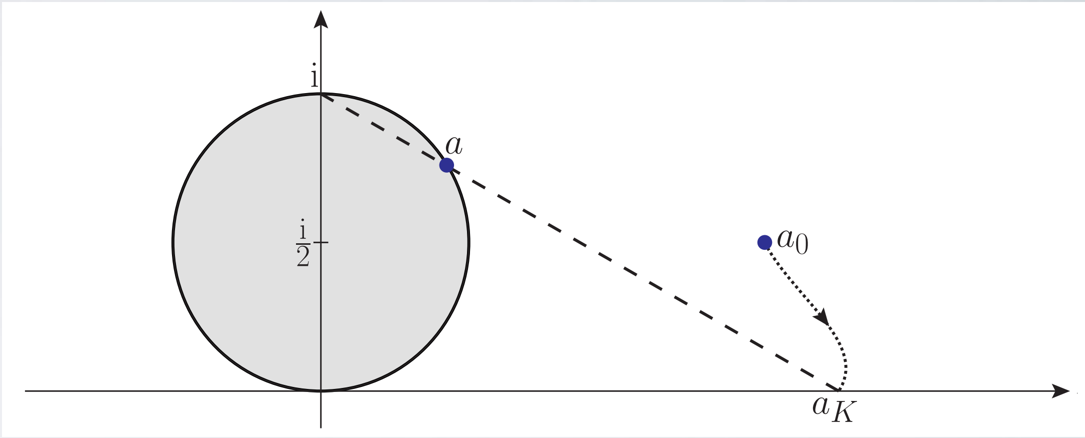

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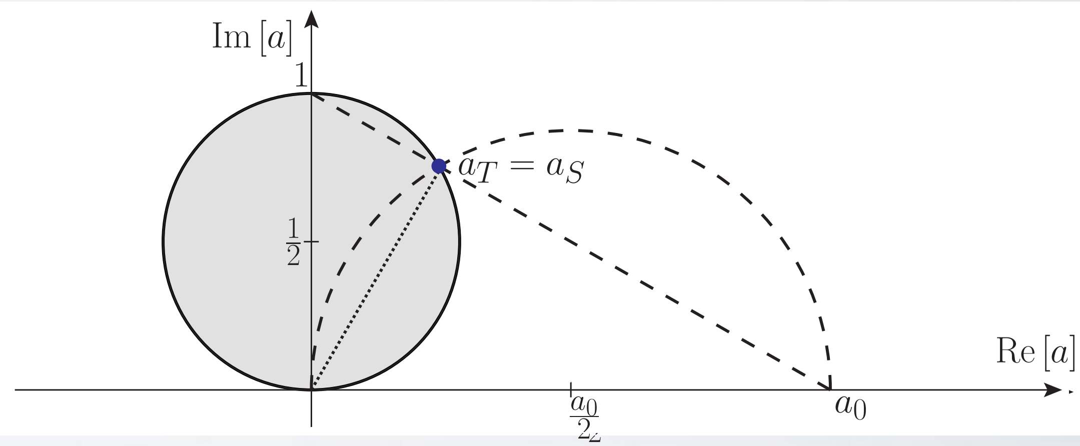

- Identical to *K* matrix for real amplitudes
- Points on Argand circle left invariant
- Does not rely on perturbation theory
- Applicable for amplitudes with imaginary parts (models with resonances)

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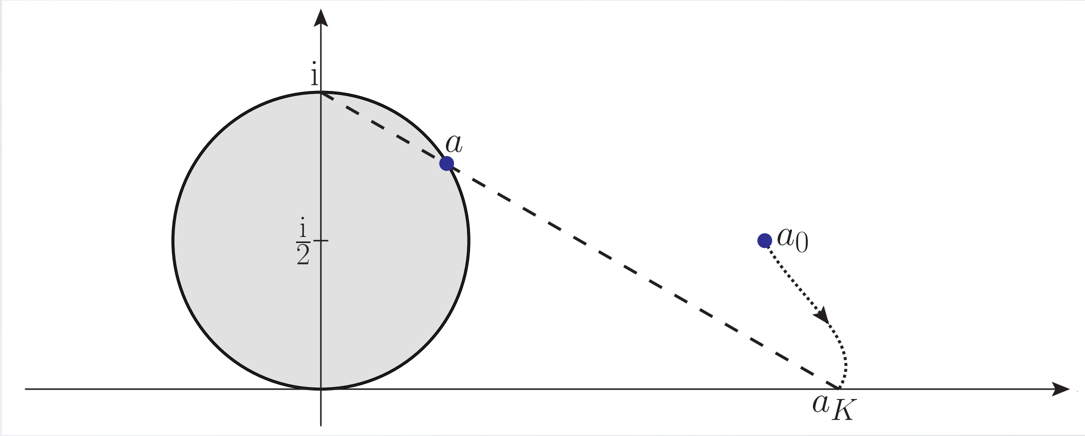
- Stereographic projection to Argand circle

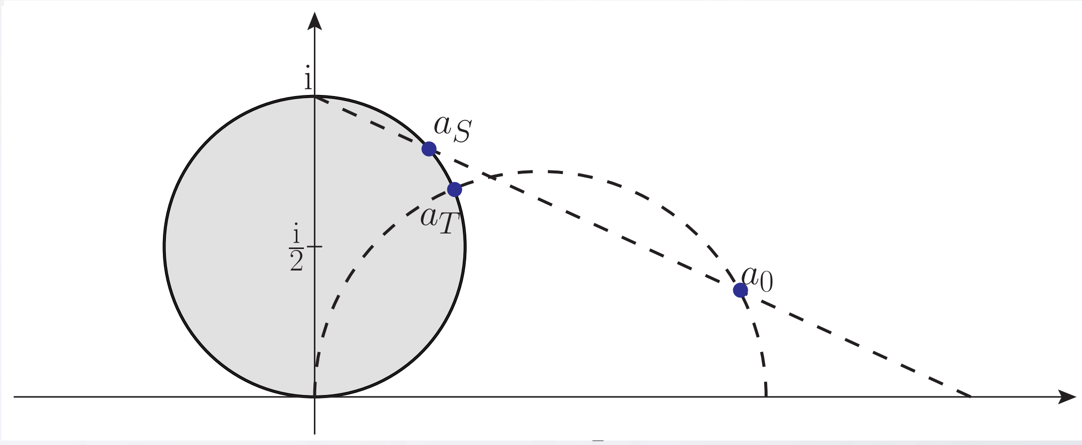
$$S = \frac{1+iK/2}{1-iK/2} \qquad a_K(s) = \frac{a(s)}{1-\mathrm{i}a(s)}$$



- 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)

The WHIZARD Event Generator

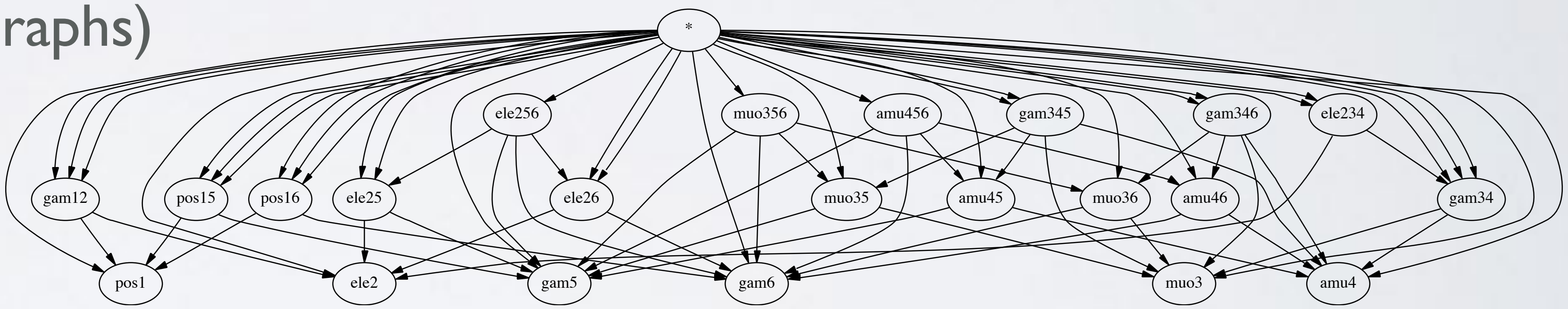
WHIZARD v2.4.0 (28 Nov. 2016) http://whizard.hepforge.org <whizard@desy.de>

WHIZARD Team: *Wolfgang Kilian, Thorsten Ohl, JRR, Simon Braß/Bijan Chokoufé/Christian Fleper/Vincent RotheMarco Sekulla/So Young Shim/Florian Staub/Christian Weiss/Zhijie Zhao* + *2 Master*

EPJ C71 (2011) 1742

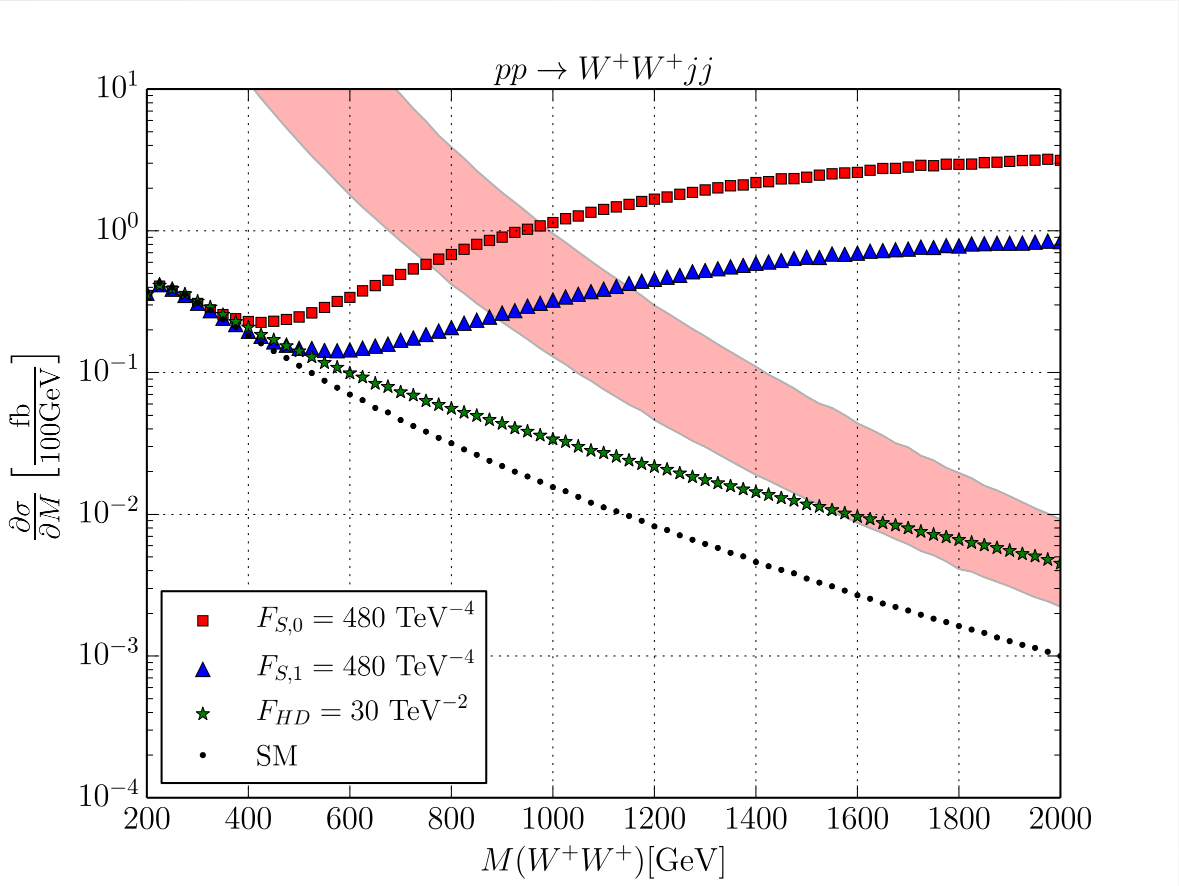
- Universal event generator for lepton and hadron colliders
- Modular package:
  - Phase space parameterization (resonances, collinear emission, Coulomb etc.)
  - O'Mega optimized matrix element generator (recursiveness via Directed Acyclical Graphs)

Ω



  - VAMP: adaptive multi-channel Monte Carlo integrator
  - CIRCE1/2: generator/simulation tool for lepton collider beam spectra
  - Lepton beam ISR — Kuraev/Fadin, 1986; Skrzypek/Jadach, 1991
  - Color flow formalism — Stelzer/Willenbrock, 2003; Kilian/Ohl/JRR/Speckner, 2011
  - NLO QCD — Chokoufe/Kilian/Lindert/Pozzorini/JRR/Weiss, 1609.03390

VBS diboson spectra



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

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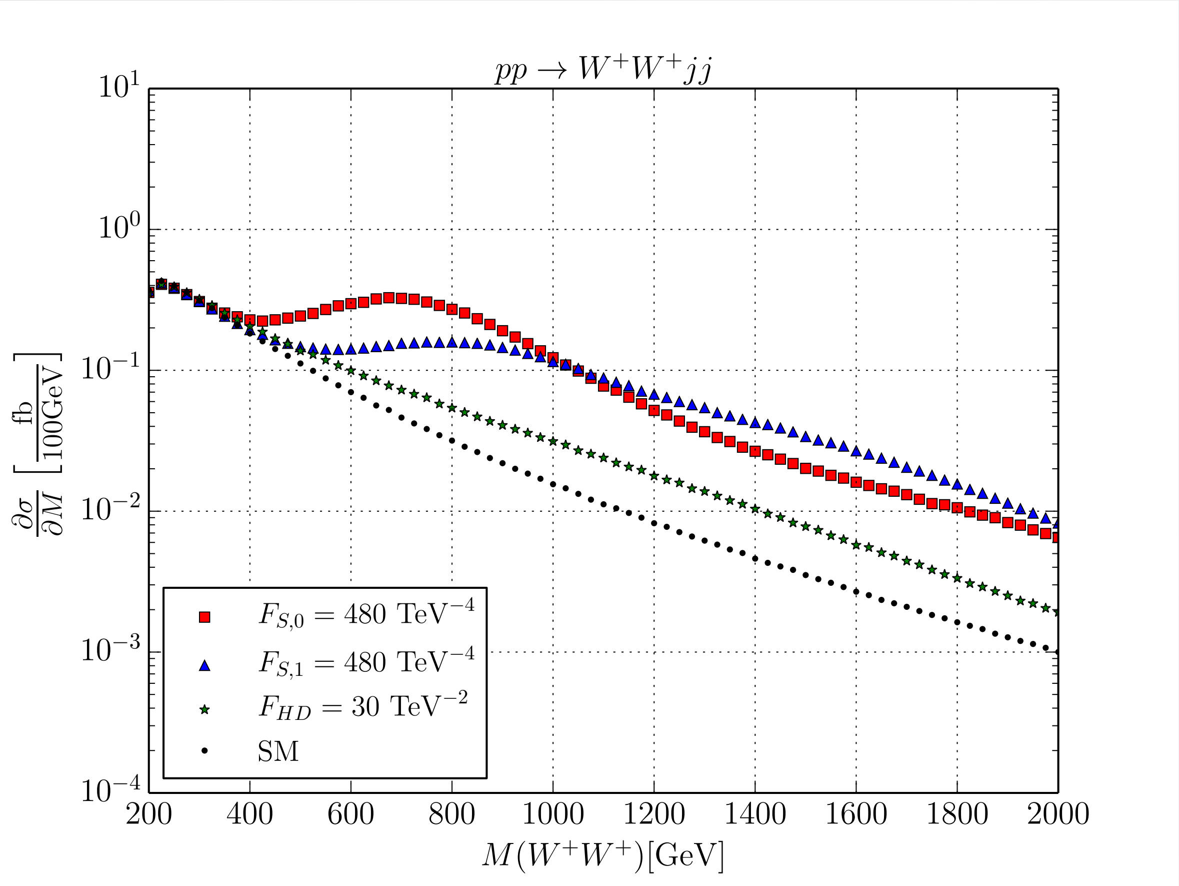

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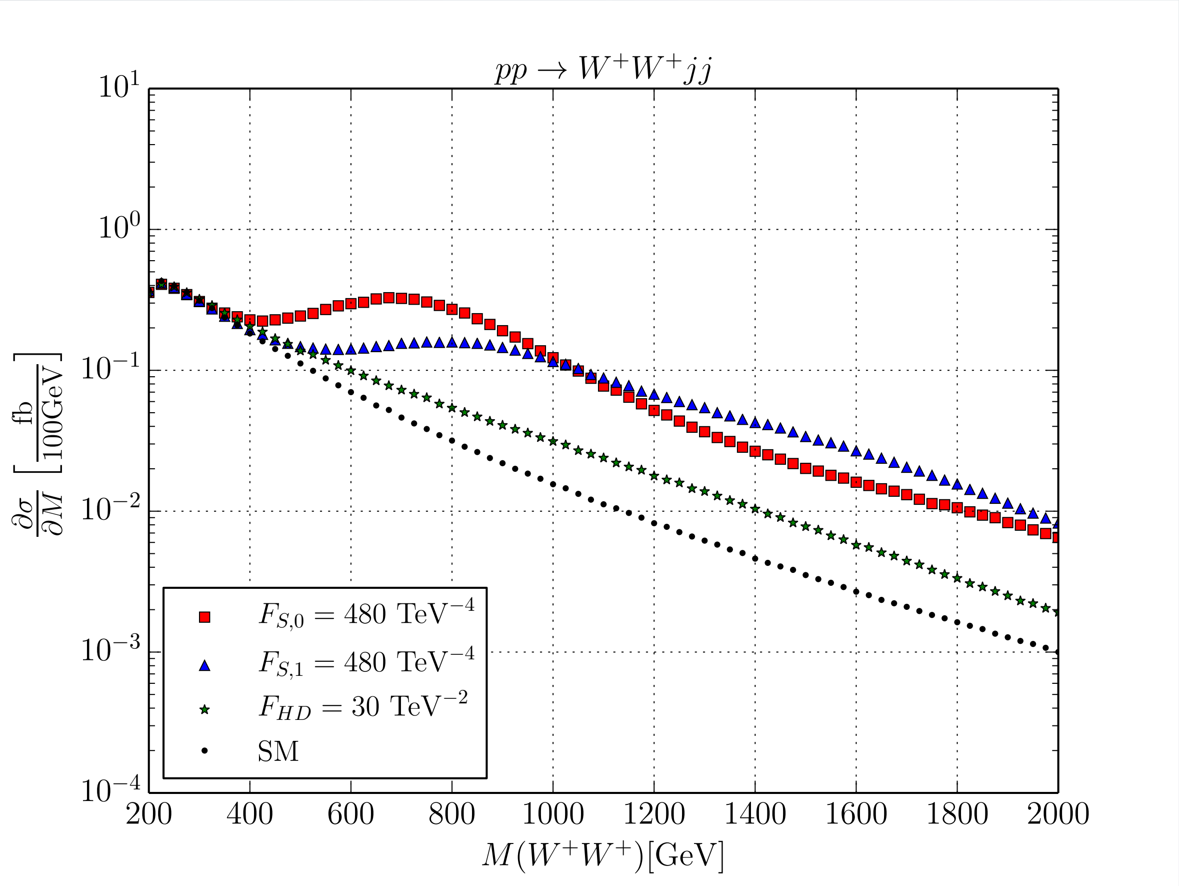

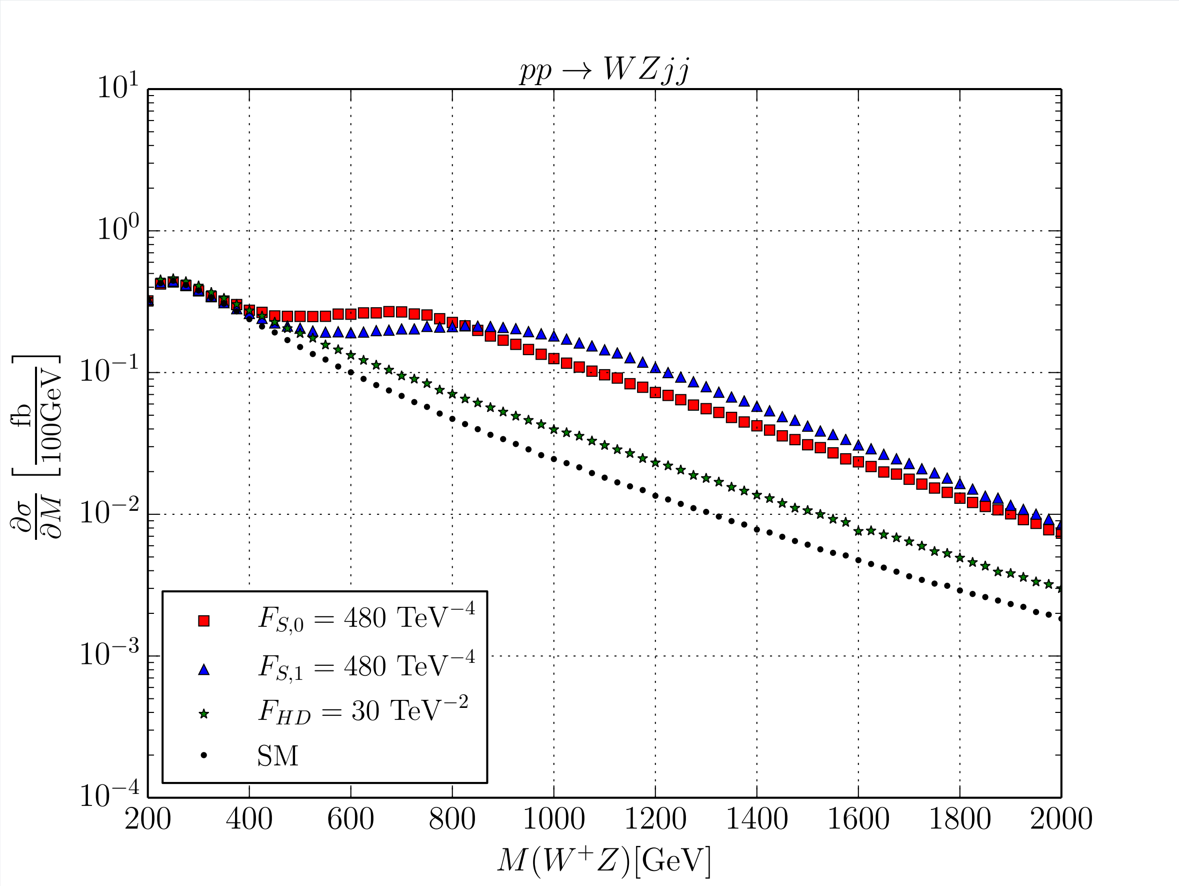

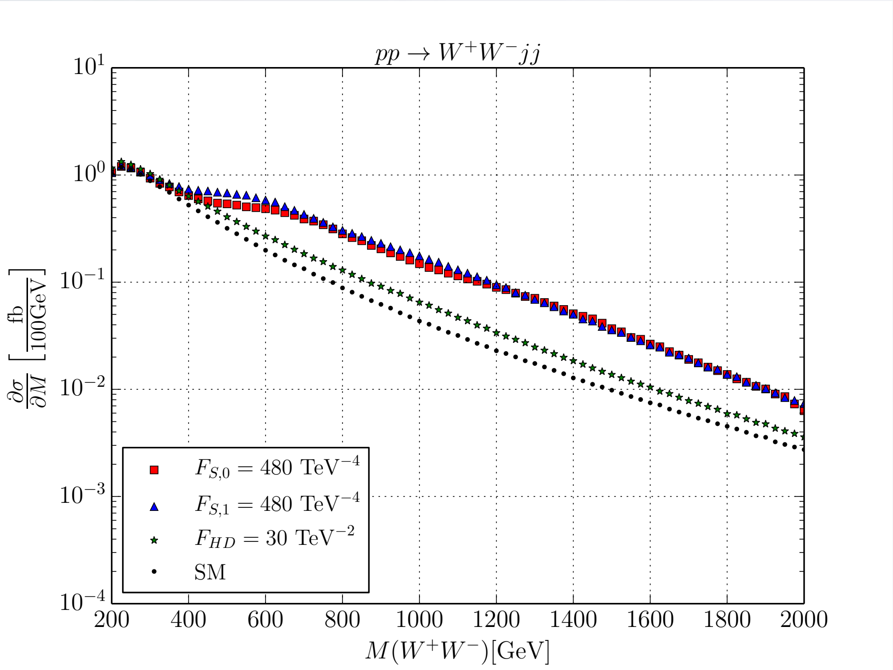

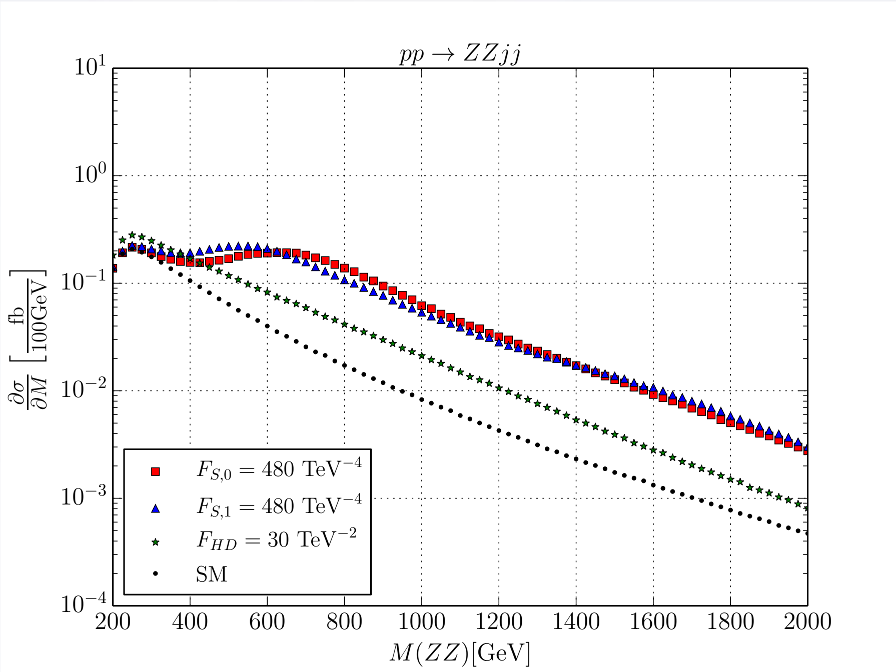

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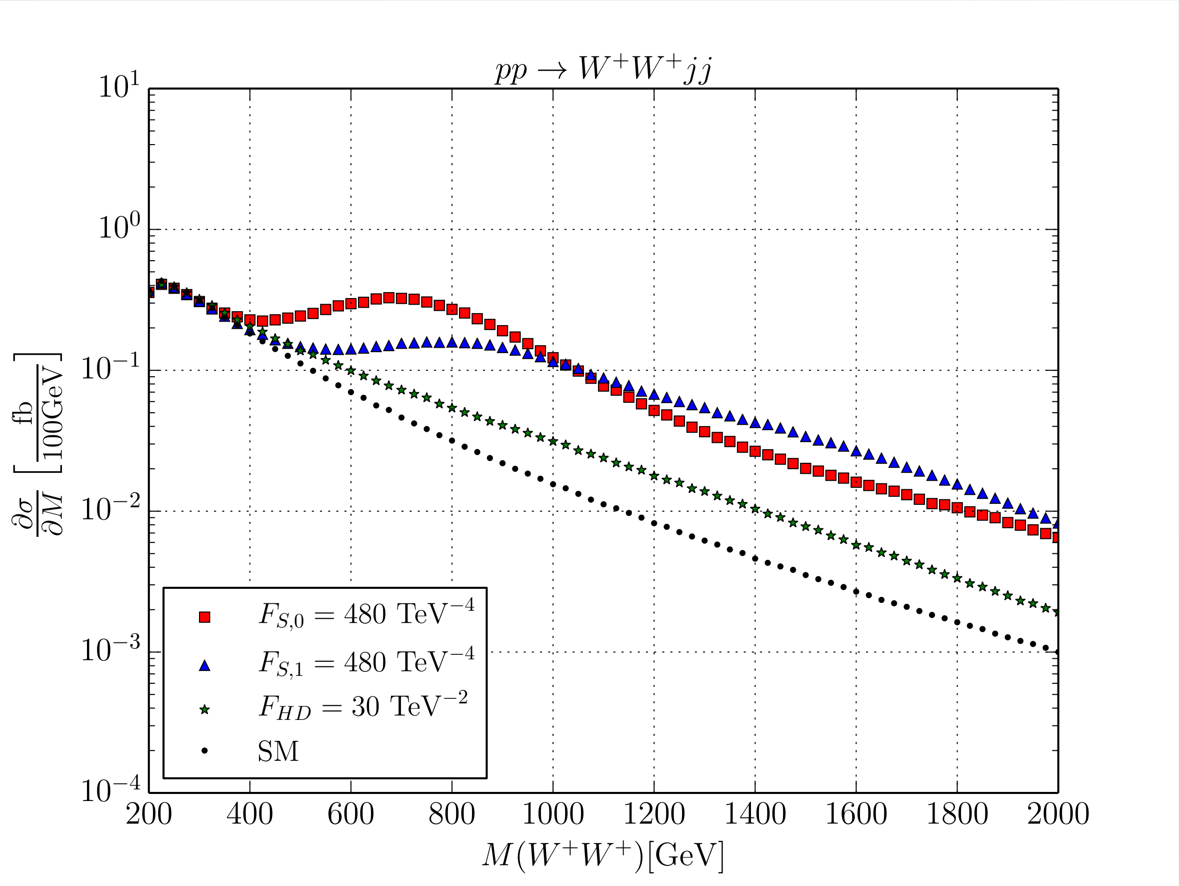

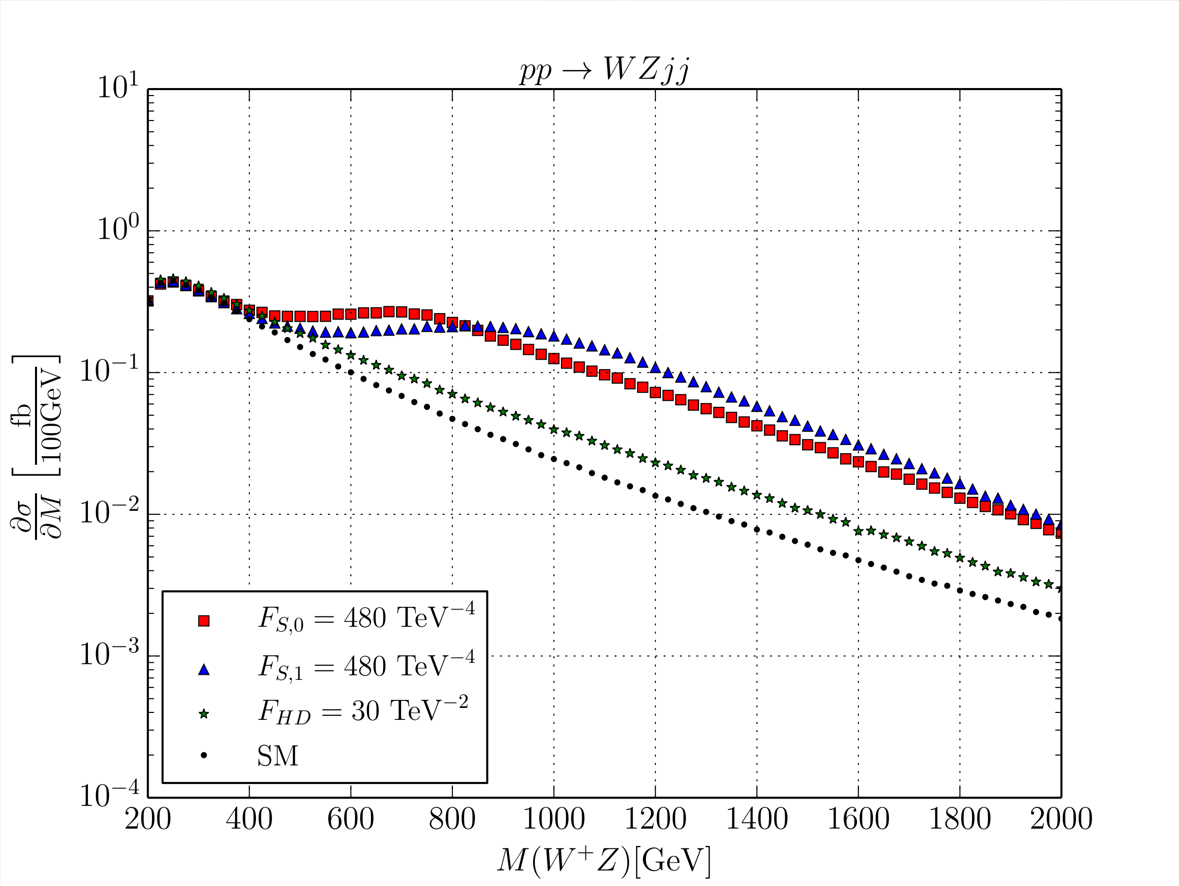

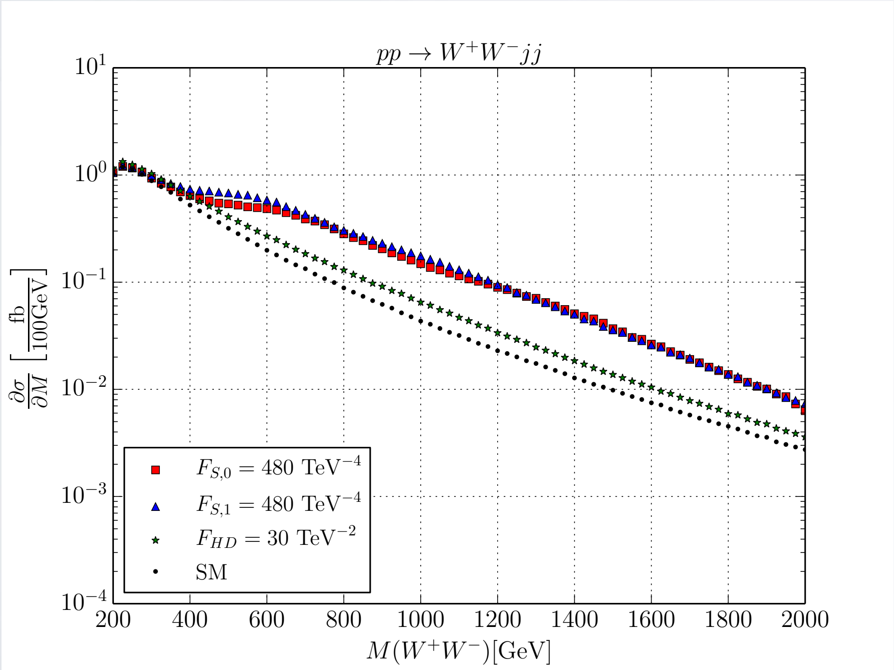

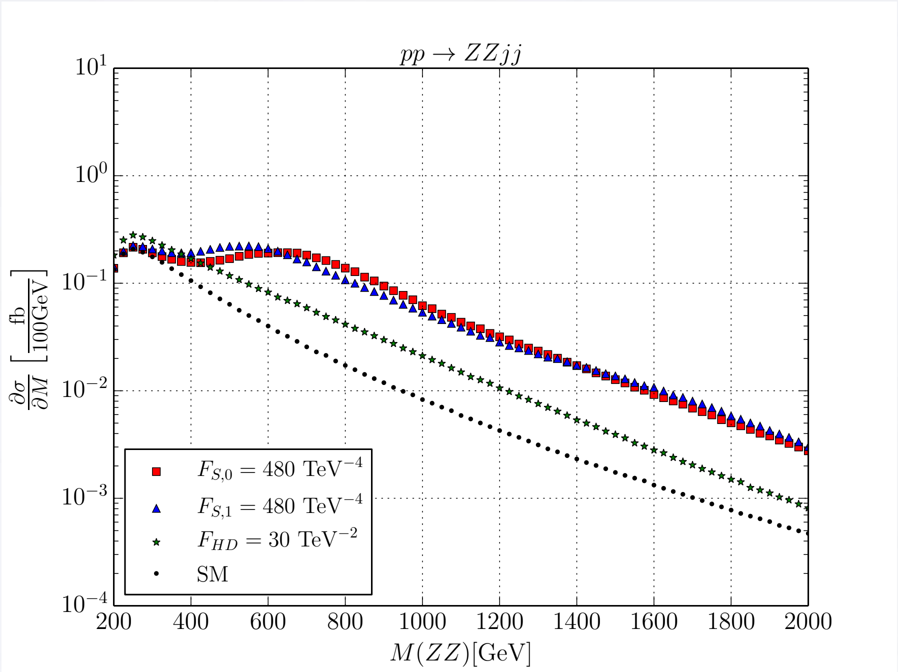

WWWW-Vertex:

$$\alpha_4 = \frac{f_{S,0}}{\Lambda^4}\frac{v^4}{8}$$
$$\alpha_4 + 2\cdot\alpha_5 = \frac{f_{S,1}}{\Lambda^4}\frac{v^4}{8}$$

WWZZ-Vertex:

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

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

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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]

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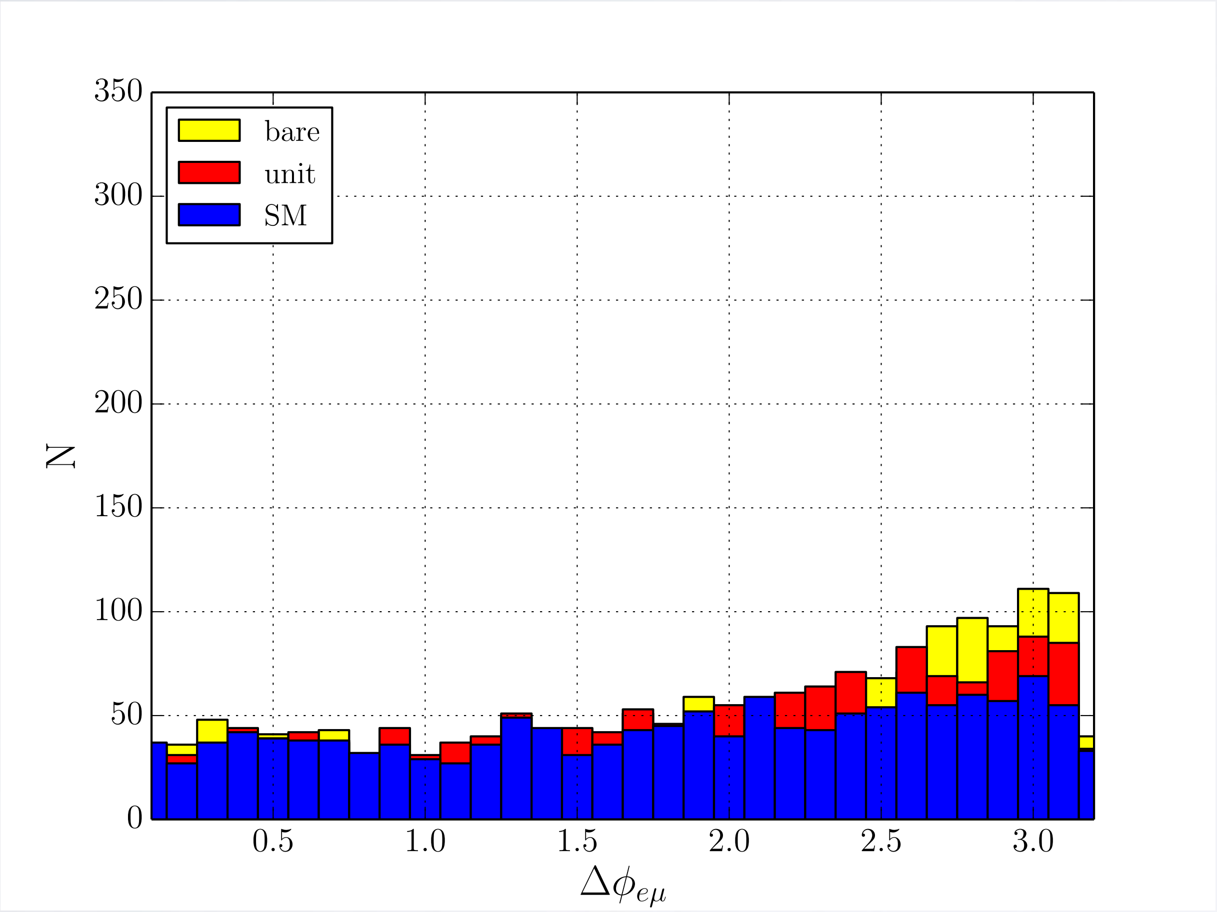

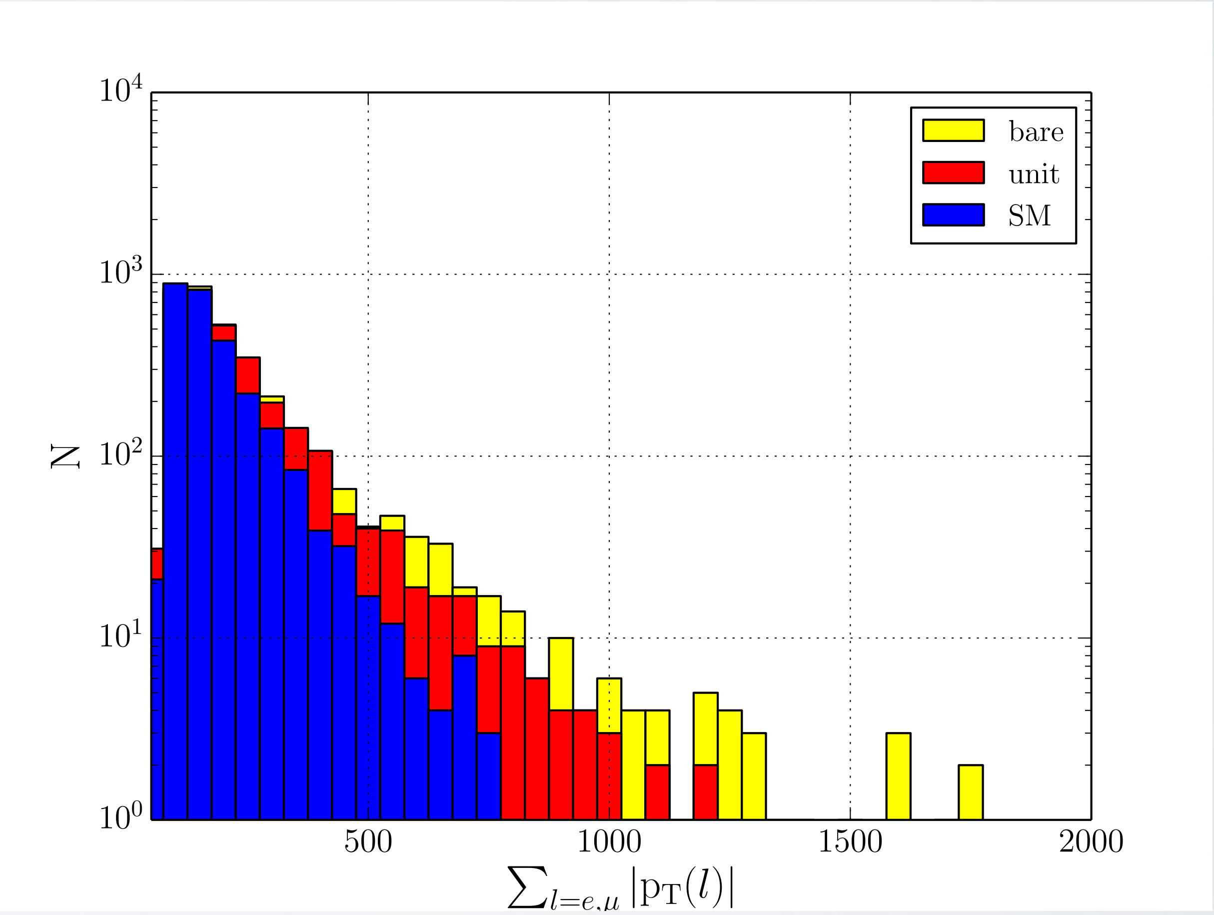

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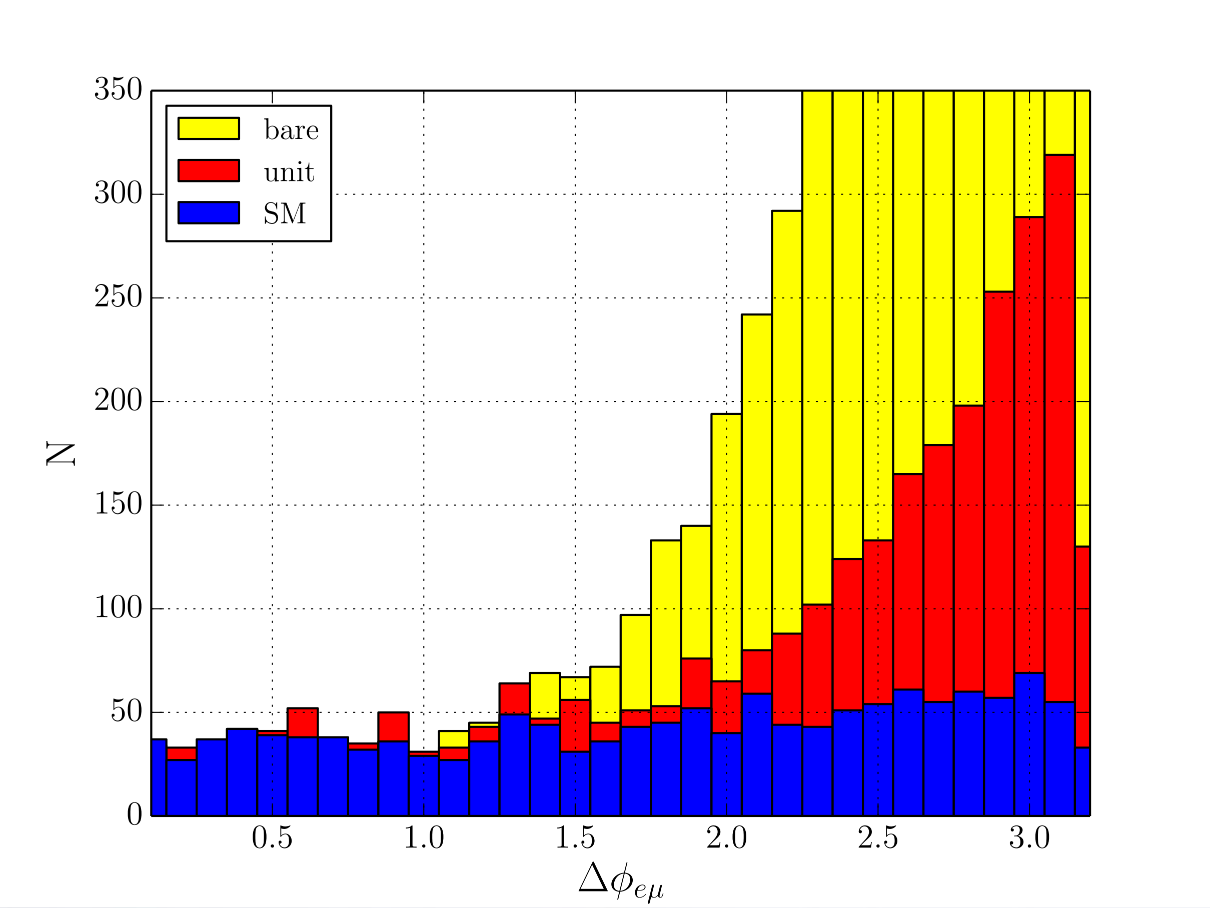

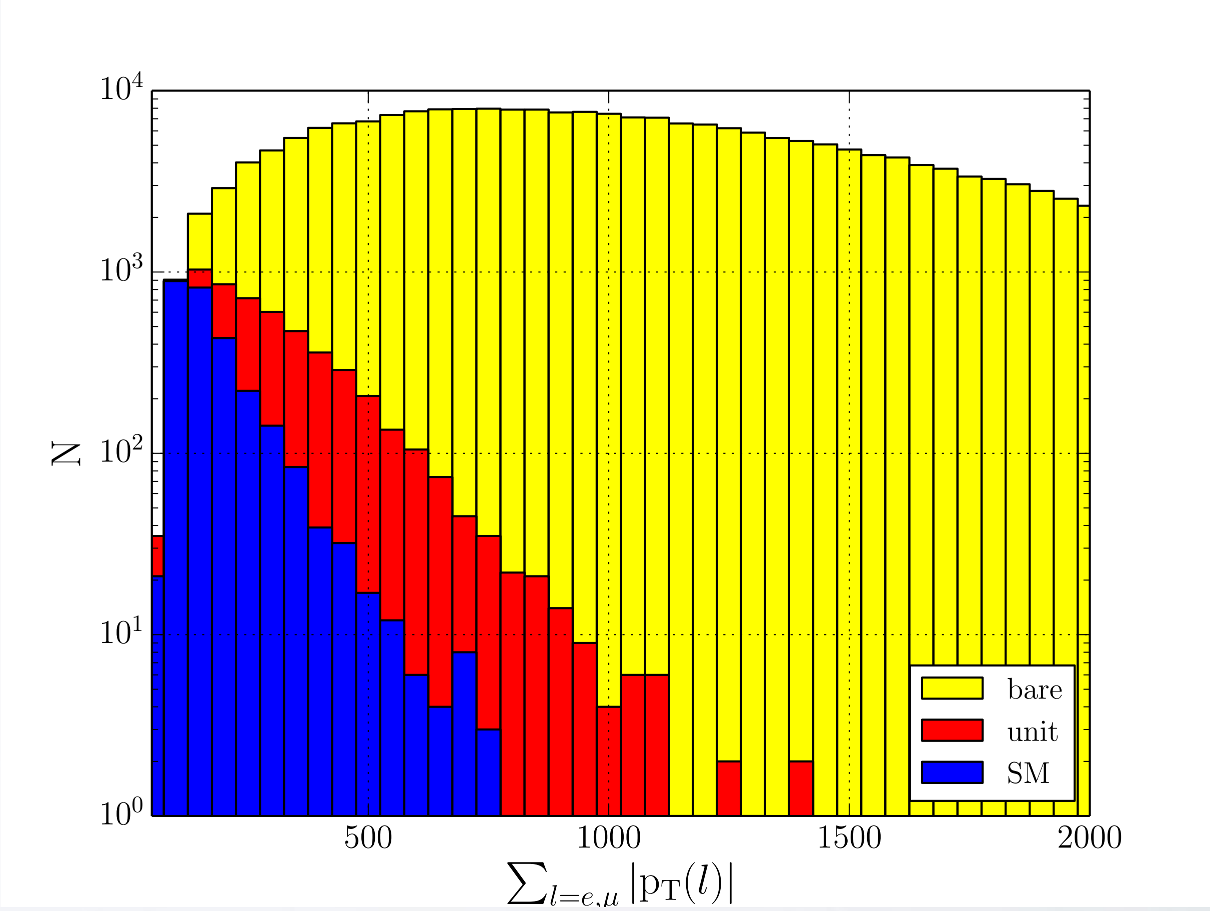

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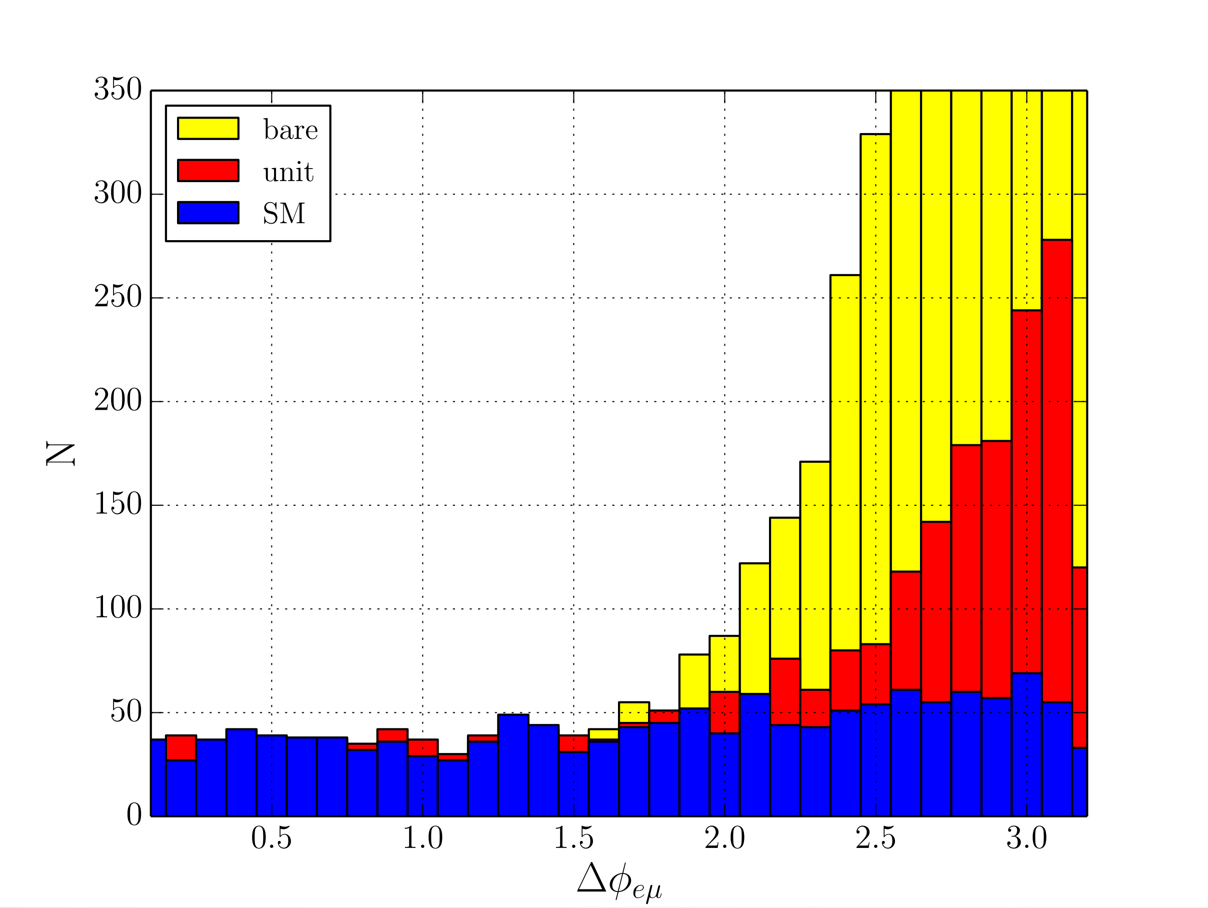

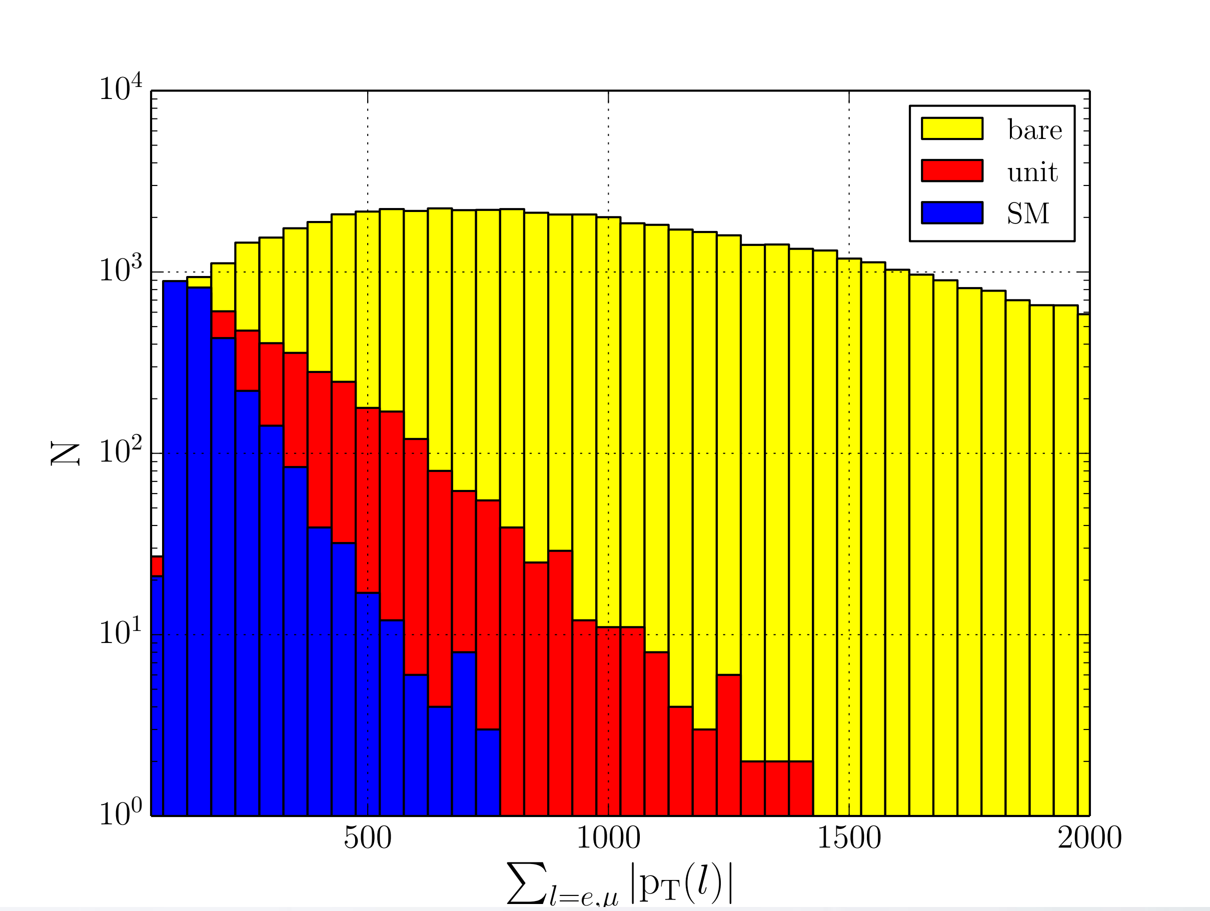

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Resonances: Quantum numbers & simplified models

- 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)

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...	...	...

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$\ldots$	$\ldots$	$\ldots$

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

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

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- Use Stückelberg formalism to make off-shell high-energy behavior explicit
- Introduce compensator fields $\Rightarrow$ no propagators with momentum factors
- Crucial for MCs

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  - $f^{\mu\nu}$: on-shell $f^{\mu\nu}$
  - ϕ: $\partial_\mu\partial_\nu f^{\mu\nu}$
  - A^μ: $\partial_\nu f^{\mu\nu}$
  - σ: $f^\mu_{\ \mu}$

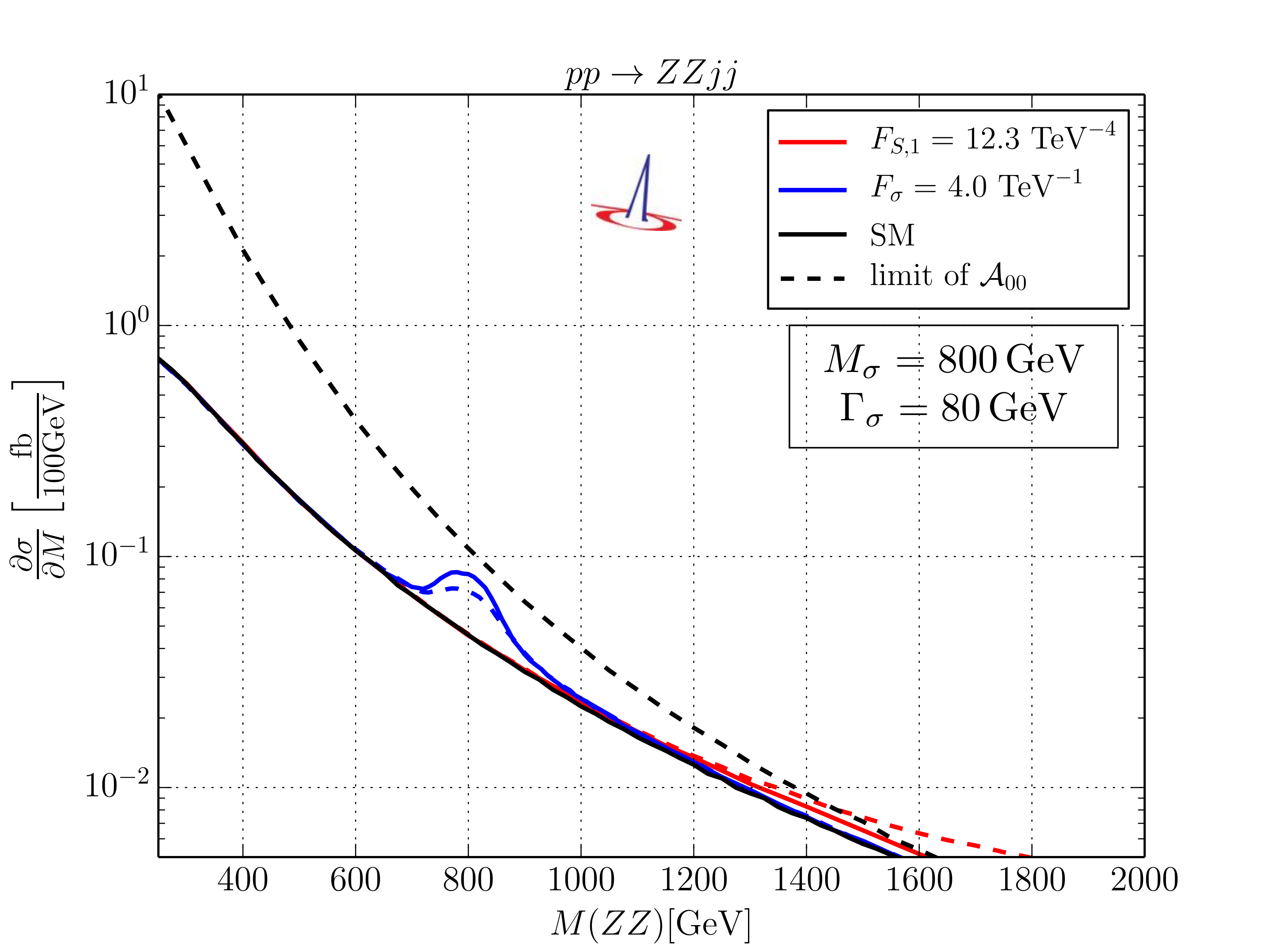
Gauge fixing: $\sigma = -\phi$

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

Comparison: Simplified Models & EFT

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

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



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- Tensor resonances better visible than scalars

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

$32\pi\Gamma/M^5$

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

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

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

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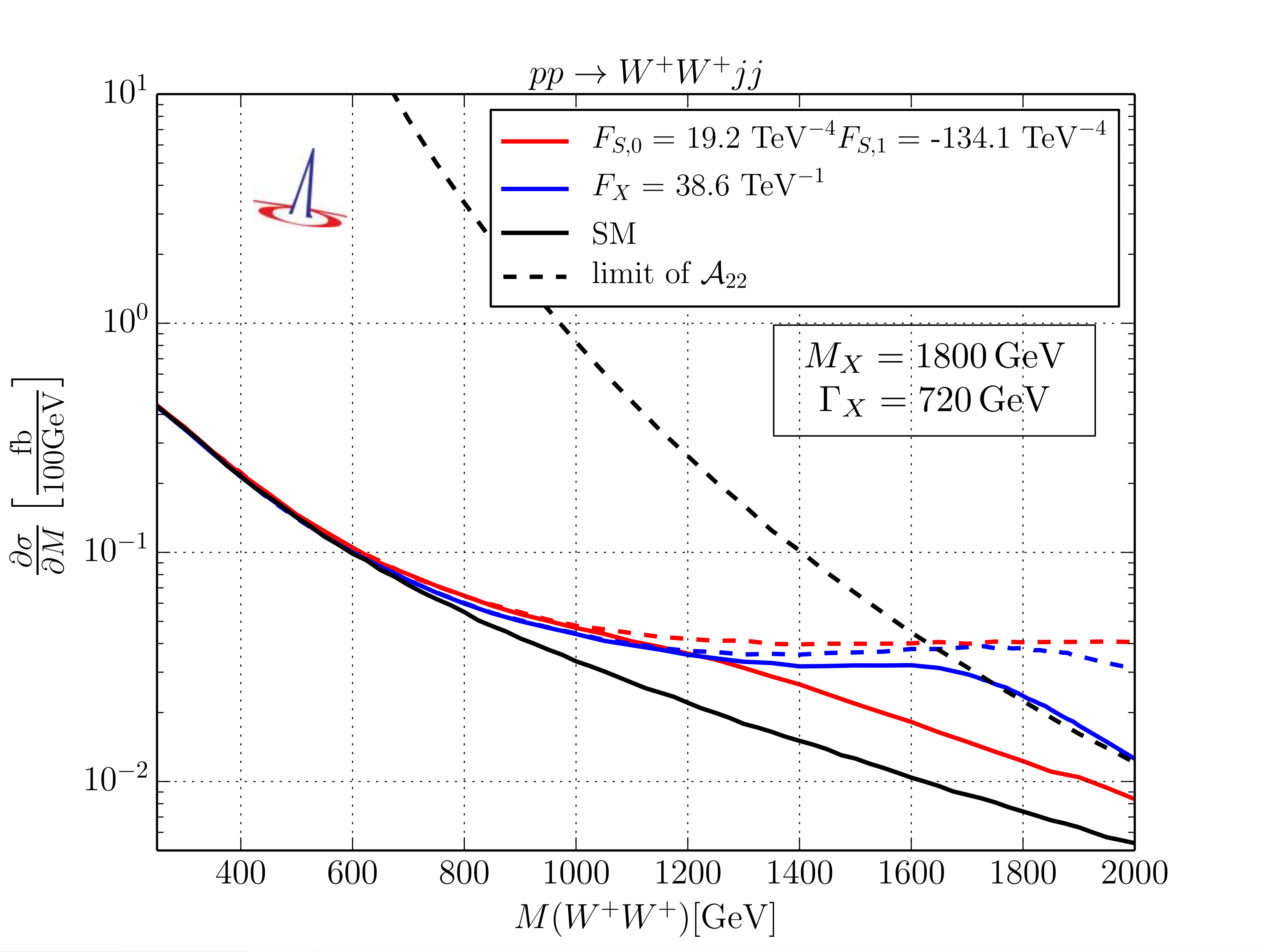

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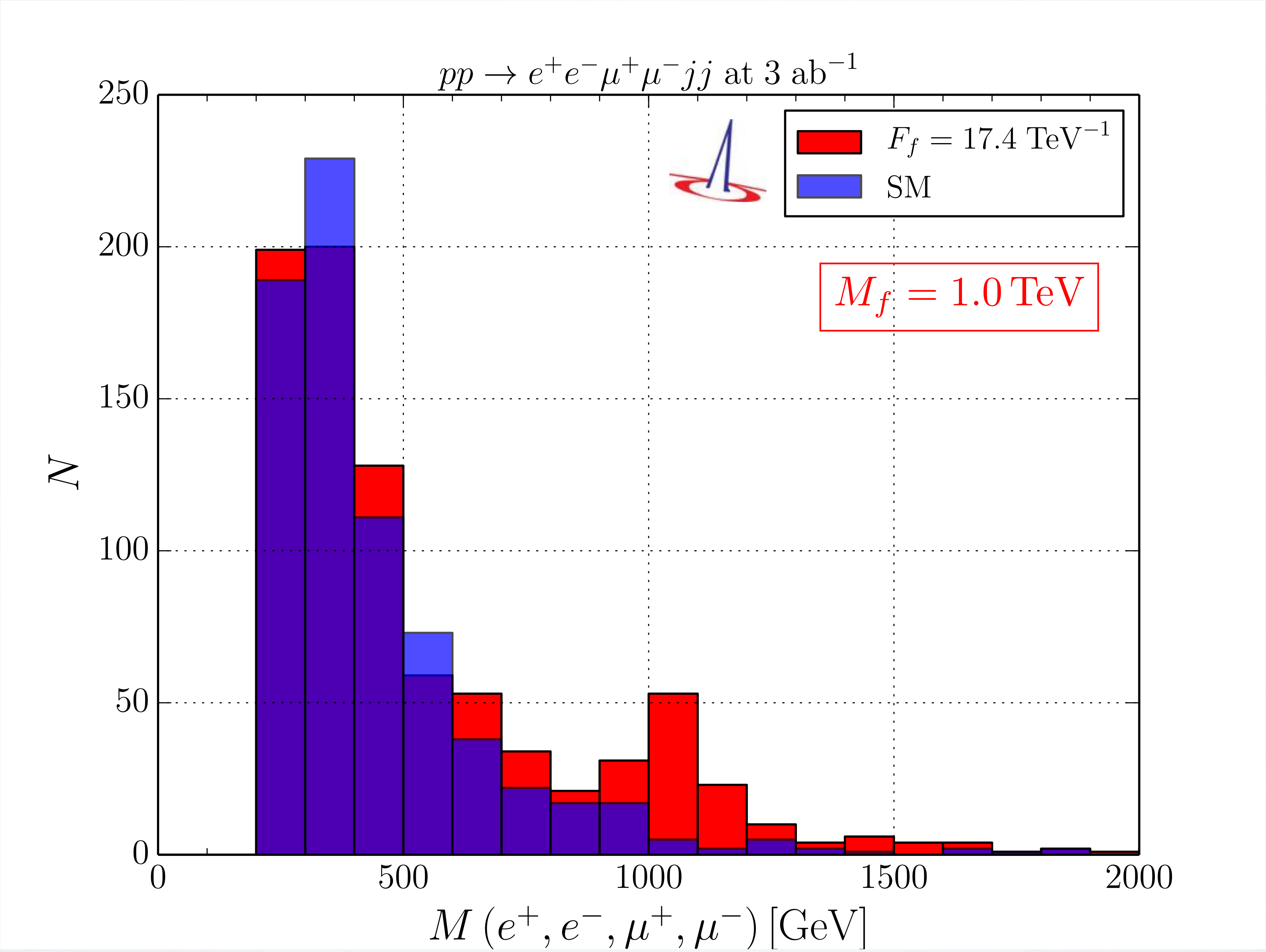
ATLAS PRL 113(2014)14, 141803 [1405.6241]

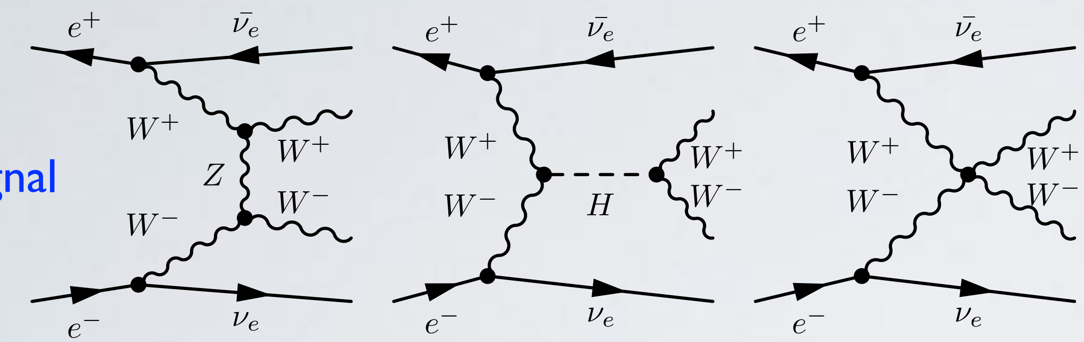
Complete LHC process at 14 TeV



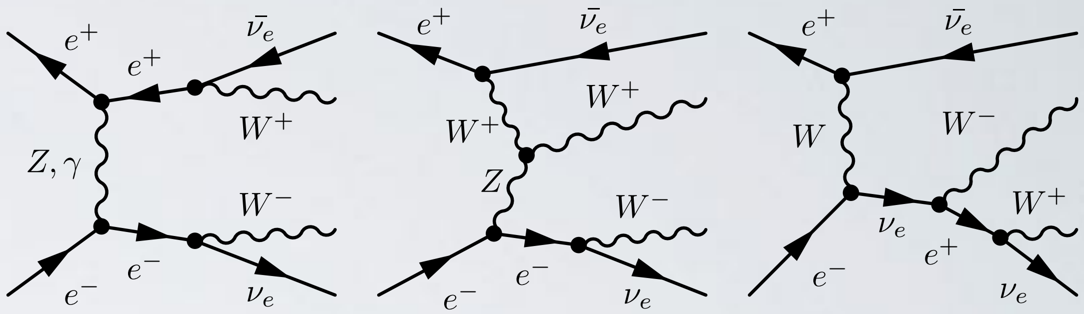
Vector Boson Scattering at Lepton Colliders

Fleper/Kilian/JRR/Sekulla: 1607.03030 (tbp EPJC)

Signal



Bkgd.



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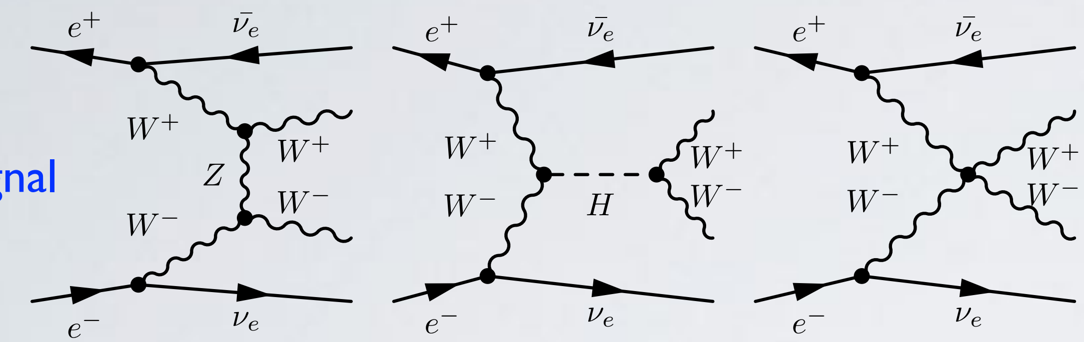

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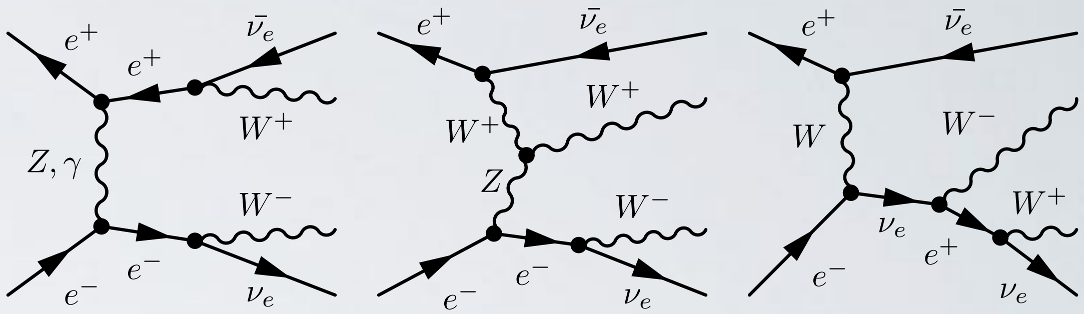

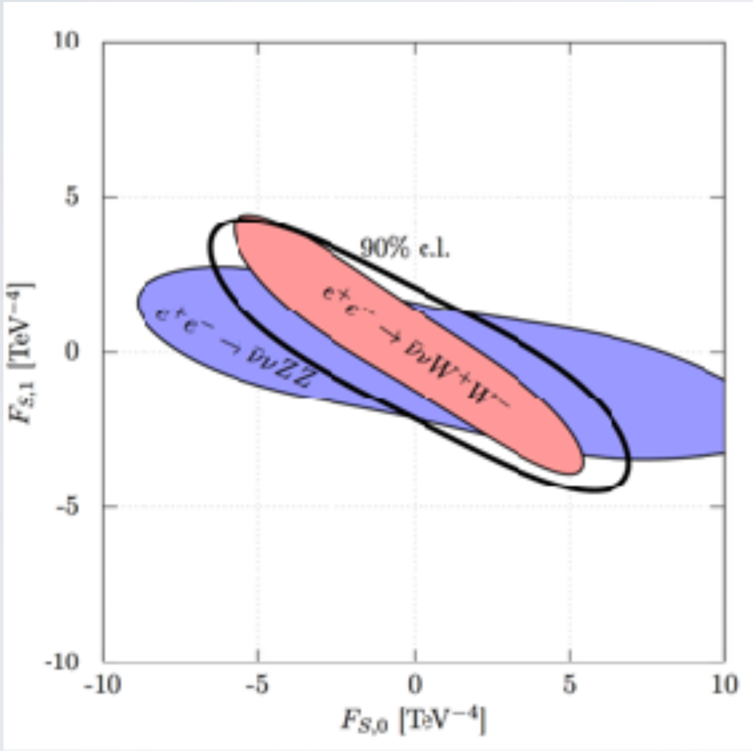

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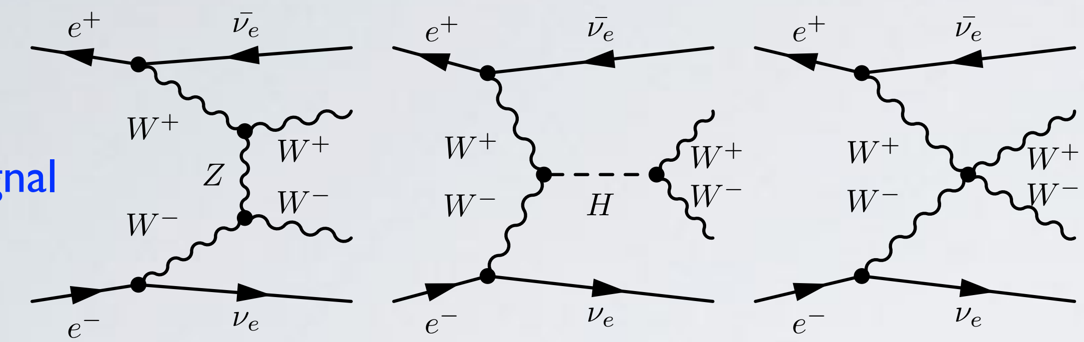

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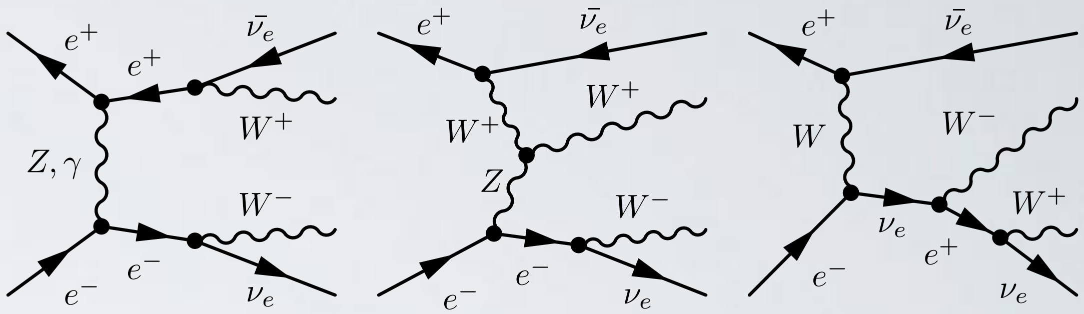

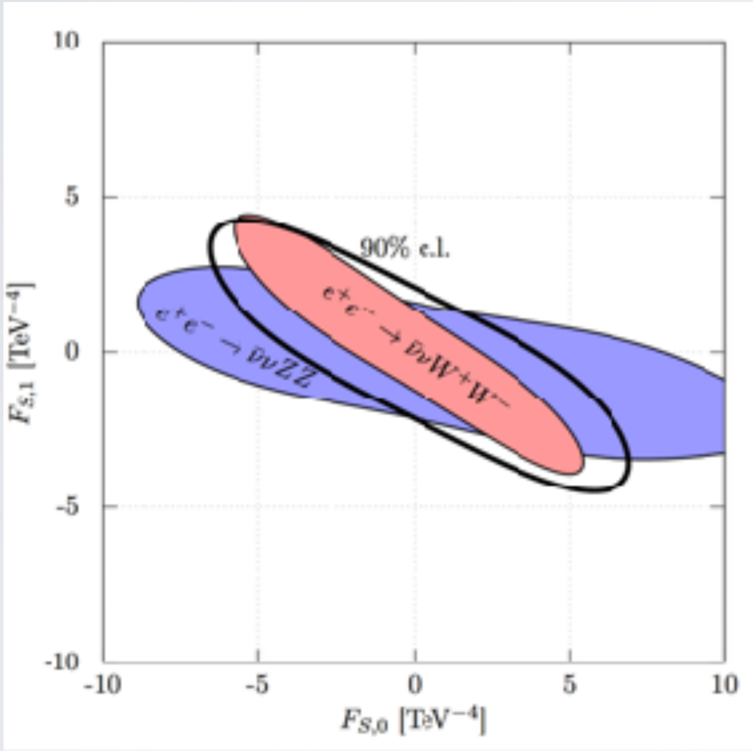

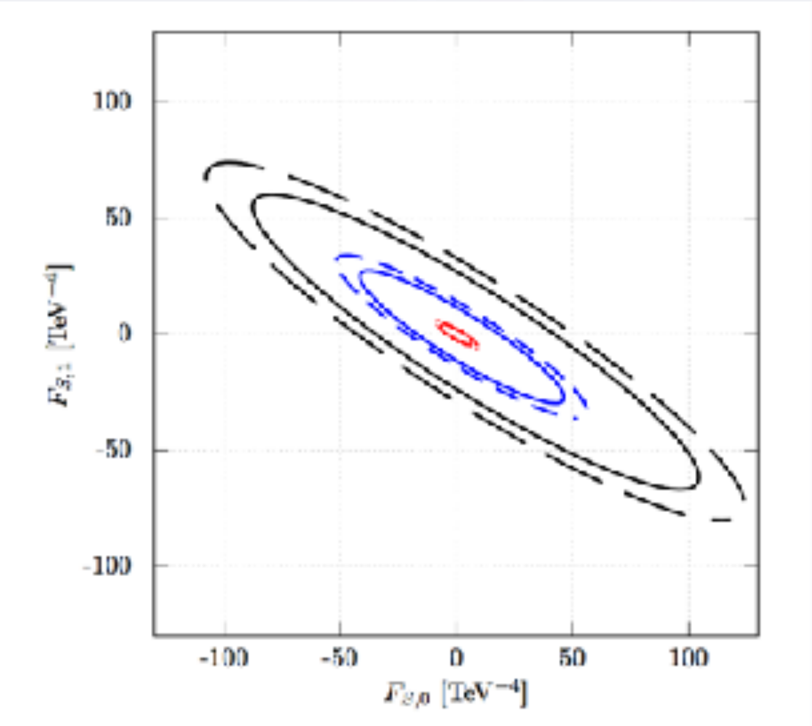

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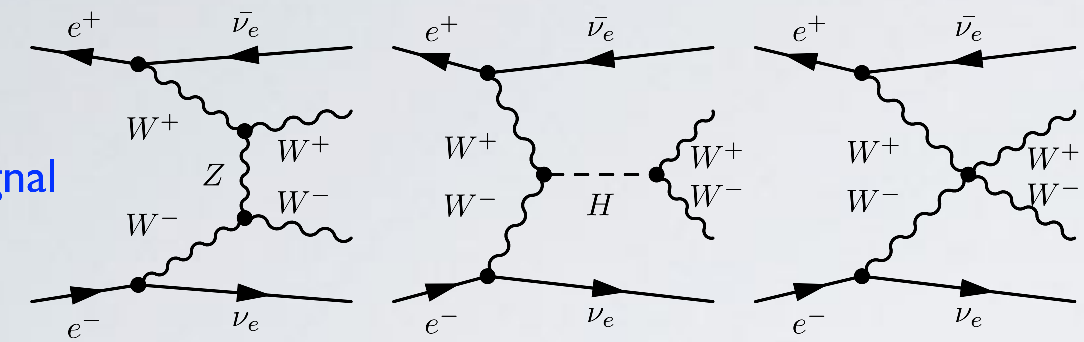
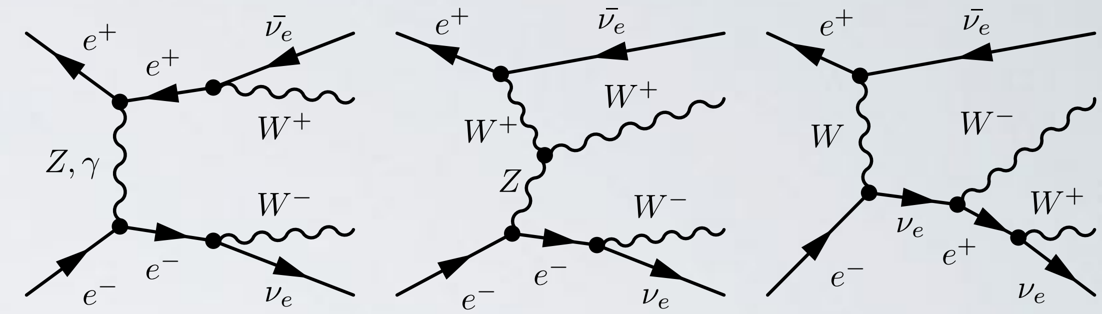
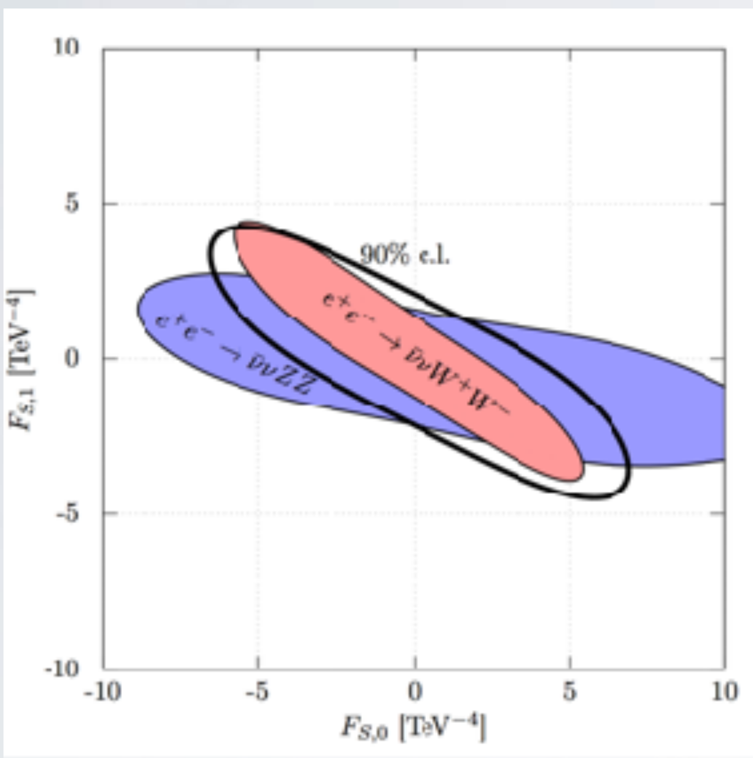
Fleper/Kilian/JRR/Sekulla: 1607.03030 (tbp EPJC)

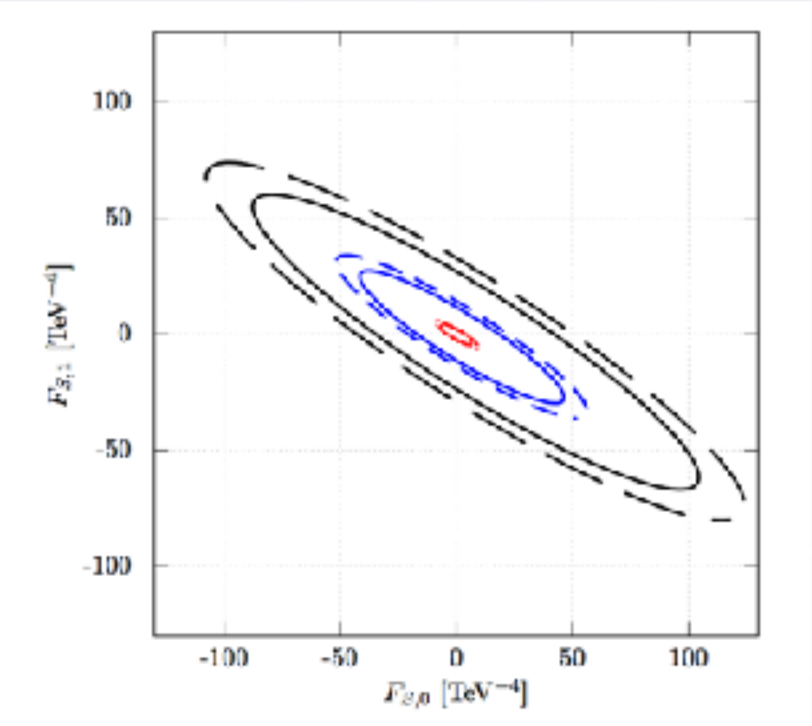
Signal

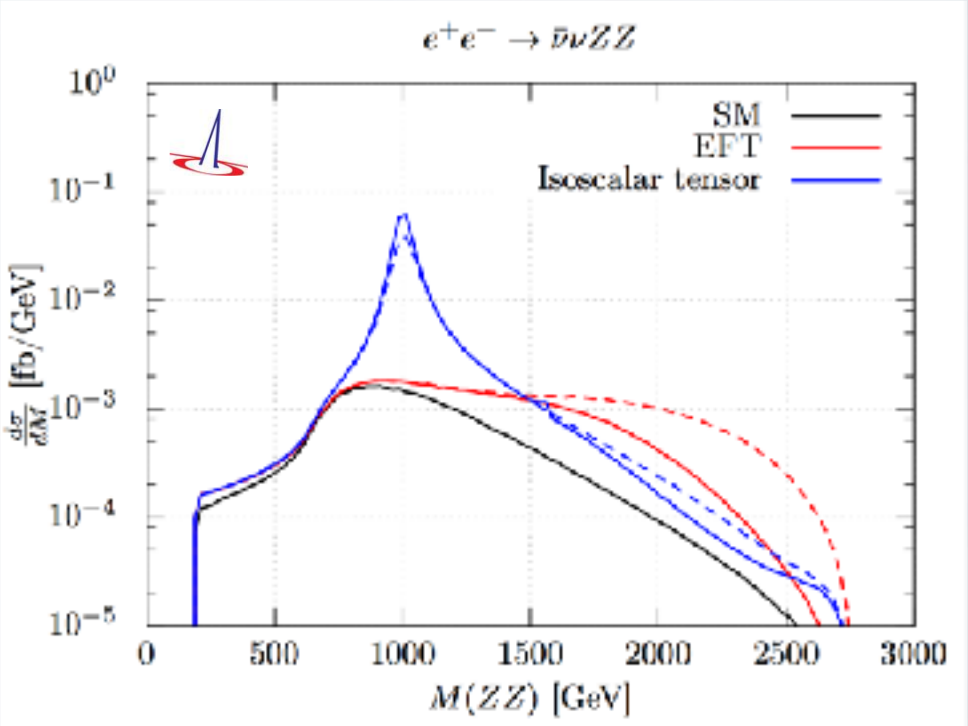


Bkgd.

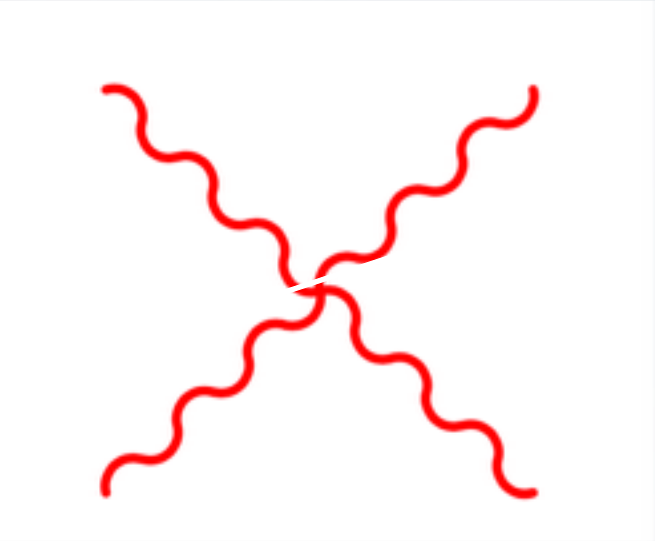








Triple [multiple] Vector Boson Production ?

Relate  to  ?

- Yes, same Feynman rule as in VBS, but …
- one external *W/Z/γ* 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

- VBS (one of) flagship measurements of LHC Runs II/III *and* a 100 TeV machine
- 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
- Unitarization: Not just a theory tool $\Longrightarrow$ "composite continuum saturation"

- Simplified models: generic electroweak resonances
- Vectors/tensors: high-energy behavior tricky [vectors special: *W*/*Z* mixing]

- Limits from LHC still incredibly puny: $M \sim$ 200-300 GeV
- Make sure that actual limits are meaningful and comparable
- Lots of space/work for improvement: V_L / V_T separation, backgrounds etc.

MBI 2017 [5th Multi-Boson Interactions]
KIT, Karlsruhe, Germany, Aug. 28-30 2017

MBI 2013	TU Dresden
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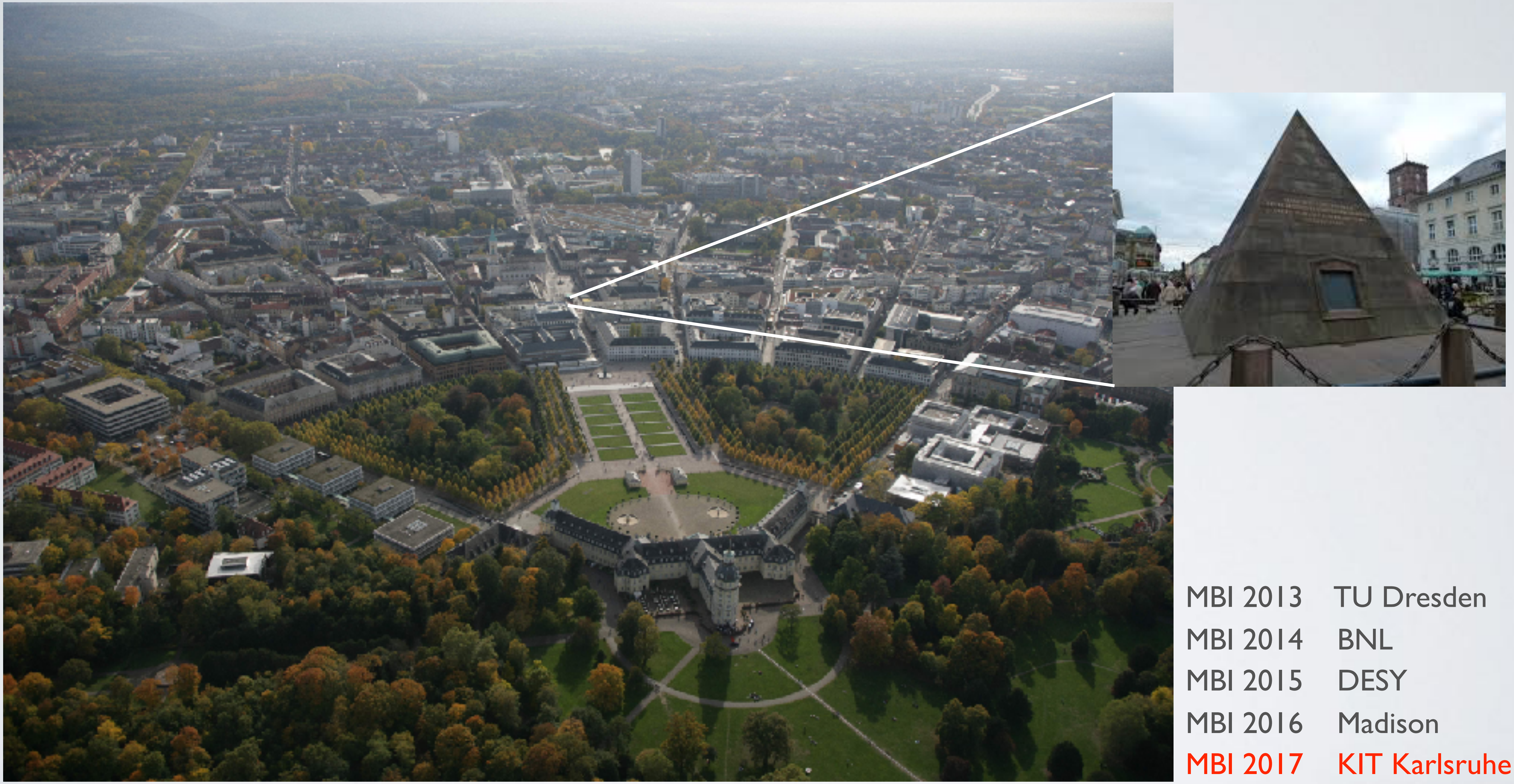

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BACKUP SLIDES

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:

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

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

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

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with the following useful definitions:

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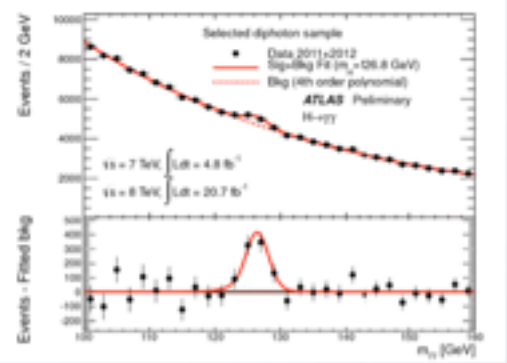
Electroweak Chiral Lagrangian

Ruled out by LHC data (Higgs discovery)



Parameterizing SM deviations

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

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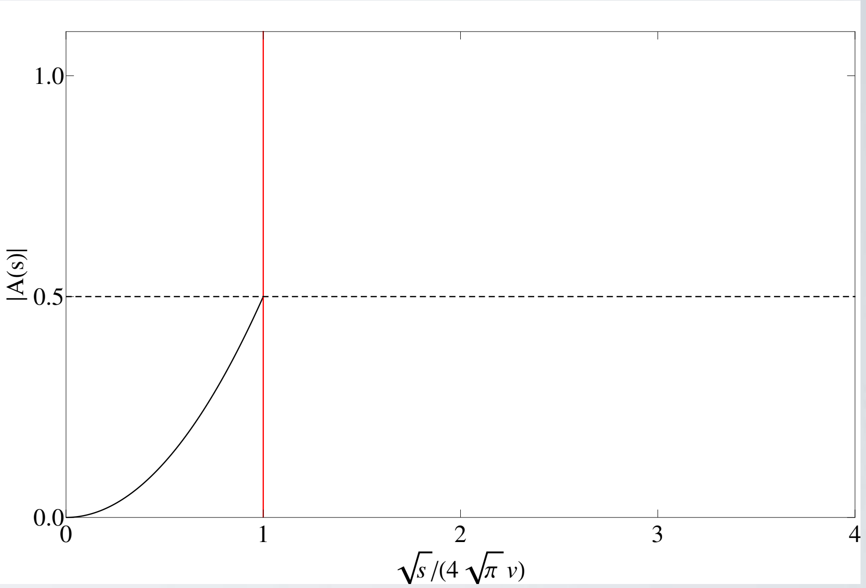
★ Effective Field Theory

- (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)

Procedures to treat unitarity violations



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unitarity bound (0th partial wave) at Λ_C
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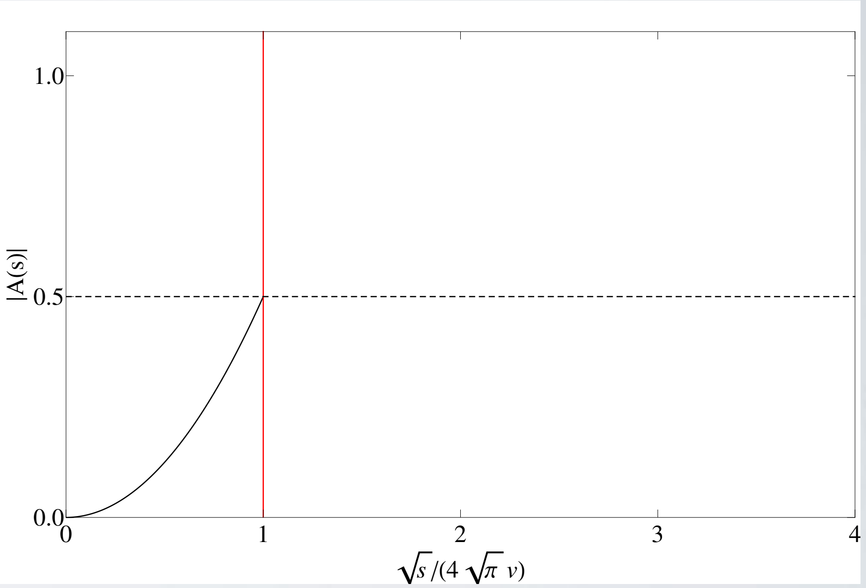
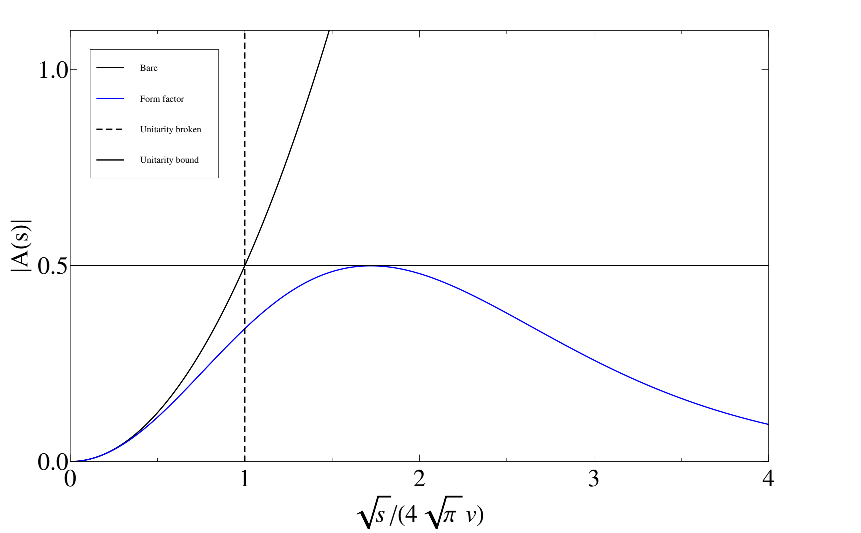


Form factor $$\frac{1}{\left(1+\frac{s}{\Lambda_{FF}}\right)^n}$$

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



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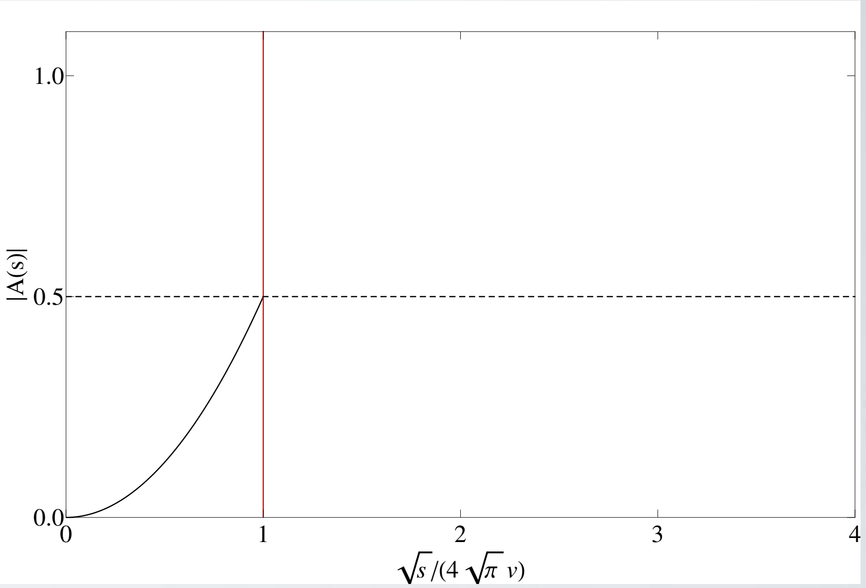

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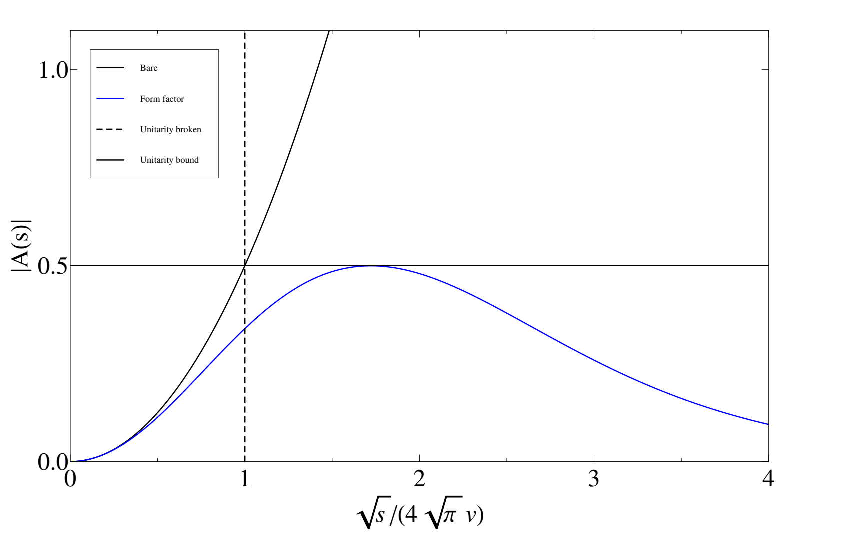
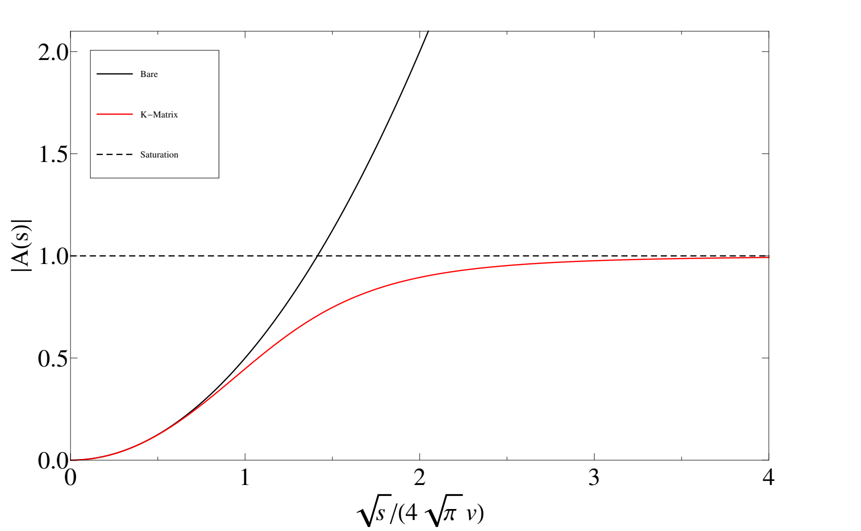


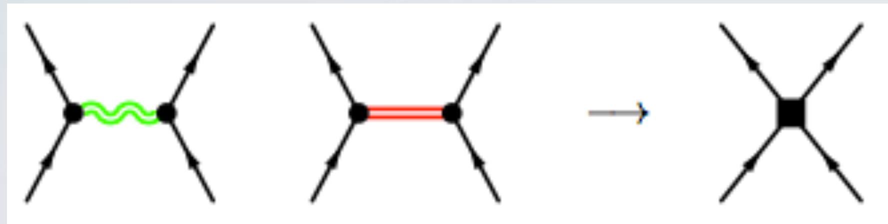
K-/T-matrix saturation

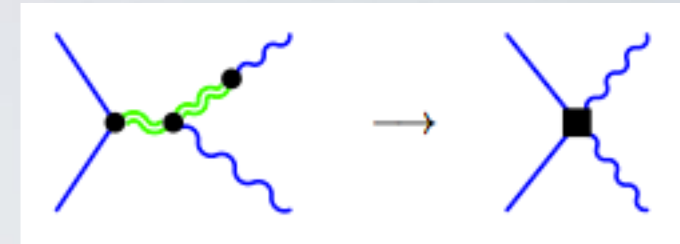
saturates the amplitude, usable for complex amplitudes, no additional parameters



Generation of Higher-dimensional Operators

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





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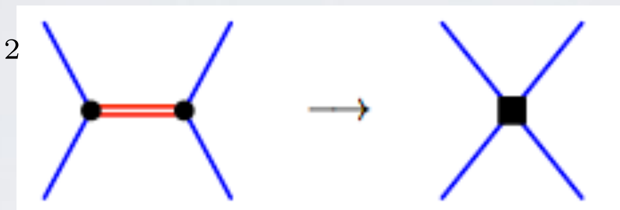

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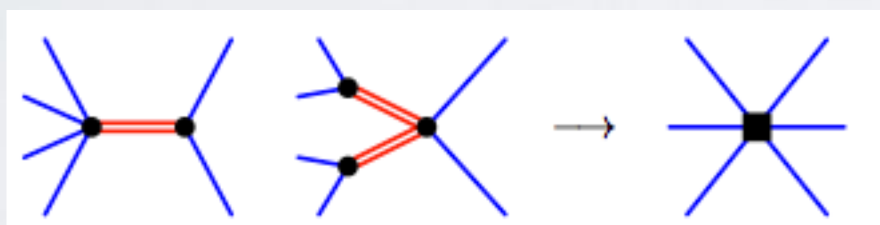
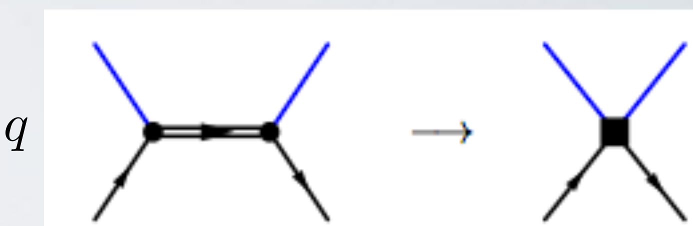


$$\mathcal{O}_{Vq} = \frac{1}{\Lambda^2}\bar{q}\Phi(\not{D}\Phi)q$$



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 ?)
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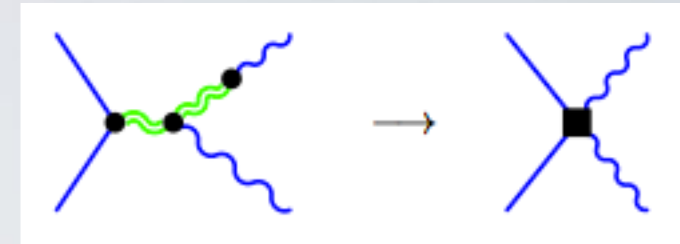

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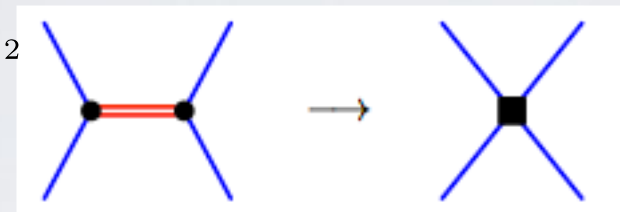

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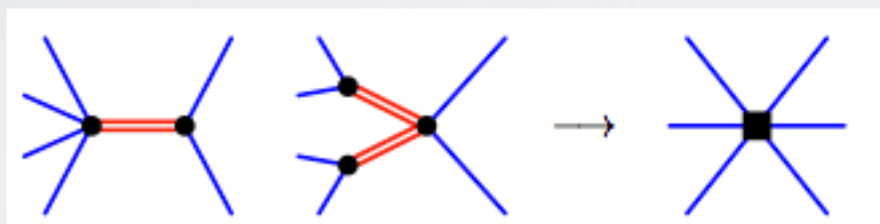

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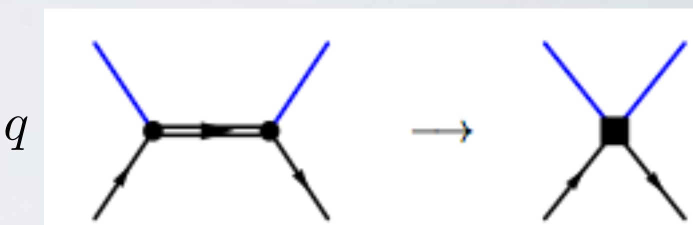

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Different power counting for weakly and strongly interacting theories

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