New Physics / Resonances in Vector Boson Scattering at the LHC

Jürgen R. Reuter, DESY

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

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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)

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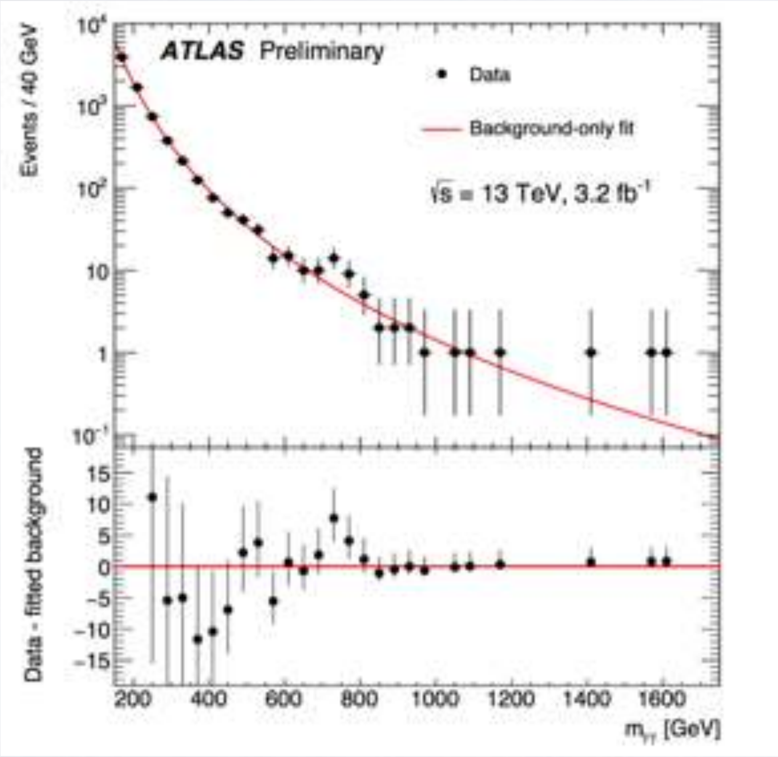
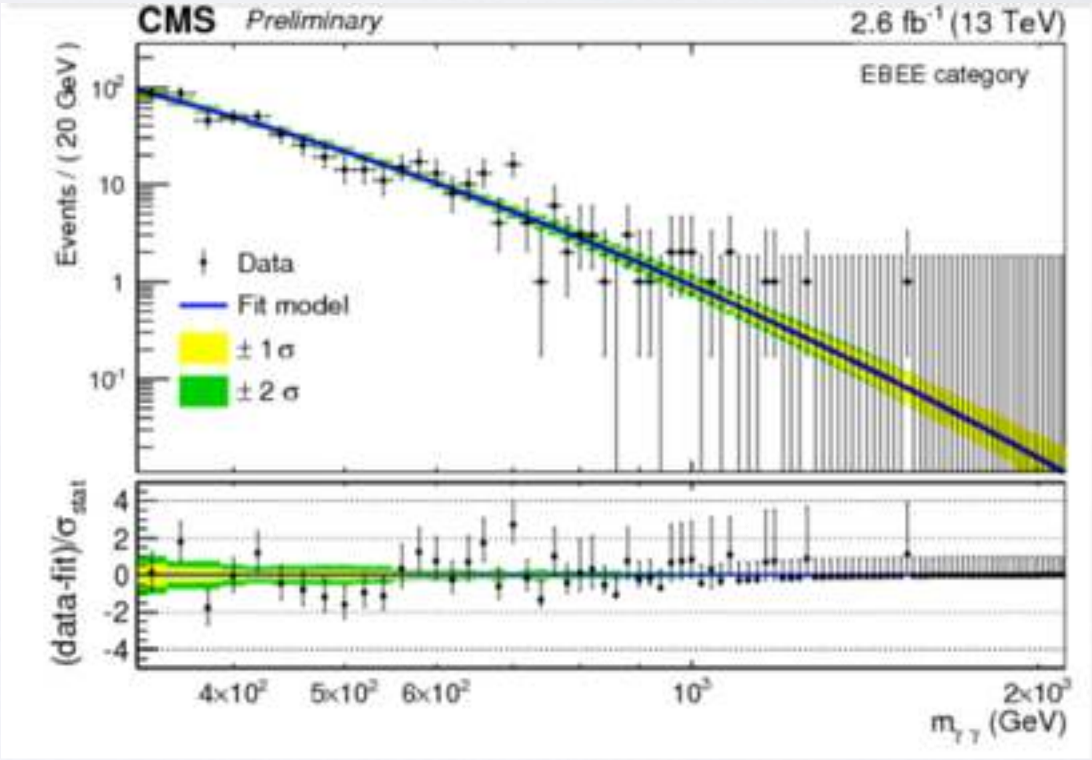


ATLAS-CONF-2015-081



CMS-PAS-EXO-15-004

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

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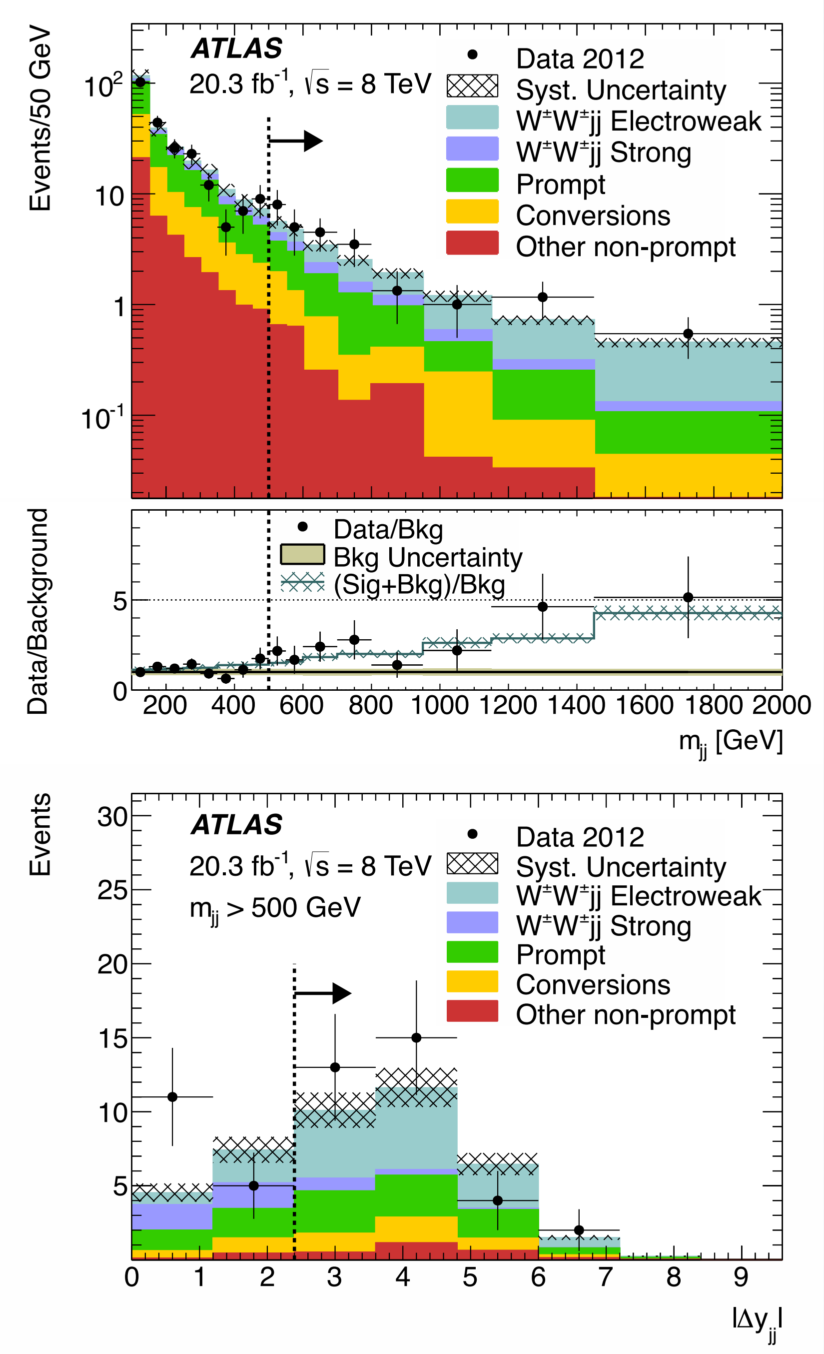

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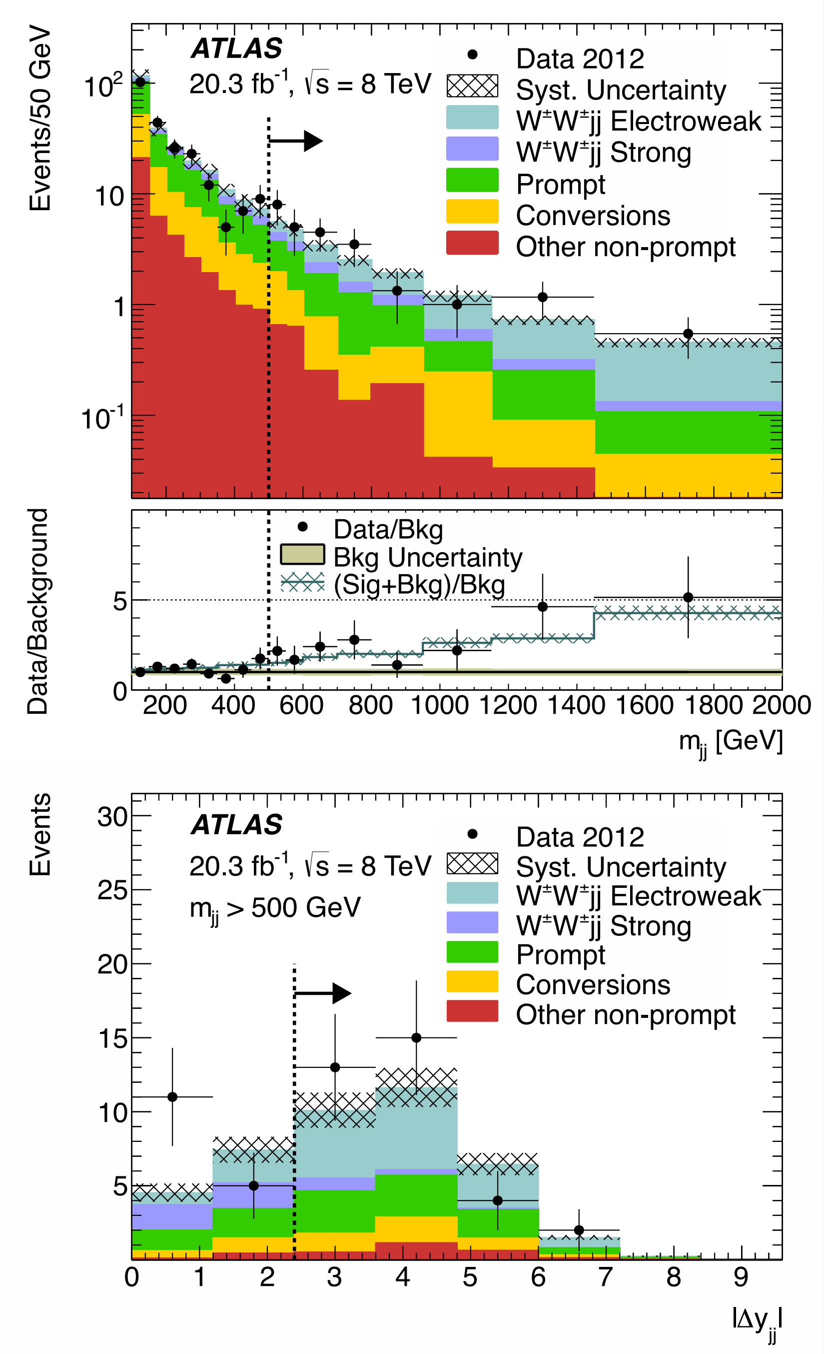

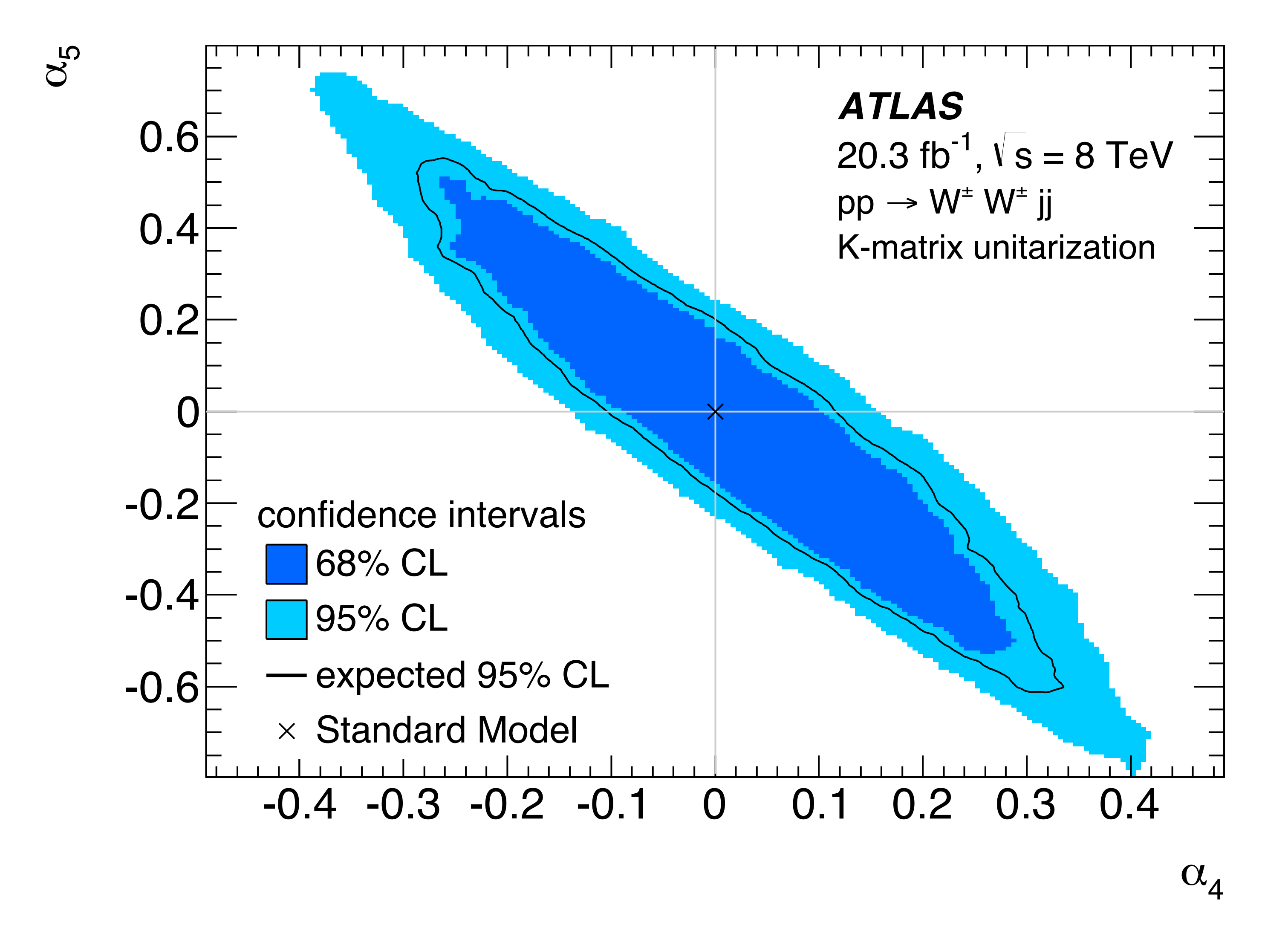

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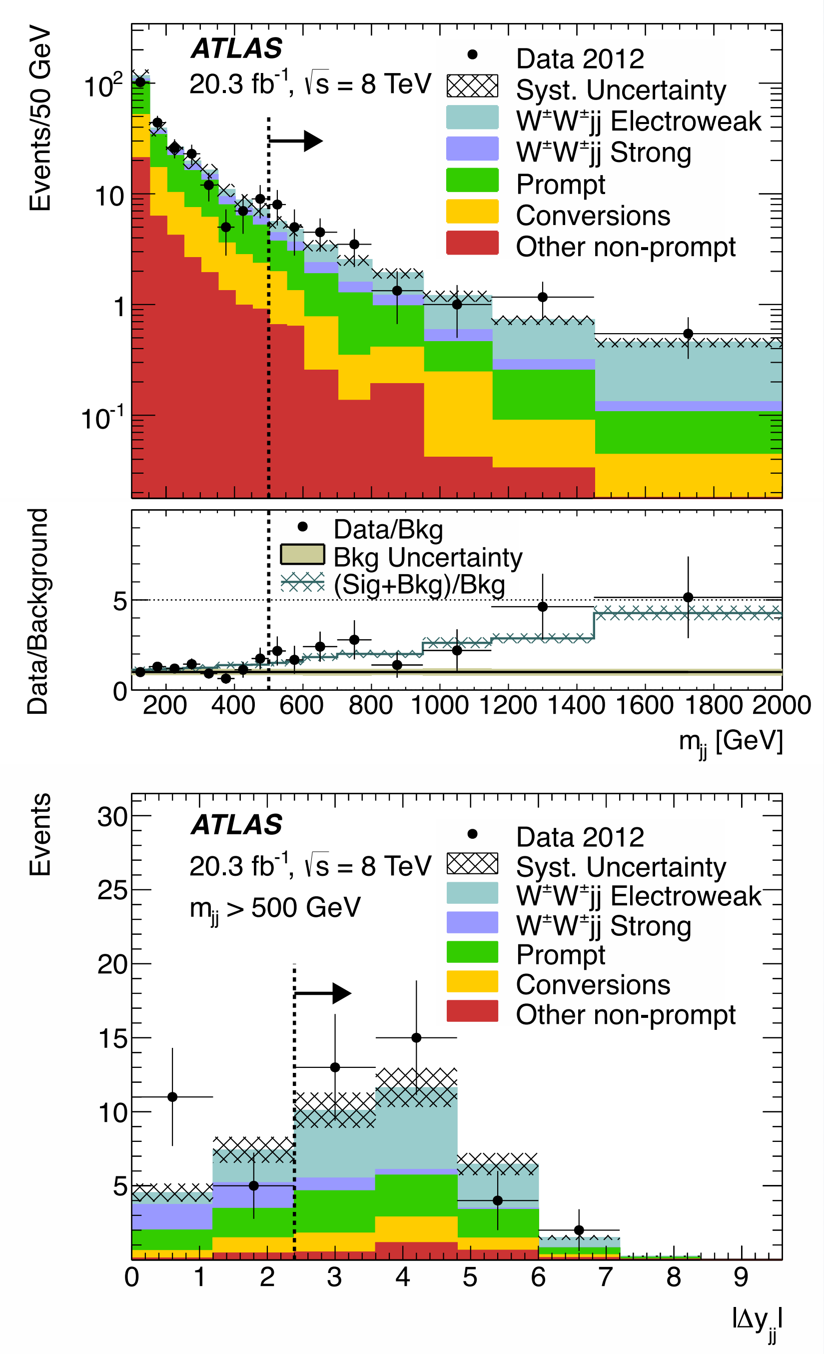
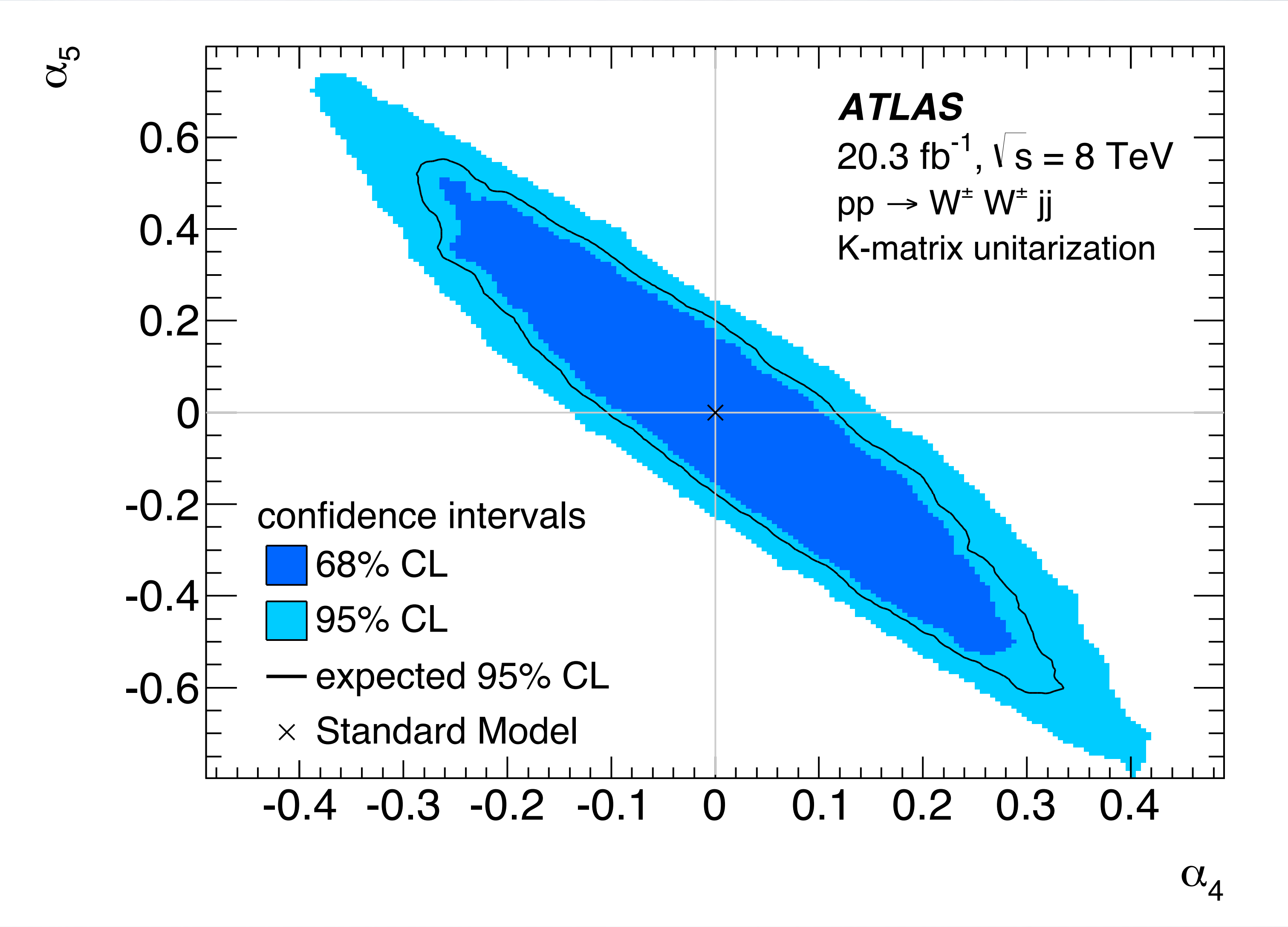


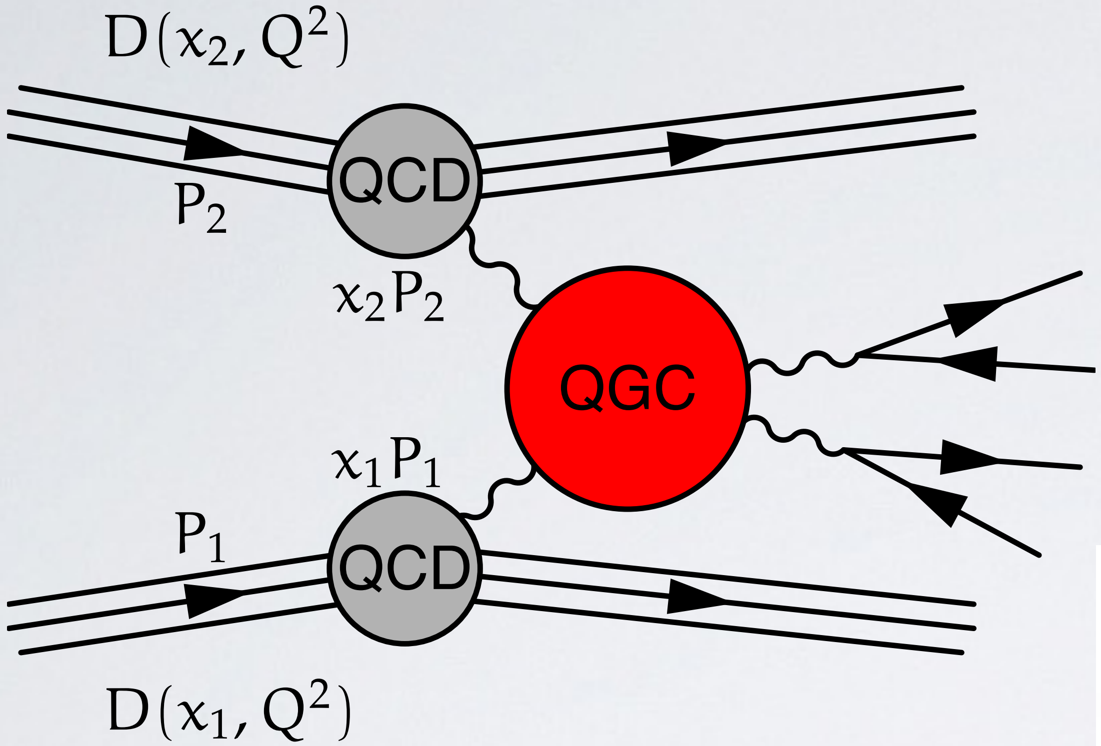


Exploration of E-frontier → look for heavy objects, including high-mass $V_L V_L$ scattering:
- requires as much integrated luminosity as possible (cross-section goes like 1/s)

F. Gianotti, 01/2014

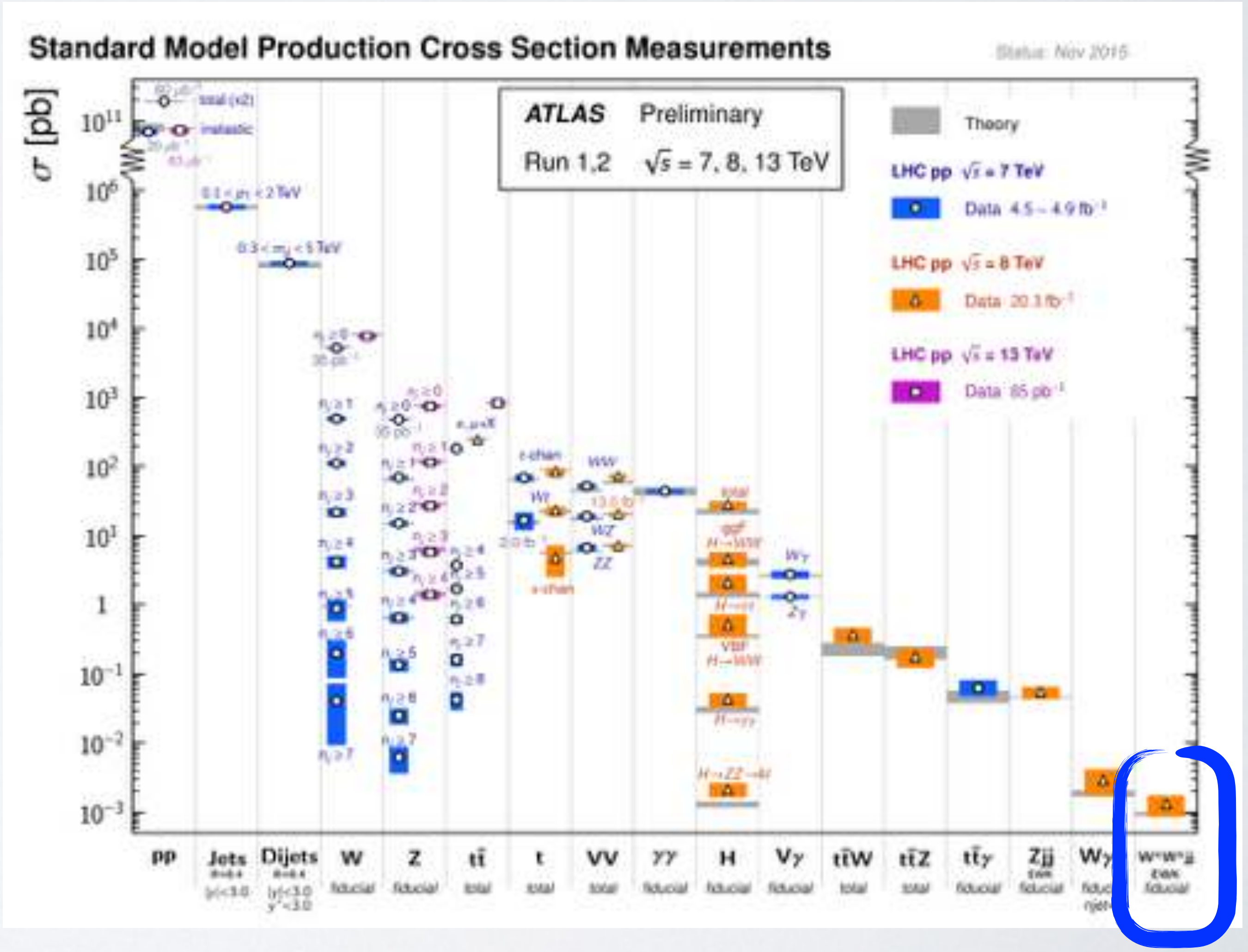
Anatomy of Vector Boson Scattering (VBS)

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



Backgrounds [+ $V_T V_T$ bkgd.]:

- $tt \to WbWb$
- 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: $\left(\Phi^\dagger \Phi\right) \Box \left(\Phi^\dagger \Phi\right) \longrightarrow \partial_\mu \left(\Phi^\dagger \Phi\right) \partial^\mu \left(\Phi^\dagger \Phi\right)$
- 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)

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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
$\mathcal{O}_\Phi = (\Phi^\dagger\Phi)^3$	$\mathcal{O}_{e\Phi} = (\Phi^\dagger\Phi)(\bar{l}\Gamma_e e\Phi)$	$\mathcal{O}_G = f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
$\mathcal{O}_{\Phi\Box} = (\Phi^\dagger\Phi)\Box(\Phi^\dagger\Phi)$	$\mathcal{O}_{u\Phi} = (\Phi^\dagger\Phi)(\bar{q}\Gamma_u u\widetilde{\Phi})$	$\mathcal{O}_{\widetilde{G}} = f^{ABC} \widetilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
$\mathcal{O}_{\Phi D} = (\Phi^\dagger D^\mu\Phi)^*(\Phi^\dagger D_\mu\Phi)$	$\mathcal{O}_{d\Phi} = (\Phi^\dagger\Phi)(\bar{q}\Gamma_d d\Phi)$	$\mathcal{O}_W = \varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$
		$\mathcal{O}_{\widetilde{W}} = \varepsilon^{IJK} \widetilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$
$X^2\Phi^2$	$\psi^2 X\Phi$	$\psi^2\Phi^2 D$
$\mathcal{O}_{\Phi G} = (\Phi^\dagger\Phi) G_{\mu\nu}^A G^{A\mu\nu}$	$\mathcal{O}_{uG} = (\bar{q}\sigma^{\mu\nu}\frac{\lambda^A}{2}\Gamma_u u\widetilde{\Phi}) G_{\mu\nu}^A$	$\mathcal{O}_{\Phi l}^{(1)} = (\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi)(\bar{l}\gamma^\mu l)$
$\mathcal{O}_{\Phi\widetilde{G}} = (\Phi^\dagger\Phi) \widetilde{G}_{\mu\nu}^A G^{A\mu\nu}$	$\mathcal{O}_{dG} = (\bar{q}\sigma^{\mu\nu}\frac{\lambda^A}{2}\Gamma_d d\Phi) G_{\mu\nu}^A$	$\mathcal{O}_{\Phi l}^{(3)} = (\Phi^\dagger i\overleftrightarrow{D}_\mu^I\Phi)(\bar{l}\gamma^\mu\tau^I l)$
$\mathcal{O}_{\Phi W} = (\Phi^\dagger\Phi) W_{\mu\nu}^I W^{I\mu\nu}$	$\mathcal{O}_{eW} = (\bar{l}\sigma^{\mu\nu}\Gamma_e e\tau^I\Phi) W_{\mu\nu}^I$	$\mathcal{O}_{\Phi e} = (\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi)(\bar{e}\gamma^\mu e)$
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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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$\mathcal{O}'_T = (\Phi^\dagger \overleftrightarrow{D}_\mu \Phi)(\Phi^\dagger \overleftrightarrow{D}^\mu \Phi)$	$\mathcal{O}'_{d\Phi} = (\Phi^\dagger\Phi)(\bar{q}\,\Gamma_d d\Phi)$	$\mathcal{O}'_W = \varepsilon^{IJK} W^{I\nu}_{\mu} W^{J\rho}_{\nu} W^{K\mu}_{\rho}$
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Operators and Multi(EW)-boson Physics (I)

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

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

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

$$\mathcal{O}_{\widetilde{W}WW} = \mathrm{Tr}[\widetilde{W}_{\mu\nu} W^{\nu\rho} W_{\rho}^{\mu}]$$
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Affect the following electroweak couplings:

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

connected to Higgs physics

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

Dimension-8 operators for Multiboson physics

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

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

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

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\mathcal{O}_{M,0} &= \mathrm{Tr}\left[W_{\mu\nu}W^{\mu\nu}\right] \cdot \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right] \\
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	WWWW	WWZZ	ZZZZ	WWAZ	WWAA	ZZZA	ZZAA	ZAAA	AAAA
$\mathcal{O}_{S,0/1}$	✓	✓	✓						
$\mathcal{O}_{M,0/1/6/7}$	✓	✓	✓	✓	✓	✓	✓		
$\mathcal{O}_{M,2/3/4/5}$		✓	✓	✓	✓	✓	✓		
$\mathcal{O}_{T,0/1/2}$	✓	✓	✓	✓	✓	✓	✓	✓	✓
$\mathcal{O}_{T,5/6/7}$		✓	✓	✓	✓	✓	✓	✓	✓
$\mathcal{O}_{T,8/9}$			✓			✓	✓	✓	✓

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$\mathcal{O}_{T,5/6/7}$		✓	✓	✓	✓	✓	✓	✓	✓
$\mathcal{O}_{T,8/9}$			✓			✓	✓	✓	✓

- 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:

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

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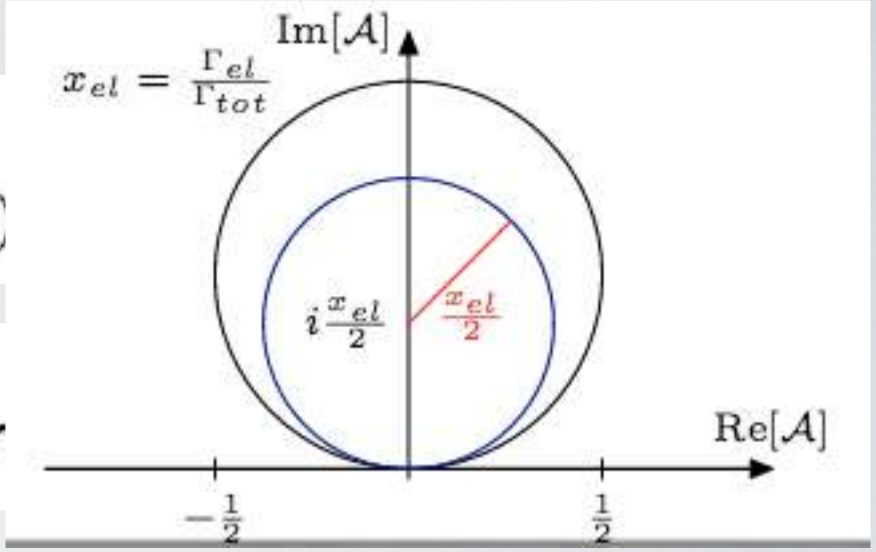
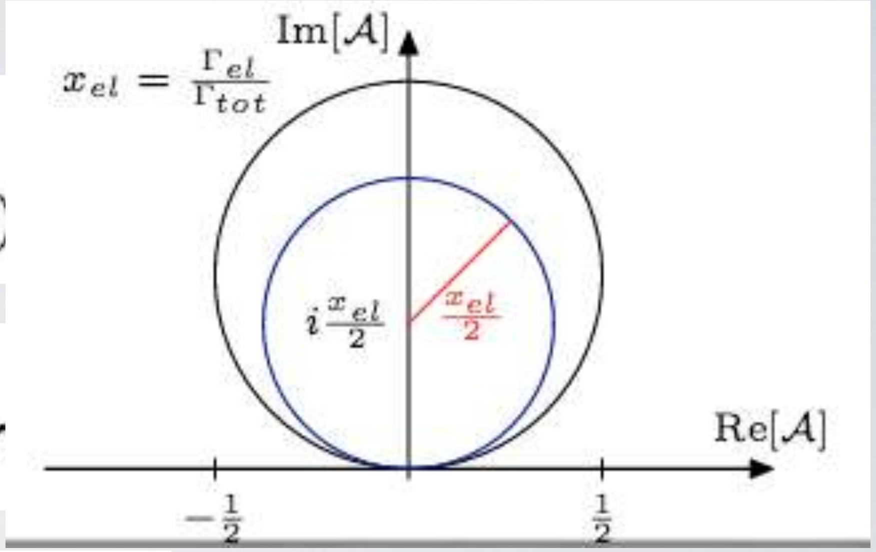


Unitarity in vector boson scattering



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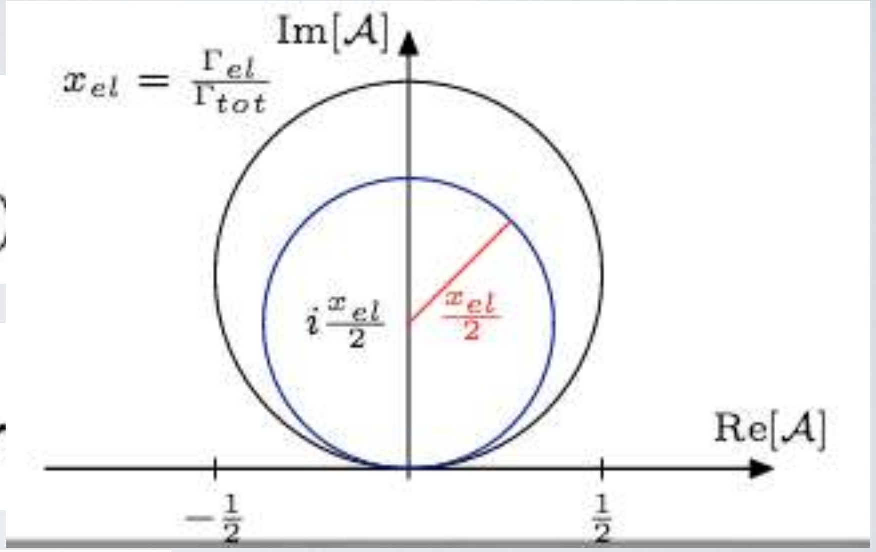

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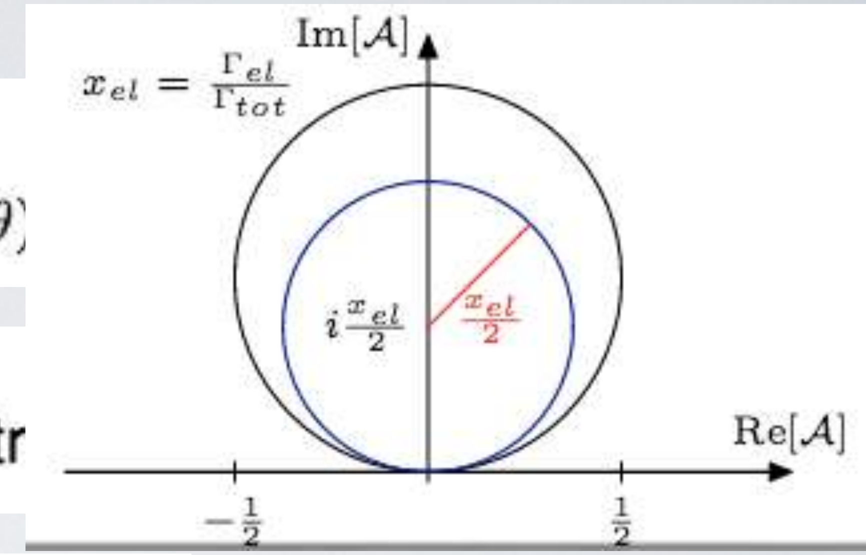
SM longitudinal isospin eigenamplitudes ($\mathcal{A}_{I,\text{spin}=J}$):

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

Unitarity in vector boson scattering



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Lee/Quigg/Thacker, 1973

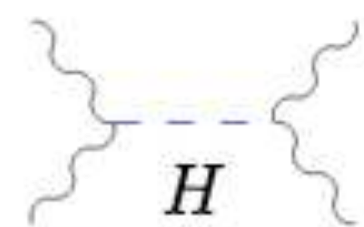
exceeds unitarity bound $|\mathcal{A}_{IJ}| \lesssim \frac{1}{2}$ at:

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

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

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

Higgs exchange:

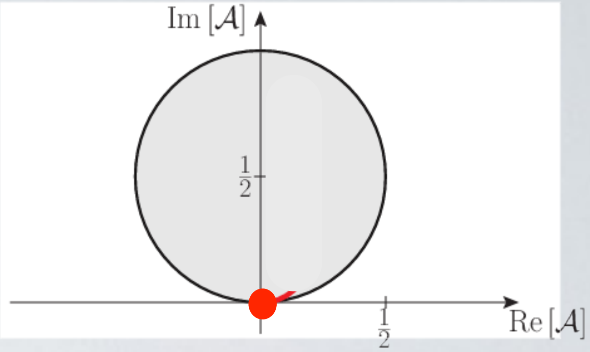


$$\mathcal{A}(s,t,u) = -\frac{M_H^2}{v^2}\frac{s}{s-M_H^2}$$

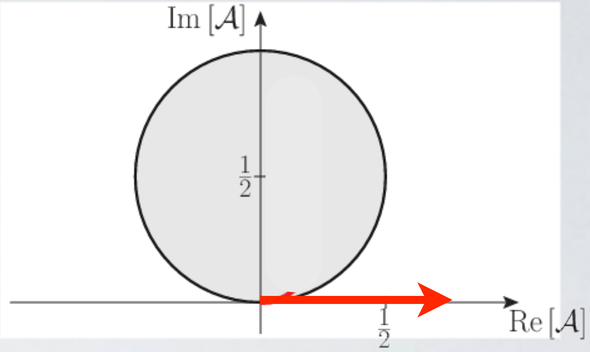
Unitarity: $M_H \lesssim \sqrt{8\pi}v \sim 1.2\,\text{TeV}$

Scenarios for New Physics in VBS

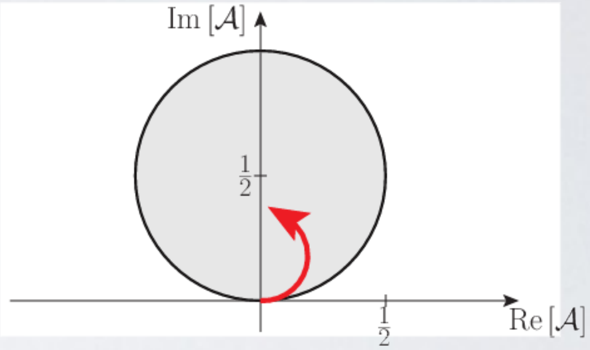
1. SM or weakly coupled physics (e.g. 2HDM):
   amplitude remains close to origin



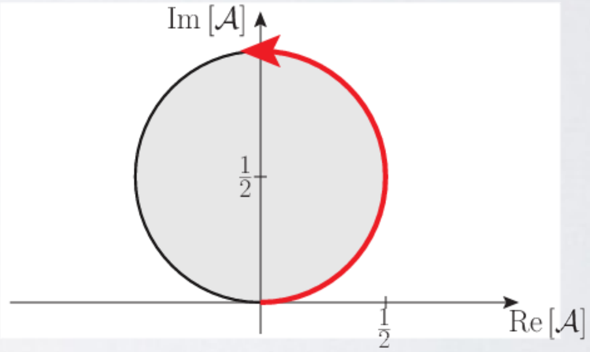
2. Rising amplitude (at least one dim-8 operator): rise beyond unitarity circle [unphys.], strongly interacting regime



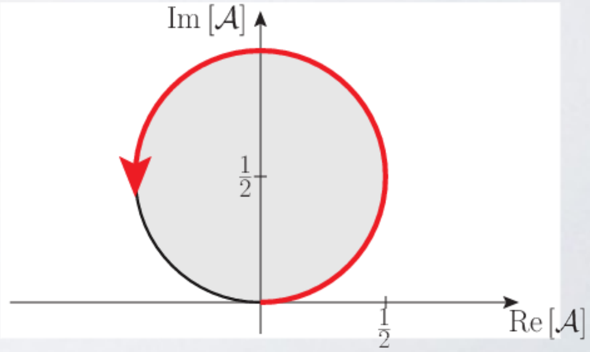
3. Inelastic channel opens (form-factor description): new channels open out, multi-boson final states



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



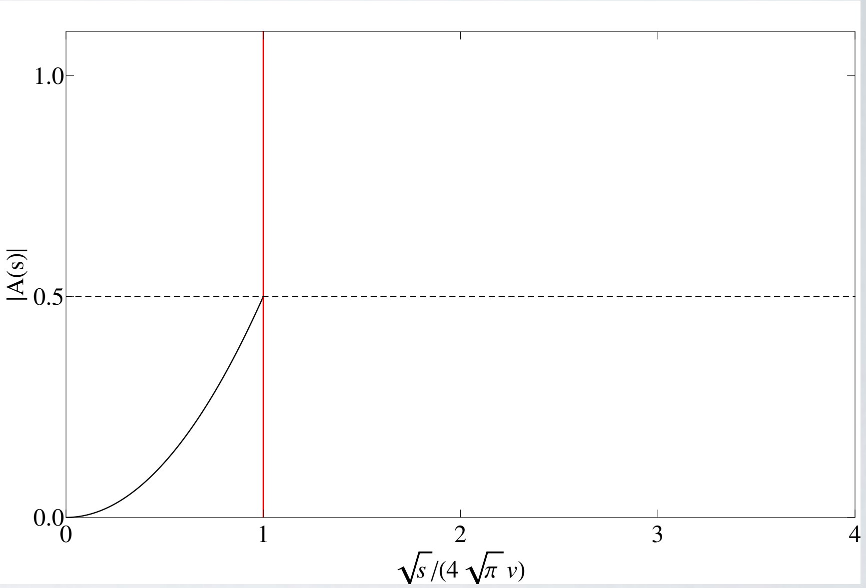
5. New resonance: amplitude turns over



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



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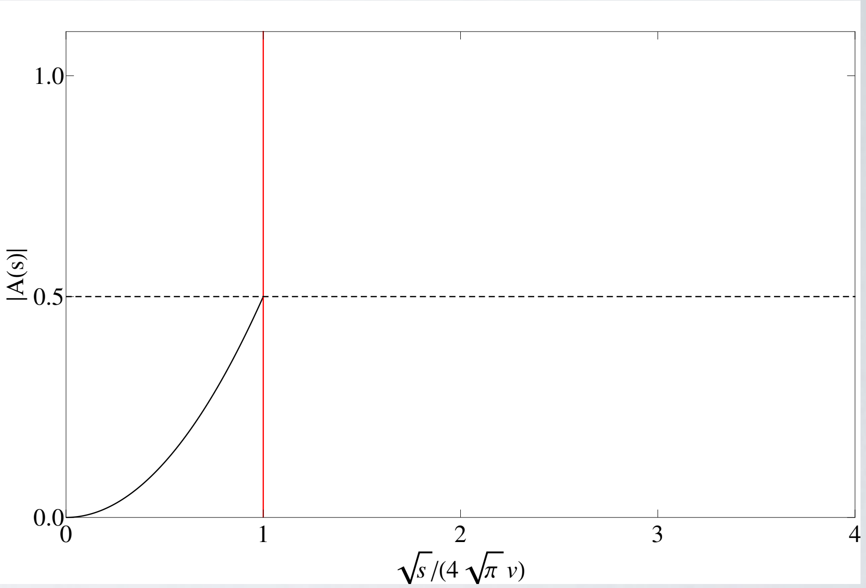

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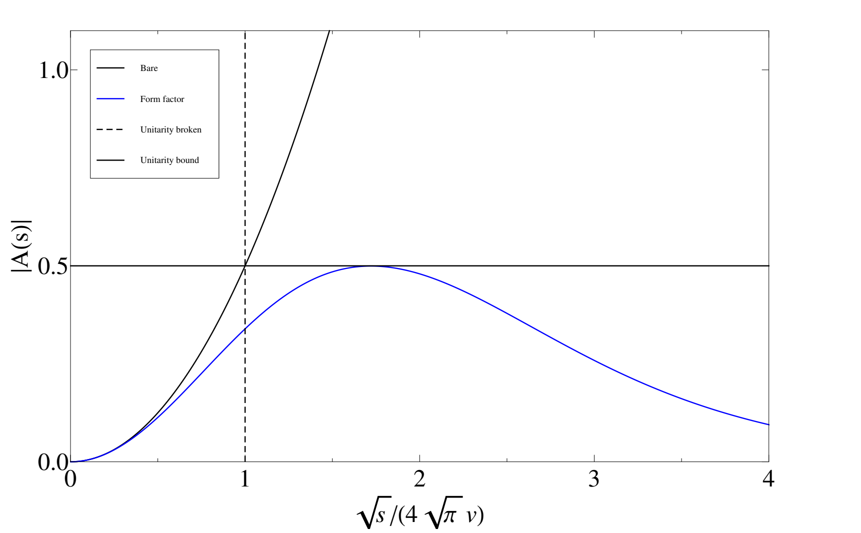

Form factor $\dfrac{1}{\left(1+\frac{s}{\Lambda_{FF}}\right)^n}$

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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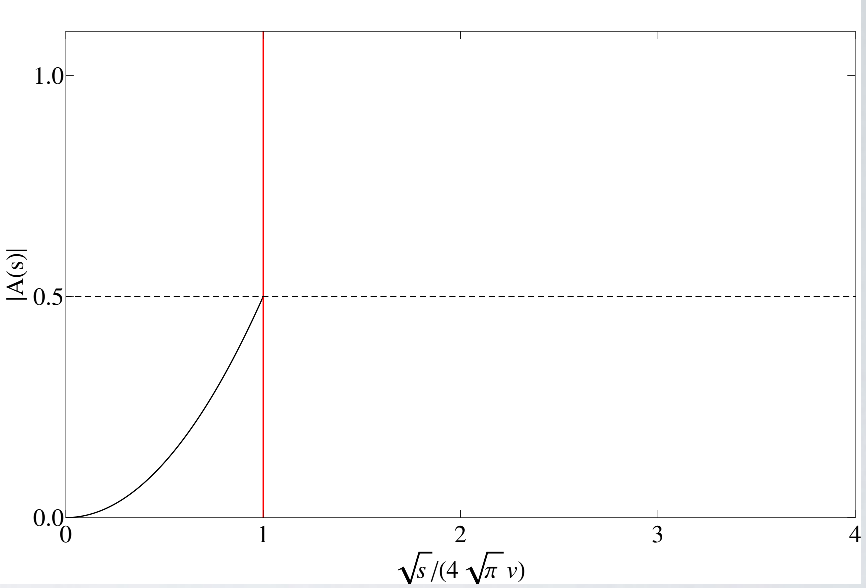

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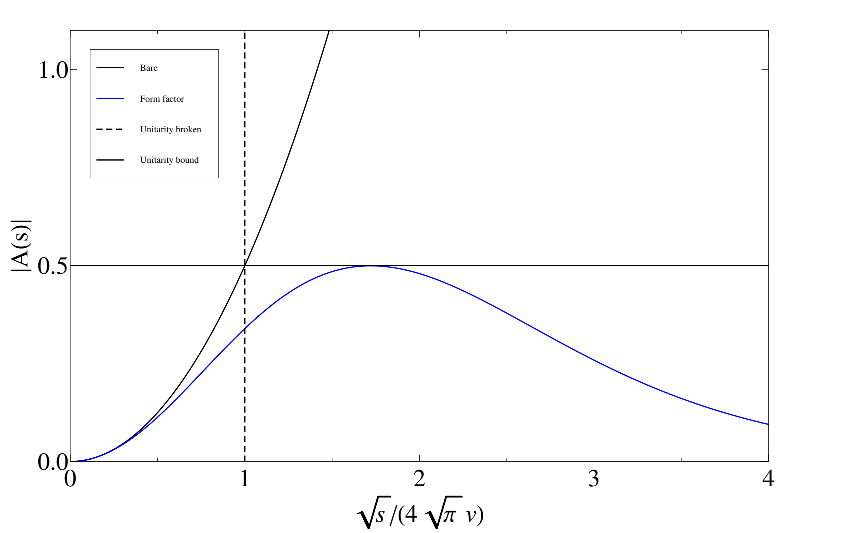

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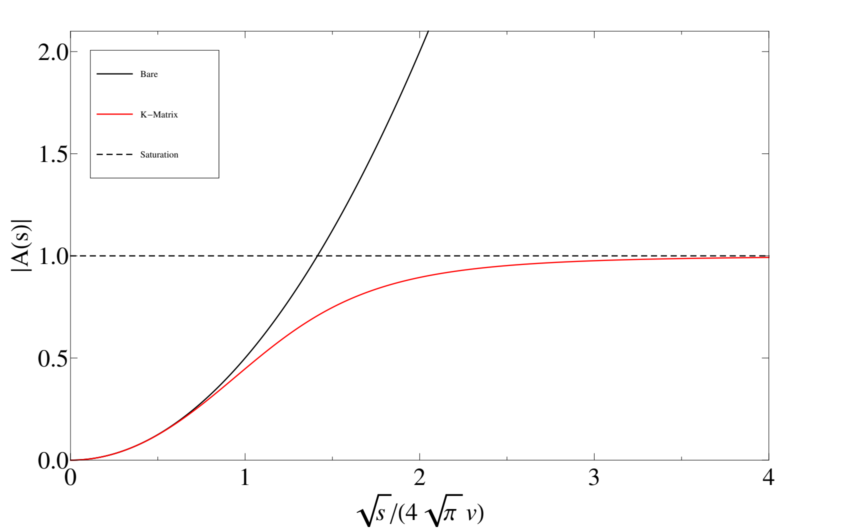


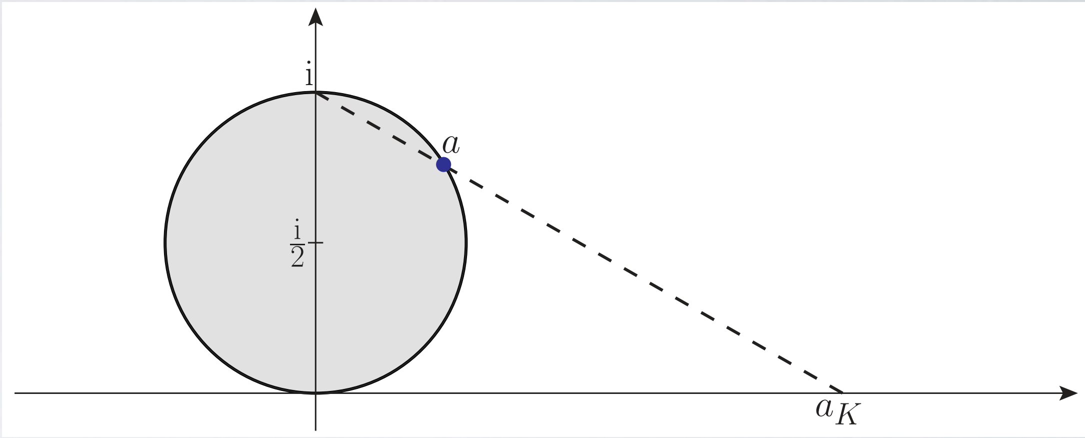
K-/T-matrix saturation

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

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



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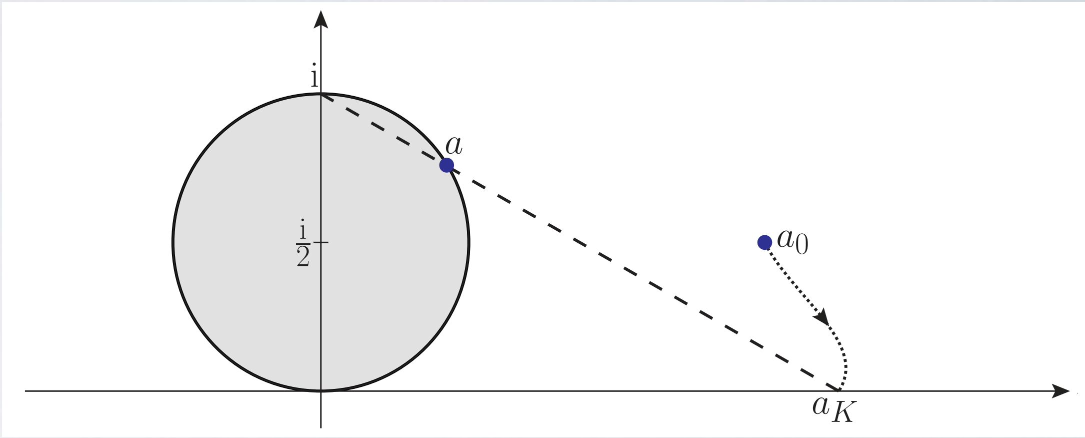

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- need to construct (orig.) *K*-matrix as self-adjoint intermediate operator

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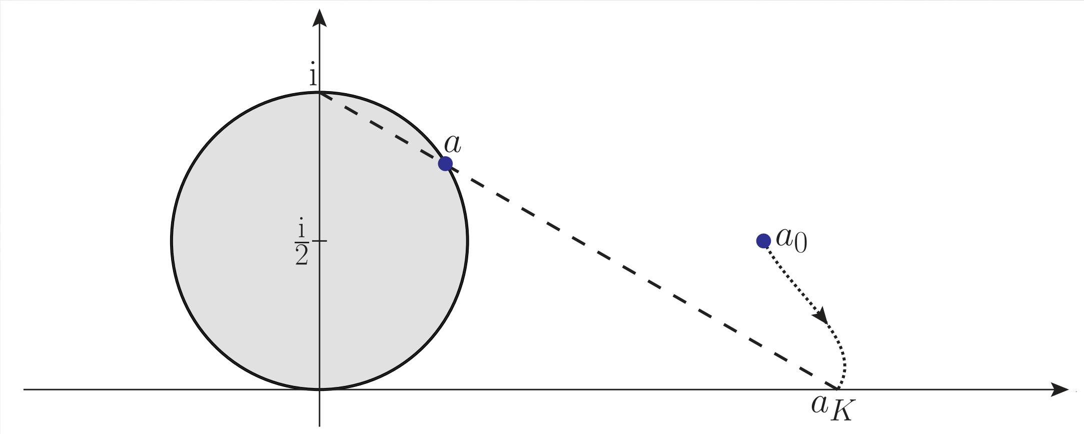

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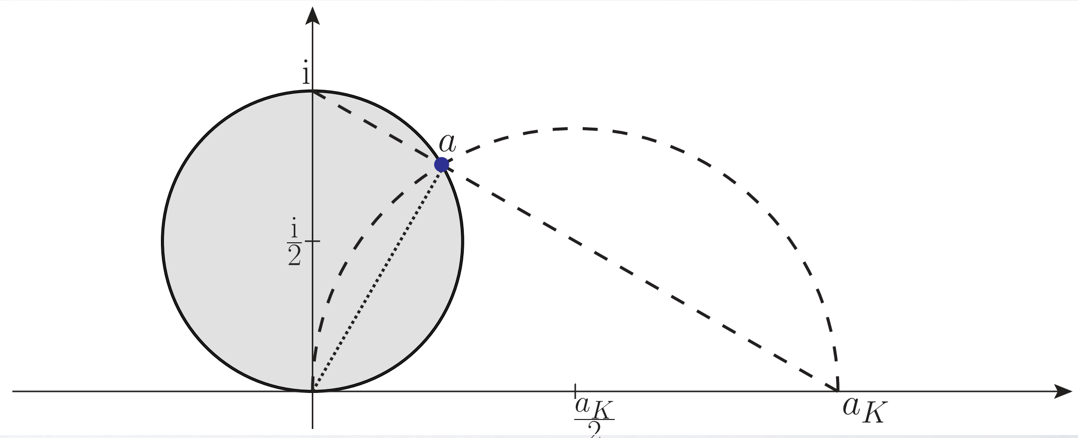
- *T*-matrix: Thales circle construction — Kilian/Ohl/JRR/Sekulla, 2014
- Defined via $\left|a - \frac{a_K}{2}\right| = \frac{a_K}{2} \quad \Rightarrow \quad a = \frac{1}{\mathrm{Re}\left(\frac{1}{a_0}\right) - \mathrm{i}}$



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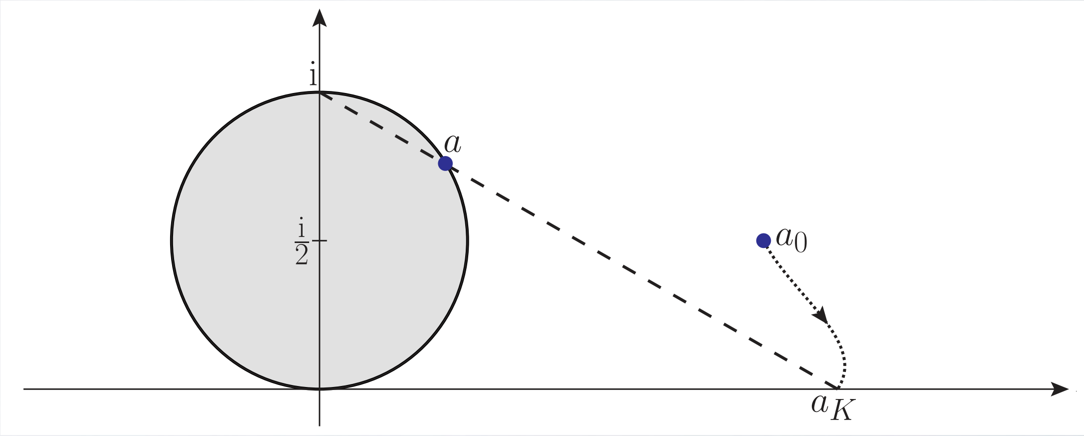
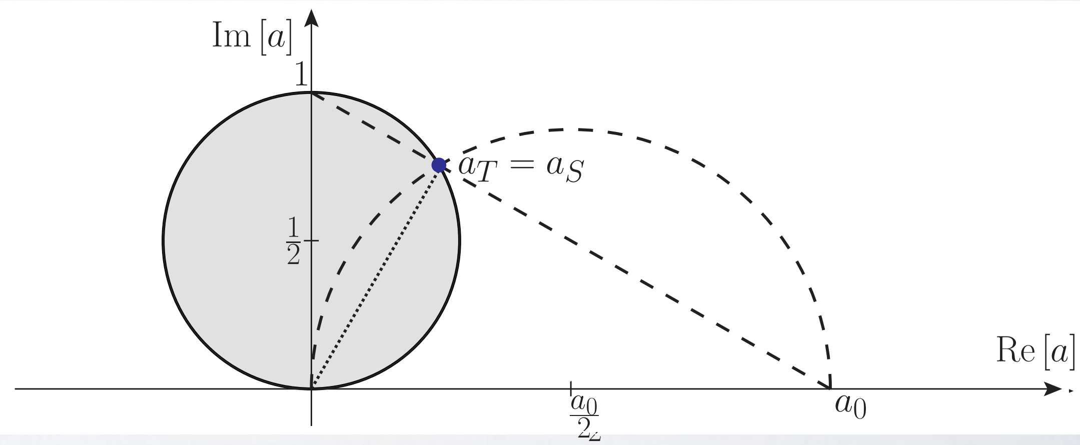


- Stereographic projection to Argand circle
- Formalism does a partial resummation of perturbative series
- need to construct (orig.) *K*-matrix as self-adjoint intermediate operator

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

- *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

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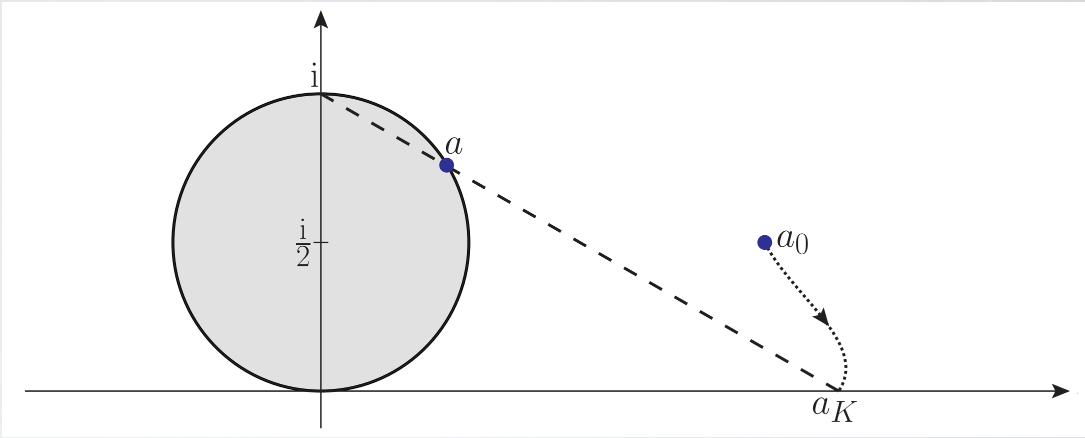

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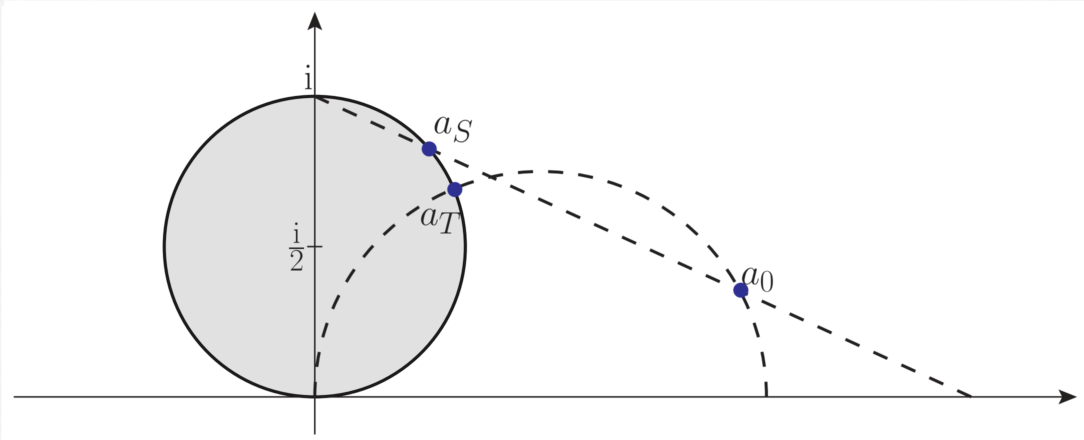

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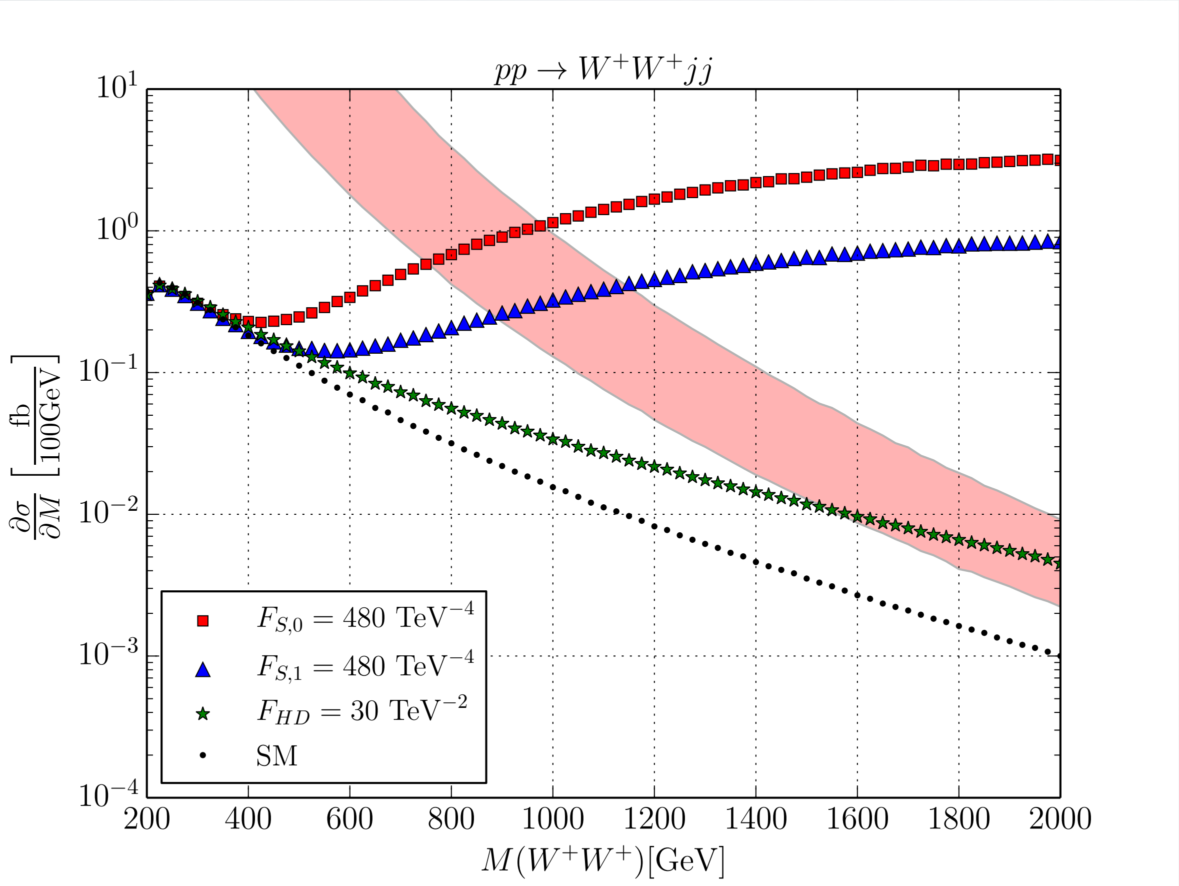
VBS diboson spectra



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:

$$\alpha_4 = \frac{f_{S,0}}{\Lambda^4}\frac{v^4}{16}$$
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General cuts: $M_{jj} > 500\,\mathrm{GeV};\ \Delta\eta_{jj} > 2.4;\ p_T^j > 20\,\mathrm{GeV};\ |\Delta\eta_j| < 4.5$

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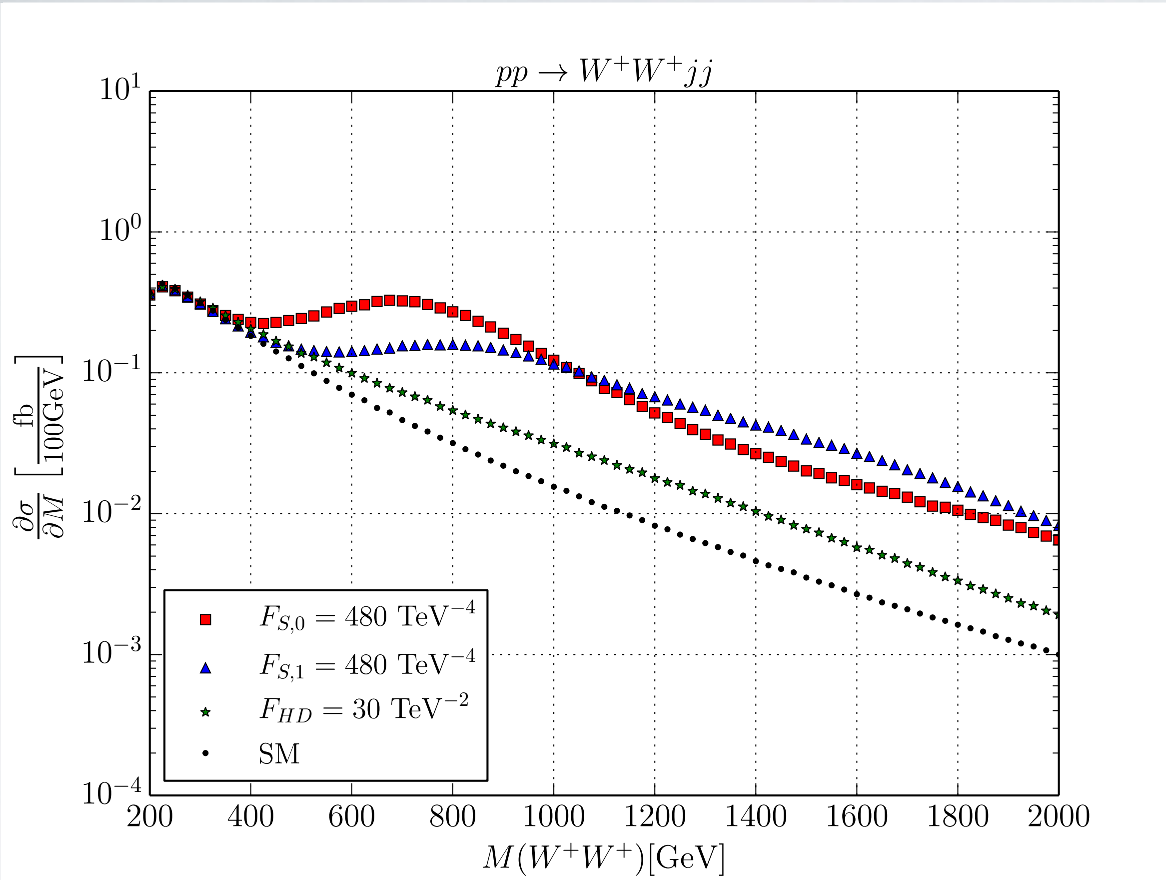

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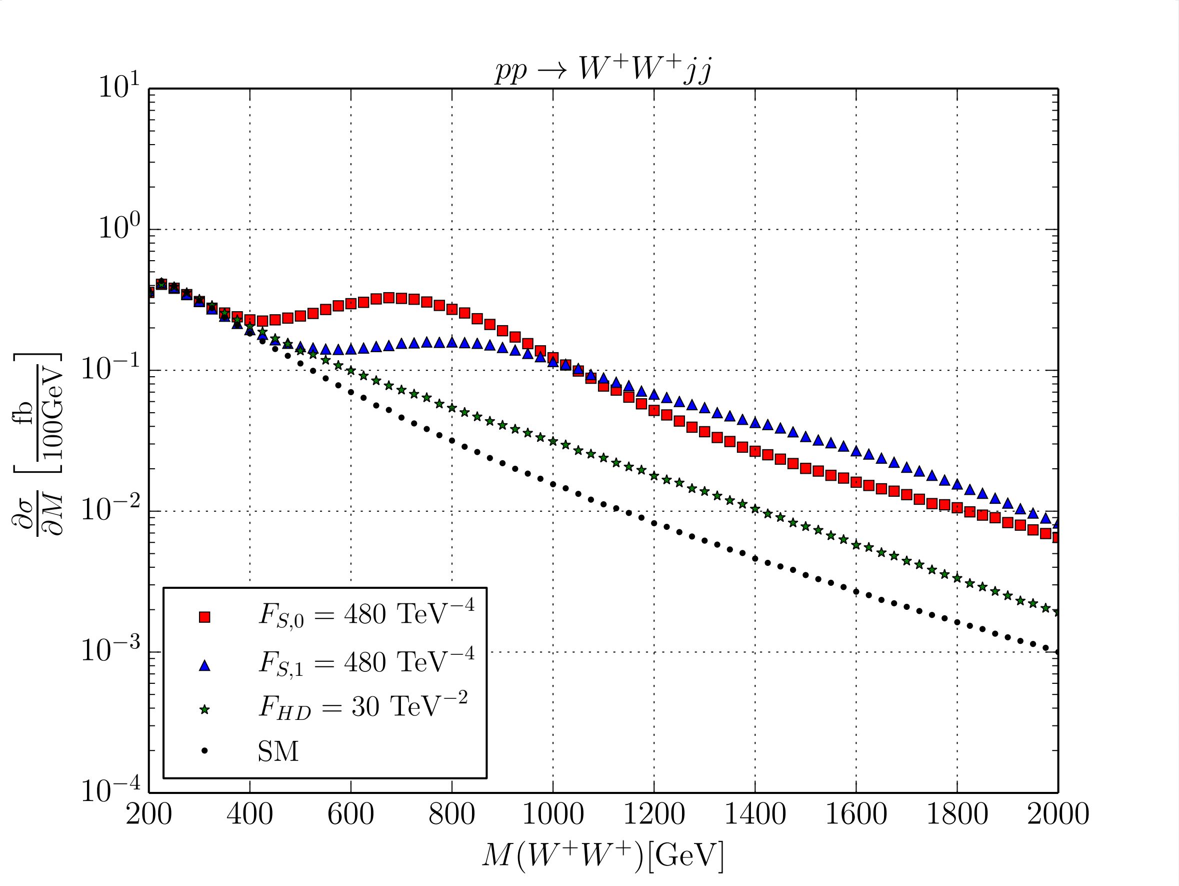

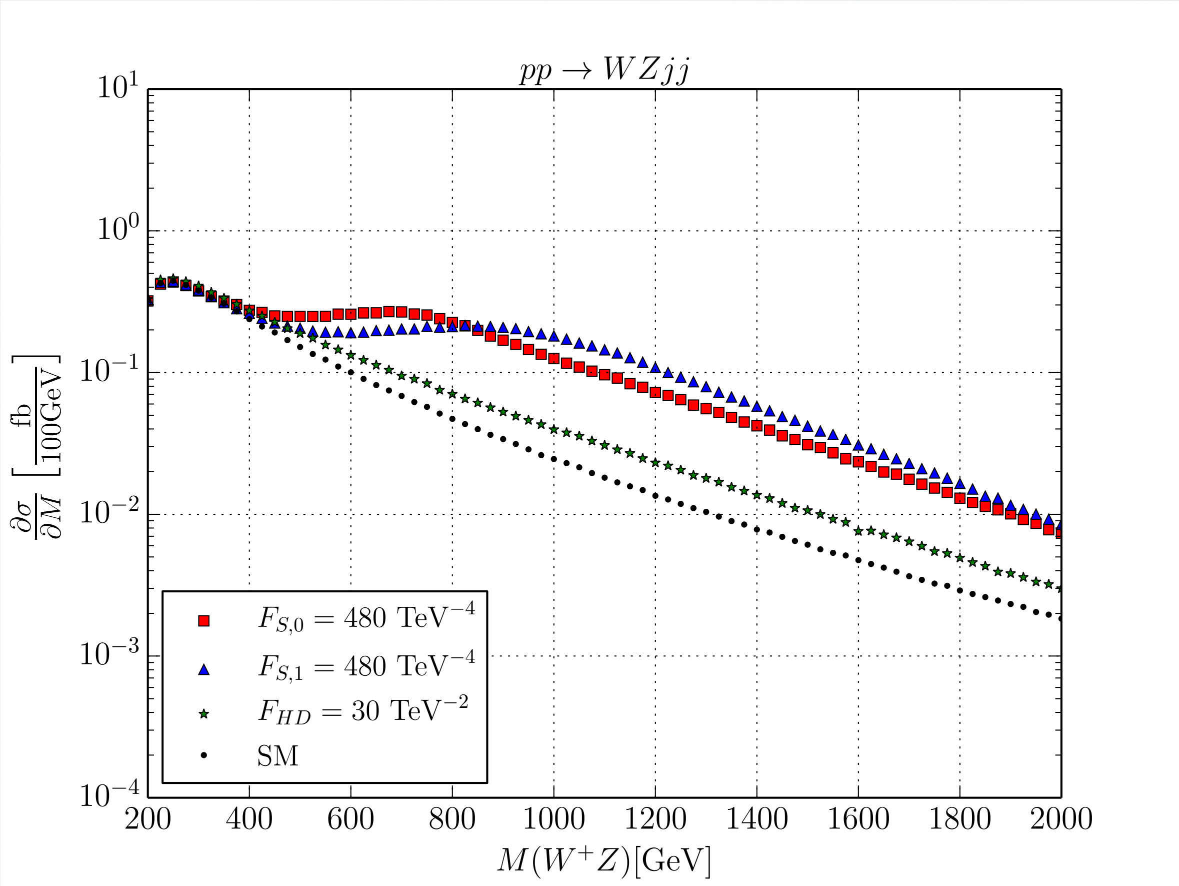

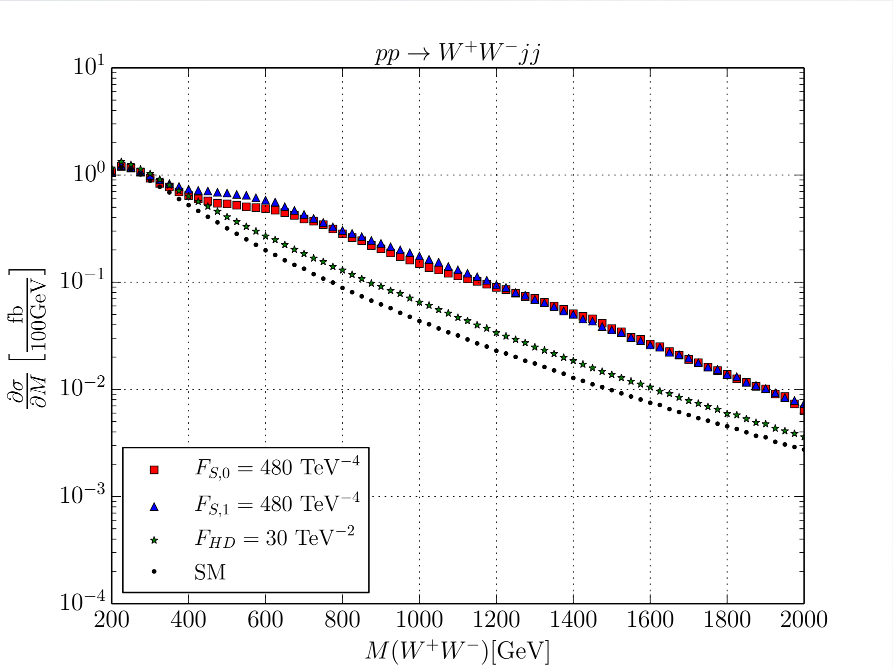

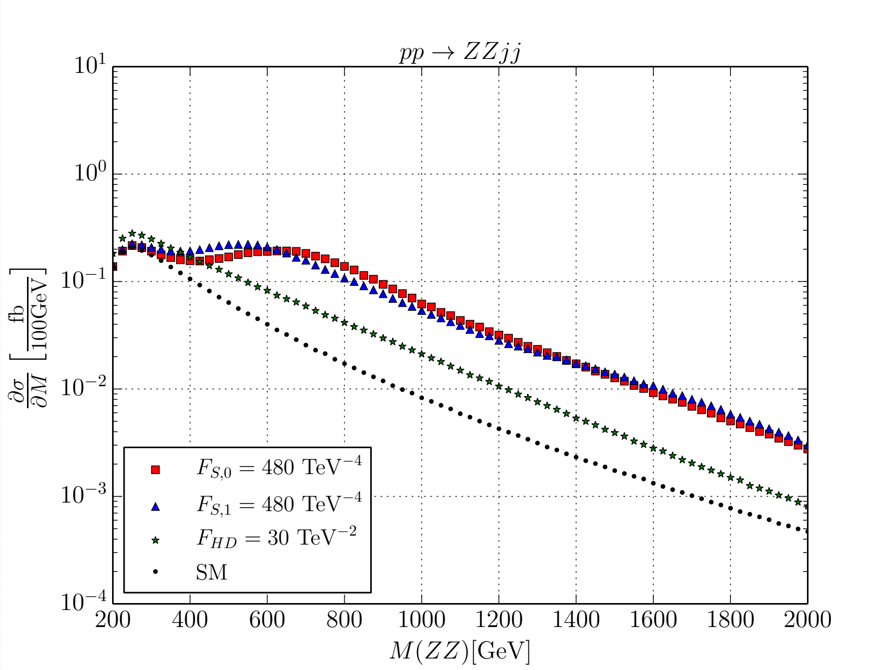

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Differential spectra in VBS

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

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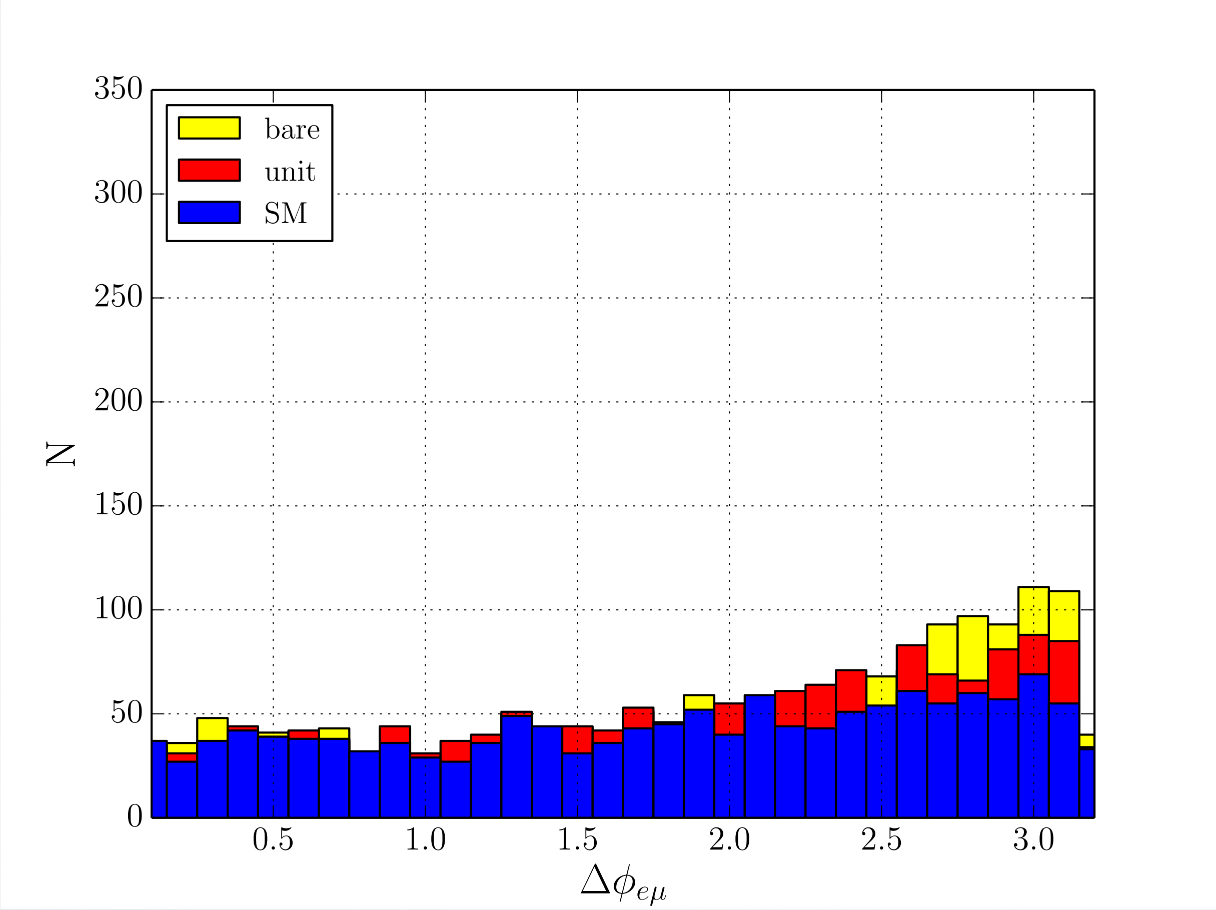

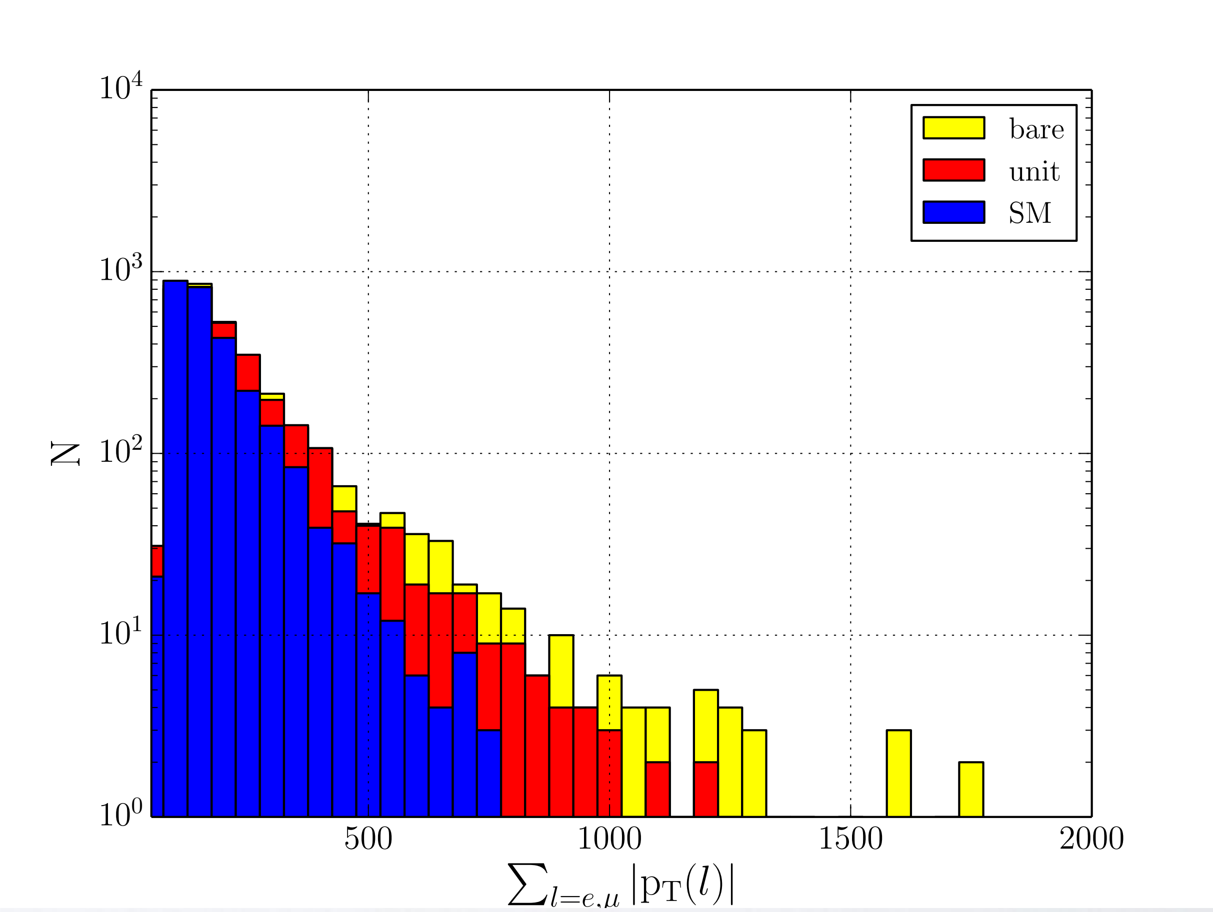

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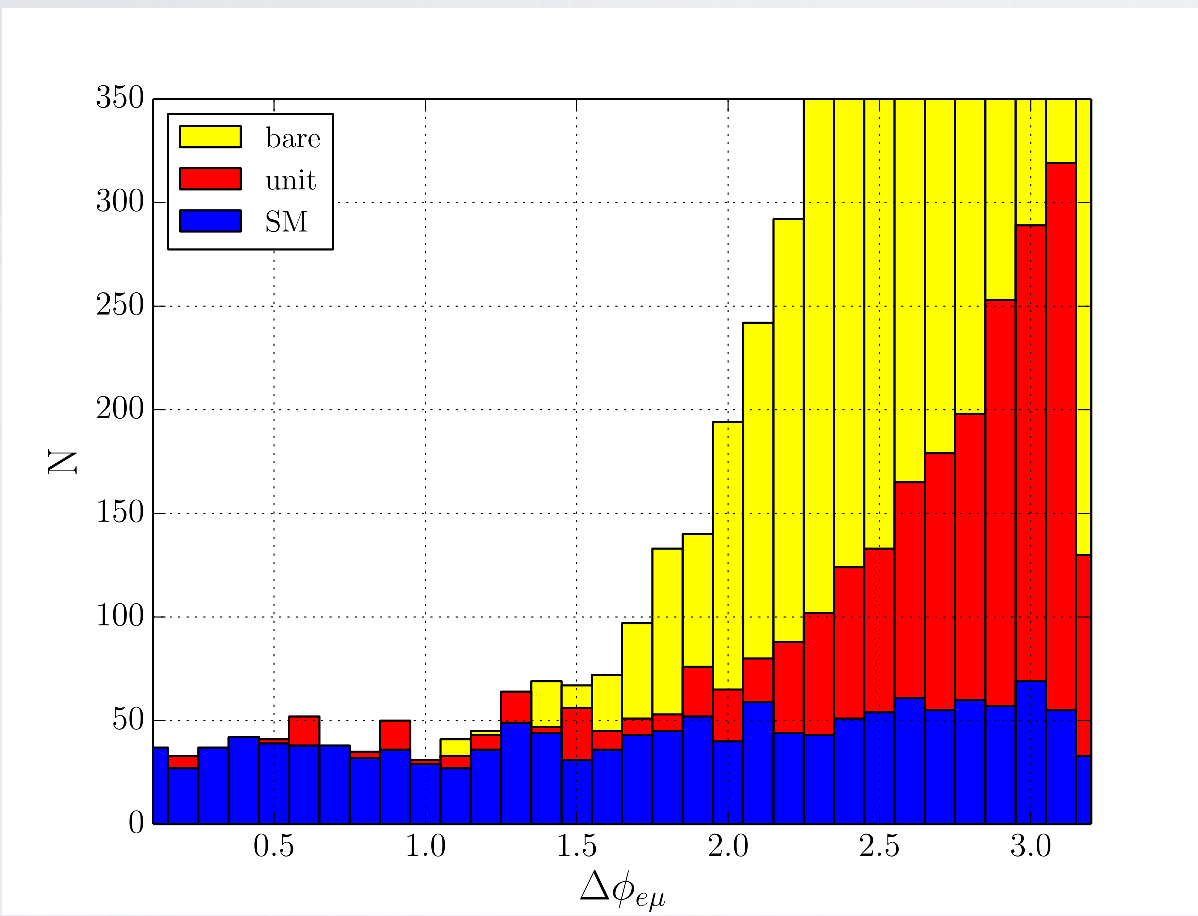

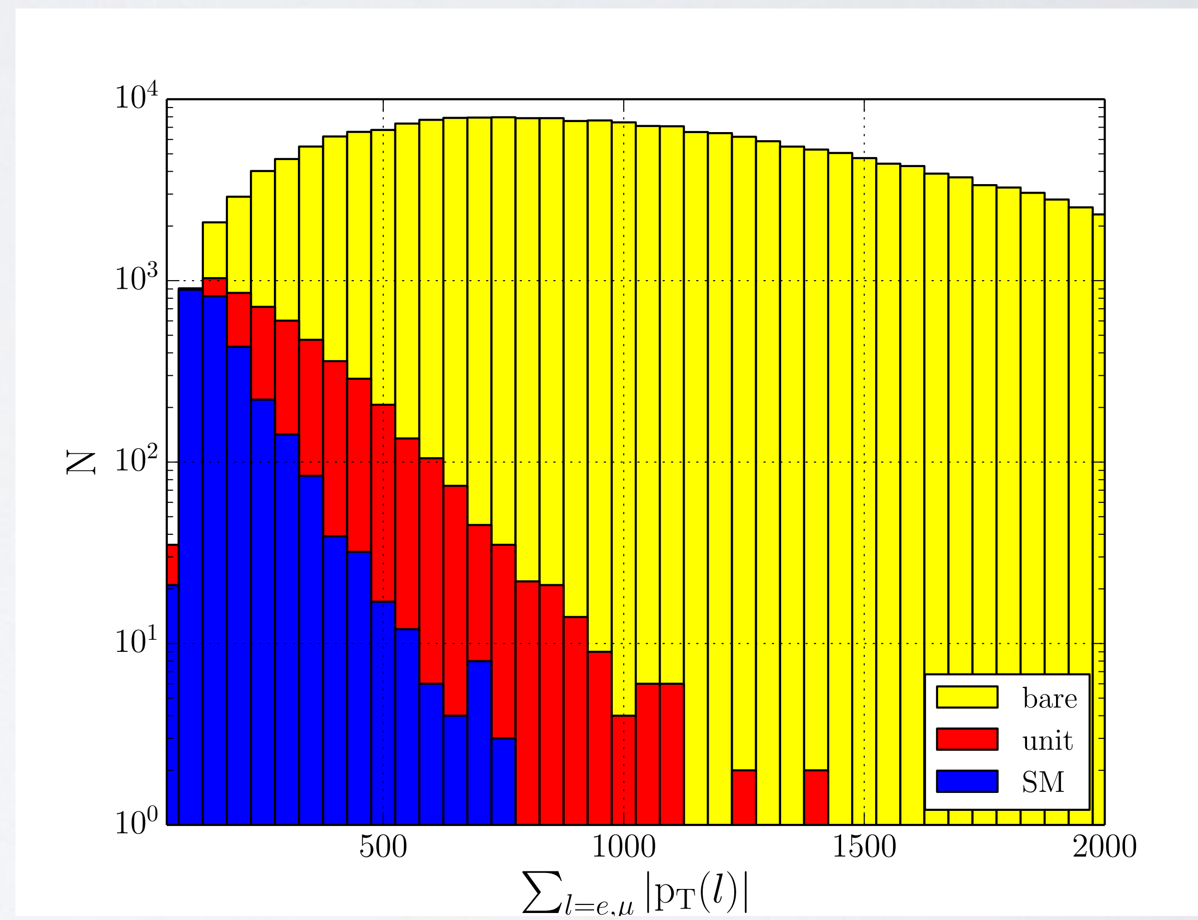

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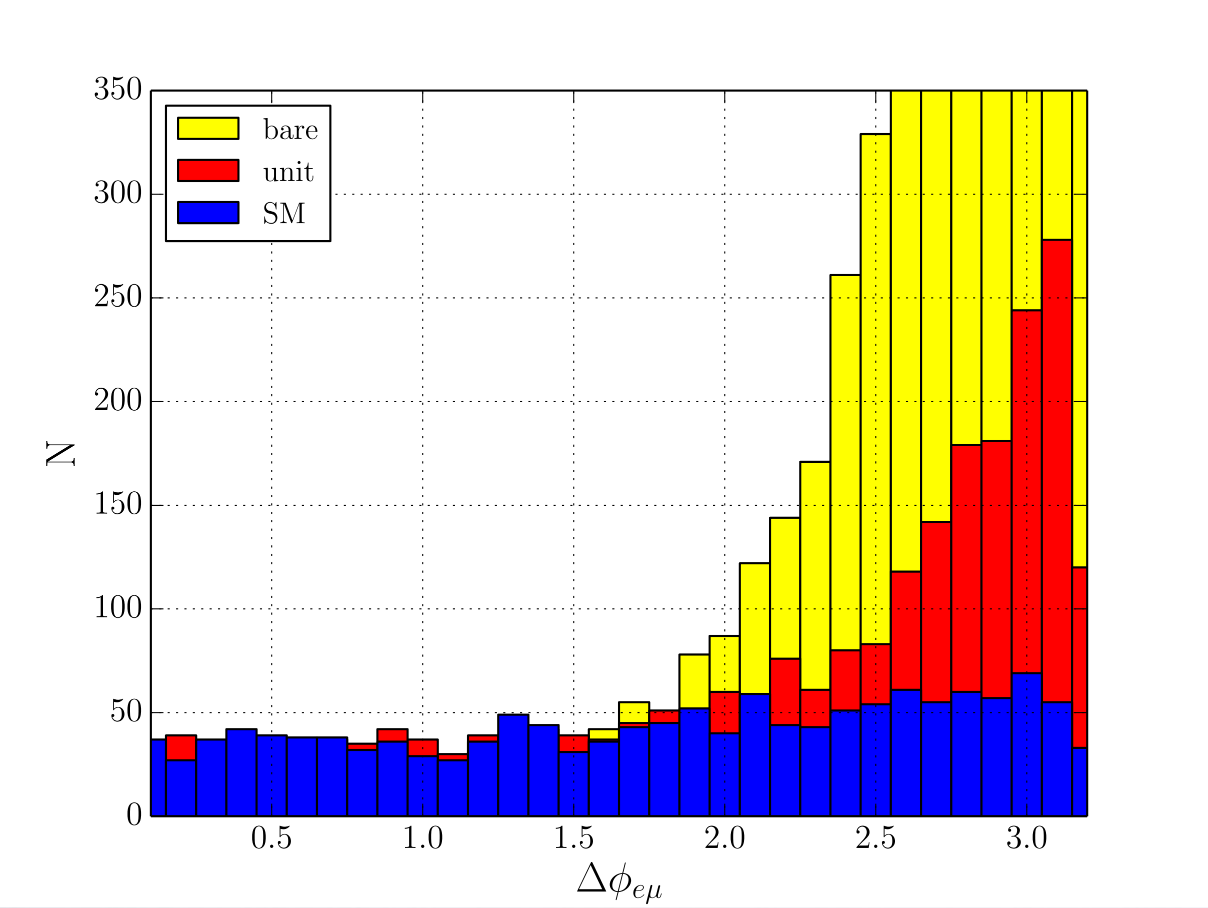

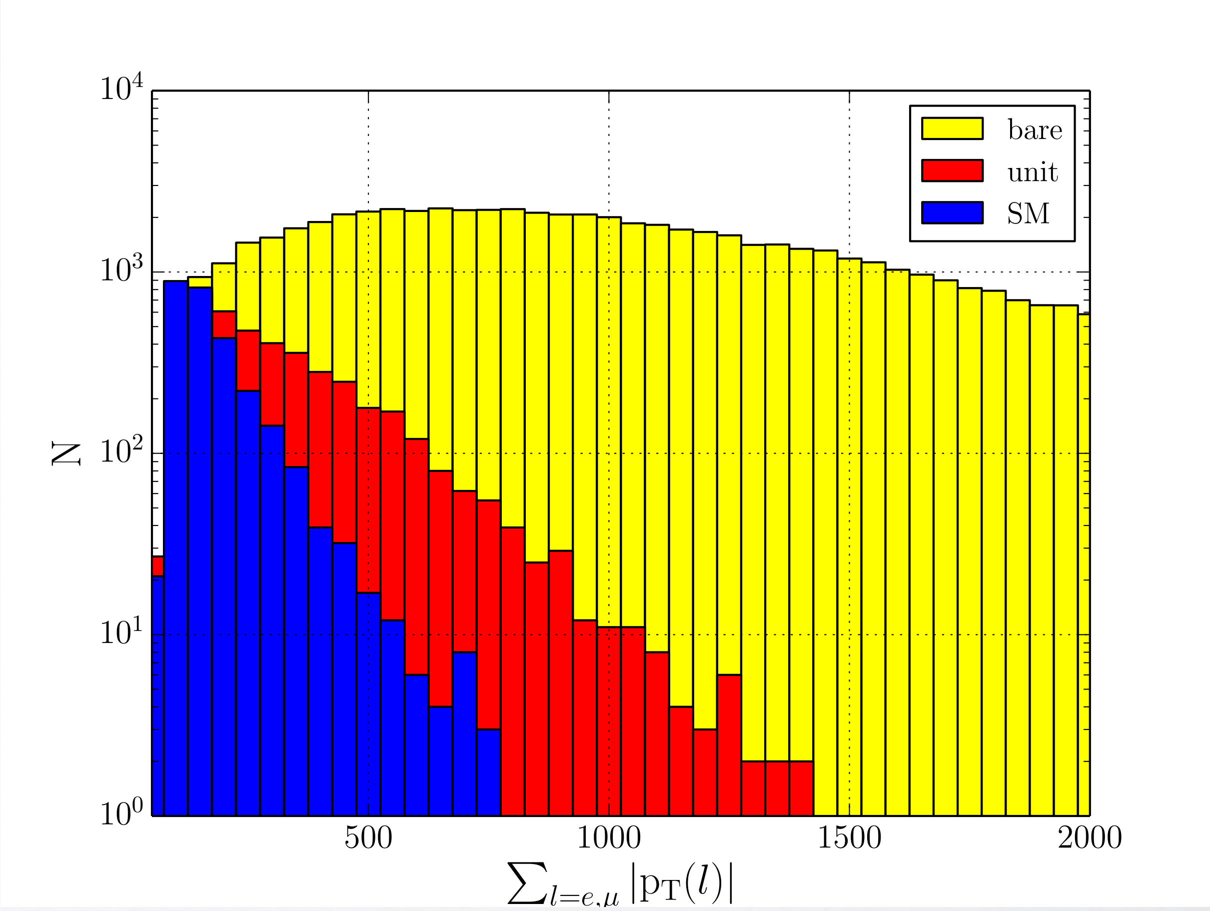

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Resonances: Quantum numbers & simplified models

- 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)
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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

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

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- Introduce compensator fields $\Rightarrow$ no propagators with momentum factors
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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: $f^\mu_{\ \mu}$

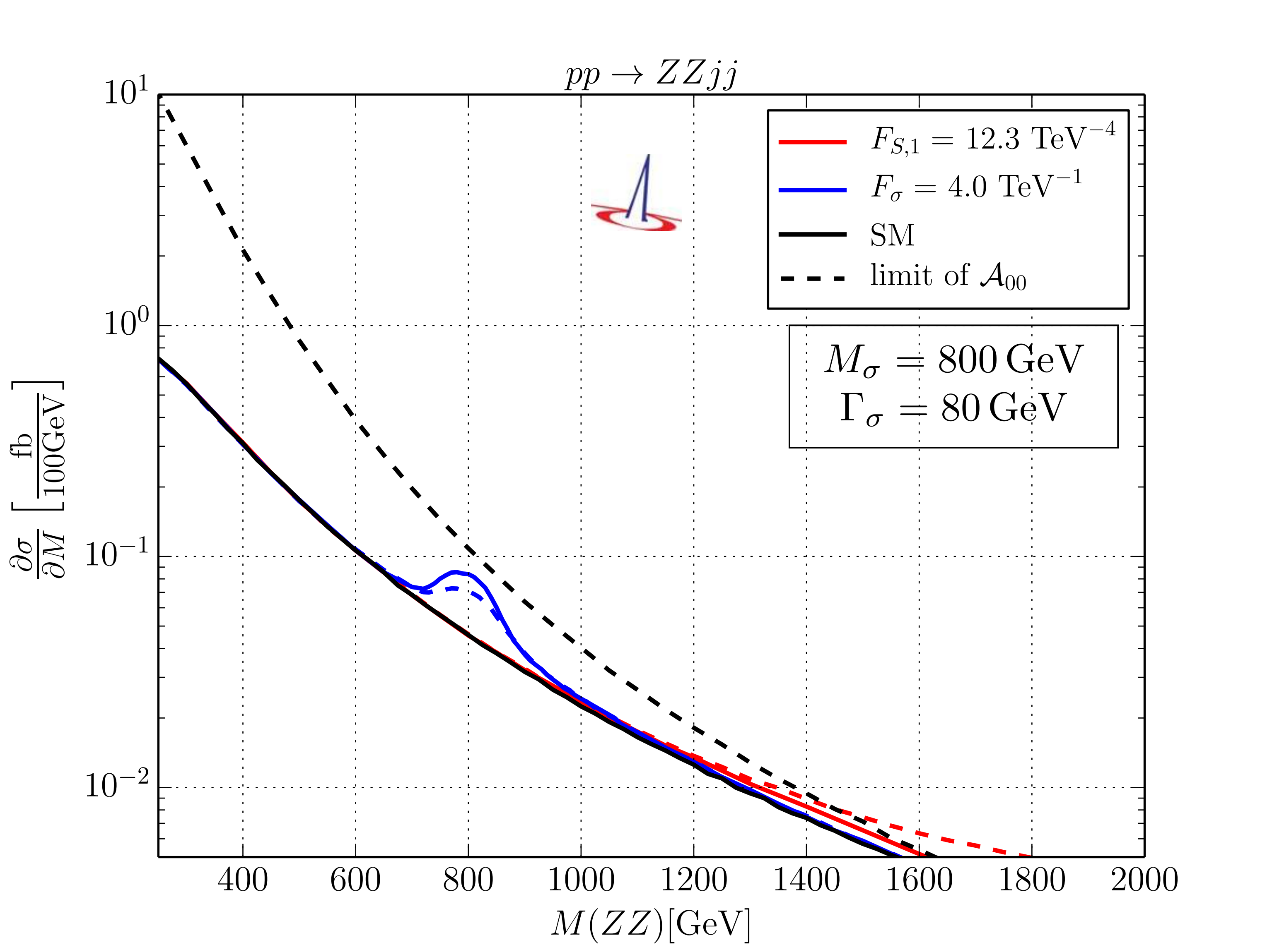
Gauge fixing: $\sigma = -\phi$

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

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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$32\pi\Gamma/M^5$

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

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

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

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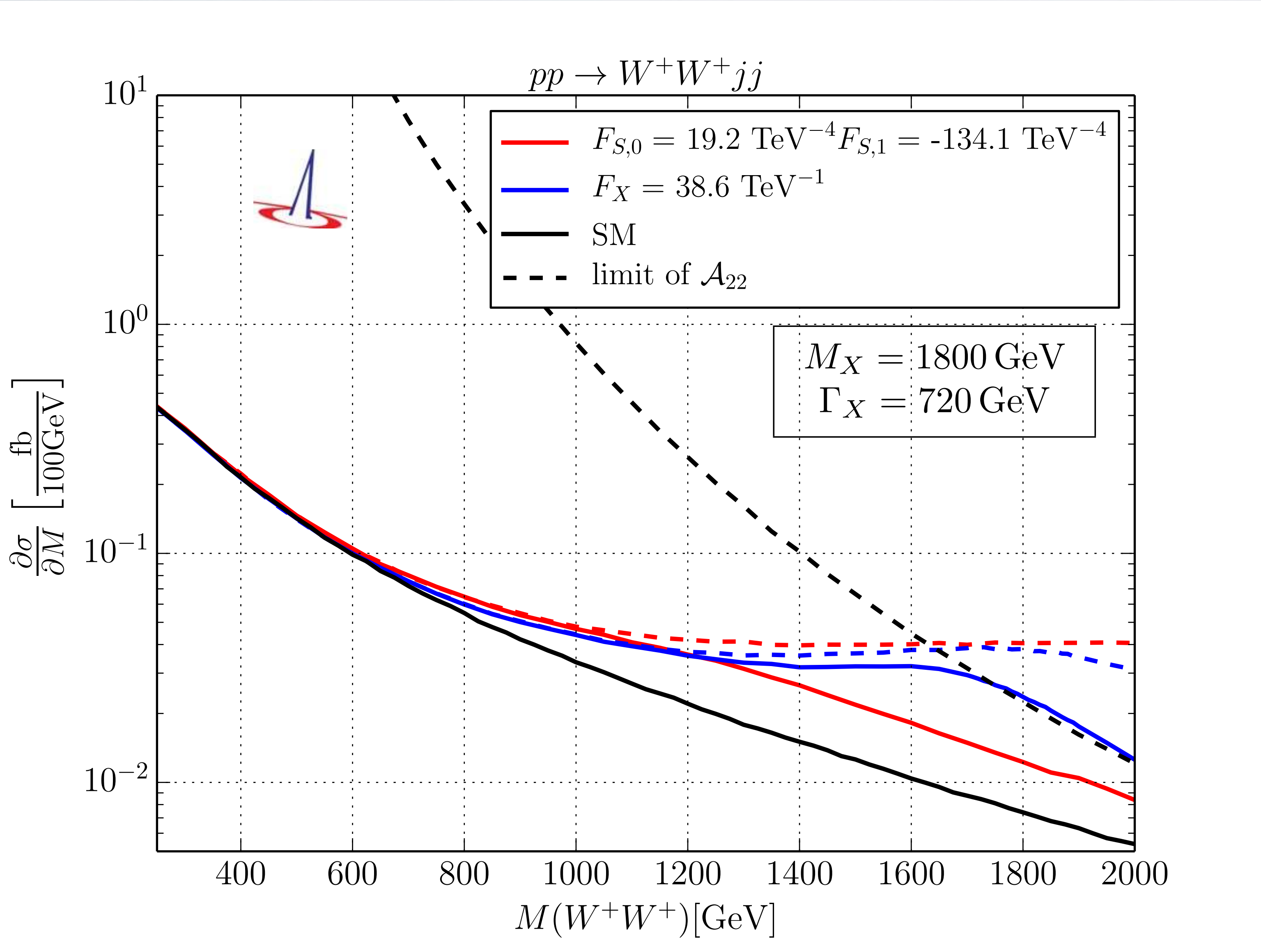

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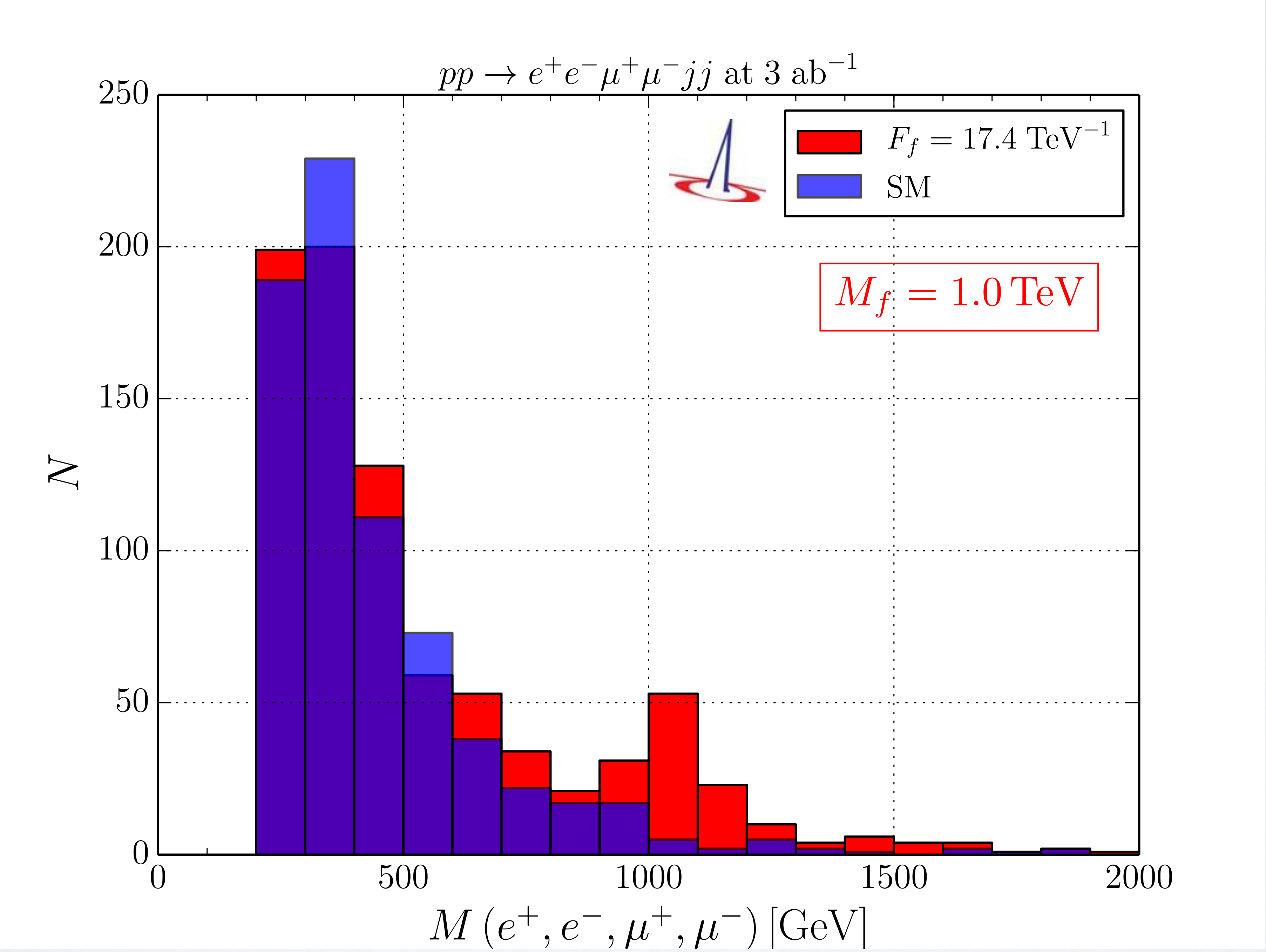
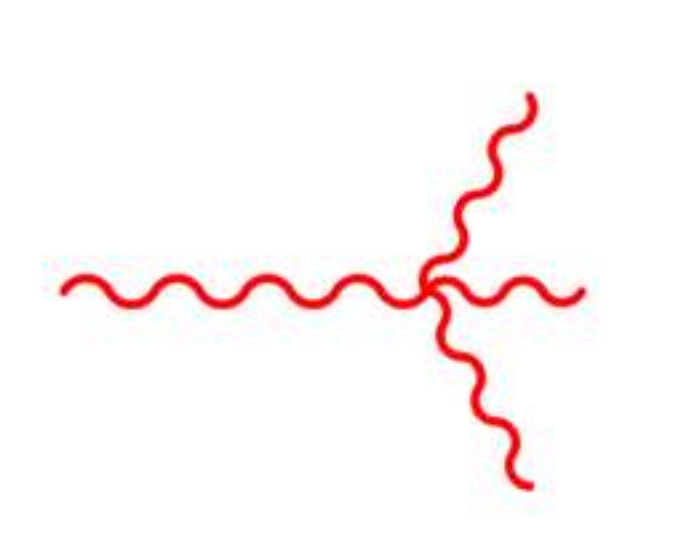
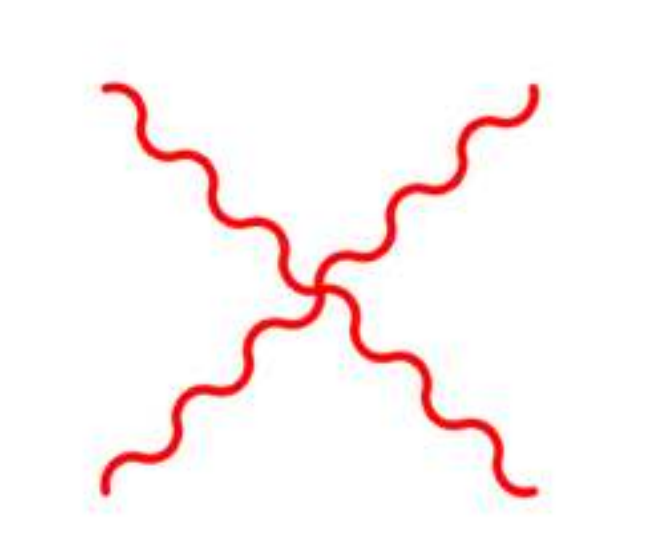
Complete LHC process at 14 TeV



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
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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

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light Higgs: also needs to be updated

ca. 1-3 TeV
[very preliminary]

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
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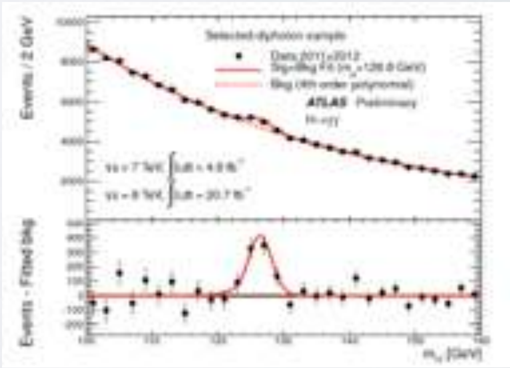
Ruled out by LHC data (Higgs discovery)



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!], ...)
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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)

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
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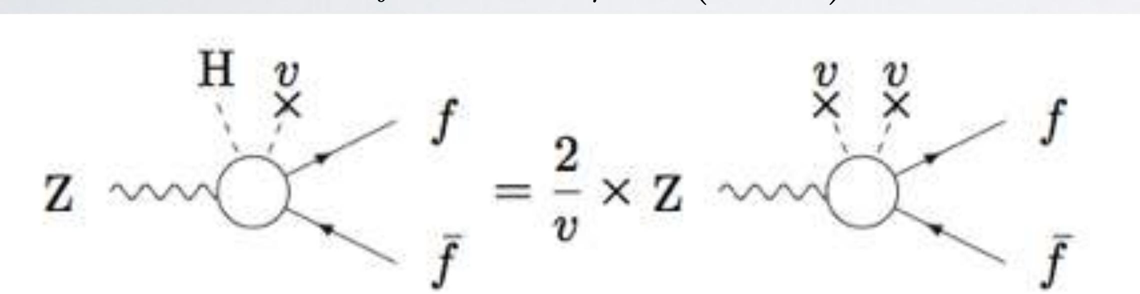

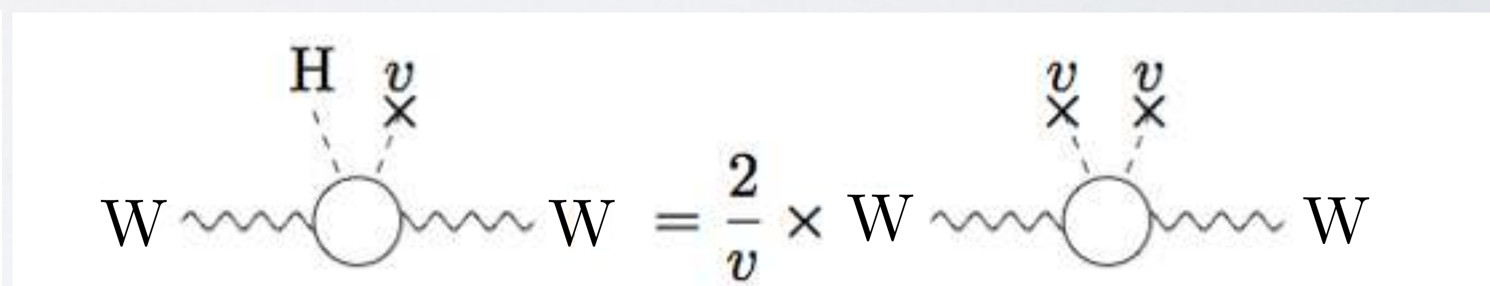

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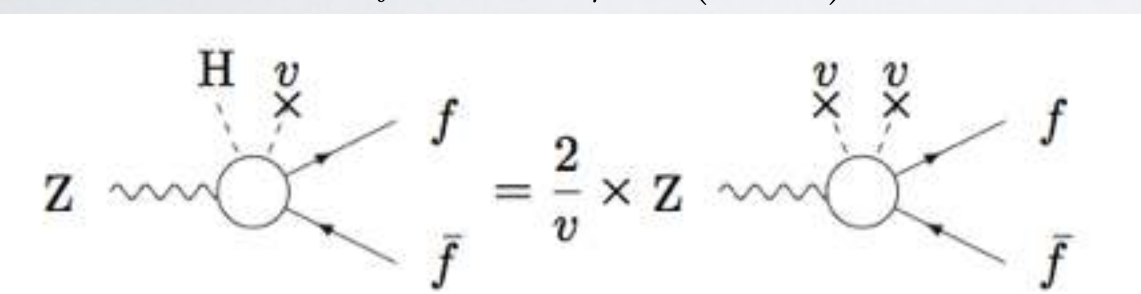

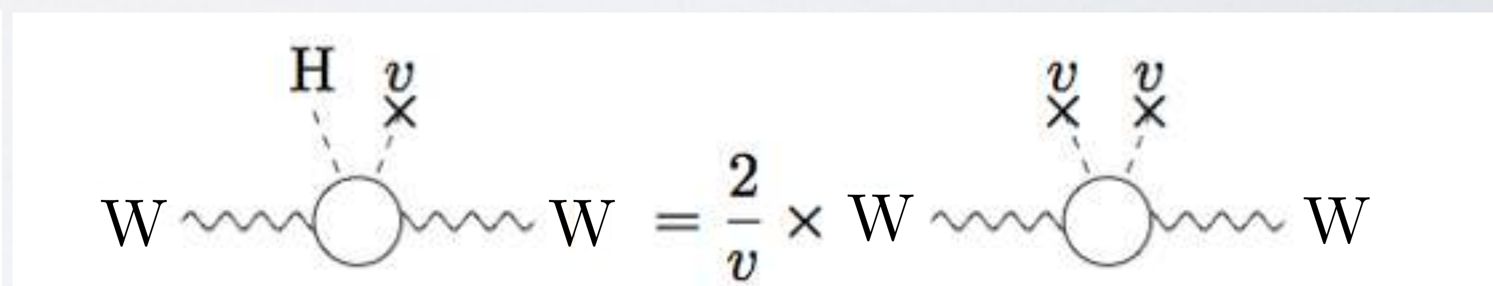

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- Often use *vev*-subtracted operators: $\mathcal{O}(\Phi^\dagger\Phi) \longrightarrow \mathcal{O}'(\Phi^\dagger\Phi - v^2)$
- EFT allows to systemically calculate higher-order corrections

How to get EFTs from New Physics

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

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- Toy Example: two interacting scalar fields φ, Φ

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

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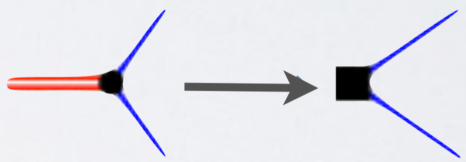

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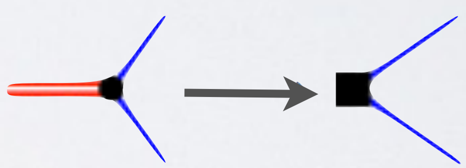
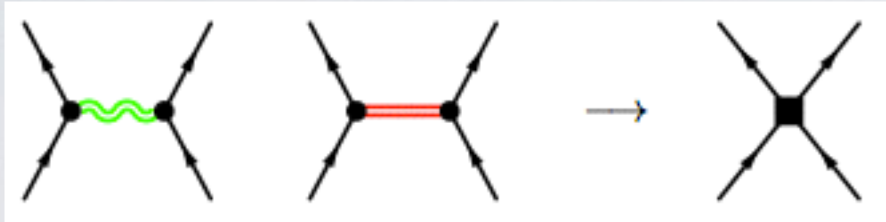


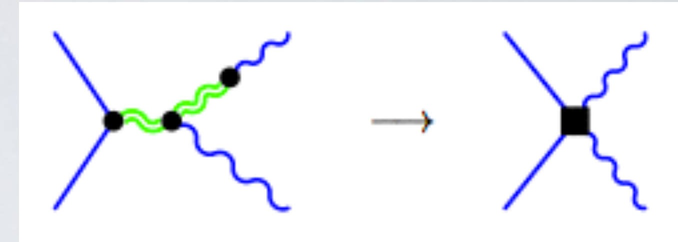
In the Lagrangian remove the high-scale d.o.f.s:

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

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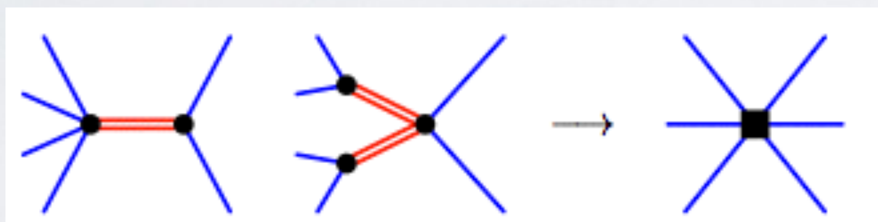
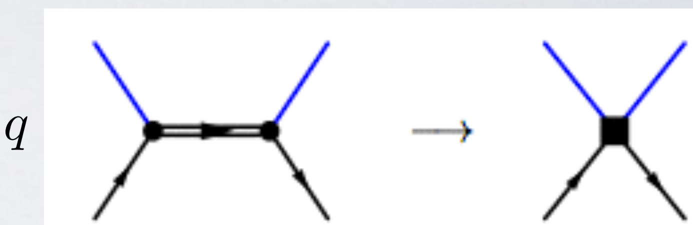
$$\mathcal{O}'_{\Phi,3} = \frac{1}{\Lambda^2}\frac{1}{3}(\Phi^\dagger\Phi - v^2/2)^3$$



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



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' ?)	$a^\pm, a^0$
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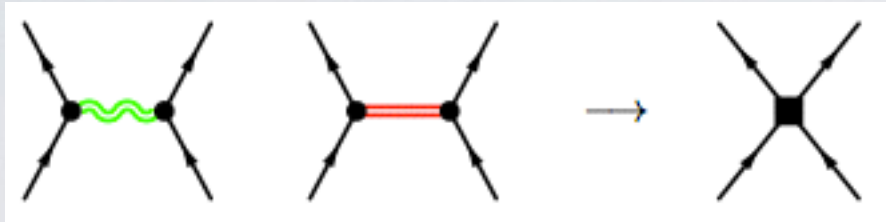

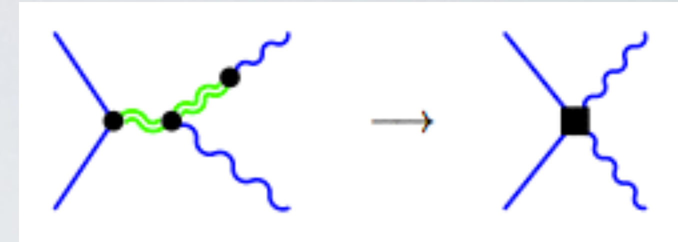

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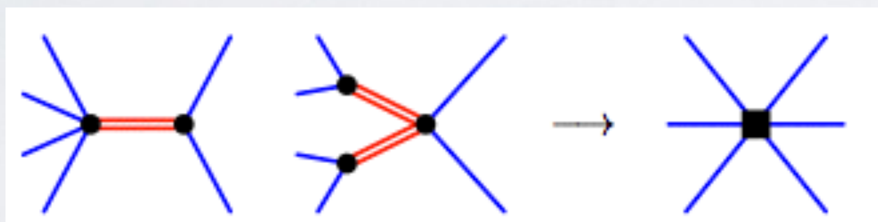

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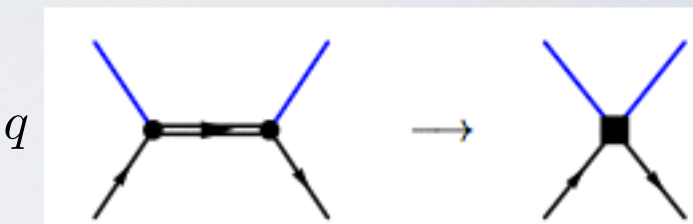

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Different power counting for weakly and strongly interacting theories

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