Electroweak Interactions at the Highest (Accessible) Energies

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Theory

New physics ...

- will explain EWSB?

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- will explain the hierarchy problem?
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$\Rightarrow$ ... maybe not.

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But is it complete?

Pragmatic Approach

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Cartography of the particle spectrum at/above the electroweak scale ($v = 100$ GeV $\rightarrow 1$ TeV)?

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- LEP could pair-produce particles up to < 100 GeV but with rather low luminosity.
- LHC as the discovery machine for TeV-scale colored particles hasn't discovered anything.
- ILC as the discovery machine for sub-TeV electroweak particles hasn't been built (yet).

Quantum Numbers

Start from $SU(3) \times SU(2)_L \times U(1)$ symmetry.
The LHC initial state has quantum numbers:

	S	C	I_L	$\lvert Y \rvert$
gg	$0, (1), 2$	$1, 8, 10, 27$	0	0
$q\bar{q}$	1	$1, 8$	$0, 1$	$1, 0$
	0	$1, 8$	$\frac{1}{2}$	$\frac{1}{2}$
qq	1	$3, 6$	$0, 1$	$\frac{1}{6}, \frac{1}{3}, \frac{2}{3}, \frac{4}{3}$
	0	$3, 6$	$\frac{1}{2}$	$\frac{1}{6}, \frac{5}{6}$

Decays typically hidden in QCD background.

Electroweak new physics

Look specifically at the EWSB (Higgs, Goldstone) sector. There is an approximate right-handed global symmetry in the SM Lagrangian.
Color-neutral, unsuppressed:

	S	I_L	I_R
$q_L\bar{q}_L$	1	0	0
	1	1	0
$q_R\bar{q}_R$	1	0	0
	1	0	1
$q_L\bar{q}_R$	0	$\frac{1}{2}$	$\frac{1}{2}$
	1	$\frac{1}{2}$	$\frac{1}{2}$

NB: the Higgs-doublet coupling is allowed but negligible (SM).

New Window: Vector-Boson Scattering (VBS)

Now add W and Z bosons as initial state:

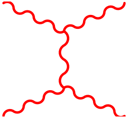
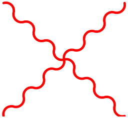
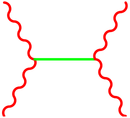
- high energy: decompose into $W_L/Z_L \sim \partial H$ and $W_T/Z_T = V$

	S	I_L	I_R
VV	$0,(1),2$	$0,1,2$	0
VH	$0,1,2$	$\frac{1}{2},\frac{3}{2}$	$\frac{1}{2}$
HH	1	1	0
	1	0	1
	$0,2$	0	0
	$0,2$	1	1

$\Rightarrow$ new window to new physics.

Anatomy of VBS

W_L, Z_L = Goldstone bosons = ∂H = factors rising with energy

$O(E^4)$  $+ O(E^4)$  $+ O(E^2)$  $= O(1)$

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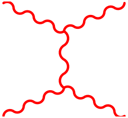
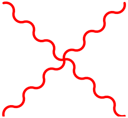
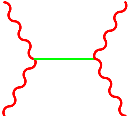
$O(E^4)$  $+ O(E^4)$  $+ O(E^2)$  $= O(1)$

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LHC: VBS discovered, consistent with SM (ATLAS 2014)

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Effective Field Theory

- Add higher-dimensional operators to the SM Lagrangian.
- Use only SM fields, respect SM gauge invariance
- Operator of dimension n carries prefactor $1/\Lambda^{n-4}$

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$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \sum_{d=5}^{\infty} \frac{1}{\Lambda^{n-4}} \mathcal{O}_n$$

Concrete Examples:

Anomalous Interactions

$$\mathcal{L}_{HD} = F_{HD}\ \mathrm{tr}\left[\mathbf{H}^\dagger\mathbf{H} - \frac{v^2}{4}\right] \cdot \mathrm{tr}\left[(\mathbf{D}_\mu\mathbf{H})^\dagger (\mathbf{D}^\mu\mathbf{H})\right] \qquad HVV \quad D = 6$$

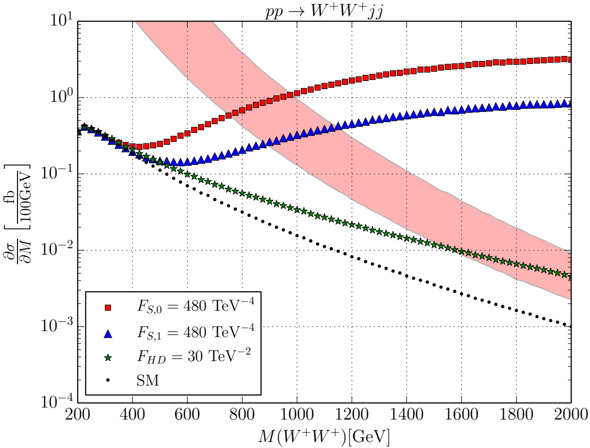
$$\mathcal{L}_{S,0} = F_{S,0}\ \mathrm{tr}\left[(\mathbf{D}_\mu\mathbf{H})^\dagger \mathbf{D}_\nu\mathbf{H}\right] \cdot \mathrm{tr}\left[(\mathbf{D}^\mu\mathbf{H})^\dagger \mathbf{D}^\nu\mathbf{H}\right] \qquad VVVV \quad D = 8$$

$$\mathcal{L}_{S,1} = F_{S,1}\ \mathrm{tr}\left[(\mathbf{D}_\mu\mathbf{H})^\dagger \mathbf{D}^\mu\mathbf{H}\right] \cdot \mathrm{tr}\left[(\mathbf{D}_\nu\mathbf{H})^\dagger \mathbf{D}^\nu\mathbf{H}\right] \qquad VVVV \quad D = 8$$

Linear Higgs/Goldstone Field Representation:

$$\mathbf{H} = \frac{1}{2}\begin{pmatrix} v + h - \mathrm{i}w^3 & -\mathrm{i}\sqrt{2}w^+ \\ -\mathrm{i}\sqrt{2}w^- & v + h + \mathrm{i}w^3 \end{pmatrix} \qquad . \tag{1}$$

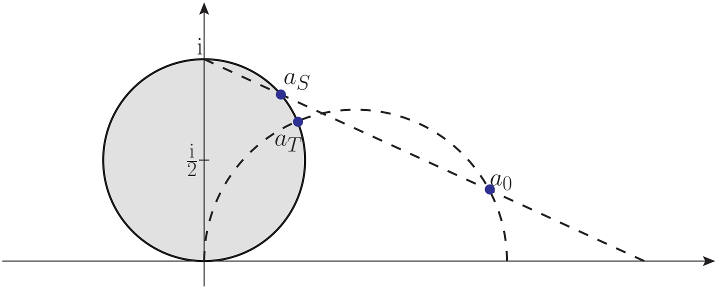
Nice, but. . .



Calculation: WHIZARD

Enforcing Unitary Scattering

Start from complex amplitude a_0:

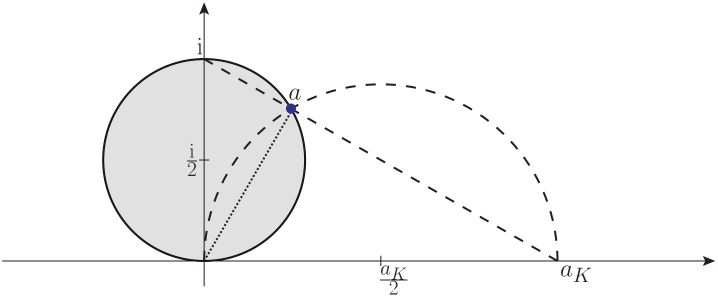


⇒ No reference to perturbative expansion, arbitrary model features

⇒ But scheme dependence for complex a_0

Enforcing Unitary Scattering

Start from real amplitude $a_0 = a_K$: Thales circle projection



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⇒ But scheme dependence for complex a_0

⇒ Unitary amplitude a_0 left invariant

Unitarization for the scattering operator

Linear Construction "Stereographic"

$$T = \frac{\mathrm{Re}\, T_0}{\mathbb{1} - \frac{\mathrm{i}}{2} T_0^\dagger}.$$

for normal matrices ($T^\dagger T = T T^\dagger$), otherwise need operator ordering

Circular Construction "Thales"

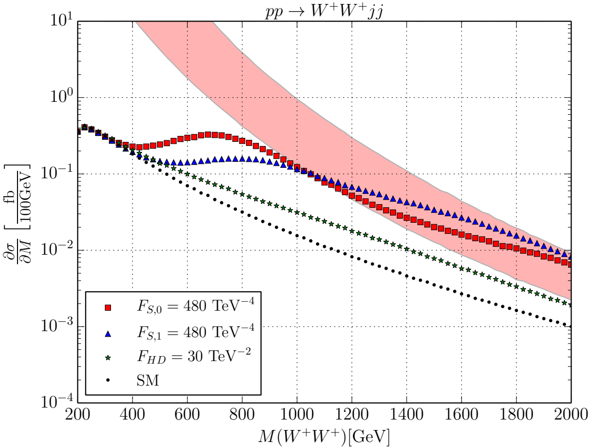
$$T = \frac{1}{\mathrm{Re}\left(\frac{1}{T_0}\right) - \frac{\mathrm{i}}{2}\mathbb{1}} \qquad .$$

Algorithm

1. Start with input model
2. Current calculations:

   Extract strong-interaction part in Goldstone limit, finite scattering matrix
3. Unitarize via T Matrix projection
4. Re-insert correction as form factor into Feynman rules
5. Extrapolate off-shell
6. Use in Monte Carlo simulation

Result: Unitarized Cross Section



Calculation: WHIZARD

Resonance models

This construction saves, first of all, the EFT. But:

- If there is a deviation large enough for LHC, we have strong interactions
- Structureless saturation of unitarity at high energy

Additional feature: Resonance / new particle

- Peak with
  1. weakly interacting limit (small width)
  2. strongly interacting limit (saturation)
  3. decoupling limit (EFT)

Simplified Models: Generic Resonances

Include global $SU(2)_R$ = custodial symmetry

(I_L, I_R)	$(0,0)$	$(1,0)$	$(0,1)$	$(1,1)$
$J=0$	σ^0	.	.	$\phi^{\pm,0}, \chi^{\pm\pm,\pm,0,0}$
1	.	W'_L/Z'_L	W'_R/Z'_R	.
2	f^0	.	.	$t^{\pm,0}, t^{\pm\pm,\pm,0,0}$
...	...	...	...	

- $I=(0,0)$: resonant in W^+W^- and ZZ scattering
- $I=(1,1)$: resonant also in $W^\pm Z$ and $W^\pm W^\pm +$ scattering

The Tensor Is Special

Massive spin-2 field in relativistic quantum field theory

On-shell: $SO(3)$ rotation group in rest frame: 5 polarization components

Off-shell: $SO(3) \times SO(3)$ Lorentz group: 10 components of symmetric tensor

- $\Rightarrow$ 5 components: genuine tensor, couples to current $J_{\mu\nu}$
- $\Rightarrow$ 3 components: vector, couples to divergence $\partial^\mu J_{\mu\nu}$
- $\Rightarrow$ $1 + 1$ components: 2 scalars, couple to J^μ_μ and $\partial^\mu \partial^\nu J_{\mu\nu}$

Embedded in Standard Model: $\partial_\mu \to D_\mu$

Tensor Lagrangian: Fierz-Pauli

$$\mathcal{L} = \frac{1}{2}\partial_\alpha f_{\mu\nu}\partial^\alpha f^{\mu\nu} - \frac{1}{2}M^2 f_{\mu\nu}f^{\mu\nu} - \partial^\alpha f_{\alpha\mu}\partial_\beta f^{\beta\mu} - f^\alpha_{\ \alpha}\partial^\mu\partial^\nu f_{\mu\nu} - \frac{1}{2}\partial_\alpha f^\mu_{\ \mu}\partial^\alpha f^\nu_{\ \nu} + \frac{1}{2}M^2 f^\mu_{\ \mu} f^\nu_{\ \nu} + f_{\mu\nu}J_2^{\mu\nu}.$$

$\Rightarrow$ resonant terms apparently rising with (s/M^2)

Tensor Lagrangian: Stückelberg

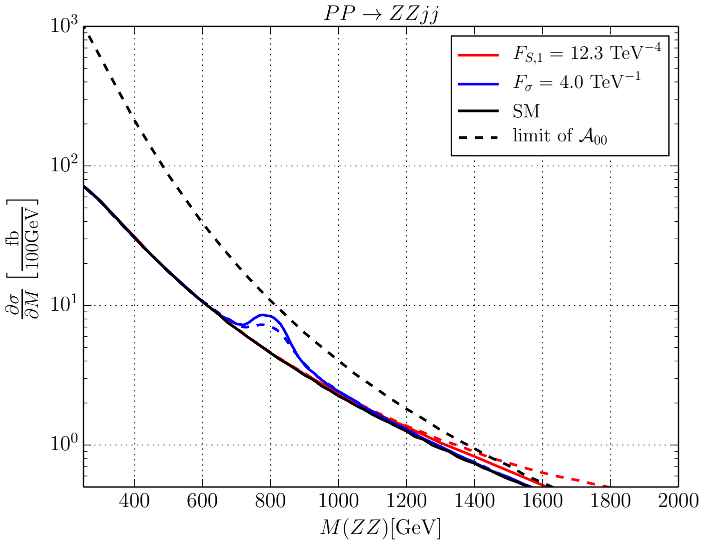
$$
\begin{aligned}
\mathcal{L} =& \frac{1}{2} f_{\mu\nu} \left(-\partial^2 - M^2\right) f^{\mu\nu} \\
&+ \frac{1}{2} f^{\mu}_{\ \mu} \left(-\frac{1}{2}\left(-\partial^2 - M^2\right)\right) f^{\nu}_{\ \nu} \\
&+ \frac{1}{2} A_{\mu} \left(-\partial^2 - M^2\right) A^{\mu} \\
&+ \frac{1}{2} \sigma \left(-\partial^2 - M^2\right) \sigma \\
&+ \left(f_{\mu\nu} - \frac{1}{\sqrt{6}} g^{\mu\nu} \sigma + \frac{1}{\sqrt{2}M} \left(\partial_\mu A_\nu + \partial_\nu A_\mu\right) + \frac{\sqrt{2}}{\sqrt{3}M^2} \partial_\mu \partial_\nu \sigma \right) J_f^{\mu\nu}.
\end{aligned}
$$

⇒ resonant terms rising with s suppressed by $m = m_W, m_Z, m_H$ factors.

⇒ other terms are nonresonant.

⇒ energy range beyond the resonance can be controlled

Results for LHC: Scalar



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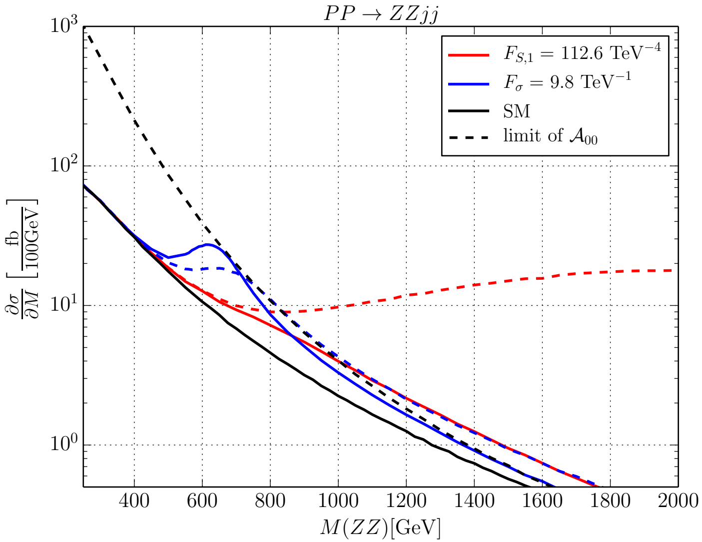

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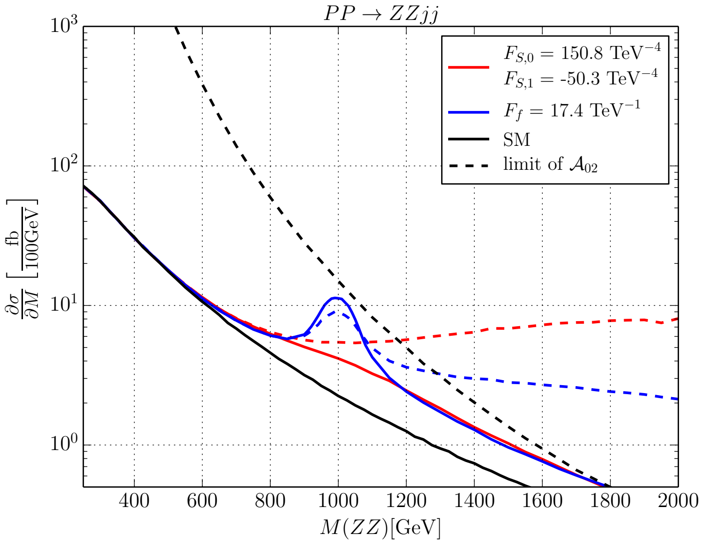

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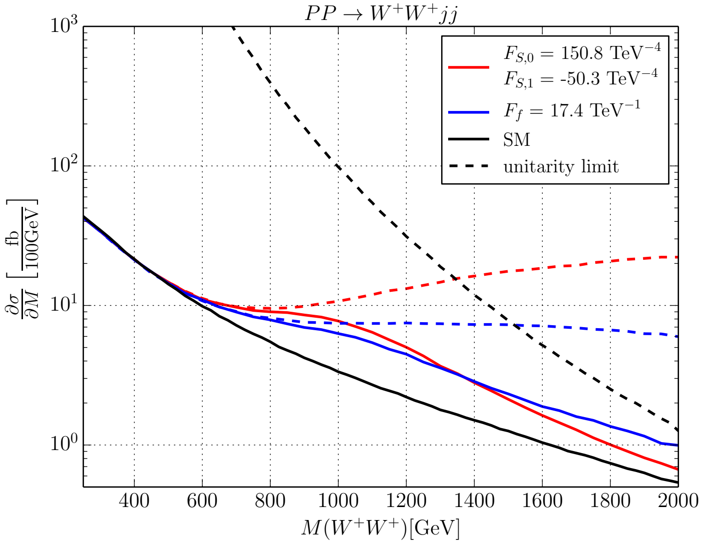

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- Effective theory: limited in scope
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$\Rightarrow$ Direct T-Matrix unitarization as catch-all scheme for new models

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- Unitary EFT extrapolation implies strongly interacting scenario
- Incorporating resonances allows interpolation to weakly interacting NP