The effective W approximation for the WW scattering and new physics

arXiv:11mm.xxxx **(results at the cross-section level)**
arXiv:12mm.xxxx **(results at the amplitude level (this talk))**

a work in progress
with
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Outline

Motivation

- Factorization in QFT
- The importance of the scattering of W bosons

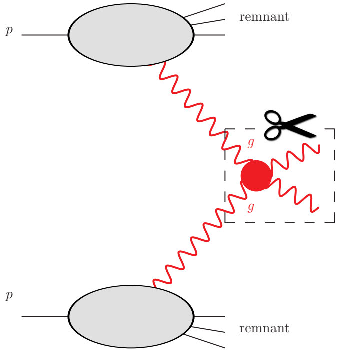
Results: $WW \to WW$ scattering from the process $qq \to qqWW$

- High energy behavior of the WW scattering amplitudes
- corrections to the EWA at the amplitude-level
- EWA and the exact amplitude

Conclusions

- Outlook on WW scattering

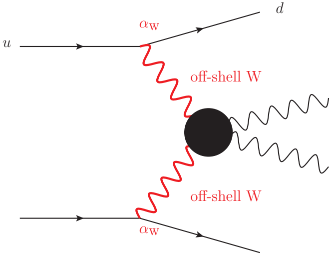
Factorization

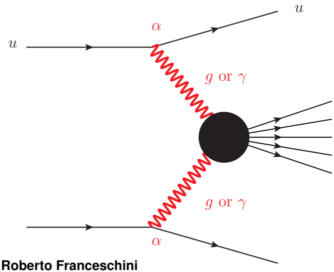


Field theory question

How this generalizes to the massive case?

Analogous, but quite different





Qualitively different

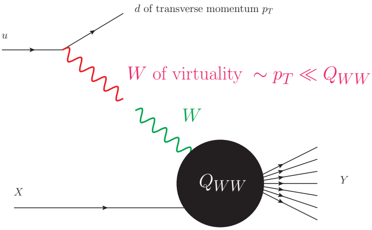
- the W is never on-shell $p_W^2 = (p_u - p_d)^2 < 0 < m_W^2$
- a third polarization mode, $\epsilon_L \sim \frac{E}{m}$
- the new mass scale m_W

Quantitative matter

- The energy of LHC is finite
- $\sigma(pp \to WWjj)$ only few fb

... you are asking for a beam of W bosons(!)

- our source of W is $f \to f' W^*$
- $ff \to f'f' W^* W^* \to X_{WW}\, f'f'$



Effective W Approximation: (Fermi ’24, Weizsäcker, Williams ’34, Cahn, Chanowitz, Dawson, Gaillard, Kane, Repko, Rolnick ’84-’85)

- each W^* has virtuality V $= \sqrt{m_W^2 - (p_f - p_{f'})^2} \sim \sqrt{p_T^2 + m_W^2}$
- $W^* W^* \to X_{WW}$ of virtuality $Q_{WW} \sim E$

$t_{hard} \sim \frac{1}{Q_{WW}} \ll \Delta t_W \sim \frac{1}{\Delta E} \sim \frac{E}{V^2}$

- $V \ll Q_{WW}$

for $ff \to ffWW$

- $p_{T,f'} \ll p_{T,W^{out}}$ and $m_W \ll p_{T,W^{out}}$

that’s pure kinematics!

- factorization of a hard (fast) process and a soft (slow) process
- expansion in $V/Q_{WW} \simeq p_{T,jet}/p_{T,W}$

Why I care so much about processes initiated by W bosons?

Status of the EWSB

A $SU(2) \times U(1)$ gauge theory

- the interactions of the Z and the W with the fermions (LEP, g-2, ...)
- the interactions among Z and W (LEP trilinear coupling, ...)

- we observed massive W and Z bosons
- $m_W = m_Z \cos \theta_W$

$SU(2) \times U(1)_Y$ is spontaneously broken

- there are three Goldstone bosons eaten by W and Z

---

all the observations fit with Goldstone bosons $\pi^{a=1,2,3}$ described by

$$\Sigma \equiv e^{\imath \sigma_a \frac{\pi^a}{v}}$$

that transforms

$$\Sigma \to L \Sigma R^\dagger$$

under $SU(2)_L \times SU(2)_R$ symmetry

$\mathcal{L} = \frac{v^2}{4} \mathrm{Tr}(D_\mu \Sigma D^\mu \Sigma)$

- the analog of the pions chiral lagrangian

Goldstone scattering

We know that there are Goldstone bosons and their interactions, can we make a prediction?

Goldstone scattering

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Yes

Goldstone scattering: is weak or strong?

$$\mathcal{L} = \frac{v^2}{4}\mathrm{Tr}(D_\mu \Sigma D^\mu \Sigma)$$

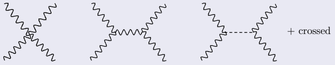
$$\mathcal{A}(\pi\pi \to \pi\pi) \sim \frac{s}{v^2}$$

- a weakly coupled moderator of the growth of the amplitude at high energy must appear
- the Goldstone bosons are strongly coupled

- establishing if the Goldstones experience a strong or a weak force is a goal for the LHC
- best done in terms of $WW \to WW$ scattering rather than a complicated $qq \to qqWW$ process (you don't want to go back to the proton!)
- ideally the experiment could measure the $WW \to WW$ process and put all our knowledge of the EWSB sector in the for of a detailed measurement of the cross-section

Probing the scattering of W_L at the LHC

What I want:



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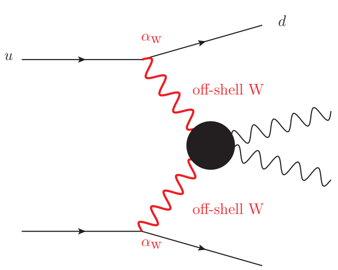

- the emission of W bosons is suppressed by α_W

- brute force: increase the energy and the flux of initial state fermions

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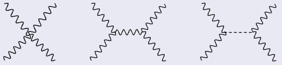

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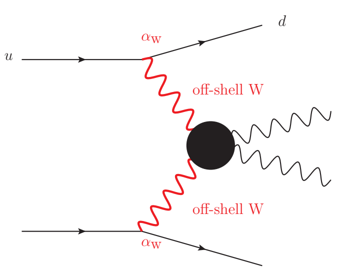

this is not a collision with real W bosons in the initial state,

- $p_W^2 = (p_u - p_d)^2 < 0$

We need a relation between scattering $ff \to ffWW$ that is observable at the LHC and the “desired” on-shell scattering $WW \to WW$

- Effective W Approximation

Probing the scattering of W_L at the LHC

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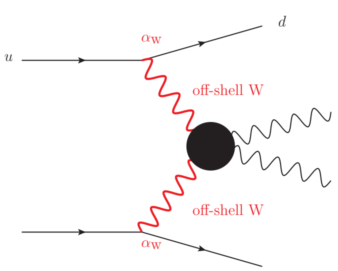

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- Effective W Approximation

Not a way to simplify the computation of the exact amplitude, but

a mean to access the physics of on-shell W bosons scattering.

Why do I want to know about the details of this factorization?

Factorization in massive gauge theories

- The same story of the massless case?

Simplicity of understanding the EWSB sector: $|\mathcal{A}_{WW\to WW}(s,t)|^2$ is all that you want

- Ideally our knowledge of the EWSB can be encoded in the behavior of a $2 \to 2$ scattering process $WW \to WW$

Effectiveness and robustness of LHC data analysis

- Where the factorization works best is where the EWSB is more at display, there you can see $WW \to WW$ and nothing else.

Status of the EWA

surprisingly no complete and clear statement

- $ff \to ffWW$ only for heavy Higgs boson or Higgless (Kunstz,Soper '88)
- $ff \to ff\,h$

Checks of the EWA

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Higgs:

- total rate: $ff \to ff\,h$ in agreement up to $\mathcal{O}(10\%)$ (Cahn '85, Altarelli et al. '87)

WW:

- $d\sigma/dm_{WW}$ easily off by a factor $\mathcal{O}(1)$ (Gunion et al. '86, Accomando et al. '06)
- $d\sigma/dp_{T,jet}dp_{T,jet}$ easily off by a factor $\mathcal{O}(1)$ (Accomando et al. '06)

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validity of the EWA has been questioned

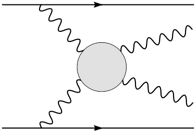
- the goal is not to compute the rate
- most of the attention was on the total cross-section
- cuts were not selecting the region $V \ll Q_{WW}$

The EWA from the expansion of the exact amplitude

Gauge invariance entangles diagrams

in a covariant gauge

- $\mathcal{A}(WW \to WW)_{off-shell} \sim \left(\frac{E}{m}\right)^2$ because $\epsilon_L \sim \frac{E}{m}$ (Kleiss,Stirling '86)
- $\mathcal{A}(WW \to WW)_{on-shell} \sim \left(\frac{E}{m}\right)^0$ cancellations due to the Higgs boson



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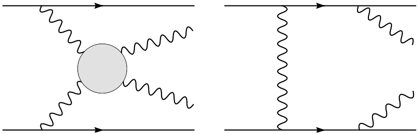
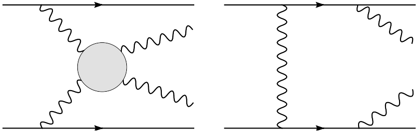


- scattering and non-scattering must cancel to tame the "bad" energy behavior

A transparent choice



covariant gauges

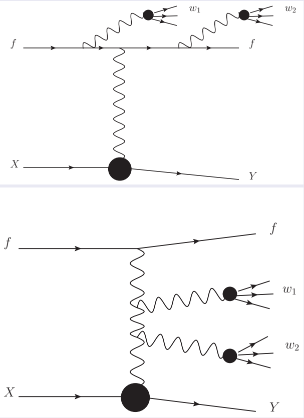
- unphysical propagating fields
- large cancellations among sets of diagrams

physical gauges, e.g. the axial gauge $n_\mu A^\mu = 0$

- only physical DoF
- the "scattering" diagram has a meaning by itself

$f\ X \to f\ Y\ WW$: Enhanced diagrams (from dimensional analysis)

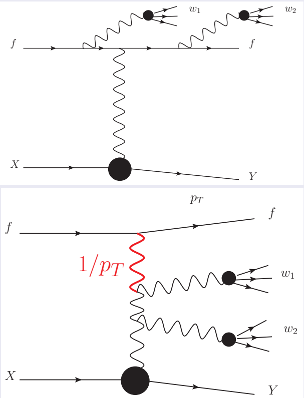
scattering ⇔ non-scattering



- reattaching W lines a non-scattering diagram becomes a scattering with the same couplings
- different numbers of fermionic and W propagators, and of g_{WWW} and g_{qqW}

$f\,X \to f\,Y\,WW$: Enhanced diagrams (from dimensional analysis)

scattering $\Leftrightarrow$ non-scattering



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- different numbers of fermionic and W propagators, and of g_{WWW} and g_{qqW}

in a "physical" gauge

- the W propagator is "well-behaved"
- ϵ_μ *not* $\sim E/m$

away from singular regions

- $\mathcal{A}_{\text{non-scattering}} \sim g^v \left(\frac{1}{E}\right)^k$
- $\mathcal{A}_{\text{scattering}} \sim g^v \frac{1}{p_{T,f}} \left(\frac{1}{E}\right)^{k-1} + \ldots$
- gauge invariant kinematical enhancement
- irrespectively of the nature of h and of m_h

$f\,X \to f\,Y\,WW$: Enhanced diagrams (from dimensional analysis)

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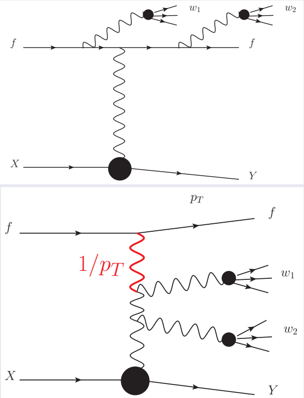

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in the EWA region: $p_T \ll Q_{ww} \sim E$

- $\mathcal{A}_{\text{full}} = \mathcal{A}_{\text{scattering}}(1 + \mathcal{O}(\frac{p_T}{Q_{ww}}))$

subleading terms are expected

- $\mathcal{A}_{\text{scattering}} \supset \frac{\mathcal{A}_{\text{contact-scattering}}}{E}$

The Axial Gauge

$n_\mu A^\mu = 0$, e.g. $n_\mu = (0,0,0,1)$

$$P_{IJ}(q) = \frac{\imath}{q^2-m^2} N_{IJ}(q)$$

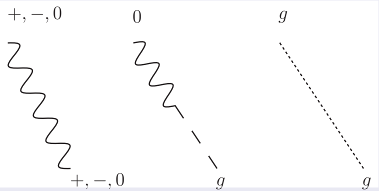
$$N_{\mu\nu} = -\eta_{\mu\nu} + \frac{q_\mu n_\nu + q_\nu n_\mu}{q_L} + \frac{q_\mu q_\nu}{q_L^2}$$

$$= \epsilon_\mu^{*\pm}\epsilon_\nu^\pm + \frac{1+\frac{q_L^2}{m^2}}{1+\frac{q_L^2}{q^2}}\epsilon_\mu^0\epsilon_\nu^0$$

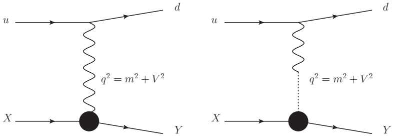
$$N_{\mu g} = -\imath \frac{m}{q_L}(n_\mu + \frac{q_\mu}{q_L}) = \epsilon_\mu^0 \epsilon_g$$

$$N_{gg} = 1 + \frac{m^2}{q_L^2} = \epsilon_g^* \epsilon_g$$

- $\epsilon_\mu^\pm = \mathcal{B}\left(\frac{q_T}{q_L}\right)\frac{1}{\sqrt{2}}(0,1,\pm\imath,0)$
- $\epsilon_\mu^0 = \frac{m}{q_L\sqrt{1+m^2/q_L^2}}\left(n_\mu + \frac{q_\mu}{q_L}\right) \sim \frac{m}{q_L}\tilde{\epsilon}_\mu^0$
- $\epsilon_g = \imath\sqrt{1+\frac{m^2}{q_L^2}}$

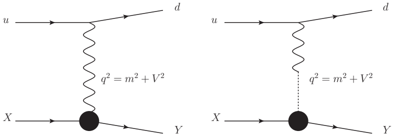


Anatomy of a scattering amplitude



$$
\begin{aligned}
\mathcal{A}_{\text{scattering}} &= \frac{\imath}{V^2}\Bigg(J^\mu \epsilon^*_{T,\mu}\epsilon_{T,\nu}\mathcal{A}^\nu_{Txy} \\
&+ J^\mu \epsilon^*_{0,\mu}\epsilon_{0,\nu}\mathcal{A}^\nu_{0xy}\frac{1+\frac{q_L^2}{m^2}}{1+\frac{q_L^2}{q^2}} \\
&+ J^\mu \epsilon^*_{0,\mu}\epsilon_g \mathcal{A}_{gxy}\Bigg)
\end{aligned}
$$

Anatomy of a scattering amplitude



$$\mathcal{A}_{\text{scattering}} = \frac{\imath}{V^2}\left(J^\mu \epsilon^*_{T,\mu}\epsilon_{T,\nu}\mathcal{A}^\nu_{Txy}\right.$$
$$+ J^\mu \epsilon^*_{0,\mu}\epsilon_{0,\nu}\mathcal{A}^\nu_{0xy}\left(1+\frac{V^2}{m^2}\right)$$
$$\left. + J^\mu \epsilon^*_{0,\mu}\epsilon_g \mathcal{A}_{gxy}\right)$$

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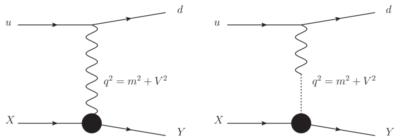


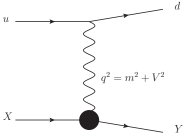
$$\mathcal{A}_{\text{scattering}} = \frac{\imath}{V^2}\left(J^{\mu}\epsilon^{*}_{T,\mu}\epsilon_{T,\nu}\mathcal{A}^{\nu}_{Txy} + J^{\mu}\epsilon^{*}_{0,\mu}\epsilon_{0,\nu}\mathcal{A}^{\nu}_{0xy}\left(1+\frac{V^2}{m^2}\right) + J^{\mu}\epsilon^{*}_{0,\mu}\epsilon_{g}\mathcal{A}_{gxy}\right)$$

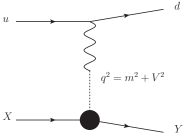
$$= \frac{1}{V^2}\left(\mathcal{A}_{\text{scattering-diag}} + \mathcal{A}_{\text{scattering-mix}}\right) + \mathcal{A}_{\text{contact-scattering}}$$

$\mathcal{A}_{\text{contact-scattering}}$

- as expected
- is representative of the size of the non-scattering diagrams
- it is a correction to $\mathcal{A}_{Txy}$ not to $\mathcal{A}_{gxy}$

Surgery on a scattering amplitude





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to make contact with on-shell

kinematical corrections

- $q_\mu = \left(\sqrt{q^2 + |\bar{q}|^2}, \bar{q}\right)$
- $q_\mu = \left(\sqrt{m^2 + |\bar{q}|^2}, \bar{q}\right)$
- $\frac{\delta q_0}{q_0} \simeq \frac{V^2}{|\bar{q}|^2} \equiv \kappa^2$
- $\frac{\delta \epsilon_\mu}{\epsilon_\mu}$, $\frac{\delta J \cdot \epsilon}{J \cdot \epsilon}$ and $\frac{\delta \mathcal{A}}{\mathcal{A}} \sim \kappa^2$
- $\bar{p}_u - \bar{p}_d = (p_T e^{\imath\phi}, xp)$

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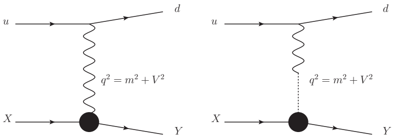

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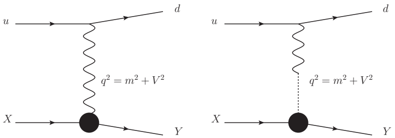

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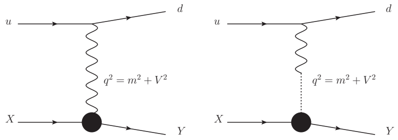
- $\bar{p}_u - \bar{p}_d = (p_T e^{\imath\phi}, xp)$

$\frac{1}{V^2} J \cdot \epsilon^*_h[p_u - p_d]$ up to $\mathcal{O}(\kappa^2)$

- $\frac{p_T e^{\pm\imath\phi}}{V^2} g_\pm(x)\,,\ \ h = \pm$
- $\frac{m}{V^2} g_0(x)\,,\ \ h = 0$

Surgery on a scattering amplitude



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&+ \frac{1}{q_L} g_0(x) \tilde{\epsilon}_0 \cdot \mathcal{A}^{\text{on}}_{0xy} + \mathcal{O}(\kappa^2)
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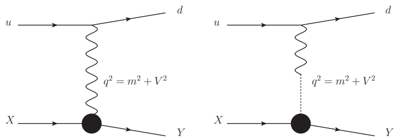


$$
\begin{aligned}
\mathcal{A}_{\text{scattering}} &= \frac{p_T}{V^2} e^{\pm\imath\phi} g_\pm(x)\epsilon_\pm \cdot \mathcal{A}^{\text{on}}_{\pm xy} \\
&+ \frac{m}{V^2} g_0(x)\left(\epsilon_g \cdot \mathcal{A}^{\text{on}}_{gxy} + \frac{m}{q_L}\tilde{\epsilon}_0 \cdot \mathcal{A}^{\text{on}}_{0xy}\right) \\
&+ \frac{1}{q_L} g_0(x)\tilde{\epsilon}_0 \cdot \mathcal{A}^{\text{on}}_{0xy} + \mathcal{O}(\kappa^2) \\
&= \frac{1}{V^2}\mathcal{A}_{\text{EWA}} + \mathcal{O}(\Delta_T) + \mathcal{O}(\kappa^2)
\end{aligned}
$$

to make contact with on-shell

kinematical corrections

- $q_\mu = \left(\sqrt{q^2 + |\bar{q}|^2}, \bar{q}\right)$
- $q_\mu = \left(\sqrt{m^2 + |\bar{q}|^2}, \bar{q}\right)$
- $\frac{\delta q_0}{q_0} \simeq \frac{V^2}{|\bar{q}|^2} \equiv \kappa^2$
- $\frac{\delta \epsilon_\mu}{\epsilon_\mu}$, $\frac{\delta J\cdot\epsilon}{J\cdot\epsilon}$ and $\frac{\delta\mathcal{A}}{\mathcal{A}} \sim \kappa^2$
- $\bar{p}_u - \bar{p}_d = (p_T e^{\imath\phi}, xp)$

non-scattering corrections

- $\Delta_T \equiv \frac{V}{q_L} \sim \kappa$ w.r.t $\mathcal{A}_{\text{scattering-diag}}$

$\frac{1}{V^2} J \cdot \epsilon^*_h [p_u - p_d]$ up to $\mathcal{O}(\kappa^2)$

- $\frac{p_T e^{\pm\imath\phi}}{V^2} g_\pm(x)$, $h = \pm$
- $\frac{m}{V^2} g_0(x)$, $h = 0$

The approximated amplitude

$\mathcal{A}_{EWA} = f_{\pm}(p_T, m, x)\mathcal{A}^{\pm}_{\text{scattering-diag}} + f_0(p_T, m, x)\mathcal{A}_{\text{scattering-mix}}$

- $\mathcal{A}_{exact} = \frac{1}{V^2}\mathcal{A}_{\text{EWA}} + \mathcal{O}(\Delta_T) + \mathcal{O}(\kappa^2) + \mathcal{A}_{\text{non-scattering}}$
- $\mathcal{A}_{\text{non-scattering}}$ is comparable to the $\mathcal{O}(\Delta_T)$ correction to $\mathcal{A}_{\text{scattering-diag}}$

$\frac{\mathcal{A}_{\text{scattering-mix}}}{\mathcal{A}_{\text{scattering-diag}}} \equiv \rho$

- ρ depends on the model and on the external states
- in typical cases $\rho \simeq \kappa^{\pm 1}$

e.g. in the Higgs model: $\Phi = \begin{pmatrix} \pi^{\pm} \\ v + \frac{h + \imath\pi}{\sqrt{2}} \end{pmatrix}$

- $v \to -v$, $h \to -h$, $\pi \to -\pi$, $\pi^{\pm} \to -\pi^{\pm}$ is a symmetry
- $\mathcal{A}(\pi_1^a ... \pi_{2k}^b ...) \sim v^{2n} \Rightarrow \mathcal{A}(LL \to LL) \sim v^{2k}$
- $\mathcal{A}(\pi_1^a ... \pi_{2k+1}^b ...) \sim v^{2n+1} \Rightarrow \mathcal{A}(LT \to LL) \sim v^{2k+1}$

The approximated amplitude

$\mathcal{A}_{EWA} = f_{\pm}(p_T, m, x)\mathcal{A}^{\pm}_{\text{scattering-diag}} + f_0(p_T, m, x)\mathcal{A}_{\text{scattering-mix}}$

- $\mathcal{A}_{exact} = \frac{1}{V^2}\mathcal{A}_{\text{EWA}} + \mathcal{O}(\Delta_T) + \mathcal{O}(\kappa^2) + \mathcal{A}_{\text{non-scattering}}$
- $\mathcal{A}_{\text{non-scattering}}$ is comparable to the $\mathcal{O}(\Delta_T)$ correction to $\mathcal{A}_{\text{scattering-diag}}$

$\rho \simeq \kappa$ the exchange of transverse bosons dominates the scattering

- $\mathcal{A}_{full} = \mathcal{A}_{EWA} + \mathcal{O}(\kappa)$

$\rho \simeq \frac{1}{\kappa}$ the exchange of Goldstone bosons dominates the scattering

- $\mathcal{A}_{full} = \mathcal{A}_{EWA} + \mathcal{O}(\kappa^2)$

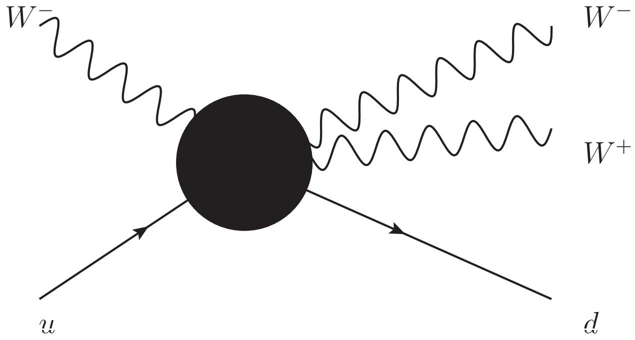
- In the suitable limit of a soft jet emission compared to the hard scattering the factorization holds at the **amplitude level** (irrespective of the mass of the Higgs)
- $d\sigma/d\phi$ now predictable with EWA
- Several sources of corrections have been identified (κ, Δ, ...)

Quantitatively we check the validity of the approximation:

- evaluating the (integratal of) the full amplitude and the EWA amplitude in fixed points of the phase space to study the behavior of the corrections
- using the approximated $\mathcal{A}_{full} \simeq \frac{1}{V^2}\mathcal{A}_{EWA}$ to generate LHE events with a parton level MC (http://code.google.com/p/ewangelion) and comparing kinematical distributions to those from the exact amplitude (MadGraph)

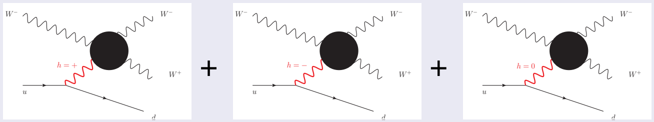
Numerical Results

$uW^+_{h_1} \to dW^+_{h_2} W^-_{h_3}$: EWA Amplitude vs. Exact Amplitude (FeynArts+FormCalc)



$uW^+_{h_1} \to dW^+_{h_2} W^-_{h_3}$: EWA Amplitude vs. Exact Amplitude (FeynArts+FormCalc)

$$A^{(h_1 h_2 h_3)}_{\text{exact}} = f_0 A^{(0)}_{(h_1 h_2 h_3)} + f_+ A^{(+)}_{(h_1 h_2 h_3)} + f_- A^{(-)}_{(h_1 h_2 h_3)} + \textbf{corrections}$$



$uW^+_{h_1} \to dW^+_{h_2} W^-_{h_3}$: EWA Amplitude vs. Exact Amplitude (FeynArts+FormCalc)

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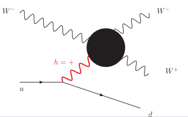

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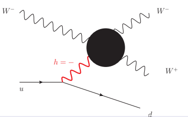

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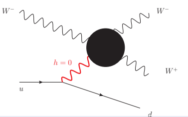


$h_1 = 0, h_2 = 0, h_3 = 0$: 3 longitudinal external states

- $f_\pm = \frac{p_T e^{\pm \imath \phi}}{V^2} g_\pm(x)$
- $f_0 = \frac{m}{V^2} g_0(x)$
- $A^{(0)}_{000} = \mathcal{O}(1) + \ldots$
- $A^{(\pm)}_{000} = \frac{v}{E} \mathcal{O}(1) + \ldots$

Agreement in the amplitude at $\mathcal{O}(p_T^2/E^2)$

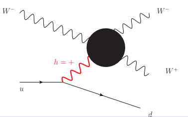
$h_1 = +, h_2 = +, h_3 = +$: 3 transverse external states

- $f_\pm = \frac{p_T e^{\pm \imath \phi}}{V^2} g_\pm(x)$
- $f_0 = \frac{m}{V^2} g_0(x)$
- $A^{(+)}_{000} = \mathcal{O}(1) + \ldots$
- $A^{(0)}_{000} = \frac{v}{E} \mathcal{O}(1) + \ldots$

Agreement in the amplitude at $\mathcal{O}(p_T/E)$

$uW^+_{h_1} \to dW^+_{h_2} W^-_{h_3}$: EWA Amplitude vs. Exact Amplitude (FeynArts+FormCalc)

$$A^{(h_1 h_2 h_3)}_{\textbf{exact}} = f_0 A^{(0)}_{(h_1 h_2 h_3)} + f_+ A^{(+)}_{(h_1 h_2 h_3)} + f_- A^{(-)}_{(h_1 h_2 h_3)} + \textbf{corrections}$$



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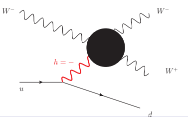

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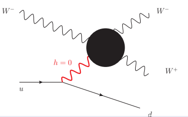

$h_1 = 0, h_2 = 0, h_3 = 0$: 3 longitudinal external states

- $f_\pm = \frac{p_T e^{\pm \imath \phi}}{V^2} g_\pm(x)$
- $f_0 = \frac{m}{V^2} g_0(x)$
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Agreement in the amplitude at $\mathcal{O}(p_T^2/E^2)$

$h_1 = +, h_2 = +, h_3 = +$: 3 transverse external states

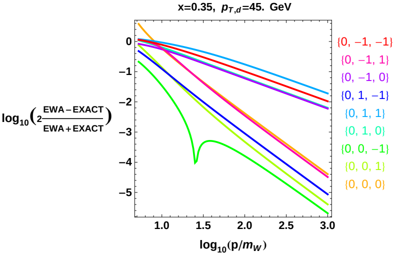
- $f_\pm = \frac{p_T e^{\pm \imath \phi}}{V^2} g_\pm(x)$
- $f_0 = \frac{m}{V^2} g_0(x)$
- $A^{(+)}_{000} = \mathcal{O}(1) + \ldots$
- $A^{(0)}_{000} = \frac{v}{E}\mathcal{O}(1) + \ldots$

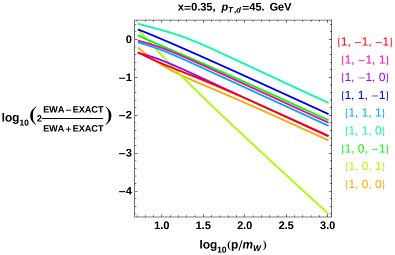
Agreement in the amplitude at $\mathcal{O}(p_T/E)$

$uW^+_{h_1} \to dW^+_{h_2} W^-_{h_3}$: EWA Amplitude vs. Exact Amplitude (FeynArts+FormCalc)

Expanding the amplitudes in $\epsilon = v/E$ interesting patterns emerge

W^+ A_0	A_1	A_{-1}	W^-	W^+	W^-	*dom. virtual*	*scaling*
1	ϵ	ϵ	0	0	0	L	−2
ϵ	ϵ^2	1	0	1	0	T	−1
ϵ	1	ϵ^2	0	−1	0	T	−1
ϵ	ϵ^2	ϵ^2	0	0	1	L	−2
ϵ^2	ϵ^3	ϵ	0	1	1	T	−1
1	ϵ	ϵ	0	−1	1	L	−2
ϵ	ϵ^2	ϵ^2	0	0	−1	L	−2
1	ϵ	ϵ	0	1	−1	L	−2
ϵ^2	ϵ	ϵ^3	0	−1	−1	T	−1
ϵ	1	ϵ^2	1	0	0	T	−1
ϵ^2	ϵ	ϵ	1	1	0	T	−1
ϵ^2	ϵ	ϵ^3	1	−1	0	T	−1
1	ϵ	ϵ	1	0	1	L	−2
ϵ	ϵ^2	1	1	1	1	T	−1
ϵ	1	ϵ^2	1	−1	1	T	−1
ϵ^2	ϵ	ϵ^3	1	0	−1	T	−1
ϵ	1	ϵ^2	1	1	−1	T	−1
ϵ^3	ϵ^2	ϵ^4	1	−1	−1	T	−1
ϵ	ϵ^2	1	−1	0	0	T	−1
ϵ^2	ϵ^3	ϵ	−1	1	0	T	−1
ϵ^2	ϵ	ϵ	−1	−1	0	T	−1
ϵ^2	ϵ^3	ϵ	−1	0	1	T	−1
ϵ^3	ϵ^4	ϵ^2	−1	1	1	T	−1
ϵ	ϵ^2	1	−1	−1	1	T	−1
1	ϵ	ϵ	−1	0	−1	L	−2
ϵ	ϵ^2	1	−1	1	−1	T	−1
ϵ	1	ϵ^2	−1	−1	−1	T	−1





$p_T \ll m$ behavior

$V = \sqrt{m_W^2 - (p_u - p_d)^2}$

$$\begin{aligned}\mathcal{A}_{exact} &= \frac{p_T}{V^2} e^{\pm \imath \phi} g_{\pm}(x) \epsilon_{\pm} \cdot \mathcal{A}^{\text{on}}_{\pm xy} \\ &+ \frac{m}{V^2} g_0(x) \left(\epsilon_g \cdot \mathcal{A}^{\text{on}}_{gxy} + \frac{m}{q_L} \tilde{\epsilon}_0 \cdot \mathcal{A}^{\text{on}}_{0xy} \right) \\ &+ \frac{1}{q_L} g_0(x) \tilde{\epsilon}_0 \cdot \mathcal{A}^{\text{on}}_{0xy} + \mathcal{O}(\kappa^2)\end{aligned}$$

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corrections at $p_{T,d} \ll m$

- if T dominates: $\mathcal{O}(\frac{V^2}{p_T q_L}) \sim \mathcal{O}(\frac{m^2}{p_T q_L})$
- if L dominates: $\mathcal{O}(\frac{\kappa V^2}{m q_L}) \sim \mathcal{O}(\frac{\kappa m}{q_L})$

$p_T \ll m$ behavior

$$V = \sqrt{m_W^2 - (p_u - p_d)^2}$$

$$\begin{aligned}\mathcal{A}_{exact} &= \frac{p_T}{V^2} e^{\pm\imath\phi} g_\pm(x)\epsilon_\pm \cdot \mathcal{A}^{\text{on}}_{\pm xy} \\ &+ \frac{m}{V^2} g_0(x)\left(\epsilon_g \cdot \mathcal{A}^{\text{on}}_{gxy} + \frac{m}{q_L}\tilde{\epsilon}_0 \cdot \mathcal{A}^{\text{on}}_{0xy}\right) \\ &+ \frac{1}{q_L} g_0(x)\tilde{\epsilon}_0 \cdot \mathcal{A}^{\text{on}}_{0xy} + \mathcal{O}(\kappa^2)\end{aligned}$$

corrections at $p_{T,d} \ll m$

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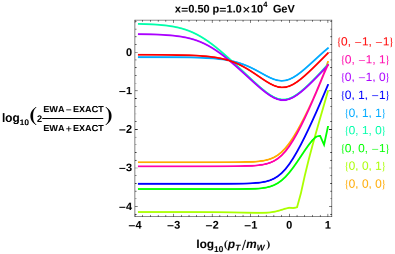
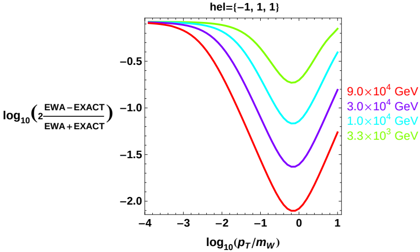
- if L dominates: $\mathcal{O}(\frac{\kappa V^2}{m q_L}) \sim \mathcal{O}(\frac{\kappa m}{q_L})$



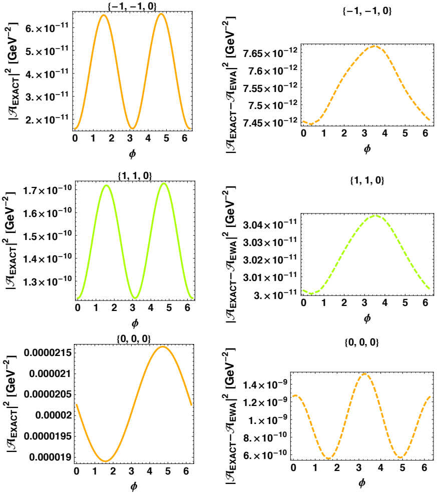


$\frac{d\sigma}{d\phi}$ from $A^{(h_1 h_2 h_3)}_{\text{exact}} = f_0 A^{(0)}_{(h_1 h_2 h_3)} + f_+ A^{(+)}_{(h_1 h_2 h_3)} + f_- A^{(-)}_{(h_1 h_2 h_3)} + \textbf{corrections}$

(PRELIMINARY)

- $f_0 = \frac{m}{V^2} g_0(x)$
- $f_\pm = \frac{p_T e^{\pm \imath \phi}}{V^2} g_\pm(x)$

$\mathcal{A}_{h\lambda(W^-_{in})\to\lambda(W^+)\lambda(W^-)}$ $h=0$	$h=-1$	$h=1$	$\lambda(W^-_{in})$	$\lambda(W^+)$	$\lambda(W^-)$	$d\sigma/d\phi$
1	ϵ	ϵ	0	0	0	$1+\epsilon\,[\sin\phi+\Delta\cdot f(\phi)]$
ϵ	ϵ^2	ϵ^2	0	0	1	$1+\epsilon\,[\sin\phi+\Delta\cdot f(\phi)]$
ϵ	ϵ^2	ϵ^2	0	0	-1	$1+\epsilon\,[\sin\phi+\Delta\cdot f(\phi)]$
ϵ	1	ϵ^2	0	1	0	$1+\epsilon\sin\phi+\Delta\cdot f(\phi)$
ϵ^2	ϵ	ϵ^3	0	1	1	$1+\epsilon\sin\phi+\Delta\cdot f(\phi)$
1	ϵ	ϵ	0	1	-1	$1+\epsilon\,[\sin\phi+\Delta\cdot f(\phi)]$
ϵ	ϵ^2	1	0	-1	0	$1+\epsilon\sin\phi+\Delta\cdot f(\phi)$
1	ϵ	ϵ	0	-1	1	$1+\epsilon\,[\sin\phi+\Delta\cdot f(\phi)]$
ϵ^2	ϵ^3	ϵ	0	-1	-1	$1+\sin\phi+\Delta\cdot f(\phi)$
ϵ	ϵ^2	1	1	0	0	$1+\epsilon\sin\phi+\Delta\cdot f(\phi)$
1	ϵ	ϵ	1	0	1	$1+\epsilon\,[\sin\phi+\Delta\cdot f(\phi)]$
ϵ^2	ϵ^3	ϵ	1	0	-1	$1+\epsilon\sin\phi+\Delta\cdot f(\phi)$
ϵ^2	ϵ	ϵ	1	1	0	$1+\sin 2\phi+\Delta f(\phi)+\epsilon\sin\phi$
ϵ	1	ϵ^2	1	1	1	$1+\epsilon\sin\phi+\Delta\cdot f(\phi)$
ϵ	ϵ^2	1	1	1	-1	$1+\epsilon\sin\phi+\Delta\cdot f(\phi)$
ϵ^2	ϵ^3	ϵ	1	-1	0	$1+\epsilon\sin\phi+\Delta\cdot f(\phi)$
ϵ	ϵ^2	1	1	-1	1	$1+\epsilon\sin\phi+\Delta\cdot f(\phi)$
ϵ^3	ϵ^4	ϵ^2	1	-1	-1	$1+\epsilon\sin\phi+\Delta\cdot f(\phi)$
ϵ	1	ϵ^2	-1	0	0	$1+\epsilon\sin\phi+\Delta\cdot f(\phi)$
ϵ^2	ϵ	ϵ^3	-1	0	1	$1+\epsilon\sin\phi+\Delta\cdot f(\phi)$
1	ϵ	ϵ	-1	0	-1	$1+\epsilon\,[\sin\phi+\Delta\cdot f(\phi)]$
ϵ^2	ϵ	ϵ^3	-1	1	0	$1+\epsilon\sin\phi+\Delta\cdot f(\phi)$
ϵ^3	ϵ^2	ϵ^4	-1	1	1	$1+\epsilon\sin\phi+\Delta\cdot f(\phi)$
ϵ	1	ϵ^2	-1	1	-1	$1+\epsilon\sin\phi+\Delta\cdot f(\phi)$
ϵ^2	ϵ	ϵ	-1	-1	0	$1+\sin 2\phi+\Delta f(\phi)+\epsilon\sin\phi$
ϵ	1	ϵ^2	-1	-1	1	$1+\epsilon\sin\phi+\Delta\cdot f(\phi)$
ϵ	ϵ^2	1	-1	-1	-1	$1+\epsilon\sin\phi+\Delta\cdot f(\phi)$

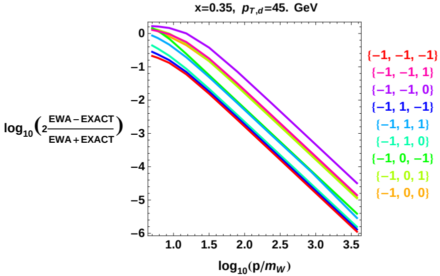


$uW^+ \to dW^+W^-$: $\int d\phi |\mathcal{A}_{EWA}|^2$ vs. $\int d\phi |\mathcal{A}_{exact}|^2$

so far $\bar{p}_{W,virtual} = \bar{p}_u - \bar{p}_d$

$$\begin{aligned}\mathcal{A}_{exact} &= \frac{p_T}{V^2} e^{\pm\imath\phi} g_\pm(x)\epsilon_\pm \cdot \mathcal{A}^{\rm on}_{\pm xy} \\ &+ \frac{m}{V^2} g_0(x)\left(\epsilon_g \cdot \mathcal{A}^{\rm on}_{gxy} + \frac{m}{q_L}\tilde{\epsilon}_0 \cdot \mathcal{A}^{\rm on}_{0xy}\right) \\ &+ \frac{1}{q_L} g_0(x)\tilde{\epsilon}_0 \cdot \mathcal{A}^{\rm on}_{0xy} + \mathcal{O}(\kappa^2)\end{aligned}$$

- $\mathcal{A} \sim p_T e^{\pm\imath\phi}\mathcal{A}_\pm + \mathcal{A}_0$
- $\int d\phi\, e^{\pm\imath\phi}\mathcal{A}_\pm\mathcal{A}_0^* + h.c. = 0$
- $|\mathcal{A}|^2 = |\mathcal{A}_\pm|^2 + |\mathcal{A}_0|^2 = |\mathcal{A}_{EWA}|^2 + \mathcal{O}(\kappa^2)$

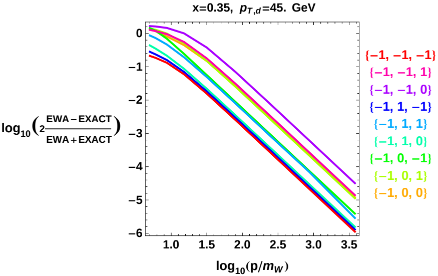


$uW^+ \to dW^+W^-$: $\int d\phi |\mathcal{A}_{EWA}|^2$ vs. $\int d\phi |\mathcal{A}_{exact}|^2$

$p_{T,W,virtual} = 0$

$$\begin{aligned}
\mathcal{A}_{exact} &= \frac{p_T}{V^2} e^{\pm\imath\phi} g_\pm(x) \epsilon_\pm \cdot \mathcal{A}^{\text{on}}_{\pm xy} \\
&+ \frac{m}{V^2} g_0(x) \left(\epsilon_g \cdot \mathcal{A}^{\text{on}}_{gxy} + \frac{m}{q_L} \tilde{\epsilon}_0 \cdot \mathcal{A}^{\text{on}}_{0xy} \right) \\
&+ \frac{1}{q_L} g_0(x) \tilde{\epsilon}_0 \cdot \mathcal{A}^{\text{on}}_{0xy} + \mathcal{O}(\kappa)
\end{aligned}$$

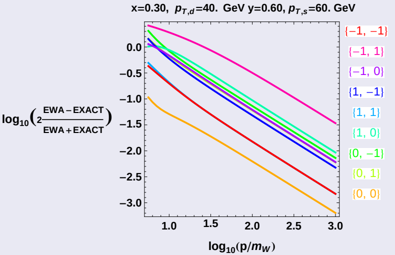
- $\mathcal{A} \sim p_T e^{\pm\imath\phi} \mathcal{A}_\pm + \mathcal{A}_0$
- $\int d\phi \; e^{\pm\imath\phi} \mathcal{A}_\pm \mathcal{A}_0^* + h.c. = 0$
- $|\mathcal{A}|^2 = |\mathcal{A}_\pm|^2 + |\mathcal{A}_0|^2 = |\mathcal{A}_{EWA}|^2 + \mathcal{O}(\kappa^2)$



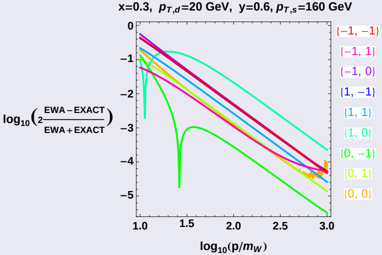
$u\bar{c} \to d\bar{s}W^+W^-$

The process studied so far, $uW^+ \to dW^+W^-$, is only a toy, but displays all the interesting physics (even more indeed), of the "interesting" process $qq \to qqWW$.

fixed jets angles



integrated amplitude



EWA vs. MadGraph: $d\sigma/dp_{T,W^+}$ for $uW^- \to dW^+W^-$ at $\sqrt{\hat{s}}$=2 TeV (PRELIMINARY)

in the $SU(2)$ Higgs model (m_h=160 GeV) in the region 30 GeV $< p_{T,d} <$ 60 GeV, $0.3 < x < 0.4$, $m_{WW} >$ 400 GeV

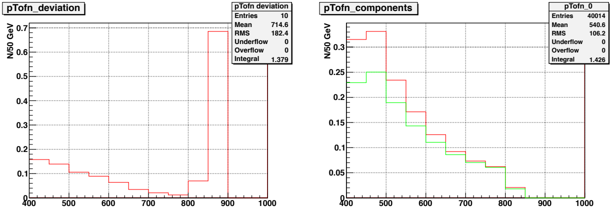


Figure 4: $d\sigma/dp_T^{W^\pm}$ for the channel 110

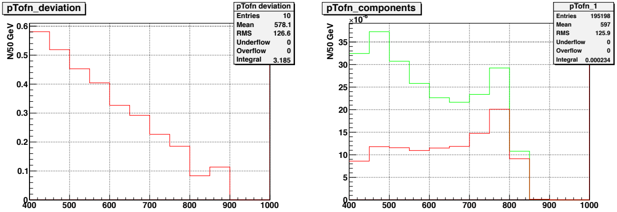


Figure 7: $d\sigma/dp_T^{W^\pm}$ for the channel 011

Conclusions on EWA and WW scattering (so far)

- on-shell WW scattering is a universal probe of the EWSB sector
- (re)-established the EWA as an expansion in $p_{T,jet}/p_{T,W_{out}}$ **to access the physics of on-shell W scattering (EWSB)**
- assessed the origin and predicted the size of the corrections
  - $\mathcal{A}$ correct up to $\mathcal{O}(\kappa^2)$ when W_L dominate
  - $\mathcal{A}$ correct up to $\mathcal{O}(\kappa)$ when W_T dominate
  - $\int d\phi |\mathcal{A}|^2$ up to $\mathcal{O}(\kappa^2)$ in all cases
- prediction of $\frac{d\sigma}{d\phi}$
- numerical checks on the details of the analytic amplitude
- EWA generator for partonic collisions checked against MadGraph

Open issues (?)

- predict the v/E structure of amplitudes in broken $SU(N)$

The example of the scalar as moderator (Higgs-like model)

$$\mathcal{L} = \frac{v^2}{4}\mathrm{Tr}(D_\mu \Sigma D^\mu \Sigma)$$

$$\mathcal{A}(\pi\pi \to \pi\pi) \sim \frac{s}{v^2}$$

The example of the scalar as moderator (Higgs-like model)

$$\mathcal{L} = \frac{v^2}{4}\mathrm{Tr}(D_\mu \Sigma D^\mu \Sigma)\left(1 + a\frac{h}{v}\right)$$

$$\mathcal{A}(\pi\pi \to \pi\pi) \sim \frac{s}{v^2}\left(1 - a^2\right)$$

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$$\mathcal{A}(\pi\pi \to hh) \sim \frac{s}{v^2}\left(a^2\right)$$

The example of the scalar as moderator (Higgs-like model)

$$\mathcal{L} = \frac{v^2}{4}\mathrm{Tr}(D_\mu \Sigma D^\mu \Sigma)\left(1 + a\frac{h}{v} + b\frac{h^2}{v^2}\right)$$

$$\mathcal{A}(\pi\pi \to \pi\pi) \sim \frac{s}{v^2}\left(1 - a^2\right)$$

$$\mathcal{A}(\pi\pi \to hh) \sim \frac{s}{v^2}\left(a^2 - b\right)$$

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an interpolator

- $a = b = 0$ corresponds to the strongly coupled Goldstones
- $a = b = 1$ corresponds to weakly coupled Goldstones, i.e. the SM

$$\mathcal{L} = |D_\mu \Phi|^2 \text{ with } \Phi = \frac{1}{\sqrt{2}}\begin{pmatrix} \pi_1 + \imath\pi_2 \\ v + h + \imath\pi_3 \end{pmatrix}$$

The example of the scalar as moderator (Higgs-like model)

$$\mathcal{L} = \frac{v^2}{4}\mathrm{Tr}(D_\mu \Sigma D^\mu \Sigma)\left(1 + a\frac{h}{v} + b\frac{h^2}{v^2}\right) + m_f \bar{\psi}_L \psi_R \left(1 + c\frac{h}{v}\right)$$

$$\mathcal{A}(\pi\pi \to \pi\pi) \sim \frac{s}{v^2}\left(1 - a^2\right)$$

$$\mathcal{A}(\pi\pi \to hh) \sim \frac{s}{v^2}\left(a^2 - b\right)$$

$$\mathcal{A}(\pi\pi \to \psi\psi) \sim \frac{\sqrt{s} m_f}{v^2}\left(1 - ac\right)$$

an interpolator

- $a = b = 0$ corresponds to the strongly coupled Goldstones
- $c = a = b = 1$ corresponds to weakly coupled Goldstones, i.e. the SM

$$\mathcal{L} = |D_\mu \Phi|^2 \text{ with } \Phi = \frac{1}{\sqrt{2}}\begin{pmatrix} \pi_1 + \imath\pi_2 \\ v + h + \imath\pi_3 \end{pmatrix}$$

on-shell WW scattering: a SM process that knows BSM

$W_L W_L \to W_L W_L$

- W_L described by the Goldstone's bosons
- $\Sigma \equiv e^{\imath\pi^a\sigma^a/v}$
- a scalar h coupled to the Goldstones

$$
\begin{aligned}
\mathcal{L} &= \frac{1}{2}(\partial h)^2 - V(h) \\
&+ \frac{v^2}{4} Tr\left(D_\mu \Sigma D^\mu \Sigma\right)\left(1 + a\frac{h}{v} + b\frac{h^2}{v^2} + \ldots\right) \\
&+ m\bar{\psi}_R \Sigma \psi_L \left(1 + c\frac{h}{v}\right) + h.c.
\end{aligned}
$$

$\mathcal{A}$ grows with the energy

$$\mathcal{A}\left(\pi\pi \to \pi\pi\right) = (1 - a^2)\frac{s}{v^2} + \ldots$$

Strong or Weak coupling

- a,b,c are in principle free parameters
- a: $W_L W_L \to W_L W_L$
- b: $W_L W_L \to hh$
- c: $W_L W_L \to f\bar{f}$
- Strong if a=0 or b=0 or c=0
- SM is a=b=c=1

- The Higgs is part of new physics

whatever breaks the EW symmetry

- measuring a,b,c tells about EWSB (and tells what is h)