electroweak interactions & beyond
on-shell & bottom up

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Technion

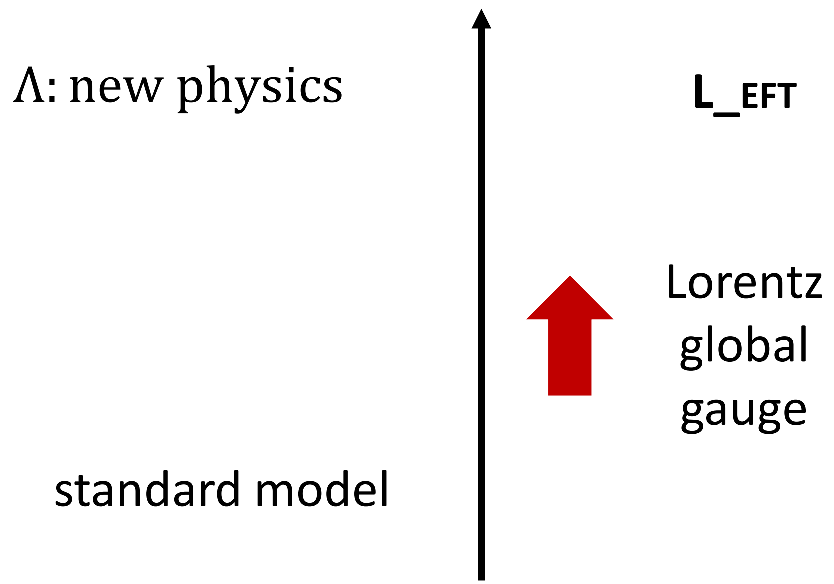
with Gauthier Durieux, Teppei Kitahara, Yaniv Weiss 1909.10551

[with Yaniv Weiss 1809.09644]

HEFT2020

Higgs Effective Theory: key to electroweak symmetry breaking

derived **bottom-up**:



Higgs Effective Theory: key to electroweak symmetry breaking

But what's *your* Higgs?

bottom-up construction:

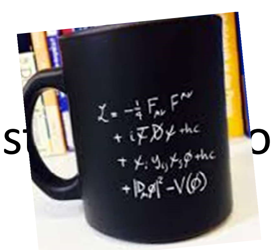
Λ: new physics

L_EFT dictated by symmetries:

Lorentz

global

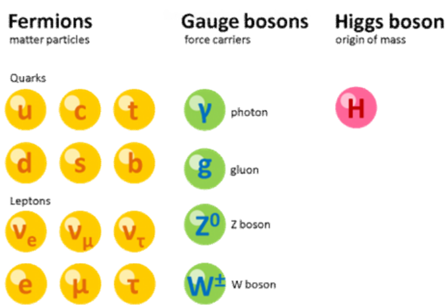
gauge



s odel

Higgs Effective Theory: key to electroweak symmetry breaking

Λ: new physics



possible new interactions
dictated by

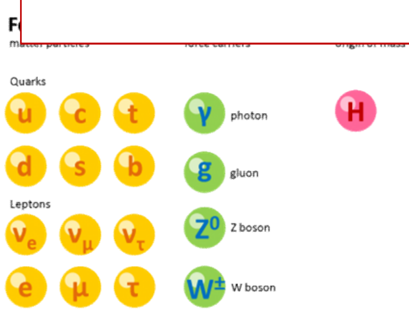
Lorentz
global

[+ properties of the S-matrix: unitarity, factorization]

Higgs Effective Theory: key to electroweak symmetry breaking

particle interactions
dictated by symmetries:

The on-shell amplitude approach is very natural for bottom-up EFT



[+ properties of the S-matrix: unitarity, factorization] many important results on SM-EFT derived/explained via ``on-shell” techniques:

(see also Machado’s talk)

vanishing SM-BSM interference — Azatov Contino Machado Riva

vanishing operator mixings — Chueng Shen; Bern Parra-Martinez Sawyer

counting of independent operators — Henning Lu Melia Murayama

more generally: general mapping of EFTs — Cohen Elvang Kiermaier

soft bootstrap & NLSM — Cheung Kampf Novotny Trnka; Elvang Jones Naulich; Low Yin

approach here: *Just do it!*

calculate amplitudes directly:

these are the physical objects one measures → direct comparison to experiment

- no operator or gauge redundancies
- electroweak EFT:
  - truly model-independent,

    eg, can choose whether to impose SU(2)xU(1)
  - *exact results* in $^{v}/_{\Lambda}$ expansion

Spinor variables

Spinor variables (in 1.5 slides)

See Camila Machado's talk

write amplitudes (both momenta, external polarizations for massless/massive particles) in terms of 2d spinors

Parke Taylor
Mangano Parke
…

→ amplitude = rational function of angle/square spinor brackets

- smallest reps of Lorentz
- compact expressions, easy to manipulate numerically

  (just complex numbers!)

- but there's more..

``dictate"
``symmetries"

charges → selection rules

the spinors carry little group (LG) ``charges”

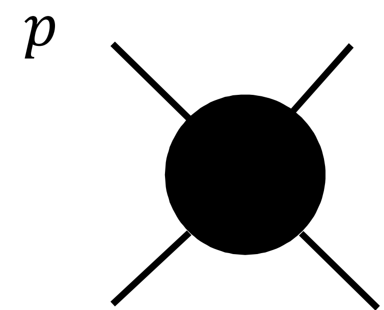
(while momenta are neutral, by definition)

and

amplitudes carry LG charges

because polarizations (external fermion, vector ..) do external momentum (massless):

$$p_{\alpha\dot{\alpha}} \equiv p_\mu \sigma^\mu_{\alpha\dot{\alpha}} = \lambda_\alpha \tilde{\lambda}_{\dot{\alpha}} \equiv |p\rangle [p|$$



under the massless little group (U(1)):

$$|p\rangle \to e^{-i\xi}|p\rangle \qquad [p| \to e^{+i\xi}[p|$$

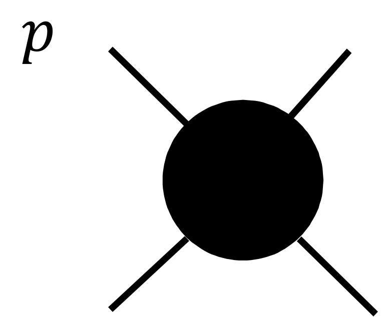
external polarizations:

Spin 1/2 : $|p\rangle \quad |p]$

Spin 1 : $\sqrt{2}\frac{|\zeta\rangle[p|}{\langle p\zeta\rangle} \qquad \sqrt{2}\frac{|p\rangle[\zeta|}{[p\zeta]}$

arbitrary lightlike momentum: gauge redundancy external momentum (**massive**): $p = p^1 + p^2$

$$\boldsymbol{p}_{\alpha\dot{\alpha}} = \boldsymbol{\lambda}_{\alpha}^{I}\tilde{\boldsymbol{\lambda}}_{I\dot{\alpha}} = |\boldsymbol{p}^I\rangle[\boldsymbol{p}_I| \qquad I = 1,2$$



Arkani-Hamed Huang Huang '17

under the little group:

$$|\boldsymbol{p}^I\rangle \to W^I_J|\boldsymbol{p}^J\rangle \qquad [\boldsymbol{p}_I| \to \left(W^{-1}\right)_I^{\ J}[\boldsymbol{p}_J|$$

W: $SU(2)$ LG transformation

external polarizations:

bold notation:
massive momentum
LG indices symmetrized

Spin 1/2 : $|\boldsymbol{p}^I\rangle$ $\qquad I = 1$: $+helicity$; $I = 2$: $-$

Spin 1 : $\varepsilon^{IJ}_{\alpha\dot{\alpha}} = \sqrt{2}\dfrac{|\mathbf{p}\rangle[\mathbf{p}|}{m}$

$I = J = 1$: $+$
$I = J = 2$: $-$
$I = 1$ $J = 2$: 0

Direct derivation of on-shell EFT amplitudes:

The on-shell EFT: defined by

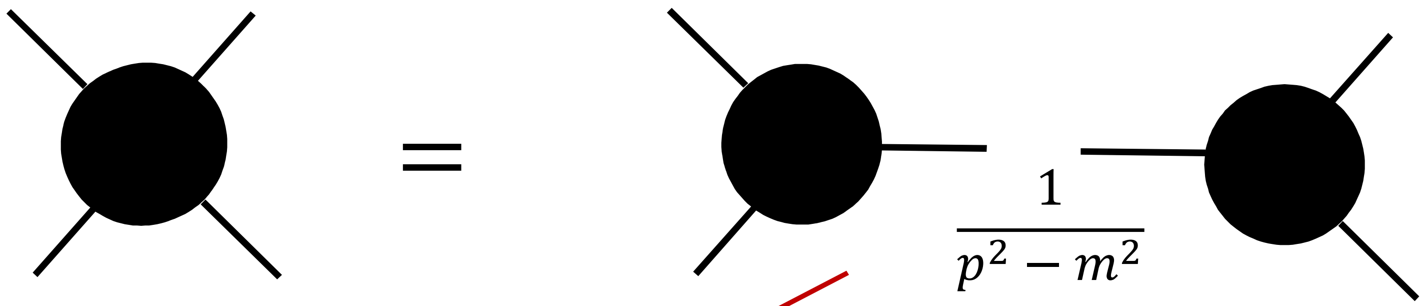
- particles (mass, spin)
- global symmetries & charges
- [unbroken gauge symmetries]

} determine 3-pt amplitudes

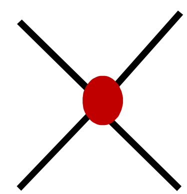
- couplings
    a. appearing in 3-point amplitudes (gauge, Yukawa, NR)
    b. contact terms appearing in higher point amplitudes (NR)

get higher point amplitudes via bootstrap:

eg: 3 point to 4 point:



+



contact terms:
generically NR couplings

determined by locality/unitarity
here: tree-level only
similarly for higher point amplitudes

Direct derivation of on-shell EFT amplitudes:

massive scalar/vector + gluons

YS Weiss 1809.09644

scalar + 3 gluon amplitudes:

scalar=Higgs or new particle, SU(3)xU(1) neutral

$$\mathcal{M}\Big(h; g^{a+}(p_1)g^{b+}(p_2)g^{c+}(p_3)\Big) = \frac{[12]\,[13]\,[23]}{\Lambda}\Bigg[f^{abc}\Bigg(-\,i\,\frac{m^4\,g_s\,c_5^{hgg}}{s_{12}s_{13}s_{23}} + \frac{a_7}{\Lambda^2}$$

$$+\frac{a_{11}}{\Lambda^6}(s_{12}s_{23}+s_{13}s_{23}+s_{12}s_{13}) + \frac{a_{13}}{\Lambda^8}s_{12}s_{13}s_{23}\Bigg)$$

$$+\,d^{abc}\,\frac{a'_{13}}{\Lambda^8}\,(s_{12}-s_{13})\,(s_{12}-s_{23})\,(s_{13}-s_{23})\Bigg]\,,$$

full amplitude:
shown up to dim-13!

example: vector + 3 gluons

vector = Z or new particle, SU(3)xU(1) neutral

$$\mathcal{M}\Big(Z'; g^{a-}(p_1); g^{b-}(p_2); g^{c+}(p_3)\Big)$$

$$= d^{abc}\,\langle 12\rangle^2 \times \Big[[34]^2\, \tilde{f}^{+}_{-4}(1;2) + [13]\,[23]\,\langle 14\rangle\,\langle 24\rangle\, \tilde{f}^{+}_{-6}(1;2) + [34]\,([31]\,\langle 14\rangle - [32]\,\langle 24\rangle)\tilde{f}^{-}_{-5}(1;2) \Big]$$

$$+ f^{abc}\,\langle 12\rangle^2 \times \Big[[34]^2\, \tilde{f}^{-}_{-4}(1;2) + [13]\,[23]\,\langle 14\rangle\,\langle 24\rangle\, \tilde{f}^{-}_{-6}(1;2) + [34]\,([31]\,\langle 14\rangle - [32]\,\langle 24\rangle)\tilde{f}^{+}_{-5}(1;2) \Big]$$

$$\tilde{f}^{+}_{-4}(1;2) = \frac{d_8}{\Lambda^4} + \frac{d^{(1)}_{10}}{\Lambda^6}\, s_{12} + \frac{d^{(1)}_{12}\, s^2_{12} + d^{(2)}_{12}\, s_{13}s_{23}}{\Lambda^8}\,, \qquad \tilde{f}^{-}_{-4}(1;2) = (s_{23} - s_{13})\Big(\frac{d^{(3)}_{10}}{\Lambda^6} + \frac{d^{(4)}_{12}}{\Lambda^8}\, s_{12}\Big)\,,$$

$$\tilde{f}^{+}_{-5}(1;2) = \frac{m\, d^{(2)}_{10}}{\Lambda^6} + \frac{m\, d^{(3)}_{12}}{\Lambda^8} s_{12}\,, \qquad \tilde{f}^{-}_{-5}(1;2) = (s_{13} - s_{23})\frac{m\, d^{(5)}_{12}}{\Lambda^8}\,,$$

$$\tilde{f}^{+}_{-6}(1;2) = \frac{m^2\, s_{12}\, d^{(6)}_{12}}{\Lambda^8}\,, \quad \tilde{f}^{-}_{-6}(1;2) = 0\,,$$

full amplitude
shown up to dim-12!

Direct derivation of on-shell EFT amplitudes: towards the on-shell electroweak theory

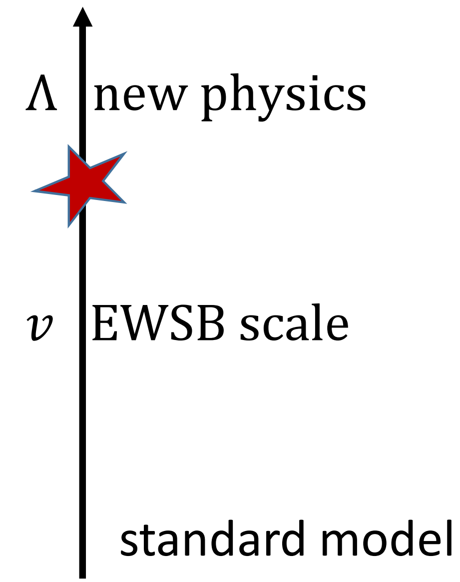
Towards the on-shell electroweak effective theory:

different possible amplitude-based approaches:

- ❑Construct *massless* amplitudes in *unbroken* phase

→ direct mapping to SMEFT operators

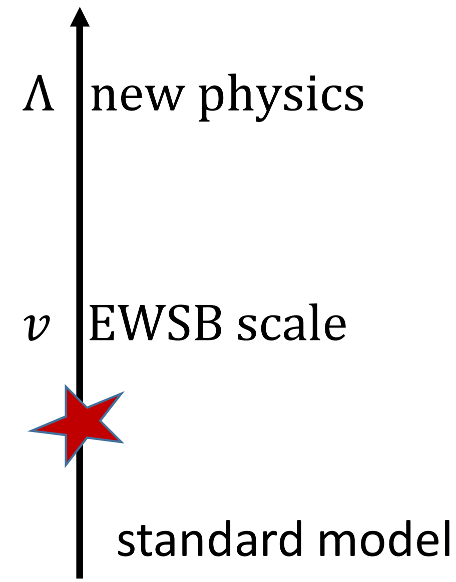
Ma Shu Xiao '19



Towards the on-shell electroweak effective theory:

different possible amplitude-based approaches:

- Construct amplitudes with
  external legs = SM particles (massless/massive)



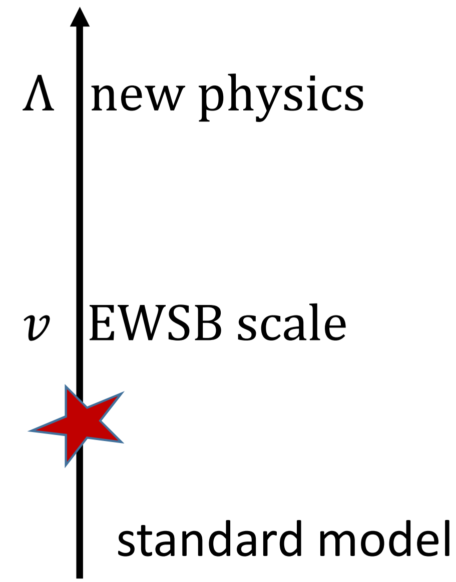
Towards the on-shell electroweak effective theory:

different possible amplitude-based approaches:

- Construct amplitudes with
  external legs = SM particles (massless/massive)

- impose SU(2)xU(1) at v

Aoude Machado '19

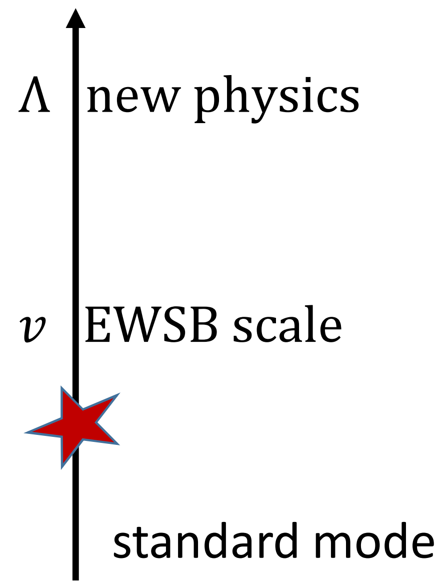


Towards the on-shell electroweak effective theory:
different possible amplitude-based approaches:

See also: Christensen Field
Christensen Field Moore Pinto
Herderschee Koren Trott
Bachu Yelleshpur

- ❑ Construct amplitudes with
  external legs = SM particles (massless/massive)

- **here:** NOT impose SU(2)xU(1) at v
  only Lorentz + global symmetries (charge, baryon/lepton)



Towards the on-shell electroweak effective theory:

different possible amplitude-based approaches:

- ❑ Construct amplitudes with

  external legs = SM particles (massless/massive)

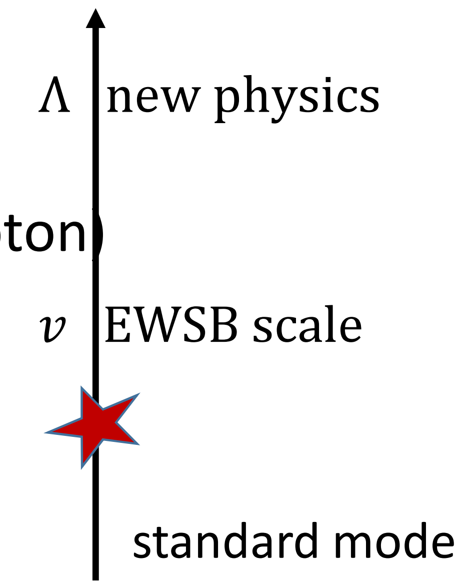
- **here:** NOT

  only Lore … epton)

theory-wise:

how does SU(2)xU(1) emerge?

how do EWSB patterns emerge?



towards the on-shell electroweak theory:
3-pt amplitudes

3-point amplitudes:

Even if kinematically forbidden (m_1+$m_2 > m_3$ for $m_1 \leq m_2 \leq m_3$), can be defined for complex momenta.

Results are exact: $p_i \cdot p_j = m^2$ → no kinematic dependence multiplies spinor structures

in matching to an EFT Lagrangian-based, Feynman diagram computation: not only all orders in perturbation theory

(in fact, non-perturbative)

but also all orders in v/Λ operator expansion

Example 1: three gauge bosons: WWZ

central to non-abelian gauge interaction

for simplicity: neglect $M_Z - M_W \ll M_Z$

Lorentz, LG scaling fix:

$$\begin{aligned}\mathcal{M}(\mathbf{1}_W^a, \mathbf{2}_W^b, \mathbf{3}_W^c) = \epsilon^{abc} \Big\{ &+ \langle\mathbf{12}\rangle\langle\mathbf{13}\rangle\langle\mathbf{23}\rangle\ c_{WWW}^{LLL}/\bar{\Lambda}^2 \\ &+ \Big(\langle\mathbf{12}\rangle\langle\mathbf{13}\rangle[\mathbf{23}] + \langle\mathbf{12}\rangle[\mathbf{13}]\langle\mathbf{23}\rangle + [\mathbf{12}]\langle\mathbf{13}\rangle\langle\mathbf{23}\rangle \\ &+ \langle\mathbf{12}\rangle[\mathbf{13}][\mathbf{23}] + [\mathbf{12}]\langle\mathbf{13}\rangle[\mathbf{23}] + [\mathbf{12}][\mathbf{13}]\langle\mathbf{23}\rangle\Big)\ c_{WWW}/m_W^2 \\ &+ [\mathbf{12}][\mathbf{13}][\mathbf{23}]\ c_{WWW}^{RRR}/\bar{\Lambda}^2 \Big\},\end{aligned}$$

Example 1: 3 gauge bosons: WWZ

central to non-abelian gauge interaction

for simplicity: neglect $M_Z - M_W \ll M_Z$

Lorentz, LG scaling fix:

completely antisymmetric 1,2,3

$$\mathcal{M}(\mathbf{1}_W^a, \mathbf{2}_W^b, \mathbf{3}_W^c) = \epsilon^{abc} \Big\{ + \langle\mathbf{12}\rangle\langle\mathbf{13}\rangle\langle\mathbf{23}\rangle \, c_{WWW}^{LLL}/\bar{\Lambda}^2$$
$$+ \Big(\langle\mathbf{12}\rangle\langle\mathbf{13}\rangle[\mathbf{23}] + \langle\mathbf{12}\rangle[\mathbf{13}]\langle\mathbf{23}\rangle + [\mathbf{12}]\langle\mathbf{13}\rangle\langle\mathbf{23}\rangle$$
$$+ \langle\mathbf{12}\rangle[\mathbf{13}][\mathbf{23}] + [\mathbf{12}]\langle\mathbf{13}\rangle[\mathbf{23}] + [\mathbf{12}][\mathbf{13}]\langle\mathbf{23}\rangle \Big) \, c_{WWW}/m_W^2$$
$$+ [\mathbf{12}][\mathbf{13}][\mathbf{23}] \, c_{WWW}^{RRR}/\bar{\Lambda}^2 \Big\},$$

→ completely antisymmetric in *a,b,c*

SU(2)

Three (and only three) degenerate spin-1 particles:

Lorentz → SU(2) gauge structure

$$\mathcal{M}(\mathbf{1}_W^a, \mathbf{2}_W^b, \mathbf{3}_W^c) = \epsilon^{abc} \Big\{ + \langle \mathbf{12} \rangle \langle \mathbf{13} \rangle \langle \mathbf{23} \rangle \, c_{WWW}^{LLL} / \bar{\Lambda}^2$$
$$+ \Big(\langle \mathbf{12} \rangle \langle \mathbf{13} \rangle [\mathbf{23}] + \langle \mathbf{12} \rangle [\mathbf{13}] \langle \mathbf{23} \rangle + [\mathbf{12}] \langle \mathbf{13} \rangle \langle \mathbf{23} \rangle$$
$$+ \langle \mathbf{12} \rangle [\mathbf{13}] [\mathbf{23}] + [\mathbf{12}] \langle \mathbf{13} \rangle [\mathbf{23}] + [\mathbf{12}] [\mathbf{13}] \langle \mathbf{23} \rangle \Big) c_{WWW} / m_W^2$$
$$+ [\mathbf{12}] [\mathbf{13}] [\mathbf{23}] \, c_{WWW}^{RRR} / \bar{\Lambda}^2 \Big\} ,$$

dimensionless couplings

EFT scale (in broken phase)

back to the real world: $M_W \neq M_Z$: $U(1)_{EM}$ emerges too!

- WWZ amplitude: 2 degenerate particles

  Bose symmetry:

  W^+W^+ and W^-W^- forbidden → EM charge conserved

- High energy limit: 4 massless spin-1 particles

  WWZ & $WW\gamma$ amplitudes: isolate W^0, B

Example 2: fermion-fermion-Z

$$\mathcal{M}(\mathbf{1}_{\psi^c}, \mathbf{2}_\psi, \mathbf{3}_Z) = \frac{c^{RRR}_{\psi^c\psi Z}}{\bar{\Lambda}}[\mathbf{13}][\mathbf{23}] + \frac{c^{LR0}_{\psi^c\psi Z}}{m_Z}\langle\mathbf{13}\rangle[\mathbf{23}] + \frac{c^{RL0}_{\psi^c\psi Z}}{m_Z}[\mathbf{13}]\langle\mathbf{23}\rangle + \frac{c^{LLL}_{\psi^c\psi Z}}{\bar{\Lambda}}\langle\mathbf{13}\rangle\langle\mathbf{23}\rangle$$

contains all helicity amplitudes:

- $\mathbf{2}] = \mathbf{2}^{I}$: $I = 1: +\,helicity$; $I = 2: -\,helicity$
- $\mathbf{3}]\mathbf{3}] = \mathbf{3}^{\{I}]\mathbf{3}^{J\}}]$: $I = J = 1: +$
  $I = J = 2: -$
  $I = 1\ J = 2: 0$

Example 2: fermion-fermion-Z

$$\mathcal{M}(\mathbf{1}_{\psi^c}, \mathbf{2}_{\psi}, \mathbf{3}_Z) = \frac{c^{RRR}_{\psi^c\psi Z}}{\bar{\Lambda}}[\mathbf{13}][\mathbf{23}] + \frac{c^{LR0}_{\psi^c\psi Z}}{m_Z}\langle\mathbf{13}\rangle[\mathbf{23}] + \frac{c^{RL0}_{\psi^c\psi Z}}{m_Z}[\mathbf{13}]\langle\mathbf{23}\rangle + \frac{c^{LLL}_{\psi^c\psi Z}}{\bar{\Lambda}}\langle\mathbf{13}\rangle\langle\mathbf{23}\rangle$$

- dimensionless couplings

Example 2: fermion-fermion-Z

$$\mathcal{M}(\mathbf{1}_{\psi^c},\mathbf{2}_{\psi},\mathbf{3}_Z)=\frac{c^{RRR}_{\psi^c\psi Z}}{\bar{\Lambda}}[\mathbf{13}][\mathbf{23}]+\frac{c^{LR0}_{\psi^c\psi Z}}{m_Z}\langle\mathbf{13}\rangle[\mathbf{23}]+\frac{c^{RL0}_{\psi^c\psi Z}}{m_Z}[\mathbf{13}]\langle\mathbf{23}\rangle+\frac{c^{LLL}_{\psi^c\psi Z}}{\bar{\Lambda}}\langle\mathbf{13}\rangle\langle\mathbf{23}\rangle$$

4 independent spinor structures:

in 3-pt amplitudes: number determined by angular momentum
= # irreps in the addition of the three spins:
here: $\mathbf{2}\times\mathbf{2}\times\mathbf{3}=\mathbf{1}+\mathbf{3}+\mathbf{3}+\mathbf{5}$

Example 2: fermion-fermion-Z

renormalizable vs NR terms: from behavior in "high energy limit" (complex momenta)

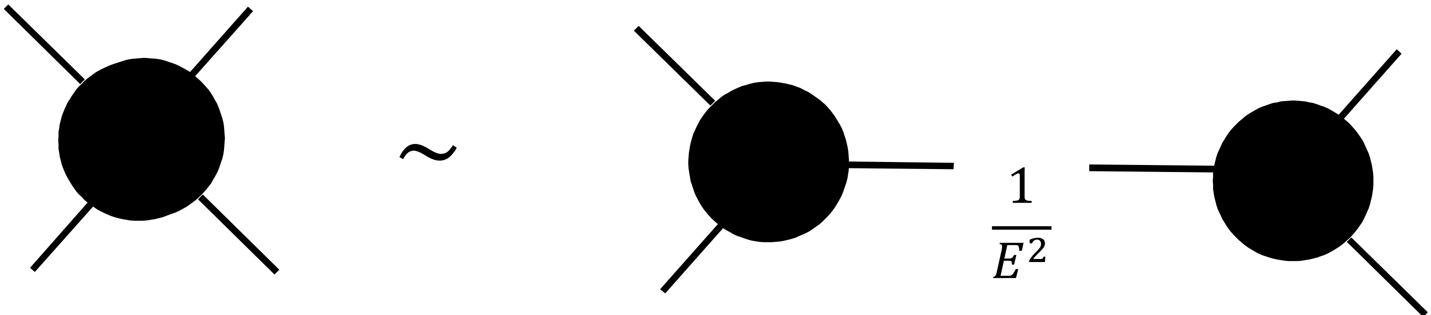
$$\mathcal{M}(\mathbf{1}_{\psi^c}, \mathbf{2}_{\psi}, \mathbf{3}_Z) = \frac{c^{RRR}_{\psi^c\psi Z}}{\bar{\Lambda}}[\mathbf{13}][\mathbf{23}] + \frac{c^{LR0}_{\psi^c\psi Z}}{m_Z}\langle\mathbf{13}\rangle[\mathbf{23}] + \frac{c^{RL0}_{\psi^c\psi Z}}{m_Z}[\mathbf{13}]\langle\mathbf{23}\rangle + \frac{c^{LLL}_{\psi^c\psi Z}}{\bar{\Lambda}}\langle\mathbf{13}\rangle\langle\mathbf{23}\rangle$$

$O(E^2)$ $O(m_Z E)$ $O(m_Z E)$ $O(E^2)$

good high energy behavior

dipole gauge dipole

= 3-pt version of perturbative unitarity:



$O(E^2)$ $O(E^2)$

$O(E^2)$

→ must be suppressed by cutoff $\bar{\Lambda}$

$$\mathcal{M}(\mathbf{1}_{\psi^c}, \mathbf{2}_{\psi}, \mathbf{3}_Z) = \frac{c^{RRR}_{\psi^c\psi Z}}{\bar{\Lambda}}[\mathbf{13}][\mathbf{23}] + \frac{c^{LR0}_{\psi^c\psi Z}}{m_Z}\langle\mathbf{13}\rangle[\mathbf{23}] + \frac{c^{RL0}_{\psi^c\psi Z}}{m_Z}[\mathbf{13}]\langle\mathbf{23}\rangle + \frac{c^{LLL}_{\psi^c\psi Z}}{\bar{\Lambda}}\langle\mathbf{13}\rangle\langle\mathbf{23}\rangle$$

Requiring a smooth high-energy limit of separate helicity amplitudes:

- In the high-energy limit, the fermion coupling to the longitudinal Z boson has a pseudo-scalar spinor structure.
- In the high-energy limit, fermions with a vector-like $LR0/RL0$ coupling to the Z boson do not interact with its longitudinal component.
- Fermions with chiral $LR0/RL0$ couplings to the Z boson, do interact with its longitudinal component in the high-energy limit, with a strength proportional to their mass.
- A massive fermion only has vector-like $LR0/RL0$ coupling to a massless vector.
- The coupling of a massless fermion to the longitudinal component of a massive vector vanishes in the high-energy limit.
- The mass of a fermion with chiral $LR0/RL0$ couplings to a massive vector, can only be taken to vanish at least as fast as the vector mass.

in high energy limit $m_Z/E \to 0$:

$$\mathcal{M}(1^-_{\psi^c}, 2^-_{\bar\psi}, 3^0_Z) \to +\langle 12\rangle \, (c^{LR0}_{\psi^c\psi Z} - c^{RL0}_{\psi^c\psi Z}) \, m_\psi/\sqrt{2} m_Z$$

either =0 or =0

vector-like fermion

fermion mass has same origin as vector mass & goes to zero at least as fast

* will refine this when discuss 4-pt amplitude

towards the on-shell electroweak theory:

4-pt amplitudes:

example: fermion-fermion-Z-h

4 point amplitudes: fermion-fermion-Z-Higgs

$\mathbf{1}_{\psi^c}, \mathbf{2}_{\psi}, \mathbf{3}_{Z}, \mathbf{4}_{h}$

1) which spinor structures are allowed?

   basis of independent spinor structures?

   12 of these:

$$[\mathbf{13}][\mathbf{23}] \quad [\mathbf{13}]\langle\mathbf{23}\rangle \quad [\mathbf{312}\rangle[\mathbf{13}] \quad \langle\mathbf{321}]\langle\mathbf{23}\rangle \quad [\mathbf{12}]\langle\mathbf{3}\ (\mathbf{1}\pm\mathbf{2})\ \mathbf{3}]$$

$$+ \quad [..] \quad \leftrightarrow \quad \langle..\rangle \qquad \text{(parity)}$$

any other structure (with correct LG transformation) can be spanned by these (with coeffs = polynomials in Lorentz invariants s_{ij}), eg,

$$[\mathbf{12}]\langle\mathbf{3123}\rangle = 2\ [\mathbf{12}]\ \langle\mathbf{3}\ \{\mathbf{1}\ (p_2\cdot p_3) - \mathbf{2}\ (p_1\cdot p_3)\}\ \mathbf{3}]/m_3$$
$$- 2(p_1\cdot p_2)[\mathbf{13}][\mathbf{23}] - m_1[\mathbf{321}\rangle[\mathbf{23}] - m_2[\mathbf{312}\rangle[\mathbf{13}]$$

Non-factorizable part:

$$
\begin{aligned}
\mathcal{M}^{\rm nf}(\mathbf{1}_{\psi^c},\mathbf{2}_{\psi},\mathbf{3}_Z,\mathbf{4}_h) = {} & \frac{c^{RRR}_{\psi^c\psi Zh}}{\bar\Lambda^2}[\mathbf{13}][\mathbf{23}] + \frac{[\mathbf{12}]}{\bar\Lambda^3}\langle\mathbf{3}\,\{c^{RR0_A}_{\psi^c\psi Zh}(\mathbf{1}+\mathbf{2}) + c^{RR0_S}_{\psi^c\psi Zh}(\mathbf{1}-\mathbf{2})\}\,\mathbf{3}] \\
& + \frac{c^{RL0}_{\psi^c\psi Zh}}{\bar\Lambda^2}[\mathbf{13}]\langle\mathbf{23}\rangle + \frac{c^{RLR}_{\psi^c\psi Zh}}{\bar\Lambda^3}[\mathbf{312}\rangle[\mathbf{13}] + \frac{c^{RLL}_{\psi^c\psi Zh}}{\bar\Lambda^3}\langle\mathbf{321}]\langle\mathbf{23}\rangle \\
& + \frac{c^{LR0}_{\psi^c\psi Zh}}{\bar\Lambda^2}\langle\mathbf{13}\rangle[\mathbf{23}] + \frac{c^{LRR}_{\psi^c\psi Zh}}{\bar\Lambda^3}[\mathbf{321}\rangle[\mathbf{23}] + \frac{c^{LRL}_{\psi^c\psi Zh}}{\bar\Lambda^3}\langle\mathbf{312}]\langle\mathbf{13}\rangle \\
& + \frac{c^{LLL}_{\psi^c\psi Zh}}{\bar\Lambda^2}\langle\mathbf{13}\rangle\langle\mathbf{23}\rangle + \frac{\langle\mathbf{12}\rangle}{\bar\Lambda^3}\langle\mathbf{3}\,\{c^{LL0_A}_{\psi^c\psi Zh}(\mathbf{1}+\mathbf{2}) + c^{LL0_S}_{\psi^c\psi Zh}(\mathbf{1}-\mathbf{2})\}\,\mathbf{3}]
\end{aligned}
$$

- coefficients = expansions in $s_{ij}/\bar{\Lambda}^2$
- **full result:** to all orders in v/Λ

Non-factorizable part:

dim 6 + dim 7

$$\mathcal{M}^{\rm nf}(1_{\psi^c}, 2_\psi, 3_Z, 4_h) = \frac{c^{RRR}_{\psi^c\psi Zh}}{\bar\Lambda^2}[13][23] + \frac{[12]}{\bar\Lambda^3}\langle 3\, \{c^{RR0_A}_{\psi^c\psi Zh}(1+2) + c^{RR0_S}_{\psi^c\psi Zh}(1-2)\}\, 3]$$
$$+ \frac{c^{RL0}_{\psi^c\psi Zh}}{\bar\Lambda^2}[13]\langle 23\rangle + \frac{c^{RLR}_{\psi^c\psi Zh}}{\bar\Lambda^3}[312\rangle[13] + \frac{c^{RLL}_{\psi^c\psi Zh}}{\bar\Lambda^3}\langle 321]\langle 23\rangle$$
$$+ \frac{c^{LR0}_{\psi^c\psi Zh}}{\bar\Lambda^2}\langle 13\rangle[23] + \frac{c^{LRR}_{\psi^c\psi Zh}}{\bar\Lambda^3}[321\rangle[23] + \frac{c^{LRL}_{\psi^c\psi Zh}}{\bar\Lambda^3}\langle 312]\langle 13\rangle$$
$$+ \frac{c^{LLL}_{\psi^c\psi Zh}}{\bar\Lambda^2}\langle 13\rangle\langle 23\rangle + \frac{\langle 12\rangle}{\bar\Lambda^3}\langle 3\, \{c^{LL0_A}_{\psi^c\psi Zh}(1+2) + c^{LL0_S}_{\psi^c\psi Zh}(1-2)\}\, 3]$$

- coefficients = expansion in $s_{ij}/\bar\Lambda^2$

at dimension 6 or 7:
coeffs just constants

Non-factorizable part:

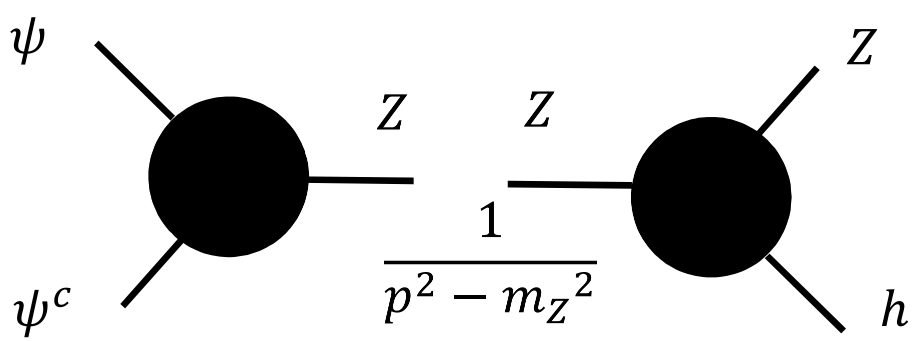
$$\mathcal{M}^{\rm nf}(1_{\psi^c},2_\psi,3_Z,4_h) = \frac{c^{RRR}_{\psi^c\psi Zh}}{\bar\Lambda^2}[13][23] + \frac{[12]}{\bar\Lambda^3}\langle 3\,\{c^{RR0_A}_{\psi^c\psi Zh}(1+2) + c^{RR0_S}_{\psi^c\psi Zh}(1-2)\}\,3]$$
$$+ \frac{c^{RL0}_{\psi^c\psi Zh}}{\bar\Lambda^2}[13]\langle 23\rangle + \frac{c^{RLR}_{\psi^c\psi Zh}}{\bar\Lambda^3}[312\rangle[13] + \frac{c^{RLL}_{\psi^c\psi Zh}}{\bar\Lambda^3}\langle 321]\langle 23\rangle$$
$$+ \frac{c^{LR0}_{\psi^c\psi Zh}}{\bar\Lambda^2}\langle 13\rangle[23] + \frac{c^{LRR}_{\psi^c\psi Zh}}{\bar\Lambda^3}[321\rangle[23] + \frac{c^{LRL}_{\psi^c\psi Zh}}{\bar\Lambda^3}\langle 312]\langle 13\rangle$$
$$+ \frac{c^{LLL}_{\psi^c\psi Zh}}{\bar\Lambda^2}\langle 13\rangle\langle 23\rangle + \frac{\langle 12\rangle}{\bar\Lambda^3}\langle 3\,\{c^{LL0_A}_{\psi^c\psi Zh}(1+2) + c^{LL0_S}_{\psi^c\psi Zh}(1-2)\}\,3]$$

coefficients = expansions in $s_{ij}/\bar\Lambda^2$:

$= \; c_6^{RRR} + c_{8,1}^{RRR} s_{12}/\bar\Lambda^2$ +.. : NR couplings (Wilson coefficients)

Factorizable part:

simply glue together 3-point amplitudes over all possible factorization channels, eg,



depends on couplings appearing in 3-pt amplitudes

Perturbative unitarity:

High energy growth: $O(E)$ or higher must be suppressed by $\bar{\Lambda}$

$$\left(c^{RL0}_{\psi^c\psi Z} - c^{LR0}_{\psi^c\psi Z}\right)\left(c^{00}_{ZZh}\, m_\psi/2m_Z - c^{LL}_{\psi^c\psi h}\right) = 0 + \mathcal{O}(m/\bar{\Lambda})$$

either ⇓ or

=0 | =0

$$m_\psi = 2\,\frac{c^{LL}_{\psi\psi Z}}{c^{00}_{ZZh}}\, m_Z$$

vector-like fermion

fermion mass from Higgs mechanism!

towards the on-shell electroweak theory:
matching to broken phase SMEFT

Matching to broken phase SMEFT (tree-level, dim-6 only):

Dedes Materkowska Paraskevas Rosiek Suxho '17

following Warsaw basis — Grzadkowski Iskrzynski Misiak Rosiek

so far: full list of 3-point couplings

couplings featured in ffZh amplitude

example: fermion-fermion-Z couplings:

$$\begin{aligned}
c^{LR0}_{\psi^c\psi Z} =& -\sqrt{2}Q_\psi \frac{\bar{g}'^2}{\sqrt{\bar{g}^2+\bar{g}'^2}} \\
&+\frac{v^2}{\Lambda^2}\left[-\sqrt{2}\frac{\bar{g}^3\bar{g}'}{(\bar{g}^2+\bar{g}'^2)^{3/2}}Q_\psi C_{\varphi WB} - \frac{1}{\sqrt{2}}\sqrt{\bar{g}^2+\bar{g}'^2}C_{\varphi\psi_R}\right], \qquad \text{(B.9)}\\
c^{RL0}_{\psi^c\psi Z} =& \sqrt{2}I_\psi \frac{\bar{g}^2}{\sqrt{\bar{g}^2+\bar{g}'^2}} - \sqrt{2}Y_\psi \frac{\bar{g}'^2}{\sqrt{\bar{g}^2+\bar{g}'^2}} \\
&+\frac{v^2}{\Lambda^2}\left[\sqrt{2}\frac{\bar{g}\bar{g}'}{(\bar{g}^2+\bar{g}'^2)^{3/2}}\left(-Y_\psi\bar{g}^2+I_\psi\bar{g}'^2\right)C_{\varphi WB} - \frac{1}{\sqrt{2}}\sqrt{\bar{g}^2+\bar{g}'^2}\left(C^1_{\varphi\psi_L}-2I_\psi C^3_{\varphi\psi_L}\right)\right], \qquad \text{(B.10)}\\
\frac{c^{RRR}_{\psi^c\psi Z}}{\bar{\Lambda}} =& \frac{v}{\Lambda^2}\left(-4I_\psi\frac{\bar{g}}{\sqrt{\bar{g}^2+\bar{g}'^2}}C_{\psi W} + 2\frac{\bar{g}'}{\sqrt{\bar{g}^2+\bar{g}'^2}}C_{\psi B}\right), \qquad \text{(B.11)}\\
c^{LLL}_{\psi^c\psi Z} =& \left(c^{RRR}_{\psi^c\psi Z}\right)^* . \qquad \text{(B.12)}
\end{aligned}$$

To conclude:

- We provided a complete toolbox for performing on-shell computations in the *physical* SM EFT:
  - full set of 3-pt amplitudes + matching to SMEFT
  - prescription for gluing spinning amplitudes
  - + one 4-pt example

- outlook:
  - high multiplicity: n>4 external legs
  - loops
  - global analyses based on on-shell amplitudes
  - searches for new physics: as in SM+new resonance examples

EFT:

- on-shell approach is natural for constructing bottom-up ``EFT" extensions of low-energy SM

  = all possible couplings of SM particles consistent with Lorentz, global symmetries, locality and unitarity

- compact analytic expressions for amplitudes: all orders in $v\ /\Lambda$ expansion,

  straightforward to go to higher orders in derivative expansion

  (non-trivial part is the spinor structure)

- truly bottom-up: can explore extensions beyond SM EFT, extra Higgses, new particles

+ **re-learning gauge theories and Higgs mechanism:**

SU(2)xU(1) structure & Higgs mechanism beautifully emerge from Lorentz
+ unitarity/good high energy limit (for $v - \Lambda$ hierarchy)

IR unification of the unbroken theory amplitudes *Arkani-Hamed Huang Huang* still need to develop more tools:

- constructing bases for massive amplitudes

  in progress with Durieux, Kitahara, Ma, Machado, Weiss

- [massless bases:
  - spinors (Durieux, Machado ‘19: GRSMEFT, SMEFT)
  - twistors (Falkowski ‘19)
  - angular momentum selection rules (Jiang Shu Xiao Zheng ’20) …]

- massive n-point functions: recursion relations

  Ochirov ‘18
  Franken Schwinn ‘19

And thanks to the organizers for a true bootstrap conference!

``bootstrap" originated in 19th century US

it meant pulling oneself up ``by one's boot straps" out of a difficult or impossible situation

(or translated to European: by one's own hair, a la Baron Munchausen)