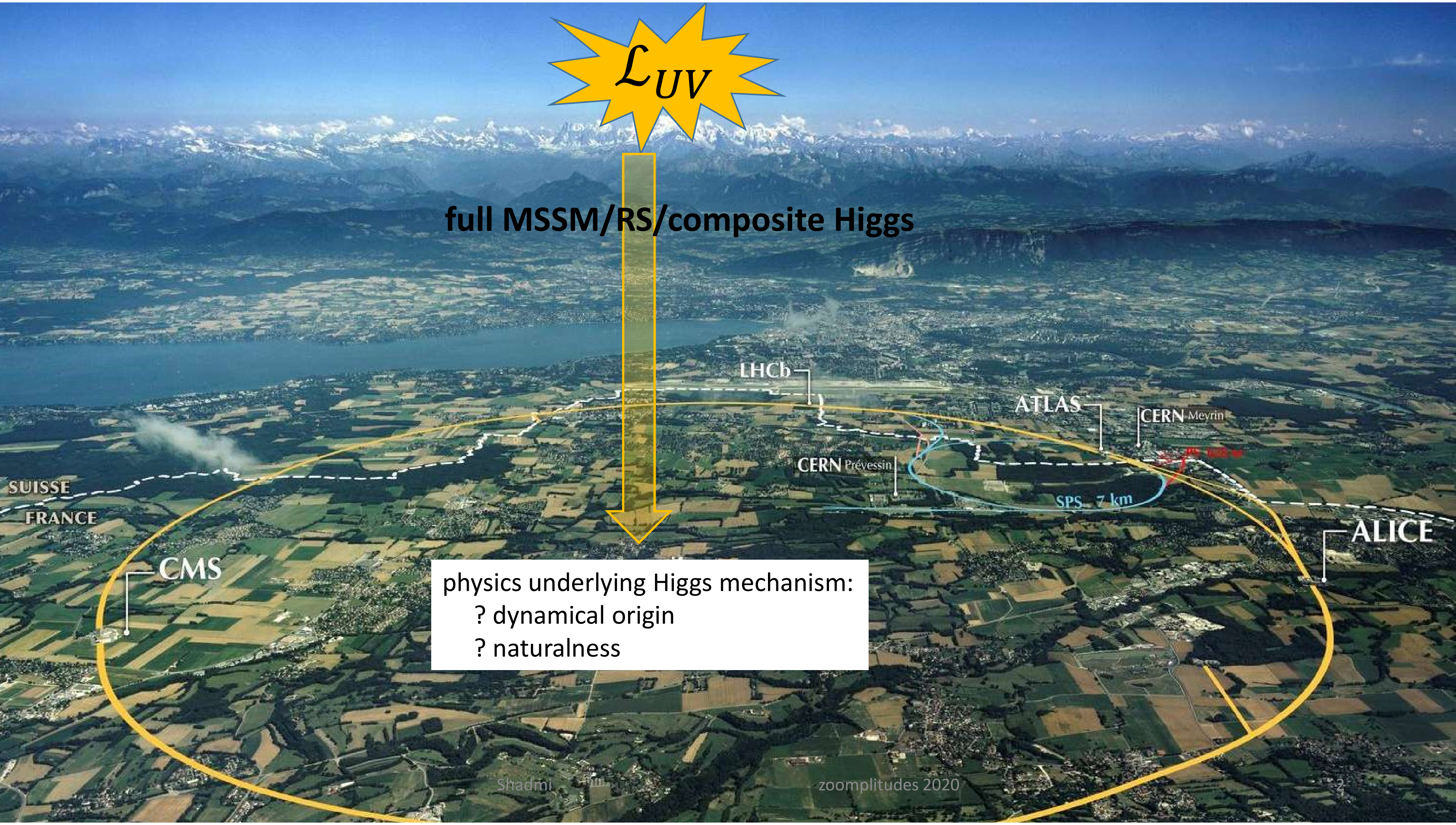
on-shell SM EFT(s)

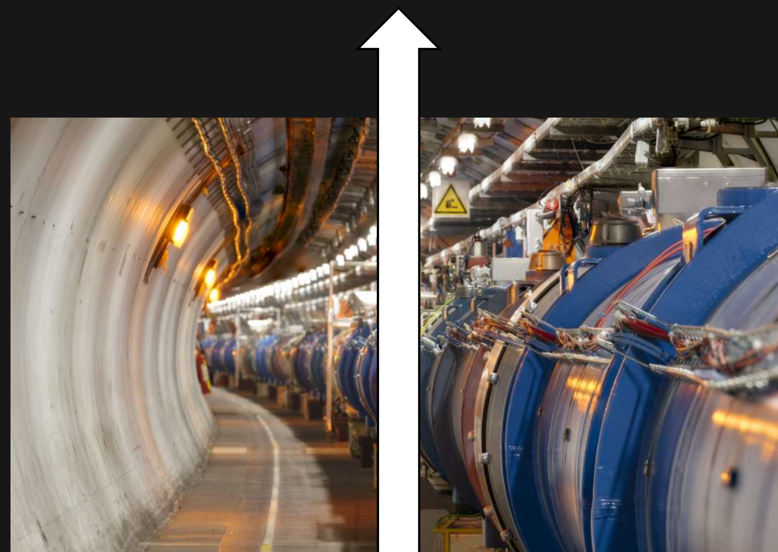
Yael Shadmi

Technion

Yaniv Weiss, YS 1809.09644
Gauthier Durieux, Teppei Kitahara, YS, Yaniv Weiss 1909.10551
Gauthier Durieux, Teppei Kitahara, Camila Machado, YS, Yaniv Weiss in progress

Amplitudes 2020


$\mathcal{L}_{UV}$
full MSSM/RS/composite Higgs
physics underlying Higgs mechanism:
? dynamical origin
? naturalness
LHCb
ATLAS
CERN Meyrin
CERN Prévessin
SPS 7 km
SUISSE
FRANCE
CMS
ALICE



IR (~ -100m)

experiment must guide the way

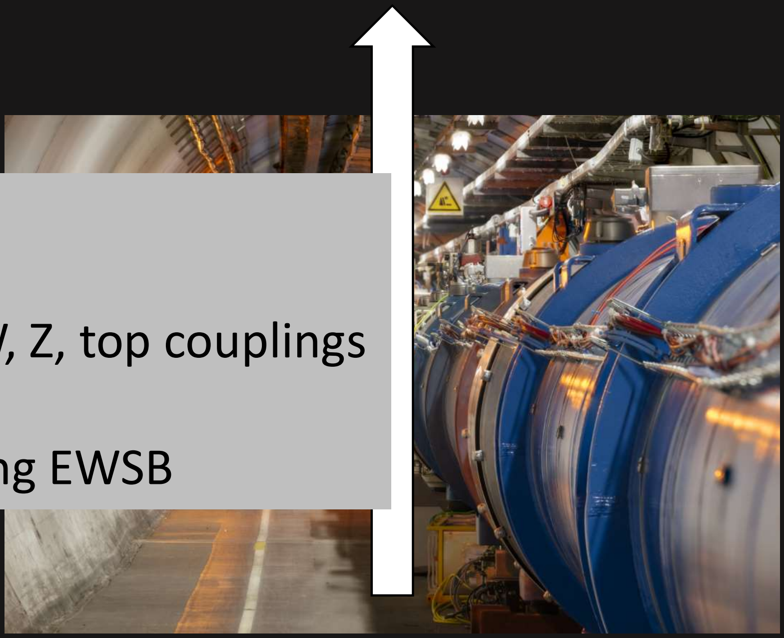
EFT: a systematic framework for parameterizing our ignorance

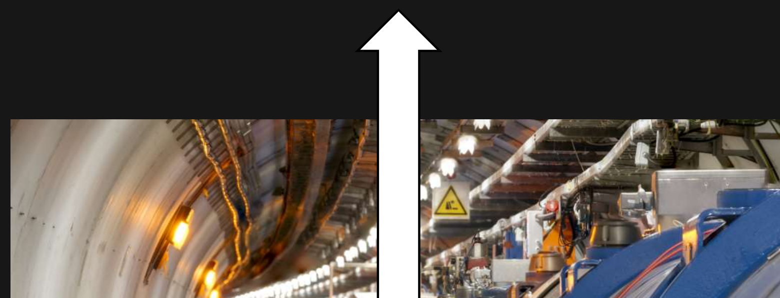
See talk by N. Craig

of special importance:

MASSive particles: higgs W, Z, top couplings

? clues to physics underlying EWSB





SM EFT (SMEFT)

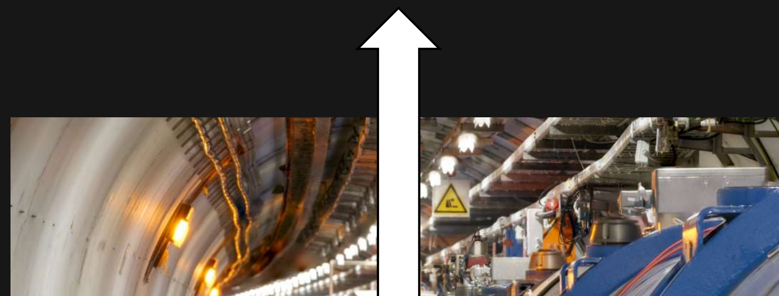
SM fields & full gauge symmetry

1) $\mathcal{L}_{EFT}$: *basis of independent operators*
eliminate field redefinitions, EOM..
Hilbert series
dim-6 fully known
counting of operators to any dimension

[dim-8: full set of operators this month!]

…
Grzadkowski Iskrzynski Misiak Rosiek
Alonso Jenkins Manohar Trott
Henning Lu Melia Murayama
Lehman Martin
…
Li Ren Shu Xiao Yu Zheng
Murphy

See talk by N. Craig



SM EFT (SMEFT)

SM fields & full gauge symmetry

2) go to broken phase: $< H >= v$
SM couplings corrected by v/Λ

3) compare to exp: fit couplings → cross-sections

goal here:

construct EFT amplitudes directly

(forget $\mathcal{L}_{EFT}$..)

Motivation:

- The EFT program is (mostly) **bottom-up**:
  starting with SM fields [+ X]:
  Lorentz, global, gauge symmetry → $\mathcal{L}_{EFT}$

→ on-shell bootstrap approach *is very natural:*

- starting with SM particles:

Lorentz, global symmetry [+ unitarity, locality] → dictate structure of on-shell amplitudes

[unbroken gauge symmetry imposed/emerges]

with unknown coefficients of contact terms ←→ Wilson coefficients

✓ **field redefinitions, gauge redundancies, EOMs, never show up**

✓ calculate and relate physical observables

✓ [on technical side: NR vertices typically complicated (lots of fields/derivatives)]

but there's more..

- SMEFT: assume SM field content; impose SU(2)xU(1) above v

more generally:

? non-linearly realized SU(2)xU(1) [HEFT]

? strong coupling somewhat above v (composite Higgs?)

? multiple Higgs fields

See talk by N. Craig

highlighted recently:
Falkowski Rattazzi
Chang Luty
Henning Lombardo Riembau Riva

❖ Processes with multiple higgs, W, Z legs provide important diagnostics (sometimes better sensitivity to Higgs couplings than processes involving Higgs external legs)

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more generally:

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a bottom-up derivation of on-shell amplitudes can capture these

❖ Processes with multiple higgs, W, Z legs provide important diagnostics
  (sometimes better sensitivity to Higgs couplings than processes involving Higgs external legs)

(hopefully) easier, compact and tractable expressions

outline

- setup
- warm-up: SM + new resonance X; gluon production & decay
- towards full SM EFT (broken electroweak phase)

amplitudes of EFTs have a long history:

starting from a general understanding of EFT amplitudes — Cohen Elvang Kiermaier

a rich program of mapping of EFTs

* soft bootstrap → non-linear sigma models — Cheung Kampf Novotny Trnka; Elvang Jones Naulich; Low Yin; ...

See talk by N. Craig

→SM EFT: many results derived/explained via amplitudes:

- vanishing SM-BSM interference — Azatov Contino Machado Riva
- vanishing operator mixings — Chueng Shen; Bern Parra-Martinez Sawyer; Craig Jiang Li Sutherland

See talk by Z. Bern

approach here: ***Just do it!***

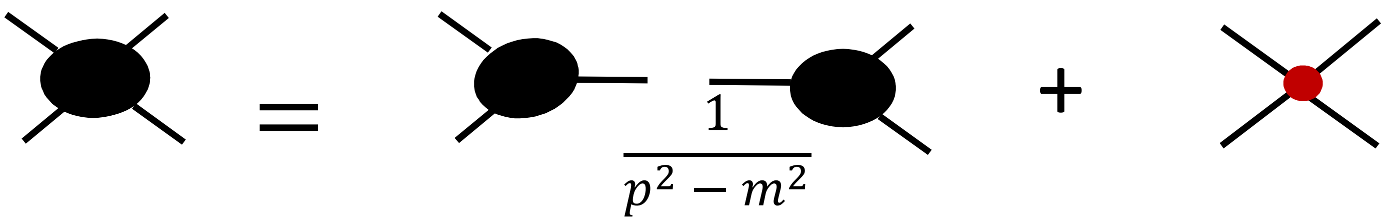
directly derive amplitudes

The on-shell EFT:

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

determine 3-pt amplitudes

- higher point amplitudes via bootstrap:



contact terms:
generically NR
couplings
(Wilson coeff's)

→ couplings

a. appearing in 3-point amplitudes (renormalizable: gauge, Yukawa **& NR**)
b. contact terms appearing in higher point amplitudes (NR)

central theme: masses

- amplitudes pov: masses lead to some **simplifications**

- EFT pov: SM EFT Lagrangian involves 2 expansions:
  (1) derivative/momentum: $\partial/\Lambda \rightarrow s_{ij}/\Lambda^2$
  (2) Higgs VEV: v/Λ [the ``geometric (field space) SM EFT”]

  Alonso Jenkins Manohar’15; Helset Martin Trott ‘20

  [working with massive amplitudes → all orders in (2)
  pragmatically: top, Z, W mass can give sizable corrections: m/E
  if high-order in (1) important: energies $\sim\Lambda$, EFT validity breaks down]

- key to EWSB: new insights from amplitudes? Higgsing as ``IR unification” of amplitudes

  Arkani-Hamed Huang Huang ’17

Massive Spinor variables

split massive external momentum: $p = p^1 + p^2$

Arkani-Hamed Huang Huang '17

$$\boldsymbol{p}_{\alpha\dot{\alpha}} = \boldsymbol{\lambda}^I_\alpha \tilde{\boldsymbol{\lambda}}_{I\dot{\alpha}} = |\boldsymbol{p}^I\rangle[\boldsymbol{p}_I|$$

$I = 1, 2$ LG index

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

$SU(2)$ LG transformation

with the momentum vector converting between them (EOM):

$$\frac{\boldsymbol{p}}{m}|\boldsymbol{p}^I] = |\boldsymbol{p}^I\rangle$$

external particle of spin-s:

$$|p^{I_1}]|p^{I_2}]\cdots|p^{I_{2s}}]$$

LG indices symmetrized

bold notation: LG indices implicit (and symmetrized)

Direct derivation of on-shell EFT amplitudes:

SM + new particle (LHC searches for new particles)

YS Weiss 1809.09644

model-independent parametrization of LHC production/decay of X:

$$Xggg \quad XXgg$$

scalar X + 3 gluons:

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

tree amplitude: shown up to dim-13!

$$M\left(X;1^{a,+},2^{b,+},3^{c,+}\right) = [12][13][23]$$

$$\{\, f^{abc}\, [\, -ig\,\frac{c_5^{Xgg}}{\Lambda}\,\frac{m^4}{s_{12}s_{13}s_{23}}$$

factorizable

$$+\frac{c_7}{\Lambda^3} + \frac{c_{11}}{\Lambda^7}\left(s_{12}s_{13} + s_{12}s_{23} + s_{13}s_{23}\right) + \frac{c_{13}}{\Lambda^9}\, s_{12}s_{13}s_{23} \; + \; \ldots\,]$$

$$+\, d^{abc}\,\frac{c'_{13}}{\Lambda^9}\,\left(s_{12}-s_{13}\right)\,\left(s_{12}-s_{23}\right)\,\left(s_{13}-s_{23}\right) + \ldots\, \}$$

- c's: Wilson coeffs
- Bose symmetry
- similarly for spin-1 resonance (no factorizable part)

scalar X + 3 gluons:

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

$$M\left(X;1^{a,+},2^{b,+},3^{c,+}\right) = [12][13][23]$$

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factorizable

$$+\frac{c_7}{\Lambda^3} + \frac{c_{11}}{\Lambda^7}\left(s_{12}s_{13} + s_{12}s_{23} + s_{13}s_{23}\right) + \frac{c_{13}}{\Lambda^9}\, s_{12}s_{13}s_{23} \;+\; \ldots]$$

$) + \ldots \}$

tree amplitude:
shown up to dim-13!

by-product:
no-brainer counting of independent operators
up to very high orders

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

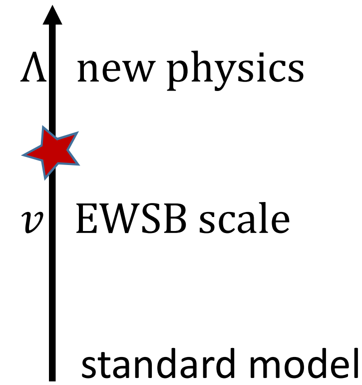
Durieux Kitahara YS Weiss '19

different possible amplitude-based approaches:

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

  → direct mapping to SMEFT operators

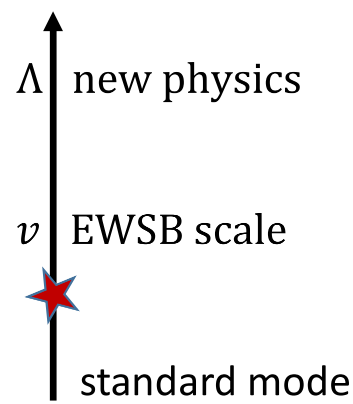
  Ma Shu Xiao '19



- ❑ Construct amplitudes with

  external legs = SM particles (massless/massive)

  - impose SU(2)xU(1) at v — Aoude Machado '19
  - not impose SU(2)xU(1) at v — Durieux Kitahara YS Weiss '19



Towards the on-shell electroweak EFT:

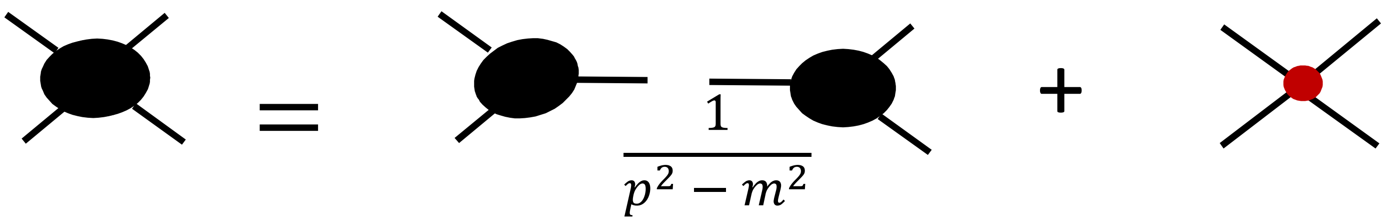
Durieux Kitahara YS Weiss '19

- **particles:** W, Z, Higgs, SM fermions..
- **global symm:** EM charge, baryon, lepton

determine 3-pt amplitudes

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

- higher point amplitudes via bootstrap:



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→ couplings

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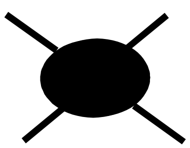
- higher point a



=

→ couplings

a. appeari
b. contact

rms:
y NR
gs
eff's)

goal: construct EFT

but along the way:

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

on-shell Higgs mechanism: how do EWSB patterns emerge?

how does SU(2)xU(1) emerge in purely bottom-up construction?

used **perturbative unitarity**

high energy growth: bad high-energy growth must be suppressed by cutoff scale

SM is the unique theory with this property

Llewellyn Smith; Joglekar;
Cornwall Levin Tiktopoulos
Lee Quigg Thacker;
Chanowitz Gaillard ‘70s
…

→ requiring perturbative unitarity, SU(2)xU(1) relations among couplings, masses should emerge

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

example 1: fermion-fermion-Z

Lorentz (LG scaling) fix:

dimensionless couplings

$$\mathcal{M}(\mathbf{1}_{\psi^c}, \mathbf{2}_{\psi}, \mathbf{3}_Z) = \frac{c_5^R}{\Lambda}[\mathbf{13}][\mathbf{23}] + \frac{g_{LR}}{m_Z}\langle\mathbf{13}\rangle[\mathbf{23}] + \frac{g_{RL}}{m_Z}[\mathbf{13}]\langle\mathbf{23}\rangle + \frac{c_5^L}{\Lambda}\langle\mathbf{13}\rangle\langle\mathbf{23}\rangle$$

EFT scale broken phase

- contains all helicity amplitudes: different choices of LG indices
- 4 independent spinor structures: number determined by angular momentum = # irreps in the addition of the three spins: here: $\mathbf{2} \times \mathbf{2} \times \mathbf{3} = \mathbf{1} + \mathbf{3} + \mathbf{3} + \mathbf{5}$

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

$$\mathcal{M}(\mathbf{1}_{\psi^c}, \mathbf{2}_{\psi}, \mathbf{3}_Z) = \frac{c_5^R}{\bar{\Lambda}}[\mathbf{13}][\mathbf{23}] + \frac{g_{LR}}{m_Z}\langle\mathbf{13}\rangle[\mathbf{23}] + \frac{g_{RL}}{m_Z}[\mathbf{13}]\langle\mathbf{23}\rangle + \frac{c_5^L}{\bar{\Lambda}}\langle\mathbf{13}\rangle\langle\mathbf{23}\rangle$$

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

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

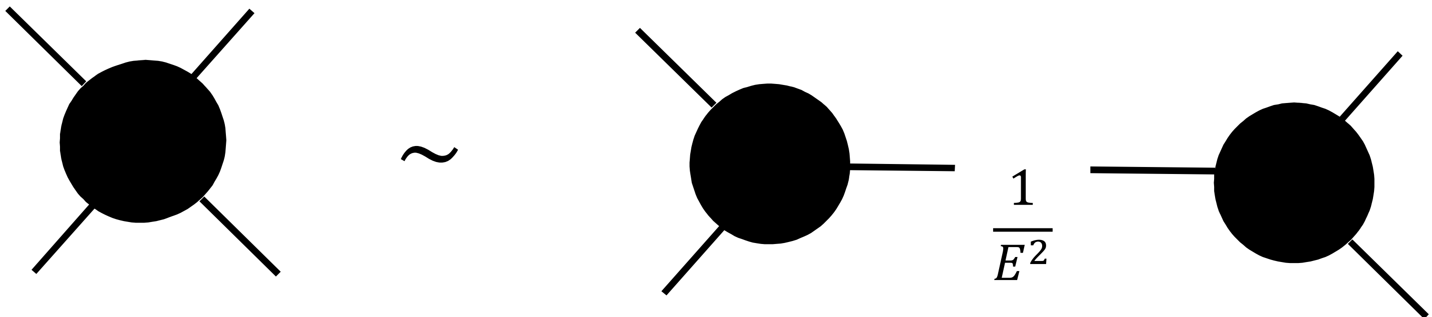
$$\mathcal{M}(\mathbf{1}_{\psi^c}, \mathbf{2}_\psi, \mathbf{3}_Z) = \frac{c_5^R}{\bar{\Lambda}}[\mathbf{13}][\mathbf{23}] + \frac{g_{LR}}{m_Z}\langle\mathbf{13}\rangle[\mathbf{23}] + \frac{g_{RL}}{m_Z}[\mathbf{13}]\langle\mathbf{23}\rangle + \frac{c_5^L}{\bar{\Lambda}}\langle\mathbf{13}\rangle\langle\mathbf{23}\rangle$$

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

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 $\bar{\Lambda}$

since 3-point:

$$\mathcal{M}(1_{\psi^c}, 2_\psi, 3_Z) = \frac{c_5^R}{\bar{\Lambda}}[13][23] + \frac{g_{LR}}{m_Z}\langle 13\rangle[23] + \frac{g_{RL}}{m_Z}[13]\langle 23\rangle + \frac{c_5^L}{\bar{\Lambda}}\langle 13\rangle\langle 23\rangle$$

- exact expression: $p_i \cdot p_j = m^2$ → 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

Pause to re-learn some QFT (Higgsing)

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

→ in HE limit:

- fermions with a vector-like coupling to the Z do not couple to its longitudinal component
- the (chiral) coupling of a fermions to the longitudinal Z is proportional to the fermion mass
- the coupling of a massive fermion to a massless vector is vector-like
- The coupling of a massless fermion to the longitudinal component of a vector vanishes
- The mass of a fermion with chiral couplings to a vector must tend to 0 at least as fast as the vector mass

…

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

$$\mathcal{M}(1^-_{\psi^c}, 2^-_{\psi}, 3^+_Z) \sim (g_L - g_R)\,\frac{m_\psi}{m_Z}\,\langle 12\rangle$$

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

Example 2: three massive gauge bosons: WWZ

central to non-abelian gauge interaction

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

Lorentz, LG scaling fix:

$$\mathcal{M}(1_W^a, 2_W^b, 3_W^c) = \epsilon^{abc}\left\{ \frac{c_6^L}{\Lambda^2}\langle 12\rangle\langle 13\rangle\langle 23\rangle + \frac{c_6^R}{\Lambda^2}[12][13][23] \right.$$

$$\left. + \frac{g}{m_W^2}\left(\langle 12\rangle\langle 13\rangle[23] + \langle 12\rangle[13]\langle 23\rangle + [12]\langle 13\rangle\langle 23\rangle\langle 12\rangle[13][23] + [12]\langle 13\rangle[23] + [12][13]\langle 23\rangle\right)\right\}$$

Example 2: three massive gauge bosons: WWZ

central to non-abelian gauge interaction

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

Lorentz, LG scaling fix:

antisymmetric in 1,2,3

$$\mathcal{M}(1_W^a, 2_W^b, 3_W^c) = \epsilon^{abc}\left\{ \frac{c_6^L}{\Lambda^2}\boxed{\langle 12\rangle\langle 13\rangle\langle 23\rangle} + \frac{c_6^R}{\Lambda^2}\boxed{[12][13][23]} \right.$$
$$\left. + \frac{g}{m_W^2}\boxed{\Big(\langle 12\rangle\langle 13\rangle[23] + \langle 12\rangle[13]\langle 23\rangle + [12]\langle 13\rangle\langle 23\rangle\langle 12\rangle[13][23] + [12]\langle 13\rangle[23] + [12][13]\langle 23\rangle\Big)}\right\}$$

→ **completely antisymmetric in *a,b,c:* SU(2)** :

3 degenerate spin-1 particles: Lorentz → SU(2) gauge structure

even simpler than massless case:

1,2,3 on equal footing as opposed to $[12]^3/[13][23]$

& masses smooth singular 3-pt kinematics

$$
\begin{aligned}
\mathcal{M}(1_W^a, 2_W^b, 3_W^c) = \epsilon^{abc} \Bigg\{ \quad & \frac{c_6^L}{\bar{\Lambda}^2} \langle 12\rangle\langle 13\rangle\langle 23\rangle + \frac{c_6^R}{\bar{\Lambda}^2} [12][13][23] \\
+\frac{g}{m_W^2} & \boxed{\Big(\langle 12\rangle\langle 13\rangle[23] + \langle 12\rangle[13]\langle 23\rangle + [12]\langle 13\rangle\langle 23\rangle\langle 12\rangle[13][23] + [12]\langle 13\rangle[23] + [12][13]\langle 23\rangle \Big)} \Bigg\}
\end{aligned}
$$

towards the on-shell electroweak theory:

4-pt amplitudes:

example: fermion-fermion-Z-higgs

4 point amplitudes: fermion-fermion-Z-Higgs

$$\mathbf{1}_{\psi^c}, \mathbf{2}_{\psi}, \mathbf{3}_Z, \mathbf{4}_h$$

1) Lorentz (LG) fixes allowed spinor structures

12 independent spin structures:

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

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

any other structure with correct LG transformation can be spanned by these (with coeffs = polynomials/rational functions of s_{ij}), eg,

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

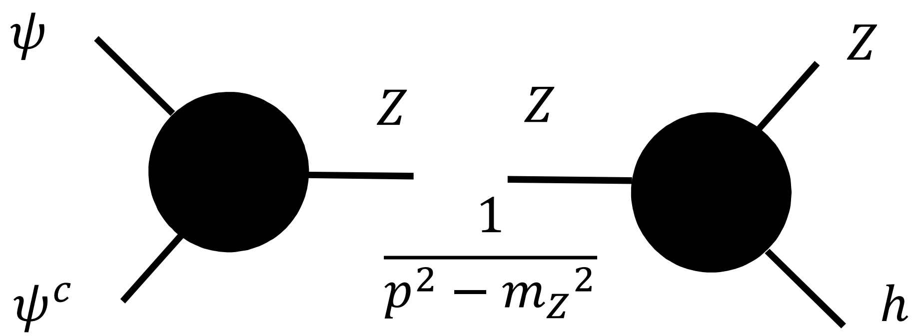
Non-factorizable part:

$$\mathcal{M}^{\rm nf}(\mathbf{1}_{\psi^c},\mathbf{2}_{\psi},\mathbf{3}_Z,\mathbf{4}_h) = \frac{c_6^{RRR}}{\bar{\Lambda}^2}[\mathbf{13}][\mathbf{23}] + \frac{c_6^{RL0}}{\bar{\Lambda}^2}[\mathbf{13}]\langle\mathbf{23}\rangle$$
$$+ \frac{c_7^{RR0}}{\bar{\Lambda}^3}[\mathbf{12}]\langle\mathbf{313}] + \frac{c_7^{\prime RR0}}{\bar{\Lambda}^3}[\mathbf{12}]\langle\mathbf{323}] + \frac{c_7^{RLR}}{\bar{\Lambda}^3}[\mathbf{312}\rangle[\mathbf{13}] + \frac{c_8^{RR0}}{\bar{\Lambda}^3}[\mathbf{12}]\langle\mathbf{3123}\rangle$$

- + angle ←→ square
- coefficients: expansions, eg, $c_6^{RRR} = \# + \#\frac{2p_1\cdot p_2}{\bar{\Lambda}^2} + \#\frac{2p_1\cdot p_3}{\bar{\Lambda}^2} + \cdots$
- result captures all orders in v/Λ

Factorizable part:

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



leading order in EFT expansion: keep just one NR vertex dont show full result here but two comments:

1. **masses:**

non-degenerate masses (broken symmetry):

separation of poles: different factorization channels:

poles at $M_Z^2 \quad M_H^2 \quad M_{f1}^2 \quad M_{f2}^2$

2. Perturbative unitarity:

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

$$\underbrace{(g_L - g_R)}_{=0} \underbrace{\left(g_{ZZh}\frac{m_\psi}{m_Z} - y\right)}_{=0} = 0 + \mathcal{O}(m/\overline{\Lambda})$$

either =0 or =0

→ vector-like fermion

→ $m_\psi = 2\,y\,\dfrac{m_Z}{g_{ZZh}}$

see also:
Maltoni Mantani Mimasu '19

fermion mass from Higgs mechanism!

towards the on-shell electroweak theory:

complete set of 4-pt (& higher) amplitudes

bases for **massless** amplitudes:

- easy to construct specific amplitudes (see eg X+gluon example above)
- general bases, classifications:
  - ``Harmonics” of spinor variables — Henning Melia ‘19
  - basic spinor structures + invariants — Durieux Machado ‘19
  - twistors — Falkowski ‘19

bases for **massless** amplitudes:

Durieux Machado '19

- systematic classification & explicit expressions for $\dim \leq 7$ amplitudes for
    - SM-EFT
    - GR-SM-EFT   Ruhdorfer Serra Weiler '19

mult.	min. dim.	helicity conf.	spinor structures
3-pt	dim-3	sss	constant
	dim-4	f^+f^+s	$[12]$
	dim-5	v^+v^+s	$[12]^2$
		$v^+f^+f^+$	$[12][13]$
	dim-6	$v^+v^+v^+$	$[12][13][23]$
4-pt	dim-4	$ssss$	constant; s_{ij}; $s_{ij}s_{kl}$
	dim-5	f^+f^+ss	$[12](s_{ij})$
	dim-6	v^+v^+ss	$[12]^2(s_{ij})$
		$v^+f^+f^+s$	$[12][13](s_{ij})$
		$f^+f^+f^+f^+$	$[12][34](s_{ij})$, $[13][24](s_{ij})$
		$f^+f^+f^-f^-$	$[12]\langle 34\rangle(s_{ij})$
		f^+f^-ss	$[1(3-4)2\rangle(s_{ij})$
	dim-7	$v^+v^+v^+s$	$[12][13][23]$
		$v^+v^+f^+f^+$	$[12]^2[34]$, $[12]([14][23]+[13][24])$
		$v^+v^+f^-f^-$	$[12]^2\langle 34\rangle$
		[illegible]	[illegible]
		[illegible]	[illegible]
		[illegible]	[illegible]
	dim-8	$v^+v^+v^+v^+$	$[12]^2[34]^2$, $[13]^2[24]^2$, $[14]^2[23]^2$
		$v^+v^+v^-v^-$	$[12]^2\langle 34\rangle^2$
		$v^+v^+f^+f^-$	$[12]^2[3(1-2)4\rangle$
		$v^+v^-f^+f^-$	$[13]\langle 24\rangle[1(3-4)2\rangle$
		v^+v^-ss	$[1(3-4)2\rangle^2$
		$v^+f^-f^-s$	$[1231]\langle 23\rangle$
	dim-9	$v^+v^+v^-s$	$[12]^2\langle 3123\rangle$
		$v^+v^-f^+f^+$	$[34][1(3-4)2\rangle^2$
	dim-10	$v^+v^+v^+v^-$	$[12]^2[3(1-2)4\rangle^2$
5-pt	dim-5	$sssss$	constant; s_{ij}
	dim-6	f^+f^+sss	$[12](s_{ij})$; $[1342]$
	dim-7	v^+v^+sss	$[12]^2$
		$v^+f^+f^+ss$	$[12][13]$
		$f^+f^+f^+f^+s$	$[12][34]$, $[13][24]$
		$f^+f^+f^-f^-s$	$[12]\langle 34\rangle$

from Durieux Machado 1912.08827

Bases for massive amplitudes

Durieux Kitahara Machado YS Weiss, in progress

for each amplitude: basis **in terms of massive spinor products**:

- basis of independent *spin structures (spin structures not related by ratios of invariants)*

Kravchuk Simmons-Duffin ’16
counting ---CFT correlators
Bonifacio Hinterbichler ’18
in terms of momenta, polarizations

vs

- basis of independent kinematic structures ← relevant for EFT amplitudes

= spin structure times polynomial in invariants

counting & construction based directly on bold massive spinor formalism

1. gluing of 3pt amplitudes
2. bolding massless amplitudes (= covariantizing wrt massive LG)

outlook

- loops: RGE, logs unaffected by masses
- n-pt amplitudes: multiple vector bosons, Higgses

Ochirov ’18: massive quark pair + n gluons
Franken Schwinn ’19: massive recursion relations

To conclude:

origin of EWSB? The LHC will supply lots of data over next decade

EFTs provide a systematic way of quantifying our ignorance

→ natural first step in going **beyond the standard model**

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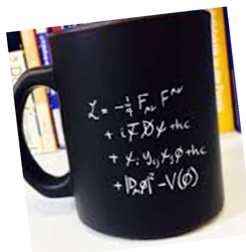

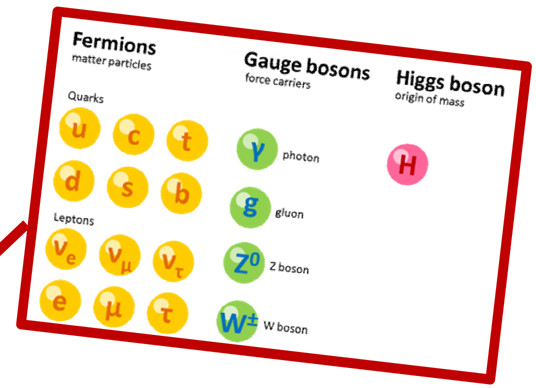

starting on-shell: many simplifications

exploring general UV theories (truly model independent)

ultimately learn about the origin of EWSB??

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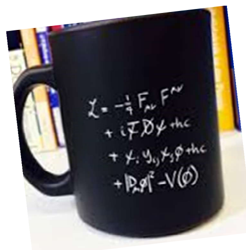

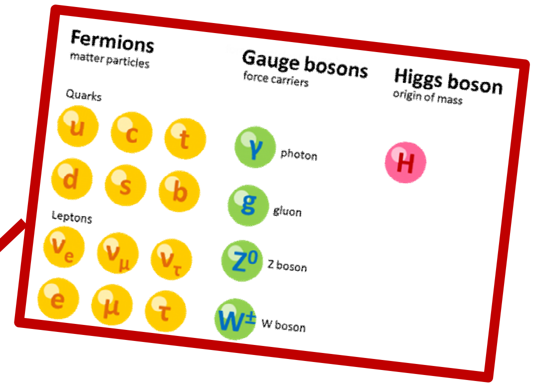

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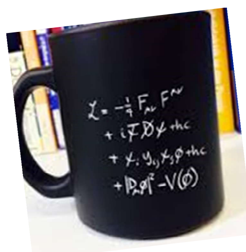

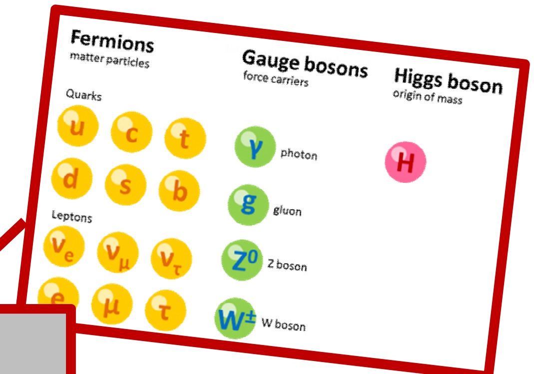

starting

ries

lots of room for progress from amplitude experts

masses

simplifying aspects

key to EWSB, naturalness

extra slides

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: 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!

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

- tree-level, dim-6 only
- following Warsaw basis Dedes Materkowska Paraskevas Rosiek Suxho '17
- so far: supplied full list of 3-point couplings

  + couplings featured in fermion-fermion-Z-h amplitude