Amplitudes for SM EFTs

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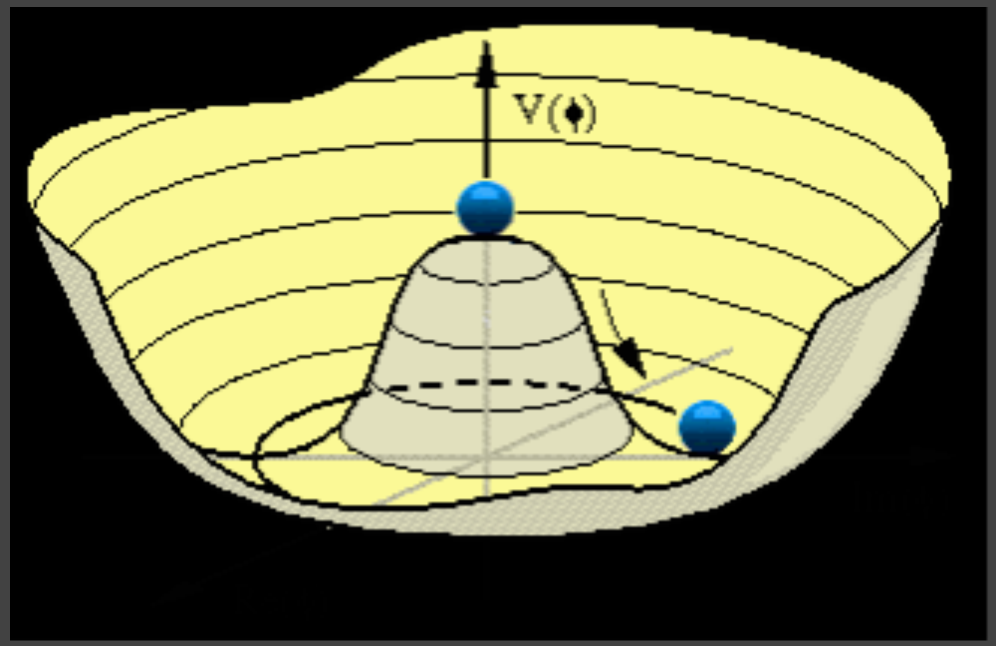
Hongkai Liu, Teng Ma, YS, Michael Waterbury '23
Reuven Balkin, Gauthier Durieux, Teppei Kitahara, YS, Yaniv Weiss '21

expanding on methods from:
YS Weiss '18
Durieux Kitahara YS Weiss '19
Durieux Kitahara Machado YS Weiss '20

Amplitudes for SM EFTs

EWSB

simple *parametrization* in terms of Higgs mechanism



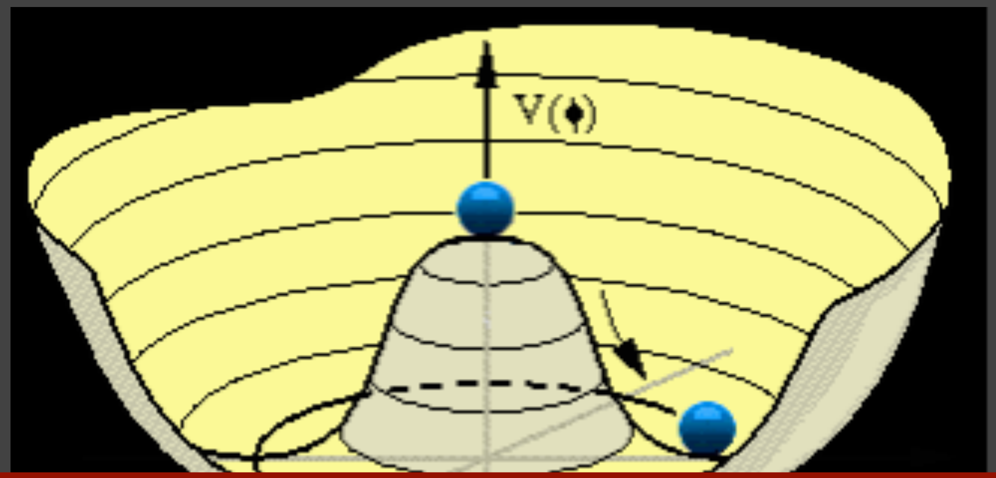
“by hand:”

? minimum away from origin

? 246 GeV scale

? stable against radiative corrections

Simple *parametrization* in terms of Higgs mechanism



"by hand:"

? minimum away from origin

? 246 GeV scale

? stable against radiative correcti

eg (weakly coupled): supersymmetric extensions of SM

stop mass + top Yukawa —> minimum away from origin

origin of scale: new dynamics: dynamical supersymmetry breaking

1890s	1982	2012	?
beta decay	W	h	
EFT footprints of W			**EFT**

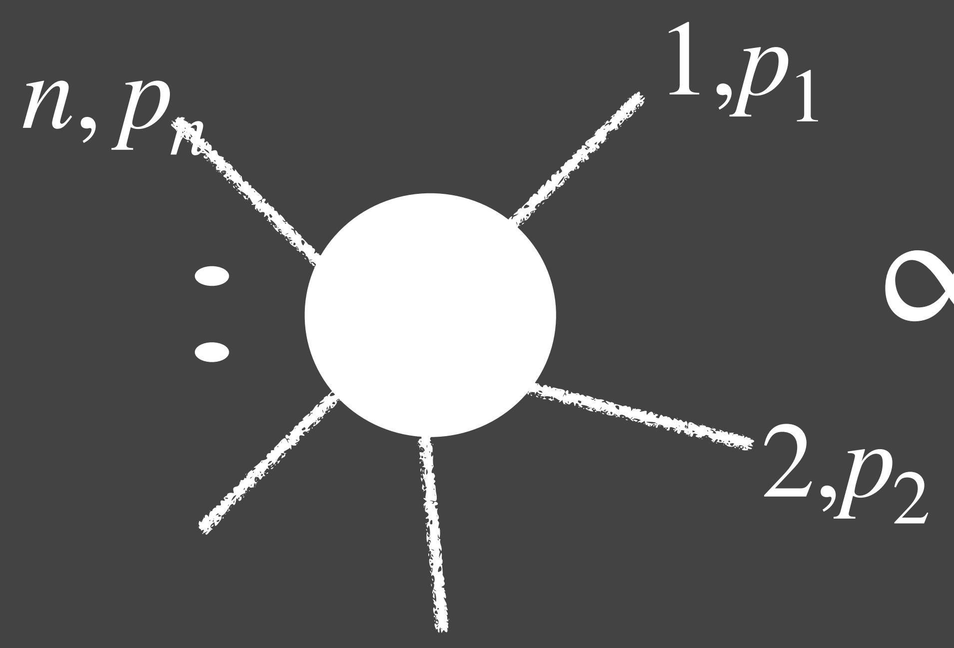
EFTs (bottom-up constructions)

SM fields: most general $\mathscr{L}$
consistent with symmetries (global, gauge)

on-shell bootstrap: SM particles: most general $\mathscr{A}$
consistent with symmetries (global, gauge)

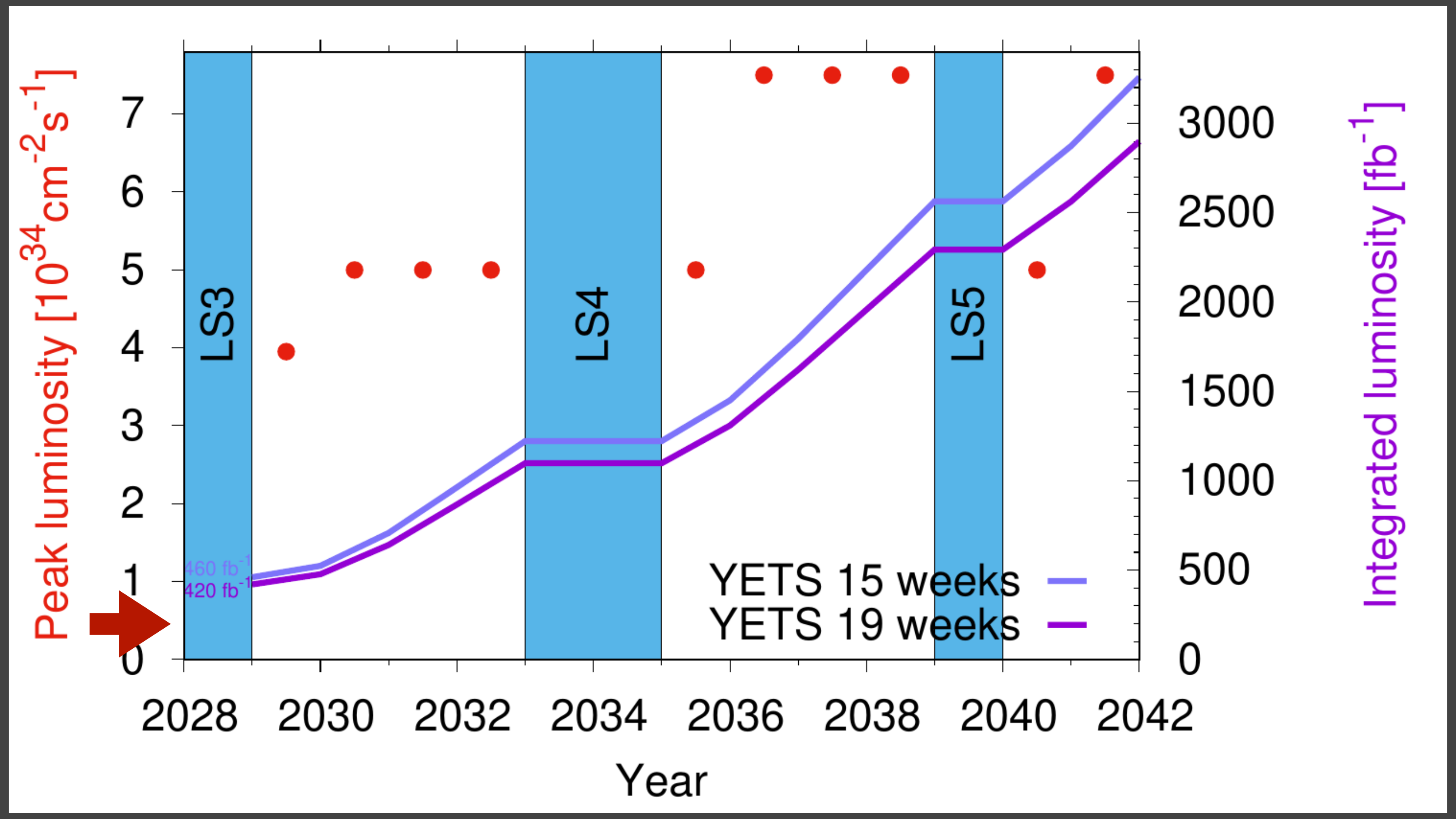
$$\mathscr{L} = \sum_i c_i \mathcal{O}_i(\phi_1, \ldots, \phi_n)$$

1-1 correspondence



$\propto c_i$

LHC: wealth of new measurements — never done before! *physics heaven*



to interpret these: SM + ? BSM

- precision (“known unknowns”)

- parametrize possible BSM effects (“unknown unknowns”)   **EFFECTIVE THEORIES**

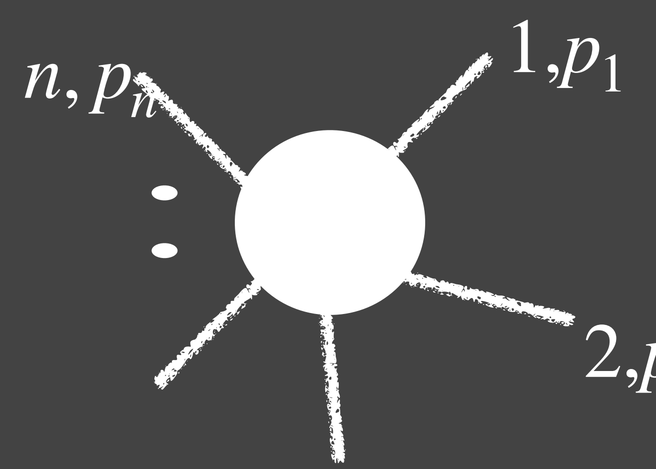
many EFT operators/amplitudes; **many** measurements

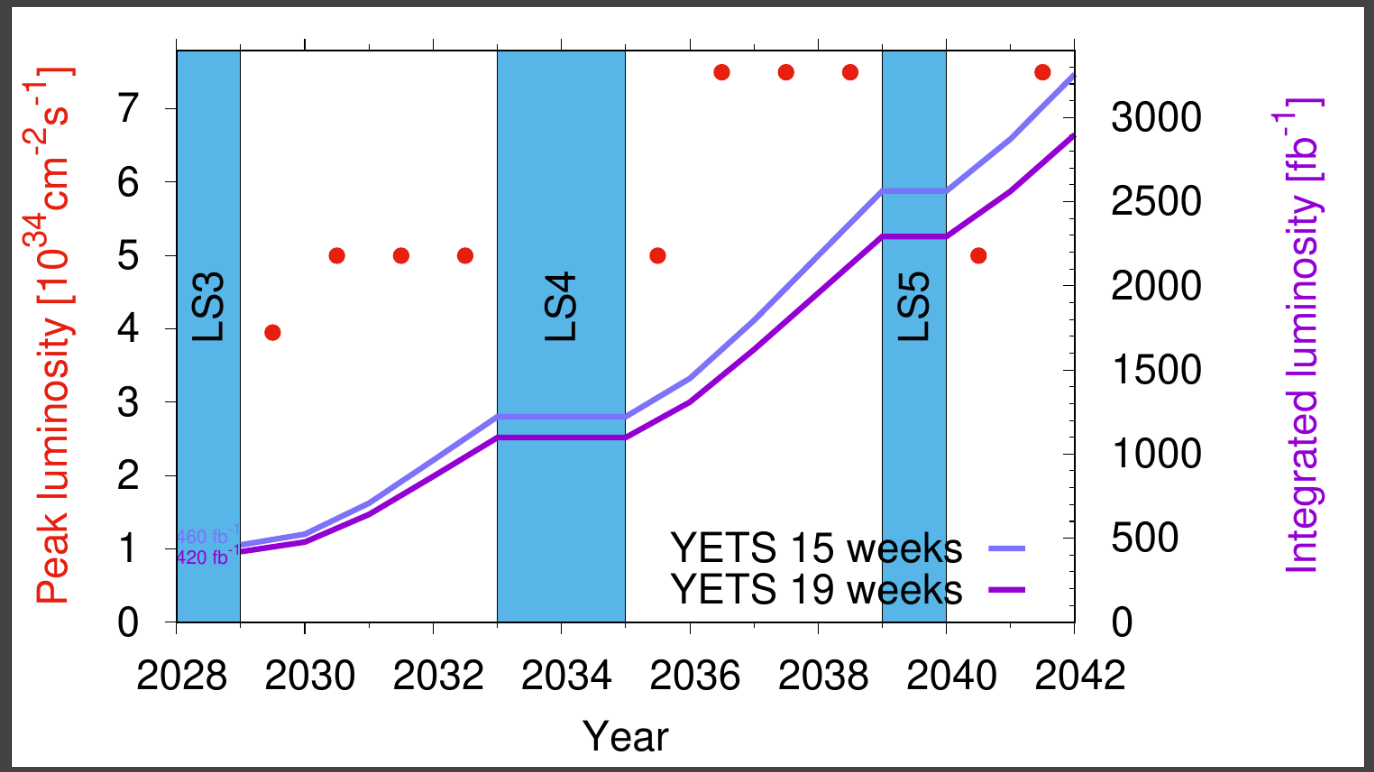
SMEFT:

$d = 6 :\sim 10^3$ (10^2 for $N_g = 1$)

$d = 8 :\sim 10^4$ (10^3 for $N_g = 1$)

$$\mathscr{L} = \sum_i c_i \mathcal{O}_i(\phi_1, \ldots, \phi_n)$$





amplitudes: direct mapping

bootstrapping amplitudes:

$$\longrightarrow \quad \mathscr{A}_{SM} + \mathscr{A}_{EFT}$$

rediscover SM

(more generally: elements of QFT)

Eg: De Angelis Accettulli-Huber ’21
comprehensive analysis

most general EFT amplitude

- model independent
- no issues of field redefinitions, basis dependence, coupling redefinition
- natural approach as we try to go beyond SM
- directly in terms of physical quantities
—> construct sensitive observables

bootstrapping amplitudes:

$$\longrightarrow \quad \mathscr{A}_{SM} + \mathscr{A}_{EFT}$$

rediscover SM

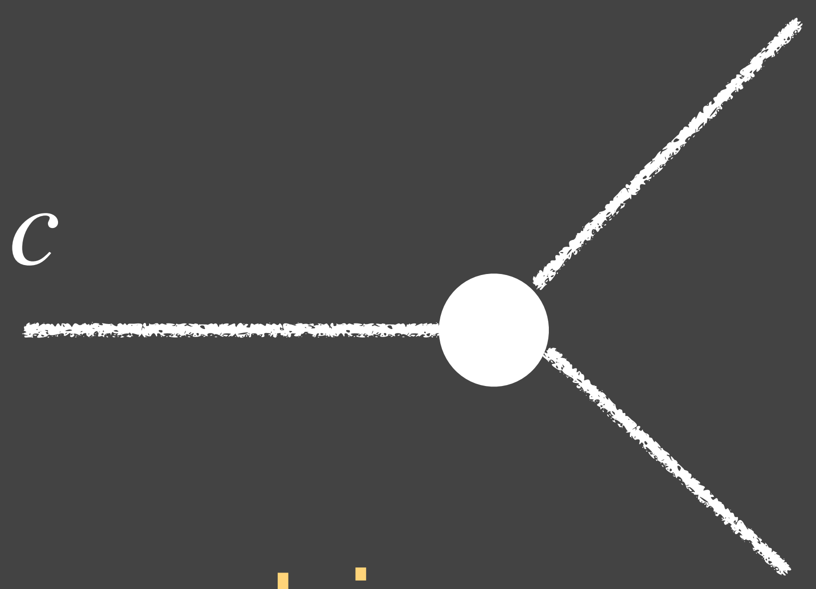
(more generally: elements of QFT)

standard QFT textbook example (Schwartz): spin-1 interactions —> Lie groups

Benincasa Cachazo '08

massive version

Durieux Kitahara YS Weiss ’19
Liu Yin ‘22



$$C^{abc}\left(\langle \mathbf{12}\rangle[\mathbf{23}]\langle \mathbf{31}\rangle + [\mathbf{12}]\langle \mathbf{23}\rangle[\mathbf{31}] \;+\; \text{perm}\right)$$

completely antisymmetric

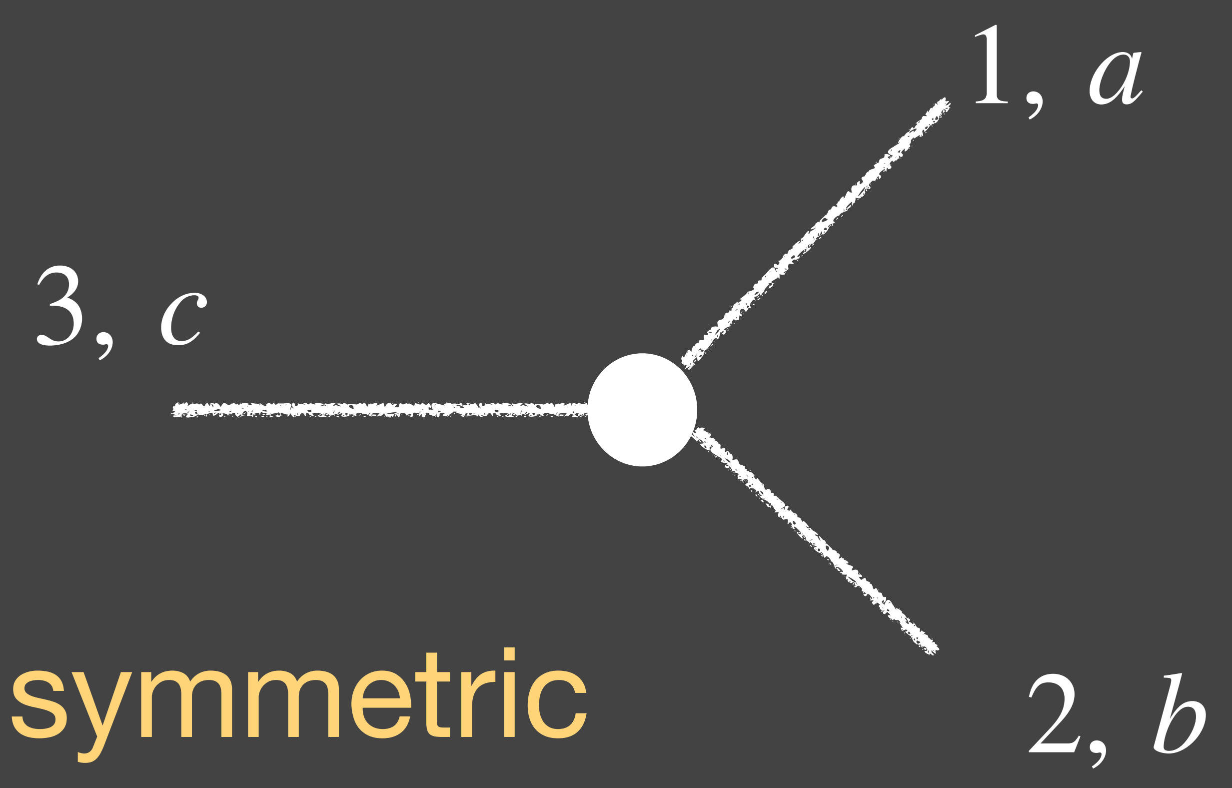
–> C^{abc} completely antisymmetric

structure constants!

(factorization of 4-pt: Jacobi id)

massive version

Durieux Kitahara YS Weiss ’19
Liu Yin ‘22



$C^{abc}\ \left(\langle 12\rangle[23]\langle 31\rangle + [12]\langle 23\rangle[31]\ +\ \text{perm}\right)$

completely antisymmetric

–> C^{abc} completely antisymmetric

power of Lorentz

structure constants!

(factorization of 4-pt: Jacobi id)

bootstrapping amplitudes:

$$\to \quad \mathscr{A}_{SM} + \mathscr{A}_{EFT}$$

rediscover SM

(more generally: elements of QFT)

standard QFT textbook example (Schwartz): spin-1 interactions —> Lie group

★ Higgs mechanism

Arkani-Hamed Huang Huang ’17

Plan:

- anatomy of the Higgs mechanism at the amplitude level

- application: on-shell derivation of SMEFT, HEFT amplitudes at ***low-energy***

On-shell Higgsing

(rediscovering SM/QFT 1)

Balkin Durieux Kitahara YS Weiss ‘21

+ Bachu ’23

main focus: contact-term part

IR unification of UV amplitudes — Arkani-Hamed Huang Huang ‘17

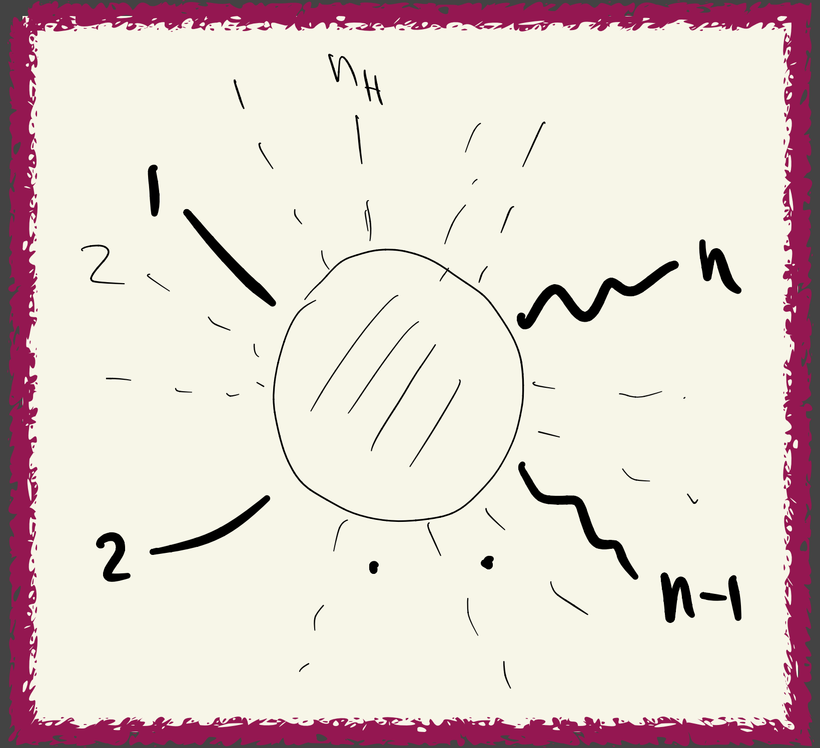
N=4 Coulomb branch amplitudes — Craig Elvang Kiermaier Slatyer ‘11

anatomy of on-shell Higgsing

Balkin Durieux Kitahara YS Weiss '21

massless amplitudes of unbroken theory —> "Higgs" to get low-energy massive amplitudes

extra Higgs legs non-dynamical: soft: $H(q_i) \quad q_i \to 0$



probe field space

+ Cheung Helset Parra-Martinez'23

matching at high energy:

$$E \gg q \sim m \ (\sim VEV \quad v)$$

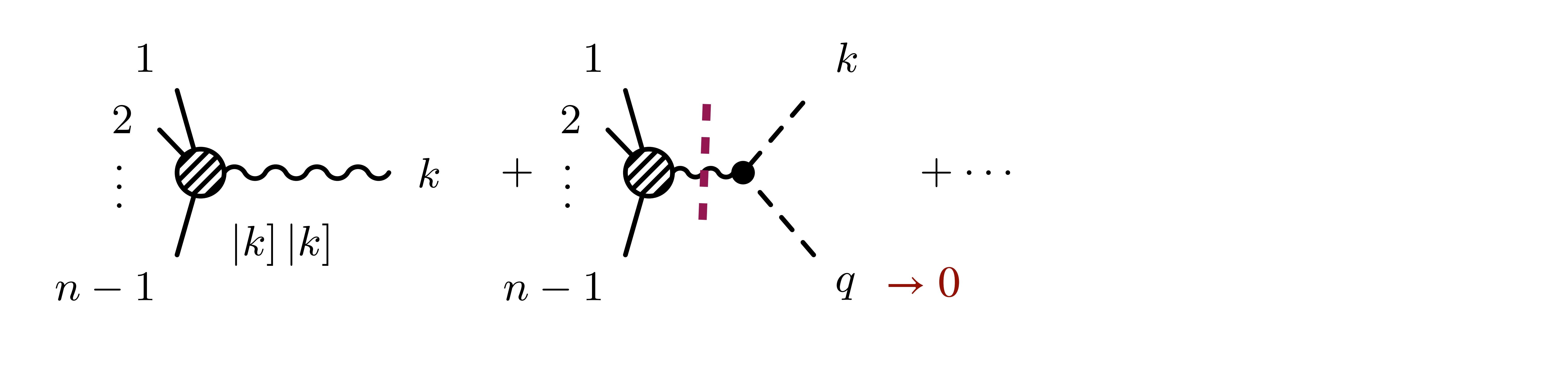
$$M_n(1,\ldots,n) \ = \ A_n(1,\ldots,n) + v \lim_{q\sim v\to 0} A_{n+1}(1,\ldots,n;H(q)) + \cdots$$

anatomy of on-shell Higgsing

- massless spinor structures get **bolded:**

n-pt amplitude with external vector n

(n+1)-pt amplitude with external Higgses n, (n+1)



$$\propto \left(\frac{1}{(k+q)^2} = \frac{1}{m^2} \right) \times \; (A_3 \propto g)$$

anatomy of on-shell Higgsing

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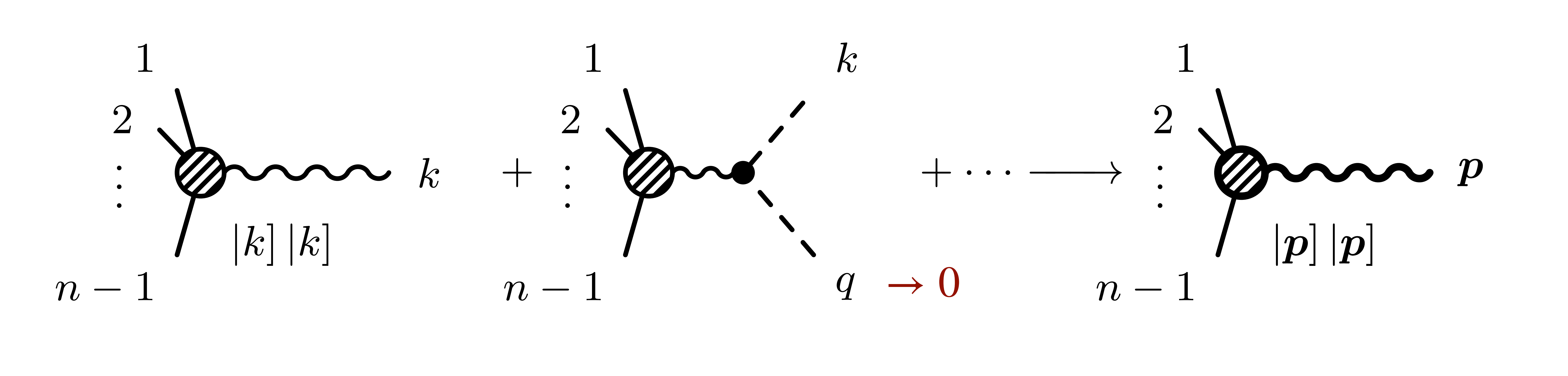

n-pt amplitude with external massive vector n

$$\propto \left(\frac{1}{(k+q)^2} = \frac{1}{m^2}\right) \times \ (A_3 \propto g)$$

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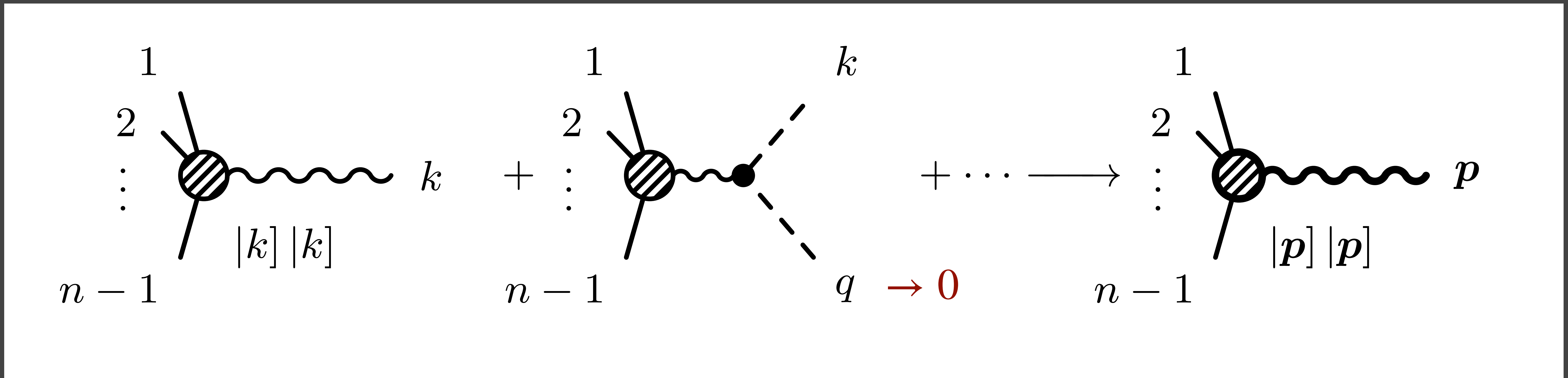

n-pt amplitude with external massive vector n

soft Higgs leg supplies second lightlike momentum to form massive momentum

$$\mathbf{p} = k + q$$

anatomy of on-shell Higgsing

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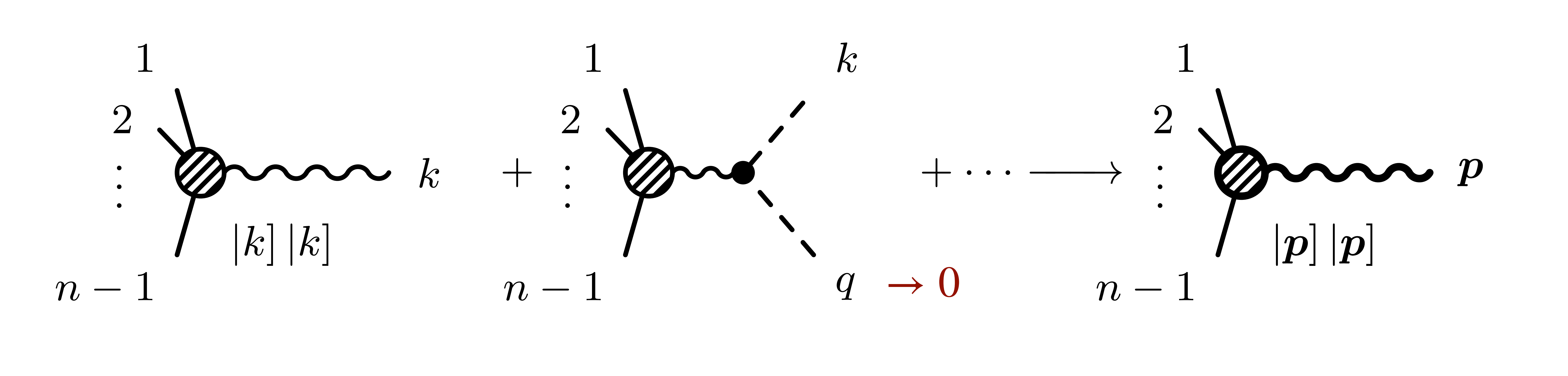

n-pt amplitude with external massive vector n

soft Higgs leg supplies second lightlike momentum to form massive momentum

$$\mathbf{p} = k + q$$

symmetrization over LG indices: exchanging k, q in Higgs legs

anatomy of on-shell Higgsing

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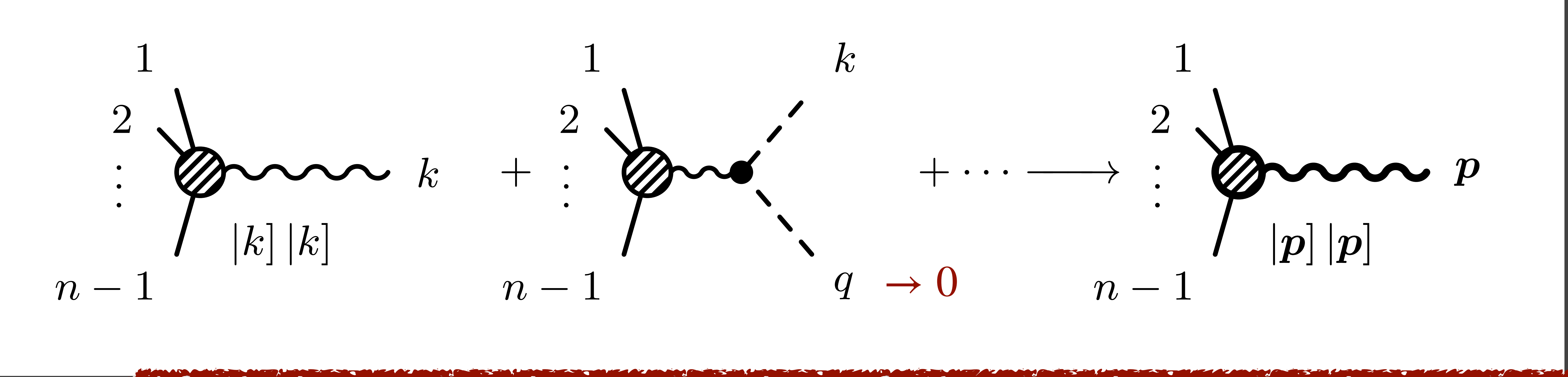
n-pt amplitude with external vector n

(n+1)-pt amplitude with external Higgses n, (n+1)



n-pt amplitude with external massive vector n

massless spinor structure gets bolded $k]k] \to \mathbf{p]p]}$

anatomy of on-shell Higgsing

just as for gauge symmetry:

power of Lorentz

Higgs mechanism <—> Lorentz symmetry

from Lorentz symmetry pov:

bolding the massless spinor structure = covariantizing wrt full massive LG

anatomy of on-shell Higgsing

contact terms:

massless fermion: $i] \;\rightarrow\; \mathbf{i}]$

massless vector $i]i] \;\rightarrow\; \mathbf{i}]\mathbf{i}]$

massless scalar with momentum insertion $p_i \;= i]\langle i$

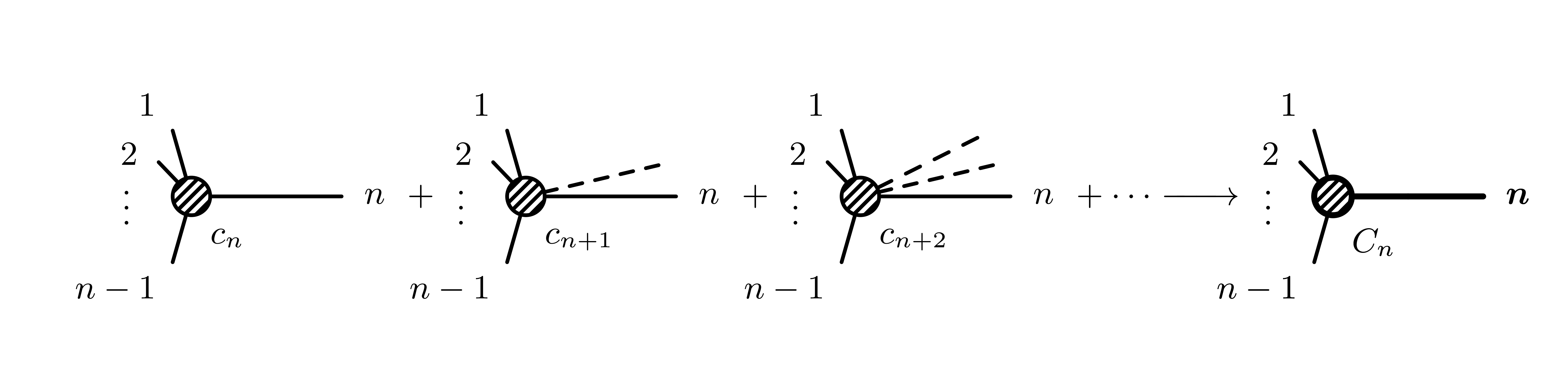
—> 1. massive *scalar* CT with momentum insertion $\mathbf{p_i}$

—> 2. massive *vector CT* $p_i = i]\langle i \;\rightarrow\; \mathbf{i}]\langle \mathbf{i}$

(longitudinal vector from Goldstone boson)

anatomy of on-shell Higgsing

- couplings get $\mathcal{O}(v)$ corrections:



$$C_n = c_n + \#\ v c_{n+1} + \#\ v^2 c_{n+2} + \dots$$

gauge invariance <—> perturbative unitarity (rediscovering SM/QFT 2)

Liu Ma YS Waterbury ’23

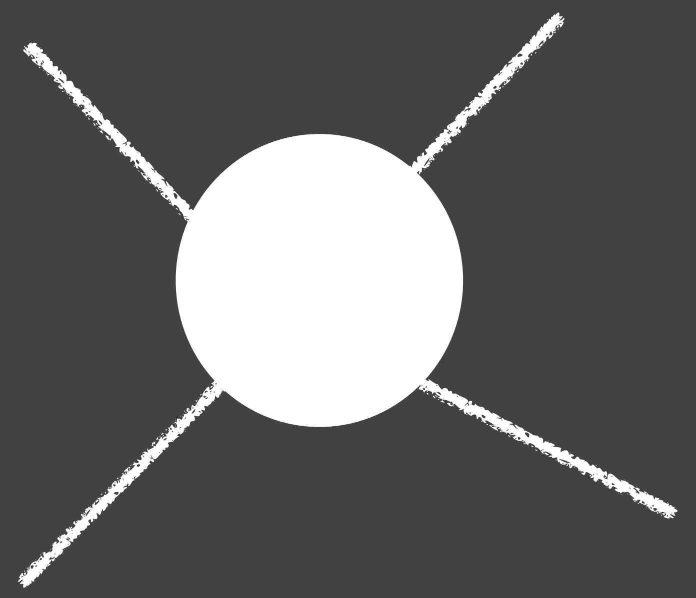
low-E SM + perturbative unitarity —> SU(3)xSU(2)xU(1) SM

relation between gauge symmetry invariance & perturbative unitarity completely transparent

with amplitudes written with LG covariant spinors

low-E amplitude featuring massive vector:

Liu Ma YS Waterbury '23



$W \quad \mathbf{p]p]}, \quad \mathbf{p\rangle p\rangle}, \quad \mathbf{p]p\rangle/M}$ <— Lorentz

problematic terms feature $\frac{\mathbf{p]p\rangle}}{M} \equiv \frac{p]^{\{I}p\rangle^{J\}}}{M}$

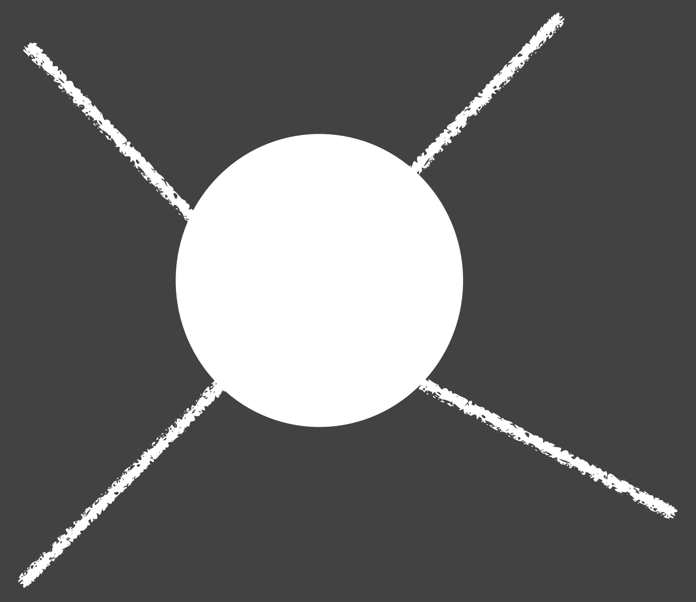
$(I,J) = (1,2) \sim \frac{E^2}{M^2}$

$(HE: \quad p]^1 \sim \sqrt{E} \quad p\rangle^1 \sim M/\sqrt{E})$

$(I,J) = (1,1) \quad \propto \quad \frac{p^1\rangle}{M}$ = finite : spurious spinor

low-E amplitude featuring massive vector:

Liu Ma YS Waterbury '23



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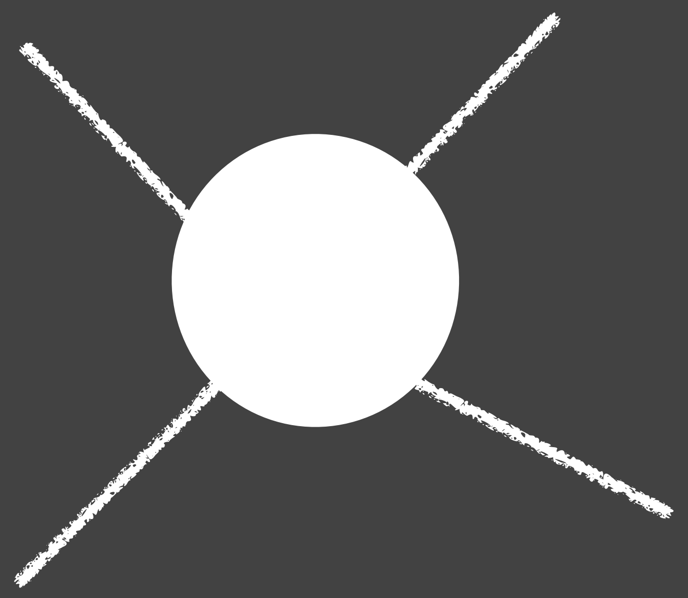
cancellation of bad energy growth <—> cancellation of spurious spinor dependence

reference spinor of massless gauge boson polarization

low-E amplitude featuring massive vector:

Liu Ma YS Waterbury ’23



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problematic terms featur

power of Lorentz

$M \qquad M$

$(I,J) = (1,2) \ \sim \dfrac{E^2}{M^2}$

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reference spinor of massless gauge boson polarization

EFT applications

On-shell applications to EFTs (massless)

- selection rules: explain zeros in
  - matrix of anomalous dimensions of EFT operators (loop cuts & generalized cuts)

    Cheung Shen ’15
    Bern Parra-Martinez Sawyer ’20

  - interference of SM x EFT amplitudes (tree)

    Azatov Contino Machado Riva ‘16

- derive anomalous dimensions of EFT operators (loop cuts & generalized cuts)

  Barratella Fernandez von Harling Pomarol ’20
  Bern Parra-Martinez Sawyer ’20
  Jiang Ma Shu ’20
  De Angelis Accettulli-Huber ’21
  Barratella ’22
  …

On-shell applications to EFTs (massless + massive)

- count (& construct) bases of EFT operators:

YS Weiss ’18
Ma Shu Xiao ’19
Remmen Rodd ’19
Li Ren Shu Xiao Yu Zheng ’20
Durieux Machado ’20
…
also used in Henning Melia Murayama ‘15

- UV matching

…

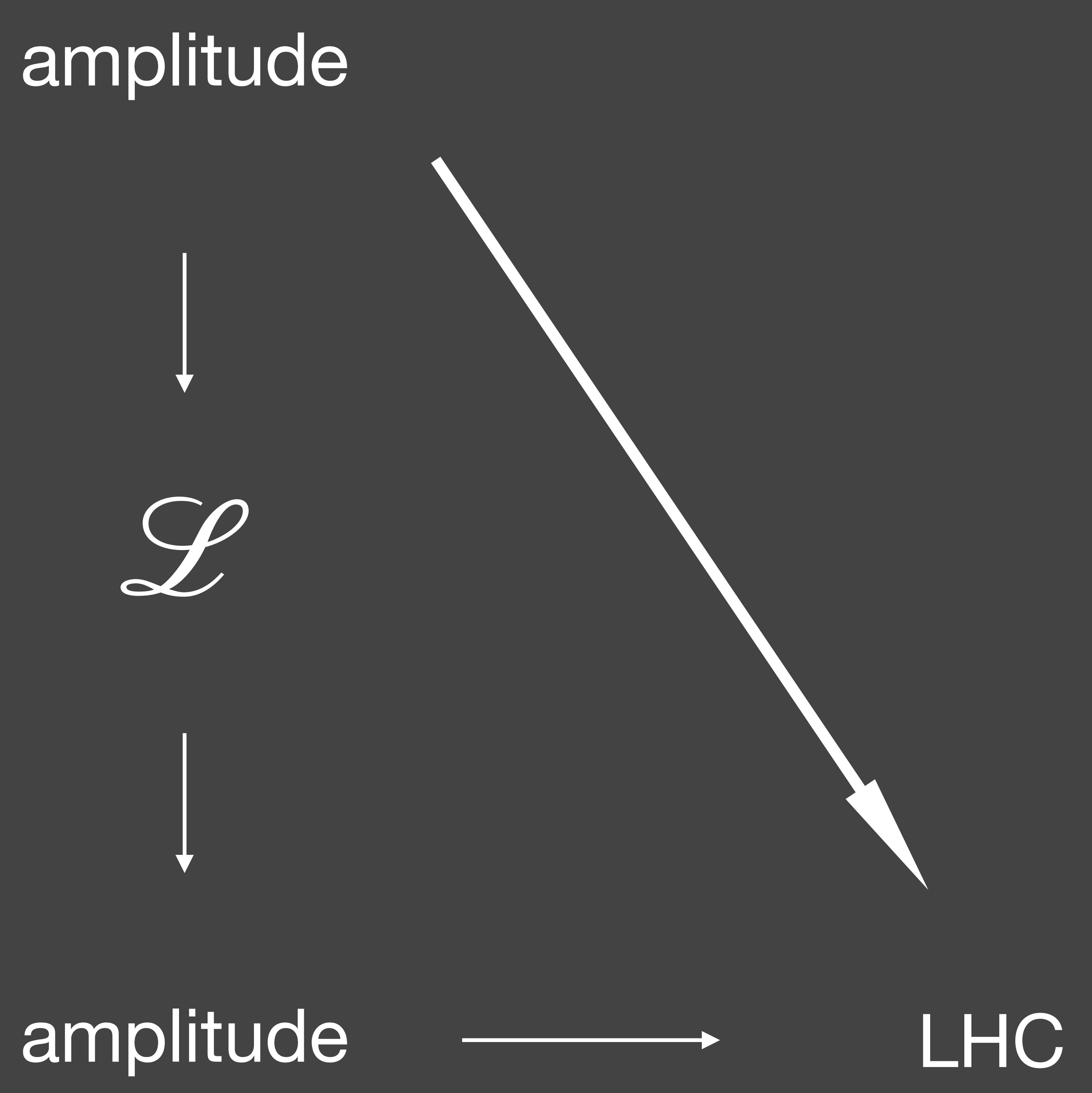
De Angelis Durieux ‘23

in many of these:

amplitude

$$\downarrow$$

$$\mathscr{L}$$


amplitude
$\mathscr{L}$
amplitude
LHC

different EFTs:

low-E: SM particles only / SM + new light particle(s)

- SMEFT: SU(3)xSU(2)xU(1) at Λ

massless SM fields, h in Higgs doublet large scale separation possible: $\Lambda \gg v$

- otherwise: only SU(3)xU(1)$_{EM}$ at Λ ; massive W, Z, h "HEFT"

full symmetry realized non-linearly; no scale separation: $\Lambda \sim v$

recent: Cohen Craig Lu Sutherland '20

…

SMEFT: to derive predictions:

- basis of operators in unbroken theory
- turn on Higgs VEV —> Lagrangian in broken theory: SM fields, couplings shift
- derive Feynman rules of broken theory in some gauge
- redefine parameters from “input” physical masses, couplings

amplitudes: working with physical dof’s, couplings only

HEFT:

“sick” EFT : eg, integrated out fields with masses from EWSB

<—> no scale separation

UV matching ambiguous — Dawson Fontes Quezada-Calonge Sanz-Cillero ‘23

amplitudes: make concrete

amplitude construction: bottom-up:

—> starting with the massive (and massless) **particles** we know:
construct **most general** amplitudes

- 3-points (renormalizable + higher-dim): dictated by little group, symmetries
- factorizable parts of higher-point amplitudes (determined by 3-pts..)
- higher-point contact terms: dictated by little group, symmetries

contact-term part of amplitude:

YS Weiss ‘18
Durieux Kitahara YS Weiss ’19
Durieux Kitahara Machado YS Weiss ’20
...

$$\mathscr{A} = \frac{[\cdot\cdot]\cdot\cdot\langle\cdot\cdot\rangle}{\Lambda^{\#}}\, P\left(\frac{s_{ij}}{\Lambda^2}\right)$$

local: no poles

$$\mathscr{A} = \frac{[\cdot\cdot]\cdot\cdot\langle\cdot\cdot\rangle}{\Lambda^{\#}} P\left(\frac{s_{ij}}{\Lambda^2}\right)$$

carries LG weight; “stripped” off

all Lorentz invariants s_{ij}

“stripped contact term” SCT

different SCTs can come from integrating out different UV fields — different suppressions

Chang Chen Liu Luty ’22

$$\mathscr{A} = \frac{[\cdot\cdot]\cdot\cdot\langle\cdot\cdot\rangle}{\Lambda^{\#}} P\left(\frac{s_{ij}}{\Lambda^2}\right)$$

carries LG weight; “stripped” of all Lorentz invariants s_{ij}
“stripped contact term” SCT

polynomial in Lorentz invariants s_{ij}
subject to kinematical constraints,
eg, $s_{12} + s_{13} + s_{23} = \sum m^2$

derivative expansion

$$\mathscr{A} = \frac{[\cdot\cdot]\cdot\cdot\langle\cdot\cdot\rangle}{\Lambda^{\#}} P\left(\frac{s_{ij}}{\Lambda^2}\right)$$

carries LG weight; “

all Lorentz inva

“stripped contact t

raints,

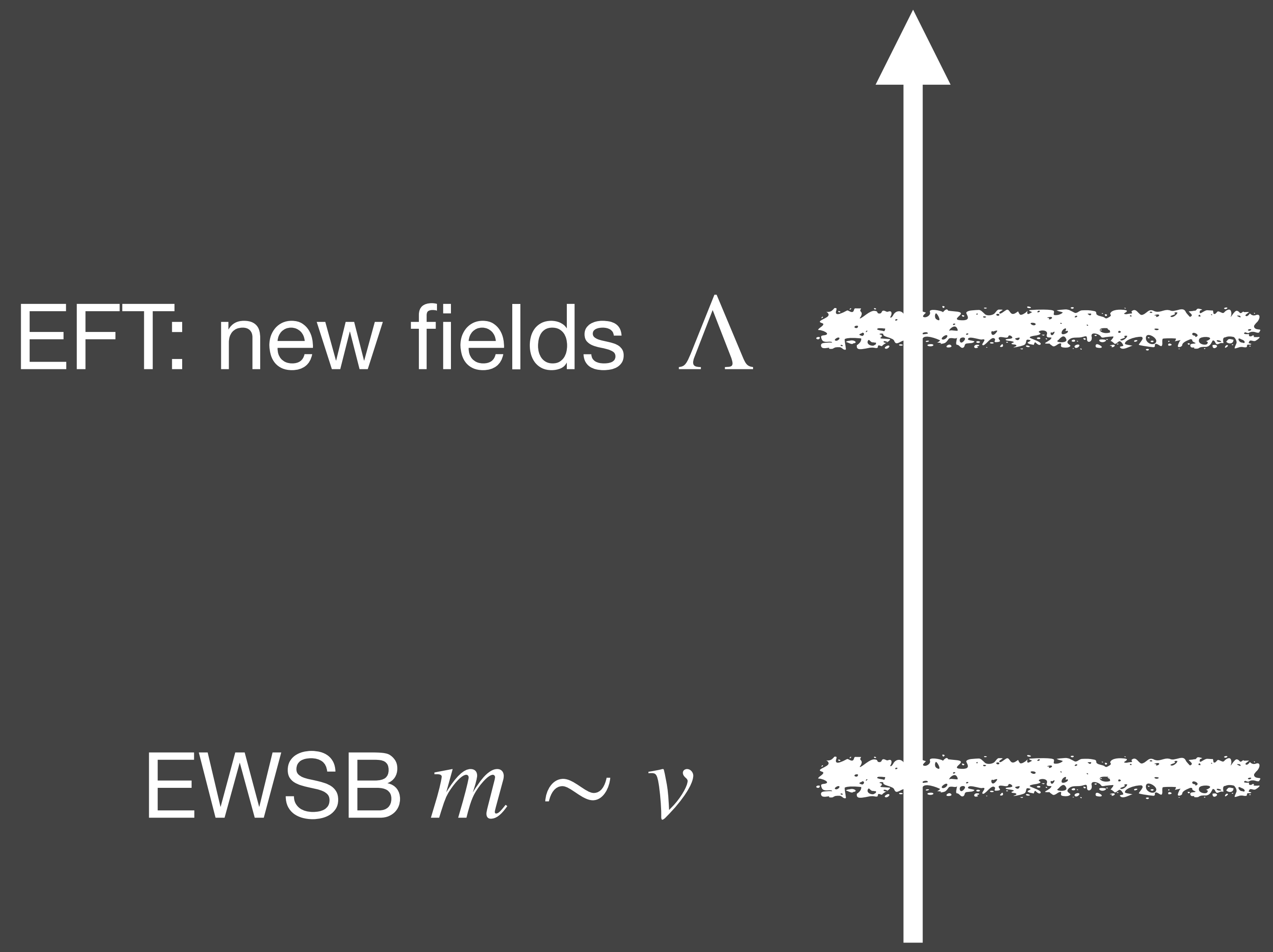
m^2

bottom up construction; input: physical particles
SU(3)xU(1)
higgs = gauge singlet

gives **HEFT** amplitudes

What about **(low-energy) SMEFT** amplitudes?

use on-shell Higgsing



massless $\mathscr{A}$ impose full SU(3)xSU(2)xU(1)

↓

derive massive $\mathscr{M}$

(contact term part only)

results: HEFT, SMEFT

HEFT inventory

(**observables**; *many more results on operators, anomalous dim's via on-shell*)

- *all HEFT 3-points (+matching to SMEFT)* — *Durieux Kitahara YS Weiss '19*
- *[all generic 3-points for spins up to 3*
- *all generic 4-pt SCTs for spins 0, 1/2, 1]* — *Durieux Kitahara Machado YS Weiss'20*
- *HEFT 4-points: hggg, Zggg, ffVh, WWhh* — *Shadmi et al '18, Durieux et al '19, Balkin et al '21*

  + some full amplitudes (factorizable + contact terms): ffWh, ffZh, WWhh

- *5V (4W+Z etc)* — *De Angelis '21*
- *Higgs, top 4pts in terms of momenta+polarizations* — *Chang et al '22, '23*
- *all HEFT 4pts up to d=8* ← — *Liu Ma YS Waterbury '23*

all HEFT 4-pts up to d=8

Liu Ma YS Waterbury ’23

[Dong Ma Shu Zhou ’22 HEFT operators]

- most relevant for collider studies: 2 to 2
- dimension counting: classify contact terms by energy growth

full set of EFT contact terms with E^2 growth: (mostly dim-6 operators)

LOW ENERGY AMPLITUDES

Massive amplitudes	E^2 contact terms
$\mathcal{M}(WWhh)$	$C^{00}_{WWhh}\langle\mathbf{12}\rangle[\mathbf{12}]$, $C^{\pm\pm}_{WWhh}(\mathbf{12})^2$
$\mathcal{M}(ZZhh)$	$C^{00}_{ZZhh}\langle\mathbf{12}\rangle[\mathbf{12}]$, $C^{\pm\pm}_{ZZhh}(\mathbf{12})^2$
$\mathcal{M}(gghh)$	$C^{\pm\pm}_{gghh}(12)^2$
$\mathcal{M}(\gamma\gamma hh)$	$C^{\pm\pm}_{\gamma\gamma hh}(12)^2$
$\mathcal{M}(\gamma Zhh)$	$C^{\pm}_{\gamma Zhh}(1\mathbf{2})^2$
$\mathcal{M}(hhhh)$	C_{hhhh}
$\mathcal{M}(f^c fhh)$	$C^{\pm\pm}_{ffhh}(\mathbf{12})$
$\mathcal{M}(f^c fWh)$	$C^{+-0}_{ffWh}[\mathbf{13}]\langle\mathbf{23}\rangle$, $C^{-+0}_{ffWh}\langle\mathbf{13}\rangle[\mathbf{23}]$, $C^{\pm\pm\pm}_{ffWh}(\mathbf{13})(\mathbf{23})$
$\mathcal{M}(f^c fZh)$	$C^{+-0}_{ffZh}[\mathbf{13}]\langle\mathbf{23}\rangle$, $C^{-+0}_{ffZh}\langle\mathbf{13}\rangle[\mathbf{23}]$, $C^{\pm\pm\pm}_{ffZh}(\mathbf{13})(\mathbf{23})$
$\mathcal{M}(f^c f\gamma h)$	$C^{\pm\pm\pm}_{ff\gamma h}(\mathbf{1}3)(\mathbf{2}3)$
$\mathcal{M}(q^c qgh)$	$C^{\pm\pm\pm}_{qqgh}(\mathbf{1}3)(\mathbf{2}3)$
$\mathcal{M}(f^c f f^c f)$	$C^{\pm\pm\pm\pm,1}_{ffff}(\mathbf{12})(\mathbf{34})$, $C^{--++}_{ffff}\langle\mathbf{12}\rangle[\mathbf{34}]$, $C^{-+-+}_{ffff}\langle\mathbf{13}\rangle[\mathbf{24}]$, $C^{-++-}_{ffff}\langle\mathbf{14}\rangle[\mathbf{23}]$ $C^{\pm\pm\pm\pm,2}_{ffff}(\mathbf{13})(\mathbf{24})$, $C^{++--}_{ffff}[\mathbf{12}]\langle\mathbf{34}\rangle$, $C^{+-+-}_{ffff}[\mathbf{13}]\langle\mathbf{24}\rangle$, $C^{+--+}_{ffff}[\mathbf{14}]\langle\mathbf{23}\rangle$

$(12) = [12]$ or $\langle 12\rangle$

C's: Wilson coefficients

most suppressed by $\bar{\Lambda}^2$
(amplitude dim-less)

Ma Liu YS Waterbury 2301.11349

- similarly: derived full set of CTs with E^3, E^4 growth
- corresponding to $d \leq 8$ HEFT operators
- clear identification of operator dimension from dim-analysis:

factors of $p]p\rangle$ (external massive vector) $\rightarrow p]p\rangle/M$

any extra powers of E compensated by powers of Λ

—> read off dimension of operator

but recall $\Lambda \sim v$; E/v terms in amplitudes reflect non-locality of HEFT

(cancel in SMEFT amplitudes: gauge invariance <—> perturbative unitarity)

SMEFT 4-pts

full list of CTs from $d \leq 6$ SMEFT

Massive $d=6$ amplitudes	SMEFT Wilson coefficients
$\mathcal{M}(W_L^+W_L^-hh) = C^{00}_{WWhh}\langle\mathbf{12}\rangle[\mathbf{12}]$	$C^{00}_{WWhh} = (c^{(+)}_{(H^\dagger H)^2} - 3c^{(-)}_{(H^\dagger H)^2})/2$
$\mathcal{M}(W_\pm^+W_\pm^-hh) = C^{\pm\pm}_{WWhh}(\mathbf{12})^2$	$C^{\pm\pm}_{WWhh} = 2c^{\pm\pm}_{WWHH}$
$\mathcal{M}(Z_LZ_Lhh) = C^{00}_{ZZhh}\langle\mathbf{12}\rangle[\mathbf{12}]$	$C^{00}_{ZZhh} = -2c^{(+)}_{(H^\dagger H)^2}$
$\mathcal{M}(Z_\pm Z_\pm hh) = C^{\pm\pm}_{ZZhh}(\mathbf{12})^2$	$C^{\pm\pm}_{ZZhh} = c_W^2 c^{\pm\pm}_{WWHH} + s_W^2 c^{\pm\pm}_{BBHH} + c_W s_W c^{\pm\pm}_{BWHH}$
$\mathcal{M}(g_\pm g_\pm hh) = C^{\pm\pm}_{gghh}(12)^2$	$C^{\pm\pm}_{gghh} = c^{\pm\pm}_{GGHH}$
$\mathcal{M}(\gamma_\pm\gamma_\pm hh) = C^{\pm\pm}_{\gamma\gamma hh}(12)^2$	$C^{\pm\pm}_{\gamma\gamma hh} = s_W^2 c^{\pm\pm}_{WWHH} + c_W^2 c^{\pm\pm}_{BBHH} - c_W s_W c^{\pm\pm}_{BWHH}$
$\mathcal{M}(\gamma_\pm Zhh) = C^{\pm}_{\gamma Zhh}(1\mathbf{2})^2$	$C^{\pm}_{\gamma Zhh} = s_W c_W c^{\pm\pm}_{WWHH} - s_W c_W c^{\pm\pm}_{BBHH} + \frac{1}{2}(s_W^2 - c_W^2)c^{\pm\pm}_{BWHH}$
$\mathcal{M}(hhhh) = C_{hhhh}$	$C_{hhhh} = -3c_{(H^\dagger H)^2} + 45\ v^2 c_{(H^\dagger H)^3}$
$\mathcal{M}(f^c_\pm f_\pm hh) = C^{\pm\pm}_{ffhh}(\mathbf{12})$	$C^{\pm\pm}_{ffhh} = 3c^{\pm\pm}_{\Psi\psi HHH}v/(2\sqrt{2})$
$\mathcal{M}(f^c_+ f'_- W_L h) = C^{+-0}_{ffWh}[\mathbf{13}]\langle\mathbf{23}\rangle$	$C^{+-0}_{ffWh} = (c^{+-,(+)}_{\Psi\Psi HH} - c^{+-,(-)}_{\Psi\Psi HH})/2$
$\mathcal{M}(f^c_- f'_+ W_L h) = C^{-+0}_{ffWh}\langle\mathbf{13}\rangle[\mathbf{23}]$	$C^{-+0}_{ffWh} = c^{-+}_{\psi_R\psi'_R HH}$
$\mathcal{M}(f^c_\pm f'_\pm W_\pm h) = C^{\pm\pm\pm}_{ffWh}(\mathbf{13})(\mathbf{23})$	$C^{\pm\pm\pm}_{ffWh} = c^{\pm\pm\pm}_{\Psi\psi WH}/2$
$\mathcal{M}(f^c_+ f_- Z_L h) = C^{+-0}_{ffZh}[\mathbf{13}]\langle\mathbf{23}\rangle$	$C^{+-0}_{e_Le_LZh} = -i\sqrt{2}c^{+-,(+)}_{\Psi\Psi HH}$, $C^{+-0}_{\nu_L\nu_LZh} = -i(c^{+-,(+)}_{\Psi\Psi HH} + c^{+-,(-)}_{\Psi\Psi HH})/\sqrt{2}$
$\mathcal{M}(f^c_- f_+ Z_L h) = C^{-+0}_{ffZh}\langle\mathbf{13}\rangle[\mathbf{23}]$	$C^{-+0,\mathrm{CT}}_{ffZh} = -i\sqrt{2}c^{-+}_{\psi\psi HH}$
$\mathcal{M}(f^c_\pm f_\pm Z_\pm h) = C^{\pm\pm\pm}_{ffZh}(\mathbf{13})(\mathbf{23})$	$C^{\pm\pm\pm}_{ffZh} = -(s_W c^{\pm\pm\pm}_{\Psi\psi BH} + c_W c^{\pm\pm\pm}_{\Psi\psi WH})/\sqrt{2}$
$\mathcal{M}(f^c_\pm f_\pm \gamma_\pm h) = C^{\pm\pm\pm}_{ff\gamma h}(\mathbf{1}3)(\mathbf{2}3)$	$C^{\pm\pm\pm}_{ff\gamma h} = (-s_W c^{\pm\pm\pm}_{\Psi\psi WH} + c_W c^{\pm\pm\pm}_{\Psi\psi BH})/\sqrt{2}$
$\mathcal{M}(q^c_\pm q_\pm g^A_\pm h) = C^{\pm\pm\pm}_{qqgh}\lambda^A(\mathbf{1}3)(\mathbf{2}3)$	$C^{\pm\pm\pm}_{qqgh} = c^{\pm\pm\pm}_{\Psi\psi GH}/\sqrt{2}$

Table 3: The low-energy E^2 contact terms (left column) and their $d = 6$ coefficients in the SMEFT (right column). $c_{(H^\dagger H)^2}$ without a superscript is the renormalizable four-Higgs coupling. The mapping for four fermion contact terms is trivial, so we do not include them here.

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to get these:

start with **massless** dim-6 SMEFT amplitudes

and Higgs these to get massive amplitudes

for completeness provide full mapping
of 4-pt $d \leq 6$ EFT amplitudes
to Warsaw basis

Ma Shu Xiao '19

Amplitude	Contact term	Warsaw basis operator	Coefficient
$\mathcal{A}(H^c_i H^c_j H^c_k H^l H^m H^n)$	$T^{+\,lmn}_{ijk}$	$\mathcal{O}_H/6$	$c_{(H^\dagger H)^3}$
$\mathcal{A}(H^c_i H^c_j H^k H^l)$	$s_{12}T^{+\,kl}_{ij}$	$\mathcal{O}_{HD}/2 + \mathcal{O}_{H\Box}/4$	$c^{(+)}_{(H^\dagger H)^2}$
$\mathcal{A}(H^c_i H^c_j H^k H^l)$	$(s_{13}-s_{23})T^{-\,kl}_{ij}$	$\mathcal{O}_{HD}/2 - \mathcal{O}_{H\Box}/4$	$c^{(-)}_{(H^\dagger H)^2}$
$\mathcal{A}(B^\pm B^\pm H^c_i H^j)$	$(12)^2\delta^j_i$	$(\mathcal{O}_{HB} \pm i\mathcal{O}_{H\tilde{B}})/2$	$c^{\pm\pm}_{BBHH}$
$\mathcal{A}(B^\pm W^{I\pm} H^c_i H^j)$	$(12)^2(\sigma^I)^j_i$	$\mathcal{O}_{HWB} \pm i\mathcal{O}_{H\tilde{W}B}$	$c^{\pm\pm}_{BWHH}$
$\mathcal{A}(W^{I+} W^{J+} H^c_i H^j)$	$(12)^2\delta^{IJ}\delta^j_i$	$(\mathcal{O}_{HW} \pm i\mathcal{O}_{H\tilde{W}})/2$	$c^{\pm\pm}_{WWHH}$
$\mathcal{A}(g^{A\pm} g^{B\pm} H^c_i H^j)$	$(12)^2\delta^{AB}\delta^j_i$	$(\mathcal{O}_{HG} \pm i\mathcal{O}_{H\tilde{G}})/2$	$c^{\pm\pm}_{GGHH}$
$\mathcal{A}(L^c_i e H^c_j H^k H^l)$	$[12]T^{+\,kl}_{ij}$	$\mathcal{O}_{eH}/2$	c^{++}_{LeHHH}
$\mathcal{A}(Q^c_{a,i} d^b H^c_j H^k H^l)$	$[12]T^{+\,kl}_{ij}\delta^b_a$	$\mathcal{O}_{dH}/2$	c^{++}_{QdHHH}
$\mathcal{A}(Q^c_{a,i} u^b H^c_j H^c_k H^l)$	$[12]\varepsilon_{im}T^{+\,ml}_{jk}\delta^b_a$	$\mathcal{O}_{uH}/2$	c^{++}_{QuHHH}
$\mathcal{A}(e^c e H^c_i H^j)$	$\langle 142]\delta^j_i$	$\mathcal{O}_{He}/2$	c^{-+}_{eeHH}
$\mathcal{A}(u^c_a u^b H^c_i H^j)$	$\langle 142]\delta^j_i\delta^b_a$	$\mathcal{O}_{Hu}/2$	c^{-+}_{uuHH}
$\mathcal{A}(d^c_a d^b H^c_i H^j)$	$\langle 142]\delta^j_i\delta^b_a$	$\mathcal{O}_{Hd}/2$	c^{-+}_{ddHH}
$\mathcal{A}(u^c_a d^b H^i H^j)$	$\langle 142]\epsilon^{ij}\delta^b_a$	$\mathcal{O}_{Hud}/2$	c^{-+}_{udHH}
$\mathcal{A}(L^c_i L^j H^c_k H^l)$	$[142\rangle T^{+\,jl}_{ik}$	$\left(\mathcal{O}^{(1)}_{HL} + \mathcal{O}^{(3)}_{HL}\right)/8$	$c^{+-,(+)}_{LLHH}$
$\mathcal{A}(L^c_i L^j H^c_k H^l)$	$[142\rangle T^{-\,jl}_{ik}$	$\left(\mathcal{O}^{(1)}_{HL} - \mathcal{O}^{(3)}_{HL}\right)/8$	$c^{+-,(-)}_{LLHH}$
$\mathcal{A}(Q^c_{a,i} Q^{b,j} H^c_k H^l)$	$[142\rangle T^{+\,jl}_{ik}\delta^b_a$	$\left(3\mathcal{O}^{(1)}_{HQ} + \mathcal{O}^{(3)}_{HQ}\right)/8$	$c^{+-,(+)}_{QQHH}$
$\mathcal{A}(Q^c_{a,i} Q^{b,j} H^c_k H^l)$	$[142\rangle T^{-\,jl}_{ik}\delta^b_a$	$(\mathcal{O}^{(1)}_{HQ} - \mathcal{O}^{(3)}_{HQ})/8$	$c^{+-,(-)}_{QQHH}$
$\mathcal{A}(L^c_i e B^+ H^j)$	$[13][23]\delta^j_i$	$-i\mathcal{O}_{eB}/(2\sqrt{2})$	c^{+++}_{LeBH}
$\mathcal{A}(Q^c_{a,i} d^b B^+ H^j)$	$[13][23]\delta^j_i\delta^b_a$	$-i\mathcal{O}_{dB}/(2\sqrt{2})$	c^{+++}_{QdBH}
$\mathcal{A}(Q^c_{a,i} u^b B^+ H^c_j)$	$[13][23]\epsilon_{ij}\delta^b_a$	$-i\mathcal{O}_{uB}/(2\sqrt{2})$	c^{+++}_{QuBH}
$\mathcal{A}(L^c_i e W^{I+} H^j)$	$[13][23](\sigma^I)^j_i$	$-i\mathcal{O}_{eW}/(2\sqrt{2})$	c^{+++}_{LeWH}
$\mathcal{A}(Q^c_{a,i} d^b W^{I+} H^j)$	$[13][23](\sigma^I)^j_i\delta^b_a$	$-i\mathcal{O}_{dW}/(2\sqrt{2})$	c^{+++}_{QdWH}
$\mathcal{A}(Q^c_{a,i} u^b W^{I+} H^c_j)$	$[13][23](\sigma^I)_{ik}\epsilon^k_j\delta^b_a$	$-i\mathcal{O}_{uW}/(2\sqrt{2})$	c^{+++}_{QuWH}
$\mathcal{A}(Q^c_{a,i} d^b g^{A+} H^j)$	$[13][23]\delta^j_i(\lambda^A)^b_a$	$-i\mathcal{O}_{dG}/(2\sqrt{2})$	c^{+++}_{QdGH}
$\mathcal{A}(Q^c_{a,i} u^b g^{A+} H^c_j)$	$[13][23]\epsilon_{ij}(\lambda^A)^b_a$	$-i\mathcal{O}_{uG}/(2\sqrt{2})$	c^{+++}_{QuGH}
$\mathcal{A}(W^{I\pm} W^{J\pm} W^{K\pm})$	$(12)(23)(31)\epsilon^{IJK}$	$(\mathcal{O}_W \pm i\mathcal{O}_{\tilde{W}})/6$	$c^{\pm\pm\pm}_{WWW}$
$\mathcal{A}(g^{A\pm} g^{B\pm} g^{C\pm})$	$(12)(23)(31)f^{ABC}$	$(\mathcal{O}_G \pm i\mathcal{O}_{\tilde{G}})/6$	$c^{\pm\pm\pm}_{GGG}$

Table 2: Massless $d = 6$ SMEFT contact terms [34] and their relations to Warsaw basis operators [3]. For each operator (or operator combination) $\mathcal{O}$ in the third column, $c\,\mathcal{O}$ generates the structure in the second column with the coefficient c given in the fourth column. c-superscripts denote charge conjugation.

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on to dim-8 SMEFT

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can have interesting effects (eg example here)

~ 1000 operators; with amplitudes, easy to concentrate on the relevant ones for a given observable

example: **WW, ZZ .. production** (sensitive probe of EWSB)

all relevant 4-pt CTs first generated at dim-8 (dim-6 SMEFT merely corrects SM-3pts)

from VVVV, VVHH etc: easy to see at amplitude level: 8 powers of $p]$ (or $p\rangle$) —> Λ^4

or 6 powers in ffVV —> SMEFT: Λ^4

VV pair production from dim=8 SMEFT: $V = W, Z, \gamma, g$

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derived all low-energy 4-pt CTs generated by dim-8 SMEFT

$VV \to VV$ $\bar{f}f \to VV$ .. (massless fermions)

- nonzero mass "resurrect" vanishing SM-SMEFT interference $\propto M_W\,,\ M_Z$
- good at $M_V \sim E \ll \Lambda$ (not just high-E where EFT not reliable)
- sensitivity to anomalous Higgs self couplings
- up/down quark SU(2) relations broken (first happens at dim-8)

VV pair production from dim=8 SMEFT: $V = W, Z, \gamma, g$

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\+ distinguish HEFT vs SMEFT:

- various coupling relations in SMEFT
- some SMEFT zeros (due to hypercharge or accidental)

2 to 2 amplitudes:

$$\mathscr{A} = \underbrace{\frac{[\cdot\cdot]\cdot\cdot\langle\cdot\cdot\rangle}{\Lambda^{\#}}}_{\text{SCT}} \; \underbrace{P\left(\frac{s}{\Lambda^2}, \frac{t}{\Lambda^2}\right)}$$

SCT: scattering angle and decay angles

P: scattering angle

? construct observables to isolate novel SCTs not appearing in SM

? systematize directly in terms of SCT bases

in progress: De Angelis Durieux Grojean YS

EFT of electroweak precision measurements & spurion analysis

Julian Northey, YS, Yotam Soreq, in progress

Z- and W-pole measurements: 3-points — simple & “exact” (no kinematic expansion)

$$M(\bar{Q}^i\, Q^j\, V) = C^i_j\, \frac{[1\mathbf{3}]\langle 2\mathbf{3}\rangle}{M_V}$$

EFT of electroweak precision measurements & spurion analysis

Julian Northey, YS, Yotam Soreq, in progress

SU(2) structure **to all orders** via "spurion" analysis

spurion = normalized Higgs VEV

$$\mathcal{M}(\overline{Q}^i, Q_j, B) \sim c_{Q1}\delta_j{}^i + c_{Q2}(\tau^a)_j{}^i(\mathcal{H}^\dagger\tau^a\mathcal{H}) \,,$$

$$\mathcal{M}(\overline{Q}^i, Q_j, W^a) \sim c_{Q3}(\tau^a)_j{}^i + c_{Q4}\delta_j{}^i(\mathcal{H}^\dagger\tau^a\mathcal{H}) + c_{Q5} i\varepsilon^{abc}(\tau^b)_j{}^i(\mathcal{H}^\dagger\tau^c\mathcal{H}) \,,$$

5 structures

C's functions of $H^\dagger H$

simple-minded (amplitude!) version of GeoSMEFT Helset Martin Trott '20

EFT of electroweak precision & spurion analysis

SU(2) structure **to all orders** via "spurion" analysis

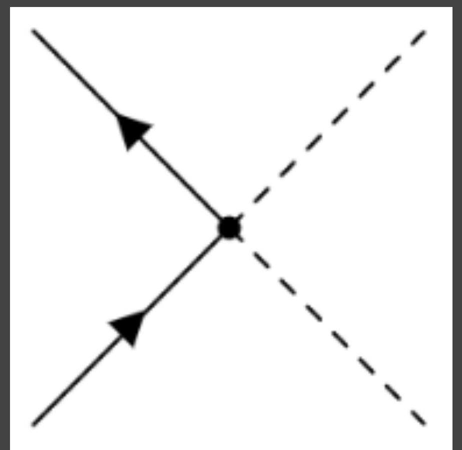
spurion = Higgs VEV

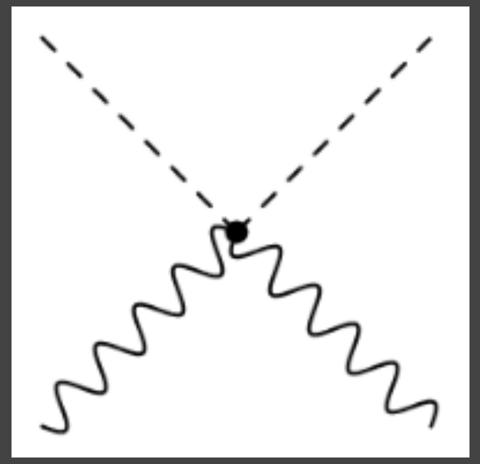
$$\mathcal{M}(\overline{Q}^i, Q_j, B) \sim c_{Q1}\delta_j{}^i + \boxed{c_{Q2}(\tau^a)_j{}^i(\mathcal{H}^\dagger\tau^a\mathcal{H})\,,}$$

$$\mathcal{M}(\overline{Q}^i, Q_j, W^a) \sim c_{Q3}(\tau^a)_j{}^i + \boxed{c_{Q4}\delta_j{}^i(\mathcal{H}^\dagger\tau^a\mathcal{H})} + c_{Q5}i\varepsilon^{abc}(\tau^b)_j{}^i(\mathcal{H}^\dagger\tau^c\mathcal{H})\,,$$

examine on-shell Higgsing to see:

start @ dim-6





EFT of electroweak precision & spurion analysis

SU(2) structure **to all orders** via "spurion" analysis

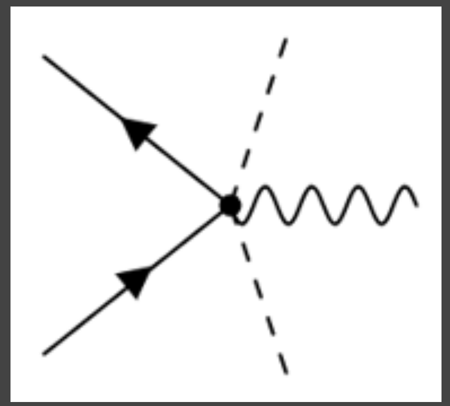
spurion = Higgs VEV

$$\mathcal{M}(\overline{Q}^i, Q_j, B) \sim c_{Q1}\delta_j^{\ i} + c_{Q2}(\tau^a)_j^{\ i}(\mathcal{H}^\dagger\tau^a\mathcal{H}) ,$$

$$\mathcal{M}(\overline{Q}^i, Q_j, W^a) \sim c_{Q3}(\tau^a)_j^{\ i} + c_{Q4}\delta_j^{\ i}(\mathcal{H}^\dagger\tau^a\mathcal{H}) + \boxed{c_{Q5}i\varepsilon^{abc}(\tau^b)_j^{\ i}(\mathcal{H}^\dagger\tau^c\mathcal{H}) ,}$$

examine on-shell Higgsing to see:

start @ dim-8



to conclude:

- amplitudes in terms of LG covariant spinors: power of Lorentz: uniform description of amplitudes of different spins; Higgsing of massless amplitudes into massive ones
- mature(ing) methods for on-shell derivations of low-energy EFT amplitudes:
  - EFT parametrization directly in terms of physical particles, couplings
  - operator bases—> kinematic spinor structures bases: promising starting point for isolating novel effects in experiment
  - clear distinction between HEFT, SMEFT

Thank you!