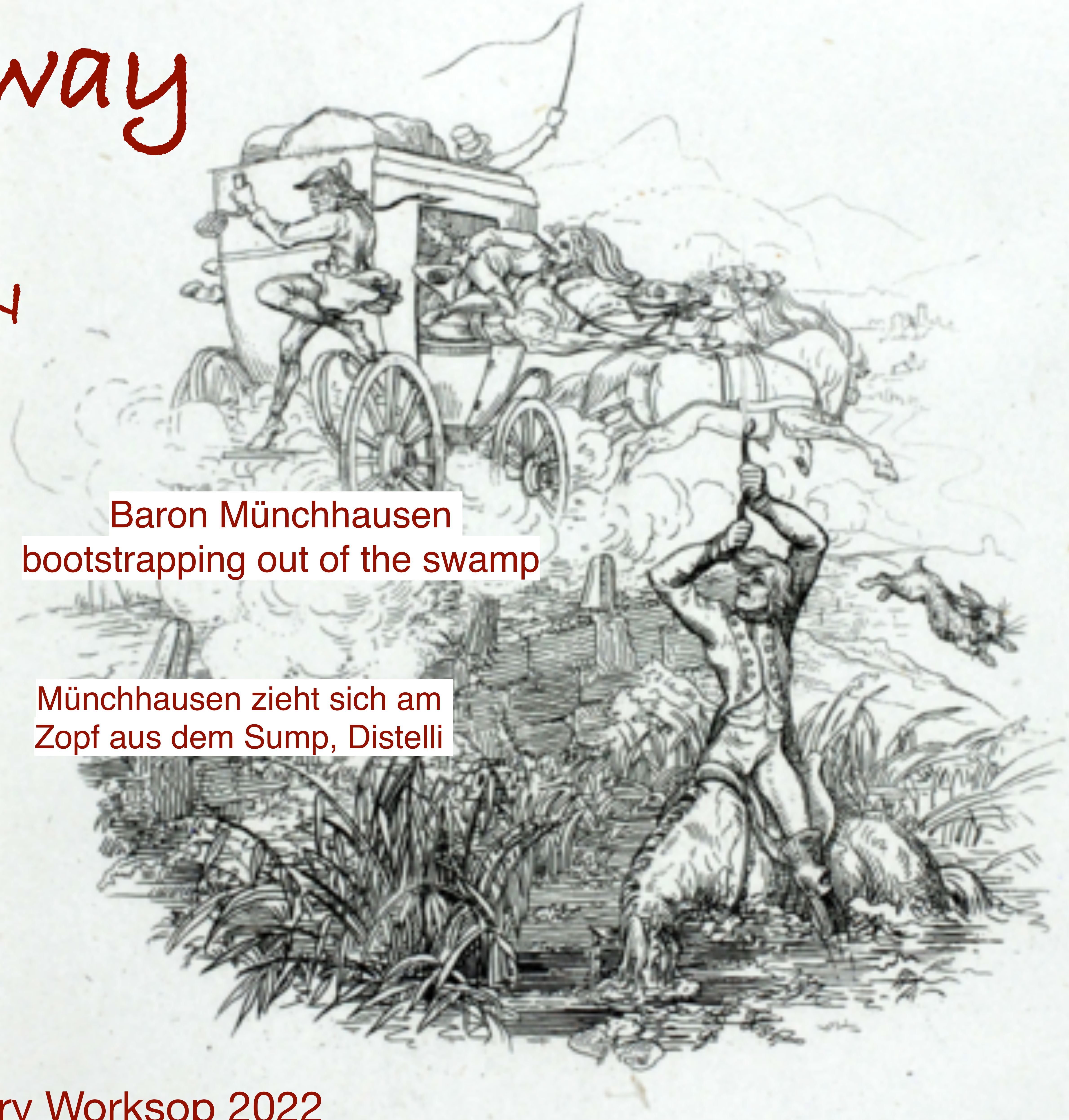
EFTs: the on-shell way

YAEL SHADMI, TECHNION



Baron Münchhausen
bootstrapping out of the swamp

Münchhausen zieht sich am
Zopf aus dem Sump, Distelli

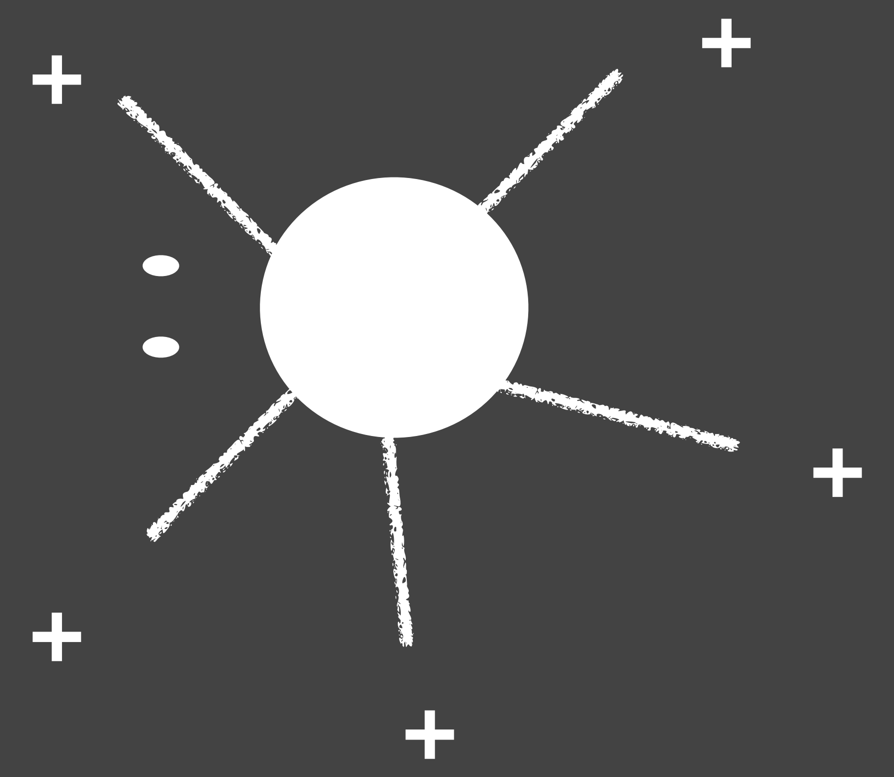
DESY Theory Worksop 2022

Why on-shell?

0) 1st clue: amplitudes: the whole is SMALLER than the sum of its parts:

gauge boson amplitudes: many Feynman diagrams (~10 million for tree 10-gluon):

Mangano Parke review



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Why on-shell?

describe massless *spin-1 particle* (2 dof’s) via *vector field* (4 dof’s)

→ more efficient: focus on physical dof’s only

Why on-shell?

1) various ways developed for expressing amplitudes: make various properties/ symmetries transparent

here:

massless & massive amplitudes in terms of **2-component spinor** products

- uniform description of amplitudes of different spins
- properties of amplitudes under Lorentz manifest: Little Group

  —> selection rules

- simple relations between massive <—> massless

Why on-shell?

2) bootstrapping amplitudes:

construct amplitudes based on their properties: little group; poles, cuts

$$\text{-->}\quad \mathscr{A}_{SM} + \mathscr{A}_{EFT}$$

rediscover SM
(more generally, gauge theory,
Higgs mechanism)

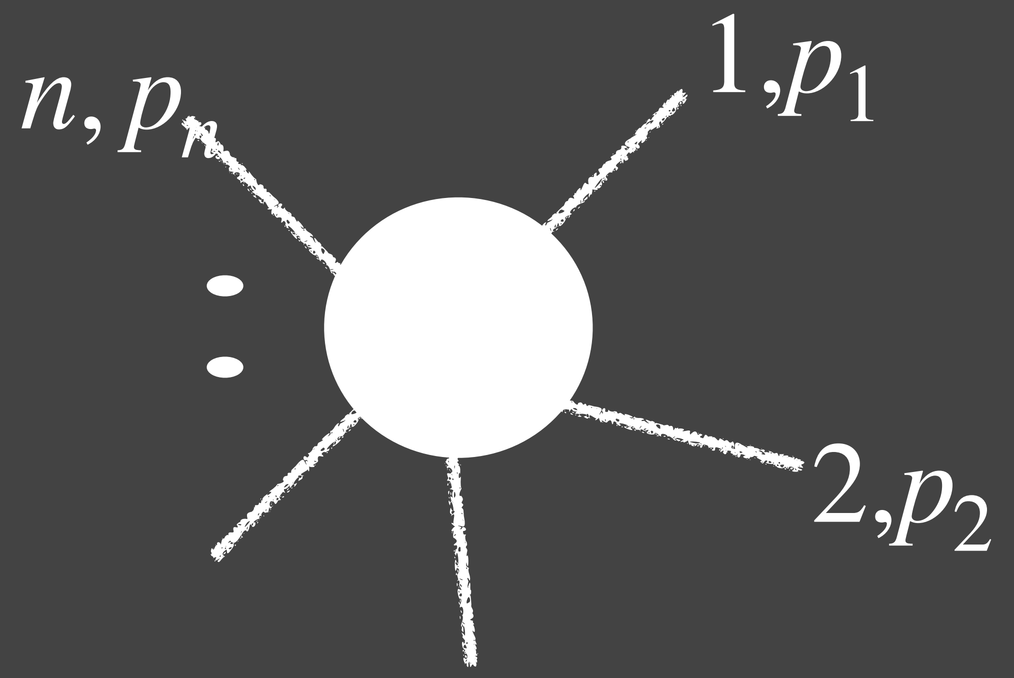
- most general EFT amplitude
- model independent
- no issues of field redefinitions, basis dependence

- natural approach as we try to go beyond SM

Plan

- amplitude basics
- sketchy overview of EFT applications
- bootstrapping amplitudes
    - rediscovering the SM
    - going BSM: on-shell EFTs

amplitude basics: spinor variables: massless



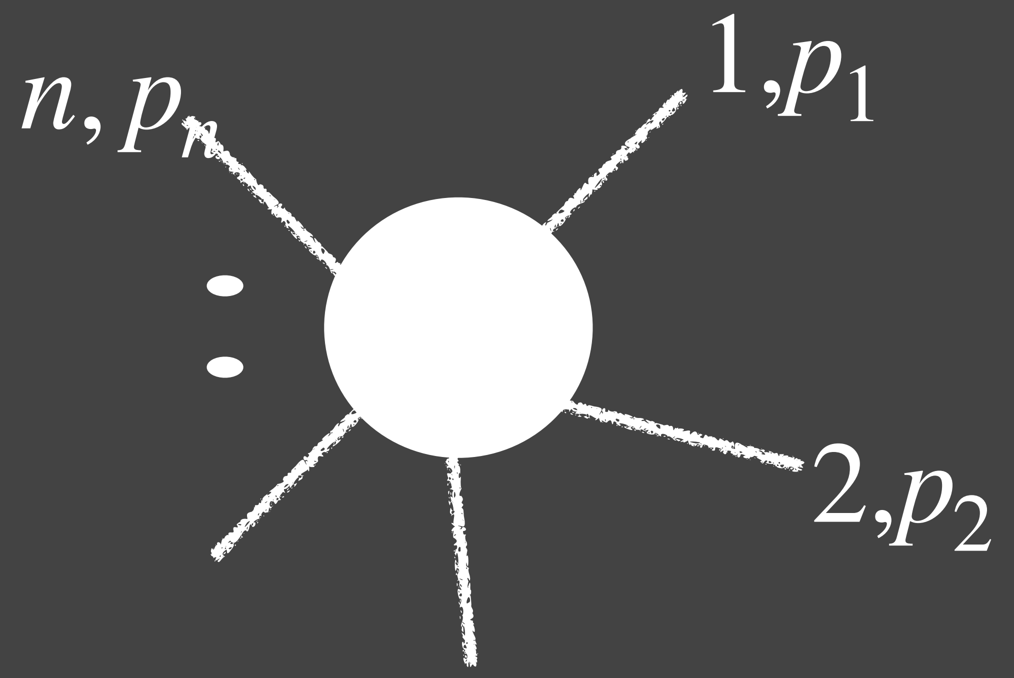
function of momenta, polarizations ($s = 1/2, \quad s = 1$)

all can be written in terms of 2-component spinors:

external $s = 1/2$ fermion $h = \pm :$ $\quad p]$ or $p\rangle$

leg $i :$ $\quad i]$ or $i\rangle$

amplitude basics: spinor variables: massless



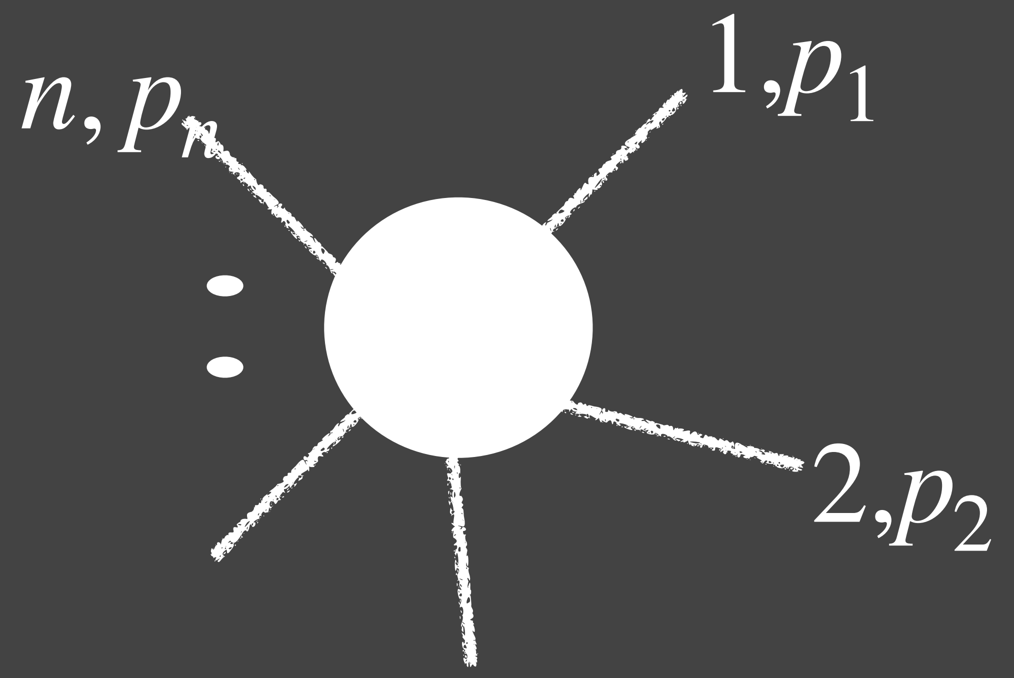
function of momenta, polarizations ($s = 1/2, \quad s = 1$)

all can be written in terms of 2-component spinors:

external momentum p_i : $\quad p_i^\mu \to p_{i,\alpha\dot{\alpha}} \equiv p_i^\mu (\sigma_\mu)_{\alpha\dot{\alpha}}$

$$\det(p_i) = 0 \quad \to \quad p_i = i\rangle[i$$

amplitude basics: spinor variables: massless



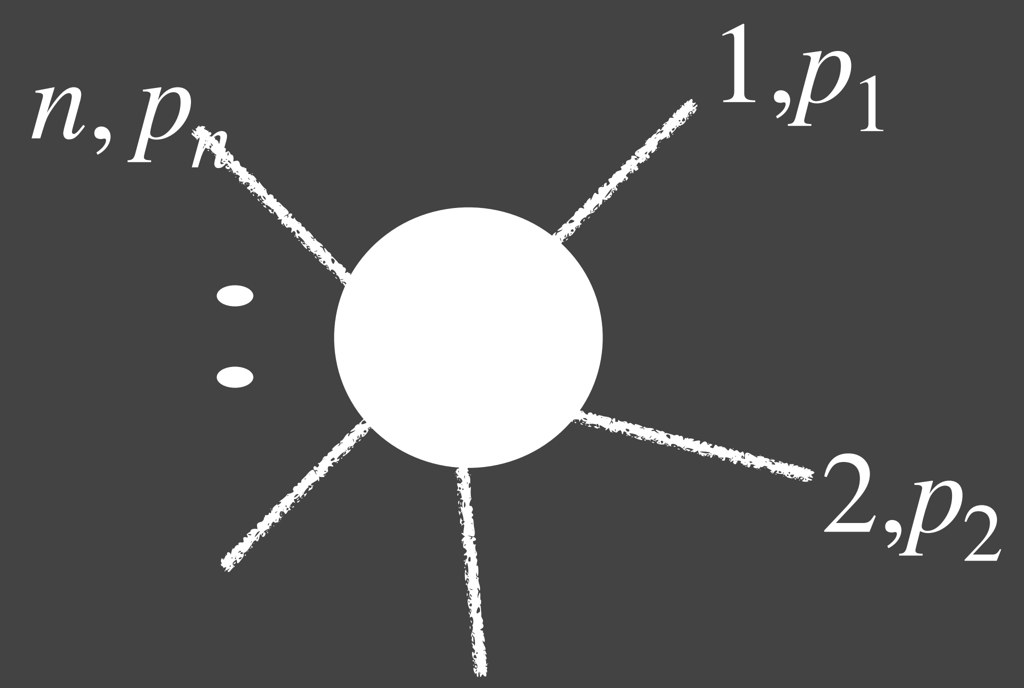
function of momenta, polarizations ($s = 1/2, \quad s = 1$)

all can be written in terms of 2-component spinors:

external spin-1 ε_i : standard polarization vectors can be written as

$$\varepsilon_i(p_i; +) \sim \frac{r\rangle[i}{\langle ir\rangle} \qquad \leftarrow \qquad \varepsilon_{i,\alpha\dot{\alpha}}$$

amplitude basics: spinor variables: massless



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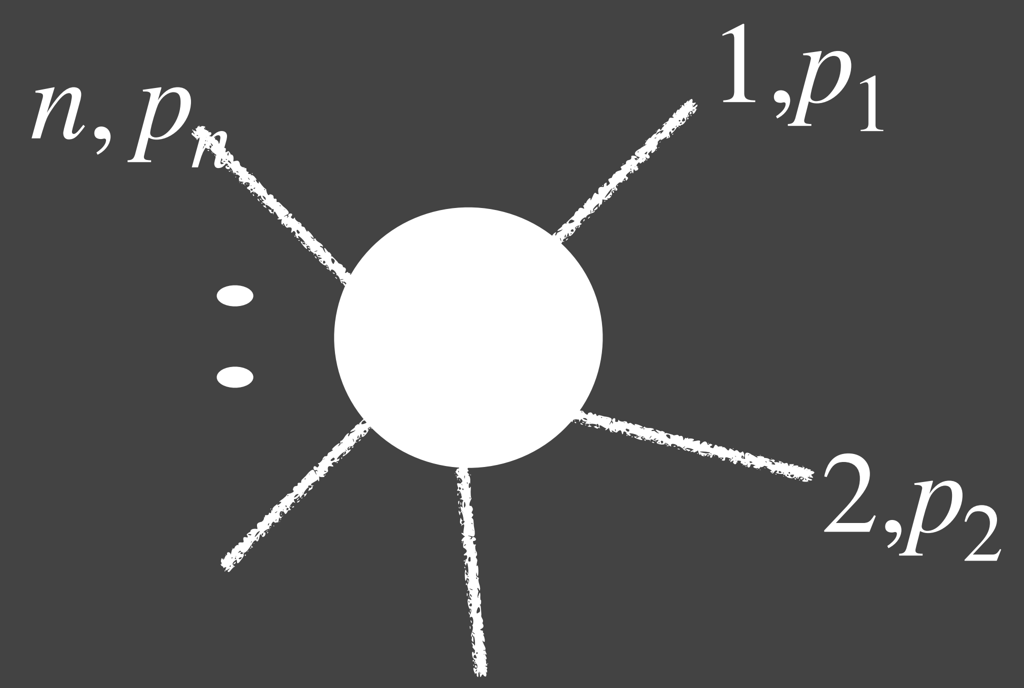
all can be written in terms of 2-component spinors:

external spin-1 ε_i : standard polarization vectors can be written as

$$\varepsilon_i(p_i; +) \sim \frac{r\rangle[i}{\langle ir\rangle}$$

arbitrary “reference” spinor
changing r <—> changing $\varepsilon_\mu(p) \quad \rightarrow \quad \varepsilon_\mu(p) + \# p_\mu$

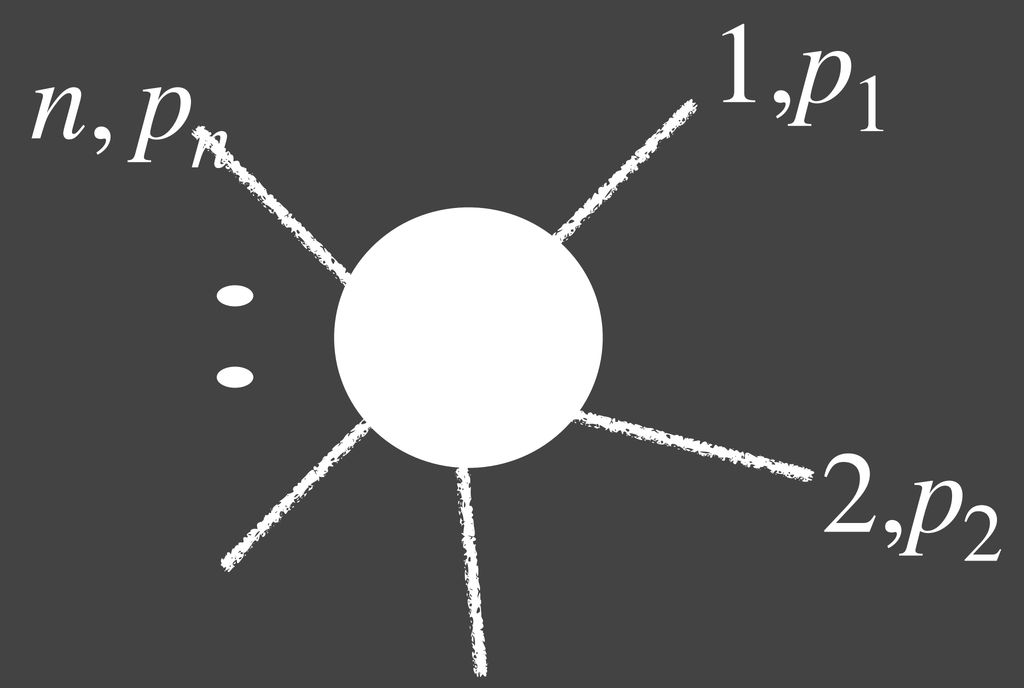
amplitude basics: spinor variables: massless



amplitude = function of spinor products $\langle ij \rangle, \ \ [ij]$

& Lorentz invariants $s_{ij} = (p_i + p_j)^2 \quad \big(= 2[ij]\langle ji \rangle \big)$

amplitude basics: spinor variables: massless



amplitude = function of spinor products $\langle ij \rangle, \quad [ij]$

& Lorentz invariants $s_{ij} = (p_i + p_j)^2 \quad \big(= 2[ij]\langle ij \rangle \big)$

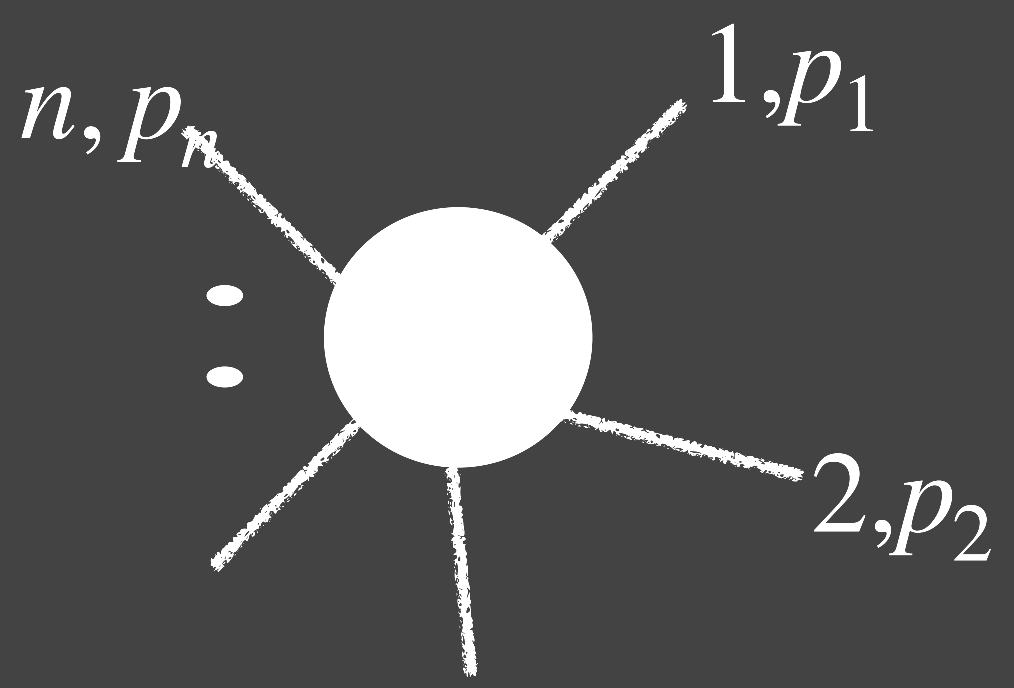
Little Group (LG) transformations transparent:

$p_i = i\rangle[i$: Lorentz transformations keeping p_i invariant:

$$i] \to e^{i\phi}\ i] : \quad charge + 1$$

$$i\rangle \to e^{-i\phi}\ i\rangle : \quad charge - 1$$

amplitude basics: spinor variables: massless



$i, h = 1/2 \qquad i]$

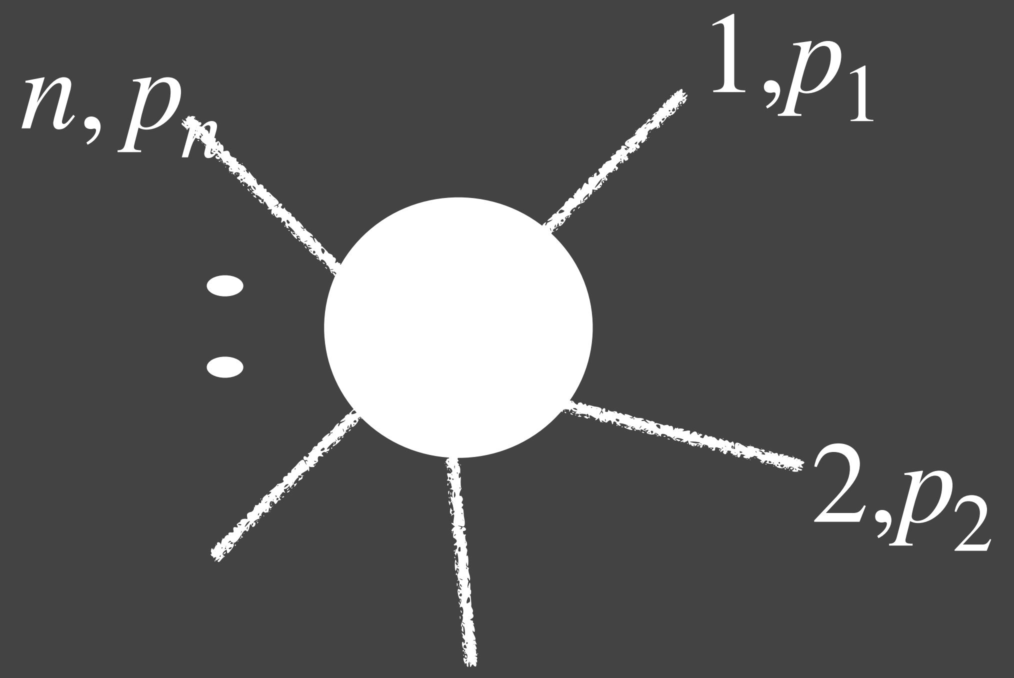
$i, h = -1/2 \qquad i\rangle$

$i, h = +1 \qquad i]i]$

$i, h = -1 \qquad i\rangle i\rangle$

selection rules:
dictate allowed form of amplitudes

amplitude basics: spinor variables: massive



$\det(p) \neq 0 \quad \rightarrow \quad p = p^{I=1} + p^{I=2}$ lightlike vectors

massless particle of definite helicity: single direction

massive particle of definite spin polarization:

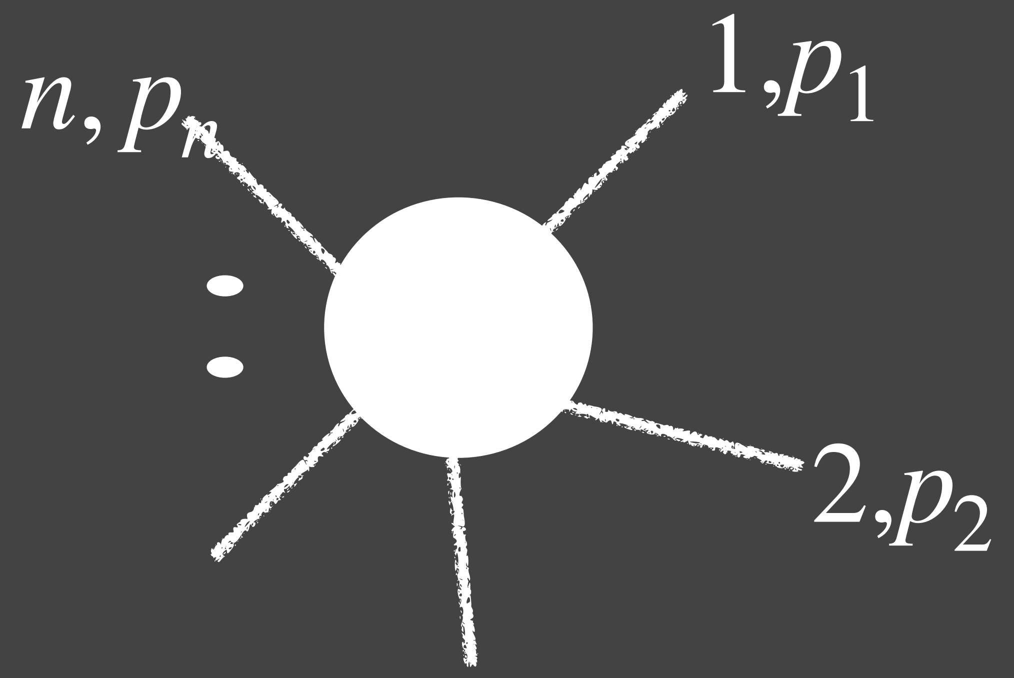
—> 2 directions: momentum + spin axis

$\det(p) \neq 0 \quad \rightarrow \quad p = p^{I=1} + p^{I=2}$

$$p = p\rangle^I [p_I$$

amplitude basics: spinor variables: massive

Arkani-Hamed Huang Huang '17



$$p = p^{I=1} + p^{I=2}$$ lightlike vectors

$$p = p\rangle^I [p_I$$

external spin-1/2 fermion: $p]^I$ $\quad I = 1,2 \quad h = \pm 1/2$

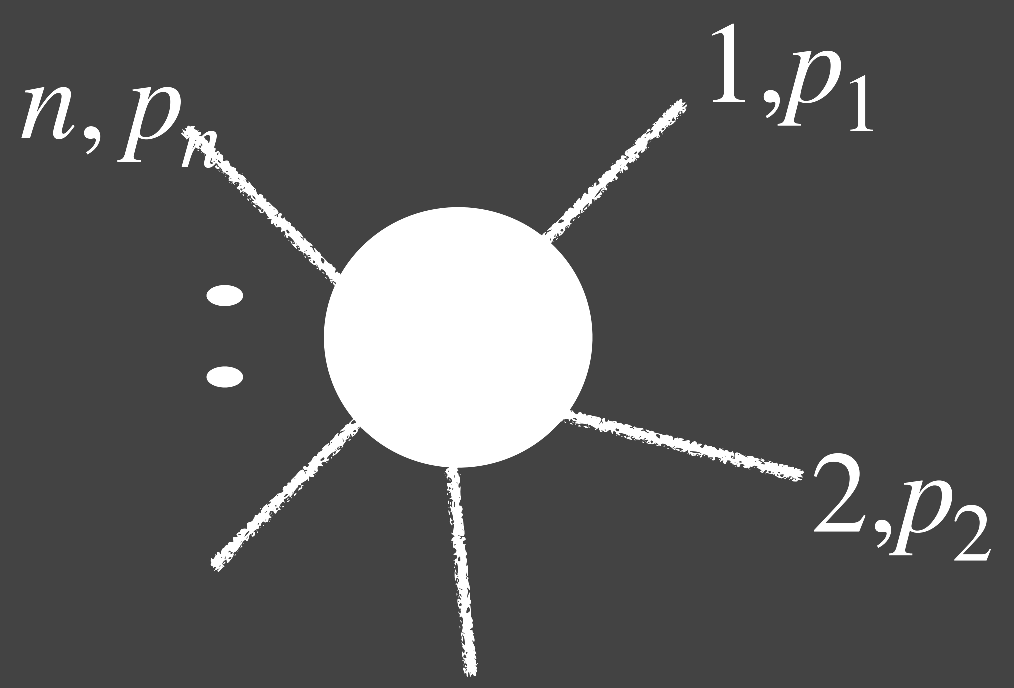
external spin-1: $\varepsilon(p) \sim \dfrac{p\rangle^{\{I}[p^{J\}}}{m}$ $\quad I = J : h = \pm 1, \quad I \neq J : h = 0$

no gauge freedom

$$\frac{\mathbf{p}\rangle[\mathbf{p}}{m}$$

BOLD notation
Arkani-Hamed Huang Huang

amplitude basics: spinor variables: massive



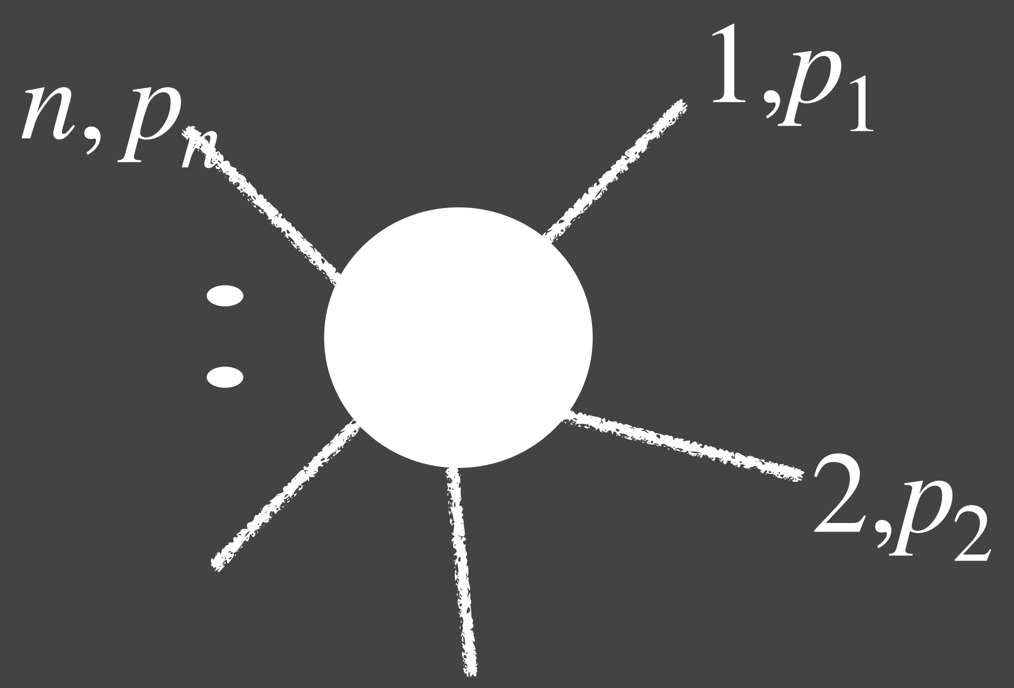
$$\mathbf{p} = \mathbf{p}\rangle^{\mathbf{I}}[\mathbf{p}_{\mathbf{I}}$$

LG transformation $\quad p\rangle^I \to W^I_J\ p\rangle^J \quad [p_I \to (W^{-1})^J_I[\ p_J$

massive LG SU(2) transformations

little-group covariant massive spinor formalism

amplitude basics: spinor variables: massive



$i, \quad s = 1/2$ $\qquad$ $\mathbf{i}]$ or $\mathbf{i}\rangle$

selection rules:
dictate allowed form of amplitudes

$i, \quad s = +1$ $\qquad$ $\mathbf{i}]\mathbf{i}]$ or $\mathbf{i}\rangle\mathbf{i}\rangle$ or $\mathbf{i}\rangle\mathbf{i}]$

amplitude basics: spinor variables:

- selection rules: dictate allowed form of amplitudes
- determine all 3-point amplitudes (*complex momenta)*

massless: easy

massive: in some cases: constructing a basis of independent spinor structures
requires some work: EOM $\mathbf{p}\ \mathbf{p}] = m\ \mathbf{p}\rangle$

explicit bases for spins ≤ 3

Durieux Kitahara YS Weiss '19
Durieux Kitahara Machado YS Weiss '20

amplitude basics: more on LG covariant massive spinors

high-energy limit:

$$p = p^{I=1} + p^{I=2} \qquad \equiv k + q$$

HE: $\qquad k = \mathcal{O}(E) \sim p \qquad q = \mathcal{O}(m^2/E)$

eg, only $\mathbf{p}]^{I=1} \sim p]$ survives; $\quad \mathbf{p}]^{I=2} = q]$ subleading

—> HE limit: simply unbold spinor structures

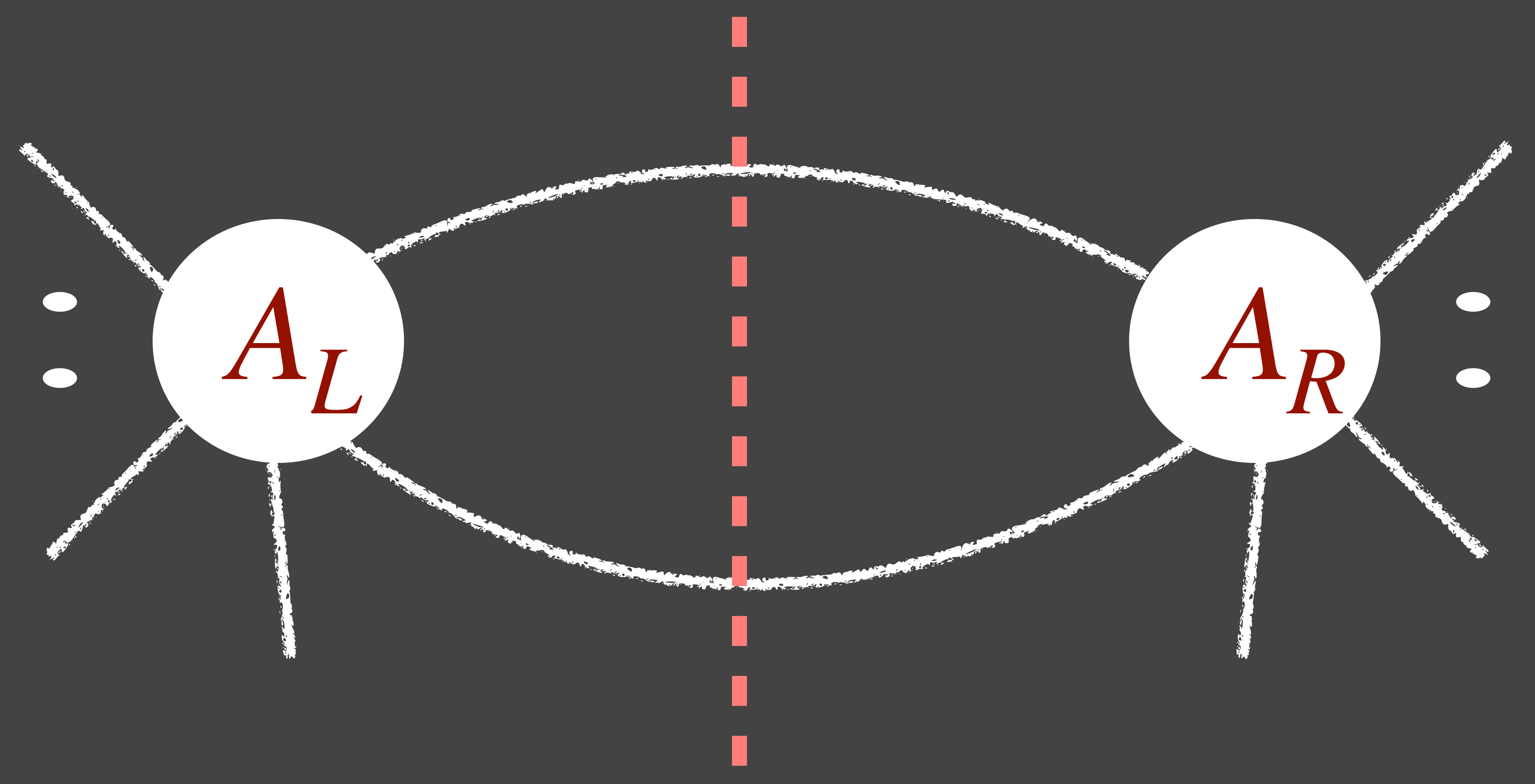
use extensively in constructing massive EFT amplitudes:

massless <—> massive amplitudes from (un)bolding

amplitude basics: factorization

tree: simple poles: residue =

loop: branch cuts:



+ generalized cuts with more propagators on-shell   "generalized unitarity"

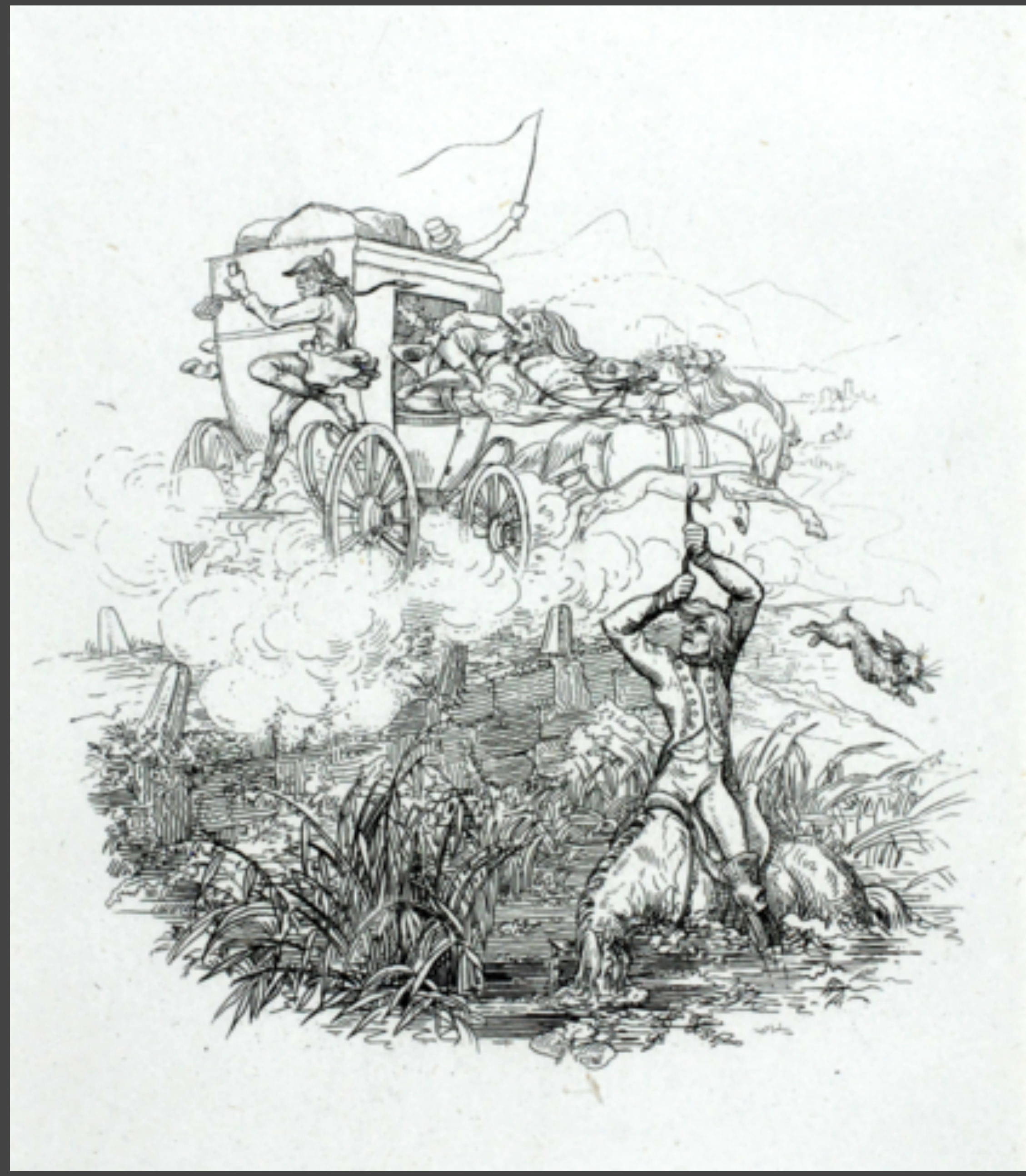
Bern Dixon Kosower '95

amplitude basics: bootstrap

construct amplitudes recursively from the bottom up: w/out Lagrangian

LG: determines all 3-point amplitude

factorization —> higher point amplitudes



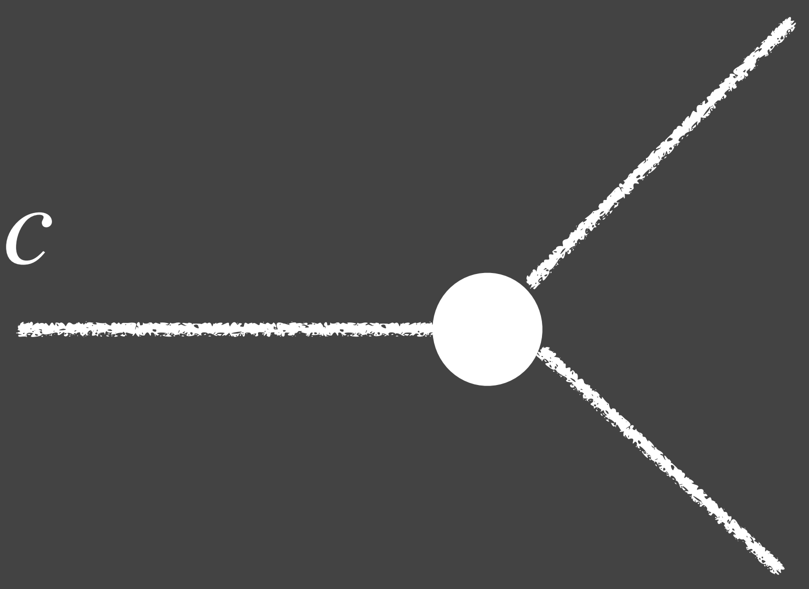
+ n-point contact-terms:
determined by LG + locality (no poles)

rediscover QFT: gauge theory massless + massive

massless SM: eg Accettulli-Huber De Angelis ‘21

example: massive degenerate spin-1 particles

Durieux Kitahara YS Weiss '19
Liu Yin '22



LG: most general amplitude:

$$C^{abc}\ \left(\langle \mathbf{12}\rangle[\mathbf{23}]\langle \mathbf{31}\rangle + [\mathbf{12}]\langle \mathbf{23}\rangle[\mathbf{31}]\ +\ \text{perm}\right)/M^2$$

$$+C'^{abc}\ \langle \mathbf{12}\rangle\langle \mathbf{23}\rangle\langle \mathbf{31}\rangle/\Lambda^2 + \mathbf{C}''^{\mathbf{abc}}\ [\mathbf{12}][\mathbf{23}][\mathbf{31}]/\Lambda^2$$

example: massive degenerate spin-1 particles

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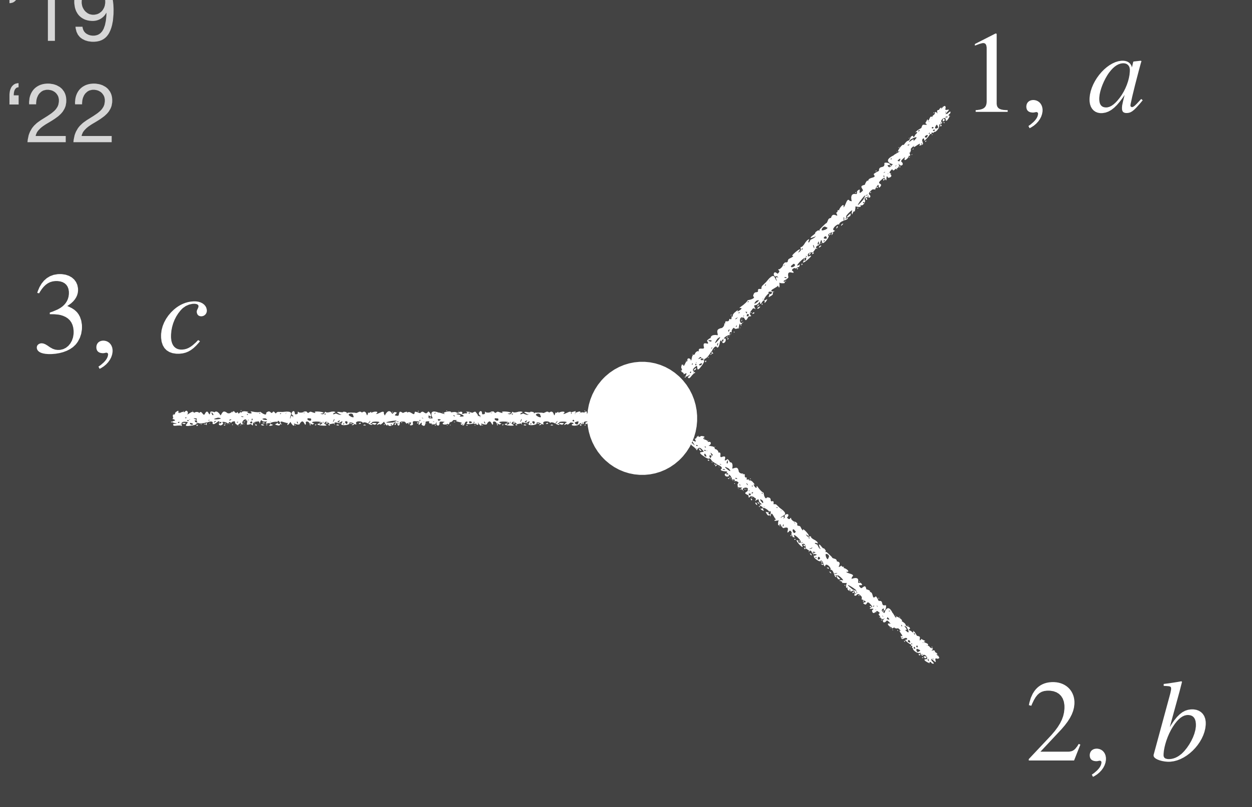

LG: most general amplitude:

$$C^{abc}\left(\langle\mathbf{12}\rangle[\mathbf{23}]\langle\mathbf{31}\rangle+[\mathbf{12}]\langle\mathbf{23}\rangle[\mathbf{31}]\ +\ \text{perm}\right)/M^2$$

completely antisymmetric

$$+C'^{abc}\ \langle\mathbf{12}\rangle\langle\mathbf{23}\rangle\langle\mathbf{31}\rangle/\Lambda^2+\mathbf{C}''^{\mathbf{abc}}\ [\mathbf{12}][\mathbf{23}][\mathbf{31}]/\Lambda^2$$

—> C^{abc} completely antisymmetric

structure constants!

+ factorization of 4-points on 3-points: Jacobi identity

example: massive degenerate spin-1 particles

Durieux Kitahara YS Weiss ’19
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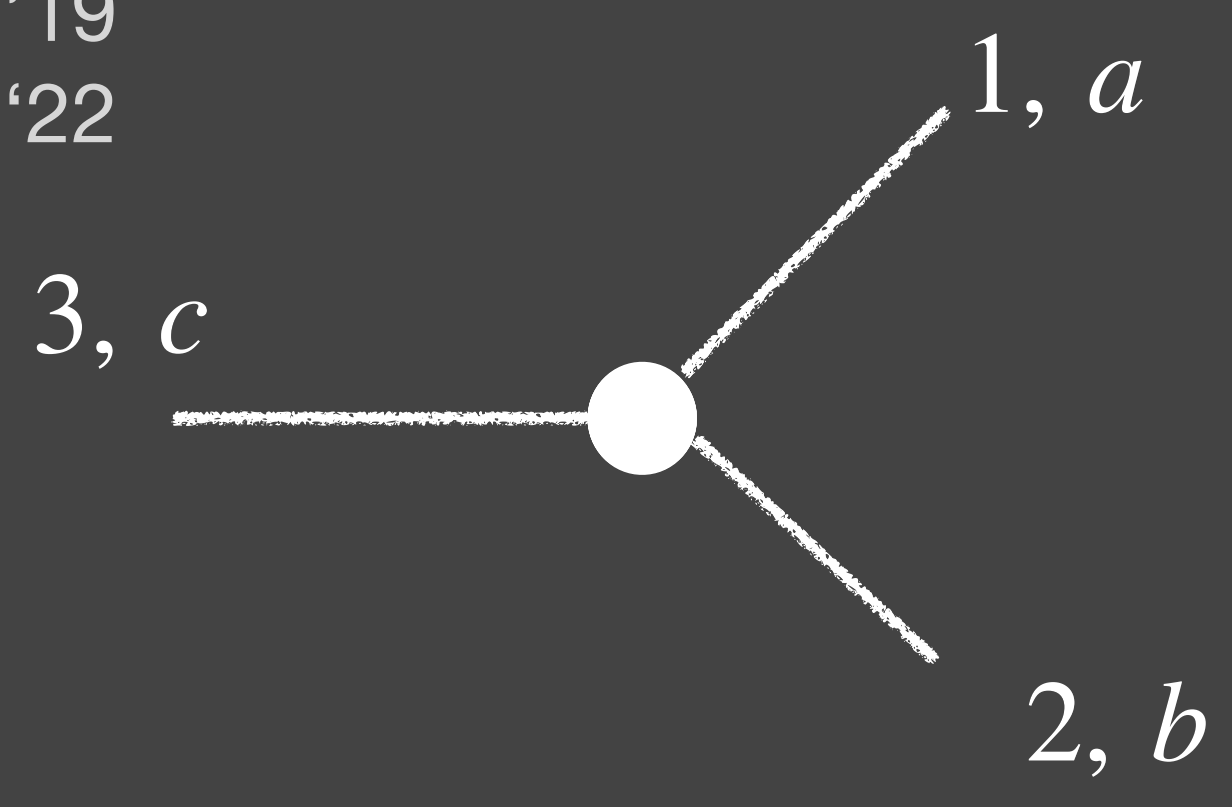

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structure constants!

+ factorization of 4-points on 3-points: Jacobi identity

vector self-coupling

Lie algebras

EFT applications

(massless) EFT applications (1)

- 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
  …

(massless+ massive) EFT applications (2)

- count & construct bases of EFT operators:

  operator (n-fields) <—> n-point contact term

  determine from LG scaling + locality (no poles)

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

will come back to this

$$\begin{tikzcd}
\text{amplitude} \arrow[d] & \\
\mathscr{L} \arrow[d] & \\
\text{amplitude} \arrow[r] & \text{LHC}
\end{tikzcd}$$

EFT applications (3)

work directly with amplitudes

bottom-up EFTs: parametrize our ignorance about the UV

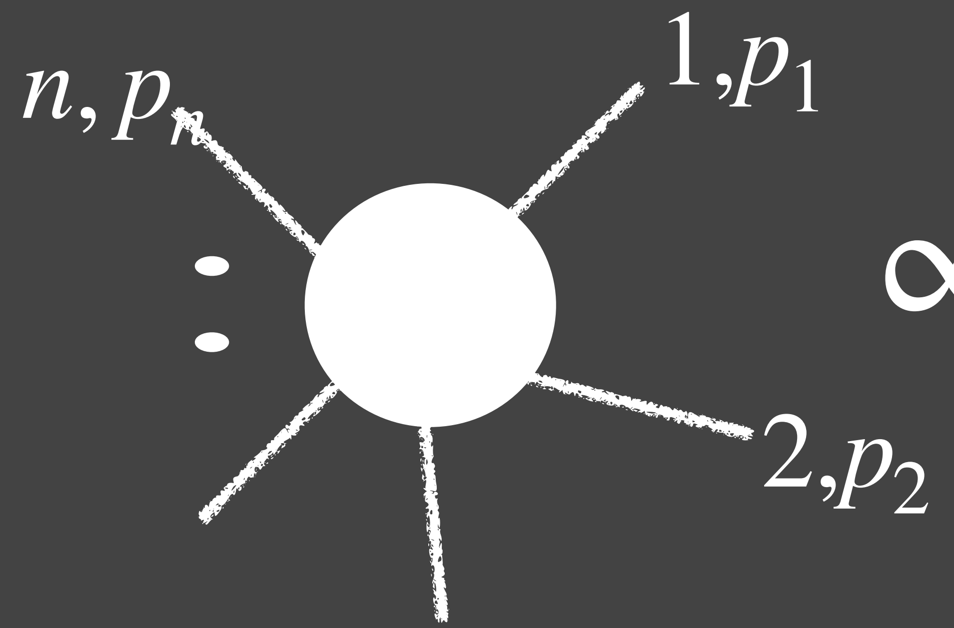
bottom-up construction of amplitudes does just that

EFT via on-shell bootstrap

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

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

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



$\propto c_i$

1-1 correspondence

EFT via on-shell bootstrap

YS Weiss ‘18
Durieux Kitahara YS Weiss ‘19

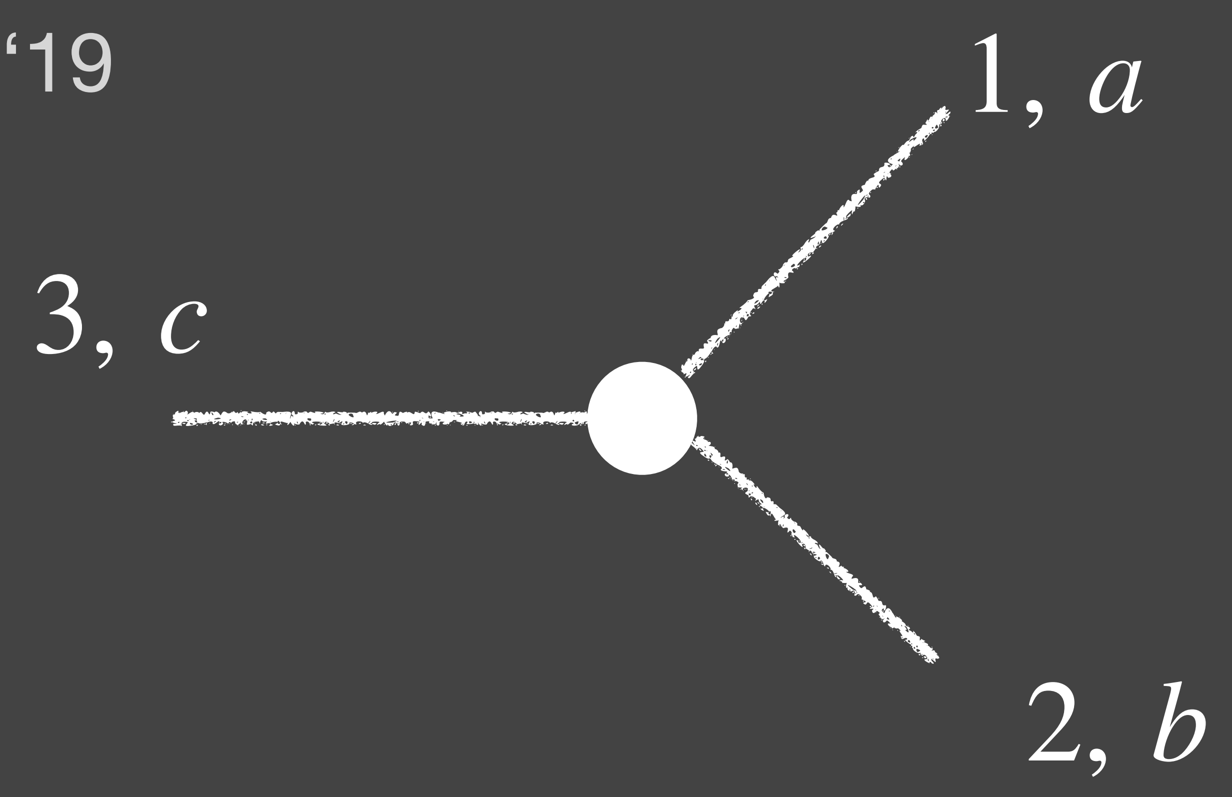
start with the massive (and massless) particles we know:
construct most general amplitudes

$W, Z, h, t\ ;\ \gamma, q, g, l$

already saw an example:

bootstrap 3-pt of degenerate massive spin-1 particles

Durieux Kitahara YS Weiss ‘19



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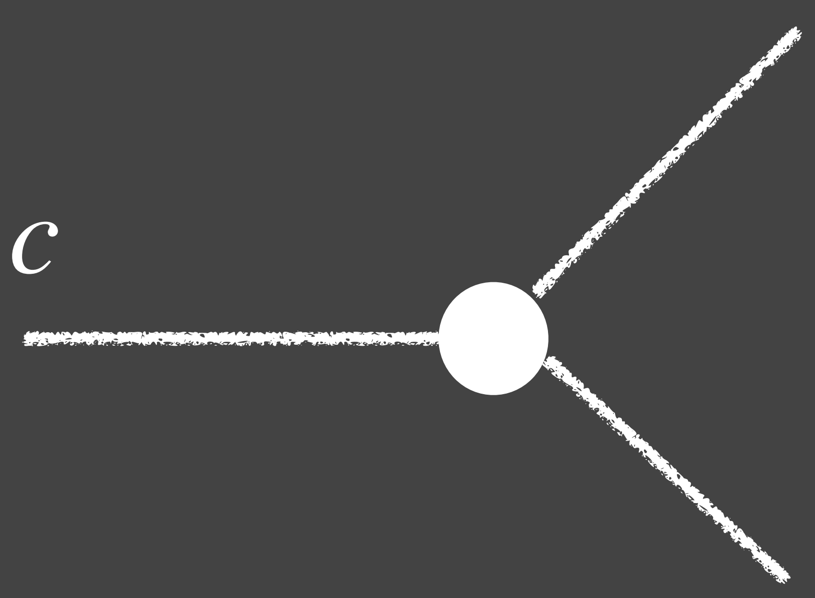
bootstrap 3-pt of degenerate massive spin-1 particles

Durieux Kitahara YS Weiss ‘19



LG: most general amplitude:

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$$+C'^{abc}\ \langle\mathbf{12}\rangle\langle\mathbf{23}\rangle\langle\mathbf{31}\rangle/\Lambda^2 + \mathbf{C}''^{\mathbf{abc}}\ [\mathbf{12}][\mathbf{23}][\mathbf{31}]/\Lambda^2$$

EFT contributions <—> $\text{tr}(G^3)/\Lambda^2 \qquad \text{tr}(G^2\tilde{G})/\Lambda^2$

Λ^2 vs M^2 normalization based on high-energy behavior

EFT via on-shell bootstrap

YS Weiss '18
Durieux Kitahara YS Weiss '19
...

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

local: no poles

EFT via on-shell bootstrap

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

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

EFT via on-shell bootstrap

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

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

EFT via on-shell bootstrap

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

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

finding operator basis:

1. finding SCT basis (exploit massless limit; massless basis)

2. finding basis of polynomials in invariants *very simple!*

only briefly today

EFT via on-shell bootstrap

YS Weiss '18

example: higgs + 3 gluons:

$$\mathcal{M}\left(h; g^{a+}(p_1)\, g^{b+}(p_2)\, g^{c+}(p_3)\right) = \frac{[12][13][23]}{\Lambda}\Bigg[$$
$$f^{abc}\left(-i\,\frac{m^4\, g_s\, c_5^{hgg}}{s_{12}s_{13}s_{23}} + \frac{c_7}{\Lambda^2} + \frac{c_{11}}{\Lambda^6}\left(s_{12}s_{23}+s_{13}s_{23}+s_{12}s_{13}\right) + \frac{c_{13}}{\Lambda^8}s_{12}s_{13}s_{23}\right)$$
$$+\, d^{abc}\,\frac{c'_{13}}{\Lambda^8}\left(s_{12}-s_{13}\right)\left(s_{12}-s_{23}\right)\left(s_{13}-s_{23}\right)\Bigg]$$
$$+\cdots$$

derivative expansion

- factorizable + EFT (most general)
- full kinematic behavior of amplitude
- going to dim-13: academic exercise: here see that nothing important beyond dim-7
- by-product: counting & classifying basis of EFT operators

EFT via on-shell bootstrap:

Durieux Kitahara YS Weiss '19

example: most general fermion-fermion-vector-scalar amplitude (contact-term part):

$$\begin{aligned}\mathcal{M}^{\text{contact}}(\mathbf{1}_{\psi^c}, \mathbf{2}_{\psi}, \mathbf{3}_Z, \mathbf{4}_h) &= \frac{C_6^{(1)}}{\bar\Lambda^2}[\mathbf{13}][\mathbf{23}] + \frac{C_6^{(2)}}{\bar\Lambda^2}[\mathbf{13}]\langle\mathbf{23}\rangle \\ &+ \frac{C_7^{(1)}}{\bar\Lambda^3}[\mathbf{312}\rangle[\mathbf{13}] + \frac{C_7^{(2)}}{\bar\Lambda^3}[\mathbf{321}\rangle[\mathbf{23}] \\ &+ \text{angle} \leftrightarrow \text{square}\end{aligned}$$

each coefficient: derivative expansion:

$$C_6^{(1)} = c_6^{(1)} + c_8^{(1,1)}\frac{\tilde s_{12}}{\bar\Lambda^2} + c_8^{(1,2)}\frac{\tilde s_{13}}{\bar\Lambda^2} + \cdots \qquad [\tilde s_{ij} \equiv 2p_i \cdot p_j]$$

massive EFT amplitude bases:

finding operator basis:

1. finding SCT basis (exploit massless limit; massless basis)
2. finding basis of polynomials in invariants *very simple!*

massive EFT amplitude bases:

systemized for massless EFTs + derivation of bases for SMEFT, GRSMEFT — Durieux Machado '20

massive EFTs + 4-points for SM particle content: spins 0, 1/2, 1
heavily exploit massless bases & bolding-unbolding

Durieux Kitahara Machado YS Weiss '20

diagrammatic representation + general algorithm for n-points massless

Accettulli-Huber De Angelis '21

+ massive: using bolding
automated, some publicly available code

De Angelis '22

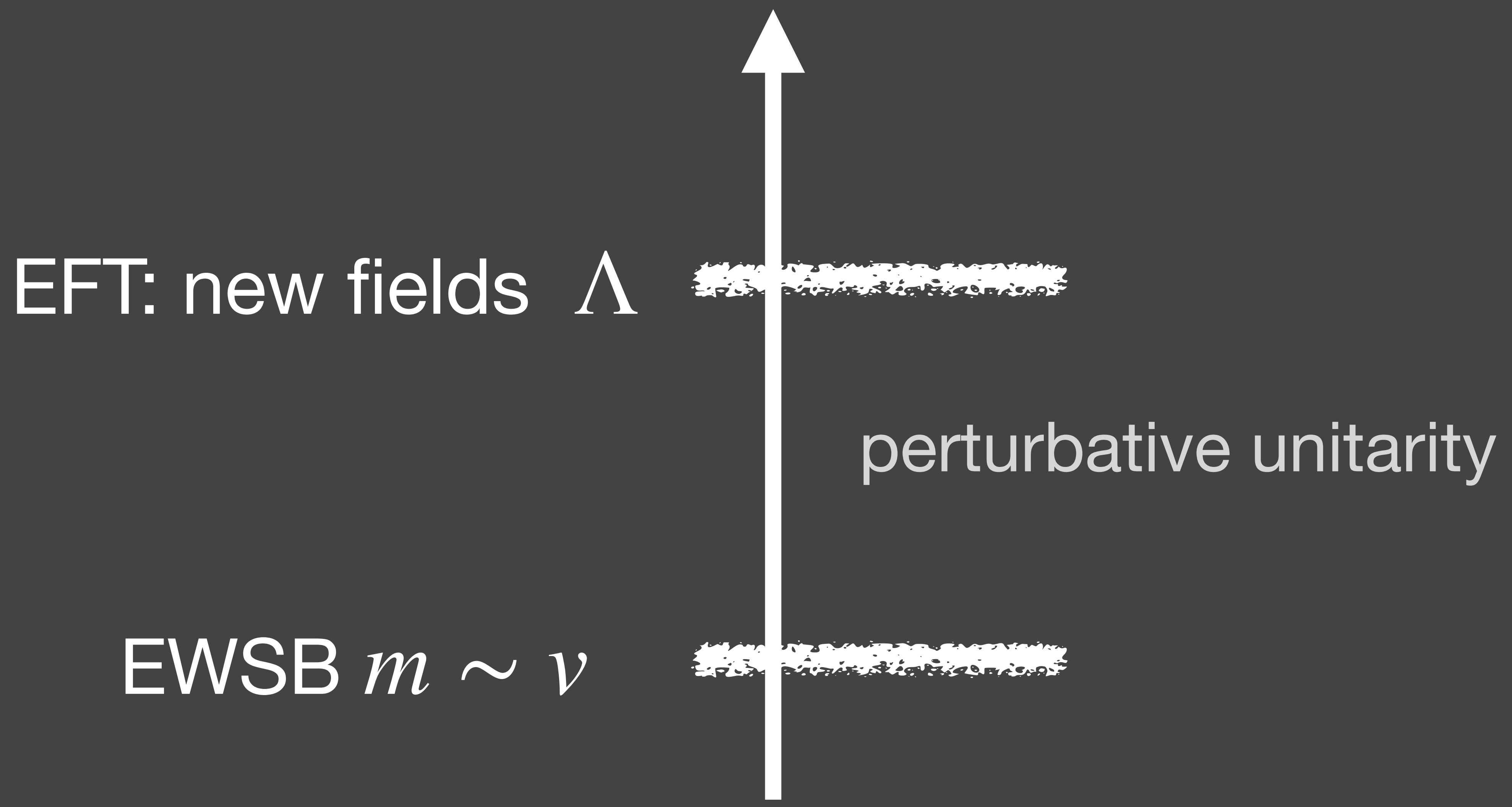
different approach: use EOM to work with just $\mathbf{p}]$-spinors — Dong Ma Shu '21

obscures mapping to operators of given dim so: have bootom-up construction of most general amplitude:

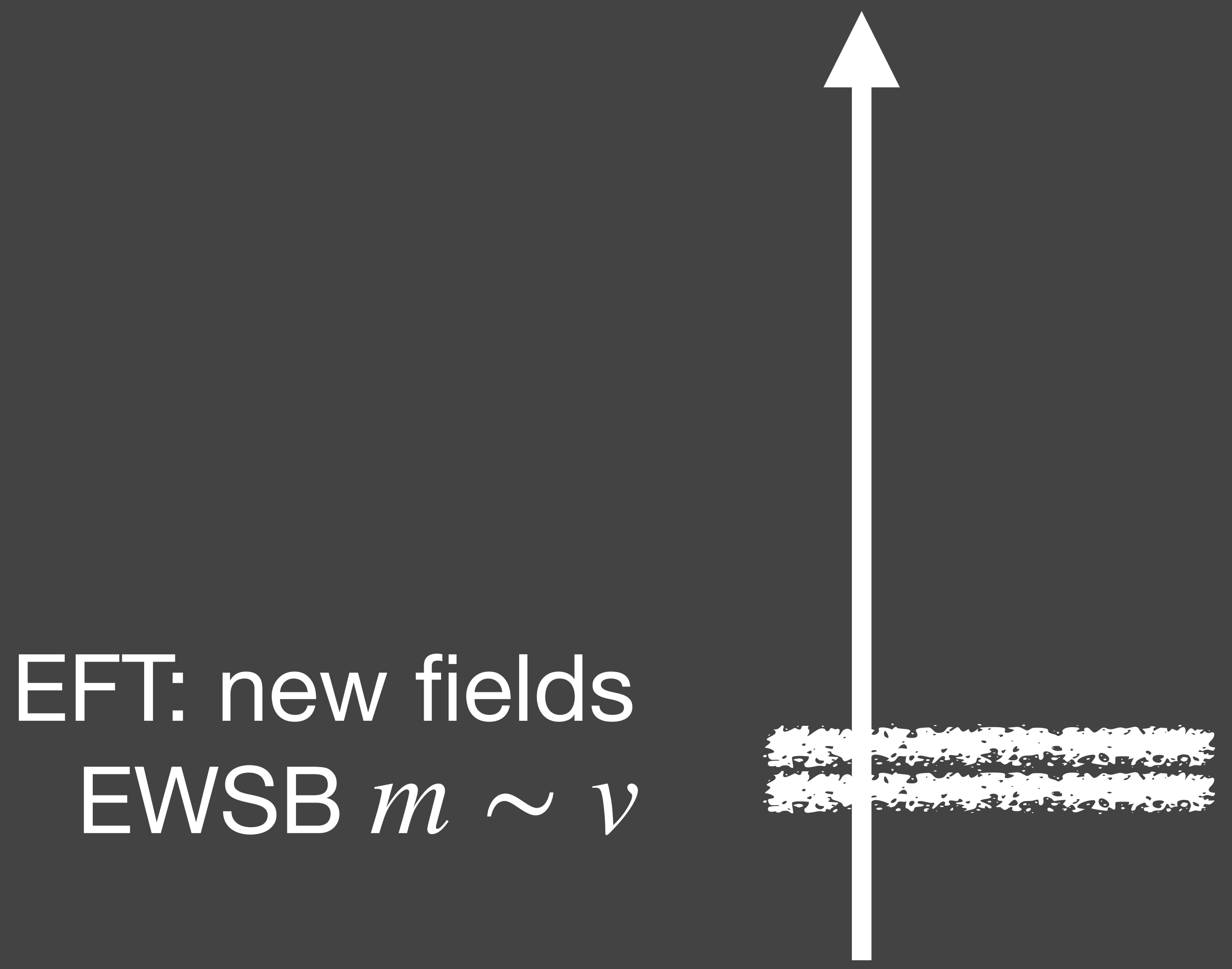
but different possible bottom-up EFTs: which amplitude gives which EFT?

bootstrap: different possible EFTs

most general amplitude: but different possible bottom-up EFTs:



large hierarchy of scales possible
SU(2)xU(1) linearly realized = “SMEFT”



cutoff ~ v

bootstrap: different possible EFTs

most general amplitude: but different possible bottom-up EFTs:

EFT: new fields Λ

EWSB $m \sim v$

to tell them apart at amplitude level:

High-Energy behavior of amplitude

$O(E^n)$ growth suppressed by powers of Λ (not mass)

heavy states decouple as Λ

bootstrap: different possible EFTs

2 approaches to getting massive SMEFT amplitudes:

1) purely bottom-up: construct amplitudes and require perturbative unitarity
   guaranteed to recover SM above EW scale

Durieux Kitahara YS Weiss ’19
(imposing SU(2)xU(1) relations) Aoude Machado ’19

2) top-down (on-shell): construct amplitudes of unbroken theory & “Higgs” them to get massive amplitudes <— *here*

Balkin Durieux Kitahara YS Weiss ‘21

bootstrap: different possible EFTs

top-down (on-shell): construct amplitudes of unbroken theory & “Higgs” them to get massive amplitudes

Balkin Durieux Kitahara YS Weiss ‘21

EFT: new fields Λ

EWSB $m \sim v$

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

derive massive $\mathscr{M}$

(contact term part only)

SMEFT amplitudes from on-shell Higgsing

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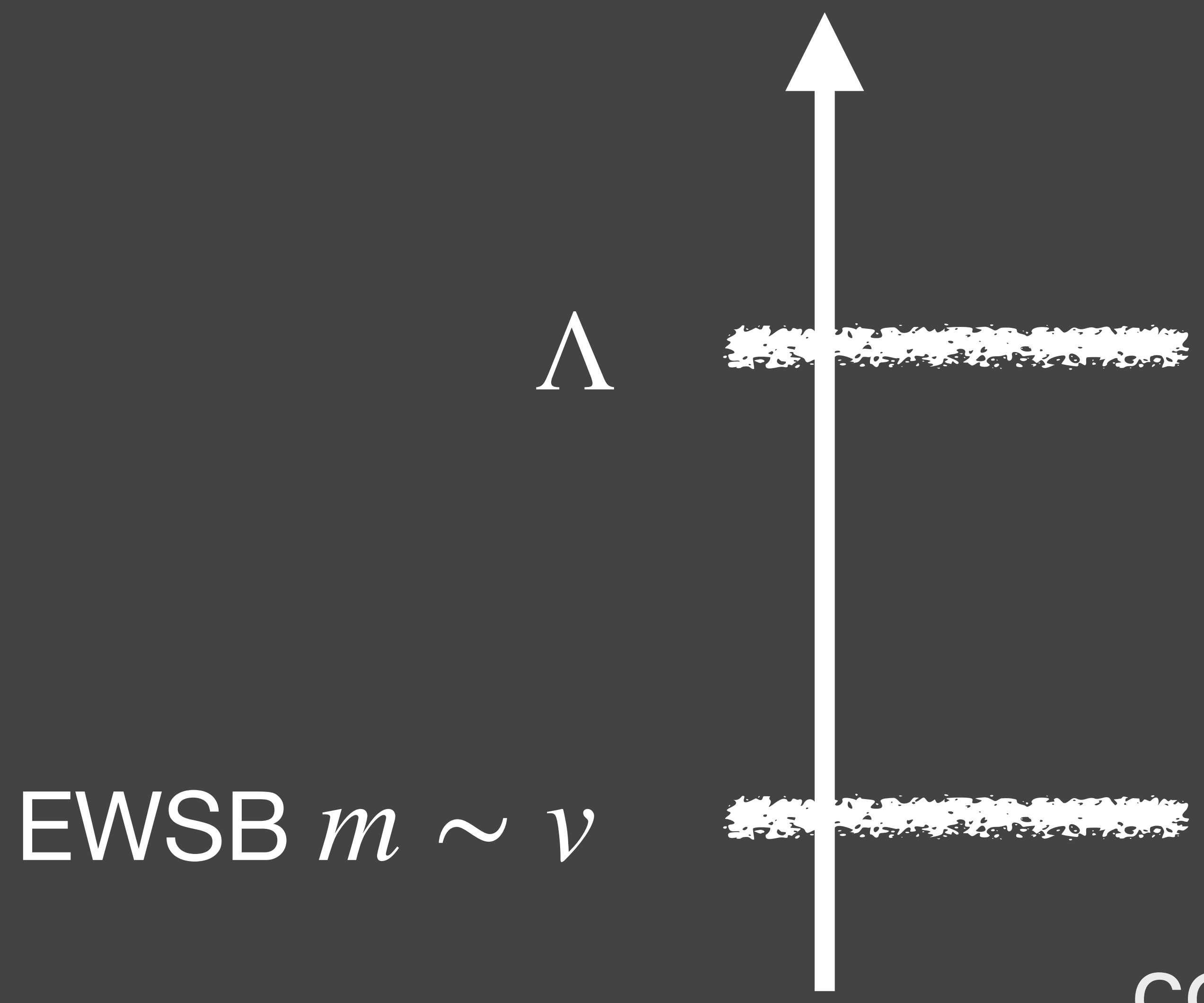


$c_i \, O_i \in \mathscr{L}$

$\big\downarrow \langle H \rangle = v$

massive amplitude:

contact term $C_i \propto \; c_i + \mathcal{O}(v)$

SMEFT amplitudes from on-shell Higgsing

Balkin Durieux Kitahara YS Weiss ‘21

Λ

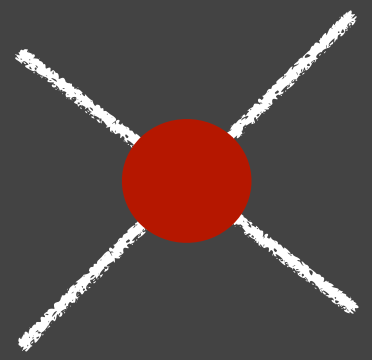
EWSB $m \sim v$

$c_i \, O_i \in \mathscr{L}$

$\langle H \rangle = v$

massive amplitude:

contact term $C_i \propto \; c_i + \mathscr{O}(v)$

$\mathscr{A}$: contact term:  $\propto \; c_i$

SMEFT amplitudes from on-shell Higgsing

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Λ

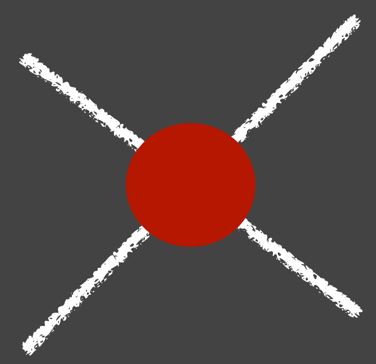
EWSB $m \sim v$

$c_i\, O_i \in \mathscr{L}$

$\langle H \rangle = v$

massive amplitude:

contact term $C_i \propto \; c_i + \mathcal{O}(v)$

$\mathscr{A}$: contact term:  $\propto \; c_i$

BOLD

exploit simple relation between massive and massless amplitudes written in terms of massive spinor formalism:

take massless contact term: BOLD spinor structure —> massive contact term

SMEFT amplitudes from on-shell Higgsing

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let's make contact with the Higgs mechanism:

low-energy n-point contact term $\propto c_i$ gets contributions from:

massless n-point contact term $\propto c_i$

massless $n + n_H$ amplitudes with n_H ***soft*** Higgs legs $\quad A_n \sim v^{n_H} A_{n+n_H}$

2 types of contributions to massive contact terms:

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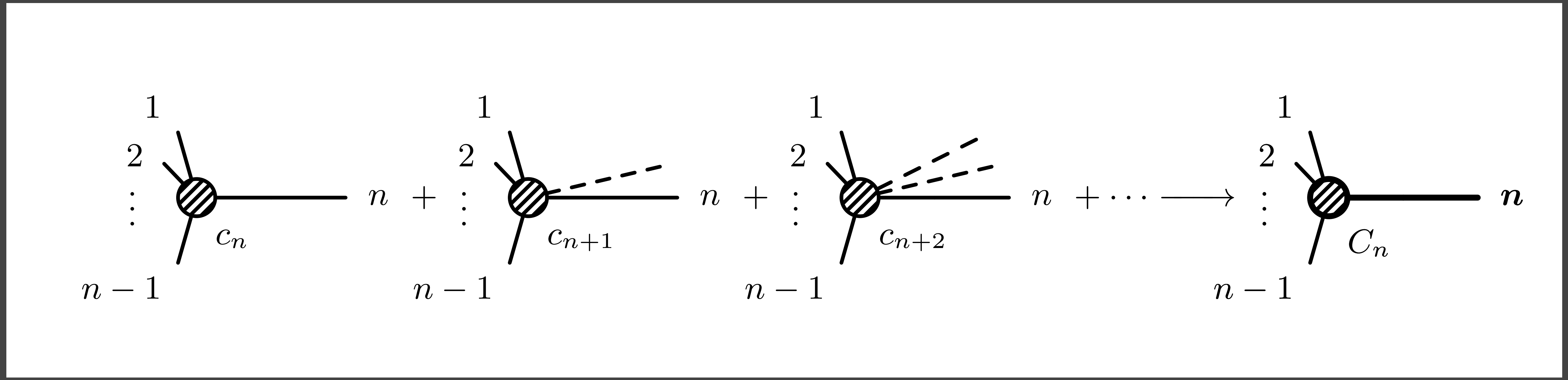
2 types of contributions to massive contact terms:

1) high-energy contact terms:
give $\mathcal{O}(v)$ corrections to C_i



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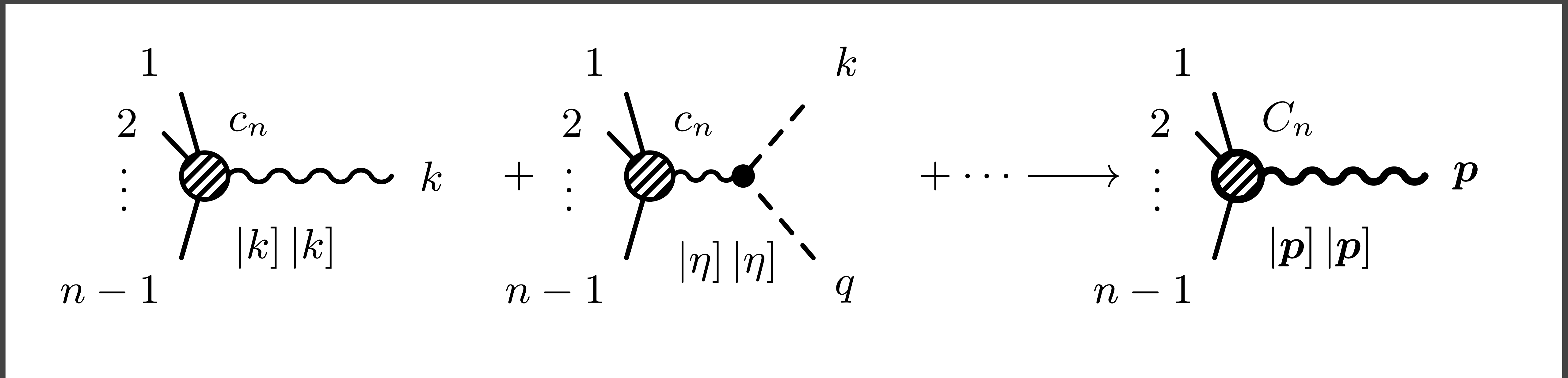
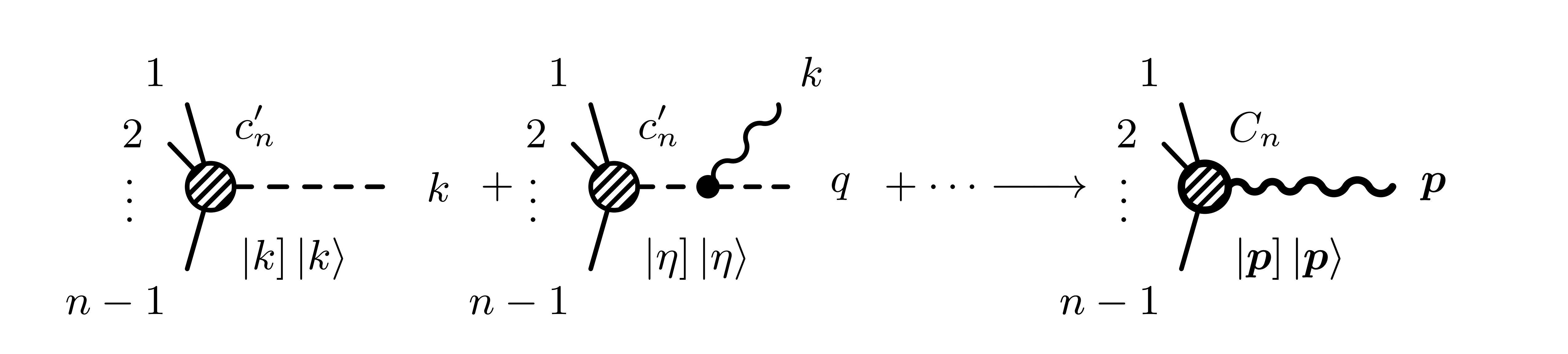
2) high-energy factorizable pieces: give subleading pieces of massive (bold) spinor structures

$\mathbf{p}]\mathbf{p}]$:



$\mathbf{p}]\mathbf{p}\rangle$:



SMEFT amplitudes from on-shell Higgsing

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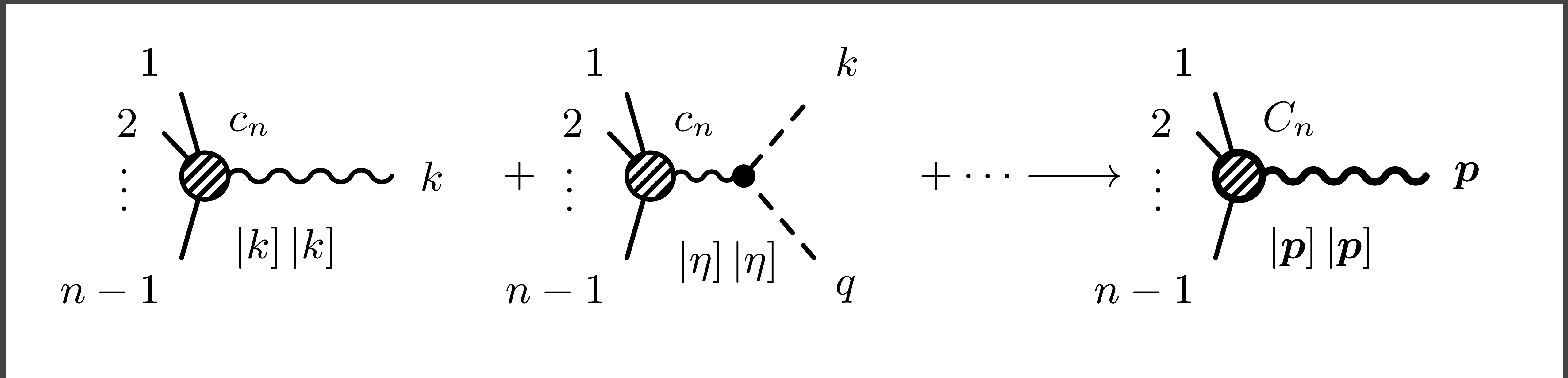
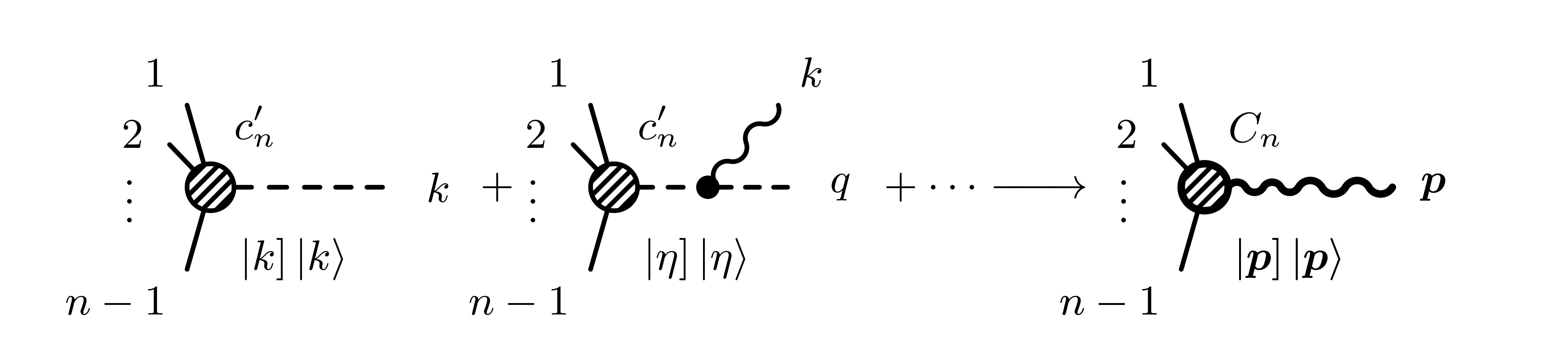


$\mathbf{p}]\mathbf{p}\rangle$:



soft Higgs leg supplies second lightlike momentum to form massive momentum

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

SMEFT amplitudes from on-shell Higgsing

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

SMEFT amplitudes from on-shell Higgsing

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in practice: to get massive contact-term: bold spinor structures = covariantize wrt massive LG

eg:

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

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

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

—> 2. massive *vector* $p_i = i]\langle i \;\to\; \mathbf{i}]\langle\mathbf{i}$ (longitudinal vector from Goldstone boson)

SMEFT amplitudes from on-shell Higgsing

Balkin Durieux Kitahara YS Weiss ’21
Liu Ma YS Waterbury, in progress

—> 4-point contact terms corresponding to the *SMEFT* at dim-6, 8

can compare with *most general* amplitudes

circumvents derivation of Feynman rules in broken phase: with everything given in terms of physical quantities

contact-terms are first (easy) step towards seeing Higgsing on-shell: ?extend to full amplitude

also derived all 3-points in a Higgsed U(1) toy model (from massless amplitudes with up to two additional Higgs legs)

to conclude:

lots of developments via amplitudes

some: relearning QFT we know: (different perspectives useful for anything of importance; hopefully also get to physics we don't know..)

eg: unbroken gauge symmetry from interactions of spin-1 particles (Lorentz, LG)

similarly for broken gauge symmetry: Higgsing as bolding = covariantizing wrt massive LG
(IR unification of massless amplitudes Arkani-Hamed et al '17)

one theory we don't know: underlying theory of EWSB: EFT parametrization

bootstrapping amplitudes: can captures most general EFTs/SMEFT (no field redifintions etc, purely physical)

model-independenl parametrization of LHC observables relating purely physical quantities:
help identify useful observables

De Angelis Durieux Grojean YS Waterbury in progress