On-shell contact terms

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#1912.08827 w/ G. Durieux

#2008.09652 w/ G. Durieux, T. Kitahara, Y. Shadmi, Y. Weiss

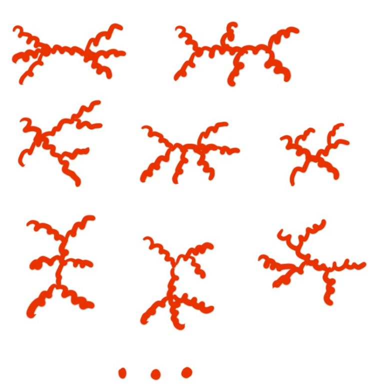
DESY.
מכון ויצמן למדע
WEIZMANN INSTITUTE OF SCIENCE

HEFT 2021

Amplitude program

↕

Avoid Lagrangians



Collider background

(gluons everywhere!)

→ Precision

Many loops and legs

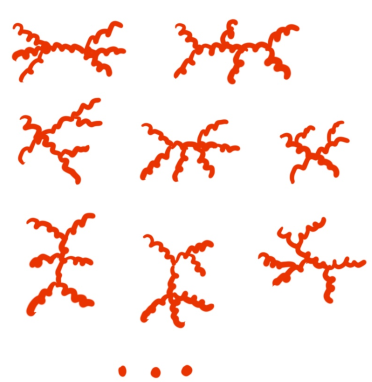
→ Insights

Hidden Mathematical structures

Amplitude program

↕

Avoid Lagrangians



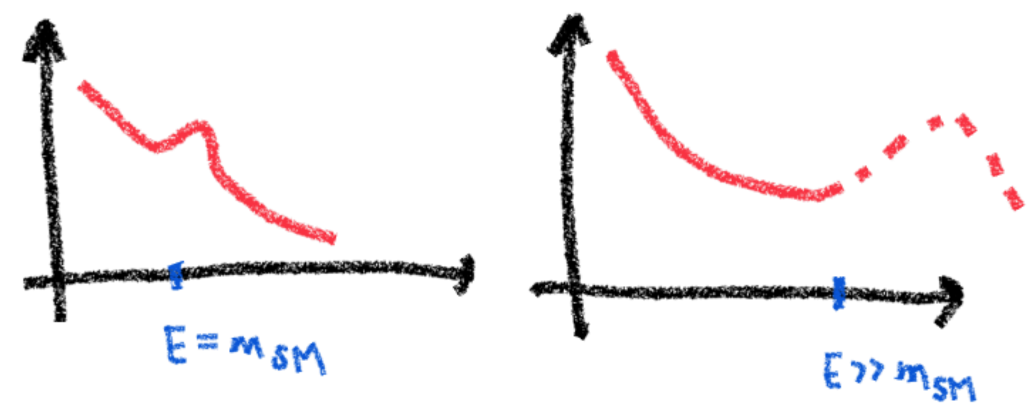
SM deviations

→ Precision

Many loops and legs

→ Insights

Hidden Mathematical structures



SM deviations → EFT

Smaller and smaller deviations allowed …

Beyond dim-8

See C. Murphy talk!

Processes with more legs

(linear vs non-linear SU(2)xU(1))

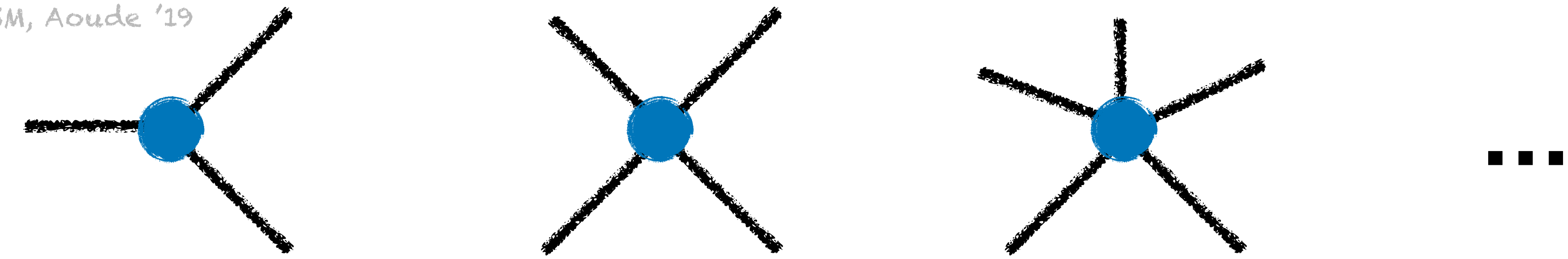
Henning, Lombardo, Riembau, Riva '19
Chang, Luty '20
Falkowski, Rattazzi '19
…

Thinking in the on-shell way may be a good idea!

On-shell-SMEFT

Lorentz symmetry, Locality, Unitarity

CSM, Aoude '19



Perturbative unitarity

Durieux, Kitahara, Shadmi, Weiss '20

Bottom-up approach

Include full v/Λ expansion

Outline

1. **Spinor basics**

(and how to go from massive to massless spinors)

2. **Massless contact terms**

3. **Massive contact terms**

Conclusions

Spinor Basics

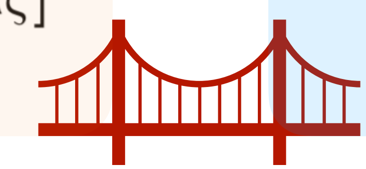
$\text{LG} = \text{U}(1)\text{, helicity}$

$$p_{\alpha\dot\beta} = \lambda_\alpha \tilde\lambda_{\dot\beta} \equiv |p\rangle_\alpha [p|_{\dot\beta}$$

$$\epsilon_+^\mu = \frac{\langle\zeta|\sigma^\mu|\lambda]}{\sqrt{2}\langle\lambda\zeta\rangle}, \qquad \epsilon_-^\mu = \frac{\langle\lambda|\sigma_\mu|\zeta]}{\sqrt{2}[\lambda\zeta]}$$

$\langle ij\rangle[ji] = s_{ij}$

UV



High-energy Limit

IR

$\text{LG} = \text{SU}(2)\text{, spins}$

$$\mathbf{p}_{\alpha\dot\beta} = \boldsymbol{\chi}_\alpha^I \epsilon_{IJ} \tilde{\boldsymbol{\chi}}_{\dot\beta}^J \equiv \epsilon_{IJ} |\mathbf{p}\rangle_\alpha^I [\mathbf{p}|_{\dot\beta}^J,$$

2s symmetrized spinors = spin-s

$$[\epsilon^\mu]^{JK} = \frac{1}{\sqrt{2}m} \langle \boldsymbol{\chi}^J|\sigma^\mu|\boldsymbol{\chi}^K]$$

bolding: $\langle\mathbf{13}\rangle\langle\mathbf{23}\rangle \propto \langle 1^I 3^J\rangle\langle 2^K 3^{J'}\rangle + \langle 1^I 3^{J'}\rangle\langle 2^K 3^J\rangle$

[Arkani-Hamed, T.-C.Huang, Y.t-Huang ’17]

$$\mathbf{p}^\mu = (E, P s_\theta c_\phi, P s_\theta s_\phi, P c_\theta)$$

$$\boldsymbol{\chi}_\alpha^I = \begin{pmatrix} \sqrt{E-P}\, c & -\sqrt{E+P}\, s^* \\ \sqrt{E-P}\, s & \sqrt{E+P}\, c \end{pmatrix}$$

$$\tilde{\boldsymbol{\chi}}_{\dot\beta}^J = \begin{pmatrix} \sqrt{E-P}\, c & -\sqrt{E+P}\, s \\ \sqrt{E-P}\, s^* & \sqrt{E+P}\, c \end{pmatrix}$$

$m/E \ll 1$ →

$$\langle\mathbf{12}\rangle^{\text{IJ}} \approx \begin{pmatrix} \left(1 - \frac{m_1^2}{8E_1^2} - \frac{m_2^2}{8E_2^2}\right)\langle 12\rangle & -\frac{m_2}{\sqrt{2E_2}}\langle 1\zeta_2^+\rangle \\ -\frac{m_1}{\sqrt{2E_1}}\langle\zeta_1^+ 2\rangle & \frac{m_1 m_2}{4E_1E_2}[12] \end{pmatrix}$$

$$[\mathbf{12}]^{\text{IJ}} \approx \begin{pmatrix} \frac{m_1 m_2}{4E_1E_2}\langle 12\rangle & -\frac{m_1}{\sqrt{2E_1}}[\zeta_1^+ 2] \\ -\frac{m_2}{\sqrt{2E_2}}[1\zeta_2^+] & \left(1 - \frac{m_1^2}{8E_1^2} - \frac{m_2^2}{8E_2^2}\right)[12] \end{pmatrix}$$

HE Limit = "Unbold"

$$\boldsymbol{p}_\mu = k_\mu + q_\mu$$

$$k_\mu = \frac{E+p}{2}(1,0,0,1)\,, \quad q_\mu = \frac{E-p}{2}(1,0,0,-1)$$

$$\sim E \qquad\qquad \sim \frac{m^2}{E}$$

$$\boldsymbol{p}_{\alpha\dot{\alpha}} = |k\rangle[k| + |q\rangle[q|$$

$$p^2 = \langle kq\rangle[qk] = m^2$$
$$p_k^2 = 0,\ p_q^2 = 0$$

$$|\mathbf{p}^1] = |k] \quad |\mathbf{p}^1\rangle = |q\rangle$$

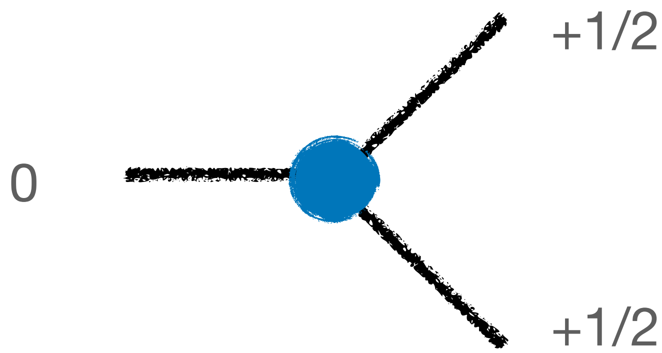
I=1 positive helicities

$$|\mathbf{p}^2\rangle = |k\rangle \quad |\mathbf{p}^2] = -|q]$$

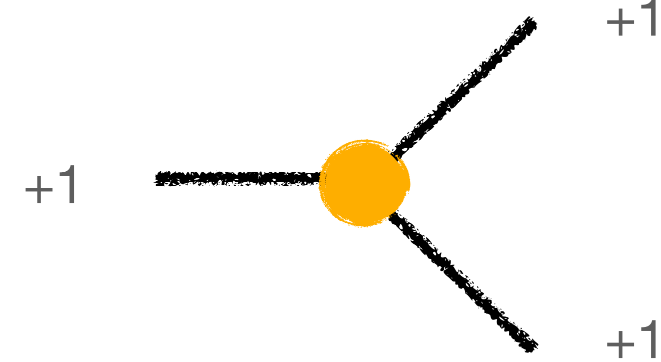
I=2 negative helicities

3-point amplitudes

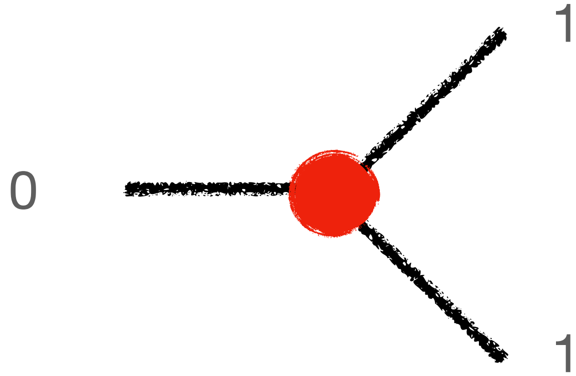
$[A_n] = 4 - n$



$$y\ [12]$$

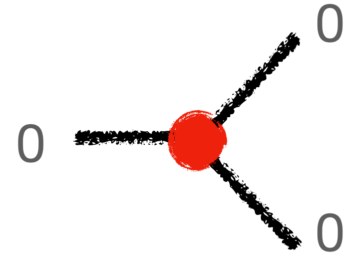


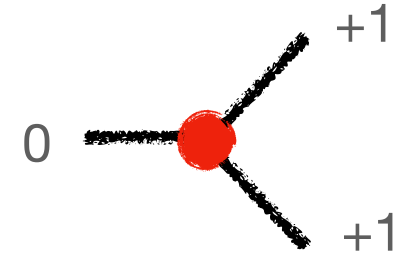
$$c_{F^3}\ \frac{[12][23][31]}{\Lambda^2}$$

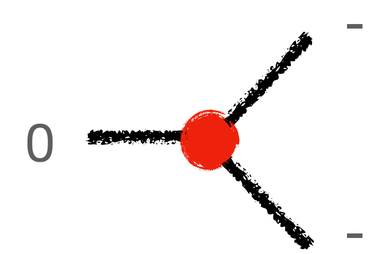


$$c_0\ \frac{\langle \mathbf{12} \rangle [\mathbf{12}]}{m} + c_+\ \frac{[\mathbf{12}]^2}{\Lambda} + c_-\ \frac{\langle \mathbf{12} \rangle^2}{\Lambda}$$

HE limit ↕ "unbold" ↕







EFT basis

Hilbert series

Henning, Xu, Melia, Murayama '16 '17 ...

On-shell methods

Elvang et al '10 ...
Cheung et al '16 ...
Low, Yin '19 ...
Shadmi, Weiss '18
Ma, Shu, Xiao '19
CSM, Durieux '19
Durieux, Kitahara, CSM, Weiss '19
Dong, Ma, Shu '21

Harmonics

Henning, Melia '19

Young Tensor

See Jiang-Hao Yu
Hao-Lin Li and Ming-Lei Xiao talks

Twistors

Falkowski '19

*not a complete list

Massless basis

(min. spinor structure) x $F(s_{ij})$

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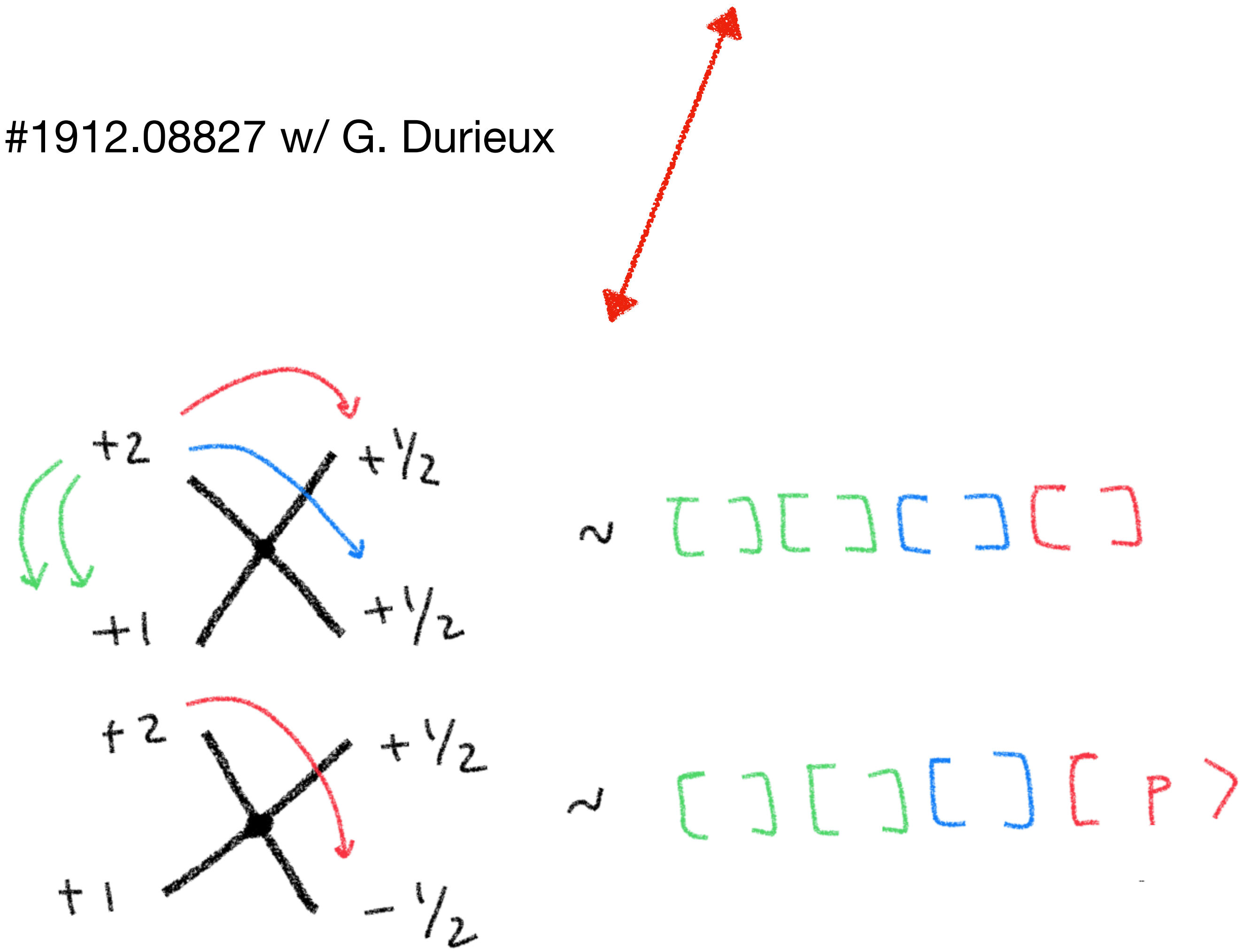

Massless basis

(min. spinor structure) x $F(s_{ij})$

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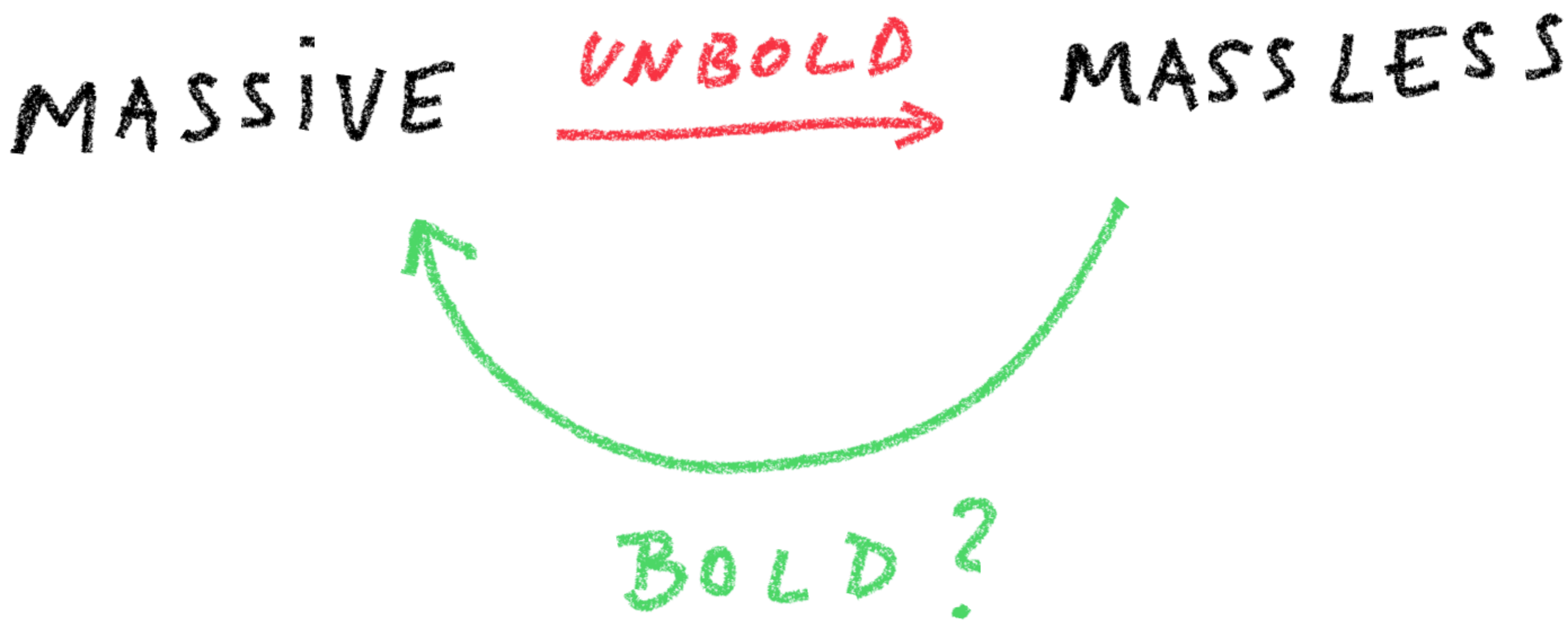
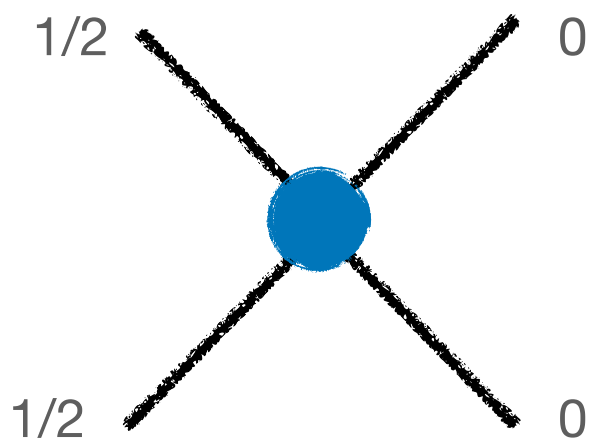
$$\dim\{\text{operator}\} \geq n - n_{\text{tensors}} + \sum_i |h_i| + \max \begin{bmatrix} \{\sum_{h_i>0} 2h_i\} \mod 2 \\ 2\max_{h_i>0}\{|2h_i|\} - \sum_{h_i>0} |2h_i| \\ 2\max_{h_i<0}\{|2h_i|\} - \sum_{h_i<0} |2h_i| \end{bmatrix}$$

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	$v^+v^+v^+s$	$[12][13][23]$
		$v^+v^+f^+f^+$	$[12]^2[34]$, $[12]([14][23]+[13][24])$
		$v^+v^+f^-f^-$	$[12]^2\langle 34\rangle$
		$v^+f^+f^-s$	$[12][123\rangle$
		v^+sss	$[1231]$
		$f^+f^+f^+f^-$	$[12][3(1-2)4\rangle$
	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	$[12]^2$
		$v^+f^+f^+ss$	$[12][13]$
		$f^+f^+f^+f^+s$	$[12][34]$, $[13][24]$
		$f^+f^+f^-f^-s$	$[12]\langle 34\rangle$
		f^+f^-sss	$[132\rangle$, $[142\rangle$
	dim-8	$v^+v^+v^+ss$	$[12][13][23]$
		$v^+v^+f^+f^+s$	$[12]^2[34]$, $[12]([14][23]+[13][24])$
		$v^+v^+f^-f^-s$	$[12]^2\langle 34\rangle$
		$v^+f^+f^+f^+f^+$	$[13][14][25]$, $[13][15][34]$, $[14][15][23]$
		$v^+f^+f^+f^-f^-$	$[12][13]\langle 45\rangle$
		$v^+f^+f^-ss$	$[12][143\rangle$, $[12][123\rangle$
		v^+ssss	$[1341]$, $[1241]$, $[1231]$
		$f^+f^+f^+f^-s$	$[13][234\rangle$, $[12][324\rangle$, $[12][314\rangle$
	…		


MASSIVE
UNBOLD
MASSLESS
BOLD?

Massive basis



$$(++00) \quad [12] \qquad D=5$$
$$(+-00) \quad [132\rangle \quad D=6$$

(+permutations)

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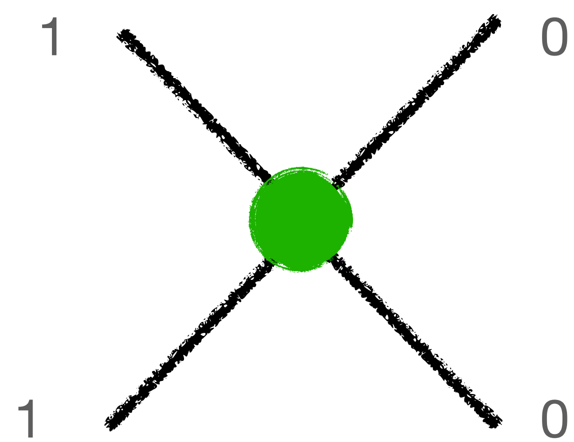
Bolding

$$\mathbf{[12] + [132\rangle}$$ (+permutations)

Minimal spinor structures

Massive basis



$$\begin{aligned}
&(0000) && [12]\langle 12\rangle,\ [131\rangle[232\rangle \\
&(+000) && [12][132\rangle \\
&(++00) && [12]^2 \\
&(+-00) && [132\rangle^2,\ [231\rangle^2
\end{aligned}$$

(+permutations)

#2008.09652
w/ G. Durieux, T. Kitahara,
Y. Shadmi, Y. Weiss

Bolding

$$[\mathbf{12}]\langle\mathbf{12}\rangle + [\mathbf{12}][\mathbf{132}\rangle + [\mathbf{12}]^2 + [\mathbf{132}\rangle^2 + [\mathbf{231}\rangle^2$$

Minimal spinor structures ? !

Massive basis

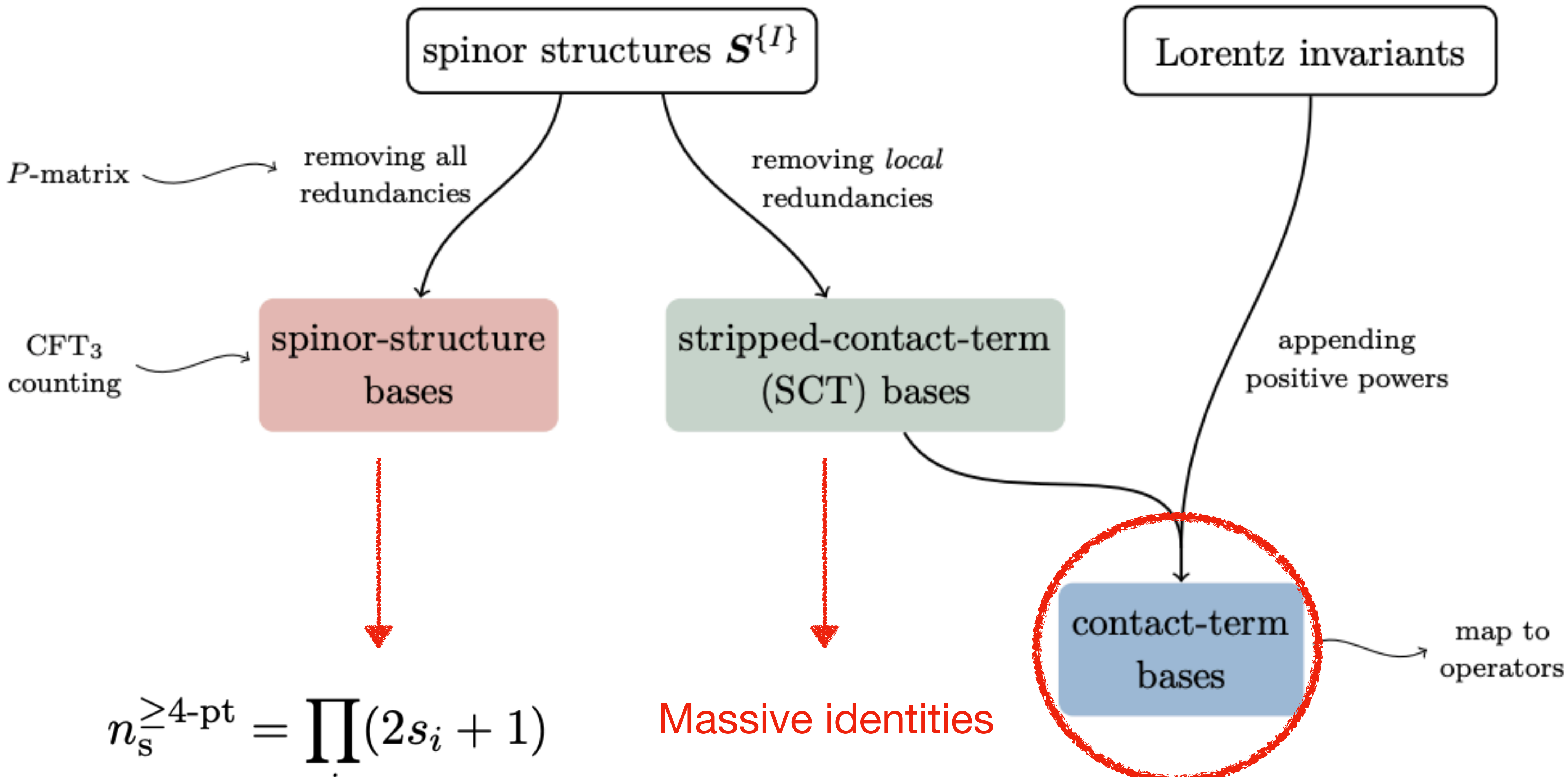
$$[12]\langle 12\rangle \tilde{s}_{13}\tilde{s}_{23} + [131\rangle[232\rangle \tilde{s}_{12} = 0$$

↓

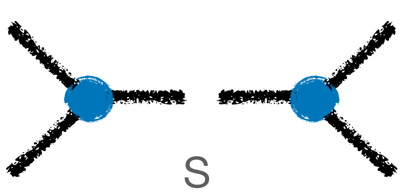
$$\begin{aligned}[\mathbf{132}\rangle^2 + [\mathbf{231}\rangle^2 = &+ [\mathbf{12}]\langle\mathbf{12}\rangle\tilde{s}_{13}\tilde{s}_{23}/m_1m_2 \\ &+ [\mathbf{131}\rangle[\mathbf{232}\rangle\tilde{s}_{12}/m_1m_2 \\ &+ ([\mathbf{12}][\mathbf{132}\rangle + \langle\mathbf{12}\rangle[\mathbf{231}\rangle)\tilde{s}_{23}/m_2 \\ &- ([\mathbf{12}][\mathbf{231}\rangle + \langle\mathbf{12}\rangle[\mathbf{132}\rangle)\tilde{s}_{13}/m_1 \\ &- ([\mathbf{12}]^2 + \langle\mathbf{12}\rangle^2)m_3^2\,.\end{aligned}$$

Massive identities

Massive basis



$$n_{\rm s}^{\geq 4\text{-pt}} = \prod_i (2s_i + 1)$$



Massive identities

$$\boldsymbol{\varepsilon}_i \equiv \sqrt{2}\, \boldsymbol{i}\rangle[\boldsymbol{i}\, / m_i$$

(Keep operators of lower dimensions)

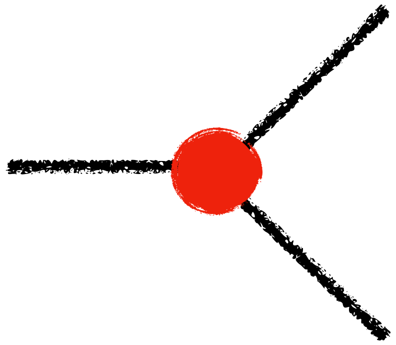
Massive basis

spins	n_{SCT}	n_{s}	hel. cat.	spinor structures	n_{perm}	$\min\{d_{\mathrm{op}}\}$
$ssss$	1	1	(0000)	constant	1	4
$vsss$	$4 \to 3$	3	(0000)	$[\mathbf{121}\rangle, [\mathbf{131}\rangle$	1	5
			(+000)	$[\mathbf{1231}] \to [\mathbf{1231}] - \langle\mathbf{1231}\rangle$	$\not{2} \to 1$	7
$ffss$	4	4	(++00)	$[\mathbf{12}]$	2	5
			(+−00)	$[\mathbf{132}\rangle$	2	6
$vvss$	$10 \to 9$	9	(0000)	$[\mathbf{12}]\langle\mathbf{12}\rangle, [\mathbf{131}\rangle[\mathbf{232}\rangle$	1	4,6
			(+000)	$[\mathbf{12}][\mathbf{132}\rangle$	4	6
			(++00)	$[\mathbf{12}]^2$	2	6
			(+−00)	$[\mathbf{132}\rangle^2 \to [\mathbf{132}\rangle^2 - \langle\mathbf{132}]^2$	$\not{2} \to 1$	8
$ffvs$	$14 \to 12$	12	(++00)	$[\mathbf{12}]\{[\mathbf{313}\rangle, [\mathbf{323}\rangle\}$	2	6
			(+−00)	$[\mathbf{13}]\langle\mathbf{23}\rangle$	2	5
			(+++0)	$[\mathbf{13}][\mathbf{23}]$	2	6
			(++−0)	$[\mathbf{12}]\langle\mathbf{3123}\rangle \to \varnothing$	$\not{2} \to 0$	8
			(+−+0)	$[\mathbf{13}][\mathbf{312}\rangle$	4	7

3-point amplitudes with $s \leq 3$

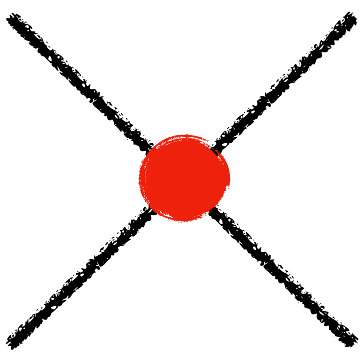
4-point amplitudes with $s \leq 1$

Massive identities



$$m_1\langle \mathbf{12}\rangle\langle \mathbf{13}\rangle[\mathbf{23}] + m_2\langle \mathbf{12}\rangle[\mathbf{13}]\langle \mathbf{23}\rangle + m_3[\mathbf{12}]\langle \mathbf{13}\rangle\langle \mathbf{23}\rangle$$
$$= m_1[\mathbf{12}][\mathbf{13}]\langle \mathbf{23}\rangle + m_2[\mathbf{12}]\langle \mathbf{13}\rangle[\mathbf{23}] + m_3\langle \mathbf{12}\rangle[\mathbf{13}][\mathbf{23}]$$

$$n^{\text{3-pt}} = \begin{cases} \dfrac{\prod_i (2s_i+1)}{2\max_j(s_j)+1} & \text{if } \sum\limits_i s_i - 2\max\limits_j(s_j) \le 0\,, \\ \prod\limits_j(\sum\limits_i s_i - 2s_j + 1) - \prod\limits_j(\sum\limits_i s_i - 2s_j) & \text{if } \sum\limits_i s_i - 2\max\limits_j(s_j) \ge 0\,. \end{cases}$$



$$\tilde{s}_{12}\; i\,\epsilon(\boldsymbol{\varepsilon_1},\boldsymbol{\varepsilon_2},\boldsymbol{\varepsilon_3},\boldsymbol{\varepsilon_4})\; m_1m_2m_3m_4$$
$$= \tilde{s}_{12}\,\{\,[\mathbf{12}][\mathbf{34}]\langle\mathbf{13}\rangle\langle\mathbf{24}\rangle - \langle\mathbf{12}\rangle\langle\mathbf{34}\rangle[\mathbf{13}][\mathbf{24}]\,\}$$
$$= +\langle\mathbf{12}\rangle\langle\mathbf{34}\rangle\,\{\,m_1\langle\mathbf{123}][\mathbf{24}] + m_2\langle\mathbf{213}][\mathbf{14}] - m_3\langle\mathbf{324}][\mathbf{12}] - m_4\langle\mathbf{423}][\mathbf{12}]\,\}$$
$$-[\mathbf{12}][\mathbf{34}]\,\{\,m_1[\mathbf{123}\rangle\langle\mathbf{24}\rangle + m_2[\mathbf{213}\rangle\langle\mathbf{14}\rangle - m_3[\mathbf{324}\rangle\langle\mathbf{12}\rangle - m_4[\mathbf{423}\rangle\langle\mathbf{12}\rangle\}$$

$$[\mathbf{1231}] + \langle\mathbf{1231}\rangle = (\tilde{s}_{13}[\mathbf{121}\rangle - \tilde{s}_{12}[\mathbf{131}\rangle)/m_1$$

$$\langle\mathbf{12}\rangle\langle\mathbf{341}][\mathbf{23}] + [\mathbf{12}][\mathbf{341}\rangle\langle\mathbf{23}\rangle = -[\mathbf{12}][\mathbf{343}\rangle\langle\mathbf{12}\rangle + [\mathbf{13}][\mathbf{242}\rangle\langle\mathbf{13}\rangle - [\mathbf{23}][\mathbf{141}\rangle\langle\mathbf{23}\rangle$$

$$\mathbf{1}][\mathbf{23}] - [\mathbf{12}][\mathbf{341}\rangle\langle\mathbf{23}\rangle = m_1(\langle\mathbf{12}\rangle\langle\mathbf{13}\rangle[\mathbf{23}] - [\mathbf{12}][\mathbf{13}]\langle\mathbf{23}\rangle)$$
$$+ m_2(\langle\mathbf{12}\rangle[\mathbf{13}]\langle\mathbf{23}\rangle - [\mathbf{12}]\langle\mathbf{13}\rangle[\mathbf{23}])$$
$$+ m_3([\mathbf{12}]\langle\mathbf{13}\rangle\langle\mathbf{23}\rangle - \langle\mathbf{12}\rangle[\mathbf{13}][\mathbf{23}])\,.$$

$$[\mathbf{132}\rangle^2 + [\mathbf{231}\rangle^2 = +[\mathbf{12}]\langle\mathbf{12}\rangle\tilde{s}_{13}\tilde{s}_{23}/m_1m_2$$
$$+ [\mathbf{131}\rangle[\mathbf{232}\rangle\tilde{s}_{12}/m_1m_2$$
$$+ ([\mathbf{12}][\mathbf{132}\rangle + \langle\mathbf{12}\rangle[\mathbf{231}\rangle)\tilde{s}_{23}/m_2$$
$$- ([\mathbf{12}][\mathbf{231}\rangle + \langle\mathbf{12}\rangle[\mathbf{132}\rangle)\tilde{s}_{13}/m_1$$
$$- ([\mathbf{12}]^2 + \langle\mathbf{12}\rangle^2)m_3^2\,.$$

$$0 = (\tilde{s}_{24} + m_2^2)\;[\mathbf{12}][\mathbf{34}] + \tilde{s}_{12}\;[\mathbf{13}][\mathbf{24}]$$
$$+ m_1\langle\mathbf{123}][\mathbf{24}] + m_2\langle\mathbf{213}][\mathbf{14}] - m_3\langle\mathbf{324}][\mathbf{12}] - m_4\langle\mathbf{423}][\mathbf{12}]$$

$$\langle\mathbf{12}\rangle\langle\mathbf{213}][\mathbf{14}]/m_1 + \langle\mathbf{12}\rangle\langle\mathbf{123}][\mathbf{24}]/m_2$$
$$= \langle\mathbf{12}\rangle\langle\mathbf{324}][\mathbf{12}]m_3/m_1m_2 + \langle\mathbf{12}\rangle\langle\mathbf{423}][\mathbf{12}]m_4/m_1m_2$$
$$- \langle\mathbf{12}\rangle[\mathbf{12}][\mathbf{34}](\tilde{s}_{24} + m_2^2)/m_1m_2 - \langle\mathbf{12}\rangle[\mathbf{13}][\mathbf{24}]\tilde{s}_{12}/m_1m_$$

$$[\mathbf{12}]^2\langle\mathbf{34}\rangle\langle\mathbf{314}]/m_4 + [\mathbf{13}]^2\langle\mathbf{24}\rangle\langle\mathbf{214}]/m_4 + [\mathbf{14}]^2\langle\mathbf{23}\rangle\langle\mathbf{213}]/m_3 =$$
$$- [\mathbf{13}][\mathbf{24}]\langle\mathbf{12}\rangle\langle\mathbf{34}\rangle(m_4^2 + \tilde{s}_{14})m_1/m_2m_3m_4$$
$$+ [\mathbf{14}]([\mathbf{12}][\mathbf{23}]\langle\mathbf{34}\rangle(m_4^2 - m_3^2) + [\mathbf{13}][\mathbf{23}]\langle\mathbf{24}\rangle m_2m_3 + [\mathbf{13}][\mathbf{24}]\langle\mathbf{23}\rangle m_2m_4)/m_3m_4$$
$$+ \langle\mathbf{34}\rangle([\mathbf{12}][\mathbf{34}]\langle\mathbf{241}](m_2^2 + \tilde{s}_{24}) + [\mathbf{13}][\mathbf{24}]\langle\mathbf{241}](m_2^2 + \tilde{s}_{12}) - [\mathbf{23}][\mathbf{24}]\langle\mathbf{141}]m_1m_2)/m_2 m$$
$$+ \langle\mathbf{34}\rangle([\mathbf{12}]\langle\mathbf{24}\rangle\langle\mathbf{123}]m_4 - [\mathbf{14}]\langle\mathbf{12}\rangle\langle\mathbf{243}]m_2 - [\mathbf{24}]\langle\mathbf{12}\rangle\langle\mathbf{143}]m_1 - [\mathbf{24}]\langle\mathbf{12}\rangle\langle\mathbf{341}]m_3)m$$
$$- ([\mathbf{12}][\mathbf{13}]\langle\mathbf{24}\rangle\langle\mathbf{34}\rangle\tilde{s}_{23}m_4 - [\mathbf{12}][\mathbf{14}]\langle\mathbf{23}\rangle\langle\mathbf{34}\rangle(m_2^2 + \tilde{s}_{24})m_3 - [\mathbf{12}][\mathbf{24}]\langle\mathbf{13}\rangle\langle\mathbf{34}\rangle m_1m_2m$$
$$+ [\mathbf{13}][\mathbf{14}]\langle\mathbf{23}\rangle\langle\mathbf{24}\rangle(m_4^2 + m_3^2 + \tilde{s}_{34})m_2 - [\mathbf{13}][\mathbf{34}]\langle\mathbf{12}\rangle\langle\mathbf{24}\rangle m_1m_2m_3 + [\mathbf{14}][\mathbf{34}]\langle\mathbf{12}\rangle\langle$$

$$[\mathbf{13}]\langle\mathbf{24}\rangle\langle\mathbf{231}] + [\mathbf{23}]\langle\mathbf{14}\rangle\langle\mathbf{132}] =$$
$$- ([\mathbf{13}]\langle\mathbf{24}\rangle\langle\mathbf{132}](m_1^2 + \tilde{s}_{14}) + [\mathbf{23}]\langle\mathbf{14}\rangle\langle\mathbf{231}](m_1^2 + \tilde{s}_{13}))/m_1m_2$$
$$+ [\mathbf{12}]([\mathbf{13}]\langle\mathbf{24}\rangle\tilde{s}_{23}/m_2 - [\mathbf{23}]\langle\mathbf{14}\rangle\tilde{s}_{13}/m_1)$$
$$+ [\mathbf{12}]\langle\mathbf{13}\rangle\langle\mathbf{24}\rangle(m_1^2 + \tilde{s}_{14})m_3/m_1m_2$$
$$- [\mathbf{12}]\langle\mathbf{24}\rangle\langle\mathbf{321}]m_3/m_2 + [\mathbf{34}]\langle\mathbf{12}\rangle\langle\mathbf{132}]m_4/m_2$$
$$- \langle\mathbf{12}\rangle([\mathbf{23}]\langle\mathbf{14}\rangle m_3 + [\mathbf{24}]\langle\mathbf{13}\rangle m_4)m_3/m_2$$
$$- [\mathbf{14}][\mathbf{23}]\langle\mathbf{12}\rangle\tilde{s}_{13}m_4/m_1m_2\,.$$

$$[\mathbf{12}][\mathbf{13}][\mathbf{23}]\langle\mathbf{4234}\rangle =$$
$$+[\mathbf{12}][\mathbf{14}][\mathbf{23}]\langle\mathbf{34}\rangle\tilde{s}_{24}m_3/m_4 - [\mathbf{13}][\mathbf{14}][\mathbf{23}]\langle\mathbf{24}\rangle(\tilde{s}_{34} + m_4^2)m_2/m_4 - [\mathbf{13}][\mathbf{23}][\mathbf{24}]\langle\mathbf{14}\rangle(\tilde{s}_{34} + m_4^2)m_1/m_4$$
$$+[\mathbf{12}][\mathbf{23}][\mathbf{34}]\langle\mathbf{431}]\tilde{s}_{24}/m_4 + [\mathbf{13}][\mathbf{23}][\mathbf{24}]\langle\mathbf{431}](\tilde{s}_{34} + m_4^2)/m_4 - [\mathbf{13}][\mathbf{14}][\mathbf{23}]\langle\mathbf{214}]m_2 - [\mathbf{13}][\mathbf{23}][\mathbf{24}]\langle\mathbf{124}]m_1$$
$$-[\mathbf{13}][\mathbf{14}][\mathbf{23}][\mathbf{24}](m_3^2 - m_2^2 - m_1^2)\,.$$

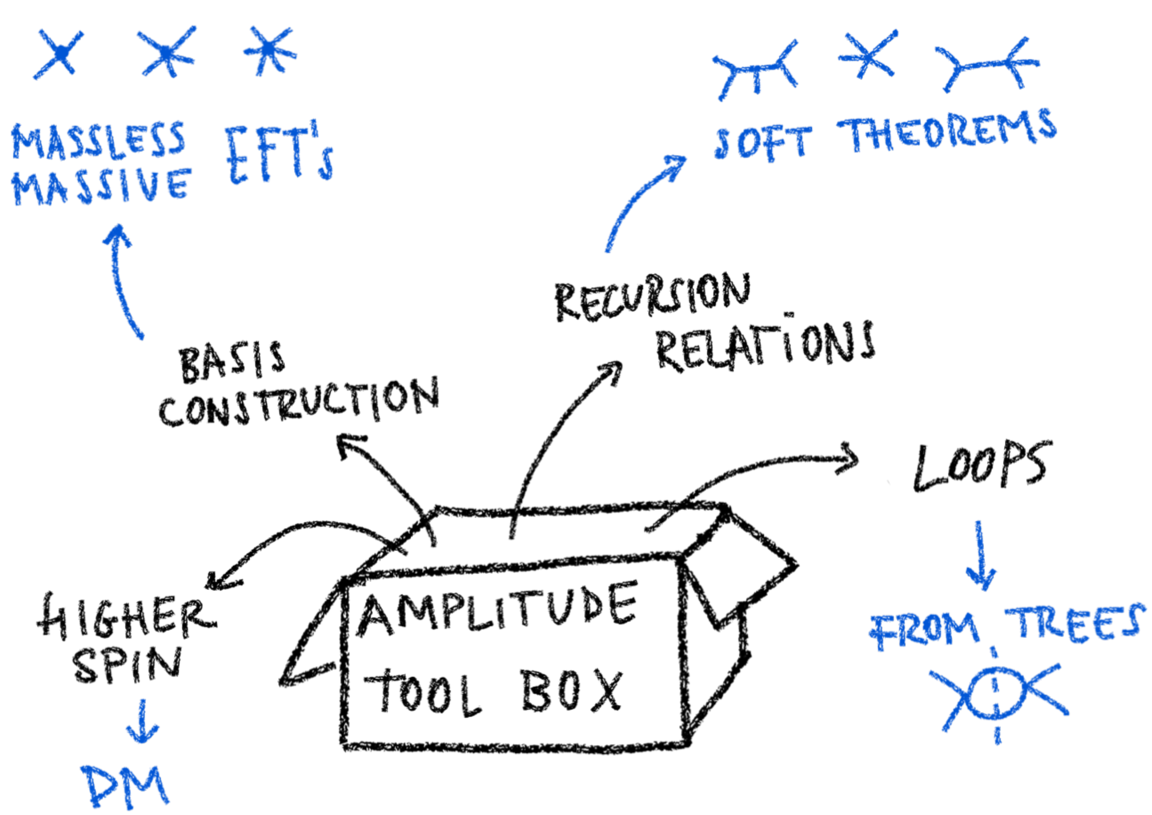
EW particle content

Broken phase: h, ψ, ψ', $W^{\pm}$, Z

$\boldsymbol{vsss}$ The only electroweak particle content possible for massive $vsss$ amplitudes is $Zhhh$. In the (0000) helicity category, the Bose symmetrization for the three scalars does not allow for a $[\mathbf{121}\rangle/m_1 + \text{perm.}$ structure that would have corresponded to an operator of dimension five. The first amplitudes therefore arise at dimension seven. An example is the manifestly symmetric $\tilde{s}_{34}[\mathbf{121}\rangle/m_1 + \tilde{s}_{24}[\mathbf{131}\rangle/m_1 + \tilde{s}_{23}[\mathbf{141}\rangle/m_1$ combination. Note that in the (+000) category, the $[\mathbf{1231}] - \langle\mathbf{1231}\rangle$ structure also vanishes upon symmetrization given its antisymmetry under the exchange of all three scalars. This can easily be seen when expressing it as $\epsilon(\boldsymbol{\varepsilon}_1, p_2, p_3, p_4)$ by using momentum conservation to eliminate p_1 in eq. (20). An antisymmetric combination of Mandelstam invariants like $(\tilde{s}_{12}-\tilde{s}_{13})(\tilde{s}_{12}-\tilde{s}_{14})(\tilde{s}_{13}-\tilde{s}_{14})$ could be used to form a contact term of dimension thirteen.

Conclusion

- First steps towards the on-shell-SMEFT
- Systematic construction of contact terms (massless/massive)
- It can be used to compute any 2-2 scattering process
- Applications beyond collider physics
  (massive contact terms were recently used to compute gravitational tidal effects)



Thank you!