Amplitudes meet BSM pheno

Alex Pomarol, IFAE & UAB (Barcelona)

of course, not the first encounter…

Amplitude methods

Extremely useful for simplifying calculations

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Example: graviton + graviton → graviton + graviton

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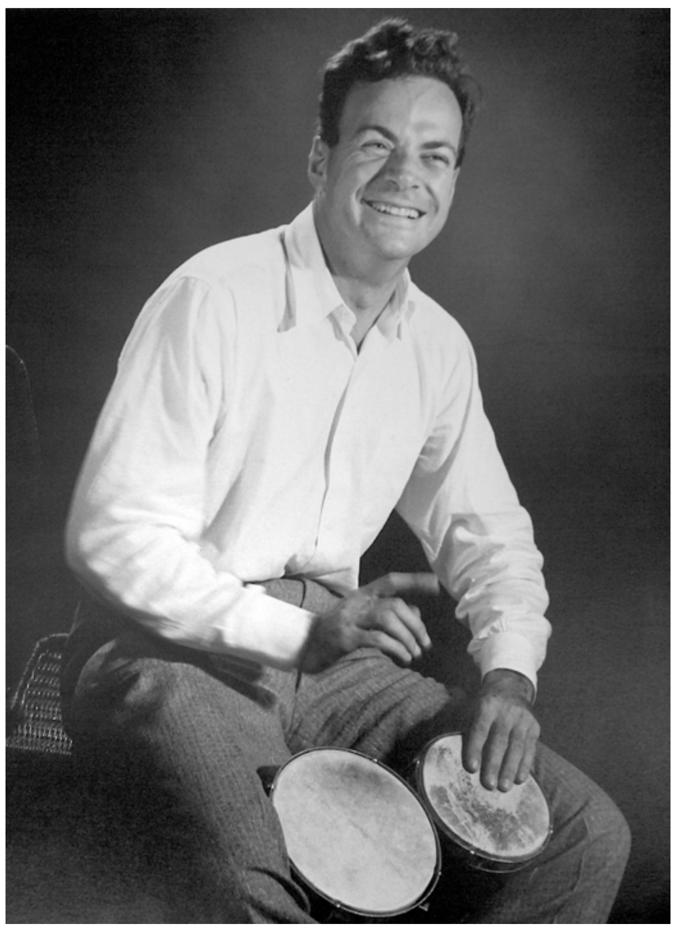

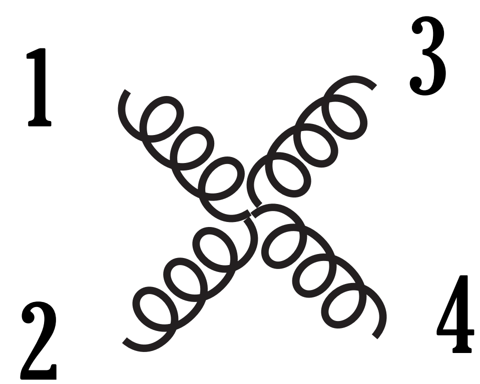

à la Feynman !

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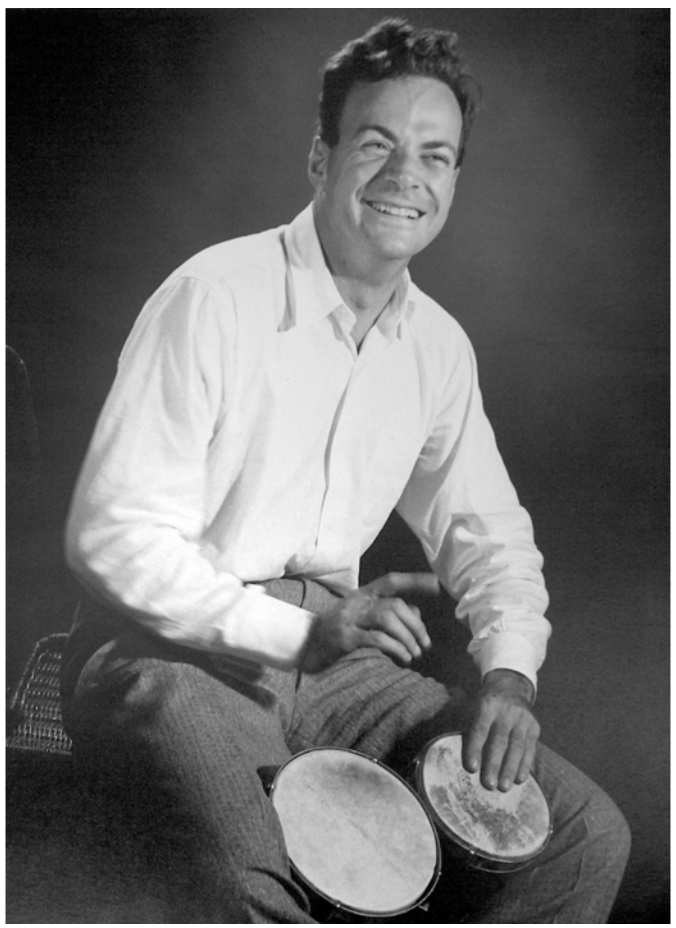

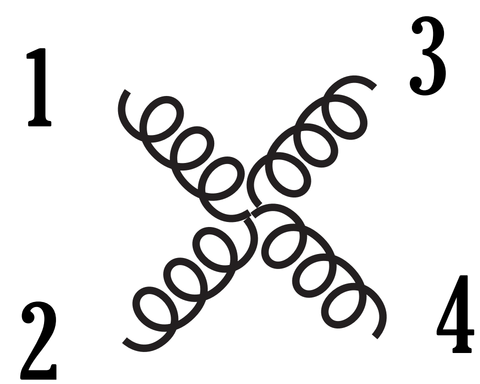

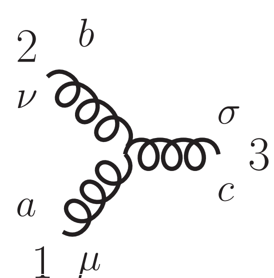

$$
\begin{aligned}
& i\mathrm{Sym}\Big[-\frac{1}{2}P_3(p_1\cdot p_2\eta_{\mu\rho}\eta_{\nu\lambda}\eta_{\sigma\tau}) - \frac{1}{2}P_6(p_{1\nu}p_{1\lambda}\eta_{\mu\rho}\eta_{\sigma\tau}) + \frac{1}{2}P_3(p_1\cdot p_2\eta_{\mu\nu}\eta_{\rho\lambda}\eta_{\sigma\tau}) \\
&\quad + P_6(p_1\cdot p_2\eta_{\mu\rho}\eta_{\nu\sigma}\eta_{\lambda\tau}) + 2P_3(p_{1\nu}p_{1\tau}\eta_{\mu\rho}\eta_{\lambda\sigma}) - P_3(p_{1\lambda}p_{2\mu}\eta_{\rho\nu}\eta_{\sigma\tau}) \\
&\quad + P_3(p_{1\sigma}p_{2\tau}\eta_{\mu\nu}\eta_{\rho\lambda}) + P_6(p_{1\sigma}p_{1\tau}\eta_{\mu\nu}\eta_{\rho\lambda}) + 2P_6(p_{1\nu}p_{2\tau}\eta_{\lambda\mu}\eta_{\rho\sigma}) \\
&\quad + 2P_3(p_{1\nu}p_{2\mu}\eta_{\lambda\sigma}\eta_{\tau\rho}) - 2P_3(p_1\cdot p_2\eta_{\rho\nu}\eta_{\lambda\sigma}\eta_{\tau\mu})\Big],
\end{aligned}
$$

à la Feynman !

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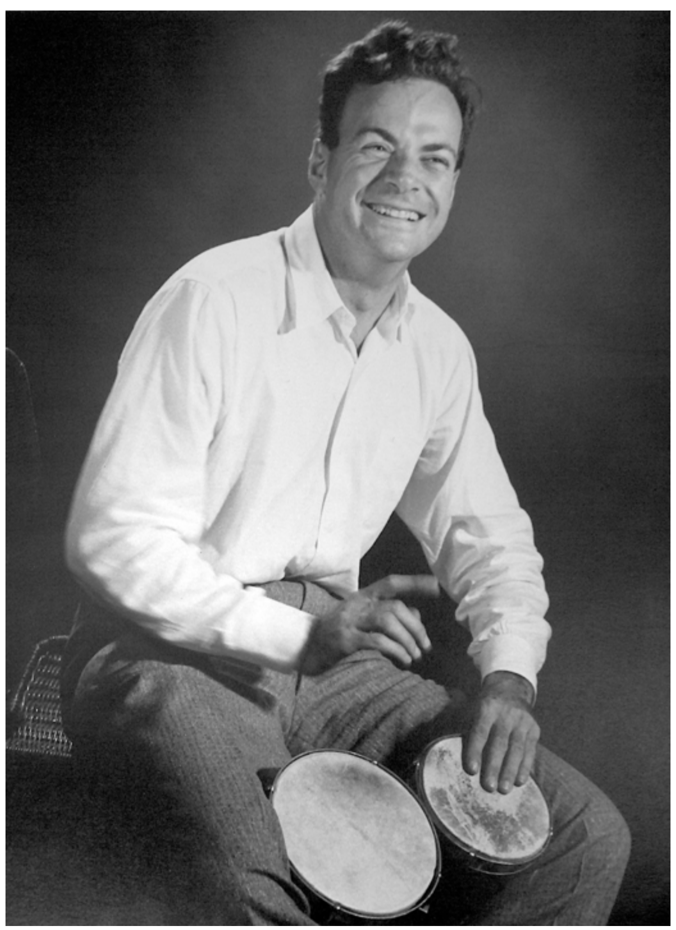

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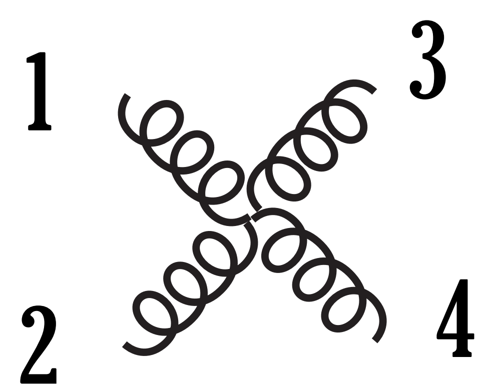
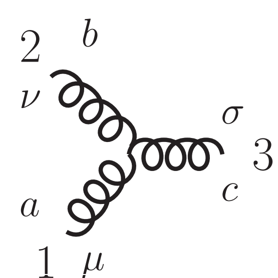
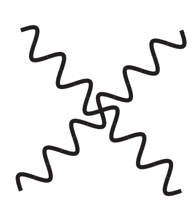




$$
\begin{aligned}
i\mathrm{Sym}\Big[&-\frac{1}{2}P_3(p_1\cdot p_2\eta_{\mu\rho}\eta_{\nu\lambda}\eta_{\sigma\tau}) - \frac{1}{2}P_6(p_{1\nu}p_{1\lambda}\eta_{\mu\rho}\eta_{\sigma\tau}) + \frac{1}{2}P_3(p_1\cdot p_2\eta_{\mu\nu}\eta_{\rho\lambda}\eta_{\sigma\tau})\\
&+ P_6(p_1\cdot p_2\eta_{\mu\rho}\eta_{\nu\sigma}\eta_{\lambda\tau}) + 2P_3(p_{1\nu}p_{1\tau}\eta_{\mu\rho}\eta_{\lambda\sigma}) - P_3(p_{1\lambda}p_{2\mu}\eta_{\rho\nu}\eta_{\sigma\tau})\\
&+ P_3(p_{1\sigma}p_{2\tau}\eta_{\mu\nu}\eta_{\rho\lambda}) + P_6(p_{1\sigma}p_{1\tau}\eta_{\mu\nu}\eta_{\rho\lambda}) + 2P_6(p_{1\nu}p_{2\tau}\eta_{\lambda\mu}\eta_{\rho\sigma})\\
&+ 2P_3(p_{1\nu}p_{2\mu}\eta_{\lambda\sigma}\eta_{\tau\rho}) - 2P_3(p_1\cdot p_2\eta_{\rho\nu}\eta_{\lambda\sigma}\eta_{\tau\mu})\Big],
\end{aligned}
$$



$$
\begin{aligned}
\mathrm{Sym}[&-\tfrac{1}{8}P_6(p\cdot p'\eta^{\mu\nu}\eta^{\sigma\tau}\eta^{\rho\lambda}\eta^{\iota\kappa})-\tfrac{1}{8}P_{12}(p^\sigma p^\tau\eta^{\mu\nu}\eta^{\rho\lambda}\eta^{\iota\kappa})-\tfrac{1}{4}P_6(p^\sigma p'^\mu\eta^{\nu\tau}\eta^{\rho\lambda}\eta^{\iota\kappa})+\tfrac{1}{8}P_6(p\cdot p'\eta^{\mu\sigma}\eta^{\nu\tau}\eta^{\rho\lambda}\eta^{\iota\kappa})\\
&+\tfrac{1}{4}P_6(p\cdot p'\eta^{\mu\nu}\eta^{\sigma\tau}\eta^{\rho\iota}\eta^{\lambda\kappa})+\tfrac{1}{4}P_{12}(p^\sigma p^\tau\eta^{\mu\nu}\eta^{\rho\iota}\eta^{\lambda\kappa})+\tfrac{1}{2}P_6(p^\sigma p'^\mu\eta^{\nu\tau}\eta^{\rho\iota}\eta^{\lambda\kappa})-\tfrac{1}{4}P_6(p\cdot p'\eta^{\mu\sigma}\eta^{\nu\tau}\eta^{\rho\iota}\eta^{\lambda\kappa})\\
&+\tfrac{1}{4}P_{24}(p\cdot p'\eta^{\mu\nu}\eta^{\sigma\rho}\eta^{\tau\lambda}\eta^{\iota\kappa})+\tfrac{1}{4}P_{24}(p^\sigma p^\tau\eta^{\mu\rho}\eta^{\nu\lambda}\eta^{\iota\kappa})+\tfrac{1}{4}P_{12}(p^\rho p'^\lambda\eta^{\mu\sigma}\eta^{\nu\tau}\eta^{\iota\kappa})+\tfrac{1}{2}P_{24}(p^\sigma p'^\rho\eta^{\tau\mu}\eta^{\nu\lambda}\eta^{\iota\kappa})\\
&-\tfrac{1}{2}P_{12}(p\cdot p'\eta^{\nu\sigma}\eta^{\tau\rho}\eta^{\lambda\mu}\eta^{\iota\kappa})-\tfrac{1}{2}P_{12}(p^\sigma p'^\mu\eta^{\tau\rho}\eta^{\lambda\nu}\eta^{\iota\kappa})+\tfrac{1}{2}P_{12}(p^\sigma p^\rho\eta^{\tau\lambda}\eta^{\mu\nu}\eta^{\iota\kappa})-\tfrac{1}{2}P_{24}(p\cdot p'\eta^{\mu\nu}\eta^{\tau\rho}\eta^{\lambda\iota}\eta^{\kappa\sigma})\\
&-P_{12}(p^\sigma p^\tau\eta^{\nu\rho}\eta^{\lambda\iota}\eta^{\kappa\mu})-P_{12}(p^\rho p'^\lambda\eta^{\nu\iota}\eta^{\kappa\sigma}\eta^{\tau\mu})-P_{24}(p_\sigma p'^\rho\eta^{\tau\iota}\eta^{\kappa\mu}\eta^{\nu\lambda})-P_{12}(p^\rho p'^\iota\eta^{\lambda\sigma}\eta^{\tau\mu}\eta^{\nu\kappa})\\
&+P_6(p\cdot p'\eta^{\nu\rho}\eta^{\lambda\sigma}\eta^{\tau\iota}\eta^{\kappa\mu})-P_{12}(p^\sigma p^\rho\eta^{\mu\nu}\eta^{\tau\iota}\eta^{\kappa\lambda})-\tfrac{1}{2}P_{12}(p\cdot p'\eta^{\mu\rho}\eta^{\nu\lambda}\eta^{\sigma\iota}\eta^{\tau\kappa})-P_{12}(p^\sigma p^\rho\eta^{\tau\lambda}\eta^{\mu\iota}\eta^{\nu\kappa})\\
&\qquad-P_6(p^\rho p'^\iota\eta^{\lambda\kappa}\eta^{\mu\sigma}\eta^{\nu\tau})-P_{24}(p^\sigma p'^\rho\eta^{\tau\mu}\eta^{\nu\iota}\eta^{\kappa\lambda})-P_{12}(p^\sigma p'^\mu\eta^{\tau\rho}\eta^{\lambda\iota}\eta^{\kappa\nu})+2P_6(p\cdot p'\eta^{\nu\sigma}\eta^{\tau\rho}\eta^{\lambda\iota}\eta^{\kappa\mu})]
\end{aligned}
$$

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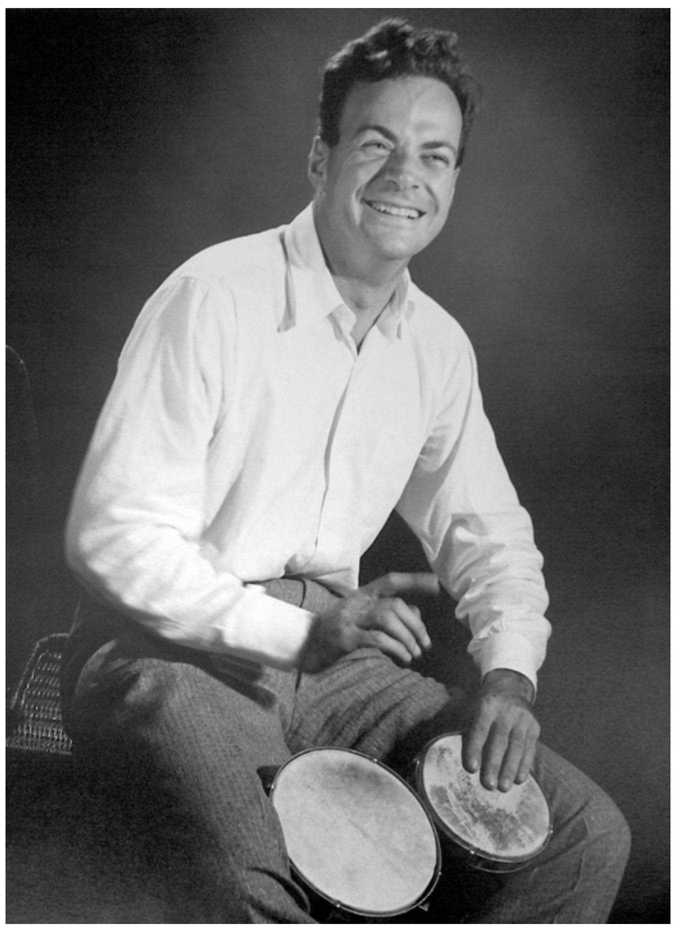

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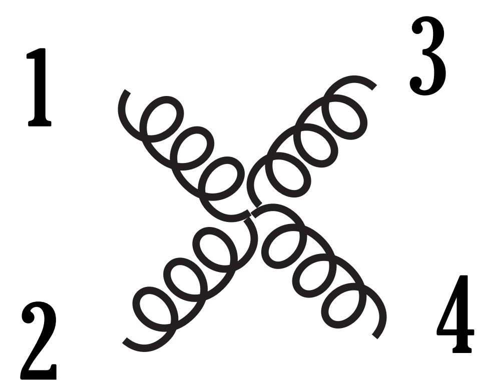

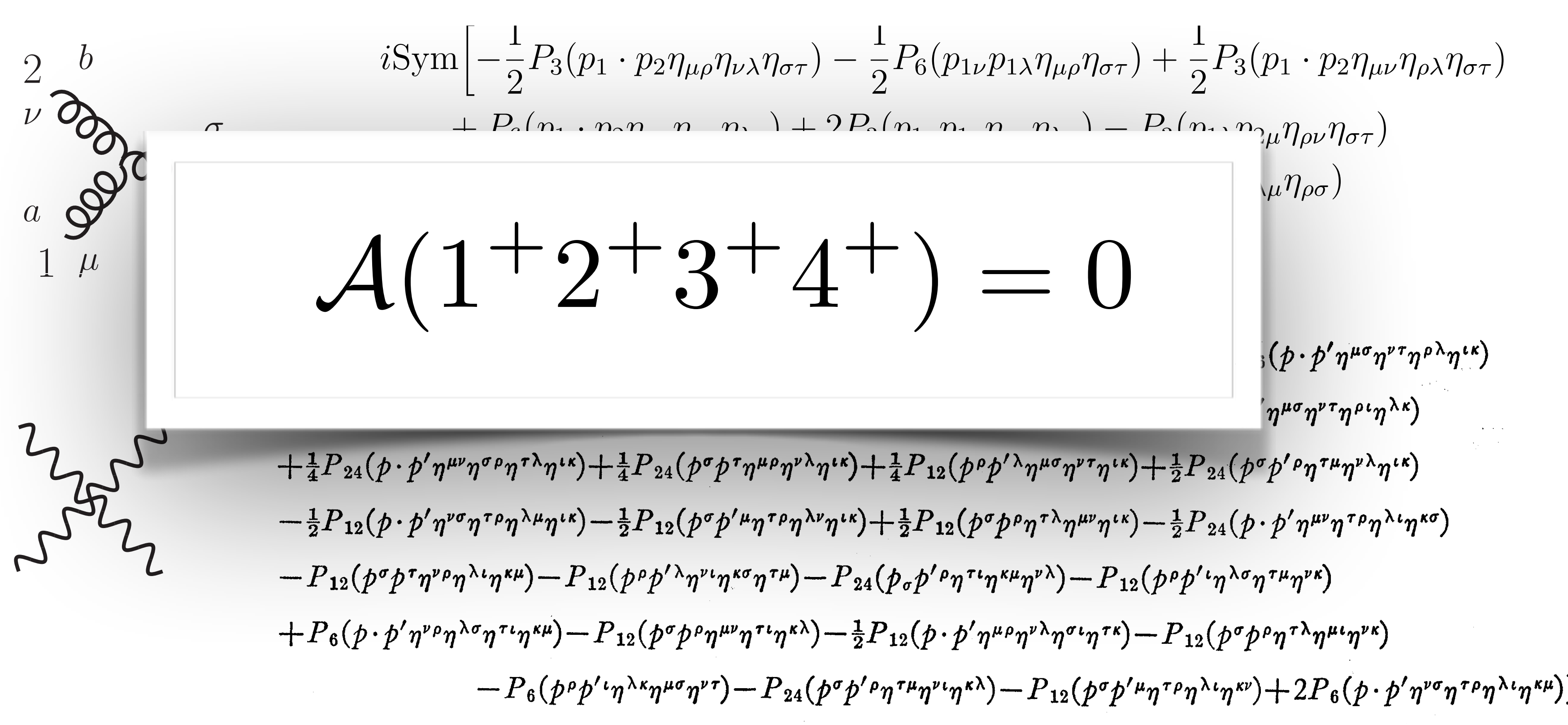

$$\mathcal{A}(1^+2^+3^+4^+) = 0$$

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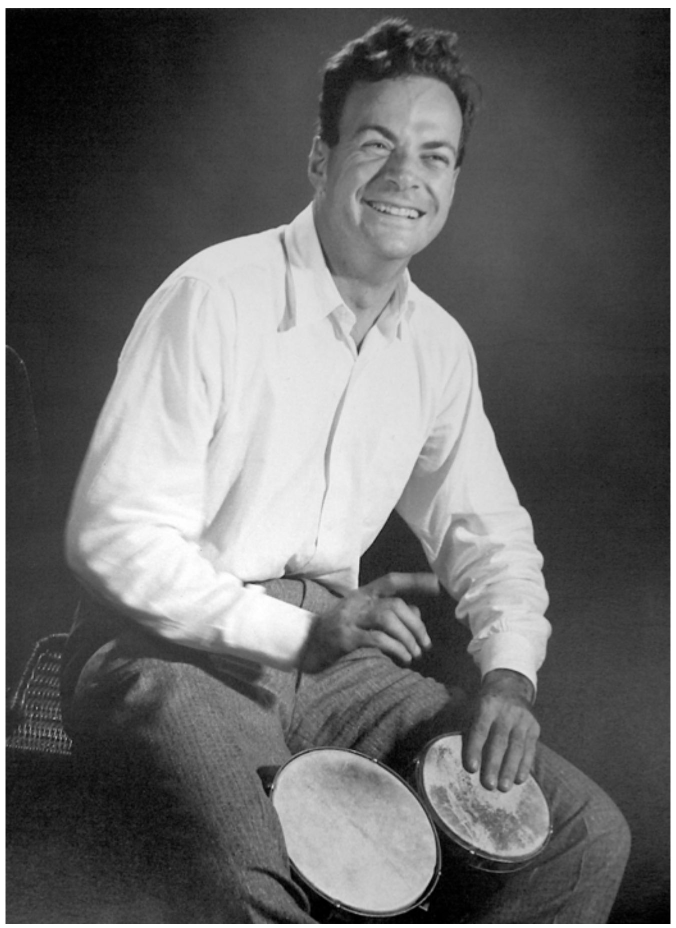

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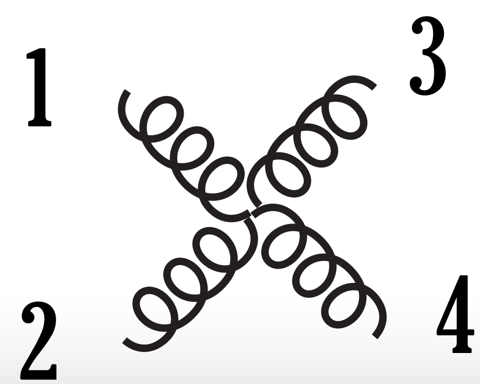
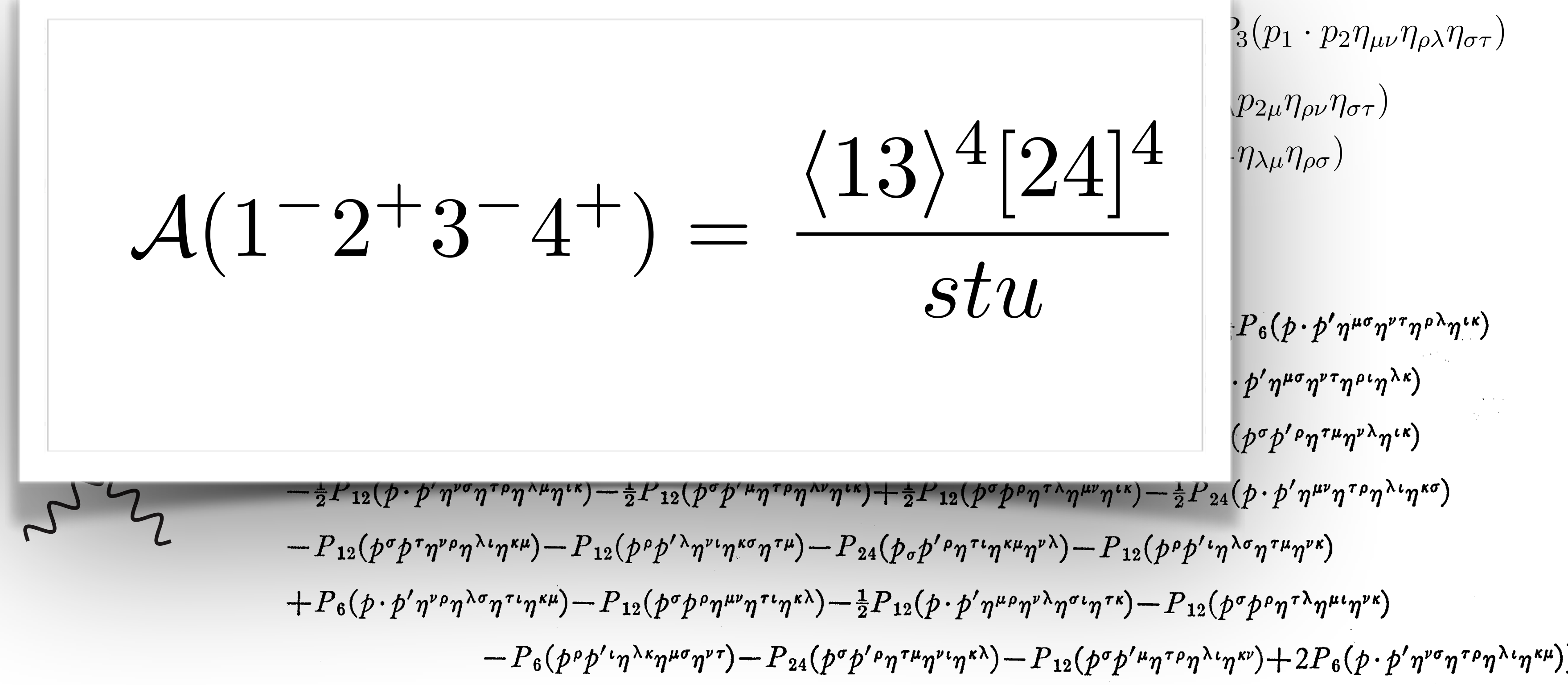


$$\mathcal{A}(1^-2^+3^-4^+) = \frac{\langle 13\rangle^4[24]^4}{stu}$$



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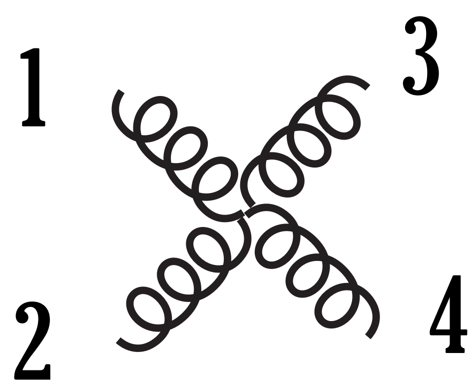

Trivial by **on-shell amplitude methods**…

…based on:

Little group (helicities)
+ locality (single poles)
+ dimensional analysis

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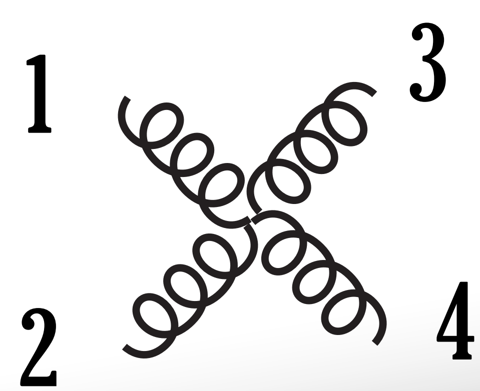

Trivial by **on-shell a**

…ba

Little grou (elicities)
+ locality (single poles)
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Impressive shortcut!
(Shouldn't we abandon the Feynman's way?)

Amplitude methods **not much used** in BSM phenomenology!

Here two little *applications*:

I. Use of amplitudes for calculating **one-loop corrections from indirect BSM effects**

many "*zeros*" are found!

☛ Crucial role plaid by **helicity** selection rules

II. BSM without Lagrangians

e.g. bottom-up approach to theories of Goldstones:

(it could be useful for composite Higgs models)

I. EFT capturing the (indirect) impact of BSMs

Assuming new-physics scale Λ is heavier than M_W,
we can perform an expansion in derivatives and SM fields

(assuming lepton & baryon number)

$$\mathcal{L}_{\rm eff} = \frac{\Lambda^4}{g_*^2}\mathcal{L}\left(\frac{D_\mu}{\Lambda}\,,\ \frac{g_H H}{\Lambda}\,,\ \frac{g_{f_{L,R}} f_{L,R}}{\Lambda^{3/2}}\,,\ \frac{g F_{\mu\nu}}{\Lambda^2}\right) \simeq \mathcal{L}_4 + \mathcal{L}_6 + \cdots$$

SM

leading deviations from the SM

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SM

leading deviations from the SM

Λ —— $\mathcal{O}_i,\mathcal{O}_j,\dots$

m_W —— $\mathcal{O}_i$

One-loop operator mixing important:

(tells us how BSM enter in observables)

$$\gamma_{c_i}=\frac{dc_i}{d\log\mu}=\gamma_{c_i}(c_j)$$

c_j = Wilson coefficient

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Many non-trivial zeros in γ_i from explicit calculations !

...deviations from the SM

Λ

One-loop operator mixing important:

(tells us how BSM enter in observables)

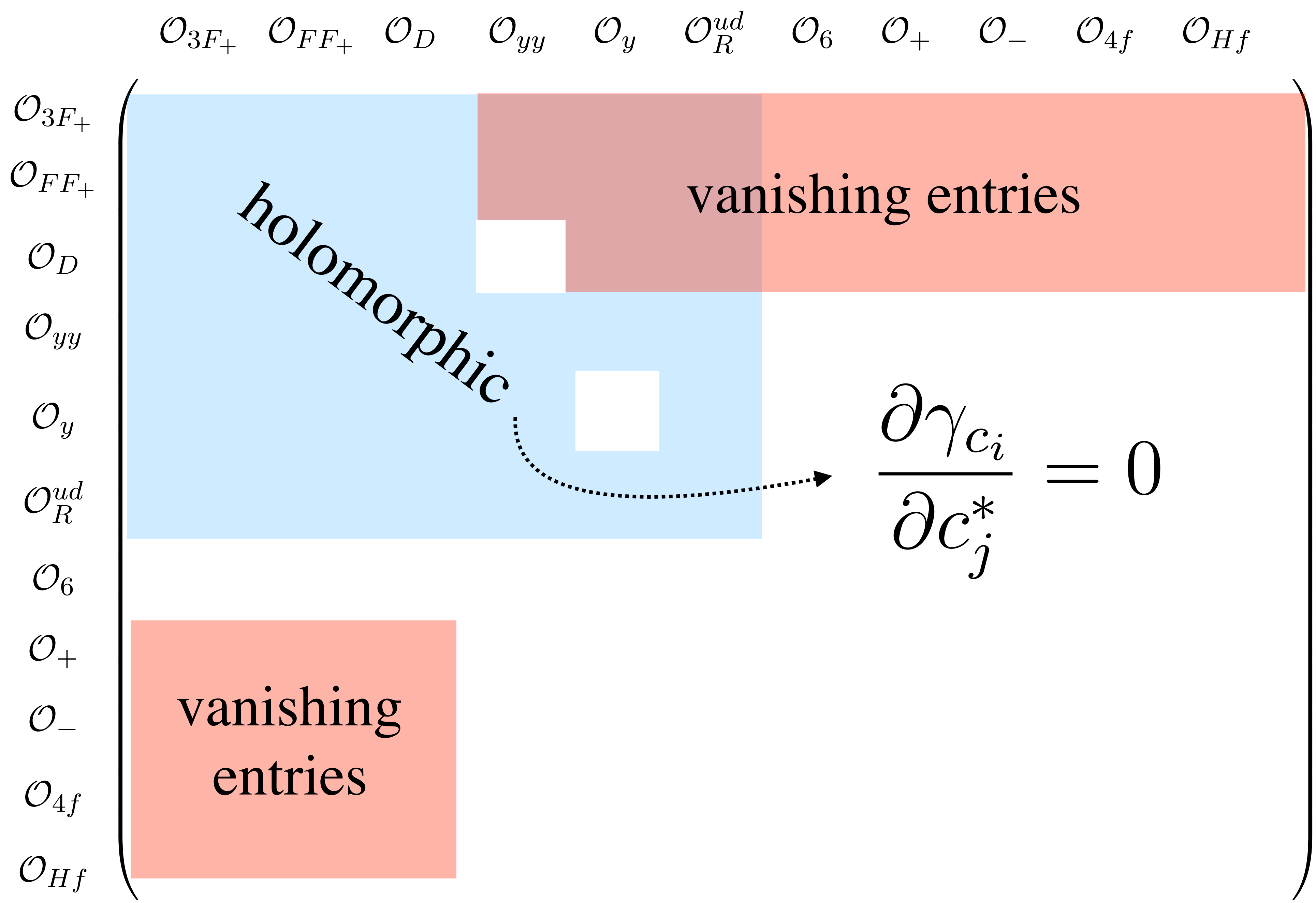
m_W $\mathcal{O}_i$

$$\boxed{\gamma_{c_i} = \frac{dc_i}{d\log\mu} = \gamma_{c_i}(c_j)}$$

c_j = Wilson coefficient

One-loop anomalous dimension of dim-6 operators

$$\gamma_{c_i}(c_j) =$$



arXiv:1412.7151 (explained from susy)

Very practical example:

Renormalization of electron EDM

Recent strong bound by ACME experiment:

$$|d_e| < 1.1 \cdot 10^{-29}\,\mathrm{e} \cdot \mathrm{cm}$$

Can provide important constraints even if BSM enters at the 2-loop level!

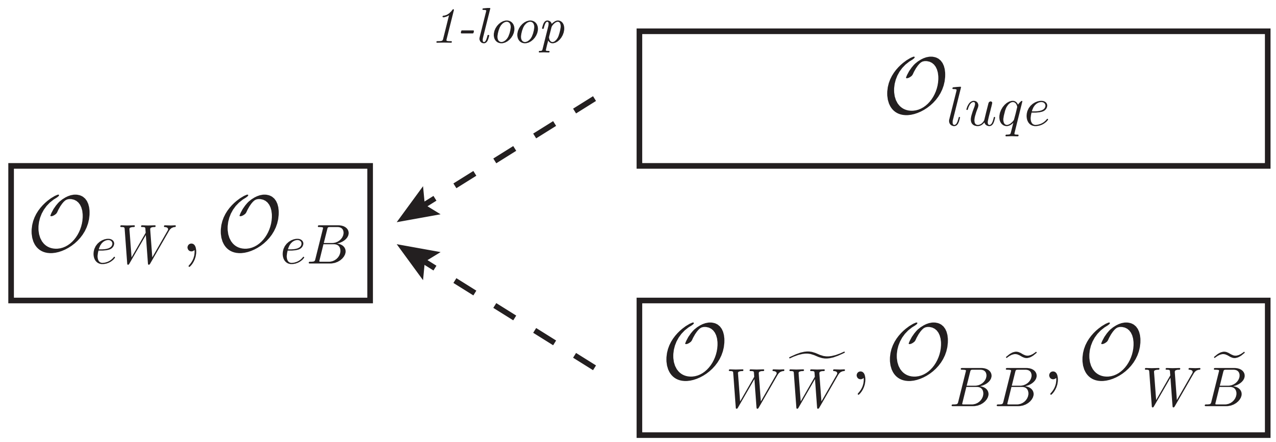
$$\frac{d_e}{e} \sim \frac{1}{(16\pi^2)^2}\frac{m_e}{\Lambda^2} \qquad \to \Lambda > 3\,\mathrm{TeV}$$

Best weapon of BSM mass destruction!

or even on dimension-8 operators!

One-loop mixing:

Panico, AP, Riembau arXiv:1810.09413



out of 59 operators

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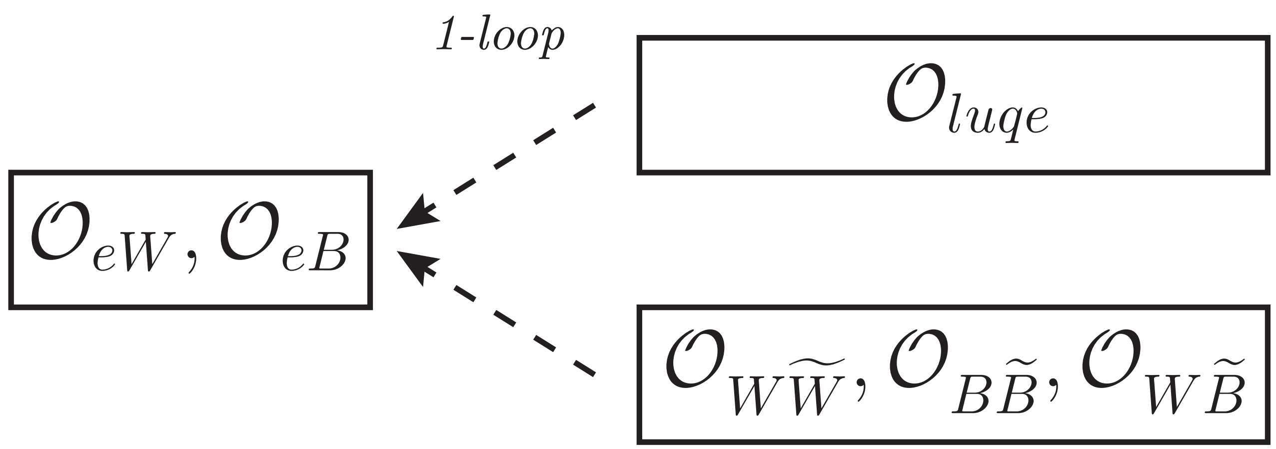

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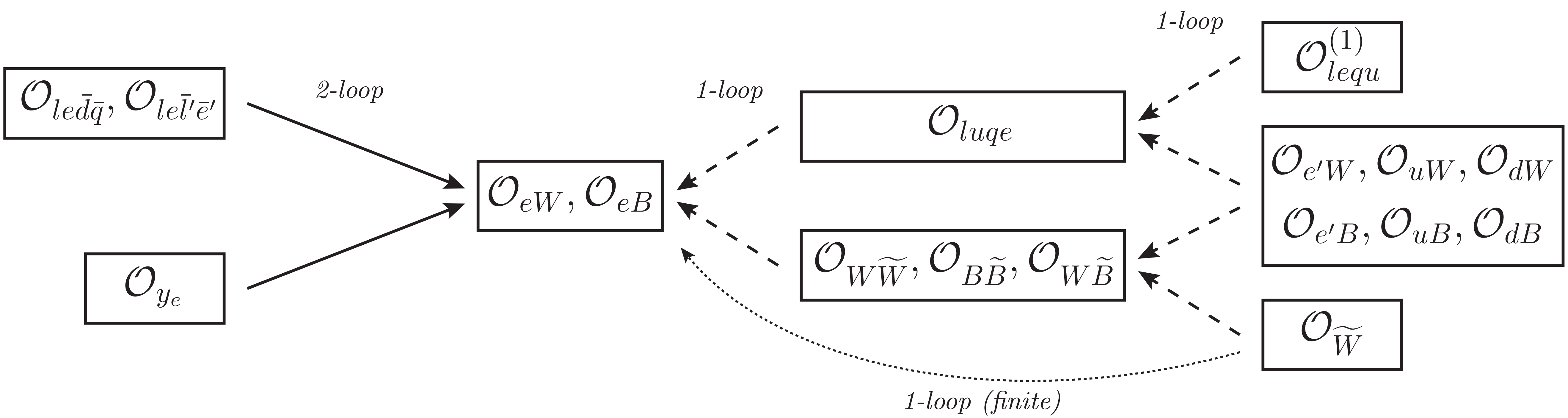

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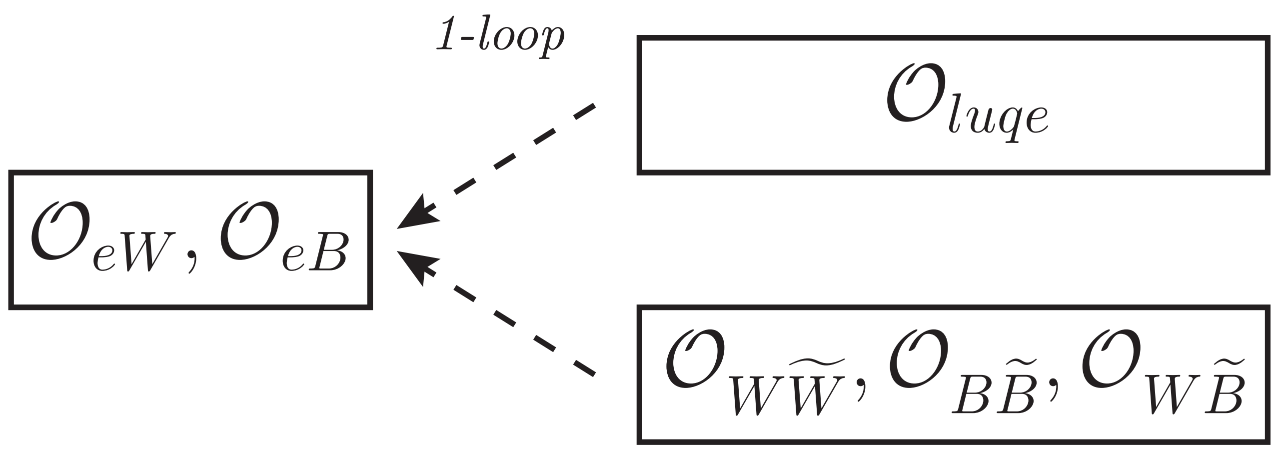

Two-loop mixing:

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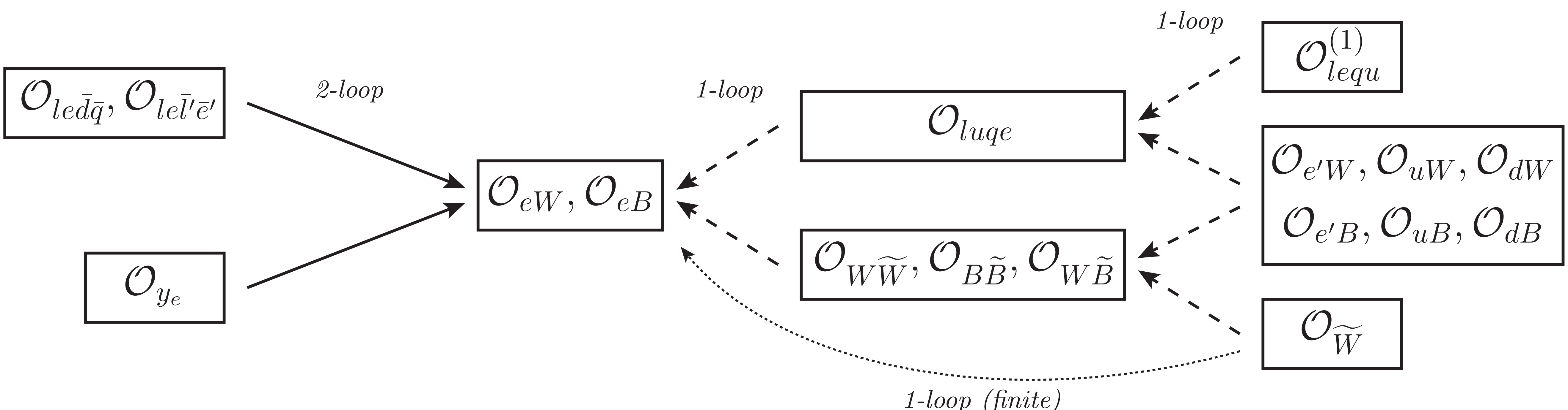


Just from **explicit calculations!**

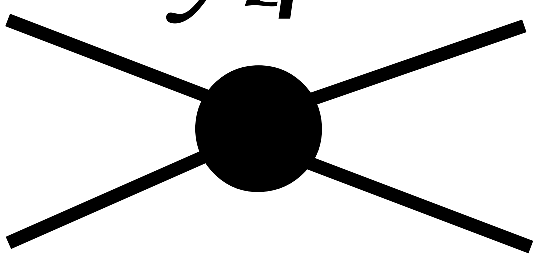
But why? Amplitude method needed!

(or susy: see arXiv:1412.7151)

From operators to on-shell amplitudes

the power of being on-shell !

$\mathcal{A}_i$

$\mathcal{O}_\mathbf{i} \longrightarrow$ 

Ghosts, Golstones,…
($p^2 \neq 0$)

only physical states ($p^2=0$)

$\hookrightarrow$ definite helicity

From operators to on-shell amplitudes

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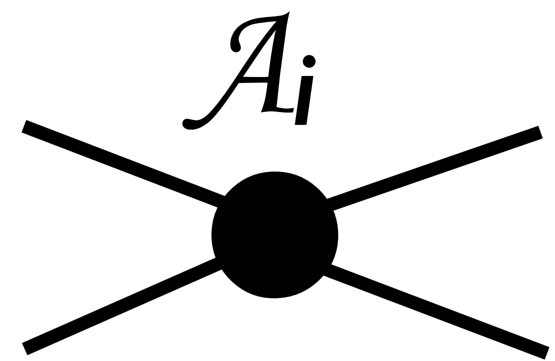
$\mathcal{O}_\mathbf{i} \longrightarrow$

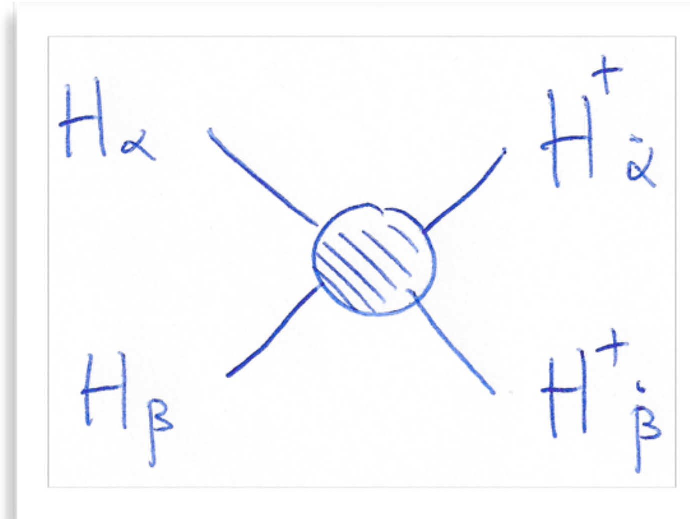


n **= number of external states**

h **= helicity of the amplitude**

Example $O(\partial^2 H^4)$:

$$\left.\begin{aligned}\mathcal{O}_H &= \frac{1}{2}(\partial^\mu |H|^2)^2 \\ \mathcal{O}_T &= \frac{1}{2}(H^\dagger \overleftrightarrow{D}_\mu H)^2\end{aligned}\right\} \longrightarrow$$

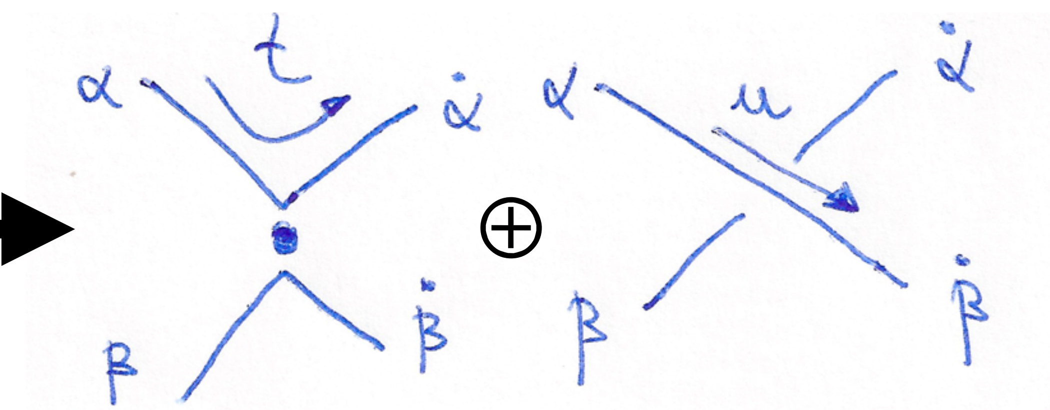


$\sim O(p^2)$

n=4; h=0

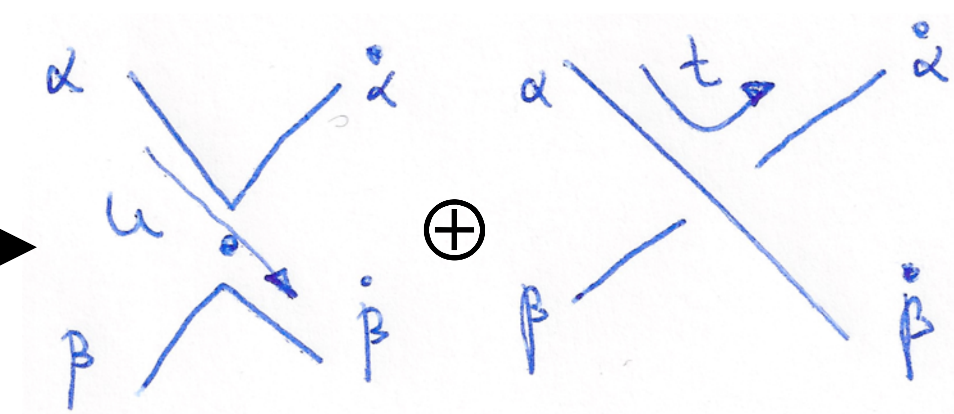
Two amplitudes:

$$A\left[t\,\delta_{\alpha\dot\alpha}\delta_{\beta\dot\beta} + u\,\delta_{\beta\dot\alpha}\delta_{\alpha\dot\beta}\right] \longrightarrow$$



flavor-momentum "alignment"

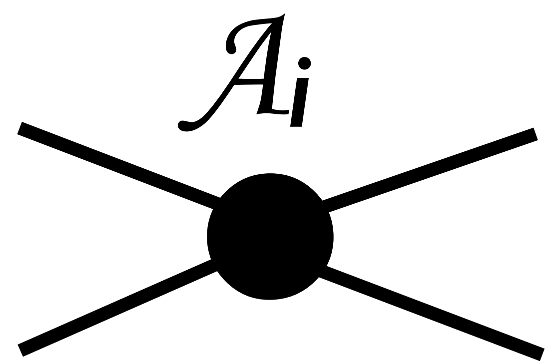
$$B\left[u\,\delta_{\alpha\dot\alpha}\delta_{\beta\dot\beta} + t\,\delta_{\beta\dot\alpha}\delta_{\alpha\dot\beta}\right] \longrightarrow$$



flavor-momentum "anti-alignment"

From operators to on-shell amplitudes

$\mathcal{O}_{\mathbf{i}} \longrightarrow$

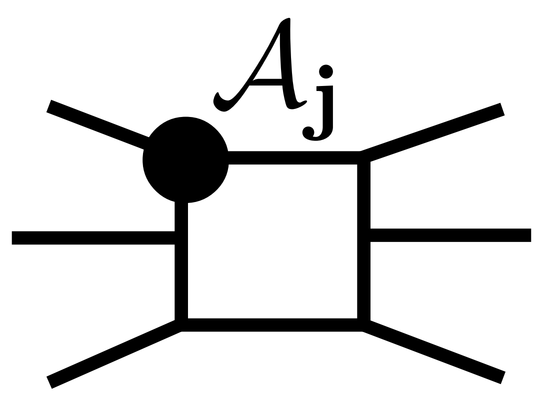


n = number of external states

h = helicity of the amplitude

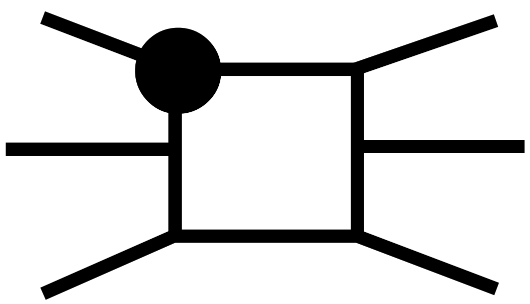
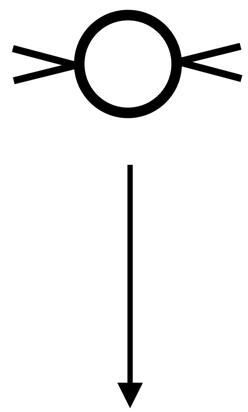
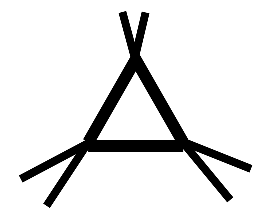
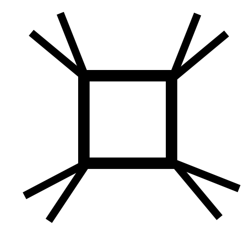
Interested here in one-loop corrections:

$\mathcal{A}_{\mathbf{i}} \;=$



After one-loop reduction to Passarino-Veltman integrals

$$\mathcal{A}_\mathbf{i} = \sum_{\text{bubble}} \mathbf{c_2 I_2} + \sum_{\text{triangle}} \mathbf{c_3 I_3} + \sum_{\text{box}} \mathbf{c_4 I_4} + \mathbf{rational}$$

divergent ☛ c_2 = anomalous dimensions

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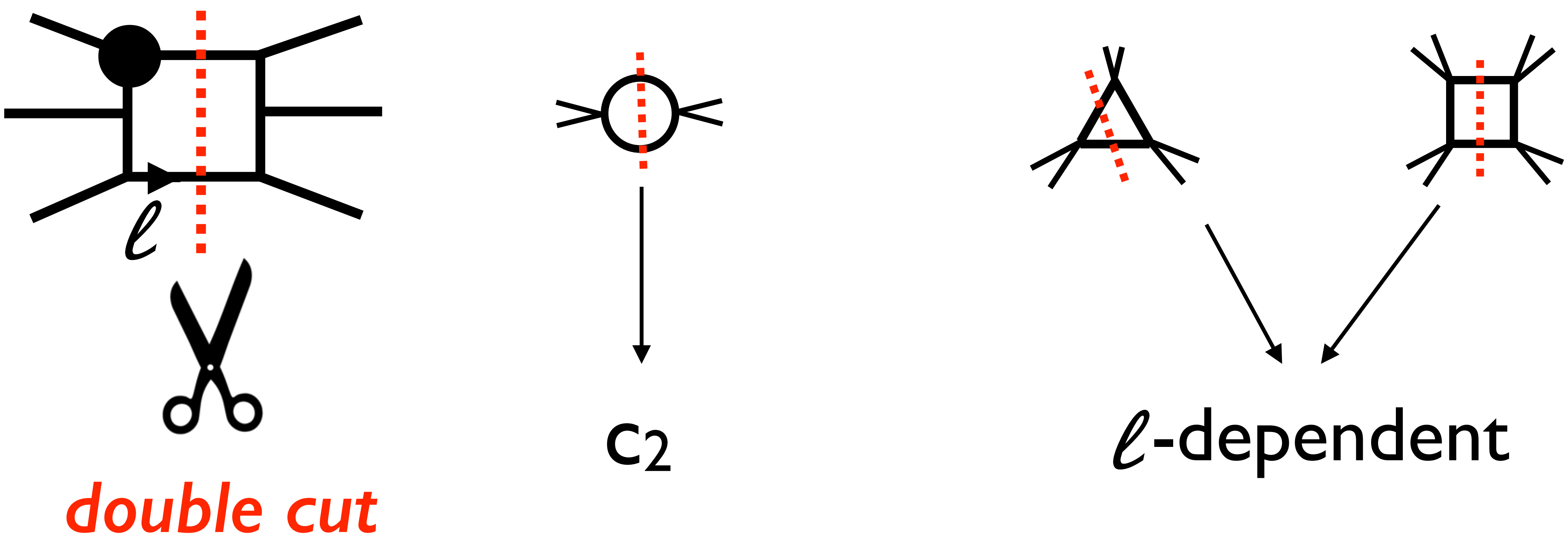

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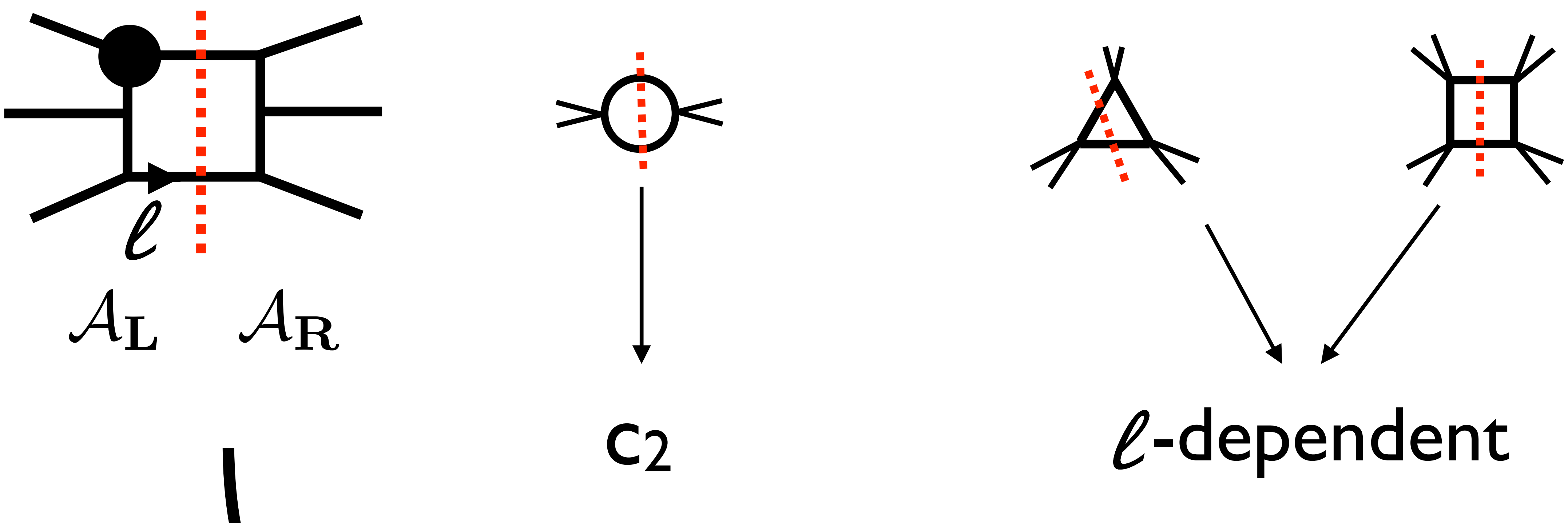


$$\sum\!\!\!\!\!\!\int \mathcal{A}_L \mathcal{A}_R$$

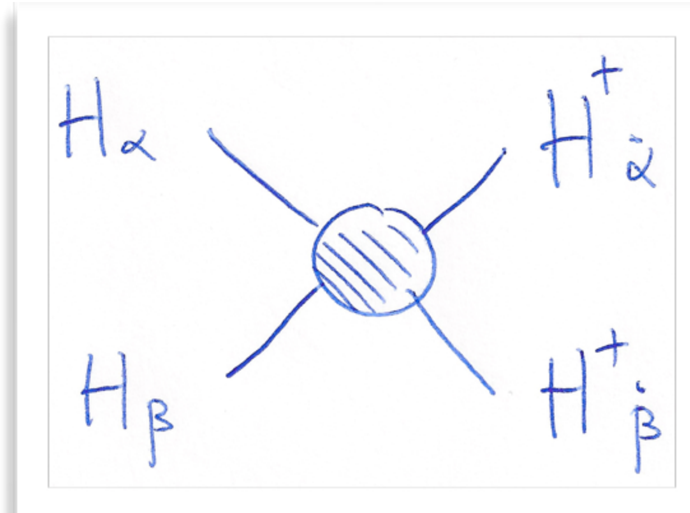
$\boldsymbol{n_i = n_L + n_R - 4}$

$\boldsymbol{h_i = h_L + h_R}$

sum over internal states & phase-space integration

Example $O(\partial^2 H^4)$:

$$\left.\begin{array}{l} \mathcal{O}_H = \frac{1}{2}(\partial^\mu |H|^2)^2 \\[2ex] \mathcal{O}_T = \frac{1}{2}(H^\dagger \overleftrightarrow{D}_\mu H)^2 \end{array}\right\} \longrightarrow$$

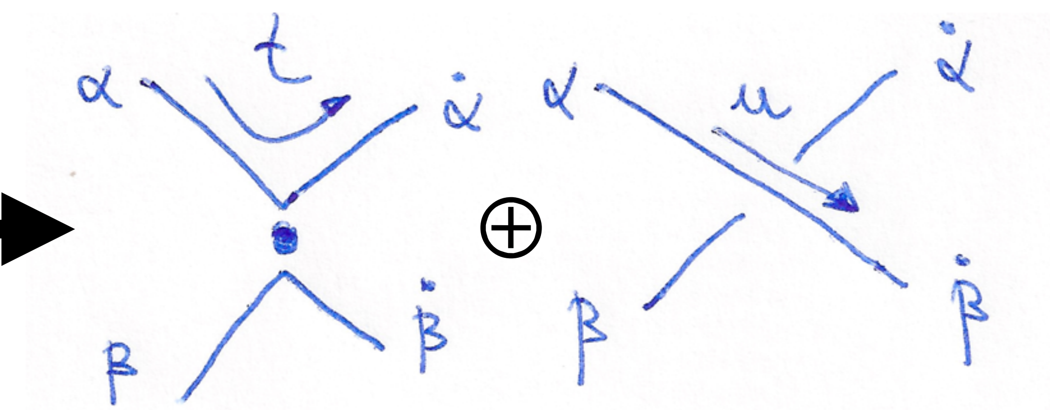


$\sim O(p^2)$

n=4; h=0

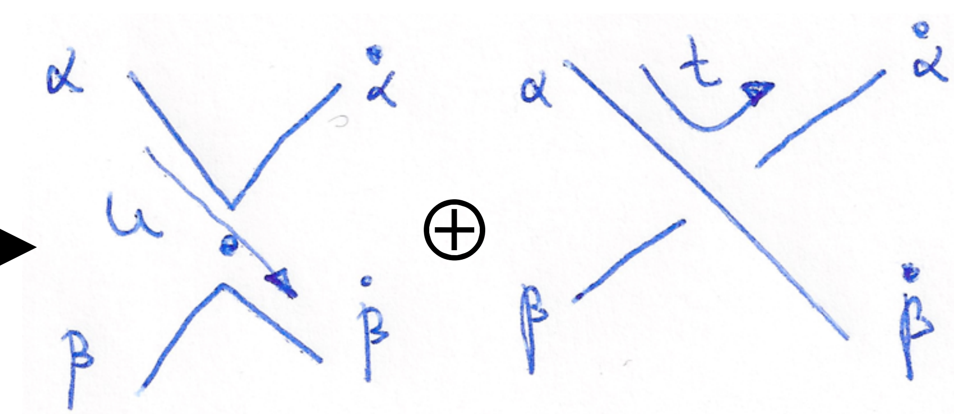
Two amplitudes:

$$A\left[t\,\delta_{\alpha\dot\alpha}\delta_{\beta\dot\beta} + u\,\delta_{\beta\dot\alpha}\delta_{\alpha\dot\beta}\right] \longrightarrow$$



flavor-momentum "alignment"

$$B\left[u\,\delta_{\alpha\dot\alpha}\delta_{\beta\dot\beta} + t\,\delta_{\beta\dot\alpha}\delta_{\alpha\dot\beta}\right] \longrightarrow$$

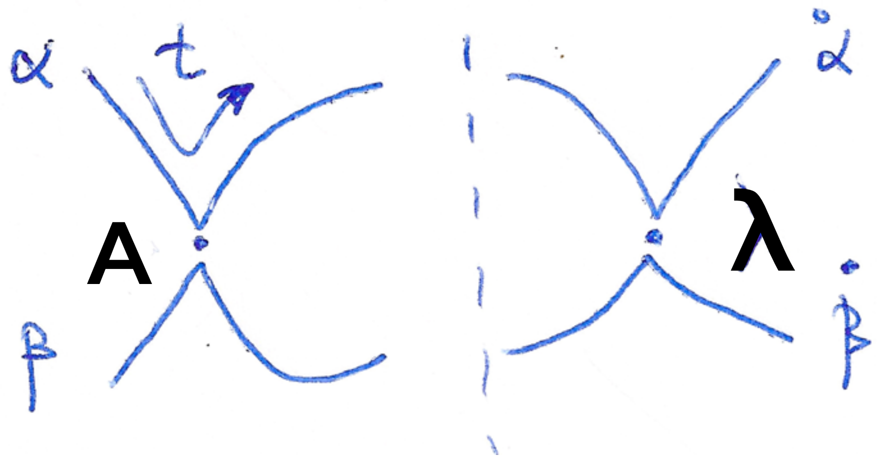


flavor-momentum "anti-alignment"

One-loop corrections

☛ *Cut & paste*

s-channel:

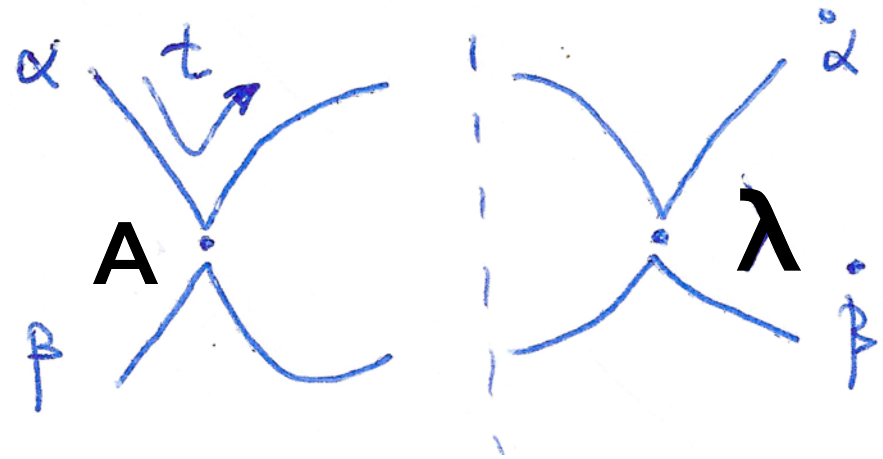


⊕ t-channel ⊕ u-channel

One-loop corrections

☛ *Cut & paste*

s-channel:



⊕ t-channel ⊕ u-channel

$$\delta A = 12 \frac{A\lambda}{16\pi^2}$$

preservation of momentum-flavor "alignment" !

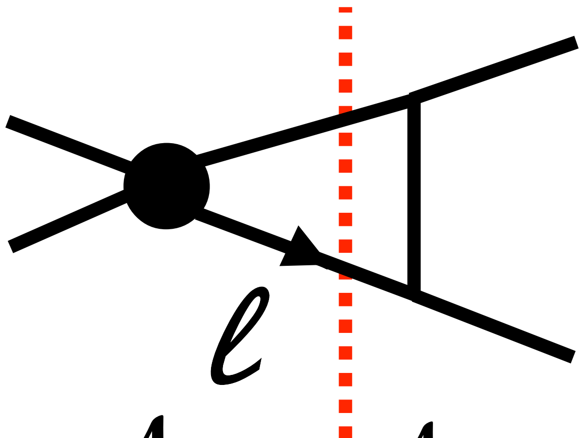
Custodial sym.!

Helicity selection rules

arXiv:1505.01844

Helicity selection rules

arXiv:1505.01844



$$\sum\!\!\!\!\!\!\int \mathcal{A}_{\mathbf{j}}\mathcal{A}_{\mathrm{SM}}$$

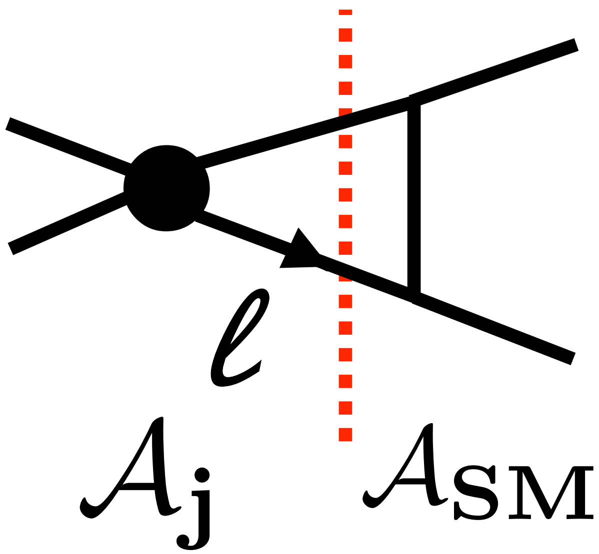
$\mathcal{A}_{\mathbf{j}}$ $\mathcal{A}_{\mathrm{SM}}$

n_j , h_j $n = 4$, h

(no contribution from n=3)

Helicity selection rules

arXiv:1505.01844

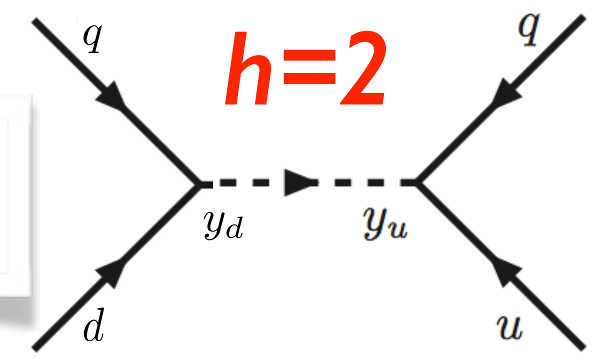


$$\longrightarrow \sum\!\!\!\!\!\!\!\int \mathcal{A}_{\mathrm{j}} \mathcal{A}_{\mathrm{SM}}$$

SM tree-level amplitude

n=4 SM amplitudes ☛ h=0

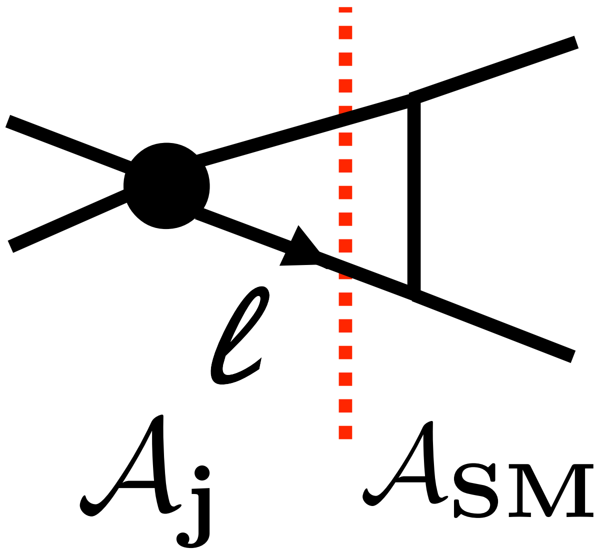
h=2



up to one exception!

Helicity selection rules

arXiv:1505.01844

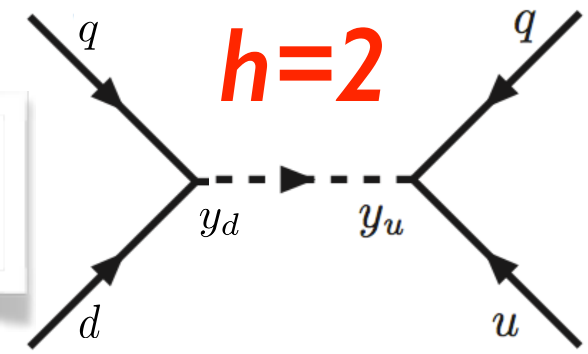


$$\sum\!\!\!\!\int \mathcal{A}_{\mathrm{j}} \mathcal{A}_{\mathrm{SM}}$$

SM tree-level amplitude

n=4 SM amplitudes ☛ h=0

h=2



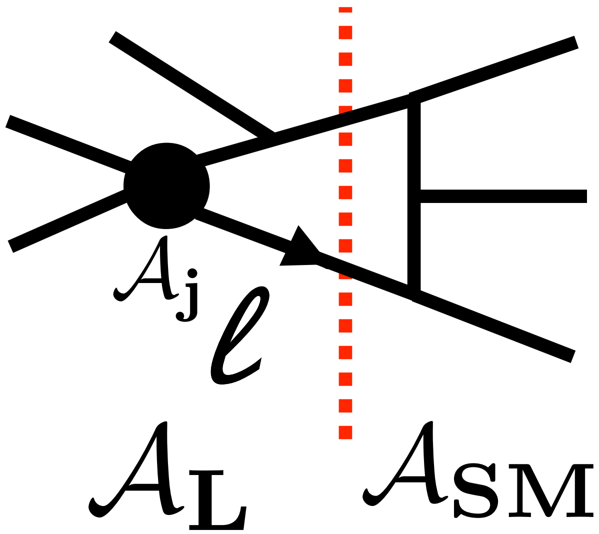
up to one exception!

$$\left.\begin{aligned} n_i &= n_j+4-4 \\ h_i &= h_j+0 \end{aligned}\right\} n_i-n_j=h_i-h_j$$

☛ $\Delta n = |\Delta h|$

Helicity selection rules

arXiv:1505.01844



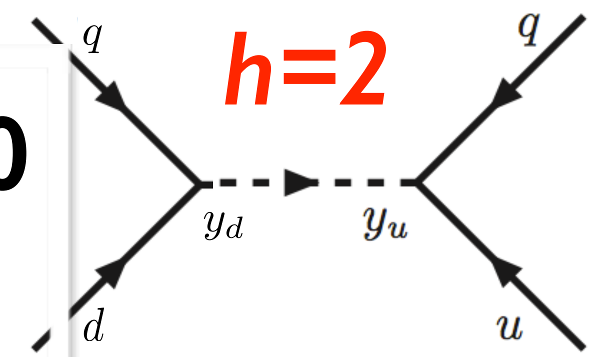
$$\sum\!\!\!\!\!\!\int \mathcal{A}_\mathrm{j}\mathcal{A}_\mathrm{SM}$$

SM tree-level amplitude

n ≥ 4 SM amplitudes ☛ h ≥ 0

☛ *n* ≥ |*h*|+4

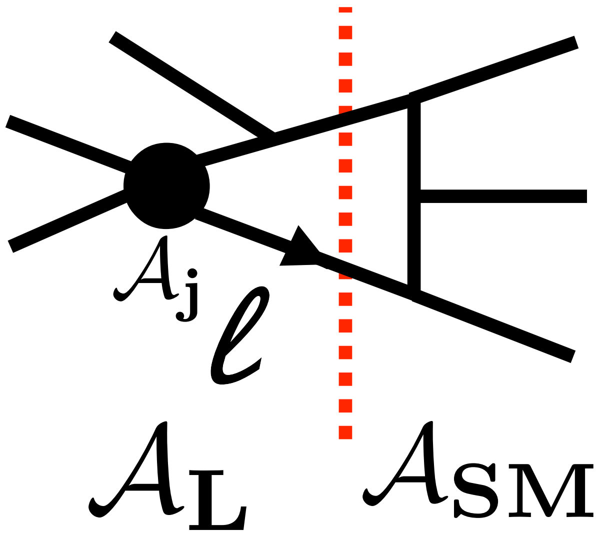
***h*=2**



up to one exception!

Helicity selection rules

arXiv:1505.01844



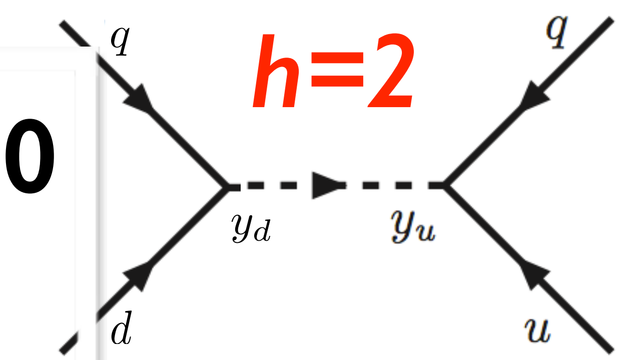
$$\sum\!\!\!\!\!\!\int \mathcal{A}_{\mathrm{j}} \mathcal{A}_{\mathrm{SM}}$$

SM tree-level amplitude

n ≥ 4 SM amplitudes ☛ h ≥ 0

☛ $n \geq |h|+4$

$h=2$



up to one exception!

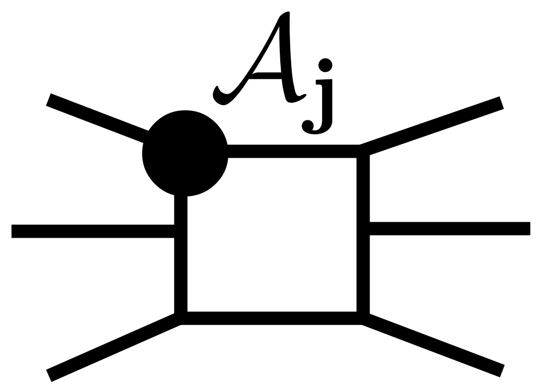
$$\left.\begin{array}{l} n_i = n_L + n_{SM} \\ h_i = h_L + h_{SM} \end{array}\right\} n_i - n_j \geq h_i - h_j + 4 - 4$$

☛ $\Delta n \geq |\Delta h|$

Helicity selection rules

arXiv:1505.01844

$\mathcal{A}_{\mathbf{i}}$ =



$\Delta n = n_i - n_j$

$\Delta h = h_i - h_j$

$$\boxed{\Delta n \geq |\Delta h|}$$

up to the exception!

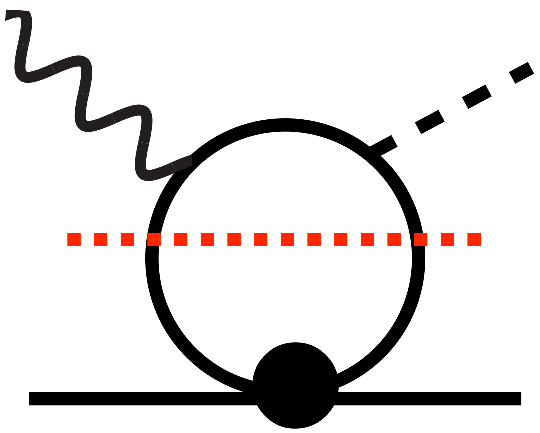
Examples:

also explained by susy techniques: arXiv:1412.7151

I. No 4-fermion $(\bar{\psi}\gamma^{\mu}\psi)^2$ corrections to dipoles

$$F_{\alpha\beta}\psi^{\alpha}\psi^{\beta}h$$

n=4; h=2



n=4; h=0

Examples:

also explained by susy techniques: arXiv:1412.7151

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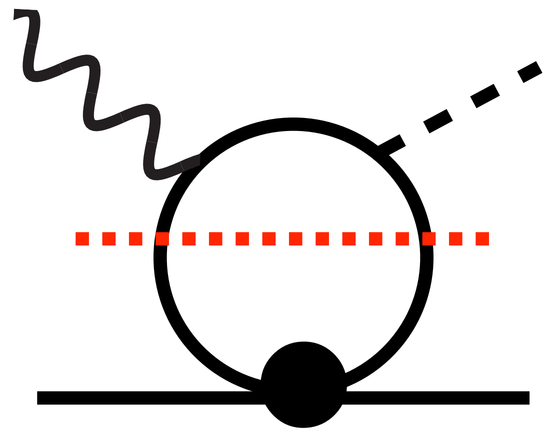

n=4; **h=2**

Examples:

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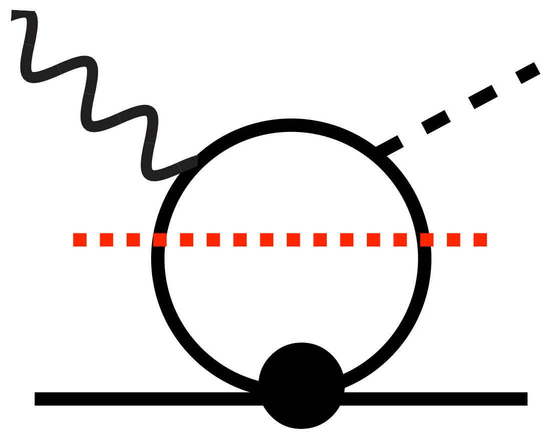
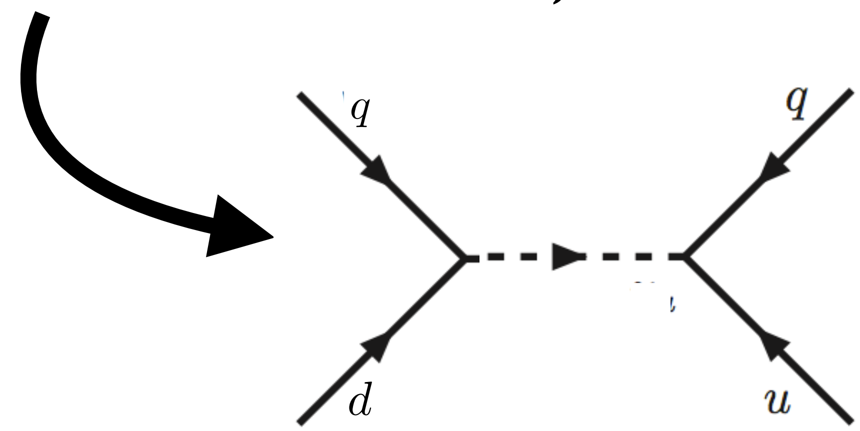


n=4; **h=2**



from scalar leptoquarks:
(3,2,7/6),(3,1,-1/3)
& extra Higgses

Examples:

also explained by susy techniques: arXiv:1412.7151

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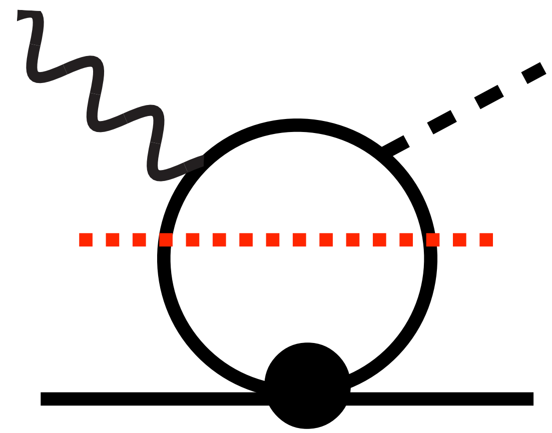
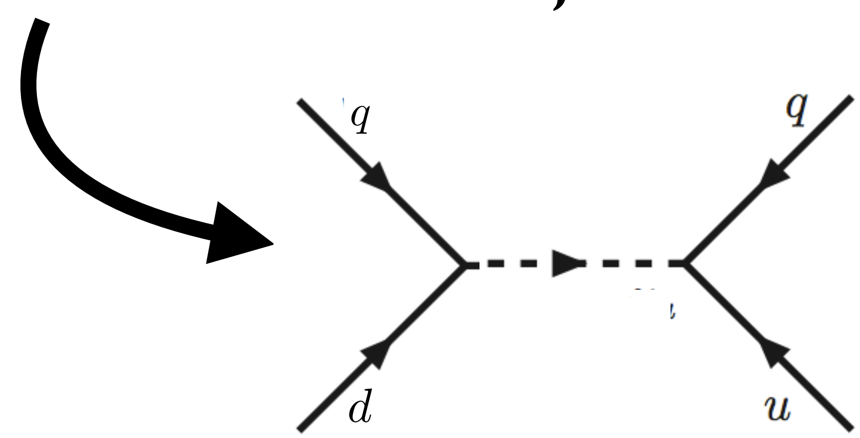


n=4; **h=2**



from scalar leptoquarks:
(3,2,7/6),(3,1,-1/3)
& extra Higgses

EDM ACME bound can reach: $\boxed{M_{LQ} > 400\text{ TeV}}$

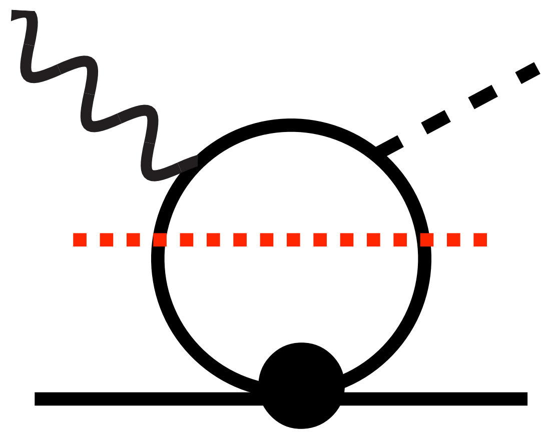
Examples:

also explained by susy techniques: arXiv:1412.7151

I. ~~No~~ 4-fermion $(\psi\psi)^2$ corrections to dipoles

$$\boxed{F_{\alpha\beta}\psi^{\alpha}\psi^{\beta}h}$$

n=4; h=2

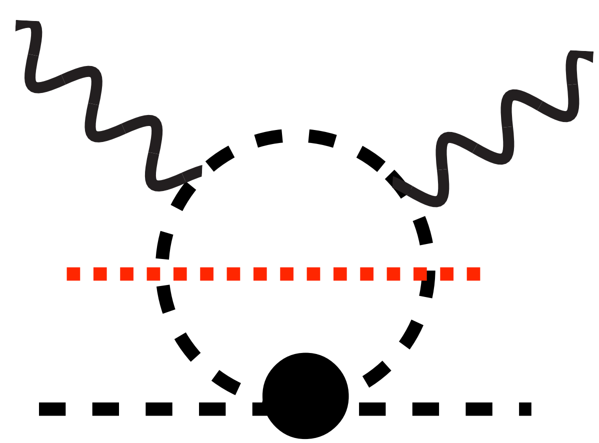


n=4; h=2

II. No p^2H^4 corrections to $H\gamma\gamma$

$$\boxed{F_{\alpha\beta}F^{\alpha\beta}h^2}$$

n=4; h=2



n=4; h=0

number of states

helicity	3	4	5	6
0		$\bar{\psi}^2\psi^2$ $p^2\lvert HH^\dagger\rvert^2$ $p\lvert H\rvert^2\bar{\psi}\psi$		$\lvert H\rvert^6$
1			$H\lvert H\rvert^2\psi\psi$	
2		$\lvert H\rvert^2F^2$ ψ^4 $HF\psi\psi$		
3	F^3			

number of states

helicity	3	4	5	6
0		$\bar{\psi}^2\psi^2$ $p^2\lvert HH^\dagger\rvert^2$ $p\lvert H\rvert^2\bar{\psi}\psi$		$\lvert H\rvert^6$
1			$H\lvert H\rvert^2\psi\psi$	
2		$\lvert H\rvert^2F^2$ ψ^4 $HF\psi\psi$		
3	F^3			

$$\boxed{\Delta n \geq |\Delta h|}$$

renormalization cone

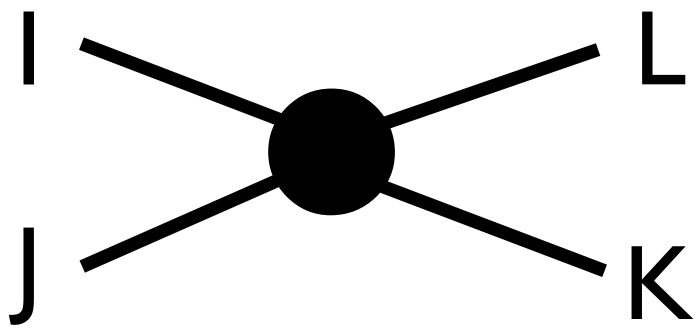
II. Bottom-up approach to Goldstone physics:

Only assume:

a) $\pi_i \in$ reps of $\mathcal{H}$ (no coset input)

b) $\mathcal{A}(1234) \to q_i$ (for $q_i \to 0$) (Adler's zeros)

in collaboration with P. Baratella & B. Harling

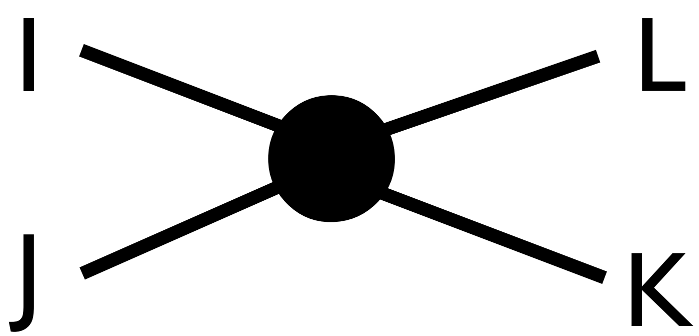


$$= \mathbf{f(s,t,u)\,T_{IJKL}} + \cdots$$

kin. functions

inv. tensors

invariant under crossing



$$= \mathbf{f(s,t,u)}\,\mathbf{T_{IJKL}} + \cdots$$

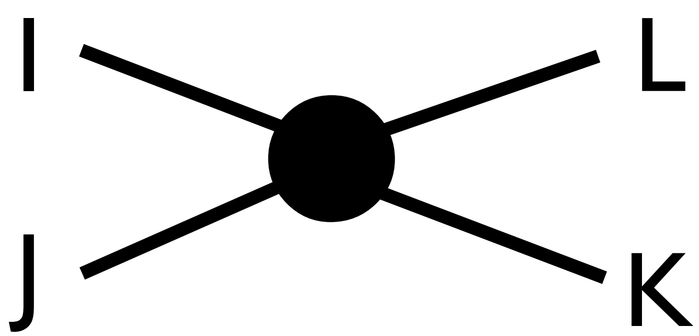
invariant under crossing

kin. functions

inv. tensors

Tensor invariants (for π ϵ Adj of SU(N)):

- single trace (6): $tr(t_I t_J t_K t_L)$
- double trace (3): $tr(t_I t_J)\,tr(t_K t_L)$



$$= \mathbf{f}(\mathbf{s},\mathbf{t},\mathbf{u})\,\mathbf{T_{IJKL}} + \cdots$$

invariant under crossing

kin. functions

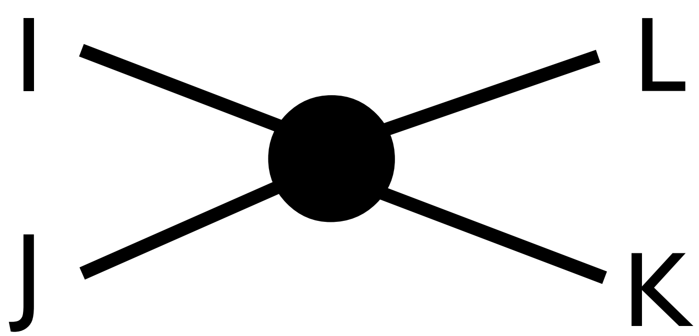
inv. tensors

Tensor invariants (for π ∈ Adj of SU(N)):

- single trace (6): $tr(t_I t_J t_K t_L)$
- double trace (3): $tr(t_I t_J)\,tr(t_K t_L)$

Kinematics:

$\mathbf{f}(\mathbf{s},\mathbf{t},\mathbf{u}) \qquad s + t + u = 0$



$$= \mathbf{f(s,t,u)}\, \mathbf{T_{IJKL}} + \cdots$$

kin. functions

inv. tensors

invariant under crossing

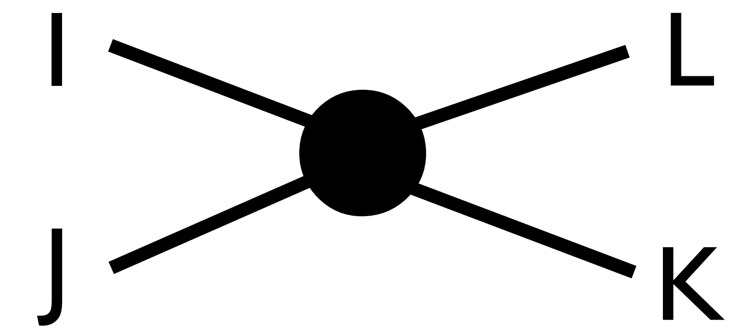
Tensor invariants (for π ϵ Adj of SU(N)):

		Under permutations:
• single trace (6):	$tr(t_I t_J t_K t_L)$	ϵ **1+2+3**
• double trace (3):	$tr(t_I t_J)\, tr(t_K t_L)$	ϵ **1+2**

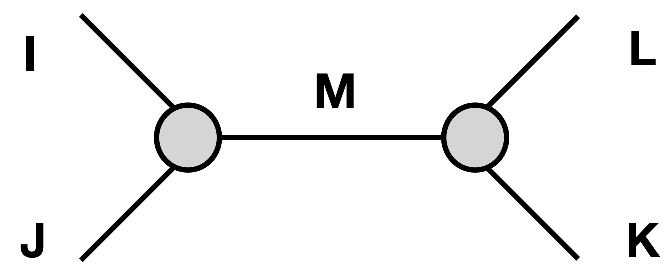
Kinematics:

$\mathbf{f(s,t,u)}$	$s+t+u=0$	ϵ **1+2**

$O(p^2)$: $\boxed{(t-u)\, f_s + (u-s)\, f_t + (s-t)\, f_u}$

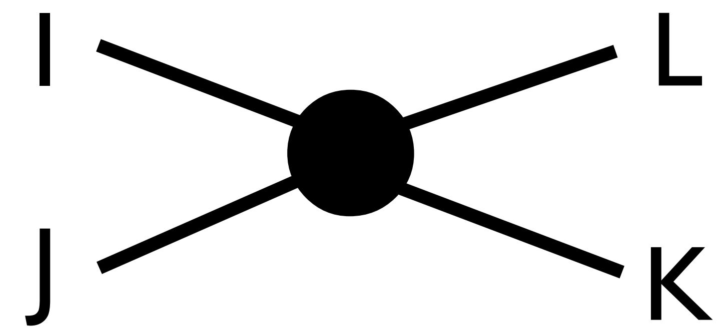


- single trace: $f_{IJM}\, f_{MKL}$



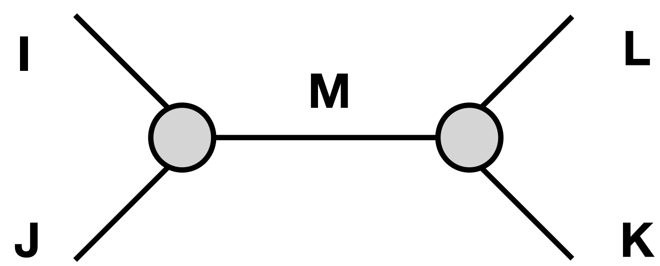
$f_s+f_t+f_u=0$ Jacobi

$s+t+u=0$



$O(p^2)$: $\boxed{(t-u)\, f_s + (u-s)\, f_t + (s-t)\, f_u}$

- single trace: $f_{IJM}\, f_{MKL}$



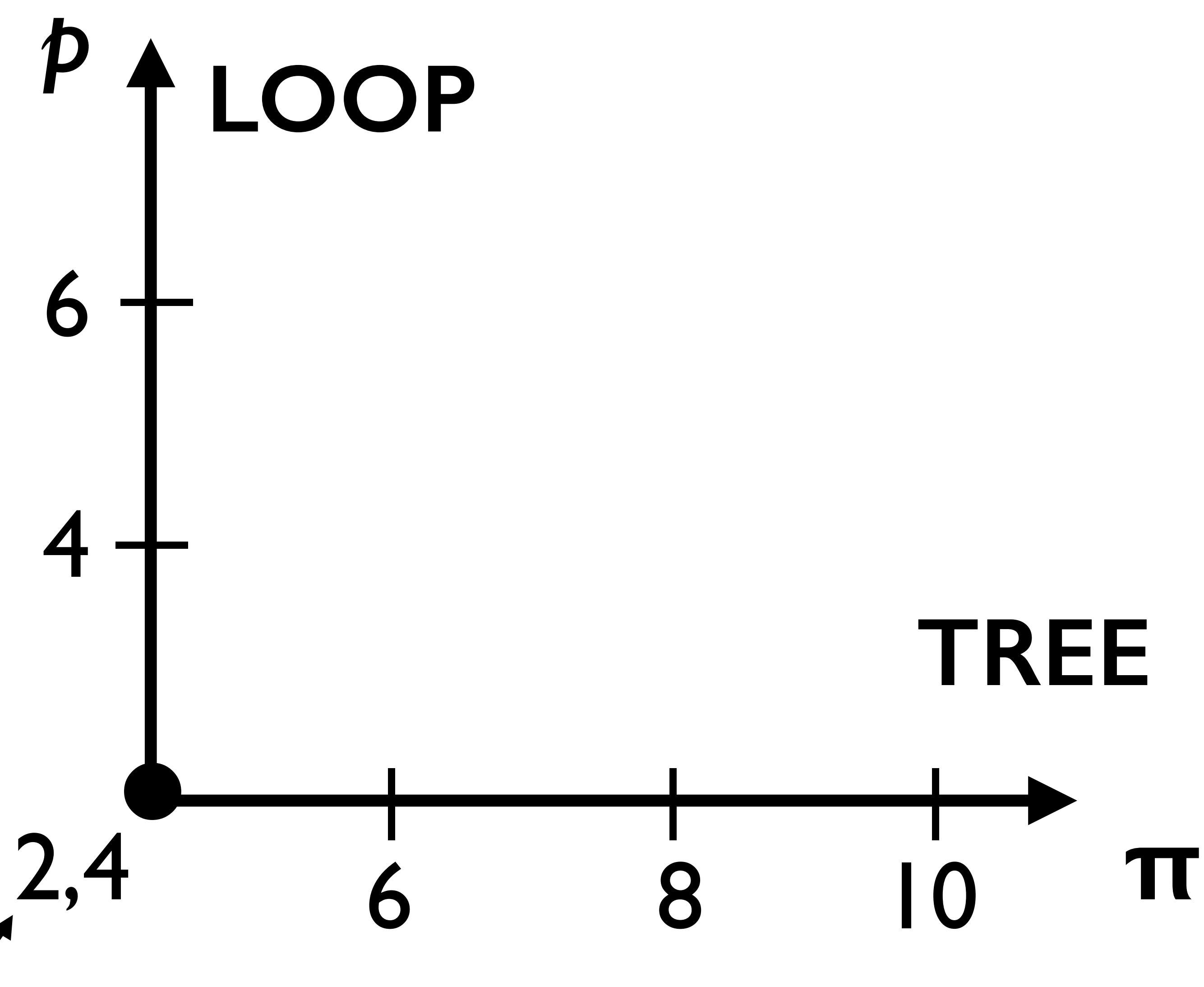
$f_s + f_t + f_u = 0$ Jacobi

$s + t + u = 0$

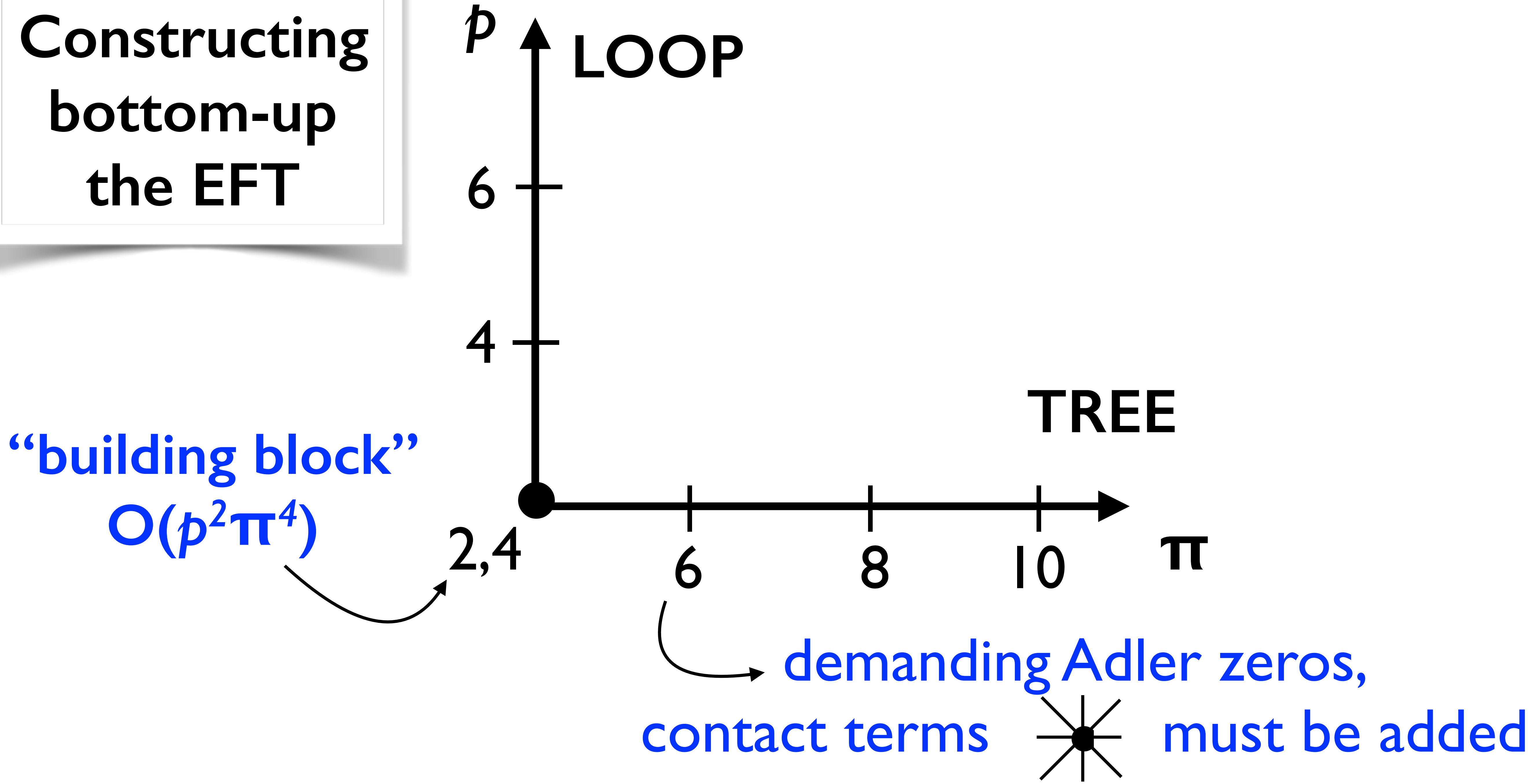
- double trace: $\delta_{IJ}\, \delta_{KL} - \delta_{IL}\, \delta_{JK}$

Constructing bottom-up the EFT

“building block”
$O(p^2\pi^4)$

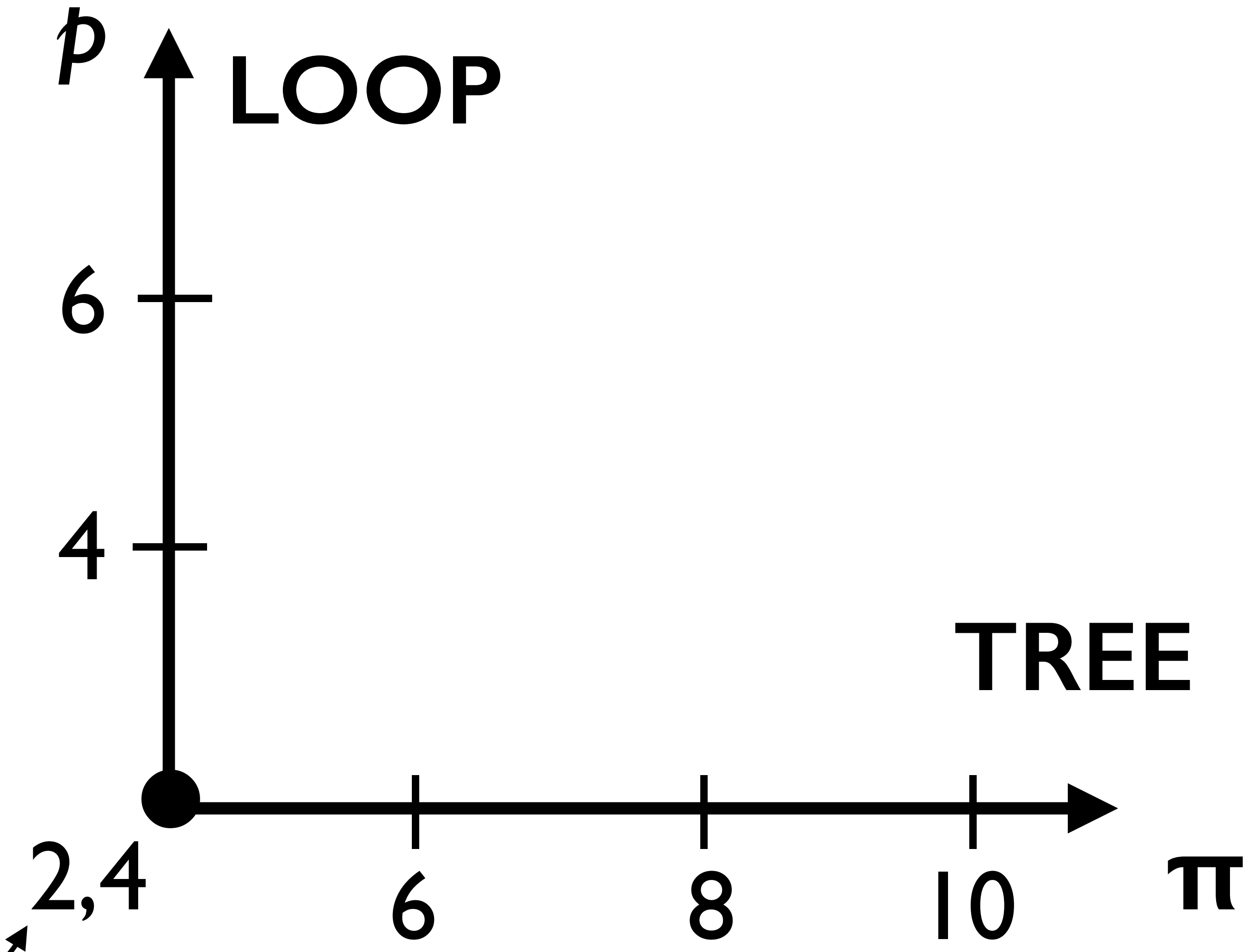


Constructing bottom-up the EFT



arXiv:1904.12859

Constructing bottom-up the EFT



"building block"
$O(p^2\pi^4)$

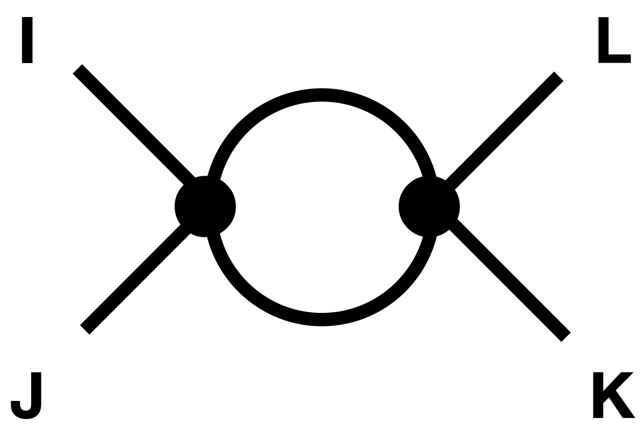
demanding Adler zeros,
contact terms must be added

arXiv:1904.12859

possible *only* for one choice at a time:

- ☛ single trace → reconstructing SU(N)xSU(N)/SU(N)
- ☞ double trace → reconstructing SO(N)/SO(N-1)

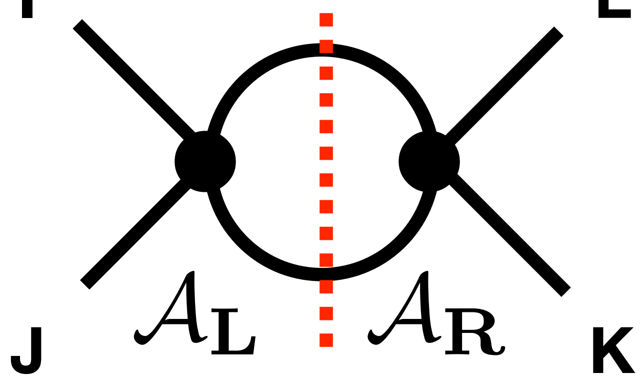
LOOPS



+ *crossing*

☛ O(p^4) amplitude

LOOPS

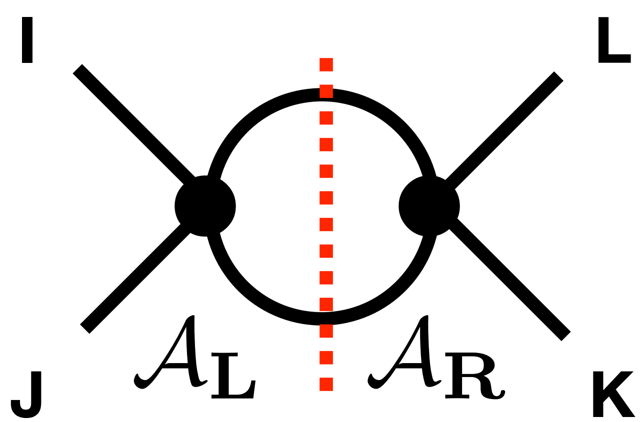


+ *crossing*

☛ O(p^4) amplitude

$$\sum\!\!\!\!\!\!\!\int \mathcal{A}_L \mathcal{A}_R$$

LOOPS



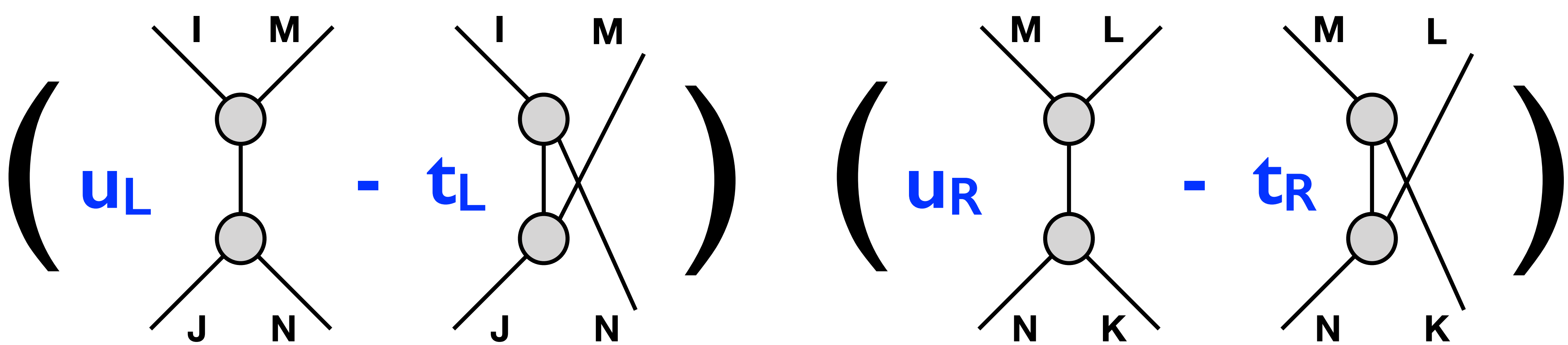
+ *crossing*

☛ $O(p^4)$ amplitude

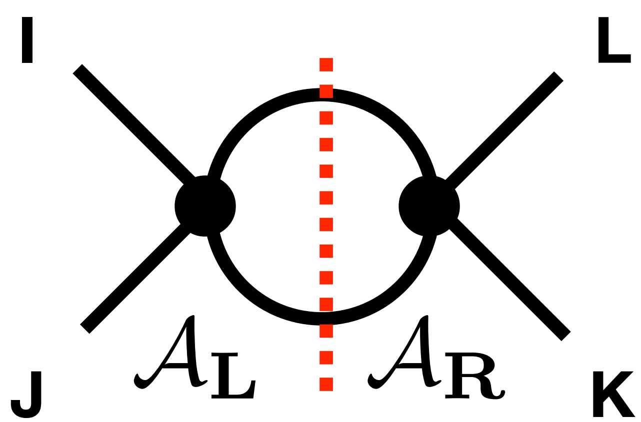
$$\sum \oint \mathcal{A}_L \mathcal{A}_R$$

thanks to Jacobi identity & s+t+u=0

- single trace:



LOOPS



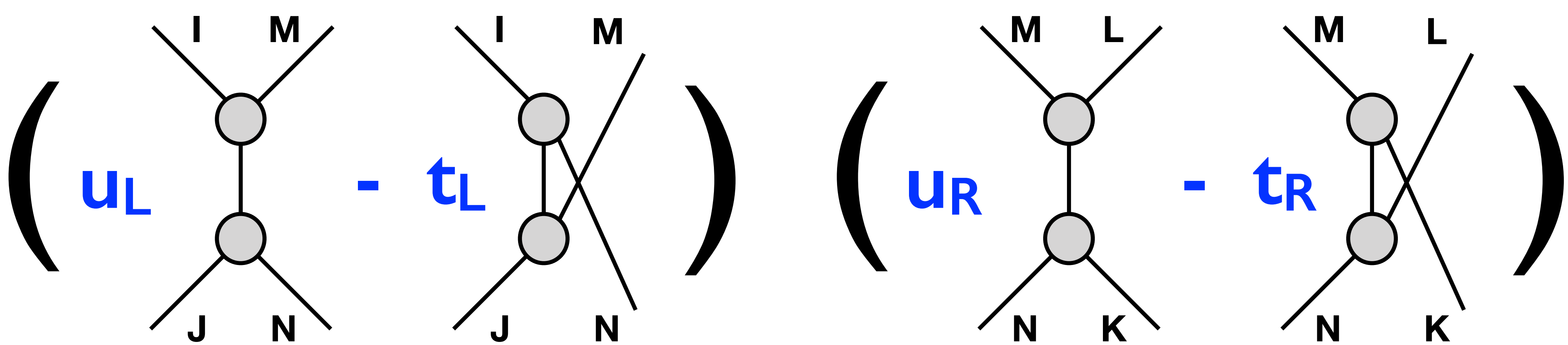
+ *crossing*

☛ $O(p^4)$ amplitude

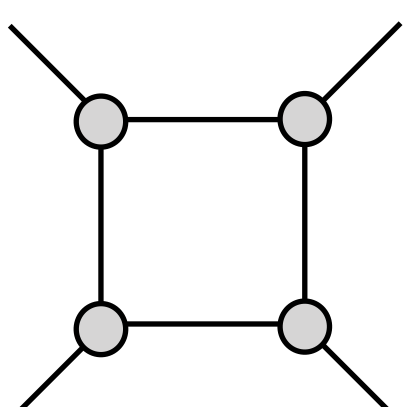
$$\sum\!\!\!\!\!\!\int \mathcal{A}_L \mathcal{A}_R$$

thanks to Jacobi identity & $s+t+u=0$

- single trace:

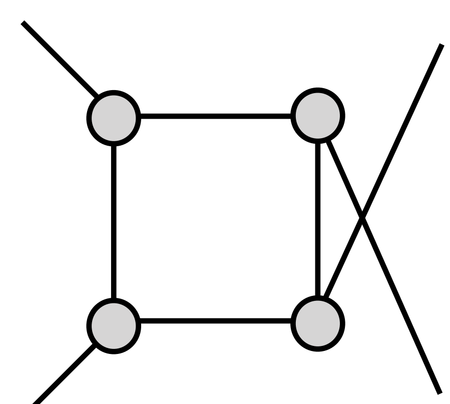


$=$



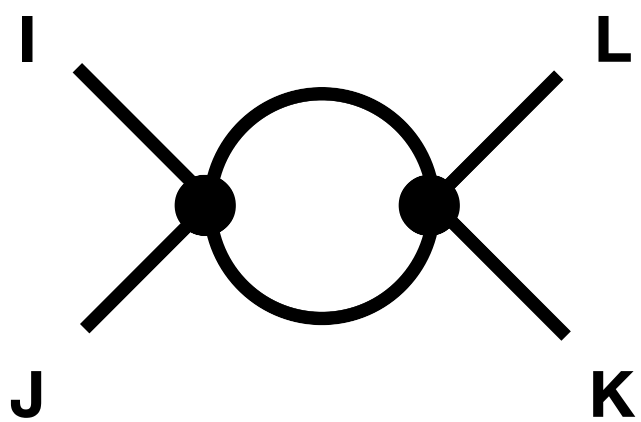
$$\sum\!\!\!\!\!\!\int (u_L u_R + t_L t_R)$$

$+$



$$\sum\!\!\!\!\!\!\int (u_L t_R + t_L u_R)$$

ONE LOOP



+ *crossing*

- single trace:

$$= (s^2 + t^2 + u^2)\ \left(\mathrm{Tr}[\, F^I\, F^J\, F^K\, F^L \,] + \textit{crossing} \right)$$

$$(F^I)_{JK} = f_{IJK}$$

Unclear why so simple!

Conclusions

- **Amplitude methods** seems quite **suited for** calculating indirect **BSM** effects, e.g. anomalous dimensions of $\mathcal{O}_6$

  ☛ many **selection rules**

- Allows to construct **BSM without Lagrangians:**

  ☛ new theories of Goldstones?

  ☛ new methods of unitarization?

A lot to do! Stay Tuned!