Ying-Ying Li

Loops and Trees in Generic EFTs

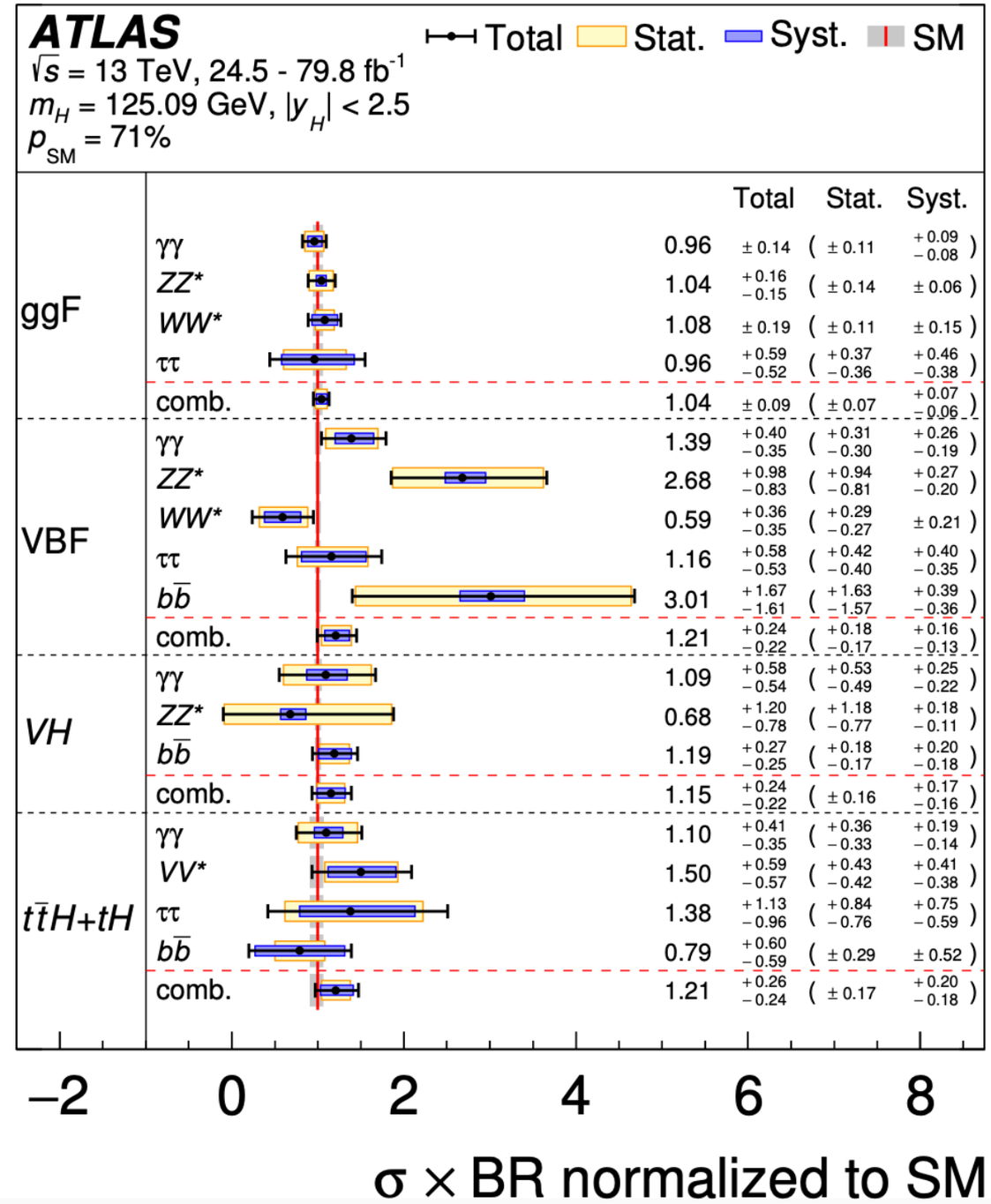
arXiv: 1811.08878, 2001.00017
In collaboration with
N. Craig, M. Jiang and D. Sutherland

March 10, 2021 Michigan Brown Bag seminars

EFT:
effective tool of parameterizing
the low energy effect of new physics

allows the interpretation of the data,
either agreement or disagreement with SM.

connect to UV via matching at threshold
scale and running to experimental scale



EFT operator ⟷ Amplitude basis

more direct connection to observables

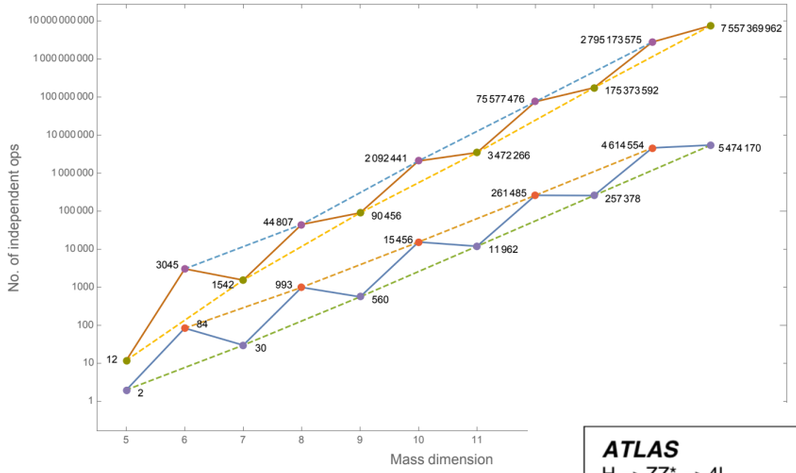
Top-down: covariant derivative expansion

[Henning, Lu, Murayama, Ellis, Zhang, et al.]

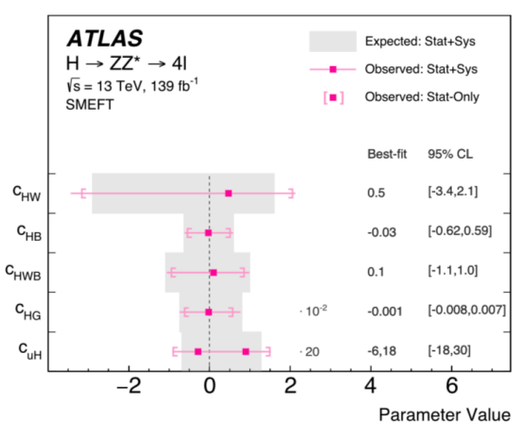
$$S_{\text{eff}} \approx S[\Phi_c] + \frac{i}{2}\text{Tr}\log\left(-\frac{\delta^2 S}{\delta\Phi^2}\bigg|_{\Phi_c}\right)$$

Bottom-up: enumerating operators

[Henning, Lu, Melia, Murayama, Lehman, Martin, et al]



Interpreting data



On-shell amplitudes

[Shadmi, et al]

'non-interference' theorem

[A.Azatov, et al, arXiv:1607.05236]

'non-renormalization'

[J. Elias-Miro, J.R.Espinosa, A. Pomarol, C. Cheung, et al]

---

tree / loop classification

[Giudice, Grojean, Pomarol, Rattazzi, et al]

LHC and future colliders provides potential excess to higher order expansion terms

HL-LHC CMS & ATLAS (3 ab^{-1}) in %									
$\mu^{\gamma\gamma}_{ggh}$	4.20	$\mu^{\gamma\gamma}_{VBF}$	12.8	$\mu^{\gamma\gamma}_{Wh}$	13.9	$\mu^{\gamma\gamma}_{Zh}$	23.3	$\mu^{\gamma\gamma}_{tth}$	9.40
	4.52		8.93		14.1		16.5		8.92
μ^{ZZ}_{ggh}	4.00	μ^{ZZ}_{VBF}	13.4	μ^{ZZ}_{Wh}	47.8	μ^{ZZ}_{Zh}	78.6	μ^{ZZ}_{tth}	24.6
	4.64		11.8		43.8		83.3		19.7
μ^{WW}_{ggh}	3.70	μ^{WW}_{VBF}	7.30	μ^{WW}_{Wh}	13.8	μ^{WW}_{Zh}	18.4	μ^{WW}_{tth}	9.70
	6.16		6.68		–		–		114
$\mu^{\tau\tau}_{ggh}$	5.50	$\mu^{\tau\tau}_{VBF}$	4.40					$\mu^{\tau\tau}_{tth}$	14.9
	8.79		8.06						73.3
$\mu^{\mu\mu}_{ggh}$	13.8	$\mu^{\mu\mu}_{VBF}$	54.0						
	18.5		36.1						
$\mu^{Z\gamma}_{ggh}$	–	$\mu^{Z\gamma}_{VBF}$	–						
	33.3		68.2						
μ^{bb}_{ggh}	24.7			μ^{bb}_{Wh}	9.40	μ^{bb}_{Zh}	6.5	μ^{bb}_{tth}	11.6
	–				10.1		5.85		14.8

μ (%)	Future Circular Colliders		
	CEPC	FCC-ee	
	240 GeV	240 GeV	365 GeV
	unpolarized		
σ_{Zh}	0.005	0.005	0.009
μ^{bb}_{Zh}	0.31†	0.30	0.50
μ^{cc}_{Zh}	3.26†	2.20	6.50
$\mu^{\tau\tau}_{Zh}$	0.82†	0.90	1.80
$\mu^{\mu\mu}_{Zh}$	17.1	19.0	40.0
μ^{WW}_{Zh}	0.98†	1.20	2.60
μ^{ZZ}_{Zh}	5.09†	4.40	12.0
$\mu^{Z\gamma}_{Zh}$	15.0	15.9	–
$\mu^{\gamma\gamma}_{Zh}$	6.84	9.00	18.0
μ^{gg}_{Zh}	1.27†	1.90	3.50

[Jorge de Blas, et al, arXiv:1907.04311]

extend the studies to dimension 8 operators and develop a more refined picture of the structures of EFT

In this talk

- Enumerate operators/helicity amplitude,

  up to dimension 8 with only four criteria

- Tree / loop classification

  tree level operators,
  loop level operator with large log enhancement,
  rational terms

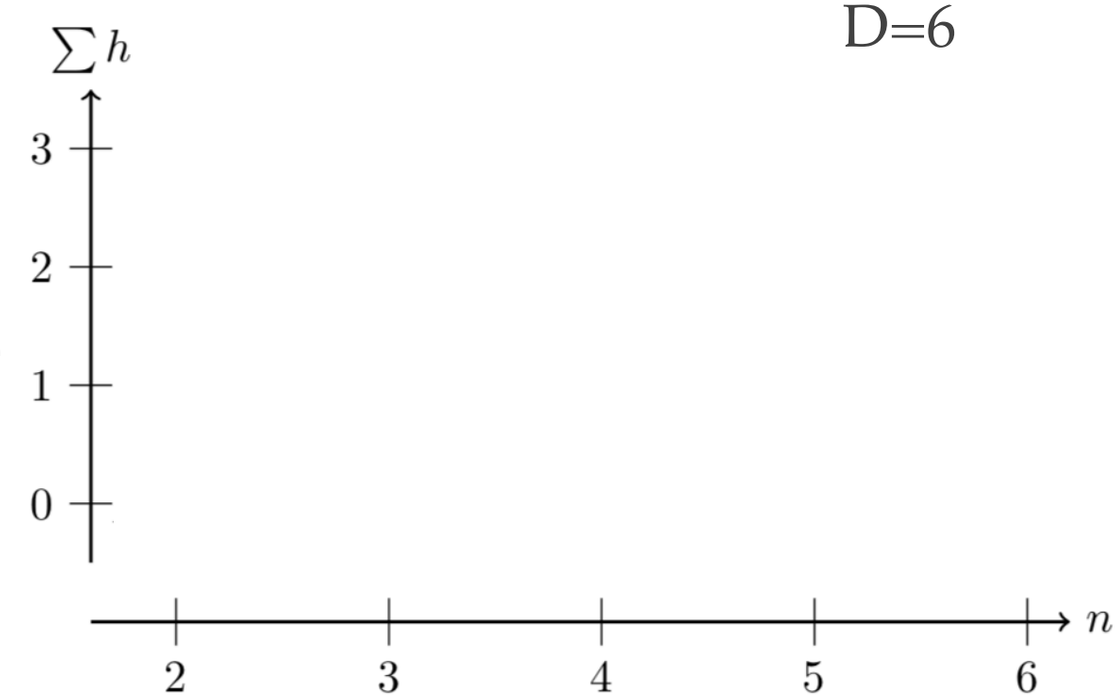
Enumerating EFT operators/Helicity amplitude

Field	Rep	Helicity
ϕ	(0,0)	0
ψ_α	$(\frac{1}{2},0)$	$\frac{1}{2}$
$\bar{\psi}_{\dot{\alpha}}$	$(0,\frac{1}{2})$	$-\frac{1}{2}$
$F_{\alpha\beta}$	(1,0)	1
$\bar{F}_{\dot{\alpha}\dot{\beta}}$	(0,1)	-1
$D_{\alpha\dot{\alpha}}$	$(\frac{1}{2},\frac{1}{2})$	

$$F_{\mu\nu}\sigma^{\mu}_{\alpha\dot{\alpha}}\sigma^{\nu}_{\beta\dot{\beta}} \equiv F_{\alpha\beta}\bar{\epsilon}_{\dot{\alpha}\dot{\beta}} + \bar{F}_{\dot{\alpha}\dot{\beta}}\epsilon_{\alpha\beta}$$

D=6

Magic Coordinate



Enumerating EFT operators/Helicity amplitude

Field	Rep	Helicity
ϕ	(0,0)	0
ψ_α	$(\frac{1}{2},0)$	$\frac{1}{2}$
$\bar{\psi}_{\dot{\alpha}}$	$(0,\frac{1}{2})$	$-\frac{1}{2}$
$F_{\alpha\beta}$	(1,0)	1
$\bar{F}_{\dot{\alpha}\dot{\beta}}$	(0,1)	-1
$D_{\alpha\dot{\alpha}}$	$(\frac{1}{2},\frac{1}{2})$	

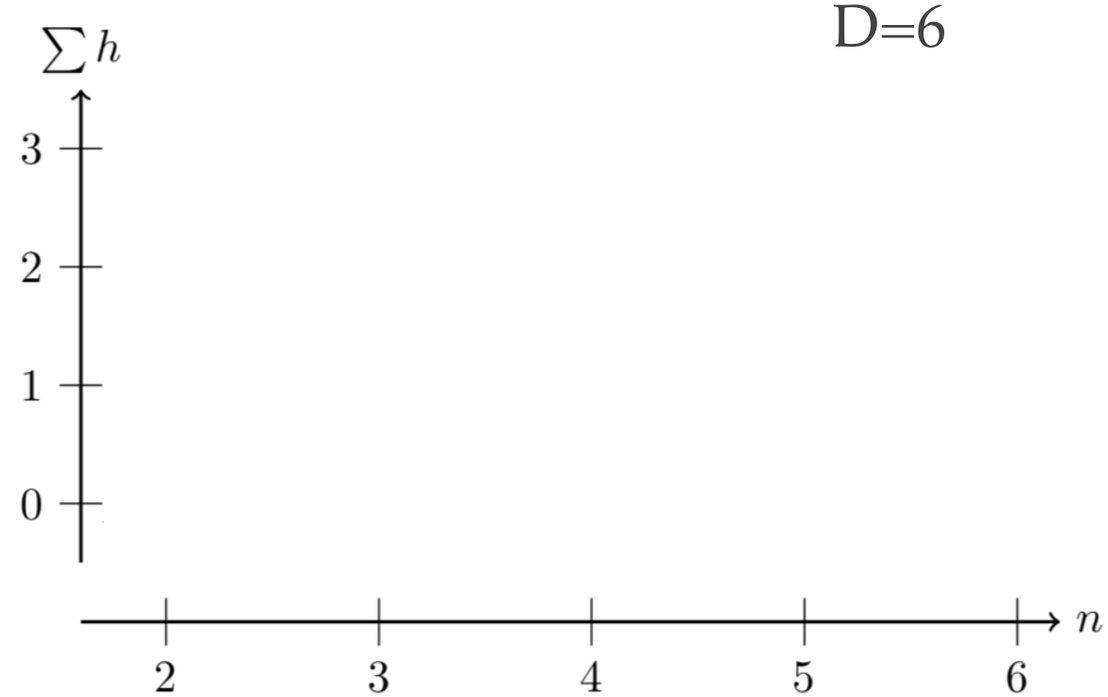
★ contains more than one field, otherwise, total derivative;

★ non vanishing Lorentz invariant:

a, even number of dotted and un-dotted indices;

b, no contraction within field strength tensor to form Lorentz invariant;

D=6



Enumerating EFT operators/Helicity amplitude

Field	Rep	Helicity
ϕ	(0,0)	0
ψ_α	$(\frac{1}{2},0)$	$\frac{1}{2}$
$\bar{\psi}_{\dot{\alpha}}$	$(0,\frac{1}{2})$	$-\frac{1}{2}$
$F_{\alpha\beta}$	(1,0)	1
$\bar{F}_{\dot{\alpha}\dot{\beta}}$	(0,1)	-1
$D_{\alpha\dot{\alpha}}$	$(\frac{1}{2},\frac{1}{2})$	

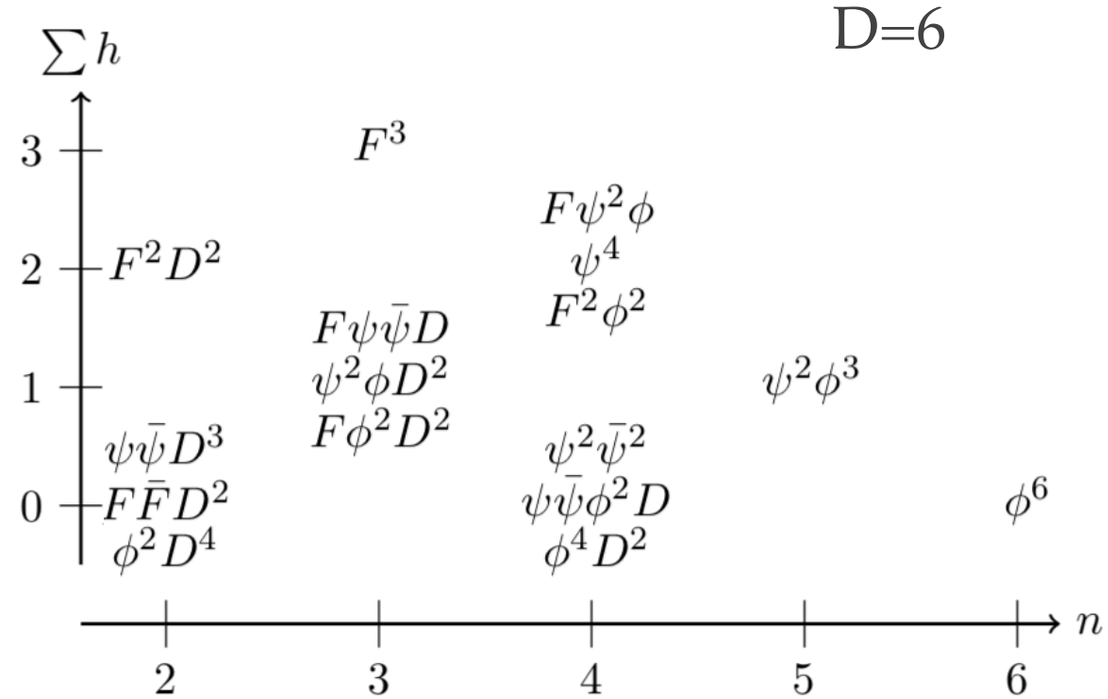
★ contains more than one field, otherwise, total derivative;

★ non vanishing Lorentz invariant:

a, even number of dotted and un-dotted indices;

b, no contraction within field strength tensor to form Lorentz invariant;

D=6



Enumerating EFT operators/Helicity amplitude

Field	Rep	Helicity
ϕ	(0,0)	0
ψ_α	$(\frac{1}{2},0)$	$\frac{1}{2}$
$\bar{\psi}_{\dot{\alpha}}$	$(0,\frac{1}{2})$	$-\frac{1}{2}$
$F_{\alpha\beta}$	(1,0)	1
$\bar{F}_{\dot{\alpha}\dot{\beta}}$	(0,1)	-1
$D_{\alpha\dot{\alpha}}$	$(\frac{1}{2},\frac{1}{2})$	

★ contains more than one field, otherwise, total derivative;

★ non vanishing Lorentz invariant:

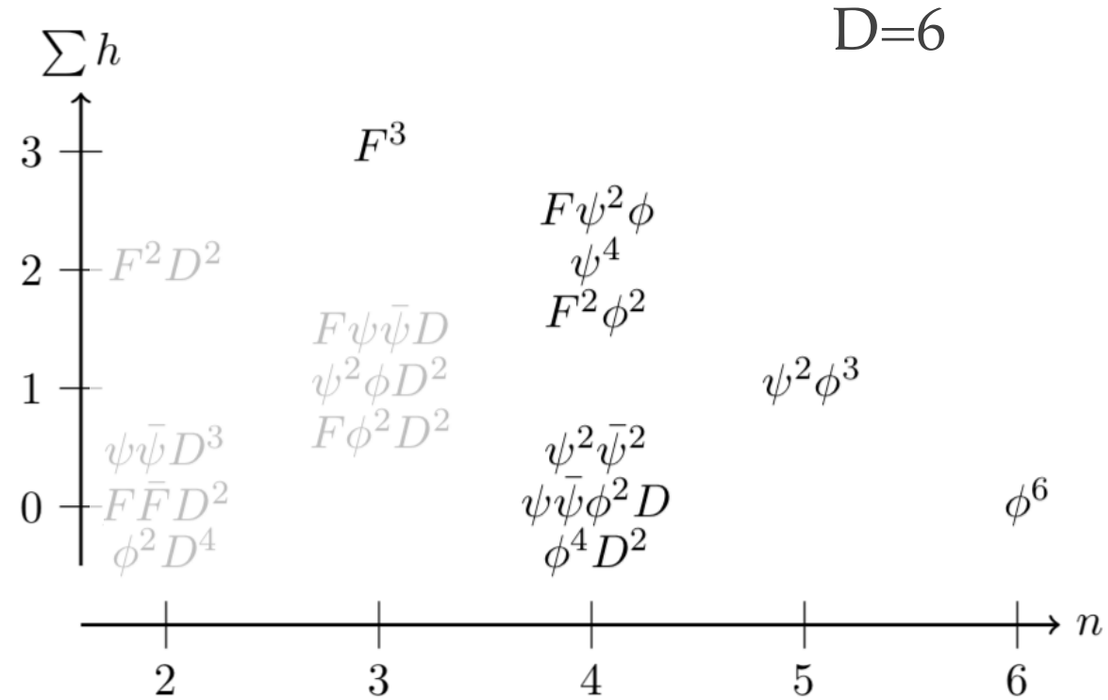
a, even number of dotted and un-dotted indices;

b, no contraction within field strength tensor to form Lorentz invariant;

★ EOM (IBP): on-shell amplitude.

less than four fields, no covariant derivatives.

D=6



Tree/Loop Classification: tree level operator

Weakly coupled UV completion

$$\mathcal{L}_{\rm UV} = -\frac{1}{2}\begin{pmatrix}\mathbf{\Phi} & \mathbf{\Psi} & \bar{\mathbf{\Psi}} & \mathbf{V}^\mu\end{pmatrix}\begin{pmatrix} D^2+M^2+\lambda\phi^2 & y\psi & y\bar{\psi} & 0 \\ y\psi & M+y\phi & -i\not{D} & 0 \\ y\bar{\psi} & i\not{D} & M+y\phi & 0 \\ 0 & 0 & 0 & \begin{matrix}-g_{\mu\nu}(D^2+M^2+g\phi^2)+ \\ D_\nu D_\mu - [D_\mu, D_\nu]\end{matrix}\end{pmatrix}\begin{pmatrix}\mathbf{\Phi} \\ \mathbf{\Psi} \\ \bar{\mathbf{\Psi}} \\ \mathbf{V}^\nu\end{pmatrix}$$

$$-\begin{pmatrix}\mathbf{\Phi} & \mathbf{\Psi} & \bar{\mathbf{\Psi}} & \mathbf{V}^\mu\end{pmatrix}\begin{pmatrix} y\psi\psi + y\bar{\psi}\bar{\psi} + \lambda\phi^3 \\ y\phi\psi \\ y\phi\bar{\psi} \\ g\bar{\psi}\sigma_\mu\psi + g\phi\overleftrightarrow{D}_\mu\phi \end{pmatrix} + \mathrm{O}(\{\mathbf{\Phi}, \mathbf{\Psi}, \bar{\mathbf{\Psi}}, \mathbf{V}\}^3)$$

$$\equiv -\frac{1}{2}\underline{\mathbf{H}}^T \underline{\underline{Q}}\,\underline{\mathbf{H}} - \underline{\mathbf{H}}^T \underline{J} + \mathrm{O}(\underline{\mathbf{H}}^3)$$

$$\underline{\mathbf{H}}_c = -\underline{\underline{Q}}^{-1}\underline{J} + \mathrm{O}(\underline{J}^2)$$

$$\mathcal{L}_{\rm EFT} = \frac{1}{2}\underline{J}^T \underline{\underline{Q}}^{-1}\underline{J} + \mathrm{O}(\underline{J}^3)$$

Tree level operator: products of currents J

Tree/Loop Classification: tree level operator

Weakly coupled UV completion

$$\mathcal{L}_{\rm UV} = -\frac{1}{2}\begin{pmatrix}\mathbf{\Phi} & \mathbf{\Psi} & \bar{\mathbf{\Psi}} & \mathbf{V}^\mu\end{pmatrix}\begin{pmatrix} D^2+M^2+\lambda\phi^2 & y\psi & y\bar{\psi} & 0 \\ y\psi & M+y\phi & -i\not{D} & 0 \\ y\bar{\psi} & i\not{D} & M+y\phi & 0 \\ 0 & 0 & 0 & \begin{matrix}-g_{\mu\nu}(D^2+M^2+g\phi^2)+\\ D_\nu D_\mu - [D_\mu, D_\nu]\end{matrix}\end{pmatrix}\begin{pmatrix}\mathbf{\Phi}\\ \mathbf{\Psi}\\ \bar{\mathbf{\Psi}}\\ \mathbf{V}^\nu\end{pmatrix}$$

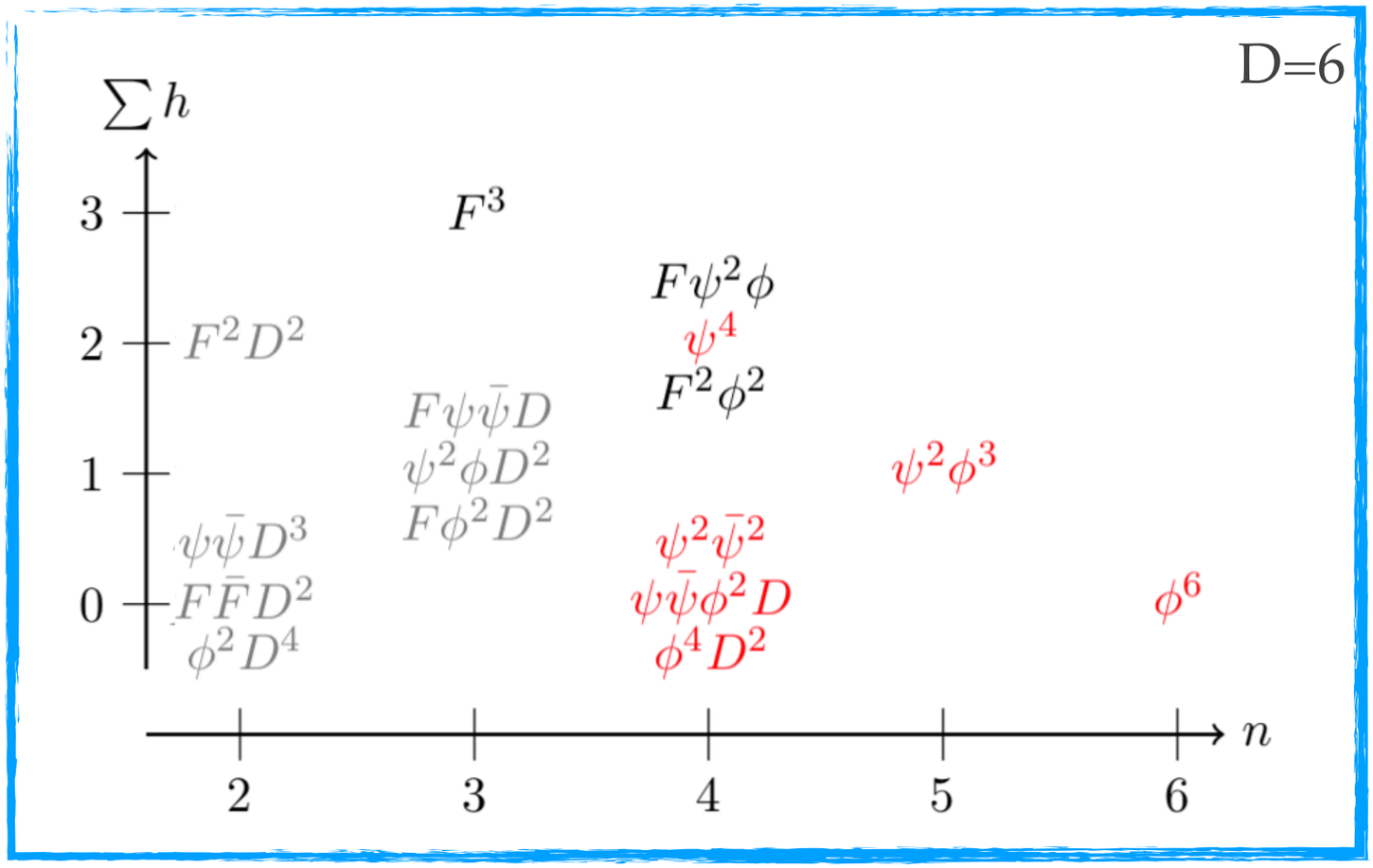
$$-\begin{pmatrix}\mathbf{\Phi} & \mathbf{\Psi} & \bar{\mathbf{\Psi}} & \mathbf{V}^\mu\end{pmatrix}\begin{pmatrix} y\psi\psi + y\bar{\psi}\bar{\psi} + \lambda\phi^3 \\ y\phi\psi \\ y\phi\bar{\psi} \\ g\bar{\psi}\sigma_\mu\psi + g\phi\overleftrightarrow{D}_\mu\phi\end{pmatrix} + \mathrm{O}(\{\mathbf{\Phi}, \mathbf{\Psi}, \bar{\mathbf{\Psi}}, \mathbf{V}\}^3)$$

$$\equiv -\frac{1}{2}\underline{\mathbf{H}}^T \underline{\underline{Q}}\,\underline{\mathbf{H}} - \underline{\mathbf{H}}^T \underline{J} + \mathrm{O}(\underline{\mathbf{H}}^3)$$

$$\underline{\mathbf{H}}_c = -\underline{\underline{Q}}^{-1}\underline{J} + \mathrm{O}(\underline{J}^2)$$

$$\mathcal{L}_{\rm EFT} = \frac{1}{2}\underline{J}^T \underline{\underline{Q}}^{-1}\underline{J} + \mathrm{O}(\underline{J}^3)$$

Tree level operator: products of currents J



Tree/Loop Classification: tree level operator

Weakly coupled UV completion

$$\mathcal{L}_{\rm UV} = -\frac{1}{2}\begin{pmatrix}\mathbf{\Phi} & \mathbf{\Psi} & \bar{\mathbf{\Psi}} & \mathbf{V}^\mu\end{pmatrix}\begin{pmatrix} D^2+M^2+\lambda\phi^2 & y\psi & y\bar{\psi} & 0 \\ y\psi & M+y\phi & -i\not{D} & 0 \\ y\bar{\psi} & i\not{D} & M+y\phi & 0 \\ 0 & 0 & 0 & \begin{matrix}-g_{\mu\nu}(D^2+M^2+g\phi^2)+\\ D_\nu D_\mu - [D_\mu, D_\nu]\end{matrix}\end{pmatrix}\begin{pmatrix}\mathbf{\Phi}\\ \mathbf{\Psi}\\ \bar{\mathbf{\Psi}}\\ \mathbf{V}^\nu\end{pmatrix}$$

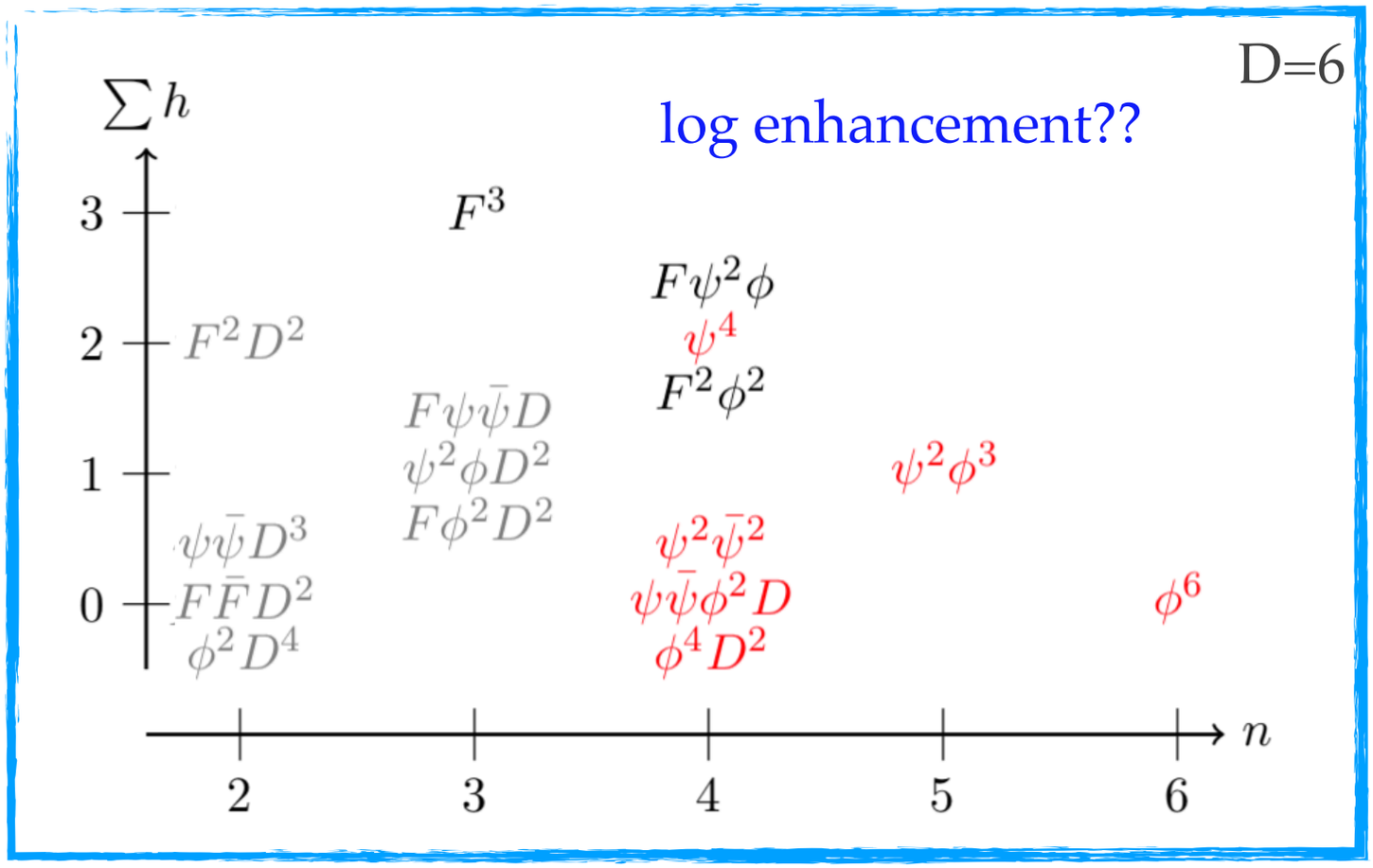
$$-\begin{pmatrix}\mathbf{\Phi} & \mathbf{\Psi} & \bar{\mathbf{\Psi}} & \mathbf{V}^\mu\end{pmatrix}\begin{pmatrix} y\psi\psi + y\bar{\psi}\bar{\psi} + \lambda\phi^3 \\ y\phi\psi \\ y\phi\bar{\psi} \\ g\bar{\psi}\sigma_\mu\psi + g\phi\overleftrightarrow{D}_\mu\phi\end{pmatrix} + \mathrm{O}(\{\mathbf{\Phi}, \mathbf{\Psi}, \bar{\mathbf{\Psi}}, \mathbf{V}\}^3)$$

$$\equiv -\frac{1}{2}\underline{\mathbf{H}}^T \underline{\underline{Q}}\,\underline{\mathbf{H}} - \underline{\mathbf{H}}^T \underline{J} + \mathrm{O}(\underline{\mathbf{H}}^3)$$

$$\underline{\mathbf{H}}_c = -\underline{\underline{Q}}^{-1}\underline{J} + \mathrm{O}(\underline{J}^2)$$

$$\mathcal{L}_{\rm EFT} = \frac{1}{2}\underline{J}^T \underline{\underline{Q}}^{-1}\underline{J} + \mathrm{O}(\underline{J}^3)$$

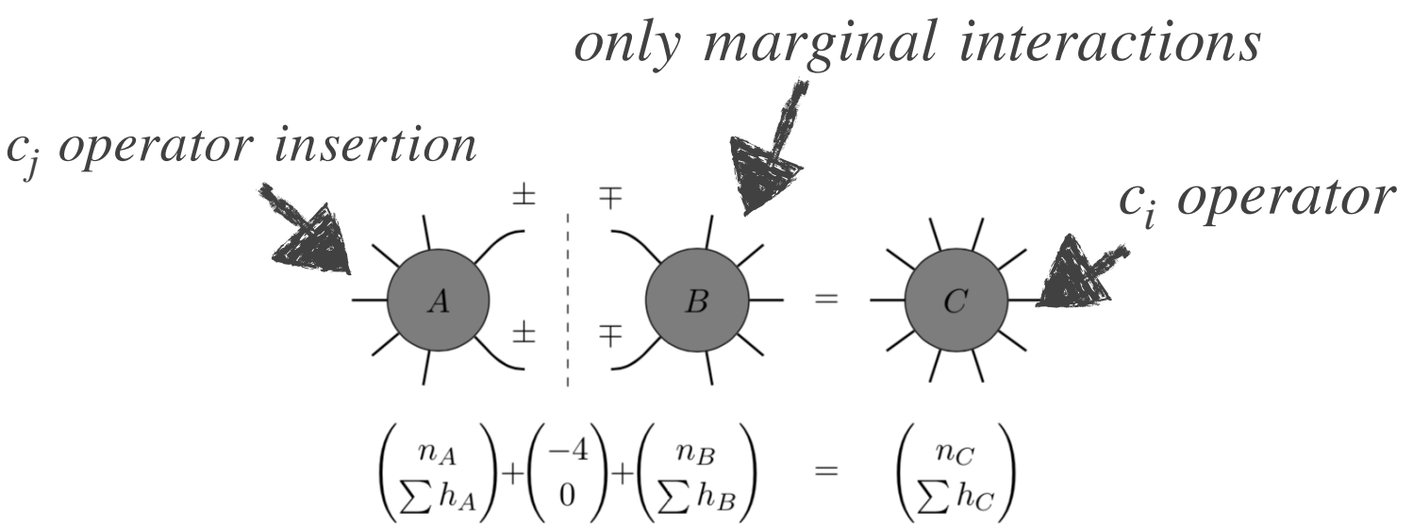
Tree level operator: products of currents J



Tree/Loop Classification: loop level operator

'non-renormalization' theorem
[C. Cheung, et al, arXiv:1505.01844, …]

$$\frac{dc_i(\mu)}{d\log\mu} = \sum_j \frac{1}{16\pi^2}\gamma_{ij}c_j$$



no kinematic singularity for two particle cut, non-renormalization

$$(n_B, \sum h_B) = (n_C + 4 - n_A, \sum h_C - \sum h_A)$$

Tree/Loop Classification: loop level operator

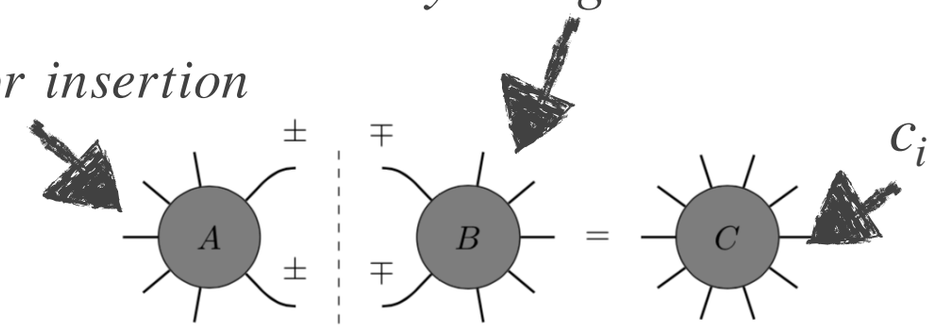
'non-renormalization' theorem
[C. Cheung, et al, arXiv:1505.01844, …]

$$\frac{dc_i(\mu)}{d\log\mu} = \sum_j \frac{1}{16\pi^2}\gamma_{ij}c_j$$

only marginal interactions

c_j *operator insertion*

c_i *operator*

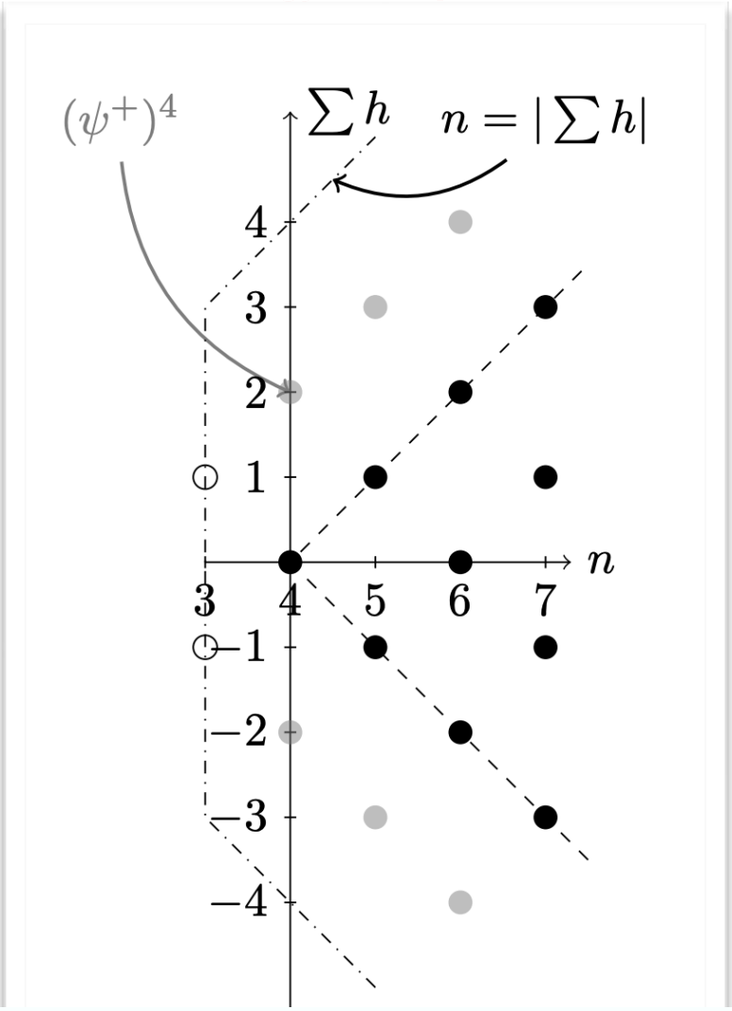


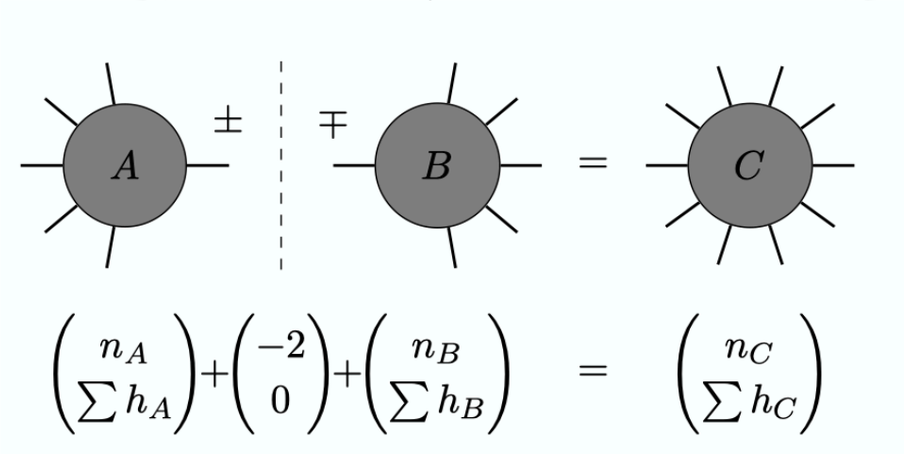
$$\begin{pmatrix} n_A \\ \sum h_A \end{pmatrix} + \begin{pmatrix} -4 \\ 0 \end{pmatrix} + \begin{pmatrix} n_B \\ \sum h_B \end{pmatrix} = \begin{pmatrix} n_C \\ \sum h_C \end{pmatrix}$$

no kinematic singularity for two particle cut, non-renormalization

$$(n_B, \sum h_B) = (n_C + 4 - n_A, \sum h_C - \sum h_A)$$

$d = 4$

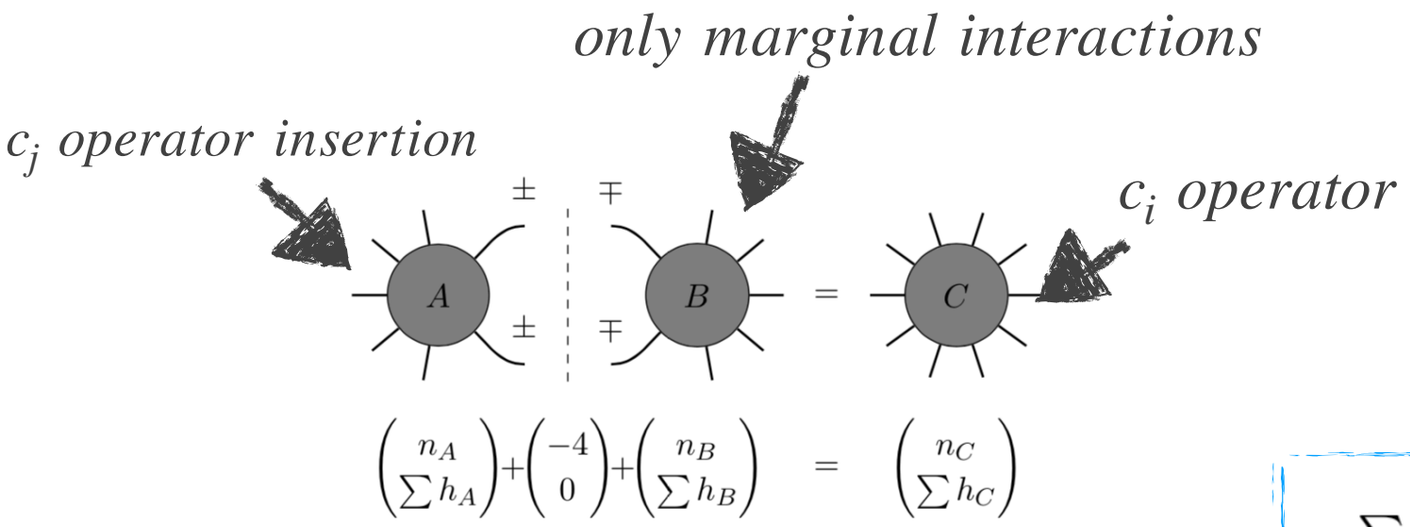




Tree/Loop Classification: loop level operator

'non-renormalization' theorem
[C. Cheung, et al, arXiv:1505.01844, …]

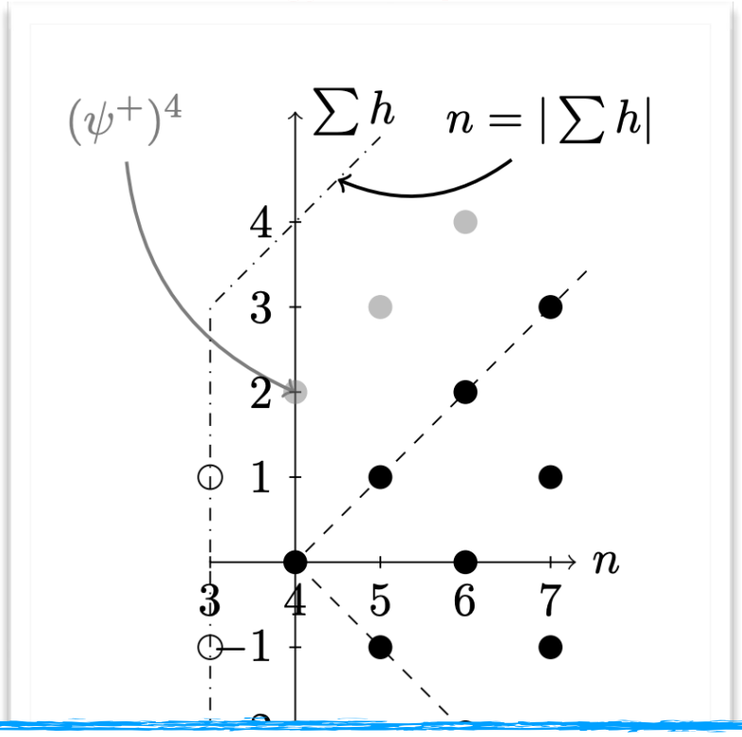
$$\frac{dc_i(\mu)}{d\log\mu} = \sum_j \frac{1}{16\pi^2}\gamma_{ij}c_j$$

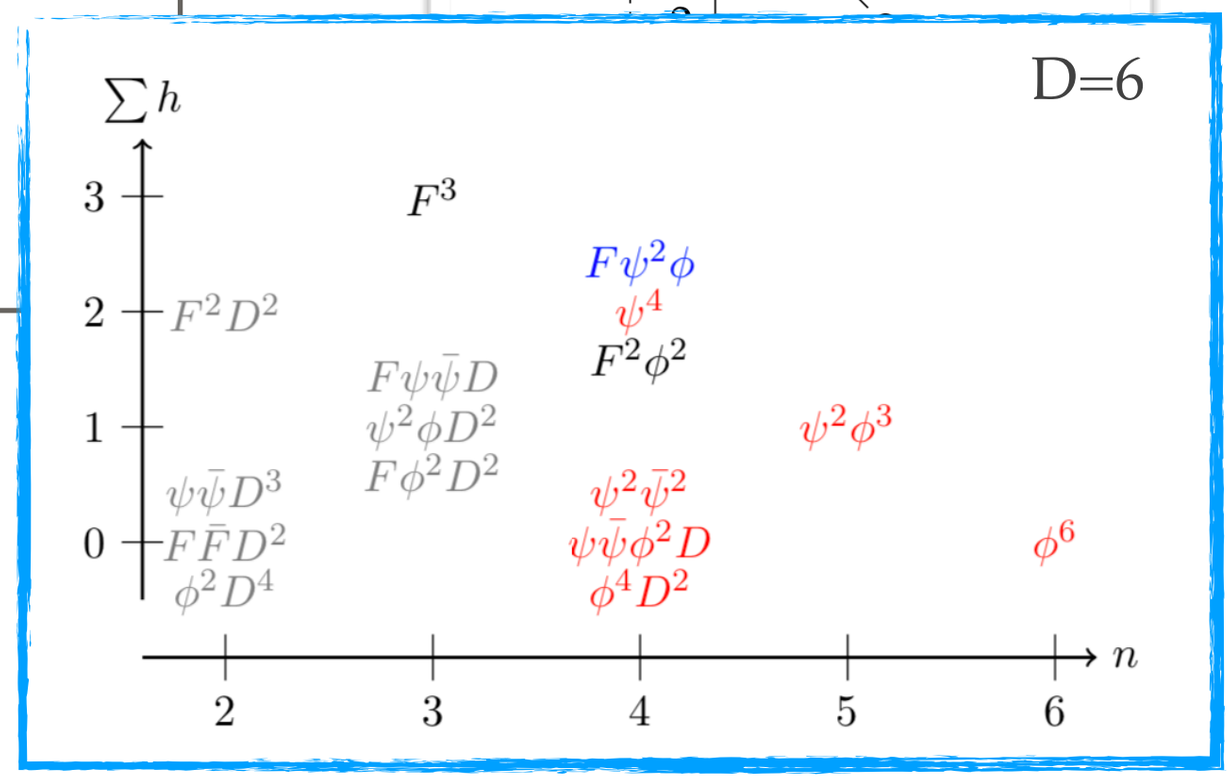


no kinematic singularity for two particle cut, non-renormalization

$$(n_B, \sum h_B) = (n_C + 4 - n_A, \sum h_C - \sum h_A)$$

$d = 4$



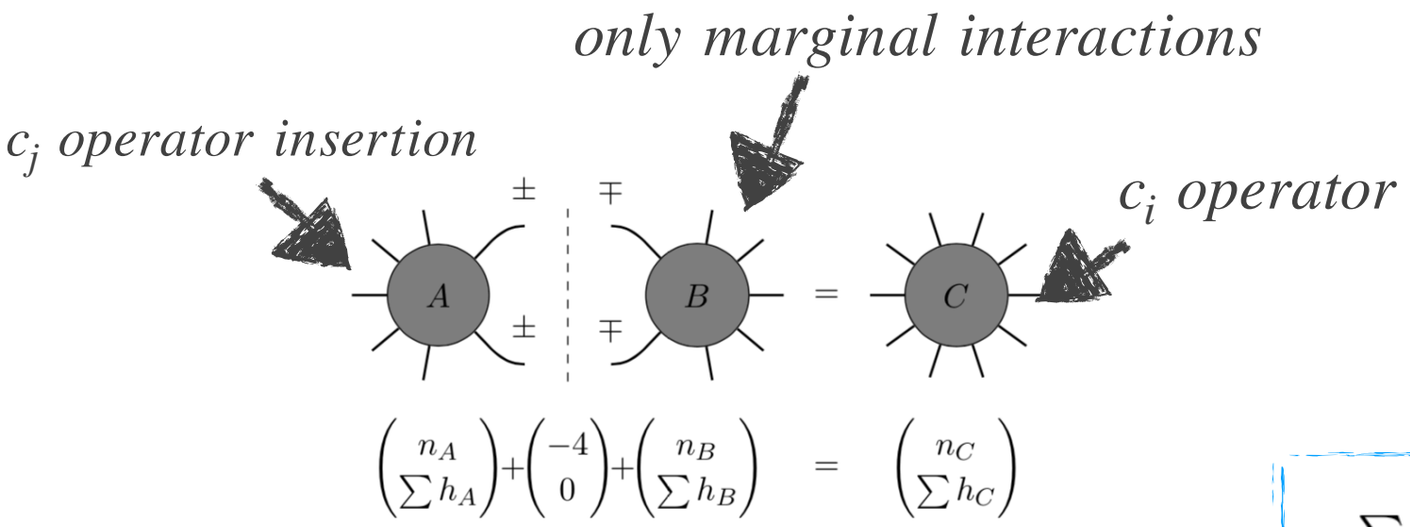


for tree level c_j only

Tree/Loop Classification: loop level operator

'non-renormalization' theorem
[C. Cheung, et al, arXiv:1505.01844, …]

$$\frac{dc_i(\mu)}{d\log\mu} = \sum_j \frac{1}{16\pi^2}\gamma_{ij}c_j$$

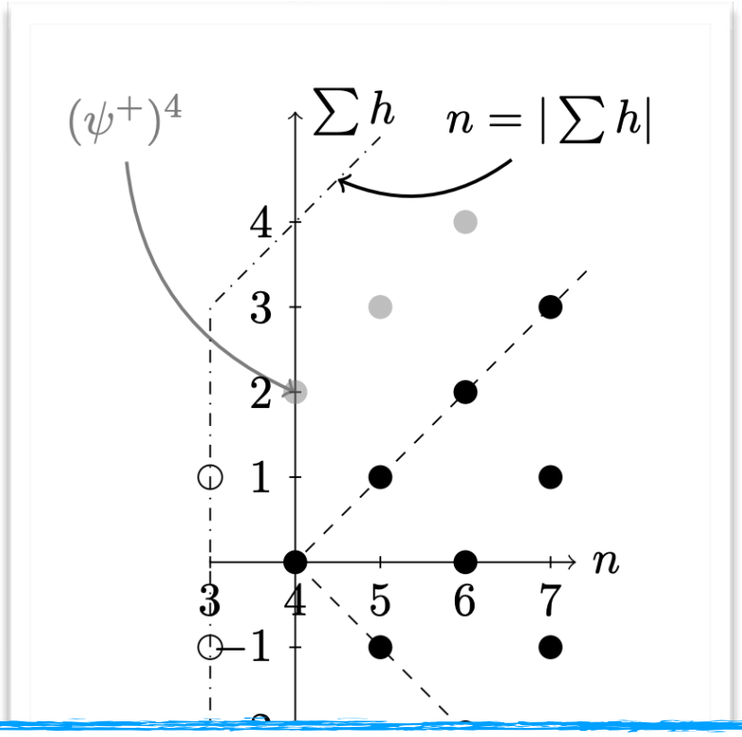


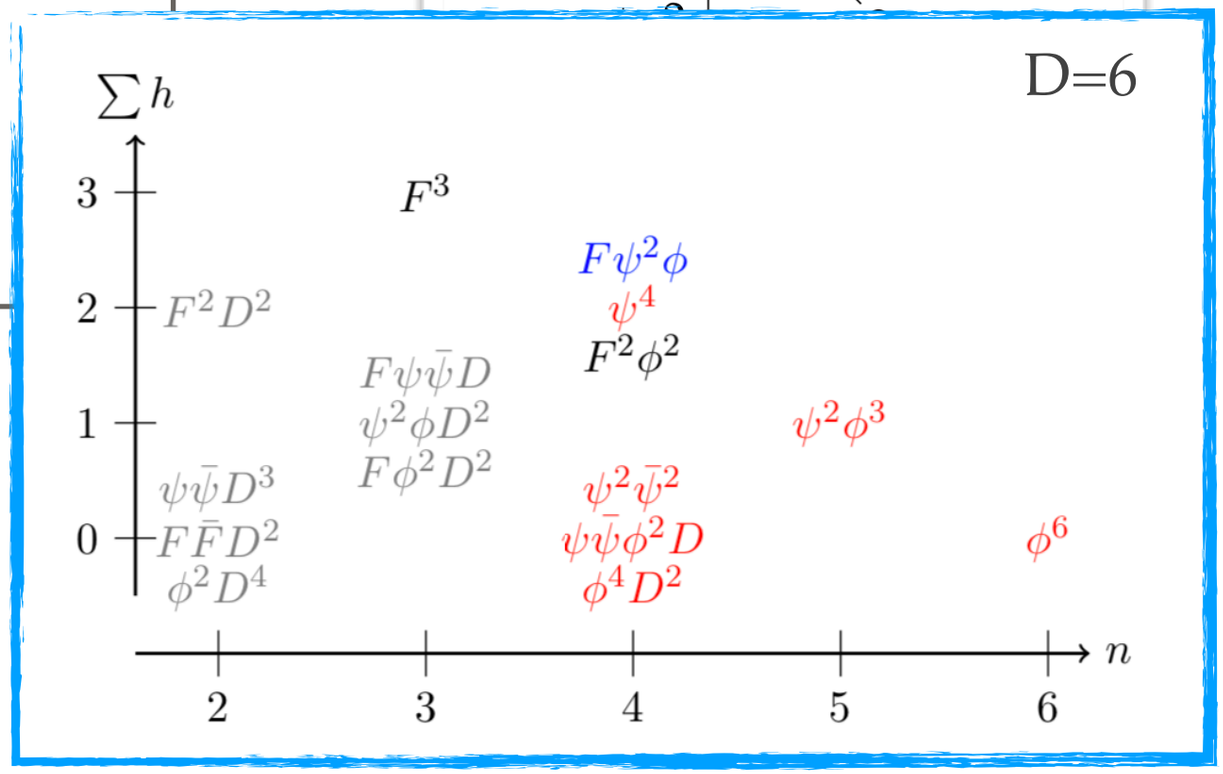
no kinematic singularity for two particle cut, non-renormalization

$$(n_B, \sum h_B) = (n_C + 4 - n_A, \sum h_C - \sum h_A)$$

tree level only renormalize tree level, except for ψ^4

$d = 4$





for tree level c_j only

Tree/Loop Classification: loop level operator

★ contains more than one field, otherwise, total derivative;

★ non vanishing Lorentz invariant:

a, even number of dotted and un-dotted indices;

b, no contraction within field strength tensor to form Lorentz invariant;

★ EOM (IBP): on-shell amplitude.

less than four fields, no covariant derivatives.

Tree level operator: products of currents J

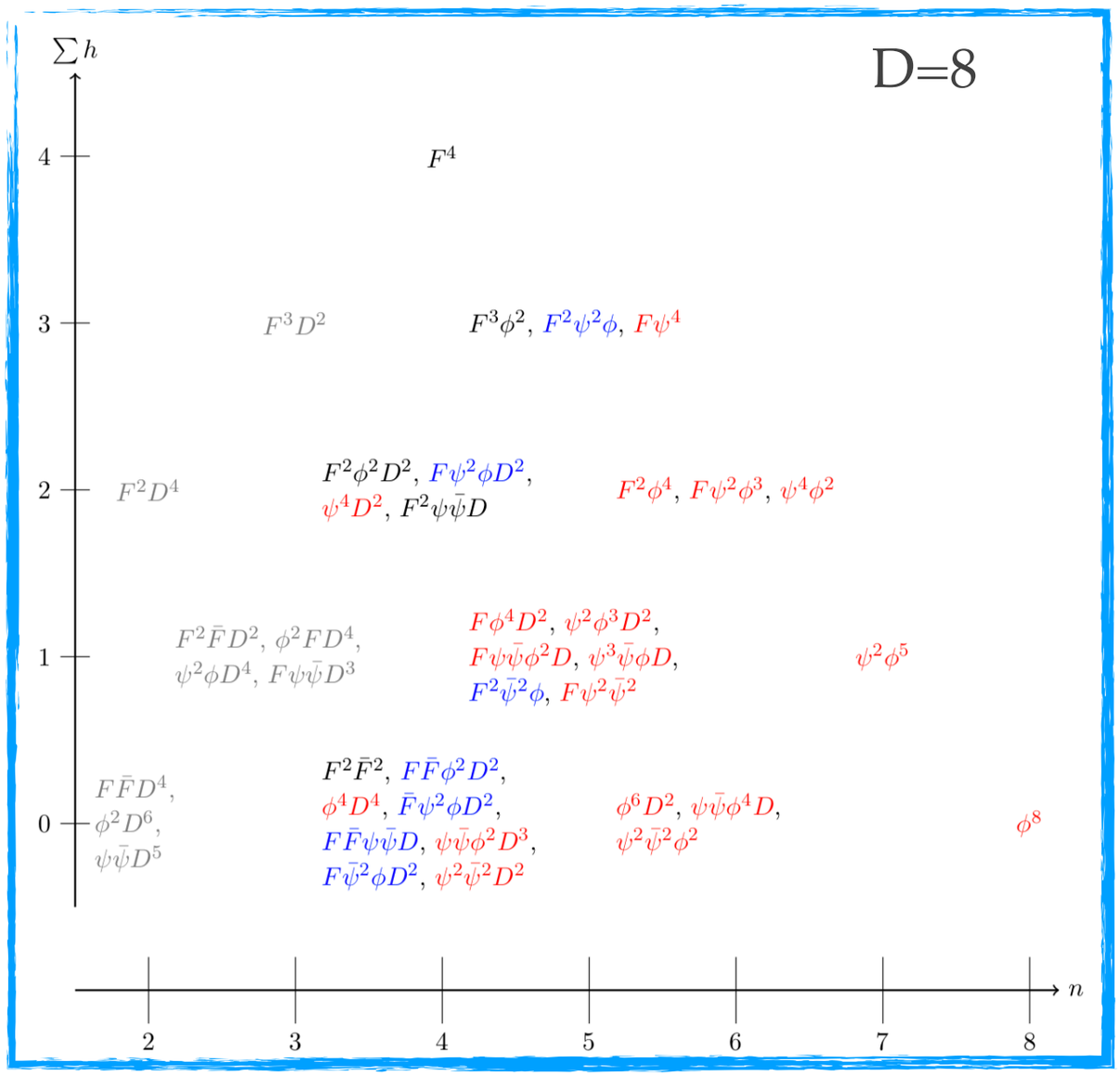
'non-renormalization' theorem

[C. Cheung, et al, arXiv:1505.01844, …]

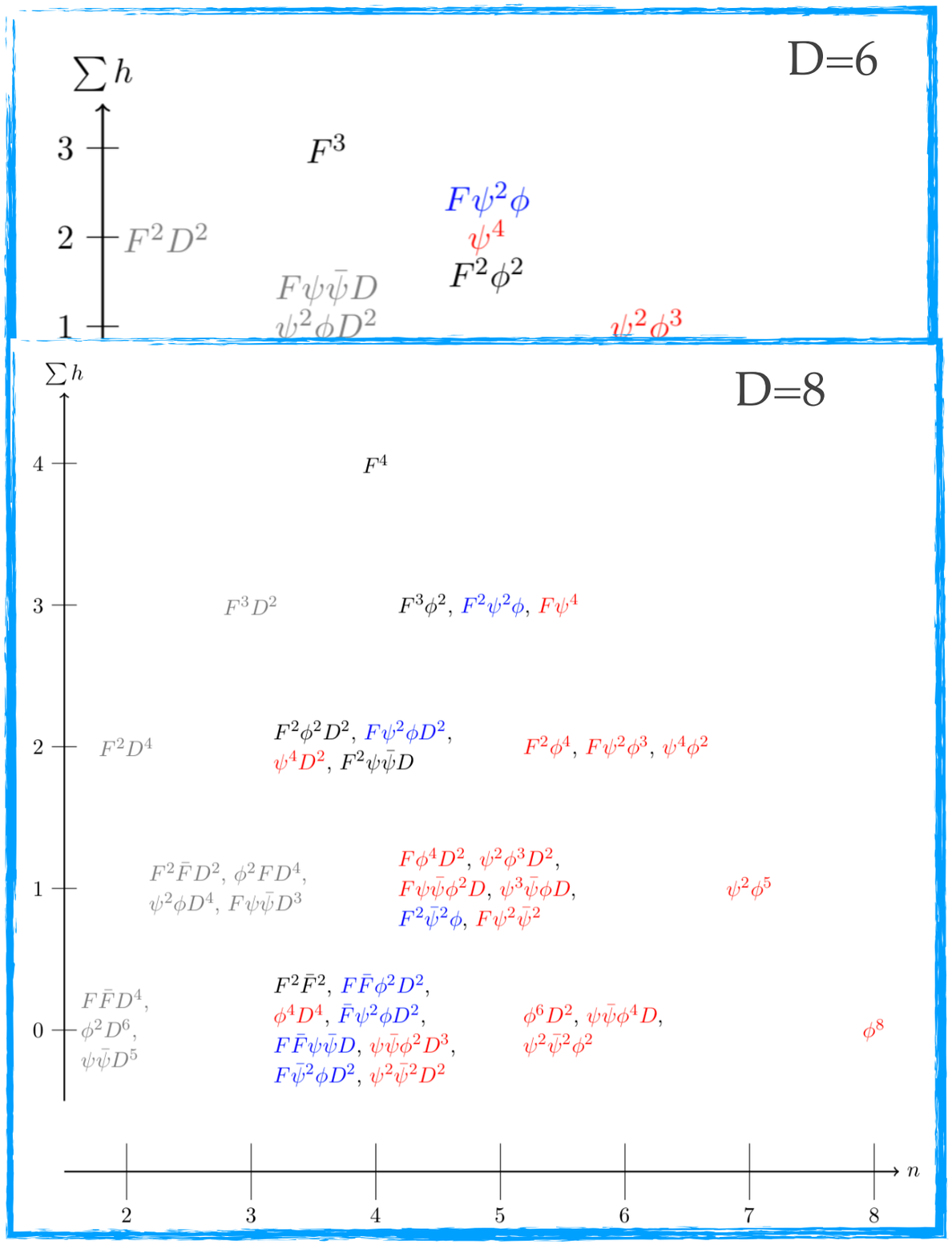
D=8

Tree level: # of field strength <=1

Sparsity of the anomalous dimension matrix persists



Contributions to observable: size of the Wilson coefficient



$$\phi^2 F^2 : h \to \gamma\gamma$$

Loop level operator
and no large log enhancement
from the running of a tree-level operator

$$F^2\phi^2 D^2 : ZZ\gamma, Z\gamma\gamma$$

Loop level operator
and no large log enhancement
from the running of a tree-level operator

Contributions to observable: interference term first

$BSM : \frac{1}{\Lambda^2}$

$$\sigma \propto |SM|^2 + \boxed{2\Re(SM * BSM)} + |BSM|^2$$

$$\frac{1}{\Lambda^2} \qquad \frac{1}{\Lambda^4}$$

Some interference term vanishes due to helicity selection rule, at tree level and d = 6

(4, 0) process	d. 4	d. 6
$V^+V^+V^-V^-$	Y(n.A.)	N
$V^+V^-\psi^+\psi^-$	Y	N
$V^+V^-\phi\phi$	Y	N
$V^+\psi^-\psi^-\phi$	Y	N
$\psi^+\psi^+\psi^-\psi^-$	Y	Y
$\psi^+\psi^-\phi\phi$	Y	Y
$\phi\phi\phi\phi$	Y	Y

(4, 2) process	d. 4	d. 6
$V^+V^+V^+V^-$	N	Y(n.A.)
$V^+V^+\psi^+\psi^-$	N	Y(n.A.)
$V^+V^+\phi\phi$	N	Y
$V^+\psi^+\psi^+\phi$	N	Y
$\psi^+\psi^+\psi^+\psi^+$	Y	Y

Loop level operators

tree level interferes with tree level

Finite mass converts the loop level generate amplitude (4,2) to (4,0): $\frac{m^2}{\Lambda^2}$

d=8 interference with SM: $\frac{1}{\Lambda^4}$

Data: $\Lambda \gg m$ interference suppressed by only loop factors will be dominating

One loop helicity structure:

Tree level

$(4,2)$ process	d. 4	d. 6
$V^+V^+V^+V^-$	N	Y(n.A.)
$V^+V^+\psi^+\psi^-$	N	Y(n.A.)
$V^+V^+\phi\phi$	N	Y
$V^+\psi^+\psi^+\phi$	N	Y
$\psi^+\psi^+\psi^+\psi^+$	Y	Y

one loop

$(4,2)$ process	d. 4	d. 6
$V^+V^+V^+V^-$		Y(n.A.)
$V^+V^+\psi^+\psi^-$	✅	Y(n.A.)
$V^+V^+\phi\phi$		Y
$V^+\psi^+\psi^+\phi$		Y
$\psi^+\psi^+\psi^+\psi^+$	Y	Y

d. 6 part is one loop, two loop level suppression!

One loop helicity structure:

Tree level

$(4,2)$ process	d. 4	d. 6
$V^+V^+V^+V^-$	N	Y(n.A.)
$V^+V^+\psi^+\psi^-$	N	Y(n.A.)
$V^+V^+\phi\phi$	N	Y
$V^+\psi^+\psi^+\phi$	N	Y
$\psi^+\psi^+\psi^+\psi^+$	Y	Y

one loop

$(4,2)$ process	d. 4	d. 6
$V^+V^+V^+V^-$		Y(n.A.)
$V^+V^+\psi^+\psi^-$	✅	Y(n.A.)
$V^+V^+\phi\phi$		Y
$V^+\psi^+\psi^+\phi$		Y
$\psi^+\psi^+\psi^+\psi^+$	Y	Y

d. 6 part is one loop, two loop level suppression

$(4,0)$ process	d. 4	d. 6
$V^+V^+V^-V^-$	Y(n.A.)	N
$V^+V^-\psi^+\psi^-$	Y	N
$V^+V^-\phi\phi$	Y	N
$V^+\psi^-\psi^-\phi$	Y	N
$\psi^+\psi^+\psi^-\psi^-$	Y	Y
$\psi^+\psi^-\phi\phi$	Y	Y
$\phi\phi\phi\phi$	Y	Y

		$(4,0)$			
		$V^+V^+V^-V^-$	$V^+V^-\psi^+\psi^-$	$V^+V^-\phi\phi$	$V^+\psi^-\psi^-\phi$
$(4,0)$	$\psi^2\bar{\psi}^2$	$\times$	0	$\times$	0^*
	$\phi^4 D^2$	$\times$	$\times$	0	$\times$
	$\phi^2\psi\bar{\psi}D$	$\times$	0	0	0

Interference: vanishes at one loop!

no interference theorem are particularly robust against some radiative corrections.

Tree/Loop Classification– Rational term

		(4, 0)				(4, 2)	
		$V^+V^+V^-V^-$	$V^+V^-\psi^+\psi^-$	$V^+V^-\phi\phi$	$V^+\psi^-\psi^-\phi$	$V^+V^+V^+V^-$	$V^+V^+\psi^+\psi^-$
(4, 0)	$\psi^2\bar{\psi}^2$	×	0	×	0^*	×	R
	$\phi^4 D^2$	×	×	0	×	×	×
	$\phi^2\psi\bar{\psi}D$	×	0	0	0	×	R
(4, 2)	$F\psi^2\phi$	×	R	R	R	×	0
	$F^2\phi^2$	R	0	R	R	0^*	0^*
	ψ^4	×	0	×	0	×	0
(4, −2)	$\bar{F}\bar{\psi}^2\phi$	×	R	R	R	×	0
	$\bar{F}^2\phi^2$	R	0	R	R	0	0
	$\bar{\psi}^4$	×	0	×	R	×	0

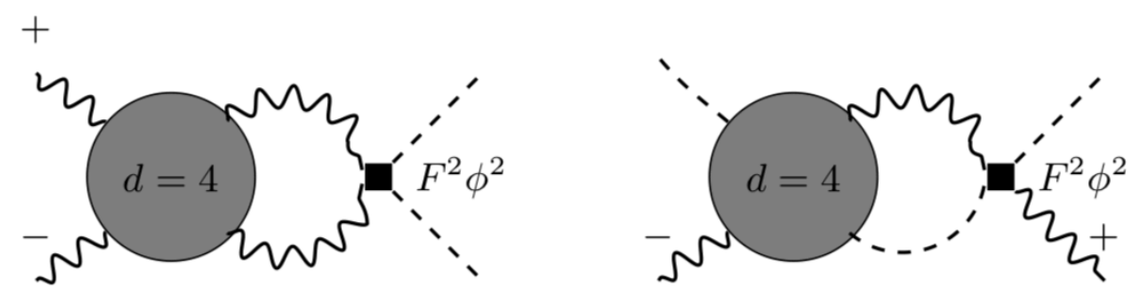
Tree/Loop Classification– Rational term

		(4, 0)				(4, 2)	
		$V^+V^+V^-V^-$	$V^+V^-\psi^+\psi^-$	$V^+V^-\phi\phi$	$V^+\psi^-\psi^-\phi$	$V^+V^+V^+V^-$	$V^+V^+\psi^+\psi^-$
(4, 0)	$\psi^2\bar{\psi}^2$	×	0	×	0*	×	R
	$\phi^4 D^2$	×	×	0	×	×	×
	$\phi^2\psi\bar{\psi}D$	×	0	0	0	×	R
(4, 2)	$F\psi^2\phi$	×	R	R	R	×	0
	$F^2\phi^2$	R	0	R	R	0*	0*
	ψ^4	×	0	×	0	×	0
(4, −2)	$\bar{F}\bar{\psi}^2\phi$	×	R	R	R	×	0
	$\bar{F}^2\phi^2$	R	0	R	R	0	0
	$\bar{\psi}^4$	×	0	×	R	×	0

Lorentz symmetry, some selection rules

—

angular momentum conservation?



$$F^2\phi^2 : F_{\alpha\beta}F^{\alpha\beta}\phi^2$$

$$(\frac{n}{2}, \frac{m}{2}) : 2J = n + m$$

n, m : # of un-contracted un-dotted, dotted indices

highest angular momentum

$$J \geq |\Delta h_f|$$ COM-frame

Tree/Loop Classification– Rational term

		(4, 0)				(4, 2)	
		$V^+V^+V^-V^-$	$V^+V^-\psi^+\psi^-$	$V^+V^-\phi\phi$	$V^+\psi^-\psi^-\phi$	$V^+V^+V^+V^-$	$V^+V^+\psi^+\psi^-$
(4, 0)	$\psi^2\bar{\psi}^2$	×	0	×	0*	×	R
	$\phi^4 D^2$	×	×	0	×	×	×
	$\phi^2\psi\bar{\psi}D$	×	0	0	0	×	R
(4, 2)	$F\psi^2\phi$	×	R	R	R	×	0
	$F^2\phi^2$	R	0	R	R	0*	0*
	ψ^4	×	0	×	0	×	0
(4, −2)	$\bar{F}\bar{\psi}^2\phi$	×	R	R	R	×	0
	$\bar{F}^2\phi^2$	R	0	R	R	0	0
	$\bar{\psi}^4$	×	0	×	R	×	0

$$(\frac{n}{2}, \frac{m}{2}) : 2J = n + m$$

n, m : # of un-contracted un-dotted, dotted indices

highest angular momentum

$J \geq |\Delta h_f|$ COM-frame

$$F^2\phi^2 : F_{\alpha\beta}F^{\alpha\beta}\phi^2$$

J		
0	$F_{\alpha\beta}F^{\alpha\beta} \to V^-V^-$	✅
0	$F_{\alpha\beta}F^{\alpha\beta} \to$	0
1	$F_{\alpha\beta}\phi \to V^-\phi$	✅
1	$F_{\alpha\beta}\phi \to \psi^-\psi^-$	✅
1	$F_{\alpha\beta}\phi \to V^+V^-$	0
0	$F_{\alpha\beta}F^{\alpha\beta} \to \psi^+\psi^-$	0

Tree/Loop Classification– Rational term

		(4, 0)				(4, 2)	
		$V^+V^+V^-V^-$	$V^+V^-\psi^+\psi^-$	$V^+V^-\phi\phi$	$V^+\psi^-\psi^-\phi$	$V^+V^+V^+V^-$	$V^+V^+\psi^+\psi^-$
(4, 0)	$\psi^2\bar{\psi}^2$	×	0	×	0*	×	R
	$\phi^4 D^2$	×	×	0	×	×	×
	$\phi^2\psi\bar{\psi}D$	×	0	0	0	×	R
(4, 2)	$F\psi^2\phi$	×	R	R	R	×	0
	$F^2\phi^2$	R	0	R	R	0*	0*
	ψ^4	×	0	×	0	×	0
(4, −2)	$\bar{F}\bar{\psi}^2\phi$	×	R	R	R	×	0
	$\bar{F}^2\phi^2$	R	0	R	R	0	0
	$\bar{\psi}^4$	×	0	×	R	×	0

Lorentz symmetry, some selection rules

—

angular momentum conservation

$$(\frac{n}{2}, \frac{m}{2}) : 2J = n + m$$

n, m : # of un-contracted un-dotted, dotted indices

highest angular momentum

$$J \geq |\Delta h_f|$$ COM-frame

more dedicate explanation with partial wave expansion, see:

[M. Jiang, et al, arXiv:2001.04481]

Tree/Loop Classification– Rational term

		(4,0)				(4,2)	
		$V^+V^+V^-V^-$	$V^+V^-\psi^+\psi^-$	$V^+V^-\phi\phi$	$V^+\psi^-\psi^-\phi$	$V^+V^+V^+V^-$	$V^+V^+\psi^+\psi^-$
(4,0)	$\psi^2\bar{\psi}^2$	×	0	×	0*	×	R
	$\phi^4 D^2$	×	×	0	×	×	×
	$\phi^2\psi\bar{\psi}D$	×	0	0	0	×	R
(4,2)	$F\psi^2\phi$	×	R	R	R	×	0
	$F^2\phi^2$	R	0	R	R	0*	0*
	ψ^4	×	0	×	0	×	0
(4,−2)	$\bar{F}\bar{\psi}^2\phi$	×	R	R	R	×	0
	$\bar{F}^2\phi^2$	R	0	R	R	0	0
	$\bar{\psi}^4$	×	0	×	R	×	0

Lorentz symmetry, some selection rules

—

angular momentum conservation

$$(\frac{n}{2}, \frac{m}{2}) : 2J = n + m$$

n, m : # of un-contracted un-dotted, dotted indices

highest angular momentum

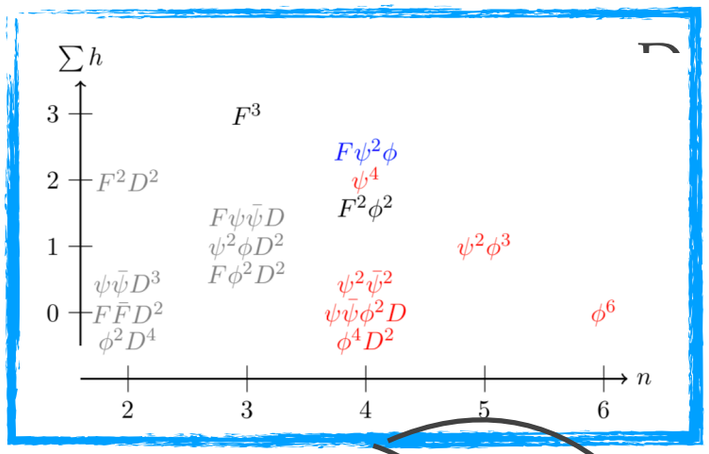
$$J \geq |\Delta h_f|$$ COM-frame

more dedicate explanation with partial wave expansion, see:

[M. Jiang, et al, arXiv:2001.04481]

Observation:
(4,0) amplitude cannot be generated at d=6 until two loop

Conclusions



With the magic coordinate, for generic EFT of scalars, fermions and vectors:

we enumerated classes of Lorentz structures of operators with FOUR criteria up to d=8;

determined the tree/loop classification and interference pattern

- Field strength operators are hard to be tree level
- Tree tends to renormalize tree only at d = 6
- Amplitude from tree operator interferes with d=4 tree amplitude
- Non-interference up to two loop

determined the helicity amplitudes up to the full one loop level

- some amplitudes at d=6 vanish completely at one loop in a weakly coupled UV theory, calls for explanations in the UV theory frame work

		(4, 0)				(4, 2)	
		$-\Lambda-\Lambda+\Lambda+\Lambda$	$-\phi_+\phi_-\Lambda+\Lambda$	$\phi\phi_-\Lambda+\Lambda$	$\phi_-\phi_-\phi_+\Lambda$	$-\Lambda+\Lambda+\Lambda+\Lambda$	$-\phi_+\phi_+\Lambda+\Lambda$
(4, 0)	$\psi^2\bar{\psi}^2$	×	0	×	0*	×	R
	ϕ^4D^2	×	×	0	×	×	×
	$\phi^2\psi\bar{\psi}D$	×	0	0	0	×	R
(4, 2)	$F\psi^2\phi$	×	R	R	R	×	0
	$F^2\phi^2$	R	0	R	R	0*	0*
	ψ^4	×	0	×	0	×	0
(4, −2)	$\bar{F}\bar{\psi}^2\phi$	×	R	R	R	×	0
	$\bar{F}^2\phi^2$	R	0	R	R	0	0
	$\bar{\psi}^4$	×	0	×	R	×	0

Thank you