QFT 2

Topic 4: EFT

EFFECTIVE FIELD THEORY

1. DIMENSIONAL ANALYSIS
2. HEURISTIC IDEA
3. UV COMPLETIONS & INTEGRATING OUT (ie @ $\mathcal{L}$-level)
4. EFT RULES
5. EXAMPLES
   - THE BLUE SKY
   - 4-FERMI THY
   - SCHRODINGER EQN
   - SM HIGGS EFFECTIVE THEORY
   - HIGGS PORTAL DM

$\underbrace{\text{RENORMALIZABLE}}_{\text{"R"}}$ VS. $\underbrace{\text{NON-RENORMALIZABLE}}_{\text{"NR"}}$

new generation: nothing wrong with these as effective theories

FACT: Λ-dependence dropped out.

FACT: Doesn't always happen!

Λ DROPS = R-THY

Λ DOESN'T DROP = NR-THY

(one way to characterize the issue)

DIMENSIONAL ANALYSIS

* $e^{iS} \Rightarrow S$ DIMENSIONLESS

$S = \int \underbrace{d^4x}_{\text{DIM LENGTH}^4 \text{ OR MASS}^{-4}} \mathcal{L}$

$[\cdot] :=$ MASS DIM OF $\cdot$ $\Longrightarrow$ $[d^4x] = -4$ THEN $[S] = 0$ $\Rightarrow [\mathcal{L}] = [S] - [d^4x] = 4$

SO $\boxed{[\mathcal{L}] = 4}$ similarly $[\partial^\mu] = [\partial_\mu] = 1$

* KEY: USE KIN. TERMS TO DET' CLASSICAL FIELD DIM

SCALARS $\mathcal{L} \supset -\frac{1}{2}\partial_\mu\phi\partial^\mu\phi \Rightarrow [\phi] = \frac{1}{2}(4 - 2[\partial^\mu]) = 1$

SPINORS $\mathcal{L} \supset i\bar{\psi}\not{\partial}\psi \Rightarrow [\psi] = [\bar{\psi}] = \frac{1}{2}(4 - [\partial^\mu]) = \frac{3}{2}$

VECTORS $\mathcal{L} \supset -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} \Rightarrow [A_\mu] = \frac{1}{2}(4 - 2[\partial^\mu]) = 1$

* LORENTZ-INV'T INTERACTIONS

INTERACTION	COUPLING DIMENSION
$m^2\phi\phi$ $\quad m\bar{\psi}\psi$ $\quad m^2A_\mu A^\mu$	$[m] = 1$
$\lambda\phi^4$	$[\lambda] = 0$
$g\phi^3$	$[g] = 1$
$y\,\phi\bar{\psi}\psi$	$[y] = 0$
$e\,\bar{\psi}\not{A}\psi$	$[e] = 0$
$G\,\bar{\psi}\psi\bar{\psi}\psi$	$[G] = -2$ FROM $[G] + 4\left(\frac{3}{2}\right) = 4$
$\sqrt{G_N}\,h\,\partial h\,\partial h$	$[\sqrt{G_N}] = -1$
	$\left(\sqrt{G_N} \sim \frac{1}{M_p}\right)$

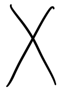
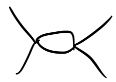
$g^{\mu\nu} := \eta^{\mu\nu} + h^{\mu\nu}$

$S \sim \int d^4x\,(\partial h\ \partial h + \sqrt{G_N}\,h\,\partial h\,\partial h$

HEURISTIC IDEA IN EXAMPLES

$\mathcal{M}$ @ INC. PERT ORDERS, DIM ANALYSIS.

$\lambda\phi^4$

$\mathcal{M} \sim$  $+$  $+ \ldots$

$\sim A\lambda + B\lambda^2 + \ldots$

FACT

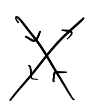
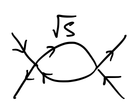
$[\lambda] = 0 \implies [A\lambda] = [A] + [\lambda] = [A]$ SO $[A] = [B]$

$\qquad\qquad\quad\; [B\lambda^2] = [B] + 2[\lambda] = [B]$

$\implies$ SCALES $\tilde{\Lambda}$ MUST APPEAR IN DIM'LESS COMBOS

↳ EG Λ OR s

$G\bar{\psi}\psi\bar{\psi}\psi$ $\qquad [G] = -2$

$\mathcal{M} \sim$  $+$ 

$\sim AG + BG^2$

BUT NOW $[B] = [A] + [2] \implies B \sim C\tilde{\Lambda}^2$ w/ $[C] = [A]$

SO $\mathcal{M} \sim AG + C\tilde{\Lambda}^2 G^2 = G(A + C\tilde{\Lambda}^2 G + \ldots)$

H.O.T. IN $\tilde{\Lambda}^2 G$

PHYSICAL THY $\quad \tilde{\Lambda}^2 = s$

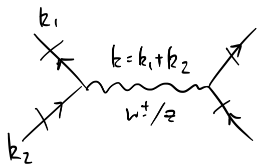
↳ $\mathcal{M}$ = PERT IN Gs ONLY GOOD FOR $s \ll G^{-1}$

$\Longrightarrow$ NEW PHYSICS @ $s \simeq \frac{1}{G_F} \simeq (90\ \text{GeV})^2 \simeq M_{W/Z}^2$

$$\boxed{\text{NR THYS ARE LOW ENERGY EFFECTIVE FIELD THEORIES "EFTS"}}$$

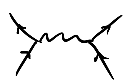
WHAT DOES THIS MEAN? EXAMPLE

WEAK INTERACTIONS



$$= (-ig)^2 \, \bar{u} \gamma^\mu u \, \frac{i}{k^2 - M_{W/Z}^2 + i\varepsilon} \, \bar{u} \gamma_\mu u$$

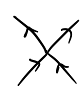
LOW ENERGY $k^2 \ll M_{W/Z}^2 \Longrightarrow$



$$\simeq -(-ig)^2 \, \bar{u} \gamma^\mu u \, \frac{i}{M_{W/Z}^2} \, \bar{u} \gamma_\mu u$$

* $\mathcal{L}_{int} = G \bar{\psi} \gamma^\mu \psi \bar{\psi} \gamma_\mu \psi$ w/ $G_F \simeq \frac{g^2}{M^2}$ $\Longrightarrow$ SAME $\mathcal{M}$ @ LOW ENERGIES

Language: "Effective Operator"



$$\simeq G_F \, \bar{u} \gamma^\mu u \, \bar{u} \gamma_\mu u$$

* $\mathcal{L}_{int}$ FAILS @ $k^2 \gtrsim M_{W/Z}^2$. UV PHYSICS REPLACES EFFECTIVE INT

CON: MANY UV MODELS COULD GIVE SAME EFF. INT.

PRO: "

IGNORANCE CAN BE BLISS!

(great that predecessors could focus on lower energy physics w/o worrying about SM details)

UV COMPLETIONS & INTEGRATING OUT

(demonstrate the basic idea in a toy example, POINT: EFT's come from UV models, but are agnostic)
(also: concretely see in Lago)

TOY THY: $\mathcal{L} = \sum_{i=1}^{2}\left(\frac{1}{2}\partial_\mu\phi^i\partial^\mu\phi_i\right) - \frac{M^2}{2}\phi_2^2 - \varepsilon\phi_1^3\phi_2$

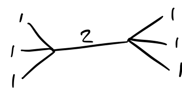
Q: WHAT DOES THY EFFECTIVELY LOOK LIKE @ $E \ll M$?

A: ϕ_2 EOM: $\partial_\mu \frac{\delta\mathcal{L}}{\delta\partial_\mu\phi_2} - \frac{\delta\mathcal{L}}{\delta\phi_2} = 0$

$$\Rightarrow \left(\Box + M^2\right)\phi_2 + \varepsilon\phi_1^3 = 0$$

$$\xrightarrow{k\text{-sp}} \left(k^2 + M^2\right)\phi_2 + \varepsilon\phi_1^3 = 0$$

PHYSICS FOR $E \ll M$, ϕ_2 ONLY INTERNAL, $k^2 \ll M^2$

EG 

$$\Rightarrow \phi_2 = \frac{-\varepsilon\phi_1^3}{k^2+M^2} = \frac{-\varepsilon\phi_1^3}{M^2}\left(\frac{1}{1+k^2/M^2}\right) \simeq \frac{-\varepsilon\phi_1^3}{M^2} + \mathcal{O}\left(\frac{k^2}{M^2}\right)$$

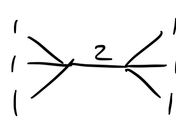
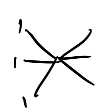
$\Rightarrow$ EFFECTIVE LAGRANGIAN

$$\mathcal{L}_{eff} = \frac{1}{2}\partial_\mu\phi_1\partial^\mu\phi^1 - \frac{M^2}{2}\left(\frac{\varepsilon^2}{M^4}\right)\phi_1^6 - \varepsilon\phi_1^3\left(\frac{-\varepsilon}{M^2}\phi_1^3\right)$$

$$= \frac{1}{2}\partial_\mu\phi_1\partial^\mu\phi^1 - \phi_1^6\left(\frac{\varepsilon^2}{2M^2} - \frac{\varepsilon^2}{M^2}\right)$$

$$\boxed{\mathcal{L}_{eff} = \frac{1}{2}\partial_\mu\phi_1\partial^\mu\phi^1 + \frac{\varepsilon}{2M^2}\phi_1^6}$$

NOTE:
- VALID EFFECTIVE DESC FOR $\frac{k^2}{M^2} \ll 1$
- ϕ_2 ABSENT, Language: "Integrated Out"
- IN PLACE OF ϕ_2, $\varepsilon\phi_1^3\phi_2$, $\exists$ ϕ_1^6

IE @ LOW E,  LOOKS LIKE 

UV COMPLETION

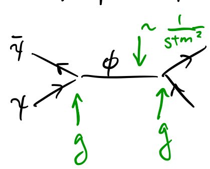
IDEA: $\mathcal{L}_{UV\ \mathrm{THY}} \xrightarrow[\text{int. out}]{\text{low en,}} \mathcal{L}_{eff}$

EFT IS UV-AGNOSTIC: $\exists\ \mathcal{L}_{eff}$ SUCH THAT

$$\begin{tikzcd} \mathcal{L}_{UV,1} \arrow[dr] & & \mathcal{L}_{UV,2} \arrow[dl] \\ & \mathcal{L}_{eff} & \\ & \mathcal{L}_{UV,3} \arrow[u] & \end{tikzcd}$$

ie multiple UV-completions of same effective theory!

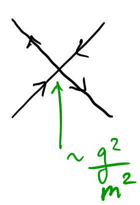
EG $\quad \mathcal{L}_{UV,1} = i\bar{\psi}\not{\partial}\psi + \frac{1}{2}\partial_\mu\phi\,\partial^\mu\phi - \frac{m^2}{2}\phi^2 - g\phi\bar{\psi}\psi$

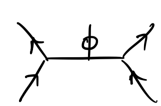
S-CHANNEL 

LOW E: $\quad \frac{s}{m^2} \ll 1$?

ϕ EOM $\simeq \quad m^2\phi + g\bar{\psi}\psi = 0 \implies \phi = -\frac{g\bar{\psi}\psi}{m^2} + \mathcal{O}\left(\frac{s}{m^2}\right)$

$$\mathcal{L}_{eff,1} = i\bar{\psi}\not{\partial}\psi - \frac{m^2}{2}\frac{g^2}{m^4}\bar{\psi}\psi\bar{\psi}\psi - g\left(\frac{-g}{m^2}\right)\bar{\psi}\psi\bar{\psi}\psi$$
$$= i\bar{\psi}\not{\partial}\psi + \frac{g^2}{m^2}\bar{\psi}\psi\bar{\psi}\psi$$

S-CH 

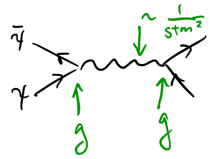
GOOD APPROX TO 

FOR $\frac{s}{m^2} \ll 1$!

(one might say this description is effective)

EG $\mathcal{L}_{UV,1} = i\bar{\psi}\not{\partial}\psi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{m^2}{2}A_\mu A^\mu - g\bar{\psi}\not{A}\psi$

S-CHANNEL

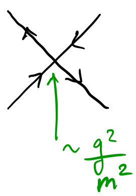


LOW E: $\frac{s}{m^2} \ll 1$?

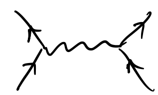
$$A_\mu \text{ EOM} \simeq m^2 A_\mu + g\bar{\psi}\gamma_\mu\psi \implies A_\mu = -\frac{g}{m^2}\bar{\psi}\gamma_\mu\psi + \mathcal{O}\left(\frac{s}{m^2}\right)$$

$$\mathcal{L}_{eff} = i\bar{\psi}\not{\partial}\psi - \frac{m^2}{2}\frac{g^2}{m^4}\bar{\psi}\gamma_\mu\psi\bar{\psi}\gamma^\mu\psi - g\left(-\frac{g}{m^2}\right)\bar{\psi}\gamma^\mu\bar{\psi}\gamma_\mu\psi\psi$$

S-CH



GOOD APPROX TO



FOR $\frac{s}{m^2} \ll 1$!

(one might say this description is effective)

POINT TWO 4-FERMI EFT'S FROM VERY DIFF $\mathcal{L}_{UV}$'s

(this was a simple example but in fact can get identical $\mathcal{L}_{eff}$ from diff $\mathcal{L}_{UV}$'s)

EX OF EXACTLY SAME $\mathcal{L}_{eff}$: SEIBERG DUALITY

$d=4$ $\mathcal{N}=1$
$G = SU(N_c)$
N_f ($\square$ & $\bar{\square}$) CHIRALS

$d=4$ $\mathcal{N}=1$
$G = SU(N_f - N_c)$
N_f $\square$ & $\bar{\square}$ CHIRALS

$\mathcal{L}_{eff}$

note: different gauge groups, identical low-energy physics!

EFT RULES

- CONSIDER LIGHT DOF
- ALLOW $\mathcal{O}$'s w $[\mathcal{O}] > d$ (= 4, for us)

KEY: SENSITIVE TO NEW UV PHYSICS, AGNOSTIC ABOUT WHAT IT IS!

(this is the power of effective field theory)

"RULES"

1. CONSIDER $\mathcal{L}$ w/ LIGHT DOF & SYMMETRY GROUP G
2. DET. MAX $[\mathcal{O}]$ DESIRED

   (always allowed in practice because increasing $\mathcal{O}$ is increasingly irrelevant)
3. WRITE DOWN ALL $\mathcal{O}$ UP TO $[\mathcal{O}]_{max}$ CONSISTENT w/ SYMMETRIES, SUPPRESSED BY APPROP Λ-POWERS & WITH DIM-LESS "WILSON COEFFS"

IE
$$\mathcal{L} = \mathcal{L}_{kin} + \sum_{k=1}^{[\mathcal{O}]_{max}} \sum_{\substack{\mathcal{O}_{k,i} \\ [\mathcal{O}_k]=k}} \underbrace{\frac{c_{k,i}}{\Lambda^{k-4}} \mathcal{O}_{k,i}}_{\text{dim of whole thing } = 4, \text{ (more gen, } d)}$$

EXAMPLES

i) THE BLUE SKY 

(see Zee VIII.3 for rel. treat)

① DOF / INGREDIENTS: PHOTONS $\Longrightarrow \mathcal{L}_{eff} \supset -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$

NEUTRAL AIR $\Longrightarrow \mathcal{L}_{eff} \supset \frac{1}{2} \partial_\mu \phi \, \partial^\mu \phi - \frac{m^2}{2} \phi^2$

(model as spin 0, same conc holds for $\frac{1}{2}$)

SYMM: $U(1)$ GAUGE & LORENTZ

② $[\mathcal{O}_{max}]$: WHATEVER LEADING ORDER γ-AIR INT. IS

③ $\cancel{A^\mu \phi \phi}$? not Lor inv't, not G-inv

$\cancel{A^\mu A_\mu \phi \phi}$? not G-inv

$\phi \phi F_{\mu\nu} F^{\mu\nu}$? G.I. & L.I. ✓

NOTHING ELSE AT $[\phi \phi F^2] = 6$

NOTE By RULE, MUST ALSO INCLUDE DIM ≤ 6 ϕ-INT

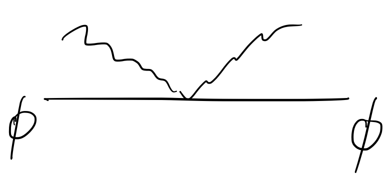
$$\Longrightarrow \mathcal{L}_{eff} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \frac{1}{2} \partial_\mu \phi \, \partial^\mu \phi - \frac{m^2}{2} \phi^2$$

$$+ c_3 \Lambda \phi^3 + c_4 \phi^4 + \frac{c_{5,1}}{\Lambda} \phi^5 + \frac{c_{5,2}}{\Lambda} \phi F^2$$

$$+ \frac{c_{6,1}}{\Lambda^2} \phi^6 + \frac{c_{6,2}}{\Lambda^2} \phi \phi F_{\mu\nu} F^{\mu\nu} + \text{H.O.O.}$$

just ~~say~~ wrote it

γ-AIR SCATTERING



Q: STEPS TO COMPUTE $\mathcal{M}$?

SCALING $\quad \phi\phi F_{\mu\nu}F^{\mu\nu} \Rightarrow$ VERT w/ $\frac{p_\mu p^\mu}{\Lambda^2}$

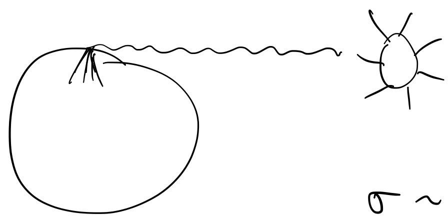
$$\Rightarrow \mathcal{M} \sim \frac{p_\mu p^\mu}{\Lambda^2} \sim \frac{E^2}{\Lambda^2} \Rightarrow \sigma \sim |\mathcal{M}|^2 \sim \frac{E^4}{\Lambda^4} \sim \frac{\omega^4}{\Lambda^4}$$

(note: not get dim'lly correct)

CAREFULLY TAKE NR $\left(\frac{E}{m} \ll 1\right)$ LIM & DIMS $\Rightarrow \sigma = A\frac{\omega^4}{\Lambda^6}$

DEFINE $d := \frac{1}{\Lambda} \Rightarrow \sigma \sim d^6 \omega^4$ RAYLEIGH'S σ

NOTE:

① 

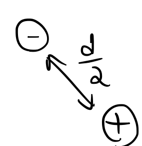
$\sigma \sim \omega^4 \Rightarrow$ BLUE LIGHT SCATTERS MORE THAN RED

$\Rightarrow$ SKY IS BLUE

② CUTOFF IS PHYSICAL

$$\Lambda \to \infty \Rightarrow d \to 0, \quad \sigma \to 0$$

Q: WHAT IS d?



A: ATOM SIZE!

(as $d \to 0$, charge density $\to 0$

$\Rightarrow$ photon coupling $\to 0$

$\Rightarrow$ scatt $\to 0$)

ii) 4-FERMI THY FOR β-DECAY

① DOF INGREDIENTS: MASSIVE FERMION

$$\Longrightarrow \mathcal{L} \supset \bar{\psi}(i\not{\partial}-m)\psi$$

$G =$ LORENTZ

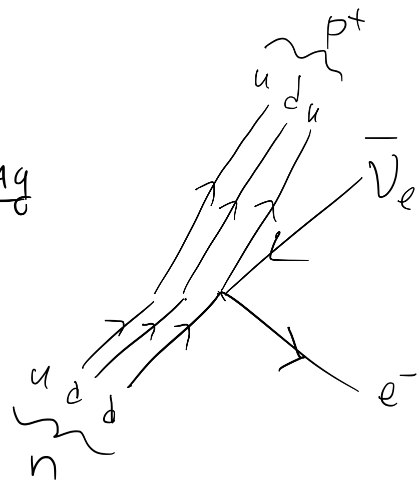
② $[\mathcal{O}]_{max}$ SET BY LEAD INT

③ RECALL BILINEARS: $\bar{\psi}\psi \quad \bar{\psi}\gamma^5\psi \quad \bar{\psi}\gamma^\mu\psi \quad \bar{\psi}\gamma^\mu\gamma^5\psi$

SQUARE ANY $\Rightarrow$ COR. INV, P-INV

$$\Rightarrow \mathcal{L}_{eff} = \bar{\psi}(i\not{\partial}-m)\psi + \frac{1}{\Lambda^2}\Big[C_{6,1}(\bar{\psi}\psi)^2 + C_{6,2}(\bar{\psi}\gamma^5\psi)^2 + C_{6,3}(\bar{\psi}\gamma^\mu\psi)^2 + C_{6,4}(\bar{\psi}\gamma^\mu\gamma^5)^2$$
$$+ C_{6,5}\Big(\bar{\psi}\gamma^\mu\Big(\frac{1-\gamma^5}{2}\Big)\psi\Big)^2 + C_{6,6}(\bar{\psi}(1-\gamma^5)\psi)^2$$
$$+ \dots\Big]$$

β-DECAY



$$n \longrightarrow \bar{\nu}_e + e^- + p^+$$

NATURE V-A CURRENT $\frac{(1-\gamma^5)}{2}$ CORRECT

EXP $\quad \frac{c}{\Lambda^2} =: G_F = \frac{1.17}{10^5\,GeV^2}$

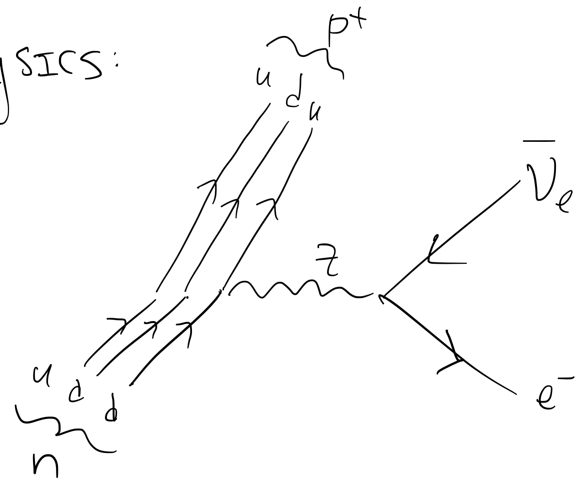
CUTOFF IS PHYSICAL

- $\mathcal{L}_{eff}$ ONLY VALID FOR $E^2 G_F \ll 1$
- IF COLLIDER E HAS $E^2 G_F \sim \mathcal{O}(1)$

PROBE NEW PHYSICS!

COLLIDER + EXP: 1983, $Sp\bar{p}S$ & UA2, $E_{COM} \simeq 600$ GeV

NEW PHYSICS:



(this is β^- decay. W in β_+ decay $p^+ + n \longrightarrow \bar{\nu}_e + e^+$)

$$G_F = \frac{\sqrt{2}}{8} \frac{g^2}{m_W^2} \qquad (\text{sim}, M_Z^2)$$

POINT: ① WEAK INTERACTIONS UV-COMPLETE FERMI THY

② GET FERMI BACK AFTER INTEGRATING OUT W, Z $\Longrightarrow$ $G_F = f(M_W, M_Z)$, ie $M_W \sim M_Z$ SETS CUTOFF!

EFT & BSM PHYSICS

0) SM OPS
1) "HIGGS PORTALS" TO DARK SECTORS
2) HIGGS EFT (sensitivity to new Higgs physics)

0) SM OPS

(from a T-shirt, suppresses detailed index structure, but all the types of operators are there!)

DIM IN RED

$$\mathcal{L} = -\frac{1}{4}\overbrace{F_{\mu\nu}F^{\mu\nu}}^{4}$$
$$+ i\overbrace{\bar{\psi}\not{D}\psi}^{4} + h.c.$$
$$+ y_{ij}\underbrace{\bar{\psi}_i\psi_j h}_{4} + h.c$$
$$+ \underbrace{|D_\mu h|^2}_{4} + m^2\underbrace{h^\dagger h}_{2} - \lambda\underbrace{(h^\dagger h)^2}_{4}$$

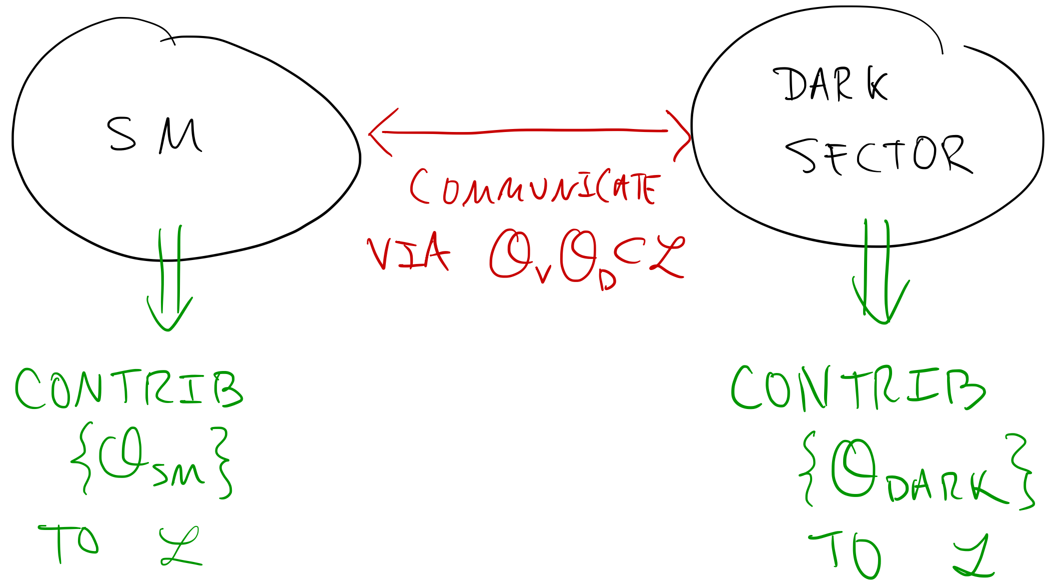
$$[\mathcal{O}_{kin}] = [\mathcal{O}_{yukawa}] = [\mathcal{O}_{\text{Higgs self-coup}}] = 4$$

$$[\mathcal{O}_{\text{Higgs mass}}] = 2$$

COLLECTIVELY CALL "$\mathcal{O}_{SM}$" TO REP. ALL OPS IN SM.

1) HIGGS PORTALS TO DARK SECTORS

GENERAL



Q: WHAT ARE LEADING SM-DARK INTS?

A: FROM LOWEST DIM OPS!

$$\mathcal{O}_{SM}\mathcal{O}_{DARK} \quad \text{S.T.} \quad [\mathcal{O}_{SM}] = \min[\{\mathcal{O}_{SM}\}]$$
$$[\mathcal{O}_{DARK}] = \min[\{\mathcal{O}_{DARK}\}]$$

NOTE: $\Longrightarrow$ $\mathcal{O}_{SM} = h^\dagger h$, SINCE IT'S THE MIN-DIM SM OP.

$\Longrightarrow$ $h^\dagger h\, \mathcal{O}_{DARK}$ IS LEADING OP

Language "Higgs Portal" to dark sector!

SCALAR DM

$$\mathcal{L} = \frac{1}{2}\partial_\mu \phi \partial^\mu \phi - \frac{1}{2} m_\phi^2 \phi^2 - \frac{1}{2}\lambda \phi^2 h^\dagger h$$

FERMION DM

$$\mathcal{L} = \bar{\chi}(i\not{\partial} - m_\chi)\chi - \frac{\lambda}{\Lambda} h^\dagger h \bar{\chi}\chi$$

VECTOR DM

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}m^2 V_\mu V^\mu - \frac{\lambda_{HV}}{2} V_\mu V^\mu h^\dagger h - \frac{\lambda_V}{4!}(V_\mu V^\mu)^2$$

DETECTION STRATEGY

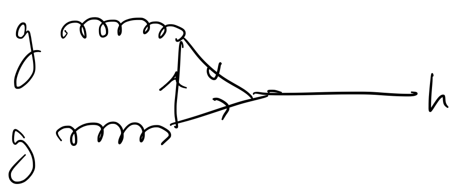
1. CONSTRAIN PARAMS w $\Omega_{obs} h^2$
2. DETERMINE SM σ's
3. CONSTRAIN w/ LHC, DD, IDD

3) SM EFT @ DIM 6

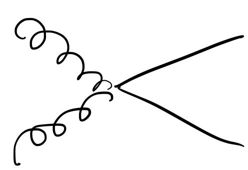
$\exists$ MANY!

SOME SIMPLE ONES RELATED TO HIGGS @ LHC

OPERATOR	COEFF	CONSTRAINT
$\mathcal{O}_{HW} = ig(D^\mu H)^\dagger \sigma^a (D^\nu H) W^a_{\mu\nu}$	$\frac{m_W^2}{\Lambda^2} C_{HW}$	$(-0.042, 0.008)$
$\mathcal{O}_{HB} = ig'(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$	$\frac{m_W^2}{\Lambda^2} C_{HB}$	$(-0.053, 0.044)$
$\mathcal{O}_g = g_s^2 \vert H\vert^2 G^A_{\mu\nu} G^{A\mu\nu}$	$\frac{m_W^2}{\Lambda^2} C_g$	$(0, 3.0) \times 10^{-5}$



vs



large coeff $\Rightarrow$ large di-Higgs production

$\mathcal{O}_\gamma = g'^2 \vert H\vert^2 B_{\mu\nu} B^{\mu\nu}$	$\frac{m_W^2}{\Lambda^2} C_\gamma$	$(-4.0, 2.3) \times 10^{-4}$