

LECTURES ON THE SMEFT

①

PART I: EFFECTIVE FIELD THEORIES

CONCEPT $\longrightarrow$ SEPARATION OF SCALES

- ① WE DON'T NEED TO KNOW QCD TO COMPUTE ELECTRONIC PROPERTIES OF ATOMS

$$r_{\text{ATOM}} \sim 10^{-10} \text{ m} \gg r_{\text{NUCLEI}} \approx 10^{-15} \text{ m}$$

- ② TO COMPUTE WEAK RADIATIVE DECAYS, $n \rightarrow p + e^- + \bar{\nu}_e$ WE DON'T NEED TO KNOW ABOUT THE EXISTENCE

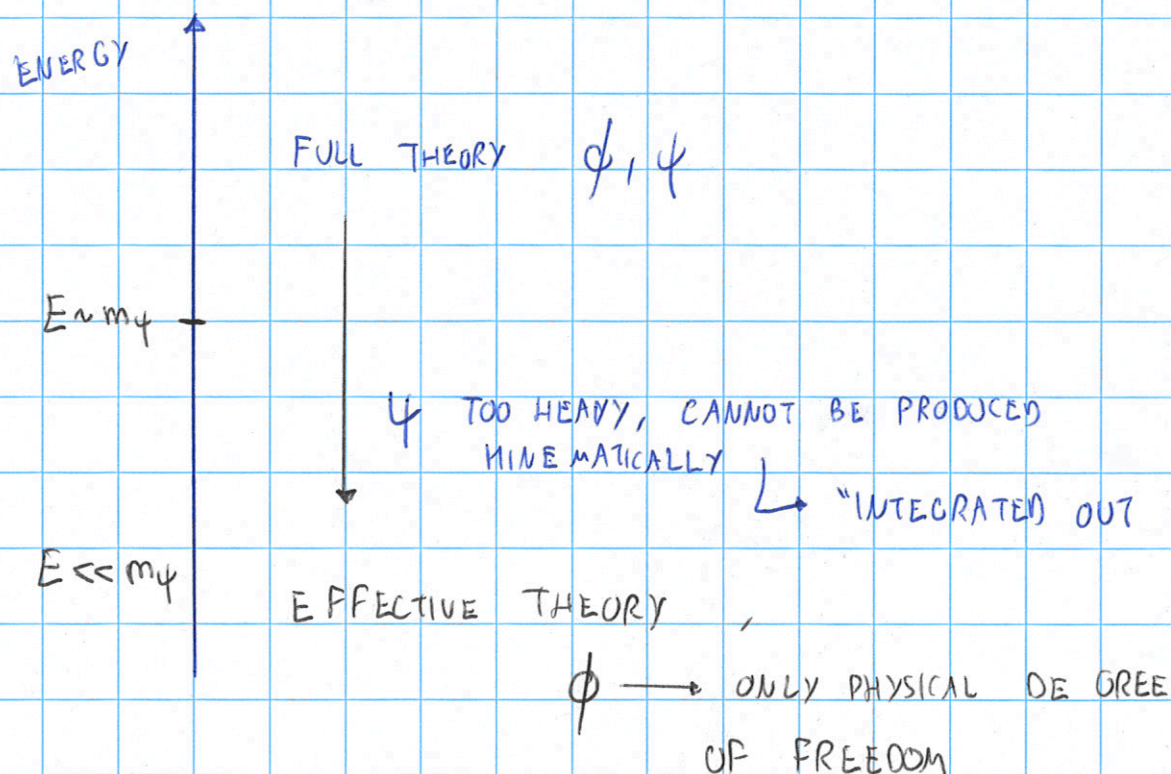
OF THE W, Z BOSONS $r_{\text{ATOM}} \quad r_{\text{NUCLEI}} \approx 10^{-15} \gg r_{\text{WEAK}} \sim 10^{-18} \text{ m}$
[$r_{\text{WEAK}} \sim M_W^{-1}$]

- ③ TO PREDICT SOLAR ECLIPSES, WE USE NEWTONIAN MECHANICS, WHICH IS ONLY AN APPROXIMATION TO SPECIAL + GENERAL RELATIVITY $v_{\text{MOON}}, v_{\text{SUN}} \ll c$

THE PHYSICS THAT TAKE PLACE AT A GIVEN SCALE [ENERGY, DISTANCE, TIME, ...] SHOULD NOT BE INFLUENCED SHOULD BE DESCRIVABLE WITHOUT DETAILED KNOWLEDGE OF WHAT HAPPENS AT VERY DIFFERENT SCALES

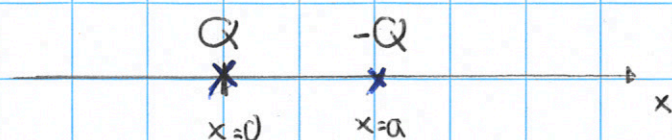
AN EFFECTIVE FIELD THEORY IS A MATHEMATICAL IMPLEMENTATION OF THIS CONCEPT

EXAMPLE A THEORY WITH TWO FIELDS, ϕ , ψ ,
WITH MASSES $m_\phi = 0$, $m_\psi \neq 0$, AND



LET'S CONSIDER SOME EXAMPLES OF "EFFECTIVE THEORIES"
AND THEN WE WILL FORMULATE EFTs MORE PRECISELY

① AN ELECTROSTATIC DIPOLE IN 1D



$$E_{TOT} = \frac{Q}{|x|} + \frac{-Q}{|x-a|} = Q \left[\frac{1}{|x|} + \frac{1}{|x-a|} \right]$$

$$x \gg a \quad E_{TOT} = \frac{Q}{x} \left[1 - \frac{1}{1-a/x} \right]$$

(3)

$$E_{\text{Tot}} = \frac{Q}{x} \left[1 - \left(1 + a/x - (a/x)^2 + \dots \right) \right]$$

$$= \frac{Q}{x} \cdot \left(\frac{a}{x} - \left(\frac{a}{x} \right)^2 + \dots \right)$$

If $x \gg a$, $E_{\text{Tot}} \approx 0$ If $x \lesssim a$ $E_{\text{Tot}} = Qa/x^2$

As x becomes closer to a , we need to include more and more terms

EFT IDEAS

- + SYSTEMATIC EXPANSION ABOUT "TRUE" RESULT
- + IMPROVABLE BY ADDING MORE TERMS
- + CONCEPTUALLY MUCH SIMPLER TO DEAL WITH AND TO COMPUTE

(2) QUANTUM ANHARMONIC OSCILLATOR

CONSIDER A GENERAL ONE-PARTICLE QUANTUM SYSTEM

$$\hat{H} \psi(x) = E \psi(x) \quad \hat{H} = -\frac{\hbar^2}{2m} \frac{d^2}{dx^2} + V(x)$$

DIFFICULT TO SOLVE

NEXT TO LOCAL MINIMUM x_0

$$V(x) \approx V(x_0) + \underbrace{\frac{dV}{dx} \Big|_{x=x_0}}_0 (x-x_0) + \frac{1}{2} \underbrace{\frac{d^2V}{dx^2} \Big|_{x=x_0}}_K (x-x_0)^2$$

$$\hat{H} = -\frac{\hbar^2}{2m} \frac{d^2}{dx^2} + \frac{1}{2} K (x-x_0)^2 \rightarrow \text{HARMONIC OSCILLATOR}$$

$$E_n = \hbar \omega \left(n + \frac{1}{2} \right) \quad \omega = \sqrt{k/m}$$

BUT WHAT IF x IS NOT CLOSE TO x_0 ?

WE CAN SLOWLY DEFORM THE EXACT SOLUTION BY INCLUDING HIGHER ORDER TERMS IN THE POTENTIAL

$$V(x) \approx V(x_0) + \frac{1}{2} K (x-x_0)^2 + \tilde{K} (x-x_0)^3$$

$$E_n = \hbar \omega \left(n + \frac{1}{2} \right) - \hbar \omega x_e \left(n + \frac{1}{2} \right)^2 \quad x_e \propto \tilde{K}$$

$$= \hbar \omega \left(n + \frac{1}{2} \right) \left[1 - x_e \left(n + \frac{1}{2} \right)^2 \right]$$

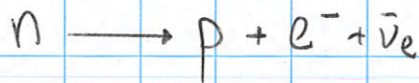
↓
"HIGHER ORDER EFFECT"

IF WE INCLUDE " x_e " EFFECTS AT ALL ORDERS

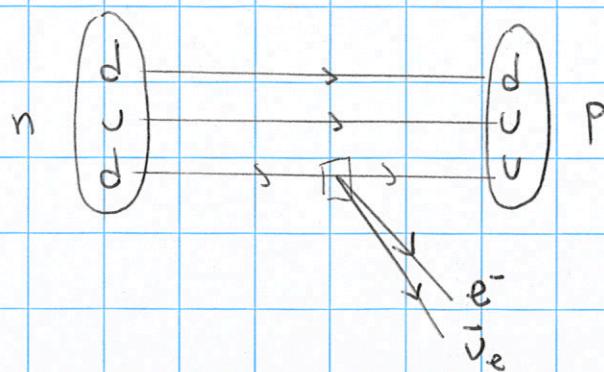
→ WE RECOVER THE FULL THEORY

③ FERMI THEORY OF THE WEAK INTERACTIONS

THIS IS A PHENOMENOLOGICAL MODEL TO DESCRIBE PROCESSES SUCH AS NEUTRON BETA DECAY



AT THE QUARK LEVEL



□ → FOUR POINT INTERACTION

AT THE LAGRANGIAN LEVEL, IT IS DESCRIBED BY

$$\mathcal{L}_{\text{FERMI}} = \frac{G_F}{\sqrt{2}} (\bar{\psi}_e \gamma^\mu (1 + \gamma_5) \psi_\nu) (\bar{\psi}_d \gamma_\mu (1 + \gamma_5) \psi_u)$$

CRUCIAL CONCEPT $\rightarrow$ DIMENSIONAL ANALYSIS

WE WORK IN NATURAL UNITS $\hbar = c = G = 1$

$\rightarrow$ WE WILL USE IT
A LOT IN THE
LECTURE

$$[S] = 0$$

$$S = \int d^4x \mathcal{L}$$

$\uparrow$
ACTION MASS-DIMENSION

WHAT ARE MASS-DIMENSIONS OF $\mathcal{L}$?

$$[d^4x] = -4 \Rightarrow [\mathcal{L}] = 4$$

$$[\psi] = 3/2$$

DIRAC EQUATION

$$\mathcal{L}_{\text{MASS}} \sim m \bar{\psi} \psi$$

$$[S] = 4 \quad [L] = 1 \quad [\bar{\psi}\psi] = 3$$

$$[G_F] = -2 \rightarrow \text{DIMENSIONFUL COUPLING CONSTANT}$$

$$G_F = 1.166 \times 10^{-5} \text{ GeV}^{-2}$$

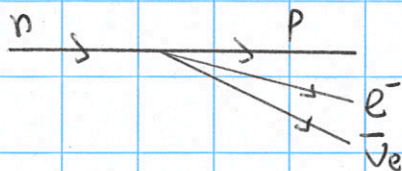
WHAT FIXES THE VALUE OF THE FERMION CONSTANT?

WHAT FIXES THE RATE OF WEAK RADIOACTIVE PROCESSES?

PERHAPS ANTHROPIC SELECTION IN THE MULTIVERSE?

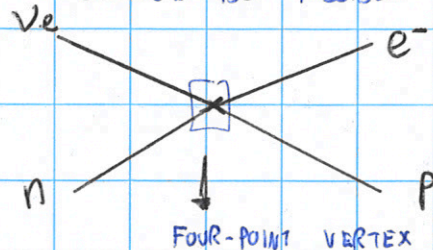
- PROBLEM 1 → WHAT FIXES VALUE OF FERMI CONSTANT?
- PROBLEM 2 → THE BEHAVIOUR OF SCATTERING AMPLITUDES

IF THIS PROCESS
IS POSSIBLE



⇒

ALSO THE CROSSED DIAGRAM
SHOULD BE POSSIBLE



WHAT IS THE CROSS-SECTION FOR $\nu_e + n \rightarrow e^- + p$ SCATTERING
IN FERMI THEORY

$$A \propto G_F$$

$$M = |A|^2 \propto G_F^2$$

$$G \propto M \propto G_F^2$$

$$[G] = -2$$

$$[G_F^2] = -4$$

CROSS SECTION
IS AN AREA

SO PURELY BASED ON DIMENSIONAL REASONS

$$G_{\nu+n \rightarrow e+p} \propto G_F^2 E_{cm}^2$$

$E_{cm} \rightarrow$ CENTER OF MASS ENERGY

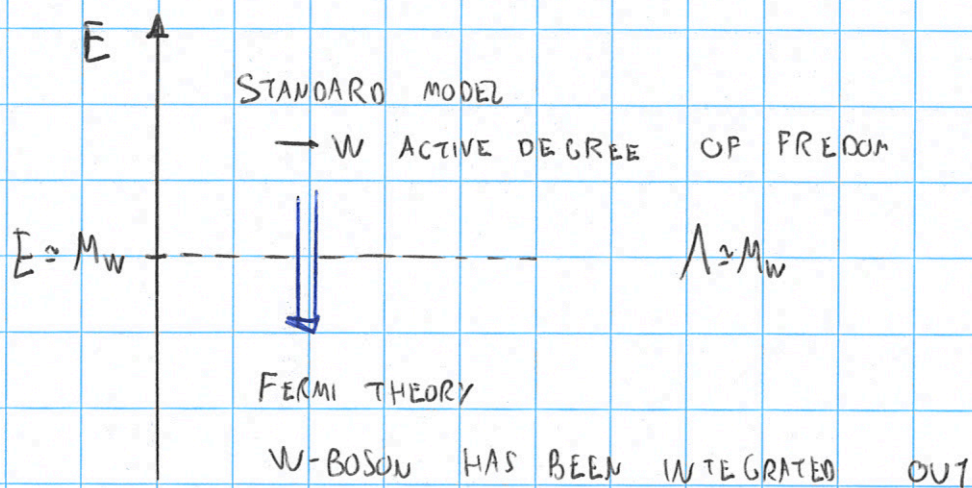
→ The cross-section grows with energy as a power law

↳ VIOLATE UNITARITY ⇒ PROBABILITY OF REACTION > 1

WHAT MAKES "PHYSICAL" SCATTERING AMPLITUDES
AT HIGH ENERGY IN FERMI THEORY?

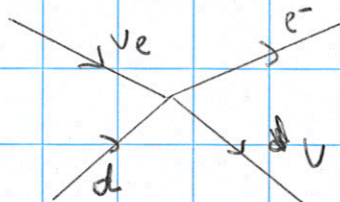
- ① WHAT DETERMINES THE VALUE OF G_F ?
- ② WHAT TAKES THE UNPHYSICAL HIGH ENERGY BEHAVIOUR OF THE THEORY?

ANSWER $\rightarrow$ FERMION THEORY IS AN EFT, VALID ONLY FOR ENERGIES BELOW SOME CUT-OFF Λ



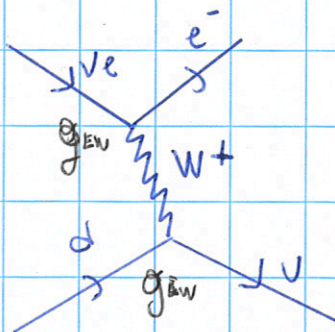
$$\mathcal{L}_{\text{FERMI}} = G_F/2 \left(\bar{\psi}_e \gamma^\mu (1 + \gamma_5) \psi_\nu \right) \left(\bar{\psi}_d \gamma_\mu (1 + \gamma_5) \psi_u \right)$$

$E_{\text{CM}} \ll M_W$



$$Q_{\text{FINAL}} = Q_{\text{INITIAL}}$$

$E_{\text{CM}} \approx M_W$



PROPAGATOR $\sim \frac{g^{\mu\nu}}{k^2 - M_W^2}$

AMP

Now we can do the MATCHING BETWEEN THE PARAMETERS OF THE EFT AND THE FULL THEORY

⇒ COMPUTE AMPLITUDES FOR SAME PROCESS AND CHECK THEY ARE EQUIVALENT

$$A_{\text{FERMI}} (\nu_e + d \rightarrow e^- + \nu) \propto G_F$$

$$A_{\text{FULL}} (\nu_e + d \rightarrow e^- + \nu) \propto g_{EW}^2 \times \frac{1}{k^2 - M_W^2} \longrightarrow$$

$\downarrow$ COUPLING CONSTANT $\downarrow$ W BOSON PROPAGATOR
 $\int \bar{\psi} \psi$ vertex

$$\xrightarrow{k^2 \ll M_W^2} A_{\text{FULL}} \propto \frac{g_{EW}^2}{M_W^2}$$

EFT VALID

MATCHING $\Rightarrow$

$G_F \propto \frac{g_{EW}^2}{M_W^2}$

$\downarrow$ PARAMETERS OF EFT $\downarrow$ PARAMETERS OF FULL THEORY

NOTE $\longrightarrow$ THE INFORMATION ABOUT THE W BOSON, DESPITE IT HAS BEEN INTEGRATED OUT, IS STILL PRESENT IN THE EFT VIA ITS PARAMETERS

A TOY EFT : SCALAR THEORIES

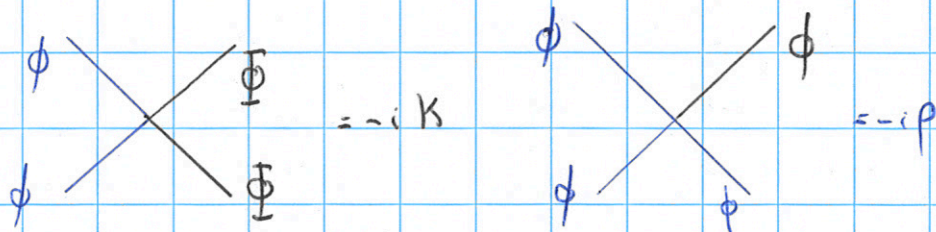
CONSIDER A "FULL THEORY" THAT CONTAINS TWO MASSIVE SCALAR FIELDS ϕ , Φ

$$\mathcal{L}_{\text{FULL}} = \mathcal{L}_{\text{KIN}} + \mathcal{L}_{\text{INT}}$$

$$\mathcal{L}_{\text{KIN}} = \frac{1}{2} (\partial_\mu \phi) (\partial^\mu \phi) - \frac{1}{2} m^2 \phi^2 + \frac{1}{2} (\partial_\mu \Phi) (\partial^\mu \Phi) - \frac{1}{2} M^2 \Phi^2$$

$$\mathcal{L}_{\text{INT}} = -\frac{1}{4} K \phi^2 \Phi^2 - \frac{1}{3!} \rho \phi^3 \Phi$$

IN THE FULL THEORY WE HAVE TWO FUNDAMENTAL VERTICES



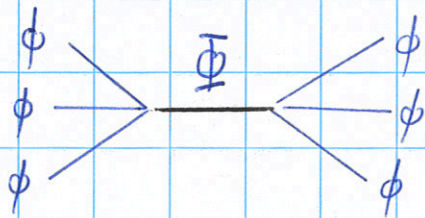
WE WANT TO CONSTRUCT AN EFFECTIVE THEORY VALID WHEN $E \ll M \Rightarrow$ THE HEAVY FIELD Φ CANNOT BE KINEMATICALLY PRODUCED, AND HAS TO BE "INTEGRATED OUT" WHEN APPEARING AS INTERNAL LINE IN FEYNMAN DIAGRAMS

→ WE NEED TO CONSTRUCT THIS EFT FROM MATCHING AMPLITUDES WITH THE FULL THEORY

$$S = E_{CM}$$

10

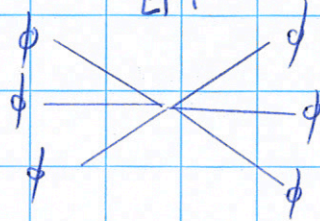
FULL THEORY



$$A_{\text{FULL}} \propto p^2 \frac{1}{-M^2 + s}$$

$$\xrightarrow{s \ll M^2} \propto \frac{p^2}{M^2}$$

EFT



$$A_{\text{EFT}} \propto C_6$$

$$\mathcal{L}_{\text{EFT}} \supset C_6 \phi^6$$

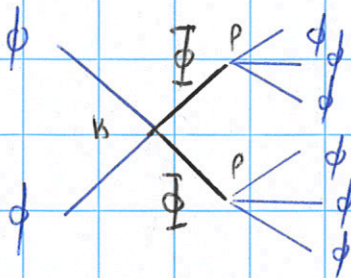
SIX-POINT VERTEX

$$C_6 \propto \frac{p^2}{M^2}$$

EFT, LOW-ENERGY
PARAMETER

FULL-THEORY, HIGH-ENERGY
PARAMETERS

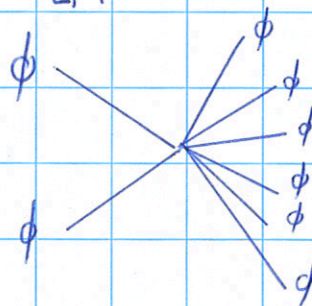
FULL THEORY



$$A_{\text{FULL}} \propto k p^2 \left(\frac{1}{s - M^2} \right)^2$$

$$\xrightarrow[M \gg s]{M \gg s} \frac{k p^2}{M^4}$$

EFT



$$\mathcal{L}_{\text{EFT}} \supset C_8 \phi^8$$

$$\mathcal{L}_{\text{EFT}} \supset \frac{1}{2} (\partial_\mu \phi)(\partial^\mu \phi) - \frac{1}{2} m^2 \phi^2 + C_6 \phi^6 + C_8 \phi^8 + \dots$$

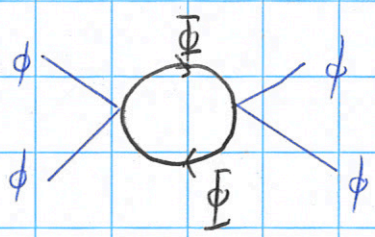
$$\propto \frac{p^2}{M^2}$$

$$\propto \frac{k p^2}{M^4}$$

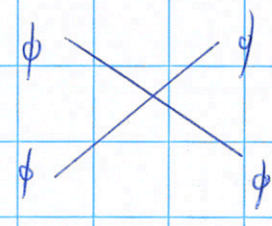
$\Rightarrow$ INFINITE TOWER OF HIGHER-DIMENSIONAL OPERATORS
IN THE EFT CAN BE GENERATED FROM THE FULL THEORY

EFT EFFECTS APPEAR ALSO VIA LOOPS

FULL THEORY



EFT



$$\mathcal{L}_{\text{EFT}} \supset C_4 \phi^4$$

$$C_4 \propto \frac{k^2}{\Lambda^2}$$

$[C_4] = 0 \rightarrow$ WE INTEGRATE Φ BUT NEED TO ACCOUNT FOR LOOP INTEGRAL

$$\int d^4k \frac{1}{k^2 - m^2} \frac{1}{(s - m)^2 - m^2}$$

FINITE
LOG-DIVERGENT

$$[] = 0$$

MATCHING CAN ALSO GENERATE DIMENSIONLESS COEFFICIENTS!!

PART II → THE SM AS AN EFT

RECALL THE STANDARD MODEL LAGRANGIAN

$$\mathcal{L}_{SM} = \mathcal{L}_{EW} + \mathcal{L}_{QCD} + \mathcal{L}_{HIGGS}$$

$$\mathcal{L}_{QCD} = \int d^4x \left[\bar{\psi}_i^{(s)} \left(i \gamma_\mu \overset{\substack{\downarrow \\ \text{COVARIANT} \\ \text{DERIVATIVE}}}{D}_\mu^{ij} - m_g \delta_{ij} \right) \psi_j^{(s)} \right] - \underbrace{\frac{1}{4} F_{\mu\nu}^a F_{\mu\nu}^a}_{\substack{\downarrow \\ \text{GLUON FIELDS} \quad \text{KINETIC TERM FOR GLUON}}}$$

$$F_{\mu\nu}^a = \partial_\mu A_\nu^a - \partial_\nu A_\mu^a - g_s f_{abc} A_\mu^b A_\nu^c$$

$$D_\mu = \partial_\mu + i g_s \tau_{ij}^a A_\mu^a$$

$\downarrow \quad \downarrow$
 COLOR INDICES

SOME INTERESTING REMARKS

- ① CHECK → ALL TERMS HAVE MASS-DIMENSION 4

$$\underbrace{[\psi A \psi]}_{\substack{\downarrow \\ \text{gluon-quark interaction}}} = 2[\psi] + [A] = 2 \times \frac{3}{2} + 1 = 4$$

$$[F_{\mu\nu}^a F^{\mu\nu a}] = 2 \times [F_{\mu\nu}^a] = 2([\partial] + [A]) = 2 \times 2 = 4$$

- ② THE STRUCTURE OF THE LAGRANGIAN IS DICTATED BY SYMMETRIES

- i) GADGE
- ii) LORENTZ SYMMETRY
- iii) DISCRETE SYMMETRIES

③ THE ALLOWED INTERACTIONS BETWEEN FIELDS ARE COMPLETELY FIXED BY SYMMETRIES

EQ GAUGE SYMMETRY

Let's show it explicitly in the QED case

$$\mathcal{L}_{\text{QED}} = \bar{\Psi} (i \gamma^\mu D_\mu - m) \Psi - \frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$

$$D_\mu = \partial_\mu + ie A_\mu \quad F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$$

U(1) GAUGE SYMMETRY $\longrightarrow$ INVARIANCE UNDER LOCAL TRANSFORMATION

$$\Psi \rightarrow e^{i\beta(x)} \Psi$$

DIFFERENT IN EACH SPACE-TIME POINT!

$$A_\mu \rightarrow A_\mu + \partial_\mu \beta(x)$$

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu \rightarrow \partial_\mu (A_\nu + \partial_\nu \beta) - \partial_\nu (A_\mu + \partial_\mu \beta)$$

$$= F_{\mu\nu} + \underbrace{\partial_\mu \partial_\nu \beta - \partial_\nu \partial_\mu \beta}_0 = F_{\mu\nu} \quad \checkmark$$

$$\bar{\Psi} D_\mu \Psi \rightarrow (\bar{\Psi} e^{-i\beta(x)}) (\partial_\mu + ie A_\mu + ie \partial_\mu \beta) e^{i\beta(x)} \Psi$$

$$e^{i\beta(x)} (i \partial_\mu \beta) \partial_\mu \Psi + e^{i\beta(x)}$$

$$\partial_\mu \beta(x) e^{i\beta(x)} \Psi + e^{i\beta(x)} \partial_\mu \Psi + e^{i\beta(x)} ie A_\mu \Psi + e^{i\beta(x)} ie \partial_\mu \beta$$

$$= \bar{\Psi} D_\mu \Psi$$

$$\boxed{\beta(x) = e \beta(x)}$$

EXERCISE $\rightarrow$ CHECK THAT YOU CANNOT ADD MORE TERMS TO THE QED/QCD LAGRANGIAN WITHOUT VIOLATING GAUGE SYMMETRY

Q: CAN THE PHOTON HAVE MASS? EQ IS $\mathcal{L} \supset m^2 A_\mu A^\mu$
ALLOWED BY THE SM SYMMETRIES?

* $[\mathcal{L}_{SM}] = 4 \rightarrow$ THE SM IS RENORMALIZABLE $\rightarrow$
VALID UP TO ARBITRARILY HIGH SCALES
[SAY UP TO $E \sim M_{\text{PLANCK}}$, WHERE QUANTUM GRAVITY SETS IN]

* ADDING OPERATORS WITH MASS-DIMENSION > 4 BREAKS RENORMALIZABILITY

$\Rightarrow$ BUT RENORMALIZABILITY IS A THEORETICAL PREJUDICE!
IF WE REQUIRE THE SM TO BE VALID UP TO ONLY $E \sim \Lambda$,
WITH $\Lambda \gg m_H$ (125 GeV) THERE IS NO NEED
TO RESTRICT TO ONLY RENORMALIZABLE OPERATORS

$$\mathcal{L}_{\text{SMEFT}} \equiv \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda} \sum_{i=1}^{N_{d5}} C_i^{(5)} \mathcal{O}_i^{(5)} + \frac{1}{\Lambda^2} \sum_{j=1}^{N_{d6}} C_j^{(6)} \mathcal{O}_j^{(6)} + \dots$$

$\downarrow$
SCALE WHERE SM
STOPS BEING VALID
[NEW PARTICLES / FORCES APPEAR]

$\rightarrow$ OPERATORS OF
MASS-DIMENSION 5

$\rightarrow$ WILSON COEFFICIENTS

{ + CAN BE FIXED BY "FULL THEORY" IF KNOWN
+ IF "FULL THEORY" UNKNOWN
 $\rightarrow$ CONSTRAIN THEM FROM DATA

MAIN ADVANTAGES OF SM-EFT

- ① MODEL-INDEPENDENCE PARAMETRISATION OF PHYSICS BEYOND THE SM
- ② CORRELATES DIFFERENT SECTORS EQ HIGGS AND TOP QUARK
- ③ SYSTEMATICALLY IMPROVABLE $\rightarrow$ NOT SOME RANDOM MODEL!

HOW ARE CROSS-SECTIONS MODIFIED, SAY OF LHC PROCESSES)

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_{j=1}^{N_{\text{d6}}} \frac{C_j^{(6)}}{\Lambda^2} \mathcal{O}_i^{(6)}$$

CONSIDER JUST ONE OPERATOR FOR SIMPLICITY

$$A_{\text{SM}} \longrightarrow A_{\text{SM}} + A_{\text{SMEFT}}^{(d=6)}$$

$$G \propto |A|^2$$

NAIVELY ONE WOULD THINK THAT

$$G_{\text{SM}} \longrightarrow G_{\text{SM}} + \frac{(C^{(6)})^2}{\Lambda^4} \approx G_{\text{SMEFT}}$$

HOWEVER IN MANY CASES THE SM AND SMEFT AMPLITUDES EXHIBIT INTERFERENCE AMONG THEM, INTRODUCING $\mathcal{O}(\Lambda^2)$ DEPENDENCE

$$G(E) = G_{\text{SM}}(E) \left[1 + \underbrace{\omega \frac{C^{(6)}}{\Lambda^2}}_{\text{DIMENSIONLESS}} V^2 + \underbrace{\omega \frac{C^{(6)} E^2}{\Lambda^2}}_{\text{DIMENSIONLESS}} + \mathcal{O}(\Lambda^{-2}) \right]$$

$\uparrow$
 ENERGY OF SCATTERING PROCESS

$V = 242 \text{ GeV} \rightarrow$ Higgs Boson Vacuum Expectation Values

LET US LOOK AGAIN AT THIS VERY IMPORTANT EXPRESSION,
WHICH DETERMINES GENERAL STRUCTURE OF SMEFT CORRECTIONS

$$G(E) = G_{SM}(E) \left[1 + \underbrace{\omega \frac{C_i v^2}{\Lambda^2}}_{\substack{\text{DIMENSIONLESS} \\ \text{ENERGY-INDEPENDENT}}} + \underbrace{\tilde{\omega} \frac{C_i E^2}{\Lambda^2}}_{\text{ENERGY-GROWING EFFECTS}} + O\left(\frac{1}{\Lambda^4}\right) \right]$$

[REMEMBER
FERMI THEORY!]

$C, \Lambda \longrightarrow$ PROCESS-INDEPENDENT, FIXED BY FULL THEORY

$\omega, \tilde{\omega} \longrightarrow$ PROCESS-DEPENDENT, COMPUTABLE USING $\mathcal{L}_{SMEFT}$

HERE WE WILL FOCUS ON THE SMEFT AT $d=6$

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \sum_{j=1}^{N_{d6}} \frac{C_j^{(d=6)}}{\Lambda^2} \mathcal{O}_j^{(d=6)}$$

WHICH $d=6$ OPERATORS ARE ALLOWED?

① CONSTRUCTED ONLY FROM SM FIELDS

$\longrightarrow$ FERMIONS $\psi_e, \psi_\nu, \psi_u, \psi_d$

$\longrightarrow$ GAUGE BOSONS A_μ, g, W_μ, Z_μ

$\longrightarrow$ HIGGS FIELD [BEFORE ELECTROWEAK SYMMETRY
BREAKING]

② SATISFY THE SAME SYMMETRIES AS IN THE SM

$\longrightarrow$ GAUGE, LORENTZ, CPT SYMMETRIES

THE SMEFT IS THE SM ONCE YOU

ELIMINATE THE RENORMALIZABILITY PREJUDICE!

EXAMPLES OF SMEFT OPERATORS

Let us take a look at explicit examples of the $O_j^{(d=6)}$ operators

[4-FERMION OPERATOR] $O_{qq}^{1(ijhe)} = (\bar{q}_i \gamma^\mu q_j) (\bar{q}_h \gamma_\mu q_e) \quad [q \rightarrow \text{quark field}]$

$i, j, h, e \rightarrow$ FERMION GENERATION INDICES $(i=1,2,3)$

IS THIS AN ALLOWED SMEFT OPERATOR? YES

- ✓ IT HAS MASS-DIMENSION -6 $[\bar{q}q\bar{q}q] = 4 \times [q] = 4 \times \frac{3}{2} = 6$
- ✓ IT IS COMPOSED ONLY BY SM FIELDS (THE QUARK FIELDS)
- ✓ IT SATISFIES THE SM SYMMETRIES

- i) LORENTZ SCALAR $\rightarrow$ LORENTZ INVARIANCE ✓
- ii) GAUGE INVARIANCE ✓

$$\psi_{\alpha}^{(i)} \xrightarrow{\text{FLAVOUR}} U_{ij}(x) \psi_{\alpha}^{(j)}$$

$\psi_{\alpha}^{(i)}$ (color) $\rightarrow$ $U_{ij}(x)$ $\xleftarrow{\text{SU(3) MATRICES GENERATORS}}$

$$U_{ij}(x) = e^{i\theta^a(x) T_{ij}^a}$$

$\Rightarrow$ ALL QUARK BILINEARS ARE INVARIANT OVER SU(3) GAUGE SYMMETRY, IRRESPECTIVE OF FLAVOR INDICES

NOTE THAT THE i, j, h, e FLAVOR INDICES CAN BE COMBINED IN MANY WAYS

$\rightarrow$ UNLESS "FLAVOUR ASSUMPTIONS" ARE INTRODUCED, THE NUMBER OF INDEPENDENT FOUR FERMION OPERATORS QUICKLY BECOMES VERY LARGE

MATCHING IN THE SMEFT

RECALL WHAT WE DISCUSSED BEFORE $\rightarrow$ THE EFT / LOW ENERGY PARAMETERS CAN BE COMPUTED IN TERMS OF THOSE OF THE FULL THEORY, PROVIDED THE LATTER IS KNOWN

$\rightarrow$ LET'S SHOW THIS WITH AN SPECIFIC EXAMPLE!

$$\mathcal{L}_{\text{SMEFT}} \supset \mathcal{L}_{\text{SM}} + \frac{a_u}{\Lambda^2} (\bar{e}_R \gamma^\mu e_R) (\bar{u}_R \gamma_\mu u_R)$$

$e_R \rightarrow$ RIGHT-HANDED ELECTRON FIELD

$u_R \rightarrow$ " " UP QUARK FIELD

ANOTHER EXAMPLE OF A DIMENSION-6 FOUR-FERMION OPERATOR

$$P_R = \frac{1+\gamma^5}{2} \quad e_R = P_R e$$

USING DIRAC ALGEBRA WE CAN REWRITE THIS OPERATOR OF THE SMEFT AS

$$\frac{a_u}{16\Lambda^2} (\bar{e} \gamma^\mu (1+\gamma^5) e) (\bar{u} \gamma_\mu (1+\gamma^5) u)$$

THIS OPERATOR CAN ARISE IN THE LOW ENERGY LIMIT OF A "FULL THEORY" WHERE THE SM IS EXTENDED BY A NEW, VERY HEAVY, Z' GAUGE BOSON, WITH $M_{Z'} \gg M_Z (\approx 90 \text{ GeV})$

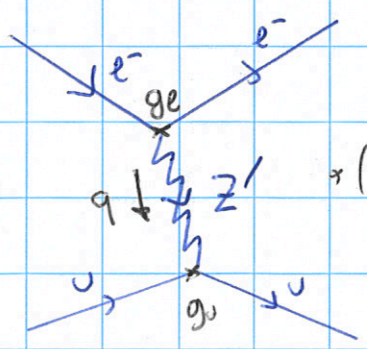
$$\mathcal{L}_{\text{FULL}} \supset \underbrace{(g_e \bar{e} \gamma^\mu (1+\gamma^5) e)}_{\text{UV PARAM } Z'-e-e \text{ COUPLING}} Z'_\mu + \underbrace{(g_u \bar{u} \gamma^\mu (1+\gamma^5) u)}_{\text{UV PARAM } Z'-u-u \text{ COUPLING}} Z'_\mu$$

[Z'_μ ONLY COUPLES TO RIGHT-HANDED FERMIONS]

WE SHOULD NOW MATCH THE "FULL" AND "EFT" THEORIES WITH AN EXPLICIT AMPLITUDE CALCULATION

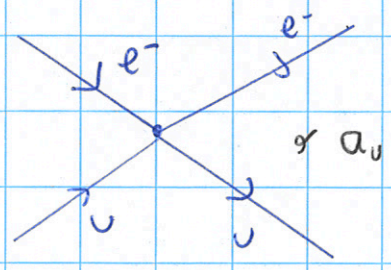
$$e^- + u \longrightarrow e^- + u$$

FULL



$$\propto (g_e g_u) \frac{1}{q^2 - M_{Z'}^2}$$

EFT



[FOUR-POINT VERTEX]

$$\left\{ \begin{array}{l} A_{\text{FULL}} \propto \frac{g_e g_u}{q^2 - M_{Z'}^2} \\ A_{\text{EFT}} \propto a_u \end{array} \right. \xrightarrow[q^2 \ll M_{Z'}^2]{\text{[EFT VALIDITY]}} \frac{g_e g_u}{M_{Z'}^2}$$

MATCHING

$$a_u \propto \frac{g_e \times g_u}{M_{Z'}^2}$$

EFT PARAM $\longrightarrow$ DETERMINED BY PARAMS OF FULL THEORY

IN A REALISTIC CALCULATION, THE UP QUARK IS PART OF THE PROTON

$$F_2^{\text{SM}}(x, Q^2) = x \frac{4e^2}{q} \left(u(x, Q^2) + \bar{u}(x, Q^2) \right)$$

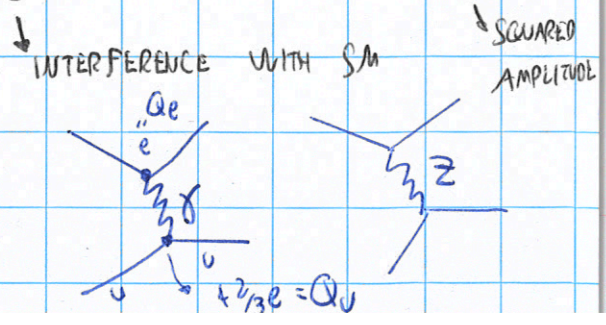
$Q^2 = -q^2$
 $x = -q^2 / 2p \cdot q$

$\hookrightarrow$ PARTON DISTRIBUTION FUNCTIONS

$$F_2^{\text{SM EFT}}(x, Q^2) = \frac{x}{12e^4} \left[4a_u e^2 \frac{Q^2}{\Lambda^2} (1 + 4K_2 S_w^4) + 3a_u^2 \frac{Q^4}{\Lambda^4} \right]$$

$$\cdot (u(x, Q^2) + \bar{u}(x, Q^2))$$

NOTE SMEFT EFFECTS GROW WITH ENERGY $\rightarrow$ ENHANCED SENSITIVITY !!



MORE ON THE SMEFT OPERATORS

SO FAR WE HAVE FOCUSED ON 4-FERMION OPERATORS, BUT THERE ARE MANY OTHERS

* PURELY BOSONIC
PURE GLUON
 [CHROMOMAGNETIC OPERATOR]

$$O_G = g_s \int_{ABC} G_{\mu\nu}^A G^{B,\mu\nu} G^{C,\mu\nu}_p$$

$$G_{\mu\nu}^A = \partial_\mu A_\nu^A - \partial_\nu A_\mu^A - g_s \int_{ABC} A_\mu^B A_\nu^C$$

CHECK THAT IT IS A BONA-FIDE SMEFT OPERATOR

- ☒ MASS-DIMENSION 6 $[O_G] = 3 \times [\partial A] = 3 \times 2 = 6$
- ☒ COMPOSED ONLY BY SM FIELDS [ONLY THE GLUON]
- ☒ SATISFIES THE SYMMETRIES OF THE SM

CAN BE VERIFIED USING PROPERTIES OF QCD COLOR ALGEBRA

eg SHOW $G_{\mu\nu}^A G^{\mu\nu A}$ is gauge invariant

$$t^A F_{\mu\nu}^A \rightarrow \cancel{t^A F_{\mu\nu}^A} U(x) t^A F_{\mu\nu}^A U^{-1}(x)$$

$$U(x) = e^{i\theta^B(x) t^B}$$

$$\text{Tr} [t^A t^B] = \frac{1}{2} \delta^{AB}$$

$$G_{\mu\nu}^A G^{\mu\nu A} = 2 G_{\mu\nu}^A G^{\mu\nu B} \text{Tr} [t^A t^B]$$

$$= 2 \text{Tr} [G_{\mu\nu}^A G^{\mu\nu B} t^A t^B]$$

↳ GAUGE INVARIANT DUE TO CYCLIC PROPERTIES OF TRACE

WHAT ARE THE PHENOM. IMPLICATIONS OF SUCH OPERATORS?
FOR EXAMPLE AT LHC?

QUARK CHROMOMAGNETIC OPERATOR

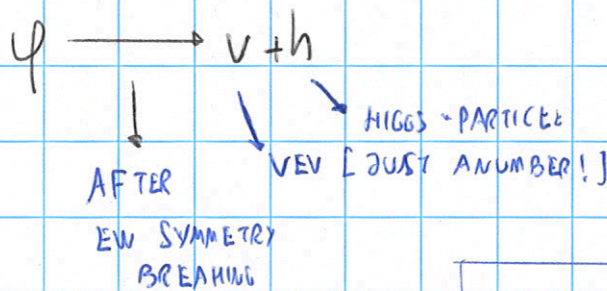
$$O_{UG}^{(ij)} = (\bar{q}_i \epsilon^{\mu\nu} T^A u_j) \tilde{\psi} G_{\mu\nu}^A$$

LEFT-HANDED SU(2) DOUBLETS
 RIGHT-HANDED FERMION SINGLET
 HIGGS FIELD
 GLUON FIELD STRENGTH

$i, j = 3$ [FLAVOR INDICES]

$$O_{UG}^{(33)} \propto \bar{t} t \psi G_{\mu\nu}$$

[IGNORE DIRAC, COLOR INDICES!]



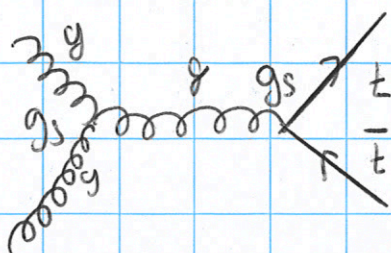
$$G_{\mu\nu} \supset A_\mu A_\nu$$

$$O_{UG}^{(33)} \supset \bar{t} t A_\mu A_\nu$$

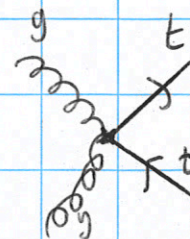
A NEW INTERACTION, ABSENT IN THE SM, BETWEEN TWO TOP QUARKS AND TWO GLUONS

(SM)

$g g_s^2$



(SMEFT)



$\propto C_{tG}$

DOMINANT DIAGRAM FOR TOP QUARK PAIR PRODUCTION AT LHC

THIS NEW INTERACTION IS THE LOW-ENERGY REMNANT OF NEW FORCES AND/OR PARTICLES AT HIGH-ENERGY

↳ MODIFIES THE PRODUCTION RATES OF TOP QUARK PAIRS @ LHC

$$G_{TOT} = G_{SM} \times \left(1 + a \frac{CtG}{\Lambda^2} + b \frac{CtG^2}{\Lambda^4} \right)$$

↓ TOTAL XSEC
 ↓ SM PREDICTION
 ↓ COMPUTABLE IN THE SMEFT
 ↓ FIXED BY SOME UNKNOWN HIGH-ENERGY THEORY
 ↓ CONstrain FROM EXP DATA!!

Let us consider another related SMEFT operator

$$O_{\psi W}^{(ij)} = (\bar{q}_i \gamma^{\mu} Z^I U_j) \tilde{\varphi} W_{\mu\nu}^I$$

THIRD GENERATION FERMIONS ↓ $i=j=3$
 SU(2) GENERATOR ↓
 FIELD-STRENGTH TENSOR FOR W BOSON ↓
 HIGGS FIELD BEFORE EWSB

$$O_{\psi W}^{(33)} = (\bar{q}_3 \gamma^{\mu} Z^I t) \tilde{\varphi} W_{\mu\nu}^I$$

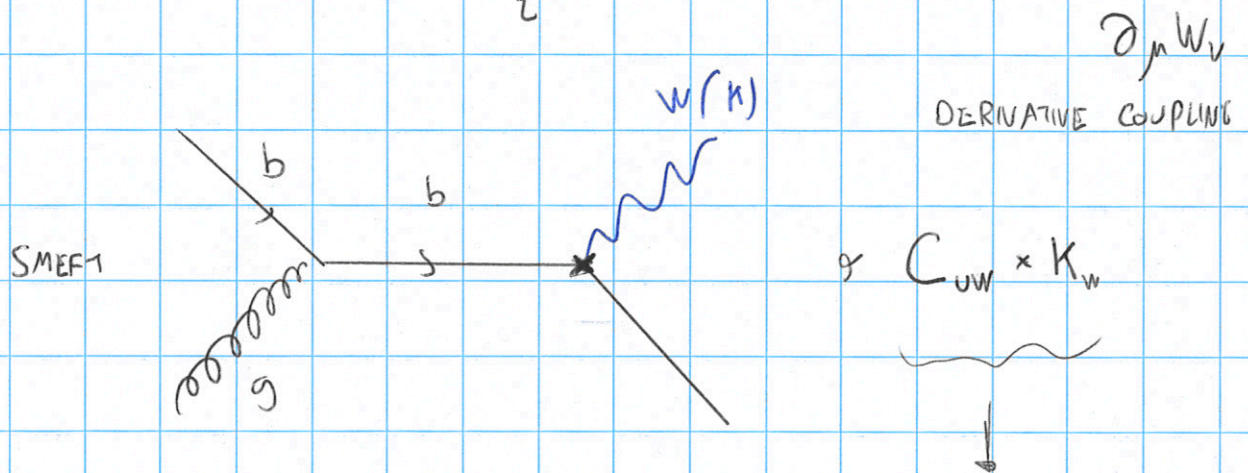
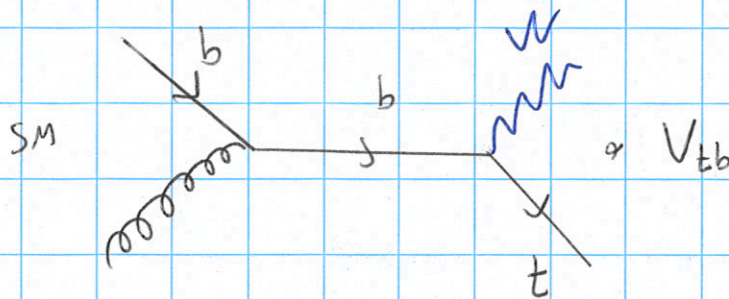
↳ SU(2) DOUBLET
 $\begin{pmatrix} t \\ b \end{pmatrix}$

WHAT ARE IMPLICATIONS

$$\mathcal{L} \supset b \times t \times (\partial_{\mu} W_{\nu})$$

SO THIS OPERATOR (AMONG OTHER IMPLICATIONS)
WILL MODIFY THE COUPLING $t-W-b$

EG SINGLE-TOP-PRODUCTION



BEYOND A SIMPLE
COUPLING RESCALING!

THIS EXAMPLE ILLUSTRATES WHY SMEFT EFFECTS ARE
MUCH MORE POWERFUL ~~THAN~~ THAN A SIMPLE RESCALING OF
COUPLINGS

ANOMALOUS COUPLING $\longrightarrow g_{BSM} = g_{SM} \times \underbrace{f}_{\text{CONSTANT}}$

SMEFT $\longrightarrow$ EFFECTIVE COUPLINGS ALSO MODIFIED,
AN IN ADDITION

- i) CORRELATE DIFFERENT PROCESSES
- ii) MODIFY FINAL-STATE KINEMATICS
(EG) ENERGY GROWING EFFECTS

RUNNING AND MIXING

A VERY POWERFUL PROPERTY OF QUANTUM FIELD THEORIES IS THAT THEY ALLOW TO RELATE PHENOMENA AT VERY DIFFERENT SCALES

EG ONCE YOU HAVE LOOP CORRECTIONS (BEYOND TREE LEVEL) THE COUPLING CONSTANTS (INCLUDING EFT COEFFICIENT!) DEPEND ON THE SCALE OF THE PROCESS

GENERAL STRUCTURE

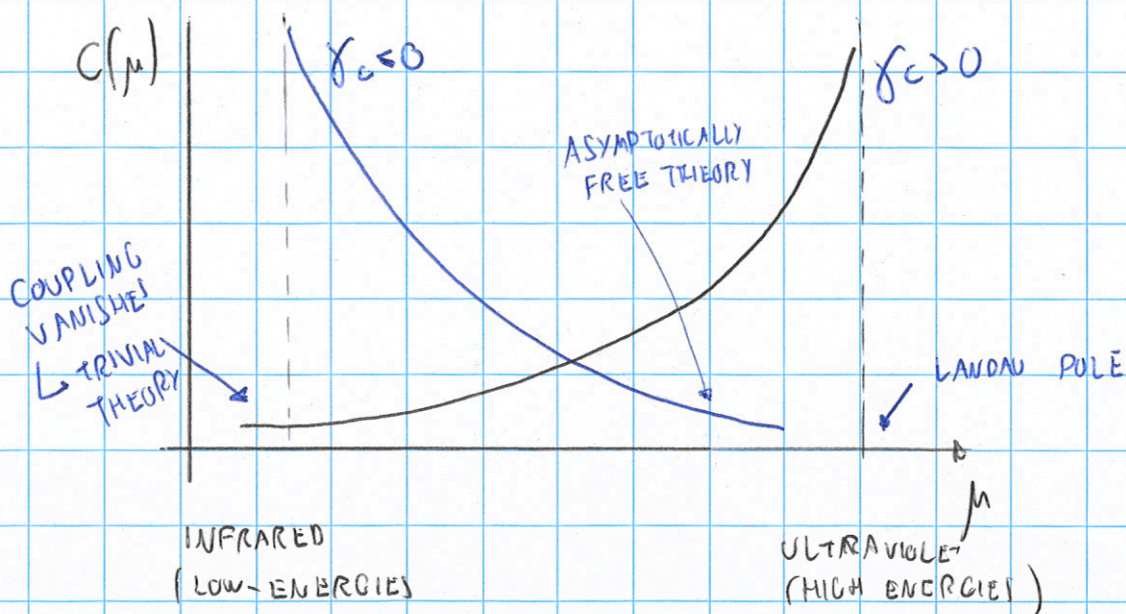
$$C(\mu) = \frac{C(\Lambda)}{1 - \gamma_c \frac{C(\Lambda)}{16\pi^2} \ln \frac{\mu^2}{\Lambda^2}}$$

REFERENCE SCALE Λ
 PHYSICAL SCALE OF PROCESS μ
 POTENTIALLY LARGE LOGS $\ln \frac{\mu^2}{\Lambda^2}$
 ANOMALOUS DIMENSION γ_c

$1 - \gamma_c \frac{C}{16\pi^2} \ln \frac{\mu^2}{\Lambda^2} = 0$
 $\frac{16\pi^2}{\gamma_c C(\Lambda)} = \ln \frac{\mu^2}{\Lambda^2}$
 $\mu^2 = \Lambda^2 e^{16\pi^2 / \gamma_c C(\Lambda)}$

$\gamma_c > 0 \Rightarrow \mu > \Lambda$
 $\gamma_c < 0 \Rightarrow \mu < \Lambda$

DEPENDING ON THE SIGN OF THE ANOMALOUS DIMENSION, WE HAVE TWO DIFFERENT POSSIBILITIES



IN THE CONTEXT OF SMEFT $\rightarrow$ IMPLICATION

$$\mathcal{L}_{\text{SM}} + \sum_{j=1}^{N_{\text{dG}}} \frac{C_j^{(d=6)}(\mu)}{\Lambda^2} \mathcal{O}_j^{(d=6)}(\mu) \neq \sum_{j=1}^{N_{\text{dG}}} \frac{C_j^{(d=6)}(\mu')}{\Lambda^2} \mathcal{O}_j^{(d=6)}(\mu') \quad \mu \neq \mu'$$

THE RENORMALIZATION GROUP EQUATIONS THAT DETERMINE THE SCALE DEPENDENCE OF THE COUPLINGS IN THE SMEFT IMPLY $\rightarrow$ OPERATOR MIXING

$$\frac{d}{d \ln \mu} C_j(\mu) = \gamma_{ij} C_i(\mu)$$

$\downarrow$ ANOMALOUS DIMENSION MATRIX
WHICH DETERMINES THE OPERATOR MIXING BETWEEN SCALES [SCALES]

THIS RUNNING AND MIXING EFFECT IS CRUCIAL IN EFT, FOR EXAMPLE ALLOWING US TO CONNECT THE SMEFT WITH THE WEAK EFT RELEVANT TO DESCRIBE FLAVOUR PHYSICS

$\rightarrow$ EXPLICIT EXAMPLE IN TOY THEORY

$$\mathcal{L}_{\text{EFT}} \supset \frac{1}{4!} C_4 \phi^4 + \frac{1}{6!} \frac{C_6}{M^2} \phi^6 \quad \text{At Low ENERGIES}$$

[Φ] MASSIVE FIELD INTEGRATED OUT, $m \ll M$ ϕ IS THE ONLY PHYSICAL DEGREE OF FREEDOM

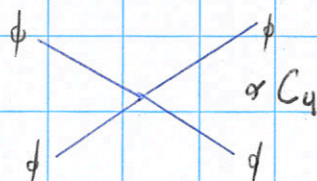
FROM DIMENSIONAL ANALYSIS

$$[C_4] = [C_6] = 0$$

CONSIDER THE 4-POINT SCATTERING AMPLITUDE

$$A(\phi\phi \rightarrow \phi\phi)$$

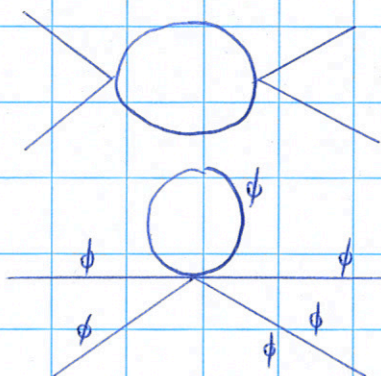
TREE LEVEL



$\propto C_4$

ONLY DIAGRAM

WHAT POSSIBLE DIAGRAMS WILL BE PRESENT AT ONE-LOOP?



$\propto C_4^2$

$\propto C_6/\Lambda^2$

THE DIAGRAMS ARE DIVERGENT

↓ THE RENORMALIZATION OF C_4 WILL INVOLVE BOTH C_4 & C_6 !

DOING THE CALCULATION ONE CAN SHOW THAT

$$\frac{d}{d \ln \mu^2} \begin{pmatrix} C_4(\mu) \\ C_6(\mu) \end{pmatrix} = \begin{pmatrix} \gamma_{44} & \gamma_{46} \\ \gamma_{64} & \gamma_{66} \end{pmatrix} \begin{pmatrix} C_4(\mu) \\ C_6(\mu) \end{pmatrix}$$

ASSUME THAT γ_{nm} ARE CONSTANTS AND THAT AT

A REFERENCE SCALE Λ $C_4(\Lambda) = 0$

$$\frac{d}{d \ln \mu^2} C_4 = \gamma_{44} C_4 + \gamma_{46} C_6$$

GENERAL SOLUTION

$$C_4(\mu) = C_4(\Lambda) \underbrace{e^{a \ln \mu/\Lambda}}_{(\mu/\Lambda)^a} + C_6(\Lambda) \underbrace{e^{b \ln \mu/\Lambda}}_{(\mu/\Lambda)^b}$$

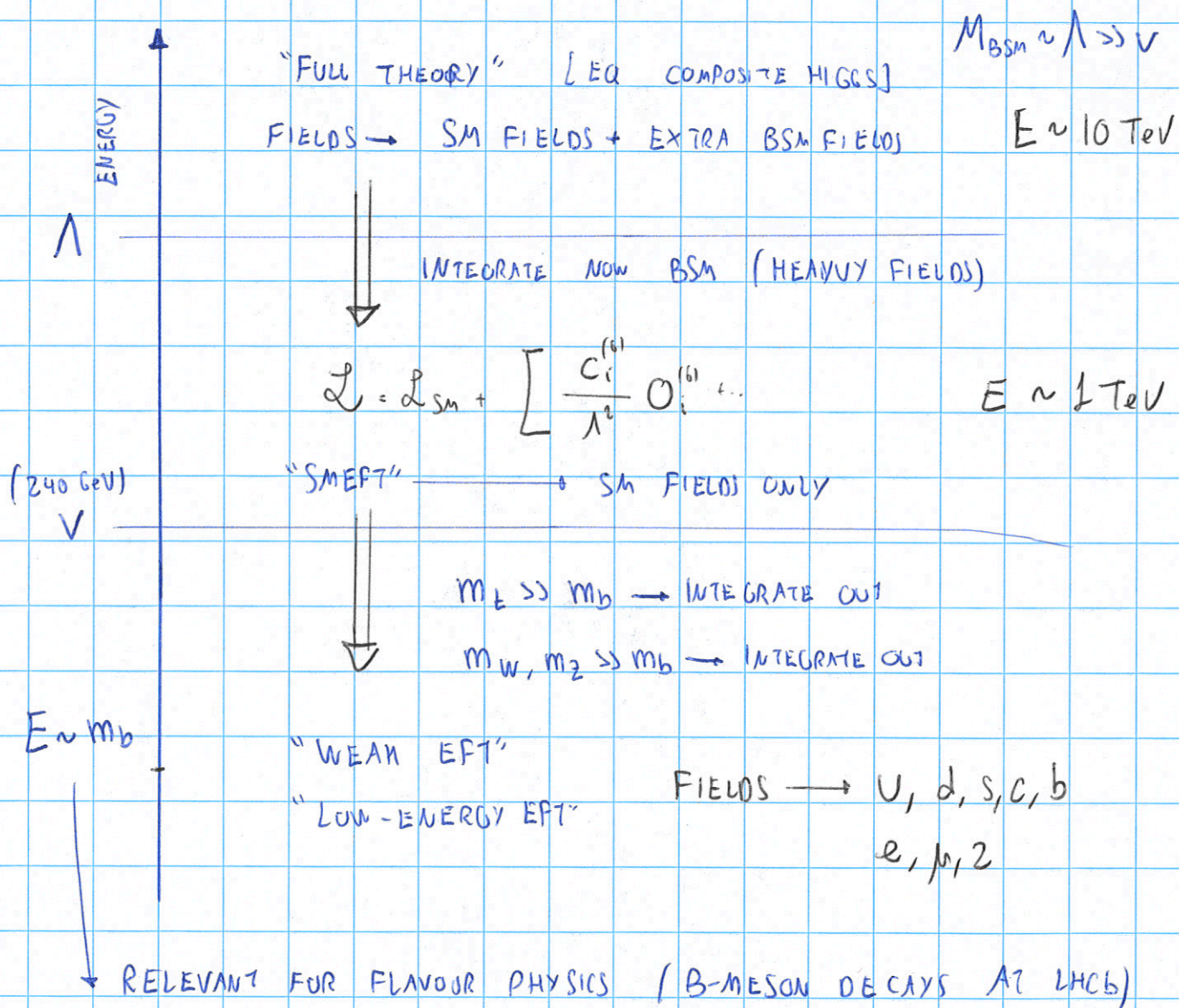
$C_4(\mu) \neq 0$ EVEN IF
 $C_4(\Lambda) = 0$!!

THE WEAK EFFECTIVE FIELD THEORY

WE NOW WANT TO MAKE THE CONNECTION BETWEEN THE SMEFT AND FLAVOUR PHYSICS [MARCEL'S AND NIELS' LECTURES]

IMPORTANT CONCEPT

EFT TOWER



IT IS POSSIBLE TO MATCH OPERATORS IN SMEFT WITH THOSE OF WEFT

$\rightarrow$ ROBUST, MODEL-INDEPENDENT CONNECTION BETWEEN HIGH-PT PHYSICS [HIGGS, TOP, EWK] AND LOW-ENERGY FLAVOR PHYSICS!

VALID UP TO $E \sim \Lambda$

VALID UP TO $E \sim m_b$

SMEFT

WEFT

↑
INTEGRATE OUT
 W, Z, E, h

WEFT OPERATORS CAN BE CONSTRUCTED ONLY OUT OF

- u, d, s, c, b QUARKS
- e, μ, τ charged leptons - ν_e, ν_μ, ν_τ
- γ, g

The WEFT depends on a number of coupling constants, fixed in terms of the

- i) SM couplings
- ii) M_W, M_Z, M_t, V
- iii) The Wilson coefficients of the SMEFT Lagrangian

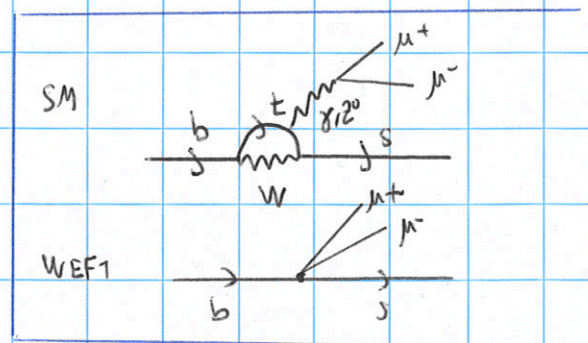
What are the symmetries of LEFT?

$m_b \ll V \rightarrow$ EW symmetry is broken!

$$SU(3) \times U(1)_Q$$

EXAMPLE $\rightarrow b \rightarrow s l^+ l^-$

FLAVOR-CHANGING NEUTRAL CURRENT



$B \rightarrow K^* \mu^+ \mu^-$ ANOMALIES

This can be interpreted
DEVIATIONS WRT SM

- WEFT $\rightarrow$ CORRELATE WITH OTHER FLAVOR DATA
- SMEFT $\rightarrow$ CORRELATE WITH HIGGS, TOP, EWM

WEFT

$$O_q^{bs\mu\mu} = \frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{e^2}{16\pi^2} (\bar{s}_L \gamma^\mu b_L) (\bar{\mu} \gamma_\mu \mu)$$

THIS OPERATOR IS OBTAINED $SM \rightarrow$ WEFT INTEGRATING
HEAVY DEGREES OF FREEDOM

MORE IN GENERAL IN THE SM THE PROCESSES WITH
FLAVOR STRUCTURE $(\bar{s} b) / (\bar{\mu} \mu)$ at $\mu = m_b \approx 5 \text{ GeV}$

$$\mathcal{L} = + \frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_{i=3,10} (C_i O_i)$$

$$C_q^{SM} = 0.29 \quad \text{but if there are new physics}$$

$$C_i = C_i^{SM} + C_i^{BSM}$$

IMAGINE THAT EXPERIMENTAL DATA IMPLY $C_i^{BSM} \neq 0$
AT A CERTAIN SIGNIFICANCE

IMPLICATIONS FOR HIGH-PT PHYSICS? SMEFT

$$\mathcal{L}_{SMEFT} \supset \frac{1}{\Lambda^2} [C_{lq}^{(1)}]_{2223} [O_{lq}^{(1)}]_{2223}$$

$$\begin{aligned} [O_{lq}^{(1)}]_{2223} &= (\bar{l}_2 \gamma^\mu l_2) (\bar{q}_2 \gamma_\mu q_3) \\ &= (\bar{\mu} \gamma^\mu \mu) (\bar{s} \gamma_\mu b) \end{aligned}$$

$$[C_{lq}^{(1)}]_{2223} \quad \text{FREE PARAMETER, TO BE CONSTRAINED FROM DATA}$$

WET

TREE
LEVEL

SMEFT

$$O_q^{bs\mu\mu}$$

MATCHING

$$[O_{lq}^{(1)}]_{2223}$$

$$\mu = m_b$$

$$\mu = \Lambda \approx 10 \text{ GeV}$$

NEED TO INCLUDE
OPERATOR RUNNING EFFECTS

*

ANOTHER EXAMPLE

$$b \rightarrow c Z \nu$$

RELEVANT FOR R_D ANOMALIES

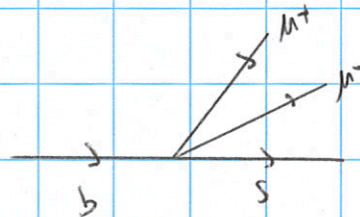
*

WHAT COULD GENERATE THE

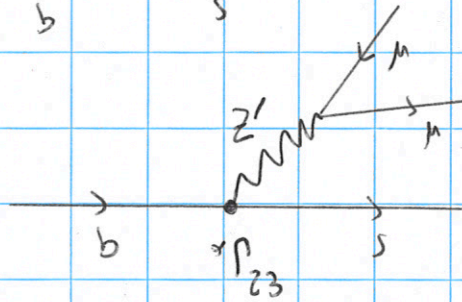
$$[O_{lq}^{(1)}]_{2223}$$

OPERATORS
IN THE SMEFT?

SMEFT



"FULL THEORY"



$$C_q^{\mu\mu} \propto \frac{P_{23}}{M_{Z'}^2}$$

IN THE SMEFT WE CAN CHECK IF THIS INTER-
PRETATION SURVIVES FROM LHC CONSTRAINTS!

BACK TO $b \rightarrow c \nu \rightarrow$ RELEVANT FOR

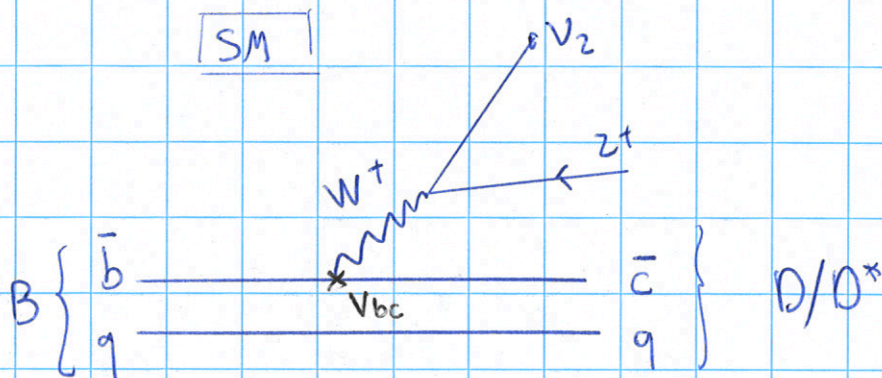
$$R(D^{(*)}) = \frac{\text{Br}[B \rightarrow D^{(*)} \nu]}{\text{Br}[B \rightarrow D^{(*)} \ell \nu]}$$

$\ell = e, \mu$

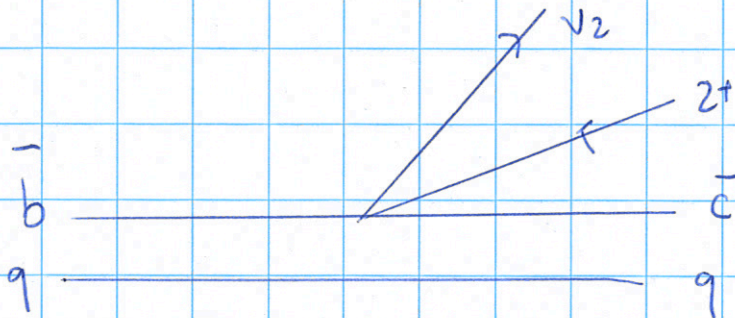
IN THE STANDARD MODEL WHAT IS THIS RATIO?

SM $\rightarrow$ LEPTON UNIVERSALITY $\rightarrow$ ALL LEPTONS HAVE SAME COUPLINGS

WHAT IS ONLY DIFFERENCE? $m_Z = 91 \text{ GeV} \gg m_\mu \approx 106 \text{ MeV}$



WEFT $\rightarrow$ INTEGRATE OUT W BOSON



$$\mathcal{L}_{\text{WEFT}} = -\frac{4G_F}{\sqrt{2}} V_{cb} \left[(1 + g_V) (\bar{c}_L \gamma_\mu b_L) (\bar{\ell}_L \gamma^\mu \nu_L) + g_S (\bar{c}_R b_L) (\bar{\ell}_L \nu_L) + g_T (\bar{c}_R \sigma_{\mu\nu} b_L) (\bar{\ell}_R \sigma^{\mu\nu} \nu_L) \right]$$

MATCHING THE WEFT TO THE SM

$\rightarrow g_V = g_S = g_T = 0 \rightarrow$ BUT THIS IS NOT TRUE IN THE SM!

FOR EXAMPLE IN THE SMEFT LAGRANGIAN ONE HAS

$$\mathcal{L}_{\text{SMEFT}} \supset \frac{[C_{\ell e d q}]_{3332}}{\Lambda^2} (\bar{\ell}_3 e_3) (\bar{d}_3 q_2)$$

COMPARE WITH

$$C = C_R + C_L$$

$$\mathcal{L}_{\text{WEFT}} \supset \frac{4 G_F V_{cb}}{\sqrt{2}} g_s (\bar{c}_R b_L) (\bar{\ell}_R \nu_R)$$

TREE-LEVEL MATCHING

$$G_F V_{cb} g_s \approx \frac{[C_{\ell e d q}]_{3332}}{\Lambda^2}$$

$$\left[g_s \approx \frac{[C_{\ell e d q}]_{3332}}{\Lambda^2} \quad \frac{1}{G_F V_{cb}} \right]$$

CRUCIAL → A NON-ZERO VALUE OF g_s IS
EFFECTIVELY A MEASUREMENT OF
 C/Λ^2 . For $C = \mathcal{O}(1) \rightarrow \Lambda \approx \sqrt{1/g_s}$

INDIRECT BUT THEORETICALLY
ROBUST MEASUREMENT OF
THE SCALE OF NEW PHYSICS/
BEYOND THE SM!

MANY MODELS CAN BE TESTED

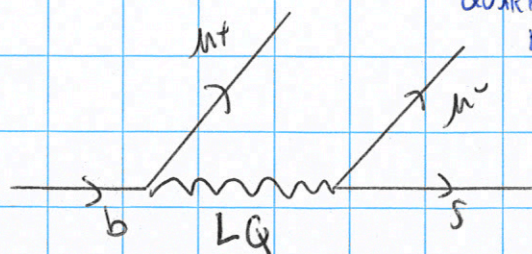
E.G. LEPTOQUARKS

$$b \rightarrow s \mu^+ \mu^-$$

SM



LEPTOQUARK



IN THE SM, NO
COUPLING BETWEEN
QUARKS AND
LEPTONS

THE SMEFT AND THE HIGGS SECTOR

The measurement of the properties of the Higgs sector is a powerful way for indirect new physics searches

IN THE SM $(H^\dagger H)$ is only $D=2$ SINGLET OPERATOR
 $\rightarrow$ IT CAN COUPLE NATURALLY TO HIDDEN SECTORS

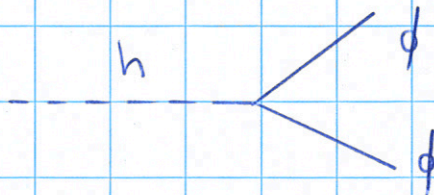
EQ ASSUME THAT WE EXTEND THE SM WITH AN EXTRA GAUGE SINGLET SCALAR FIELD (DOES NOT INTERACT WITH ANY OF THE SM PARTICLES)

$$\mathcal{L}_{\text{Full}} \supset \lambda (H^\dagger H) \phi^2 \longrightarrow \text{RENORMALIZABLE OPERATOR}$$

HOW WE CAN PROBE THIS MODEL EXPERIMENTALLY?

AFTER EW SB $H \rightarrow v + h$

$$\lambda (H^\dagger H) \phi^2 \longrightarrow \lambda v h \phi^2$$



The new singlet scalar field modifies the total Higgs width

$$BR(h \rightarrow \text{invisible}) > BR(h \rightarrow \text{invisible})|_{\text{SM}}$$

$h \rightarrow \nu\nu\nu$

AGAIN, SMEFT ALLOWS CORRELATING ANY POTENTIAL DEVIATION IN THE HIGGS BOSON COUPLINGS WITH ANOMALIES IN THE FLAVOR OF TOP SECTOR

$$O_{HG} = (H^\dagger H) G_{\mu\nu}^A G^{\mu\nu, A}$$

LET'S DO OUR USUAL CHECK-LIST TO MAKE SURE THAT IT BELONGS TO THE SMEFT

* $\Delta = 6$ $[HH] = 2$ $[G_{\mu\nu}] = 2$

* Built upon only SM fields

* Gauge invariant? Yes

$$\mathcal{L}_{SM} \supset \underbrace{m^2 (H^\dagger H) + \frac{1}{4} G_{\mu\nu}^A G^{\mu\nu, A}}$$

↓ BOTH TERMS ARE GAUGE INVARIANT SEPARATELY

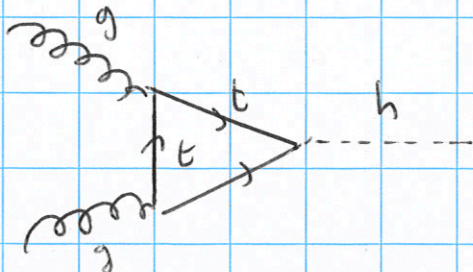
WHAT TYPE OF HIGGS PROCESSES WILL BE AFFECTED?

$$H \rightarrow h + \nu \quad \mathcal{L}_{SMEFT} \supset \frac{C_{HG}}{\Lambda^2} v h (\partial_\mu A_\nu) (\partial^\nu A^\mu)$$

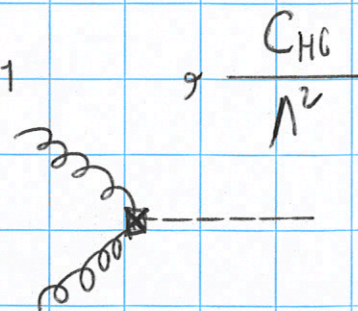
→ A COUPLING BETWEEN THE GLUONS AND THE HIGGS, ABSENT IN THE SM

GLUON-FUSION

SM



SMEFT



THIS RESULT IS ALSO INTERESTING SINCE IT ILLUSTRATES THE EXPECTED SIZE OF HIGGS COUPLINGS MODIFIED

$$C \sim C_{SM} \left(1 + \frac{v^2}{\Lambda^2} \right)$$

SINCE THERE ARE NO OTHER DIMENSIONFUL ^{QUANTITIES} ~~UNITS~~!

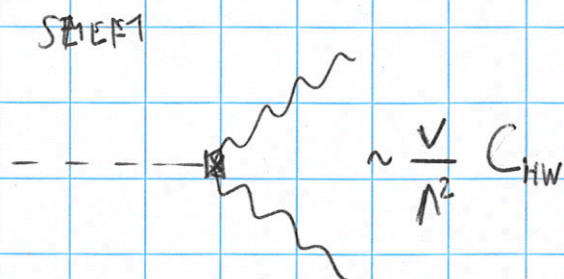
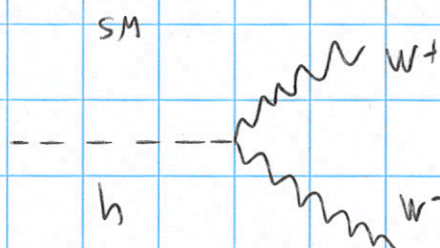
$\Lambda \sim 1 \text{ TeV} \rightarrow$ few-percent deviations at most

Let's consider another operator

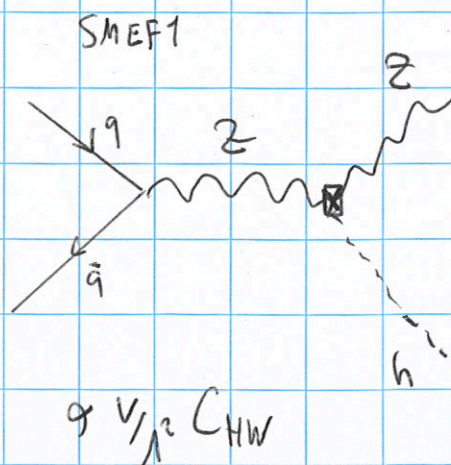
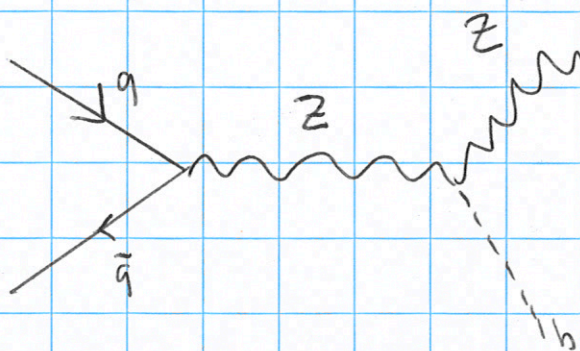
$$O_{HW} \propto (H+H) W_{\mu\nu}^I W^{\mu\nu, I}$$

after EWSB $H \rightarrow v+h \Rightarrow O_{HW} \supset v h (\partial_\mu W_\nu)(\partial_\nu W_\mu)$

$\Rightarrow$ Modifies the hWW , hZZ couplings



HIGGS
BUT ALSO ASSOCIATED PRODUCTION



ANOTHER IMPORTANT DIMENSION-6 OPERATOR IS

$$\mathcal{L}_{\text{SMEFT}} \supset \frac{C_H}{\Lambda^2} |H|^6$$

This operator modifies the Higgs potential

$$\mathcal{L}_{\text{SMEFT}} \supset \underbrace{-\mu^2 H^2 - \frac{1}{4} \lambda H^4 + \frac{C_H}{\Lambda^2} H^6}_{V(H)}$$

$$\frac{dV(H)}{dH} = 0 \quad \rightarrow \quad \text{DIFFERENT VEV / DIFFERENT MINIMUM OF THE POTENTIAL}$$

C_H will modify double Higgs production

$\propto \lambda + \overbrace{C_H / \Lambda^2 v^2}^{\text{SMEFT CORRECTION}}$

HIGGS SELF INTERACTION ESSENTIAL PART OF PHYSICS PROGRAM AT LHC

SUMMARY AND DISCUSSIONS

- If we remove the (philosophical) assumption that the SM must be valid up to say M_{Planck} , then it is understood as a EFT valid up to $E \approx \Lambda$

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \left[\frac{C_j^{(6)}}{\Lambda^2} \mathcal{O}_j^{(6)} + \left[\frac{C_j^{(8)}}{\Lambda^4} \mathcal{O}_j^{(8)} + \dots \right] \right]$$

- The Wilson coefficients $\{C_j^{(6)}\}$ need to be constrained from data
- Any theory of BSM physics that has the SM as its low energy limit can be parametrized by the SMEFT
- Can robustly correlate deviations from the SM between different sectors (like flavor & Higgs)

- IN THE ABSENCE OF EVIDENCE FOR NEW HEAVY PARTICLES OR FORCES AT THE LHC, THE SMEFT IS THE MOST PROMISING WAY TO ROBUSTLY IDENTIFY SUBTLE ANOMALIES THAT CAN POINT TO THE WAY FORWARD