TO SUMMARIZE, THE BOTTOM-UP CONSTRUCTION OF THE LEFT/WEFT REQUIRES THE FOLLOWING INGREDIENTS

1) DoF $\longrightarrow \gamma, g,\ u, d, s, c, b,\ e, \mu, \tau,\ \nu_e, \nu_\mu, \nu_\tau$
2) Symmetries $\longrightarrow SU(3)_c \otimes U(1)_{em}$
3) POWER - COUNTING $\sim m/v$ (or m/M_W) WITH m LIGHT MASS

$\sim p/v$ (or p/M_W) WITH $p \ll M_W$

Q AT LEADING ORDER IN THE EFT EXPANSION, HOW DOES SUCH LAGRANGIAN LOOK-LIKE?

[THINK $M_W \to \infty$ LIMIT]

$\hookrightarrow$ NOTHING BUT QED + QCD LAGRANGIAN, SINCE WEAKLY INTERACTING PARTICLES HAVE BEEN INTEGRATED OUT

$\boxed{Q}$ WILL NEUTRINOS BE PRESENT IN LEFT AT LEADING ORDER?

$\hookrightarrow$ NO, NEUTRAL UNDER RELEVANT GAUGE SYMMETRY!

$$\mathcal{L}_{LEFT} = \mathcal{L}_{QED+QCD} + \mathcal{O}\left(v^{-1}\right)$$

$\hookrightarrow$ EXPANSION PARAMETER

$$\mathcal{L}_{QED+QCD} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} - \frac{1}{4} G^A_{\mu\nu} G^{A\mu\nu} + \theta_{QCD} \frac{g^2}{32\pi^2} G^A_{\mu\nu} \tilde{G}^{A\mu\nu} + \sum_{\psi = u,d,e,\nu_L} \bar{\psi}\, i \not{D}\, \psi - \left[\sum_{\psi = u,d,e} \bar{\psi}_R\, m_\psi\, \psi_L + h.c. \right]$$

WITH THE COVARIANT DERIVATIVE GIVEN BY

$$D_\mu = \partial_\mu + i g T^A G_\mu^A + i e Q A_\mu$$

IF ACCIDENTAL SYMMETRIES OF SM DISREGARDED,
THERE IS A MAJORANA MASS TERM FOR NEUTRINOS WITH $\Delta L = 2$

TO CONSTRUCT FULL LEFT, RECIPEE IS TO ADD
ALL HIGHER-DIMENSIONAL OPERATORS CONSISTENT WITH
PARTICLE CONTENT AND FUNDAMENTAL SYMMETRIES

$$\mathcal{L}_{LEFT} = \mathcal{L}_{QED+QCD} + \sum_{d \geq 5} \sum_{i=1}^{n_d} L_i^{(d)} \mathcal{O}_i^{(d)}$$

$$L_i^{(d)} \propto v^{4-d}$$ [WILSON COEFFICIENT]

$\boxed{Q}$ IS LEFT AT $\mathcal{O}(v^0)$ A CHIRAL THEORY?

$\mathcal{L}_{QCD+QED}$ IS VECTOR GAUGE THEORY
→ SAME INTERACTIONS FOR LEFT AND RIGHT-HANDED FERMIONS

$\mathcal{L}_{LEFT}$ → DIFFERENT INTERACTIONS FOR
LEFT AND RIGHT-HANDED FERMIONS

NOW, LET'S SEE WHICH KIND OF HIGHER-DIMENSIONAL
OPERATORS WE CAN CONSTRUCT IN LEFT

$X = F_{\mu\nu}$, or $G_{\mu\nu}$
4 → FERMIONS

$\boxed{Q}$ WHAT HAPPENS AT DIM-5?
WHICH KIND OF OPERATOR DO ARISE?

$\dim(X) = 2 \qquad \dim(\psi) = 3/2$

$\dim(O) = 5 \to O = \psi^2 X$

$\dim(O) = 6 \qquad O = X^3, \psi^4$

↳ FOUR-FERMION OPERATORS ARISING IN FERMI THEORY

Q BASED ON POWER COUNTING, ARE OTHER TYPES OF OPERATORS POSSIBLE?

YES, INCLUDING DERIVATIVES.

$[\partial] = 1$

$\dim(O) = 6 \qquad O \sim (\partial X)^2$

Q WHY THIS IS NOT CONSIDERED?

BECAUSE IT IS <u>REDUNDANT</u>, AND CAN BE REDUCED TO PREVIOUS LIST OF OPERATORS USING EOM

$$\partial_\mu F^{\mu\nu} = e \sum_{\psi = u,d,e} \bar{\psi} \gamma^\nu Q \psi$$

$$(D_\mu G^{\mu\nu})^A = g \sum_{\psi = u,d} \bar{\psi} T^A \gamma^\nu \psi$$

WHICH IMPLIES THAT WE CAN REWRITE OPERATORS AS

$$O \sim (\partial X)^2 \sim (\psi^2)^2 \sim \psi^4$$

WHICH IS ALREADY INCLUDED IN THE LIST

HENCE, WHICH OPERATORS ENTER THE LEFT?

$$\dim(\mathcal{O}) = 5 \to \mathcal{O} \sim \psi^2 X$$

$$\mathcal{O}_{uG} = \bar{u}_L \, \sigma^{\mu\nu} T^A u_R \, G^A_{\mu\nu}$$

$$G^A_{\mu\nu} = \partial_\mu G^A_\nu - \partial_\nu G^A_\mu - g f^{ABC} G^B_\mu G^C_\nu$$

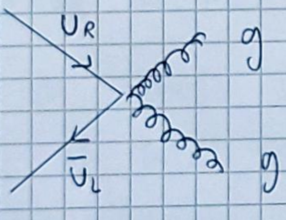
$\boxed{Q}$ WHERE CAN WE SEE IN THIS OPERATOR THAT THE "FUNDAMENTAL THEORY" IS CHIRAL?

↳ INTERACTIONS DEPEND ON QUARK CHIRALITY

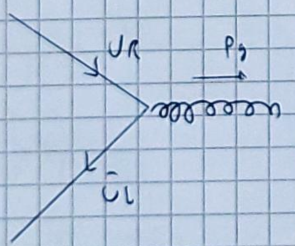
$\boxed{Q}$ WHAT KIND OF FEYNMAN RULES WOULD THIS OPERATOR INDUCE? CAN WE TRACE THEM BACK TO PROCESSES IN THE "FUNDAMENTAL THEORY"?

$$\mathcal{O}_{uG} \sim \psi^2 X \qquad X \sim \partial G, \, G^2$$

$$\sim \psi^2 \partial G \quad , \quad \psi^2 G^2$$



$\propto C_{uG}/V$



$\propto C_{uG}/V \cdot p_g$

Q) WHAT "SM" PROCESSES ARE RESPONSIBLE?

DISCUSS EXERCISE SESSION

Q) SHOULD WE REPRODUCE IN ALL CASES SM PROCESSES?

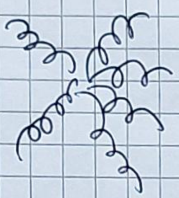
$\dim(O) = 6 \rightarrow O \sim X^3, \psi^4$

$O_G \sim f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$

Q WHAT KIND OF INTERACTIONS?

$G_\nu^{A\rho} \sim \partial_\mu G, G^2$

$O_G \sim (\partial G)^3, (\partial G)^2 G^2, (\partial G) G^4, G^6$



$\sim C_G$ (MULTIJET PRODUCTION @ LHC)

Q DOES THIS FEYNMAN RULE ARISE IF I MATCH THE LEFT TO THE SM?

NO! WE ARE ~~NOT~~ BUILDING THE LEFT BOTTOM-UP SO SOME OPERATORS WILL BE ABSENT IN THE SM

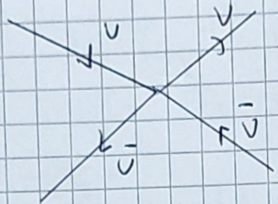
AND OF COURSE WE HAVE FOUR-FERMION OPERATORS, SOME OF THEM WE HAVE SEEN ALREADY IN THE DISCUSSION OF FERMI THEORY

$$\left.\begin{array}{l} (\bar{L}L)(\bar{R}R) \\ (\bar{R}R)(\bar{R}R) \\ (\bar{L}L)(\bar{R}R) \end{array}\right\} \rightarrow$$

PURELY LEPTONIC, SEMI-LEPTONIC, NON-LEPTONIC

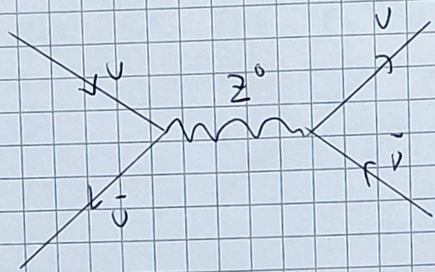
$$O_{\nu\nu}^{V,LL} \propto \frac{C_{\nu\nu}^{V,LL}}{v^2} \left(\bar{\psi}_\nu^L \gamma^\mu \psi_\nu^L\right)\left(\bar{\psi}_\nu^L \gamma_\mu \psi_\nu^L\right)$$

COUPLES NEUTRINOS WITH UP-TYPE QUARKS



$$\propto C^{V,LL}_{\nu u}/v^2$$

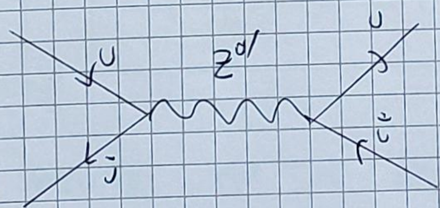
Q) DOES THIS OPERATOR ARISE FROM A SM REACTION? IF SO, WHICH ONE?



HENCE IN THE MATCHING TO SM WE FIND NON-ZERO VALUE OF COEFFICIENT WILSON

$$C^{V,LL}_{\nu u}/v^2 \propto \frac{g_{EW}^2}{M_Z^2} \neq 0$$

THIS WILSON COEFFICIENT CAN ALSO RECIEVE BSM CONTRIBUTIONS EG' OF THE FORM



$$m_{Z'} \gg m_Z$$

$$\frac{C^{V,LL}_{\nu u}}{v^2} \propto \frac{g_{EW}^2}{M_Z^2} + a\,\frac{g_{Z'}^2}{M_{Z'}^2} + \dots$$

THE LEFT CAN ALSO BE MATCHED TO SMEFT, TO BE DISCUSSED IN SUBSEQUENT LECTURES