Model-independent approaches to New Physics

1. Motivation

→ Higgs boson discovery: SM matter, gauge and global symmetry content provide an excellent classification of low energy physics $Q^2 \lesssim v^2 = (246\,\text{GeV})^2$

m. scalars, vectors ↔ gauge + Higgs
massless m. vectors ↔ gauge
m. fermions ↔ mass. Yukawa
QFT → Lorentz, internal

→ current energy reach $\lesssim$ 13 TeV has not revealed any clear hints for new physics. However stats are low.

→ most new physics searches tailored to specific UV theories (SUSY, 2HDMs, ADD, RS, ..) Are we missing something?

SM flawed
ν_s, hierarchy, ~~CP~~, strong CP, ...

LHC: no resonances up to few TeV

→ new physics weakly coupled or large energy scale

→ simp./concrete UV scenarios

→ EFT

focus of this course

EFT: separate off UV physics by defining an effective theory below a certain characteristic energy scale of the UV theory

undergrad example: <u>multipole expansion</u>

Poisson equation: $\Delta\phi = -\frac{\rho(\vec{x})}{\varepsilon_0}$

Green's function $\Delta_{\vec{x}} \frac{1}{|\vec{x}-\vec{x}_0|} = -4\pi\,\delta^{(3)}(\vec{x}-\vec{x}_0)$

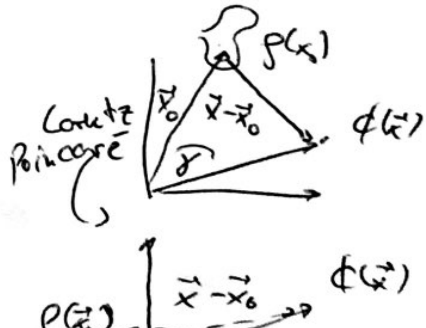
$$\Rightarrow \quad -4\pi\rho(\vec{x}) = \int d^3\vec{x}_0 \; -4\pi\,\delta^{(3)}(\vec{x}-\vec{x}_0)\,\rho(\vec{x}_0)$$

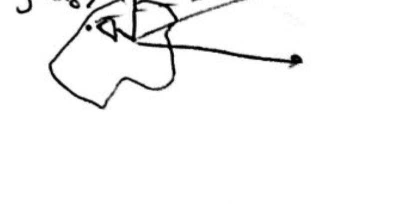
$$= \int d^3\vec{x}_0 \left[\Delta_{\vec{x}} \frac{1}{|\vec{x}-\vec{x}_0|}\right] \rho(\vec{x}_0)$$

$$= \Delta_{\vec{x}} \left\{ \int d^3\vec{x}_0 \, \frac{\rho(\vec{x}_0)}{|\vec{x}-\vec{x}_0|} \right\}$$

$$\rightarrow \quad \phi(\vec{x}) = \frac{1}{4\pi\varepsilon_0} \int d^3\vec{x}_0 \, \frac{\rho(\vec{x}_0)}{|\vec{x}-\vec{x}_0|}$$

$$\frac{1}{|\vec{x}-\vec{x}_0|} = \sum_{\ell=0}^{\infty} P_\ell(\underset{\sphericalangle(\vec{x},\vec{x}_0)}{\cos\gamma}) \, \frac{\overset{|\vec{x}_0| =}{r'^{\ell}}}{\underset{= |\vec{x}|}{r^{\ell+1}}}$$





$$P_\ell(\cos\gamma) = \sum_{m=-\ell}^{\ell} \frac{4\pi}{2\ell+1} Y_{\ell m}(\theta,\varphi)\, Y^*_{\ell m}(\theta_0^*,\varphi_0^*)$$ completeness

$$\Rightarrow \quad \phi(\vec{x}) = \frac{1}{4\pi\varepsilon_0} \sum_{\ell=0}^{\infty}\sum_{m=-\ell}^{\ell} \frac{4\pi}{2\ell+1} Y_{\ell m}(\theta,\varphi)$$

$$\cdot \frac{1}{r^{\ell+1}} \underbrace{\int_{V(\rho)} d^3\vec{x}_0\, \rho(\vec{x}_0)\, Y^*_{\ell m}(\theta_0,\varphi_0)\cdot r'^{\ell}}_{\text{multipoles } q_{\ell m}}$$

if we are interested in the physics away from the charge localisation $\sim a$. For such localised $\rho(\vec{x})$: $q_{\ell m} \sim a^\ell$
density

$$\Rightarrow \quad \phi(\vec{x}) \simeq \frac{1}{4\pi\varepsilon_0 r} \sum_{\ell m} c_{\ell m} \left(\frac{a}{r}\right)^\ell Y_{\ell m}(\theta,\varphi)$$

→ at $r \gg a$ only leading term is relevant.

→ the complete solution is Taylor-expanded in the <u>dimensionless</u> ratio of characteristic length scales $\frac{a}{r}$ — a: characteristic length scale of problem; r: scale of measurement

Fourier-transforming this yields a characteristic ratio of <u>frequencies</u>

→ in the quantum world frequencies ~ energies
So this ~~becomes~~ should become a UV ratio of characteristic measurement and momentum scales

$$\sim \frac{1}{r} \quad << \quad \sim 1/a$$

→ this is indeed the case! Harmonic oscillator

$$\left[-\frac{\hbar^2}{2m}\frac{d^2}{dx^2} + \frac{m\omega^2}{2}x^2 \right] \psi(x) = E\,\psi(x)$$

$$x_0 = \sqrt{\frac{\hbar}{\omega m}}$$

$$\rightarrow \psi_n(x) = \frac{1}{\sqrt{2^n n!}} \frac{\pi^{-1/4}}{\sqrt{x_0}} e^{-\frac{1}{2}\frac{x^2}{x_0^2}} H_n\left(\frac{x}{x_0}\right)$$

$$= \frac{1}{\sqrt{x_0}} \cdot f\left(\frac{x}{x_0}\right)$$

$x << x_0$ → QM relevant

$x >> x_0$ → $\psi_n \to 0$, QM "irrelevant" as $\langle \psi_n | \hat{x} | \psi_n \rangle = 0$ trivial when $|\psi_n\rangle = |0\rangle$ (not HO ground state)

→ bookkeeping hierachies is "natural" in both classical and quantum physics
short-distance physics should <u>not</u> impact long-distance physics.
↪ Wilsonian renormalisation etc.
Appelquist/Carrazone

2. EFT in the SM as input data

→ Fermi theory '34 phenomenologically successful, but non-renormalisable.

→ Higgs mechanism ⇝ UV completion of Fermi.

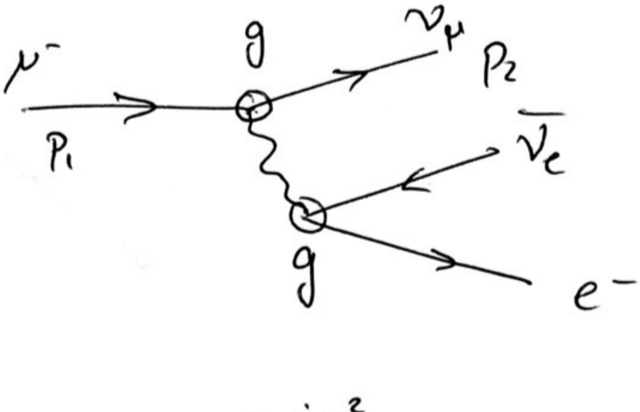
masses, e.g. $m_W^2 = \frac{g^2 \langle \Phi \rangle^2}{4}$ ← Higgs vev

$SU(2)_L$ gauge coupling

→ However, parameters in Lagrangian are <u>not</u> observables, but can be related to physical processes consistently to all orders of perturbation theory (renormalisability, renormalisation)

→ the more precise we know the input data, the more precise "new process" predictions as functions of input observables (EWPD)

Best way to fix $\langle \phi \rangle$ is through μ decay. Determined extremely well!



$$i\mathcal{M} = \ldots \frac{-ig^2}{t - m_W^2} \ldots \quad , \quad t = (p_1 - p_2)^2$$

$$(p_2 - p_1)^2 = \underbrace{p_1^2}_{=m_\mu^2} - 2p_1 \cdot p_2 - \underbrace{p_2^2}_{=0}$$

$$= m_\mu^2 - 2\left(E_\mu E_\nu - \vec{p}_\mu \cdot \vec{p}_\nu \right)$$

$$\overset{\mu \text{ at rest}}{=} m_\mu^2 - 2 m_\mu E_\nu$$

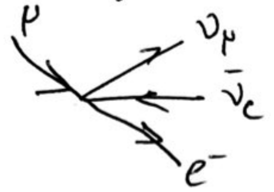
$$\Rightarrow \quad t < m_\mu^2 \ll m_W^2$$

so
$$\frac{-ig^2}{t - m_W^2} = \frac{+ig^2}{m_W^2} \frac{1}{1 - \underbrace{\frac{t}{m_W^2}}_{< m_\mu^2/m_W^2 \,\hat{=}\, \left(\frac{0.1\text{ GeV}}{80\text{ GeV}}\right)^2 \sim 10^{-6}}}$$

$$= \frac{+ig^2}{m_W^2} \left(\sum_{n=0}^{\infty} \left(\frac{t}{m_W^2} \right)^n \right)$$

very good approximation to only consider the leading term $\rightarrow$ 4 fermion interaction

[$SU(2)_L \times U(1)_Y$ invariant!]



$$\Rightarrow \mathcal{L}_{weak} = \frac{G_F}{\sqrt{2}} \left[\bar{\nu}_\mu \gamma^\alpha (1-\gamma_5) \mu \right] \left[\bar{e} \gamma_\alpha (1-\gamma_5) \nu_e \right]$$

with measured $G_F = \frac{g^2}{8 m_W^2} = \frac{1}{2v^2} = 1.66639(1) \cdot 10^{-5}\,\text{GeV}^{-2}$

$$\Rightarrow \quad v \,\hat{=}\, 246 \text{ GeV}$$

$\rightarrow$ $\mathcal{L}_{weak}$ is $d=6$, non-renormalisable, but arises from matching or "integrating out" the W boson

→ as such $\mathcal{L}_{weak}$ has lost all its memory of physics at scales $t \simeq m_W^2$.

The geometric series requires $\frac{t}{m_W^2} < 1$ to converge. ⇒ cannot trust $\mathcal{L}_{weak}$ anymore if momentum transfers test the UV completion, in this case the ELW SM.

if we approach $t \simeq m_W$ we also can't truncate at $d = 6$ level

3. Electroweak precision physics as EFT

→ Z boson pheno measured precisely at LEP.

$$\hat{\alpha} = 1/137.0359895(61)$$
$$\hat{G}_F = 1.16639(1) \cdot 10^{-5}\,\text{GeV}^{-2}$$
$$\hat{m}_Z = 91.1875 \pm 0.0021\,\text{GeV}$$
$$\hat{m}_W = 80.426 \pm 0.034\,\text{GeV}$$
$$\hat{S}_\theta^2 = 0.23150 \pm 0.00016$$
$$\hat{\Gamma}_{e^+e^-} = 83.984 \pm 0.086\,\text{GeV}$$
$$\vdots$$

use minimal set to extract parameters

$$\hat{\alpha} = \frac{e^2}{4\pi}$$
$$\hat{G}_F = (\sqrt{2}\,v^2)^{-1}$$
$$\hat{m}_Z^2 = \frac{e^2 v^2}{4 S_\theta^2 C_\theta^2}$$

etc

predict remaining quantities

$\gtrsim 5$ sigma tension!

→ electroweak precision effects are relevant.

→ look at one particular famous subset of precision observables : <u>Peskin, Takeuchi '90</u> (8)

Let's assume that new states couple predominantly to the gauge sector of $SU(2)_L \times U(1)_Y$

$$\mathcal{L}_{eff} = \mathcal{L}_{SM}(\underbrace{\bar{e}_i}_{\text{SM quantities}}) + \hat{\mathcal{L}}_{new}$$

leading deformation will be $d=4$

$$\hat{\mathcal{L}}_{new} = -\frac{A}{4}\hat{F}^2 - \frac{B}{2}\hat{W}^+\hat{W}^- - \frac{C}{4}\hat{Z}^2$$
$$+ \frac{G}{2}\hat{F}\hat{Z} - w\,\bar{m}_W^2\,\hat{W}^+_\mu\hat{W}^{-\mu} - z/2\,\bar{m}_Z\,\hat{Z}^\mu\hat{Z}_\mu$$

redefine fields to have canonical normalisation

$$\hat{A}^\mu = \left(1-\frac{A}{2}\right)A_\mu + G Z_\mu$$
$$\hat{W}_\mu = \left(1-\frac{B}{2}\right)W_\mu$$
$$\hat{Z}_\mu = \left(1-\frac{C}{2}\right)Z_\mu$$

at linear order we then have

$$\mathcal{L}_{eff} = \{\text{kinetic terms}\}$$
$$+ (1+w-B)\,\bar{m}_W^2\,W^2 + \frac{1}{2}(1+z-C)\,\bar{m}_Z^2 Z^2$$

and charged & neutral currents will also be modified

$$\mathcal{L}_{em} = -\bar{e}\left(1-\frac{A}{2}\right)\cdot\ \{SM\}$$

$$\mathcal{L}_{cc} = -\frac{\bar{e}}{\bar{s}_\theta\sqrt{2}}\left(1-\frac{B}{2}\right)\ \{SM\}$$

$$\mathcal{L}_{NC} = -\frac{\bar{e}}{\bar{s}_\theta\bar{c}_\theta}\left(1-\frac{C}{2}\right)\left[\{SM\} + \bar{f}\left[Q\,\bar{s}_\theta\,\bar{c}_\theta\,G\right]\gamma^\mu f Z_\mu\right]$$

need to eliminate $\bar{e}, \bar{m}_Z, \bar{s}_\theta$ through measurement

(i) $\bar{e}$: electron scattering at low energy

$$\overbrace{e^2 = 4\pi\alpha}^{\text{SM relation}} = \bar{e}^2(1-A) \Rightarrow \bar{e} = e\left(1+\frac{A}{2}\right)$$

measured

(ii) Z mass: resonance fit

$$m_Z^2 = \bar{m}_Z^2(1+z-G') \Rightarrow \bar{m}_Z^2 = m_Z^2(1-z+G')$$

(iii) Fermi constant

use SM relation for $\bar{m}_Z$.

$$\frac{G_F}{\sqrt{2}} = \frac{\bar{e}^2(1-B)}{8\,\bar{s}_\theta^2\,\bar{m}_W^2(1+\omega-B)} = \frac{\bar{e}^2}{8\,\bar{s}_\theta^2\,\bar{c}_\theta^2\,\bar{m}_Z^2}(1-\omega)$$

SM prediction

$$\frac{G_F}{\sqrt{2}} = \frac{e^2}{8\,s_\theta^2\,c_\theta^2\,m_Z^2}$$

use this to define

$$\bar{s}_\theta = s_\theta^2\left[1+\frac{c_\theta^2}{c_\theta^2-s_\theta^2}(A-G'-\omega+z)\right]$$

by construction $\mathcal{L}_Z \supset m_Z^2/2\, Z^2$

$$\mathcal{L}_{em} = -e\,\{SM\}$$

but W mass takes the hit

$$m_W^2 = m_Z^2\, c_\theta^2 \left[1 - B + C + w - z - \frac{s_\theta^2}{c_\theta^2 - s_\theta^2}\{A - C - w + z\}\right]$$

as well as the charged currents.

We have introduced 6 new interactions, 3 can be absorbed into field redefinitions.
3 remaining ones can be chosen as Peskin Takeuchi parameters

$$\alpha S = 4 s_\theta^2 c_\theta^2 \left(A - C - \frac{c_\theta^2 - s_\theta^2}{c_\theta s_\theta} G\right)$$

$$\alpha T = w - z \leftarrow \text{mass splitting } m_W/m_Z$$

$$\alpha U = 4 s_\theta^2 \left(A - \frac{1}{s_\theta^2} B + \frac{c_\theta^2}{s_\theta^2} C - 2\frac{c_\theta}{s_\theta} G\right)$$

→ the modifications we introduced are related to two point function renormalisations

Lorentz decomposition

$$\overset{\mu}{V_1} \sim\sim \overset{\nu}{V_2} \qquad \Pi^{\mu\nu}_{V_1V_2} = \Pi_{V_1V_2}(p^2)\, g^{\mu\nu} + \tilde{\Pi}_{V_1V_2}(p^2)\, p^\mu p^\nu$$

only these terms relevant for field and mass renormalisation

S, T, U are functions of $\Pi_{WW}, \Pi_{ZZ}, \Pi_{AZ}, \Pi_{AA}$

dimension 6 operators : Higgs doublet

$$S \sim O_{WB} = (H^{+} T^{a} H)\, W^{a}_{\mu\nu} B^{\mu\nu}$$

T^{a}: SU(2) generator

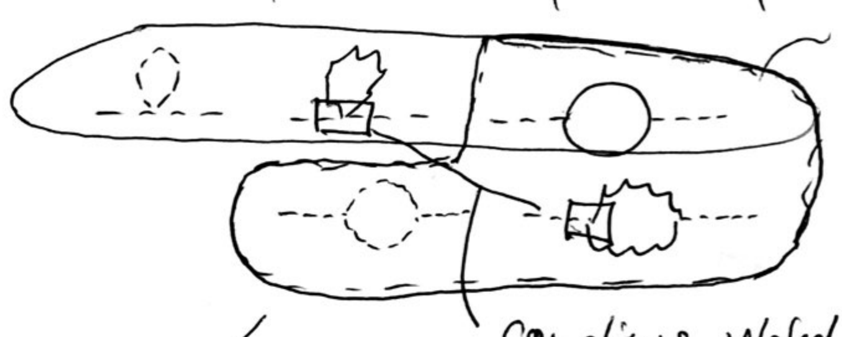
$$T \sim O_{H} = (H^{+} D_{\mu} H)^{2}$$

D_{μ}: covariant derivative

these operators are tightly constrained under the above assumptions! → GFitter plot.

4. EFT in the Higgs era

→ after Higgs discovery, an argument similar to S, T, U can be made for the Higgs, and potentially more importantly:



$$A_0(p^2) \sim \int^{\Lambda} \frac{d^4 q}{(2\pi)^4} \frac{1}{q^2} \sim \Lambda^2$$

↳ Veltman condition

↳ mass renormalisation now an input

couplings related due to gauge invariance

wave function renormalisation

$$\mathcal{L}_{SM} \to \mathcal{L}_{SM} + \frac{1}{2} \delta Z_H (\partial_\mu h)^2 - m_t \bar{t} t \cdot \frac{h}{v} + \ldots$$

canonical normalisation

$$\mathcal{L}_{SM} - (Y_t - \delta Z_H)\, \bar{t} t h$$

model-independent way to look for naturalness through precision Higgs coupling measurements.

relevant operator for this $\delta \mathcal{L}_H \sim \partial^\mu (H^\dagger H)\, \partial_\mu (H^\dagger H)$

dim 6 ☺

We have seen a number of dim 6 operators that are motivated, gauge invariant etc. In the most general approach to look for new physics we need to add all operators that are consistent with field and symmetry content

$$\mathcal{L}_{d6} = \mathcal{L}_{SM} + \sum_i \frac{c_i}{\Lambda^2} \mathcal{O}_i$$

"Warsaw" basis.

→ 59 B-conserving ⊗ flavor ⊗ h.c. = 2499 parameters most of them in the fermion sector

→ like in all examples: for perturbative UV matching to work $Q^2 \ll \Lambda^2 \simeq m^2_{stop}$ e.g.

→ phenomenological application limited to concrete sectors, typically Higgs & top.

5 EFT measurements at the LHC

→ EFTs used in flavour physics abundantly due to a series of factorisation theorems BBNS...

→ expected scale separation is similar

$$\frac{m_b}{m_W} \simeq 20 \qquad 20 \cdot v \simeq 5\,\text{TeV}$$

⇝ realistic for new physics @ LHC

however LHC scans a range of energy while flavor measurements have clear scale separation.

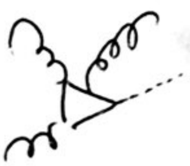
- opportunity: use energy-dependent distributions to constrain EFT
- limitation: running of parameters c_i over a large range of energy can be important

example $h \to gg$

$$\sim \left[m_h^2 \, \varepsilon_2 \cdot \varepsilon_3 - 2 \, \varepsilon_2 \cdot k_1 \, \varepsilon_3 \cdot k_1 \right] \delta^{a_2 a_3} \cdot \left[-2 + (m_h^2 - 4 m_t^2) \, C_0(m_h, m_t) \right]$$

→ for $m_t \to \infty$ non-decoupling (due to $y_t = \frac{\sqrt{2} m_t}{v}$)
tensor structure is $\sim h \, G^a_{\mu\nu} G^{a\mu\nu} \subset H^\dagger H \, G^a_{\mu\nu} G^{a\mu\nu} \cdot c_G$

→ fitting Higgs interactions we would like to disentangle the top Yukawa coupling modifications from the presence of heavy quark-like contributions discussed above for $m_t \to \infty$.



SM: $p_{T,H}$ distribution is damped for $\sqrt{s} \gtrsim 2 m_t$

$H^\dagger H (G^{a\mu\nu})^2$: $p_{T,H}$ distribution undamped ($m_t \to \infty$)

So studying differential (unfolded) distributions will improve coupling fit as inclusive rate has a blind direction $\Delta y_t - H^\dagger H G^2$.

→ Show Higgs fit plots.

<u>note on</u>

<u>Validity</u>:

→ from structure $\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{d6}/\Lambda^2$

dimension 6

$$\Rightarrow \mathcal{M} = \mathcal{M}_{SM} + \mathcal{M}_{d6}/\Lambda^2$$

$$\Rightarrow |\mathcal{M}|^2 = |\mathcal{M}_{SM}|^2 + 2\,\mathrm{Re}\,\mathcal{M}_{SM}^* \frac{\mathcal{M}_{d6}}{\Lambda^2} + \underbrace{|\mathcal{M}_{d6}|^2/\Lambda^4}_{\text{dimension 8}}$$

Can also arise from interference with $d=8$ operators

→ for a given value of Λ, can define a range of validity such that

$$2\,\mathrm{Re}\,\mathcal{M}_{SM}^* \frac{\mathcal{M}_{d6}}{\Lambda^2} \lesssim |\mathcal{M}_{SM}|^2 \quad \text{"linearisation in } c_i\text{"}$$

accidental cancellations can be circumvented through off-shellness or $(d6)^2$-specific considerations

6 Higher order effects in EFT

→ although d6 is non-renormalisable, we can technically renormalise it when truncating the d>6 contributions ↳ identify large radiative SM corrections to d6 interactions

→ Let's focus on $O_G = H^\dagger H \, G^a_{\mu\nu} G^{a\mu\nu}$ in unbroken phase.

$$\mathcal{L} = \mathcal{L}^{\overset{\text{unrenormalised}}{0}}_{SM} + \frac{C^0_G}{\Lambda^2} H^\dagger_0 H_0 \, G^a_{\mu\nu,0} G^{a\mu\nu,0}$$

mult. renorm. ↳

$$= \mathcal{L}_{SM}(Z_G, Z_H, G_R, H_R, \dots) \qquad \boxed{Z_i = 1 + \delta Z_i}$$

$$+ \frac{Z_C \, C_{G,R}}{\Lambda^2} H^\dagger_R H_R \, G^2_R \cdot Z_H \cdot Z_G$$

① need Higgs wave function renormalisation

→ δZ_H

$$\delta Z_H = \frac{-1}{64\pi^2}\Big[\,3\overbrace{g_1^2}^{\text{hypercharge}} + 9\underbrace{g^2}_{\text{weak coupling}} - g_1^2\,\xi_B - 3g^2\,\overbrace{\xi_W}^{\text{gauge fixing}}\Big]\,\bar{\Delta}$$

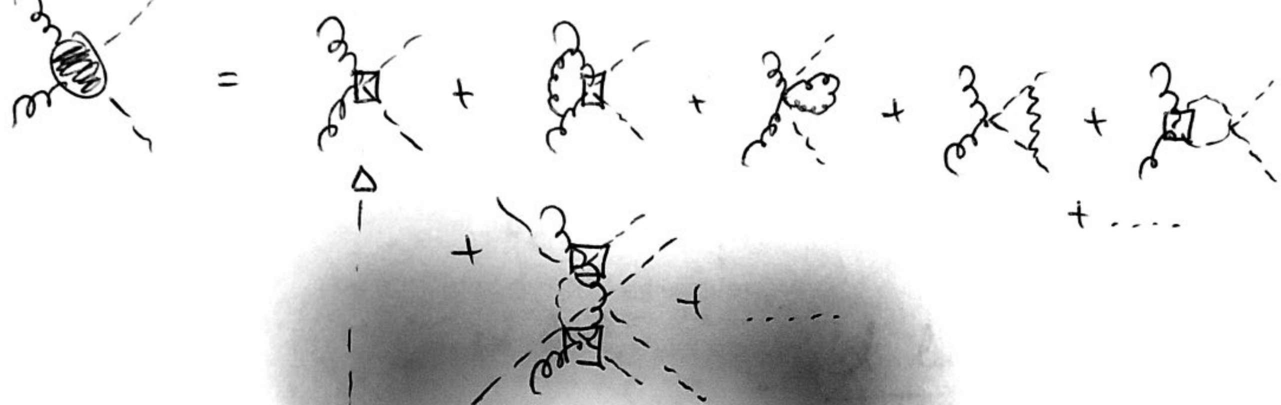
$$\bar{\Delta} = \left[\frac{4\pi\mu^2}{m^2}\right]^{\varepsilon} \frac{\Gamma(1+\varepsilon)}{\varepsilon}$$

(2) need gluon wave function renormalisation

 $\rightarrow \delta Z_G = -\frac{g_s^2}{32\pi^2}(5-3\xi_G)\bar{\Delta}$

(3) amputated $\langle H^0 H^0 G^{02}\rangle = \langle O_G^0\rangle = \frac{1}{Z_H Z_G}\langle O_{G,R}\rangle$

$= C_{G,R} Z_4 \langle O_R\rangle$



neglect d 8

$$= C_{G,R}\langle O_G^0\rangle$$

$$+ C_{G,R}\langle O_G^0\rangle \cdot \underbrace{\frac{\bar{\Delta}}{64\pi^2}\left[g_1^2\xi_B + 3(6g_3^2 - 8\lambda + 2g_s^2\xi_G + g^2\xi_W)\right]}_{=\delta Z_4}$$

$$= C_{G,R}\langle O_{G,R}\rangle \cdot (1 - \delta Z_H - \delta Z_G + \delta Z_4)$$

$$= C_{G,R}\langle O_{G,R}\rangle \, (1 + \delta Z_c)$$

$$\Rightarrow C_G^0 = C_{G,R}\overbrace{(1 \pm \delta Z_H \pm \delta Z_G + \delta Z_4)}^{1+\delta Z_c}$$

RGE :

$$0 = \mu \frac{d C_G^0}{d\mu} = \frac{d C_G^0}{d \ln\mu} = \frac{d(Z_c C_{G,R})}{d \ln\mu}$$

$$= \frac{d Z_c}{d \ln\mu} C_{G,R} + \frac{d C_{G,R}}{d \ln\mu} \cdot Z_c$$

$$\Leftrightarrow \quad \frac{d C_{G,R}}{d \ln\mu} = -\frac{1}{Z_c} \frac{d Z_c}{d \ln\mu} \cdot C_{G,R}$$

$$= -\frac{d \ln Z_c}{d \ln\mu} C_{G,R} = -\frac{d \ln(1+\delta Z_c)}{d \ln\mu} \cdot C_{G,R}$$

$$= \underbrace{-\frac{d\,\delta Z_c}{d \ln\mu}}_{\to \gamma \text{ "anomalous dimension"}} \cdot C_{G,R}$$

$$\gamma_{C_G} = -\lim_{\varepsilon\to 0} \frac{d\,\delta Z_c}{d \ln\mu} = -\frac{3}{2} g_1^2 - \frac{9}{2} g^2 + 12\lambda - \underbrace{14 g_s^2}_{\text{dominates RGE flow}} \Big(+ \overset{\text{fermions in}}{6} Y_t^2\Big)$$

Can we resum this?

$$\beta(g_s) = \frac{\partial g_s}{\partial \ln\mu} = \gamma_{g_s} \cdot g_s = -7 g_s^3$$

these fore $\gamma_{c_G} = \dots + 2\gamma_{g_s}$

if we normalised $\frac{c_G g_s^2}{\Lambda} H^2 G^2$ we would have $\delta Z_c^{g_s} = \delta Z_4 - \delta Z_G - \delta Z_H - 2\delta Z_{g_s}$ and as

$$\gamma_c^{g_s} = -\frac{d\delta Z_c^{g_s}}{d\ln\mu} = -\frac{d\delta Z_c}{d\ln\mu} + 2\frac{d\delta Z_{g_s}}{d\ln\mu}$$

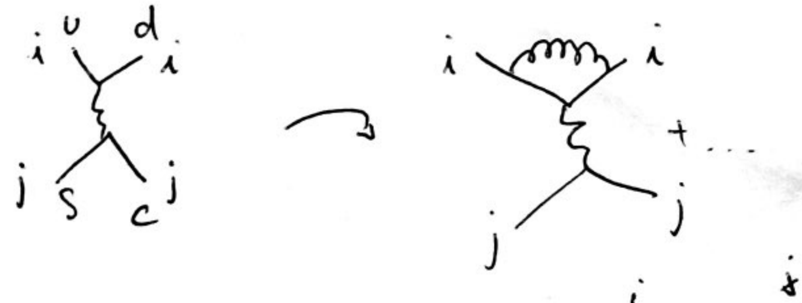
$$= \gamma_c - 2\gamma_{g_s}$$

$$= -\frac{3}{2}g_1^2 - \frac{9}{2}g^2 + 12\lambda$$

the running of the strong coupling can be include through a proper normalisation

→ this operator is special as the radiative corrections are entirely proportional to O_G itself

in general new structures will be sourced and γ becomes a matrix



but also

in the 4 fermion EFT

$$\gamma = \frac{g_s^2}{16\pi^2}\begin{bmatrix} -2 & 6 \\ 6 & -2 \end{bmatrix}$$

operator mixing very important