Beyond Standard Model
(BSM)

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Effetive Field Theory (EFT)

- Why EFT ?
- SM (Ren + Nonren) as an EFT
- EFT for Dark Matter Physics

Why EFT ? (weak coupling case)

- We don’t know what happens at energy higher than it is affordable
- High Energy physics can leave footprints in low energy regime, which can be adequately described by effective lagrangian with an infinite tower of local operators
- If new physics scale is much higher than experimental energy scale, the lowest dim nonrenormalizable operators will give the dominant corrections to the SM prdictions
  Fermi’s theory of weak interaction is a good example
- One can do meaningful phenomenology with a few number of unknown parameters
- Existing proof : the very most successful SM down to $r \lesssim 10^{-18}$ m
- In any case, we are living with EFT any way in real life

Why EFT ? (strong coupling case)

- In a strongly coupled theory such as QCD where nonperturbative aspects are very important, it is ususally very difficult to solve a problem
- Very often physical dof is different from fields in the lagrangian
  (quarks and gluon vs. hadrons in QCD)
- Useful (often critical) to construct EFT based on the symmetries of the underlying strongly interacting theory, using the relevant dof only
- Most important to identify the relevant dof and relevant symmetries
- Many examples in QCD: chiral lagrangian [$+$ (axial) vector mesons, heavy hadrons], NRQCD for heavy quarkonium, HQET for heavy hadrons, SCET etc.

Naive Dimensional Analysis

- Natural Units in HEP:

$$c = \hbar = 1 \to [\vec{L} = \vec{r} \times \vec{p}] = 0$$

$$[L] = [T] = [\vec{p}]^{-1}$$

$$E = \sqrt{(pc)^2 + (mc^2)^2} \quad \longrightarrow \quad E = \sqrt{p^2 + m^2},$$

$$\text{QM Amp} \sim \int_{\text{path}} e^{iS/\hbar} \quad \longrightarrow \quad [\text{Action}] = 0 = [\int d^4x \mathcal{L}]$$

- $[E] = [p] = [M] = [L]^{-1} = [T]^{-1}$
- Everything will be in mass dimensions:

$$[\mathcal{L}] = 4, \quad [\sigma(= \text{Area})] = -2, \quad [\tau(= \Gamma^{-1})] = -1$$

- Both the decay rate ($\Gamma \equiv \tau^{-1}$) and the cross section (σ) are given by

  Fermi's Golden Rule

  with suitable flux facors

$$|\mathcal{M}|^2 \times \text{phase space} \left(\equiv \Pi_{i=1^n} \frac{d^3\vec{p}_i}{(2\pi)^3 2E_i}) \right) \times (2\pi)^4 \delta(\sum_i p_i - \sum_f p_f)$$

- Note that $[\Gamma] = +1$ and $[\sigma] = -2$
- It is often enough to do the dimensional analysis for Γ and σ, when there is only one important mass scale from the phase space integration
- A number of easy examples will be given in this lecture

Scalar fields

- Lagrangian for a real scalar field:

$$\mathcal{L} = \frac{1}{2}\partial_\mu \phi \partial^\mu \phi - \frac{m^2}{2}\phi^2 - \mu\phi^3 - \frac{\lambda}{4}\phi^4 + \sum_{i=1}^{\infty} \frac{C_{4+i}}{\Lambda^i}\phi^{4+i}$$

- $[\partial] = +1, [\mathcal{L}] = 4 \rightarrow [\phi] = 1$
- $[m] = [\mu] = +1$ and $[\lambda] = [C_i] = 0$
- C_i terms are nonrenormalizable interaction terms ($\phi^{d>4}$: Irrelevant operators $\rightarrow$ Will discuss shortly)
- Field op ϕ create or annihilate a particle of mass m:

$$\phi \sim a(p)e^{-ip\cdot x} + a^\dagger(p)e^{+ip\cdot x}$$

- Complex scalar $\phi \sim a + b^\dagger$ with a and b relevant to particle and antiparticle

Fermion fields

- Lagrangian for fermion fields :

$$\mathcal{L} = \overline{\psi}(i\partial\cdot\gamma - m_\psi)\psi + \frac{C}{\Lambda^2}(\overline{\psi}\psi)^2 + \ldots.$$

- $[\psi] = 3/2\ ,\ [m] = 1\ ,\ [C] = 0$
- C term: nonrenormalizable (irrelevant at low energy)
- Dirac field operator:

$$\begin{aligned} \psi &\sim bu + d^\dagger v \\ \overline{\psi} &\sim b^\dagger \overline{u} + d\overline{v} \end{aligned}$$

- Fermi's theory of weak interaction is the classic example

- Dimensional analysis for $\psi\overline{\psi}$ scattering

$$\mathcal{M}(\psi(p_1, s_1)\overline{\psi}(p_2, s_2) \to \psi(p_3, s_3)\overline{\psi}(p_4, s_4)) \sim \frac{1}{\Lambda^2}$$

$$\sigma \sim \left(\frac{1}{\Lambda^2}\right)^2 \times (phasespace) \sim \left(\frac{1}{\Lambda^2}\right)^2 \times s$$

- Mandelstam variables for $2 \to 2$ scattering:

$$s \equiv (p_1 + p_2)^2, t = (p_3 - p_1)^2, u = (p_4 - p_1)^2$$

$$s + t + u = \sum_{i=1}^{4} m_i^2$$

- Cross section becomes zero as $s \to 0$: Irrelevant

Unitarity Violation

- What happen at high energy ?

$$\sigma \to \infty \to$$

Violation of perturbative Unitarity near $\sqrt{s} \sim \Lambda/\sqrt{C}$
$\to$ New dof's will come into play for cure (e.g., $W^\pm$ or Z^0)

- This is the wonder of Nature with special relativity and quantum mechanics
- In the SM, the pointlike interaction is replaced by the $W^\pm, Z^0$ propagator, which cuts off the bad high energy behavior
- $\sigma \sim 1/s$ at very high energy scale $\sqrt{s} \gg m_{W,Z}$

Vector fields

- Lagrangian for abelian gauge field with a charged particle (QED):

$$\begin{aligned} \mathcal{L} &= -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \overline{\psi}(iD\cdot\gamma - m_\psi)\psi \\ F_{\mu\nu} &\equiv \partial_\mu A_\nu - \partial_\nu A_\mu \\ D_\mu\psi &\equiv (\partial_\mu + ieA_\mu)\,\psi \end{aligned}$$

- $[A_\mu] = 1, [F_{\mu\nu}] = 2, [e] = 0$
- Dimensionless coupling $e \to$ Renormalizable interaction (marginal operator, meaning that it is important at all energy scales)
- RG equation for e may run into a Landau pole, above which the coupling diverge $\to$ Either new theory before/around Landau pole, or low energy theory is free field theory

Renormalizable Opertors

- dim 0 : $I_{\rm op}$ (cosmological constant)
- dim 1 : S (scalar tadpole)
- dim 2 : S^2 , $A_\mu A^\mu$ (mass terms for bosons)
- dim 3 : $\overline{\psi}\psi$ (Fermion mass term) , S^3 (self interaction of singlet scalar)
- dim 4 : $S\overline{\psi}\psi$ (Yukawa interaction) , S^4 (Scalar self coupling) , A_μ^4 , $\partial_\mu A_\nu A^\mu A^\nu$ (self interactions of gauge fields)

NB: S, S^3 etc possible only for gauge singlet S

nabelian Gauge Symmetry and Renormalizability

- Renormalizable Interactions are only 3 types:

$$B^3,\ B^4,\ \overline{F}FB$$

- Power counting renormalizable interactions for spin-1:

$$\mathcal{L} = -\frac{1}{4}(\partial_\mu A^a_\nu - \partial_\nu A^a_\mu)^2 + m_A^2 \frac{1}{2} A_{\mu a} A^{\mu a} + \partial_\mu A^a_\nu A^{\mu b} A^{\nu c} + + A^a_\mu A^b_\nu A^{\mu c} A^{\nu}$$

(all possible contraction over group indices)

- Although this is power counting renormalizable, it is not
- Only special type of lagrangian consistent with local Nonabelian gauge symmetry is renormalizable
- Local gauge symmetry is really a powerful principle for a spin-1 object
- Similar example for complex scalar and Majorana fermion with supersymmetry (Wess-Zumino model) to

Some remarks on QFT

- QFT is the basic framework for particle physics, and is a marriage of QM and Special Relativity
- Spin-Statistics theorem
  - Bosons : totally symmetric wavefunction
  - Fermions : totally antisymmetric wavefunction
  - Intrinsic $P(B,F) = (+B,-F)$
- CPT is a symmetry of any local QFT
  $\to CP$ violation implies T (time-reversal) violation
- CPT theorem: $m_n = m_{\bar{n}}$ and $\tau_n = \tau_{\bar{n}}$, $\mu_n = \mu_{\bar{n}}$
- However, a partial width of n and $\bar{n}$ can be different $\to$ Direct CP Violation :

$$\Gamma(n \to f) \neq \Gamma(\bar{n} \to \bar{f})$$

- No renormalizable interactions possible for $s \geq 3/2$
  (Higher spin would be OK for composite particles)

Heavy Quarknia Quantum Numbers

- Bound State of spin-1/2 Q and $\bar{Q}$ with ${}^{2S+1}L_J$:

$$P = (-1)^{L+1}, \quad C = (-1)^{L+S} \to 0^{-+}, 1^{--}, 1^{++}, 1^{+-},$$

- Bound State of spin-0 Q and $\bar{Q}$ with ${}^{2S+1}L_J$ (with $S = 0$ and $L = J$):

$$P = (-1)^{L}, \quad C = (-1)^{L} \to 0^{++}, 1^{--}, 2^{++}, \text{etc.}$$

- No place for π (with 0^{-+})
- Observed J^{PC} clearly says that quarks are spin-1/2 fermions, not scalars
- Exotic mesons don't follow the above assigment

Effective Lagrangian Approach

- If new physics scale is high enough, it is legitimate to integrate out the heavy d.o.f.
- The low energy physics can be described in terms of effective lagrangian :

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{ren}} + \sum_{d=5}^{\infty} \frac{\mathcal{O}^{(d)}}{\Lambda_d^{d-4}}$$

  where all the operators in $\mathcal{L}_{\text{eff}}$ are made of light d.o.f. with their local gauge symmetries
- Effects of the nonrenormalizable operators $\sim (E/\Lambda_d)^{d-4}$ relative to the amplitude from $\mathcal{L}_{\text{ren}}$
- EFT is useful, as long as $E \ll \Lambda_d$, since we can keep only a few of the NR operators

SM as an EFT: Below e^+e^- Threshold

- Only relevant quantum dof is photon A_μ
- If E increases, we need to include more and more NR operators
- Eventually, unitarity will be broken $\rightarrow$ We have to include new d.o.f.'s in the EFT, and redefine the EFT with more d.o.f.
- QED at $E \ll 2m_e$: A_μ, local $U(1)$ and P, C

$$\mathcal{L}_{\mathrm{EET}} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \frac{e^4}{(4\pi)^2 \Lambda^4} F^4 + \ldots$$

  where $\Lambda \sim m_e$
- This effective lagrangian describes $\gamma\gamma$ scattering, the cross section of which will break unitarity when E reaches $2m_e$

SM as an EFT: Below e^+e^- Threshold

- The cross section grows like $\sim s^3$:

$$\sigma(\gamma\gamma \to \gamma\gamma) \sim \frac{e^8}{\Lambda^8} s^3$$

  and see at which energy scale unitarity is violated

- Unitarity will be restored due to a new process that opens up: $\gamma\gamma \to e^+e^-$

- One has to redefine the effective lagrangian near e^+e^- threshold, by including the electron/positron fields explicitly

Digress on Unitarity

- Unitarity is the most profound thing in QM
- Scattering Operator S is unitary:

$$\langle f|S|i\rangle = S_{fi} = \delta_{fi} + i(2\pi)^4\delta^4(p_i - p_f)T_{fi}$$

- Unitarity: $S^\dagger S = SS^\dagger = 1$

$$T_{fi} - T^*_{fi} = i(2\pi)^2 \sum_n \delta^4(p_f - f_n) T_{fn} T^*_{in}$$

- If interaction is weak, we can ignore the RH $\rightarrow$ T becomes Hermitian $T_{fi} = T^*_{if}$
- Optical theorem for $f = i$:

$$2\mathrm{Im}T_{ii} = (2\pi)^4 \sum_n |T_{in}|^2 \delta^4(P_i - P_n)$$

Rayleigh Scattering: Why is Sky Blue ?

- Photon scattering with neutral atom A where

$$E_\gamma \ll \Delta E_{n1} \equiv E_n - E_1$$

$\rightarrow$ Elastic scattering of light on neutral atoms

- Atom is described by nonrelativistic Schrödinger wave function ψ_A with dim 3/2:

$$\mathcal{L} = \psi_A^\dagger \left(i\frac{\partial}{\partial t} - H \right) \psi_A + \frac{e^2}{\Lambda^3} \psi_A^\dagger \psi_A F_{\mu\nu} F^{\mu\nu} + \ldots.$$

- $\Lambda \sim \Delta E_{21}, r_0$??
- Note that photon couples to a neutral atom. How ???

- No coupling of photon to neutral objects only at renormalizable level
- Photon couples to neutral particle at nonrenormalizable level due to quantum fluctuation can involve charged particles in the loop
- Likewise, gluons can couple to photons
- γA scattering cross section :

$$\sigma(\gamma A \to \gamma A) \sim \frac{e^4}{\Lambda^6} E_\gamma^4 \sim \frac{1}{\lambda_\gamma^4}$$

for $E_\gamma \ll \Delta E_{2,1}$

- Blue light scatters more than red light $\to$ Sky is blue, and we can enjoy the beautiful sunrise/sunset in red

Van der Waals Force

- Potential between neutral atoms are described by two-photon exchange diagrams from the previous lagrangian $\psi_A^\dagger \psi_A F^2$
- Additional contact interaction has to be considered:

$$\frac{1}{\Lambda^2}\left(\psi_A^\dagger \psi_A\right)^2$$

- Calculate the two contributions and discuss what is the form of the force between two neutral atoms (Van der Waals interaction) ?
- What is a in the exponent in $V(r) \sim r^a$?
- What if we consider the neutral atom relativistically ? (Itzykson and Zuber, QFT)

QED as an EFT below $\mu^+\mu^-$ threshold

- QED at $2m_e \le E \ll 2m_\mu$: $A_m u$, e, $\bar{e}$, local $U(1)$ and P, C

$$\mathcal{L}_{\text{Eff}} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \overline{e}(iD - m_e)e + \frac{e^4}{(4\pi)^2\Lambda_1^4}F^4 + \frac{e}{(4\pi)^2\Lambda_2}\overline{e}\sigma^{\mu\nu}eF_{\mu\nu}$$

  where $\Lambda_1 \sim m_\mu$, and $\Lambda_{2,3} \sim O(1)$ TeV or larger (see later discussions on these points)

- NP scale in each NR operator is independent (different from each other) in general, since the origin can be different
- Scale for F^4 is now $\sim m_\mu$, unlike the previous case

QED as an EFT below $\mu^+\mu^-$ threshold

- Additional $1/(4\pi)^2$ suppression for NR operators generated at one-loop level, compared with NR operators generated at tree level, even if their operator dim's are the same
- If we impose $SU(2)_L \times U(1)_Y$ instead of $U(1)_{\rm em}$, the Λ_2 term should be replaced by

$$\frac{e}{(4\pi)^2\Lambda_2^2}\overline{e_L}\sigma^{\mu\nu}He_R F_{\mu\nu} \to \frac{ev}{\sqrt{2}(4\pi)^2\Lambda_2^2}\overline{e_L}\sigma^{\mu\nu}e_R F_{\mu\nu}$$

and the effect becomes smaller for the same Λ_2, or the bound on Λ_2 becomes stronger

QED as an EFT above $\mu^+\mu^-$ threshold

- QED at $E \ll 2m_\pi$: A_μ, e, $\bar{e}$, μ, $\bar{\mu}$, local $U(1)$ and P, C

$$\mathcal{L}_{\text{Eff}} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \overline{e}(iD - m_e)e + \overline{\mu}(iD - m_\mu)\mu + \frac{e^4}{(4\pi)^2\Lambda_1^4}F^4 + \frac{e}{(4\pi)^2\Lambda_2}\overline{e}\sigma^{\mu\nu}eF_{\mu\nu} + \frac{e}{(4\pi)^2\Lambda_3}\overline{\mu}\sigma^{\mu\nu}\mu F_{\mu\nu} + \frac{e}{(4\pi)^2\Lambda_4}\overline{e}\sigma^{\mu\nu}\mu F_{\mu\nu} + \frac{e^2}{\Lambda_5^2}(\overline{e}e)(\overline{e}\mu) + H.c.$$

where $\Lambda_1 \sim m_\pi$, $\Lambda_{2,3} \gtrsim XX$ TeV , and $\Lambda_{4,5} \gtrsim XX$ TeV or larger

- $\Lambda_{2,3}$ terms contribute to $(g-2)_{e,\mu}$
- $\Lambda_{4,5}$ generate $\mu \to e\gamma$ and $\mu \to 3e$

Nucleons and neutron β decay

- proton + neutron known to make a nucleus of an atom
- $m_p \approx m_n \to$ approximate isospin symmetry
- β decay of $n \to pe\overline{\nu_e}$ is known
- Effective lagrangian for protons and neutrons

$$
\begin{aligned}
\mathcal{L} &= \overline{p}(iD\cdot\gamma - m_p)p + \frac{\kappa_p}{2m_p}\overline{p}\sigma^{\mu\nu}pF_{\mu\nu} + (p \to n) \\
&- \mathcal{L}(A_\mu) + \frac{G_F}{\sqrt{2}}(\overline{p}\gamma^\mu n)(\overline{e}\gamma_\mu \nu_e) + H.c.
\end{aligned}
$$

where $D_\mu p = (\partial_\mu + ie_p A_\mu)p$

- Dim 5 term generate the anomalous magnetic moments of p and n, in addition to the $g = 2$ for the pointlike g-factors for charged spin-1/2 fermions
- $\kappa_{p,n} \sim O(1)$ is needed to fit the data:

EM Polarizabilities of Nucleons

- Higher Dim operators with nucleons and em fields:

$$C_1 \frac{e^2}{\Lambda^3} F_{\mu\nu} F^{\mu\nu} \; \overline{N} N + C_2 \frac{e^2}{\Lambda^3} F_{\rho\mu} F^{\rho}_{\nu} \; \overline{N} \sigma^{\mu\nu} N + \ldots$$

- C_1 and C_2 related with the electric and magnetic polarizabilities of nucleons
- In particular, neutron couples to photons at nonrenormalizable level again
- There is no absolutely dark matter, namely which has absolutely no interactions with light at all
- Neutrinos and dark matters interact with photons, but their interaction rates are suppressed by $(E/\Lambda)^{\text{positive power}}$ and thus $\ll 1$
- Need higher energy to see these effects (or much shorter wavelength photon)

Neutron β decay

- Fermi's 4-fermion interaction theory describes the neutron β decay
- It is an irrelevant operator : $G_F m_p^2 \simeq 10^{-5}$
- Neutron life time for $n \to p e^- \overline{\nu_e}$

$$\Gamma_n = \tau_n^{-1} \sim \frac{G_F^2}{2(4\pi)^3} (\Delta m)^5 \sim (XX)^{-1}$$

where $\Delta m = m_n - m_p \simeq 1.3$ MeV

- $\tau_n^{\text{exp}} = 881$ sec
- Fermi assumed parity conservation ($V \times V$)

Muon Decay $\mu \to e\overline{\nu_e}\nu_\mu$

- Apply the Fermi's theory of weak interaction with replacing (p, n) by (ν_μ, μ)

$$\mathcal{L}_{CCweak} = -\frac{G_F}{\sqrt{2}}(\overline{\nu_\mu}\gamma^\mu \mu)(\bar{e}\gamma_\mu \nu_e) + H.c.$$

- Muon lifetime :

$$\tau^{-1} = \Gamma_\mu = \frac{G_F^2}{2(4\pi)^3} m_\mu^5$$

cf. Compare with the exact expression:

$$\tau^{-1} = \Gamma_\mu \sim \frac{G_F^2}{192\pi^3} m_\mu^5 \propto m_\mu^5$$

- $\Gamma \propto m^5$ is a generic behavior of a fermion decaying through 4-fermion (dim 6) operators (τ, proton decays etc.)

Tau lepton decays

- $m_\tau = 1.777$ GeV $\sim (2m_p - m_\mu)$
- Similar behavior for τ lepton decays

$$\Gamma_{\tau\to e}/\Gamma_{\mu\to e} = (m_\tau/m_\mu)^5 = (1.777/0.105)^5 \sim 1.4 \times 10^6$$

$$e\overline{\nu_e} : \mu\overline{\nu_\mu} : (\overline{u}d + \overline{u}s) = 1:1:1 \to 1:1:N_c$$

- Data $= 17\% : 17\% : 66\%$
- Another evidence for $N_c = 3$:
- Including the QCD corrections to hadronic τ decays,

$$1:1:N_c(1+\alpha_s/\pi + ...)$$

Neutrino Oscillation $\nu_e \leftrightarrow \nu_\mu$

- Both ν_e and ν_μ are electrically neutral
  $\rightarrow$ Both of them can have Majorana masses, including the mass mixing between the two
- Assume they are both LH particles (as observe in CC weak interaction processes)
- Mass terms for the two Majorana neutrinos:

$$\mathcal{L}_{\nu\text{mass}} = \frac{1}{2} m_{\alpha\beta} \overline{\nu^{\ c}_{\alpha L}} \nu_{\beta L} + H.c.$$

- Two mass eigenvalues will be different in general: $\Delta m^2 \neq 0$, with a mixing angle θ

Neutrino Oscillation

- Neutrino oscillation probability:

$$
\begin{aligned}
P(\nu_e \to \nu_\mu) &= \sin^2 2\theta \sin^2 \left(\frac{\Delta m^2 L}{4E} \right) \\
&= \sin^2 2\theta \sin^2 \left(\frac{1.27 \Delta m^2 (\mathrm{eV}^2) L(\mathrm{km})}{4EGeV)} \right)
\end{aligned}
$$

- For 3 active neutrinos, two Δm^2's and 3×3 mixing matrix (MNS matrix)
- Neutrino oscillations were in fact observed atmospheric and solar neutrino oscillations
- Write down the effective lagrangian for $\nu_\mu \to \nu_e \gamma$. Estimate the coefficient of this operator from the 1-loop diagram in the SM and the lifetime of ν_μ in this mode.

Weinberg operator for neutrino mass

- If we impose $SU(2)_L \times U(1)_Y$ local gauge symmetry instead of $U(1)_{\rm em}$, the above neutrino mass terms will be replaced by dim-5 Weinberg operator breaking with $\Delta L = 2$:

$$\frac{y_{\alpha\beta}}{\Lambda_{\alpha\beta}} (L_\alpha H)(J_\beta H) + H.c.$$

  with $\Lambda_{\alpha\beta} \sim 10^{12-16}$ GeV $\sim M_N$ (RH Majorana mass scale in seesaw mechanism)
- This is the only dim-5 operator which is invariant under the full SM gauge symmetry $SU(3)_C \times SU(2)_L \times U(1)_Y$
- This nonrenormalizable terms can be made renormalizable (UV complete) by introducing the RH singlet neutrinos (Type-I seesaw), or by triplet Higgs fields (Type-II seesaw)

Proton Decay

- These decays are kinematically allowed, but never been observed

$$\begin{aligned}\tau(p \to e^+\pi^0) &> 8.2 \times 10^{33}\text{yr} \\ \tau(p \to K^+\nu) &> 6.7 \times 10^{32}\text{yr}\end{aligned}$$

- Why proton is so stable ?

$$\tau_p > \tau_{\text{universe}} = 4 \times 10^{17}\text{ sec}$$

- Consider operators $\overline{e}p\pi^0$ (dim 4), and $\overline{e}\gamma^\mu p\partial_\mu\pi^0$(dim 5), both give dangerously short lifetime for proton

Proton Decay

- One possible way out: p and π are composite of quarks, and B and L violation occurs at very high energy scale, where proton is no longer a good description with the following dim-6 operators:

$$\frac{g^2}{\Lambda^2} uude$$

(ignoring Dirac structure)

- SUch operators can be generated in (SUSY) GUT, or MSSM with $R-$parity violation
- Calculate the lower bound on the scale Λ from the lower bound on the proton lifetime.

$\Delta B = 2$ Process: $n - \overline{n}$ Oscillation

- This is possible since electric charge is conserved

$$\mathcal{L}_{n-\bar{n}} \sim \mu n n, \quad \text{or} \quad \frac{g^4}{\Lambda^5} uddudd$$

- Sensitive probe of new physics with $\Delta B = 2$
  e.g. Z_3 baryon parity in the MSSM
- Experimental bound:

$$\tau(\text{free}) > 8.6 \times 10^7 \text{sec}, \quad \tau(\text{bound}) > 8.6 \times 10^7 \text{sec}$$

Estimate the transition rate for $n - \overline{n}$ using the above 6-quark operators, and derive the bound on the scale Λ.

CP violation in $K_L \to \pi\pi$

- How to describe CP violation ?
- Wolfenstien (1964) proposed a superweak model :

$$\mathcal{L}_{\text{superweak}} \sim a G_F^2 \left(\bar{d}\Gamma s\right)^2$$

Can accommodate $\epsilon_K = 2 \times 10^{-3}$, if $a \sim$
(Similar model was also proposed for $B_d - \overline{B_d}$ mixing)

- The story changed after Weinberg proposed the SM, and the renormalizability was proved
  - Two Higgs doublet model (2HDM) with spontaneous CP violation
  - Three or more families by Kobayashi-Maskawa (KM) $\to$ Current paradigm (SM with 3 generations), and has been very well verified in the B, K systems (superweak model excluded)
  - Any new flavor and/or CP violation should be

Why not n or e EDM's ?

- CPT conserved in QFT
- CP violated, P and C violated; so why not T violation ?
- n or e EDM's would break both P and T
  cf. Usually said to be CP violating (better not use)
- Effective lagrangian for EDM

$$\mathcal{L}_{\rm EDM} = i\frac{d_n}{2m_n}\overline{n}i\gamma_5\sigma^{\mu\nu}n\ F_{\mu\nu} + H.c.$$

  and similarly for e, μ, p .....
- EDM constraints ($d_n = e/\Lambda$):

$$d_e = (0.7 \pm 0.7) \times 10^{-26} e \cdot {\rm cm}\ ,\ d_n < 2.9 \times 10^{-26} e \cdot {\rm cm}$$

- Bounds on new physics: $\Lambda >$ Few TeV for $O(1)$ phase

Implications on the new physics

- How to describe CP violation ?
- Most new physics models at TeV scale are strongly constrained by FCNC and EDM
- New phase should be very small (essentially zero), or new particles better be heavier than a few TeV (more than 10's of TeV) in order to evade these bounds from EDM's and FCNC's
- Severe fine tuning needed in the flavor and CPV sector
- Real fine tuning problem of generic BSM
- Hidden sector scenarios are less constrained by these however

FCNC and GIM

- If there were only three familes with

$$\begin{pmatrix} u_L \\ d_L \cos\theta_C + s \sin\theta_C \end{pmatrix}, u_R, d_R, s_R,$$

there would be huge contribution to $K^0 \to \mu^+\mu^-$ mediated by W^0 gauge boson of $SU(2)_L$

- Precition vs. Data:

$$\frac{\Gamma(K_L \to \mu^+\mu^-)}{\Gamma(K^+ \to \mu\nu_\mu)} = O(1), \quad vs. \quad \sim 3 \times 10^{-7}(\text{Data})$$

- In nature (in the kaon system), FCNC is highly suppressed
- What is wrong ? How to cure the theory ?

GIM

- GIM introduced another quark called "charm" ($\equiv c$) with the orthogonal coupling to the down type quarks

$$\begin{pmatrix} u_L \\ d_L \cos\theta_C + s \sin\theta_C \end{pmatrix}, \quad \begin{pmatrix} c_L \\ -d_L \sin\theta_C + s \cos\theta_C \end{pmatrix}, \quad u_R, d_R, s_R$$

- Then W^0 coupling is flavor diagonal, and no tree level contribution to $K_L \to \mu\mu$
- FCNC processes can occur only at one-loop or higher loops
- $m_c \sim 1.5$ GeV will explain Δm_K (Gaillard, Lee, Rosner 1974)
- Charm quark discovered in 1975
  $\to$ "Triumph of Theoretical Physics"

Kobayashi-Maskawa Model for CP violation

- KM considered n families of the Weinberg-Salam model (1974 ?)
- Counted the number of CPV phases which cannot be rotated away:

$$n_{\rm angle+cpphase} = 2n^2 - n^2 - (2n-1) = (n-1)^2$$
$$n_{\rm cpphase} = ({\rm above}) - \frac{n(n-1)}{2} = \frac{(n-1)(n-2)}{2}$$

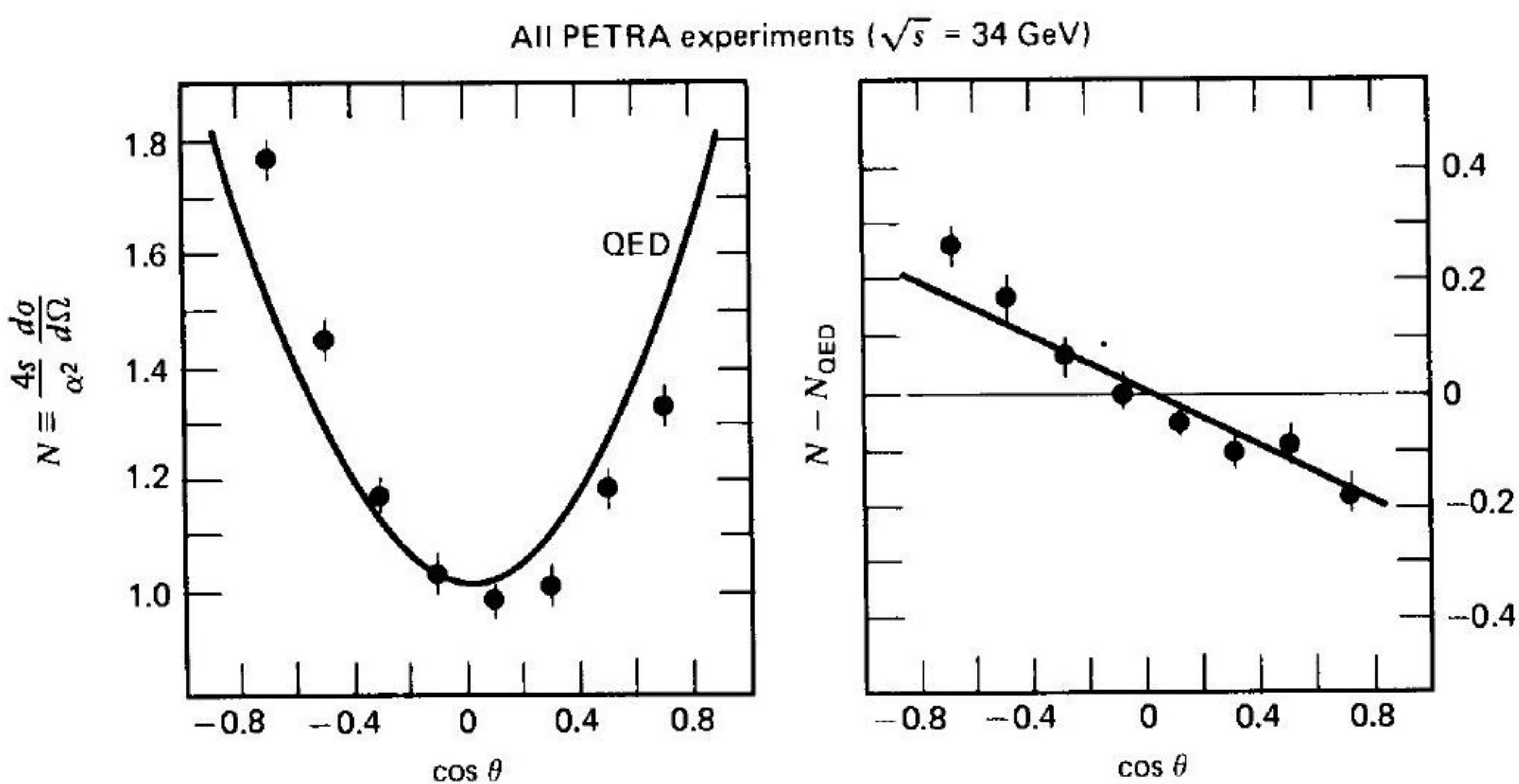
- $n = 3 \rightarrow 1$ CPV phase (KM phase)
- $n = 4 \rightarrow 3$ CPV phase $\rightarrow$ Very interesting phenomenology
- The 5th quark (bottom or beauty) was discovered in 197x in the $b\bar{b}$ bound system: $\Upsilon \rightarrow \mu^+\mu^-$
- And finally the 6th quark (top or truth) was discovered at Tevatron in 1995

EFT below $W^\pm$ and Z^0

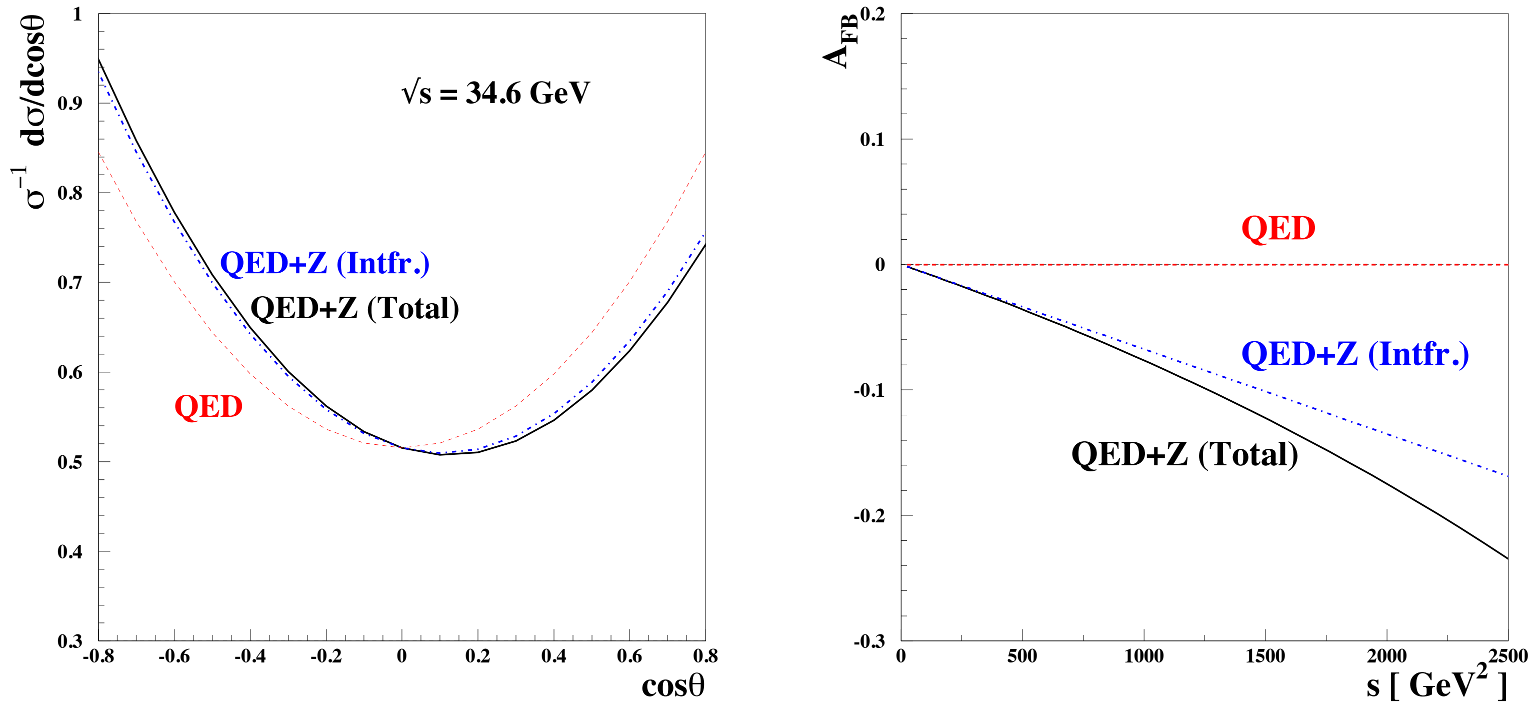
- SM with 3 families of chiral fermions with $W^\pm$ and Z^0
- Before the discovery of $W^\pm$ and Z^0, the EFT would be

$$\mathcal{L}_{\text{ren QED}} + \mathcal{L}_{\text{ren QCD}} + \frac{g^2}{\Lambda^2}\left(\overline{e}\Gamma e\right)\left(\overline{\mu}\Gamma\mu\right) + \ldots.$$

  where $\Gamma = 1, \gamma^5$, γ^μ, $\gamma^5\gamma^\mu$, $\sigma^{\mu\nu}$
- The first evidence of asymmetry was found in angular distribution of muons from e^+e^- collisions at PETRA in the 80's ($\sqrt{s} \sim 30$ GeV , well below the Z^0 pole)
- Source of A_{FB} is a term linear in $\cos\theta$ from interference between γ or Z vector coupling and the axial vector Z coupling.



All PETRA experiments ($\sqrt{s}$ = 34 GeV)
$N \equiv \frac{4s}{\alpha^2}\frac{d\sigma}{d\Omega}$
1.8
1.6
1.4
1.2
1.0
QED
−0.8
−0.4
0
0.4
0.8
cos θ
$N - N_{QED}$
0.4
0.2
0
−0.2
−0.4
−0.8
−0.4
0
0.4
0.8
cos θ



- Since $\sqrt{s} \ll M_Z$, good approx. to assume 4 fermion interactions by integrating out Z boson
- $A_{\rm FB} \simeq -\frac{3G_F}{\sqrt{2}}\ \frac{s}{4\pi\alpha}(g_L - g_R)^2 \equiv kG_F s$
- $k \simeq -7$ from EFT, whereas $k = -5.78$ from the full expression

Dim 6 operators with SM gauge sym

- Buchmüller and Wyler [Nucl.Phys. B268 (1986) 621] made a catalogue of dim 6 operators that are invariant under the SM gauge group

$$G_{\rm SM} \equiv SU(3)_C \times SU(2)_L \times U(1)_Y$$

- We already studied some of them in $\mu \to e\gamma$, e/n EDM's, $\mu \to 3e$, etc., assuming $U(1)_{\rm em}$ symmetry, not the full $G_{\rm SM}$
- Assuming $G_{\rm SM}$ will introduce additional $1/\Lambda$ factor often, because LH and RH fermions are now different because of $G_{\rm SM}$
- For example,

$$\frac{1}{\Lambda} e\bar{e}\sigma^{\mu\nu} e F_{\mu\nu} \to \frac{1}{\Lambda^2} e\overline{e_L}\sigma^{\mu\nu} H e_R F_{\mu\nu}$$

Finally, EFT for CDM ?

- About 25% of the universe is made of nonbaryonic DM

$$p = \frac{1}{3}\rho \;\; \text{(Rel)}, \quad \text{or} \quad p = 0 \;\; \text{(Nonrel)}$$

- The rest is the so-called Dark Energy $p = -\rho$
- No informations on the mass and the spin of the CDM
- $\tau_{DM} > 10^{26??}$ sec and no electric charge
- Many many possible models for the CDM
  - Some CDM models solve the hierarchy problems (neutralino, gravitino in SUSY models). strong CP problem (axion) or both (axino)
  - Simplest extension of the SM (real singlet scalar, Mojorana fermion, etc.)
  - Hidden sector CDM

EFT for CDM

- A number of study done with all possble Lorentz structures:

$$\frac{1}{\Lambda^2}\,(\overline{\chi}\chi)\,\mathcal{O}_{\rm SM}$$

  $\mathcal{O}_{\rm SM}$ is the SM gauge singlet operator
  - Thermal relic density from $\chi\chi \to$ (SM particles)
  - Direct detection from $\chi N \to \chi N$
  - Collider signatures from $q\bar{q} \to \overline{\chi}\chi + g(\gamma)$
- Used for complementarity of light CDM scenarios vs. collider constraints
- However these three processes involve very different kinematic ranges, and very often the messengers are not very heavy
- Eventually EFT approach becomes not so useful quantitatively [See M. Drees' talk at Lepton Photon 2011]

EFT dictates that CDM decay

- Instead, EFT for CDM says that χ should decay into the SM particles by higher dim operators such as

$$\frac{1}{\Lambda^2}\left(\overline{e}e\right)\left(\overline{\nu}\chi\right), \mathrm{etc.}$$

  unless DM number is protected by some local gauge symmetry
- $\Lambda \sim 10^{16}$ GeV can make $\tau(\chi)$ long enough ($\gg 10^{26}$ sec)
- Could be used for positron excess observed by PAMELA
- What renormalizable interactions would generate such nonrenormalizable interactions that make χ decay ?