Flavor Physics and Search for New Physics

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- What is flavor ?
- P and CP violations in the kaon system
- Neutrino oscillations
- Charged lepton flavor violation ?
  ($\mu \to e\gamma$, $\tau \to 3\mu$, etc.)
- Flavor physics in SUSY models
- Grand Unification (GUT) and Proton decay
- Summary

What is flavor ?

- e (electron) and μ (muon) has the electric charge, but different masses $\rightarrow$ Different names: flavors
- Flavor : particle identity
- Quark flavors : conserved by strong and em interactions, but broken by weak interaction
  $e^+e^- \rightarrow \mu^+\mu^-$ or $q\bar{q}$ (w/ $q = u, d, s, c, b, t$)
  $d \rightarrow ue\bar{\nu}_e$ (weak)
- Lepton flavors are broken in the neutrino sector

$$\nu_\mu \rightarrow \nu_\tau, \quad \nu_e \rightarrow \nu_\mu, etc.$$

Parity P

- Parity : $\vec{x} \rightarrow -\vec{x}, t \rightarrow t$

$$E \rightarrow E, \quad \vec{p} \rightarrow -\vec{p}(\text{vector}), \quad \vec{S} \rightarrow +\vec{S}(\text{axial vector})$$

- Parity (AB) = Relative P $\times$ Intrinsic P(A) $\times$ Intrinsic P(B)
- Intrinsic $P(B, F) = (+B, -F)$
- Intrinsic parity of p, n, e : even
- Intrinsic parity of π, γ : odd
- Parity is conserved in strong and em interactions, but broken in weak interactions (maximally in the charged current weak int., but partly in neutral current weak int.)

Charge Conjugation C

- particle $\leftrightarrow$ Anti-particle

$$\begin{aligned} C & \quad |p^\mu; \text{Additive internal quantum numbers}\rangle \\ \equiv & \quad |p^\mu; -\text{Additive internal quantum numbers}\rangle \end{aligned}$$

- Additive internal quantum number :
  electric charge, baryon number, flavor, ...
- Some particles are their own antiparticles
  (Absolutely neutral $\neq$ electrically neutral)
  $\gamma(-), \pi^0(+), \eta(-)$ gluons $(-)$,
  NB: $n \neq \overline{n}$, $K^0 \neq \overline{K^0}$, $B^0 - \overline{B^0}$, etc.
- Charge conjugation is conserved in strong and em interactions, but broken in weak interactions
- CP: another useful transformation

P and C quantum no.'s of some particles

particles	P	C
p	$+1$	$+1$
n	$+1$	$+1$
e^-	$+1$	$+1$
γ, gluons	-1	-1
$\pi^0, \eta, \ldots$	-1	$+1$
$\rho^0, J/\psi, \ldots$	-1	-1
$q\bar{q}(^{2S+1}L_J)$	$(-1)^{L+1}$	$(-1)^{L+S}$
$\pi^+\pi^-$ with L	$(-1)^L$	$(-1)^L$

Some consequences of QFT

- QFT is the basic framework for particle physics, and is a marriage of quantum mechanics and Lorentz symmetry in 4-dim
- Spin-Statistics theorem
  - Bosons : totally symmetric wavefunction
  - Fermions : totally antisymmetric wavefunction
  - Intrinsic $P(B,F) = (+B,-F)$
- A particle and its antiparticle have the same mass, lifetime, magnetic moment.....
- CPT is a symmetry of any local QFT
  $\rightarrow CP$ violation implies T (time-reversal) violation

P violation in the K (kaon) system

- $\theta - \tau$ puzzle in 1955 :
  - Two seemingly different particles have the same mass and the same life time, but decay into two different J^P states:

$$\theta \to 2\pi \qquad J^P(2\pi) = 0^+$$
$$\tau \to 3\pi \qquad J^P(3\pi) = 0^-$$

  - Are they the same or different ?
- T.D. Lee and C.N. Yang (1956) : There is no evidence of P conservation in the weak decays of hadrons, and suggested experiments to see this
- In 1957, several experiments confirmed P and C are maximally violated in weak interactions (β decay, π and μ decays)

$K^0 - \overline{K^0}$ mixing: CP violation

- $CP|K^0\rangle \equiv |\overline{K^0}\rangle$ and $|K^0_{1,2}\rangle \equiv (|K^0\rangle \pm |\overline{K^0}\rangle)/\sqrt{2}$
-

$$
\begin{aligned}
CP|K_1^0\rangle &= +|K_1^0\rangle \\
CP|K_2^0\rangle &= -|K_2^0\rangle
\end{aligned}
$$

- If CP is conserved, then

$$K_1 \to 2\pi \quad \text{and} \quad K_2 \to 3\pi$$

- Christensen, Cronin, Fitch and Turlay observed $K_2 \to 2\pi$: CP violation in the neutral kaon system (1964)
- T violation is confirm in the late 1990's

$K^0 - \overline{K^0}$ mixing: CP violation-II

- Mass eigenstates of the full Hamiltonian:

$$\begin{aligned} |K_L\rangle &\sim |K_2\rangle + \epsilon|K_1\rangle \\ |K_S\rangle &\sim |K_1\rangle + \epsilon|K_2\rangle \end{aligned}$$

  with $\epsilon \sim 2 \times 10^{-3} e^{i\pi/4}$

- $\Delta m \equiv m_L - m_S = 3.5 \times 10^{-6}$ eV $\sim 10^{-14} m_K \sim \Gamma_S/2$
- $\tau_S = 0.9 \times 10^{-10}$ sec $\quad \tau_L = 5.2 \times 10^{-8}$ sec
- Mass eigenstate is a CP admixture (CP violation in the mixing)
- In the SM, $K^0 - \overline{K^0}$ mixing from the W box diagram
- CP violation in the decay: Re $(\epsilon^{'}/\epsilon) \sim 10^{-3}$

$K^0 - \overline{K^0}$ mixing : Prediction of "charm"

- Flavor changing neutral current (FCNC) is highly suppressed in Nature

$$K^0 \to \pi^- \mu^+ \nu \quad \text{vs} \quad K_L \to \mu^+ \mu^-$$

- GIM mechanism: assume a hypothetical new quark "charm" $(u, d)_L$ and $(c, s)_L$
- Gaillard and B.W.Lee calculated the charm cont. to $K^0 - \overline{K^0}$ mixing and other FCNC processes $\to$ predicted $m_c \sim 1 - 2$ GeV
- Soon, charm quark with the predicted mass was found in J/ψ resonance
- Same story in the $B^0 - \overline{B^0}$ system ($\to$ heavy top)

Standard model (SM): Matter

Fundamental Constituent of Matter : Spin 1/2 Fermions

- Leptons do not feel strong interactions
- Quarks and gluons do ! (Masses in GeV)

$$\begin{pmatrix} \nu_e \ (\sim 0) \\ e \ (0.511\mathrm{MeV}) \end{pmatrix}_L, \quad \begin{pmatrix} \nu_\mu \ (\sim 0) \\ \mu \ (0.106) \end{pmatrix}_L, \quad \begin{pmatrix} \nu_\tau \ (\sim 0) \\ \tau \ (1.777) \end{pmatrix}_L,$$

$$\begin{pmatrix} u^\alpha \ (\sim 0.003) \\ d^\alpha (\sim 0.005) \end{pmatrix}_L, \quad \begin{pmatrix} c^\alpha (\sim 1.50) \\ s^\alpha (\sim 0.12) \end{pmatrix}_L, \quad \begin{pmatrix} t^\alpha (\sim 175) \\ b^\alpha (\sim 5) \end{pmatrix}_L$$

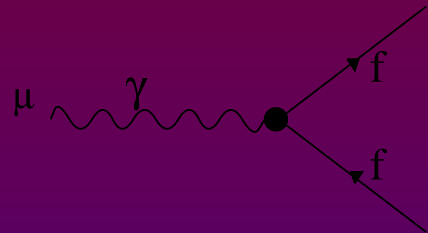
$$e_R,\ \mu_R,\ \tau_R,\ u_R,\ c_R,\ t_R,\ d_R,\ s_R,\ b_R\ (N_{eR},\ N_{\mu R},\ N_{\tau R})$$

SM : Forces (Interactions)

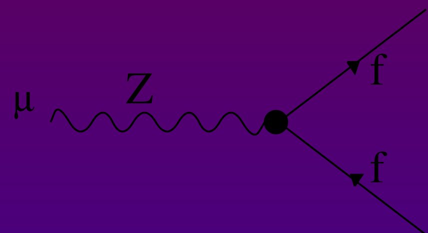
Interactions and Their Force Quanta

- Gravity (spin-2 massless graviton G)
  $\rightarrow$ making stars, galxies,..
- Electromagnetic Interactions (spin-1 photon γ)
  $\rightarrow$ making atoms and molecules
- Weak Interaction (spin-1 massive vector bosons $W^{\pm}, Z^0$)
  $\rightarrow$ Radioactivity (e.g., $n \rightarrow pe^- \bar{\nu}$)
- Strong Interaction (spin-1 massless gluons g)
  $\rightarrow$ quarks and gluons, to nucleons, to nucleus
- Mathematically, all interactions except gravity are described by $SU(3)_C \times SU(2)_L \times U(1)_Y$ gauge theory

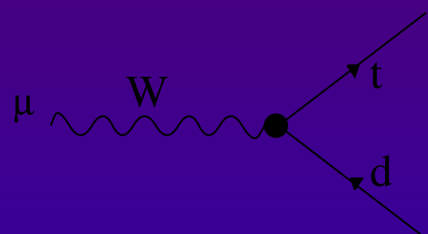
Feynman rules for gauge interactions



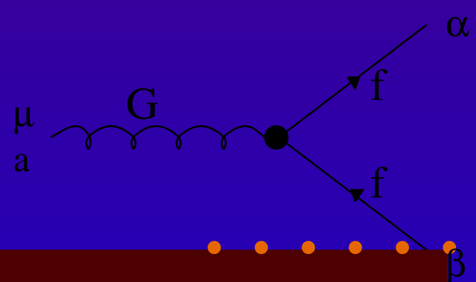
$$-ie\gamma_\mu Q_f$$



$$i\frac{g_2}{2\cos\theta_W}\gamma_\mu\left(v_f - a_f\gamma_5\right)$$



$$i\frac{g_2}{2\sqrt{2}}\gamma_\mu\left(1-\gamma_5\right)V_{td}$$



$$-ig_s\gamma_\mu\left(T^a\right)_{\alpha\beta}$$

Flavor and CP violation in SM

- Weak eigenstates are mixtures of mass eigenstates
- Cabibbo - Kobayashi – Maskawa (CKM) matrix describes flavor mixing and CP violation in the charged weak current interaction
- Unitarity : $VV^\dagger = 1$

$$\begin{pmatrix} d^{'} \\ s^{'} \\ b^{'} \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

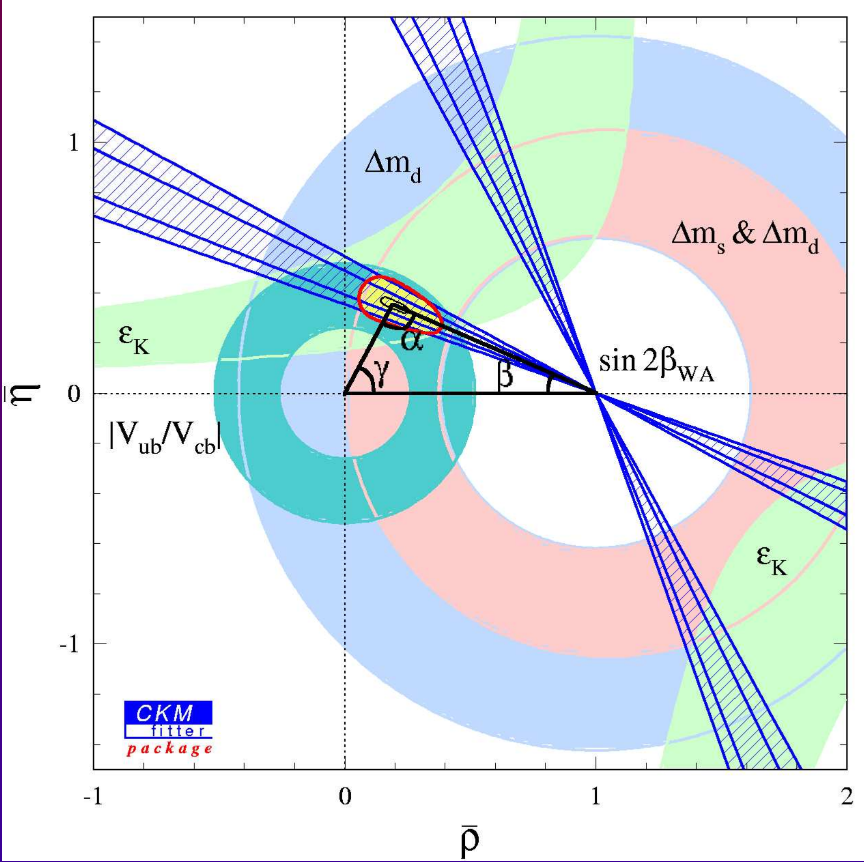
CKMology

- Wolfenstein parametrization:

$$V_{CKM} \simeq \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 - iA^2\lambda^4\eta & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

- Current date : $\lambda = 0.22, \quad A = (0.826 \pm 0.083)$
- Small mixing and Hierarchical structure
  $\lambda \sim 0.2, \lambda^2 \sim 0.04, \lambda^3 \sim 0.008$
- Why are quark masses and mixings so hierarchical ?
  cf. Neutrino sector has completely different behavior !

Constraints in the $\rho - \eta$ plane



Homework : New plot including the new data on $B_s - \overline{B_s}$ mixing

Neutrino oscillations

- Neutrinos are hard to detect, and their masses are not precisely known
- Mass limits from direct searches:
  - $m_\nu < 3$ eV from tritium β decay
  - $m_\nu < 0.19$ keV from $\pi \to \mu\nu_\mu$
  - $m_\nu < 18.2$ MeV from $\tau \to 5\pi + \nu_\tau$
- Indirect bound from cosmology : $\sum m_\nu < 2(11)$ eV from WMAP data analysis
- Why are they so small compared with other fermion masses ?
  $m_e = 0.511$ MeV

Neutrino oscillations - II

- Suppose neutrinos have nonvanishing and different masses
- Then flavor eigenstates are superposition of mass eigenstates:

$$|\nu_\alpha\rangle = \sum_{i=1} U_{\alpha i} |\nu_i\rangle$$

  where U is unitary
- $\alpha = e, \mu, \tau, \quad i = 1, 2, ...n$
- Then ν_μ at production point can be (partially) converted to ν_e, etc. at the detection point $\rightarrow$ Neutrino flavor oscillations
- $P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 2\theta_{\alpha\beta} \ \sin^2\left(\frac{1.27\Delta m^2(eV^2) \ L(km)}{E_\nu(GeV)}\right)$
- Solar neutrino puzzle, Atmospheric neutrino puzzle,

Current data on neutrinos

- Global analysis of solar, atmospheric, reactor and other neutrino experiments
- $\Delta m^2_{12} \simeq 5 \times 10^{-4}$ eV^2, $\Delta m^2_{23} \simeq 3 \times 10^{-3}$ eV^2
- $$U \simeq \begin{pmatrix} \frac{2}{\sqrt{6}} & \frac{1}{\sqrt{3}} & U_{e3} \\ -\frac{1}{\sqrt{6}} + \frac{\sqrt{3}}{2} U^*_{e3} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} - \frac{1}{2} U_{e3} \\ -\frac{1}{\sqrt{6}} - \frac{\sqrt{3}}{2} U^*_{e3} & -\frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{2}} - \frac{1}{2} U_{e3} \end{pmatrix}$$
- $|U_{e3}| \leq 0.11$
- Large mixing in the neutrino sector, unlike the small mixing in the quark sector (WHY ?)
- Phase of $U_{e3} \rightarrow$ CPV in the leptonic sector

Future of Neutrino Expt's

- Measure $|U_{e3}|$ from reactor neutrino experiments and T2K in Japan
- Search for CP violation in the neutrino sector

$$P(\nu_\alpha \to \nu_\beta) \neq P(\overline{\nu_\alpha} \to \overline{\nu_\beta})$$

- Is neutrino Dirac or Majorana particle ?
- Neutrinoless double beta decay ($0\nu\beta\beta$):

$$|m_{ee}| \equiv |\sum_i U_{ei}^2 m_i| < O(1)\text{eV}$$

depending on the neutrino spectra, and will be searched for in several experiments

What can we learn from neutrinos ?

- ν Oscil. $\longrightarrow$ New physics beyond the SM
  cf. neutrinos are massless within the renormalizable SM of GSW
- One clue: $m_\nu \ll$ other fermions masses (WHY?)
- Seesaw mechanism
- Radiative generation (Zee, Babu, Ma, ...): neutrino masses are naturally small, because they are generated by one-loop or two-loop effects
- Neutrino physics provides clues on high energy scale physics (GUT or TeV scales), depending on the mechanisms to generate neutrino masses

Seesaw Mechanism

- Add N_R to ν_L and consider Two state problem

$$\psi = \begin{pmatrix} \nu_L \\ N_R \end{pmatrix} \qquad M = \begin{pmatrix} 0 & m_D \\ m_D & M_R \end{pmatrix}$$

- Diagonalize M:
  $m_\nu \simeq i\frac{m_D^2}{M_R}, \quad M_\nu \simeq M_R, \quad m_D = m_e$
  $M_R \sim O(10^{12-16})$ GeV $\rightarrow m_\nu \lesssim O(1)$ eV
- Light Neutrino due to heavy M_R:
  Seesaw : Very Natural

Charged lepton flavor violation (LFV) ?

- LFV in neutrino sector has been confirmed
- How about in the charged lepton sector ?
- Upper bounds on Br for some modes (2004 PDG) :

Mode	Br
$\mu \to e\gamma$	$1.2 < \times 10^{-11}$
$\mu \to 3e$	$< 1.0 \times 10^{-12}$
$\tau \to e\gamma$	$< 2.7 \times 10^{-6}$
$\tau \to \mu\gamma$	$< 1.1 \times 10^{-6}$
$\tau \to 3\mu$	$< 1.9 \times 10^{-6}$
$\tau \to \mu\eta$	$< 9.6 \times 10^{-6}$

Charged LFV - II ?

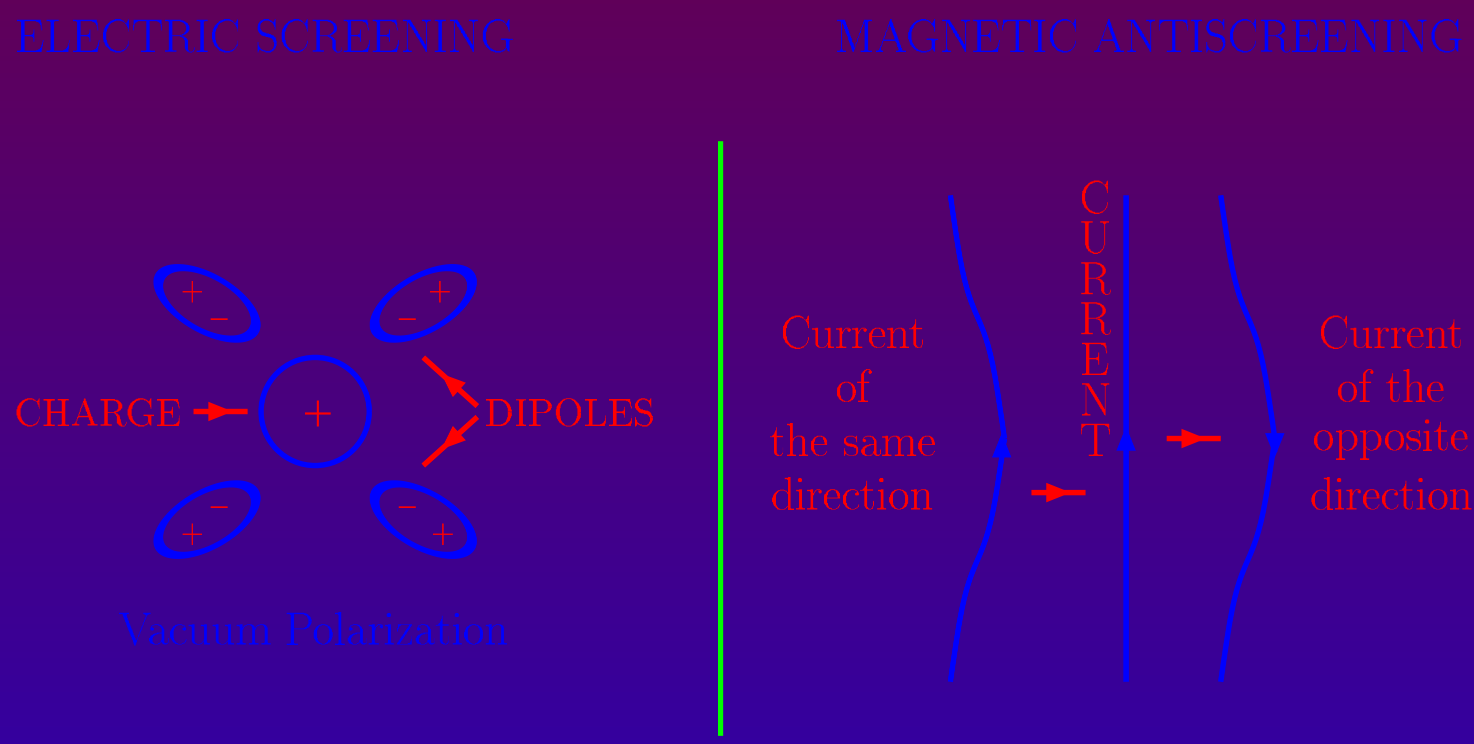
- Why is it so small in the charged lepton sector, whereas it is large in the neutrino sector ?
  Answer: Not well understood yet
- Charged LFV can be enhanced in SUSY models or some physics beyond the SM
- Search for charged LFV's still going on :
  $\mu \to e\gamma$ (MEG)
  $\mu^- \, \mathrm{Ti} \to e^- \, \mathrm{Ti}$ (MECO)
  $\tau \to \mu\gamma, \; 3\mu, \; \mu\eta$, etc. ($B, \tau$ factories)

Why SUSY ?

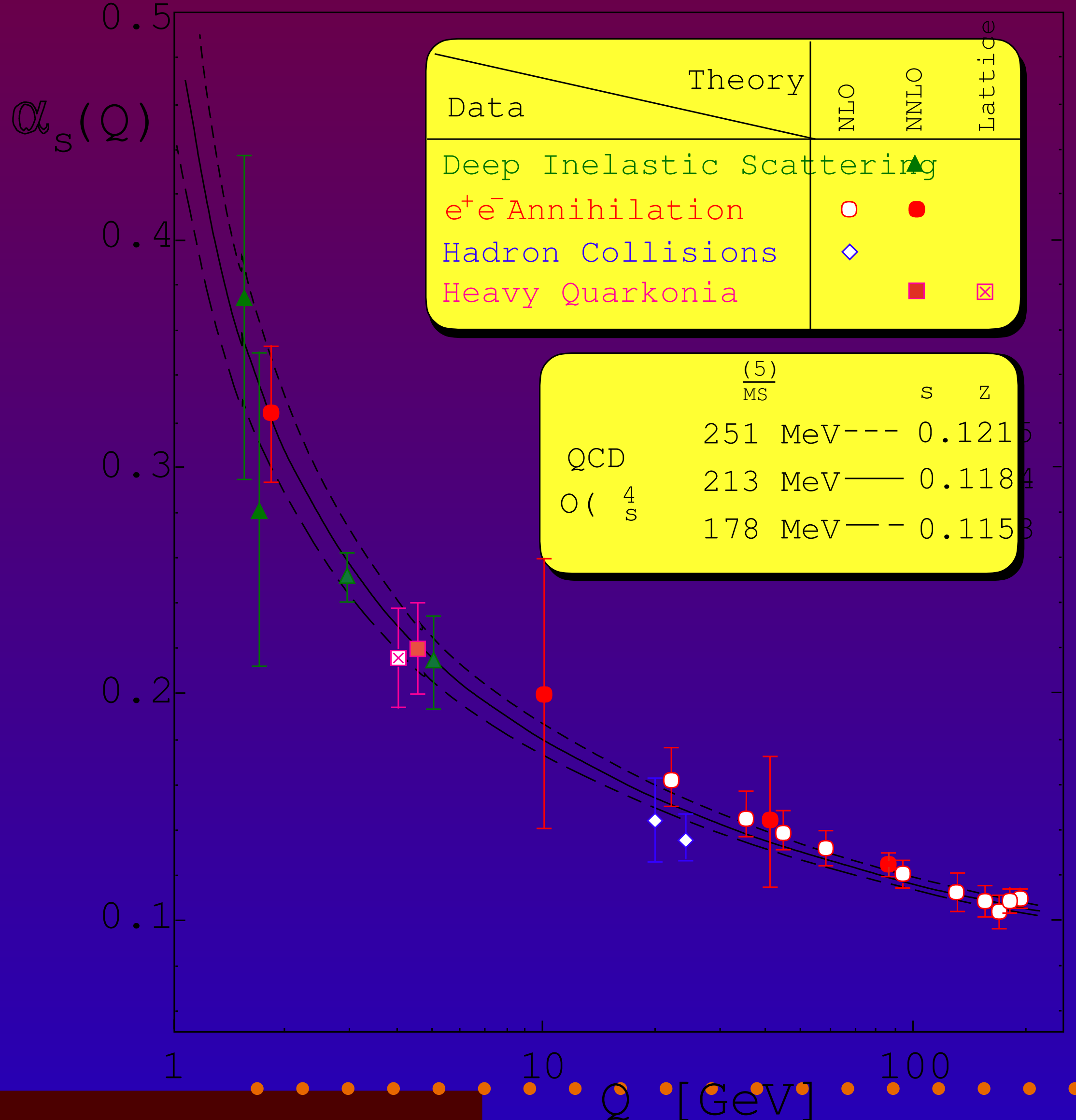
- SUSY : FERMION $\leftrightarrow$ BOSON
- Maximal Symmetry of S-matrix in Rel. Local QFT with graded Lie algebra (Haag, Lopusansky and Sohnius)
- Can solve Technical Hierarchy Problem
- Better High Energy Behavior in SUSY QFT
- Low Energy Measurements of 3 Gauge Couplings + SUSY $\rightarrow$ SUSY GUT
- Cold dark matter if $R-$parity is conserved (Bonus)
- Essential in String Theories (quantum theory of gravity)
- Local SUSY (SUGRA) includes Gravity

Gauge coupling unification

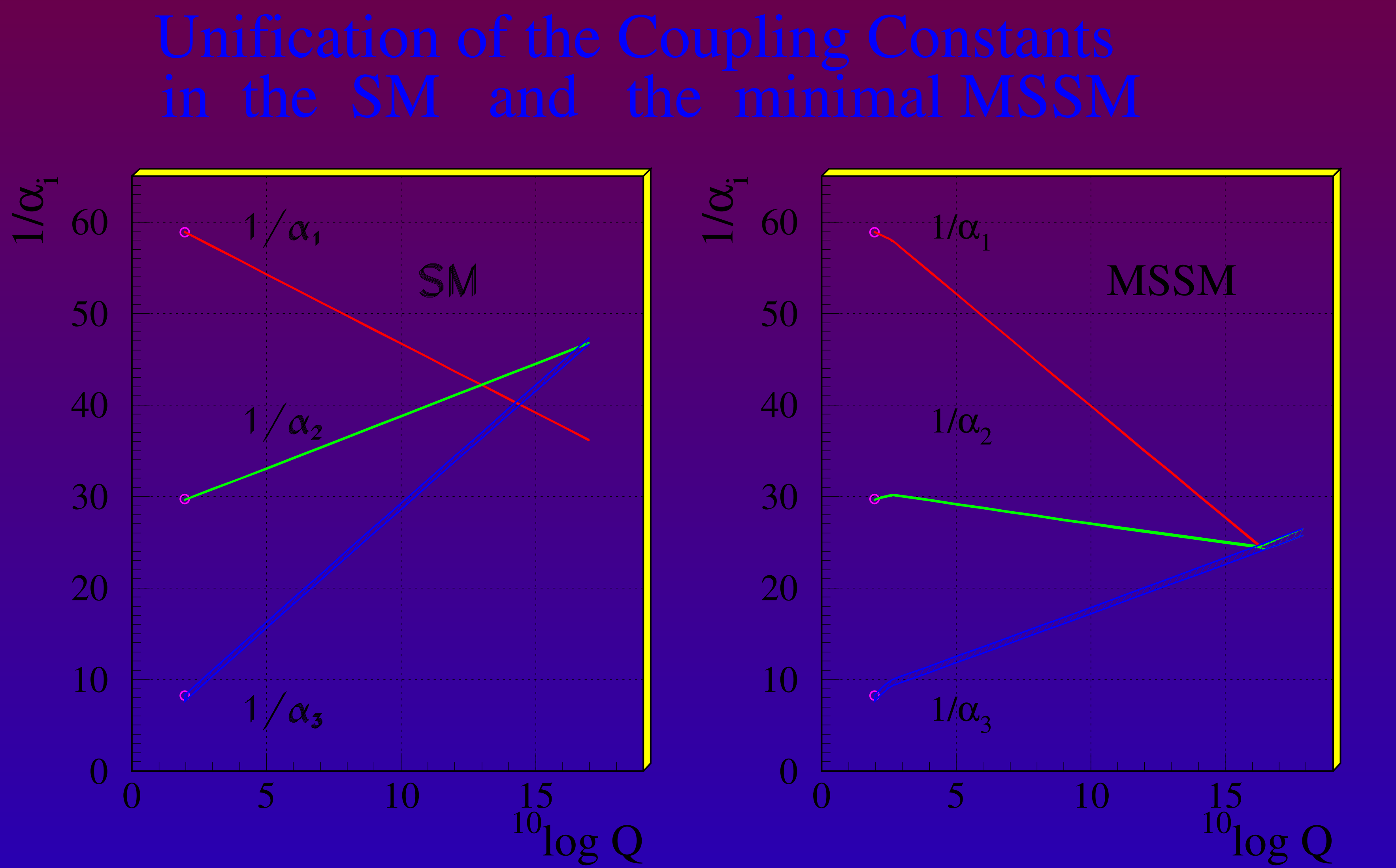
– Evidence for GUT : Gauge Coupling Unification –



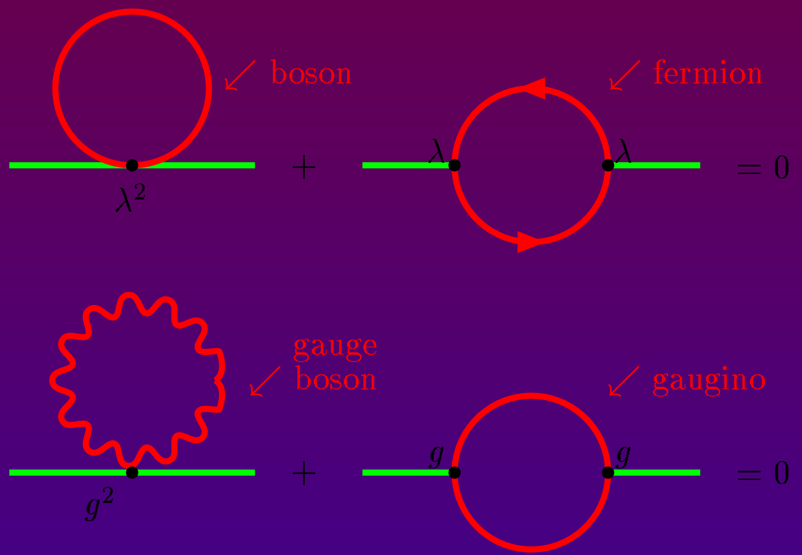
Running of strong coupling



Running of 3 gauge couplings



Solving Gauge Hierarchy Problem



- Fermion Loop Contribution

$$\Delta m_H^2 = \frac{|\lambda_f|^2}{16\pi^2}\left[-2\Lambda_{UV}^2 + 6m_f^2\ \ln(\Lambda_{UV}/m_f) + \ldots\right]$$

- Scalar Loop Contribution

$$\Delta m_H^2 = \frac{\lambda_S}{16\pi^2}\left[+\Lambda_{UV}^2 - 2m_S^2\ \ln(\Lambda_{UV}/m_S) + \ldots\right]$$

Solving Gauge Hierarchy Problem-II

- $\Lambda_{UV} \sim M_{pl} \sim 10^{19}$ GeV vs. $m_H \sim 10^2$ GeV
  $\rightarrow$ Technical Gauge Hierarchy Problem
- Dangerous Λ_{UV}^2 terms cancel, if $\lambda_S = |\lambda_f|^2$
- The result will be
  $\Delta m_H^2 = m_{soft}^2 \, \left[\frac{\lambda}{16\pi^2} \, \ln(\Lambda_{UV}/m_{soft}) + ...\right]$
- m_{soft} cannot be too huge
- These two relations can be realized in **SUSY**
  $*$ scalar quartic self couplings are related with Yukawa couplings
  $*$ f and S have the same masses in SUSY limit

MSSM

- SUSY must be (spontaneously) broken in reality
- SUSY Breaking Effects can be parametrized in terms of Soft-SUSY Breaking terms ($\mathcal{L}_{soft}$)
- Sparticles get masses around $O(100 \text{ GeV})$ to $O(1)$ TeV, and could be discovered at LHC
- MSSM $\equiv$ SM + One more Higgs Doublet + SUSY + $\mathcal{L}_{soft}$
- 105 more parameters in MSSM compared to the SM : More mass parameters, mixing angle and CPV phases.

SUSY interactions

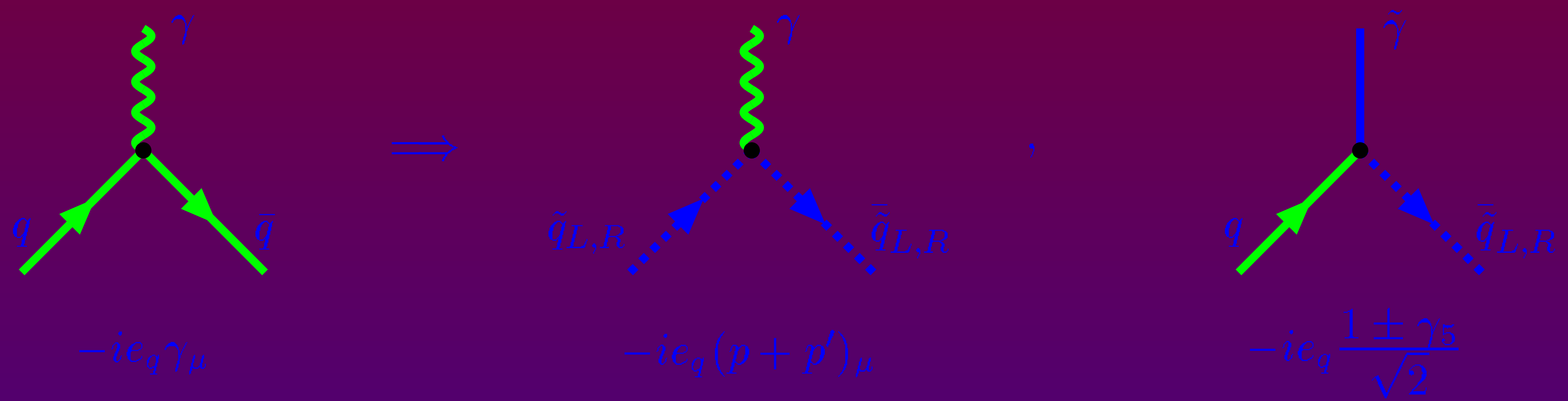


Figure 1: Gauge-matter interaction

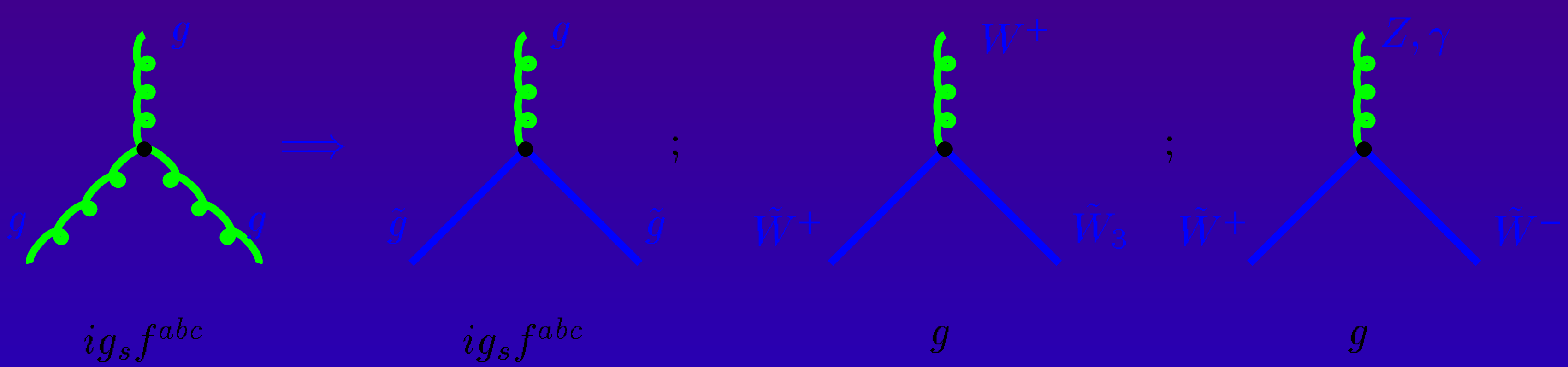


Figure 2: Gauge self-interaction

SUSY interactioins -II

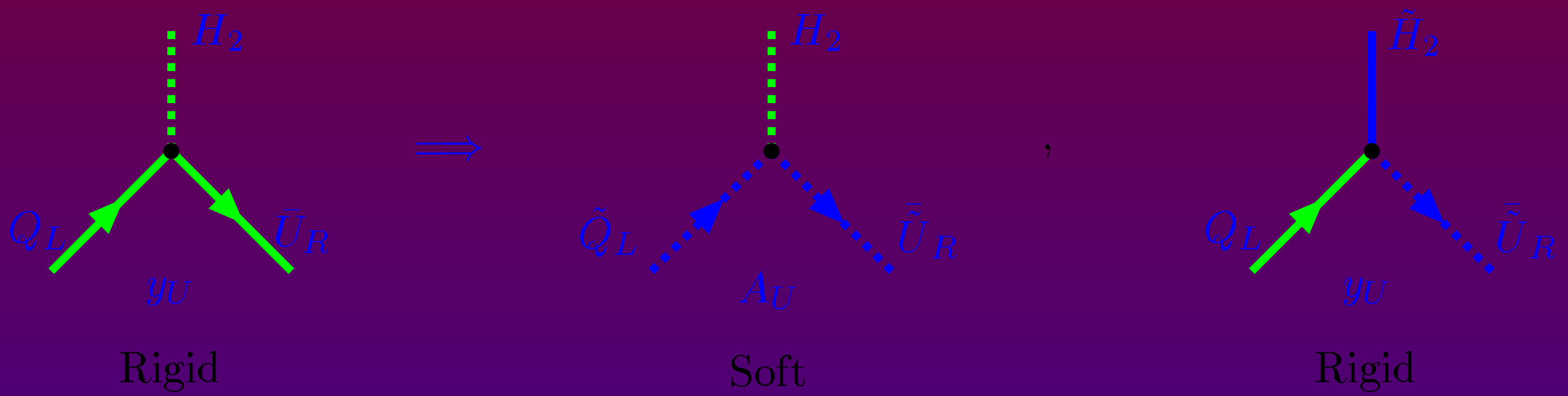


Figure 3: Yukawa-type interaction

To estalish MSSM, all these relations should be verified at LHC and ILC

$B_s - \overline{B_s}$ mixing in SM

- Dominated by the box diagram with $W - t$ in the loop
- The mixing is almost real within the SM , and depend on V_{ts}
- Any phase in the mixing is a clear signal of physics beyond the SM
- $\Delta M_d/\Delta M_s$ depends on $|V_{td}|^2/|V_{ts}|^2$ with less hadronic uncertainties than individuals
  $\rightarrow$ Important for CKM Phenomenology

First observations of $B_s - \overline{B}_s$ mixing

- The WA until this March : $\Delta M_s > 14.4$ ps^{-1}
- D0 : 17 ps$^{-1} < \Delta M_s < 21\text{ps}^{-1}$
- CDF : $\Delta M_s = (17.33^{+0.42}_{-0.21}(\text{stat}) \pm 0.07(\text{sys}))$ ps^{-1}
- Constraint on V_{ts} from $\Delta M_d / \Delta M_s$
  $|V_{td}|/|V_{ts}| = 0.208^{+0.008}_{-0.007}(\text{stat} + \text{sys})$
- The Belle result from $b \rightarrow d\gamma$
  $|V_{td}|/|V_{ts}| = 0.199^{+0.026}_{-0.025}(\text{exp})^{+0.018}_{-0.015}(\text{theor})$
- Excellent agreement of two measurements
  $\rightarrow$ Another test of the CKM paradigm and strong constraint on new physics scenarios

$B_s - \overline{B_s}$ mixing in SUSY models

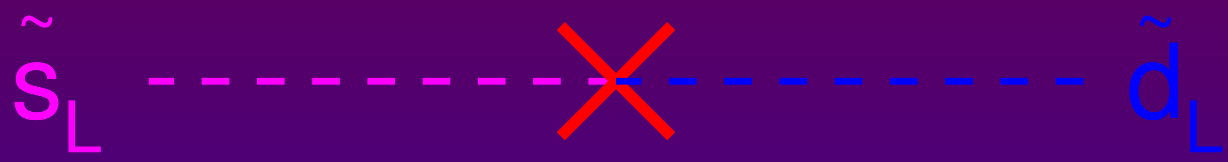
- Additional contributions from $H^- - t$, $\chi^- - \tilde{U}_i$ and $\tilde{D}_i - g(\tilde{\chi^0})$
- In generic SUSY models, the squark-gluino loop is parametrically stronger, since it is strong interaction
- Assume that the dominant new physics contribution comes from down squark-gluino loop diagrams
- See Ko, Kramer, Park, Eur.J.Phys. (2002) for $B_d - \overline{B_d}$ mixing, $A_{\rm SL}^d$ and CPV in $B \to X_d \gamma$
- See Kane, Ko, Kolda, Park, Wang^2, PRL (2003) and PRD (2004) for $B_d \to \phi K_s$ and $B_s - \overline{B_s}$ mixing and related issues

Digress on SUSY FCNC/CP problem

- Supersymmetrizing SM doubles the particle spectrum, introducing more than 100 new parameters in the soft SUSY breaking sector.
- Soft SUSY breaking parameters are complex and flavor violating, and a generic supersymmetric standard model results in huge FCNC and CP violation.
- Squark mass matrix need not be diagonalized simultaneously with the quark mass mztrix $\longrightarrow$ gluino mediated FCNC and CPV
- There must be some mechanism which controls FCNC and CP. This may be due to the SUSY breaking mediation mechanism and/or some flavor symmetry.

Digress-II

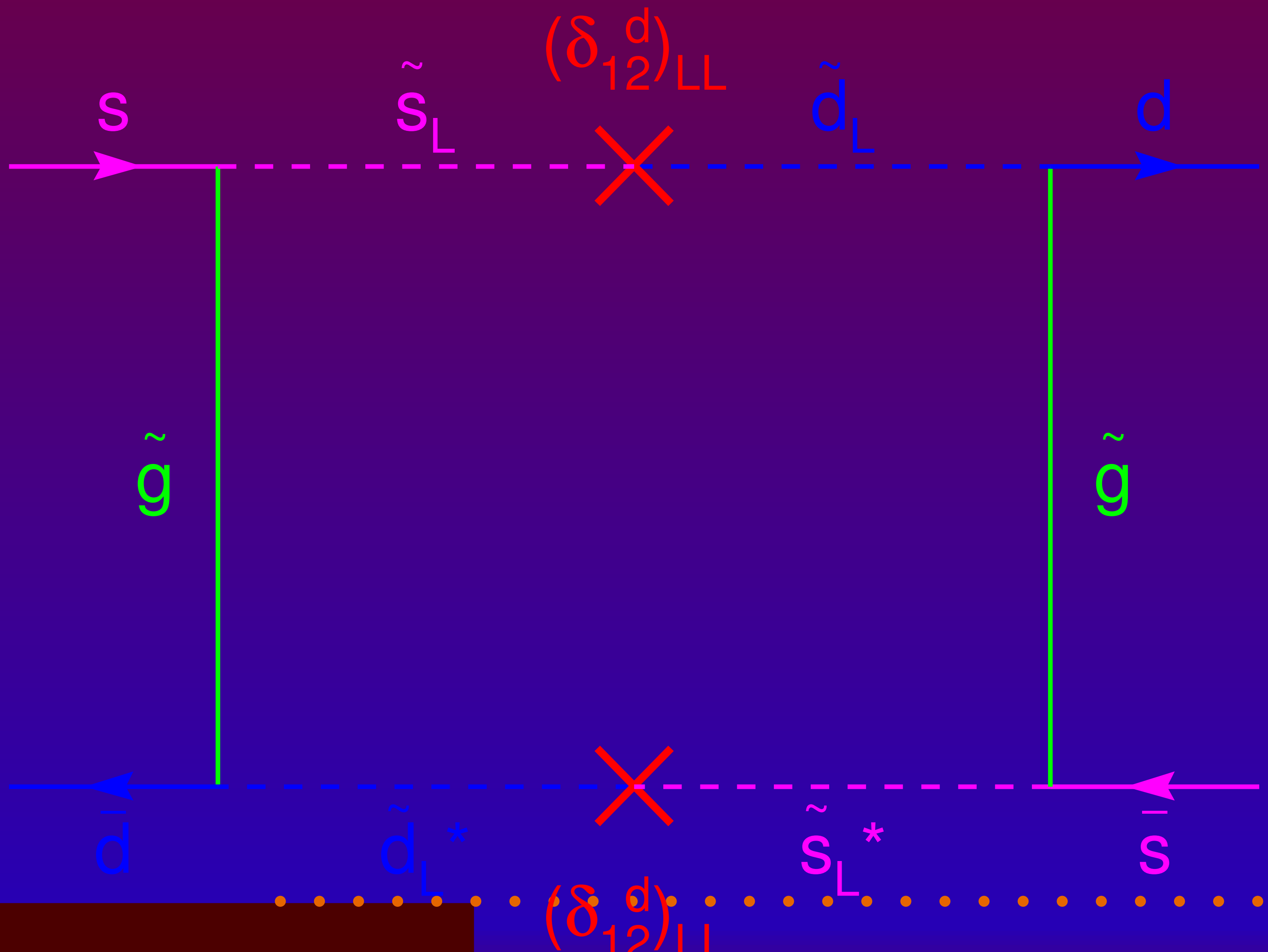
- Mass insertion approximation is a useful tool to present flavor violation in the sfermion sector. $(\delta^d_{12})_{LL}$: dimensionless transition strength from $\widetilde{s}_L$ to $\widetilde{d}_L$.



- We can do the same for $b_A \to d_B$ and $b_A \to s_B$ $(A, B = L, R$: chiralities of superpartners of squarks)
- If $\delta \sim O(1)$, large FCNC and CPV with strong couplings
- SUSY FCNC/CP problem δ's should be small $\lesssim 10^{-1} - 10^{-3}$ depending on $AB = LL, RR, LR, RL$

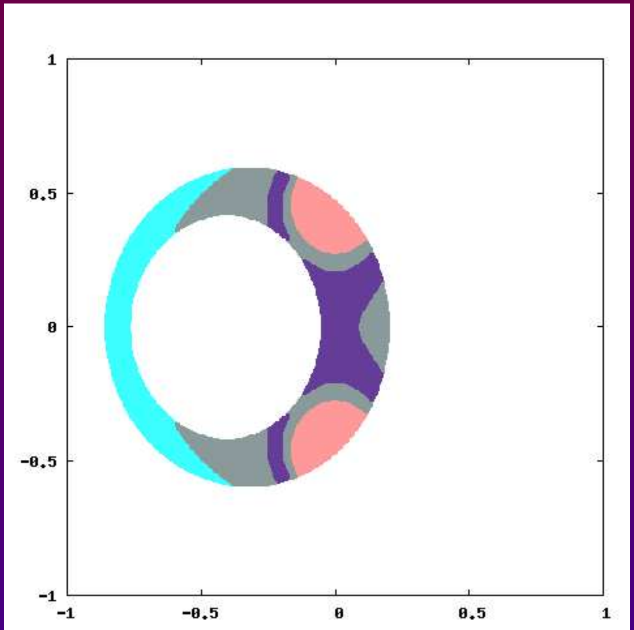
SUSY contributions to ϵ_K

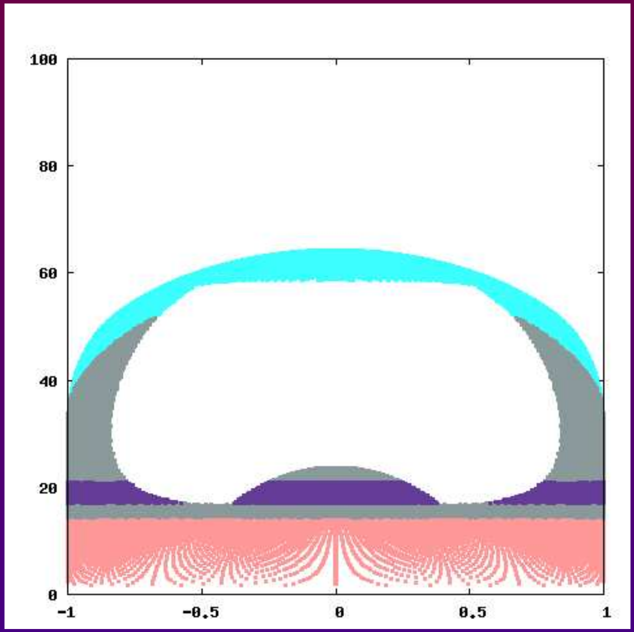
- Diagrams:



LL insertion ($\tan\beta = 3$)

- $m_{\tilde{q}} = m_{\tilde{g}} = -\mu = 350$ GeV for $\tan\beta$ = 3

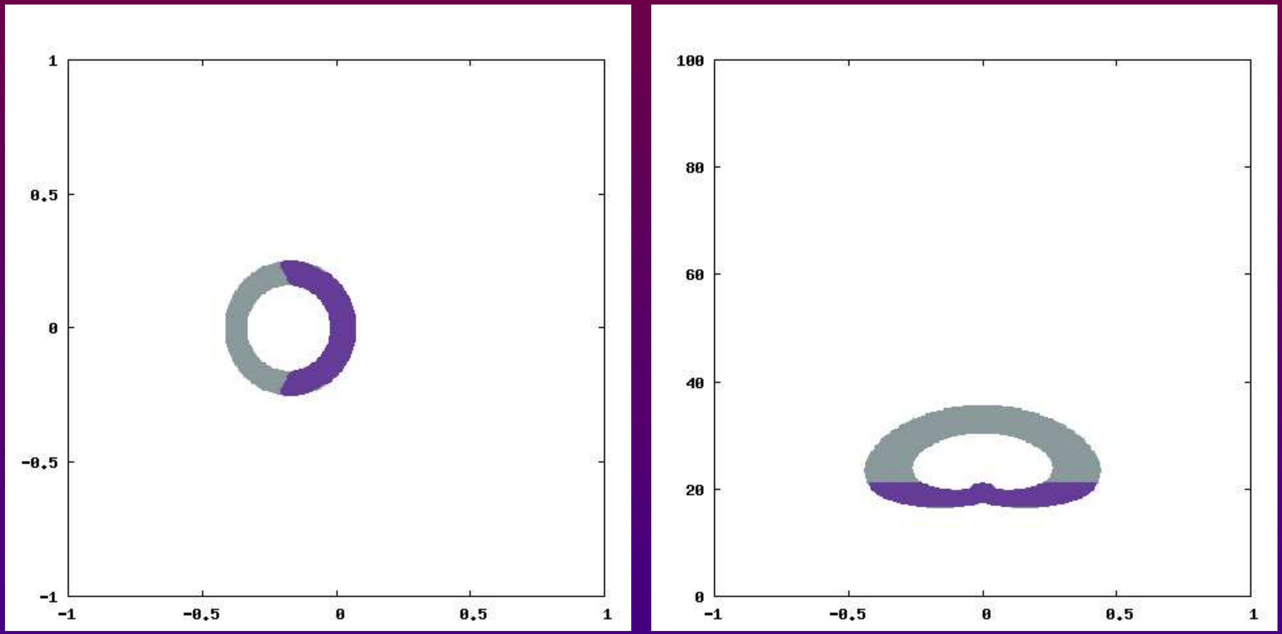




- $\Delta M_s > 14.4$ ps^{-1} for a cyan region
- 17 ps^{-1} < ΔM_s < 21 ps^{-1} for a blue region,
- Lightest down-type squark mass squared > (100 GeV)^2
- A transparent red mask is imposed over the region where lightest down-type squark mass squared >

LL insertion ($\tan\beta = 10$)

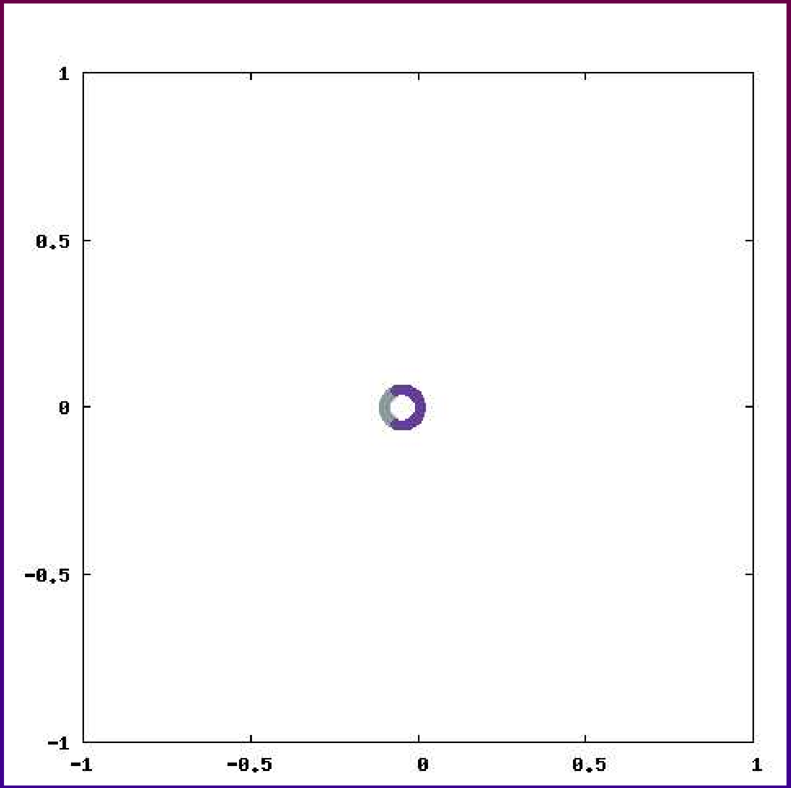
- $m_{\tilde{q}} = m_{\tilde{g}} = -\mu = 350$ GeV for $\tan\beta$ = 10

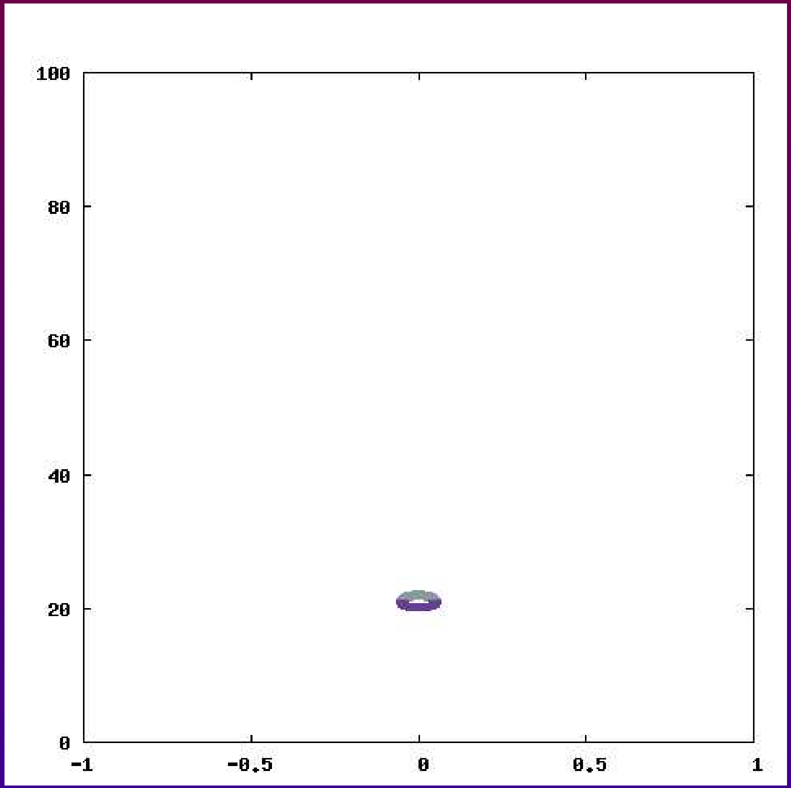


- $\Delta M_s > 14.4$ ps^{-1} for a cyan region
- 17 ps^{-1} < ΔM_s < 21 ps^{-1} for a blue region,
- Strongly constrained $(\delta^d_{23})_{LL}$ mixing, mainly by $B \to X_s\gamma$

LL insertion ($\tan\beta = 40$)

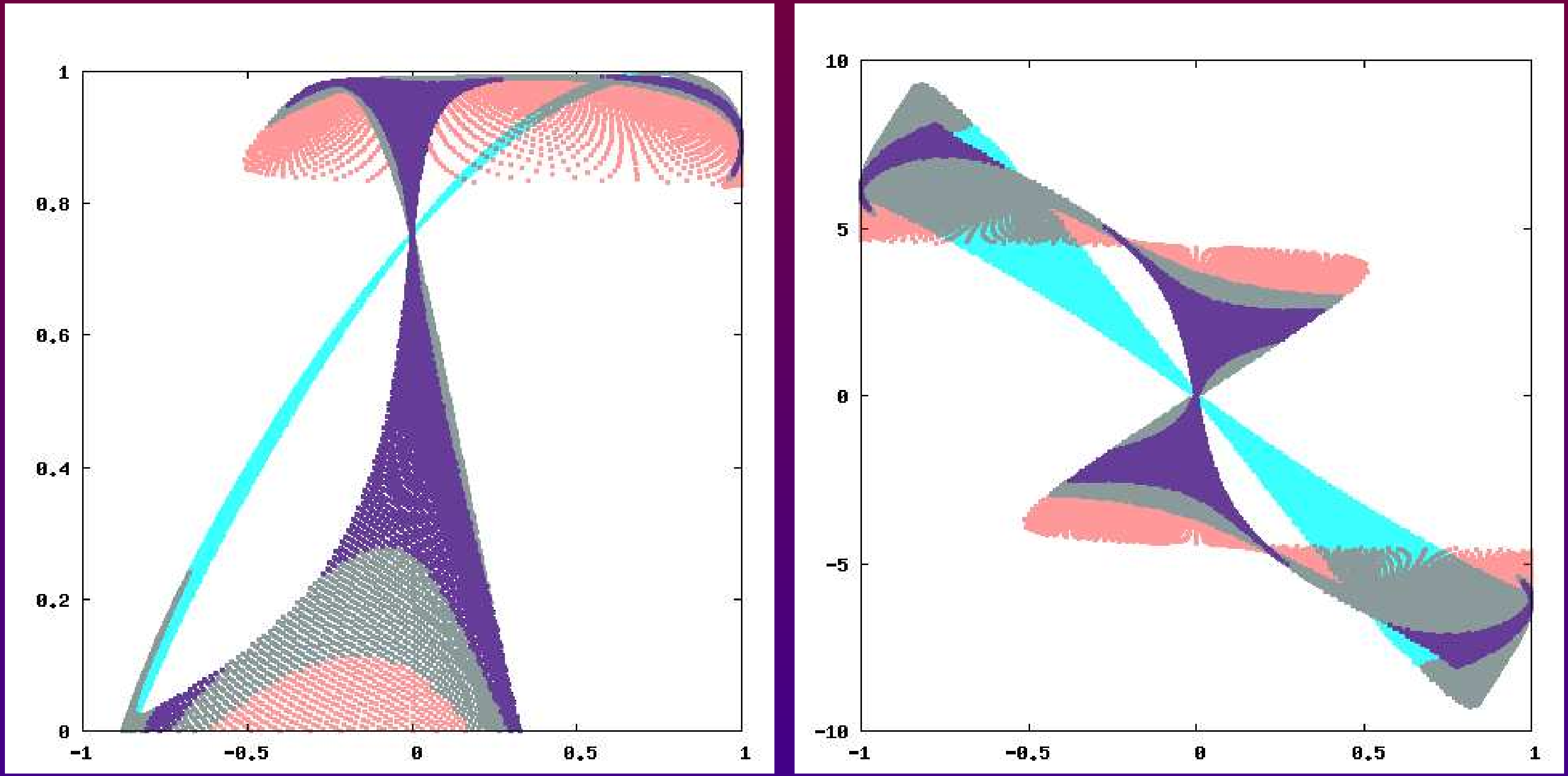
- $m_{\tilde{q}} = m_{\tilde{g}} = -\mu = 350$ GeV for $\tan\beta$ = 40





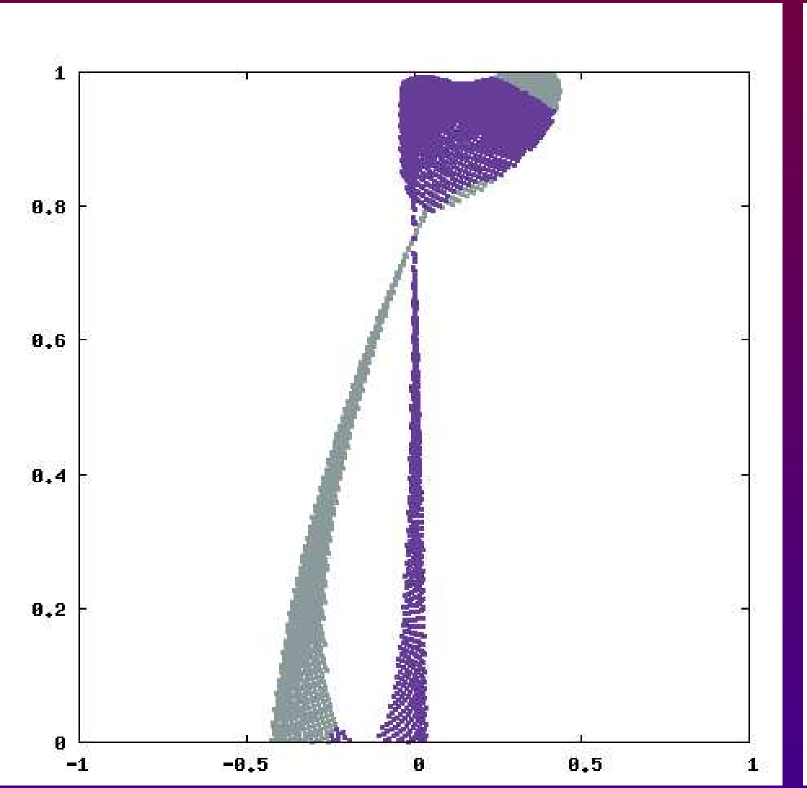
- The constraint even stronger for large $\tan\beta = 40$ due to the induced LR or RL mixing through double mass insertion
(Baek, Jang, Ko and Park, PRD 117701 (2000))

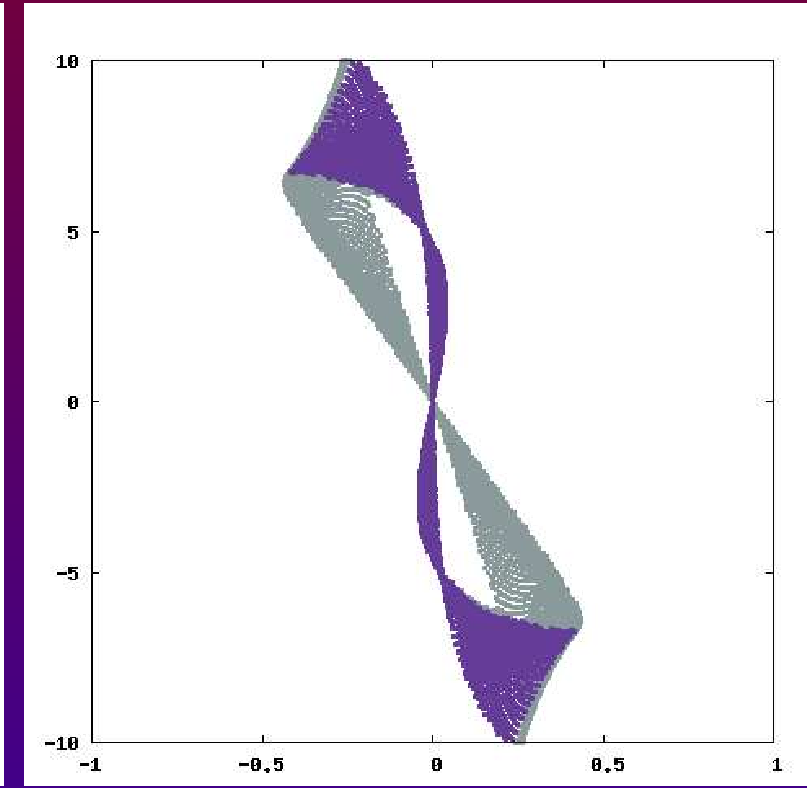
LL insertion ($\tan\beta = 3$)



- $S_{\phi K}$ vs $S_{\psi\phi}$ and A_{CP} vs. $S_{\psi\phi}$

LL insertion ($\tan\beta = 10$)





- $S_{\phi K}$ vs $S_{\psi\phi}$ and $A_{\rm CP}$ vs. $S_{\psi\phi}$

Implications for SUSY flavor models

- Alignment of quark and squark mass matrices can be achieved by flavour symmetries ($U(1), S_3$,....)

	Model	LL	RR	
A	LNS1	λ^2	λ^4	$LL \gg RR$
	NS,Moroi a	λ^2	1	$LL \ll RR$
	Moroi b	λ^2	$\lambda^{1/2}$	$LL \ll RR$
B	BHRR, PT b	λ^2	λ^2	$LL = RR$
	[?]	λ^3	λ^5	$LL \gg RR$
	PS	λ^2	λ^4	$LL \gg RR$
B+C	PT a	λ^2	λ^2	$LL = RR$
C	CKN	λ^2		$LL \gg RR$

- A:alignment, B:non-abelian, C:heavy squarks
- Some models are now excluded by $B_s - \overline{B_s}$ mixing

Grand Unification

- Unification $\rightarrow$ Progress in theoretical physics
  Maxwell's E & M, QM and Special Relativity $\rightarrow$ QFT, ...
- Unanswered Questions within SM
  - Why $Q_p = -Q_e$ and $U(1)_Y$ quantum numbers ?
  - Why 3 different forces ? Are they UNIFIABLE ?
    $SU(3)_c \times SU(2)_L \times U(1)_Y \rightarrow G_{\rm GUT}$
  - Why proton is stable ?
    $\tau(p \rightarrow e^+\pi^0) > 1.6 \times 10^{33}$ years
  - Why 3 generations ?
  - Quantum Gravity ?
  - Many other questions ...

GUT and proton decay in $SU(5)$

- $5^* = (d_1^c, d_2^c, d_3^c, e^-, \nu_e)_L^T$

$$10 = \begin{pmatrix} 0 & u_3^c & -u_2^c & -u^1 & -d^1 \\ & 0 & u_1^c & -u^2 & -d^2 \\ & & 0 & -u^3 & -d^3 \\ & & & 0 & -e^+ \\ & & & & 0 \end{pmatrix}_L$$

$$1 = N_L^c$$

- SM particles fit into $5^* + 10 + 1$ of $SU(5)$

Quark–Lepton Unification

Flavor physics in SUSY GUT

- Large neutrino mixing $\nu_\mu \leftrightarrow \nu_\tau \rightarrow$ large $b_L^c - s_L^c$ (or $b_R - s_R$) mixing
- In SUSY GUT, this implies
  - Large $\tilde{b}_R - \tilde{s}_R$ mixing $\rightarrow$ Large $b \rightarrow s$ transition

    $B \rightarrow \phi K_S$ CP asymmetry, $B_s - \overline{B_s}$ mixing

    (see the following discussion on this)
  - Large $\tilde{\tau}_L - \tilde{\mu}_L$ mixing $\rightarrow$ Large $\tau \rightarrow \mu\gamma$

$SU(5)$ GUT: gauge bosons

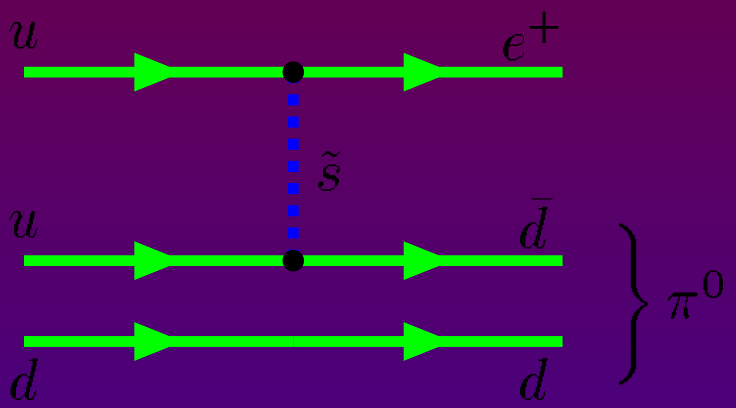
- 24 Gauge bosons in adjoint

$$\begin{pmatrix} G^1_1 - \frac{2B}{\sqrt{30}} & G^1_2 & G^1_3 & \bar{X}^1 & \bar{Y}^1 \\ G^2_1 & G^2_2 - \frac{2B}{\sqrt{30}} & G^2_3 & \bar{X}^2 & \bar{Y}^2 \\ G^3_1 & G^3_2 & G^3_3 - \frac{2B}{\sqrt{30}} & \bar{X}^3 & \bar{Y}^3 \\ X_1 & X_2 & X_3 & \frac{W^3}{\sqrt{2}} + \frac{3B}{\sqrt{30}} & W^+ \\ Y_1 & Y_2 & Y_3 & W^- & -\frac{W^3}{\sqrt{2}} + \frac{3B}{\sqrt{30}} \end{pmatrix}$$

- X, Y gauge bosons couple to quark + lepton (Leptoquarks) $\rightarrow$ Proton decays
  cf. Similar if $R-$parity is violated in the MSSM

$SU(5)$ GUT and proton decay

- Superheavy X, Y gauge boson excahnge:



$$p \to e^+ \pi^0$$

$$\tau^{-1} \sim \frac{\alpha_{\rm GUT}^2 m_p^5}{M_X^4}$$

- NonSUSY $SU(5)$: $M_X \simeq 3 \times 10^{14}$ GeV $\to \tau \simeq 10^{30\pm1}$ years EXCLUDED
- SUSY SU(5) is OK with proton decay exp. and Gauge Coupling Unif.

Summary and Outlook

- Flavor physics played a crucial role in the particle physics in the last century :
- P Violation : SM is chiral gauge theory
- CP violation : CP phase (CKM)
- Suppression of FCNC and GIM mechanism :
  $*$ Existence of new particles in the loop (c, t)
  $*$ Strong constraint on new physics (δ's in SUSY models)
- Neutrino oscillation : neutrinos have tiny masses, and the SM of Weinberg and Salam should be extended to accommodate it
- Proton decay probes physics at $E \sim 10^{16}$ GeV and possible unification of quarks and leptons (GUT)

Summary and Outlook-II

- For the next decade or so, B factories and neutrino experiments will be the main experiments for flavor physics
- Complementary to Colliders such as Tevatron, LHC and ILC, where the origin of mass and thus flavor will be explored
- Nice surprise from flavor physics ?
  CPV in the $B_s - \overline{B_s}$ mixing and neutrino sector,
  $\mu \to e\gamma$, Proton decay, ...
- Even more exciting : CPT violation in the neutrino sector or in the $K^0 - \overline{K^0}$ mixing ?
  $\to$ Tests of relativistic local QFT, the holy grail of modern particle physis