IV. **Low Energy Probes of SUSY**

- How is SUSY broken? $M_{SUSY} \neq M_{SM}$
- How viable is SUSY dark matter ?
- Is there enough SUSY CP violation to account for the matter-antimatter asymmetry?

High precision, low energy measurements can probe new physics in the “desert”

Complementary to Z^0 pole

- LEP & SLD programs are complete
- Sensitivity to off Z^0 - resonance physics
- Precision is improving

Precision ~ Mass Scale

$$\delta_{SUSY} = \frac{\Delta O^{SUSY}}{O^{SM}} \approx \frac{\alpha}{\pi}\left(\frac{M}{\tilde{M}}\right)^2$$

$M = m_\mu$ $\quad \delta \sim 2 \times 10^{-9}$

$\delta^{exp} \sim 1 \times 10^{-9}$

$M = M_W$ $\quad \delta \sim 10^{-3}$

Weak decays

$$d \to u\, e^- \bar{\nu}_e$$

$$s \to u\, e^- \bar{\nu}_e$$

$$b \to u\, e^- \bar{\nu}_e$$

$$(u \quad c \quad t) \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1 \qquad \text{SM}$$

$$0.9968 \pm 0.0001 \qquad \text{Expt}$$

0.9487 ± 0.0001 $\quad 0.0488 \pm 0.0000$ $\quad 0.0000 \pm 0.0000$

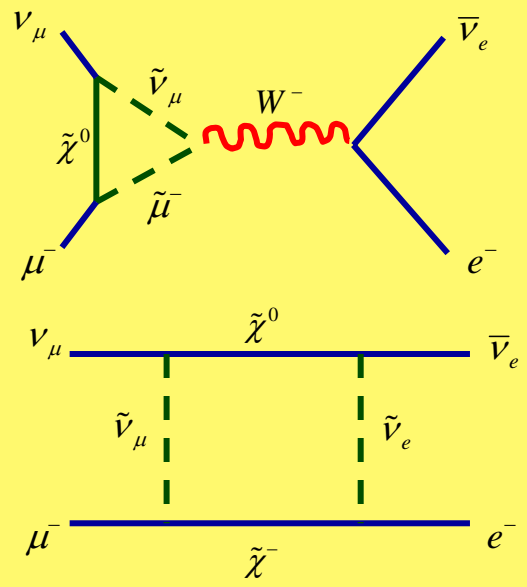
Weak decays

$$d \to u\, e^-\, \bar{\nu}_e$$

$$s \to u\, e^-\, \bar{\nu}_e$$

$$b \to u\, e^-\, \bar{\nu}_e$$

$$(u \quad c \quad t)\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}\begin{pmatrix} d \\ s \\ b \end{pmatrix}$$



$$\frac{\mathcal{O}^{SUSY}}{\mathcal{O}^{SM}} \sim 0.00$$

$+\cdots$

SUSY

$$\frac{G_F^\beta}{G_F^\mu} = |V_{ud}|\left(1 + \Delta r_\beta - \Delta r_\mu\right)$$

New physics

Weak decays

$$\frac{G_F^{\beta}}{G_F^{\mu}} = |V_{ud}|\left(1+\Delta r_{\beta}-\Delta r_{\mu}\right)$$

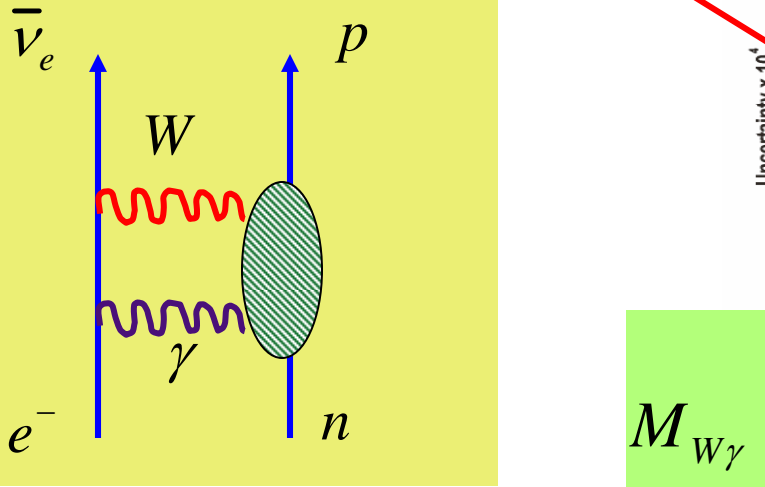
SM theory input

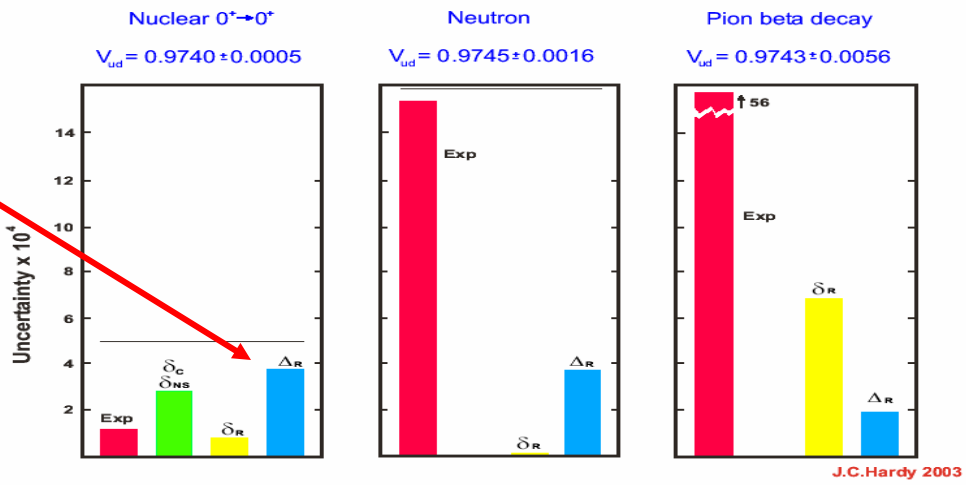
β-decay

$$n \to p\, e^-\, \bar{\nu}_e$$

$$A(Z,N) \to A(Z-1,N+1)\, e^+\, \nu_e$$

$$\pi^+ \to \pi^0\, e^+\, \nu_e$$





$$M_{W\gamma} = \frac{G_F}{\sqrt{2}}\frac{\hat{\alpha}}{2\pi}\left[\ln\left(\frac{M_Z^2}{\Lambda^2}\right) + C_{\gamma W}(\Lambda)\right]$$

Weak decays

$$\frac{G_F^{\beta}}{G_F^{\mu}} = |V_{ud}|\left(1+\Delta r_{\beta}-\Delta r_{\mu}\right)$$

β-decay

$$n \rightarrow p\, e^{-}\, \bar{\nu}_e$$

$$A(Z,N) \rightarrow A(Z-1,N+1)\, e^{+}\, \nu_e$$

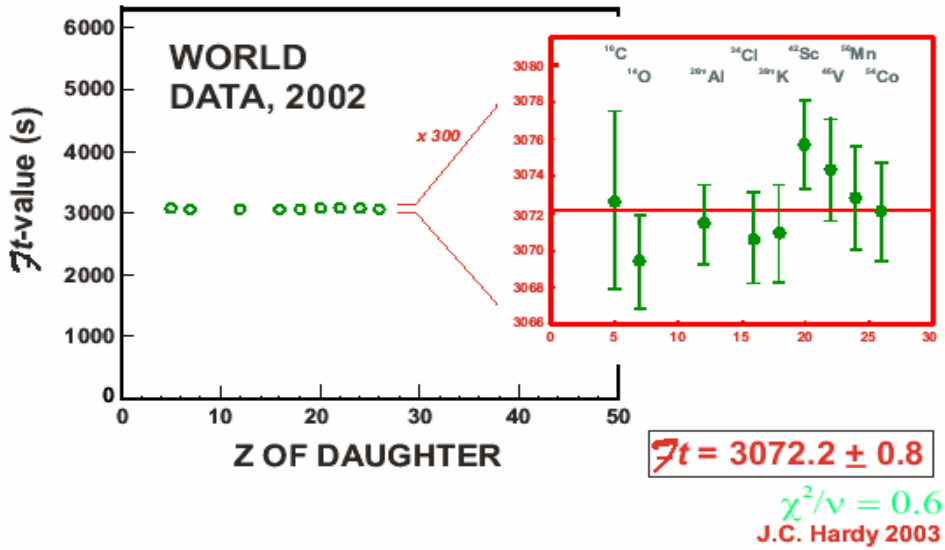
$$\pi^{+} \rightarrow \pi^{0}\, e^{+}\, \nu_e$$

$0^+ \rightarrow 0^+$ "Superallowed"

$$Ft = ft\left(1+\delta_R+\delta_{NS}\right)\left(1-\delta_C\right)$$

$$= K/2\left(G_F^{\beta}\right)^2$$

Nuclear structure-dependent corrections



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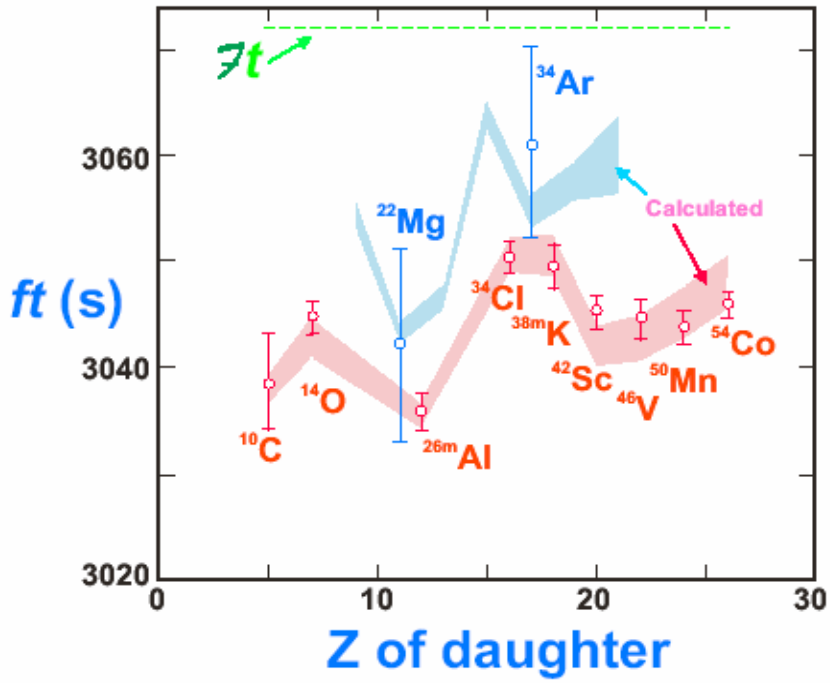

Weak decays

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β-decay

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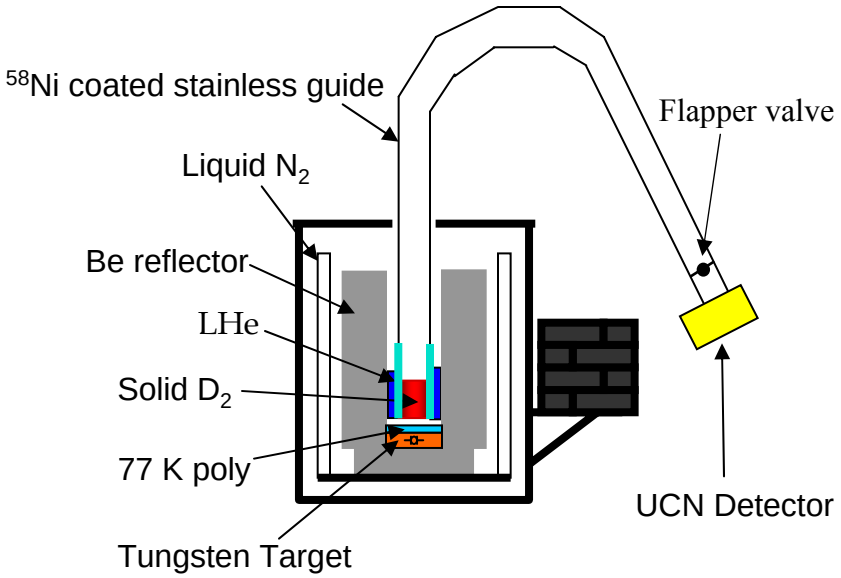
$$A(Z,N) \rightarrow A(Z-1,N+1)\, e^{+}\, \nu_e$$

$$\pi^{+} \rightarrow \pi^{0}\, e^{+}\, \nu_e$$

Ultra cold neutrons



LANSCE: "UCN A"

$$dW \propto 1 + a\frac{\vec{p}_e \cdot \vec{p}_{\nu}}{E_e E_{\nu}} + A\vec{\sigma}_n \cdot \frac{\vec{p}_e}{E_e} + \cdots$$

Future SNS: Pulsed Cold Neutrons: "abBA"

Weak decays

$$\frac{G_F^{\beta}}{G_F^{\mu}} = |V_{ud}|\left(1+\Delta r_{\beta}-\Delta r_{\mu}\right)$$

β-decay

$$n \rightarrow p\, e^{-}\, \bar{\nu}_e$$

$$A(Z,N) \rightarrow A(Z-1,N+1)\, e^{+}\, \nu_e$$

$$\pi^{+} \rightarrow \pi^{0}\, e^{+}\, \nu_e$$

$$dW \propto \frac{1}{\tau_n} F(E_e)\left[1 + a\frac{\mathbf{p}_e\cdot\mathbf{p}_\upsilon}{E_e\cdot E_\upsilon} + b\frac{m_e}{E_e} + A\frac{\sigma_n\cdot\mathbf{p}_e}{E_e} + B\frac{\sigma_n\cdot\mathbf{p}_\upsilon}{E_\upsilon}\right]$$

$$\tau_n \propto 1/(g_V^2 + 3g_A^2)$$

$$a = \frac{1-\left(\frac{g_A}{g_V}\right)^2}{1-3\left(\frac{g_A}{g_V}\right)^2}$$

$$b = 0$$

$$A = -2\frac{\left(\frac{g_A}{g_V}\right)^2 + \left(\frac{g_A}{g_V}\right)}{1-3\left(\frac{g_A}{g_V}\right)^2}$$

$$B = 2\frac{\left(\frac{g_A}{g_V}\right)^2 - \left(\frac{g_A}{g_V}\right)}{1-\left(\frac{g_A}{g_V}\right)^2}$$

Future SNS: Pulsed Cold Neutrons: “abBA”

G. Greene

Decay correlations

Weak decays

$$\frac{G_F^{\beta}}{G_F^{\mu}} = |V_{ud}|\left(1+\Delta r_{\beta}-\Delta r_{\mu}\right)$$

β-decay

$$n \rightarrow p\, e^{-}\, \bar{\nu}_e$$

$$A(Z,N) \rightarrow A(Z-1,N+1)\, e^{+}\, \nu_e$$

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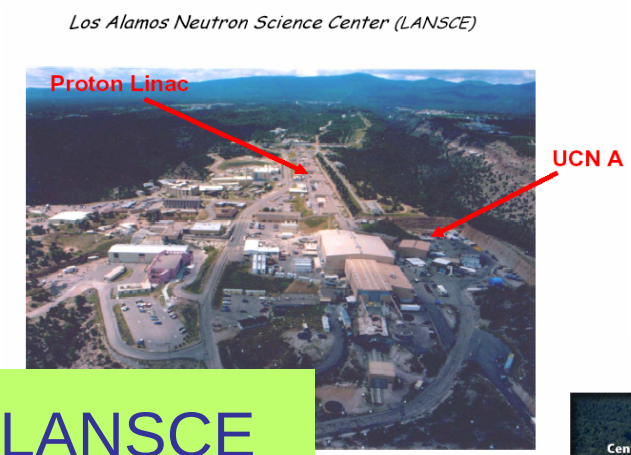


LANSCE

SNS

NIST

Weak decays

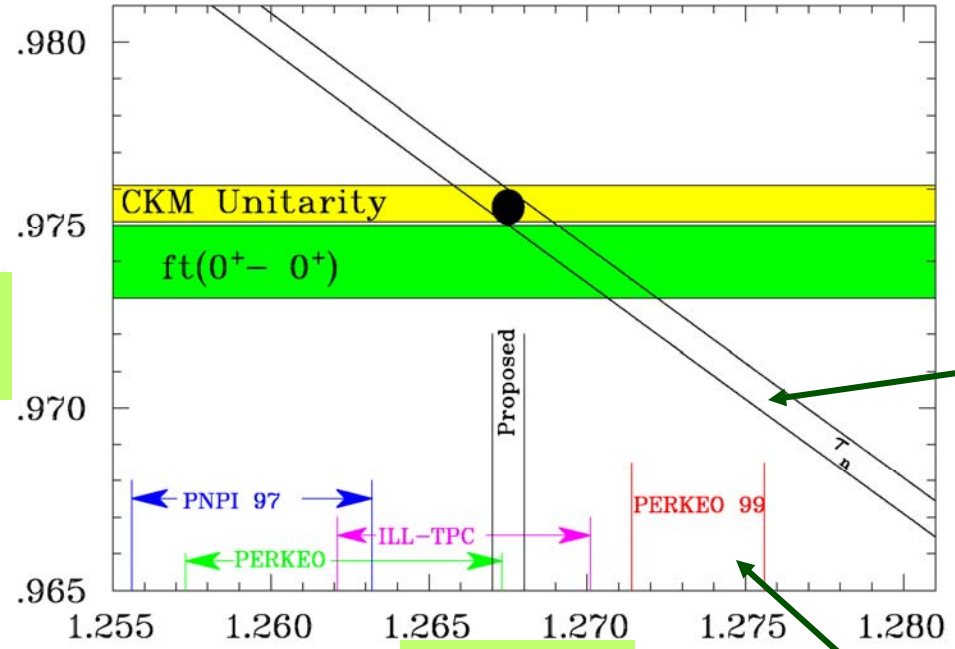
$$\frac{G_F^{\beta}}{G_F^{\mu}} = |V_{ud}|\left(1+\Delta r_{\beta}-\Delta r_{\mu}\right)$$

β-decay

$$n \rightarrow p\, e^{-}\, \bar{\nu}_e$$

$$A(Z,N) \rightarrow A(Z-1,N+1)\, e^{+}\, \nu_e$$

$$\pi^{+} \rightarrow \pi^{0}\, e^{+}\, \nu_e$$



V_{ud}

$\tau_n \sim g_v^2+3g_A^2$

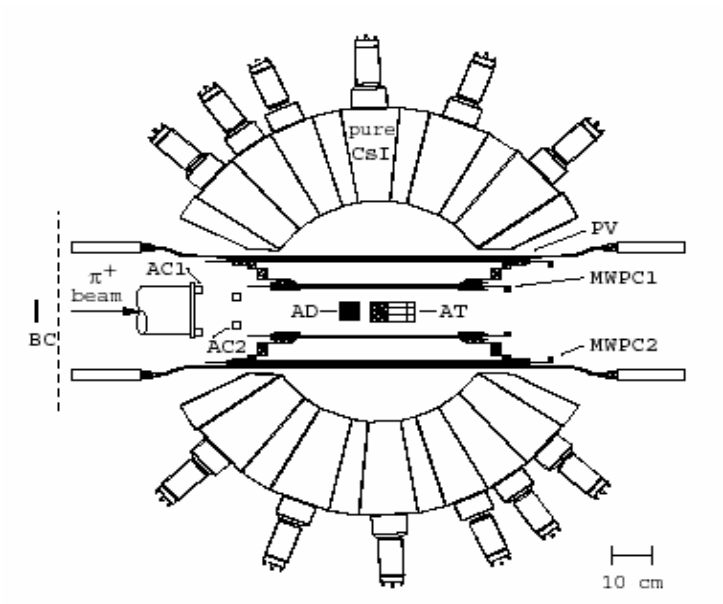
g_v/g_A

ILL, Grenoble

Weak decays

$$\frac{G_F^{\beta}}{G_F^{\mu}} = |V_{ud}|\left(1+\Delta r_{\beta}-\Delta r_{\mu}\right)$$

PSI: “Pi-Beta”



β-decay

$$n \rightarrow p\, e^{-}\, \bar{\nu}_e$$

$$A(Z,N) \rightarrow A(Z-1,N+1)\, e^{+}\, \nu_e$$

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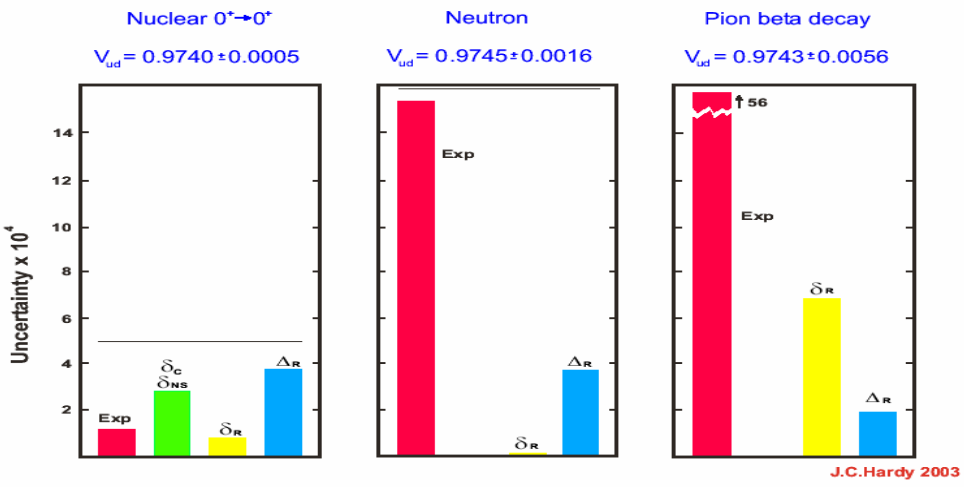


$$\Gamma\left(\pi^{+} \rightarrow \pi^{0} e^{+} \nu_e\right) / \Gamma\left(\pi^{+} \rightarrow \mu^{+} \nu_{\mu}\right) \sim 1 \times 10^{-8}$$

Weak decays

$$d \to u\, e^-\, \bar{\nu}_e$$

$$s \to u\, e^-\, \bar{\nu}_e$$

$$b \to u\, e^-\, \bar{\nu}_e$$

$$\begin{pmatrix} u & c & t \end{pmatrix} \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

kaon decay

$$K^+ \to \pi^0\, e^+\, \nu_e$$

$$\frac{G_F^K}{G_F^\mu} = |V_{us}| \left(1 + \Delta r_K - \Delta r_\mu\right)$$

Value of V_{us} important

SUSY Loops: Too small

Weak decays

$$d \to u\, e^-\, \bar{\nu}_e$$

$$s \to u\, e^-\, \bar{\nu}_e$$

$$b \to u\, e^-\, \bar{\nu}_e$$

$$\begin{pmatrix} u & c & t \end{pmatrix} \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

kaon decay

$$K^+ \to \pi^0\, e^+\, \nu_e$$

$$\Gamma = |V_{us}|^2 \frac{G_F^2\, S_{ew}\, M_K^5}{192\pi^3} \cdot |f_+(0)|^2 \cdot \left(1 + \Delta_{SU(2)} + \Delta_{EM}\right) \cdot I_{PS}(m_i, \lambda)$$

SM Theory

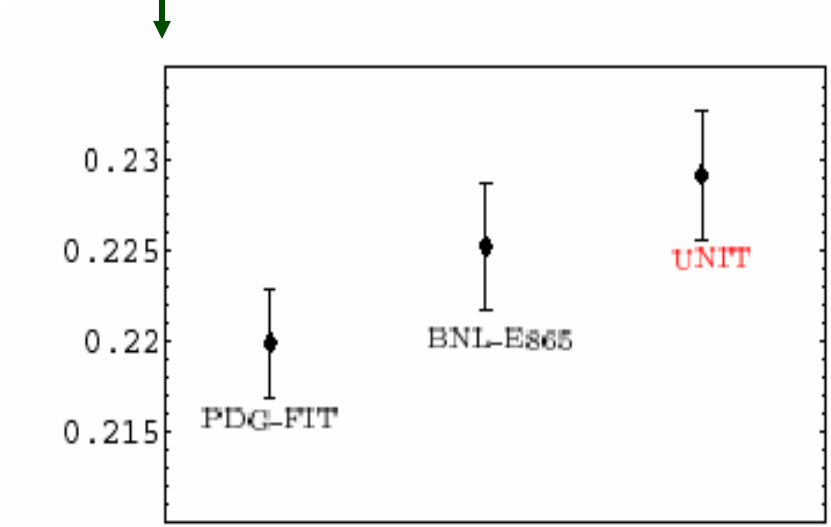
Weak decays

$$\frac{G_F^K}{G_F^\mu} = |V_{us}|\left(1 + \Delta r_K - \Delta r_\mu\right)$$

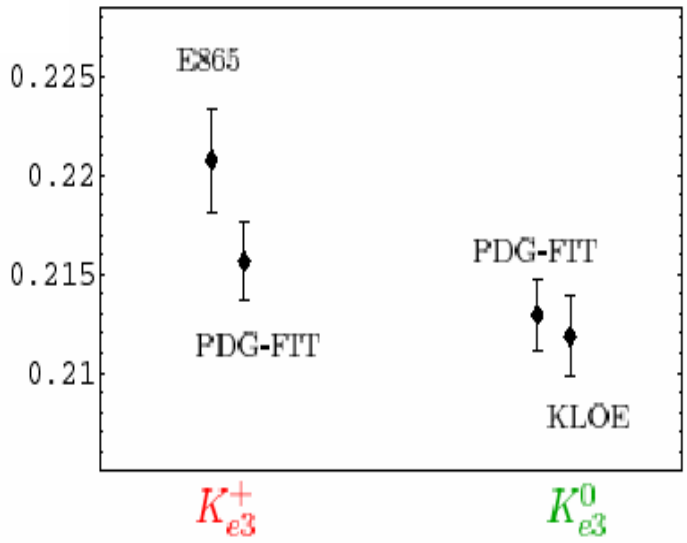
kaon decay

$$K^+ \to \pi^0\, e^+\, \nu_e$$

V_{us}



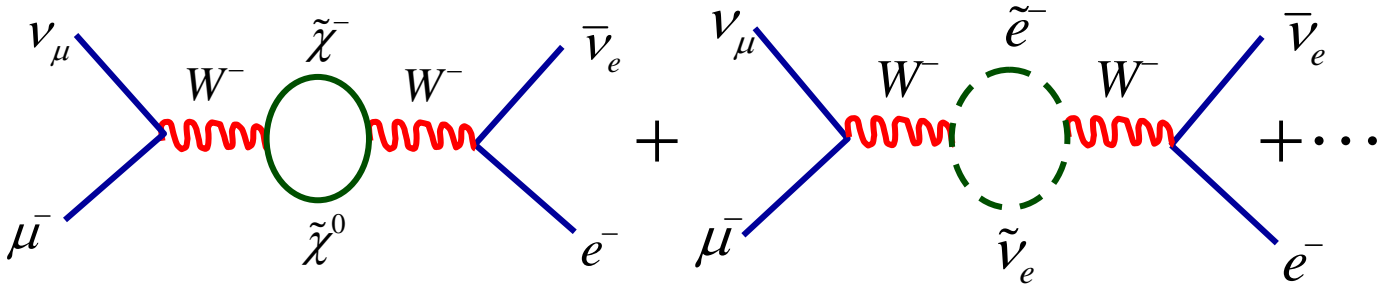
$|V_{us}| \cdot f_+^{K^0\pi^-}(0)$



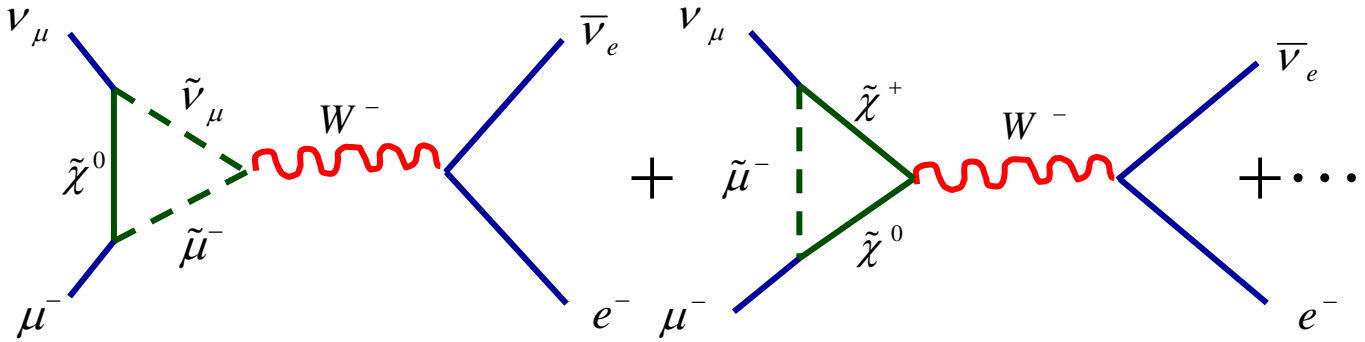
SUSY Radiative Corrections

Δr_μ

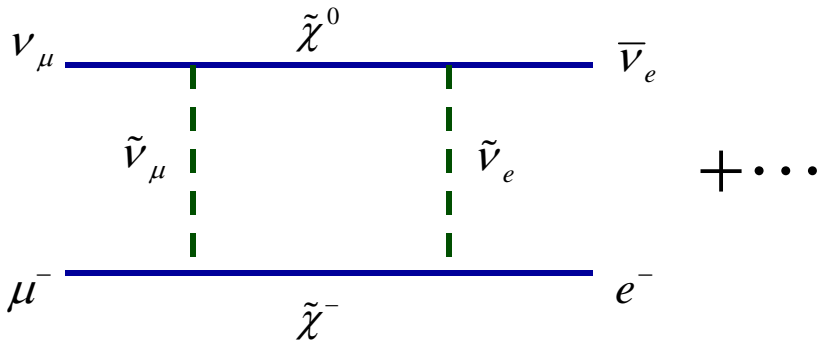
Propagator



Vertex & External leg



Box



Other Inputs

1. Muon (g-2): Size of error bar crucial

2. W Mass:

$$G_F^{\mu} = \frac{\pi \alpha M_Z^2}{\sqrt{2} M_W^2 \left(M_Z^2 - M_W^2\right)\left(1 - \Delta r_{\mu}\right)}$$

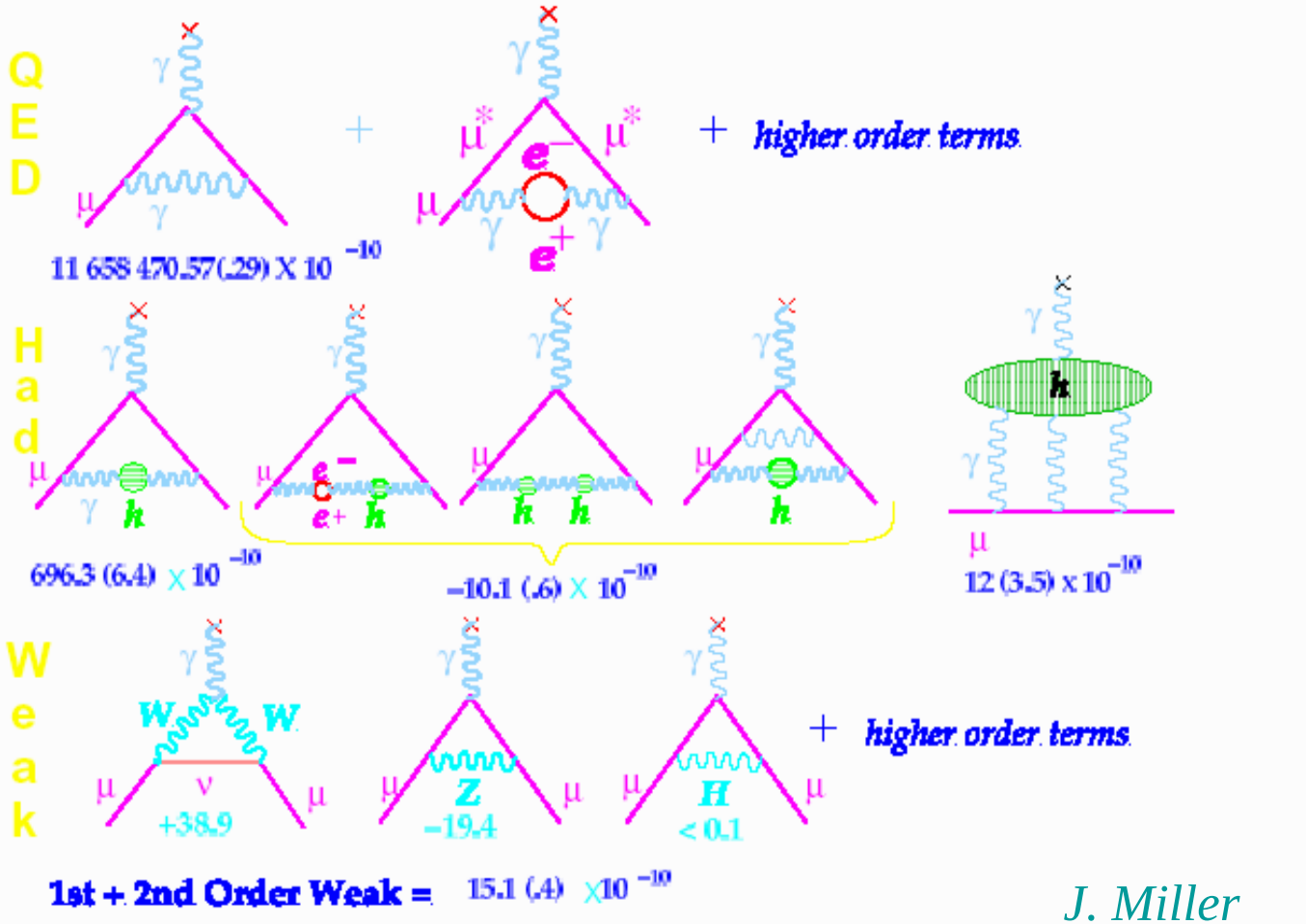
$$-0.0091 \leq \Delta r_{\mu}^{SUSY} \leq 0.003$$

m_t , M_H

3. Superpartner Masses: Start analysis with collider lower bounds and vary later

Muon g-2

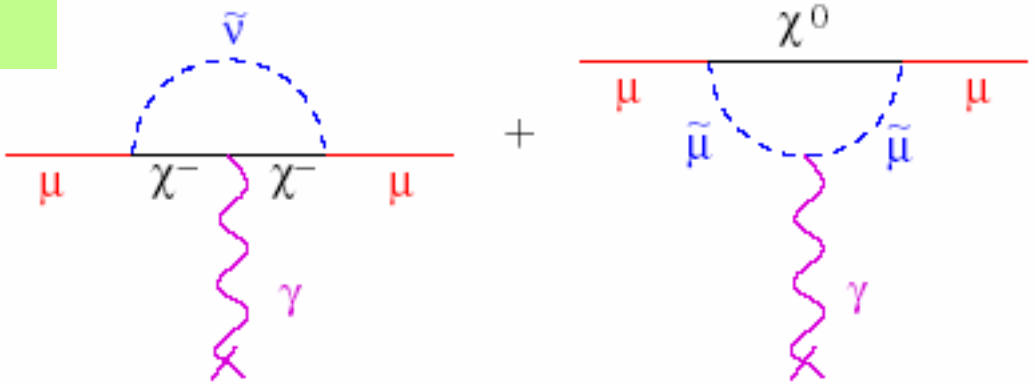
SM Theory



J. Miller

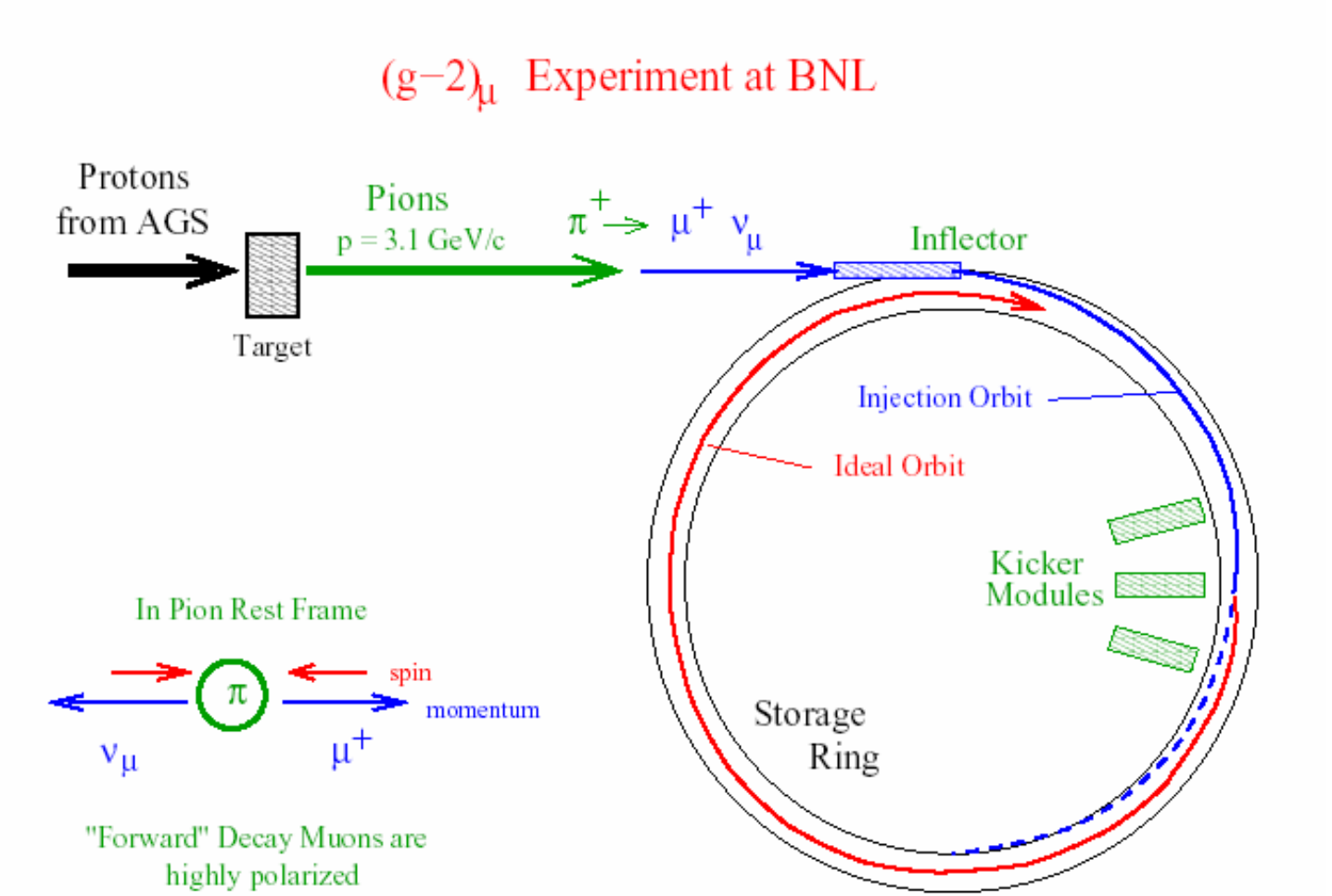
Muon g-2

SUSY

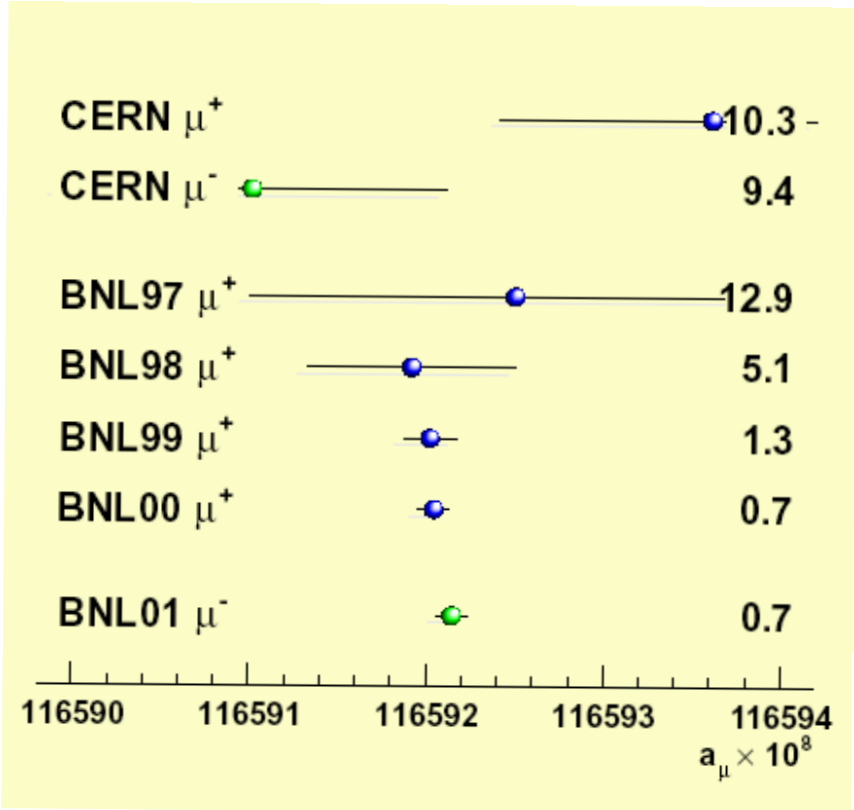


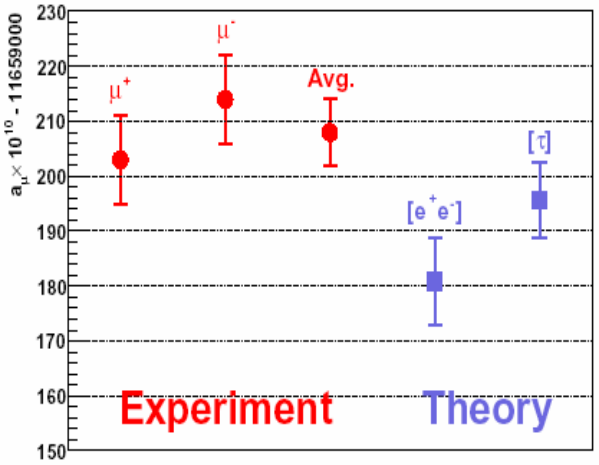
SUSY

Muon g-2


$(g-2)_\mu$ Experiment at BNL
Protons from AGS
Pions
p = 3.1 GeV/c
$\pi^+ \rightarrow \mu^+ \nu_\mu$
Inflector
Target
Injection Orbit
Ideal Orbit
Kicker Modules
Storage Ring
In Pion Rest Frame
spin
momentum
π
ν_μ
μ^+
"Forward" Decay Muons are highly polarized

Muon g-2





$\Delta a_\mu(ee) = (23.9 \pm 9.9) \times 10^{-10}$ 2.4 s.d.

$\Delta a_\mu(\tau) = (7.6 \pm 8.9) \times 10^{-10}$ 0.9 s.d.

W Boson & Top Quark Masses

M_Z=91.1875 +/- 0.0021

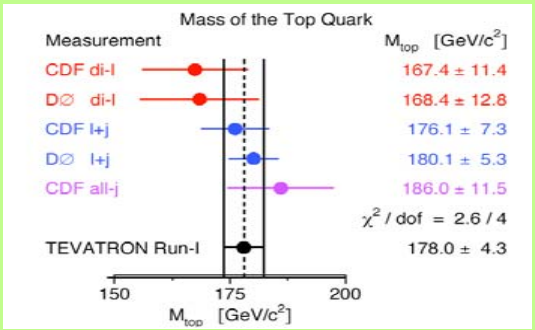
$$G_F^{\mu} = \frac{\pi \alpha M_Z^2}{\sqrt{2} M_W^2 \left(M_Z^2 - M_W^2\right)\left(1 - \Delta r_{\mu}\right)}$$

$m_t \ldots$

Most precisely measured

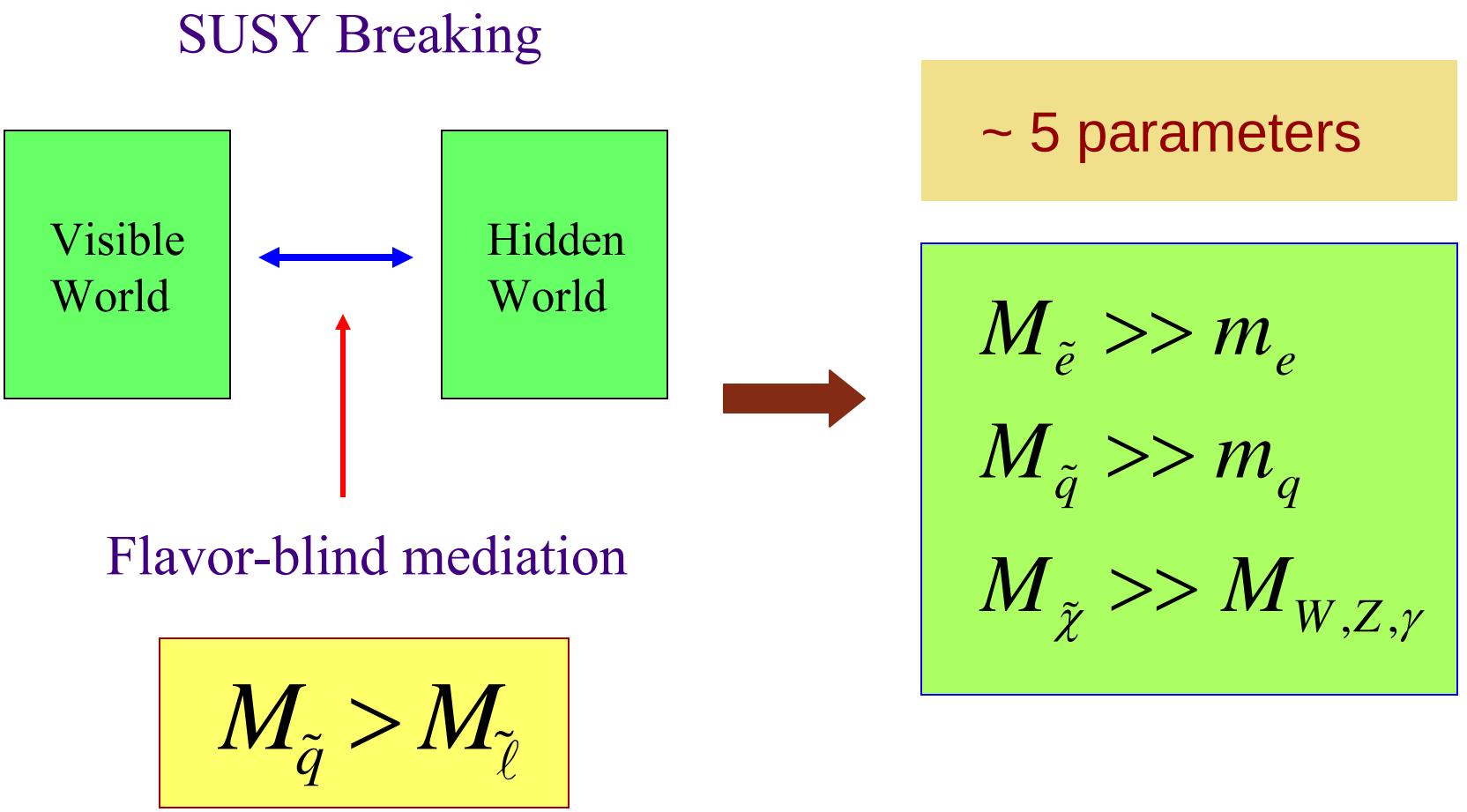
Dominant uncertainties

$$-0.0091 \leq \Delta r_{\mu}^{SUSY} \leq 0.0003$$



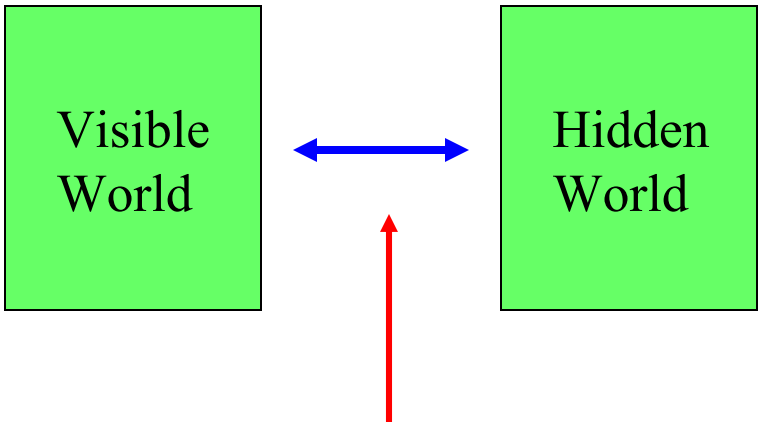
M_t=178.0 +/- 2.7 +/- 3.3

SUSY theory must explain why no SUSY particles yet seen



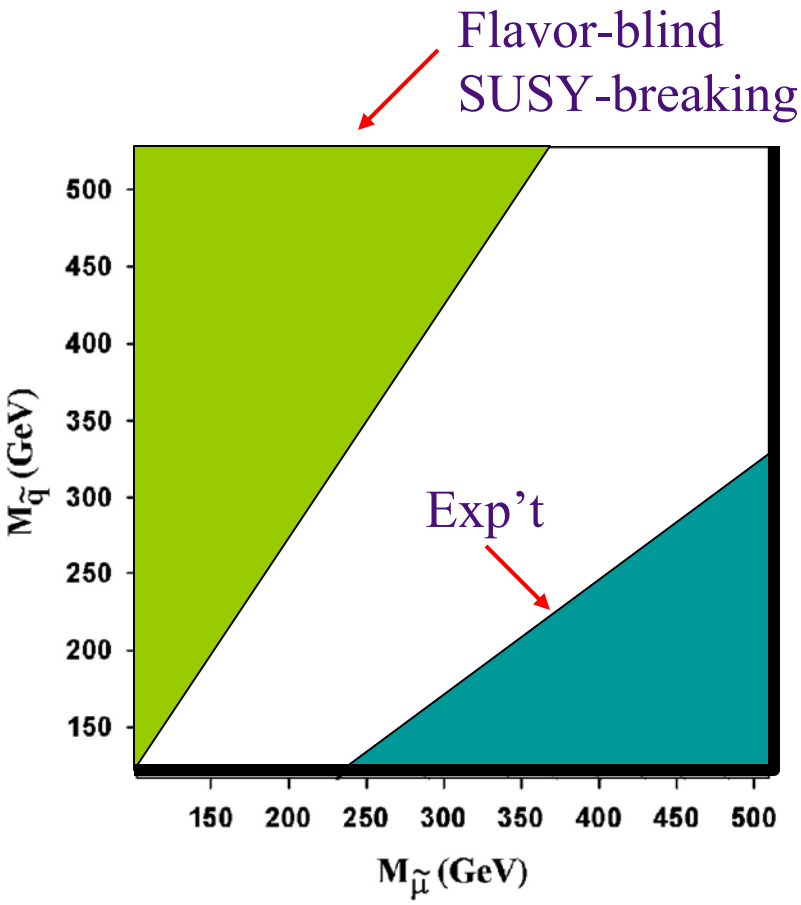
SUSY Theory clashes with Experiment

SUSY Breaking



Flavor-blind mediation

$$M_{\tilde{q}} > M_{\tilde{\ell}}$$



$$M_{\tilde{\mu}L} > M_{\tilde{q}L}$$

Kurylov & R-M

CC (non) universality & the MSSM

Data appear to conflict with MSSM & models having flavor-blind SUSY-breaking mediation

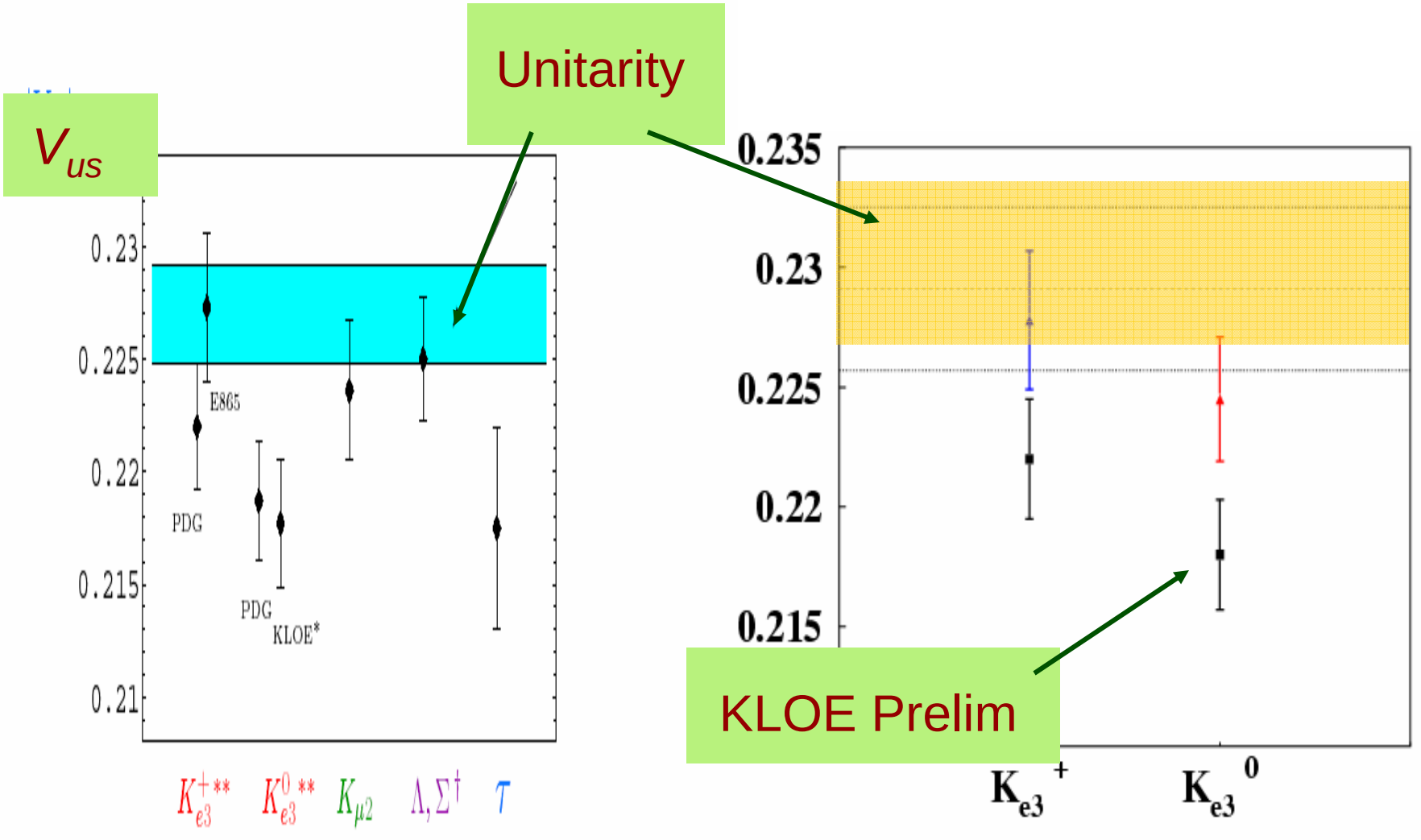
Possible resolutions:

1. $M_{SUSY} > TeV$ — New ideas needed !
2. Hadronic effects in SM predictions — Better control of non-pQCD
3. Something is wrong with exp't — Exp't: n β–decay, K_{e3} decay
4. New models of SUSY-breaking — ???
5. Go beyond the MSSM — Break R-parity — But NuTeV

LANSCE, NIST, SNS…

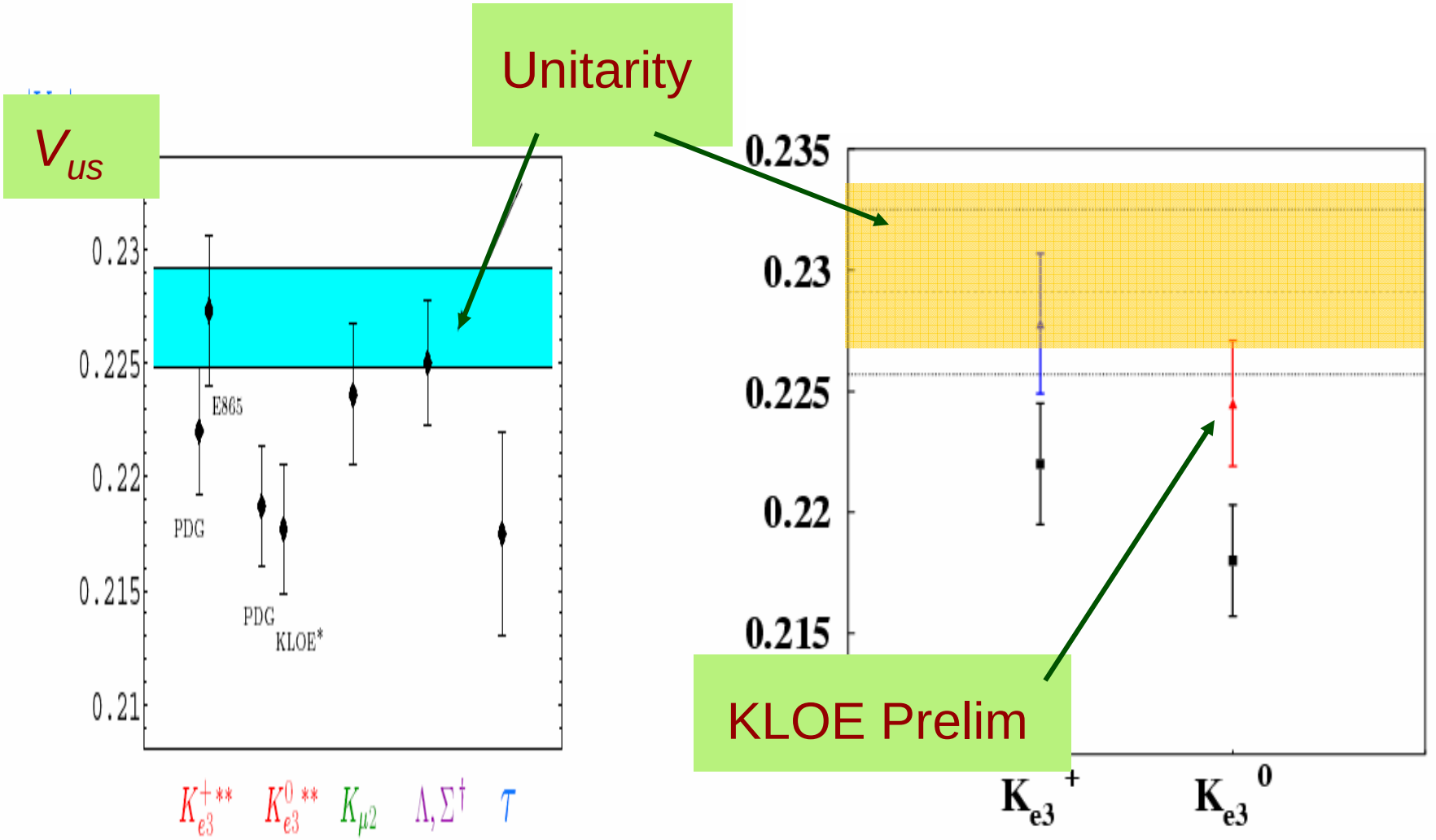
SUSY irrelevant to low energy observables

Kaon Decays & V_{us}



Cirigliano & De Lucia

Kaon Decays & V_{us}



CC (non) universality & the MSSM

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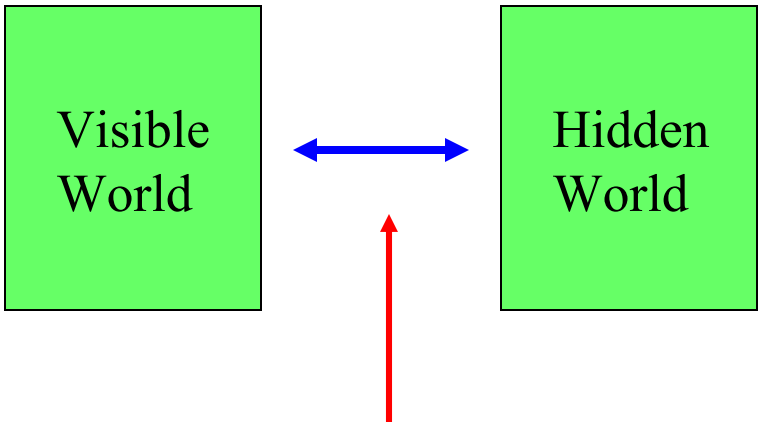
SUSY Theory OK if no SUSY dark matter

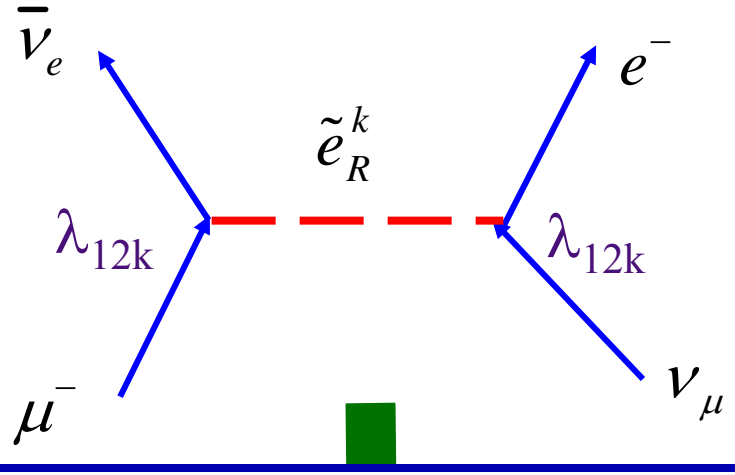
SUSY Breaking

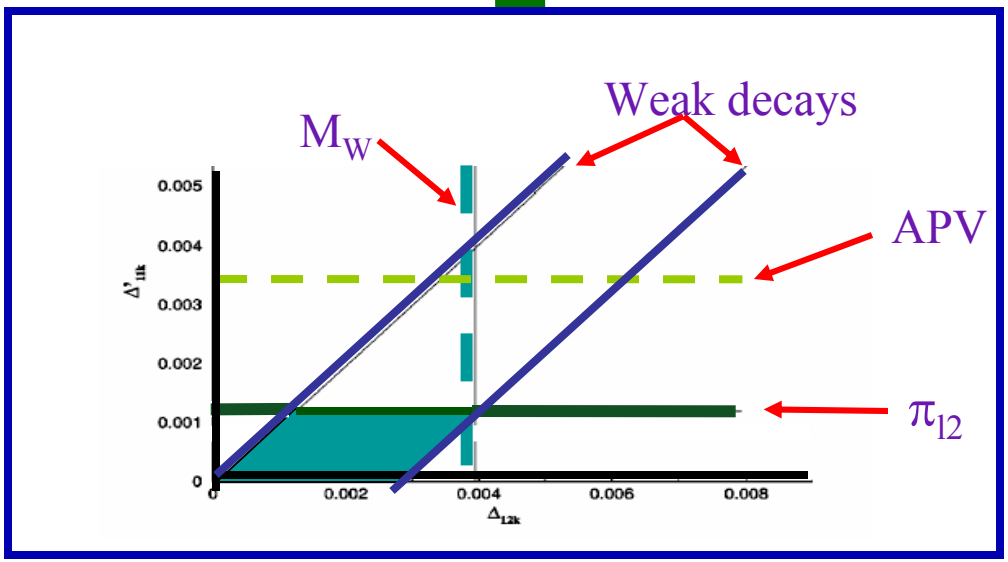


Flavor-blind mediation

$$\chi^0 \not\rightarrow e^- \mu^+ \bar{\nu}_e$$

"R parity violation" (RPV)





R-Parity Violation (RPV)

$\Delta L=1$

$$W_{RPV} = \lambda_{ijk}\, L^i L^j E^k + \lambda'_{ijk}\, L^i Q^j D^k + \mu'_i\, L^i H_u$$

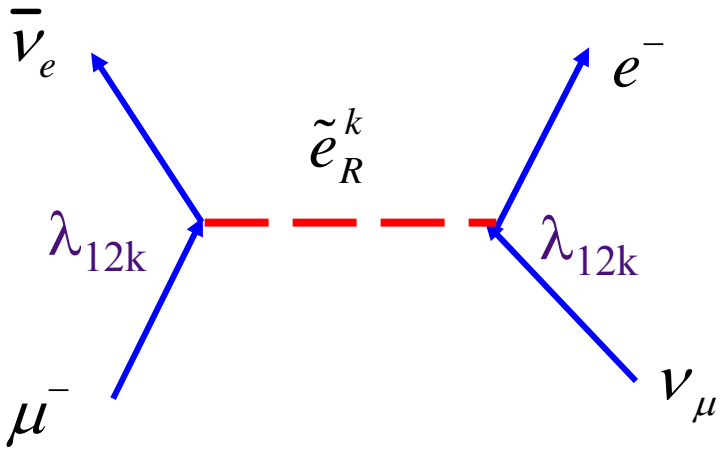
$$+ \lambda''_{ijk} U^i D^j D^k$$

$\Delta B=1$ proton decay:
Set $\lambda''_{ijk} = 0$

L^i, Q^i $SU(2)_L$ doublets

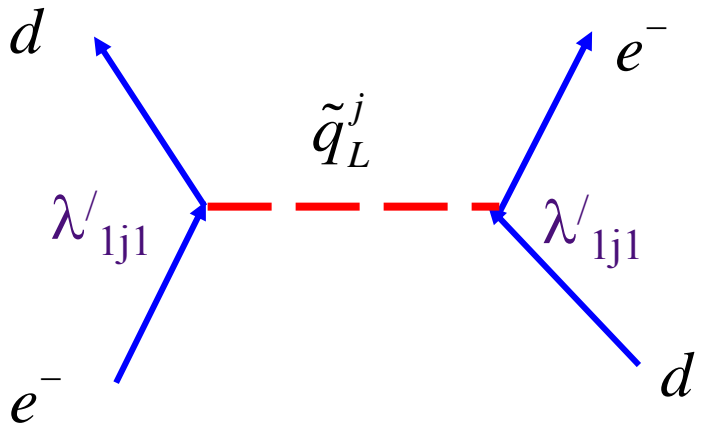
E^i, U^i, D^i $SU(2)_L$ singlets

Four-fermion Operators



$\Delta L=1$

$$\Delta_{12k} = \frac{|\lambda_{12k}|^2}{4\sqrt{2}G_F M^2_{\tilde{e}_R^k}}$$



$\Delta L=1$

$$\Delta'_{1j1} = \frac{|\lambda'_{iji}|^2}{4\sqrt{2}G_F M^2_{\tilde{q}_L^j}}$$