Low Energy Precision Tests of Supersymmetry

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M.R-M & S. Su, hep-ph/0612057

J. Erler & M.R-M, PPNP 54, 351 (2005)

Outline

I. *Motivation: Why New Symmetries ?*
Why Low Energy Probes ?

II. Prime Suspect: Supersymmetry

III. Low Energy Precision Tests

- *Weak Decays*
- *PVES*

I. Motivation

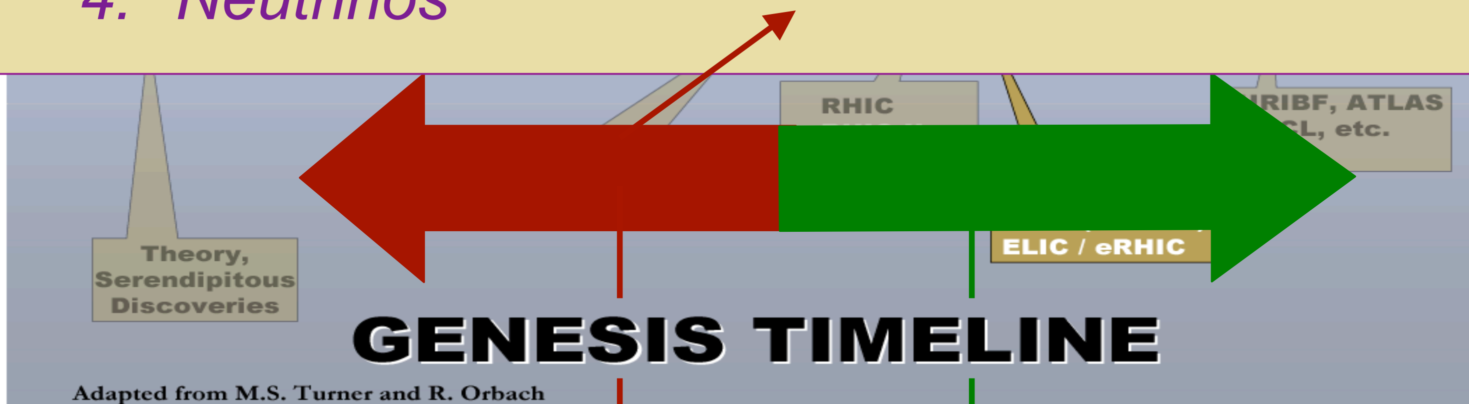
Why New Symmetries ?
Why Low Energy Probes ?

Fundamental Symmetries & Cosmic History

Puzzles the Standard Model can't solve

1. *Origin of matter*
2. *Unification & gravity*
3. *Weak scale stability*
4. *Neutrinos*

What are the symmetries (forces) of the early universe beyond those of the SM?



Beyond the SM

SM symmetry (broken)

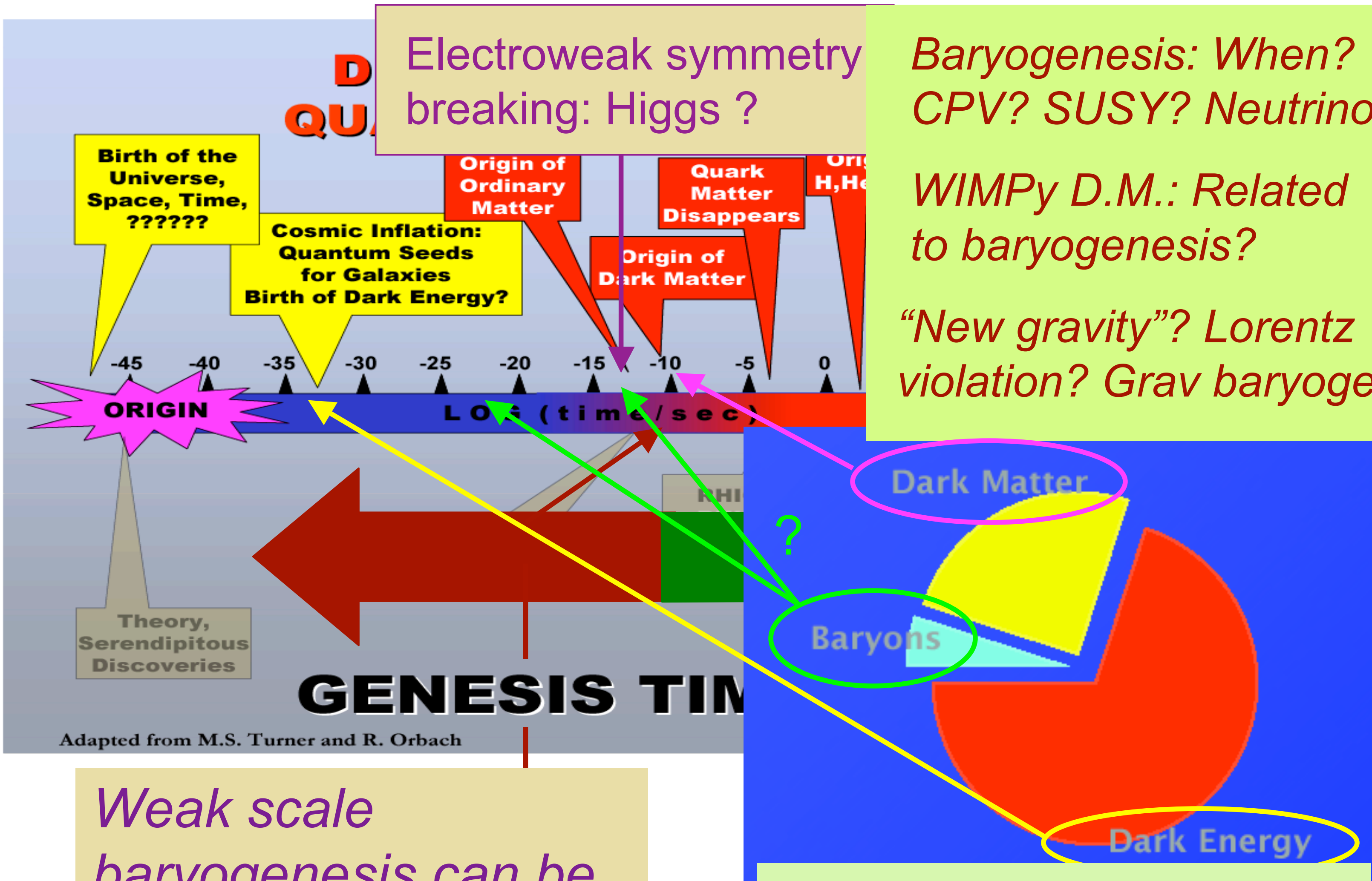
Fundamental Symmetries & Cosmic History

Electroweak symmetry breaking: Higgs ?

Baryogenesis: When? CPV? SUSY? Neutrinos?

WIMPy D.M.: Related to baryogenesis?

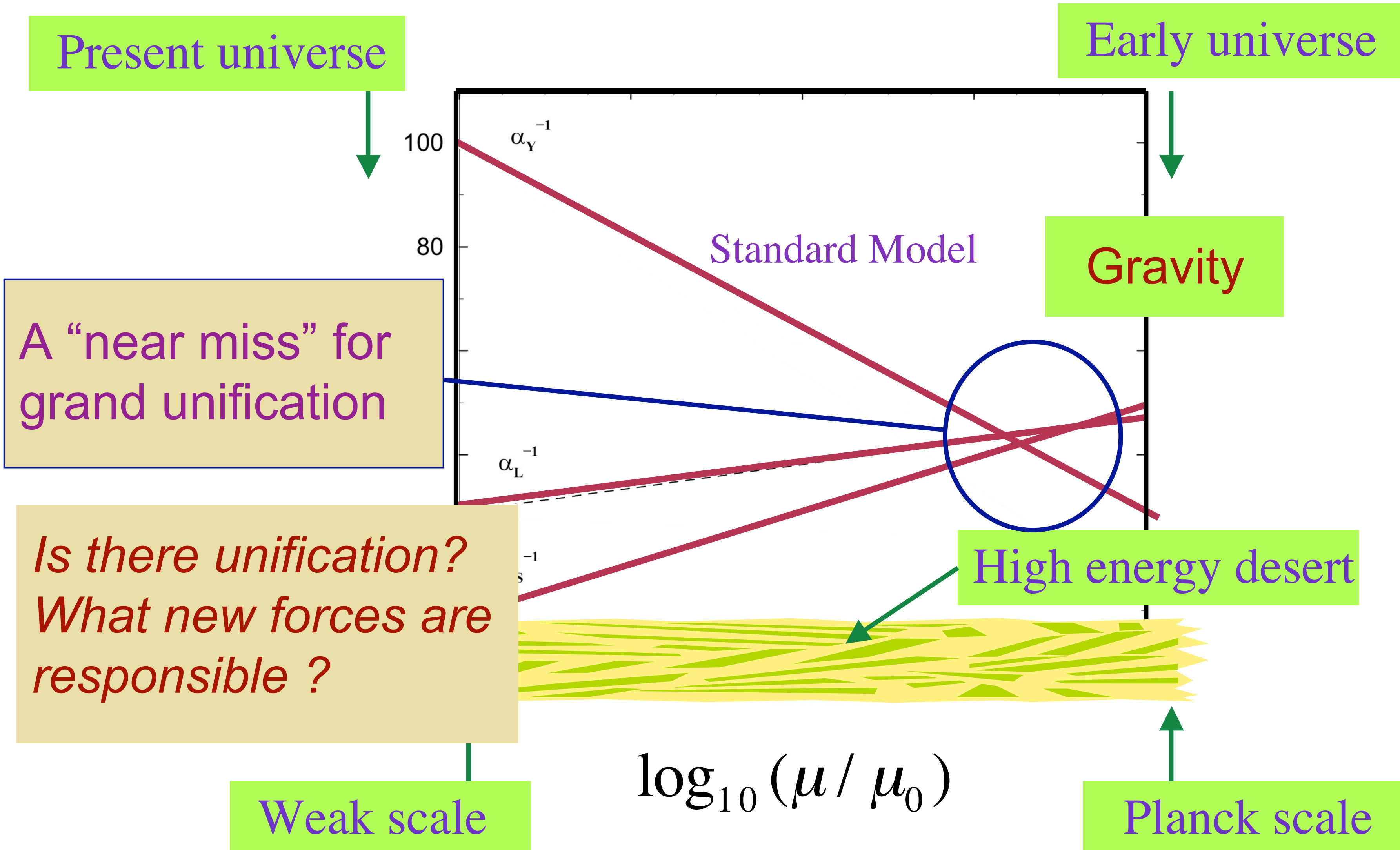
"New gravity"? Lorentz violation? Grav baryogen ?



"Known Unknowns"

Weak scale baryogenesis can be tested experimentally

Fundamental Symmetries & Cosmic History



Fundamental Symmetries & Cosmic History

$G_F \sim 1/M_{WEAK}^2$

Weak Int Rates:

Solar burning

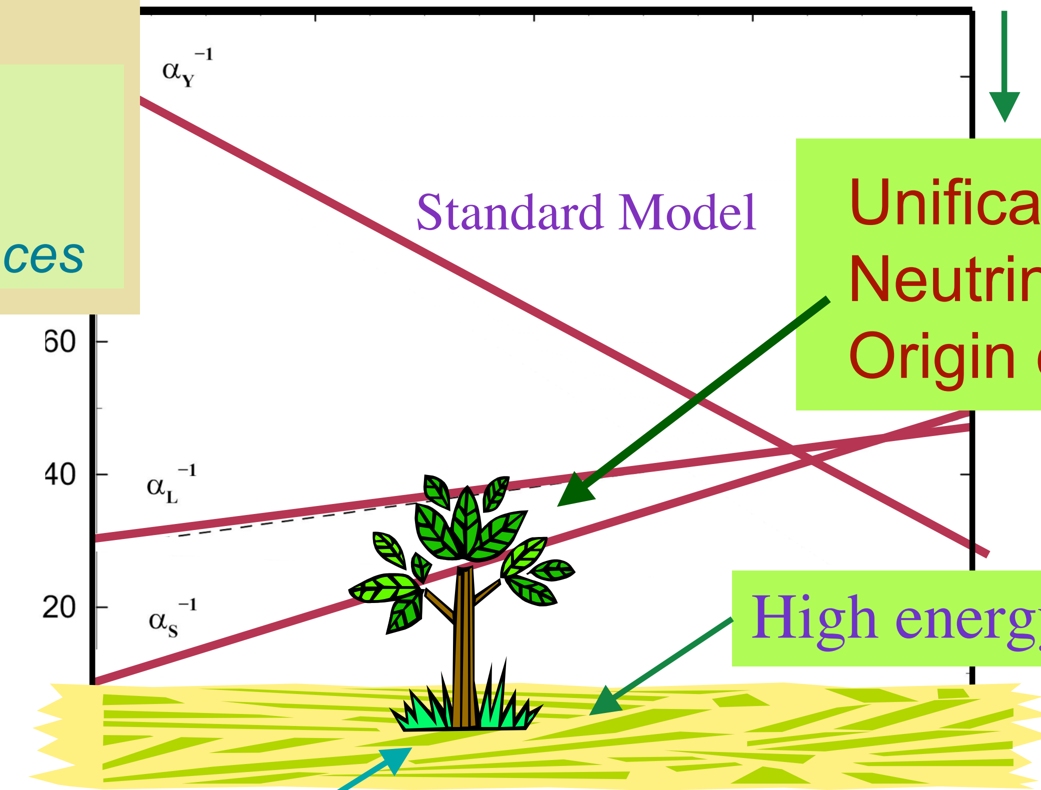
Element abundances

Weak scale unstable:

Why is G_F so large?

Early universe

Unification
Neutrino mass
Origin of matter



High energy desert

$\log_{10}(\mu / \mu_0)$

Weak scale

Planck scale

There must have been additional symmetries in the earlier Universe to

- *Unify all matter, space, & time*
- *Stabilize the weak scale*
- *Produce all the matter that exists*
- *Account for neutrino properties*
- *Give self-consistent quantum gravity*

Supersymmetry, GUT’s, extra dimensions…

What are the new fundamental symmetries?

Two frontiers in the search

Collider experiments (pp, e^+e^-, etc) at higher energies ($E \gg M_Z$)

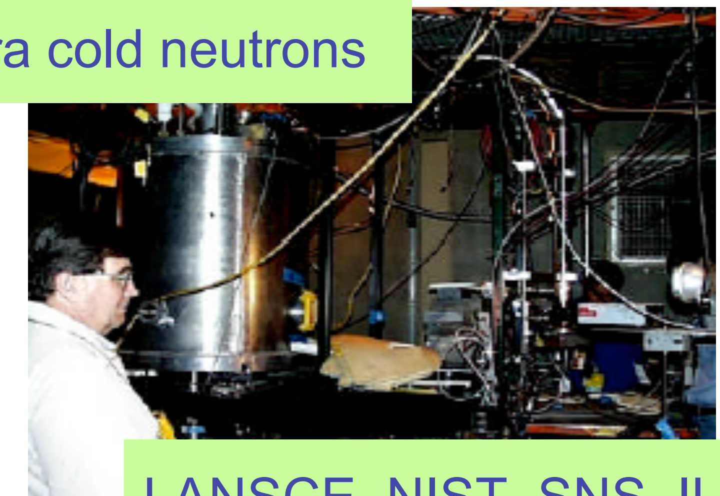
Large Hadron Collider

CERN

High energy physics

Indirect searches at lower energies ($E < M_Z$) but high precision

Ultra cold neutrons



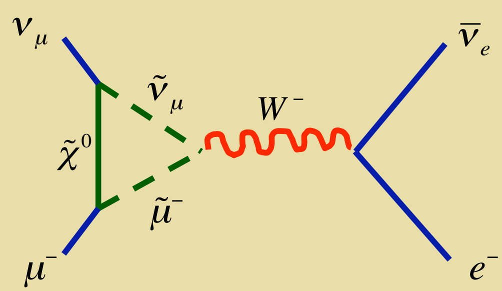
LANSCE, NIST, SNS, ILL

Particle, nuclear & atomic physics

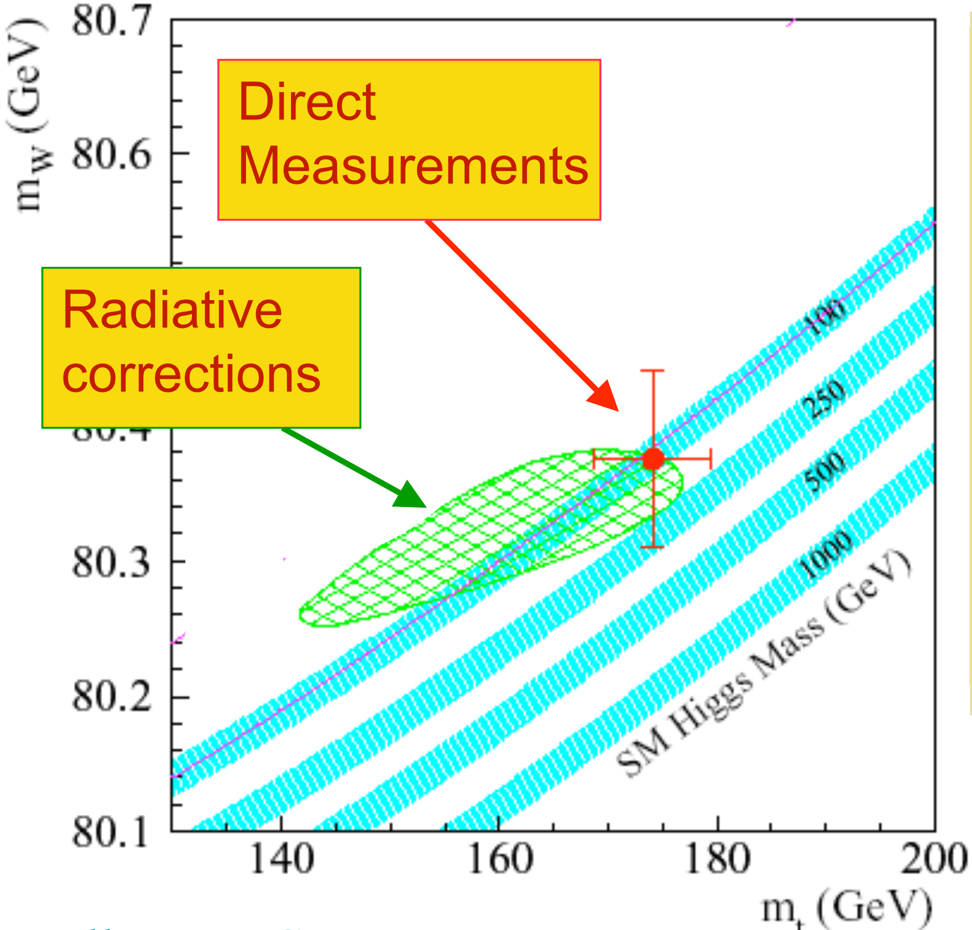
Precision Probes of New Symmetries

New Symmetries

1. *Origin of Matter*
2. *Unification & gravity*
3. *Weak scale stability*
4. *Neutrinos*



Precision Probes of New Symmetries



J. Ellison, UCI

Probing Fundamental Symmetries beyond the SM:

Use precision low-energy measurements to probe virtual effects of new symmetries & compare with collider results

Stunning SM Success

Precision, low energy measurements can probe for new symmetries in the desert

Precision ~ Mass Scale

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

$M=m_\mu$ $\delta \sim 2 \text{ x } 10^{-9}$

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

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

Interpretability

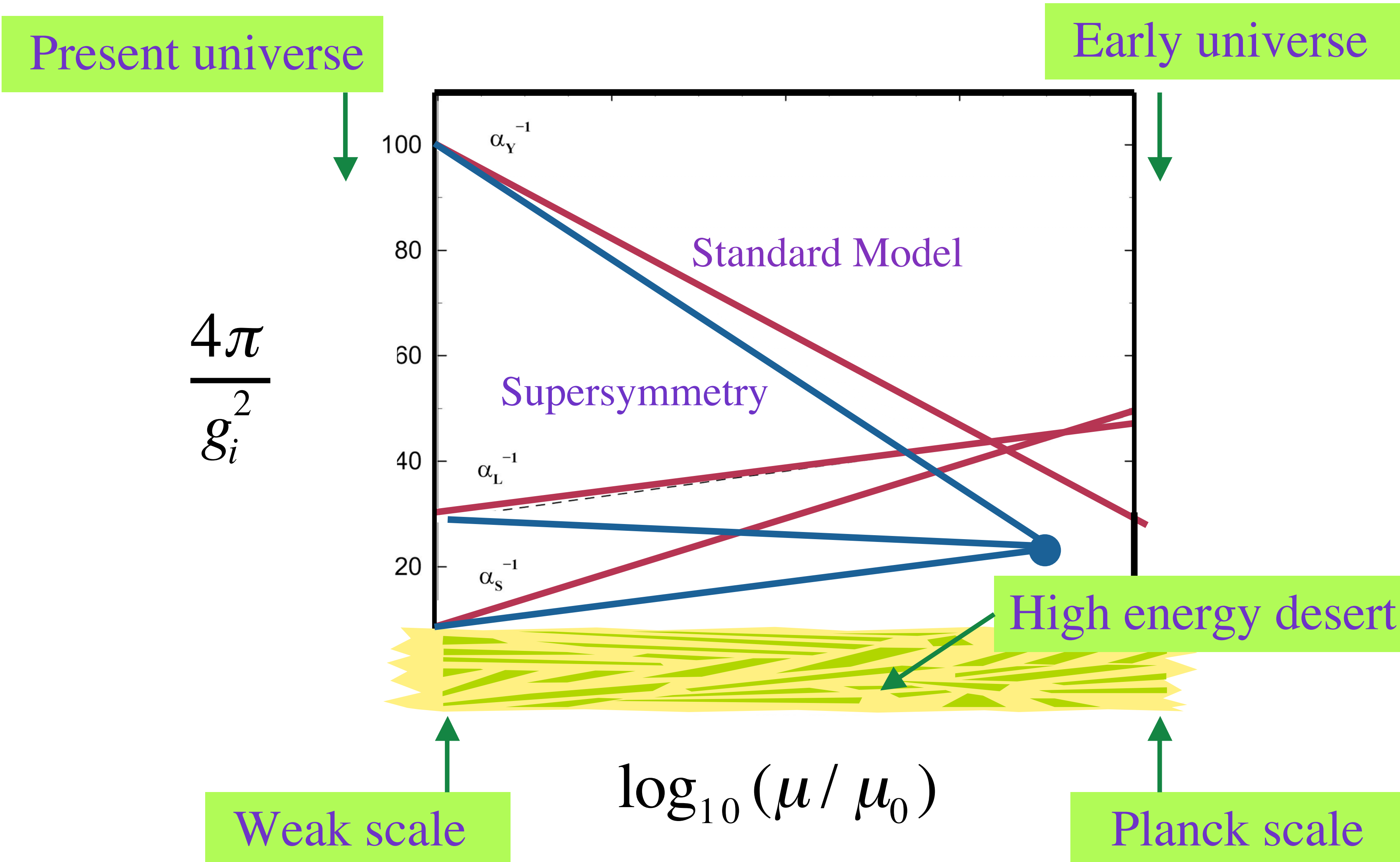
- *Precise, reliable SM predictions*
- *Comparison of a variety of observables*
- *Special cases: SM-forbidden or suppressed processes*

II. Prime suspect: Supersymmetry

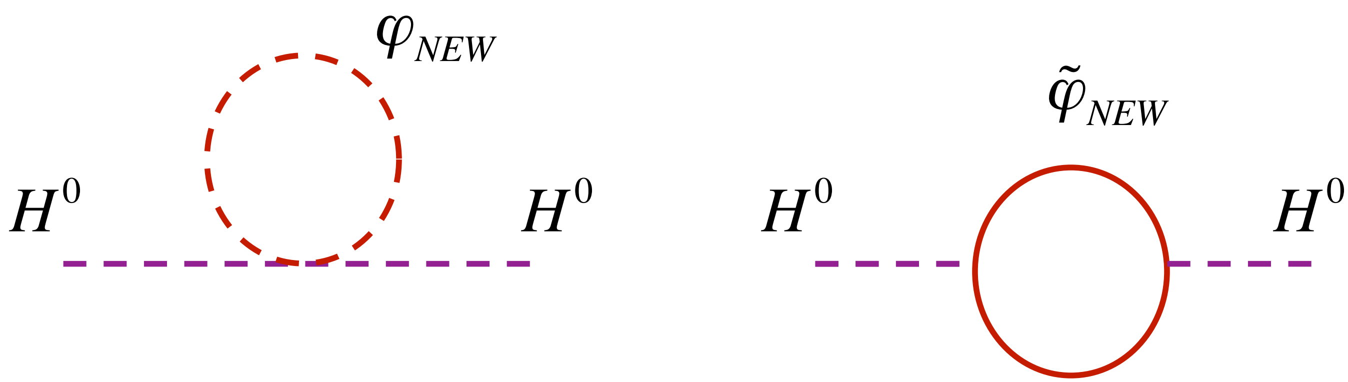
SUSY: a candidate symmetry of the early Universe

• ***Unify all forces***	*3 of 4*
• ***Protect G_F from shrinking***	*Yes*
• ***Produce all the matter that exists***	*Maybe so*
• ***Account for neutrino properties***	*Maybe*
• ***Give self-consistent quantum gravity***	*Probably necessary*

Couplings unify with SUSY



SUSY protects G_F from shrinking



$$\Delta M^2_{WEAK} \sim M^2_{\varphi} - M^2_{\tilde{\varphi}} + \log terms$$

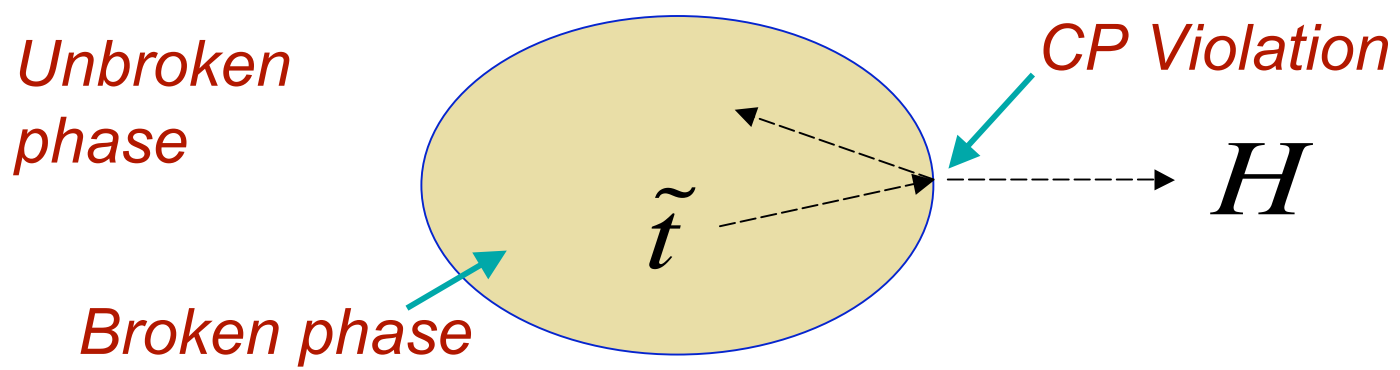
=0 if SUSY is exact

SUSY may help explain observed abundance of matter

Cold Dark Matter Candidate

χ^0 Lightest SUSY particle

Baryonic matter: electroweak phase transition



SUSY: a candidate symmetry of the early Universe

Supersymmetry

Fermions	Bosons
$e_{L,R}\,,\; q_{L,R}$	
	$W, Z, \gamma\,, g$
	H

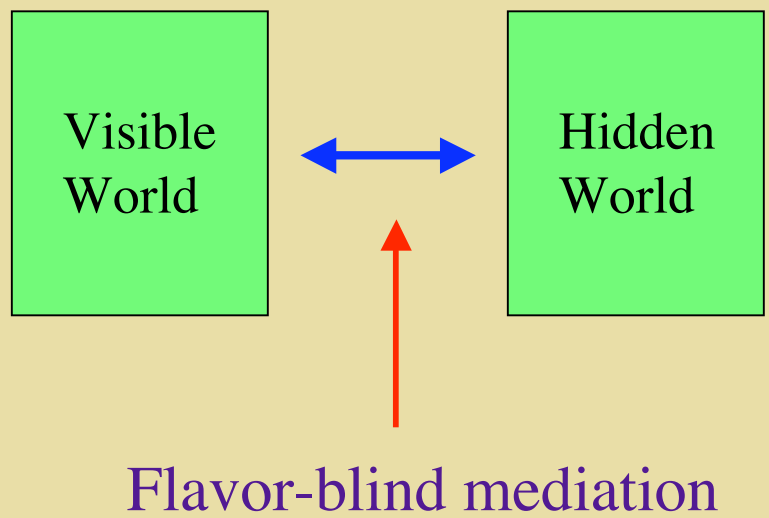
105 new parameters: masses, mixing angles, CPV phases (40)

$$
\begin{aligned}
\mathcal{L}_{\rm soft} = & -\frac{1}{2}\left(M_3 \tilde{g}\tilde{g} + M_2 \tilde{W}\tilde{W} + M_1 \tilde{B}\tilde{B}\right) + c.c. \\
& -\left(\bar{\tilde{u}}\,\mathbf{a_u}\tilde{Q}H_u - \bar{\tilde{d}}\,\mathbf{a_d}\tilde{Q}H_d - \bar{\tilde{e}}\,\mathbf{a_e}\tilde{L}H_d\right) + c.c. \\
& -\tilde{Q}^\dagger \mathbf{m_Q^2}\tilde{Q} - \tilde{L}^\dagger \mathbf{m_L^2}\tilde{L} - \bar{\tilde{u}}\,\mathbf{m_u^2}\bar{\tilde{u}}^\dagger - \bar{\tilde{d}}\,\mathbf{m_d^2}\bar{\tilde{d}}^\dagger - \bar{\tilde{e}}\,\mathbf{m_e^2}\bar{\tilde{e}}^\dagger - m_{H_u}^2 H_u^* H_u - m_{H_d}^2 H_d^* H_d \\
& -\left(b H_u H_d + c.c.\right)
\end{aligned}
\qquad (16)
$$

Models: relate weak scale parameters to each other at high scales ("hidden sector")

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

$$M_{\tilde{\chi}} >> M_{W,Z,\gamma}$$



How is SUSY broken?

SUSY and R Parity

$$P_R = (-1)^{3(B-L)}(-1)^{2S}$$

If nature conserves P_R → vertices have even number of superpartners

Consequences

- Lightest SUSY particle $\left(\tilde{\chi}^0\right)$ is stable → viable dark matter candidate
- Proton is stable
- Superpartners appear only in loops

R-Parity Violation (RPV)

$\Delta L=1$

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

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

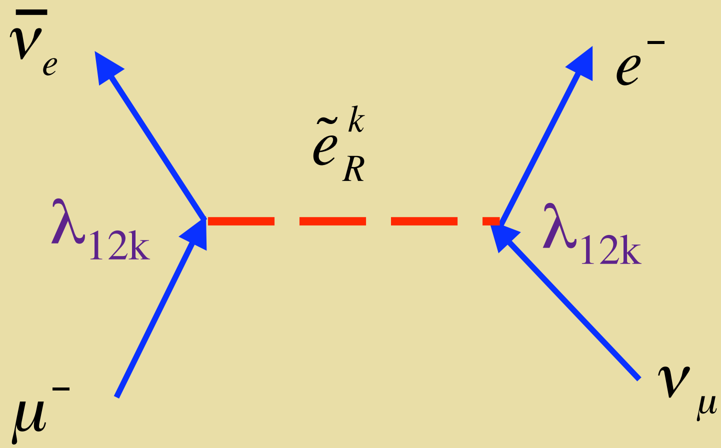
$\Delta B=1$

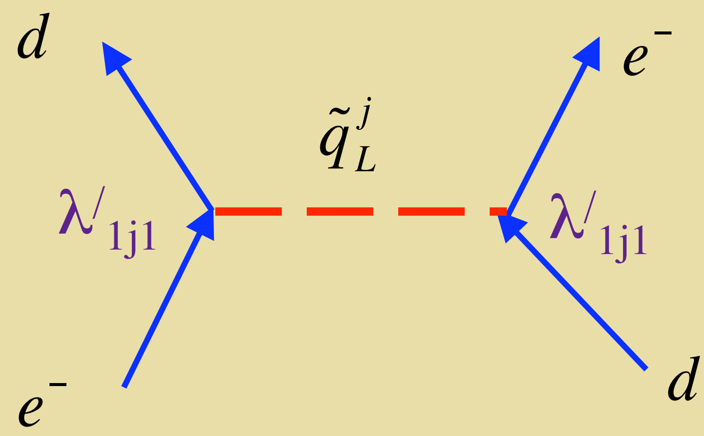
proton decay:
Set $\lambda''_{ijk} = 0$

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

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

RPV : Four-fermion Operators





ΔL=1

ΔL=1

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

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

III. SUSY & Weak Decays

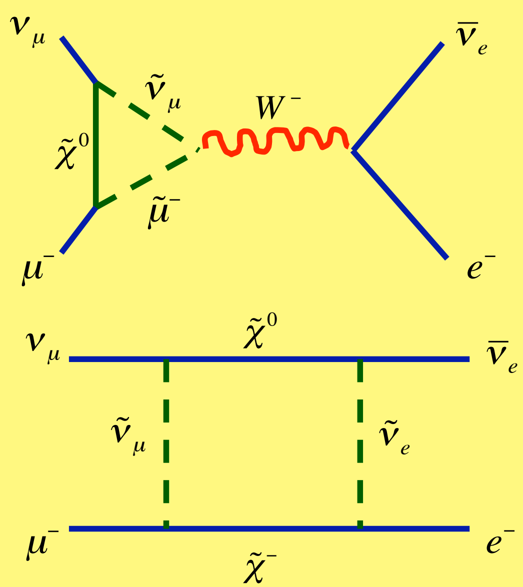
Weak Decays & SUSY

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

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

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

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



$$\frac{\delta O^{SUSY}}{O^{SM}} \sim 0.001$$

$+ \cdots$

SUSY

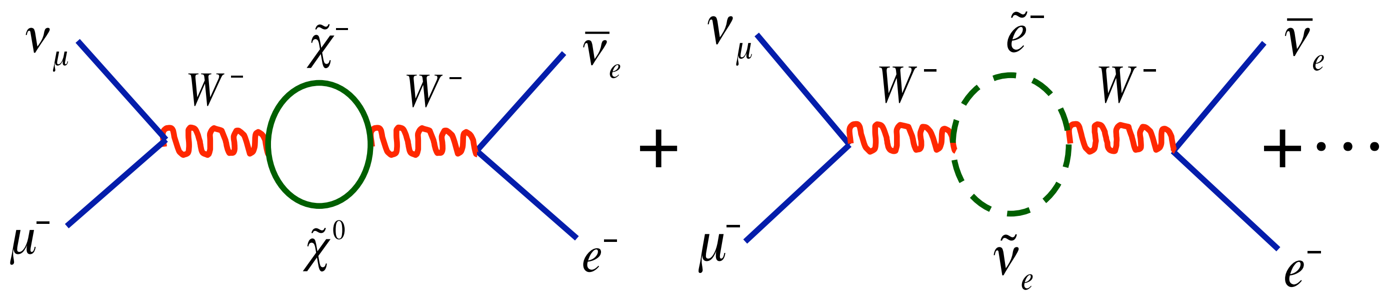
$$\frac{G_F^\beta}{G_F^\mu} = |V_{ud}|\left(1 + \Delta r_\beta - \Delta r_\mu\right)$$

New physics

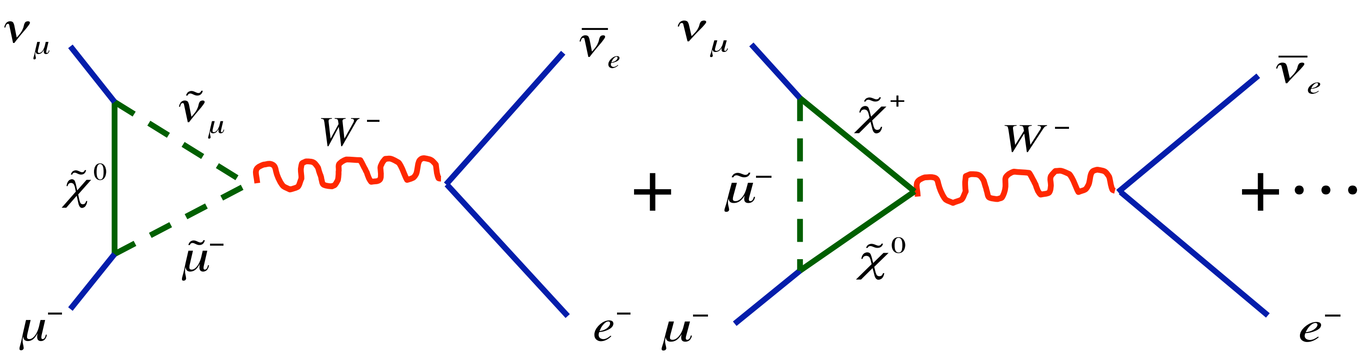
SUSY Radiative Corrections

Δr_μ

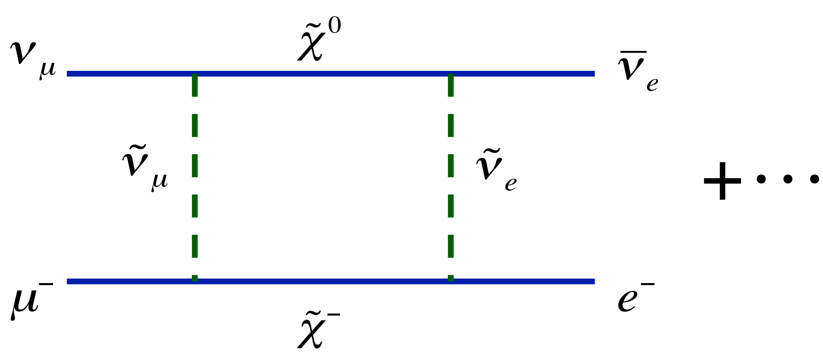
Propagator



Vertex &
External leg



Box

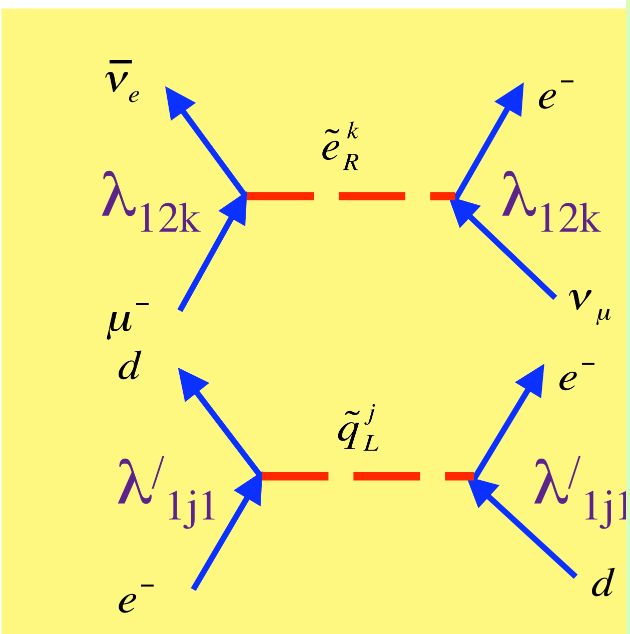


Weak Decays & SUSY

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

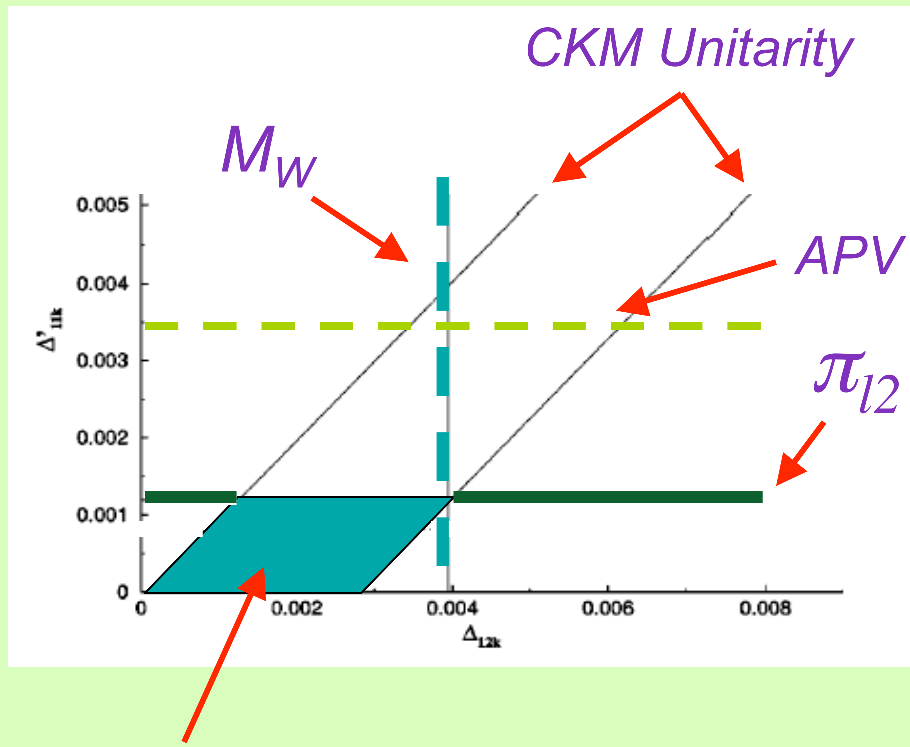
$s \rightarrow u\, e^- \,\bar{\nu}_e$

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



R Parity Violation

Kurylov, R-M, Su



No long-lived LSP or SUSY DM

Weak decays

$$d\Gamma(K^+_{\ell 3}) = \frac{G_\mu^2 m_K^5}{128\pi^3} S_{\rm EW} C(t) |V_{us}|^2 |f_+^K(0)|^2 \left[1 + \frac{\lambda_+^K t}{m_\pi^2}\right]^2 \left[1 + 2\Delta^K_{SU(2)} + 2\Delta^{K\ell}_{EM}\right]$$

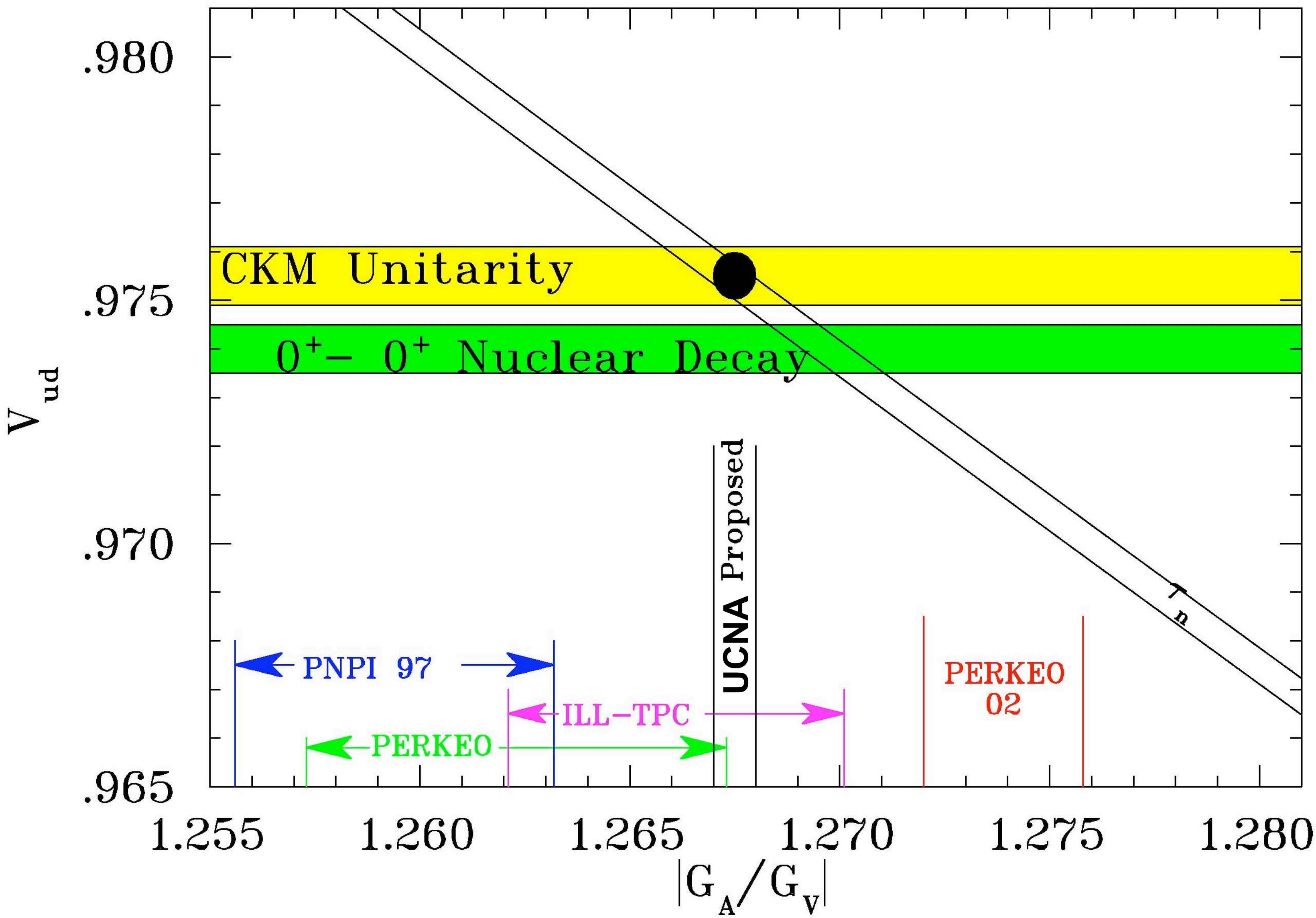
$$f_+^K(0)_{\rm lattice} = \begin{cases} 0.960 \pm 0.005_{\rm stat} \pm 0.007_{\rm sys} & \text{quenched, Wilson[119]} \\ 0.962(6)(9) & \text{unquenched, staggered[120]} \\ 0.952(6) & \text{unquenched, Wilson[121]} \\ 0.955(12) & \text{unquenched, doman wall[122]} \end{cases}$$

$$f_+^K(0)_{{\rm large}\, N_C} = 0.984 \pm 0.012$$

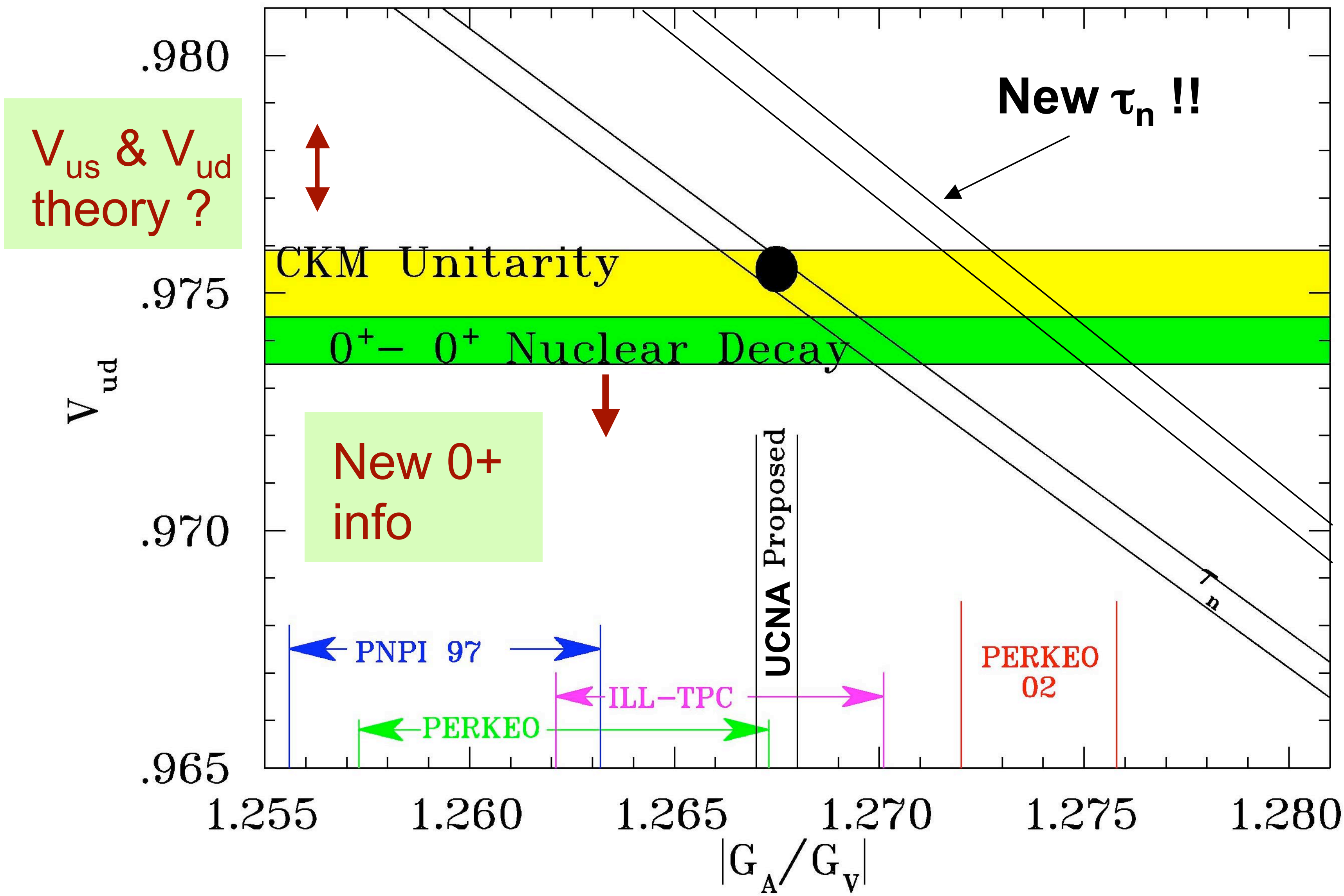
Value of V_{us} important

Situation Unsettled

CKM Summary: PDG04



CKM Summary: New V_{us} & τ_n ?

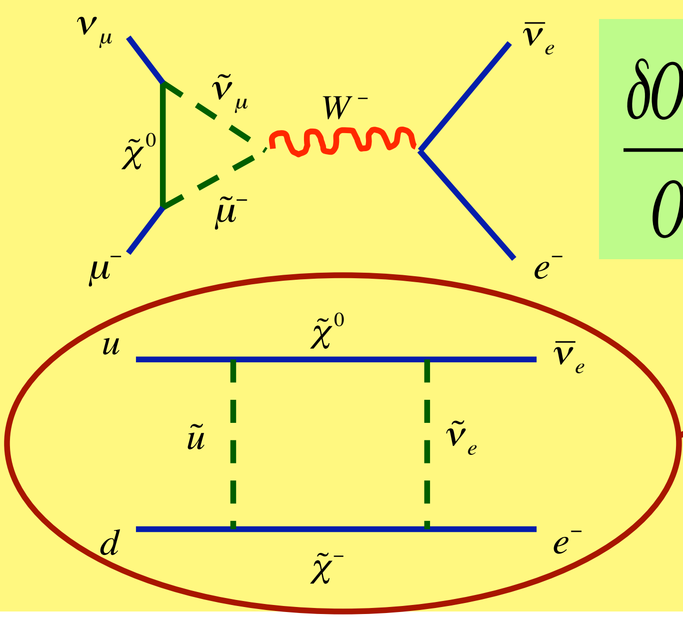


Weak decays & new physics

Correlations

$$d \rightarrow u\, e^- \, \bar{\nu}_e$$
$$s \rightarrow u\, e^- \, \bar{\nu}_e$$
$$b \rightarrow u\, e^- \, \bar{\nu}_e$$

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



$+\cdots$

SUSY

$$\frac{\delta O^{SUSY}}{O^{SM}} \sim 0.001$$

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

Non (V-A) x (V-A) interactions: m_e/E

β-decay at SNS, RIACINO?

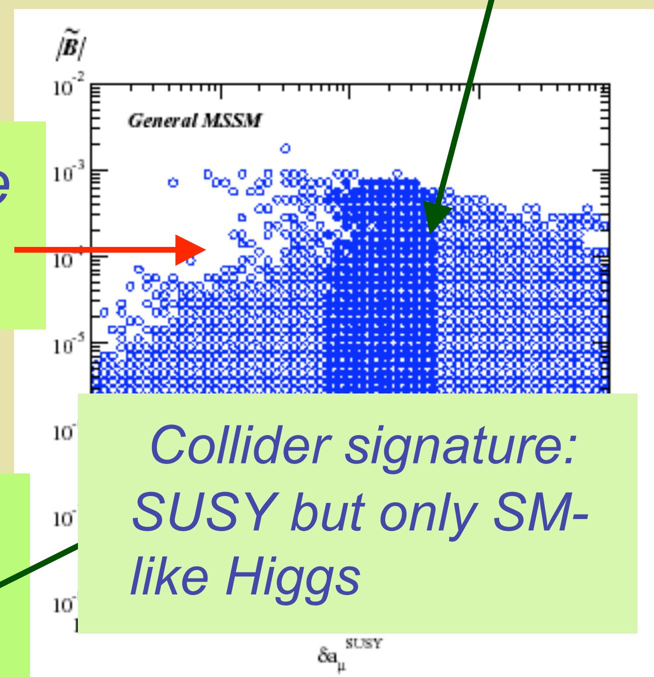
Weak decays & SUSY : Correlations

Chiral symmetry breaking in SUSY

Is χSB / m_f as in SM ?

$\vec{J} \cdot \vec{p}_\nu$

Large χ symmetry breaking: New SUSY models



Future exp't ?

Collider signature: SUSY but only SM-like Higgs

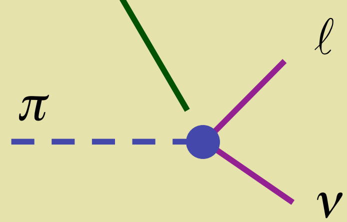
Mass suppressed χ symmetry breaking: "alignment" models

Profumo, R-M, Tulin

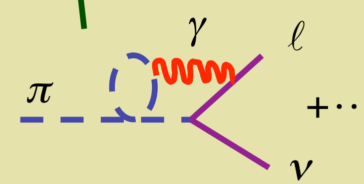
Pion leptonic decay & SUSY

$$\Gamma[\pi^- \to \ell^- \bar{\nu}_\ell(\gamma)] = \frac{G_\mu^2|V_{ud}|^2}{4\pi} F_\pi^2 m_\pi m_\ell^2 \left[1 - \frac{m_\ell^2}{m_\pi^2}\right]$$

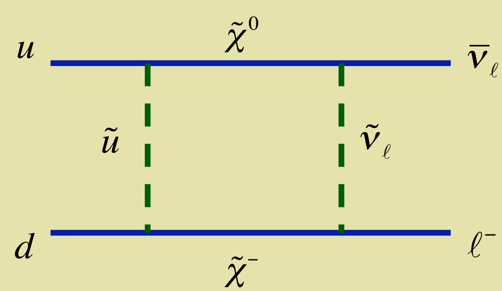
SM strong interaction effects: parameterized by F_π Hard to compute



SM radiative corrections also have QCD effects



To probe effects of new physics in Δ_{NEW} we need to contend with QCD



Pion leptonic decay & SUSY

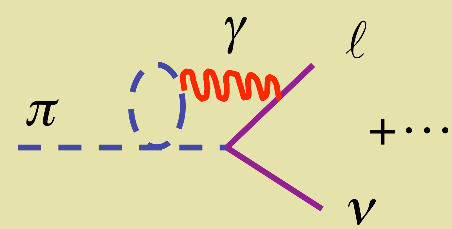
New TRIUMF, PSI

$$R_{e/\mu} = \frac{\Gamma[\pi^- \to e^-\bar{\nu}_e(\gamma)]}{\Gamma[\pi^- \to \mu^-\bar{\nu}_\mu(\gamma)]} = \frac{m_e^2}{m_\mu^2}\left[\frac{m_\pi^2 - m_e^2}{m_\pi^2 - m_\mu^2}\right]^2 \left\{1 + \frac{\alpha}{\pi}\left[F\left(\frac{m_e}{m_\pi}\right) - F\left(\frac{m_\mu}{m_\pi}\right) + C_{QCD}^{e-\mu}(\mu)\right] + \Delta_{NEW}^{e-\mu}\right\}$$

Leading QCD uncertainty:

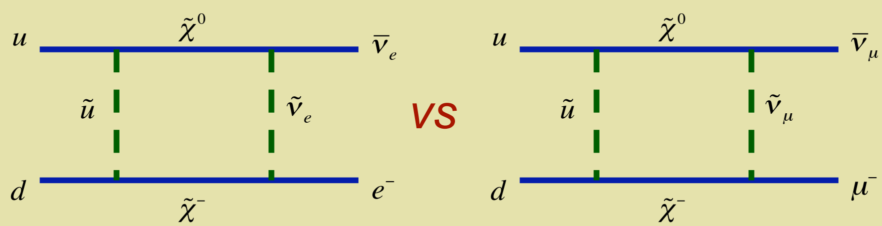
$$\frac{\delta R_{e/\mu}}{R_{e/\mu}^{SM}} \approx 5 \times 10^{-4}$$

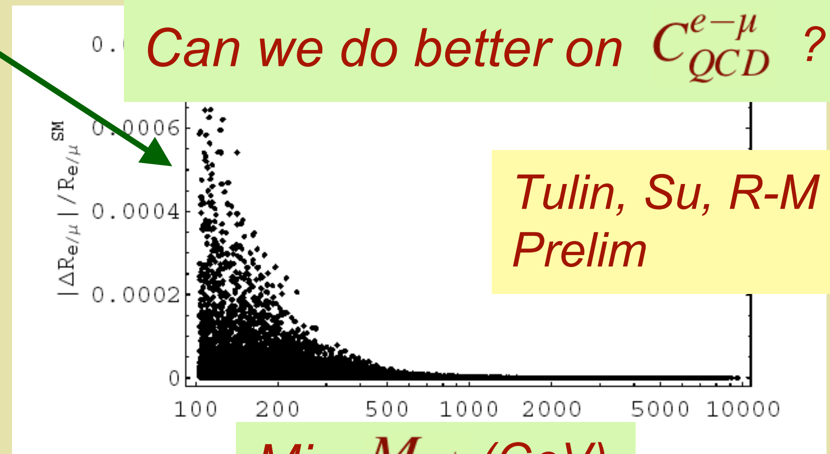
Marciano & Sirlin



Can we do better on $C_{QCD}^{e-\mu}$?

Probing Slepton Universality

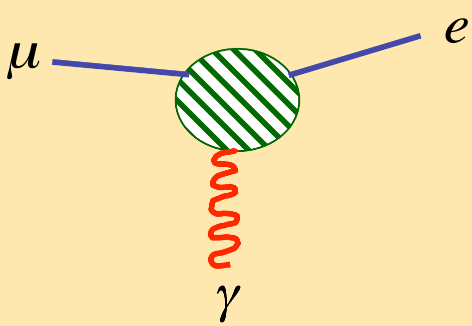




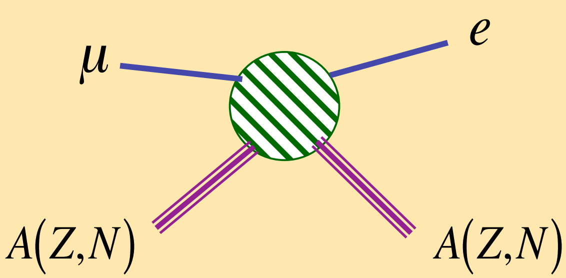
Tulin, Su, R-M
Prelim

Min $M_{\tilde{\chi}^\pm}$ (GeV)

Lepton Flavor & Number Violation

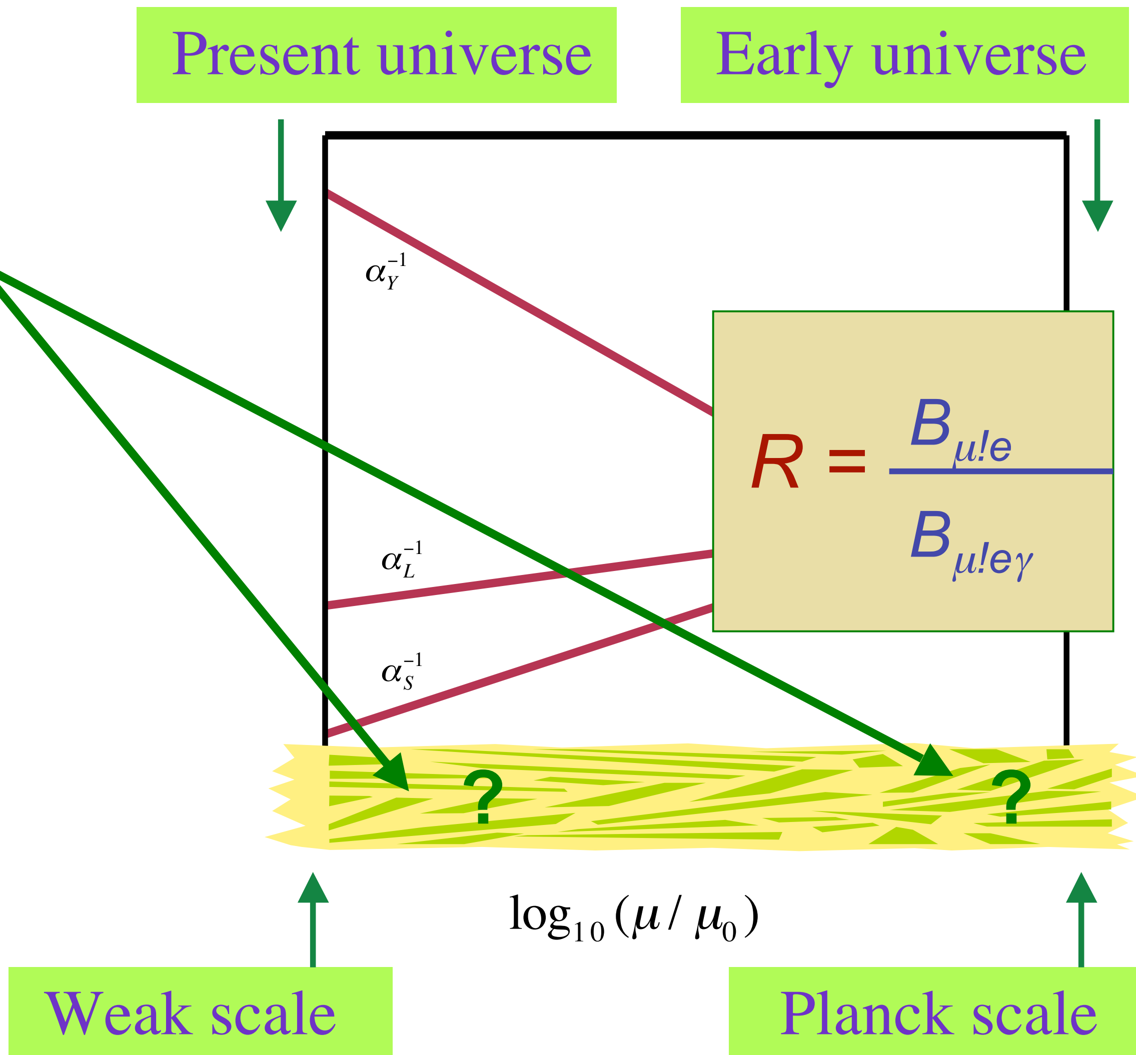


MEG: $B_{\mu!e\gamma} \sim 5 \times 10^{-14}$



MECO: $B_{\mu!e} \sim 5 \times 10^{-17}$

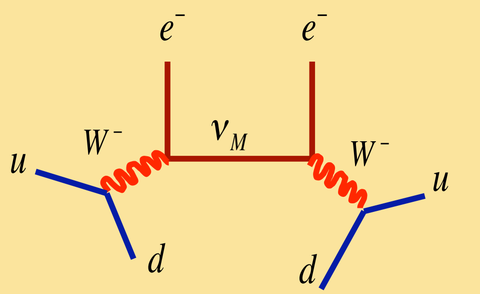
Also PRIME



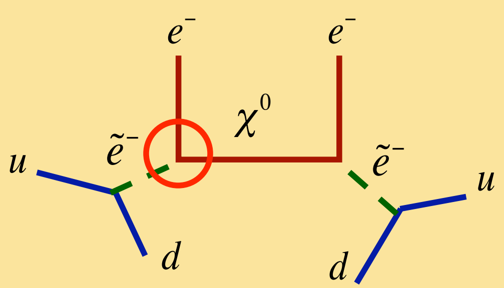
Lepton Flavor & Number Violation

Raidal, Santamaria;
Cirigliano, Kurylov, R-M, Vogel

$0\nu\beta\beta$ decay



Light ν_M exchange ?



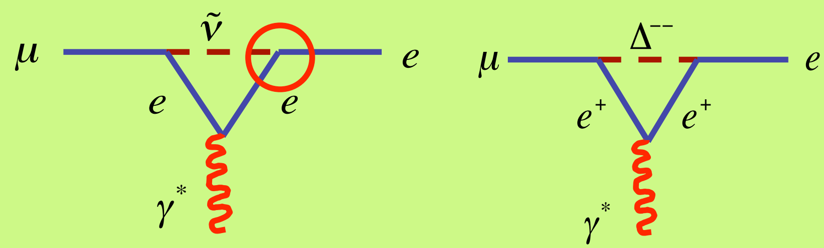
Heavy particle exchange ?

LFV Probes of RPV: μ!e

$$|\lambda_{131}\lambda_{231}| \leq 1.1\times 10^{-5}\left(\frac{m_{\tilde{\ell}}}{100\ \mathrm{GeV}}\right)^2$$

$$|\lambda'_{111}\lambda'_{211}| \leq 6.0\times 10^{-7}\left(\frac{m_{\tilde{q}}}{100\ \mathrm{GeV}}\right)^2$$

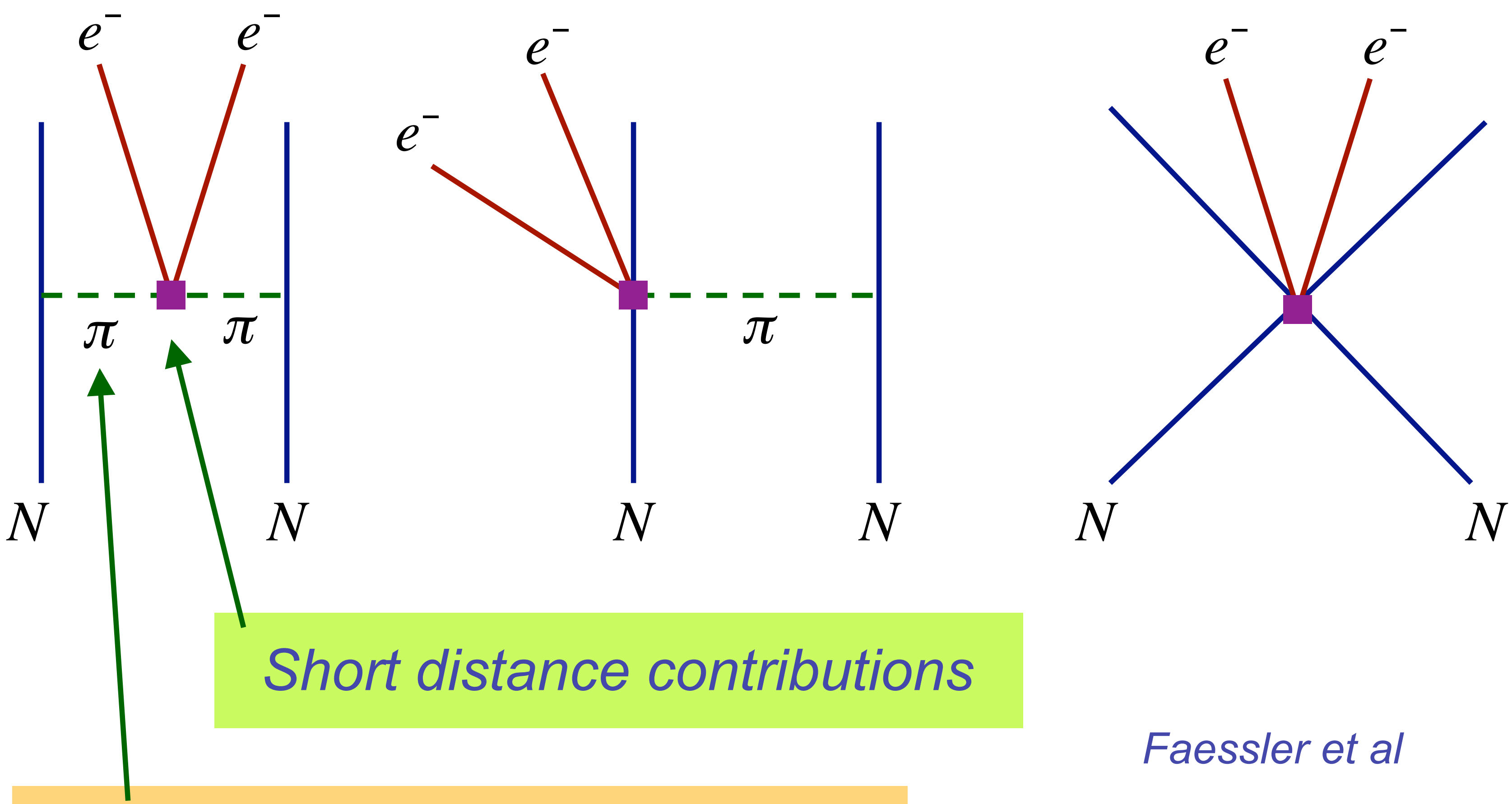
$\lambda_{k11}{}^{/}$ ~ 0.008 for m_{SUSY} ~ 1 TeV



Logarithmic enhancements of *R*

Low scale LFV: *R ~ O(1)* GUT scale LFV: *R ~ O(α)*

Lepton Flavor & Number Violation



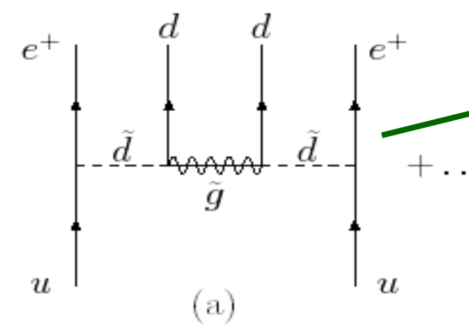
Short distance contributions

Long range nuclear effects (π's)

Faessler et al

Prezeau, R-M, Vogel

Lepton Flavor & Number Violation

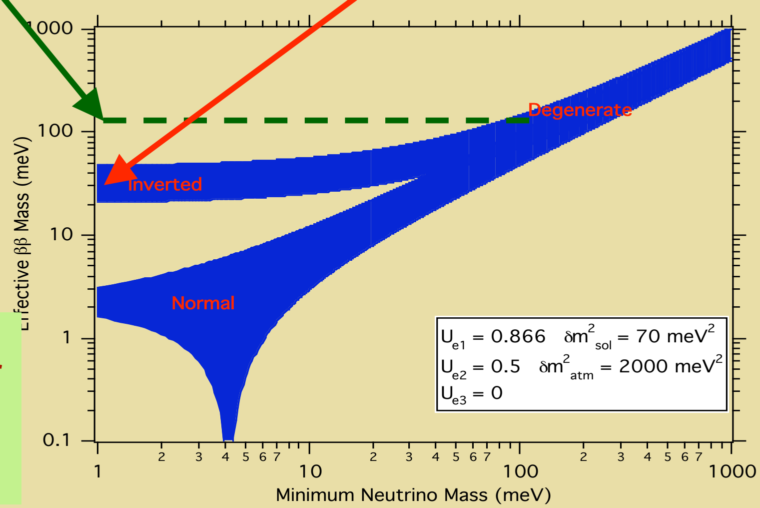


$$\lambda'_{111} \leq 2 \times 10^{-4} \left(\frac{m_{\tilde{q}}}{100\,\mathrm{GeV}}\right)^2 \left(\frac{m_{\tilde{g}}}{100\,\mathrm{GeV}}\right)^{1/2}$$

λ_{111}' ~ 0.06 for m_{SUSY} ~ 1 TeV

$0\nu\beta\beta$ signal equivalent to degenerate hierarchy

Loop contribution to m_ν of inverted hierarchy scale



IV. SUSY & PVES

Q_W and SUSY Radiative Corrections

Tree Level

$$Q_W^f = g_V^f \, g_A^e$$

Radiative Corrections

Flavor-dependent

$$Q_W^f = \rho_{PV} \, (2 I_3^f - 4 Q_f \kappa_{PV} \sin^2\theta_W) + \lambda_f$$

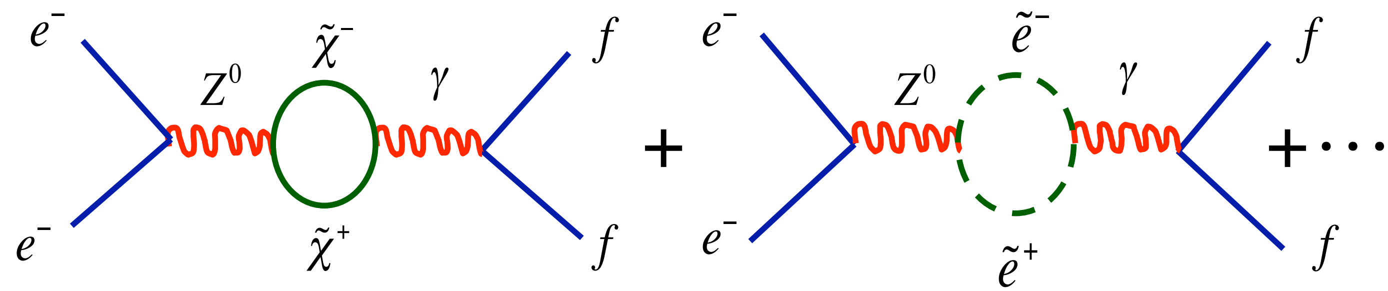
Constrained by Z-pole precision observables

Scale-dependent effective weak mixing

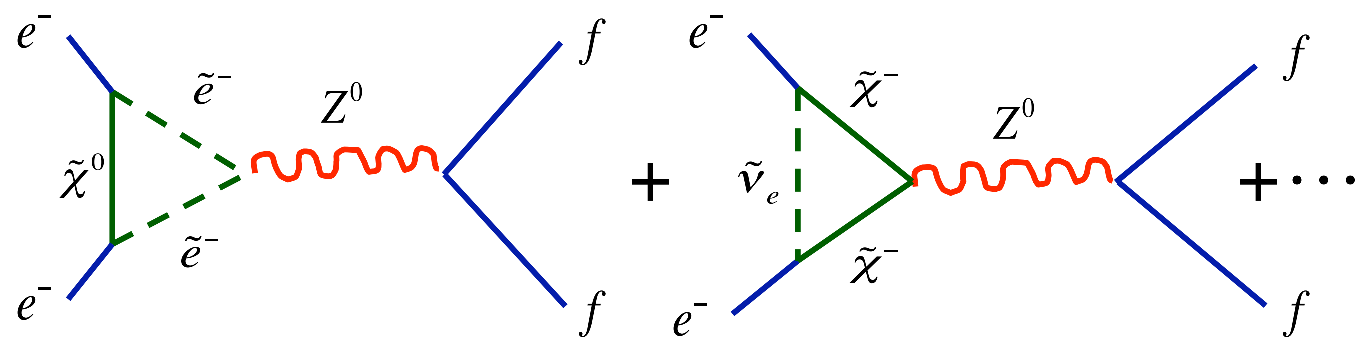
Flavor-independent

SUSY Radiative Corrections

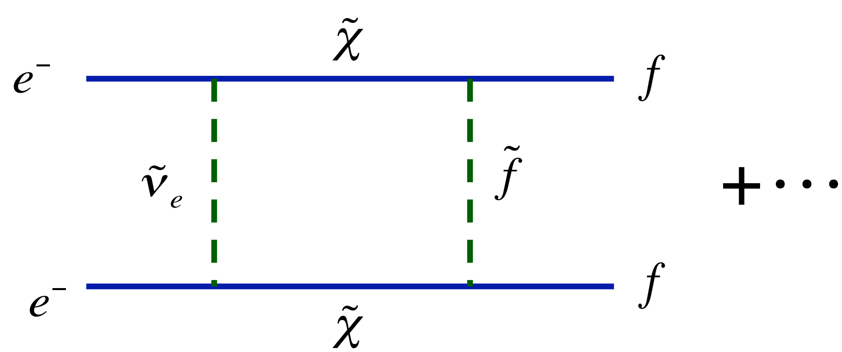
Propagator



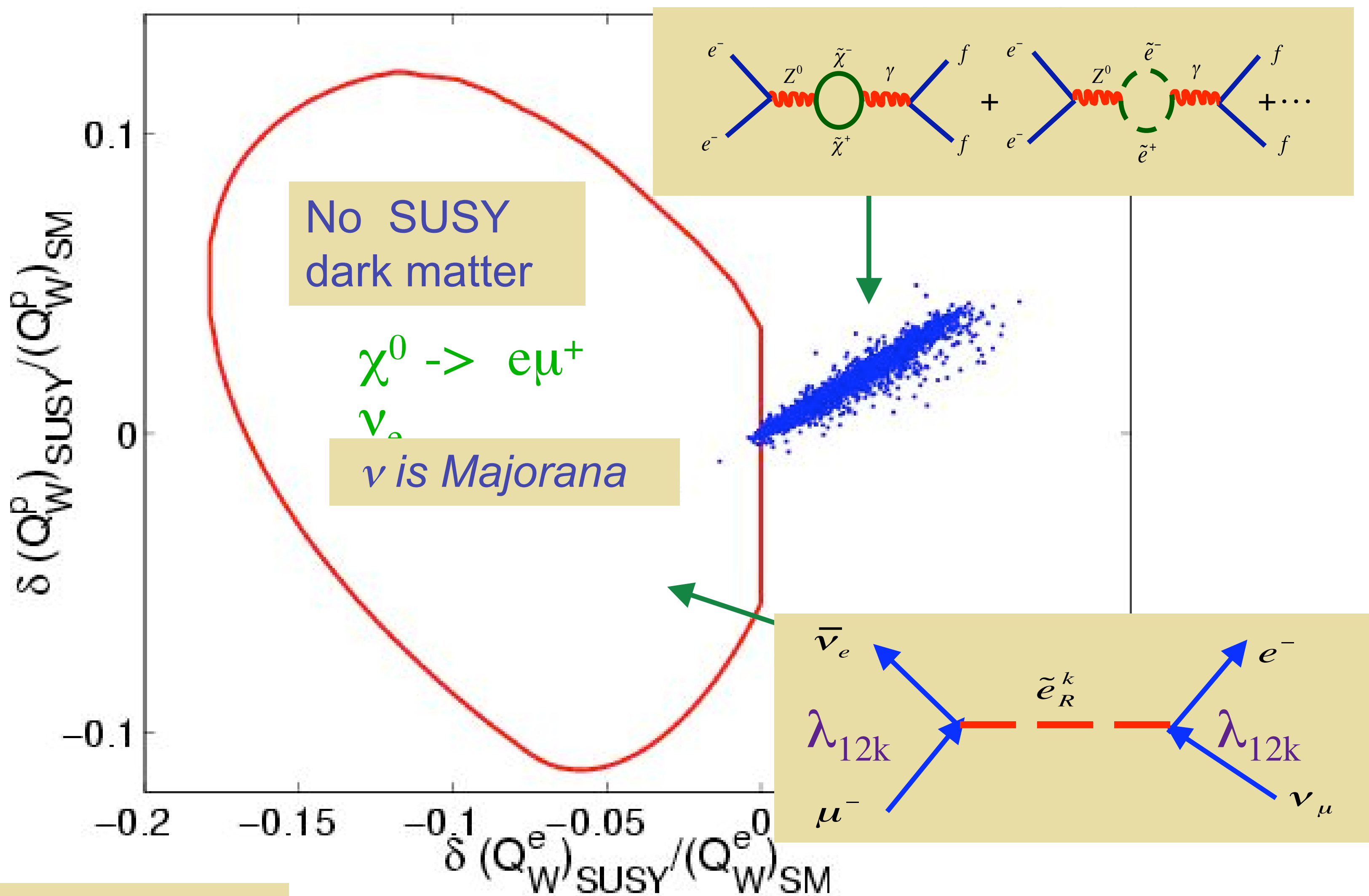
Vertex &
External leg



Box

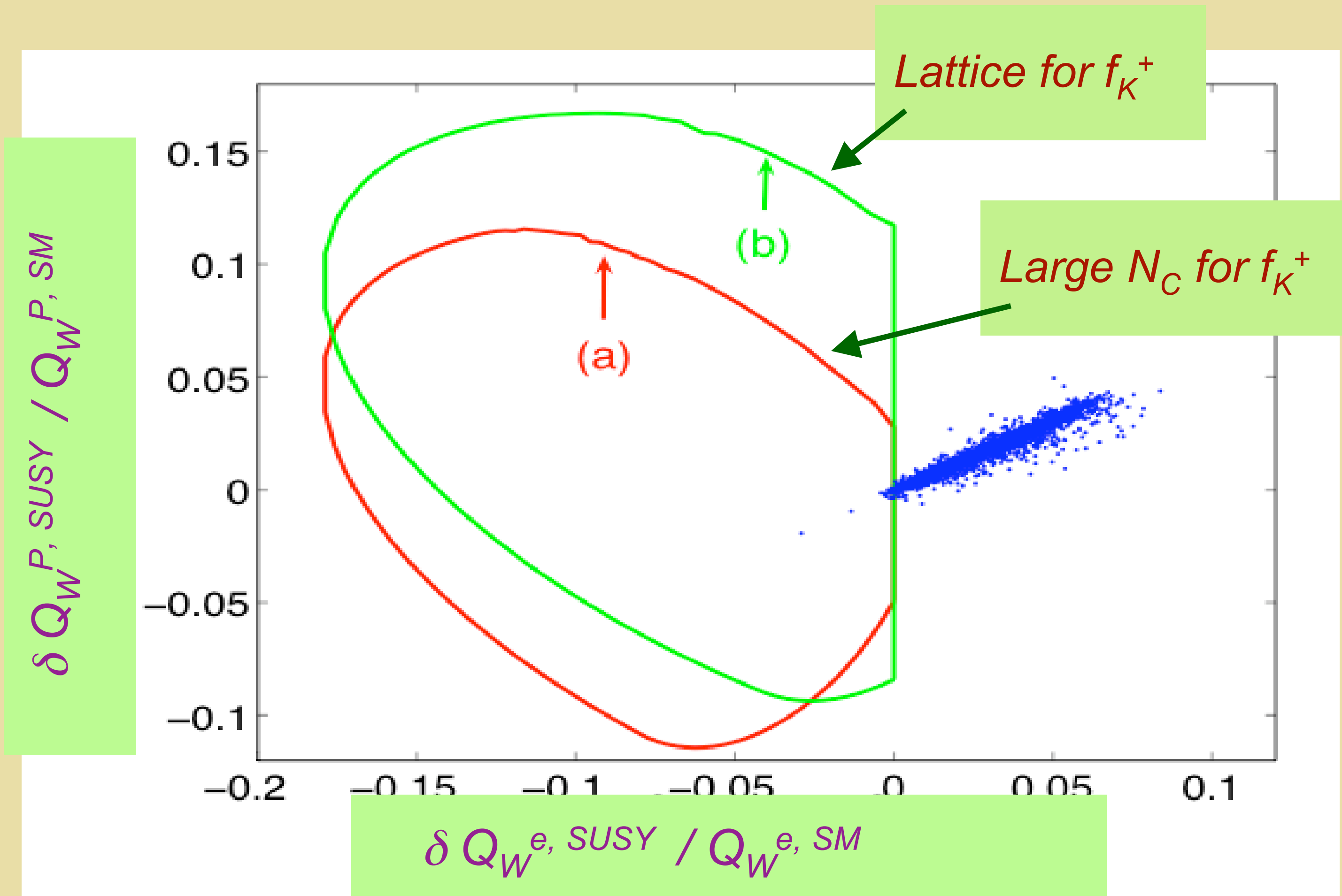


Probing SUSY with PV eN Interactions



Kurylov, Su, MR-M

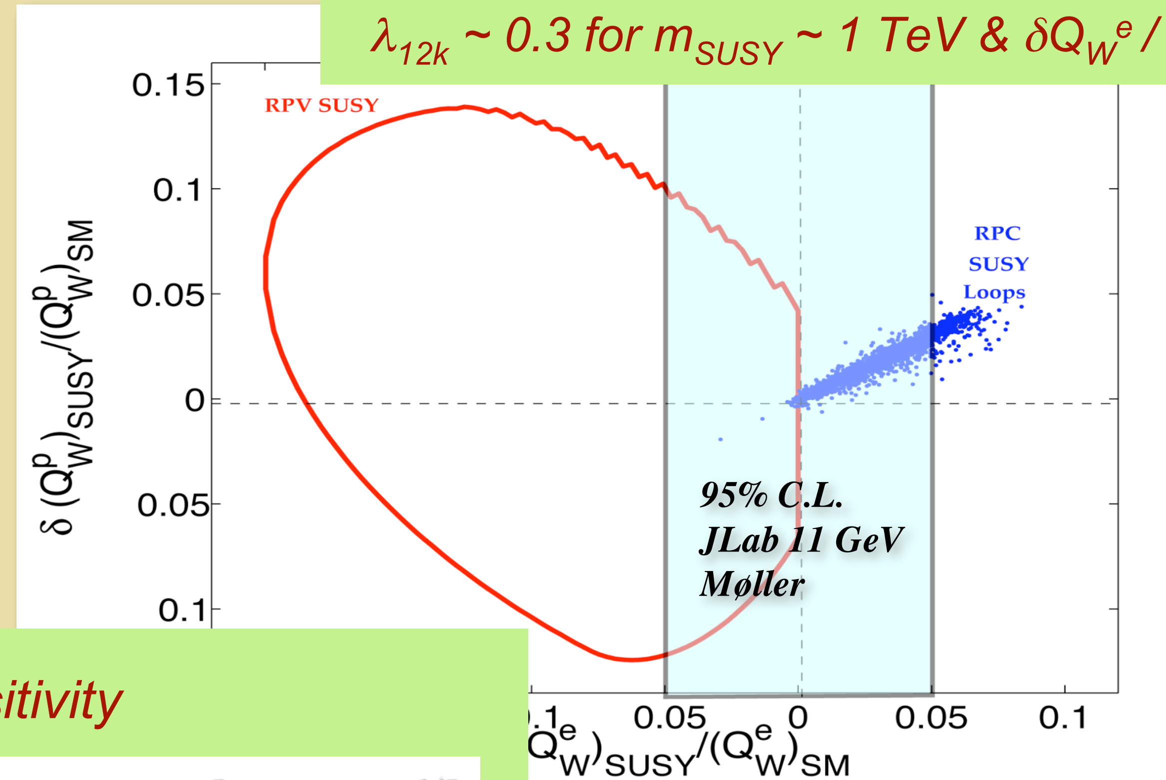
Probing SUSY with PV eN Interactions



Probing SUSY with PV eN Interactions

$$\frac{\delta Q_W^e}{Q_W^e} \approx -30\,\Delta_{12k}(\tilde{e}_R^k) \approx -45\left(\frac{100\,GeV}{m_{\tilde{e}_R^k}}\right)^2 |\lambda_{12k}|^2$$

λ_{12k} ~ 0.3 for m_{SUSY} ~ 1 TeV & $\delta Q_W^e / Q_W^e$ ~ 5%



0νββ sensitivity

$$\lambda'_{111} \le 2\times 10^{-4}\left(\frac{m_{\tilde{q}}}{100\,\mathrm{GeV}}\right)^2\left(\frac{m_{\tilde{g}}}{100\,\mathrm{GeV}}\right)^{1/2}$$

λ'_{111} ~ 0.06 for m_{SUSY} ~ 1 TeV

Probing SUSY with PV eN Interactions

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$0\nu\beta\beta$ sensitivity

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λ_{111}' ~ 0.06 for m_{SUSY} ~ 1 TeV

LFV Probes of RPV: $\mu!e\gamma$

$$|\lambda_{131}\lambda_{231}| \leq 2.3\times 10^{-4}\left(\frac{m_{\tilde{\ell}}}{100\ \mathrm{GeV}}\right)^2$$
$$|\lambda'_{111}\lambda'_{211}| \leq 7.6\times 10^{-5}\left(\frac{m_{\tilde{q}}}{100\ \mathrm{GeV}}\right)^2$$

λ_{k31} ~ 0.15 for m_{SUSY} ~ 1 TeV

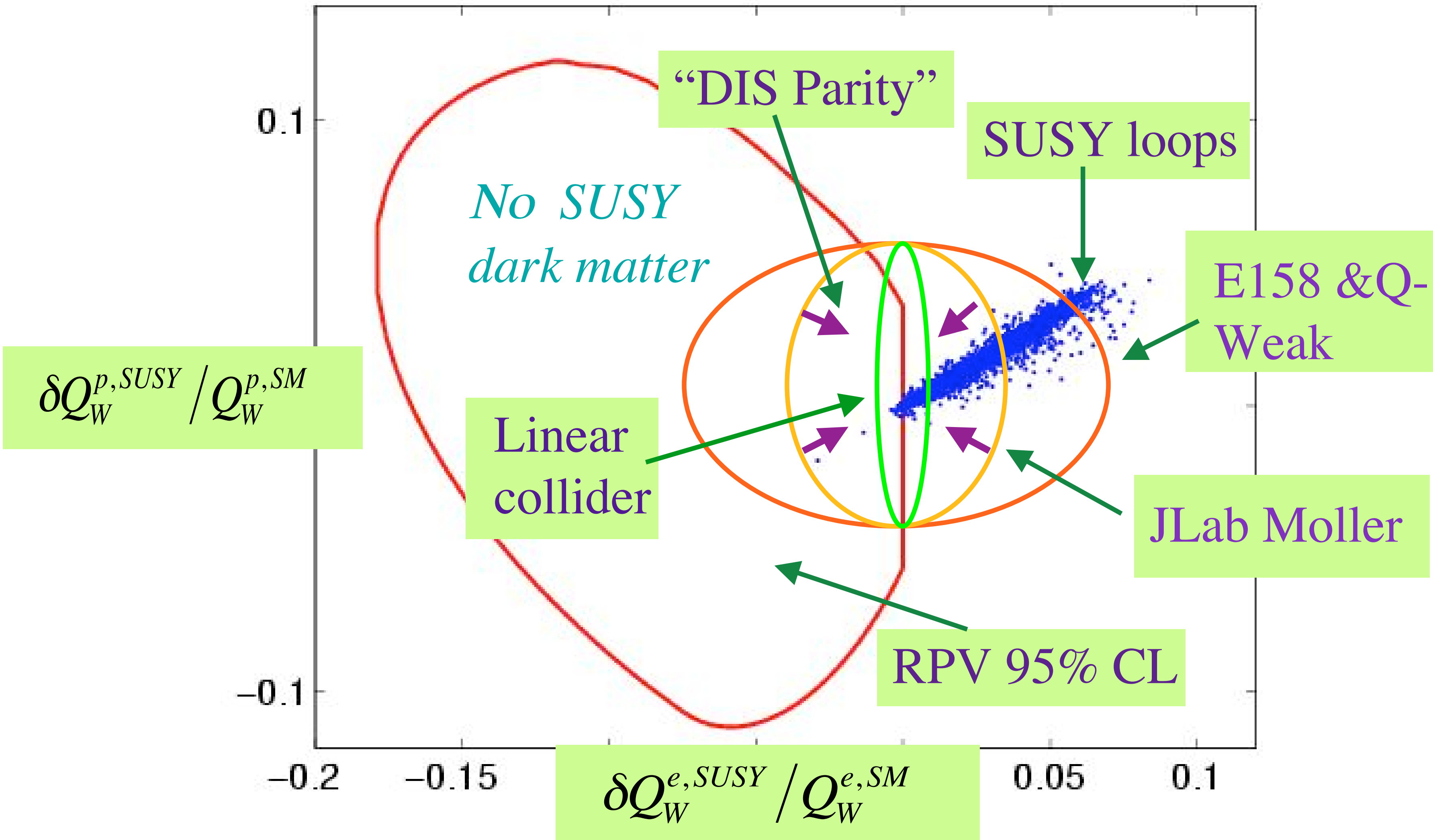
LFV Probes of RPV: $\mu!e$

$$|\lambda_{131}\lambda_{231}| \leq 1.1\times 10^{-5}\left(\frac{m_{\tilde{\ell}}}{100\ \mathrm{GeV}}\right)^2$$
$$|\lambda'_{111}\lambda'_{211}| \leq 6.0\times 10^{-7}\left(\frac{m_{\tilde{q}}}{100\ \mathrm{GeV}}\right)^2$$

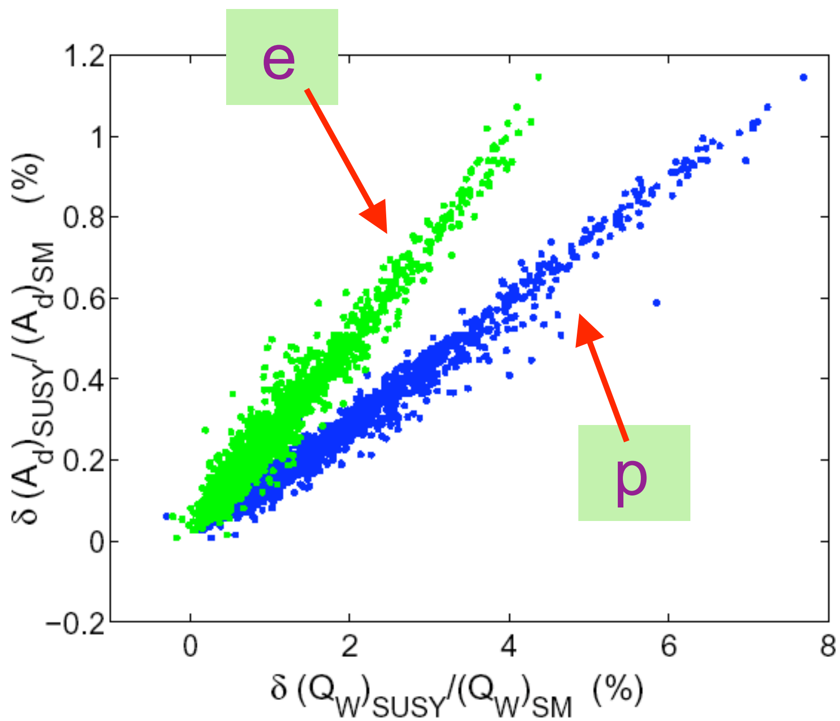
λ_{k31} ~ 0.03 for m_{SUSY} ~ 1 TeV

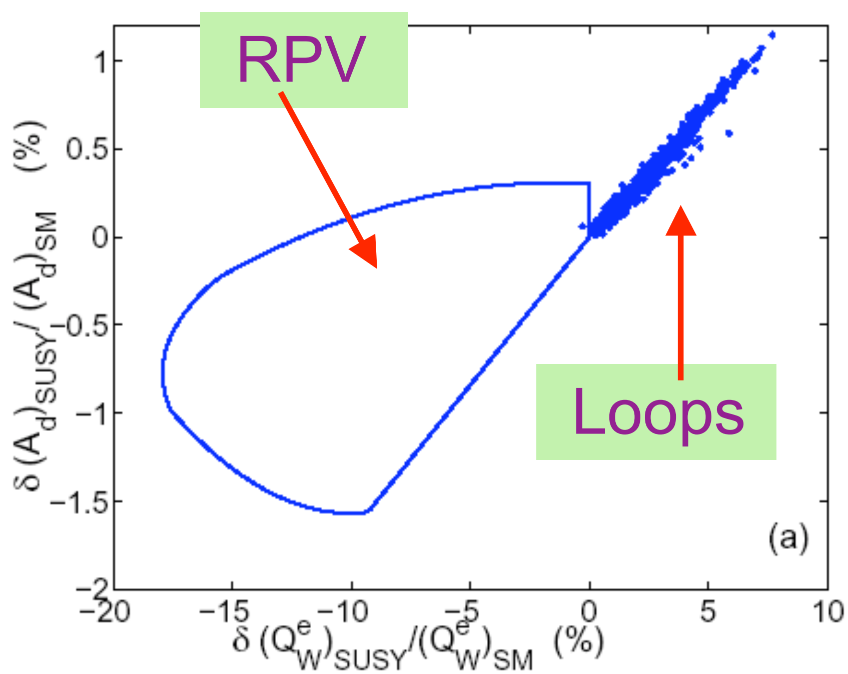
Comparing Q_w^e and Q_W^p

Kurylov, R-M, Su



Comparing A_d^{DIS} and $Q_w^{p,e}$





Low Energy Probes of SUSY

We're making progress…

…won't leave until the job is done…

…and open to new ideas.