Probing Supersymmetry with Neutral Current Scattering Experiments

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Sub-Z precision measurements

- neutral current scattering
- heavy quark physics
- CP violation, EDM
- Rare K-decay, CKM unitarity
- muon g-2
- lepton flavor violation

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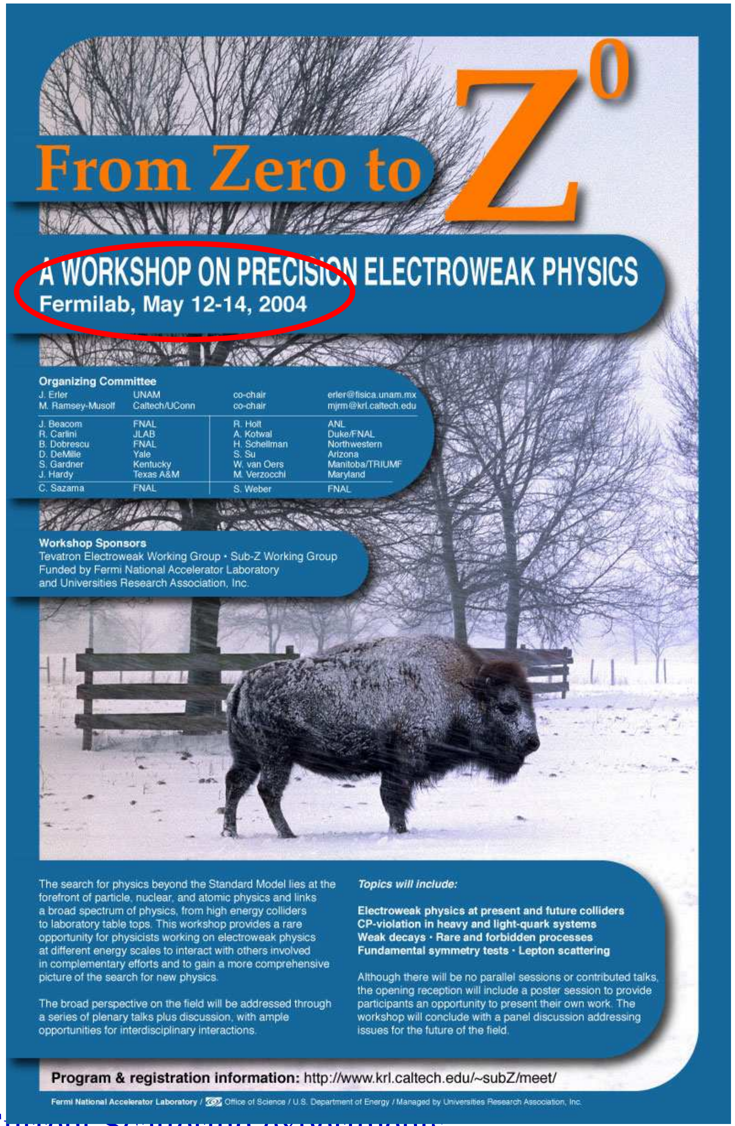


- polarized ee scattering (SLAC E158)
- polarized ep scattering (JLab Qweak)
- neutrino-nucleus scattering (NuTeV)

A. Kurylov, M. Ramsey-Musolf, SS

Outline

- motivation
- parity-violating electron scattering experiments
- radiative corrections to weak charge Q_W
- analysis of SUSY contributions to Q_W
  - MSSM contributions
  - RPV analysis
  - distinguish various new physics / SUSY
- NuTeV experiment
  - MSSM contributions
  - RPV analysis
- conclusion

Motivation

- high precision low energy experiment available

  size of loop effects from new physics: $(\alpha/\pi)(M/M_{new})^2$

  - muon g-2: $M=m_\mu$, $\delta^{new} \sim 2\times10^{-9}$, $\delta^{exp} < 10^{-9}$
  - β-decay, π-decay: $M=m_W$, $\delta^{new} \sim 10^{-3}$, $\delta^{exp} \sim 10^{-3}$
  - parity-violating electron scattering: $M=m_W$, $\delta^{new} \sim 10^{-3}$,

$$\mathcal{L}_{PV} = -\frac{G_\mu}{2\sqrt{2}} Q_W^f \bar{e}\gamma^\mu\gamma_5 e \bar{f}\gamma_\mu f$$

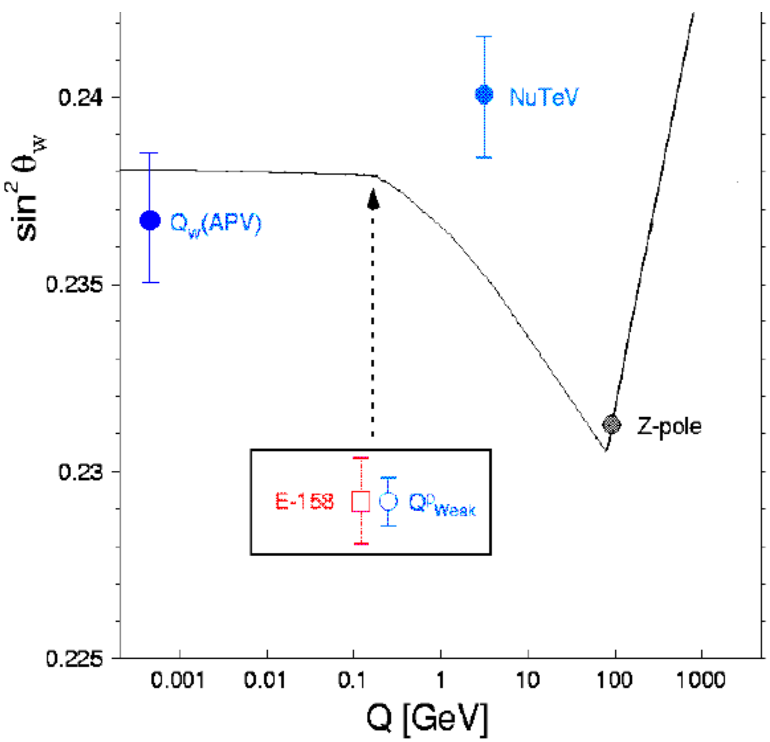
$Q^{e,p}_W \sim 1-4\sin^2\theta_W \sim 0.1$

✓ $1/Q^{e,p}_W \approx 10$ more sensitive to new physics

✓ need $\delta^{exp} \sim 10^{-2}$ "easier" experiment

- probe new physics off the Z-resonance
  - sensitive to new physics not mix with Z
- indirect+direct: complementary information
  - consistency test of theory at loop level

Test of $\sin^2\theta_W$ running



- $\sin^2\theta_W(0) - \sin^2\theta_W(m_Z^2) = +0.007$
  - Q^{Cs}_W: agree $Q^2=0$
  - NuTeV: $+3\sigma$ $\bar{Q}^2=20$ (GeV)^2
- parity-violating electron scattering (PVES)

  ee Moller scattering (SLAC) Q^e_W

  ep elastic scattering (J-lab) Q^p_W

$\delta \sin^2\theta_W \sim 0.0007$ at $\bar{Q}^2=0.03$ (GeV)^2

✓ clean environment: Hydrogen target
✓ theoretically clean: small hadronic uncertainties
✓ tree level ~ 0.1 ⇒ sensitive to new physics

Goal

Develop consistency checks for theories of new physics using the low energy precision measurements

- **minimal Supersymmetric extension of SM (MSSM)**

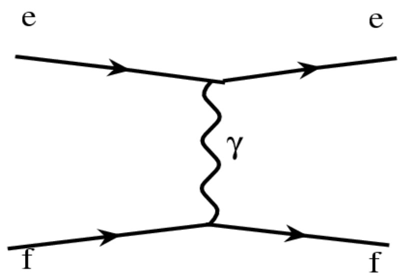
  SUSY: most promising candidate for new physics
  - solution to Hierarchy problem
  - gauge coupling unification
  - provide a natural electroweak symmetry breaking
  - dark matter candidate ? (PVES)

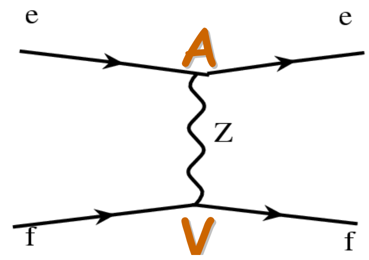
  ❖ **with R-parity : loop corrections**

  ❖ **without R-parity: tree-level contribution**

- **low-energy precision measurements**
  - **PVES: weak charge Q^e_W , Q^p_W , (Q^{Cs}_W) - NuTeV: $R^{\nu(\bar{\nu})}$**

Weak charge Q_W





$$A_{LR} \equiv \frac{N_+ - N_-}{N_+ + N_-} \propto Q^f_W$$

$$\mathcal{L}_{PC} = \frac{e^2}{q^2} Q_e Q_f \bar{e}\gamma^\mu e \bar{f}\gamma_\mu f \qquad \mathcal{L}_{PV} = \frac{G_\mu}{\sqrt{2}} g_A^e Q_W^f \bar{e}\gamma^\mu\gamma_5 e \bar{f}\gamma_\mu f$$

$g^e_A = I^e_3$

weak charge $Q^f_W = 2g^f_V = 2\, I^f_3 - 4Q_f s^2$

	ep Q_{weak} exp Q^p_W	ee Moller exp Q^e_W
$Q^{e,p}_W$ tree	$1-4s^2$	$-(1-4s^2)$
$Q^{e,p}_W$ loop	0.0721	-0.0449
exp precision	4%	8%
$\delta \sin^2\theta_W$	0.0007	0.0009
SM running	10 σ	8 σ

Q^{Cs}_W : $\delta \sin^2\theta_W = 0.0021$ NuTeV: $\delta \sin^2\theta_W = 0.0016$

General structure of radiative corrections to Q^f_W

Including radiative corrections: $\mathcal{L} = -\frac{G_\mu}{2\sqrt{2}} Q^f_W \bar{e}\gamma_\mu\gamma^5 e \bar{f}\gamma^\mu f$

$$Q^f_W = \rho\,(2I^f_3 - 4\,\kappa\,Q_f\,s^2) + \lambda_f$$

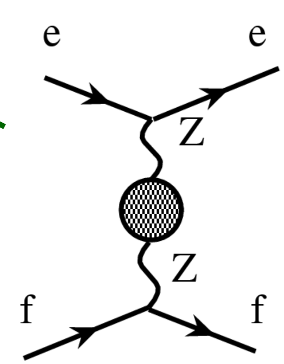
ρ, κ: universal, λ_f: depend on fermion species

$\rho = 1 + \delta\rho^{SM} + \delta\rho^{SUSY}$, $\kappa = 1 + \delta\kappa^{SM} + \delta\kappa^{SUSY}$, $\lambda_f = \lambda_f^{SM} + \lambda_f^{SUSY}$

ρ

$$\rho = 1 + \frac{\delta\hat{G}_\mu}{G_\mu} + \frac{\hat{\Pi}_{ZZ}(0)}{m_Z^2}$$

correction to muon life time

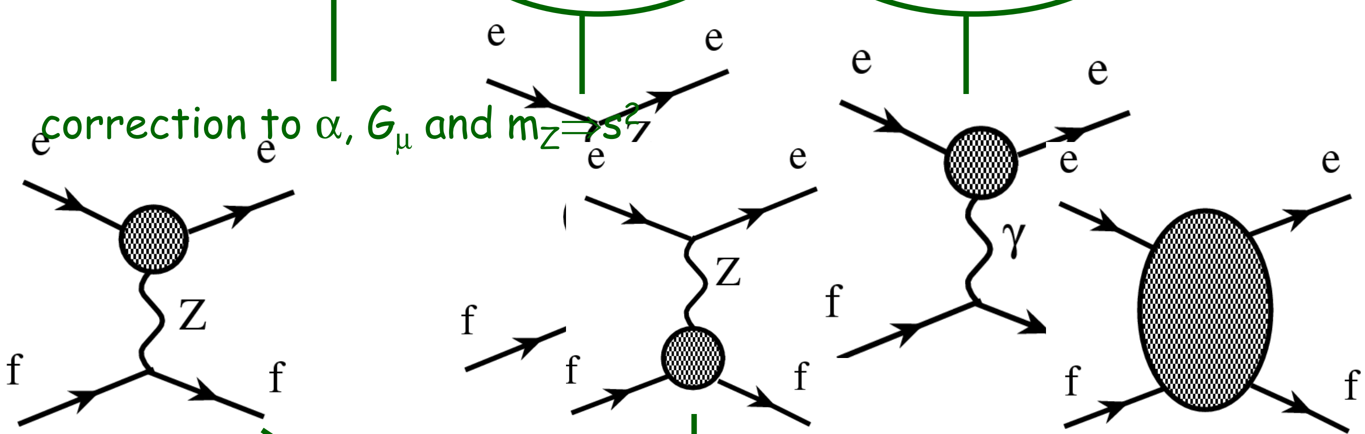


Radiative contributions

$$Q^f_W = \rho\,(2I^f_3 - 4\,\kappa\,Q_f\,s^2) + \lambda_f$$

κ

$$\kappa = 1 + \frac{\delta\hat{s}^2}{\hat{s}^2} + \frac{\hat{c}}{\hat{s}}\frac{\hat{\Pi}_{\gamma Z}(q^2)}{q^2} - 4\hat{c}^2\hat{F}_{A;e}(q^2)$$



λ_f

$$\lambda_f = 2(g^f_V\,\delta V^e_A + g^e_A\,\delta V^f_V + \delta^{ef}_{box})$$

MSSM particle contents

SM particle — Spin differ by 1/2 — superpartner

Names		spin 0	spin 1/2
squarks, quarks	Q	$(\tilde{u}_L, \tilde{d}_L)$	(u_L, d_L)
(× 3 families)	$\bar{U}$	$\tilde{u}_R^*$	$u_R^\dagger$
	$\bar{D}$	$\tilde{d}_R^*$	$d_R^\dagger$
sleptons, leptons	L	$(\tilde{\nu}, \tilde{e}_L)$	(ν, e_L)
(× 3 families)	$\bar{E}$	$\tilde{e}_R^*$	$e_R^\dagger$
Higgs, higgsinos	H_u	(H_u^+, H_u^0)	$(\tilde{H}_u^+, \tilde{H}_u^0)$
	H_d	(H_d^0, H_d^-)	$(\tilde{H}_d^0, \tilde{H}_d^-)$

mass parameter

$\tilde{m}_{qL}^2$, $\tilde{m}_{qR}^2$, $\tilde{m}_{qLR}^2$

$\tilde{m}_{lL}^2$, $\tilde{m}_{lR}^2$, $\tilde{m}_{lLR}^2$

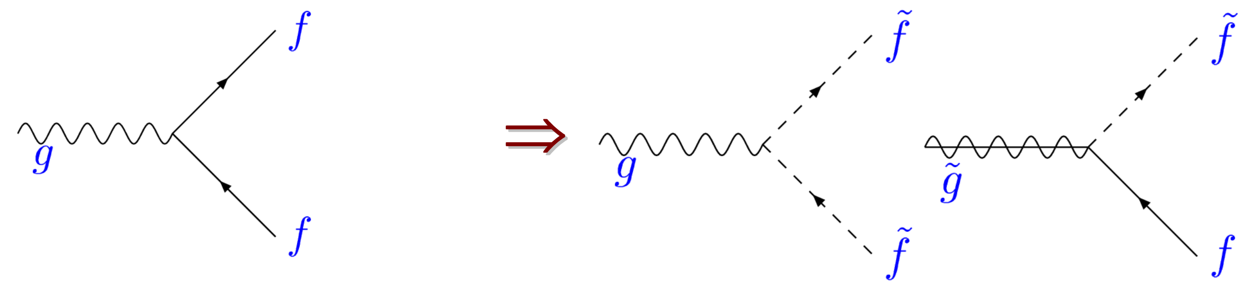
μ, $\tan\beta = v_u/v_d$

Names	spin 1/2	spin 1
gluino, gluon	$\tilde{g}$	g
winos, W bosons	$\tilde{W}^\pm, \tilde{W}^0$	$W^\pm, W^0$
bino, B boson	$\tilde{B}^0$	B^0

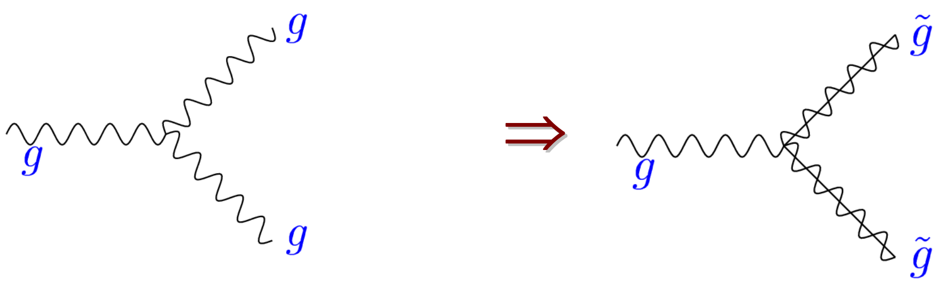
M_3
M_2
M_1

SUSY interactions

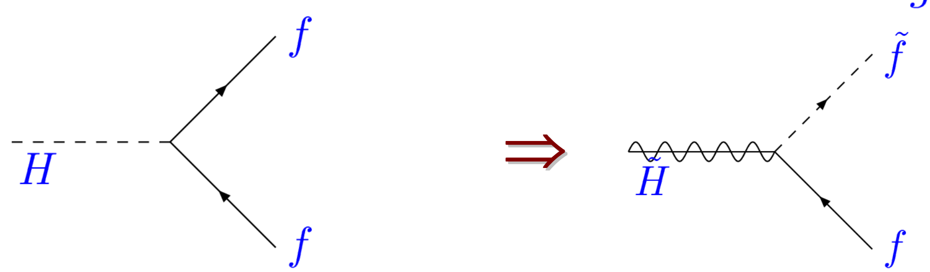
replace two SM particles into SUSY partners



$\propto$ gauge coupling



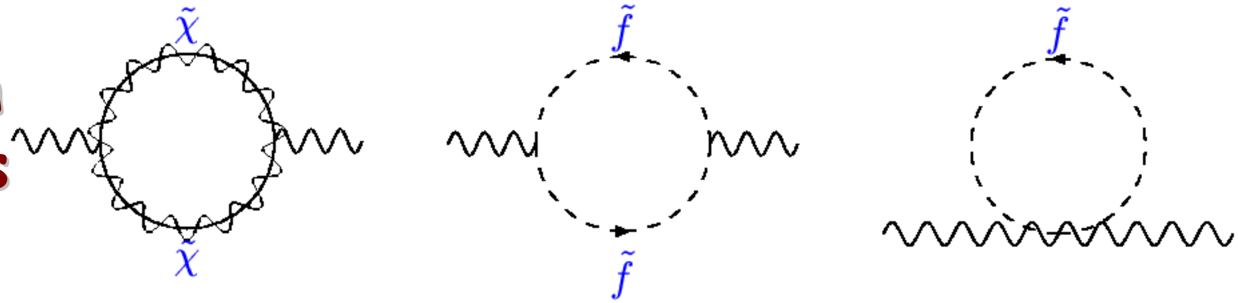
$\propto$ gauge coupling



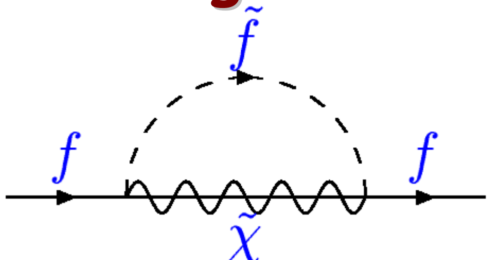
$\propto$ Yukawa coupling

One loop SUSY contributions to PVES

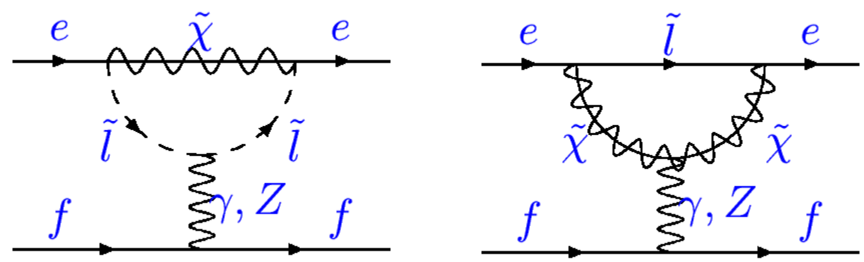
- **gauge boson self-energies**



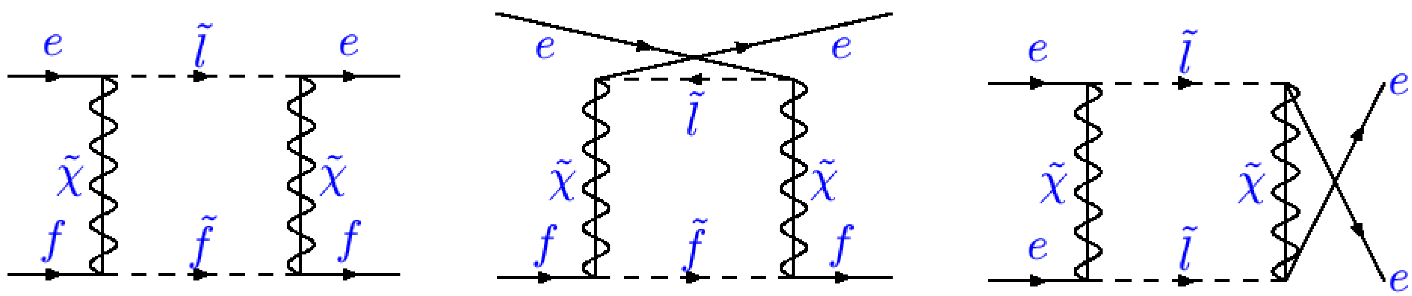
- **external leg corrections**



- **vertex corrections**



- **box diagrams**



Numerical analysis

Model-independent analysis

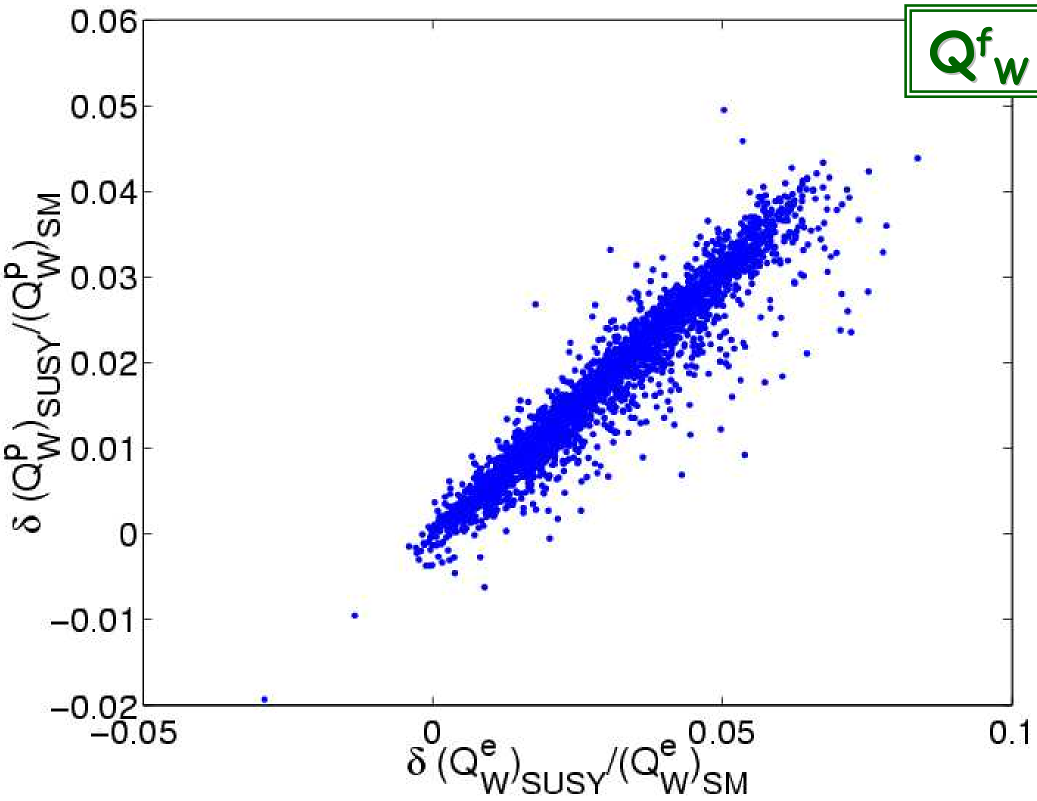
- **MSSM parameter range: random scan**

$$50\ \text{GeV} < \tilde{m}_q,\ \tilde{m}_l,\ M_{1,2},\ \mu < 1000\ \text{GeV}$$
$$1.4 < \tan\beta < 60$$

  * hard to impose bounds on certain MSSM parameter
  * show the possible range of MSSM corrections

- impose exp search limit on SUSY particles
- impose S-T 95% CL constraints
- impose g-2 constraints (2nd slepton LR mixing)

Correction to weak charge



$$Q^f_W = \rho\,(2T^f_3 - 4Q_f\,\kappa\,s^2) + \lambda_f$$

- Q^e_W and Q^p_W correlated

dominant : $\delta\kappa$ (<0)

$\Rightarrow$

<u>negative</u> shift in $\sin^2\theta_W$

$\delta\,(Q^p_W)_{SUSY} / (Q^p_W)_{SM} < 4\%$, $\delta\,(Q^e_W)_{SUSY} / (Q^e_W)_{SM} < 8\%$

Dominant contributions

$$Q^f_W = \rho\,(2T^f_3 - 4Q_f\,\kappa\, s^2) + \lambda_f$$

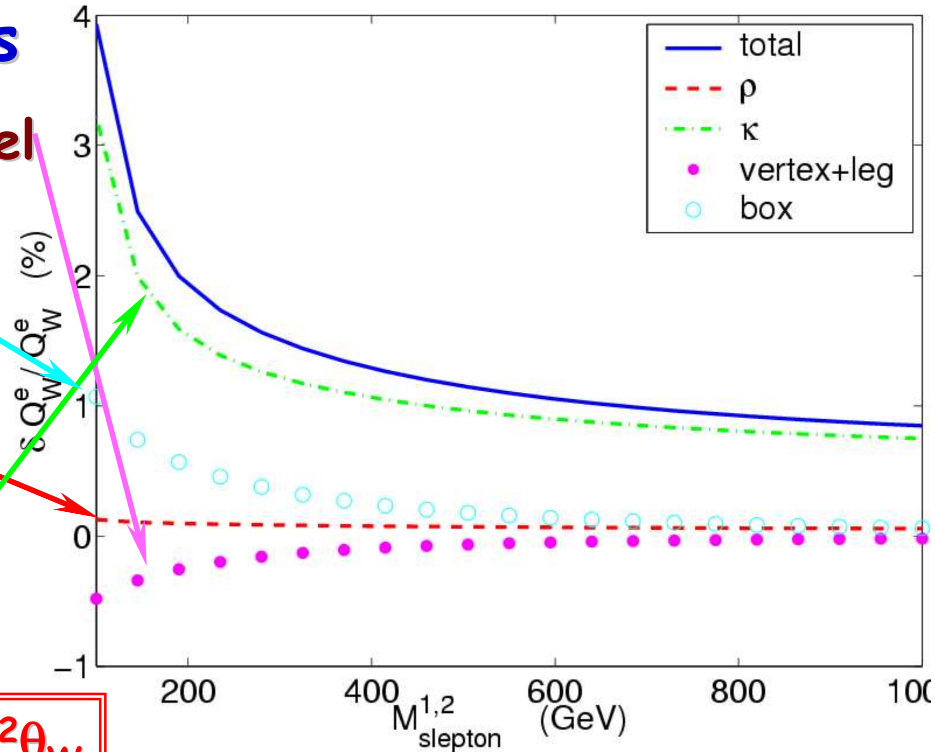
- **non-universal corrections**

– vertex + wavefunction : cancel
– box diagrams numerically suppressed

- **$\delta\rho$ contribution**

suppressed by $(1-4\,s^2)$

- **dominant contribution from $\delta\kappa$**



$\delta\kappa$ (<0) $\Rightarrow$ negative shift in $\sin^2\theta_W$

Various contributions to δκ

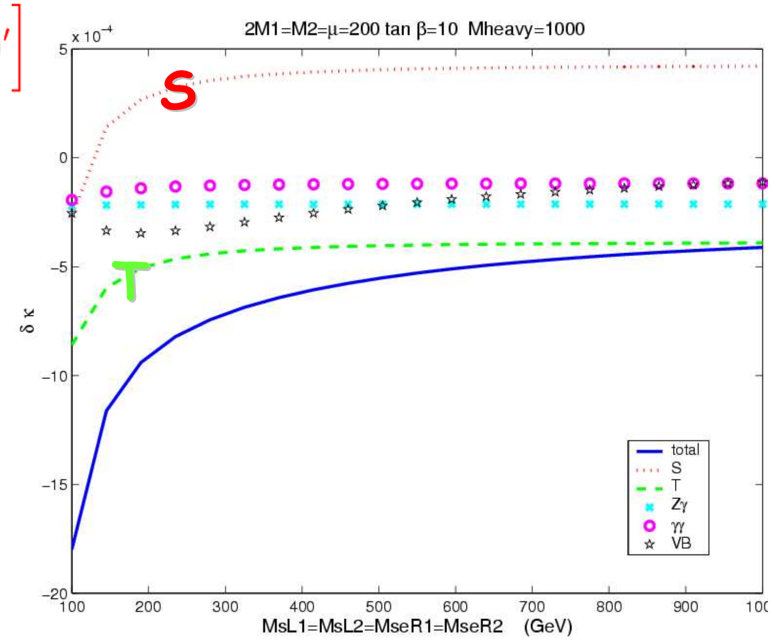
$$\delta\kappa = \left(\frac{\hat{c}^2}{\hat{c}^2-\hat{s}^2}\right)\left(\frac{\hat{\alpha}}{4\hat{s}^2\hat{c}^2}S - \hat{\alpha}T + \hat{\delta}^{\mu}_{VB}\right) - 4\hat{c}^2\hat{F}_{A;e}(q^2)$$

$$+\frac{\hat{c}}{\hat{s}}\left[\frac{\hat{\Pi}_{\gamma Z}(q^2)}{q^2} - \frac{\hat{\Pi}_{\gamma Z}(m_Z^2)}{m_Z^2}\right] - \left(\frac{\hat{c}^2}{\hat{c}^2-\hat{s}^2}\right)\left[\frac{\hat{\Pi}_{\gamma\gamma}(m_Z^2)}{m_Z^2} - \hat{\Pi}_{\gamma\gamma}(0)'\right]$$

- **within δκ**

- various terms have comparable importance

- oblique approximation gives a poor description



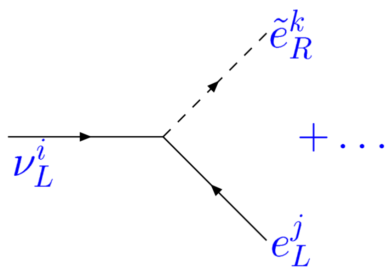
- **δκ <0** **(δ $(Q^{e,p}_W)_{SUSY}$ / $(Q^{e,p}_W)_{SM}$ >0)**

⇒ reduction in effective $\sin^2\theta_W$

R-parity

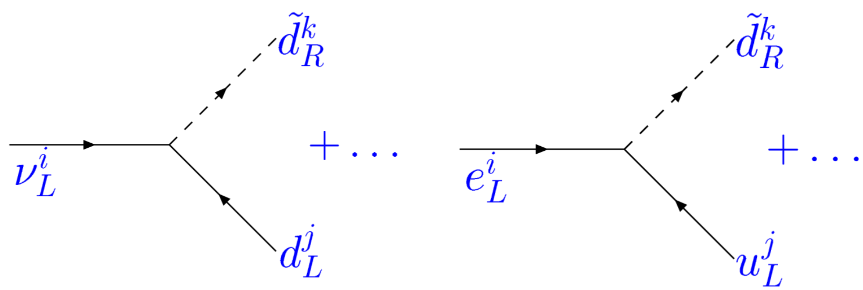
- General MSSM, including B,L-violating operators

λ_{ijk}



$\Delta L = -1$

λ'_{ijk}

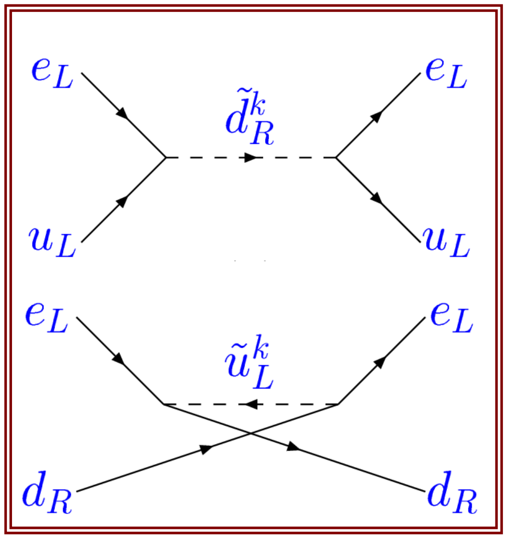


- dangerous ⇒ introduce proton decay
- R-parity SM particle: even superparticle: odd
  - stable LSP as dark matter candidate
- RPV: only look at L-violating operator

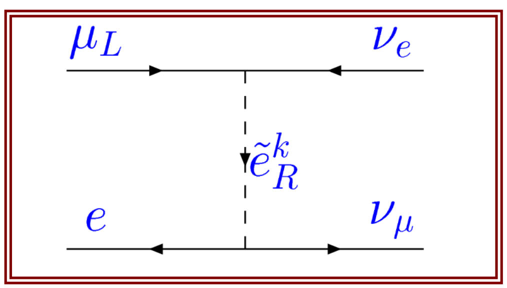
R-parity violating (RPV)

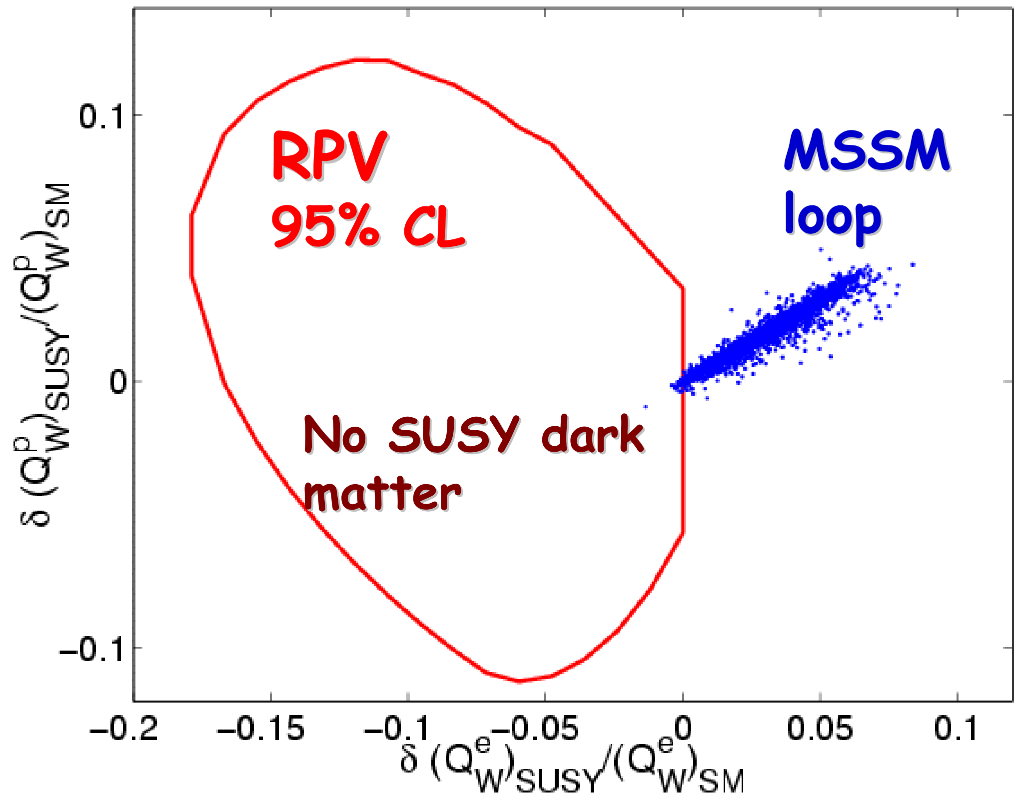
- RPV operators contribute to $Q^{e,p}_W$ at tree level

δQ^p_W



G_μ





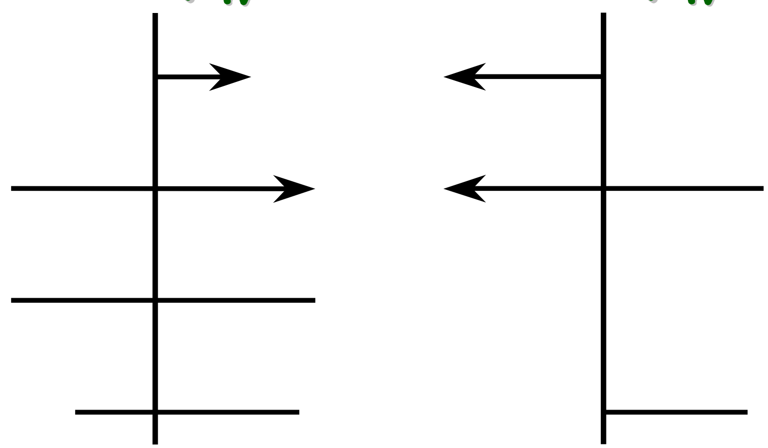
Correlation between Q^p_W and Q^e_W

- **SUSY correction to heavy nuclei Q_W**
  - $\delta Q_W(Z,N) = (2Z+N)\,\delta Q^u_W + (2N+Z)\,\delta Q^d_W$

$\delta Q^u_W > 0$ $\delta Q^d_W < 0$	$\Rightarrow$	$\delta Q_W(Z,N) / Q_W(Z,N) < 0.2\ \%$ for Cs

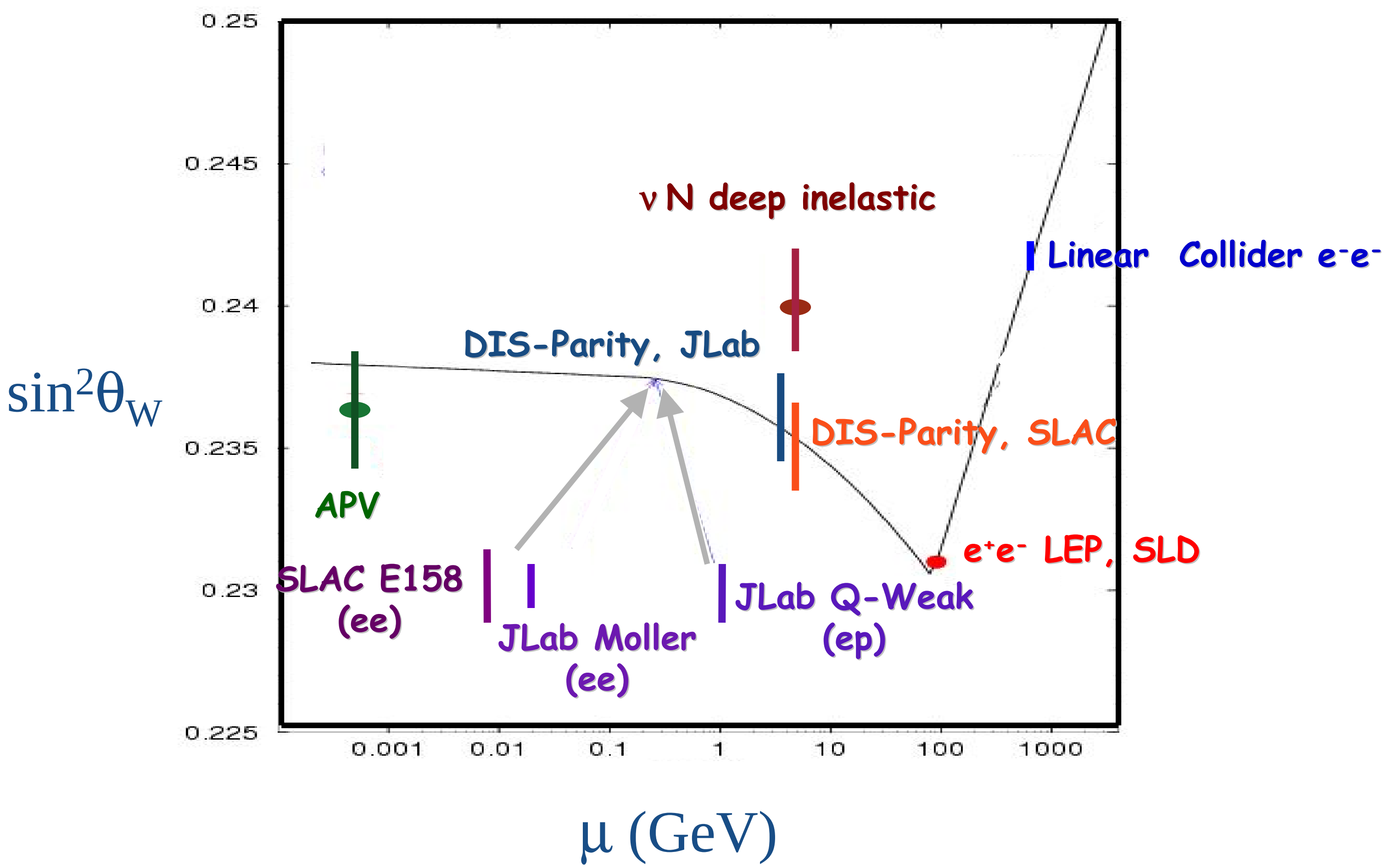
- **Distinguish new physics**

	δQ^p_W	δQ^e_W	δQ^{Cs}_W
MSSM:			small
extra Z':			sizable
leptoquark:			
RPV SUSY			



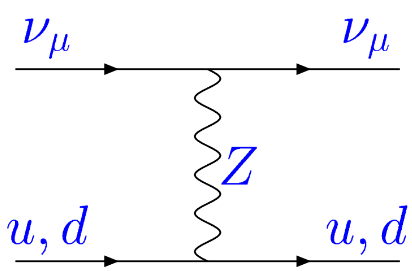
Additional PV electron scattering ideas

Czarnecki, Marciano Erler *et al.*

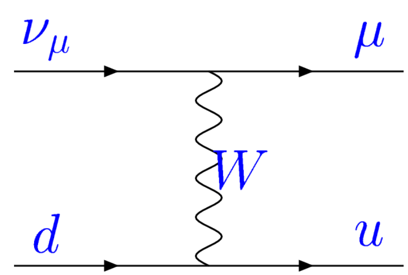


NuTeV experiment

NC



CC



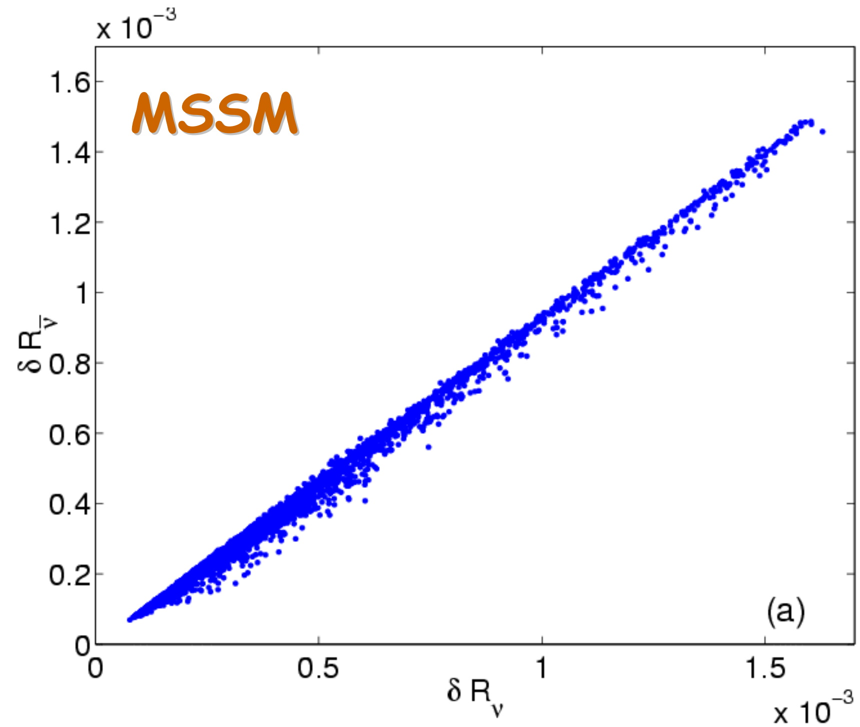
$$R^{\nu(\bar{\nu})} \equiv \frac{\sigma(\nu N \to \nu X)}{\sigma(\overset{(-)}{\nu} N \to l^{-(+)} X)}$$

$\delta R^{\nu} = -0.0033 \pm 0.0015$

$\delta R^{\bar{\nu}} = -0.0019 \pm 0.0026$

wrong-sign contribution!

Davidson et. al., JHEP 02, 037, 2002

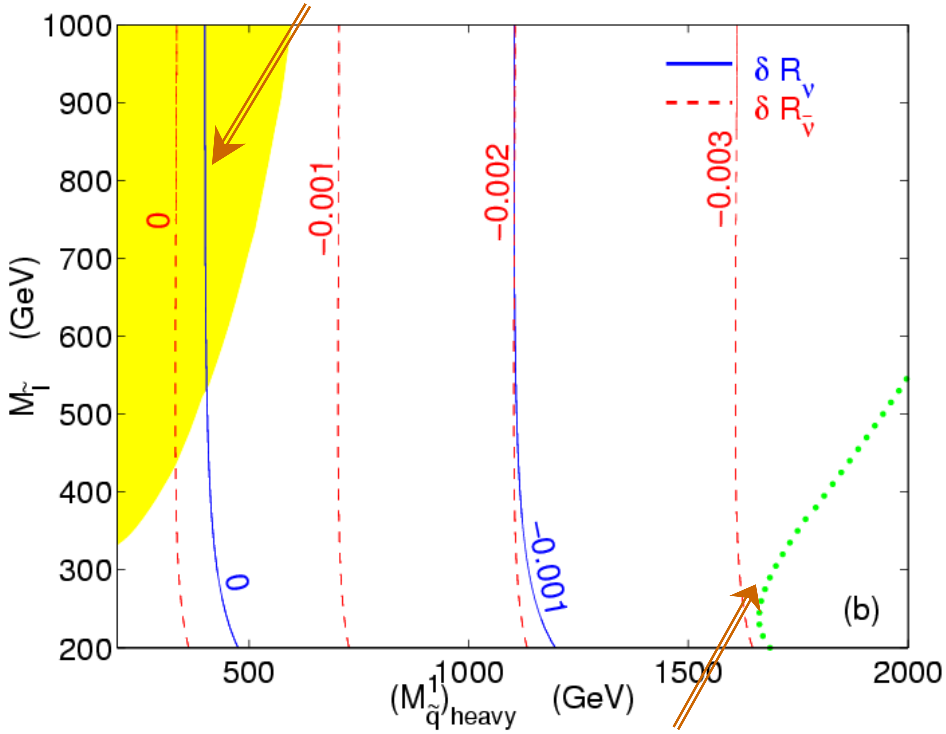


Gluino contribution

negative gluino contribution

CC data constraints

Kurylov, Ramsey-Musolf,PRL88,071804,2002



unitarity deviation decrease by 1/3 σ

- large LR-mixing both up/down sector
- inconsistent with current CC data
- constraints relaxed if first row CKM unitarity confirmed
- could partially account for deviation in $\sin^2\theta_W$

Deviation of $\sin^2\theta_W$

- extracted using Paschos-Wolfenstein relation

$$R^- \equiv \frac{R_\nu - rR_{\bar\nu}}{1-r} = \frac{1}{2}(1 - 2\sin^2\theta_W) + \cdots$$

- in practice, modified version $\tilde{R}^- \equiv \dfrac{R_\nu - \xi R_{\bar\nu}}{1-r}$

  ξ different from r
  $\Rightarrow$ charm quark mass uncertainties

	1C	0C
m_c	constrained	free
ξ	0.249	0.453
$\delta\sin^2\theta_W$	-1.6×10^{-3}	-1×10^{-4}

- gluino contributions $\propto \xi - r$

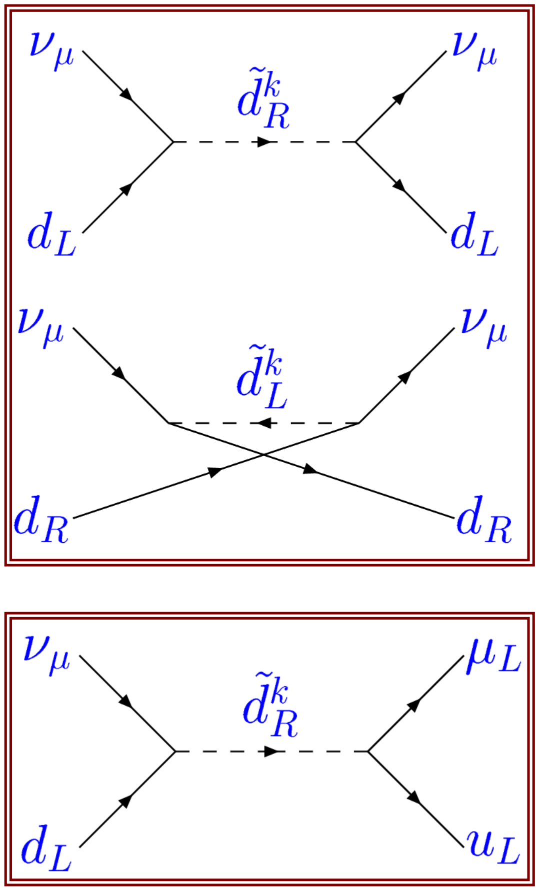
$$\tilde{R}^- = \frac{\alpha_s}{3\pi}(\xi - r)\frac{1+r}{r(1-r)}\hat{s}^2\left(1-\frac{5}{9}\hat{s}^2\right)\Big(2V_2\left[M_{\tilde g}, (M^1_{\tilde q})_{\text{heavy}}, (M^1_{\tilde q})_{\text{light}}\right]$$
$$- V_2\left[M_{\tilde g}, (M^1_{\tilde q})_{\text{heavy}}, (M^1_{\tilde q})_{\text{heavy}}\right] - V_2\left[M_{\tilde g}, (M^1_{\tilde q})_{\text{light}}, (M^1_{\tilde q})_{\text{light}}\right]\Big)$$

R-parity violating (RPV)

- RPV operators contribute to $R^{\nu(\bar{\nu})}$ at tree level

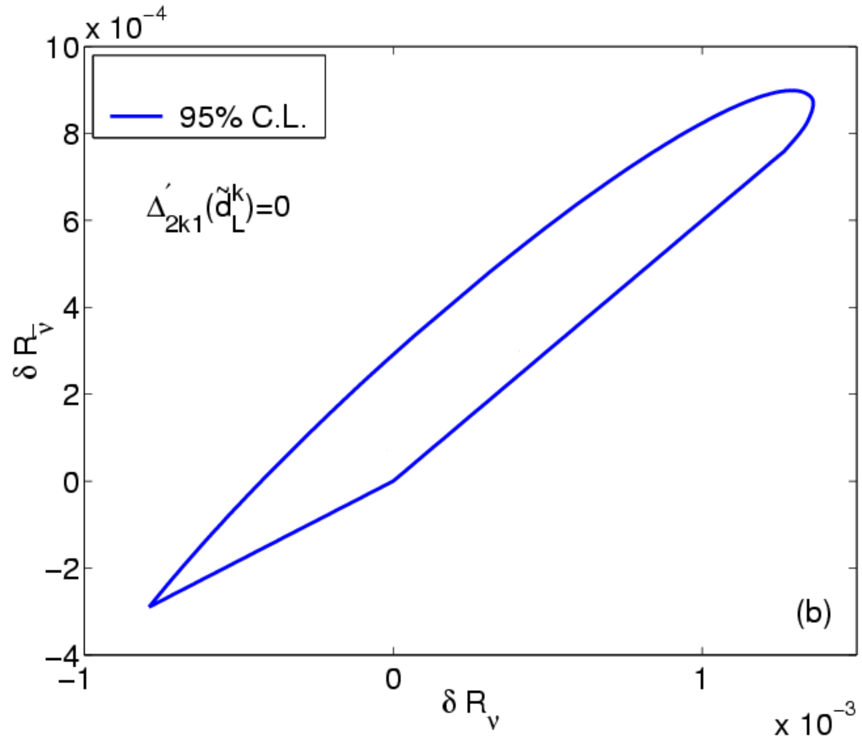
NC

CC



either wrong sign or too small

hard to explain NuTeV deviation



Conclusion

Parity-violating ee and ep scattering

- could be used to test SM and probe new physics
- MSSM contribution to Q^e_W and Q^p_W is 8% and 4% $\approx 1\ \sigma_{exp}$
  need higher exp precision to constrain SUSY
- correlation between Q^e_W and Q^p_W
  - distinguish various new physics
  - distinguish various SUSY scenario
    whether dark matter is SUSY particle ?

SUSY is not responsible for the NuTeV deviation

- other new physics ?
- hadronic effects ?