

Probing Supersymmetry with Neutral Current Scattering Experiments



Shufang Su • U. of Arizona

Sub-Z precision measurements

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

...

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

A. Kurylov, M. Ramsey-Musolf, SS

From Zero to Z^0

A WORKSHOP ON PRECISION ELECTROWEAK PHYSICS
Fermilab, May 12-14, 2004

Organizing Committee

J. Eiler	UNAM	co-chair	erler@fisica.unam.mx
M. Ramsey-Musolf	Caltech/UCorn	co-chair	mjm@krl.caltech.edu
J. Beacom	FNAL	R. Holt	ANL
R. Coates	JLAB	A. Kotwal	Duke-FNAL
B. Dobrescu	FNAL	H. Schellman	Northwestern
D. Deleese	Yale	S. Su	Arizona
S. Gardner	Kentucky	W. van Oers	Marilab/TRIUMF
J. Hardy	Texas A&M	M. Verzocchi	Maryland
C. Sazama	FNAL	S. Weber	FNAL

Workshop Sponsors
Tevatron Electroweak Working Group • Sub-Z Working Group
Funded by Fermi National Accelerator Laboratory
and Universities Research Association, Inc.

The search for physics beyond the Standard Model lies at the forefront of particle, nuclear, and atomic physics and links a broad spectrum of physics, from high energy colliders to laboratory table tops. This workshop provides a rare opportunity for physicists working on electroweak physics at different energy scales to interact with others involved in complementary efforts and to gain a more comprehensive picture of the search for new physics.

The broad perspective on the field will be addressed through a series of plenary talks plus discussion, with ample opportunities for interdisciplinary interactions.

Topics will include:
Electroweak physics at present and future colliders
CP-violation in heavy and light-quark systems
Weak decays • Rare and forbidden processes
Fundamental symmetry tests • Lepton scattering

Although there will be no parallel sessions or contributed talks, the opening reception will include a poster session to provide participants an opportunity to present their own work. The workshop will conclude with a panel discussion addressing issues for the future of the field.

Program & registration information: <http://www.krl.caltech.edu/~subZ/meet/>

Fermi National Accelerator Laboratory / Office of Science / U.S. Department of Energy / Managed by Universities Research Association, Inc.

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: $(\alpha/\pi)(M/M_{\text{new}})^2$

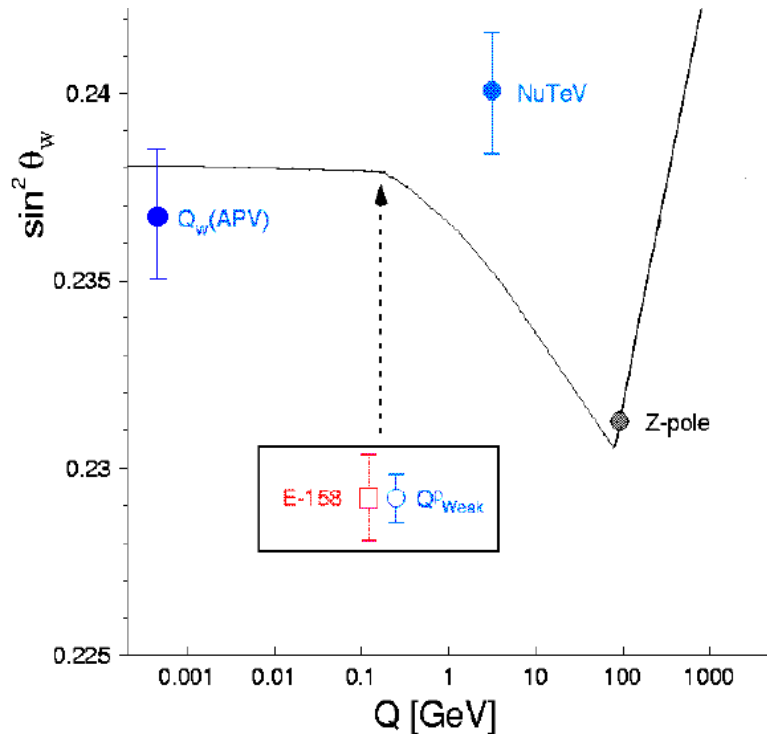
- muon $g-2$: $M=m_\mu$, $\delta^{\text{new}} \sim 2 \times 10^{-9}$, $\delta^{\text{exp}} < 10^{-9}$
- β -decay, π -decay: $M=m_W$, $\delta^{\text{new}} \sim 10^{-3}$, $\delta^{\text{exp}} \sim 10^{-3}$
- parity-violating electron scattering: $M=m_W$, $\delta^{\text{new}} \sim 10^{-3}$,

$$\mathcal{L}_{PV} = -\frac{G_\mu}{2\sqrt{2}} Q_W^f \bar{e} \gamma^\mu \gamma_5 e \bar{f} \gamma_\mu f \quad Q^{e,p}_W \sim 1-4 \sin^2 \theta_W \sim 0.1$$

- ✓ $1/Q^{e,p}_W \approx 10$ more sensitive to new physics
- ✓ need $\delta^{\text{exp}} \sim 10^{-2}$ "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

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

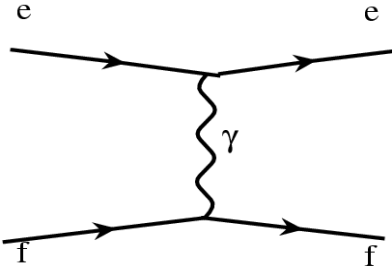
- ✓ clean environment: Hydrogen target
- ✓ theoretically clean: small hadronic uncertainties
- ✓ tree level $\sim 0.1 \Rightarrow$ sensitive to new physics

Goal

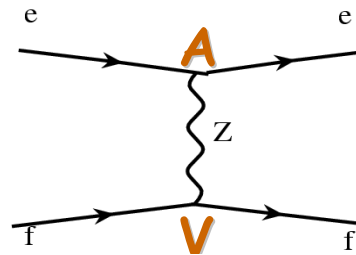
Develop consistency checks for theories of new physics using the low energy precision measurements

- 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_W^e , Q_W^p , (Q_W^{Cs}) - NuTeV: $R^{\nu(\bar{\nu})}$

Weak charge Q_W



$$\mathcal{L}_{PC} = \frac{e^2}{q^2} Q_e Q_f \bar{e} \gamma^\mu e \bar{f} \gamma_\mu f$$



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

$$A_{LR} \equiv \frac{N_+ - N_-}{N_+ + N_-} \propto Q_W^f$$

$$g_A^e = I_3^e$$

$$\text{weak charge } Q_W^f = 2g_V^f = 2 I_3^f - 4Q_f s^2$$

	ep Q_{weak} exp Q_W^p	ee Moller exp Q_W^e
$Q^{e,p}_W$ 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

$$Q_W^{Cs} : \delta \sin^2 \theta_W = 0.0021$$

$$\text{NuTeV: } \delta \sin^2 \theta_W = 0.0016$$

General structure of radiative corrections to Q_W^f

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

$$Q_W^f = \rho (2I_3^f - 4 \kappa Q_f s^2) + \lambda_f$$

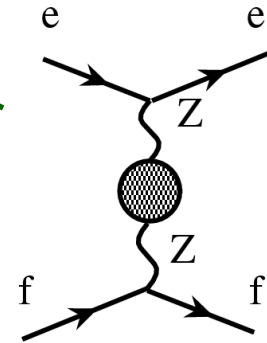
ρ, κ : universal, λ_f : depend on fermion species

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

ρ

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

correction to muon life time



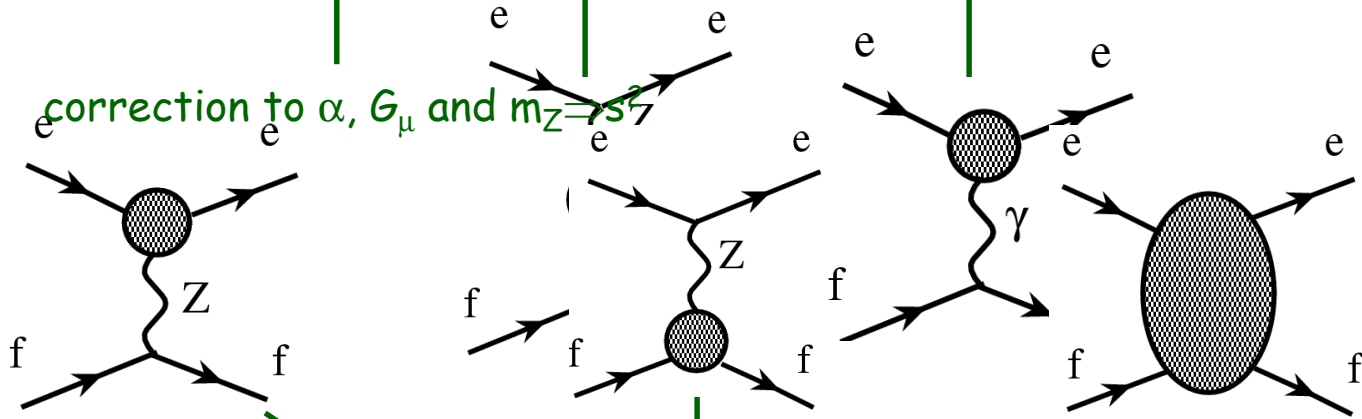
Radiative contributions

$$Q_W^f = \rho (2I_3^f - 4 \kappa Q_f s^2) + \lambda_f$$

κ

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

correction to α , G_μ and $m_Z = s^2$



λ_f

$$\lambda_f = 2(g_V^f \delta V_A^e + g_A^e \delta V_V^f + \delta_{box}^{ef})$$

MSSM particle contents

SM particle

Spin differ by 1/2

superpartner

Names		spin 0	spin 1/2
squarks, quarks (× 3 families)	Q	$(\tilde{u}_L, \tilde{d}_L)$	(u_L, d_L)
	\bar{U}	\tilde{u}_R^*	u_R^\dagger
	\bar{D}	\tilde{d}_R^*	d_R^\dagger
sleptons, leptons (× 3 families)	L	$(\tilde{\nu}, \tilde{e}_L)$	(ν, e_L)
	\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

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

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

$$\mu, \quad \tan\beta = v_u/v_d$$

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

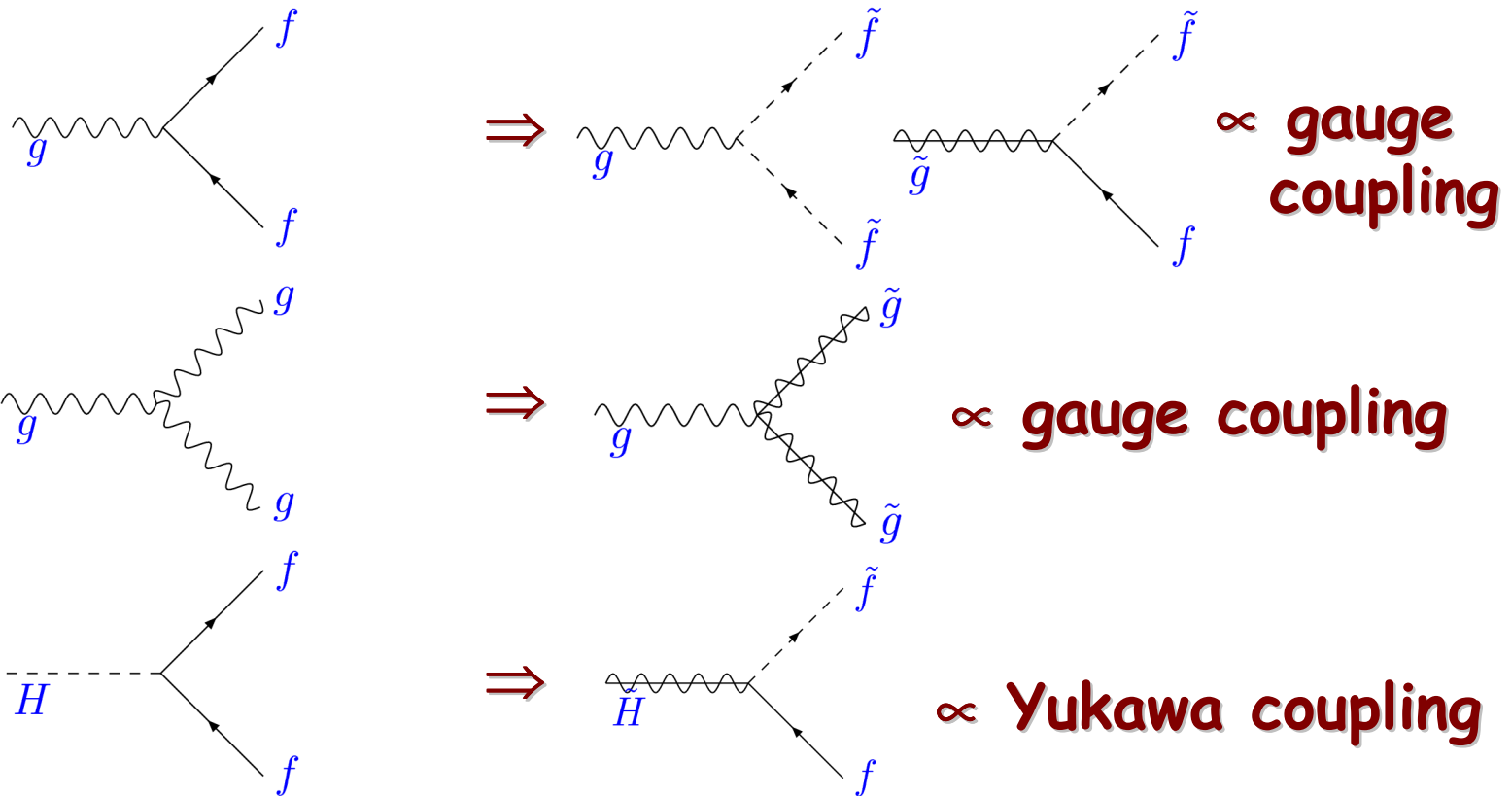
$$M_3$$

$$M_2$$

$$M_1$$

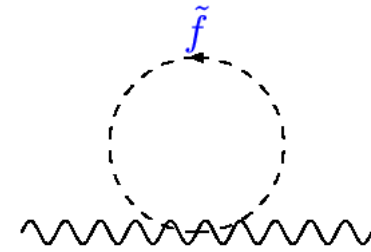
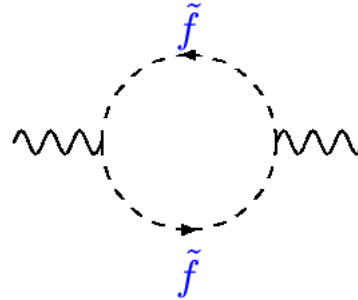
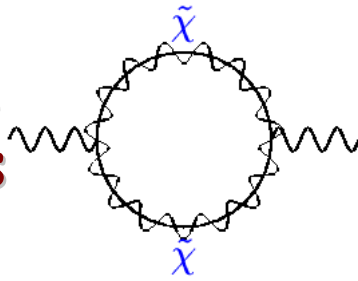
SUSY interactions

replace **two** SM particles into SUSY partners

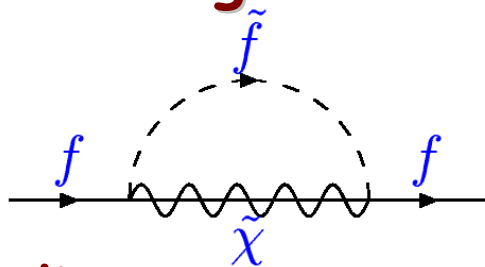


One loop SUSY contributions to PVES

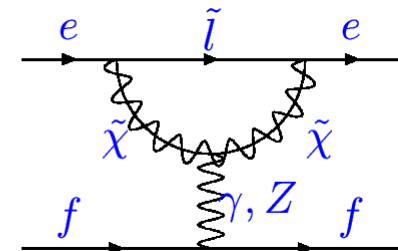
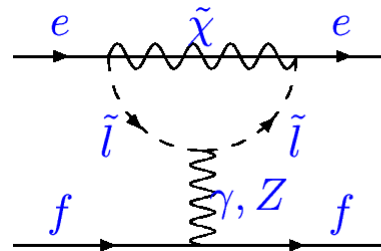
- gauge boson self-energies



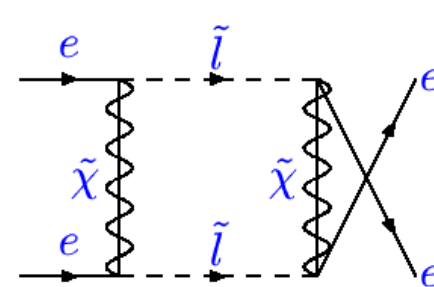
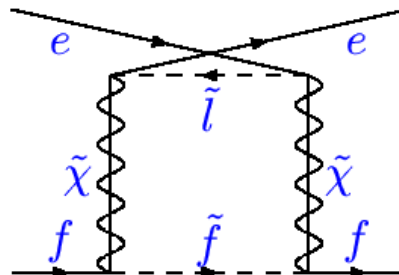
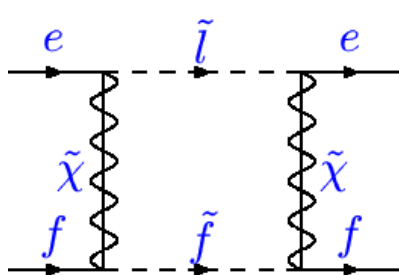
- external leg corrections



- vertex corrections



- box diagrams



Numerical analysis

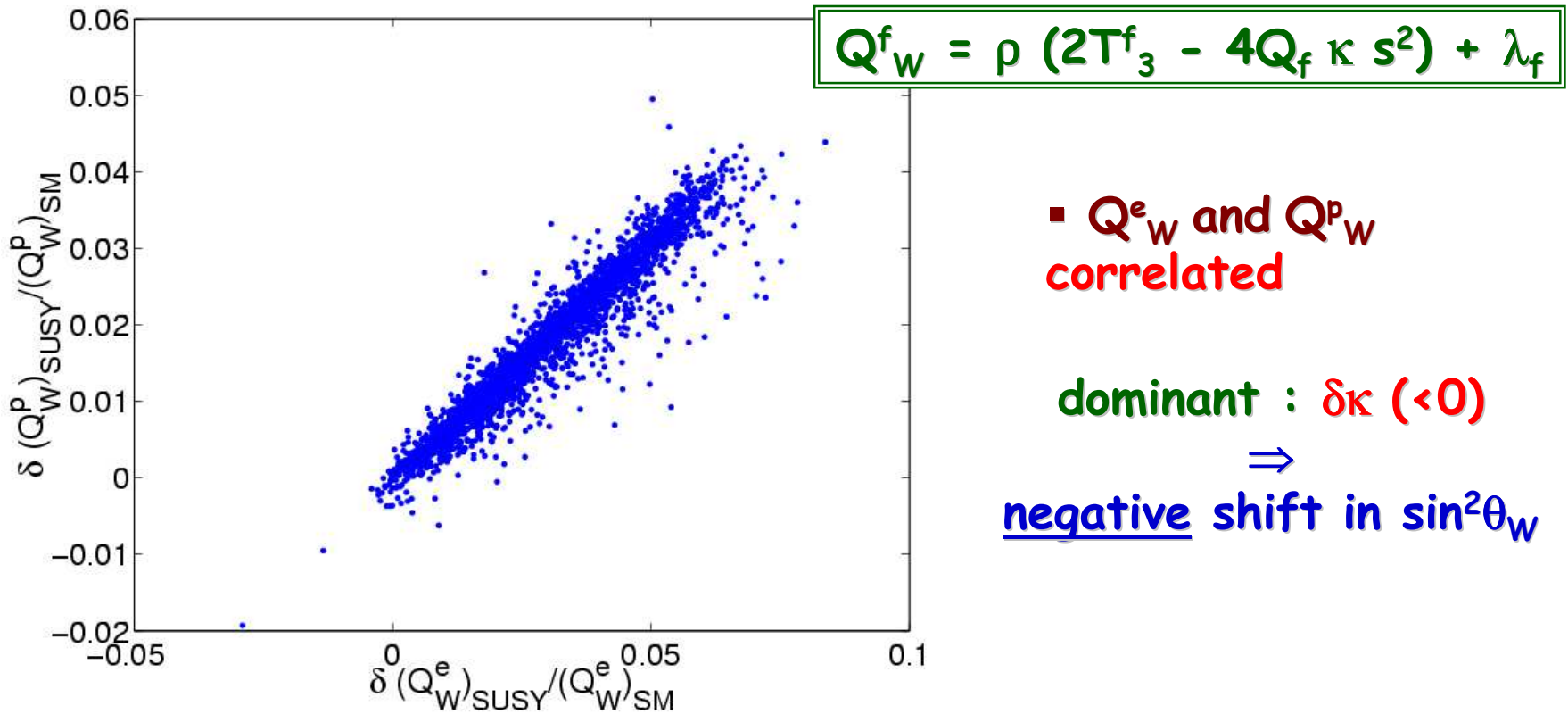
Model-independent analysis

- **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



$\delta(Q_W^p)_{SUSY} / (Q_W^p)_{SM} < 4\%, \delta(Q_W^e)_{SUSY} / (Q_W^e)_{SM} < 8\%$

Dominant contributions

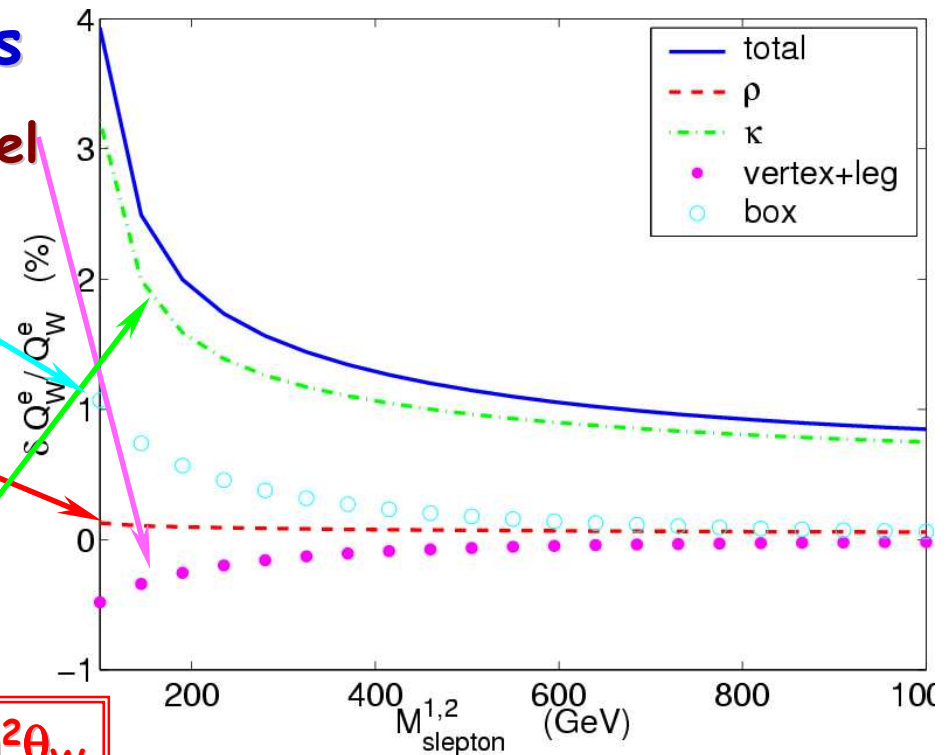
$$Q_W^f = \rho (2T_3^f - 4Q_f \kappa s^2) + \lambda_f$$

- **non-universal corrections**

- vertex + wavefunction : cancel
- box diagrams numerically suppressed

- $\delta\rho$ contribution suppressed by $(1-4s^2)$

- dominant contribution from $\delta\kappa$



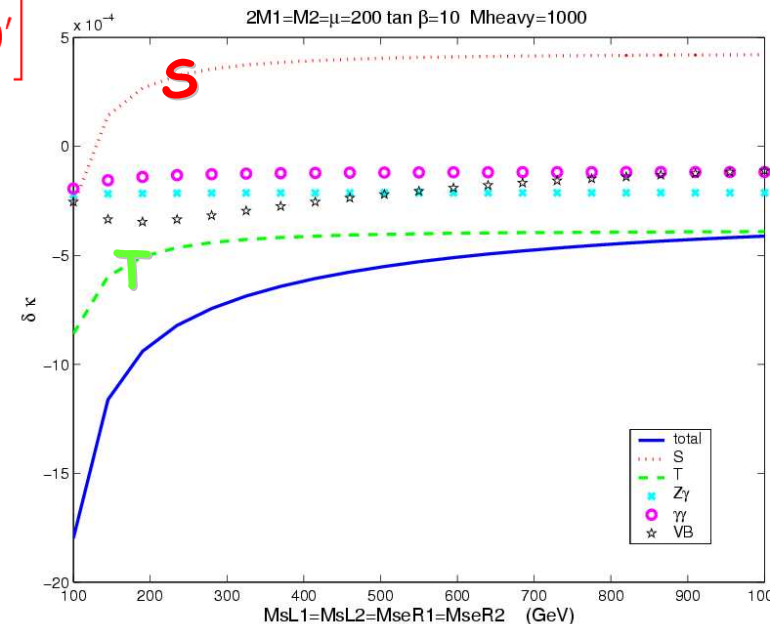
$\delta\kappa (<0) \Rightarrow$ negative shift in $\sin^2\theta_W$

Various contributions to $\delta\kappa$

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

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

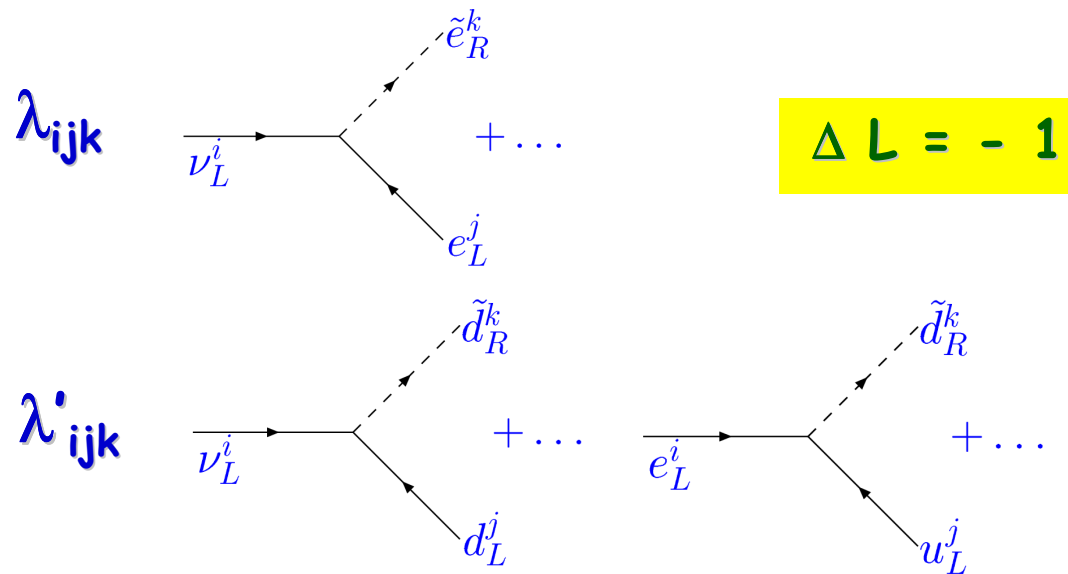
- **within $\delta\kappa$**
- various terms have comparable importance
- oblique approximation gives a **poor** description



- $\delta\kappa < 0$ ($\delta (Q^{e,P_W})_{SUSY} / (Q^{e,P_W})_{SM} > 0$)
 \Rightarrow **reduction in effective $\sin^2\theta_W$**

R-parity

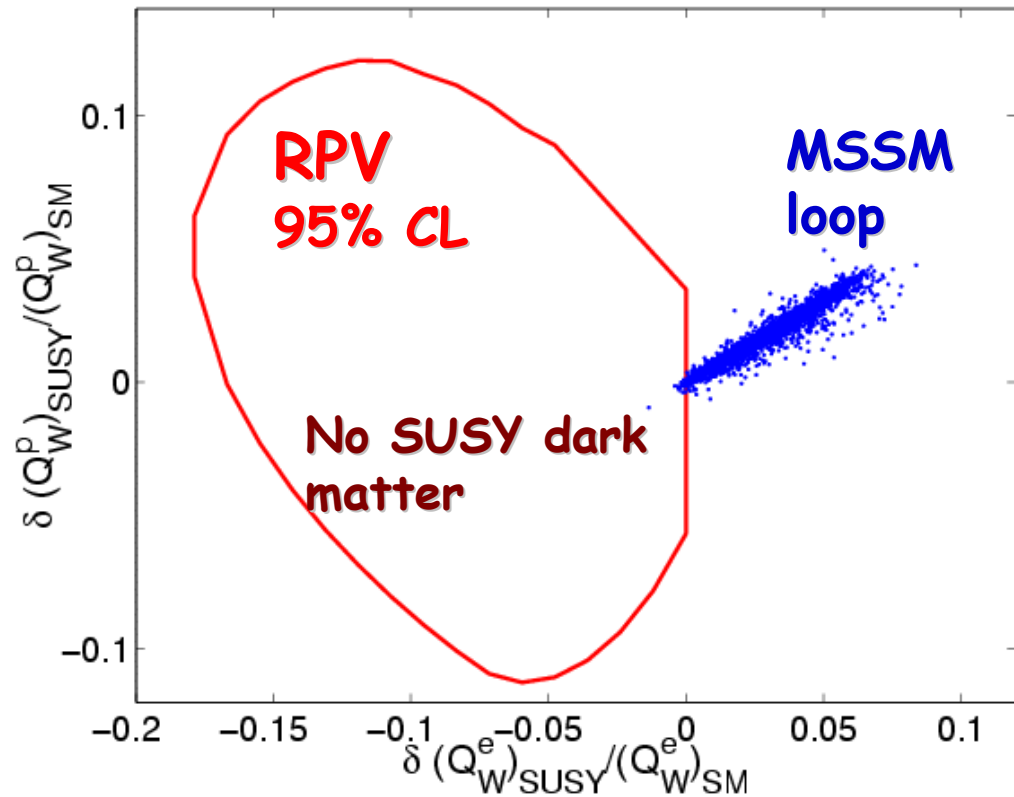
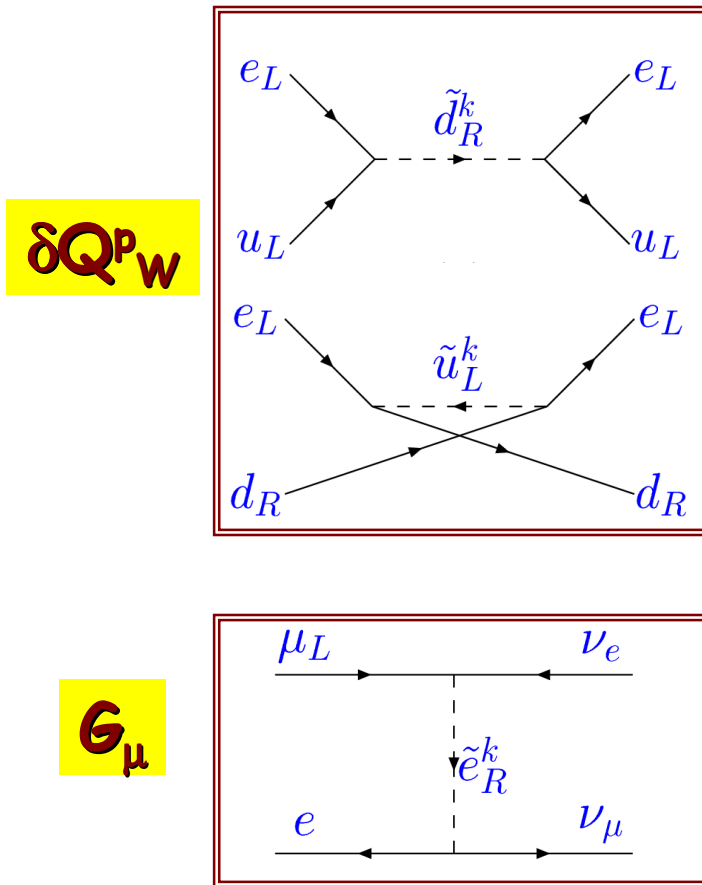
- General MSSM, including **B,L-violating** operators



- **dangerous** \Rightarrow 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



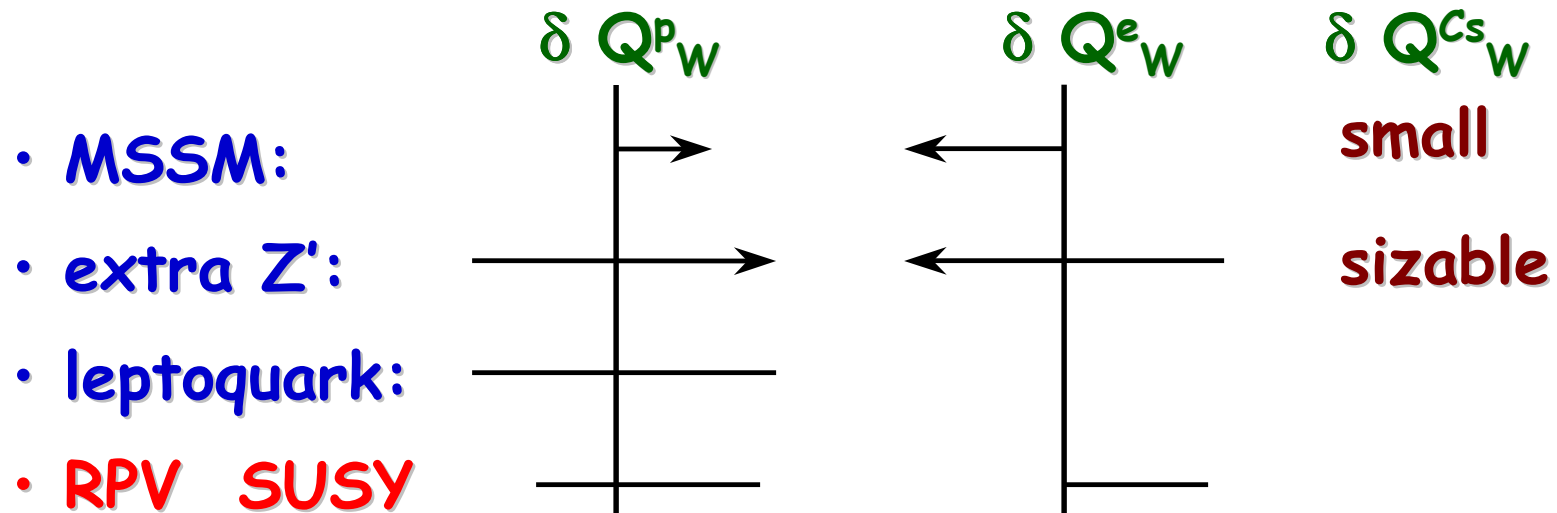
Correlation between Q_W^p and Q_W^e

➤ SUSY correction to heavy nuclei Q_W

- $\delta Q_W(Z,N) = (2Z+N) \delta Q_W^u + (2N+Z) \delta Q_W^d$

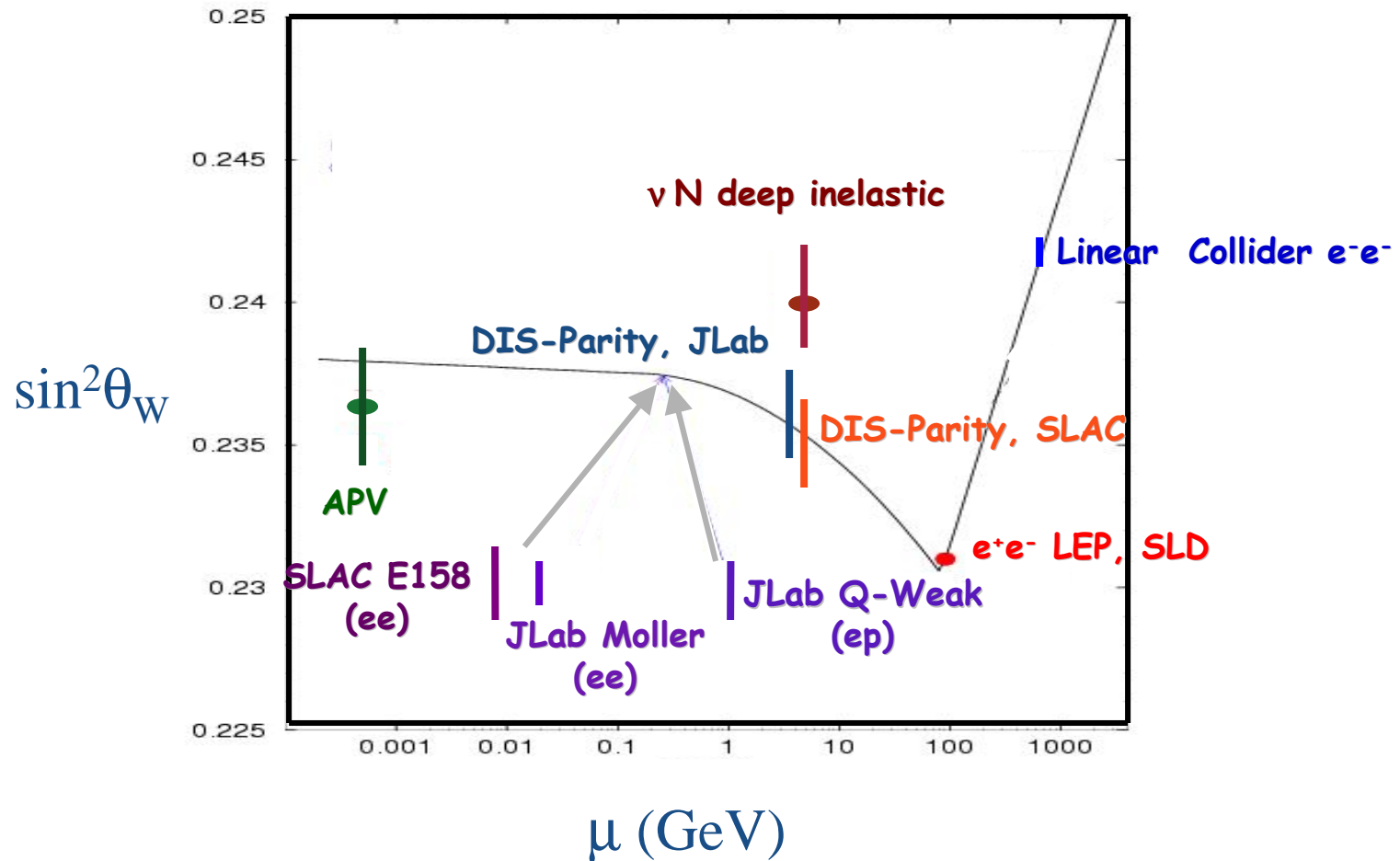
$\delta Q_W^u > 0$ $\delta Q_W^d < 0$	\Rightarrow	$\delta Q_W(Z,N) / Q_W(Z,N) < 0.2\%$ for Cs
--	---------------	---

➤ Distinguish new physics

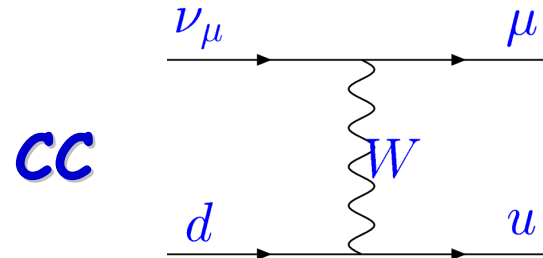
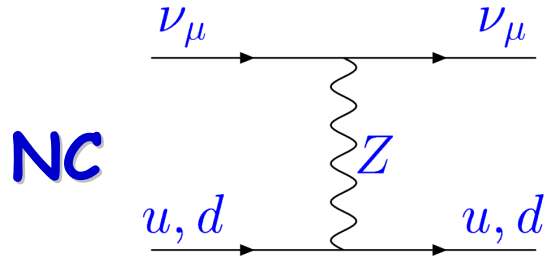


Additional PV electron scattering ideas

Czarnecki, Marciano □ Erler *et al.*



NuTeV experiment



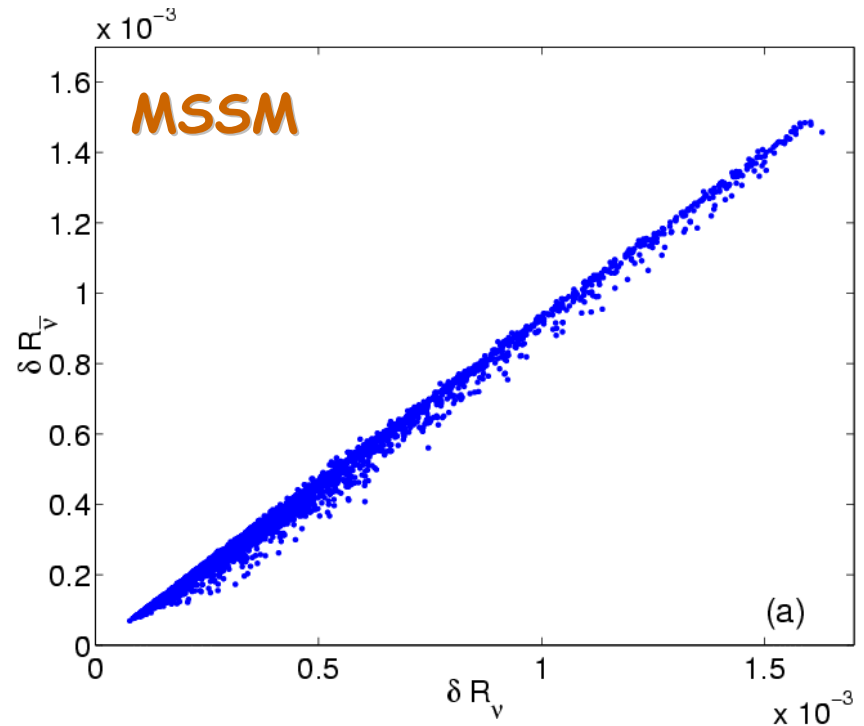
$$R^{\nu(\bar{\nu})} \equiv \frac{\sigma(\nu N \rightarrow \nu X)}{\sigma(\bar{\nu} N \rightarrow l^{-(+)X)}$$

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

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

wrong-sign contribution!

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

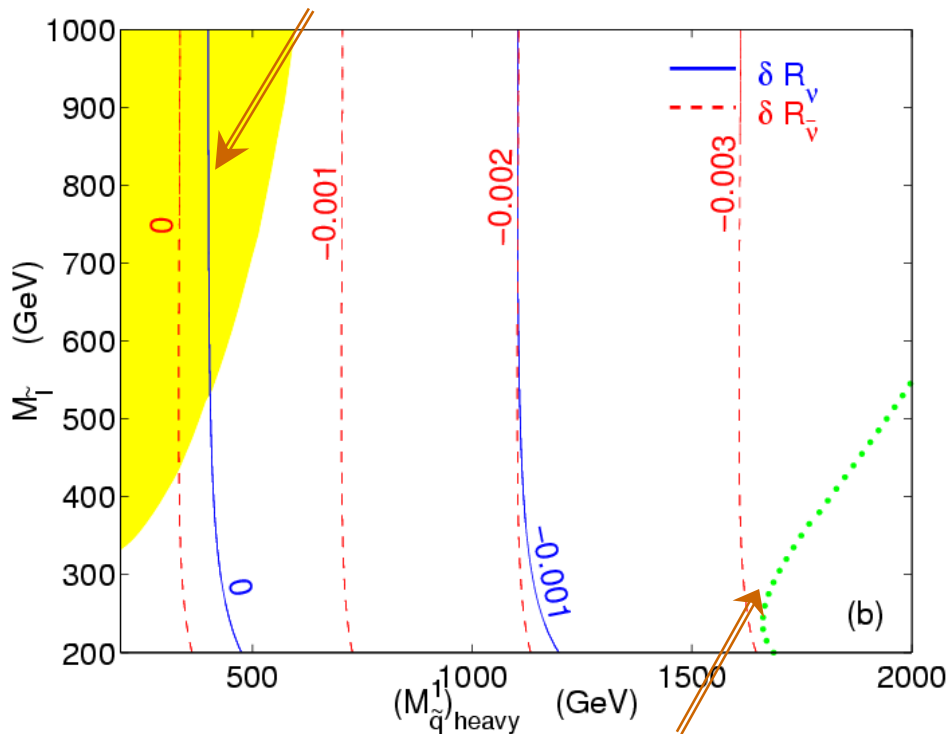


Glino contribution

negative gluino contribution

CC data constraints

Kurylov, Ramsey-Musolf, PRL88,071804,2002



unitarity deviation decrease by $1/3 \sigma$

- 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

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

- in practice, modified version

$$\tilde{R}^- \equiv \frac{R_\nu - \xi R_{\bar{\nu}}}{1 - r}$$

ξ different from r
 \Rightarrow charm quark mass
 uncertainties

- gluino contributions

$$\propto \xi - r$$

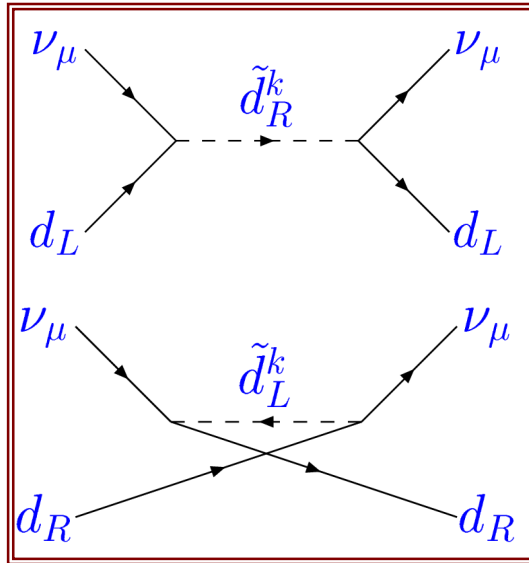
	1C	0C
m_c	constrained	free
ξ	0.249	0.453
$\delta\sin^2\theta_W$	-1.6×10^{-3}	-1×10^{-4}

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

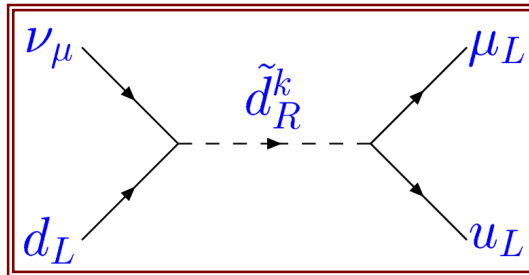
R-parity violating (RPV)

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

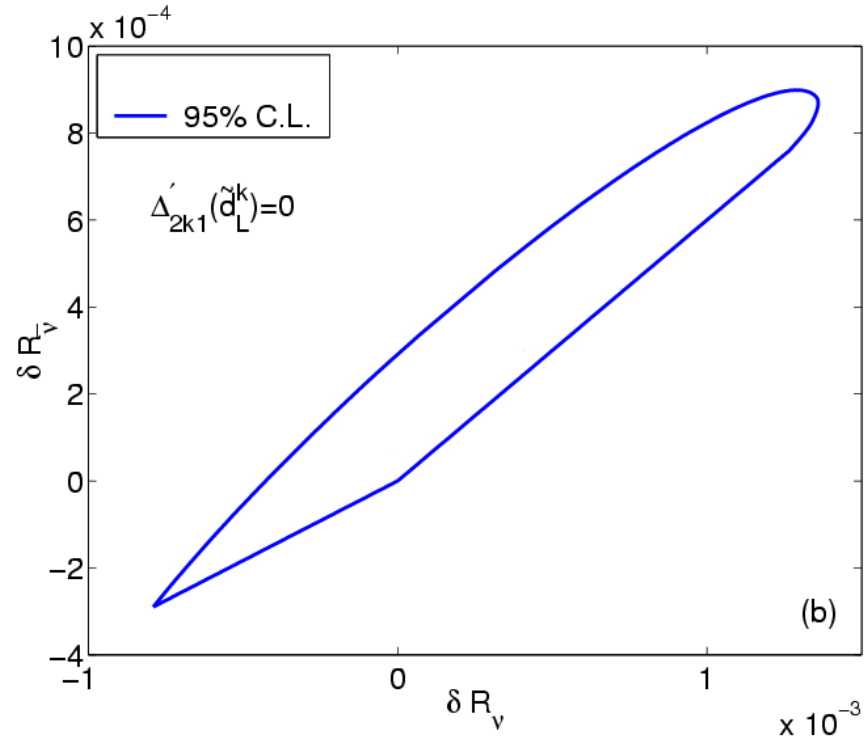
NC



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_W^e and Q_W^p is 8% and 4% $\approx 1 \sigma_{\text{exp}}$
need higher exp precision to constrain SUSY
- correlation between Q_W^e and Q_W^p
 - 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 ?