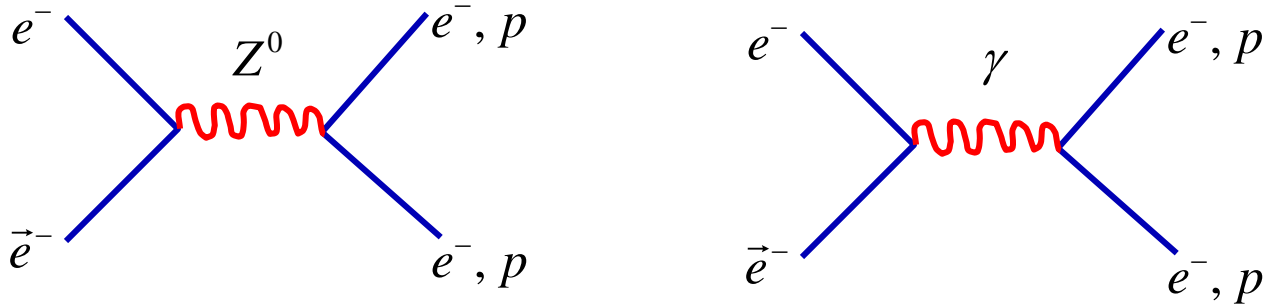
SUSY can affect scattering

Parity-Violating electron scattering

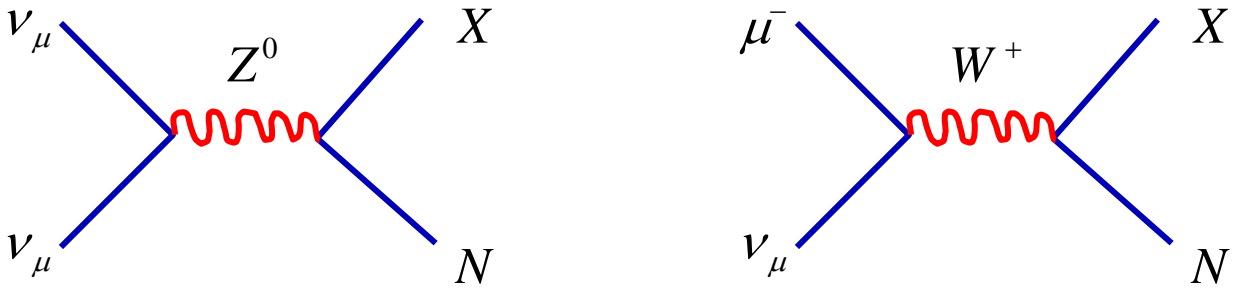


$$A_{LR} = \frac{G_F Q^2}{4\sqrt{2}\pi\alpha}\left[Q_W + F(Q^2,\theta)\right]$$

"Weak Charge" ~ $1 - 4\sin^2\theta_W \sim 0.1$

SUSY can affect scattering

Neutrino-nucleus deep inelastic scattering



Cross section ratios $R^- = \left(1 - 2\sin^2\theta_W\right)^2$

Neutral currents mix

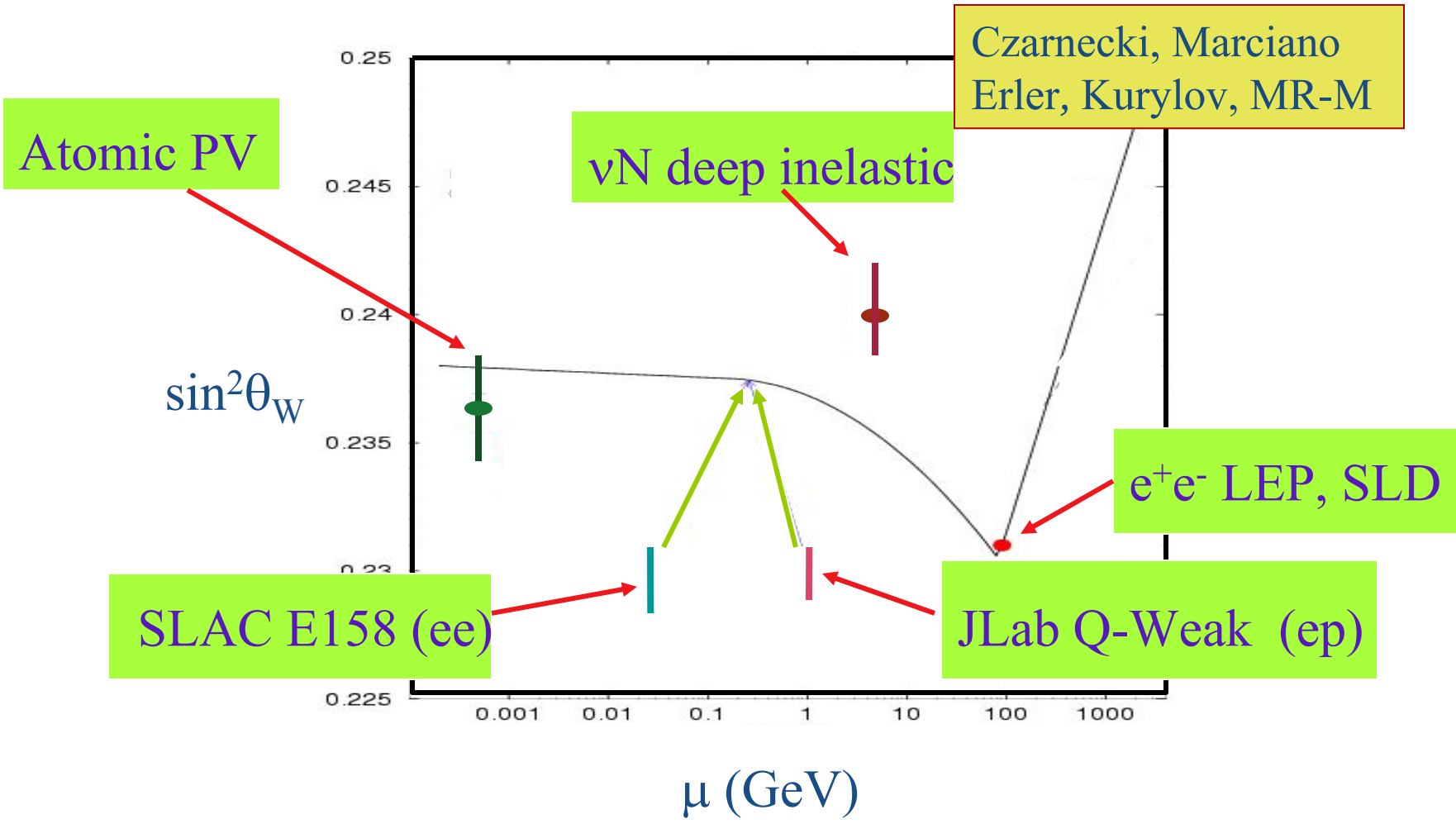
$$\cdot J_\mu{}^Z = J_\mu{}^0 + 4\,Q \sin^2\theta_W \cdot J_\mu{}^{EM}$$

$$\sin^2\theta_W = \frac{g(\mu)_Y^2}{g(\mu)^2 + g(\mu)_Y^2}$$

$SU(2)_L$ $U(1)_Y$

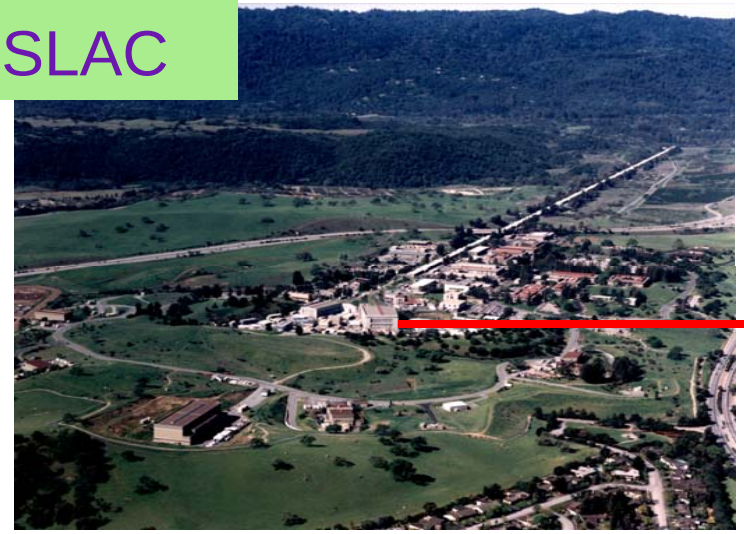
Weak mixing depends on scale

Weak Mixing Angle: Scale Dependence



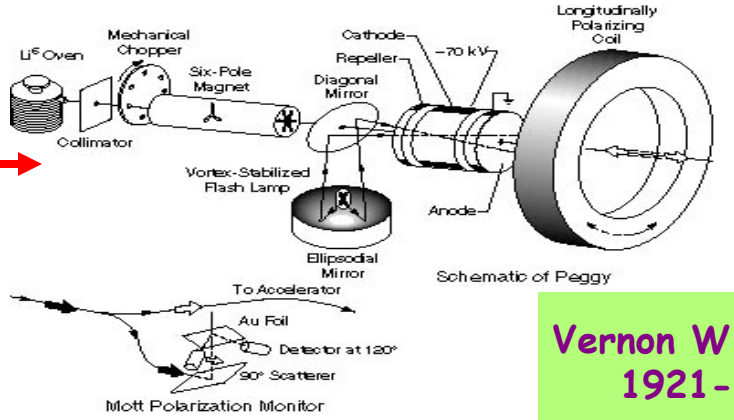
PV Electron Scattering

SLAC



E158

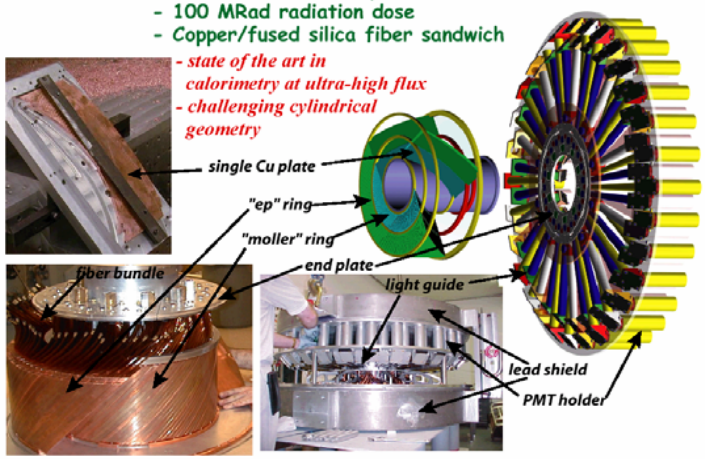
A precision measurement of the Weak Mixing Angle in Møller Scattering



Vernon W. Hughes
1921-2003

Jefferson Lab

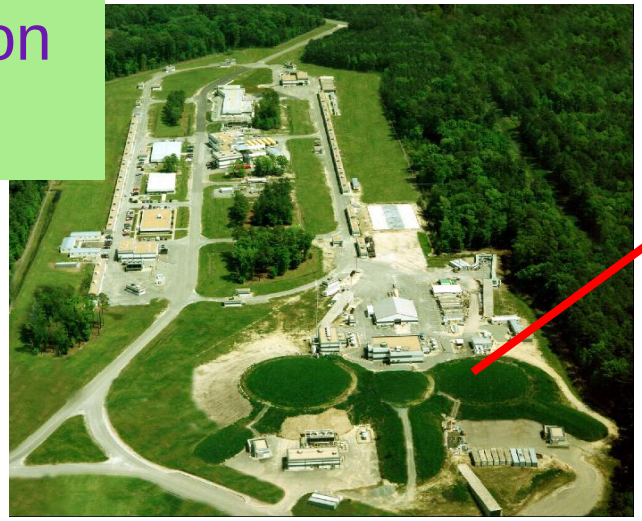
- 20 million electrons/pulse at 120 Hz
- 100 MRad radiation dose
- Copper/fused silica fiber sandwich



PV Electron Scattering

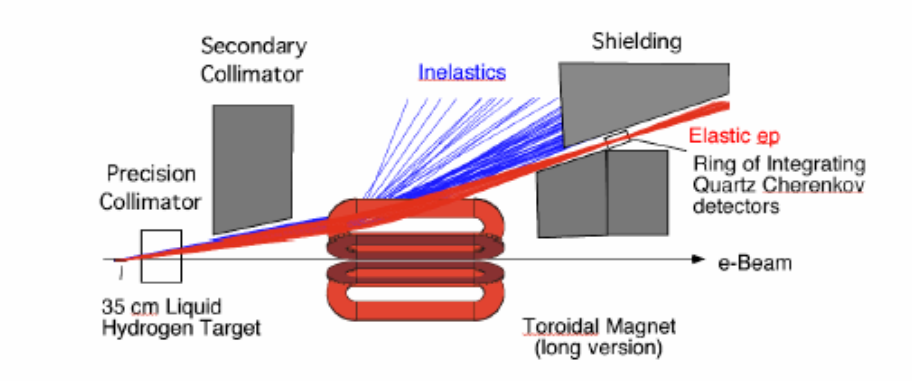
SLAC

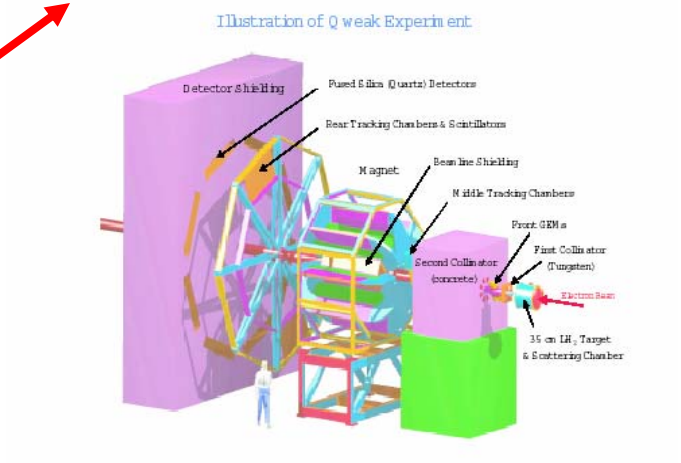
Jefferson Lab



A SEARCH FOR NEW PHYSICS

Qweak





Interpretation of precision measurements

How well do we now the SM predictions?

Some QCD issues

Proton Weak Charge

$$A_{LR} = \frac{G_F Q^2}{4\sqrt{2}\pi\alpha}\left[Q_W^p + F^p(Q^2,\theta)\right]$$

Weak charge

Form factors: MIT, JLab, Mainz

Q^2=0.03 (GeV/c)^2

Q^2>0.1 (GeV/c)^2

Interpretation of precision measurements

How well do we now the SM predictions?

Some QCD issues

Proton Weak Charge

$$A_{LR} = \frac{G_F Q^2}{4\sqrt{2}\pi\alpha}\left[Q_W^p + F^p(Q^2,\theta)\right]$$

$F^P(Q^2, \theta \to 0) \sim Q^2$

Use χPT to extrapolate in small Q^2 domain and current PV experiments to determine LEC's

Q_W and SUSY Radiative Corrections

Tree Level

$$Q_W^f = g_V^f$$

Radiative Corrections

Flavor-dependent

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

Normalization

Scale-dependence of weak mixing

Flavor-independent

Universal corrections

$$\delta\rho_{PV} = \hat{\alpha}T - \hat{\delta}^{\mu}_{VB}$$

muon decay

$$\delta\kappa^{SUSY}_{PV} = -\hat{\alpha}\left(\frac{\hat{c}^2}{\hat{c}^2-\hat{s}^2}\right)T + \hat{\alpha}\left(\frac{1}{4\hat{s}^2(\hat{c}^2-\hat{s}^2)}\right)S$$

$$+\frac{\hat{c}}{\hat{s}}\left[\frac{\hat{\Pi}_{Z\gamma}(q^2)}{q^2} - \frac{\hat{\Pi}_{Z\gamma}(M_Z^2)}{M_Z^2}\right] + \left(\frac{\hat{c}^2}{\hat{c}^2-\hat{s}^2}\right)\left[\frac{\Delta\hat{\alpha}}{\hat{\alpha}} - \frac{\hat{\Pi}_{\gamma\gamma}(M_Z^2)}{M_Z^2}\right] + \hat{\delta}^{\mu}_{VB}$$

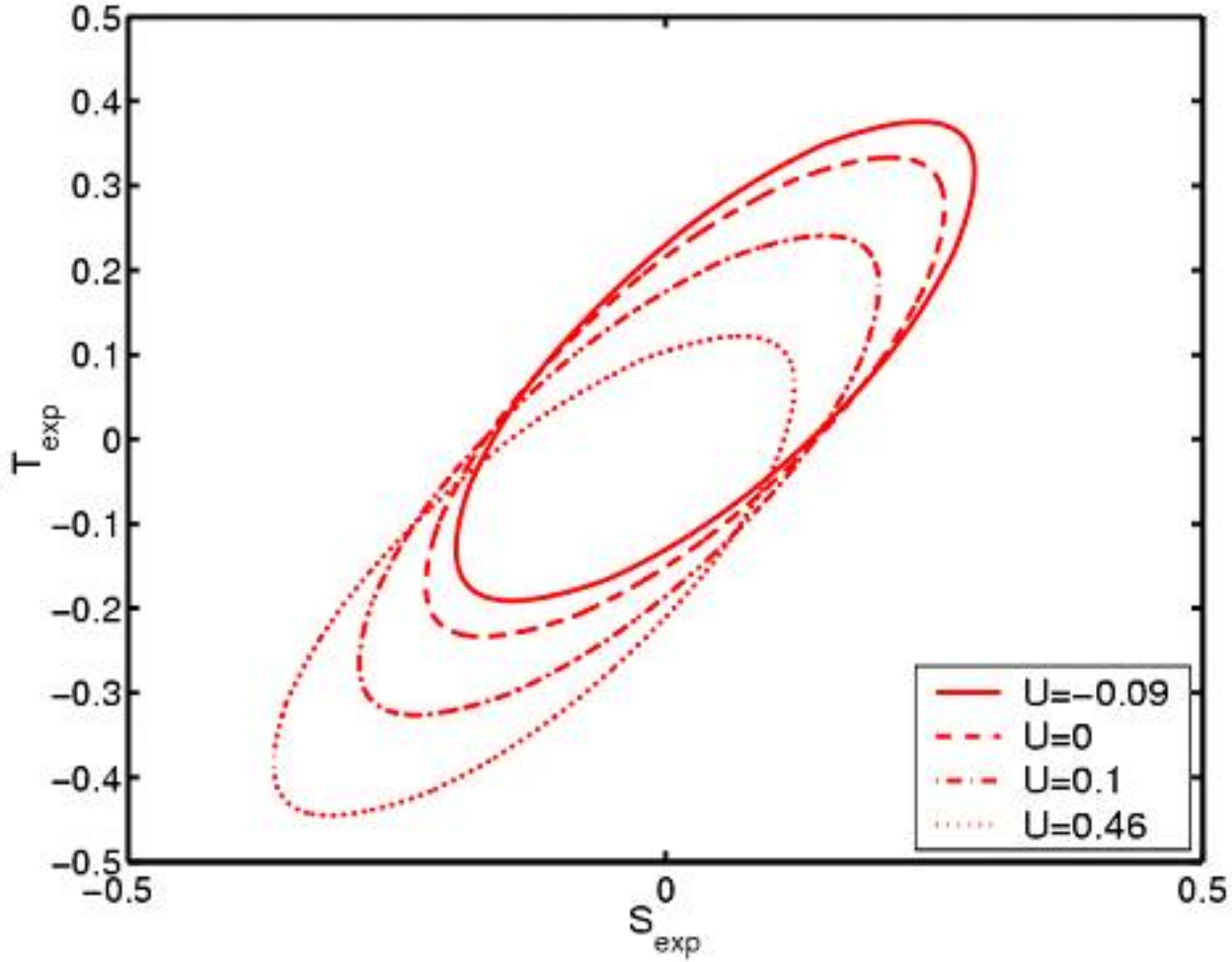
$$S, T, \hat{\Pi}_{VV'}$$

gauge boson propagators

Oblique Parameters

SM fit only

No SUSY effects

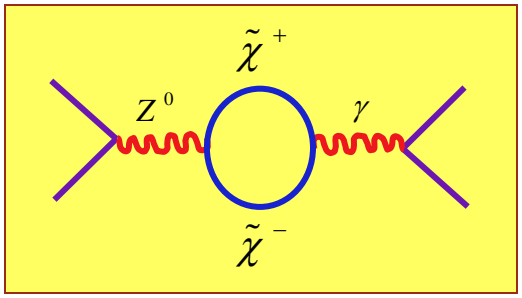


Parameter Space Scan

Parameter	Min	Max
$\tan\beta$	1.4	60
$\tilde{M}$	50 GeV	1000 GeV
$M^{L}_{\tilde{L}_{LR}}$	-1000 GeV	1000 GeV

Comparing Q_w^e and Q_W^p

105 parameters: random scan



QuickTime™ and a TIFF (Uncompressed) decompressor are

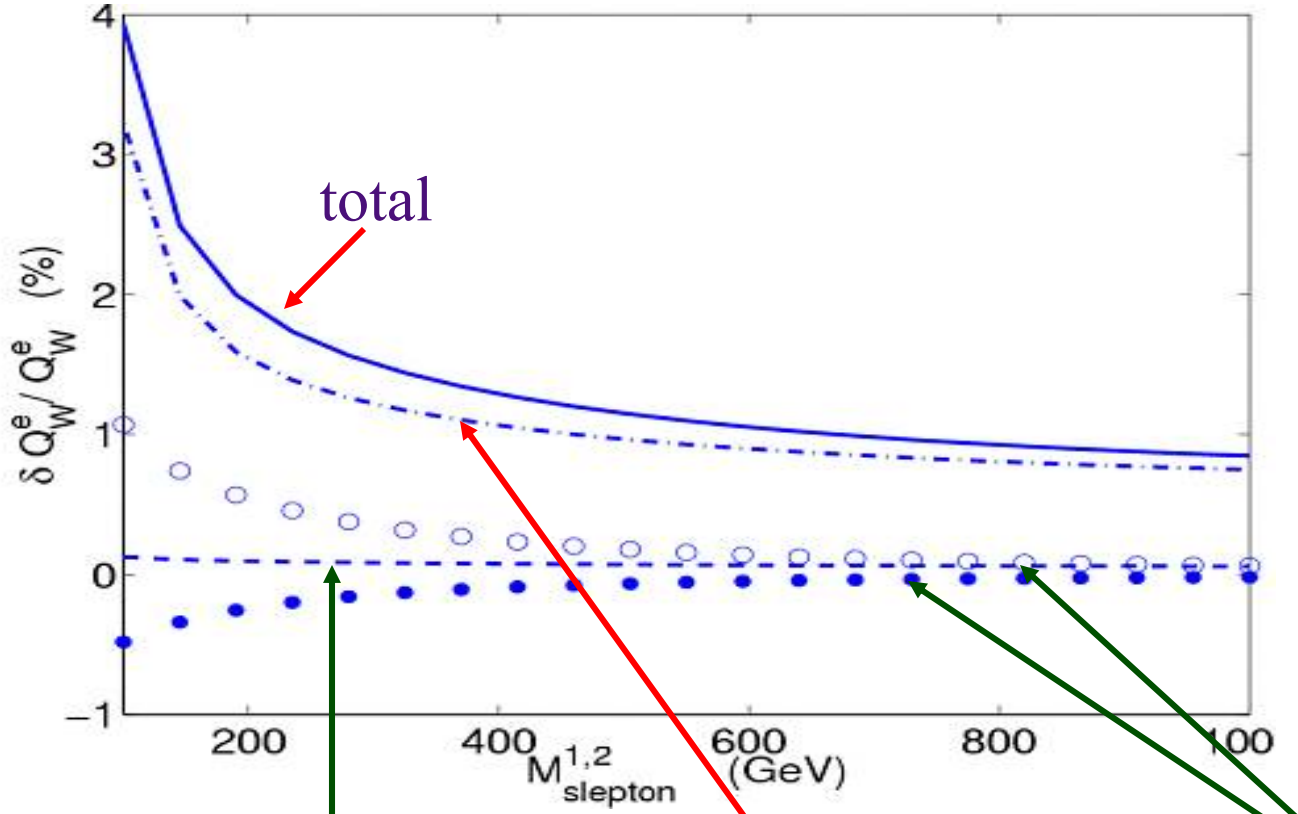
3000 randomly chosen SUSY parameters but effects are correlated

Effects in $\sin^2\theta_W$ dominate

Negligible SUSY loop impact on cesium weak charge

Kurylov, Su, MR-M

Correlated Radiative Corrections



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

RPV Corrections to Weak Charges

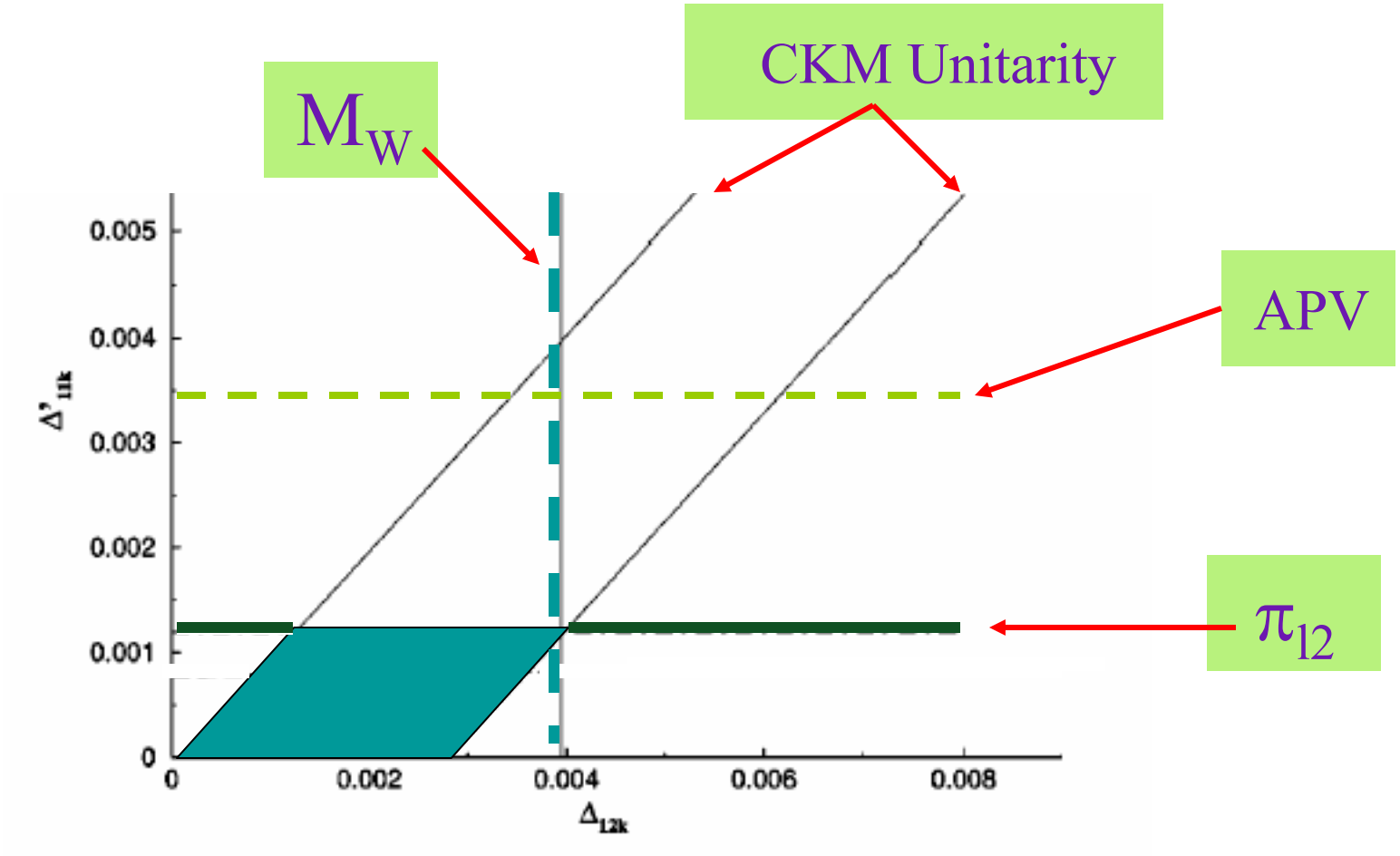
$$\frac{\Delta Q_W^p}{Q_W^p} \approx \left(\frac{2}{1-4\hat{s}^2}\right)\left[-2\lambda_{\hat{s}}\Delta_{12k}(\tilde{e}_R^k) + 2\Delta'_{11k}(\tilde{d}_R^k) - \Delta'_{1j1}(\tilde{q}_L^j)\right]$$

$$\frac{\Delta Q_W^e}{Q_W^e} \approx -\left(\frac{4}{1-4\hat{s}^2}\right)\lambda_{\hat{s}}\Delta_{12k}(\tilde{e}_R^k)$$

shift in $\sin^2\theta_W$

$$\lambda_{\hat{s}} \approx \frac{\hat{s}^2(1-\hat{s}^2)}{1-2\hat{s}^2}$$

Other constraints, cont'd.



Comparing Q_w^e and Q_W^p

SUSY loops

No SUSY dark matter

χ^0 ->

QuickTime™ and a TIFF (Uncompressed) decompressor are needed to see this picture.

ν is Majorana

RPV 95% CL fit to weak decays, M_W, *etc.*

Kurylov, Su, MR-M

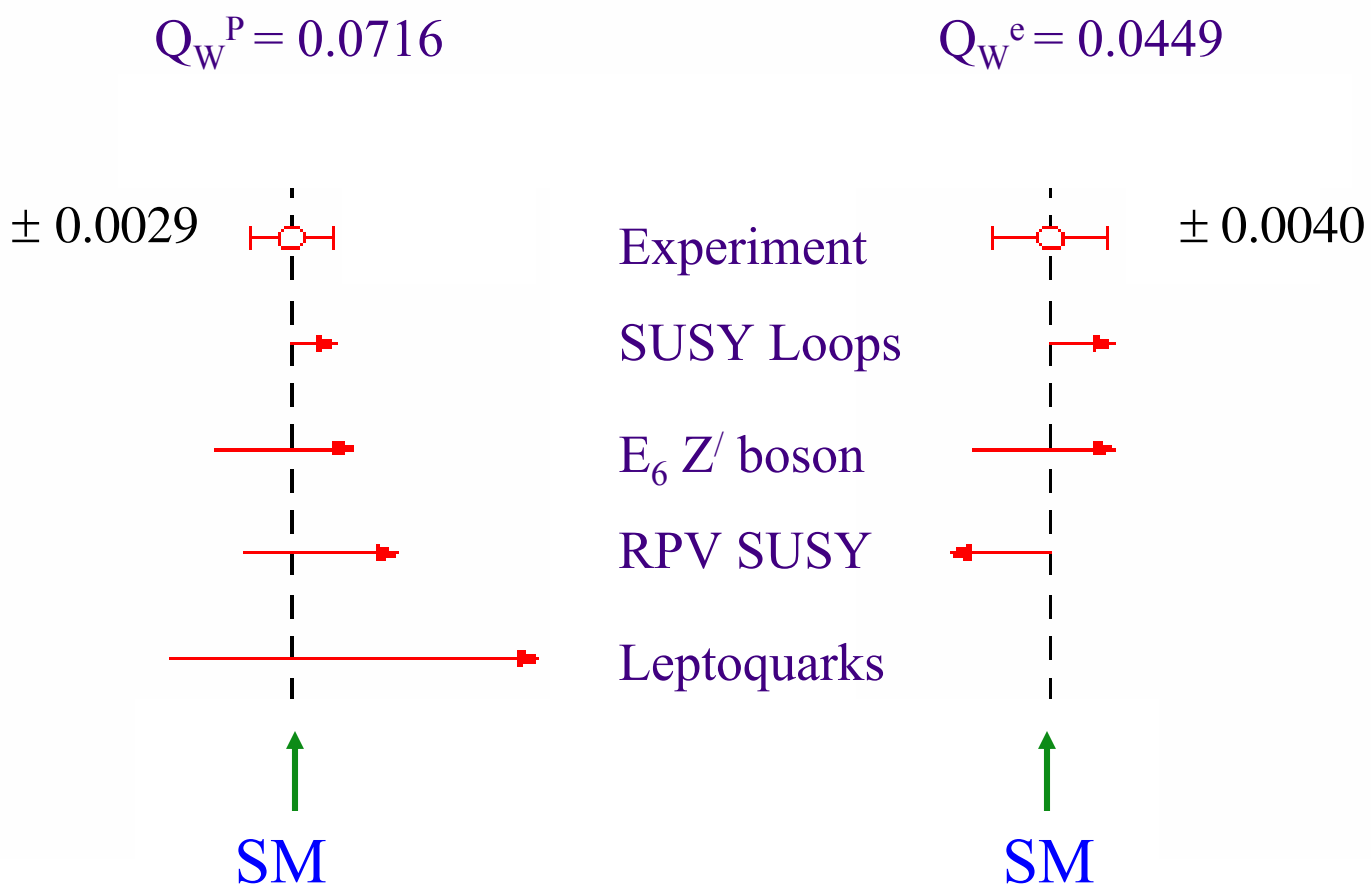
Comparing Q_W^e and Q_W^p

Can be a *diagnostic tool* to determine whether or not

- the early Universe was *supersymmetric*
- there is *supersymmetric* dark matter

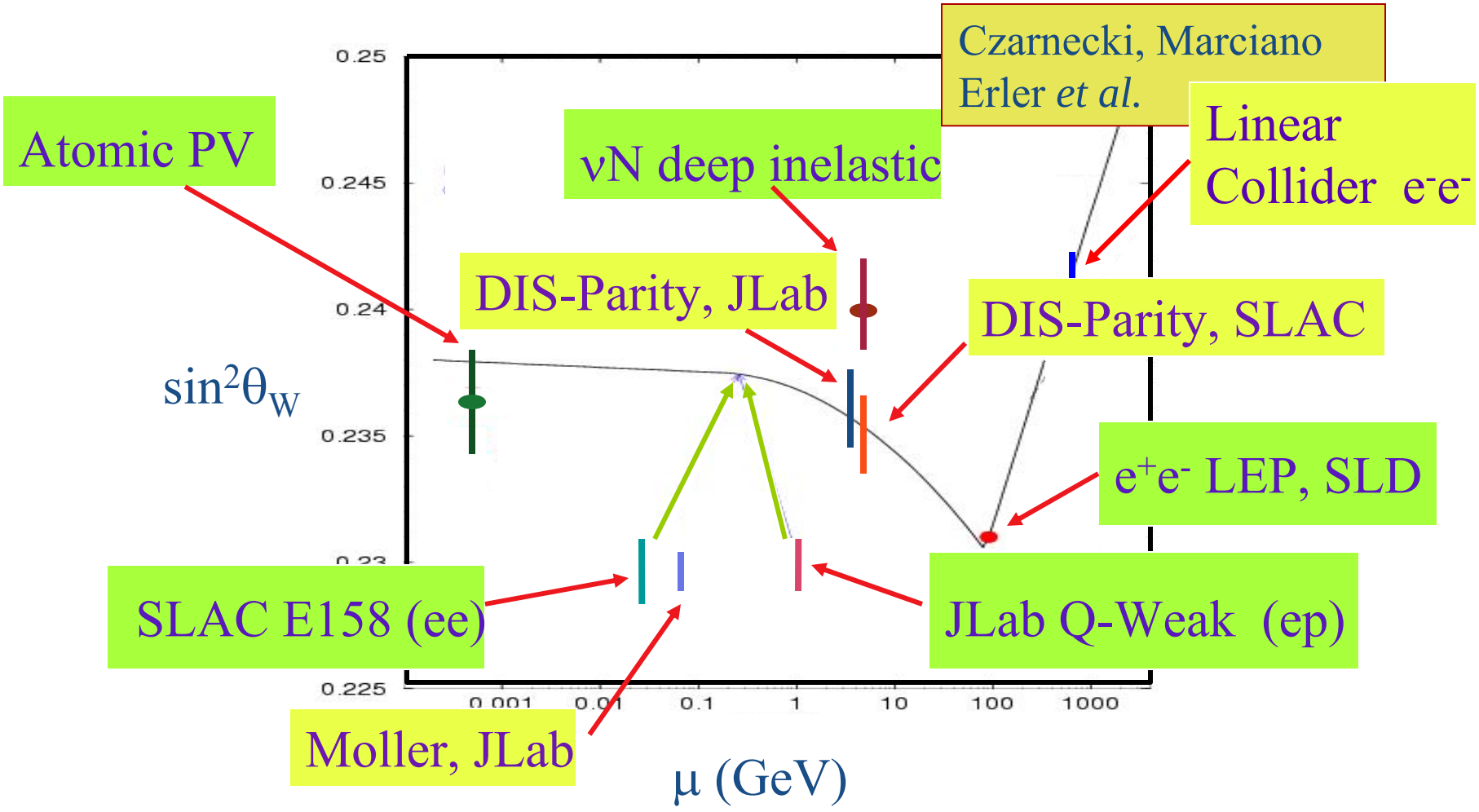
The weak charges can serve a similar diagnostic purpose for other models for high energy symmetries, such as *left-right symmetry*, *grand unified theories with extra U(1) groups*, etc.

Comparing Q_w^e and Q_w^p

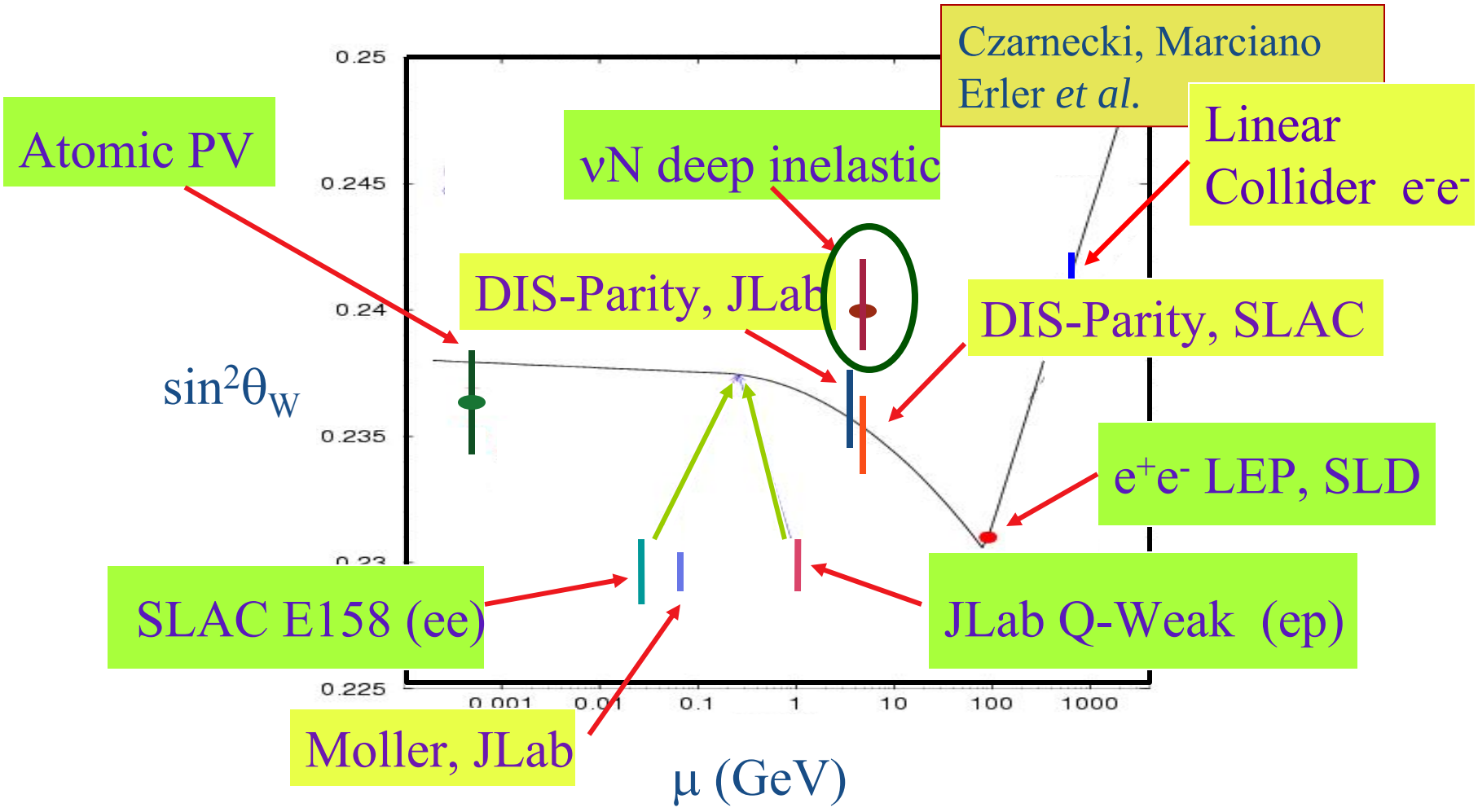


Erler, Kurylov, R-M

Additional PV electron scattering ideas



Additional PV electron scattering ideas



Neutrino-nucleus deep inelastic scattering conflicts with SUSY

Cross section ratios

$$R_\nu = \sigma_{\nu N}^{NC} / \sigma_{\nu N}^{CC}$$

$$R_{\bar\nu} = \sigma_{\bar\nu N}^{NC} / \sigma_{\bar\nu N}^{CC}$$

Exp't vs. SM Theory: NuTeV

$$R_\nu^{\exp} - R_\nu^{SM} = -0.0033 \pm 0.0005$$

$$R_{\bar\nu}^{\exp} - R_{\bar\nu}^{SM} = -0.0015 \pm 0.0010$$

$$R^- = \frac{R_\nu - r R_{\bar\nu}}{1-r} = (1 - 2\sin^2\theta_W)/2 + \cdots \qquad r = \sigma_{\nu N}^{CC} / \sigma_{\bar\nu N}^{CC}$$

ν-Nucleus DIS, Cont'd.

Cross section ratios

$$R_\nu = \sigma_{\nu N}^{NC} / \sigma_{\nu N}^{CC} = g_L^2 + r g_R^2 \qquad g_{L,R}^2 = \left(\frac{\rho_{\nu N}^{NC}}{\rho_{\nu N}^{CC}} \right)^2 \sum_q (\varepsilon_{L,R}^q)^2$$

$$R_{\bar{\nu}} = \sigma_{\bar{\nu} N}^{NC} / \sigma_{\bar{\nu} N}^{CC} = g_L^2 + r^{-1} g_R^2 \qquad r = \sigma_{\nu N}^{CC} / \sigma_{\bar{\nu} N}^{CC}$$

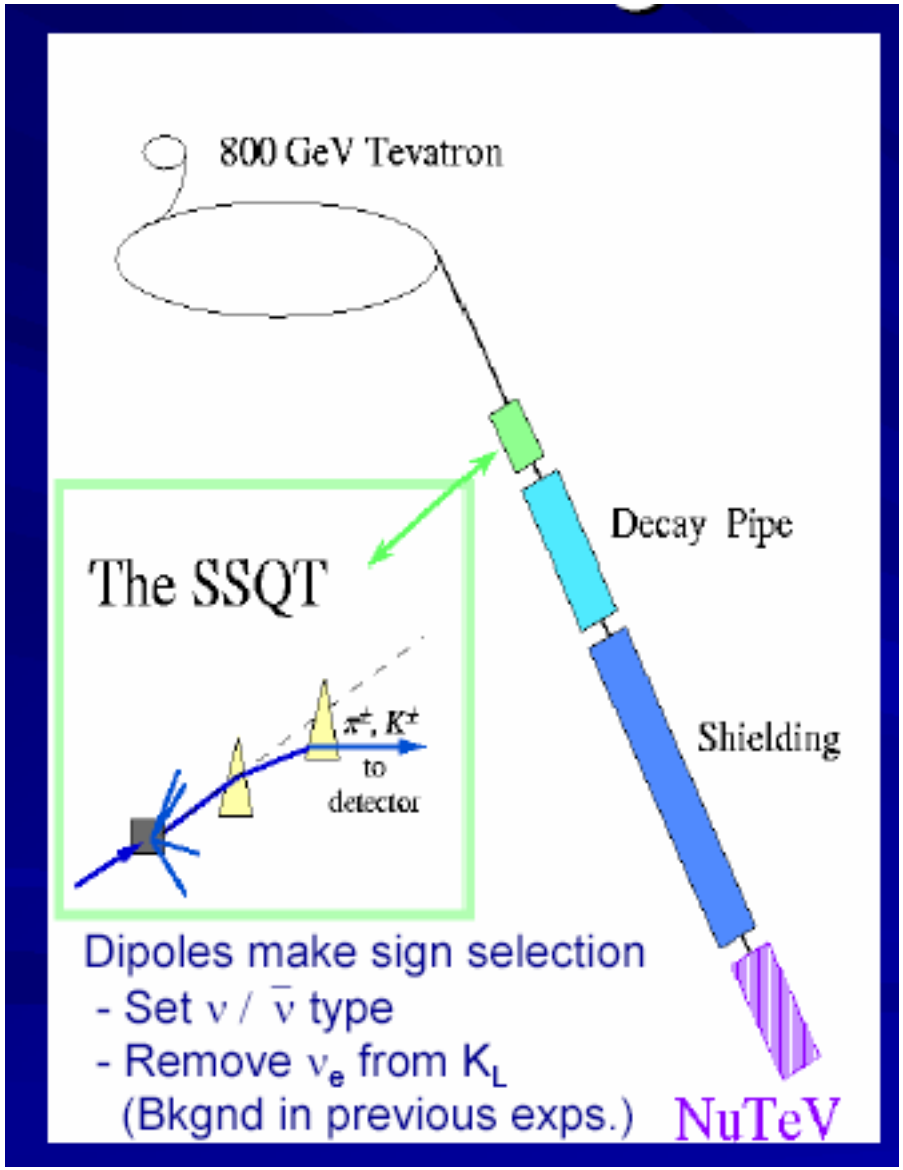
Radiative corrections

$$\varepsilon_L^q = I_L^3 - Q_q \kappa_\nu \sin^2\theta_W + \lambda_L^q$$

$$\varepsilon_L^q = -Q_q \kappa_\nu \sin^2\theta_W + \lambda_R^q$$

$\delta\rho^{NC,CC}$
$\delta\kappa_\nu$
$\lambda_{L,R}$

ν–Nucleus DIS: NuTeV



- Beam identifies neutral currents as ν or $\bar{\nu}$
  ($\bar{\nu}$ in ν mode 3×10^{-4},
  ν in $\bar{\nu}$ mode 4×10^{-3})
- Beam only has ~1.6% electron neutrinos
  ⇒ Important background for isolating true NC event

K. McFarland, Rochester

NuTeV-SM Discrepancy

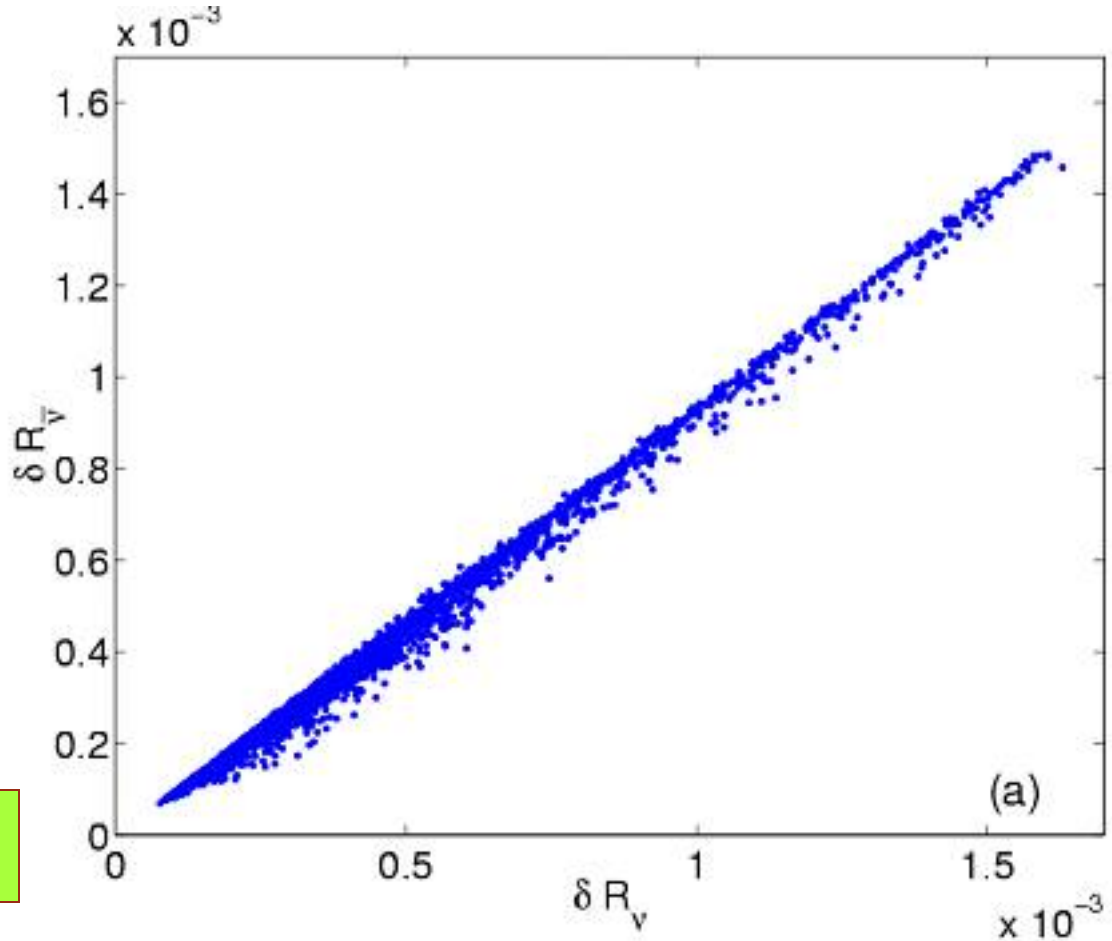
$$R_\nu^{\exp} - R_\nu^{SM} = -0.0033 \pm 0.0000$$

$$R_{\bar{\nu}}^{\exp} - R_{\bar{\nu}}^{SM} = -0.0019 \pm 0.0001$$

Paschos-Wolfenstein Relation

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

ν-Nucleus DIS: SUSY Loop Corrections



wrong sign

NuTeV

Kurylov, SU, MR-M

RPV Effects

$$\delta\rho_{\nu N}^{NC} = \Delta_{12k}(\tilde{e}_R^k)$$

$$\delta\rho_{\nu N}^{CC} = \Delta_{12k}(\tilde{e}_R^k) + \Delta'_{21k}(\tilde{d}_R^k)$$

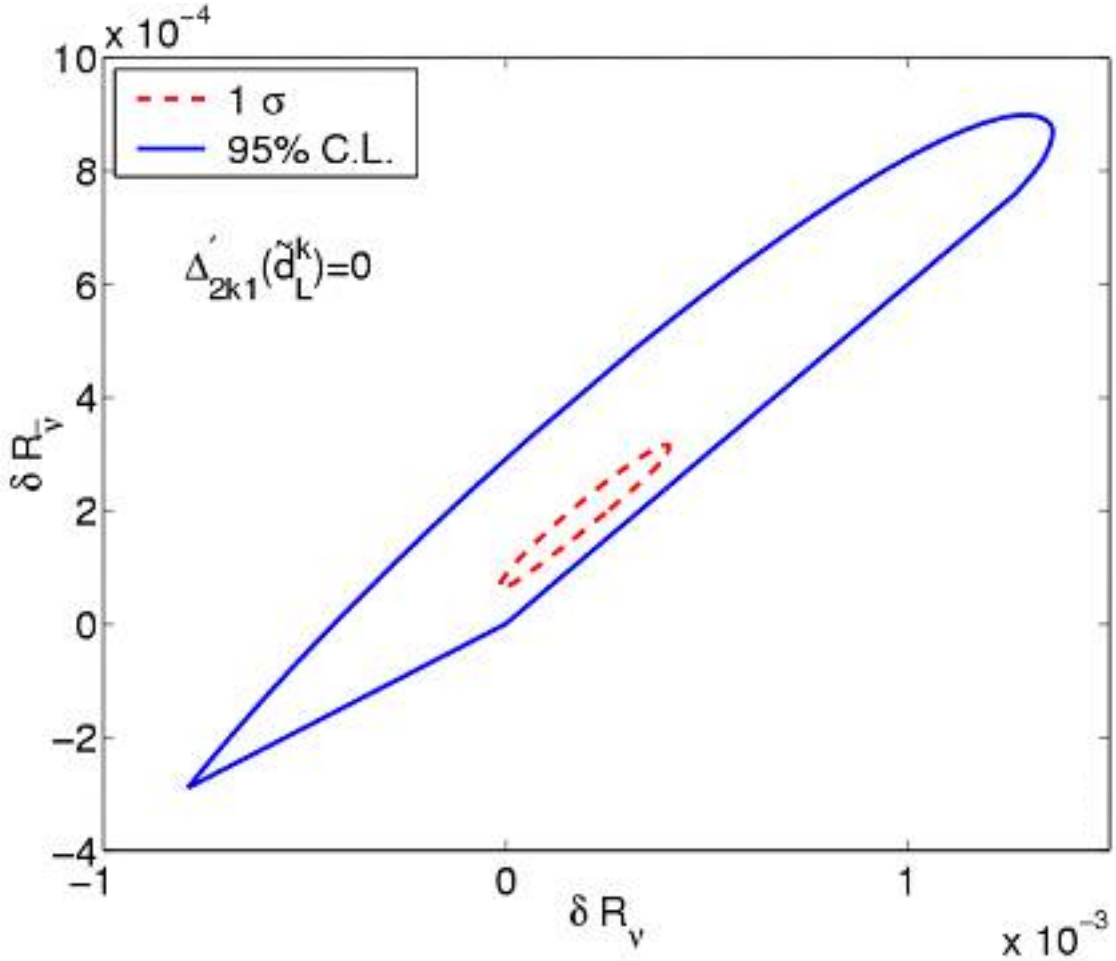
$$\delta\varepsilon_L^d = \frac{1}{3}\lambda_s\Delta_{12k}(\tilde{e}_R^k) - \Delta'_{21k}(\tilde{d}_R^k)$$

$$\delta\varepsilon_R^d = \frac{1}{3}\lambda_s\Delta_{12k}(\tilde{e}_R^k) - \Delta'_{2k1}(\tilde{d}_L^k)$$

unconstrained elsewhere

$$\delta\varepsilon_L^u = \delta\varepsilon_R^u = -\frac{2}{3}\lambda_s\Delta_{12k}(\tilde{e}_R^k)$$

ν-Nucleus DIS: RPV Effects

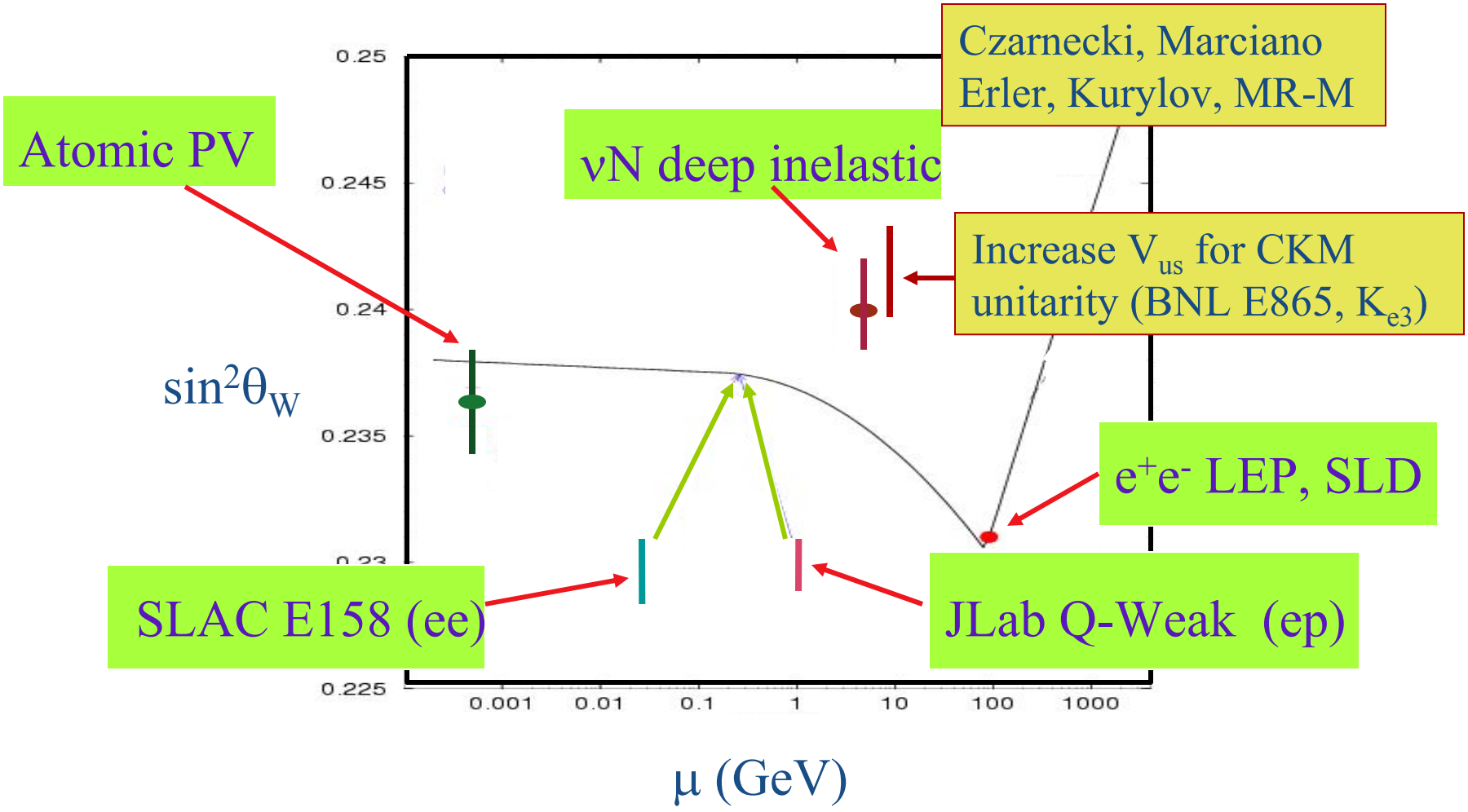


wrong sign

NuTeV

Kurylov, SU, MR-M

νN scattering conflicts with SUSY



NuTeV Anomaly: An explanation?

Isospin Violation in PDFs

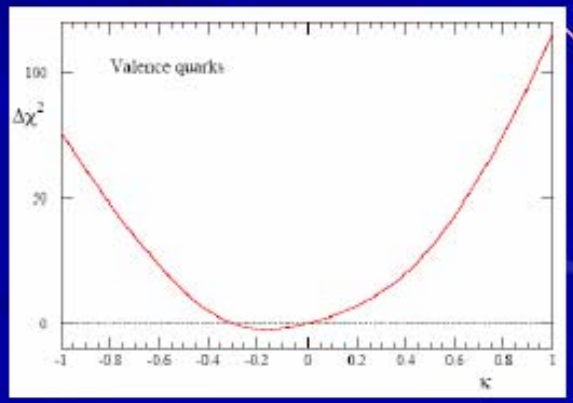
- Naively, effect is ~ $(m_d-m_u)/M_N$=0.5%
  - roughly, a 5% momentum excess of d_v^p over u_v^n quarks would move NuTeV to SM value

G.P. Zeller et al., Phys.Rev.D65:111103,2002)

- Theory offers little guidance
  - full range of bag models predict 0-2% effects

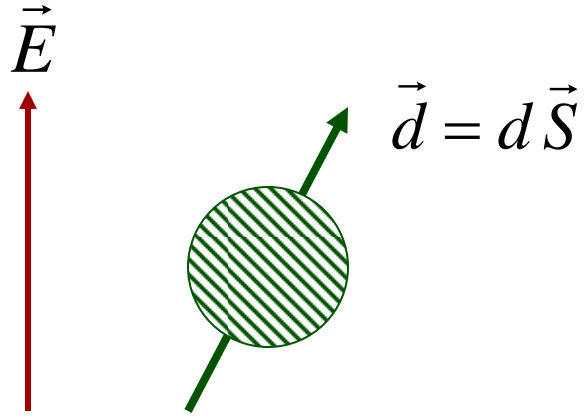
(Rodtonov, Thomas, Londergan, MPL A9 1799)

- Little experimental constraint
  - valiant effort by MRST!
  - they conclude zero, negative or positive effect all allowed in fit
    - best fit moves NuTeV toward SM for whatever that is worth!



Martin et al, hep-ph/0308087

Electric dipole moment (EDM) searches may test SUSY CP-violation

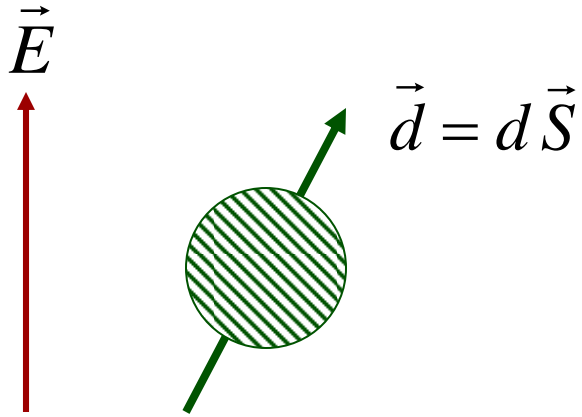


$$\nu_{EDM} = -\frac{d\vec{S}\cdot\vec{E}}{h}$$

T-odd , CP-odd
by CPT theorem

C: $e^- \$ e^+$ P: E $-E, S $ S

Electric dipole moment (EDM) searches may test SUSY CP-violation



SM: CKM

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

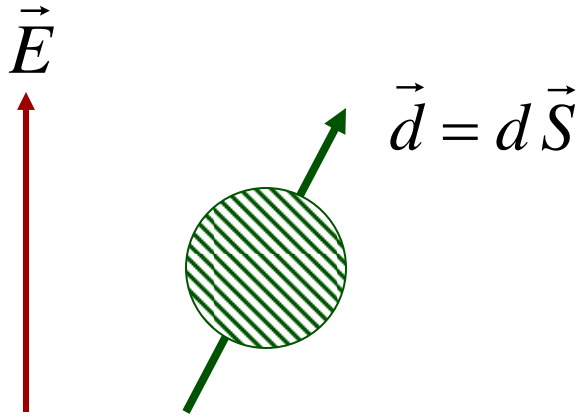
$$\theta_1, \quad \theta_2, \quad \theta_3, \quad e^{i\delta}$$

$$\nu_{EDM} = -\frac{d\vec{S}\cdot\vec{E}}{h}$$

T-odd , CP-odd
by CPT theorem

C: $e^- \$ e^+$ P: E $-E, S $ S

Electric dipole moment (EDM) searches may test SUSY CP-violation



SM: Strong CP

$$L_{StrongCP} = \theta_{QCD} \frac{\alpha_s}{8\pi} G^{\mu\nu} \tilde{G}_{\mu\nu}$$

Gluons: systems with quarks

$$\nu_{EDM} = -\frac{d\vec{S} \cdot \vec{E}}{h}$$

T-odd , CP-odd
by CPT theorem

C: e^- $ e^+ P: E $-E, S $ S

Electric dipole moment (EDM) searches may test SUSY CP-violation

CKM

f	d_{SM}	d_{exp}	d_{future}
e^-	$< 10^{-40}$	$< 1.6\times10^{-27}$	$\rightarrow 10^{-31}$
n	$< 10^{-30}$	$< 6.3\times10^{-26}$	$\rightarrow 10^{-29}$
^{199}Hg	$< 10^{-33}$	$< 2.1\times10^{-28}$	$\rightarrow 10^{-32}$
μ	$< 10^{-28}$	$< 1.1\times10^{-18}$	$\rightarrow 10^{-24}$

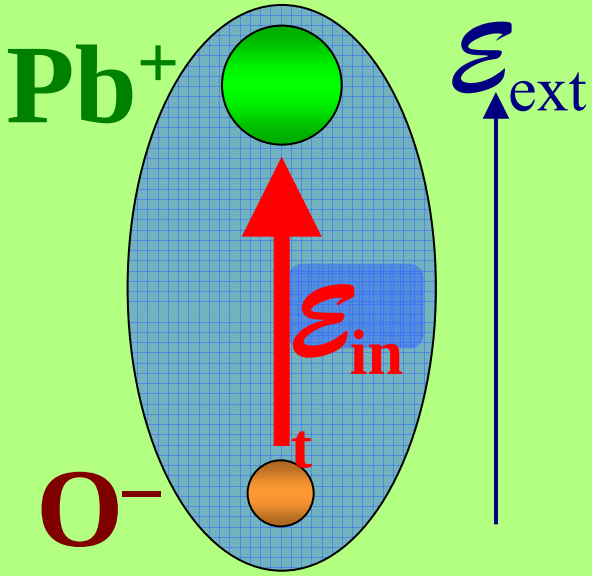
If SUSY CP violation is responsible for abundance of matter, will these experiments see an EDM?

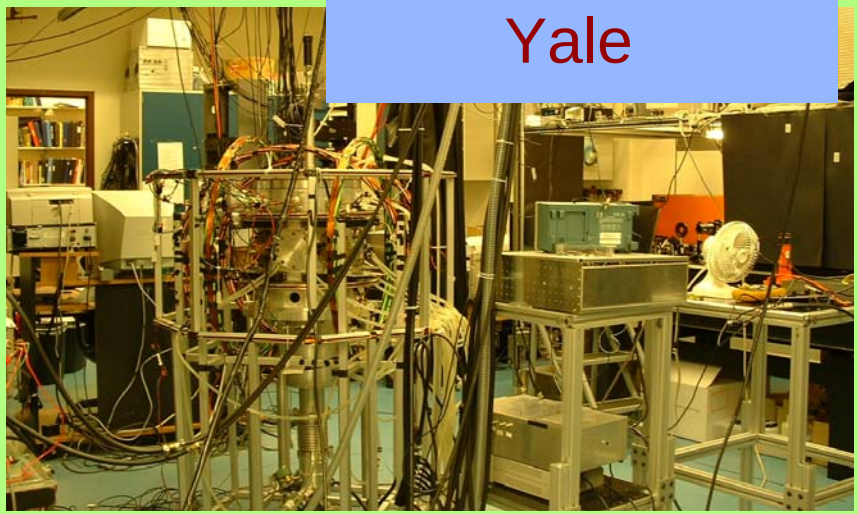
Electric dipole moment (EDM) searches may test new CP-violation

DeMille, Romalis

CKM

f	d_{SM}	d_{exp}	d_{future}
e^-	$< 10^{-40}$	$< 1.6\times10^{-27}$	$\rightarrow 10^{-31}$
n	$< 10^{-30}$	$< 6.3\times10^{-26}$	$\rightarrow 10^{-29}$





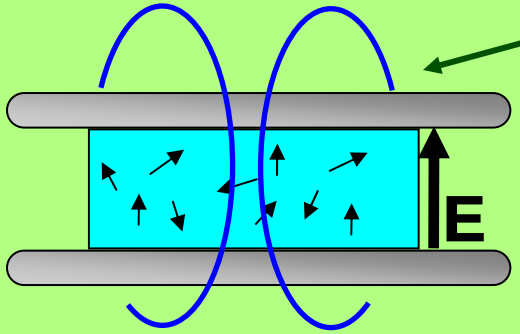
Electric dipole moment (EDM) searches may test new CP-violation

CKM

f	d_{SM}	d_{exp}	d_{future}
e^-	$< 10^{-40}$	$< 1.6\times10^{-27}$	$\rightarrow 10^{-31}$
n	$< 10^{-30}$	$< 6.3\times10^{-26}$	$\rightarrow 10^{-29}$

1: B from E

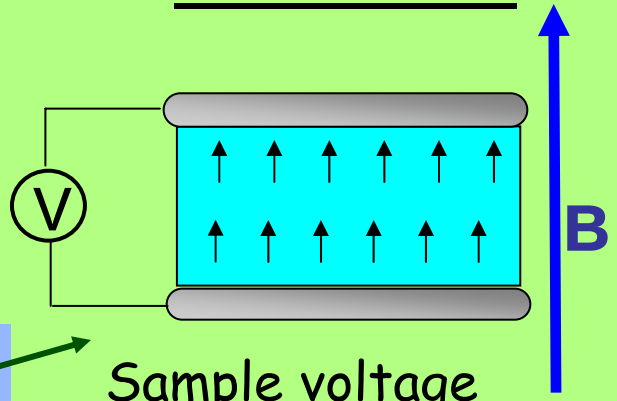
LANL



Sample magnetization
$M \propto d_e E/T$

2: E from B

Amherst

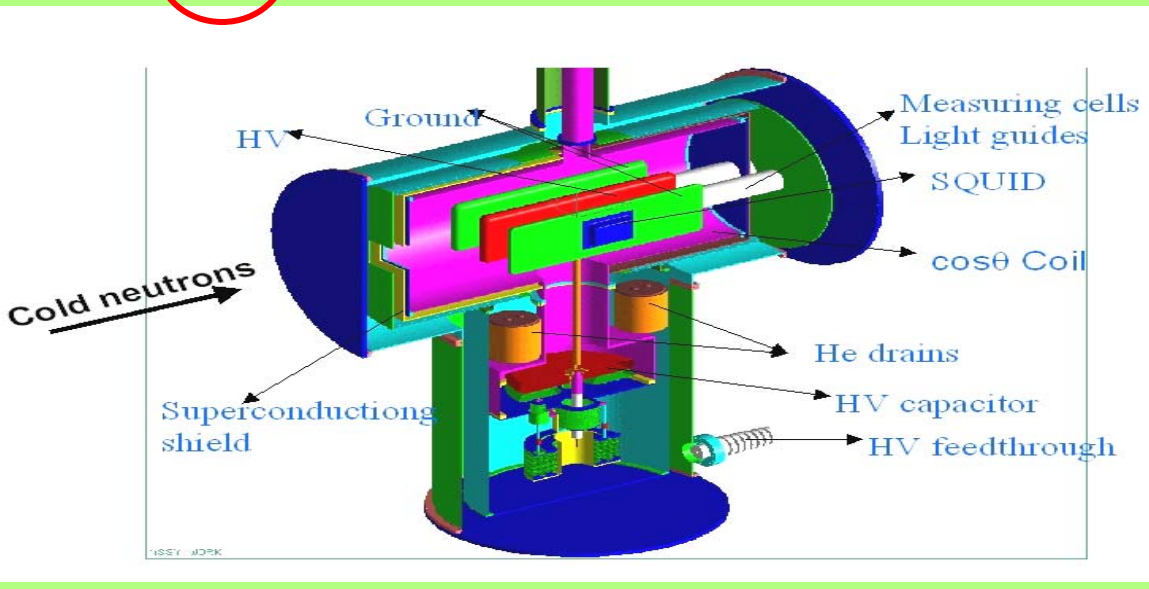


Sample voltage
$V \propto d_e$

Electric dipole moment (EDM) searches may test new CP-violation

CKM

f	d_{SM}	d_{exp}	d_{future}
e^-	$< 10^{-40}$	$< 1.6\times10^{-27}$	$\rightarrow 10^{-31}$
n	$< 10^{-30}$	$< 6.3\times10^{-26}$	$\rightarrow 10^{-29}$



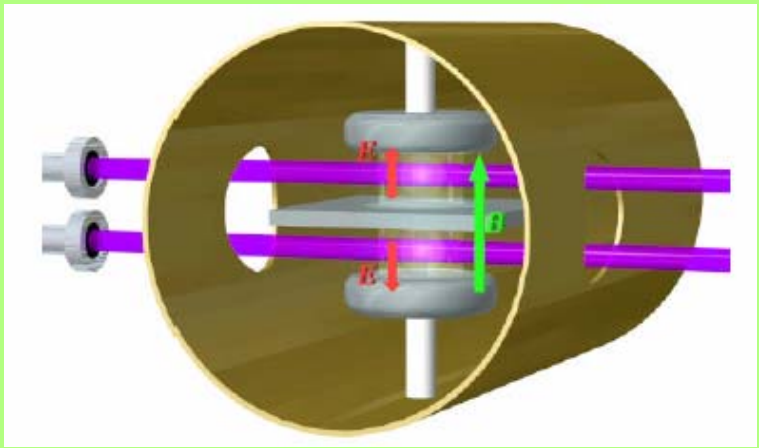
LANSCE!SNS

Superfluid He UCN converter with high E-field

Electric dipole moment (EDM) searches may test new CP-violation

CKM

f	d_{SM}	d_{exp}	d_{future}
e^-	$< 10^{-40}$	$< 1.6\times10^{-27}$	$\rightarrow 10^{-31}$
n	$< 10^{-30}$	$< 6.3\times10^{-26}$	$\rightarrow 10^{-29}$
^{199}Hg			
μ			



Washington

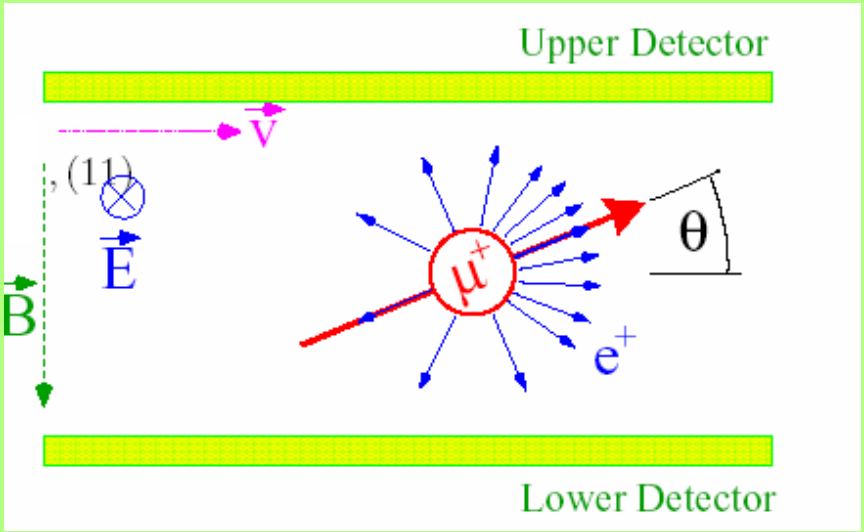
Princeton

Argonne…

Electric dipole moment (EDM) searches may test new CP-violation

CKM

f	d_{SM}	d_{exp}	d_{future}
e^-	$< 10^{-40}$	$< 1.6\times10^{-27}$	$\rightarrow 10^{-31}$
n	$< 10^{-30}$	$< 6.3\times10^{-26}$	$\rightarrow 10^{-29}$
^{199}Hg			
μ			

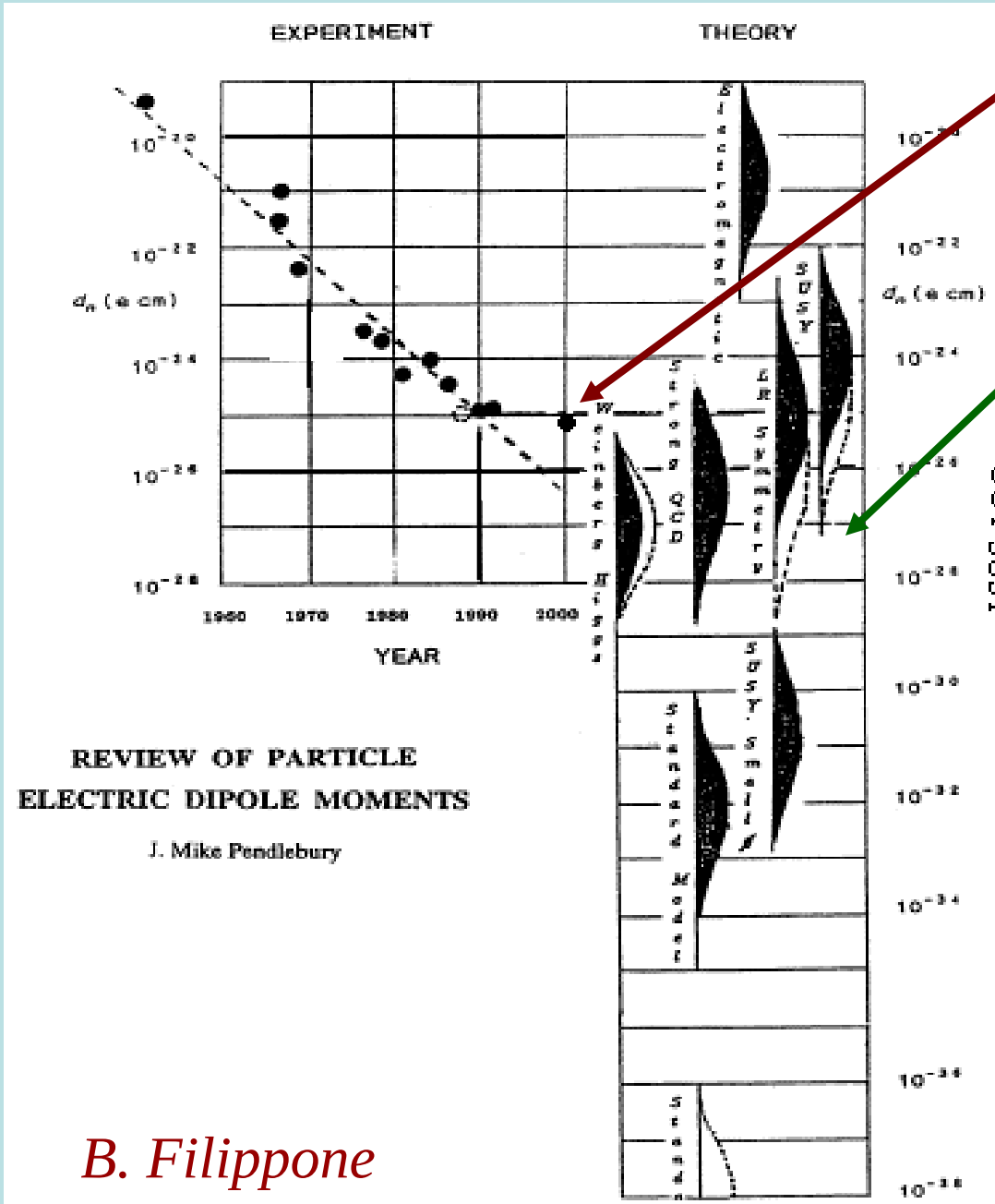


Storage ring:

BNL

JPARC…

Also deuteron



Present n-EDM limit

Proposed n-EDM limit

GUT SUSY

Electroweak Baryogenises

Matter-Antimatter Asymmetry in the Universe

Better theory

B. Filippone

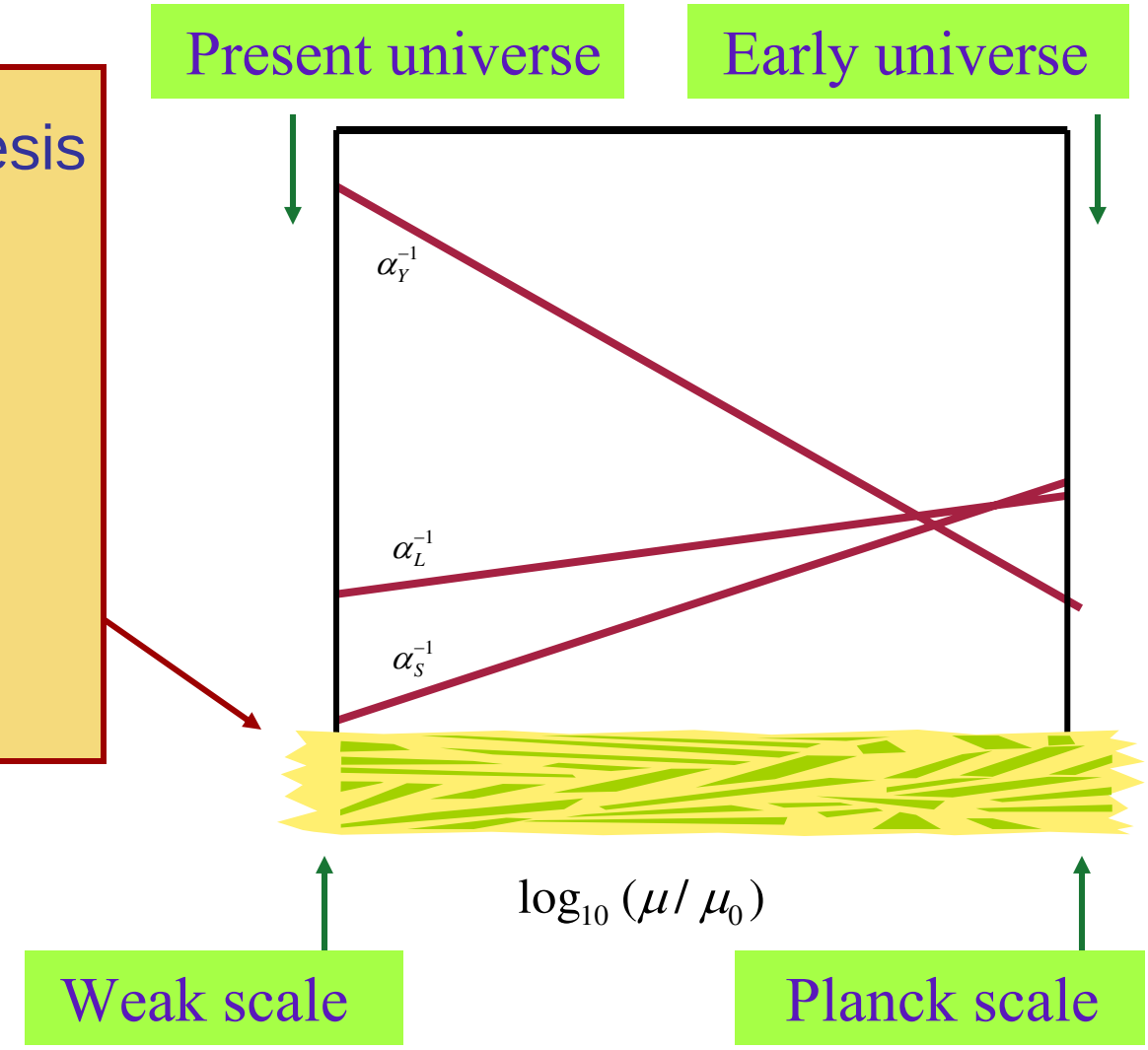
"n-EDM has killed more theories than any other single experiment"

Electric dipole moment (EDM) searches may test **SUSY CP-violation**

Weak Scale Baryogenesis

- B violation
- C & CP violation
- Nonequilibrium dynamics

Sakharov, 1967



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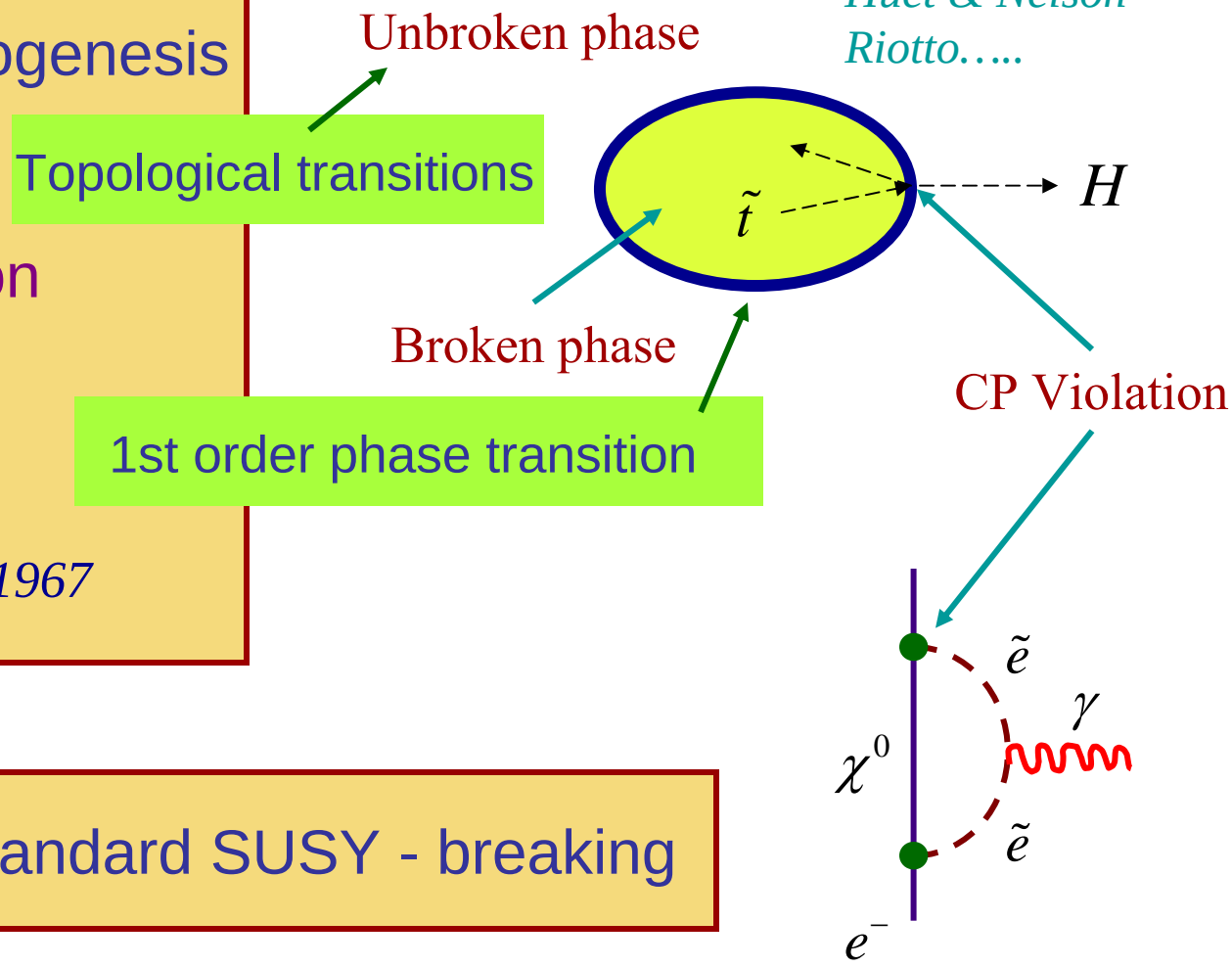
Cohen, Kaplan, Nelson
Huet & Nelson
Riotto…..



EDM: Standard SUSY - breaking

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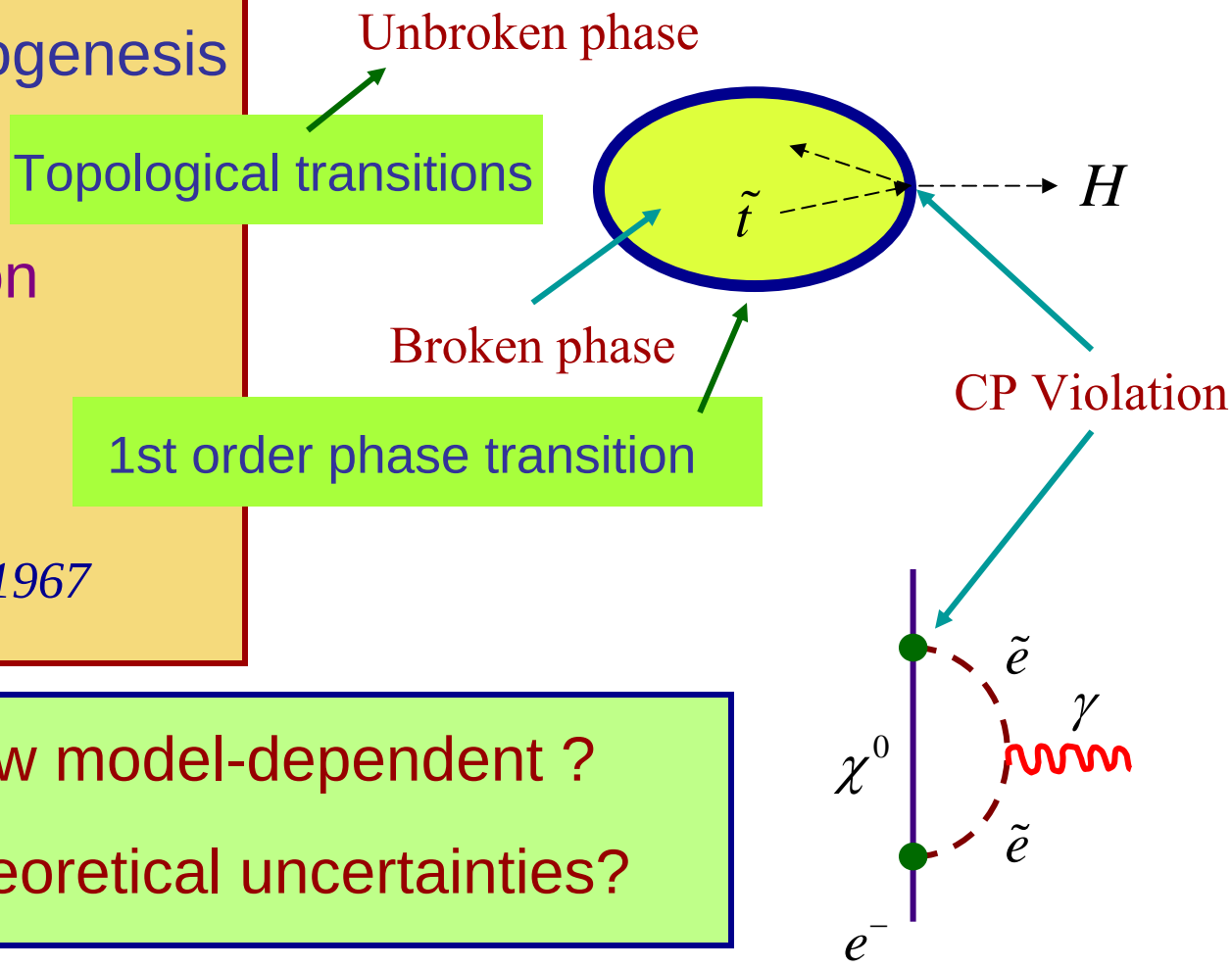
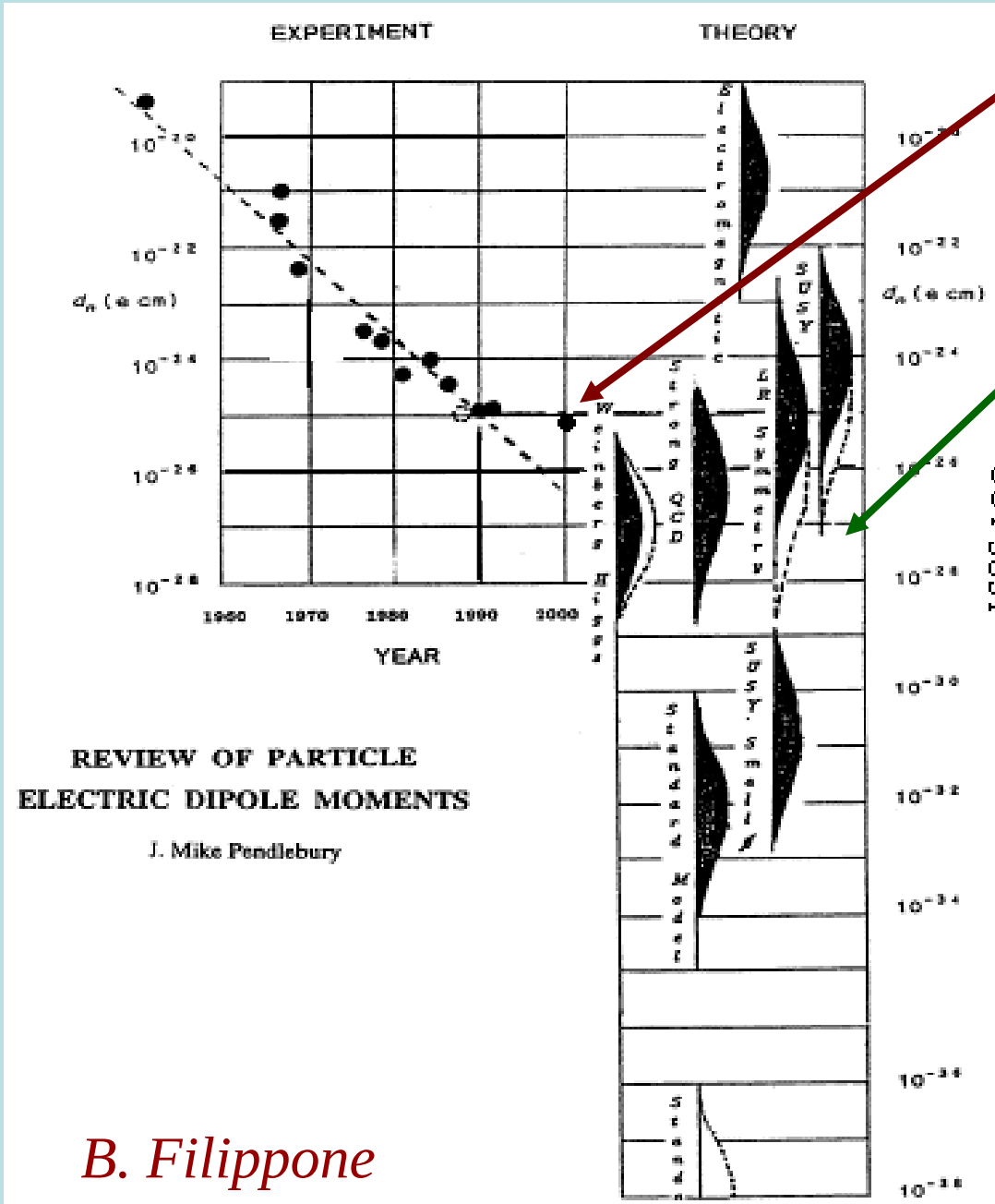


- How model-dependent ?
- Theoretical uncertainties?



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