ElW Physics at an EIC: BSM Physics & QCD

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NPAC

Theoretical Nuclear, Particle, Astrophysics & Cosmology

http://www.physics.wisc.edu/groups/particle-theory/

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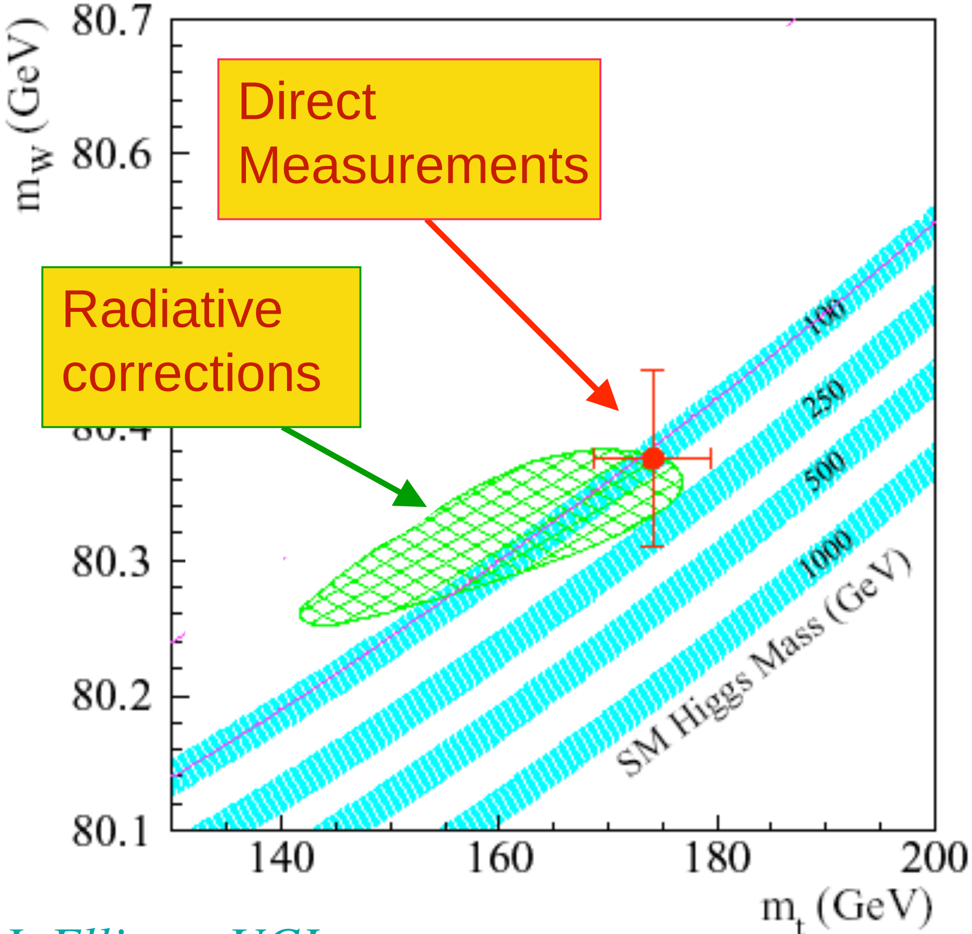
Outline

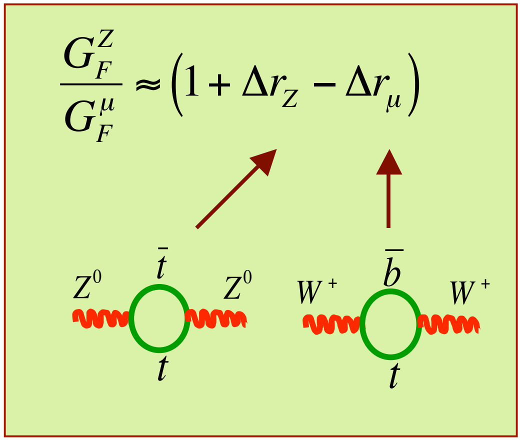
- *Context: NP BSM Studies*
- *Lepton flavor violation:* $e^- + A \to \tau^- + A$
- *Neutral Current Processes: PV DIS & PV Moller*

Questions

- *What are the opportunities for probing the "new Standard Model" and novel aspects of nucleon structure with electroweak processes at an EIC?*
- *What EIC measurements are likely to be relevant after a decade of LHC operations and after completion of the Jefferson Lab electroweak program?*
- *How might a prospective EIC electroweak program complement or shed light on other key studies of neutrino properties and fundamental symmetries in nuclear physics?*

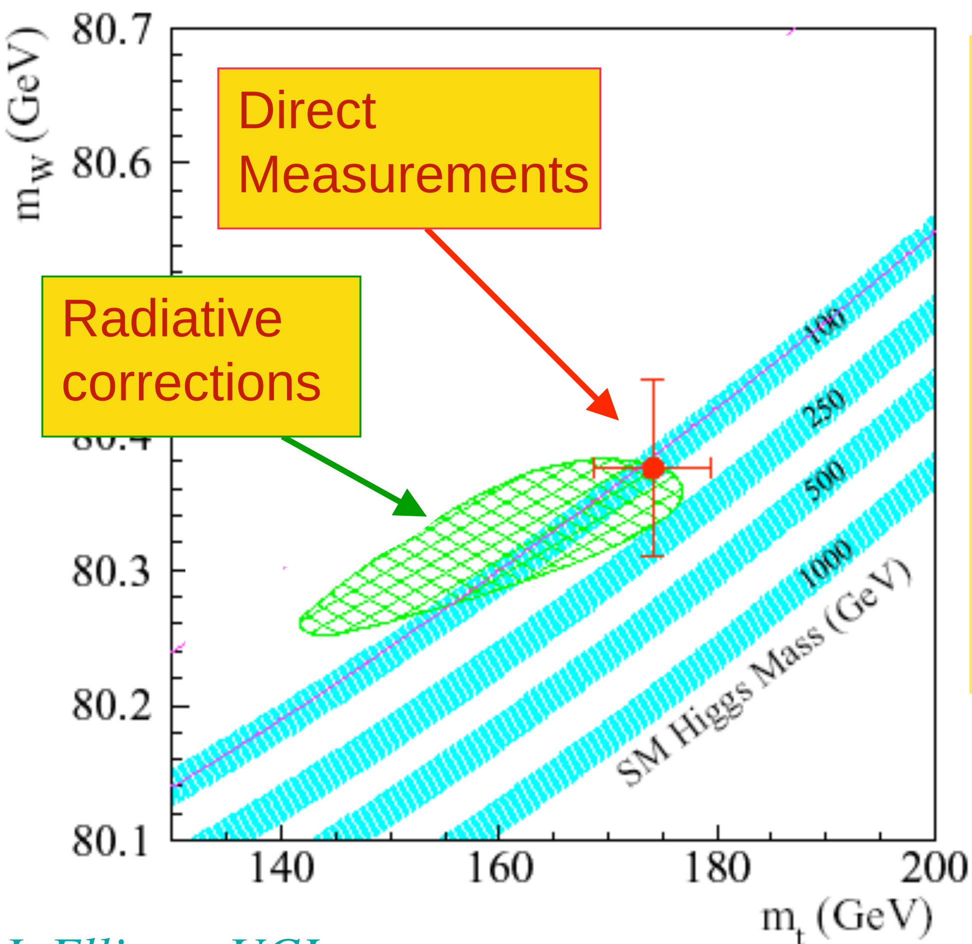
Precision & Energy Frontiers





J. Ellison, UCI

Precision & Energy Frontiers

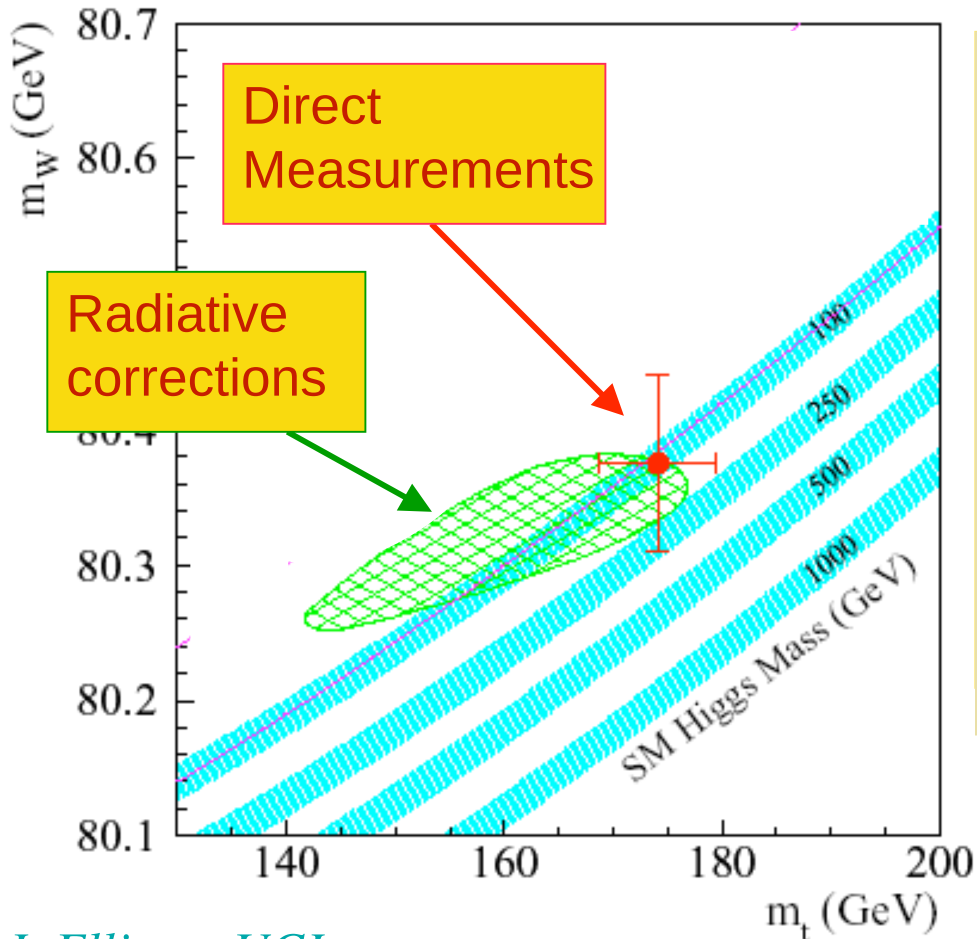


- Precision measurements predicted a range for m_t before top quark discovery
- $m_t >> m_b$!
- m_t is consistent with that range
- It didn't have to be that way

Stunning SM Success

J. Ellison, UCI

Precision & Energy Frontiers



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

J. Ellison, UCI

Precision Probes of the New SM

Precision ~ Mass Scale

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

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

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

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

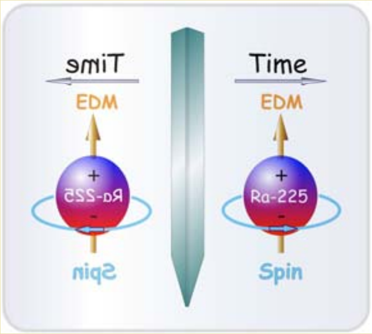
Interpretability

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

Discovery

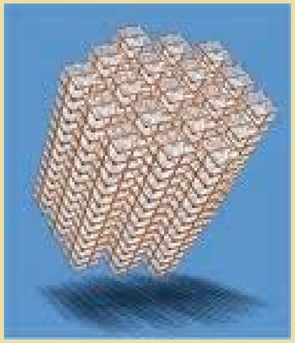
Rare Processes: NP Experiments

EDM Searches



- *nucleon*
- *atoms*
- *leptons*

$0\nu\beta\beta$ Searches

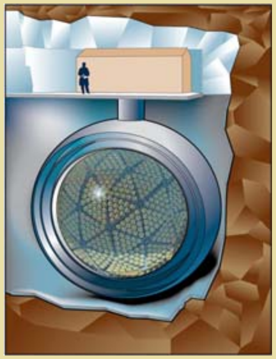


- *Cuore*
- *Exo*
- *Majorana*
- *SNO +*

CLFV Searches

- *mu2e*
- *PRIME*
- *EIC*

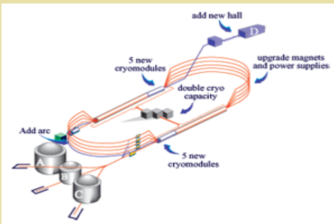
Dark Matter Searches



- *CLEAN*
- *WARP*

Precision Tests: NP Experiments

PV Electron Scattering



- Q-Weak
- 12 GeV Moller
- PV DIS

EIC ?

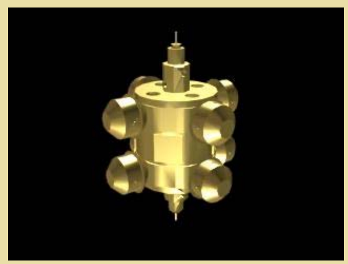
Muons

- g_μ-2
- μA->eA

Weak Decays

- n decay correlations
- nuclear β decay
- pion decays
- muon decays

Torsion Balances



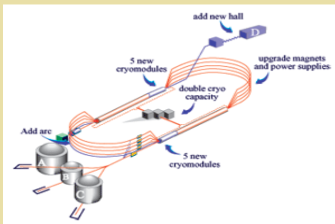
- Equiv Prin Tests
- Non-grav forces

Neutrinos

- oscillations
- β & $\beta\beta$ decay

EW Probes of QCD: NP Experiments

PV Electron Scattering

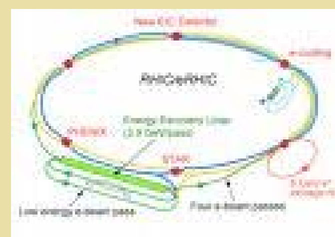


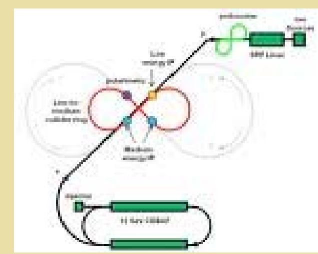
- *SAMPLE, G0, HAPPEX, PVA4*
- *PREX*
- *PV DIS*

Hadronic PV

- *FNPB/SNS*
- *NIST*

EIC





- *PVDIS*
- *CC DIS*

Lepton Number & Flavor Violation

Uncovering the flavor structure of the new SM and its relationship with the origin of neutrino mass is an important task. The observation of charged lepton flavor violation would be a major discovery in its own right.

- *LNV & Neutrino Mass*
- *$0\nu\beta\beta$ Mechanism Problem*
- *CLFV as a Probe*
- *$\tau \rightarrow e$ Conversion at EIC ?*

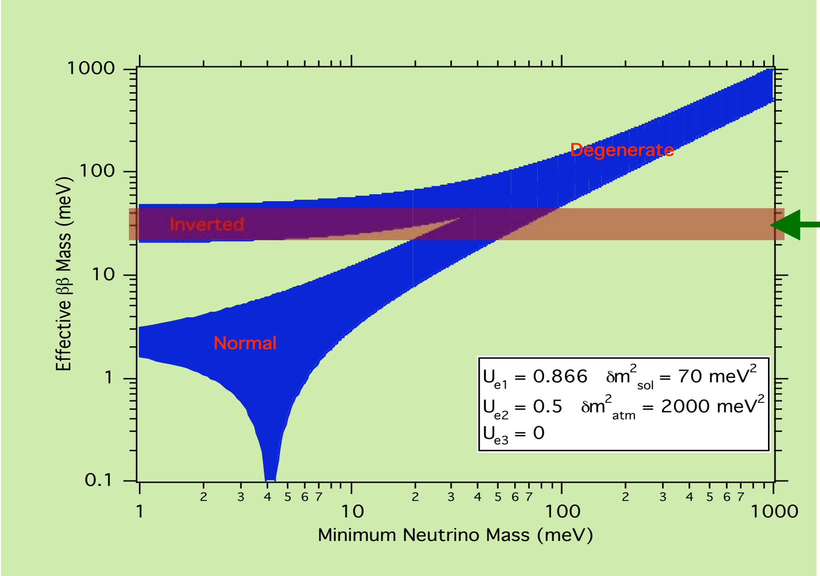
$0\nu\beta\beta$-Decay: LNV? Mass Term?

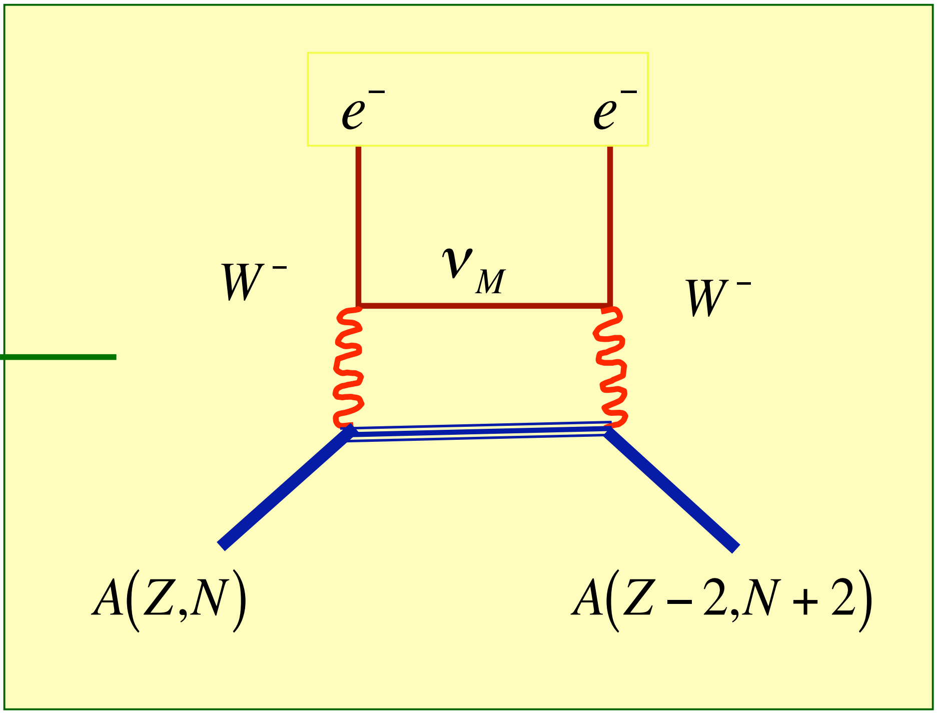
$$\mathcal{L}_{mass} = y\bar{L}\tilde{H}\nu_R + h.c.$$

Dirac

$$\mathcal{L}_{mass} = \frac{y}{\Lambda}\bar{L}^c\tilde{H}\tilde{H}^T L$$

Majorana





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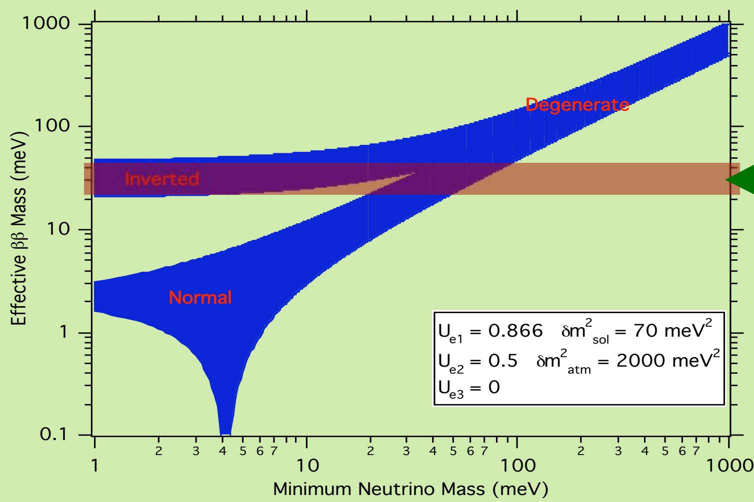
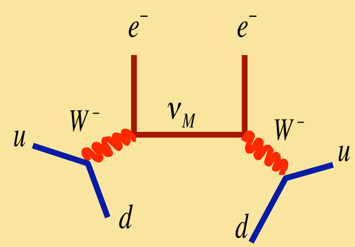
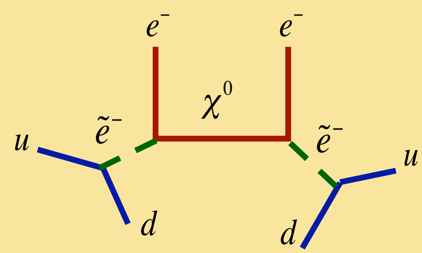


Theory Challenge: matrix elements+ mechanism

$$\langle m_\nu \rangle^{EFF} = \sum_k |U_{ek}|^2 m_k \, e^{2i\delta}$$





$0\nu\beta\beta$-Decay: Mechanism

$$\mathcal{L}_{mass} = y\bar{L}\tilde{H}\nu_R + h.c.$$

Dirac

$$\mathcal{L}_{mass} = \frac{y}{\Lambda}\bar{L}^c\tilde{H}\tilde{H}^T L$$

Majorana

Mechanism: does light ν_M exchange dominate ?

$$\frac{A_{\rm heavy}}{A_{\rm light}} \sim \frac{M_W^2\, k_{\rm eff}^2}{\Lambda^5\, m_\nu^{\rm eff}}$$

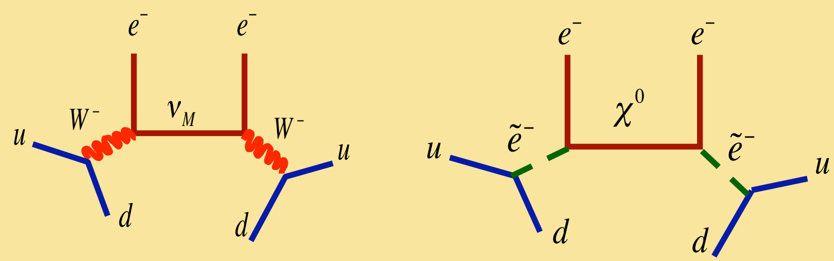
O(1) for Λ ~ TeV

How to calc effects reliably ?

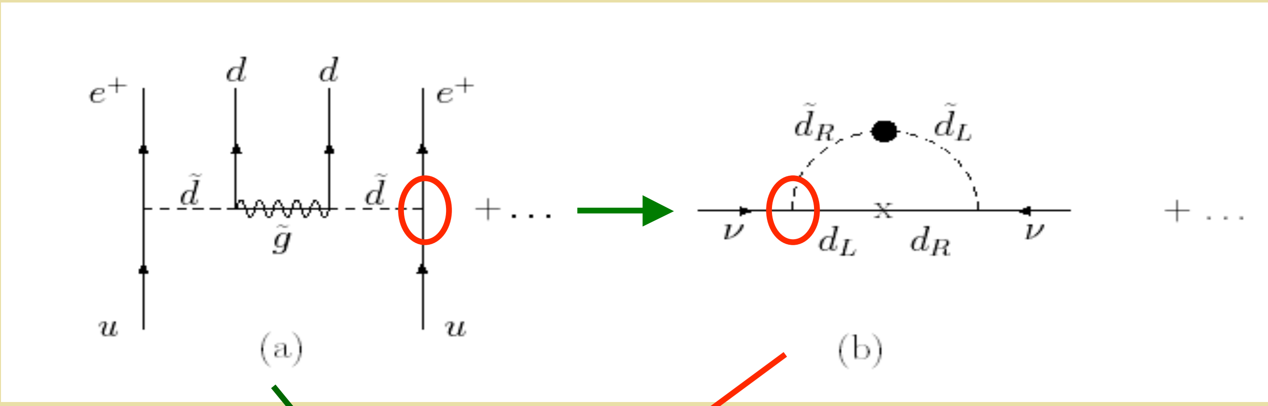
How to disentangle H & L ?

Theory Challenge: matrix elements+ mechanism

$$\langle m_\nu \rangle^{EFF} = \sum_k |U_{ek}|^2 m_k\, e^{2i\delta}$$

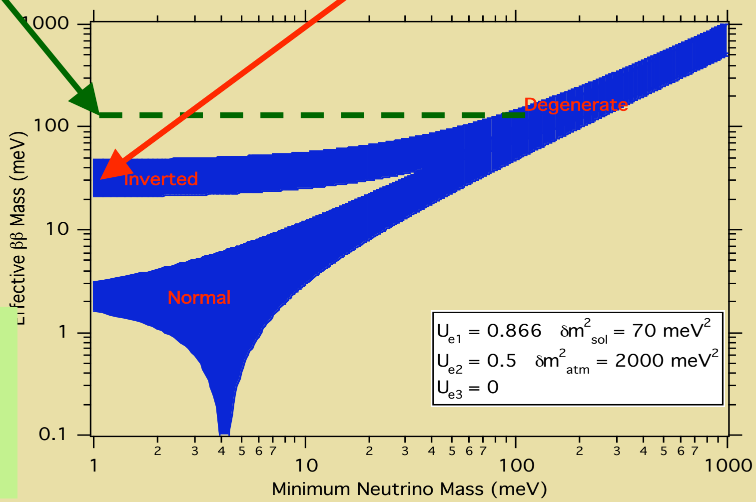


$0\nu\beta\beta$-Decay: Interpretation



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

Loop contribution to m_ν of inverted hierarchy scale



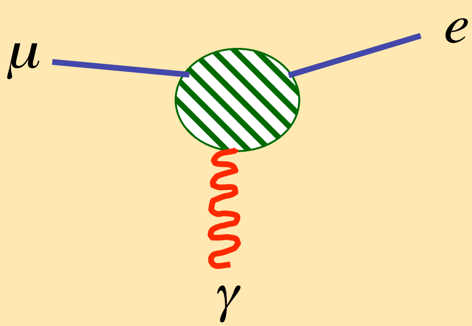
Sorting out the mechanism

- *Models w/ Majorana masses (LNV) typically also contain CLFV interactions*

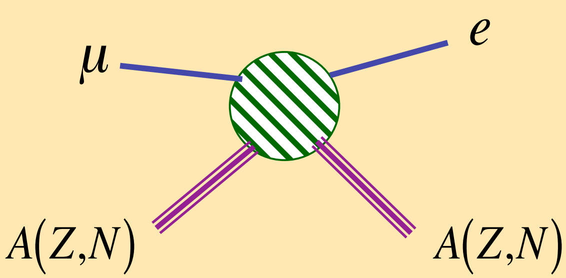
  RPV SUSY, LRSM, GUTs (w/ LQ's)

- *If the LNV process of $0\nu\beta\beta$ arises from TeV scale particle exchange, one expects signatures in CLFV processes*
- *$\tau \to e$ Conversion at EIC could be one probe*

CLFV, LNV & the Scale of New Physics



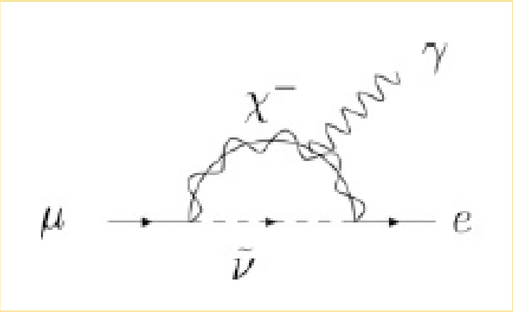
MEG: $B_{\mu \to \varepsilon\, \gamma} \sim 5 \times 10^{-14}$



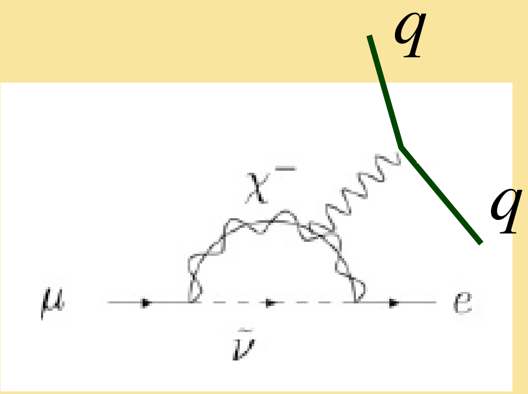
μ2e: $B_{\mu \to e} \sim 5 \times 10^{-17}$

Also PRIME

CLFV, LNV & the Scale of New Physics



$\mu \to e\gamma$: M1



$\mu \to e$: M1 $\to$ R ~ α

Also PRIME

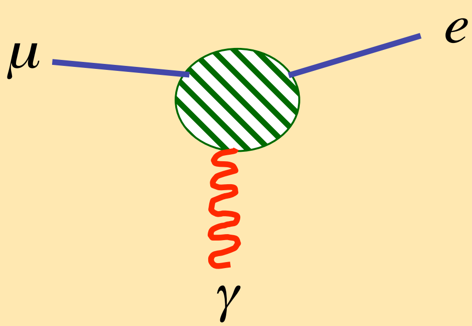
Comparison of results could provide diagnostic for scale of CLV

$$R = \frac{B_{\mu\text{->}e}}{B_{\mu\text{->}e\gamma}}$$

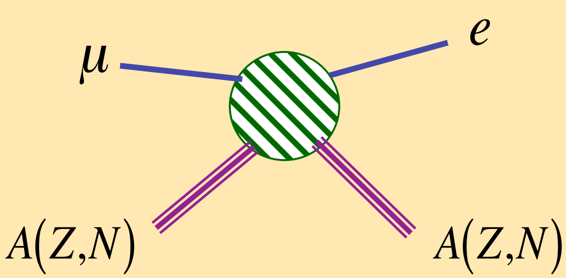
- *High scale CLNV $\to$ M1 transitions and R ~ α*
- *Low scale CLNV $\to$ Penguin operator for conversion and R ~ 1*

Lepton Flavor & Number Violation

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



MEG: $B_{\mu\text{->}e\gamma}$ ~ 5 x 10^{-14}



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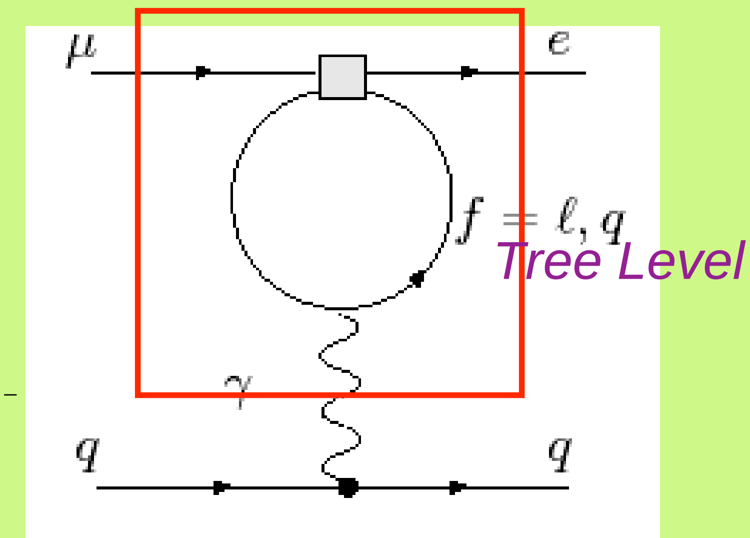
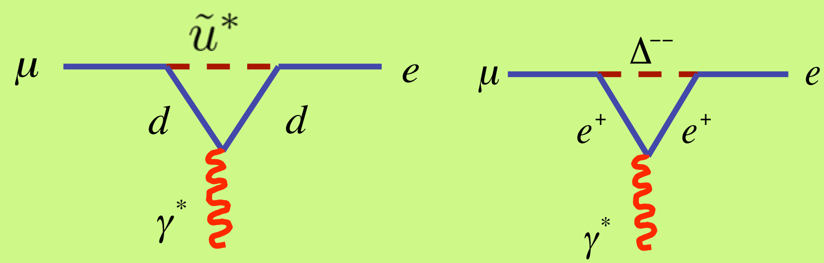




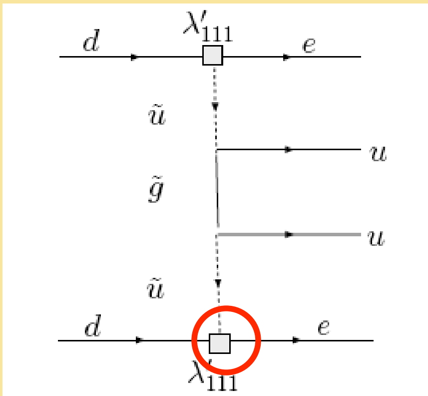
Logarithmic enhancements of *R*

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

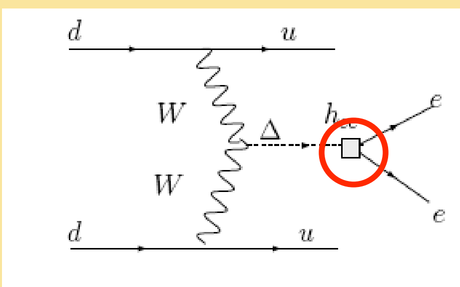
Lepton Flavor & Number Violation

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

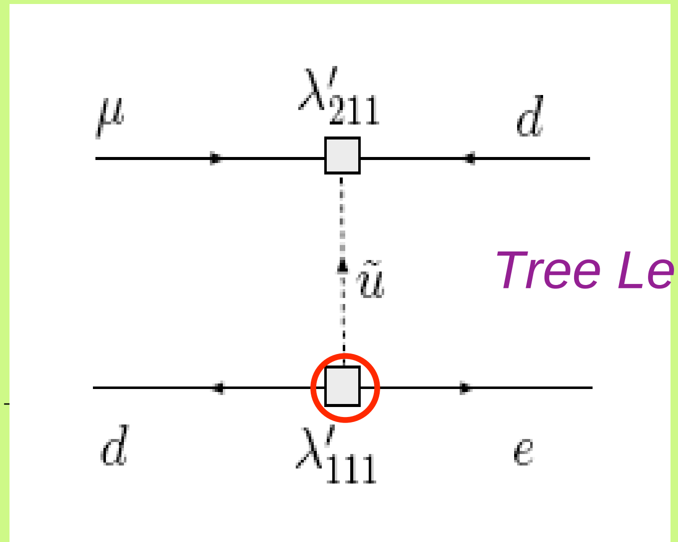
$0\nu\beta\beta$ decay



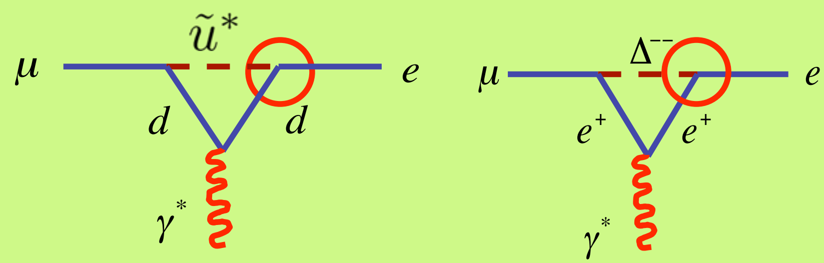
RPV SUSY



LRSM



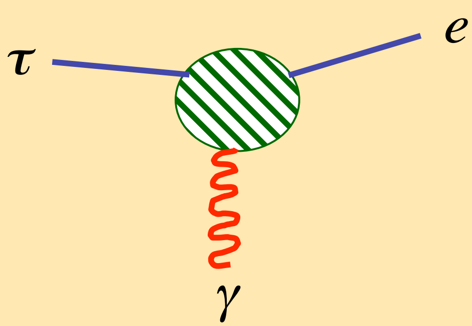
Tree Level



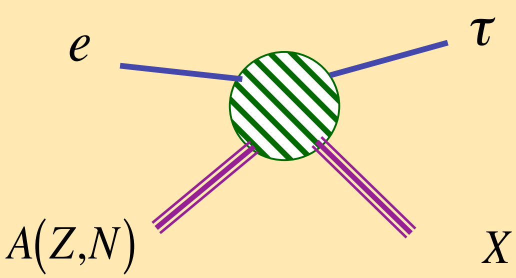
Logarithmic enhancements of *R*

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

τ CLFV & EIC : Loops



Exp: $B_{\tau\to e\gamma} \sim 1.1 \times 10^{-7}$



EIC: $\sigma \sim 10^{3}\, |A^{1}_{\tau e}|^{2}$ fb

$B_{\tau\to e\gamma} = 48\,\pi^{3}\,\alpha\,|A^{2}_{\tau e}|^{2}$

$|A^{2}_{\tau e}|^{2} < 10^{-8}$ ← *M1 operator*

If $|A^{2}_{\tau e}|^{2} \sim |A^{1}_{\tau e}|^{2}$ ← *Penguin op*

EIC: $\sigma \sim 10^{-5}$ fb

Log enhancement:

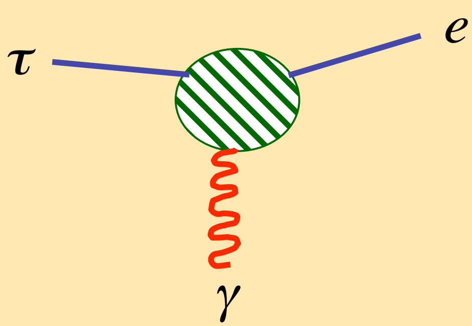
$|A^{1}_{\tau e}|^{2} / |A^{2}_{\tau e}|^{2} \sim |\ln m_e / 1\ \text{TeV}|^{2} \sim 100$

Need ~ 1000 fb^{-1}

Refined σ analysis: Gonderinger & R-M

Tree-level τ CLFV: need ~ 10 fb^{-1}

τ CLFV & Other Probes



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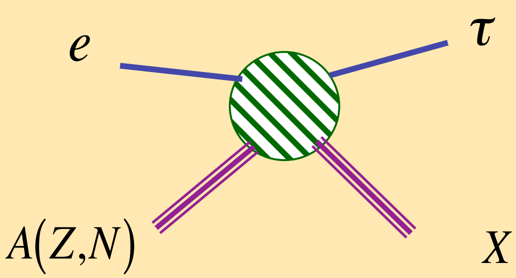


EIC: $\sigma \sim 10^3\,|\,A^1{}_{\tau e}|^2$ fb

Doubly Charged Scalars

$\mu \to e(\gamma)$	$\tau \to e(\gamma)$
$h_{\mu e}\, \boxed{h_{ee}}$	$\boxed{h_{ee}}\, h_{e\tau}$
$+\, h_{\mu\mu}\, h_{\mu e}$	$+\, h_{e\mu}\, h_{\mu\tau}$
$+\, h_{\mu\tau}\, h_{\tau e}$	$+\, h_{e\tau}\, h_{\tau\tau}$

$0\nu\beta\beta$ if LH; PV Moller if RH

All $h_{ab} \leftrightarrow m_\nu$ if part of see-saw

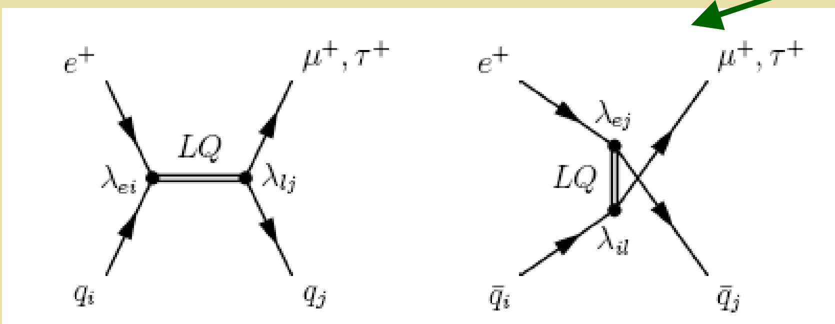
LHC: Δ^{++}, Δ^{--} BRs (in pair prod)

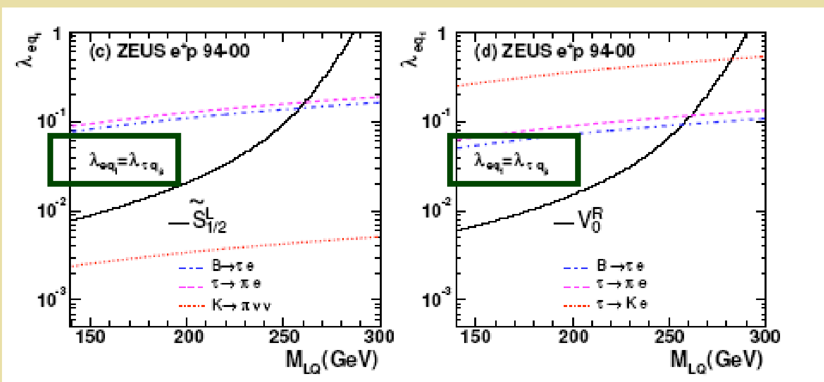
Possible for effects in τ-e CLFV are >> than in μ-e CLFV

Tree-level τ CLFV : HERA & Rare Decays

Leptoquark Exchange:
Like RPV SUSY /w $\lambda^{\prime}$

τeqq eff op





HW Assignment:

- *Induce $\tau \to e\gamma$ at one loop?* ✔
- *Consistent with $B_{\tau \to e\gamma}$? HERA & rare decay limits look stronger* ✔
- *Connection w/ m_ν & $0\nu\beta\beta$ in GUTS ?*
- *Applicable to other (non-LQ) models that generate tree-level ops?*

Veelken (H1, Zeus) (2007)

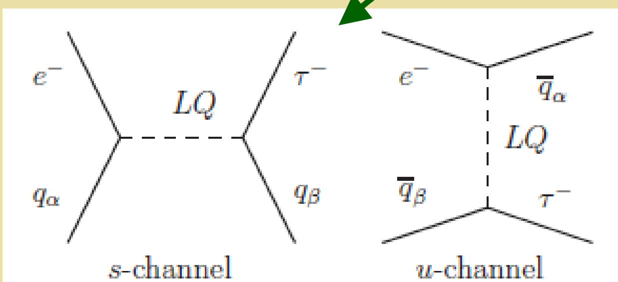
$$|\lambda_{lq}|^2 < 10^{-4}\,(M_{LQ}\,/\,100\text{ GeV})^2$$

Gonderinger, R-M in process

τ CLFV: EIC, HERA & Rare Decays

HERA & EIC

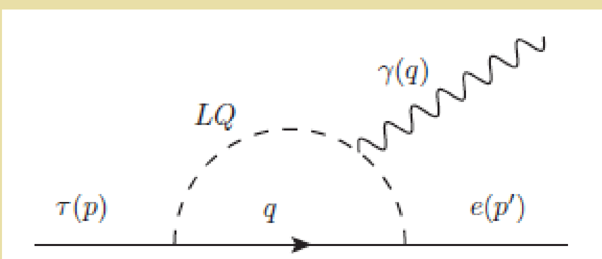
τeqq eff op

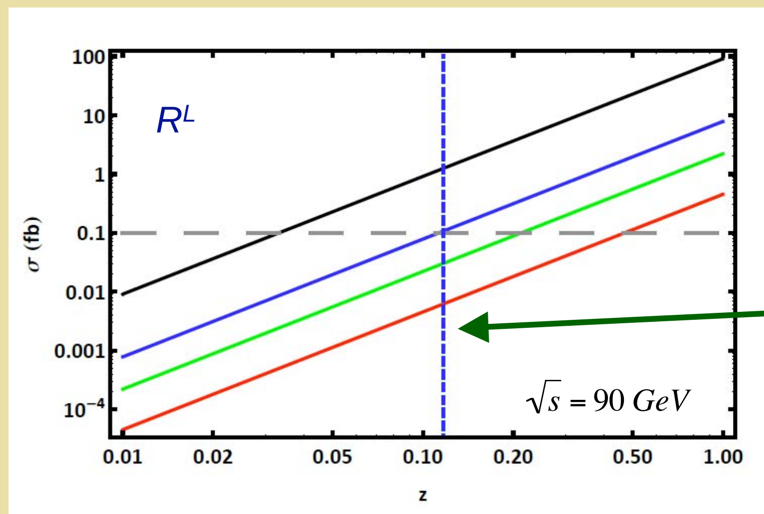


General Classification

$$\mathcal{L} = h_2^L \bar{u}\ell R_2^L + h_2^R \bar{q} i\tau_2 e R_2^R + \tilde{h}_2 \bar{d}\ell \tilde{R}_2^L + g_1^L \bar{q}^c i\tau_2 \ell S_1^L + g_1^R \bar{u}^c e S_1^R + \tilde{g}_1 \bar{d}^c e \tilde{S}_1^R + g_3 \bar{q}^c i\tau_2 \vec{\tau}\ell S_3 + h_1^L \bar{q}\gamma^\mu \ell U_{1\mu}^L + h_1^R \bar{d}\gamma^\mu e U_{1\mu}^R + \tilde{h}_1 \bar{u}\gamma^\mu e \tilde{U}_{1\mu}^R + h_3 \bar{q}\gamma^\mu \vec{\tau}\ell U_{3\mu} + g_2^L \bar{d}^c \gamma^\mu \ell V_{2\mu}^L + g_2^R \bar{q}^c \gamma^\mu e V_{2\mu}^R + \tilde{g}_2 \bar{u}^c \gamma^\mu \ell \tilde{V}_{2\mu}^L + \text{H.c.},$$

Rare Decays





$\tau \to e\,\gamma$

$z = (\lambda^2 / M^2) / (\lambda^2 / M^2)_{HERA}$

Gonderinger, R-M in process

Neutral Current Probes: PV

- *Effective eq PV couplings in SM & beyond*
- *New physics ? SUSY, Z', LQ as illustration*
- *Probing QCD*

$C_{1,2}$ and Radiative Corrections

$$L_{PV}^{eq} = \frac{G_\mu}{\sqrt{2}} \sum_q \left[C_{1q} \bar{e}\gamma^\mu\gamma_5 e \bar{q}\gamma_\mu q + C_{2q} \bar{e}\gamma^\mu e \bar{q}\gamma_\mu\gamma_5 q \right]$$

Radiative Corrections

Flavor-dependent

$$C_{1f} = \rho_{PV}(2I_3^f - 4Q_f \kappa_{PV} \sin^2\theta_W) + \lambda_f$$

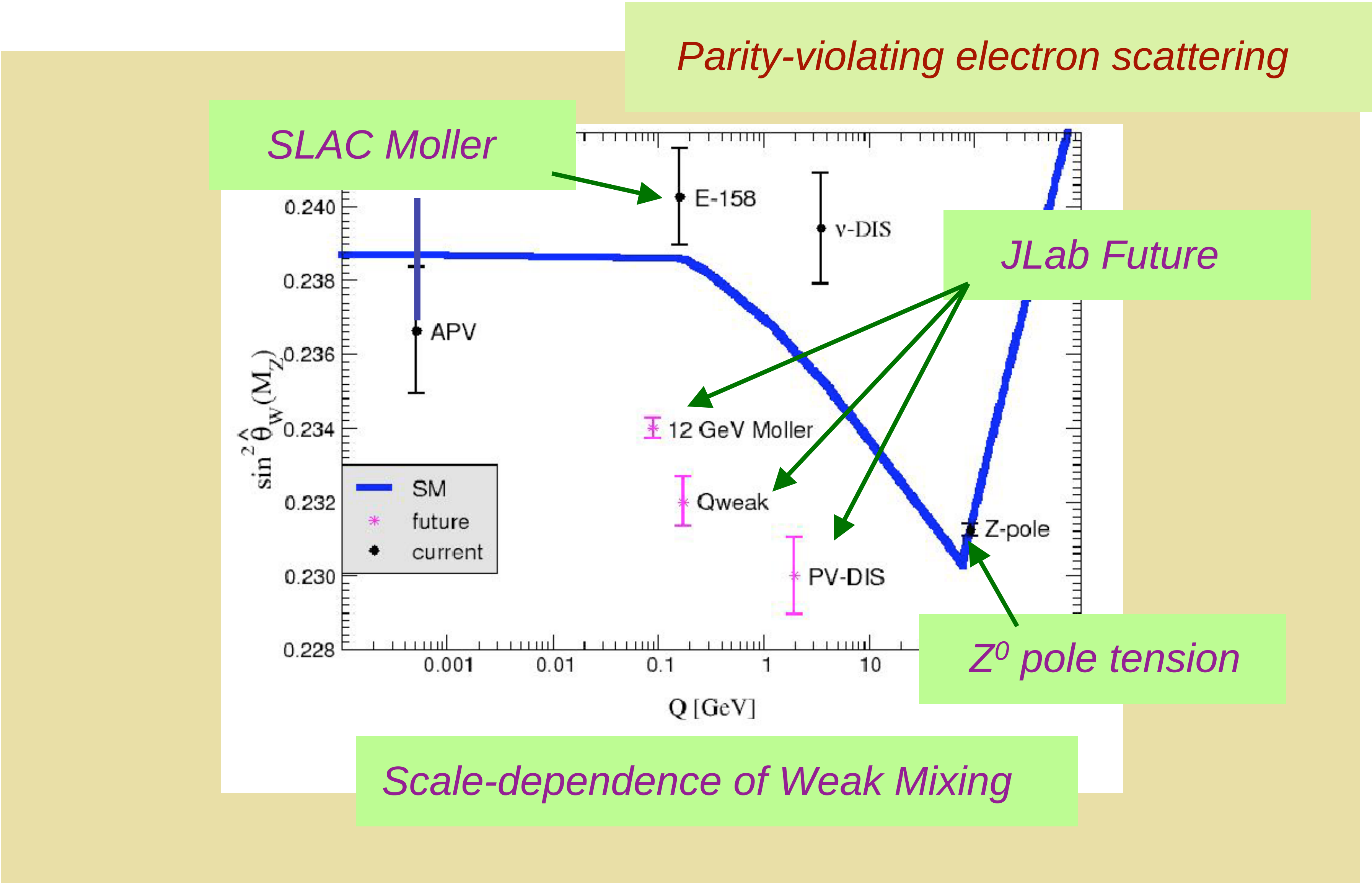
Constrained by Z-pole precision observables

Large logs in κ :

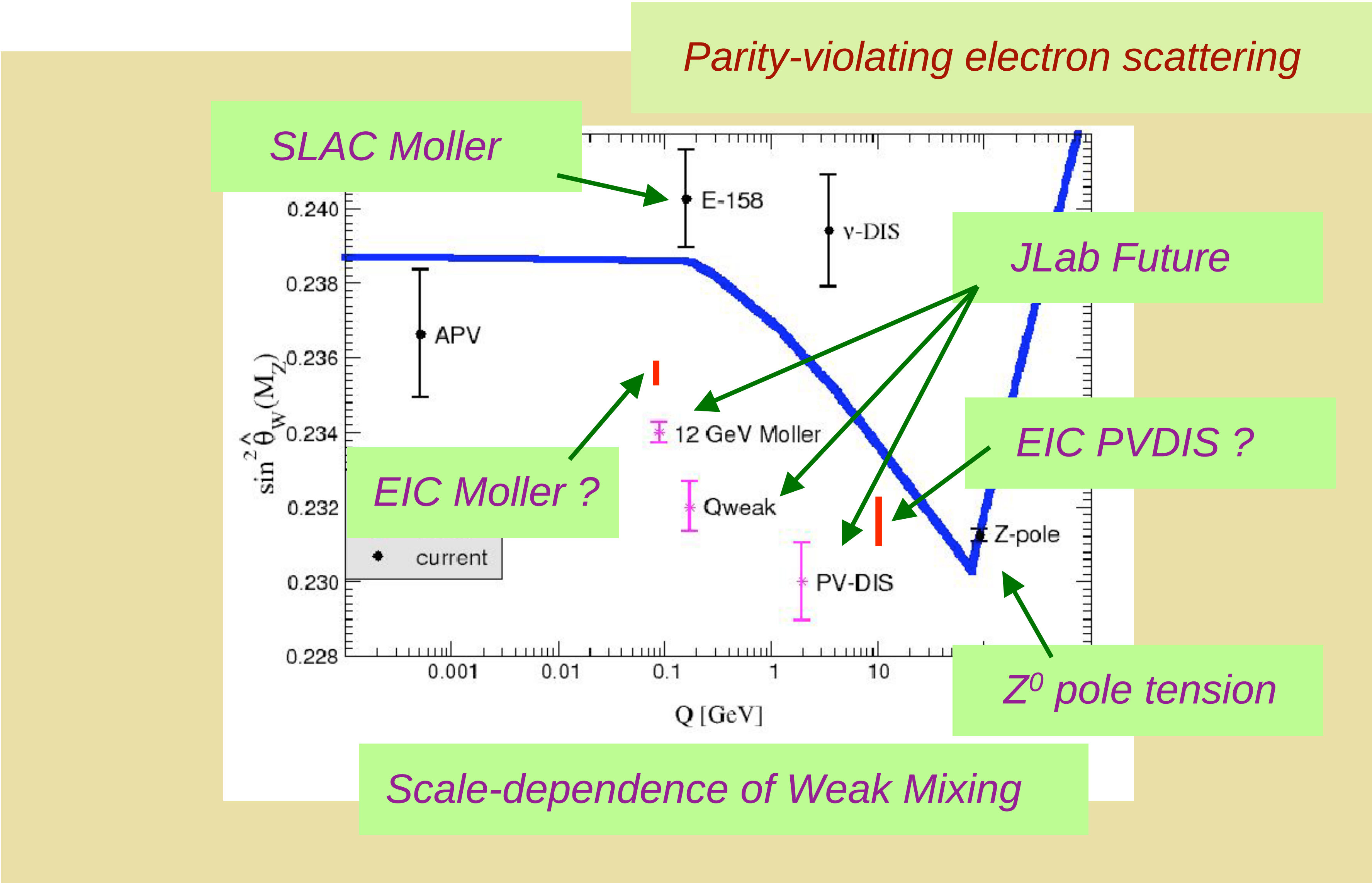
Sum to all orders with running $\sin^2\theta_W$ & RGE

Flavor-indeper

Weak Mixing in the Standard Model

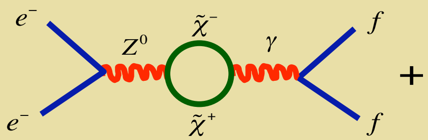


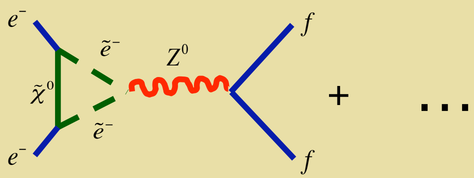
PVES at an EIC



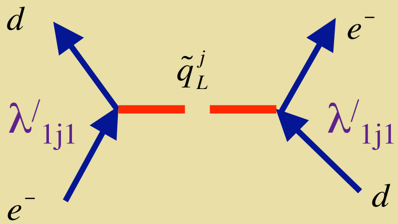
PVES & New Physics

SUSY



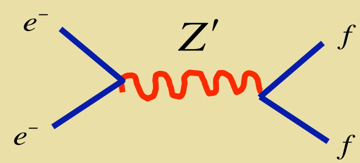


Radiative Corrections



RPV

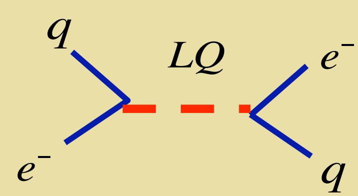
Z′ Bosons



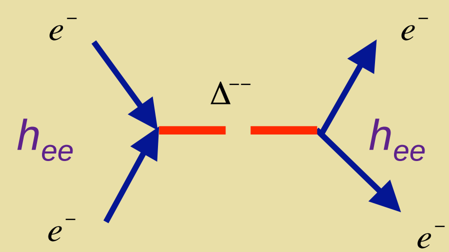
Semi-leptonic only

Moller only

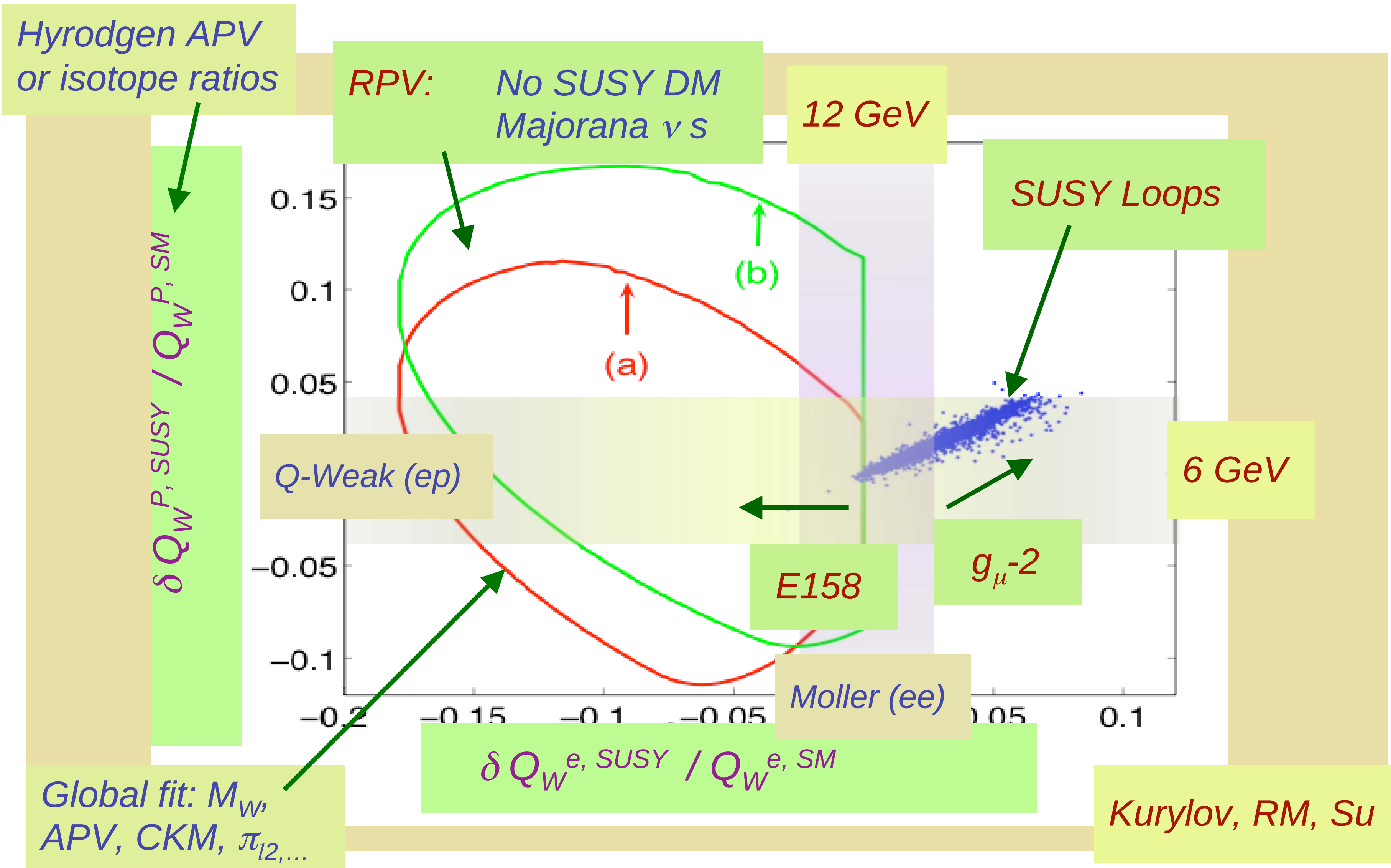
Leptoquarks



Doubly Charged Scalars

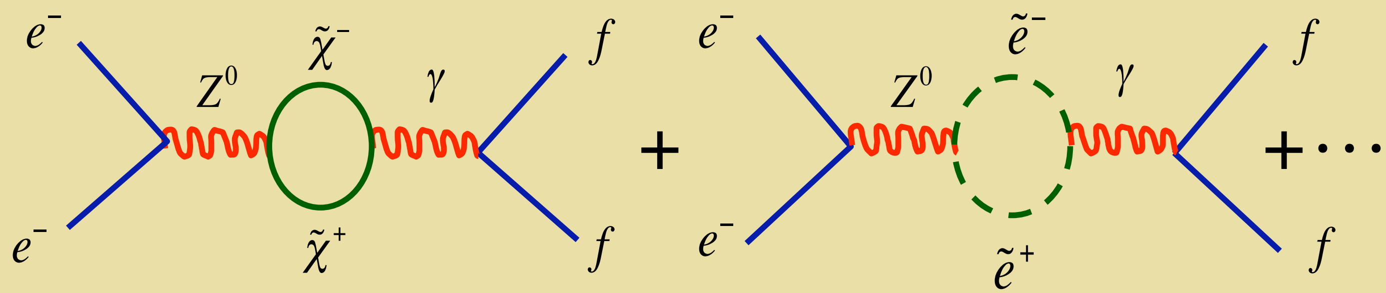


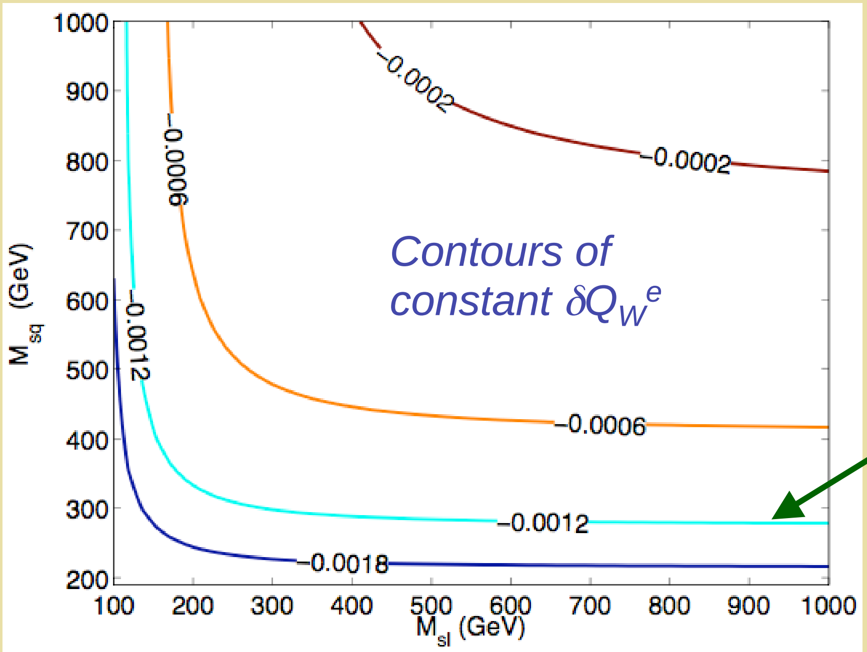
PVES & APV Probes of SUSY



Probing Sfermion Mass Scale

SUSY Loops: Kurylov, SU, MR-M

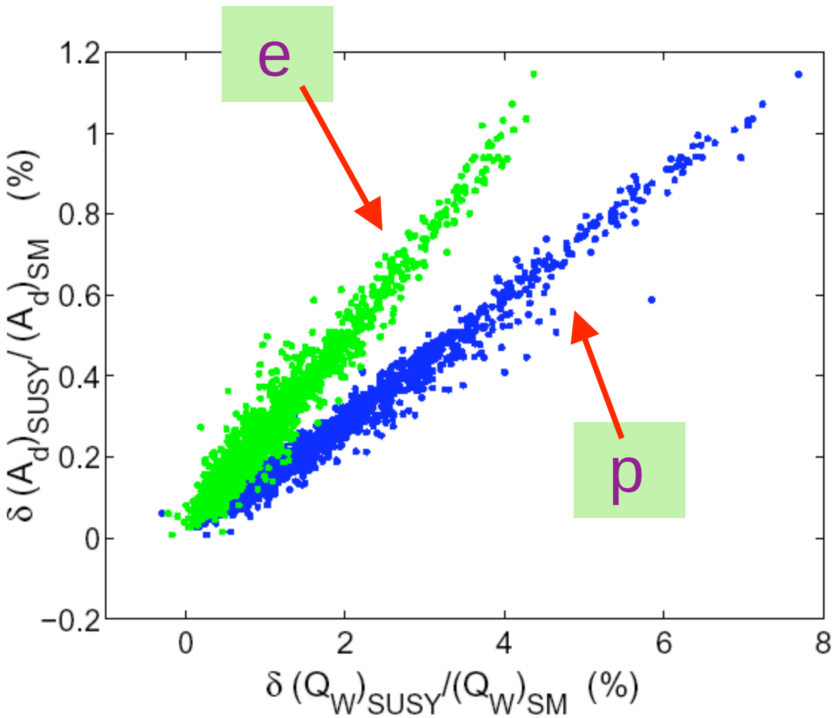


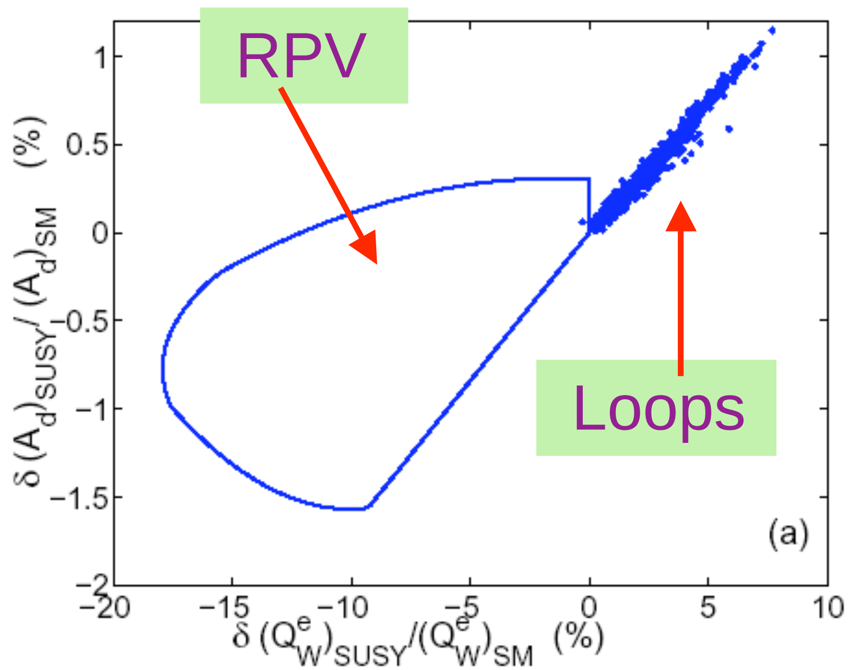


Jlab Moller 1σ

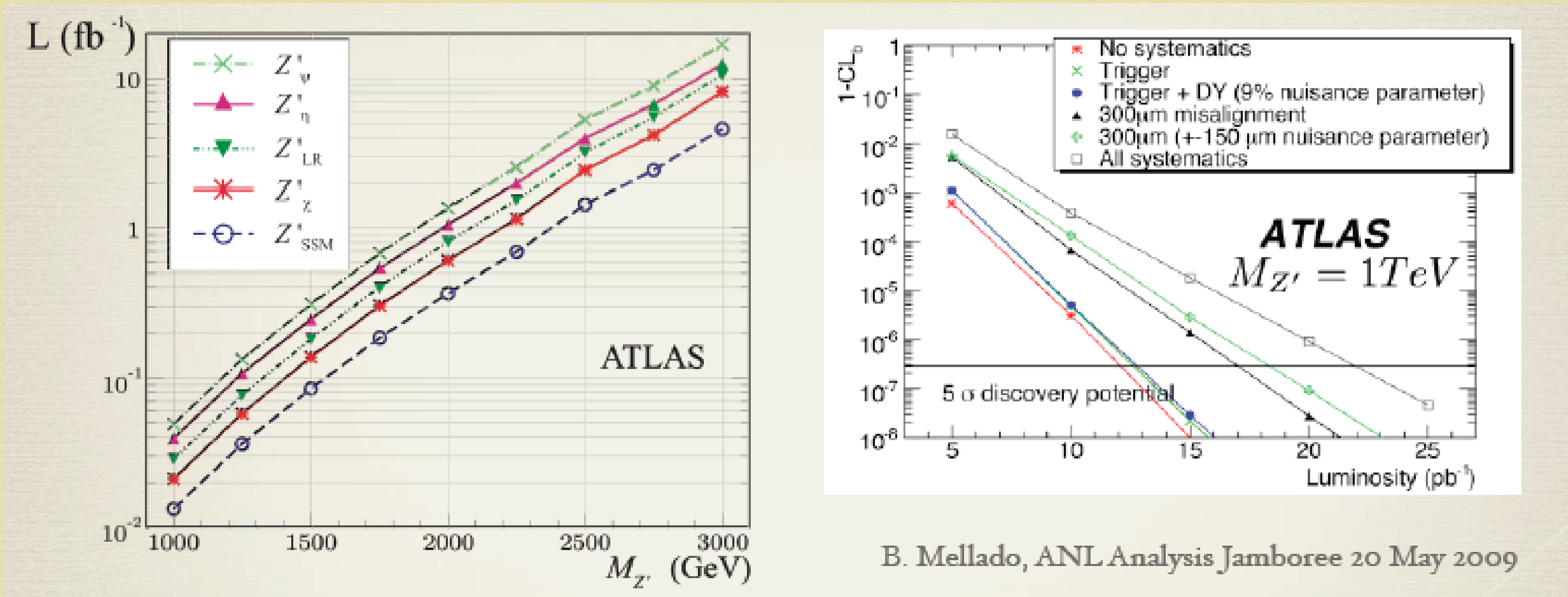
Su, R-M Preliminary

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





Probing Z' : LHC Discovery

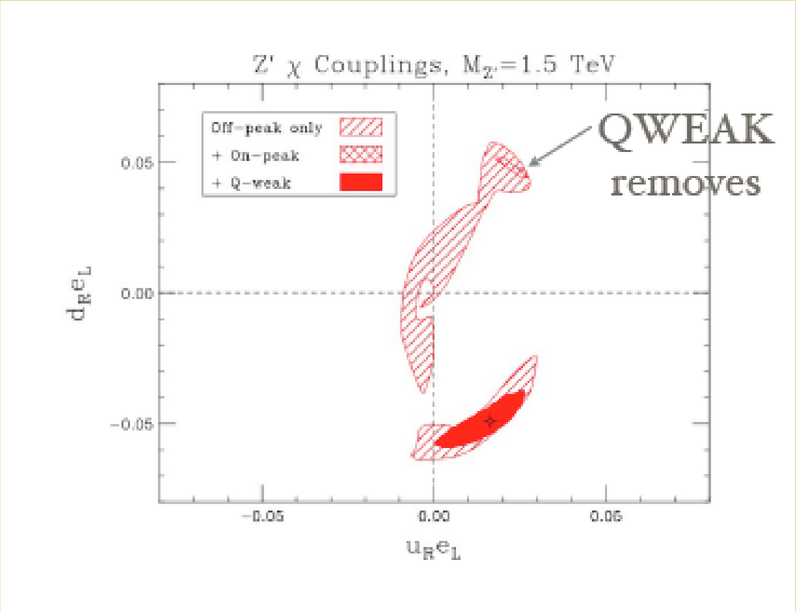


Petriello (CIPANP 09)

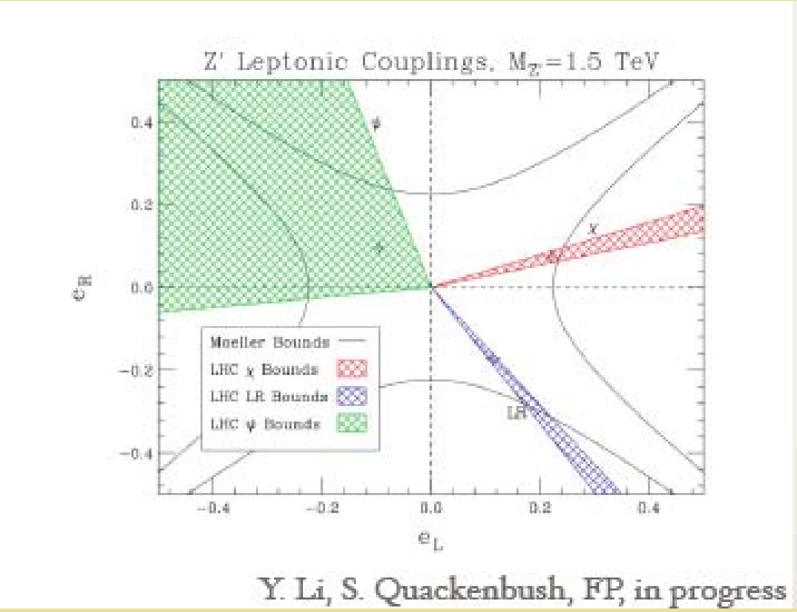
Probing Z' : PVES & LHC

Petriello (CIPANP 09)

PV Couplings: $q_R e_L$



Leptonic PV Couplings: $e_{L,R}$



Qweak: Break LHC Sign Degeneracy

LHC: Cone in e_L - e_R plane
Moller: Hyperbola

See also Chang, Ng, & Wu: 0901.0163

Probing Leptoquarks with PVES

General classification: $SU(3)_C \times SU(2)_L \times U(1)_Y$

$$\mathcal{L} = h_2^L \bar{u} \ell R_2^L + h_2^R \bar{q} i\tau_2 e R_2^R + \tilde{h}_2 \bar{d} \ell \tilde{R}_2^L + g_1^L \bar{q}^c i\tau_2 \ell S_1^L + g_1^R \bar{u}^c e S_1^R + \tilde{g}_1 \bar{d}^c e \tilde{S}_1^R + g_3 \bar{q}^c i\tau_2 \vec{\tau} \ell S_3 + h_1^L \bar{q} \gamma^\mu \ell U_{1\mu}^L + h_1^R \bar{d} \gamma^\mu e U_{1\mu}^R + \tilde{h}_1 \bar{u} \gamma^\mu e \tilde{U}_{1\mu}^R + h_3 \bar{q} \gamma^\mu \vec{\tau} \ell U_{3\mu} + g_2^L \bar{d}^c \gamma^\mu \ell V_{2\mu}^L + g_2^R \bar{q}^c \gamma^\mu e V_{2\mu}^R + \tilde{g}_2 \bar{u}^c \gamma^\mu \ell \tilde{V}_{2\mu}^L + \text{H.c.},$$

SU(5) GUT:
m_ν , τ_{prot}

$LQ \in 15_H$

*Dorsner & Fileviez Perez, NPB **723** (2005) 53*

*Fileviez Perez, Han, Li, R-M NPB **819** (2009) 139*

Q-Weak sensitivities:

LQ	Consistency	$\Delta Q_W(p)/Q_W(p)$	LQ	Consistency	$\Delta Q_W(p)/Q_W(p)$
S_1^L	0.57	9%	$U_{1\mu}^L$	0.26	−8%
S_1^R	0.01	−6%	$U_{1\mu}^R$	0.56	6%
$\tilde{S}_1^R$	0.44	−6%	$\tilde{U}_{1\mu}^R$	0.99	25%
S_3	0.76	10%	$U_{3\mu}$	0.31	−4%
R_2^L	0.44	−13%	$V_{2\mu}^L$	0.87	9%
R_2^R	0.89	15%	$V_{2\mu}^R$	0.11	−7%
$\tilde{R}_2^L$	0.13	−4%	$\tilde{V}_{2\mu}^L$	0.56	14%

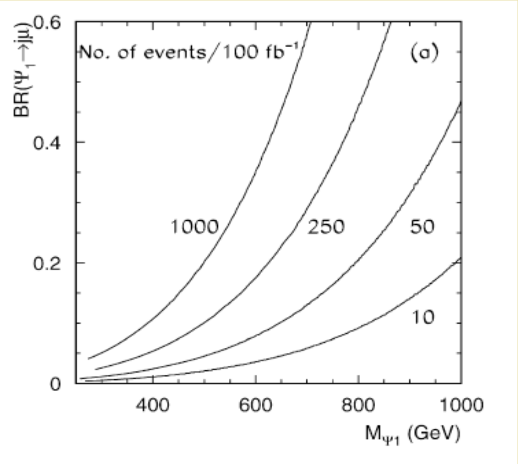
Leptoquarks: PVES, m_ν & LHC

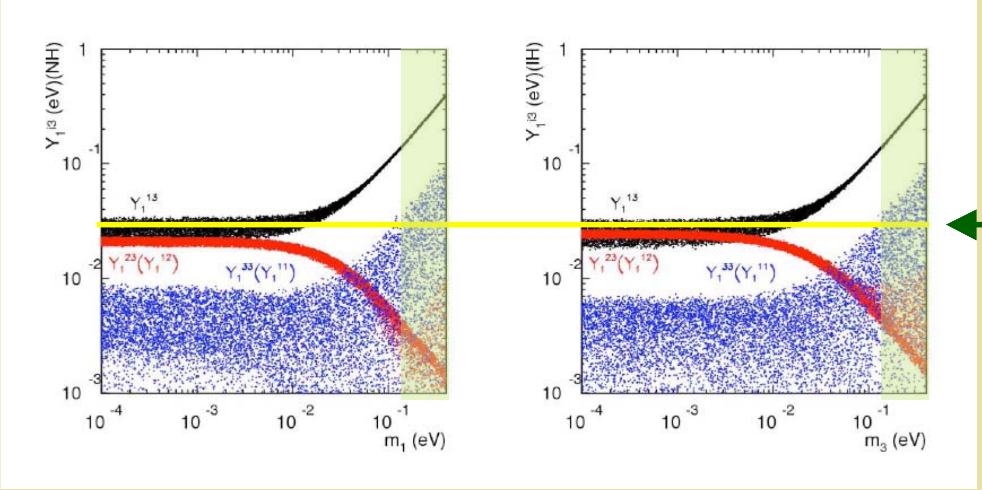
PV Sensitivities

$$\lambda_S \le \gamma_q \, (M_{LQ}/100\,\mathrm{GeV})$$

Observable	Precision	γ_u	γ_d
$Q_W(\mathrm{Cs})$	1.3%	0.04	0.042
	0.35%	0.021	0.022
$\mathcal{R}_1$	0.3%	0.04	0.028
	0.1%	0.023	0.016
$Q_W(^1\mathrm{H})/Q_{EM}(^1\mathrm{H})$	10%	0.05	0.036
	3%	0.028	0.02
$Q_W(0^+,0)/Q_{EM}(0^+,0)$	1%	0.033	0.033
$Q_W(e)/Q_{EM}(e)$	7%		
$A_{LR}(N\rightarrow\Delta)$	1%	0.06	0.06
$\tilde{a}_1$	1%	0.05	0.07

LHC Search



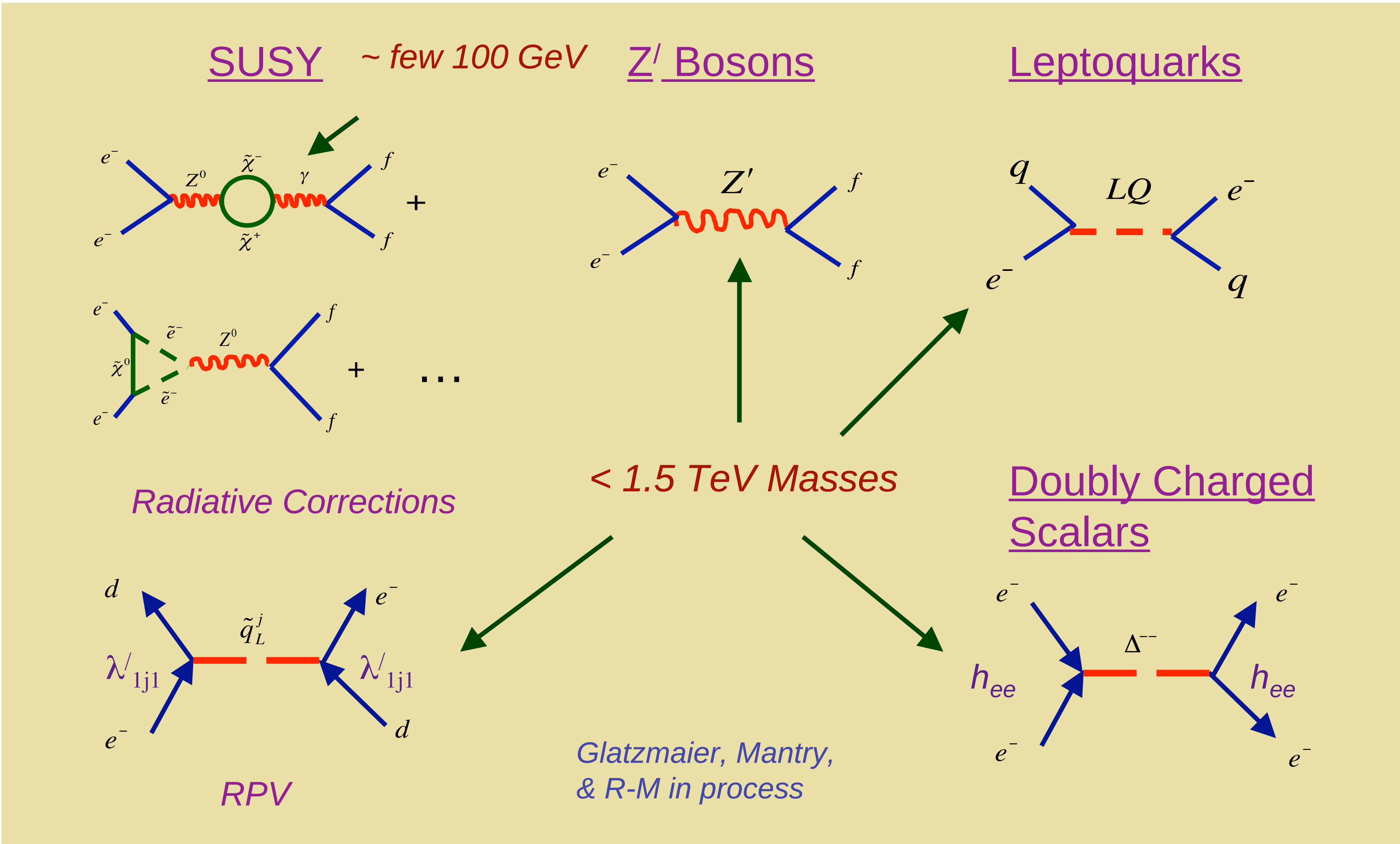


$$\lambda_S = \sqrt{2} Y_\nu^{11} = M_\nu / v_\Delta$$

4% Q_W^p
(M_{LQ}=100 GeV)

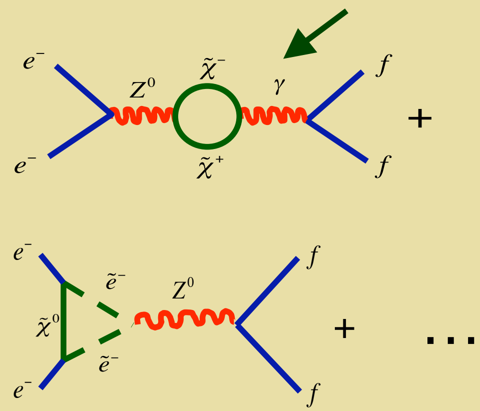
Fileviez Perez, Han, Li, R-M
*NPB **819** (2009) 139*

PVES, New Physics, & the LHC



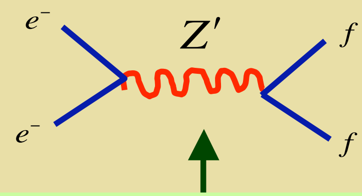
PVES, New Physics, & the LHC

SUSY *~ few 100 GeV*

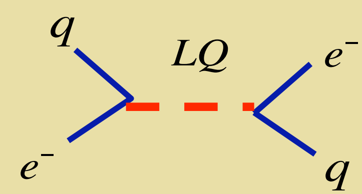


Radiative Corrections

Z' Bosons



Leptoquarks

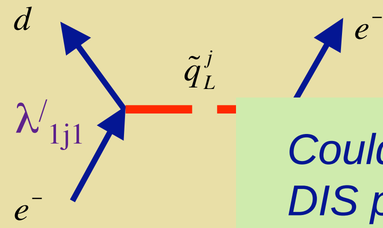


Moller: ~ 2.5% on A_{PV}

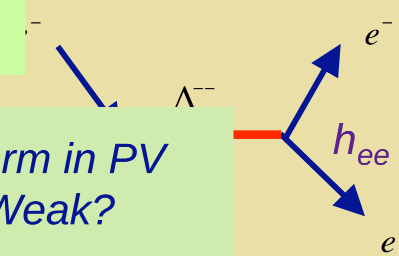
PVDIS: ~ 0.5% on A_{PV}

Need L ~ 10^{33} - 10^{34}

Doubly Charged Scalars



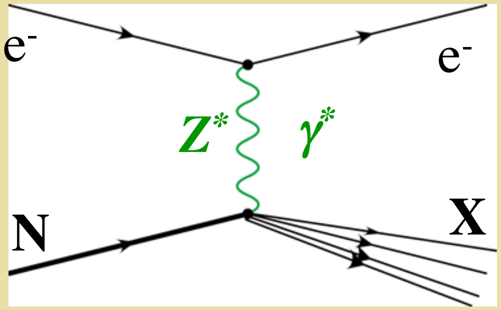
RPV



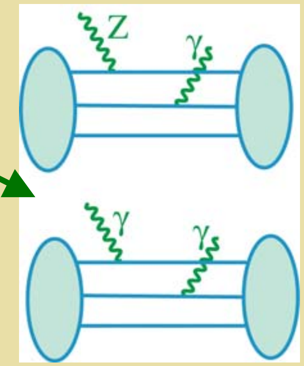
Could a separate determination of the C_{2q} term in PV DIS provide a more powerful probe than Q-Weak?

Theoretically cleaner at EIC energies compared to Jlab PVDIS: larger Q^2 & smaller HT uncertainties ?

Deep Inelastic PV: Beyond the Parton Model & SM

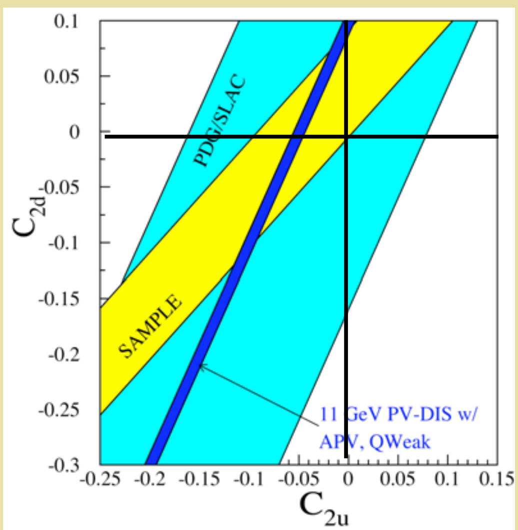


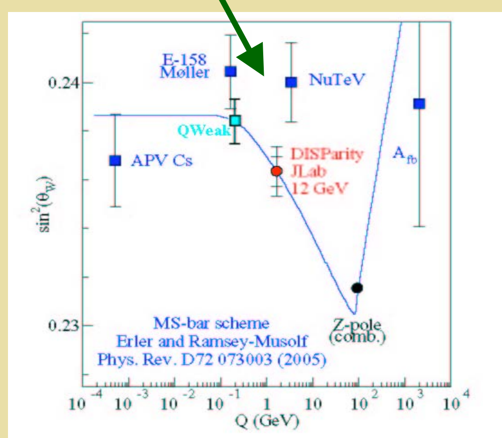
Higher Twist: qq and qqg correlations

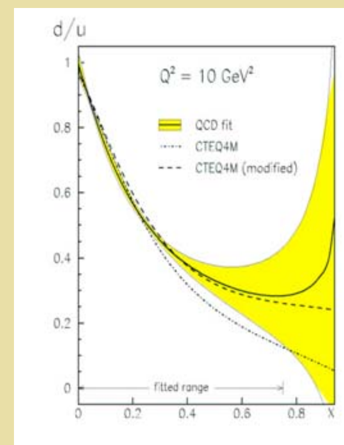


Charge sym in pdfs

$$u^p(x) = d^n(x)?$$
$$d^p(x) = u^n(x)?$$







Electroweak test: e-q couplings & $sin^2\theta_W$

d(x)/u(x): large x

PVDIS & QCD

Low energy effective PV eq interaction

$$L^{eq}_{PV} = \frac{G_\mu}{\sqrt{2}} \sum_q \left[C_{1q} \bar{e} \gamma^\mu \gamma_5 e \bar{q} \gamma_\mu q + C_{2q} \bar{e} \gamma^\mu e \bar{q} \gamma_\mu \gamma_5 q \right]$$

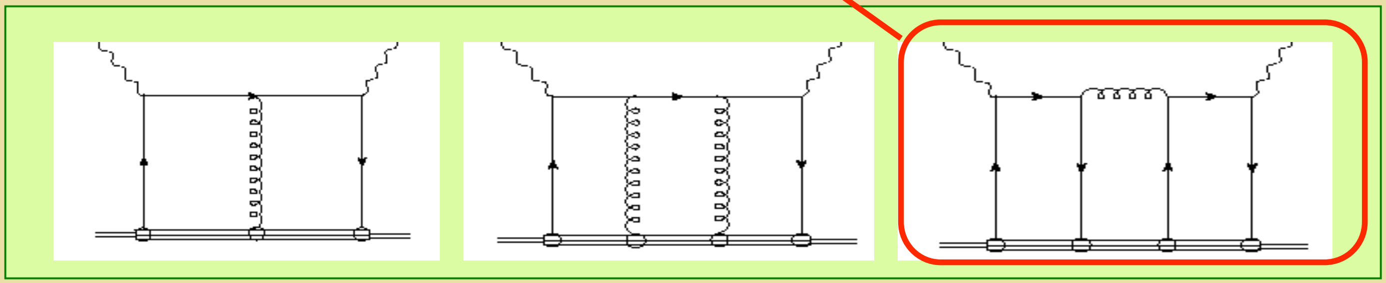
PV DIS eD asymmetry: leading twist

$$A^{eD}_{PV} = \frac{3 G_\mu Q^2}{2\sqrt{2}\pi\alpha} \left[\frac{2C_{1u} - C_{1d} + Y(2C_{2u} - C_{2d})}{5} \right] +$$

Higher Twist (J Lab)

CSV (J Lab, EIC)

d/u (J Lab, EIC)



Bjorken & Wolfenstein '78

Isospin decomposition:

$$\langle VV \rangle \equiv l_{\mu\nu} \int \langle D | V^{\mu}(x) V^{\nu}(0) | D \rangle e^{iq\cdot x} d^4x$$

V = isovector

S = isoscalar

y-independent term: C_{1q}

$$\frac{A_{AV}^{eD}}{Q^2} \propto \frac{\langle VV \rangle [\epsilon_{AV}(e,u) - \epsilon_{AV}(e,d)] + \frac{1}{3} \langle SS \rangle [\epsilon_{AV}(e,u) + \epsilon_{AV}(e,d)]}{\langle VV \rangle + \frac{1}{9} \langle SS \rangle}$$

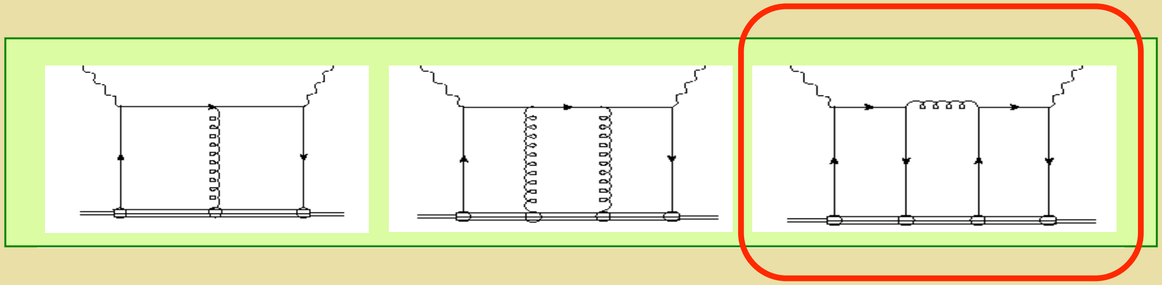
Differences in VV and SS:

$$\langle (V-S)(V+S) \rangle \propto l_{\mu\nu} \int \langle D | \bar{u}(x) \gamma^{\mu} u(x) \bar{d}(0) \gamma^{\nu} d(0) | D \rangle e^{iq\cdot x} d^4x$$

C_{1q} *terms are "contaminated" only by 4q, double handbag* $\tau = 4$ *effects*

Bjorken & Wolfenstein '78

Isolates 4q HT operator: PVDIS a unique probe



- *Possible extraction of C_{1q} term at EIC w/ y-dependence?*
- *Comparison with Jlab PVDIS to extract four-quark HT correction ?*

y-independent term: C_{1q}

$$\left(2C_{1u} - C_{1d}\right)\left(1 + \beta\Gamma^{ud}\right)$$

$\beta \sim -1.6$

On-going theoretical work:

- *QCD evolution of HT contributions*
- *Use of neutrino data for HT in C_{2q} term*

Belitsky, Glatzmaier, Mantry, Paz, R-M, Sacco

C_{1q} terms are "contaminated" only by 4q, double handbag $\tau = 4$ effects

PVDIS & CSV

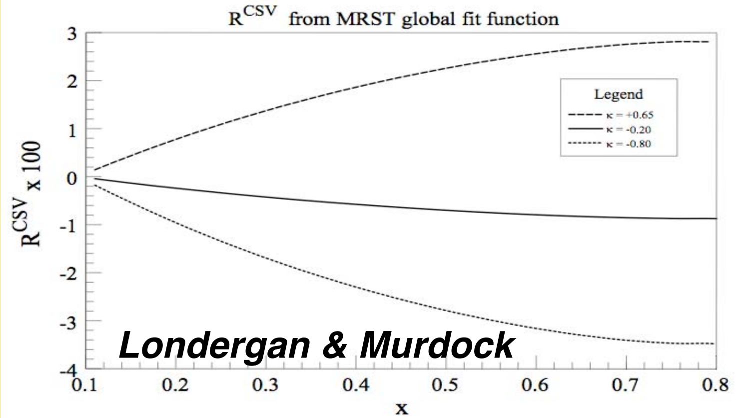
$$A_{PV}^{eD} = \frac{3G_\mu Q^2}{2\sqrt{2}\pi\alpha}\left[\frac{2C_{1u} - C_{1d} + Y(2C_{2u} - C_{2d})}{5}\right]$$

$$u^p(x) = d^n(x)?$$
$$d^p(x) = u^n(x)?$$

•Direct observation of parton-level CSV would be very exciting!
•Important implications for high energy collider pdfs
•Could explain significant portion of the NuTeV anomaly

$$\delta u(x) = u^p(x) - d^n(x)$$
$$\delta d(x) = d^p(x) - u^n(x)$$

$$\longrightarrow \quad R^{CSV} = \frac{\delta A_{PV}(x)}{A_{PV}(x)} = 0.28\frac{\delta u(x) - \delta d(x)}{u(x) + d(x)}$$



Few percent $\delta A/A$

Adapted from K. Kumar

PVDIS & CSV

$$A_{PV}^{eD} = \frac{3G_\mu Q^2}{2\sqrt{2}\pi\alpha}\left[\frac{2C_{1u} - C_{1d} + Y(2C_{2u} - C_{2d})}{5}\right]$$

$$u^p(x) = d^n(x)?$$
$$d^p(x) = u^n(x)?$$

- ***Direct observation of parton-level CSV would be very exciting!***
- ***Important implications for high energy collider pdfs***
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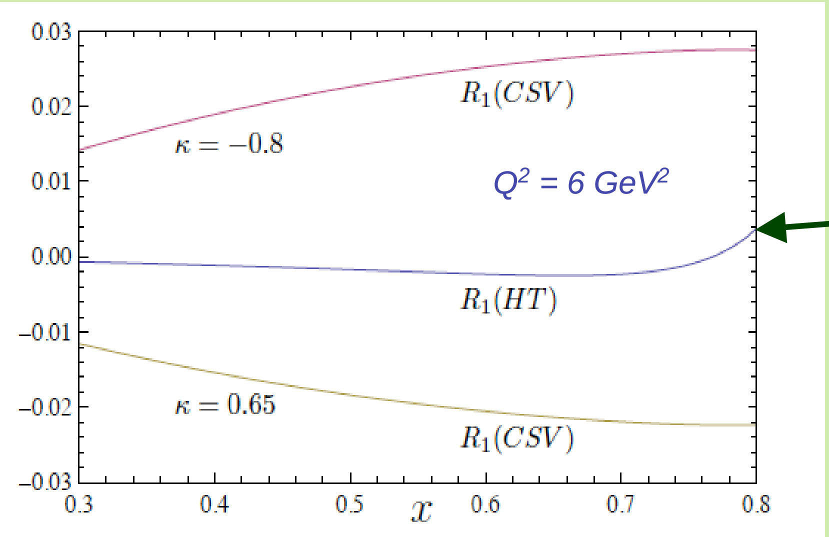


HT & CSV in C_{1q} term

HT:MIT BM

Mantry, R-M, Sacco
arXiv:1004.3307 [hep-ph]

Summary

- Precision studies and symmetry tests are poised to discovery key ingredients of the new Standard Model during the next decade
- There may be a role for an EIC in the post-LHC era
- Promising: PV Moller & PV DIS for neutral currents
- Homework: Charged Current probes -- can they complement LHC & low-energy studies?
- Intriguing: LFV with $e \to \tau$ conversion: $\int L\, dt \sim 10 \to 10^3 \quad fb^{-1}$

Back Matter

Direct probes of LNV

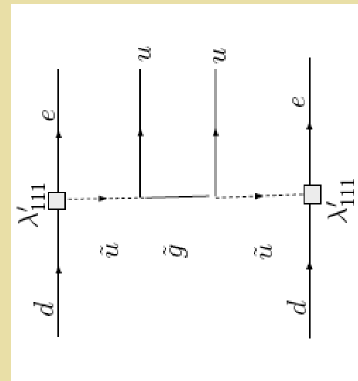
$e^- + A(Z,N) \to \mu^+ \ (\tau^+) + X$

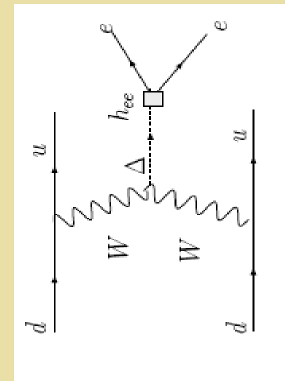
$$\mathcal{L}(q,e) = \frac{G_F^2}{\Lambda_{LNV}} \sum_{j=1}^{14} C_j(\mu)\, O_j^{++}\, \bar{e}\Gamma_j \ell^c \quad + \quad h.c.$$

e.g. $$O_{1+}^{ab} = \bar{q}_L \gamma^\mu \tau^+ q_L \ \bar{q}_R \gamma_\mu \tau^+ q_R$$

Suppressed?

Like $0\nu\beta\beta$ with: $e \to \mu \ (\tau)$

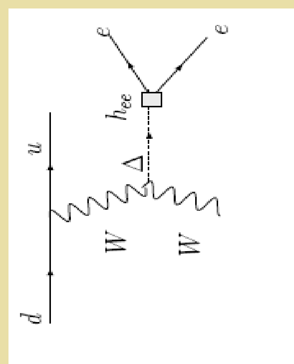




$\lambda'_{111} \to \lambda'_{211}, \lambda'_{311}$

$h_{ee} \to h_{e\mu}, h_{e\tau}$

$e^- + A(Z,N)$
$\to \mu^+ \ (\tau^+) + W^- + X$



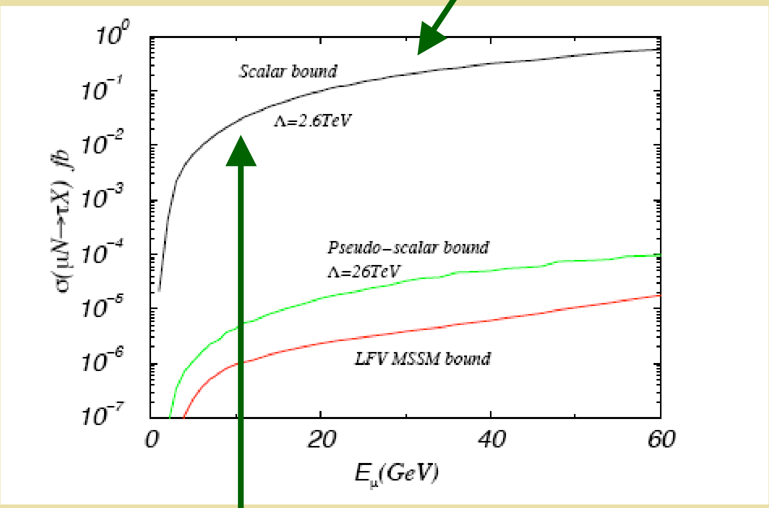
LHC: $q\bar{q}' \to W^{+*}$
$\to \Delta^{++} \Delta^{-}$

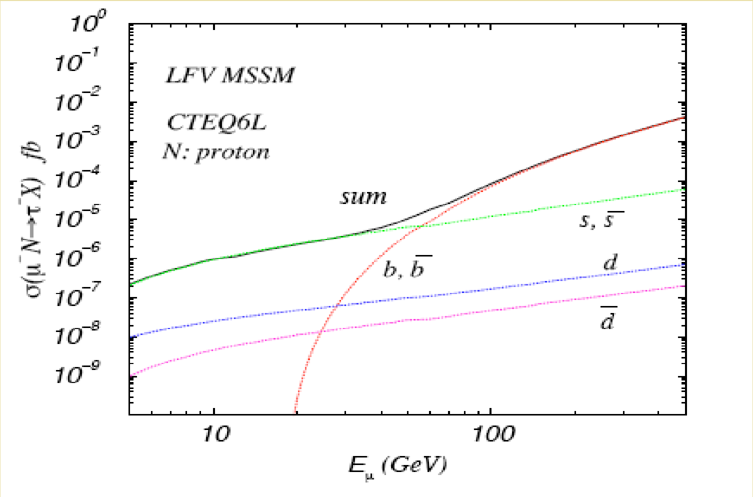
LFV with τ leptons: recent theory

Kanemura et al (2005)

τμqq eff op

SUSY Higgs Exchange





$|\lambda_{lq}|^2 < 2 \times 10^{-2} (M_{LQ} / 100 \text{ GeV})^2$

$|\lambda_{lq}|^2 < 10^{-4} (M_{LQ} / 100 \text{ GeV})^2$ HERA

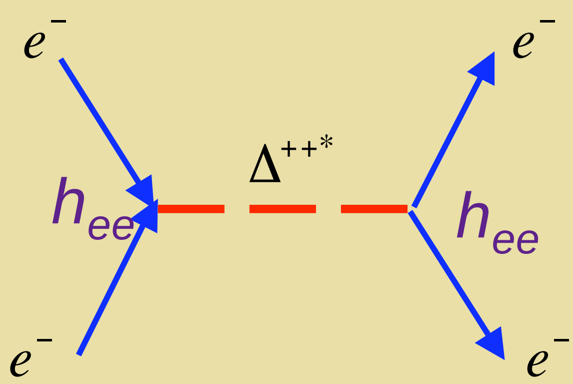
PVES & 0νββ Decay

See saw & doubly charged Higgs

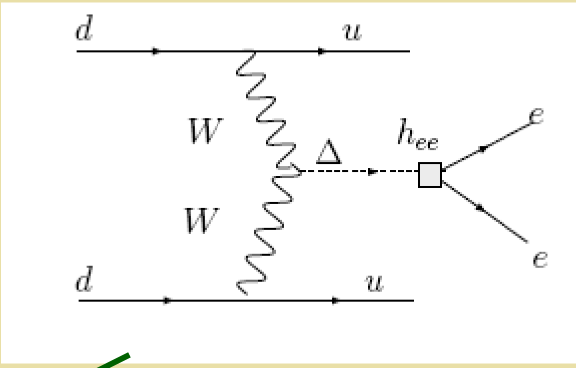
$$\mathcal{L}_M = Y_\nu\, \bar{5}^T 15_H 5 \supset Y_\nu\, [\, \ell_L^T C\epsilon\Delta\ell_L + \sqrt{2}\bar{d}_R\ell_L\epsilon\tilde{R}_2^L\,]$$

Δ^{++} (also LRSM)

PV Moller

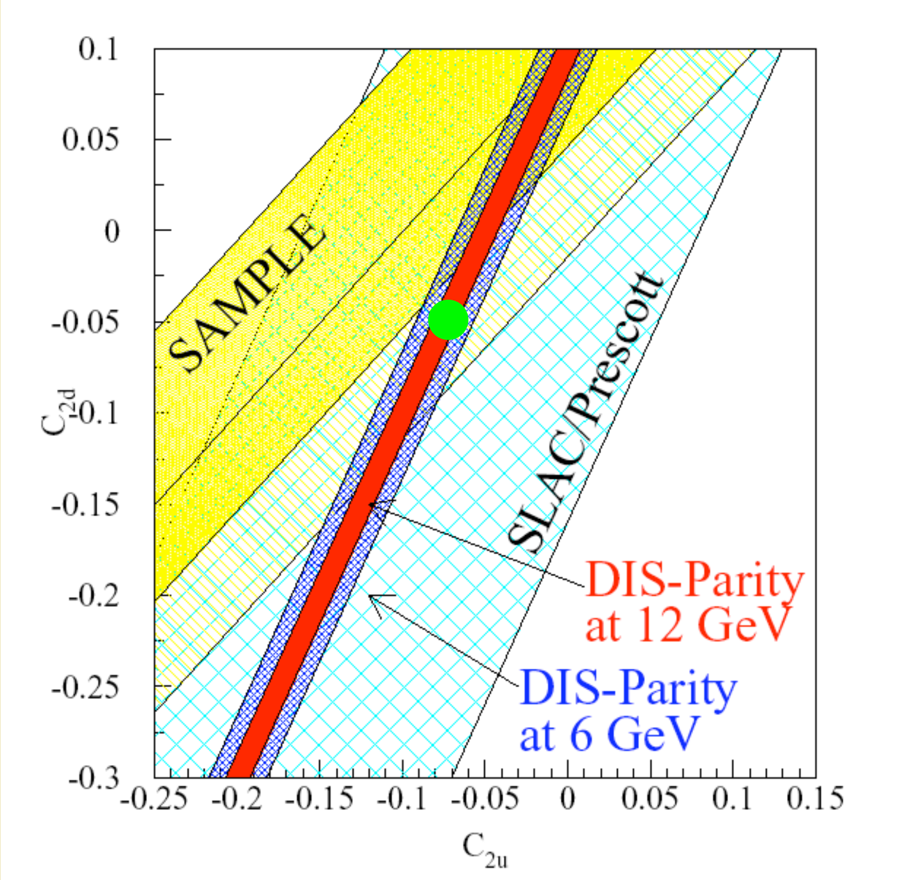


0νββ Decay



$$h_{ee} < 10^{-7} \times (M_W\ /100\ \mathrm{GeV})^3 (M_\Delta/100\ \mathrm{GeV})^2$$

Model Independent Constraints



P. Reimer, X. Zheng

Effective PV e-q interaction & Q_W

Low energy effective PV eq interaction

$$L_{PV}^{eq} = \frac{G_\mu}{\sqrt{2}} \sum_q \left[C_{1q} \bar{e}\gamma^\mu \gamma_5 e \bar{q}\gamma_\mu q + C_{2q} \bar{e}\gamma^\mu e \bar{q}\gamma_\mu \gamma_5 q \right]$$

Weak Charge:

$N_u C_{1u} + N_d C_{1d}$

Proton:

$Q_W^P = 2 C_{1u} + C_{1d} = 1-4 \sin^2\theta_W \sim 0.1$

Electron:

$Q_W^e = C_{1e} = -1+4 \sin^2\theta_W \sim -0.1$

Effective PV e-q interaction & PVDIS

Low energy effective PV eq interaction

$$L_{PV}^{eq} = \frac{G_\mu}{\sqrt{2}} \sum_q \left[C_{1q} \bar{e} \gamma^\mu \gamma_5 e \bar{q} \gamma_\mu q + C_{2q} \bar{e} \gamma^\mu e \bar{q} \gamma_\mu \gamma_5 q \right]$$

Weak Charge:

$N_u C_{1u} + N_d C_{1d}$

Proton:

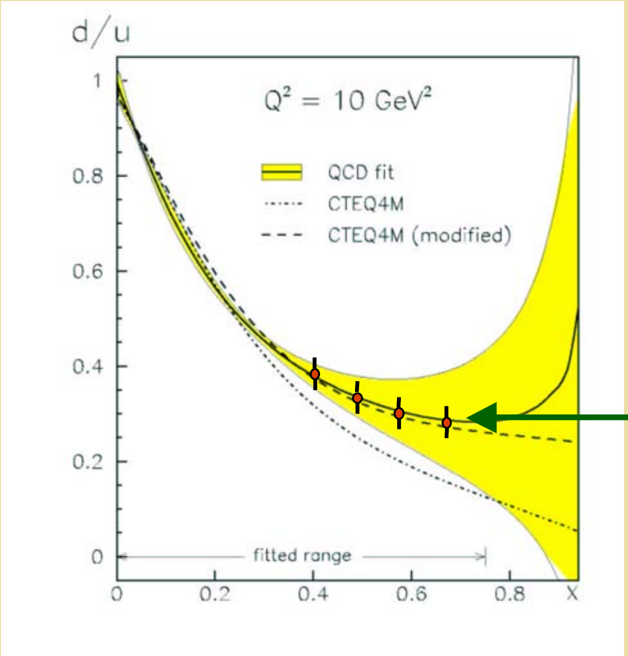
$Q_W^P = 2 C_{1u} + C_{1d} = 1\text{-}4 \sin^2\theta_W \sim 0.1$

Electron:

$Q_W^e = C_{1e} = -1+4 \sin^2\theta_W \sim -0.1$

PVDIS & d(x)/u(x): x→1

Adapted from K. Kumar



SU(6): d/u~1/2

Valence Quark: d/u~0

Perturbative QCD: d/u~1/5

δA/A ~ 0.01

PV-DIS off the proton (hydrogen target)

Very sensitive to d(x)/u(x)

$$A_{PV} = \frac{G_F Q^2}{\sqrt{2}\pi\alpha}\left[a(x) + f(y)b(x)\right] \longrightarrow a(x) = \frac{u(x) + 0.91d(x)}{u(x) + 0.25d(x)}$$

C-Odd SD Structure Functions

$$g_1^{\gamma} = \frac{2}{9}(\Delta u + \Delta c + \Delta\bar{u} + \Delta\bar{c}) + \frac{1}{18}(\Delta d + \Delta s + \Delta\bar{d} + \Delta\bar{s})$$

$$g_1^{\gamma z} = \left(\frac{1}{3} - \frac{8}{9}\sin^2\theta_W\right)(\Delta u + \Delta c + \Delta\bar{u} + \Delta\bar{c}) + \left(\frac{1}{6} - \frac{2}{9}\sin^2\theta_W\right)(\Delta d + \Delta s + \Delta\bar{d} + \Delta\bar{s}) \simeq \frac{1}{9}\sum_q(\Delta_q + \Delta_{\bar{q}})$$

C-odd

$$g_5^{\gamma z} = \frac{1}{6}\left[2(\Delta u + \Delta c - \Delta\bar{u} - \Delta\bar{c}) + (\Delta d + \Delta s - \Delta\bar{d} - \Delta\bar{s})\right]$$

$$g_5^{z} = \frac{1}{2}\left(\frac{1}{2} - \frac{4}{3}\sin^2\theta_W\right)(\Delta u + \Delta c - \Delta\bar{u} - \Delta\bar{c}) + \frac{1}{2}\left(\frac{1}{2} - \frac{2}{3}\sin^2\theta_W\right)(\Delta d + \Delta s - \Delta\bar{d} - \Delta\bar{s})$$

C-odd

Anselmino, Gambino, Kalinowski '94

Target Spin Asymmetries

Polarized Long & trans target spin asymmetries (parity even)

$$\Delta^L \sigma_{nc}^{\ell N}(\lambda = 1) = -16\pi m_N E \frac{\alpha^2}{Q^4} xy(2-y)\, g_1^\gamma$$

$$\Delta^T \sigma_{nc}^{\ell N}(\lambda = 1) = -8 m_N \frac{\alpha^2}{Q^4} \cos(\alpha - \phi)\sqrt{2xym_N E(1-y)}\, xy\, g_1^\gamma$$

Unpolarized Long & trans target spin asymmetry (parity odd)

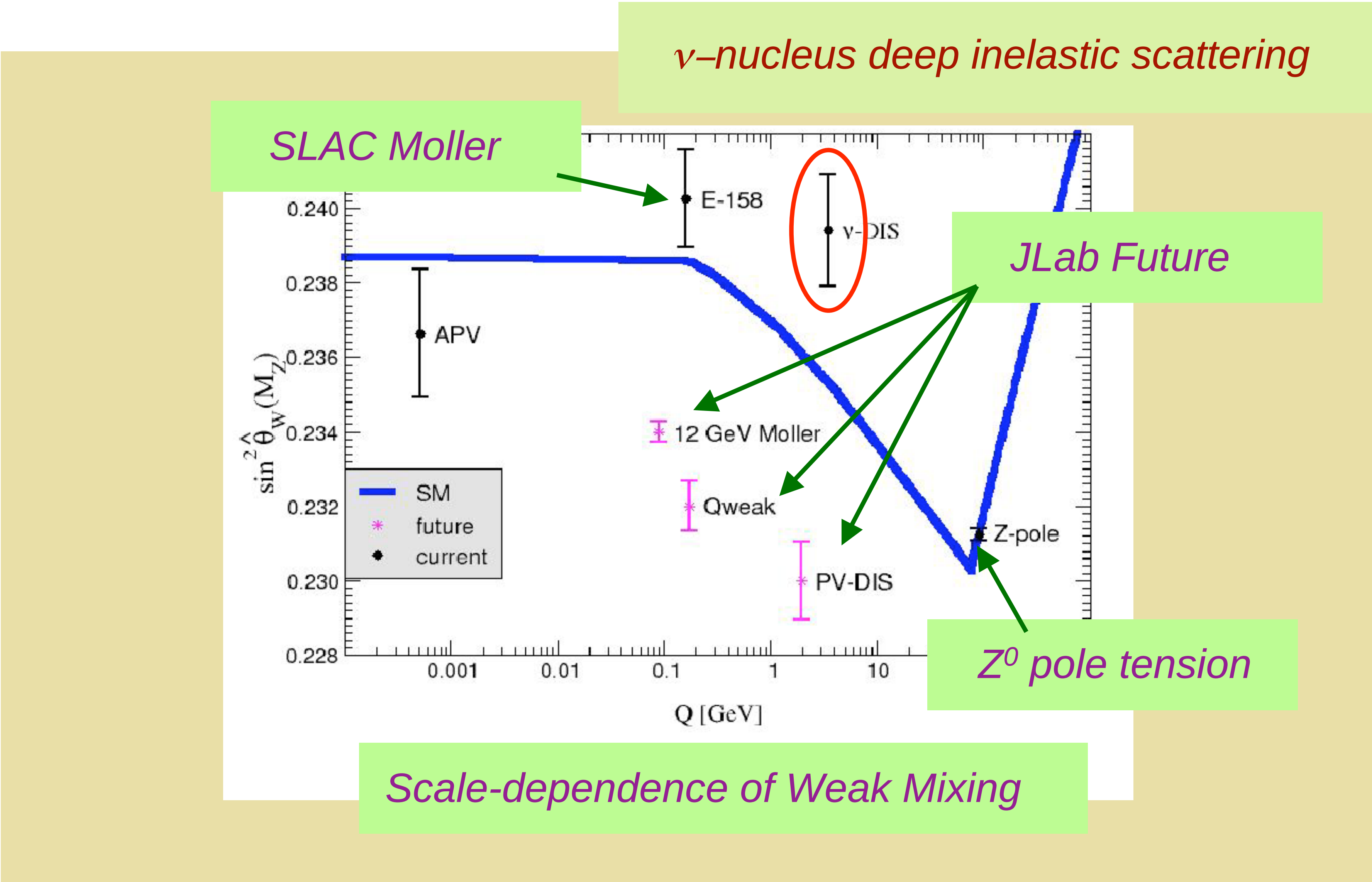
$$\Delta^L \sigma_{nc}^{\ell^- N}(\langle\lambda\rangle = 0) = 16\pi m_N E \frac{\alpha^2}{Q^4} \eta^{\gamma Z}\; x \left\{ y(2-y) g_A\; g_1^{\gamma Z} + (2 - 2y + y^2) g_V\; g_5^{\gamma Z} \right\}.$$

Bilenky et al '75; Anselmino et al '94

Charged Current Processes

- *The NuTeV Puzzle*
- *HERA Studies*
- *W Production at an EIC ? CC/NC ratios ?*

Weak Mixing in the Standard Model



The NuTeV Puzzle

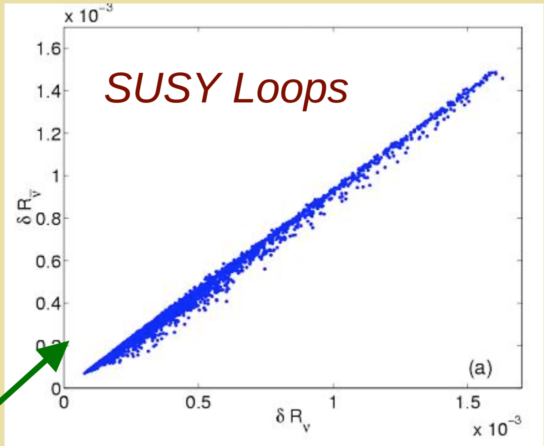
$$R_\nu = \sigma^{NC}_{\nu N} / \sigma^{CC}_{\nu N} = g_L^2 + r g_R^2 \qquad g^2_{L,R} = \left(\frac{\rho^{NC}_{\nu N}}{\rho^{CC}_{\nu N}}\right)^2 \sum_q (\varepsilon^q_{L,R})^2$$

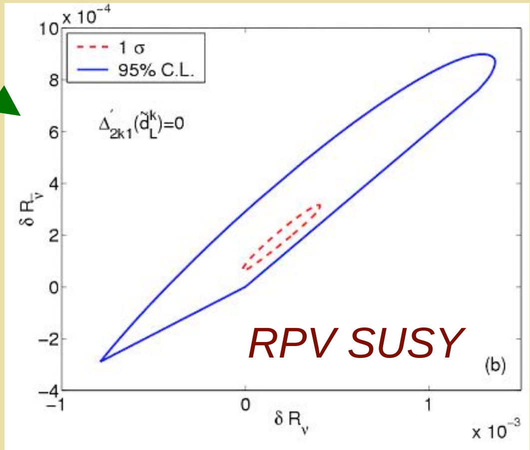
$$R_{\bar\nu} = \sigma^{NC}_{\bar\nu N} / \sigma^{CC}_{\bar\nu N} = g_L^2 + r^{-1} g_R^2 \qquad r = \sigma^{CC}_{\nu N} / \sigma^{CC}_{\bar\nu N}$$

$$R_\nu^{\exp} - R_\nu^{SM} = -0.0033 \pm 0.0007$$

$$R_{\bar\nu}^{\exp} - R_\nu^{SM} = -0.0019 \pm 0.0016$$

Wrong sign





Paschos-Wolfenstein

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

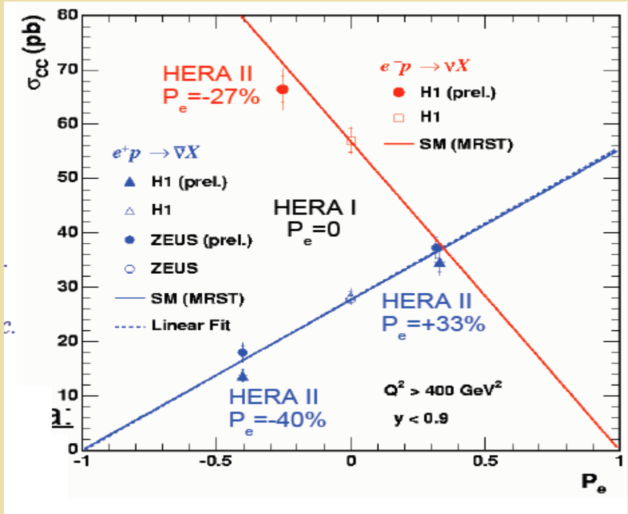
Other New CC Physics?

Low-Energy Probes

Nuclear & neutron β–decay	$\delta O / O^{SM} \sim 10^{-3}$
Pion leptonic decay	$\delta O / O^{SM} \sim 10^{-4}$
Polarized μ-decay	$\delta O / O^{SM} \sim 10^{-2}$

HERA W production

$\delta O / O^{SM} \sim 10^{-1}$



A. Schoning (H1, Zeus)

Other New CC Physics?

Low-Energy Probes

CC Structure Functions: more promising?

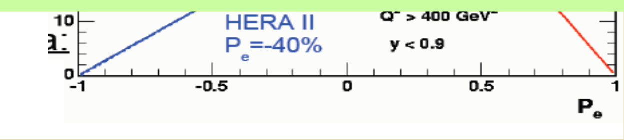
$$g_1^{W^-} = (\Delta u + \Delta c + \Delta \bar{d} + \Delta \bar{s})$$

$$g_3^{W^-} = 2x(\Delta\ u + \Delta c - \Delta \bar{d} - \Delta \bar{s})$$

$$2x g_5^{W^-} = g_3^{W^-}$$

$$\Delta^L \sigma_{cc}^{\ell^\mp N} = 64\pi m_N E \frac{\alpha^2}{Q^4} \eta^W \times \left\{ \pm xy \left[2 - y + \frac{x m_N}{E}(1-y) \right] g_1^{W^\mp} + x \left[y^2 + (1-y) \left(2 - \frac{xym_N}{E} \right) \right] g_5^{W^\mp} \right\},$$

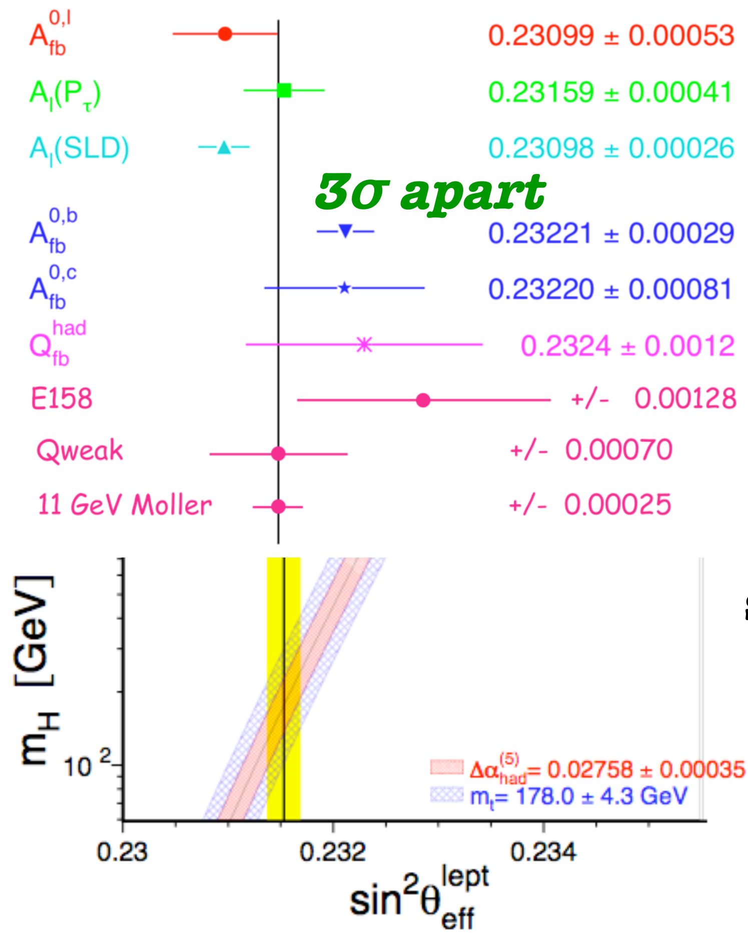
$$\Delta^T \sigma_{cc}^{\ell^\mp N} = 32 m_N \frac{\alpha^2}{Q^4} \eta^W \sqrt{xym_N[2(1-y)E - xym_N]} \cos(\alpha - \phi) \times x(1-y) \left(\mp g_1^{W^\mp} + g_5^{W^\mp} \right).$$



A. Schoning (H1, Zeus)

Z Pole Tension

W. Marciano



The Average: $\sin^2\theta_W = 0.23122(17)$

$\Rightarrow m_H = 89^{+38}_{-28}$ GeV

$\Rightarrow S = -0.13 \pm 0.10$

Rules out Technicolor!

Favors SUSY!

A_{LR}	A_{FB} ($Z \to bb$)
(also APV in Cs)	(also Moller @ E158)
$\sin^2\theta_W = 0.2310(3)$	$\sin^2\theta_W = 0.2322(3)$
↓	↓
$m_H = 35^{+26}_{-17}$ GeV	$m_H = 480^{+350}_{-230}$ GeV
$S = -0.11 \pm 17$	$S = +0.55 \pm 17$
Rules out the SM!	**Rules out SUSY!** **Favors Technicolor!**

- Precision $\sin^2\theta_W$ measurements at colliders very challenging
- Neutrino scattering cannot compete statistically
- No resolution of this issue in next decade

K. Kumar

Probing Z' with PVES

Heterotic string motivated Z'

$$E_8 \times E_8'$$

$$\begin{aligned} E_8 &\rightarrow E_6 \\ E_6 &\rightarrow SO(10) \times U(1)_\psi \\ &\rightarrow SU(5) \times U(1)_\chi \times U(1)_\psi \end{aligned}$$

$$Z' = \cos\phi\, Z_\psi + \sin\phi\, Z_\chi$$

$$\Delta Q_W^f = \zeta\, h_V^f \qquad \zeta = \frac{8\sqrt{2}\pi\alpha'}{M_{Z'}^2 G_F}$$

$$h_v^d = -h_V^e = [\sin^2\phi - \sqrt{15}\sin\phi\cos\phi/3]/20 \qquad h_v^u = 0$$