Precision Electroweak Physics and QCD at an EIC

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NPAC

Theoretical Nuclear, Particle, Astrophysics & Cosmology

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

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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?*

Outline

- *Lepton flavor violation:* $e^- + A \to \tau^- + A$
- *Neutral Current Processes: PV DIS & PV Moller*
- *Charged Current Processes:* $e^- + A \to \not{E}_T + j$

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Disclaimer: some ideas worked out in detail; others need more research

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*
- τ K *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

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

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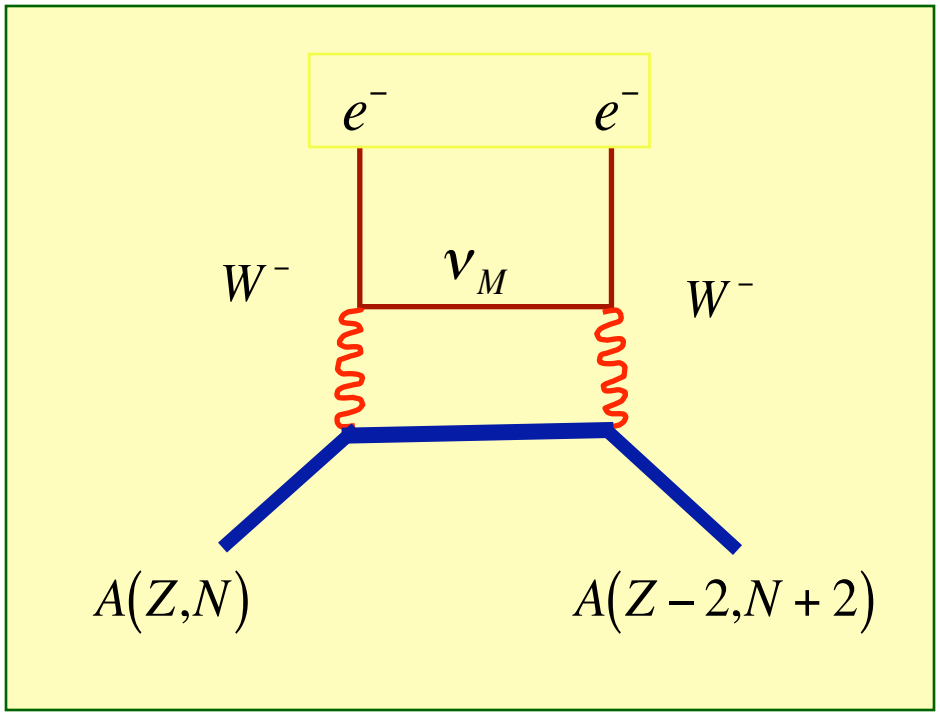

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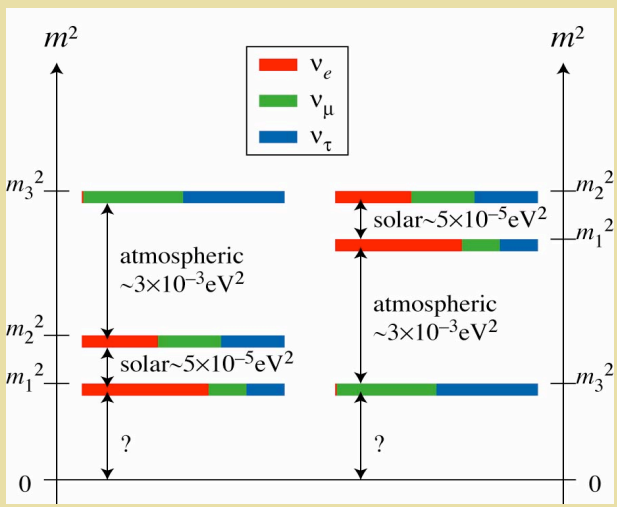
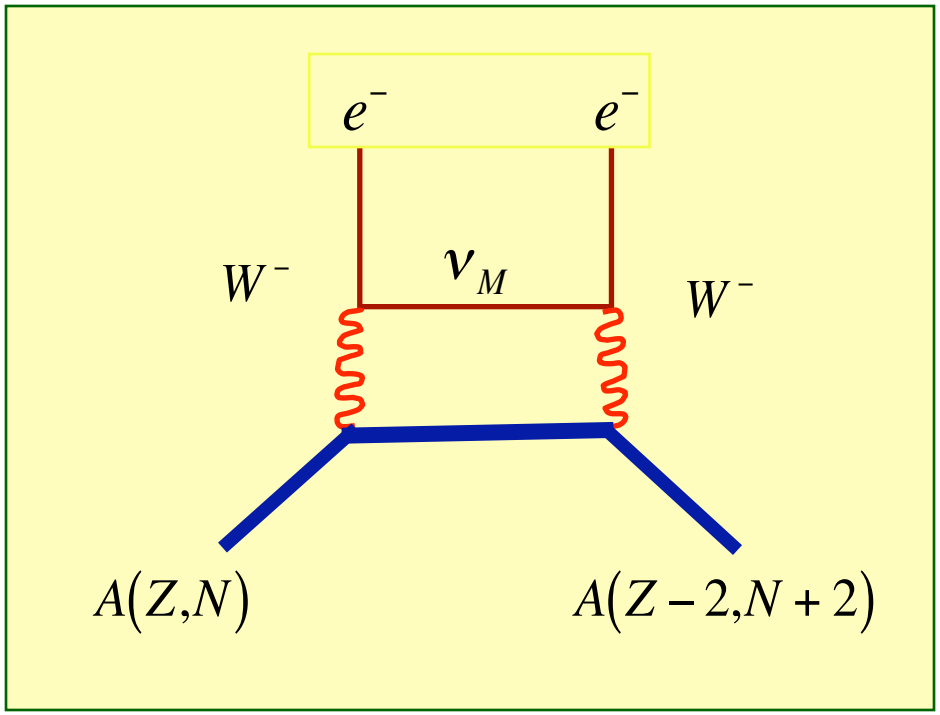
m_ν^{EFF} & neutrino spectrum



Normal *Inverted*



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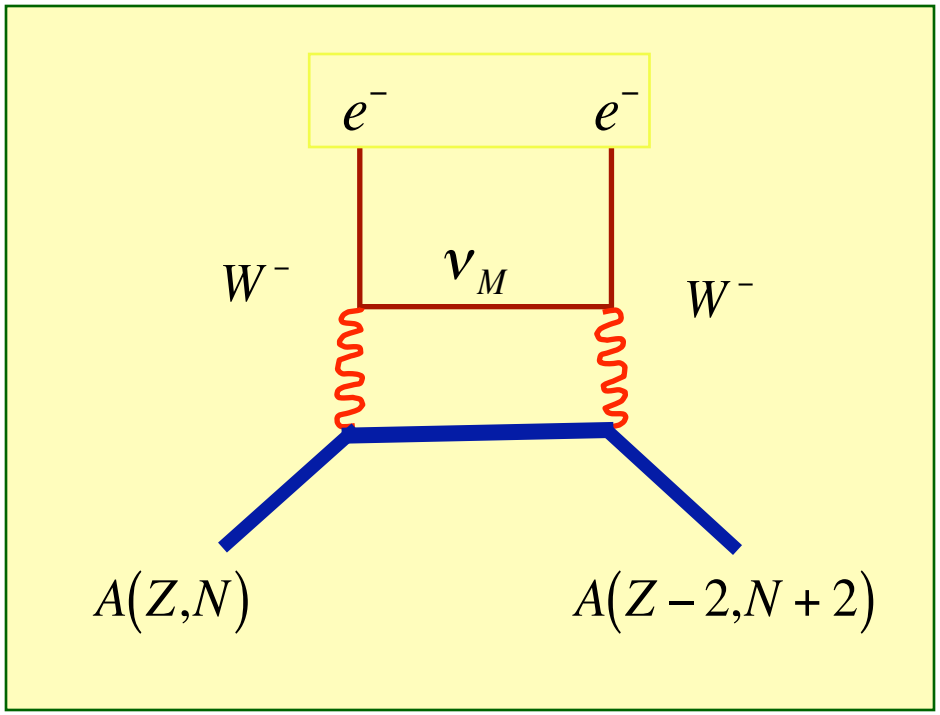

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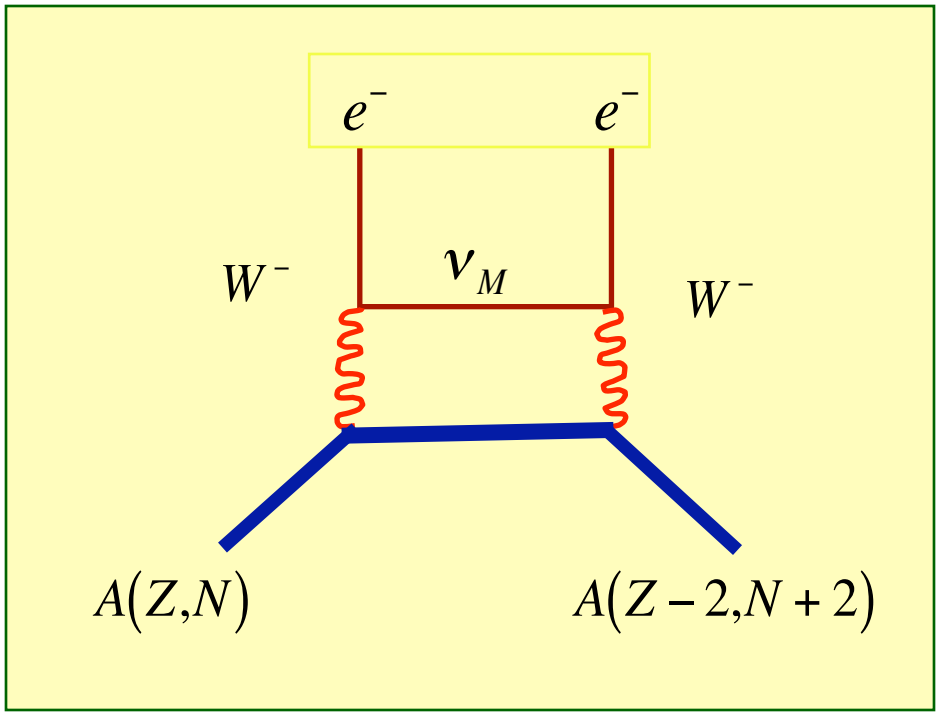

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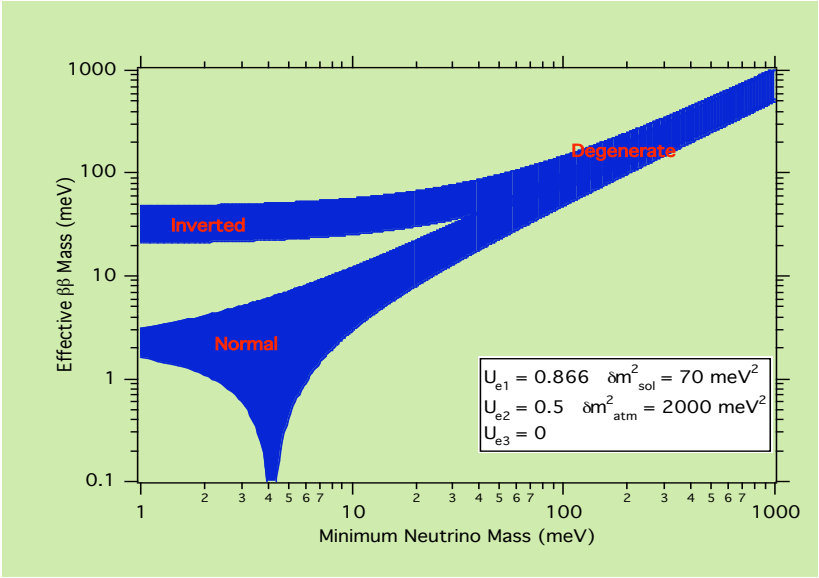

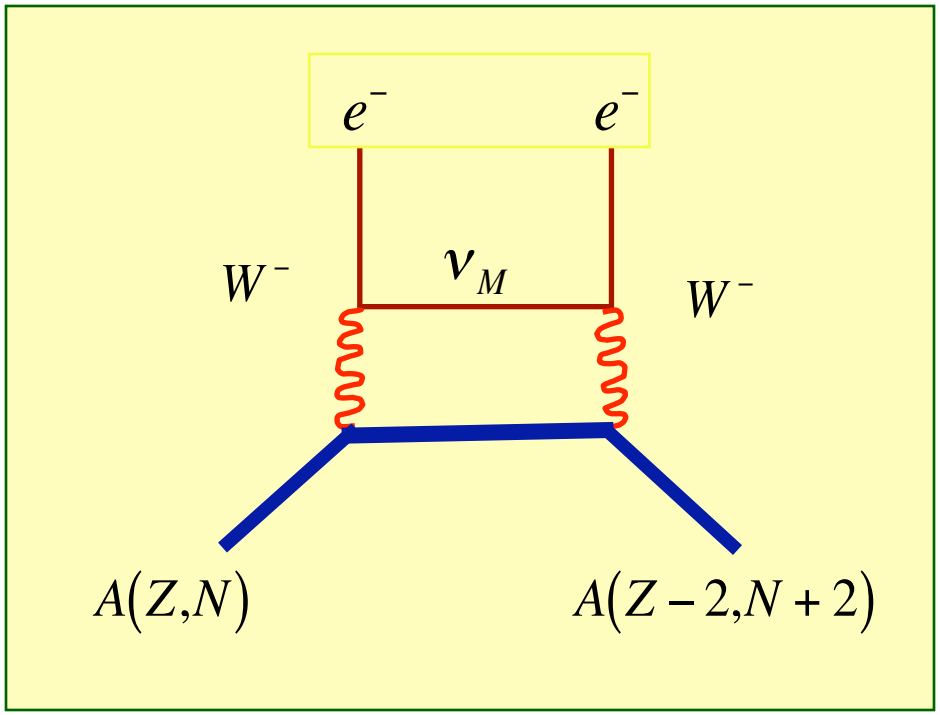

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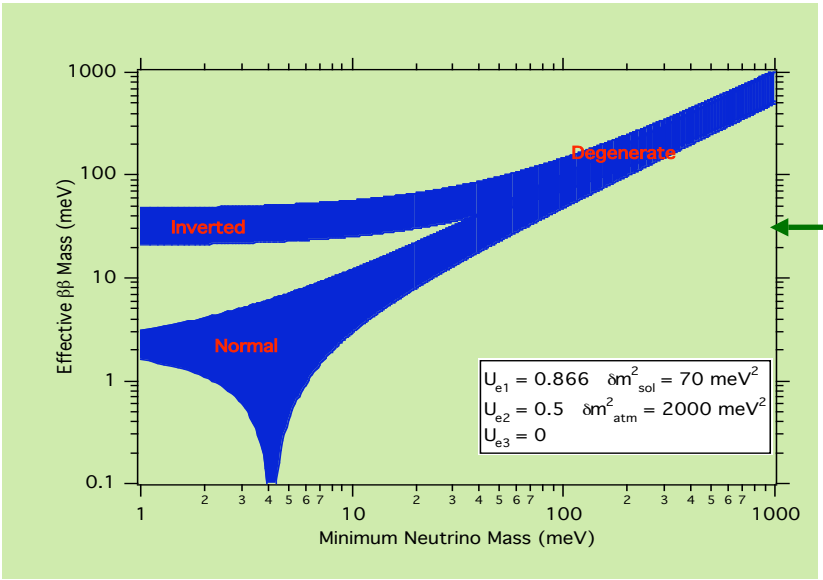

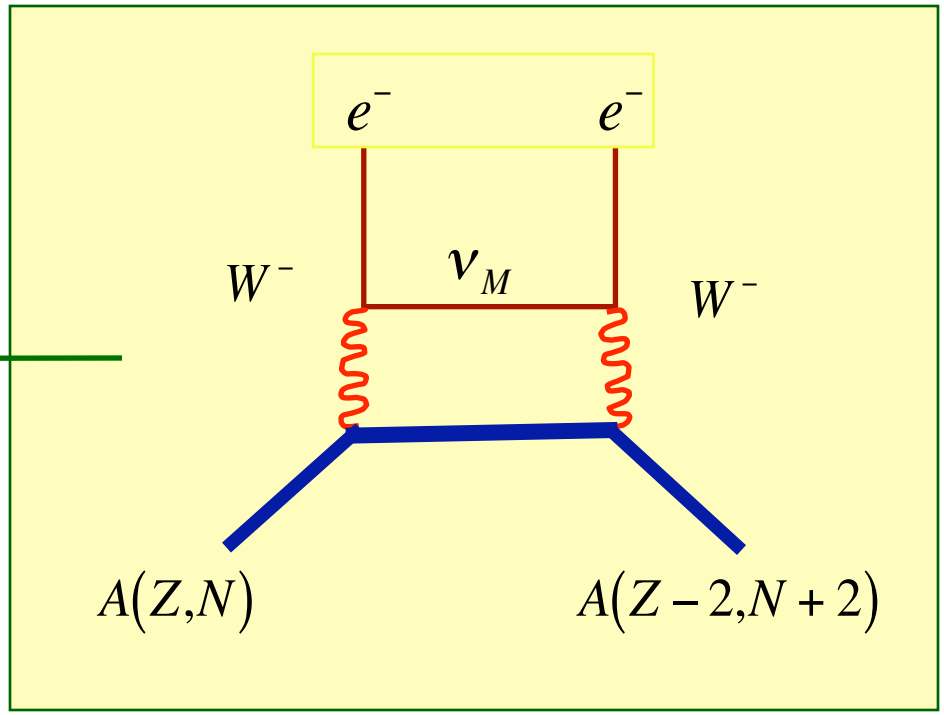

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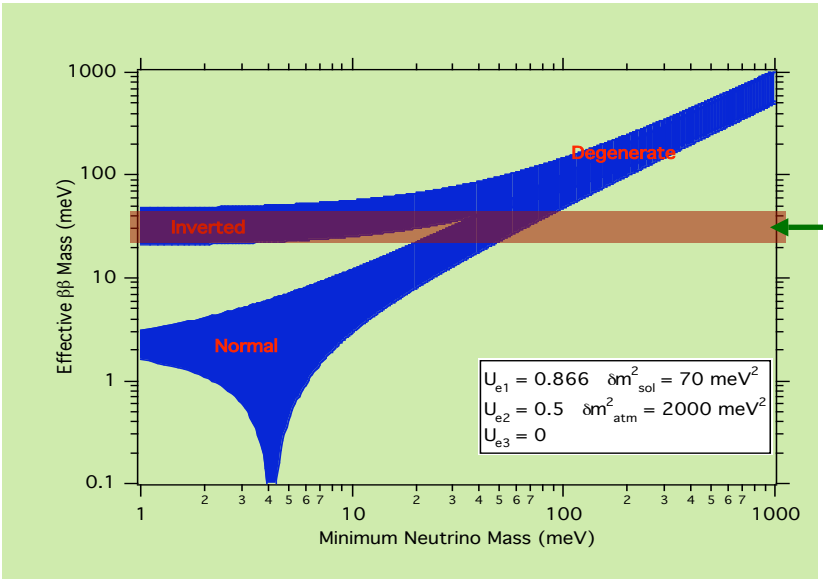

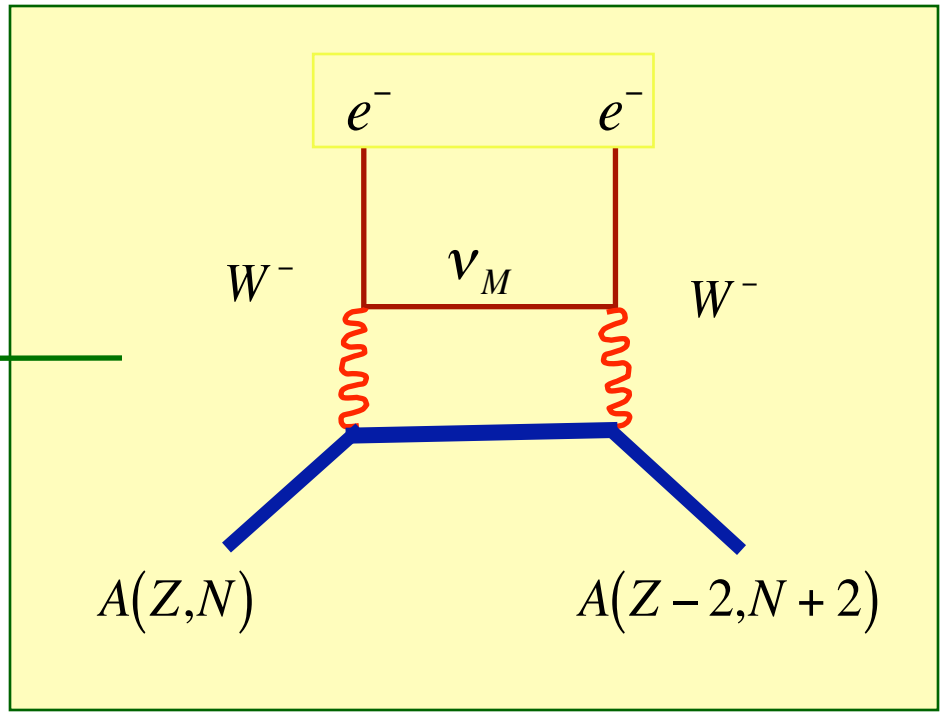

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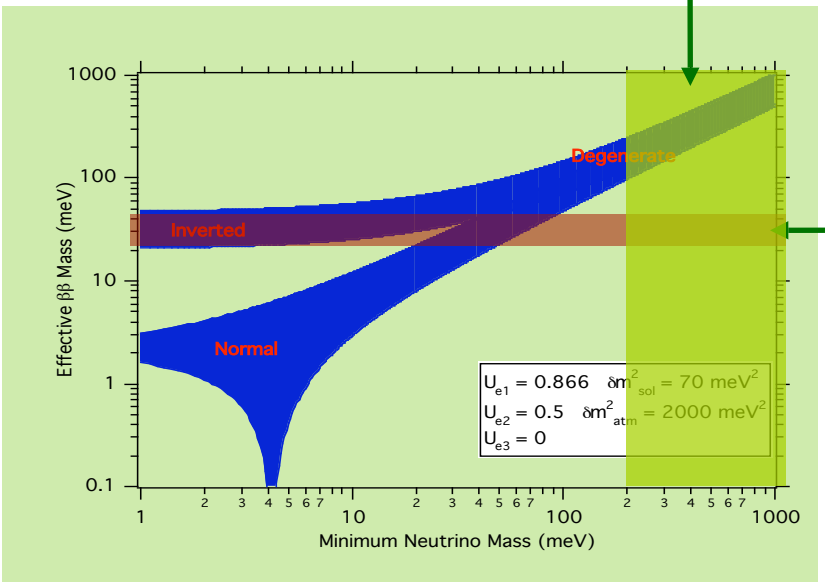

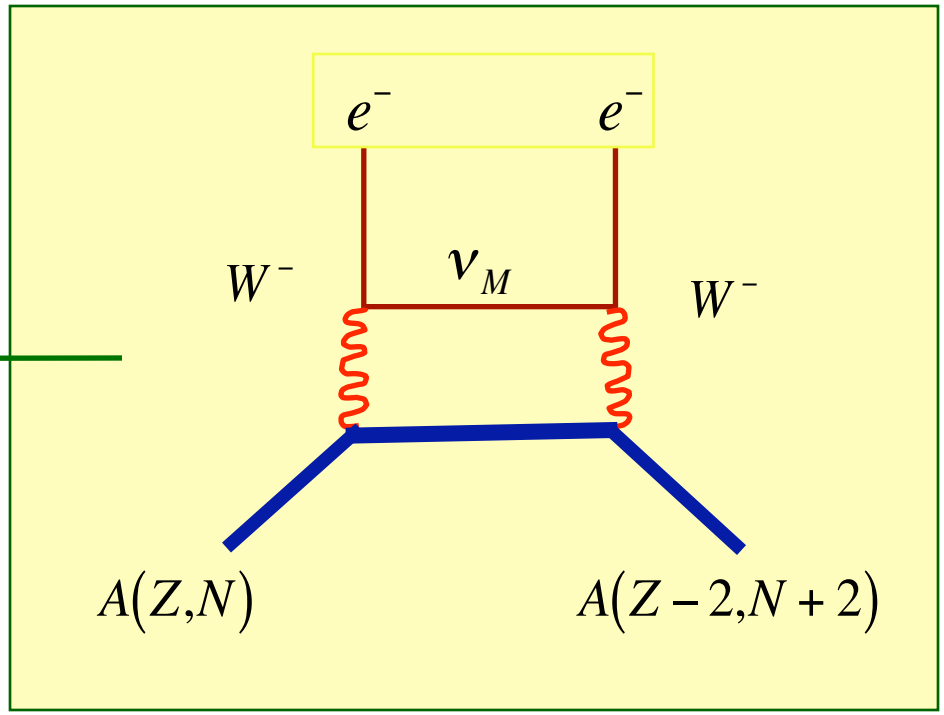

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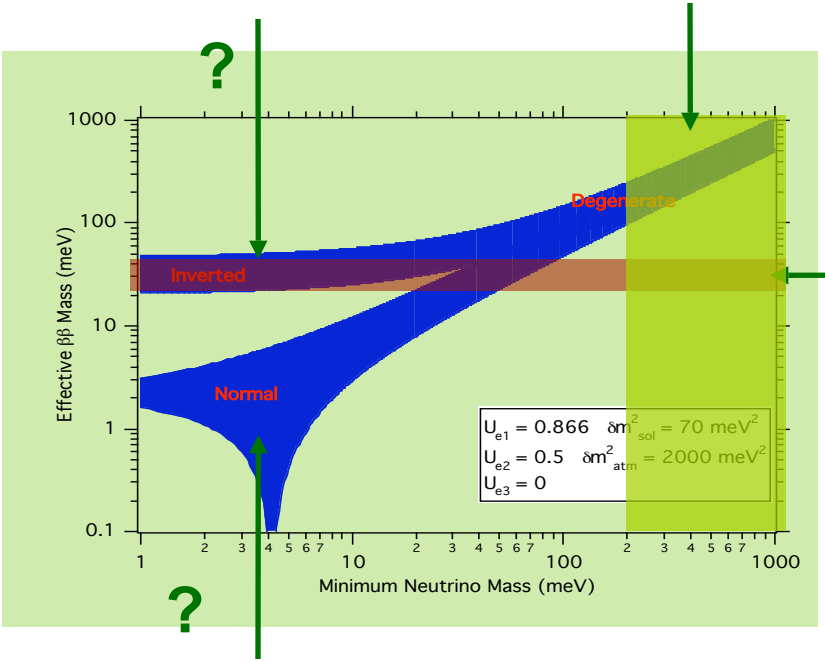

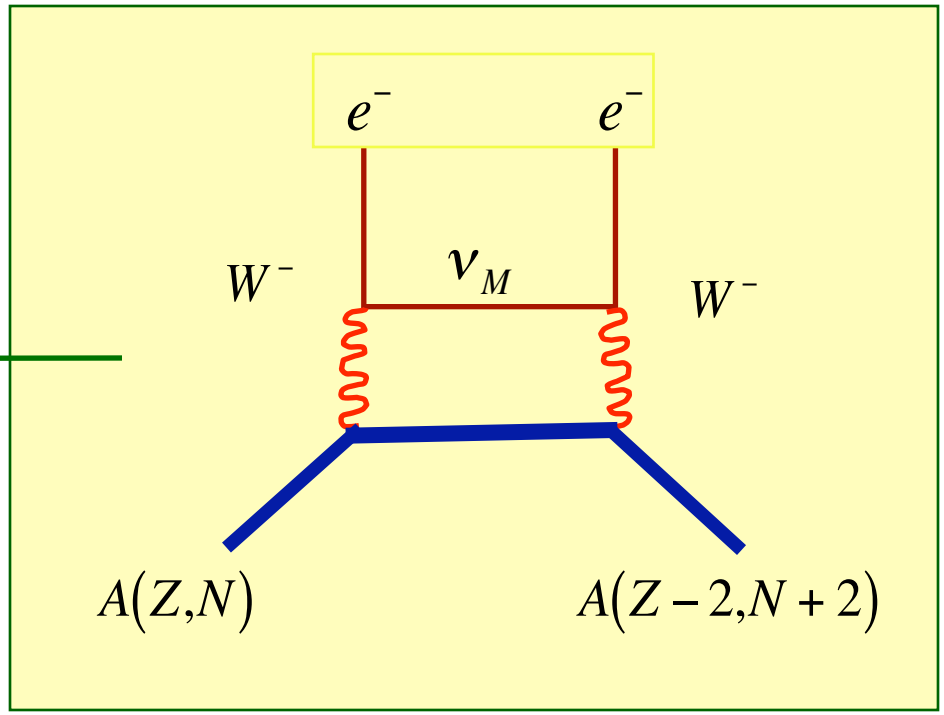

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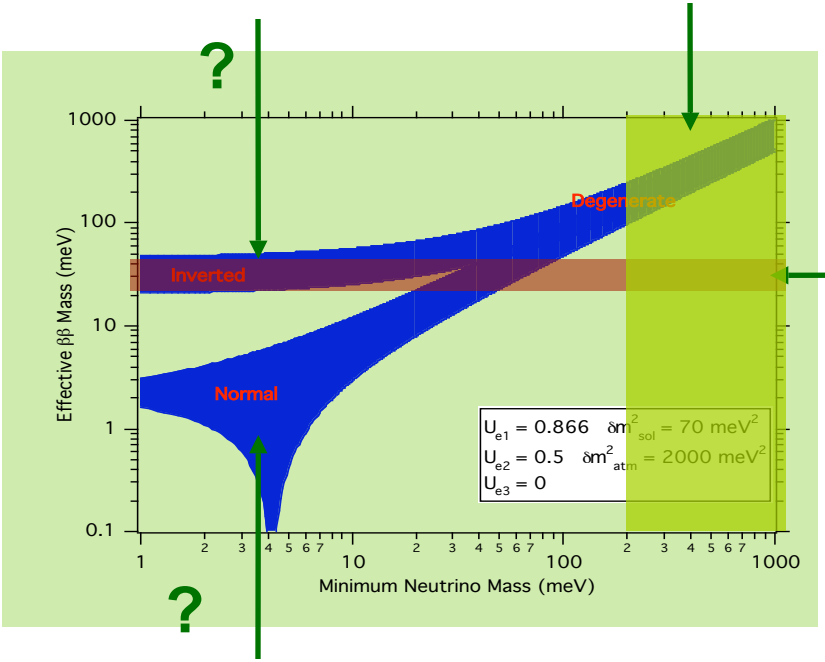
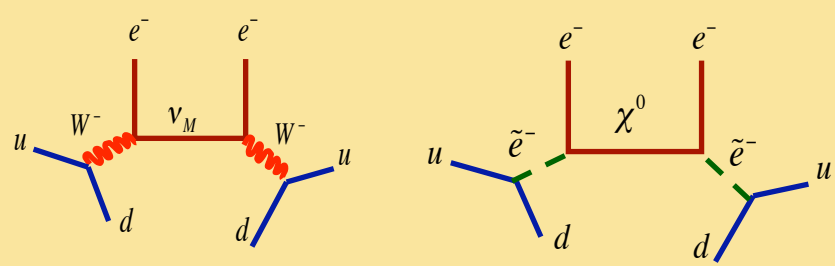


Theory Challenge: matrix elements + mechanism

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



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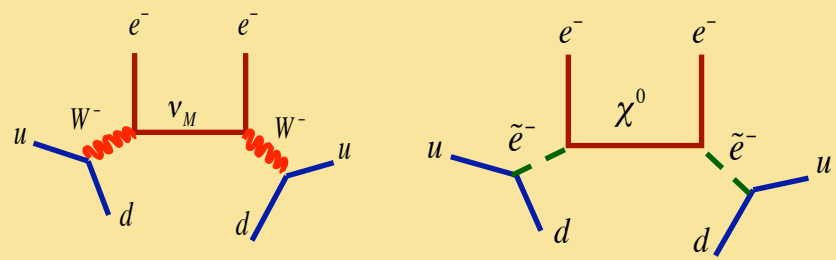

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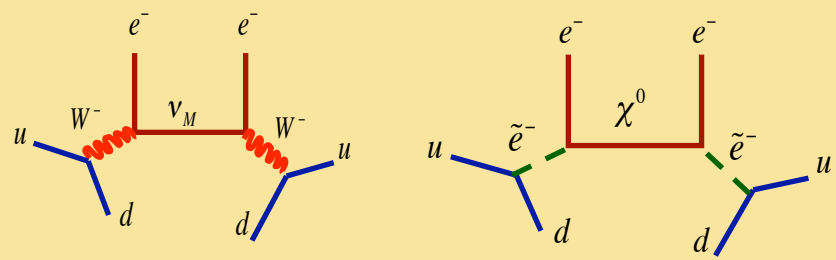

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$$\frac{A_{\text{heavy}}}{A_{\text{light}}} \sim \frac{M_W^2\, k_{\text{eff}}^2}{\Lambda^5\, m_\nu^{\text{eff}}}$$

O(1) for Λ ~ TeV

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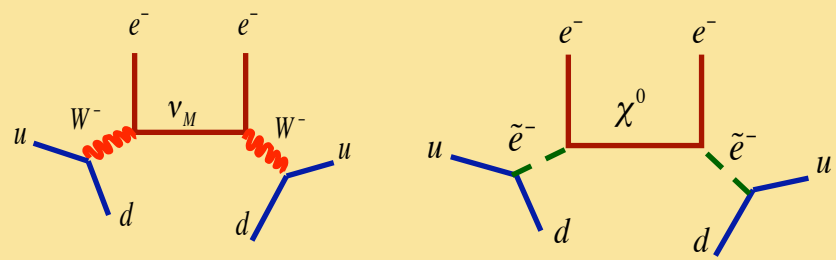

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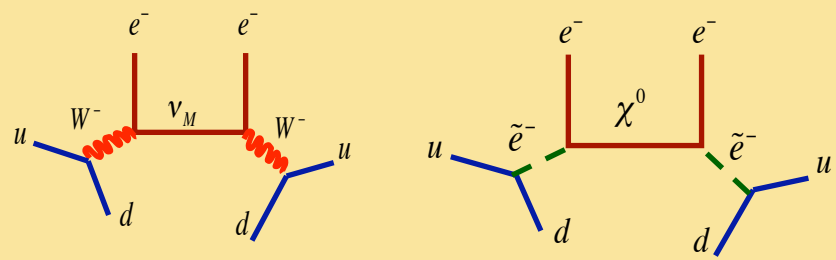

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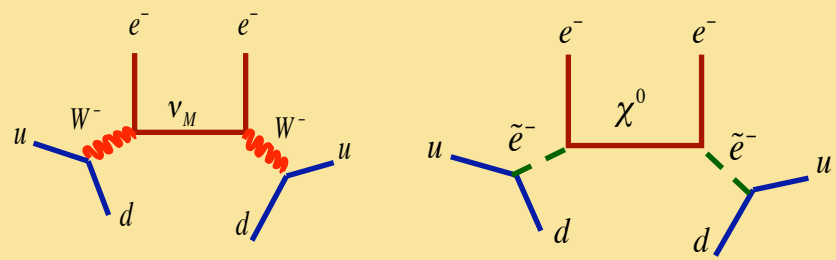

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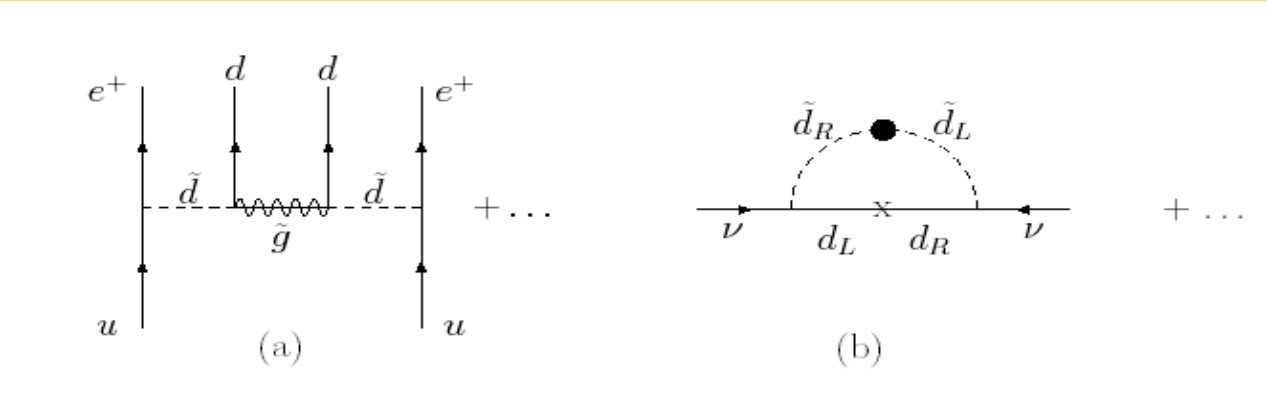

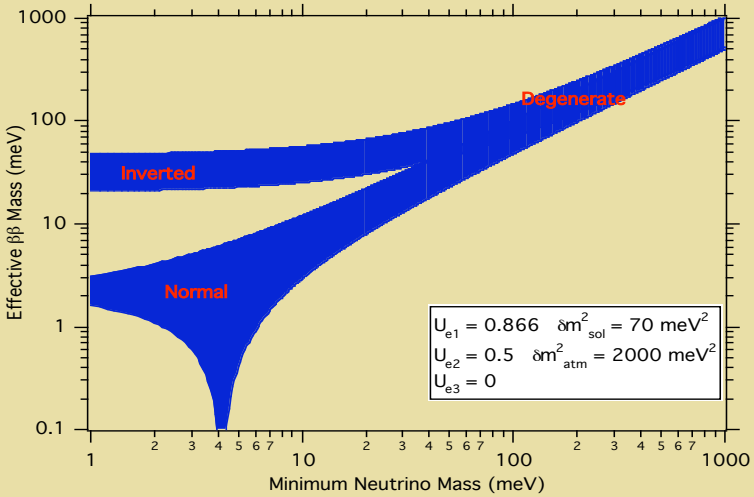

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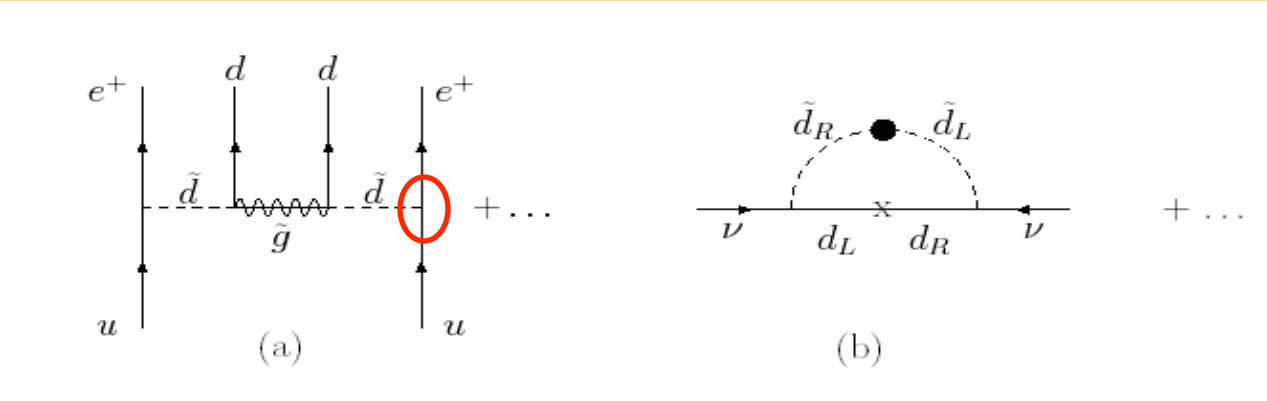

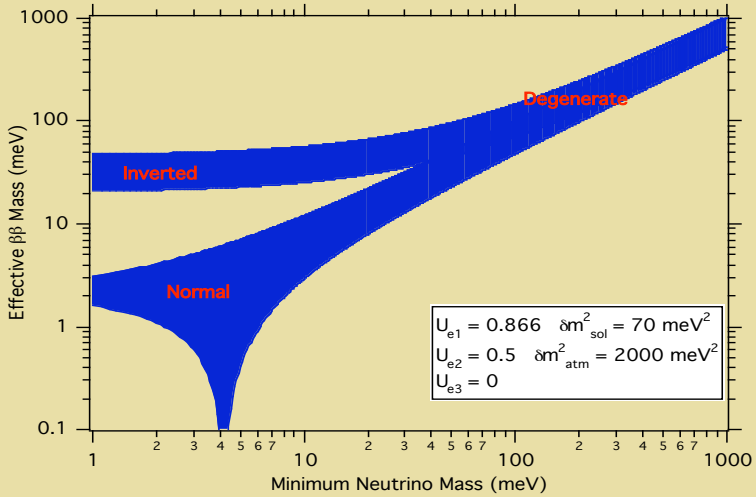

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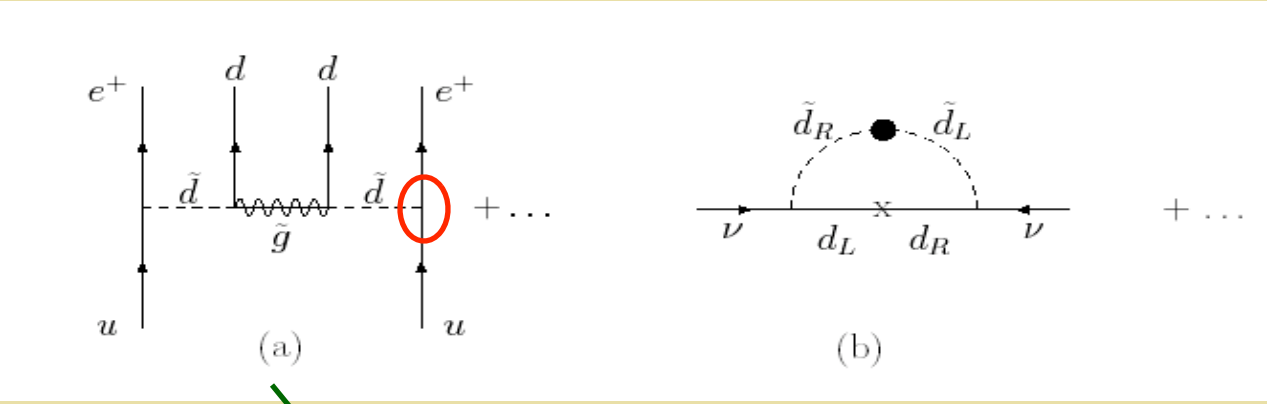

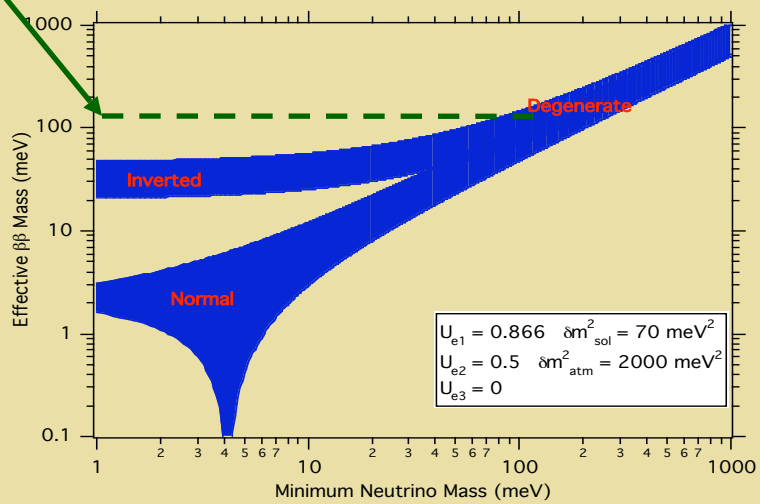

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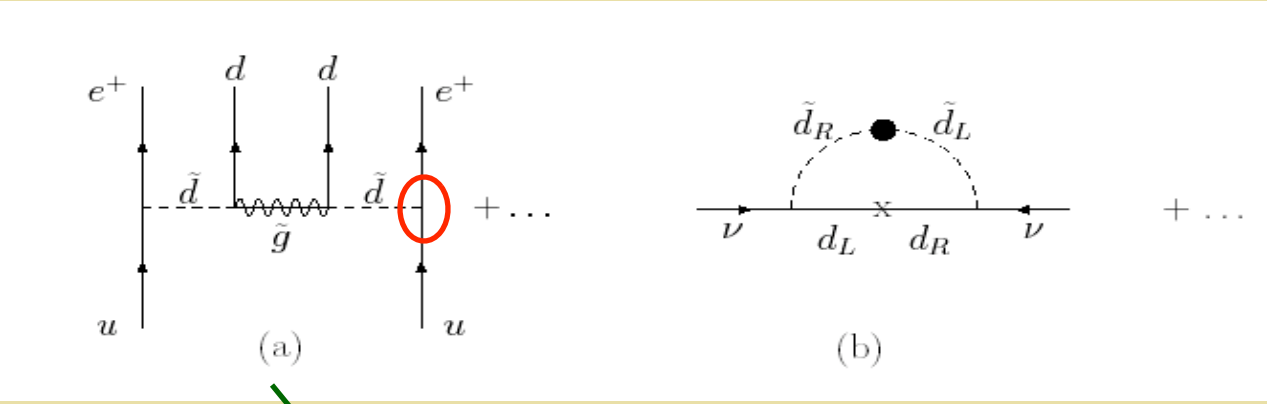
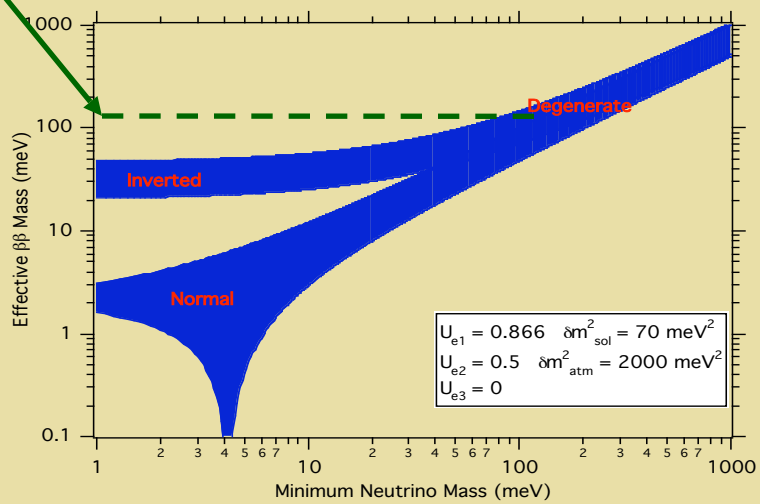


0νββ signal equivalent to degenerate hierarchy



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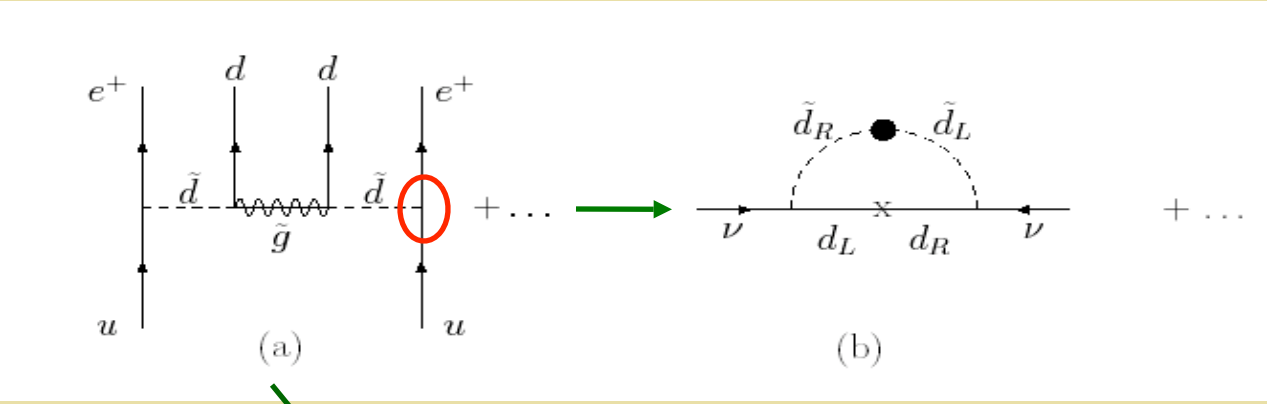

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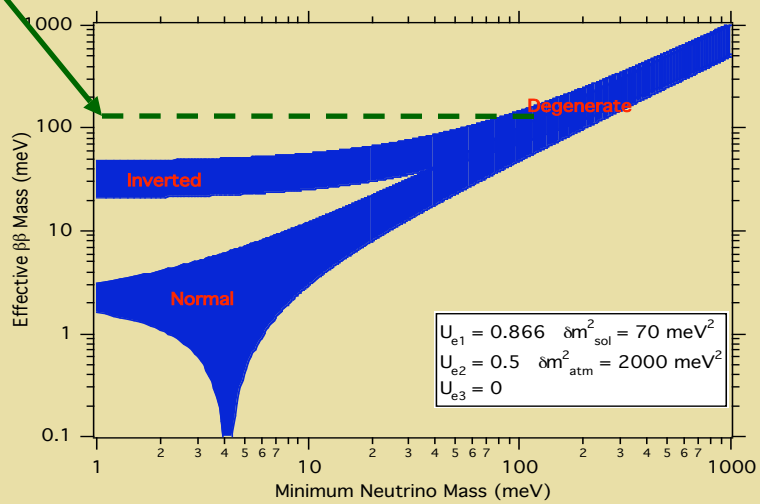

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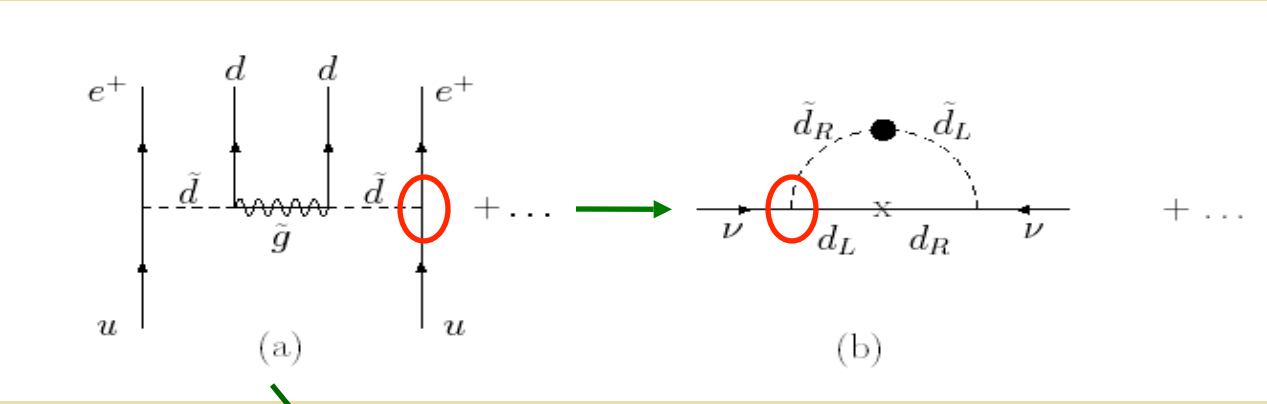

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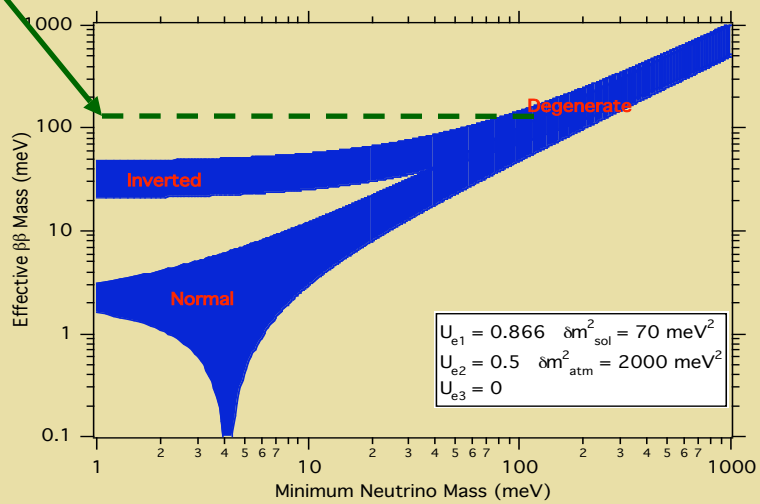

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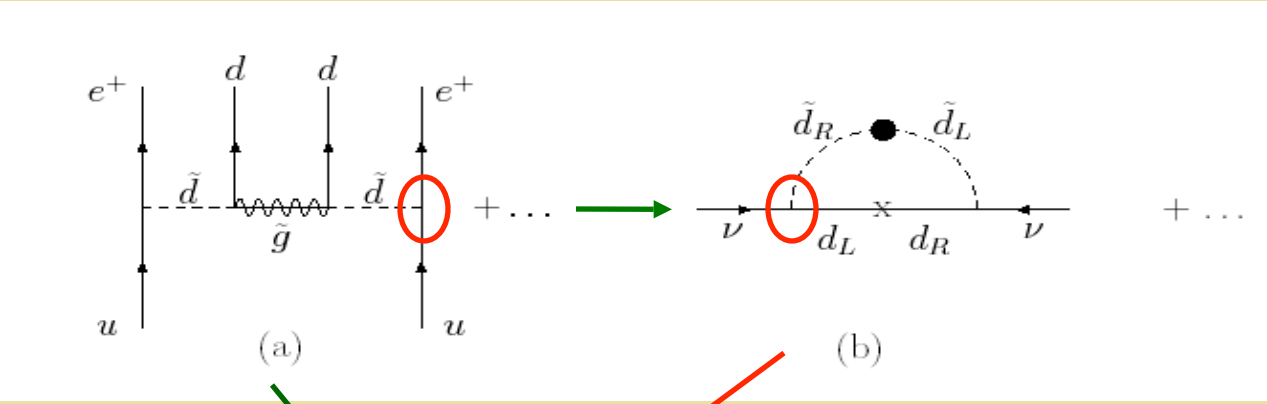

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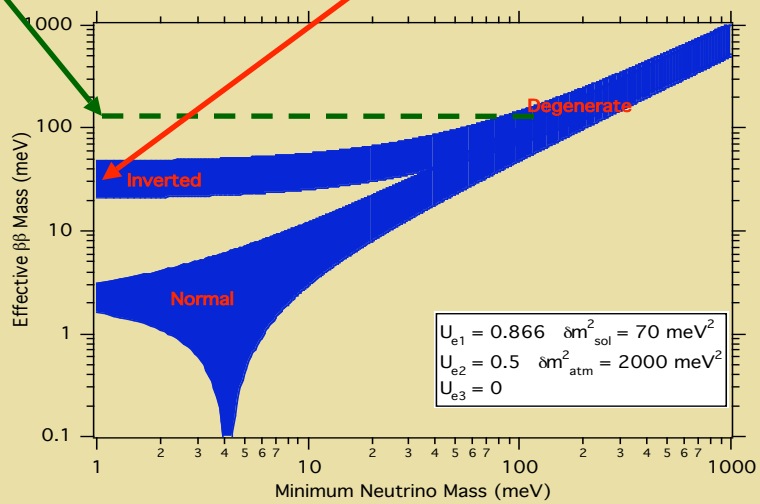

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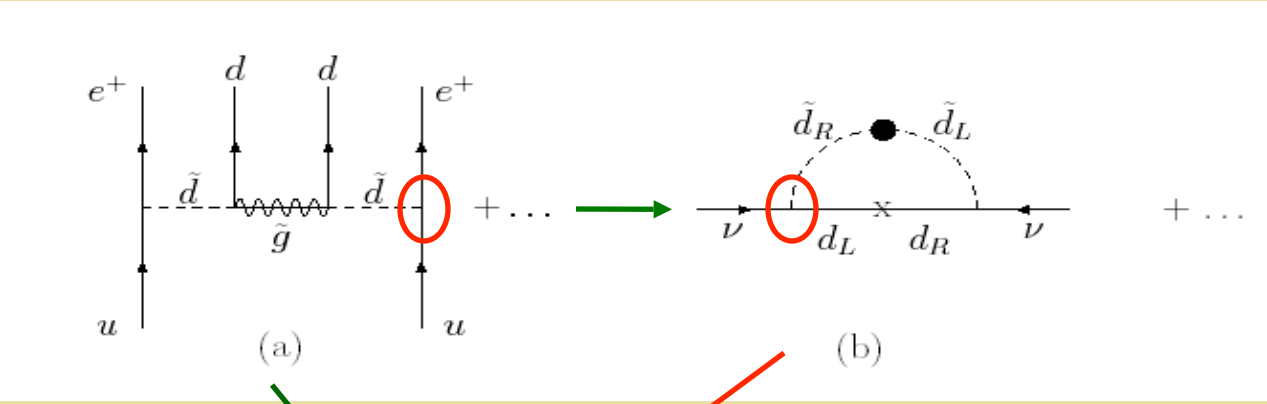
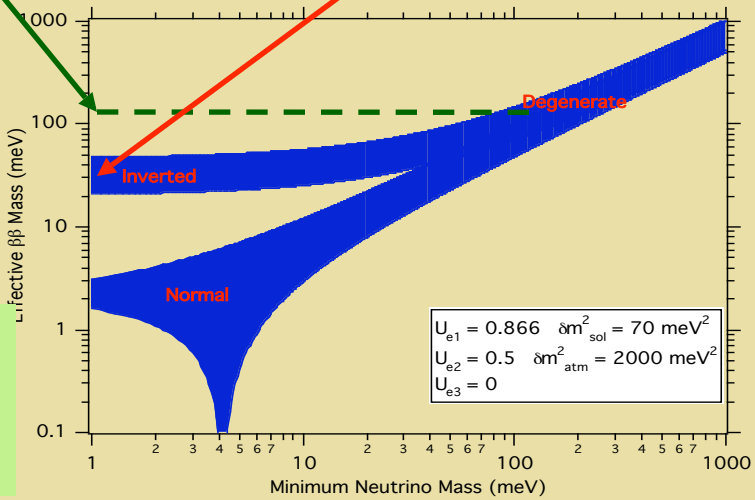


$0\nu\beta\beta$ signal equivalent to degenerate hierarchy

Loop contribution to m_ν of inverted hierarchy scale



Sorting out the mechanism

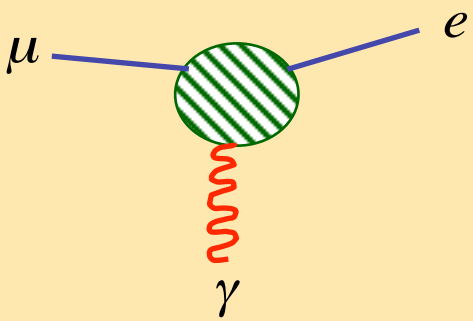
- *Models w/ Majorana masses (LNV) typically also contain CLFV interactions*

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

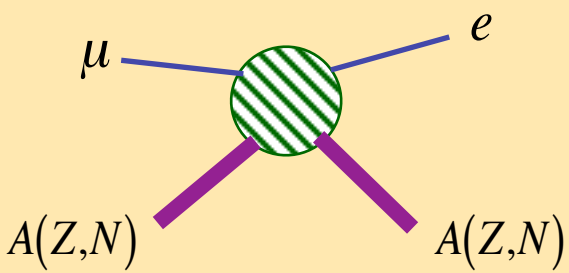
- *If the LNV process of* $0\nu\beta\beta$ *arises from TeV scale particle exchange, one expects signatures in CLFV processes*

- τ K *e Conversion at EIC could be one probe*

CLFV, LNV & the Scale of New Physics

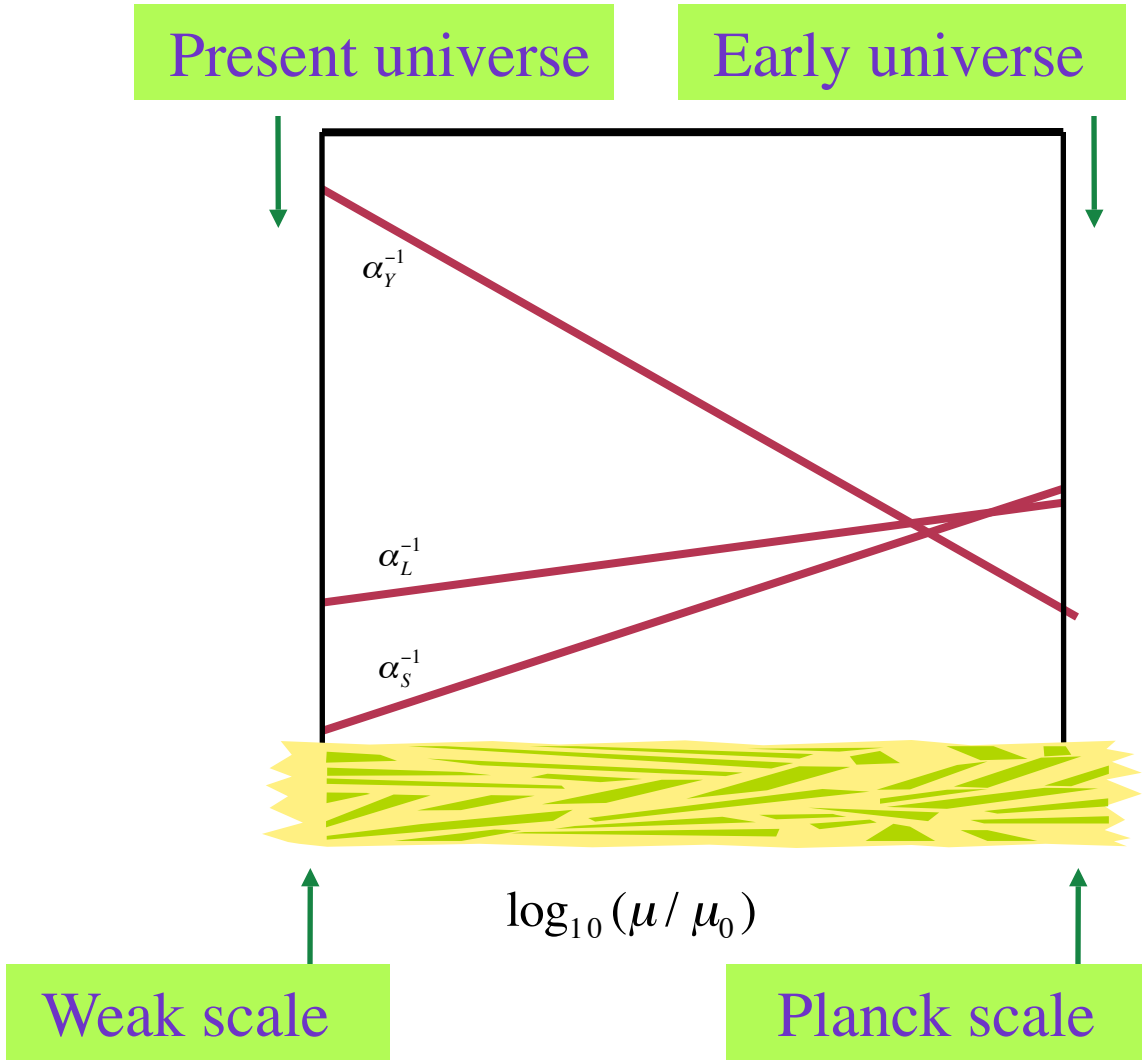


MEG: $B_{\mu \to \varepsilon \gamma} \sim 5 \times 10^{-14}$

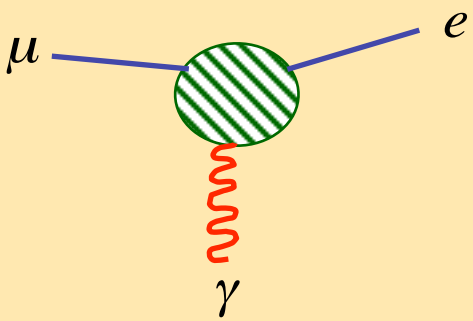


μ2e: $B_{\mu \to e} \sim 5 \times 10^{-17}$

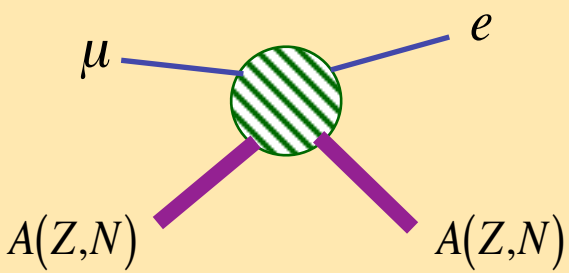
Also PRIME



CLFV, LNV & the Scale of New Physics

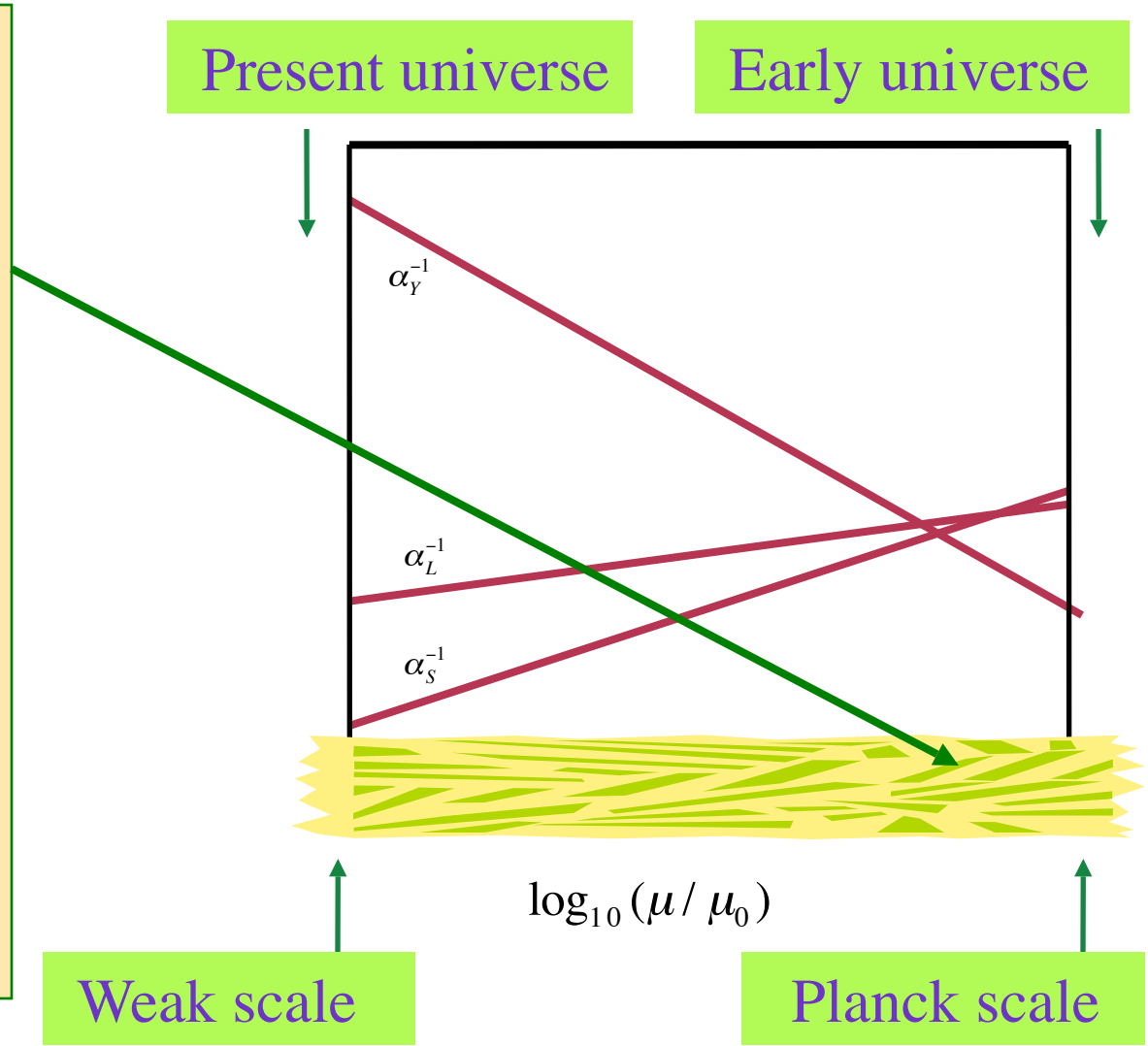


MEG: $B_{\mu \to \varepsilon \gamma} \sim 5 \times 10^{-14}$

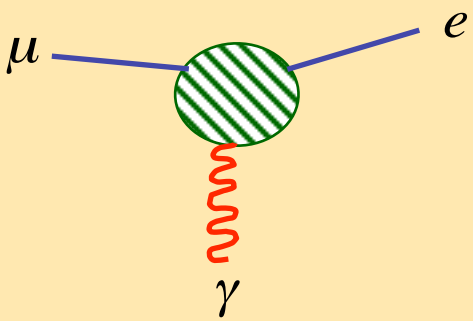


μ2e: $B_{\mu \to e} \sim 5 \times 10^{-17}$

Also PRIME



CLFV, LNV & the Scale of New Physics



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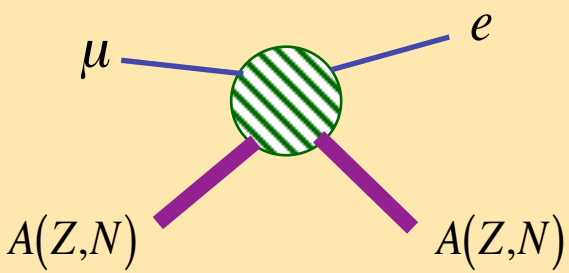

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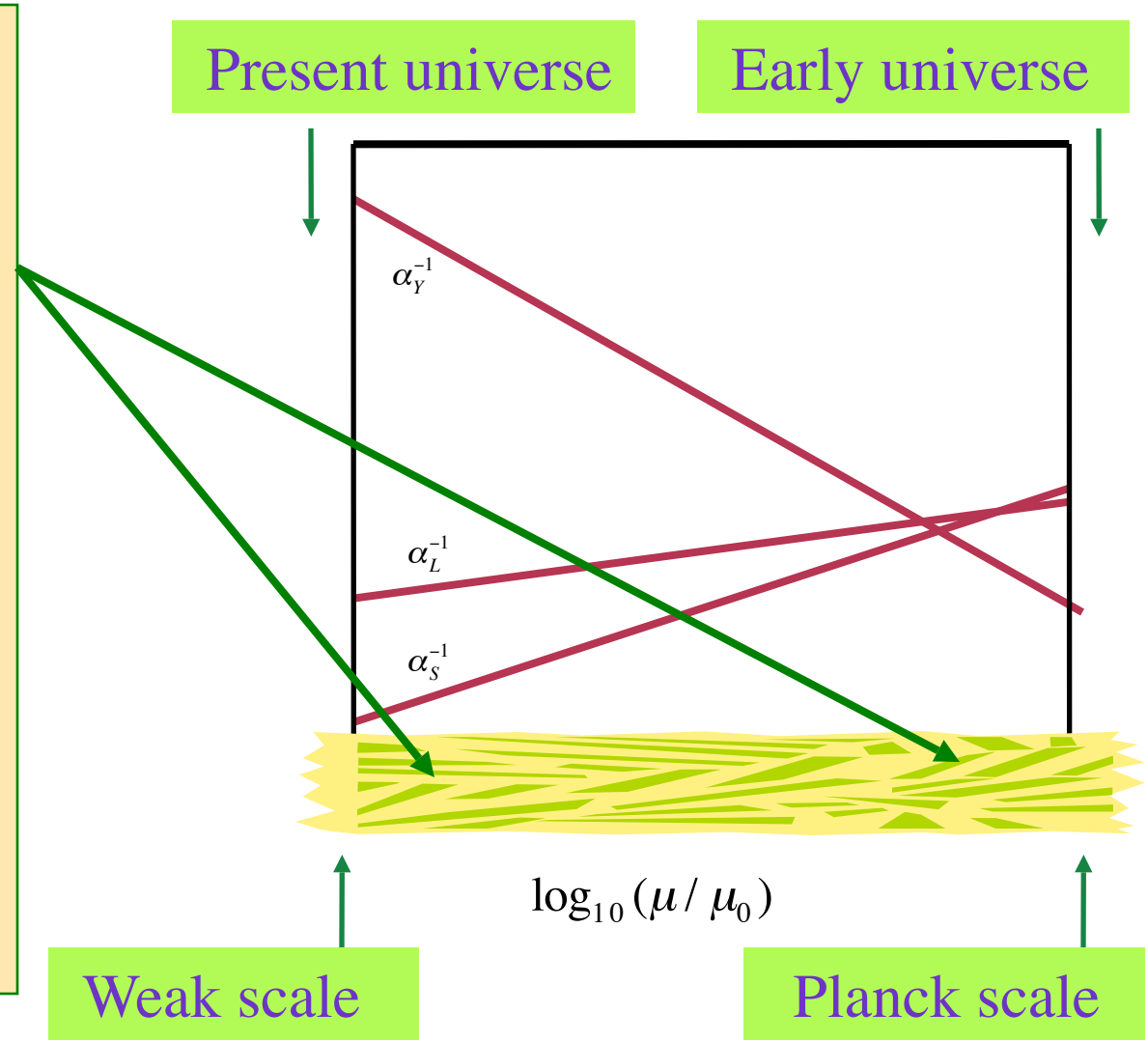
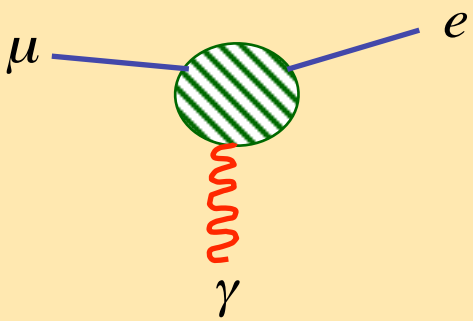


CLFV, LNV & the Scale of New Physics



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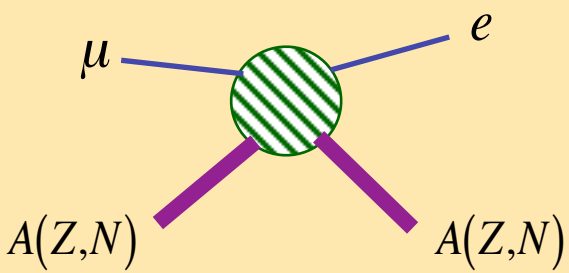

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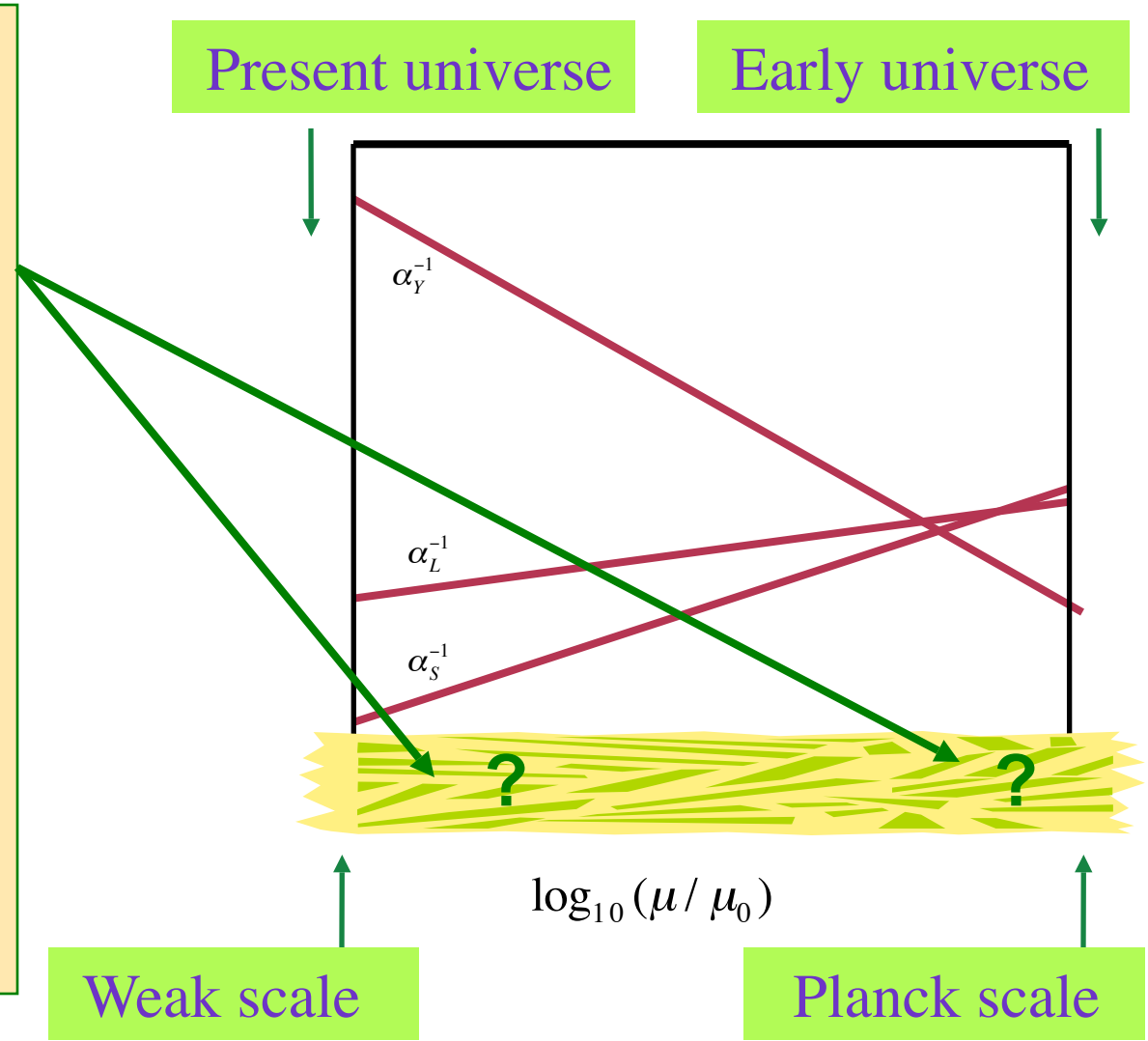

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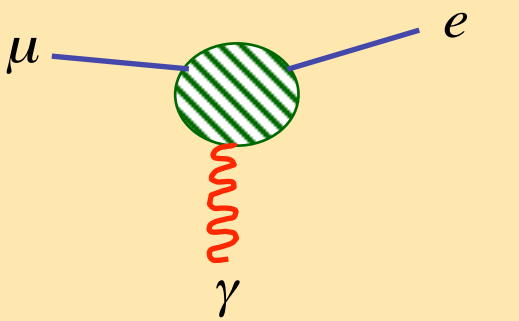

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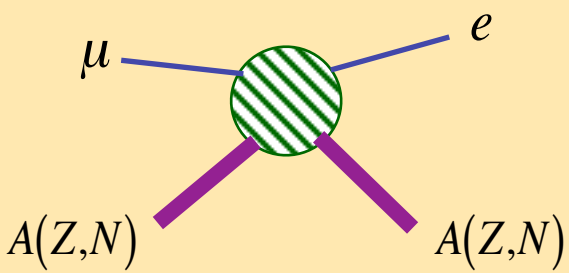

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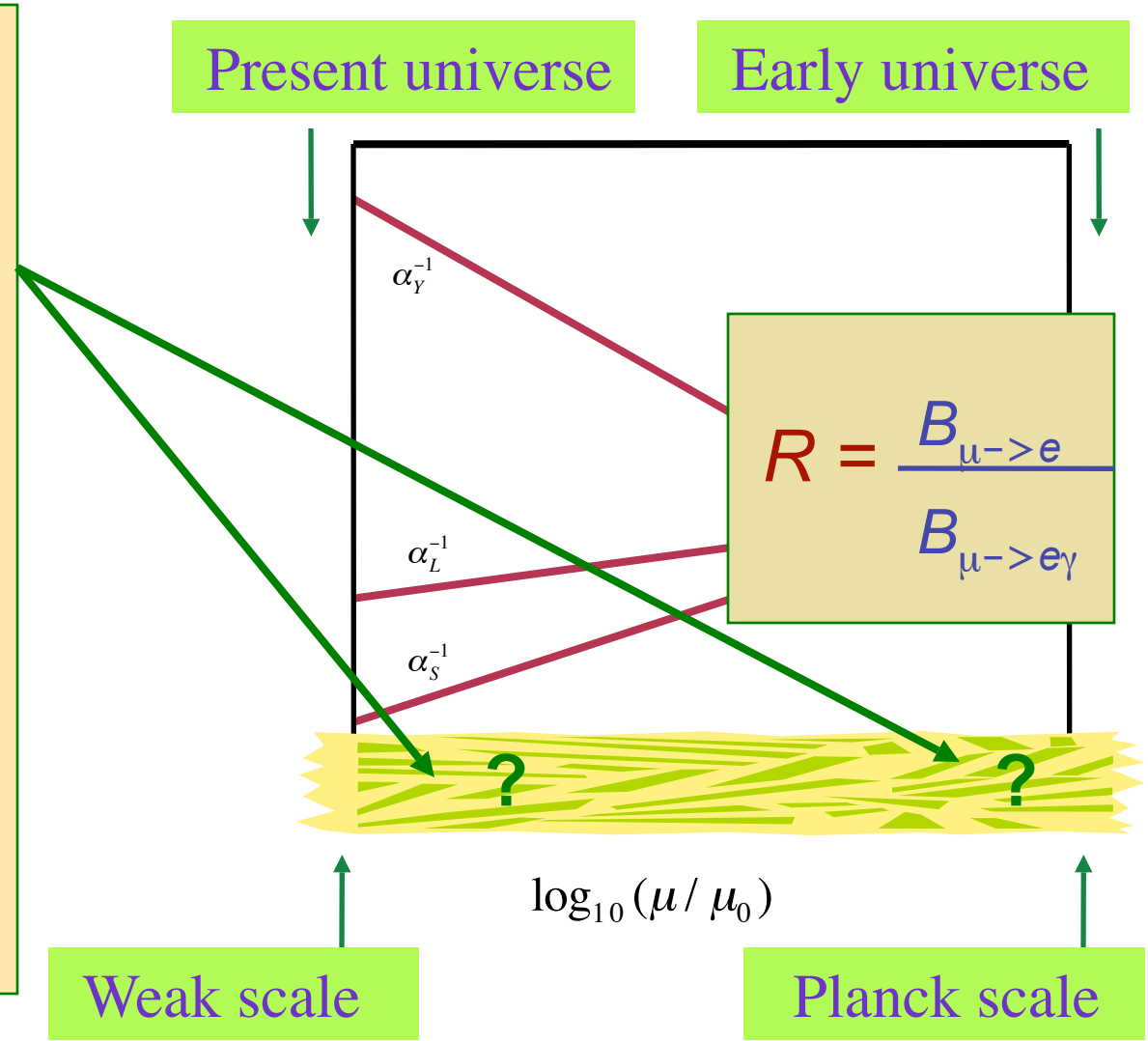

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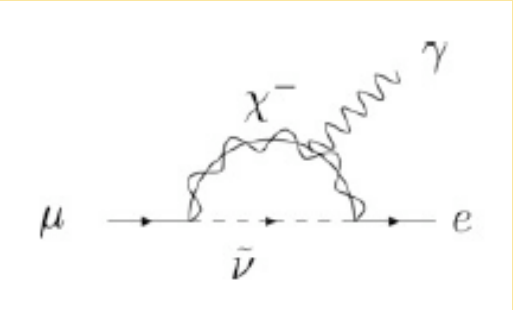
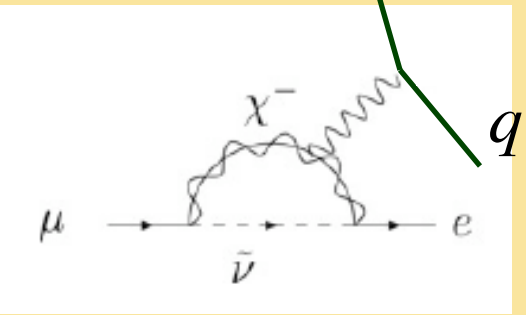


μ !eγ : *M1*



μ !e : *M1* ! *R* ~ α

Also PRIME

Present universe

Early universe

α_Y^{-1}

α_L^{-1}

α_S^{-1}

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

?

?

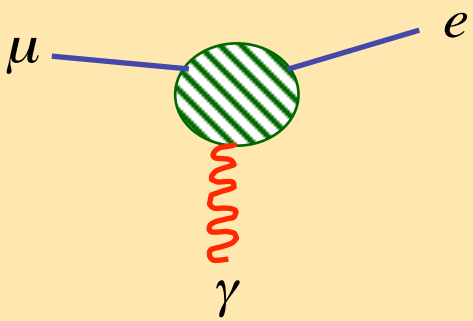
$\log_{10}(\mu/\mu_0)$

Weak scale

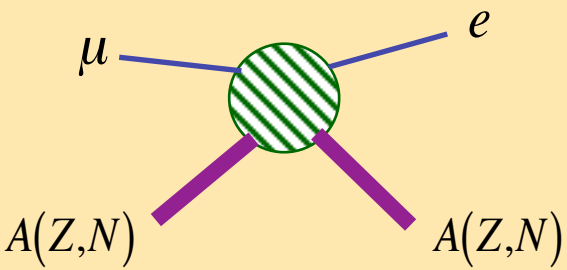
Planck scale

Lepton Flavor & Number Violation

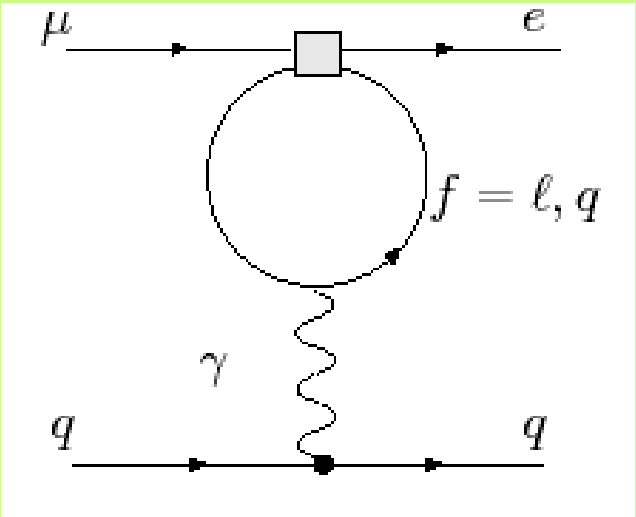
Raidal, Santamaria;
Cirigliano, Kurylov, R-M, Vogel



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



μ2e: $B_{\mu->e}$ ~ 5 x 10^{-17}



Lepton Flavor & Number Violation

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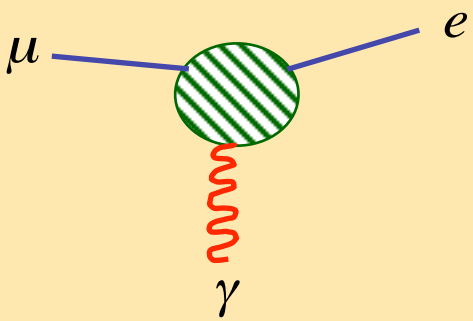

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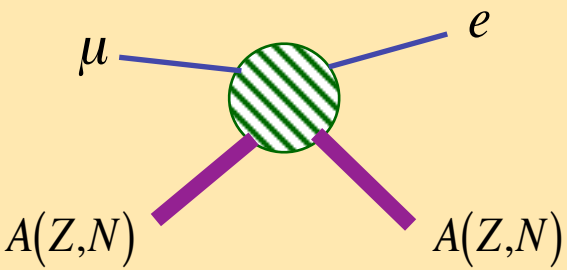

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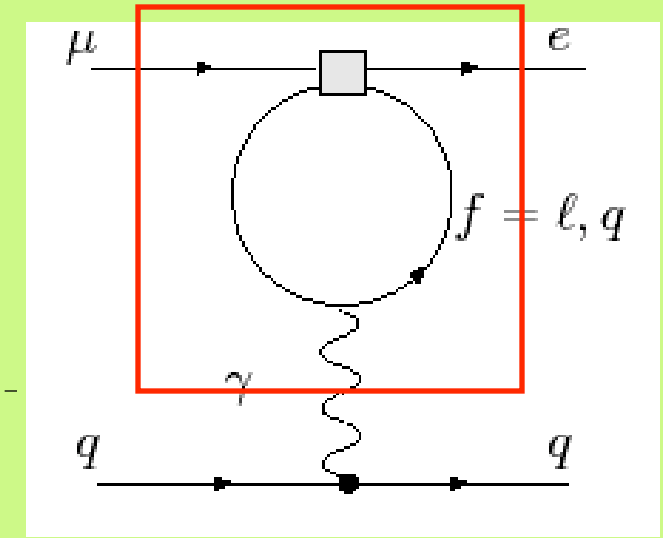

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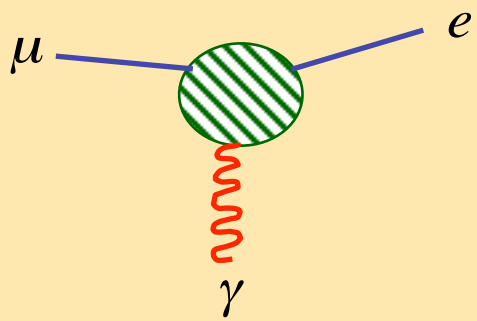
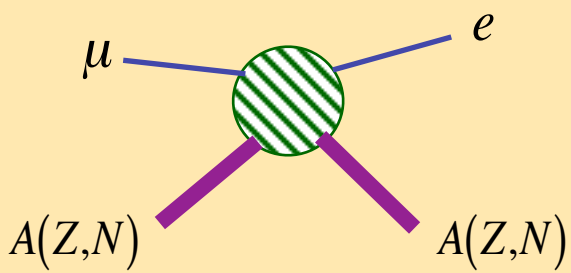


MEG: $B_{\mu->e\gamma}$ ~ 5 x 10^{-14}



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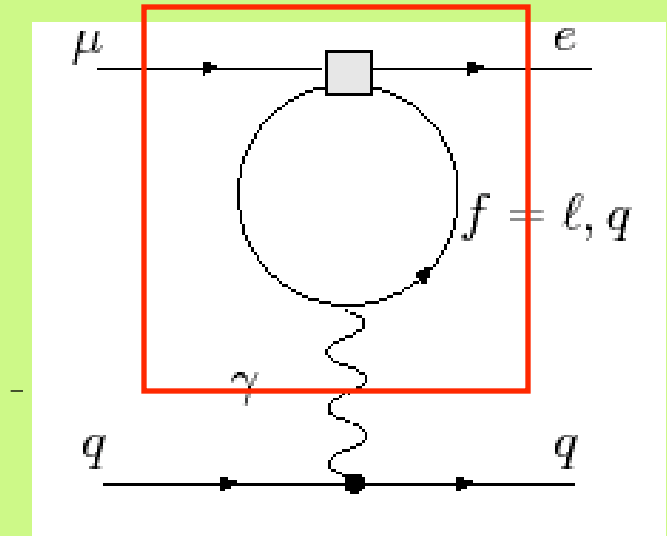
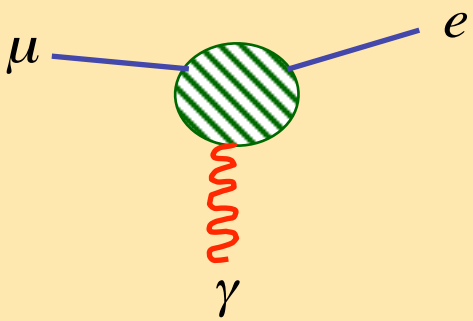


Logarithmic enhancements of *R*

Lepton Flavor & Number Violation

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



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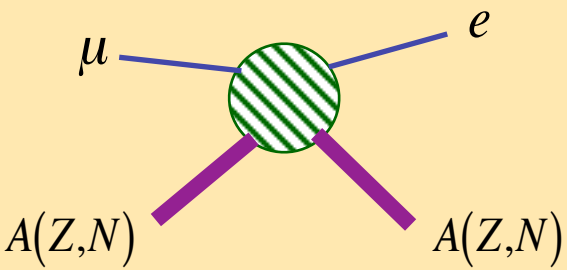
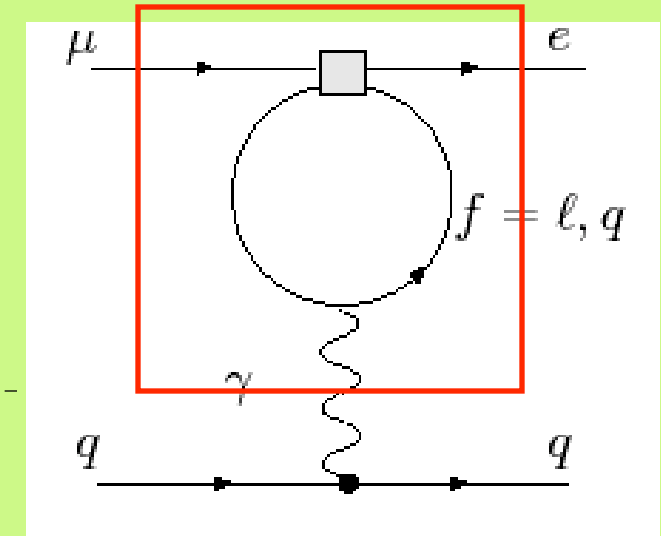
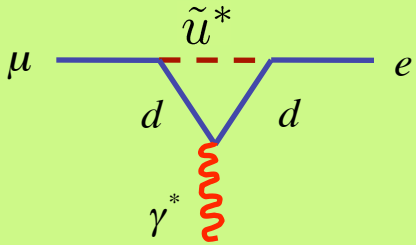


μ2e: $B_{\mu->e}$ ~ 5 x 10^{-17}





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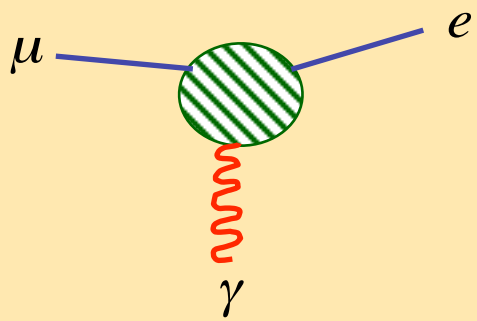

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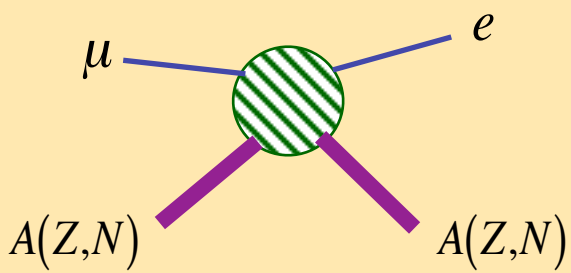

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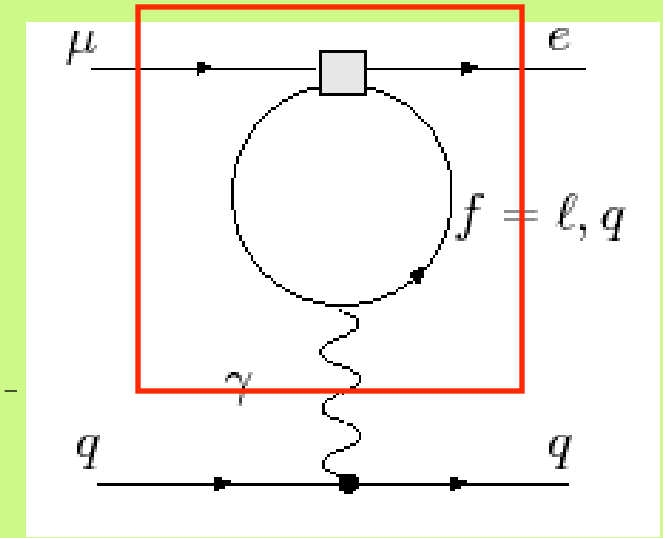

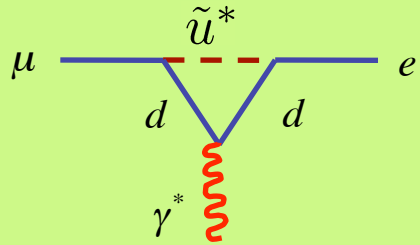

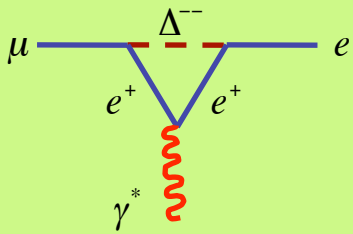

Logarithmic enhancements of *R*

Lepton Flavor & Number Violation

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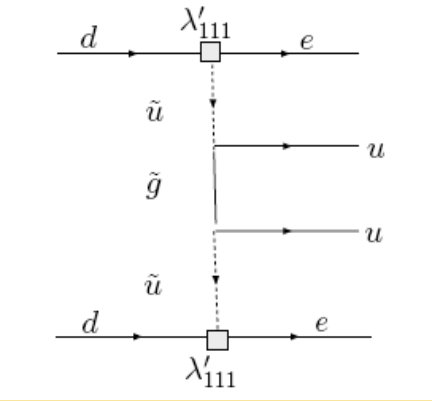
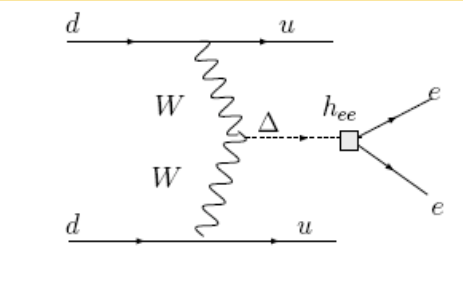
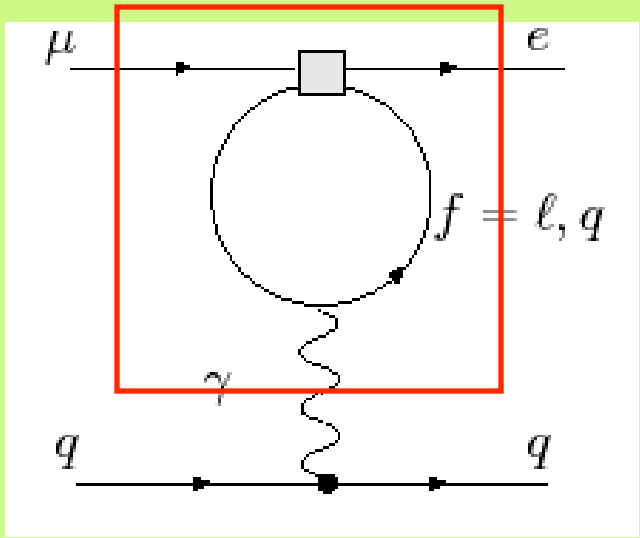
0νββ decay

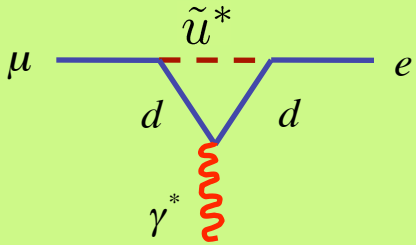


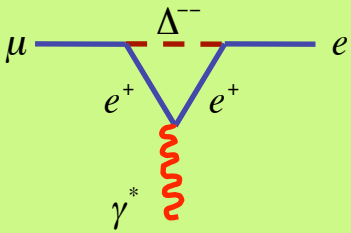
RPV SUSY



LRSM







Logarithmic enhancements of *R*

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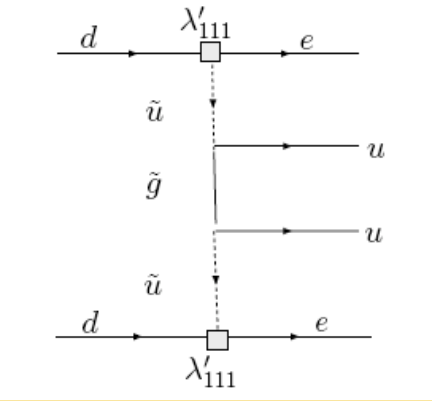

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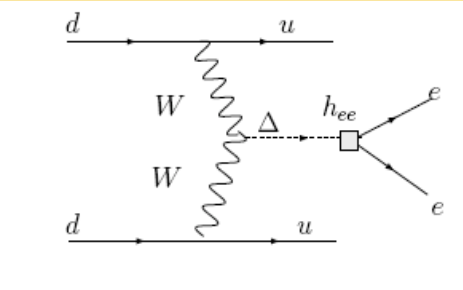
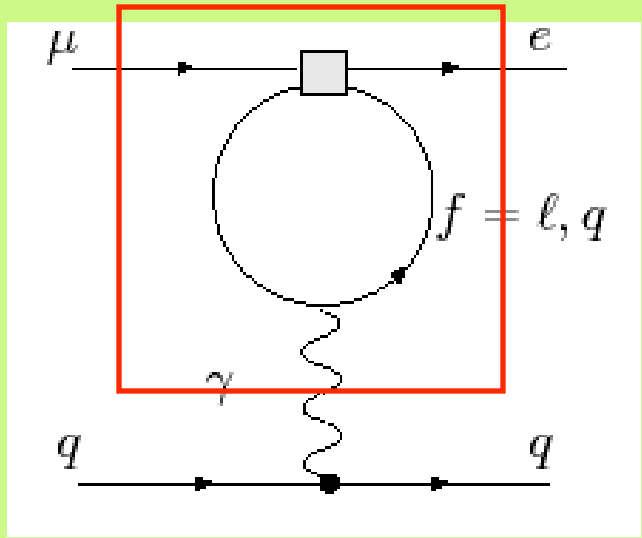
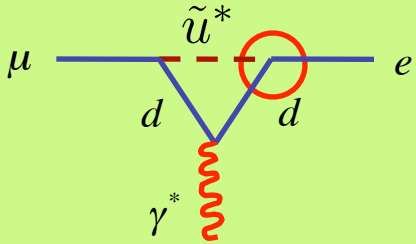
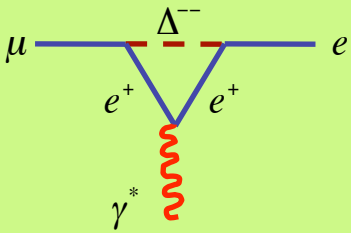


LRSM







Logarithmic enhancements of *R*

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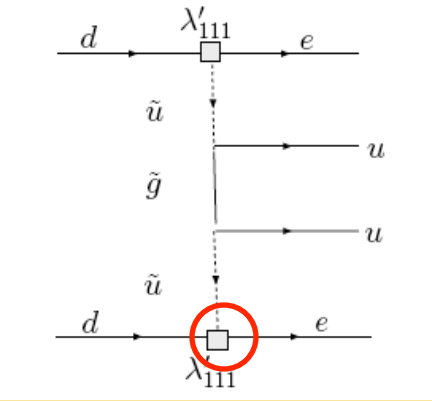
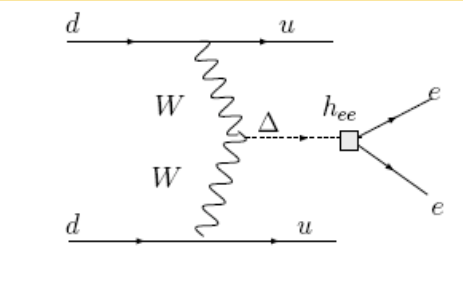
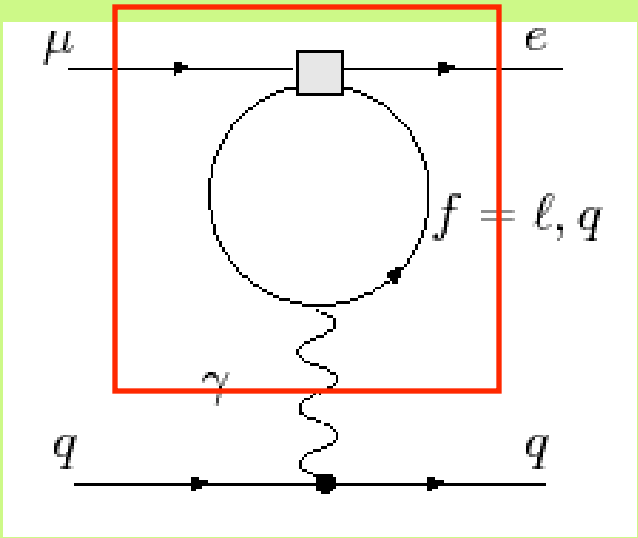
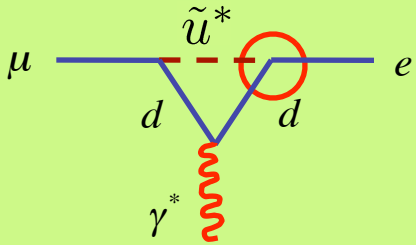


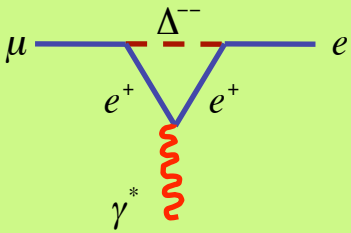
RPV SUSY



LRSM







Logarithmic enhancements of *R*

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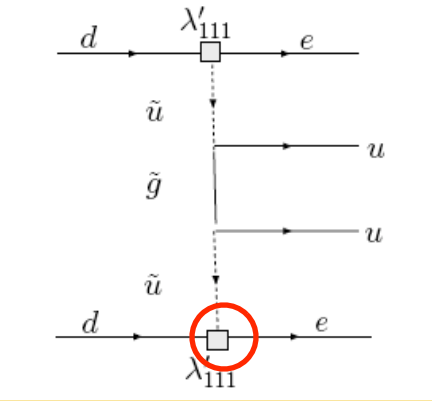

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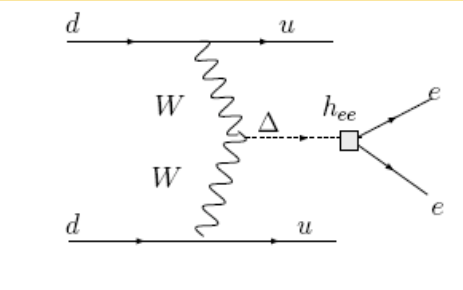
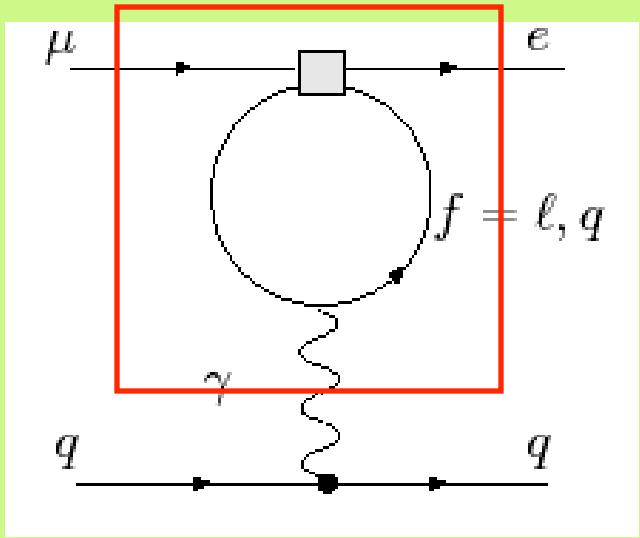
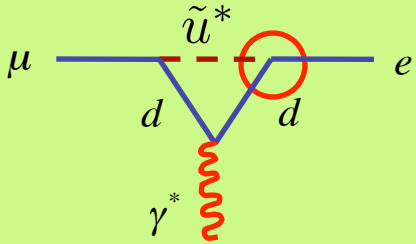
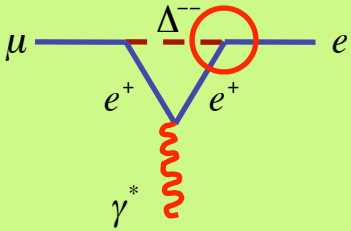


LRSM







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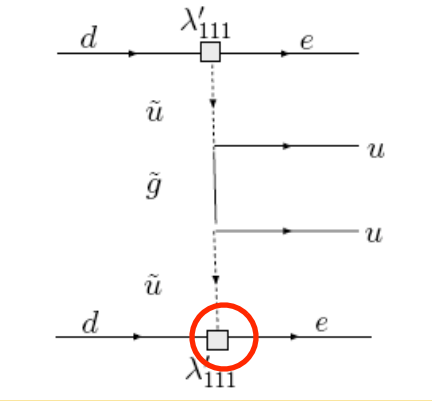

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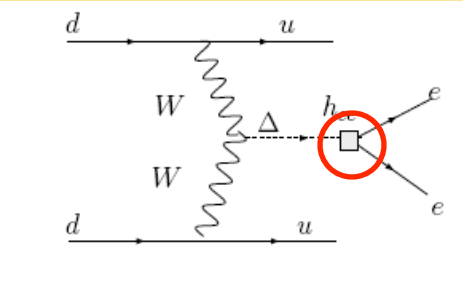
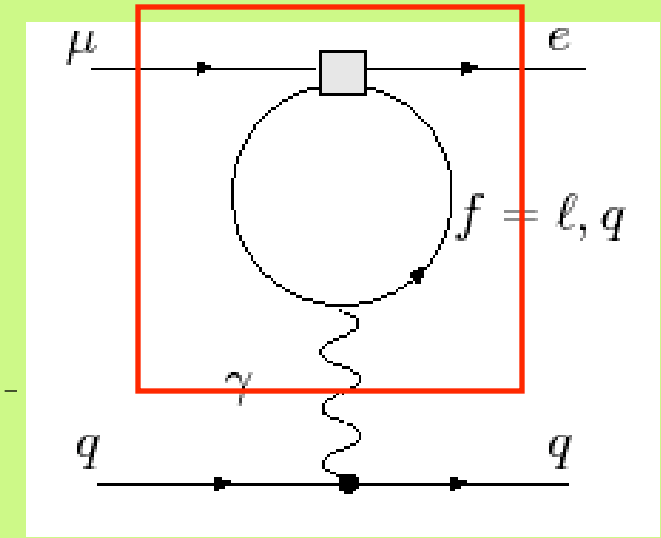
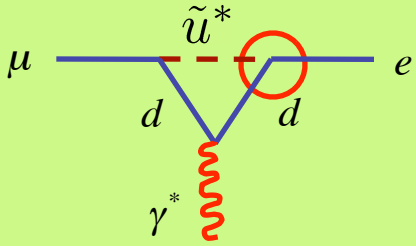
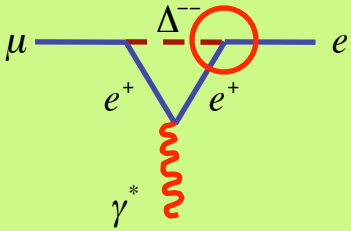


LRSM





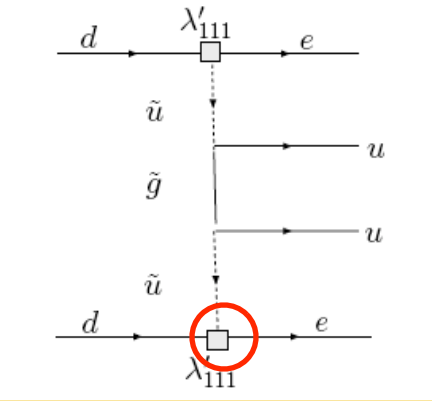


Logarithmic enhancements of *R*

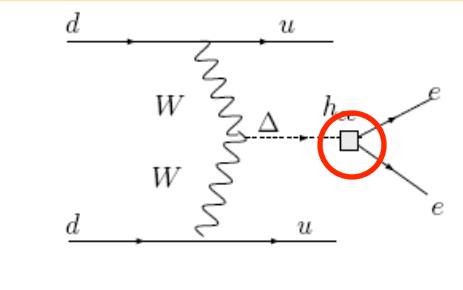
Lepton Flavor & Number Violation

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

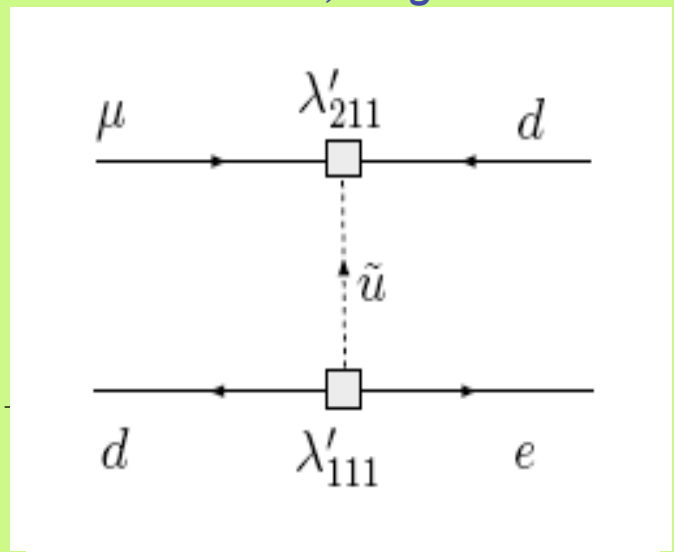
0νββ decay

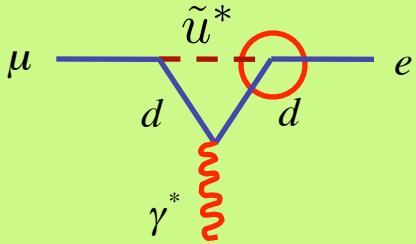


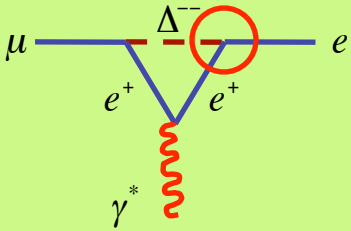
RPV SUSY



LRSM







Logarithmic enhancements of *R*

Lepton Flavor & Number Violation

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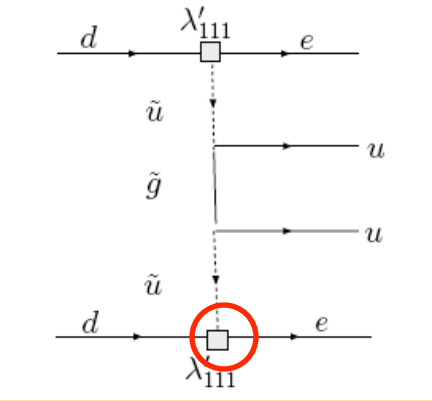

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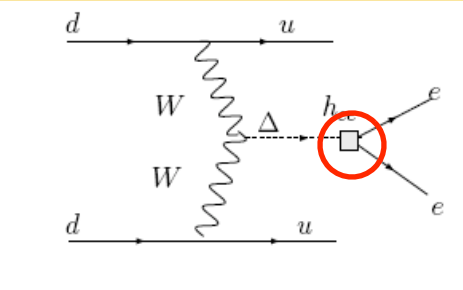
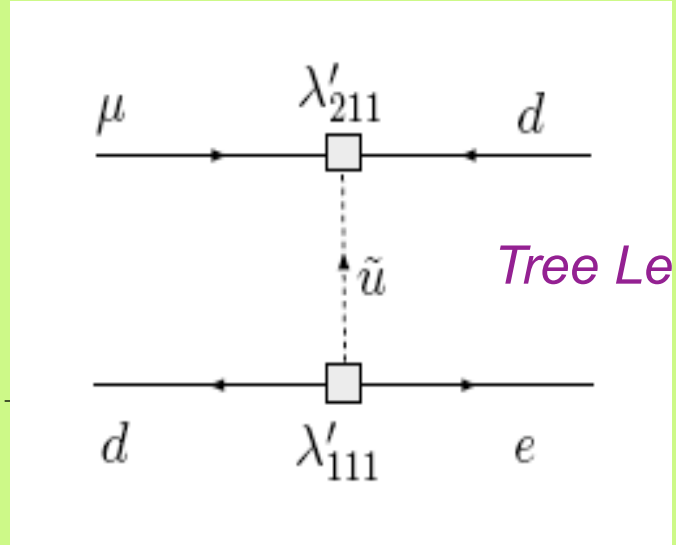
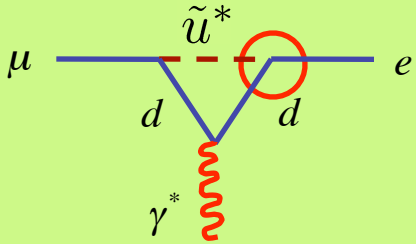
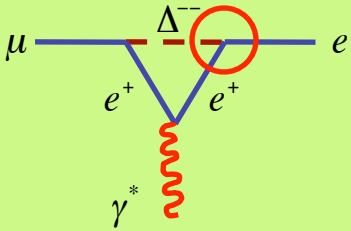


LRSM



Tree Level





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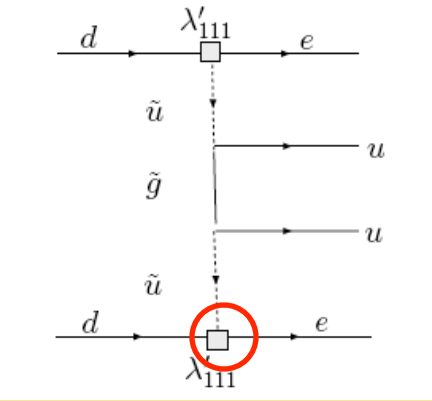

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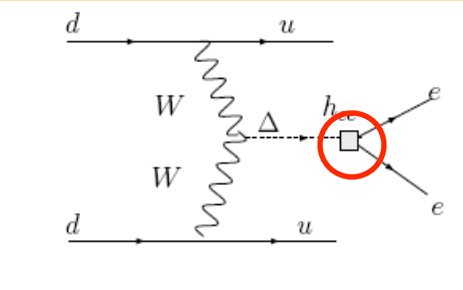

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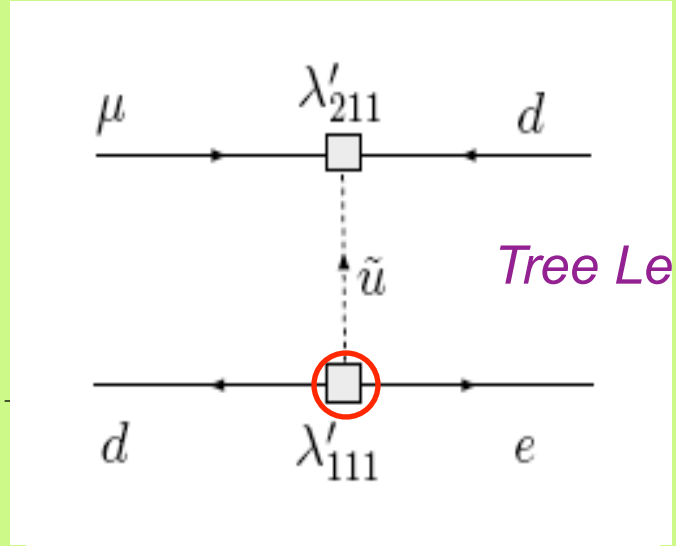

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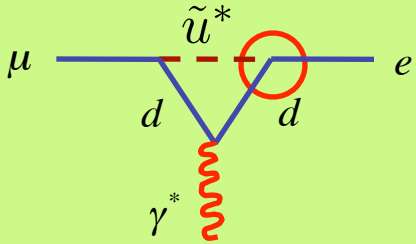

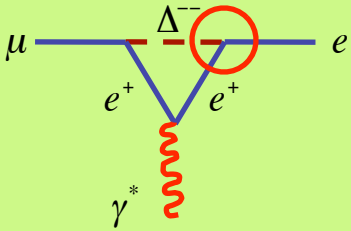

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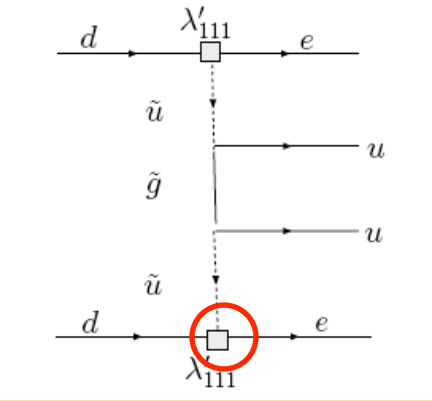

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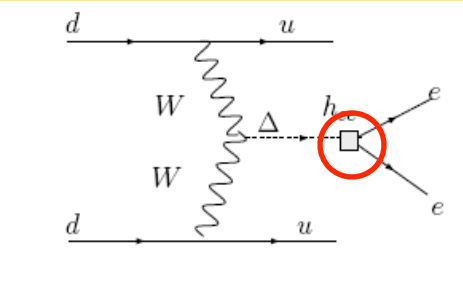

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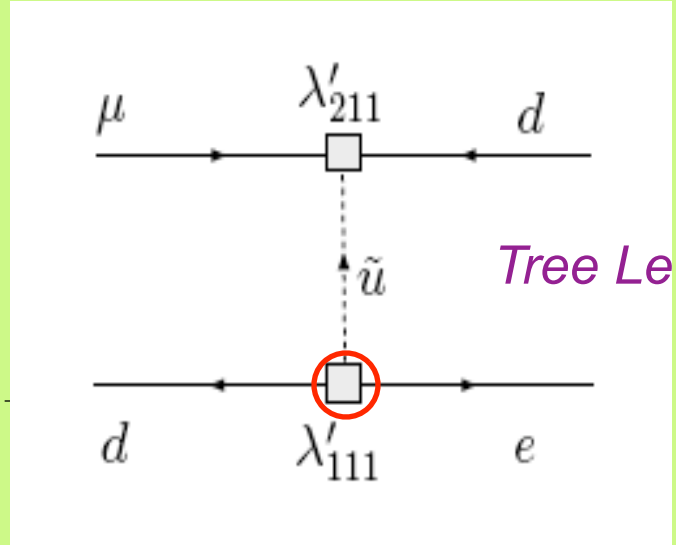

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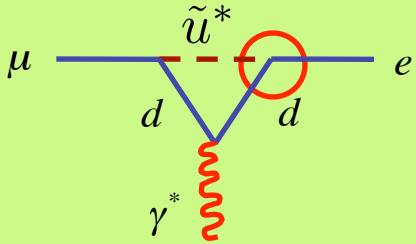
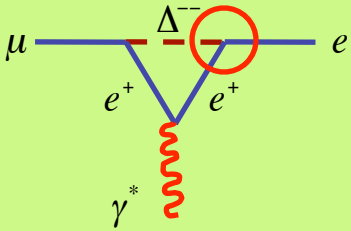


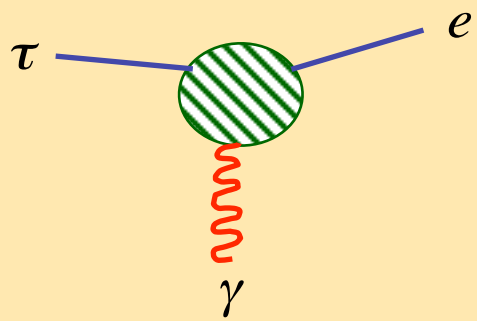


Logarithmic enhancements of *R*

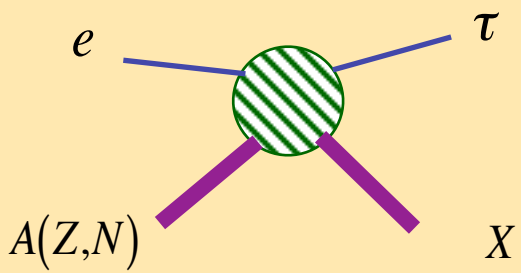
Low scale LFV: *R* ~ *O(1)* GUT scale LFV: *R* ~ *O*(α)

τ Lepton Flavor & Number Violation

Raidal, Santamaria;
Cirigliano, Kurylov, R-



Exp: $B_{\tau->e\gamma}$ ~ 1.1 x 10^{-7}



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

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

$|A^2_{\tau e}|^2 < 10^{-8}$

If $|A^2_{\tau e}|^2 \sim |A^1_{\tau e}|^2$

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

Log or tree-level enhancement:

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

Need ~ 1000 fb

τ Lepton Flavor & Number Violation

Raidal, Santamaria;
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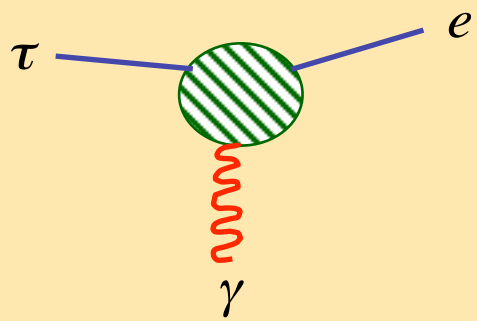
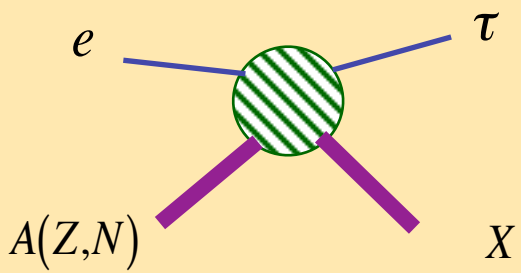


Exp: $B_{\tau->e\gamma} \sim 1.1 \times 10^{-7}$



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M1 operator

If $|A^2_{\tau e}|^2 \sim |A^1_{\tau e}|^2$

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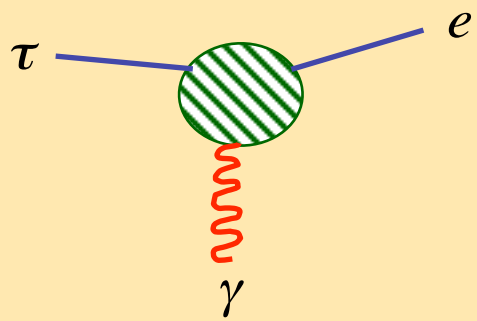

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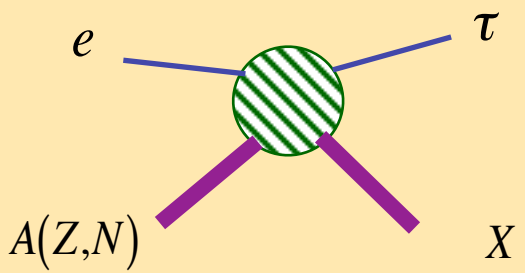

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τ *Lepton Flavor & Number Violation*

Raidal, Santamaria;
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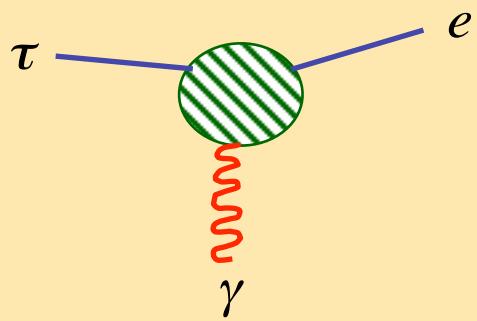

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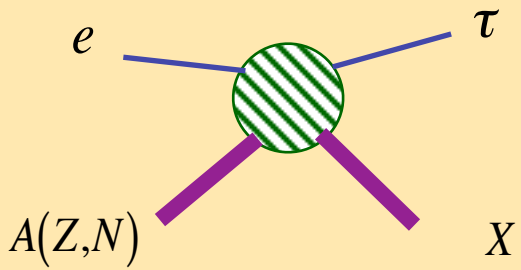

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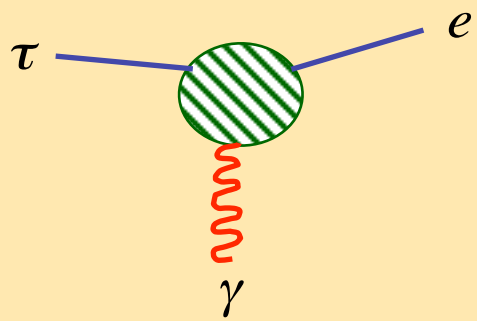

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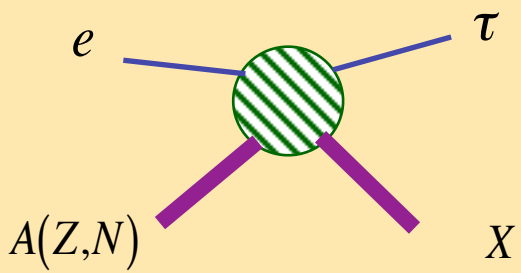

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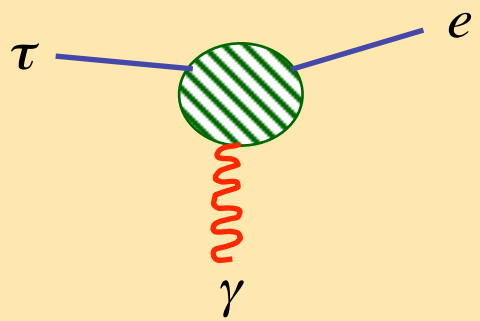
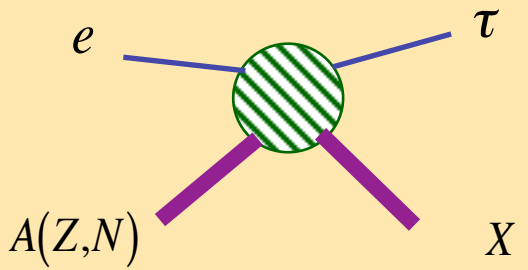
Need ~ 1000 fb

τ *CLFV & Other Probes*



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

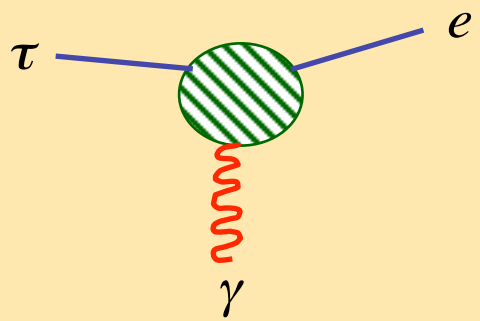


EIC: $\sigma \sim 10^3 \, | A^1_{\tau e}|^2$ fb

Doubly Charged Scalars

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

τ *CLFV & Other Probes*



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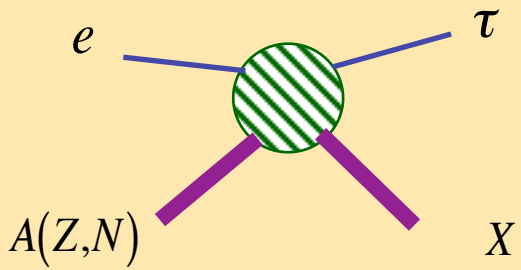

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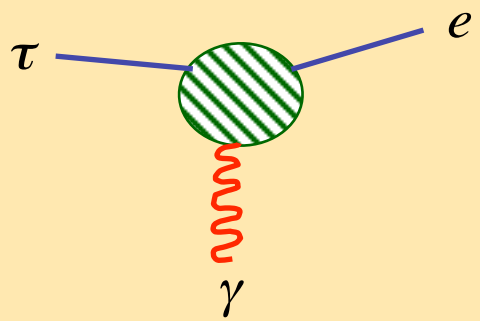
Doubly Charged Scalars

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

τ *CLFV & Other Probes*



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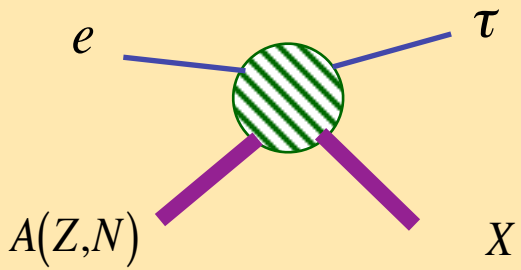

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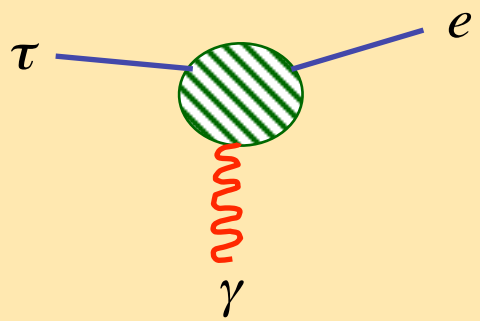
$0\nu\beta\beta$ *if RH; PV Moller if LH*

τ *CLFV & Other Probes*



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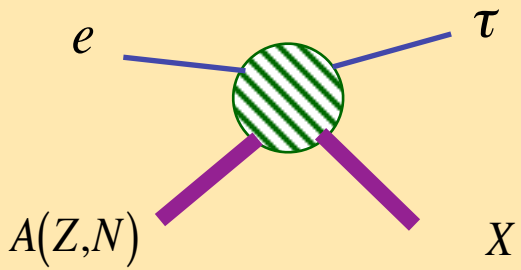

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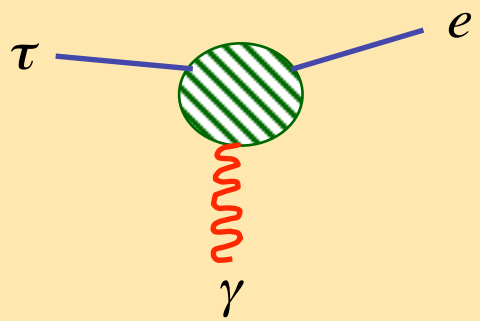
$+ h_{\mu\tau} h_{\tau e}$	$+ h_{e\tau} h_{\tau\tau}$

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

All h_{ab} \$ m_ν *if part of see-saw*

τ *CLFV & Other Probes*



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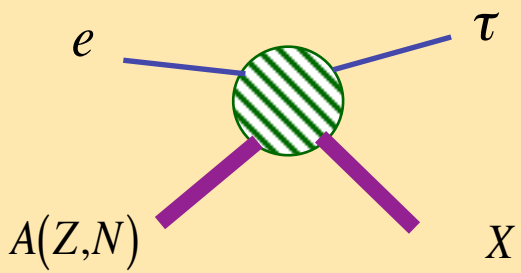

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$+ h_{\mu\mu} h_{\mu e}$	$+ h_{e\mu} h_{\mu\tau}$
$+ h_{\mu\tau} h_{\tau e}$	$+ h_{e\tau} h_{\tau\tau}$

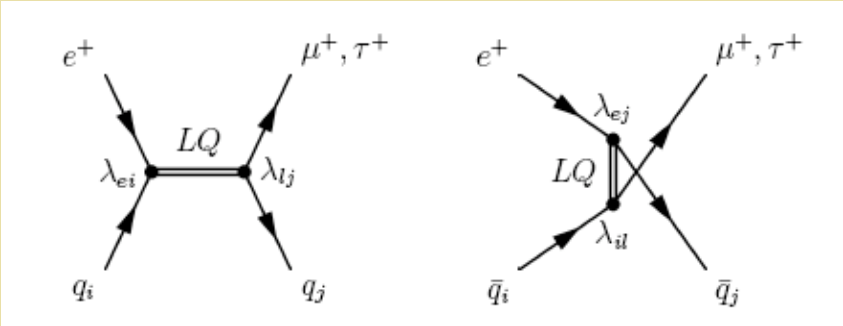
$0\nu\beta\beta$ if RH; PV Moller if LH

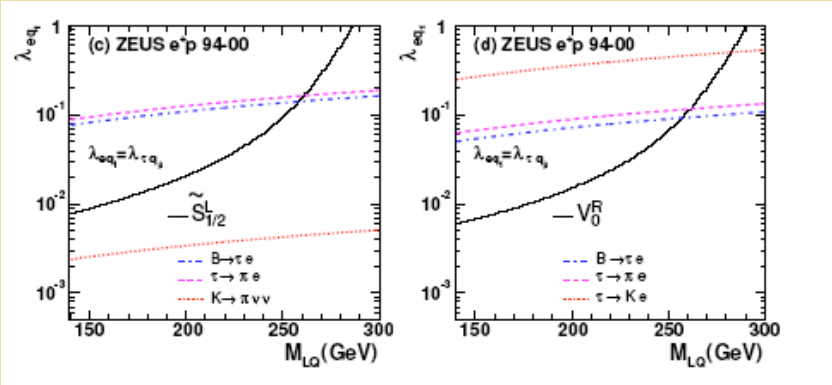
All h_{ab} \$ m_ν if part of see-saw

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

LFV with τ leptons: HERA

Leptoquark Exchange:
Like RPV SUSY /w λ/



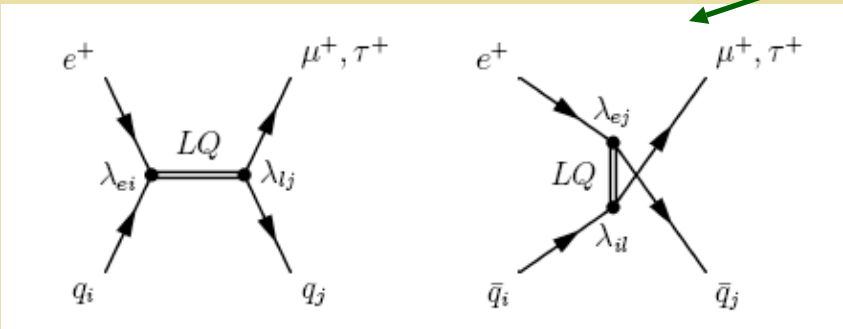


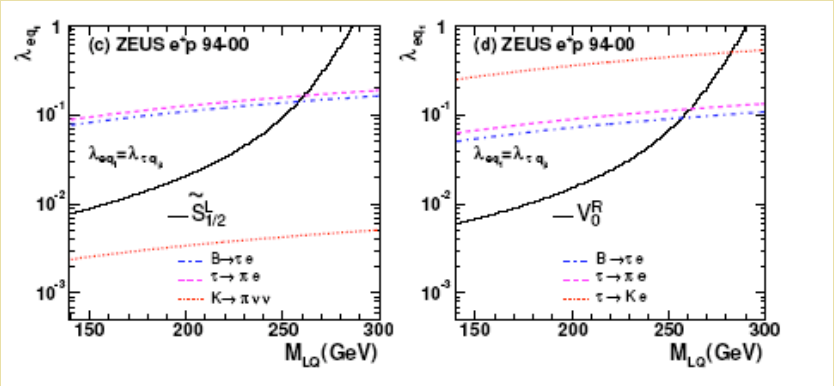
Veelken (H1, Zeus) (2007)

LFV with τ leptons: HERA

Leptoquark Exchange:
Like RPV SUSY /w λ/

τeqq eff op





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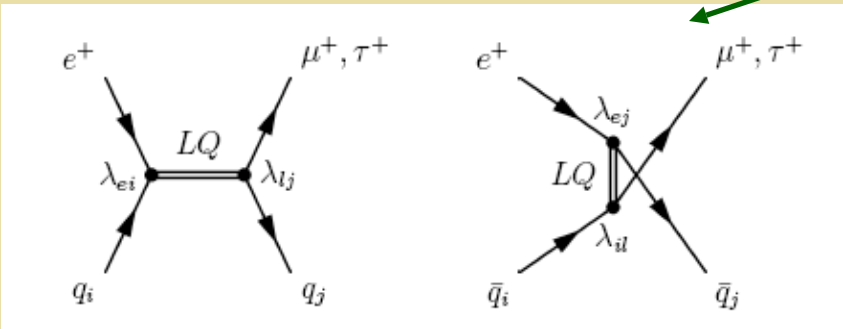

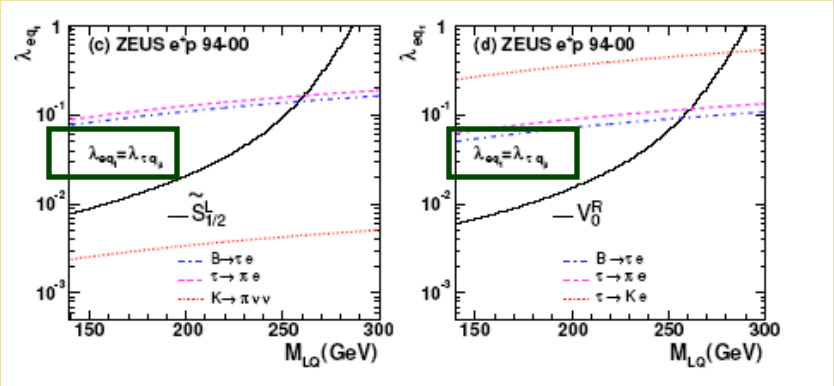

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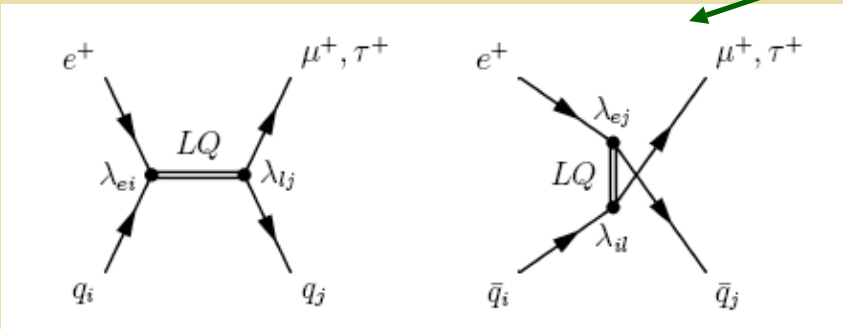

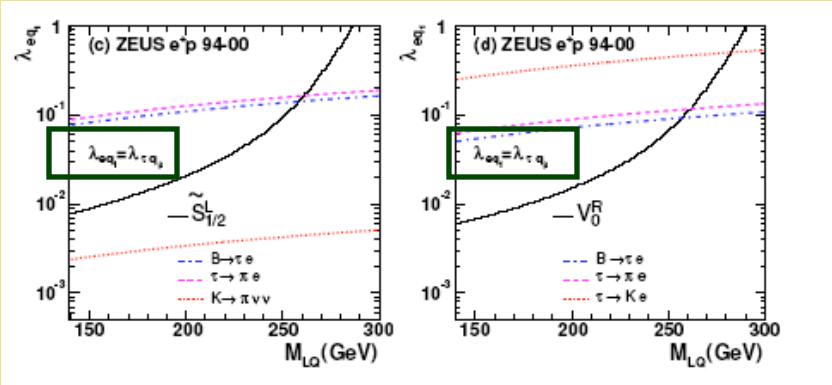

$|\lambda_{lq}|^2 < 10^{-4}\,(M_{LQ}\,/\,100\text{ GeV})^2$

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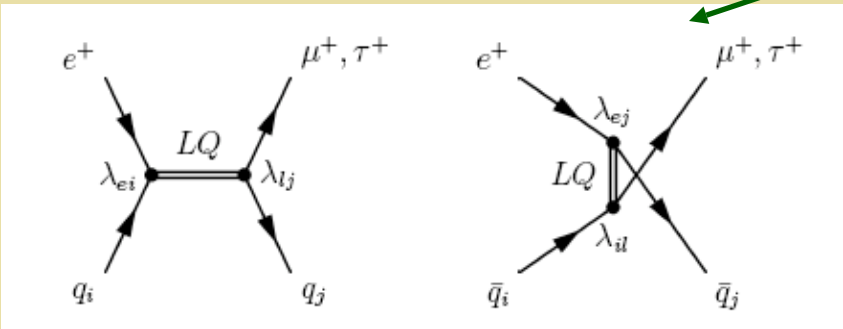
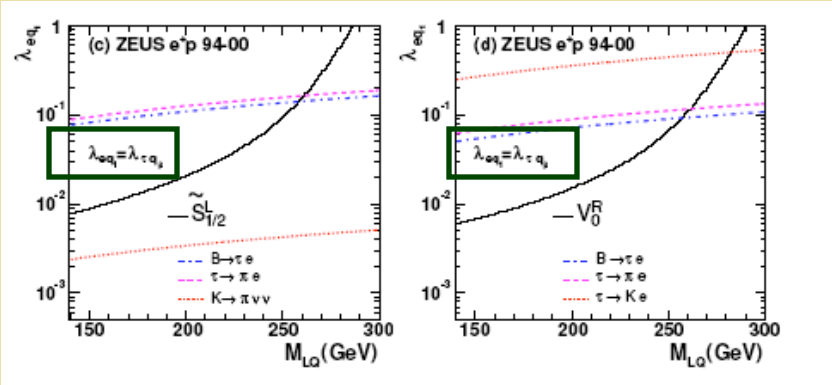




$|\lambda_{lq}|^2 < 10^{-4} (M_{LQ} / 100 \text{ GeV})^2$

HW Assignment:

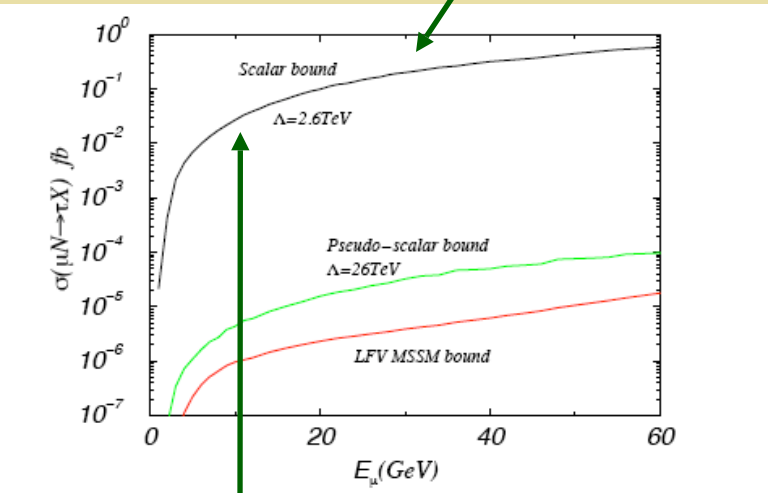
- *Induce τKeγ at one loop?*
- *Consistent with $B_{\tau K e\gamma}$? HERA limits look stronger*
- *Connection w/ m_ν & $0\nu\beta\beta$ in GUTS ?*
- *Applicable to other models that generate tree-level ops?*

Veelken (H1, Zeus) (2007)

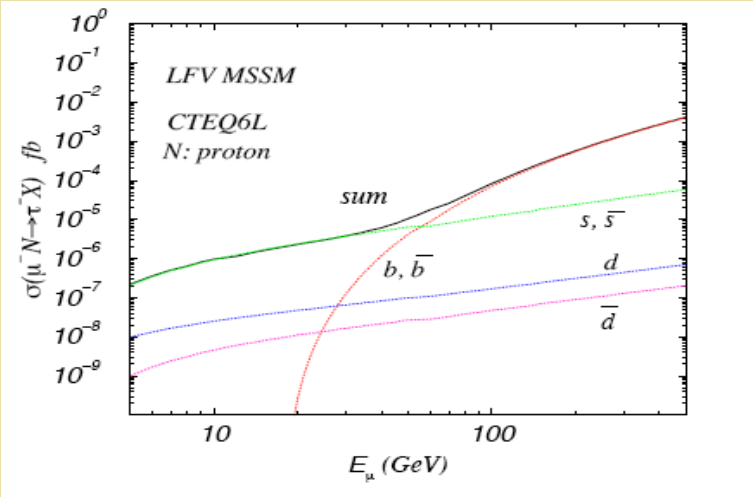
LFV with τ leptons: recent theory

Kanemura et al (2005)

τμqq eff op



SUSY Higgs Exchange



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

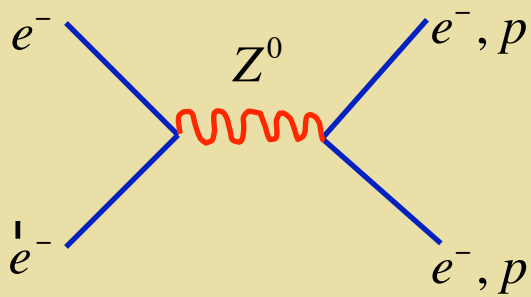
$|\lambda_{lq}|^2 < 10^{-4} (M_{LQ} / 100\ \text{GeV})^2$ HERA

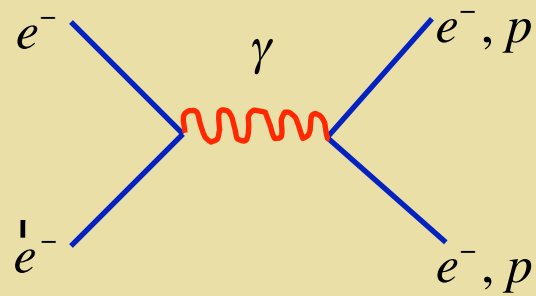
Neutral Current Probes: PV

- *Basics of PV electron scattering*
- *Standard Model: What we know*
- *New physics ? SUSY as illustration*
- *Probing QCD*

PV Electron Scattering

Parity-Violating electron scattering





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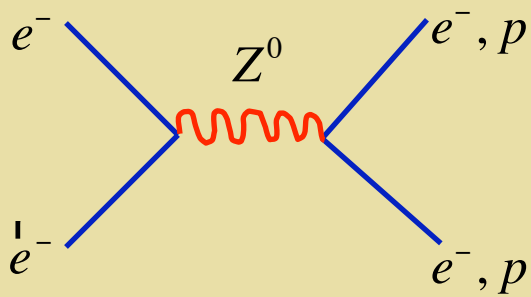

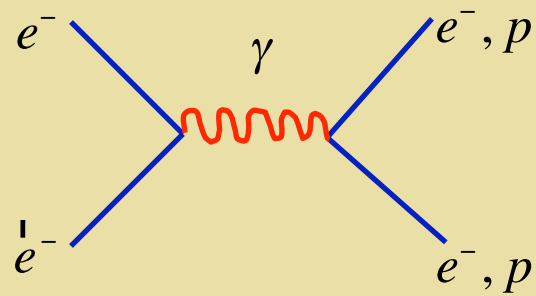

$$A_{PV} = \frac{N_{\uparrow\uparrow} - N_{\uparrow\downarrow}}{N_{\uparrow\uparrow} + N_{\uparrow\downarrow}} = \frac{G_F Q^2}{4\sqrt{2}\pi\alpha}\left[Q_W + F(Q^2,\theta)\right]$$

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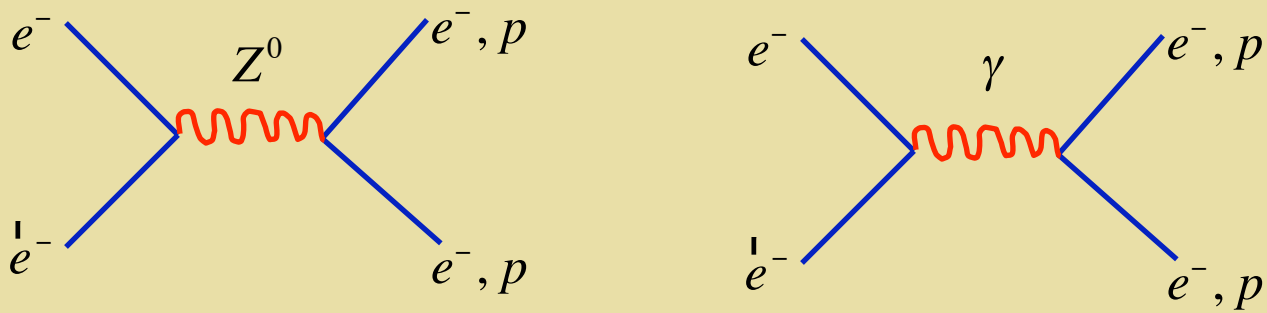

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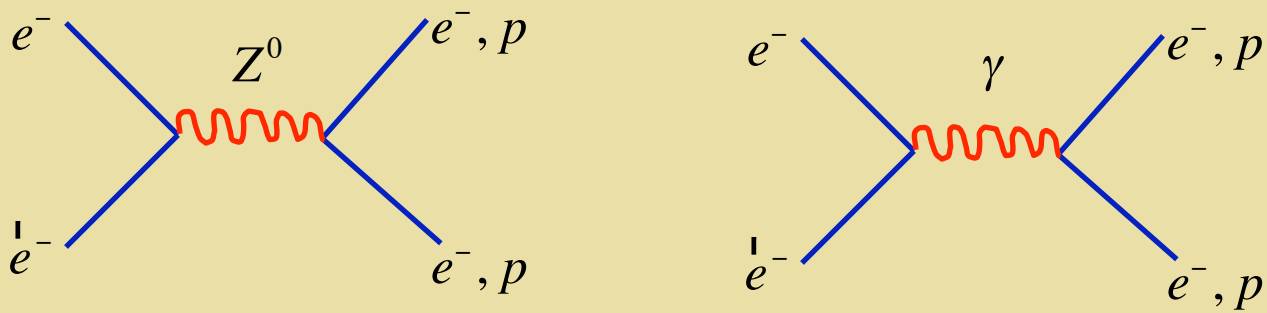

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"Weak Charge" ~ 0.1 in SM

Enhanced transparency to new physics

Small QCD uncertainties (Marciano & Sirlin; Erler & R-M)

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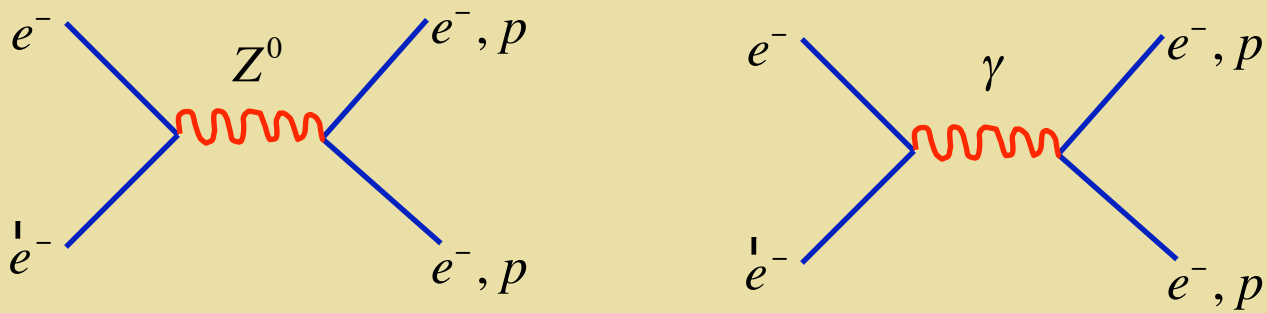

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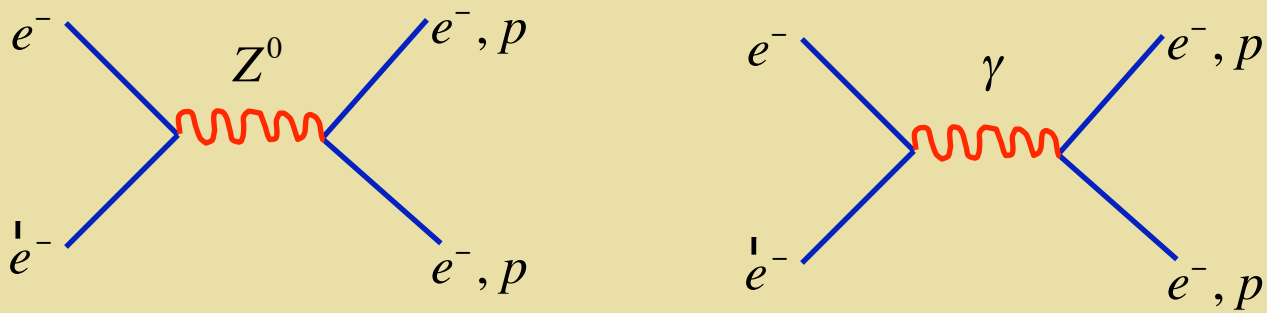

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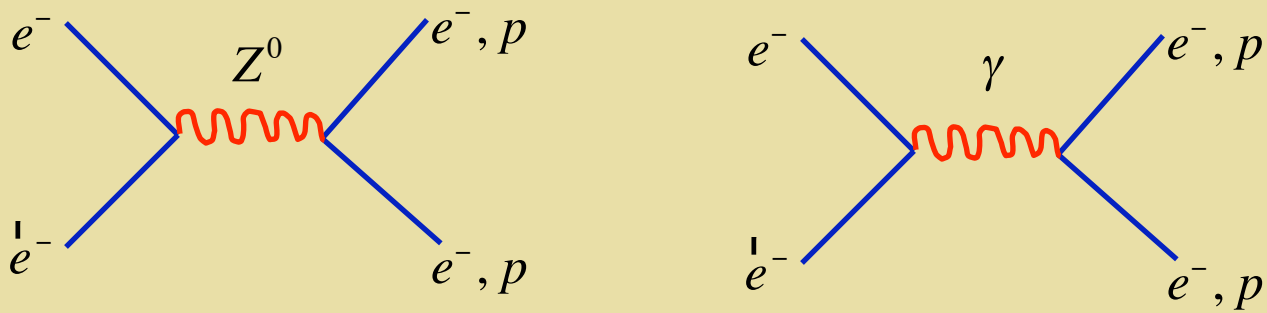

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Effective PV e-q interaction & Q_W

Low energy effective PV eq interaction

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

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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:

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

Q_W and Radiative Corrections

Tree Level

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

Q_W and Radiative Corrections

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Radiative Corrections

Q_W and Radiative Corrections

Tree Level

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

Radiative Corrections

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

Q_W and Radiative Corrections

Tree Level

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Radiative Corrections

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

Normalization

Scale-dependent effective weak mixing

Flavor-independent

Q_W and Radiative Corrections

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Constrained by Z-pole precision observables

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Q_W and Radiative Corrections

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Radiative Corrections

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

Constrained by Z-pole precision observables

Large logs in κ :

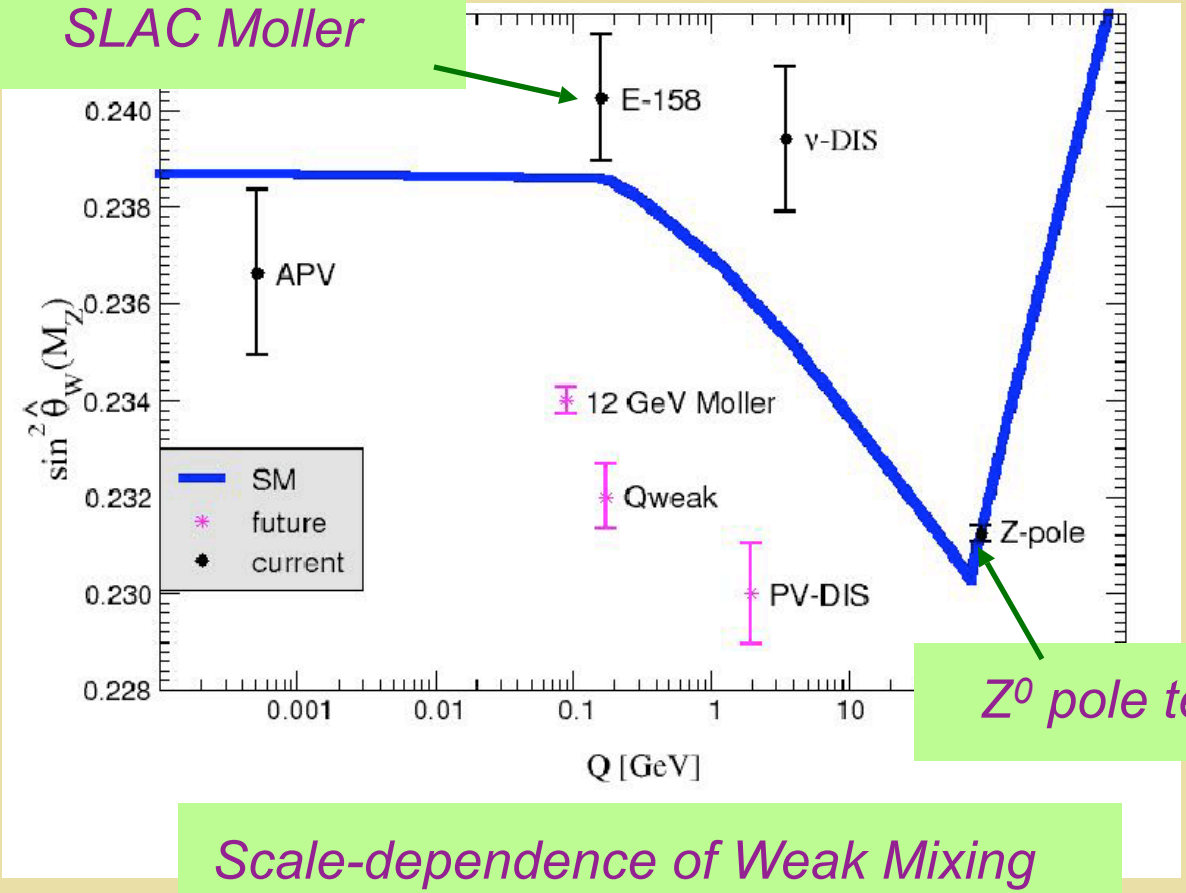
Sum to all orders with running $\sin^2\theta_W$ *& RGE*

Flavor-indeper

Weak Mixing in the Standard Model

Parity-violating electron scattering

SLAC Moller



Z^0 pole tension

Scale-dependence of Weak Mixing

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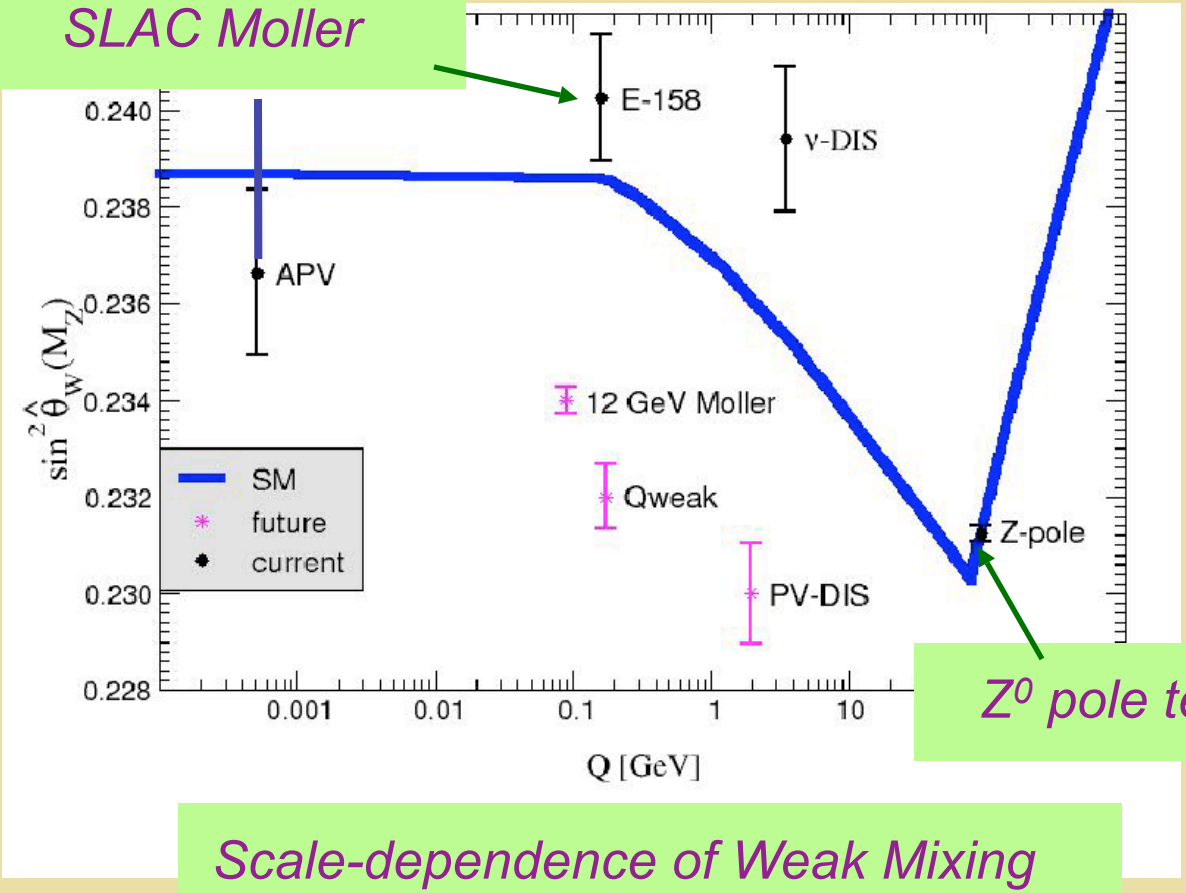

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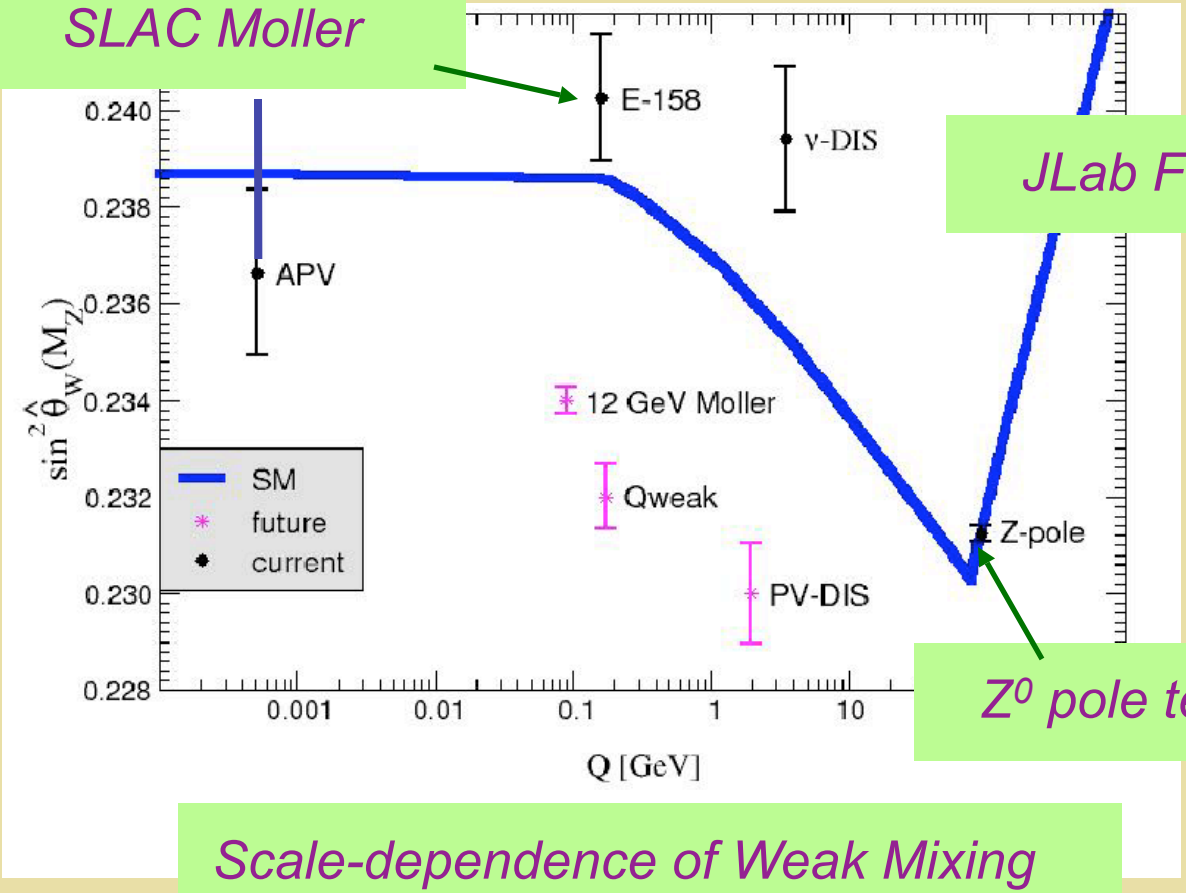

JLab Future

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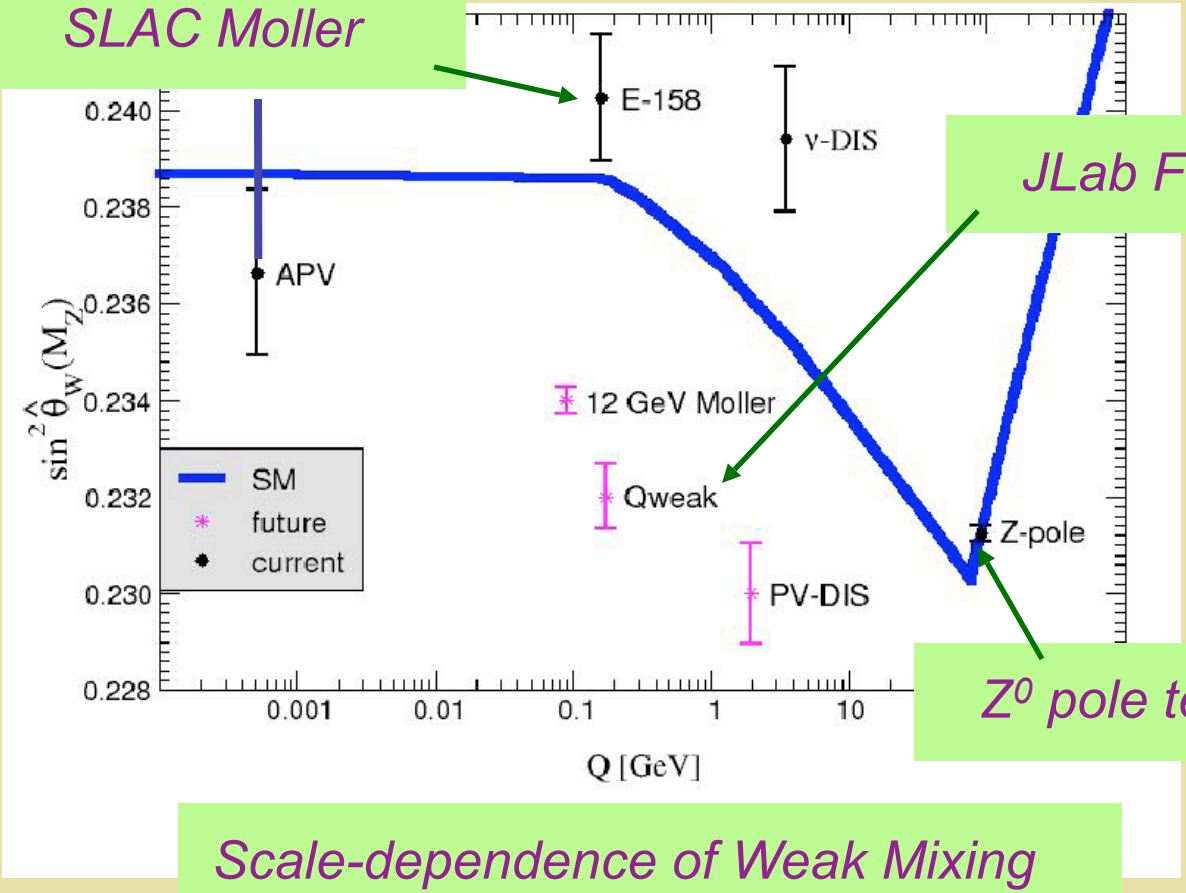

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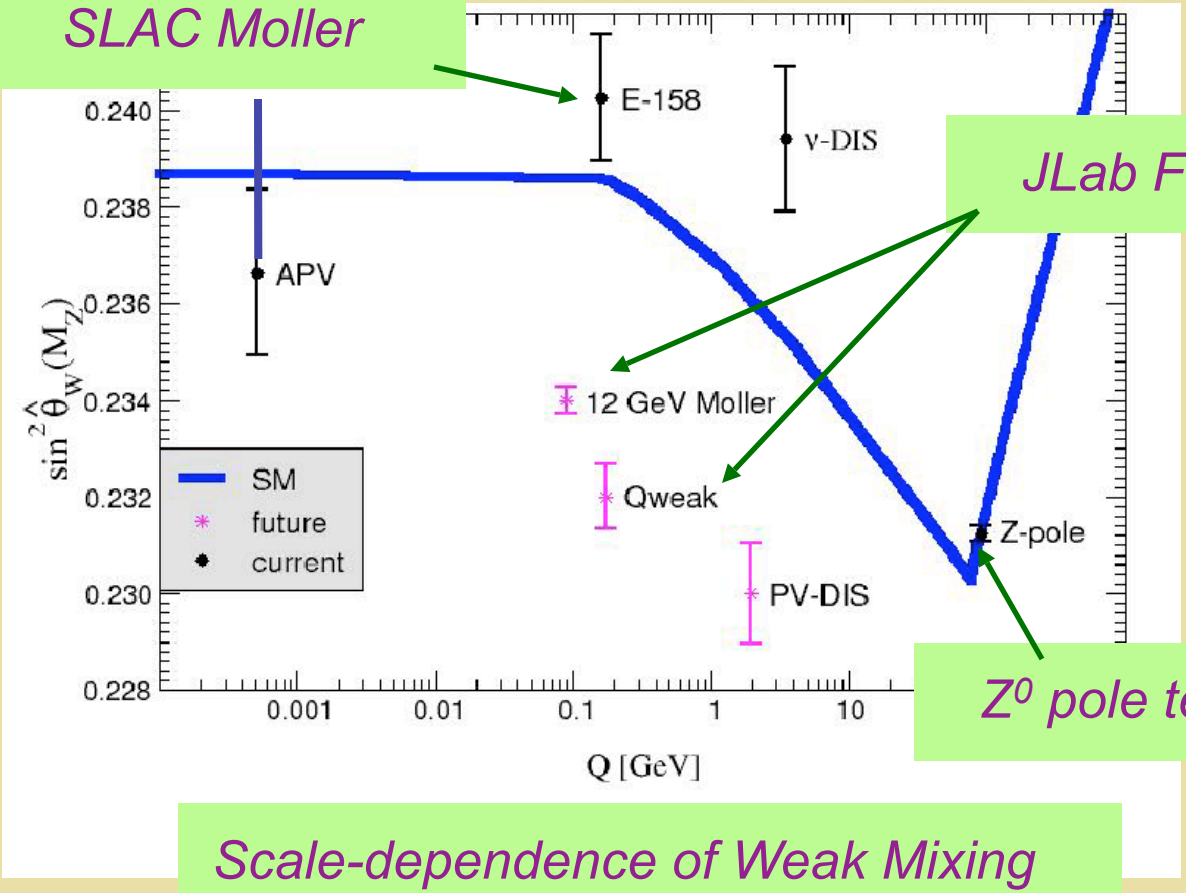

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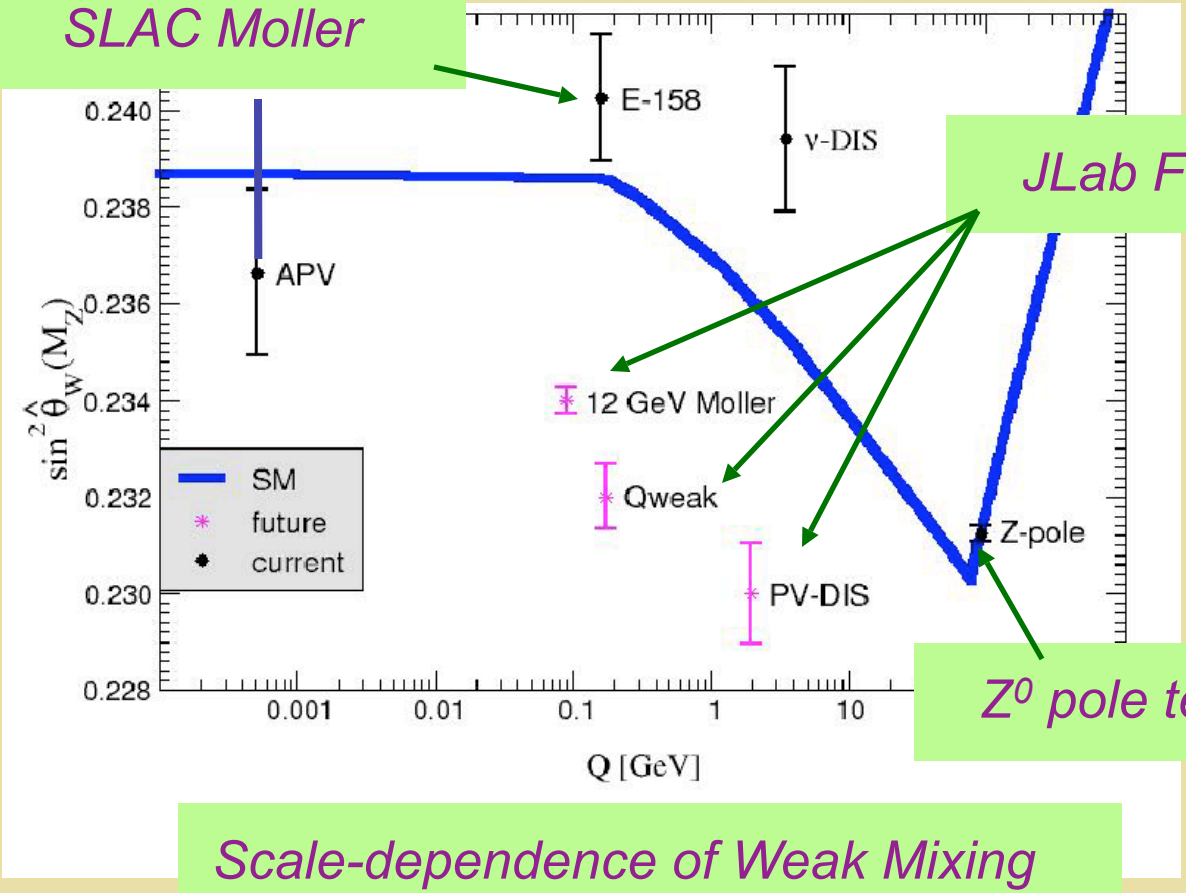

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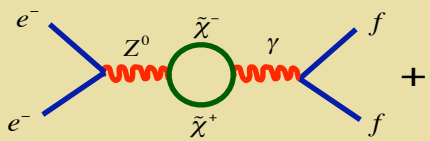
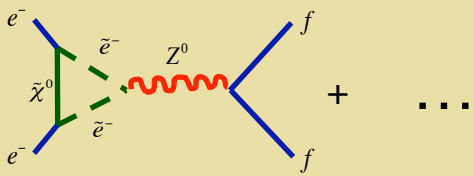
Scale-dependence of Weak Mixing

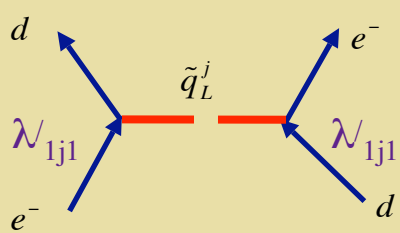
PVES & New Physics

SUSY



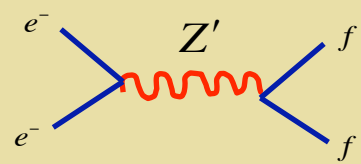


Radiative Corrections

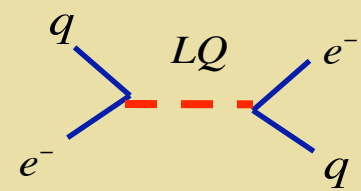


RPV

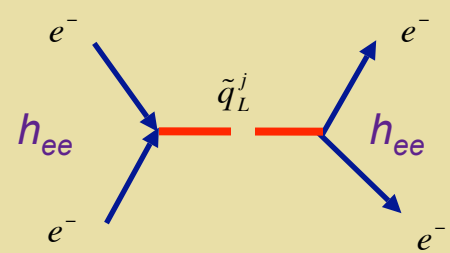
Z/ Bosons



Leptoquarks



Doubly Charged Scalars



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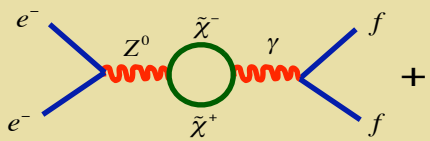
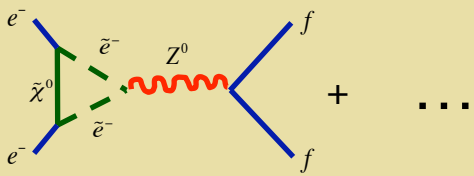
SUSY





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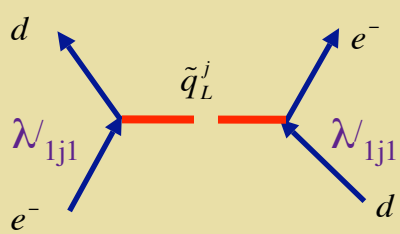

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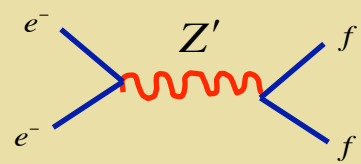
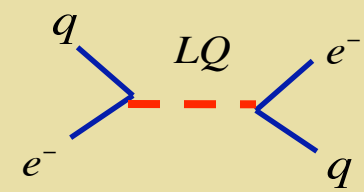


Semi-leptonic only

Leptoquarks



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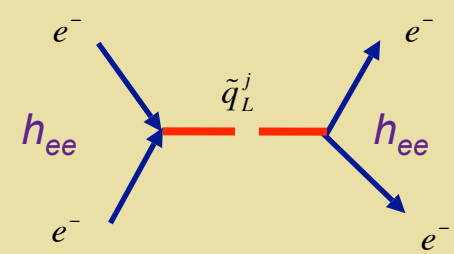

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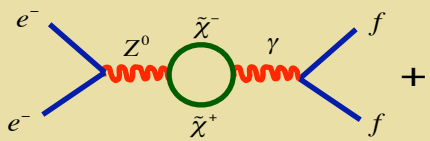
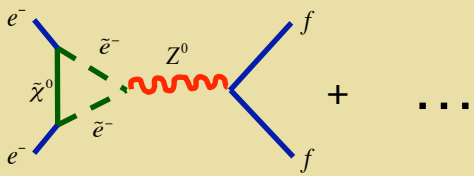
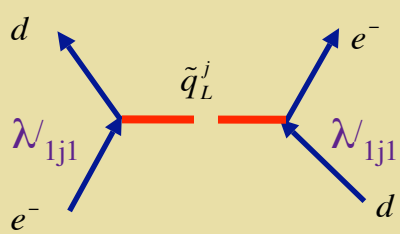


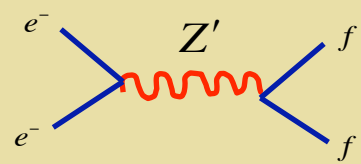


Radiative Corrections

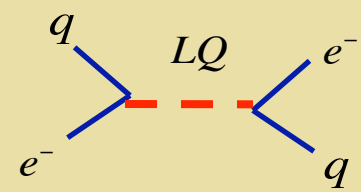


RPV

Z/ Bosons



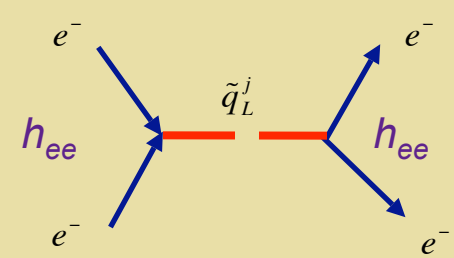
Leptoquarks



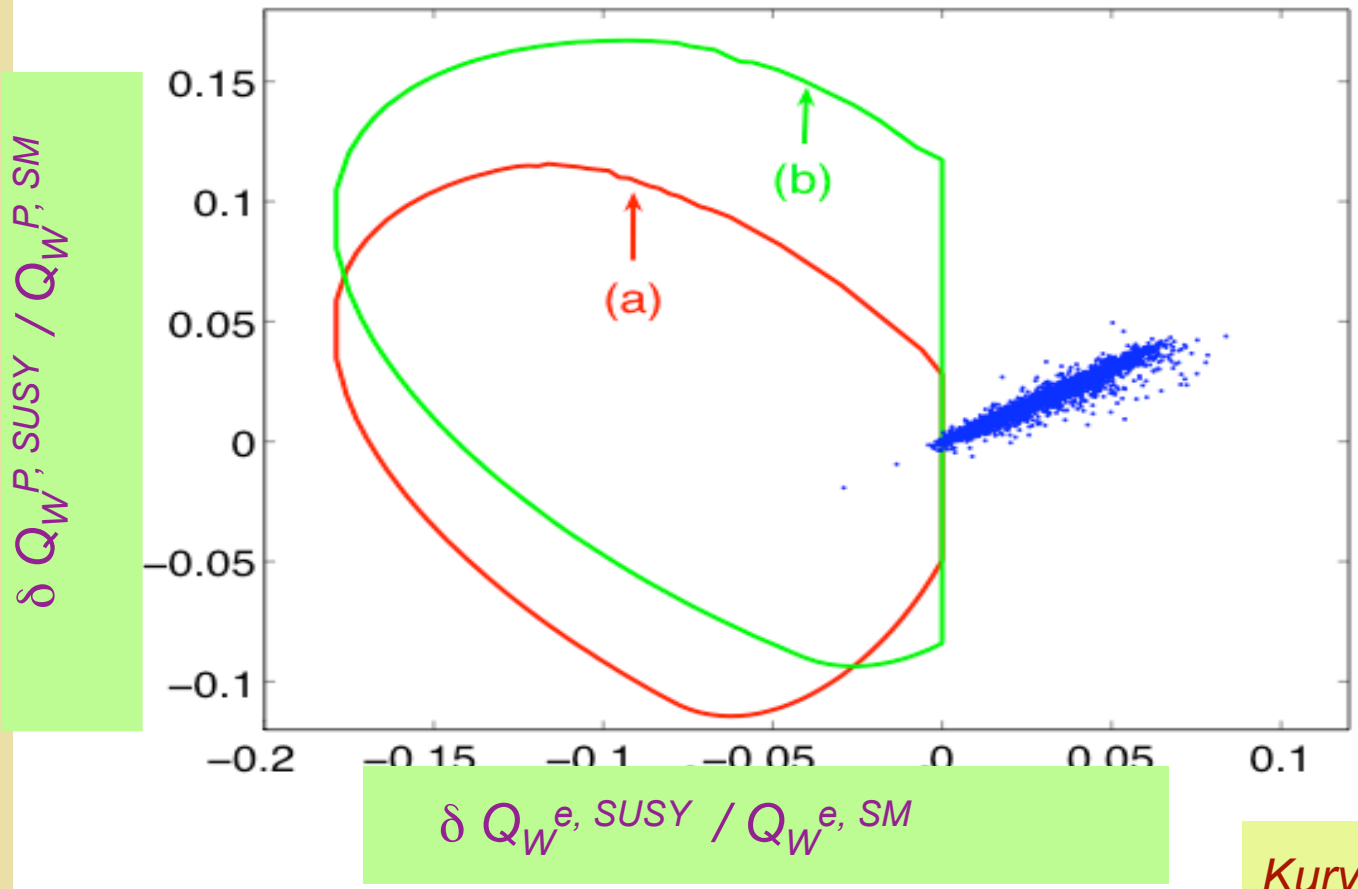
Semi-leptonic only

Doubly Charged Scalars

Moller only

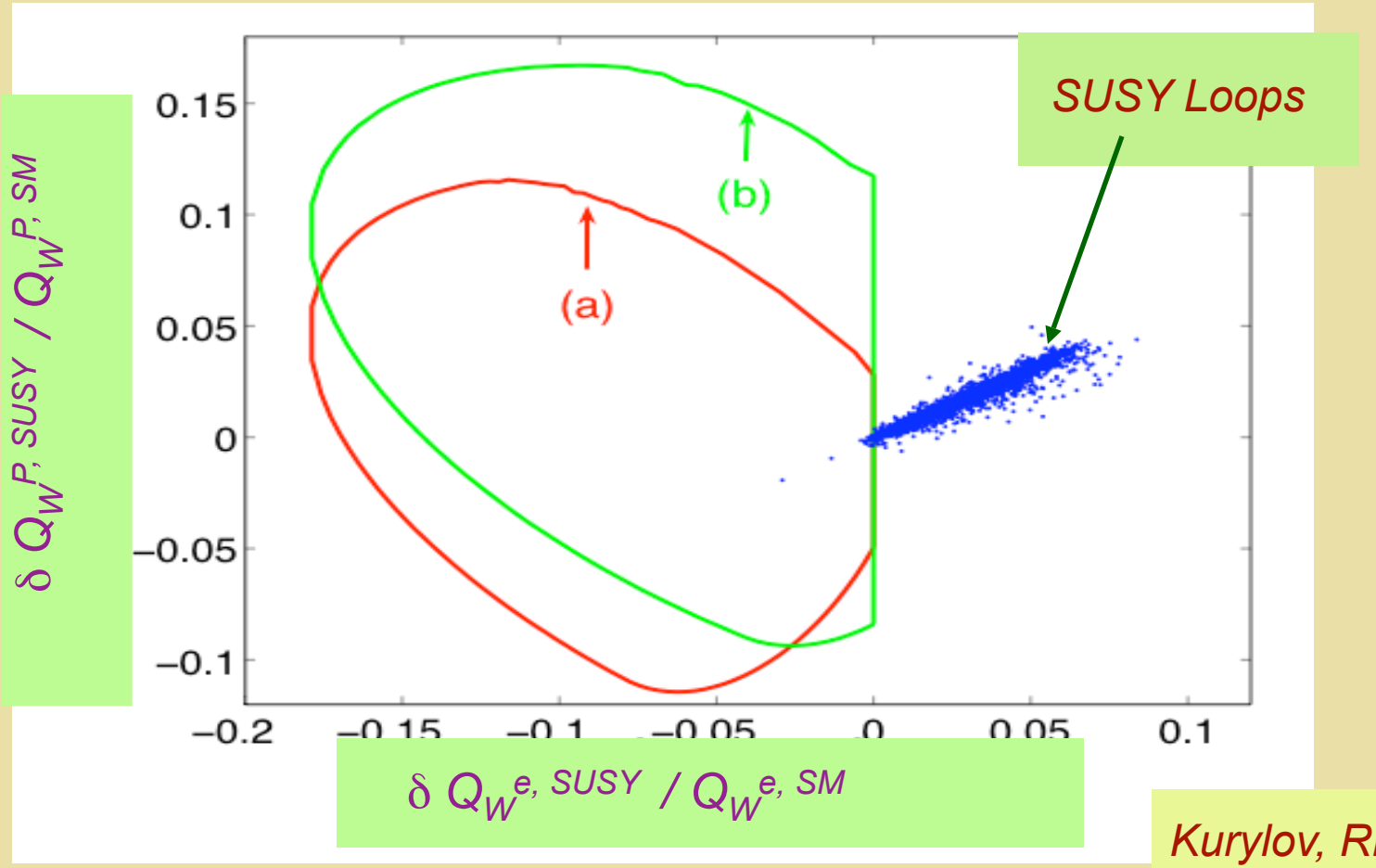


PVES & APV Probes of SUSY



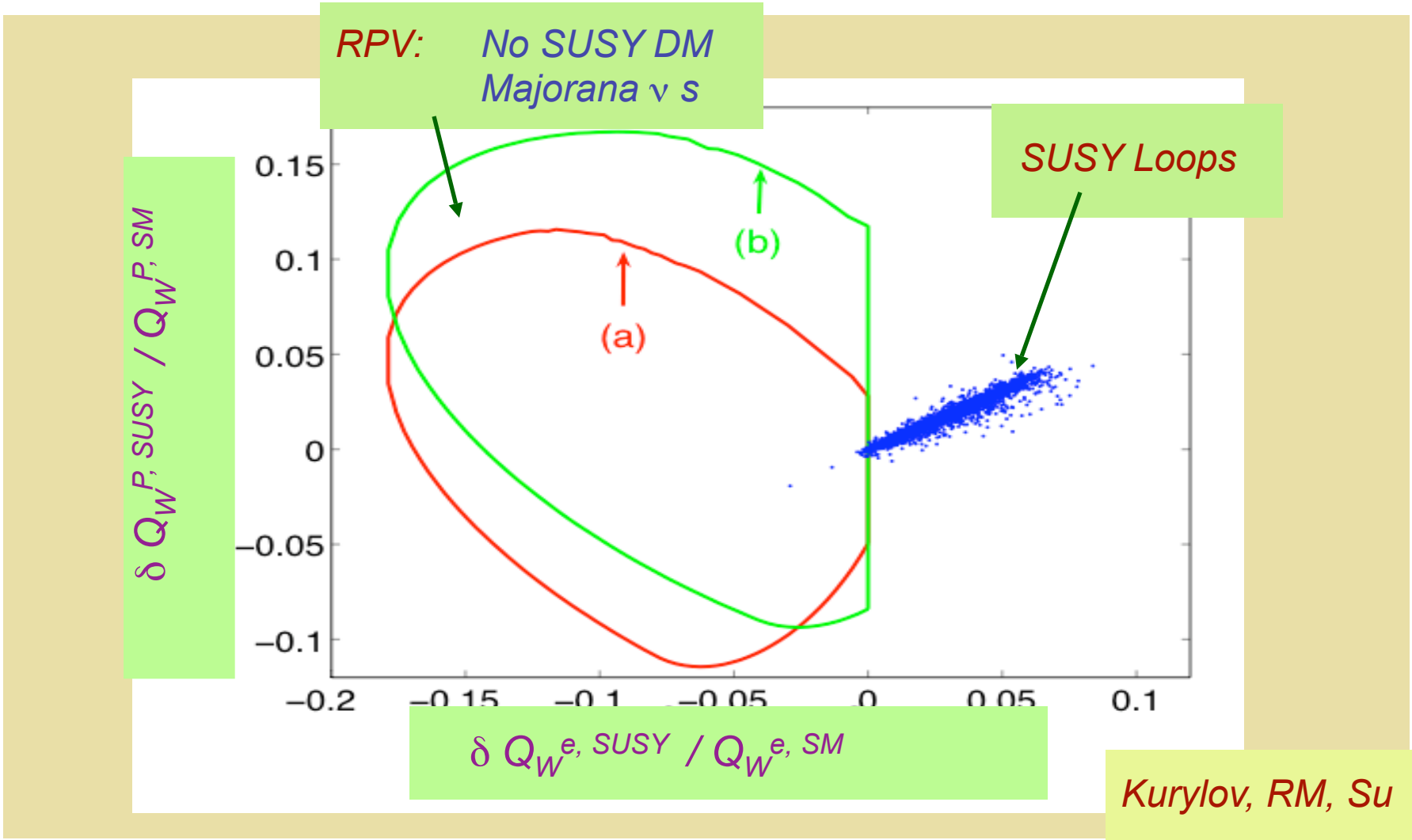
Kurylov, RM, Su

PVES & APV Probes of SUSY



Kurylov, RM, Su

PVES & APV Probes of SUSY



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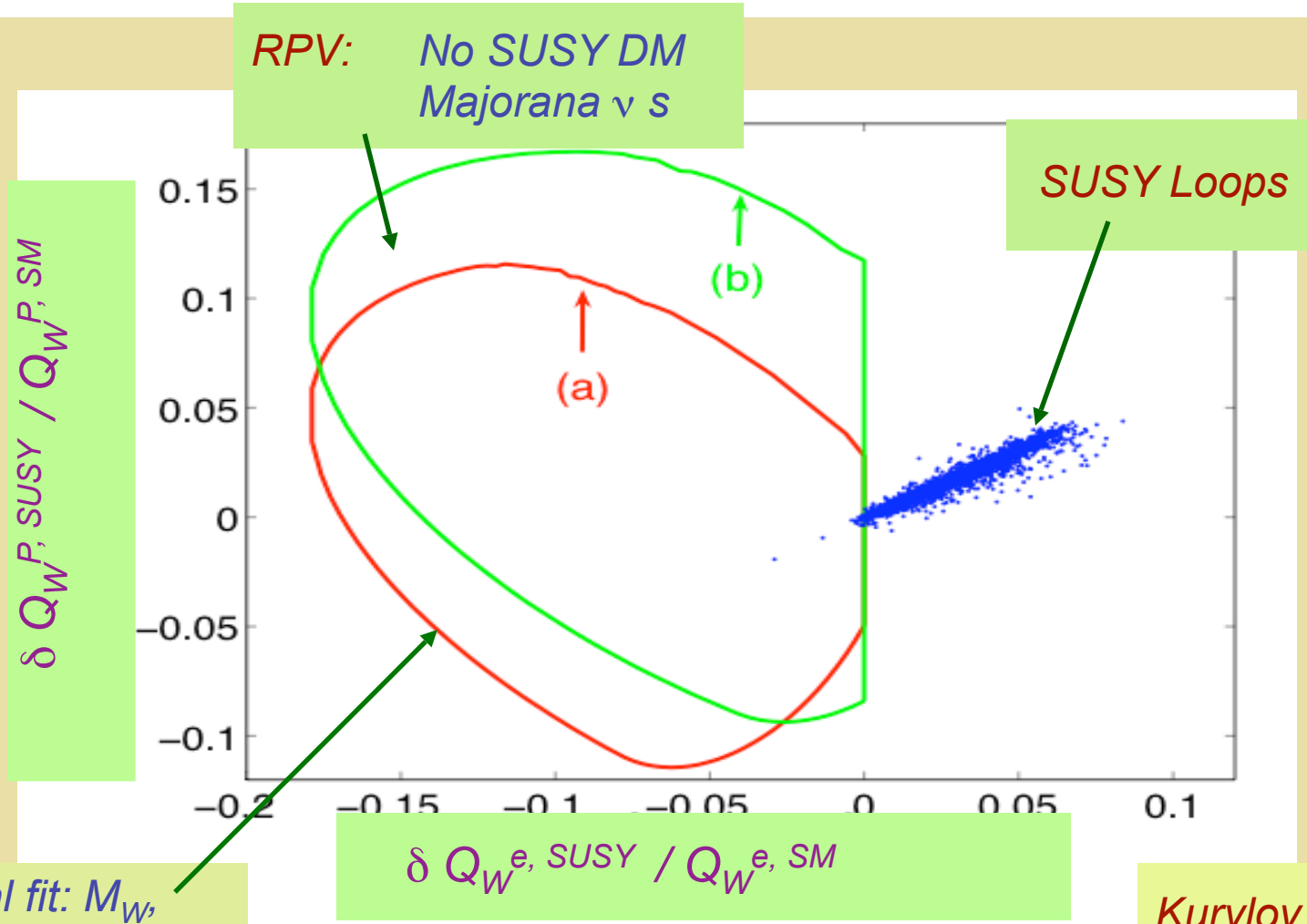
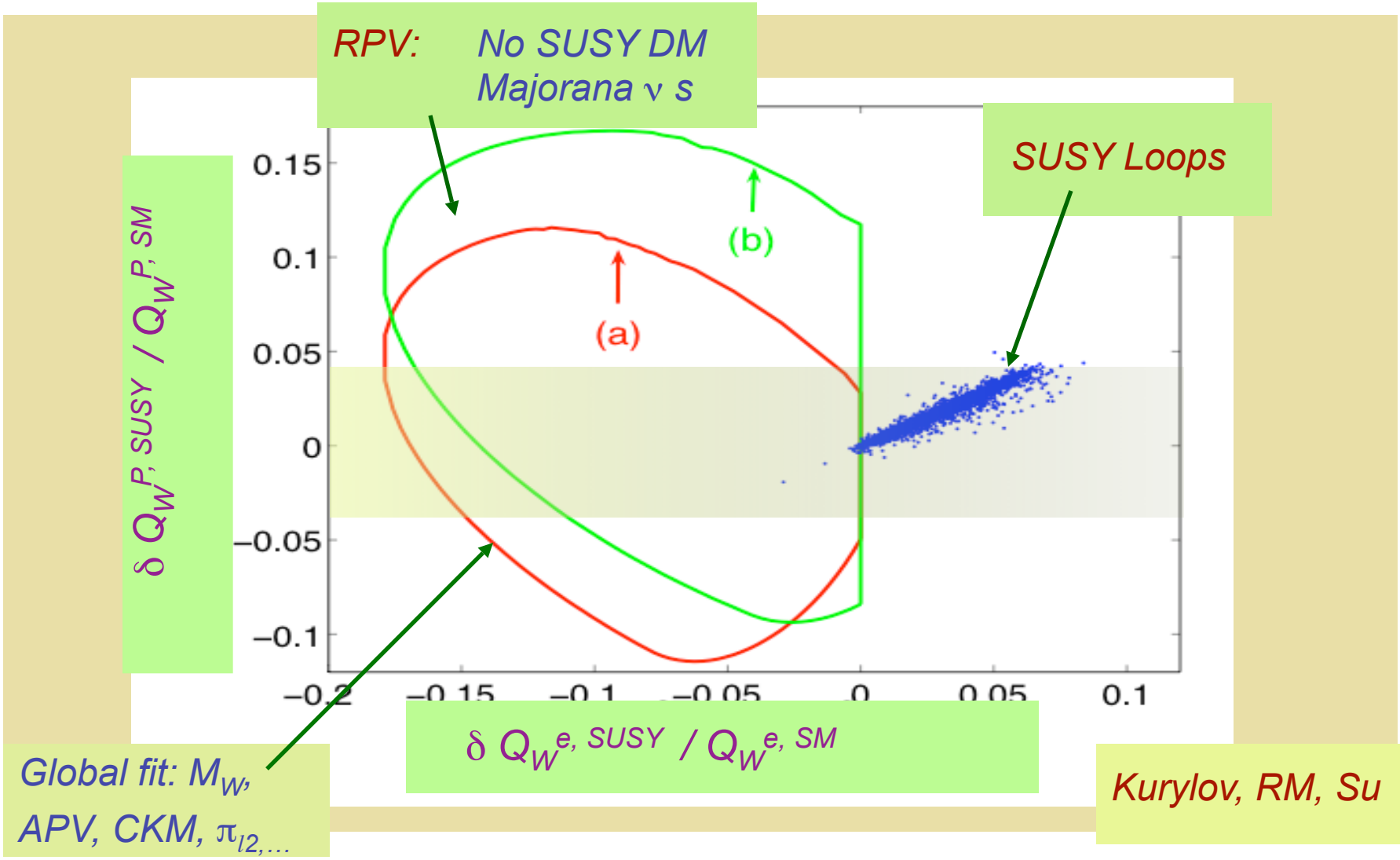


Global fit: M_W, APV, CKM, $\pi_{l2,\ldots}$

Kurylov, RM, Su

PVES & APV Probes of SUSY



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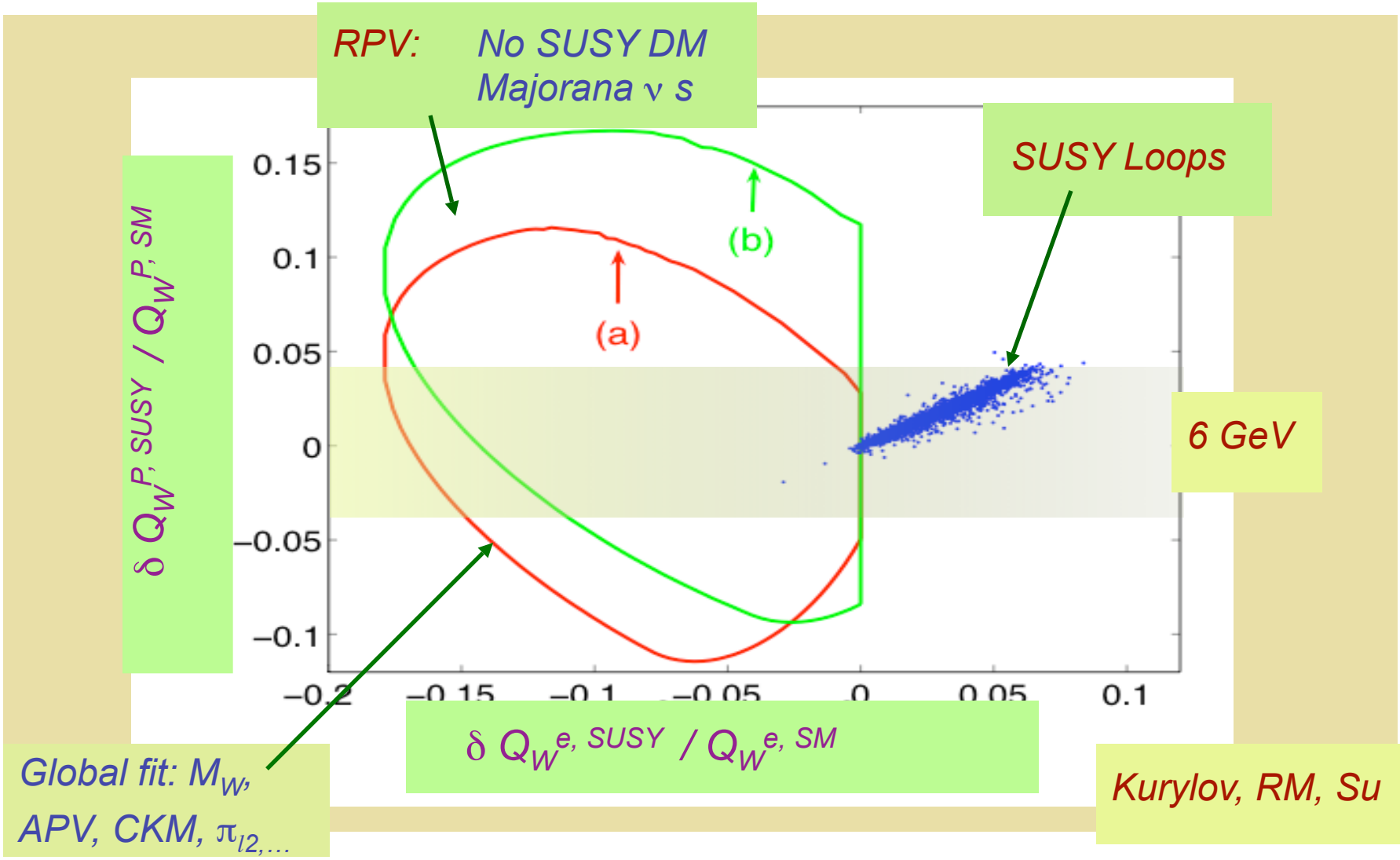

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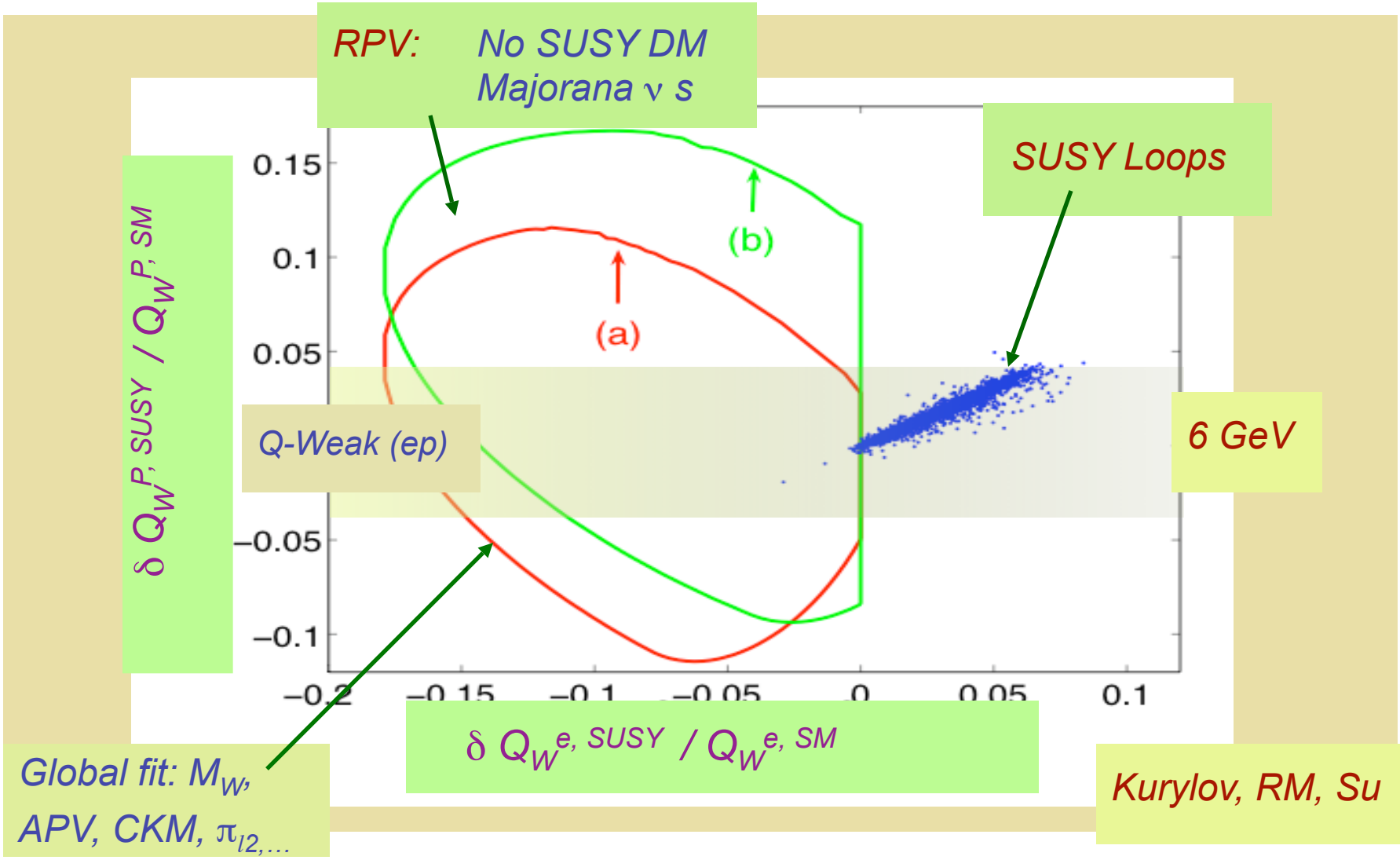
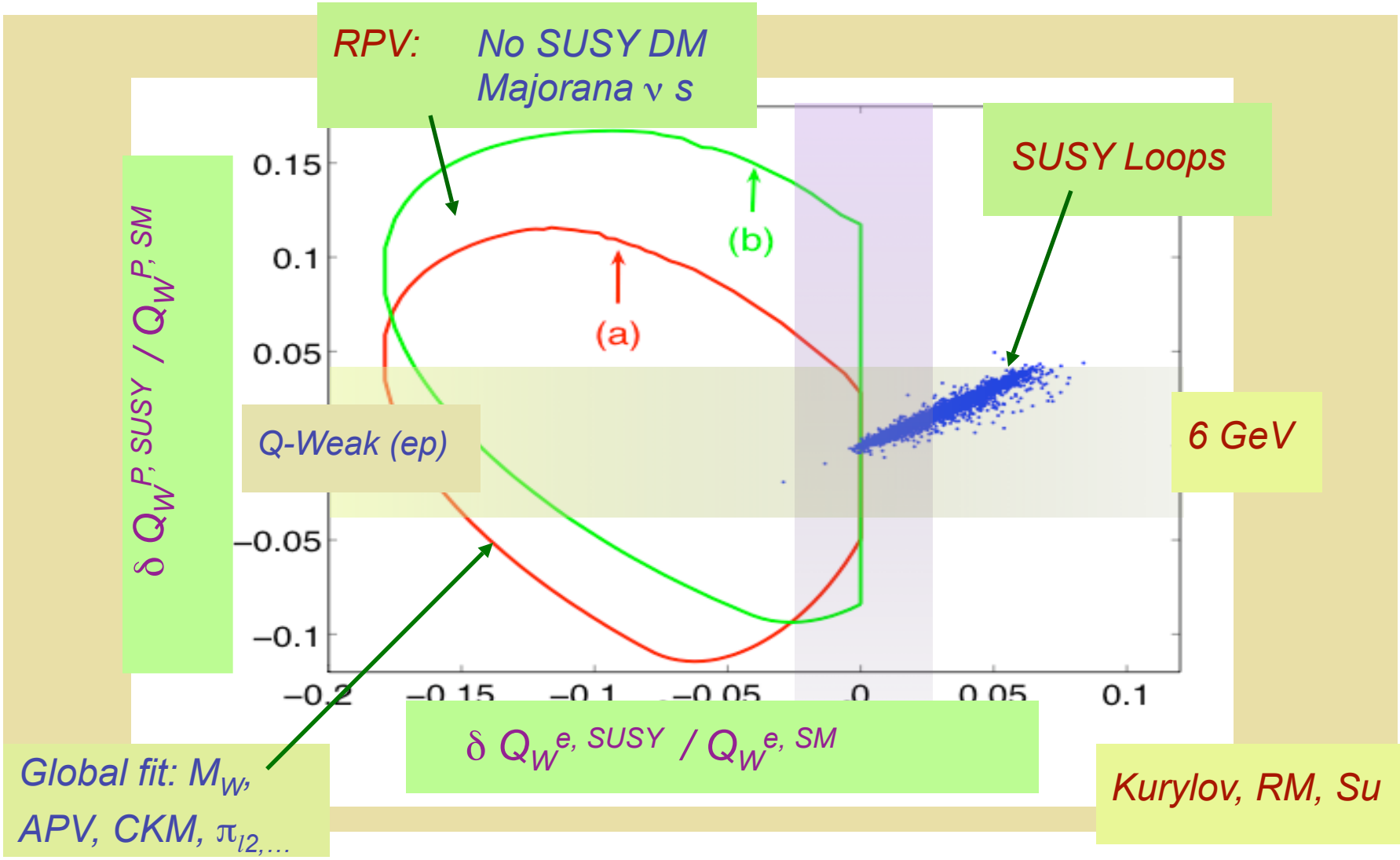


PVES & APV Probes of SUSY



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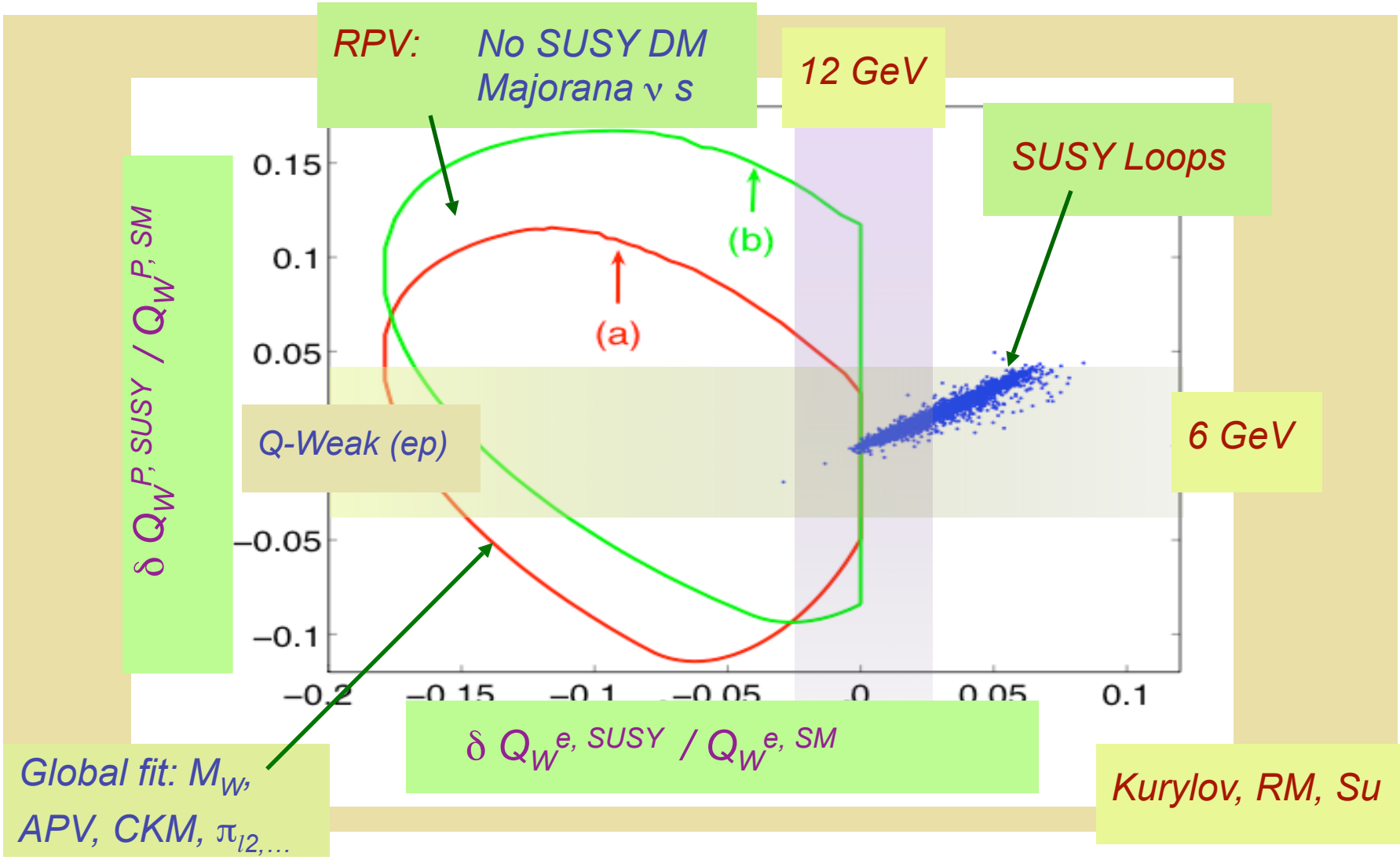

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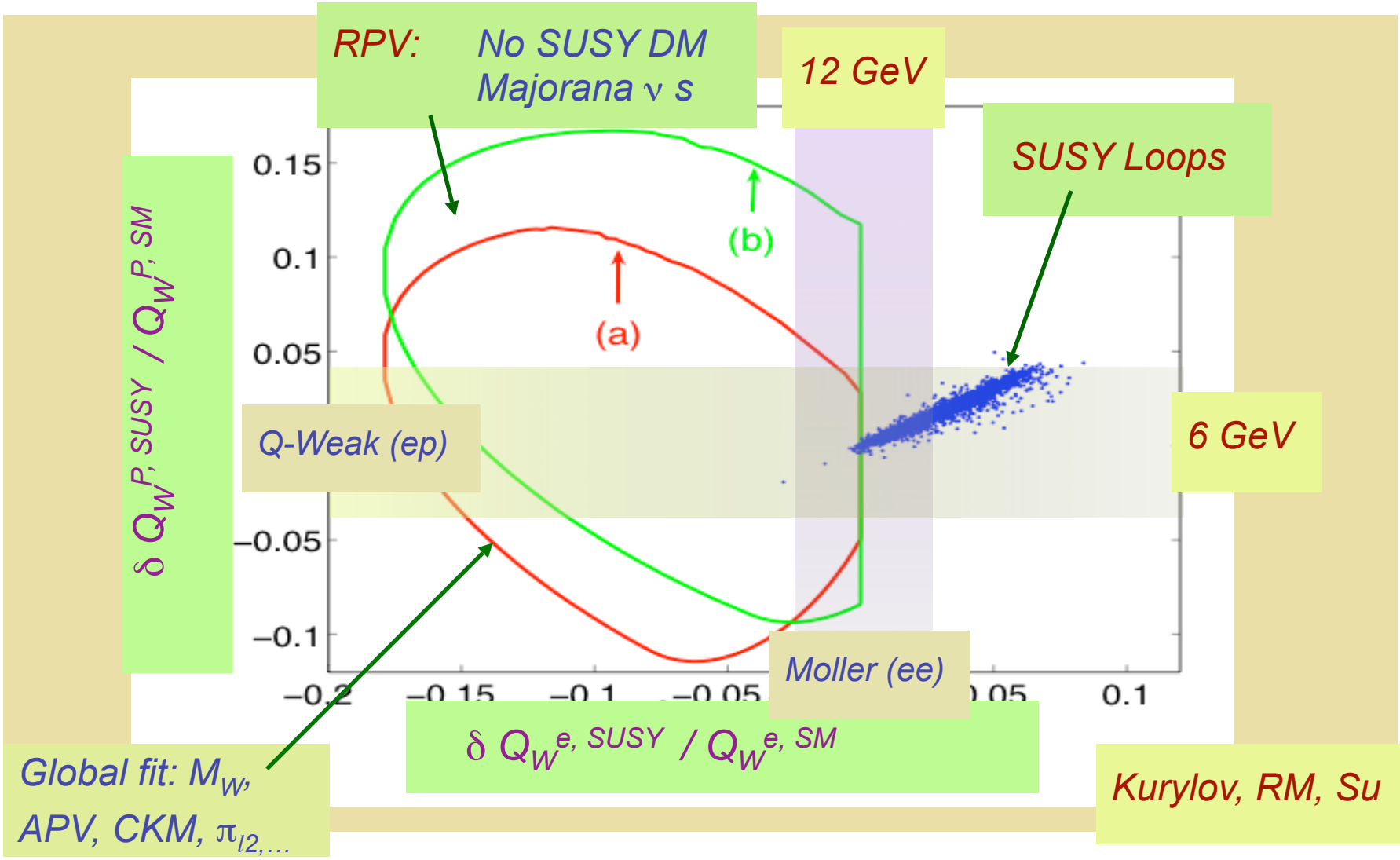

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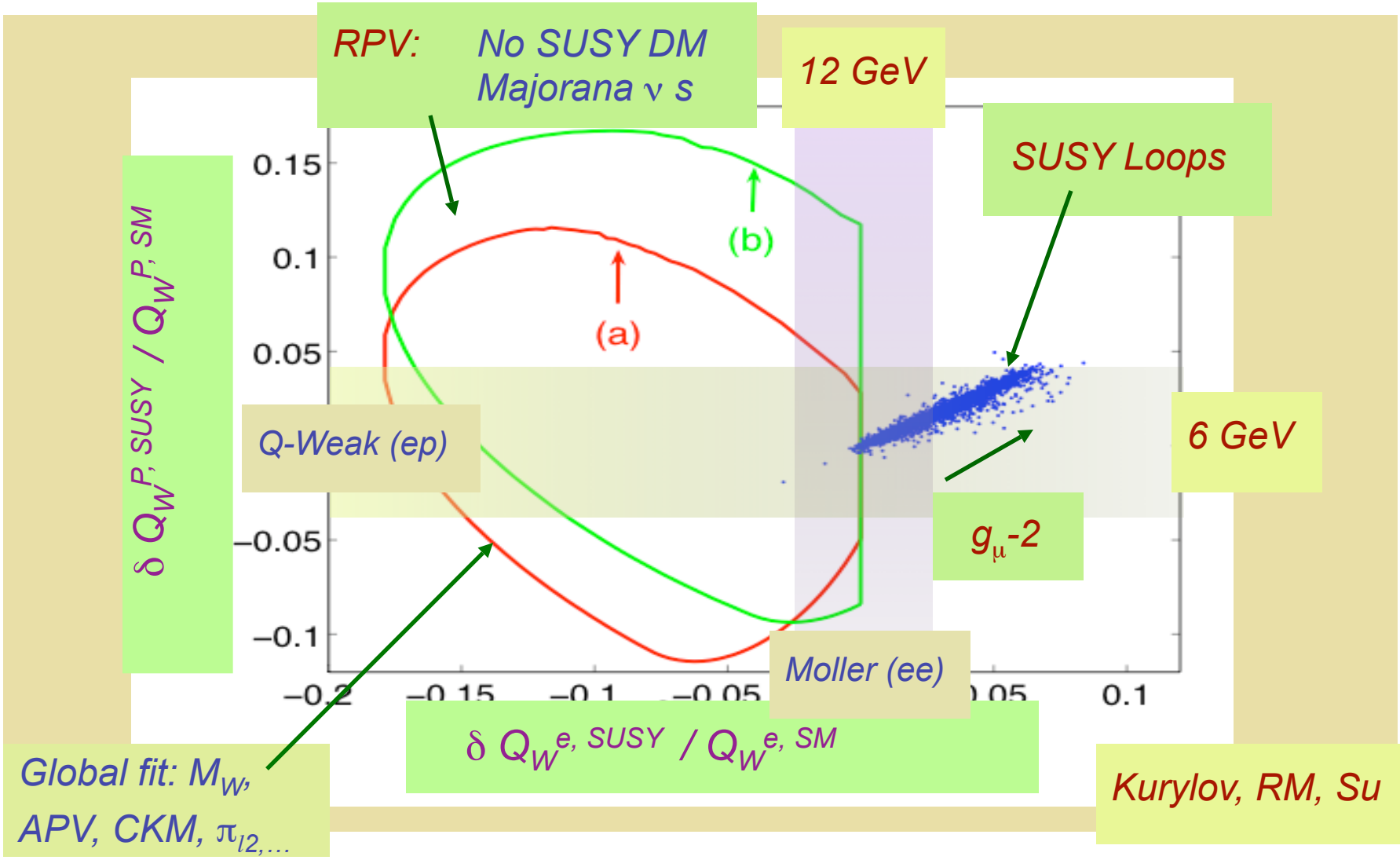

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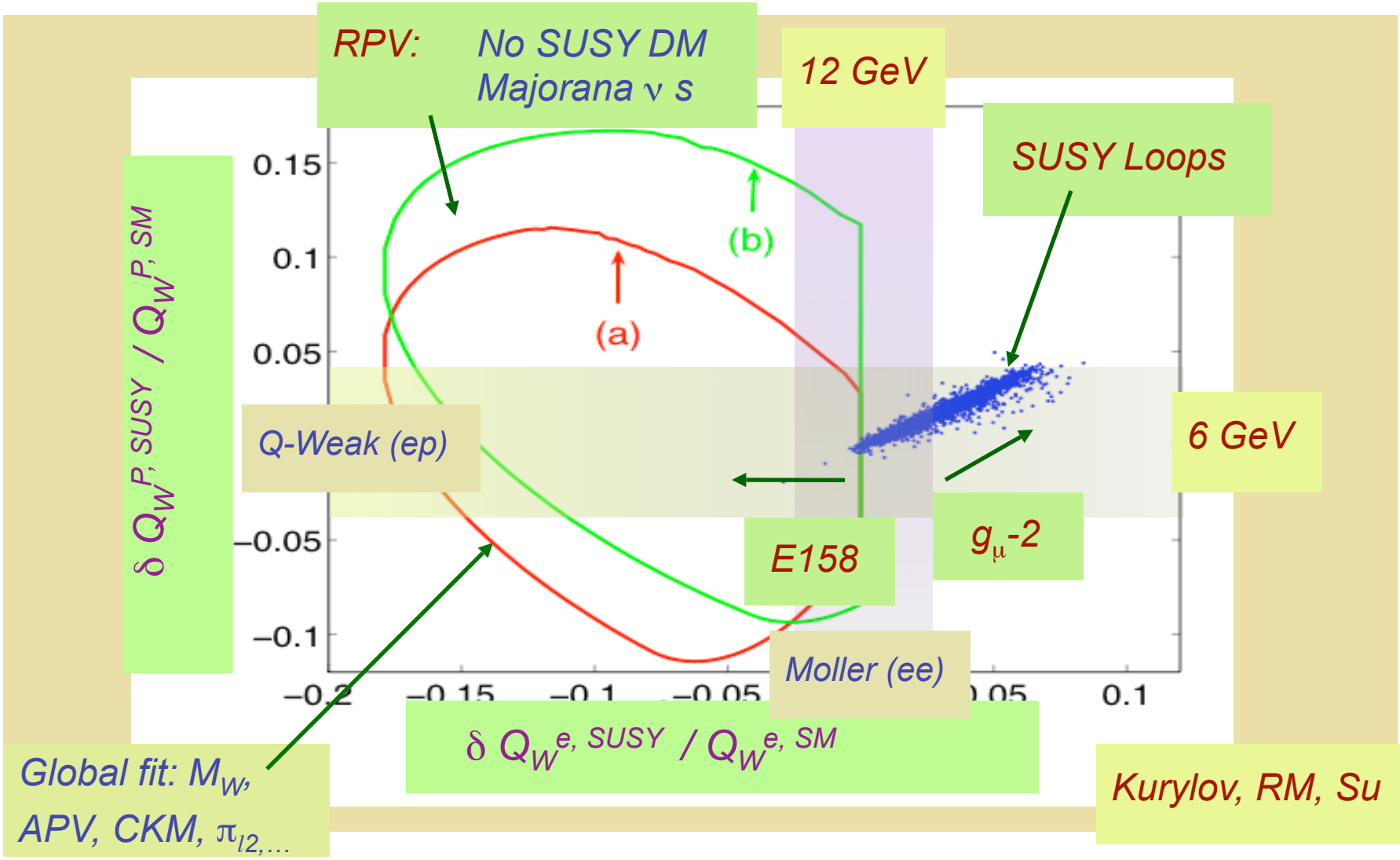

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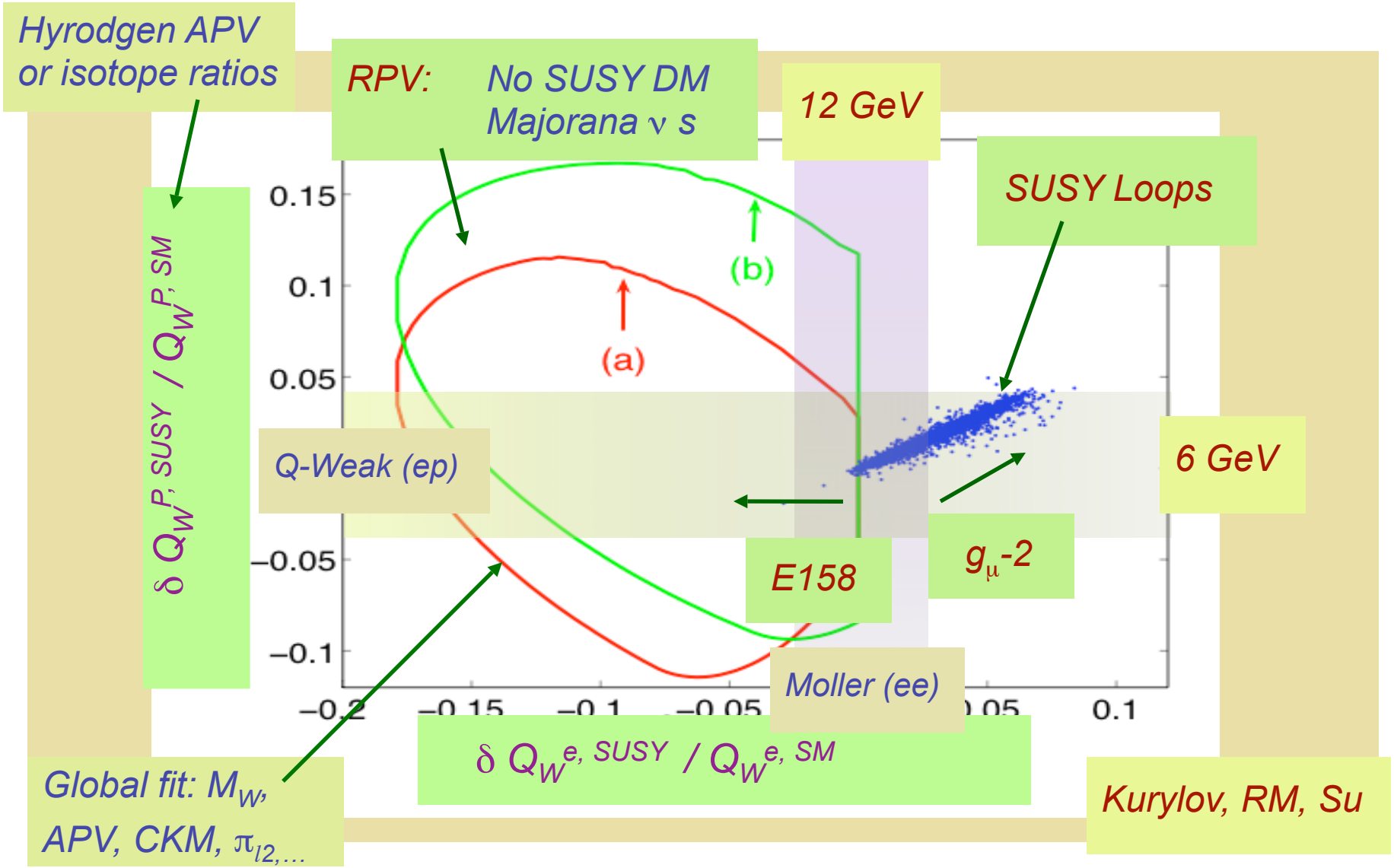

Effective PV e-q interaction & PVDIS

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:

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

Effective PV e-q interaction & PVDIS

Low energy effective PV eq interaction

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

PV DIS eD asymmetry: leading twist

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

$$Y = \frac{1-(1-y)^2}{1+(1-y)^2 - y^2 R/(1+R)} \qquad R(x,q^2) = \frac{\sigma_L}{\sigma_R} \approx 0.2$$

Effective PV e-q interaction & PVDIS

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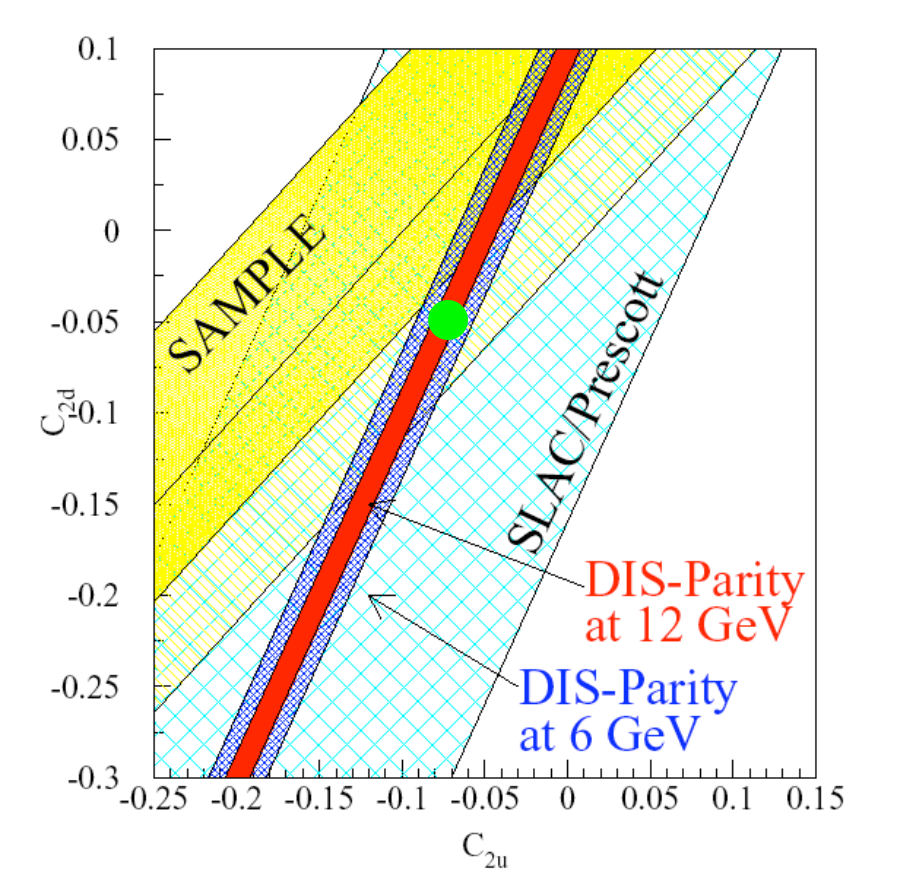
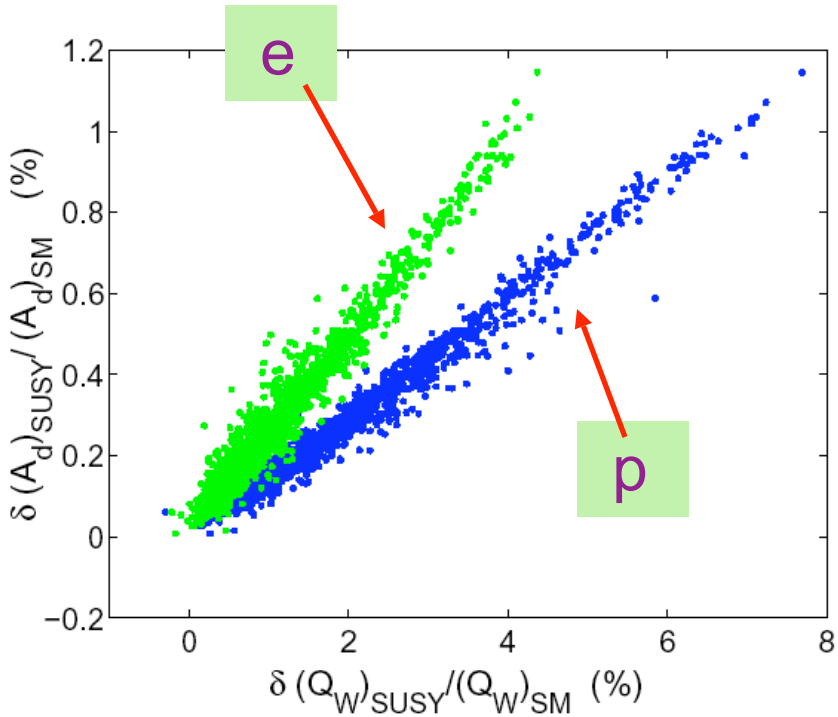
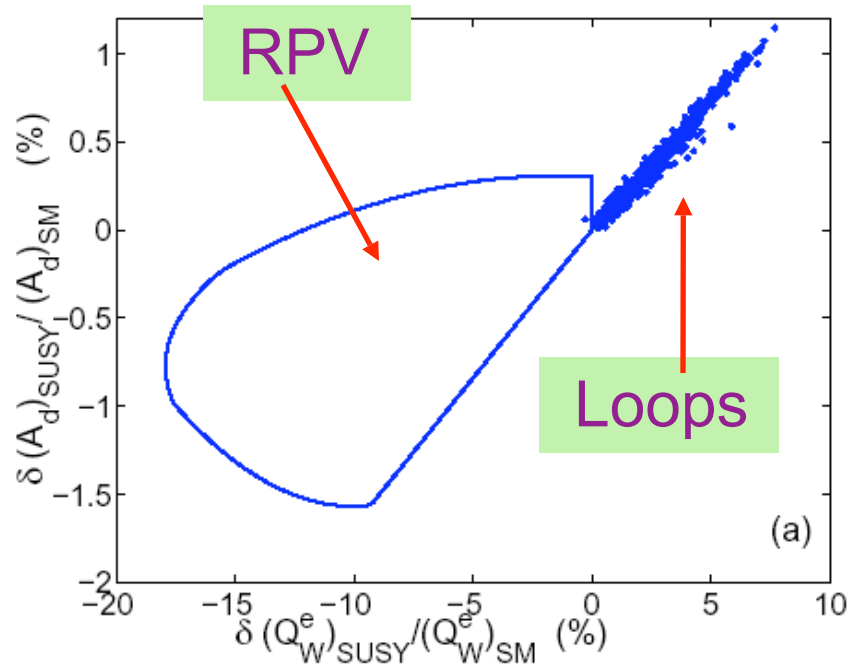
Model Independent Constraints



P. Reimer, X. Zheng

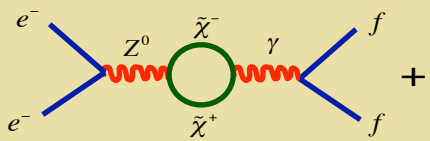
Comparing A_d^{DIS} and $Q_w^{p,e}$

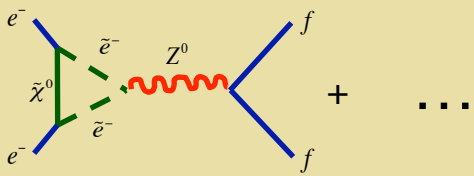




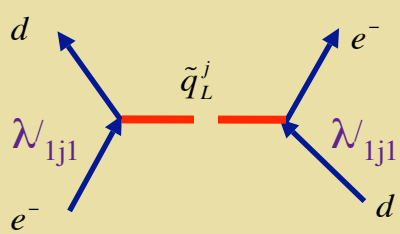
PVES, New Physics, & the LHC

SUSY



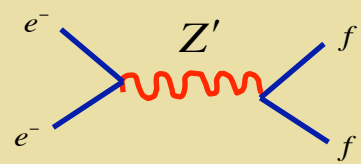


Radiative Corrections

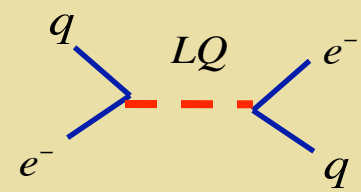


RPV

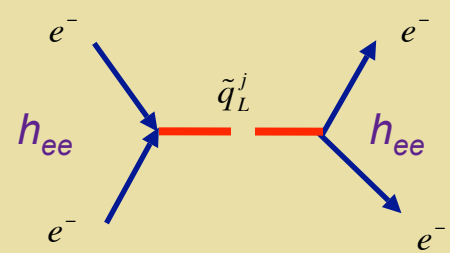
Z/ Bosons



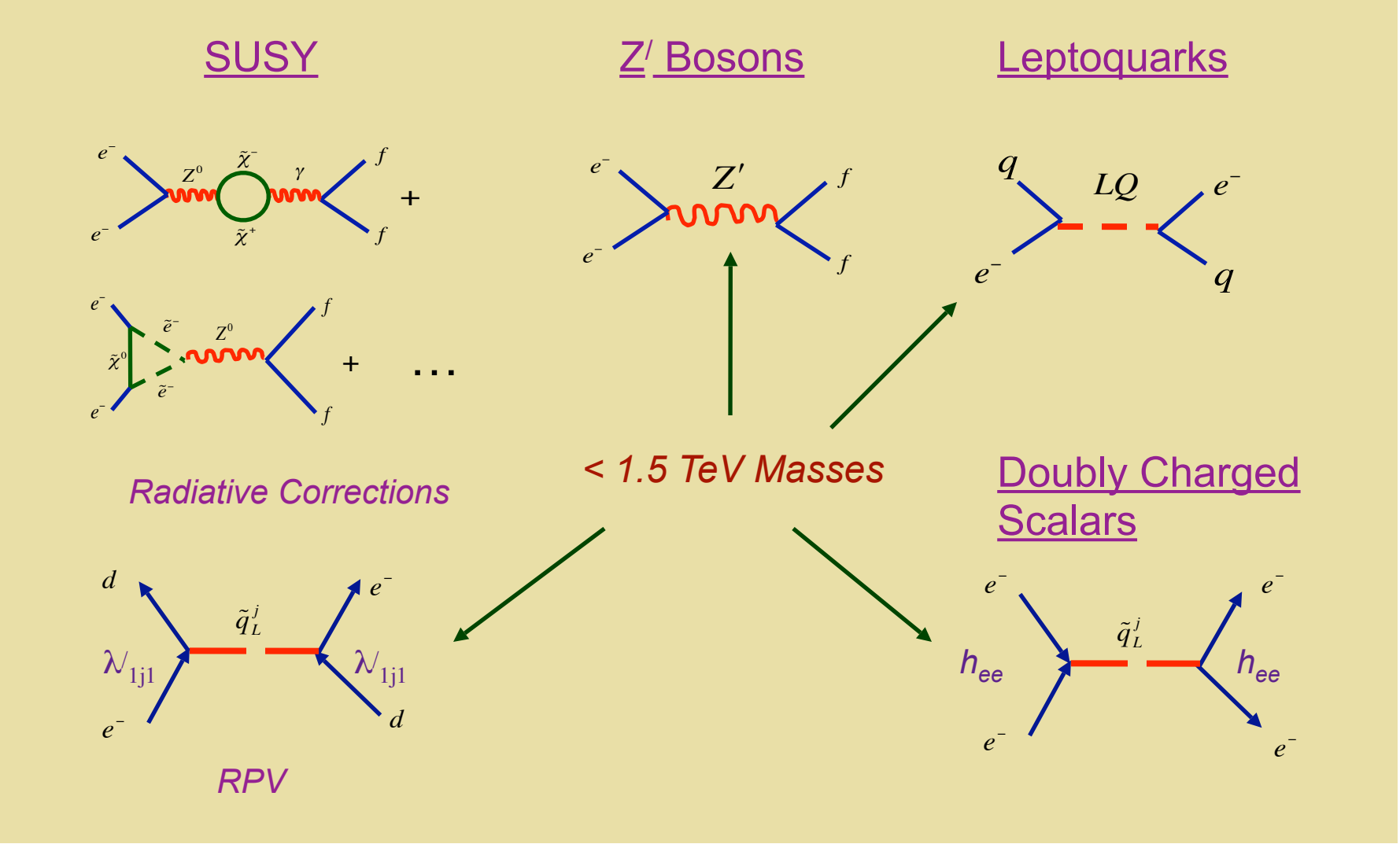
Leptoquarks



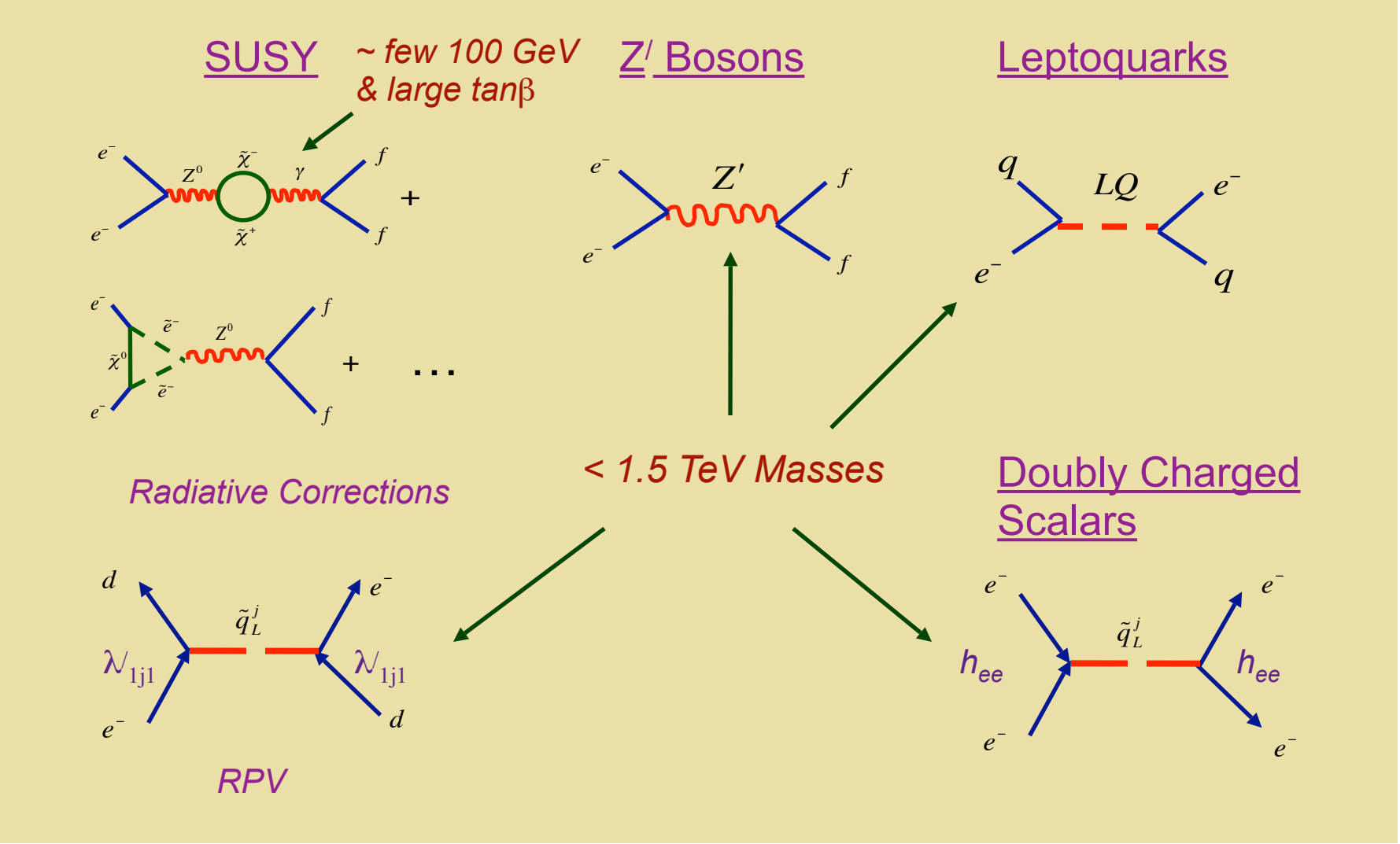
Doubly Charged Scalars



PVES, New Physics, & the LHC



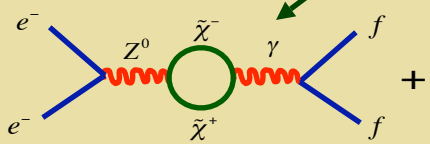
PVES, New Physics, & the LHC

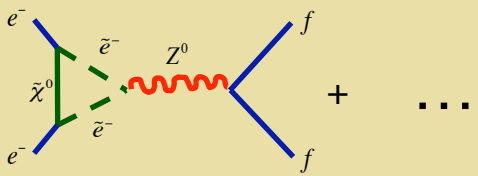


PVES, New Physics, & the LHC

SUSY

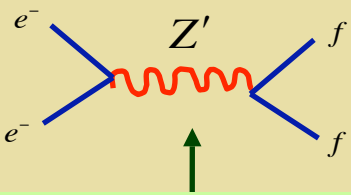
~ few 100 GeV & large tanβ



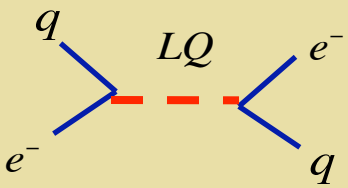


Radiative Corrections

Z′ Bosons



Leptoquarks

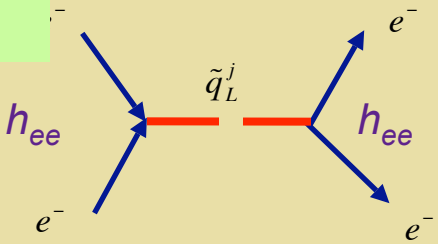


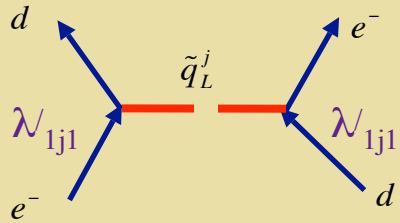
Moller: ~ 2.5% on A_{PV}

PVDIS: ~ 0.5% on A_{PV}

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

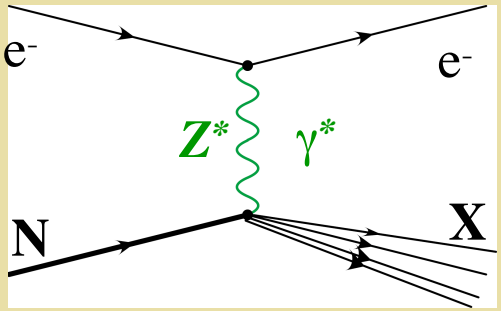
Doubly Charged Scalars





RPV

Deep Inelastic PV: Beyond the Parton Model & SM



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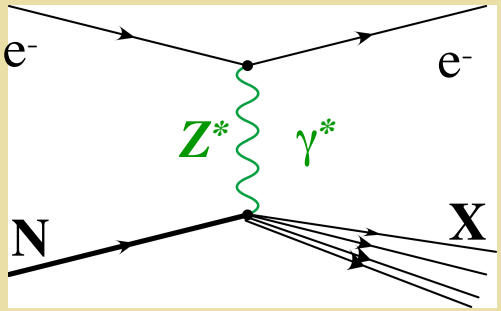
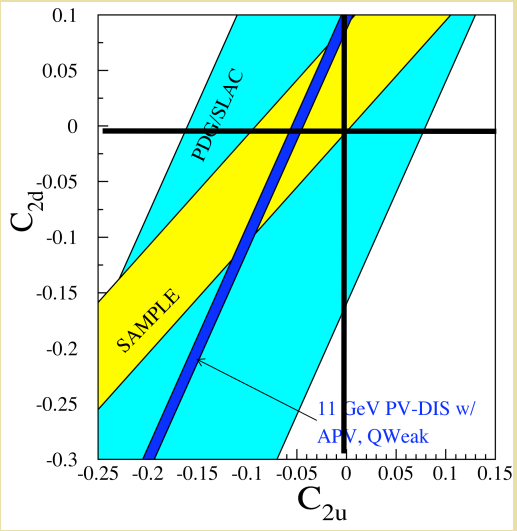
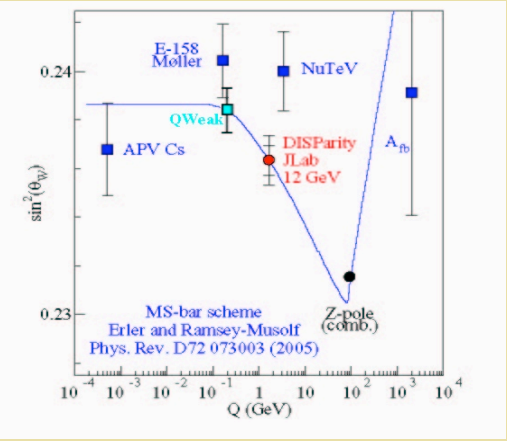
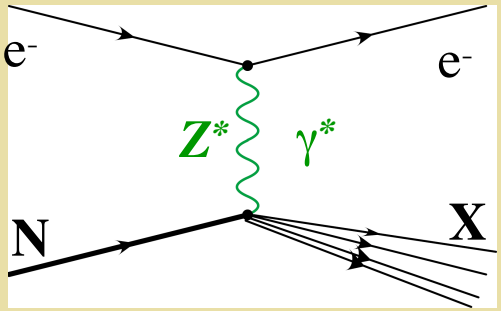




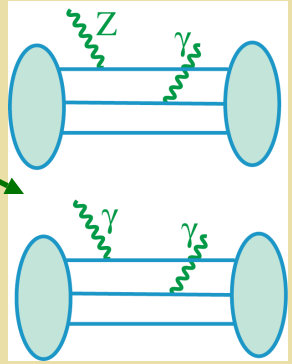


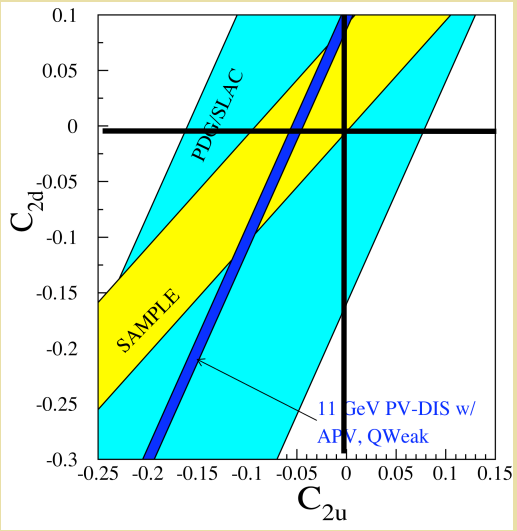
Electroweak test: e-q couplings & $\sin^2\theta_W$

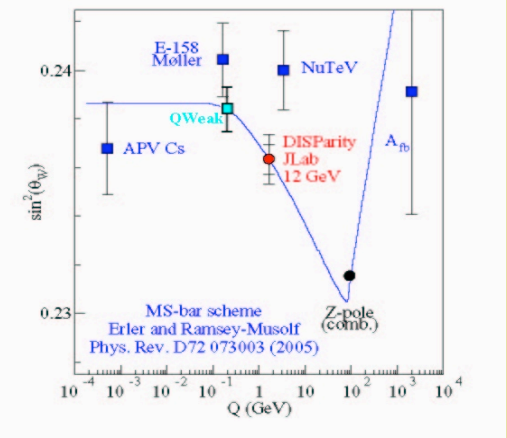
Deep Inelastic PV: Beyond the Parton Model & SM



Higher Twist: qq and qqg correlations







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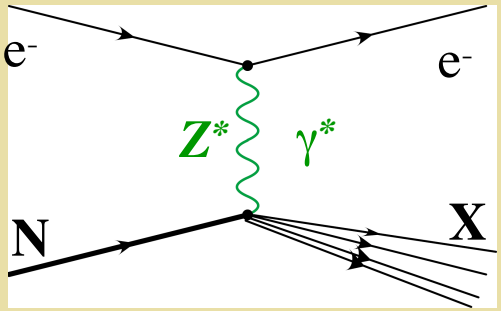

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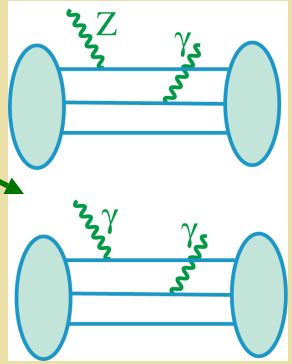
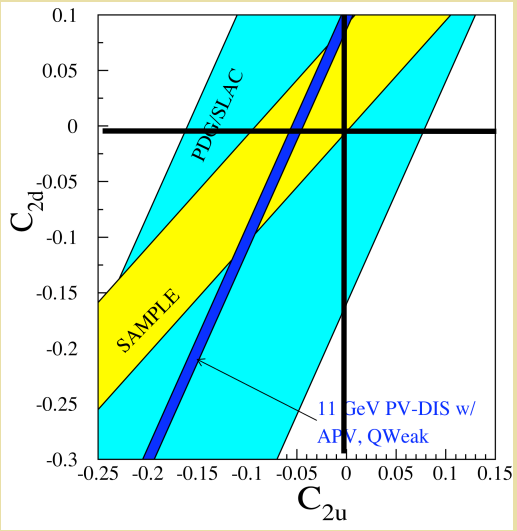
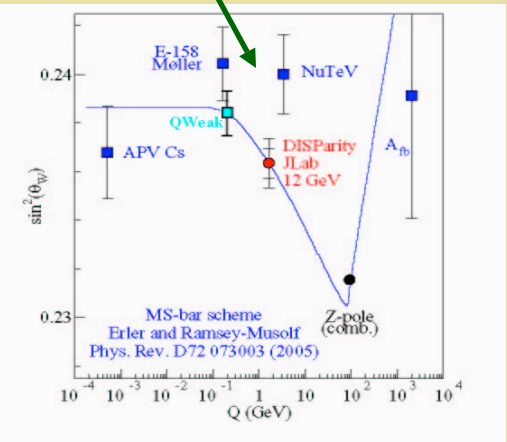


Charge sym in pdfs

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

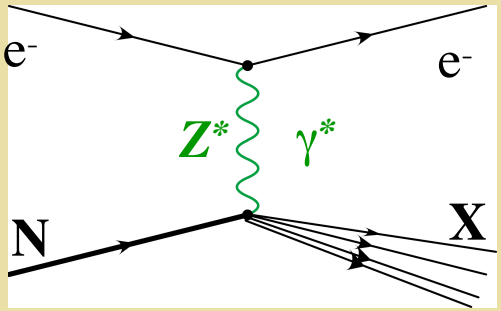
$$d^p(x) = u^n(x)?$$





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

Deep Inelastic PV: Beyond the Parton Model & SM



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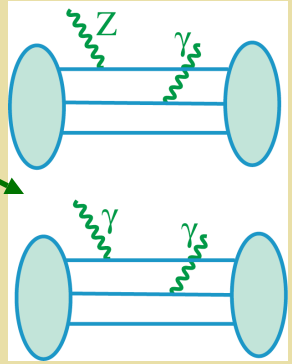

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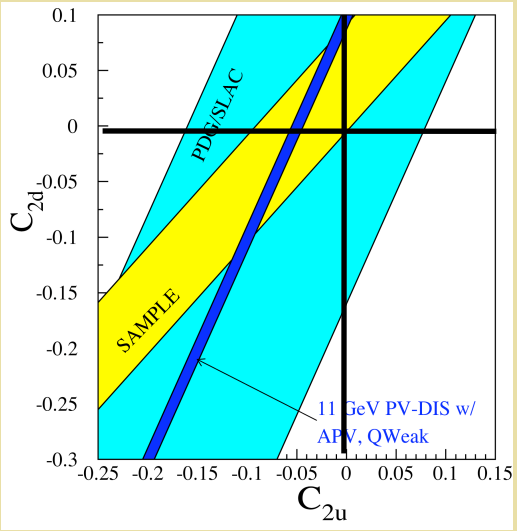

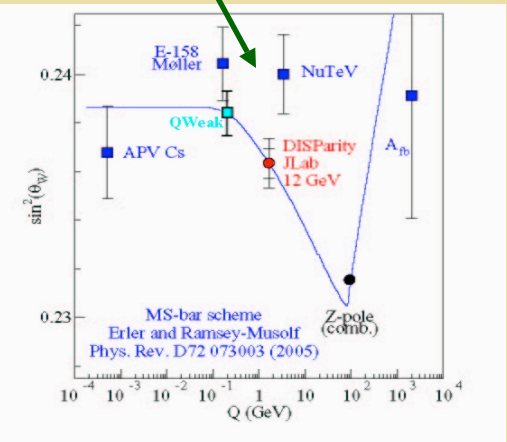

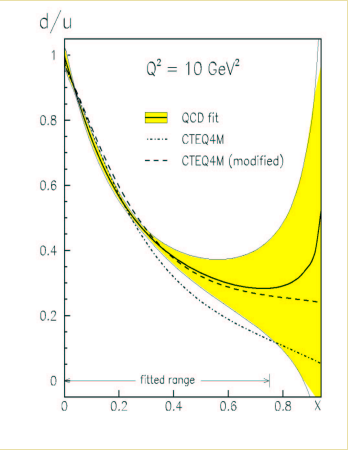

Electroweak test: e-q couplings & $\sin^2\theta_W$

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

PVDIS & QCD

Low energy effective PV eq interaction

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

PV DIS eD asymmetry: leading twist

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

$$Y = \frac{1-(1-y)^2}{1+(1-y)^2 - y^2 R/(1+R)} \qquad R(x,q^2) = \frac{\sigma_L}{\sigma_R} \approx 0.2$$

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Higher Twist (J Lab)

CSV (J Lab, EIC)

d/u (J Lab, EIC)

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Adapted from K. Kumar

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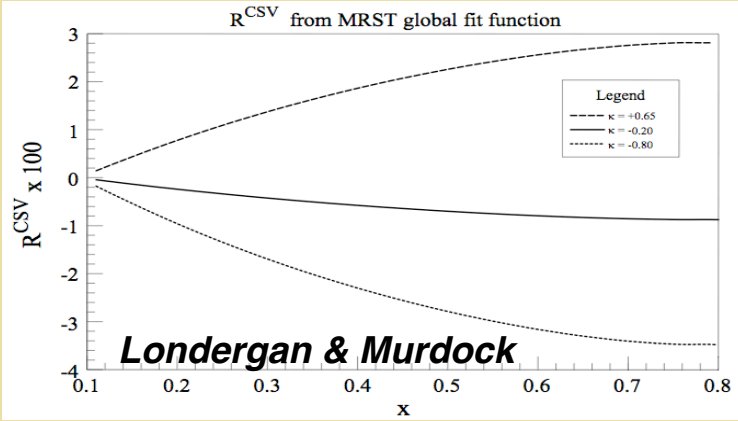

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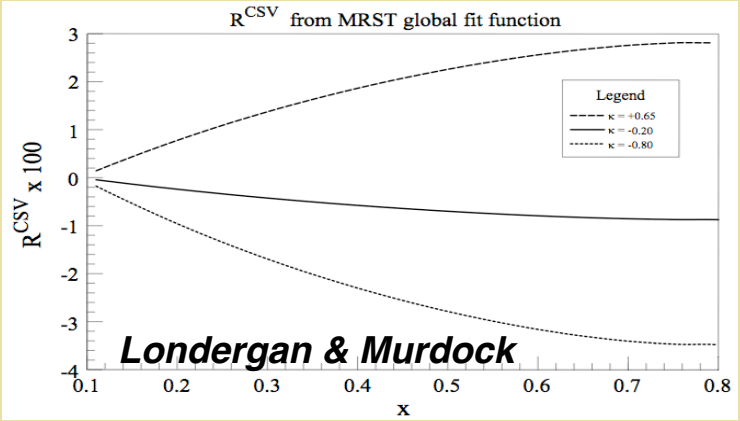
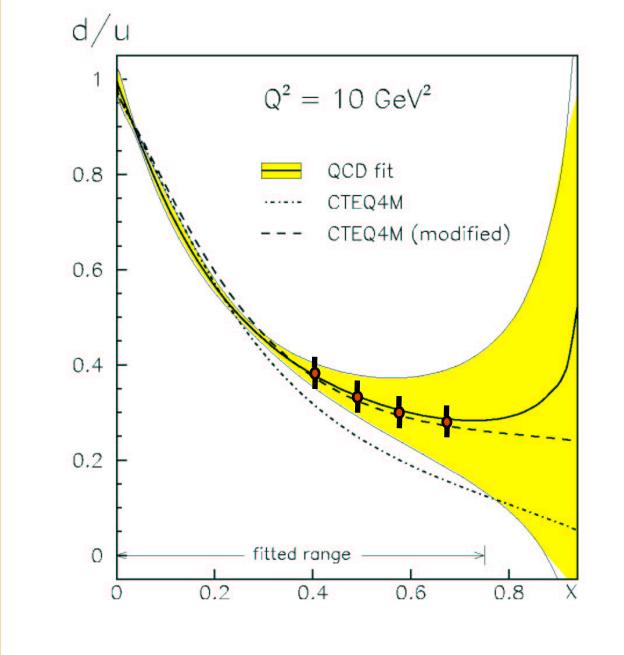


Few percent δA/A

Adapted from K. Kumar

*PVDIS & d(x)/u(x): x*K*1*

Adapted from K. Kumar



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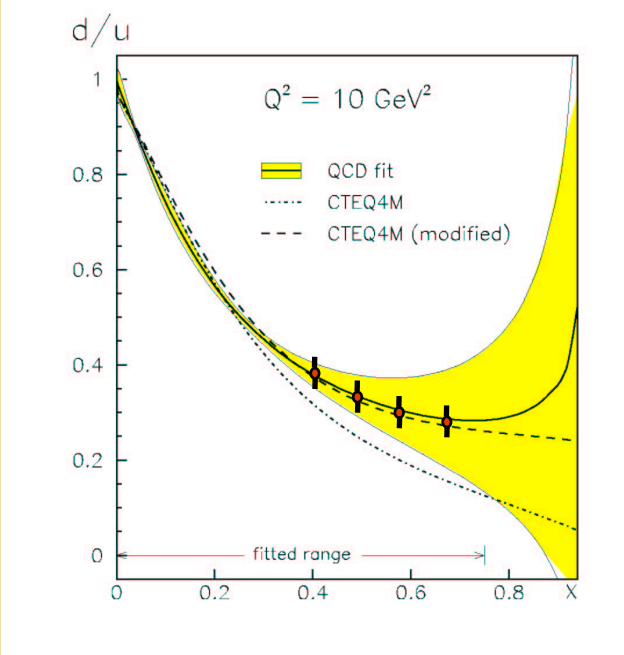

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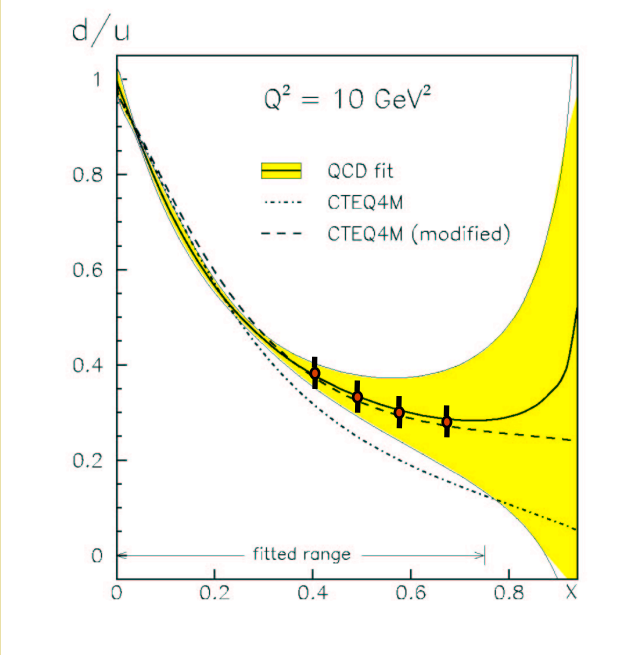

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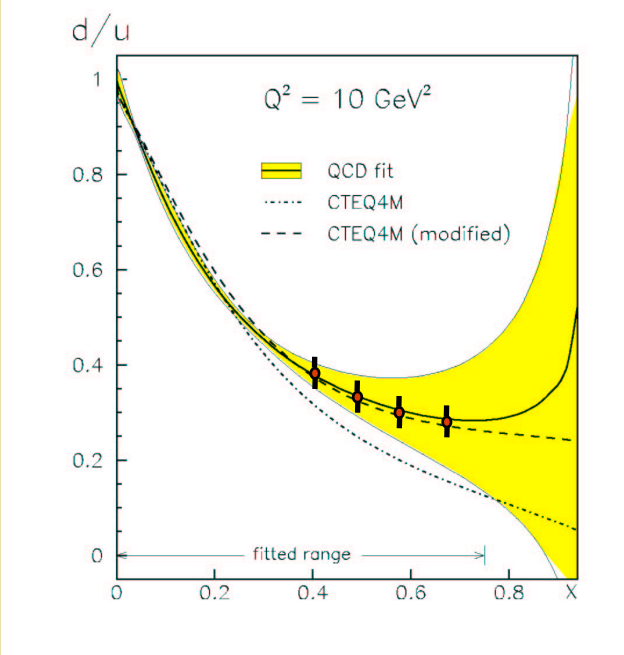

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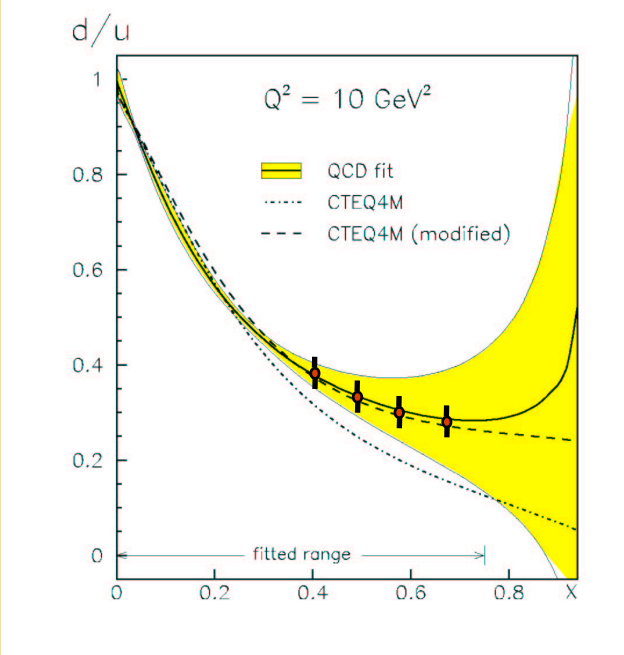

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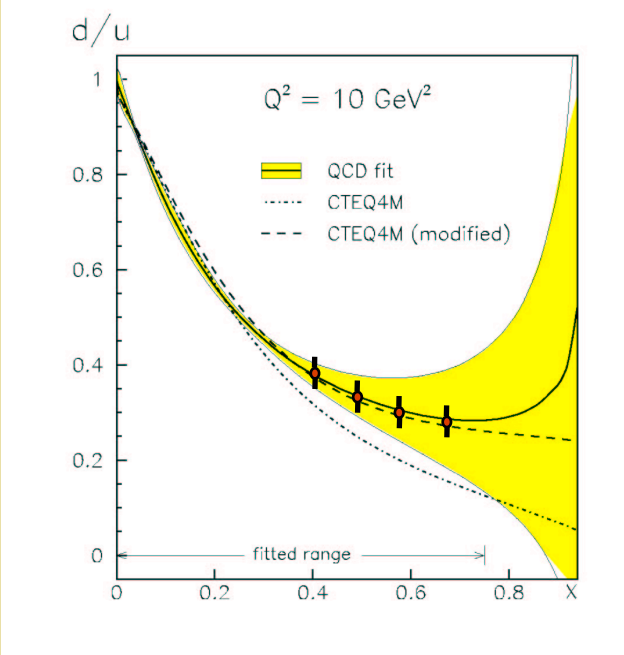

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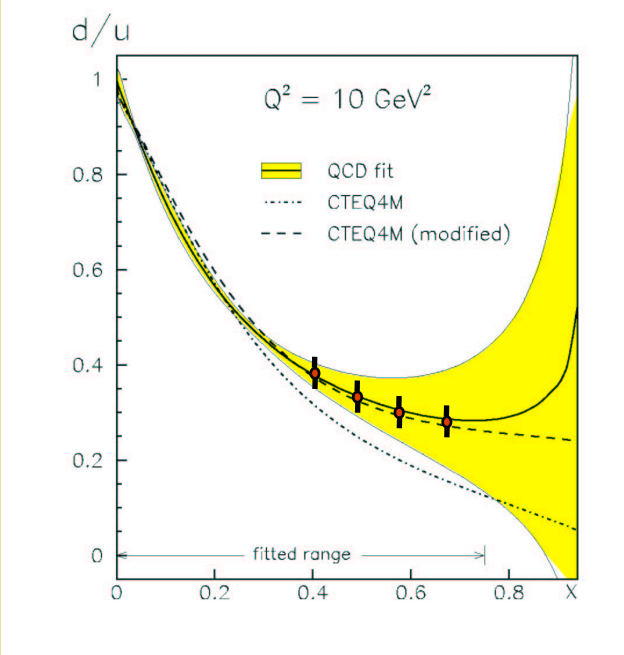

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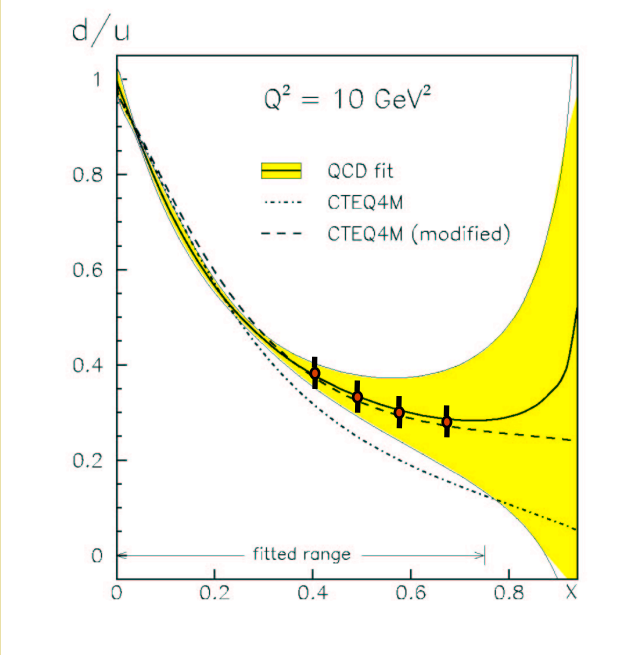

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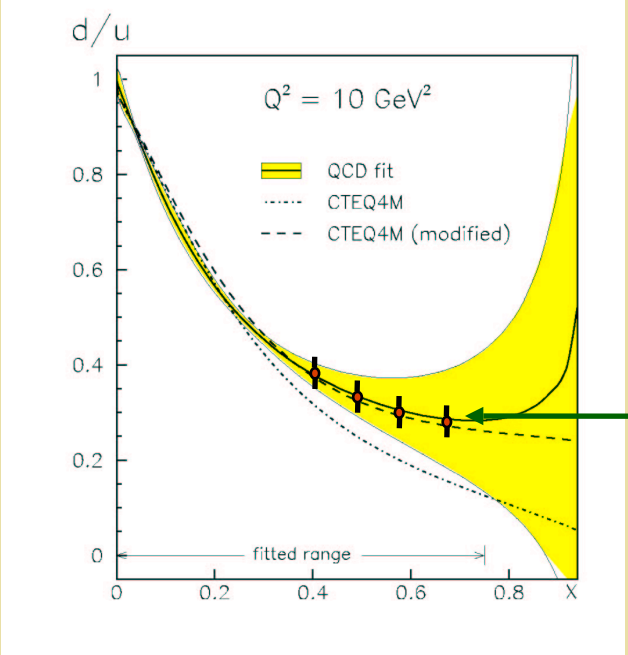

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C-Odd SD Structure Functions

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

$$g_1^{\gamma z} = \left(\frac{1}{3} - \frac{8}{9}\sin^2\theta_w\right)(\Delta u + \Delta c + \Delta\bar{u} + \Delta\bar{c})$$

$$+ \left(\frac{1}{6} - \frac{2}{9}\sin^2\theta_w\right)(\Delta d + \Delta s + \Delta\bar{d} + \Delta\bar{s}) \simeq \frac{1}{9}\sum_q(\Delta_q + \Delta_{\bar{q}})$$

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

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Anselmino, Gambino, Kalinowski '94

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C-odd

Anselmino, Gambino, Kalinowski '94

Target Spin Asymmetries

Polarized Long & trans target spin asymmetries (parity even)

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

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

Unpolarized Long & trans target spin asymmetry (parity odd)

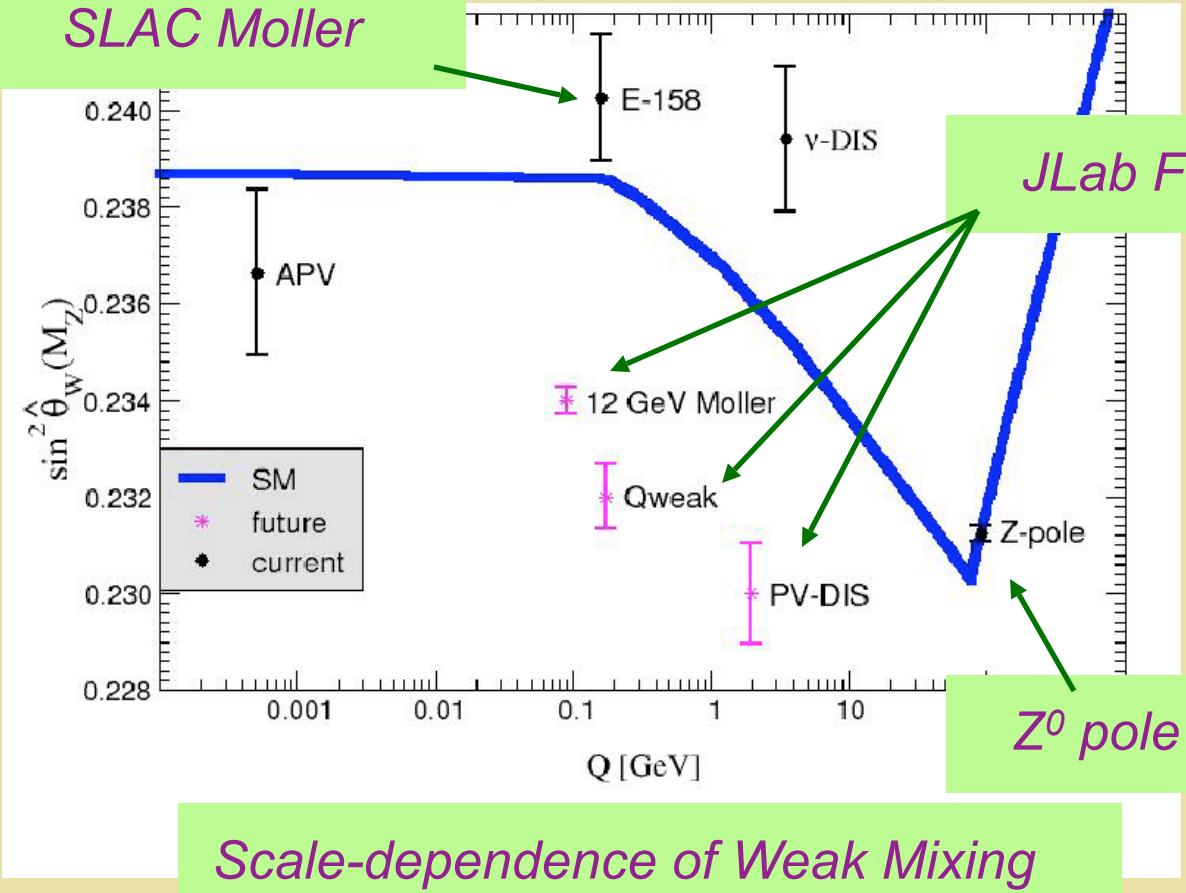
$$\Delta^L \sigma_{nc}^{\ell^- N}(\langle\lambda\rangle = 0) = 16\pi m_N E \frac{\alpha^2}{Q^4} \eta^{\gamma Z}\; x \left\{ y(2-y) g_A\; g_1^{\gamma Z} + (2 - 2y + y^2) g_V\; g_5^{\gamma Z} \right\}.$$

Bilenky et al '75; Anselmino et al '94

PVES at an EIC

Parity-violating electron scattering

SLAC Moller



JLab Future

Z^0 pole tension

Scale-dependence of Weak Mixing

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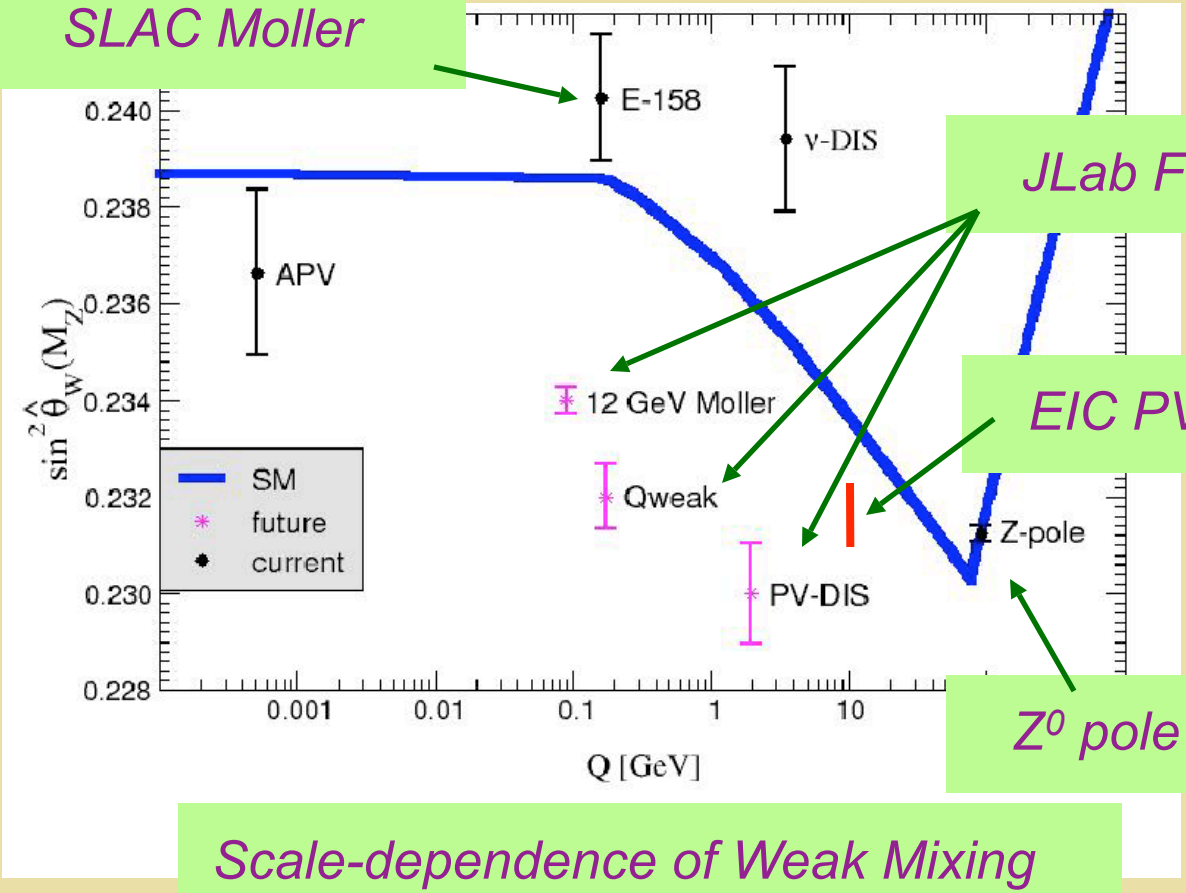

JLab Future

EIC PVDIS ?

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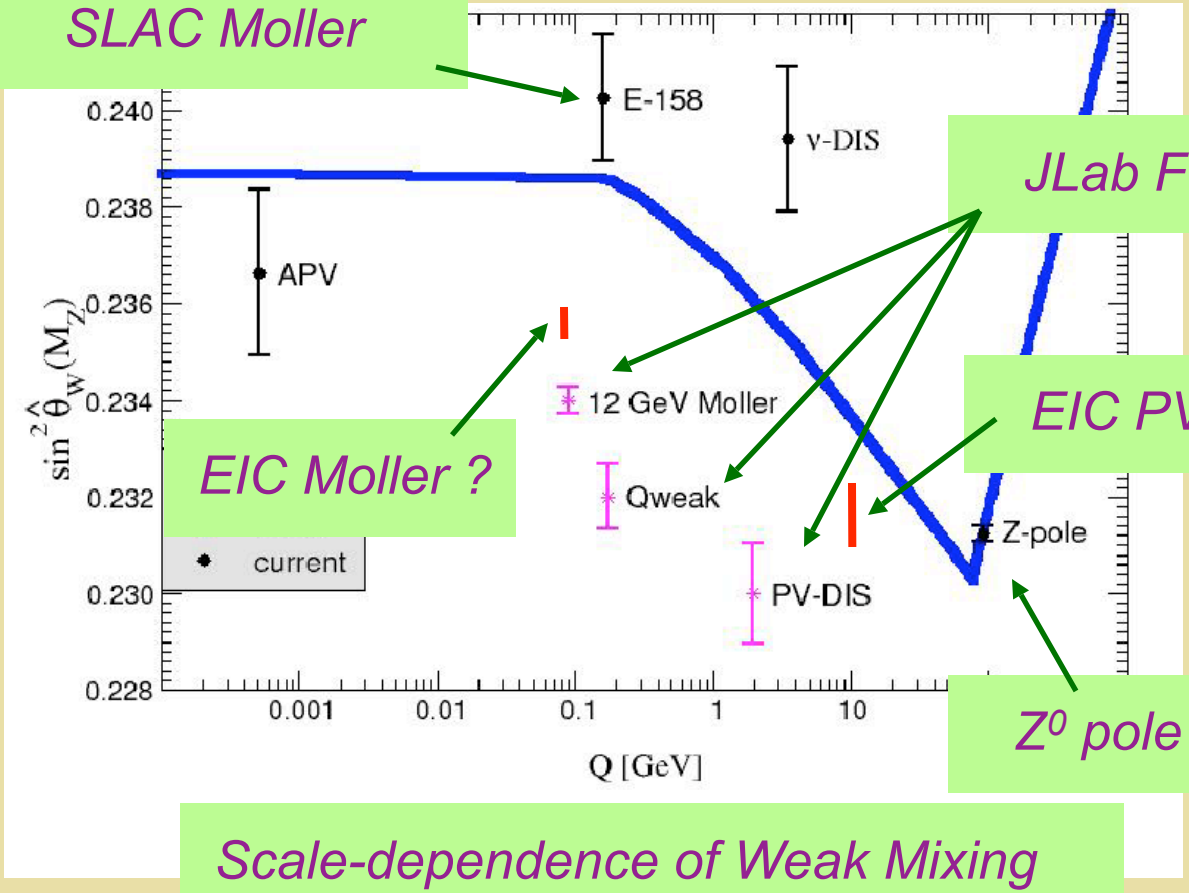


Scale-dependence of Weak Mixing

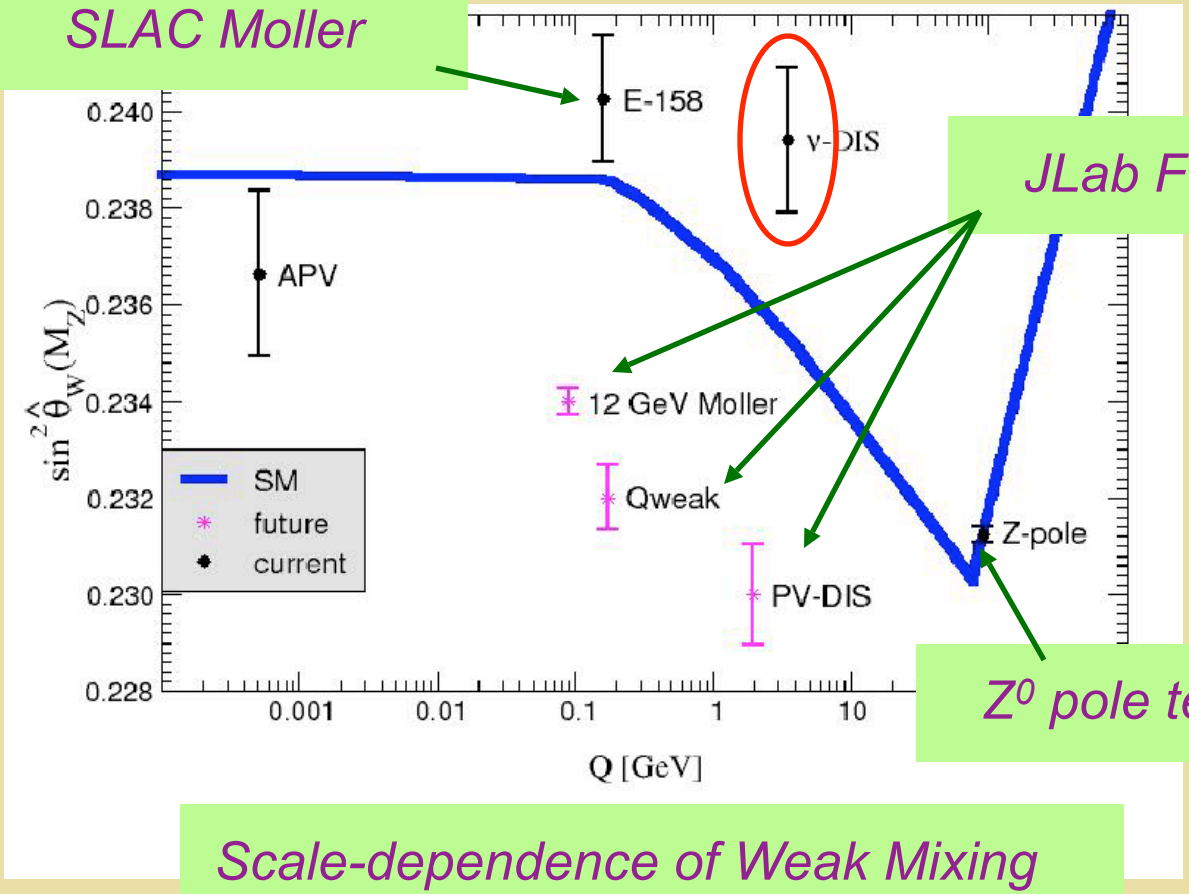
Charged Current Processes

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

Weak Mixing in the Standard Model

ν–nucleus deep inelastic scattering

SLAC Moller



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The NuTeV Puzzle

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

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

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

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

Paschos-Wolfenstein

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

The NuTeV Puzzle

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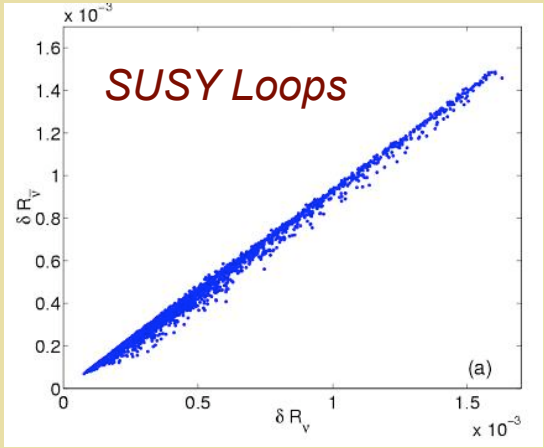

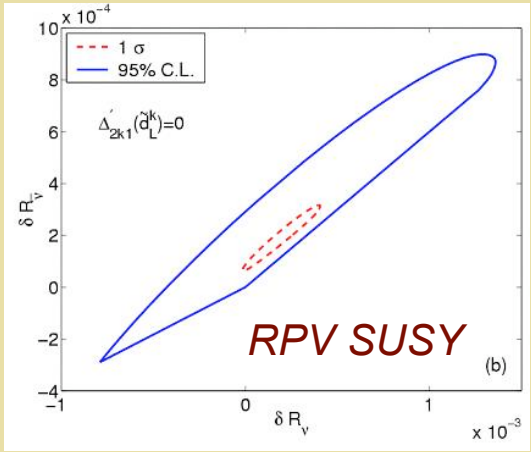

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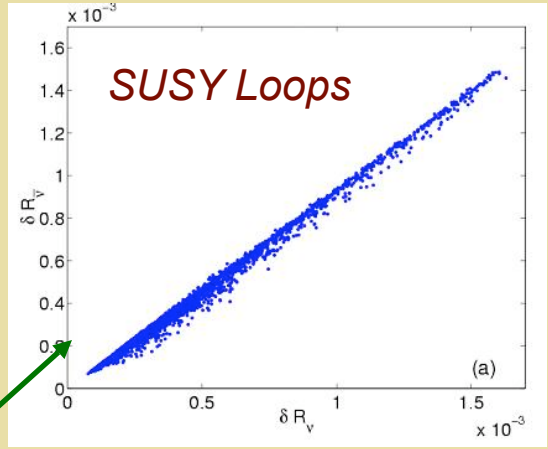
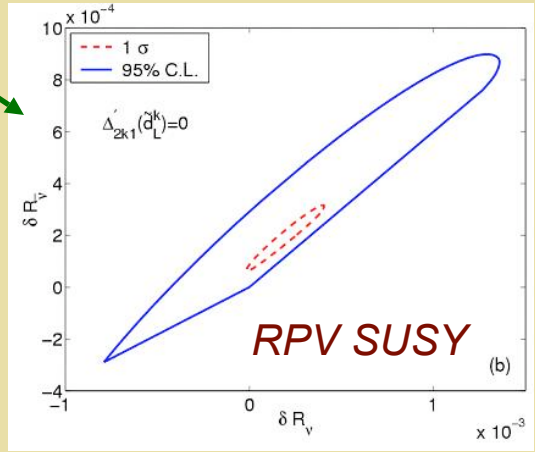
Wrong sign





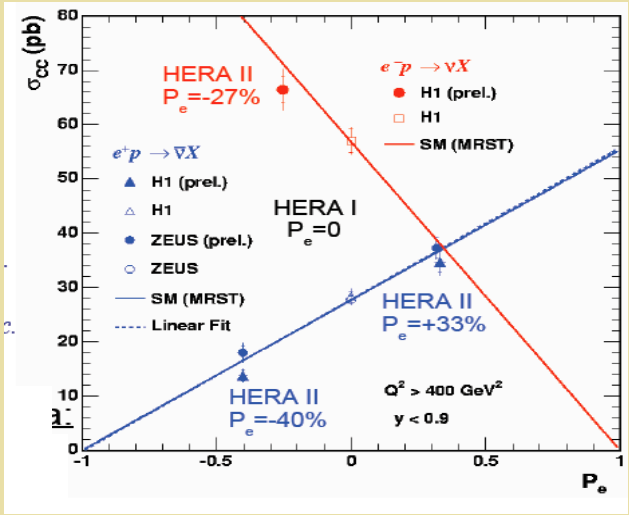
Other New CC Physics?

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

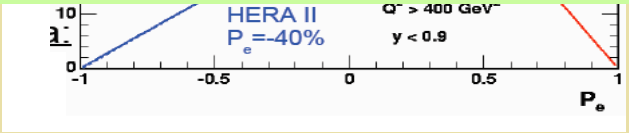
CC Structure Functions: more promising?

$$g_1^{W^-} = (\Delta u + \Delta c + \Delta \bar{d} + \Delta \bar{s})$$
$$g_3^{W^-} = 2x(\Delta\ u + \Delta c - \Delta \bar{d} - \Delta \bar{s})$$

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

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

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



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- *Intriguing: LFV with eKτ conversion:* $\int L\,dt \sim 10^3 \quad fb$

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$0\nu\beta\beta$ *sensitivity*

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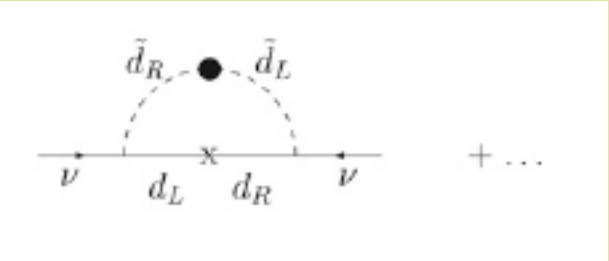

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LNV Probes of RPV: m_ν

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λ_{k31} ~ 0.02 for m_{SUSY} ~ 1 TeV

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Probing Leptoquarks with PVES

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

$$\mathcal{L} = h_2^L \bar{u} \ell R_2^L + h_2^R \bar{q} i \tau_2 e R_2^R + \tilde{h}_2 \bar{d} \ell \tilde{R}_2^L + g_1^L \bar{q}^c i \tau_2 \ell S_1^L$$
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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%
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$\tilde{S}_1^R$	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%
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m_ν , τ_{prot}

LQ 2 15_H

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

Fileviez Perez, Han, Li, R-M 0810.4238

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

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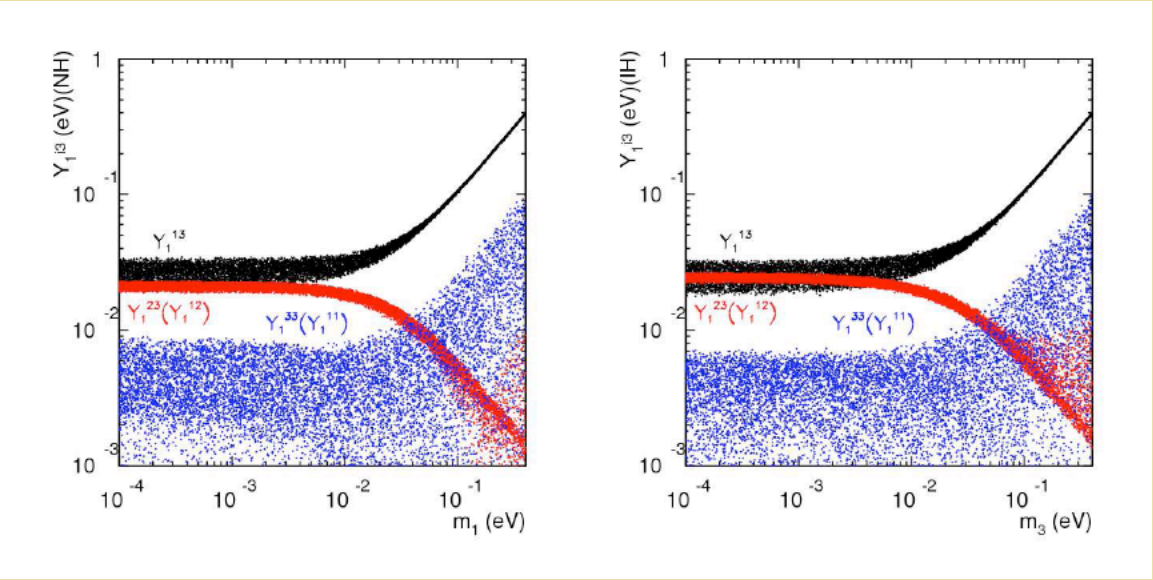

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$\mathcal{R}_1$	0.3%	0.04	0.028
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$Q_W(^1\mathrm{H})/Q_{\mathrm{EM}}(^1\mathrm{H})$	10%	0.05	0.036
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$Q_W(e)/Q_{\mathrm{EM}}(e)$	7%		
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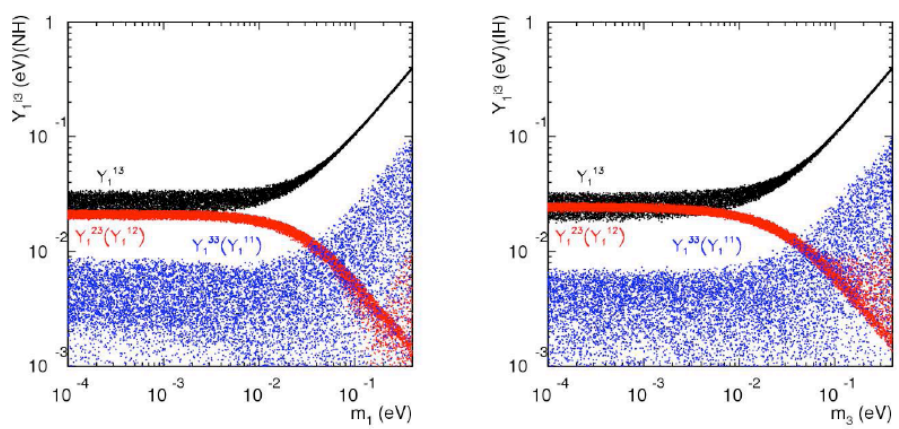

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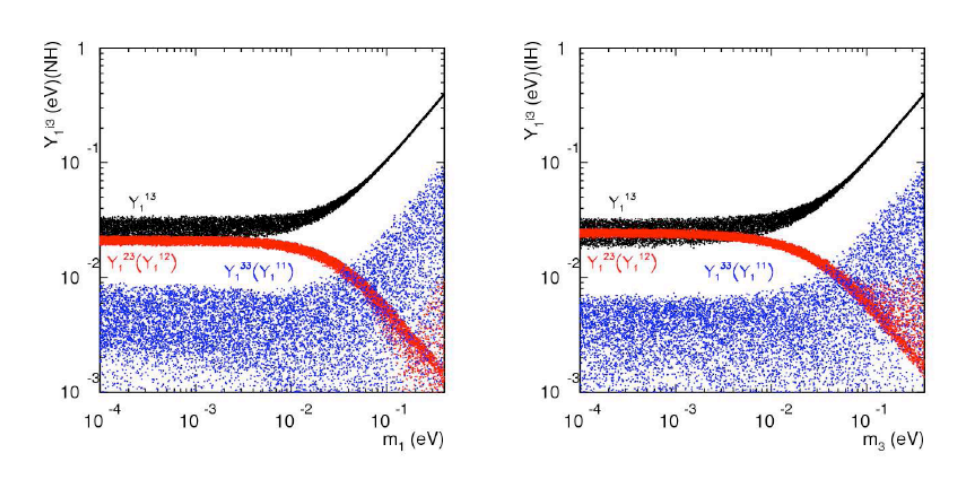

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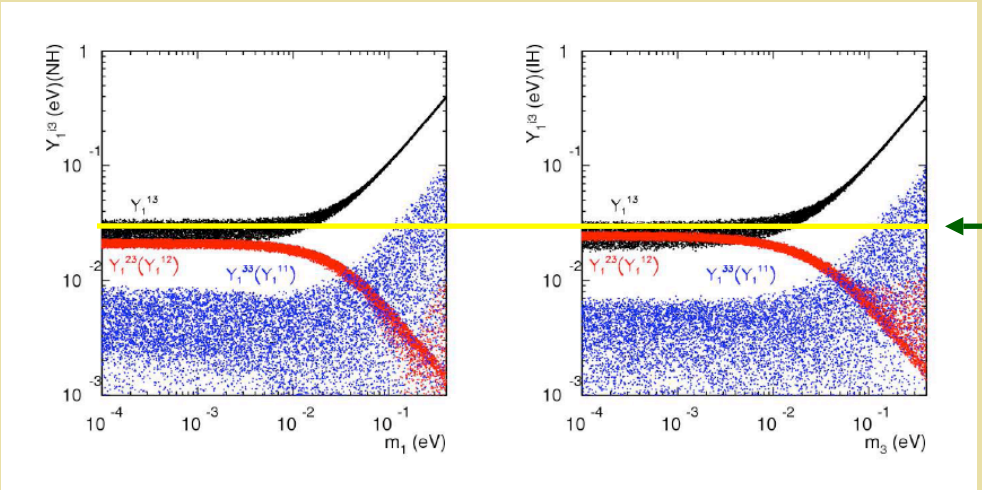

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4% Q_W^p
(M_{LQ}=100 GeV)

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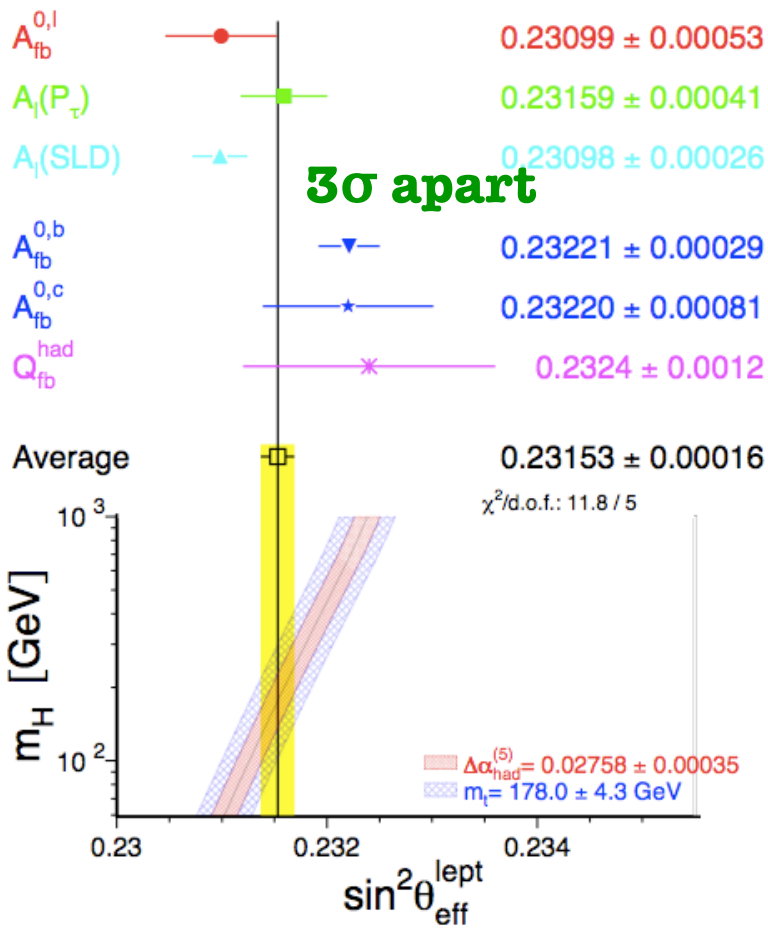
Z Pole Tension



W. Marciano

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

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

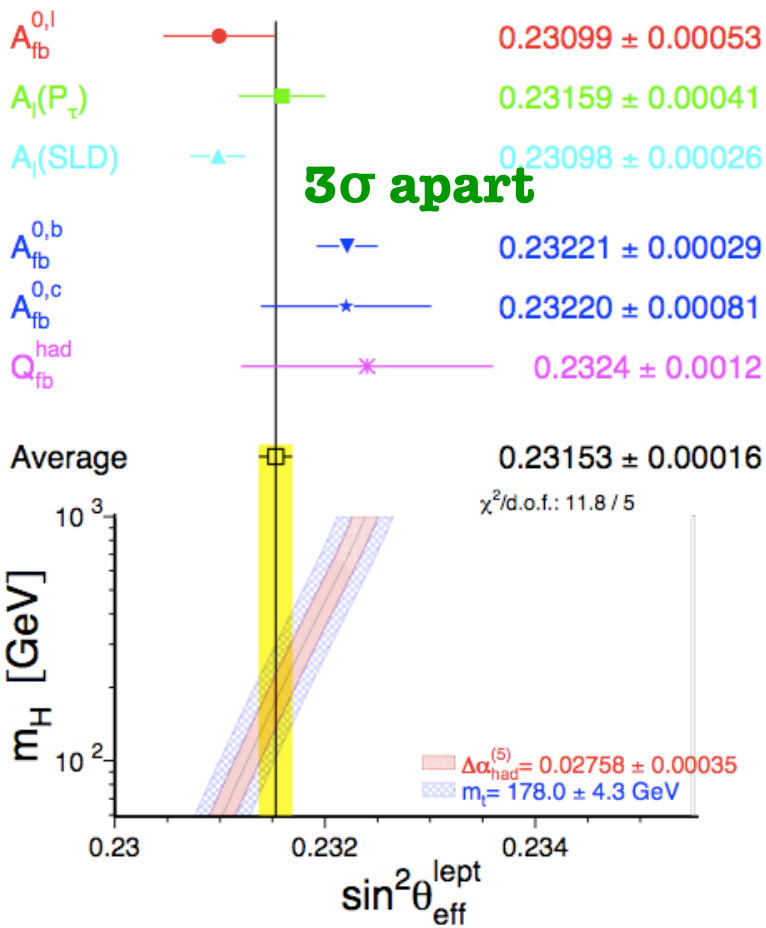
$\Rightarrow S = -0.13 \pm 0.10$

Rules out Technicolor!

Favors SUSY!

K. Kumar

Z Pole Tension



W. Marciano

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

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

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A_{LR}

(also APV in Cs)

A_{FB} ($Z \to bb$)

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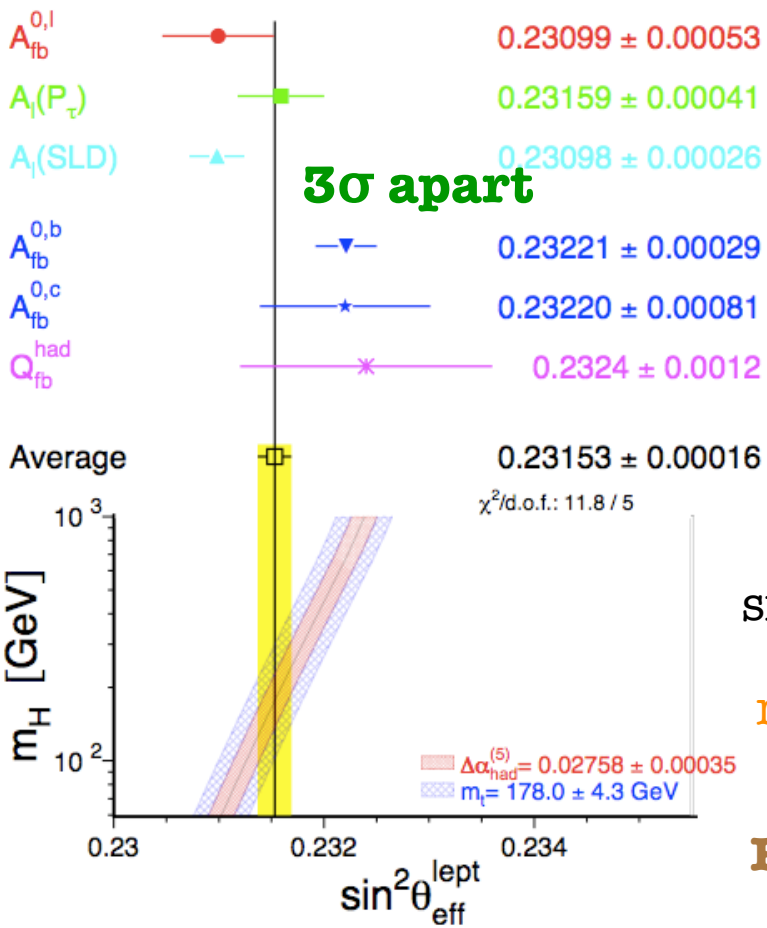

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$\sin^2\theta_W = 0.2310(3)$

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$m_H = 35\ ^{+26}_{-17}$ GeV

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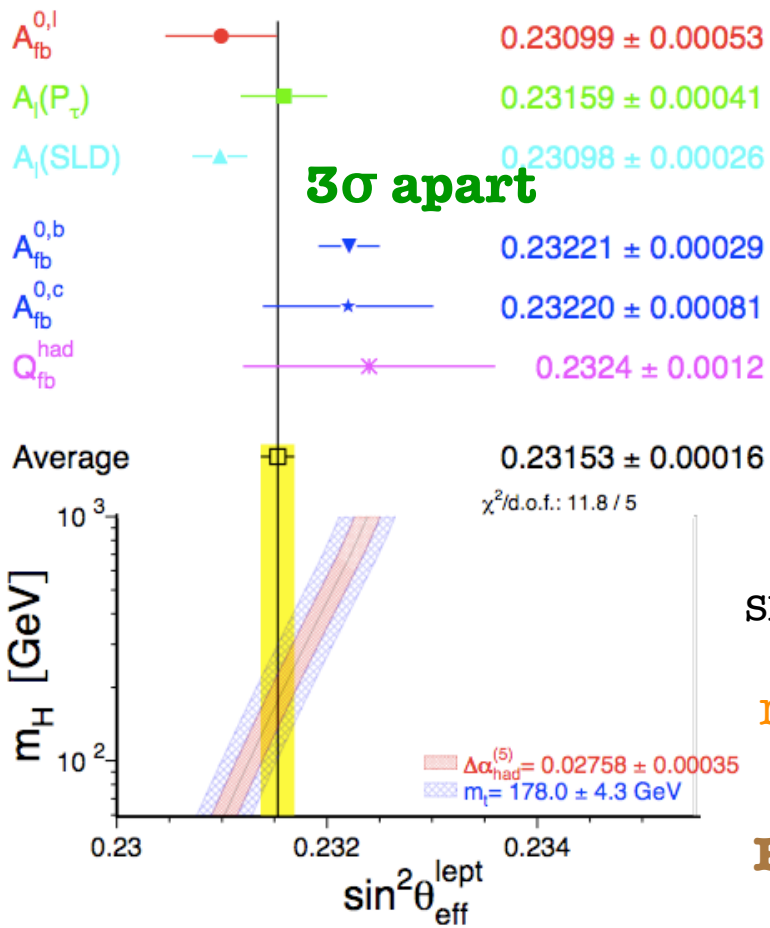

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K. Kumar

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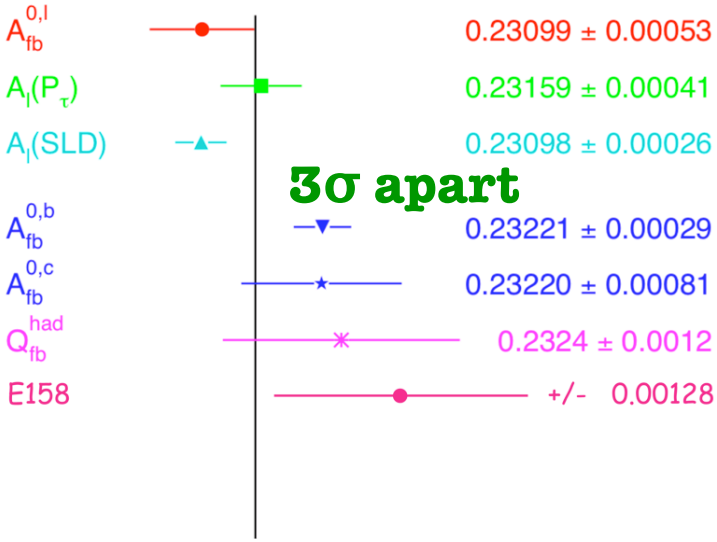

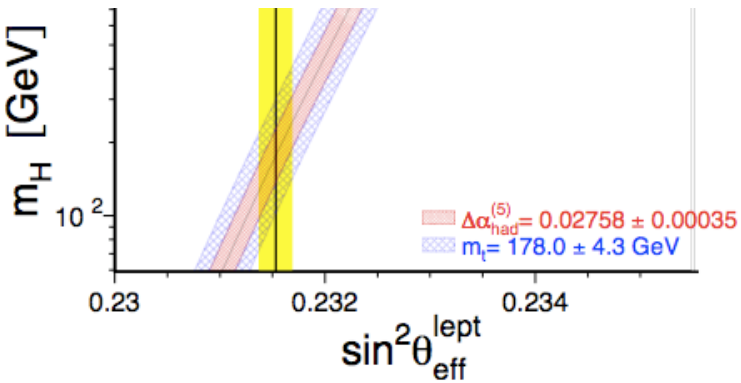

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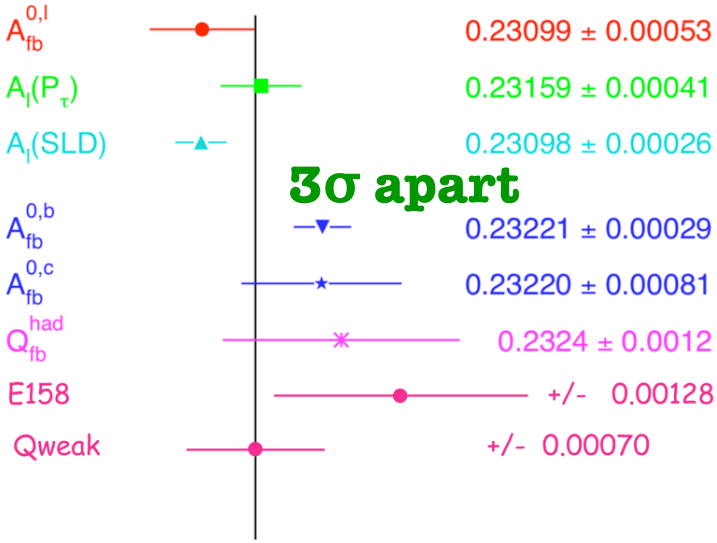

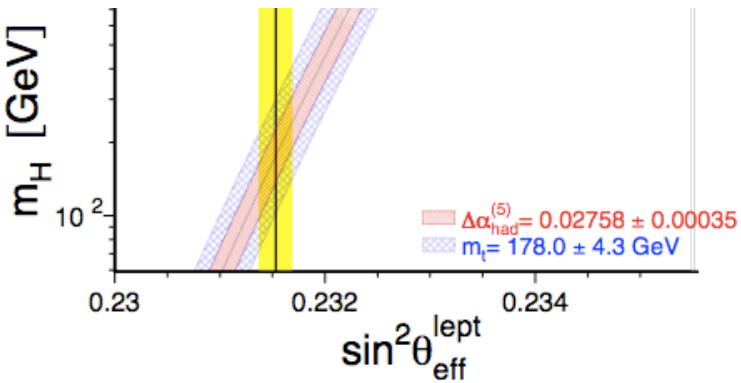

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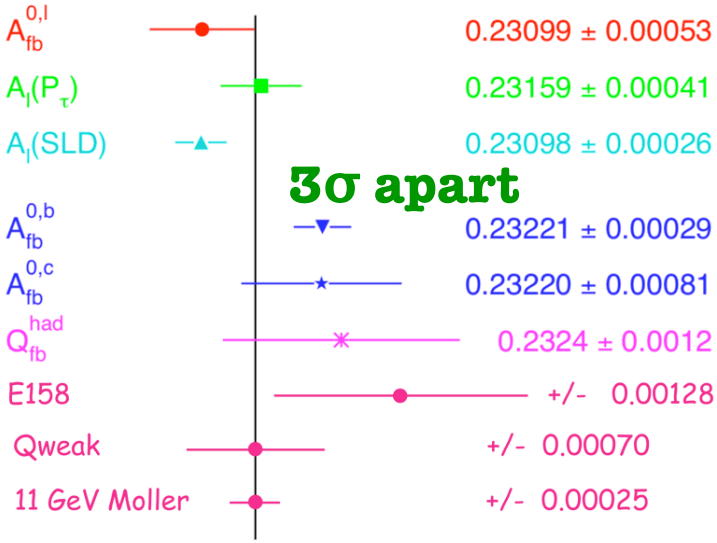

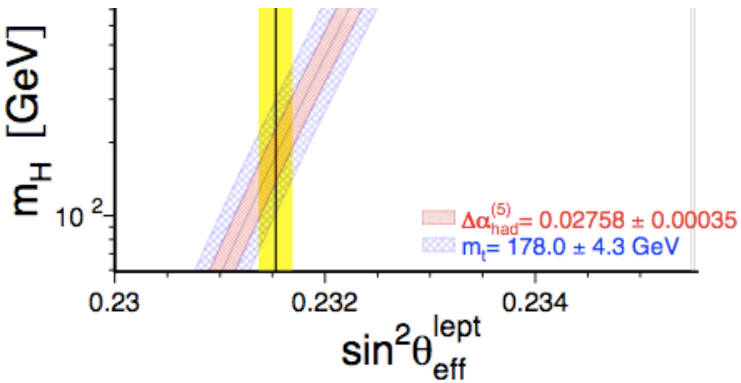

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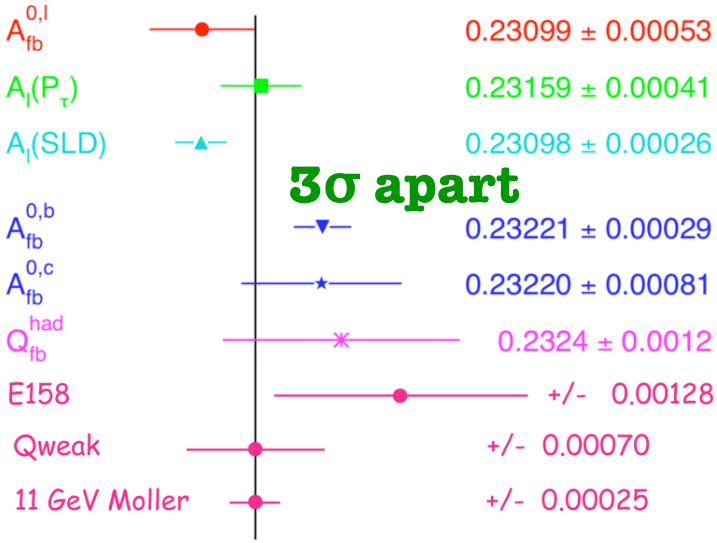

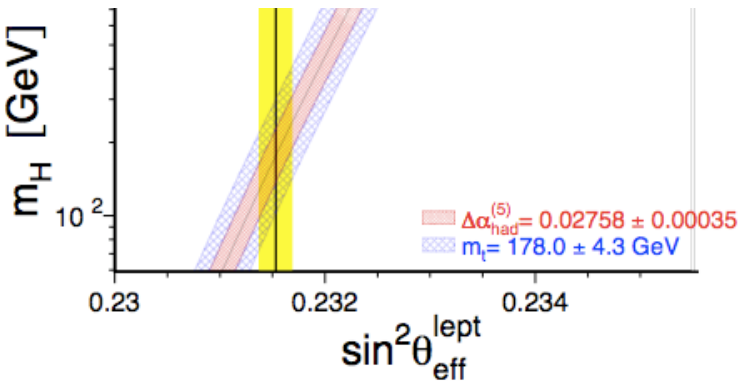

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- Precision $\sin^2\theta_W$ measurements at colliders very challenging
- Neutrino scattering cannot compete statistically
- No resolution of this issue in next decade

K. Kumar