Electroweak Precision Tests in the LHC Era

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Theoretical Nuclear, Particle, Astrophysics & Cosmology

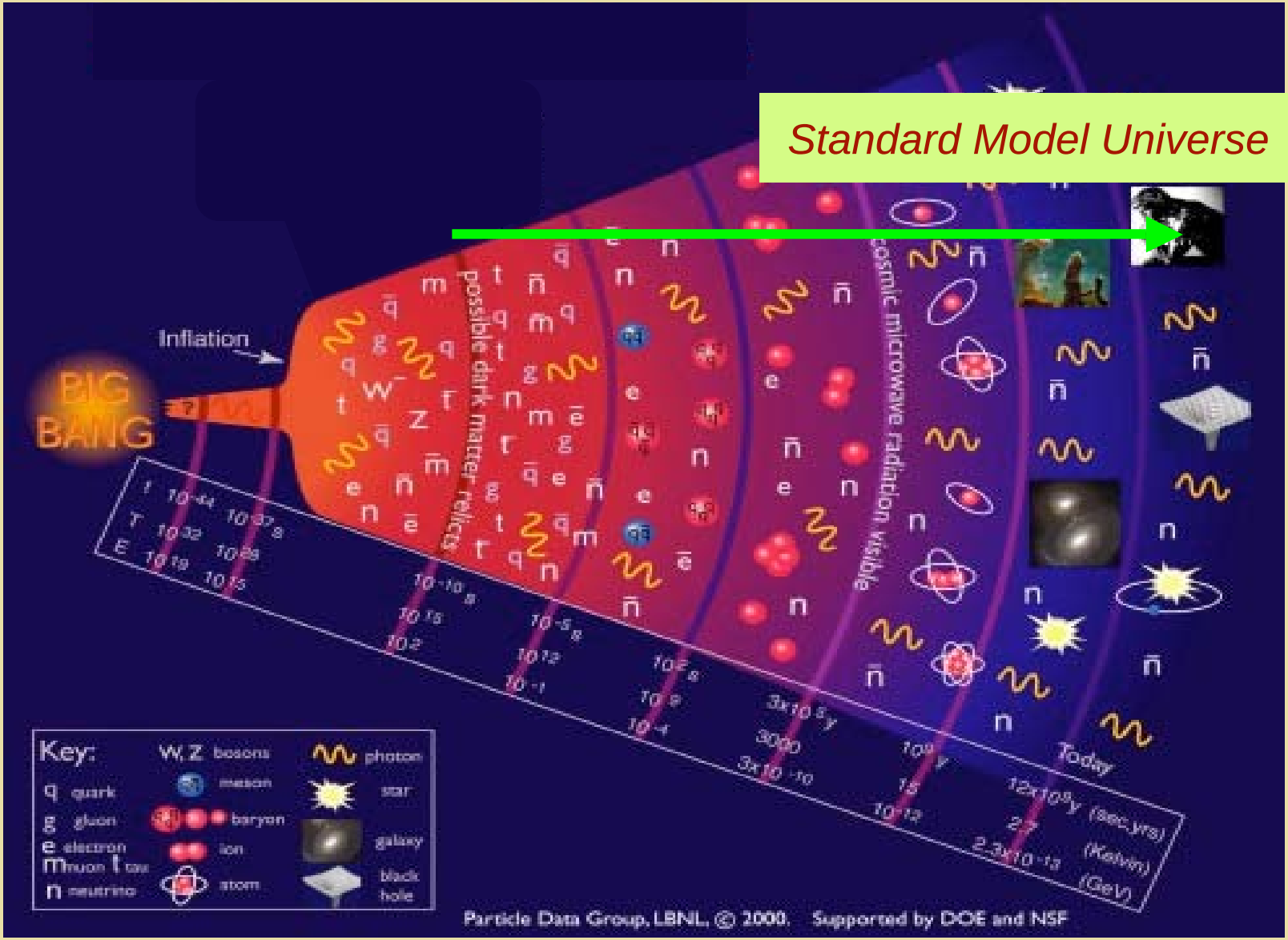
http://www.physics.wisc.edu/groups/particle-theory/

JLab Users Meeting , June 2011

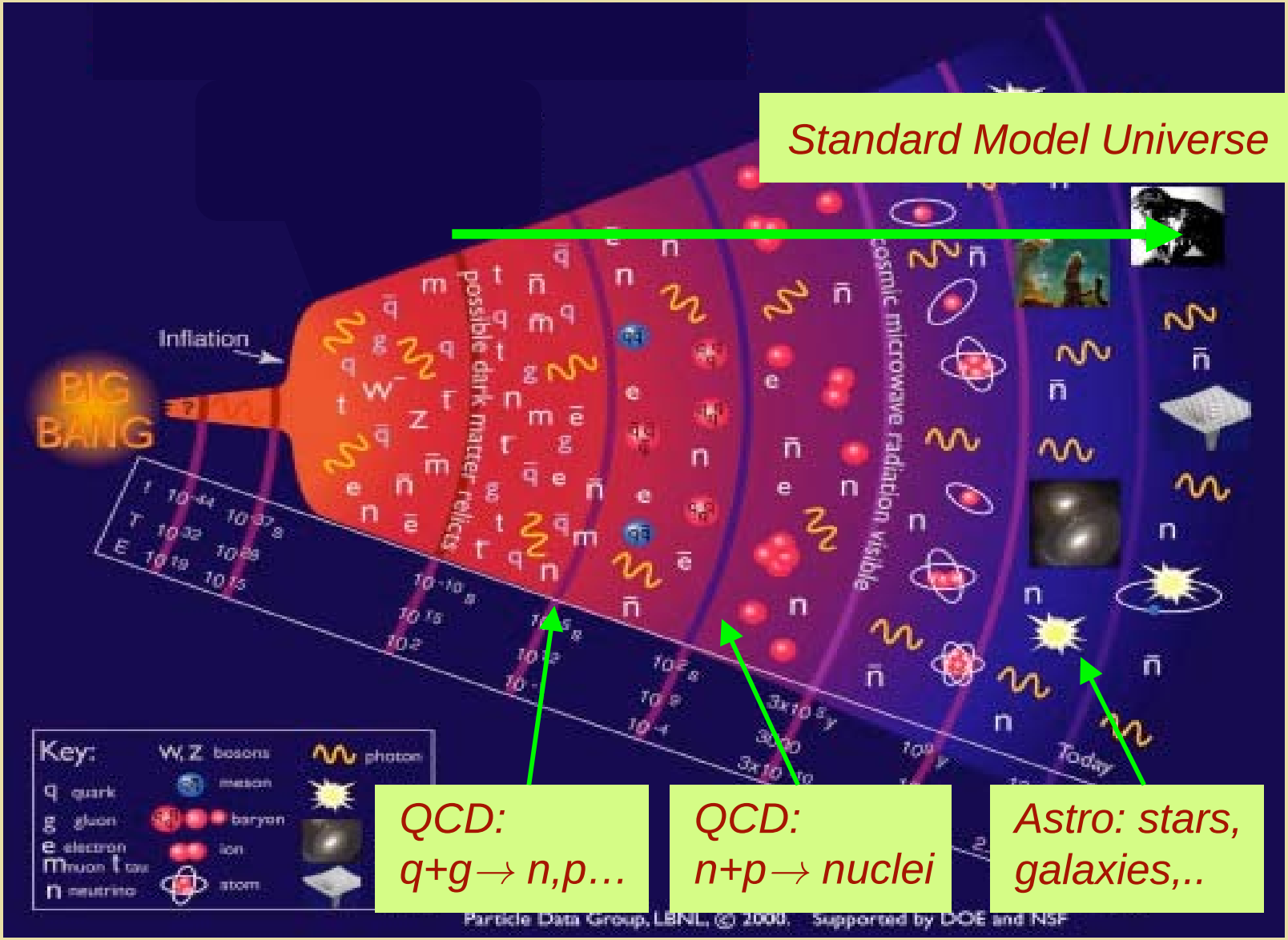
Open Questions

What are the fundamental laws of nature and how do they explain what we observe ?

Symmetries & Cosmic History



Symmetries & Cosmic History

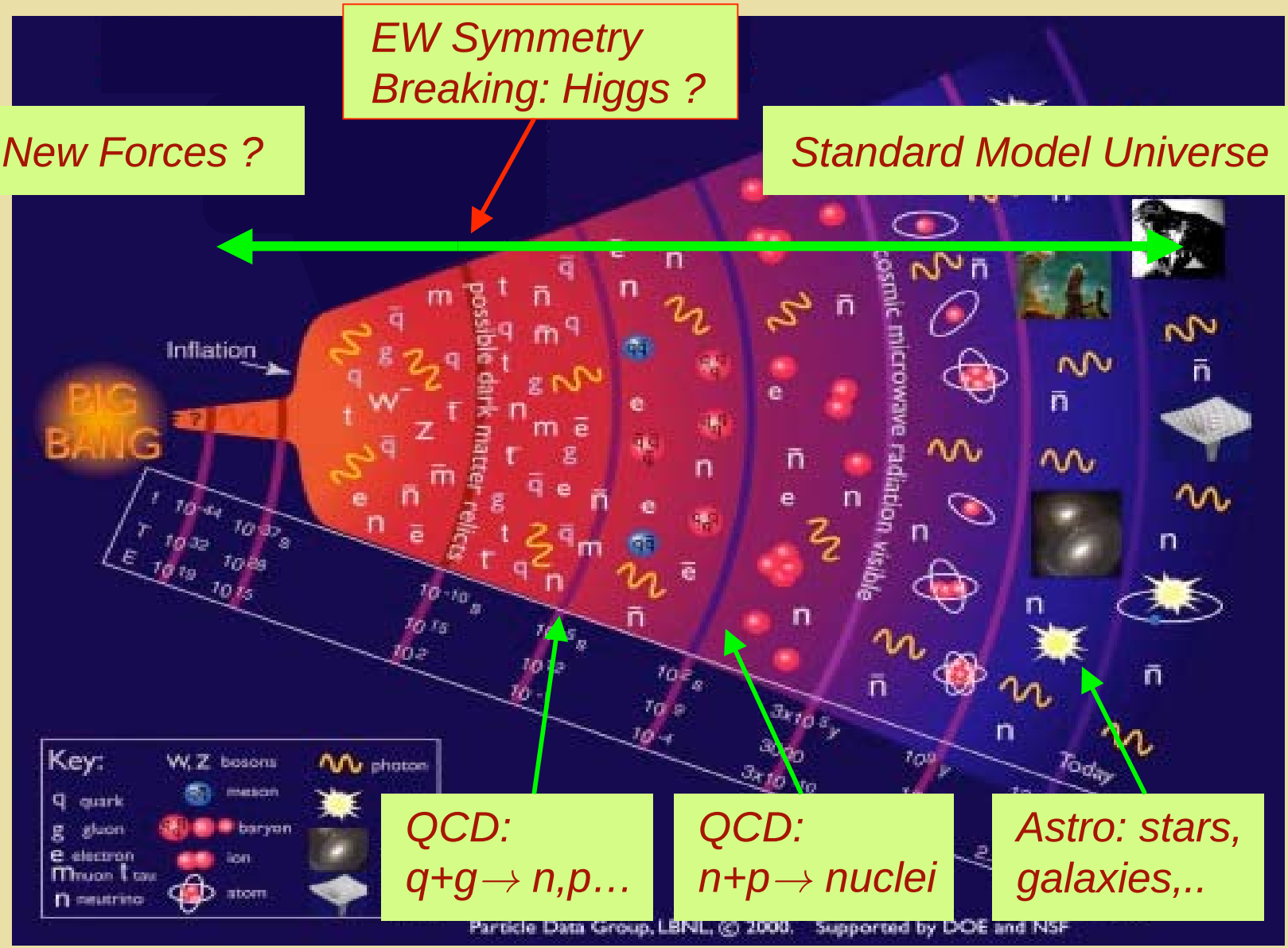


Open Questions

What are the fundamental laws of nature and how do they explain what we observe ?

- *Was there unification of forces in the early Universe ?*
- *What is the origin of visible matter ?*
- *What are the dark matter and energy and what is the structure of the dark Universe ?*
- *What is the origin of flavor and why are the flavor structures of neutrinos & quarks so distinct ?*
- *Do scalar fields account for dynamics of the Universe (inflation, dark matter & energy, phase transitions & visible matter, EWSB…)?*

Symmetries & Cosmic History



EW Symmetry Breaking: Higgs ?

New Forces ?

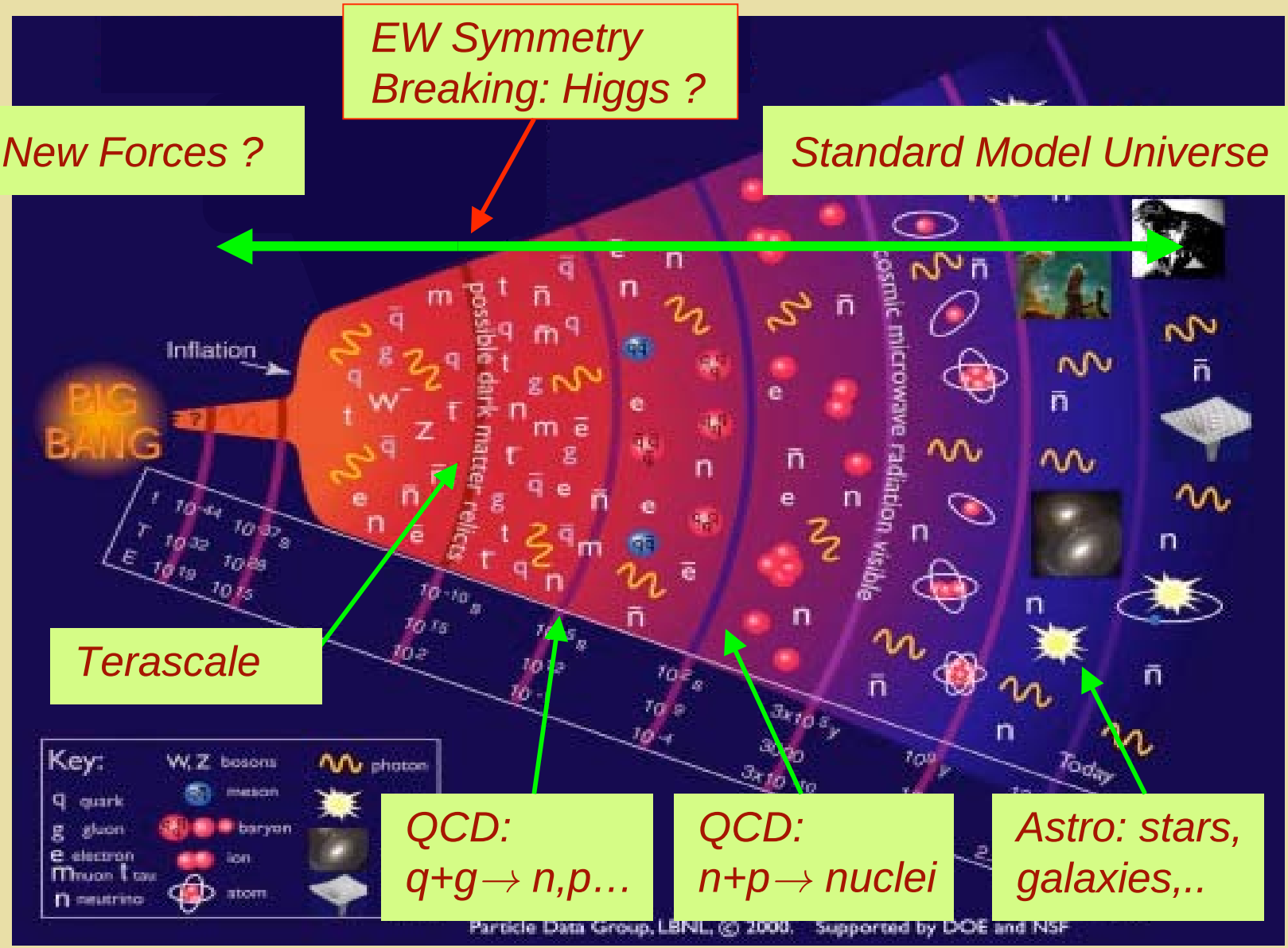
Standard Model Universe

QCD: q+g→ n,p…

QCD: n+p→ nuclei

Astro: stars, galaxies,..

Symmetries & Cosmic History



EW Symmetry Breaking: Higgs ?

New Forces ?

Standard Model Universe

Terascale

QCD: q+g→ n,p…

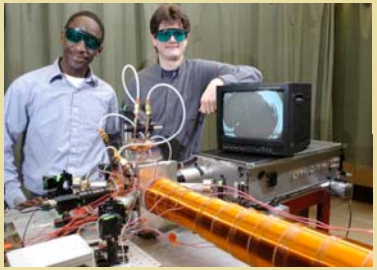
QCD: n+p→ nuclei

Astro: stars, galaxies,..

Three Frontiers

The search for the "New Standard Model" of fundamental interactions lives at three frontiers

Energy Frontier



Precision Frontier

Astrophysics Frontier

This Talk

- *Precision, energy, & astrophysical frontiers provide complementary information*
- *QCD is challenging for both precision & energy frontiers*
- *JLab experiments have a key role as part of the overall nuclear physics BSM program*

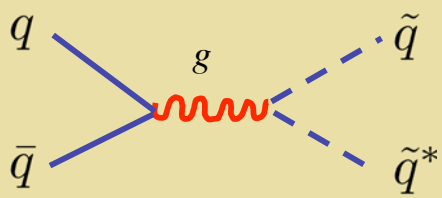
Outline

- *Precision & energy frontiers*
- *PVES: a diagnostic tool*
  - *Semi-leptonic/leptonic complementarity: Q-Weak & Moller*
  - *QCD issues for Q-Weak*
- *CLFV: a new opportunity*
- *Probing the dark universe*

Precision & Energy Frontiers

Collider Challenges: Superpartner Search

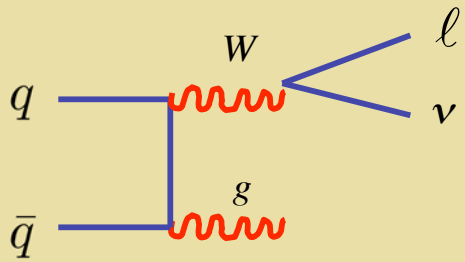
Drell-Yan production of squarks



$$\tilde{q} \to q + \tilde{\chi}_1^0$$
$$\tilde{q} \to q' + \tilde{\chi}^{\pm} \to \ell + \nu + q' + \tilde{\chi}_1^0$$

Final state: 2j + $\not{E}_T$, 2j + ℓ + $\not{E}_T$

St'd Model Backgrounds

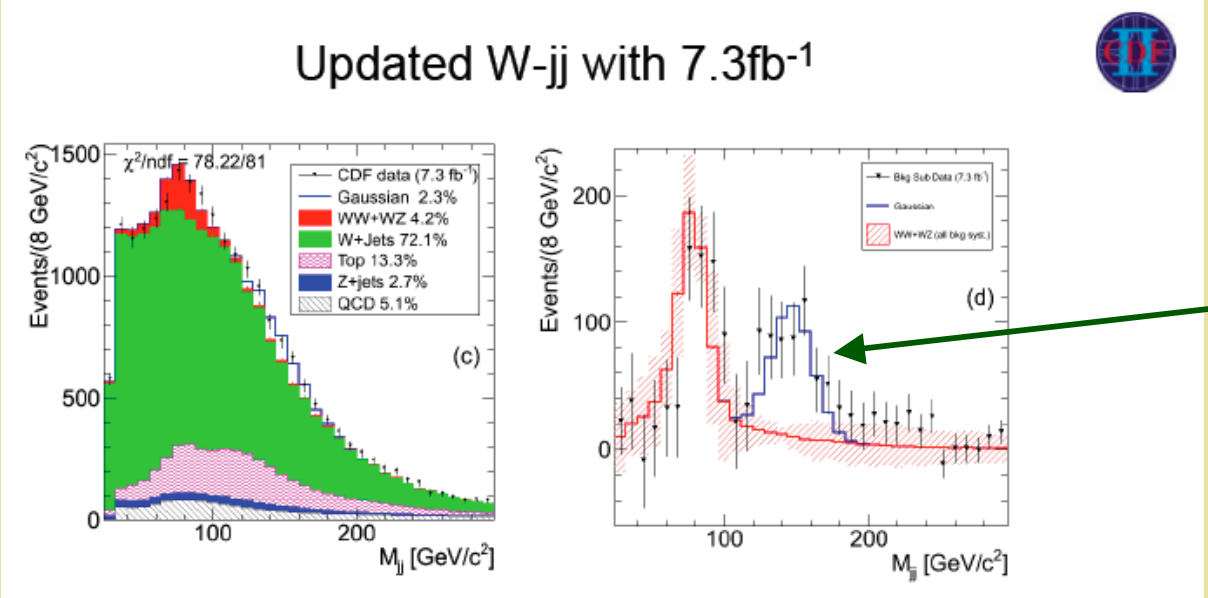


Jets + $\not{E}_T$

Collider Challenges: QCD

Tevatron anomalies: W + jj

G. Punzi, Blois '11

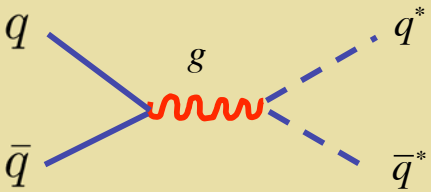


Close to 5σ

- *BSM ? Leptophobic Z', RPV SUSY,…*
- *SM/QCD: tops? Subtraction of W + (n> 3) j ?*

Collider Challenges: Other BSM Searches

Drell-Yan production of KK quarks

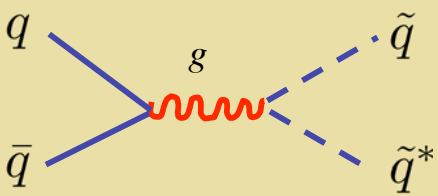


$$q^* \to q + \gamma^*$$ *UED*

$$q^* \to q' + W^* \to q' + \ell + \nu^*$$

Final state: 2j + $\not{E}_T$, 2j + ℓ + $\not{E}_T$

Drell-Yan production of squarks



$$\tilde{q} \to q + \tilde{\chi}_1^0$$

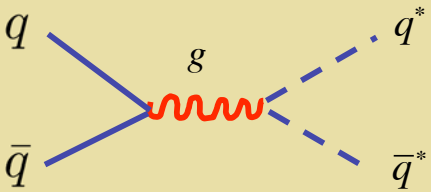
$$\tilde{q} \to q' + \tilde{\chi}^{\pm} \to \ell + \nu + q' + \tilde{\chi}_1^0$$

Final state: 2j + $\not{E}_T$, 2j + ℓ + $\not{E}_T$

How to distinguish between scenarios ?

Collider Challenges: Other BSM Searches

Drell-Yan production of KK quarks



$q^* \to q + \gamma^*$ *UED*

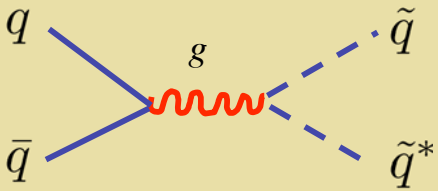
$\not{E}_T$

Additional challenges:

- *Determining spin*
- *Determining SU(N) quantum numbers*

"LHC inverse problem"

Drell-Yan production of squarks



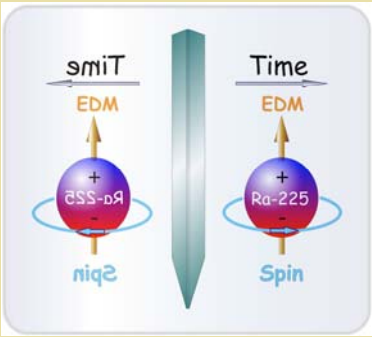
$q \to q + \chi \to \ell + \nu + q + \tilde{\chi}_1^0$

Final state: 2j + $\not{E}_T$, 2j + ℓ + $\not{E}_T$

What complementary info from precision studies ?

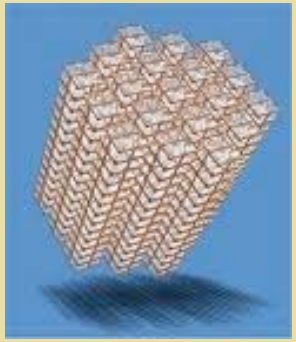
Rare Processes: Experiments

EDM Searches



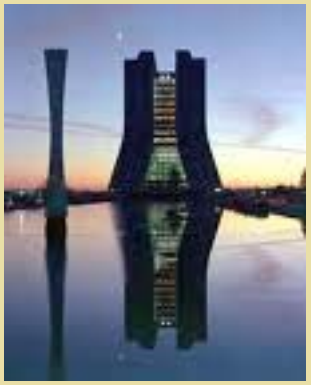
- *nucleon*
- *atoms*
- *leptons*

$0\nu\beta\beta$ Searches



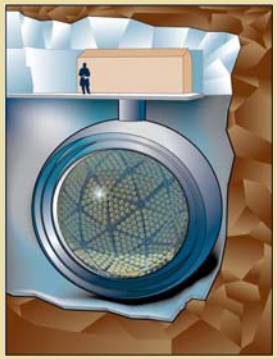
- *Cuore*
- *Exo*
- *Majorana*
- *SNO +*

CLFV Searches



- *mu2e*
- *COMET*
- *EIC*

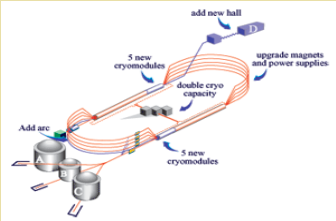
Dark Matter & Exotic Searches



- *CLEAN*
- *WARP*
- *APEX*
- *.....*

Precision Tests: Experiments

PV Electron Scattering



- *Q-Weak*
- *12 GeV Moller*
- *PV DIS*

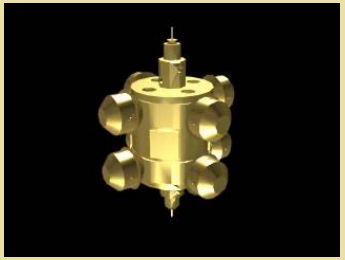
Muons

- *g_μ-2*
- *μA->eA*

Weak Decays

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

Torsion Balances



- *Equiv Prin Tests*
- *Non-grav forces*

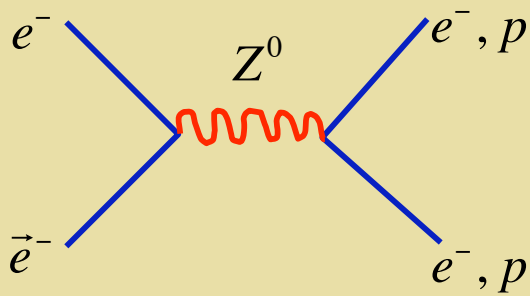
Neutrinos

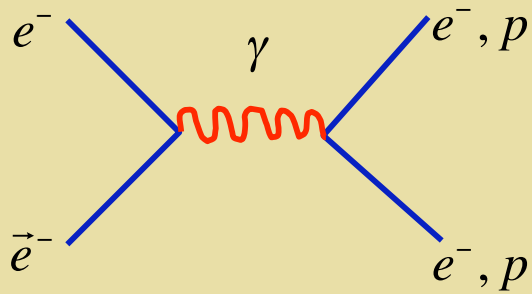
- *oscillations*
- *β & $\beta\beta$ decay*

Parity Violation Electron Scattering

Weak Charge & PVES

Parity-Violating electron scattering

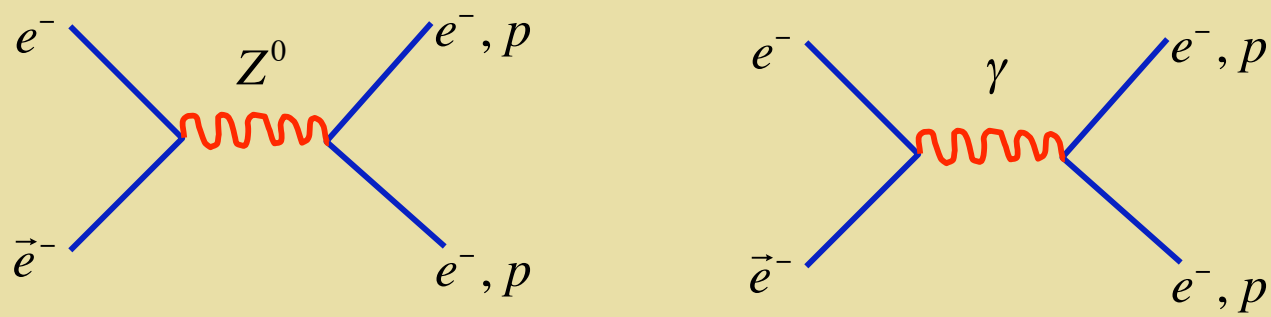




$$A_{PV} = \frac{N_{\uparrow\uparrow} - N_{\uparrow\downarrow}}{N_{\uparrow\uparrow} + N_{\uparrow\downarrow}} = \frac{G_F Q^2}{4\sqrt{2}\pi\alpha}\left[Q_W + F(Q^2,\theta)\right]$$

Weak Charge & PVES

Parity-Violating electron scattering



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"Weak Charge" ~ 0.1 in SM

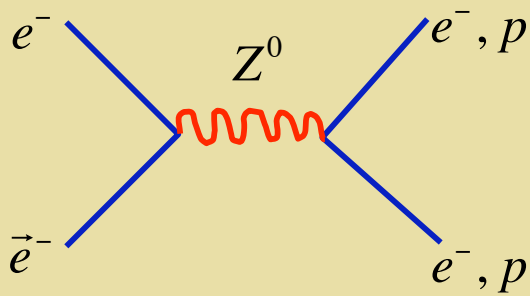
Enhanced transparency to new physics: need 10^{-2} precision

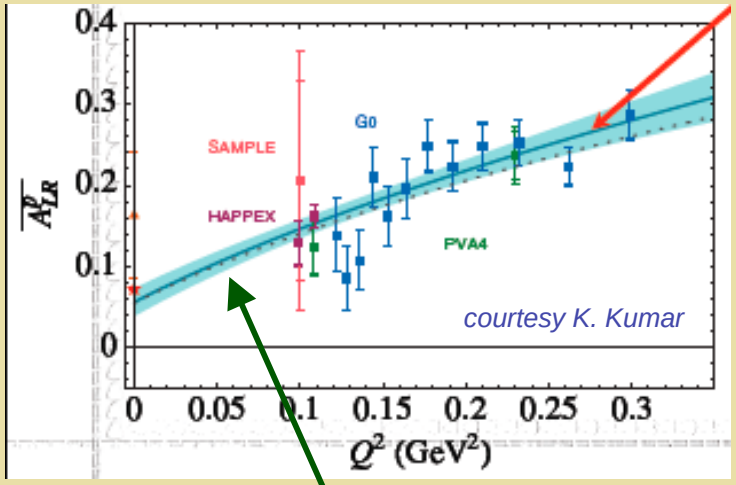
Small QCD uncertainties (Marciano & Sirlin; Erler & R-M)

QCD effects (s-quarks): measured (MIT-Bates, Mainz, JLab); $Z\gamma$ box…

Weak Charge & PVES

Parity-Violating electron





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Effective PV e-q interaction & Q_W

Low energy effective PV eq interaction

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

Effective PV e-q interaction & Q_W

Low energy effective PV eq interaction

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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:

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

Effective PV e-q interaction & Q_W

Low energy effective PV eq interaction

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

SM:

C_{1q} (SM): tree-level + radiative corrections

BSM:

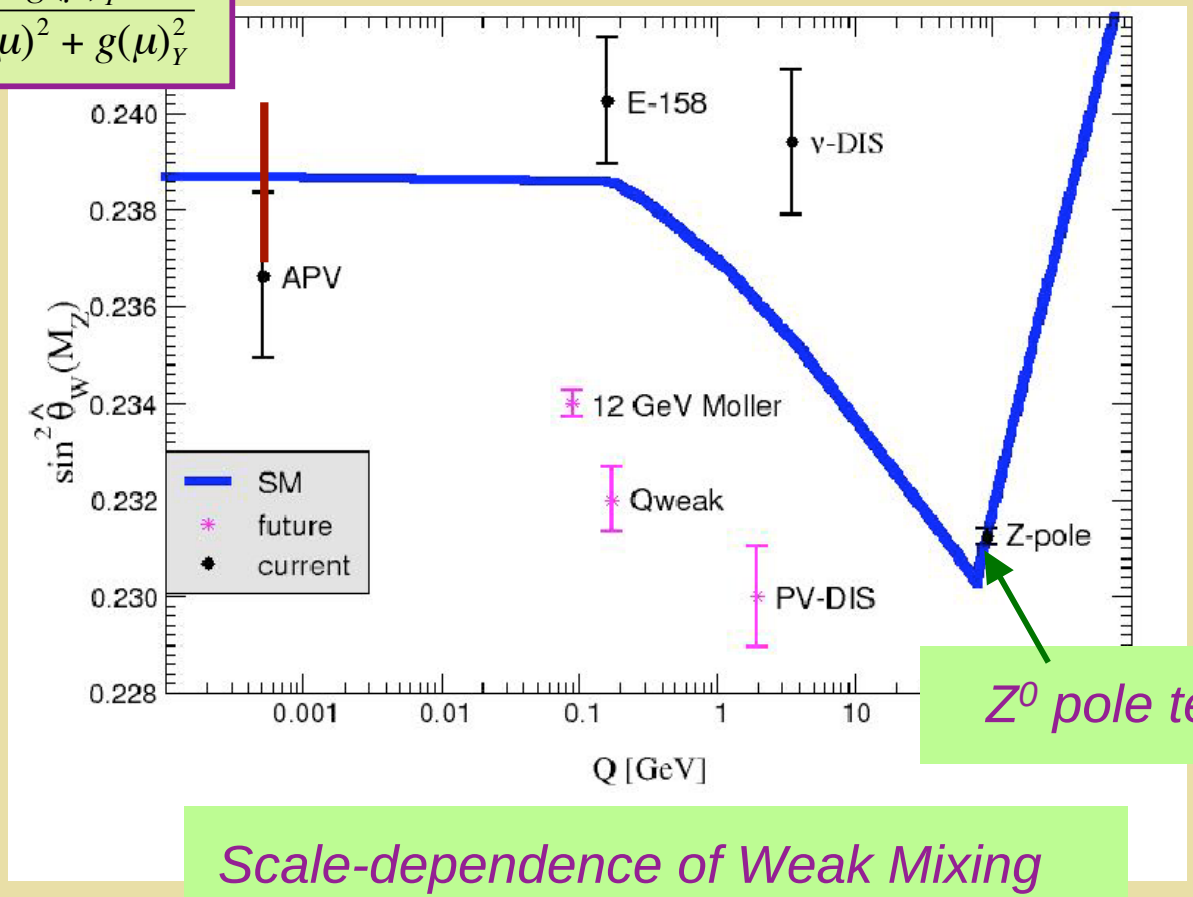
ΔC_{1q}: new contributions from loops

ΔC_{1q}: new tree-level contributions

Illustrate with SUSY

Weak Mixing in the Standard Model

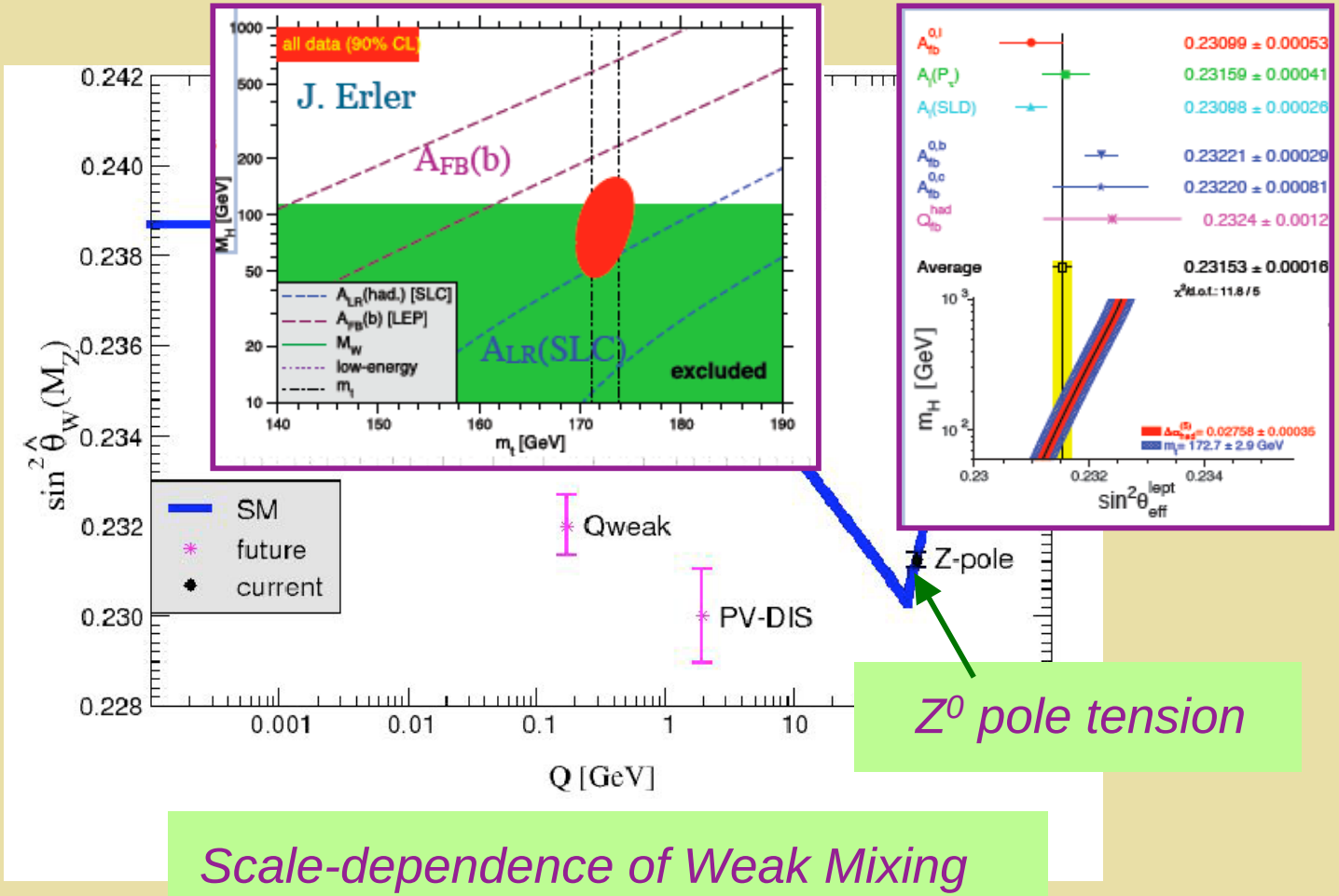
$$\sin^2\theta_W = \frac{g(\mu)_Y^2}{g(\mu)^2 + g(\mu)_Y^2}$$



Z^0 pole tension

Scale-dependence of Weak Mixing

Weak Mixing in the Standard Model



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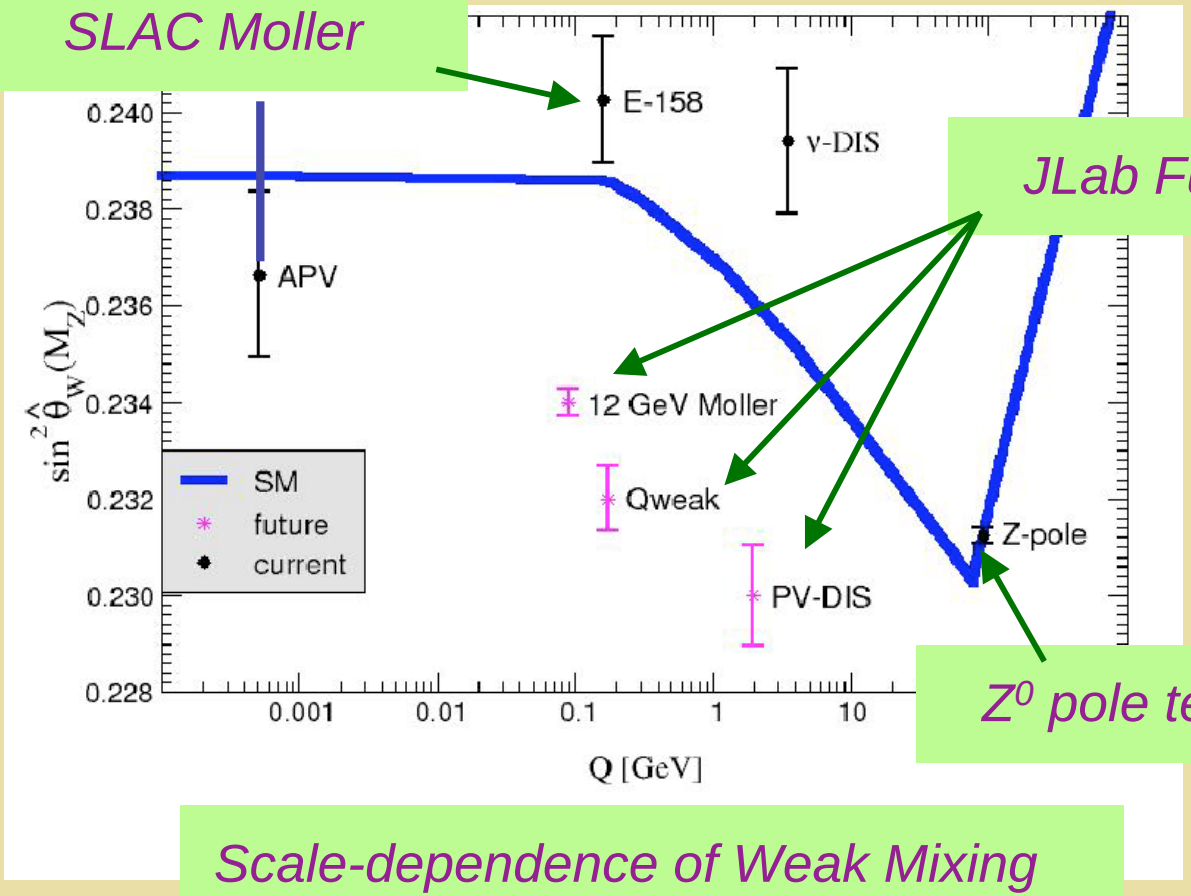
Scale-dependence of Weak Mixing

Weak Mixing in the Standard Model

Parity-violating electron scattering

SLAC Moller



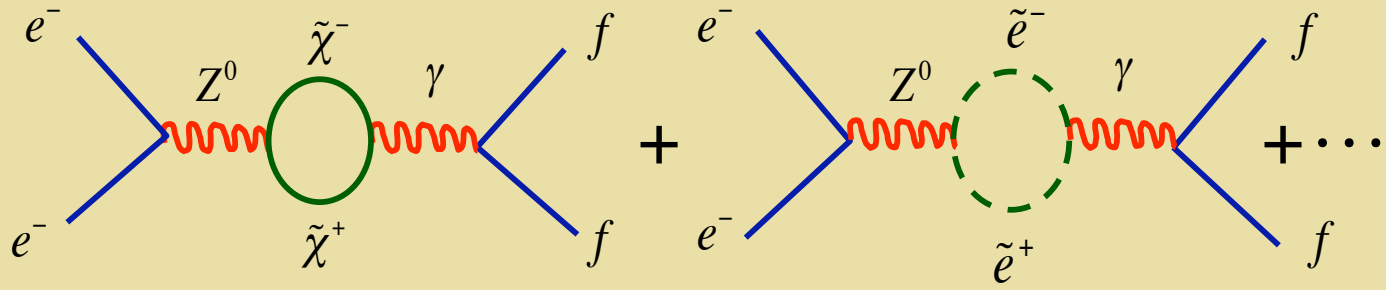
JLab Future

Z^0 pole tension

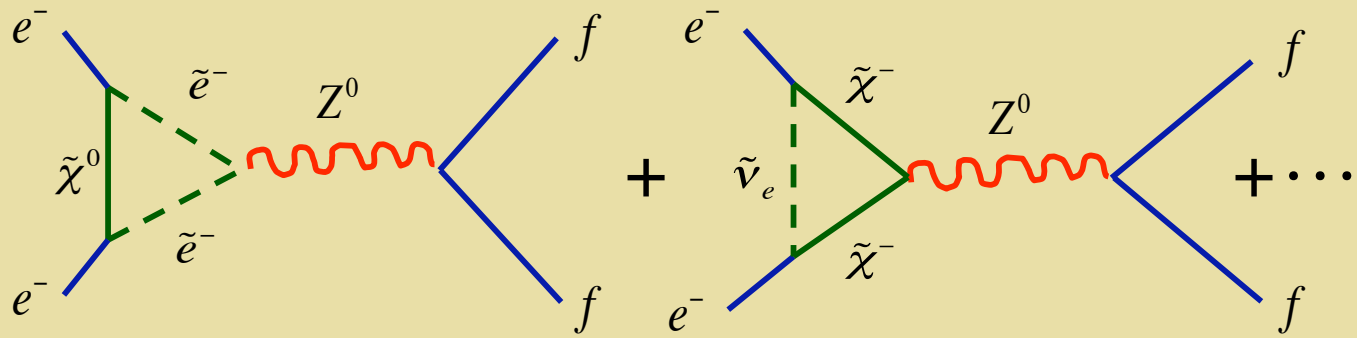
Scale-dependence of Weak Mixing

Loops: SUSY Radiative Corrections

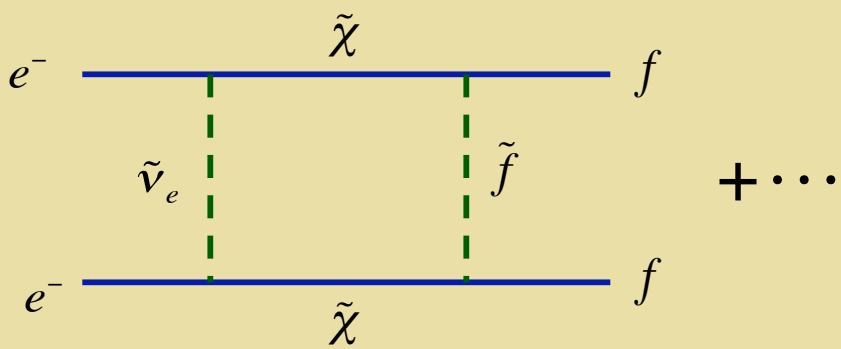
Propagator



Vertex & External leg

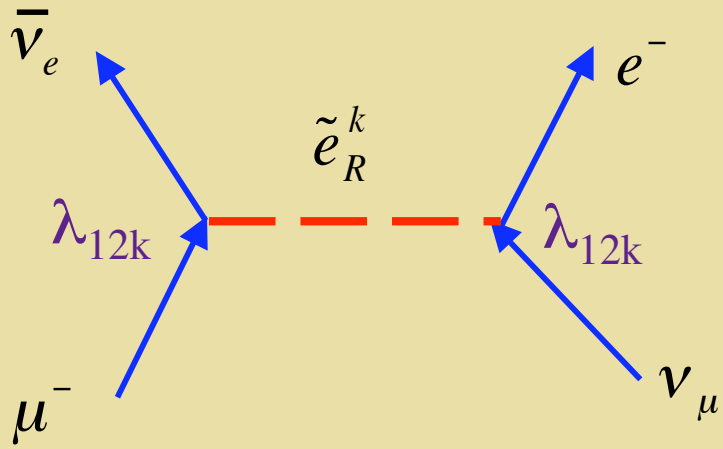


Box



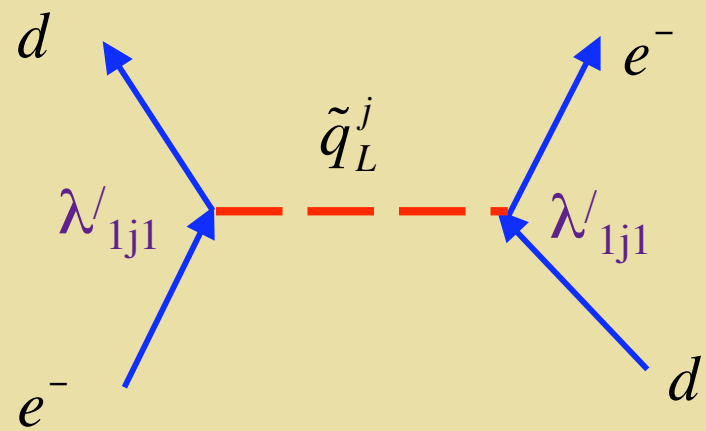
Kurylov, RM, Su

Tree-level: SUSY w/ R Parity-Violation



$\Delta L=1$

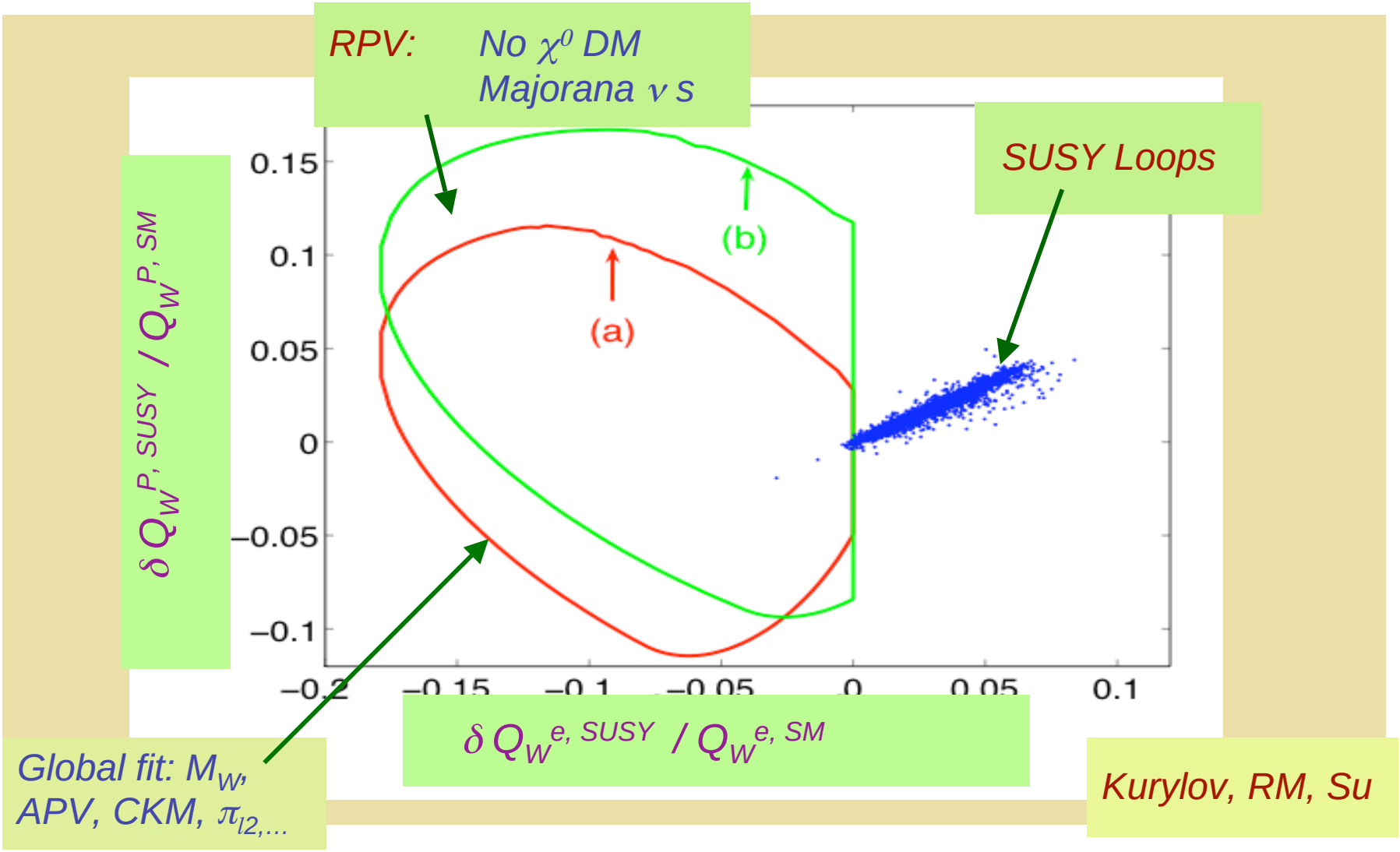
$$\Delta_{12k} = \frac{|\lambda_{12k}|^2}{4\sqrt{2}G_F M^2_{\tilde{e}_R^k}}$$



$\Delta L=1$

$$\Delta'_{1j1} = \frac{|\lambda'_{iji}|^2}{4\sqrt{2}G_F M^2_{\tilde{q}_L^j}}$$

PVES: Diagnostic Tool



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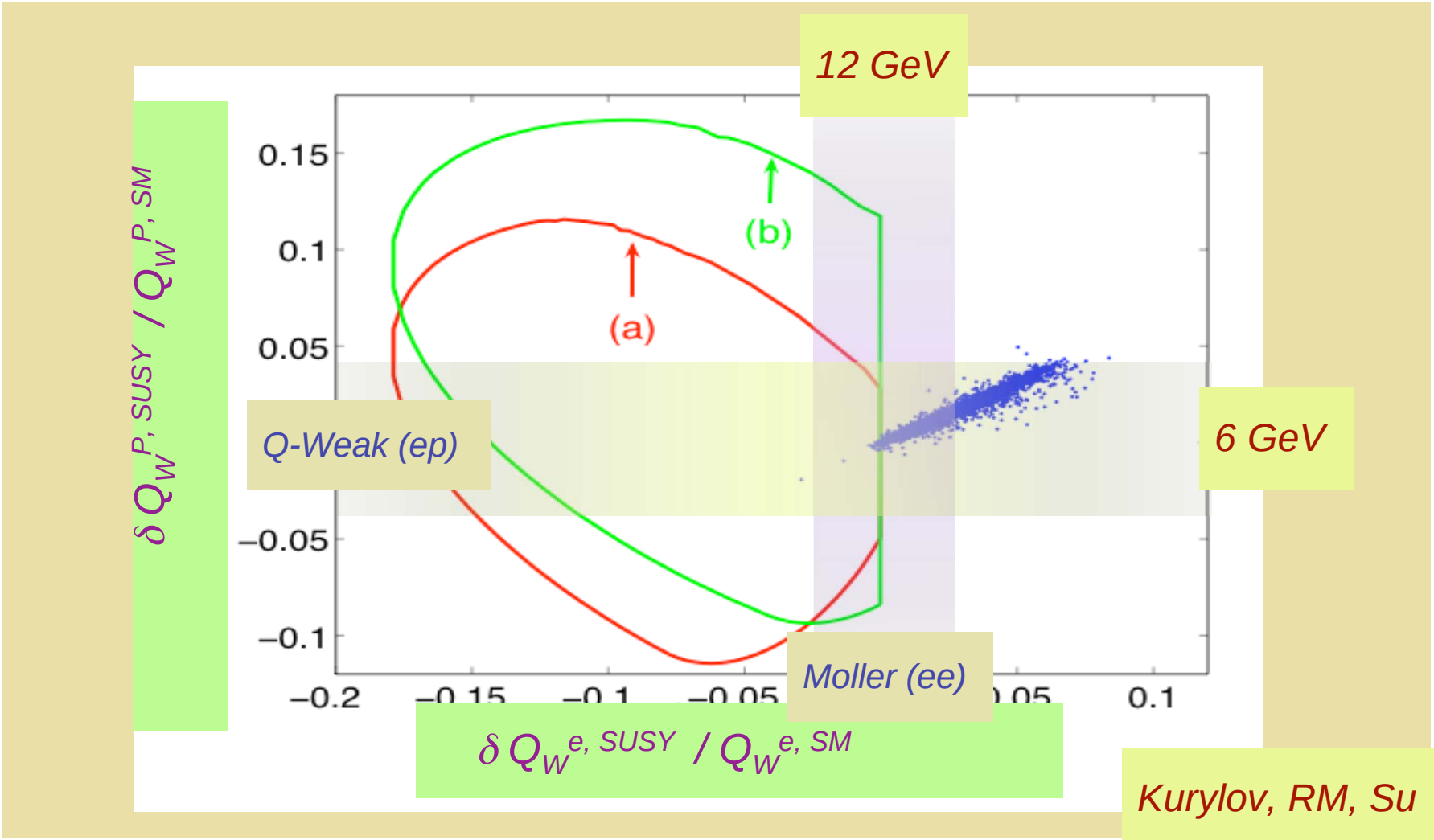
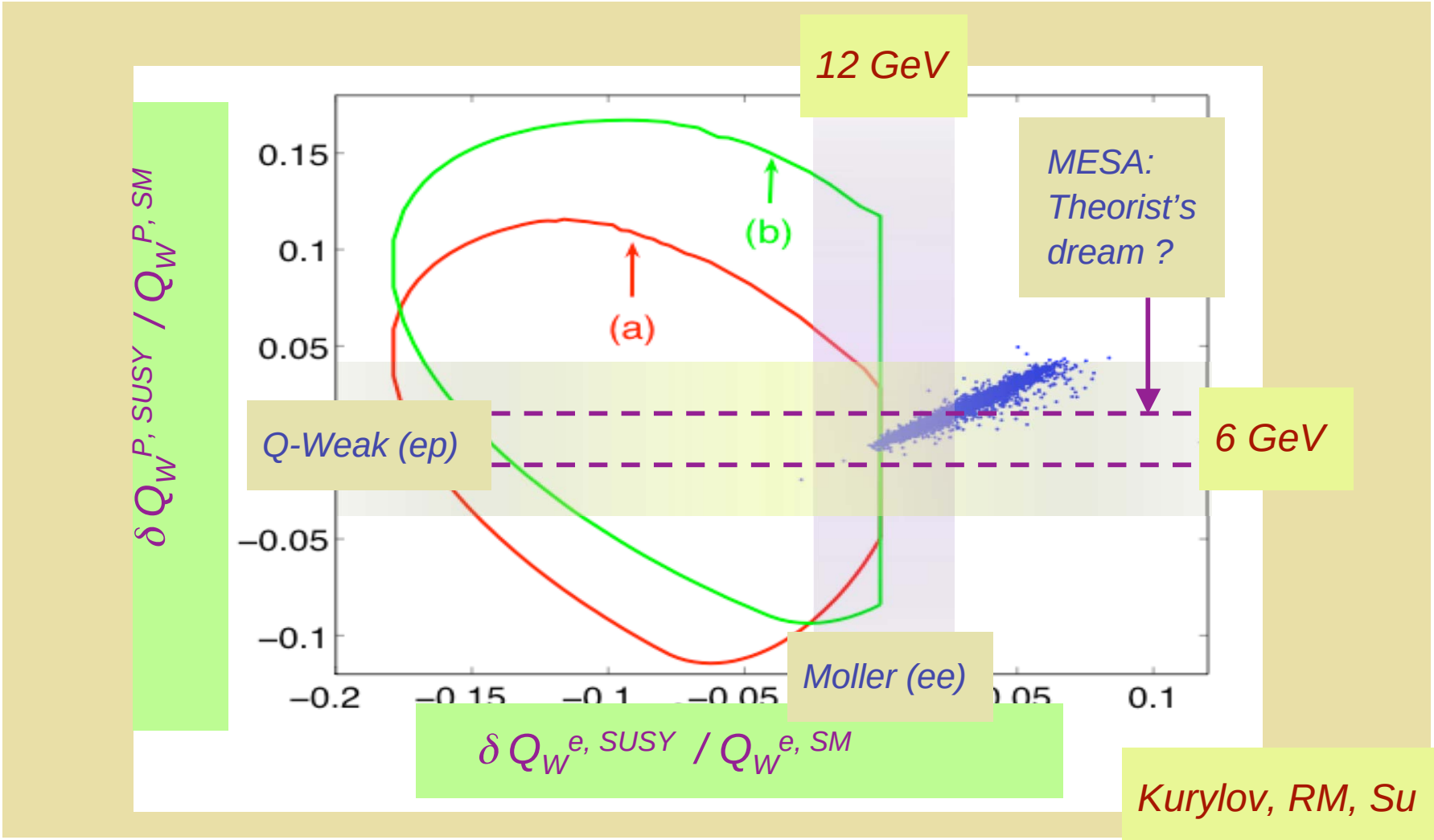
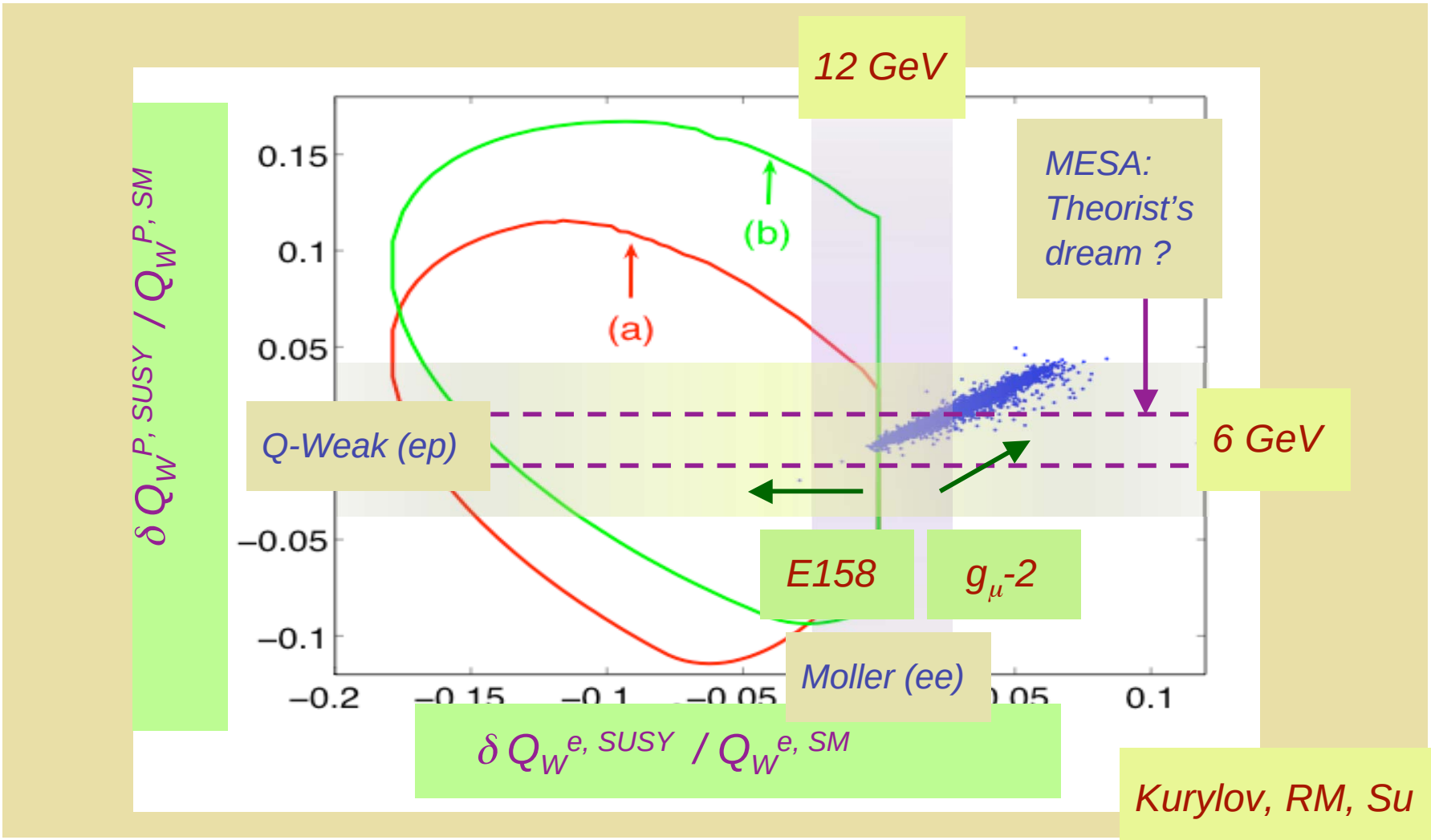


PVES: Diagnostic Tool

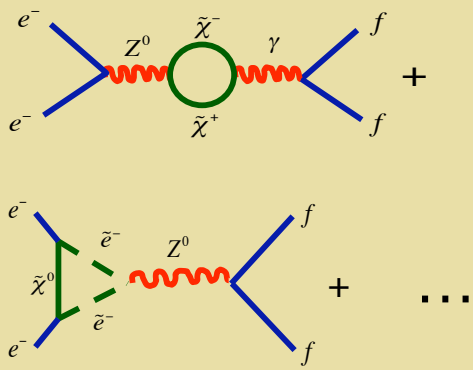


PVES: Diagnostic Tool

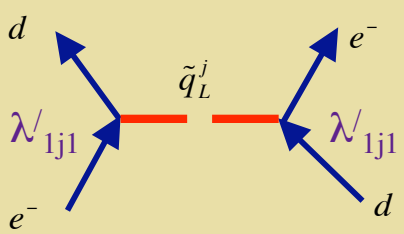


SUSY or Something Else ?

SUSY

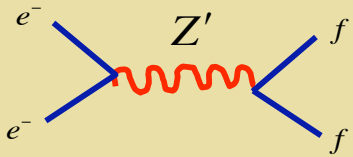


Radiative Corrections

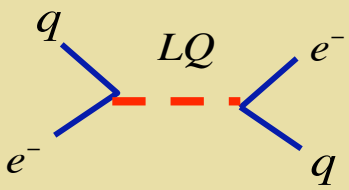


RPV

Z' Bosons



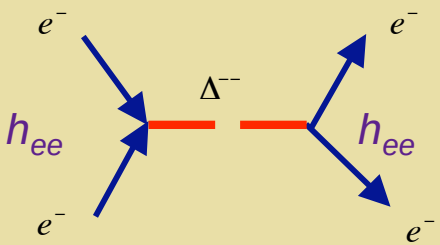
Leptoquarks



Semi-leptonic only

Doubly Charged Scalars

Moller only



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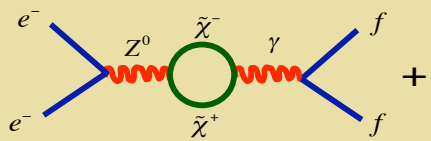
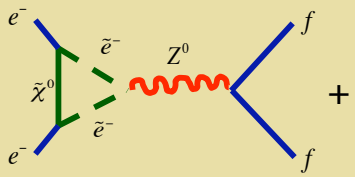
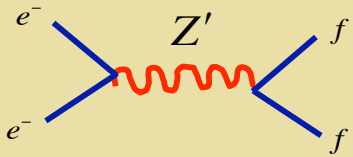


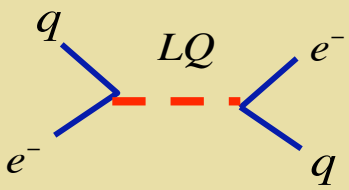


Radiative Correct

Z' Bosons



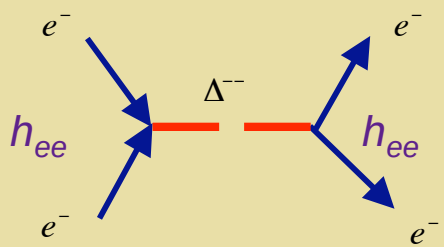
Leptoquarks

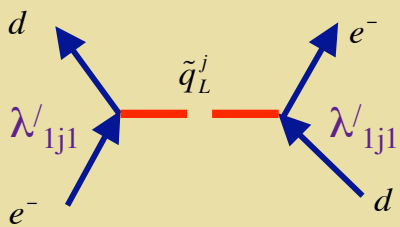


How well do we know the SM prediction for A_{PV} ?

Doubly Charged Scalars

Moller only





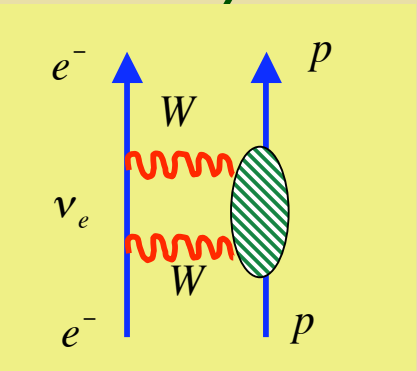
RPV

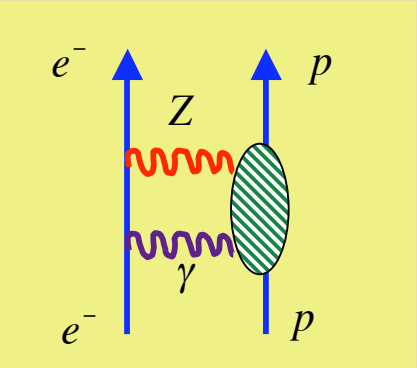
Radiative Correction Uncertainties

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

Erler, Kurylov & R-M

E-Independent





$$\Box_{\gamma Z} = \frac{5\hat{\alpha}}{2\pi}(1 - 4\hat{s}^2)\left[\ln\left(\frac{M_Z^2}{\Lambda^2}\right) + C_{\gamma Z}(\Lambda)\right]$$

$$\Box_{WW} = \frac{\hat{\alpha}}{4\pi\hat{s}^2}\left[2 + 5\left(1 - \frac{\alpha_s(M_W^2)}{\pi}\right)\right]$$

Radiative Correction Uncertainties

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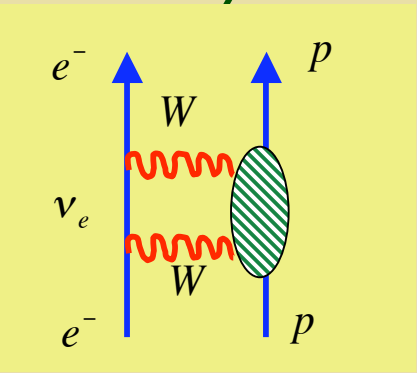

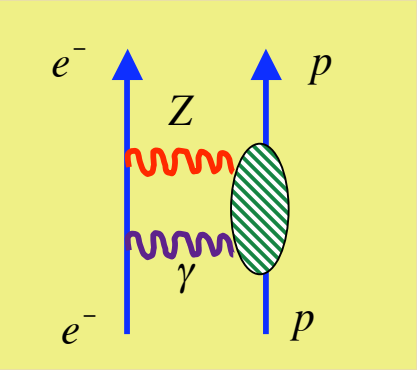

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$\delta Q_W \sim 0.7\%$

$$\Box_{WW} = \frac{\hat{\alpha}}{4\pi\hat{s}^2}\left[2 + 5\left(1 - \frac{\alpha_s(M_W^2)}{\pi}\right)\right]$$

$\delta Q_W \sim 0.1\%$

Order α_s^2

Radiative Correction Uncertainties

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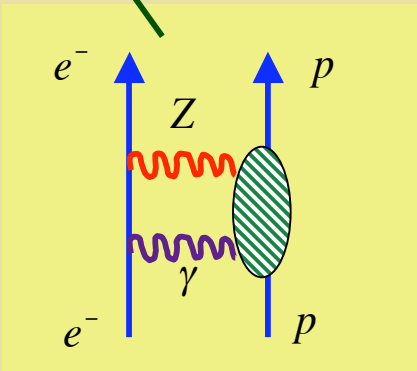
E-dependent: E = 1.165 GeV



Ref. [11]	Ref. [15]	Ref. [17]	This work **
$(3 \pm 3)10^{-3}$	$(4.7^{+1.1}_{-0.4})10^{-3}$	$(5.7 \pm 0.9)10^{-3}$	$(5.4 \pm 2.0)10^{-3}$

[11] Gorchtein & Horowitz

[15] Sibirtsev et al

[17] Rislow & Carlson

** *Gorchtein, Horowitz, R-M*

1102.3910 [nucl-th]

Radiative Correction Uncertainties

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

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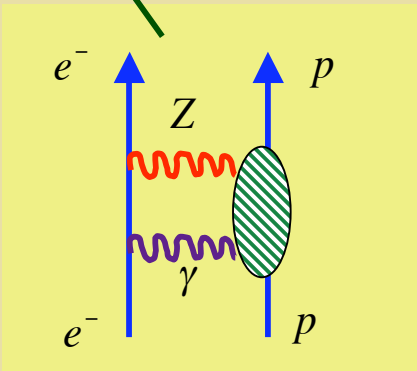

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Equivalent to ~ 2.8% uncertainty in Q_W

[11] Gorchtein & Horowitz

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** *Gorchtein, Horowitz, R-M*

1102.3910 [nucl-th]

Includes estimate of model uncertainty

Radiative Correction Uncertainties

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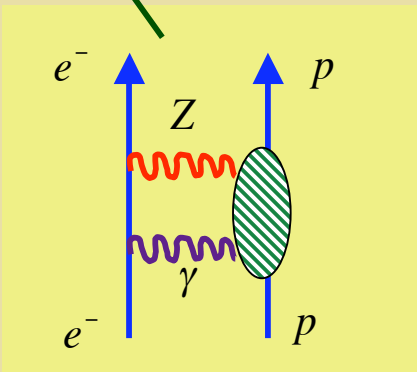

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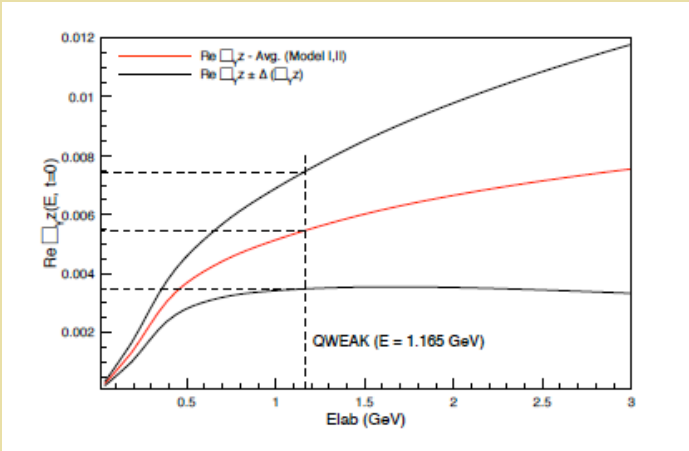
Lower energy measurement



E = 180 MeV, Q^2 =0

[1.32 +/- 0.05 (mod avg) +/- 0.27 (bkg)

$^{+0.11}_{-0.08}$ (res)] x 10^{-3}

Radiative Correction Uncertainties

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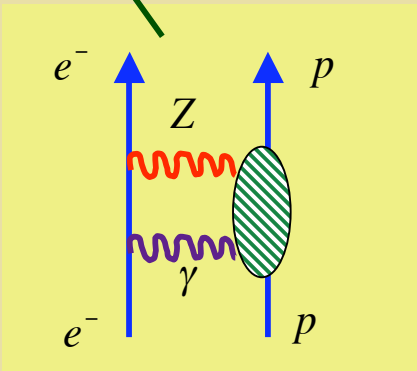
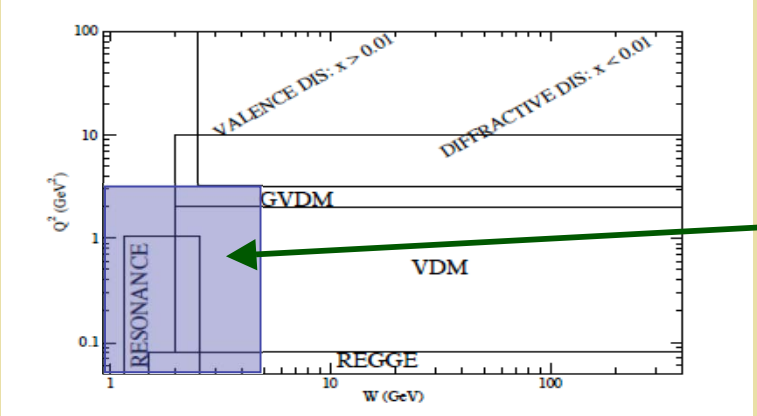


Additional measurements



Dominant contributions; scarce data

Measure A_{PV} in extrapolation region: direct probe of $F^{\gamma Z}$

Radiative Correction Uncertainties

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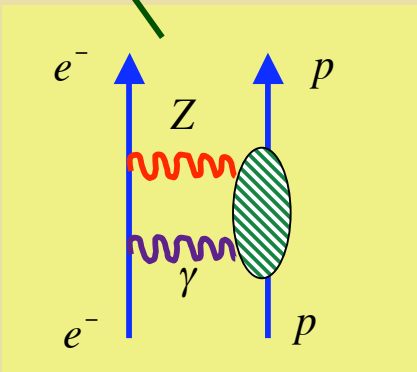
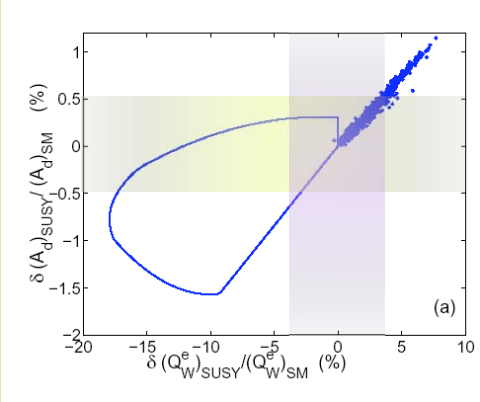


PVDIS: SOLID….

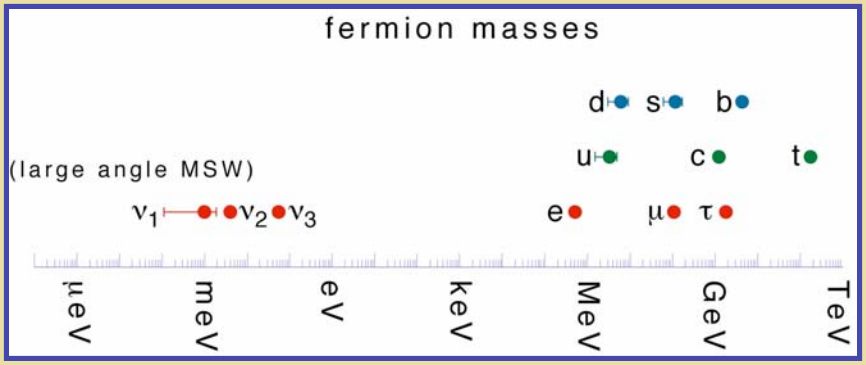


PVDIS w/ 0.5% precision:

- *Free from QCD RC uncertainties*
- *Comparable BSM sensitivity*
- *Other QCD issues: CSV, HT…*

Charged Lepton Flavor Violation: A New Opportunity

Flavor Puzzles: Masses & Mixing



Neutrino Mixing versus Quark Mixing

Leptons

$$U_\ell = \begin{pmatrix} 0.85 & -0.52 & 0.053 \\ 0.33 & 0.62 & -0.72 \\ -0.40 & -0.59 & -0.70 \end{pmatrix}$$

Quarks

$$V_q = \begin{pmatrix} 0.976 & 0.22 & 0.003 \\ -0.22 & 0.98 & 0.04 \\ 0.007 & -0.04 & 1 \end{pmatrix}$$

Why so different???

Courtesy: R.D. McKeown

Flavor Puzzles: FCNCs AWOL

- ***GIM mechanism suppresses FCNC in the SM, but not necessarily in BSM scenarios***
- ***Neutrinos oscillate: flavor not conserved***
- ***Why is flavor conserved by charged leptons (so far) ?***

CLFV: Experiments

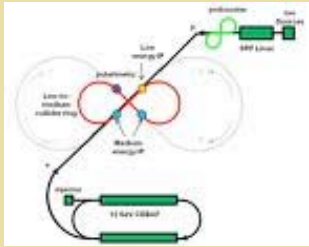
$\mu \to e\gamma$

$\tau \to e\gamma$

$\mu \to e$

$\mu \to e$

- *MEG*
- *COMET*
- *mu2e*
- *Belle II*
- *EIC*



EIC: $e \to \tau$

CLFV: $\mu \to e\gamma$ Status

Laboratory	Collaboration	Year Published	Upper Limit (90%c.l.)
Cosmic rays	*E. P. Hincks & B. Pontecorvo*	1947	$0^{+0.06-0.0}$
Columbia	*S. Lokanathan & J. Steinberger*	1955	$2 \cdot 10^{-5}$
Columbia	*D. Berley et al.*	1959	$2 \cdot 10^{-6}$
CERN	*J. Ashkin et al.*	1959	$(1.2 \pm 1.5) \cdot 10^{-6}$
LRL Berkeley	*S. Frankel et al.*	1960	$1.2 \cdot 10^{-6}$
Columbia	*D. Bartlett et al.*	1962	$6 \cdot 10^{-8}$
LRL Berkeley	*S. Frankel et al.*	1962	$1.9 \cdot 10^{-7}$
LRL Berkeley	*S. Frankel et al.*	1963	$4.3 \cdot 10^{-8}$
Chicago	*S. Parker et al.*	1964	$2.2 \cdot 10^{-8}$
TRIUMF	*P. Depommier et al.*	1977	$3.6 \cdot 10^{-9}$
SIN	*A. van der Schaaf et al.*	1977	$1.1 \cdot 10^{-9}$
LAMPF	*J. D. Bowman et al.*	1979	$1.9 \cdot 10^{-10}$
SIN	*A. van der Schaaf et al.*	1980	$1.0 \cdot 10^{-9}$
LAMPF	*W. W. Kinnison et al.*	1982	$1.7 \cdot 10^{-10}$
TRIUMF	*G. Azuelos et al.*	1983	$1.0 \cdot 10^{-9}$
LAMPF	*R. D. Bolton et al.*	1986	$4.9 \cdot 10^{-11}$
LAMPF	*R. D. Bolton et al.*	1988	$4.9 \cdot 10^{-11}$
LAMPF	*M. L. Brooks et al.*	1999	$1.2 \cdot 10^{-11}$
PSI	*MEG Collaboration*	2009	$2.8 \cdot 10^{-11}$
PSI	*MEG Collaboration*	2012	$\mathcal{O}\ 10^{-13}$

MEG

P-R Kettle, PSI 2010

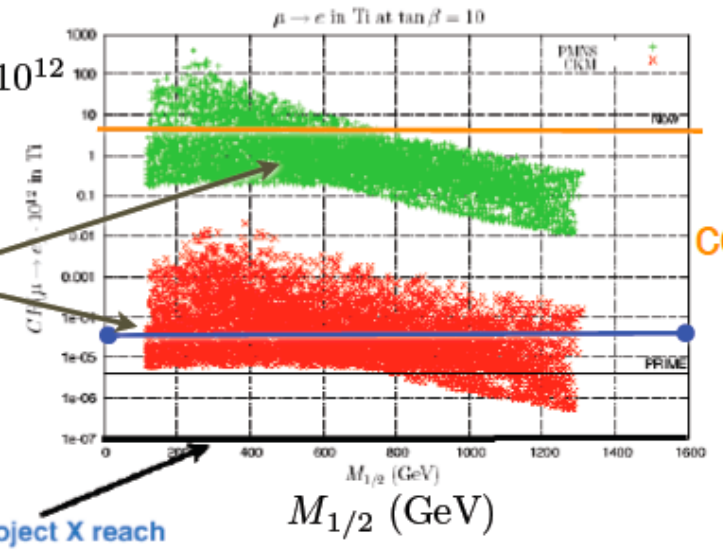
And Muon-Electron Conversion

mu2e

$\tan\beta = 10$

Neutrino-Matrix Like (PMNS) Minimal Flavor Violation(CKM)

$\mathrm{BR}(\mu \to e) \times 10^{12}$



Current μe conversion

Mu2e

measurement can distinguish between PMNS and MFV

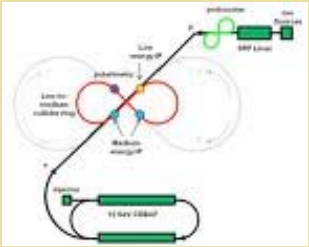
Project X reach

$M_{1/2}$ (GeV)

L. Calibbi, A. Faccia, A. Masiero, S. Vempati, hep-ph/0605139

complementarity between Lepton Flavor Violation (LFV) and LHC experiments

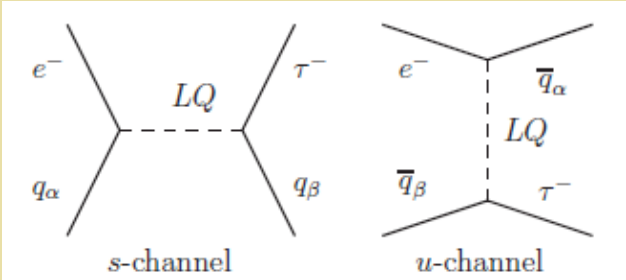
A New Opportunity: CLFV at an EIC



$$e \rightarrow \tau$$

τ CLFV w/ Leptoquarks: EIC & HERA

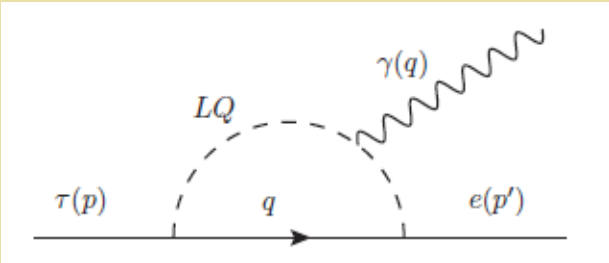
HERA & EIC



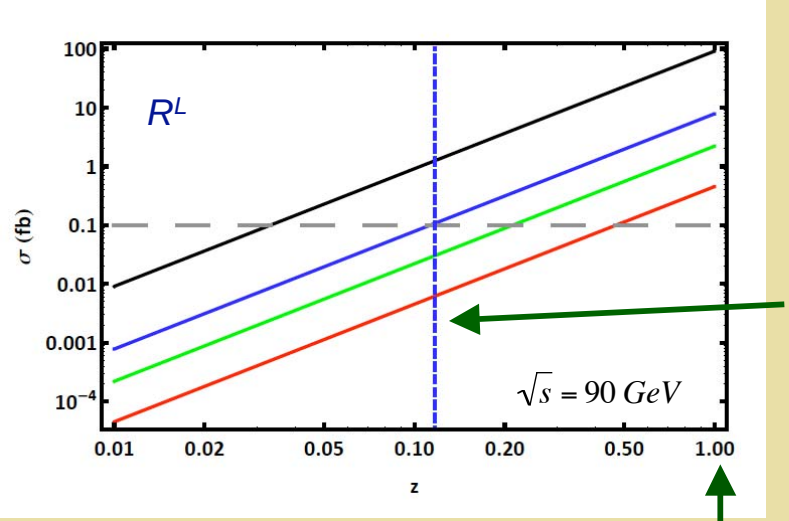
General Classification

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

Rare Decays



Gonderinger, R-M JHEP 1006:045



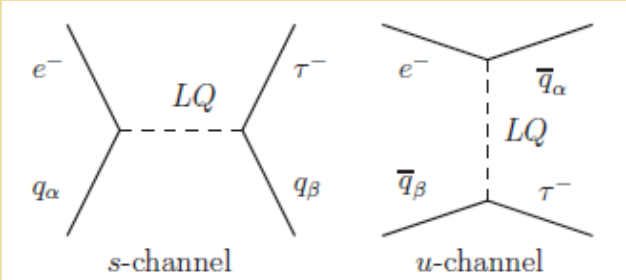
$\tau \to e\ \gamma$

HERA

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

τ CLFV w/ Leptoquarks: EIC & HERA

HERA & EIC



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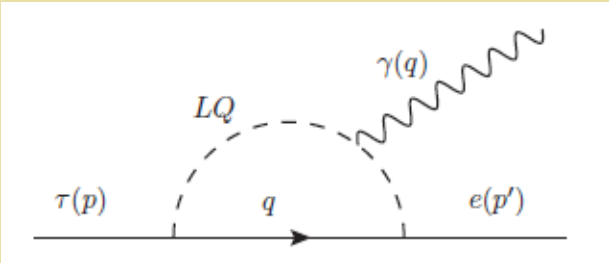
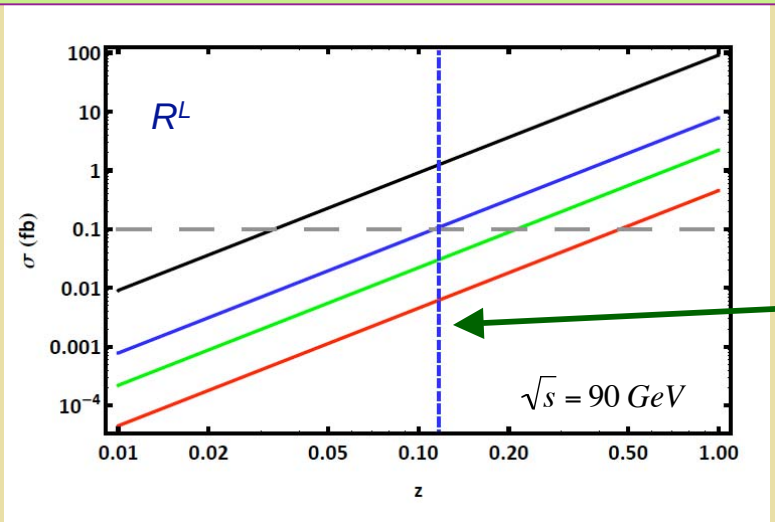
$$+ g_1^R \bar{u}^c e S_1^R + \tilde{g}_1 \bar{d}^c e \tilde{S}_1^R + g_3 \bar{q}^c i \tau_2 \vec{\tau} \ell S_3 + h_1^L \bar{q} \gamma^\mu \ell U_{1\mu}^L$$

Extend HERA reach & compete with super B factories w/ 10 to 100 fb^{-1}

Rare Decays





$\tau \to e\ \gamma$

Gonderinger, R-M JHEP 1006:045

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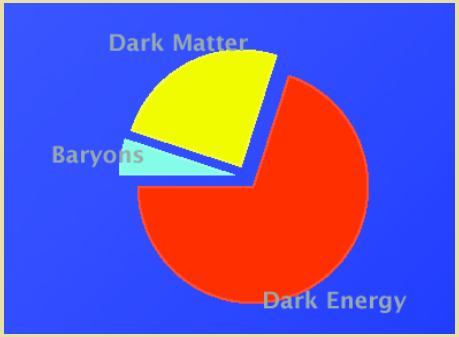
Probing the Dark Universe

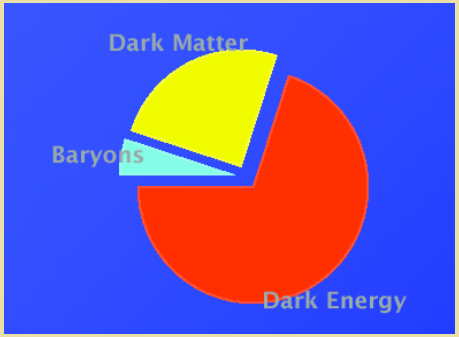
Dark Forces

New interactions in the dark sector ?



Dark Forces: Long Range ?

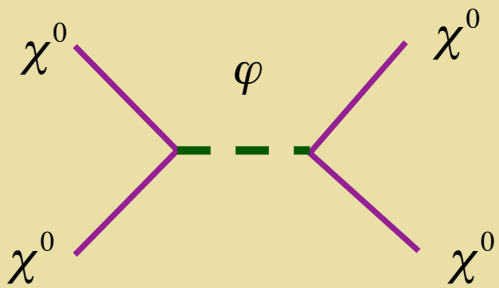
New interactions in the dark sector ?



Long-range, non-grav dark force ?

Violation of weak equiv principle (WEP)

Galactic tidal streams & CMB



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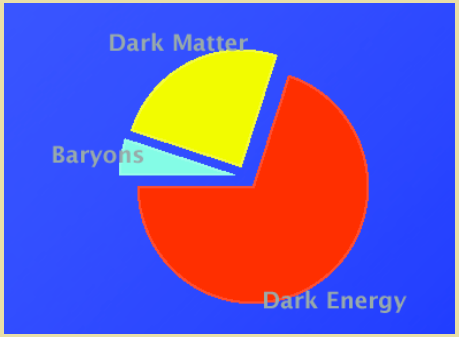

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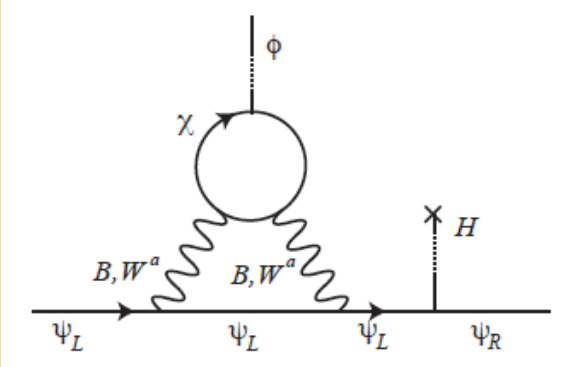
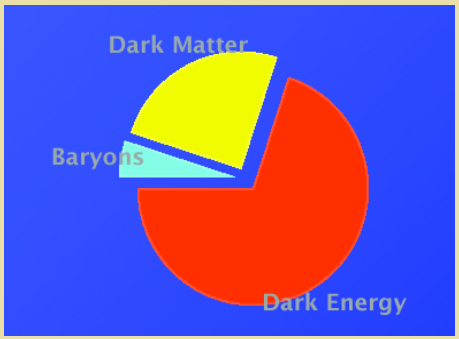
Non-sterile DM & terrestrial WEP tests



Carroll, Mantry, RM, Stubbs
Bovy & Farrar

Long Range Dark Forces: Probes

New interactions in the dark sector ?



Long-range, non-grav dark force

Violation of weak equiv principle (WEP)

Galactic tidal streams & CMB

Eot-Wash

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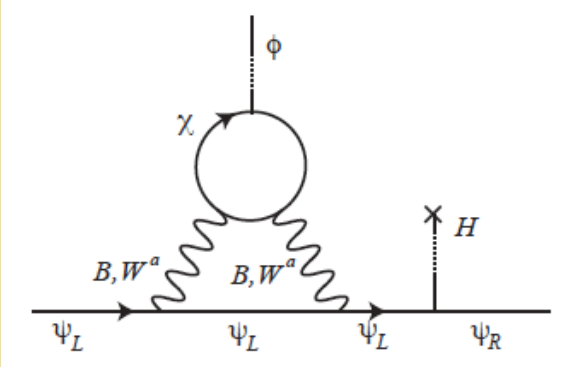

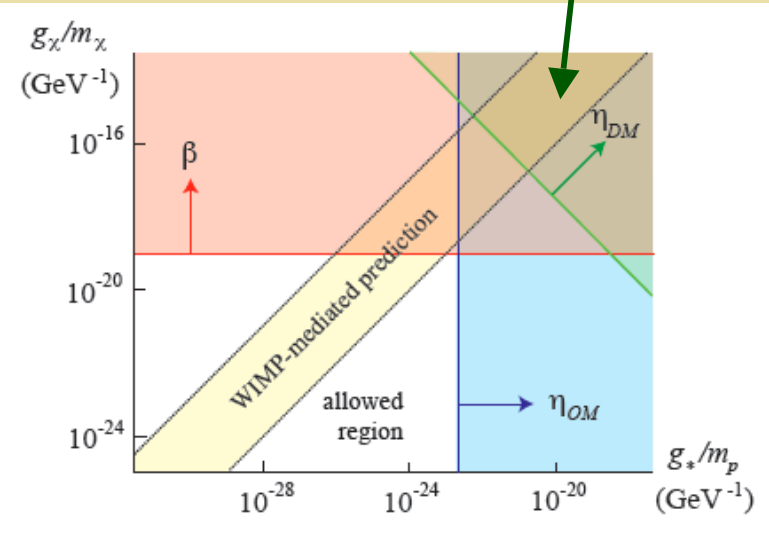

Carroll, Mantry, RM, Stubbs
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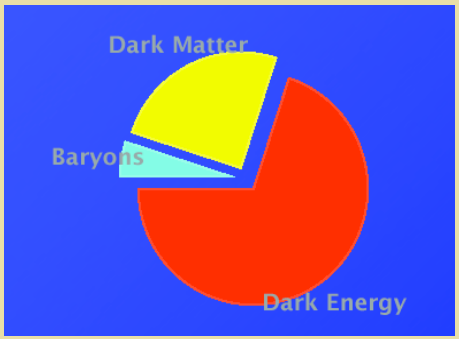
Long Range Dark Forces: Probes

New interactions in the dark sector ?



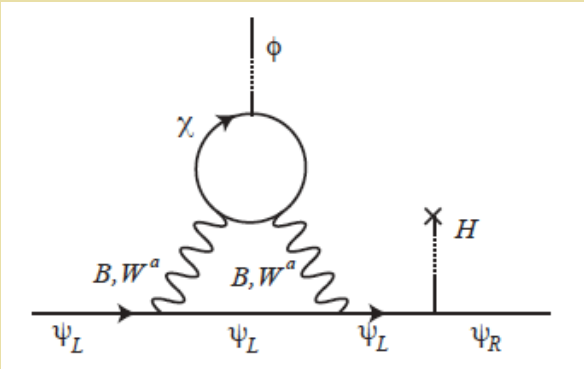
Long-range, non-grav dark force

Violation of weak equiv principle (WEP)

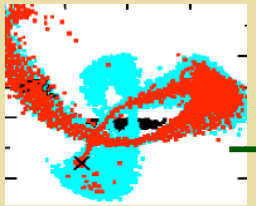
Galactic tidal streams & CMB

Eot-Wash

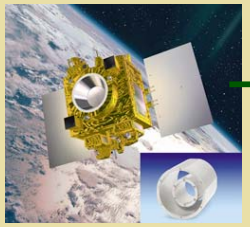
Non-sterile DM & terrestrial WEP tests



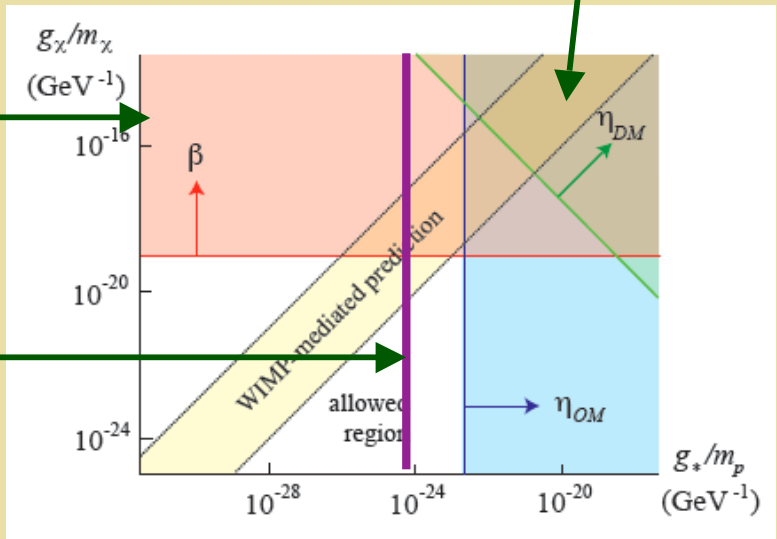
Carroll, Mantry, RM, Stubbs
Bovy & Farrar



Kesden & Kamionkowski



Microscope



Dark Forces: Long Range ?

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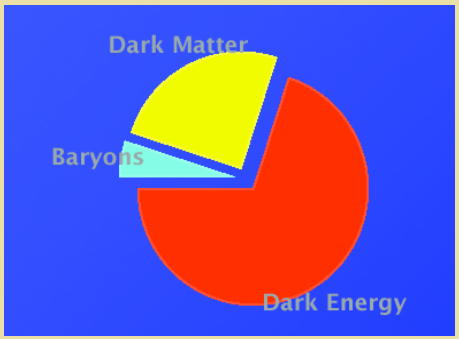
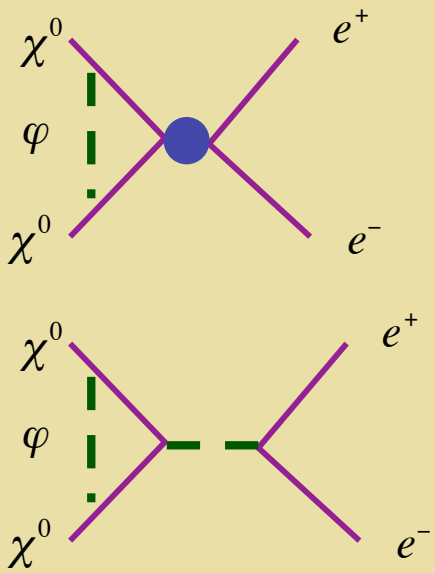
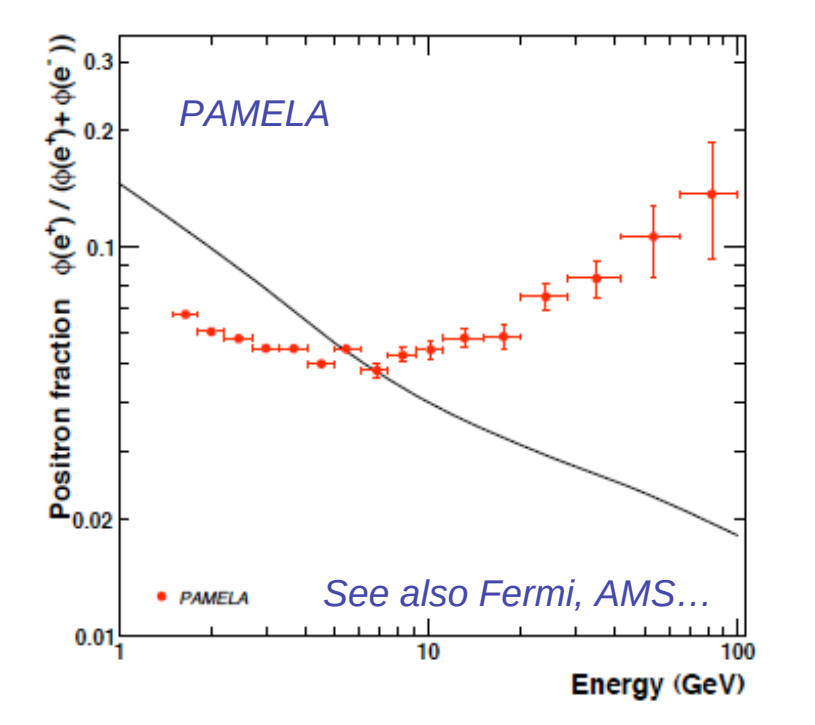


Long-range, non-grav dark force ?

"Sommerfeld enhancement" : e^+e^- & γ

Search with electron scattering





Dark Forces: Long Range ?

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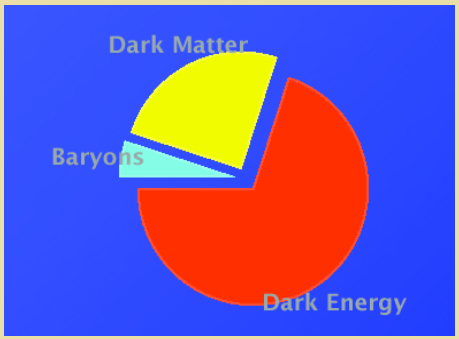

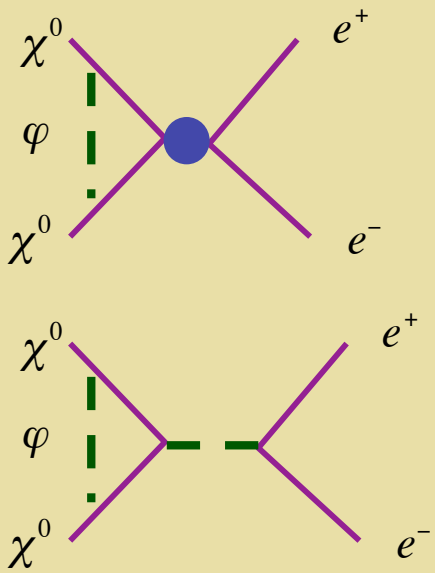

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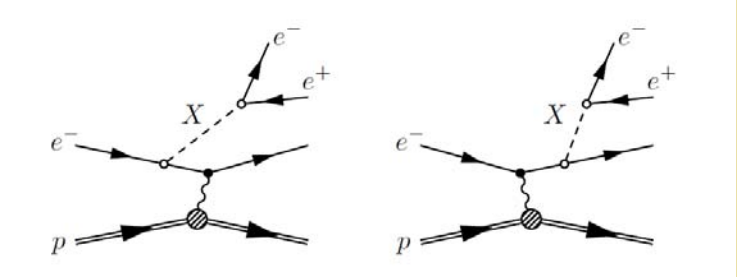
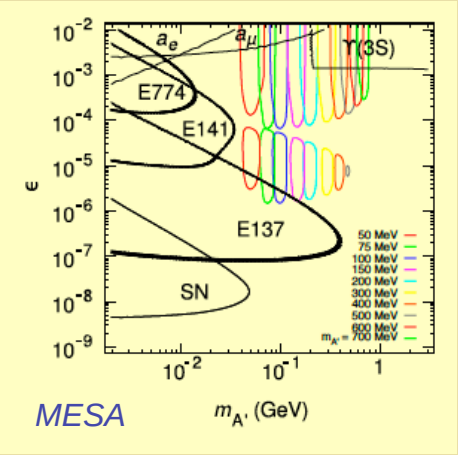
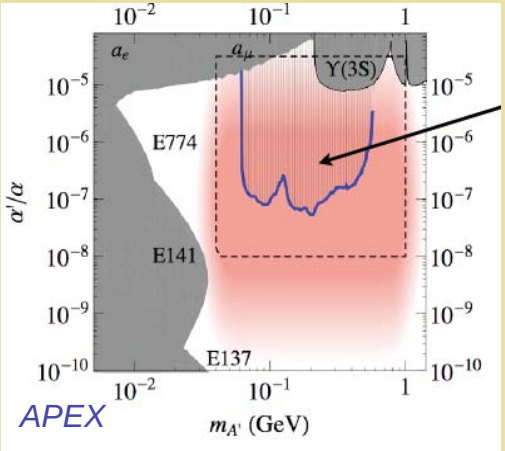






The Precision Frontier

Fifty years of PV in nuclear physics

High precision tests of the weak and strong interaction have played an essential role in developing and testing the Standard Model of elementary particle physics

Z factories at CERN & SLAC

The Precision Frontier

Fifty years of PV in nuclear physics

During the coming decade, precision studies at low and high energies will be a vital complement to the LHC in searching for the "new" Standard Model

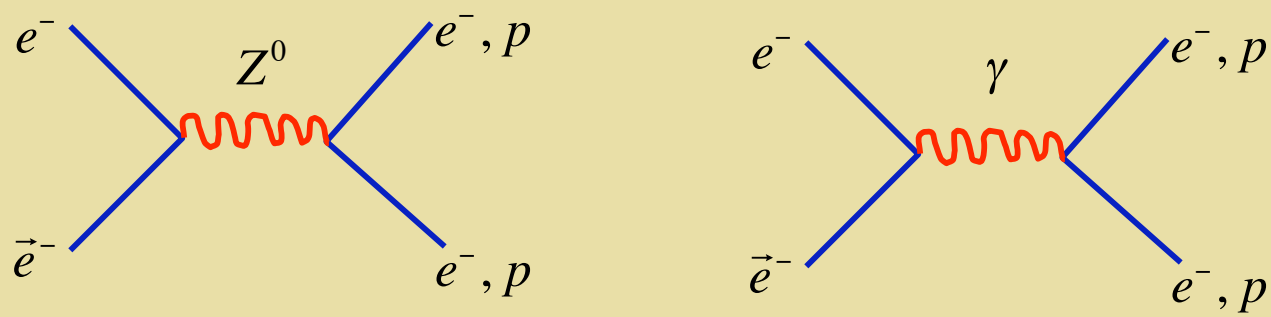
ANL, JLAB, ILL, PSI, + ….

Z factories at CERN & SLAC

Back Up Slides

Defining Weak Charge

Parity-Violating electron scattering



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

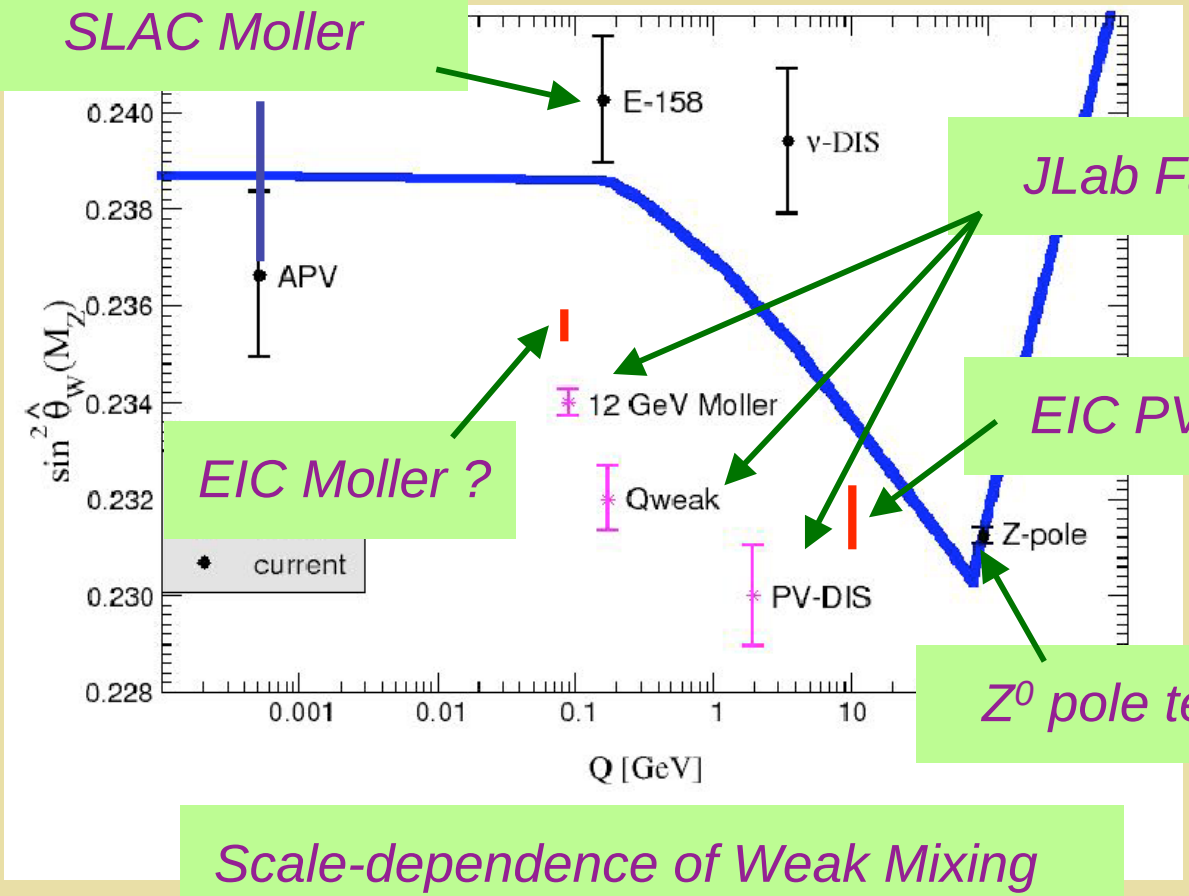
$$A^{PV} = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} = \frac{G_F t}{4\sqrt{2}\pi\alpha_{em}} \frac{W^{\mathrm{PV}}}{W^{\mathrm{EM}}}$$

$$Q_W^p = \lim_{t \to 0} \frac{W^{\mathrm{PV}}}{W^{\mathrm{EM}}}\bigg|_{E=0}$$

Weak Mixing in the Standard Model

Parity-violating electron scattering

SLAC Moller



JLab Future

EIC PVDIS ?

EIC Moller ?

Z^0 pole tension

Scale-dependence of Weak Mixing

Weak Mixing in the Standard Model

Erler & R-M

$$\hat{s}^2 \frac{d\hat{\alpha}}{dt} - \hat{\alpha}\frac{d\hat{s}^2}{dt} = \frac{b_2}{\pi}\hat{\alpha}^2 + \sum_j \frac{b_{2j}}{\pi^2}\hat{\alpha}^2\hat{\alpha}_j + \cdots$$

Full $SU(2)_L \times U(1)_Y$ RGE

$$\sin^2\hat{\theta}_W(\mu) = \frac{\hat{\alpha}(\mu)}{\hat{\alpha}(\mu_0)}\sin^2\hat{\theta}_W(\mu_0) + \frac{\sum_i N_i^c \gamma_i Q_i T_i}{\sum_i N_i^c \gamma_i Q_i^2}\left[1 - \frac{\hat{\alpha}(\mu)}{\hat{\alpha}(\mu_0)}\right],$$

Relate running of $\sin^2\theta_W$ to running of α

Weak Mixing in the Standard Model

Erler & R-M

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Relate running of $\sin^2\theta_W$ to running of α

1. *Run α & $\sin^2\theta_W$ to $\mu \sim m_c$*
2. *Bound s-quark contribution to $\alpha(m_c)$ -- relative to u and d contributions -- using heavy quark and $SU(3)_f$ limits*

Weak Mixing in the SM: Uncertainties

Erler & R-M

$$\hat{s}^2 \frac{d\hat{\alpha}}{dt} - \hat{\alpha}\frac{d\hat{s}^2}{dt} = \frac{b_2}{\pi}\hat{\alpha}^2 + \sum_j \frac{b_{2j}}{\pi^2}\hat{\alpha}^2\hat{\alpha}_j + \cdots$$

Full $SU(2)_L \times U(1)_Y$ RGE

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Uncertainties: $\sin^2\theta_W(0)$

+/- 3×10^{-5} : $\Delta\alpha^{(3)}(m_c)$

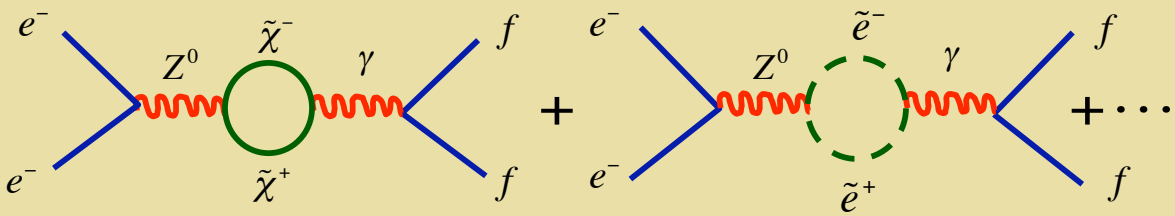
+/- 5×10^{-5}: $\Delta\alpha^{(2)}(m_s)$

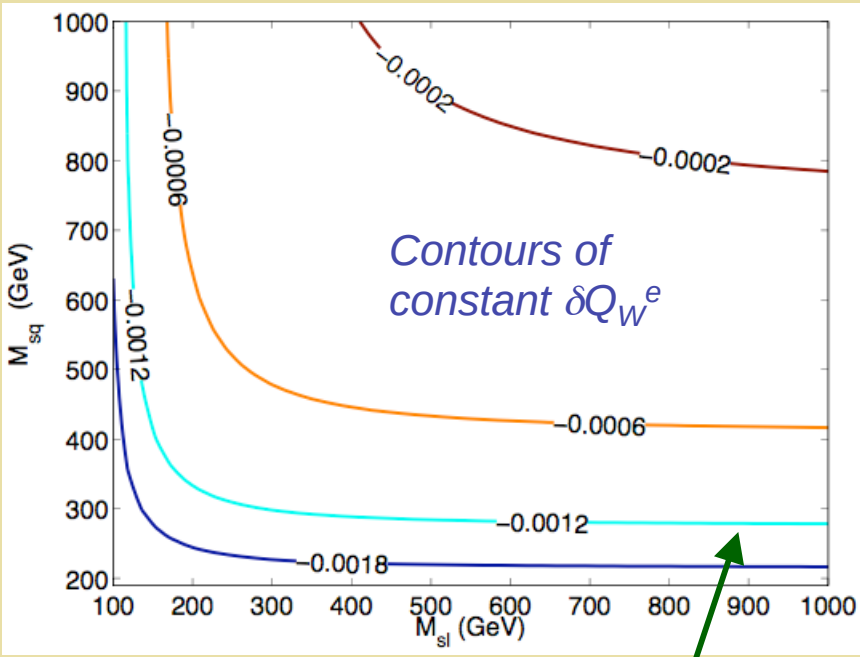
+/- 3×10^{-5}: OZI

+/- 1.5×10^{-4} : $\sin^2\theta_W(M_Z)$

Probing Sfermion Mass Scale

SUSY Loops: Kurylov, SU, MR-M



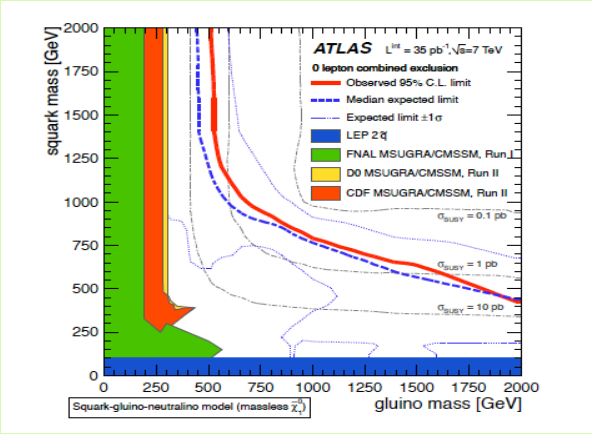


Su, R-M Preliminary

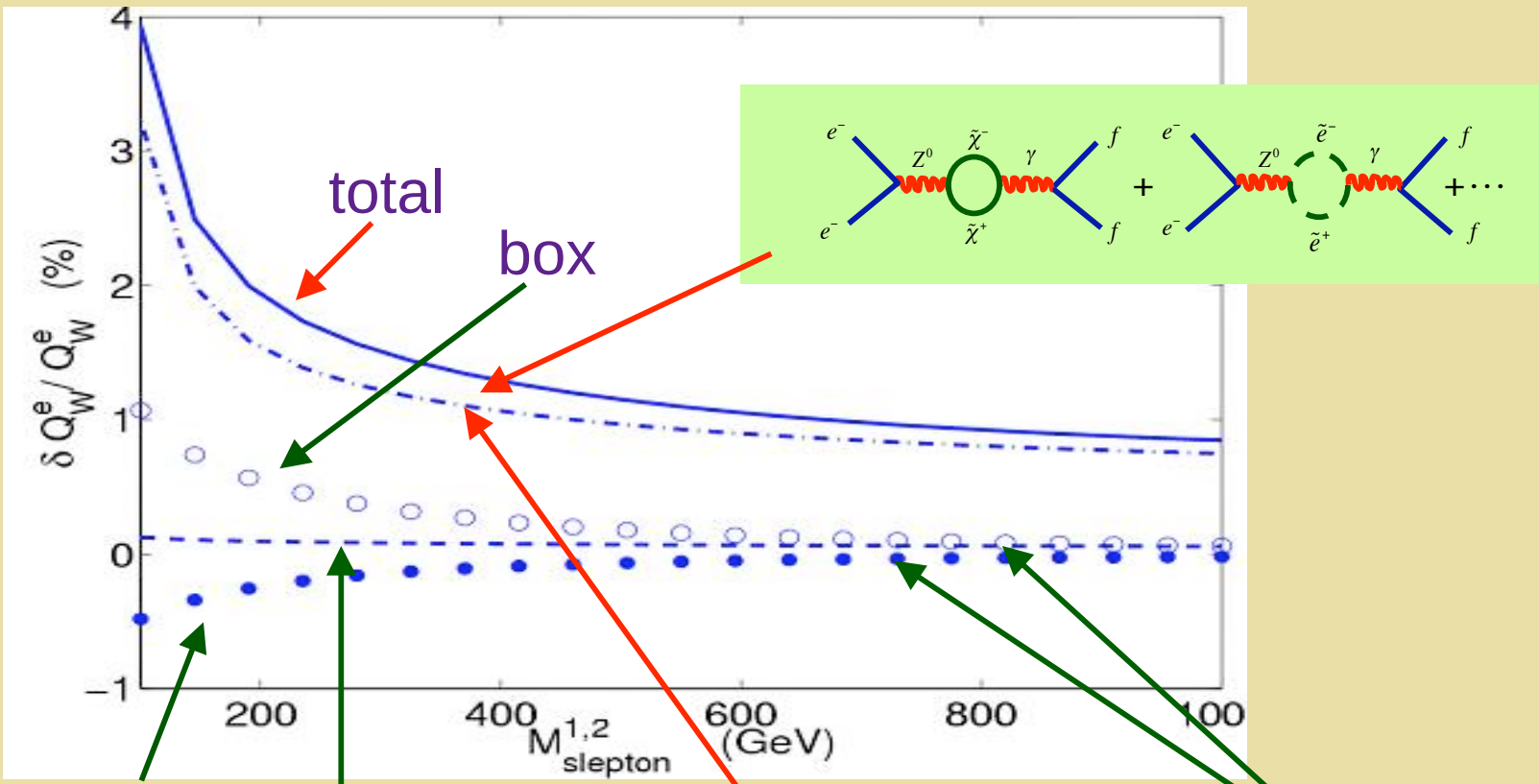
Jlab Moller 1σ

ATLAS Exclusion: simplified model

arXiv: 1102.5290



Unpacking SUSY Radiative Corrections



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

$C_{1,2}$ and Radiative Corrections

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

Radiative Corrections

Flavor-dependent

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

Normalization

Scale-dependent effective weak mixing

Flavor-independent

$C_{1,2}$ and Radiative Corrections

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

Radiative Corrections

Flavor-dependent

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

Constrained by Z-pole precision observables

Scale-dependent effective weak mixing

Flavor-independent

$C_{1,2}$ and Radiative Corrections

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Radiative Corrections

Flavor-dependent

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

Constrained by Z-pole precision observables

Large logs in κ :

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

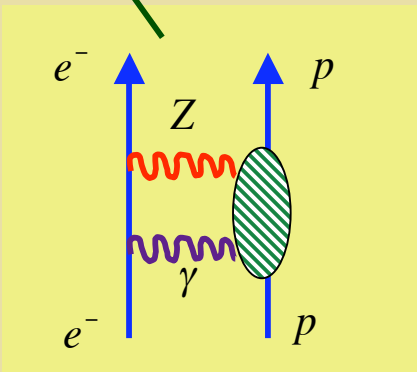
Flavor-indeper

Radiative Correction Uncertainties

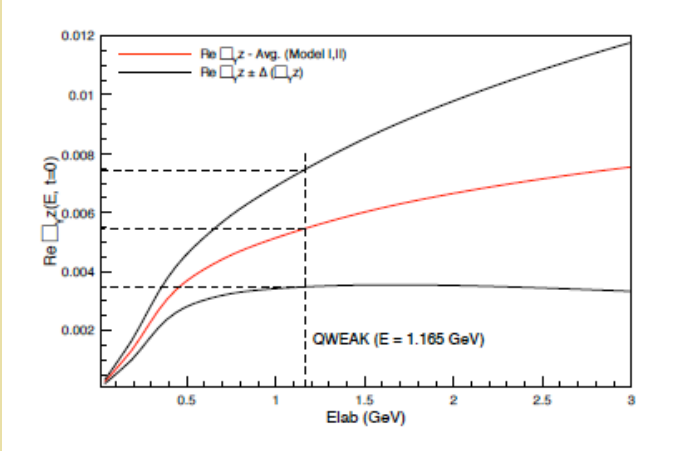
$$A_{PV} = \frac{N_{\uparrow\uparrow} - N_{\uparrow\downarrow}}{N_{\uparrow\uparrow} + N_{\uparrow\downarrow}} = \frac{G_F Q^2}{4\sqrt{2}\pi\alpha}\left[Q_W + F(Q^2, E)\right]$$

E-dependent: E = 1.165 GeV

Ref. [11]	Ref. [15]	Ref. [17]	This work
$(3 \pm 3)10^{-3}$	$(4.7^{+1.1}_{-0.4})10^{-3}$	$(5.7 \pm 0.9)10^{-3}$	$(5.4 \pm 2.0)10^{-3}$



Lower energy measurement



APV isotope ratios: E ~ 180 MeV, Q^2 ~ 0

$$Q_W(N') - Q_W(N) \approx -N' + N + (N' - N)\Delta Q_W^N$$
$$= (N - N')\left[1 - \Delta Q_W^N\right]$$

$$Q_W(N') + Q_W(N) \approx -(N + N') + (N + N')\Delta Q_W^N + 2Z\Delta Q_W^P$$
$$= -(N + N')\left[1 - \Delta Q_W^N - \left(\frac{2Z}{N + N'}\right)\Delta Q_W^P\right]$$

PVDIS & QCD

Low energy effective PV eq interaction

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

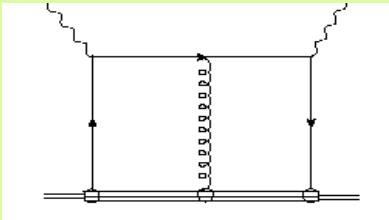
PV DIS eD asymmetry: leading twist

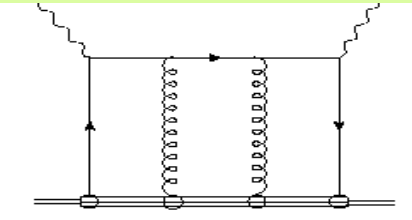
$$A_{PV}^{eD} = \frac{3 G_\mu Q^2}{2\sqrt{2}\pi\alpha} \left[\frac{2C_{1u} - C_{1d} + Y(2C_{2u} - C_{2d})}{5} \right] +$$

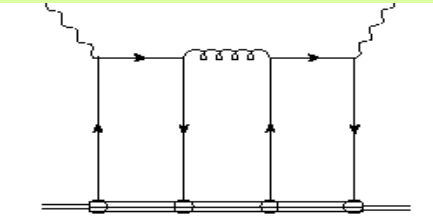
Higher Twist (J Lab)

CSV (J Lab, EIC)

d/u (J Lab, EIC)

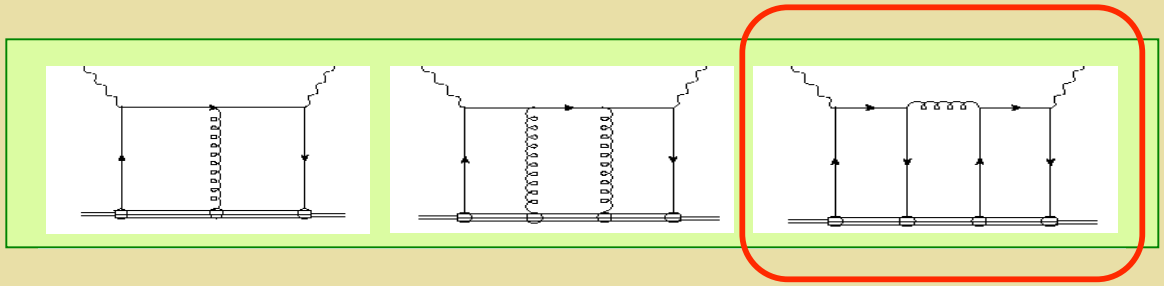






Bjorken & Wolfenstein '78

Isolates 4q HT operator: PVDIS a unique probe



y-independent term: C_{1q}

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

Differences in VV and SS:

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

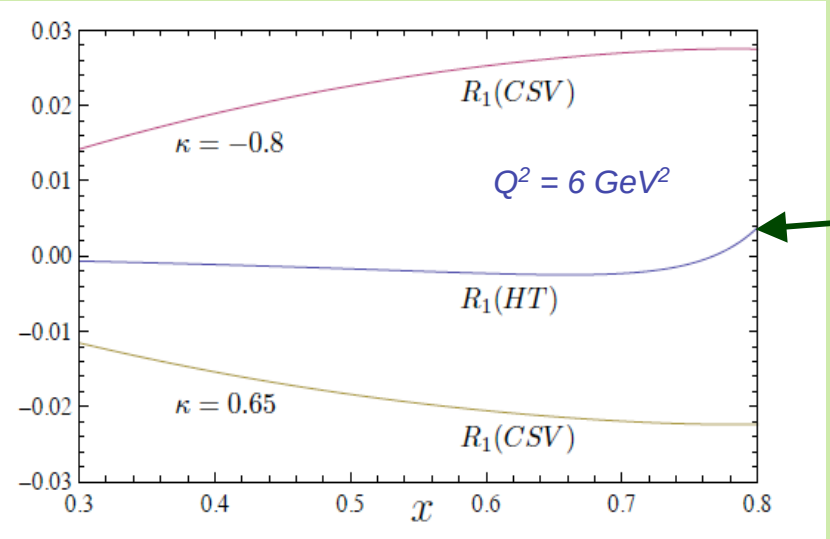
C_{1q} terms are "contaminated" only by 4q, double handbag $\tau = 4$ effects

PVDIS: CSV & HT

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

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

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



HT & CSV in C_{1q} term

HT:MIT BM

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

PVDIS & CSV

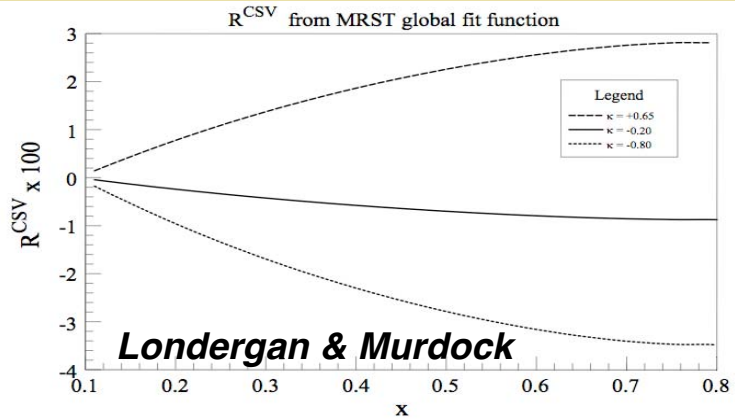
$$A_{PV}^{eD} = \frac{3G_\mu Q^2}{2\sqrt{2}\pi\alpha}\left[\frac{2C_{1u} - C_{1d} + Y(2C_{2u} - C_{2d})}{5}\right]$$

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

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

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

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



Few percent δA/A

Adapted from K. Kumar