Fundamental Symmetries in Nuclei: Tackling the Strong Interaction and Hunting for New Physics

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About MJRM:

Science

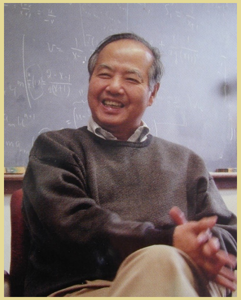
Family

Friends

My pronouns: he/him/his
 # MeToo

USTC Colloquium June 4, 2024

T. D. Lee Institute / Shanghai Jiao Tong U.



Director

A point of convergence of the world's top scientists

A launch pad for the early-career scientists

A world famous source of original innovation

Founded 2016

100+

faculty members from 17 countries and regions, with over 40% of them foreign (non-Chinese) citizens

Theory & Experiment

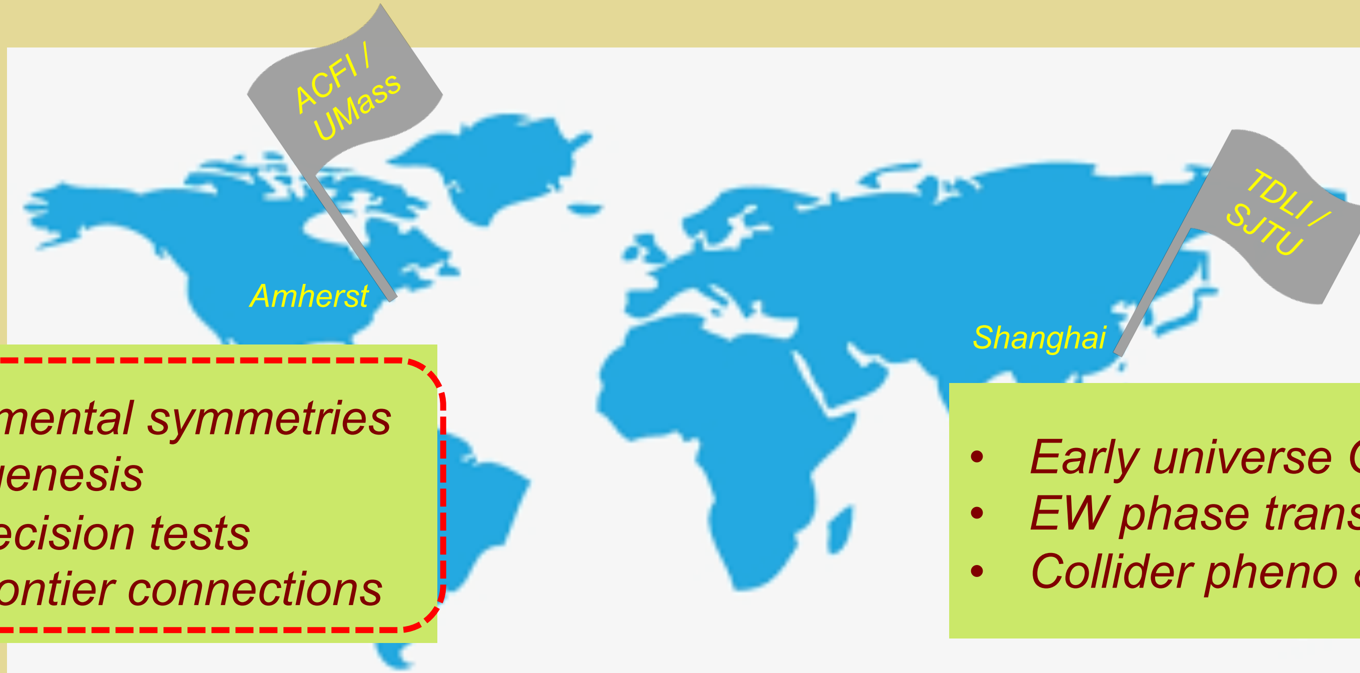
Particle & Nuclear Physics	Astronomy & Astrophysics	Quantum Science
Dark Matter & Neutrino	Laboratory Astrophysics	Topological Quantum Computation

https://tdli.sjtu.edu.cn/EN/

https://www.youtube.com/watch?v=z0awD6q8FTI

MJRM: Scientist & "Ambassador"

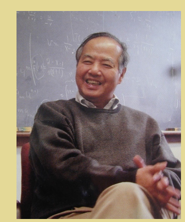
This talk



- *Fundamental symmetries*
- *Baryogenesis*
- *EW precision tests*
- *Inter-frontier connections*

- *Early universe QFT*
- *EW phase transition*
- *Collider pheno & Higgs*

- ***Global effort: ~ 20 researchers***
- ***Foster scientific connections***
- ***Science First ! 科学 第一 ！***



Key Theme for This Talk

- *Fundamental symmetry tests with nuclei & hadrons address compelling questions about the fundamental laws of nature both within and beyond the Standard Model*
- *Advances in experimental sensitivities challenge theory to push the state-of-the-art in Standard Model computations and delineate the broader implications of of these experiments for our understanding of the strong interaction and beyond Standard Model physics*
- *Theoretical developments are meeting this challenge head on, uncovering new puzzles, and pointing toward the next horizon in experimental sensitivity*

Outline

I. Context

II. Four Quests

Today

A. Parity-violation with electrons

Another time

B. Lepton Number: $0\nu\beta\beta$-Decay

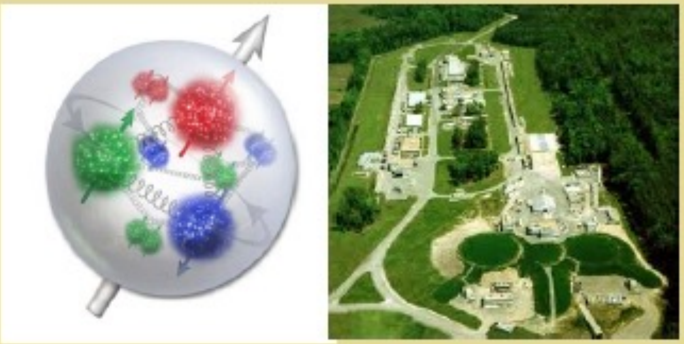
C. β–Decay: 65 years after Wu et al

D. CP: Electric Dipole Moments & the Origin of Matter

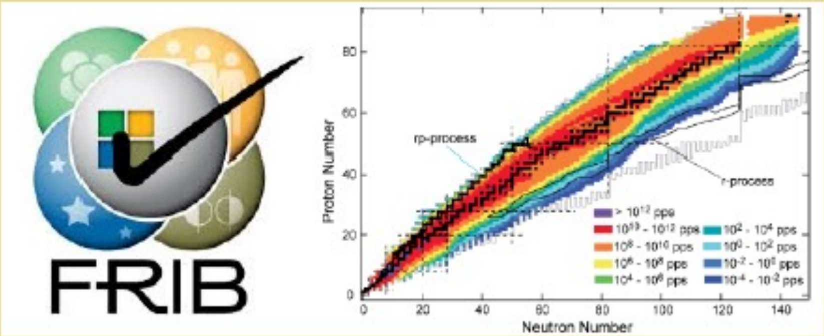
III. Concluding Remarks

I. Context

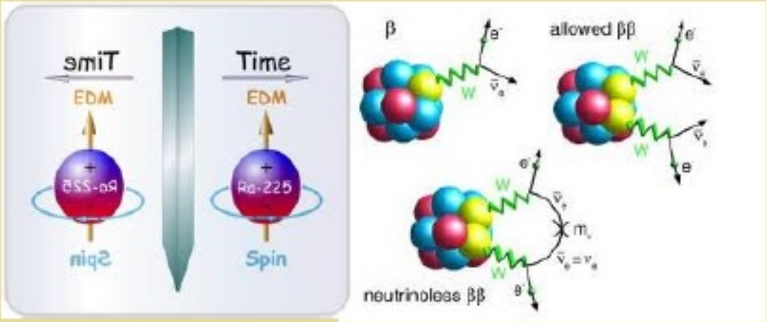
Nuclear Physics Today



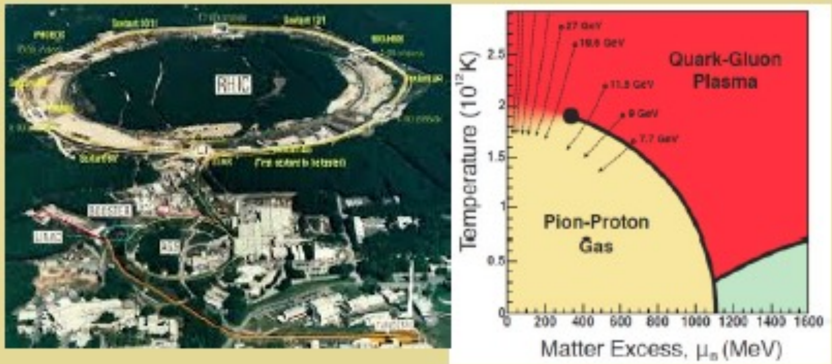
Hadron structure & dynamics: "cold QCD"



Rare isotopes: nuclear structure & astrophysics



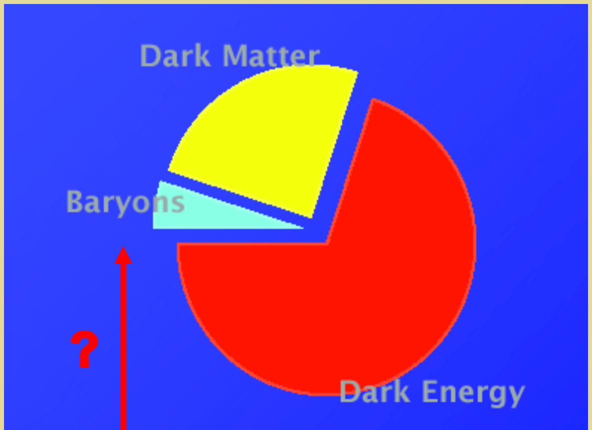
Fundamental symmetries & neutrinos: "Intensity Frontier"

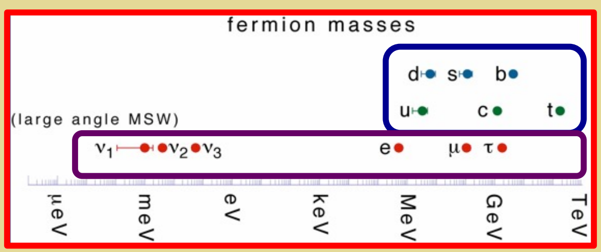


Relativistic heavy ions: "hot & dense QCD"

Fundamental Questions

Matter, Energy & Mass

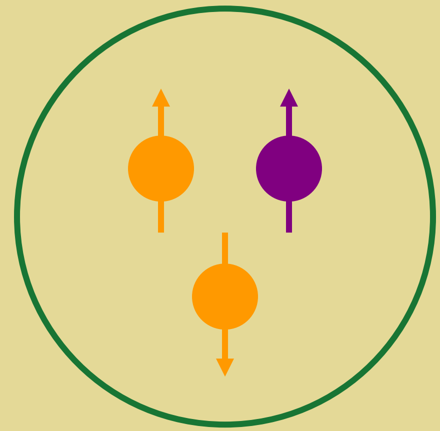




Origin of m_f

Beyond Standard Model

Nucleon & Nuclear Structure



How does QCD build nucleons and nuclei with quarks & gluons ?

Within Standard Model

Fundamental Symmetries

- *Discrete: parity (P), charge conjugation (C), time-reversal (T),…*

Parity:

$$\vec{x} \longrightarrow -\vec{x}$$
$$\vec{S} \longrightarrow \vec{S}$$

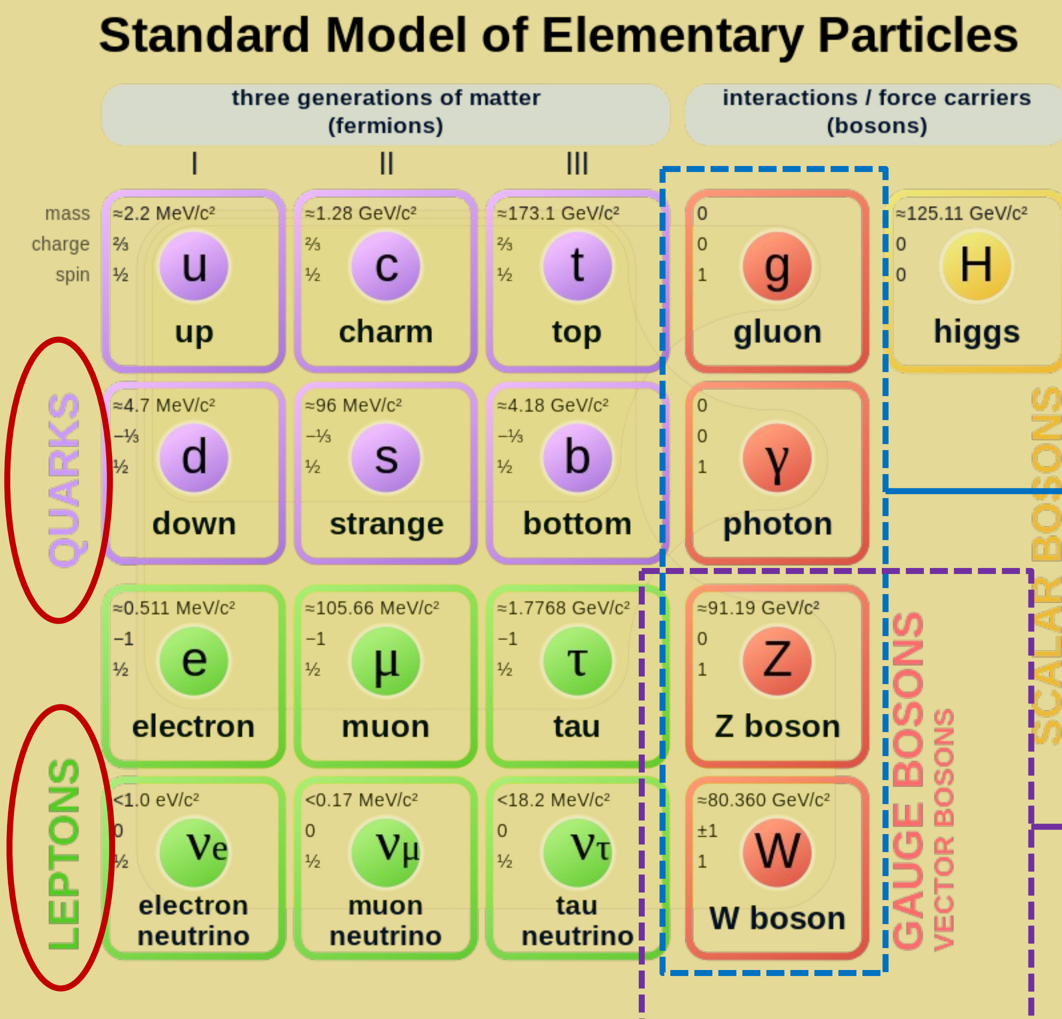
- *Continuous: QED U(1), weak isospin $SU(2)_L$, color $SU(3)_C$, chiral, …*

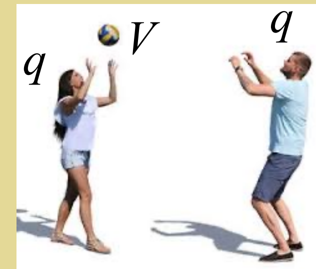
SU(N):

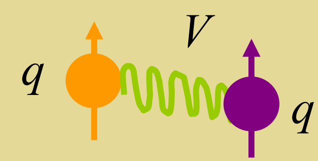
$$\psi \longrightarrow U\,\psi \quad , \qquad U = \exp\left[i\vec{\alpha}(x)\cdot\vec{T}\right]$$

Standard Model

$SU(3)_C \times SU(2)_L \times U(1)_Y$: Strong, EM, & Weak







$V = g, \gamma, W, Z$

Weak force violates P, CP, T

Nuclei & Hadrons as Laboratories

EDM searches: BSM CPV, Origin of Matter **CP Violation**	$0\nu\beta\beta$ decay searches: Nature of neutrino, Lepton number violation, Origin of Matter **Lepton Number Violation**
Electron & muon prop's & interactions: SM Precision Tests, BSM "diagnostic" probes **Parity Violation**	Radioactive decays & other tests SM Precision Tests, BSM "diagnostic" probes **Parity Violation**

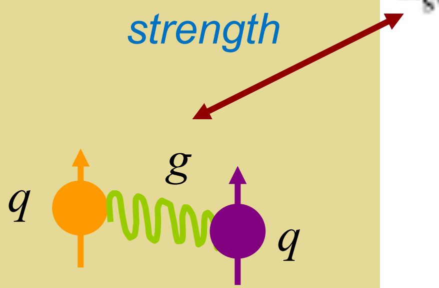
Today

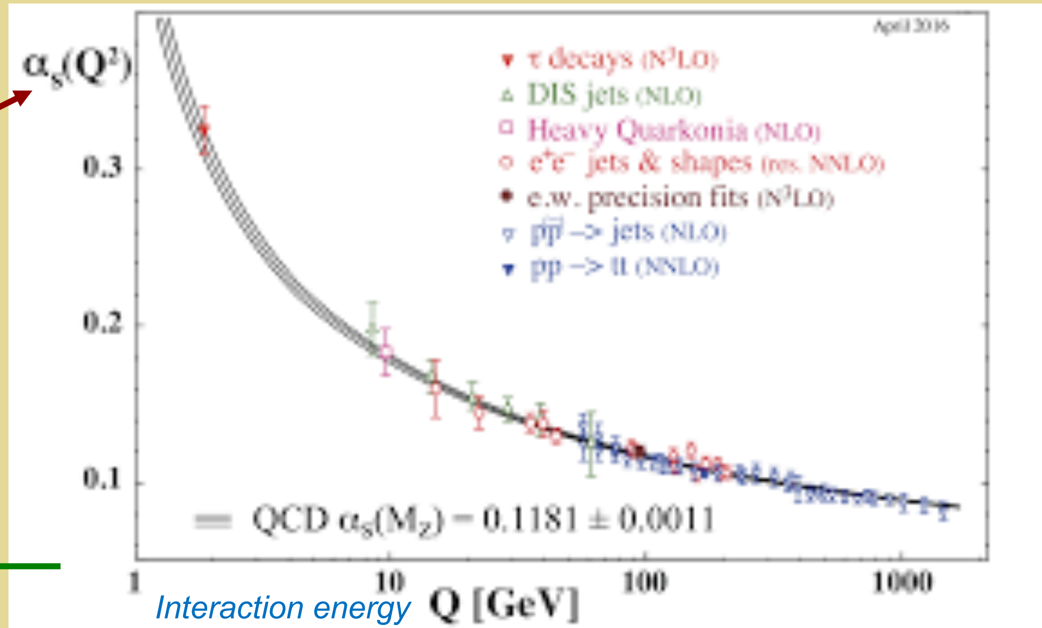
Theoretical Challenges

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

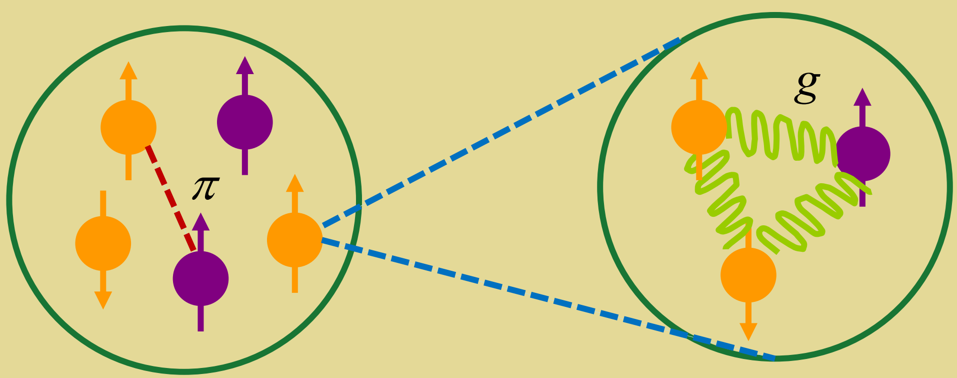
Low-Energy QCD Is Strong

Interaction strength





Nuclei & hadrons



Nucleus

Nucleon

Theoretical Challenges

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

BSM physics

Nuclei as laboratories

"I want you to better understand me"

"I am incomplete, but I need you"

Electroweak probes

Theoretical Challenges

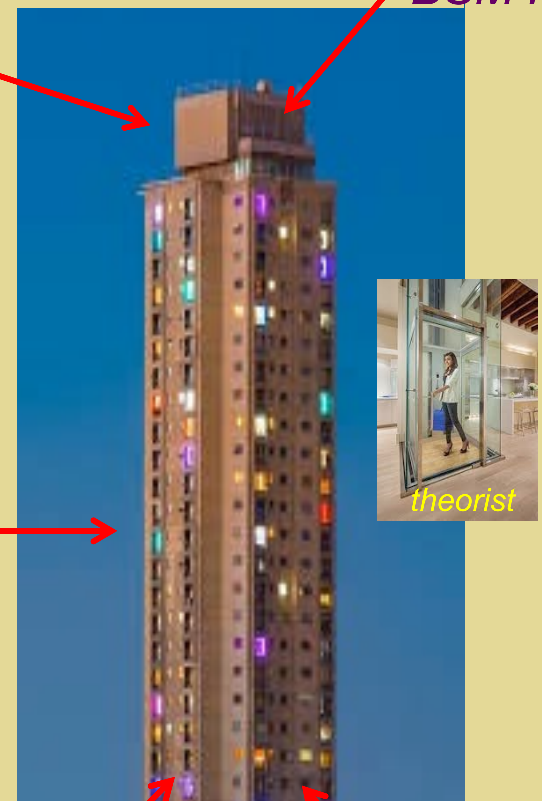
Early Universe

BSM Physics

Energy Scale

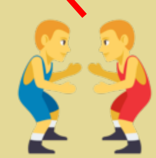
BSM Scale

Weak Scale:
246 GeV



Experiments

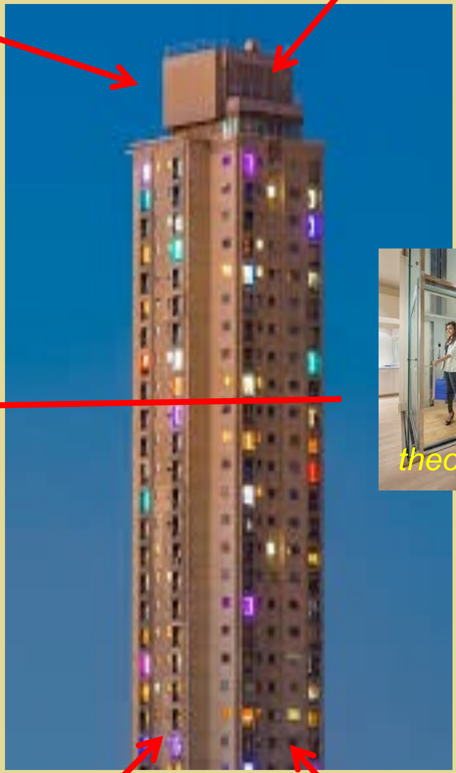
Theory



Theoretical Challenges

Early Universe

BSM Physics

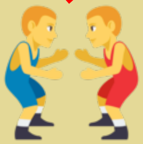


Precision Electroweak Studies

- ***Perturbation theory***
- ***Effective Field Theory***
- ***Non-equilibrium QFT***
- ***Dispersion Relations***
- ***Collider simulations & phenomenology***

Experiments

Theory



Theoretical Challenges

- ***How reliably can we interpret electroweak processes at the nuclear and hadronic scales in terms of***
  - ***nucleon & nuclear structure ?***
  - ***beyond Standard Model physics ?***

- ***What is the theoretical error bar ?***

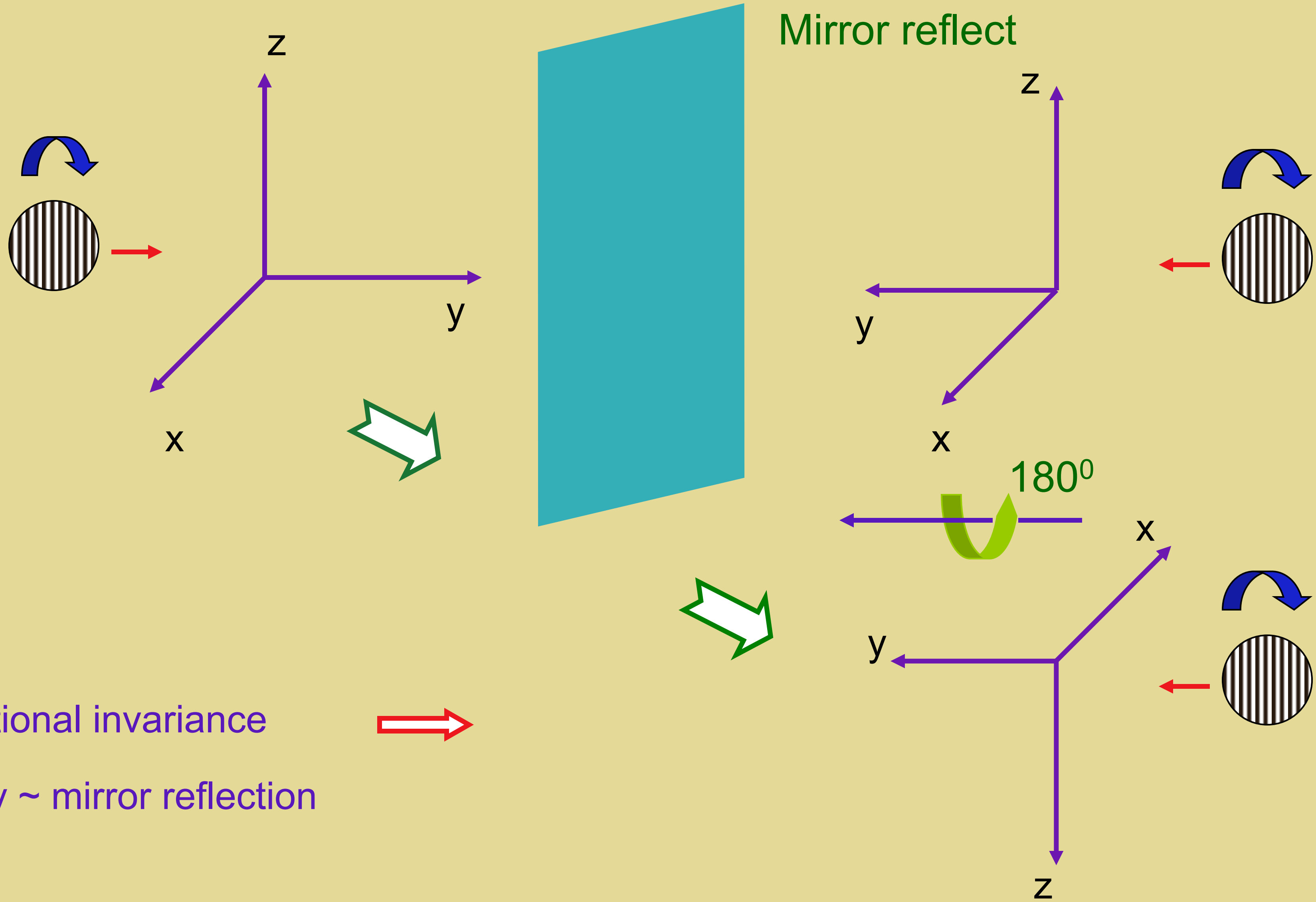
IIA. Parity-Violation with Electrons

Symmetries Score Card

Force	P	C	T	CPT
Gravity	Yes	Yes	Yes	Yes
E.M.	Yes	Yes	Yes	Yes
Strong	Yes	Yes	Yes	Yes
Weak	No	No	No	Yes

C: $e^+ \longleftrightarrow e^-$ T: $t \longleftrightarrow -t$

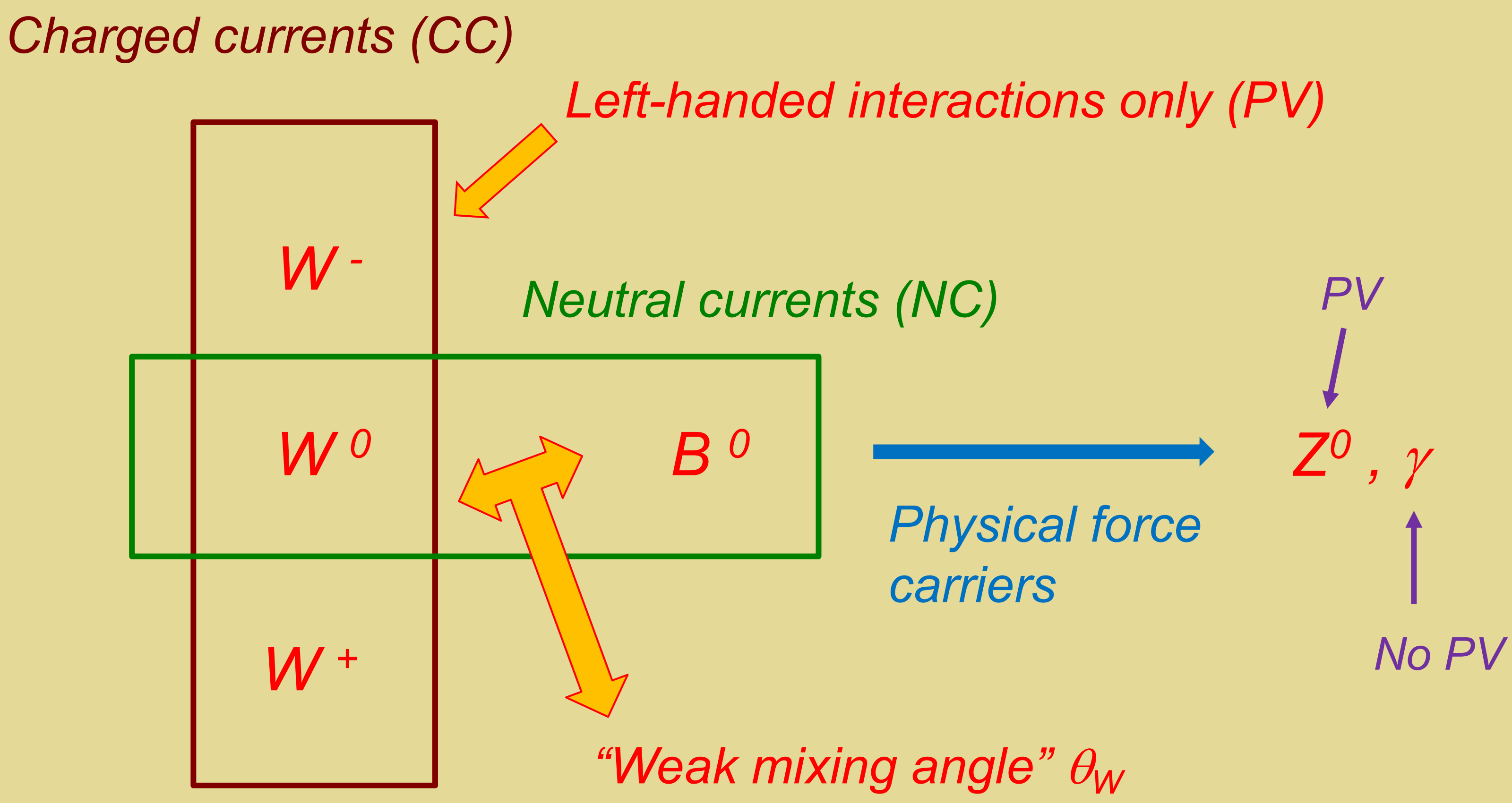
Exploit Parity Symmetry



Rotational invariance ⇒

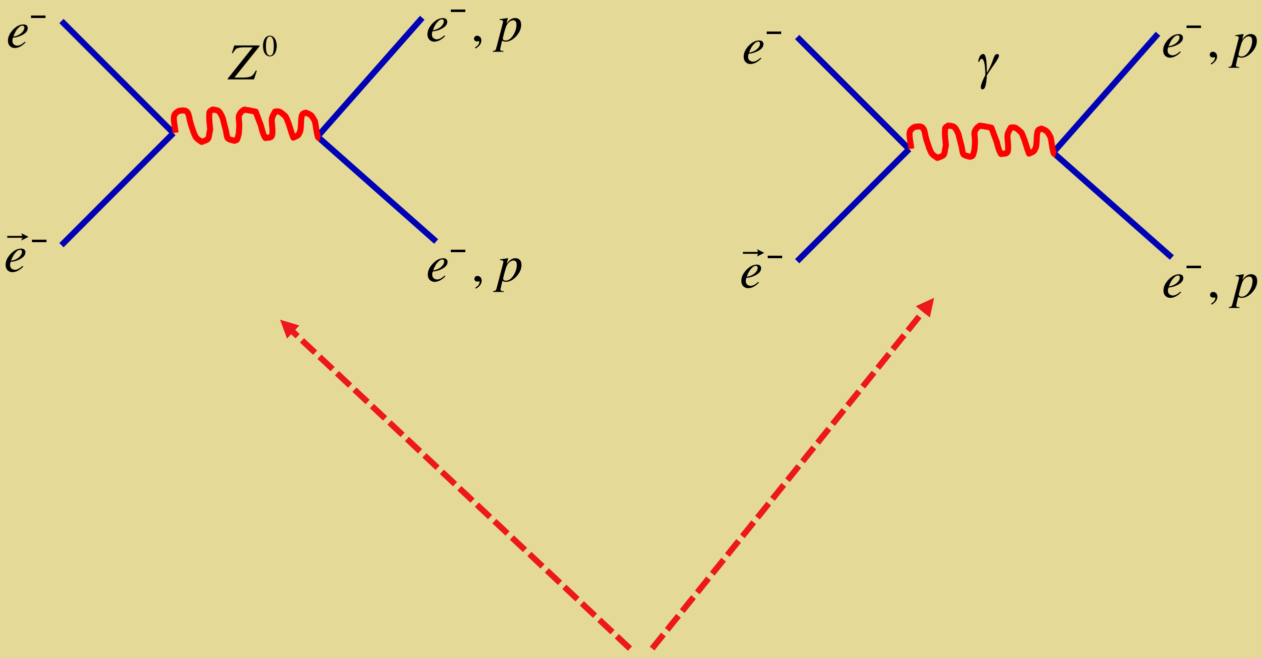
Parity ~ mirror reflection

Fermion Electroweak Interactions & PV

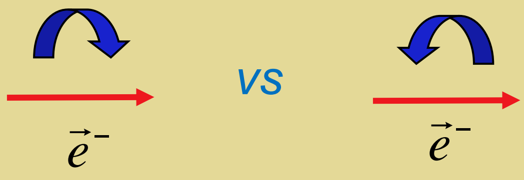


Weak interaction flavor basis:
"primordial" force carriers

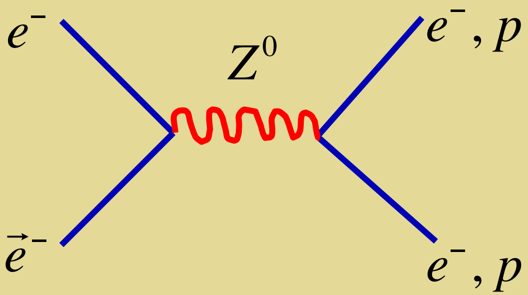
Parity-Violation: Scattering & Atoms

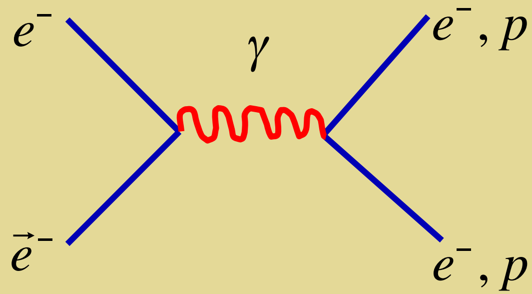


PV: quantum interference



Parity-Violation & Weak Charges





Parity-Violating electron scattering

Sensitive to weak mixing

$$A_{PV} = \frac{N_{\uparrow\uparrow} - N}{N_{\uparrow\uparrow} + N} \sim 10^{-6}\left(\frac{Q}{M_p}\right)^2 \left[Q_W + F(Q^2,\theta)\right]$$

Atomic parity-violation

$$E_1^{PV} / \beta = i\, e\, \mathcal{M} \times 10^{-11}\, a_0\, (Q_W / N) / \beta$$

Weak Charge & Weak Mixing

Near cancellation

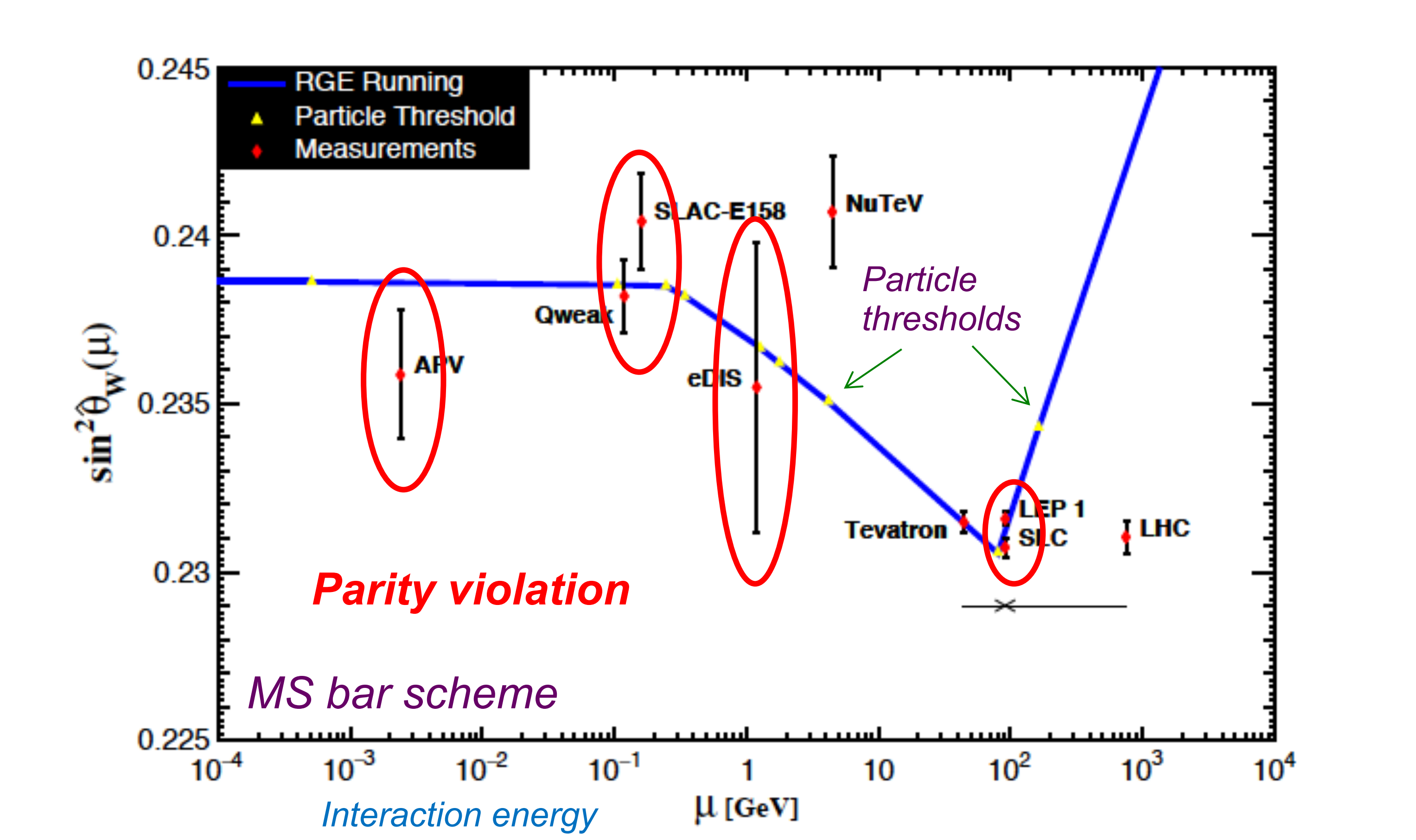
$$Q_W^P = -Q_W^e = 1 - 4\sin^2\theta_W$$

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

$SU(2)_L$ — $U(1)_Y$

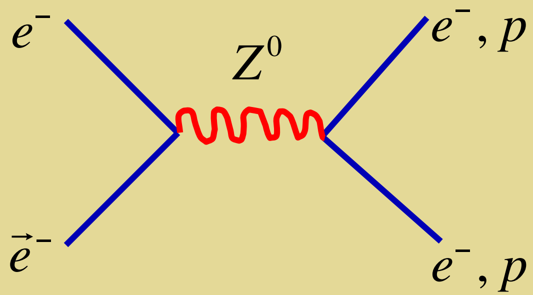
Weak mixing depends on scale

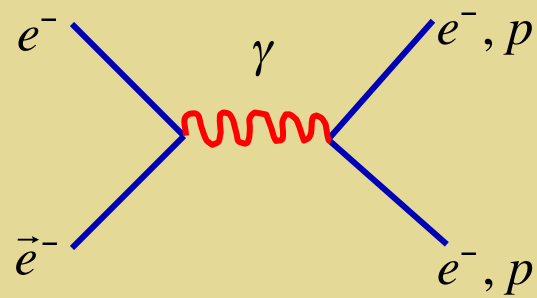
Weak Mixing Depends on Energy Scale



Marciano & Czarnecki '00
Erler & MJRM '05
Erler & Ferro-Hernandez '18

Parity-Violation & Weak Charges





Parity-Violating electron scattering

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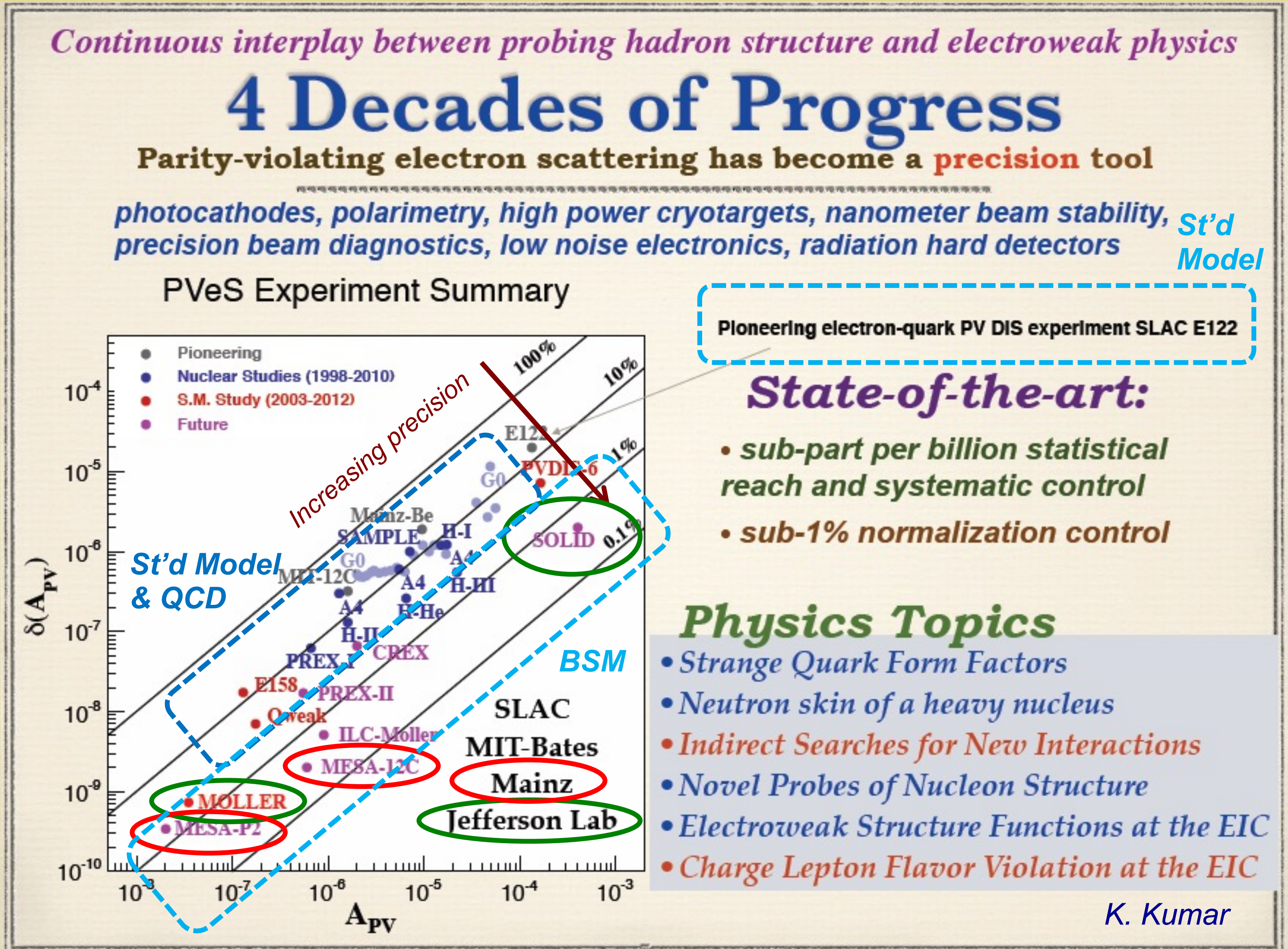
"Weak Charge" ~ 0.1 in SM

Enhanced transparency to beyond Standard Model physics

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

Nucleon internal structure: strong interaction (QCD) dynamics at low energy

PV Electron Scattering



PV Electron Scattering

Continuous interplay between probing hadron structure and electroweak physics

4 Decades of Progress

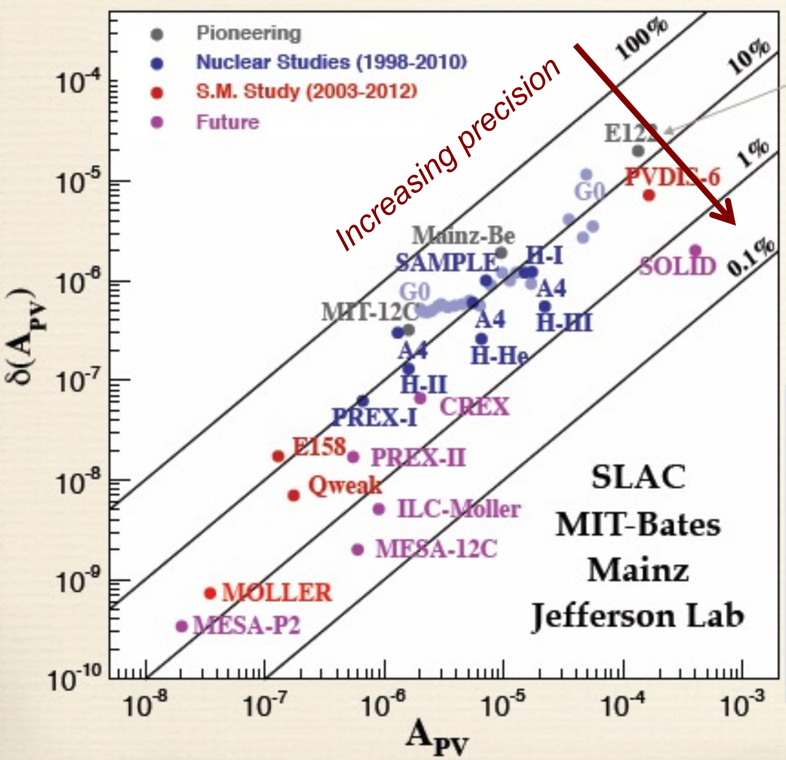
Parity-violating electron scattering has become a precision tool

photocathodes, polarimetry, high power cryotargets, nanometer beam stability, precision beam diagnostics, low noise electronics, radiation hard detectors

St'd Model

PVeS Experiment Summary

Pioneering electron-quark PV DIS experiment SLAC E122



State-of-the-art:

- *sub-part per billion statistical reach and systematic control*
- *sub-1% normalization control*

Physics Topics

- *Strange Quark Form Factors*
- *Neutron skin of a heavy nucleus*
- *Indirect Searches for New Interactions*
- *Novel Probes of Nucleon Structure*
- *Electroweak Structure Functions at the EIC*
- *Charge Lepton Flavor Violation at the EIC*

K. Kumar

SLAC '77: PV Deep Inelastic Scattering

Glashow-Weingerg-Salam:
Standard Model

PARITY NON-CONSERVATION IN INELASTIC ELECTRON SCATTERING ☆

C.Y. PRESCOTT, W.B. ATWOOD, R.L.A. COTTRELL, H. DeSTAEBLER, Edward L. GARWIN, A. GONIDEC [1], R.H. MILLER, L.S. ROCHESTER, T. SATO [2], D.J. SHERDEN, C.K. SINCLAIR, S. STEIN and R.E. TAYLOR
Stanford Linear Accelerator Center, Stanford University, Stanford, CA 94305, USA

J.E. CLENDENIN, V.W. HUGHES, N. SASAO [3] and K.P. SCHÜLER
Yale University, New Haven, CT 06520, USA

M.G. BORGHINI
CERN, Geneva, Switzerland

K. LÜBELSMEYER
Technische Hochschule Aachen, Aachen, West Germany

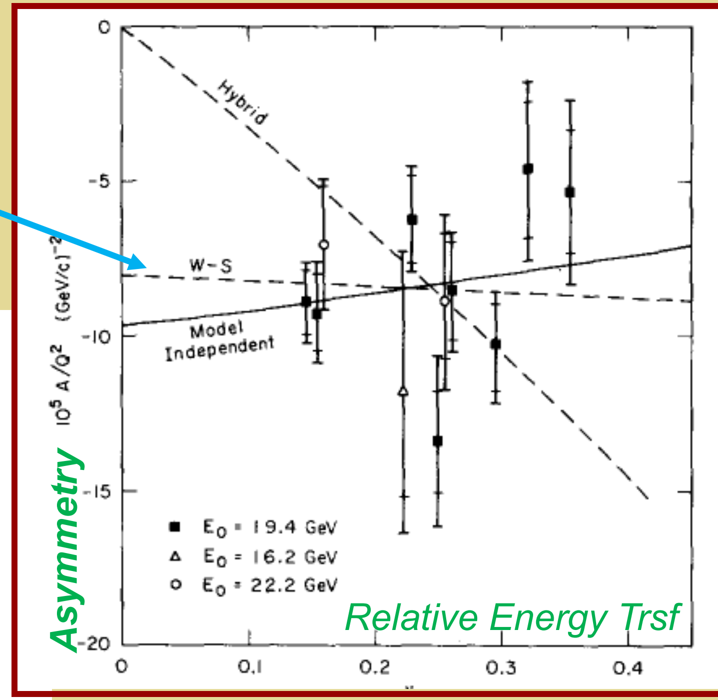
and

W. JENTSCHKE
II. Institut für Experimentalphysik, Universität Hamburg, Hamburg, West Germany

Received 14 July 1978

We have measured parity-violating asymmetries in the inelastic scattering of longitudinally polarized electrons from deuterium and hydrogen. For deuterium near $Q^2 = 1.6\ (\mathrm{GeV}/c)^2$ the asymmetry is $(-9.5 \times 10^{-5})Q^2$ with statistical and systematic uncertainties each about 10%.

Phys. Lett. B77, 347 (1977)



Phys. Lett. B84, 524 (1979)

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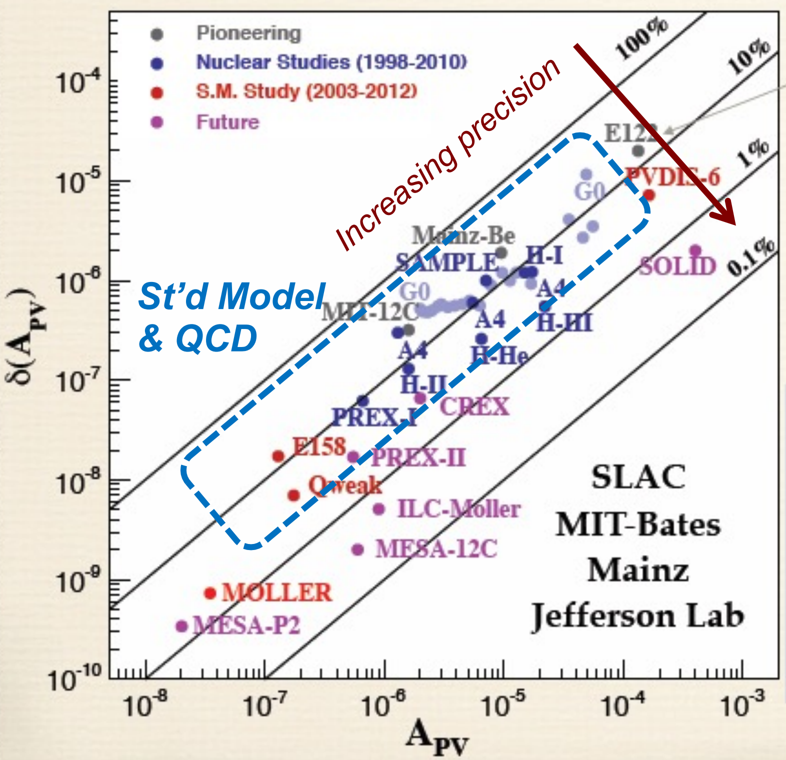

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K. Kumar

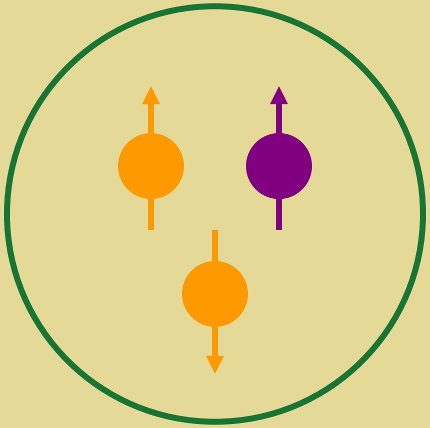
The Spin Crisis

Where does the Nucleon Spin come from?

$$\frac{1}{2} = \frac{1}{2}\,\Delta\Sigma + \Delta G + L_q + L_G$$

quark spin — *gluon spin* — *orbital motion*

VS



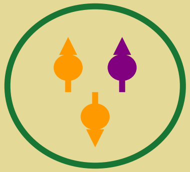
The Spin Crisis

Volume 206, number 2 PHYSICS LETTERS B 19 May 1988

A MEASUREMENT OF THE SPIN ASYMMETRY AND DETERMINATION OF THE STRUCTURE FUNCTION g_1 IN DEEP INELASTIC MUON–PROTON SCATTERING

European Muon Collaboration

$$A = \frac{d\sigma^{\uparrow\downarrow} - d\sigma^{\uparrow\uparrow}}{d\sigma^{\uparrow\downarrow} + d\sigma^{\uparrow\uparrow}}$$



$\Delta s = 0$

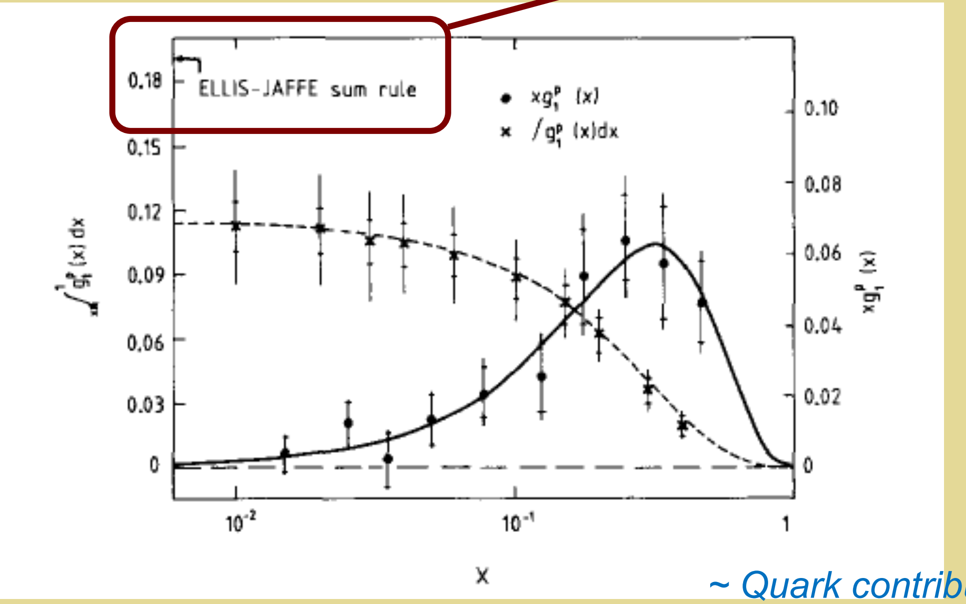
$$\langle S_z \rangle_u = 0.373 \pm 0.019 \pm 0.039\,,$$

$$\langle S_z \rangle_d = -0.254 \pm 0.019 \pm 0.039\,,$$

$$\langle S_z \rangle_s = -0.113 \pm 0.019 \pm 0.039\,,$$

$$\langle S_z \rangle_{u+d+s} = 0.006 \pm 0.058 \pm 0.117$$

Large negative strange sea polarization & small $\Delta\Sigma$

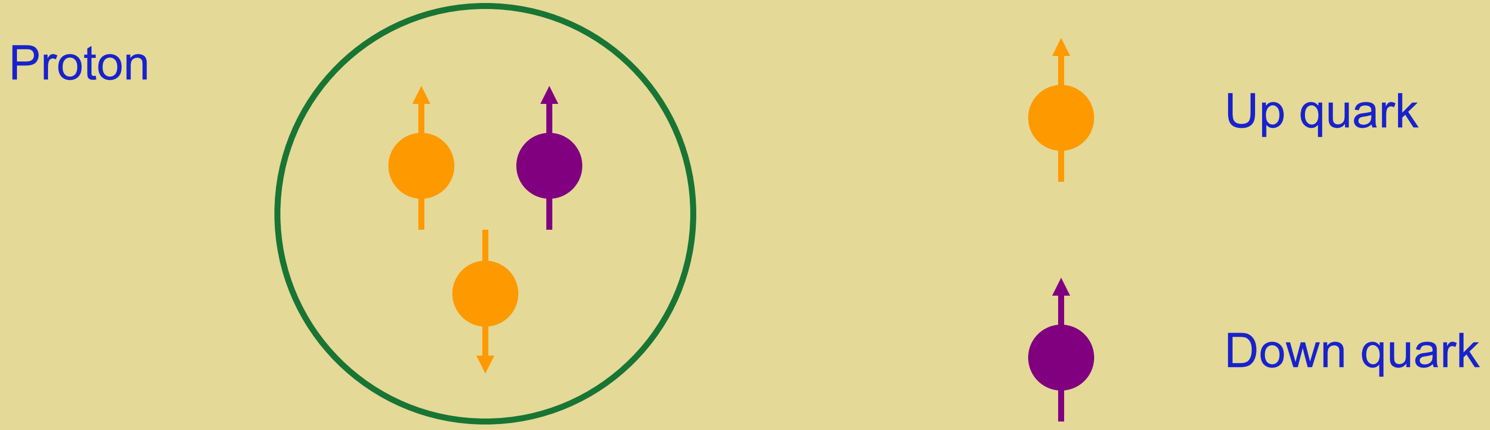


What about s-quarks & nucleon magnetic moment and charge distribution ?

$$g_1(x) = \frac{1}{2} \sum e_i^2 \left[q_i^+(x) - q_i^-(x) \right] \rightarrow \Delta q$$

~ Quark contribution to nucleon spin

The Constituent Quark Model gives a successful description



$$Q^P = 2\,Q^U + Q^D$$

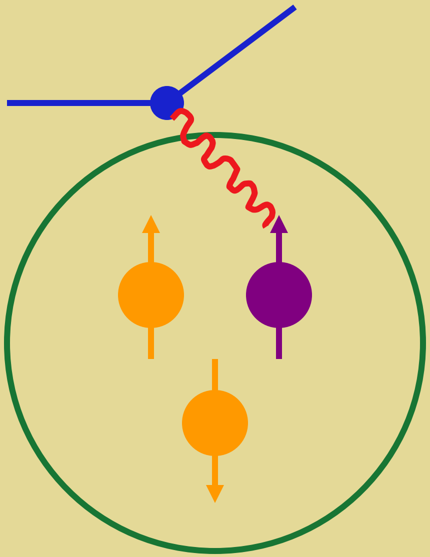
$$\kappa^P = Q^U\,\kappa^U{}_P + Q^D\,\kappa^D{}_P$$

$$Q^U = 2/3$$

$$Q^D = -1/3$$

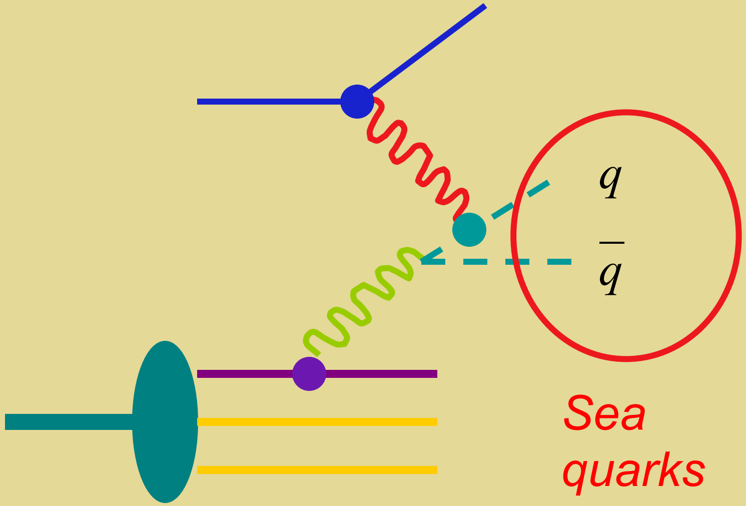
The Quark Model vs. QCD

Quantum Chromodynamics



Constituent quarks (QM)

Q^P , μ^P



Current quarks (QCD)

$F^P_2(x)$

We can uncover the sea with the Z^0

Light QCD quarks:

u $m_u \sim 5$ MeV

d $m_d \sim 10$ MeV

s $m_s \sim 150$ MeV

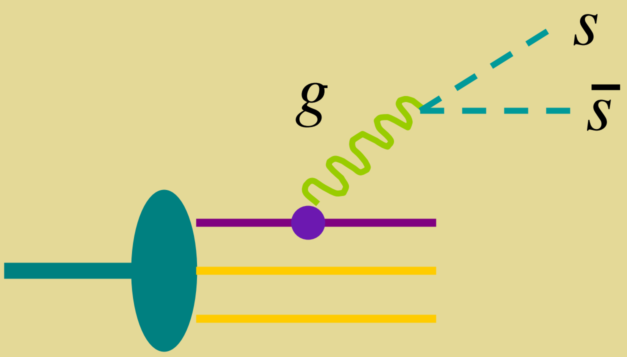
Lives only in the sea

Heavy QCD quarks:

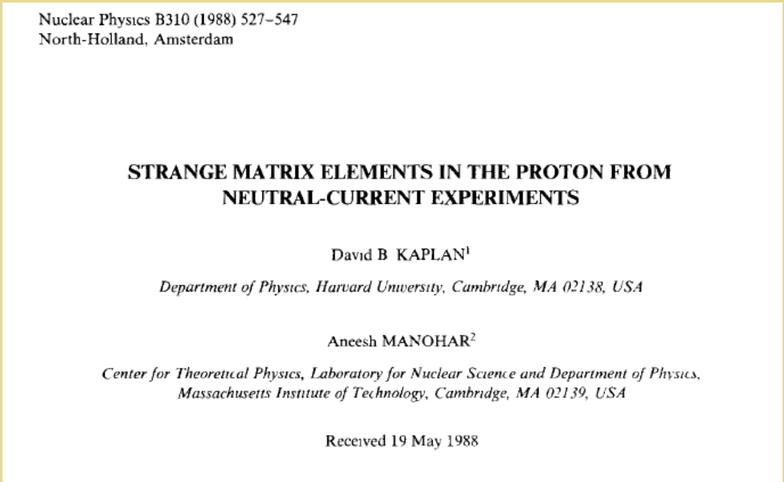
c $m_c \sim 1500$ MeV

b $m_b \sim 4500$ MeV

t $m_t \sim 175{,}000$ MeV



Weak Neutral Current is a Probe



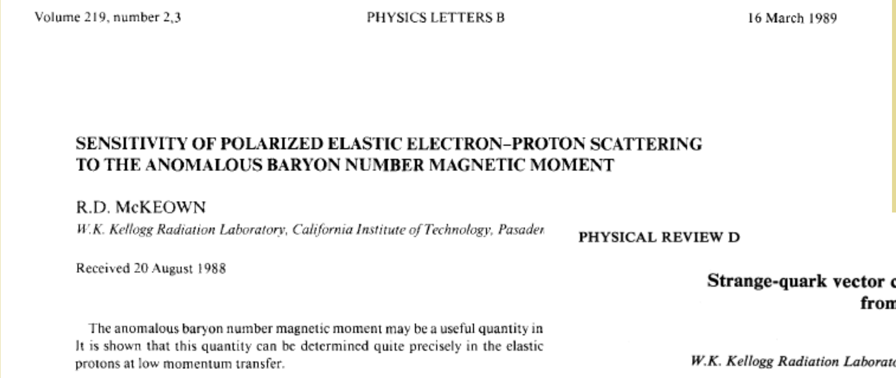
Nuclear Physics B310 (1988) 527–547
North-Holland, Amsterdam

STRANGE MATRIX ELEMENTS IN THE PROTON FROM NEUTRAL-CURRENT EXPERIMENTS

David B KAPLAN[1]
Department of Physics, Harvard University, Cambridge, MA 02138, USA

Aneesh MANOHAR[2]
Center for Theoretical Physics, Laboratory for Nuclear Science and Department of Physics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

Received 19 May 1988



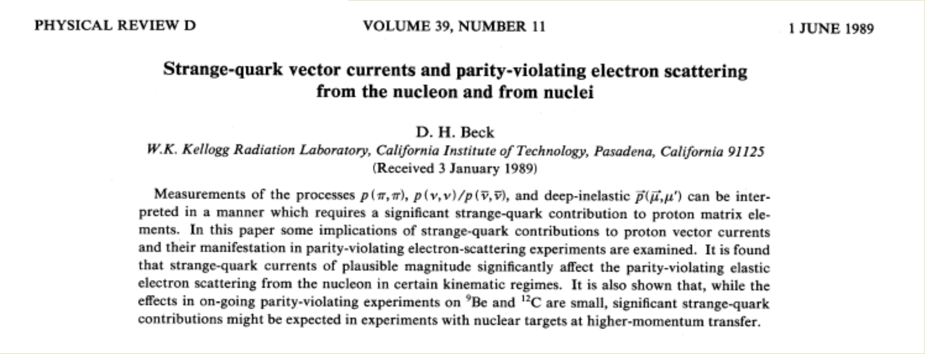
Volume 219, number 2,3 PHYSICS LETTERS B 16 March 1989

SENSITIVITY OF POLARIZED ELASTIC ELECTRON–PROTON SCATTERING TO THE ANOMALOUS BARYON NUMBER MAGNETIC MOMENT

R.D. McKEOWN
W.K. Kellogg Radiation Laboratory, California Institute of Technology, Pasader

Received 20 August 1988

The anomalous baryon number magnetic moment may be a useful quantity in
It is shown that this quantity can be determined quite precisely in the elastic
protons at low momentum transfer.



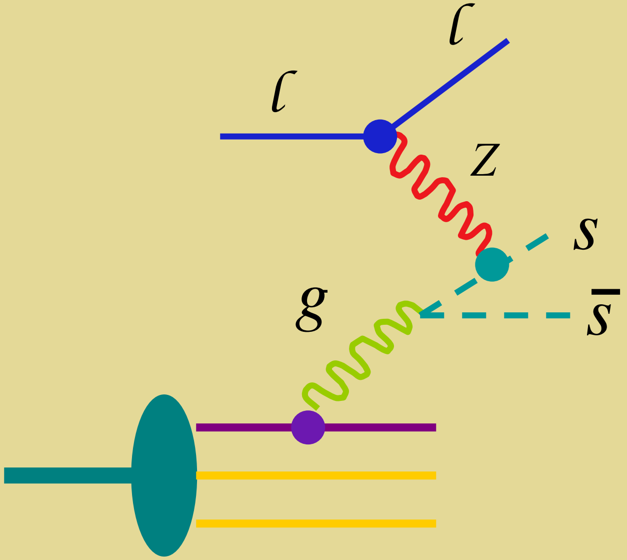
PHYSICAL REVIEW D VOLUME 39, NUMBER 11 1 JUNE 1989

Strange-quark vector currents and parity-violating electron scattering from the nucleon and from nuclei

D. H. Beck
W.K. Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California 91125

(Received 3 January 1989)

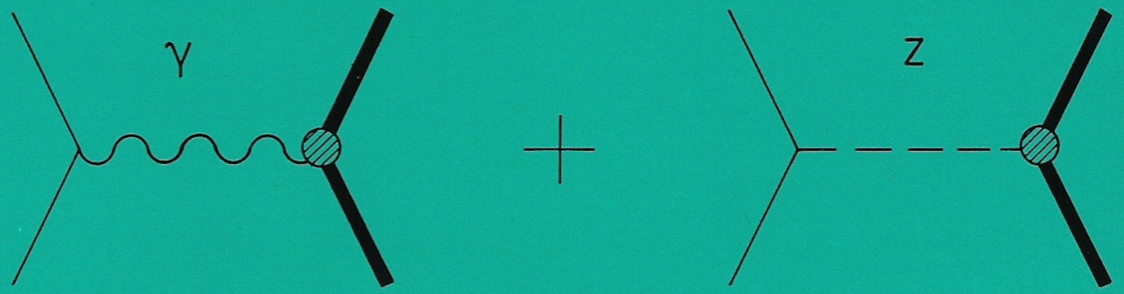
Measurements of the processes $p(\pi,\pi)$, $p(\nu,\nu)/p(\bar{\nu},\bar{\nu})$, and deep-inelastic $\vec{p}(\vec{\mu},\mu')$ can be interpreted in a manner which requires a significant strange-quark contribution to proton matrix elements. In this paper some implications of strange-quark contributions to proton vector currents and their manifestation in parity-violating electron-scattering experiments are examined. It is found that strange-quark currents of plausible magnitude significantly affect the parity-violating elastic electron scattering from the nucleon in certain kinematic regimes. It is also shown that, while the effects in on-going parity-violating experiments on ^{9}Be and ^{12}C are small, significant strange-quark contributions might be expected in experiments with nuclear targets at higher-momentum transfer.



Proceedings of the workshop held at the
California Institute of Technology

PARITY VIOLATION in ELECTRON SCATTERING

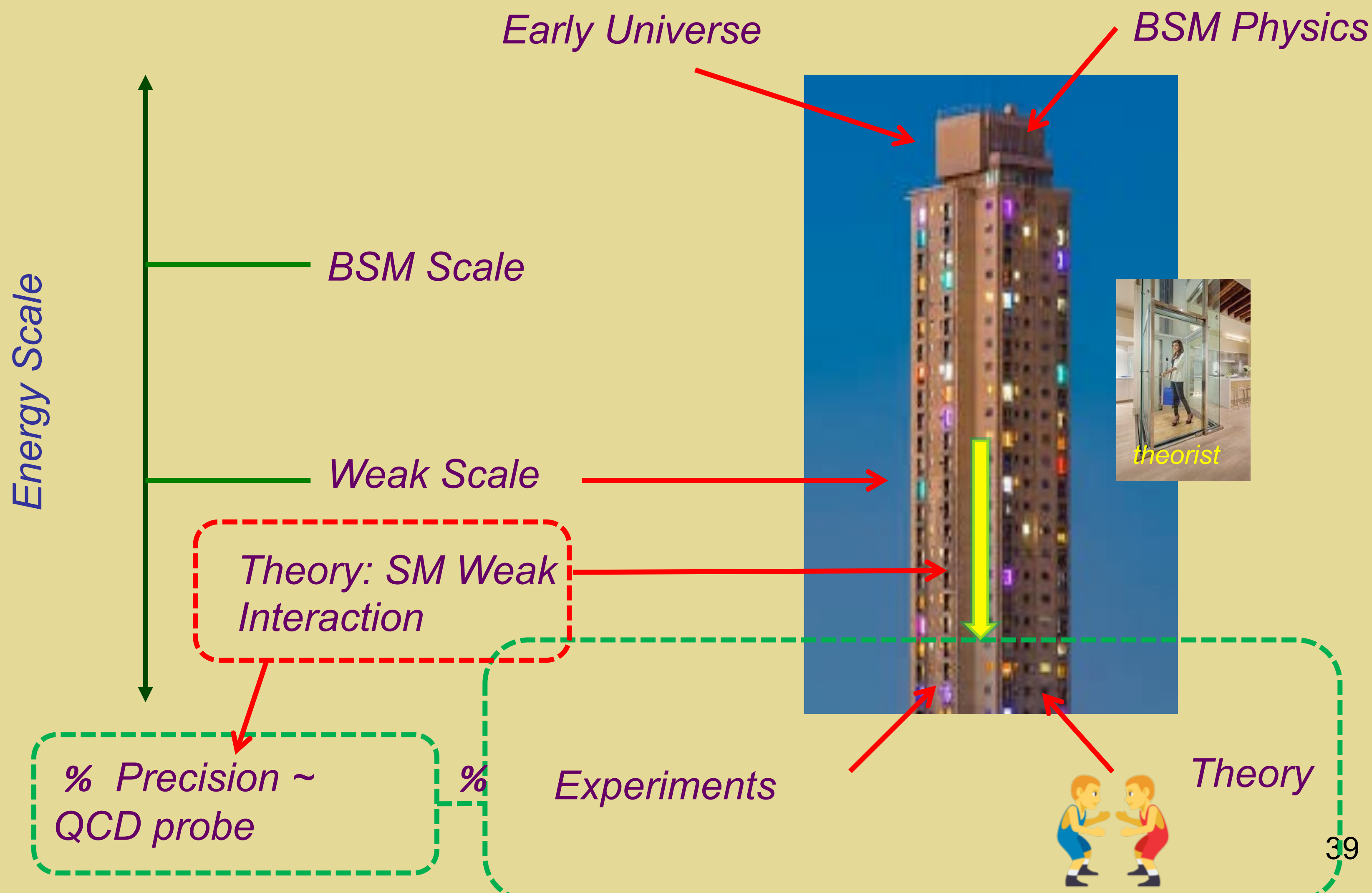
California Institute of Technology
February 23 — 24, 1990



Editors
E. J. Beise
R. D. McKeown

Theoretical interpretation

Theoretical Challenges



Electroweak Radiative Corrections

Volume 242, number 3,4 PHYSICS LETTERS B 14 June 1990

ELECTROWEAK CORRECTIONS TO PARITY-VIOLATING NEUTRAL CURRENT SCATTERING

M.J. MUSOLF
Center For Theoretical Physics, Laboratory for Nuclear Science and Department of Physics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

and

Barry R. HOLSTEIN
Department of Physics and Astronomy, University of Massachusetts, Amherst, MA 01003, USA

PHYSICAL REVIEW D VOLUME 43, NUMBER 9 1 MAY 1991

Observability of the anapole moment and neutrino charge radius

M. J. Musolf
Center for Theoretical Physics, Laboratory for Nuclear Science and Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

Barry R. Holstein
Astronomy, University of Massachusetts, Amherst, Massachusetts 01003
(Received 25 September 1990)

PHYSICAL REVIEW D, VOLUME 65, 033001

Electroweak radiative corrections to parity-violating electroexcitation of the Δ

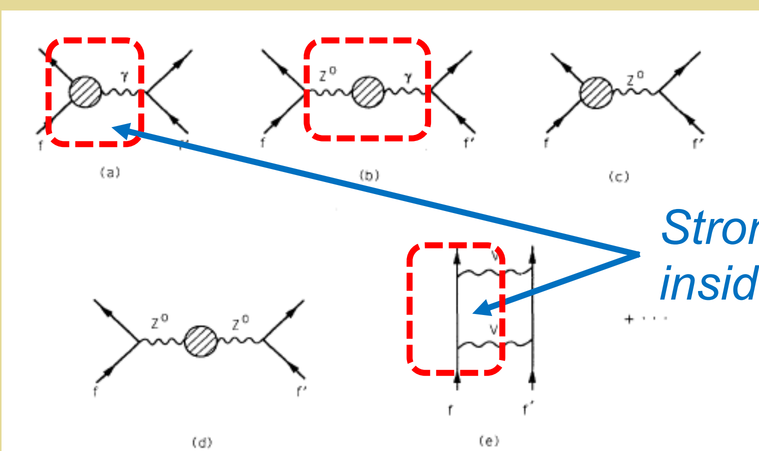
Shi-Lin Zhu,[1,2] C. M. Maekawa,[2] G. Sacco,[1,2] B. R. Holstein,[3] and M. J. Ramsey-Musolf[1,2,4]
[1]*Department of Physics, University of Connecticut, Storrs, Connecticut 06.*
[2]*Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, Calij*
[3]*Department of Physics, University of Massachusetts, Amherst, Massachusetts*
[4]*Theory Group, Thomas Jefferson National Accelerator Facility, Newport News, Vi*
(Received 10 July 2001; published 20 December 2001)

PHYSICAL REVIEW D 72, 073003 (2005)

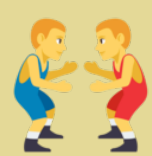
Weak mixing angle at low energies

Jens Erler[1] and Michael J. Ramsey-Musolf[2]
[1]*Instituto de Física, Universidad Nacional Autónoma de México, 01000 México D.F., Mexico*
[2]*Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California 91125, USA*
(Received 21 October 2004; revised manuscript received 11 July 2005; published 13 October 2005)

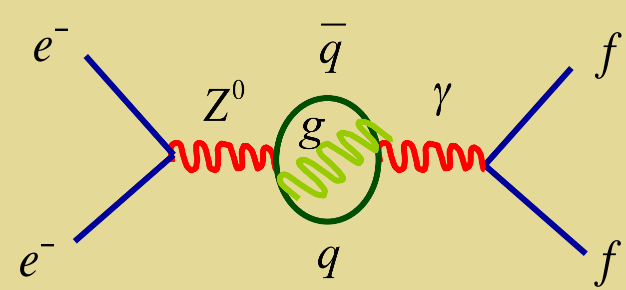
"Quantum corrections"



Strong interaction: inside proton



Strong interaction



Strange Quarks: G_M^P & G_E^P

Interpreting the asymmetry

Nuclear Physics **A546** (1992) 509–587
North-Holland

NUCLEAR
PHYSICS A

The interpretation of parity-violating electron-scattering experiments*

M.J. Musolf and T.W. Donnelly

Center for Theoretical Physics, Laboratory for Nuclear Science and Department of Physics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

Received 3 February 1992

Strange Magnetism vs Electroweak Radiative Corrections

Interpreting the asymmetry

3.1.1. *Backward angles.* In the $\theta \to 180°$ limit, $\varepsilon \to 0$ and we have

$$\frac{W^{\mathrm{p.v.}}}{F^2} \to (1-4\sin^2\theta_W)(1+R_V^p) - \frac{1}{G_M^p}\left[(1+R_V^n)G_M^n + (1+R_V^{(0)})G_M^{(s)}\right] + \sqrt{\frac{1}{\tau}+1}\,(-1+4\sin^2\theta_W)\frac{\tilde{G}_A^p}{G_M^p}.$$

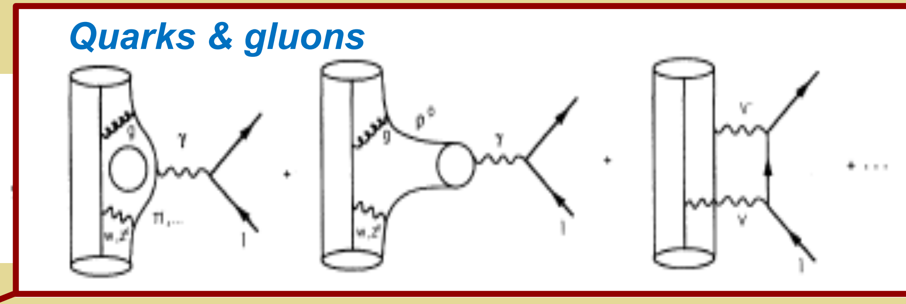
$$\tilde{G}_A^p = -g_A G_D^A\left[1+R_A^p-(1+R_A^{(0)})\eta\right], \qquad \eta = \frac{G_A^{(s)}(0)}{g_A}$$

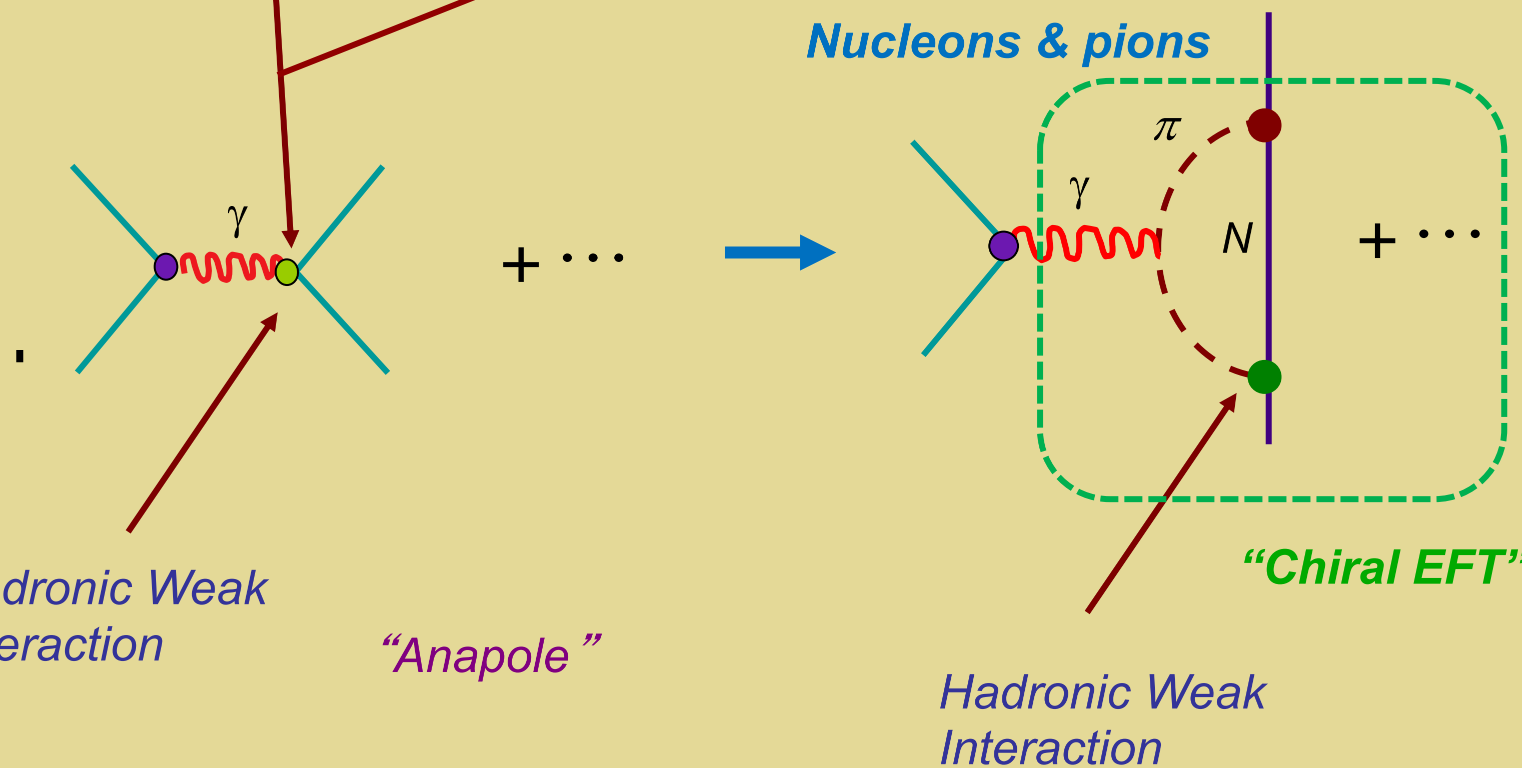
Radiative correction

Non-perturbative strong interactions

Strange Quarks: Radiative Corrections

$$\tilde{G}_A^p = -g_A G_D^A[1 + R_A^p - (1 + R_A^{(0)})\eta]$$





EW Radiative Corrections & EFT

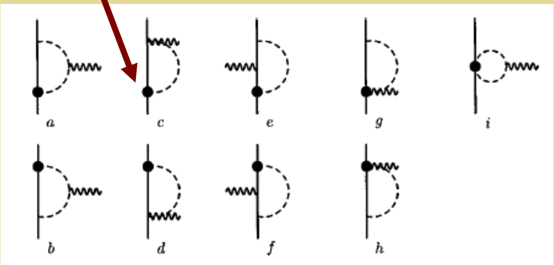
Chiral pert theory:
"effective field theory"
for low-energy QCD

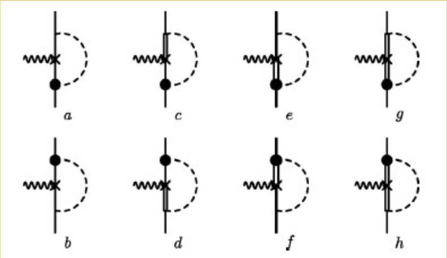
PHYSICAL REVIEW D, VOLUME 62, 033008

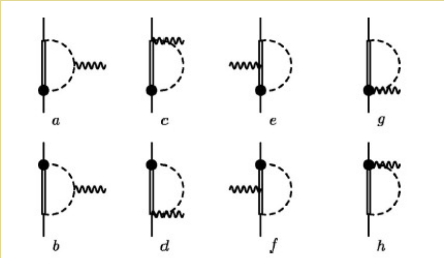
Nucleon anapole moment and parity-violating *ep* scattering

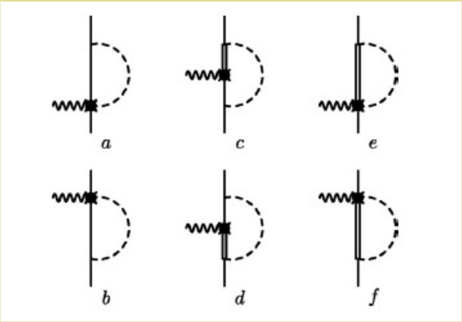
Shi-Lin Zhu,[1] S. J. Puglia,[1] B. R. Holstein,[3] and M. J. Ramsey-Musolf[1,2]
[1]*Department of Physics, University of Connecticut, Storrs, Connecticut 06269*
[2]*Theory Group, Thomas Jefferson National Laboratory, Newport News, Virginia 23606*
[3]*Department of Physics and Astronomy, University of Massachusetts, Amherst, Massachusetts 01003*
(Received 29 February 2000; published 12 July 2000)

Hadronic Weak Interaction







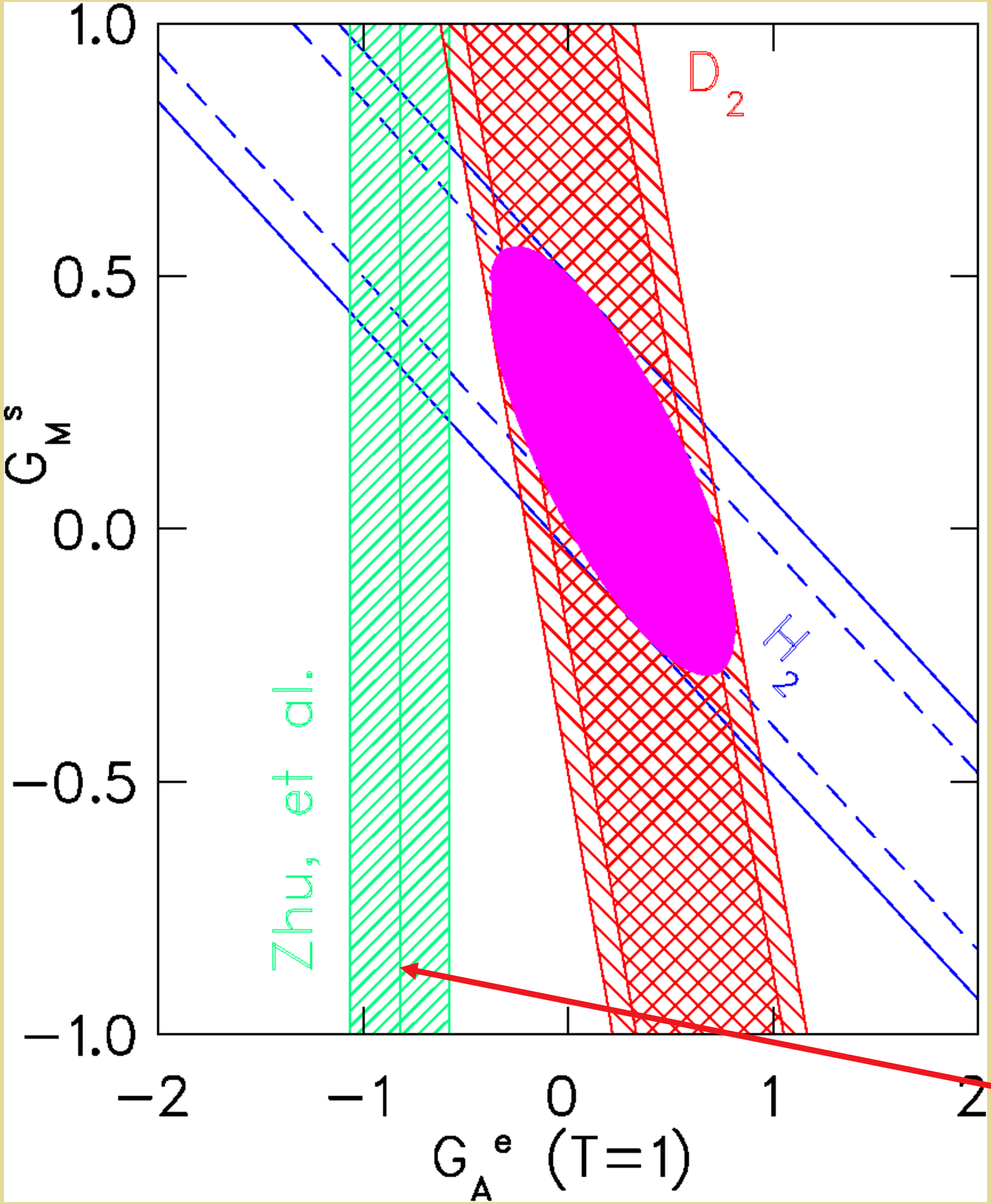


Source	$R_A^{T=1}$	$R_A^{T=0}$
One-quark (SM)	−0.35	0.05
Anapole	−0.06±0.24	0.01±0.14
Total	−0.41±0.24	0.06±0.14

Quantify theoretical uncertainty

SAMPLE Results

R. Hasty et al., Science 290, 2117 (2000).



at Q^2=0.1 (GeV/c)^2

- s-quarks contribute less than 5% (1σ) to the proton's magnetic moment.

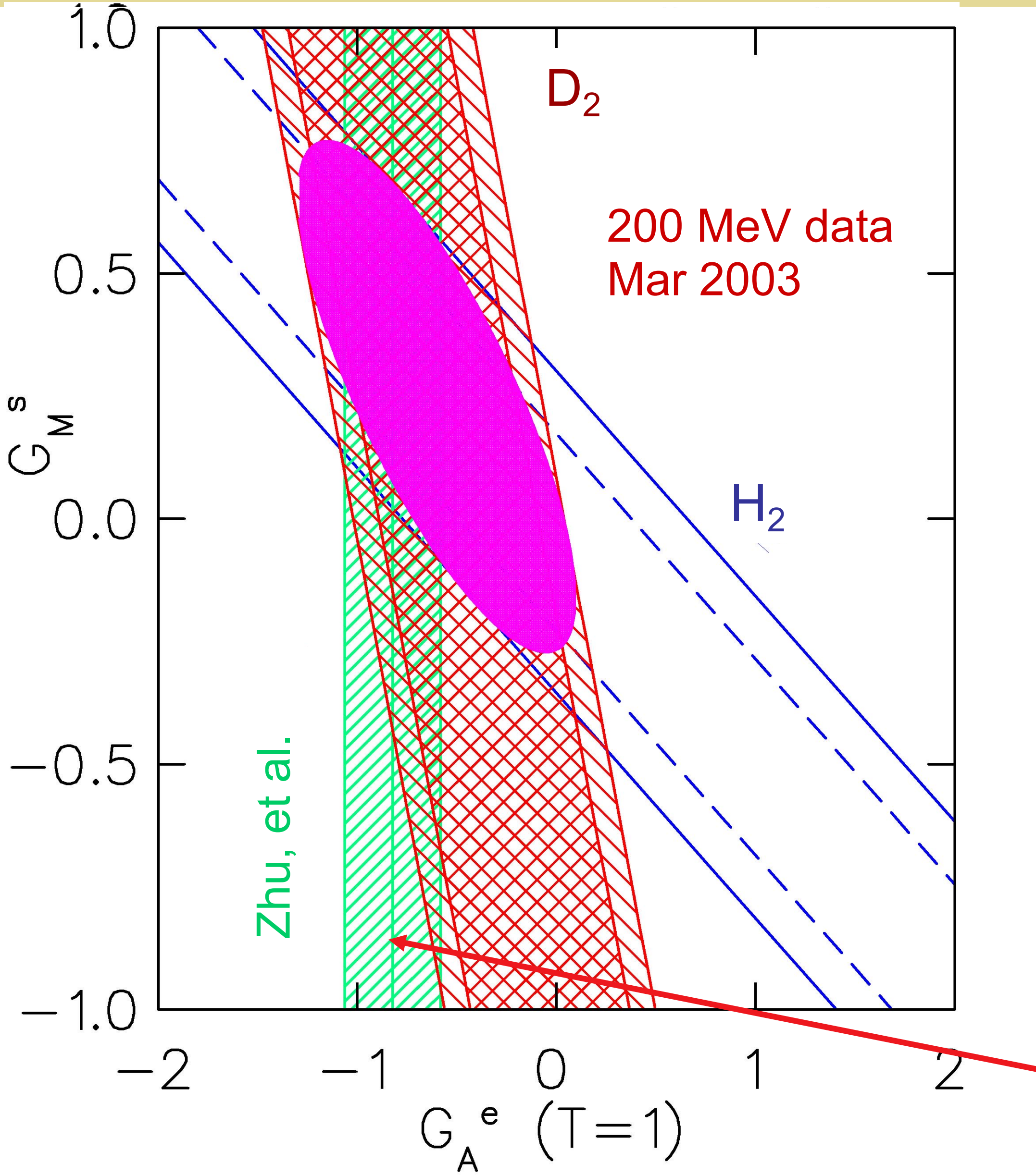
- ***Problem with theory ?***
- ***Experimental issue ?***

Radiative corrections

E. Beise, U Maryland

SAMPLE Results

R. Hasty et al., Science 290, 2117 (2000).



at Q^2=0.1 (GeV/c)^2

- s-quarks contribute less than 5% (1σ) to the proton's magnetic moment.

200 MeV update 2003:
Improved EM radiative corr.
Improved acceptance model
Correction for π background

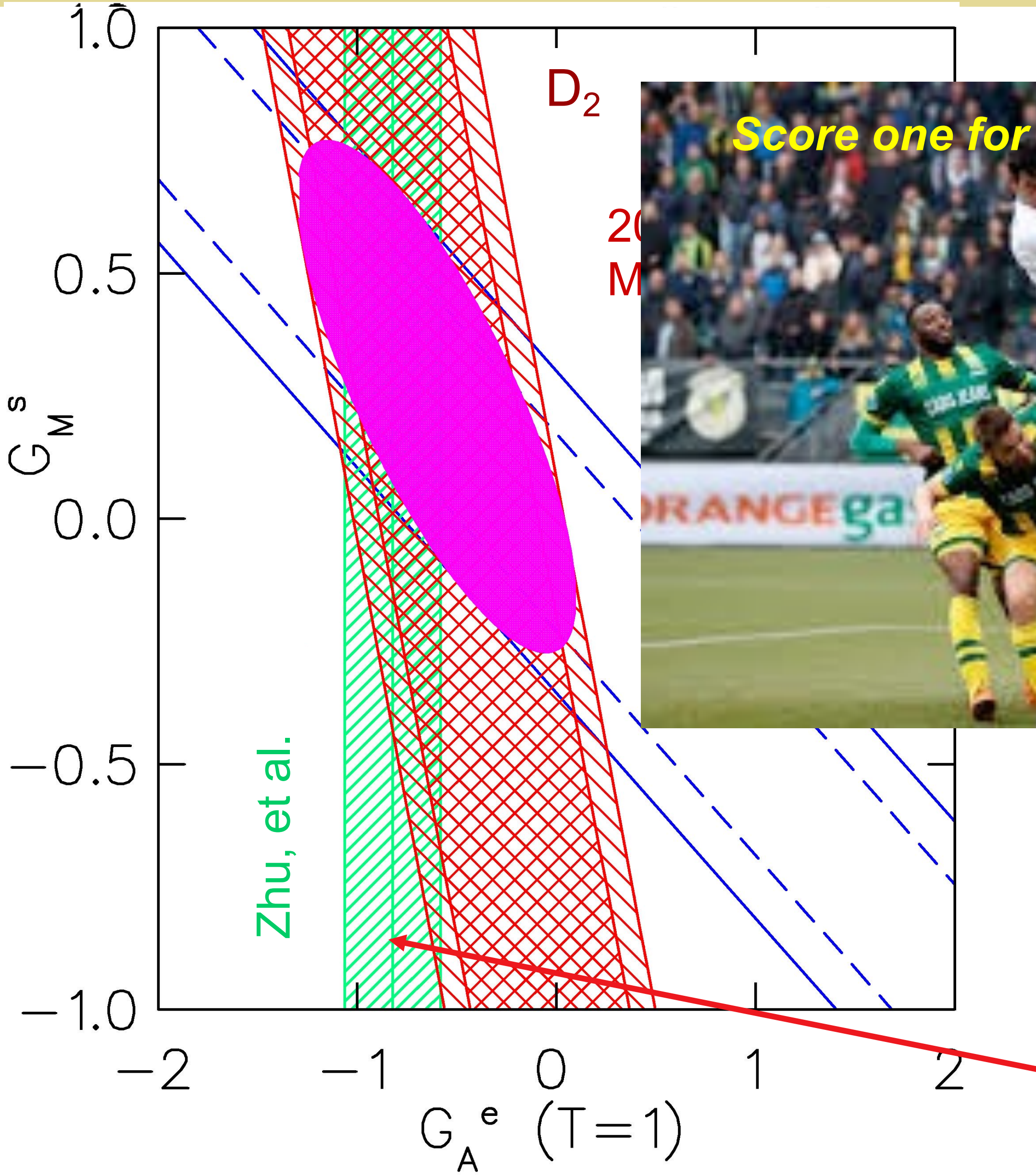
125 MeV:
no π background
similar sensitivity
to G_A^e(T=1)

Radiative corrections

E. Beise, U Maryland

SAMPLE Results

R. Hasty et al., Science 290, 2117 (2000).



at Q^2=0.1 (GeV/c)^2

ss

ent.

corr.

nodel

round

125 MeV:

no π background

similar sensitivity

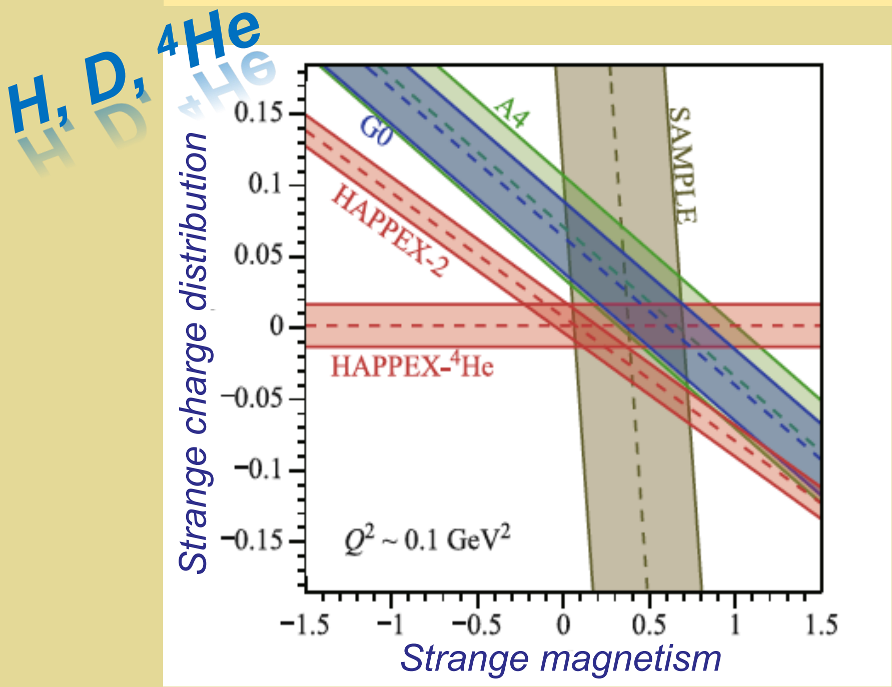
to G_A^e(T=1)

Radiative corrections

E. Beise, U Maryland

Strange Quarks: Proton Magnetism & Charge Distribution

If strange quarks – not part of the quark model picture – give a sizeable contribution to the nucleon spin and mass, what about their effects on electromagnetic properties ?



- *Small s-quark effects on E.M. properties*
- *We wouldn't have known this w/o enormous exp't effort and rigorous precision EW calculations & reliable statement of theoretical uncertainty*

P. Souder & K. Paschke, Front Phys 11 (2016) 111301

PV Electron Scattering

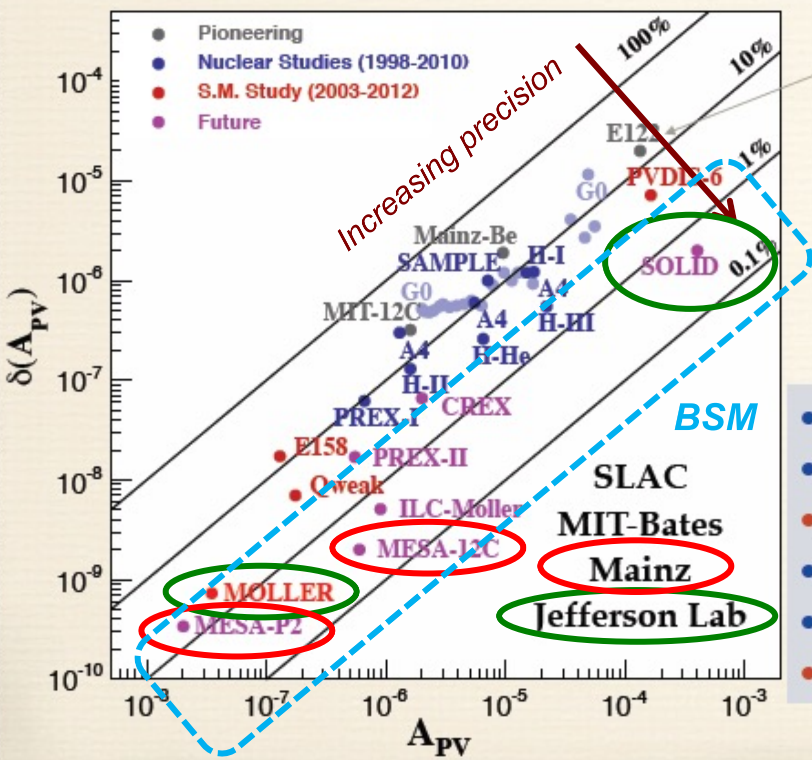
Continuous interplay between probing hadron structure and electroweak physics

4 Decades of Progress

Parity-violating electron scattering has become a precision tool

photocathodes, polarimetry, high power cryotargets, nanometer beam stability, precision beam diagnostics, low noise electronics, radiation hard detectors

PVeS Experiment Summary



Pioneering electron-quark PV DIS experiment SLAC E122

State-of-the-art:

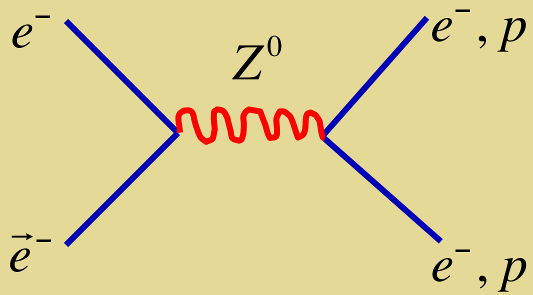
- *sub-part per billion statistical reach and systematic control*
- *sub-1% normalization control*

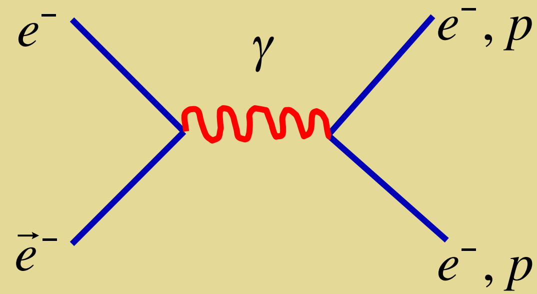
Physics Topics

- *Strange Quark Form Factors*
- *Neutron skin of a heavy nucleus*
- *Indirect Searches for New Interactions*
- *Novel Probes of Nucleon Structure*
- *Electroweak Structure Functions at the EIC*
- *Charge Lepton Flavor Violation at the EIC*

K. Kumar

Parity-Violation & Weak Charges





Parity-Violating electron scattering

$$A_{PV} = \frac{N_{\uparrow\uparrow} - N}{N_{\uparrow\uparrow} + N} \sim 10^{-6} \left(\frac{Q}{M_p}\right)^2 \left[Q_W + F(Q^2,\theta)\right]$$

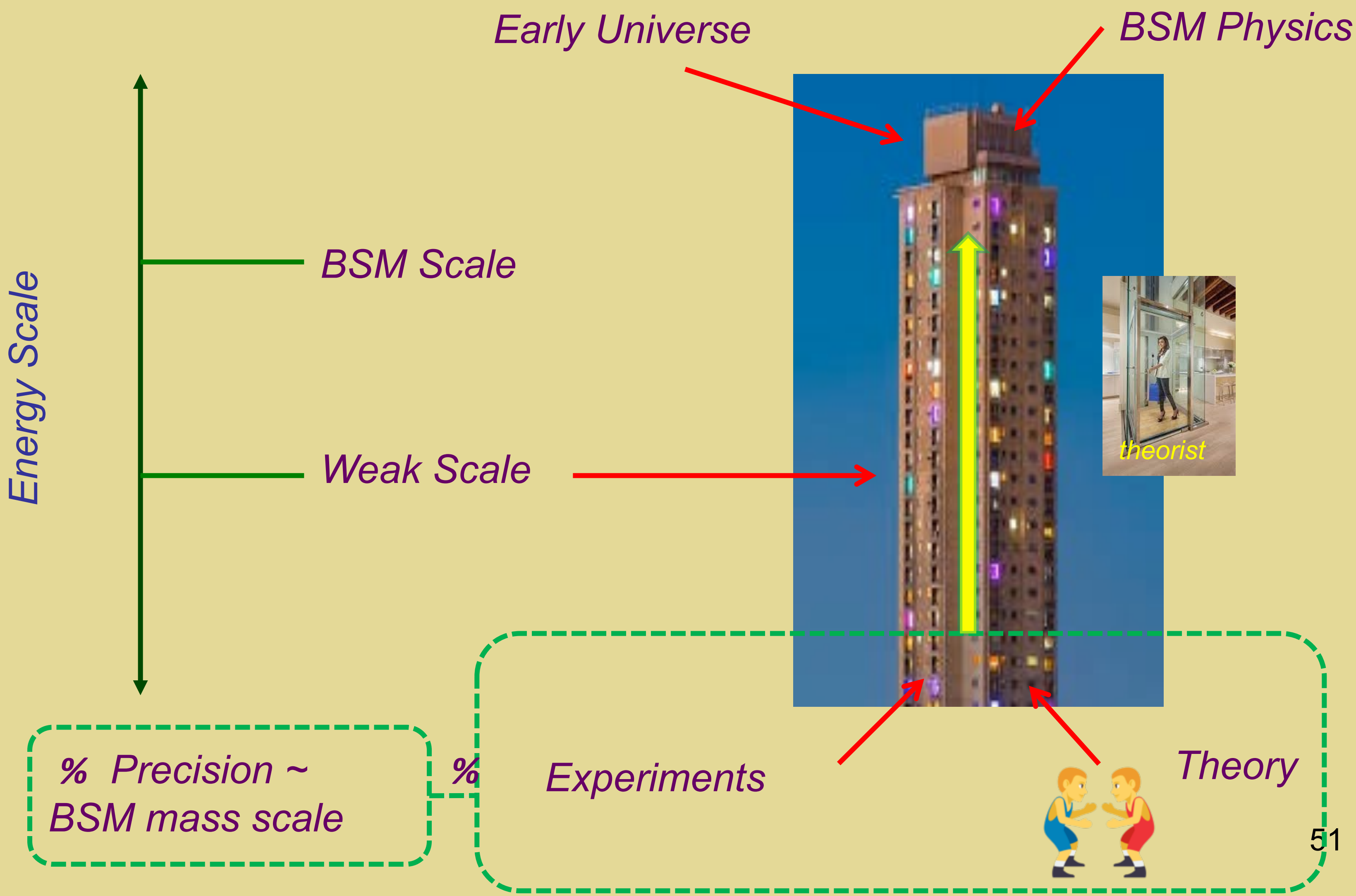
"Weak Charge" ~ 0.1 in SM

Enhanced transparency to BSM physics

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

QCD effects (s-quarks): measured (MIT-Bates, Mainz, JLab)

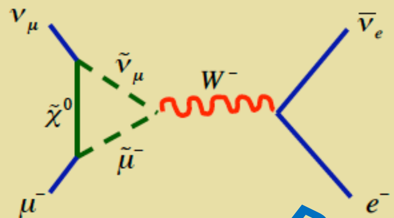
Theoretical Challenges



Intensity Frontier: BSM Footprints

New Symmetries

1. *Origin of Matter*
2. *Unification & gravity*
3. *Weak scale stability*
4. *Neutrinos*





Precision + pattern

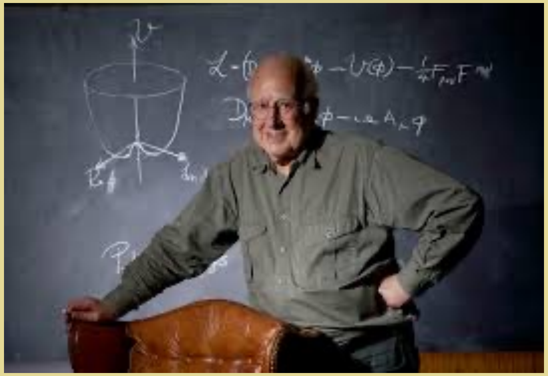


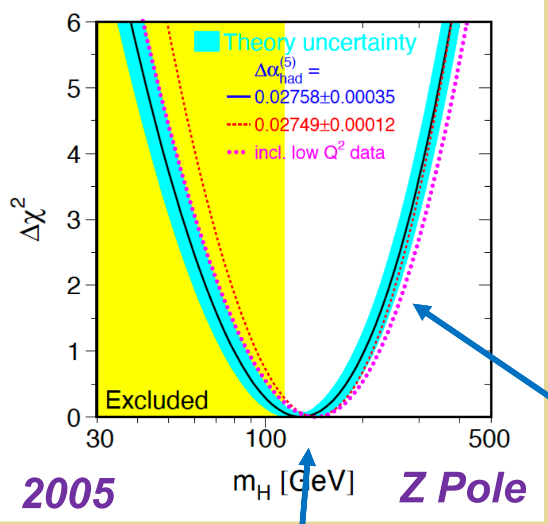


High energy searches: does the observed BSM "species" fit the footprints ?

Fundamental symmetry tests: draw inferences about BSM scenarios from a variety of measurements

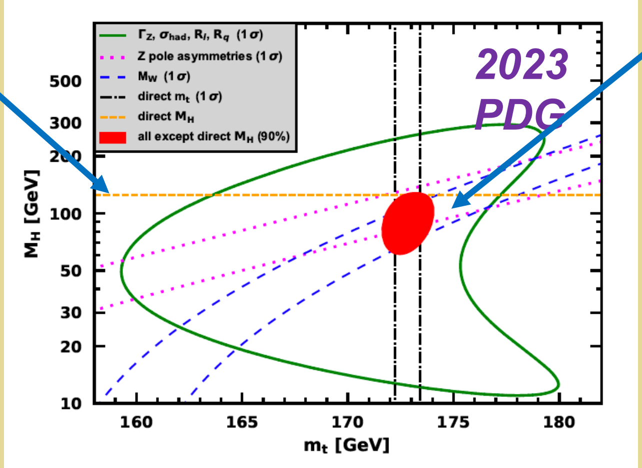
Higgs Boson: EW Precision + Direct Observation





Higgs boson direct measurement

EW precision measurements



Electroweak Radiative Corrections

PHYSICAL REVIEW D 68, 016006 (2003)

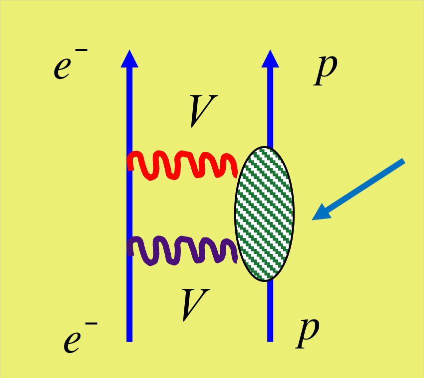
Weak charge of the proton and new physics

Jens Erler,[1,2,*] Andriy Kurylov,[3,†] and Michael J. Ramsey-Musolf[2,3,4,‡]
[1]*Instituto de Física, Universidad Nacional Autónoma de México, 04510 México D.F., Mexico*
[2]*Institute for Nuclear Theory, University of Washington, Seattle, Washington 98195, USA*
[3]*Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California 91125, USA*
[4]*Department of Physics, University of Connecticut, Storrs, Connecticut 06269, USA*
(Received 27 February 2003; published 17 July 2003)

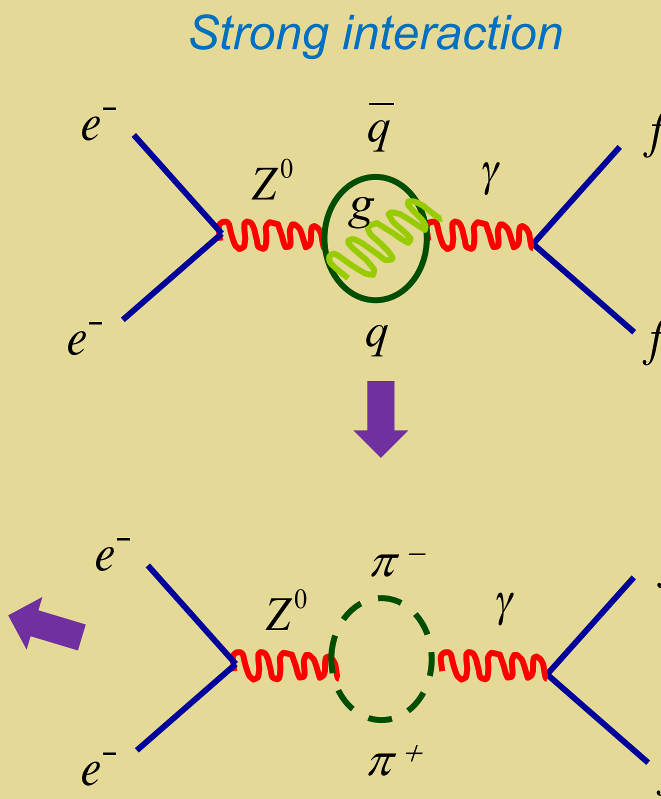
PHYSICAL REVIEW D 72, 073003 (2005)

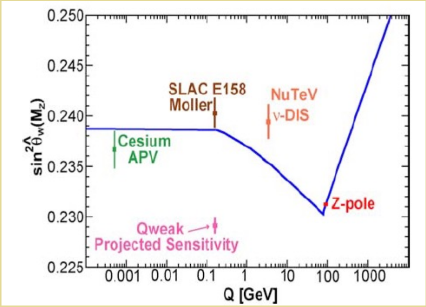
Weak mixing angle at low energies

Jens Erler[1] and Michael J. Ramsey-Musolf[2]
[1]*Instituto de Física, Universidad Nacional Autónoma de México, 01000 México D.F., Mexico*
[2]*Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California 91125, USA*
(Received 21 October 2004; revised manuscript received 11 July 2005; published 13 October 2005)



Strong interaction: inside proton





Pertrubative

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

Non-pertrubative

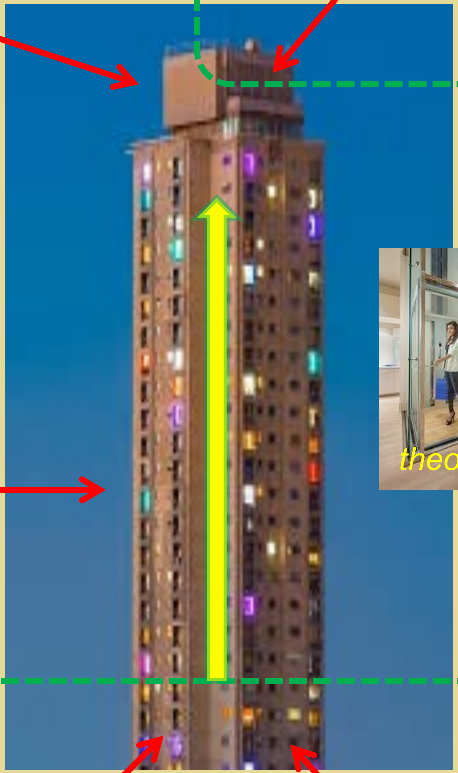
$$\Box_{\gamma Z}=\frac{5\hat{\alpha}}{2\pi}(1-4\hat{s}^2)\left[\ln\left(\frac{M_Z^2}{\Lambda^2}\right)+C_{\gamma Z}(\Lambda)\right],$$

Theoretical Challenges

Footprints

Early Universe

BSM Physics



Energy Scale

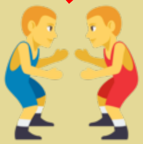
BSM Scale

Weak Scale

% Precision ~
BSM mass scale

%

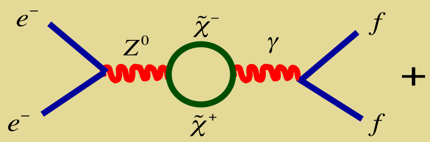
Experiments

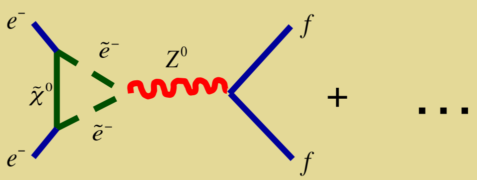


Theory

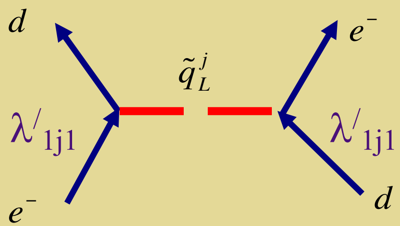
Deviations: BSM "Footprints"

SUSY





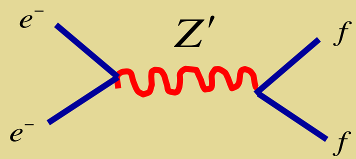
Radiative Corrections



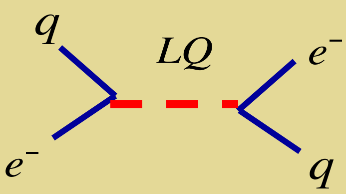
RPV

SUSY footprints ?

Z' Bosons



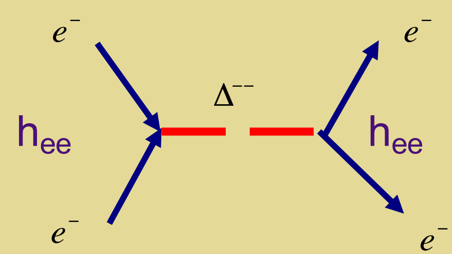
Leptoquarks



Semi-leptonic only

Doubly Charged Scalars

Moller only



Theoretical Challenges

Volume 456, Nos. 1–2, January 2008 ISSN 0370-1573

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LOW-ENERGY PRECISION TESTS OF SUPERSYMMETRY

M.J. RAMSEY-MUSOLF, S. SU

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Physics Letters B 582 (2004) 222–228

PHYSICS LETTERS B

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Supersymmetric effects in parity-violating deep inelastic electron–nucleus scattering

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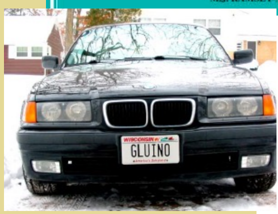
Editor: H. Georgi



PHYSICAL REVIEW D 68, 035008 (2003)

Probing supersymmetry with parity-violating electron scattering

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S. Su
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(Received 13 March 2003; published 15 August 2003)

VOLUME 88, NUMBER 7 PHYSICAL REVIEW LETTERS 18 FEBRUARY 2002

Charged Current Universality in the Minimal Supersymmetric Standard Model

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(Received 24 September 2001; published 1 February 2002)

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Nuclear Physics B 667 (2003) 321–348

NUCLEAR PHYSICS B

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Supersymmetric effects in deep inelastic neutrino–nucleus scattering

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[a] California Institute of Technology, Pasadena, CA 91125, USA
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[c] Institute for Nuclear Theory, University of Washington, Seattle, WA 98195, USA

Received 29 January 2003; received in revised form 19 May 2003; accepted 11 June 2003

Footprints

BSM Physics

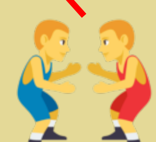
SUSY ?

% Precision ~
BSM mass scale

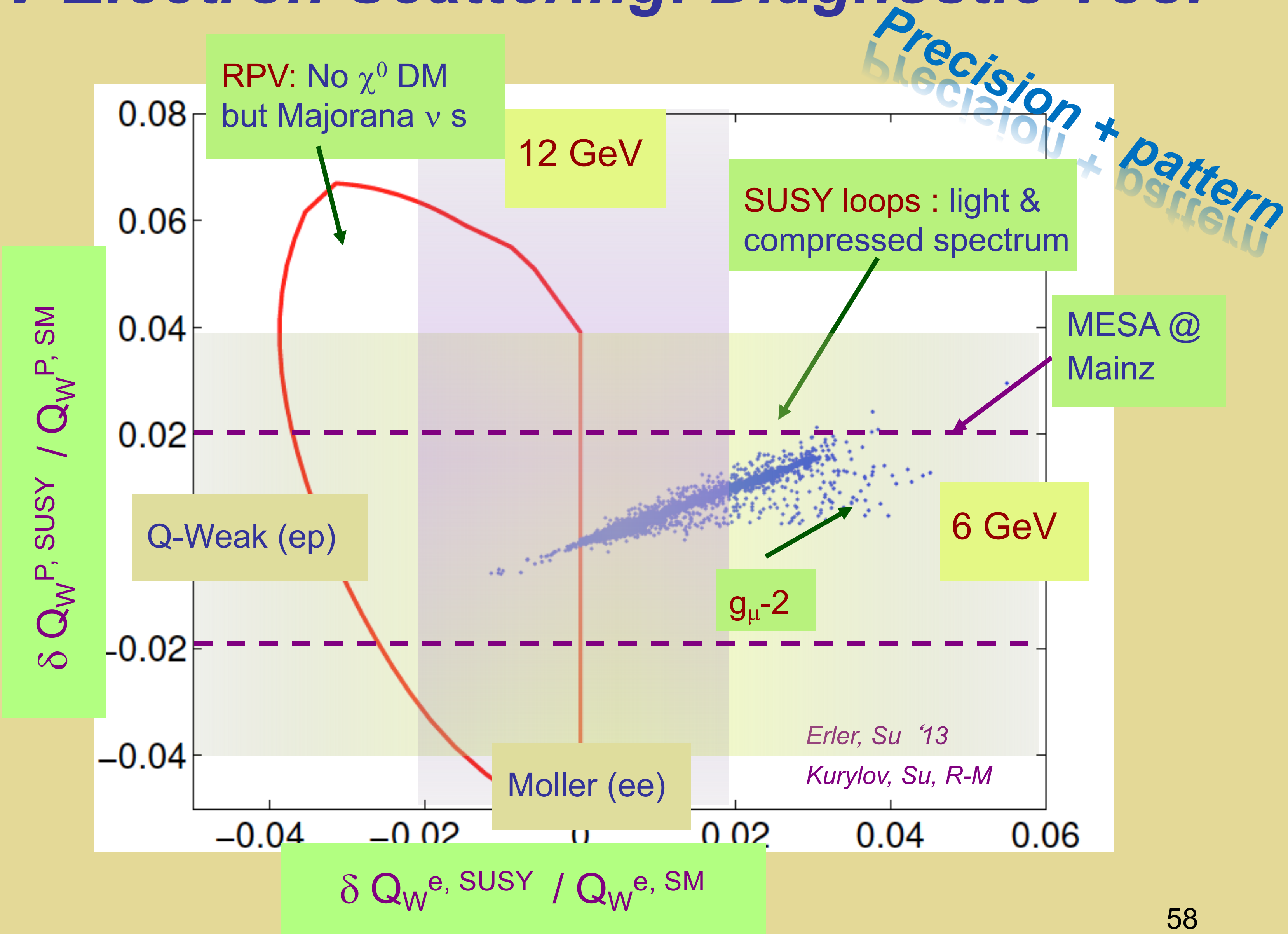
%

Experiments

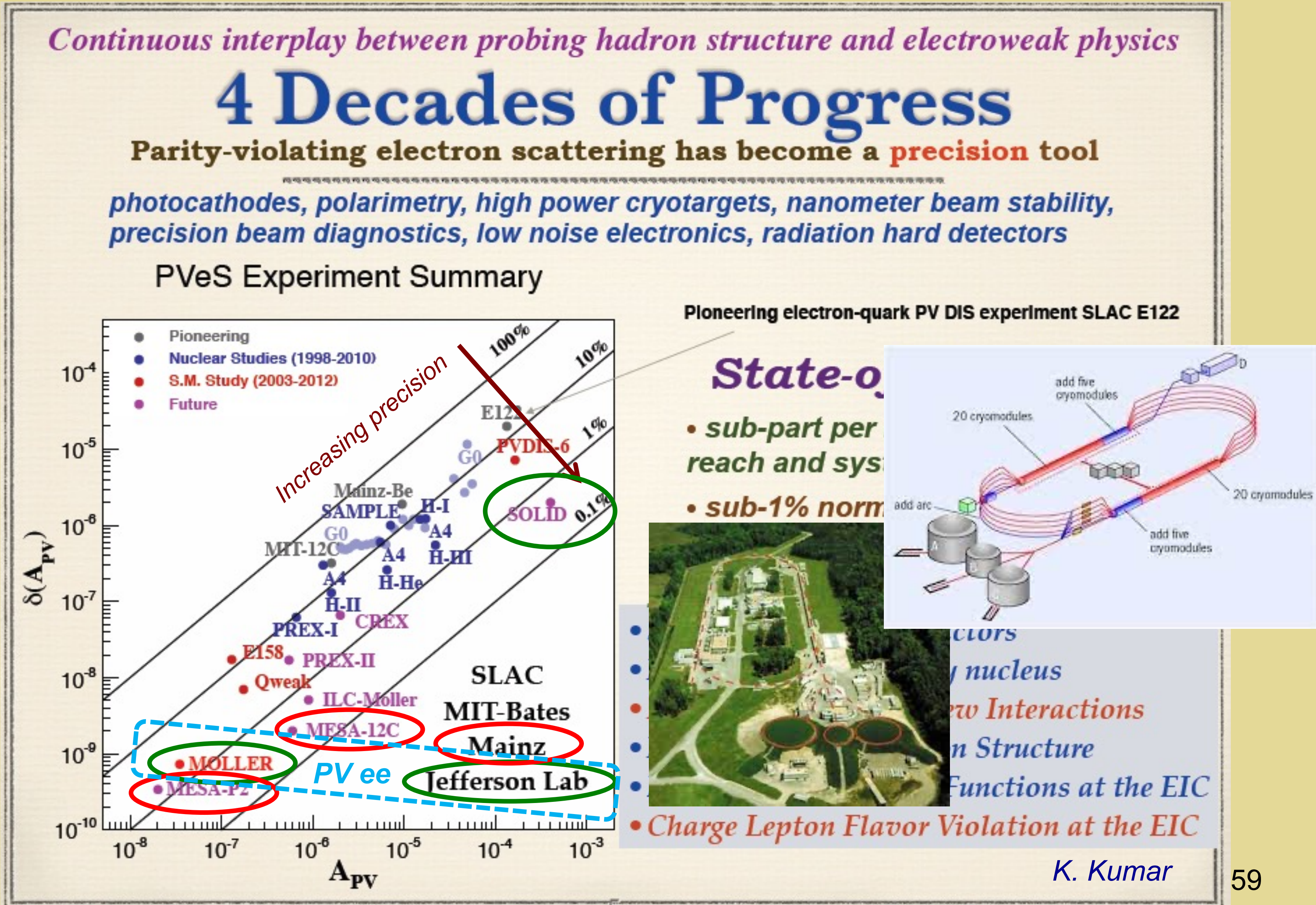
Theory



PV Electron Scattering: Diagnostic Tool

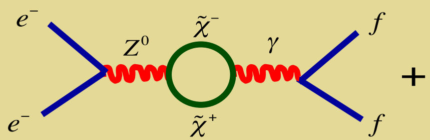


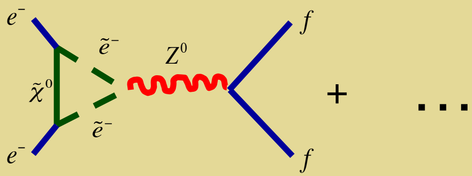
PV Electron Scattering



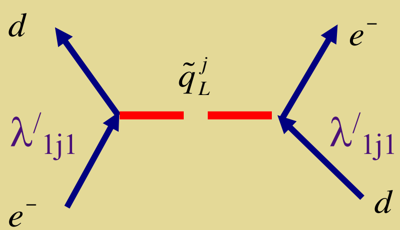
Deviations: BSM "Footprints"

SUSY



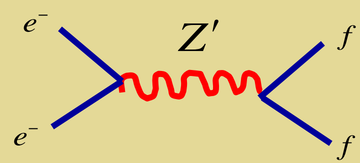


Radiative Corrections

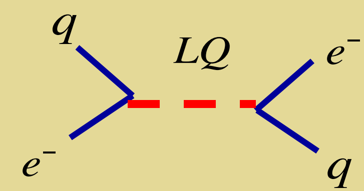


RPV

Z/ Bosons



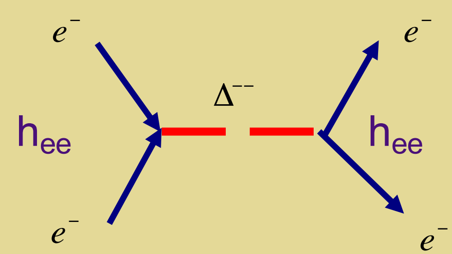
Leptoquarks



Semi-leptonic only

Doubly Charged Scalars

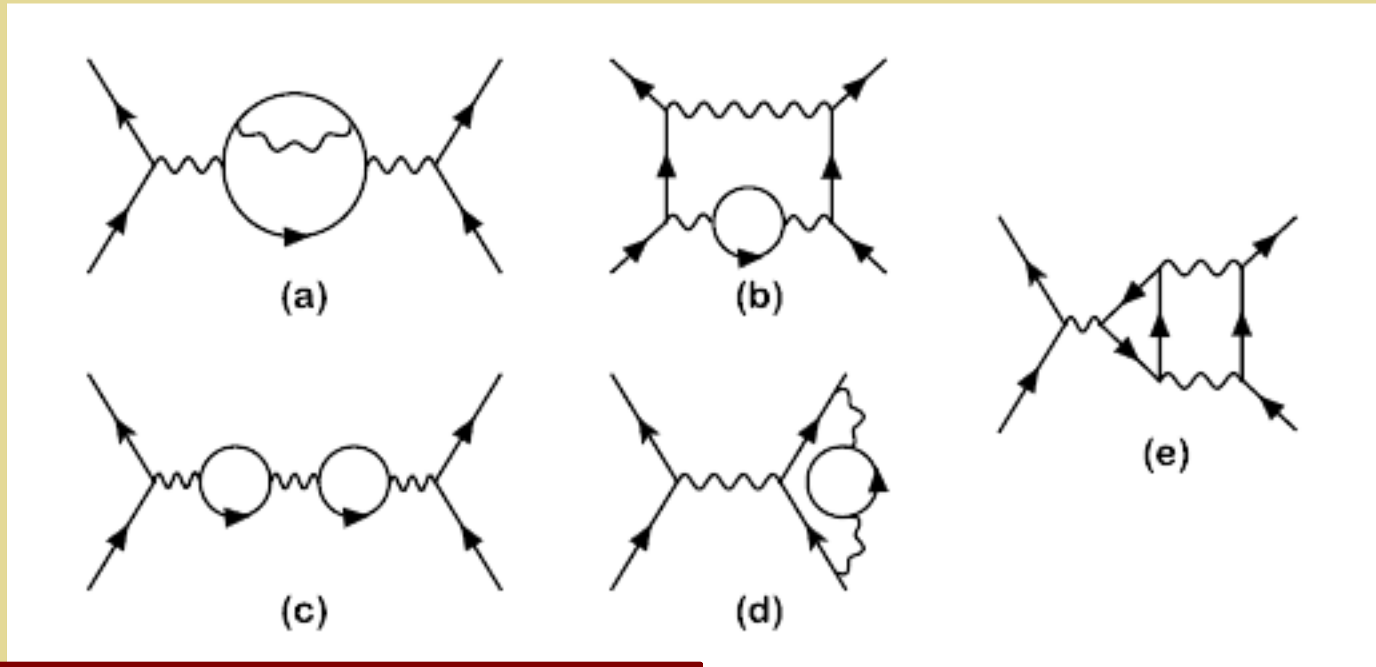
Moller only



PV Moller scattering

Two-Loop EW Radiative Corrections

Closed fermion loops: gauge invariant



PHYSICAL REVIEW LETTERS **126,** 131801 (2021)

Parity-Violating Møller Scattering at Next-to-Next-to-Leading Order: Closed Fermion Loops

Yong Du,[1,*] Ayres Freitas,[2,†] Hiren H. Patel,[3,‡] and Michael J. Ramsey-Musolf[4,1,5,§]

[1]*Amherst Center for Fundamental Interactions, Physics Department, University of Massachusetts Amherst, Amherst, Massachusetts 01003 USA*
[2]*Pittsburgh Particle Physics Astrophysics and Cosmology Center (PITT-PACC), Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, Pennsylvania 15260, USA*
[3]*Department of Physics and Santa Cruz Institute for Particle Physics, University of California, Santa Cruz, California 95064, USA*
[4]*Tsung-Dao Lee Institute and School of Physics and Astronomy, Shanghai Jiao Tong University, Shanghai 200240, China*
[5]*Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California 91125 USA*

(Received 17 January 2020; revised 22 July 2020; accepted 23 February 2021; published 29 March 2021)

Two-Loop EW Radiative Corrections

$\delta(Q^e_W) = \pm\ 2.1\ \%\ (\text{stat.}) \pm 1.1\ \%\ (\text{syst.})$

Exp't precision (goal)

BSM probe !

Quantity	Contribution ($\times 10^{-3}$)	% shift*
$1 - 4\sin^2\theta_W$	$+74.4$	
$\Delta Q^e_{W\,(1,1)}$	-29.0	- 39%
$\Delta Q^e_{W\,(1,0)}$	$+\ 3.1$	+ 4%
$\Delta Q^e_{W\,(2,2)}$	$-\ 2.12^{+0.014}_{-0.024}$	- 4.4%
$\Delta Q^e_{W\,(2,1)}$	$+\ 1.65^{+0.010}_{-0.007}$	+ 3.4%
$\Delta Q^e_{W\,(2,0)}$	$\pm\ 0.18$ (estimate)	+/- 0.4%

Must ! (- 4.4%, + 3.4%)

Safe ! (+/- 0.4%)

Loop order

# of closed fermion loops

* Relative to preceding order

Du, Freitas, Patel, MJRM PRL 126 (2021) 131801 [1912.08220]

III. Concluding Remarks

Nuclei & Hadrons as Laboratories

Powerful !

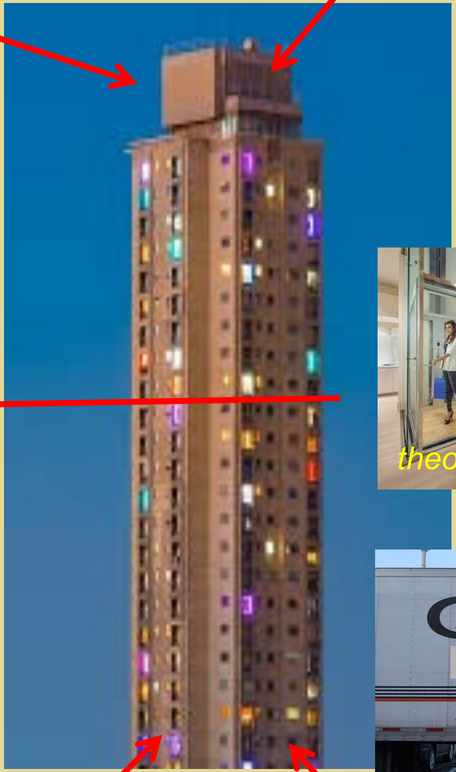
EDM searches: *BSM CPV, Origin of Matter* **CP Violation**	*$0\nu\beta\beta$ decay searches:* *Nature of neutrino, Lepton number violation, Origin of Matter* **Lepton Number Violation**
Electron & muon prop's & interactions: *SM Precision Tests, BSM "diagnostic" probes* **Parity Violation**	*Radioactive decays & other tests* *SM Precision Tests, BSM "diagnostic" probes* **Parity Violation**

Theoretical Challenges

Connecting physics at multiple scales

Early Universe

BSM Physics

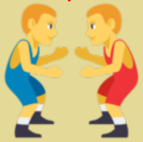


Precision Electroweak Studies

- ***Perturbation theory***
- ***Effective Field Theory***
- ***Non-equilibrium QFT***
- ***Dispersion Relations***
- ***Collider simulations & phenomenology***

Experiments

Theory



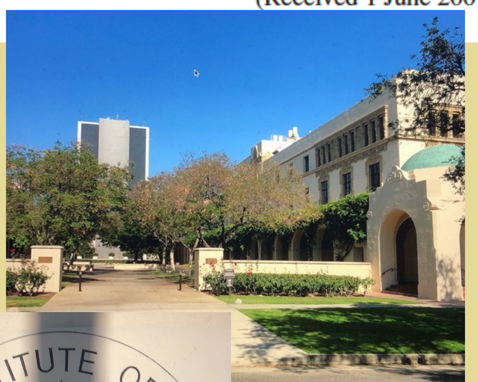
Theory & Exp't: Close Collaboration

Career-long teamwork !

PHYSICAL REVIEW C **76**, 025202 (2007)

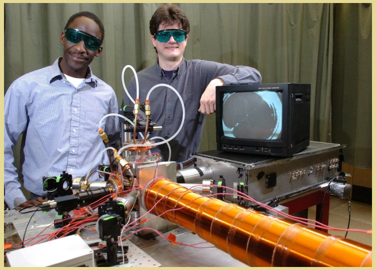
Global analysis of nucleon strange form factors at low Q^2

Jianglai Liu,* Robert D. McKeown, and Michael J. Ramsey-Musolf†
W. K. Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California 91125, USA
(Received 1 June 2007; published 2 August 2007)

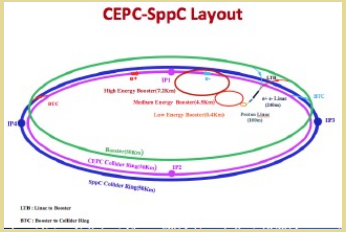


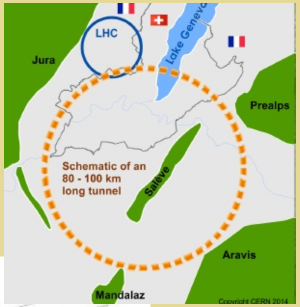
Exciting Challenges Remain

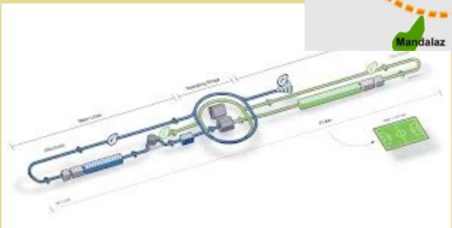
Atomic EDMs



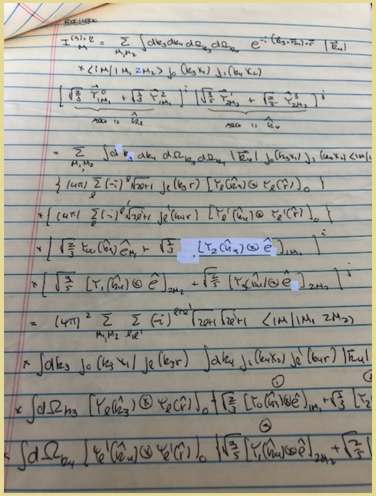
Future Circular e^+e^- & pp







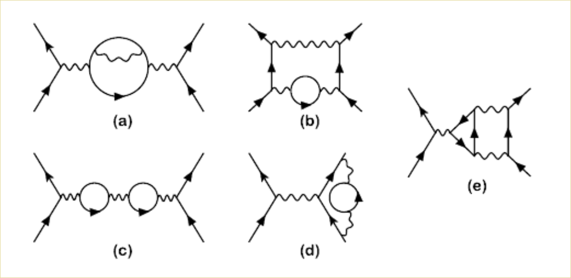
Electron-nucleus interaction



Welcome to join !

"Old School"
theoretical physics

Electroweak precision calc's



谢谢

Back Up Slides

Fermion Electroweak Interactions & PV

Charged currents (CC)

Left-handed only

W^- $$J_\mu^{W+} = \bar{\psi}_L \gamma_\mu \tau^+ \psi_L$$

Neutral currents (NC)

PV

$$J_\mu^{W3} = \bar{\psi}_L \gamma_\mu \frac{\tau^3}{2} \psi_L \qquad J_\mu^B = \bar{\psi} \gamma_\mu \frac{\hat{Y}}{2} \psi$$

Z^0 , γ

W^+ $$J_\mu^{W-} = \bar{\psi}_L \gamma_\mu \tau^- \psi_L$$

No PV

"Weak mixing angle" θ_W

Weak interaction flavor basis

Electroweak Radiative Corrections

PHYSICAL REVIEW D **68**, 016006 (2003)

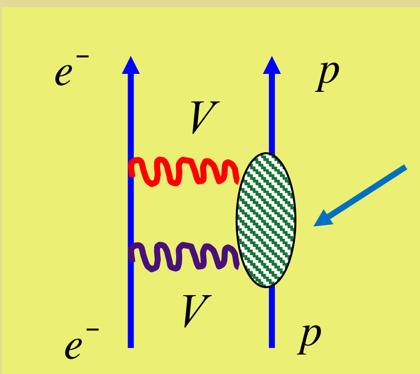
Weak charge of the proton and new physics

Jens Erler,[1,2,*] Andriy Kurylov,[3,†] and Michael J. Ramsey-Musolf[2,3,4,‡]
[1]*Instituto de Física, Universidad Nacional Autónoma de México, 04510 México D.F., Mexico*
[2]*Institute for Nuclear Theory, University of Washington, Seattle, Washington 98195, USA*
[3]*Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California 91125, USA*
[4]*Department of Physics, University of Connecticut, Storrs, Connecticut 06269, USA*
(Received 27 February 2003; published 17 July 2003)

PHYSICAL REVIEW D **72**, 073003 (2005)

Weak mixing angle at low energies

Jens Erler[1] and Michael J. Ramsey-Musolf[2]
[1]*Instituto de Física, Universidad Nacional Autónoma de México, 01000 México D.F., Mexico*
[2]*Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California 91125, USA*
(Received 21 October 2004; revised manuscript received 11 July 2005; published 13 October 2005)



Strong interaction: inside proton

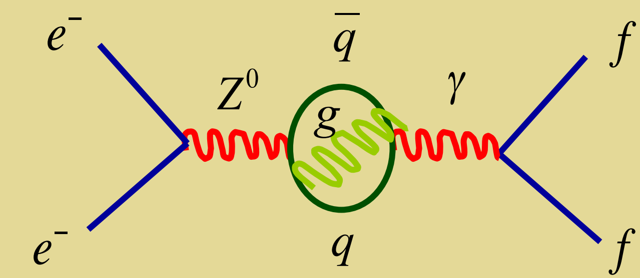
Pertrubative

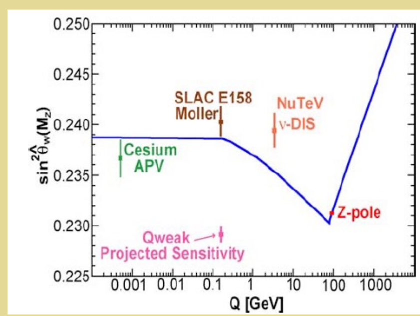
$$\Box_{WW}=\frac{\hat{\alpha}}{4\pi\hat{s}^2}\left[2+5\left(1-\frac{\alpha_s(M_W^2)}{\pi}\right)\right],$$

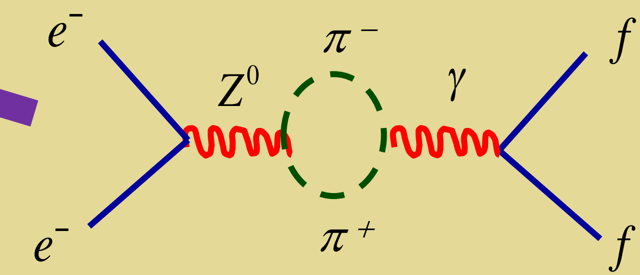
Non-pertrubative

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

Strong interaction







Weak Mixing in the SM: Uncertainties

Erler & R-M

Full $SU(2)_L \times U(1)_Y$ **Renormalization Group**

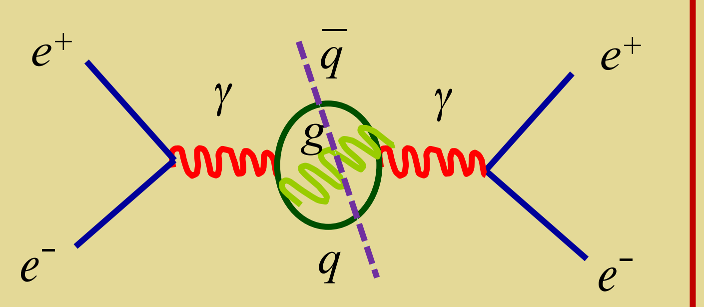
$$\hat{s}^2 \frac{d\hat{\alpha}}{dt} - \hat{\alpha}\frac{d\hat{s}^2}{dt} = \frac{b_2}{\pi}\hat{\alpha}^2 + \sum_j \frac{b_{2j}}{\pi^2}\hat{\alpha}^2\hat{\alpha}_j + \cdots$$

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

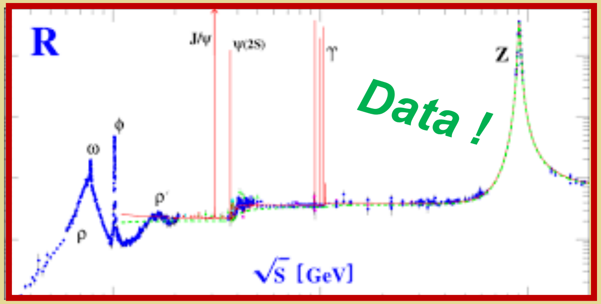
$$\Delta\alpha_{\mathrm{HAD}}(M_Z^2) = \frac{\alpha M_Z^2}{3\pi} P \int_{4m_\pi^2}^{\infty} \frac{R(s)}{s(M_Z^2 - s)} ds$$

$R = \sigma(e^+e^- \to \text{had}) / \sigma(e^+e^- \to \mu^+\mu^-)$

Dispersion Relation



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



0νββ-Decay: LNV? Mass Term?

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

Dirac

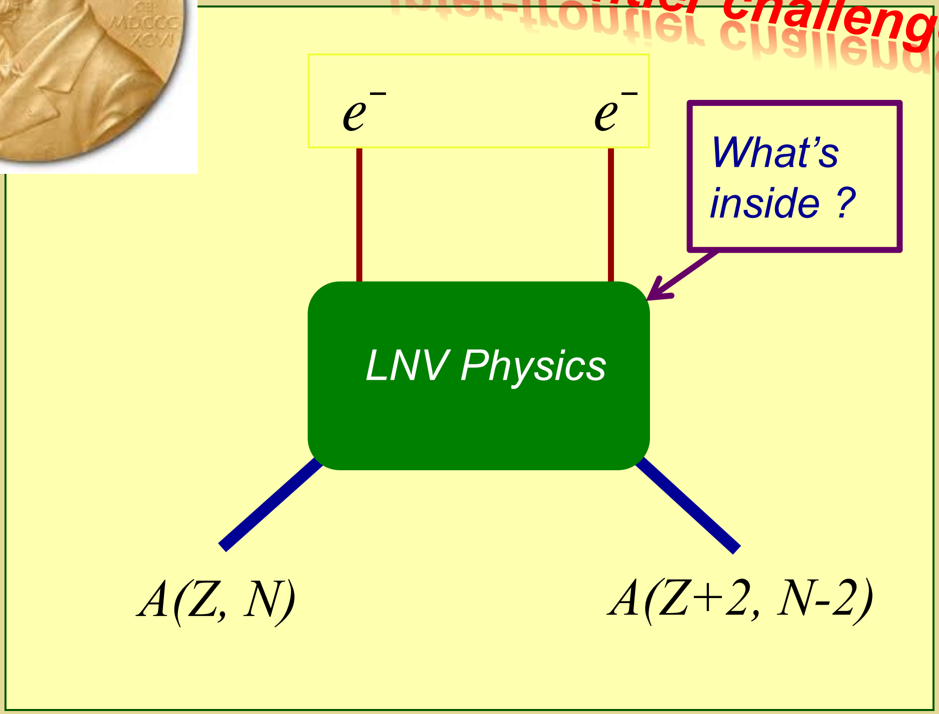
$$\mathcal{L}_{\text{mass}} = \frac{y}{\Lambda}\bar{L}^c H H^T L \ + \ \text{h.c.}$$

Majorana

Impact of observation

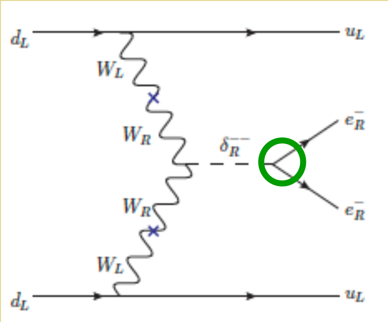
- *Total lepton number not conserved at classical level*
- *New mass scale in nature, Λ*
- *Key ingredient for standard baryogenesis via leptogenesis*

Inter-frontier challenge

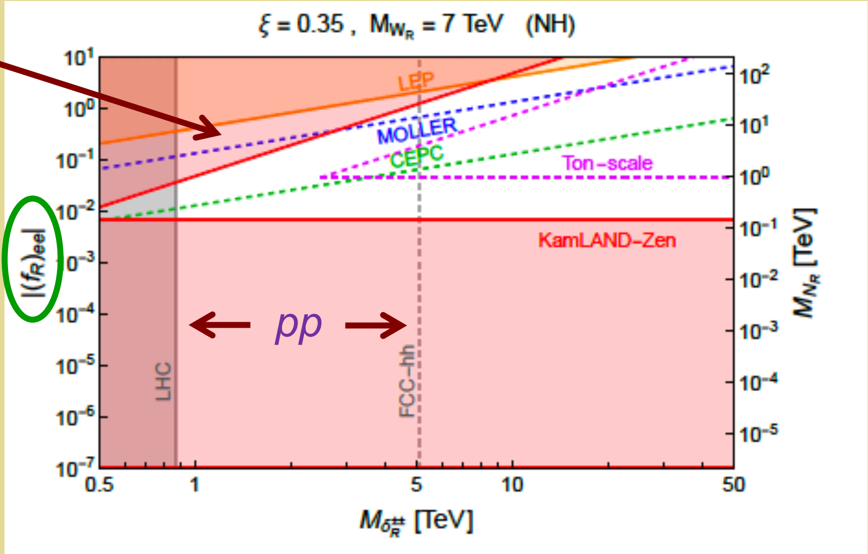


$0\nu\beta\beta$-Decay & PVES

$0\nu\beta\beta$ Decay, PV $e^-e^- \rightarrow e^-e^-$, $e^+e^- \rightarrow e^+e^-$ & pp collisions



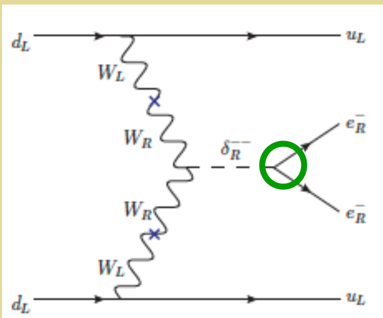
MLRM type II Seesaw: δ^{--}

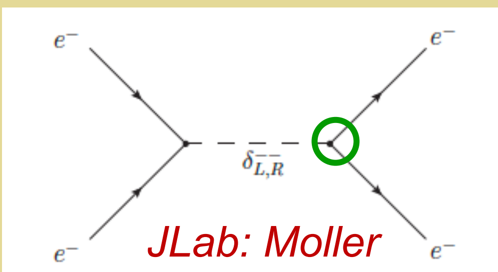


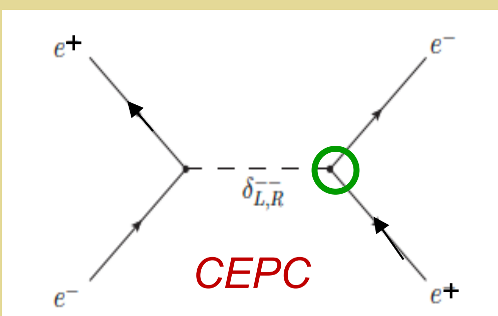
G. Li, MJRM, S. Urrutia-Quiroga, J.C. Vasquez

$0\nu\beta\beta$-Decay & PVES

$0\nu\beta\beta$ Decay, PV $e^-e^- \to e^-e^-$, $e^+e^- \to e^+e^-$ & pp collisions







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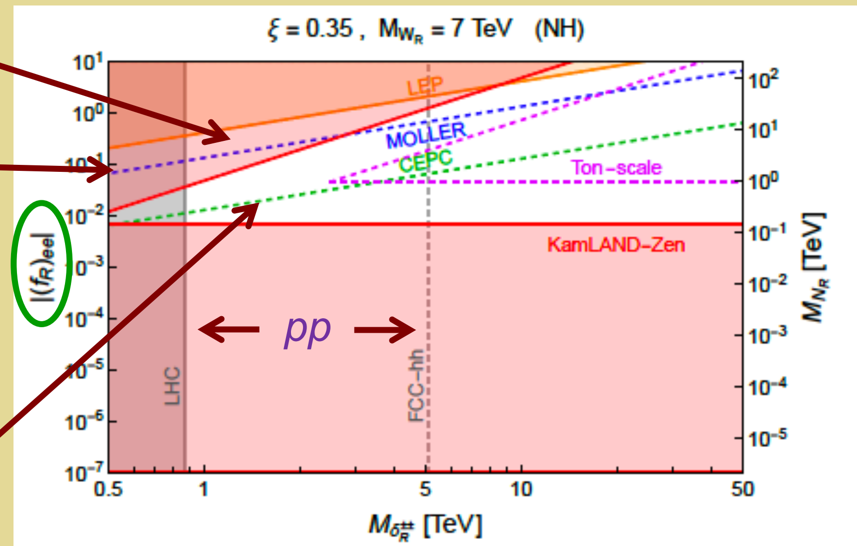
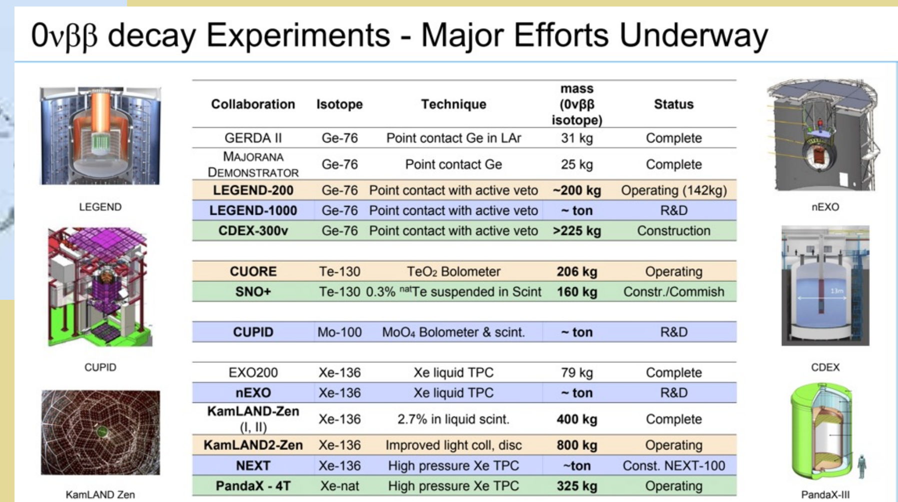


G. Li, MJRM, S. Urrutia-Quiroga, J.C. Vasquez

NLDBD Experimental Horizons

Thanks: J. Wilkerson



0νββ decay Experiments - Major Efforts Underway

Collaboration	Isotope	Technique	mass (0νββ isotope)	Status
GERDA II	Ge-76	Point contact Ge in LAr	31 kg	Complete
MAJORANA DEMONSTRATOR	Ge-76	Point contact Ge	25 kg	Complete
LEGEND-200	Ge-76	Point contact with active veto	**~200 kg**	Operating (142kg)
LEGEND-1000	Ge-76	Point contact with active veto	**~ ton**	R&D
CDEX-300v	Ge-76	Point contact with active veto	**>225 kg**	Construction
CUORE	Te-130	TeO_2 Bolometer	**206 kg**	Operating
SNO+	Te-130	0.3% ^{nat}Te suspended in Scint	**160 kg**	Constr./Commish
CUPID	Mo-100	MoO_4 Bolometer & scint.	**~ ton**	R&D
EXO200	Xe-136	Xe liquid TPC	79 kg	Complete
nEXO	Xe-136	Xe liquid TPC	**~ ton**	R&D
KamLAND-Zen (I, II)	Xe-136	2.7% in liquid scint.	**400 kg**	Complete
KamLAND2-Zen	Xe-136	Improved light coll, disc	**800 kg**	Operating
NEXT	Xe-136	High pressure Xe TPC	**~ton**	Const. NEXT-100
PandaX - 4T	Xe-nat	High pressure Xe TPC	**325 kg**	Operating

- ***Global effort to deply "ton scale" expt's → 100 x better lifetime sensitivity***
- ***Top priority for U.S. nuclear science***

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

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

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