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

NTNP Meeting, Seattle
June 1, 2023

Goals for This Talk

- *Provide the NTNP collaboration a framework for communicating the scientific motivation, significance, and impact of FSNN theory to our colleagues within and beyond nuclear physics*
- *Illustrate the multifaceted role for FSNN theory in this context*
- *Summarize some of the open challenges that the NTNP collaboration can address*

Key Themes

- *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*

Caveats & Thanks

- *Most of the work referred to in this talk will involve my collaborations – due to time limitations in preparing this talk and not due to any judgement about the importance of work not cited*
- *Many colleagues have made important contributions not cited today, and our field is enriched by this work*
- *I owe a debt of gratitude to the many students, post-docs, and faculty collaborators with whom I've had the privilege of working over the years on the topics discussed today*

Outline

I. Context: Scientific Quest

II. Four Quests

Today A. Parity-violation with electrons

B. β–Decay: 65 years after Wu et al

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

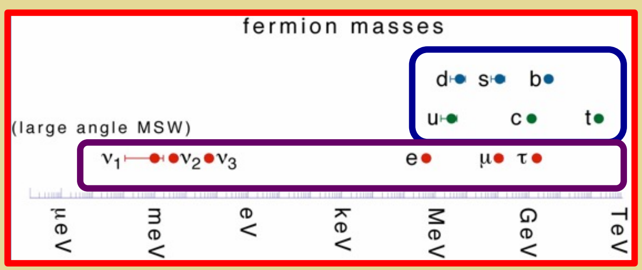
Time permitting D. CP: Electric Dipole Moments & the Origin of Matter

III. Concluding Remarks

I. Context

Fundamental Questions

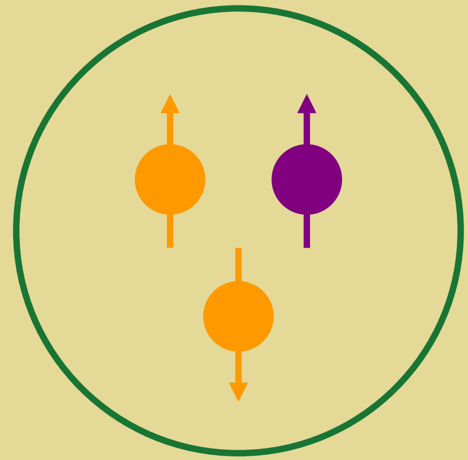
Matter, Energy & Mass



Origin of m_f

Beyond Standard Model

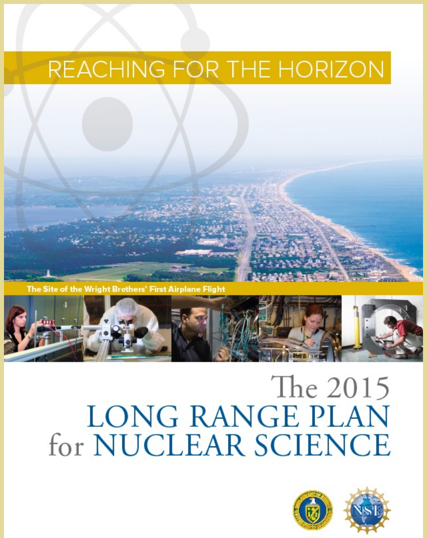
Nucleon & Nuclear Structure



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

Within Standard Model

Nuclear Science Strategic Vision



1. How did visible matter come into being and how does it evolve?
2. How does subatomic matter organize itself and what phenomena emerge?
3. Are the fundamental interactions that are basic to the structure of matter fully understood?
4. How can the knowledge and technical progress provided by nuclear physics best be used to benefit society?"

- **What are the absolute masses of neutrinos, and how have they shaped the evolution of the universe?**
- **Are neutrinos their own antiparticles?**
- **Why is there more matter than antimatter in the present universe?**
- **What are the unseen forces that disappeared from view as the universe expanded and cooled?**

RECOMMENDATION II

The excess of matter over antimatter in the universe is one of the most compelling mysteries in all of science. The observation of neutrinoless double beta decay in nuclei would immediately demonstrate that neutrinos are their own antiparticles and would have profound implications for our understanding of the matter-antimatter mystery.

We recommend the timely development and deployment of a U.S.-led ton-scale neutrinoless double beta decay experiment.

Nuclei & Hadrons as Laboratories

EDM searches:

BSM CPV, Origin of Matter

CP Violation

Challenges (see also J Engel talk)

$0\nu\beta\beta$ 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

Illustrative story

Challenges (see also CY Seng talk)

Theoretical Challenges

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

BSM physics

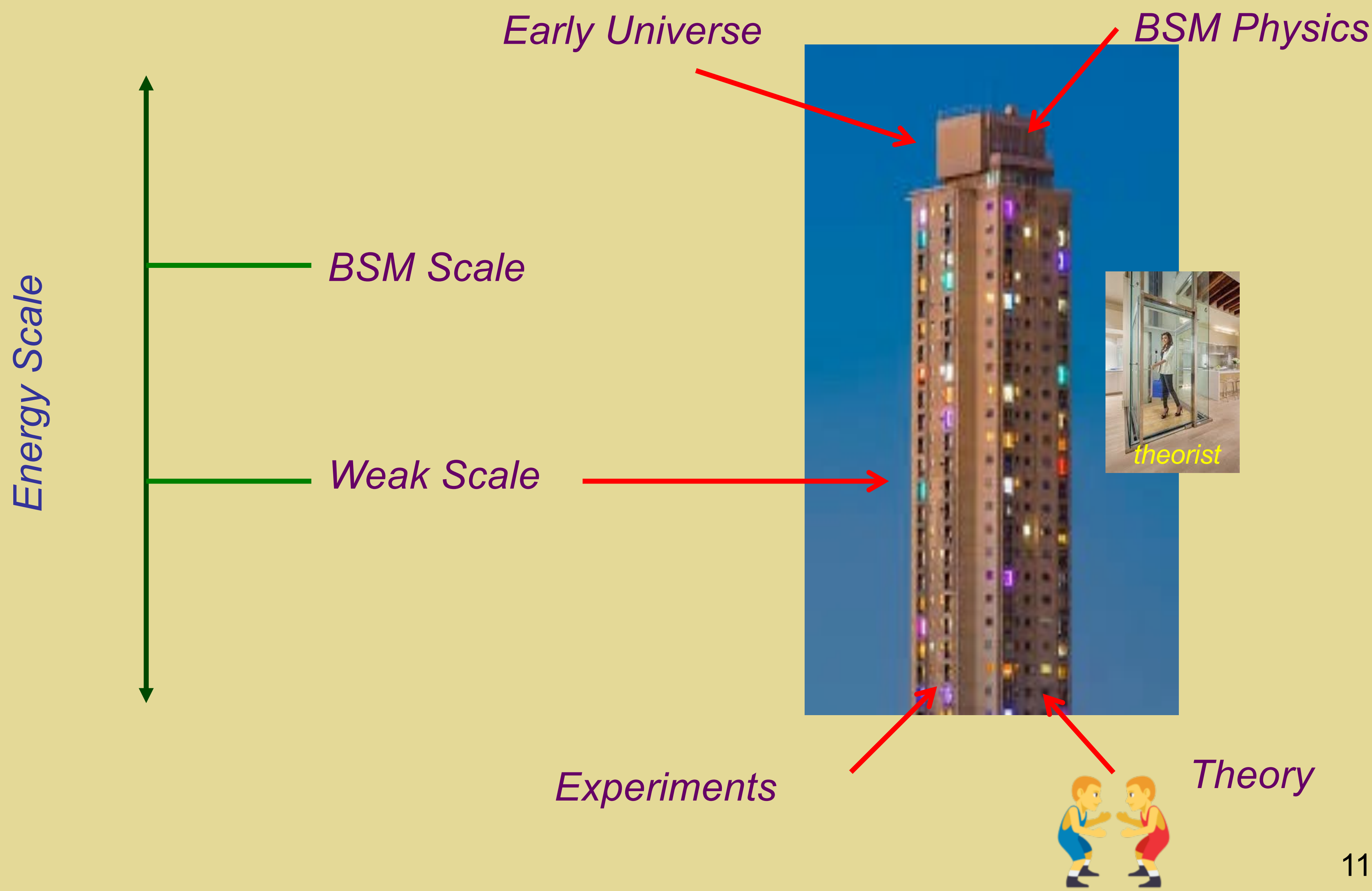
Nuclei as laboratories

"I want you to better understand me"

"I am incomplete, but I need you"

Electroweak probes

Theoretical Challenges



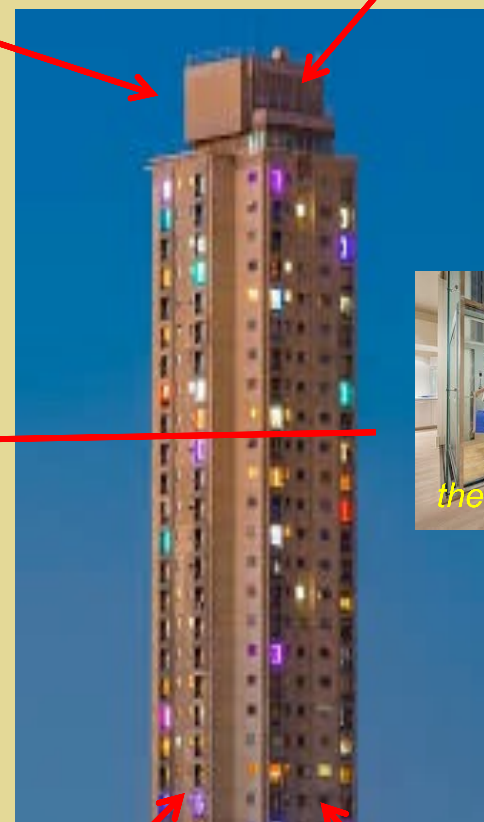
Theoretical Challenges

Early Universe

BSM Physics

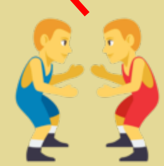
Precision Electroweak Studies

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



Experiments

Theory

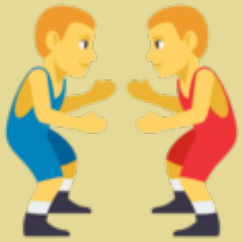


Theoretical Challenges

- What level of precision/sensitivity is needed to have significant scientific impact ?

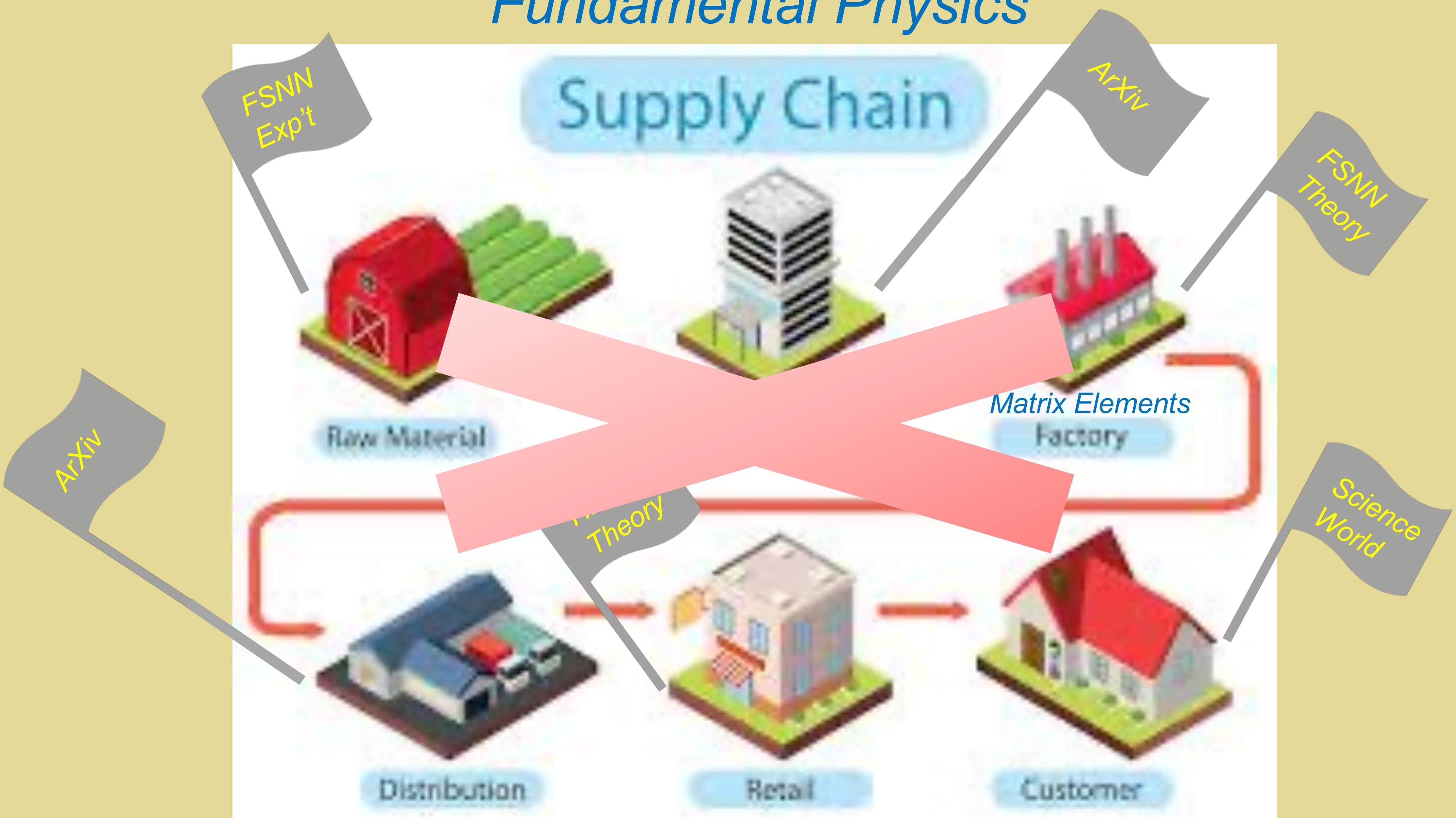
- How reliably can we interpret electroweak processes at the nuclear and hadronic scales in terms of
    - nucleon & nuclear structure ?
    - beyond Standard Model physics ?

- What is the theoretical error bar ?



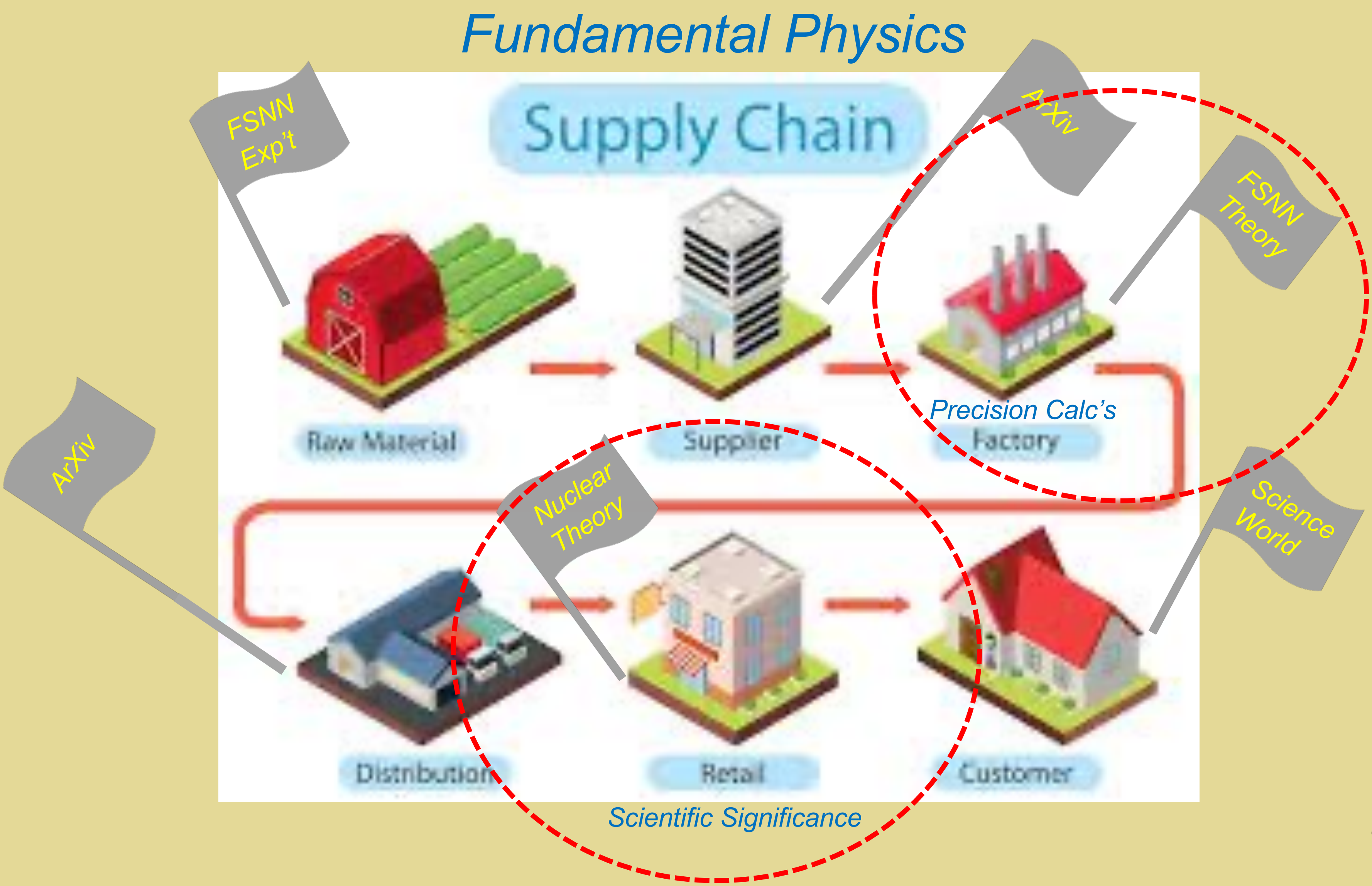
FSNN Theory: An Urban Legend

Fundamental Physics



Scientific Significance

FSNN Theory: Comprehensive Role



Theoretical Challenges

Connecting physics at multiple scales

Early Universe

BSM Physics

Precision Electroweak Studies

- ***Perturbation theory***
- ***Effective Field Theory***
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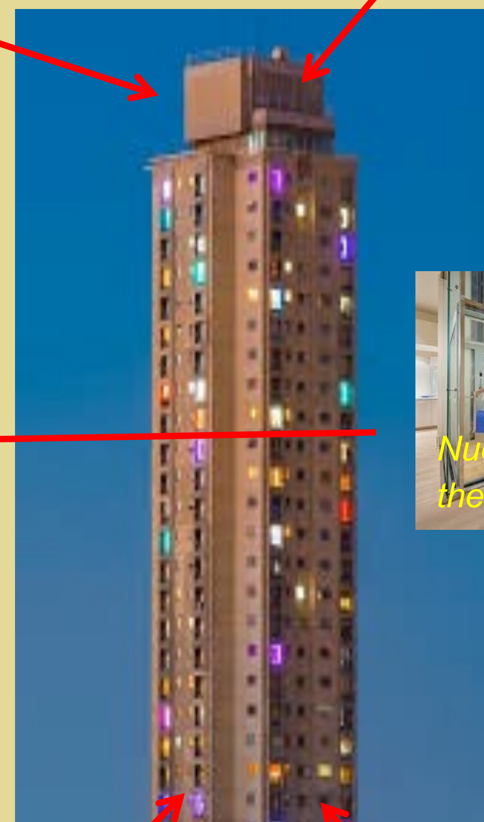
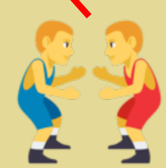


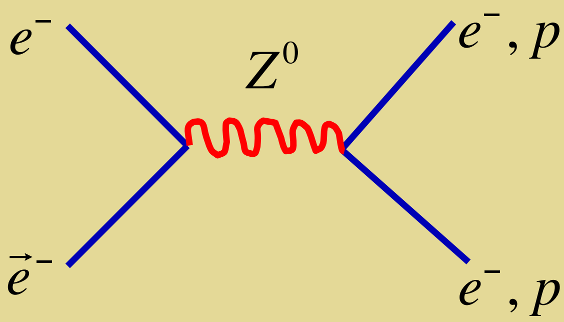
Experiments

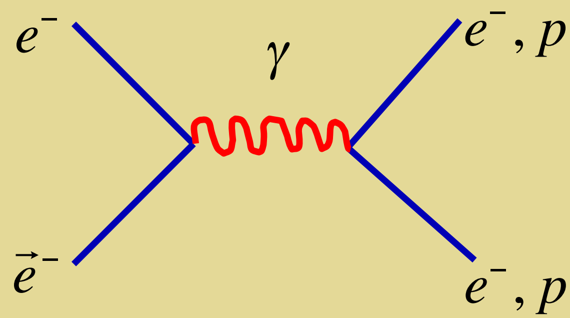
Theory



IIA. Parity-Violation with Electrons

Parity-Violation & Weak Charges





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" ≠ 0 in SM

Sensitivity to BSM physics

Challenge: reducing the theoretical uncertainties

QCD effects (s-quarks)

Challenge: precision electroweak probe

PV Electron Scattering

Continuous interplay between probing hadron structure and electroweak physics

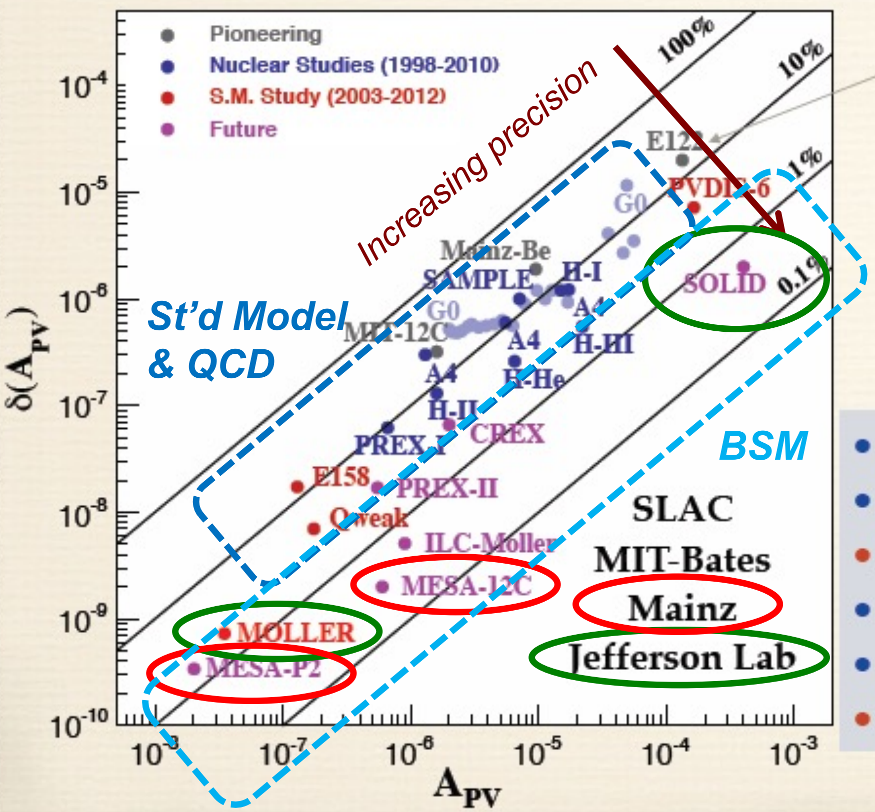
4 Decades of Progress

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

Electroweak Radiative Corrections

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

ELECTROWEAK CORRECTIONS TO PARITY-VIOLATING NEUTRAL CURRENT SCATTERING

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and

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PHYSICAL REVIEW D VOLUME 43, NUMBER 9 1 MAY 1991

Observability of the anapole moment and neutrino charge radius

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

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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, Cali*
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(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]
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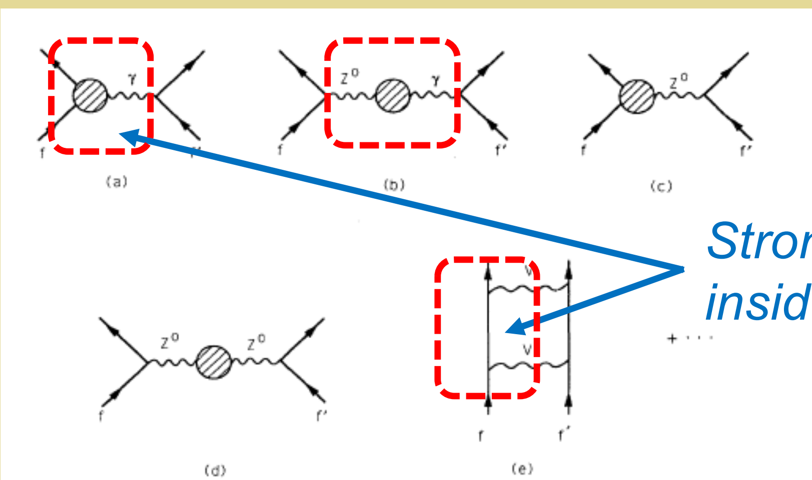
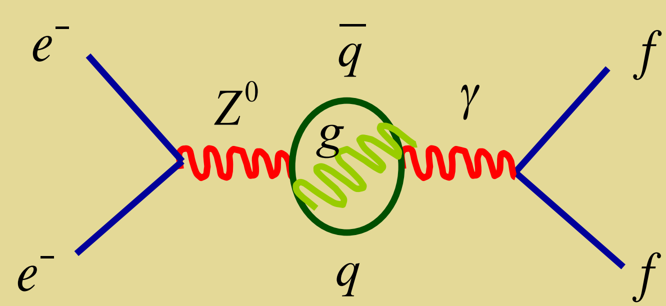
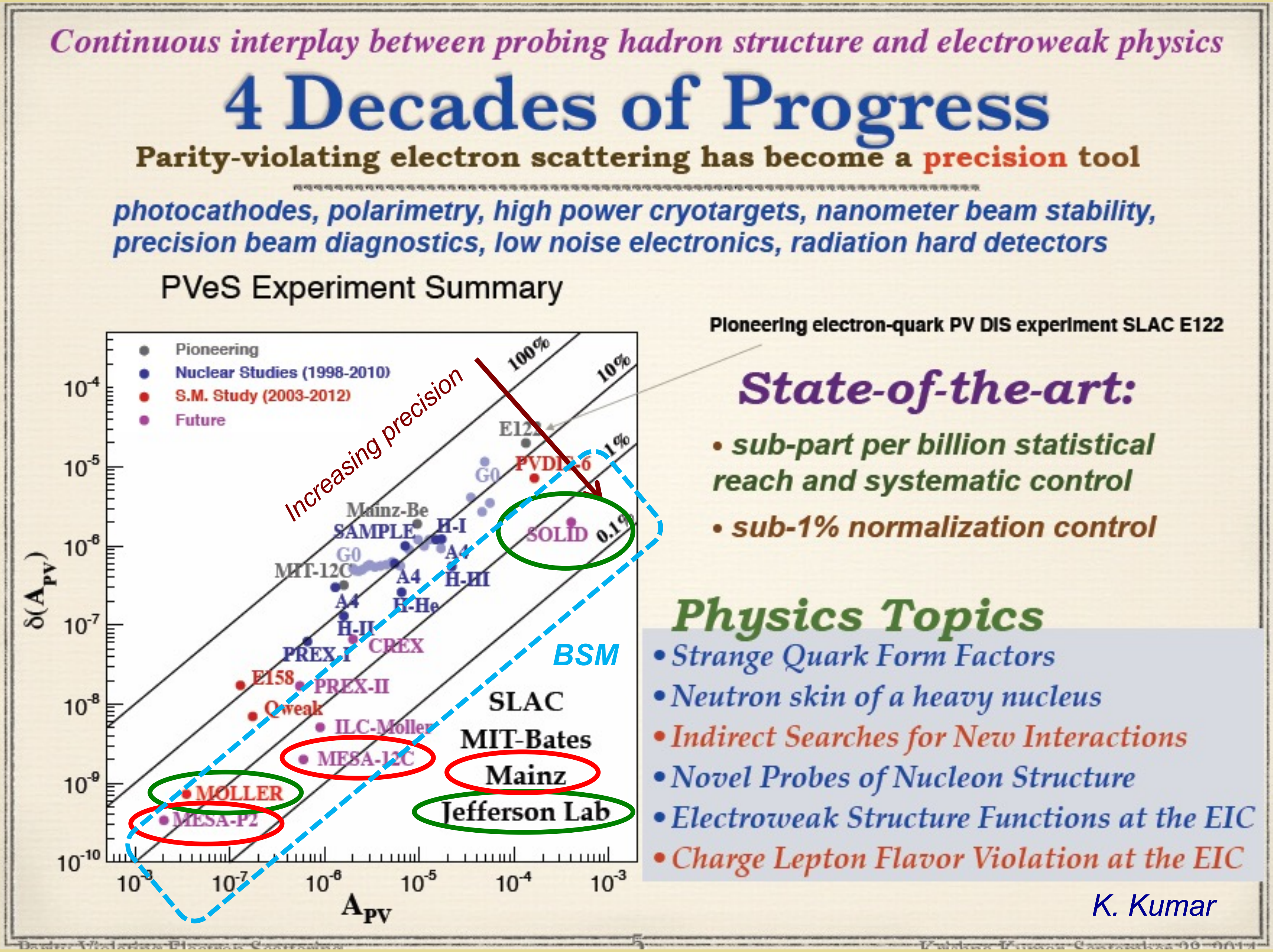


Strong interaction: inside proton

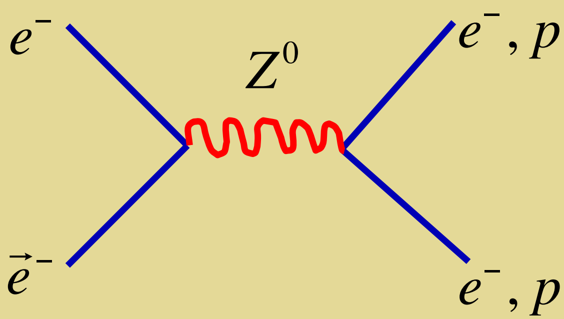
Strong interaction

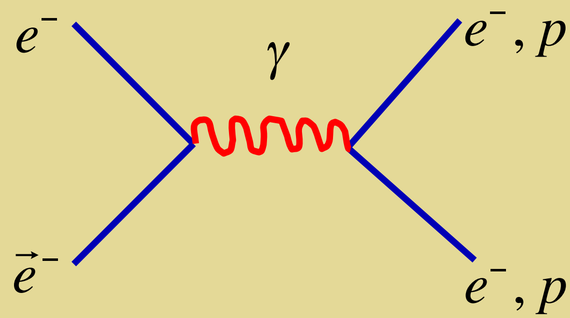


PV Electron Scattering



Parity-Violation & Weak Charges





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"Weak Charge" ≠ 0 in SM

Sensitivity to BSM physics

Challenge: reducing the theoretical uncertainties

Weak Charge & Weak Mixing

Near cancellation

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

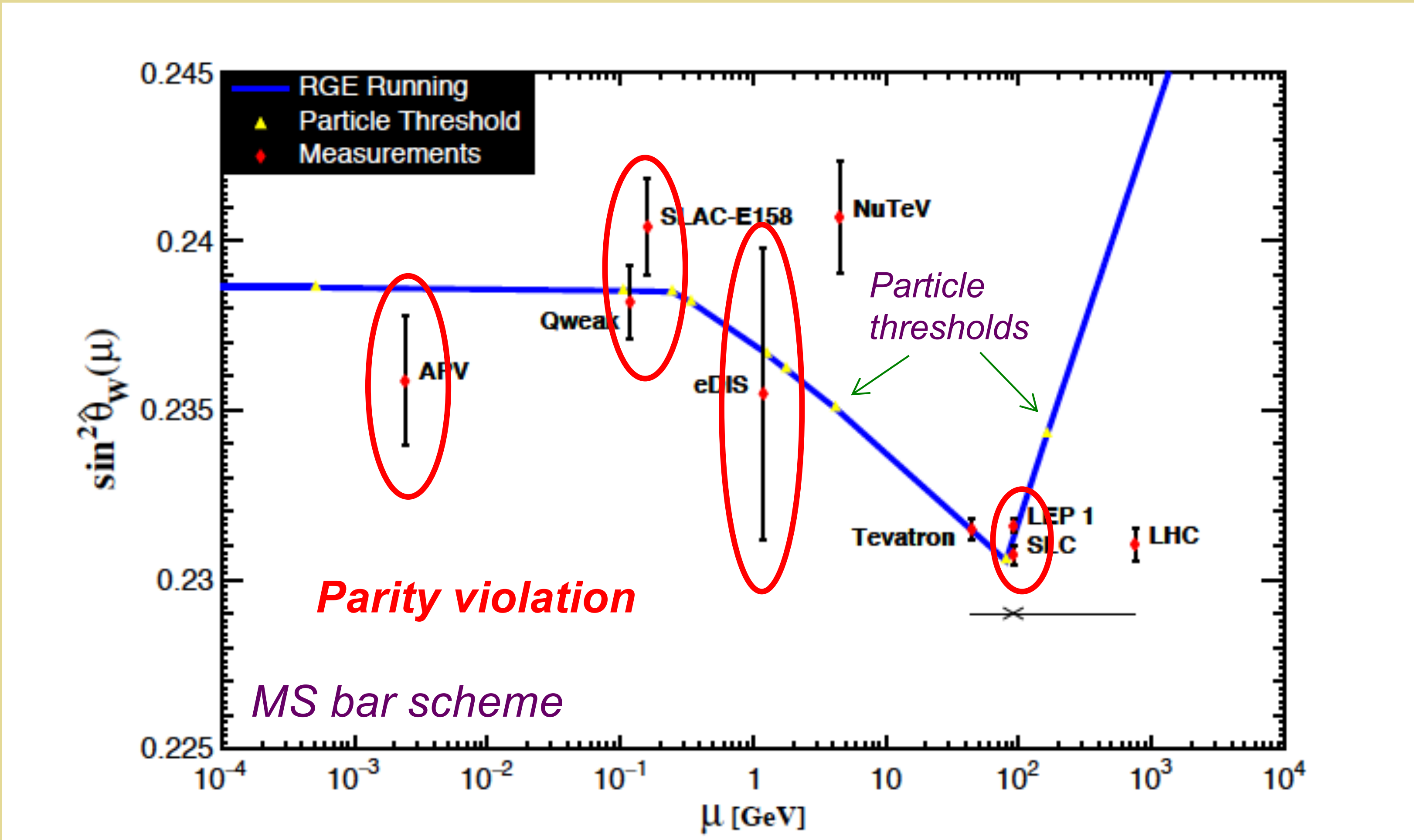
$$\sin^2\theta_W = \frac{g(\mu)_Y^2}{g(\mu)^2 + g(\mu)_Y^2}$$

$SU(2)_L$

$U(1)_Y$

Weak mixing depends on scale

Weak Mixing: Energy Scale Dependence



Marciano & Czarnecki ’00
Erler & MJRM ‘05
Erler & Ferro-Hernandez ‘18

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*
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[3]*Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California 91125, USA*
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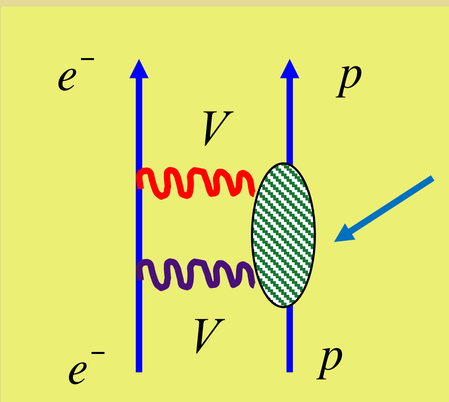


Strong interaction: inside proton

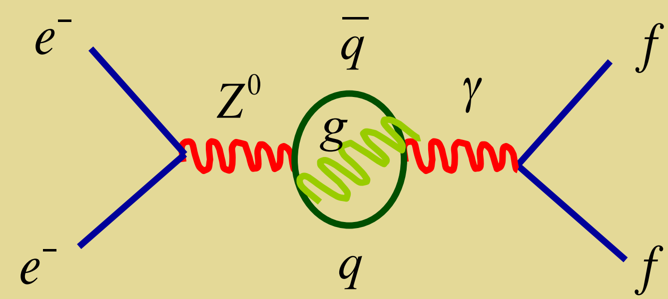
Pertrubative

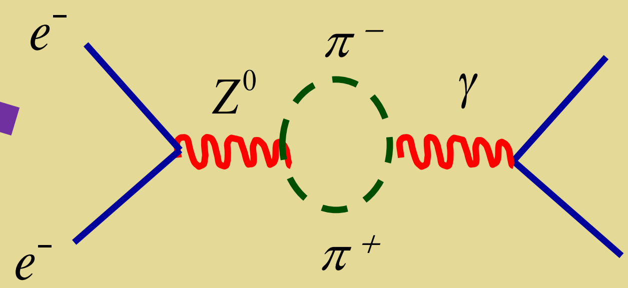
$$\Box_{WW}=\frac{\hat{\alpha}}{4\pi\hat{s}^2}\left[2+5\left(1-\frac{\alpha_s(M_W^2)}{\pi}\right)\right],$$

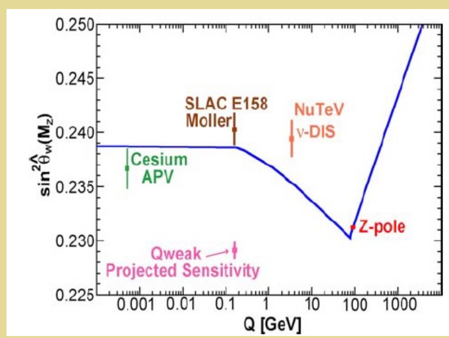
Non-pertrubative

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

Strong interaction







Weak Mixing in the SM: Uncertainties

Erler & R-M

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

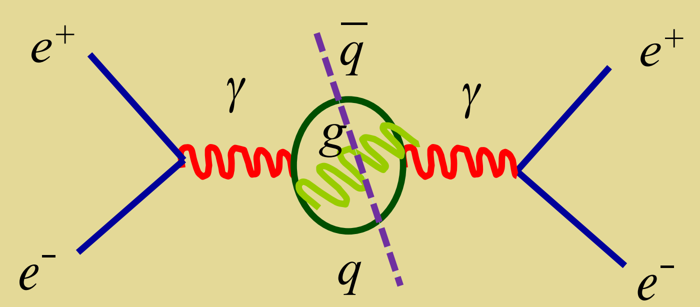
$$\hat{s}^2 \frac{d\hat{\alpha}}{dt} - \hat{\alpha}\frac{d\hat{s}^2}{dt} = \frac{b_2}{\pi}\hat{\alpha}^2 + \sum_j \frac{b_{2j}}{\pi^2}\hat{\alpha}^2\hat{\alpha}_j + \cdots$$

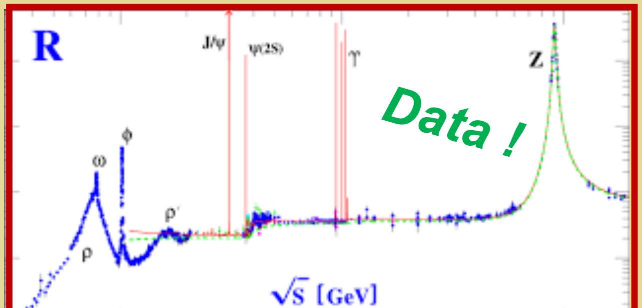
$$\sin^2\hat{\theta}_W(\mu) = \frac{\hat{\alpha}(\mu)}{\hat{\alpha}(\mu_0)}\sin^2\hat{\theta}_W(\mu_0) + \frac{\sum_i N_i^c \gamma_i Q_i T_i}{\sum_i N_i^c \gamma_i Q_i^2}\left[1 - \frac{\hat{\alpha}(\mu)}{\hat{\alpha}(\mu_0)}\right],$$

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

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

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*

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

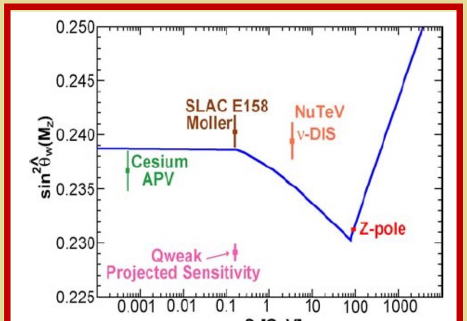
Uncertainties: $\sin^2\theta_W(0)$

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

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

+/- 3×10^{-5}: OZI

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



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Electroweak Radiative Corrections

PHYSICAL REVIEW D 68, 016006 (2003)

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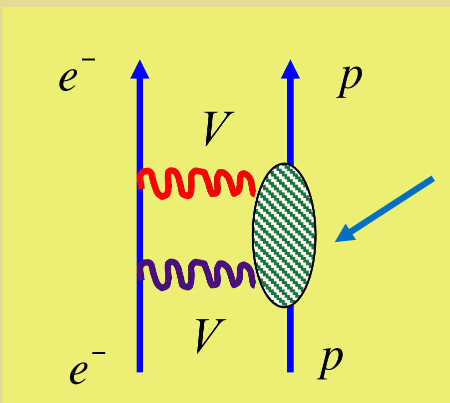

Strong interaction: inside proton

Pertrubative

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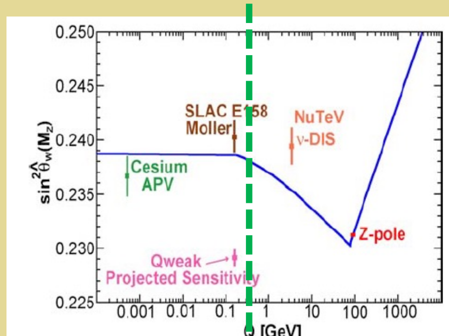
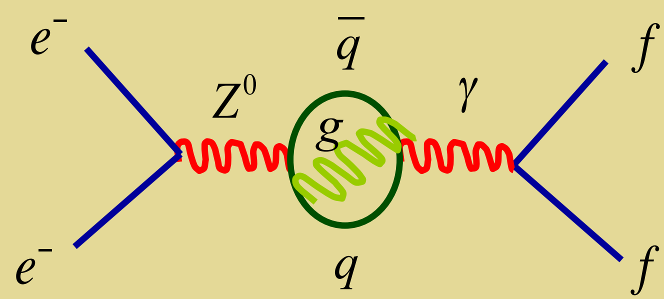
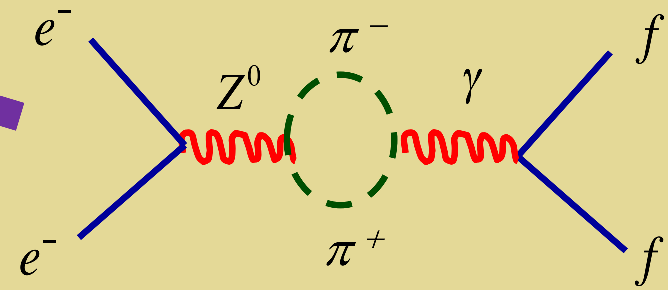
Non-pertrubative

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



Strong interaction



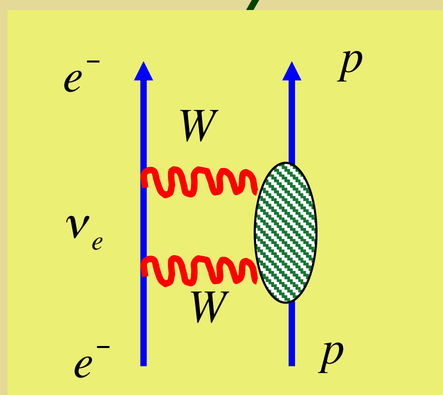


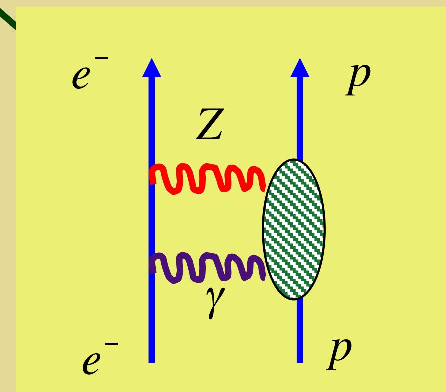
Radiative Correction Uncertainties

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

Erler, Kurylov & R-M

E-Independent





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

$\delta Q_W \sim 0.7\%$

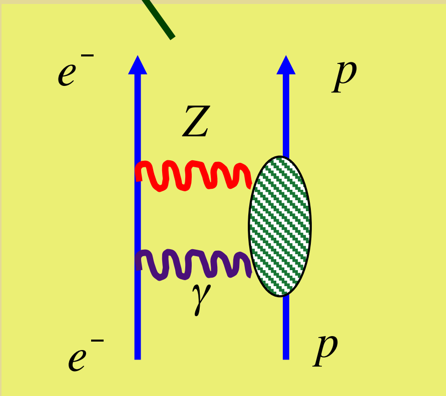
$$\Box_{WW} = \frac{\hat{\alpha}}{4\pi\hat{s}^2}\left[2+5\left(1-\frac{\alpha_s(M_W^2)}{\pi}\right)\right]$$

$\delta Q_W \sim 0.1\%$

Order α_s^2

Radiative Correction Uncertainties

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



E-dependent: E = 1.165 GeV

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

Equivalent to ~ 2.8% uncertainty in Q_W

[11] Gorchtein & Horowitz

[15] Sibirtsev et al

[17] Rislow & Carlson

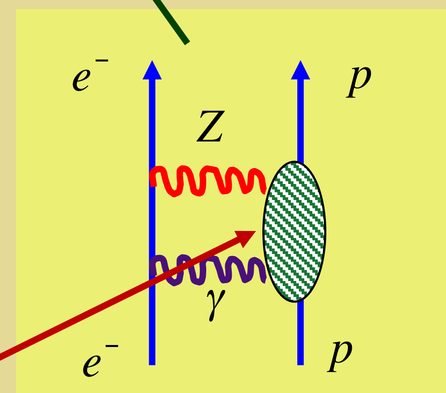
*** Gorchtein, Horowitz, R-M*

1102.3910 [nucl-th]

Includes estimate of model uncertainty

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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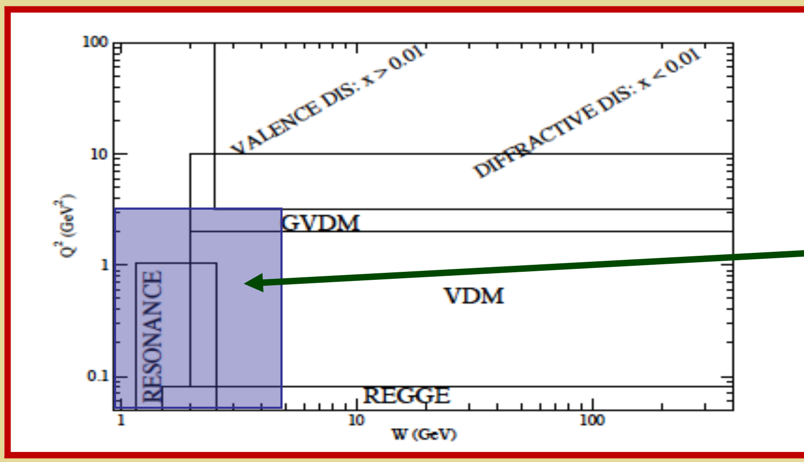
$(3 \pm 3)10^{-3}$	$(4.7^{+1.1}_{-0.4})10^{-3}$	$(5.7 \pm 0.9)10^{-3}$	$(5.4 \pm 2.0)10^{-3}$

Dispersion Theory : photo- & lepto-production



Unpack contributions to structure function $F^{\gamma Z}$

Dominant contributions; scarce data

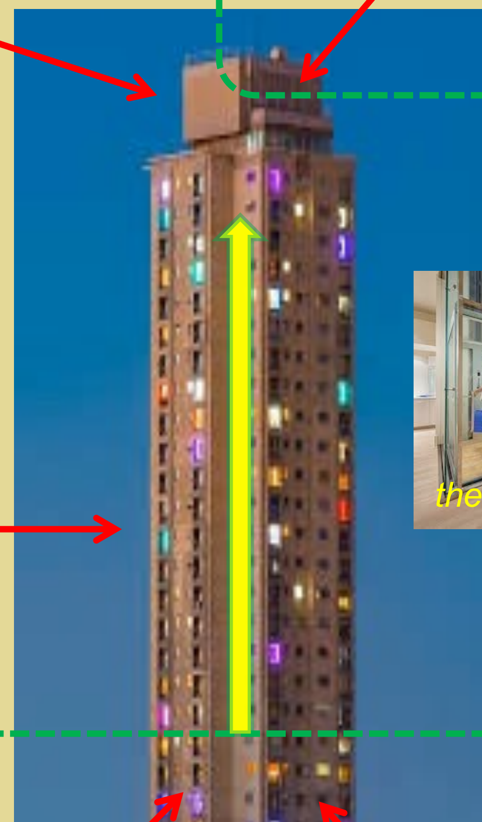
Measure A_{PV} in extrapolation region: direct probe of $F^{\gamma Z}$

Theoretical Challenges

Footprints

Early Universe

BSM Physics



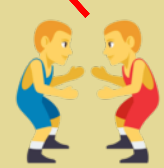
Energy Scale

BSM Scale

Weak Scale

↗ Precision ~
↗ BSM mass scale

Experiments

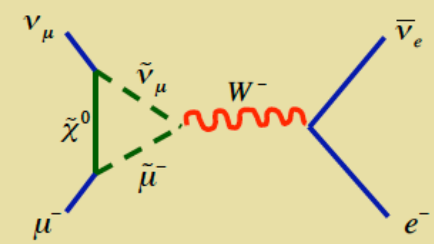


Theory

Intensity Frontier: BSM Footprints

New Symmetries

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



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

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

Precision ~ BSM Mass Scale

Precision ~ Mass Scale

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

Loop effect

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

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

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

Interpretability

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

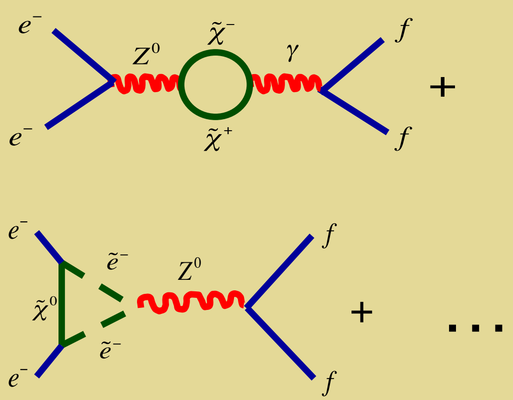
$\Lambda < 1$ *TeV (loop)* *Above example*

$\delta_{NEW} \sim C \; (M_W / \Lambda)^2$

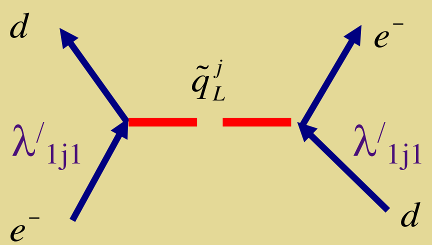
$\Lambda \sim 10$ *TeV (tree)*

Deviations: BSM "Footprints"

SUSY



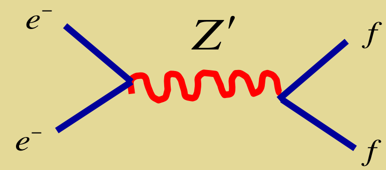
Radiative Corrections



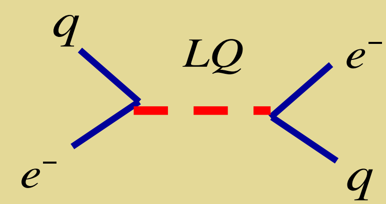
RPV

SUSY footprints ?

Z/ Bosons



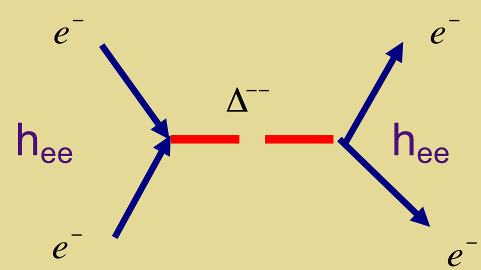
Leptoquarks



Semi-leptonic only

Doubly Charged Scalars

Moller only



Theoretical Challenges

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

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PHYSICS REPORTS

A Review Section of Physics Letters

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

A. Kurylov [a], M.J. Ramsey-Musolf [a,b], S. Su [a,c]

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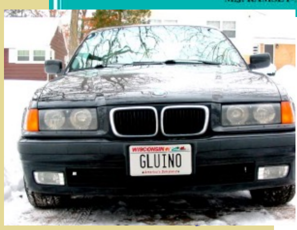
[b] Department of Physics, University of Connecticut, Storrs, CT 06269, USA
[c] Department of Physics, University of Arizona, Tucson, AZ 85721, USA

Received 21 October 2003; received in revised form 7 December 2003; accepted 17 December 2003
Editor: H. Georgi



PHYSICAL REVIEW D 68, 035008 (2003)

Probing supersymmetry with parity-violating electron scattering

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VOLUME 88, NUMBER 7 PHYSICAL REVIEW LETTERS 18 FEBRUARY 2002

Charged Current Universality in the Minimal Supersymmetric Standard Model

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[2] Department of Physics, University of Connecticut, Storrs, Connecticut 06269

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Supersymmetric effects in deep inelastic neutrino–nucleus scattering

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Footprints

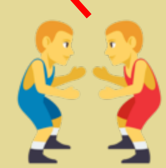
BSM Physics

SUSY ?

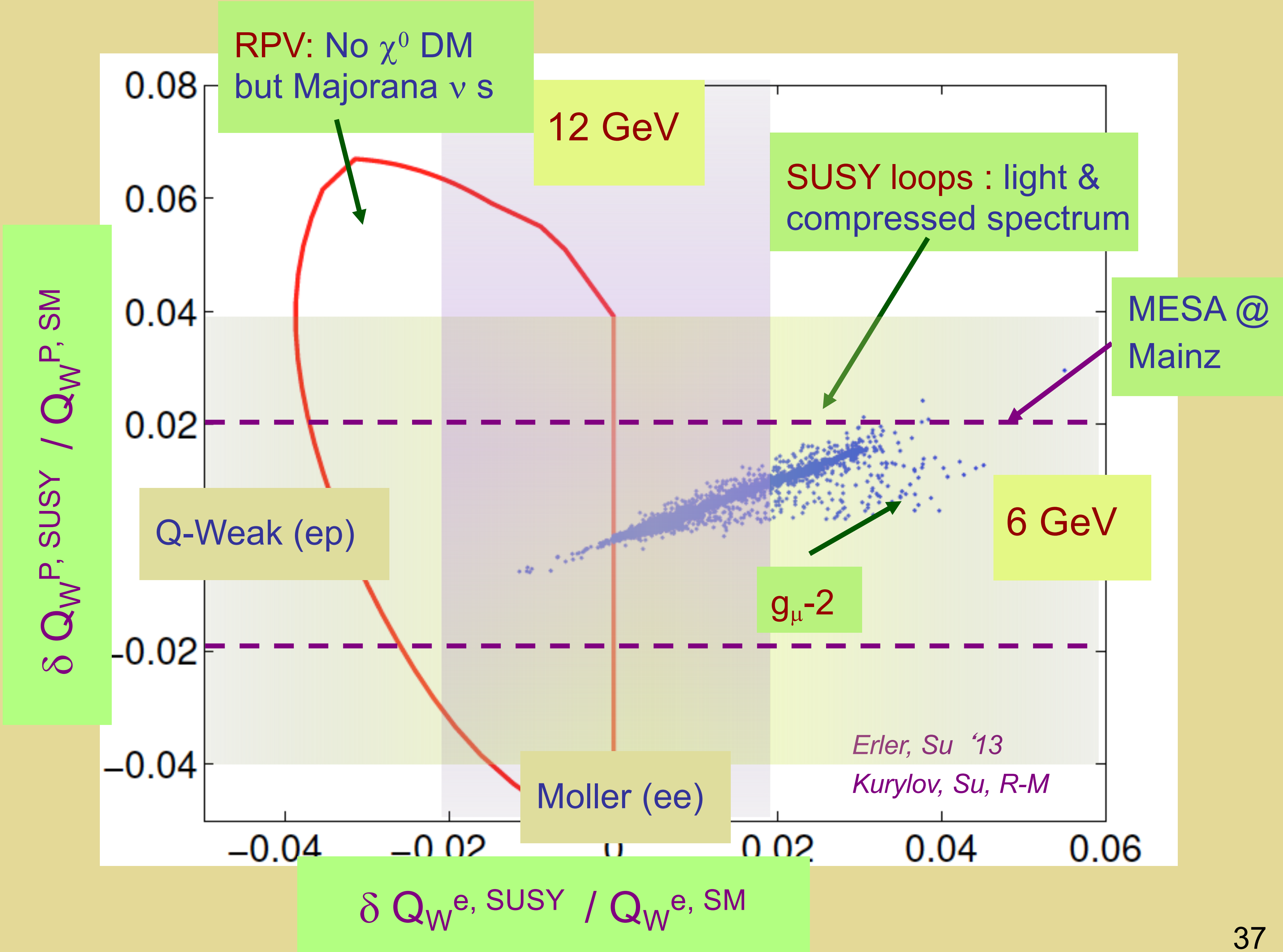
↗ Precision ~
↗ BSM mass scale

Experiments

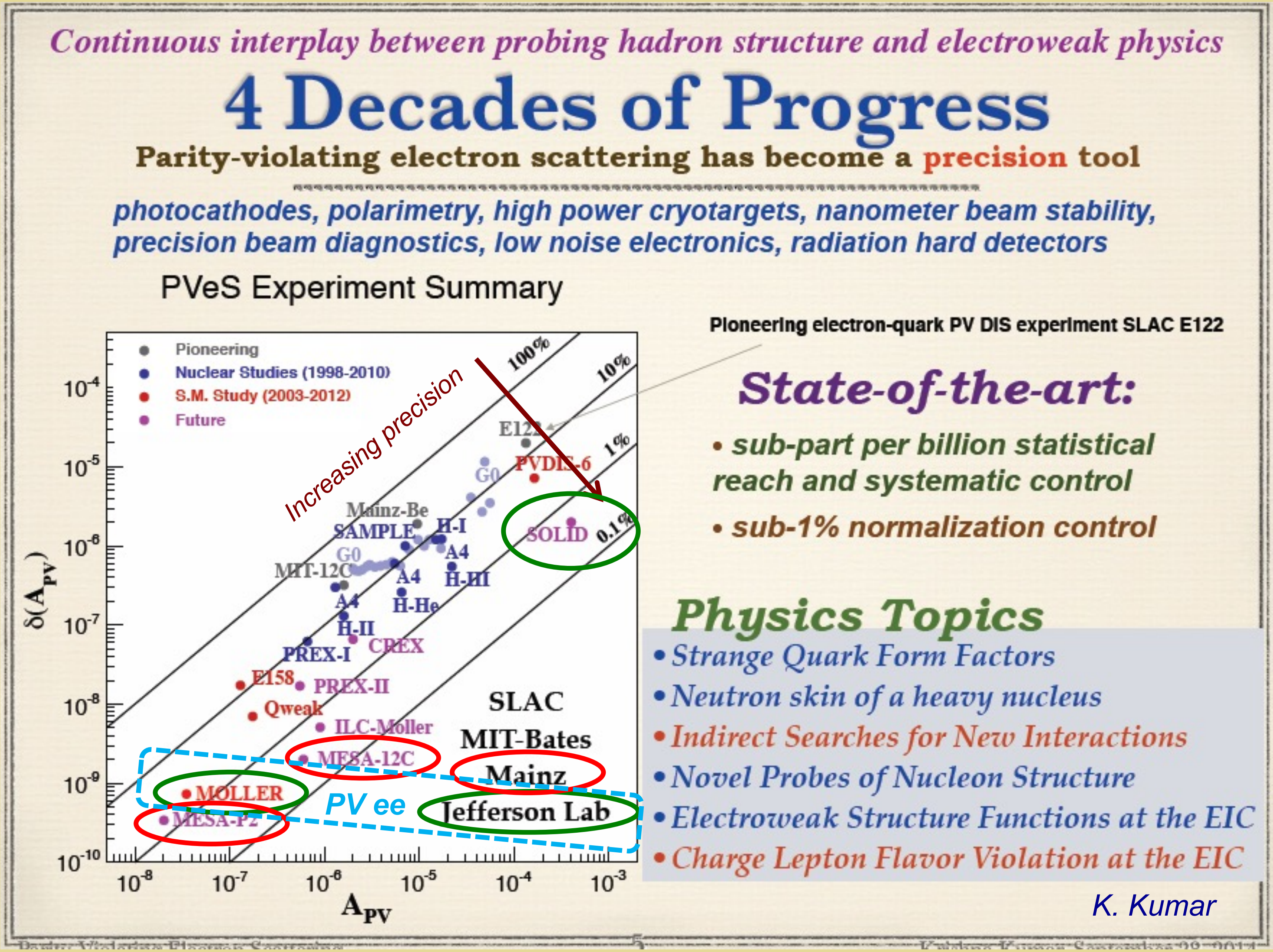
Theory



PV Electron Scattering: Diagnostic Tool



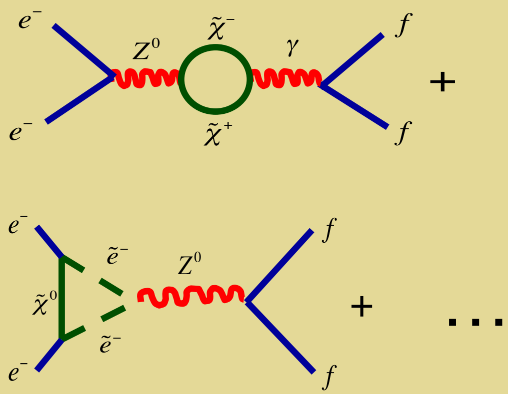
PV Electron Scattering



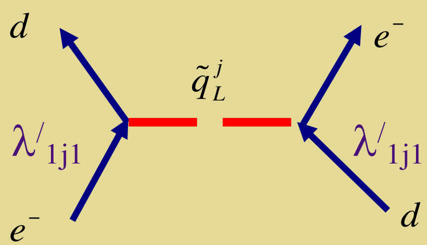
K. Kumar

Deviations: BSM "Footprints"

SUSY

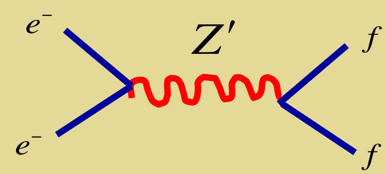


Radiative Corrections

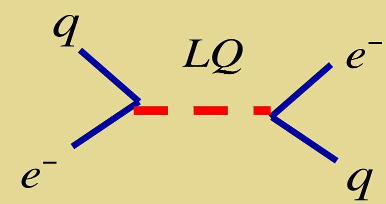


RPV

Z/ Bosons



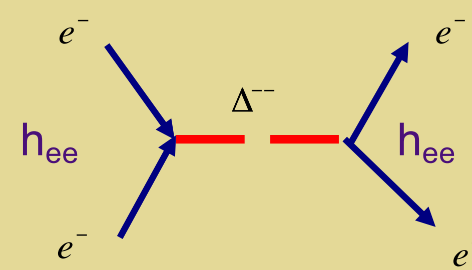
Leptoquarks



Semi-leptonic only

Doubly Charged Scalars

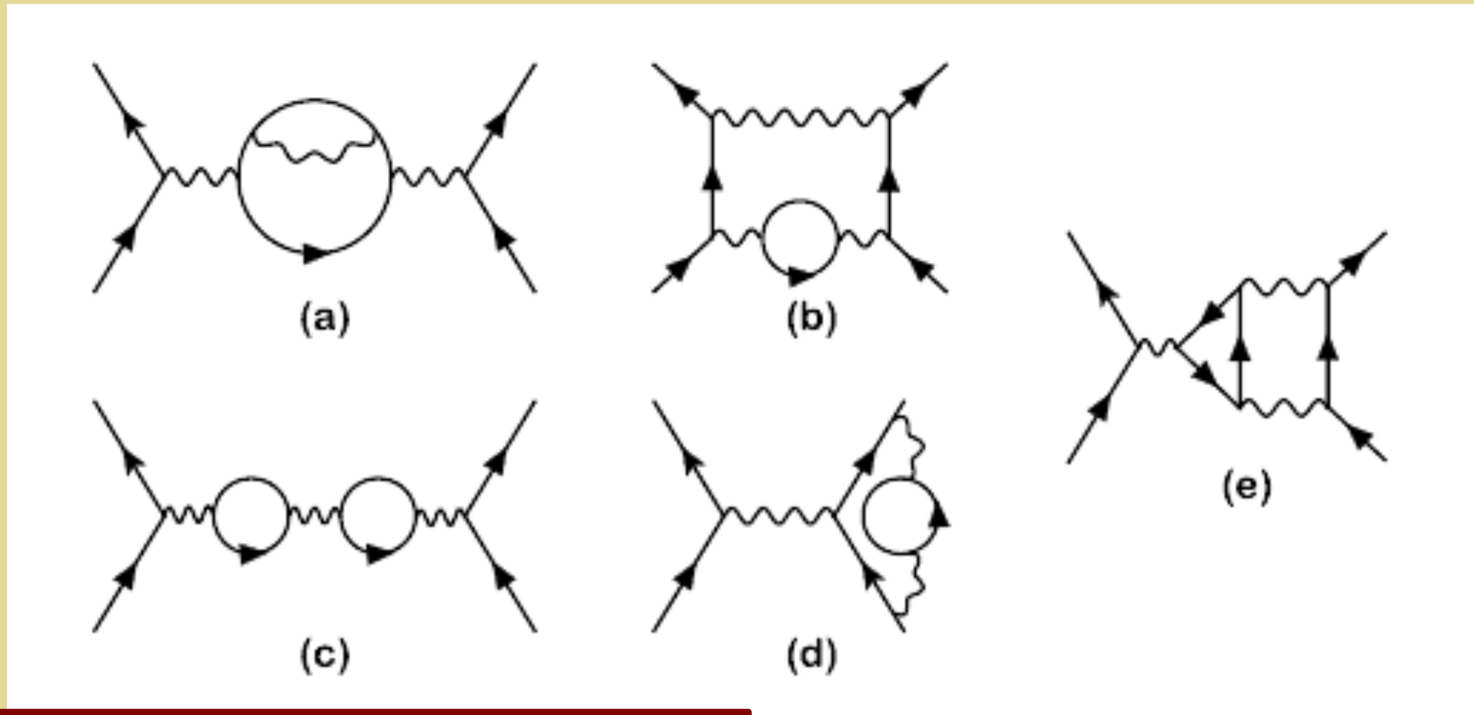
Moller only



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,§]

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[2]*Pittsburgh Particle Physics Astrophysics and Cosmology Center (PITT-PACC), Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, Pennsylvania 15260, USA*

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[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

$\delta(Q^e{}_W) = \pm 2.1\ \%\ (stat.) \pm 1.1\ \%\ (syst.)$ **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 !

Safe !

Loop order

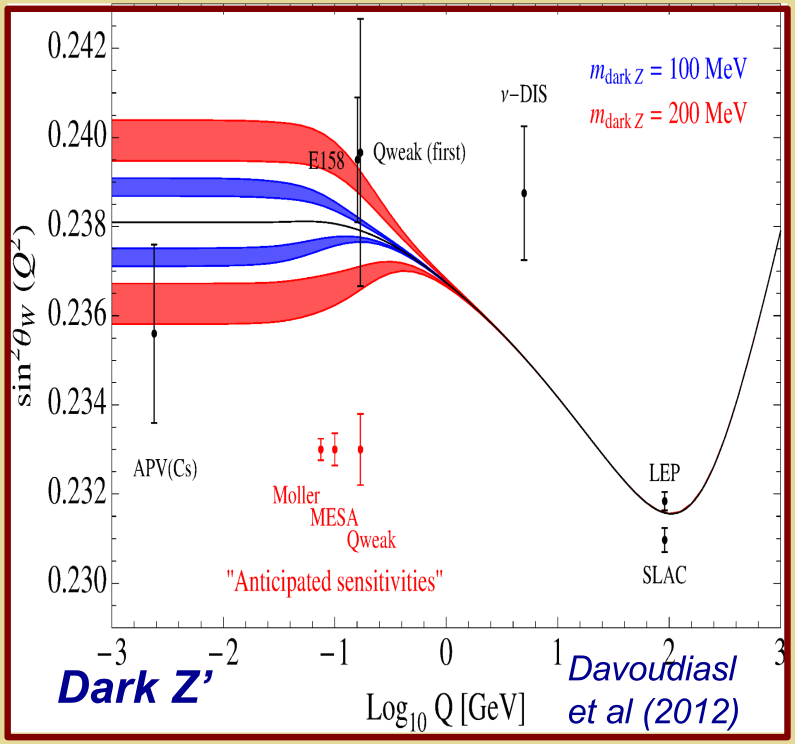
# of closed fermion loops

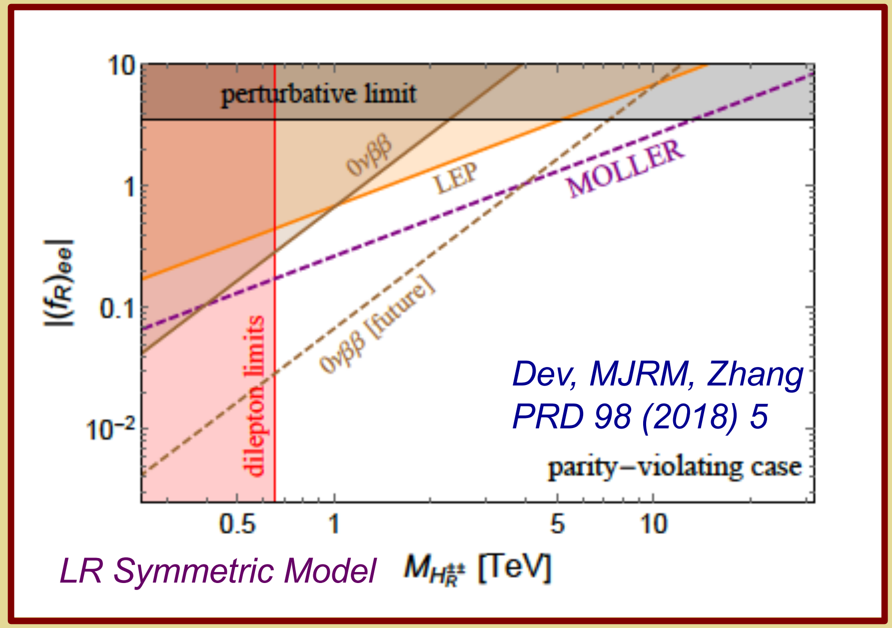
** Relative to preceding order*

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

PV Moller Scattering

Search for additional neutral weak force that is inaccessible to the Large Hadron Collider



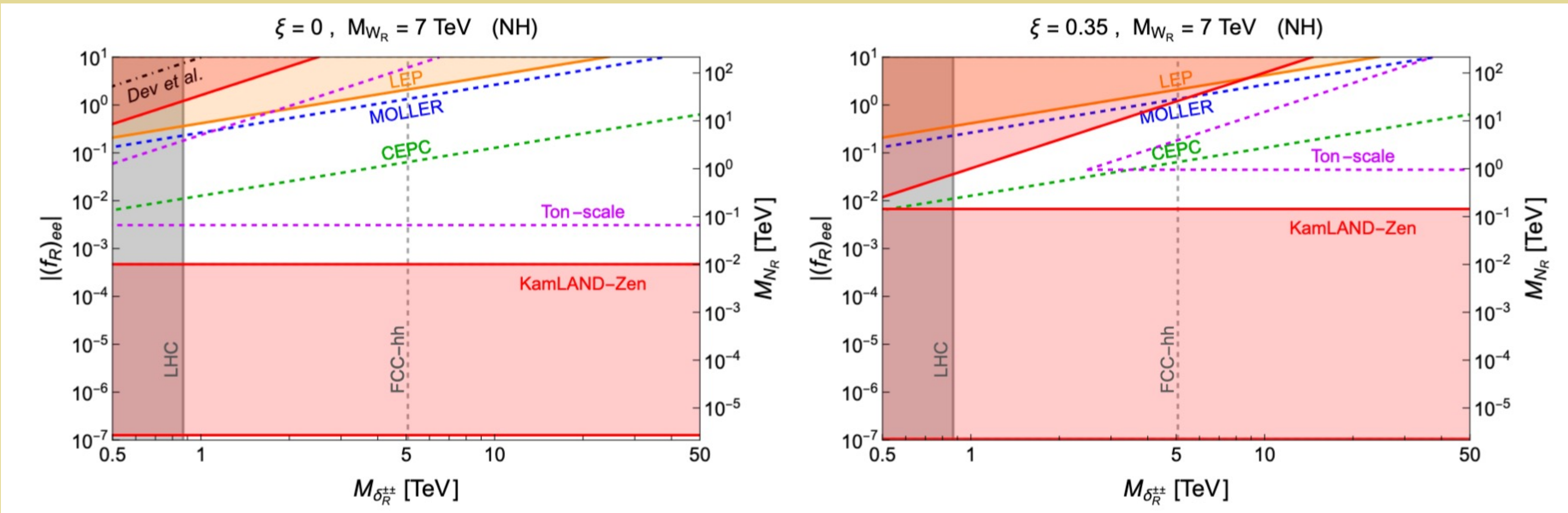


Dark Sector: Z'

Type II Seesaw: H^{++}

PV Moller Scattering

Interplay with $0\nu\beta\beta$ decay & collider searches



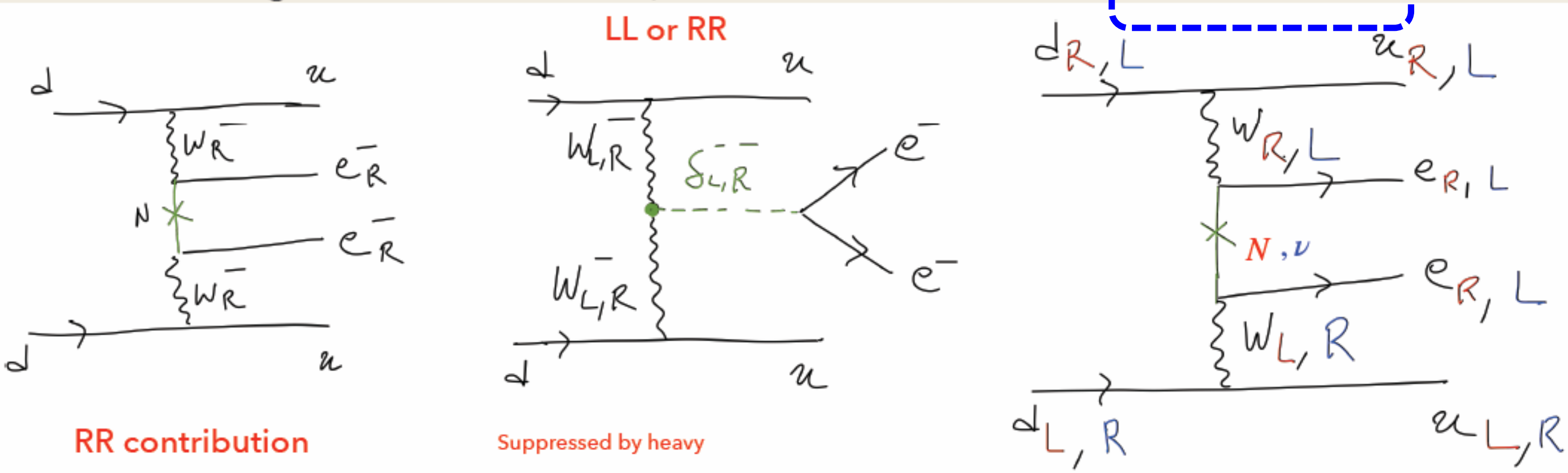
Type II Seesaw & H^{++} : G. Li, MJRM, S. Urrutia-Quiroga, J.C. Vasquez

Minimal LR Symmetric Model: $0\nu\beta\beta$-Decay

Long range chiral enhancement

- There are the following contributions (on top of the usual light neutrino contribution)

LR contribution



RR contribution

Suppressed by heavy

δ^{++} masses and LFV constraints (Tello and Senjanovic. ArXiv: 1011.3522)

ATLAS limit ~ 800 GeV) (arXIv: 1710.09748)

The Blue contributions are

Suppressed by small heavy-light

Neutrino mixing

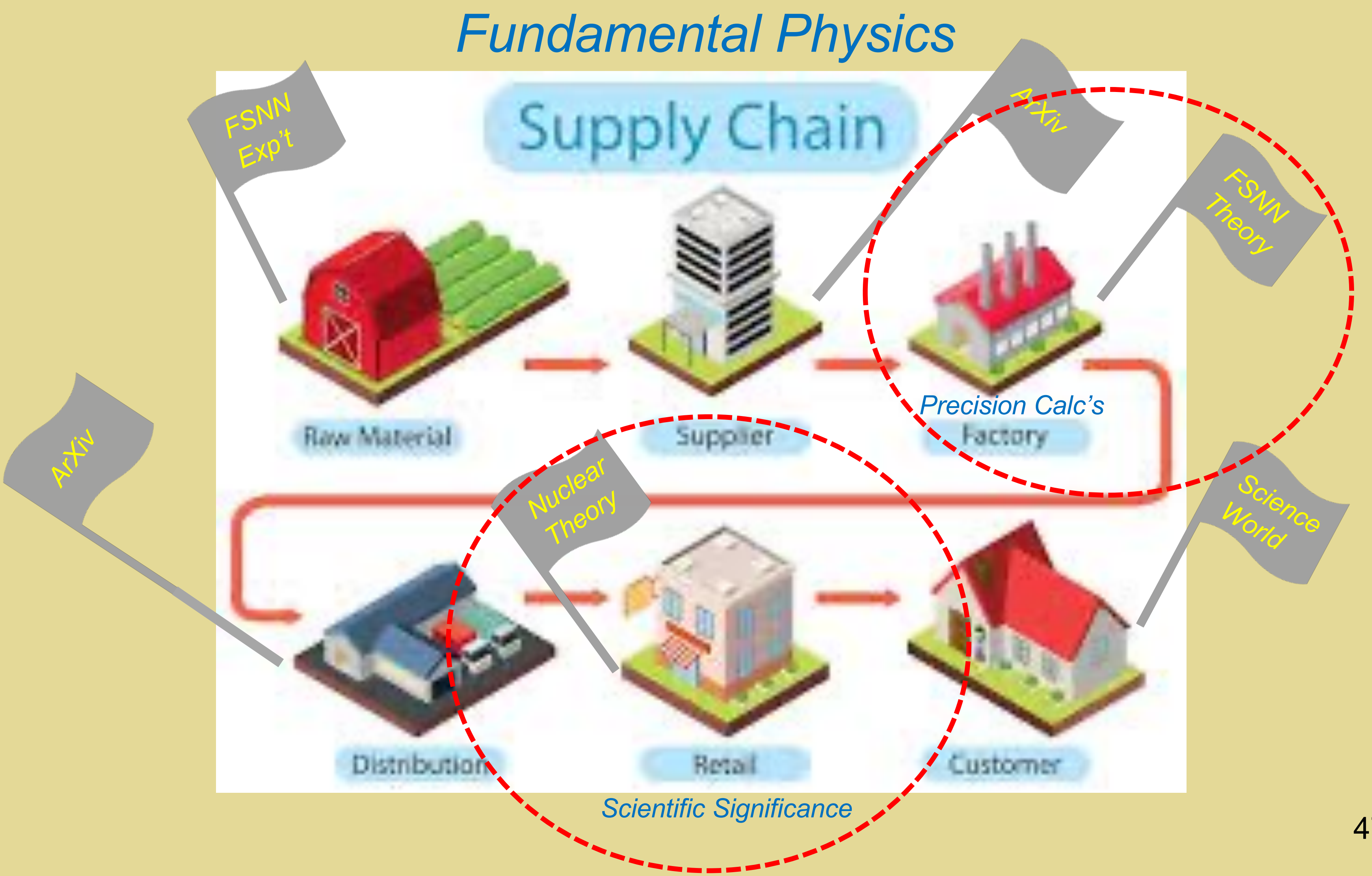
Thanks! Juan Carlos Vasquez

PVES: Lessons

- ***Integrated** treatment of physics at a **wide range of scales** is essential → draws on multiple theoretical tools and variety of expertise*
- ***Sustained effort** over many years required*
- ***Close collaboration with experimentalists:** experimental advances challenge theory while theoretical advances open new horizon for experiment*
- *Fundamental interaction physics is **multifaceted & dynamic** → must continually incorporate results from multiple frontiers*

III. Concluding Remarks

FSNN Theory: Comprehensive Role



Theoretical Challenges

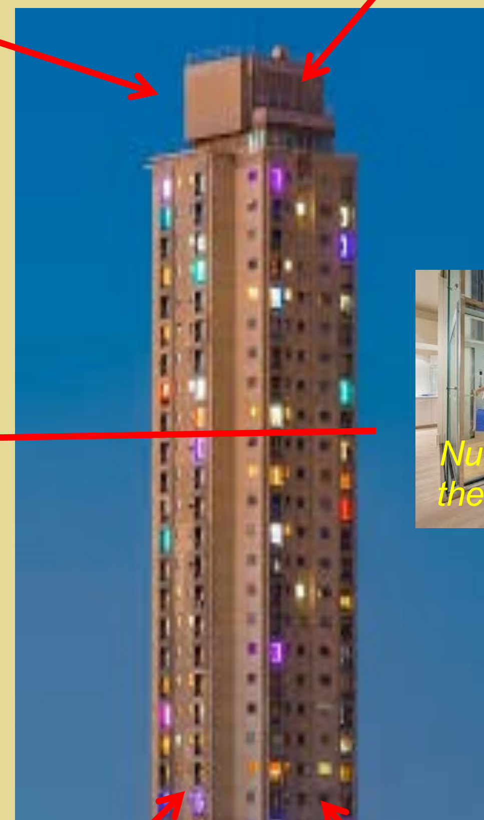
Connecting physics at multiple scales

Precision Electroweak Studies

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

Early Universe

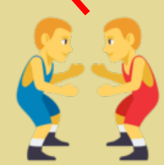
BSM Physics



+ other important methods not in my personal scientific tool kit !

Experiments

Theory



Key Themes

- *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*

Theory & Exp't: Close Collaboration

Career-long teamwork !

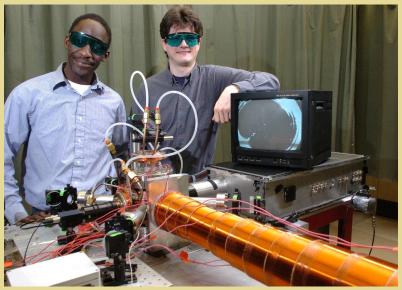
PHYSICAL REVIEW C **76**, 025202 (2007)

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

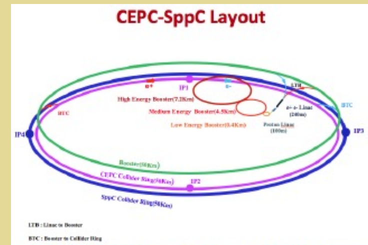
Jianglai Liu,* Robert D. McKeown, and Michael J. Ramsey-Musolf†
W. K. Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California 91125, USA
(Received 1 June 2007; published 2 August 2007)

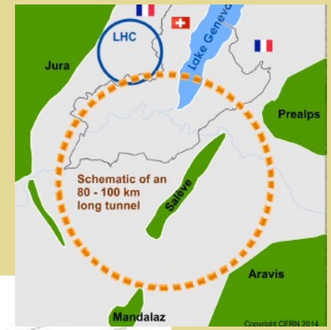
Exciting Challenges Remain

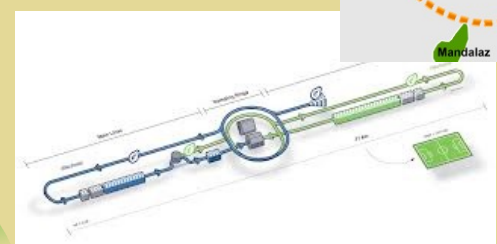
Atomic EDMs



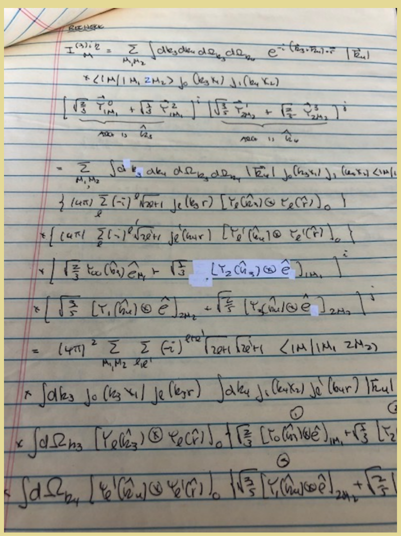
Future Circular e^+e^- & pp







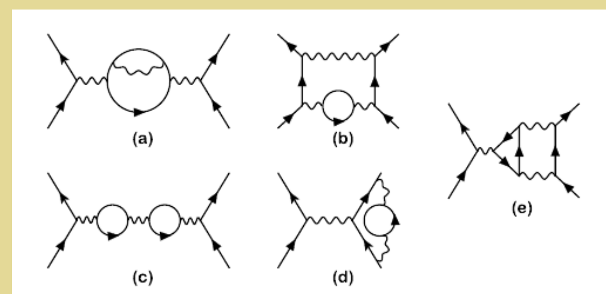
Electron-nucleus interaction



Welcome to join !

"Old School" theoretical physics

Electroweak precision calc's



Thank You !

谢谢

Back Up Slides

IIB. Beta-Decay

Weak Decays: CKM Unitarity

$$d \rightarrow u\, e^- \,\bar{\nu}_e$$

$$s \rightarrow u\, e^- \,\bar{\nu}_e$$

$$b \rightarrow u\, e^- \,\bar{\nu}_e$$

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

2018 Status

$$\Delta_{\mathrm{CKM}} = (|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2)_{\mathrm{exp}} - 1$$

0.94906 ± 0.00041

0.05031 ± 0.00022

0.00002

Theory challenge: reduce uncertainty

$$\Delta_{\mathrm{CKM}} = -0.0006 \pm 0.0005$$

Error Budget

2018 Status

$$\Delta_{\mathrm{CKM}} = (|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2)_{\mathrm{exp}} - 1$$

0.94906 ± 0.00041 $\qquad$ 0.05031 ± 0.00022 $\qquad$ 0.00002

Theory challenge:
reduce uncertainty

Future goal: 10^{-4} precision

$$\Delta_{CKM} \sim C \ (v/\Lambda)^2$$

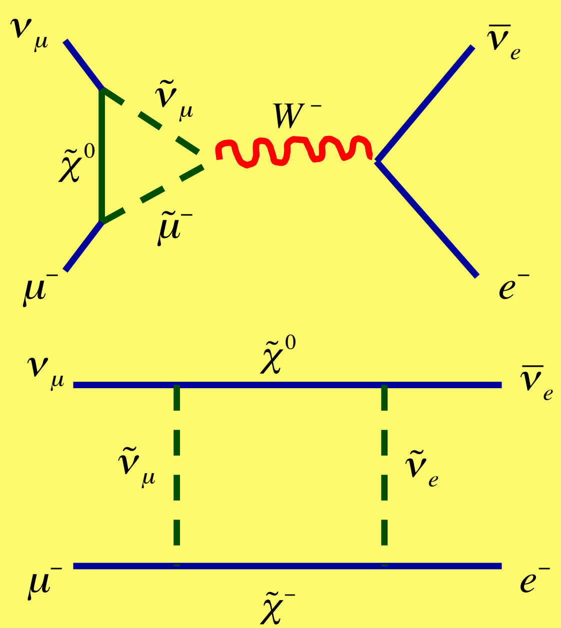
$\Lambda \sim 10$ *TeV (tree)*

$\Lambda < 1$ *TeV (loop)*

CKM Unitarity & BSM Physics

$$d \to u\, e^- \,\bar{\nu}_e$$
$$s \to u\, e^- \,\bar{\nu}_e$$
$$b \to u\, e^- \,\bar{\nu}_e$$

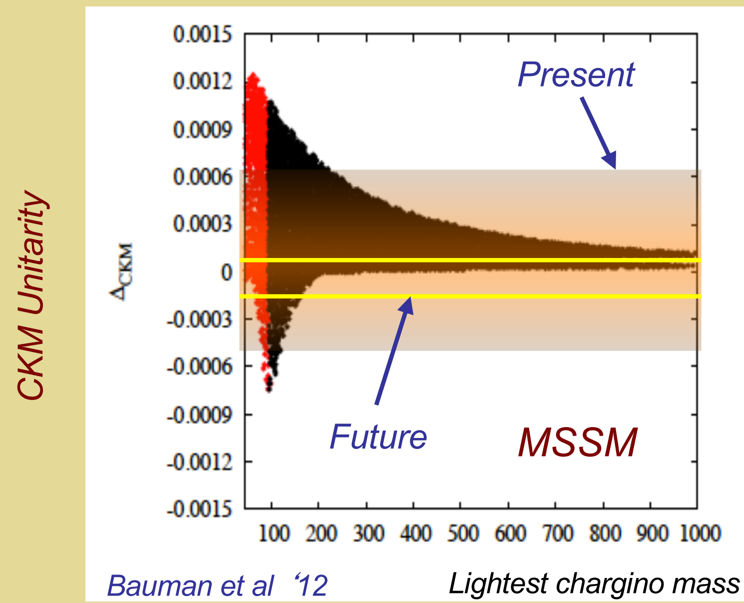
$$\begin{pmatrix} u & c & t \end{pmatrix} \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$



$$\frac{\delta O^{SUSY}}{O^{SM}} \sim 0.001$$

$$+\cdots$$

SUSY



Next generation: ~ 10^{-4} precision

SM Theory: Radiative Corrections & Ft Values

Corrected ft values:

$$\mathcal{F}t = ft\,(1+\delta_R')\,(1+\delta_{NS}-\delta_C)\,(1+\Delta_E^{NS})$$

Outer correction

Nuclear struct part of $M_{\gamma W}$

E-independent

Nucl wavef'n

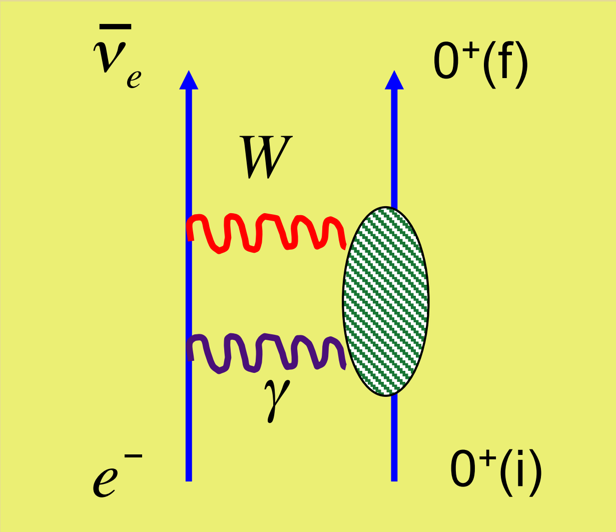
Not a RC

Nuclear struct part of $M_{\gamma W}$

E-dependent

Theoretical Challenge: Wγ Box

Dominant source of uncertainty:



$$M_{\gamma W} = \frac{G_F V_{ud}}{\sqrt{2}} \frac{\alpha}{8\pi} \left[\ln\left(\frac{M_Z^2}{\Lambda^2}\right) + C_{\gamma W}(\Lambda) \right]$$

Short distance: perturbative

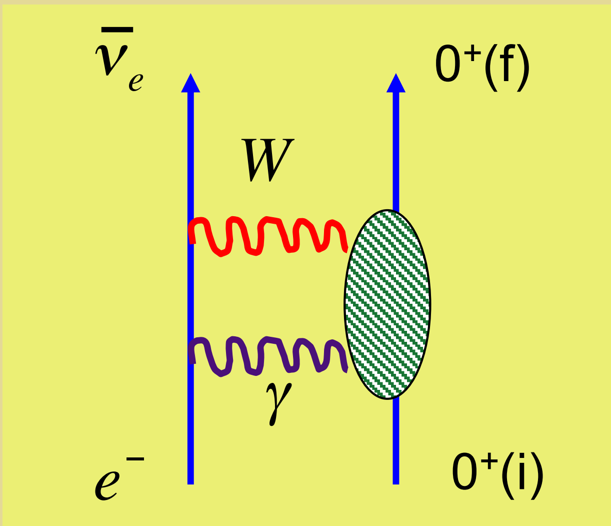
Long distance: non-perturbative

Long distance

Sensitive to hadronic & nuclear dynamics

Theoretical Challenge: Wγ Box

Dominant source of uncertainty:



$$M_{\gamma W} = \frac{G_F V_{ud}}{\sqrt{2}} \frac{\alpha}{8\pi} \left[\ln \left(\frac{M_Z^2}{\Lambda^2} \right) + C_{\gamma W}(\Lambda) \right]$$

Short distance: perturbative

Long distance: non-perturbative

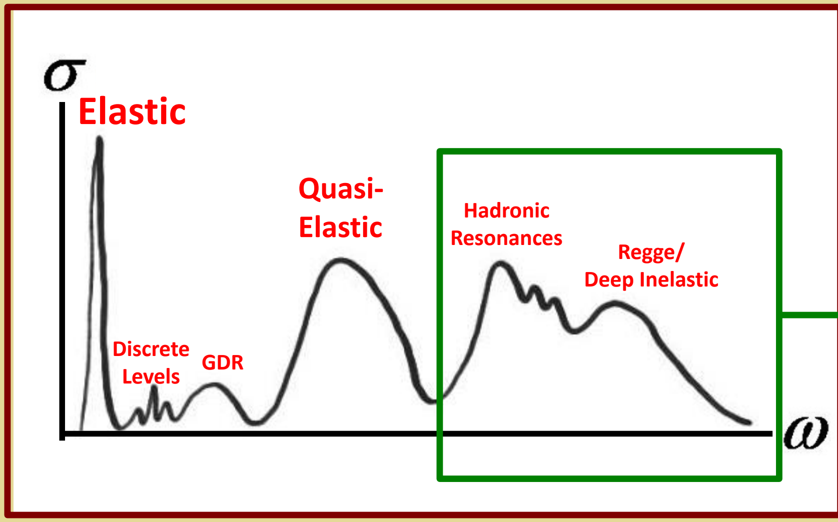
Long distance

Sensitive to hadronic & nuclear dynamics

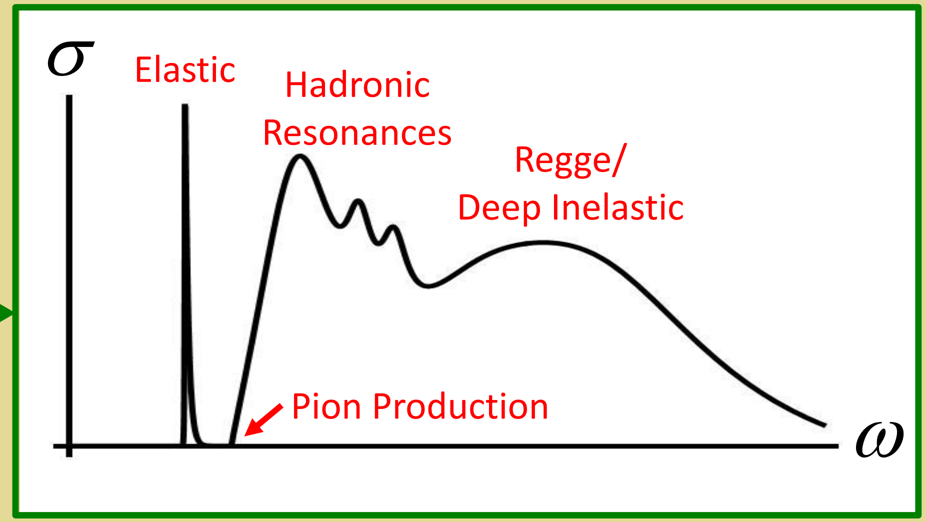
Dispersion Relations: Incorporate experimental data

Input for $C_{\gamma W}$: Had & Nuc Response F'n

Nuclei



Free nucleons

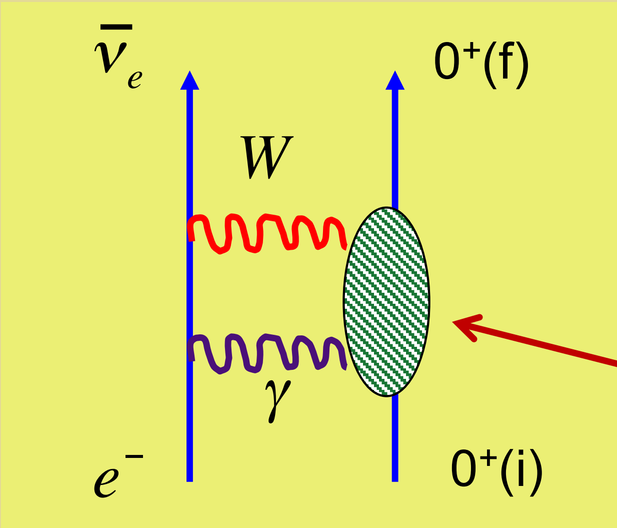


PHYSICAL REVIEW LETTERS **121**, 241804 (2018)

Reduced Hadronic Uncertainty in the Determination of V_{ud}

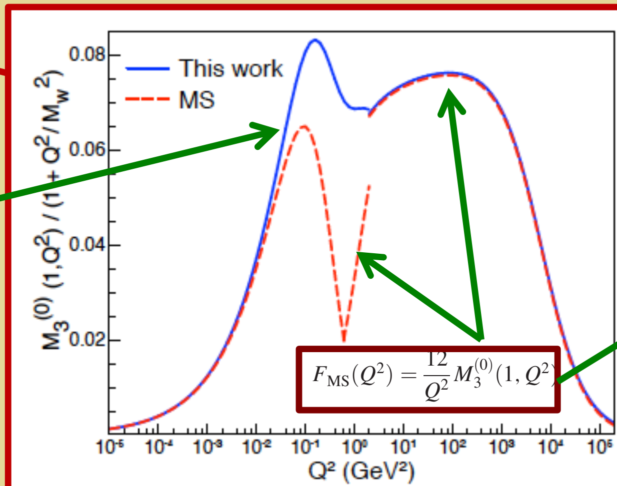
Chien-Yeah Seng,[1] Mikhail Gorchtein,[2,*] Hiren H. Patel,[3] and Michael J. Ramsey-Musolf[3,4]
[1]*INPAC, Shanghai Key Laboratory for Particle Physics and Cosmology, MOE Key Laboratory for Particle Physics, Astrophysics and Cosmology, School of Physics and Astronomy, Shanghai Jiao-Tong University, Shanghai 200240, China*
[2]*Institut für Kernphysik, PRISMA Cluster of Excellence Johannes Gutenberg-Universität, Mainz D-55128, Germany*
[3]*Amherst Center for Fundamental Interactions, Department of Physics, University of Massachusetts, Amherst, Massachusetts 01003, USA*
[4]*Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California 91125, USA*

Interlude: β – Decay, V_{ud} , & CKM Unitarity

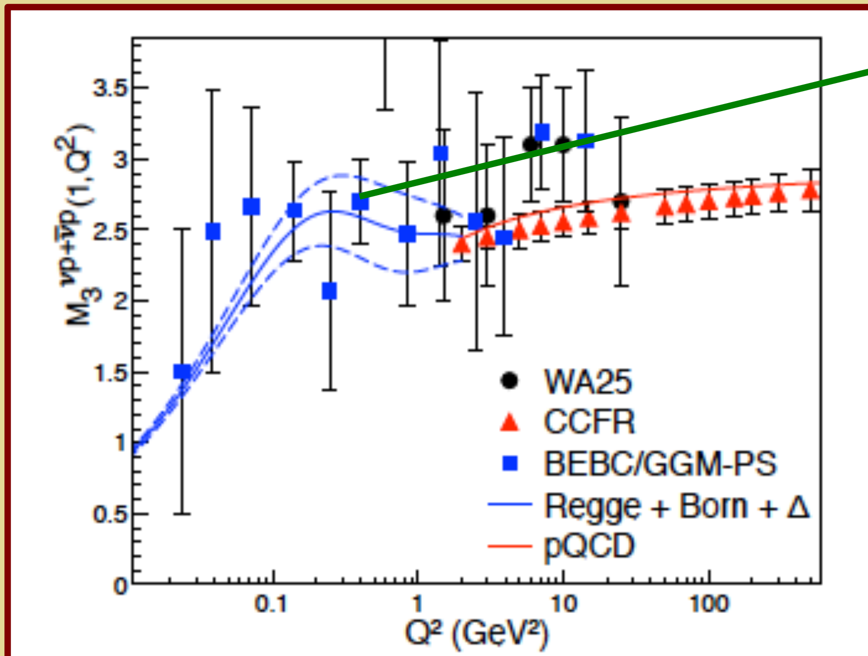


Single nucleon (one-body) : use dispersion relations to obtain from νp scattering → radiative correction depends on Nachtmann moment

Factor of 2 reduction in V_{ud} uncertainty



Previous state-of-the-art



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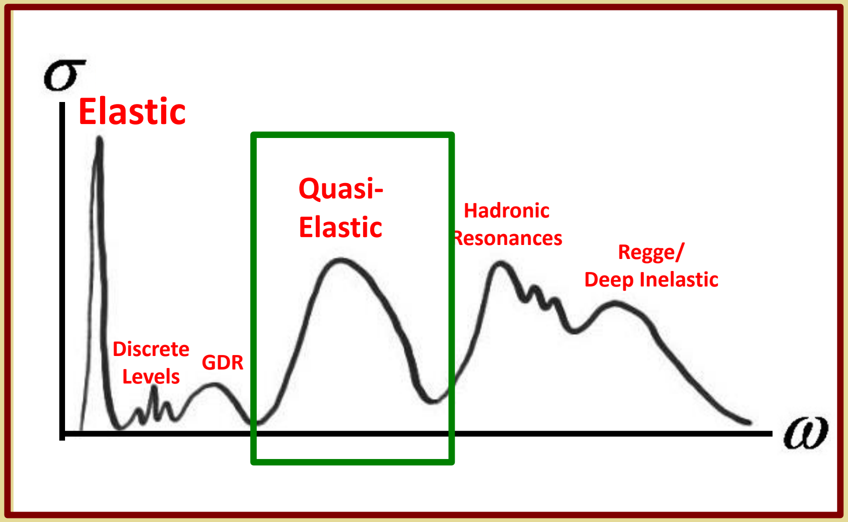
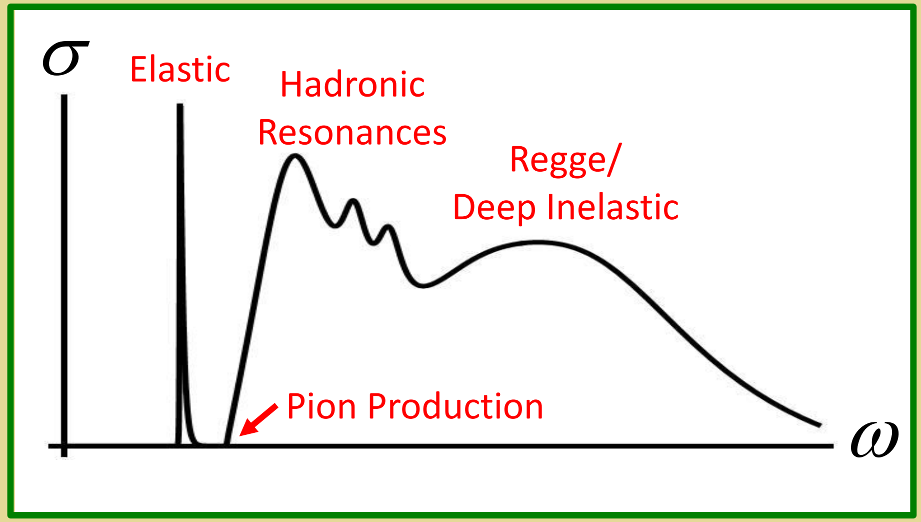
Input for $C_{\gamma W}$: Had & Nuc Response F’n

Nuclei



Free nucleons



PHYSICAL REVIEW D **100,** 013001 (2019)

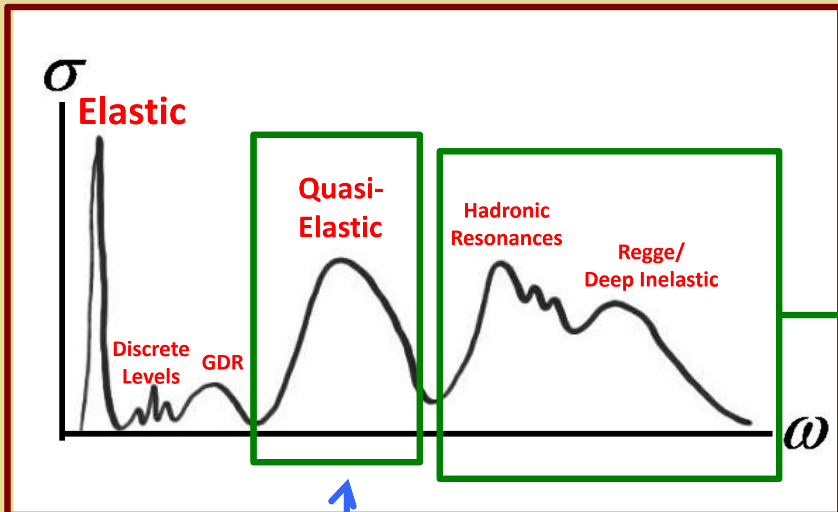
Dispersive evaluation of the inner radiative correction in neutron and nuclear β decay

Chien-Yeah Seng,[1,2,*] Mikhail Gorchtein,[3,6,†] and Michael J. Ramsey-Musolf[4,5,‡]

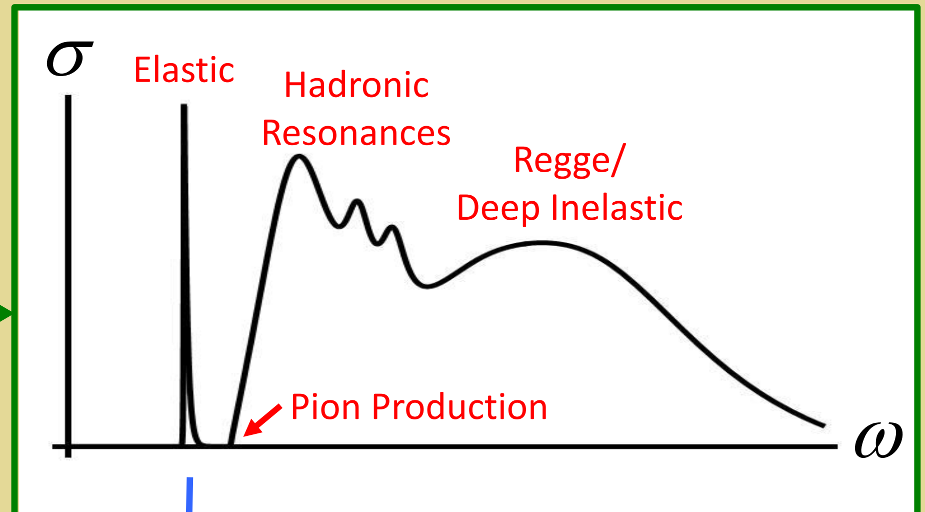
[1]*INPAC, Shanghai Key Laboratory for Particle Physics and Cosmology, MOE Key Laboratory for Particle Physics, Astrophysics and Cosmology, School of Physics and Astronomy, Shanghai Jiao-Tong University, Shanghai 200240, China*
[2]*Helmholtz-Institut für Strahlen- und Kernphysik and Bethe Center for Theoretical Physics, Universität Bonn, 53115 Bonn, Germany*
[3]*Institut für Kernphysik, PRISMA Cluster of Excellence Johannes Gutenberg-Universität, 55128 Mainz, Germany*
[4]*Amherst Center for Fundamental Interactions, Department of Physics, University of Massachusetts, Amherst, Massachusetts 01003, USA*
[5]*Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California 91125 USA*
[6]*Helmholtz Institut Mainz, Johannes Gutenberg-Universität Mainz, 55128 Mainz, Germany*

Leptoproduction: Had & Nuc Response

Nuclei



Free nucleons



Quasielastic response

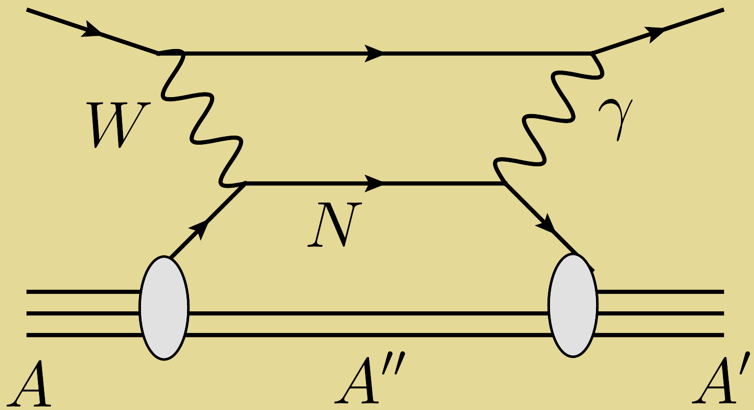
Part of δ_{NS} : " C_B^{Nucl} "

$$\Delta\delta_{NS} = \delta_{NS}^{QE} - \delta_{NS}^{B} = -(5.1 \pm 3.2) \times 10^{-4}$$

Our evaluation

Towner & Hardy previous

Impact on δ_{NS}



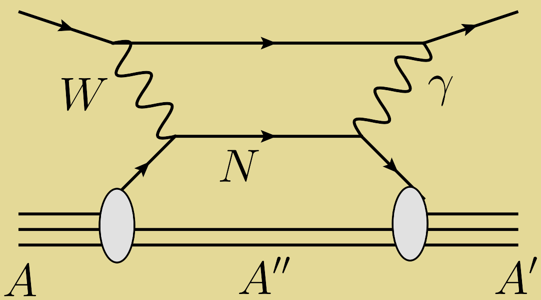
$$\Delta\delta_{NS} = \delta_{NS}^{QE} - \delta_{NS}^{B} = -(5.1 \pm 3.2) \times 10^{-4}$$

Neglects A-dep variations

Ave over 20 transitions

Optimistic:
- *Correlations*
- *2-body currents*
- *Rel corrections*

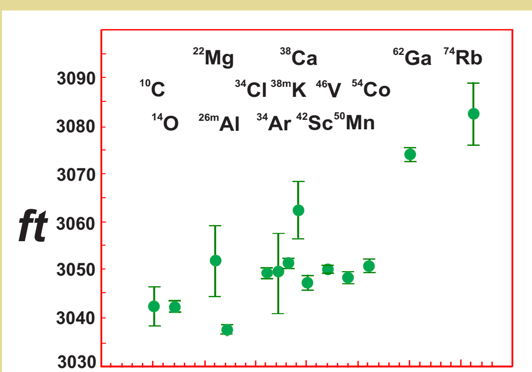
Refinements

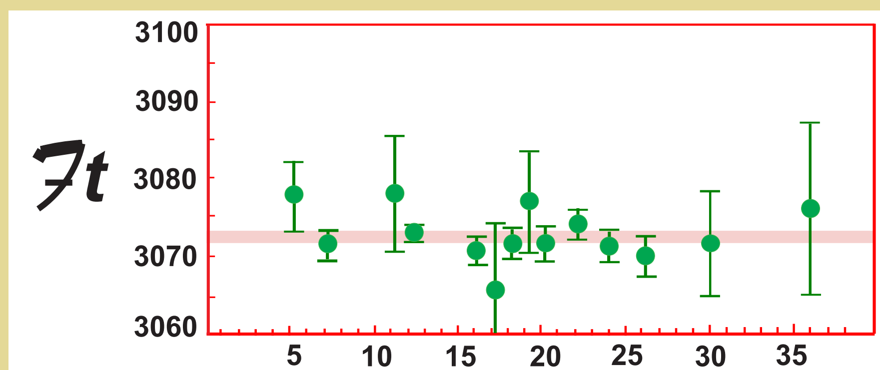


Apply state-of-art methods

- *Correlations*
- *2-body currents*
- *Rel corrections*

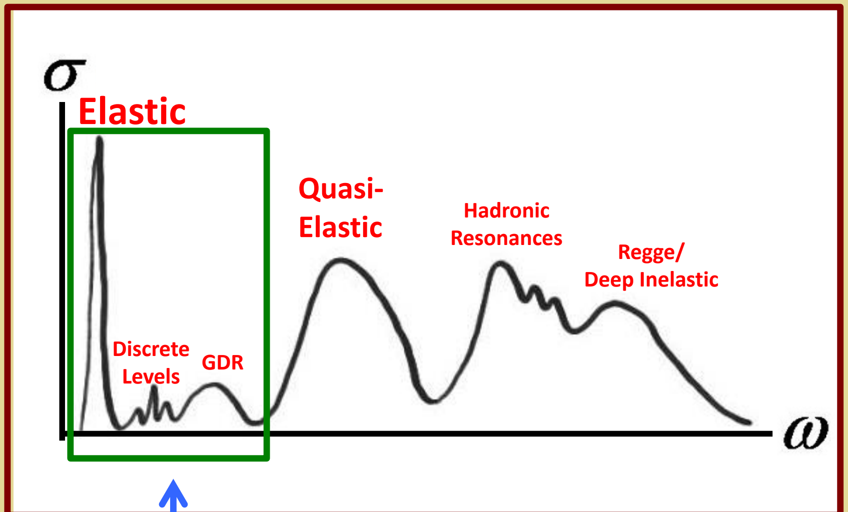
Consistency w/ CVC ?



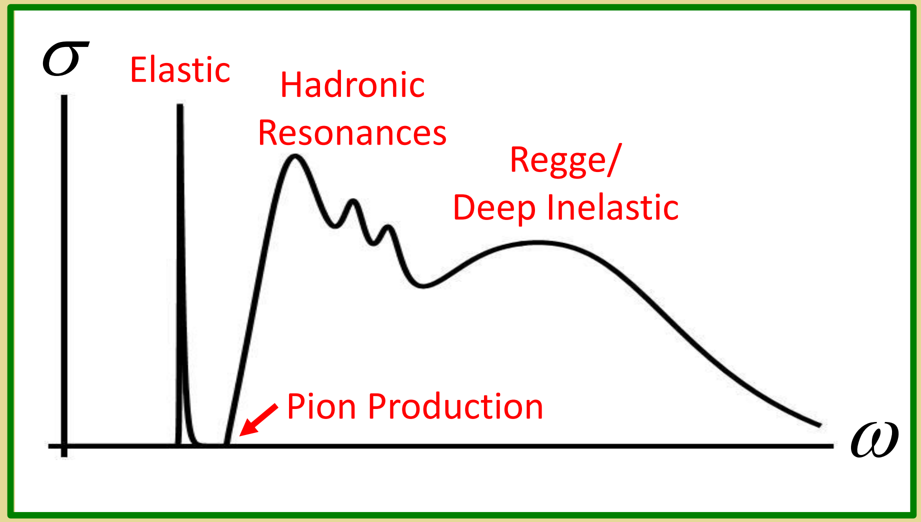


Other Nuclear Corrections

Nuclei



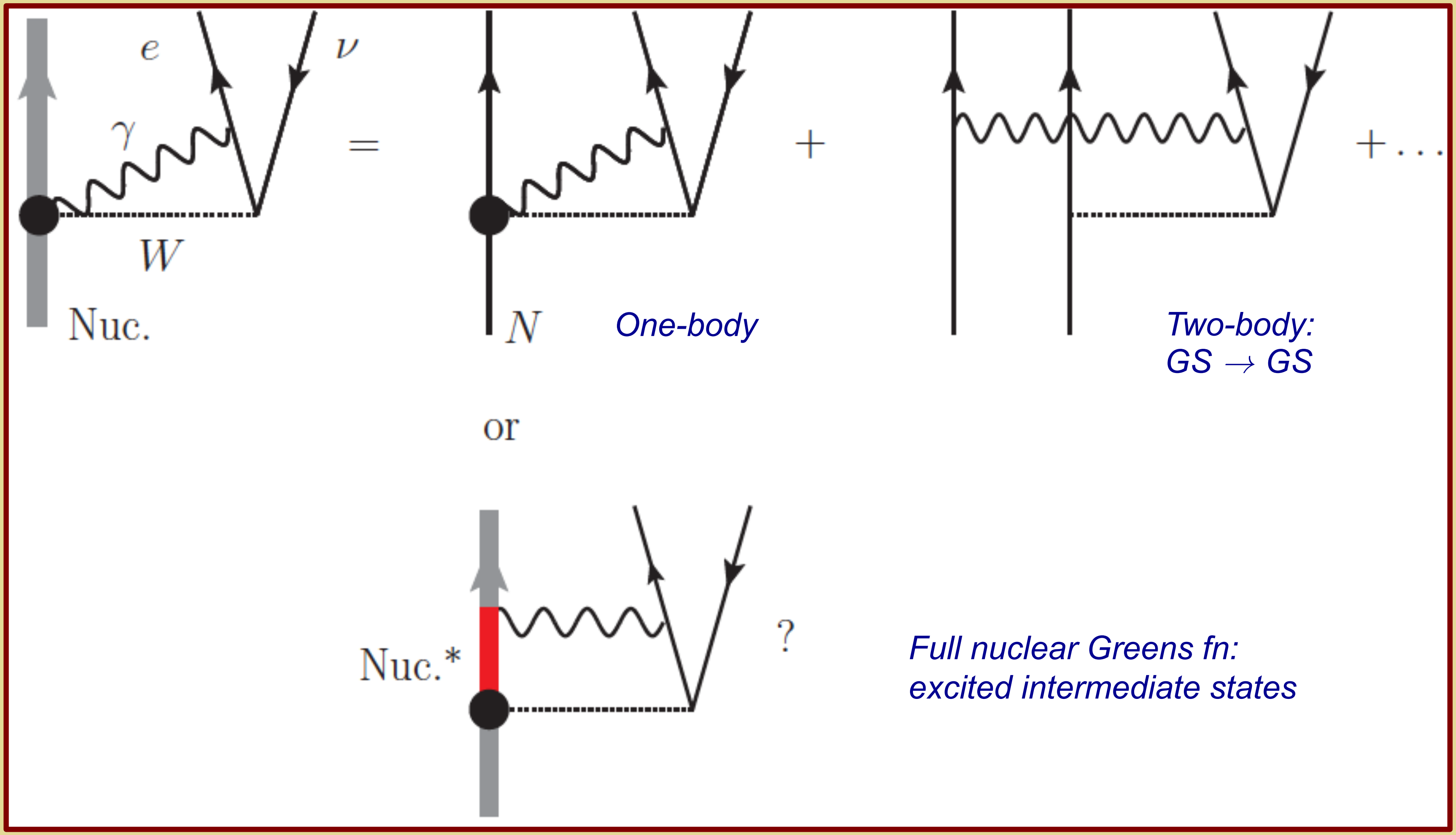
Free nucleons



Low-lying transitions

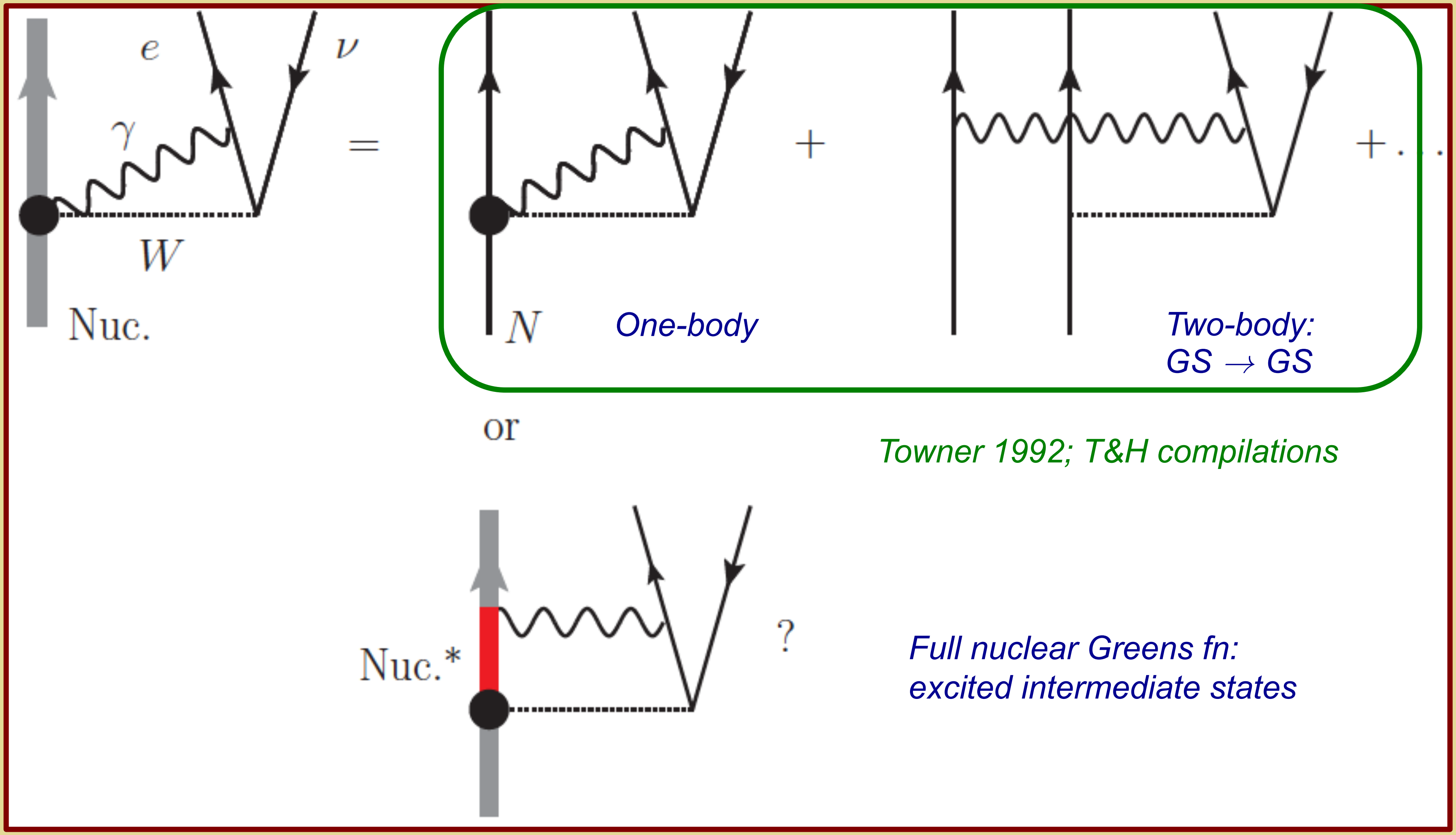
Part of δ_{NS}

$0^+ \rightarrow 0^+$ Decay: δ_{NS}



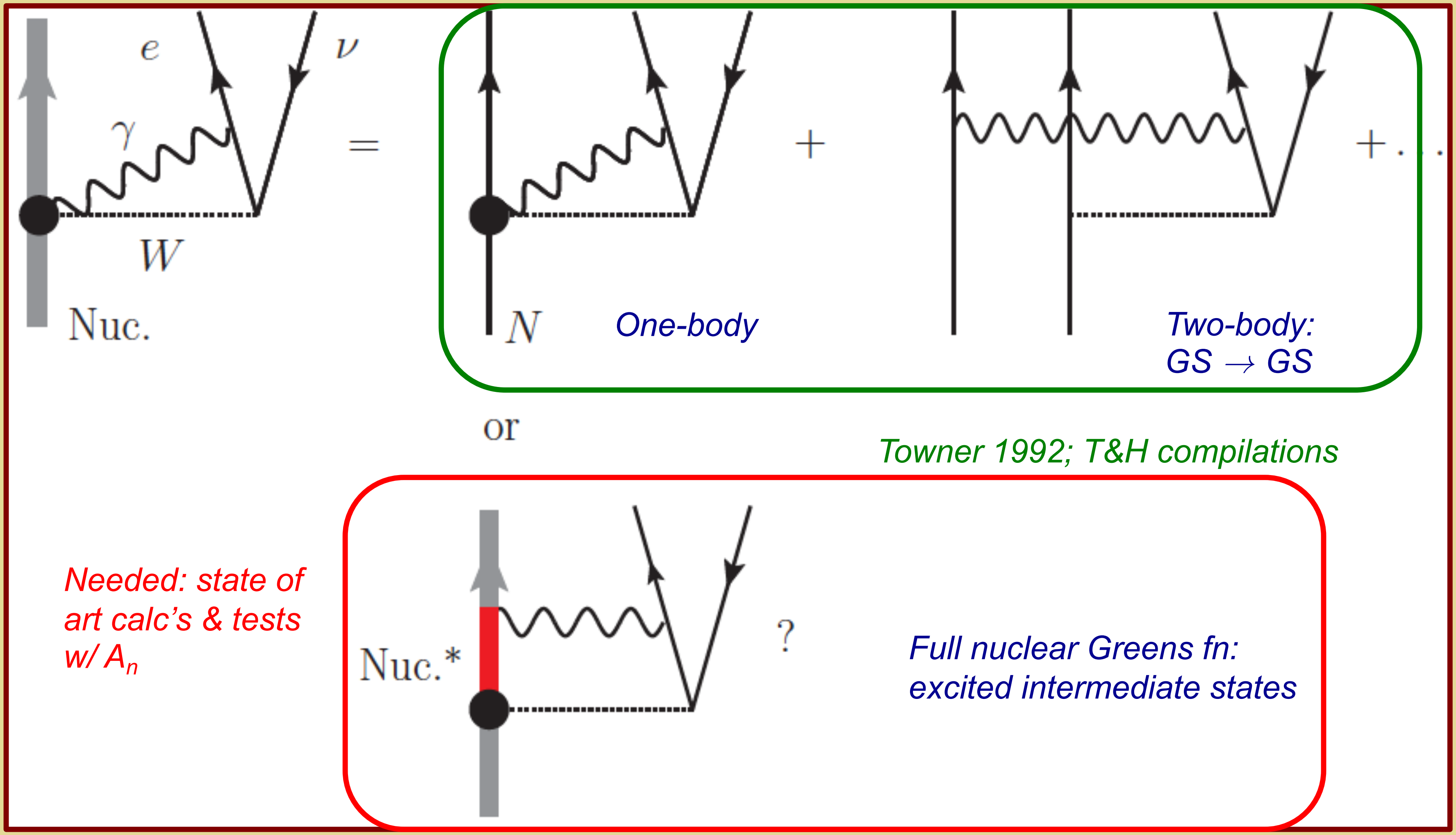
J. Engel

$0^+ \to 0^+$ Decay: δ_{NS}



J. Engel

$0^+ \rightarrow 0^+$ Decay: δ_{NS}



Needed: state of art calc's & tests w/ A_n

J. Engel

IID. EDMs

EDMs & SM Physics

$$d_n \sim (10^{-16}\ e\ cm)\ \times\ \theta_{QCD} + d_n^{CKM}$$

EDMs & SM Physics

$$d_n \sim (10^{-16}\ e\ cm)\ x\ \ \theta_{QCD} + \boxed{d_n^{CKM}}$$

$$\boxed{d_n^{CKM} = (1 - 6)\ x\ 10^{-32}\ e\ cm}$$

C. Seng arXiv: 1411.1476

EDMs & BSM Physics

$$d \sim (10^{-16}\ e\ cm)\ \times\ (\upsilon / \Lambda)^2\ \times\ \sin\phi\ \times\ y_f\, F$$

EDMs & BSM Physics

$$d \sim (10^{-16}\ e\ cm)\ \times\ (\upsilon / \Lambda)^2\ \times\ \boxed{\sin\phi}\ \times\ y_f\, F$$

CPV Phase: large enough for baryogenesis ?

EDMs & BSM Physics

$$d \sim (10^{-16}\ e\ cm)\ \ x\ \ \boxed{(\upsilon / \Lambda)^2}\ \ x\ \ \sin\phi\ \ x\ \ y_f\, F$$

BSM mass scale: TeV ? Much higher ?

υ = 246 GeV	Higgs vacuum expectation value
Λ > 246 GeV	Mass scale of BSM physics

EDMs & BSM Physics

$$d \sim (10^{-16}\ e\ cm)\ \ x\ \ (\upsilon / \Lambda)^2\ x\ \ \sin\phi\ \ x\ \boxed{y_f F}$$

BSM dynamics: perturbative? Strongly coupled?

y_f	Fermion f Yukawa coupling
F	Function of the dynamics

EDMs & BSM Physics

$$d \sim (10^{-16}\ e\ cm)\ \times \boxed{(\upsilon / \Lambda)^2} \times \boxed{\sin\phi} \times \boxed{y_f F}$$

Need information from at least three "frontiers"

- Baryon asymmetry — Cosmic Frontier
- High energy collisions — Energy Frontier
- EDMs — Intensity Frontier

Specific Illustrations: “Portals”

- *Higgs boson*

This talk

- *Top quark*
- *Dark photon*

Back up slides / question period

Where is BSM CPV hiding ?

The Higgs Portal

What is the CP Nature of the Higgs Boson ?

- *Interesting possibilities if part of an extended scalar sector*

- *Two Higgs doublets ?*

$$H \rightarrow H_1 \, , \, H_2$$

- *New parameters:*

$$\tan \beta = \langle H_1 \rangle / \langle H_2 \rangle$$
$$\sin \alpha_b$$

What is the CP Nature of the Higgs Boson ?

- *Interesting possibilities if part of an extended scalar sector*

- *Two Higgs doublets ?*

$$H \rightarrow H_1 , H_2$$

- *New parameters:*

$$\tan \beta = \langle H_1 \rangle / \langle H_2 \rangle$$

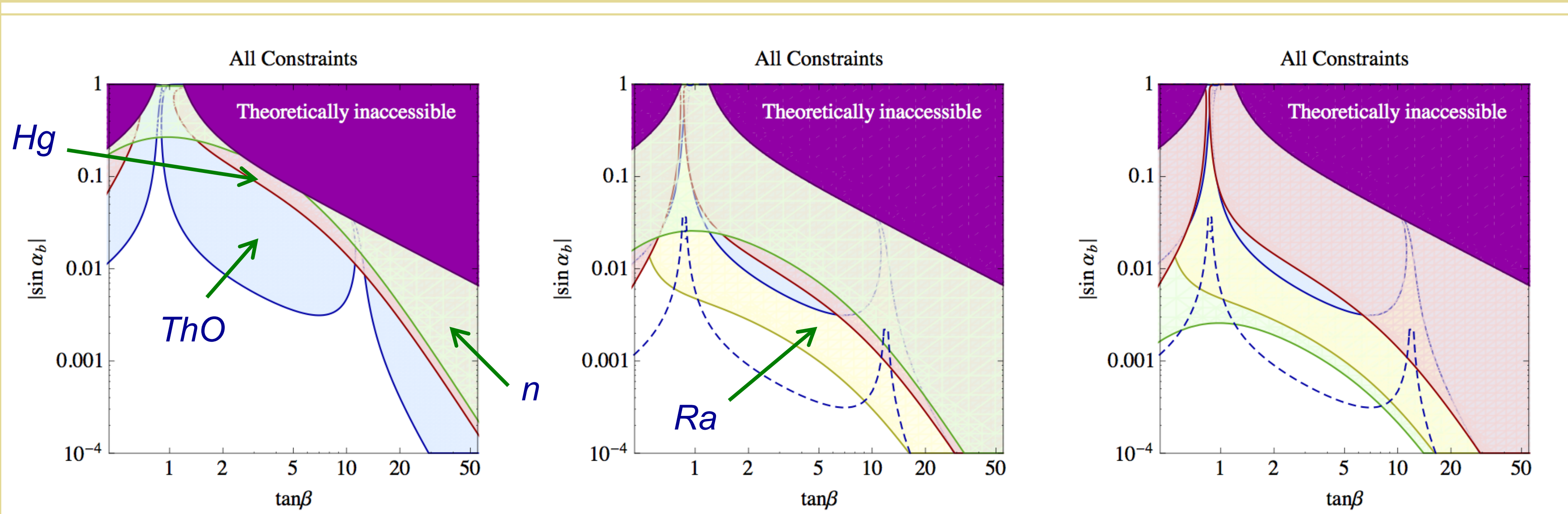
$$\boxed{\sin \alpha_b}$$

CPV : scalar-pseudoscalar mixing from $V(H_1, H_2)$

Higgs Portal CPV: EDMs

2014 Status

CPV & 2HDM: Type II illustration *$\lambda_{6,7}$ = 0 for simplicity*



Present *New ThO: ACME*

Future:

- d_n x 0.1
- d_A(Hg) x 0.1
- d_{ThO} x 0.1
- d_A(Ra) [10^{-27} e cm]

Future:

- d_n x 0.01
- d_A(Hg) x 0.1
- d_{ThO} x 0.1
- d_A(Ra)

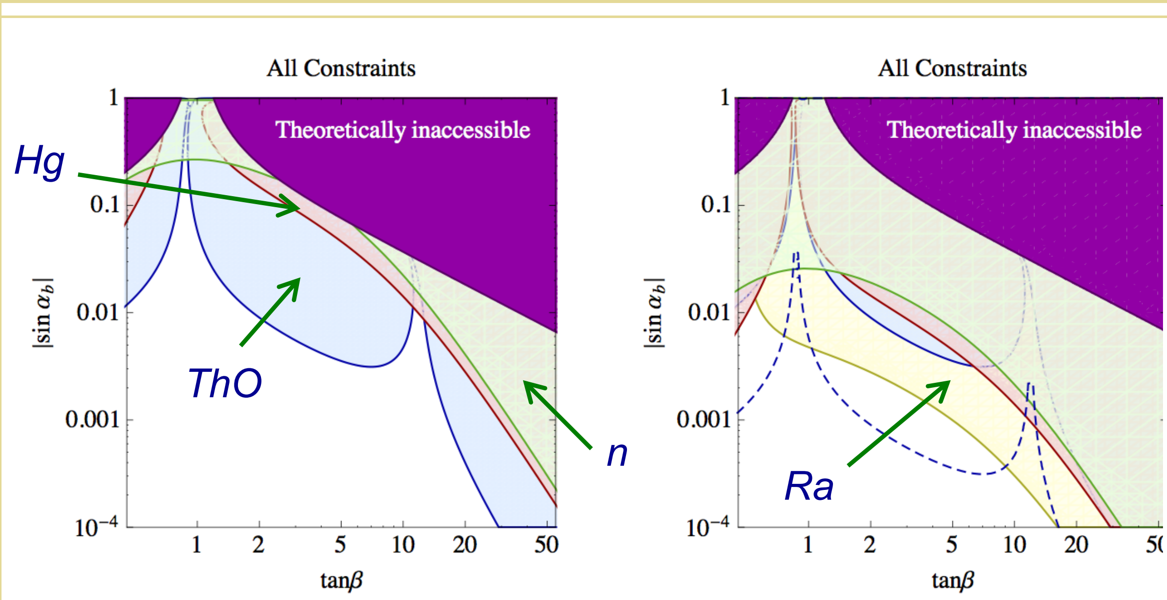
$\sin\alpha_b$: CPV scalar mixing

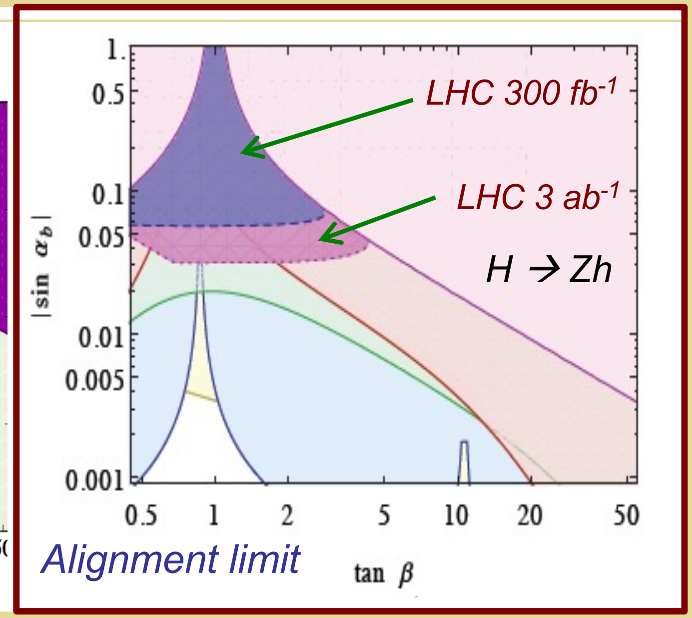
Inoue, R-M, Zhang: 1403.4257

Higgs Portal CPV: EDMs & LHC

2017 Status

CPV & 2HDM: Type II illustration $\lambda_{6,7}$ *= 0 for simplicity*





Chen, Li, R-M: 1708.00435

Present

New ThO: ACME

Future:

- d_n x 0.1
- $d_A(Hg)$ x 0.1
- d_{ThO} x 0.1
- $d_A(Ra)$ [10^{-27} e cm]

Future:

- d_n x 0.01
- $d_A(Hg)$ x 0.1
- d_{ThO} x 0.1
- $d_A(Ra)$

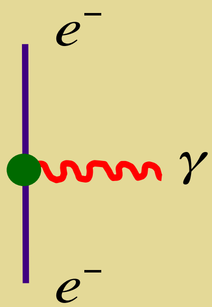
sin α_b : CPV scalar mixing

Inoue, R-M, Zhang: 1403.4257

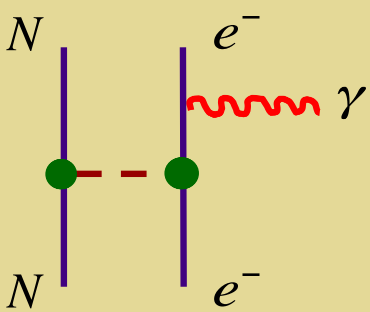
EDM Complementarity

Paramagnetic Systems: Two Sources

Electron
EDM



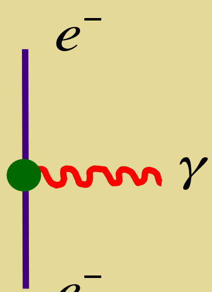
(Scalar q)
x (PS e-)

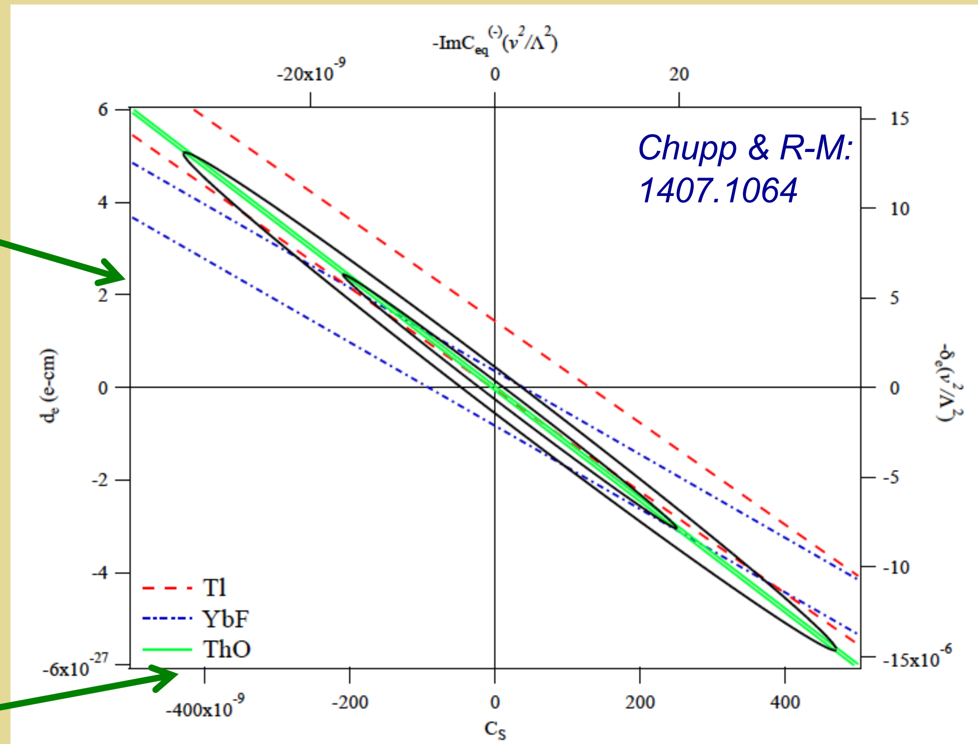


Tl, YbF, ThO…

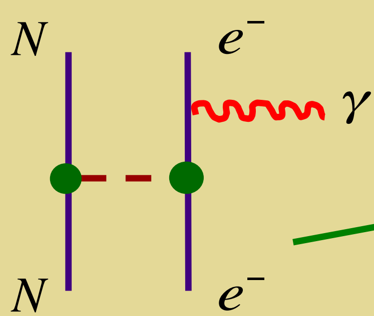
Paramagnetic Systems: Two Sources

Electron EDM





(Scalar q) x (PS e-)



$\Lambda \gtrsim (1.5\ \mathrm{TeV}) \times \sqrt{\sin\phi_{\mathrm{CPV}}}$ Electron EDM (global)

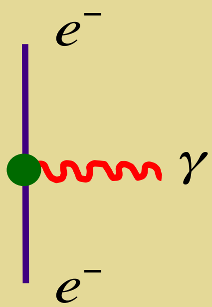
$\Lambda \gtrsim (1300\ \mathrm{TeV}) \times \sqrt{\sin\phi_{\mathrm{CPV}}}$ C_S (global)

LHC inaccessible

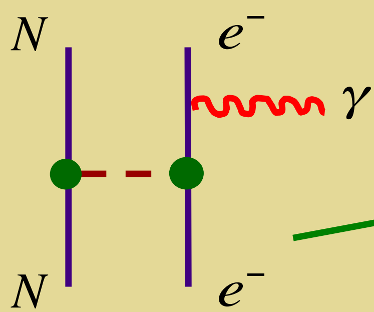
Tl, YbF, ThO…

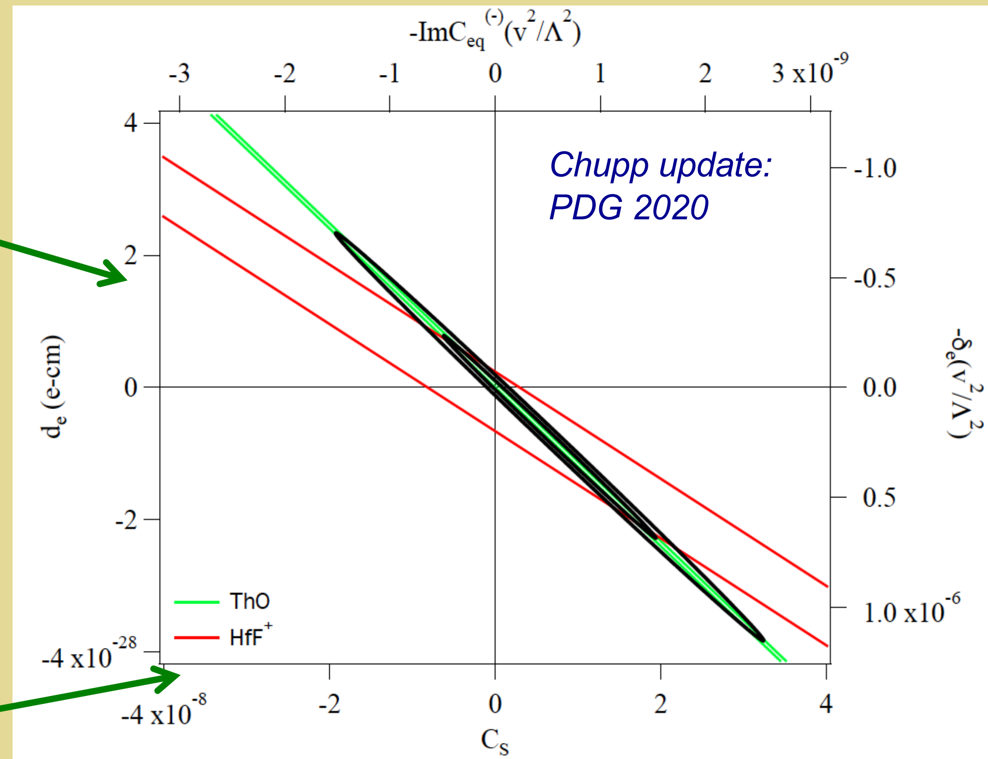
Paramagnetic Systems: Two Sources

Electron EDM



(Scalar q) x (PS e-)





Update: slightly stronger

$\Lambda \gtrsim (1.5\ \mathrm{TeV}) \times \sqrt{\sin\phi_{\mathrm{CPV}}}$ Electron EDM (global)

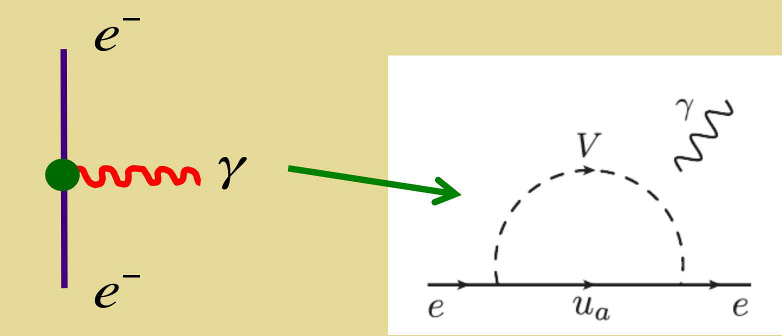
$\Lambda \gtrsim (1300\ \mathrm{TeV}) \times \sqrt{\sin\phi_{\mathrm{CPV}}}$ C_S (global)

LHC inaccessible

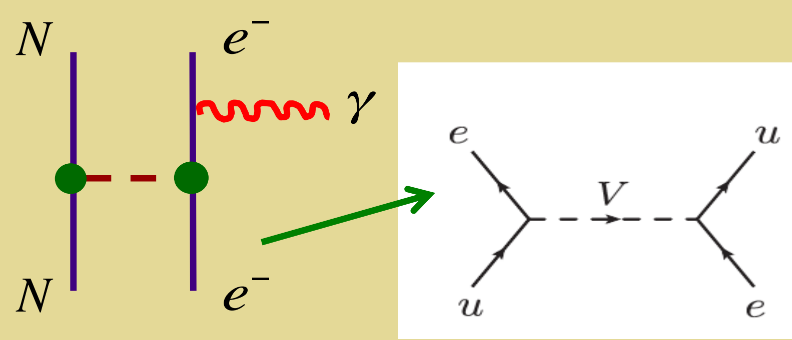
ThO, Hf+ ***New Dec '22***

Illustrative Example: Leptoquark Model

Electron EDM



(Scalar q) x (PS e⁻)

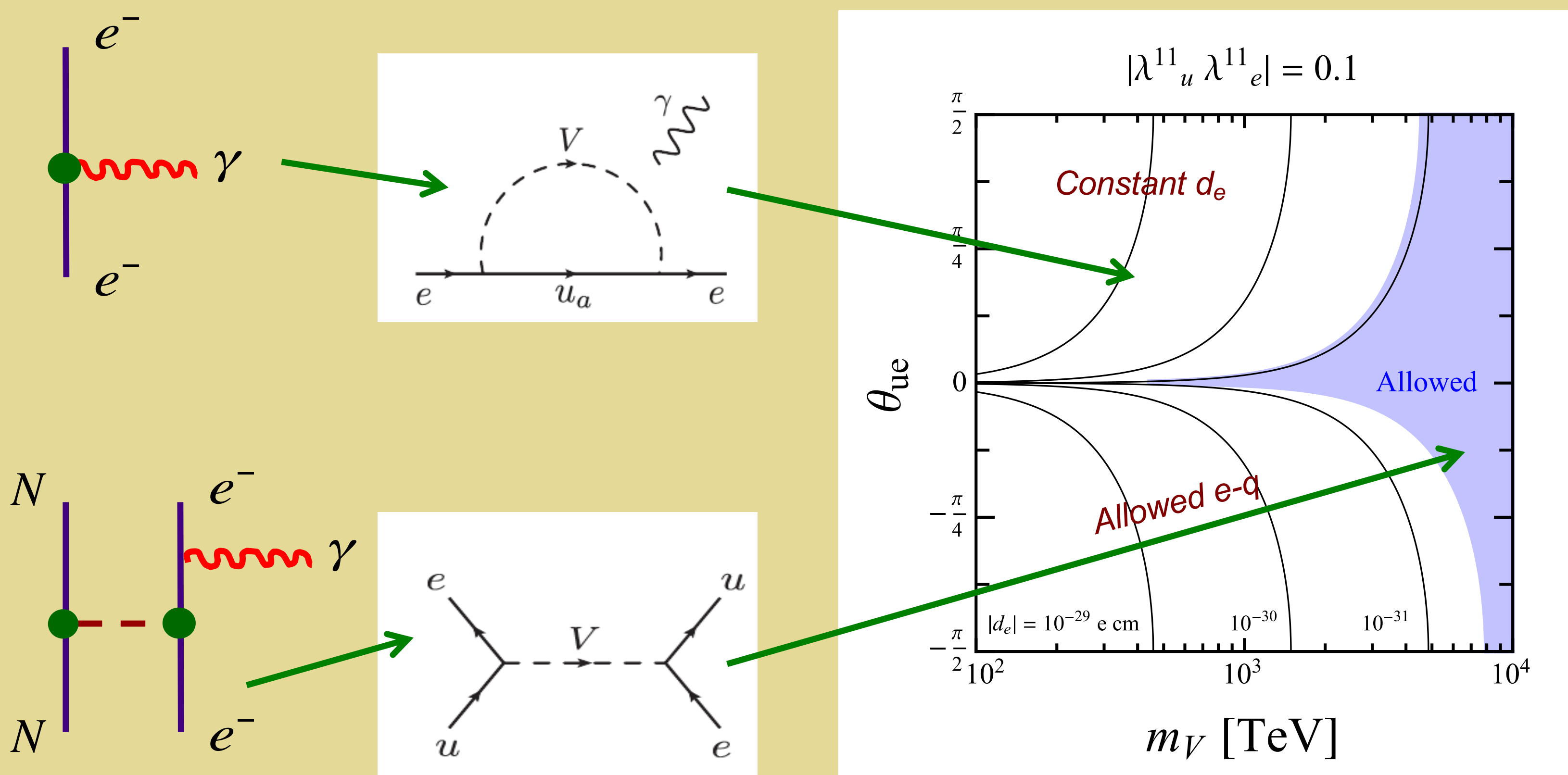


(3, 2, 7/6)

$$\mathcal{L} \ni -\lambda_u^{ab}\bar{u}_R^a X^T \epsilon L^b - \lambda_e^{ab}\bar{e}_R^a X^\dagger Q^b + \text{h.c.}$$

Illustrative Example: Leptoquark Model

Electron EDM



(Scalar q) x (PS e-)

Fuyuto, R-M, Shen 1804.01137

(3, 2, 7/6)

$$\mathcal{L} \ni -\lambda_u^{ab} \bar{u}_R^a X^T \epsilon L^b - \lambda_e^{ab} \bar{e}_R^a X^\dagger Q^b + \text{h.c.}$$

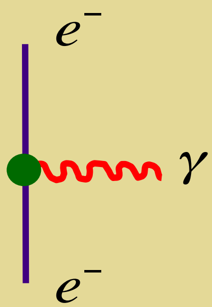
See also: Dekens et al 1809.09114

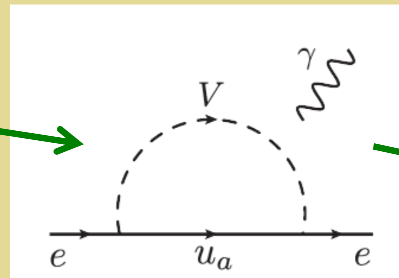
Illustrative Example: Leptoquark Model

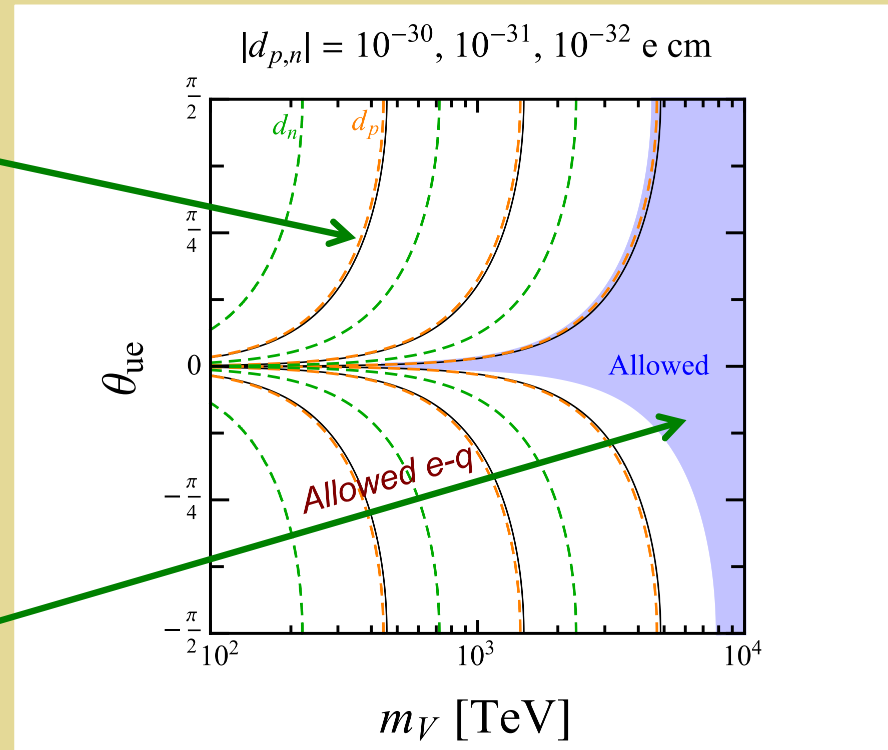
Orange: $|d_p|$ = 10^{-30} , 10^{-31} , 10^{-32} e cm

Green: $|d_n|$ = 10^{-30} , 10^{-31} , 10^{-32} e cm

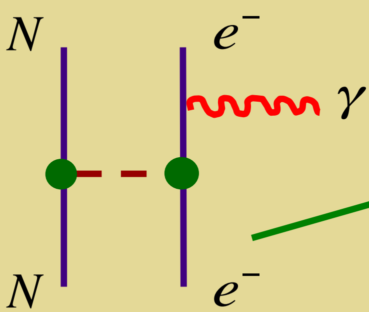
Electron EDM

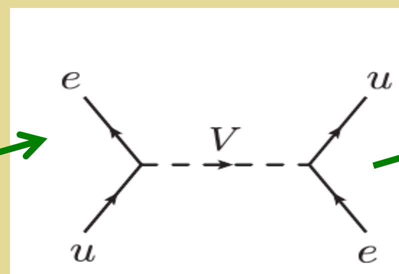






(Scalar q)
x (PS e-)





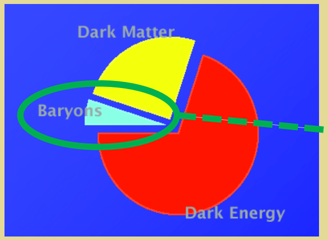
Fuyuto, R-M, Shen 1804.01137

See also: Dekens et al 1809.09114

(3, 2, 7/6)

$$\mathcal{L} \ni -\lambda_u^{ab}\bar{u}_R^a X^T \epsilon L^b - \lambda_e^{ab}\bar{e}_R^a X^\dagger Q^b + \text{h.c.}$$

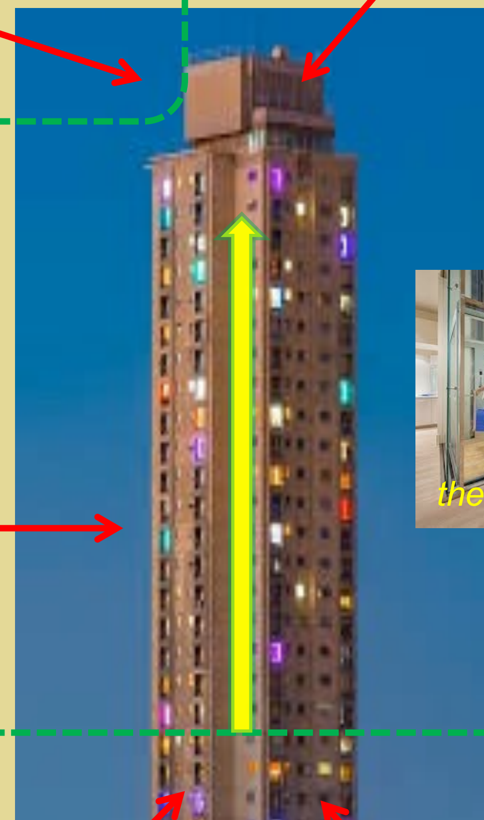
Theoretical Challenges: EDMs



Early Universe

Baryon Asym

BSM Physics



Energy Scale

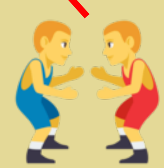
BSM Scale

Weak Scale

↗ Precision ~
↗ BSM mass scale

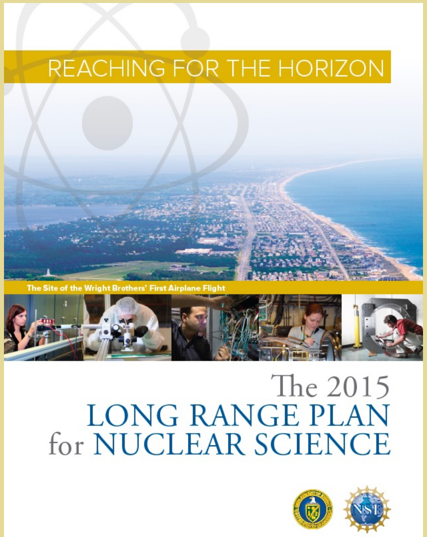
Experiments

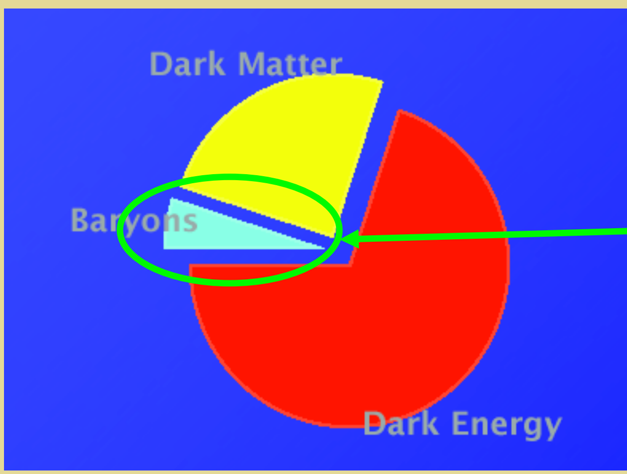
Theory



Matter Over Antimatter

EDM searches





Sidebar 5.2: Matter over Antimatter

Why is there more matter than antimatter in the present universe?

This question is one of the most compelling in physics, and its answer is vital to explaining the fundamental origin, evolution, and structure of the nuclear matter that we observe today.

By many accounts, the fireball generated during the Big Bang was democratic: it contained the same number of electrons and quarks (matter) as positrons and antiquarks (antimatter). While it is possible that something gave the Big Bang a slight preference for more matter than antimatter, the subsequent period of cosmic inflation—a brief period of rapid spacetime expansion in the early universe—would have rendered that imbalance imperceptible today. What happened then, to tip the balance in favor of the matter that makes up nuclei, stars, and life itself?

Physicists do not yet have a definitive answer, but we do know the ingredients for one. According to physicist and Nobel Prize winner Andrei Sakharov, the forces in the early universe must have violated certain fundamental symmetries in ways not seen in the Standard Model. Fundamental symmetry tests in nuclear physics are looking for evidence of such violation, while nuclear theorists are working to relate the results of these tests to the matter-antimatter imbalance.

One of the most powerful probes is the experimental search for an as-yet unseen property of neutrons, protons, electrons, and atoms known as a permanent electric dipole moment, or EDM. As indicated in Figure 1, its discovery would indicate a violation of time-reversal symmetry. In many candidates for the new Standard Model, this violation is intimately connected with the origin of the matter-antimatter imbalance. For example, new supersymmetric, time-reversal-violating interactions would have generated this imbalance about 0.000000001 seconds after the Big Bang, while leaving observable "footprints" today in the guise of permanent EDMs.

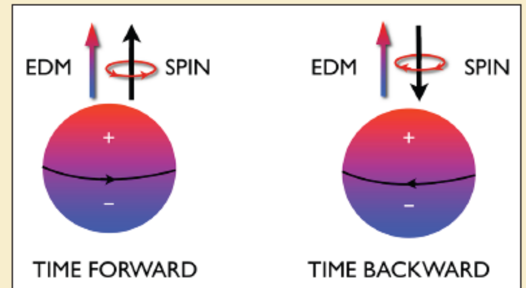
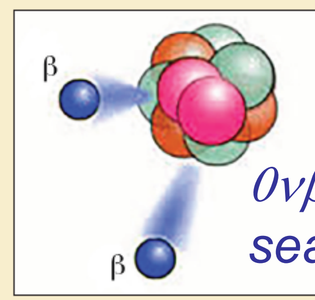


Figure 1: If an EDM is observed, then time-reversal transformation (T) is not a symmetry of nature: it takes a particle with EDM parallel to the spin and transforms it to the same particle with EDM anti-parallel to the spin—a different object that does not exist.

Another powerful probe is the search for the neutrinoless double beta decay of atomic nuclei (see Figure 2 and Sidebar 5.1). The observation of this nuclear decay would immediately imply that neutrinos are their own antiparticles and indicate a never-before-seen breakdown in the balance between leptons and their antiparticles. This symmetry violation would point to the existence of very heavy cousins of today's neutrinos whose decays in the early universe—possibly well before 10 picoseconds after the Big Bang—generated the excess of matter over antimatter.



$0\nu\beta\beta$ decay searches

Figure 2: Neutrinoless double beta involves the radioactive decay of a nucleus whereby two electrons are emitted without their usual antineutrino partners.

Ingredients for Baryogenesis

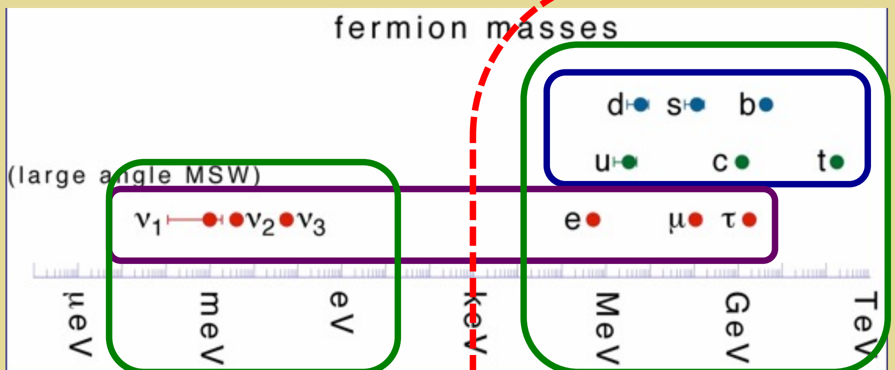
Scenarios: leptogenesis, EW baryogenesis, Afflek-Dine, asymmetric DM, cold baryogenesis, post-sphaleron baryogenesis…

	Standard Model	BSM
• B violation (sphalerons)	✓	✓
• C & CP violation	✖	✓
• Out-of-equilibrium or CPT violation	✖	✓

Electroweak Baryogenesis

Was Y_B generated in conjunction with electroweak symmetry-breaking?

Fermion Masses & Baryon Asymmetry



Partners

Partners

Something else ?

Higgs Mechanism

Leptogenesis: Baryon asymmetry & m_ν from lepton number violation

Electroweak baryogenesis: Baryon asymmetry & m_f from EW symmetry breaking

EDM probes

Ingredients for Baryogenesis

Scenarios: leptogenesis, EW baryogenesis, Afflek-Dine, asymmetric DM, cold baryogenesis, post-sphaleron baryogenesis…

	Standard Model	BSM
• B violation (sphalerons)	✓	✓
EDM • C & CP violation	✖	✓
• Out-of-equilibrium or CPT violation	✖	✓

First order EWPT

CPV in EW Baryogenesis

PHYSICAL REVIEW D **71,** 075010 (2005)

Resonant relaxation in electroweak baryogenesis

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Supergauge interactions and electroweak baryogenesis

Daniel J.H. Chung,[a] Björn Garbrecht,[a] Michael. J. Ramsey-Musolf[a,b] and Sean Tulin[c]

PRL **102,** 061301 (2009) PHYSICAL REVIEW LETTERS week ending 13 FEBRUARY 2009

Yukawa Interactions and Supersymmetric Electroweak Baryogenesis

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PHYSICAL REVIEW D **81,** 103503 (2010)

Flavored quantum Boltzmann equations

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New Journal of Physics
The open access journal for physics

Electroweak baryogenesis

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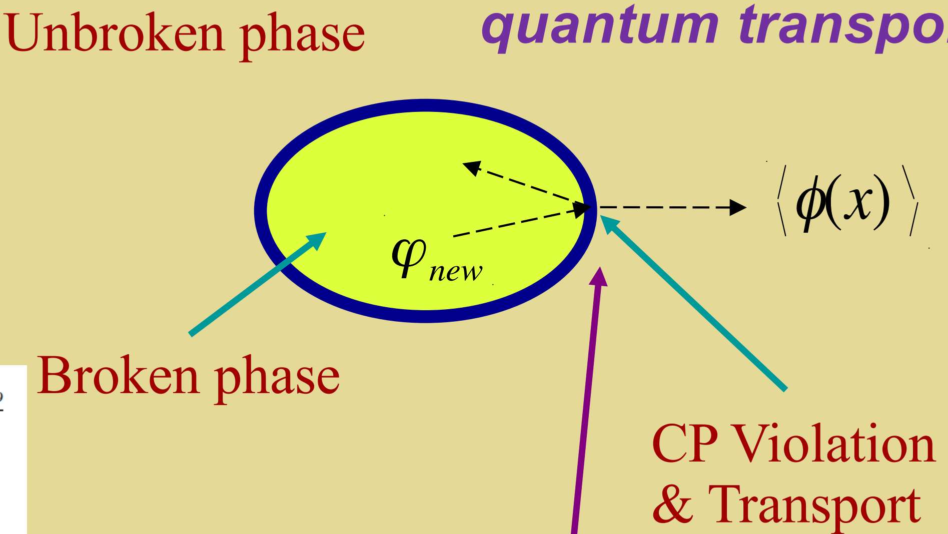
Non-equilibrium QFT: quantum transport



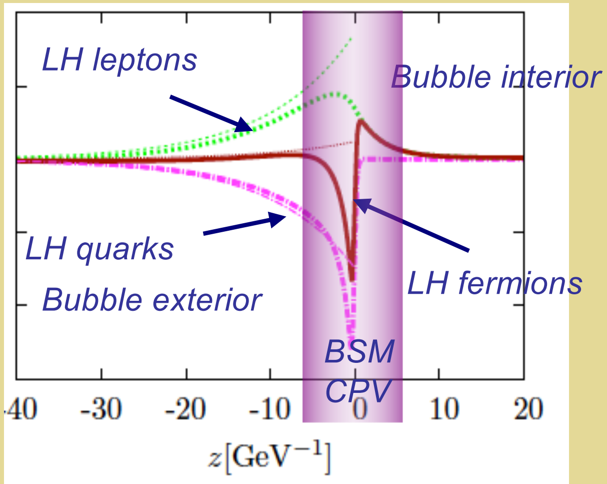
Transport: A Competition *R-M et al*

$\Gamma(A+B\rightarrow C)\neq\Gamma(\bar{A}+\bar{B}\rightarrow\bar{C})$ *CPV*

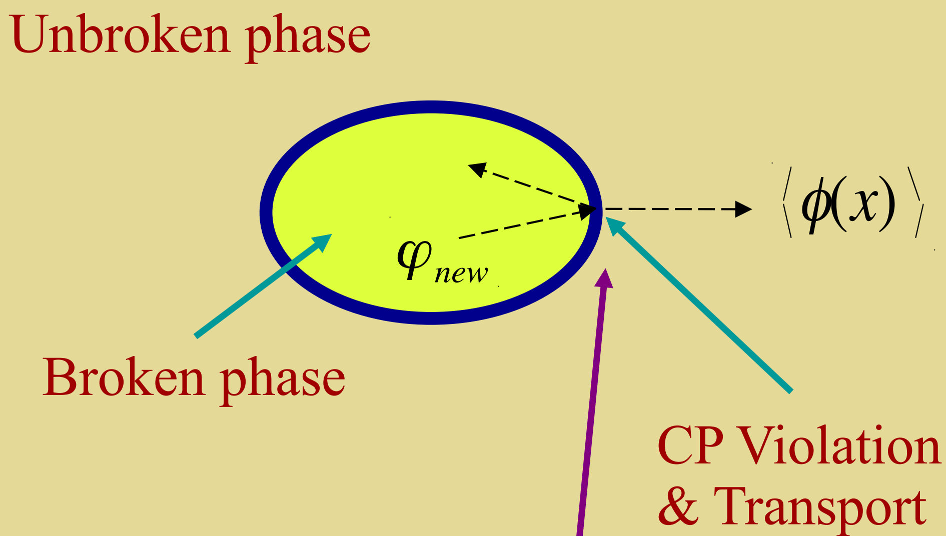
$\Gamma(A+B\leftrightarrow C)$ *Chem Eq*

$\Gamma(A+B\leftrightarrow A+B)$ *Diffusion*

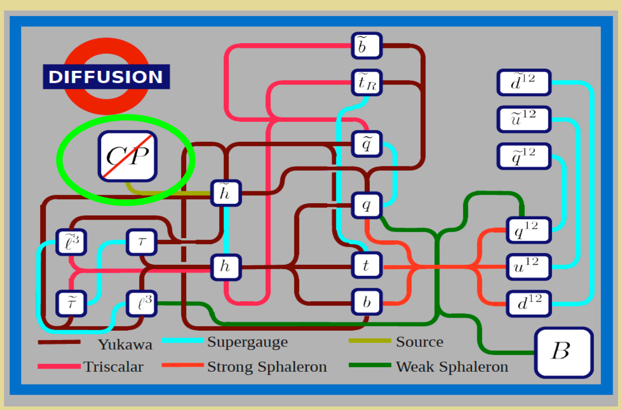
CPV in EW Baryogenesis: SUSY



MSSM: Chung, Garbrecht, R-M, Tulin '09



MSSM: ~ 30 Coupled Boltzmann Eqns



Thanks: B. Garbrecht

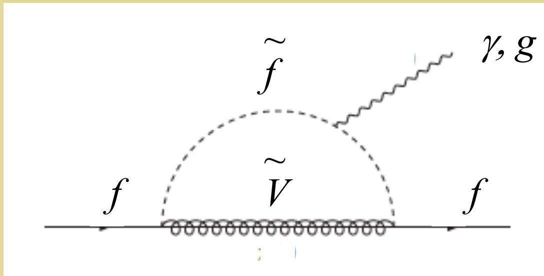
Transport: A Competition *R-M et al*

$$\Gamma(A+B\to C)\neq\Gamma(\bar{A}+\bar{B}\to\bar{C})$$ *CPV*

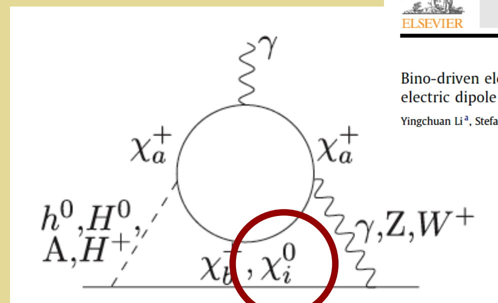
$$\Gamma(A+B\leftrightarrow C)$$ *Chem Eq*

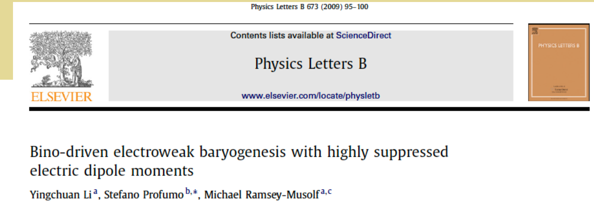
$$\Gamma(A+B\leftrightarrow A+B)$$ *Diffusion*

EDMs & EWBG: MSSM & Beyond



Heavy sfermions: LHC consistent & suppress 1-loop EDMs

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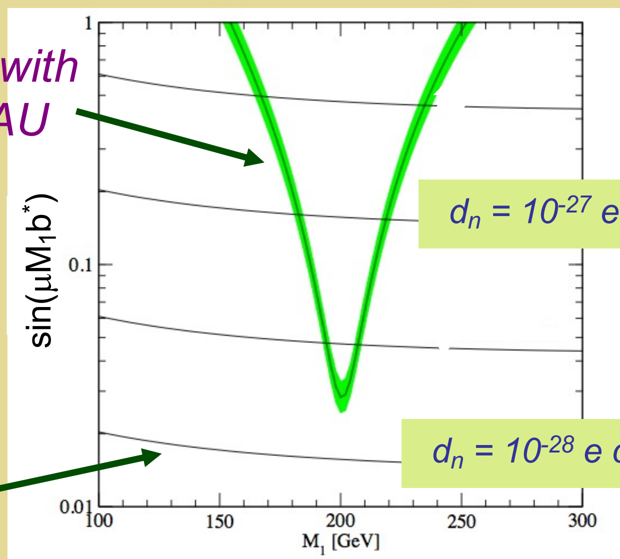
Bino-driven electroweak baryogenesis with highly suppressed electric dipole moments

Yingchuan Li[a], Stefano Profumo[b,*], Michael Ramsey-Musolf[a,c]

Sub-TeV EW-inos: LHC & EWB - viable but non-universal phases

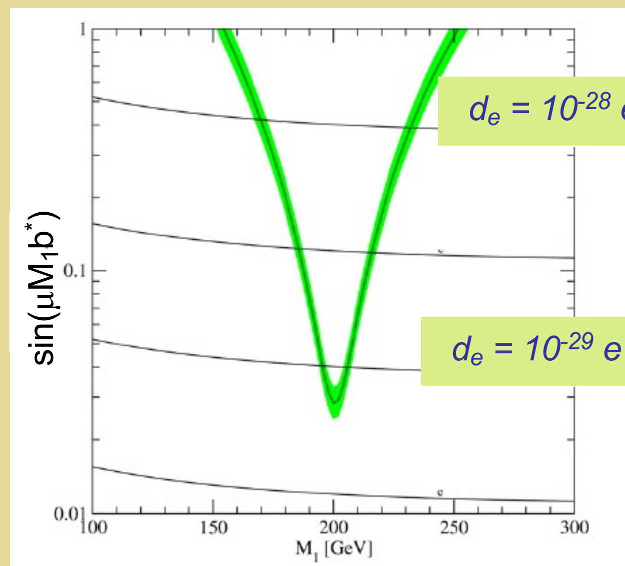
Compatible with observed BAU



$d_n = 10^{-27}$ e cm

$d_n = 10^{-28}$ e cm

Next gen d_n



$d_e = 10^{-28}$ e cm

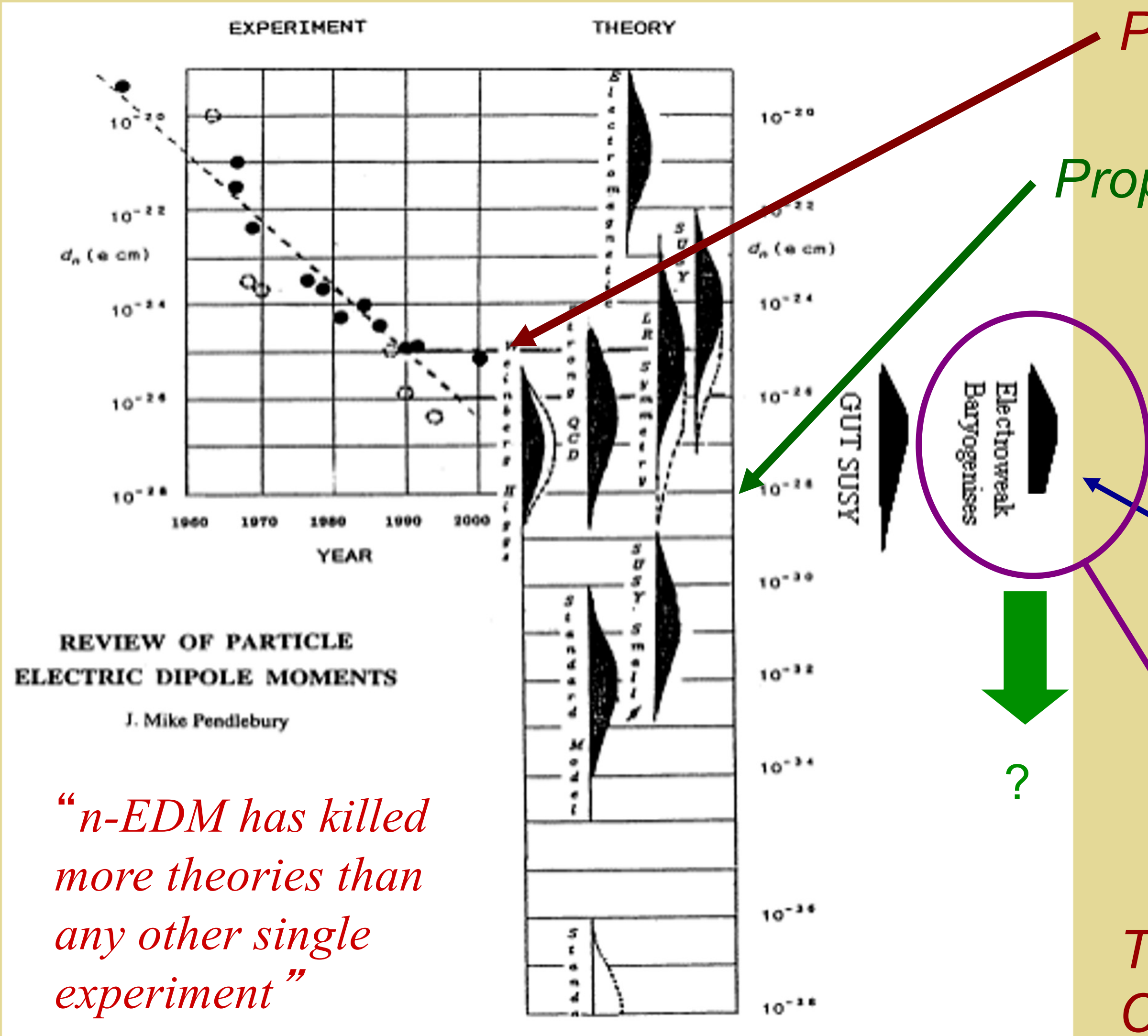
$d_e = 10^{-29}$ e cm

ACME: ThO

Li, Profumo, RM '09-'10

2010 Status

EDMs: What We May Learn



Present n-EDM limit

Proposed n-EDM limit

Matter-Antimatter Asymmetry in the Universe: **MSSM**

Theory: How robust ? Can EDMs kill EW baryogenesis ?

EDM Theory: Challenges

Atomic & nuclear matrix elements

Schiff moments & $\gamma\gamma$

2013 Status

Nucl.	Best value a_0	a_1	a_2
^{199}Hg	0.01	± 0.02	0.02
^{129}Xe	-0.008	-0.006	-0.009
^{225}Ra	-1.5	6.0	-4.0

Range a_0	a_1	a_2
0.005–0.05	-0.03–$(+0.09)$	0.01–0.06
-0.005–(-0.05)	-0.003–(-0.05)	-0.005–(-0.1)
-1–(-6)	4–24	-3–(-15)

Engel, R-M, van Kolck '13

Hadronic matrix elements

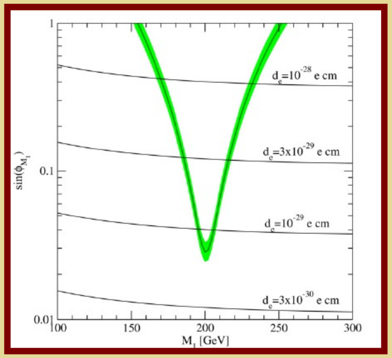
Dim 6 operators

2013 Status

Param	Coeff	Best value[a]	Range
$\bar{\theta}$	α_n	0.002	(0.0005–0.004)
	α_p	0.002	(0.0005–0.004)
$\mathrm{Im}\, C_{qG}$	β_n^{uG}	4×10^{-4}	$(1-10) \times 10^{-4}$
	β_n^{dG}	8×10^{-4}	$(2-18) \times 10^{-4}$
$\tilde{d}_q$	$e\tilde{\rho}_n^u$	-0.35	$-(0.09-0.9)$
	$e\tilde{\rho}_n^d$	-0.7	$-(0.2-1.8)$
$\tilde{\delta}_q$	$e\tilde{\zeta}_n^u$	8.2×10^{-9}	$(2-20) \times 10^{-9}$
	$e\tilde{\zeta}_n^d$	16.3×10^{-9}	$(4-40) \times 10^{-9}$
$\mathrm{Im}\, C_{q\gamma}$	$\beta_n^{u\gamma}$	0.4×10^{-3}	$(0.2-0.6) \times 10^{-3}$
	$\beta_n^{d\gamma}$	-1.6×10^{-3}	$-(0.8-2.4) \times 10^{-3}$
d_q	ρ_n^u	-0.35	(-0.17)–0.52
	ρ_n^d	1.4	0.7–2.1
δ_q	ζ_n^u	8.2×10^{-9}	$(4-12) \times 10^{-9}$
	ζ_n^d	-33×10^{-9}	$-(16-50) \times 10^{-9}$
$C_{\tilde{G}}$	$\beta_n^{\tilde{G}}$	2×10^{-7}	$(0.2-40) \times 10^{-7}$
$\mathrm{Im}\, C_{\varphi ud}$	$\beta_n^{\varphi ud}$	3×10^{-8}	$(1-10) \times 10^{-8}$
$\mathrm{Im}\, C_{quqd}^{(1,8)}$	β_n^{quqd}	40×10^{-7}	$(10-80) \times 10^{-7}$
$\mathrm{Im}\, C_{eq}^{(-)}$	$g_S^{(0)}$	12.7	11–14.5
$\mathrm{Im}\, C_{eq}^{(+)}$	$g_S^{(1)}$	0.9	0.6–1.2

Robust EWBG computations

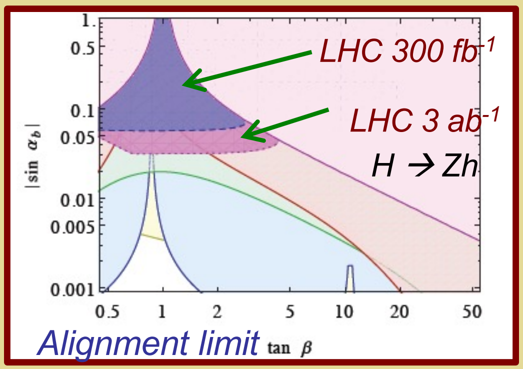
Non-eq QFT & early univ CPV



2010 Status

Interplay w/ hep BSM searches

New results from LHC



2017 Status