Nuclear Searches for Physics Beyond The Standard Model

Where am I coming from?

(Mostly Experimental!)

- **80-86: Nuclear Astrophysics**
- **86-92: Electro-nuclear Physics @ SLAC**
- **93-00: Electro-nuclear @ Jefferson Lab & DESY**
- **00- …: Ultra-Cold Neutrons**

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National Nuclear Physics Summer School
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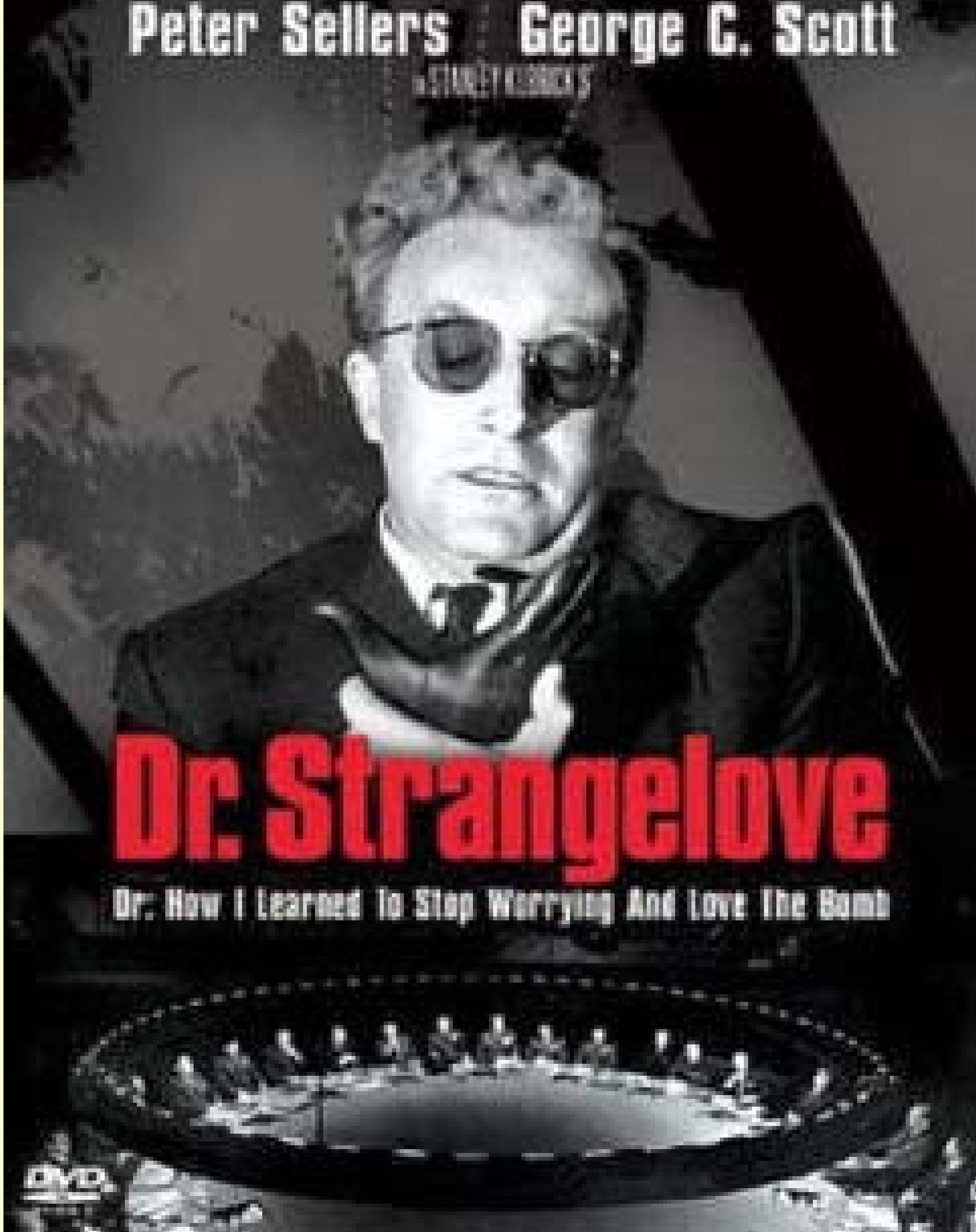
Nuclear Searches for Physics Beyond The Standard Model

What does the title mean?

- **What is Nuclear Physics?**
- **What is Standard Model?**
- **What is Beyond the Standard Model?**
- **What are the Searches (experiments!)?**

One View of Nuclear Physics



What is Nuclear Physics?

Not easy to define but several definitions exist:

- Physics of hadrons …
  - Strongly interacting particles
  - Realm of QCD
- What Nuclear Physicists do …
  - Neutrinos and Muons included

What is the Standard Model?

1. The Fermi/Feynman/Weinberg/ Salam/Glashow/… Electroweak Quantum Field Theory
   - Gives Unification of Weak Interactions & Electricity and Magnetism

2. The Politzer/Gross/Wilcek Quantum Field Theory of Strong Interactions
   - Quantum ChromoDynamics (QCD)

What is Beyond the Standard Model?

- Anything that is inconsistent with existing experiments
- A new phenomenolgy (i.e. not String Theory!) that "fixes" apparent problems in the Standard Model

  (may also create a few problems?!)

  - Super Symmetry (SUSY)
    - New symmetry for Fermions and Bosons
    - May incorporate Extra Dimensions (more than the usual 4 spacetime dimensions)

What are the Experimental Searches?

- Not Neutrino Physics (save for Joe F.)
- Neutral Weak Phenomena
  - Measurements of $\sin^2\theta_W$ and $(g-2)_\mu$
- Charged Weak Phenomena
  - Measurements of β-decay, μ-decay, V_{ud}, V_{us}
- Rare and Forbidden Processes
  - Searches for Electric Dipole Moments (EDM)
- Neutrons and physics beyond the Standard Model
  - Ultra-Cold Neutrons: Decays & EDM's

Most of my Lectures!

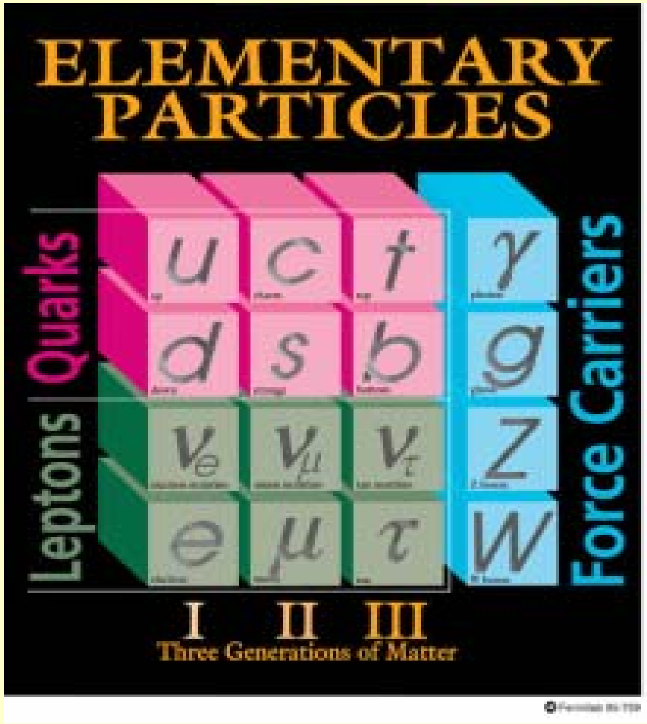
Overview of Lectures

1. Theoretical introduction & experimental interlude
   - Standard Model & Beyond
   - Summary of Experimental approaches
   - Introduction to Ultra-Cold Neutrons
2. Neutron & nuclear decay rates and correlations
3. Overview of EDM physics
   - Theoretical Motivation
   - Experimental techniques
4. Experimental status of EDM searches

References

- “Weak Interactions of quarks and Leptons”
  - Commins and Bucksbaum
- “Gauge Theory of Weak Interactions” – Greiner and Muller
- Particle Data Group
- Phys. 203 Lectures Notes

The Standard Model



A Quantum Field Theory based on a simple symmetry principle

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

Standard Electroweak Model

Assumes a local SU(2)xU(1) gauge invariance among weak isodoublets

$$\begin{pmatrix}\nu_e \\ e\end{pmatrix}_L, \begin{pmatrix}\nu_\mu \\ \mu\end{pmatrix}_L, \begin{pmatrix}\nu_\tau \\ \tau\end{pmatrix}_L, \begin{pmatrix}u \\ d_W\end{pmatrix}_L, \begin{pmatrix}c \\ s_W\end{pmatrix}_L, \begin{pmatrix}t \\ b_W\end{pmatrix}_L$$

and weak isosinglets

$$e_R, \mu_R, \tau_R, u_R, d_{R_W}, c_R, s_{R_W}, t_R, b_{R_W}$$

with 4 massless vector (spin 1: $J_z = \pm 1$)
gauge bosons $W_1, W_2, W_3,$ (SU(2)) B (U(1))

and 4 massless scalar (spin 0) bosons

12 Degrees of Freedom

Standard Electroweak Model

Then due to spontaneous symmetry breaking

12 degrees of freedom become

3 Massive gauge bosons → W^+, W^-, Z^0

$$\mathbf{J_z = 0, \pm 1}$$

1 Massless gauge boson → A_μ (γ)

$$\mathbf{J_z = \pm 1}$$

1 Massive scalar boson → Higgs (H)

Standard Electroweak Model

$$\mathcal{L}_{EW} =$$

$$\mathcal{L}_{EW} =$$

Standard Electroweak Model

$$
\begin{aligned}
L_{EW} = & \sum_i \overline{\psi}_i \left(i \partial\!\!\!/ - m_i - \frac{g m_i H}{2M_W} \right) \psi_i \\
& - \frac{g}{2\sqrt{2}} \sum_i \overline{\psi}_i \gamma^\mu (1-\gamma^5)(T^+ W_\mu^+ + T^- W_\mu^-) \psi_i \\
& - e \sum_i q_i \overline{\psi}_i \gamma^\mu \psi_i A_\mu \\
& - \frac{g}{2\cos\theta_W} \sum_i \overline{\psi}_i \gamma^\mu (g_V^i - g_A^i \gamma^5) \psi_i Z_\mu .
\end{aligned}
$$

Note: Vector – Axial Vector
V-A

$$A = B\cos\theta_W + W_3\sin\theta_W$$

$$W^{\pm} = \frac{1}{\sqrt{2}}\left(W_1 \mp W_2\right)$$

$$Z = -B\sin\theta_W + W_3\cos\theta_W$$

$T^{\pm}$ are the isospin raising and lowering operators

$g_V^i = T_3^i - 2q_i\sin^2\theta_W$ — q_i = particle charge

$g_A^i = T_3^i$ — $T_3 = +\frac{1}{2}$ for upper states: e.g. ν_L, u_L, …

$T_3 = -\frac{1}{2}$ for lower states: e.g. d_{WL} , e_L

Standard Electroweak Model

- The d_w, s_w, b_w weakly interacting quarks are related to the strongly interacting "mass eigenstates" d,s,b via the Cabibbo-Kobayashi-Maskawa matrix:

Weak eigenstates **Mass eigenstates**

$$\begin{pmatrix} d_w \\ s_w \\ b_w \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Three independent angles and single complex phase is possible (gives "CP" Violation -more later)

Standard Model of QCD

$$L_{\mathrm{QCD}} = -\frac{1}{4} F^{(a)}_{\mu\nu} F^{(a)\mu\nu} + i \sum_q \overline{\psi}^i_q \gamma^\mu (D_\mu)_{ij} \psi^j_q - \sum_q m_q \overline{\psi}^i_q \psi_{qi} ,$$

$$F^{(a)}_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu - g_s f_{abc} A^b_\mu A^c_\nu ,$$

$$(D_\mu)_{ij} = \delta_{ij} \partial_\mu + i g_s \sum_a \frac{\lambda^a_{i,j}}{2} A^a_\mu ,$$

A^a_μ are the 8 gluon fields ($a = 1 - 8$)

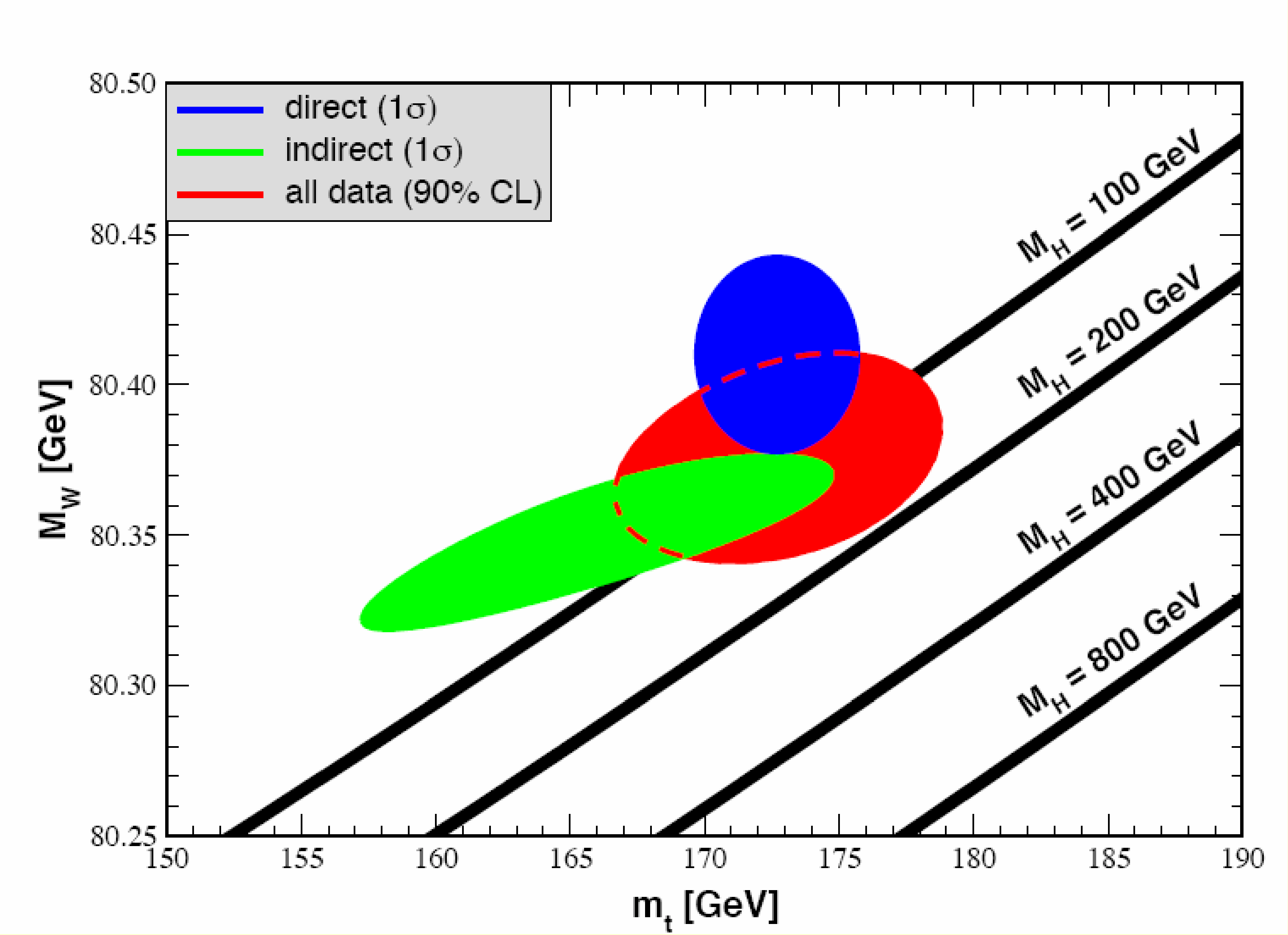
Beyond the Standard Model:

1. Testing the Standard Model

Precision measurements compared to precision calculations

- Particle properties
  - Magnet/Electric Moments
- Basic theoretical predictions
  - Energy dependence of the coupling constants
- Nuclei, Neutron and Muon decay parameters
  - Is (V-A) the complete picture?

Example of precision lower energy data "predicting" new phyiscs



Example: Muon Decay

$$\mathbf{M} = \frac{G_F}{\sqrt{2}} \sum_i \bar{u}_e \theta_i u_\mu \bar{u}_{\nu_\mu} \theta_i (C_i + C_i^{/}) v_{\nu_e}$$

$$\text{where } \theta_i = 1, \; \gamma^5, \; \gamma^\mu, \; \gamma^\mu\gamma^5, \; \sigma^{\mu\nu}$$

$$\quad\quad\quad\quad\quad\quad \mathrm{S} \quad \mathrm{P} \quad \mathrm{V} \quad \mathrm{A} \quad \mathrm{T}$$

S = Scalar
P = Pseudoscalar
V = Vector
A = Axial Vector
T = Tensor

and C_i, $C_i^{/}$ are 10 complex numbers and 1 arbitrarty phase (19 real numbers)

In Standard Model

$$C_V = C_V^{/} \;\&\; C_A = C_A^{/}$$

$$\mathrm{Im}(C_i) = 0$$

$$C_S = C_S^{/} = C_P = C_P^{/} = C_T = C_T^{/}$$

Beyond the Standard Model:
2. SUperSYmmetry (SUSY)

What's Right with the Standard Model?

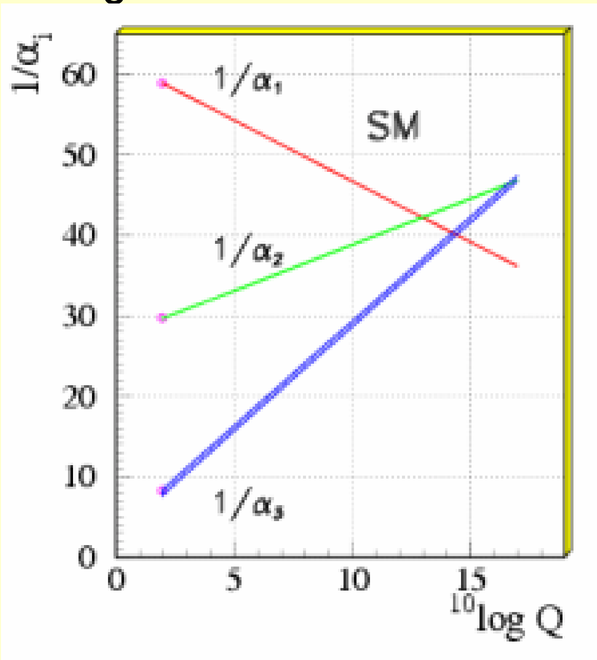
- appears to "explain" all elementary particle observables at present energies using 19 parameters fixed by data (not including neutrino masses/mixing)
  - 3 coupling constants α_s, α_W, α_{EM}
  - 9 lepton & quark masses
  - 4 CKM parameters
  - M_Z, M_H, θ_{QCD}

What's wrong with the Standard Model?

$$M_P = \sqrt{\frac{\hbar c}{G}}$$

1. "Gauge Hierarchy Problem"
   - Why is Planck mass (10^{19} GeV) so much larger than the electroweak masses (~ 10^2 GeV)
     - Planck mass is where all forces have same strength

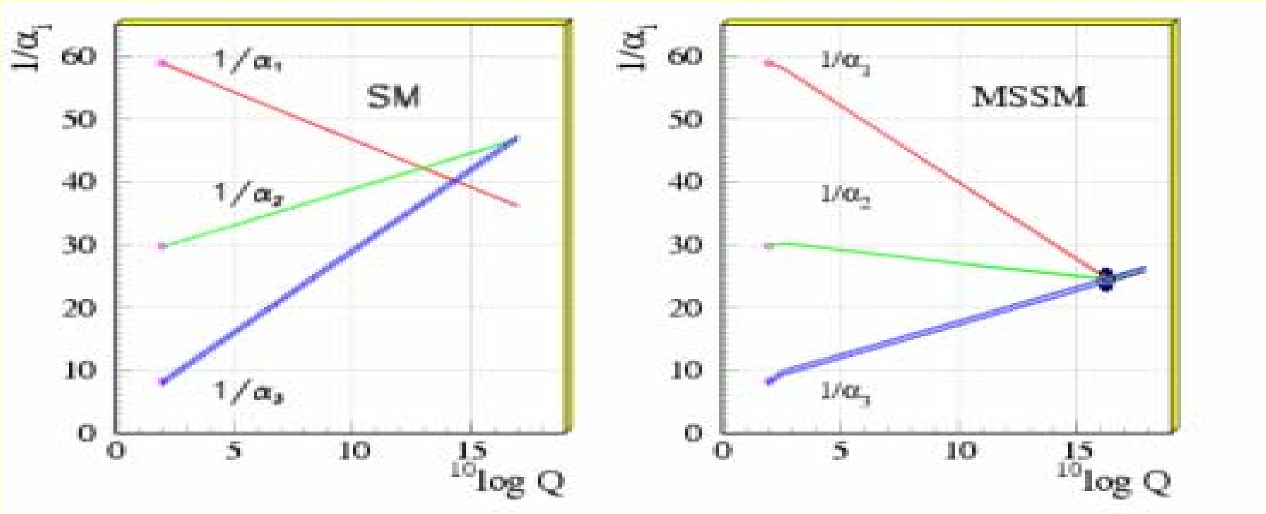
2. Does not allow α_s, α_W, α_{EM} to become unified at a single energy



3. Cannot account for the observed Cosmological Dark Matter (what is it??)

Why SUSY?

1. May be capable of "solving" gauge hierarchy (supersymmetry is realized at very high masses but is broken at ~ TeV)
2. Can permit unification of strong & electroweak couplings at the Planck mass (if M_{SUSY} ~ TeV)



3. Can have a heavy SUSY particle as the dark matter (the Lightest SUSY Particle LSP)

What's in SUSY?

- Each particle of the Standard Model has a partner in SUSY
  - Leptons and quarks have boson partners
  - Gauge particles and Higgs have fermion partners
- Many new couplings arise
- Minimal Supersymmetric Standard Model (MSSM)
  - Minimal set of new particles/couplings to produce a self-consistent model that is consistent with the standard model for energies < TeV

Table 1: The fields of the MSSM and their SU(3)×SU(2)×U(1) quantum numbers are listed. Only one generation of quarks and leptons is exhibited. For each lepton, quark and Higgs super-multiplet, there is a corresponding anti-particle multiplet of charge-conjugated fermions and their associated scalar partners.

Field Content of the MSSM					
Super-Multiplets	Boson Fields	Fermionic Partners	SU(3)	SU(2)	U(1)
gluon/gluino	g	$\widetilde{g}$	8	0	0
gauge/	$W^{\pm}, W^0$	$\widetilde{W}^{\pm}, \widetilde{W}^0$	1	3	0
gaugino	B	$\widetilde{B}$	1	1	0
slepton/	$(\widetilde{\nu}, \widetilde{e}^-)_L$	$(\nu, e^-)_L$	1	2	-1
lepton	$\tilde{e}_R^-$	e_R^-	1	1	-2
squark/	$(\widetilde{u}_L, \widetilde{d}_L)$	$(u, d)_L$	3	2	1/3
quark	$\widetilde{u}_R$	u_R	3	1	4/3
	$\widetilde{d}_R$	d_R	3	1	$-2/3$
Higgs/	(H_d^0, H_d^-)	$(\widetilde{H}_d^0, \widetilde{H}_d^-)$	1	2	-1
higgsino	(H_u^+, H_u^0)	$(\widetilde{H}_u^+, \widetilde{H}_u^0)$	1	2	1

What's in SUSY?

- Great Names:
  - Squarks, sleptons, gauginos, winos, binos, neutralinos,...
- In MSSM
  - 124 parameters - 19 from Standard Model & 105 new parameters (from SUSY and also from SUSY breaking)
    - 36 mixing angles for squarks & sleptons
    - 40 CP-violating phases for squarks & sleptons
    - 21 squark & slepton masses
    - 5 couplings and 3 phases from gauginos/higgsinos

- How to break Supersymmetry?

  (lots of options)

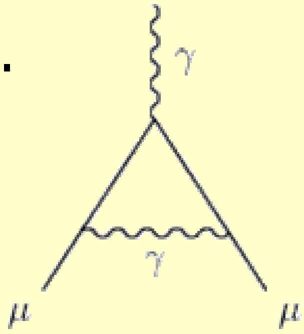
  - Gravity mediated (MSUGRA) and Gauge mediated symmetry breaking
  - Often includes hidden and visible sectors (particles that don't interact with Standard Model Particles
  - Extra dimensions (small - <.1mm) may allow these hidden particles (10 dimensions in string theory 11 dimensions in M-theory)

Quick!! → back to reality

Some Experimental Examples

- Muon (or electron) magnetic moment
  - Pure Dirac particle has g = 2
  - Quantum loops cause g = 2 + corrections

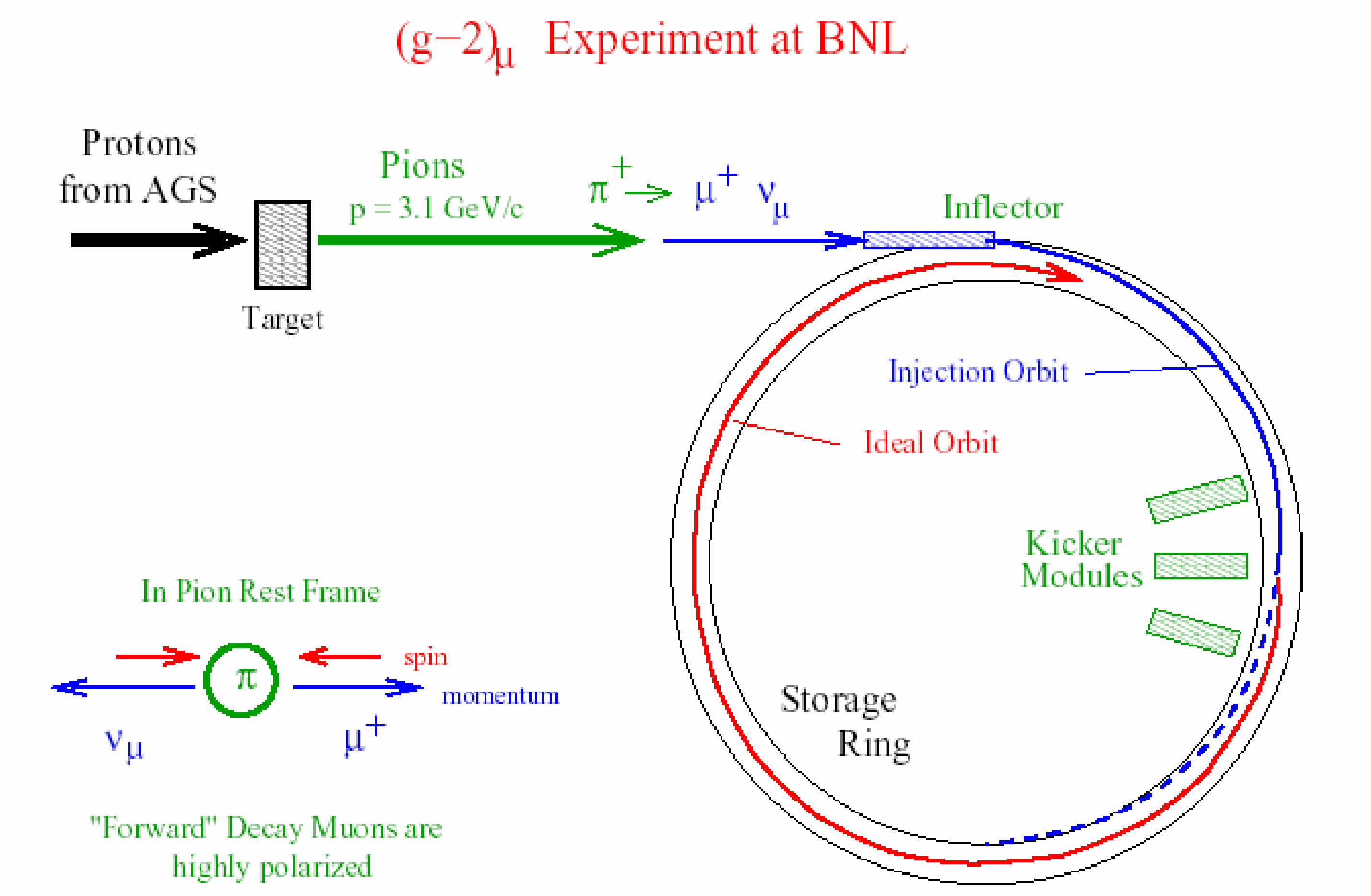
e.g.



$= \alpha/2\pi \sim 0.00117$

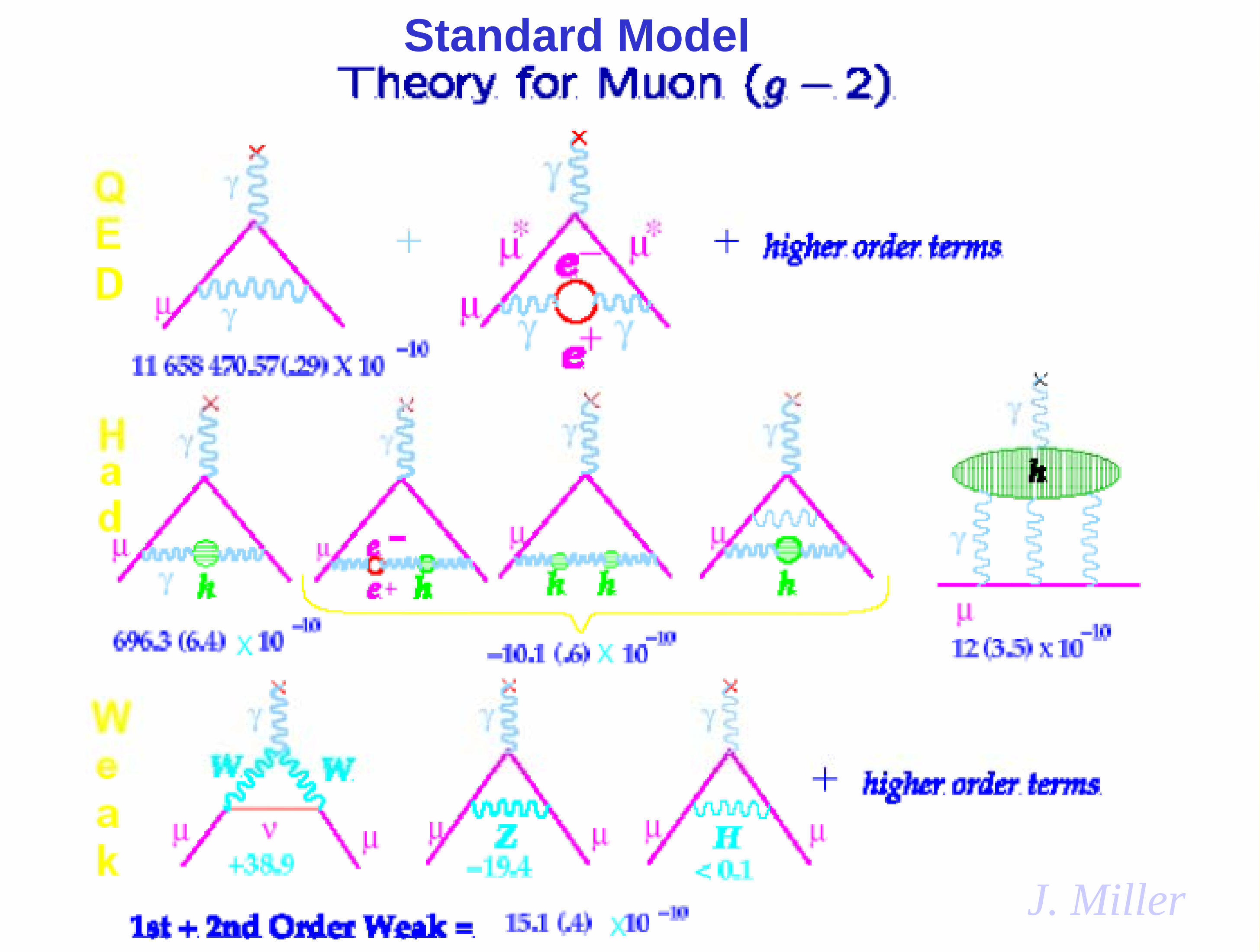
  - Loop corrections can include VERY heavy particles in the loops
  - Up to 5 loops have been calculated

Muon g-2



James Miller - The Muon Magnetic Moment Anomaly: Experiment

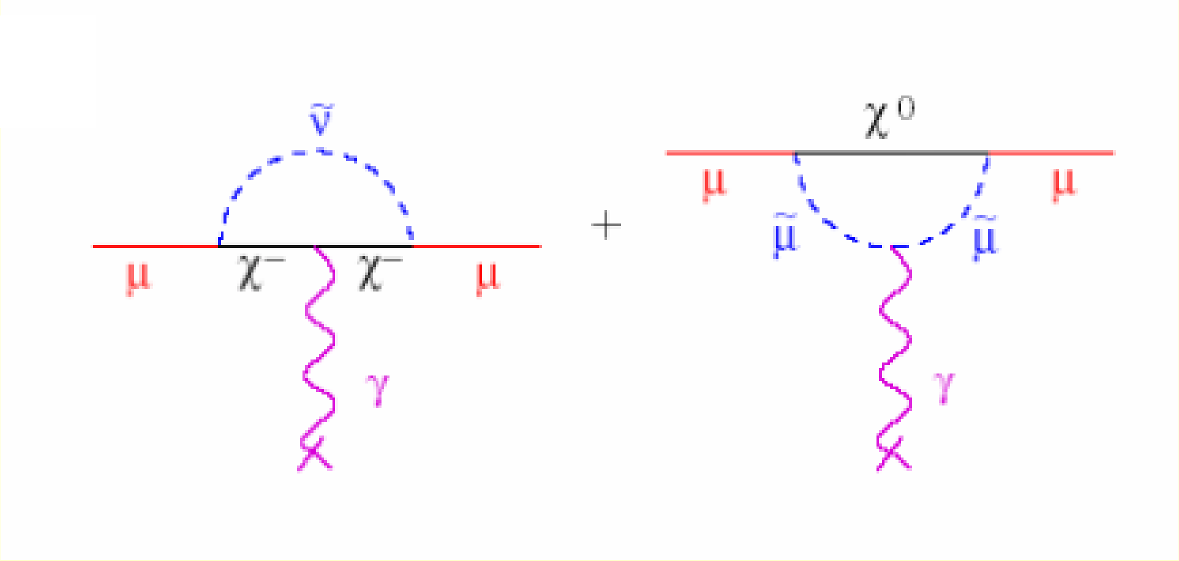
Muon g-2



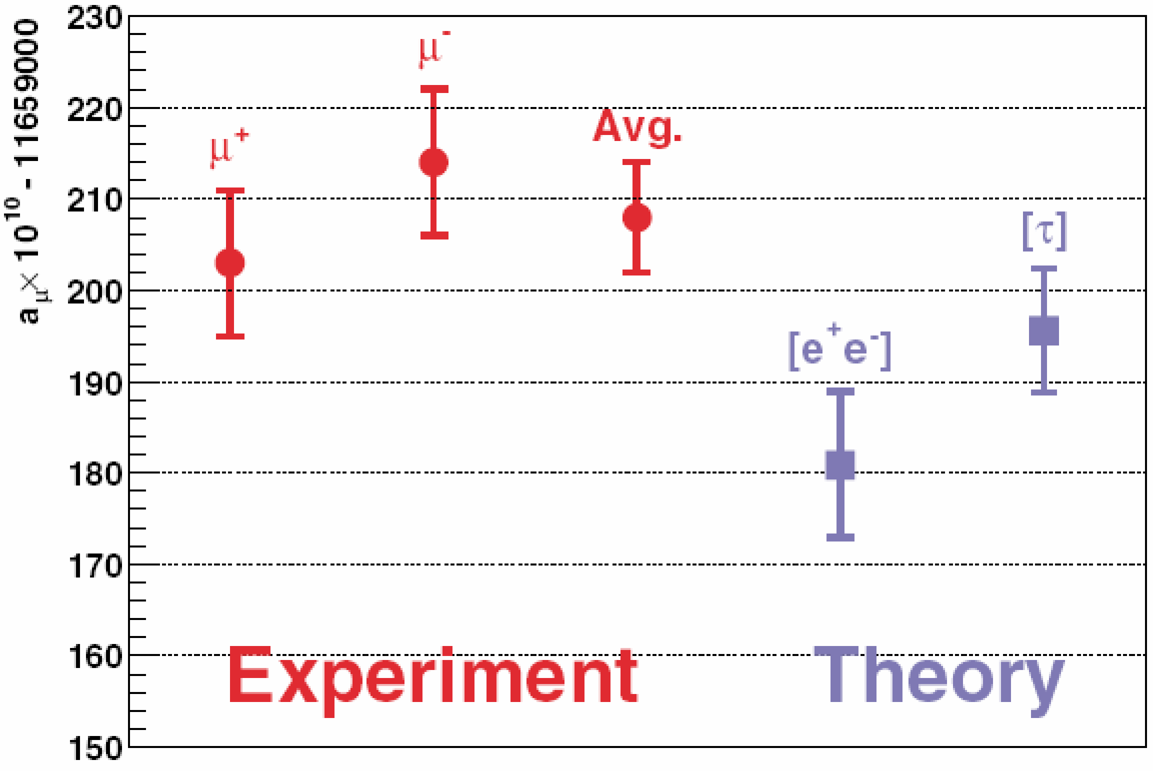
Standard Model
Theory for Muon (g − 2)
QED
higher order terms
11 658 470.57(.29) X 10 −10
Had
696.3 (6.4) X 10 −10
−10.1 (.6) X 10 −10
12 (3.5) x 10 −10
Weak
+38.9
−19.4
< 0.1
higher order terms
1st + 2nd Order Weak = 15.1 (.4) X10 −10
J. Miller

Muon g-2

SUSYContributions



BNL $(g-2)_\mu$



230
220
210
200
190
180
170
160
150
a_μ × 10^10 - 11659000
μ+
μ-
Avg.
[e+e-]
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Experiment
Theory