The Exact and Approximate Symmetries of Electroweak Interactions

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Unique Low Energy Tests exploiting the special properties of Leptons, Nucleons and Nuclei

Outline of Lectures

- Standard Model of Electroweak Interactions
- Searches for Violations of Discrete Symmetries
- Precision Low Energy Electroweak Measurements
- Electroweak Probes of Hadron Structure

Introductory Remarks

- Student background and preparation varies
  - Some of you will have had nuclear and/or particle physics at an advanced level; but not all of you
  - I will try to have a few slides each lecture on very basic undergraduate and graduate subatomic physics
- As postdoctoral researchers, you will learn to cope with imperfect knowledge
  - Qualitative rather than quantitative understanding
  - I am an experimentalist! I will focus on measurements but theory is critical. A complementary theory lecture by Vincenzo Cirigliano
- I will try to communicate the "big picture"
  - necessary general knowledge for students focused on other subfields

Acknowledgements

- Betsy Beise
- Jens Erler
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- Robert McKeown
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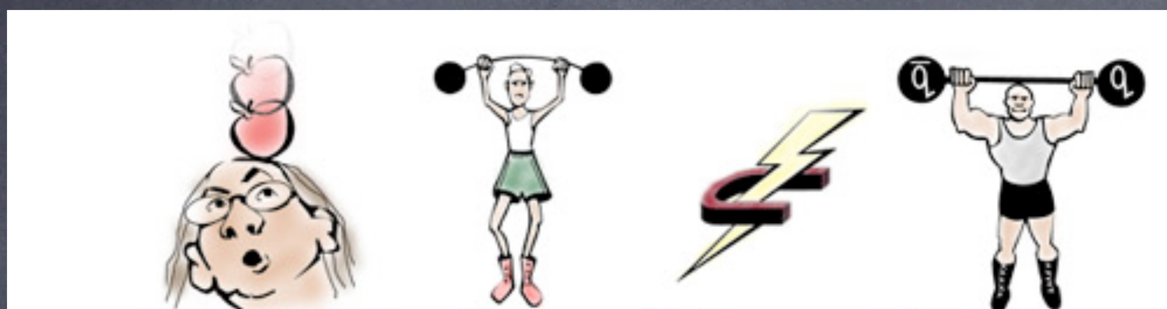
- Chris Quigg
- Michael Ramsey-Musolf
- Michael Romalis
- Paul Souder
- www.particleadventure.org
- ...

Outline of Lecture #1

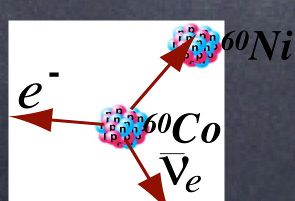
- Electroweak Interactions: a minimalist view
- Why do we think we have the correct effective low energy electroweak theory?
- Why do we think we have more work to do?
- The path forward

Fundamental Interactions

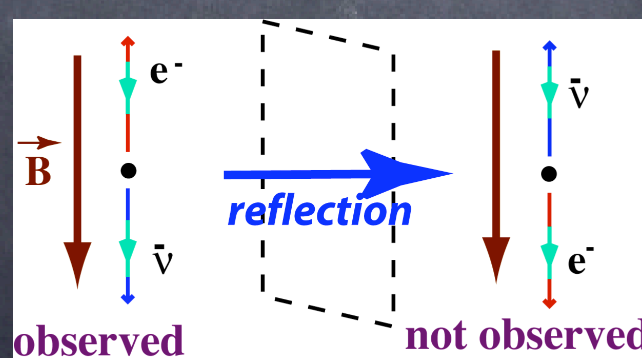


	Gravity	Weak (Electroweak)	Electromagnetic	Strong
Carried By	Graviton (not yet observed)	$W^+ \; W^- \; Z^0$	Photon	Gluon
Acts on	All	Quarks and Leptons	Quarks and Charged Leptons and $W^+ \; W^-$	Quarks and Gluons

Radio-activity *Electricity & Magnetism* *Nuclei & Nucleons*



Weak decay of ^{60}Co Nucleus

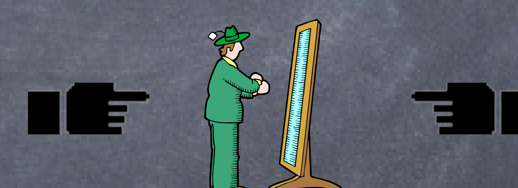


Gravity and Electromagnetic

Infinite range

Strong and Weak

10^{-15} meter



parity transformation

$$x, y, z \longrightarrow -x, -y, -z$$

$$\vec{p} \longrightarrow -\vec{p}, \;\; \vec{L} \longrightarrow \vec{L}, \;\; \vec{s} \longrightarrow \vec{s}$$

Charged Weak Interactions have pure V-A structure (maximal parity violation)

Quantum Electrodynamics

Free fermions fields are solutions to the Dirac equation $(i\gamma_\mu \partial^\mu - m)\psi = 0$

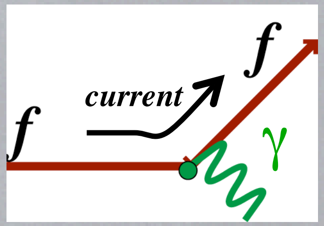
Corresponding Lagrangian: $\mathcal{L} \sim \quad \overline{\psi}(i\gamma_\mu \partial^\mu - m)\psi$

Local gauge invariance gives rise to interaction with photon field: $-J_\mu A^\mu$

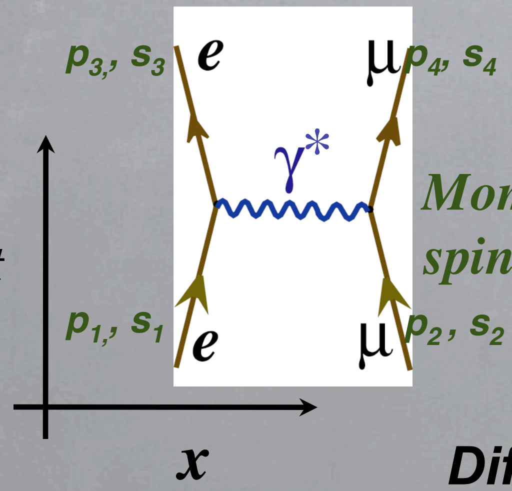
Conserved electromagnetic current

$J^\mu = q\overline{\psi}\gamma^\mu\psi$ ***4-vector***

Feynman Rules: emission and absorption of virtual photons by fermion electromagnetic current



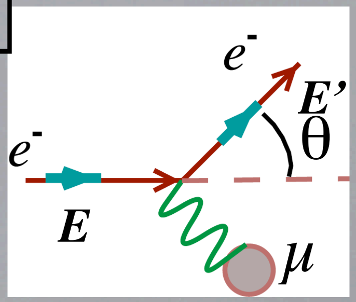
electron-muon scattering



Momenta and spins p and s

$$\mathcal{M} \sim -\frac{g_e^2}{(p_1 - p_3)^2}\left[\overline{u}^{s_3}(p_3)\gamma_\mu u^{s_1}(p_1)\right]\left[\overline{u}^{s_4}(p_4)\gamma^\mu u^{s_2}(p_2)\right]$$

Differential Cross Section $\dfrac{d\sigma}{d\Omega} = \dfrac{4\alpha^2 E'^2}{q^4}\cos^2\dfrac{\vartheta}{2}$



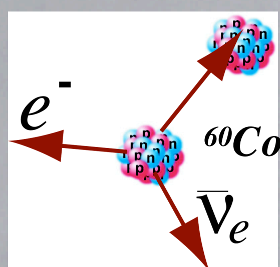
4-momentum transfer

$$q^2 = -4EE'\sin^2\frac{\theta}{2}$$

Weak Interactions

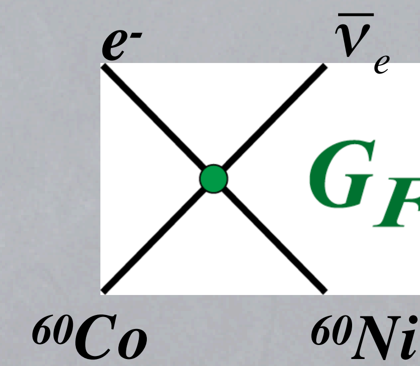
$J^\mu \sim \bar{\psi}\gamma^\mu\psi$ *vector* $\qquad J^\mu \sim \bar{\psi}\gamma^\mu\gamma^5\psi$ *axial-vector* $\qquad$ *V-A Interaction*

V X A gives rise to pseudo-scalars



$$\mathcal{M} \sim -\frac{G_F}{\sqrt{2}}\left[\bar{u}(Co)\gamma_\mu(1-\gamma^5)u(Ni)\right]\left[\bar{u}(e)\gamma^\mu(1-\gamma^5)v(\bar{\nu})\right]$$

4-Fermi Contact interaction with maximal parity violation



For massless particles: $\gamma^5 u = (\vec{p}\bullet\vec{\Sigma})u$

$$\vec{\Sigma} \equiv \begin{pmatrix} \vec{\sigma} & 0 \\ 0 & \vec{\sigma} \end{pmatrix}$$

$\vec{p}\bullet\vec{\Sigma} \equiv h$

helicity operator

$$\Sigma u = +u \Rightarrow \frac{(1-\gamma^5)}{2}u = 0 \qquad \Sigma u = -u \Rightarrow \frac{(1-\gamma^5)}{2}u = u$$

$$P_L \equiv \frac{(1-\gamma^5)}{2} \qquad P_R \equiv \frac{(1+\gamma^5)}{2}$$

$$-\frac{G_F}{\sqrt{2}}\left[\bar{u}_L(Co)\gamma_\mu u_L(Ni)\right]\left[\bar{u}_L(e)\gamma^\mu v_R(\bar{\nu})\right]$$

Left- and right-handed projections

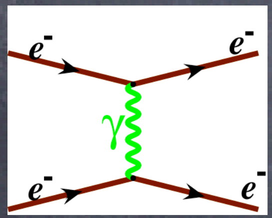
$$P_{L,R}u \equiv u_{L,R} \qquad P_iP_j = \delta_{ij}P_j \qquad \sum_i P_i = I$$

Only left-handed particles participate in charged weak interactions

Charge & Handedness

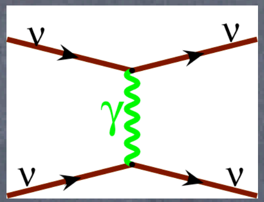
Electric charge determines strength of electric force

Electrons and protons have same charge magnitude: same strength



observed

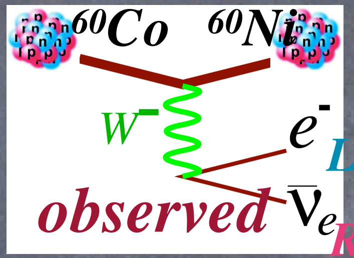
Neutrinos are "charge neutral": do not feel the electric force



not observed

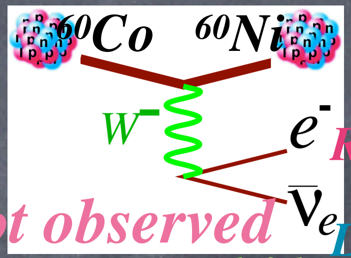
Weak charge determines strength of weak force

Left-handed particles (Right-handed antiparticles) have weak charge



right-handed anti-neutrino

Right-handed particles (left-handed antiparticles) are "weak charge neutral"



not observed

left-handed anti-neutrino

Important: Helicity ≠ Chirality if m≠0!

Helicity operator commutes with free-particle Hamiltonian

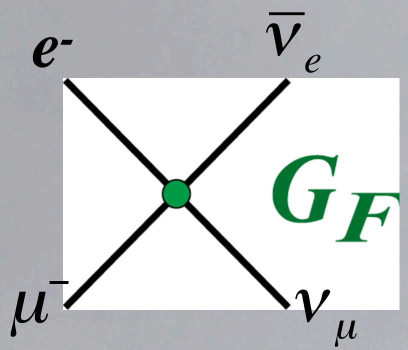
Conserved but not Lorentz invariant!

(Can race past a massive particle and observe it spinning the other way)

Chirality operator not conserved, but Lorentz invariant!

Freely propagating left-chiral projection will develop a right-chiral component

Weak Decay & Scattering



$$\mathcal{M} \sim -\frac{G_F}{\sqrt{2}}\left[\bar{u}(\nu_\mu)\gamma_\mu(1-\gamma^5)u(\mu)\right]\left[\bar{u}(e)\gamma^\mu(1-\gamma^5)v(\bar{\nu}_e)\right]$$

Each decay mode provides a partial width Γ_i

Lifetime

$$\tau = \frac{1}{\sum_i \Gamma_i}$$

Partial width has units of energy

$$\Gamma_\mu = \frac{G_F^2 m_\mu^5}{192\pi}$$

Conversion factor: 197 MeV-fm

Muon lifetime in vacuum: 2.2 μs

Gedanken Experiments: The luxury of being a theorist

Consider

$$\bar{\nu}_e + e^- \rightarrow \bar{\nu}_\mu + \mu^-$$

Can use same $\mathcal{M}$

$$\sigma = \frac{G_F E^2}{3\pi^2}$$

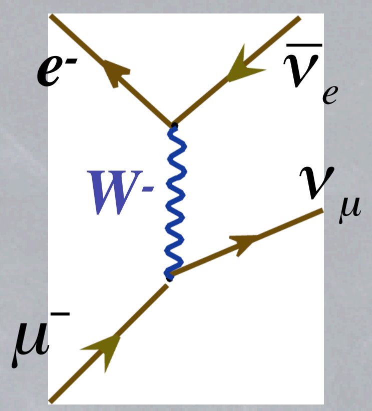
For E ~ 1 TeV, probability > 1!

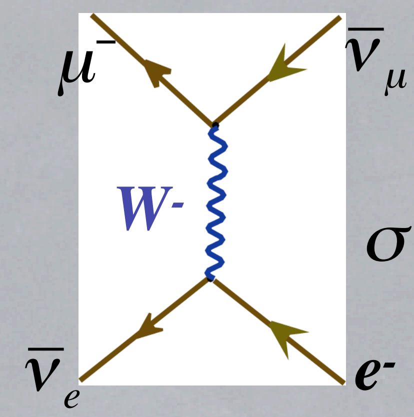
More particles going out than coming in

Massive Vector Bosons

$$\mu^- \rightarrow \nu_\mu + \bar{\nu}_e + e^-$$

$$\frac{G_F}{\sqrt{2}} = \frac{g_W^2}{8M_W^2}$$





$$\bar{\nu}_e + e^- \rightarrow \bar{\nu}_\mu + \mu^-$$

$$\sigma \approx \frac{2g_W^4}{3\pi} \frac{4E^2}{4(E^2 - m_W^2)^2}$$

Mass of the W between 10 and 100 GeV

$$V = \frac{1}{4\pi\varepsilon_0} \frac{q}{r} e^{-\left[\frac{mc}{\hbar}\right] r}$$

Short range

Real W production

$$u + \bar{d} \rightarrow W^+ \rightarrow e^+ + \nu_e$$

Fixed target: $M^2_{new} \sim 2ME$

Collider: $M^2_{new} \sim 4E^2$

Very short lifetime ⟺ **Large width**

$$A + B \rightarrow W^+ \rightarrow C + D$$

$$p(E) = \frac{\Gamma}{2\pi} \frac{1}{(E - m_W)^2 + (\Gamma/2)^2}$$

$$\sigma_{peak} \approx \frac{4\pi}{3m_W^2} \frac{\Gamma_{AB}}{\Gamma_{tot}} \frac{\Gamma_{CD}}{\Gamma_{tot}}$$

Vector Boson Production at Colliders

$$\frac{\Gamma_{AB}}{\Gamma_{tot}}$$

Relative probability of A+B decay w.r.t. total probability: Branching Ratio

Count possibilities: $e^+\nu_e, \mu^+\nu_\mu, \tau^+\nu_\tau, u\bar{d}, c\bar{s}$

1 1 1 3 3

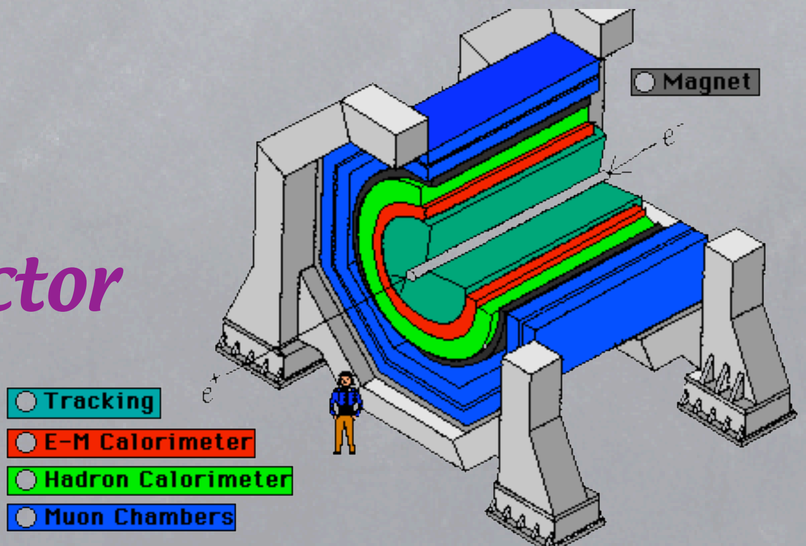
→ ***Few nbarn***

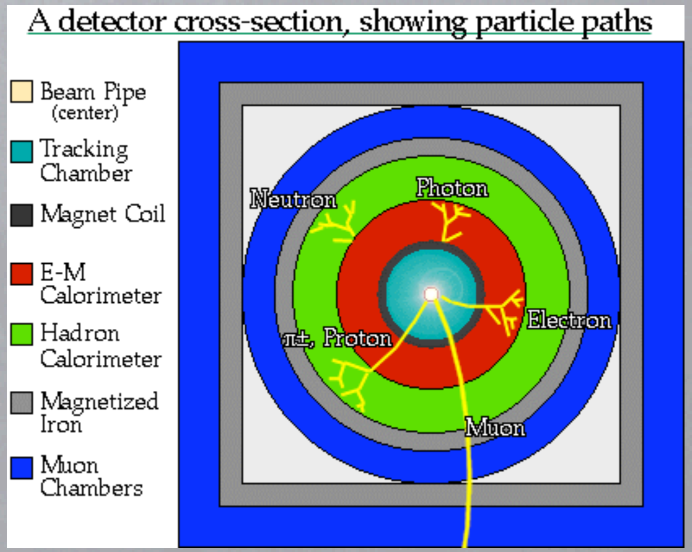
Need ppbar collider with luminosity $\mathcal{L} \sim 10^{27}/cm^2/s$

$N \sim \mathcal{L}\sigma T = 10^{27} \times 10^{-9} \times 10^{-24} \times 10^{7}$ → ***Few events!***

Challenge: QCD background: 40 mbarn!

- e^+e^- or p-pbar or p-p
- "hermetic" detector
- Collision at heart of detector
- Engineering and technological challenges





W signal: highly energetic lepton with energy imbalance

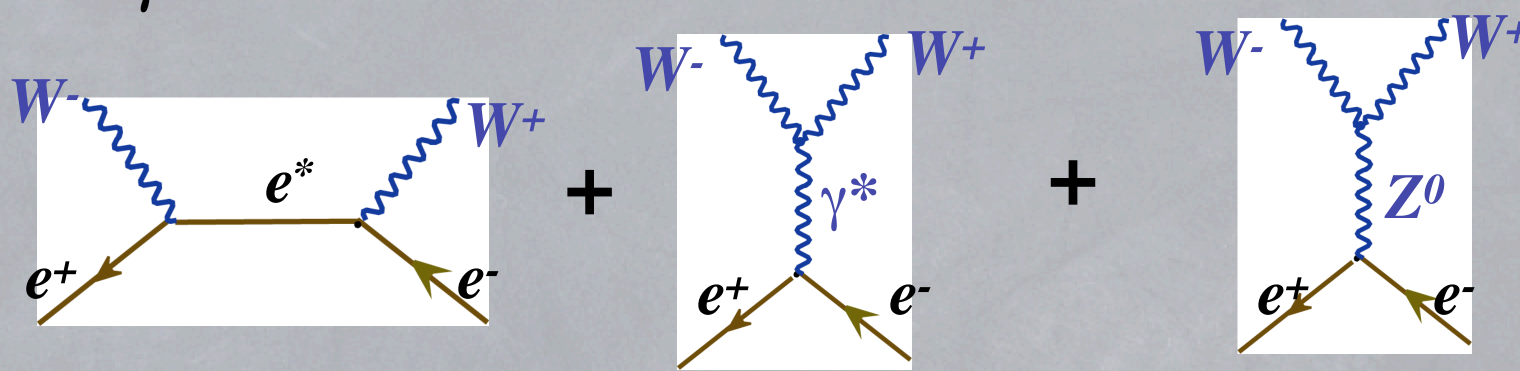
The Z Boson & Unification

More gedanken experiments

$$e^+\nu_e \rightarrow W^+\gamma$$

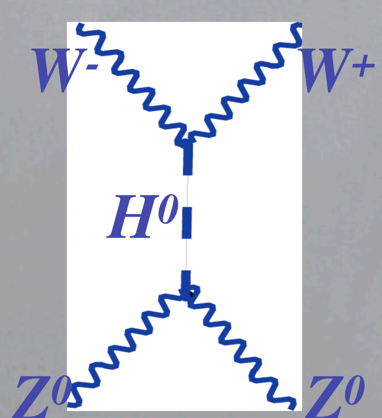
Electron-positron collisions

$$e^+e^- \rightarrow W^+W^-$$



Unitarity violation forces important constraints

- *Need WWγ vertex: same charge as electron!*
- *Need a new, neutral massive weak boson: the Z^0*
- *One free parameter: θ_W, the weak mixing angle*

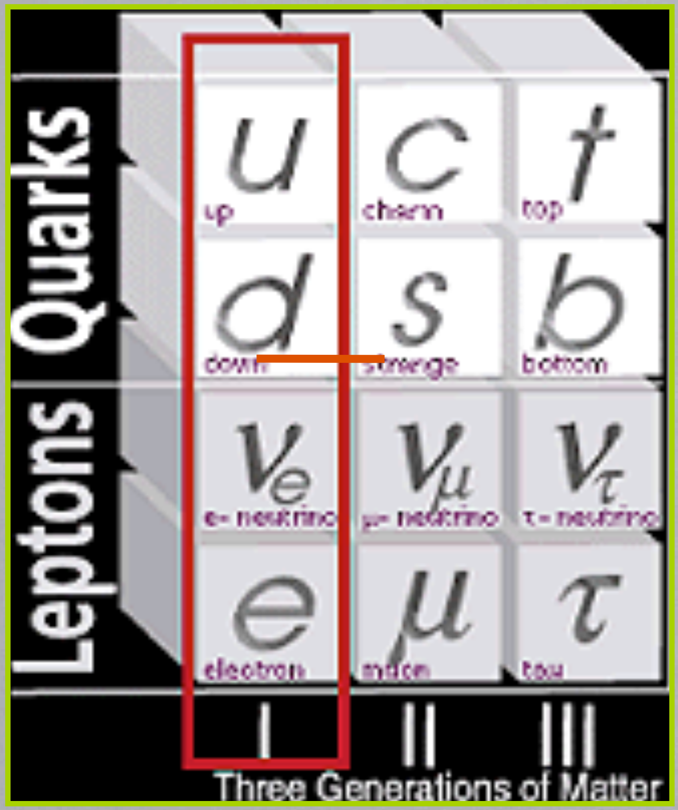


Scattering of longitudinal vector bosons (m=0)

- eeZ couplings depend on $\sin^2\theta_W$

$$\frac{m_W}{m_Z} = \cos\theta_W$$

W & Z Charges



- Left-handed particles in isodoublets
- Right-handed particles iso-singlets
- Including neutrinos!

	Left-	Right-
γ Charge	$q = 0, \pm 1, \pm \frac{1}{3}, \pm \frac{2}{3}$	$q = 0, \pm 1, \pm \frac{1}{3}, \pm \frac{2}{3}$
W Charge	$T = \pm \frac{1}{2}$	$T = 0$
Z Charge	$T - q \sin^2 \theta_W$	$-q \sin^2 \theta_W$

- *Ws have no couplings to right-handed particles*
- *Zs couple to both (provided the particles are charged): introduce g_L and g_R*

Also use g_V and g_A:

$$g_V = g_L + g_R \qquad g_A = g_L - g_R$$

Vector and Axial-vector couplings

Z Decays

electron-positron collisions at "Z-Factories"

SLC @ SLAC and LEP @ CERN

$$e^+e^- \rightarrow Z^0 \rightarrow l^+l^-, q\bar{q}$$

Count possibilities: $6(e^+e^-) + 6(u\bar{u}) + 9(d\bar{d})$

$$\Gamma_{f\bar{f}} \propto g_L^2 + g_R^2$$

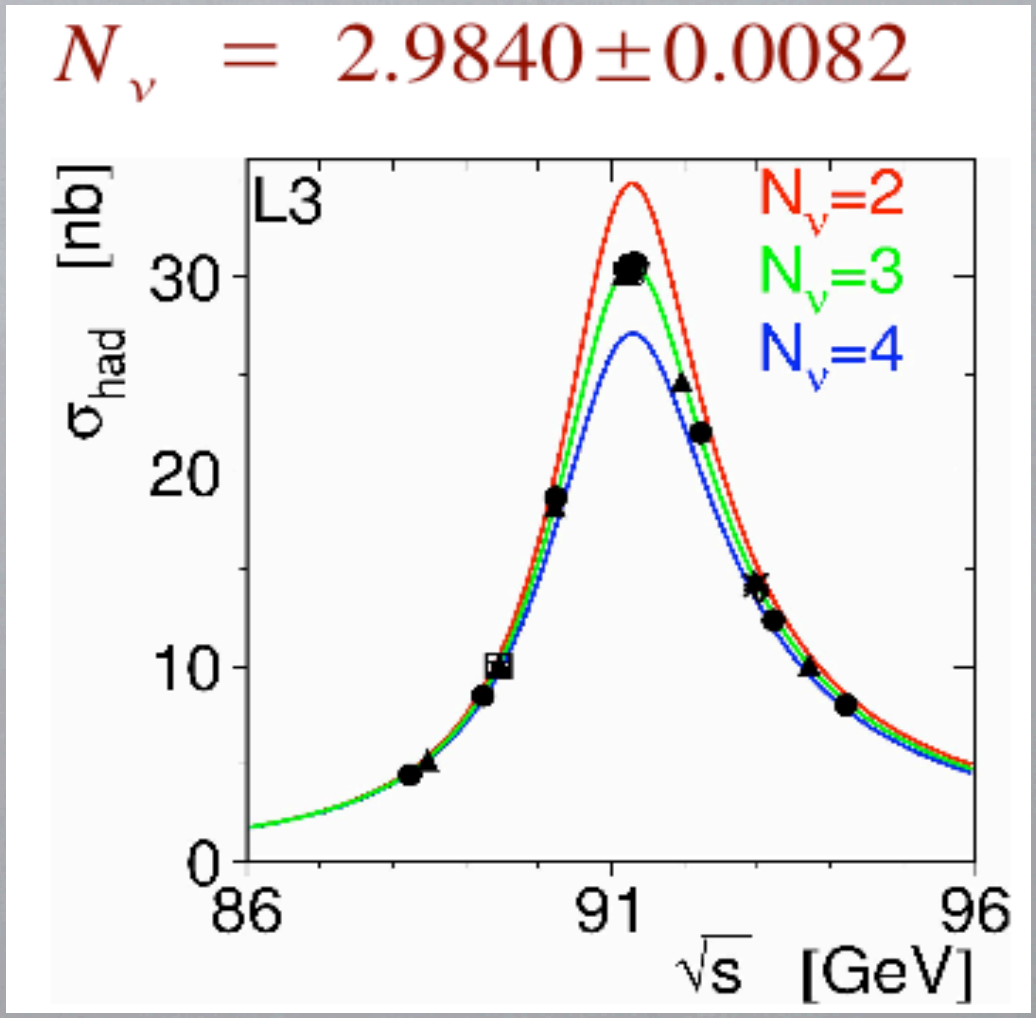
B.R.(leptons): 3.3% each, B.R.(quarks):70%

$$\sigma_{Z\rightarrow hadrons} \approx \frac{12\pi}{m_Z^2}(0.033\times 0.7)$$

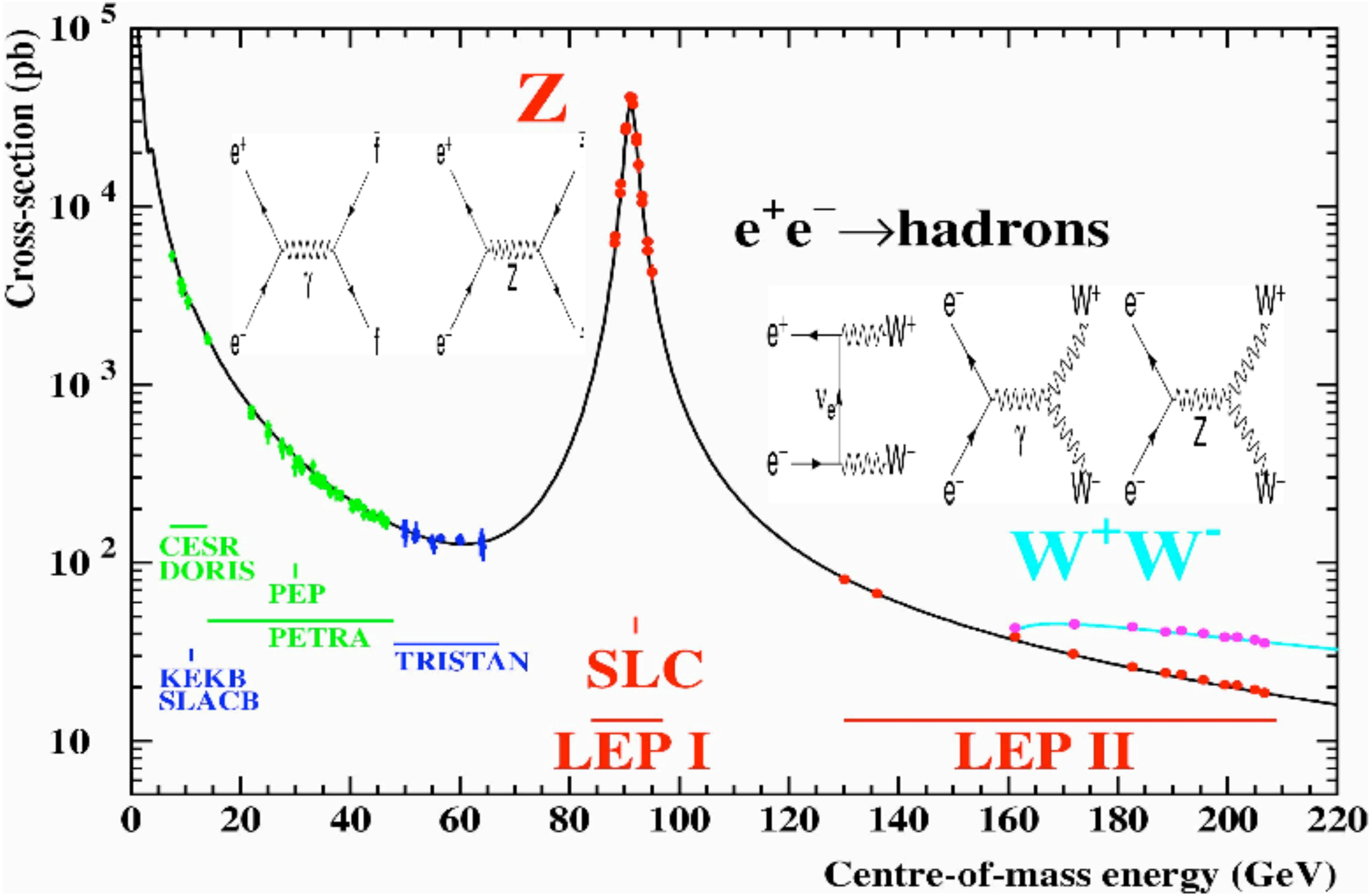
40 nbarn! 200 times larger than QED

$$\sigma(E) = \frac{\Gamma_{ee}\Gamma_{ff}}{(E-m_Z)^2 + (\Gamma/2)^2}$$

Can measure total width without identifying all final states!

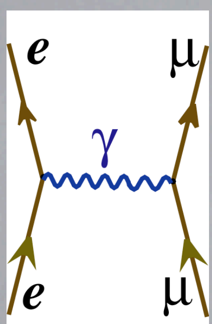


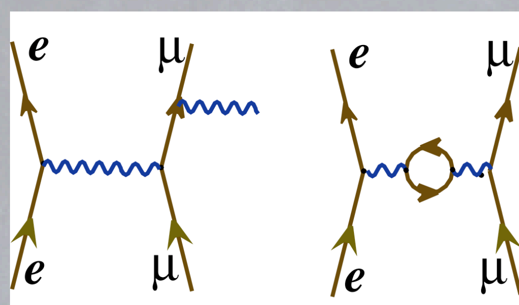
e^+e Interactions



Perturbation Theory & Charge Renormalization

From Feynman rules: ***Construct all possible diagrams consistent with known conservation laws***

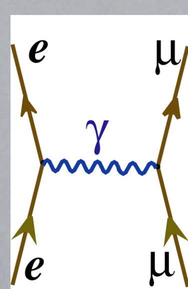




Amplitude is sum of all possible states: Feynman's path integral formulation of QM

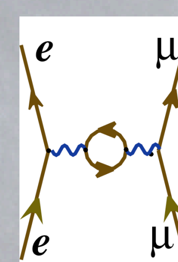
Problem: Total amplitude diverges

Start with



$$M_1 \sim \frac{e^2}{q^2}$$

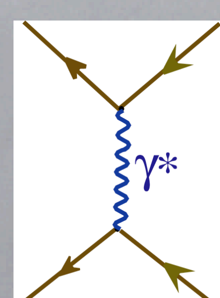
Add

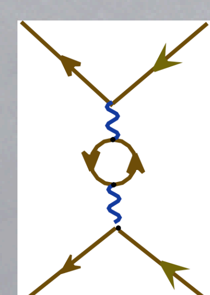


Introduce parameter $\Sigma_{\gamma\gamma}(q^2)$ **(It is infinite)**

$$M_1 \sim i\frac{e^2}{q^2} + i\frac{e^2}{q^2}\frac{i\Sigma_{\gamma\gamma}(q^2)}{q^2} \qquad e^2 \Rightarrow e^2(1+\Sigma_{\gamma\gamma}(q^2))$$

Now consider





Introduce parameter $\Pi_{\gamma\gamma}(p^2)$ **(Also infinite)**

$$M_2 \sim \frac{e^2}{p^2}(1-\Pi_{\gamma\gamma}(p^2))$$

$$M_2 \sim \frac{e^2}{p^2}(1-[\Pi_{\gamma\gamma}(p^2)-\Pi_{\gamma\gamma}(q^2)])$$ **Finite!**

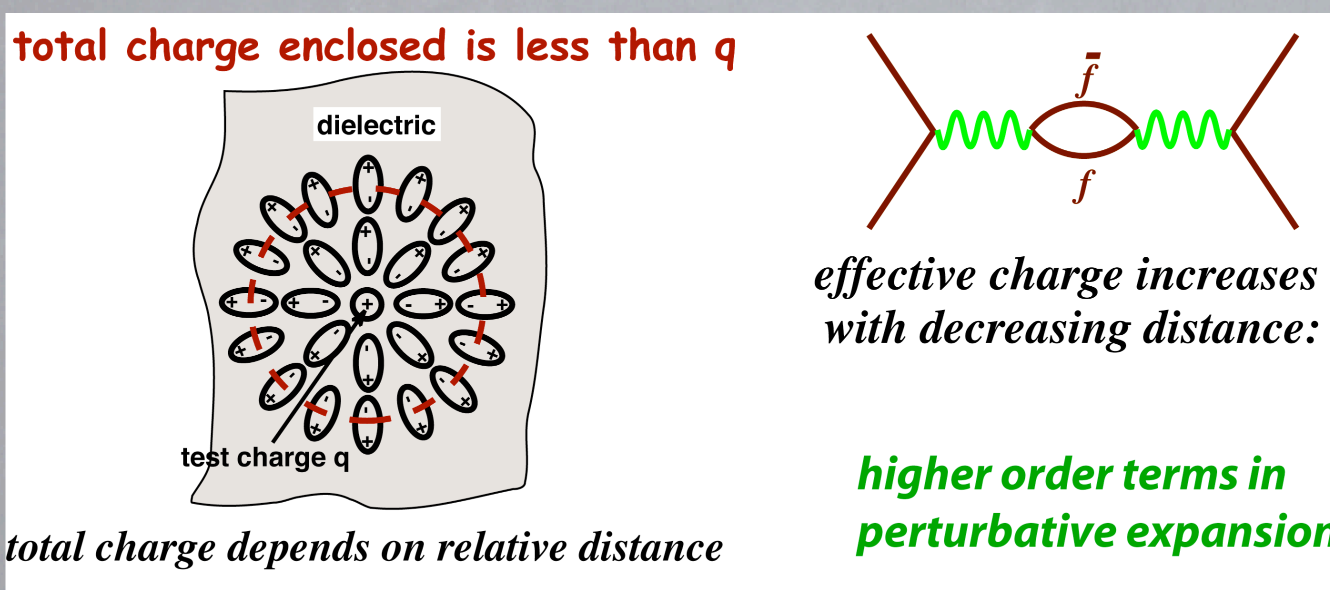
Running Couplings

- *Feynman rules with electric charge*
- *Calculate $\sigma_1(e)$ for a test process*
- *Measure $\sigma_1(e)$ and extract e*
- *Calculate $\sigma_2(e)$ for another process*

Not all Quantum Field Theories behave this way:

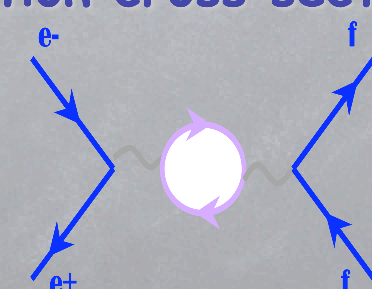
The ones that do are renormalizable theories

Electroweak theory: t'Hooft and Veltman
QCD: Gross, Politzer and Wilczek



Fine structure constant: 1/137 at low energy, 1/128 at Z pole

The shift $\Delta\alpha$ can be determined analytically for lepton loops and by a dispersion integral over the e+e- annihilation cross section for light quarks (u,d,s,c,b)



$\alpha(m^2_Z) = \alpha/(1-\Delta\alpha)$

$$\Delta\alpha_{lepton} = \sum_{l=e,\mu,\tau} \frac{\alpha}{3\pi}\left(\log\frac{m_Z^2}{m_l^2} - \frac{5}{3}\right) + \ldots$$

Optical theorem

$$\Delta\alpha_{hadron} = -\frac{\alpha}{3\pi}\int_{4m_\pi^2}^{\infty} \frac{m_Z^2\,ds}{s\left[s-m_Z^2\right]} \frac{\sigma(e^+e^- \to q\bar{q})}{\sigma(e^+e^- \to \mu^+\mu^-)}$$

Electroweak Input Parameters

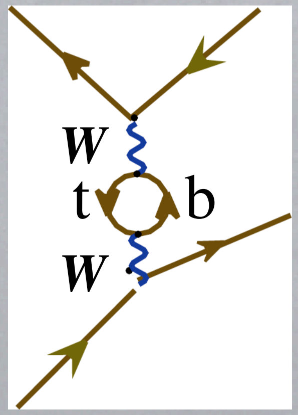
For electroweak interactions, there are three parameters needed:

1. *Scale of electromagnetism (electric charge)*
2. *Scale of the weak interaction (weak vector boson mass)*
3. *Weak mixing angle (ratio of the weak vector boson masses)*

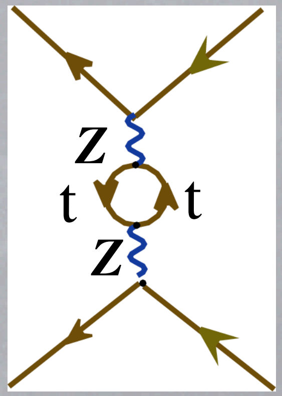
Parameters are chosen from experimental measurements:

1. electron g-2, thomsen scattering
2. The muon lifetime
3. The mass of the Z boson

Z mass know to 23 parts per million!



Muon decay



Z production

The answer differs from what you would get at tree level

$$\Pi_{WW} - \Pi_{ZZ} \propto m_t^2 - m_b^2$$

EW Global Fits

Electroweak Precision Data

Very high Q^2 physics at LEP, SLC, and the Tevatron:
- More than 1000 measurements with (correlated) uncertainties
- Combined to 17 precision electroweak observables

Z boson physics (LEP-1,SLD):
- 5 Z lineshape and leptonic forward-backward asymmetries
- 2 Polarised leptonic asymmetries P_τ, $A_{LR(FB)}$
- 1 Inclusive hadronic charge asymmetry
- 6 Heavy quark flavour results (Z decays to b and c quarks)

W boson & top quark physics – ongoing at Tevatron's Run-II:
- 2 W boson mass and width (LEP-2, Tevatron)
- 1 Top quark mass (Tevatron)

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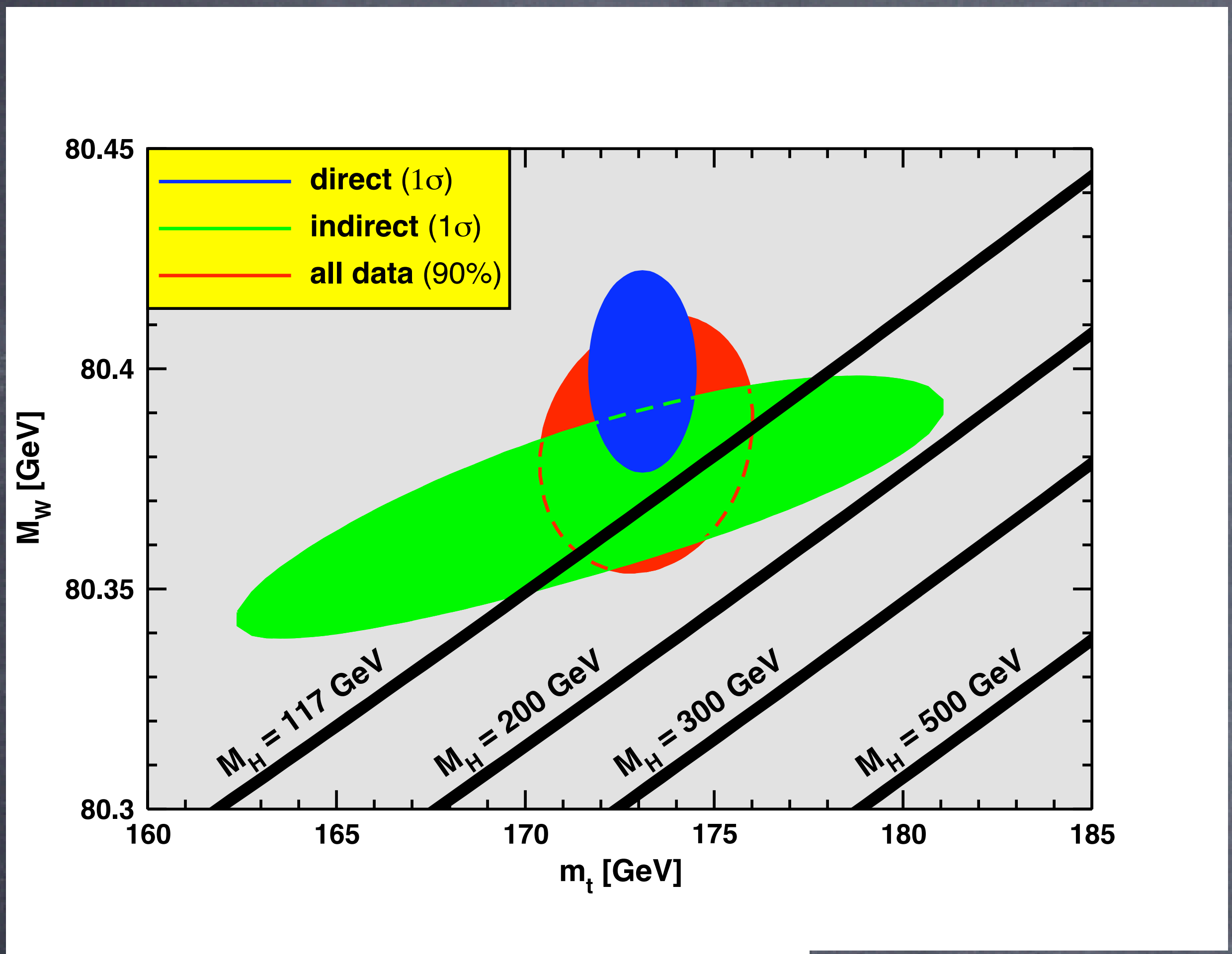
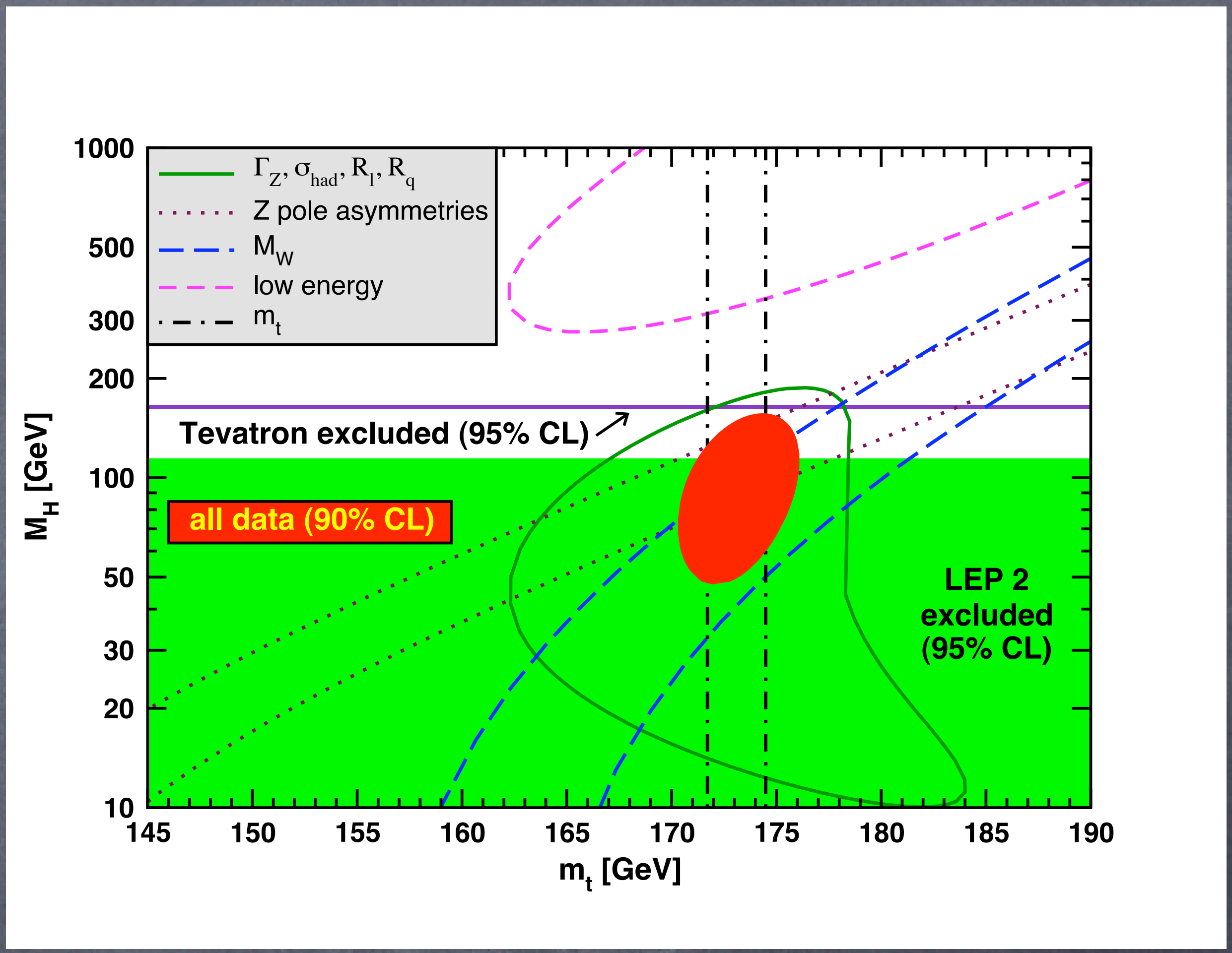
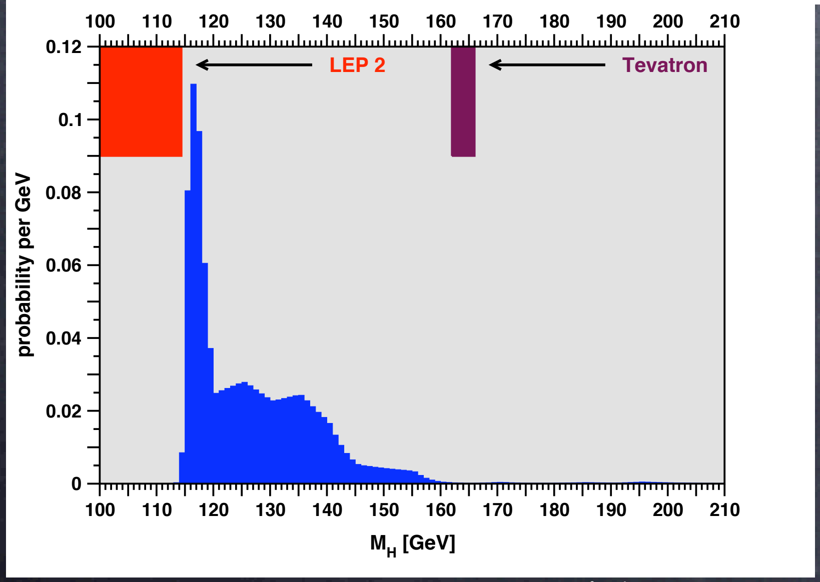
J. Erler

The Top and the Higgs







- Most precise observables: M_W and Z pole asymmetries
- Direct and Indirect Measurements agree
- Extraordinary accomplishment of theory and experiment
- Higgs Boson is expected in a narrow range: 115-160 GeV

The Electroweak Theory

- Effective low energy theory of weak and electromagnetic interactions
- Tested at the 1% accuracy or better from microns to attometers
- Theoretical framework allows precision calculations
- Testing consistency provides access to phenomena much heavier than scale of measurements

Open Questions

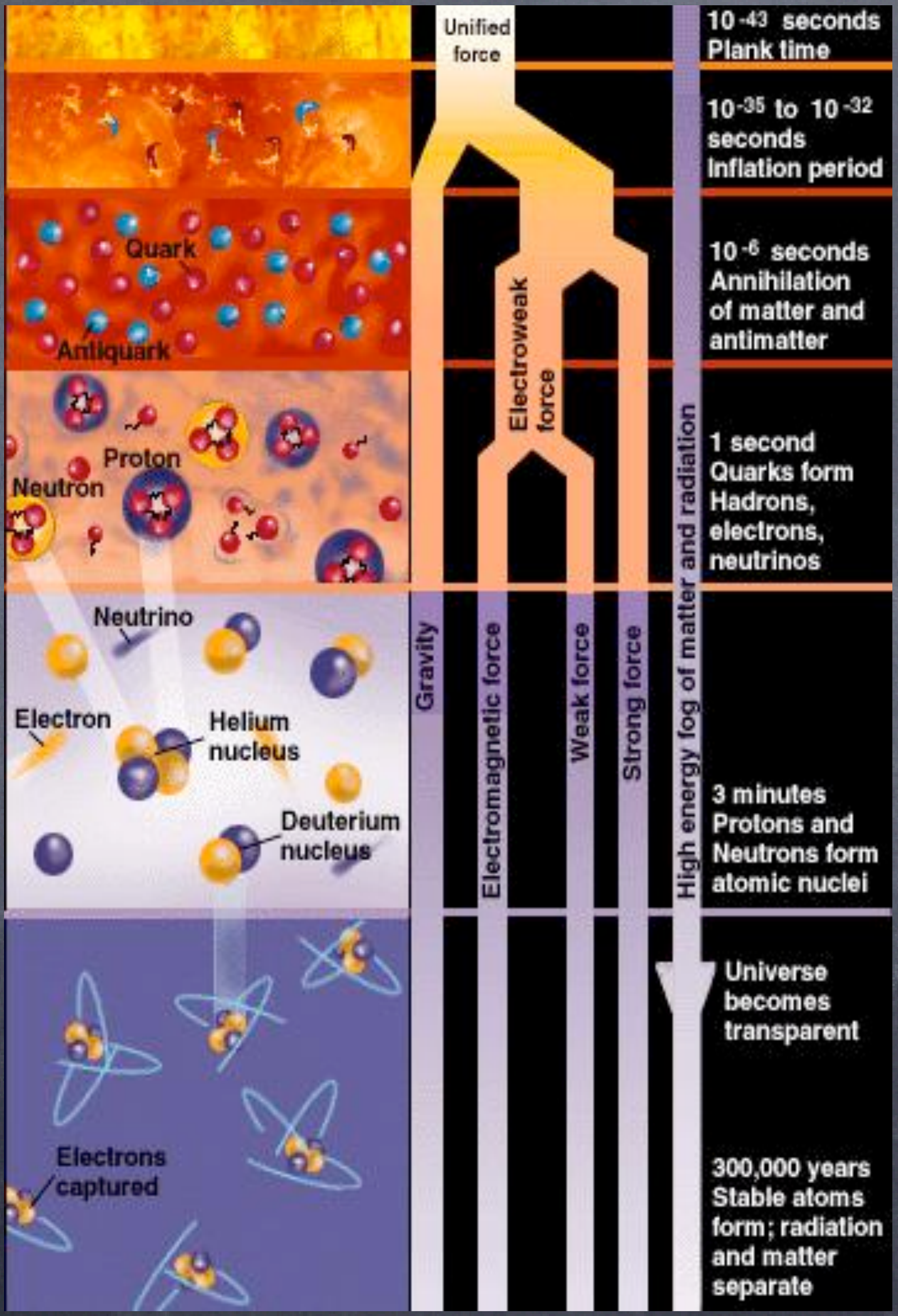
- Why is the weak boson scale 100 GeV?
- Why are there 3 generations of particles?
- How did matter come to dominate over anti-matter?
- Were there as yet unobserved new forces in the early universe?
- Is there a unifying framework to describe all forces?
- Why are neutrinos so light?
- Why is the top so heavy?
- ...

Time and Length Scales

attometers

↑

femtometers



femtometers

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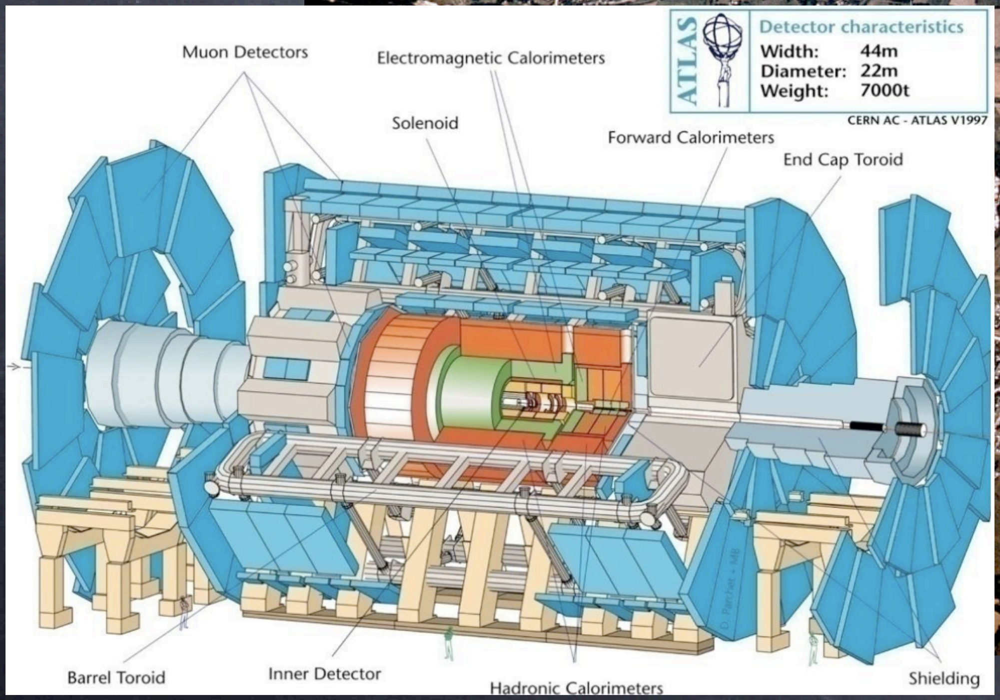
picometers

The Large Hadron Collider

Comprehensive Access to the Scale of Electroweak Symmetry-Breaking



Beyond the Electroweak Theory: 2 Approaches

Compelling arguments for "New Dynamics" at the TeV Scale

A comprehensive search for clues requires:

Large Hadron Collider *as well as* **Lower Energy: $Q^2 << M_Z^2$**

Nuclear/Atomic systems address several topics; complement the LHC:

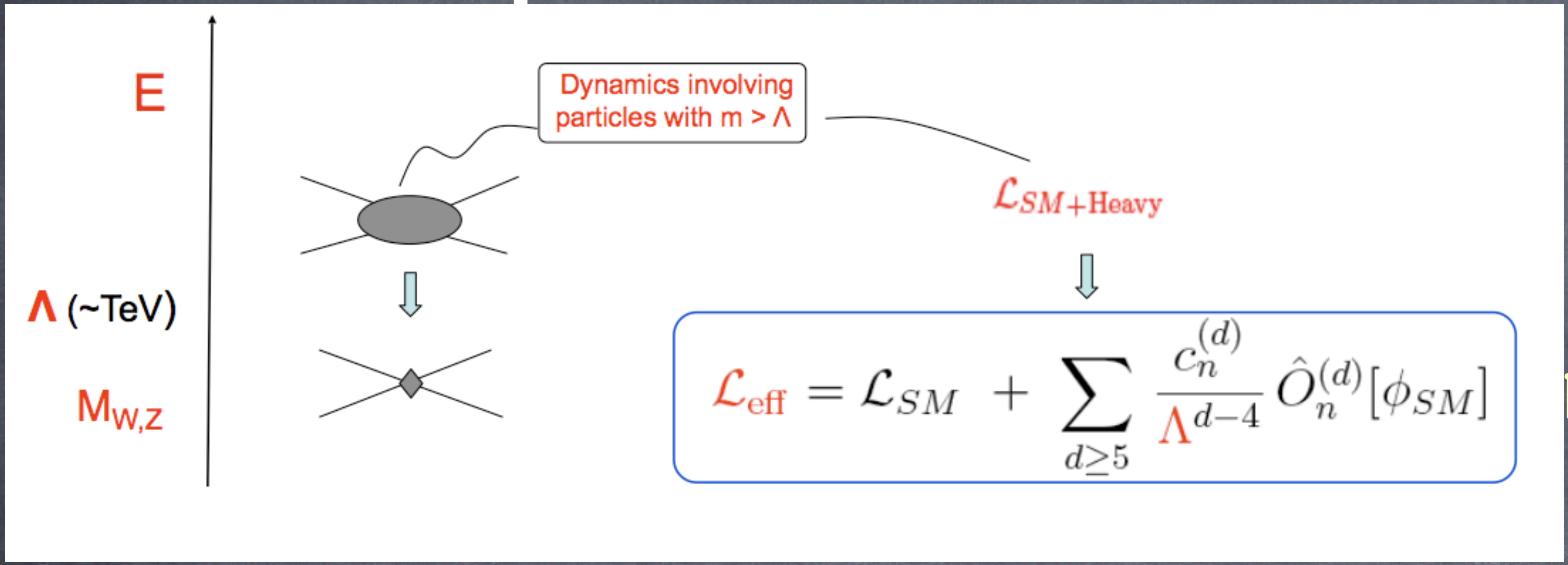
- ***Neutrino mass and mixing*** *$0\nu\beta\beta$ decay, θ_{13}, β decay, long baseline neutrino expts*
- ***Rare or Forbidden Processes EDMs, charged LFV,*** *$0\nu\beta\beta$ decay*
- ***Dark Matter Searches***
- ***Low Energy Precision Electroweak Measurements:***

Complementary signatures to augment LHC new physics signals

- ***Neutrons:*** *Lifetime, Asymmetries (LANSCE, NIST, SNS...)*
- ***Muons:*** *Lifetime, Michel parameters, g-2 (BNL, PSI, TRIUMF, FNAL, J-PARC...)*
- ***Parity-Violating Electron Scattering*** *Low energy weak neutral current couplings, precision weak mixing angle (SLAC, JLab)*

V. Cirigliano

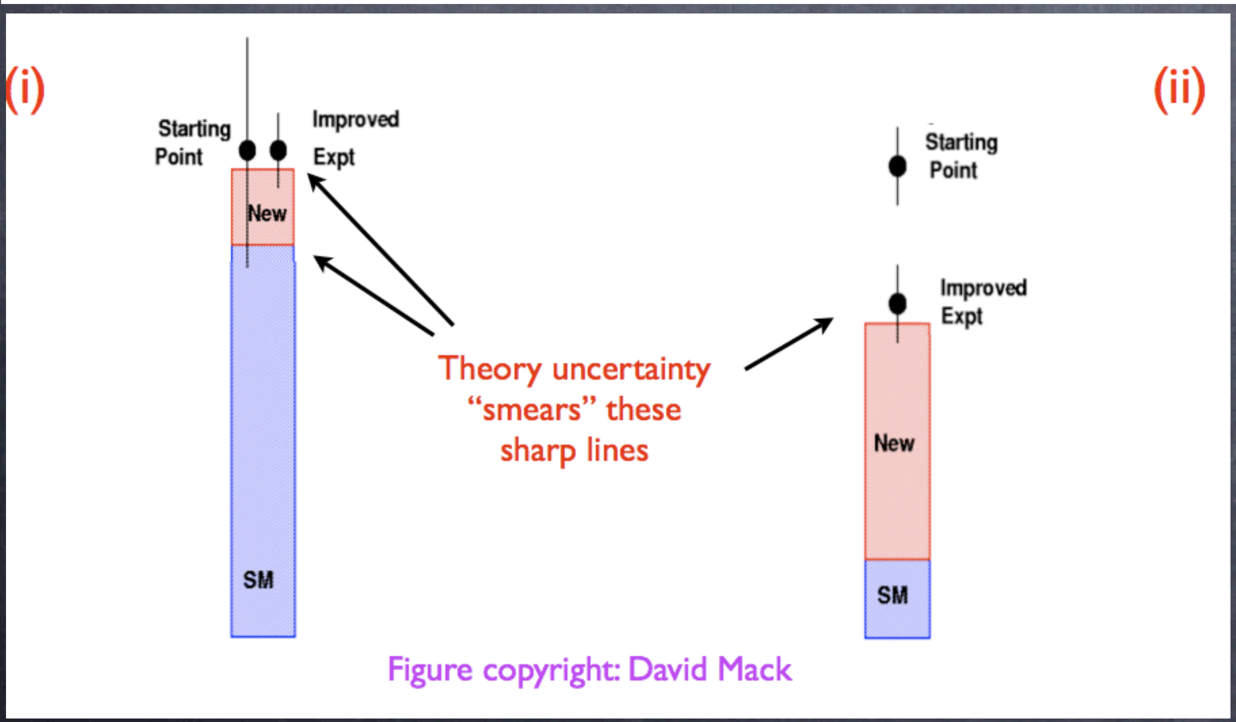
A Framework for a Comprehensive Search



Interplay:

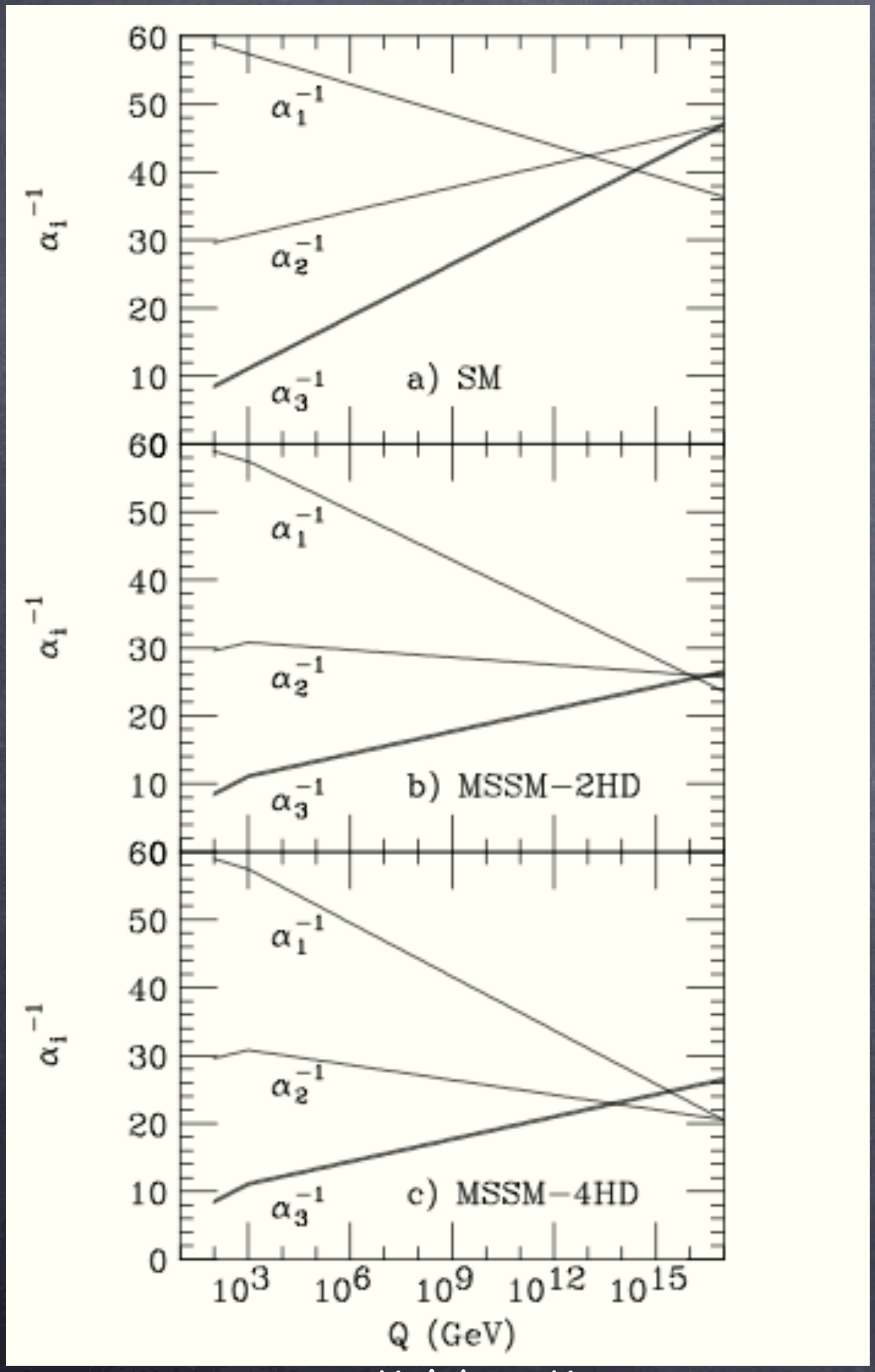
Theoretical Cleanliness

Experimental Feasibility



- SM process must be calculated at the level of radiative corrections
- Non-perturbative QCD effects play a significant role: auxiliary theory and experimental programs
- Vincenzo Cirigliano on Thursday

An Example: Supersymmetry



- Every particle has a supersymmetric sparticle partner
- sparticles stabilize the scalar sector of the theory in the presence of radiative corrections
- remarkable (but not compelling) that couplings unify at a common GUT scale
- SUSY processes calculable at the level of radiative corrections: important for precision low energy measurements

Summary

"Textbook EW Physics"

- A very successful theoretical framework exists to describe electroweak interactions over a wide range of energy scales
- There are many unanswered questions regarding the high energy behavior and its implications for the early universe
- The theoretical and experimental progress sets the stage for further research at low energies and at colliders

Rest of the Lectures

- Lecture 2: Symmetries and Conservation Laws. Particular focus on EDMs and Charged Lepton Flavor violation experiments
- Lecture 3: Precision Electroweak measurements at low energy using electron, muon, neutron and other hadron beams
- Lecture 4: Precision Electroweak Probes of Hadron Structure