



FERMILAB-CERN
HADRON COLLIDER PHYSICS
Summer School 2014

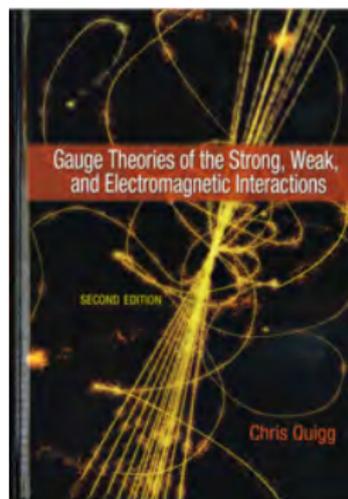
The Standard Model: Current Status & Open Questions

Chris Quigg

Fermilab

Tentative Outline

- 1 Why Hadron Colliders? What Is a Proton?
- 2 Constructing the Electroweak Theory
- 3 Validating the Electroweak Theory
- 4 The Higgs Boson and Beyond



The Standard Model: Current Status & Open Questions

Chris Quigg

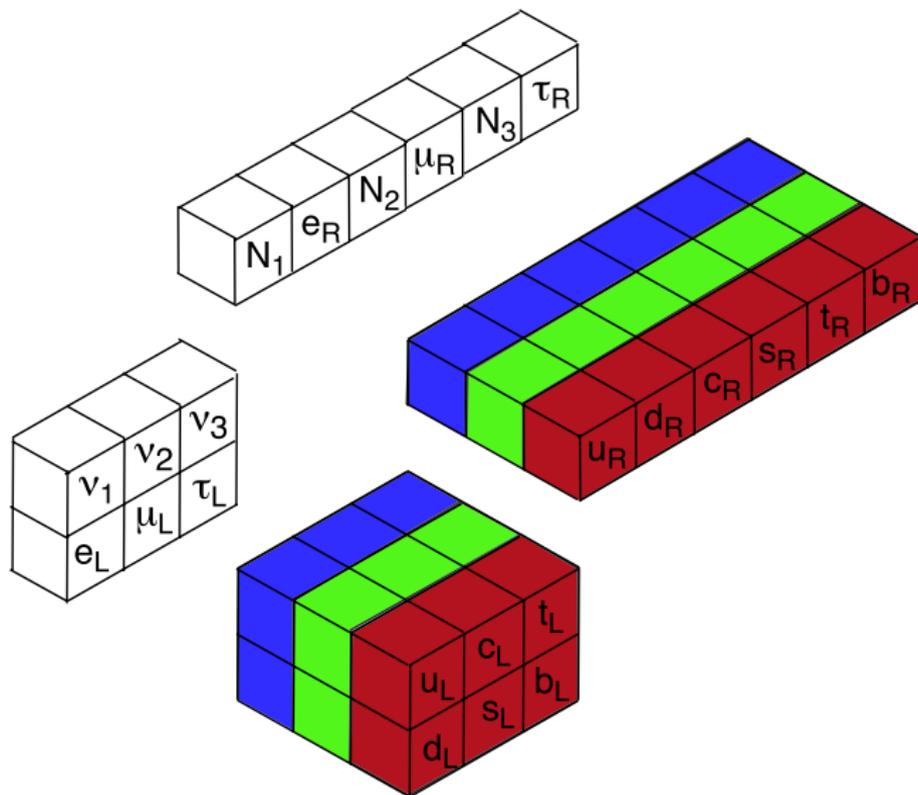
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Our Conception of Matter—the Nanoworld

If, in some cataclysm, all of scientific knowledge were to be destroyed, and only one sentence passed on to the next generation of creatures, what statement would contain the most information in the fewest words? I believe it is the atomic hypothesis that all things are made of atoms — little particles that move around in perpetual motion, attracting each other when they are a little distance apart, but repelling upon being squeezed into one another. In that one sentence, you will see, there is an enormous amount of information about the world, if just a little imagination and thinking are applied.

— R. P. Feynman, *The Feynman Lectures on Physics*

Our Conception of Matter—the Nanonanoworld



Our Conception of Matter—the Attoworld

Pointlike constituents ($r < 10^{-18}$ m)

$$\begin{pmatrix} u \\ d \end{pmatrix}_L \quad \begin{pmatrix} c \\ s \end{pmatrix}_L \quad \begin{pmatrix} t \\ b \end{pmatrix}_L$$

$$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L \quad \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}_L \quad \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}_L$$

Few fundamental forces, derived from gauge symmetries

$$SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$$

Electroweak symmetry breaking: Higgs mechanism?

Problem 1

In the spirit of Feynman's characterization of the atomic hypothesis, compose a sentence that expresses the “enormous amount of information about the world” captured in the standard model of particle physics, “if just a little imagination and thinking are applied.”

Why Hadron Colliders? \rightsquigarrow Eric Prebys Lectures

Discovery machines

W^\pm, Z^0, t, H, \dots

Precision instruments

M_W, m_t, B_s oscillation frequency, \dots

Large energy reach · High event rate

Why Hadron Colliders?

Explore a rich diversity of elementary processes
at the highest accessible energies:

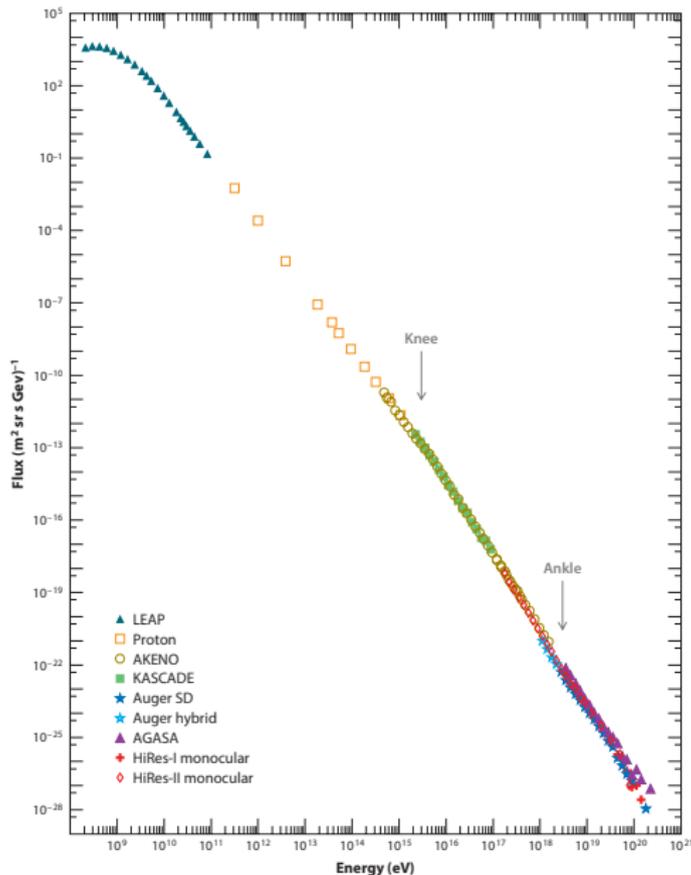
$$(q_i, \bar{q}_i, g, \gamma, W^\pm, Z, \dots) \otimes (q_j, \bar{q}_j, g, \gamma, W^\pm, Z, \dots)$$

Example: quark-quark collisions at $\sqrt{s} = 1 \text{ TeV}$

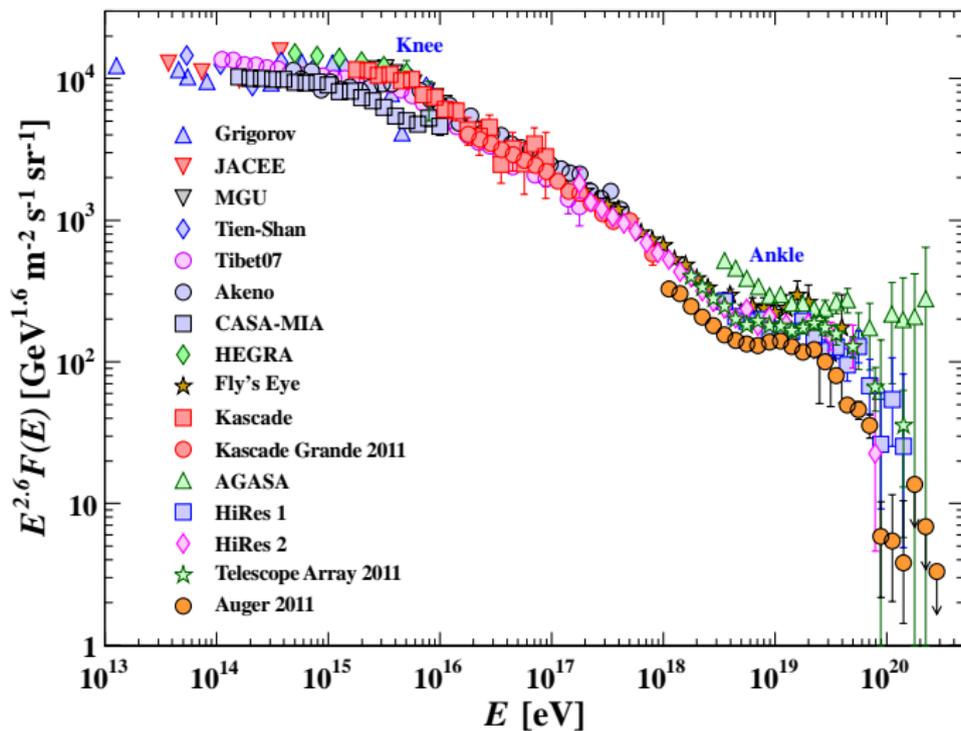
If 3 quarks share half the proton's momentum ($\langle x \rangle = \frac{1}{6}$),
require pp collisions at $\sqrt{s} = 6 \text{ TeV}$

\rightsquigarrow Fixed-target machine with beam momentum
 $p \approx 2 \times 10^4 \text{ TeV} = 2 \times 10^{16} \text{ eV}$ (*cf.* cosmic rays).

Cosmic-ray Spectrum

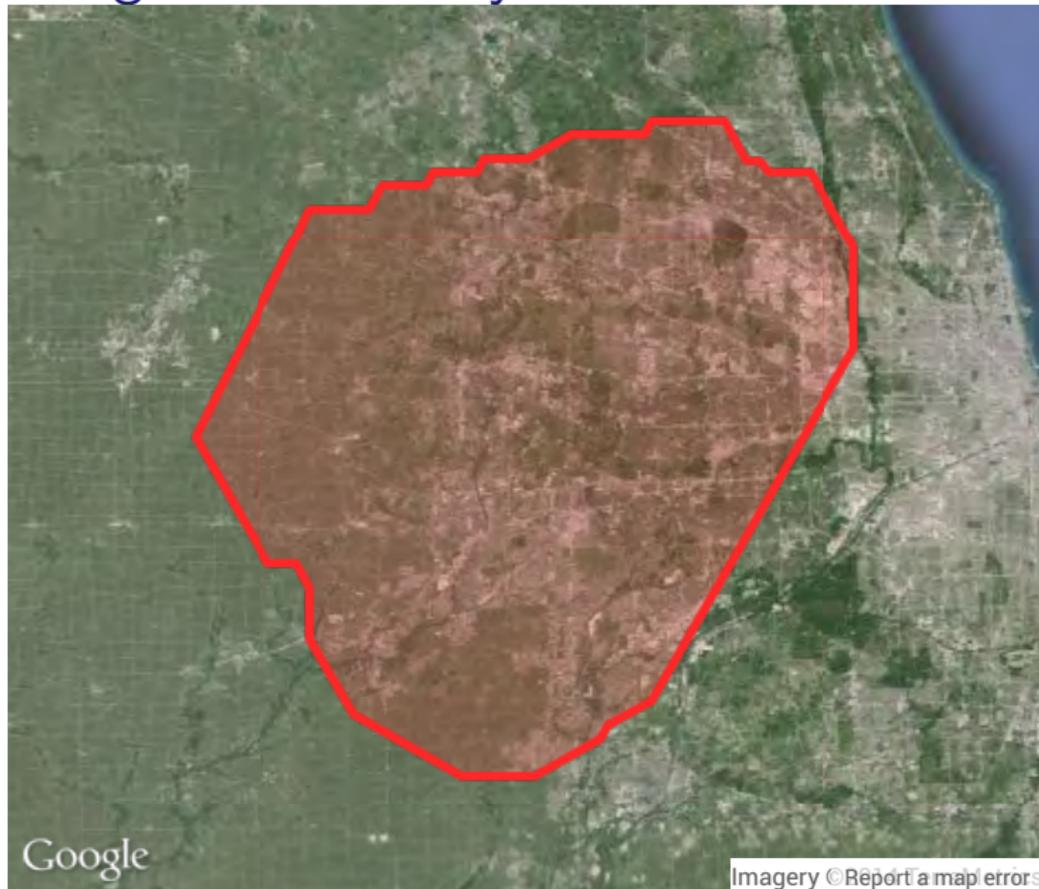


Cosmic-ray Spectrum



$$\frac{dI}{dE}(2 \times 10^{16} \text{ eV}) = (3 - 5) \times 10^{-16} \text{ m}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \text{ eV}^{-1}$$

Pierre Auger Observatory over Fermilab



Some Great Cosmic-Ray Observatories

$$E > 10^{19} \text{ eV: } 1 \text{ km}^{-2} \text{ century}^{-1}$$

Pierre Auger Observatory (Mendoza, Argentina):
~ 3000 km² array of 1600 shower detectors plus 4
atmospheric fluorescence detectors

Telescope Array (Utah, USA):
~ 750 km² array of 500 scintillation detectors plus 3
atmospheric fluorescence telescopes

Problem 2

Plot the correspondence between c.m. energy, \sqrt{s} , and fixed-target beam momentum, p_{lab} , for pp collisions over the range $10 \text{ GeV} \leq \sqrt{s} \leq 100 \text{ TeV}$. Note in particular the values of p_{lab} that correspond to $\sqrt{s} = 8, 14, 100 \text{ TeV}$.

How to achieve?

Fixed-target, $p \approx 2 \times 10^4$ TeV

Ring radius is

$$r = \frac{10}{3} \cdot \left(\frac{p}{1 \text{ TeV}} \right) / \left(\frac{B}{1 \text{ tesla}} \right) \text{ km.}$$

Conventional copper magnets ($B = 2$ teslas) \rightsquigarrow

$$r \approx \frac{1}{3} \times 10^5 \text{ km.}$$

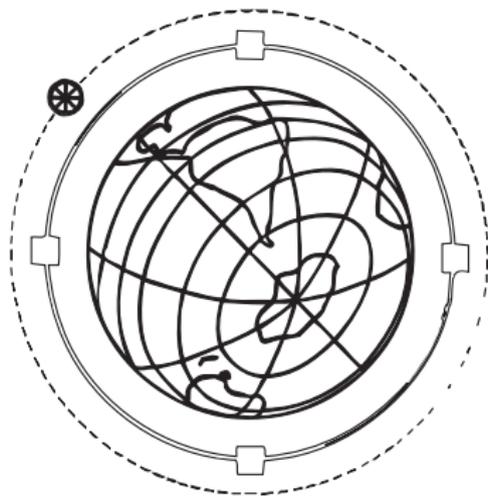
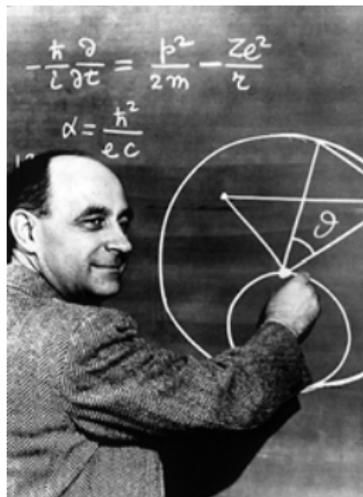
$\approx \frac{1}{12}$ size of Moon's orbit

10-tesla field reduces the accelerator to mere Earth size ($R_{\oplus} = 6.4 \times 10^3$ km).

Fermi's Dream Machine (1954)

5000-TeV protons to reach $\sqrt{s} \approx 3 \text{ TeV}$

2-tesla magnets at radius 8000 km



Projected operation 1994, cost \$170 billion
(inflation assumptions not preserved)

Key Advances in Accelerator Technology

- Alternating-gradient (“strong”) focusing, invented by Christofilos, Courant, Livingston, and Snyder.

Before and After . . .

Synchrotron	Beam Tube	Magnet Size
Bevatron (6.2 GeV)	1 ft × 4 ft	9½ ft × 20½ ft
FNAL Main Ring (400 GeV)	~ 2 in × 4 in	14 in × 25 in
LHC (→ 7 TeV)	56 mm	(SC)

- The idea of colliding beams.
- Superconducting accelerator magnets based on “type-II” superconductors, including NbTi and Nb₃Sn.

Key Advances . . .

- Active optics to achieve real-time corrections of the orbits makes possible reliable, highly tuned accelerators using small-aperture magnets. Also “cooling,” or phase-space compaction, of stored (anti)protons.
- The evolution of vacuum technology. Beams stored for approximately 20 hours travel $\sim 2 \times 10^{10}$ km, about 150 times the Earth–Sun distance, without encountering a stray air molecule.
- The development of large-scale cryogenic technology, to maintain many km of magnets at a few kelvins.

Hadron Colliders through the Ages

- CERN Intersecting Storage Rings: pp collider at $\sqrt{s} \rightarrow 63$ GeV. Two rings of conventional magnets.
- $S\bar{p}pS$ Collider at CERN: $\bar{p}p$ collisions at $\sqrt{s} = 630(\rightarrow 900)$ GeV in conventional-magnet SPS.
- Fermilab Tevatron Collider: $\bar{p}p$ collisions at $\sqrt{s} \approx 2$ TeV with 4-T SC magnets in a 2π -km tunnel.
- Brookhaven Relativistic Heavy-Ion Collider: 3.45-T dipoles in 3.8-km tunnel. Polarized pp , $\sqrt{s} \rightarrow 0.5$ TeV
- Large Hadron Collider at CERN: 14-TeV pp collider in the 27-km LEP tunnel, using 9-T magnets at 1.8 K.
- An Even Bigger Collider?

High-energy collider parameters, 2012 *Review of Particle Properties* §28

Tevatron: $\bar{p}p$ at $\sqrt{s} = 1.96$ TeV



Large Hadron Collider at CERN



Competing technologies?

- None for quark–gluon interactions
- None for highest energies (derate composite protons)
- **Lepton–lepton collisions:** LEP ($\sqrt{s} \approx 0.2$ TeV) was the last great electron synchrotron?

Synchrotron radiation \Rightarrow linear colliders for higher \sqrt{s}

\rightsquigarrow International Linear Collider

- ▶ Challenge to reach 1 TeV; \mathcal{L} a *great challenge*
- ▶ Can we surpass 1 TeV? CLIC, ...

Competing technologies?

- **Lepton-hadron collisions:** HERA ($e^\pm p$) as example; energy intermediate between e^+e^- , pp

$e^\pm(u, d)$ leptoquark channel, proton structure, γp

High \mathcal{L} a challenge: beam profiles don't match

(Far) future: $\mu^\pm p$ collider?

- **Heavy-ion collisions:** RHIC the prototype; LHC (relatively) modest energy per nucleon; quark-gluon plasma; new phases of matter

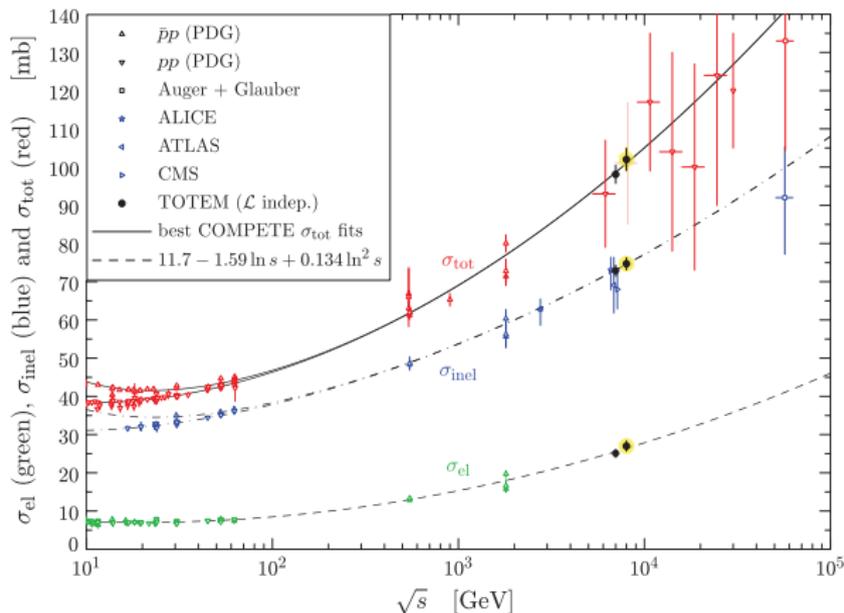
Unorthodox projectiles?

- $\gamma\gamma$ Collider: Backscattered laser beams; enhancement of linear collider capabilities
- $\mu^+\mu^-$ collider: Advantage of elementary particle, disadvantage of muon decay ($2.2\mu\text{s}$).

Small ring to reach very high effective energies?

Muon storage ring (neutrino factory) would turn bug into feature!

$p^\pm p$ Interaction Rates



$$\sigma_{\text{tot}} \quad (101.7 \pm 2.9) \text{ mb}$$

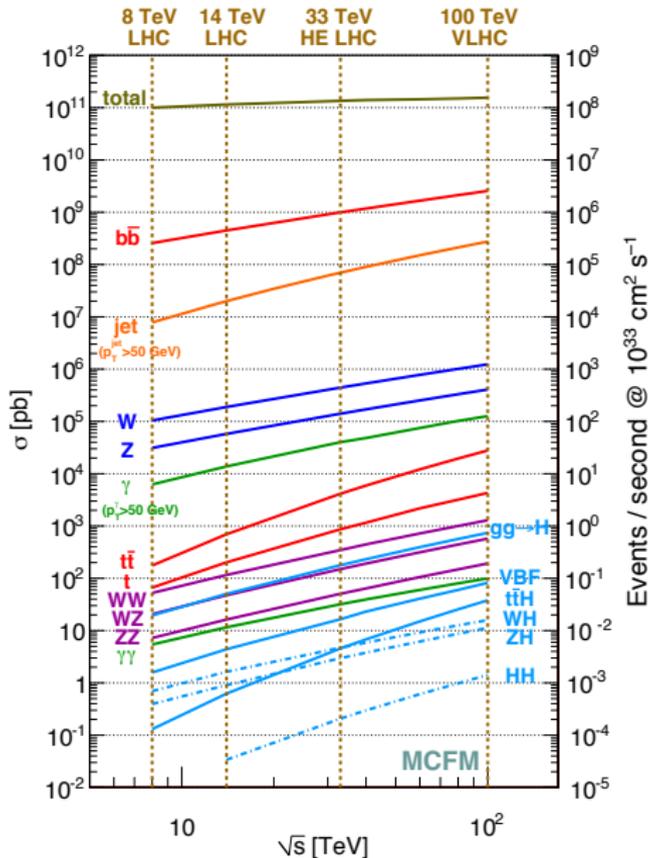
$$\sigma_{\text{inel}} \quad (74.7 \pm 1.7) \text{ mb}$$

$$\sigma_{\text{el}} \quad (27.1 \pm 1.4) \text{ mb}$$

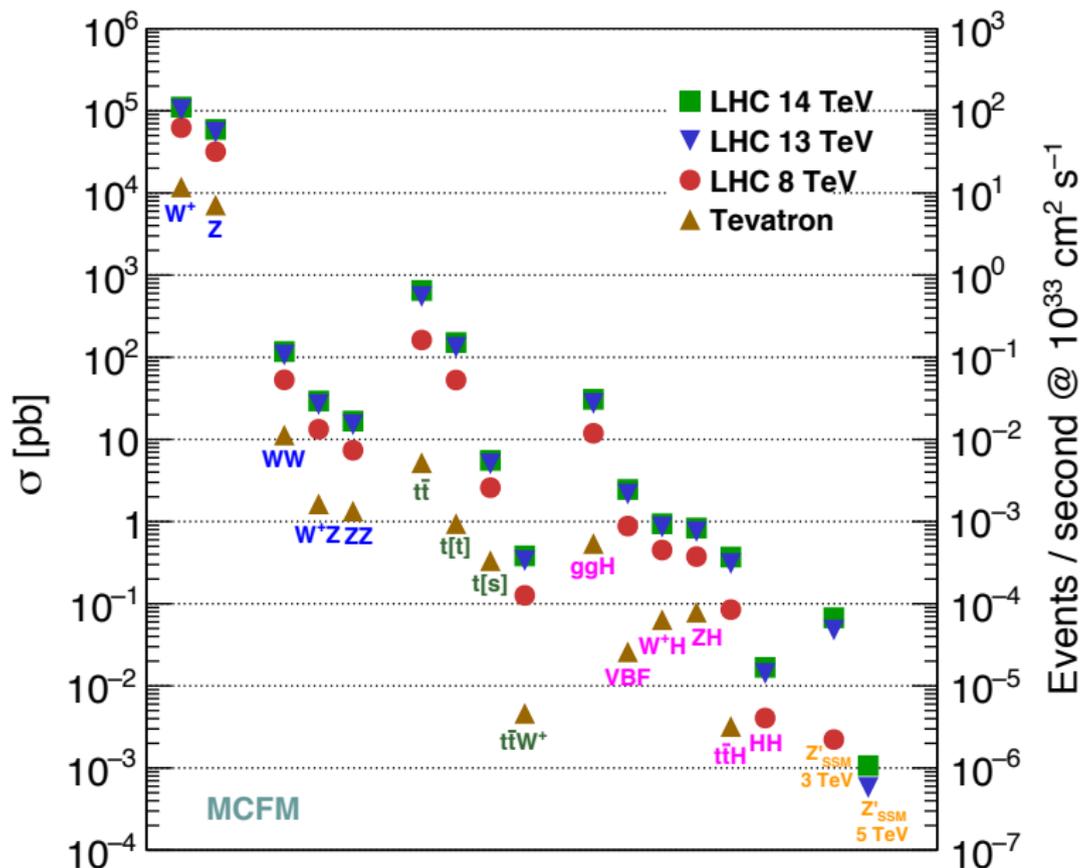
$$\sigma_{\text{tot}} \approx 10^{11} \text{ pb}$$

TOTEM

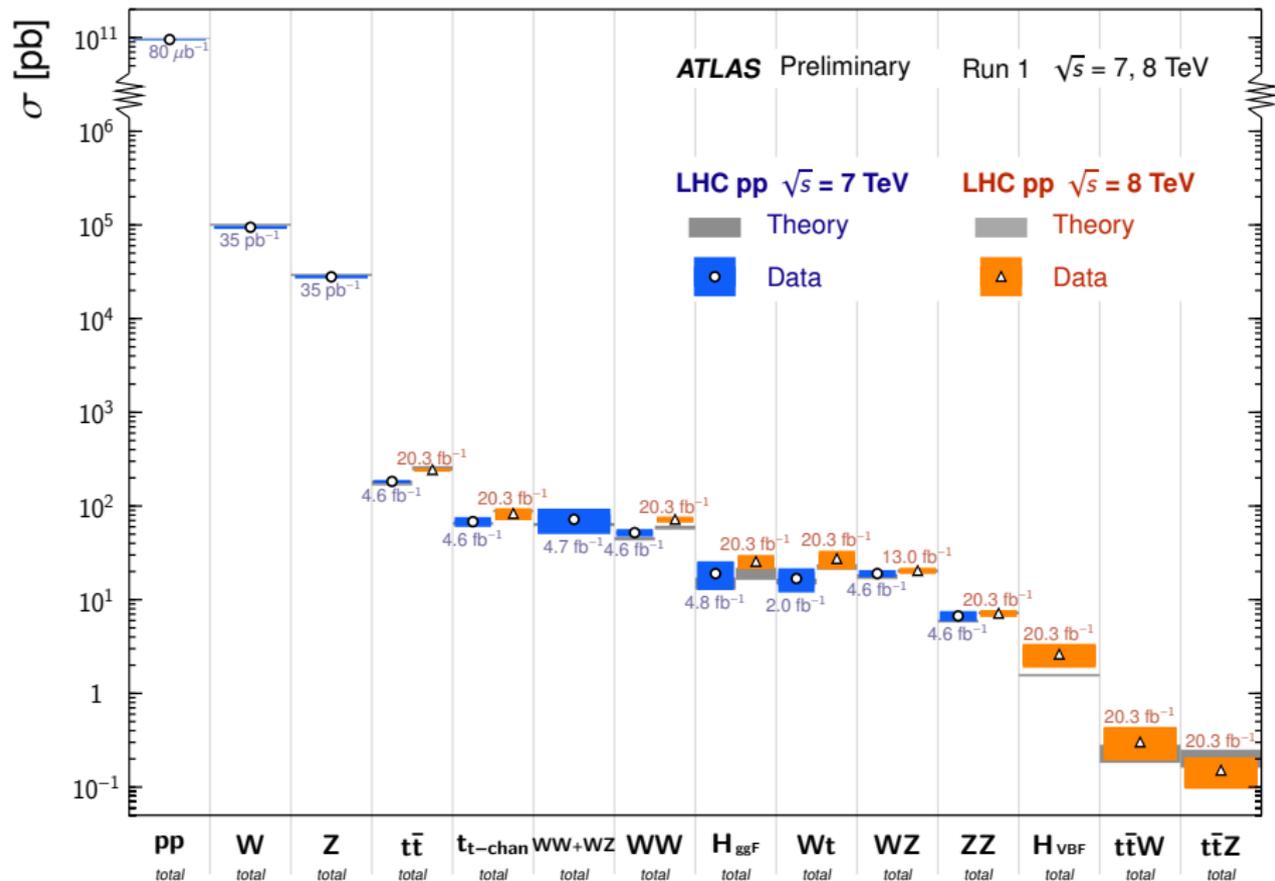
Collider Cross Sections



Standard-model Cross Sections



Standard-model Cross Sections



Luminosity

Number N of events of interest

$$N = \sigma \int dt \mathcal{L}(t)$$

$\mathcal{L}(t)$: instantaneous luminosity [in $\text{cm}^{-2} \text{s}^{-1}$]

Bunches of n_1 and n_2 particles collide head-on at frequency f :

$$\mathcal{L}(t) = f \frac{n_1 n_2}{4\pi\sigma_x\sigma_y}$$

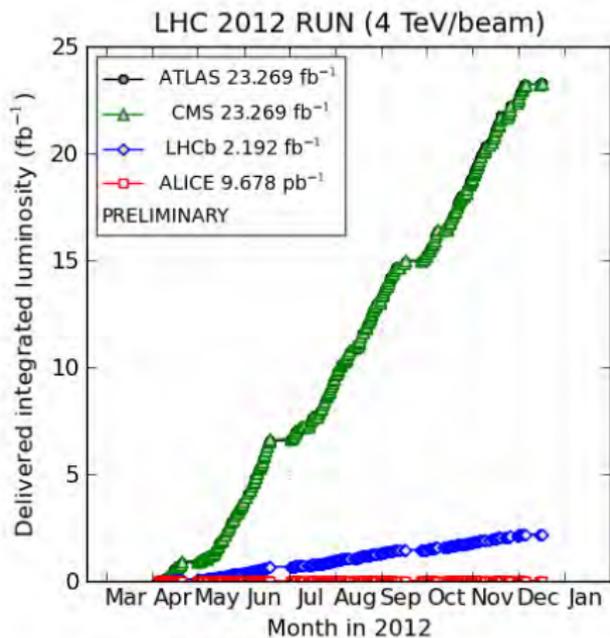
$\sigma_{x,y}$: Gaussian rms \perp beam sizes

Edwards & Syphers, 2012 *Review of Particle Physics*, §27

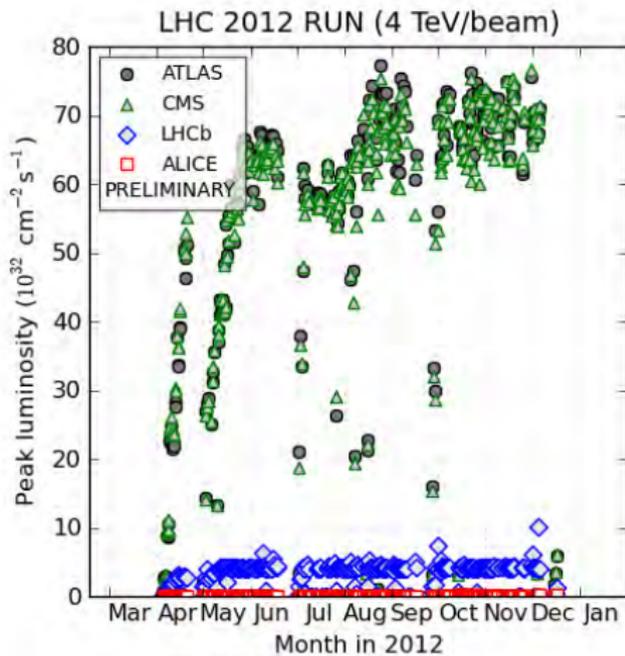
LHC lumi calculator

Zimmerman, "LHC: The Machine," SSI 2012

LHC Luminosity Growth



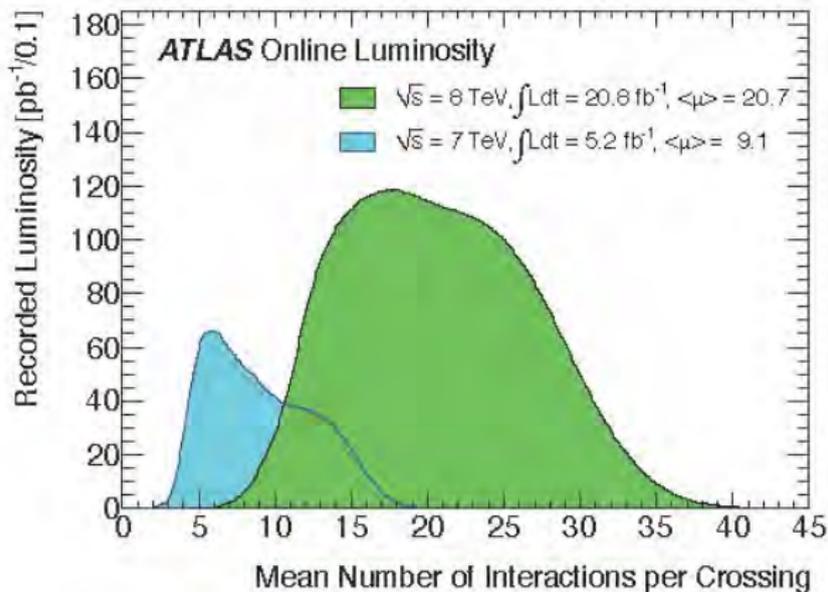
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(generated 2013-01-29 18:28 including fill 3453)

1400 \otimes 1400 bunches cross every 50 ns (25 ns in future?)

High Luminosity and Pileup



Problem 3

(a) Estimate the integrated luminosity required to make a convincing observation of each of the standard-model final states shown in the ATLAS plot [above](#). Take into account the gauge-boson branching fractions given in the *Review of Particle Physics*.

(b) Taking a nominal year of operation as 10^7 s, translate your results into the required average luminosity.

$$\text{Hard scattering } \sigma \propto 1/\hat{s} \rightsquigarrow \mathcal{L} \propto \hat{s}$$

What Is a Proton?

(For hard scattering) a broad-band, unseparated beam of quarks, antiquarks, gluons, & perhaps other constituents, characterized by parton densities

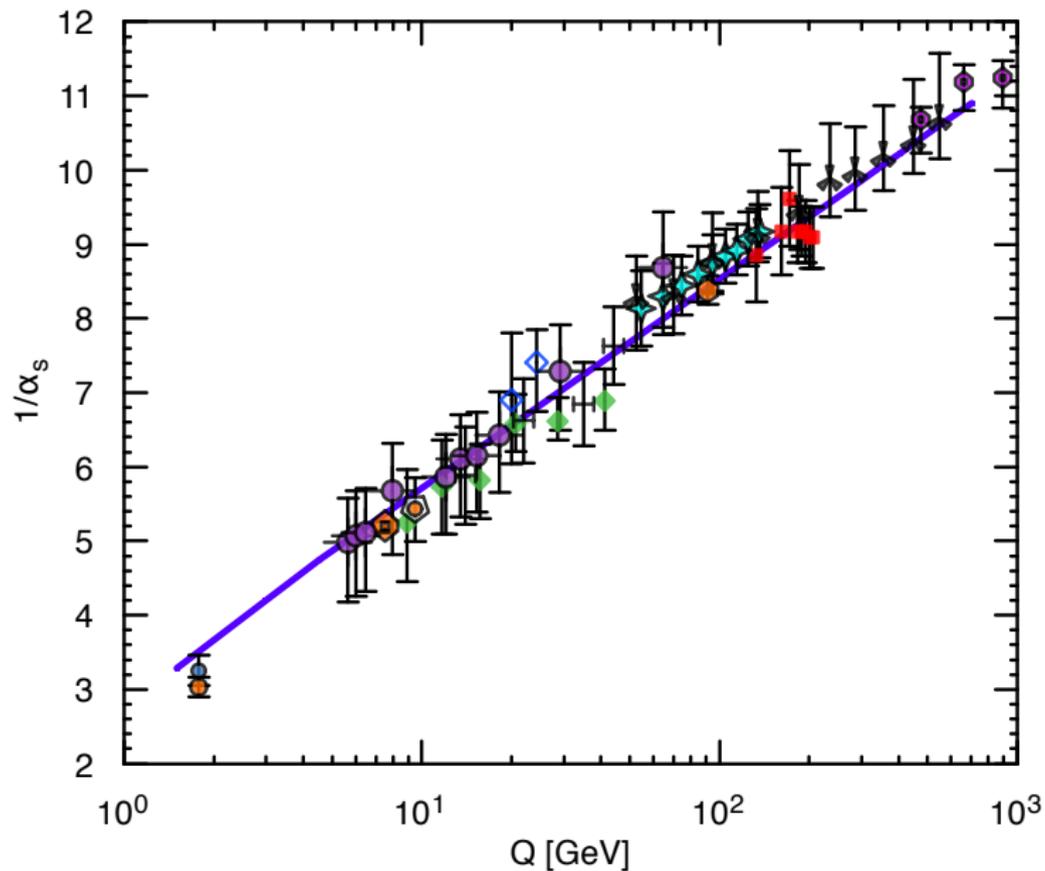
$$f_i^{(a)}(x_a, Q^2),$$

... number density of species i with momentum fraction x_a of hadron a seen by probe with resolving power Q^2 .

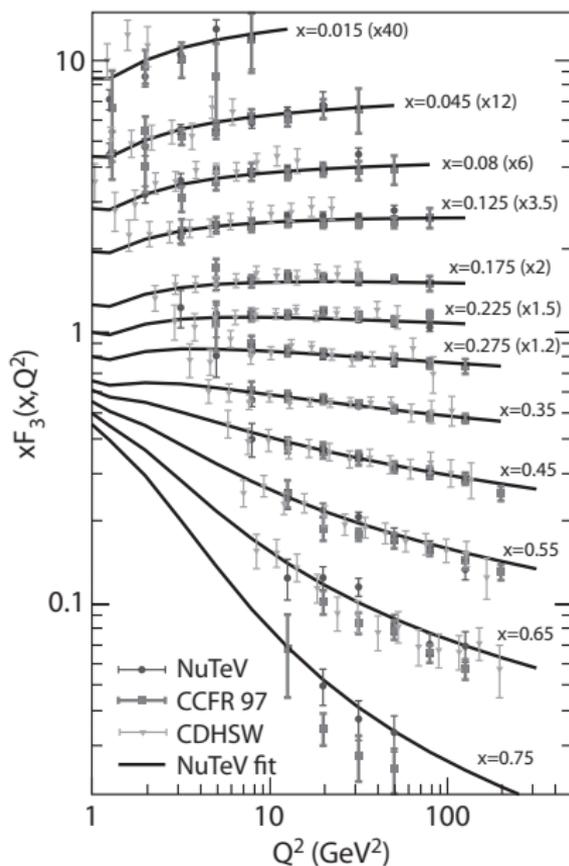
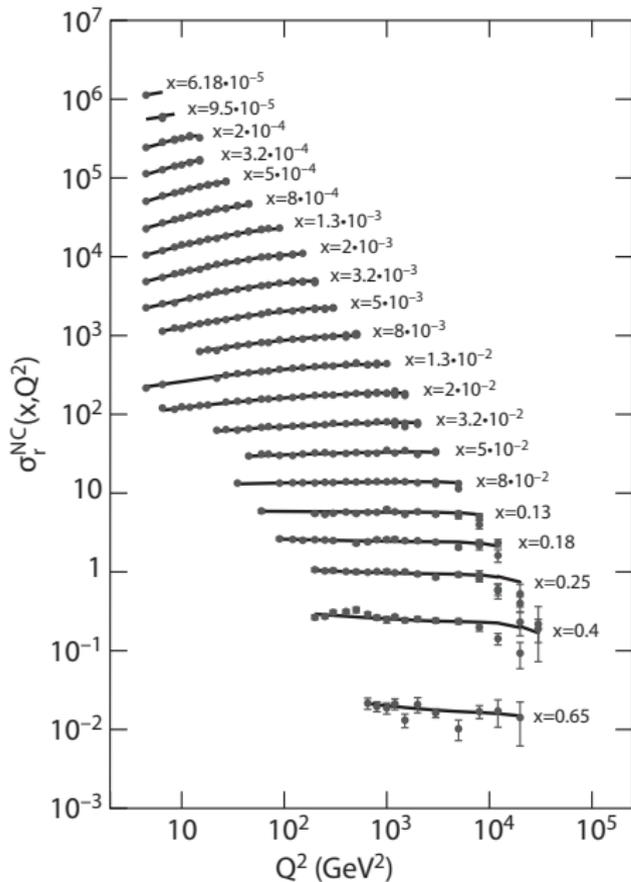
Q^2 evolution given by QCD perturbation theory

$$f_i^{(a)}(x_a, Q_0^2): \text{ nonperturbative}$$

Evolution of the Strong Coupling Constant

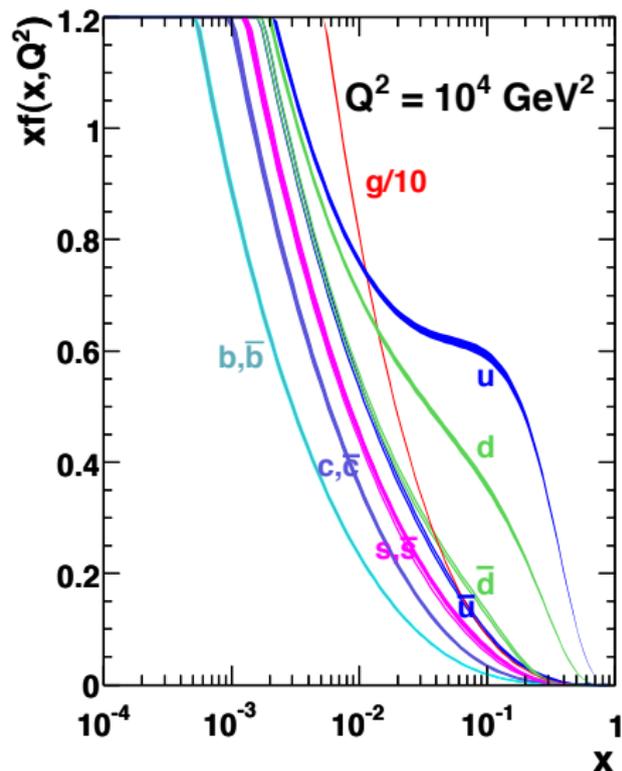
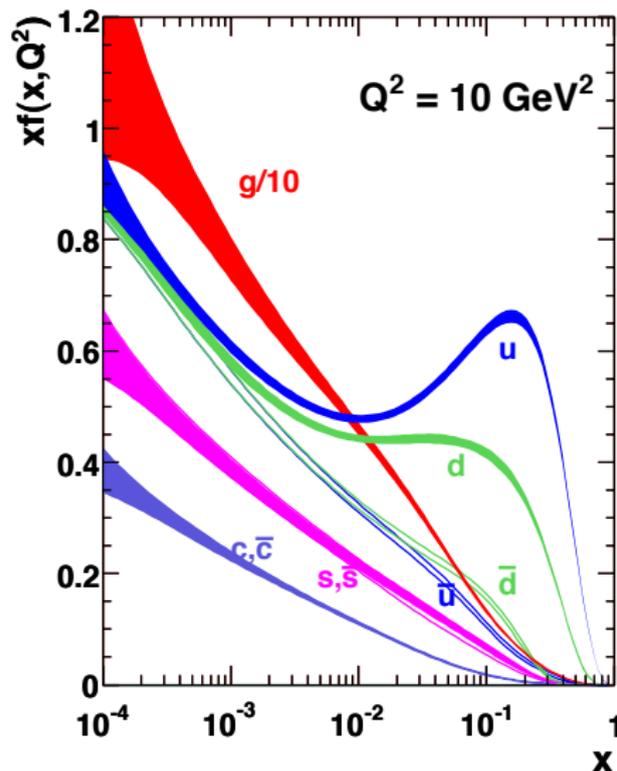


Deeply Inelastic Scattering $\rightsquigarrow f_i^{(a)}(x_a, Q_0^2)$



What Is a Proton?

MSTW 2008 NLO PDFs (68% C.L.)



Parton Distribution Functions Literature

The state of the art is reviewed in A. De Roeck & R. S. Thorne, *Prog. Part. Nucl. Phys.* **66**, 727 (2011).

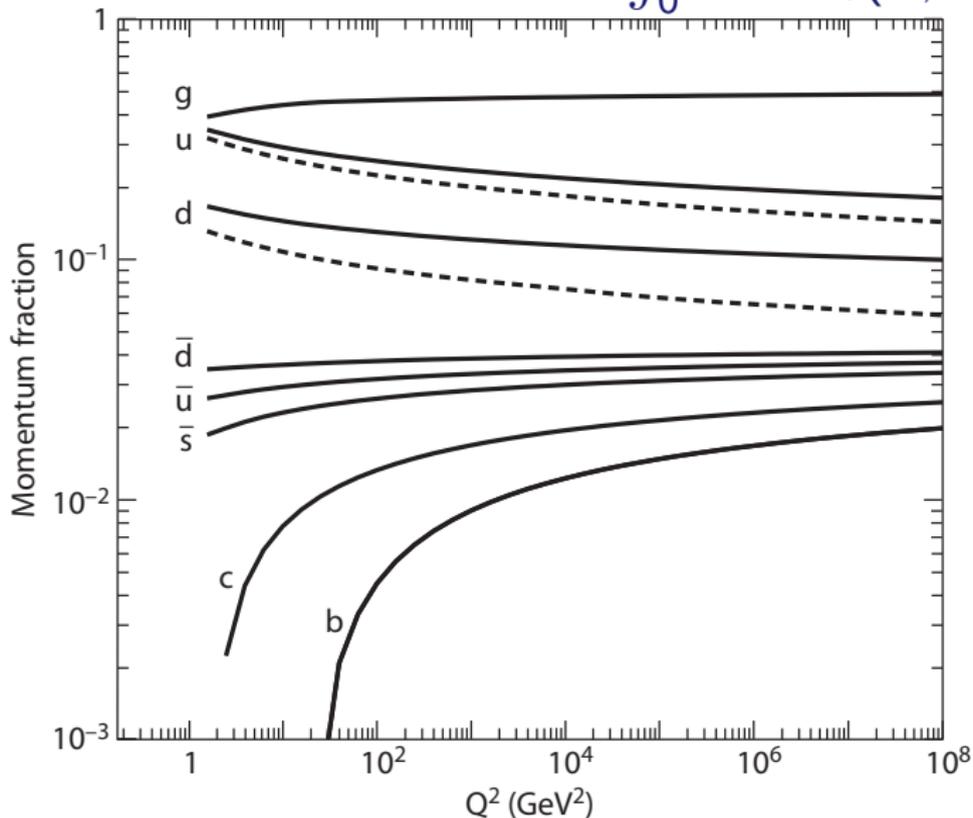
Recommendations and assessments of uncertainties are given by the PDF4LHC Working Group.

Convenient access to many sets of parton distributions is available through the Durham HEPData Project Online.

A common interface to many modern sets of PDFs is M. R. Whalley & A. Buckley, “LHAPDF: the Les Houches Accord Parton Distribution Function Interface.”

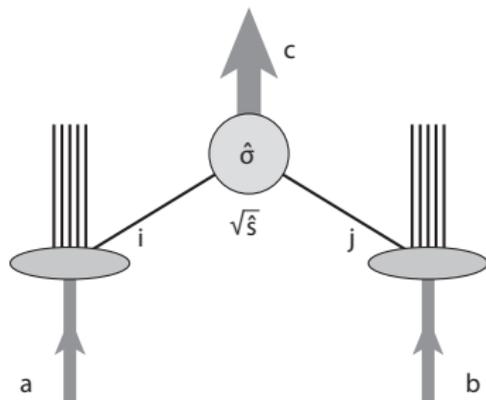
J. Huston, “PDFs for the LHC” (12 August 2014)

Flavor Content of the Proton: $\int_0^1 dx x f_i(x, Q^2)$



Asymptotic limit ($Q^2 \rightarrow \infty$): $g : \frac{8}{17}$; $q_s : \frac{3}{68}$; $q_v : 0$

Hard-scattering cross sections



$$d\sigma(a + b \rightarrow c + X) = \sum_{ij} \int dx_a dx_b \delta(\tau - x_a x_b) \cdot \\ f_i^{(a)}(x_a, Q^2) f_j^{(b)}(x_b, Q^2) d\hat{\sigma}(i + j \rightarrow c + X),$$

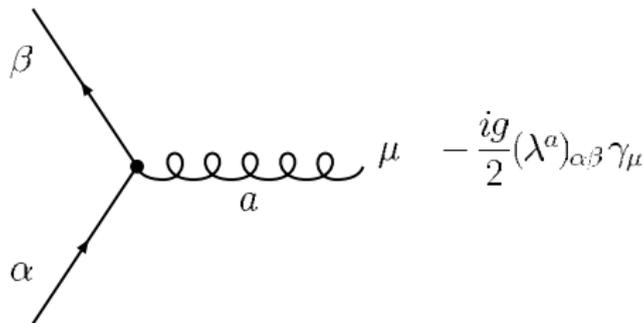
$d\hat{\sigma}$: elementary cross section at energy $\sqrt{\hat{s}} = \sqrt{x_a x_b s}$
($\tau = \hat{s}/s$)

Example Leading-Order Calculation

Compute the differential cross section $d\sigma/dt$ for the elementary reaction $ud \rightarrow ud$, neglecting quark masses. Show that

$$d\sigma(ud \rightarrow ud)/d\hat{t} = \frac{4\pi\alpha_s^2}{9\hat{s}^2} \cdot \frac{\hat{s}^2 + \hat{u}^2}{\hat{t}^2},$$

where \hat{s} , \hat{t} , \hat{u} are the usual Mandelstam invariants for the parton-parton collision.



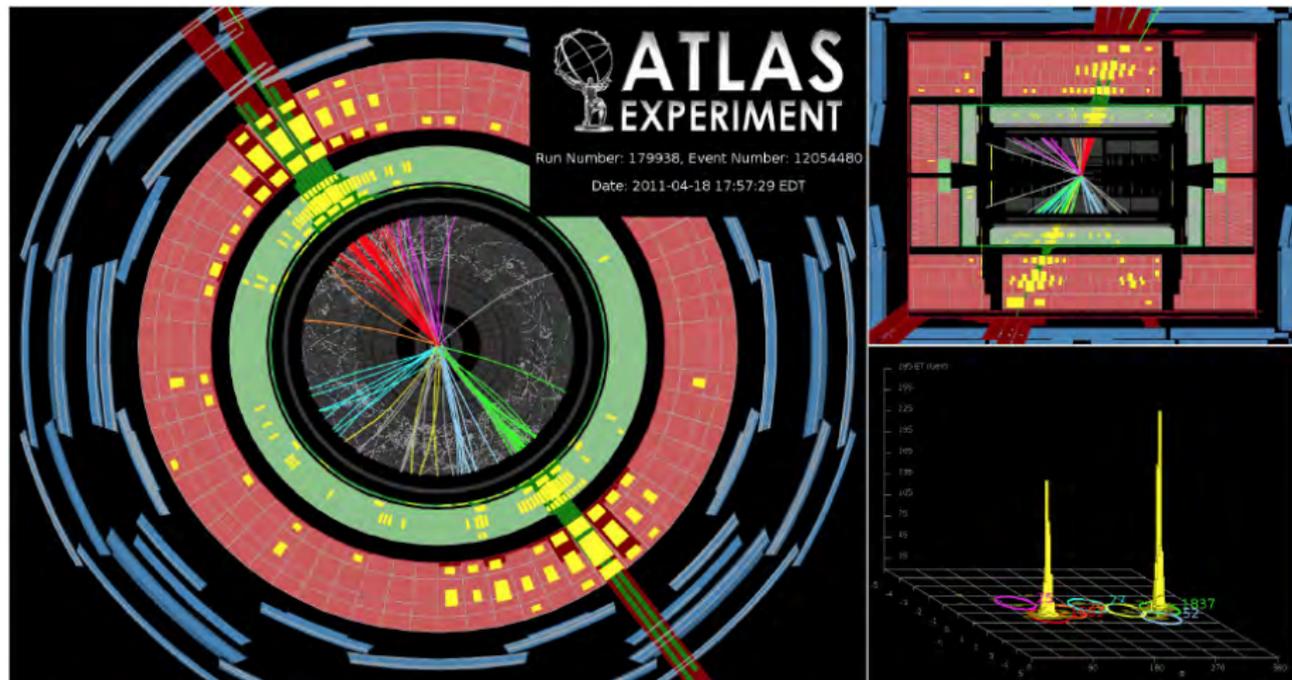
Problem 4

(a) Express the $ud \rightarrow ud$ cross section in terms of c.m. angular variables, and note that the angular distribution is reminiscent of that for Rutherford scattering, $d\sigma/d\Omega^* \propto 1/\sin^4(\theta^*/2)$.

(b) In the search for new interactions, the angular distribution for quark-quark scattering, inferred from dijet production in $p^\pm p$ collisions, is a sensitive diagnostic. Show that when re-expressed in terms of the variable $\chi = (1 + \cos \theta^*)/(1 - \cos \theta^*)$, the angular distribution for ud scattering is $d\sigma/d\chi \propto \text{constant}$.

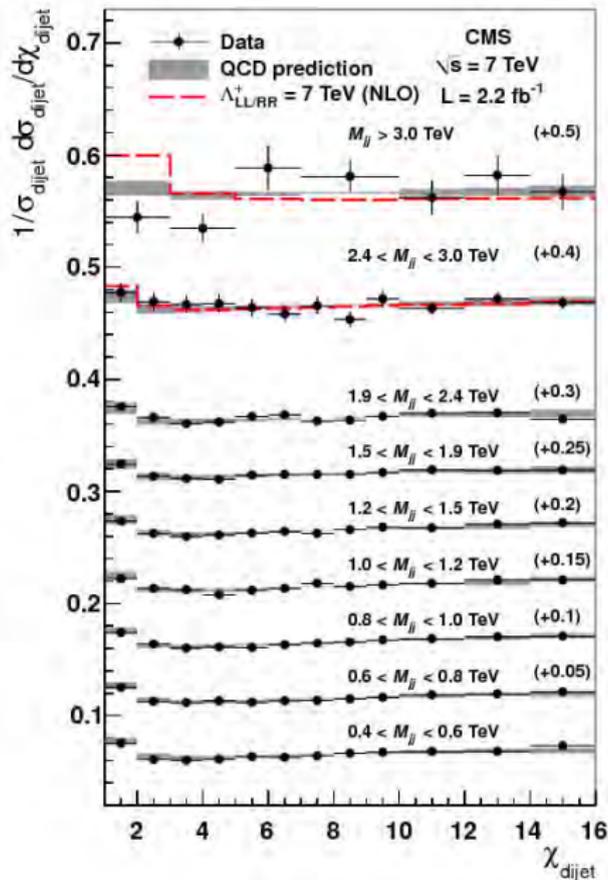
(c) The rapidity variable, $y = \frac{1}{2} \ln[(E + p_z)/(E - p_z)]$, is useful in the study of high-energy collisions because it shifts simply under Lorentz boosts. Show that in the extreme relativistic limit, measuring the jet rapidities in the reaction $p^\pm p \rightarrow \text{jet}_1 + \text{jet}_2$ leads directly to a determination of the variable χ for parton-parton scattering as $\chi = \exp(y_1 - y_2)$. For early LHC studies, see G. Aad *et al.* [ATLAS Collaboration], *Phys. Lett. B* **694**, 327 (2011); V. Khachatryan *et al.* [CMS Collaboration], *Phys. Rev. Lett.* **106**, 201804 (2011).

Probing Elementarity



E_{\perp} : 1.8 TeV + 1.8 TeV · Dijet mass: 4 TeV

Probing Elementarity



Physics Potential versus Energy

arXiv:0908.3660v2 [hep-ph] 8 Sep 2009

LHC Physics Potential *vs.* Energy

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Parton luminosities are convenient for estimating how the physics potential of Large Hadron Collider experiments depends on the energy of the proton beams. I present parton luminosities, ratios of parton luminosities, and contours of fixed parton luminosity for gg , $u\bar{d}$, and $q\bar{q}$ interactions over the energy range relevant to the Large Hadron Collider, along with example analyses for specific processes.

arXiv:1101.3201v2 [hep-ph] 1 Feb 2011

LHC Physics Potential *vs.* Energy: Considerations for the 2011 Run

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Parton luminosities are convenient for estimating how the physics potential of Large Hadron Collider experiments depends on the energy of the proton beams. I quantify the advantage of increasing the beam energy from 3.5 TeV to 4 TeV. I present parton luminosities, ratios of parton luminosities, and contours of fixed parton luminosity for gg , $u\bar{d}$, $q\bar{q}$, and $q\bar{q}$ interactions over the energy range relevant to the Large Hadron Collider, along with example analyses for specific processes. This note extends the analysis presented in Ref. [1]. Full-size figures are available as pdf files at lutece.fnal.gov/PartonLum11/.

EHLQ, *Rev. Mod. Phys.* **56**, 579 (1984)

Ellis, Stirling, Webber, *QCD & Collider Physics*

MRSW08NLO examples + RKE Lecture 3, SUSSP 2009

Full-page figures: lutece.fnal.gov/PartonLum11

High-energy p : broadband unseparated beam of q, \bar{q}, g

Parton Luminosities + Prior Knowledge = Answers

Taking into account $1/\hat{s}$ behavior of hard scattering,

$$\frac{\tau}{\hat{s}} \frac{d\mathcal{L}}{d\tau} \equiv \frac{\tau/\hat{s}}{1 + \delta_{ij}} \int_{\tau}^1 \frac{dx}{x} [f_i^{(a)}(x) f_j^{(b)}(\tau/x) + f_j^{(a)}(x) f_i^{(b)}(\tau/x)]$$

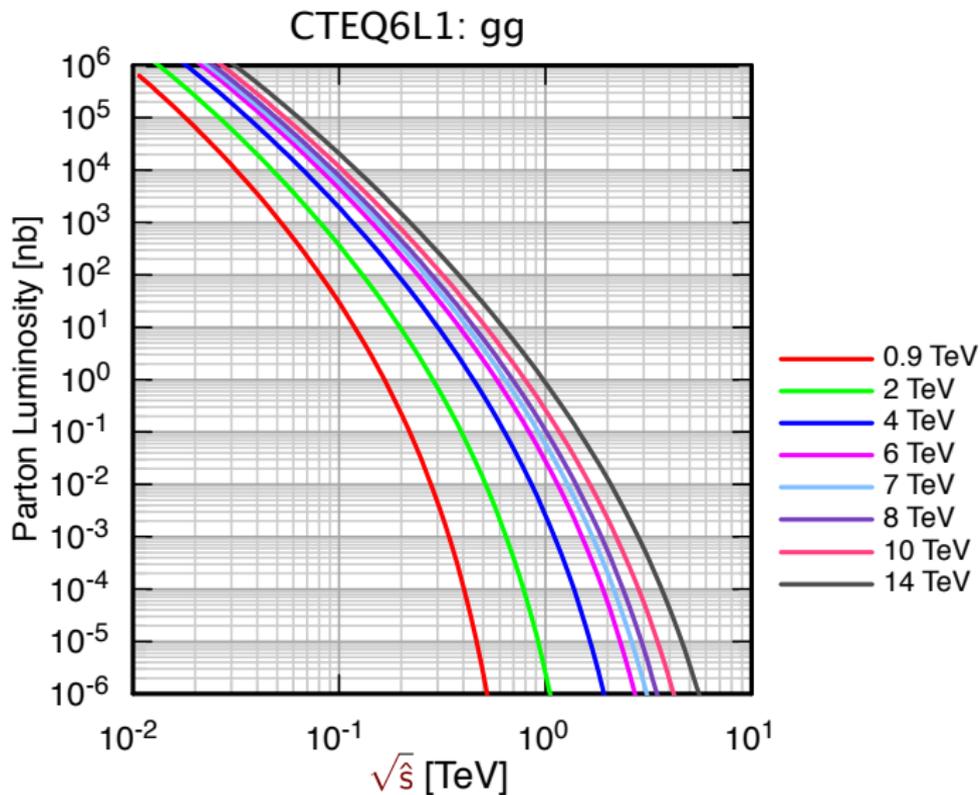
is a convenient measure of parton ij luminosity.

$$f_i^{(a)}(x): \text{ pdf; } \quad \tau = \hat{s}/s$$

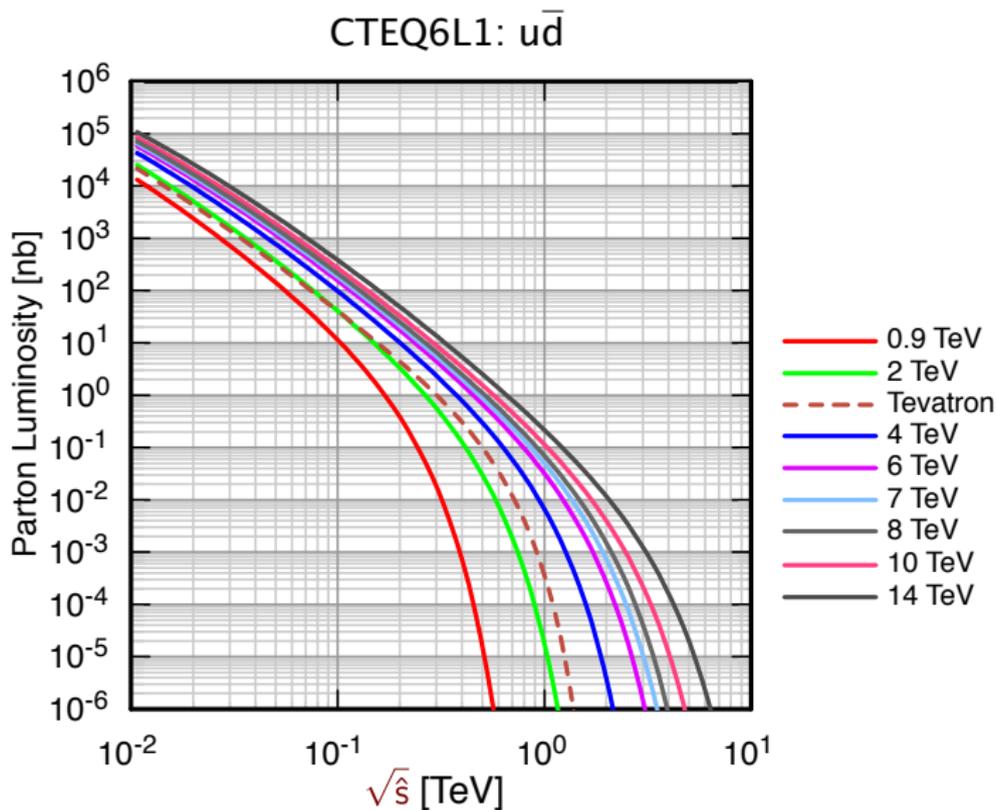
$$\sigma(s) = \sum_{\{ij\}} \int_{\tau_0}^1 \frac{d\tau}{\tau} \cdot \frac{\tau}{\hat{s}} \frac{d\mathcal{L}_{ij}}{d\tau} \cdot [\hat{s} \hat{\sigma}_{ij}(\hat{s})]$$

EHLQ §2; QCD & Collider Physics, §7.3

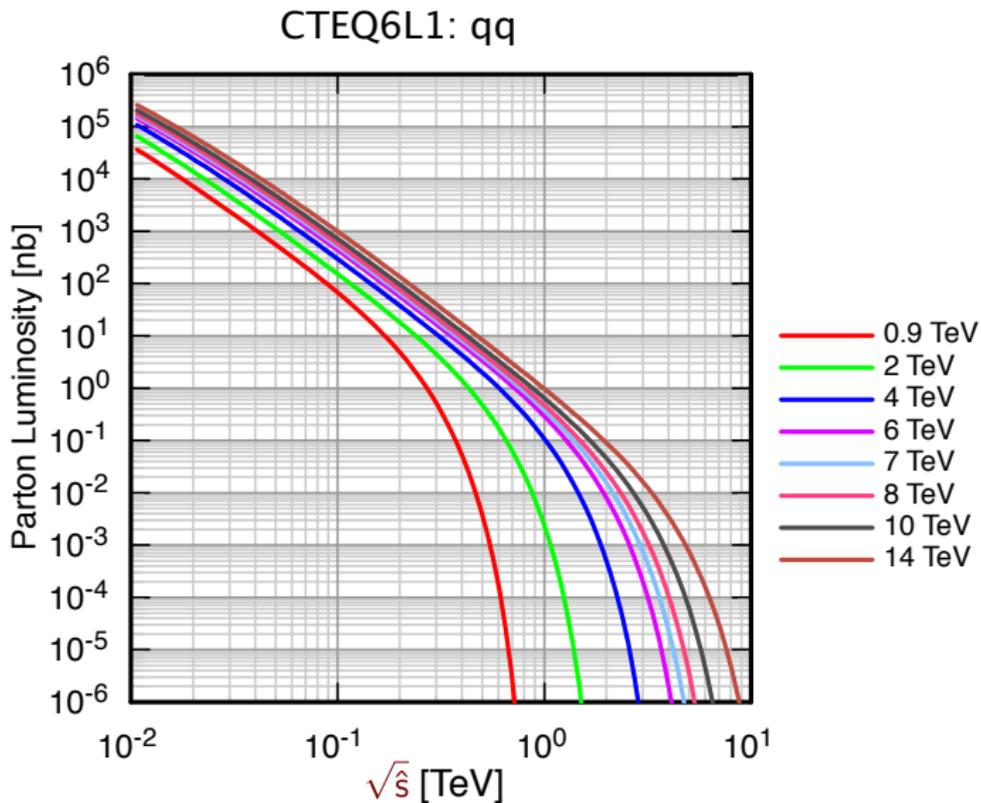
Parton Luminosity



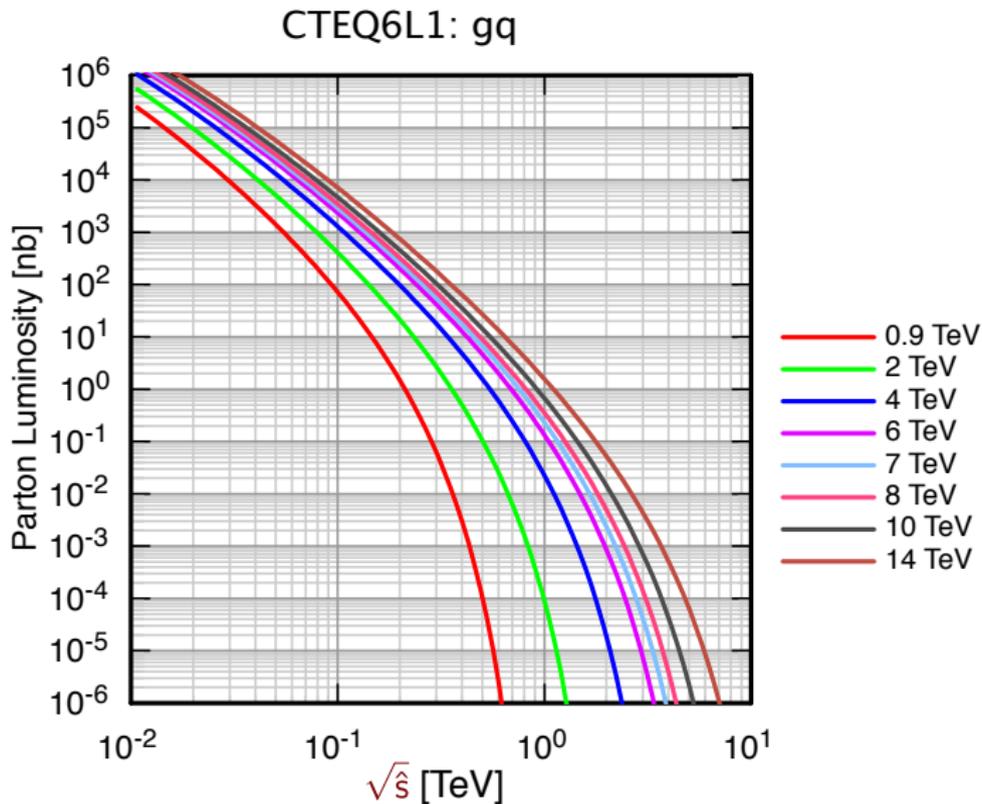
Parton Luminosity



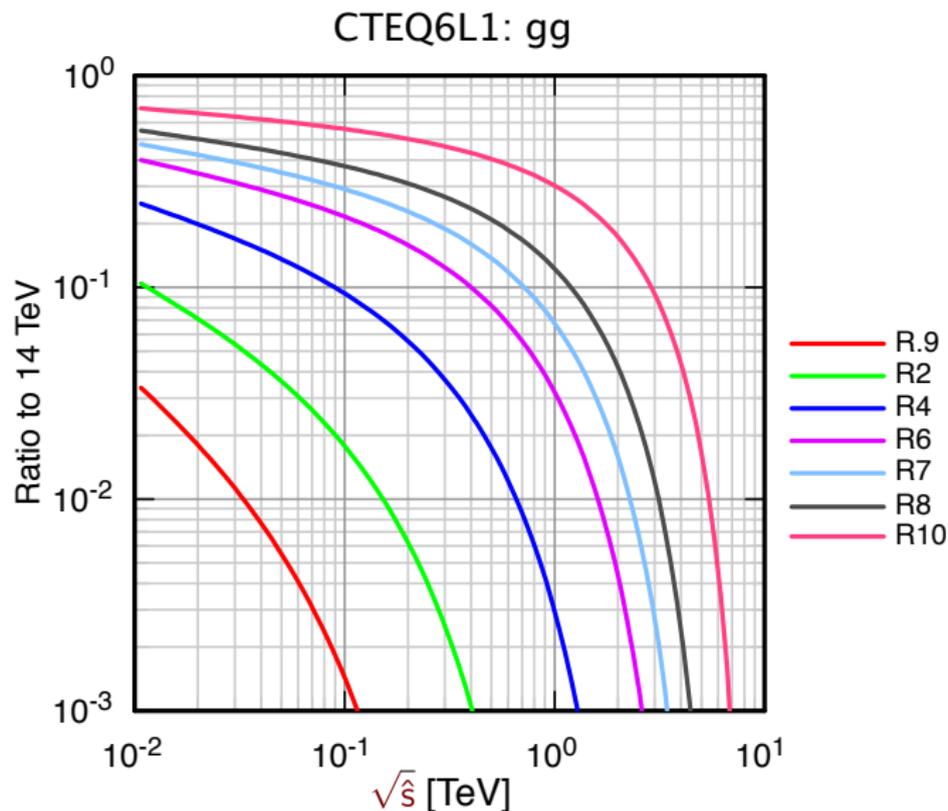
Parton Luminosity (light quarks)



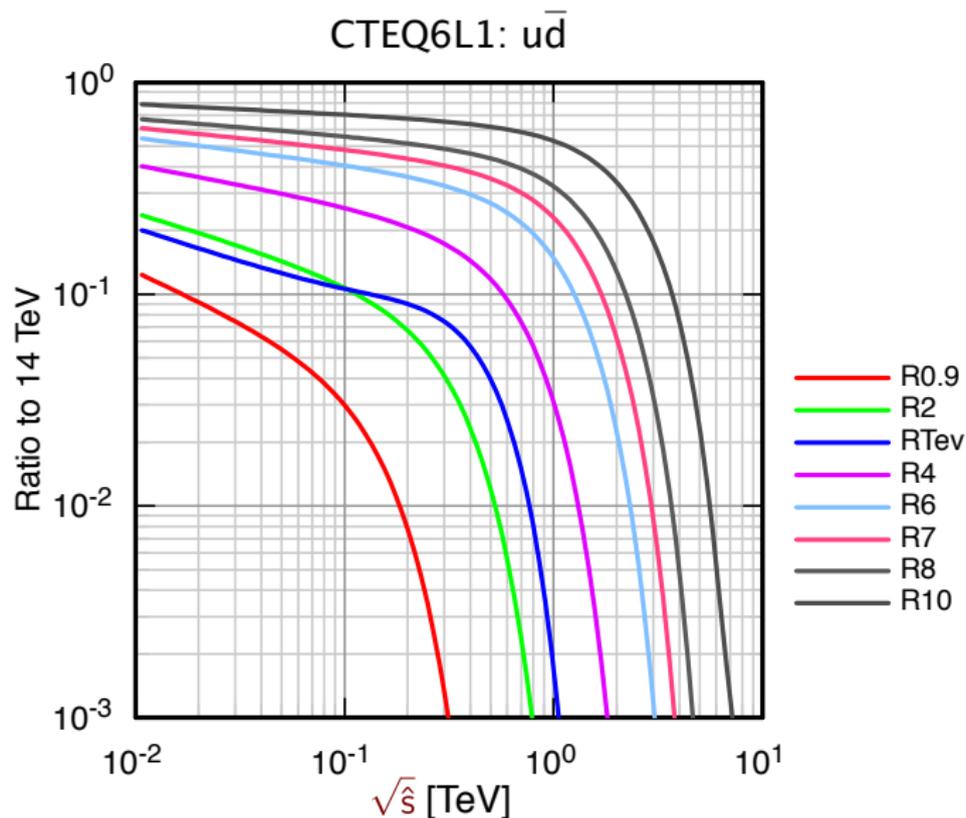
Parton Luminosity (gluon–light quarks)



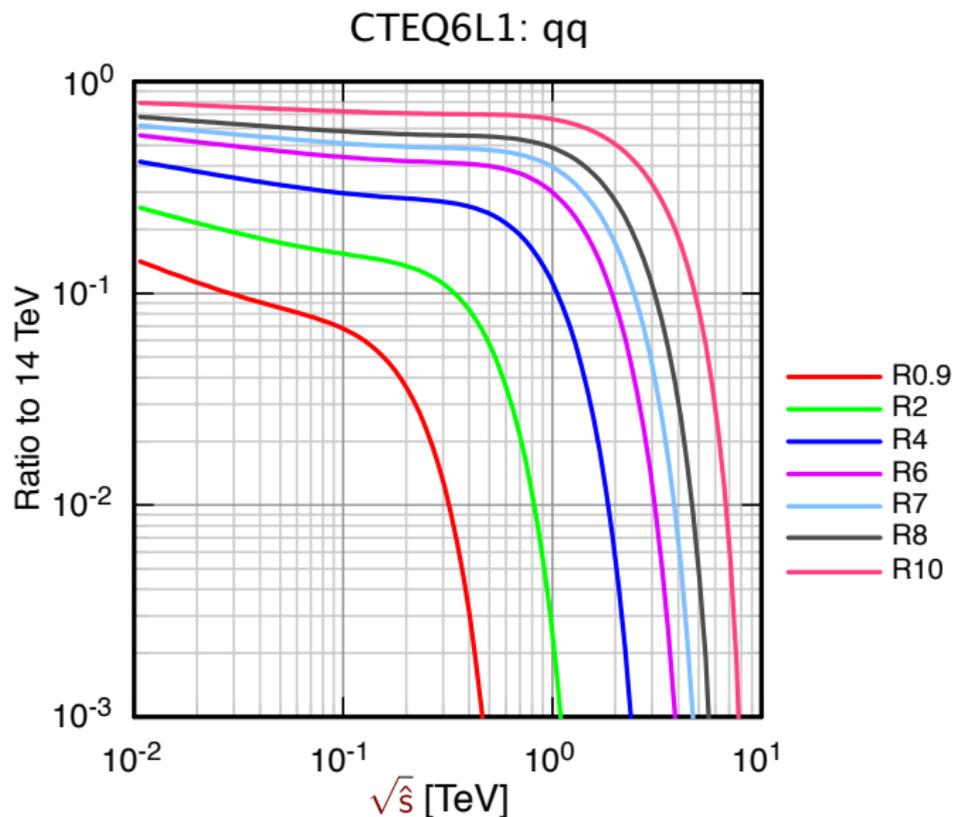
Luminosity Ratios



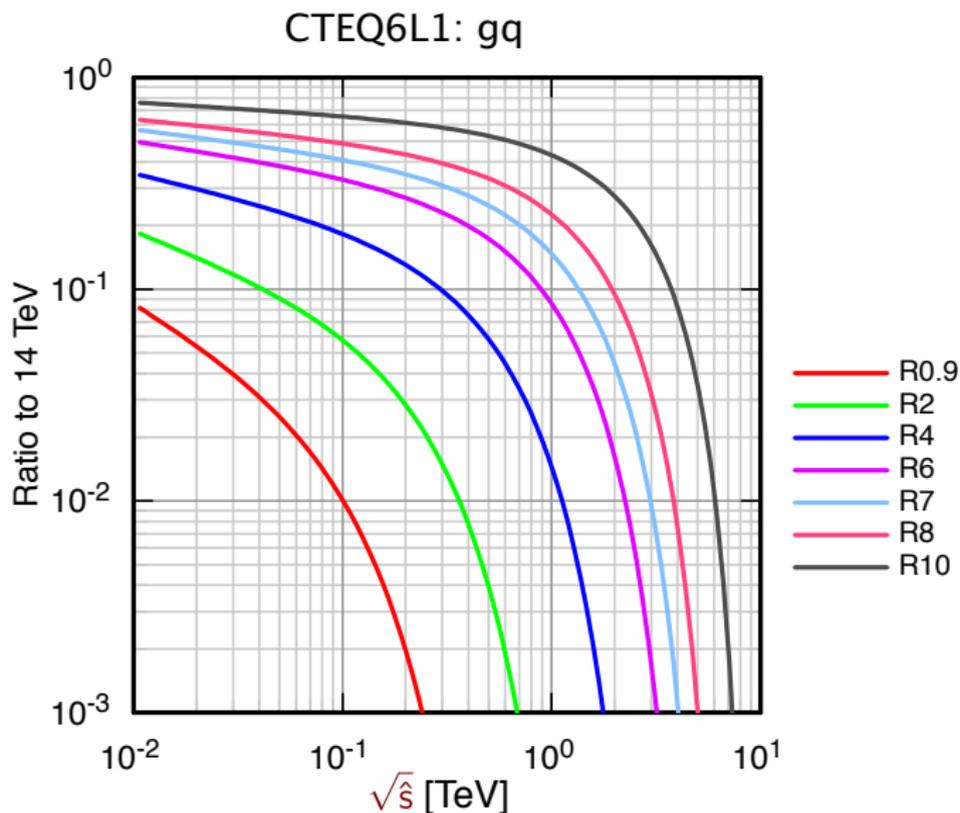
Luminosity Ratios



Luminosity Ratios



Luminosity Ratios



Problem 5

- (a) Referring to the gg luminosity ratios, estimate the increased yield of $H(125)$ at 14 TeV compared with 8 TeV.
- (b) Referring to the $u\bar{d}$ luminosity ratios, estimate the increased yield of $W'(2 \text{ TeV})$ and $W'(4 \text{ TeV})$ at 14 TeV compared with 8 TeV.
- (c) Referring to the qq luminosity ratios, estimate the increased yield of dijets at $\sqrt{\hat{s}} = 2 \text{ TeV}$ and $\sqrt{\hat{s}} = 4 \text{ TeV}$ at 14 TeV compared with 8 TeV.
- (d) Compare your estimates with the explicit Standard-model Cross Sections calculated using MCFM.

The Standard Model: Current Status & Open Questions

Chris Quigg

Fermilab

Parity violation in weak decays

1956 Wu *et al.*: correlation between spin vector \vec{J} of polarized ^{60}Co and direction \hat{p}_e of outgoing β particle

Parity leaves spin (axial vector) unchanged $\mathcal{P} : \vec{J} \rightarrow \vec{J}$

Parity reverses electron direction $\mathcal{P} : \hat{p}_e \rightarrow -\hat{p}_e$

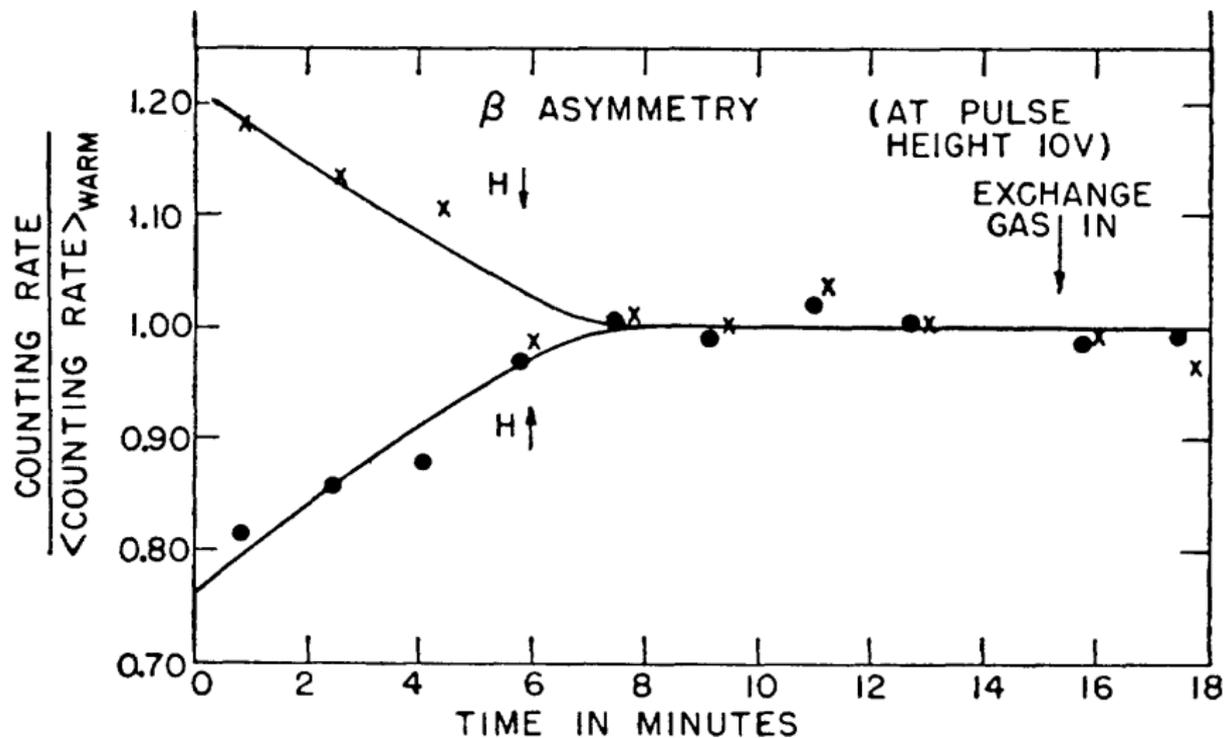
Correlation $\vec{J} \cdot \hat{p}_e$ is *parity violating*

Parity links left-handed, right-handed ν ,

$$\nu_L \begin{array}{c} \leftarrow \\ \longrightarrow \end{array} \mathcal{P} \begin{array}{c} \leftarrow \\ \longrightarrow \end{array} \cancel{\nu_R}$$

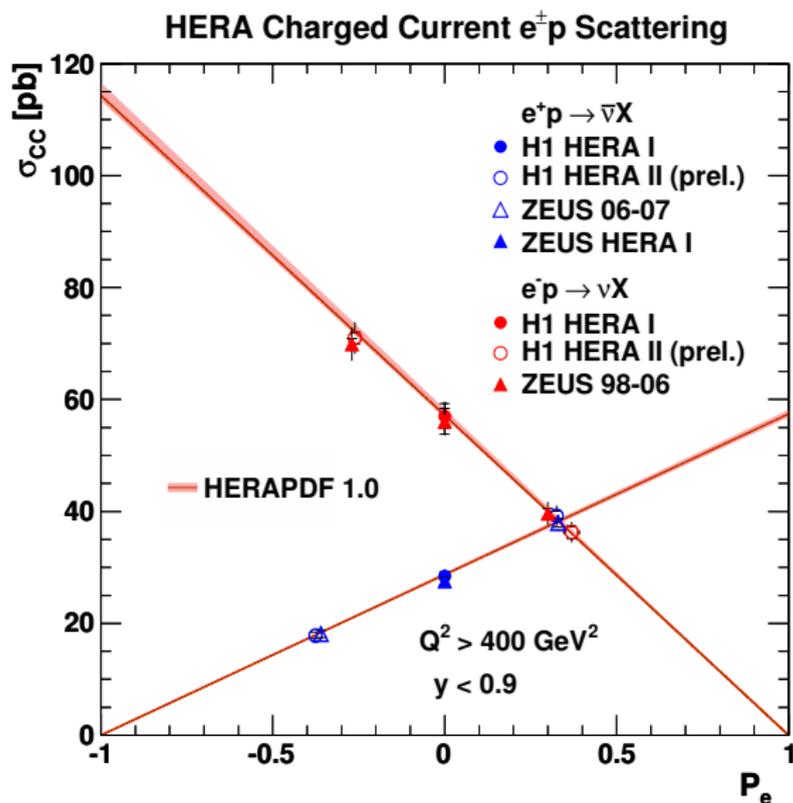
\Rightarrow build a manifestly parity-violating theory with only ν_L .

Parity violation in ^{60}Co decay



Left-handed Charged-current Interaction

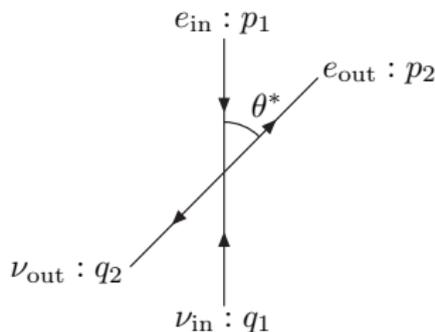
Polarized $e^\pm p \rightarrow (\bar{\nu}, \nu) + \text{anything}$ — no RHCC



Effective Lagrangian for the Weak Interactions

$$\mathcal{L}_{V-A} = \frac{-G_F}{\sqrt{2}} \bar{\nu} \gamma_\mu (1 - \gamma_5) e \bar{e} \gamma^\mu (1 - \gamma_5) \nu$$

with $G_F = 1.166\,378\,7(6) \times 10^{-5} \text{ GeV}^{-2}$. $\bar{\nu}e$ scattering:



$$\mathcal{M} = -\frac{iG_F}{\sqrt{2}} \bar{\nu}(\nu, q_1) \gamma_\mu (1 - \gamma_5) u(e, p_1) \bar{u}(e, p_2) \gamma^\mu (1 - \gamma_5) \nu(\nu, q_2)$$

\mathcal{L}_{V-A} Consequences

$$\frac{d\sigma_{V-A}(\bar{\nu}e \rightarrow \bar{\nu}e)}{d\Omega_{\text{cm}}} = \frac{|\overline{\mathcal{M}}|^2}{64\pi^2 s} = \frac{G_F^2 \cdot 2mE_\nu(1-z)^2}{16\pi^2}; \quad z = \cos\theta^*$$

$$\sigma_{V-A}(\bar{\nu}e \rightarrow \bar{\nu}e) = \frac{G_F^2 \cdot 2mE_\nu}{3\pi} \approx 0.574 \times 10^{-41} \text{ cm}^2 \left(\frac{E_\nu}{1 \text{ GeV}} \right)$$

Repeat for νe scattering:

$$\frac{d\sigma_{V-A}(\nu e \rightarrow \nu e)}{d\Omega_{\text{cm}}} = \frac{G_F^2 \cdot 2mE_\nu}{4\pi^2}$$

$$\sigma_{V-A}(\nu e \rightarrow \nu e) = \frac{G_F^2 \cdot 2mE_\nu}{\pi} \approx 1.72 \times 10^{-41} \text{ cm}^2 \left(\frac{E_\nu}{1 \text{ GeV}} \right)$$

Problem 6

Trace the origin of the factor-of-three difference between the νe and $\bar{\nu} e$ cross sections, which arises from the left-handed nature of the charged-current weak interaction. Analyze the spin configurations for forward and backward scattering for the two cases, and show how angular momentum conservation accounts for the different angular distributions.

The Two-Neutrino Experiment

Lederman, Schwartz, Steinberger, 1962

- Make a beam of high-energy ν from $\pi \rightarrow \mu\nu$
- Observe $\nu N \rightarrow \mu + X$
not $\nu N \rightarrow e + X$

\Rightarrow neutrino produced in $\pi \rightarrow \mu\nu$ decay is ν_μ

Suggests family structure

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L \quad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L$$

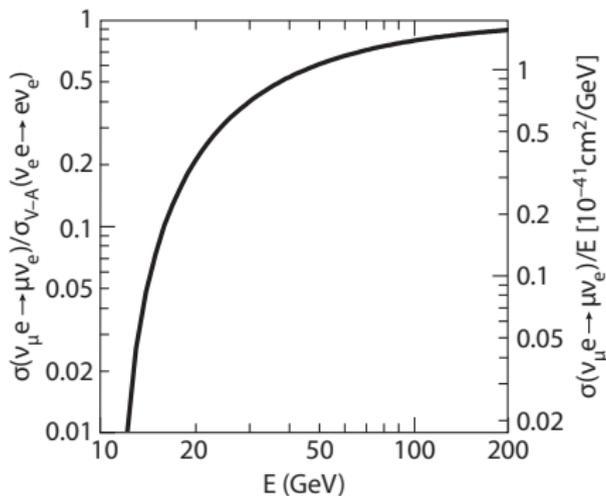
Generalize the effective Lagrangian:

$$\mathcal{L}_{V-A}^{(e\mu)} = \frac{-G_F}{\sqrt{2}} \bar{\nu}_\mu \gamma_\mu (1 - \gamma_5) \mu \bar{e} \gamma^\mu (1 - \gamma_5) \nu_e + \text{h.c.}$$

(Inverse) Muon Decay

$$\Gamma(\mu \rightarrow e \bar{\nu}_e \nu_\mu) = \frac{G_F^2 m_\mu^5}{192\pi^3}$$

$$\sigma(\nu_\mu e \rightarrow \mu \nu_e) = \sigma_{V-A}(\nu_e e \rightarrow \nu_e e) \left[1 - \frac{(m_\mu^2 - m_e^2)}{2m_e E_\nu} \right]^2$$



Partial-wave Unitarity (Probability Conservation)

PW unitarity constrains the modulus $|\mathcal{M}_{J=0}| < 1$ for an s-wave amplitude.

Equivalently, the contribution to the cross section is bounded by $\sigma_0 < \pi/p_{\text{cm}}^2$.

$$\mathcal{M}_0 = \frac{G_F \cdot 2m_e E_\nu}{\pi\sqrt{2}} \left[1 - \frac{(m_\mu^2 - m_e^2)}{2m_e E_\nu} \right]$$

Satisfies unitarity constraint for

$$E_\nu < \pi/G_F m_e \sqrt{2} \approx 3.7 \times 10^8 \text{ GeV},$$

or $E_{\text{cm}} \lesssim 300 \text{ GeV}$

Physics must change before $\sqrt{s} = 600 \text{ GeV}$

Problem 7

Using the measured lifetimes of the muon and the tau lepton, $\tau_\ell = \hbar/\Gamma_\ell$, and the branching fractions into the $e\bar{\nu}_e\nu_\ell$ channel to determine the Fermi couplings for muon and tau interactions, G_μ and G_τ . Compare these two values with each other and with the standard value of G_F .

The equality of G_μ , G_τ , and G_F supports the notion that the leptonic (charged-current) weak interactions are of universal strength.

Introduction: J. R. Patterson, "Lepton Universality," *SLAC Beam Line* (Spring 1995).

Recent BaBar study, *Phys. Rev. Lett.* **105**, 051602 (2008).

Electroweak theory antecedents

Lessons from experiment and theory

- Parity-violating $V - A$ structure of charged current
- Cabibbo universality of leptonic and semileptonic processes
- Absence of strangeness-changing neutral currents
- Negligible neutrino masses; left-handed neutrinos
- Unitarity: four-fermion description breaks down at $\sqrt{s} \approx 620 \text{ GeV}$ $\nu_\mu e \rightarrow \mu \nu_e$
- $\nu\bar{\nu} \rightarrow W^+W^-$: divergence problems of *ad hoc* intermediate vector boson theory

Formulate electroweak theory

Three crucial clues from experiment:

- Left-handed weak-isospin doublets,

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L \quad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L \quad \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L \\ \begin{pmatrix} u \\ d' \end{pmatrix}_L \quad \begin{pmatrix} c \\ s' \end{pmatrix}_L \quad \begin{pmatrix} t \\ b' \end{pmatrix}_L ;$$

- Universal strength of the (charged-current) weak interactions;
- Idealization that neutrinos are massless.

First two clues suggest $SU(2)_L$ gauge symmetry

A theory of leptons

$$L = \begin{pmatrix} \nu_e \\ e \end{pmatrix}_L \quad R \equiv e_R$$

weak hypercharges $Y_L = -1$, $Y_R = -2$

Gell-Mann–Nishijima connection, $Q = I_3 + \frac{1}{2}Y$

$SU(2)_L \otimes U(1)_Y$ gauge group \Rightarrow gauge fields:

- weak isovector \vec{b}_μ , coupling g

$$b_\mu^\ell = b_\mu^\ell - \varepsilon_{jkl} \alpha^j b_\mu^k - (1/g) \partial_\mu \alpha^\ell$$

- weak isoscalar \mathcal{A}_μ , coupling $g'/2$

$$\mathcal{A}_\mu \rightarrow \mathcal{A}_\mu - \partial_\mu \alpha$$

Field-strength tensors

$$F_{\mu\nu}^\ell = \partial_\nu b_\mu^\ell - \partial_\mu b_\nu^\ell + g \varepsilon_{jkl} b_\mu^j b_\nu^k, \text{SU}(2)_L$$

$$f_{\mu\nu} = \partial_\nu \mathcal{A}_\mu - \partial_\mu \mathcal{A}_\nu, \text{U}(1)_Y$$

Interaction Lagrangian

$$\mathcal{L} = \mathcal{L}_{\text{gauge}} + \mathcal{L}_{\text{leptons}}$$

$$\mathcal{L}_{\text{gauge}} = -\frac{1}{4}F_{\mu\nu}^l F^{\ell\mu\nu} - \frac{1}{4}f_{\mu\nu} f^{\mu\nu},$$

$$\begin{aligned}\mathcal{L}_{\text{leptons}} &= \bar{R} i\gamma^\mu \left(\partial_\mu + i\frac{g'}{2}\mathcal{A}_\mu Y \right) R \\ &+ \bar{L} i\gamma^\mu \left(\partial_\mu + i\frac{g'}{2}\mathcal{A}_\mu Y + i\frac{g}{2}\vec{T} \cdot \vec{b}_\mu \right) L.\end{aligned}$$

Mass term $\mathcal{L}_e = -m_e(\bar{e}_R e_L + \bar{e}_L e_R) = -m_e \bar{e}e$

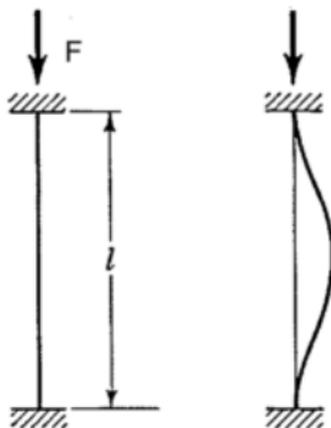
would violate local gauge invariance

Theory: 4 massless gauge bosons (\mathcal{A}_μ b_μ^1 b_μ^2 b_μ^3);

Nature: 1 (γ)

Symmetric law need not imply symmetric outcome

Buckling rod (L. Euler) *spontaneous symmetry breaking*



radius R , moment of inertia $I = \pi R^2/4$, elastic modulus E

$$\text{Critical point: } F_{\text{cr}} = \pi^2 IE / \ell^2$$

symmetric solution **unstable**, ground state degenerate

Symmetric law need not imply symmetric outcome



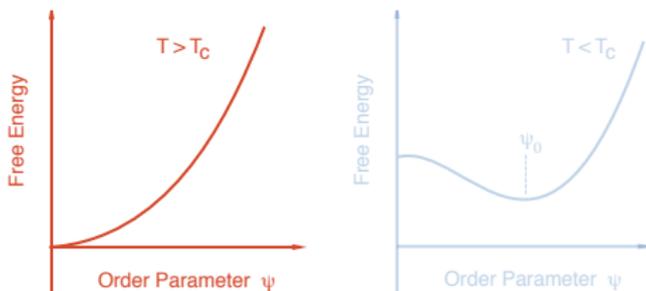
Massive Photon? *Hiding Symmetry*

Recall **2** miracles of superconductivity:

- No resistance Meissner effect (exclusion of **B**)

Ginzburg–Landau Phenomenology (not a theory from first principles)

normal, **resistive** charge carriers + superconducting charge carriers



$$\mathbf{B} = 0: \quad G_{\text{super}}(0) = G_{\text{normal}}(0) + \alpha |\psi|^2 + \beta |\psi|^4$$

$$T > T_c: \quad \alpha > 0 \quad \langle |\psi|^2 \rangle_0 = 0$$

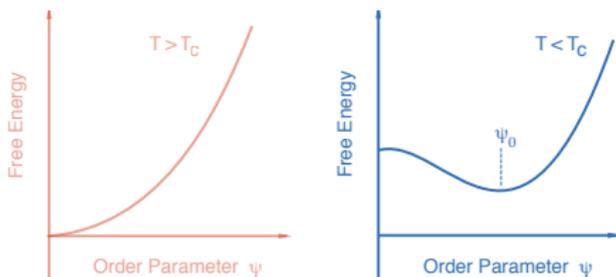
Massive Photon? *Hiding Symmetry*

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$$T < T_c: \quad \alpha < 0 \quad \langle |\psi|^2 \rangle_0 \neq 0$$

In a nonzero magnetic field ...

$$G_{\text{super}}(\mathbf{B}) = G_{\text{super}}(0) + \frac{\mathbf{B}^2}{8\pi} + \frac{1}{2m^*} \left| -i\hbar\nabla\psi - \frac{e^*}{c}\mathbf{A}\psi \right|^2$$

$$\left. \begin{array}{l} e^* = -2 \\ m^* \end{array} \right\} \text{ of superconducting carriers}$$

Weak, slowly varying field: $\psi \approx \psi_0 \neq 0$, $\nabla\psi \approx 0$

Variational analysis \rightsquigarrow

$$\nabla^2 \mathbf{A} - \frac{4\pi e^{*2}}{m^* c^2} |\psi_0|^2 \mathbf{A} = 0$$

wave equation of a *massive photon*

Photon – *gauge boson* – acquires mass
within superconductor

origin of Meissner effect

Hiding EW Symmetry

Higgs mechanism: relativistic generalization of Ginzburg-Landau superconducting phase transition

- Introduce a complex doublet of scalar fields

$$\phi \equiv \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \quad Y_\phi = +1$$

- Add to \mathcal{L} (gauge-invariant) terms for interaction and propagation of the scalars,

$$\mathcal{L}_{\text{scalar}} = (\mathcal{D}^\mu \phi)^\dagger (\mathcal{D}_\mu \phi) - V(\phi^\dagger \phi),$$

where $\mathcal{D}_\mu = \partial_\mu + i\frac{g'}{2}\mathcal{A}_\mu Y + i\frac{g}{2}\vec{\tau} \cdot \vec{b}_\mu$ and

$$V(\phi^\dagger \phi) = \mu^2(\phi^\dagger \phi) + |\lambda|(\phi^\dagger \phi)^2$$

- Add a Yukawa interaction $\mathcal{L}_{\text{Yukawa}} = -\zeta_e [\bar{R}(\phi^\dagger L) + (\bar{L}\phi)R]$

Unique and degenerate vacuum states

(a)



(b)



- Arrange self-interactions so vacuum corresponds to a broken-symmetry solution: $\mu^2 < 0$
Choose minimum energy (vacuum) state for vacuum expectation value

$$\langle \phi \rangle_0 = \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix}, \quad v = \sqrt{-\mu^2/|\lambda|}$$

Hides (breaks) $SU(2)_L$ and $U(1)_Y$

but preserves $U(1)_{em}$ invariance

Invariance under \mathcal{G} means $e^{i\alpha\mathcal{G}}\langle\phi\rangle_0 = \langle\phi\rangle_0$, so $\mathcal{G}\langle\phi\rangle_0 = 0$

$$\tau_1 \langle \phi \rangle_0 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix} = \begin{pmatrix} v/\sqrt{2} \\ 0 \end{pmatrix} \neq 0 \quad \text{broken!}$$

$$\tau_2 \langle \phi \rangle_0 = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix} \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix} = \begin{pmatrix} -iv/\sqrt{2} \\ 0 \end{pmatrix} \neq 0 \quad \text{broken!}$$

$$\tau_3 \langle \phi \rangle_0 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix} = \begin{pmatrix} 0 \\ -v/\sqrt{2} \end{pmatrix} \neq 0 \quad \text{broken!}$$

$$Y \langle \phi \rangle_0 = Y_\phi \langle \phi \rangle_0 = +1 \langle \phi \rangle_0 = \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix} \neq 0 \quad \text{broken!}$$

Examine electric charge operator Q on the (neutral) vacuum

$$\begin{aligned} Q\langle\phi\rangle_0 &= \frac{1}{2}(\tau_3 + Y)\langle\phi\rangle_0 \\ &= \frac{1}{2} \begin{pmatrix} Y_\phi + 1 & 0 \\ 0 & Y_\phi - 1 \end{pmatrix} \langle\phi\rangle_0 \\ &= \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix} \\ &= \begin{pmatrix} 0 \\ 0 \end{pmatrix} \quad \text{unbroken!} \end{aligned}$$

Four original generators are broken, *electric charge is not*

- $SU(2)_L \otimes U(1)_Y \rightarrow U(1)_{\text{em}}$ (will verify)
- Expect massless photon
- Expect gauge bosons corresponding to

$$\tau_1, \tau_2, \frac{1}{2}(\tau_3 - Y) \equiv K \quad \text{to acquire masses}$$

Expand about the vacuum state

Let $\phi = \begin{pmatrix} 0 \\ (v + \eta)/\sqrt{2} \end{pmatrix}$; in *unitary gauge*

$$\begin{aligned} \mathcal{L}_{\text{scalar}} &= \frac{1}{2}(\partial^\mu \eta)(\partial_\mu \eta) - \mu^2 \eta^2 \\ &+ \frac{v^2}{8} [g^2 |b_\mu^1 - ib_\mu^2|^2 + (g' \mathcal{A}_\mu - gb_\mu^3)^2] \\ &+ \text{interaction terms} \end{aligned}$$

“Higgs boson” η has acquired (mass)² $M_H^2 = -2\mu^2 > 0$

$$\text{Define } W_\mu^\pm = \frac{b_\mu^1 \mp ib_\mu^2}{\sqrt{2}}$$

$$\frac{g^2 v^2}{8} (|W_\mu^+|^2 + |W_\mu^-|^2) \iff M_{W^\pm} = gv/2$$

$$(v^2/8)(g' \mathcal{A}_\mu - gb_\mu^3)^2 \dots$$

Now define orthogonal combinations

$$Z_\mu = \frac{-g' \mathcal{A}_\mu + gb_\mu^3}{\sqrt{g^2 + g'^2}} \quad A_\mu = \frac{g \mathcal{A}_\mu + g' b_\mu^3}{\sqrt{g^2 + g'^2}}$$

$$M_{Z^0} = \sqrt{g^2 + g'^2} v/2 = M_W \sqrt{1 + g'^2/g^2}$$

A_μ remains massless

$$\begin{aligned}
 \mathcal{L}_{\text{Yukawa}} &= -\zeta_e \frac{(v + \eta)}{\sqrt{2}} (\bar{e}_R e_L + \bar{e}_L e_R) \\
 &= -\frac{\zeta_e v}{\sqrt{2}} \bar{e} e - \frac{\zeta_e \eta}{\sqrt{2}} \bar{e} e
 \end{aligned}$$

electron acquires $m_e = \zeta_e v / \sqrt{2}$

Higgs-boson coupling to electrons: m_e/v (\propto mass)

Desired particle content ... plus a Higgs scalar

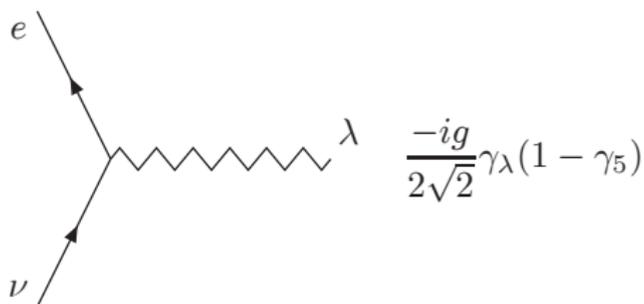
Values of couplings, electroweak scale v ?

What about interactions?

Interactions ...

$$\mathcal{L}_{W-e} = -\frac{g}{2\sqrt{2}} [\bar{\nu} \gamma^\mu (1 - \gamma_5) e W_\mu^+ + \bar{e} \gamma^\mu (1 - \gamma_5) \nu W_\mu^-]$$

+ similar terms for μ and τ



W

$$= \frac{-i(g_{\mu\nu} - k_\mu k_\nu / M_W^2)}{k^2 - M_W^2} .$$

Compute $\nu_\mu e \rightarrow \mu \nu_e$

$$\sigma(\nu_\mu e \rightarrow \mu \nu_e) = \frac{g^4 m_e E_\nu [1 - (m_\mu^2 - m_e^2)/2m_e E_\nu]^2}{16\pi M_W^4 (1 + 2m_e E_\nu/M_W^2)}$$

Reproduces 4-fermion result at low energies if

$$\frac{g^4}{16M_W^4} = 2G_F^2 \Rightarrow \frac{g}{2\sqrt{2}} = \left(\frac{G_F M_W^2}{\sqrt{2}} \right)^{\frac{1}{2}}$$

Using $M_W = gv/2$, determine the electroweak scale

$$v = (G_F \sqrt{2})^{-\frac{1}{2}} \approx 246 \text{ GeV}$$

$$\Rightarrow \langle \phi^0 \rangle_0 = (G_F \sqrt{8})^{-\frac{1}{2}} \approx 174 \text{ GeV}$$

W -propagator modifies HE behavior

$$\sigma(\nu_\mu e \rightarrow \mu \nu_e) = \frac{g^4 m_e E_\nu [1 - (m_\mu^2 - m_e^2)/2m_e E_\nu]^2}{16\pi M_W^4 (1 + 2m_e E_\nu/M_W^2)}$$

$$\lim_{E_\nu \rightarrow \infty} \sigma(\nu_\mu e \rightarrow \mu \nu_e) = \frac{g^4}{32\pi M_W^2} = \frac{G_F^2 M_W^2}{\sqrt{2}}$$

no asymptotic growth with energy!

Partial-wave unitarity respected for

$$s < M_W^2 [\exp(\pi\sqrt{2}/G_F M_W^2) - 1]$$

Problem 8

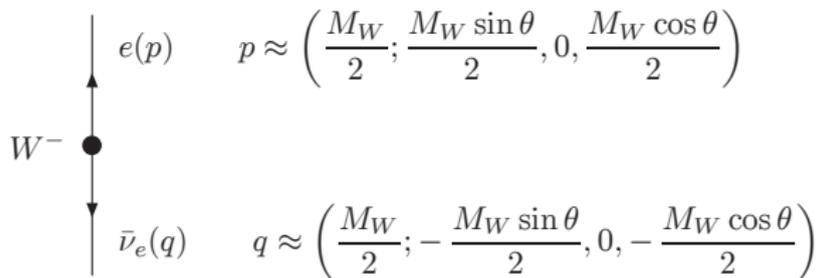
- (a) Write the cross section given on the preceding page for $\sigma(\nu_\mu e \rightarrow \mu \nu_e)$ in terms of G_F , rather than g .
- (b) Now put aside the threshold factor that results from the muon–electron mass difference. Plot the cross section for $1 \text{ GeV} \leq E_\nu \leq 10 \text{ TeV}$. Also plot the point-coupling expression over the same range.
- (c) At what value of E_ν does the W -boson propagator begin to have a perceptible effect on the cross section?
- (d) How well would you have to determine the cross section to derive a useful estimate of M_W ?

A. Aktas, *et al.* (H1 Collaboration), *Phys. Lett. B* **632**, 35 (2006);
Z. Zhang, *Nucl. Phys. Proc. Suppl.* **191**, 271 (2009).

W-boson properties

No prediction yet for M_W (haven't determined g)

Leptonic decay $W^- \rightarrow e^- \nu_e$


$$e(p) \quad p \approx \left(\frac{M_W}{2}; \frac{M_W \sin \theta}{2}, 0, \frac{M_W \cos \theta}{2} \right)$$
$$\bar{\nu}_e(q) \quad q \approx \left(\frac{M_W}{2}; -\frac{M_W \sin \theta}{2}, 0, -\frac{M_W \cos \theta}{2} \right)$$

$$\mathcal{M} = -i \left(\frac{G_F M_W^2}{\sqrt{2}} \right)^{\frac{1}{2}} \bar{u}(e, p) \gamma_\mu (1 - \gamma_5) v(\nu, q) \varepsilon^\mu$$

$\varepsilon^\mu = (0; \hat{\varepsilon})$: W polarization vector in its rest frame

$$|\mathcal{M}|^2 = \frac{G_F M_W^2}{\sqrt{2}} \text{tr} [\not{\varepsilon} (1 - \gamma_5) \not{q} (1 + \gamma_5) \not{\varepsilon}^* \not{p}] ;$$

$$\text{tr}[\dots] = [\varepsilon \cdot q \varepsilon^* \cdot p - \varepsilon \cdot \varepsilon^* q \cdot p + \varepsilon \cdot p \varepsilon^* \cdot q + i \epsilon_{\mu\nu\rho\sigma} \varepsilon^\mu q^\nu \varepsilon^{*\rho} p^\sigma]$$

$$\text{tr}[\dots] = [\varepsilon \cdot q \varepsilon^* \cdot p - \varepsilon \cdot \varepsilon^* q \cdot p + \varepsilon \cdot p \varepsilon^* \cdot q + i \epsilon_{\mu\nu\rho\sigma} \varepsilon^\mu q^\nu \varepsilon^{*\rho} p^\sigma]$$

decay rate is independent of W polarization; look first at longitudinal pol.

$\varepsilon^\mu = (0; 0, 0, 1) = \varepsilon^{*\mu}$, eliminate $\epsilon_{\mu\nu\rho\sigma}$

$$|\mathcal{M}|^2 = \frac{4G_F M_W^4}{\sqrt{2}} \sin^2 \theta$$

$$\frac{d\Gamma_0}{d\Omega} = \frac{|\mathcal{M}|^2}{64\pi^2} \frac{\mathcal{S}_{12}}{M_W^3}$$

$$\mathcal{S}_{12} = \sqrt{[M_W^2 - (m_e + m_\nu)^2][M_W^2 - (m_e - m_\nu)^2]} = M_W^2$$

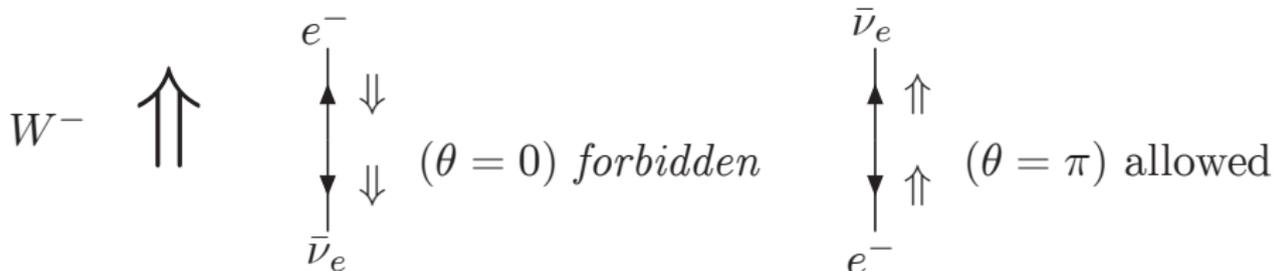
$$\frac{d\Gamma_0}{d\Omega} = \frac{G_F M_W^3}{16\pi^2 \sqrt{2}} \sin^2 \theta$$

$$\Gamma(W \rightarrow e\nu) = \frac{G_F M_W^3}{6\pi \sqrt{2}}$$

Other helicities: $\varepsilon_{\pm 1}^{\mu} = (0; -1, \mp i, 0)/\sqrt{2}$

$$\frac{d\Gamma_{\pm 1}}{d\Omega} = \frac{G_F M_W^3}{32\pi^2 \sqrt{2}} (1 \mp \cos\theta)^2$$

Extinctions at $\cos\theta = \pm 1$ are consequences of angular momentum conservation:



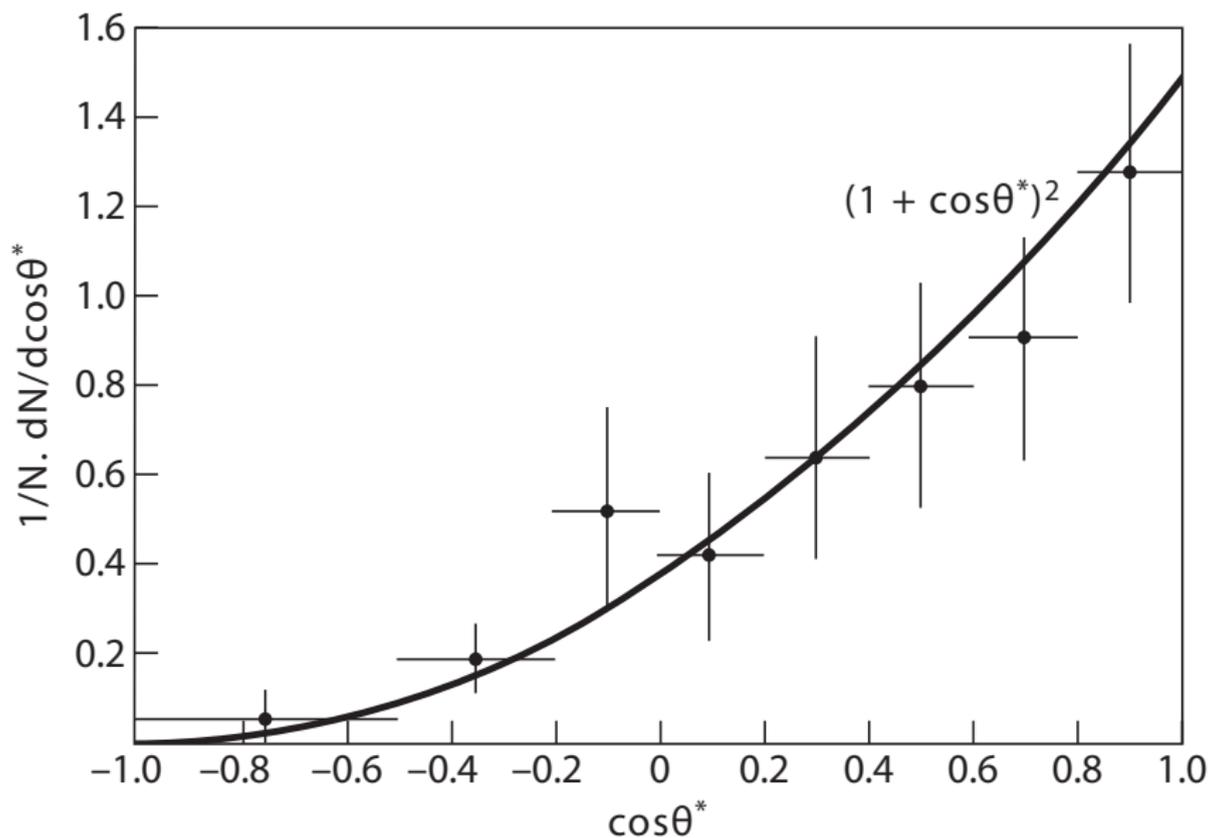
(situation reversed for $W^+ \rightarrow e^+ \nu_e$)

e^+ follows polarization direction of W^+

e^- avoids polarization direction of W^-

important for discovery of W^\pm in $\bar{p}p$ ($\bar{q}q$) C violation

UA1 $W \rightarrow e\nu$ decay angular distribution



The Standard Model: Current Status & Open Questions

Chris Quigg

Fermilab

Interactions ...

$$\mathcal{L}_{A-\ell} = \frac{gg'}{\sqrt{g^2 + g'^2}} \bar{e} \gamma^\mu e A_\mu$$

... vector interaction; $\Rightarrow A_\mu$ as γ , provided we identify

$$gg' / \sqrt{g^2 + g'^2} \equiv e$$

Define $g' = g \tan \theta_W$

θ_W : weak mixing angle

$$g = e / \sin \theta_W \geq e$$

$$g' = e / \cos \theta_W \geq e$$

$$Z_\mu = b_\mu^3 \cos \theta_W - \mathcal{A}_\mu \sin \theta_W \quad A_\mu = \mathcal{A}_\mu \cos \theta_W + b_\mu^3 \sin \theta_W$$

$$\mathcal{L}_{Z-\nu} = \frac{-g}{4 \cos \theta_W} \bar{\nu} \gamma^\mu (1 - \gamma_5) \nu Z_\mu$$

Purely left-handed!

Interactions ...

$$\mathcal{L}_{Z-e} = \frac{-g}{4 \cos \theta_W} \bar{e} [L_e \gamma^\mu (1 - \gamma_5) + R_e \gamma^\mu (1 + \gamma_5)] e Z_\mu$$

$$L_e = 2 \sin^2 \theta_W - 1 = 2x_W + \tau_3$$

$$R_e = 2 \sin^2 \theta_W = 2x_W$$

Z-decay calculation analogous to W^\pm

$$\Gamma(Z \rightarrow \nu \bar{\nu}) = \frac{G_F M_Z^3}{12\pi\sqrt{2}}$$

$$\Gamma(Z \rightarrow e^+ e^-) = \Gamma(Z \rightarrow \nu \bar{\nu}) [L_e^2 + R_e^2]$$

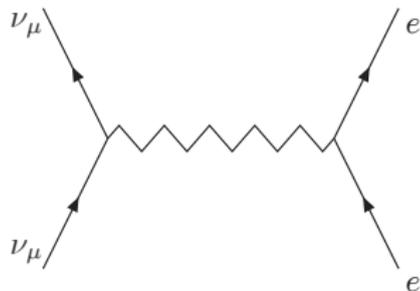
In the Electroweak Theory ...

- Electromagnetism is mediated by a massless photon, coupled to the electric charge;
- Mediator of charged-current weak interaction acquires a mass $M_W^2 = \pi\alpha / G_F \sqrt{2} \sin^2 \theta_W$,
- Mediator of (new!) neutral-current weak interaction acquires mass $M_Z^2 = M_W^2 / \cos^2 \theta_W$;
- Massive neutral scalar particle, the Higgs boson, appears, but its mass is not predicted;
- Fermions can acquire mass—values not predicted.

Determine $\sin^2 \theta_W$ to predict M_W, M_Z

Neutral-current interactions

New νe reaction, not in $V - A$



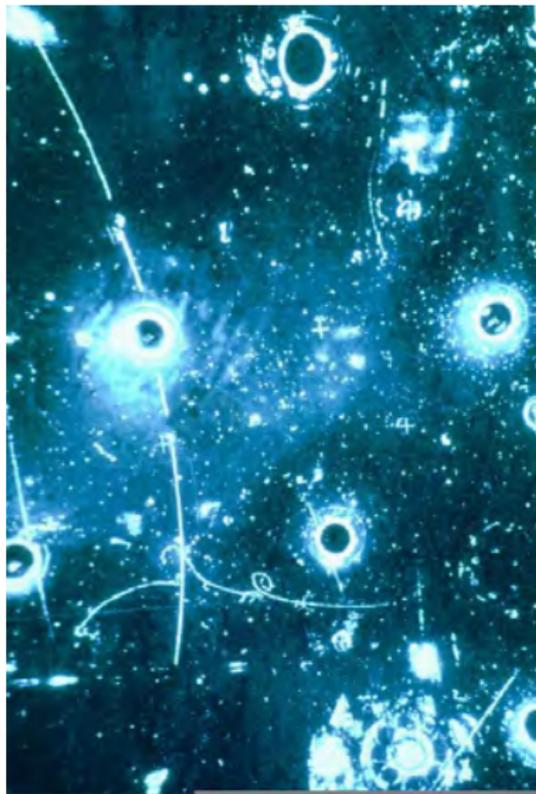
$$\sigma(\nu_\mu e \rightarrow \nu_\mu e) = \frac{G_F^2 m_e E_\nu}{2\pi} [L_e^2 + R_e^2/3]$$

$$\sigma(\bar{\nu}_\mu e \rightarrow \bar{\nu}_\mu e) = \frac{G_F^2 m_e E_\nu}{2\pi} [L_e^2/3 + R_e^2]$$

$$\sigma(\nu_e e \rightarrow \nu_e e) = \frac{G_F^2 m_e E_\nu}{2\pi} [(L_e + 2)^2 + R_e^2/3]$$

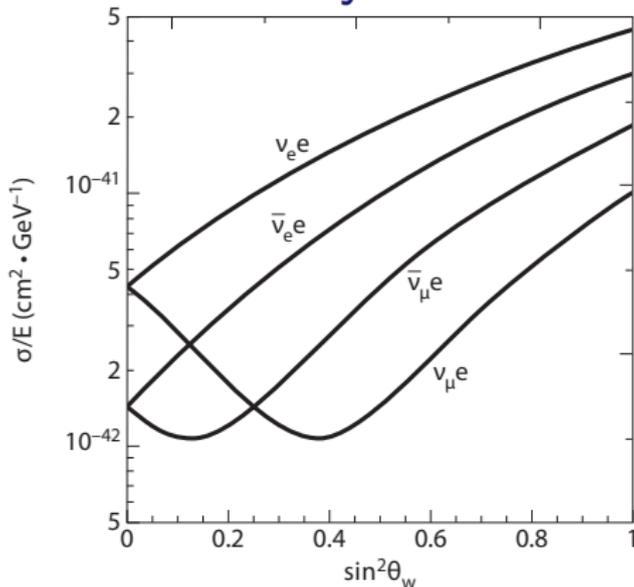
$$\sigma(\bar{\nu}_e e \rightarrow \bar{\nu}_e e) = \frac{G_F^2 m_e E_\nu}{2\pi} [(L_e + 2)^2/3 + R_e^2]$$

Gargamelle $\nu_\mu e$ event (1973)



$\leftarrow \bar{\nu}_\mu$

“Model-independent” analysis



Measure all cross sections to determine chiral couplings L_e and R_e or traditional vector and axial couplings v and a

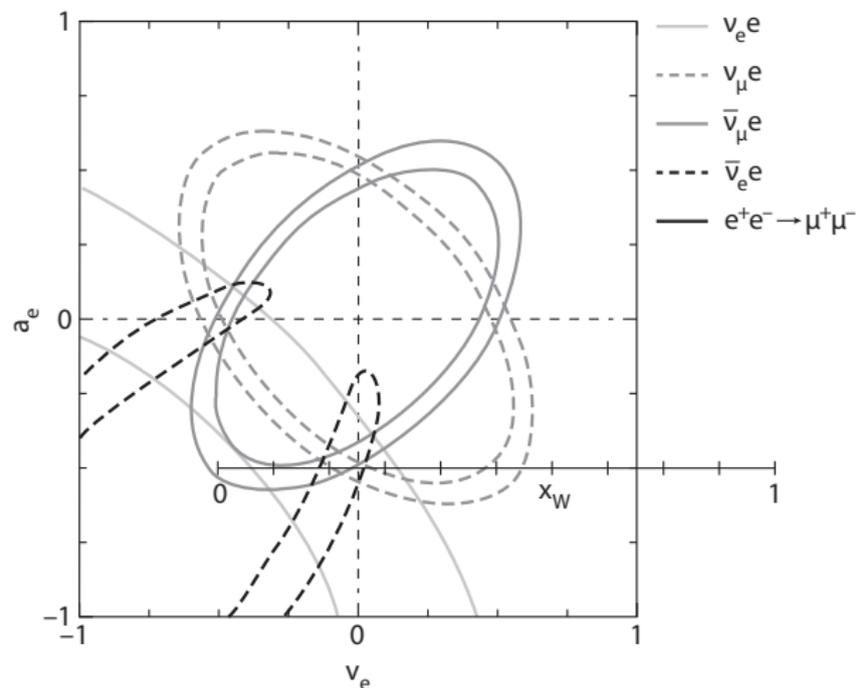
$$a = \frac{1}{2}(L_e - R_e) \quad v = \frac{1}{2}(L_e + R_e)$$

$$L_e = v + a$$

$$R_e = v - a$$

model-independent in V, A framework

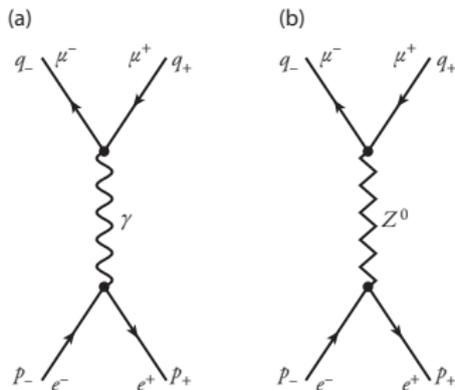
Neutrino–electron scattering



$$x_W \equiv \sin^2 \theta_W$$

Twofold ambiguity remains even after measuring all four cross sections:
 same cross sections result if we interchange $R_e \leftrightarrow -R_e$ ($\nu \leftrightarrow a$)

Consider $e^+e^- \rightarrow \mu^+\mu^-$



$$\begin{aligned}
 \mathcal{M} = & -ie^2 \bar{u}(\mu, q_-) \gamma_\lambda Q_\mu v(\mu, q_+) \frac{g^{\lambda\nu}}{s} \bar{v}(e, p_+) \gamma_\nu u(e, p_-) \\
 & + \frac{i}{2} \left(\frac{G_F M_Z^2}{\sqrt{2}} \right) \bar{u}(\mu, q_-) \gamma_\lambda [R_\mu(1 + \gamma_5) + L_\mu(1 - \gamma_5)] v(\mu, q_+) \\
 & \times \frac{g^{\lambda\nu}}{s - M_Z^2} \bar{v}(e, p_+) \gamma_\nu [R_e(1 + \gamma_5) + L_e(1 - \gamma_5)] u(e, p_-)
 \end{aligned}$$

muon charge $Q_\mu = -1$

$$e^+e^- \rightarrow \mu^+\mu^- \dots$$

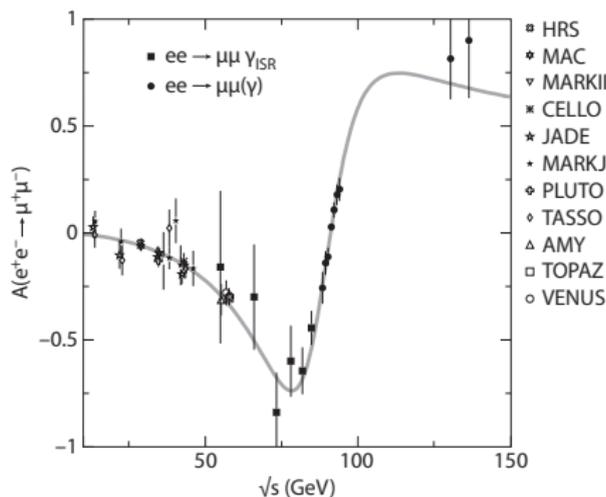
$$\begin{aligned} \frac{d\sigma}{dz} &= \frac{\pi\alpha^2 Q_\mu^2}{2s} (1+z^2) \\ &\quad - \frac{\alpha Q_\mu G_F M_Z^2 (s - M_Z^2)}{8\sqrt{2} [(s - M_Z^2)^2 + M_Z^2 \Gamma^2]} \\ &\quad \times [(R_e + L_e)(R_\mu + L_\mu)(1+z^2) + 2(R_e - L_e)(R_\mu - L_\mu)z] \\ &\quad + \frac{G_F^2 M_Z^4 s}{64\pi [(s - M_Z^2)^2 + M_Z^2 \Gamma^2]} \\ &\quad \times [(R_e^2 + L_e^2)(R_\mu^2 + L_\mu^2)(1+z^2) + 2(R_e^2 - L_e^2)(R_\mu^2 - L_\mu^2)z] \end{aligned}$$

Measuring F–B asymmetry resolves ambiguity

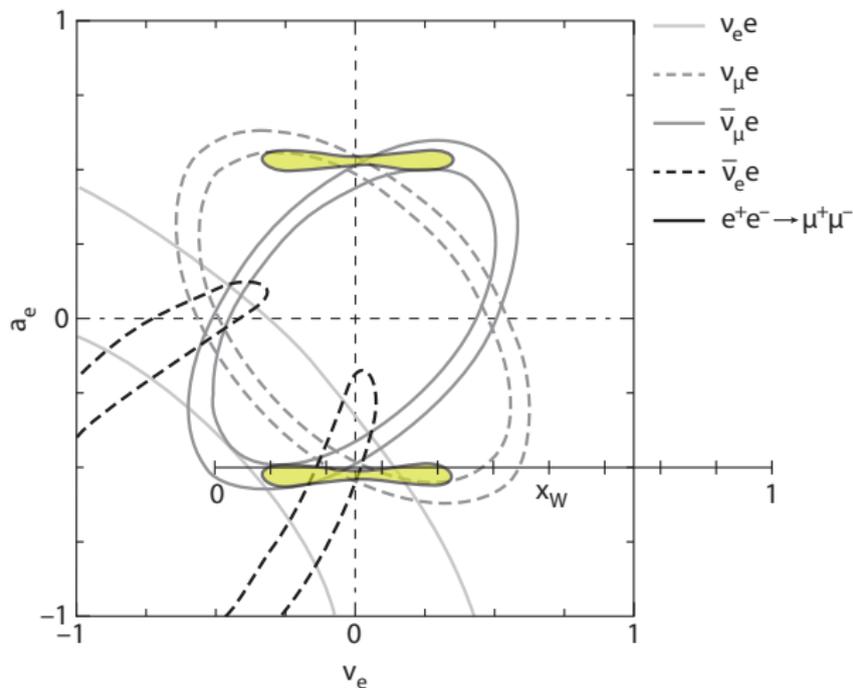
$$A \equiv \left(\int_0^1 dz d\sigma/dz - \int_{-1}^0 dz d\sigma/dz \right) / \int_{-1}^1 dz d\sigma/dz$$

$$\lim_{s/M_Z^2 \ll 1} A = \frac{3G_F s}{16\pi\alpha Q_\mu \sqrt{2}} (R_e - L_e)(R_\mu - L_\mu)$$

$$\approx -6.7 \times 10^{-5} \left(\frac{s}{1 \text{ GeV}^2} \right) (2a_e)(2a_\mu) = -\frac{3G_F s a^2}{4\pi\alpha \sqrt{2}}$$



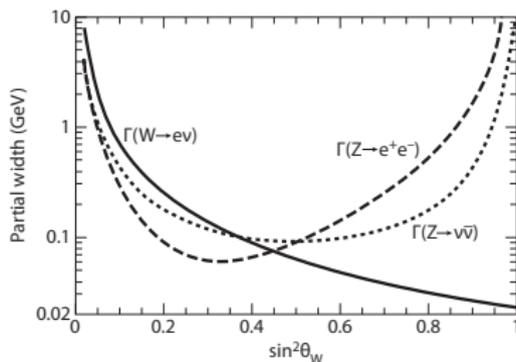
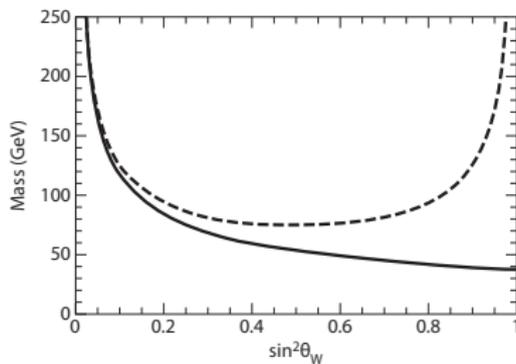
Neutrino-electron scattering + $e^+e^- \rightarrow \mu^+\mu^-$



Validate EW theory, measure $\sin^2 \theta_W$

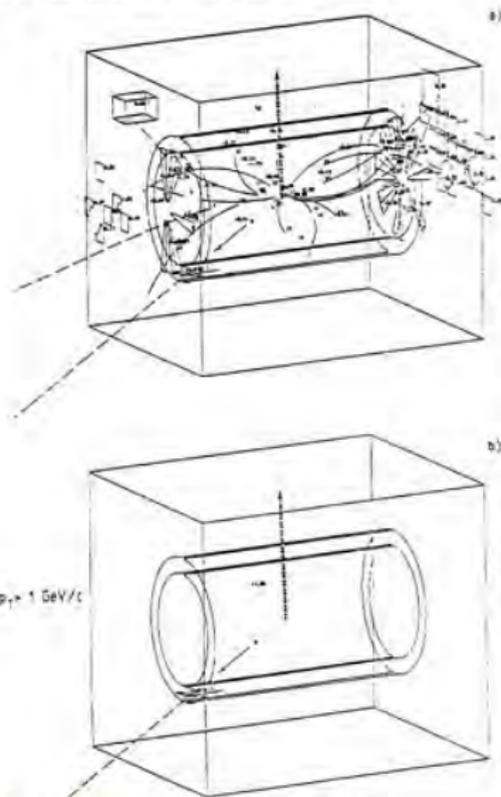
With a measurement of $\sin^2 \theta_W = \alpha/\alpha_2$, predict

$$M_W^2 = \pi\alpha/G_F\sqrt{2}\sin^2\theta_W \approx (37.28 \text{ GeV})^2/\sin^2\theta_W \quad M_Z^2 = M_W^2/\cos^2\theta_W$$



First Z from UA1

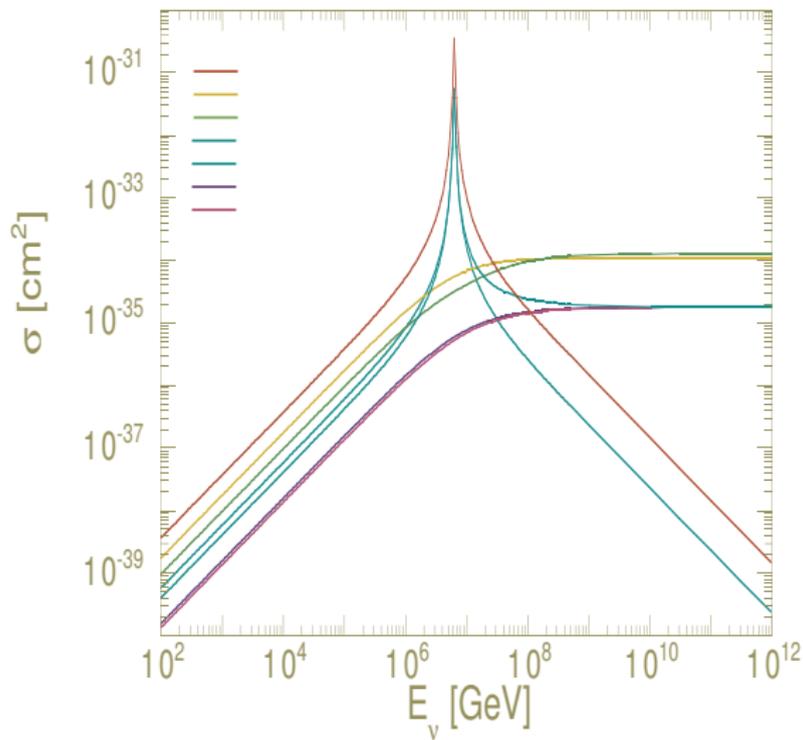
568 Intermediate Vector Bosons W^+ , W^- , and Z^0



CLibPDF / www.fastio.com

Fig. 16a,b

νe cross sections ...



At low energies: $\sigma(\bar{\nu}_e e \rightarrow \text{hadrons}) > \sigma(\nu_\mu e \rightarrow \mu \nu_e) > \sigma(\nu_e e \rightarrow \nu_e e) > \sigma(\bar{\nu}_e e \rightarrow \bar{\nu}_\mu \mu) > \sigma(\bar{\nu}_e e \rightarrow \bar{\nu}_e e) > \sigma(\nu_\mu e \rightarrow \nu_\mu e) > \sigma(\bar{\nu}_\mu e \rightarrow \bar{\nu}_\mu e)$

Electroweak interactions of quarks

- Left-handed doublet

$$L_q = \begin{pmatrix} u \\ d \end{pmatrix}_L \quad \begin{array}{ccc} I_3 & Q & Y = 2(Q - I_3) \\ \frac{1}{2} & +\frac{2}{3} & \frac{1}{3} \\ -\frac{1}{2} & -\frac{1}{3} & \end{array}$$

- two right-handed singlets

$$\begin{array}{ccc} & I_3 & Q & Y = 2(Q - I_3) \\ R_u = u_R & 0 & +\frac{2}{3} & +\frac{4}{3} \\ R_d = d_R & 0 & -\frac{1}{3} & -\frac{2}{3} \end{array}$$

Electroweak interactions of quarks

- CC interaction

$$\mathcal{L}_{W-q} = \frac{-g}{2\sqrt{2}} \left[\bar{u}_e \gamma^\mu (1 - \gamma_5) d W_\mu^+ + \bar{d} \gamma^\mu (1 - \gamma_5) u W_\mu^- \right]$$

identical in form to $\mathcal{L}_{W-\ell}$: universality \Leftrightarrow weak isospin

- NC interaction

$$\mathcal{L}_{Z-q} = \frac{-g}{4 \cos \theta_W} \sum_{i=u,d} \bar{q}_i \gamma^\mu [L_i(1 - \gamma_5) + R_i(1 + \gamma_5)] q_i Z_\mu$$

$$L_i = \tau_3 - 2Q_i \sin^2 \theta_W \quad R_i = -2Q_i \sin^2 \theta_W$$

equivalent in form (not numbers) to $\mathcal{L}_{Z-\ell}$

Trouble in Paradise

Universal $u \leftrightarrow d$, $\nu_e \leftrightarrow e$ not quite right

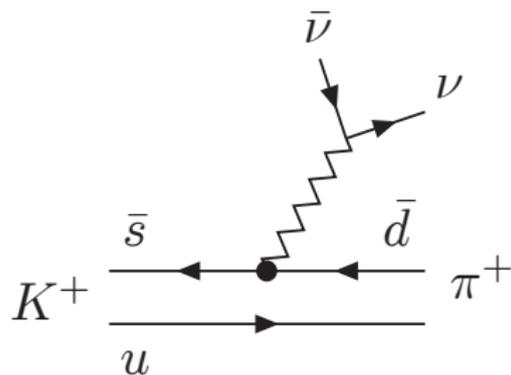
$$\text{Good: } \begin{pmatrix} u \\ d \end{pmatrix}_L \rightarrow \text{Better: } \begin{pmatrix} u \\ d_\theta \end{pmatrix}_L$$

$$d_\theta \equiv d \cos \theta_C + s \sin \theta_C \quad \cos \theta_C = 0.9736 \pm 0.0010$$

“Cabibbo-rotated” doublet perfects CC interaction (up to small third-generation effects) but \Rightarrow serious trouble for NC

$$\begin{aligned} \mathcal{L}_{Z-q} = & \frac{-g}{4 \cos \theta_W} Z_\mu \{ \bar{u} \gamma^\mu [L_u(1 - \gamma_5) + R_u(1 + \gamma_5)] u \\ & + \bar{d} \gamma^\mu [L_d(1 - \gamma_5) + R_d(1 + \gamma_5)] d \cos^2 \theta_C \\ & + \bar{s} \gamma^\mu [L_d(1 - \gamma_5) + R_d(1 + \gamma_5)] s \sin^2 \theta_C \\ & + \bar{d} \gamma^\mu [L_d(1 - \gamma_5) + R_d(1 + \gamma_5)] s \sin \theta_C \cos \theta_C \\ & + \bar{s} \gamma^\mu [L_d(1 - \gamma_5) + R_d(1 + \gamma_5)] d \sin \theta_C \cos \theta_C \} \end{aligned}$$

Strangeness-changing NC highly suppressed!



BNL E-787/E-949 has three
 $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ candidates, with
 $\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = 1.73_{-1.05}^{+1.15} \times 10^{-10}$
Phys. Rev. Lett. **101**, 191802 (2008)

(SM: ≈ 0.85 : Brod–Gorbahn, *Phys. Rev. D* **78**, 034008 (2008))

Glashow–Iliopoulos–Maiani

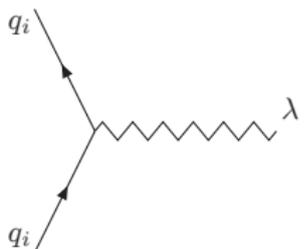
two LH doublets: $\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L$ $\begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}_L$ $\begin{pmatrix} u \\ d_\theta \end{pmatrix}_L$ $\begin{pmatrix} c \\ s_\theta \end{pmatrix}_L$

$$(s_\theta = s \cos \theta_C - d \sin \theta_C)$$

+ right-handed singlets, $e_R, \mu_R, u_R, d_R, c_R, s_R$

Required new charmed quark, c

Cross terms vanish in \mathcal{L}_{Z-q} ,



$$\frac{-ig}{4 \cos \theta_W} \gamma_\lambda [(1 - \gamma_5)L_i + (1 + \gamma_5)R_i] \quad ,$$

$$L_i = \tau_3 - 2Q_i \sin^2 \theta_W \quad R_i = -2Q_i \sin^2 \theta_W$$

flavor-diagonal interaction!

Straightforward generalization to n quark doublets

$$\mathcal{L}_{W-q} = \frac{-g}{2\sqrt{2}} [\bar{\Psi}\gamma^\mu(1 - \gamma_5)\mathcal{O}\Psi W_\mu^+ + \text{h.c.}]$$

composite $\Psi = \begin{pmatrix} u \\ c \\ \vdots \\ d \\ s \\ \vdots \end{pmatrix}$ flavor structure $\mathcal{O} = \begin{pmatrix} 0 & U \\ 0 & 0 \end{pmatrix}$

U : unitary quark mixing matrix

Weak-isospin part: $\mathcal{L}_{Z-q}^{\text{iso}} = \frac{-g}{4\cos\theta_W} \bar{\Psi}\gamma^\mu(1 - \gamma_5) [\mathcal{O}, \mathcal{O}^\dagger] \Psi$

Since $[\mathcal{O}, \mathcal{O}^\dagger] = \begin{pmatrix} I & 0 \\ 0 & -I \end{pmatrix} \propto \tau_3$

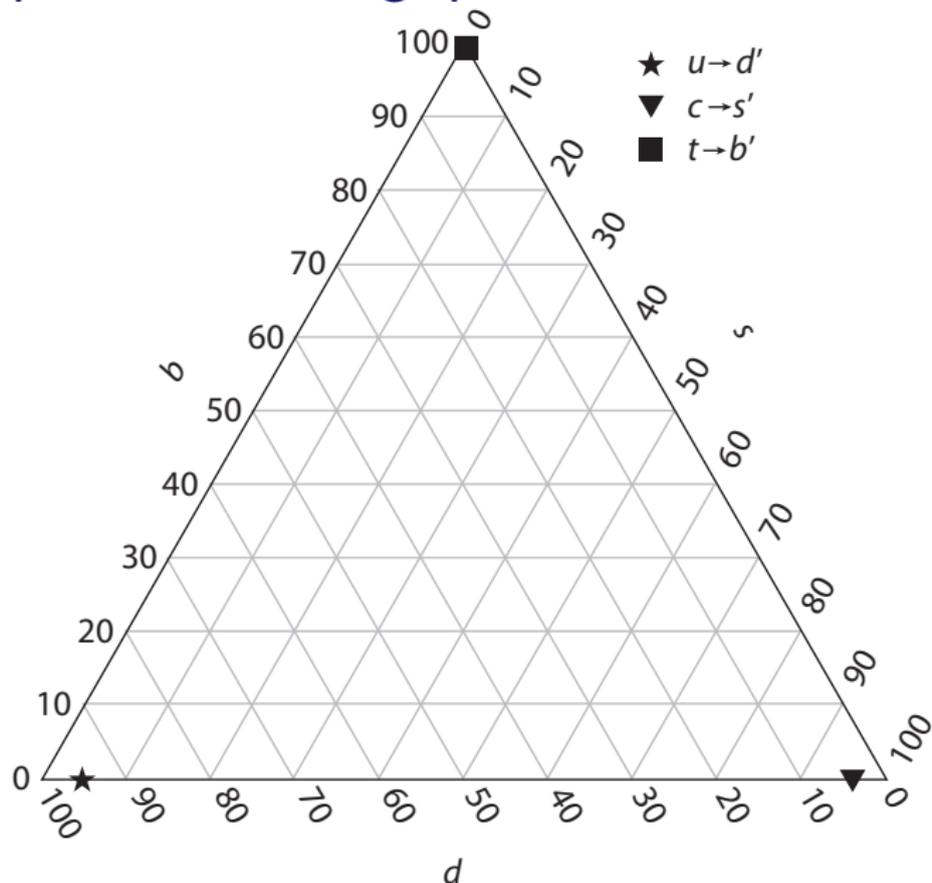
\Rightarrow NC interaction is flavor-diagonal

General $n \times n$ mixing matrix U : $n(n-1)/2$ real \angle , $(n-1)(n-2)/2$ complex phases

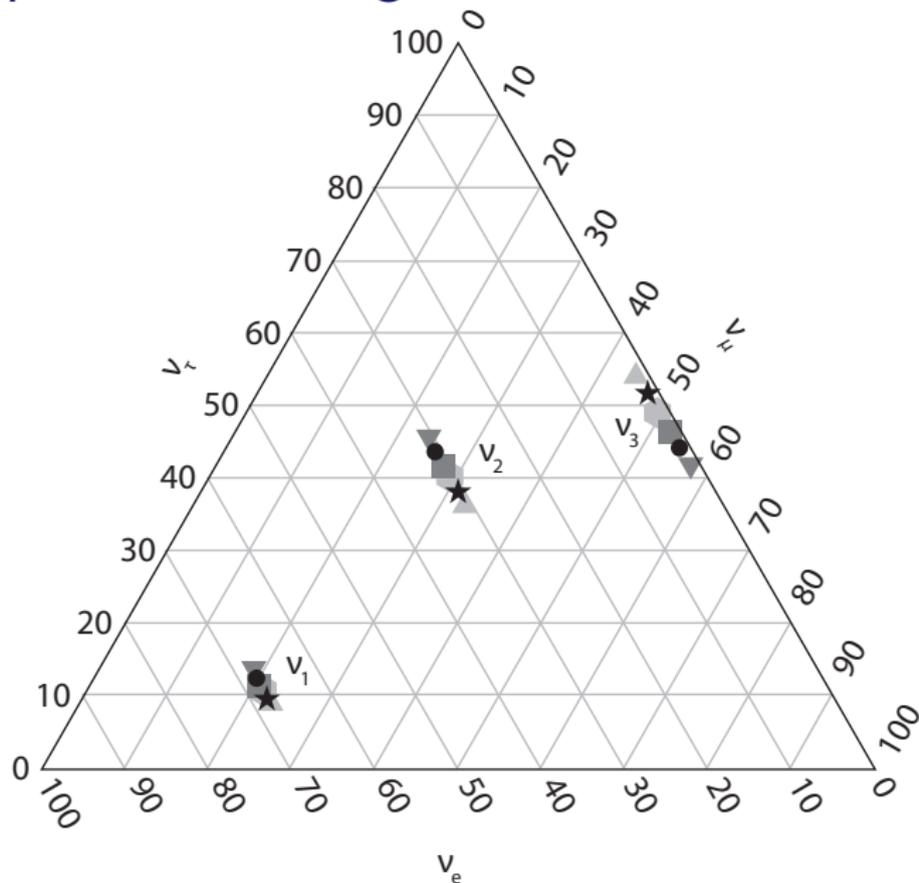
3×3 (Cabibbo–Kobayashi–Maskawa): 3 \angle + 1 phase

\Rightarrow CP violation

Family patterns among quarks



Family patterns among neutrinos



Problem 9

Refer to the master formula for γ - Z interference given in the expression [above](#) for $e^+e^- \rightarrow \mu^+\mu^-$.

(a) In the γ - Z interference regime, show that the asymmetries for heavy-quark production are

$$A(c\bar{c}) = \frac{3}{2}A(\mu^+\mu^-),$$

$$A(b\bar{b}) = 3A(\mu^+\mu^-).$$

(b) What values would you expect for these asymmetries at $\sqrt{s} = 40$ GeV?

Problem 10

Three observables concerning the b quark are sensitive to different combinations of the chiral couplings:

$\Gamma(Z^0 \rightarrow b\bar{b})$ is determined by $(L_b^2 + R_b^2)$, $A_{\text{peak}}^{(b\bar{b})}$ is sensitive to $(L_b^2 - R_b^2)/(L_b^2 + R_b^2)$, and the low-energy

forward-backward asymmetry $A(b\bar{b})$ is proportional to $(R_b - L_b)$. Generalize the standard $SU(2)_L \otimes U(1)_Y$ electroweak theory to include right-handed

charged-current interactions of b , so that

$L_b = \tau_{3L} - 2Q_b X_W$ and $R_b = \tau_{3R} - 2Q_b X_W$. Working to leading order, display allowed regions in the I_{3L} - I_{3R} plane and determine the weak-isospin quantum numbers of b .

For a thorough analysis and useful compendium of data, see D. Schaile and P. M. Zerwas, *Phys. Rev. D***45**, 3262 (1992).

Successful predictions of $SU(2)_L \otimes U(1)_Y$:

- neutral-current interactions
- necessity of charm
- existence and properties of W^\pm and Z^0

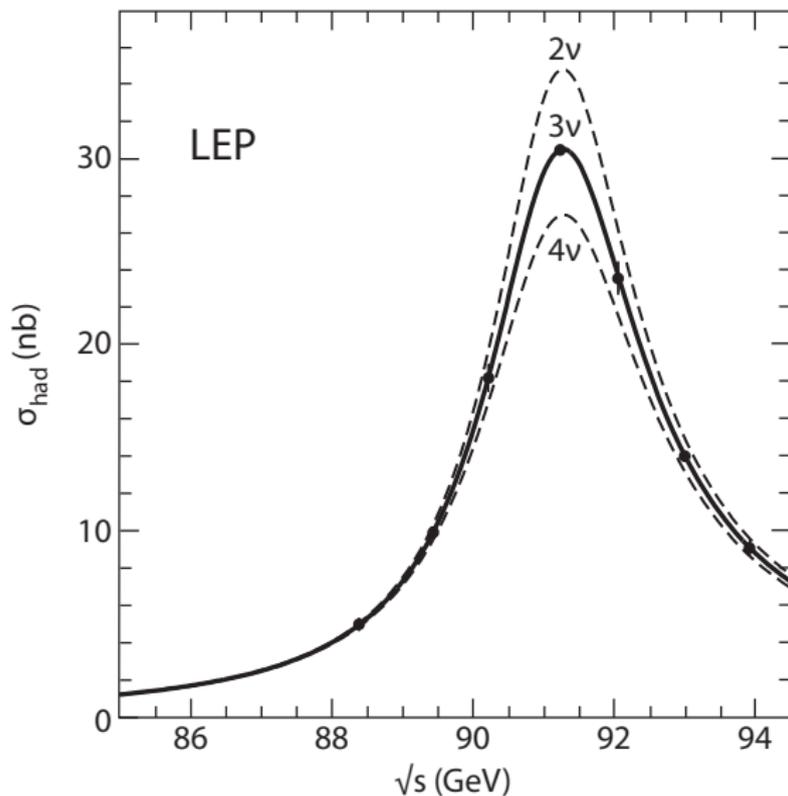
+ a decade of precision EW tests (one-per-mille)

M_Z	$91\,187.6 \pm 2.1$ MeV
Γ_Z	2495.2 ± 2.3 MeV
$\sigma_{\text{hadronic}}^0$	41.540 ± 0.037 nb
Γ_{hadronic}	1744.4 ± 2.0 MeV
Γ_{leptonic}	83.984 ± 0.086 MeV
$\Gamma_{\text{invisible}}$	499.0 ± 1.5 MeV

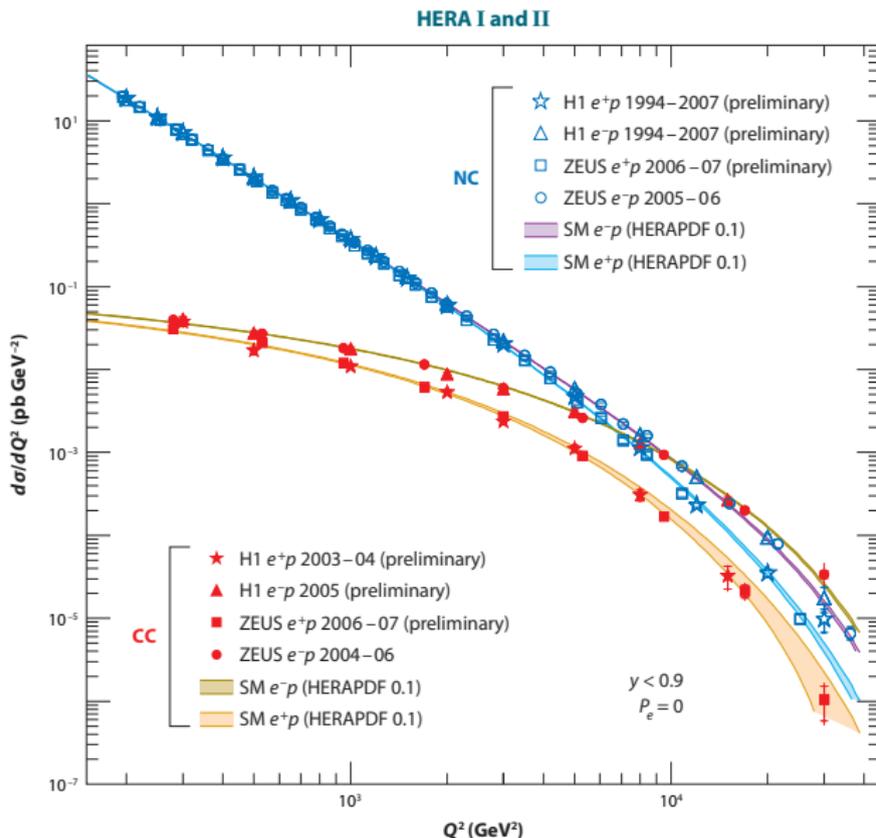
$$\Gamma_{\text{invisible}} \equiv \Gamma_Z - \Gamma_{\text{hadronic}} - 3\Gamma_{\text{leptonic}}$$

$$\text{light } \nu : N_\nu = \Gamma_{\text{invisible}}/\Gamma^{\text{SM}}(Z \rightarrow \nu_i \bar{\nu}_i) = 2.92 \pm 0.05 \quad (\nu_e, \nu_\mu, \nu_\tau)$$

Three light neutrinos

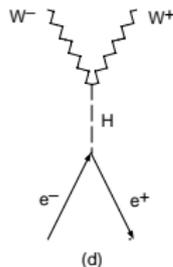
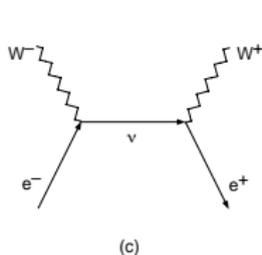
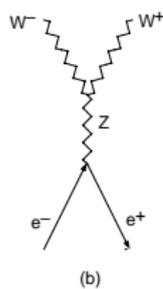
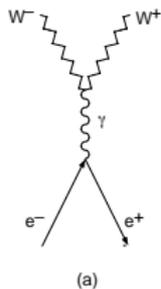


Electroweak theory tests: tree level



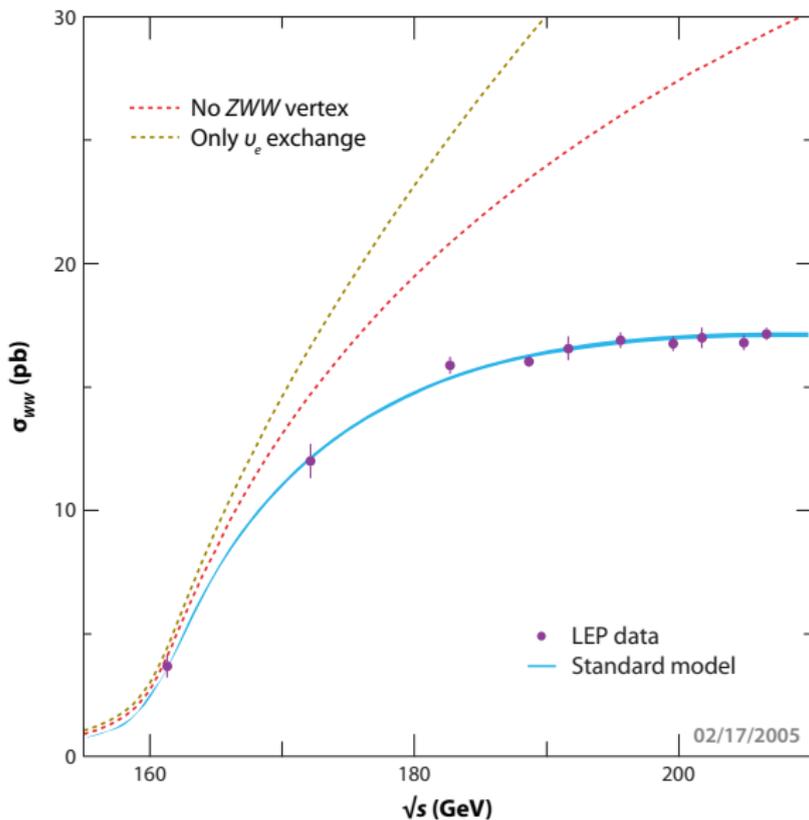
Electroweak theory tests: tree level

S -matrix analysis of $e^+e^- \rightarrow W^+W^-$



Individual $J = 1$ partial-wave amplitudes $\mathcal{M}_\gamma^{(1)}$, $\mathcal{M}_Z^{(1)}$, $\mathcal{M}_\nu^{(1)}$ have unacceptable high-energy behavior ($\propto s$)

Electroweak theory tests: tree level



... sum is well-behaved; gauge symmetry!

Why a Higgs boson “must” exist

$J = 0$ amplitude exists because electrons have mass, and can be found in “wrong” helicity state

$$\mathcal{M}_\nu^{(0)} \propto s^{\frac{1}{2}} : \text{unacceptable HE behavior}$$

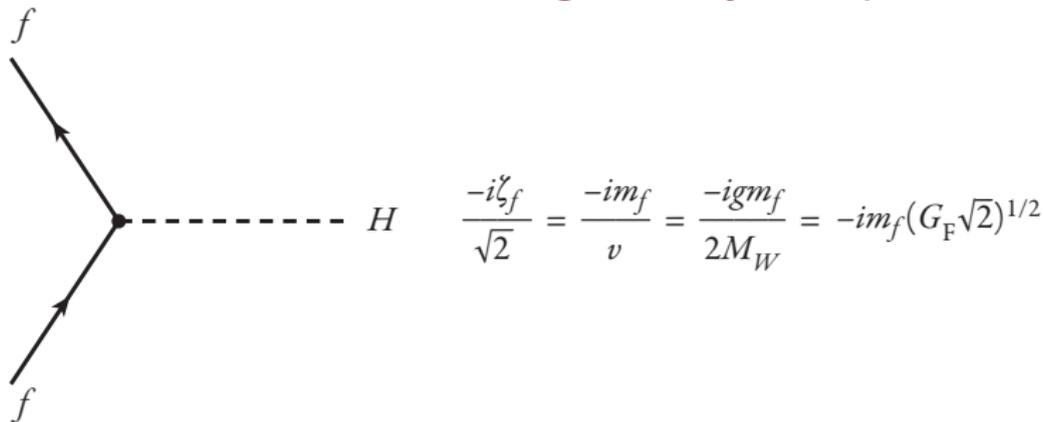
saturate p.w. unitarity at

$$\sqrt{s_e} \simeq \frac{4\pi\sqrt{2}}{\sqrt{3} G_F m_e} \approx 1.7 \times 10^9 \text{ GeV}$$

Divergence canceled by Higgs-boson contribution

$\Rightarrow H e \bar{e}$ coupling must be $\propto m_e$,

because “wrong-helicity” amplitudes $\propto m_e$



If the Higgs boson did not exist, something else would have to cure divergent behavior

If gauge symmetry were unbroken ...

- no Higgs boson; no longitudinal gauge bosons
- no extreme divergences; no wrong-helicity amplitudes

... and no viable low-energy phenomenology

In spontaneously broken theory ...

- gauge structure of couplings eliminates the most severe divergences
- lesser—but potentially fatal—divergence arises because the electron has mass ... due to SSB
- SSB provides its own cure—the Higgs boson

Similar interplay and compensation *must exist* in any acceptable theory

Anticipating m_t

$$\rho \equiv \frac{M_W^2}{M_Z^2 \cos^2 \theta_W}$$

measures relative strength of NC, CC at low energies

$$\sigma(\nu_\mu e \rightarrow \nu_\mu e) = \frac{G_F^2 m E}{2\pi} \rho^2 \left[(2x_W - 1)^2 + \frac{4x_W^2}{3} \right]$$

$$\sigma(\bar{\nu}_\mu e \rightarrow \bar{\nu}_\mu e) = \frac{G_F^2 m E}{2\pi} \rho^2 \left[\frac{(2x_W - 1)^2}{3} + 4x_W^2 \right]$$

$$\sigma(\nu_\mu e \rightarrow \mu \nu_e) = \frac{2G_F^2 m E}{\pi} \left[1 - (\mu^2 - m^2)/2mE \right]^2$$

Anticipating m_t

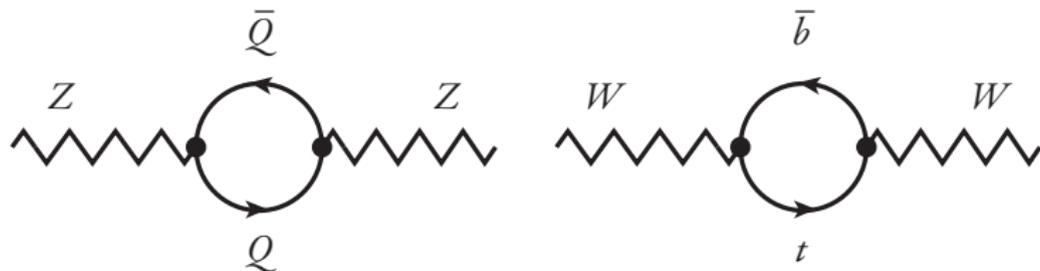
$\sigma(\nu_\mu e \rightarrow \nu_\mu e) / \sigma(\nu_\mu e \rightarrow \mu \nu_e)$ determines x_W
comparison of NC and CC cross sections yields ρ .

CHARM-II Collaboration:

$$\sin^2 \theta_W(\nu_\mu e) = 0.237 \pm 0.007 \text{ (stat.)} \pm 0.007 \text{ (sys.)}$$

$$\rho(\nu_\mu e) = 1.006 \pm 0.014 \text{ (stat.)} \pm 0.033 \text{ (sys.)}$$

SM with a single Higgs doublet, $\rho = 1$ at tree level.
Quantum corrections:



Anticipating m_t

With $\rho = 1 + \Delta\rho$,

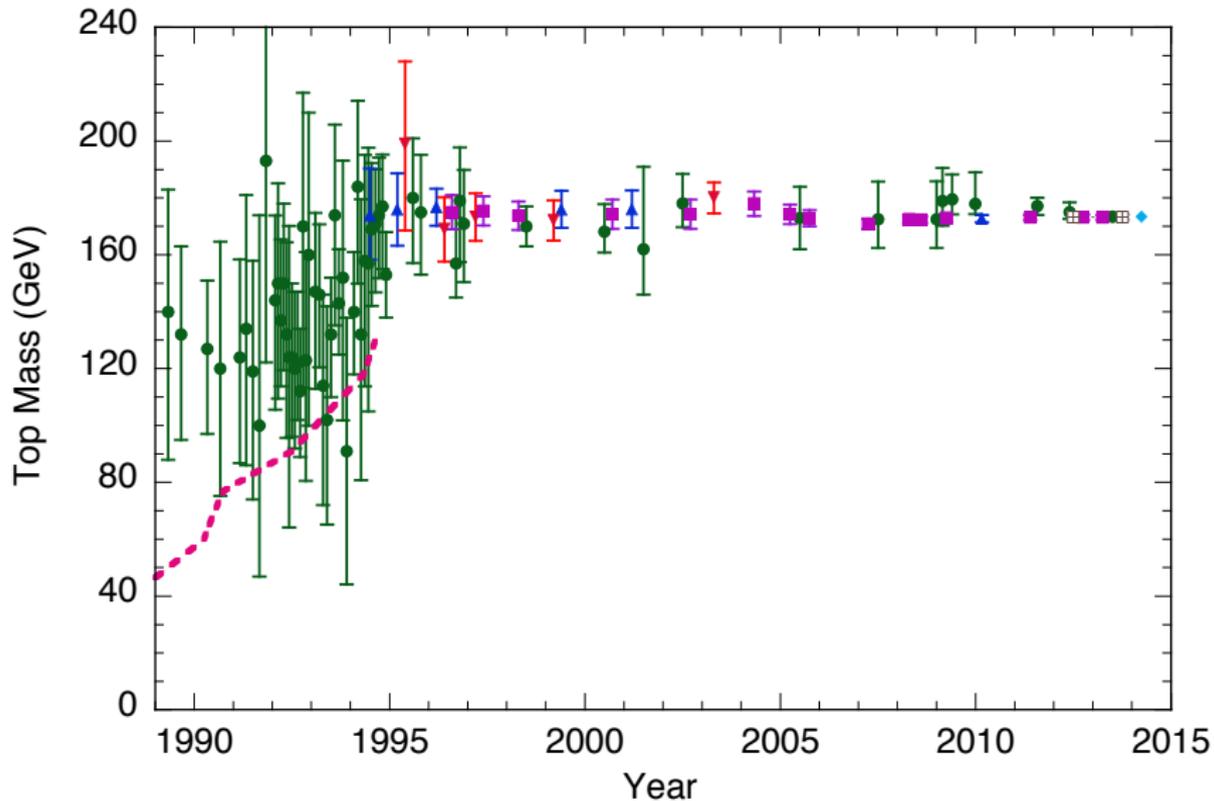
$$\Delta\rho = \frac{3G_F}{8\pi^2\sqrt{2}} \left[m_b^2 + m_t^2 + \frac{2m_t^2 m_b^2}{(m_t^2 - m_b^2)} \ln \left(\frac{m_b^2}{m_t^2} \right) \right].$$

- (i) In limit $m_b \rightarrow m_t$, $\Delta\rho \rightarrow 0$ independent of m_t ;
- (ii) In limit $m_b \ll m_t$

$$\Delta\rho \rightarrow \frac{3G_F m_t^2}{8\pi^2\sqrt{2}}.$$

Acute probe of m_t !

Electroweak theory tests: loop level



The importance of the 1-TeV scale ...

EW theory does not predict Higgs-boson mass

▷ Conditional *upper bound* from Unitarity

Compute amplitudes \mathcal{M} for gauge boson scattering at high energies, make a partial-wave decomposition

$$\mathcal{M}(s, t) = 16\pi \sum_J (2J + 1) a_J(s) P_J(\cos \theta)$$

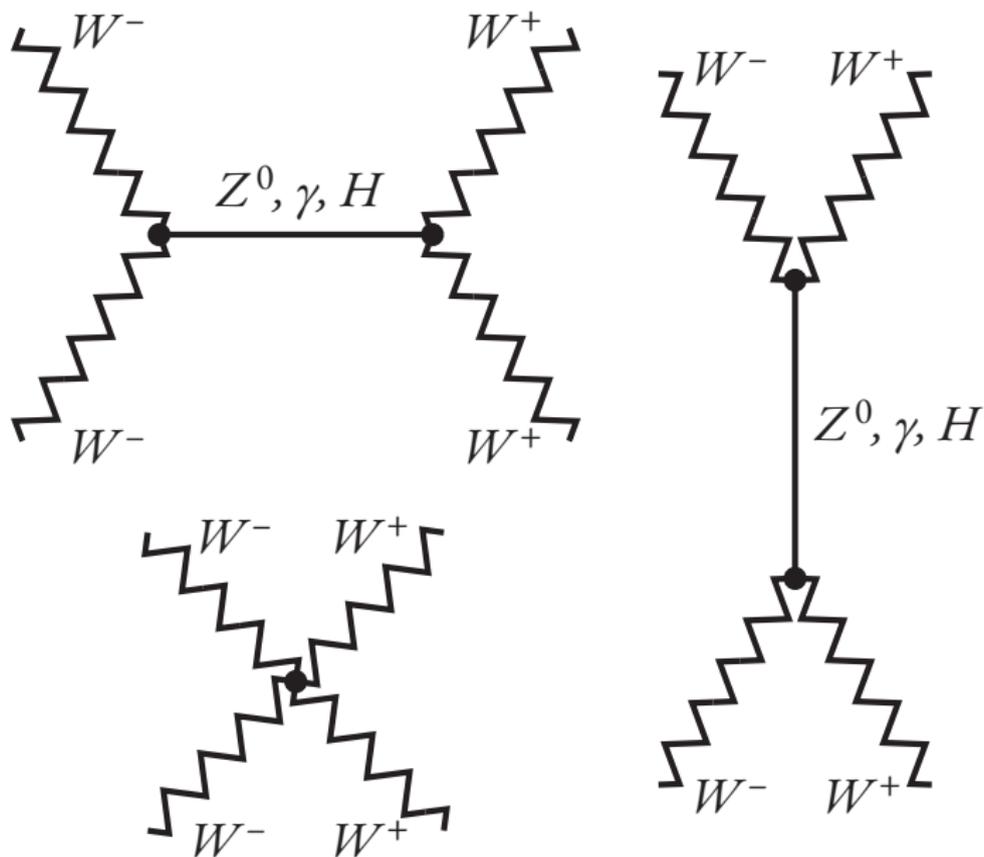
Most channels decouple – pw amplitudes are small at “all” energies – $\forall M_H$.

Four interesting channels:

$$W_L^+ W_L^- \quad Z_L^0 Z_L^0 / \sqrt{2} \quad HH / \sqrt{2} \quad HZ_L^0$$

L : longitudinal, $1/\sqrt{2}$ for identical particles

The importance of the 1-TeV scale ...



The importance of the 1-TeV scale . .

In HE limit, s -wave amplitudes $\propto G_F M_H^2$

$$\lim_{s \gg M_H^2} (a_0) \rightarrow \frac{-G_F M_H^2}{4\pi\sqrt{2}} \cdot \begin{bmatrix} 1 & 1/\sqrt{8} & 1/\sqrt{8} & 0 \\ 1/\sqrt{8} & 3/4 & 1/4 & 0 \\ 1/\sqrt{8} & 1/4 & 3/4 & 0 \\ 0 & 0 & 0 & 1/2 \end{bmatrix}$$

Require that largest eigenvalue respect partial-wave unitarity condition $|a_0| \leq 1$

$$\Rightarrow M_H \leq \left(\frac{8\pi\sqrt{2}}{3G_F} \right)^{1/2} \approx 1 \text{ TeV}$$

condition for perturbative unitarity

The importance of the 1-TeV scale . . .

If the bound is respected

- weak interactions remain weak at all energies
- perturbation theory is everywhere reliable

If the bound is violated

- perturbation theory breaks down
- weak interactions among W^\pm , Z , H become strong on 1-TeV scale

New phenomena are to be found in the EW interactions at energies not much larger than 1 TeV

Divergence cancellation in WW scattering

In general, the diagrams for WW scattering contribute

$$a_J = A(q/M_W)^4 + B(q/M_W)^2 + C$$

A terms cancelled by gauge symmetry

Residual B terms cancelled by Higgs exchange

C term scale set by M_H

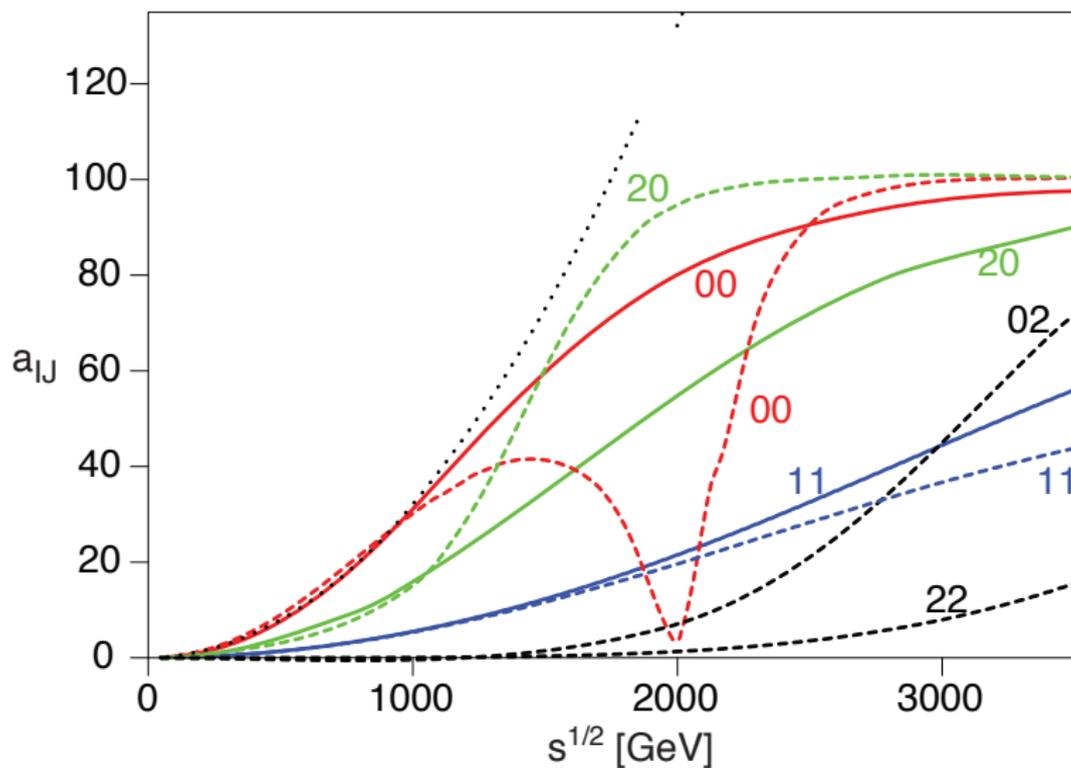
Higgs boson's key role in high-energy behavior

$a_{J=0}$ and a_{11} attractive; a_{20} repulsive

Motivates study of WW scattering at high energies

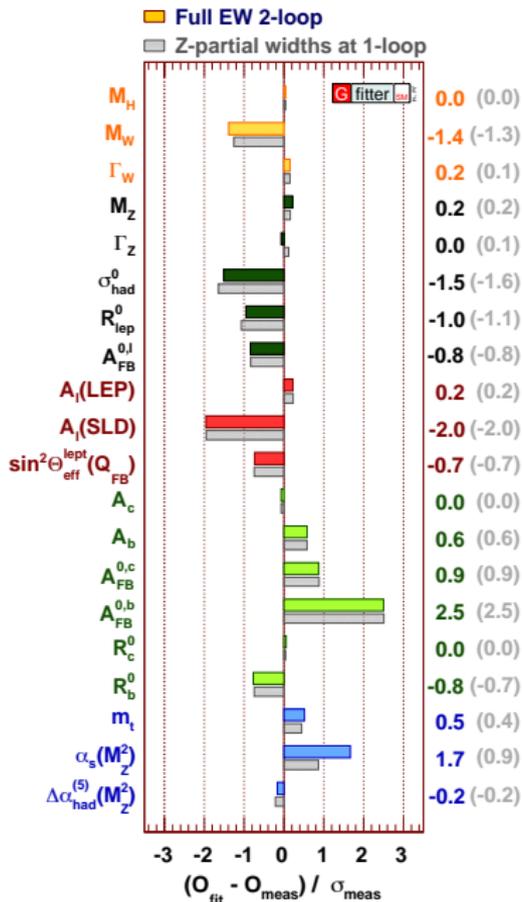
ATLAS $W^\pm W^\pm$ study

High-energy WW scattering (K -matrix unitarization)

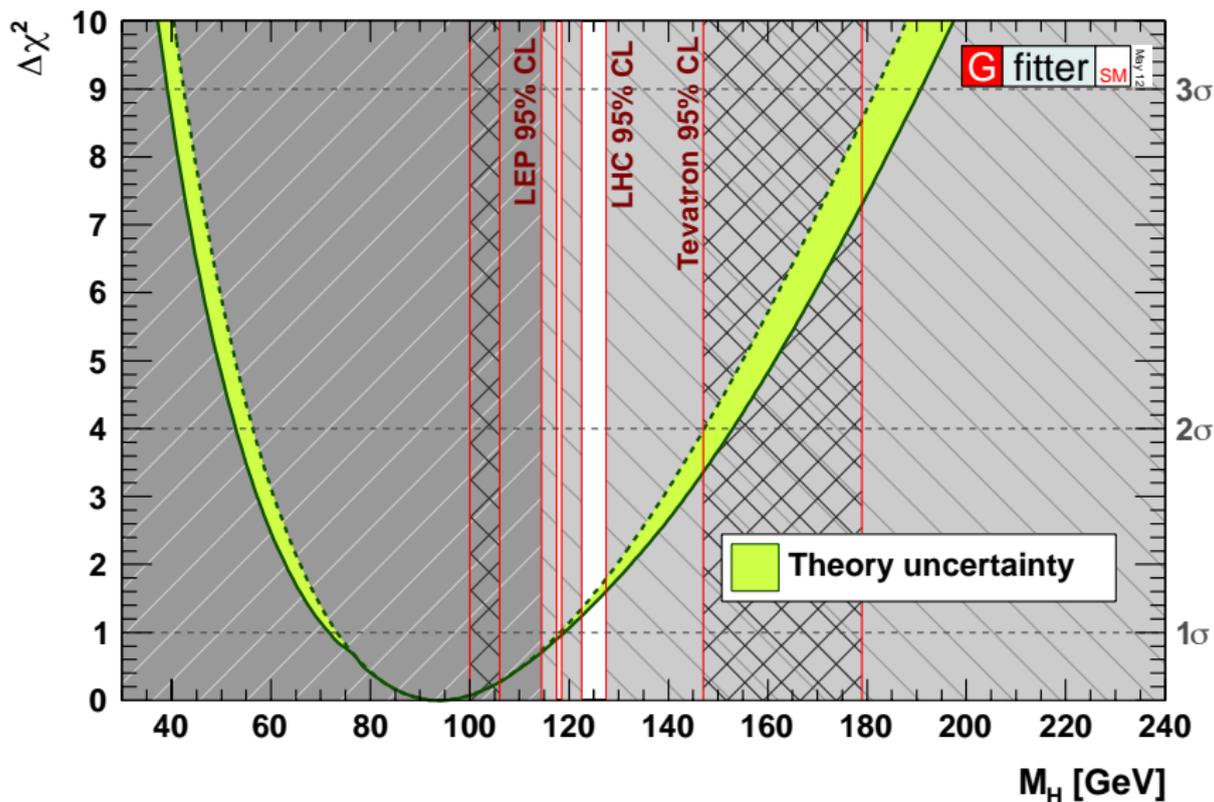


\cdots ununitarized a_{00} ; $—$ LO; $- -$ NLO

Electroweak theory tests: loop level (Gfitter *now*)



Electroweak theory tests: Higgs influence *before*



The Standard Model: Current Status & Open Questions

Chris Quigg

Fermilab

Unanswered Questions in the Electroweak Theory

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Key Words

electroweak symmetry breaking, Higgs boson, 1-TeV scale, Large Hadron Collider (LHC), hierarchy problem, extensions to the Standard Model

Abstract

This article is devoted to the status of the electroweak theory on the eve of experimentation at CERN's Large Hadron Collider (LHC). A compact summary of the logic and structure of the electroweak theory precedes an examination of what experimental tests have established so far. The outstanding unconfirmed prediction is the existence of the Higgs boson, a weakly interacting spin-zero agent of electroweak symmetry breaking and the giver of mass to the weak gauge bosons, the quarks, and the leptons. General arguments imply that the Higgs boson or other new physics is required on the 1-TeV energy scale.

Even if a "standard" Higgs boson is found, new physics will be implicated by many questions about the physical world that the Standard Model cannot answer. Some puzzles and possible resolutions are recalled. The LHC moves experiments squarely into the 1-TeV scale, where answers to important outstanding questions will be found.

What is the nature of the mysterious new force that hides electroweak symmetry?

- A *fifth* fundamental force of a new character, based on interactions of an elementary scalar
- A new gauge force, perhaps acting on undiscovered constituents
- A residual force that emerges from strong dynamics among the weak gauge bosons
- An echo of extra spacetime dimensions

We have explored examples of all four, theoretically.

Which path has Nature taken?

Search for the Standard-Model Higgs Boson

$$\Gamma(H \rightarrow f\bar{f}) = \frac{G_F m_f^2 M_H}{4\pi\sqrt{2}} \cdot N_c \cdot \left(1 - \frac{4m_f^2}{M_H^2}\right)^{3/2}$$

$\propto M_H$ in the limit of large Higgs mass; $\propto \beta^3$ for scalar

$$\Gamma(H \rightarrow W^+W^-) = \frac{G_F M_H^3}{32\pi\sqrt{2}} (1-x)^{1/2} (4-4x+3x^2) \quad x \equiv 4M_W^2/M_H^2$$

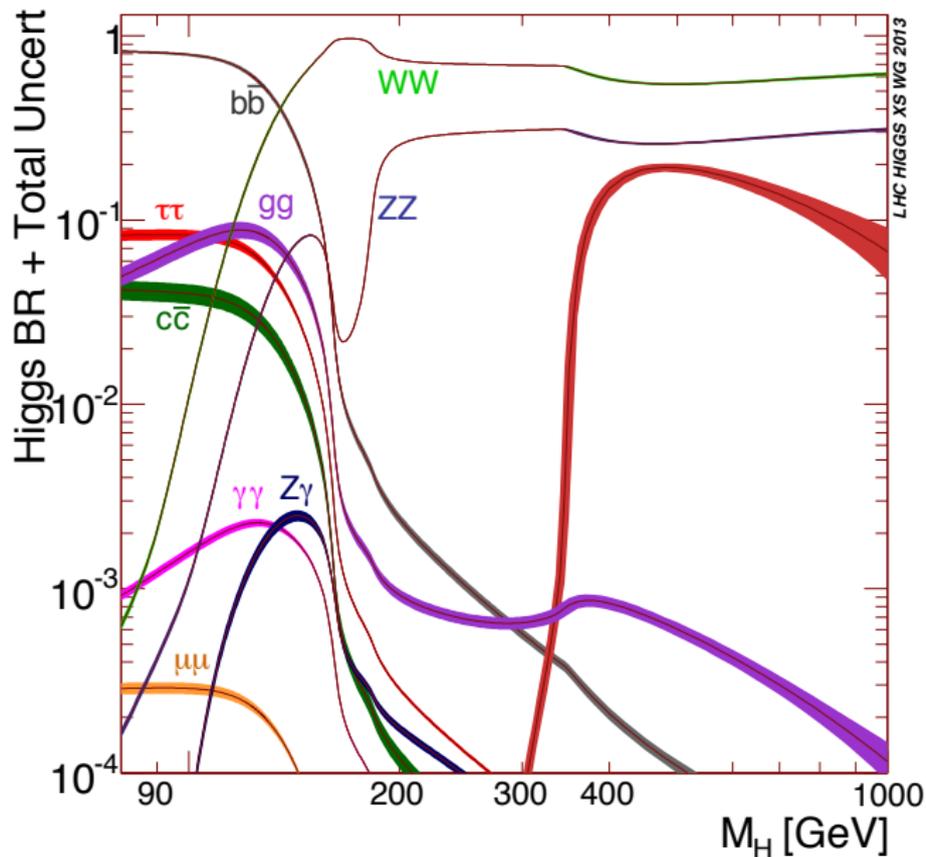
$$\Gamma(H \rightarrow Z^0Z^0) = \frac{G_F M_H^3}{64\pi\sqrt{2}} (1-x')^{1/2} (4-4x'+3x'^2) \quad x' \equiv 4M_Z^2/M_H^2$$

asymptotically $\propto M_H^3$ and $\frac{1}{2}M_H^3$, respectively

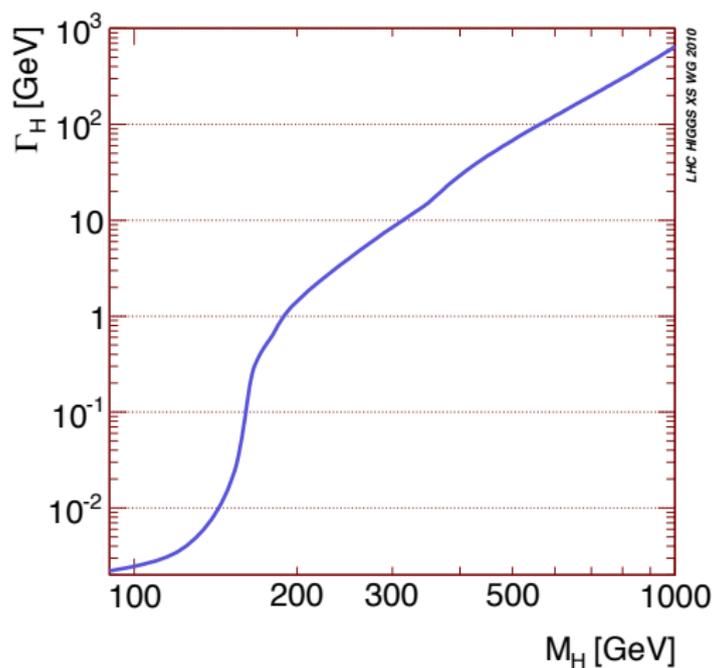
$2x^2$ and $2x'^2$ terms \Leftrightarrow decays into transverse gauge bosons

Dominant decays for large M_H : pairs of longitudinal weak bosons

Standard-model Higgs Boson Branching Fractions



Total width of the standard-model Higgs boson



Below W^+W^- threshold, $\Gamma_H \lesssim 1$ GeV

Far above W^+W^- threshold, $\Gamma_H \propto M_H^3$

A few words on Higgs production ...

$e^+e^- \rightarrow H$: hopelessly small

$\mu^+\mu^- \rightarrow H$: scaled by $(m_\mu/m_e)^2 \approx 40\,000$

$e^+e^- \rightarrow HZ$: prime channel

Hadron colliders:

$gg \rightarrow H \rightarrow b\bar{b}$: background ?!

$gg \rightarrow H \rightarrow \tau\tau, \gamma\gamma$: rate ?!

$gg \rightarrow H \rightarrow W^+W^-$: best Tevatron sensitivity

$\bar{p}p \rightarrow H(W, Z)$: prime Tevatron channel for light Higgs

At the LHC:

Many channels accessible, search sensitive up to 1 TeV

Higgs search in e^+e^- collisions

$\sigma(e^+e^- \rightarrow H \rightarrow \text{all})$ is *minute*, $\propto m_e^2$

Even narrowness of low-mass H is not enough to make it visible ... Sets aside a traditional strength of e^+e^- machines—*pole physics*

Most promising:

associated production $e^+e^- \rightarrow HZ$
(has no small couplings)

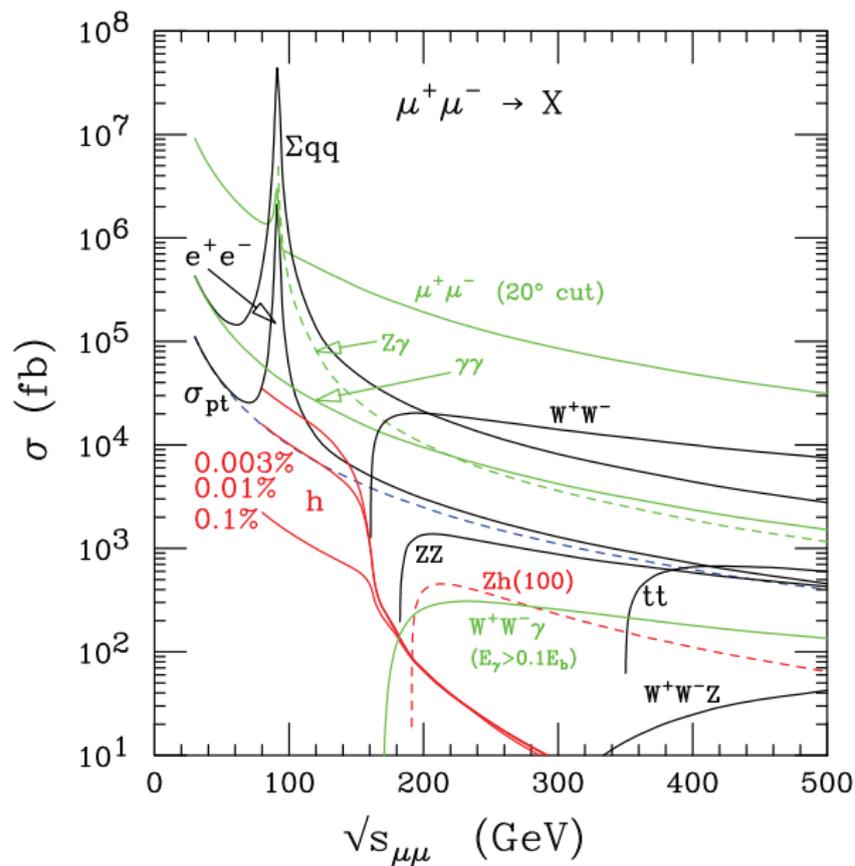


$$\sigma = \frac{\pi\alpha^2}{24\sqrt{s}} \frac{K(K^2 + 3M_Z^2)[1 + (1 - 4x_W)^2]}{(s - M_Z^2)^2 x_W^2(1 - x_W)^2}$$

K : c.m. momentum of H

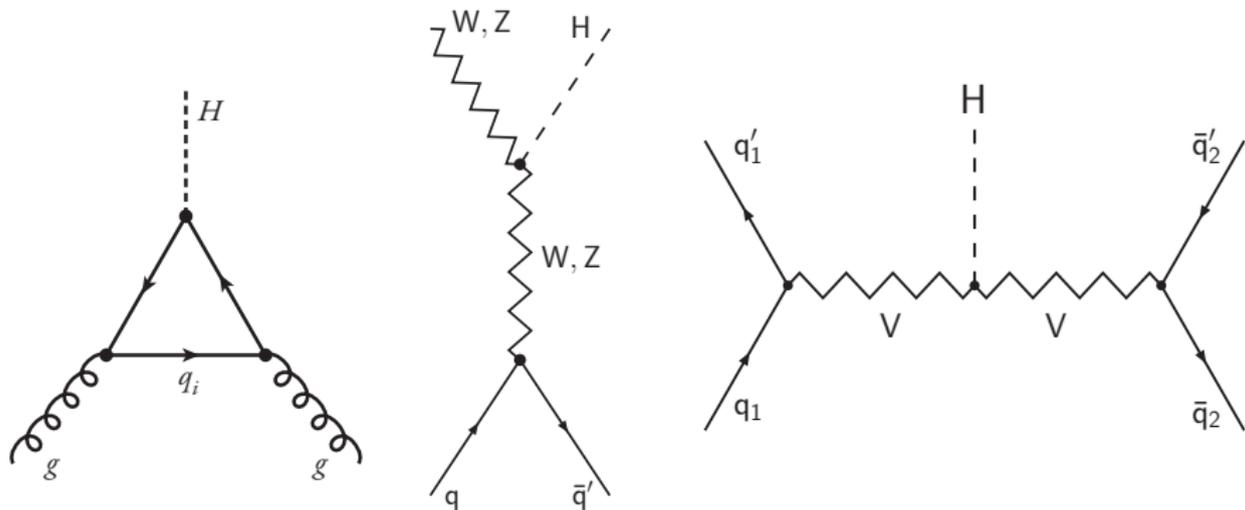
$x_W \equiv \sin^2 \theta_W$

$$l^+l^- \rightarrow X \dots$$



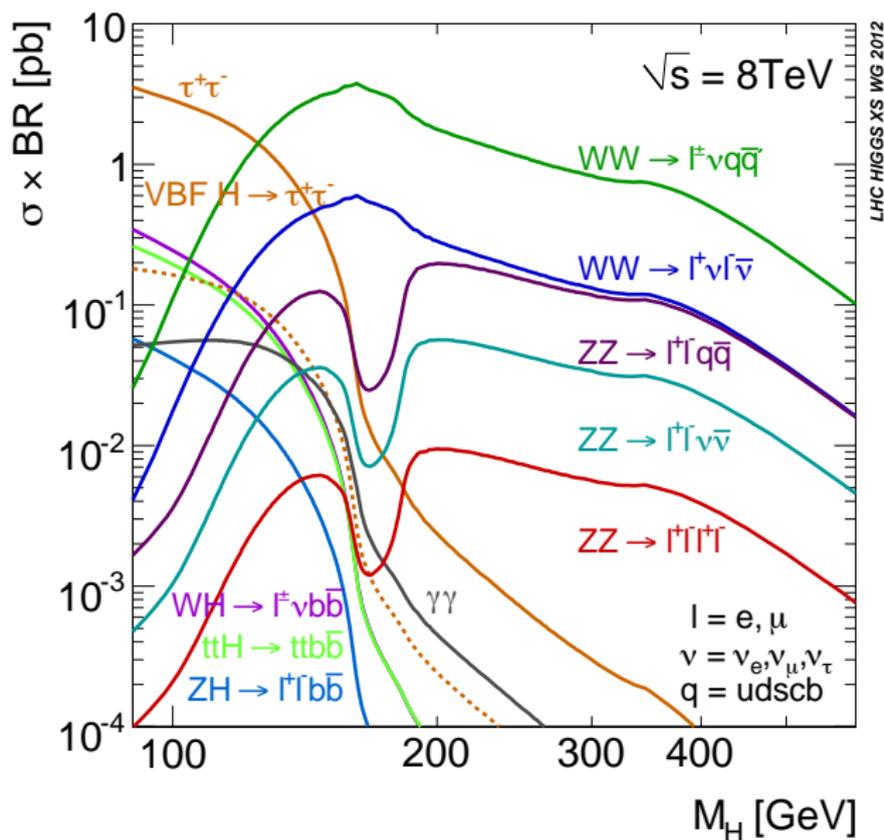
LHC: Multiple looks at the new boson

3 production mechanisms, ≥ 5 decay modes

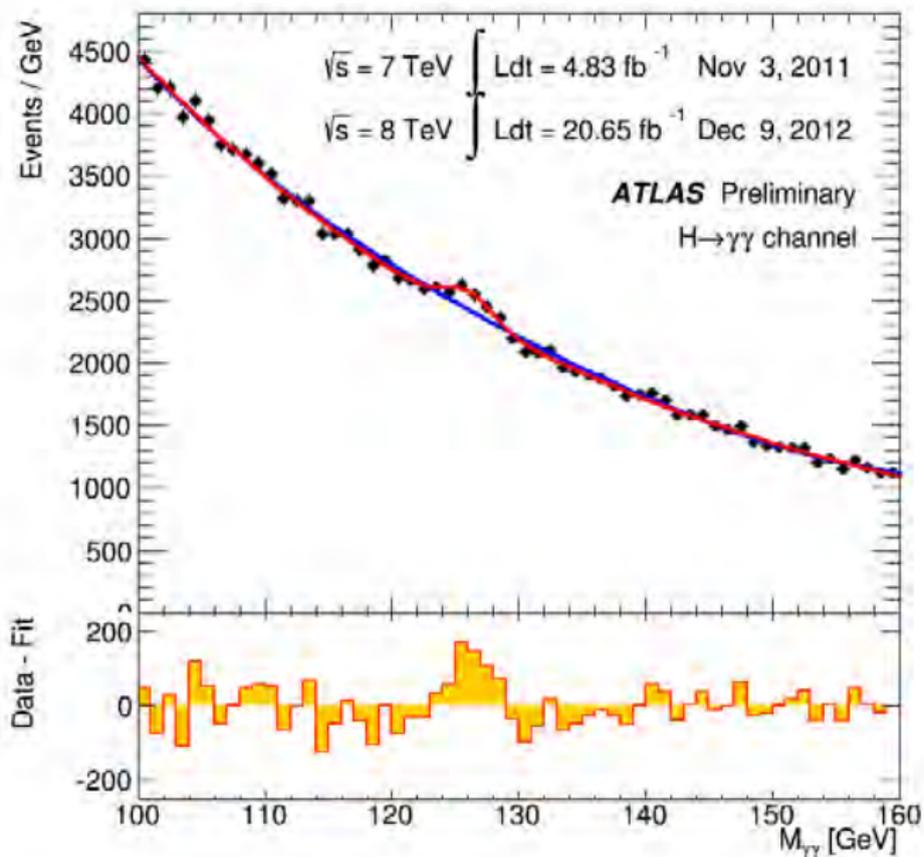


$\gamma\gamma, WW^*, ZZ^*, b\bar{b}, \tau^+\tau^-, Z\gamma(?)$

Higgs-boson production and decay: 8 TeV

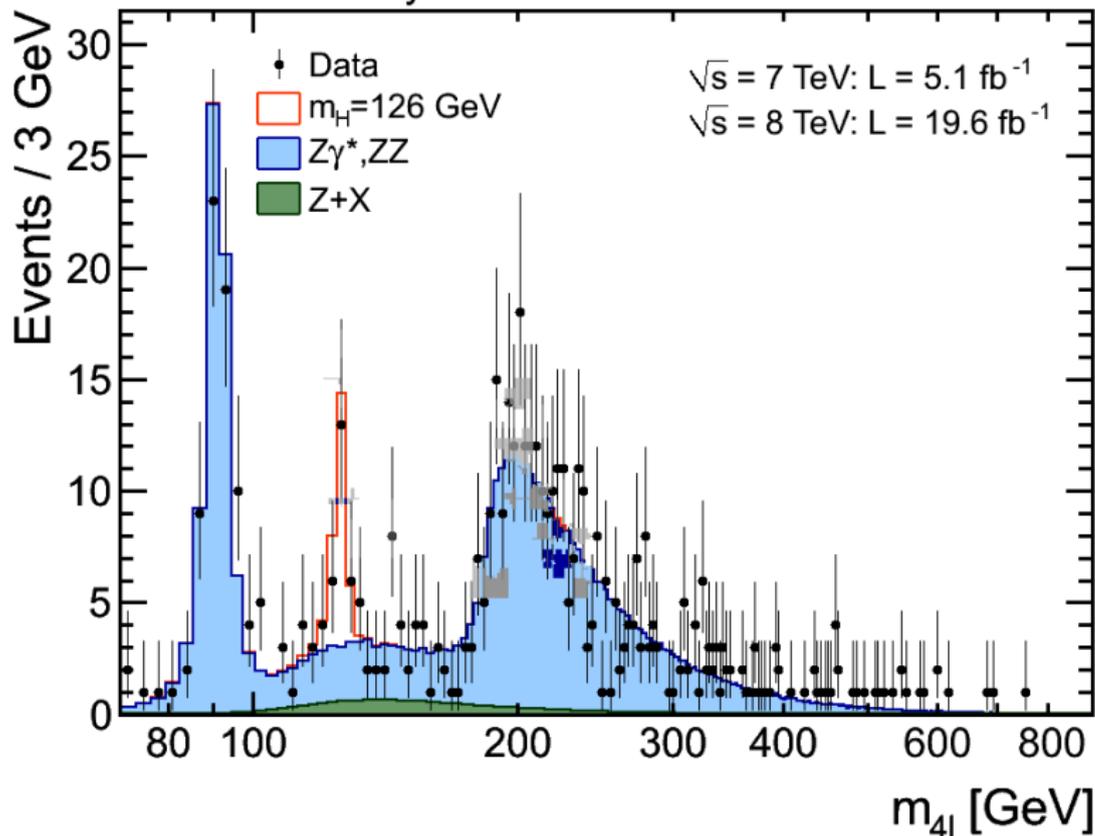


ATLAS $\gamma\gamma$ signal 2013

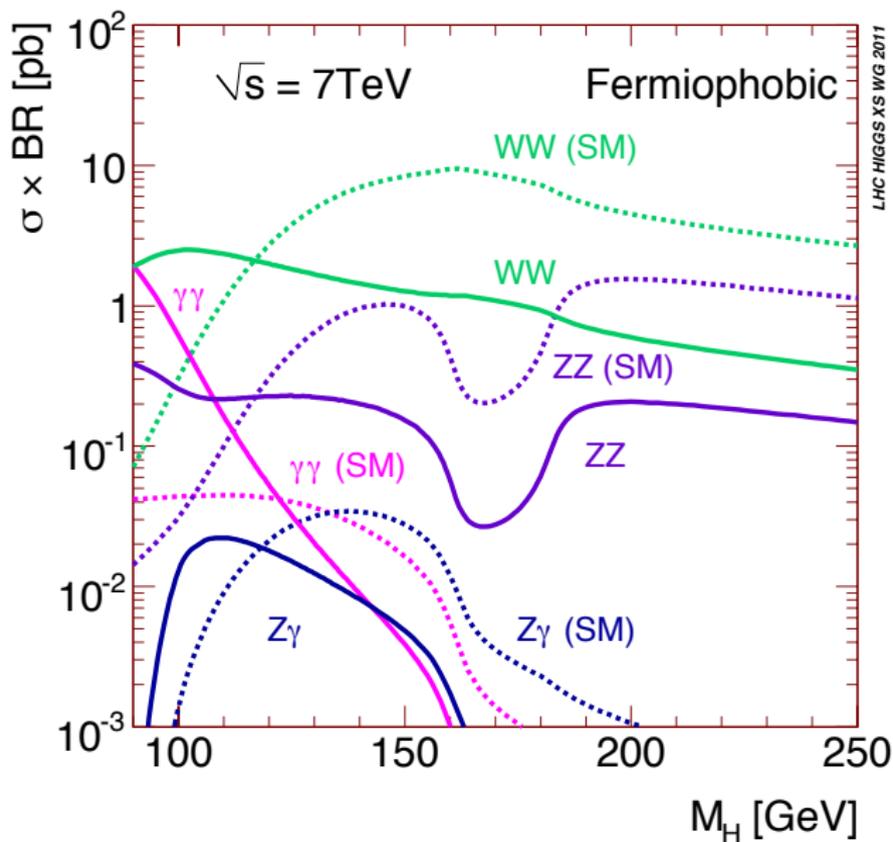


CMS 4μ signal 2013

CMS Preliminary



Distinguishing SM, bosogamous Higgs bosons



Problem 11

Suppose that a signal for a putative Higgs boson is found in the $\gamma\gamma$, W^+W^- , and ZZ channels with a mass $M_H = 125$ GeV. Refer to the products of production cross section times branching fraction shown in the figure on the [preceding page](#).

- What values of $\sigma \times \text{BR}$ are expected for the three rates in the standard electroweak theory?
- What values of $\sigma \times \text{BR}$ are expected if the “Higgs boson” does not couple at all to fermions?
- How precisely must the rates be determined by experiment to distinguish between the standard and bosogamous alternatives?

Evolution of evidence at the LHC

Evidence is developing as it would for
a “standard-model” Higgs boson

Unstable neutral particle near 125 GeV

ATLAS: $M_H = 125.36 \pm 0.37$ (stat) ± 0.18 (syst) GeV

CMS: $M_H = 125.03^{+0.26}_{-0.27}$ (stat) $^{+0.13}_{-0.15}$ (syst) GeV

decays to $\gamma\gamma$, W^+W^- , ZZ

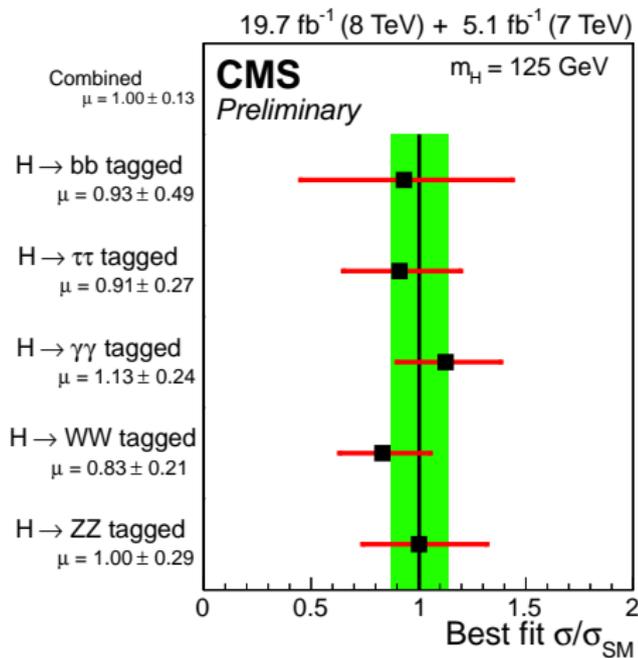
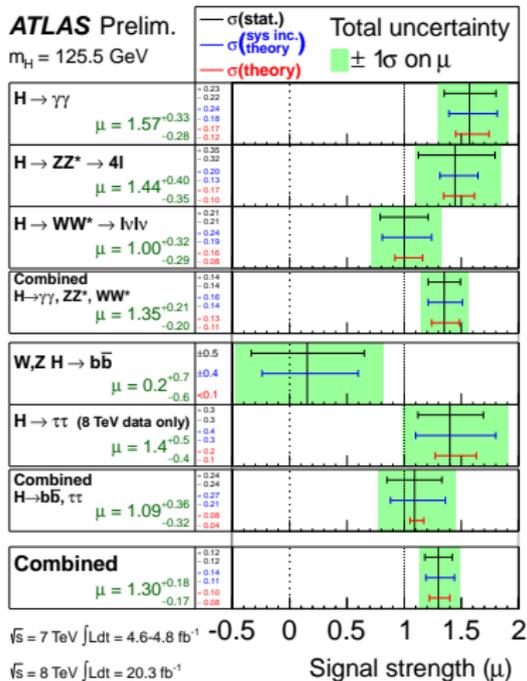
likely spin-parity 0^+

evidence for $\tau^+\tau^-$, $b\bar{b}$; $t\bar{t}$ from production
only third-generation fermions tested

Links to ATLAS & CMS Results

ATLAS

CMS



Problem 12

Understanding the everyday world. What would the world be like, without a (Higgs) mechanism to hide electroweak symmetry and give masses to the quarks and leptons?

(No EWSB agent at $v \approx 246$ GeV)

Consider effects of **all** standard-model interactions!

$$SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$$

What would I tell my mother?



Why Electroweak Symmetry Breaking Matters

PHYSICAL REVIEW D **79**, 096002 (2009)

Gedanken worlds without Higgs fields: QCD-induced electroweak symmetry breaking

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(Received 29 January 2009; published 4 May 2009)

To illuminate how electroweak symmetry breaking shapes the physical world, we investigate toy models in which no Higgs fields or other constructs are introduced to induce spontaneous symmetry breaking. Two models incorporate the standard $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$ gauge symmetry and fermion content similar to that of the standard model. The first class—like the standard electroweak theory—contains no bare mass terms, so the spontaneous breaking of chiral symmetry within quantum chromodynamics is the only source of electroweak symmetry breaking. The second class adds bare fermion masses sufficiently small that QCD remains the dominant source of electroweak symmetry breaking and the model can serve as a well-behaved low-energy effective field theory to energies somewhat above the hadronic scale. A third class of models is based on the left-right-symmetric $SU(3)_c \otimes SU(2)_L \otimes SU(2)_R \otimes U(1)$ gauge group. In a fourth class of models, built on $SU(4)_{PS} \otimes SU(2)_L \otimes SU(2)_R$ gauge symmetry, the lepton number is treated as a fourth color and the color gauge group is enlarged to the $SU(4)_{PS}$ of Pati and Salam (PS). Many interesting characteristics of the models stem from the fact that the effective strength of the weak interactions is much closer to that of the residual strong interactions than in the real world. The Higgs-free models not only provide informative contrasts to the real world, but also lead us to consider intriguing issues in the application of field theory to the real world.

DOI: [10.1103/PhysRevD.79.096002](https://doi.org/10.1103/PhysRevD.79.096002)

PACS numbers: 11.15.-q, 12.10.-g, 12.60.-i

Without a Higgs mechanism . . .

Electron and quarks would have no mass

QCD would confine quarks into protons, etc.

Nucleon mass little changed

Surprise: QCD would hide EW symmetry,
give tiny masses to W, Z

Massless electron: *atoms lose integrity*

No atoms means no chemistry, no stable composite structures like liquids, solids, . . . no template for life.

Character of the world would be utterly different

Questions for ATLAS and CMS

Fully accounts for EWSB (W, Z couplings)?

Couples to fermions?

Top from production, need direct observation for b, τ

Accounts for fermion masses?

Fermion couplings \propto masses?

Are there others?

Quantum numbers?

SM branching fractions to gauge bosons?

Decays to new particles? via new forces?

All production modes as expected?

Implications of $M_H \approx 125$ GeV?

Any sign of new strong dynamics?

Standard-model shortcomings

- No explanation of Higgs potential
- No prediction for M_H
- Doesn't predict fermion masses & mixings
- M_H unstable to quantum corrections
- No explanation of charge quantization
- Doesn't account for three generations
- Vacuum energy problem
- Beyond scope: dark matter, matter asymmetry, etc.

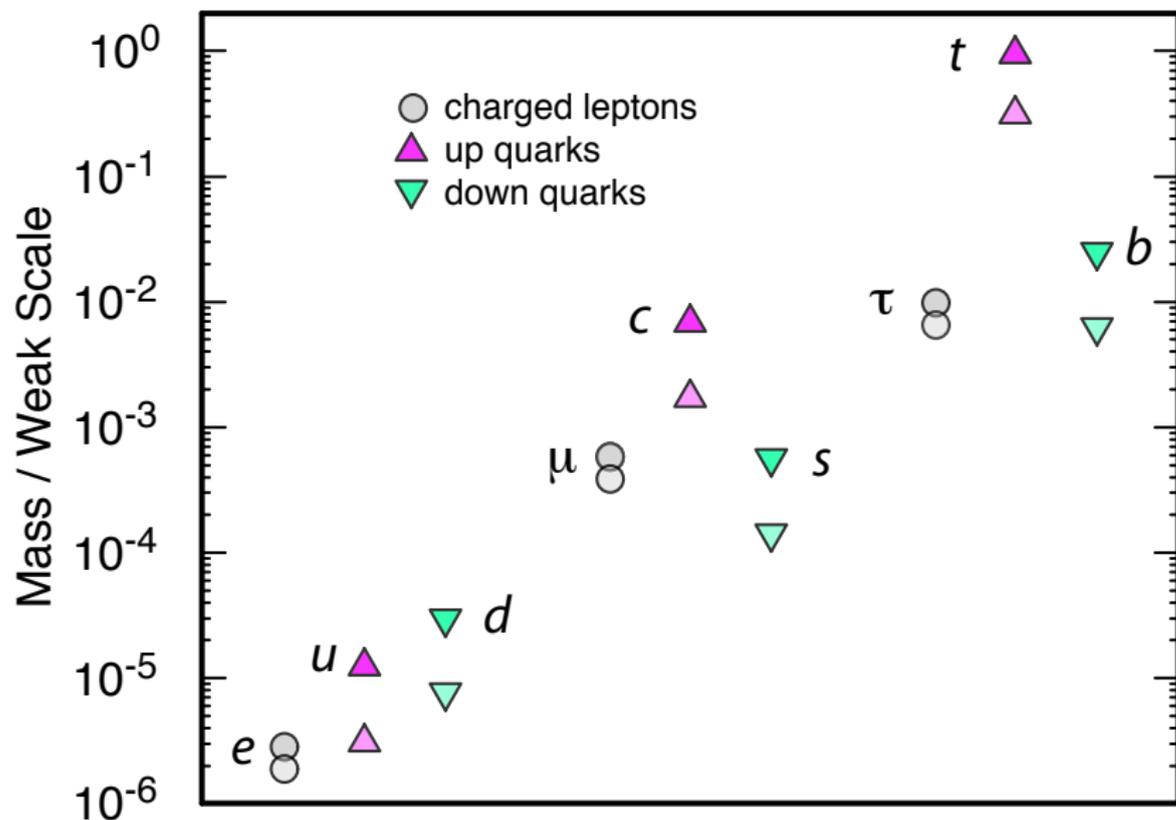
~> imagine more complete, predictive extensions

Parameters of the Standard Model

- 3 coupling parameters: α_s , α_{EM} , $\sin^2 \theta_W$
- 2 parameters of the Higgs potential
- 1 vacuum phase of QCD
- 6 quark masses
- 3 quark mixing angles
- 1 CP-violating phase
- 3 charged-lepton masses
- 3 neutrino masses
- 3 leptonic mixing angles
- 1 leptonic CP-violating phase (+ Majorana)

≥ 26 arbitrary parameters

Fermion mass is accommodated, not explained



Flavor physics . . . \rightsquigarrow S. Stone Lectures
may be where we see, or diagnose, the break in the SM

Some opportunities (see [Buras, Flavour Theory: 2009](#))

- CKM matrix from tree-level decays (LHC**b**)
- $\mathcal{B}(B_{s,d} \rightarrow \mu^+ \mu^-)$
- $D^0 - \bar{D}^0$ mixing; CP violation
- FCNC in top decay: $t \rightarrow (c, u)\ell^+ \ell^-$, etc.
- Correlate virtual effects with direct detection of new particles to test identification
- Tevatron experiments demonstrate capacity for very precise measurements: e.g., B_s mixing.

All fermion mass is physics beyond the standard model!

The unreasonable effectiveness of the Standard Model

Issues for the Future (Now!)

- 1 What is the agent that hides electroweak symmetry? Might there be several Higgs bosons?
- 2 Is the “Higgs boson” elementary or composite? How does the Higgs boson interact with itself? What triggers electroweak symmetry breaking?
- 3 Does the Higgs boson give mass to fermions, or only to the weak bosons? What sets the masses and mixings of the quarks and leptons? (*How*) is fermion mass related to the electroweak scale?
- 4 Are there new flavor symmetries that give insights into fermion masses and mixings?
- 5 What stabilizes M_H below 1 TeV?

Issues for the Future (Now!)

- 6 Does the different behavior of LH and RH fermions with respect to CC weak interactions reflect a fundamental asymmetry in the laws of nature?
- 7 What will be the next symmetry recognized in Nature? Are there additional heavy gauge bosons? Is Nature supersymmetric? Is the electroweak theory part of some larger edifice?
- 8 Are all flavor-changing interactions governed by the standard-model Yukawa couplings? If so, why?
- 9 Are there additional sequential quark & lepton generations? Or new exotic (vector-like) fermions?
- 10 What resolves the strong CP problem?

Issues for the Future (Now!)

- 11 What are the dark matters? Any flavor structure?
- 12 Is EWSB an emergent phenomenon connected with strong dynamics? How would that alter our conception of unified theories of the strong, weak, and electromagnetic interactions?
- 13 Is EWSB related to gravity through extra spacetime dimensions?
- 14 What resolves the vacuum energy problem?
- 15 (When we understand the origin of EWSB), what lessons does EWSB hold for unified theories? ... for inflation? ... for dark energy?

Issues for the Future (Now!)

- 16 What explains the baryon asymmetry of the universe?
Are there new (CC) CP-violating phases?
- 17 Are there new flavor-preserving phases? What would observation, or more stringent limits, on electric-dipole moments imply for BSM theories?
- 18 (How) are quark-flavor dynamics and lepton-flavor dynamics related (beyond the gauge interactions)?
- 19 At what scale are the ν masses set? Do they speak to the TeV scale, unification scale, Planck scale, ...?

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- 19 At what scale are the ν masses set? Do they speak to the TeV scale, unification scale, Planck scale, ...?
- 20 How are we prisoners of conventional thinking?

Thank you & Good luck!