Status of the Standard Model

Tara Shears

Overview

- What is the Standard Model?
  - What does it describe?
  - What does it need as inputs?
- Experimental tests
  - Verification of theory
  - Adding the missing parameters
  - Check internal consistency
- Shortcomings
  - Experimental problems
  - Philosophical problems

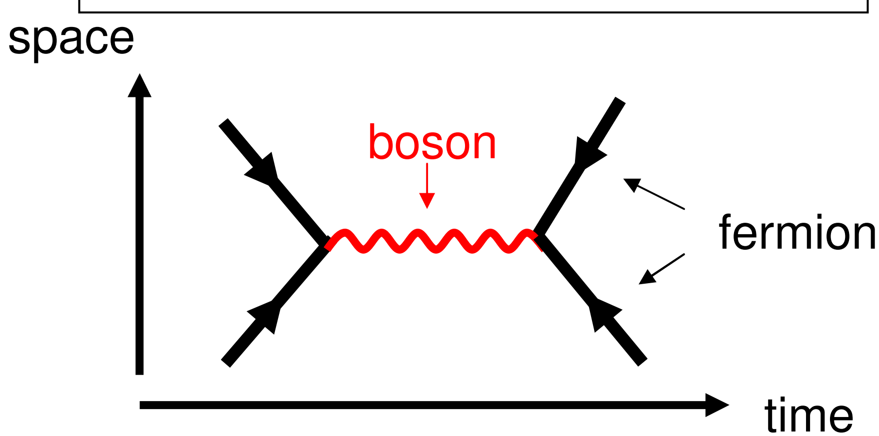
See also pp plenaries and parallel sessions for more details

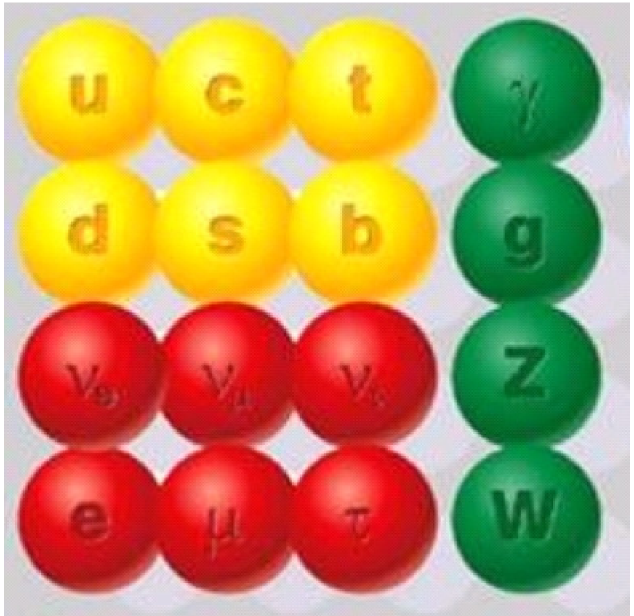
What does the Standard Model describe?

SM describes matter – force interactions;

- 12 types of matter particle (fermion)
- 3 forces, mediated by force carrying particle (boson)

We use the SM to predict experimental observations





Quarks (3 generations)

Leptons (3 generations)

Force carriers

Constructing the Standard Model

SM is a field theory. Describe force - matter interactions by Lagrangians

$$L = -1/4 F_{\mu\nu} F^{\mu\nu} + \bar{\Psi}(i\gamma^{\mu} D_{\mu} - m)\Psi$$

Field strength of force field F

Boson-fermion interaction, fermion movement

Fermion mass

Lagrangian L obeys **local gauge invariance**

Doesn't change as a function of space and time: $\Psi \rightarrow e^{-i\theta(x,t)}\Psi$

Consequence that bosons must be massless

Each force described by L of similar form (details of F, D, Ψ vary)

Constructing the Standard Model

$$L_{SM} = L_{EM} + L_{WEAK} + L_{STRONG}$$

EM force	Weak force	Strong force
Electric charge (1)	Weak charge (2)	Colour charge (3)
Massless photon	Massive $W^{\pm}$,Z	8 massless gluons
Coupling g	Coupling g_W	Coupling g_s

Value unknown/
not predicted

Constructing the Standard Model

$$L_{SM} = L_{EM} + L_{WEAK} + L_{STRONG}$$

EM force	Weak force	Strong force
Abelian	Non-abelian	Non-abelian
Only charged particles couple	Only left handed particles couple	Only quarks couple
	quark mixing (3 generations, CP)	
	Neutrino mixing (3 generations, CP)	

Value unknown/ not predicted

Constructing the Standard Model

$$L_{SM} = L_{EM} + L_{WEAK} + L_{STRONG} + L_{HIGGS}$$

Bosons are **massless** in SM theory

Introduce Higgs field (m_H, value of Higgs potential v):

Couples to particles to give mass (amount ~ coupling strength)

Keeps Lagrangian invariant

Consequences:

Unifies weak and electromagnetic forces

Massive Z is mixture of massless em + weak bosons

Relates Mw, Mz and weak, electromagnetic couplings:

$\tan \theta_W = g_W / g$

$M_W = M_Z \cos \theta_W$

(SM good at predicting relations)

Constructing the Standard Model

$$L_{SM} = L_{EM} + L_{WEAK} + L_{STRONG} + L_{HIGGS}$$

Other considerations:

- Theory must be renormalisable

- Force strength "runs" with energy

  EM: charge screening

  Weak/Strong: boson self interaction alters apparent charge

- Although theory is easy to write down, it's less easy to use
  - Most tests are of electroweak sector

Testing the SM

1. Test any assumptions we've made
2. Measure unknown parameters in different ways and check consistency
3. Compare predicted quantities to measurements
4. Check internal consistency of entire SM framework

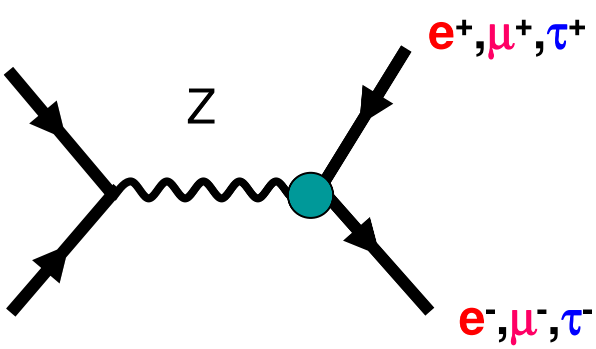
Lepton universality

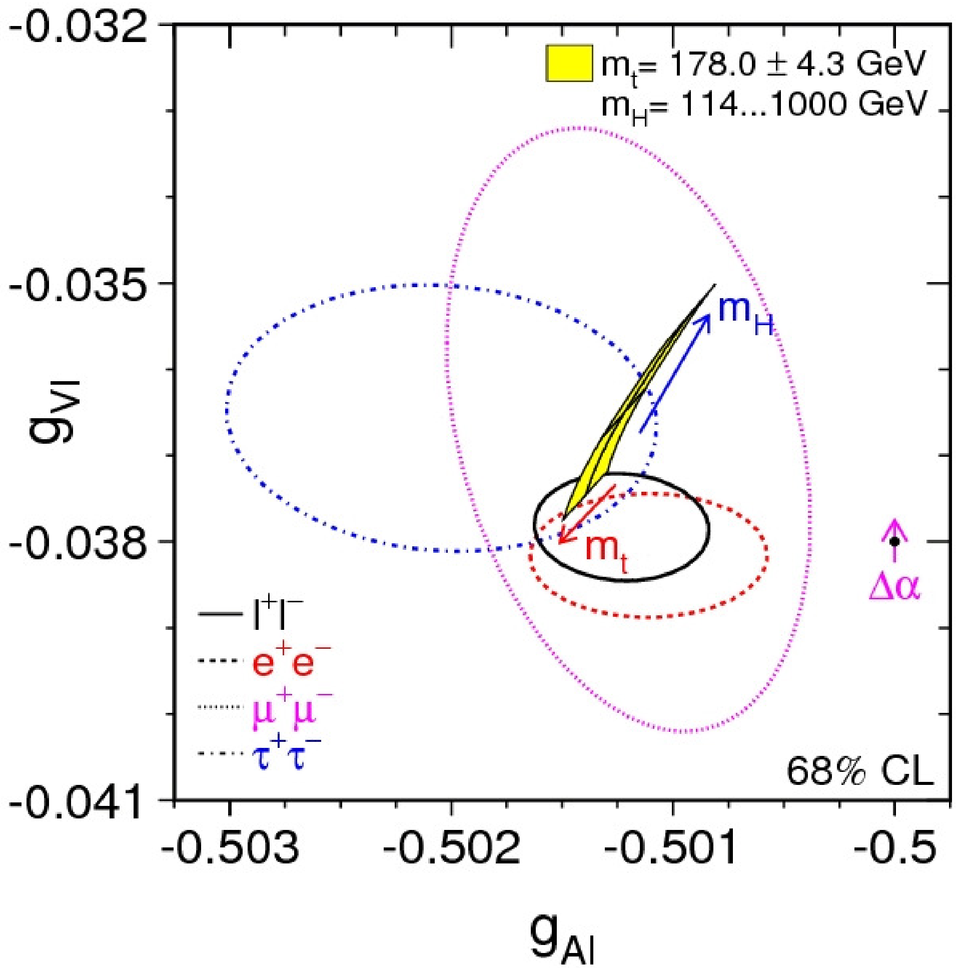
Assumed in SM that e, μ, τ have similar ewk couplings

Test Z couplings to ee $\mu\mu$ $\tau\tau$

Find all measurements consistent with each other

Also consistent with SM prediction





3 generations of matter

No info on # generations in SM

Use Z lineshape: SM relates width to possible decay products

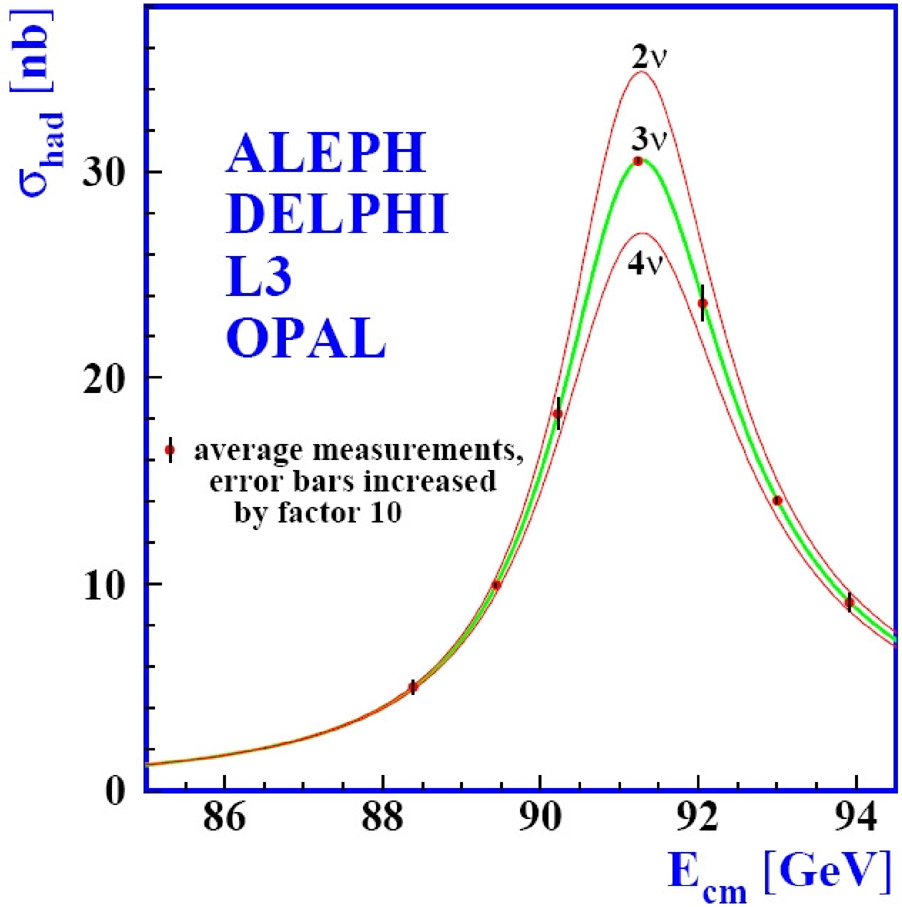
Measure Γ_{had}, Γ_{ee}, σ_{had}

σ_{had} is a function of Γ_Z, Γ_{had}, Γ_{ee}

$\Gamma_Z = \Gamma_{had} + \Gamma_{ll} + \Gamma_{inv}$

Assume $\Gamma_{inv} = N\nu\Gamma_{\nu\nu}$

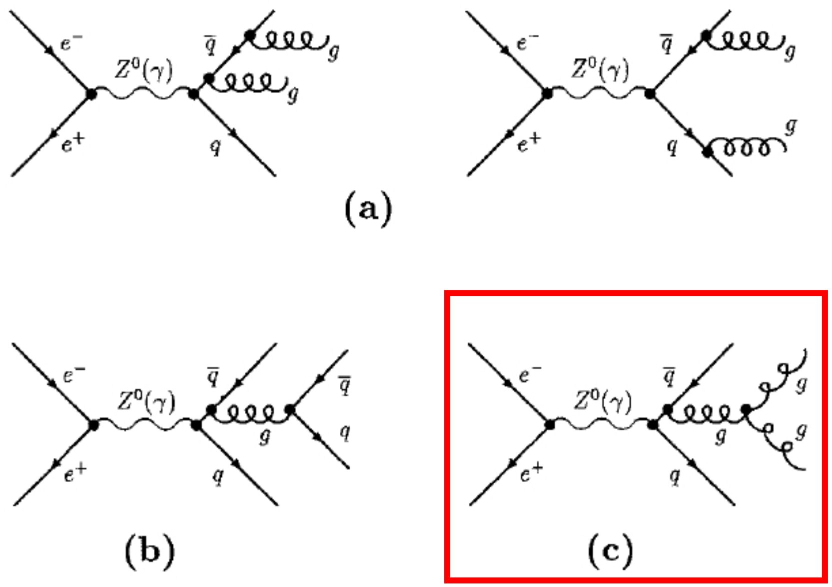
Calculate $N\nu$



$N\nu = 2.984 \pm 0.008$

Non-abelian strong force

Rate of 4 jet production at LEP:



SM contribution from **triple gluon coupling**

Difference demonstrates non-abelian couplings

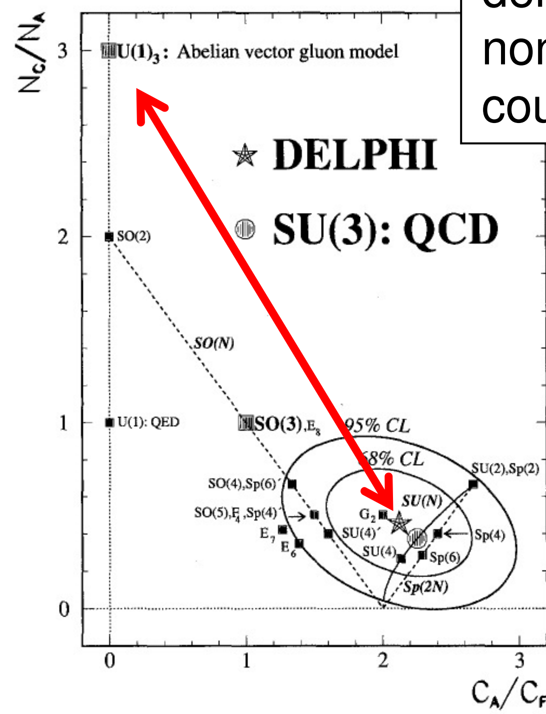
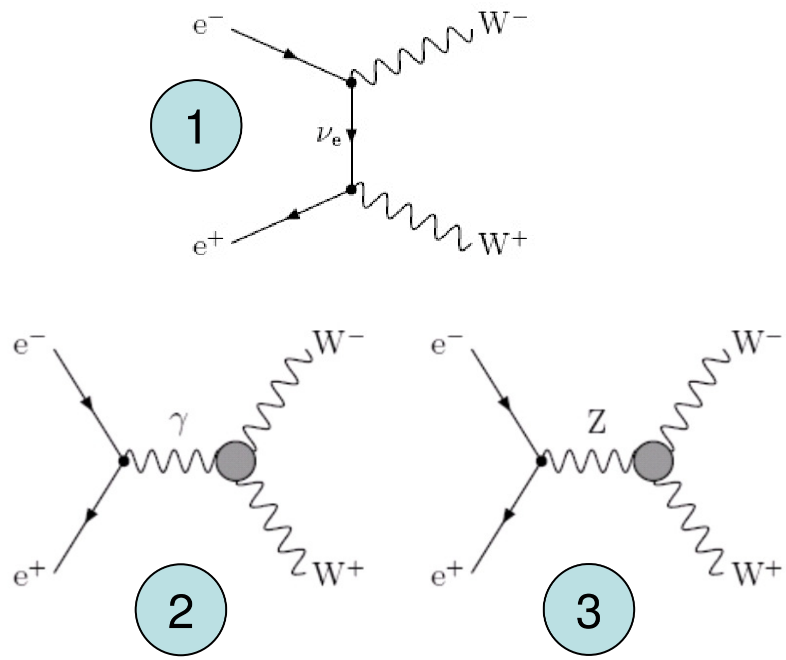


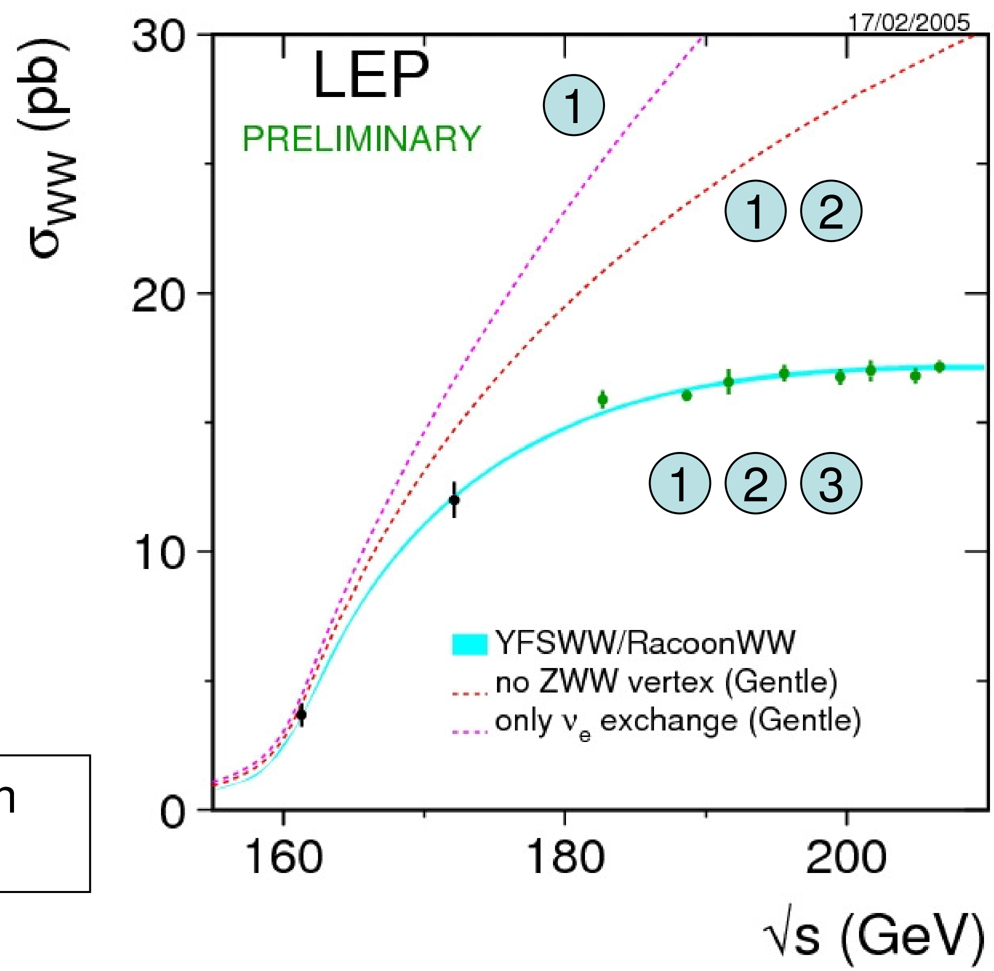
Fig. 10. 68% and 95% CL contour plots for the measured variables C_A/C_F and N_C/N_A, and expections from different gauge theories. C_A/C_F = ratio of coupling strength of $g \to gg$ to $q \to qg$; N_C/N_A = number of quark colours divided by the number of gluons.

Zeit. Phys. C59 (3) (1993) 357

Non-abelian weak force



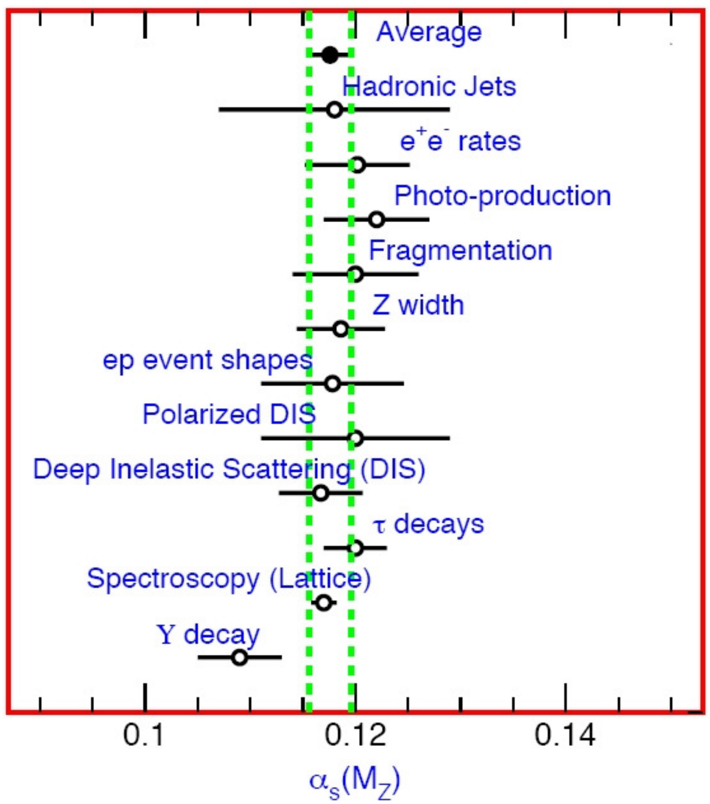
Check rate of $e^+e^- \rightarrow WW$ production at LEP



LEP 4fermion working group

Couplings

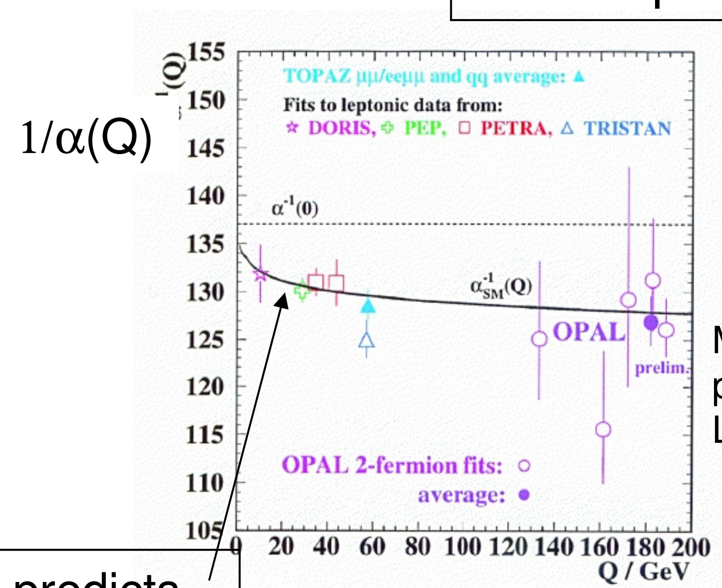
Strong coupling



Many measurements give consistent answer

Particle data group

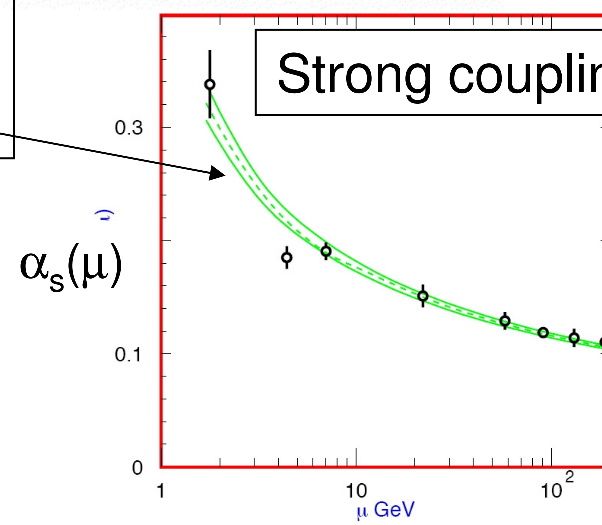
EM coupling



M. Kobel, proceedings LP97

SM predicts evolution with energy

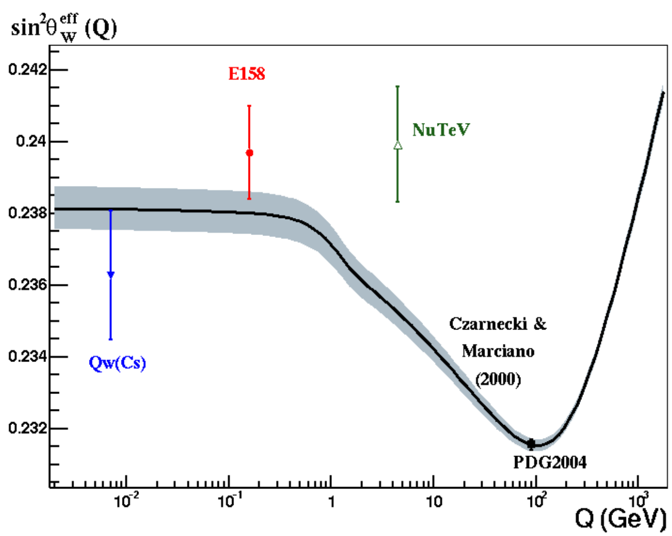
Strong coupling



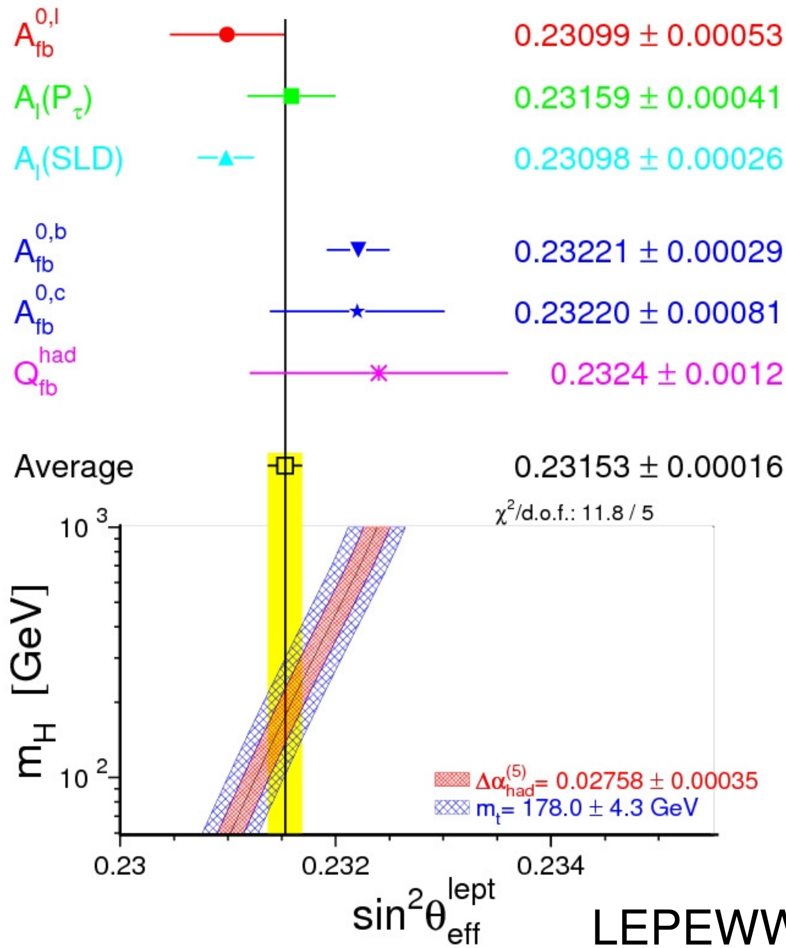
$\sin^2 \theta_W$

Relates weak, em couplings and M_W, M_Z

Consistent result extracted from many different measurements



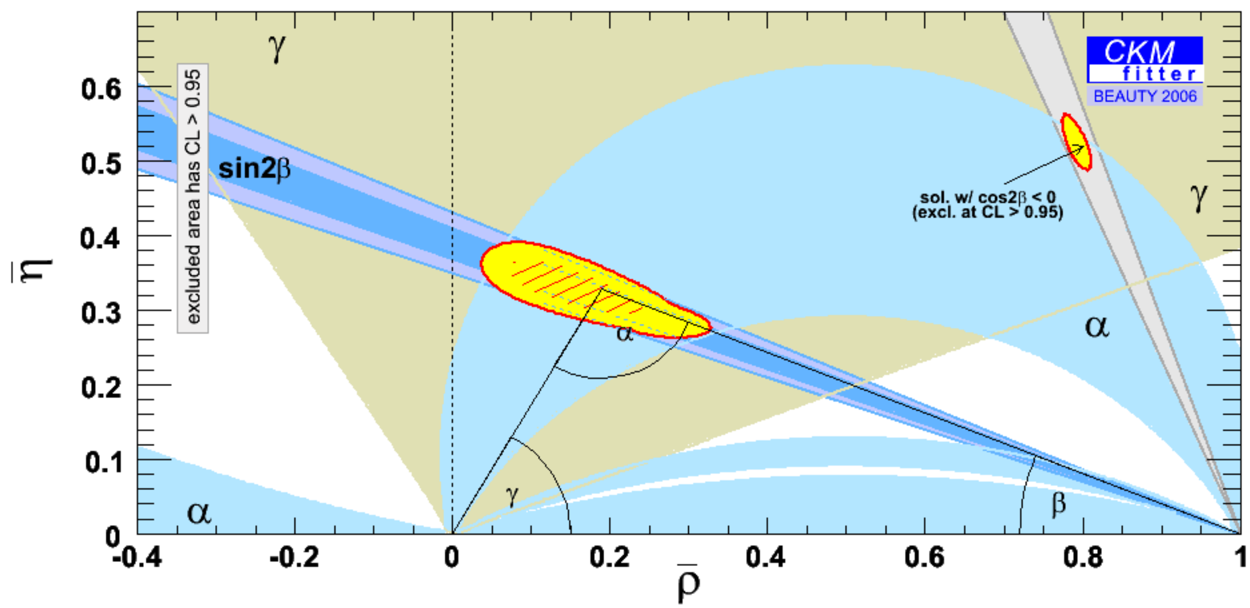
Energy evolution



LEPEWWG

Quark mixing

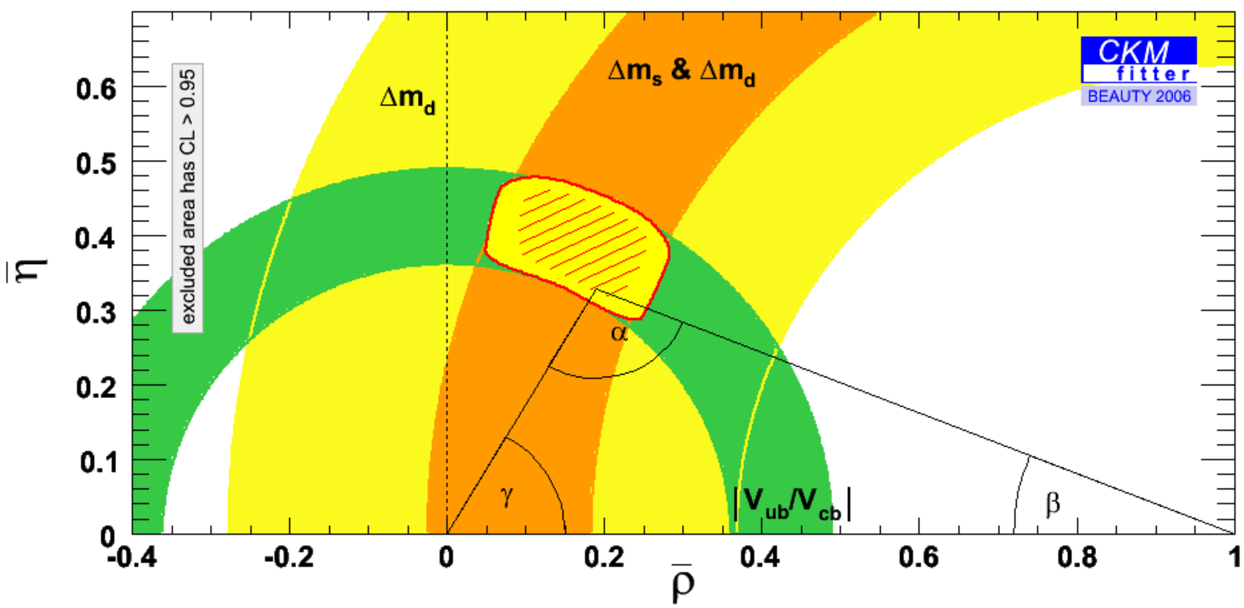
Many measurements of the 4 parameters describing quark mixing and CP violation



B and anti-B meson decay rates

Quark mixing

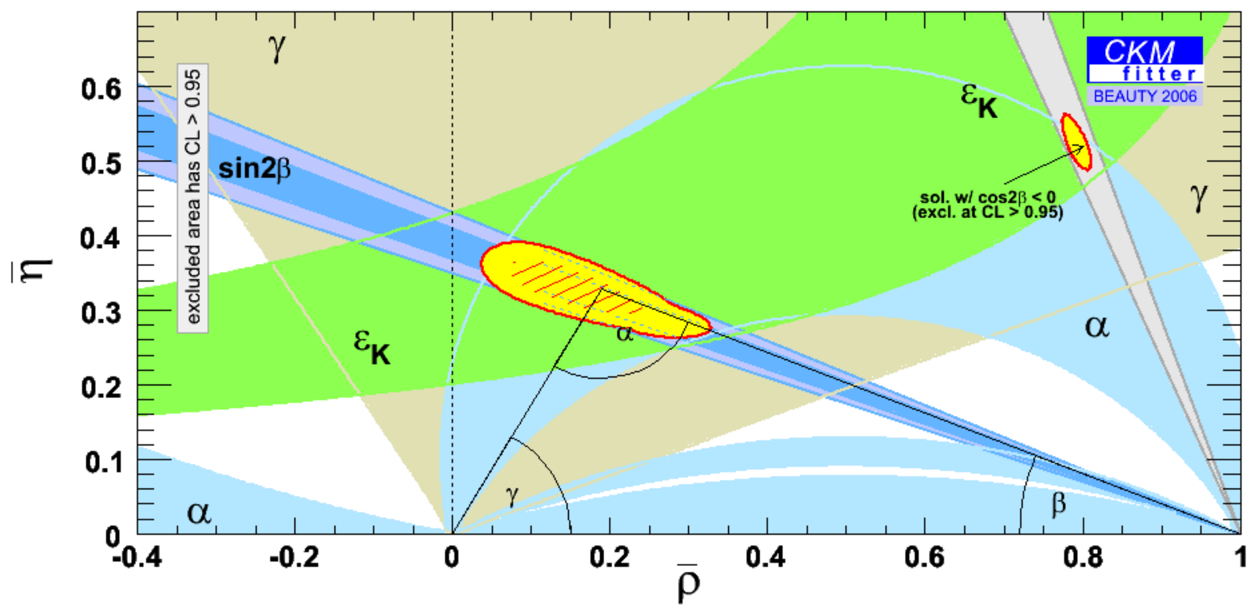
Many measurements of the 4 parameters describing quark mixing and CP violation



B meson mixing, ratio of b decay to u, c quarks

Quark mixing

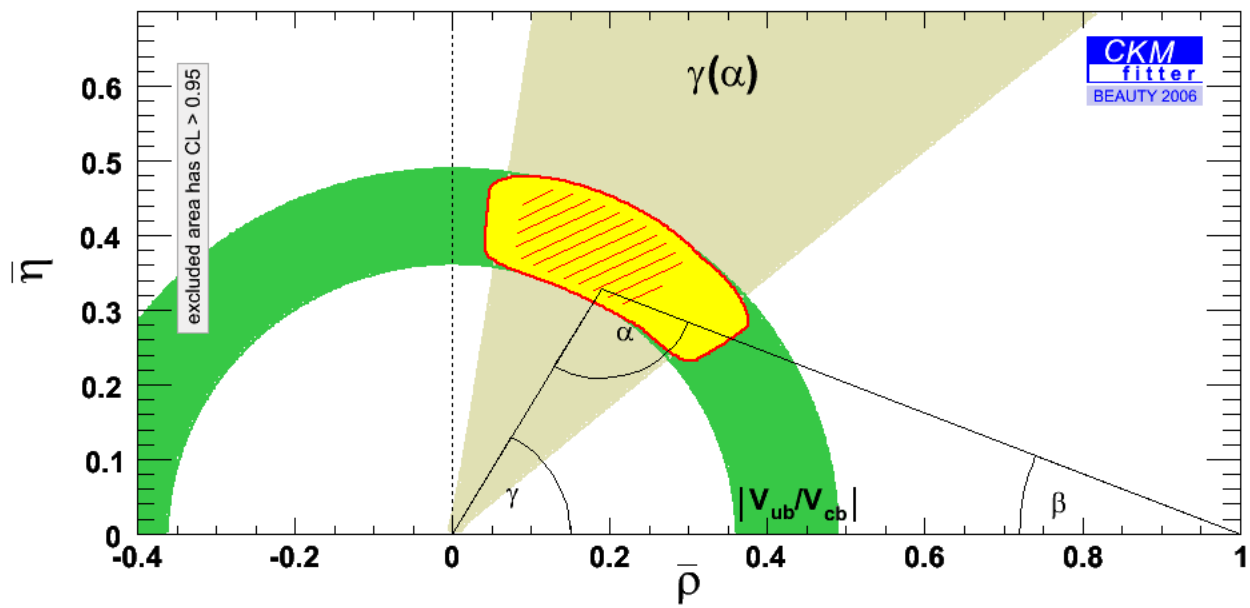
Many measurements of the 4 parameters describing quark mixing and CP violation



CP violation in kaon and B meson sectors

Quark mixing

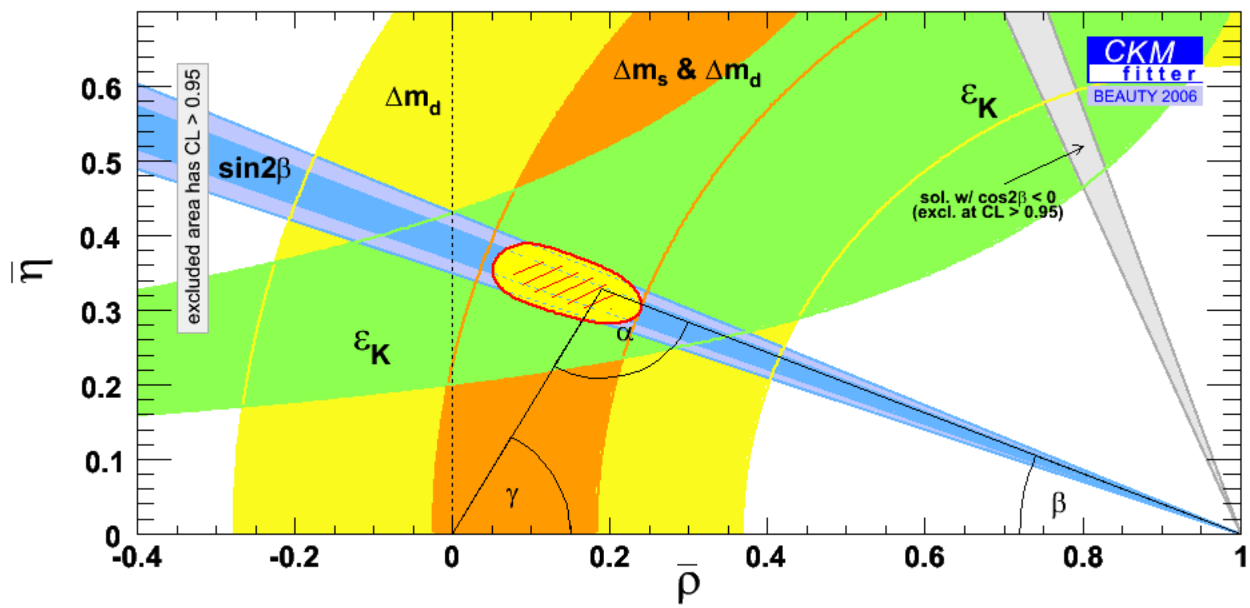
Many measurements of the 4 parameters describing quark mixing and CP violation



Leading order B meson decay rates

Quark mixing

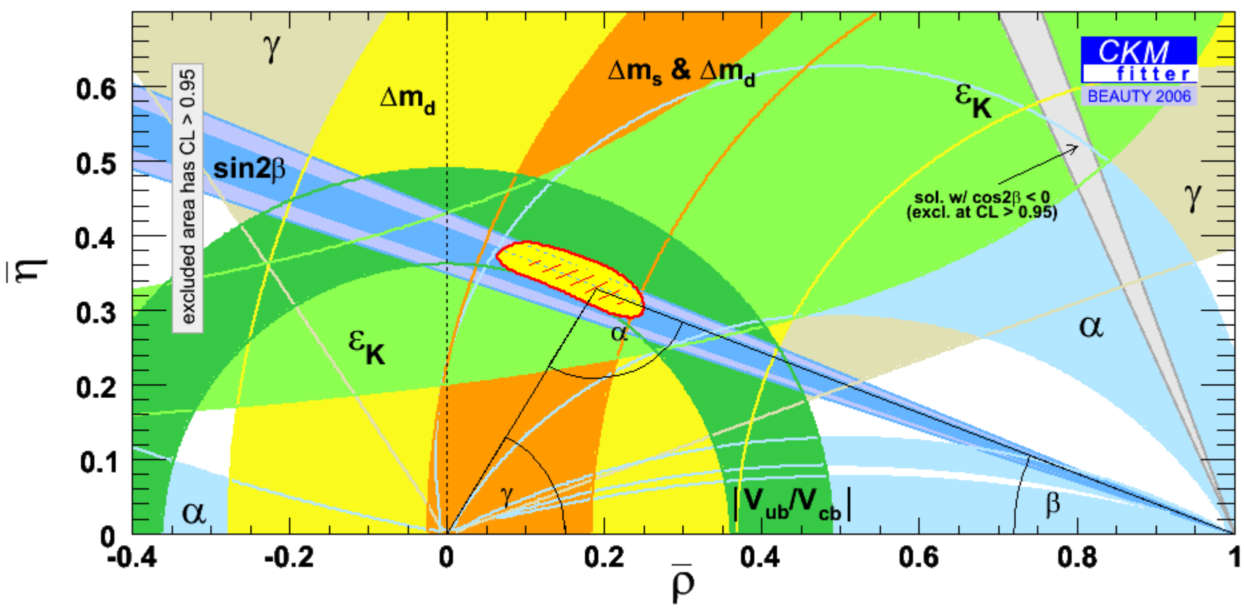
Many measurements of the 4 parameters describing quark mixing and CP violation



Measurements with higher order contributions

Quark mixing

Many measurements of the 4 parameters describing quark mixing and CP violation



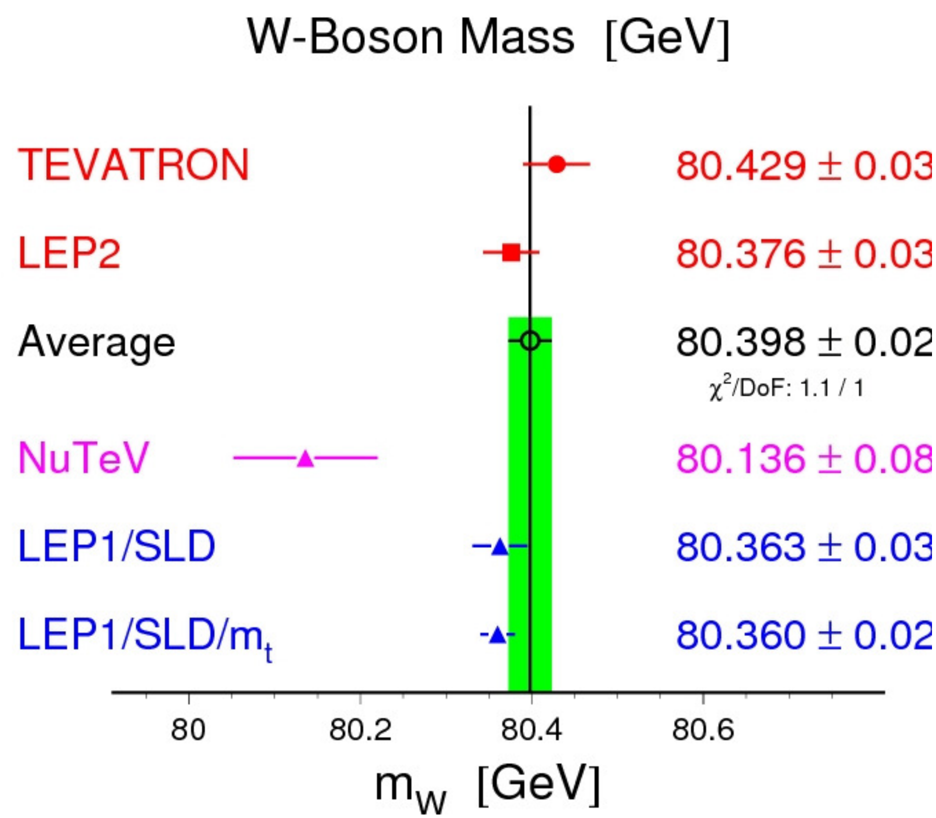
All measurements consistent

W boson mass

Direct measurement

Inferred (NuTeV $\sin^2\theta_W + M_Z$)

SM prediction

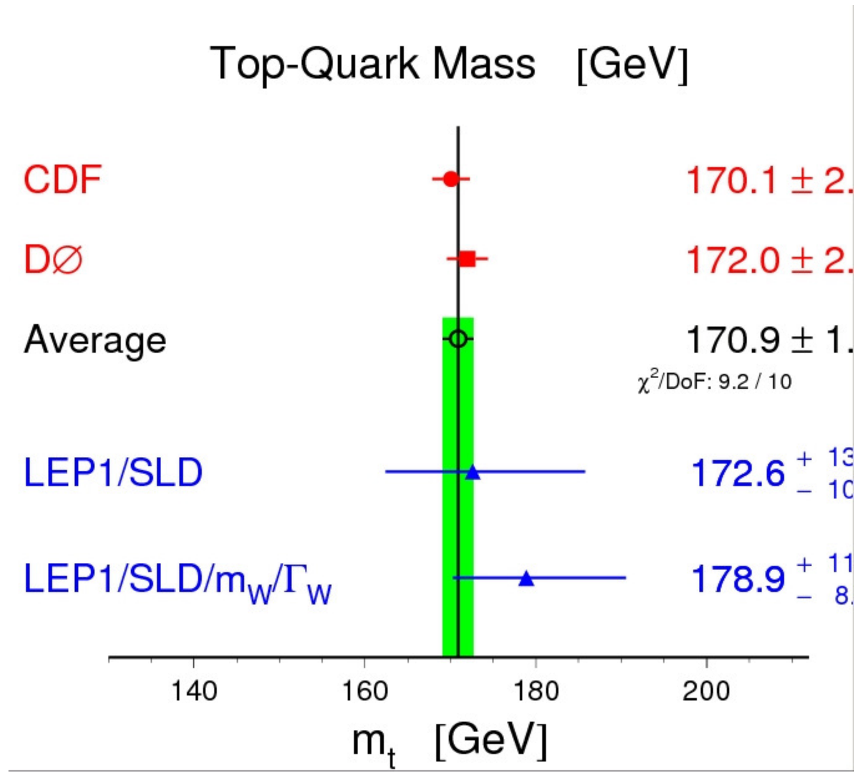


Consistent (NuTeV result low)

Top quark mass

Direct measurement

SM prediction



Consistent

Internal consistency

Many consistency checks possible

- Here fit to Z, W top quark results is shown
- χ^2/ndf = 18.2/13 (Probability ~15 %)

Shortcomings

1. Experimental

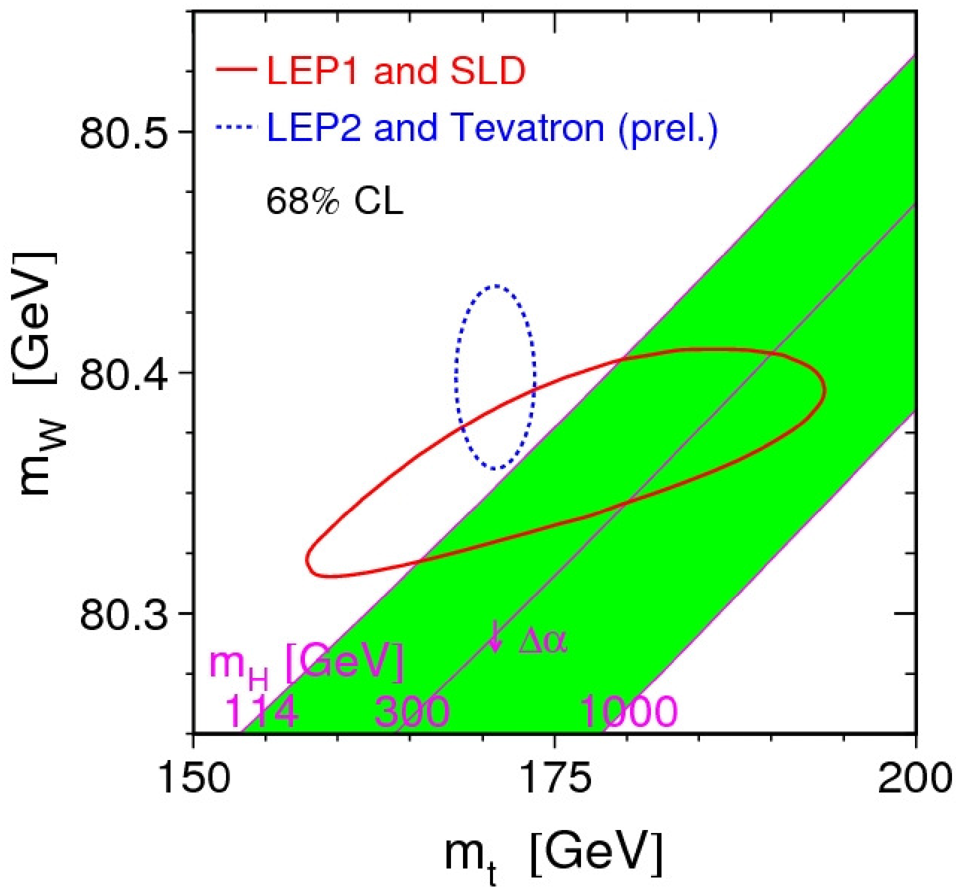
- Still haven't experimentally verified all of SM
- Any differences wrt predictions could signal New Physics

2. Philosophical

- There is a lot we still don't understand
- What lies beyond the limits of the SM?

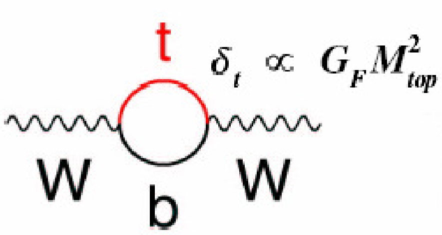
Higgs

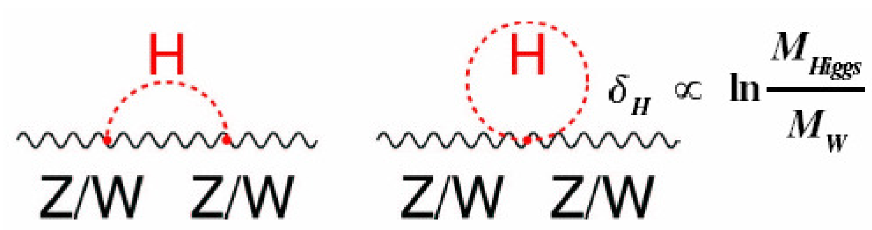
Cornerstone of SM. Theory collapses without it. Where is it?



Can constrain mass from measured W, top mass with SM.

Can constrain from other ewk measurements with SM

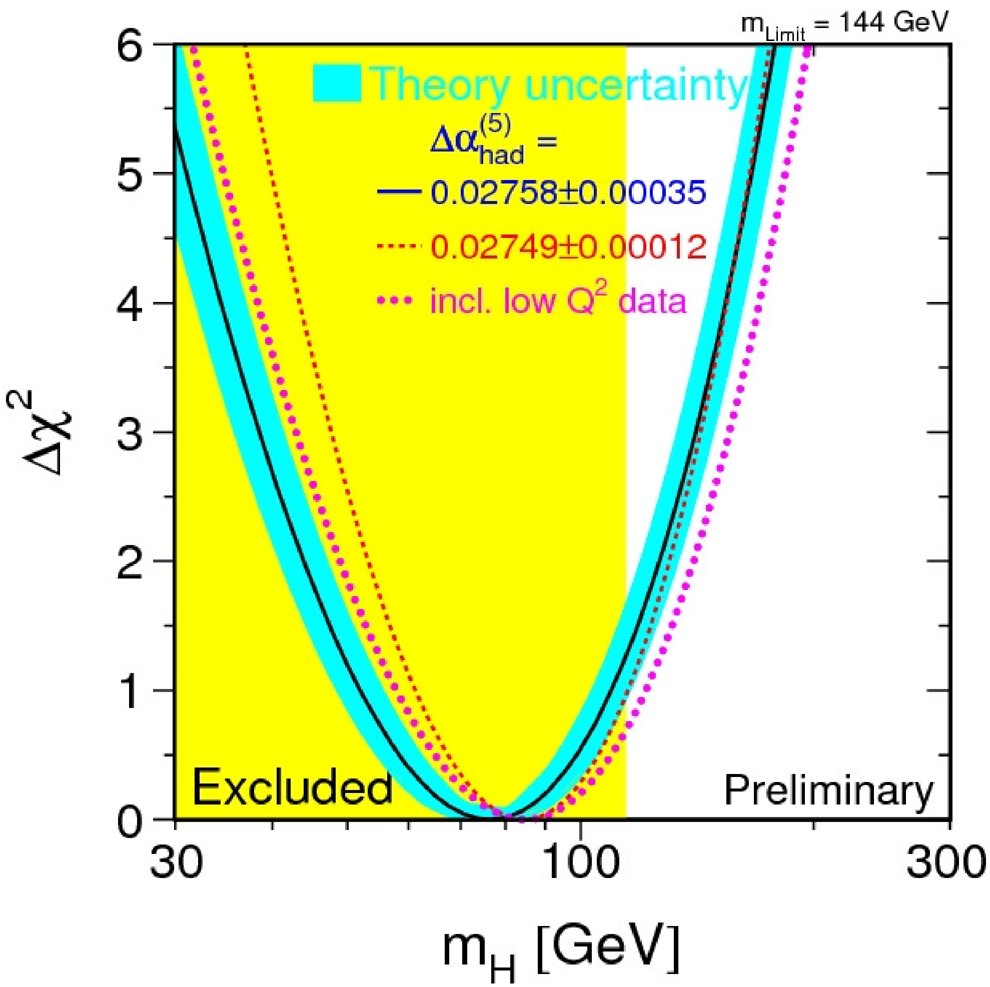


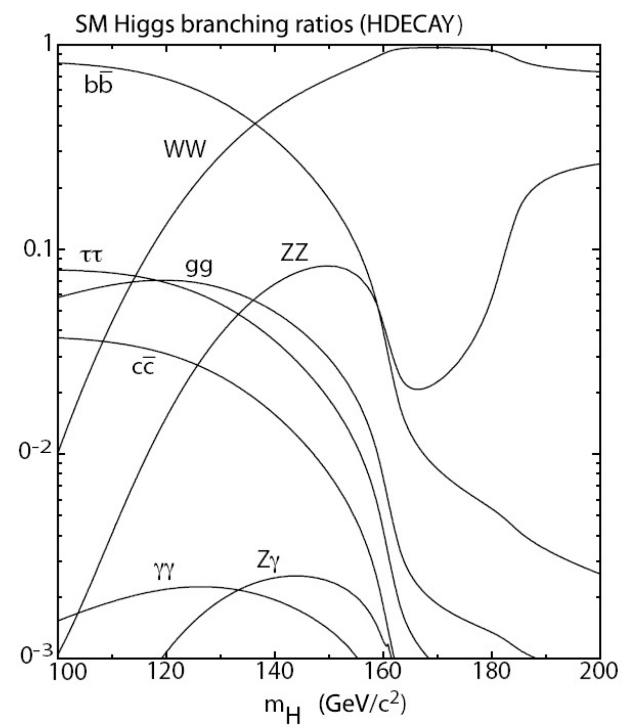


Fit to SM parameters implies m_H < 144 GeV @95% cl

m_H>114 GeV from direct experimental searches @95% cl

SM predicts how often H produced + experimental signature as function of mH

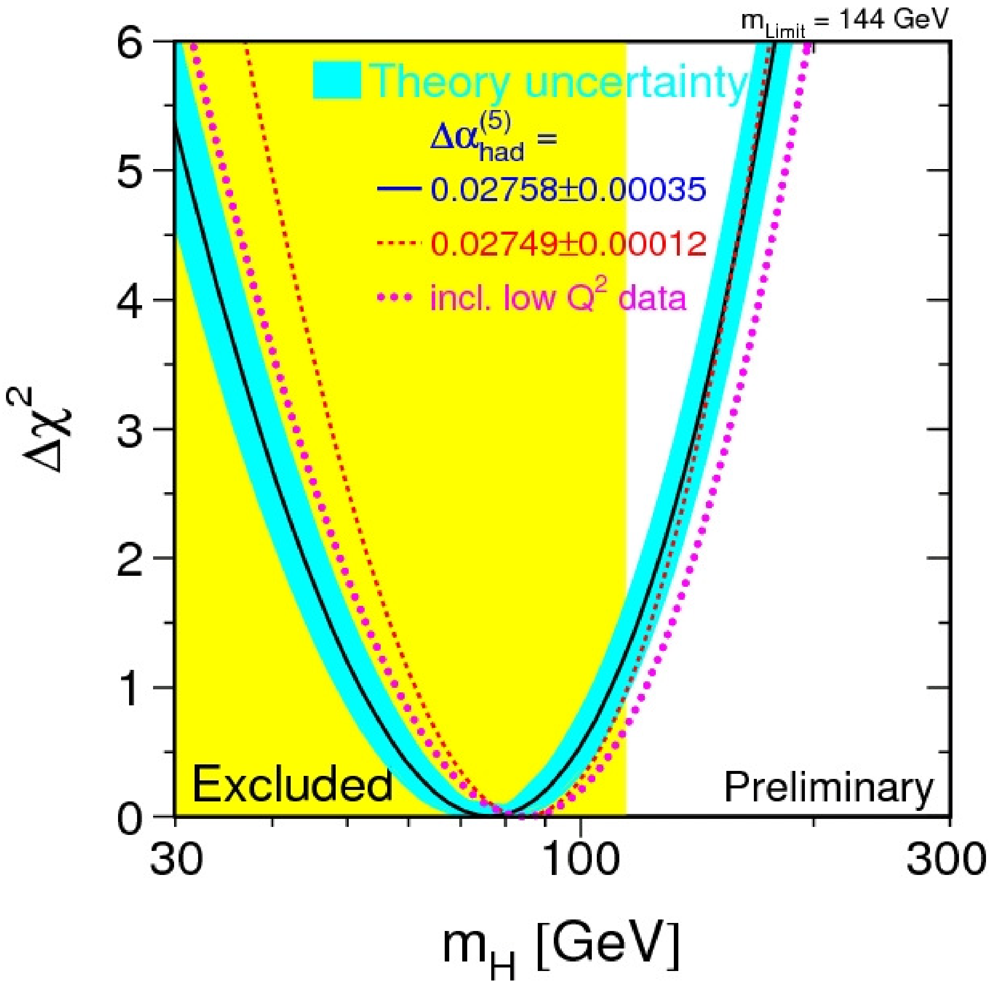


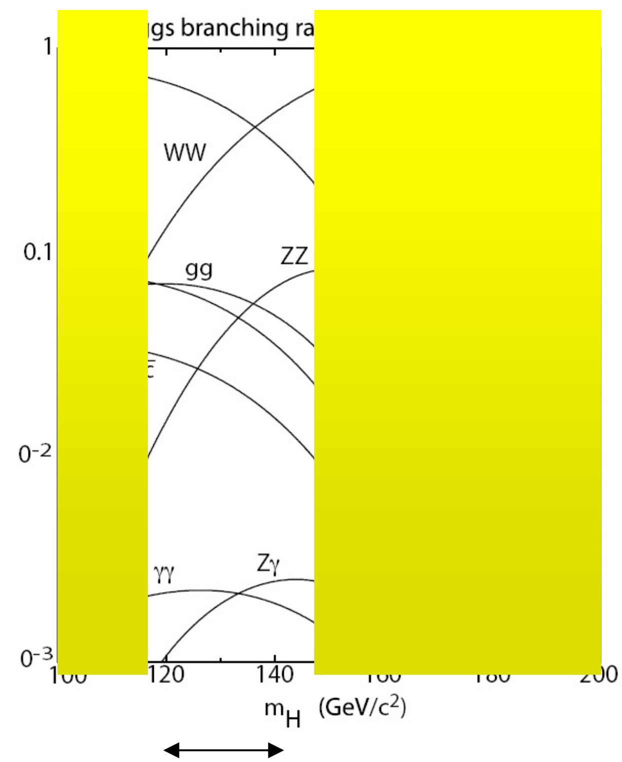


m_H>114 GeV from direct experimental searches @95% cl

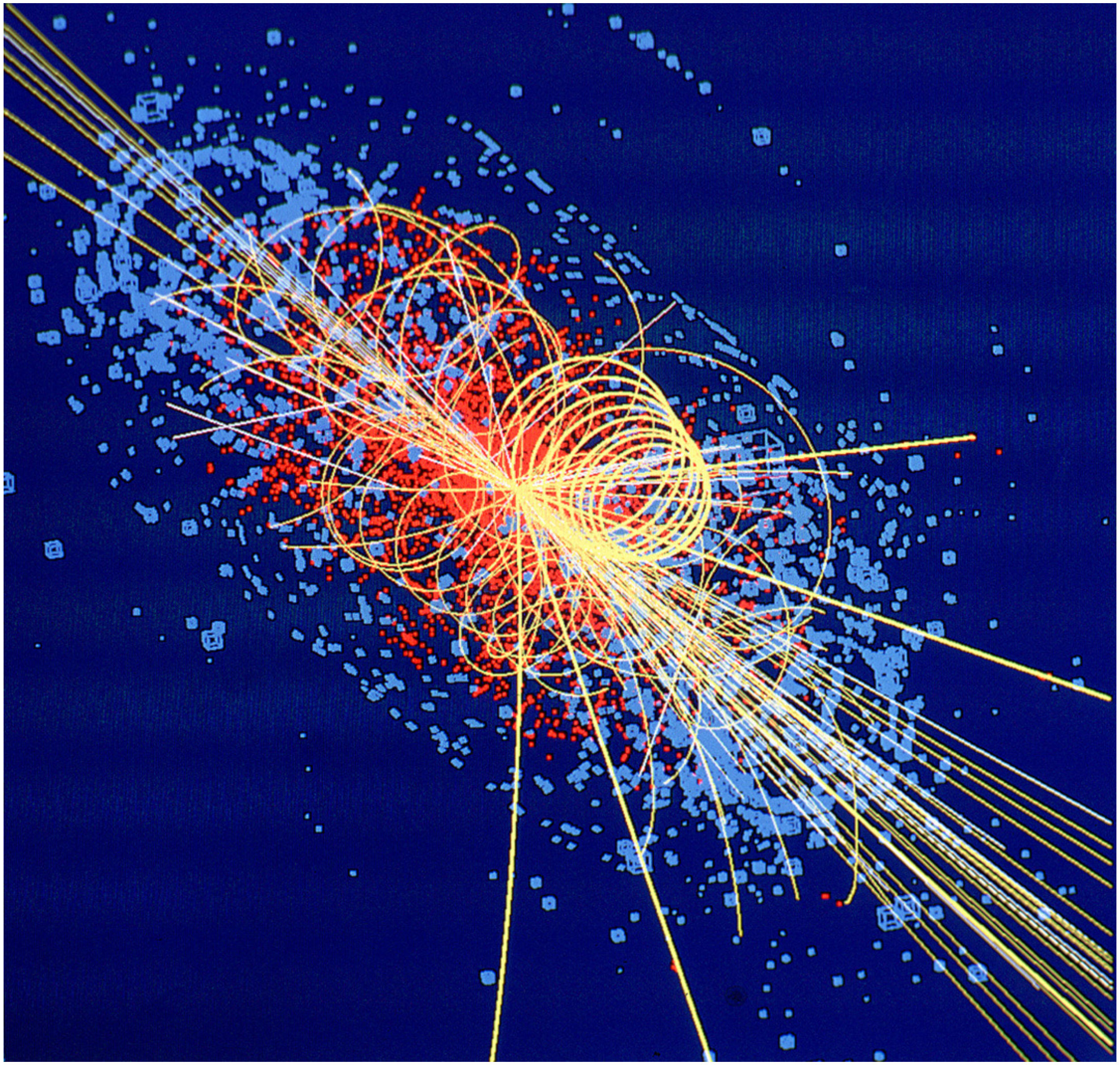
Fit to SM parameters implies m_H < 144 GeV @95% cl

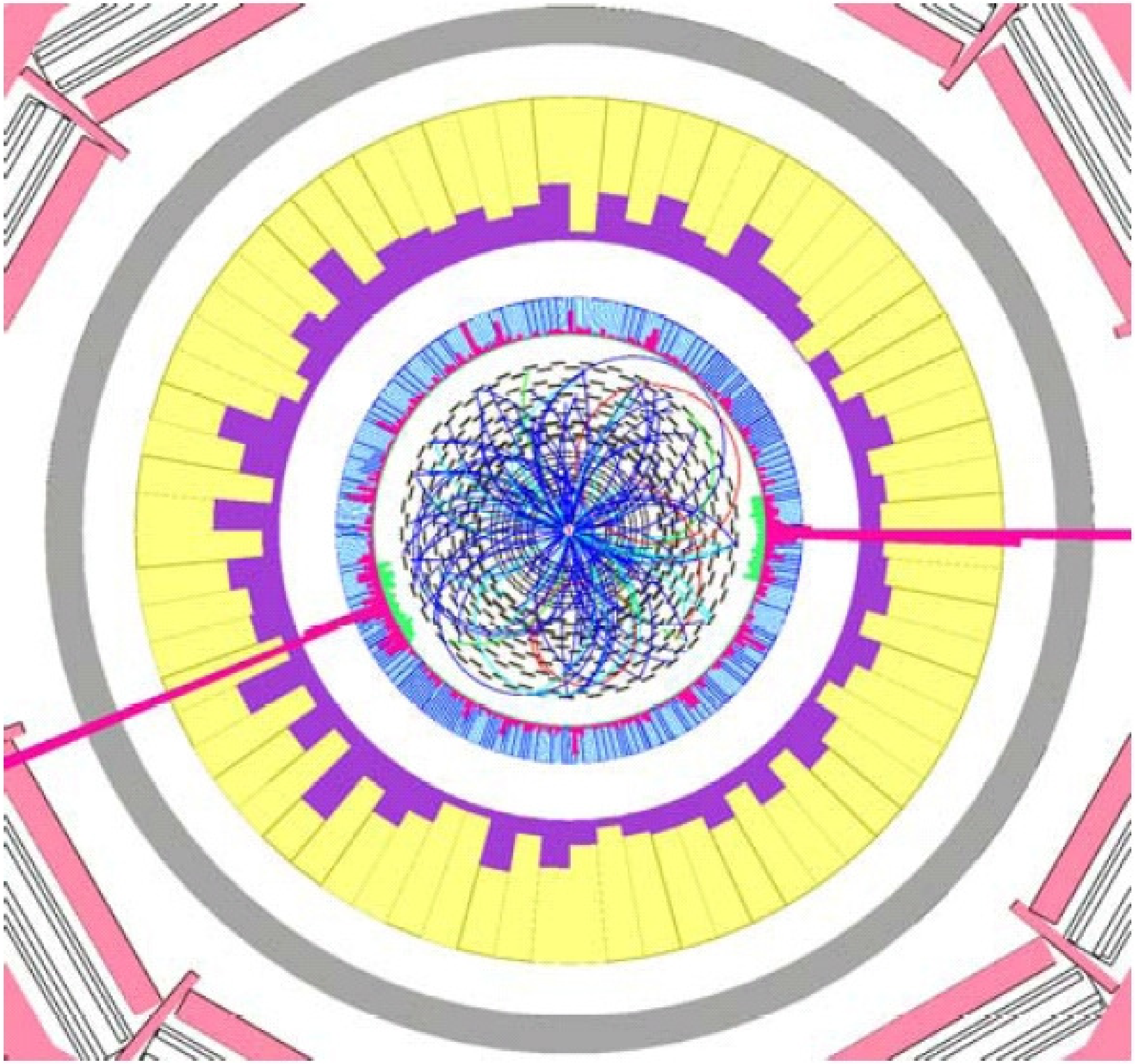
SM predicts how often H produced + experimental signature as function of mH

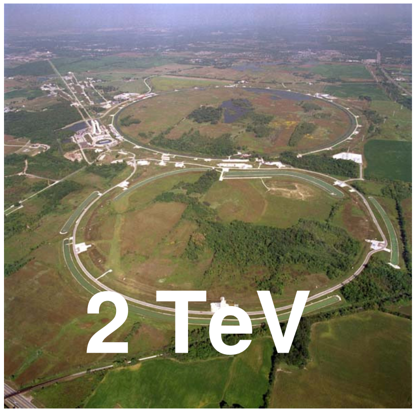


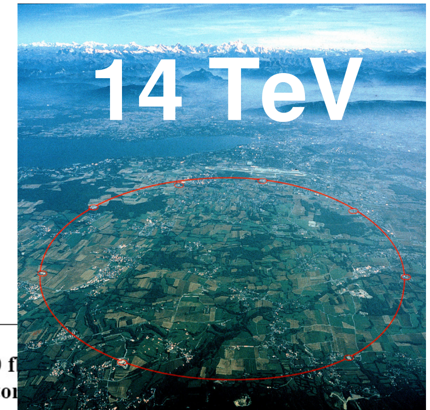


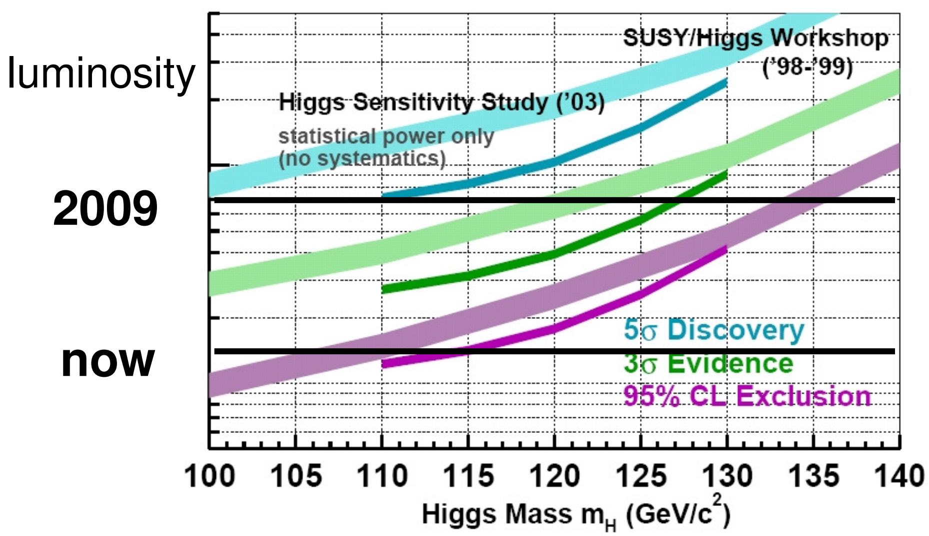
95% cl bounded allowed region

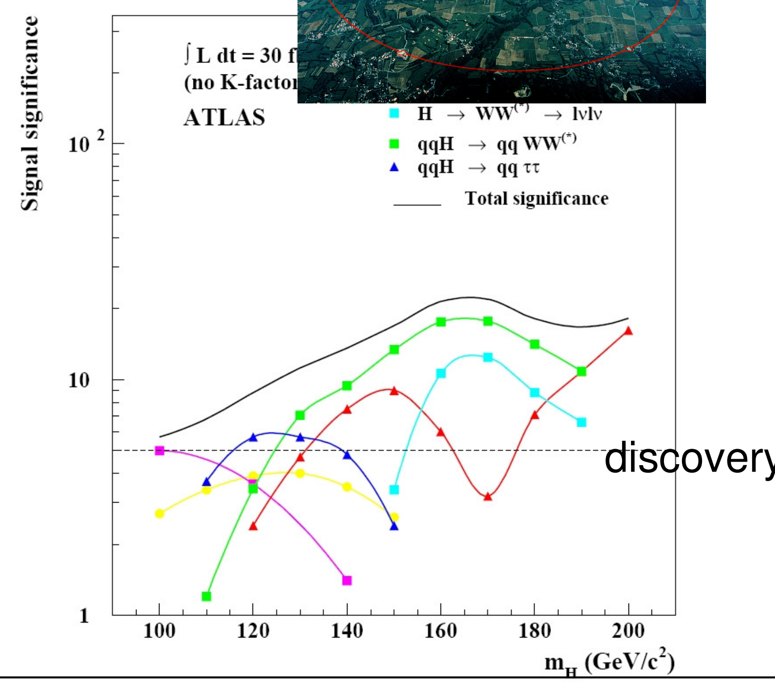










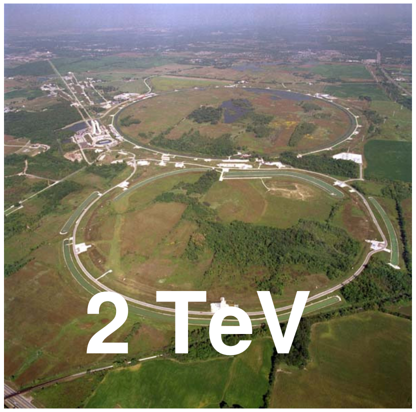


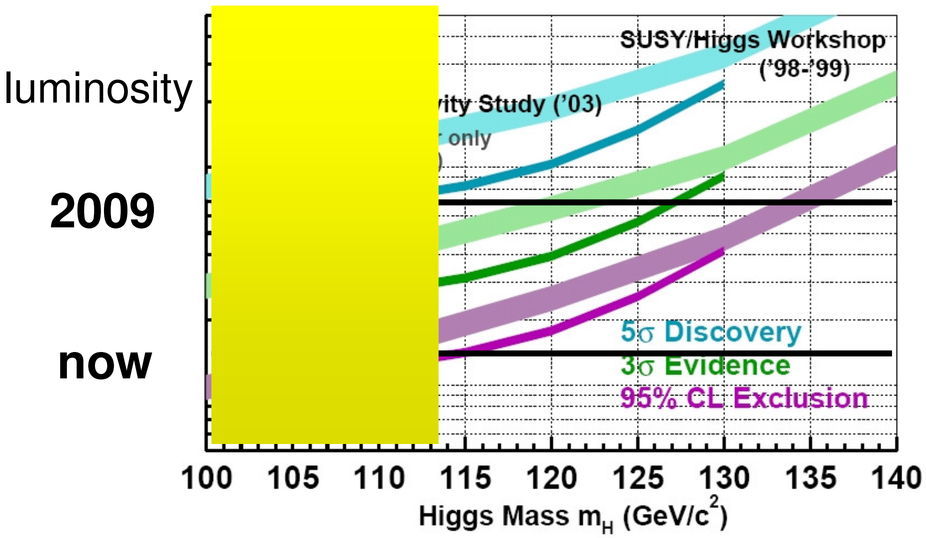
Tevatron: need more data to discover Higgs at 5σ

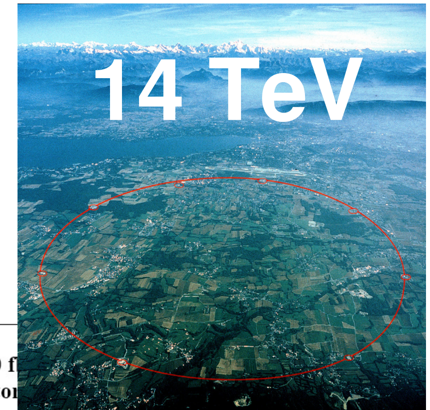
LHC: sufficient energy to make Higgs

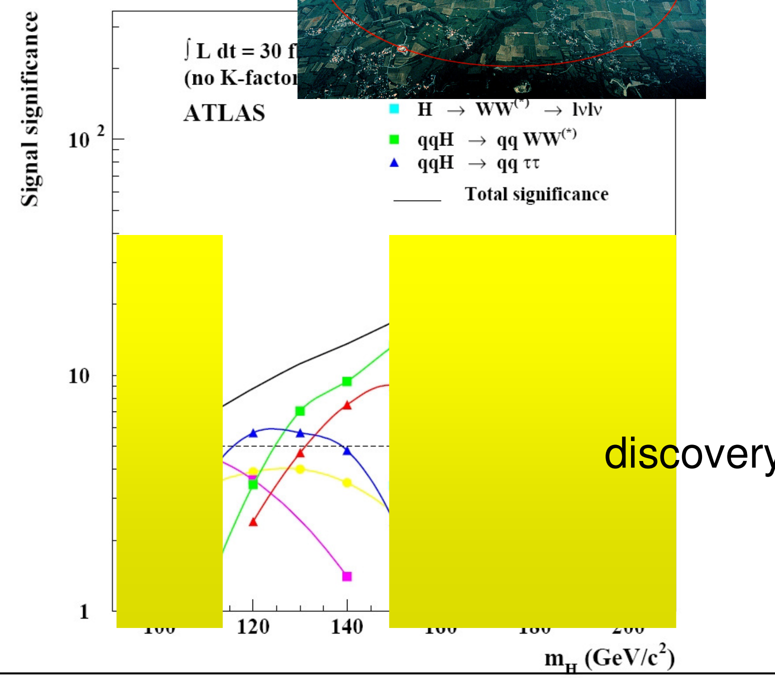
Enough data to see it … if it exists .. but search difficult

ATLAS scientific note 2003-024









Tevatron: need more data to discover Higgs at 5σ

LHC: sufficient energy to make Higgs

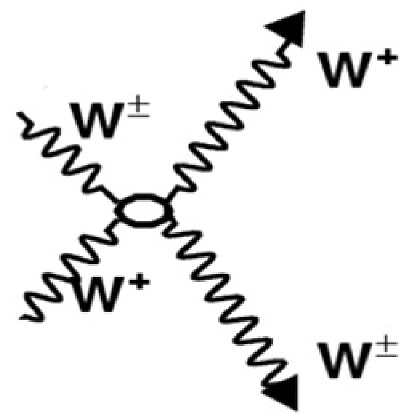
Enough data to see it … if it exists .. but search difficult

ATLAS scientific note 2003-024

Any more info from SM?

Always possible Higgs could be heavier if assumptions in SM fit incorrect

But **m_H < 1 TeV or predicted WW scattering cross-section starts to violate unitarity**



If we don't see Higgs at LHC then:

it doesn't exist …..

or it's too heavy to make ..

If no Higgs with mass < 1 TeV there must be **New Physics** to keep WW scattering finite.

Experimental disagreements?

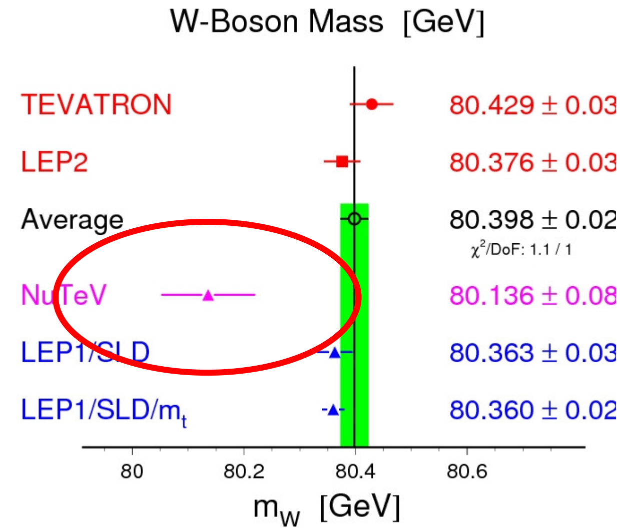
NuTeV $\sin^2\theta_W$ (~ 3 σ)

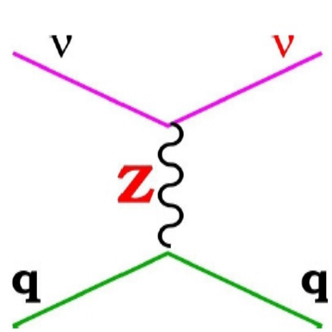
Extract from ratio of neutral:charged ν nucleon couplings

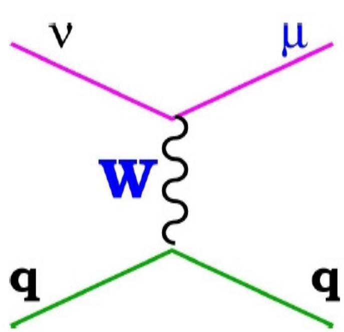
New Physics? (eg. Z', new fermions)

Or analysis? (uncertainties in pdfs, radiative corrections)

Phys. Rept. 427 (2006) 257







Experimental disagreements?

Couplings of b quarks?

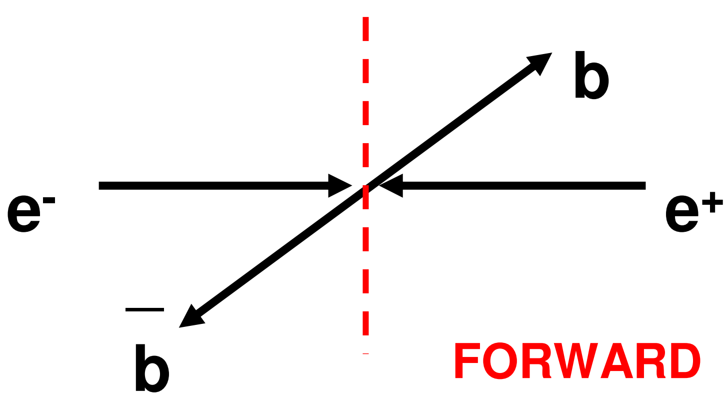
A_{fb} measured vs. SM prediction (2.8 σ)

No identified experimental explanation

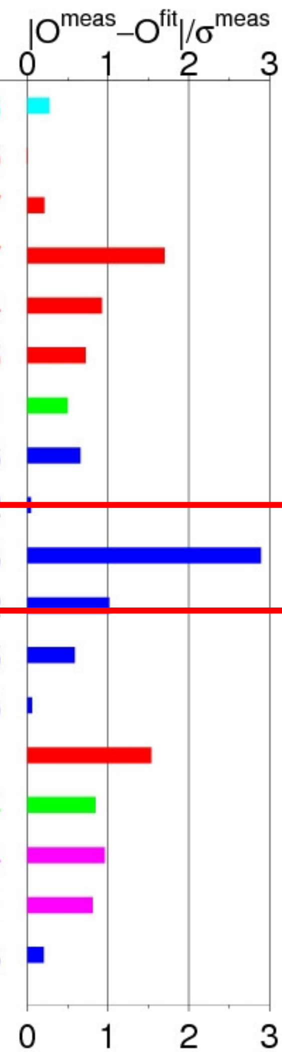
Assumed to be a fluctuation

(Phys. Rept. 427 (2006) 257)

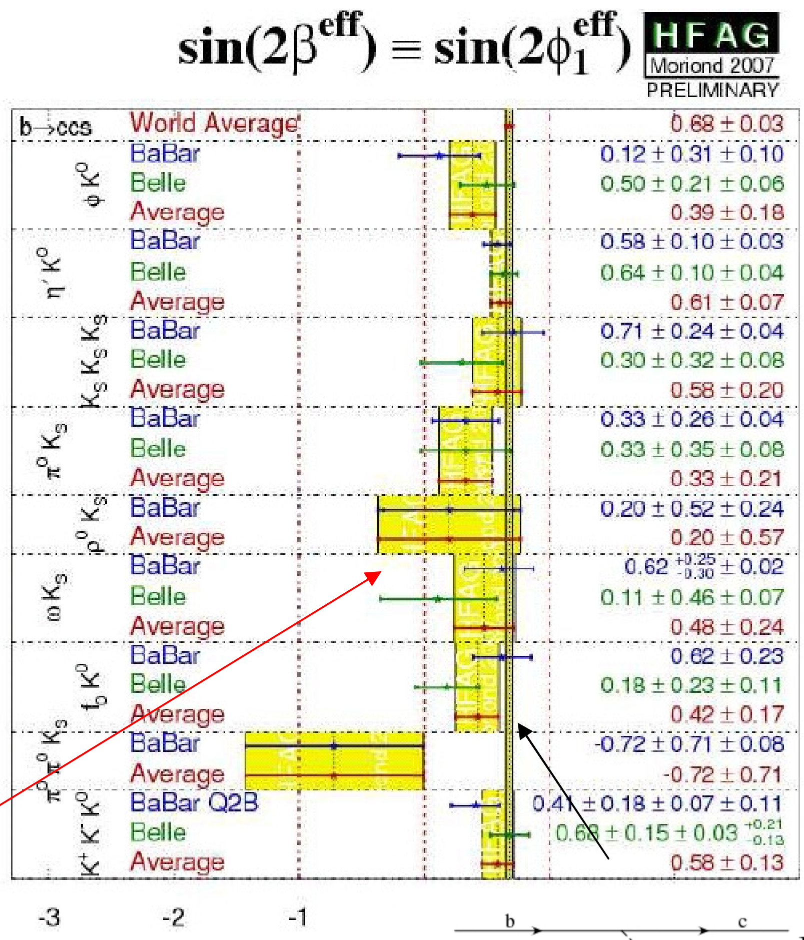
$A_{fb} = (Nf - Nb)/(Nf+Nb)$



	Measurement	Fit
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02758 ± 0.00035	0.02768
m_Z [GeV]	91.1875 ± 0.0021	91.1875
Γ_Z [GeV]	2.4952 ± 0.0023	2.4957
σ^0_{had} [nb]	41.540 ± 0.037	41.477
R_l	20.767 ± 0.025	20.744
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.01645
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481
R_b	0.21629 ± 0.00066	0.21586
R_c	0.1721 ± 0.0030	0.1722
$A^{0,b}_{fb}$	0.0992 ± 0.0016	0.1038
$A^{0,c}_{fb}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1481
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.398 ± 0.025	80.374
Γ_W [GeV]	2.140 ± 0.060	2.091
m_t [GeV]	170.9 ± 1.8	171.3



Experimental disagreements?

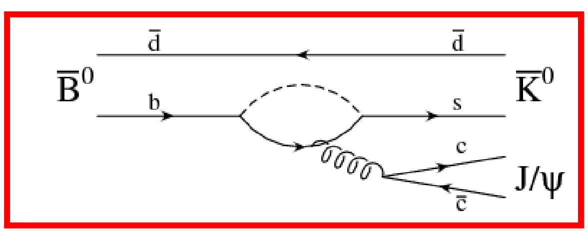


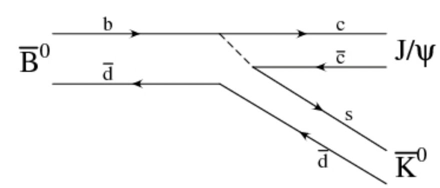
Measurements of quark mixing parameters?

Hints of difference in measurements from B decays involving "penguins"

Fluctuation? New Physics?

More data needed to confirm





What else is wrong?

Fine tuning:

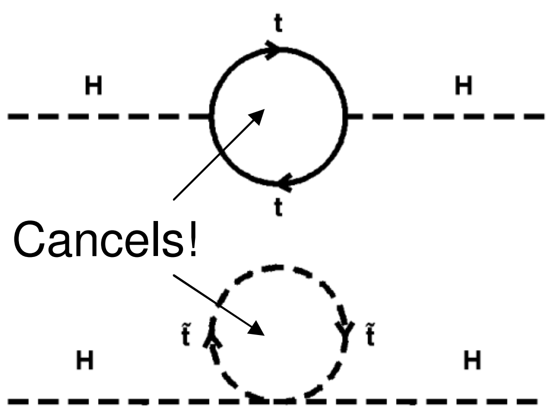
Higgs mass calculation: bare mass + radiative corrections + loops

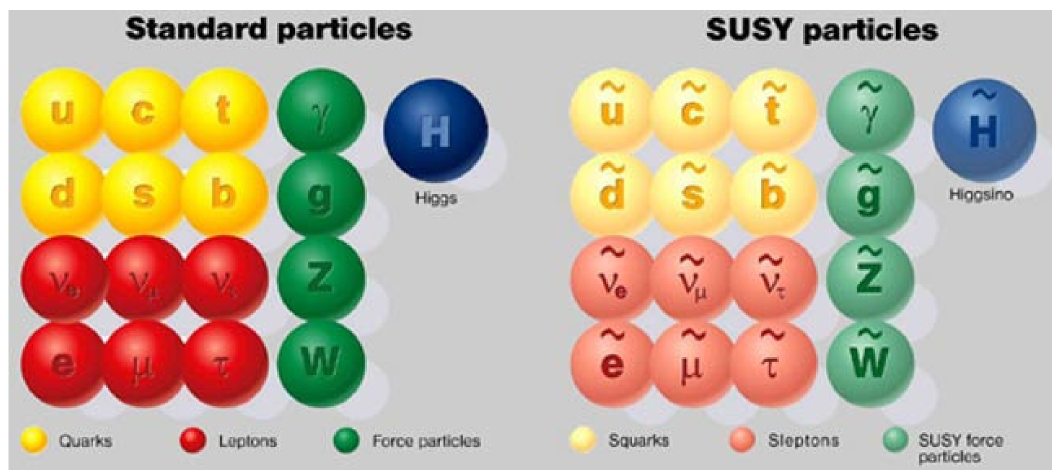
very careful choice of parameters to ensure mass ~ 100 GeV

Supersymmetry:

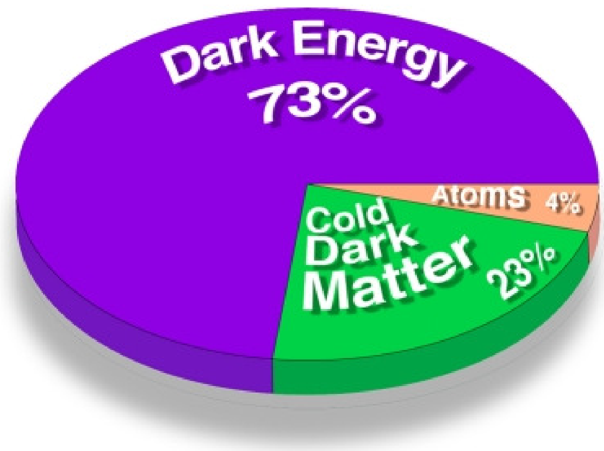
Symmetry between fermions and bosons

New supersymmetric particles can cancel divergences in mH calculation





4% of the universe?



SM with electroweak and strong interactions only describes 4% of the universe

Source: Robert Kirshner
Source: NASA/WMAP Science Team

Dark energy:

?

Dark matter?

Try Supersymmetry ….

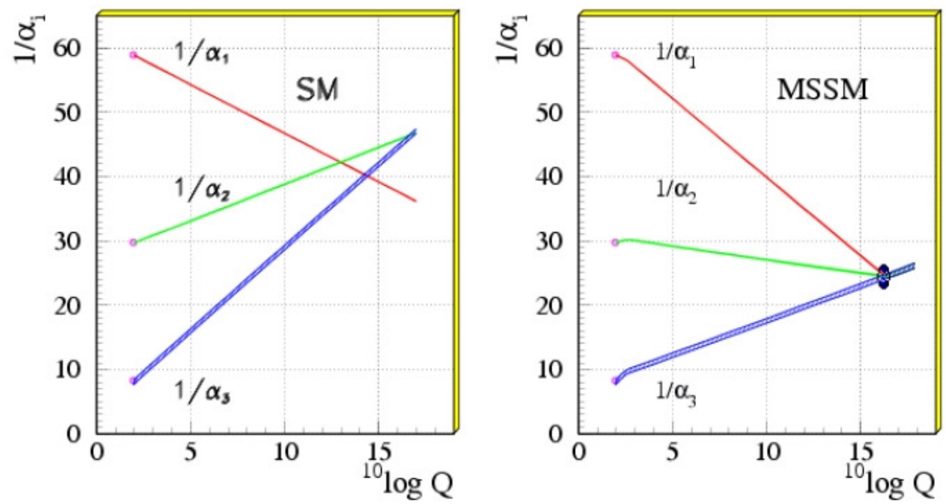
Lightest supersymmetric particle is a dark matter candidate (massive and unobservable)

Why 3 forces? 3 generations?

What if there is 1 force, which fractured at high energy to give what we see today?

Forces "run" with energy ….. and don't agree at high energy

New Physics (eg. SUSY) can modify their evolution to join up → unification?



Particles – why so many ingredients of matter?

Why are their masses so different?

And finally ….

Gravity

Can't describe it in SM

Can include it in string theory – not very testable

Large extra dimensions could be observed at LHC

CP violation

Consistent picture in SM but insufficient to explain matter – antimatter asymmetry of the universe

? Answer lies in new physics?

Many open questions not addressed by the SM

Conclusions

- Standard Model is the theoretical framework used to describe matter – force interactions
- Incomplete – doesn't explain all of the universe
- **Remarkably successful**
  - experimental tests so far very compatible with predictions
- Last piece of the jigsaw remains – to confirm or deny existence of the Higgs at the Tevatron or LHC.

Extra

g-2

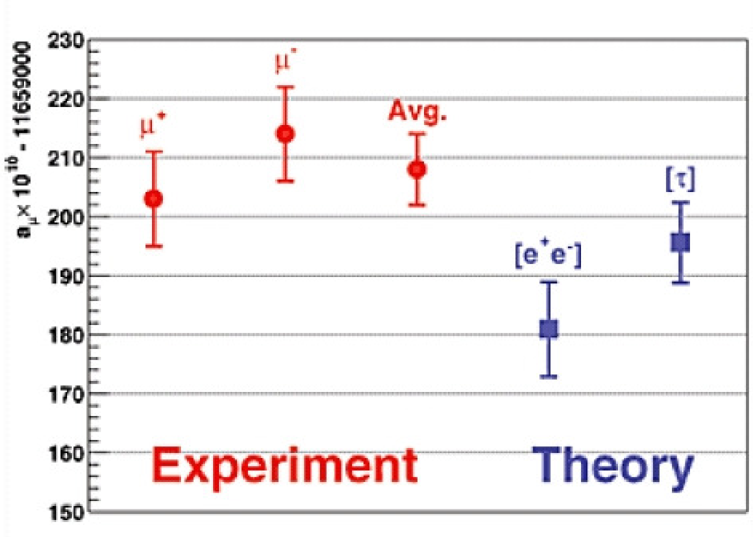
Anomalous magnetic moment of the muon

$a_\mu = ½(g-2)$

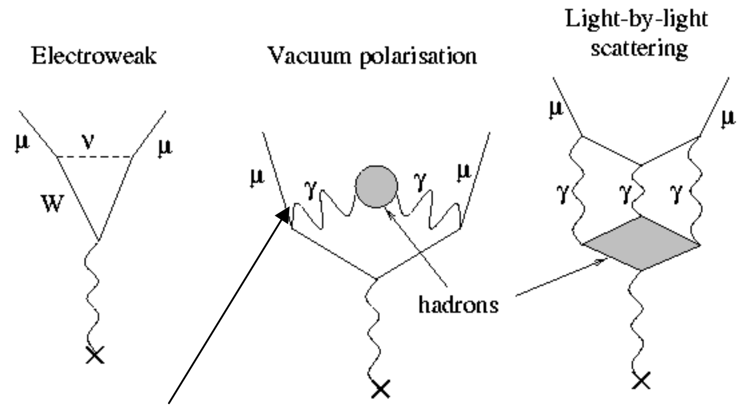
- non zero value due to higher order corrections
- Measure spin "wobble" in magnetic field (v. accurate)

$a_\mu = (11\ 659\ 208.0 \pm 6.0) \times 10^{-10}$
cf. $(11\ 658\ 471.81 \pm 0.02) \times 10^{-10}$
EWK: $(15.4 \pm 0.2) \times 10^{-10}$
Vac. : $(692.2 \pm 9.2) \times 10^{-10}$
Light: $(12.0 \pm 3.5) \times 10^{-10}$

- Investigations / new e^+e^- measurements ongoing.



The results from E821 for the muon anomalous magnetic moment.



Non-peturbative

contribution can be normalised from measurements of $e^+e^- \to \pi^+\pi^-$ (3σ) or $\tau^+\tau^- \to \pi^+\pi^-$ (ok)

g-2 for electron

Anomalous magnetic moment of the electron $a_e = 1/2(g-2)$

- Most precisely measured SM parameter
- $a_e = 0.001\ 159\ 652\ 180\ 85(76)$

$\Rightarrow \alpha^{-1} = 137.035\ 999\ 710(96)$

Corrections:

QCD: $1.671(19) \times 10^{-12}$

Weak: $0.030(01) \times 10^{-12}$

QED test.

Tests over different energy scales

Predict quantity with high energy measurements – extrapolate to low energy and compare.

Atomic parity violation in caesium

Extract weak charge Q_W(proportional to Z couplings, no. protons, no. neutrons)

Measure -72.74 ± 0.46 cf. SM -72.91 ± 0.03

nuTeV extraction of $\sin^2\theta_W$ ~ 3σ different

Moller scattering with polarised electron beam (E-158)

Extract $\sin^2\theta_W = 0.2333 \pm 0.0015$ cf. 0.2314 ± 0.0001