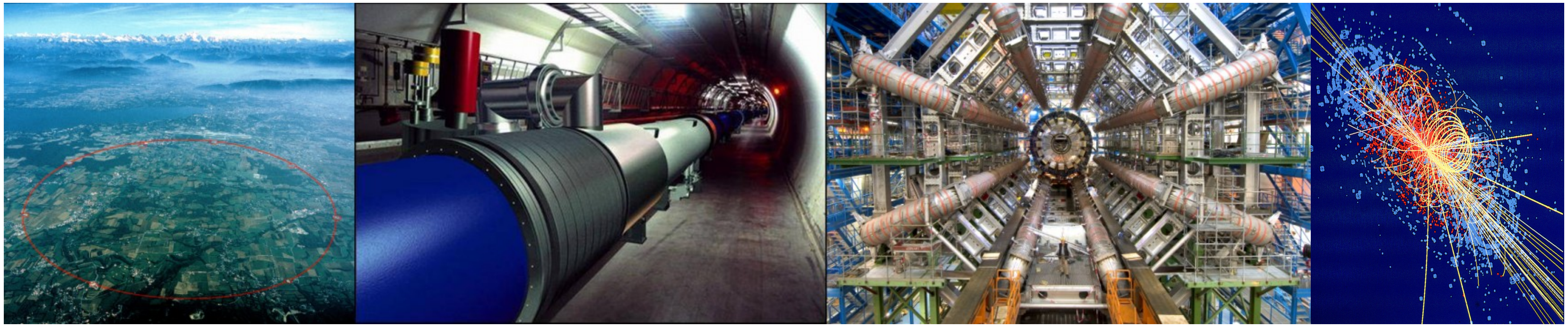
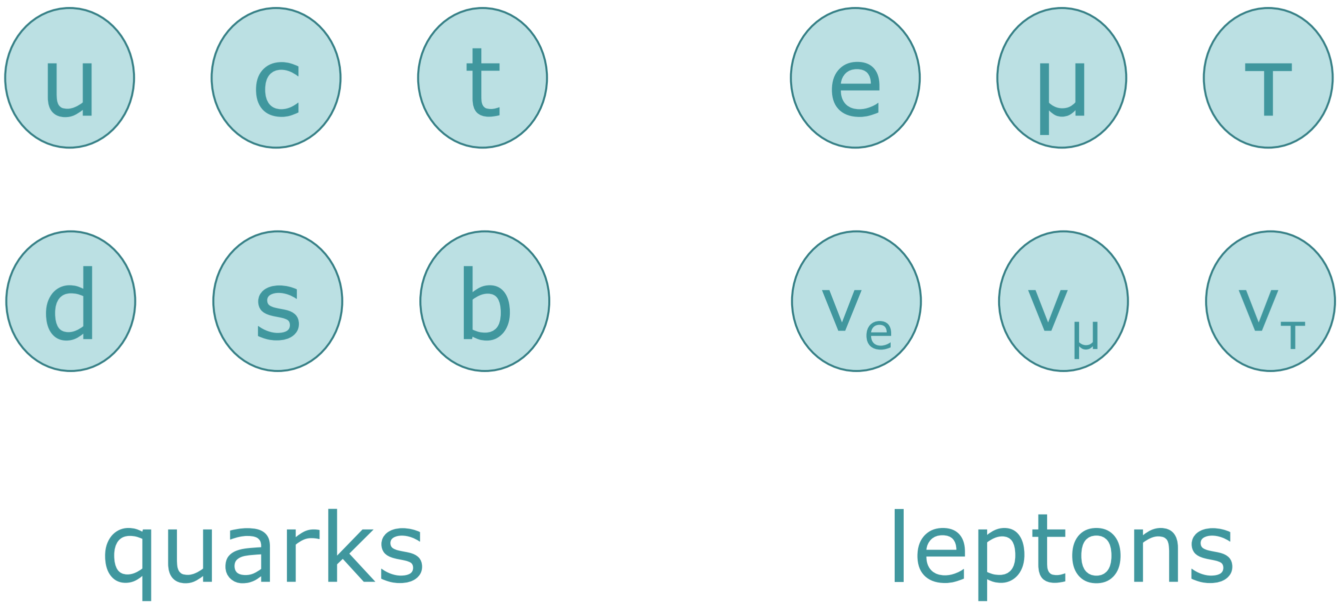


The Standard Model

Tara Shears

- What is the Standard Model?
- Experimental tests
  - How good is our understanding for LHC?
- Shortcomings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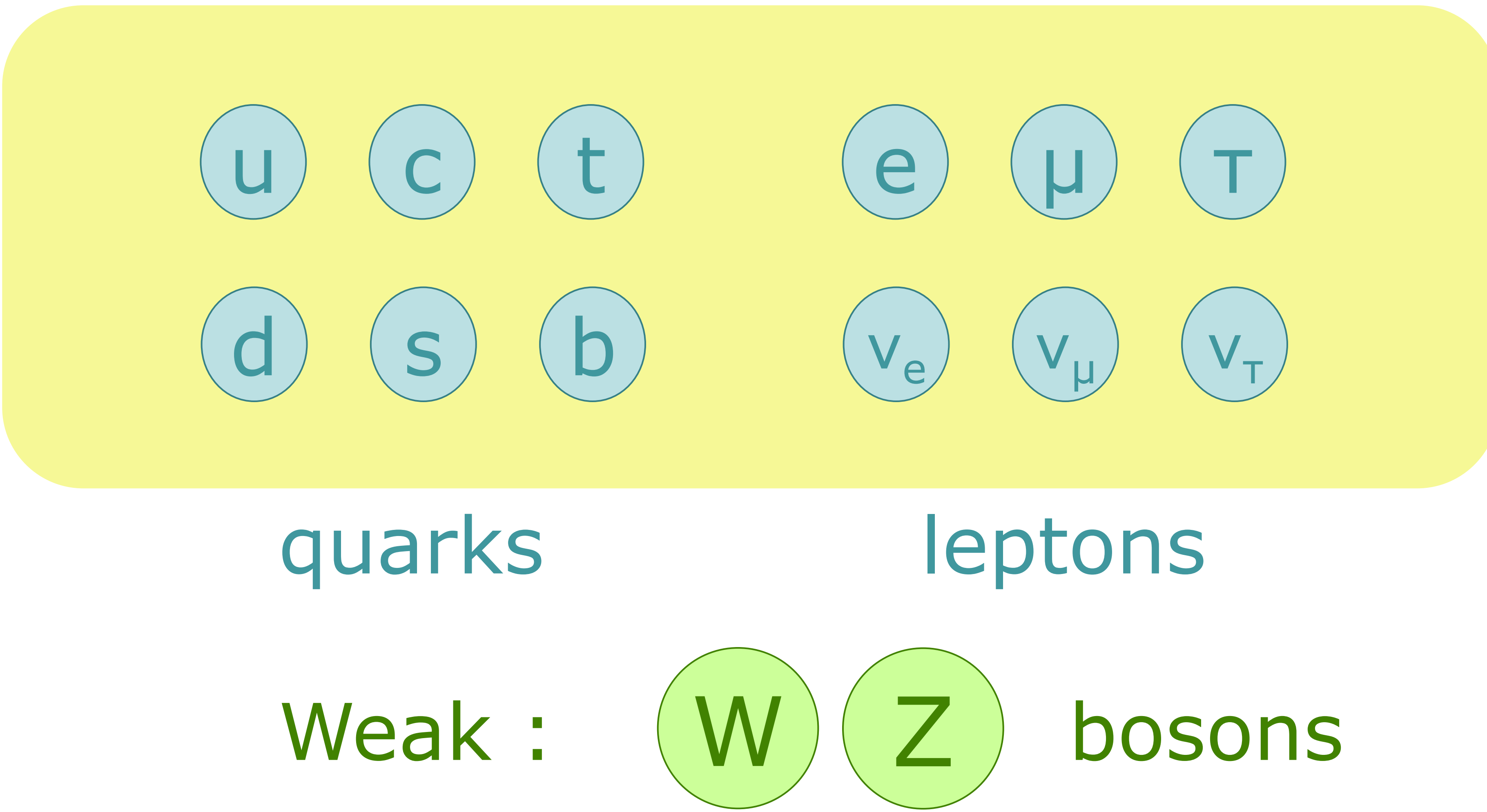
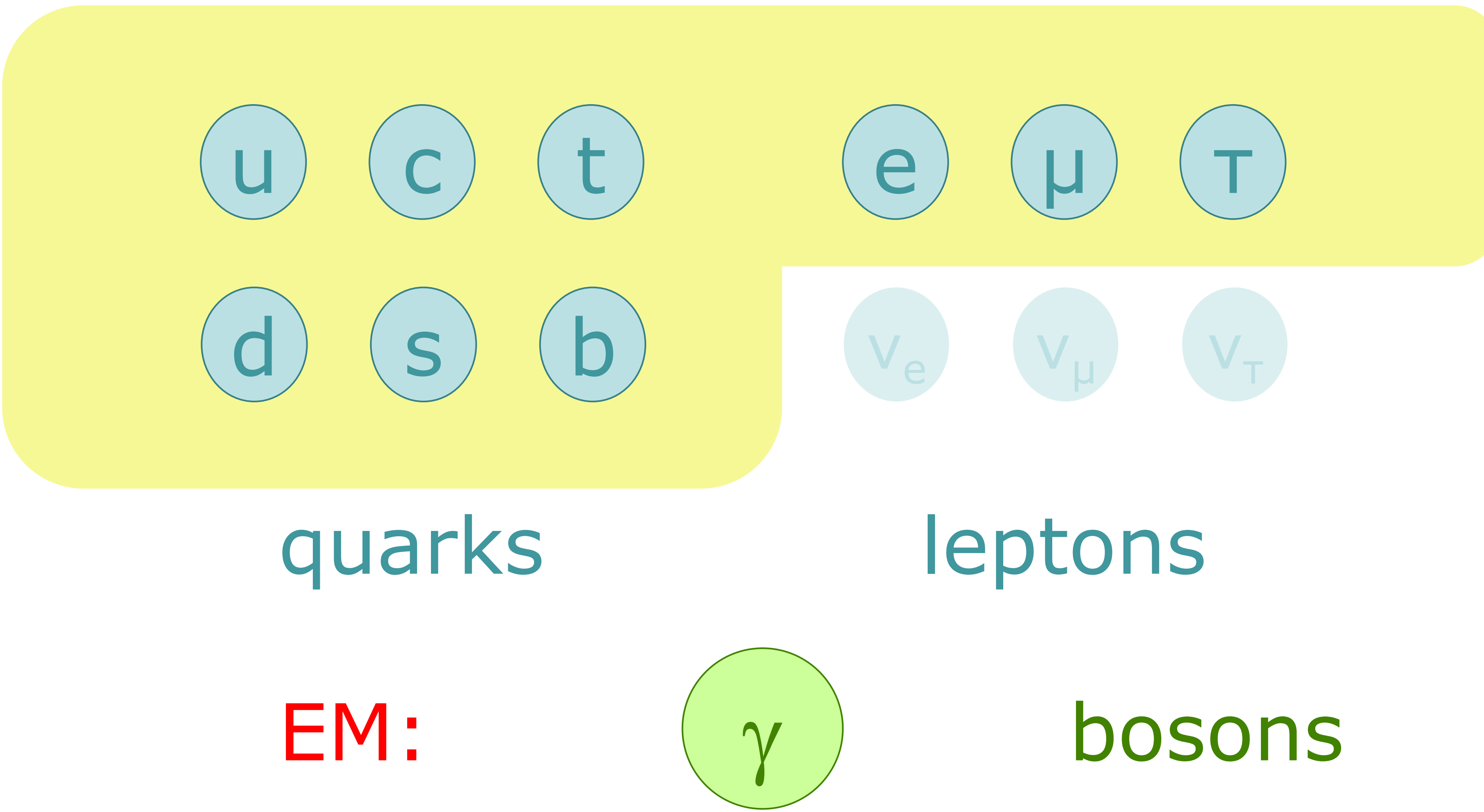
quarks
leptons

1. What does the Standard Model describe?

2. Constructing the theory

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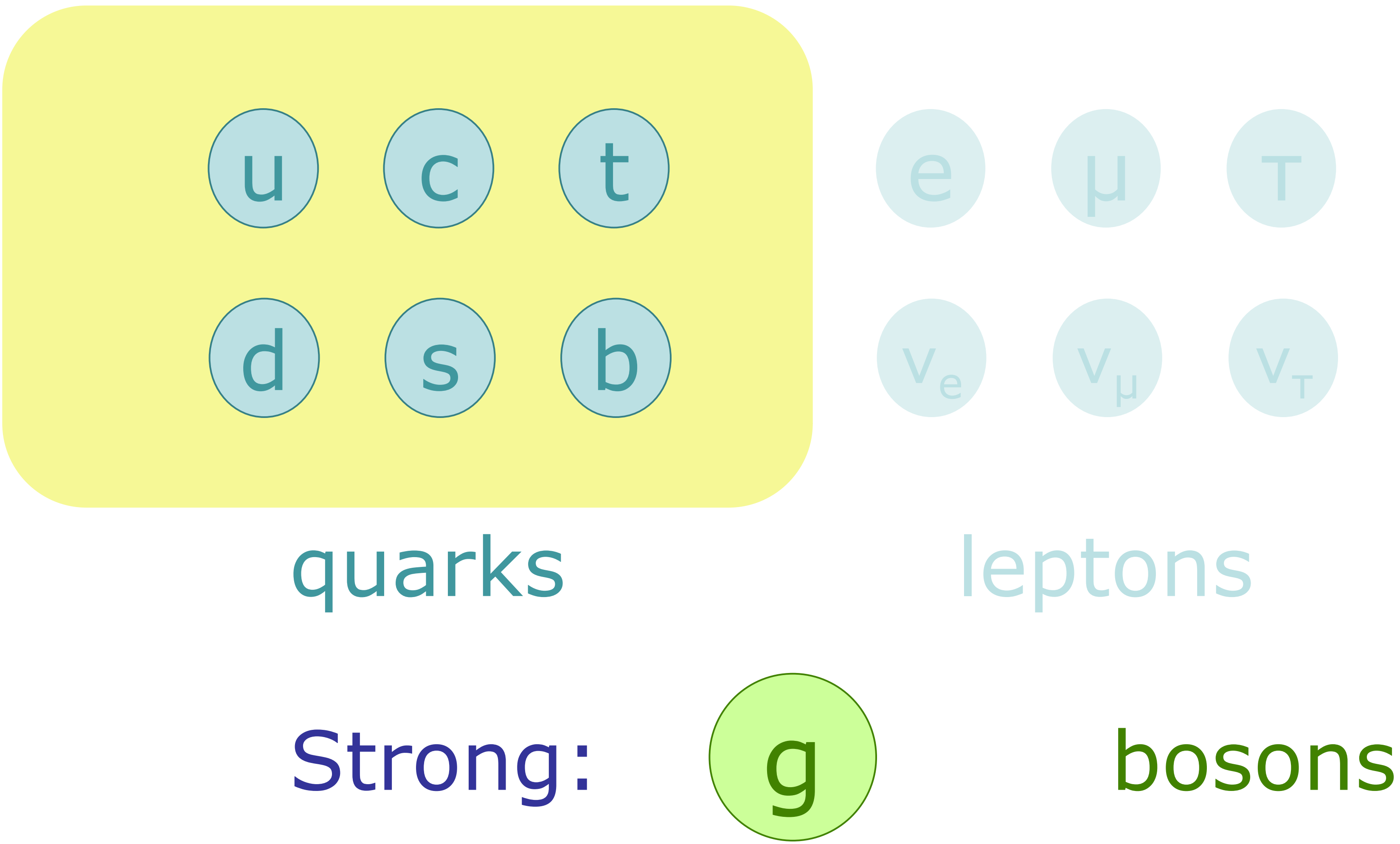
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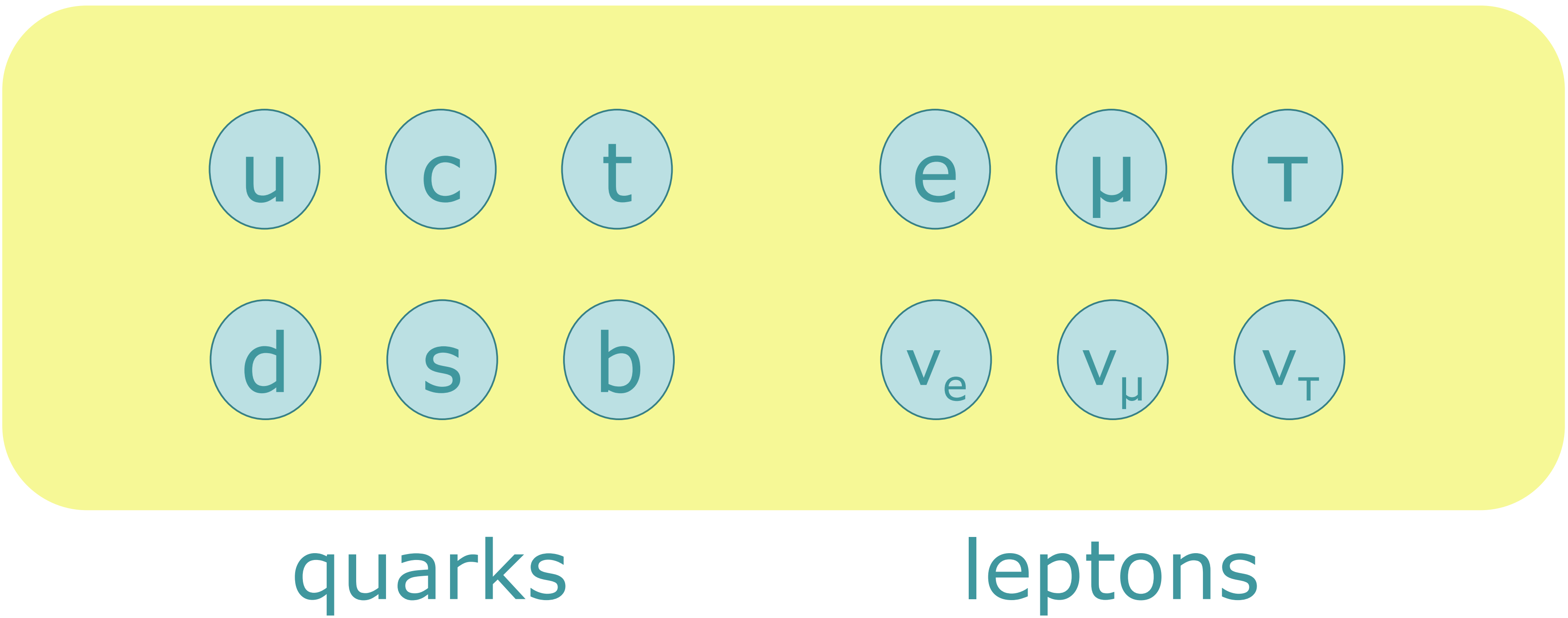
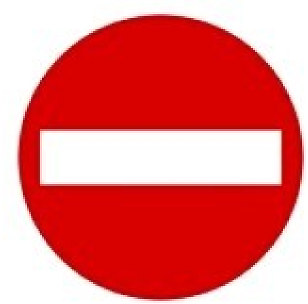


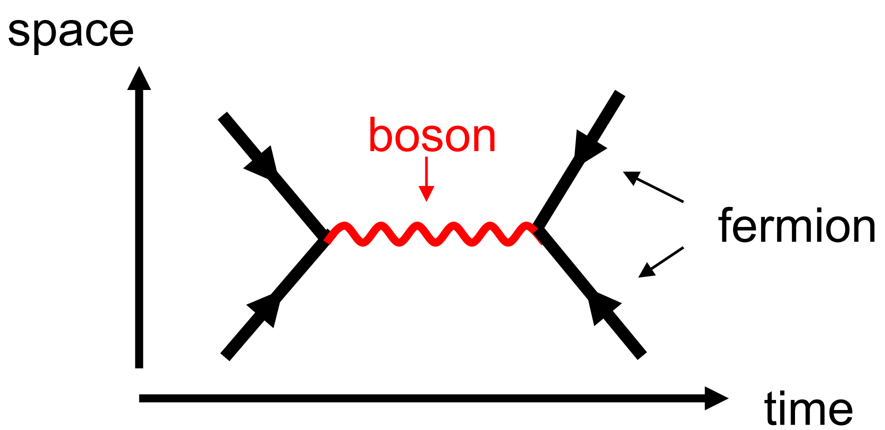
(and gravity)



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



SM is a quantum 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)

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

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

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

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

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

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)

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

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

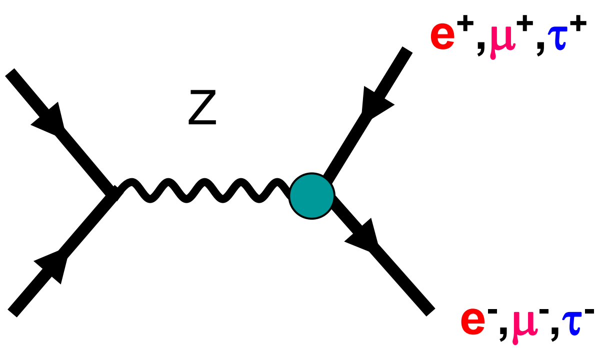
1. Test any assumptions we’ve made
2. Measure unknown parameters in different ways and check consistency
3. Compare predicted quantities to measurements, check internal consistency of SM framework
4. How well will this work for LHC?

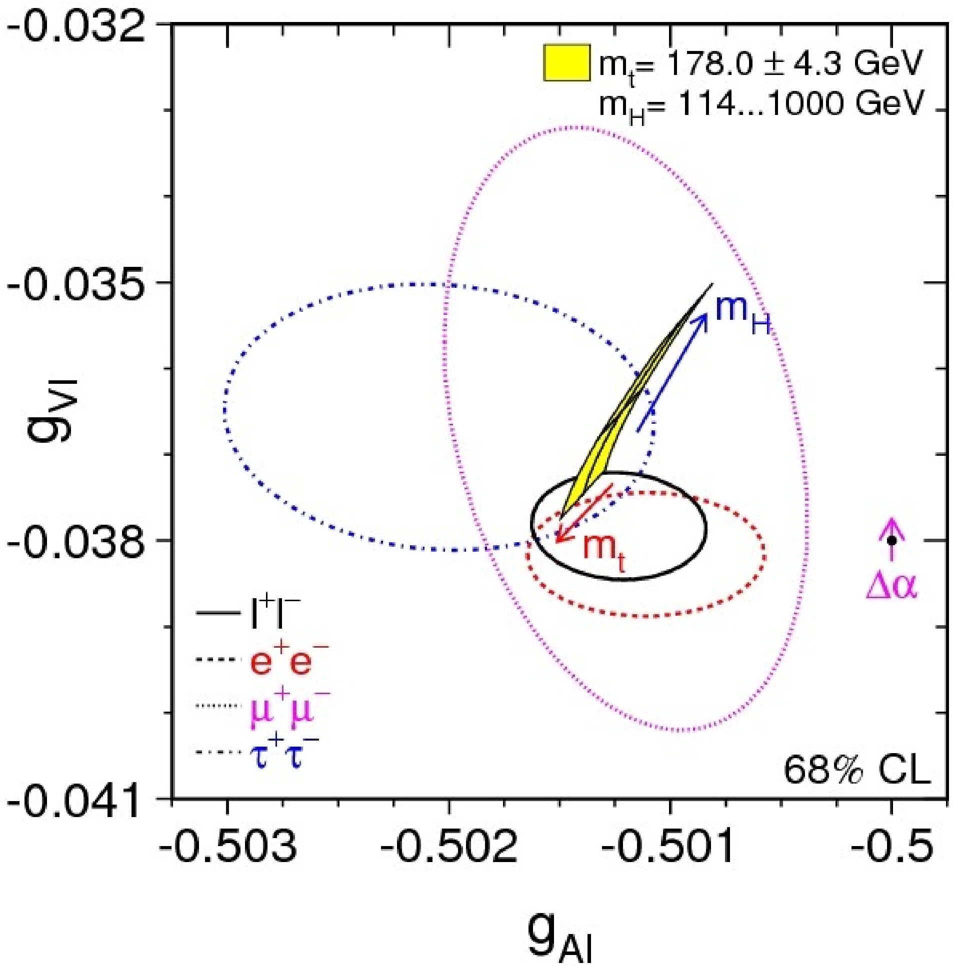
Lepton universality:

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

Test Z couplings to ee, μμ, ττ

Find all measurements **consistent** with each other and SM prediction.





3 generations of matter

No info on # generations in SM

Use Z lineshape: SM relates width to possible decay products

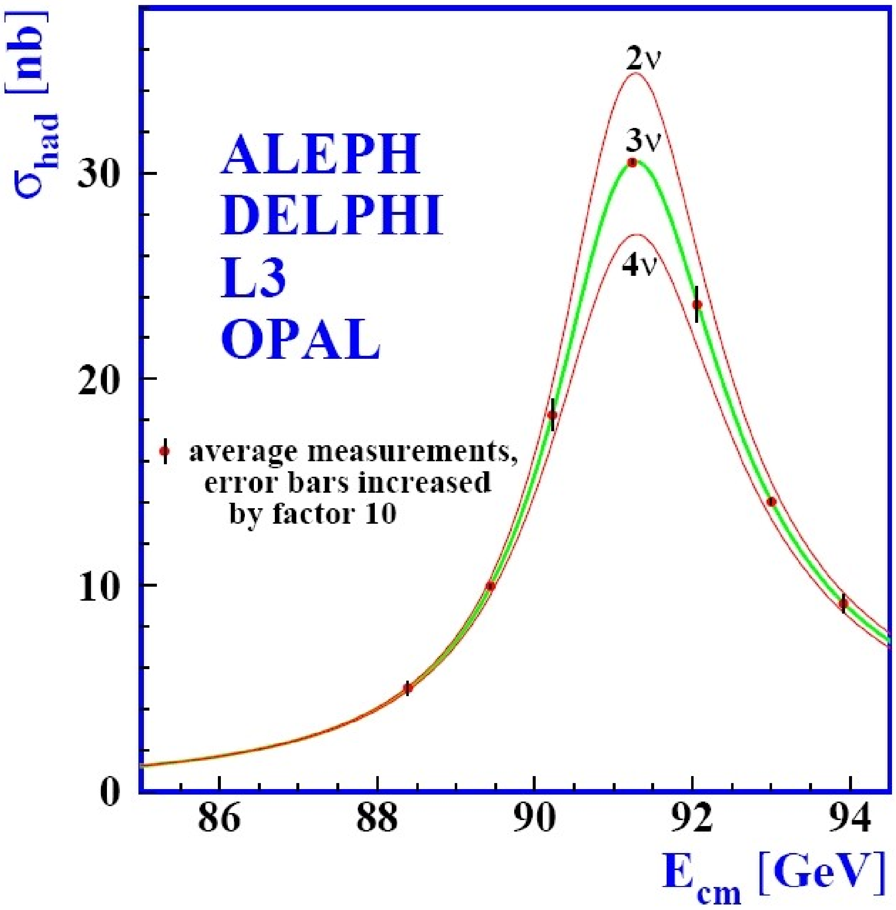
Measure Γ_{had}, Γ_{ee}, σ_{had}

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

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

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

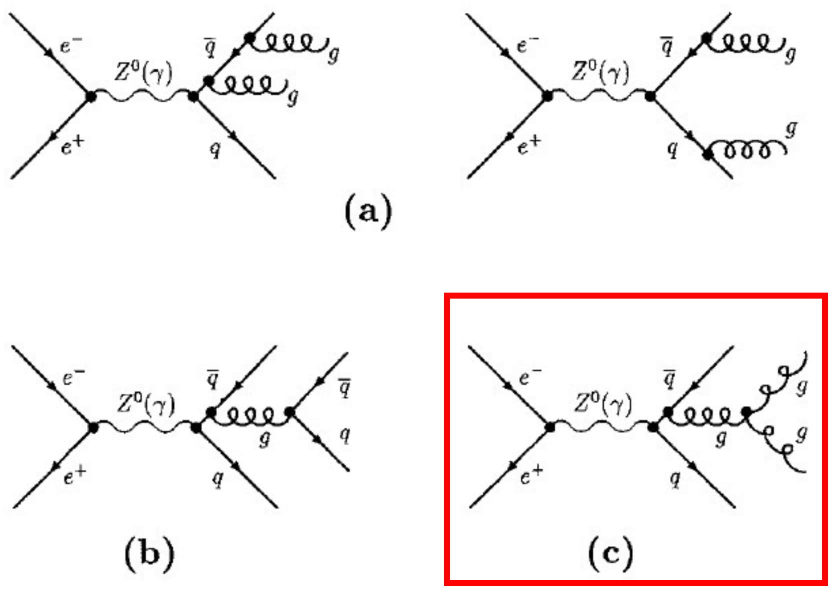
Calculate $N\nu$



$N\nu = 2.984 \pm 0.008$

Non-abelian strong force

Rate of 4 jet production at LEP:



SM contribution from **triple gluon coupling**

Difference demonstrates non-abelian couplings

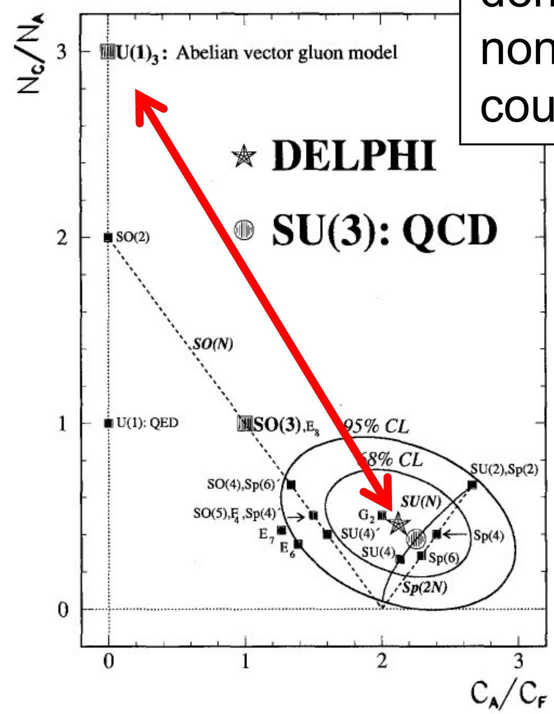
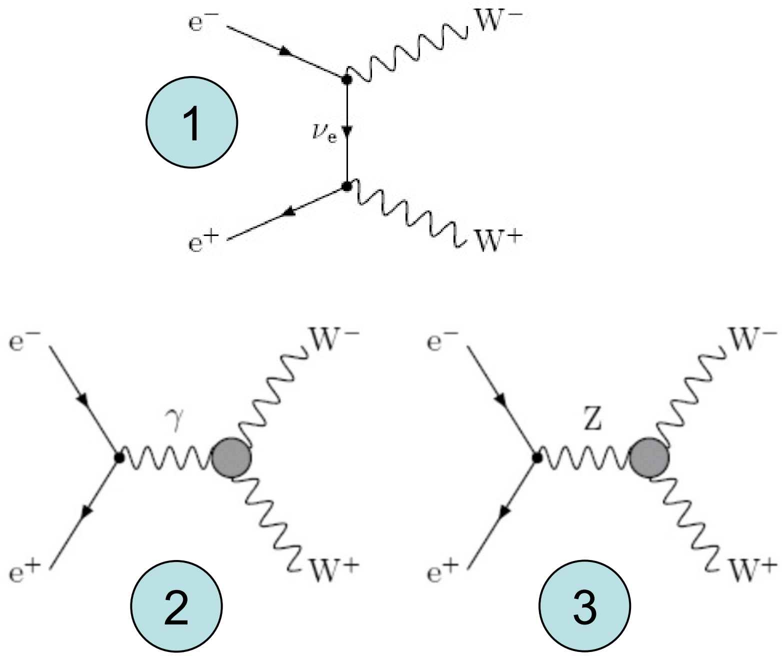
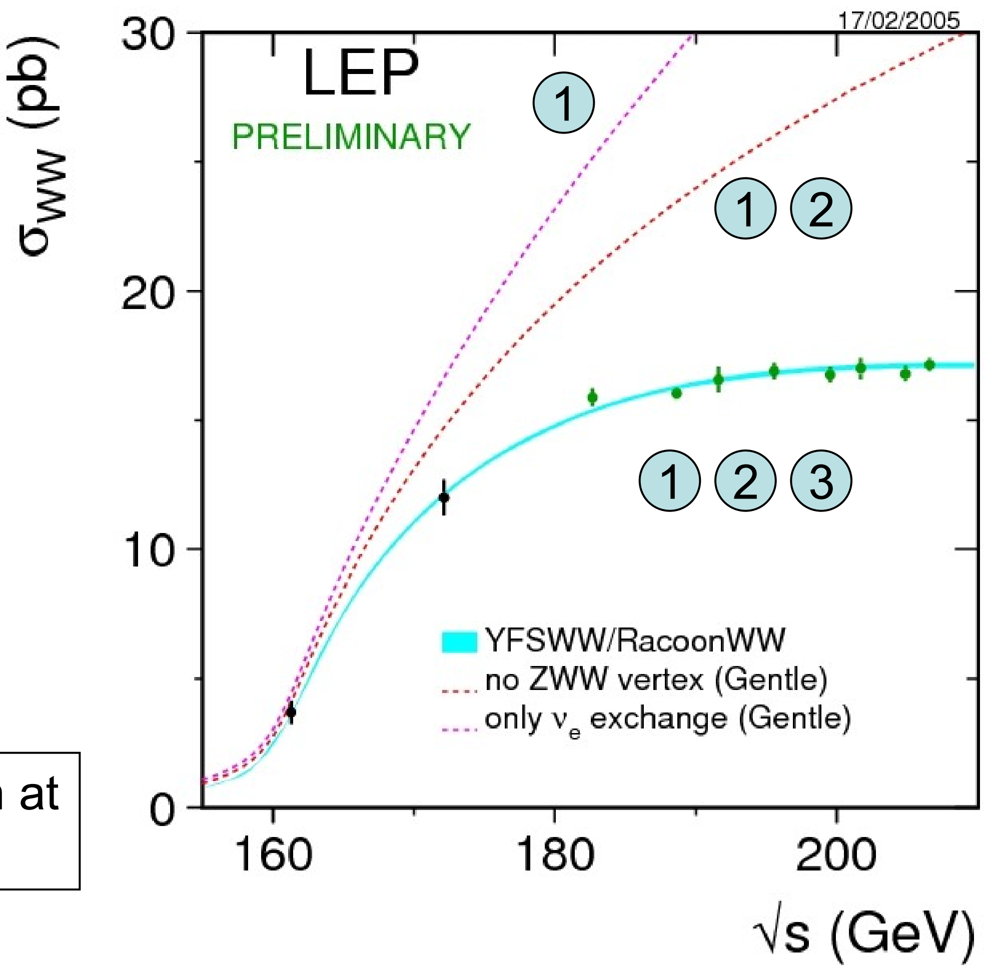


Fig. 10. 68% and 95% CL contour plots for the measured variables C_A/C_F and N_C/N_A, and expections from different gauge theories. C_A/C_F = ratio of coupling strength of $g \to gg$ to $q \to qg$; N_C/N_A = number of quark colours divided by the number of gluons.

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

Non-abelian weak force



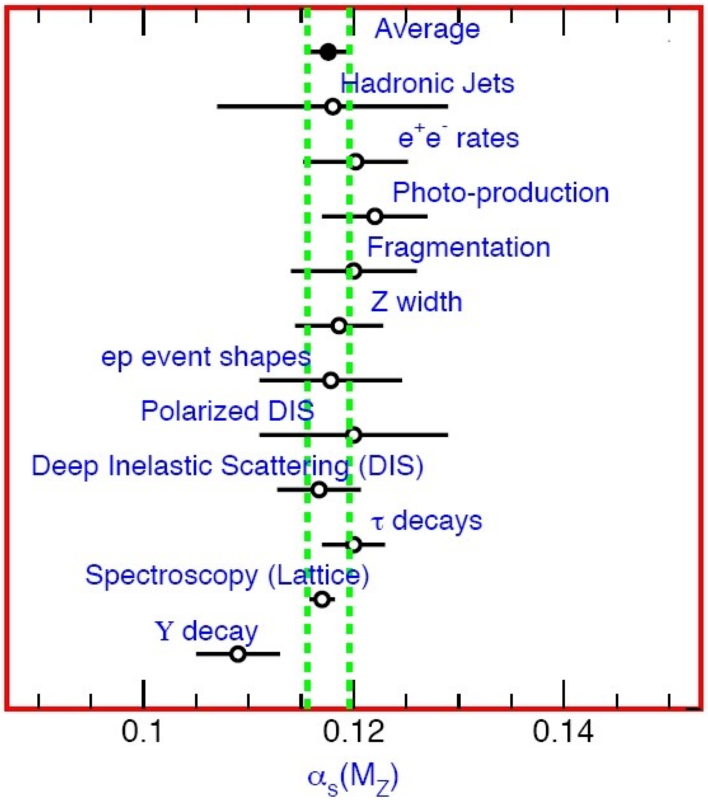


Check rate of $e^+e^- \rightarrow WW$ production at LEP

LEP 4fermion working group

Couplings

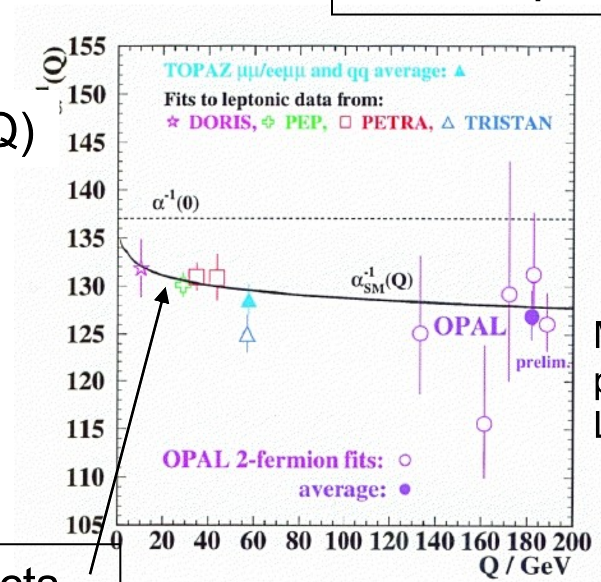
Strong coupling



Many measurements give consistent answer

EM coupling

$1/\alpha(Q)$

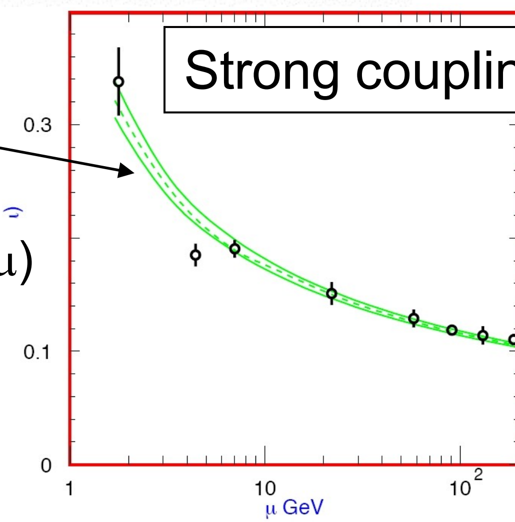


M. Kobel, proceedings LP97

SM predicts evolution with energy

Strong coupling

$\alpha_s(\mu)$

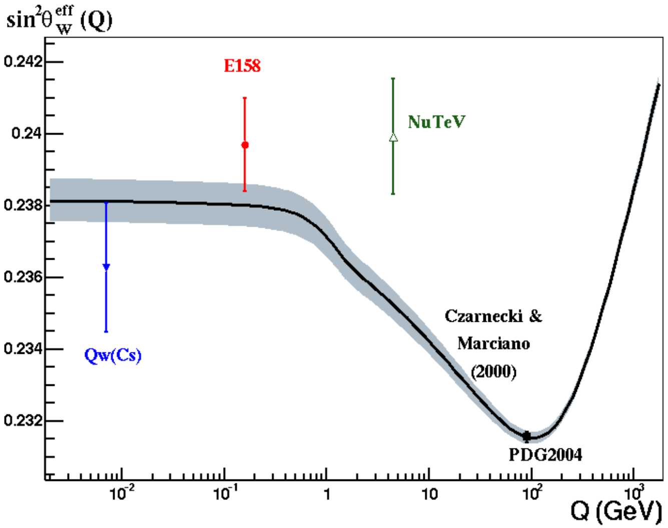


Particle data group

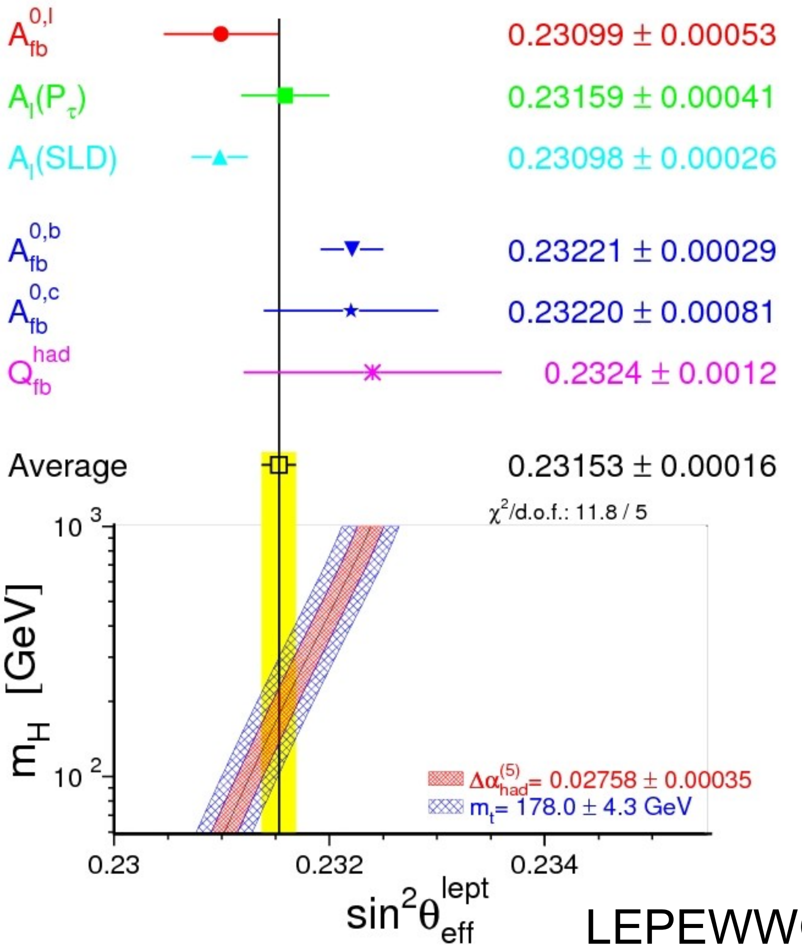
$\sin^2\theta_W$

Relates weak, em couplings and M_W, M_Z

Consistent result extracted from many different measurements



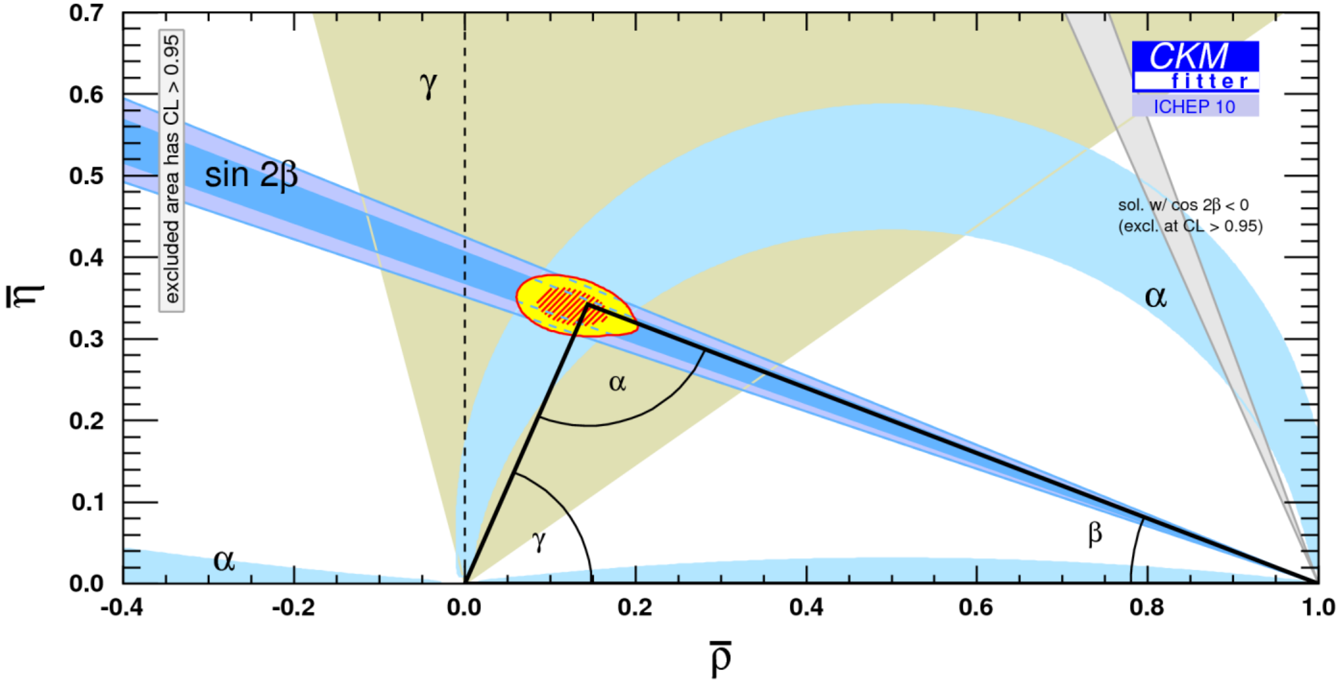
Energy evolution



LEPEWWG

Quark mixing

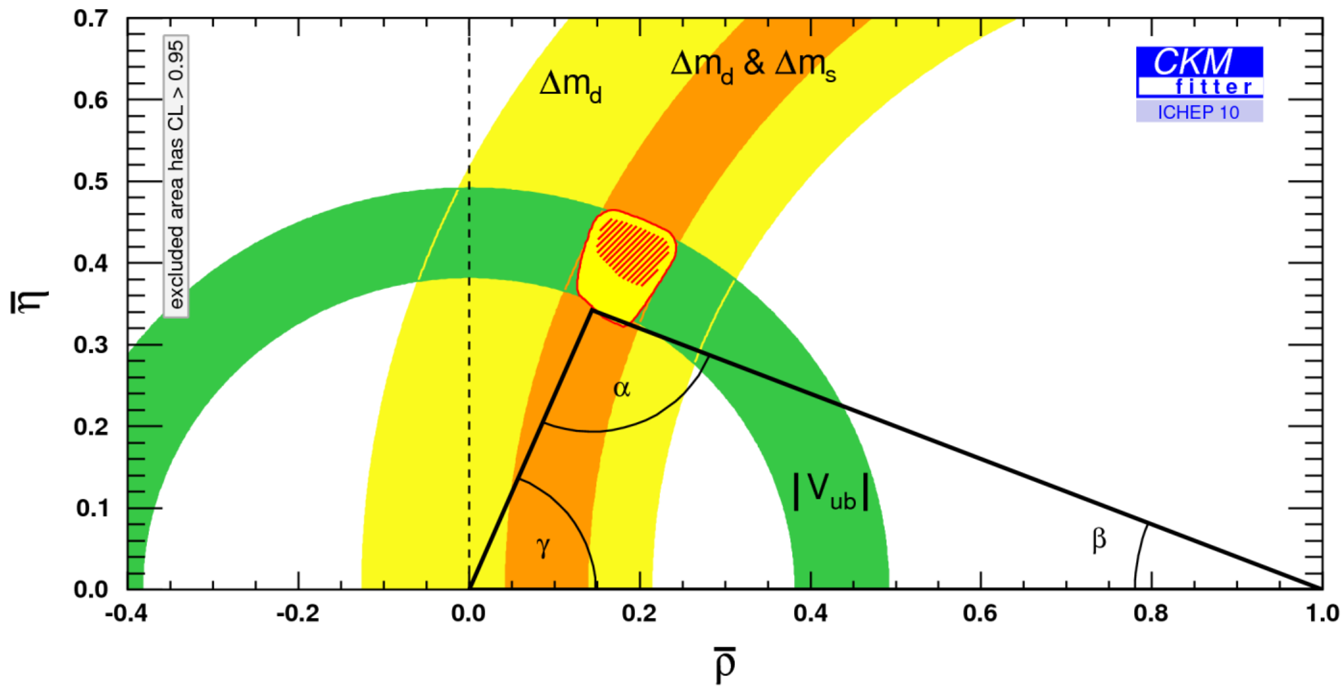
Many measurements of the 4 parameters describing quark mixing and CP violation



B and anti-B meson decay rates

Quark mixing

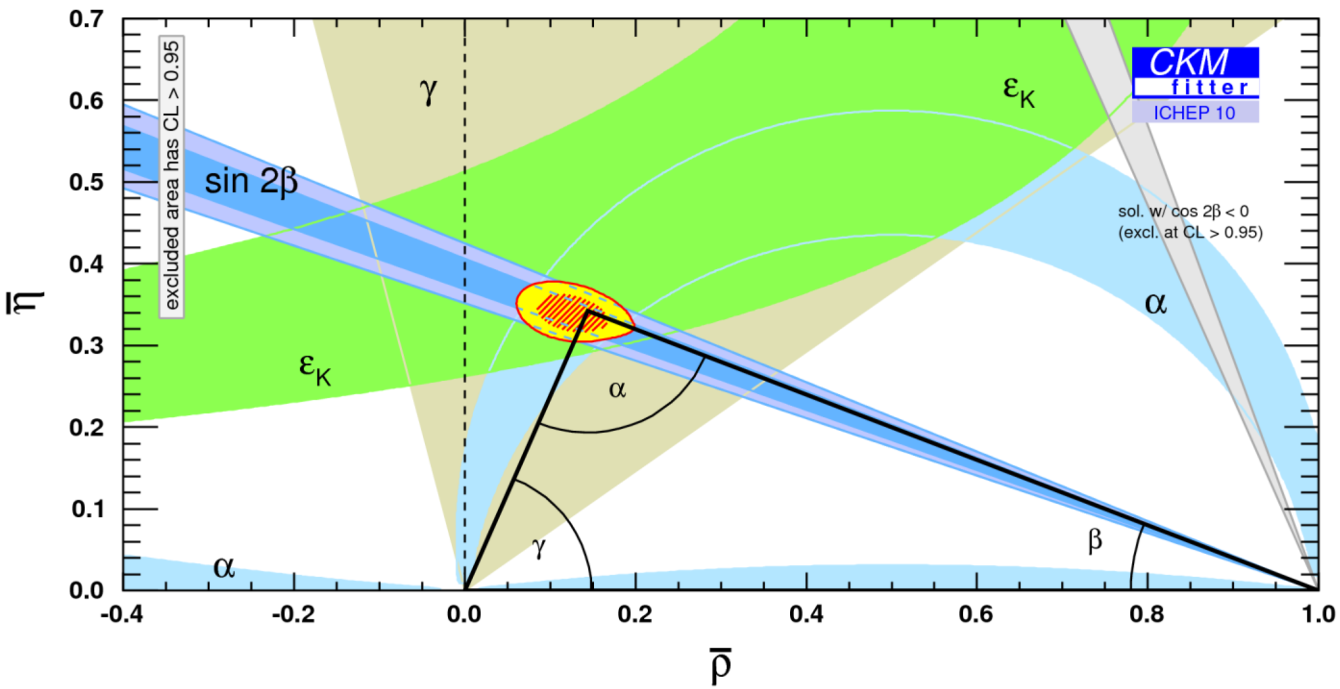
Many measurements of the 4 parameters describing quark mixing and CP violation



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

Quark mixing

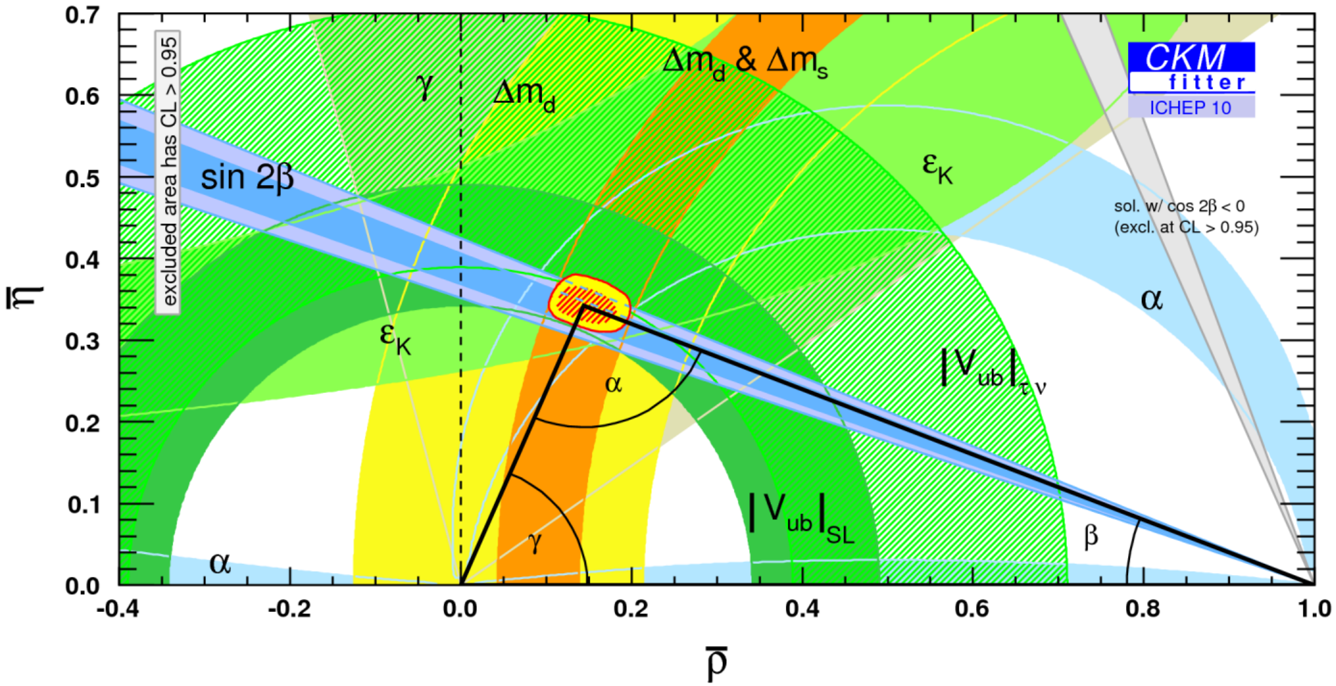
Many measurements of the 4 parameters describing quark mixing and CP violation



CP violation in kaon and B meson sectors

Quark mixing

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



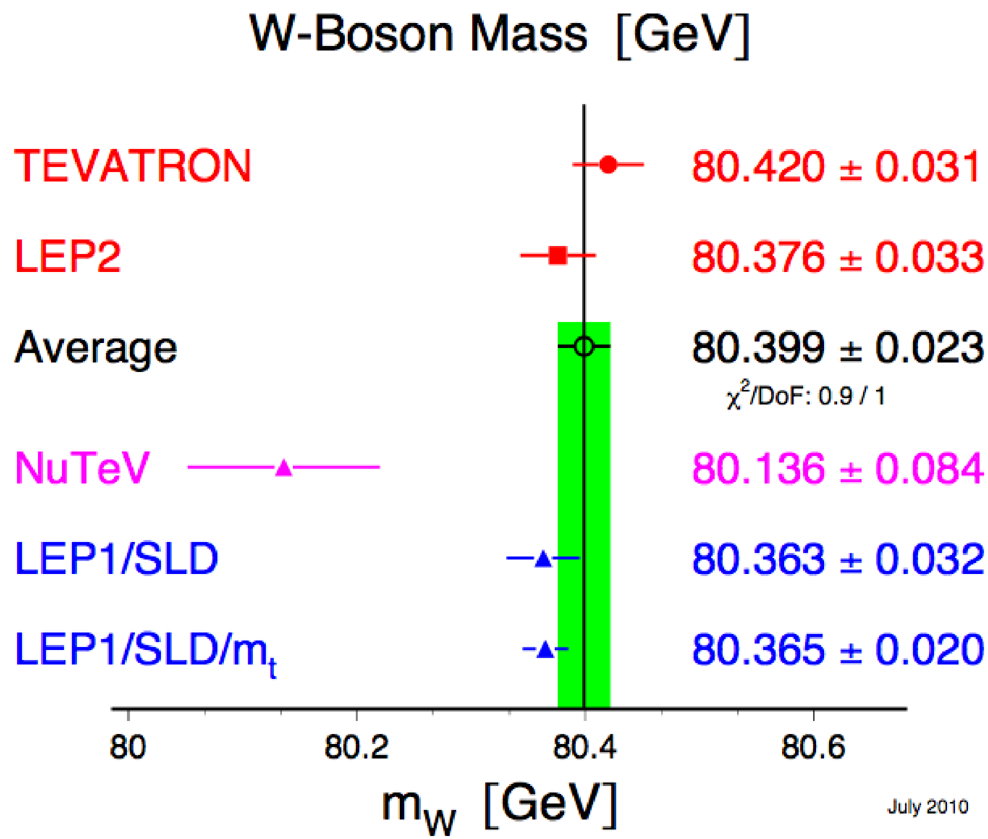
All measurements consistent

W boson mass

Direct measurement

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

SM prediction

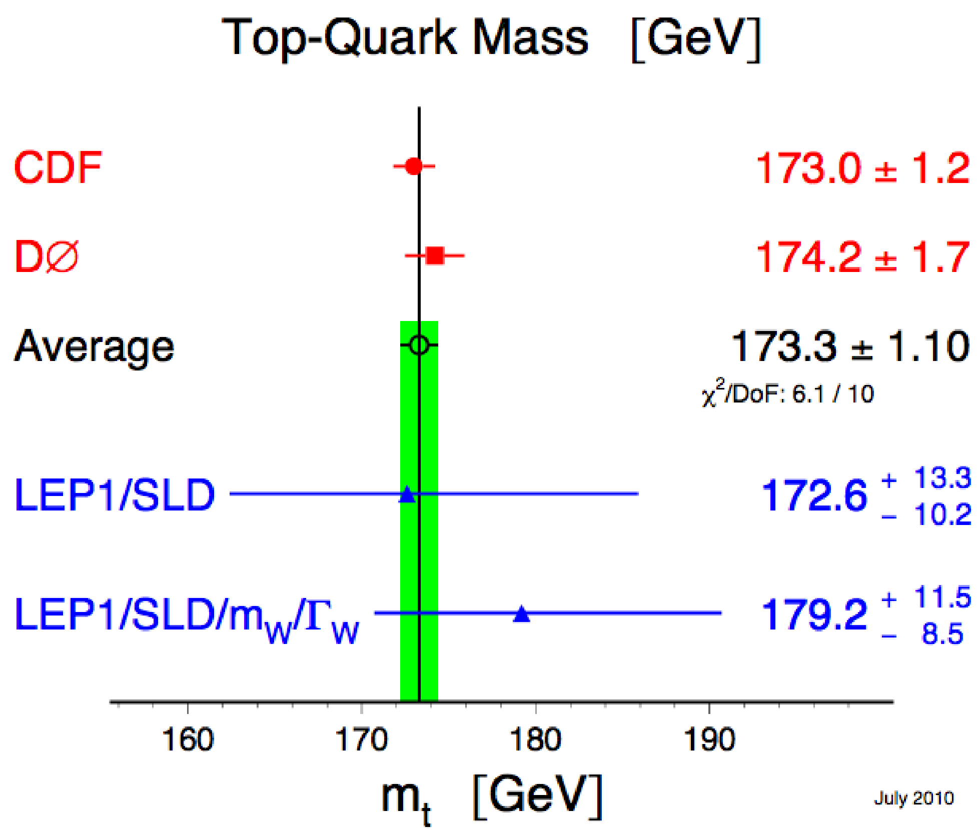


Consistent (NuTeV result low)

Top quark mass

Direct measurement →

SM prediction →

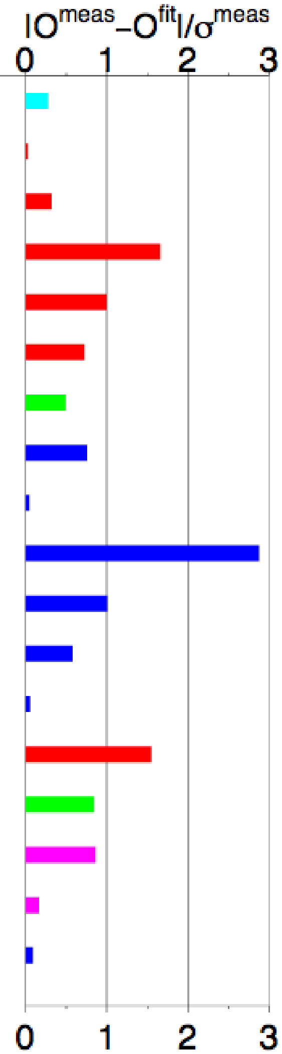


Consistent

Many internal consistency checks possible

- Fit to Z, W, top quark results shown here.
- Results are **consistent**.

	Measurement	Fit
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02758 ± 0.00035	0.02768
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959
σ^0_{had} [nb]	41.540 ± 0.037	41.479
R_l	20.767 ± 0.025	20.742
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.01645
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481
R_b	0.21629 ± 0.00066	0.21579
R_c	0.1721 ± 0.0030	0.1723
$A^{0,b}_{fb}$	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]	80.399 ± 0.023	80.379
Γ_W [GeV]	2.085 ± 0.042	2.092
m_t [GeV]	173.3 ± 1.1	173.4



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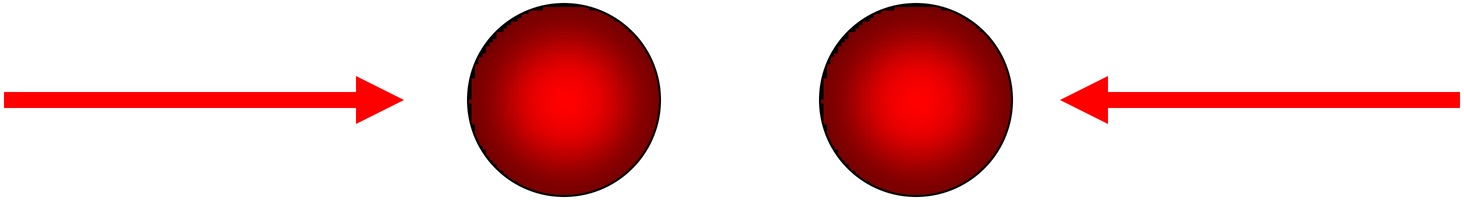
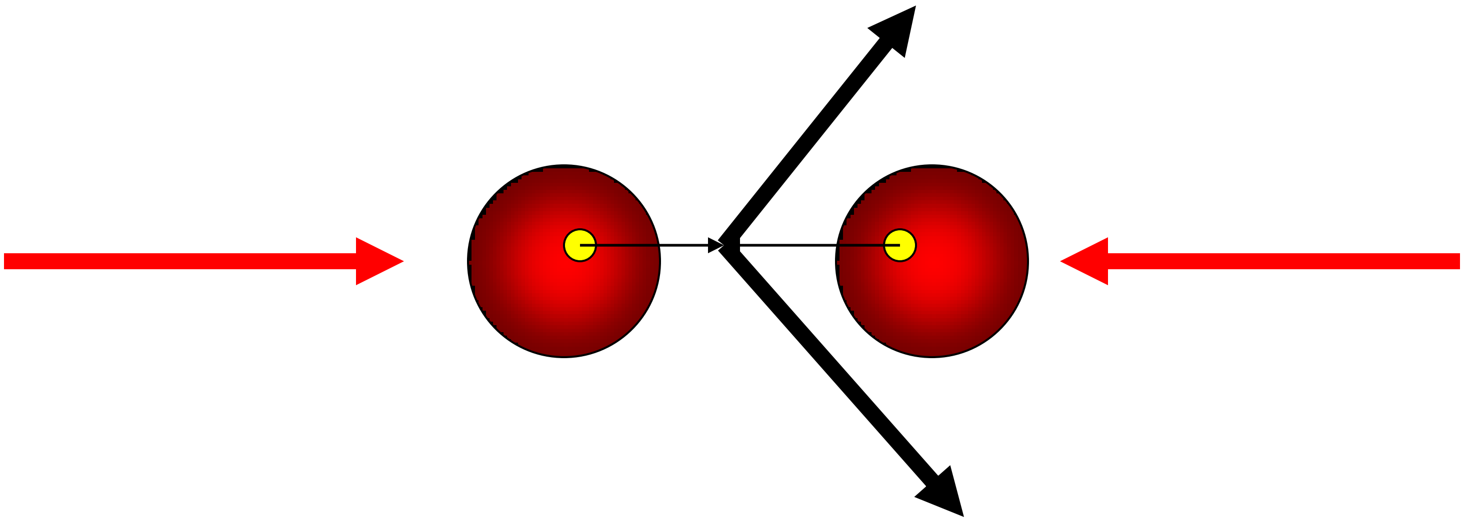
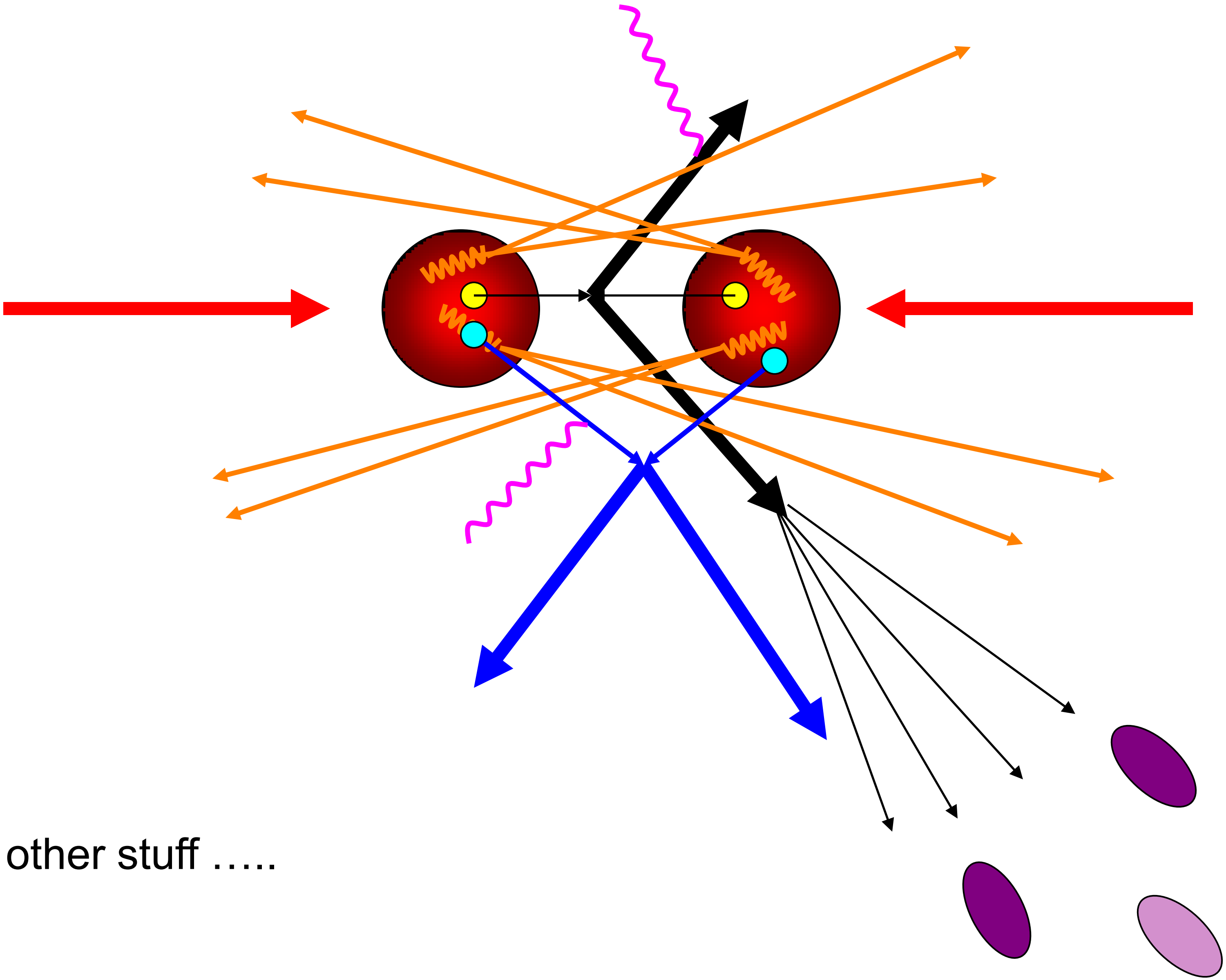


LHC: proton proton collisions



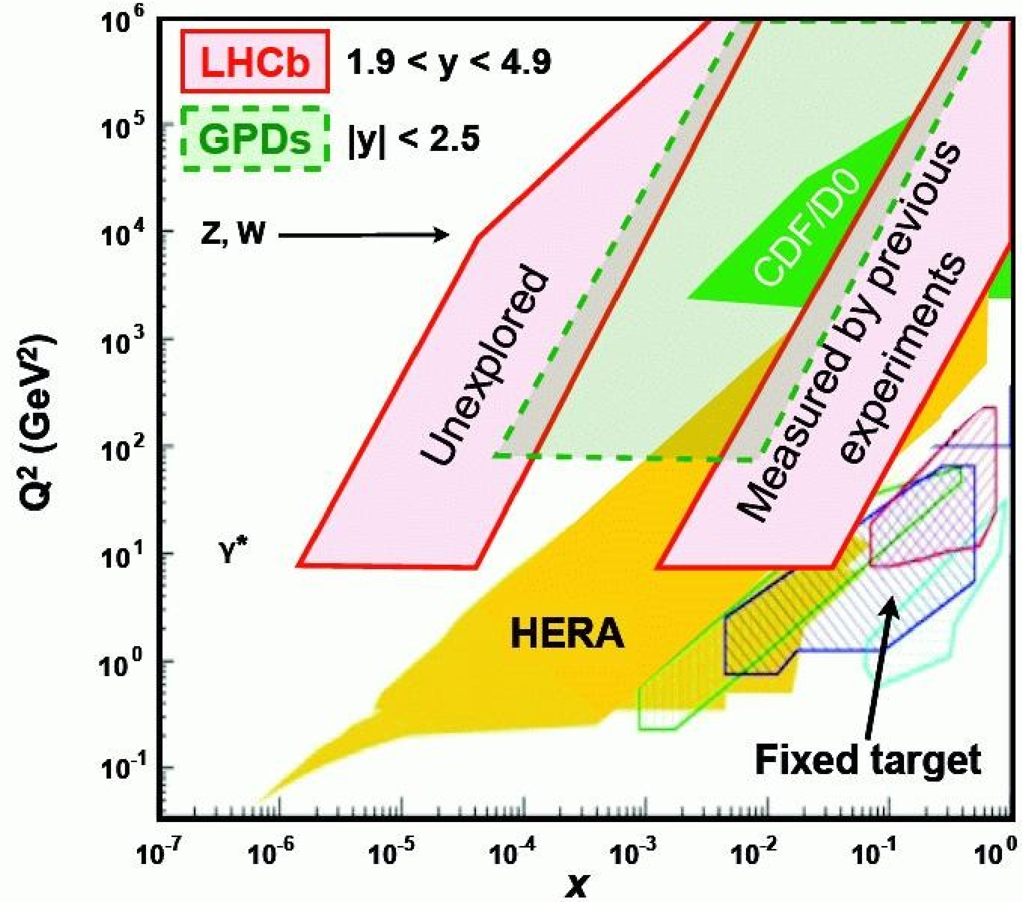
Parton energies described by **parton density functions** (PDFs)
Cross-section of interest: **SM calculation** ⊗ PDF



+ other stuff …..

… complicated, but we have predictions that include these effects

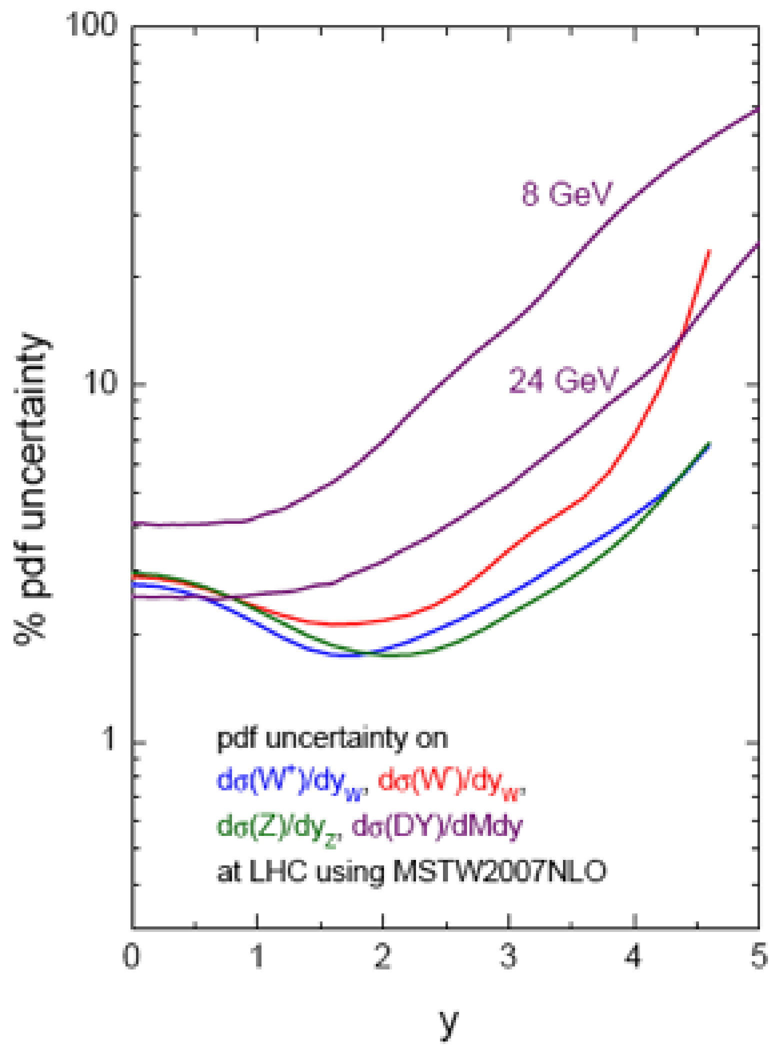
Behaviour of partons parametrised by previous experimental data, and extrapolated to LHC energies.



W, Z production:

- PDF uncertainty dominates precision.
- Known to 1-2% in regions covered by detectors

LHC can make precision tests of the SM at new energies



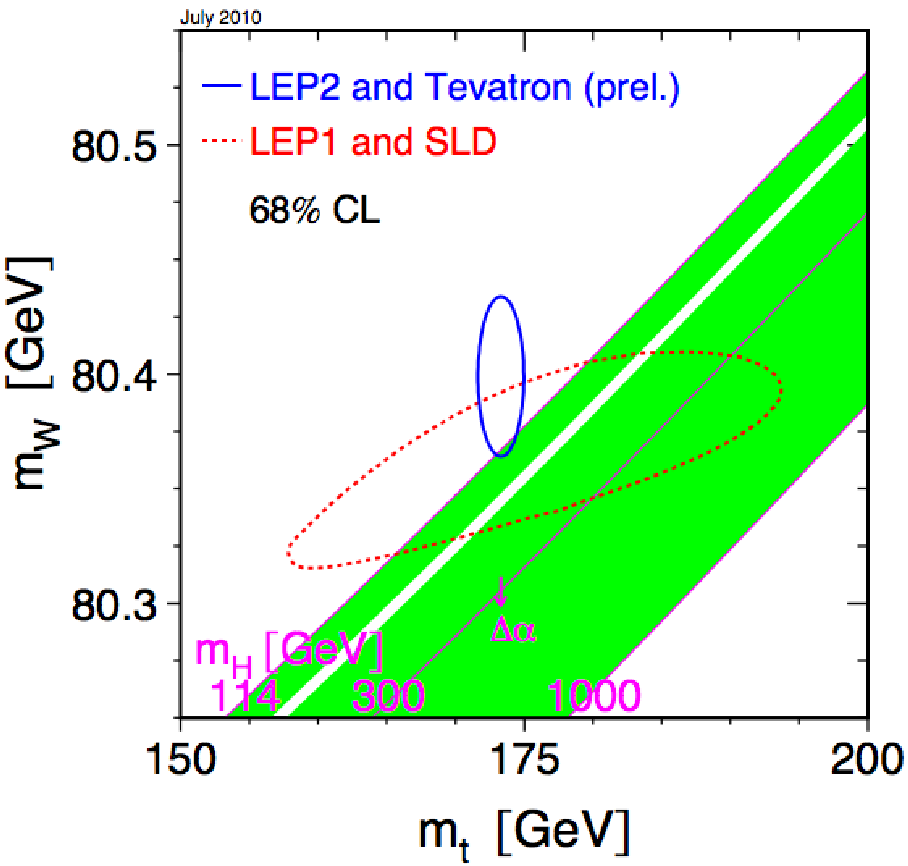
1. Experimental

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

2. Philosophical

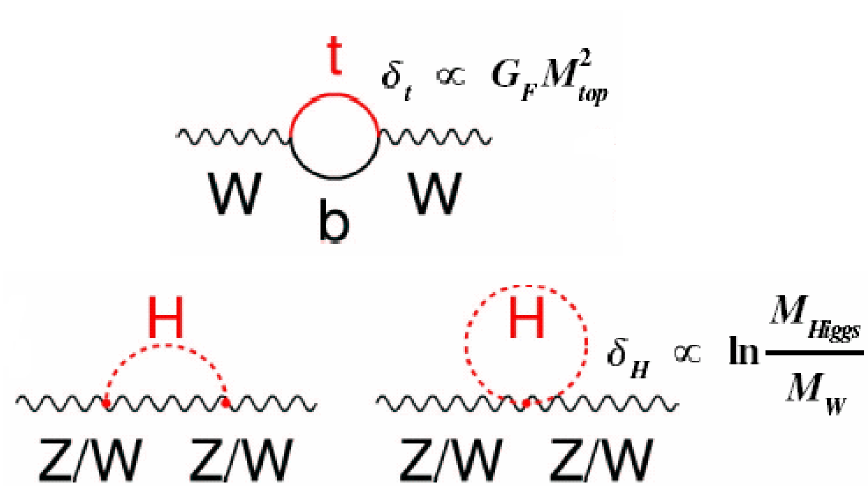
- There is a lot we still don’t understand
- What lies beyond the limits of the SM?

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

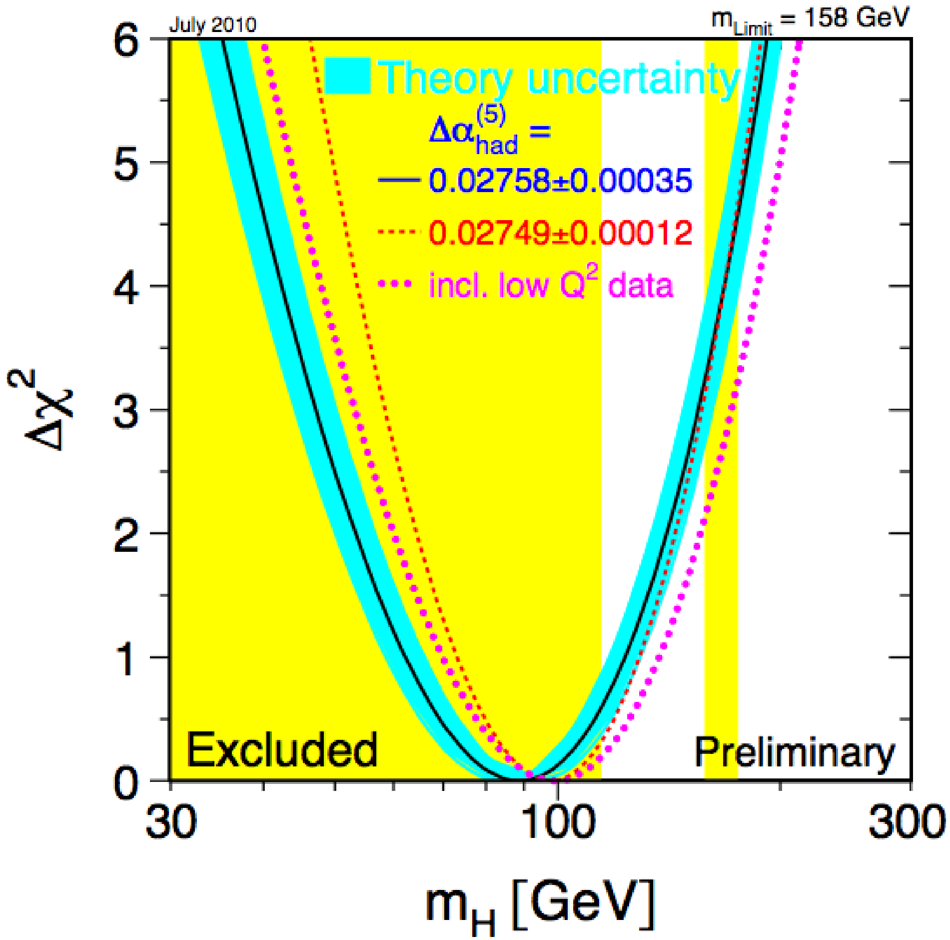


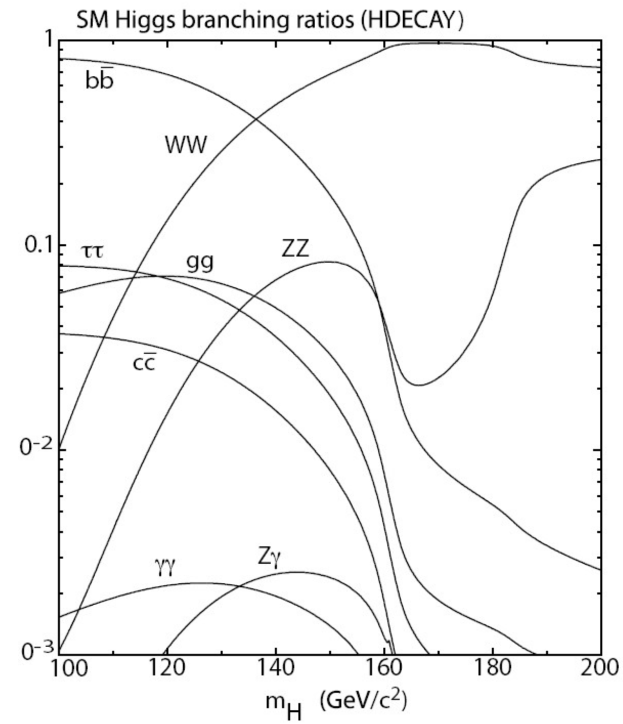
Can constrain mass from measured W, top mass with SM.

Can constrain from other ewk measurements with SM



1. Experimental; Higgs





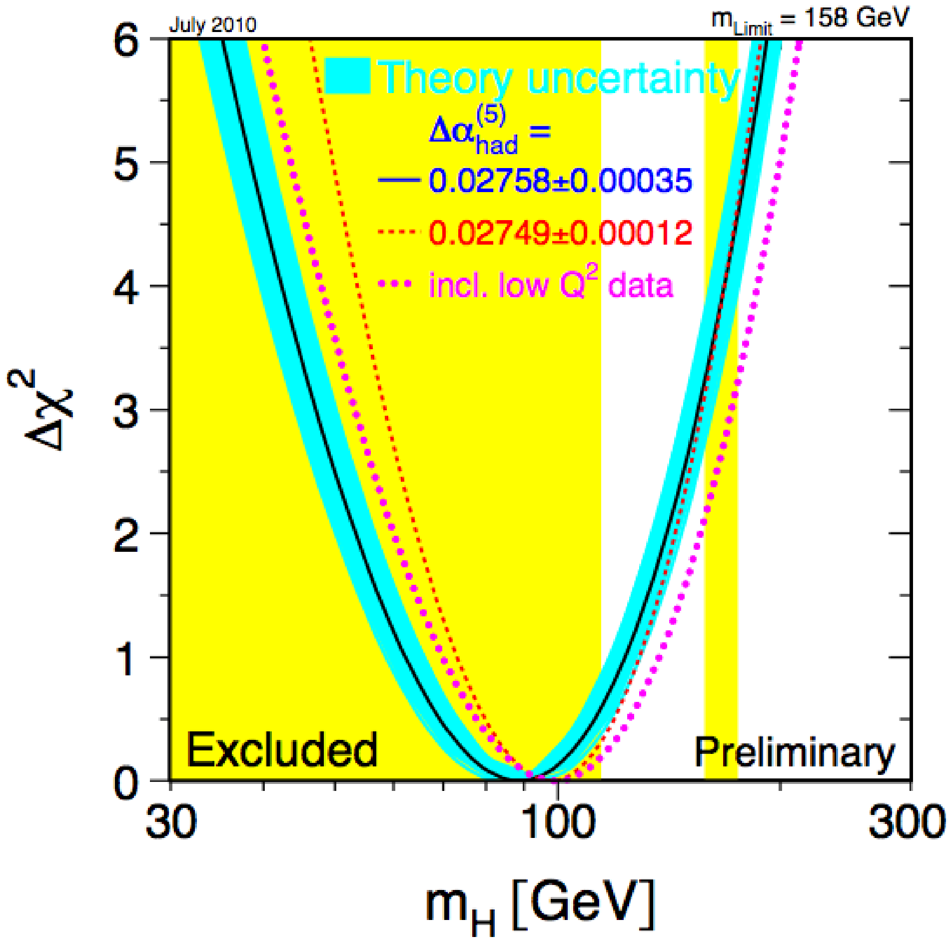
Fit to SM $\Rightarrow$ m_H < 158 GeV @95% cl

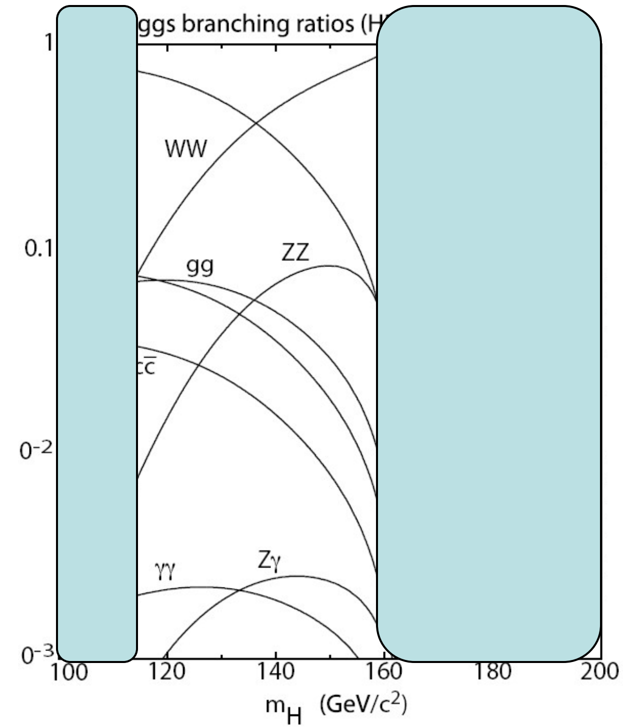
m_H>114 GeV from direct experimental searches @95% cl

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

1. Experimental; Higgs

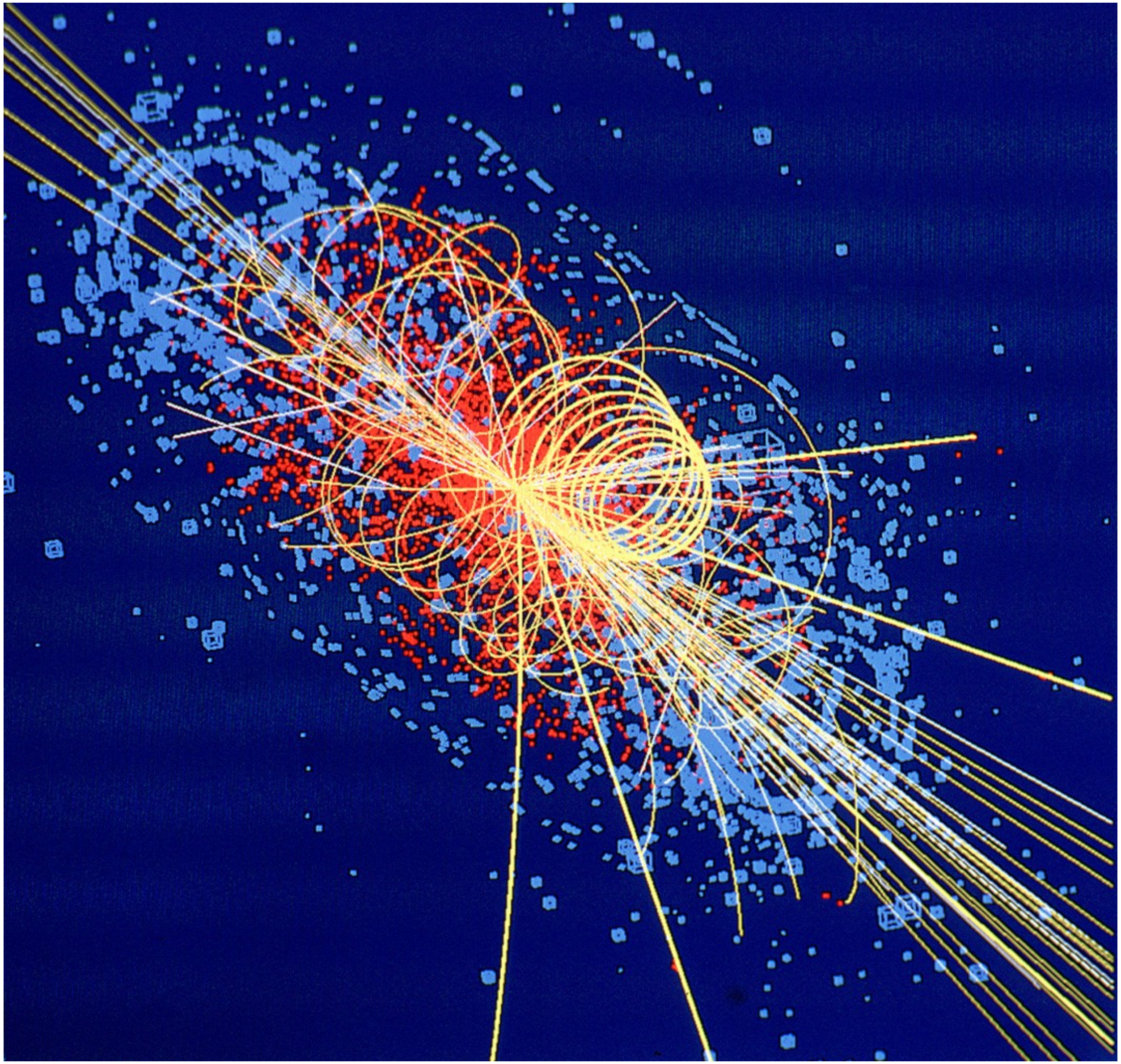
2. Philosophical



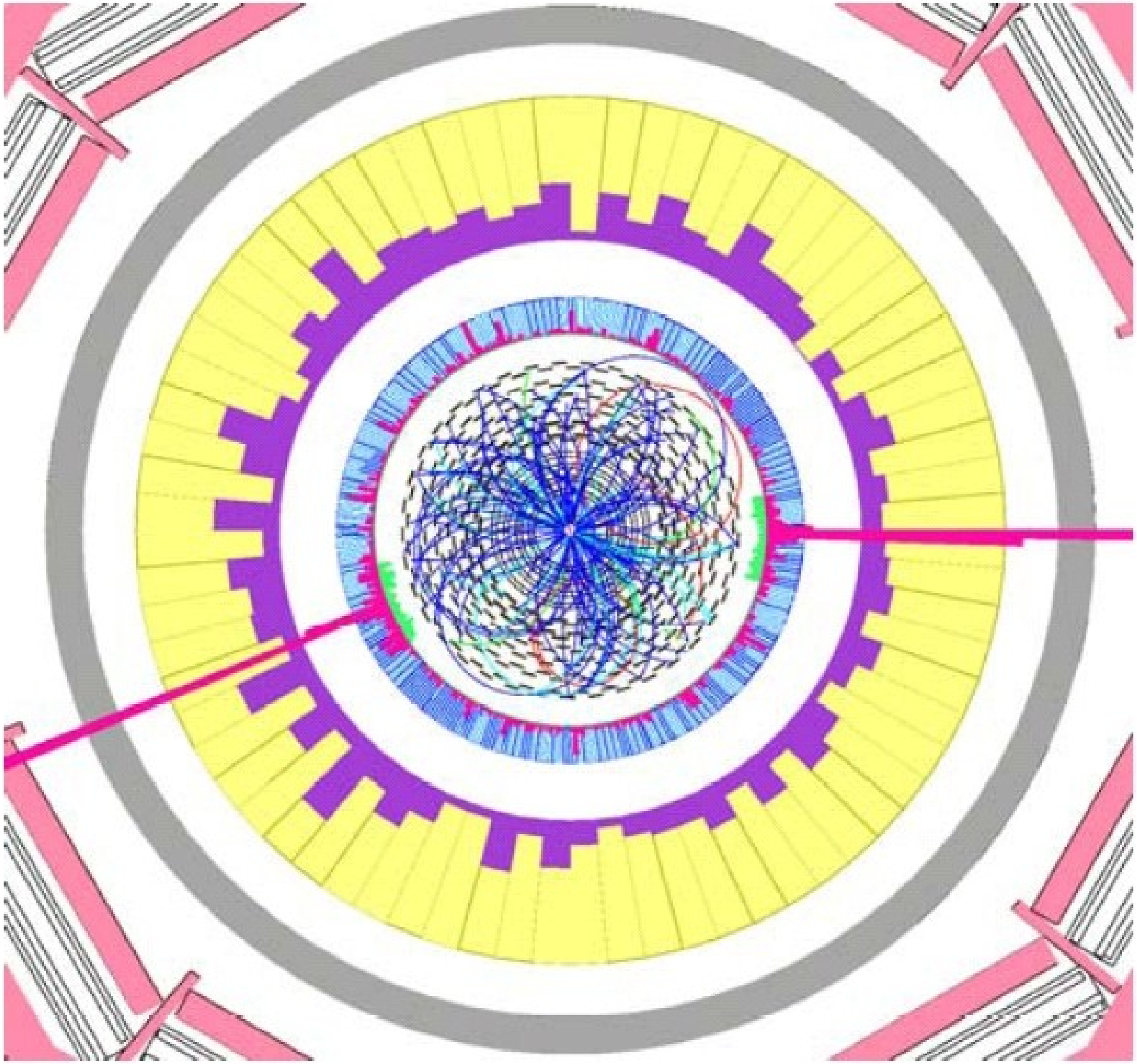


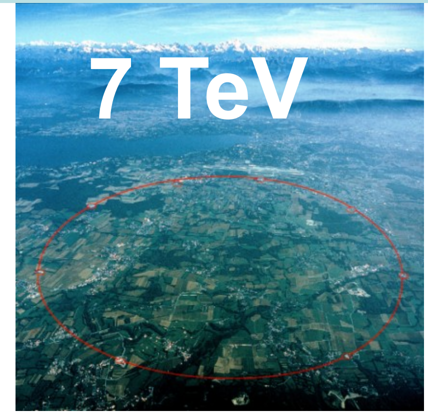
1. Experimental; Higgs

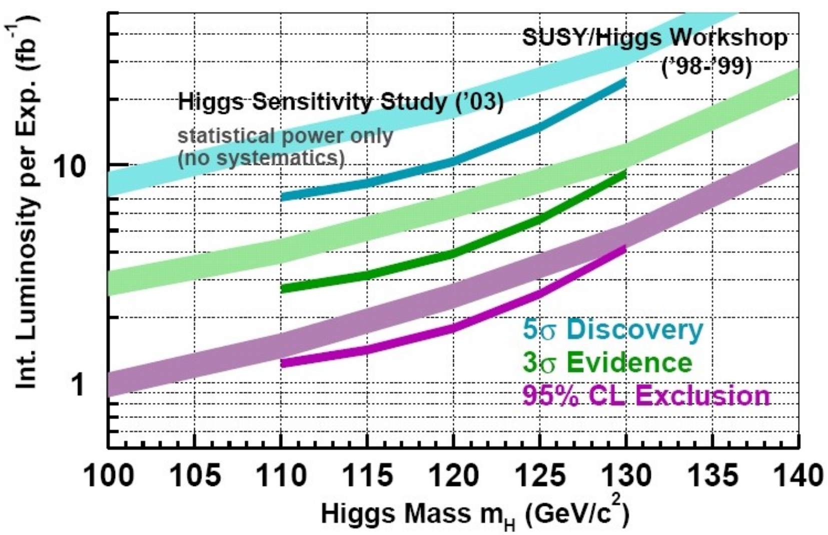
2. Philosophical

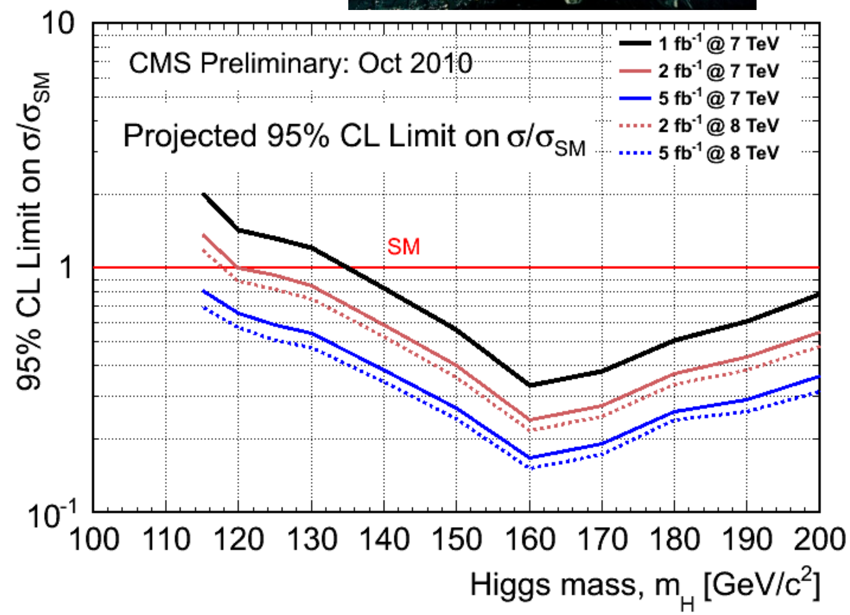


1. Experimental; Higgs









Tevatron: could exclude Higgs

LHC: could exclude Higgs (5 fb^{-1} data)

could discover Higgs (more data)

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

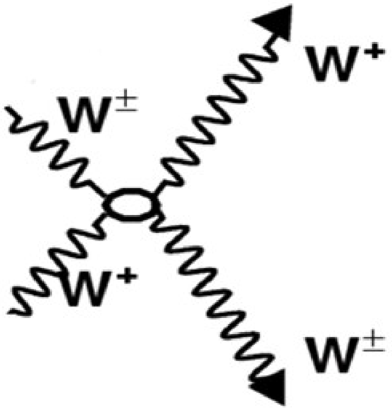
But **m_H < 1 TeV or predicted WW scattering cross-section starts to violate unitarity**

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.



1. Experimental; inconsistencies

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)

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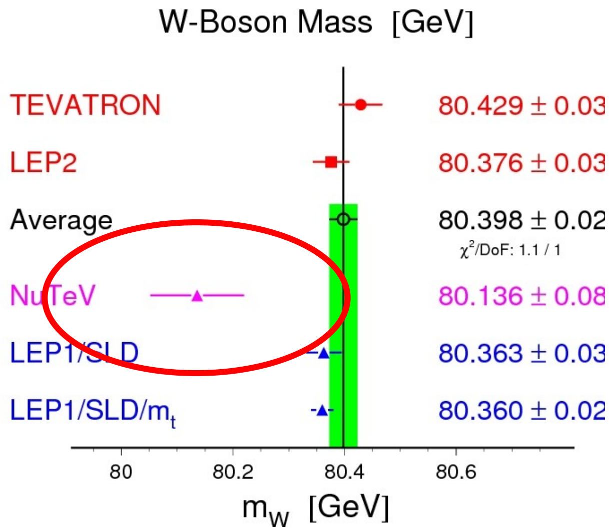
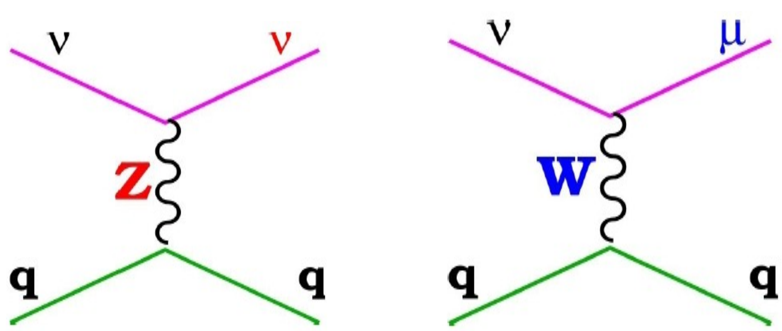


LHC: can measure M_W, provide better inputs



Couplings of $Z \rightarrow b$ quarks?

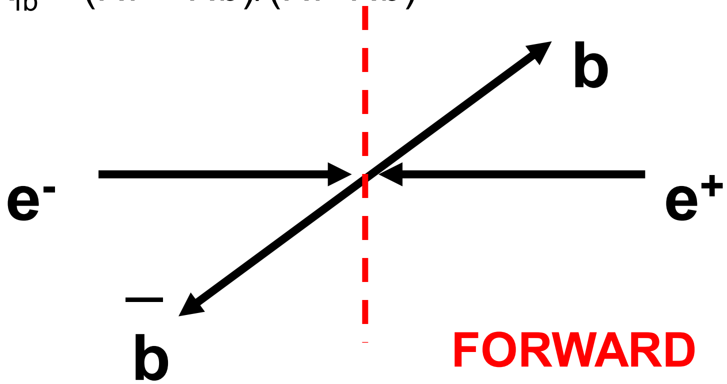
A_{fb} measured vs. SM prediction (2.8 σ)

No identified experimental explanation

Assumed to be a fluctuation

(Phys. Rept. 427 (2006) 257)

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



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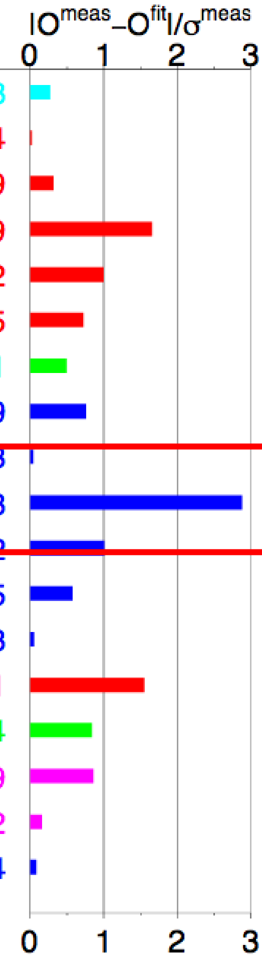

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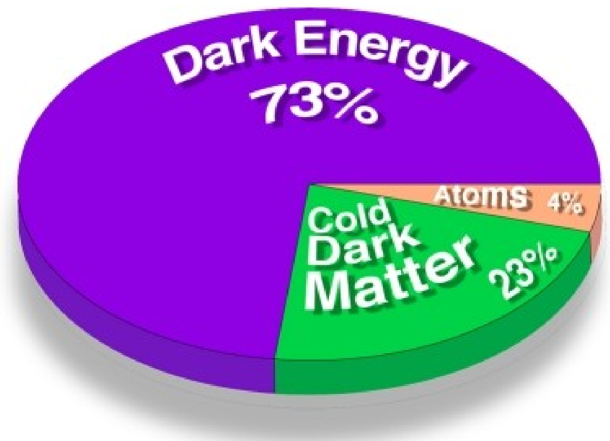
LHC can investigate

4% of the universe?



Source: Robert Kirshner
Source: NASA/WMAP Science Team

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

Dark energy:

?

Dark matter?

Try Supersymmetry ….

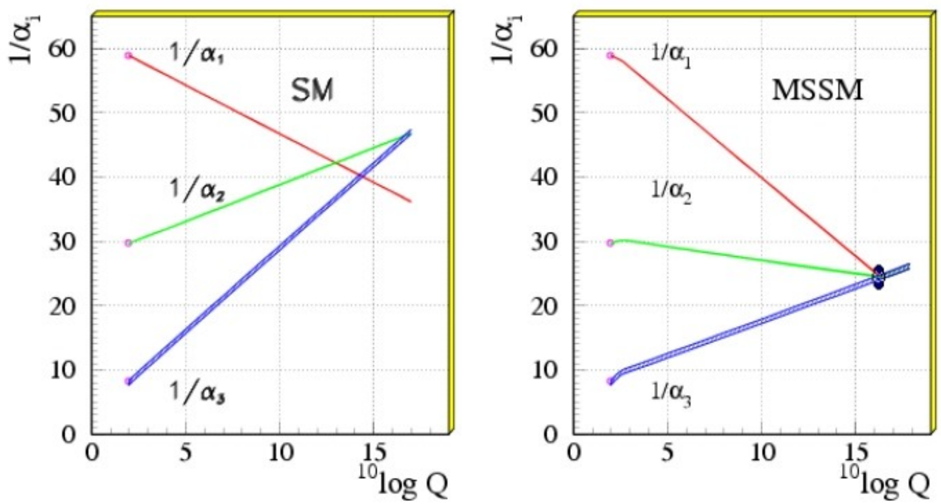
Lightest supersymmetric particle is a dark matter candidate (massive and unobservable)

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

- Standard Model is the theoretical framework used to describe particle physics
- Incomplete – doesn't explain all of the universe
- **Remarkably successful**
  - Experimental tests so far very compatible with predictions
  - Predictions are precise for LHC observations
- **LHC**: look for Higgs; look for cracks….