Prospects of 4^{th} Generation Quark Hunt with the LHC

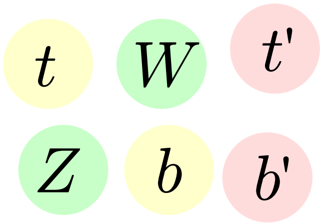
Ping Yeh
National Taiwan University

2007/4/19

National Tsing-Hua University

Outline

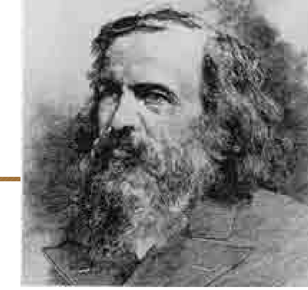
- Composition of Materials
- Quarks
- Generations
- The Large Hadron Collider and Hunt for the 4th generation
- Summary



Chemistry in mid-19th century

- Elements are identified since 17th century.
  - No more air, earth, fire, and water!
- New elements are being discovered one by one
  - 1700: 12 are known (Pt, Au, Ag, Cu, Fe, Sn, Pb, Zn, Hg, C, As, S)
  - 1800: +15 (H, N, O, P, Cl, Ti, Cr, Mo, W, Mn, Co, Ni, Sb, Te, Bi)
  - 1869: +36 (...)
- Why are there so many elements? How many more are there? Why some of them are similar to each other?
- so many elements, are they really *elementary*?

Mendeleev's periodic table: 1869



Ueber die Beziehungen der Eigenschaften zu den Atomgewichten der Elemente. Von D. Mendelejeff. — Ordnet man Elemente nach zunehmenden Atomgewichten in verticale Reihen so, dass die Horizontalreihen analoge Elemente enthalten, wieder nach zunehmendem Atomgewicht geordnet, so erhält man folgende Zusammenstellung, aus der sich einige allgemeinere Folgerungen ableiten lassen.

analogous elements →

atomic weight ↓

			Ti = 50	Zr = 90	? = 180
			V = 51	Nb = 94	Ta = 182
			Cr = 52	Mo = 96	W = 186
			Mn = 55	Rh = 104,4	Pt = 197,4
			Fe = 56	Ru = 104,4	Ir = 198
			Ni = Co = 59	Pd = 106,6	Os = 199
H = 1			Cu = 63,4	Ag = 108	Hg = 200
	Be = 9,4	Mg = 24	Zn = 65,2	Cd = 112	
	B = 11	Al = 27,4	? = 68	Ur = 116	Au = 197?
	C = 12	Si = 28	? = 70	Sn = 118	
	N = 14	P = 31	As = 75	Sb = 122	Bi = 210?
	O = 16	S = 32	Se = 79,4	Te = 128?	
	F = 19	Cl = 35,5	Br = 80	J = 127	
Li = 7	Na = 23	K = 39	Rb = 85,4	Cs = 133	Tl = 204
		Ca = 40	Sr = 87,6	Ba = 137	Pb = 207
		? = 45	Ce = 92		

Ga and Ge!

1. Die nach der … ordneten Elemente zeigen eine stufenweise Abänderung in den Eigenschaften.
2. Chemisch-analoge Elemente haben entweder übereinstimmende Atomgewichte (Pt, Ir, Os), oder letztere nehmen gleichviel zu (K, Rb, Cs).
3. Das Anordnen nach den Atomgewichten entspricht der *Werthigkeit* der Elemente und bis zu einem gewissen Grade der Verschiedenheit im chemischen Verhalten, z. B. Li, Be, B, C, N, O, F.
4. Die in der Natur verbreitetsten Elemente haben *kleine* Atomgewichte

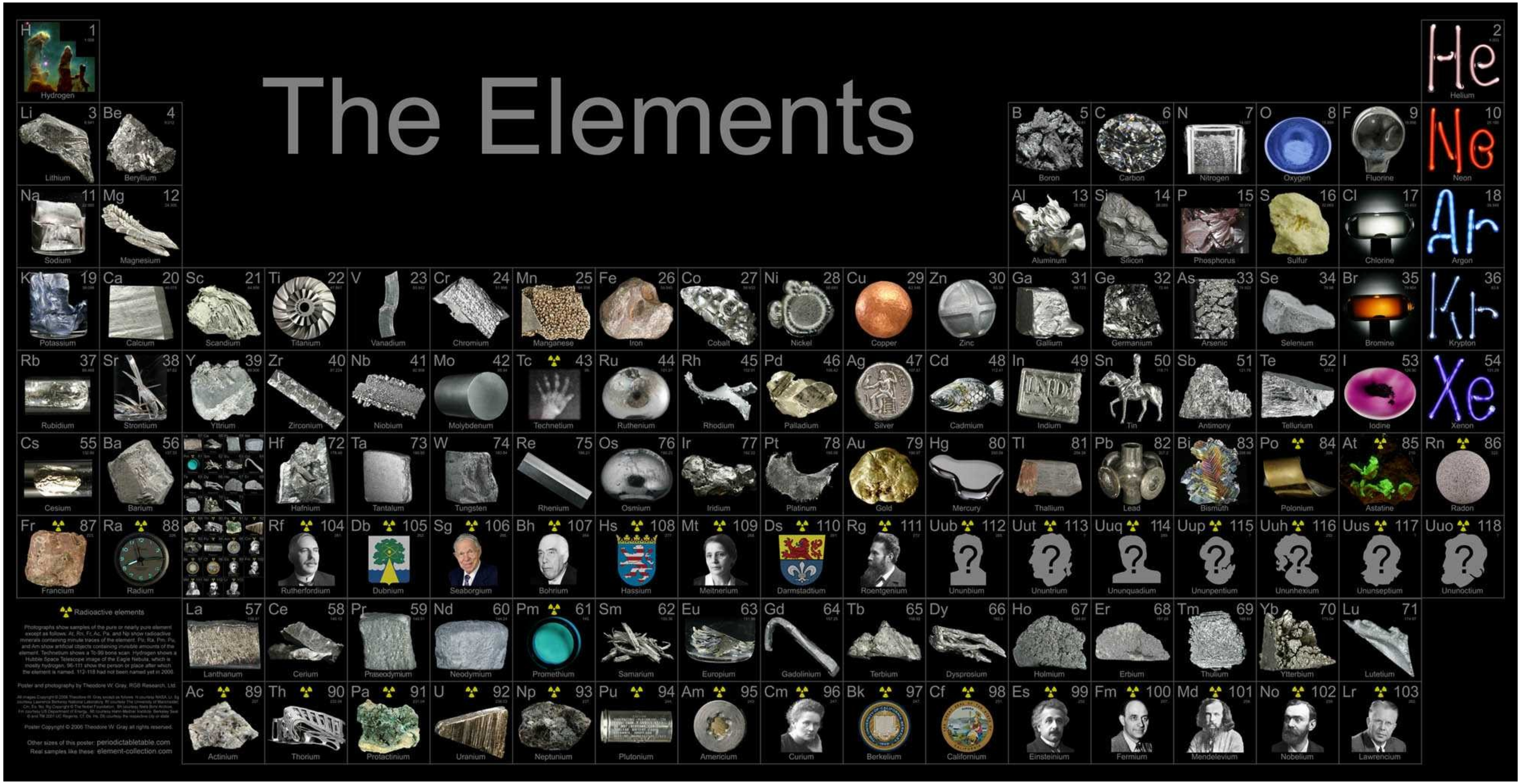
http://www.scs.uiuc.edu/~mainzv/exhibit/mendeleev.htm

By ordering the elements according to increasing atomic weight in vertical rows so that the horizontal rows contain analogous elements, still ordered by increasing atomic weight, one obtains the following arrangement, from which a few general conclusions may be derived.

1. The elements, if arranged according to their atomic weights, exhibit an evident stepwise variation of properties.
2. Chemically analogous elements have either similar atomic weights (Pt, Ir, Os), or weights which increase by equal increments (K, Rb, Cs).
3. The arrangement according to atomic weight corresponds to the valence of the element and to a certain extent the difference in chemical behavior, for example Li, Be, B, C, N, O, F.
4. ...
5. ...
6. One can predict the discovery of many new elements, for example analogues of Si and Al with atomic weights of 65-75.
7. A few atomic weights will probably require correction; for example Te cannot have the atomic weight 128, but rather 123-126.
8. ...

Z. Chem. 1869, 12, 405

The periodic table now



http://www.theodoregray.com/PeriodicTable/Posters. Permission to use granted by Theodore Gray.

Classification and composition

- Periodicity ⇒ inner structure, physics at a smaller scale
  - structure: atom = nucleus + electrons,
    atomic number = number of electrons
  - physics: Quantum mechanics explains the periodicity and behavior of atoms

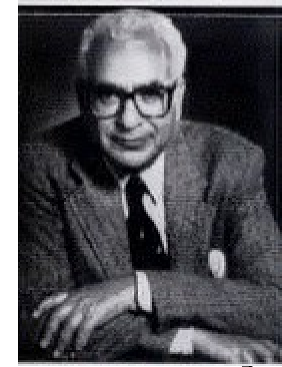
- complicated & many becomes simple & few
  - with predictive power!

- Beautiful

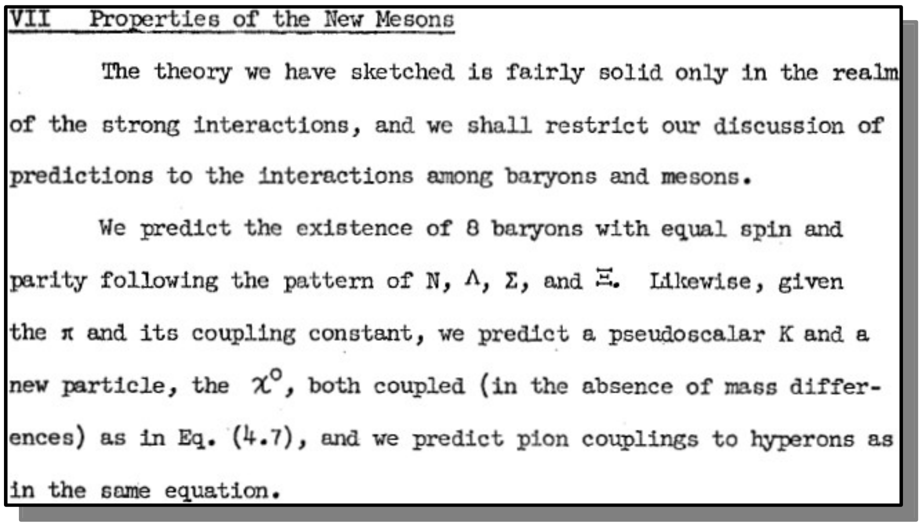
Particle physics in mid-20th century

- The first sub-atomic particle, the π meson, is discovered in cosmic rays.
- Accelerators are built – don't need to depend on the particle rain to get particles anymore
- New elementary particles are discovered!
  - π^0, K^+, K^-, $\bar{K}^+$, $\bar{K}^-$, K^0, $\bar{K}^0$, ... (mesons, spin = 0)
  - ρ^0, K^{*+}, K^{*-},... (mesons, spin = 1)
  - Λ, Σ^+, Σ^0, Σ^-, Ξ^0, Ξ^-,... (baryons, spin = ½)
  - Δ, ... (baryons, spin = 3/2)
  - Too many!!
- The once simple and beautiful picture of the microscopic world is messy again. Are they really *elementary*?

Gell-Mann's eight-fold way: 1961



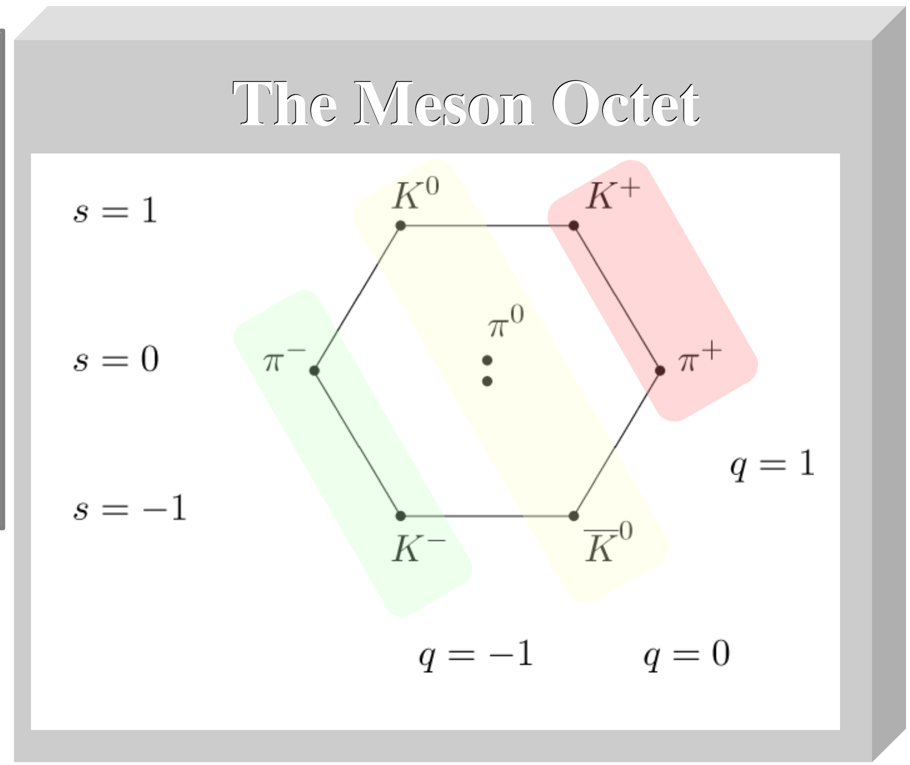
八正道：正見、正思惟、正語、正業、正命、正勤、正念、正定等，是八條通往涅槃的捷徑。



VII Properties of the New Mesons

The theory we have sketched is fairly solid only in the realm of the strong interactions, and we shall restrict our discussion of predictions to the interactions among baryons and mesons.

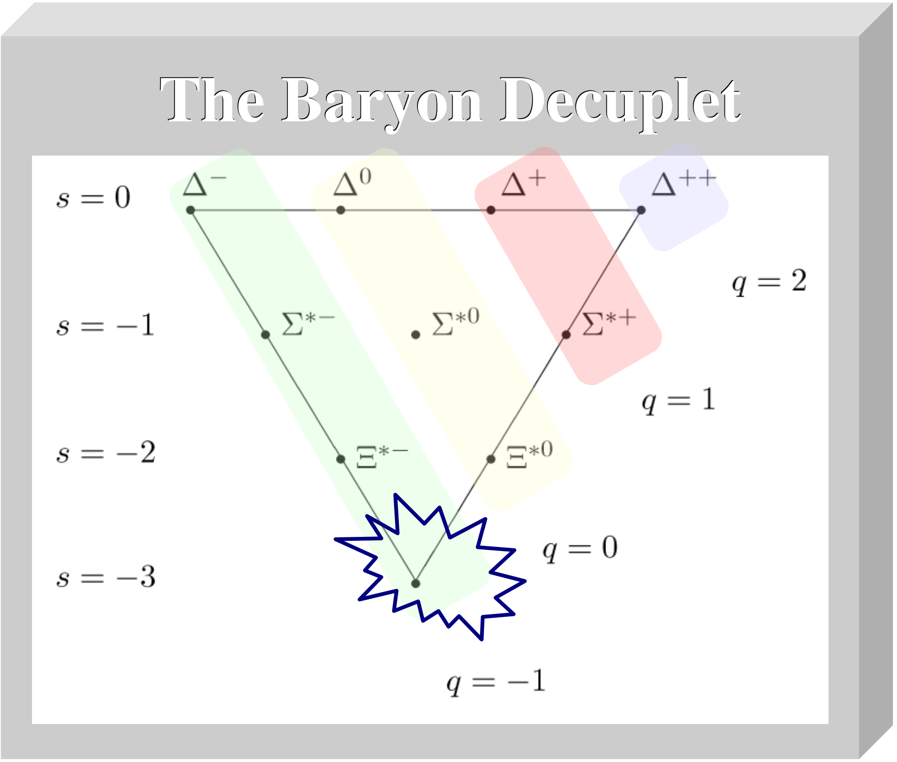
We predict the existence of 8 baryons with equal spin and parity following the pattern of N, Λ, Σ, and Ξ. Likewise, given the π and its coupling constant, we predict a pseudoscalar K and a new particle, the χ^0, both coupled (in the absence of mass differences) as in Eq. (4.7), and we predict pion couplings to hyperons as in the same equation.



1969

"for his contributions and discoveries concerning the classification of elementary particles and their interactions"

- Other particles can be organized in a similar way.



Ping Yeh, Prospects of 4th generation quark hunt

Quarks

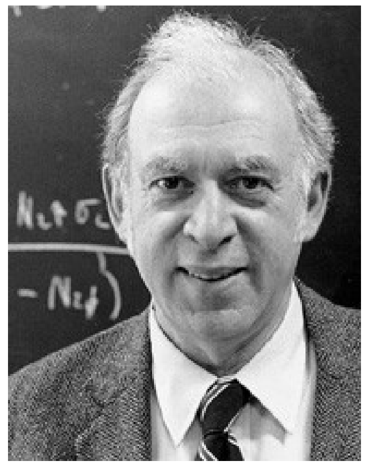
- Murray Gell-Mann's 8-fold way of hadron classification was a success
  - first as a taxonomy, too.
  - composition of hadrons?

- "quarks"
  - With assumed properties of quarks, the 8-fold way can be explained. - 1964.
  - but nobody saw any quarks $\Rightarrow$ are they only mathematical tools?

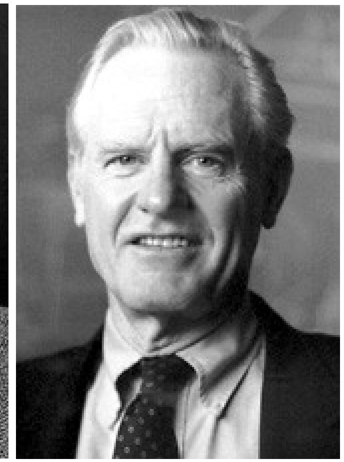
Discovery of Quarks

- Jerry Friedman et. al., deep inelastic scattering, 1967

1990



Jerome I. Friedman



Henry W. Kendall

Richard E. Taylor

"for their pioneering investigations concerning deep inelastic scattering of electrons on protons and bound neutrons, which have been of essential importance for the development of the quark model in particle physics"

Three Times a Charm

- Or is it four?
- Sam C.C. Ting and Richter, 1974

1976

Burton Richter

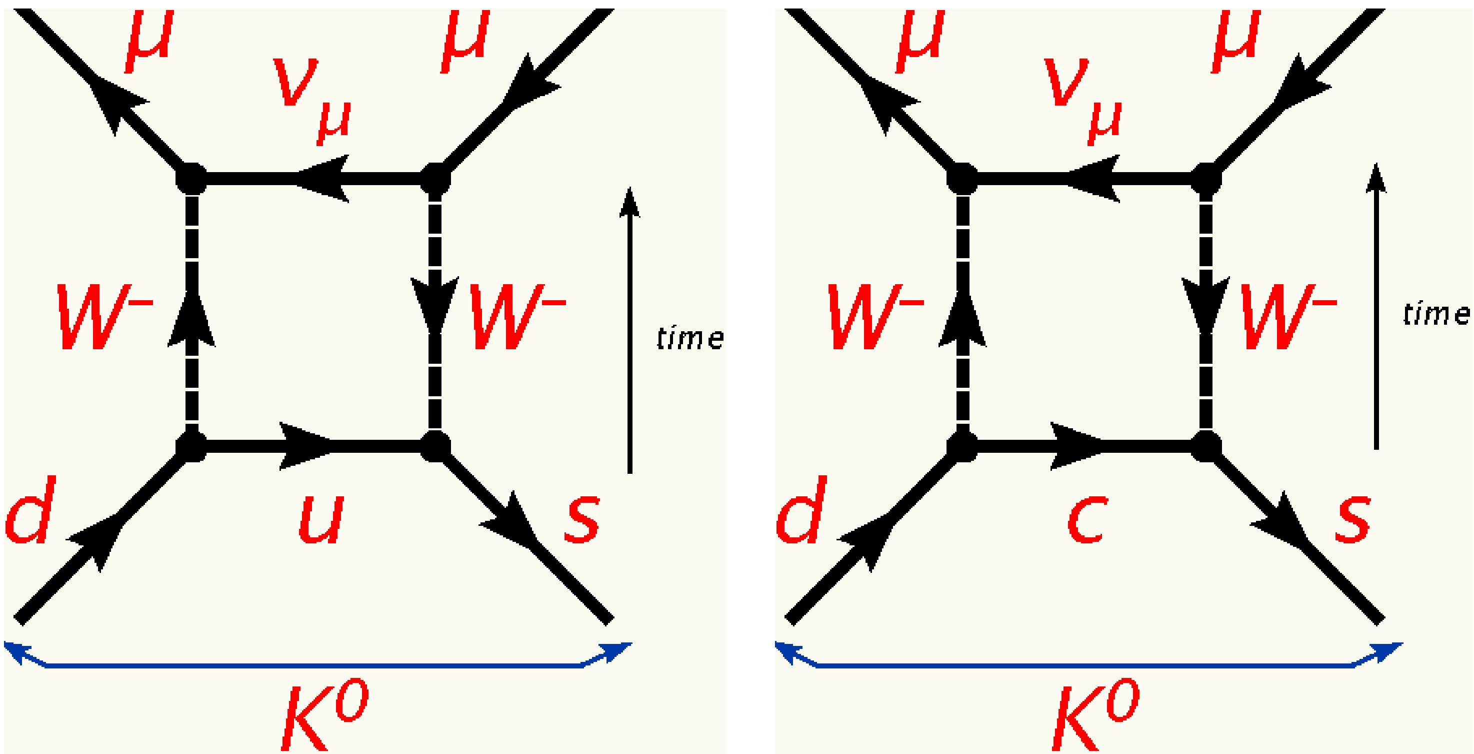
Samuel C. C. Ting

"for their pioneering work in the discovery of a heavy elementary particle of a new kind"

Why Does Nature Need Charm Quarks?

- Lack of Flavor-Changing Neutral Currents requires it
  - GIM mechanism

$K^0 \rightarrow \mu^+ + \mu^-$ Now the diagrams cancel.



$$\mathcal{M}_1 \propto \sin\theta_c \cos\theta_c \;,\; \mathcal{M}_2 \propto -\sin\theta_c \cos\theta_c$$

Discovery of the Bottom Quark

- Leon Lederman, 1977

1989

Leon M. Lederman | Melvin Schwartz | Jack Steinberger

"for the neutrino beam method and the demonstration of the doublet structure of the leptons through the discovery of the muon neutrino"

Discovery of the Top Quark

- CDF & D0 experiments, 1995, Tevatron.
  - each collaboration has ~ 300 physicists
- Proton anti-proton collision at center of mass energy 1.8 TeV.
- pairly produced, each quark or anti-quark decays to a W boson and a b quark. b-tagging was essential in reducing W+jets backgrounds.

Why Does Nature Need 3 Generations?

- Not to be a boring universe!

- The Cabibbo 2x2 quark-mixing matrix can be all real
  - No complex phases.
  - CP violation not possible.

- However, the existence of current matter-dominated universe requires sizable CP violation.
  - The beauty of Nature needs 3 generations to exist!

Why 4 Generations?

- Again, three times a charm…

but

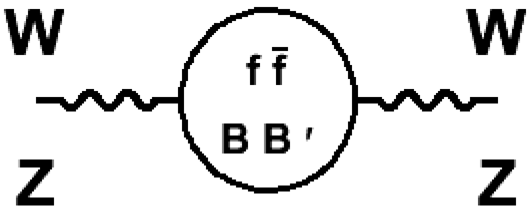
- Currently found CP violations are too small to account for the matter anti-matter asymmetry of the universe
  - 4th generation can bring in more CP violating channels
- The door to the 4th generation is not yet closed.
  - Will be closed if not found in the LHC!
  - Experimentalists should exhaust the possibilities and put the case to rest.

The Constraints on the 4th Generation

- Naming the 4th generation: the "primes": b', t', τ', ν_τ'.
- LEP: number of neutral leptons = 2.994±0.012 for mass < $m_Z/2$.
  - If 4th generation exists, m(ν_τ') > $m_Z/2$.
- Quantum loop corrections: virtual particle contribution
  - Electroweak S, T, U parameters

Electroweak S, T, U Parameters

- Parameters that are zero for standard model and O(1) for new physics from the self energies of W and Z.



$$T \equiv \frac{1}{\hat{\alpha}(M_Z)}\left\{\frac{\Pi^{new}_{WW}(0)}{M_W^2}-\frac{\Pi^{new}_{ZZ}(0)}{M_Z^2}\right\}$$

$$S \equiv \frac{4\hat{s}_Z^2\hat{c}_Z^2}{\hat{\alpha}(M_Z)}\left\{\frac{\Pi^{new}_{ZZ}(M_Z^2)-\Pi^{new}_{ZZ}(0)}{M_Z^2}-\frac{\hat{c}_Z^2-\hat{s}_Z^2}{\hat{c}_Z\hat{s}_Z}\frac{\Pi^{new}_{Z\gamma}(M_Z^2)}{M_Z^2}-\frac{\Pi^{new}_{\gamma\gamma}(M_Z^2)}{M_Z^2}\right\}$$

$$S+U \equiv \frac{4\hat{s}_Z^2}{\hat{\alpha}(M_Z)}\left\{\frac{\Pi^{new}_{WW}(M_W^2)-\Pi^{new}_{WW}(0)}{M_W^2}-\frac{\hat{c}_Z}{\hat{s}_Z}\frac{\Pi^{new}_{Z\gamma}(M_Z^2)}{M_Z^2}-\frac{\Pi^{new}_{\gamma\gamma}(M_Z^2)}{M_Z^2}\right\}$$

S, T, U and the 4th Generation

PDG06

PDG04

$$S = -0.13 \pm 0.10 \; (-0.08)$$
$$T = -0.17 \pm 0.12 \; (+0.09)$$
$$U = 0.22 \pm 0.13 \; (+0.01)$$

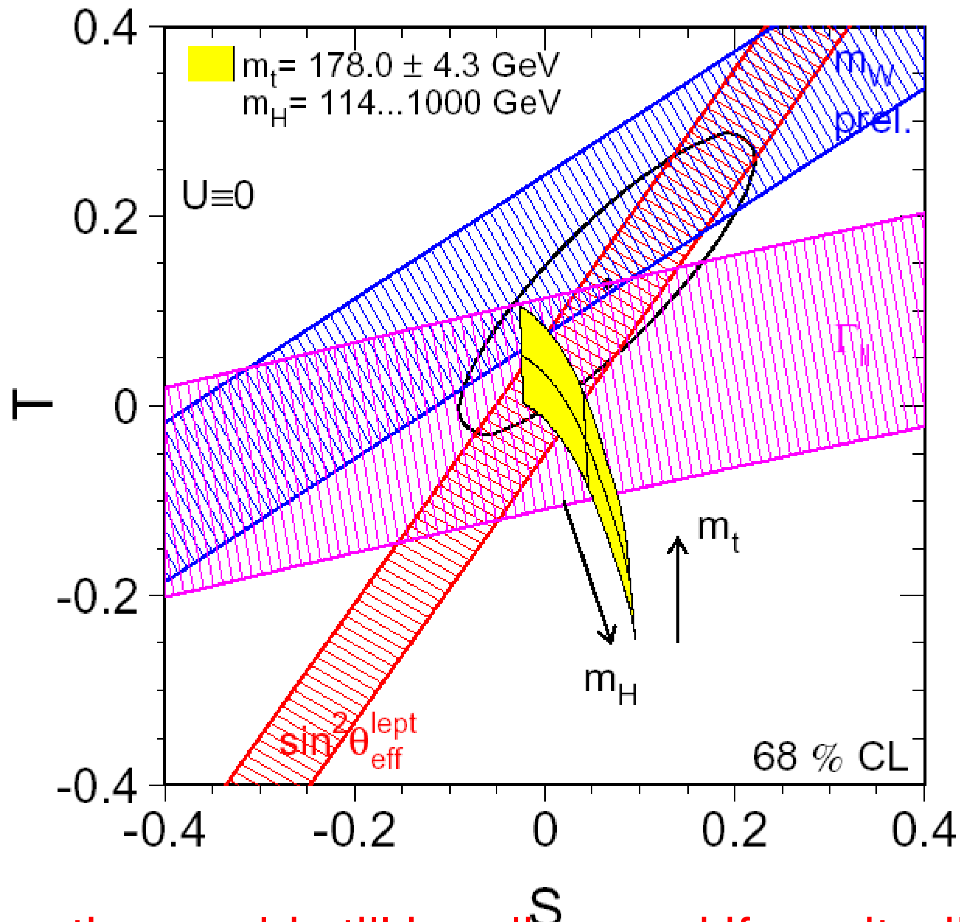
S = -0.13±0.10(-0.08)
T = -0.13±0.11(+0.09)
U = 0.20±0.12(+0.01)

99.999%

An extra generation of ordinary fermions is excluded at the 99.95% CL on the basis of the S parameter alone, corresponding to $N_F = 2.92 \pm 0.27$ for the number of families. This result assumes that there are no new 2.81±0.24 o T or U and therefore that any new families are degenerate. In princip on can be relaxed by allowing T to vary as well, since $T > 0$ is expected from a non-degenerate extra family. However, the data currently favor $T < 0$, thus strengthening the exclusion limits. A more detailed analysis is required if the extra neutrino (or the extra down-type quark) is close to its direct mass limit [167]. This can drive S to small or even negative values but at the expense of too-large contributions to T. These results are in agreement with a fit 0.1231±0.0020 number of light neutrinos, $N_\nu = 2.986 \pm 0.007$ (which favors a larger value for $\alpha_s(M_Z) = 0.1228 \pm 0.0021$ mainly from R_ℓ and τ_τ). However, the S parameter fits are valid even for a very heavy fourth family neutrino.

New LEP Results on S, T, U

ALEPH, DELPHI, L3, OPAL, SLD Collaborations



hep-ex/0509008

$S = 0.07 \pm 0.10$

$T = 0.13 \pm 0.10$

$U = 0$ (2005)

2σ shift in BOTH

S and T → Positive

$S = -0.13 \pm 0.10\ (-0.08)$

$T = -0.17 \pm 0.12\ (+0.09)$

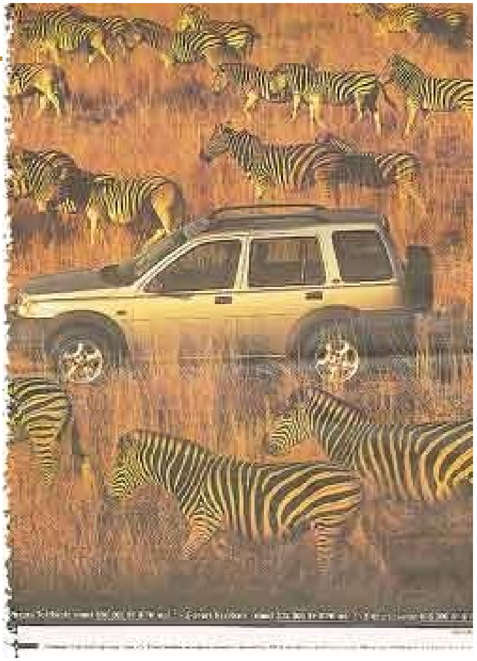
$U = 0.22 \pm 0.13\ (+0.01)$

(2003)

A 4th generation could still be alive, and if yes it will appear soon

The 4x4 Mixing Matrix

- Toughly built, for uncharted territories!
- (n-1)*n/2 angles, (n-2)*(n-1)/2 phases
  - 3x3: 3 angles, 1 phase
  - 4x4: 6 angles, 3 phases
- 3 new angles
- 2 new phases: more CP violating channels!

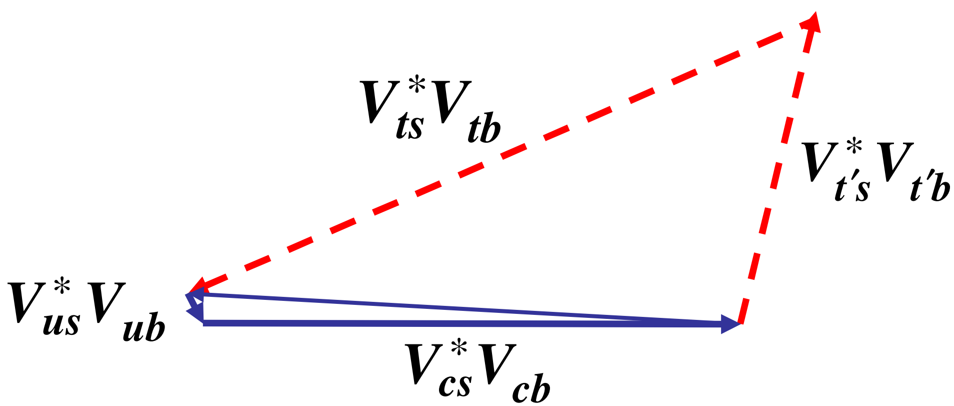


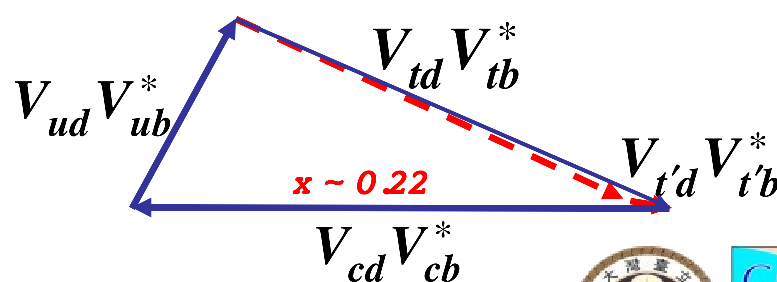
The "Double Cabibbo" Scenario

$$V^4_{CKM} =$$

Large/Imaginary

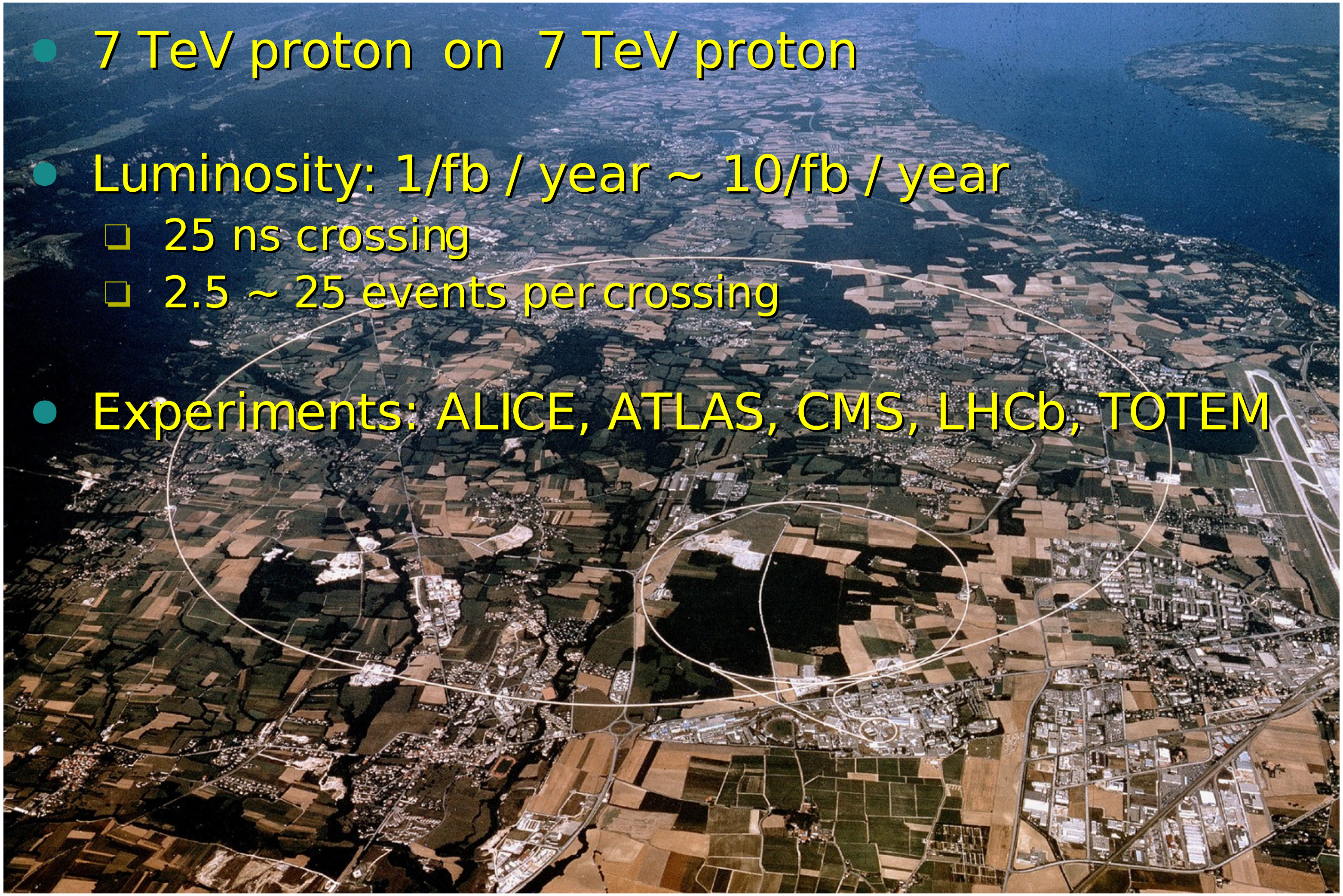
$$\begin{pmatrix} 0.9745 & 0.2225 & 0.0038\, e^{-i\,60^\circ} & 0.0281\, e^{i\,61^\circ} \\ -0.2241 & 0.9667 & 0.0415 & 0.1164\, e^{i\,66^\circ} \\ 0.0073\, e^{-i\,25^\circ} & -0.0555\, e^{-i\,25^\circ} & 0.9746 & 0.2168\, e^{-i\,1^\circ} \\ -0.0044\, e^{-i\,10^\circ} & -0.1136\, e^{-i\,70^\circ} & -0.2200 & 0.9688 \end{pmatrix}$$



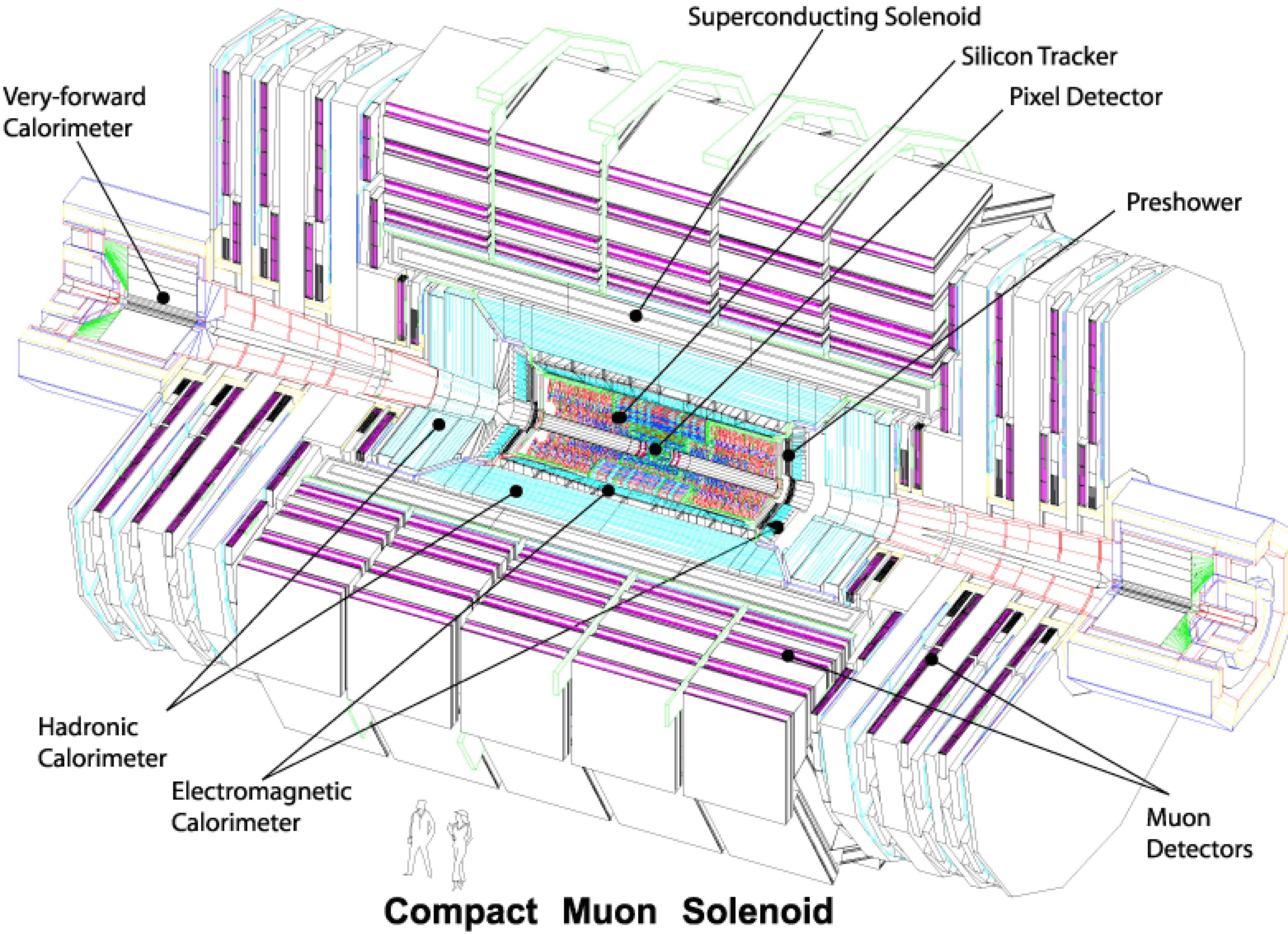


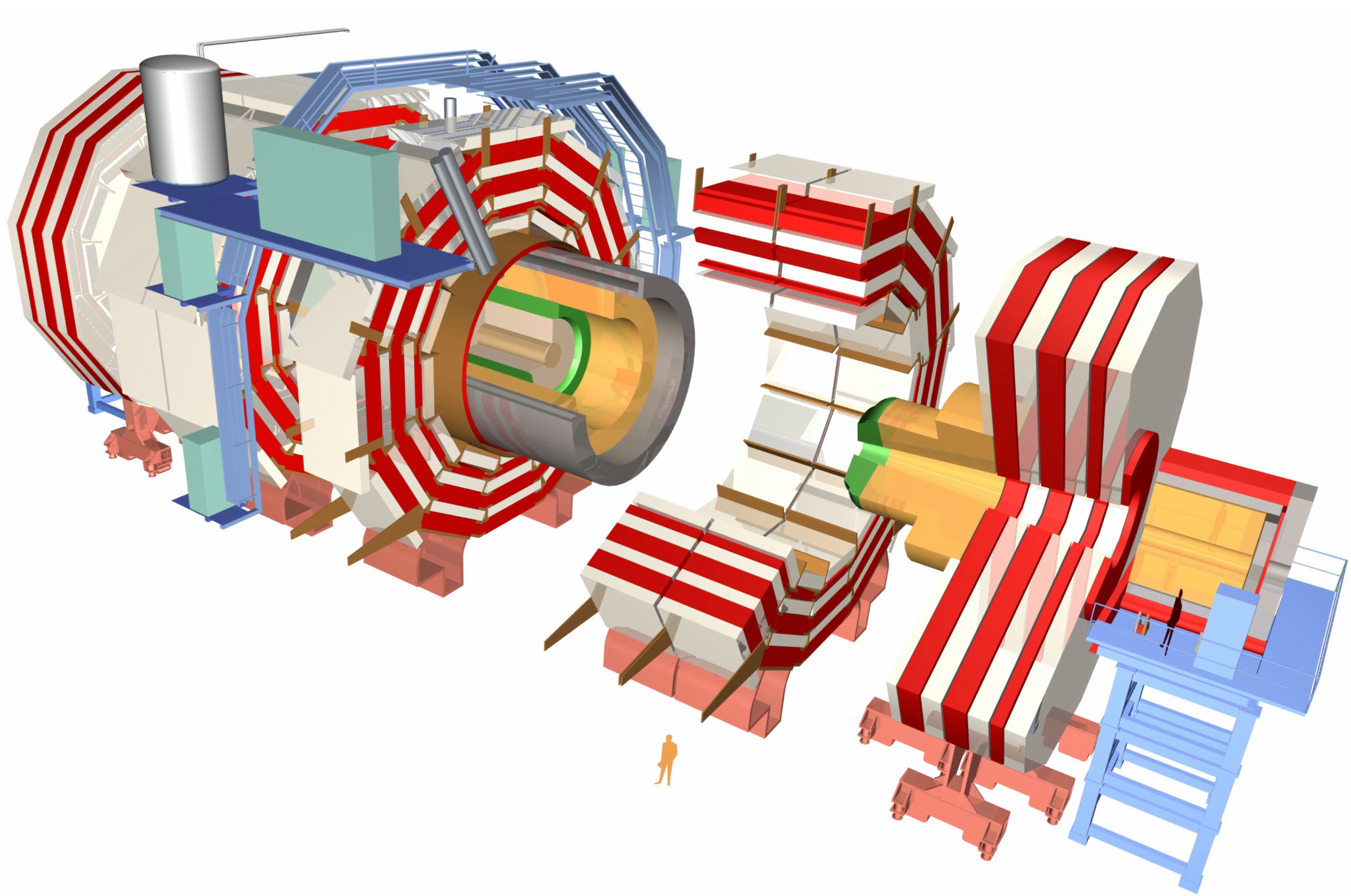
The Large Hadron Collider

- 7 TeV proton on 7 TeV proton
- Luminosity: 1/fb / year ~ 10/fb / year
  - 25 ns crossing
  - 2.5 ~ 25 events per crossing
- Experiments: ALICE, ATLAS, CMS, LHCb, TOTEM



The Compact Muon Solenoid Detector





The final year of construction

BBC | Home | News | Sport | Radio | TV | Weather | Languages

UK version | International version | About the versions

BBC NEWS

OPEN The News in 2 minutes

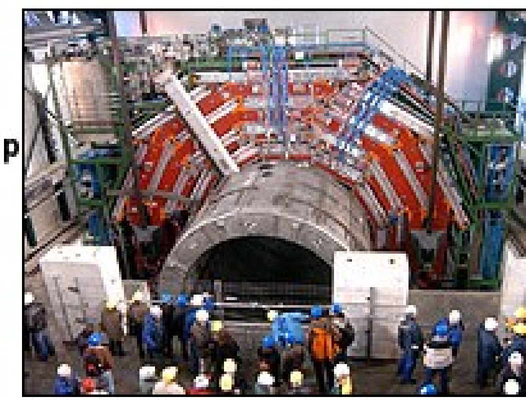
News Front Page

Last Updated: Wednesday, 28 February 2007, 18:09 GMT

E-mail this to a friend | Printable version

Milestone for giant physics lab

The construction of a giant underground laboratory on the French-Swiss border that will help take physics into a new era has reached a major milestone.



YB0 is the biggest and most impressive element of the CMS

A 2,000-tonne piece of machinery has been successfully lowered by crane into a man-made cavern 100m below ground.

Health

Science/Nature

The Schedule

- 2007: LHC commisioning
  - 900 GeV run
  - proton proton collision by Christmas 2007
  - CMS: partial detector (no pixel, no endcap ECAL)
- Q1 & Q2 2008: final detector installation
  - Commisioning the full detector
- June 2008: LHC start-up
  - 14 TeV run
  - physics? various estimates... 1/fb in 2008 if very lucky
- 2009 and beyond: LHC running
  - pouring of data and physics!

The Hunt

Before Hitting the Road...

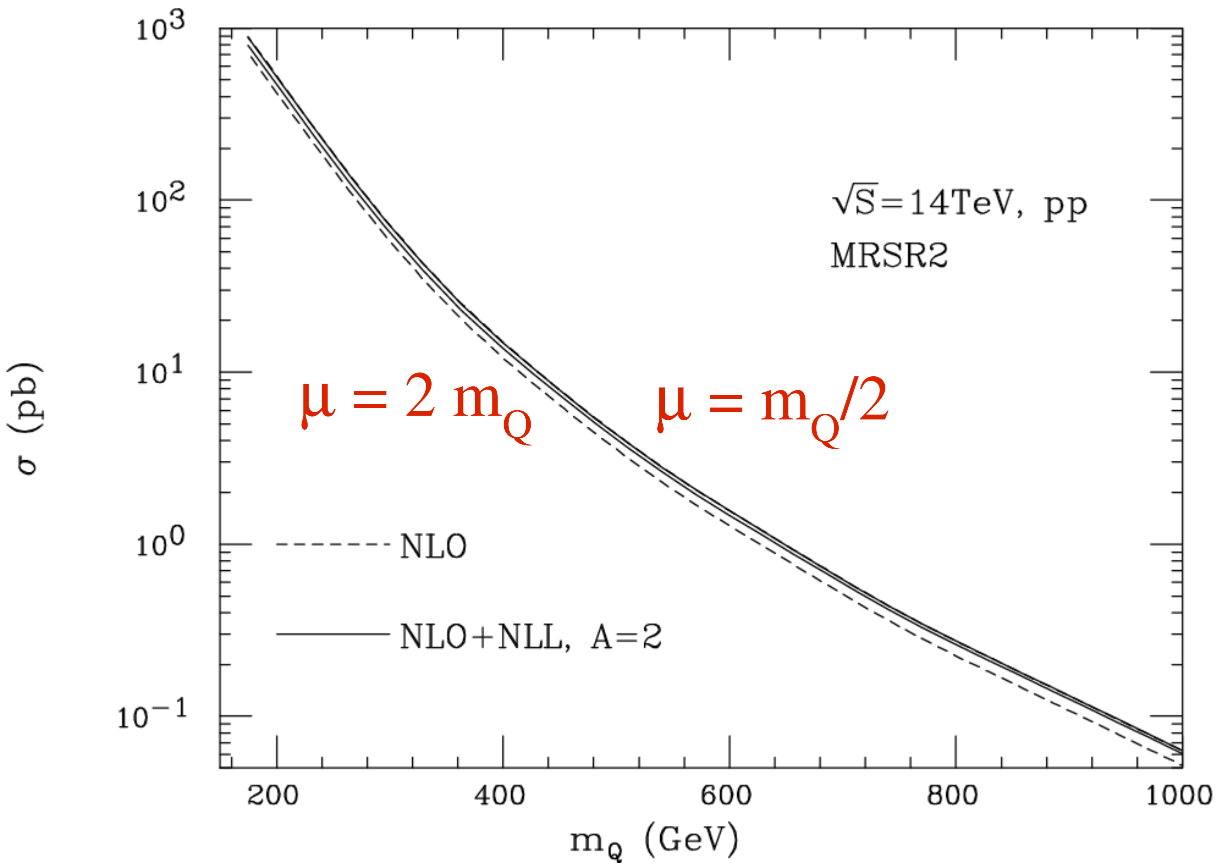
- How many 4G quarks will be produced if they exist? -- the production cross section
- What do they look like? -- the decay channels and signatures
- Where do they hide? -- the backgrounds
- How good is your dog? -- the efficiency
- How big a turf do you need to cover? -- the yield and discovery reach

Apologies

- The results are not yet approved by the CMS collaboration
  - estimated time: summer
- CMS policy forbids results obtained with any CMS-specific software/parameters to be shown in public without prior approval
- What's shown/stated here are generator studies without CMS specific parameters.

Heavy Quark Production in the LHC

- Expect: dominated by pair production
  - Bonciani et al, NPB529, 424, 1998 (Next to leading log resummation)



$\sigma(200) = 498$ (pb)

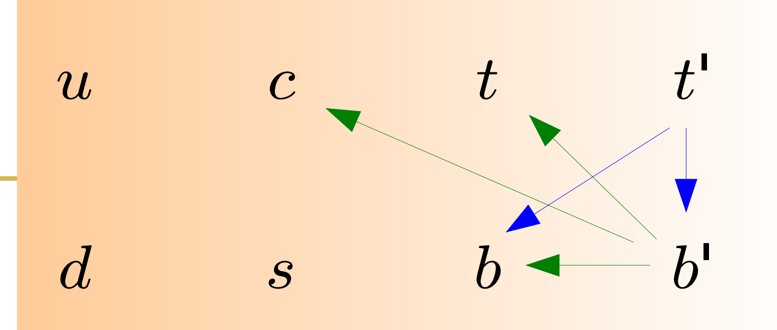
$\sigma(220) = 324$

$\sigma(240) = 215$

$\sigma(300) = 69$

$\sigma(400) = 14.9$

Decay Scenario



- b'
  - low mass < $m_t + m_W$ < high mass

virtuality?

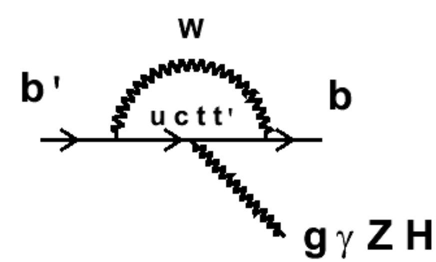
$t + W$

$b' \to tW$ / cW / bZ / $b\gamma$ / bH possible

- t'
  - low mass < $m_{b'} + m_W$ < high mass

$b + W$
$(b' + W)^*$

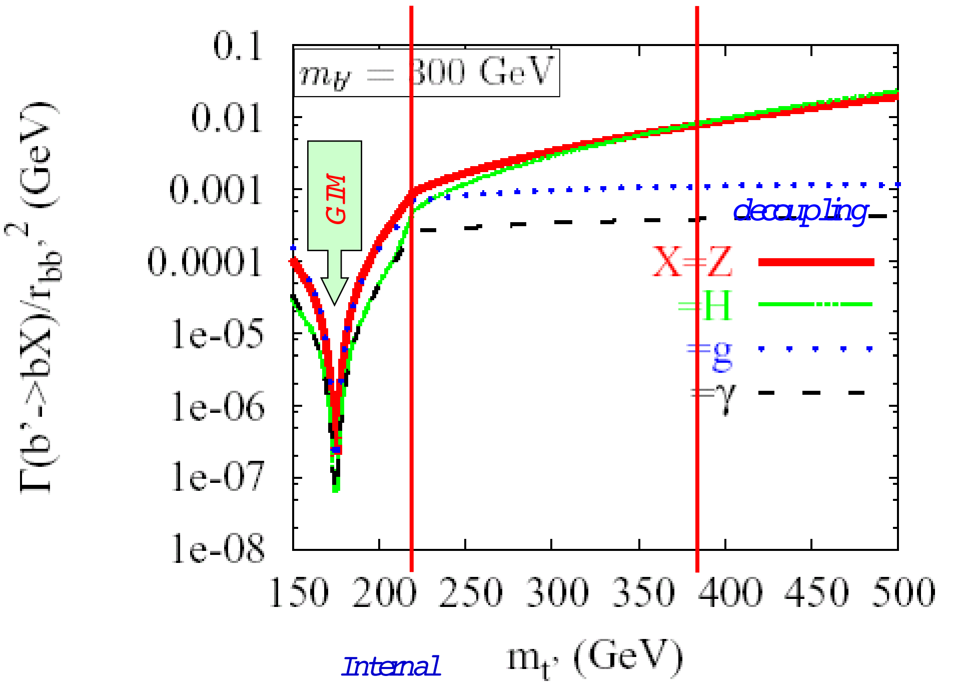
$b' + W$



g Yeh, Prospects of 4th generation quark hunt

Branching Ratios: b' to bZ

- depends on mass of t'



Ping Yeh

Search Strategy

- b' search:
  - pair production: two b' decays
  - $b' \to (tW, cW, bZ) \times (tW, cW, bZ) =$

    [tW tW] { 10 final state particles, high mass search }
    [tW cW] { 8 final state particles }
    [tW bZ] { clean, sizeable BR? }
    [cW cW] { tt-like without b-tagging }
    [cW bZ] { clean and simple final state }
    [bZ bZ] { clean, BR may be too small }

  - the branching ratios depend on b' mass, and should be measured if b' exists.

$$\sigma B_1 B_2 = \frac{N_{obs} - N_{bkg}}{(\int L\, dt)\, \epsilon}$$

need 4 modes to disentangle

- t' search: "heavy top pair"

Ping Yeh, Prospects of 4th generation quark hunt

$tWbZ$ Search

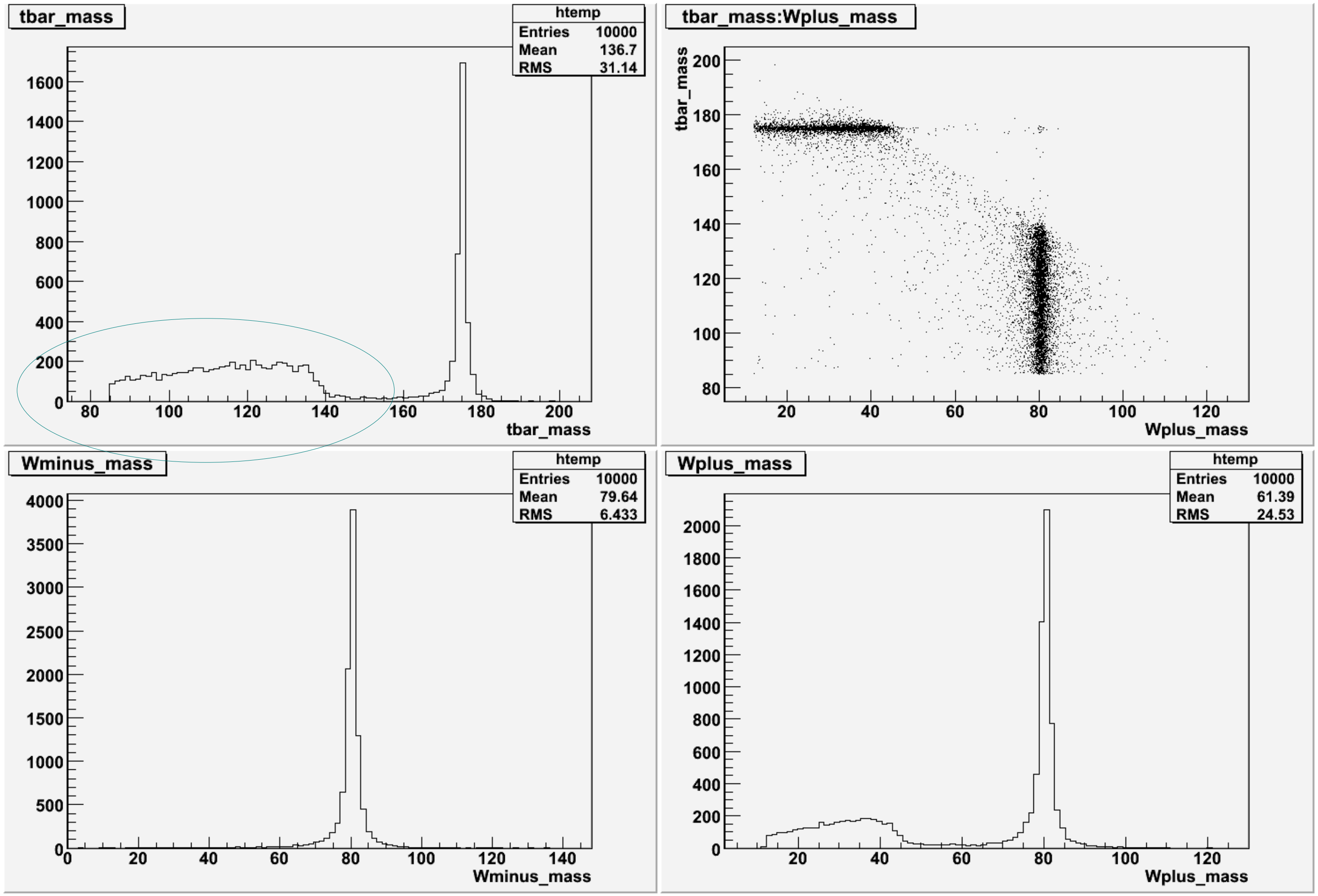
- $Z \to e^+e^-$ (3.36%), $W \to \mu\nu$ (10.57%), $t \to b\,W$ (hadrons, 67.6%). Sub-branching ratio = 0.24%.
  - Exchanging $e \leftrightarrow \mu$ doubles the SBR. Allowing all e or all μ doubles again (ambiguities).
- Expected backgrounds:
  - Z + jets with a fake muon or a soft muon from heavy quark decay (cross section ~ a few nb)
  - ZW + jets (SM cross section < pb)
  - ZZ + jets with one muon (from Z) undetected, one fake muon or one muon from heavy quark decay (SM cross section << pb)
- Z + jets has the highest cross section, but fake muons (typically O(10^{-4})) and soft muons (typically O(10^{-2})) reduces it to O(10 pb).

Event Selection

- $e^+ e^-$: $p_T > 20$ GeV, $|\eta| < 2.4$. $75 < m(e^+ e^-) < 105$
- μ^-: $p_T > 20$ GeV, $|\eta| < 2.1$.
- jets: $|\eta| < 2.4$.
  - jet 1: $p_T > 60$ GeV
  - jet 2: $p_T > 40$ GeV
  - jet 3: $p_T > 30$ GeV
  - jet 4: $p_T > 20$ GeV
- No requirement on missing energy or b-tagging.

The virtuality in b'→ tW decay

mb' = 220



Expected Efficiencies & Yields

- signal efficiency ~ O(0.4).
- For 1/fb, expect N = O($2*10^5$) * B_1 * B_2 events for 200 GeV b'.
  - a guess of branching ratios: B1 ~ 0.7, B2 ~ 0.01 -> N ~ O(10^3)
- Z + jets: requires detector performance (fake rate, acceptances)
  - shouldn't be large
- Signal for 200 ~ 240 GeV b' should be visible.

Conclusion

- The door leading to 4th generation is closing and re-opening by the electroweak S, T, U parameters.
- Instead of relying on indirect / loop constraints, a direct search and put the case to rest: discover it or bury it!
  - unless it is extremely heavy…
- The b' decay, depending on its mass, exhibits rich phenomena. Once existence is established, more interesting topics emerge:
  - Higgs search in $b' \rightarrow bH$ decay.
  - Angles and phases in the 4x4 CKM matrix
  - CP violation