Physics to be explored at the LHC

(Large Hadron Collider)

2011.05.28 at Maskawa-Juku in Kyoto Sangyo Univ.

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1961		SU(2)$\times$U(1)[Glashow], SSB[Nambu]
1964	CP violation	[Higgs]
1967		[Weinberg-Salam]
1971	DIS scaling	[GIM], Renormalization[tHooft]
1972		[Kobayashi-Maskawa]
1973	Neutral Current	Asymptotic Freedom, SU(5)[GG] $\star$
1974	J/ψ	Supersymmetry, GUT[GQW] $\star$
1975	e^+e^- jets, τ	
1976	Υ, the SM	
1977		
1978		
1979	pol. ep $\rightarrow$ eX	SM of elementary particles
1980		
1981		Hierarchy [Technicolor vs SUSY]
1982	W, Z	Supergravity models
1983	gluon jets	
1984		
1985		Radiative EWSB $\star$
1986	$B^0\overline{B}^0$ oscillation	D=10 Superstring
1987		
1988		gauge mediation models
1989		

1990	N_ν=3	
1991	$\alpha_1 = \alpha_2 = \alpha_3$ in MSSM ⋆	
1992		
1993	EW precision physics ⋆	
1994	top	
1995		
1996		D=11 M theory, brane ⋆
1997		anomaly mediation
1998	neutrino oscillation	large EXD [ADD]
1999		large EXD [RS]
2000		
2001		
2002		Little Higgs models
2003		Higgsless models, [KKLT]
2004		
2005	muon g-2 [BNL] ⋆	
2006		
2007		
2008	LHC started, suffered accident.	
2009	LHC collision !	
2010	LHC physics !	

Elementary particles of the SM (1'st generation)

	particle			quantum number			spin
				SU(3)	SU(2)	$U(1)_Y$	
quarks	$\begin{pmatrix} u_L \\ d_L \end{pmatrix}$	$\begin{pmatrix} u_L \\ d_L \end{pmatrix}$	$\begin{pmatrix} u_L \\ d_L \end{pmatrix}$	3	2	$\frac{1}{6}$	$\frac{1}{2}$
	u_R	u_R	u_R	3	1	$\frac{2}{3}$	
	d_R	d_R	d_R	3	1	$-\frac{1}{3}$	
leptons		$\begin{pmatrix} \nu_{eL} \\ e_L \end{pmatrix}$		1	2	$-\frac{1}{2}$	
		e_R		1	1	-1	
		ν_R		1	1	0	
gauge bosons		$(A_1, A_2, A_3, A_4, A_5, A_6, A_7, A_8)$		8	1	0	1
		(W_1, W_2, W_3)		1	3	0	
		B		1	1	0	
Higgs boson		$\begin{pmatrix} h^0 \\ h^- \end{pmatrix}$		1	2	$-\frac{1}{2}$	0
Graviton		G		1	1	0	2

All the interactions of the elementary particles are governed by their $SU(3)_{color} \times SU(2)_L \times U(1)_Y$ quantum numbers. However, the following questions arise:

- Why are there 3 types of quarks with the quantum numbers (3,2,1/6), (3,1,2/3), (3,1,-1/3) and 3 types of leptons with (1,2,-1/2), (1,1,-1), (1,1,0) ?

- Why SU(2) doublets are left-handed, and singlets are right-handed ?

- Why 3 times repetitions of the same set ?

- How are the masses and mixings of quarks and leptons determined ?

In addition, we wonder

- Why are there 3 gauge symmetries SU(3), SU(2), and U(1) ?

- How are the 3 gauge couplings α_s, α_W, α_Y determined ?

Although we do not yet know the answers to the above questions, in the first half of the 1970's, a satisfactory answer to some of them, in particular, the questions;

- Why are the electric or hyper-charges quantized ?

- Why $\alpha_s > \alpha_W > \alpha_Y$?

were found. It is the Grand Unification Theory (GUT).

By using the fact that the anti-particle of a right-handed particle is left-handed, we express all quarks and leptons in terms of left-handed fields.

		SU(3)	SU(2)	Y	Y^3	$I_3^2 Y$
quark	$\begin{pmatrix} u_L \\ d_L \end{pmatrix}$	3	2	$\frac{1}{6}$	$(\frac{1}{6})^3 \times 6$	$(\frac{1}{2})^2(\frac{1}{6}) \times 6$
	u_R^c	3^*	1	$-\frac{2}{3}$	$(-\frac{2}{3})^3 \times 3$	0
	d_R^c	3^*	1	$\frac{1}{3}$	$(\frac{1}{3})^3 \times 3$	0
lepton	$\begin{pmatrix} \nu_{eL} \\ e_L \end{pmatrix}$	1	2	$-\frac{1}{2}$	$(-\frac{1}{2})^3 \times 2$	$(\frac{1}{2})^2(-\frac{1}{2}) \times 2$
	e_R^c	1	1	1	$1^3 \times 1$	0
	ν_R^c	1	1	0	0	0
Sum					0	0

We then observe that the anomalies which appear in the gauge boson 3-point functions cancell only after summing both quark and lepton contributions, and only after summing contributions from left-handed fermions and right-handed fermions (left-handed anti-fermions).

This suggests strongly that quarks and leptons, as well as left-handed doublets and the anti-particles of right-handed singlets, may be different components of a multiplet that transforms jointly under the Lorentz transformation and a symmetry transformation. This idea was proposed by Georgi and Glashow in 1973, by using the symmetry group SU(5).

In the SU(5) theory, 16 fermions of 1 generation are represented by 3 multiplets, $\underline{5}^*$, $\underline{10}$, $\underline{1}$:

$$\underline{5}^* = \begin{pmatrix} d_R^c \\ d_R^c \\ d_R^c \\ -e_L \\ \nu_L \end{pmatrix} \qquad \underline{10} = \begin{pmatrix} 0 & u_R^c & -u_R^c & u_L & d_L \\ & 0 & u_R^c & u_L & d_L \\ & & 0 & u_L & d_L \\ & & & 0 & e_R^c \\ & & & & 0 \end{pmatrix} \qquad \underline{1} = \nu_R^c$$

Among the $5 \times 5 - 1 =$24 gauge bosons, one can be identified as the hypercharge $\mathrm{U(1)_Y}$ gauge boson (B), and the quantization of the hypercharges follows from the tracelessness of the SU(5) generators:

$$\underline{24} = \frac{1}{\sqrt{2}} \begin{pmatrix} & 8 \quad \text{gluons} & & X^- & Y^- \\ & & & X^- & Y^- \\ & & & X^- & Y^- \\ X^+ & X^+ & X^+ & W^3/\sqrt{2} & W^+ \\ Y^+ & Y^+ & Y^+ & W^- & -W^3/\sqrt{2} \end{pmatrix} + \frac{B}{2\sqrt{15}} \begin{pmatrix} -2 & & & & \\ & -2 & & & \\ & & -2 & & \\ & & & 3 & \\ & & & & 3 \end{pmatrix}$$

In order to break the SU(5) symmetry down to the standard model, we introduce 3 types of Higgs bosons, $\underline{24}$, $\underline{5}$ and $\underline{5}^*$:

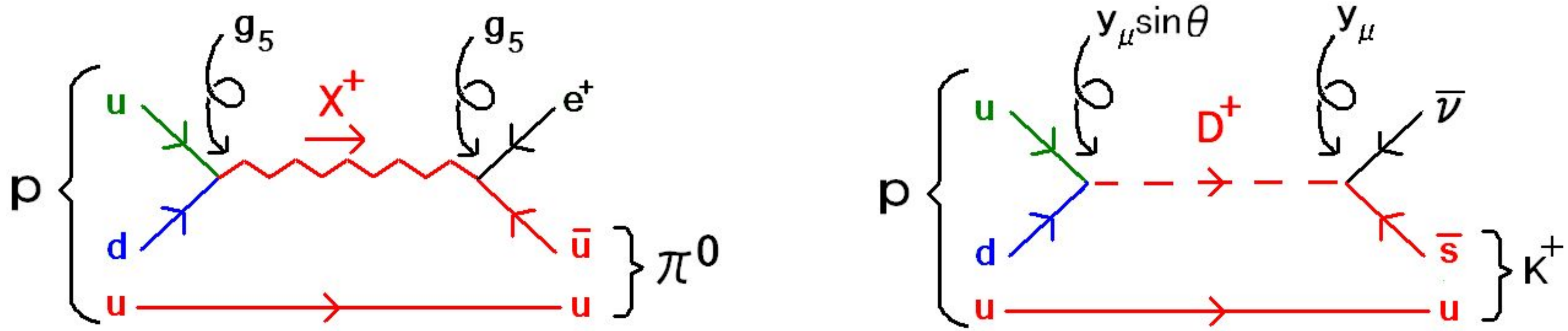
$$\underline{24}_{\mathrm{H}} = \Sigma \qquad \underline{5}^*_{\mathrm{H}} = \begin{pmatrix} D^+ \\ D^+ \\ D^+ \\ h_d^- \\ h_d^0 \end{pmatrix} \qquad \underline{5}_{\mathrm{H}} = \begin{pmatrix} D^- \\ D^- \\ D^- \\ h_u^+ \\ h_u^0 \end{pmatrix}$$

The SU(5) GUT thus gives us a satisfactory answer to the fundamental question of the charge quantization, explaining the origin of the 1/3 units of the quark charge in particular. Once this is recognized, it is no more possible to regard quarks and leptons as independent unrelated particles.

However, this model had two serious phenomenological problems:

- $\alpha_s = \alpha_{\mathrm{W}} = \frac{5}{3}\alpha_{\mathrm{Y}}$
- proton decays

First, the proton decays in this theory as follows:



In order for protons and nuclei to be stable enough, we should require

$$m_{\mathrm{X}} = m_{\mathrm{Y}} \gtrsim 10^{15}\mathrm{GeV} \qquad m_{\mathrm{D}} \gtrsim 10^{13}\mathrm{GeV}$$

After the symmetry breakdown, the 24 gauge bosons split into 12 heavy bosons (X,Y) and the 12 massless gauge bosons which can be identified as 8 gluons, 3 SU(2) gauge bosons and the hyperchage gauge boson B. Half of the 24 Higgs boson are absorbed by X and Y, and the remaining half become heavy. The 5 plets of Higgs bosons split into heavy triplets D and massless doublets, which become the SM Higgs doublet. It may be worth noting that a pair of Higgs quintets are required at this stage, in order to make D massive.

Heavy particles do not contribute to the quantum corrections at energy scales below their masses (decoupling). Only light particles contribute to radiative corrections. Accordingly, the unique gauge coupling of SU(5) receive different radiative corrections below the X, Y, D masses for different vertices, such as:

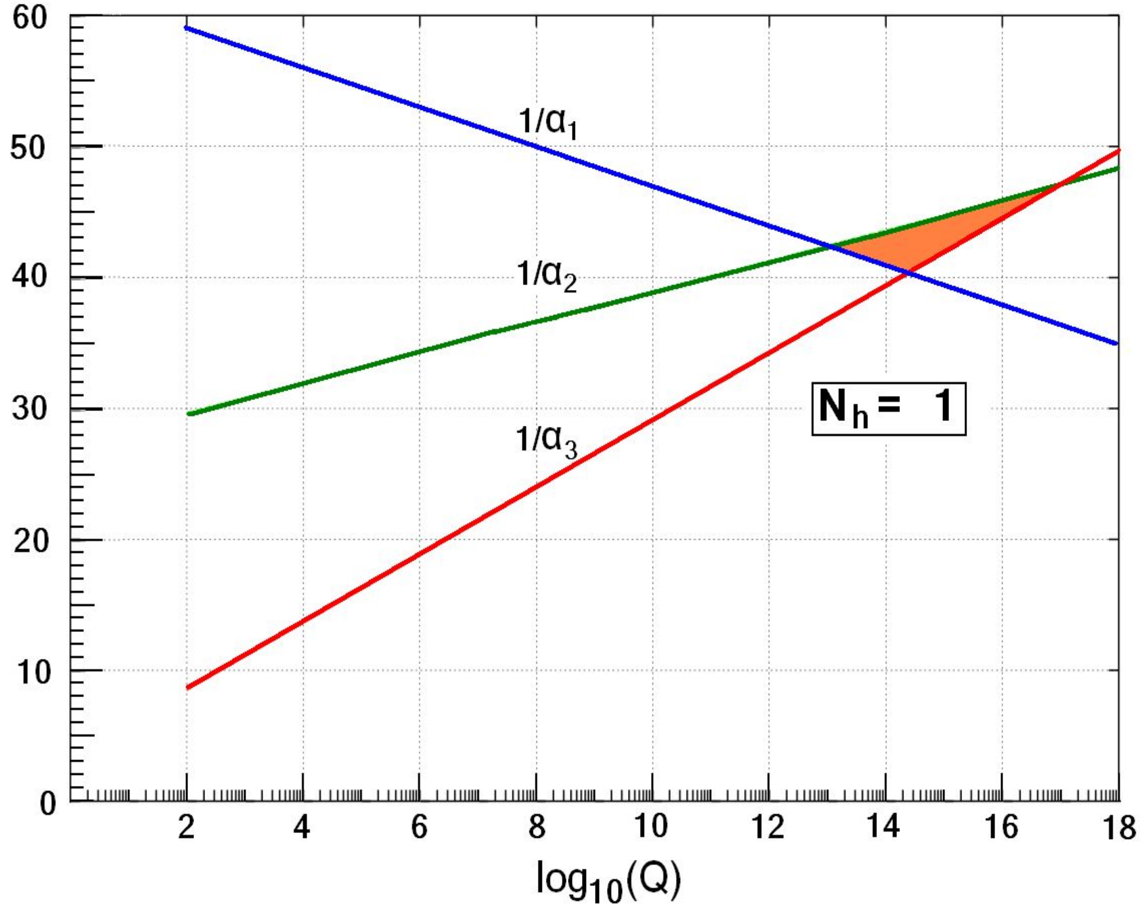
q-q-g, **l-ν-W**, **l-l-B**

vertices. This was noticed by Georgi、Quinn、and Weinberg in 1974. Each effective coupling receives radiative corrections as:

$$
\begin{aligned}
\frac{\pi}{\alpha_3(m_Z)} &= \frac{\pi}{\alpha_5(m_X)} - b_3 \ln\left(\frac{m_X}{m_Z}\right) \qquad & b_3 &= \frac{11}{2} \quad 0 \quad && -\frac{2}{3}N_{gen} \\
\frac{\pi}{\alpha_2(m_Z)} &= \frac{\pi}{\alpha_5(m_X)} - b_2 \ln\left(\frac{m_X}{m_Z}\right) \qquad & b_2 &= \frac{11}{3} \quad -\frac{1}{12}N_h && -\frac{2}{3}N_{gen} \\
\frac{\pi}{\alpha_1(m_Z)} &= \frac{\pi}{\alpha_5(m_X)} - b_1 \ln\left(\frac{m_X}{m_Z}\right) \qquad & b_1 &= 0 \quad -\frac{1}{20}N_h && -\frac{2}{3}N_{gen}
\end{aligned}
$$

where the coefficients b_3, b_2, b_1 receive contributions from all the light particles that couple to the SU(3), SU(2), U(1) gauge bosons, respectively. The first terms are from the self-coupled gauge bosons, which are positive (asymptotic free) and proportional to n for SU(n), the second terms count the number of the Higgs doublets, and the last term receive contributions from quarks and leptons. If the quarks and leptons of each generation are all light, then their contributions are common for all the three couplings, since one generation of quarks and leptons form complete SU(5) multiplets.

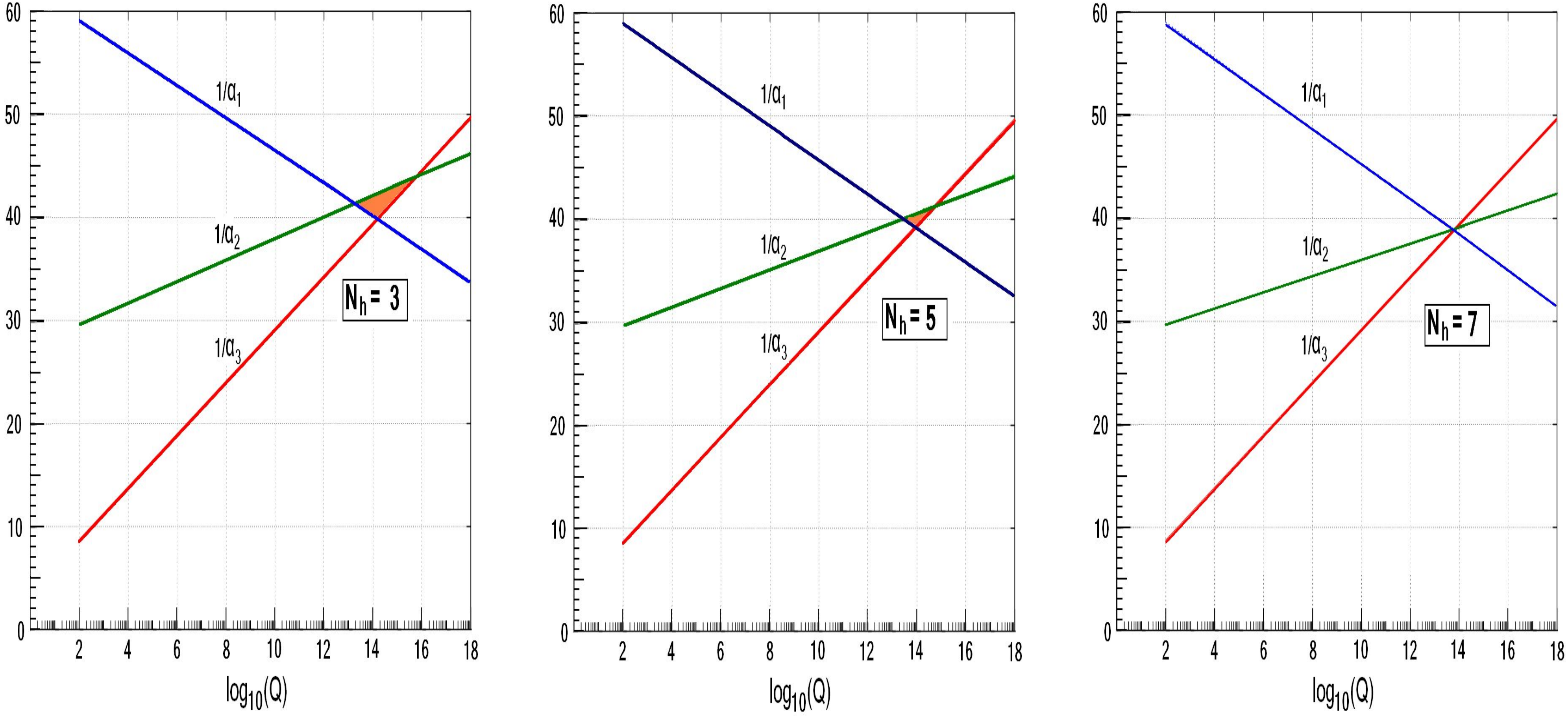
If the grand unification of the three couplings take place, the above equations should give a unique GUT coupling $\alpha_5(m_X)$ at the GUT scale, m_X. This prediction can hence be tested by inserting the measured values of the three couplings at the Z boson mass scale.



drown by K.Senda

The above result follows from the 3 gauge coupling strengths measured at the m_Z scale, if we assume 3 generation of quarks and leptons and 1 Higgs doublet in the SM (minimum SM). The idea of the Grand Unification of the 3 gauge couplings is clearly a great success qualitatively, since the ordering of the three gauge coupling strengths, $\alpha_3(m_Z) > \alpha_2(m_Z) > \alpha_1(m_Z)$ agree with the ordering $b_3 > b_2 > b_1$, which in tern refrects the ordering $3 > 2 > 1$ of the gauge group SU(**3**), SU(**2**), U(**1**).

The quantitative disagreement of the unification may suggest new particles in the TeV region. For instance, if we introduce N_h Higgs doublets we find



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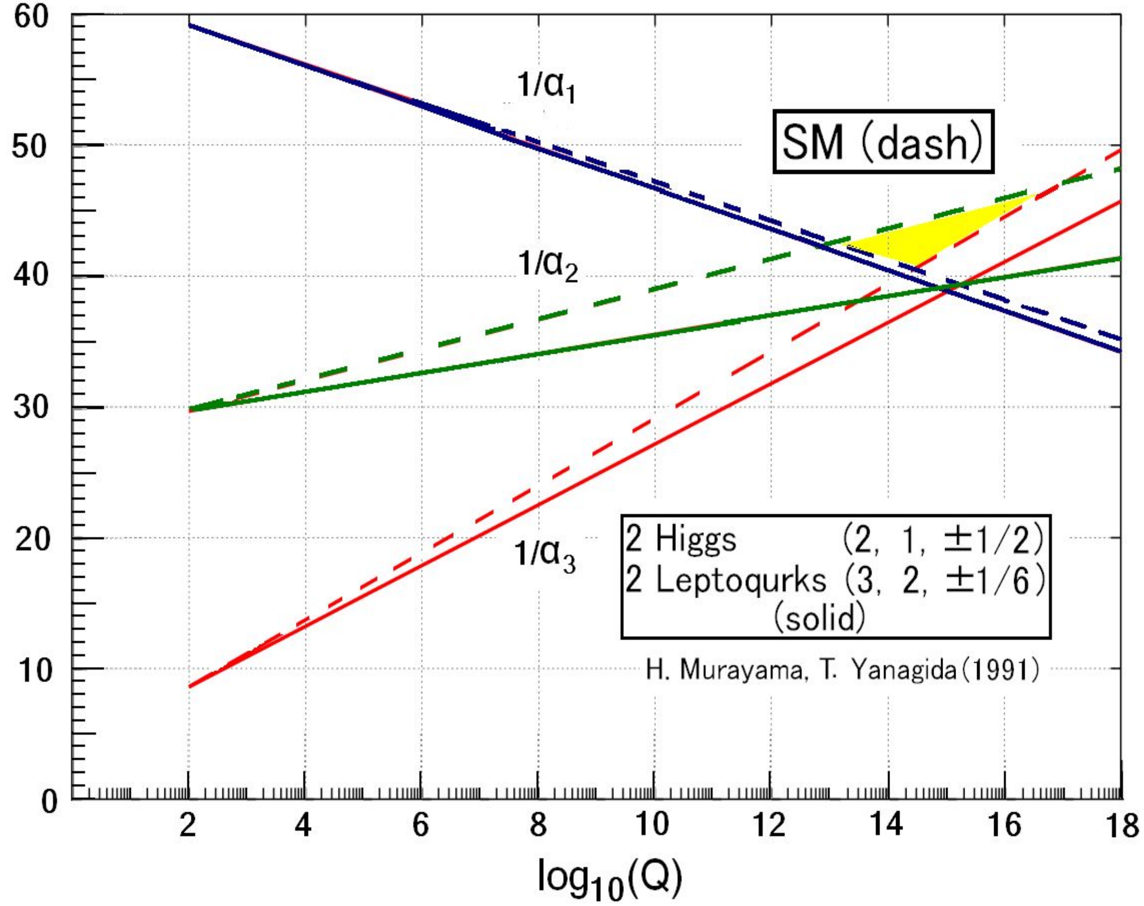
The unification is achieved for $N_h = 7$, but the GUT scale becomes rather small, which contradicts with the observed proton longevity. In order to avoid this, we should make the slope of the SU(3) coupling b_3 small, suggesting new colored particles at TeV scale.

As a simplest example, instead of introducing 6 additional Higgs doublet, we may introduce a pair of color-triplet and SU(2) doublet scalar bosons. Now both the SU(3) and SU(2) couplings run slower, and they meet at large enough mass scale. By arranging their hypercharge to make them 'lepto-quarks', the U(1) coupling meets at the same point.



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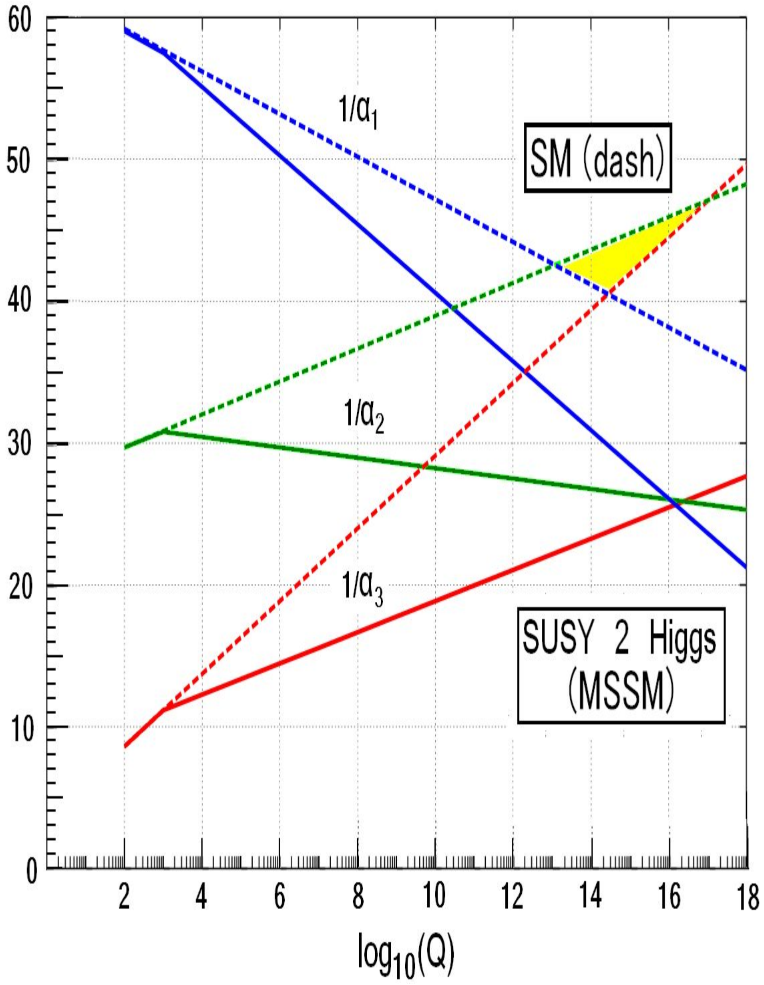
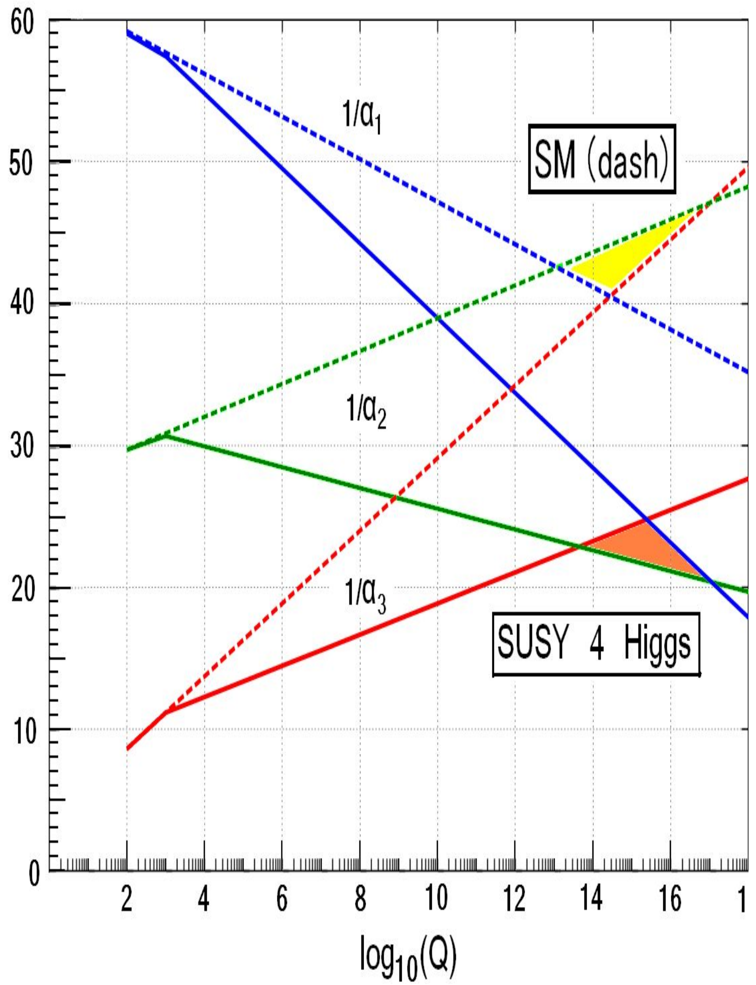
This example shows that it is relatively easy to find a common solution for the unification of the 3 gauge couplings and the proton longevity. How about the Supersymmetric SM ?





The unification occurs only for the MSSM (Minimum Supersymmetric SM), where there is only one pair of Higgs supermultiplets. The effective number of the Higgs doublet is 6, since the Higgsinos contribute twice the Higgs bosons to the running of SU(2) and U(1) couplings. The two couplings meats at higher scale because the winos make the SU(2) couplings run slower. Miraculously, the gluino contribution to the SU(3) couplings make the 3 couplings meet at one point, $m_{MSSMGUT} = 2 \times 10^{16}$ GeV.

What is so super about **SUPER-SYMMETRY** ?

It is the only known extention of the Einstein's space-time symmetry, called Lorentz or Poincare symmetry, where the space-time is considered as a part of more general space, the super-space, which contains dimensions of non-commutative (fermionic) coordinates.

Supersymmetry transforms **fermions (matter)** into **bosons (force)**, and vice versa. Since fermions anti-commutes while bosons commutes, their contributions to quantum fluctuations tend to cancell.

We learned that the idea of Grand Unification works only when there is a hierarchy between the unification scale $\sim 10^{16}$ GeV and the electroweak scale $\sim 10^{2}$ GeV.

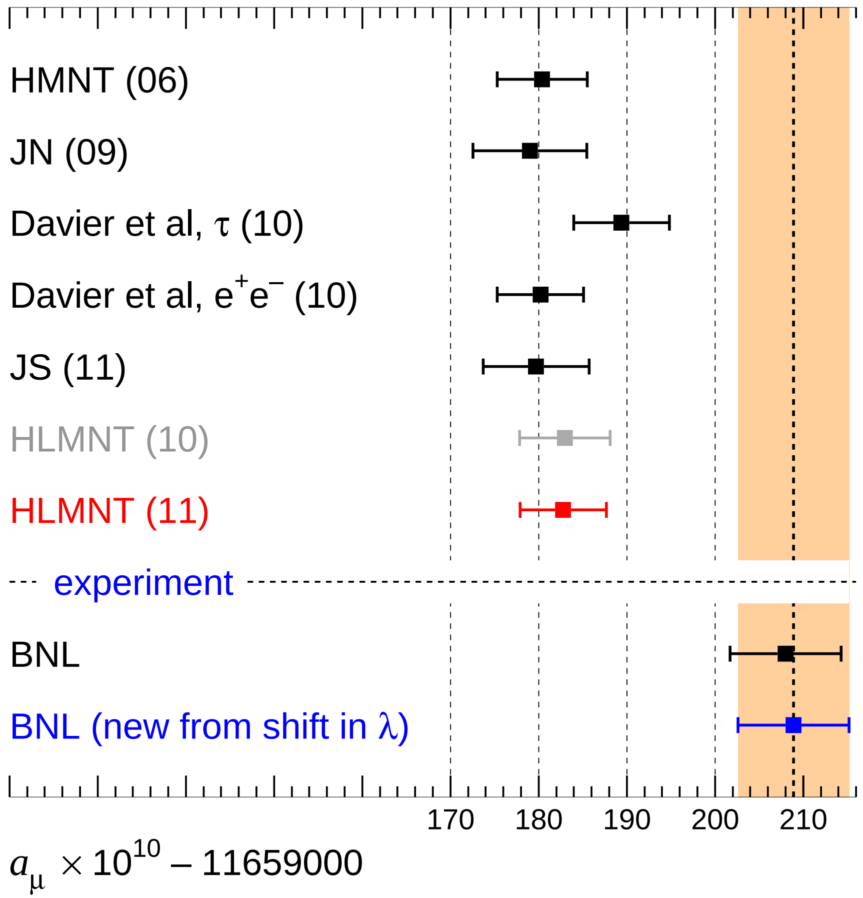
Supersymmetry is the only known symmetry which can suppress quantum fluctuations of spinless boson mass, the Higgs boson mass, which should be 10^{14} times smaller than the unification scale.

Because we do not observe spinless partners of the photon, electron, quarks and gluons, the supersymmetry should be broken. The beautiful idea is that what we think is the electroweak gauge symmetry breaking scale is indeed the supersymmetry breaking scale, and that we will discover superpartners of all the SM particles in the mass scale of W, Z and the top quarks.

Particle masses and physics scales in Logarithms of [GeV] units.

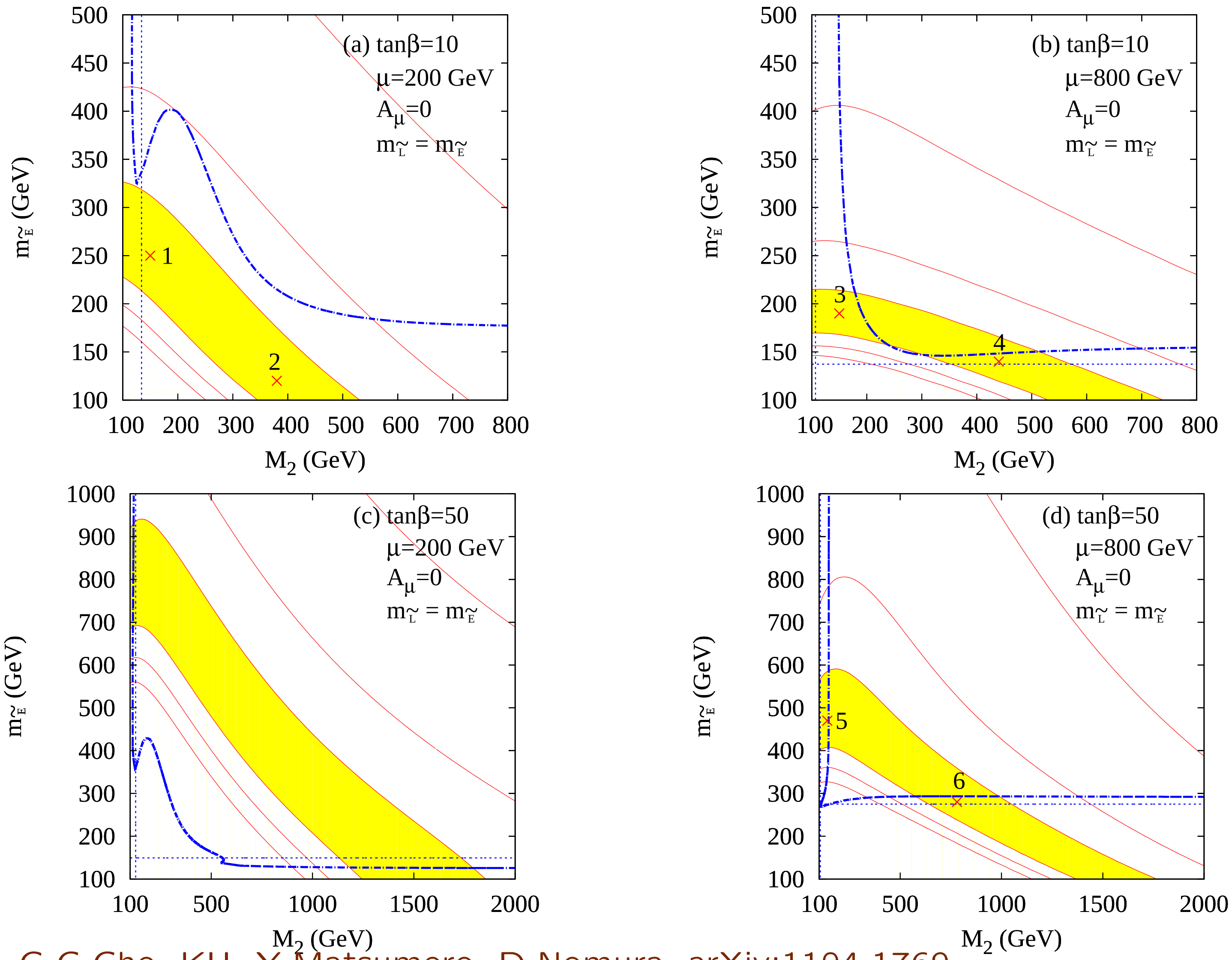
17	Quantum Gravity	$\longleftarrow$	super-string, extra space dimension
16	Grand Unification (**GUT**)	$\longleftarrow$	**SUSY-GUT** Unification
15			
14			
13			
12			
11			
10			
9			
8			
7			
6			
5			
4			
3	**Gauge Symmetry Breakdown**	$\longleftarrow$	**Supersymmetry Breakdown**
2	W, Z, top, Higgs		
1			
0	charm, bottom, tau, proton		
-1	strange, mu, pi		
-2			
-3	up, down, electron		
-4			
-5			
-6			
-7			
-8			
-9			
-10	neutrinos		

There may be a hint of new physics from the muon g-2 measurement.



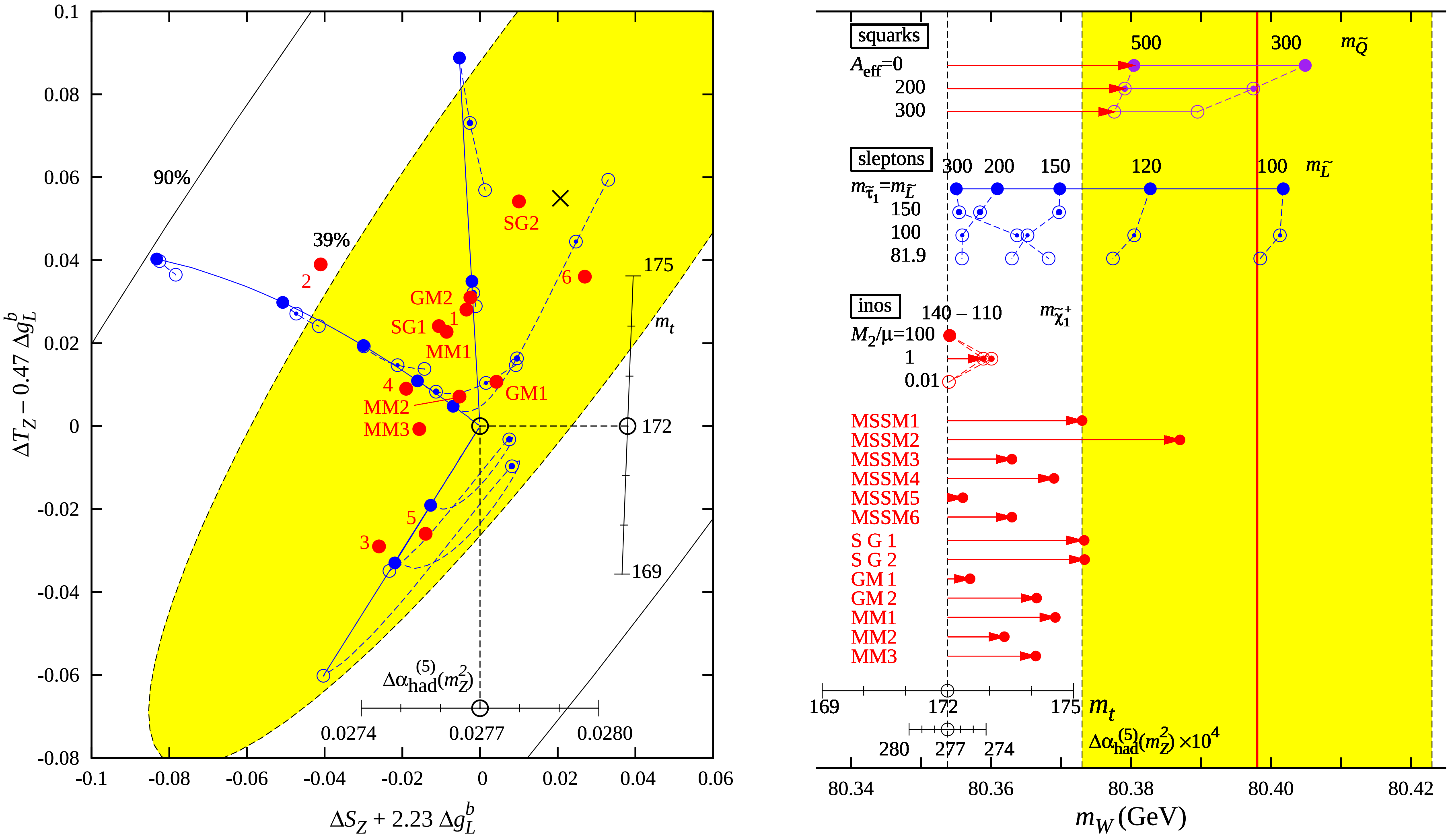
KH, R.Liao, A.D.Martin, D.Nomura, T.Teubner, arXiv:1105.3149

SUSY signal ?



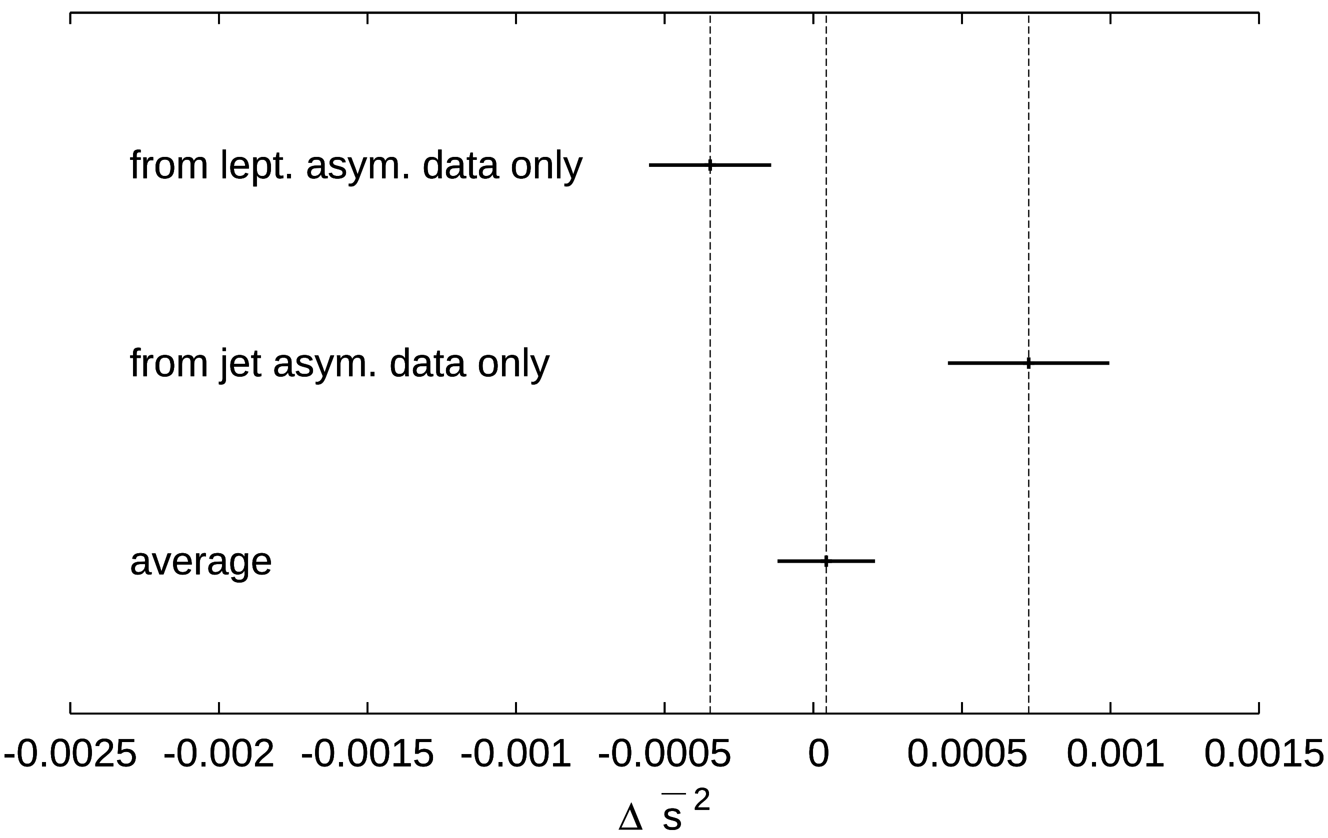
G.C.Cho, KH, Y.Matsumoro, D.Nomura, arXiv:1104.1769

How about the electroweak data on Z and W properties ?



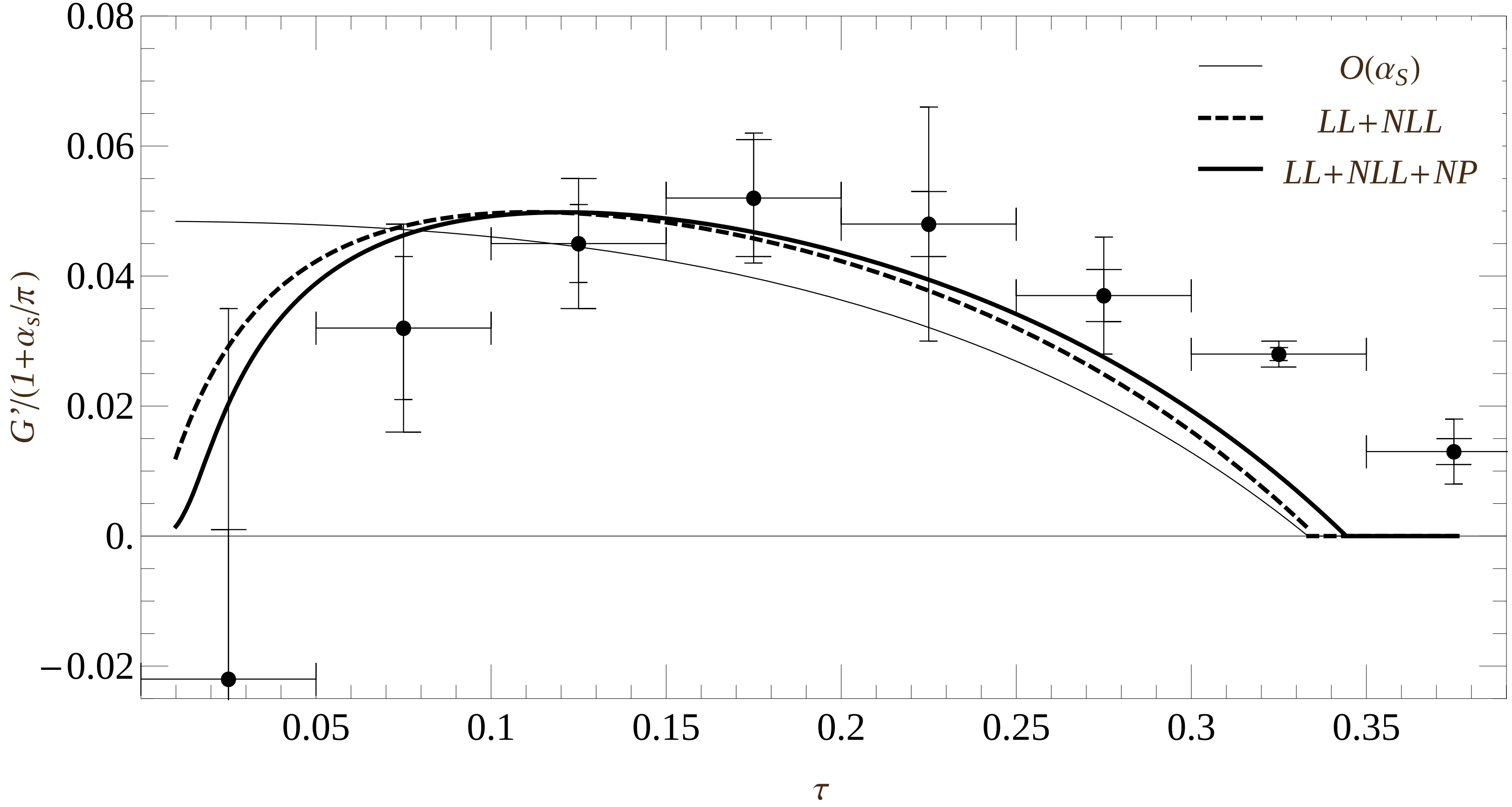
G.C.Cho, KH, Y.Matsumoro, D.Nomura, arXiv:1104.1769

Discrepancy in the weak mixing angle measurements ?



The allowed range of the weak mixing parameter from the leptonic and the jet asymmetry data, separately, and from their naive combination.

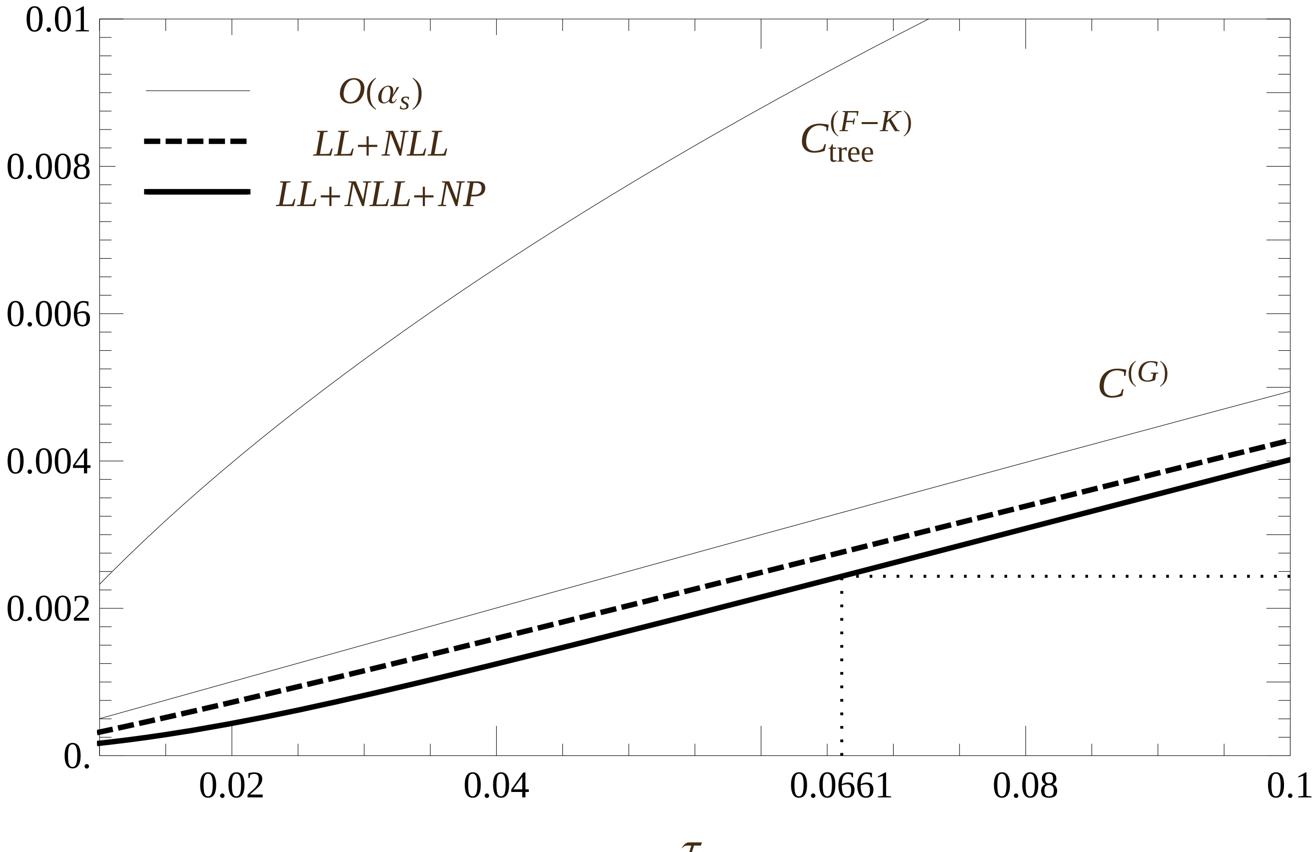
In a recent work with Grisha Kirilin, we analysed e^+e^- jet angular distribution by using SCET;



KH, G.Kirilin, arXiv:1006.5330[JHEP].

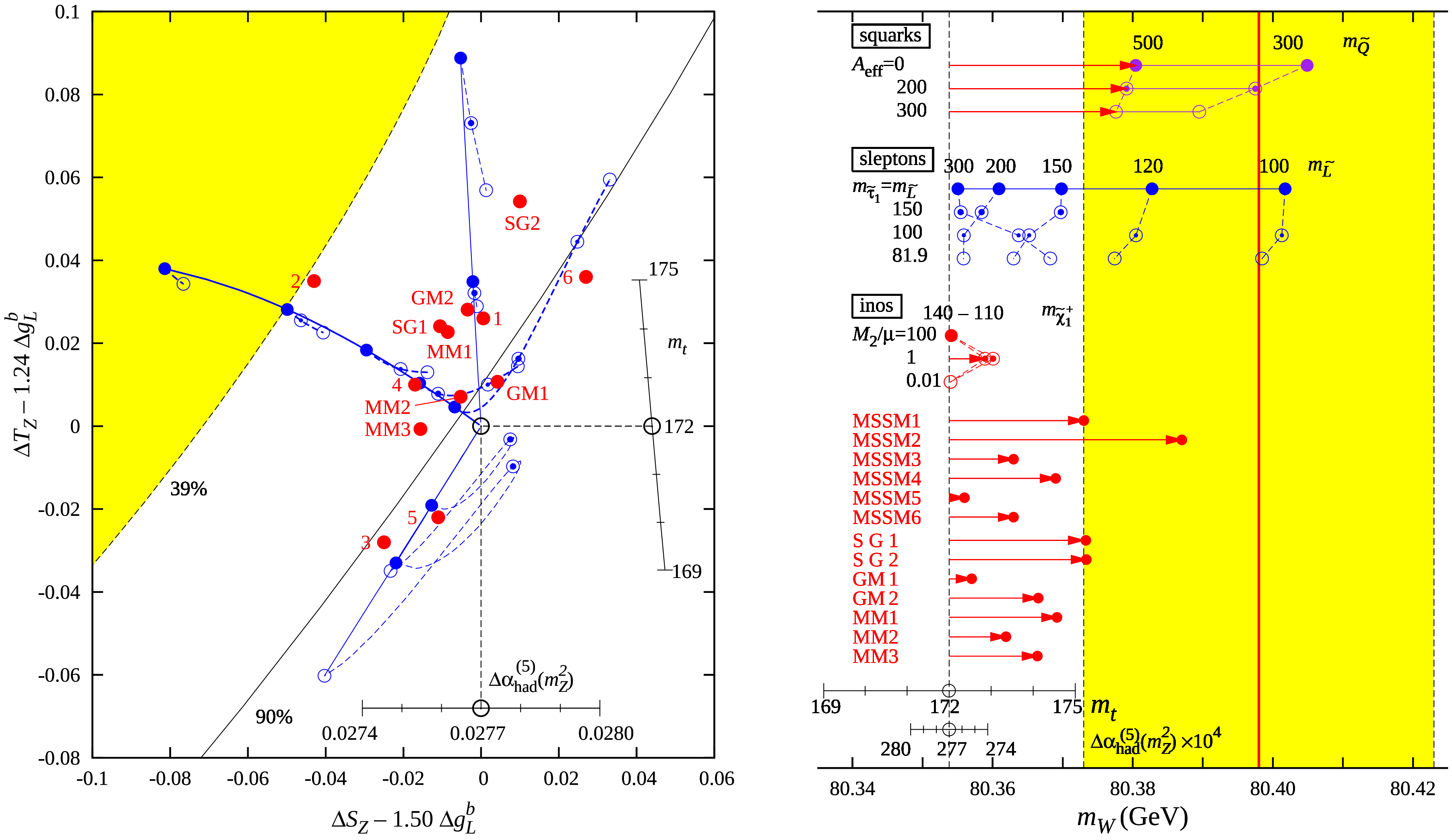
Shape of power suppressed parton shower whose $J_z = 0$ and the jet polar angle distribution $\sim \sin^2\theta$.

The $J_z = 0$ jet contribution turned out to be negligibly small, but the major correction to the asymmetry comes from one-hard one-soft b-quark configuration, whose jet shape is difficult to evaluate even with SCET;



KH, G.Kirilin, arXiv:1006.5330[JHEP].

What if we remove all the jet asymmetry data from the analysis ?



G.C.Cho, KH, Y.Matsumoro, D.Nomura, arXiv:1104.1769

LHC status and schedule

2008.09.10	LHC starts circulating beam at 450 GeV.
2008.09.19	6 ton Helium leakage at sector 3-4 magnets.
2008.10.21	Official inauguration of the LHC.
2009.11.23	First collisions at 900 GeV (ALICE,ATLAS,CMS,LHCb)
2009.12.08	First collisions at 2.36 TeV
2010.03.29	First collisions at 7 TeV
2010.end	$\sim$ 0.04 fb^{-1} at 7 TeV
2011.end	1$\sim$3 fb^{-1} at 7 TeV ?
$\sim$2012	3$\sim$10 fb^{-1} at 7$\sim$9 TeV ?
$\sim$2014	First collisions at 14 TeV ?
$\sim$2015	$\sim$10 fb^{-1} at 14 TeV ?
$\sim$2018	$\sim$100 fb^{-1} at 14 TeV ?
$\sim$202?	$\sim$1000 fb^{-1} at 14 TeV with sLHC ?

or DLHC ? or LC ?

What shall the LHC experiments tell us ?

They will uncover physics behind SSB of gauge symmetry.

- Light Higgs boson with family of new particles.

  → weakly coupled SSB
  → solutions to g-2, DM, Baryogenesis ?
  → TeV scale probes (SLHC, ILC, ...) of Unification !

- Heavy or no Higgs boson.

  → strongly coupled SSB
  → TeV particles that couple to W and Z should exist.
  → Search for them at LHC, DLHC, ... !

- Medium Light Higgs boson

  → ∼ 200 GeV Higgs can be discovered in 2011 !.
  → Unification without SUSY ?
  → How about g-2 ?, DM ?, Baryogenesis ?
  → SUSY with strong interactions ?
  → How about g-2 ? How about Unification ?

What shall we do during the LHC era ?

Let us

participate in

this

event of the century !

We are extremely lucky to

be living as a physicist

TODAY !!!