ILC Physics

a theorist's perspective

Koji TSUMURA (Kyoto from Dec 1st)

Toku-sui annual workshop 2013

KEK, Dec. 17-19, 2013

Plan of my talk

STATUS

Where are we?

New Era of the SM

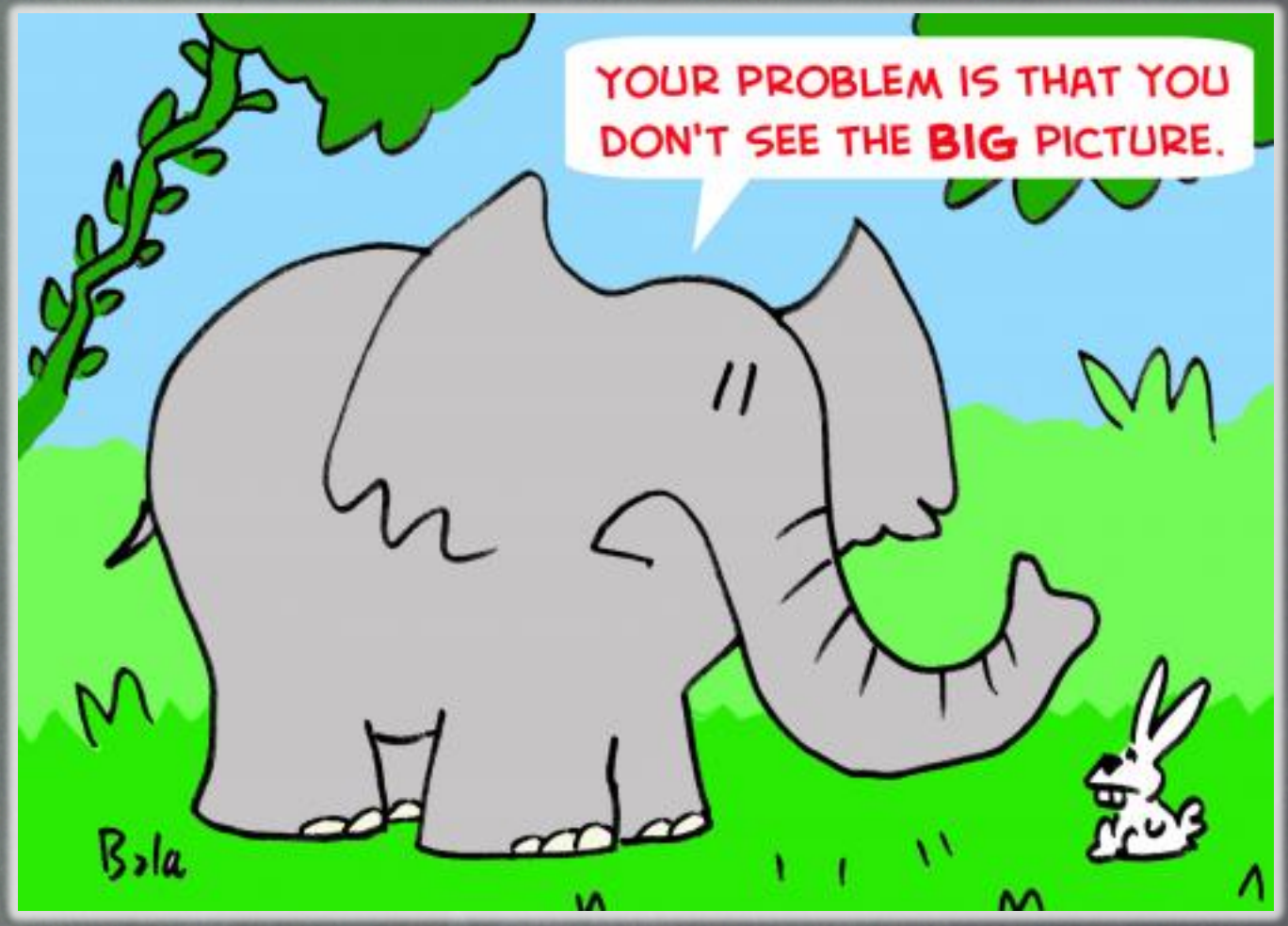
What we need to do?

Physics Beyond the SM

Why? Where is it?

ILC Physics

What do we do?


YOUR PROBLEM IS THAT YOU DON'T SEE THE BIG PICTURE.
Bola

Status

Where are we ?

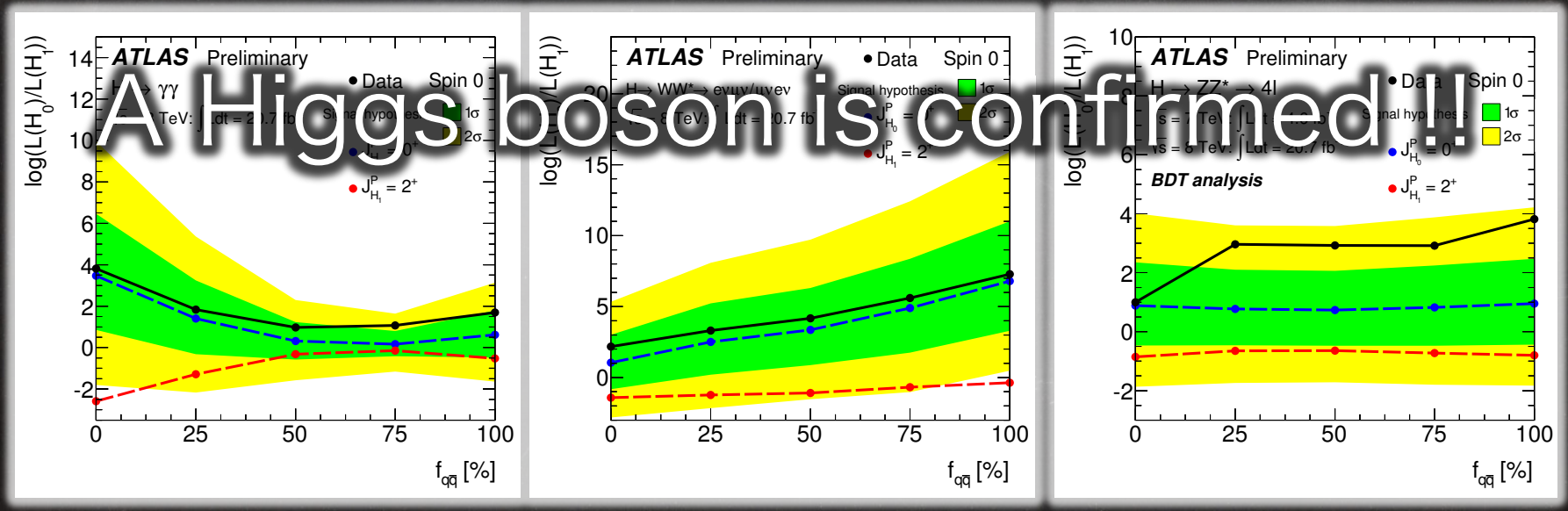
2012

A new particle is found !!

2013

3 decay channels are seen (≥3σ, each)
Spin 0 is favored

$H \to \gamma\gamma$ $H \to WW$ $H \to ZZ$



A Higgs boson is confirmed !!

The Review of Particle Physics (2013)

July 2013

Higgs Bosons — H^0 and $H^\pm$

Mass determined

H^0 Mass $m = 125.9 \pm 0.4$ GeV

H^0 signal strengths in different channels

Combined Final States $= 1.07 \pm 0.26$ (S = 1.4)

WW^* Final State $= 0.88 \pm 0.33$ (S = 1.1)

ZZ^* Final State $= 0.89^{+0.30}_{-0.25}$

$\gamma\gamma$ Final State $= 1.65 \pm 0.33$

3 decay channels are seen

$b\bar{b}$ Final State $= 0.5^{+0.8}_{-0.7}$

$\tau^+\tau^-$ Final State $= 0.1 \pm 0.7$

NEW →

CERN seminars on Nov. 26 & Dec. 3

H^0 DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
WW^*	seen	–
ZZ^*	seen	–
$\gamma\gamma$	seen	–
$b\bar{b}$	possibly seen	–
$\tau^+\tau^-$	possibly seen	–

Mass Limits for the Standard Model Higgs

Mass $m >$ 122 and none 127–600 GeV, CL = 95%

The limits for H_1^0 and A^0 in supersymmetric models refer to the $m_h^{\max}$ benchmark scenario for the supersymmetric parameters.

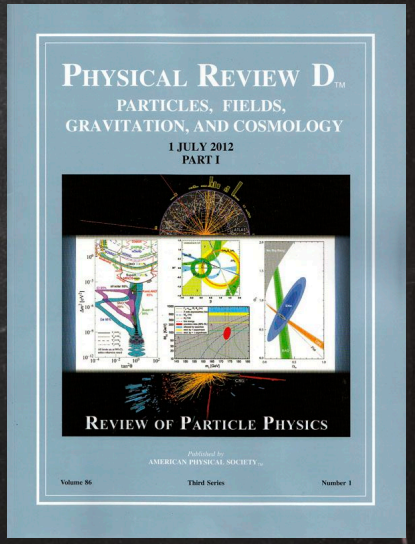
H_1^0 in Supersymmetric Models ($m_{H_1^0} < m_{H_2^0}$)

Mass $m >$ 92.8 GeV, CL = 95%

A^0 Pseudoscalar Higgs Boson in Supersymmetric Models [n]

Mass $m >$ 93.4 GeV, CL = 95% $\tan\beta > 0.4$

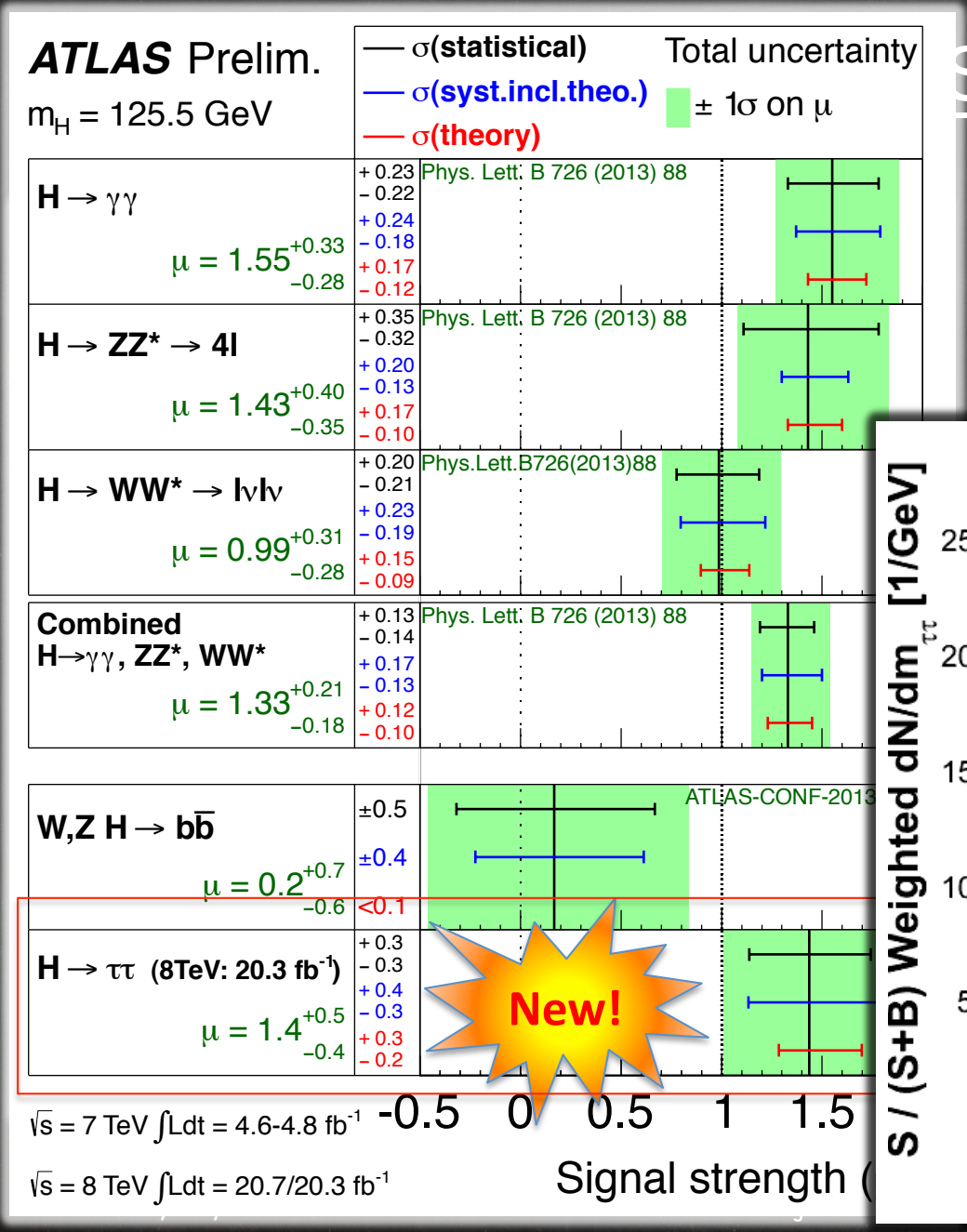
$H^\pm$ Mass $m >$ 79.3 GeV, CL = 95%

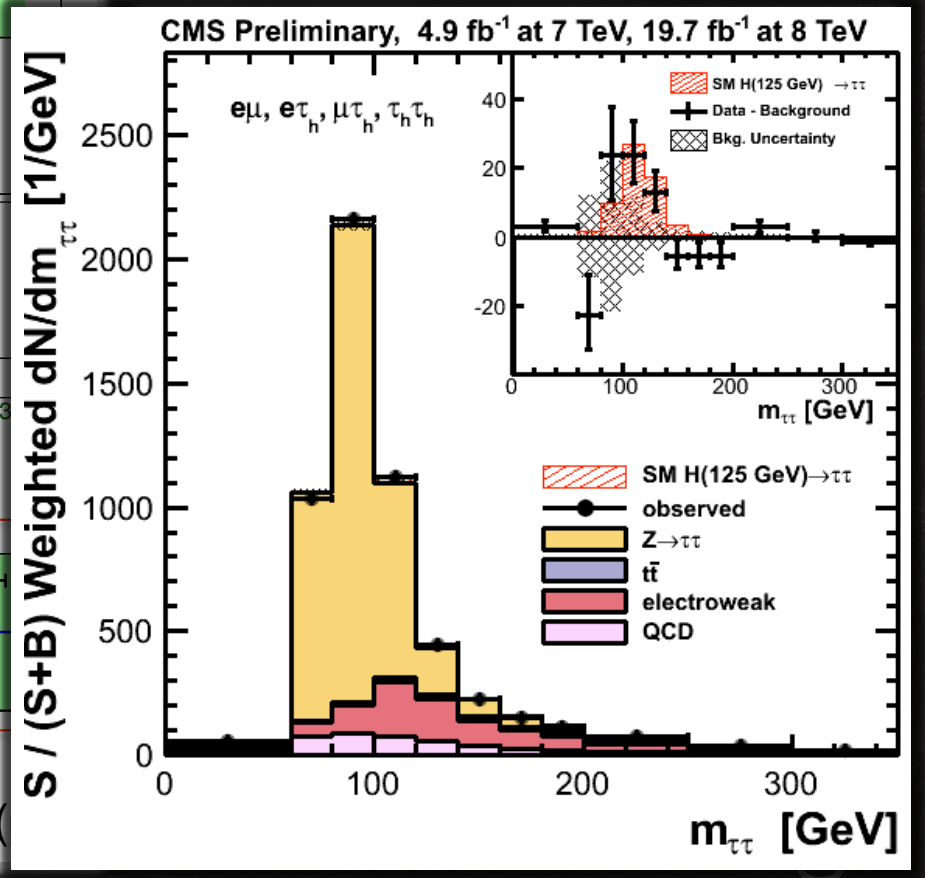


sults

CERN seminars
on Nov. 26 & Dec. 3

A fermionic decay channel ($\tau\tau$) is almost seen





So far, so GOOD.

New Era of the SM started

What we need ?

SM is successful

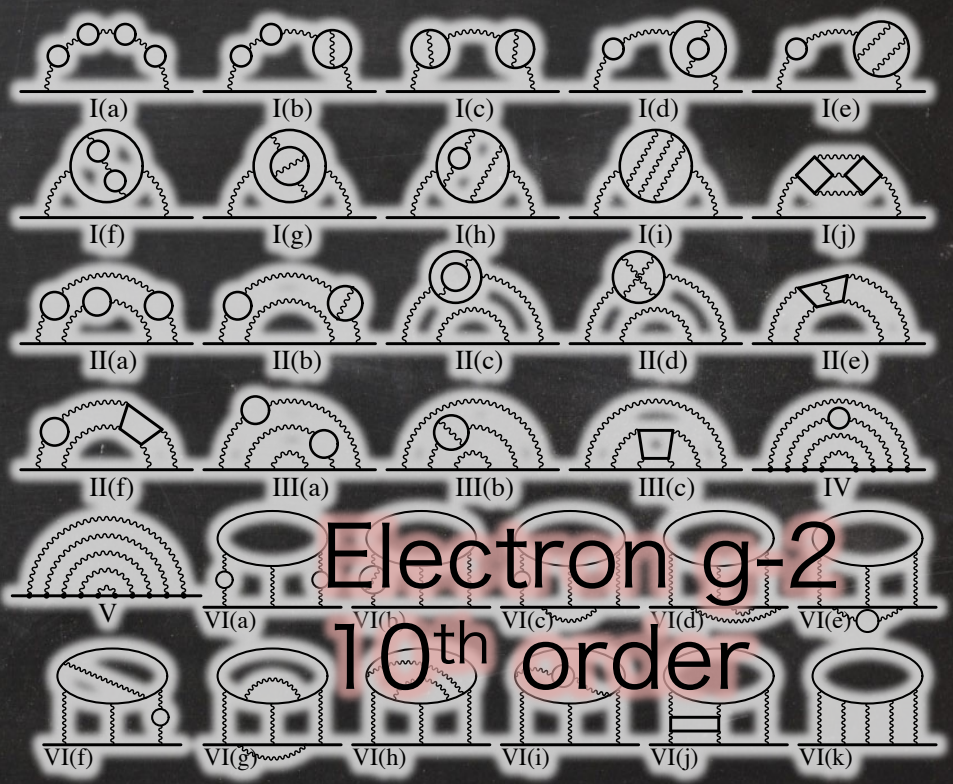
EM: 

EW: 

QCD: 

Higgs: 

Precision test



Electron g-2
10th order

SM is successful

EM: 

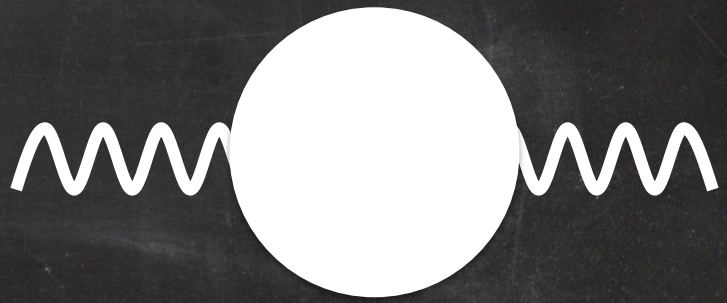
EW: 

QCD: 

Higgs: 

Precision test

W, Z, h, t, b

W, Z 

~~New Physics~~

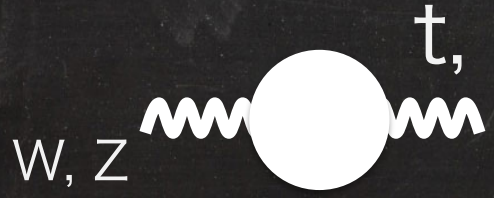
EW precision (LEP)

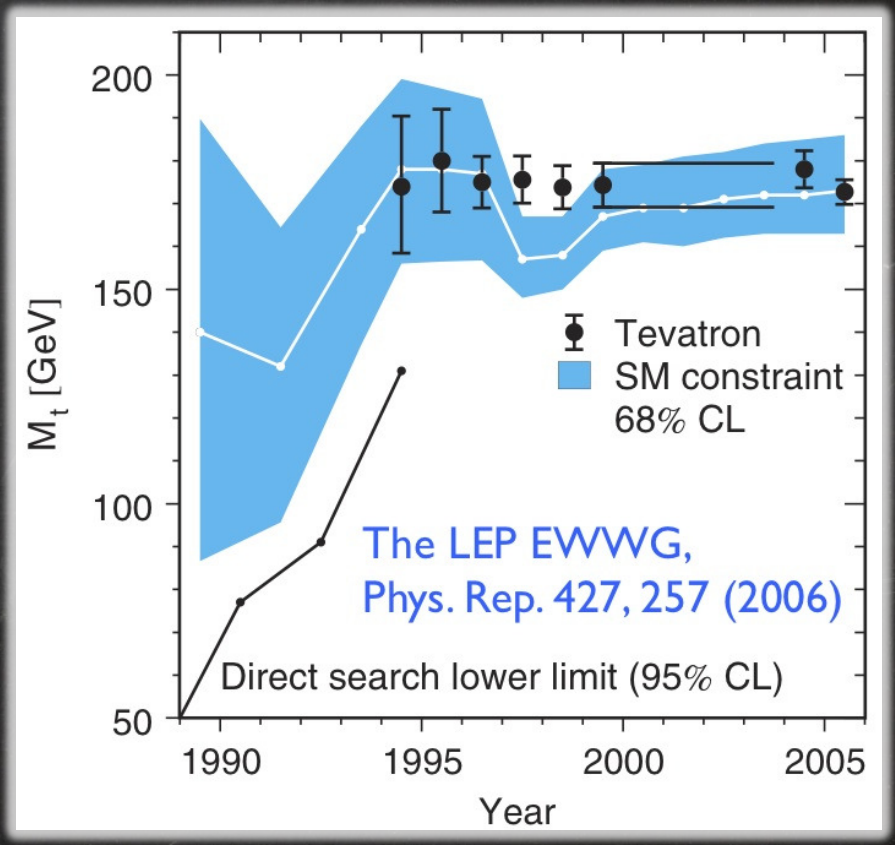
SM is successful

“Deviation” in ρ → Predict M_t

EW:

$$\delta\rho_t \simeq \frac{3G_F m_t^2}{8\sqrt{2}\pi^2}$$



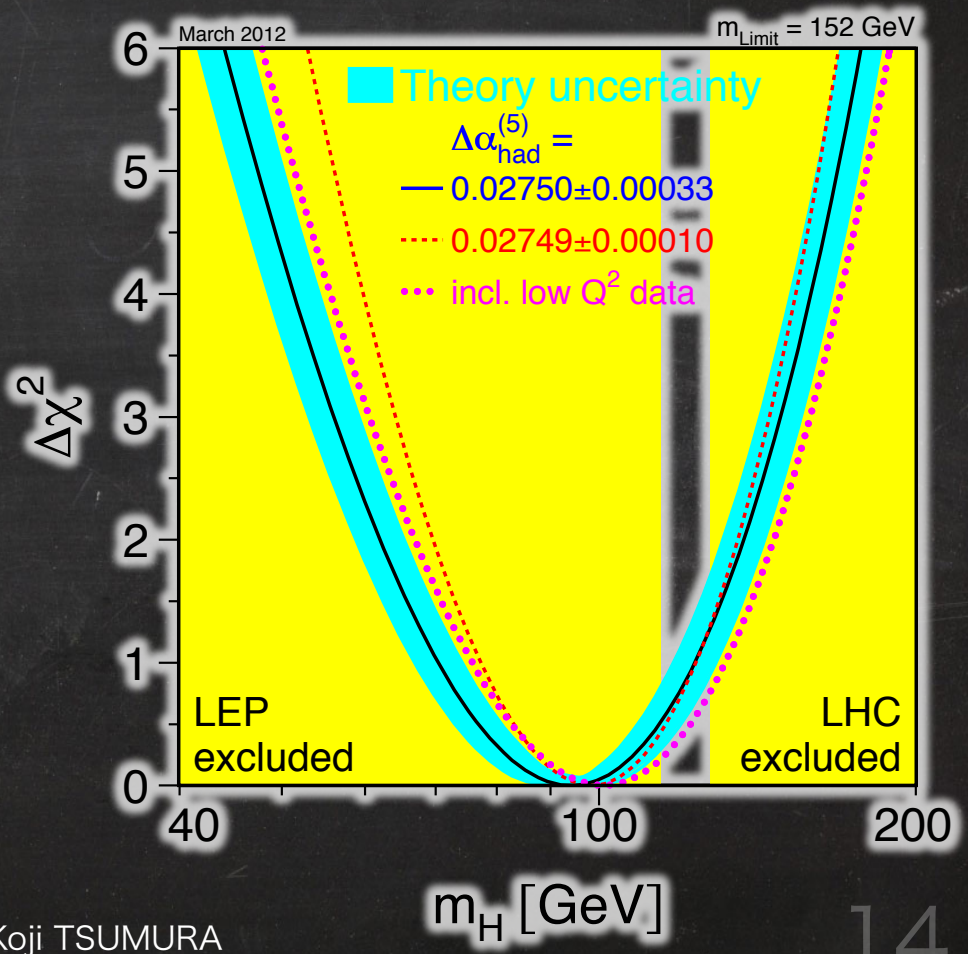


SM is successful

"Deviation" in ρ → Predict M_h

EW:

$$\delta\rho_h \simeq -\frac{3G_F m_Z^2 s_W^2}{8\sqrt{2}\pi^2}\left(\log\frac{m_h^2}{m_W^2} - \frac{5}{6}\right)$$



SM is successful

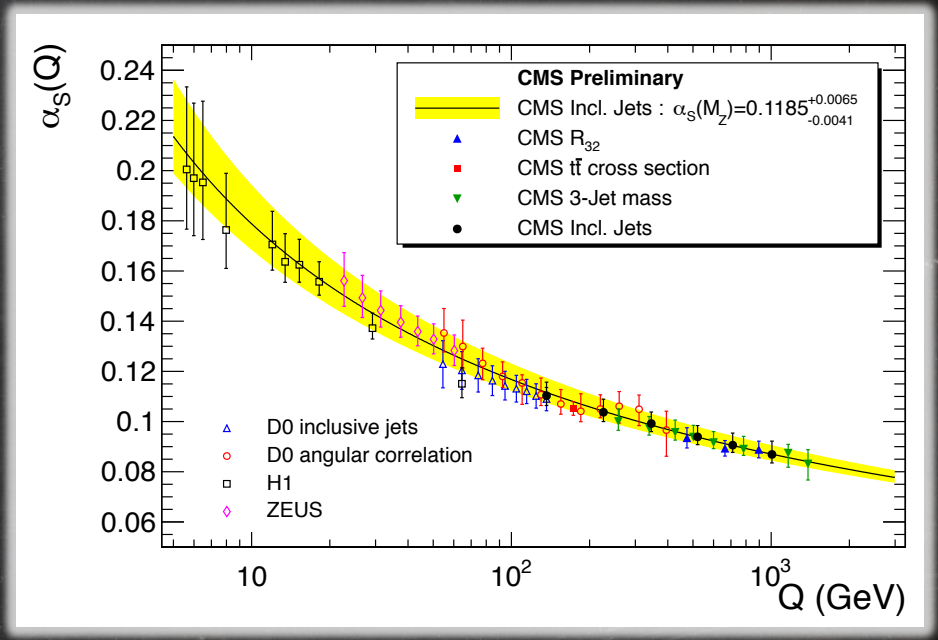
EM: 

EW: 

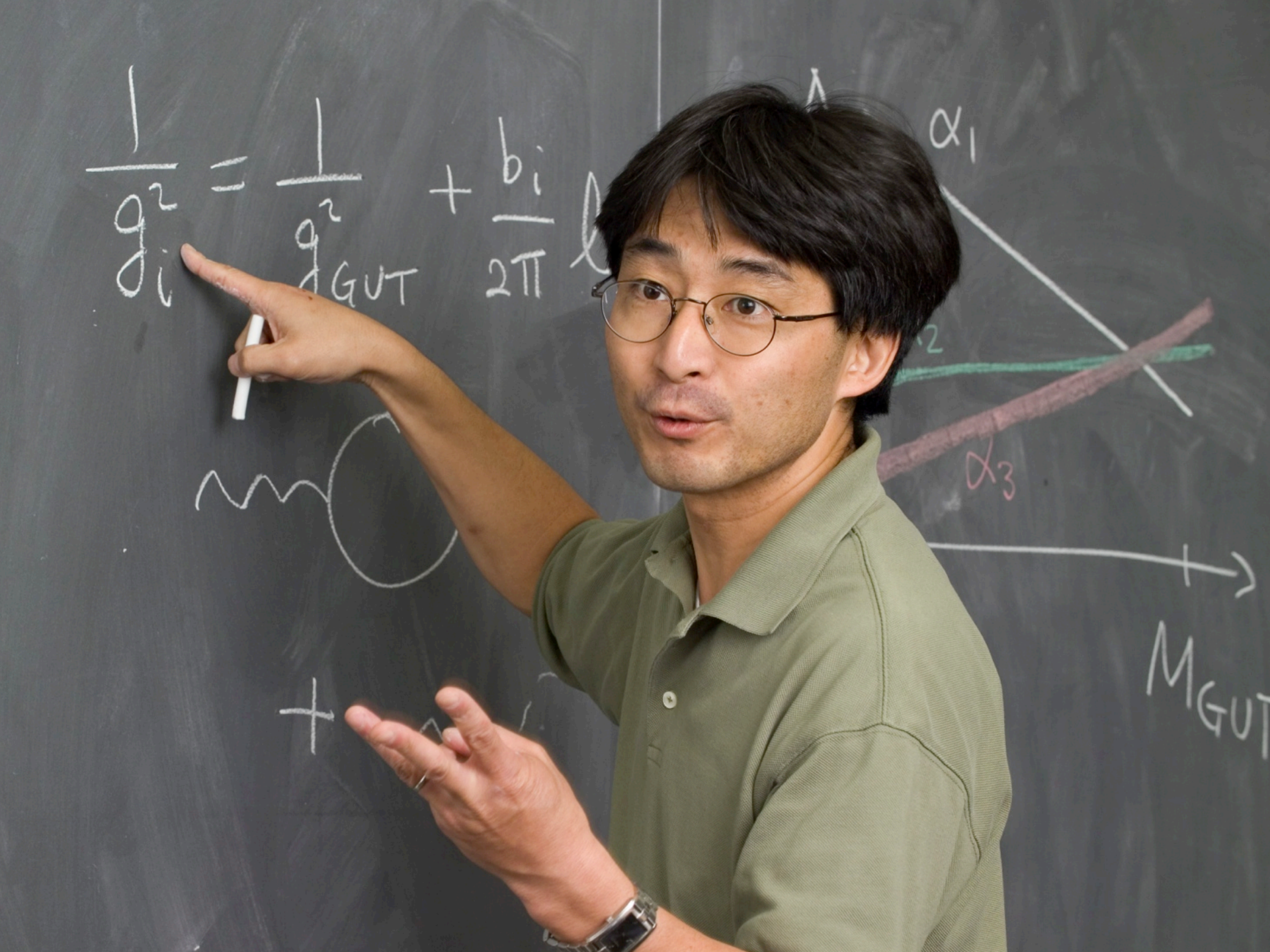
QCD: 

Higgs: 

Precision test



pQCD ≥1TeV (LHC)


$\frac{1}{g_i^2} = \frac{1}{g_{GUT}^2} + \frac{b_i}{2\pi}$
α_1
α_2
α_3
M_{GUT}

SM is successful

EM: 

EW: 

QCD: 

Higgs: 

Why not?

Higgs precision (ILC)

Higgs force
(Origin of mass)

$$h \to v + h$$

Why Higgs?

“Energy Frontier” study for Snowmass 2013

Introduction

the discovery of the Higgs boson has changed our viewpoint …

1st, the Higgs boson completes the particle spectrum of the SM.

It is clear now exactly what the model does not explain.

2nd, one of the key mysteries concerns the Higgs boson itself.

3rd, the Higgs boson itself give us a new experimental approach.

We are here !!

This is a new tool to probe New Physics scale.

What is the SM ?

Matter contents → quarks, lepton, Higgs (completed)

Gauge symmetry → gluon, W, Z, γ (tested)

Renormalizability → loop corrections (tested)

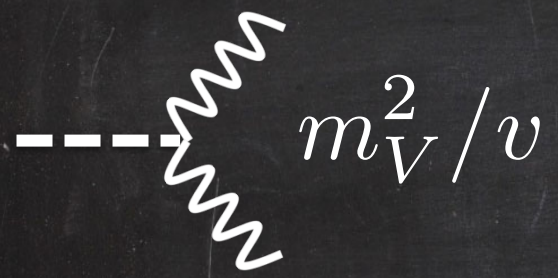
All parameters are now fixed!!

Not yet Tested !!

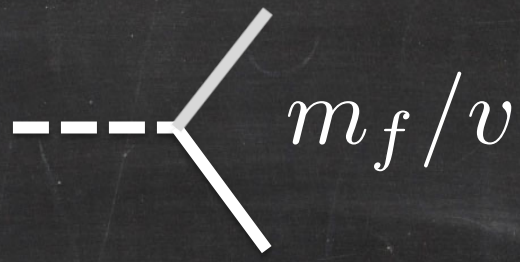
What is the origin of mass ?

Higgs mechanism ? Fermion Mass hierarchy, mixing, CP violation ?

$$\Phi^0 \to (v+h)/\sqrt{2}$$



Higgs mechanism



Yukawa interaction

Higgs self-interaction

$$\mathcal{L} = +\left|D_\mu \Phi\right|^2 - \left[+\mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2\right]$$

$$+\left[+Y_{ij} F_L f_R \Phi + \mathrm{H.c.}\right]$$

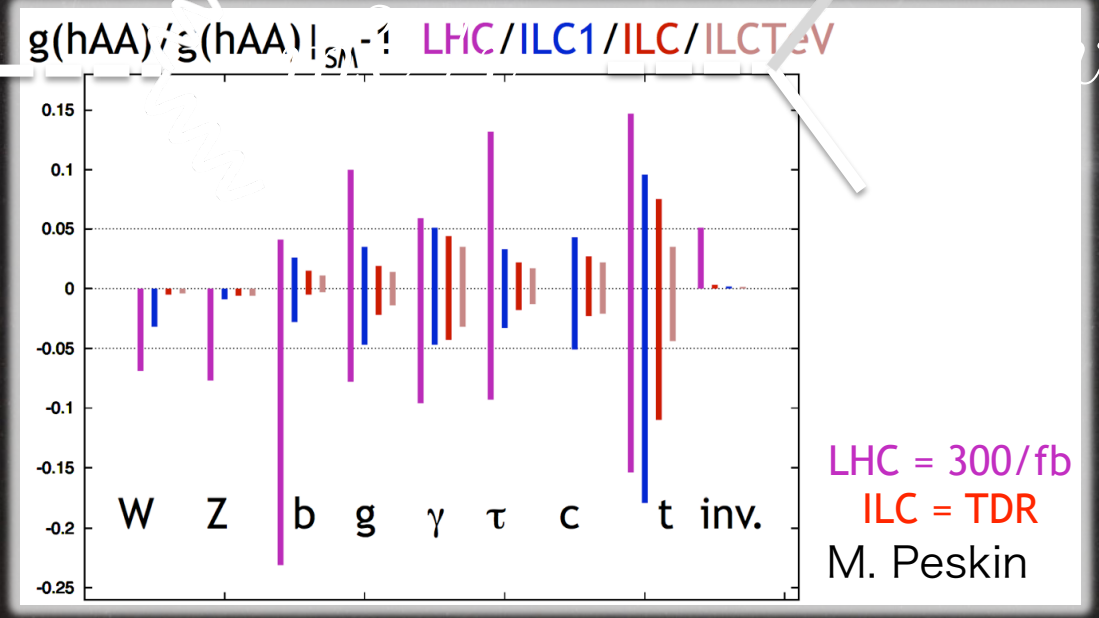
(New) non-Gauge force

Not yet Teste

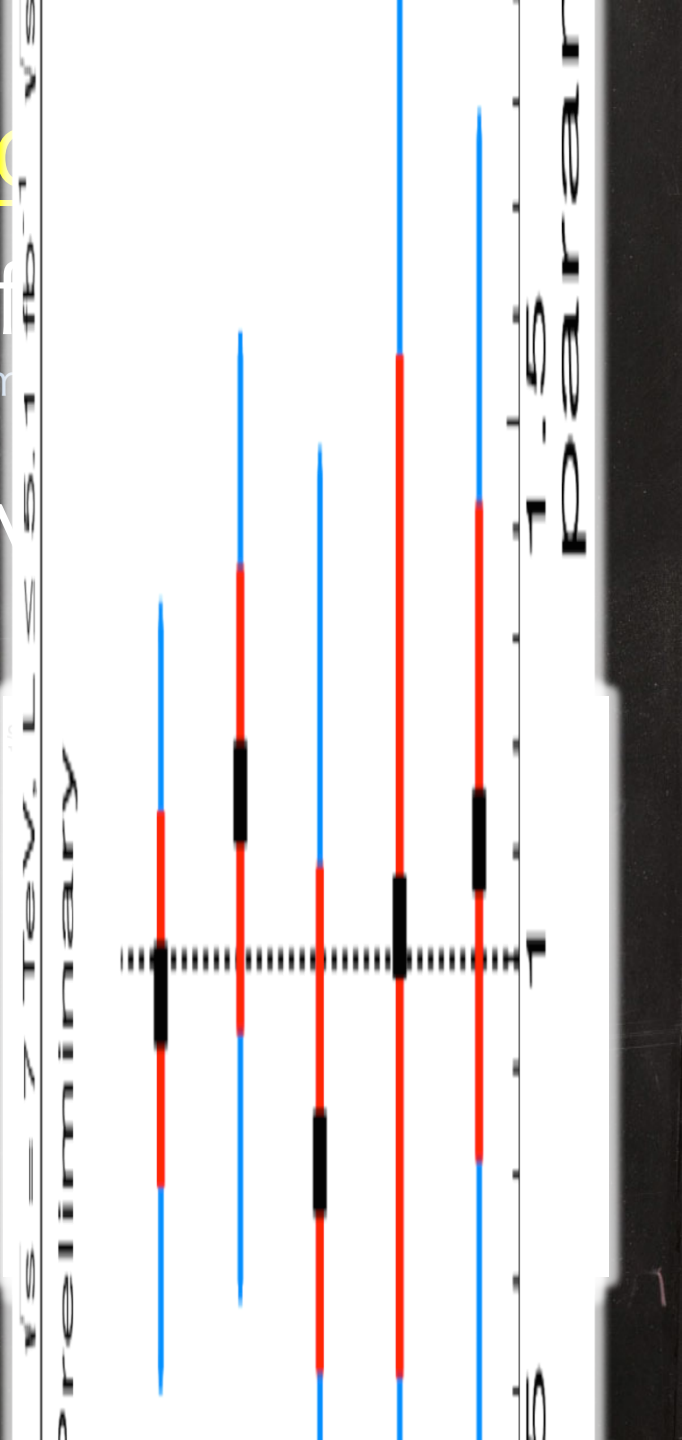
What is the origin of

Higgs mechanism ? Fermion Mass hierarchy, m

$$\Phi^0 \to (v+h)/\sqrt{}$$



LHC = 300/fb
ILC = TDR
M. Peskin



coupling Δg/g	Baseline			LumiUP		
	250 GeV	+ 500 GeV	+ 1 TeV	250 GeV	+ 500 GeV	+ 1 TeV
HZZ	1.3%	1.0%	1.0%	0.61%	0.51%	0.51%
HWW	4.8%	1.2%	1.1%	2.3%	0.58%	0.56%
Hbb	5.3%	1.6%	1.3%	2.5%	0.83%	0.66%
Hcc	6.8%	2.8%	1.8%	3.2%	1.5%	1.0%
Hgg	6.4%	2.3%	1.6%	3.0%	1.2%	0.87%
Hττ	5.7%	2.3%	1.7%	2.7%	1.2%	0.93%
Hγγ	18%	8.4%	4.0%	8.2%	4.5%	2.4%
Hμμ	-	-	16%	-	-	10%
Htt	-	14%	3.1%	-	7.8%	1.9%
Γ_0	11%	5.0%	4.6%	5.4%	2.5%	2.3%
Br(Inv)	<0.95%	<0.95%	<0.95%	0.44%	0.44%	0.44%
HHH	-	83%	21%	-	46%	13%

M_h as an input

Need further precision in δM_W to discriminate two

M. Baak

Parameter	Scenario	δ_{meas}	$\delta_{\text{pred tot (fit)}}$	$\delta_{\text{theo par}}$	δM_H	δM_Z	δm_t	$\delta \Delta\alpha^{(5)}_{\text{had}}$	$\delta\alpha_s$
			error due to uncertainty ($\pm 1\sigma$)						
	Present	15	11.0	4.0	0.2	2.6	5.2	1.8	1.7
M_W [MeV]	LHC	8	6.1	1.0	–	2.6	3.6	1.8	1.7
	ILC	5	3.6	1.0	–	2.6	0.9	0.9	0.4
	Present	16	9.5	4.7	0.2	1.5	2.8	3.5	1.0
$\sin^2\theta^{\ell}_{\text{eff}}$ (◦)	LHC	16	3.9	1.0	–	1.5	1.9	1.6	1.0
	ILC	1.3	1.2	1.0	–	1.5	0.3	1.6	0.2

(◦) In units of 10^{-5}.

If we see deviations between two, it should be a New Physics Effect.

- M_W and $\sin^2\theta^{l}_{\text{eff}}$ are (and will be) sensitive probes of new physics!

Uncertainty on M_W from Global Fit is reduced to 15 MeV w/ M_h.
[More precise than direct measurements (≈20MeV) !!]

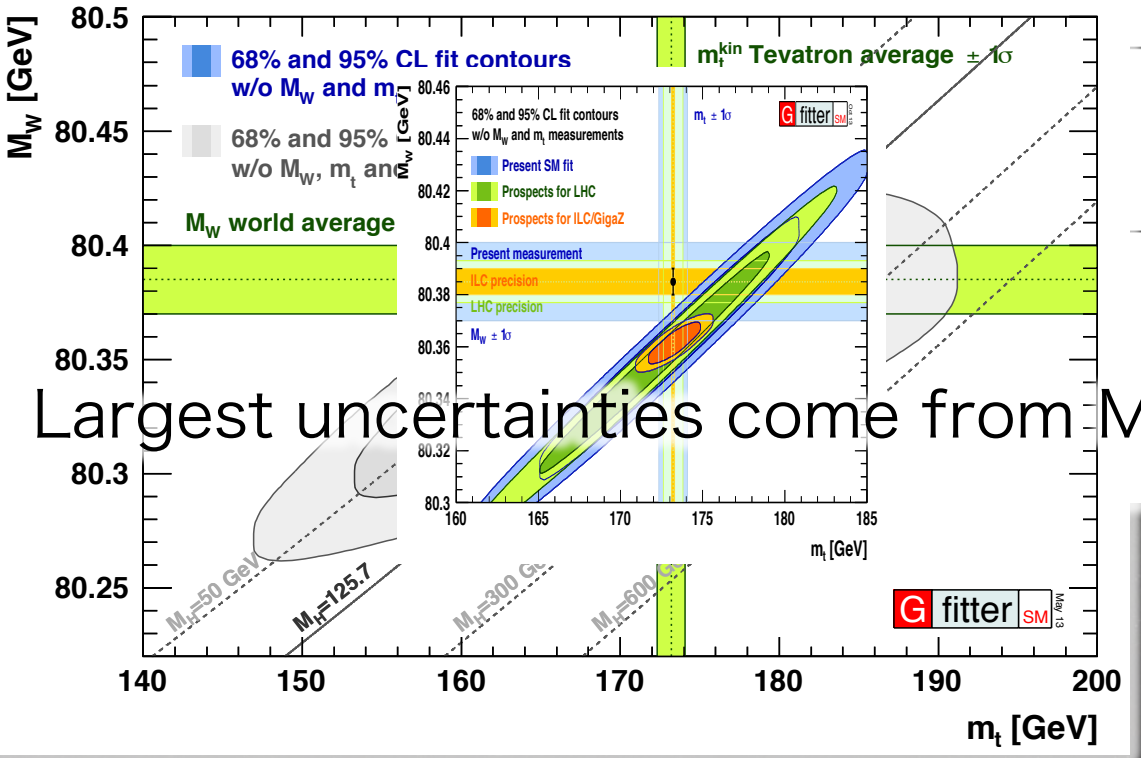
M_t as an input

M. Baak

Parameter	Scenario	δ_{meas}	$\delta_{\text{pred tot (fit)}}$	$\delta_{\text{theo par}}$	δM_H	δM_Z	δm_t	$\delta\Delta\alpha_{\text{had}}$	$\delta\alpha_s$
		error due to uncertainty ($\pm 1\sigma$)							
	Present	15	11.0	4.0	0.2	2.6	5.2	1.8	1.7
M_W [MeV]	LHC	8	6.1	1.0	–	2.6	3.0	0.9	1.7
	ILC								0.4
	Present								1.0
$\sin^2\theta^{\ell}_{\text{eff}}$ (◦)	LHC								1.0
	ILC								0.2

(◦) In units of 10^{-5}.

- M_W and $\sin^2\theta^{l}_{\text{eff}}$ a



Largest uncertainties come from M_t

Need Theorist's effort

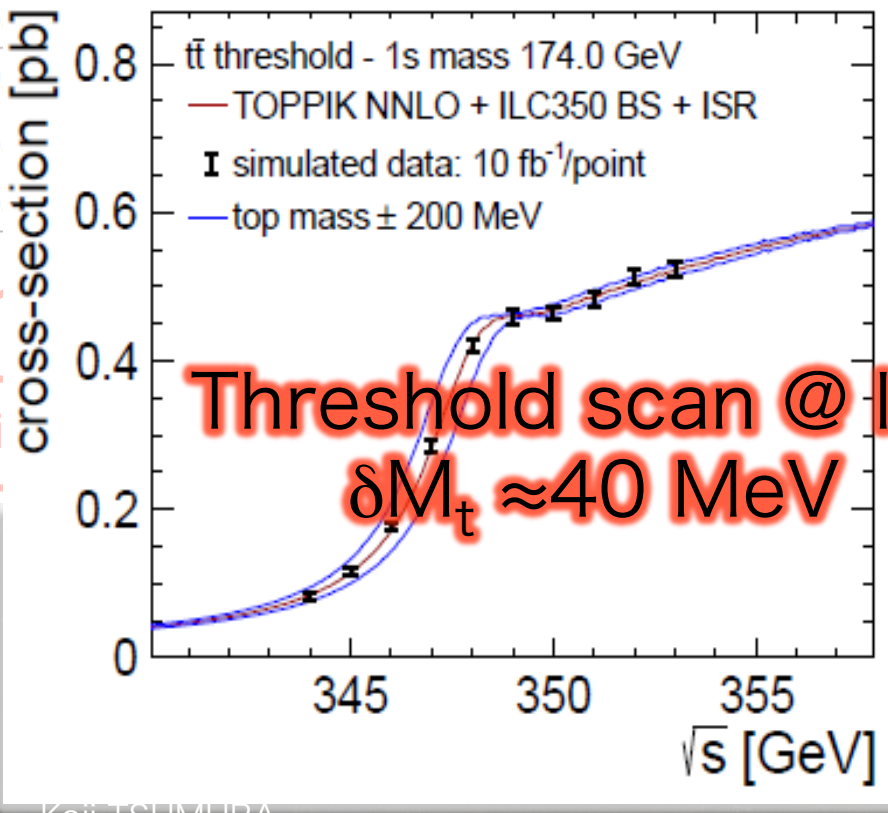
M_t as an input

M. Baak

Parameter	Scenario	δ_{meas}	$\delta_{\text{pred tot (fit)}}$	$\delta_{\text{theo par}}$	δM_H	δM_Z	δm_t	$\delta\Delta\alpha_{\text{had}}$	$\delta\alpha_s$
			err[illegible] to uncertainty ($\pm 1\sigma$)						
	Present	15	11.0	4.0	0.2	2.6	5.2	1.8	1.7
M_W [MeV]	LHC	8	6.1	[illegible]	–	2.6	[illegible]	0.9	1.7
	ILC	5	3						0.4
	Present	16	9						1.0
$\sin^2\theta^{\ell}_{\text{eff}}$ (◦)	LHC	16	3						1.0
	ILC	1.3	3						0.2

(◦) In units of 10^{-5}.

- M_W and $\sin^2\theta^{l}_{\text{eff}}$ are (and wi



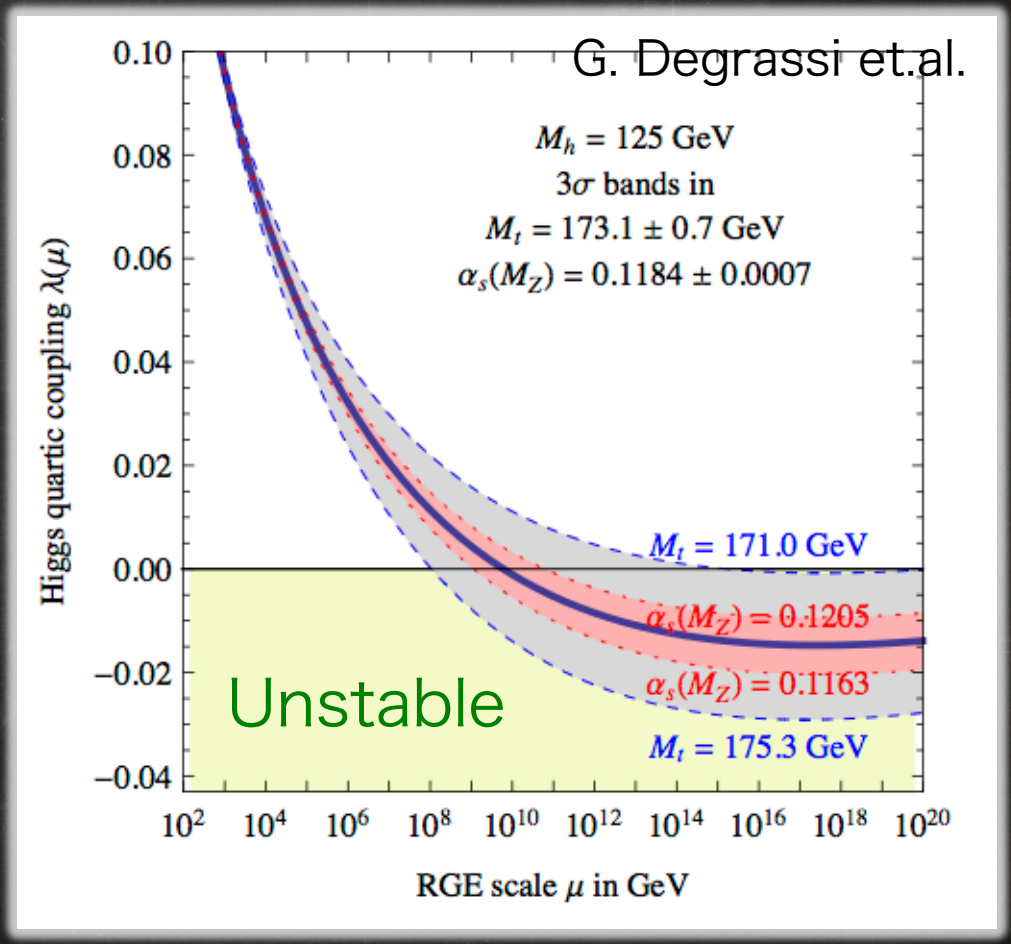
Threshold scan @ ILC
$\delta M_t \approx 40$ MeV

M_t as an input

$$16\pi^2\mu\frac{d\lambda}{d\mu} = 24\lambda^2 - 6y_t^4 + \cdots$$

To be or not to be.

Our vacuum may be unstable



To confirm our safety,
we need more accurate M_t.

Beyond the SM

Why ? Where is it ?

What is the Beyond SM ?

The SM is now completed.

What is the mechanism for charge quantization ? GUT?

PQ sym.? Why does the strong interaction not break CP ?

What is the correct theory of neutrino mass ? Seesaw?

What is the mechanism that led to baryon asymmetry ?

Leptogenesis?
EW baryogenesis?

What is dark matter ? WIMP? Axion?

Cosmological const.? What is dark energy ?

What was the mechanism of cosmic inflation? Inflaton?

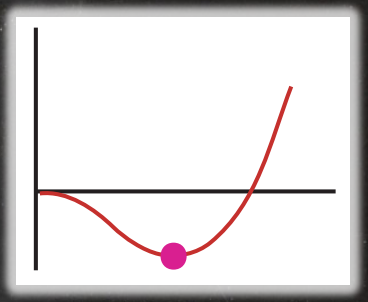
TOE? How are the four forces and matter unified ?

How can gravity be quantized ? String?

…

viXtra.org

No Principle at all !!



Why $\mu^2<0$?

Are there any underlying dynamics ?

Fine-tuning $\delta m_h^2 \approx \Lambda^2$?

Why is the Higgs so light ?

Minimal Higgs sector ?

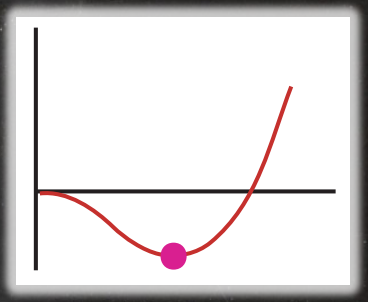
Why does the nature choose one doublet ?

$$\mathcal{L} = -\left[+\mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2\right] + \left[+Y_{ij} F_L f_R \Phi + \text{H.c.}\right]$$

Dynamical Symmetry Breaking

Why $\mu^2<0$?

Are there any underlying dynamics ?



No reason!!

Dynamics

[BCS theory for superconductors]

Attractive force → cooper-pair → symmetry breaking

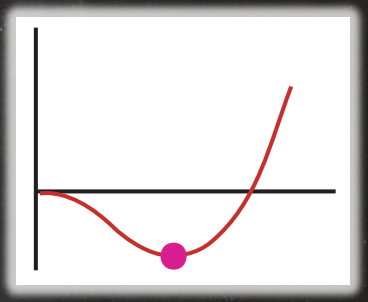
[Chiral symmetry breaking]

QCD → $q\bar{q}$ condensate → symmetry breaking

EW Symmetry Breaking

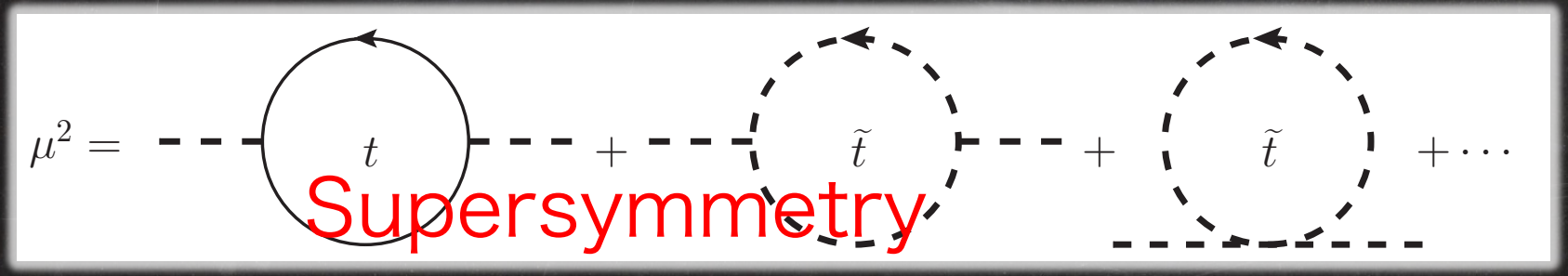
Why $\mu^2<0$?

Are there any underlying dynamics ?



No reason!!

Dynamics



$\mu^2<0$ is induced from radiative corrections (dynamically)

EW Symmetry Breaking

Why $\mu^2<0$?

Are there any underlying dynamics ?

No reason!!

Dynamics

To have a dynamical sym. breaking, new particle/interaction is needed.

Little Higgs, ⋯

$\mu^2<0$ is induced from radiative corrections (dynamically)

Is the Higgs mass natural ?

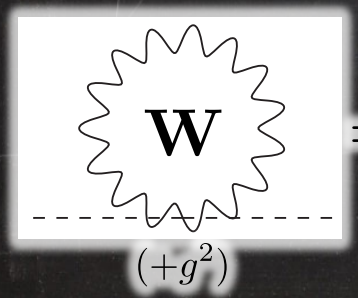
Fine-tuning $\delta m_h^2 \approx \Lambda^2$?

Why is the Higgs so light ?

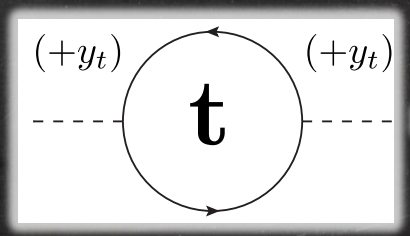
$$m_h^2 \ll\ll\ll\ll\ll \Lambda^2$$

$$(125\,\mathrm{GeV})^2 \qquad M_{\mathrm{GUT}}^2 \simeq (10^{16}\,\mathrm{GeV})^2$$

Quantum corrections to the Higgs mass



$$= (+g^2)\,\Lambda^2$$



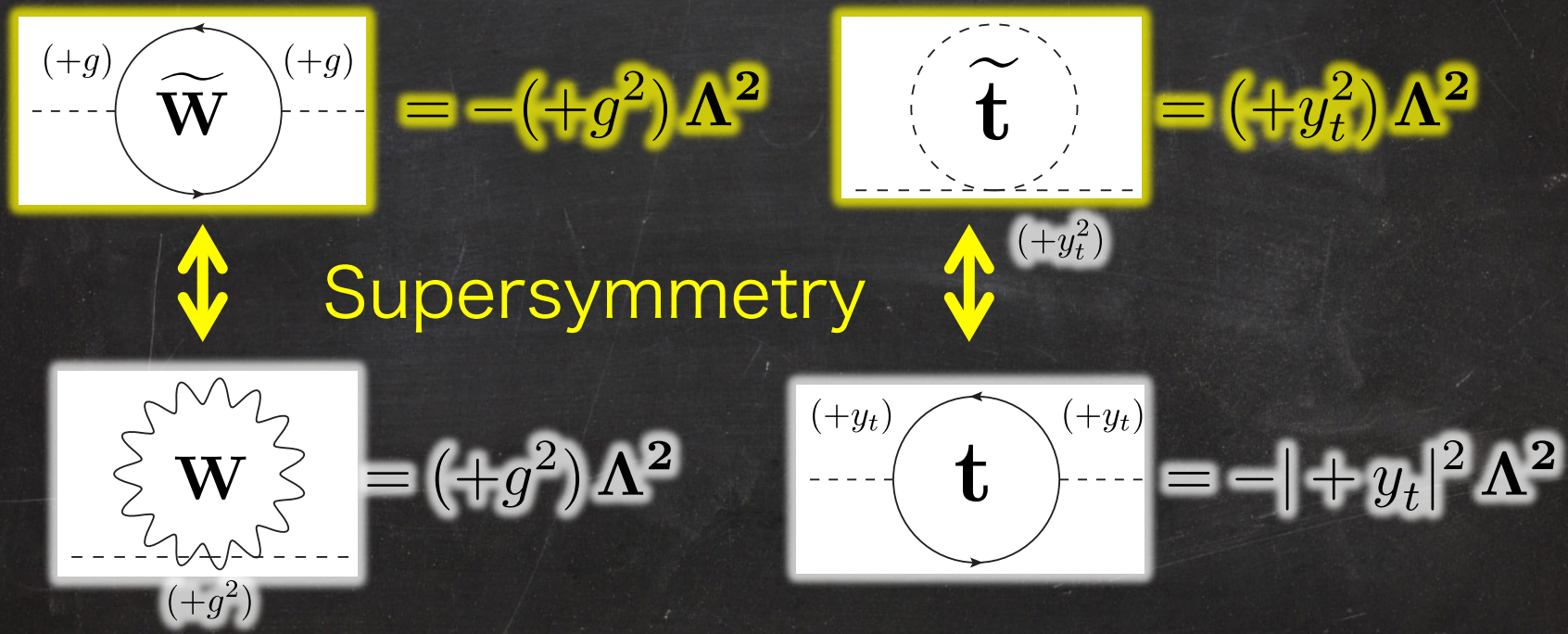
$$= -|+y_t|^2\,\Lambda^2$$

Unnatural (cancellation w/ counter terms)

Is the Higgs mass natural ?

Fine-tuning $\delta m_h^2 \approx \Lambda^2$?

Why is the Higgs so light ?

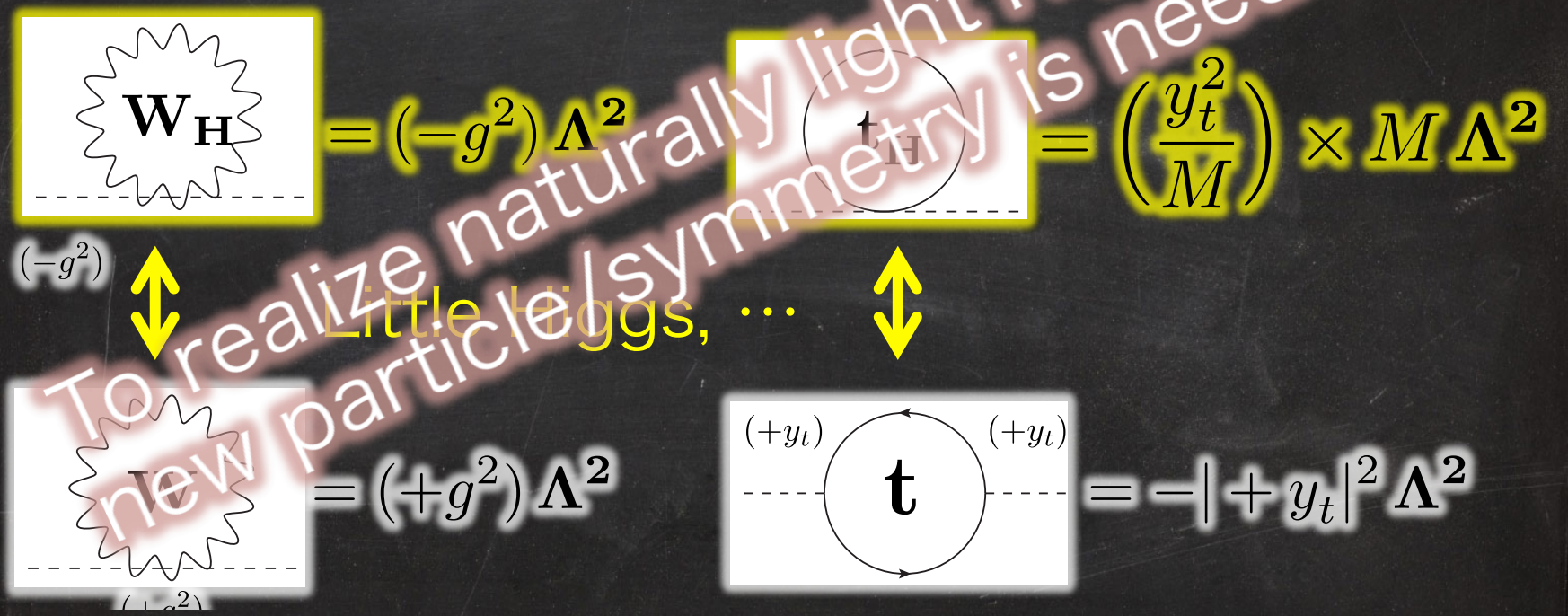


SUSY holds naturally light Higgs mass

Is the Higgs mass natural ?

Fine-tuning $\delta m_h^2 \approx \Lambda^2$?

Why is the Higgs so light ?



To realize naturally light Higgs, new particle/symmetry is needed.

There can be mixing with partners of Gauge bosons, top quarks.
Precision EW and top studies are necessary.

Non-minimal Higgs sector ?

Most likely to be a doublet,
but possible mixing w/ other multiplets

Additional Higgs bosons are introduced !!
H, A, H^+, H^{++}, ⋯

SM-like Higgs couplings deviate from SM

Extended Gauge sym.

Singlet
Additional doublet
Triplet
SUSY
⋯
Septet
⋯

Neutrino mass

Not yet thought of

$$\mathcal{L} = + \left| D_\mu \Phi \right|^2 - \left[+ \mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2 \right]$$
$$+ \left[+ Y_{ij} F_L f_R \Phi + \mathrm{H.c.} \right]$$

Minimality?

Non-minimal Higgs sector ?

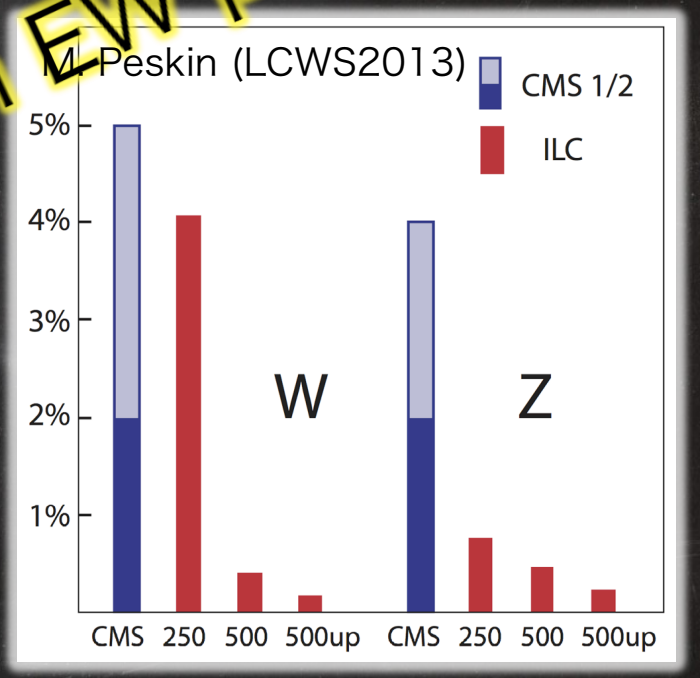
Most likely to be a doublet,
but possible mixing w/ other multiplets

Additional Higgs bosons are introduced
H, A, H^+, H^{++}, ⋯

SM-like Higgs couplings deviate from SM

$$\frac{\delta\lambda_x}{\lambda_x} \simeq \frac{m_h^2}{M^2}$$

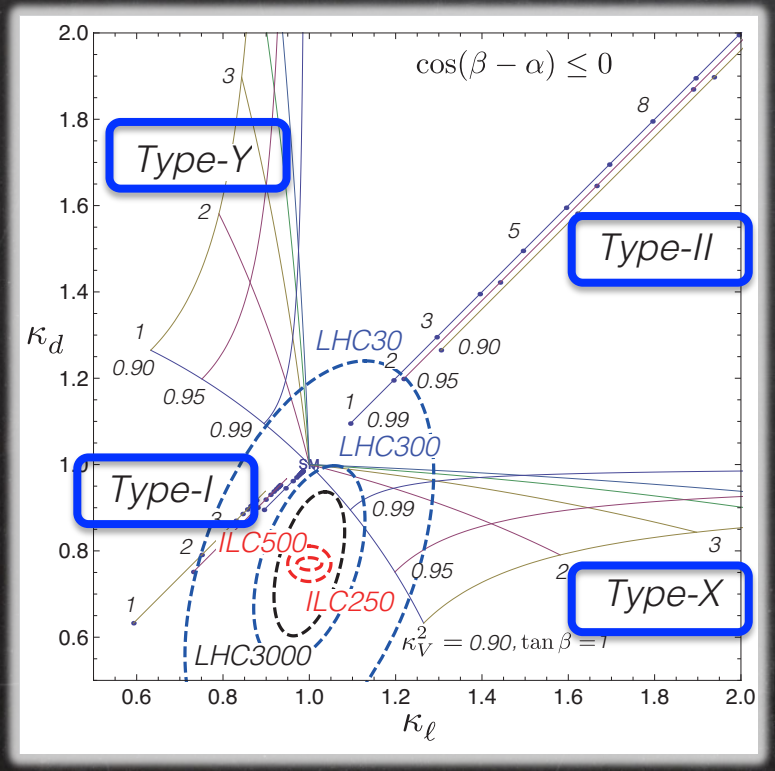
Remember successes in EW precision



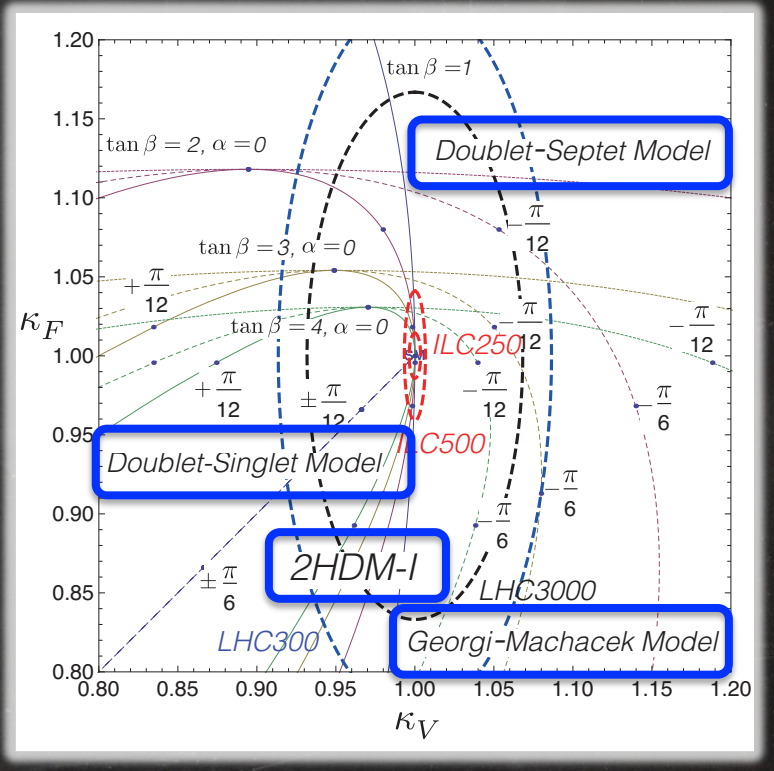
At least 1 % precision for M>1TeV (M is a new Higgs scale)
[pre-factor: loop suppression, tanβ enhancement, non-decoupling effect]

Model discrimination

$hb\bar{b}$



$hf\bar{f}$

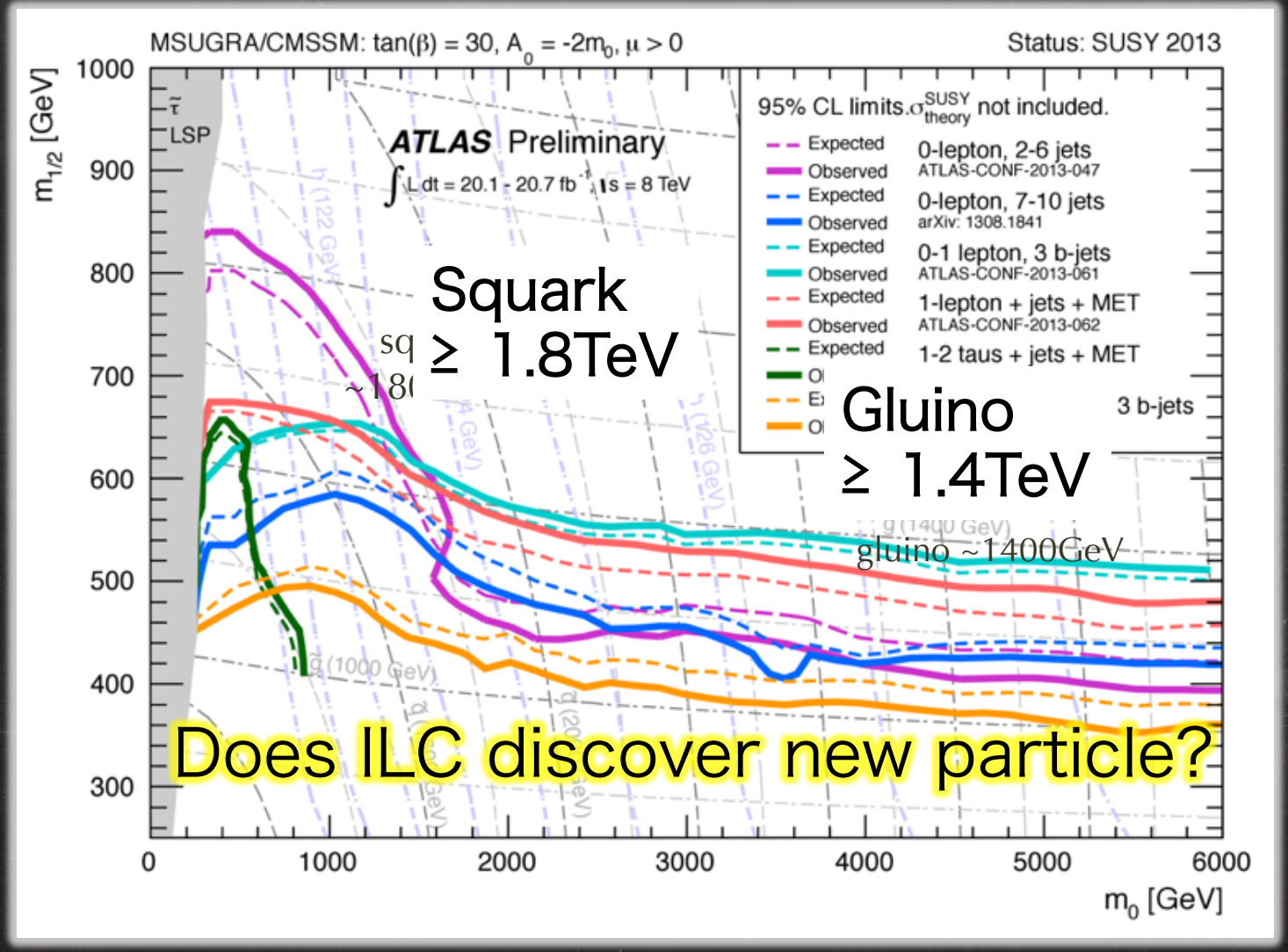


$h\tau\bar{\tau}$

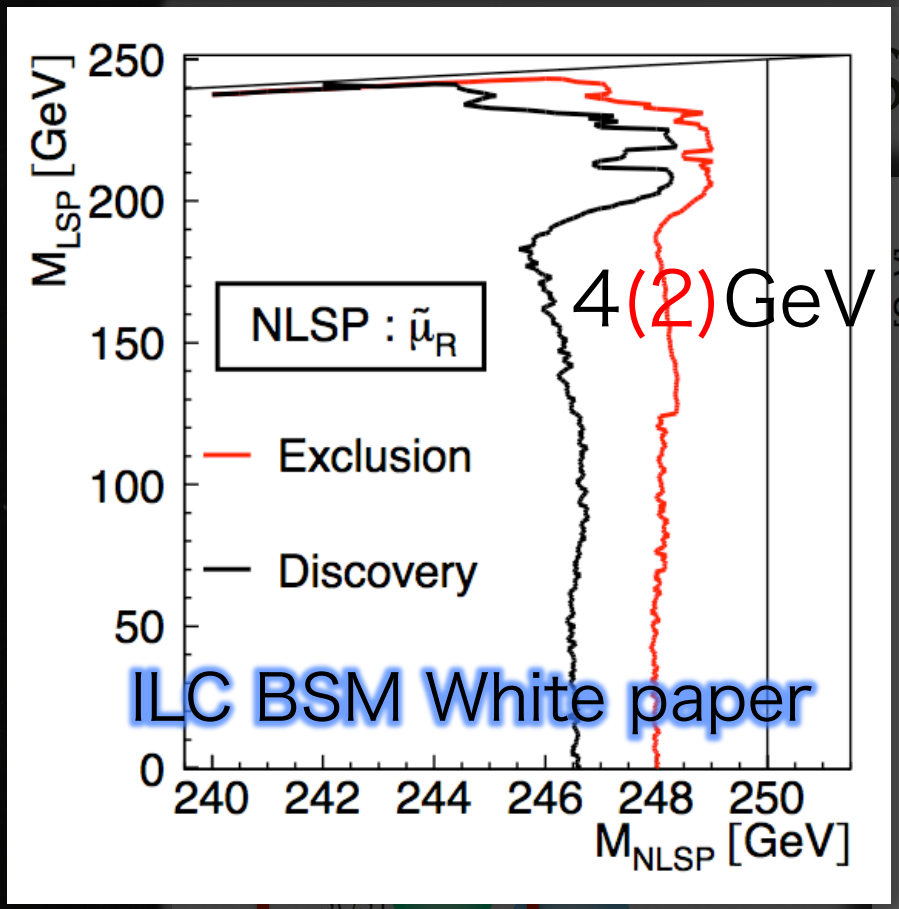
hVV

So far, No New Physics.

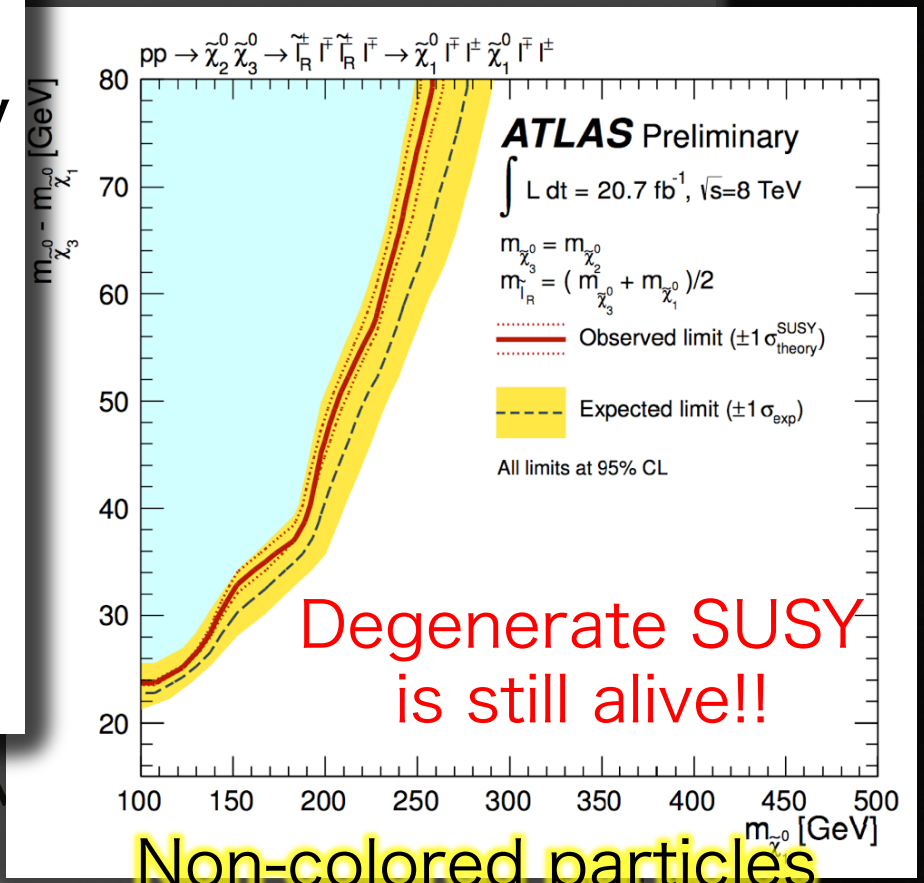
SUSY confronts LHC data



Light or Heavy SUSY?



Y theorists



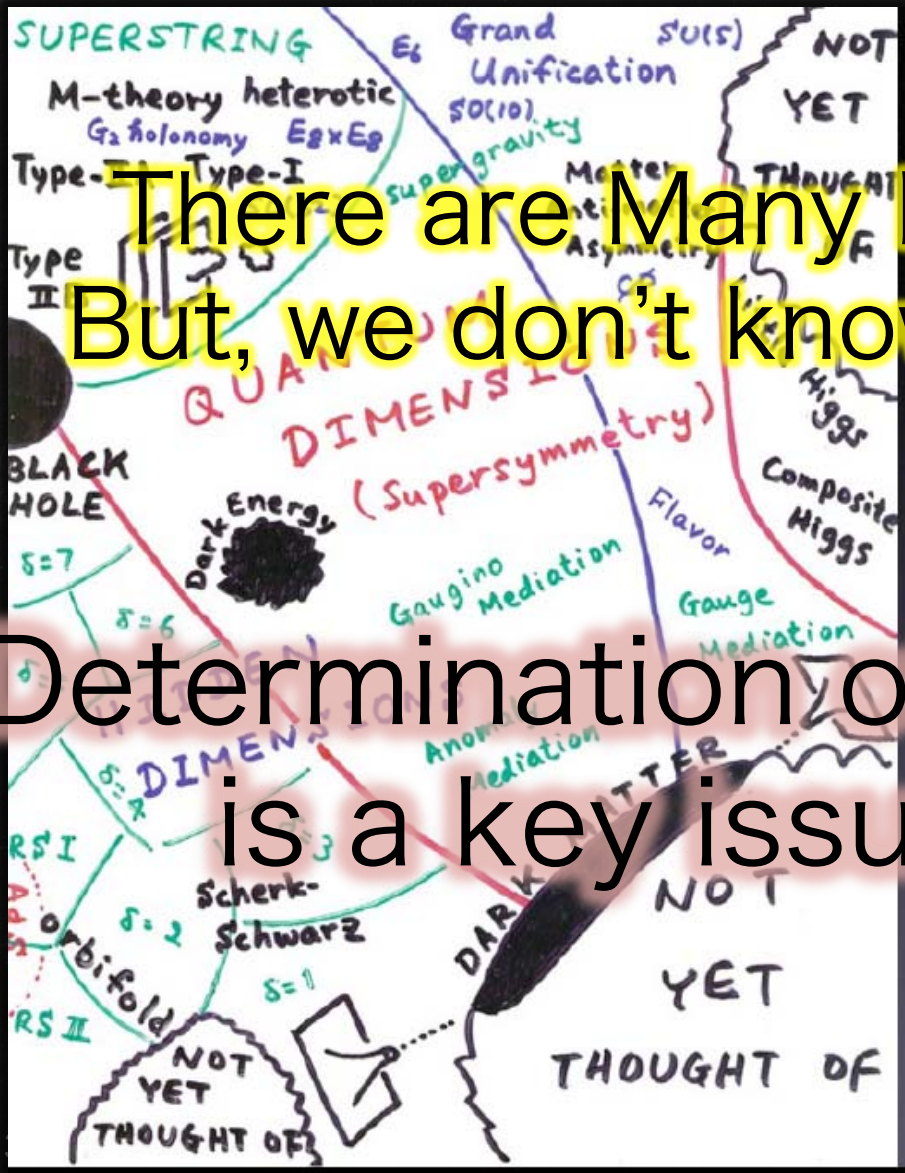
Lot's of

R parity
violation

Non-colored particles
are still targets @ ILC

M. Nojiri

New Physics Zoo



There are Many Motivations.
But, we don't know where is it.

Determination of New Scale is a key issue @ ILC

- We really don't know what is going on at TeV
- stupid theorists!
- Can we zoom in onto a point on this map?
- Expect the unexpected

H. Murayama

ILC Physics

ILC Physics

Any Deviations
= New Physics

Precision Higgs/top/EW study

- Model independent determination of Higgs couplings (%-level)
  - Invisible(exotic) Higgs decay / Total width
  - Precise determination of M_W (few MeV)
  - Improvement of Triple Gauge coupling measurement
  - Precise determination of M_t (100 MeV)
  - Precision measurement of top coupling (incl. rare decay)
  - Improvement of α_s @ Giga-Z
  - Higgs self-coupling measurement
    (experimental reconstruction of Higgs potential)

Search for New Particles in LHC blind spots

- Light EW new particle (Higgsino, new Higgs, DM)
  - Follow up any discovery @ LHC

Summary

Any Deviations
= New Physics

Precision Higgs/top/EW study

- Model independent determination of Higgs couplings (%-level) Ono Kawada Calancha Tian
  - Invisible(exotic) Higgs decay / Total width Watanuki Tomita Ishikawa
  - Precise determination of M_W (few MeV)
  - Improvement of Triple Gauge coupling measurement
  - Precise determination of M_t (100 MeV) Horiguchi
- Precision measurement of top coupling (incl. rare decay)
  - Improvement of α_s @ Giga-Z
  - Higgs self-coupling measurement Kurata

(experimental reconstruction of Higgs potential)

Search for New Particles in LHC blind spots

- Light EW new particle (Higgsino, new Higgs, DM) Tanabe Mori
  - Follow up any discovery @ LHC

Summary

Summary~~Plan~~ of my talk

STATUS

Where are we?

New Era of the SM

What we need to do?

Physics Beyond the SM

Why? Where is it?

ILC Physics

What do we do?

A Higgs boson is confirmed.

No New Physics, so far.

Precision measurement of h, t, W/Z.

(Direct search for New Physics).

Indirect search for New Physics.

Higgs forces are totally unknown !!

SM is NOT satisfactory…

(ν, DM, DE, Baryogenesis, inflation, GUT, string,…)

We don't know the scale.

Determination of New Scale is a key issue @ ILC.

Thank you for your attention