Physics at the ILC

A theory perspective

Koji TSUMURA (Kyoto U.)

ILD Meeting 2014

6-9 Sep. 2014, Oshu, Iwate, Japan

Higgs 2014

Citation: K.A. Olive *et al.* (Particle Data Group), Chin. Phys. **C38**, 090001 (2014) (URL: http://pdg.lbl.gov)

H^0 $J = 0$

Mass $m = 125.7 \pm 0.4$ GeV

H^0 Signal Strengths in Different Channels

Combined Final States $= 1.17 \pm 0.17$ (S = 1.2)

$WW^* = 0.87^{+0.24}_{-0.22}$

$ZZ^* = 1.11^{+0.34}_{-0.28}$ (S = 1.3)

$\gamma\gamma = 1.58^{+0.27}_{-0.23}$

$b\overline{b} = 1.1 \pm 0.5$

$\tau^+\tau^- = 0.4 \pm 0.6$

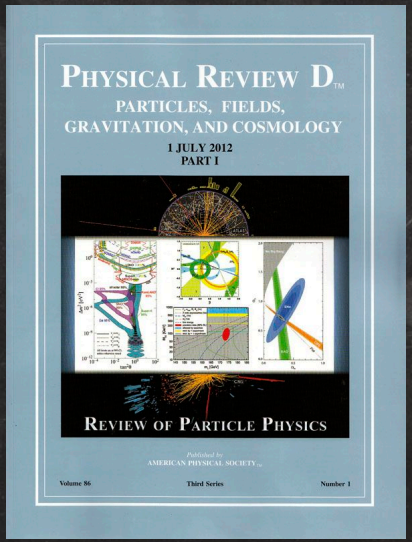
$Z\gamma <$ 9.5, CL = 95%

(Not yet included in PDG2014)

Diphoton-Excess : > 2σ → 1σ

Discrepancy of Mh in ZZ & γγ : 2.5 σ → within 2σ

Fermionic decay channels (ττ & bb) : 2σ → > 4σ



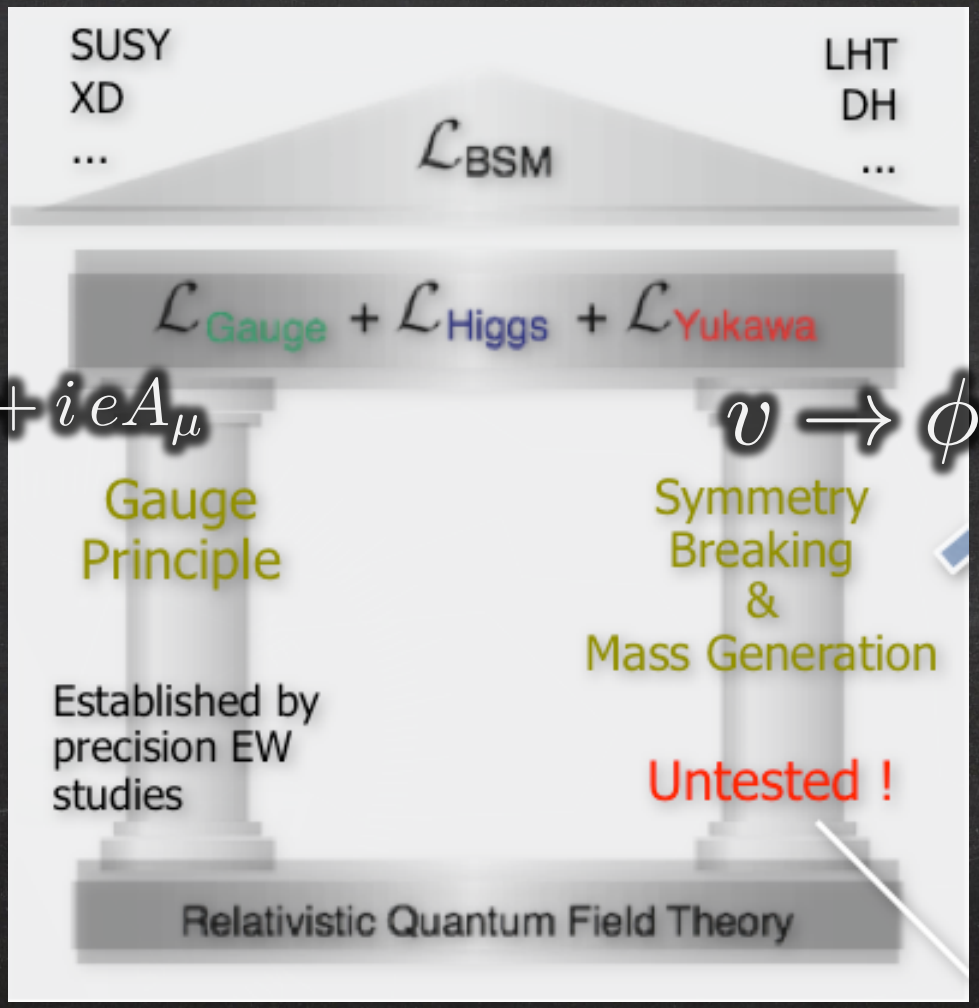
Plan

- Gauge force vs Higgs force
- Mysteries of EW sym. Breaking
  - Higgs, top, New Physics
- Naturalness Revisited
- EW / TeV scale and Decoupling
- Summary

2 pillars in SM

Gauge Force

$$\partial_\mu \to D_\mu = \partial_\mu + ieA_\mu$$



Higgs Force

$$v \to \phi \sim v + h$$

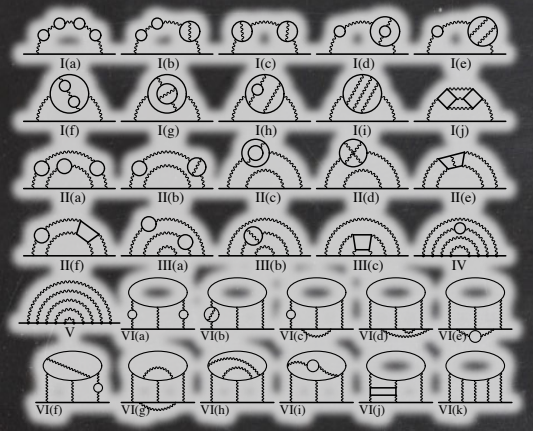
K. Fujii

Gauge Force

$$\partial_\mu \rightarrow D_\mu = \partial_\mu + i\,e A_\mu$$

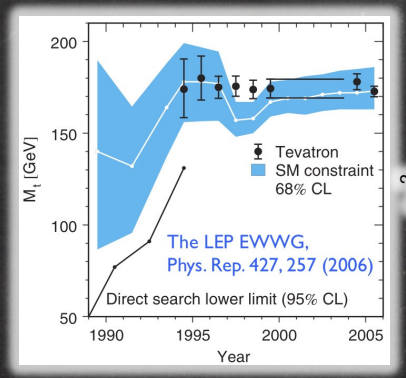
Very well-established !!

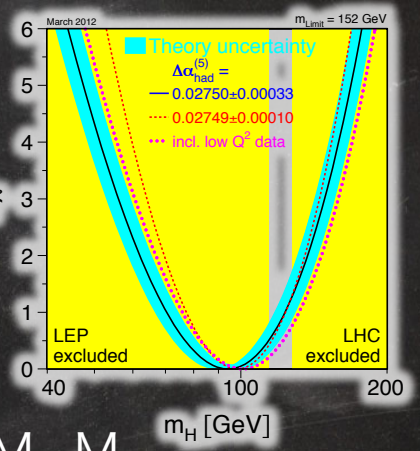
QED 10th order



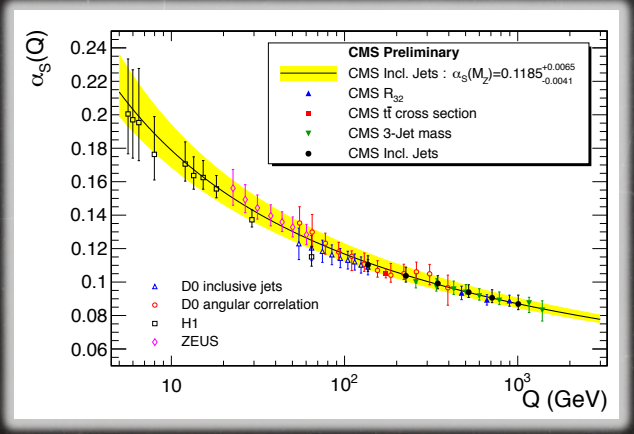
W, Z, h, t, b, NP

EWPT (1-loop)





Predict M_t, M_h



pQCD ≥1TeV (LHC)

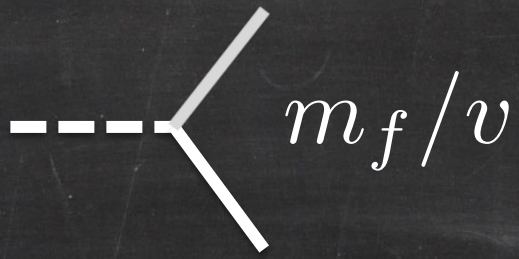
Higgs Force $v \to \phi \sim v + h$

What is the origin of mass ?

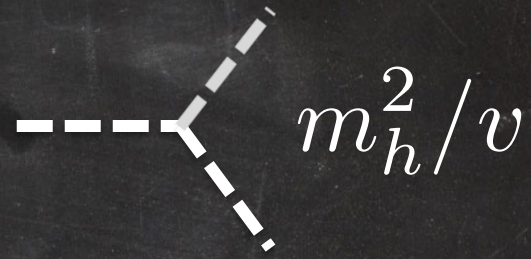
Higgs mechanism ? Fermion Mass hierarchy, mixing, CP violation ?

Higgs mechanism

Normalization
of Higgs coupling



Yukawa interaction



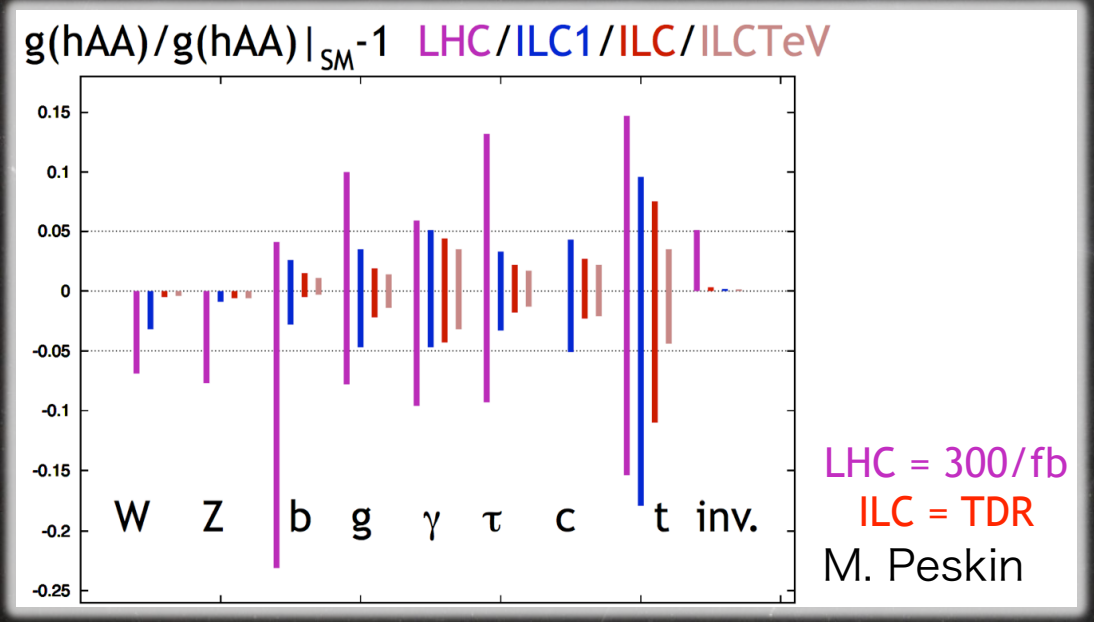
Higgs self-interaction

(New) non-Gauge force

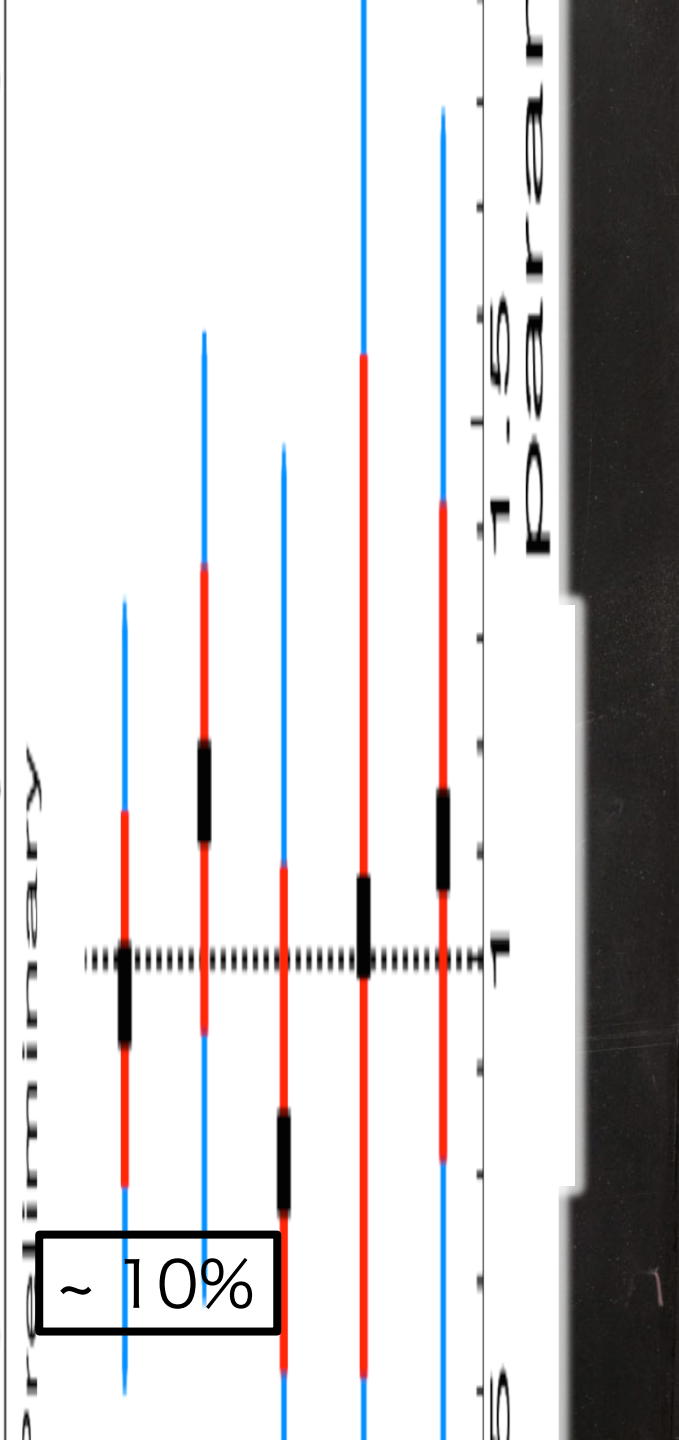
Higgs Force $v \to \phi \sim v$

What is the origin o

Higgs mechanism ? Fermion Mass hierarchy,



~ 0.1%

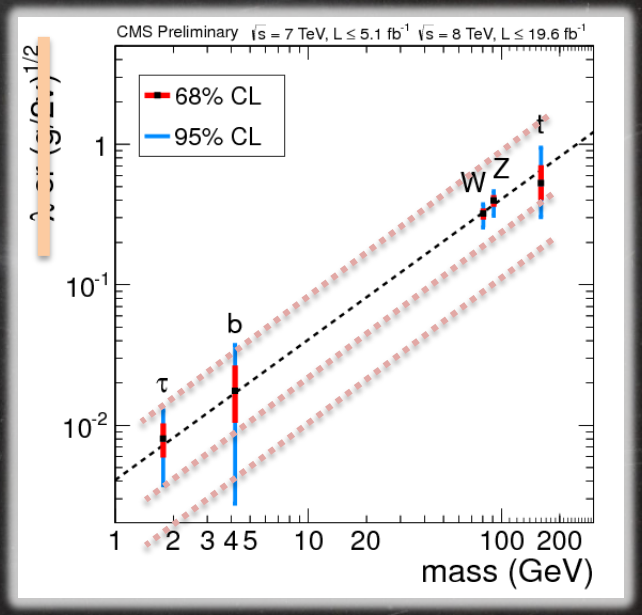


Higgs Force $v \to \phi \sim v + h$

What is the origin of mass ?

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

Actually, LHC only see ratios of BRs !!



Direct measurement of Total Width of h

(Experimental reconstruction)

$$Y_1 = \sigma_{ZH} = F_1 \cdot g^2_{HZZ}$$ Recoil !!

$$Y_2 = \sigma_{ZH} \times \mathrm{Br}(H \to b\bar{b}) = F_2 \cdot \frac{g^2_{HZZ} g^2_{Hb\bar{b}}}{\Gamma_T}$$

$$Y_3 = \sigma_{\nu\bar{\nu}H} \times \mathrm{Br}(H \to b\bar{b}) = F_3 \cdot \frac{g^2_{HWW} g^2_{Hb\bar{b}}}{\Gamma_T}$$

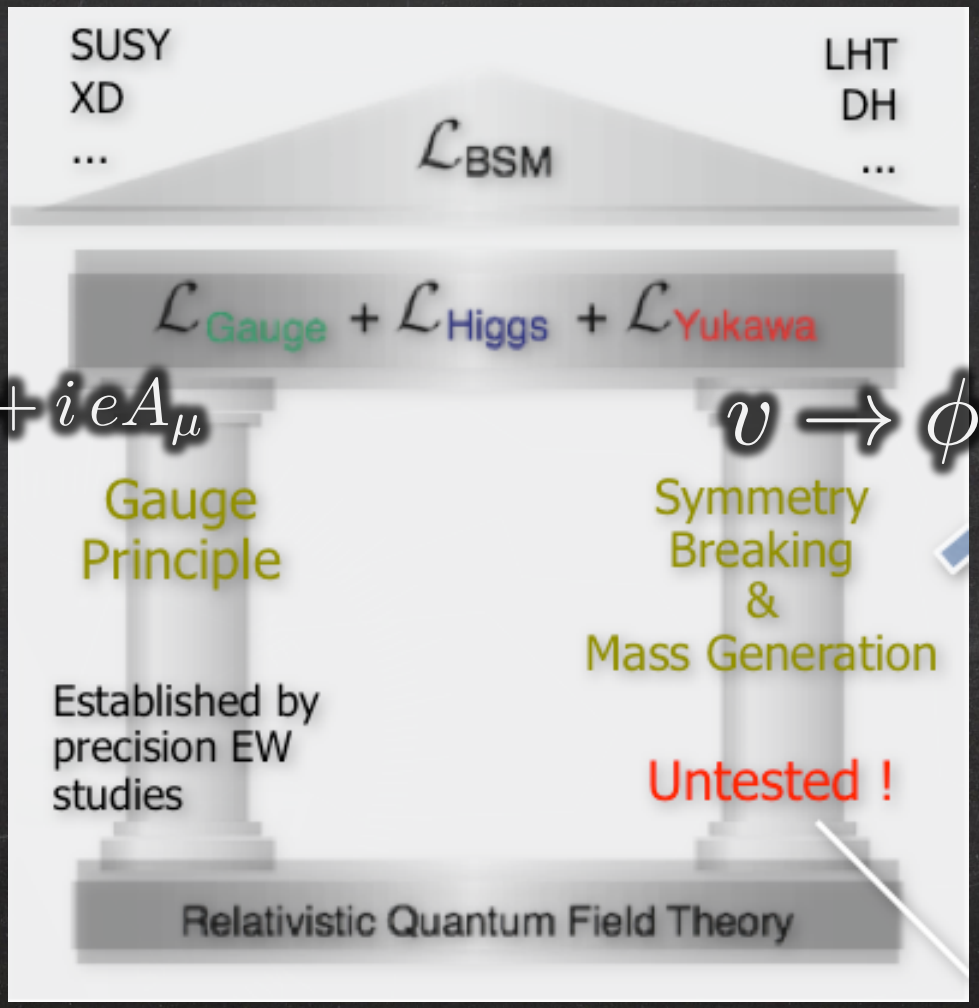
$$Y_4 = \sigma_{\nu\bar{\nu}H} \times \mathrm{Br}(H \to WW^*) = F_4 \cdot \frac{g^4_{HWW}}{\Gamma_T}$$

2 pillars in SM

Gauge Force

$$\partial_\mu \to D_\mu = \partial_\mu + ieA_\mu$$

~0.1% (1-loop)



Higgs Force

$$v \to \phi \sim v + h$$

~10%

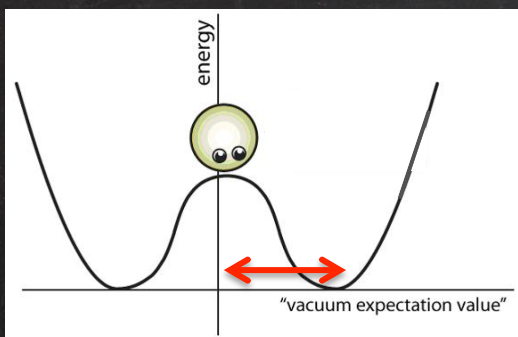
~0.1%
+ Total width

Any deviation form the SM could be understood as NP

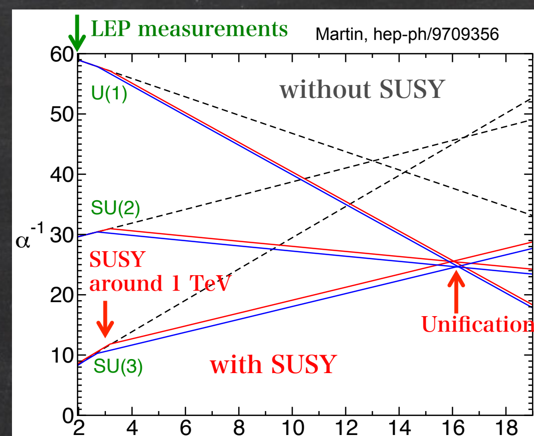
Mysteries of EWSB

Where does the EW scale come from?

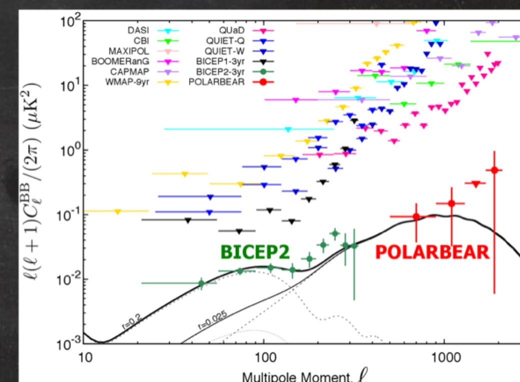
EW scale : v ~ 246 GeV



GUT : M_{GUT} ~ 10^{16} GeV



Planck : M_{Pl} ~ 10^{19} GeV



Unif. of EW and strong
Unif. of Matter

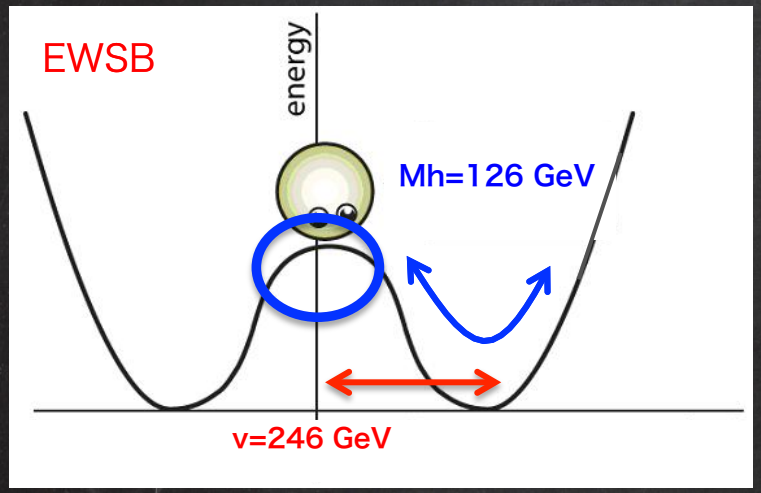
Unif. of Gauge and Gravity

10^2 <<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<< 10^{16} 10^{19}

Hierarchy

Mysteries in Higgs sector

(Within the SM,) Precise value of M_h fixes Curvature



- ✓ Input for all Higgs BR & xsec !!
- ✓ Input for RGE analysis !!

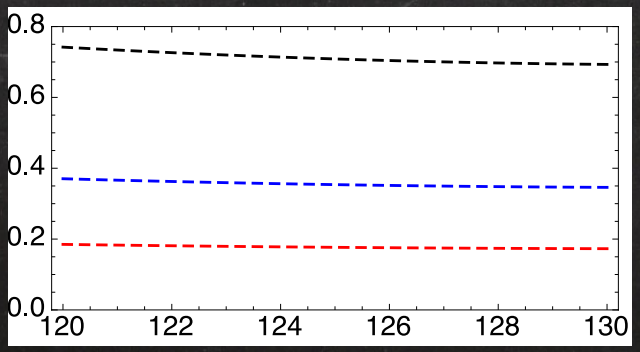
$$\frac{d\lambda}{d\ln\mu} = \frac{3}{8\pi^2}\left[\lambda^2 + \lambda y_t^2 - y_t^4 + \cdots\right]$$

Least Requirement : as low as M_t error

"Off-shell"

$$\left|\frac{\Delta\Gamma_{WW^*}}{\Gamma_{WW^*}}\right| [\%]$$

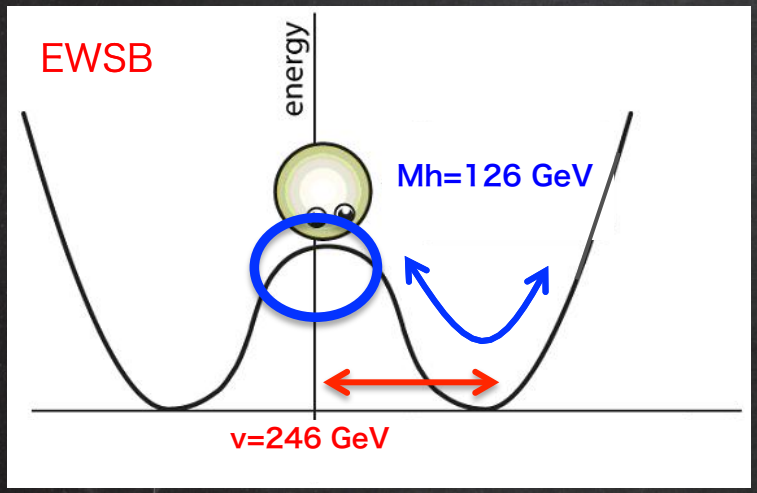
- Tree-level
- Neglect W width & fermion masses



$$M_h^2 = 2\lambda v^2$$

Mysteries in Higgs sector

(Within the SM,) Precise value of M_h fixes Curvature



Higgs precision (SUSY)

$$M_h^2 \simeq M_Z^2 + \frac{3G_F M_t^4}{\sqrt{2}\pi^2}\left[\log\frac{M_{\tilde{t}}^2}{M_t^2} + \frac{X_t^2}{M_{\tilde{t}}^2} - \frac{X_t^4}{12M_{\tilde{t}}^4}\right]$$

Accurate M_h, M_t → New Physics

Least Requirement : as low as M_t error

EW precision

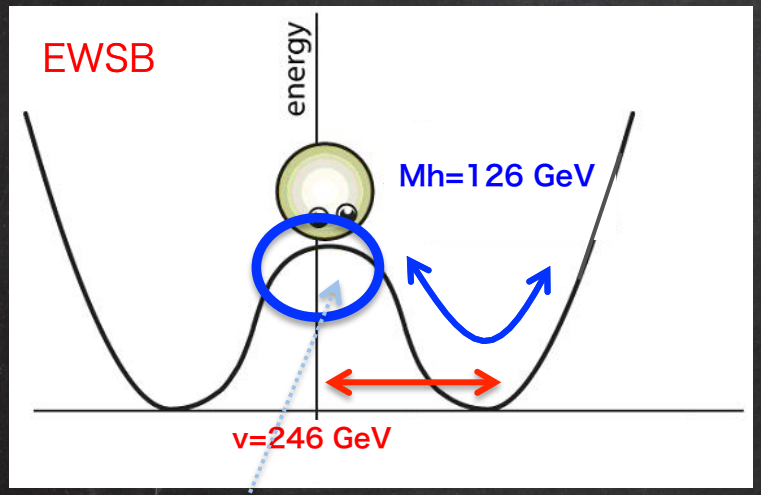
Accurate ρ → Predict M_t

Accurate ρ + M_t → Predict M_h

$$\delta\rho \simeq \frac{3G_F M_t^2}{8\sqrt{2}\pi^2} - \frac{3G_F M_Z^2 s_W^2}{8\sqrt{2}\pi^2}\left[\log\frac{M_h^2}{M_W^2} - \frac{5}{6}\right]$$

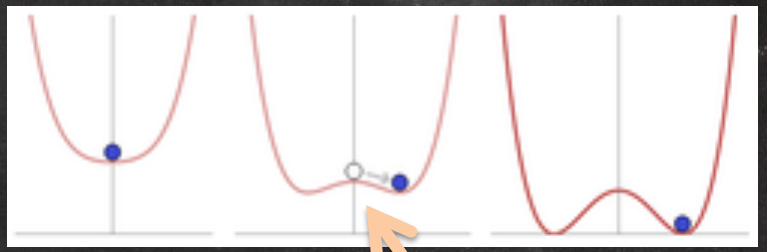
Mysteries in Higgs sector

What is the trigger of EWSB ?



Analog to "Natural theories"

- BCS theo. for superconductivity
- Chiral sym. breaking in QCD



Quantum effect

What is the origin of $\mu^2 < 0$?

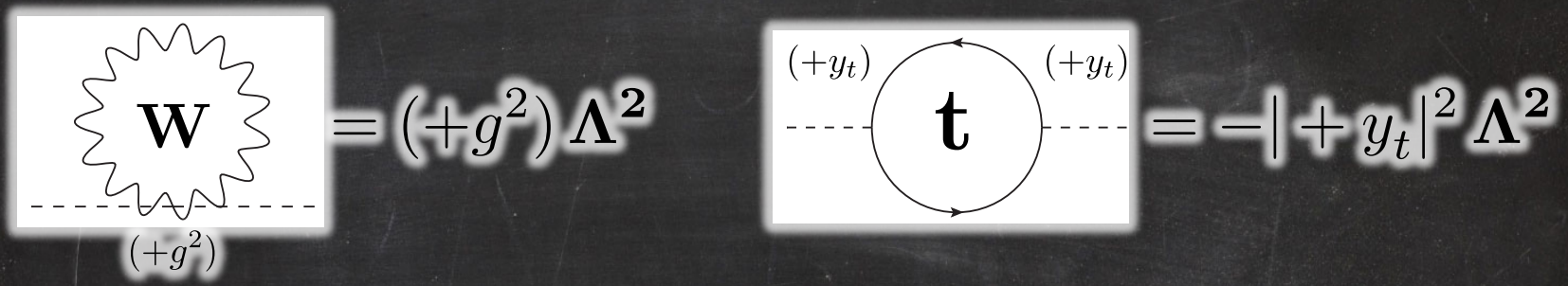
→ Dynamical EWSB from New Physics

- SM (+conformal sym.)
- SUSY (supersymmetry)
- Composite Higgs (some global sym.)
- Gauge-Higgs Unif. (gauge sym.)

Mysteries in Higgs sector

Fine-tuning problem is solved at the same time !!

Without mechanism M_h tends to be heavy : Naturalness Problem $\delta M_h^2 \approx \Lambda^2$



Key : $\delta M_h^2 \approx 0$ by sym.

What is the origin of $\mu^2 < 0$?

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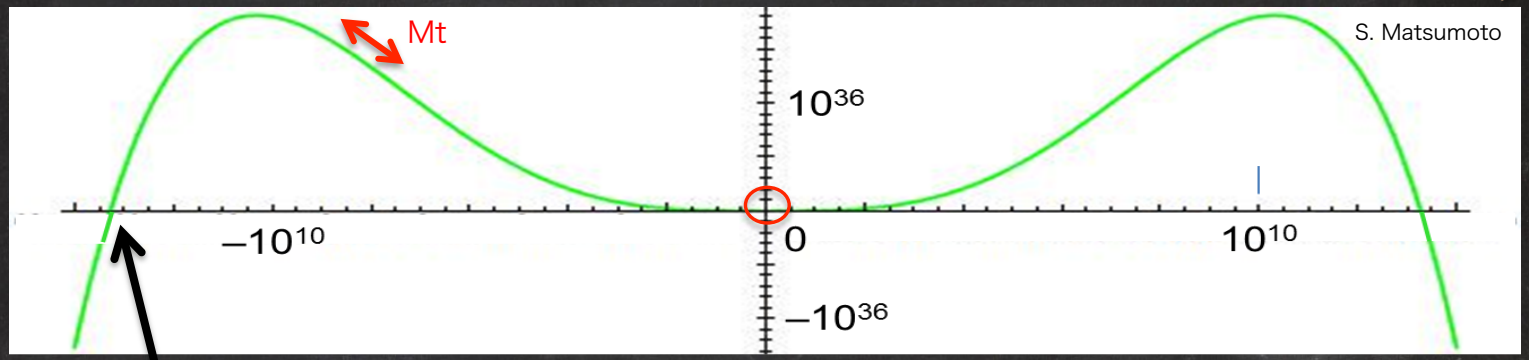
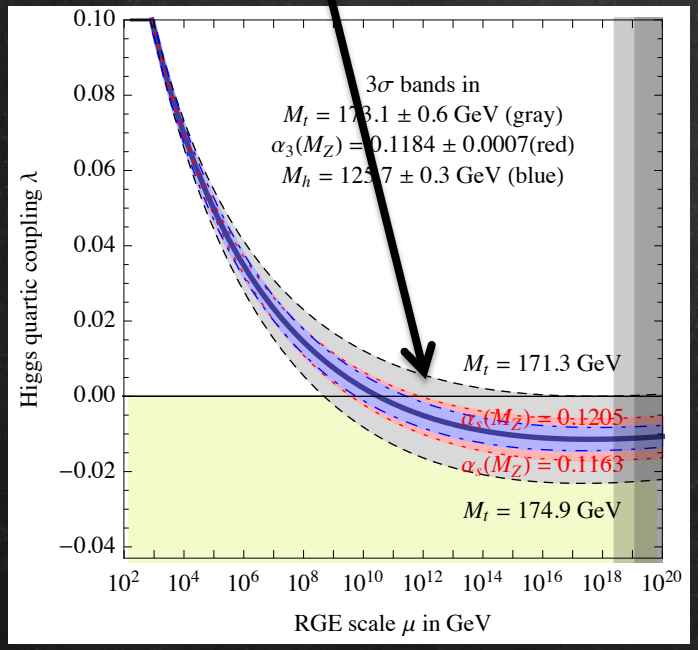
Higgs potential Stability

Precise value of Mt measures the stability of Higgs pot.

Flat potential (λ~0) suggests inflation?



Mt=174.34, Mh=126GeV



Gravity (String) scale ?

Does SM valid up to Planck?

Precise value of Mt measures the stability of Higgs pot.

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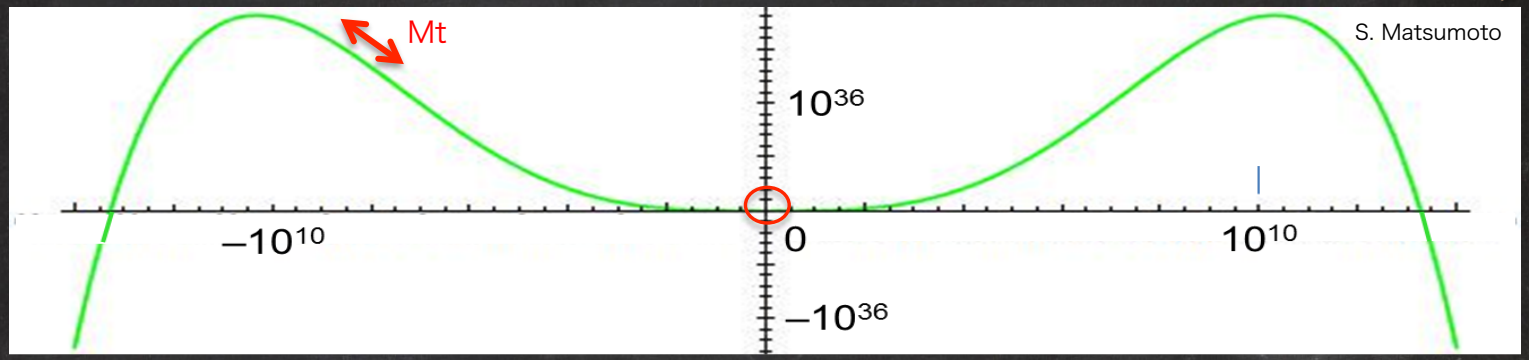

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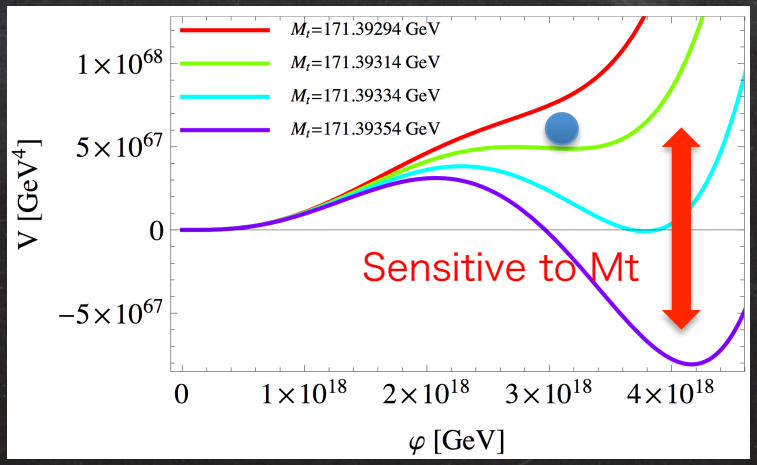

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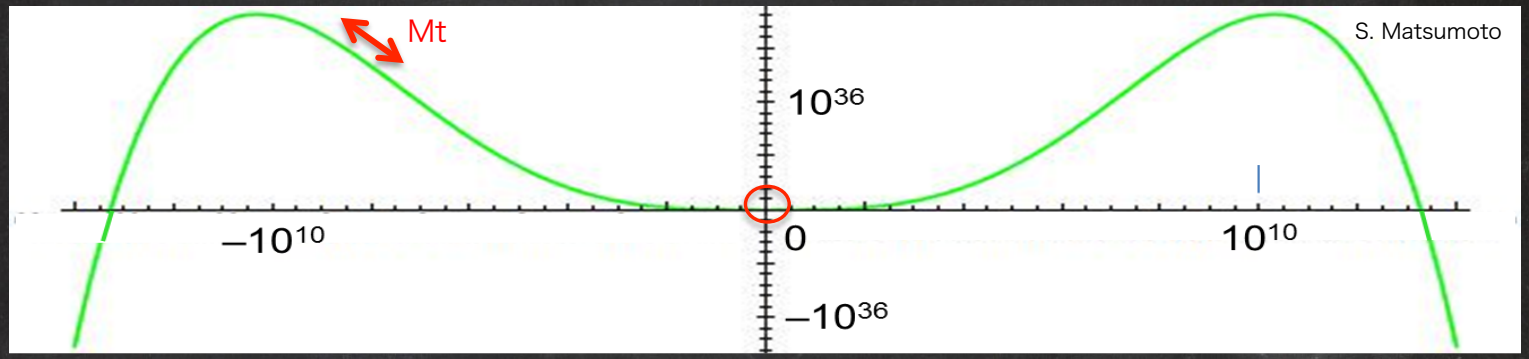

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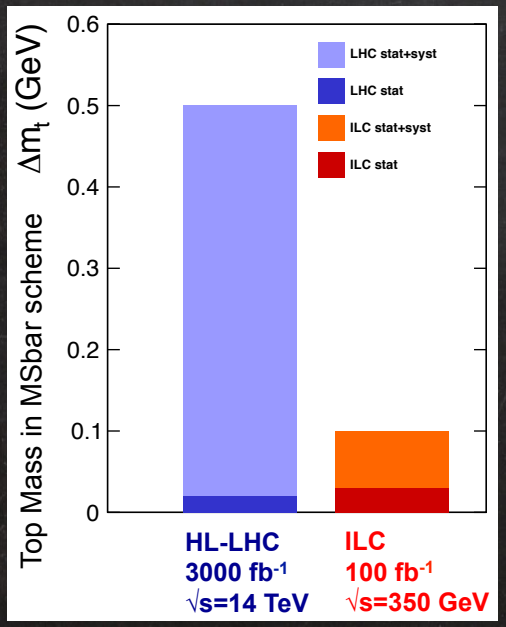

Required precision depends on central value of Mt

Least Requirement : as low as m_h & α_s errors
[ΔMt < 300 MeV from current errors]

Indirect search for New Physics

Model independent search

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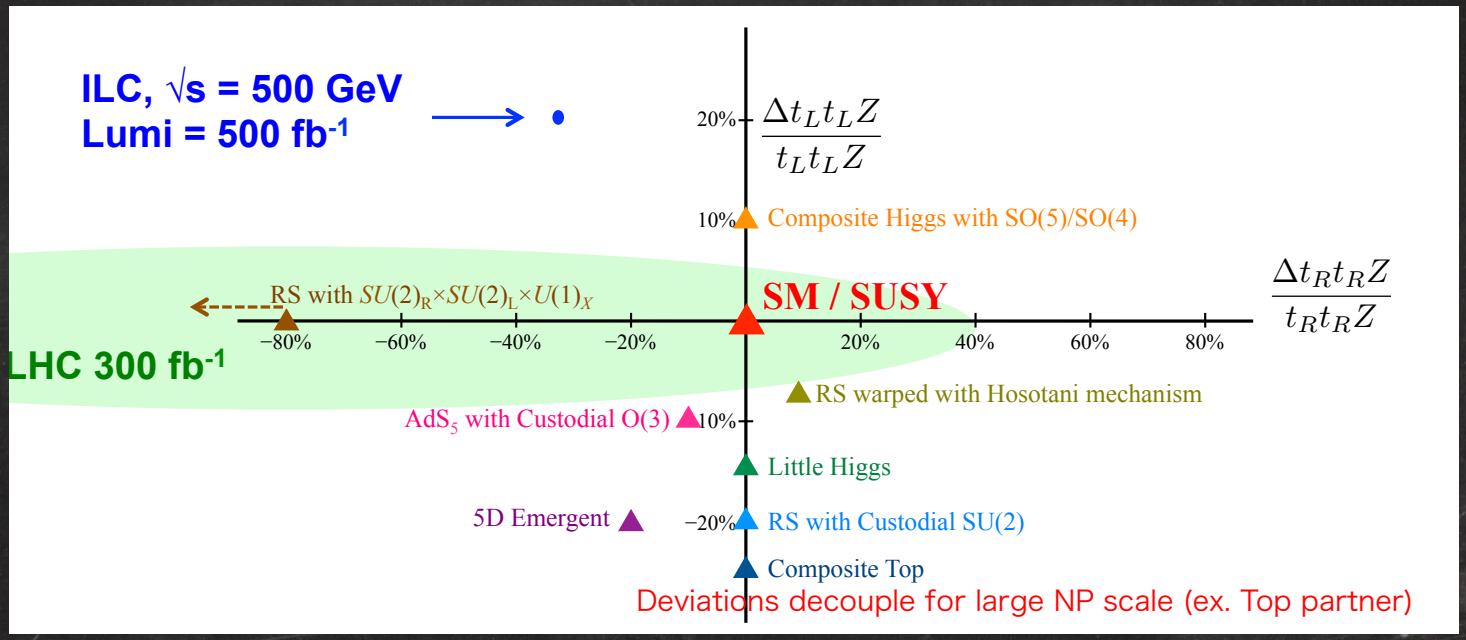
EWSB and top

Top as a probe of Composite Higgs

(motivated by QCD-like strong dynamics)



- ✓ Anomalous top coupling measurement
- ✓ Top FCNC decay (ex. t→cZ, t→ch)

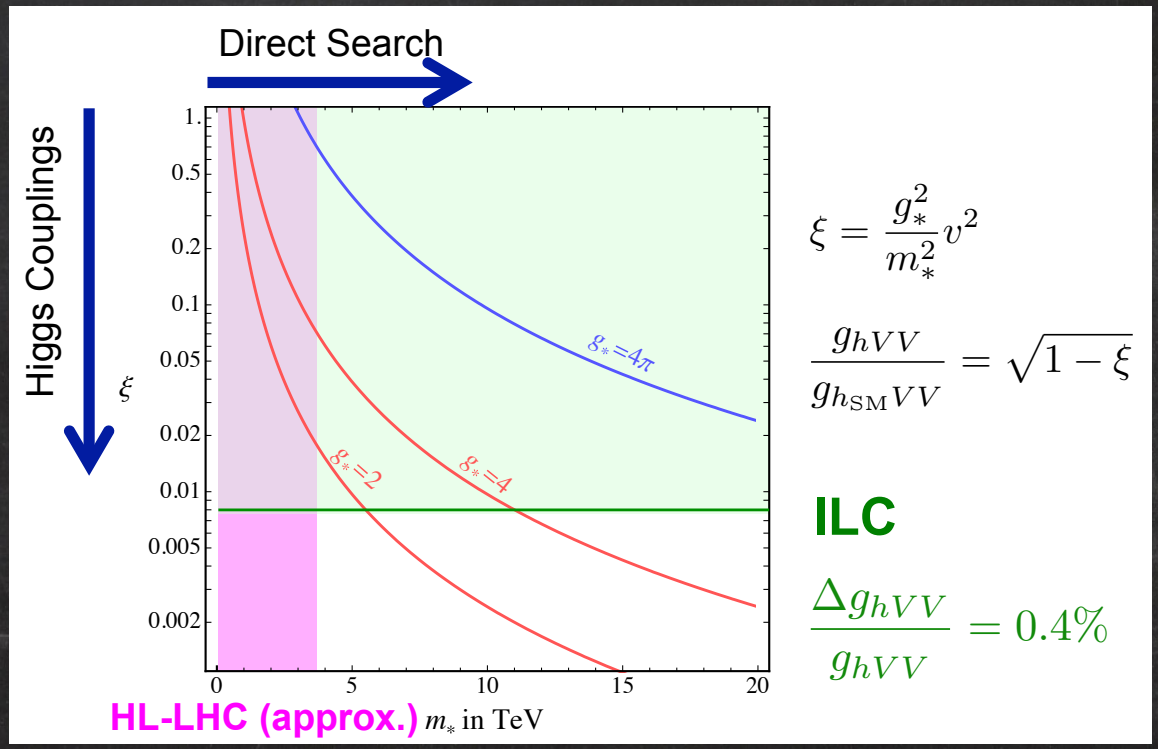
Charm-Tag would be an advantage @ ILC

Top-Gauge coupling precision limits indirect search potential

EWSB and Higgs

Higgs as a probe of Composite Higgs

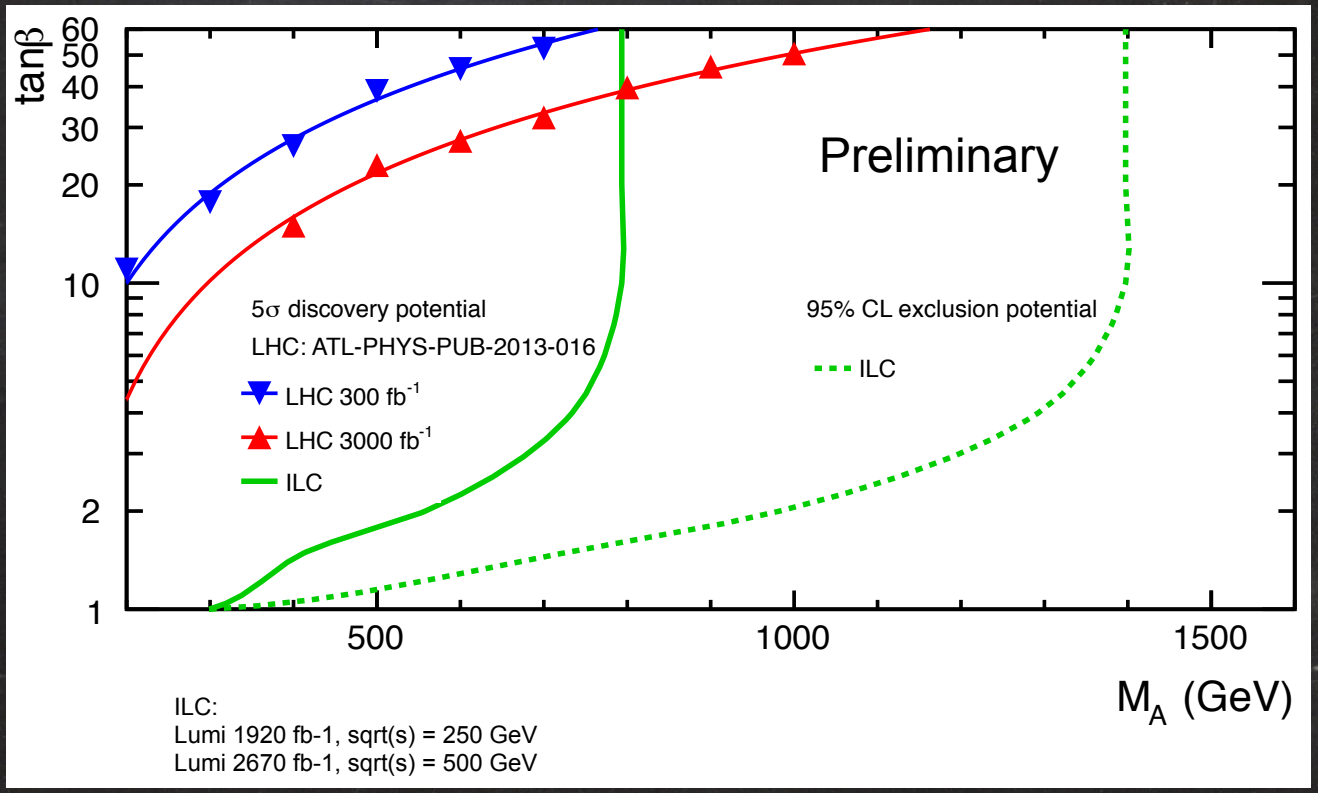
(motivated by QCD-like strong dynamics)



Higgs-Gauge coupling precision limits indirect search potential

EWSB and Higgs

Higgs as a probe of SUSY Higgs



Yukawa coupling precision is important for sort of 2HDMs

Minimality/Simplicity

Minimality Principle ?

Nature does not always respect Minimality

- ⭘ SU(2) x U(1) → $U(1)_{EM}$
- ✖ SU(2) → $U(1)_{EM}$ w/o Neutral current (Z)

New Physics often requires ext. Higgs sector

SM	→ 1HDM
MSSM	→ 2HDM (4HDM, ⋯)
Composite Higgs	→ depend on models
Gauge Higgs	→ depend on models
Ext. Gauge sym.	→ 1HDM + singlet
v inspired	→ depend on models

(Type-II seesaw : 1HDM+Triplet)

Non-minimal Higgs sector ?

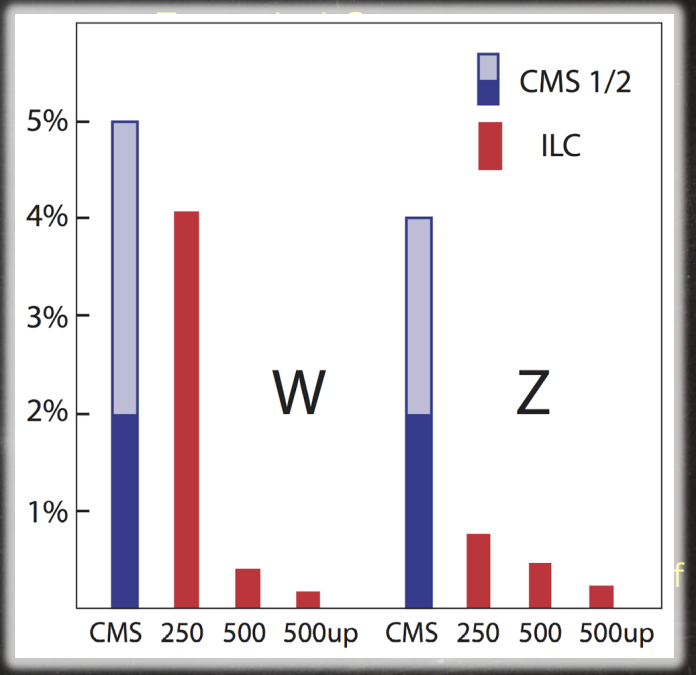
Most likely to be a doublet, but possible mixing w/ other multiplets

New Particle in EW sector !!

→ Direct search : H, A, H^+, H^{++}, ⋯

h_{125} as a probe : coupling deviations

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

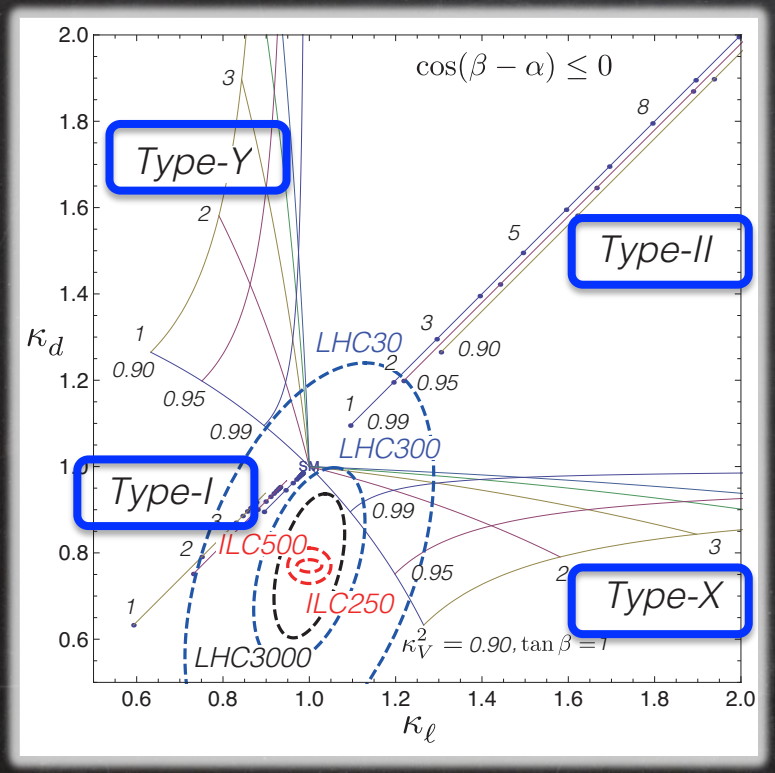


At least 1 (0.1) % precision for M > 1 (3) TeV (M is a new Higgs scale)

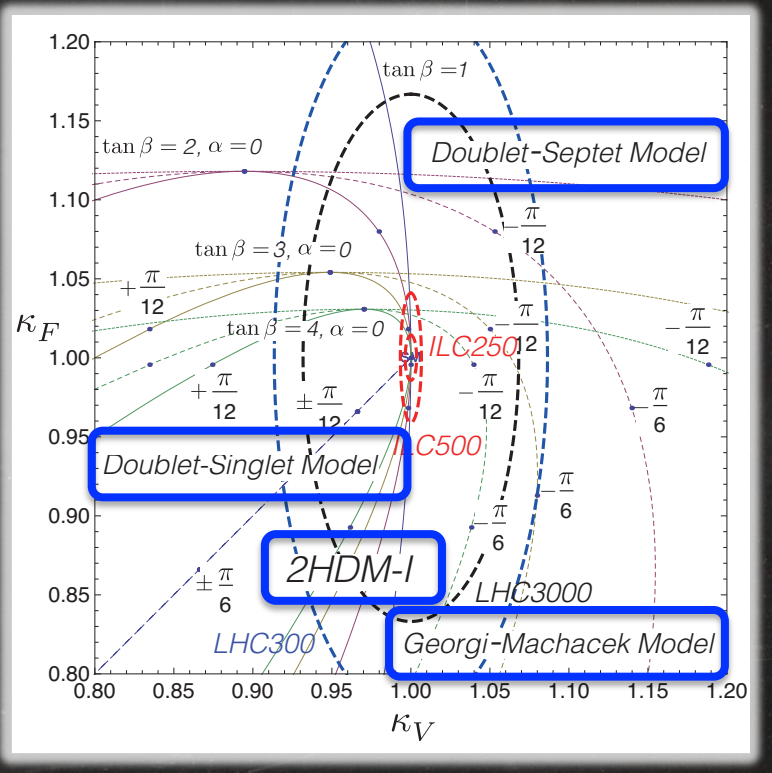
[pre-factor: loop suppression, tanβ enhancement, non-decoupling effect]

Fingerprint Models

$hb\bar{b}$



$hf\bar{f}$



$h\tau\bar{\tau}$

hVV

Model independent approach → Probe NP scale/pattern

Direct search for New Physics

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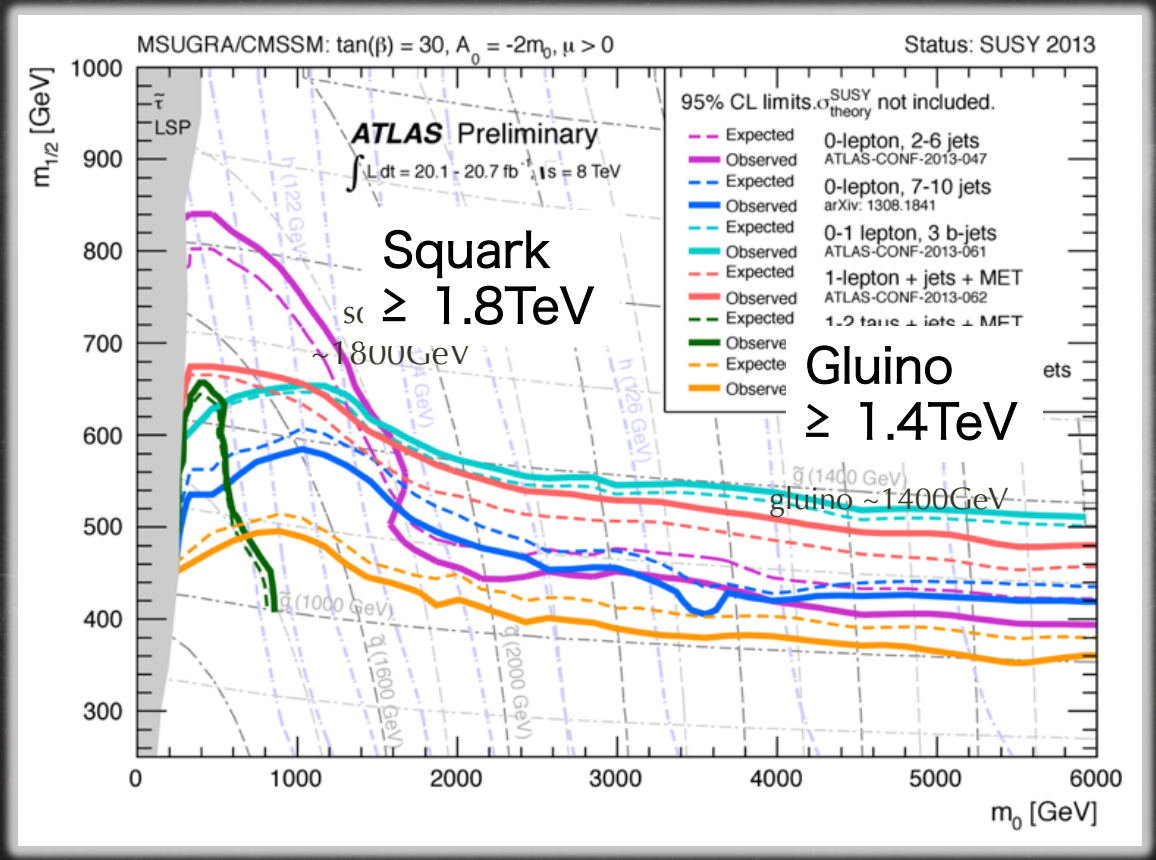
Do we still have a chance in EW scale?

LHC has been extensively searched for
New colored particle : > 1TeV



Do we still have a chance in EW scale?

LHC has been extensively searched for New colored particle : > 1TeV

Top-down

SUSY (supersymmetry)

Composite Higgs (some global sym.)

Gauge-Higgs Unif. (gauge sym.)

Need Mechanism to split colored and non-colored sector

(unless New Physics is decoupled)

(re)consider Naturalness

Bottom-up

Non-Minimal extended Model

(too many possibility)

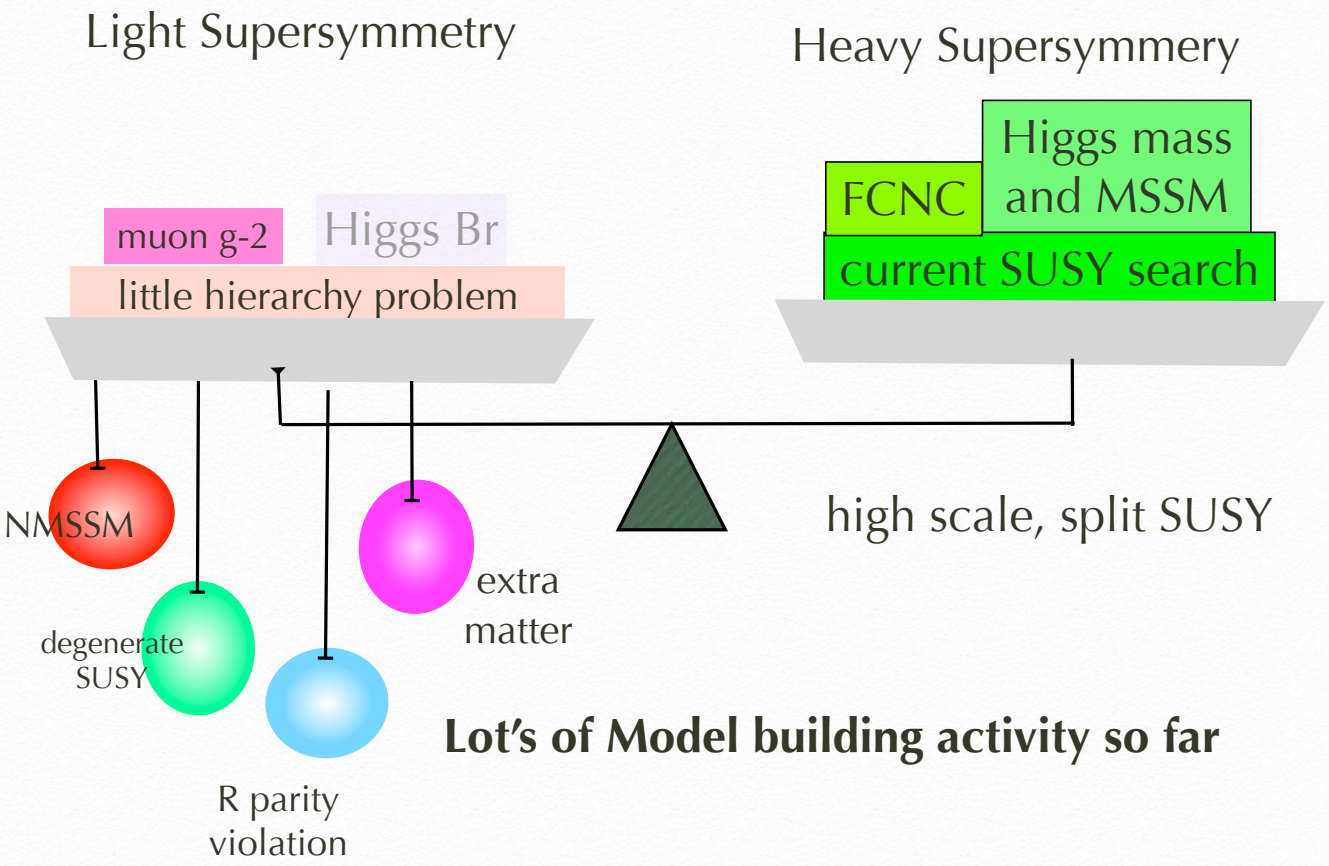
Need Motivation!!

DM, ν, g-2, etc.

- ✓ Positron excess in cosmic ray
- ✓ 3.5 keV gamma line
- ✓ PeV ν @ IceCUBE
- ✓ Inflation ? [BICEP2]
- ✓ Proton charge radius
- ✓ ν anomalies (LSND, MiniBooNe)
- ✓ Top FB asymmetry [CDF, D0]
- ✓ Lepton universality [LEP]
- ✓ Inclusive & Exclusive Vub
- ✓ W+W+ scatt. [LHC]

M. Nojiri

Mind of SUSY theorists



Naturalness Revisited

Naturalness in SUSY $\frac{g^2+g'^2}{4}v^2 \simeq -\mu^2 - M^2_{\rm SUSY} + \frac{3y_t^2}{4\pi^2}M^2_{\rm SUSY}\ln\frac{\Lambda}{\rm TeV}\cdots$

	SM	EW-SUSY	TeV-SUSY	HS(100TeV)
Fine-tuning level	10^{-32}	Natural	10^{-3}	10^{-6}
Flavor/CP problem	None	Serious	Serious	Mild
Coupling unification	Not Unify	Unify	Unify	Unify
Proton decay	None	Serious	Serious	Mild
Dark Matter	None	OK	OK	OK
Simplicity	Simple	Complex	Complex	Simple
Testability	Good	Good	Bad	BAD

Reweighting Criterion ? or Inventing Mechanism ?

(Need to pay a price)

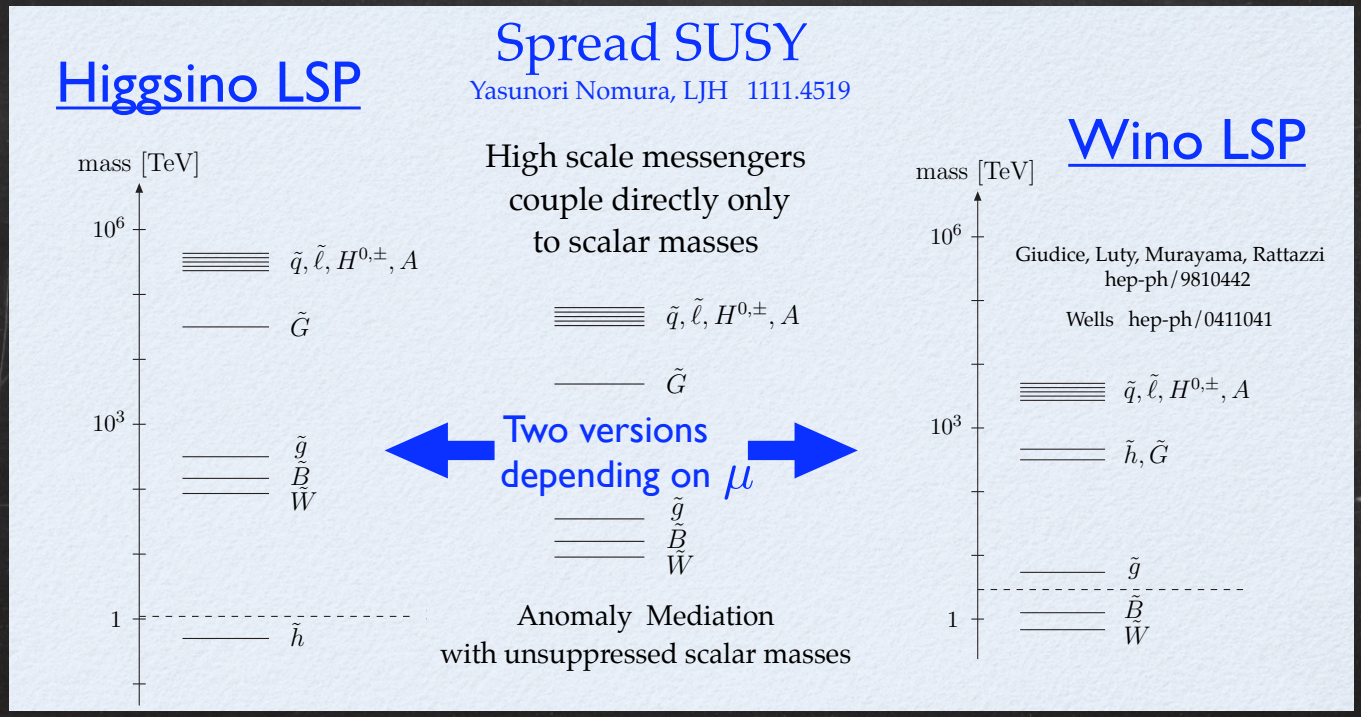
Mechanism

Natural SUSY : Higgs ~ gaugino ~ scalar

Mechanism

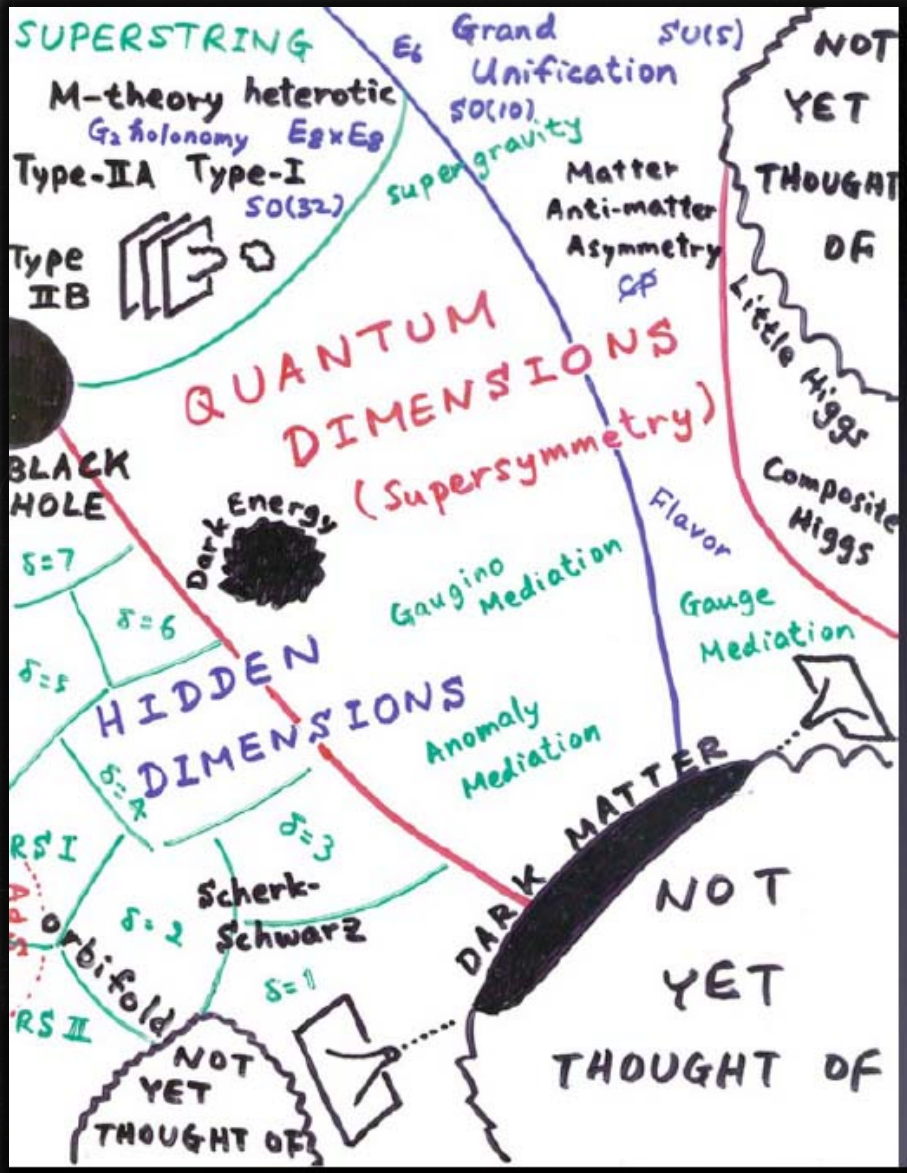
Higgs < gaugino < scalar

1-loop 1-loop



L. Hall

Zoo of New Physics



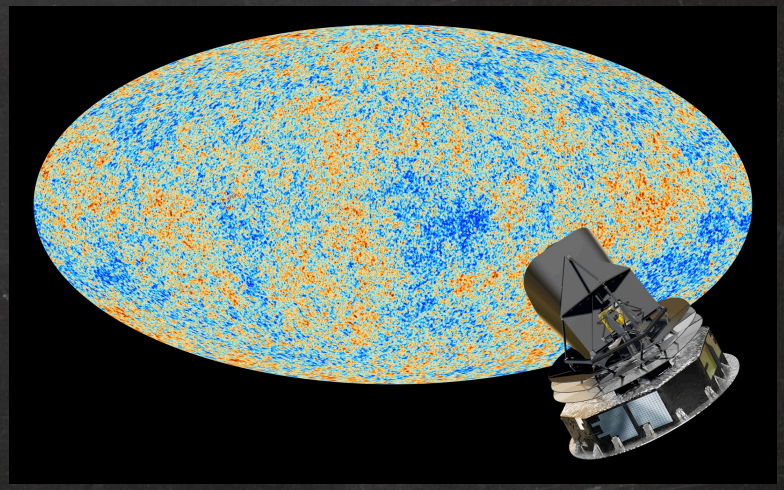
- We really don't know what is going on at TeV
- stupid theorists!
- Can we zoom in onto a point on this map?
- Expect the unexpected

H. Murayama

EW/TeV scale & DM

Evidence for DM

- ✓ Galaxy Rotation Curve
- ✓ Velocity Dispersion of Galaxies
- ✓ Galaxy Clusters and Gravitational Lensing
- ✓ Sky surveys and baryon acoustic oscillations
- ✓ Cosmic Microwave Background (CMB)
- ✓ Type Ia supernovae distance measurements
- ✓ Lyman-Alpha Forest
- ✓ Structure Formation



O(100)GeV [EW/TeV scale] + weak int.

$$\Omega_{\rm DM} h^2 \simeq \frac{0.1{\rm pb}\cdot c}{\langle \sigma v \rangle}$$

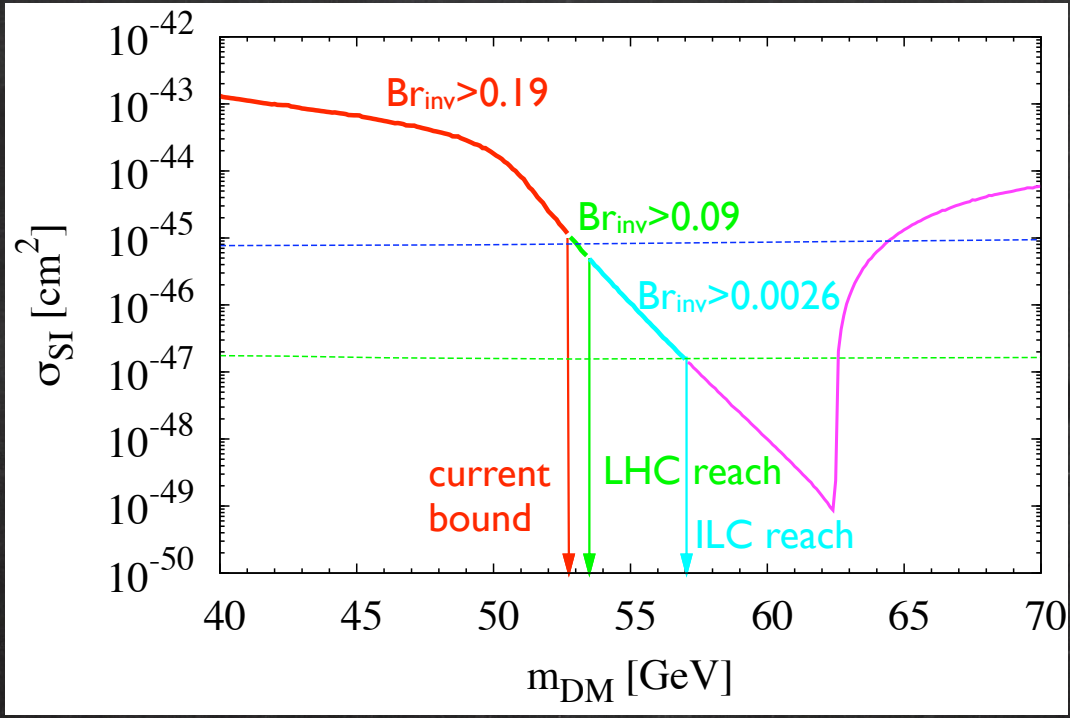
Lower bound on WIMP annih. xsec !!

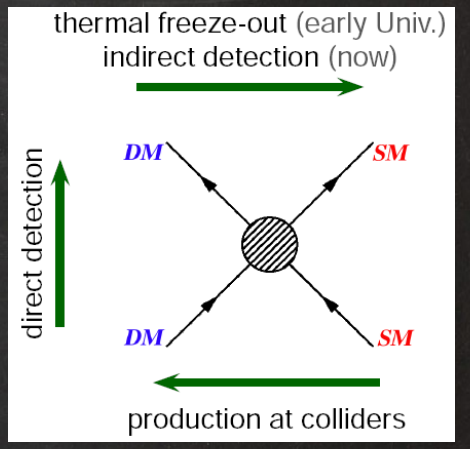
(annih. xsec must be large enough to eliminate too many DM)

Higgs Invisible Decay

Ex. SM + gauge singlet DM

Abe, Kitano





Current best bound of
DM direct detection (LUX2013)

XENON1T (~ 2017 ?)

1 order improvement is expected @ LZ

Improve Inv. Decay search
or Mono-photon search ?

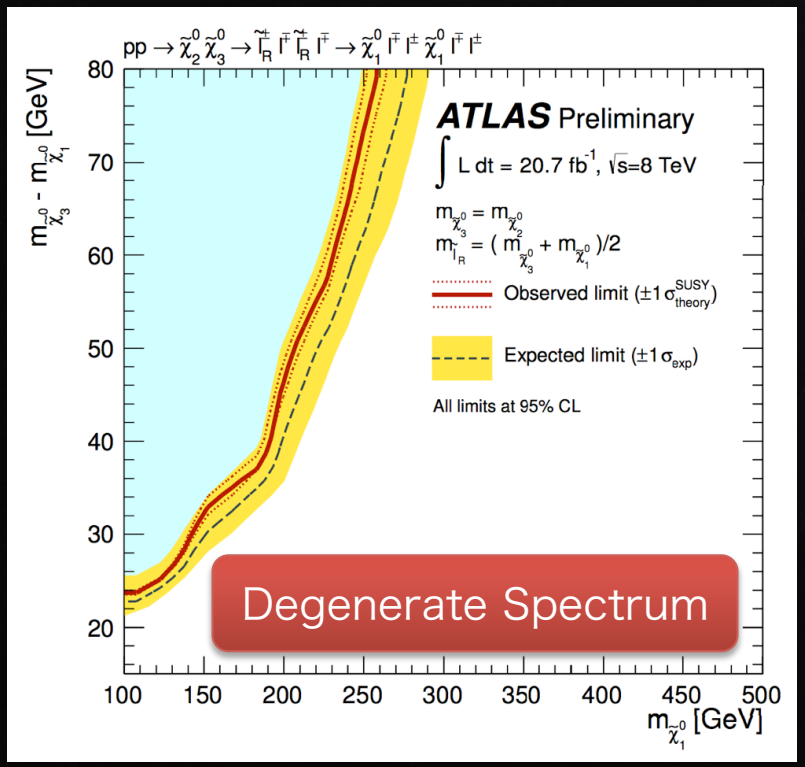
$$\Omega_{\rm DM}h^2 \simeq \frac{0.1{\rm pb}\cdot c}{\langle\sigma v\rangle}$$

Lower bound on WIMP annih. xsec !!

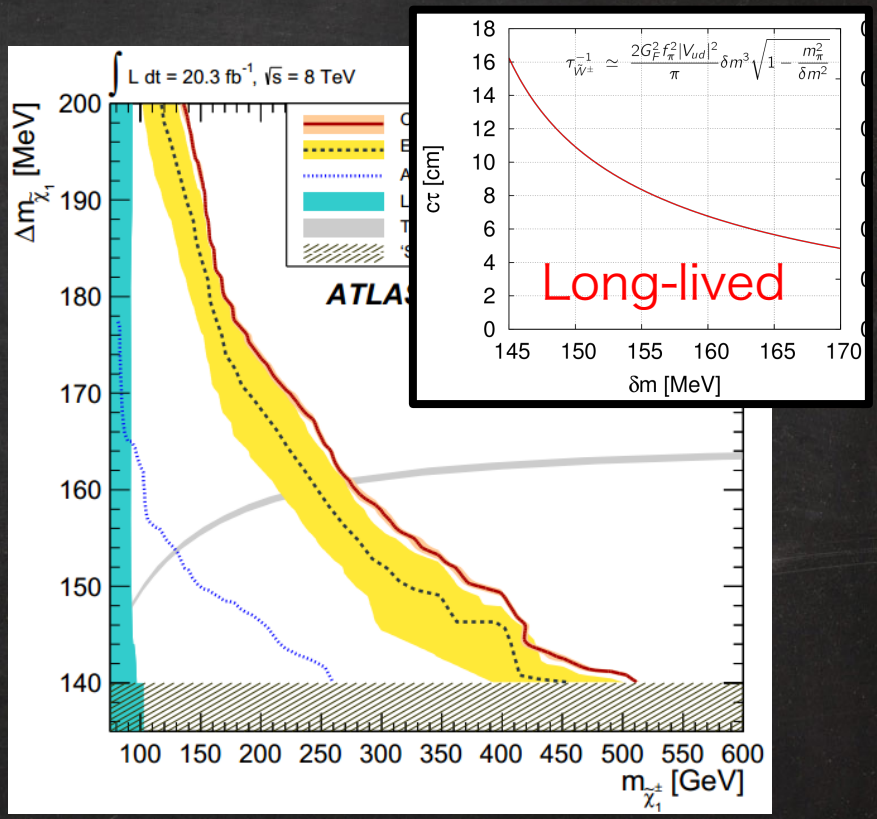
(annih. xsec must be large enough to eliminate too many DM)

Do we still have a chance in EW scale?

LHC14 and/or HL-LHC will further constrain non-colored particle



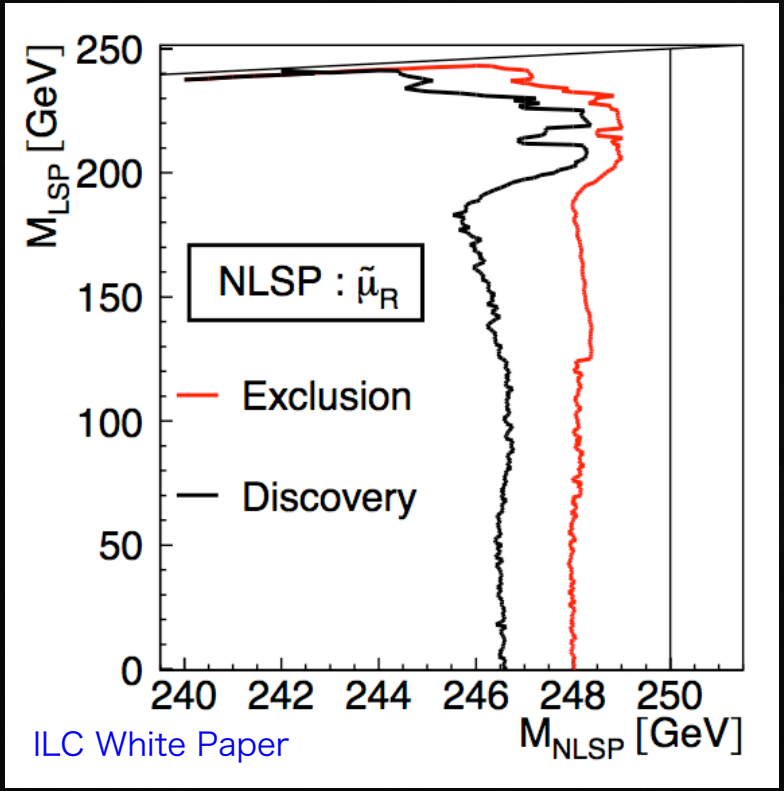
ΔM > 20 GeV

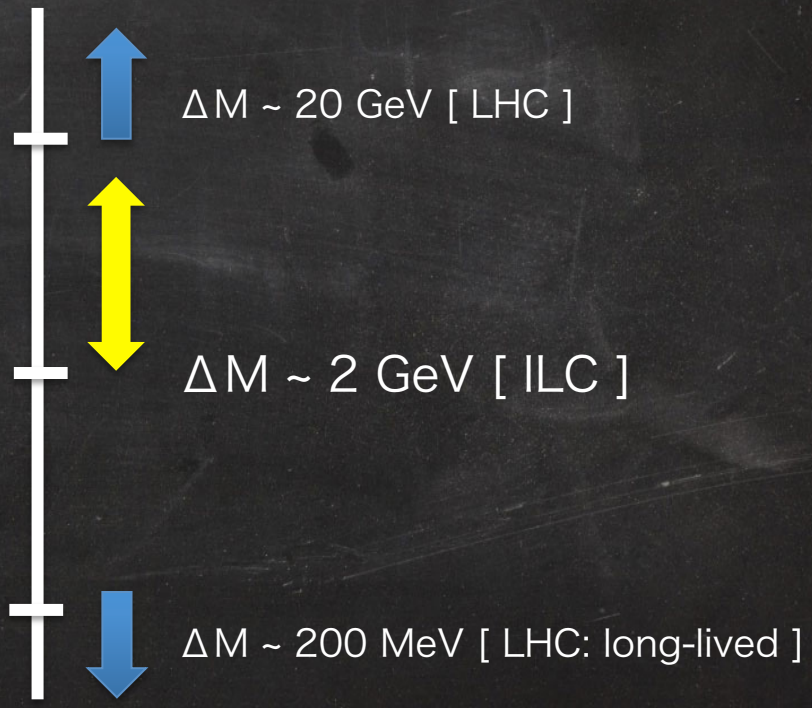


ΔM < 200 MeV

Do we still have a chance in EW scale?

LHC14 and/or HL-LHC will further constrain non-colored particle

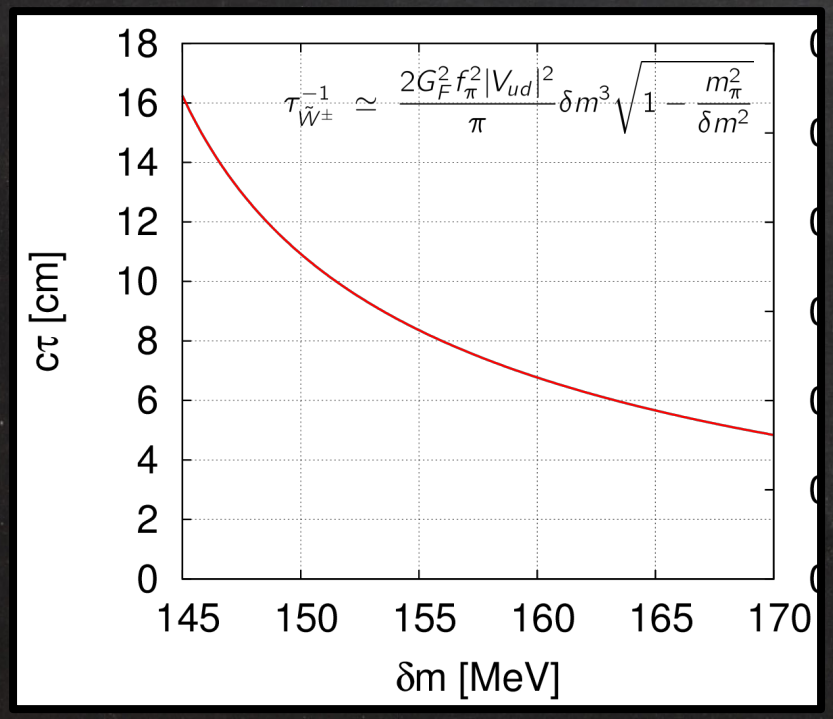


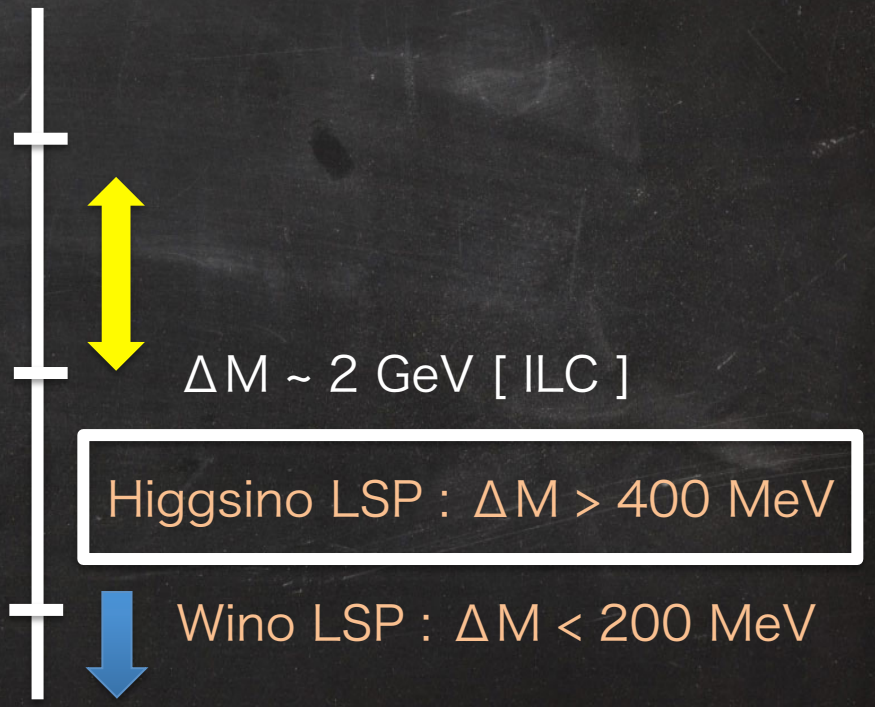


Decoupling & Degeneracy

Decoupling preserves SU(2) structure

→ “Natural” Degeneracy





Summary

- Higgs force is still unknown
- EWSB & "(revised)Natualness" are still guiding principle
  - Links to New Physics
- There are many NP indications

- ✓ Dark Matter
- ✓ Origin of neutrino mass
- ✓ Muion g-2
- ✓ Positron excess in cosmic ray
- ✓ 3.5 keV gamma line
- ✓ PeV ν @ IceCUBE
- ✓ Inflation ? [BICEP2]
- ✓ Proton charge radius
- ✓ ν anomalies (LSND, MiniBooNe)
- ✓ Top FB asymmetry [CDF, D0]
- ✓ Lepton universality [LEP]
- ✓ Inclusive & Exclusive Vub
- ✓ W+W+ scatt. [LHC]

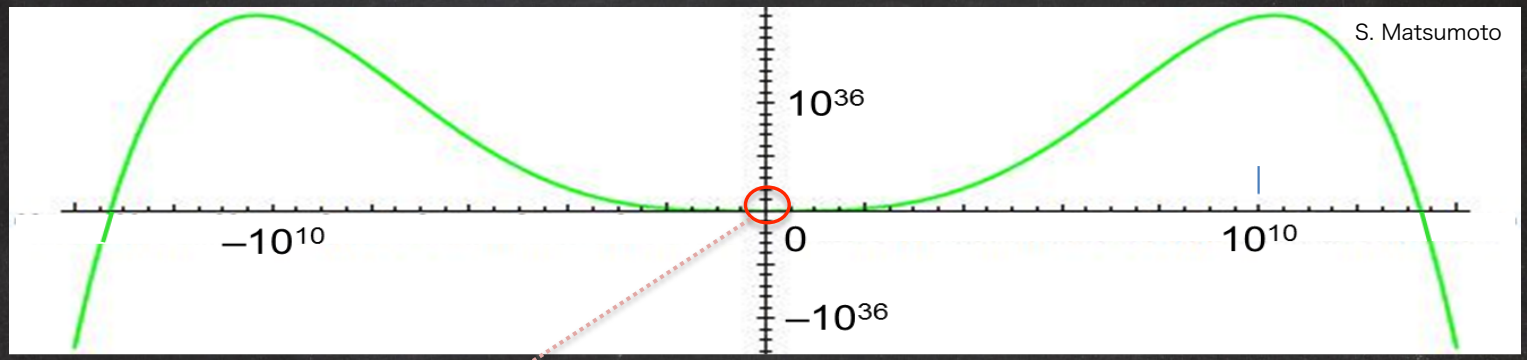
ILC

- Precise determination of Mass & Couplings
- Direct & Indirect search for New Physics

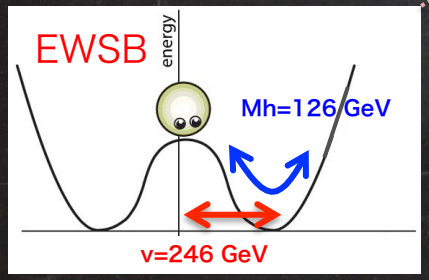
Fin.

Mysteries in Higgs sector

Is the EW scale natural ?



Mt=174.34, Mh=126GeV



Grand desert
(Hierarchy)

(Within the SM,) Precise value of M_h fixes Curvature

Independent reconstruction of Higgs pot. : λ_{hhh}

[measure of EW phase transitions]

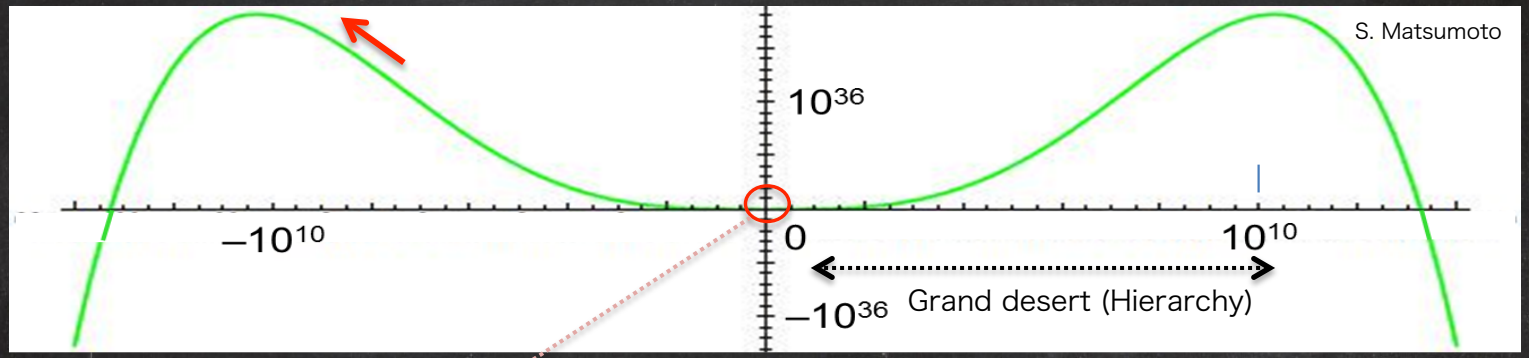
Only the probe of mass-coupling relation : $M_h^2=2\lambda v^2$

Summary

Where does the EW scale come from?

Mt, anomalous top couplings

Flat potential (λ~0) suggests inflation?



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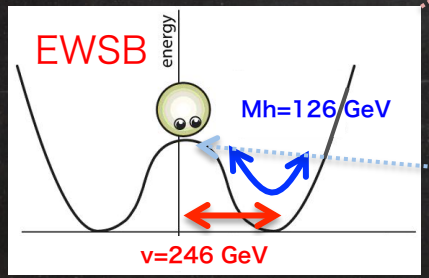

Possible connection w/ DM

Dynamical generation of EW from New Physics

M_h, Higgs couplings inc. λ_{hhh}