Kaoru, KAERU, and Supersymmetry

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University of Alabama

KAERU Conference @ Kavli IPMU, Mar. 25-26, 2015

Kaoru

is a great theorist,
mentor,
supporter,
good friend,
my old colleague at KEK

My first postdoc position at KEK: 1998-2001
Tenured position at KEK: 2002-2009

Collaborations with Kaoru (Chair) for SUSY 2004 conference at KEK, Tsukuba

The conference was successful with 232 participants

SUSY 2004 conference poster (a scrap)

SUSY 2004 conference @Tsukuba

According to the oldest history book of Japan written in 8'th century, Izanagi (god) and Izanami (goddess) jointly stirred mud with a pike, and a drop of spearhead started our world.

The original idea of the post is given by Satomi Okada, and the poster was designed by an artist, Kazuyuki Asakura of Studio-R in Shibuya

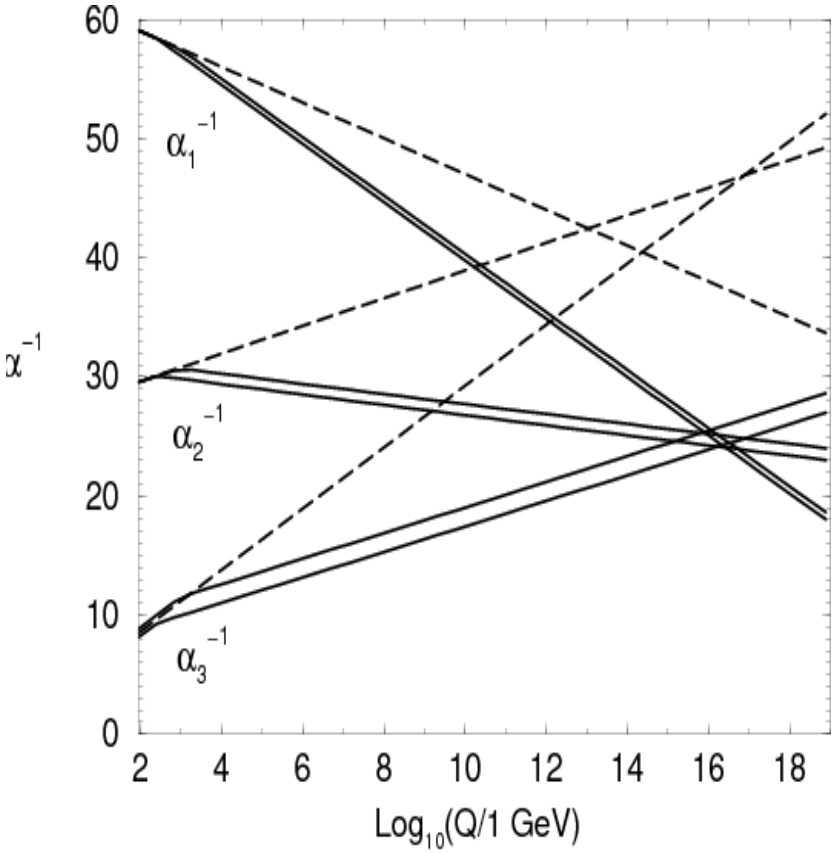
Kaoru and I visited Studio-R several times to discuss the poster

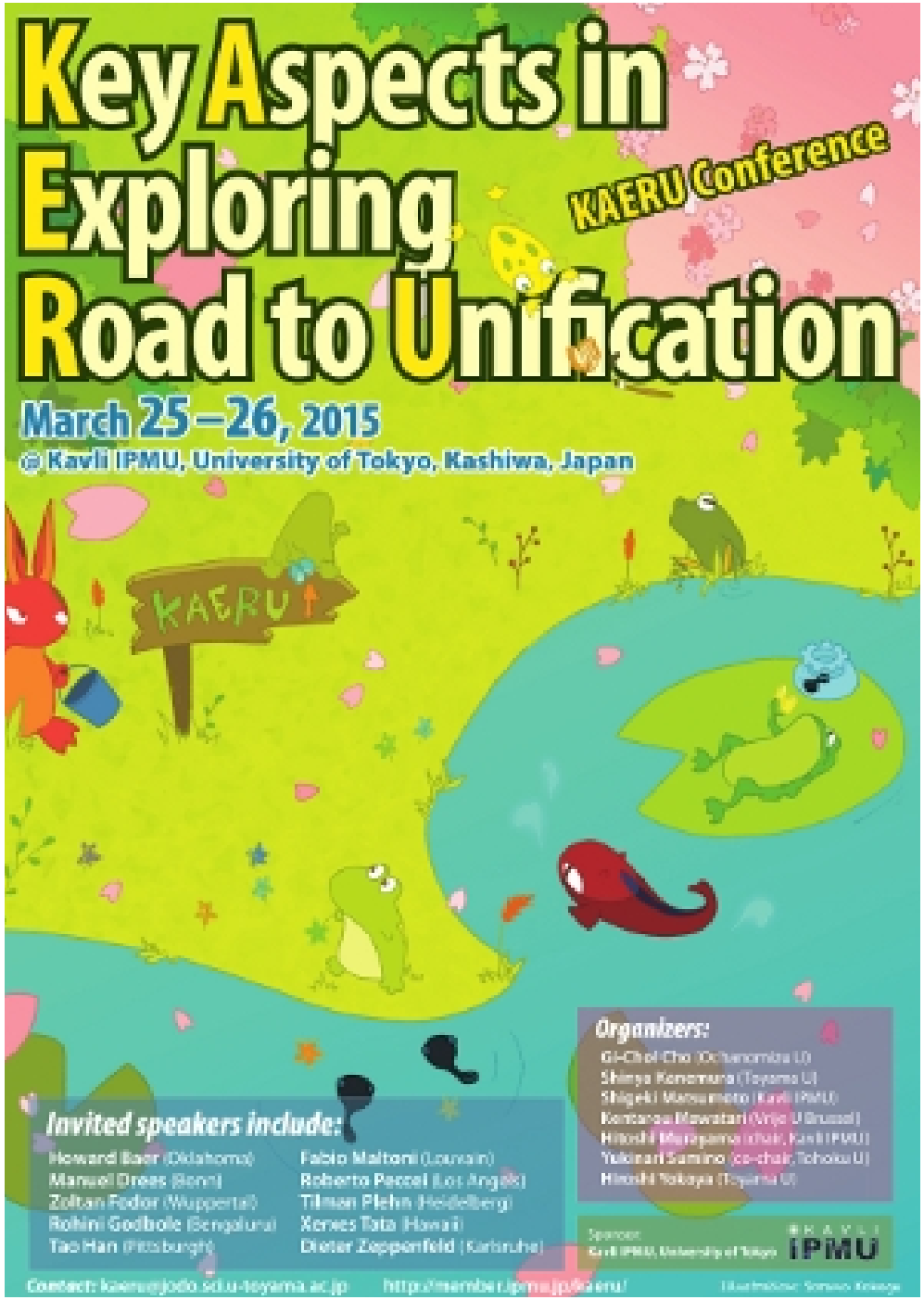
KAERU = frog in Japanese
= Kaoru's favorite animal

and

Unification……

Supersymmetry





I was thinking about my talk @ KAERU…. something related to Kaoru's work

One day I got KAERU conference poster

Something familiar to me……

Aha, SUSY!

SUSY 2004

The 12th International Conference on Supersymmetry and Unification of Fundamental Interactions

June 17-23, 2004

Epochal Tsukuba, Tsukuba, Japan.

Organized by KEK

What happened for SUSY after SUSY 2004, or for physics beyond the SM in general?

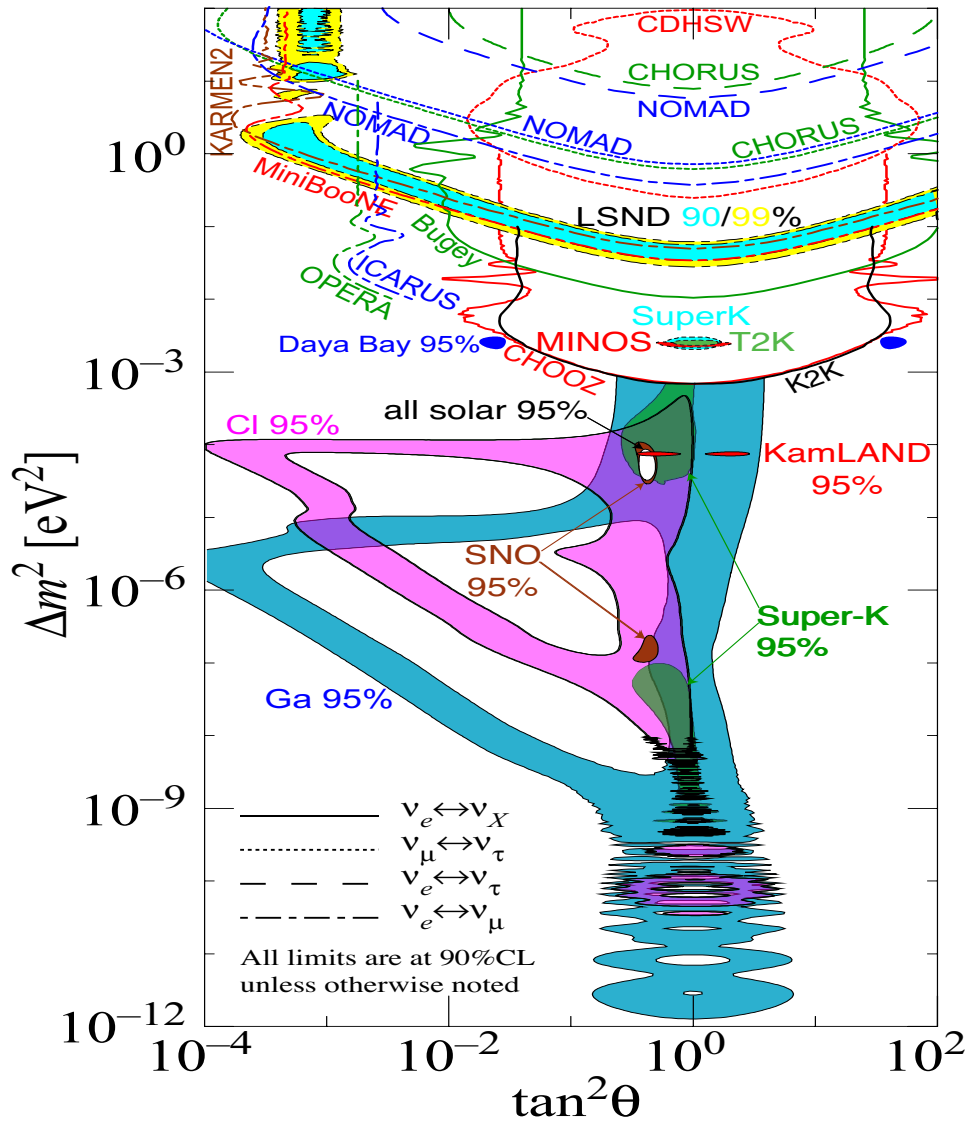
11 years have passed!

Neutrino oscillation experiments

- Reactor angle measurement (Double Chooz, Daya Bay, RENO)

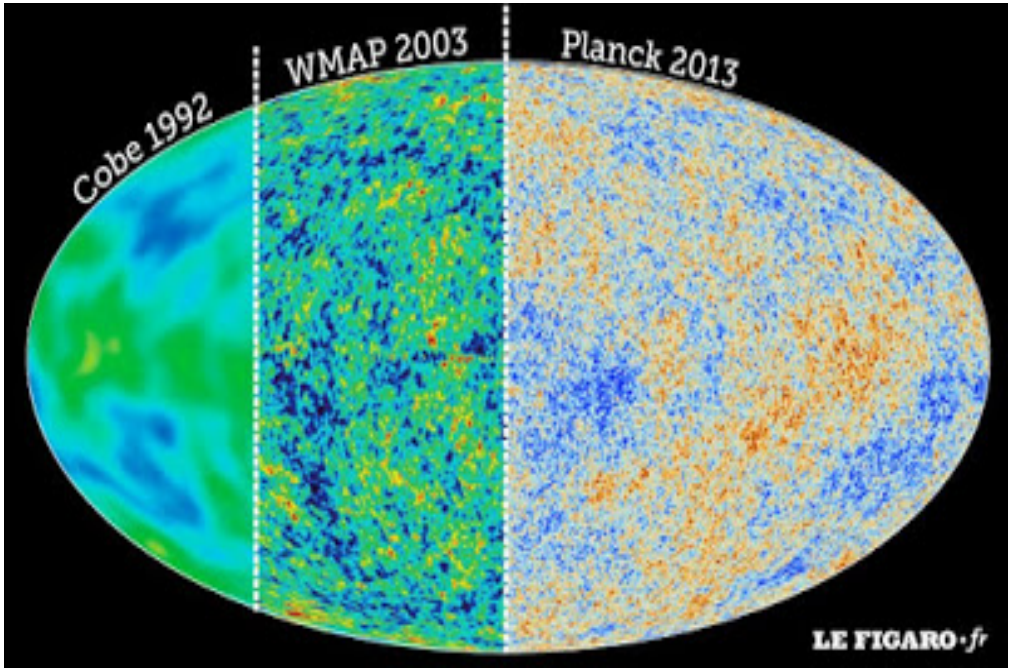
Daya Bay (217 days live time)

$$\sin^2 2\theta_{13} = 0.090^{+0.008}_{-0.009}$$



http://hitoshi.berkeley.edu/neutrino

CMB Observations: Cobe → WMAP→ Planck



Planck 2015 arXiv:1502.01589

Parameter	[1] *Planck* TT+lowP
$\Omega_b h^2$	0.02222 ± 0.00023
$\Omega_c h^2$	0.1197 ± 0.0022
$100\theta_{MC}$	1.04085 ± 0.00047
τ	0.078 ± 0.019
$\ln(10^{10} A_s)$	3.089 ± 0.036
n_s	0.9655 ± 0.0062
H_0	67.31 ± 0.96
Ω_m	0.315 ± 0.013
σ_8	0.829 ± 0.014
$10^9 A_s e^{-2\tau}$	1.880 ± 0.014

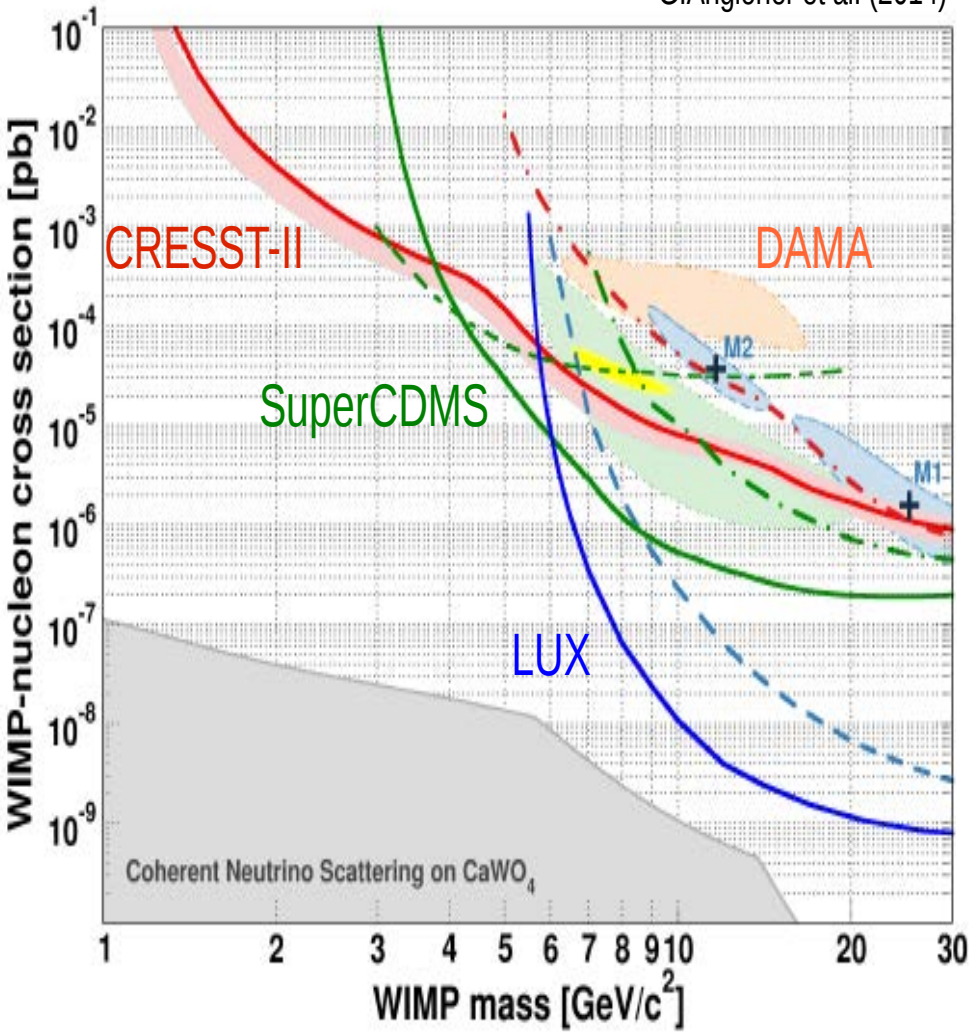
The observational cosmology is now a precision science!

$$T = 2.725 \text{ K}$$

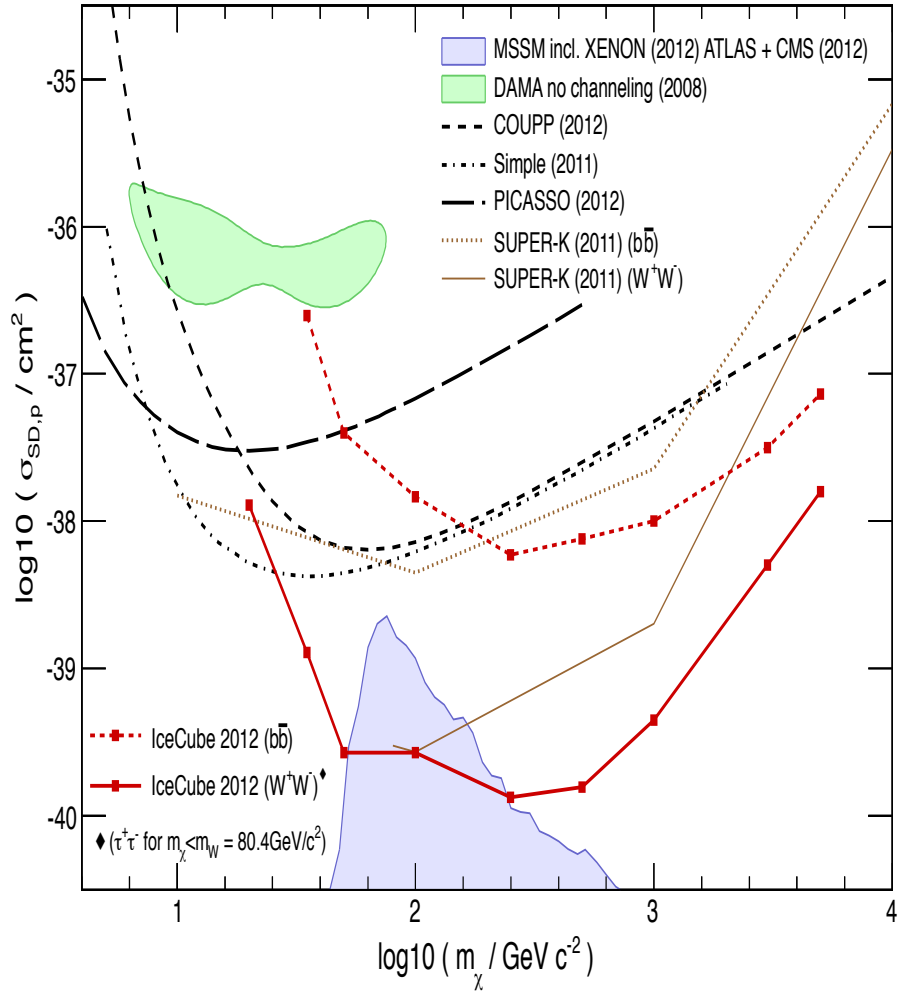
$$\frac{\delta T}{T} \sim 10^{-5}$$

Direct/Indirect Dark Matter Search

G.Angloher et al. (2014)



79-string IceCube



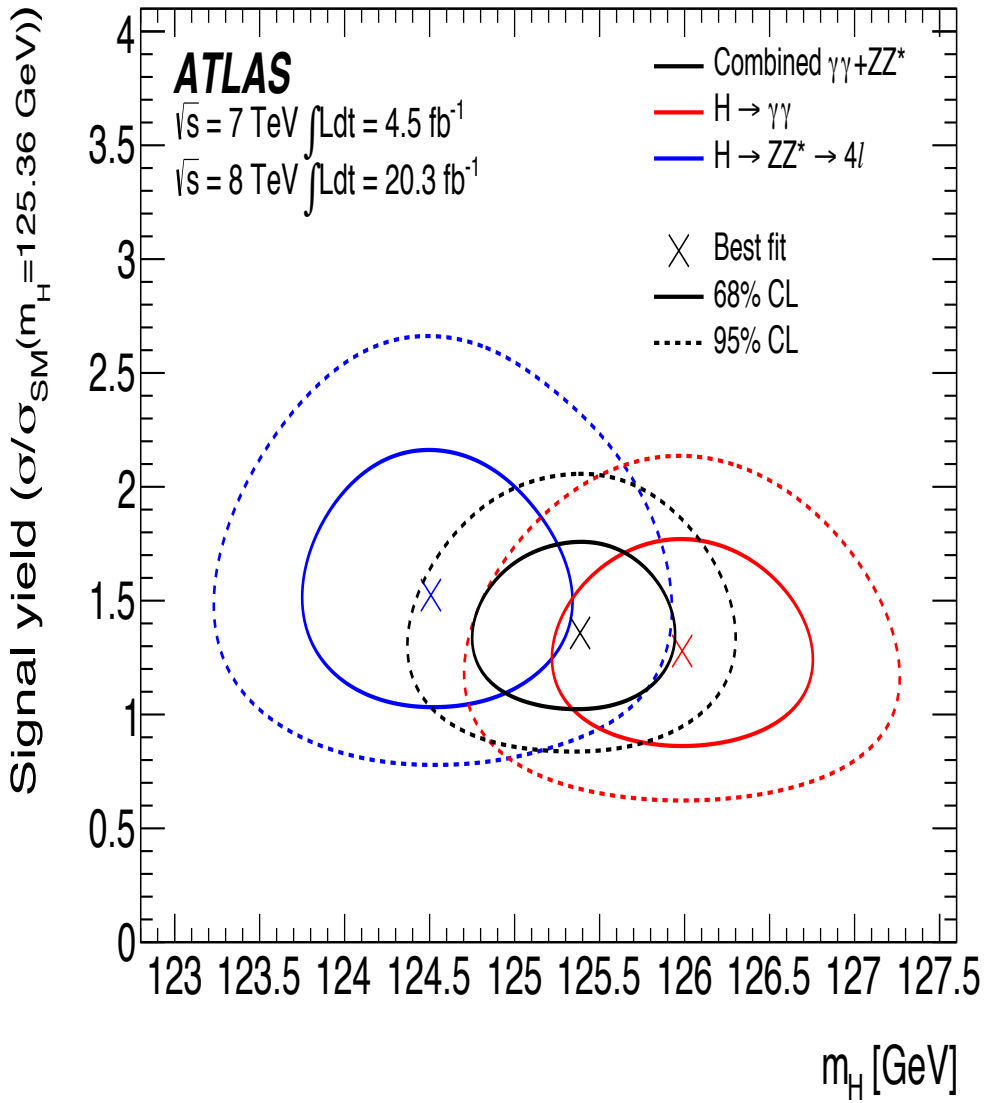
Discovery of a new scalar particle (Higgs boson)!

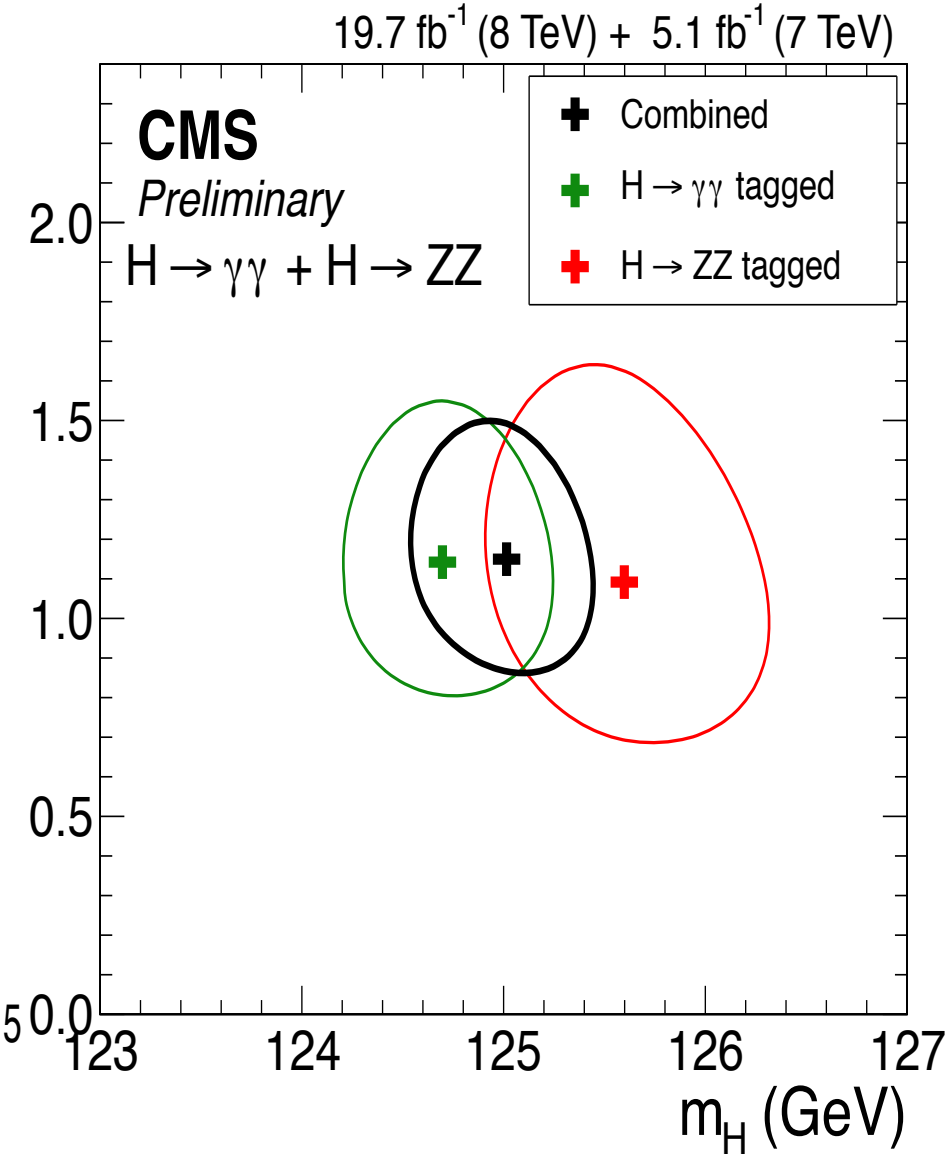
- A new scalar particle, most likely the Higgs boson, has been discovered independently by ATLAS and CMS collaborations

- First announcement on July 4th, 2012
  "Higgsdependence" Day

arXiv: 1406.3827

CMS PAS HIG-14-009





$$m_H = 125.36 \pm 0.37\,(\text{stat}) \pm 0.18\,(\text{syst})\ \text{GeV}$$

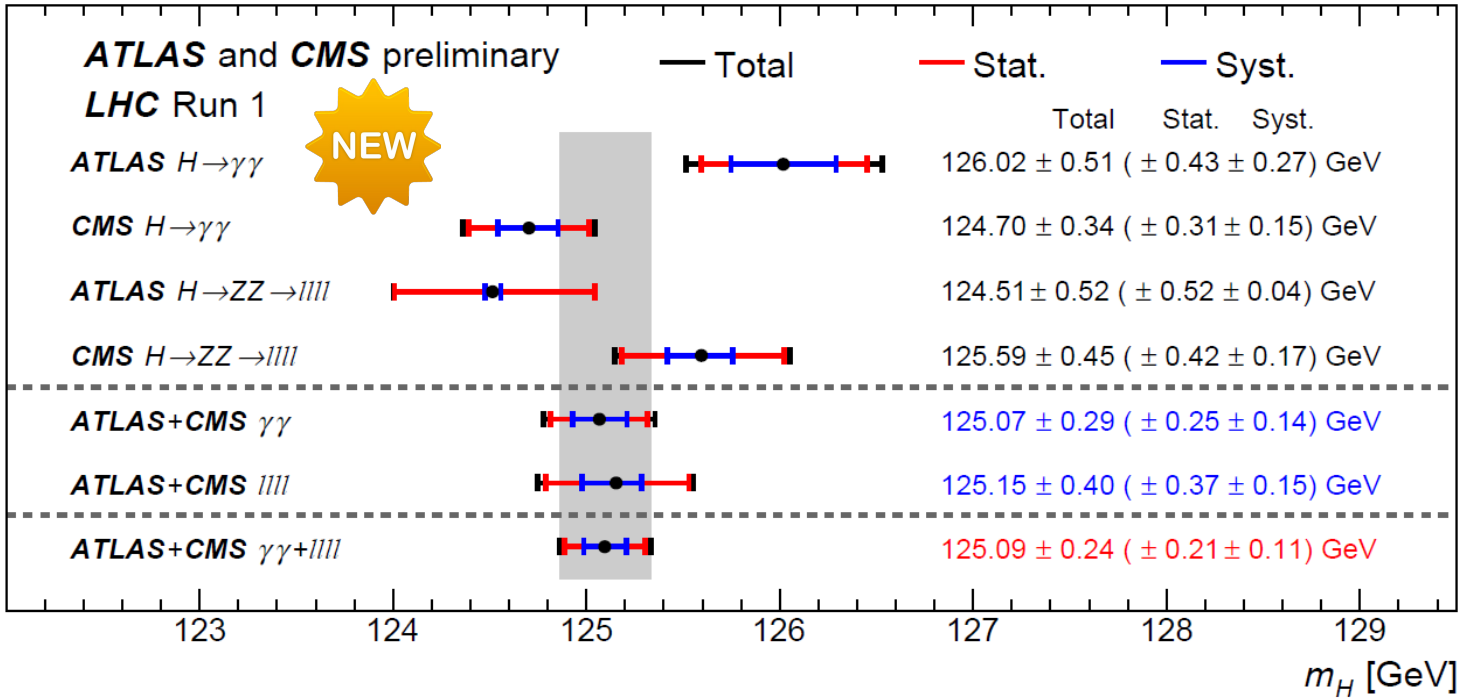
$$125.03\,^{+0.26}_{-0.27}\,(\text{stat.})\,^{+0.13}_{-0.15}\,(\text{syst.})\ \text{GeV}$$

ATLAS+CMS Higgs mass combination

… and the ATLAS+CMS combined Higgs boson mass is:

$$m_H = 125.09 \pm 0.24 \text{ GeV}$$ **(0.19% precision!)**

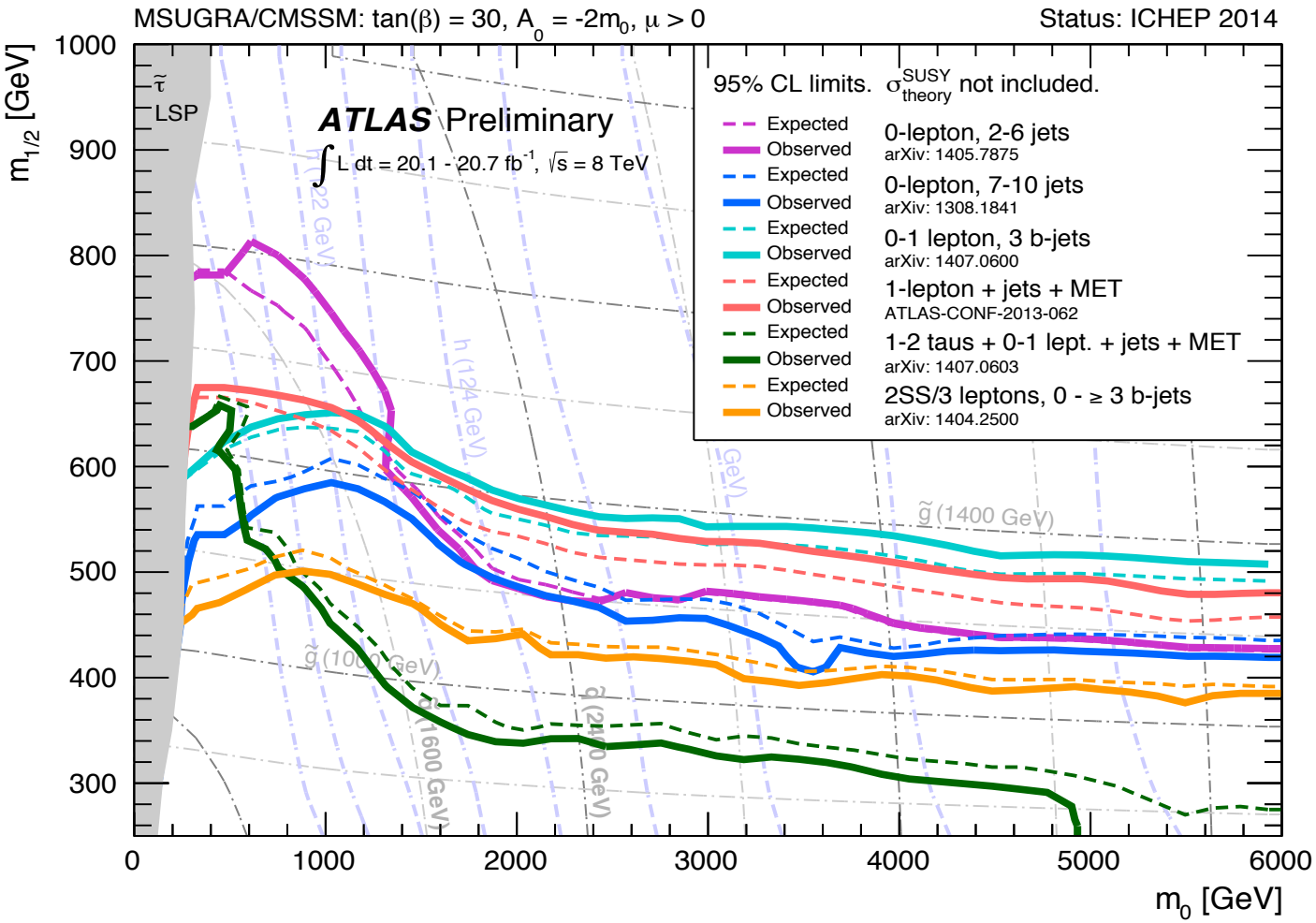
$$= 125.09 \pm 0.21(\text{stat.}) \pm 0.11(\text{syst.}) \text{ GeV}$$



Compatibility of the 4 m_H measurements with the combined mass: 7-10%

SUSY search @ LHC

Example) CMSSM parameterization



No sparticle signal at LHC so far

However, SUSY is still our favorite way of SM extension

MSSM is better than SM

- Radiative electroweak symmetry breaking
- Higgs mass prediction
- Successful gauge coupling unification
- Dark matter candidate (LSP neutralino/gravitino)

although fine-tuning issue becomes more serious as sparticle mass bounds go up

Impact of Higgs mass measurement on MSSM

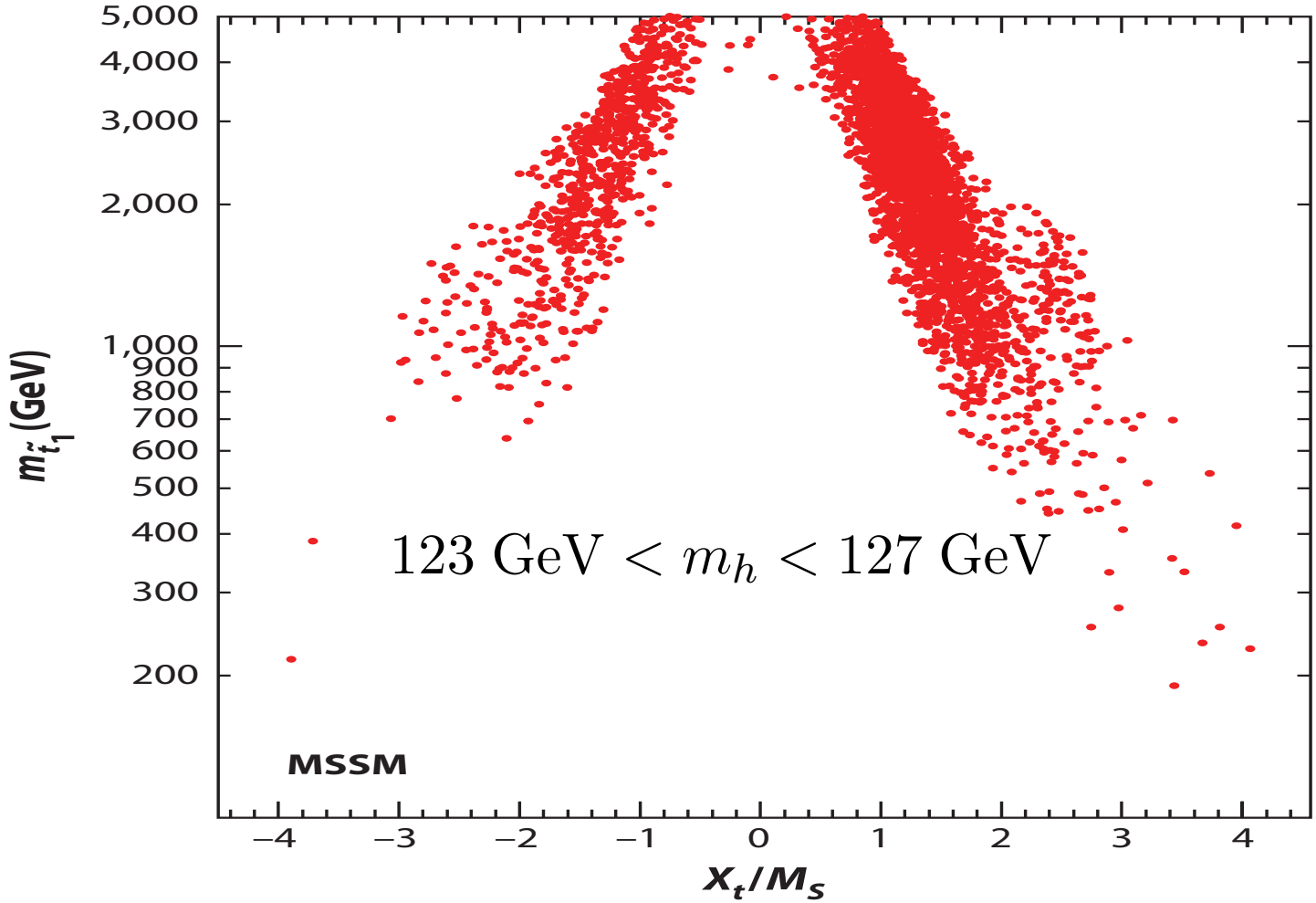
$$m_h^2 \approx m_Z^2 \cos^2 2\beta + \frac{3m_t^4}{2\pi^2 v^2}\left\{\ln\frac{M_S^2}{m_t^2} + \frac{X_t^2}{M_{\tilde{t}}^2}\left(1 - \frac{X_t^2}{12M_S^2}\right) + \frac{1}{16\pi^2}\left(\frac{3m_t^2}{v^2} - 32\pi\alpha_s\right)\left[\frac{2X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12M_S^2}\right)\ln\frac{M_S^2}{m_t^2} + \left(\ln\frac{M_S}{m_t^2}\right)^2\right]\right\},$$

where $v \simeq 246$ GeV, $M_S \equiv \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$, $X_t \equiv A_t - \mu \cot\beta$

- Tree-level < m_Z + SUSY breaking corrections
- Higgs mass 125-126 GeV gives constraints on soft SUSY breaking parameters

Parameter scan in viable MSSM

Cao et al., JHEP 1203 (2012) 086



$1 \leq \tan\beta \leq 60,\ \ 90\ \mathrm{GeV} \leq m_A \leq 1\ \mathrm{TeV},\ \ 100\ \mathrm{GeV} \leq \mu \leq 2\ \mathrm{TeV},$

$100\ \mathrm{GeV} \leq M_{Q_3}, M_{U_3} \leq 5\ \mathrm{TeV},\ \ |A_t| \leq 5\ \mathrm{TeV},$

$100\ \mathrm{GeV} \leq m_{\tilde{l}} \leq 1\ \mathrm{TeV},\ \ 50\ \mathrm{GeV} \leq M_1 \leq 500\ \mathrm{GeV},$

Require to satisfy a variety of phenomenological constraints: DM, B-phys, XENON100

- If Xt contribution is large, the lighter stop mass can be less than 1 TeV, otherwise the stop mass scale is <u>multi-TeV</u>

Example: <u>Minimal Gauge Mediation Scenario</u>

Messengers **5+5*:** $W_{mess} = \sum_{i=1}^{N_m} S\overline{\Phi}_i\Phi_i \qquad S = M + \theta^2 F$

Gaugino mass: $M_i(\mu) = \frac{\alpha_i(\mu)}{4\pi}\Lambda N_m,$

Sfermion mass: $m^2_{\tilde{f}}(\mu) = \sum_i 2C_i \left(\frac{\alpha_i(\mu)}{4\pi}\right)^2 \Lambda^2 \; N_m \; G_i(\mu, M),$

where $G_i(\mu, M) = \xi_i^2 + \frac{N_m}{b_i}(1-\xi_i^2)$ with $\xi_i = \alpha_i(M)/\alpha_i(\mu)$.

Soft masses are controlled by $N_m, M, \Lambda = \frac{F}{M}, \tan\beta, \mathrm{sgn}(\mu)$

Sample mass spectrum

$\tan\beta$	10			45
N_m	1	2	4	1
M	9.16×10^{12}	2.66×10^{13}	8.28×10^{13}	1.51×10^{13}
Λ	1.23×10^{6}	6.73×10^{5}	3.47×10^{5}	1.05×10^{6}
h_0	125			
H_0	7123	6304	5607	4418
A_0	7123	6304	5607	4419
$H^{\pm}$	7123	6304	5608	4419
$\tilde{g}$	7726	8300	8424	6719
$\tilde{\chi}^0_{1,2}$	1693, 3141	1856, 3424	1909, 3509	1454, 2707
$\tilde{\chi}^0_{3,4}$	5147, 5148	4717, 4719	4365, 4369	4370, 4372
$\tilde{\chi}^{\pm}_{1,2}$	3141, 5149	3424, 4719	3509, 4369	2707, 4372
$\tilde{u}, \tilde{c}_{1,2}$	9227, 10123	8491, 9193	7837, 8389	7983, 8757
$\tilde{t}_{1,2}$	7274, 9260	6829, 8455	6413, 7745	6296, 7695
$\tilde{d}, \tilde{s}_{1,2}$	9034, 10123	8346, 9193	7733, 8389	7812, 8757
$\tilde{b}_{1,2}$	8990, 9258	8308, 8452	7698, 7742	7107, 7693
$\tilde{\nu}_{e,\mu}$	4989	4242	3580	4330
$\tilde{\nu}_{\tau}$	4976	4231	3571	4084
$\tilde{e}, \tilde{\mu}_{1,2}$	3305, 4990	2783, 4243	2290, 3581	2895, 4330
$\tilde{\tau}_{1,2}$	3267, 4977	2750, 4232	2262, 3572	2070, 4087

To obtain 125 GeV Higgs mass, sparticle masses 1 TeV -10 TeV

- Neutralino mass is 1.5-2 TeV → over abundance
- But, in GMSB, LSP is not neutralino, but gravitino

$$m_{\tilde{G}} = \frac{M\Lambda}{\sqrt{3}M_P}$$

<u>SuperWIMP scenario</u>

Feng, Rajaraman & Takayama, PRL 91, 011302 (2003)
Feng, Su & Takayama, PRD 70, 075019 (2004)

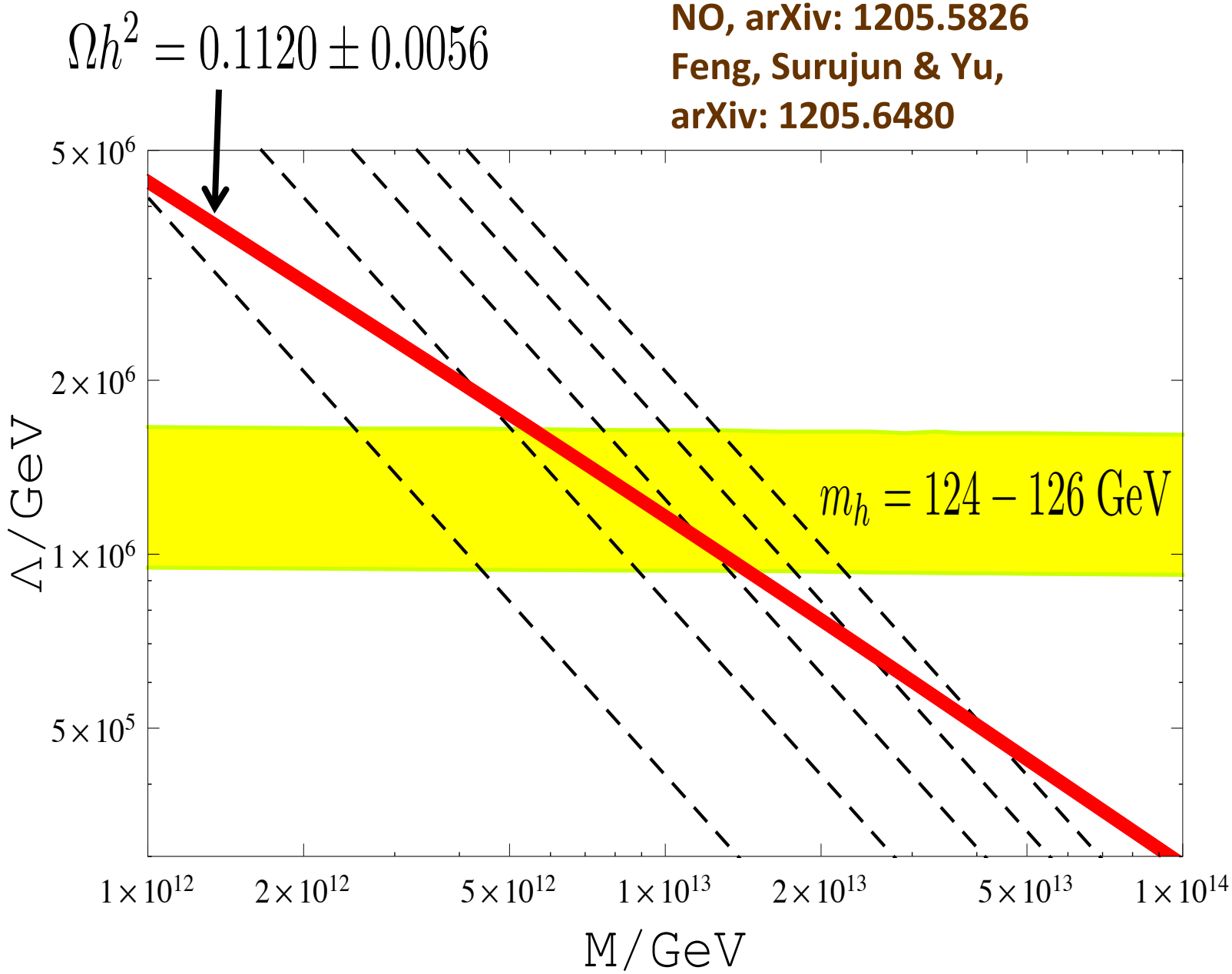
- Neutraino behaves like WIMP DM
- Late-time decay of relic neutralino

$$\tau_{\tilde{B}} \simeq 0.74\,\mathrm{sec} \times \left(\frac{m_{\tilde{G}}}{1\,\mathrm{GeV}}\right)^2 \left(\frac{1\,\mathrm{TeV}}{m_{\tilde{B}}}\right)^5$$

- LSP gravitino abundance is calculable

$$\Omega_{DM}h^2 = \Omega_X h^2 \times \left(\frac{m_{DM}}{m_X}\right)$$

NO, arXiv: 1205.5826
Feng, Surujun & Yu,
arXiv: 1205.6480



$m_{\tilde{G}} = 1, 2, 3, 4,$ and 5 GeV

NO, arXiv: 1205.5826

$\tan\beta$	10			45
N_m	1	2	4	1
M	9.16×10^{12}	2.66×10^{13}	8.28×10^{13}	1.51×10^{13}
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$\tilde{\tau}_{1,2}$	3267, 4977	2750, 4232	2262, 3572	2070, 4087
$m_{\tilde{G}}$	2.66	4.24	6.81	3.77
$\Omega_{\tilde{G}} h^2$	0.112			

- 125-126 Higgs mass may indicate heavy sparticles with mass a few - 10 TeV
- No sparticle signature at LHC so far

Is there any indication of low mass sparticle?

Muon g-2 anomaly

$$\Delta a_\mu \equiv a_\mu(\mathrm{exp}) - a_\mu(\mathrm{SM}) = (28.6 \pm 8.0) \times 10^{-10}$$

Muon (g-2) Collaboration
PRD 73 (2006) 072003;
PRD 80 (2009) 052008

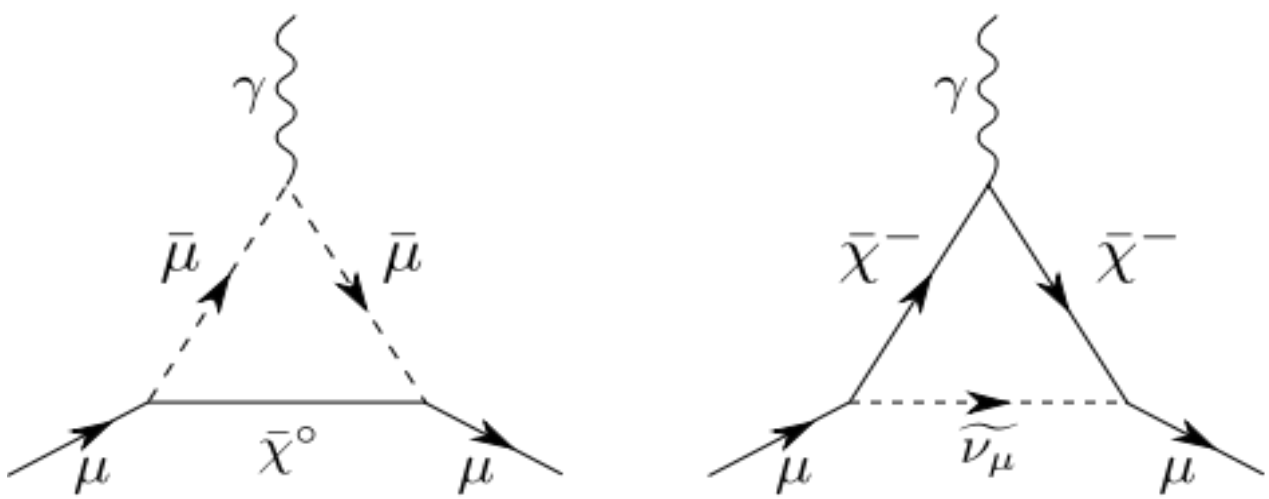
Hagiwara, Liao, Nomura & Teubner
J. Phys. G 38 (2011) 085003
Davier, Hoecker, Malaescu & Zhang
Eur. Phys. J C71 (2011) 1515

$$\Delta a_\mu \equiv a_\mu(\mathrm{exp}) - a_\mu(\mathrm{SM}) = (28.6 \pm 8.0) \times 10^{-10}$$

- SUSY is a primary candidate which can fill the gap

$$\begin{aligned}\Delta a_\mu &= \frac{\alpha\, m_\mu^2\, \mu\, M_2 \tan\beta}{4\pi \sin^2\theta_W\, m_{\tilde{\mu}_L}^2} \left[\frac{f_\chi(M_2^2/m_{\tilde{\mu}_L}^2) - f_\chi(\mu^2/m_{\tilde{\mu}_L}^2)}{M_2^2 - \mu^2}\right] \\ &+ \frac{\alpha\, m_\mu^2\, \mu\, M_1 \tan\beta}{4\pi \cos^2\theta_W\, (m_{\tilde{\mu}_R}^2 - m_{\tilde{\mu}_L}^2)} \left[\frac{f_N(M_1^2/m_{\tilde{\mu}_R}^2)}{m_{\tilde{\mu}_R}^2} - \frac{f_N(M_1^2/m_{\tilde{\mu}_L}^2)}{m_{\tilde{\mu}_L}^2}\right]\end{aligned}$$

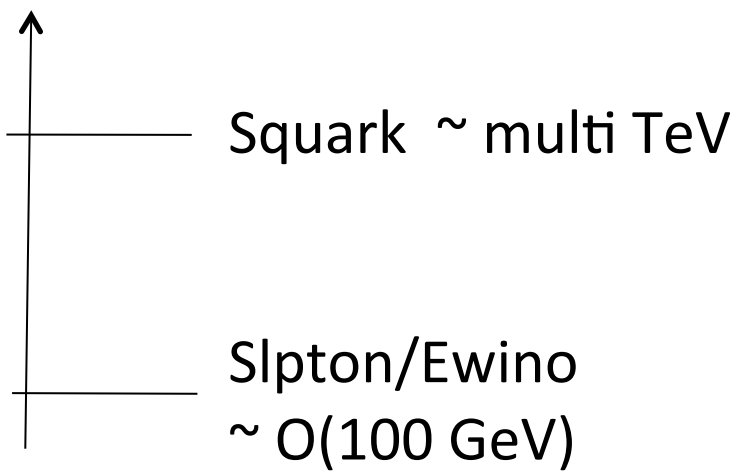
Moroi, PRD 53 (1996) 6565



To explain the discrepancy,

- Smuon mass , wino/neutralino mass = O(100 GeV)
- But, 125-126 GeV Higgs → heavy squark

Reconciling these facts, we may consider
mass splitting between squark & slepton and EWino



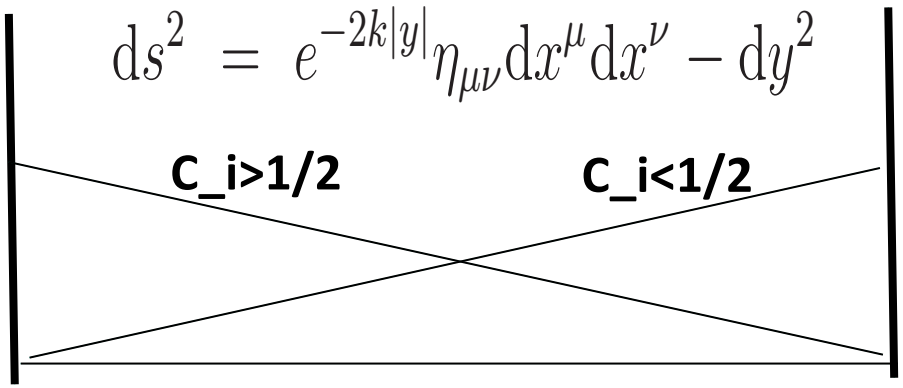
For realization, see, for example,
Evanse, Ibe, Shirai & Yangida,
PRD 85 (2012) 095004
"generic gauge mediation"

DM candidate: gravitino

Model with geometrical splitting of soft masses

5D MSSM with Randall-Sundrum background

$$\mathrm{d}s^2 = e^{-2k|y|}\eta_{\mu\nu}\mathrm{d}x^\mu \mathrm{d}x^\nu - \mathrm{d}y^2$$



Effective 4D cutoff

$$\Lambda_{IR} = \omega M_P$$

$$\omega = e^{-kR\pi} \ll 1$$

(1) Configuration of bulk chiral multiplet:

$$S_{5D\,chiral} = \int \mathrm{d}y \int \mathrm{d}^4x e^{-4k|y|} \left[\int \mathrm{d}^4\theta e^{2k|y|} \left(\Phi_i^\dagger e^{-V}\Phi_i + \Phi_i^c e^V \Phi_i^{c\,\dagger}\right) + \int \mathrm{d}^2\theta e^{k|y|}\, \Phi_i^c \{\partial_y - \chi/\sqrt{2} - (3/2 - c_i)k\}\Phi_i + \mathrm{h.c.} \right]$$

C_i > 1/2 : localized around y=0

C_i < 1/2 : localized around y=pi R

(2) Configulation of bulk gauge multiplet: flat

SUSY breaking on a brane (hidden brane)

Soft mass spectrum V.S 5D wave function configuration

- Flat: volume suppression: $\tilde{m} \times \frac{1}{RM_5}$
- Localized around the brane: $\tilde{m}$
- Localized around the other brane: $\tilde{m} \times \omega^{\alpha}$

By arranging bulk masses for squarks (stops) so as to localize them around the hidden brane, we can achieve

$$m_{\tilde{q}}^2 \gg m_{\tilde{\ell}}^2, m_{\chi}^2$$

Numerical analysis for RGE running mass, Higgs mass, neutralino DM abundance, and muon g-2

NO & Tran, in preparation

$$\Lambda_{IR} = 100 \text{ TeV}$$

$$m_{\tilde{g}}(\Lambda_{IR}) = 1.2 \text{ TeV}, \quad \frac{M_i}{g_i^2} = const$$

$$m_{\tilde{\ell}_{1,2}}(\Lambda_{IR}) = 350 \text{ GeV}$$

$$m_{\tilde{\ell}_3}(\Lambda_{IR}) = 482 \text{ GeV}$$

$$m_{H_u}(\Lambda_{IR}) = 3.5 \text{ TeV}$$

$$m_{H_d}(\Lambda_{IR}) = 3.0 \text{ TeV}$$

$$m_{\tilde{q}}(\Lambda_{IR}) = 11 \text{ TeV}$$

$$A_0(\Lambda_{IR}) = 0 \qquad \tan\beta = 30$$

Outputs at low energy

LSP neutralino: 261 GeV

NLS smuon: 307 GeV

$\mu = 1.7 \text{ TeV}$

- ✓ SM-like Higgs mass: $m_h = 125.6 \text{ GeV}$
- ✓ DM relic abundance: $\Omega_{\tilde{\chi}_0} h^2 = 0.113$
- ✓ Muon g-2: $\Delta a_\mu = 28.4 \times 10^{-10}$

Future prospects

What if

colored new particles are unfortunately out of reach of LHC,
but color-singlet new particles are relatively light?

- Color singlet particle search becomes more important

- LHC search is not easy with small cross section & large background

ILC is ideal for this purpose

- Well-defined initial state
- Clean environments
- Adjustable energy
- Polarized beam

History

JLC (Japan Linear Collider)
Kaoru led many theorists & experimentalists

J(Joint) LC , GLC

ILC

ILC study study

Example) discrimination of dark matter modes

Asano, Saito, Suehara, Fujii, Hundi, Itoh, Matsumoto, NO, Takubo & Yamamoto , PRD 84 (2011) 115003

Variety of WIMP DM models, in which DM particle is accompanied by "charged partner"

DM particle production at ILC

$$e^+e^- \to \chi^+\chi^- \to \chi^0\chi^0 W^+W^-$$

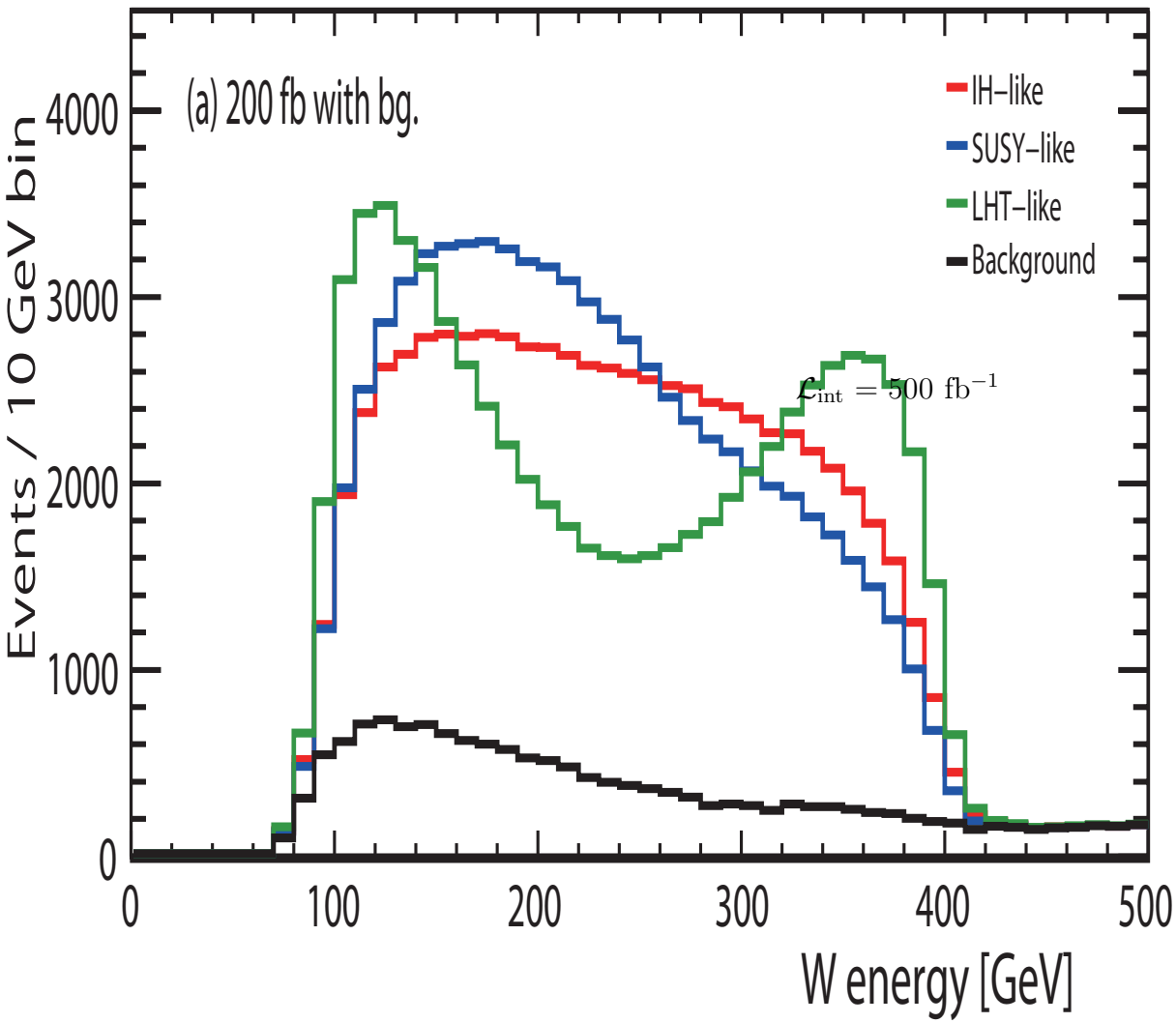
SUSY: fermions

Little Higgs with T-parity: vectors

Inert Higgs model: scalars

Monte-Carlo simulation study

$$\sqrt{s} = 500 \text{ GeV} \qquad \mathcal{L}_{\text{int}} = 500 \text{ fb}^{-1}$$



Mass determination accuracy is

~ 0.2 %

Summary

- 11 years after SUSY 2004
- Lots of progress in experiments and theories
- LHC Higgs discovery (expected)
  Higgs mass ~ 125 GeV (unexpected)
  no SUSY signal (unexpected)
- Higgs mass may indicate very heavy squarks
- Muon g-2 anomaly may indicate light EWinos & sleptons
- Color-singlet sparticle search will become more important
- Hopes: LHC Run 2 and High Luminosity LHC
  International Linear Collider

Special thanks to

Kaoru

It was great for me to be in KEK with you for several years, and to work together for academic activities!

Thanks so much for your supports for me!

We wish you a healthy, productive & happy new life after retirement!