Physics of Dark matter and Universe in the LHC era

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Particle physics has been

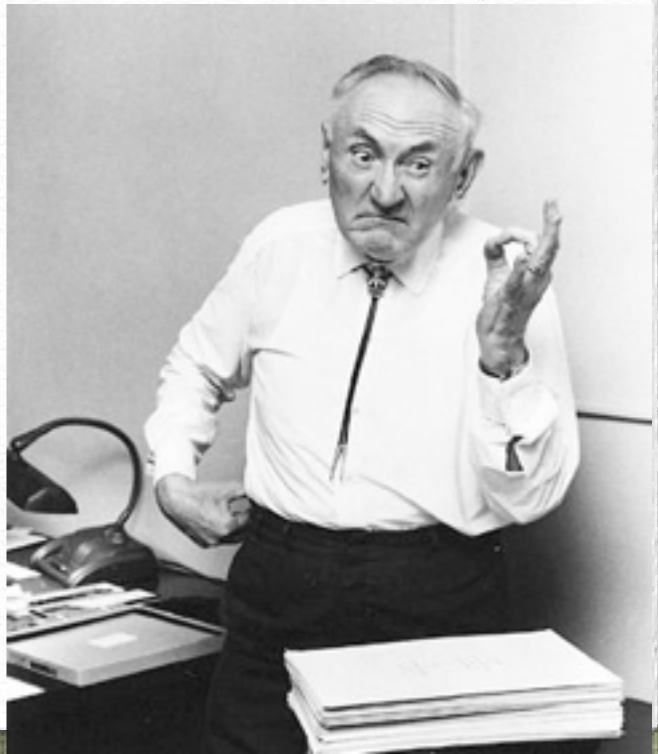
- ….. answering the big question
- Purpose of this talk
  - What particle physics have done in the past
  - What LHC is doing right now
  - Thinking about future

study of Matter as science

- Pre-Science Greece, China idea of element
- Atom (Modern Chemistry)
  →Nuclei+electron (physics)
- Nuclear physics: nuclei→ proton+neutron
- particle physics: proton→quark **gauge symmetry**
- **Dark Matter** (BSM) from rotation curve, lensings

John Dalton

Fritz Zwicky



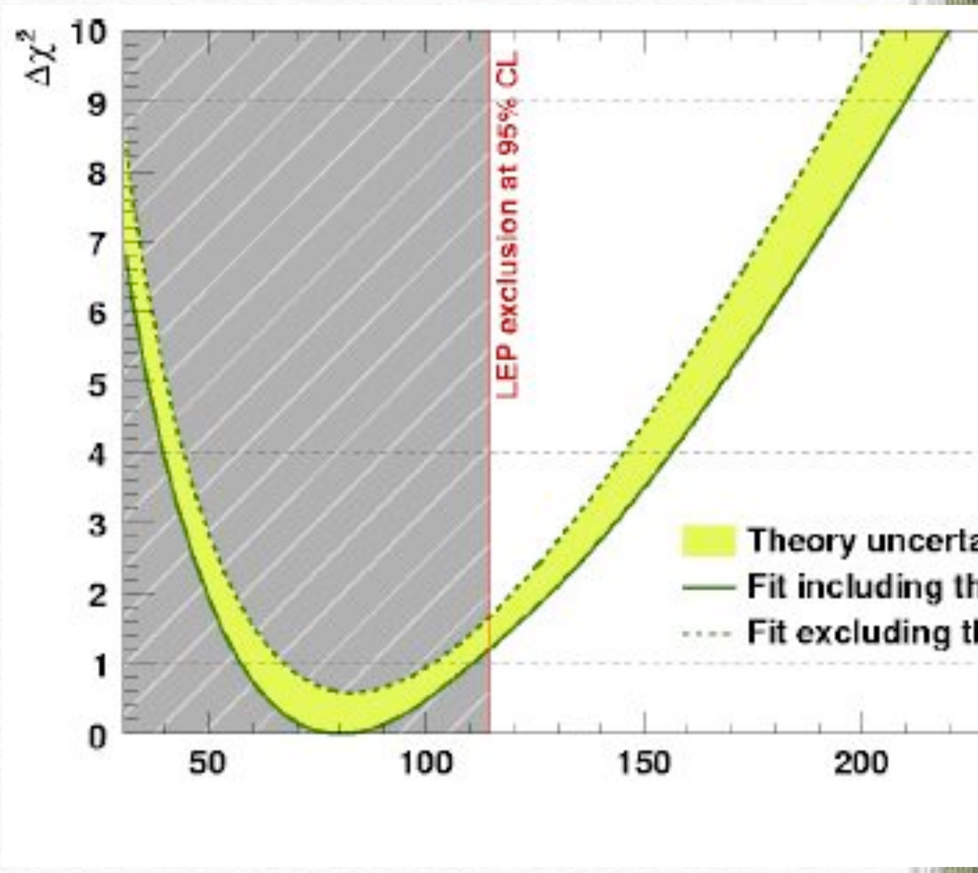
Rutherford

Gell-Mann

Weinberg

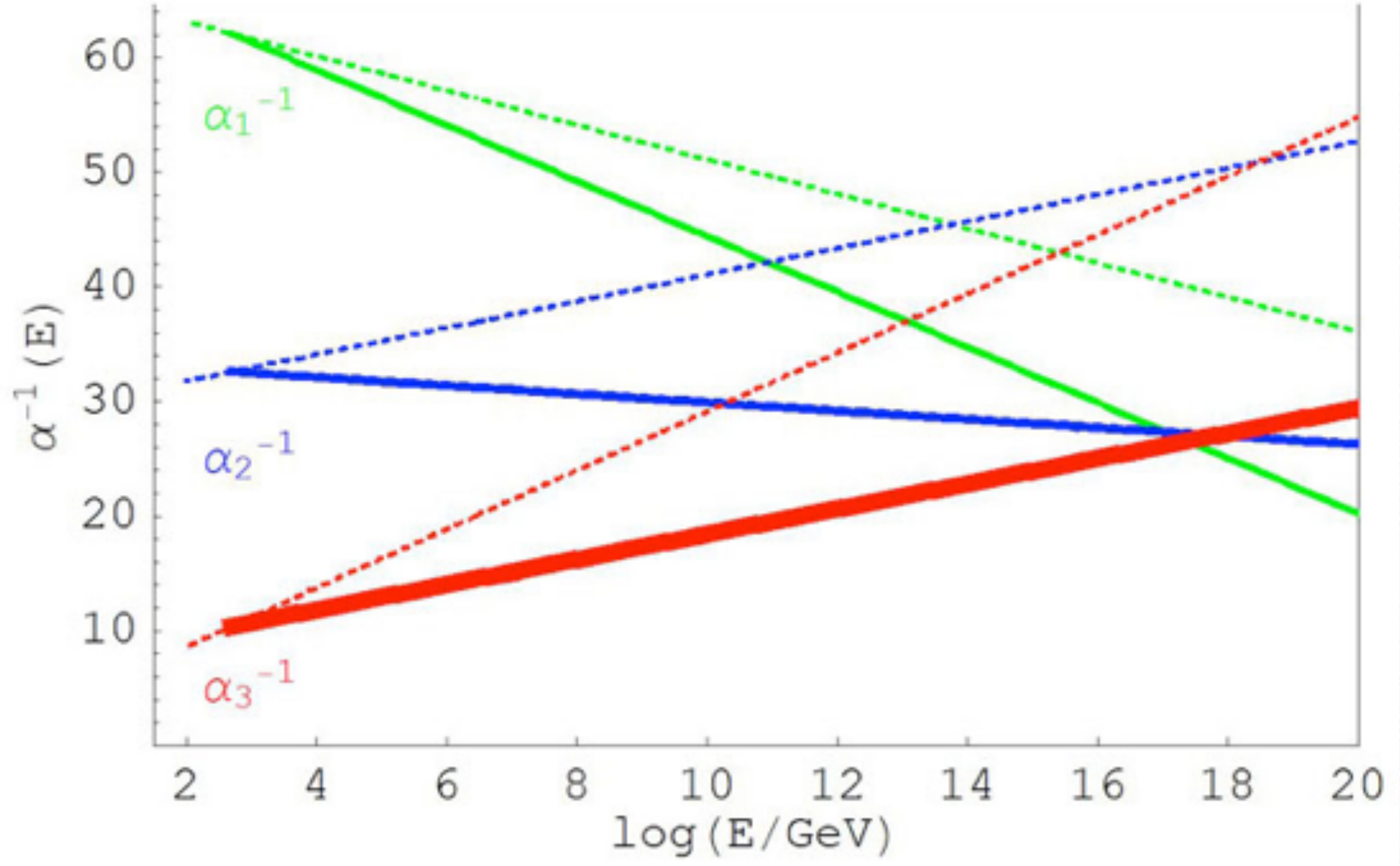
Looking back LEP era

EW precision



- No deviation of standard model. **Field Theory wins**
- Technicolor becomes very difficult to realize
- People have left to **effective theory: Little Higgs model** or **composite model** wheeven Higgs boson is NG boson of some global symmetry **without specifying** the origin of symmetry breaking
- **Important Lessons** have been learned in this approach
  - top sector need to be enlarged → top partner
  - Z2 symmetry separating new sector from SM sector → TeV scale new physics **(stable spin 1 particle as dark matter)**

LEP gauge coupling unification and supersymmetry



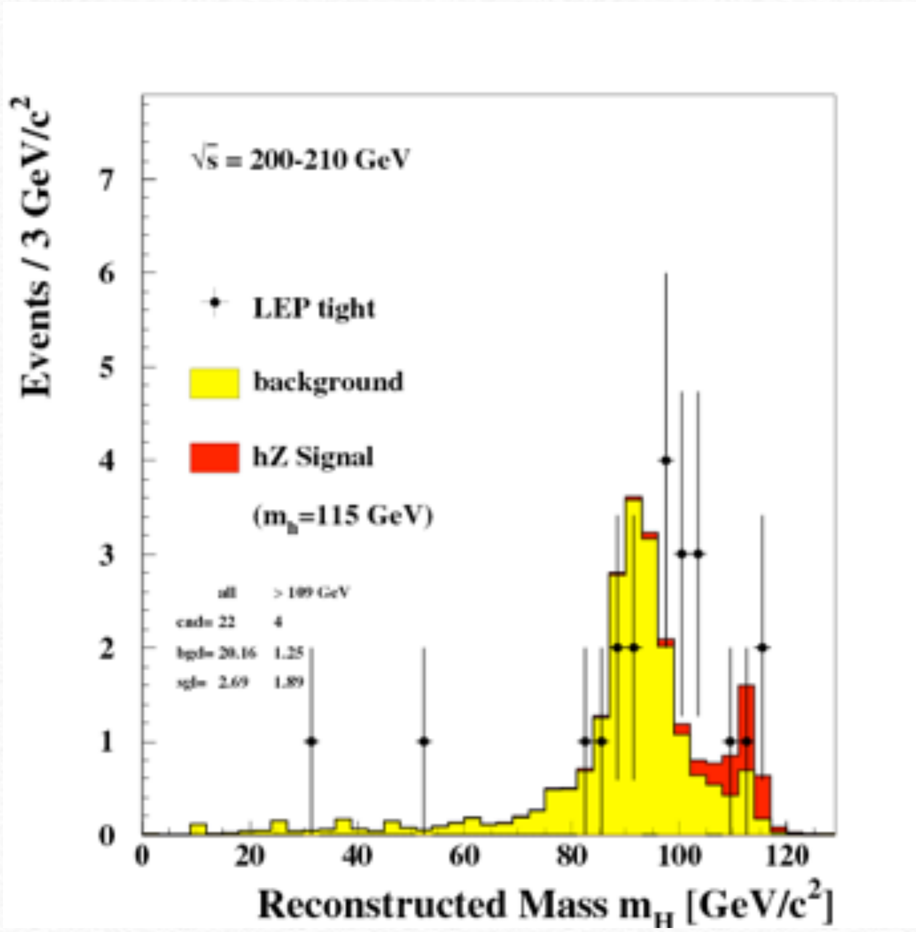
- We thought(in early 90's) 1TeV SUSY + 10^16 GeV coupling Unification (GUT) is promising. Connection to **String theory**
- It is later realized that squark scalar masses can be heavy keeping coupling unification unchanged (split SUSY)
- Lightest supersymmetric particle(LSP) as Dark matter;
- **Spin 1/2 gauge singlet(Bino) , doublet(Higgsino), and Adjoint(Wino)**

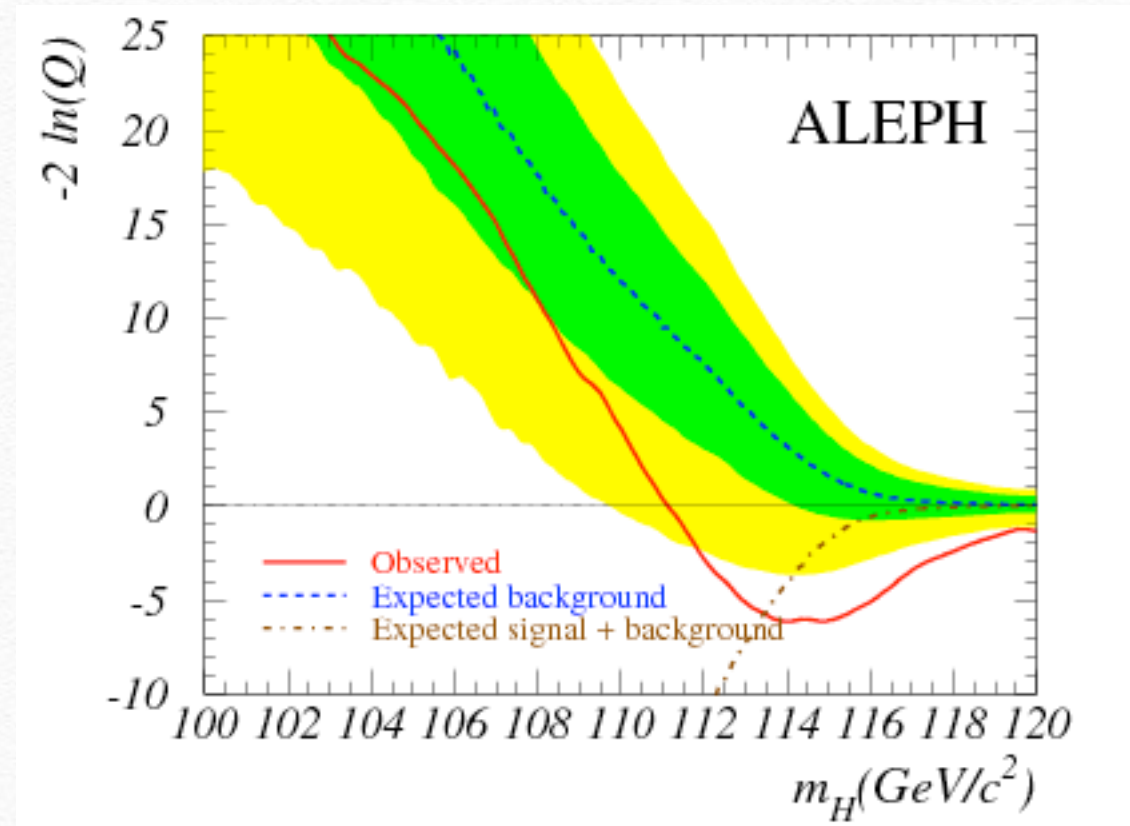
The legend : The 115 GeV Higgs Odyssey

John Ellis (CERN) 2000

(at that time we were planning to start LHC at 2005)

On his way home from Troy, Odysseus had arrived within reach of Ithaca when a great storm blew up. He was swept away, and only several years later was he able to return to reclaim his rights from the rapacious suitors, with the aid of his son Telemachus. Some wonder whether this epic is repeating itself, if the Higgs weighs 115 GeV. If so, are CMS and ATLAS cast in the role of Telemachus? In this paper, I first discuss how close to Ithaca LEP may have been, the fact that a 115 GeV Higgs boson would disfavour technicolour, its potential implications for supersymmetry, and finally the prospects for completing the Higgs Odyssey.





What Odssyey had been doing for 12years: role of Model building

2years (budget) + 2 (delay)+ 2(He) was added

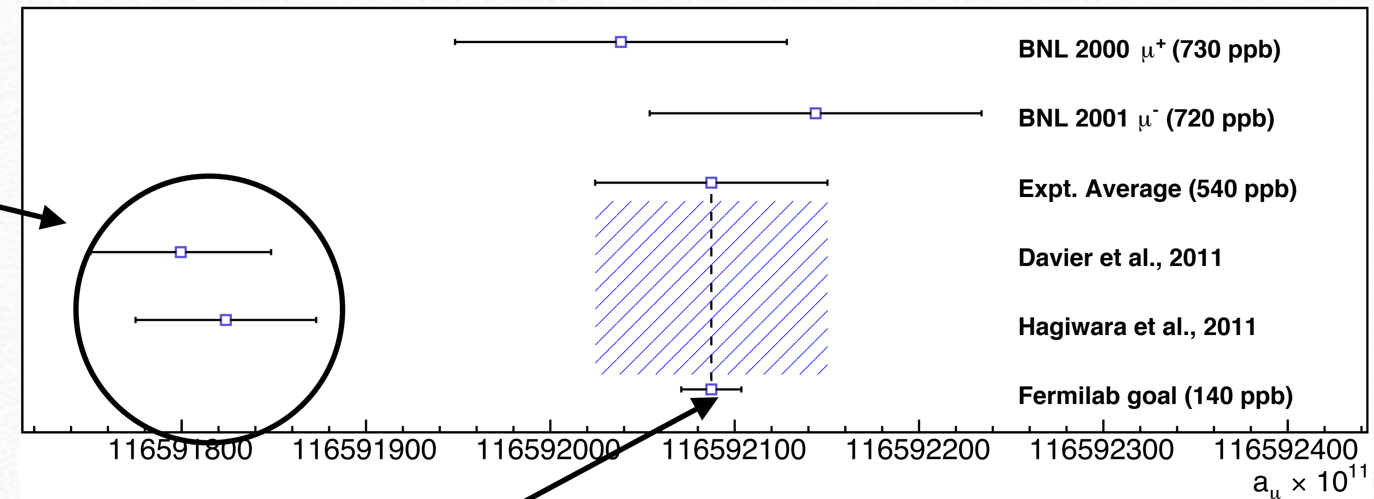
- Gauge Mediation: Low energy SUSY breaking, and **gravitino dark matter** (spin 3/2, effectively spin 1/2 goldstino, Late decay, connection to BBN)
- Anomaly Mediation :suppressed gaugino mass, **wino dark matter**, moduli decay for generation
- Little Hierarchy argument in SUSY: How SUSY~1TeV (compatible with 115GeV) can be natural?

- **Large Extra dimension(1998) Warped Extra dimension(1999) Universal Extra dimension** : Planck scale can be same order in EW scale. Yukawa coupling can have geometrical meaning, U(1) **gauge boson KK dark matter**
- **Little Higgs models (2001)** & **Minimal composite models**

deviations from SM

muon g-2 (more than 3σ)

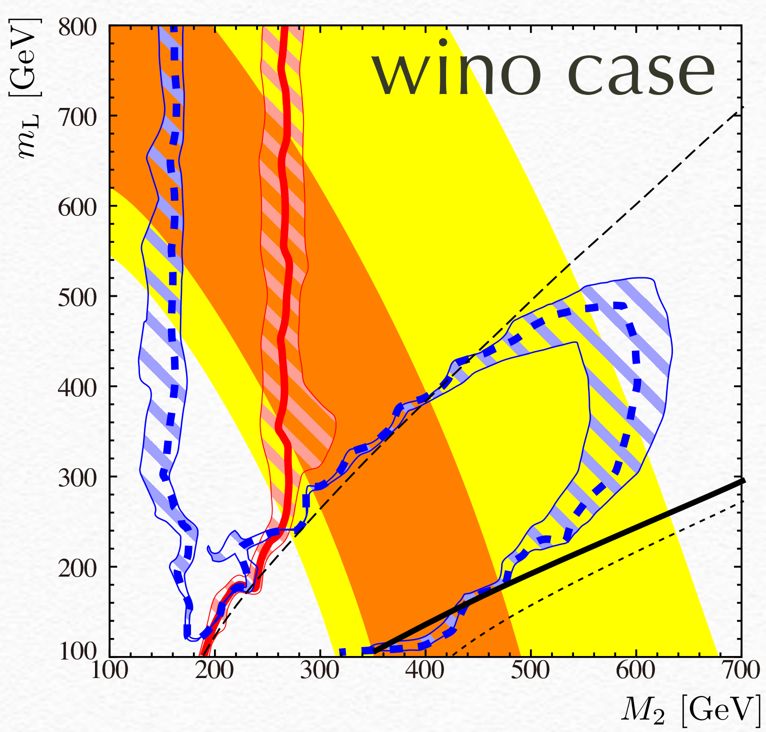
Theoretical error
light by light→lattice
hadronic vacuum
→BESIII VEP2000 BaBar



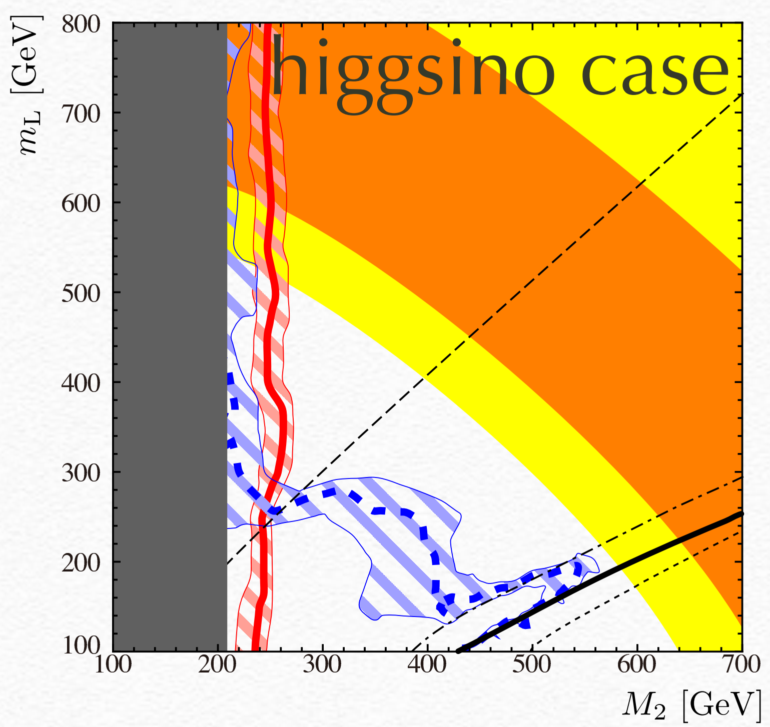
new data from 2017
Fermilab E989 J-PARC E 34

from 1510.00346 Gray

Require charged particle couples to muons(tanbeta =40)



(b) $\mu = 2M_2$, $m_R = 3\,\text{TeV}$



(c) $\mu = M_2/2$, $m_R = 3\,\text{TeV}$

LHC currently does not have access to the case that m(slepton)> m(wino)

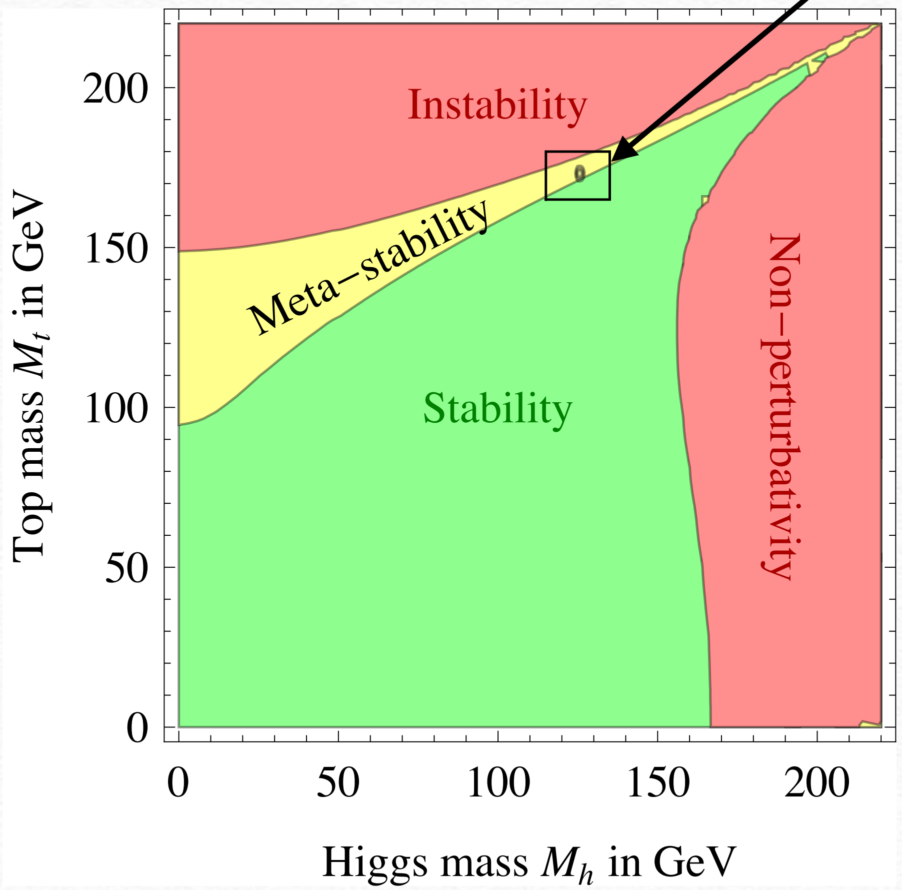
Endo Hamaguchi , Iwamoto ,Yoshinaga
JHEP 1401(2014) 123

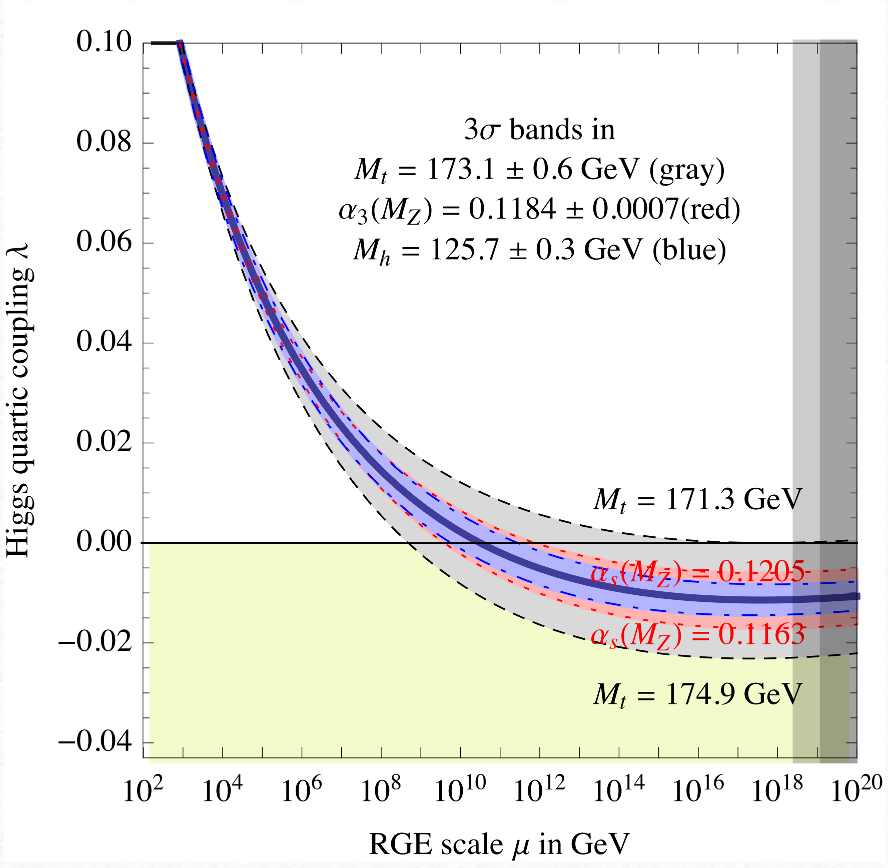
What LHC have done so far

- finding SM Higgs boson at 125GeV
- not finding SUSY ~TeV range
- not finding any top partner <TeV range
- Finding bumps and peaks with low significances

Higgs boson and Universe

Tevatron and LHC





Recent Cosmological issues:

Kearney, Yoo, Zurek Physical Revew D91 123537

probability of Higgs field falls in unstable region during the inflation can be significant.

potential danger developing anti-de Sitter patches

Espinosa, Giudice, Morgante, Riotto,Senatore Strumia, Tetradis JHEP 1509(2015) 174

lower limit to reheating temperature depending on the Higgs coupling to gravy and Habble constant during the inflation.

Potential "meta stability" is fragile

- Interaction of Higgs boson has not determined precisely
- **Dark matter sector can couple to Higgs sector of SM only**
- potential stability is sensitive to the unknown four point coupling therefore may not be essential.

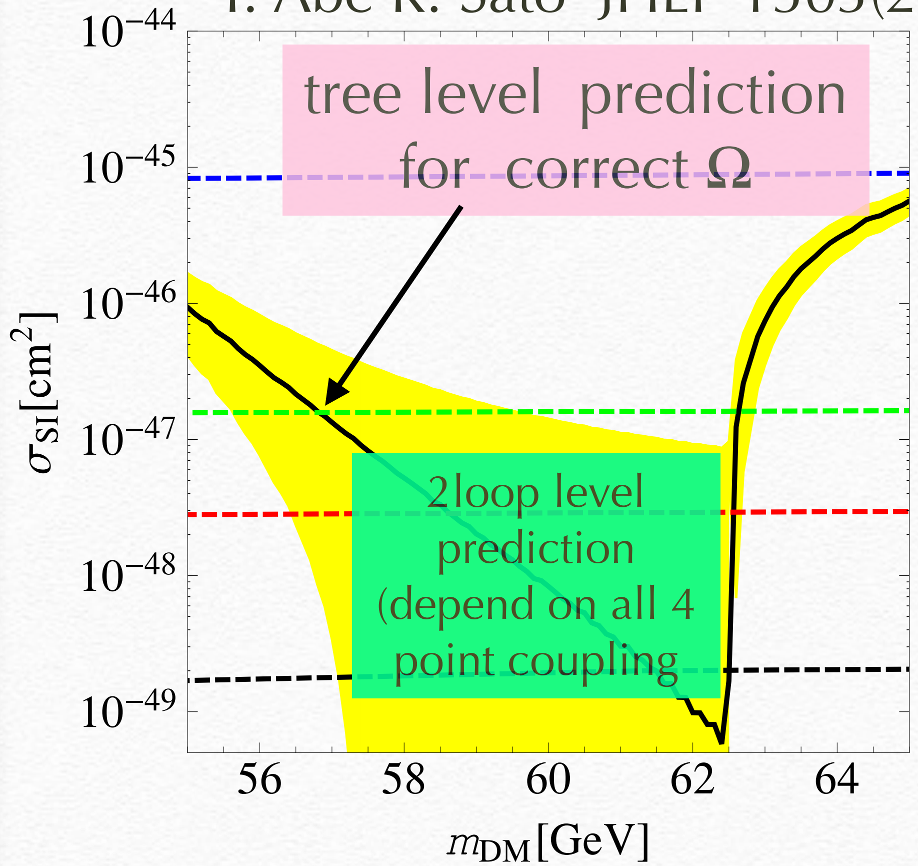
Z2 parity in extra Higgs sector

singlet $\mathcal{L}_{S1} = -\frac{m_1^2}{2}s^2 - \frac{\lambda_{sH}}{2}s^2|H|^2 - \frac{\lambda_s}{4!}s^4.$

T. Abe R.Kitano R. Sato
PRD 91(2015) 095004

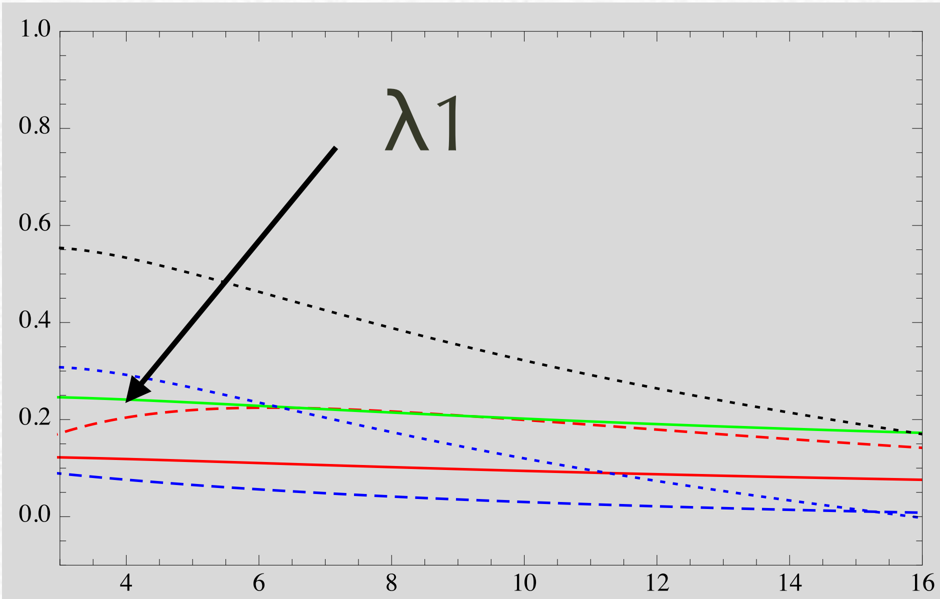
doublet $\mathcal{L}_{S2} = -m_2^2|H_2|^2 - \lambda_1|H|^4 - \lambda_2|H_2|^4 - \lambda_3|H|^2|H_2|^2 - \lambda_4|H^\dagger H_2|^2 - \frac{\lambda_5}{2}\left[(H_2^\dagger H)^2 + h.c.\right].$

T. Abe R. Sato JHEP 1503(2015) 109

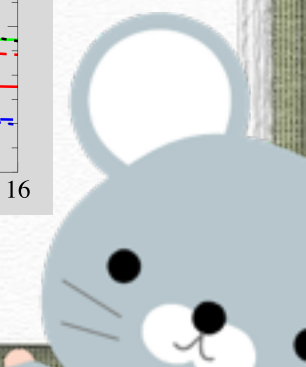


and vacuum can be stable

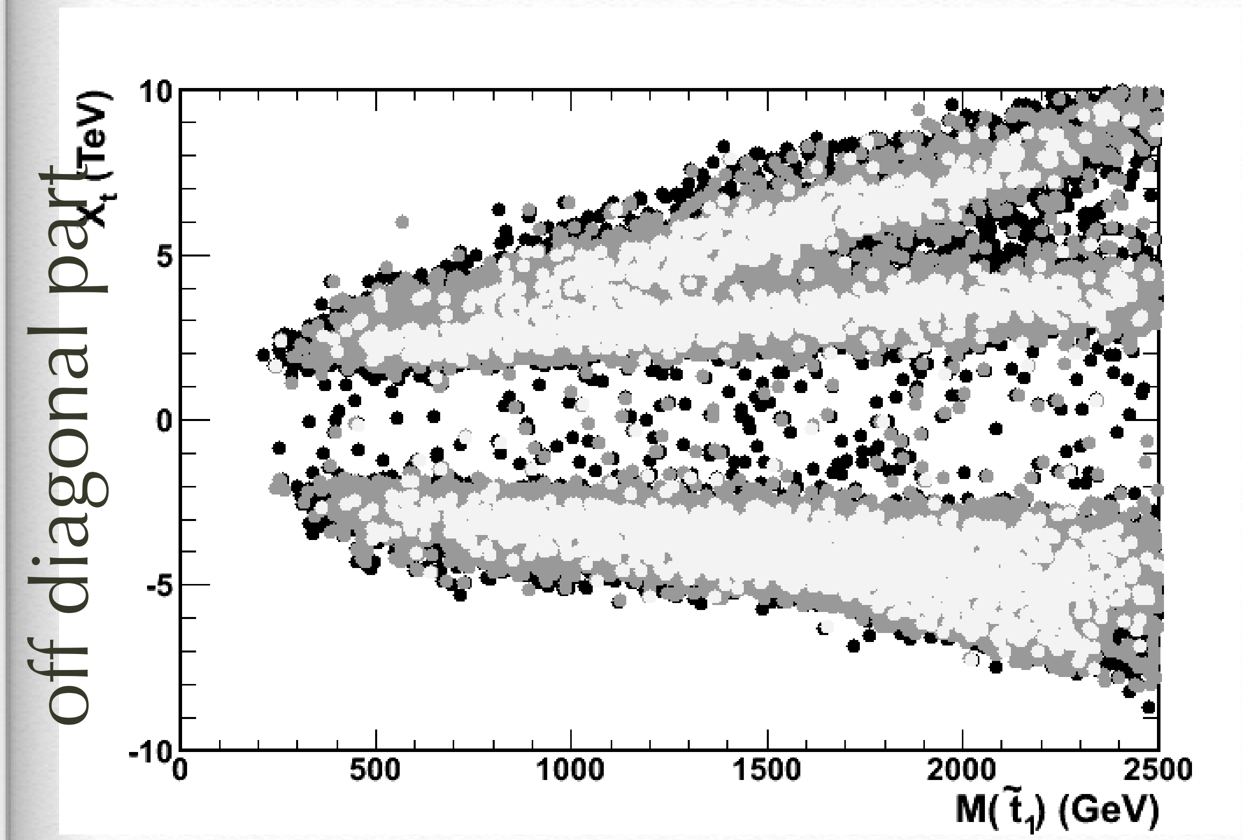
(Thanks to Abe-san)

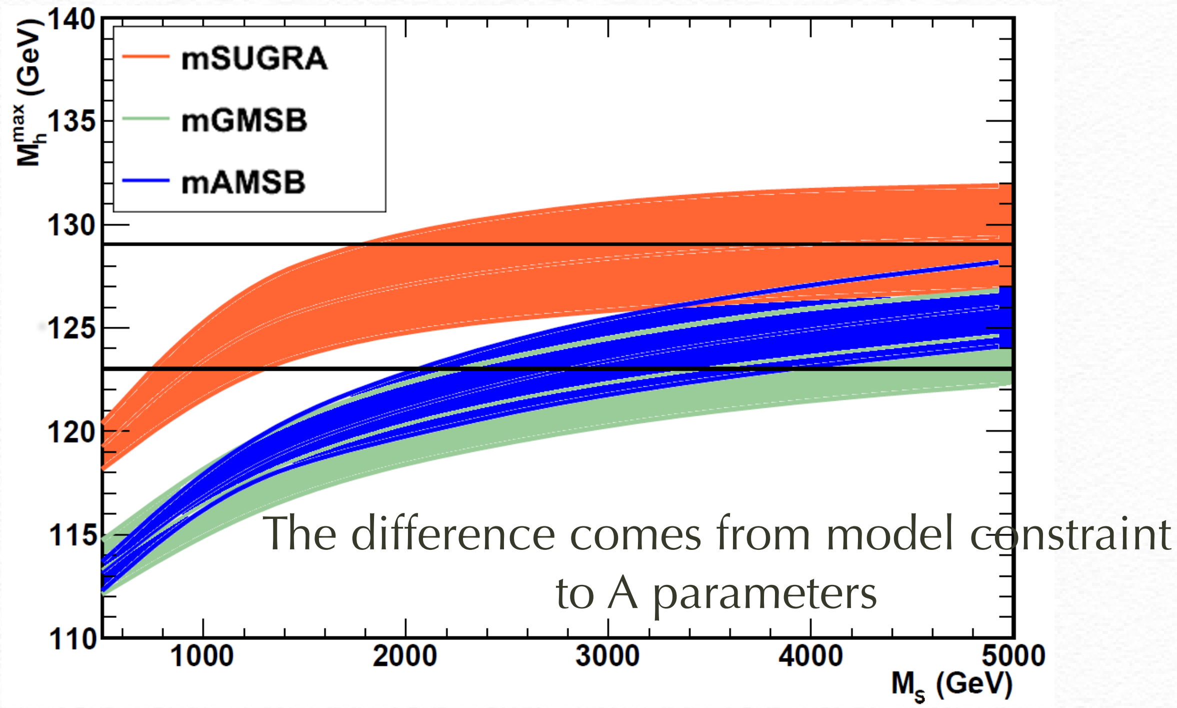


泰山鳴動鼠一匹



Supersymmetry? (vacuum is bounded from below)
stop mass and its left-right mixing is greatly constrained.





large stop mixing required

large SUSY scale required

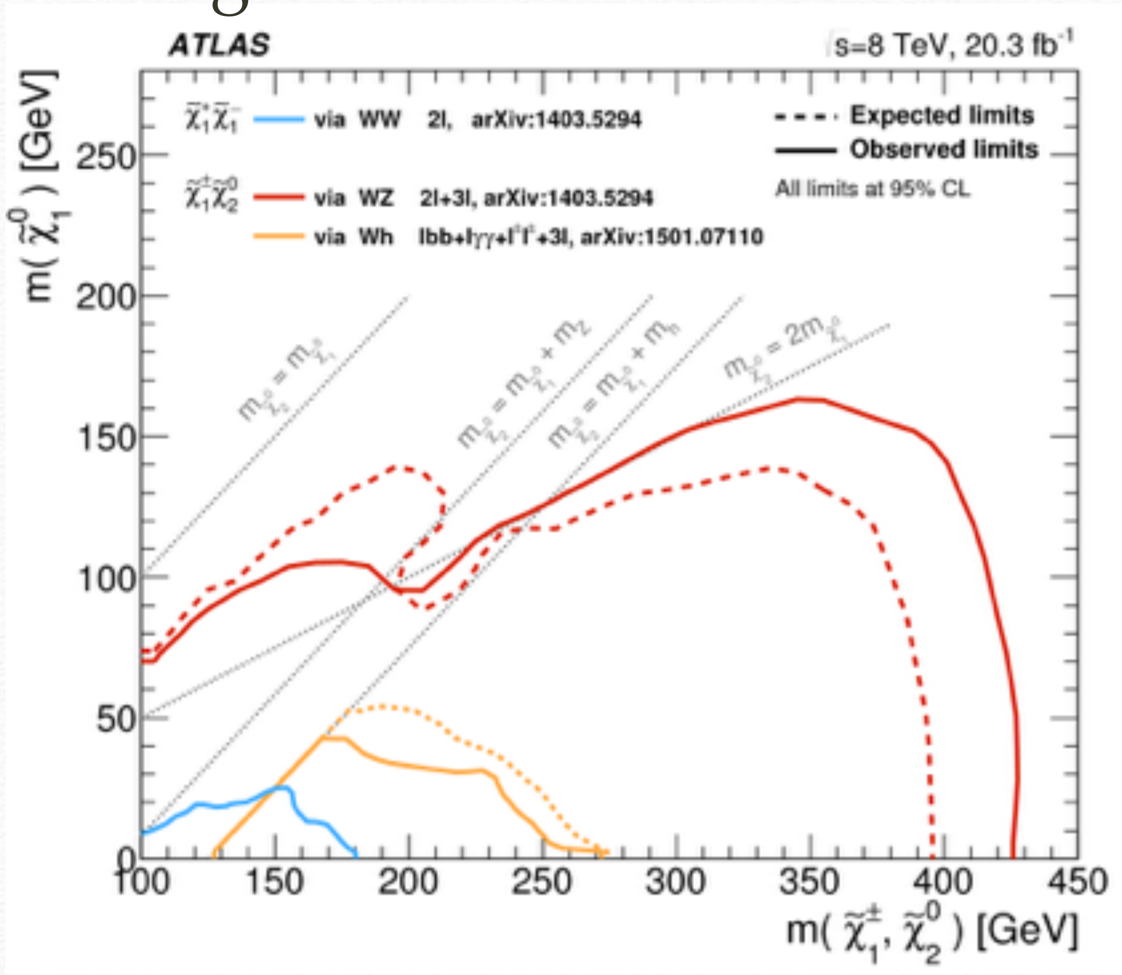
Tension is strong for gauge mediation→model extension
(see for example JHEP 1506(2015) 144)

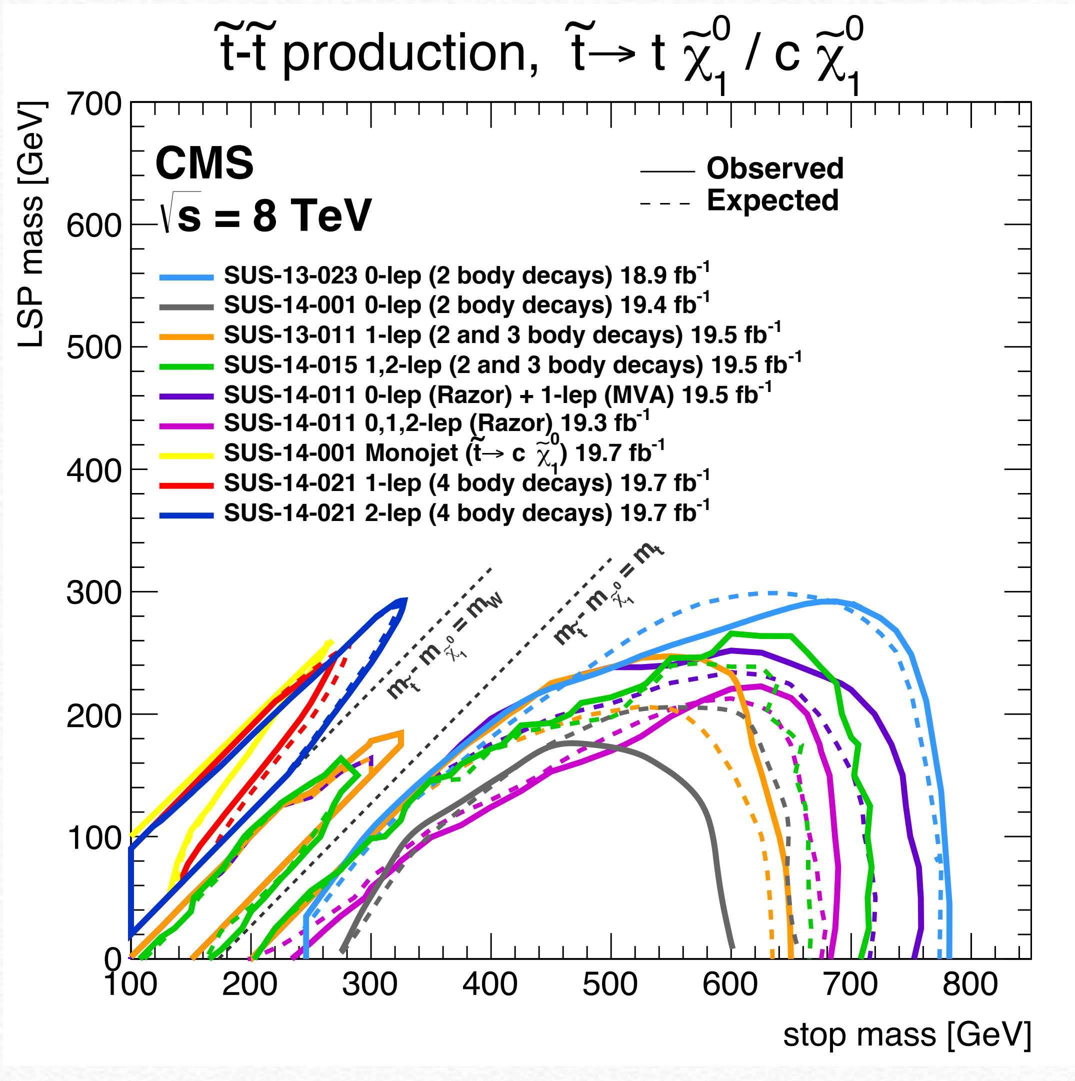
$$M_S = \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$$

Searches at LHC

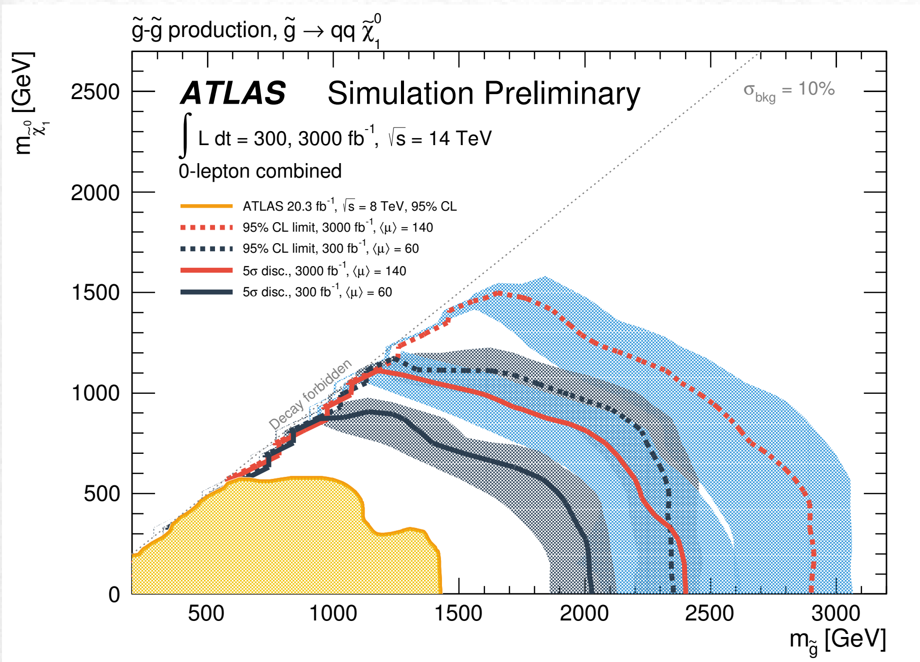
- g-2 implies light EW SUSY particles and and relatively light dark matter
- Higgs mass→ heavy or mixed stop, do not want to miss it by any chance.
- Need care of degenerate SUSY

light EWino search





Waiting for LHC runII data LHC at 13TeV toward HL-LHC

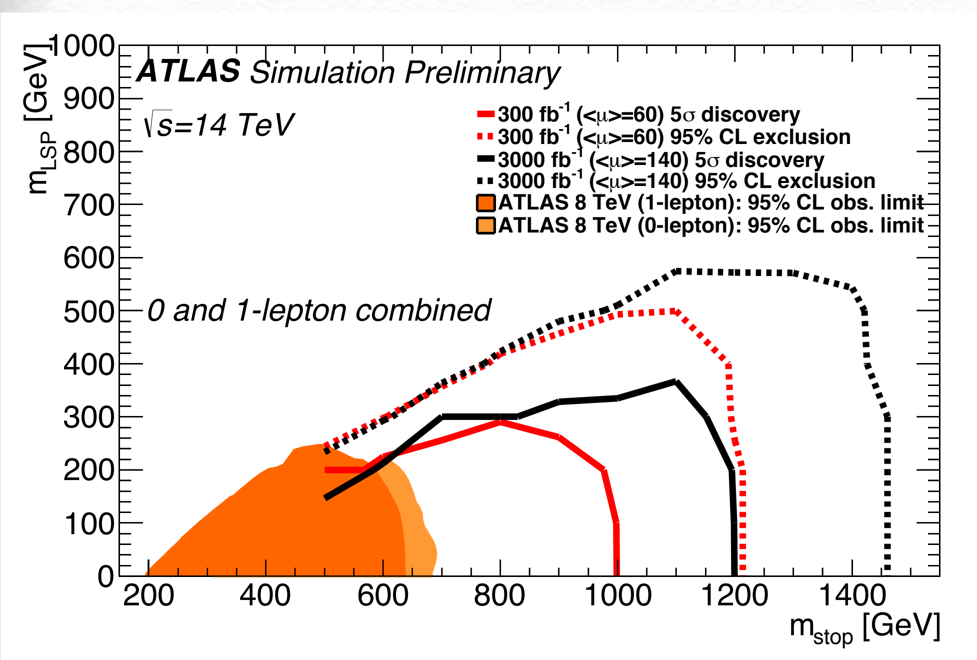


(a) $\tilde{q}\tilde{q}$

.... and It is not so impressive

Exclude gluino mass up to 3TeV and (up to 1.5TeV for degenerate)

scalar top up to 1.4TeV (discovery 1.2TeV)



discovery potential of stop
—Future prospects 1309.1514

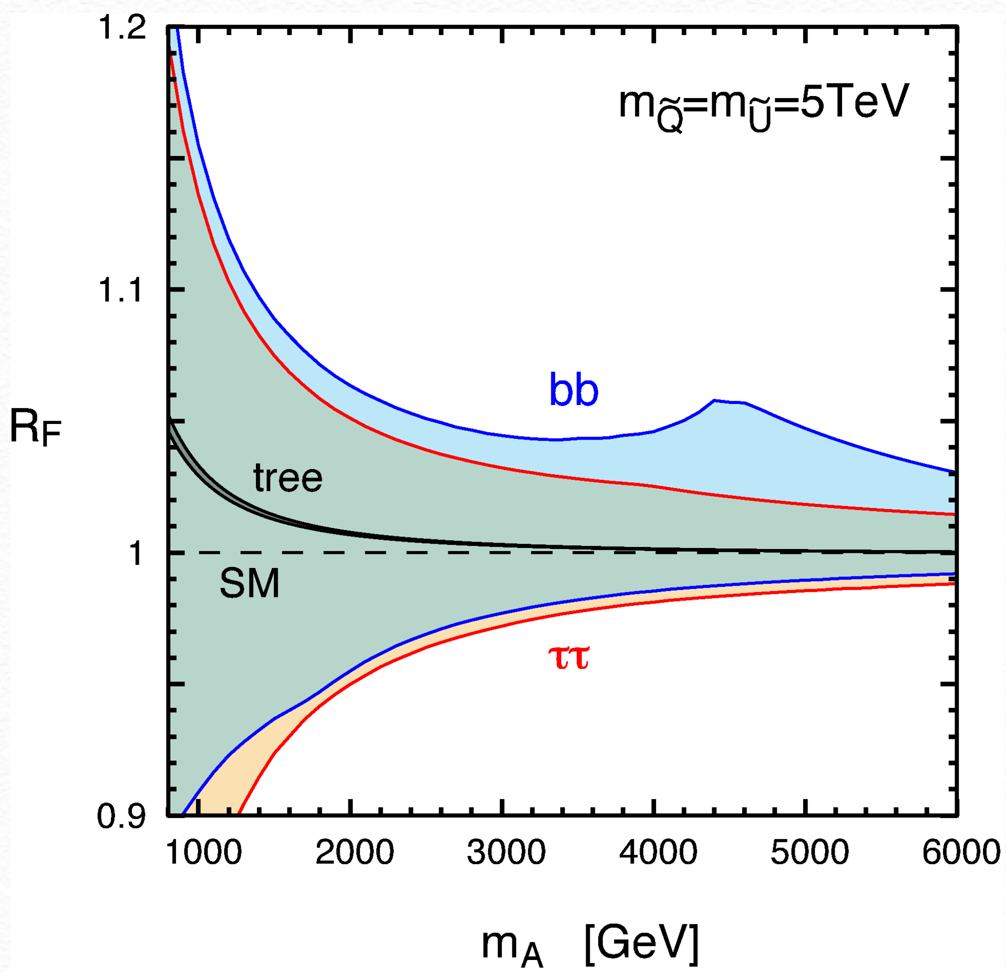
Collider	Energy	Luminosity	Cross Section	Mass
LHC8	8 TeV	20.5 fb^{-1}	10 fb	650 GeV
LHC	14 TeV	300 fb^{-1}	3.5 fb	1.0 GeV
HL LHC	14 TeV	3 ab^{-1}	1.1 fb	1.2 TeV
HE LHC	33 TeV	3 ab^{-1}	91 ab	3.0 TeV
VLHC	100 TeV	1 ab^{-1}	200 ab	5.7 TeV

High scale SUSY

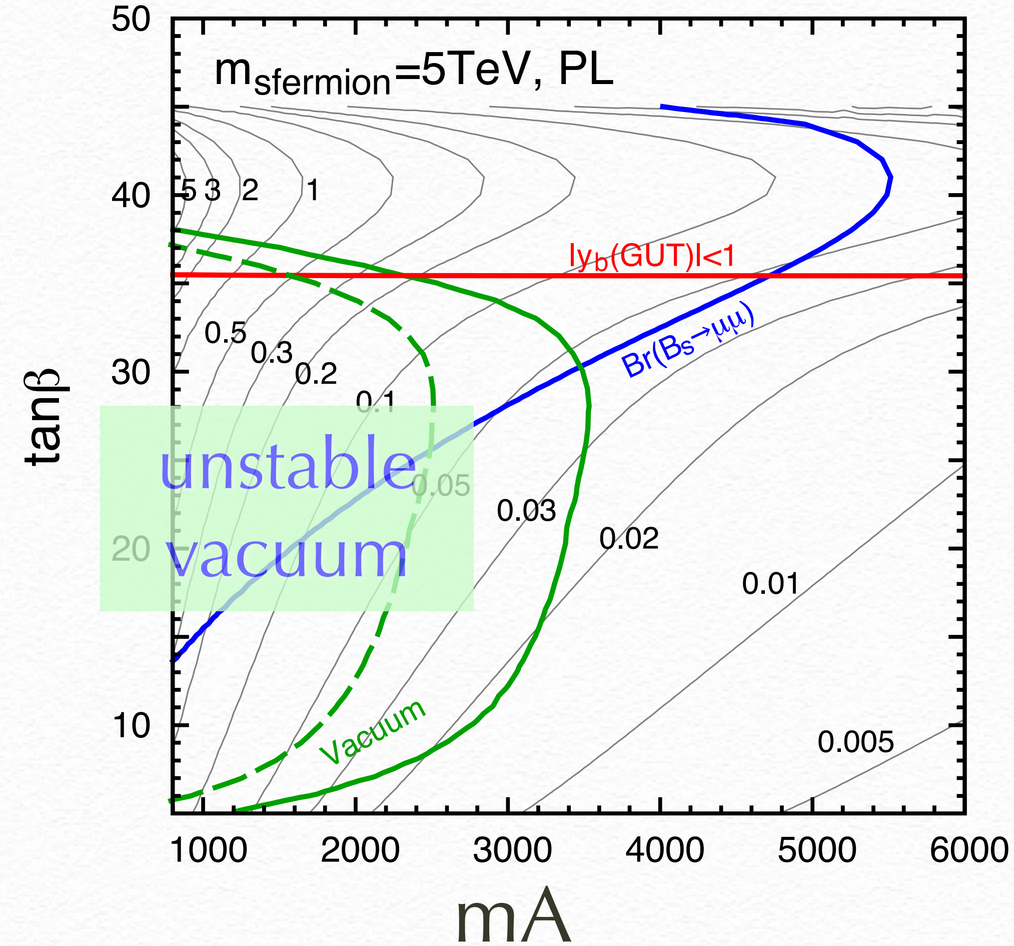
- Correction to the Higgs coupling is comparable to the proposed ILC sensitivity. (Large stop mixing→non-decoupling correction for moderate mA)
  - Flavor physics(Belle II, J-PARC)
    low scale SUSY → large At
    High scale SUSY →rooms for non-universal squark mass
  - **CCB constraint** from $A_tH_ut_Lt_R$ term has been considered seriously **but $\mu H_d t_L t_R$ can be same order. Large scale uncertainty**

Endo, Moroi, MN JHEP 1504(2015) 176

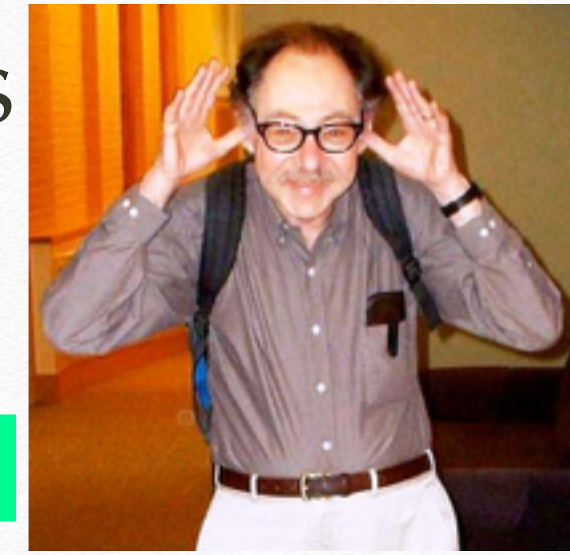
upper limit to Hbb coupling deviation



coupling deviation in mA and tanβ plane



comment precise numerical calculations of lifetime of metastable vacuum



Callan & Coleman('77)

$$\gamma \equiv \mathcal{A} e^{-\mathcal{B}},$$

Euclidean action of bounce solution

and fluctuation which is often ignored

solution of the equation of motion in the bounce background

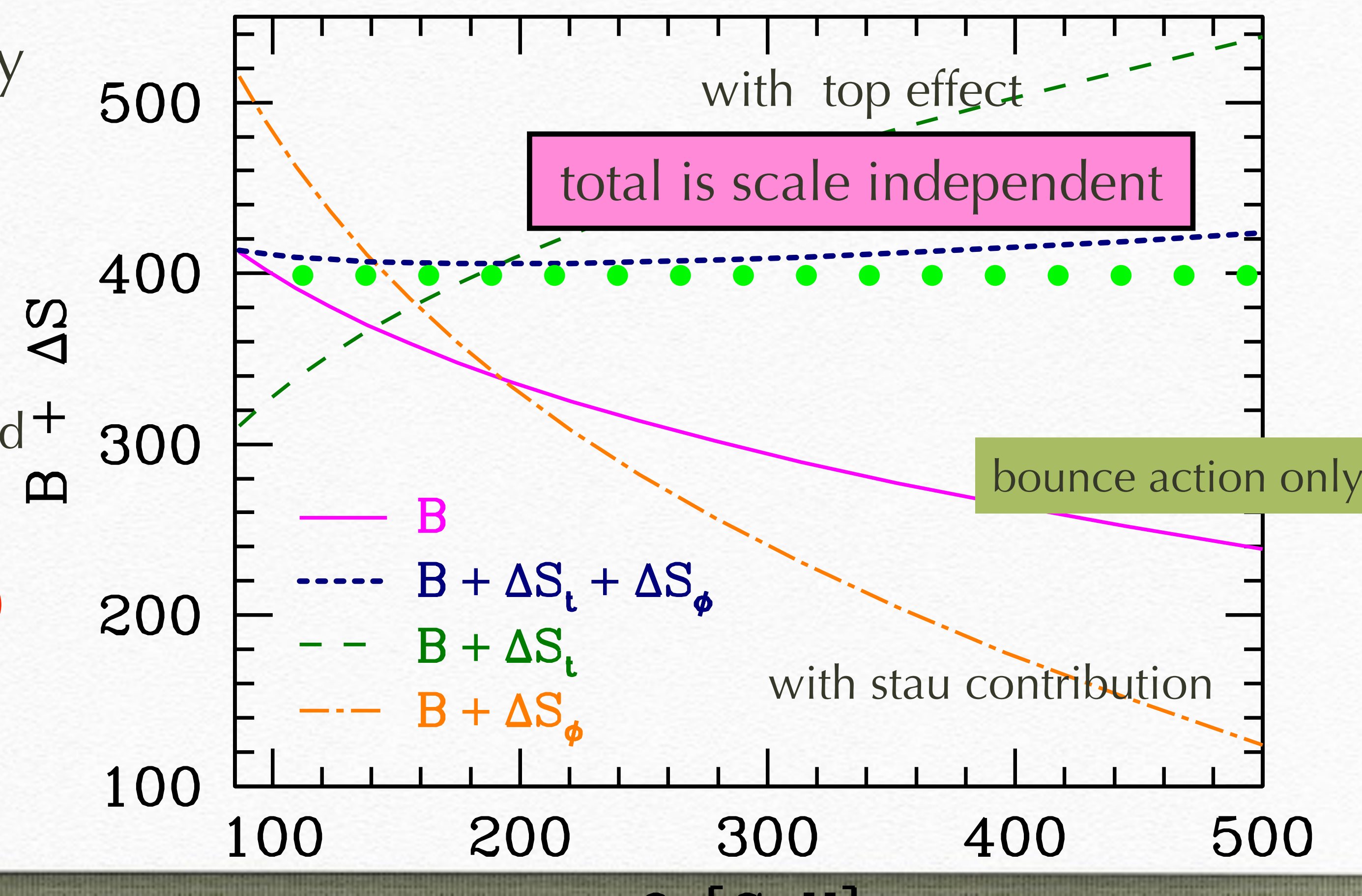
$$\mathrm{Det}\left[\frac{-\partial^2 + W}{-\partial^2 + \bar{W}}\right] = \prod_J \mathrm{Det}\left[\frac{-\Delta_J + W}{-\Delta_J + \bar{W}}\right] = \prod_J \det(\varphi_J/\bar{\varphi}_J)^{N_J}\Big|_{r=\infty}$$

only total γ is scale independent.
If A is ignored , the scale uncertainty is huge.

It is possible to numerically compute γ in full (Thanks to the good computers, and good numerical packages and a talented PD)

Endo, Moroi, MN, Shoji (1511.04860)

low energy effective theory of scalar tau Higgs, and top with false vacuum



EFT and simplified models for DM study at LHC

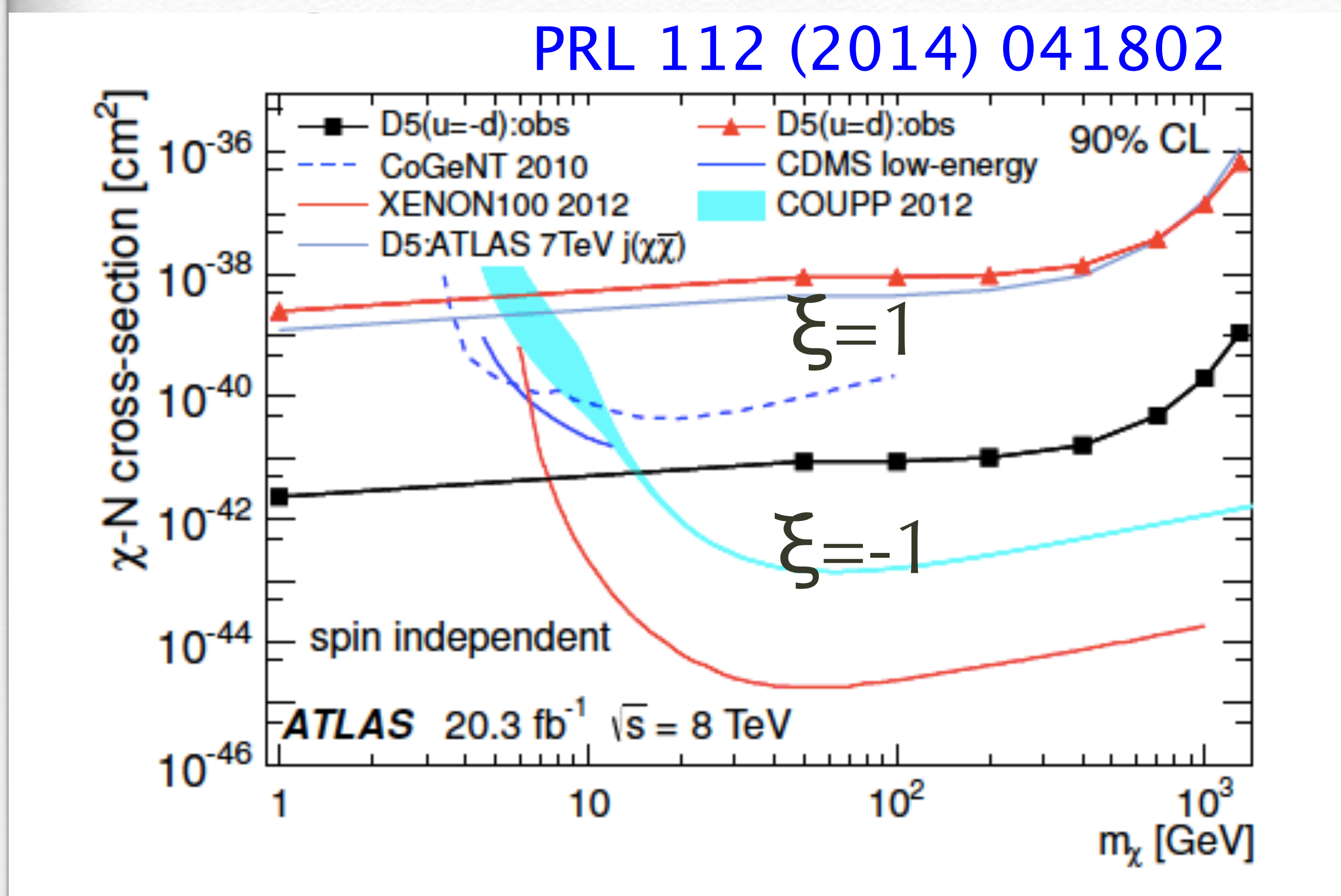
- Dark matter scattering depends on the low energy higher dimensional operators
- **Question: can we compare the sensitivity of the Dark Matter search to LHC**
- A proposal: add the effective operator to the Lagrangian and see the effect, Goodman et al, 2010 Phys. Lett. B 695(2011) 185-188, PRD82 (2010) 116010
  - **Merit? the effect of the same operator.**
  - **Demerit: In many theory involving DM, the phenomenology is quite different at LHC**
- **recent trend is simplified model (specify mediator and renormalizable theory only)**

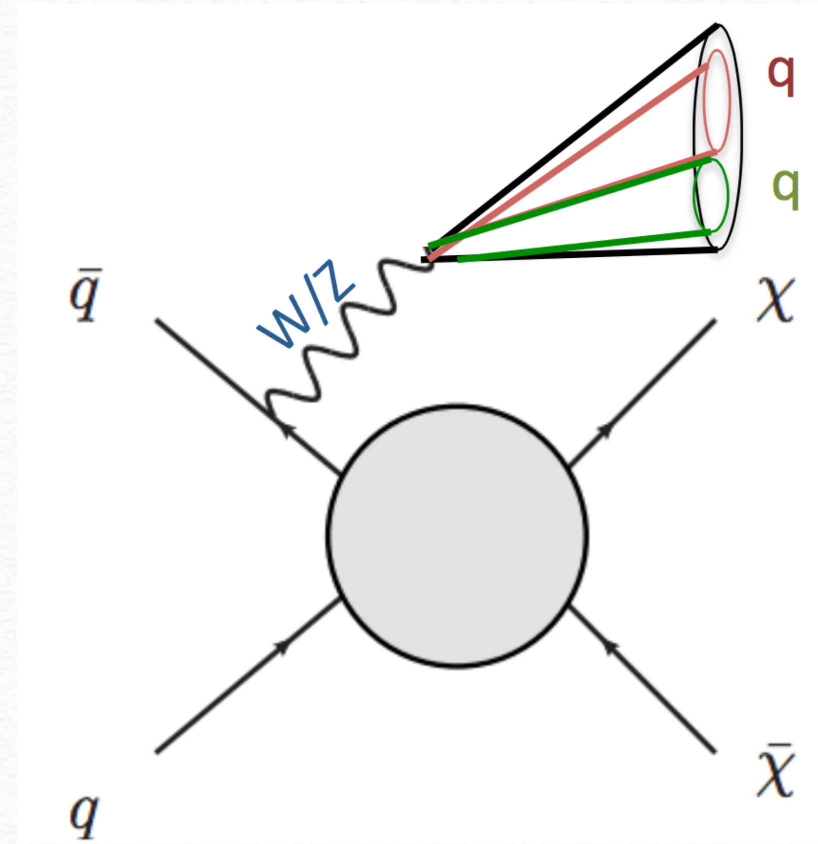
Name	Operator	Coefficient
D1	$\bar{\chi}\chi\bar{q}q$	m_q/M_*^3
D2	$\bar{\chi}\gamma^5\chi\bar{q}q$	im_q/M_*^3
D3	$\bar{\chi}\chi\bar{q}\gamma^5 q$	im_q/M_*^3
D4	$\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$	m_q/M_*^3
D5	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D6	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D7	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D8	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D9	$\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$	$1/M_*^2$
D10	$\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi\bar{q}\sigma_{\alpha\beta}q$	i/M_*^2
D11	$\bar{\chi}\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^3$
D12	$\bar{\chi}\gamma^5\chi G_{\mu\nu}G^{\mu\nu}$	$i\alpha_s/4M_*^3$
D13	$\bar{\chi}\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^3$
D14	$\bar{\chi}\gamma^5\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$\alpha_s/4M_*^3$

Mono-W or Mono-Z search problem

Bai and Tait Phys. Lett B723:384-387

$$\frac{1}{\Lambda^2}\,\overline{\chi}\gamma_\mu\chi\ \left(\overline{u}\gamma^\mu u + \xi\,\overline{d}\gamma^\mu d\right)$$





The operator is manifestly SU(2) non-invariant but calculating amplitude with gauge boson.

Only calculable in Unitary gauge(namely non-Unitary)

W_L amplitude blows up (sign of inconsistency) overestimating the effect.

No ultraviolet completion having this huge enhancement found so far.

top partner example of a gauge invariant model with gauge non-invarint EFT (not DM)

arXiv 1512.04855 Han, Park, MN

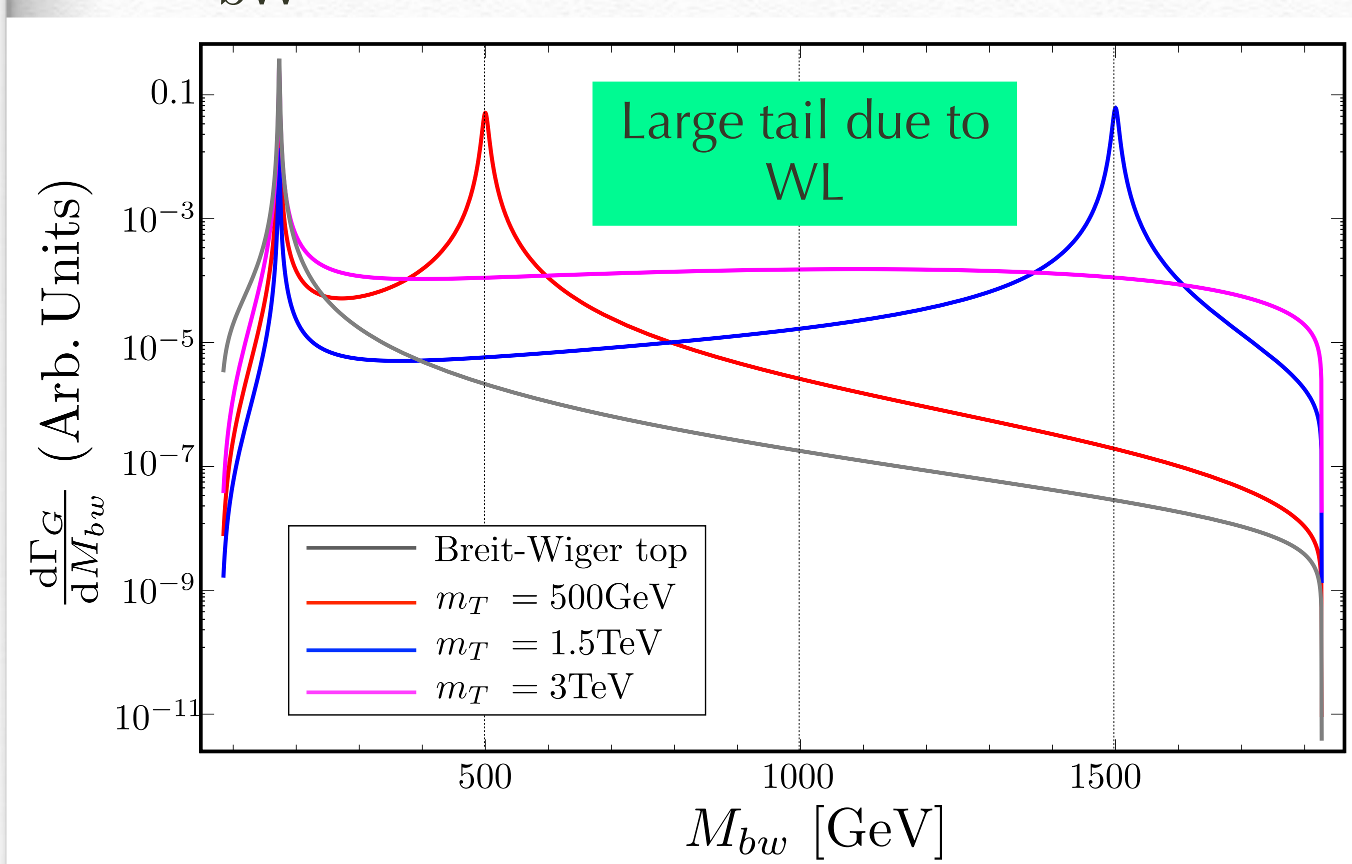
color octet massive spin 1: G
vector like top partner: T
Q-T mixing: y

$$\mathcal{L} \ni c_1 g_s G_\mu \bar{T}\gamma^\mu T + c_2 g_s G_\mu \bar{t}_R \gamma^\mu t_R + c_3 g_s G_\mu \bar{Q}_L \gamma^\mu Q_L - M\bar{T}T - (y\bar{Q}_L \tilde{H} T_R + y_t \bar{Q}_L \tilde{H} t_R + h.c.), \qquad (1)$$

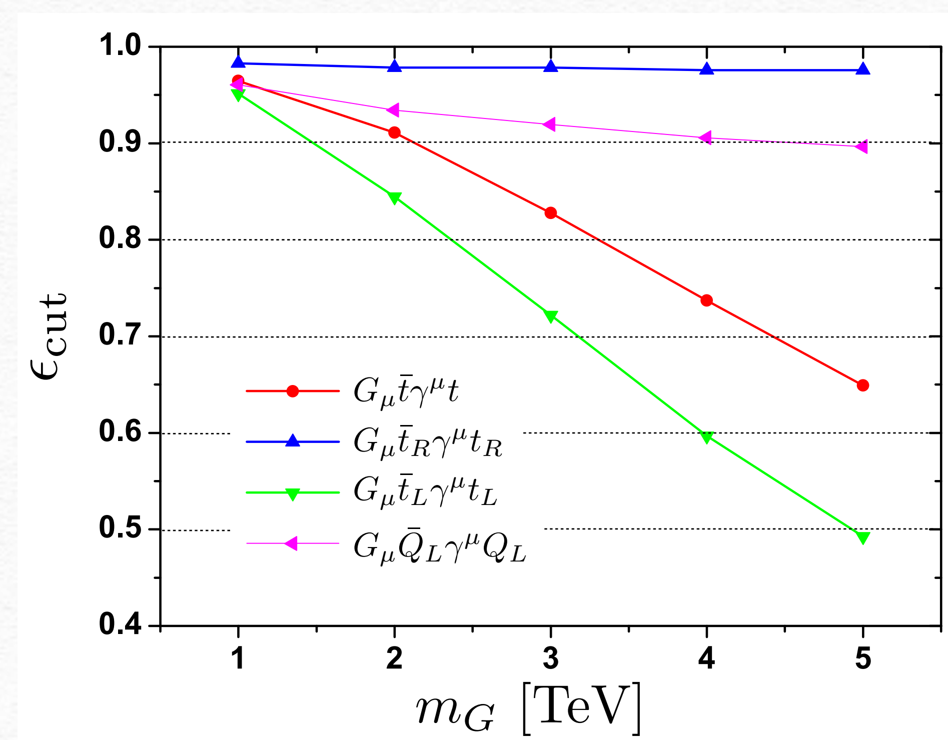
non SU (2) invariant effective action

coupling structure
$G_\mu \bar{t}\gamma^\mu t$
$G_\mu \bar{t}_R\gamma^\mu t_R$
$G_\mu \bar{t}_L\gamma^\mu t_L$
$G_\mu \bar{Q}_L\gamma^\mu Q_L$

m_{bW} distribution of G → t bW



[G→ tt]/ [G→ (tt+ t bw)]



thoughts

- We currently have no data, but BSM models still shine (though I have been always in phenomenology side myself)
- Only full model, and correct field theory can connect dark matter physics with high energy phenomena
- We should not give up chasing the right answer.