expectation for e^+e^- colliders

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Collider physics should address big questions

Because it is very costly

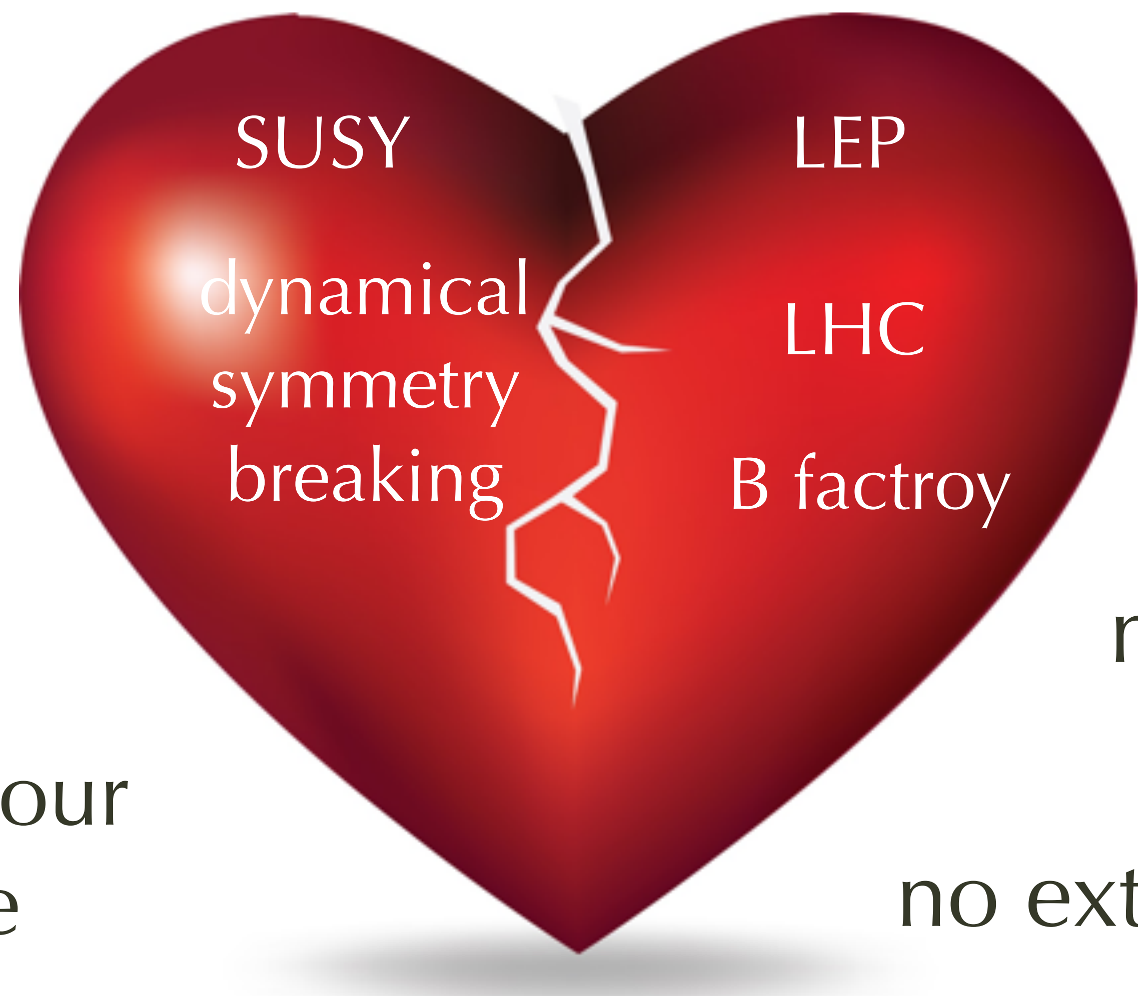
existing Mystery

Matter content &gauge interaction

Why Higgs boson is light?

dark matter

baryons in our Universe



Constraints

no large EW correction

no extra FCNC

no proton decay

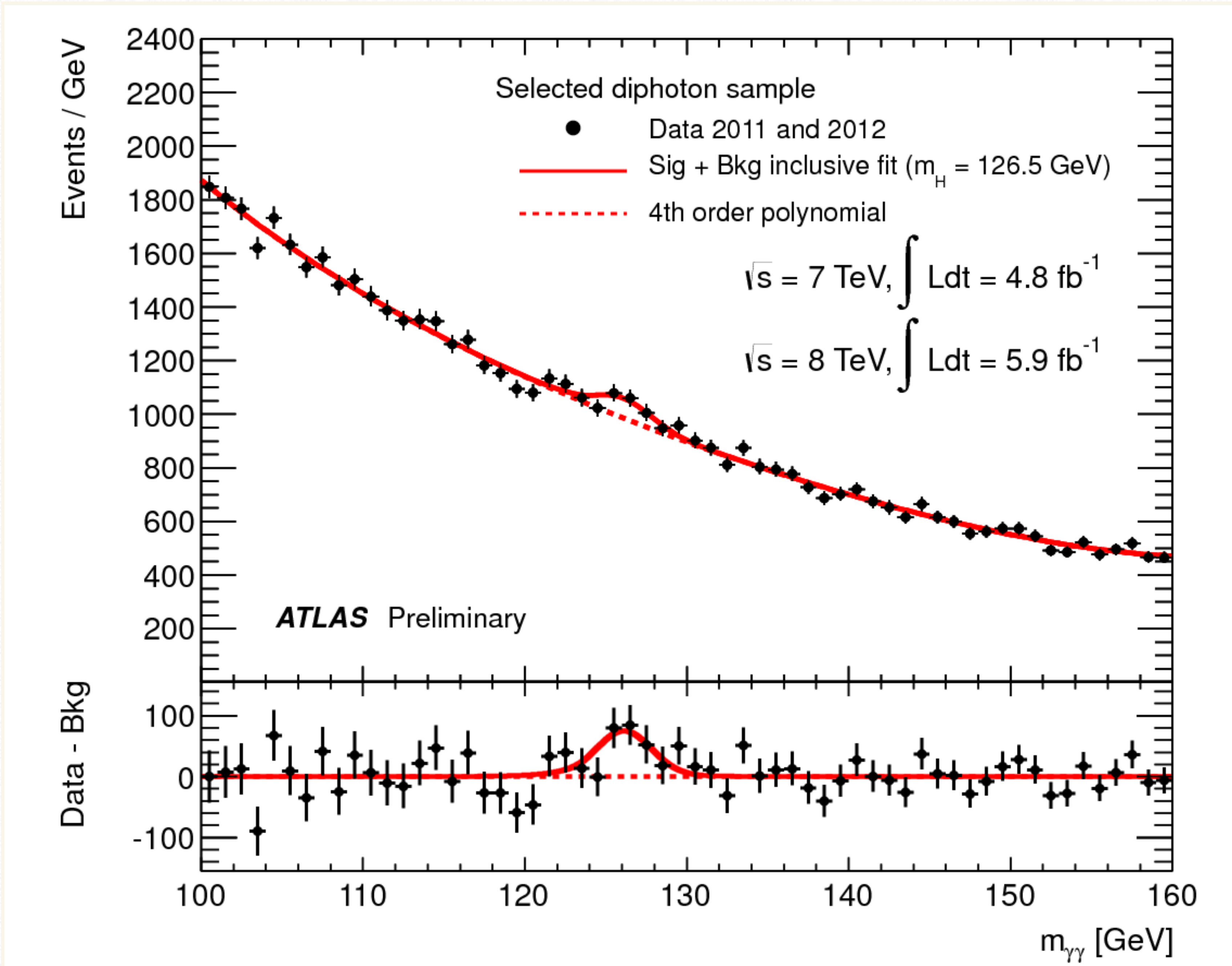
no extra CP violation

ILC Physics

- Higgs coupling precision at future collider
- SUSY and Higgs boson
- SUSY direct searches at LHC and beyond
- Dynamical models

Is this outstanding project?
I don't draw any conclusion. you decide.

Success of LHC



Higgs boson as a window of new physics

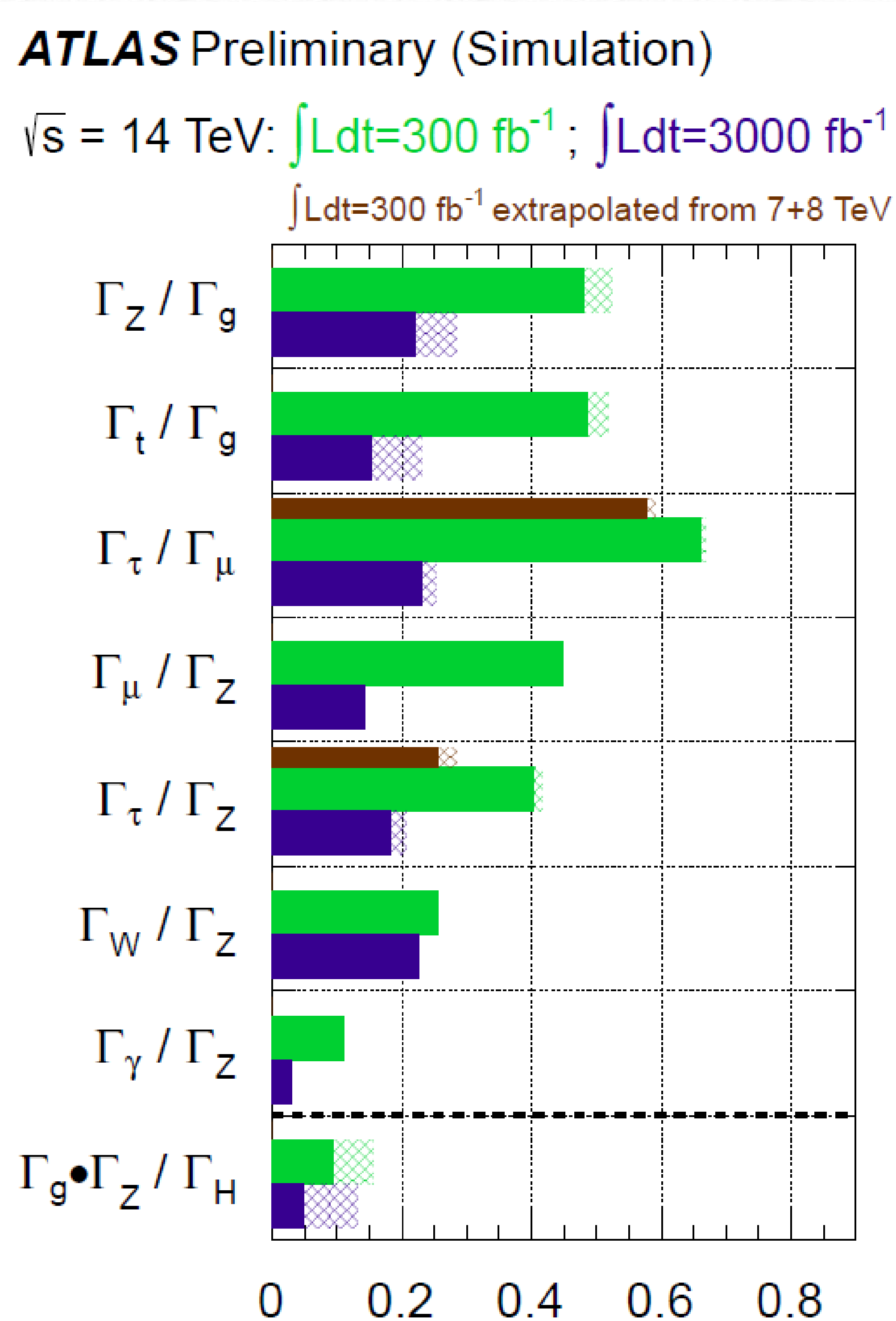
Higgs boson is a "new window" but..

- Large statistics
  - 2018年 14TeV L~2x10^{34} $cm^{-2}s^{-1}$ 25ns (Phse 1)
  - 2022年 L~5x10^{34} $cm^{-2}s^{-1}$ (Phase II)
- big systematical errors in σ(gg→h)
- Hopes in "ratios"

3000 fb^{-1} :

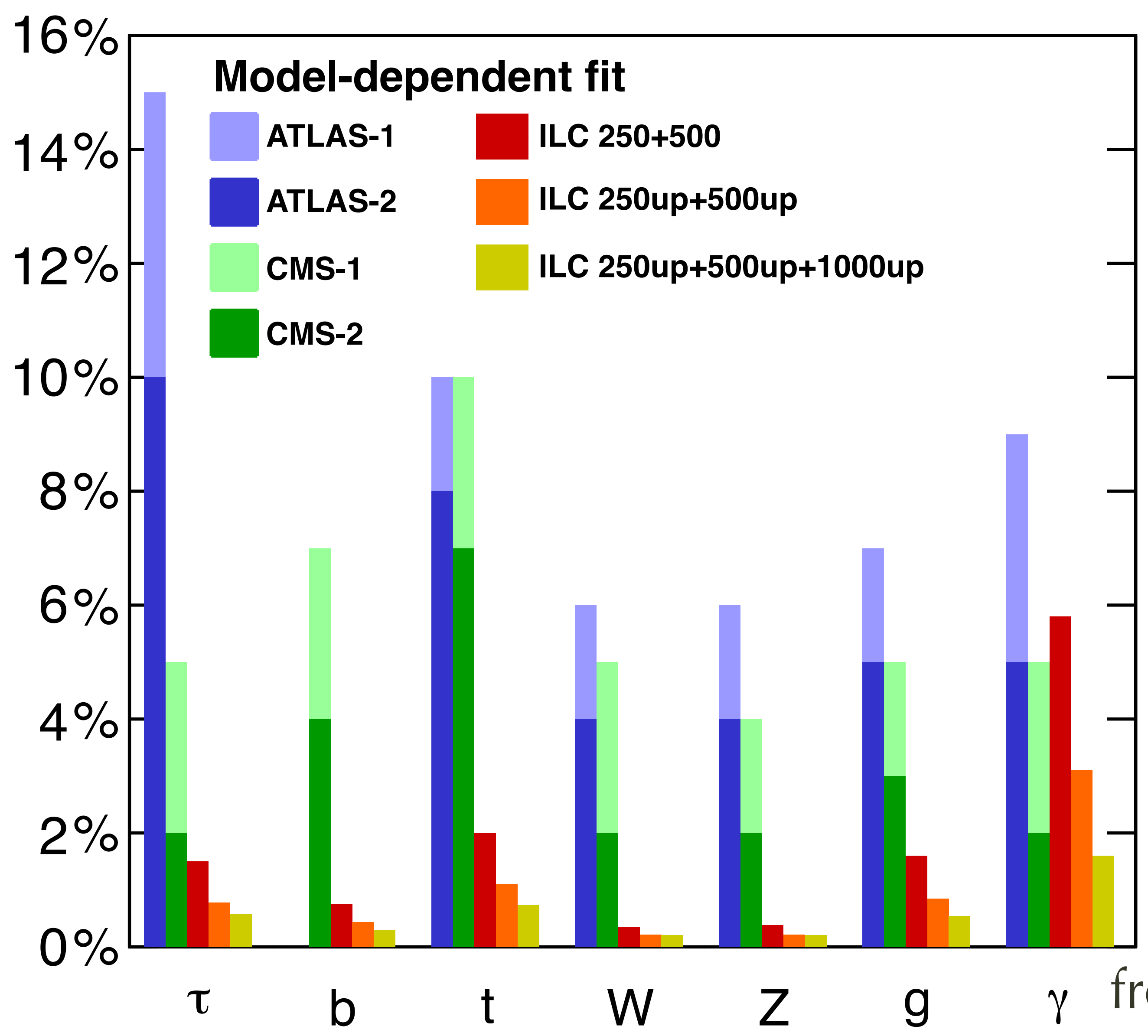
Observable	ATLAS-HL	CMS-HL-1	CMS-HL-2
$\sigma(gg)\cdot BR(\gamma\gamma)$	$5 \oplus 19$	$4 \oplus 12.3$	$0.9 \oplus 6.2$
$\sigma(WW)\cdot BR(\gamma\gamma)$	$15 \oplus 15$	$10 \oplus 2.4$	$4.4 \oplus 1.2$
$\sigma(gg)\cdot BR(WW)$	$5 \oplus 18$	$6 \oplus 12.3$	$1.6 \oplus 6.2$
$\sigma(WW)\cdot BR(WW)$	$9 \oplus 8$	$24 \oplus 2.4$	$8.9 \oplus 1.2$
$\sigma(gg)\cdot BR(ZZ)$	$4 \oplus 11$	$4 \oplus 12.3$	$1.6 \oplus 6.2$
$\sigma(WW)\cdot BR(ZZ)$	$16 \oplus 13$	$7 \oplus 12.3$	$1.9 \oplus 6.2$
$\sigma(WW)\cdot BR(\tau\tau)$	$12 \oplus 15$	$8 \oplus 2.4$	$2.8 \oplus 1.2$
$\sigma(Wh)\cdot BR(b\bar{b})$	—	$8 \oplus 3.8$	$4.4 \oplus 1.7$
$\sigma(t\bar{t}h)\cdot BR(b\bar{b})$	—	$35 \oplus 11.7$	$16 \oplus 5.9$
$\sigma(t\bar{t}h)\cdot BR(\gamma\gamma)$	$17 \oplus 12$	$28 \oplus 11.7$	$12 \oplus 5.9$
$\sigma(Zh)\cdot BR(invis)$	—	$10 \oplus 4.3$	$3.5 \oplus 2.2$

from 1312.4974



With e+e- collider

Higgs Couplings (1/2)



ATLAS/CMS:
Lumi 3000 fb-1, sqrt(s) = 14 TeV

ILC 250:
Lumi 417 fb-1, sqrt(s) = 250 GeV

ILC 500:
Lumi 833 fb-1, sqrt(s) = 500 GeV

ILC 250up:
Lumi 1920 fb-1, sqrt(s) = 250 GeV

ILC 500up:
Lumi 2670 fb-1, sqrt(s) = 500 GeV

ILC 1000up:
Lumi 4170 fb-1, sqrt(s) = 1 TeV

from Tanabe talk in Toyama '14

W coupling error reduces significantly with 500 GeV e+e- colliders

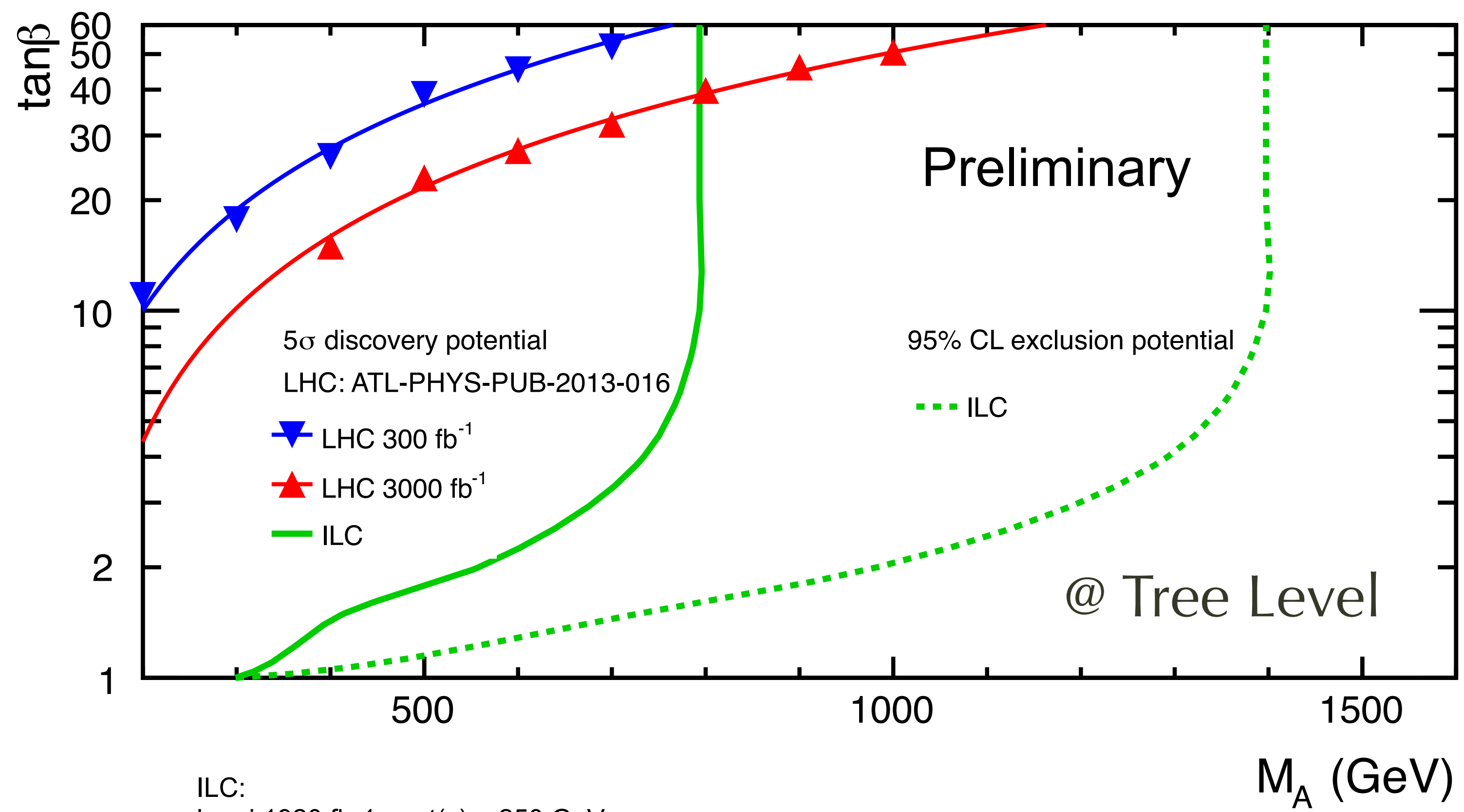
access to tth (and ttZ), and WWh (250GeV 4.6%→ 500GeV 0.46%

Higgs precision measurement and new physics

- SUSY two Higgs doublet model h, A0, H,H+

Heavy Higgs Mass Reach

- **LHC:** Heavy Higgs direct search
- **ILC:** Indirect search via effect on Higgs couplings BR(h→WW)/BR(h→bb) and BR(h→WW)/BR(h→ττ)



ILC:
Lumi 1920 fb-1, sqrt(s) = 250 GeV
Lumi 2670 fb-1, sqrt(s) = 500 GeV

from Tanabe

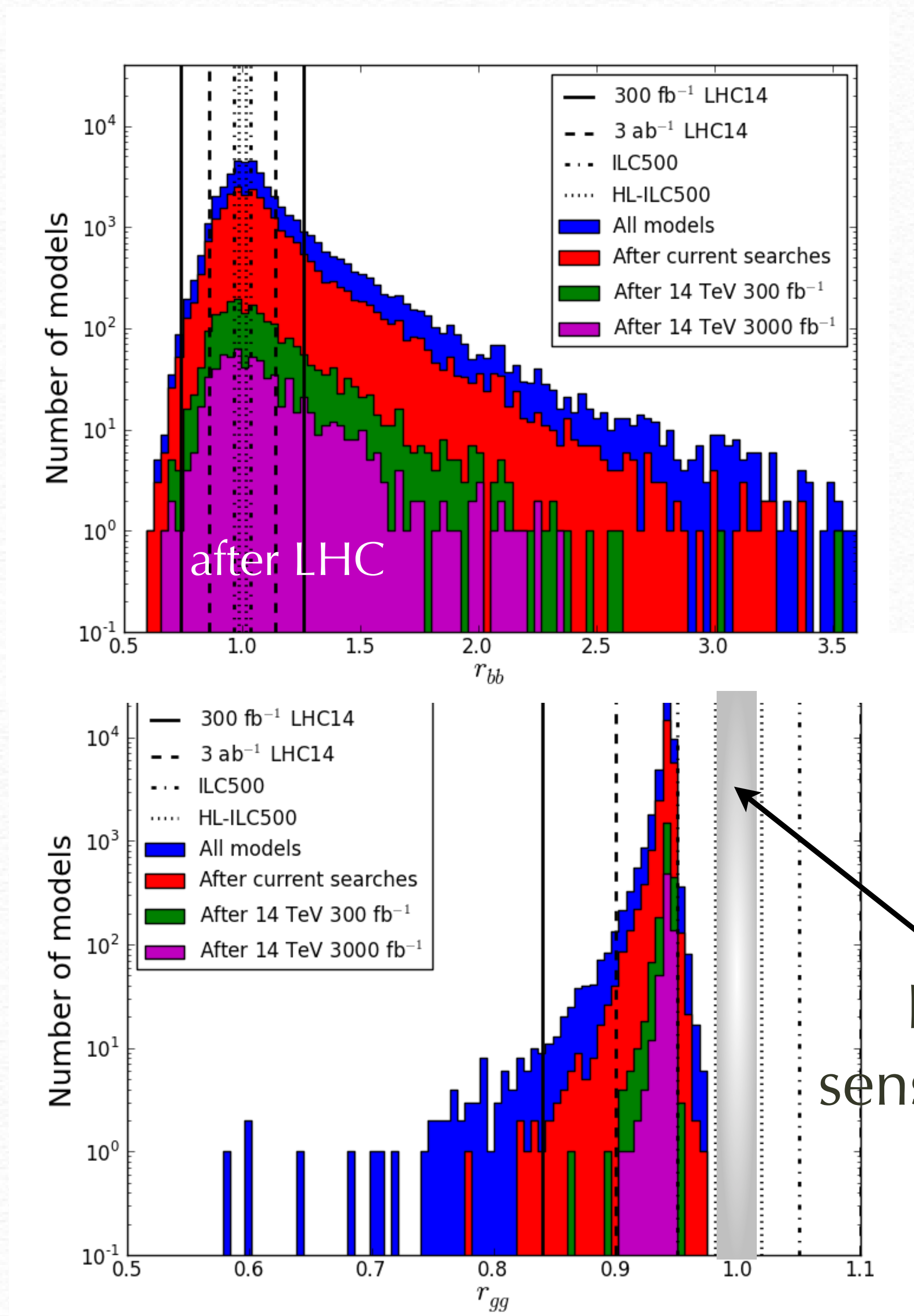
* One loop correction from the SUSY sector gives additional twist to the SUSY prediction

g(Hbb) - mA and tanβ x μ x M_3/M_{SUSY}

g(Hgg) -squark effects have not decouple even for M_{SUSY}~4TeV

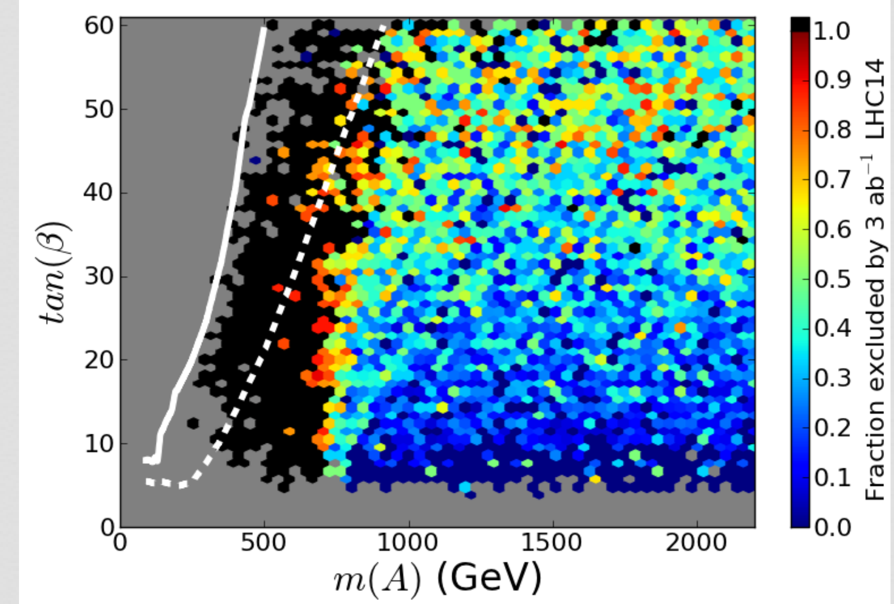
arxiv 1407.7021 Chill-Rowley et al

probing existence of BSM model (stop)

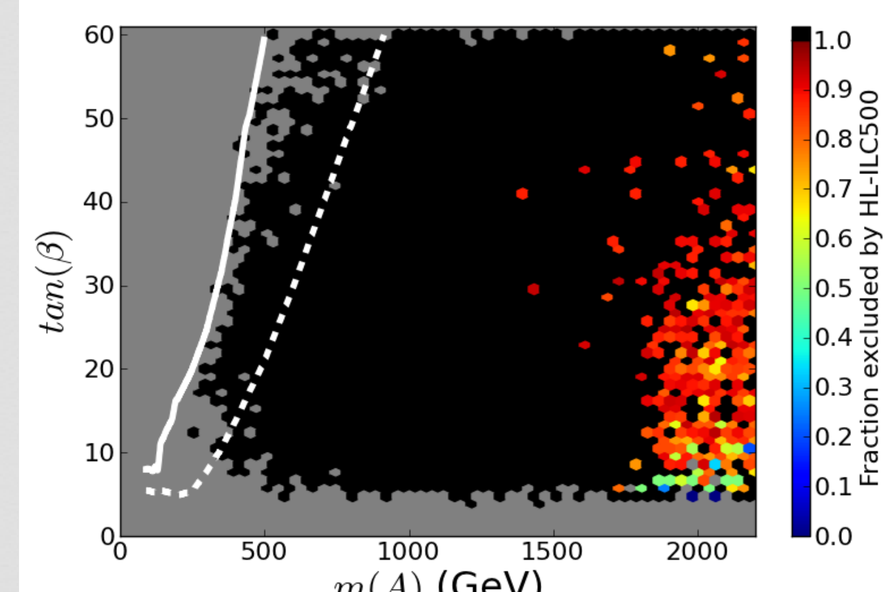


fraction of excluded points

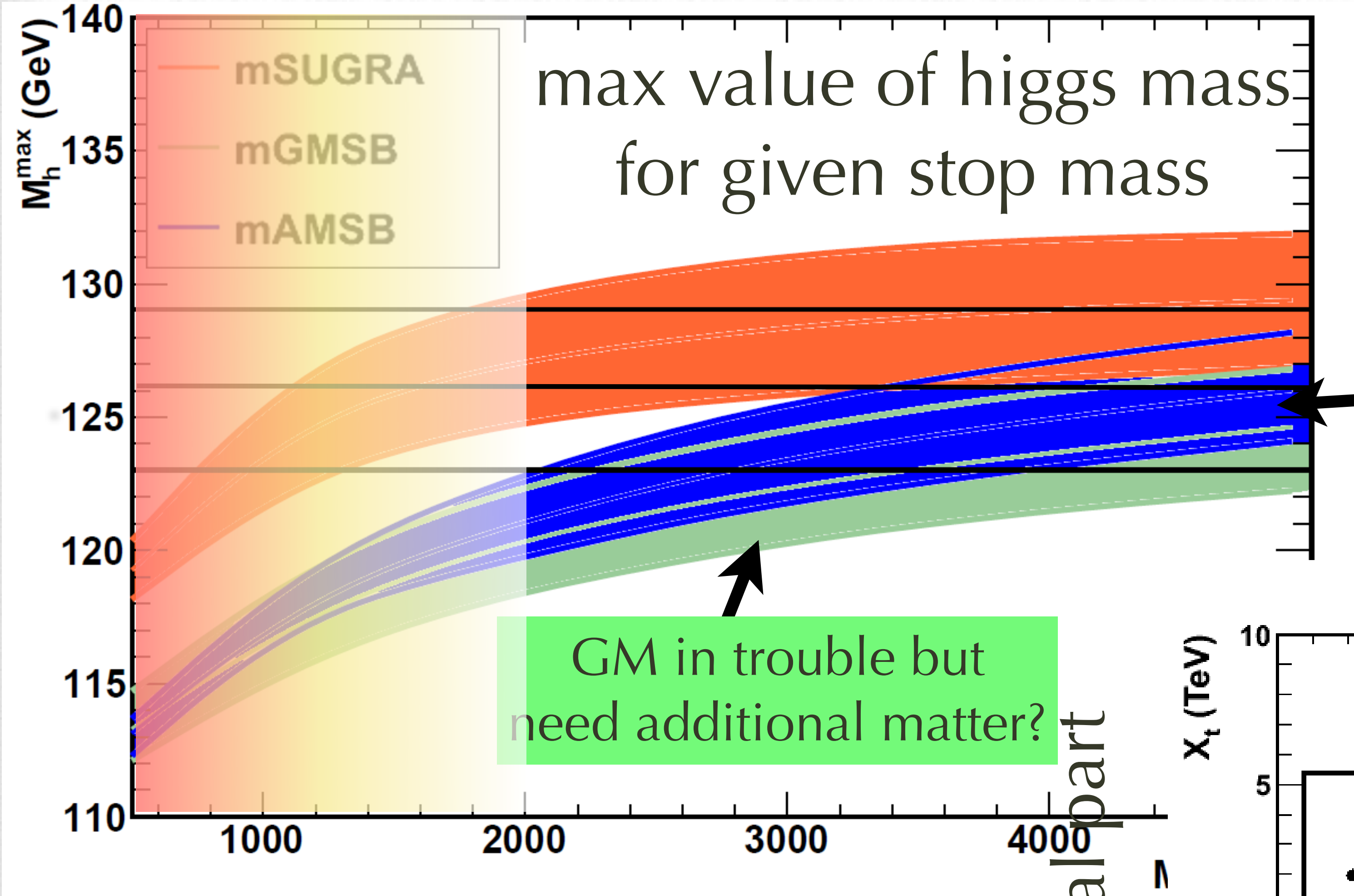
at LHC



at ILC



Some models are more constrained by Higgs Mass

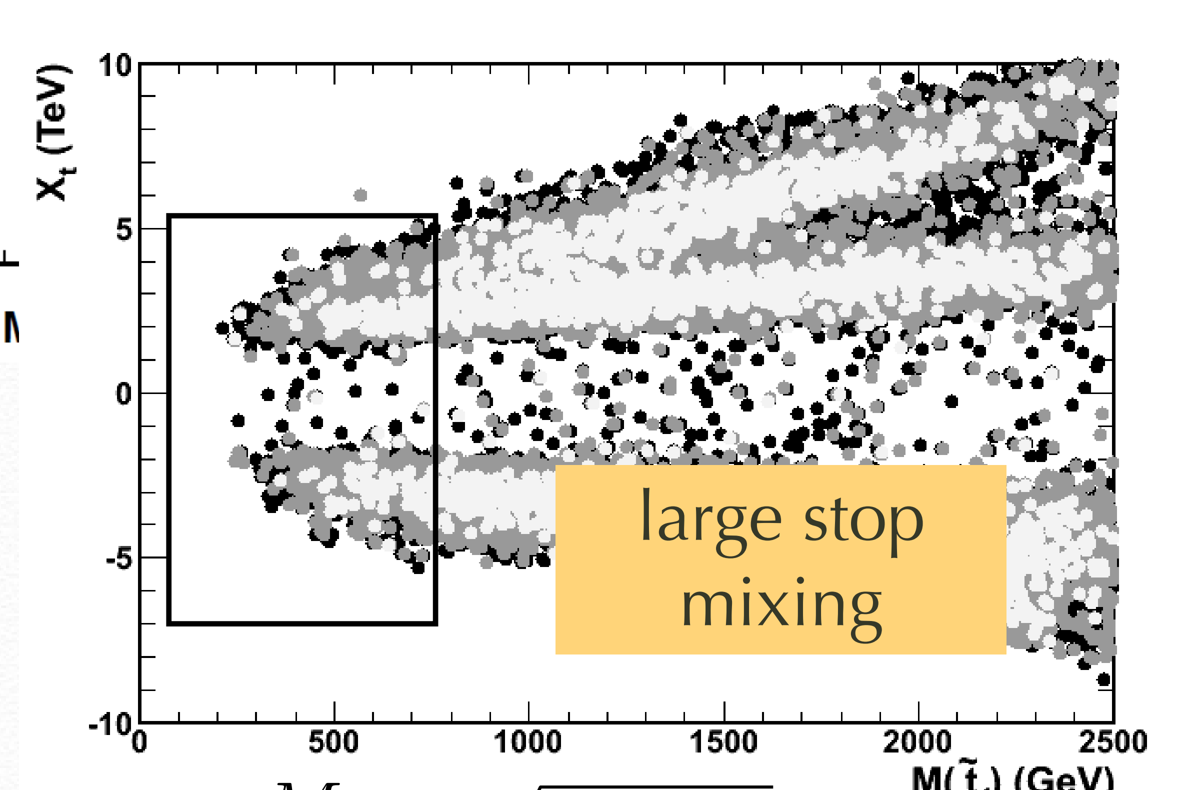


max value of higgs mass for given stop mass

AMSB -> large squark mass is natural

GM in trouble but need additional matter?

off diagonal part



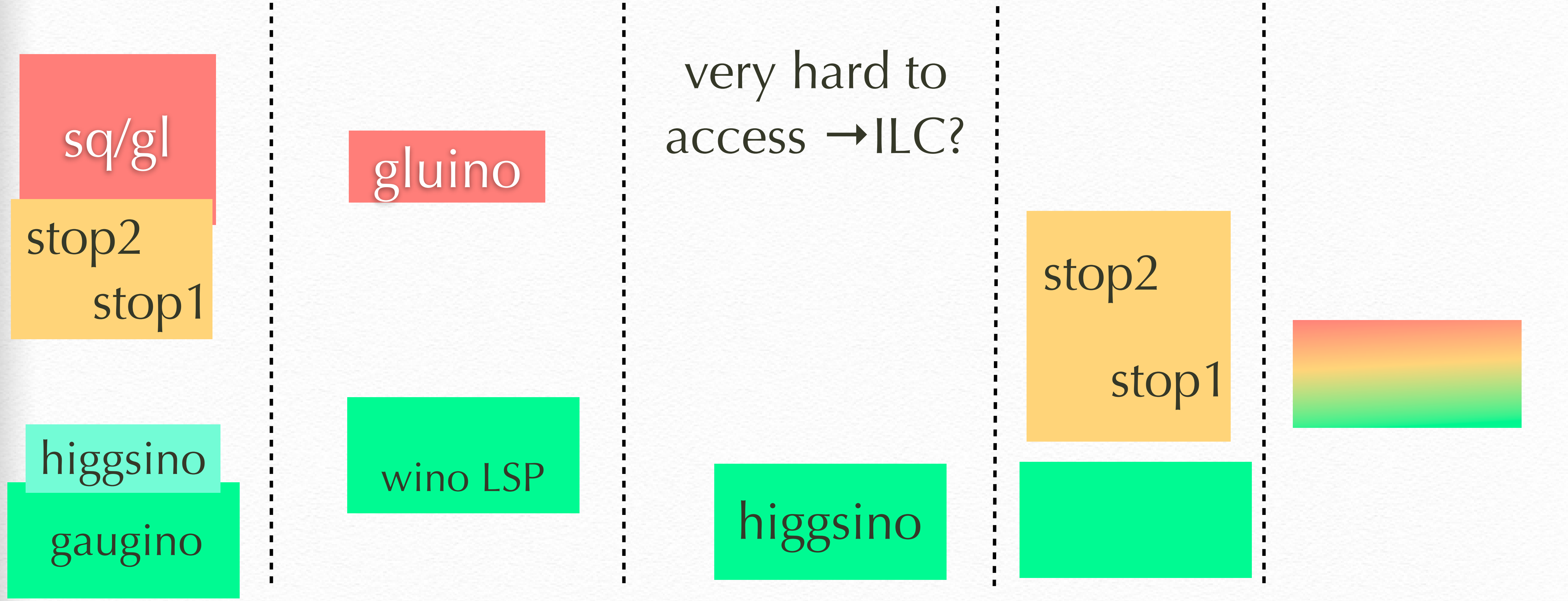
large stop mixing

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

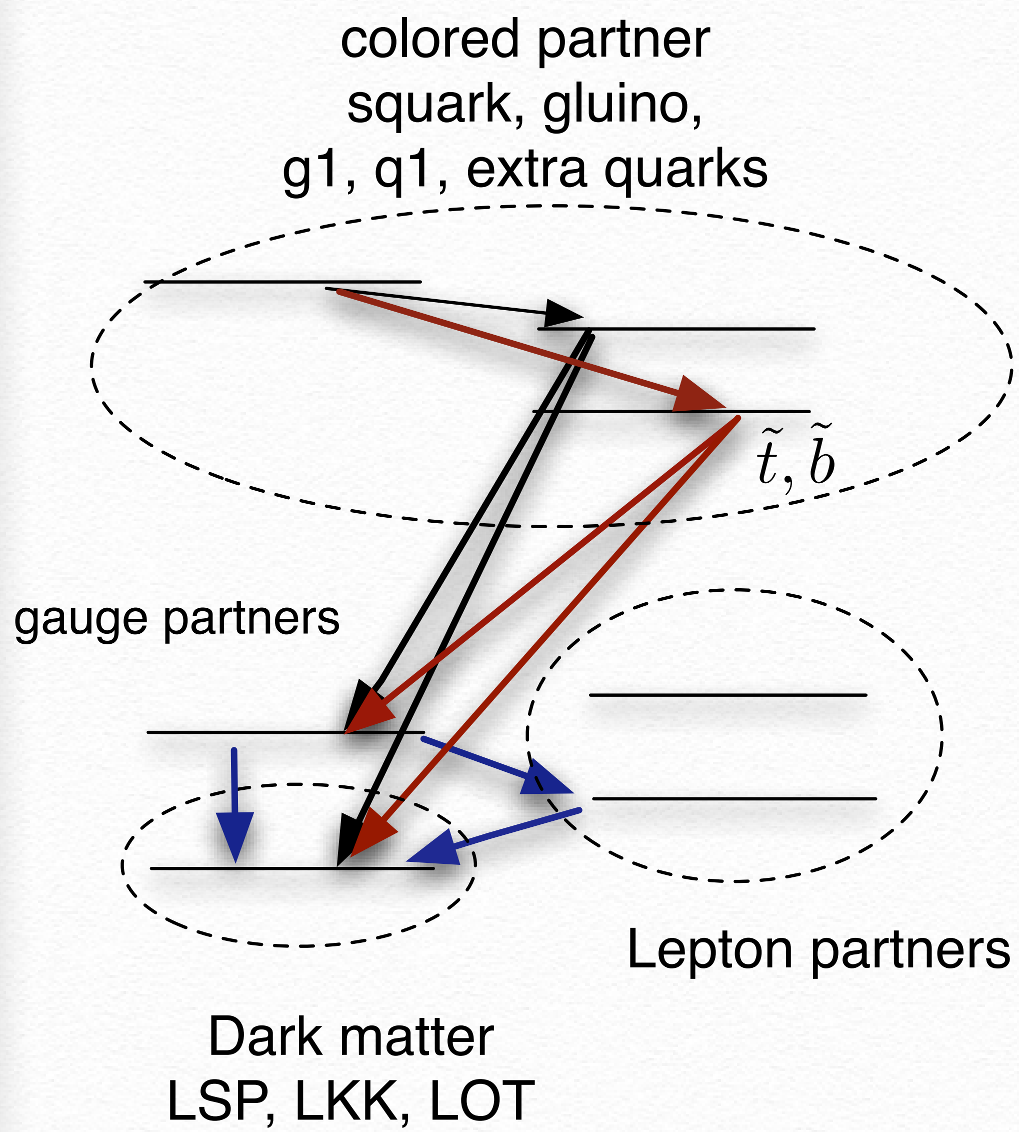
Hints on the SUSY breaking mechanism: **high scale/ Large mixing/non-minimal** SUSY more seriously

SUSY spectrum on market

MSUGRA classic	heavy scalar AM	light higgsino or stop for naturalness	degenerate (KKLT)
still viable	no FCNC no cosmological problem	Small cross section	Light SUSY still possible



SUSY searches at Hadron colliders



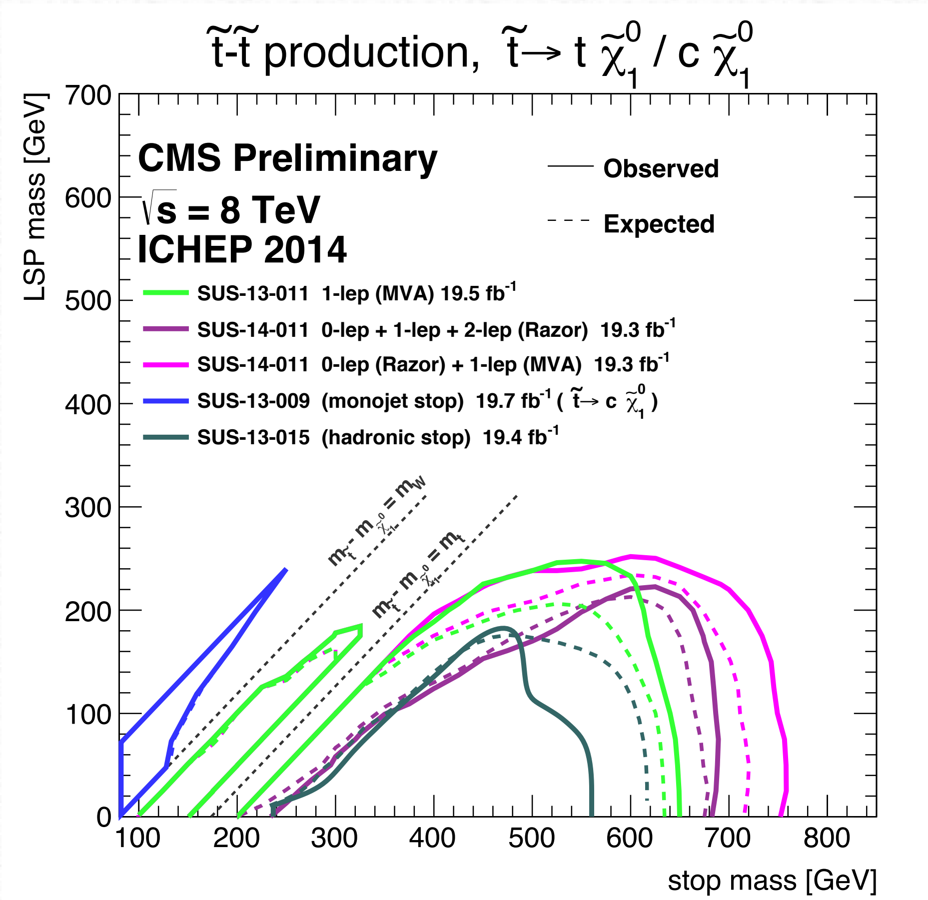
- **"SUSY signature"**
  - "Models with new colored particles decaying into a stable neutral particle--LS
- Signal:
  High P_T jets hiph P_T leptons and E_{Tmiss}

assume mass difference is large

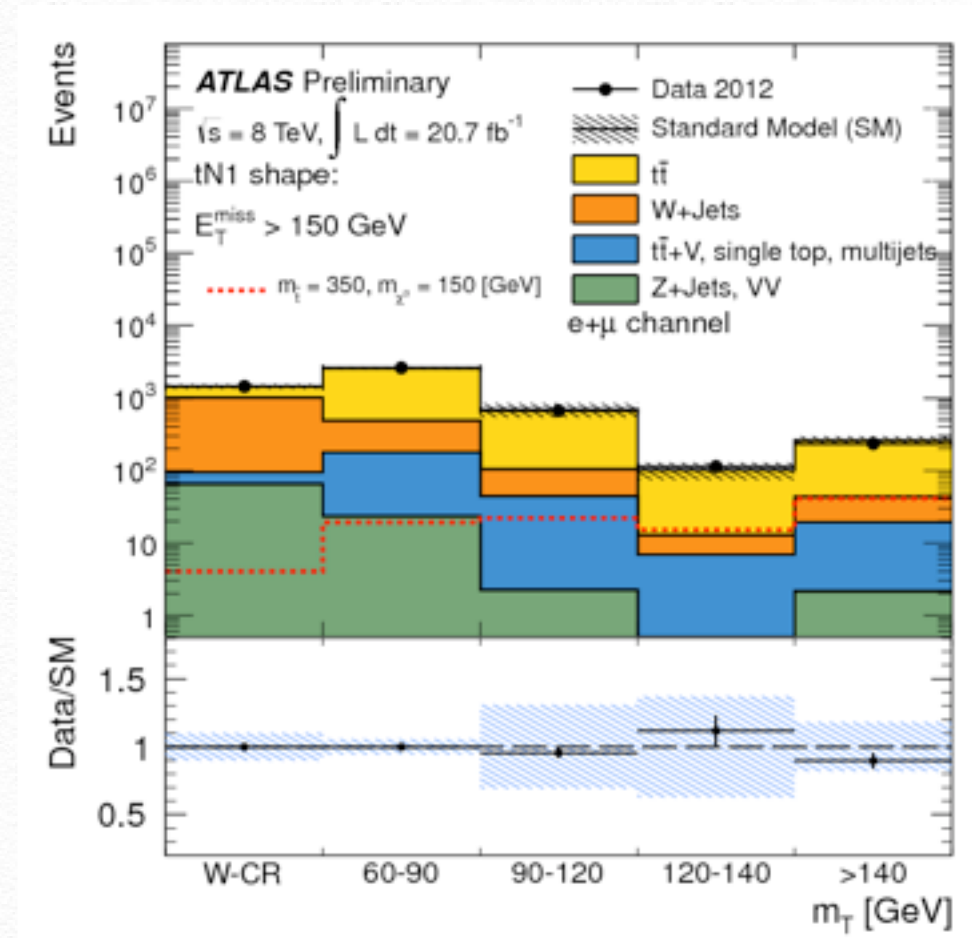
Production of W, Z, and top with additional jets would be significant background

Controlling backgrounds

The bound is model independent



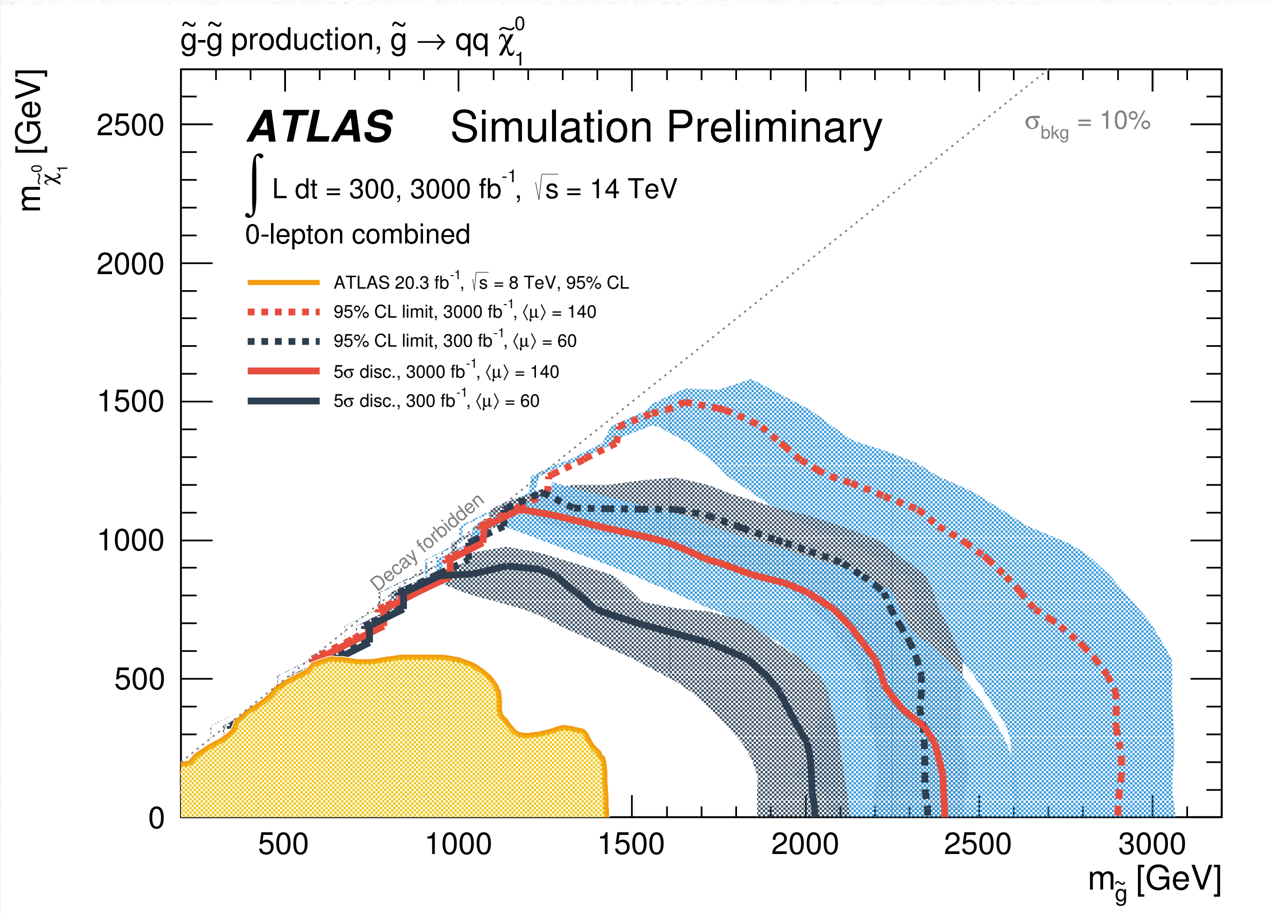
exclude up to the region
where mstop~mLSP+mt +30GeV



stop 350GeV and LSP 150GeV
There are no region with
S/N>0.1 in this plot!

The limit is based on the understanding of background

LHC 13TeV



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

gluino mass up to 3TeV and
LSP mass up to 1.5TeV

scalar top up to 1.4TeV and
LSP mass 0.5TeV

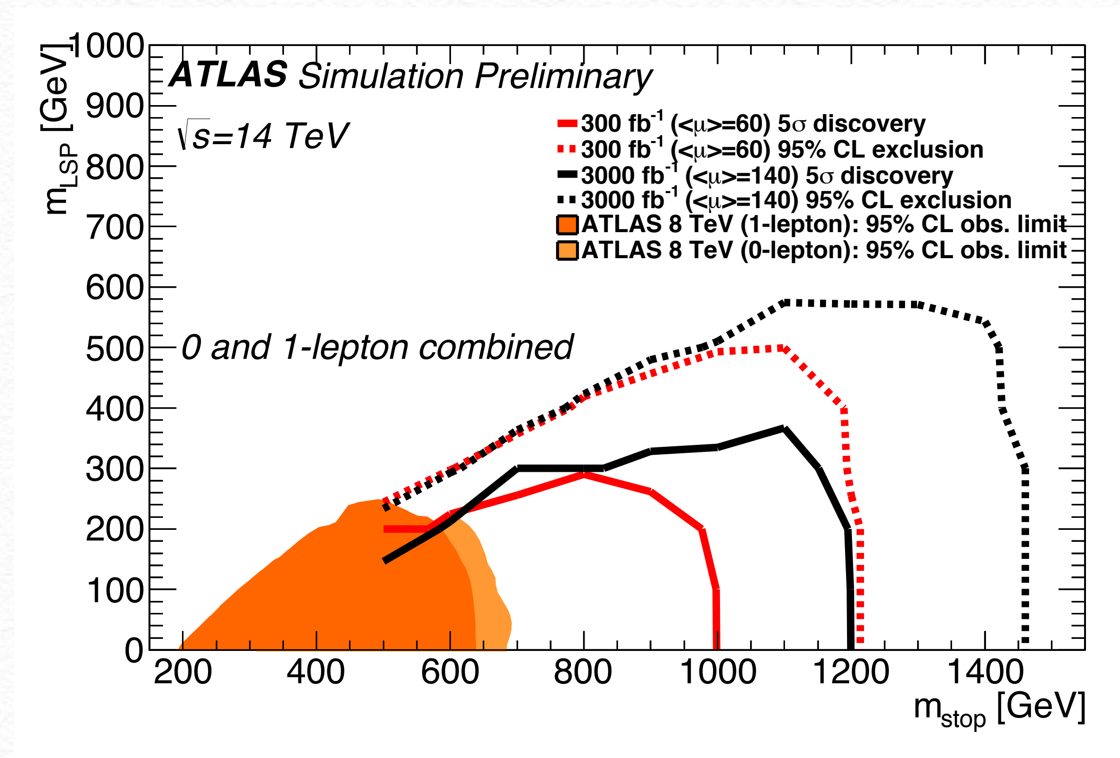


Figure 5: The 95% CL exclusion limits (dashed) and 5σ discovery reach (solid) for 3 3000 fb^{-1} (black) in the $\tilde{t}$, $\tilde{\chi}^0_1$ mass plane assuming $\tilde{t} \to t + \tilde{\chi}^0_1$ with a branching rati results are shown for the combination of the 1-lepton and 0-lepton analyses. The obse the analyses of 8 TeV data are also shown.

SUSY at 100TeV collider

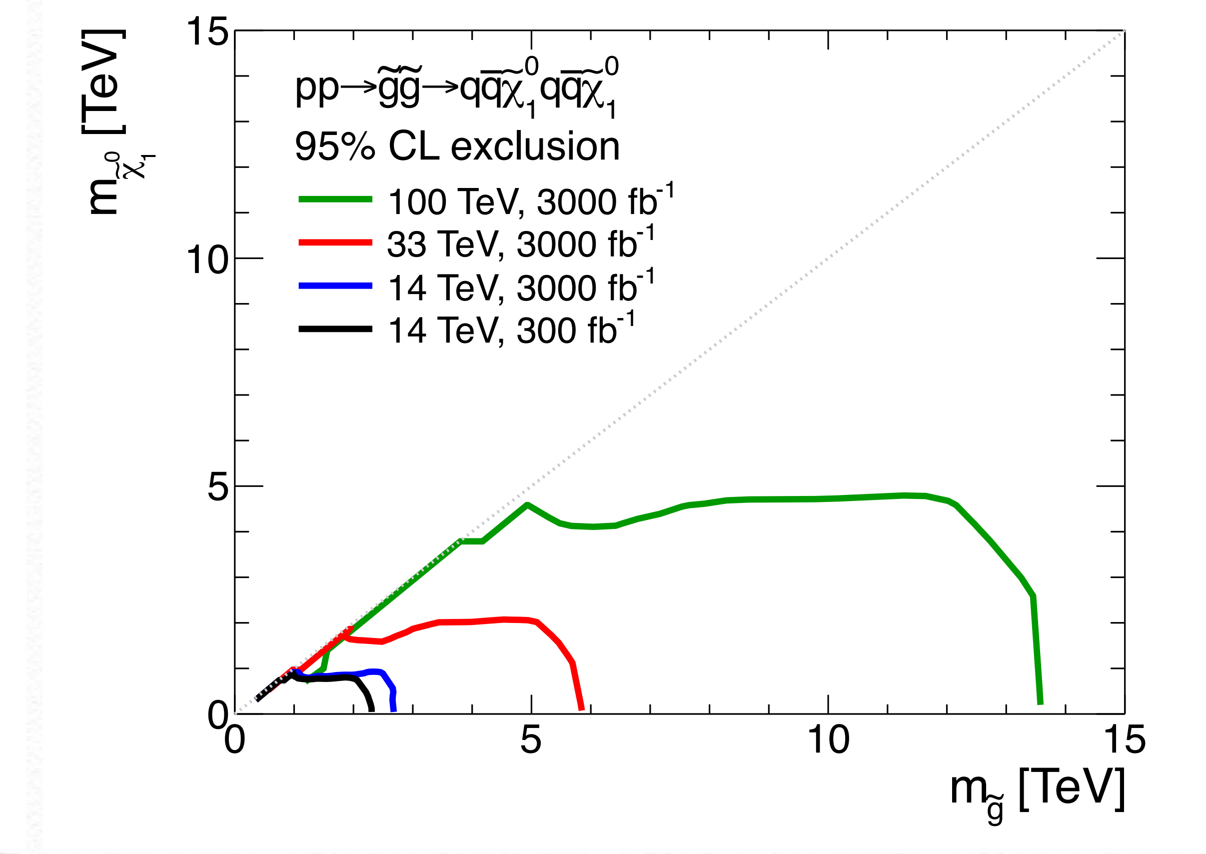
VHE-LHC Reach

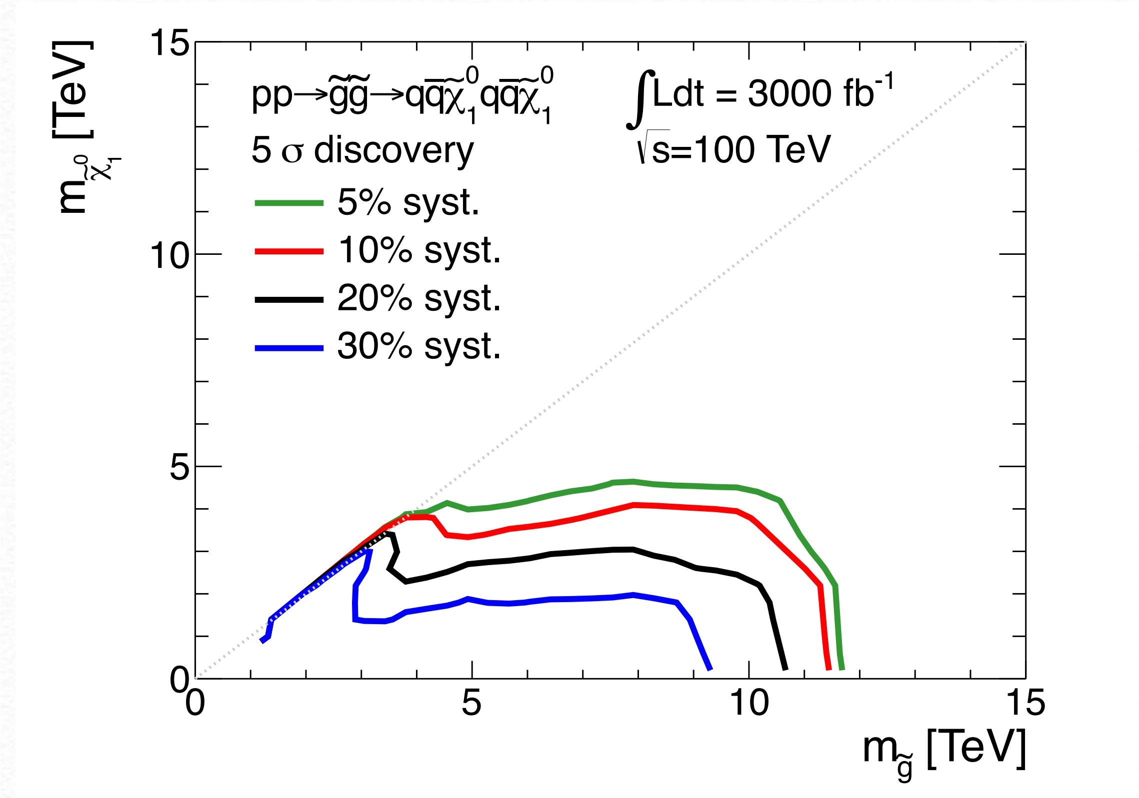
LSP mass up to ~5(2)TeV at 100(33)TeV

LSP mass reduce to 2TeV for 30% sys error

overlap with the region covered by ILC g(hgg) measurements

1311.6480 Cohen et al





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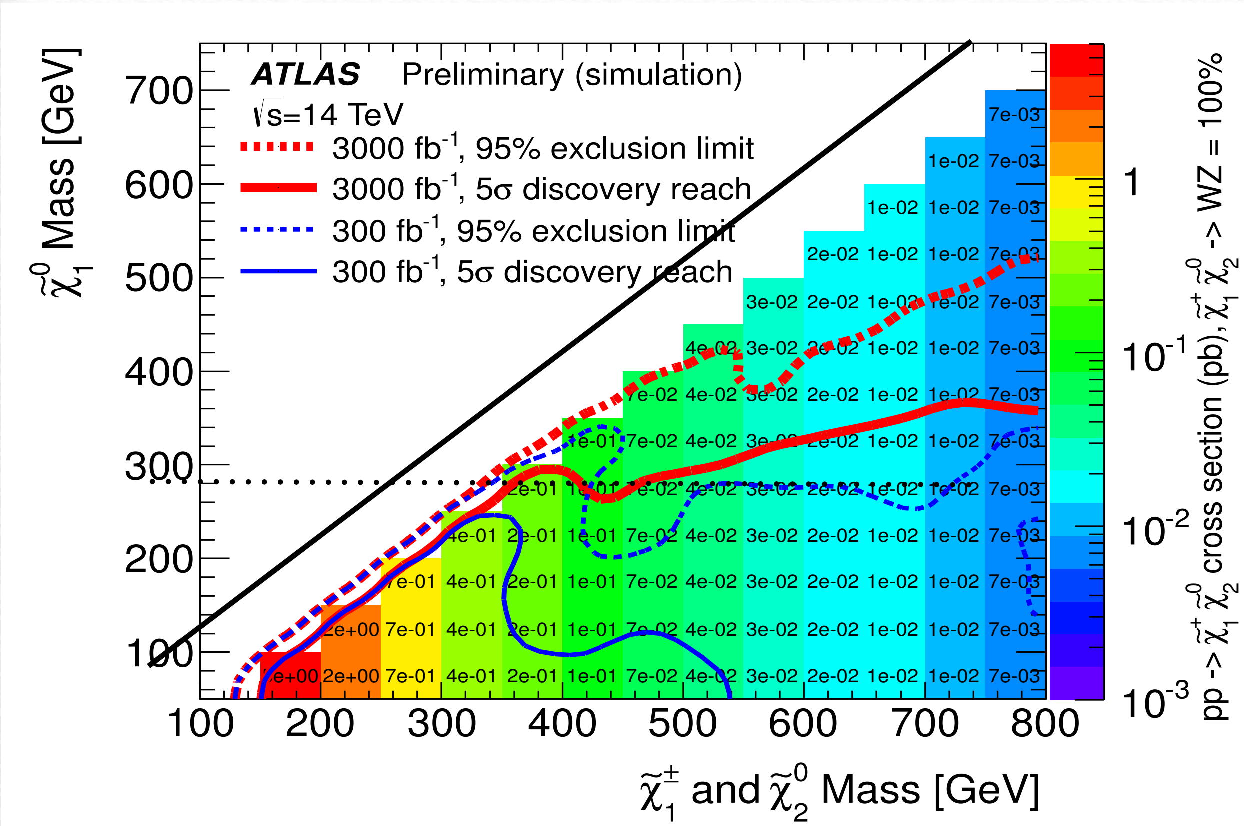
EW SUSY at HL-LHC



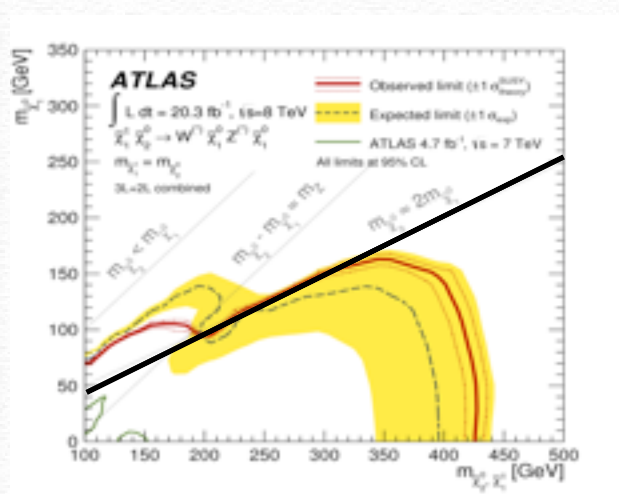
(b)

LHC will be sensitive to Lepton channel !

(with good lepton trigger rate)

- We now have a strong motivation to keep trigger rate as low as possible for Higgs physics

current limit



Problem: Not much sensitivity to EW SUSY particles decaying into Higgs boson

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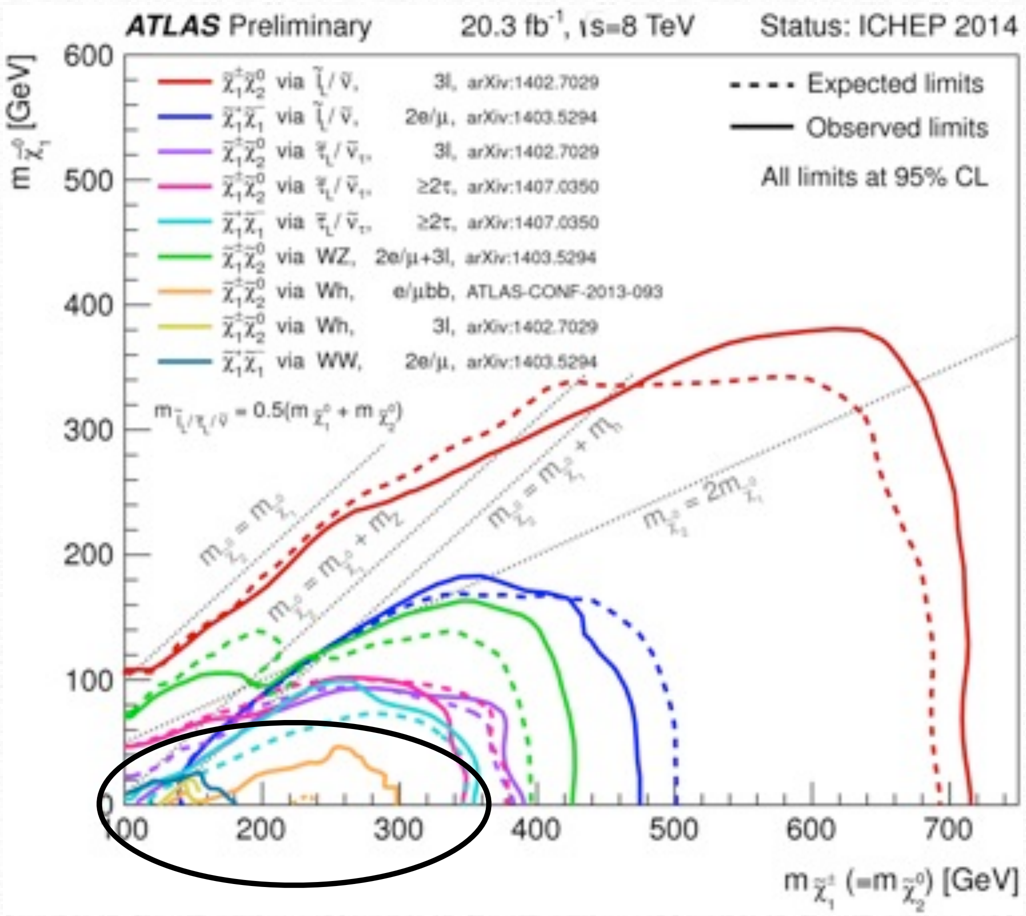
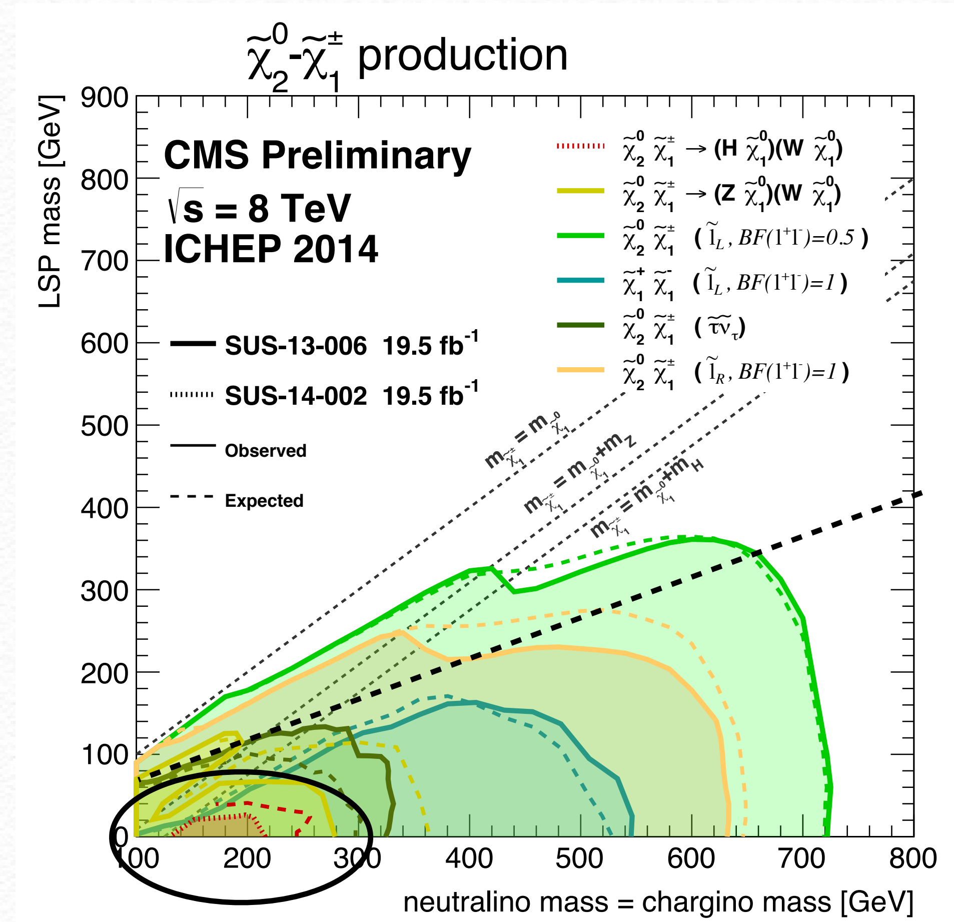
EW SUSY search via lepton decay mode





V
erlap w
W and Z backgrounds

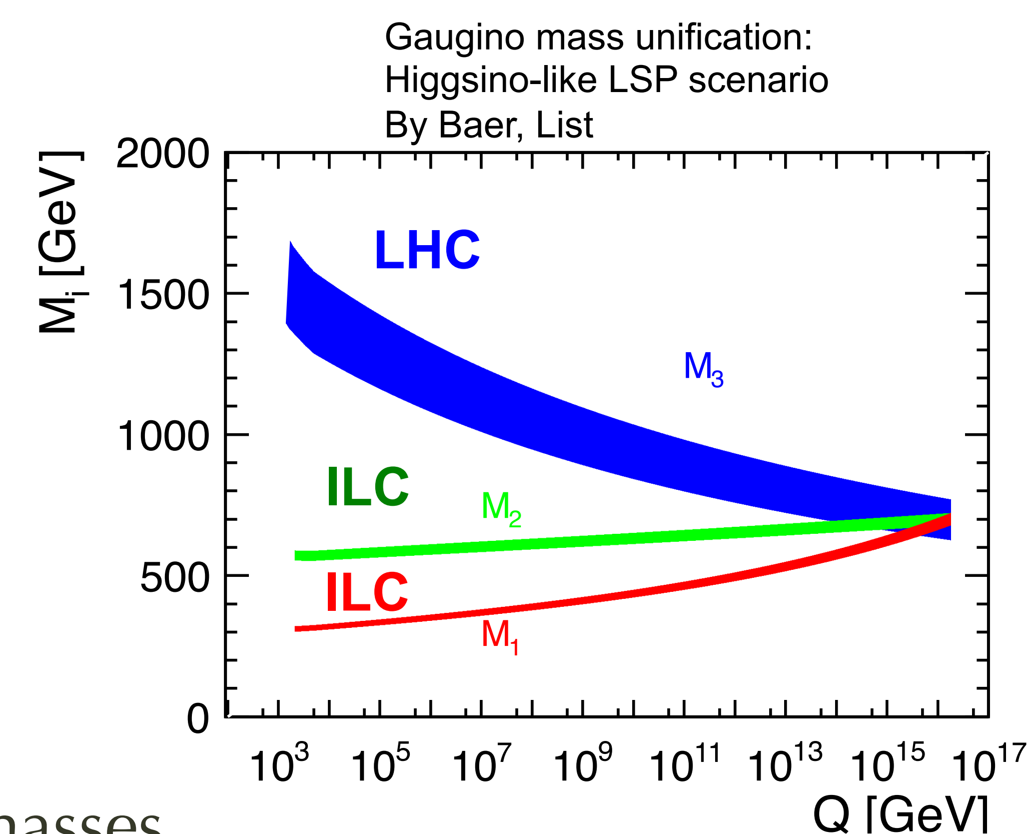
strong bound on wino decaying into sleptons (cross section)
No serious bound if decaying into higgs boson
limited bound on $M_1=0.5M_2$ line

ILC has very good sensitivity for doublet(Higgsino) or triplet(Wino) LSP and NLSP up to its kinematical reach

EW-ino at ILC

- Keep in mind that relevant parameters are more restricted now.
- covering some important model parameter regions that LHC cannot do
  - Heavy squark
  - Higgsino or Wino LSP
- discovery→ precision tells more

parameters that LSP is higgsino accessible at ILC wile others are not
→cross section measurement recover gaugino masses



1307.0782
"point RNS" μ=125GeV
gluino mass 1.8TeV heavy squark

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Dynamical models

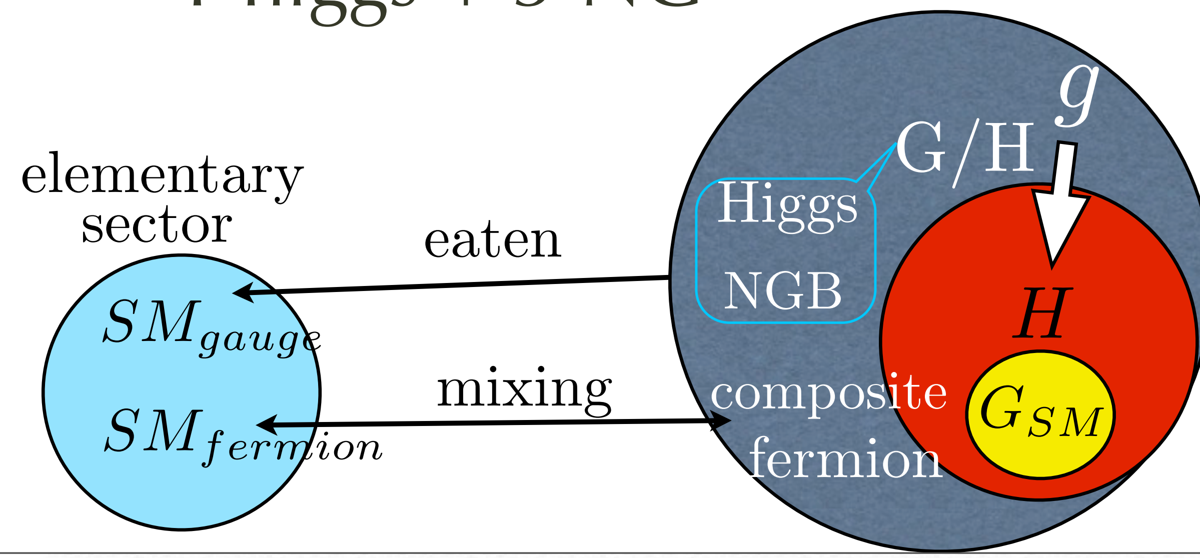
Minimal Composite Higgs Model (MCHM)

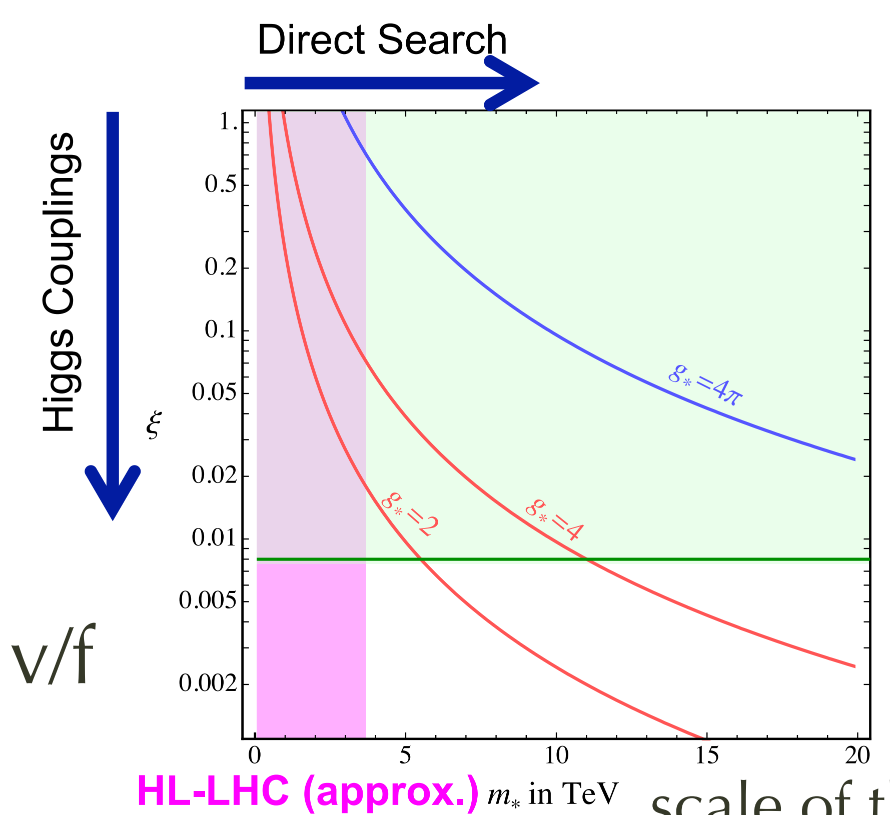
SO(5)xU(1)x→ SO(4)xU(1)$_X$

4 NG→SU(2) doublet
1 higgs + 3 NG

building block of higgs sector

$$\Sigma = \Sigma_0 e^{\Pi/f}$$
$$\Sigma = \left(0,\ 0,\ 0,\ \sin\frac{h(x)}{f}, \cos\frac{h(x)}{f}\right)$$





$$\xi = \frac{g_*^2}{m_*^2} v^2 \quad = v_2/f_2$$

$$\frac{g_{hVV}}{g_{h_{SM}VV}} = \sqrt{1-\xi}$$

ILC

$$\frac{\Delta g_{hVV}}{g_{hVV}} = 0.4\%$$

scale of the resonance
of strong dynamics

expected reach up to
v/f ~ 0.09

top partners in Minimal Composite Higgs Model

$$\Psi = \frac{1}{\sqrt{2}} \begin{pmatrix} B - X \\ i(B+X) \\ T+U \\ i(T-U) \\ \sqrt{2}\tilde{T} \end{pmatrix}$$

field	T^3_L	T^3_R	X	$Y = T^3_R + X$	$Q_{EM} = T^3_L + Y$
X	$1/2$	$1/2$	$2/3$	$7/6$	$5/3$
U	$-1/2$	$1/2$	$2/3$	$7/6$	$2/3$
T	$1/2$	$-1/2$	$2/3$	$1/6$	$2/3$
B	$-1/2$	$-1/2$	$2/3$	$1/6$	$-1/3$
$\tilde{T}$	0	0	$2/3$	$2/3$	$2/3$

$(2, 2)$ (X, U, T, B)

$(1, 1)$ ($\tilde{T}$)

MCHM5 arXiv:1110.5646

$$\mathcal{L}_{Yukawa+Mass} = \underbrace{-Yf(\bar{\Psi}_L \Sigma^T)(\Sigma \Psi_R)}_{\text{(proto) yukawa}} \underbrace{- M \bar{\Psi}_L \Psi_R}_{\text{vector mass}} \underbrace{- \Delta_L \bar{q}_L Q_R - \Delta_R \bar{\tilde{T}}_L t_R}_{\text{mixing}}$$

composite $Q = (T, B)^T$ ⟷ q_L elementary(SM)

$\tilde{T}$ ⟷ t_R

bigger representation such as 10, 14... may be

strongly constrained by T, S, Zbb, higg potential

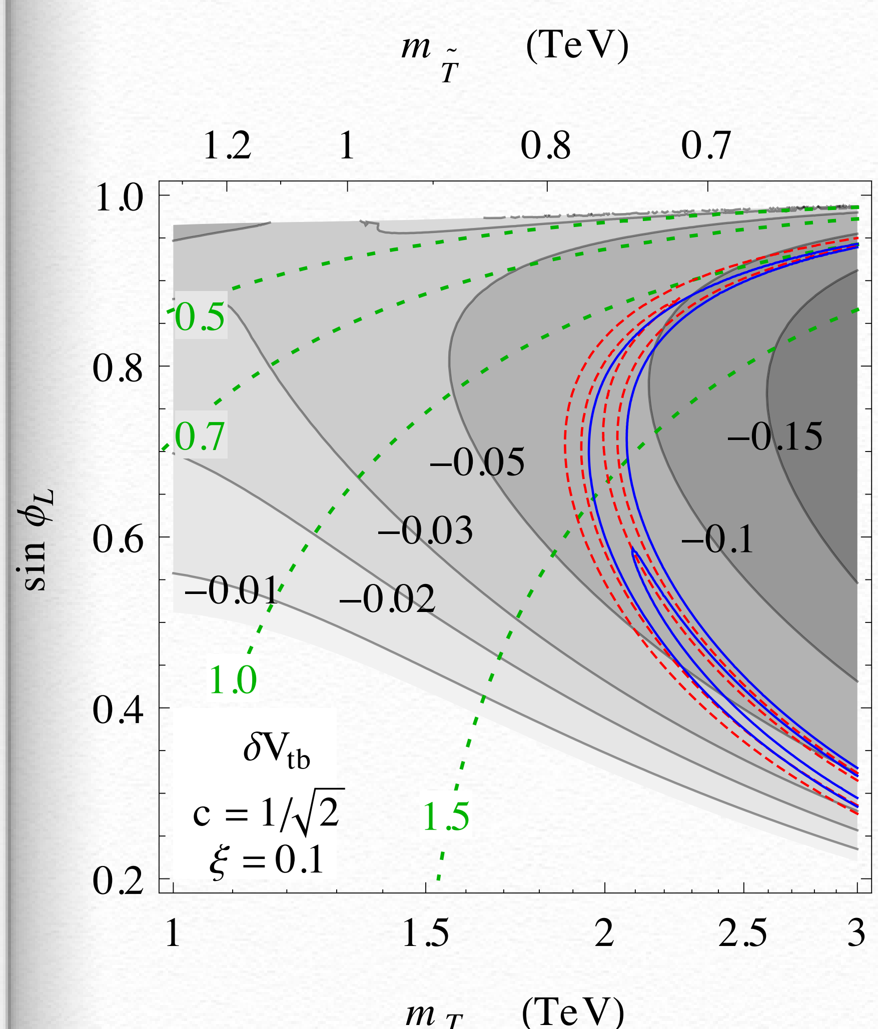
interesting effect in Hgg, Hγγ, Htt, ttZ

ttZ coupling in MCHM

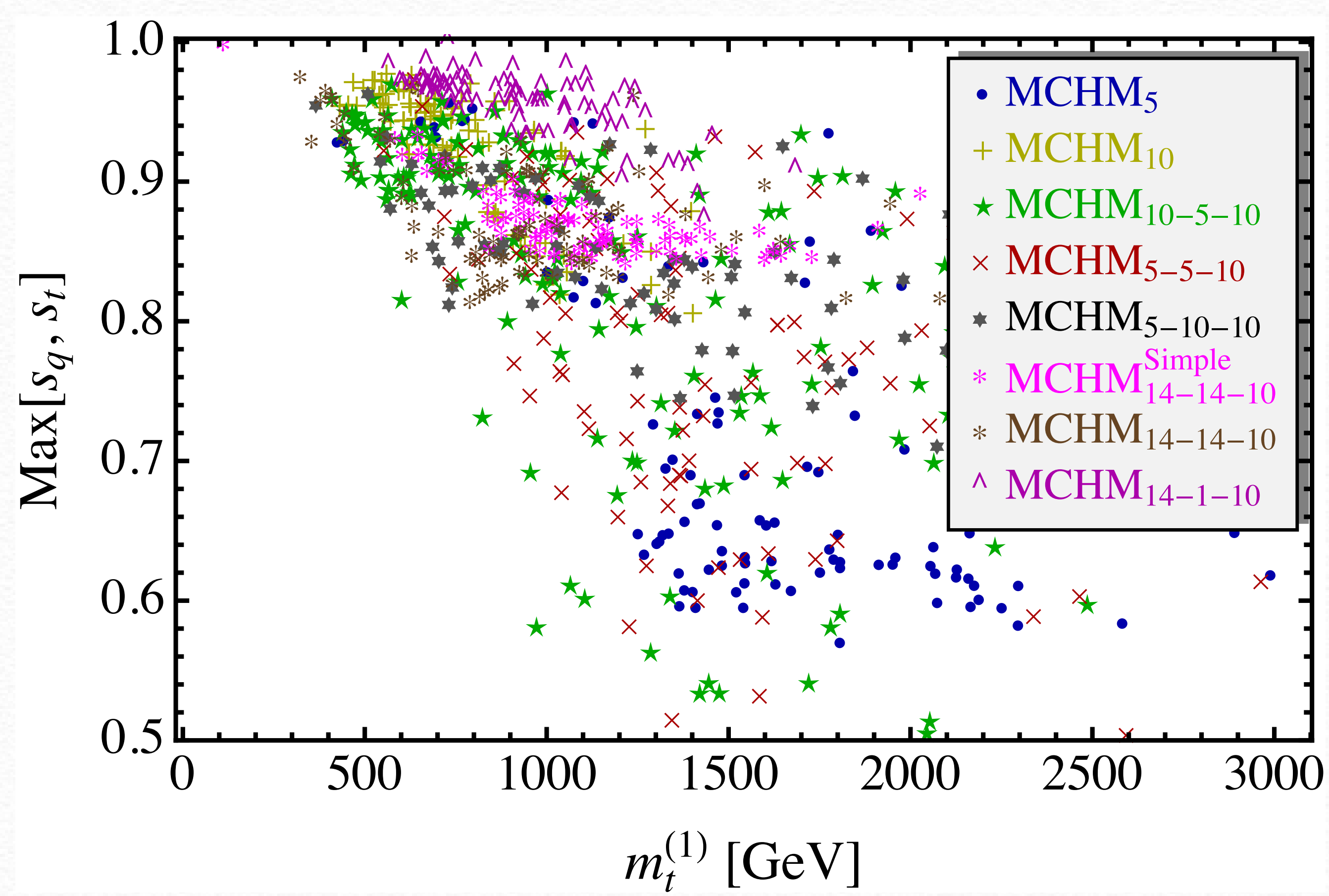
from e+e- → ttbar ILC precision would be
Left coupling 0.6%
Right coupling 1.4%

Grojean et al 1306.4655

$\delta g_{tL}/g_{tL}$ =-0.05~-0.1



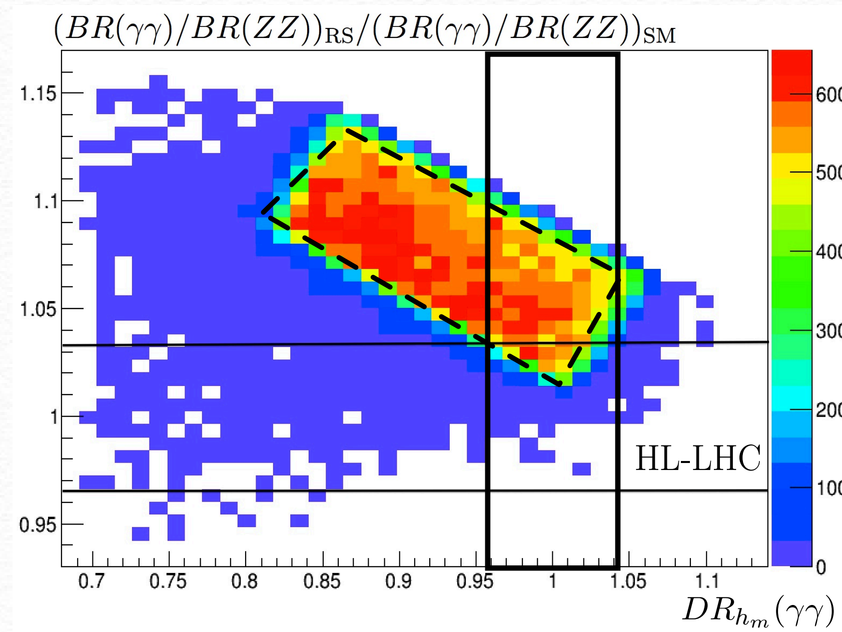
Carena et al 1402.2987
stop mixing angle in various models



Extra-dim : 0(10)TeV RS model with ILC

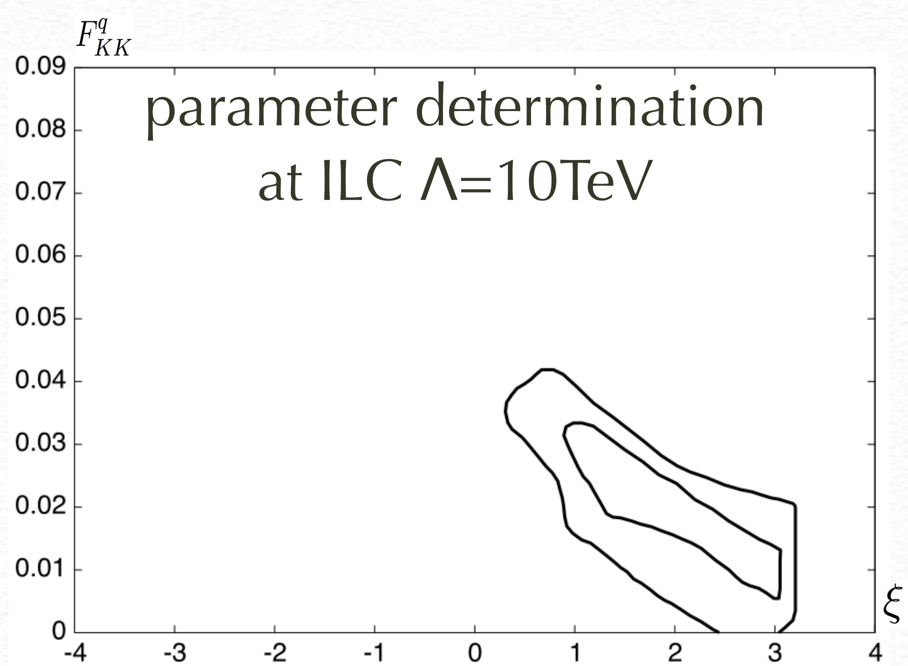
- 5dim RS with bulk Fermions → explain fermion mass via bulk profile
- not accessible at 14TeV LHC due to flavor constraint
- additional complexity Raidon-Higgs mixing.
  - KK contribution to Higgs decay though loop, large KK yukawa coupling
  - Radion: direct coupling to light gauge bosons.

Kubota Nojiri 1404.3013



(a)

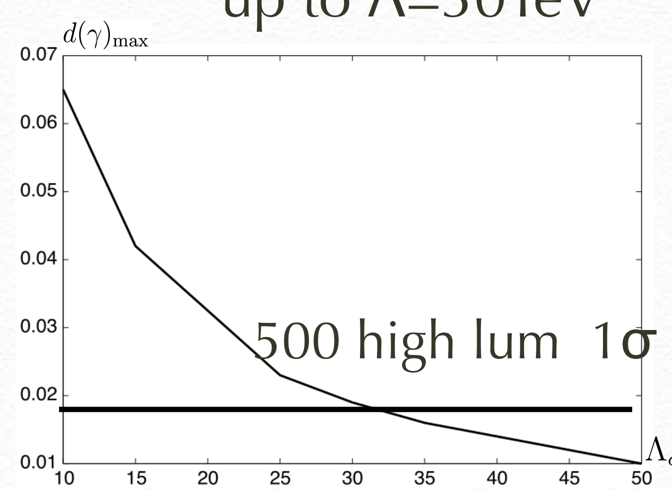
KK contribution

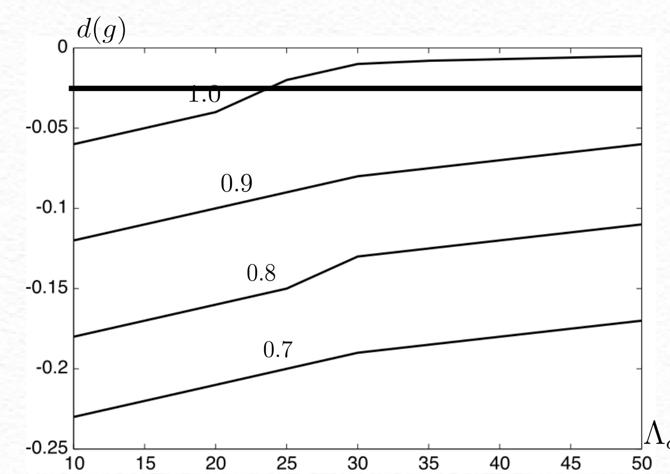


mixing parameter

max coupling deviation

up to Λ=30TeV





conclusions

- LHC will prove BSM directly. Energy Upgrade explore new physics beyond 10TeV scale
- "A new Higgs window" for BSM. Precision study of the Higgs boson nature at high luminosity e+e- collider now looks viable future program.