Various New Physics Models
and
The Future of Particle Physics

Nobuchika Okada

(Theory Group, KEK)

JPS Meeting @ Yamagata U., Sep. 21th, 2008

1. Introduction

The Standard Model (SM) of particle physics

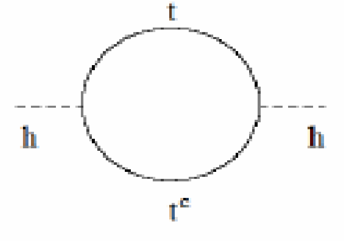
1. The best theory describing the nature of particle physics, which is in excellent agreement of almost of all current experiments
2. However, there are several theoretical problems & recent experimental results suggest New Physics Beyond the SM
3. Many New Physics Models have been proposed
4. Collider Experiments may reveal New Physics in the near future

Problems in the Standard Model

(A) Theoretical (conceptual) problem

Quantum corrections of Higgs mass → quadratic divergence

$$\Delta M_H^2 =$$



$$\sim \frac{1}{16\pi^2}\,\Lambda_{\text{New}}^2$$

$$M_{\text{Phys}}^2 = M_0^2 + \Delta M_H^2 \to \mathcal{O}(M_W^2)$$

If $\Lambda_{\text{New}}^2 \gg M_W^2$, we need to explain the reason

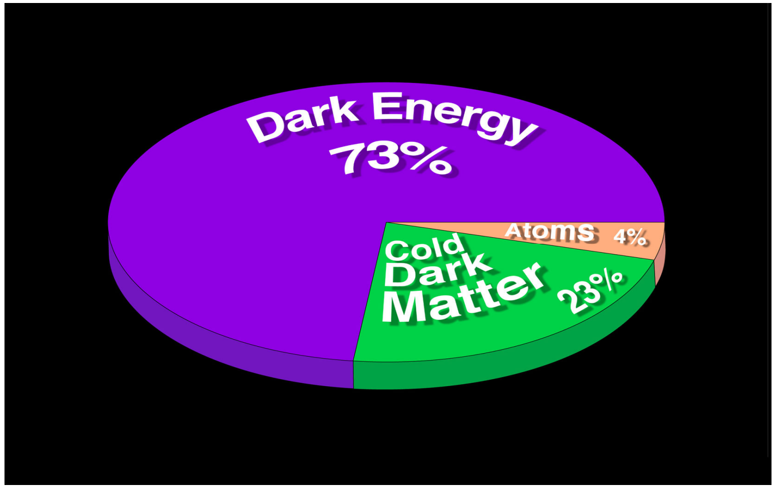
→ hierarchy problem

(fine-tuning problem: Big # - Big# → small #)

No such a problem → New Physics around TeV

(B) Experimental observations which the SM cannot explain

Wilkinson Microwave Anisotropy Probe (**WMAP**) satellite has established the energy budget in the present Universe with a great accuracy



(1) Dark Matter

$$0.096 \leq \Omega_{DM} h^2 \leq 0.122$$

Massive, charge neutral, stable

Suitable candidate: weakly interacting massive particle (**WIMP**) → **No Candidate in the SM → Need New Physics**

$$\Omega h^2 = \frac{1.07 \times 10^9 x_f \mathrm{GeV}^{-1}}{\sqrt{g_*} M_{\mathrm{Pl}} \langle \sigma \mathrm{v} \rangle} \sim 0.1 \to \quad \langle \sigma v \rangle \sim \alpha^2 \left(\frac{1}{1\ \mathrm{TeV}} \right)^2$$

TeV scale New Physics can account for DM physics!

Neutrinos are massless in the Standard Model

(2)Neutrino Oscillation Data

→ **Evidence of New Physics beyond the SM**

neutrino non-zero mass & flavor mixings

Oscillation data

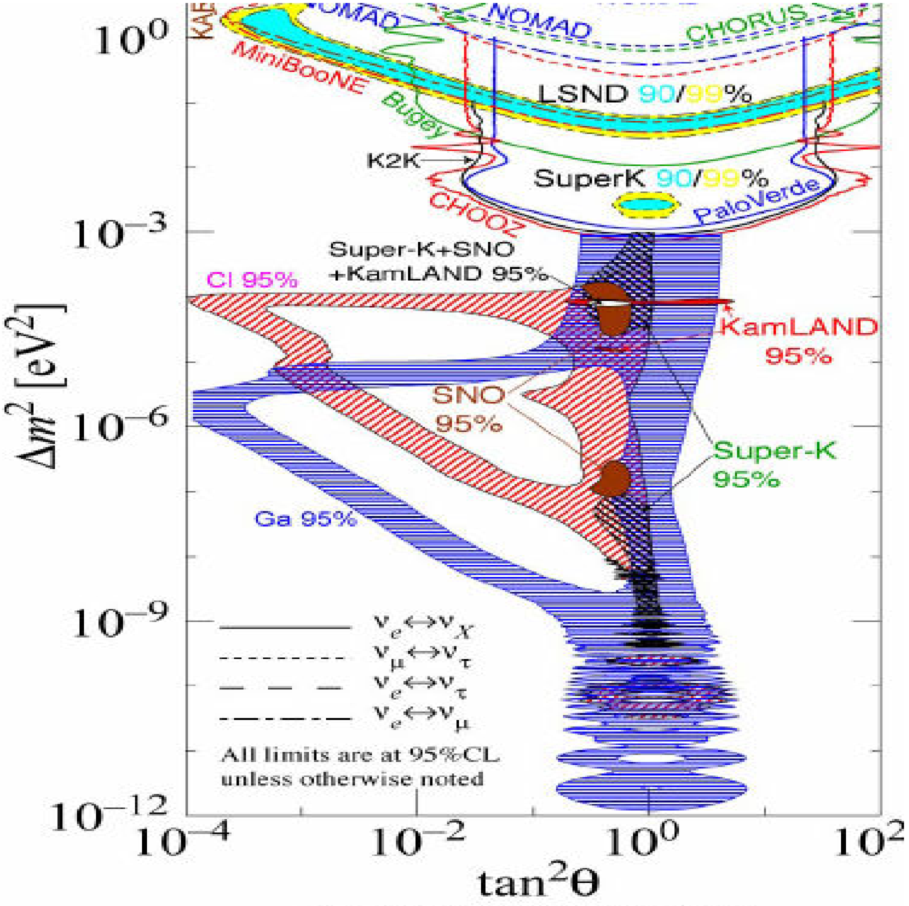
$$7.2 \times 10^{-5} < \Delta m_{12}^2(\mathrm{eV}^2) < 9.2 \times 10^{-5}$$

$$1.4 \times 10^{-3} < \Delta m_{23}^2(\mathrm{eV}^2) < 3.3 \times 10^{-3}$$

$$0.25 < \sin^2\theta_{12} < 0.39$$

$$\sin^2 2\theta_{23} > 0.9$$

$$|U_{e3}| < 0.22.$$



http://hitoshi.berkeley.edu/neutrino

2. New Physics Models & Future Collider Experiments

TeV scale New Physics

(1) motivated to solve the hierarchy problem

(2) suitable for WIMP Dark Matter

There are many TeV scale New Physics Models proposed

Common feature of New Physics Models

- New Particles → ``partners'' of SM particles
- New interactions between New & SM particles

Accessible at future Collider Experiments

Large Hadron Collider (LHC)

turned on! (9/10/2008)

Hadron collider: **pp**

$\sqrt{s} = 14$ TeV

Initial states: $gg,\ gq(\bar{q}),\ q\bar{q},\ qq'$

International Linear Collider (ILC)

from 20XX ?

Lepton collider: e^+e^-

$\sqrt{s} = 500$ GeV – 1 TeV **?**

Initial states e^+e^-

LHC: high energy machine

→ high New Particle discovery potential

ILC: more precise measurements

→ discriminate New Physics Models

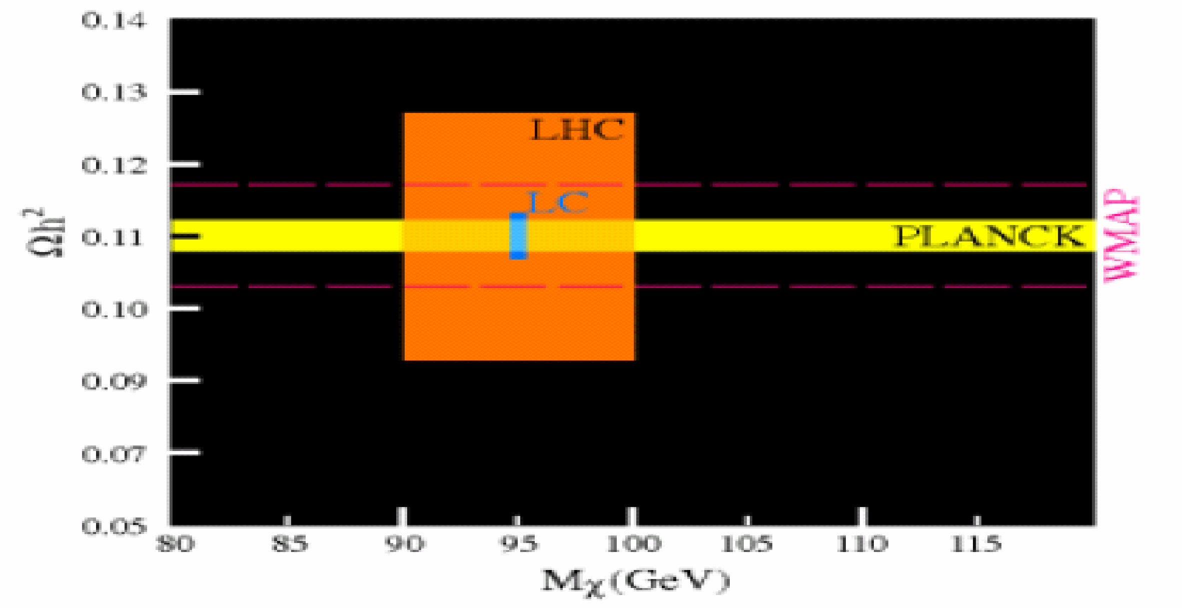
consistency check with other observation

Ex) calculate DM relic density by using parameters measured

Ex)

Supersymmetric

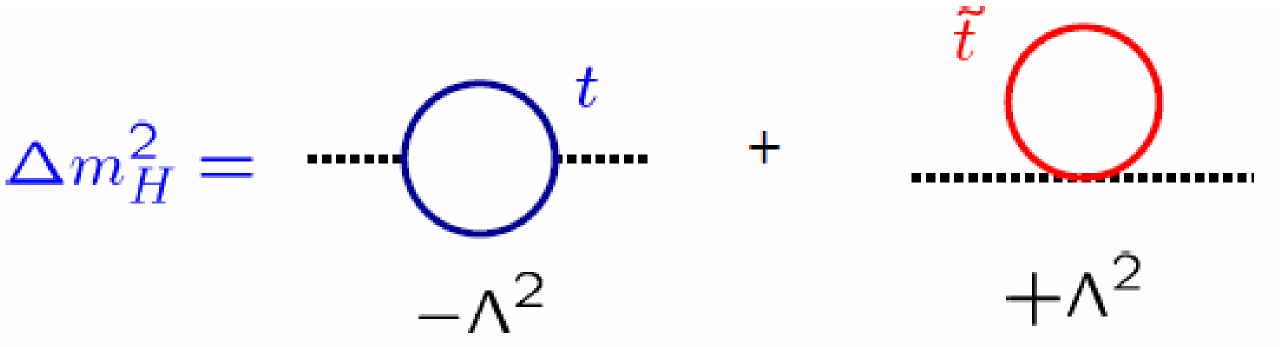
model



Sample1: Supersymmetric (SUSY) model

SUSY trans: fermion ←→ boson

No quadratic divergence



Cancellation by New Particle (SUSY partner) contributions

More theoretically,

quantum corrections to fermion mass → No Λ^2

= quantum corrections to scalar

Because of SUSY

Minimal Supersymmetric Standard Model (MSSM)

SUSY version of SM

SM particles		Superpartners
quark, lepton (1/2)	⟷	squark, slepton (0)
gauge boson (1)		gaugino (1/2)
Higgs (0)		Higgsino (1/2)

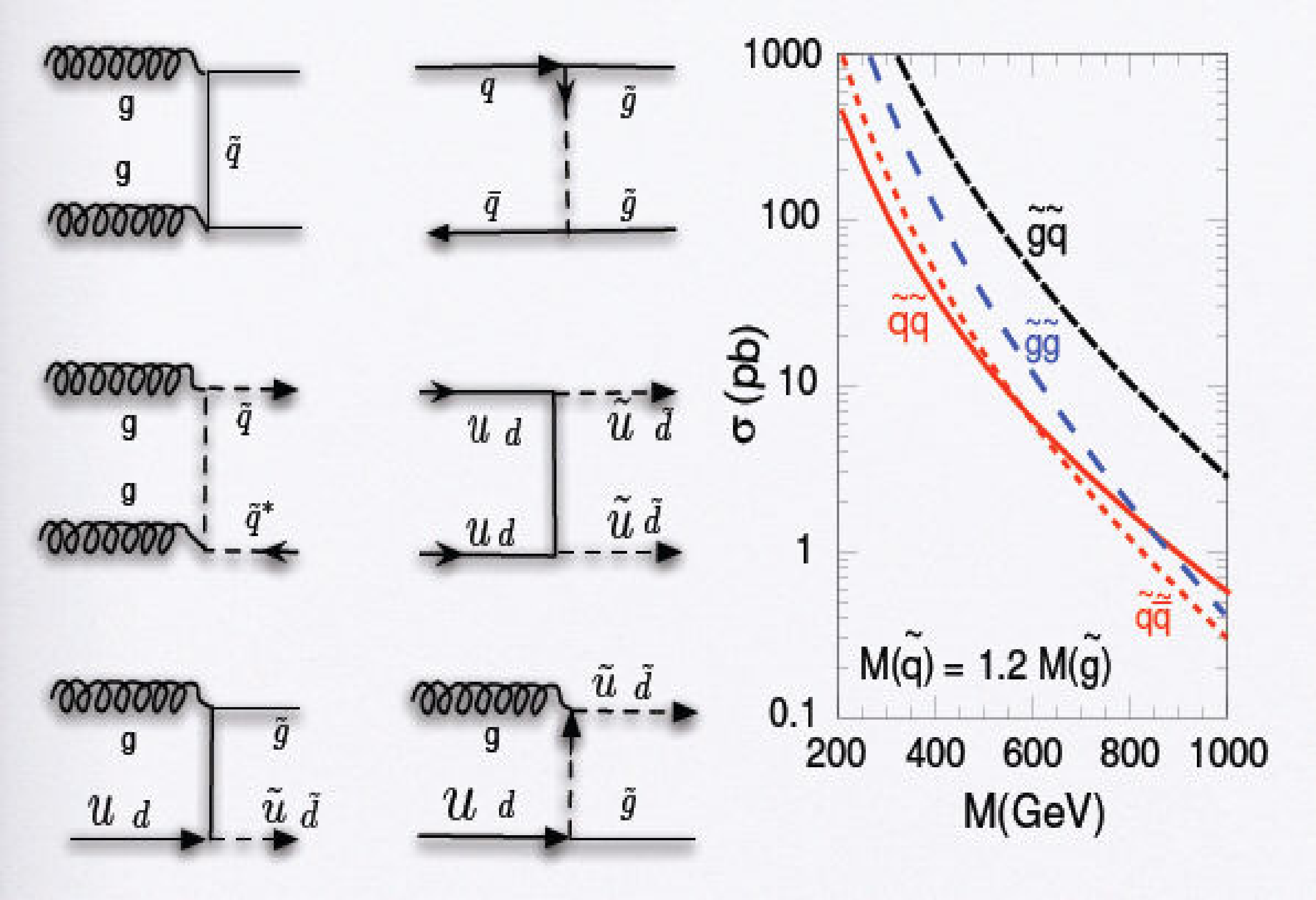
But, SUSY should be broken, otherwise $m_{\tilde{e}} = m_e$

→ Superpartners have mass 100 GeV- 1 TeV

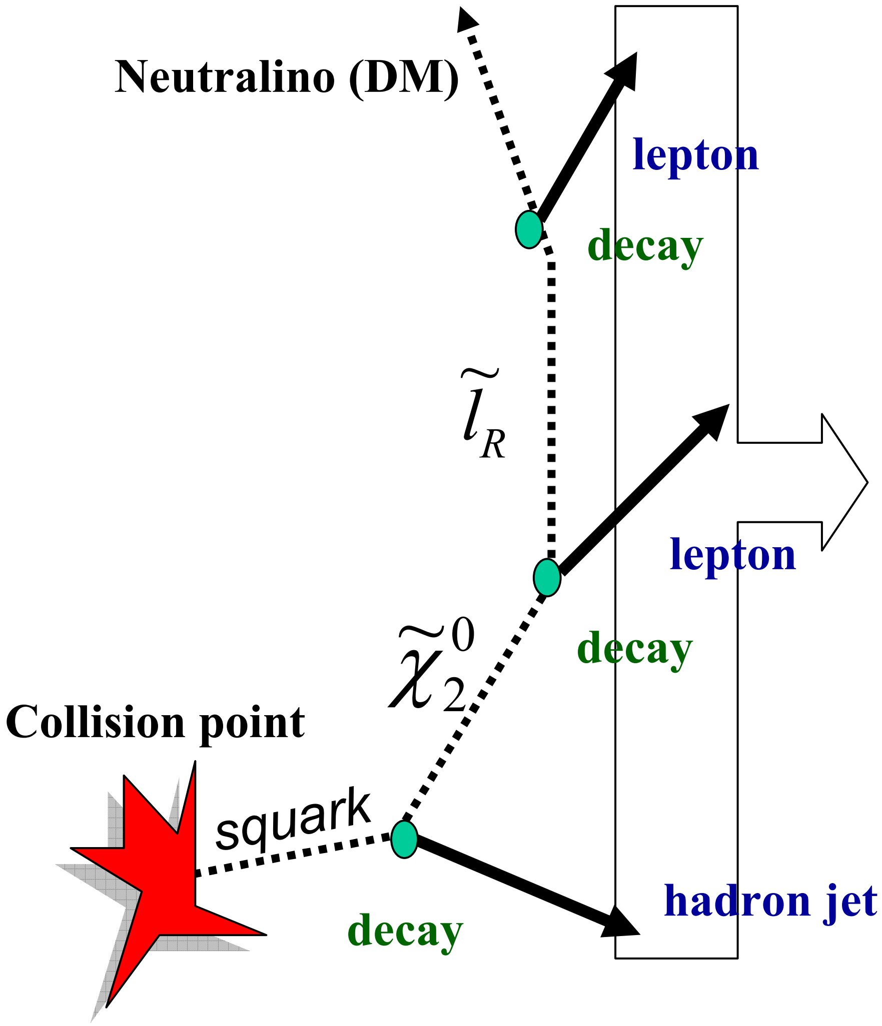
$$\boxed{\Lambda_{\text{New}} \to \tilde{m}}$$

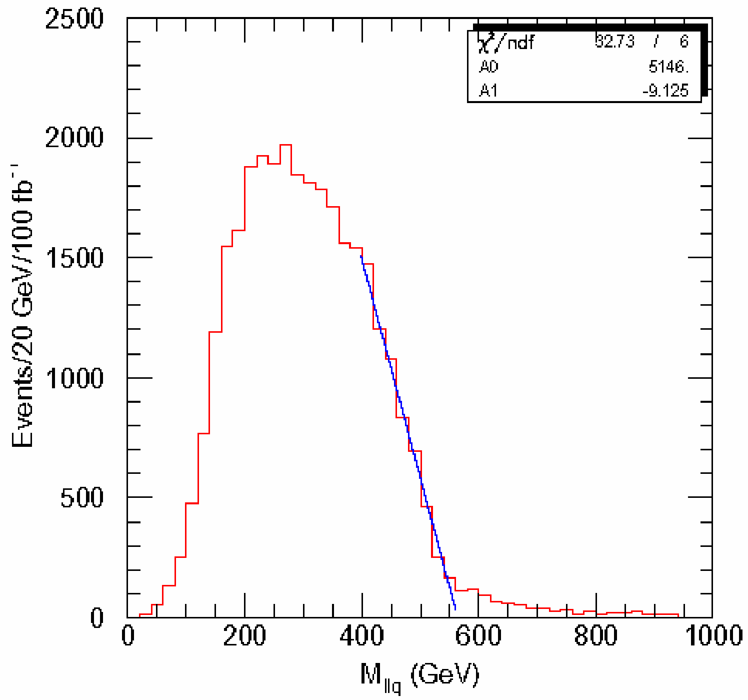
Neutralino is the DM candidate with R-parity conservation

Discover SUSY at LHC



Discovery of superpartner & mass measurements





Jll invariant mass distribution

$$M_{\ell\ell q}^{\max} = \left[\frac{\left(M_{\tilde{q}_L}^2 - M_{\tilde{\chi}_2^0}^2\right)\left(M_{\tilde{\chi}_2^0}^2 - M_{\tilde{\chi}_1^0}^2\right)}{M_{\tilde{\chi}_2^0}^2} \right]^{1/2} = 552.4\,\mathrm{GeV}\,.$$

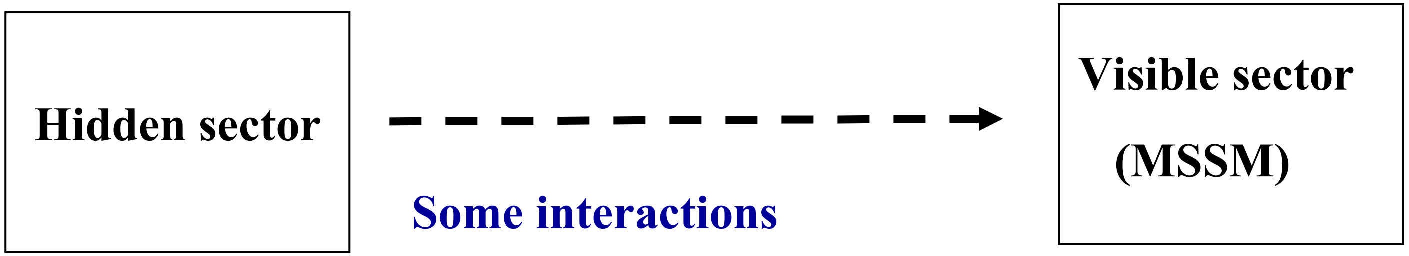
Suppose…..

Sparticles have been discovered at LHC

Sparticle masses have been measured @ LHC (+ILC)

What can we learn?

→ Mechanism of SUSY breaking mediation



Some interactions

(gravity, gauge,….)

SUSY breaking

$\langle F_X \rangle \neq 0$

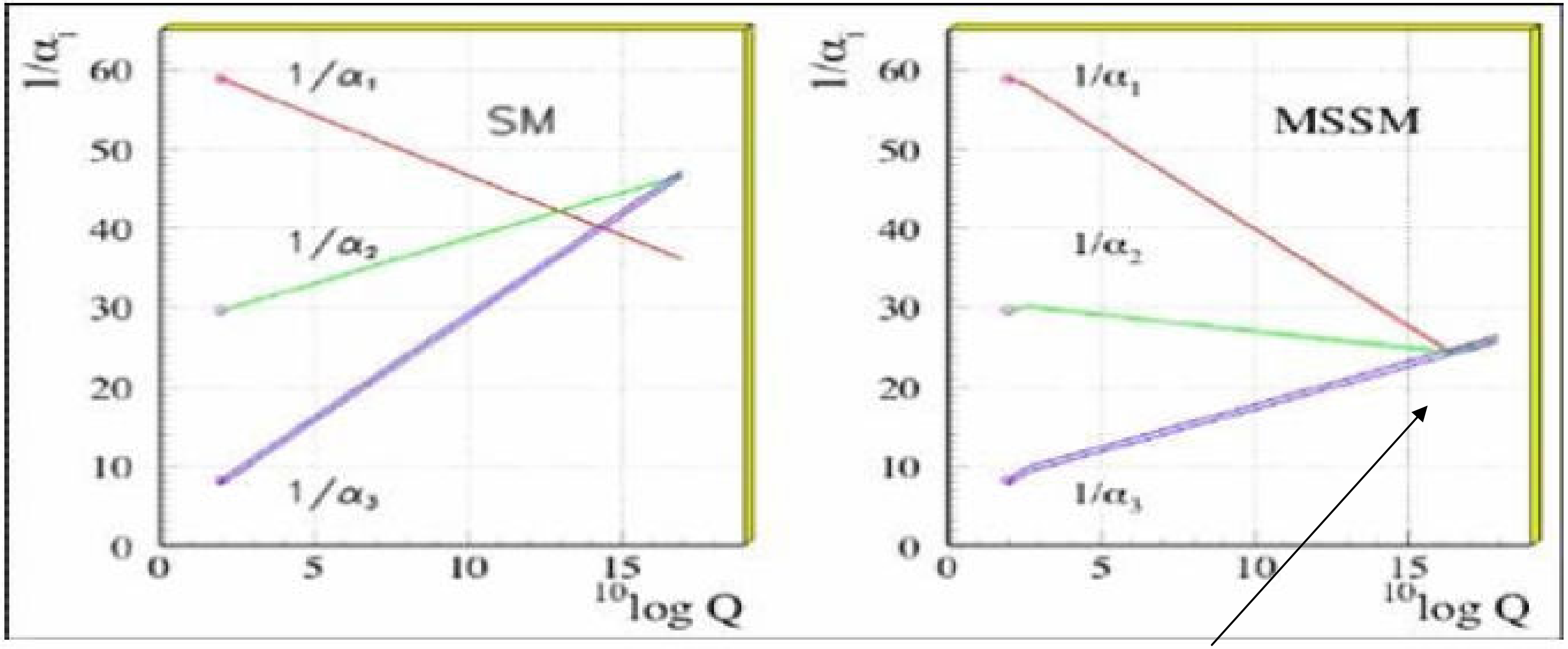
Some fields (messenger fields)

Sparticle masses carry the information of SUSY breaking mediation @ higher energies

Interesting theoretical paradigm: Grand Unification

RGE extrapolations of SM gauge couplings w/ MSSM particle contents suggest Grand Unified Theories (GUTs)

Three gauge couplings meet at one point



Gauge coupling unification

$M_{\mathrm{GUT}} \sim 10^{16}\ \mathrm{GeV}$

GUT models:

(1) $SU(5) \supset SU(3)_c \times SU(2)_L \times U(1)_Y$

Matters: 5* + 10

(2)$SO(10) \supset SU(3)_c \times SU(2)_L \times U(1)_Y$

Matters: 16

Sparticle masses to probe GUT model?

If sparticle masses (SUSY breaking) are generated

at scale > GUT scale

→The same multiplets have the same masses

SU(5) GUT: $m_{\tilde{D}} = m_{\tilde{L}} = m_5;\ m_{\tilde{Q}} = m_{\tilde{U}} = m_{\tilde{E}} = m_{10}$

SO(10)-like GUT: $m_{\tilde{Q}} = m_{\tilde{U}} = m_{\tilde{D}} = m_{\tilde{L}} = m_{\tilde{E}} = m_0$

To probe SU(5) GUT via sparticle mass spectrum

SU(5) extension of CMSSM

Gogoladze, Khalid, N.O., Shafi

in preparation

$m_{1/2},\ \tan\beta,\ A_0,\ \mathrm{sgn}(\mu)$

$m_0 \to m_5,\ m_{10}$

Gaugino Mass: $\frac{M_1(\mu)}{\alpha_1(\mu)} = \frac{M_2(\mu)}{\alpha_2(\mu)} = \frac{M_3(\mu)}{\alpha_3(\mu)} = \frac{M_{1/2}}{\alpha_{\mathrm{GUT}}}$

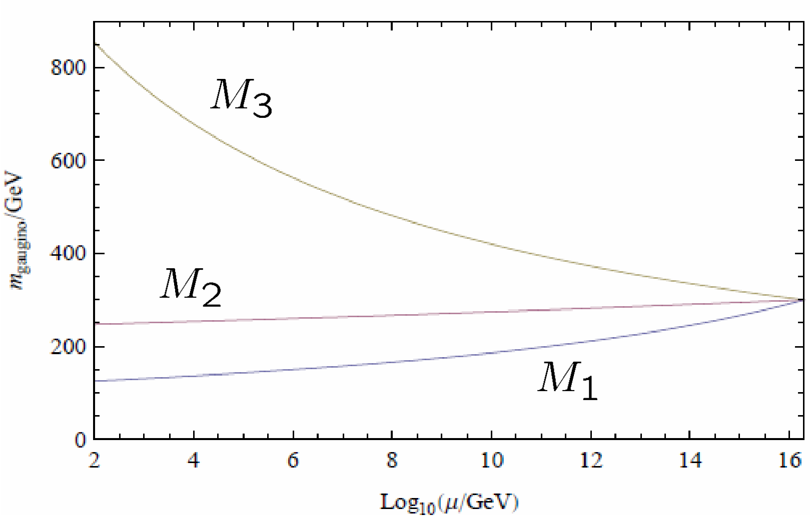
Sfermion masses (t1st & 2$^{\mathrm{nd}}$ generations):

$$\text{5*-plet} \begin{cases} m_{\tilde{d}^c} \simeq m_5^2 + 5.4 M_{1/2}^2 \\ m_{\tilde{L}} \simeq m_5^2 + 0.54 M_{1/2}^2 \end{cases}$$

$$\text{10-plet} \begin{cases} m_{\tilde{Q}} \simeq m_{10}^2 + 6.0 M_{1/2}^2 \\ m_{\tilde{u}^c} \simeq m_{10}^2 + 5.5 M_{1/2}^2 \\ m_{\tilde{e}^c} \simeq m_{10}^2 + 0.15 M_{1/2}^2 \end{cases}$$

Gaugino mass unification

$$\frac{M_1(\mu)}{\alpha_1(\mu)} = \frac{M_2(\mu)}{\alpha_2(\mu)} = \frac{M_3(\mu)}{\alpha_3(\mu)}$$



Sfermion mass spectrum (1,2 generation)

SU(5)

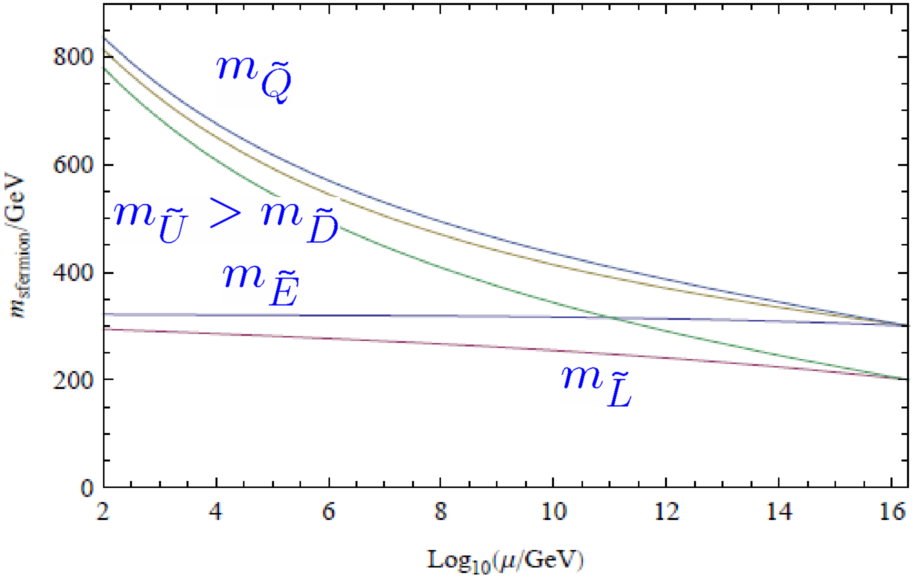
$m_{\tilde{D}} = m_{\tilde{L}} = 200$ GeV

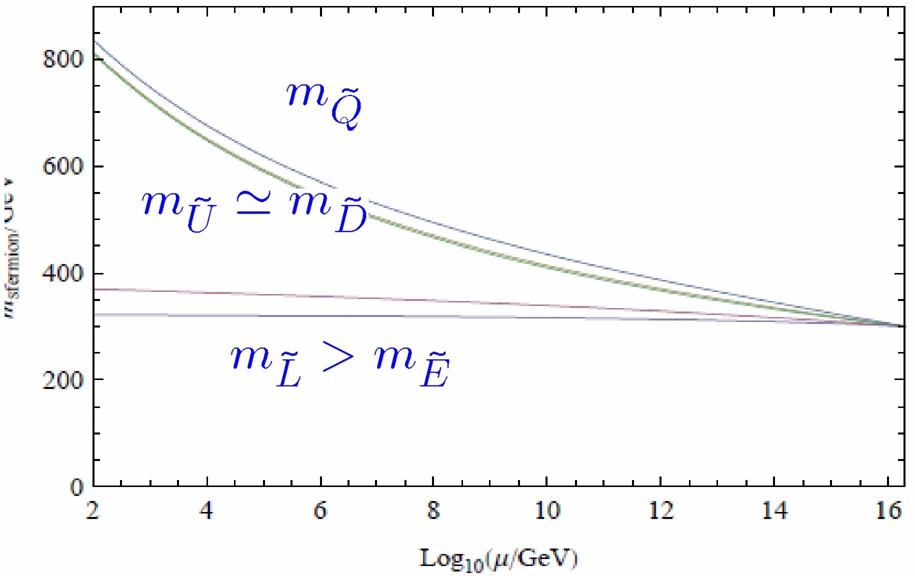
$m_{\tilde{Q}} = m_{\tilde{U}} = m_{\tilde{E}} = 300$ GeV

@ GUT

SO(10) **(CMSSM)**

$m_{\tilde{Q}} = m_{\tilde{U}} = m_{\tilde{D}} = m_{\tilde{L}} = m_{\tilde{E}} = 300$ GeV

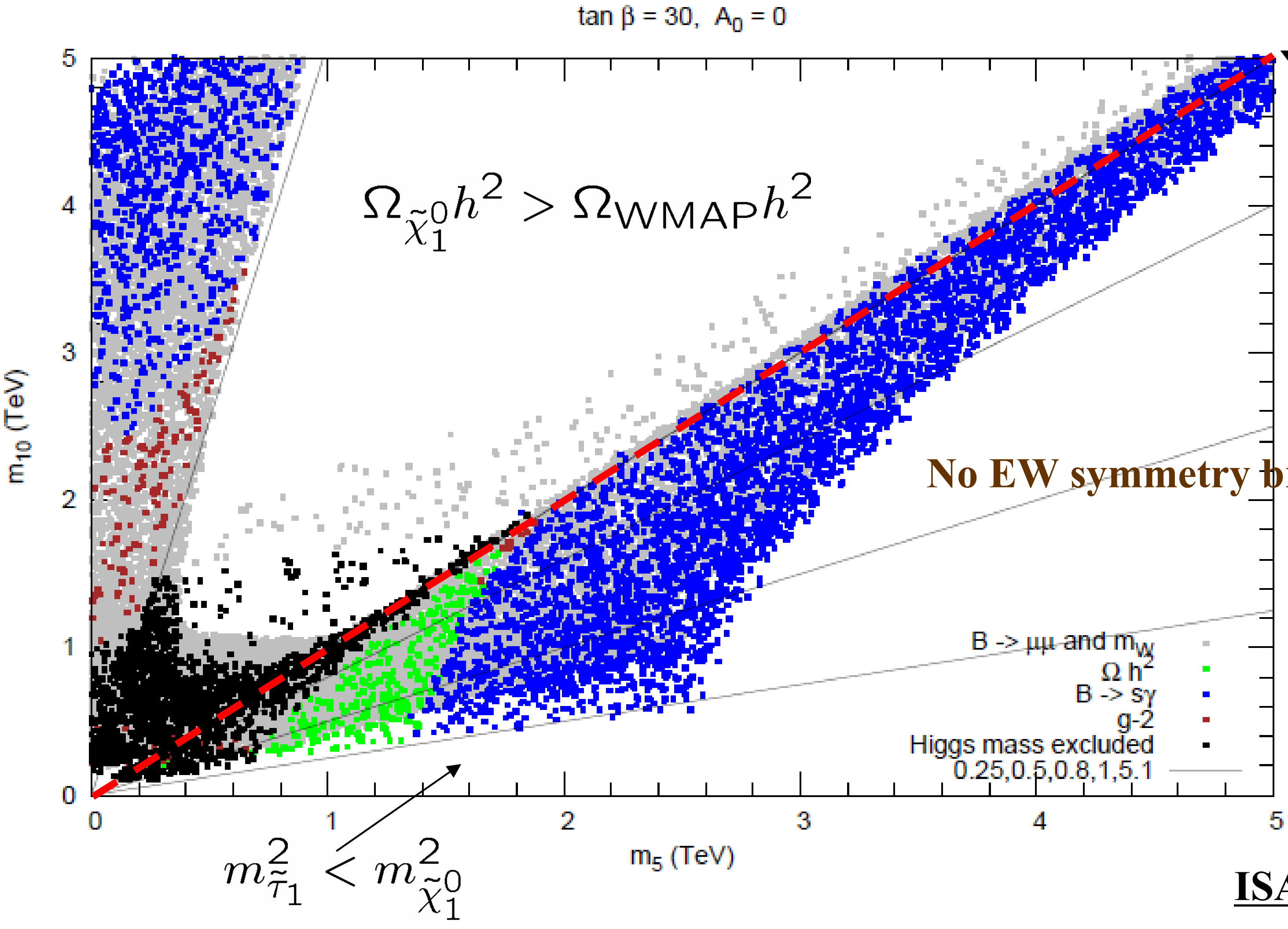




Parameters satisfying several experimental constraints

Gogoladze, Khalid, N.O., Shafi

in preparation



$\Omega_{\tilde{\chi}_1^0} h^2 > \Omega_{\rm WMAP} h^2$

$m^2_{\tilde{\tau}_1} < m^2_{\tilde{\chi}_1^0}$

No EW symmetry breaking

CMSSM

$m_5 = m_{10}$

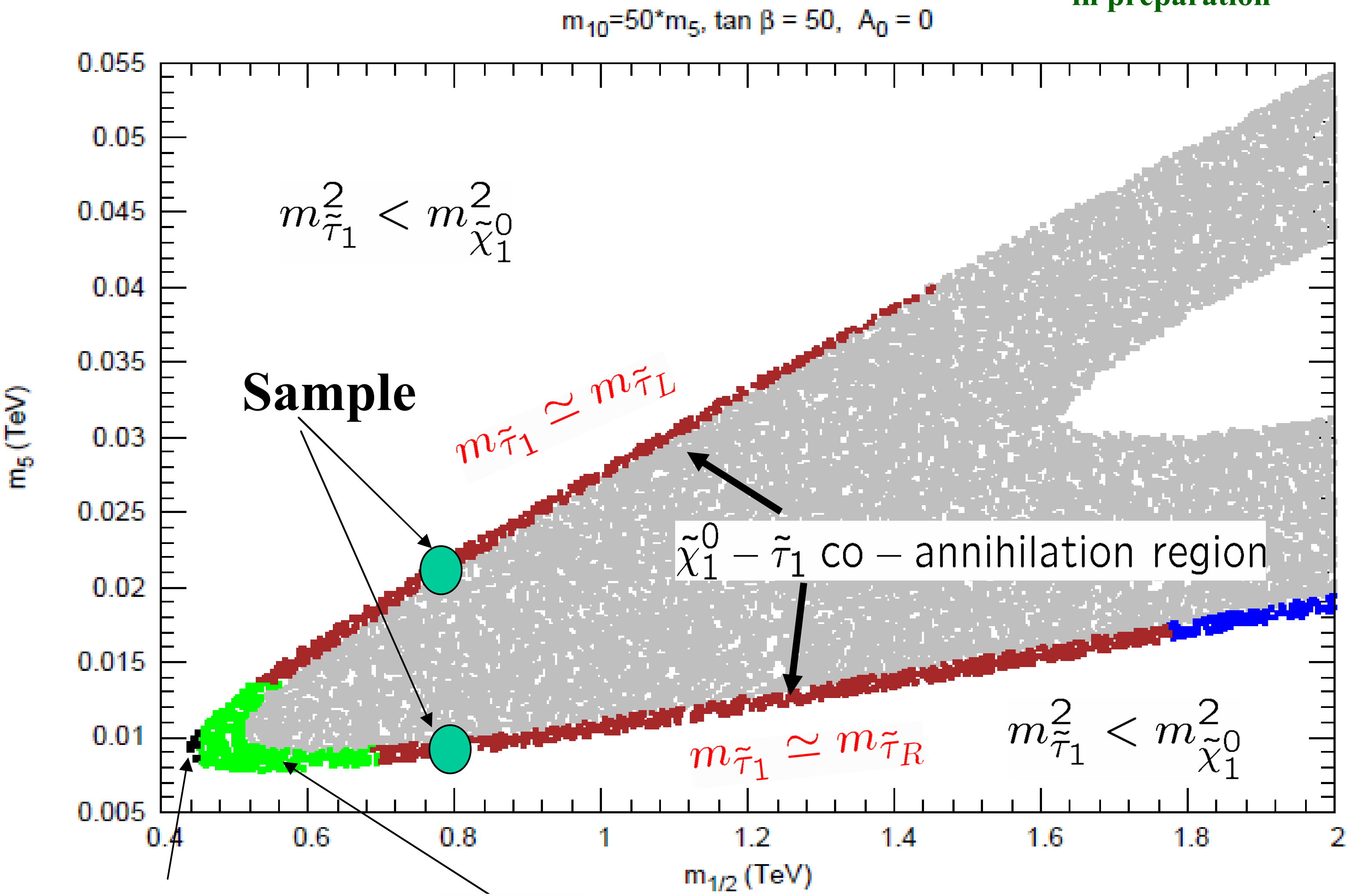
ISAJET

Allowed region for $m_{10} = 50 \times m_5$, $\tan\beta = 50$, $A_0 = 0$

Two branches

Gogoladze, Khalid, N.O., Shafi

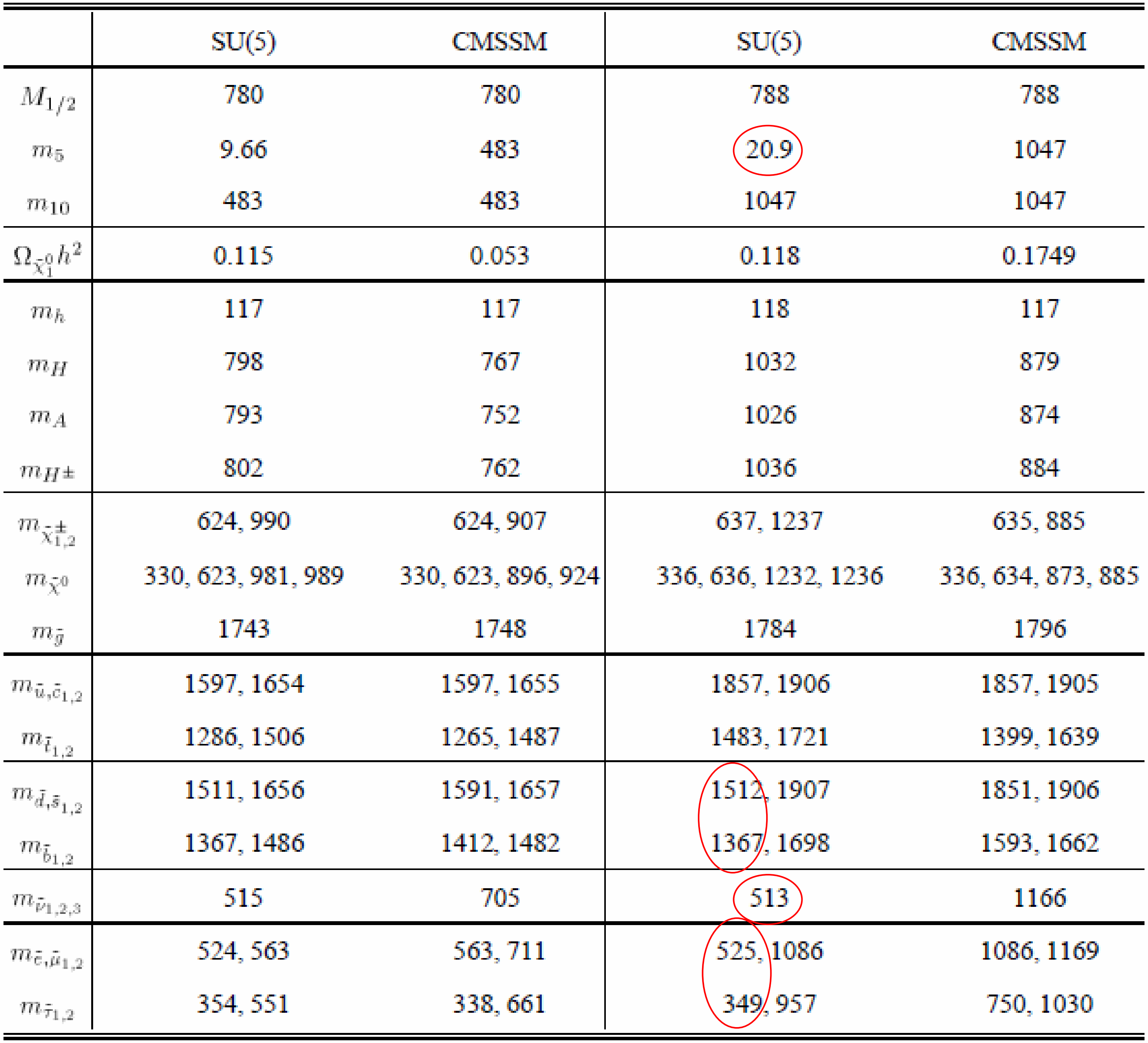
in preparation



Excluded by Higgs mass

$b \to s\gamma$

ISAJET



	SU(5)	CMSSM	SU(5)	CMSSM
$M_{1/2}$	780	780	788	788
m_5	9.66	483	20.9	1047
m_{10}	483	483	1047	1047
$\Omega_{\tilde{\chi}_1^0}h^2$	0.115	0.053	0.118	0.1749
m_h	117	117	118	117
m_H	798	767	1032	879
m_A	793	752	1026	874
$m_{H^\pm}$	802	762	1036	884
$m_{\tilde{\chi}^\pm_{1,2}}$	624, 990	624, 907	637, 1237	635, 885
$m_{\tilde{\chi}^0}$	330, 623, 981, 989	330, 623, 896, 924	336, 636, 1232, 1236	336, 634, 873, 885
$m_{\tilde{g}}$	1743	1748	1784	1796
$m_{\tilde{u},\tilde{c}_{1,2}}$	1597, 1654	1597, 1655	1857, 1906	1857, 1905
$m_{\tilde{t}_{1,2}}$	1286, 1506	1265, 1487	1483, 1721	1399, 1639
$m_{\tilde{d},\tilde{s}_{1,2}}$	1511, 1656	1591, 1657	1512, 1907	1851, 1906
$m_{\tilde{b}_{1,2}}$	1367, 1486	1412, 1482	1367, 1698	1593, 1662
$m_{\tilde{\nu}_{1,2,3}}$	515	705	513	1166
$m_{\tilde{e},\tilde{\mu}_{1,2}}$	524, 563	563, 711	525, 1086	1086, 1169
$m_{\tilde{\tau}_{1,2}}$	354, 551	338, 661	349, 957	750, 1030

Sample 2: Little Higgs Model

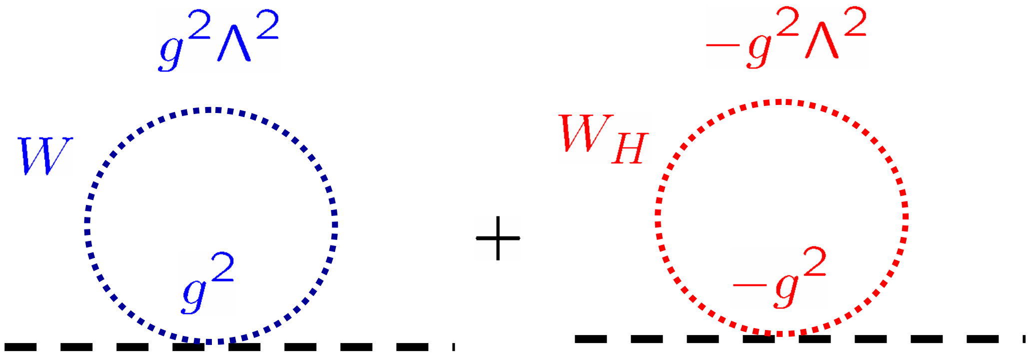
Arkani-hamed, Sohen, Georgi, Nelson, Katz,
Gregoile, Wacker, 2002

Higgs as a pseudo-NG boson associated with a global symmetry breaking @ $f \sim 1$ TeV

SUSY alternative, but similar structure

No quadratic divergence @ 1-loop level

$$\Delta M_H^2 =$$



$$= 0$$

Quadratic divergence is cancelled

by Little Higgs Partner contributions

same spin

Little Higgs Model

quark, lepton (1/2)		heavy quark, heavy lepton (1/2)
gauge boson (1)	↔	heavy gauge boson (1)
Higgs (0)		heavy Higgs (0)
SM particles		**LH partners**

H.C. Cheng & I. Low,
2003, 2004

T-parity: possible to imposed in the model

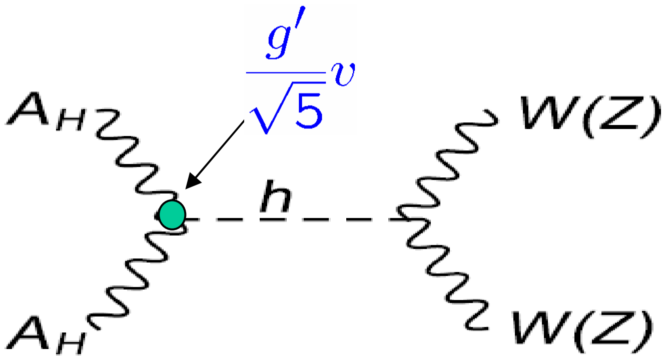
under which LH partners have ``odd parity''

→ heavy ``Photon'' A_H **becomes stable**

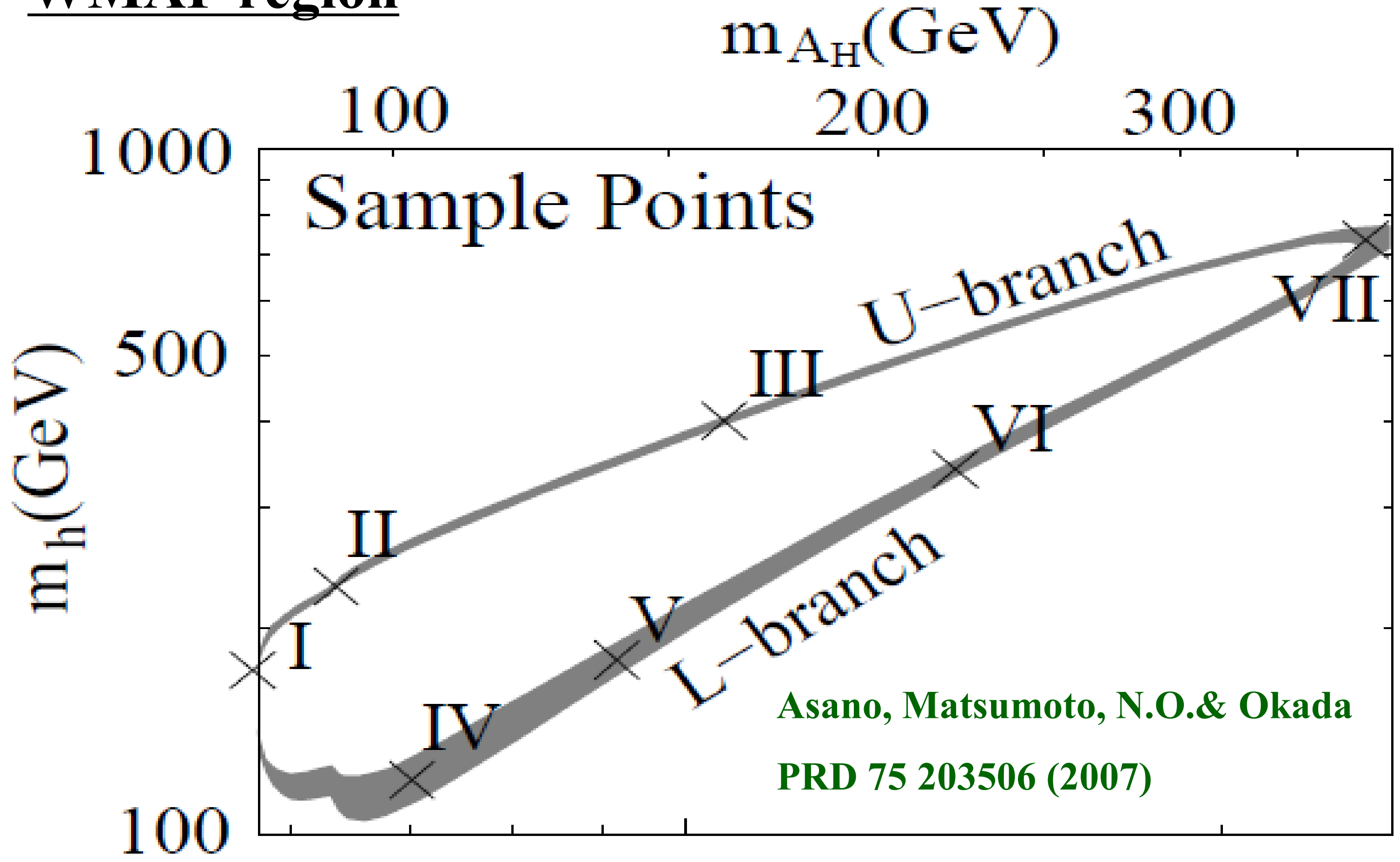
→ DM candidate!

Relic density calculation

Main annihilation processes:



WMAP region

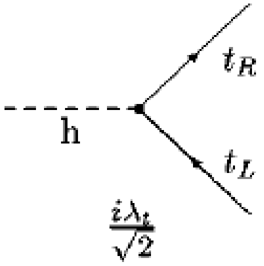


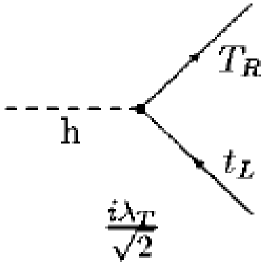
Asano, Matsumoto, N.O.& Okada

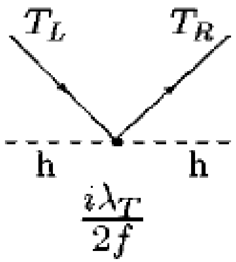
PRD 75 203506 (2007)

Collider studies on ``Heavy Top Quark''

Vector-like SU(2) singlet top quark ``LH partner'' is introduced



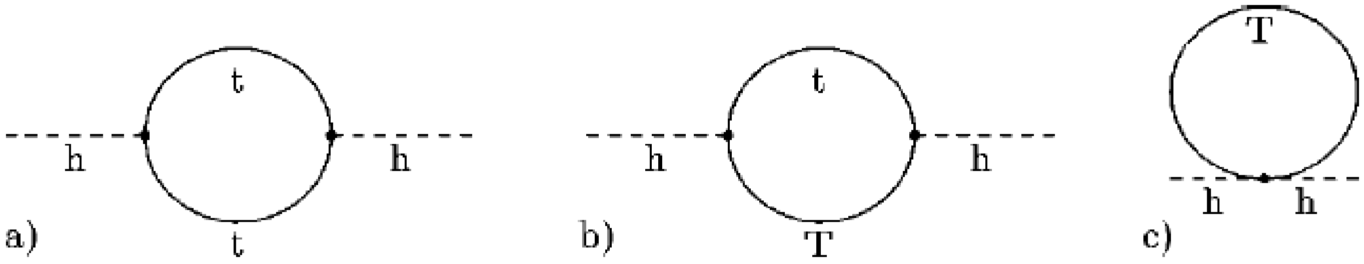




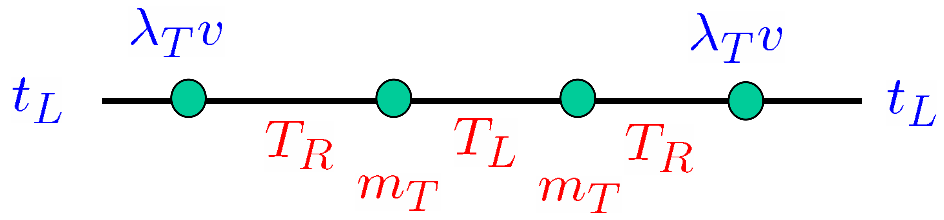
Mass spectrum:

$$\begin{cases} m_t = \lambda_t v \\ m_T = \dfrac{\lambda_t^2 + \lambda_T^2}{\lambda_T} f \end{cases}$$

Cancellation of quadratic divergence via T contributions



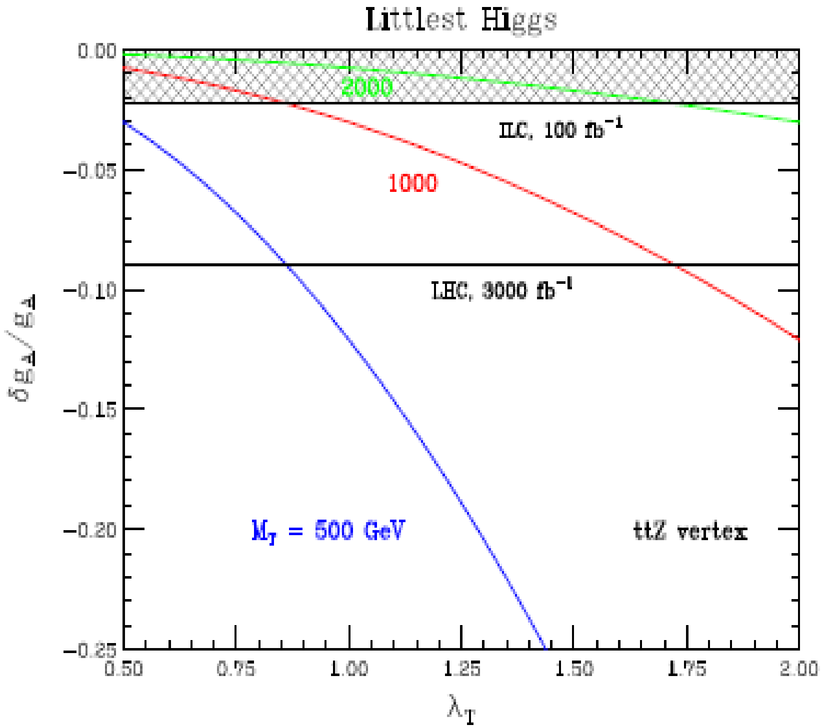
Anomalous top coupling with Z and W via t and T mixing



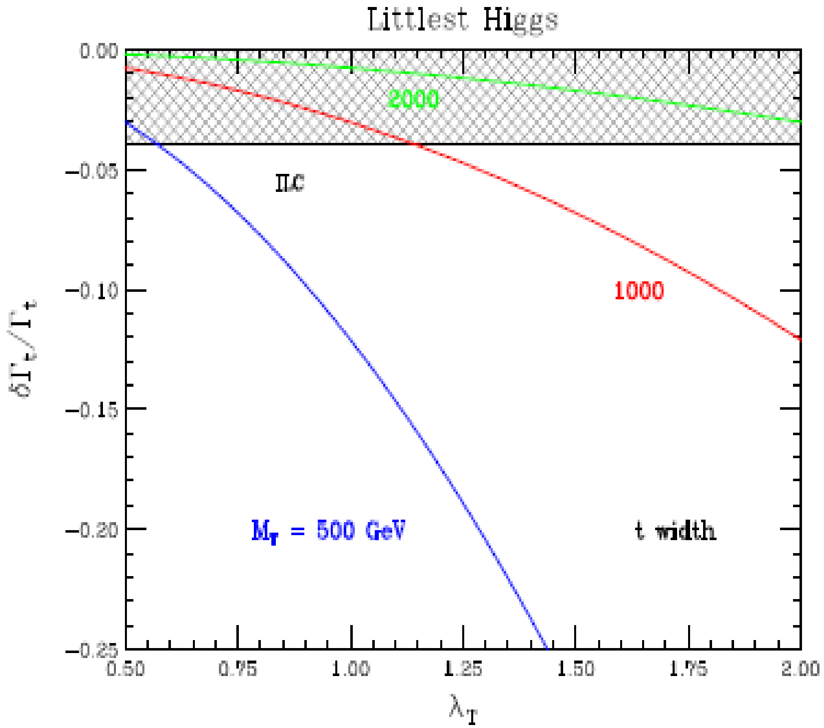
$$\delta g_L^{Zt} = \frac{\lambda_T^2 v^2 g_A^Z}{m_T^2},$$

$$\delta g_L^{Wt} = -\frac{1}{4}\frac{\lambda_T^2 v^2 g^W}{m_T^2}$$

Berger, Perelstein & Petriello, hep-ph/0512053



Anomalous coupling



Anomalous top decay width

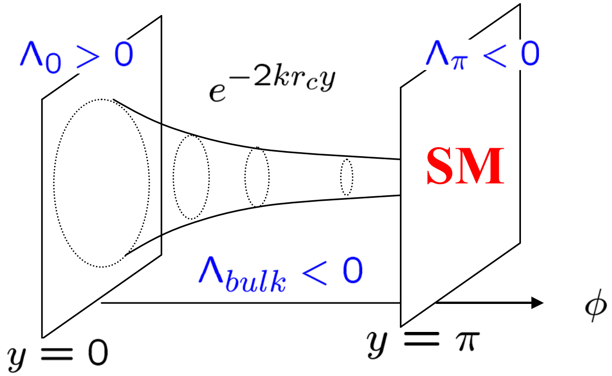
Sample 3: Warped Extra-dimensions

Randall & Sundrum, 1999

5 D Brane World Scenario with a warped geometry

$$\Lambda_{\rm New} = M_{Pl} \times e^{-\pi r \kappa} \sim \mathrm{TeV}$$

with $r\kappa \sim 12$



Slice of AdS

kappa: AdS curvature

New Particle: Kaluza-Klein graviton + radion

KK graviton

- **KK mode mass:** $m_n = m_1 \times \left(\dfrac{x_n}{x_1}\right)$

  $x_1 \simeq 3.83,\ x_2 \simeq 7.02,\ x_3 \simeq 10.2\ ,\cdots$

- **Interaction:** $\mathcal{L}_{int}^{(n)} = -\dfrac{1}{\Lambda_\pi} G_{\mu\nu}^{(n)} T_{SM}^{\mu\nu};\qquad \Lambda_\pi = \dfrac{m_1}{x_1}\left(\dfrac{\bar{M}_P}{\kappa}\right)$

Radion

- **Radion mass: determined by radius stabilization** $m_\phi \ll m_1$

- **Interaction:** $\mathcal{L}_{int} = \dfrac{1}{\sqrt{6}\Lambda_\pi}\phi\, T_{SM}{}^{\mu}_{\mu}$

Resonance hunting

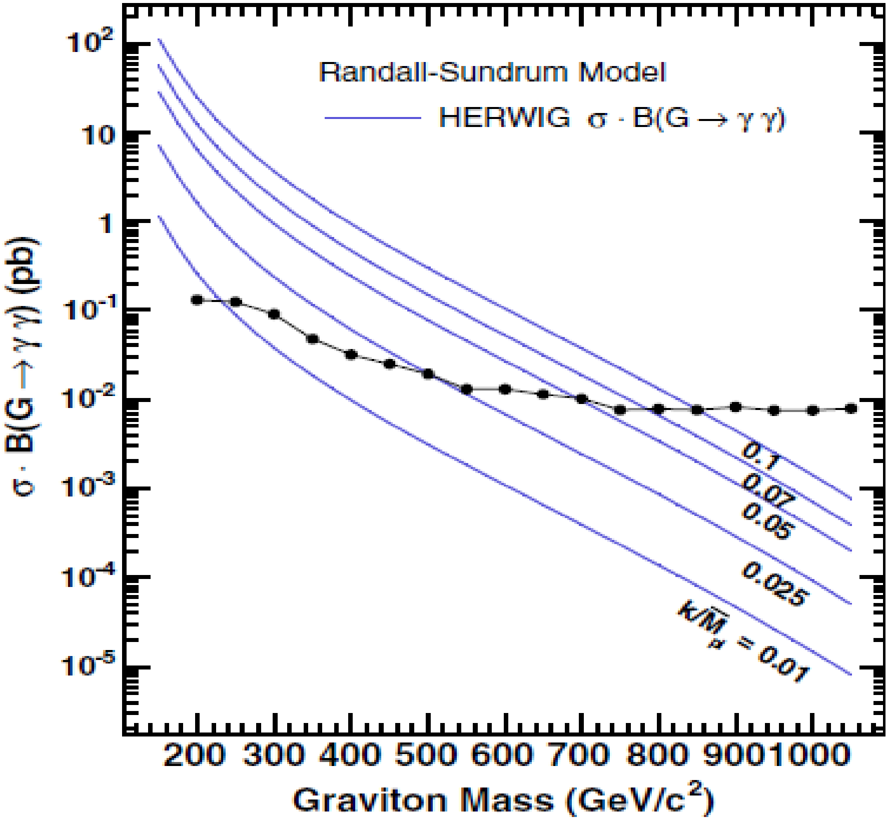
KK graviton production @ hadron collider

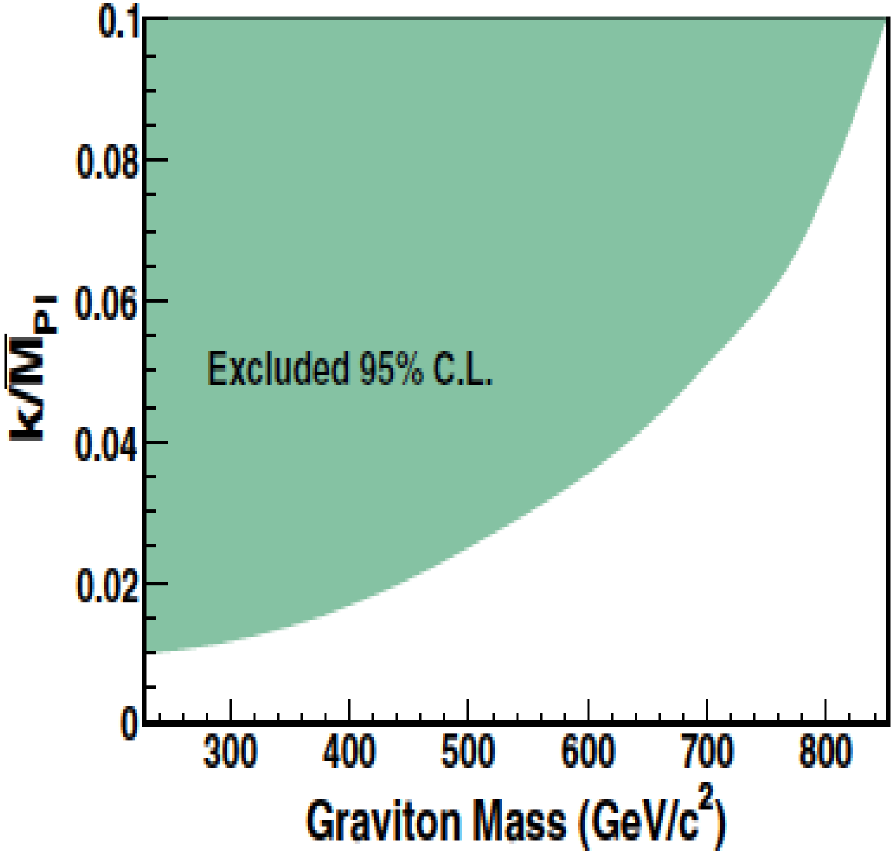
$$gg, q\bar{q} \to G_{KK}^{(n)} \to \gamma\gamma, \ell^+\ell^-, \cdots$$

CDF bounds $1.2\mathrm{fb}^{-1}$

For $\kappa/\bar{M}_{\mathrm{PL}} = 0.1$

$m_1 \geq 850$ GeV

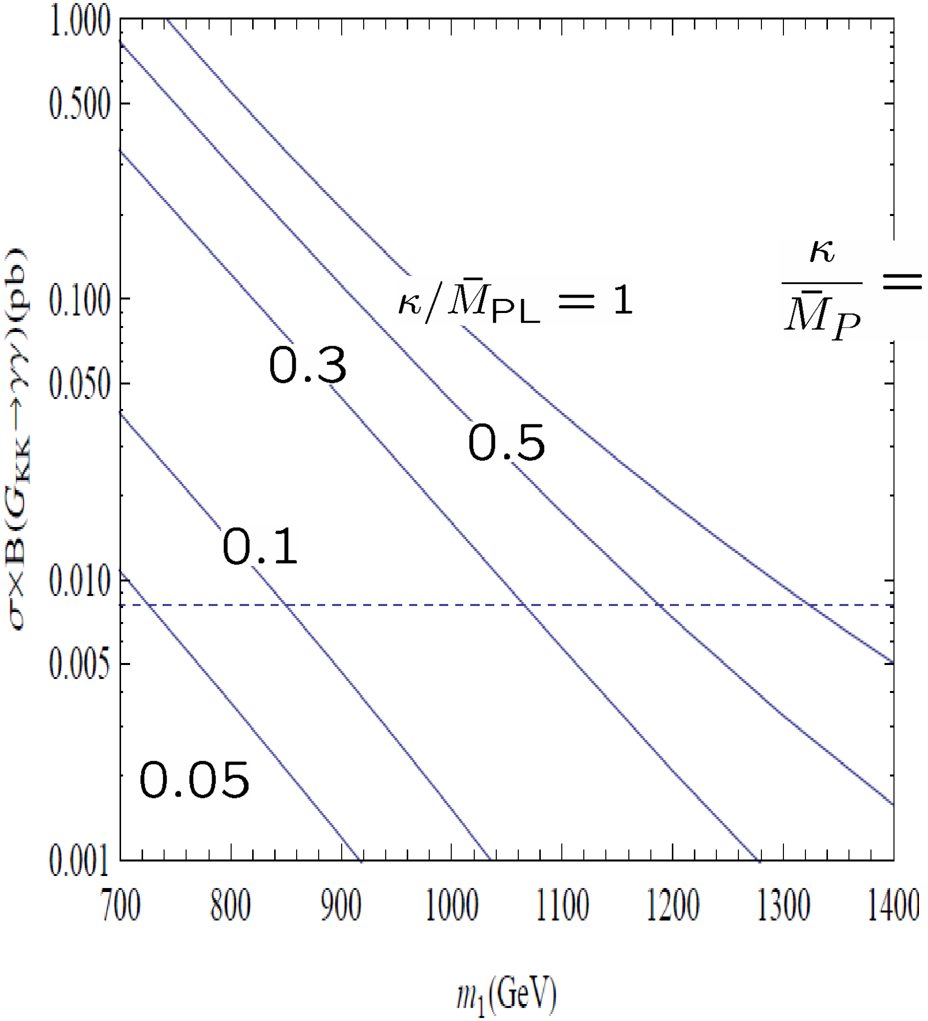




Validity of the model: neglecting higher curvature term

Naïve dimensional analysis → $\kappa/\bar{M}_{\rm PL} \sim 1$ **is <u>still OK</u>**

Agashe, Davoudiasl, Perez, Soni, PRD 76, 036006 (2007)



$$\frac{\kappa}{\bar{M}_P} = 0.3 \to m_1 \gtrsim 1.07\ \text{TeV},\ \ \Lambda_\phi \gtrsim 2.27\ \text{TeV}$$

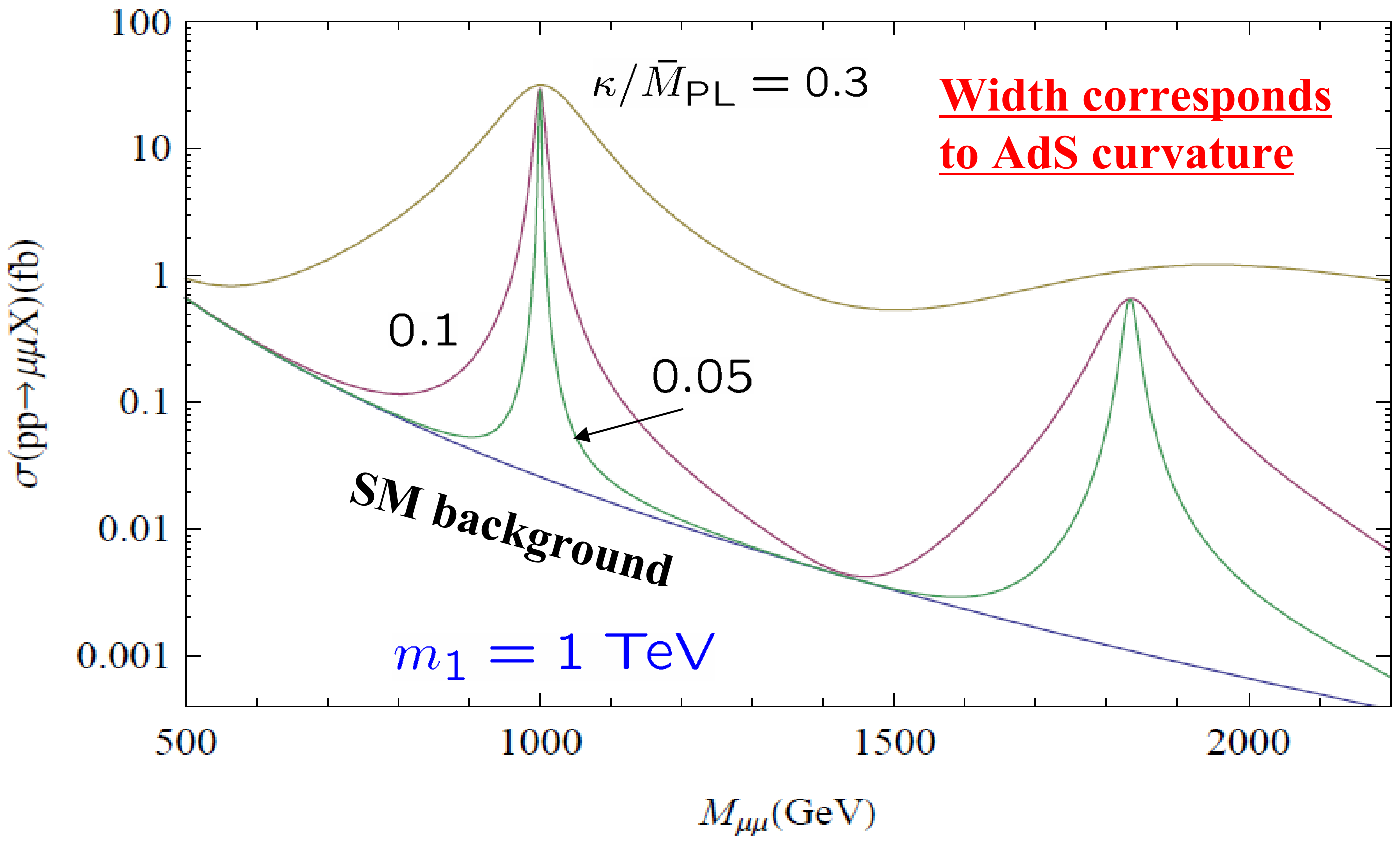
$$0.5 \to m_1 \gtrsim 1.19\ \text{TeV},\ \ \Lambda_\phi \gtrsim 1.52\ \text{TeV}$$

$$0.7 \to m_1 \gtrsim 1.27\ \text{TeV},\ \ \Lambda_\phi \gtrsim 1.16\ \text{TeV}$$

$$1.0 \to m_1 \gtrsim 1.32\ \text{TeV},\ \ \Lambda_\phi \gtrsim 0.85\ \text{TeV}$$

What happens @ LHC?

$pp \to G_{KK}^{(n)} \to \mu^+\mu^- X$ $E_{cm} = 14$ TeV



$\kappa/\bar{M}_{\rm PL} = 0.1$

$\sigma \sim 655$ fb **for** $800 \text{ GeV} \le M_{\mu\mu} \le 120 \text{ GeV}$

$\sigma_{\rm SM} \sim 76$ fb

Similar resonances in different models

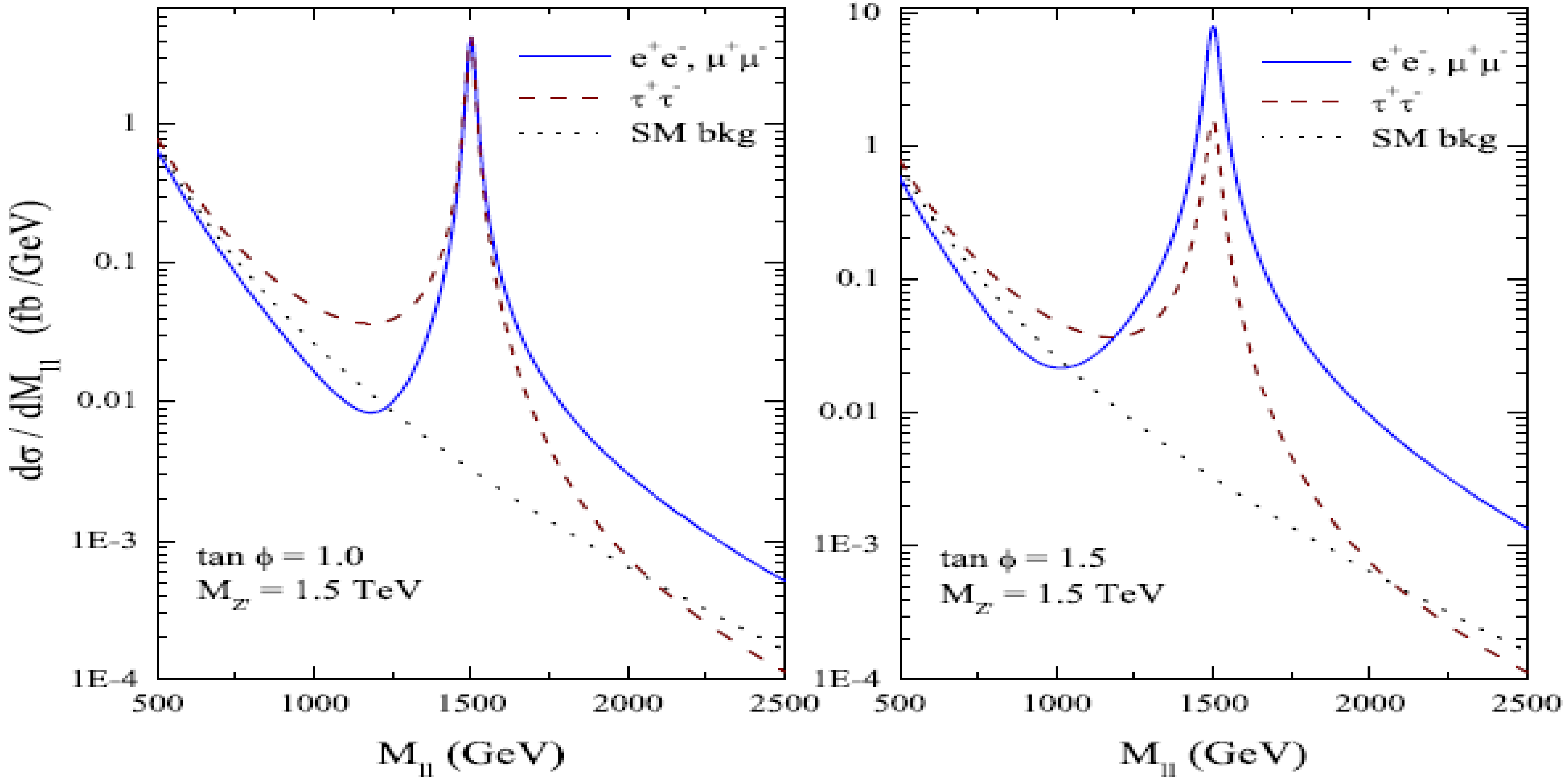
Many models with Z' boson (neutral current)

Ex) String inspired, E6, SO(10), LR models etc.

Even Z' models with flavor dependent couplings

Chen & N.O.,

to appear in PLB



What can we do with ILC?

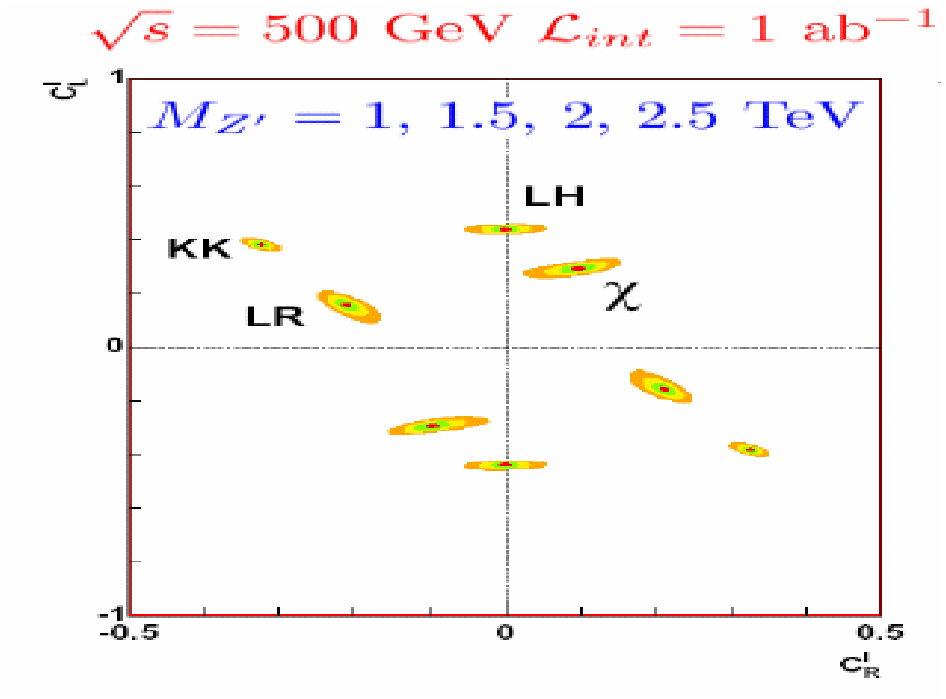
Z’ resonance can be found at LHC

Z’ mass is measured in some precision

→ Distinguish the models by precision measurement @ ILC

(cross section, FB asymmetry, LR asymmetry)

changing $\sqrt{s}$, polarized beam, final state polalization



In some cases,

positoron polarization is

very effective to reduce

back ground

Godfrey, Kalyniak, Reuter

Exotic resonance (charged current)

Mohapatra, N.O. & Yu

PRD 77, 011701 (2008)

A class of SUSY (partial) GUT models predicts some exotic R-parity even states → exotic resonance @ LHC

Diquark Higgs production @LHC

Color sextet SUSY-NG modes associated with B-L breaking

Chacko & Mohapatra, PRD 59 055004 (1999)

Dutta, Mimura & Mohapatra, PRL 96 061801 (2006)

Diquark Higgs $\left\{ \right.$

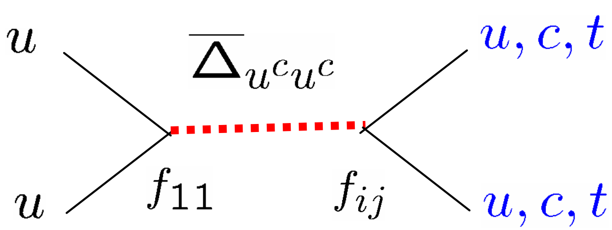
- baryon number -2/3
- color sextet
- mass around 100GeV-1TeV
- R-parity Even → resonant production at LHC
- plays an important role in $n - \bar{n}$ oscillation

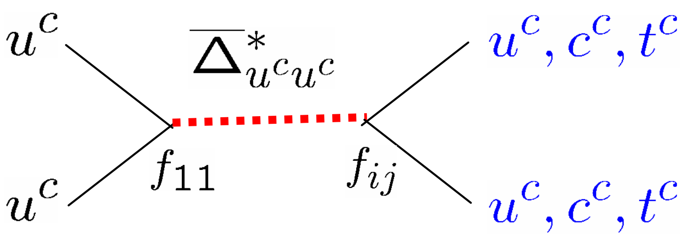
Coupling between diquark and fermions

$$W_Y \supset f_{ij}\Delta_{u^c u^c}\, u_i^c u_j^c$$

f_{ij} ←→ m_ν **: Collider Exps ←→Neutrino Oscillation Pheno.**

Diquark production @ LHC





We concentrate on the final states which include

at least one (anti-) top quark

Top quark with mass around 175 GeV electroweakly decays

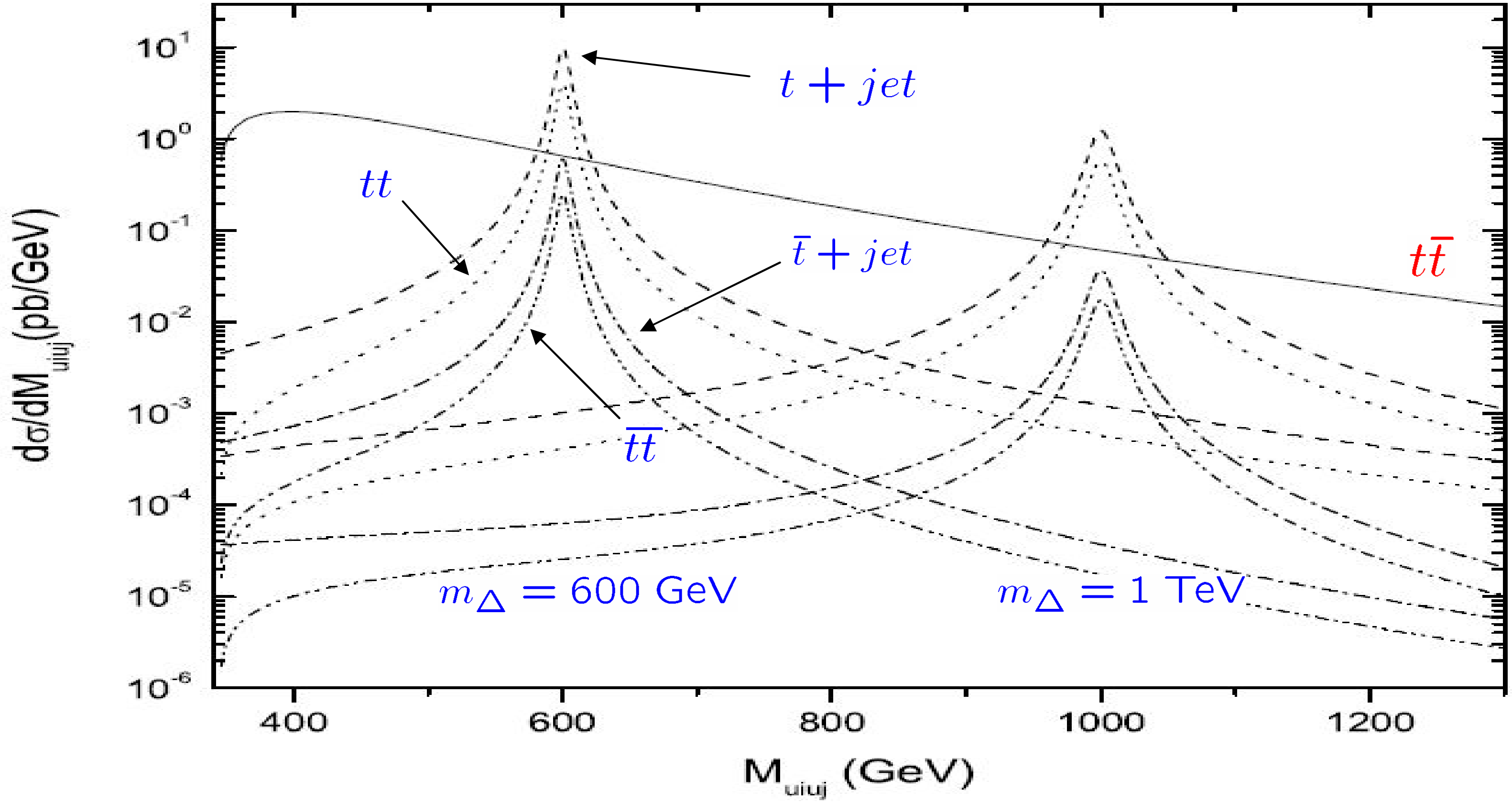
before hadronizing, so can be an ideal tool to probe new physics!

Cross section as a function of the invariant mass @ LHC

$E_{\text{CMS}} = 14 \text{ TeV}$

Mohapatra, N.O. & Yu

PRD 77, 011701 (2008)



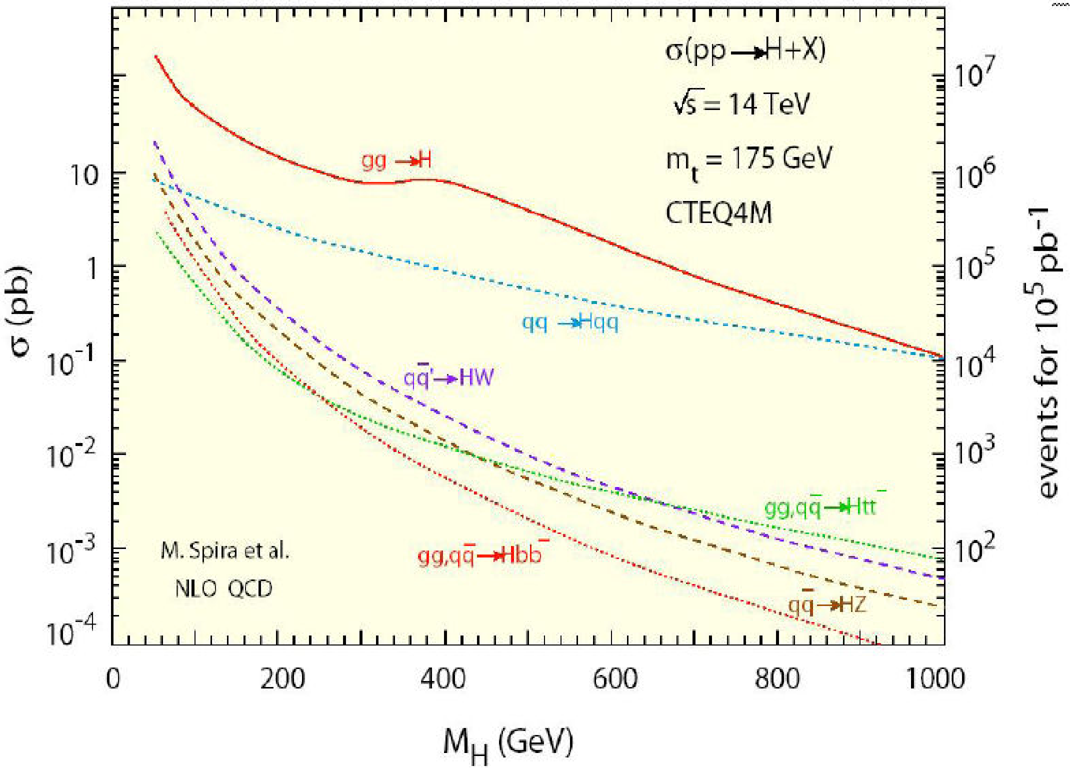
Diquark has a baryon number & LHC is ``pp'' machine

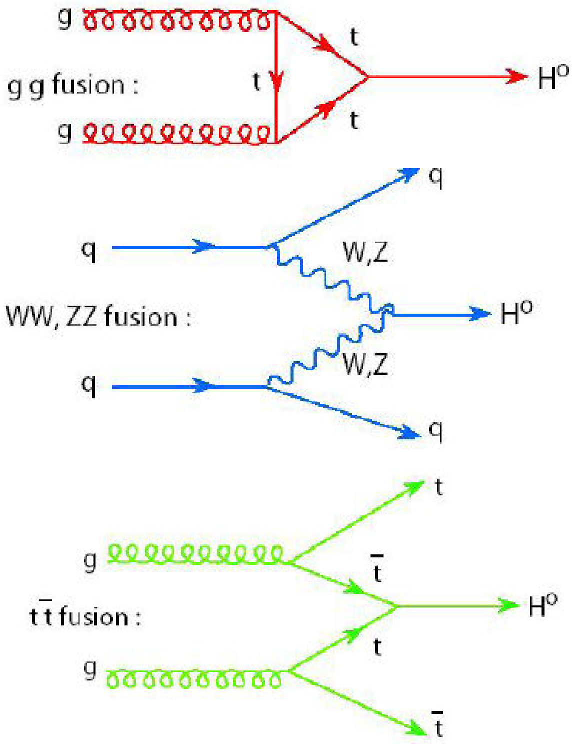
→ $\sigma(tt) \gg \sigma(\overline{tt}), \quad \sigma(t + jet) \gg \sigma(\bar{t} + jet)$

3. New Physics Implication for Higgs boson mass

Higgs boson : the last particle in the SM to be observed
the origin of the EW symmetry breaking
and the mass generation

Higgs boson production @LHC



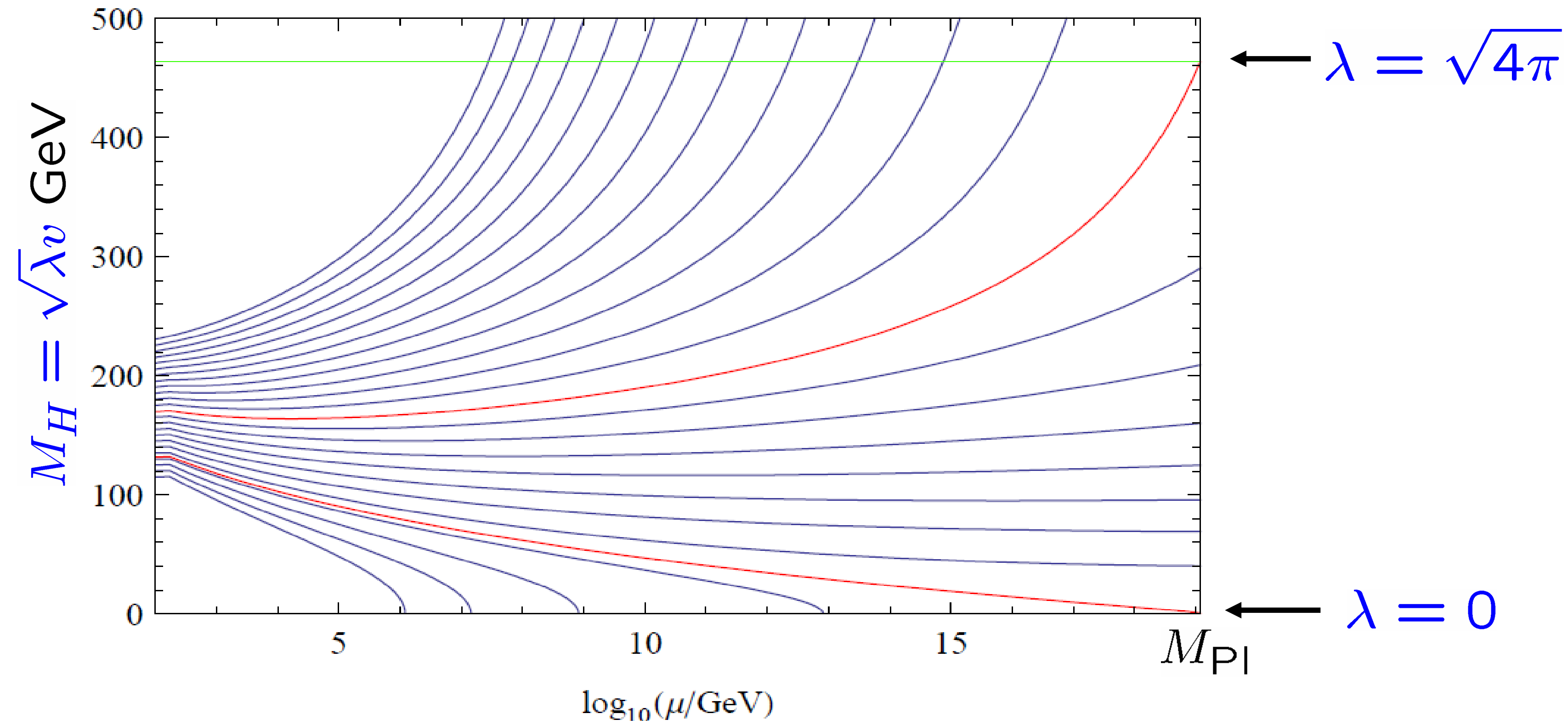


According to the Higgs potential in the SM,

The Higgs quartic coupling determines $M_H^2 = \lambda v^2$ $(v = 246\text{GeV})$

Once Higgs mass is measured, its high energy behavior

can be understood via RGE running of $\lambda(\mu)$



Theoretical bound on Higgs boson mass

$$\begin{cases} \textbf{Perturbativity bound: } \lambda(\mu) \leq \sqrt{4\pi} \\ \textbf{Stability bound: } \lambda(\mu) \geq 0 \end{cases}$$

for $M_W \leq \mu \leq \Lambda_{\rm cut}$

In the SM, if we fix $\Lambda_{\rm cut} = M_{Pl} = 1.2 \times 10^{19}$ GeV

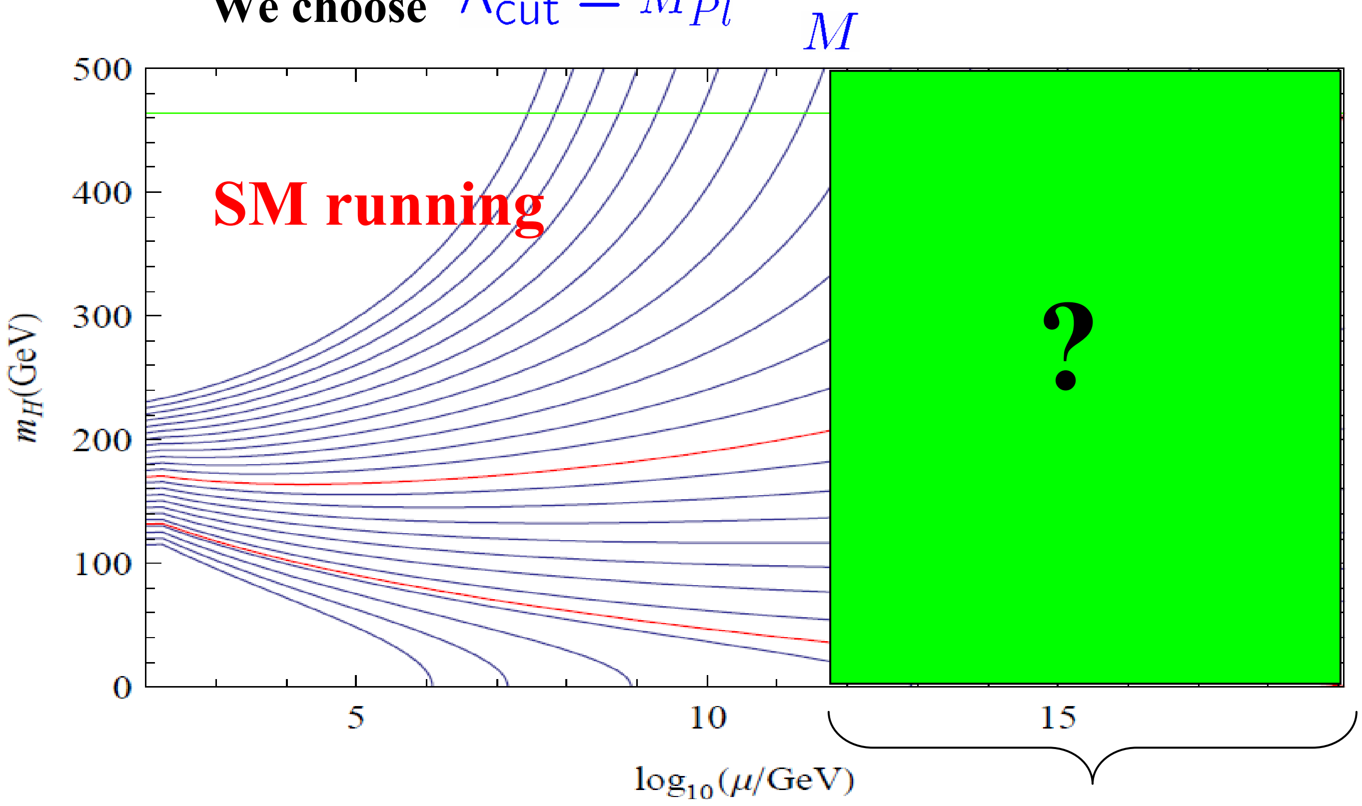
Higgs mass should be in the range $127 \leq M_H({\rm GeV}) \leq 170$

If some New Physics takes place at $M_W \leq \Lambda_{\rm New} \leq \Lambda_{\rm cut}$ **and couples Higgs in some way, this Higgs mass bound can be altered**

Running mass: $m_H(\mu) = \sqrt{\lambda} v$

Suppose
- **some New Physics takes place at M**
- **New Particles contributes to Higgs quartic RGE**

We choose $\Lambda_{\text{cut}} = M_{Pl}$



Running is altered

by New Physics contributions

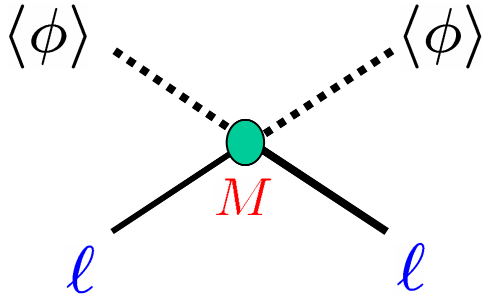
Neutrino oscillations data→ neutrino mass & mixing

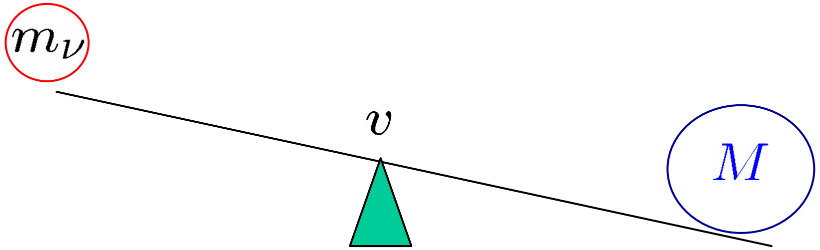
→ **Evidence of New Physics**

Seesaw Mechanism: mechanism to naturally explain tiny mass

Effective operator: $\mathcal{L} = \frac{\phi\phi\ell\ell}{M} \to v\left(\frac{v}{M}\right)\nu\nu$

If the seesaw scale $M \gg v$ → $m_\nu = v\left(\frac{v}{M}\right) \ll v$



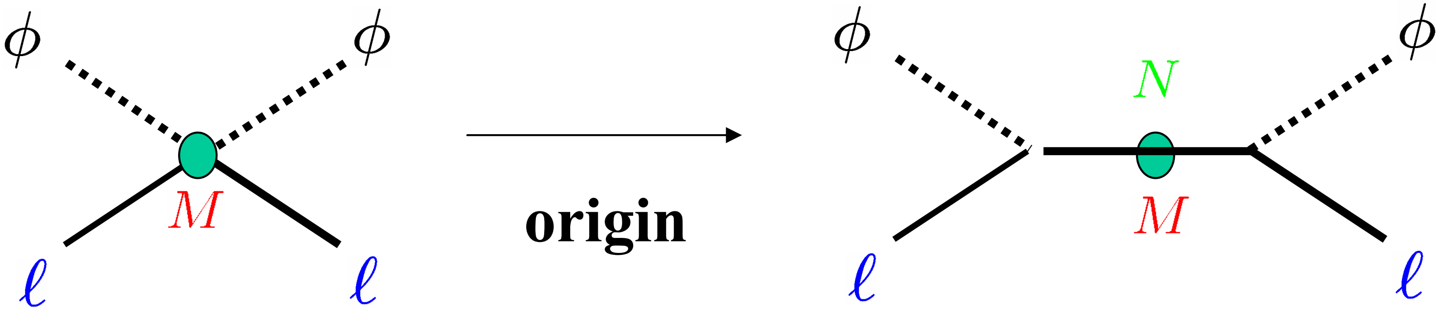


Naturally, $m_\nu \sim \mathcal{O}(\sqrt{\Delta m^2_{12}}) - \mathcal{O}(\sqrt{\Delta m^2_{23}}) = 0.1 - 0.01$ eV

→ $M \lesssim 10^{14}$ GeV $\ll M_{Pl}$

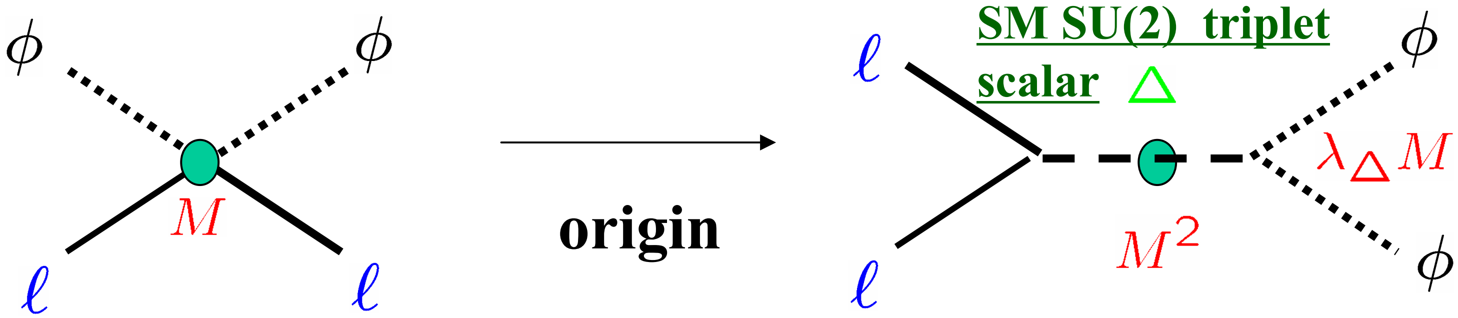
The seesaw scale lies in intermediate scale or less

Type I Seesaw



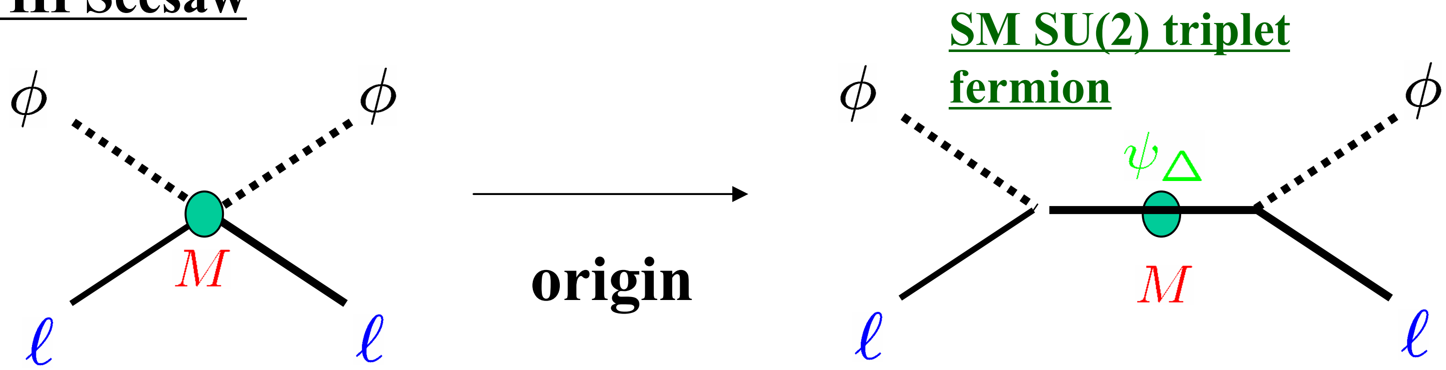
SM singlet fermion

Type II Seesaw



SM SU(2) triplet scalar $\triangle$

Type III Seesaw



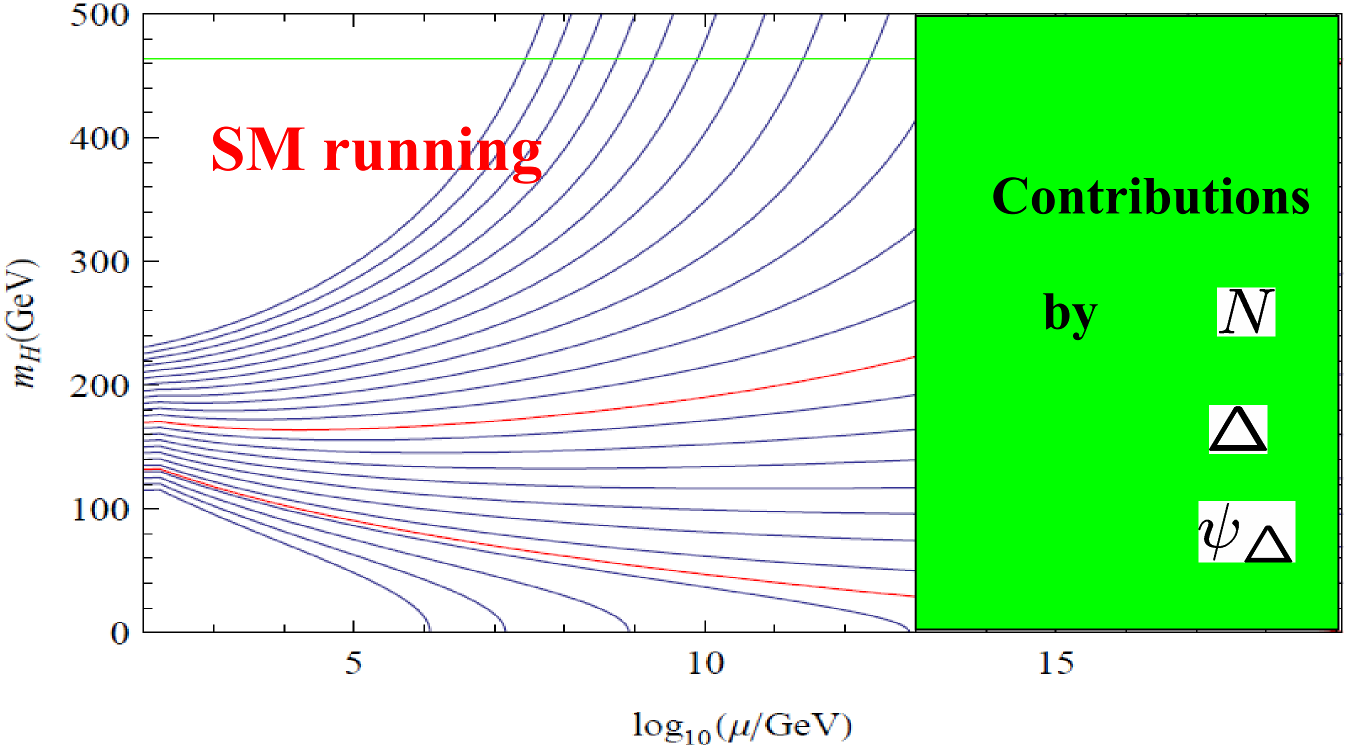
SM SU(2) triplet fermion

In all seesaw scenarios, new particles couple to Higgs doublet

→ **contribute to Higgs quartic RGE for** $\mu > M$

Running mass: $m_H(\mu) = \sqrt{\lambda} v$

We choose $\Lambda_{\text{cut}} = M_{Pl}$ M



SM running

Contributions

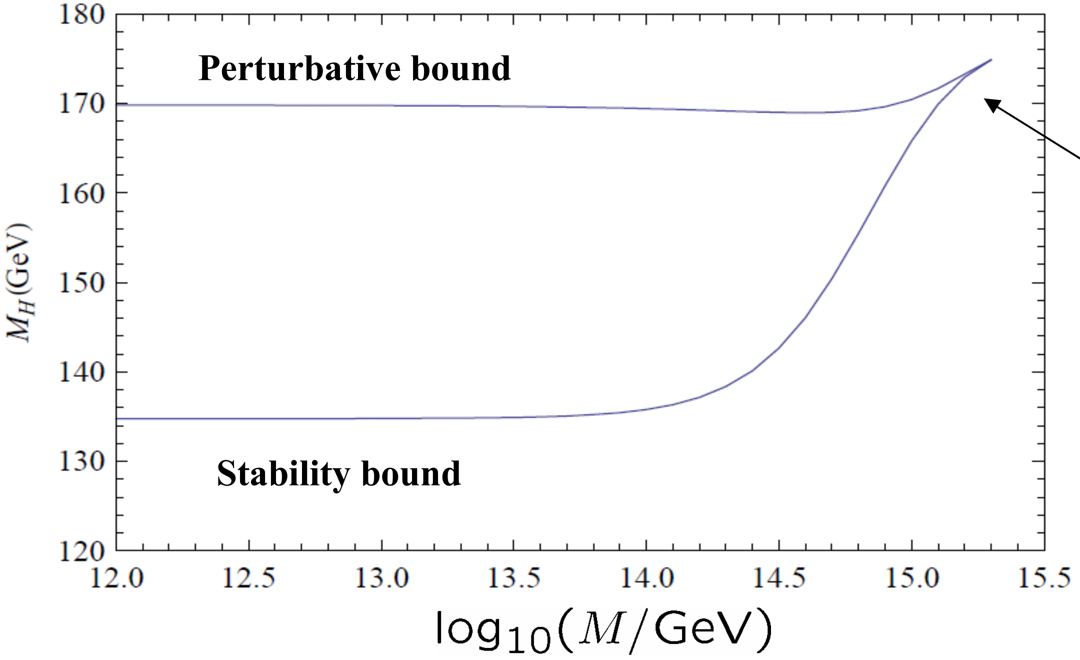
by N **: type I**

Δ **: type II**

ψ_Δ **: type III**

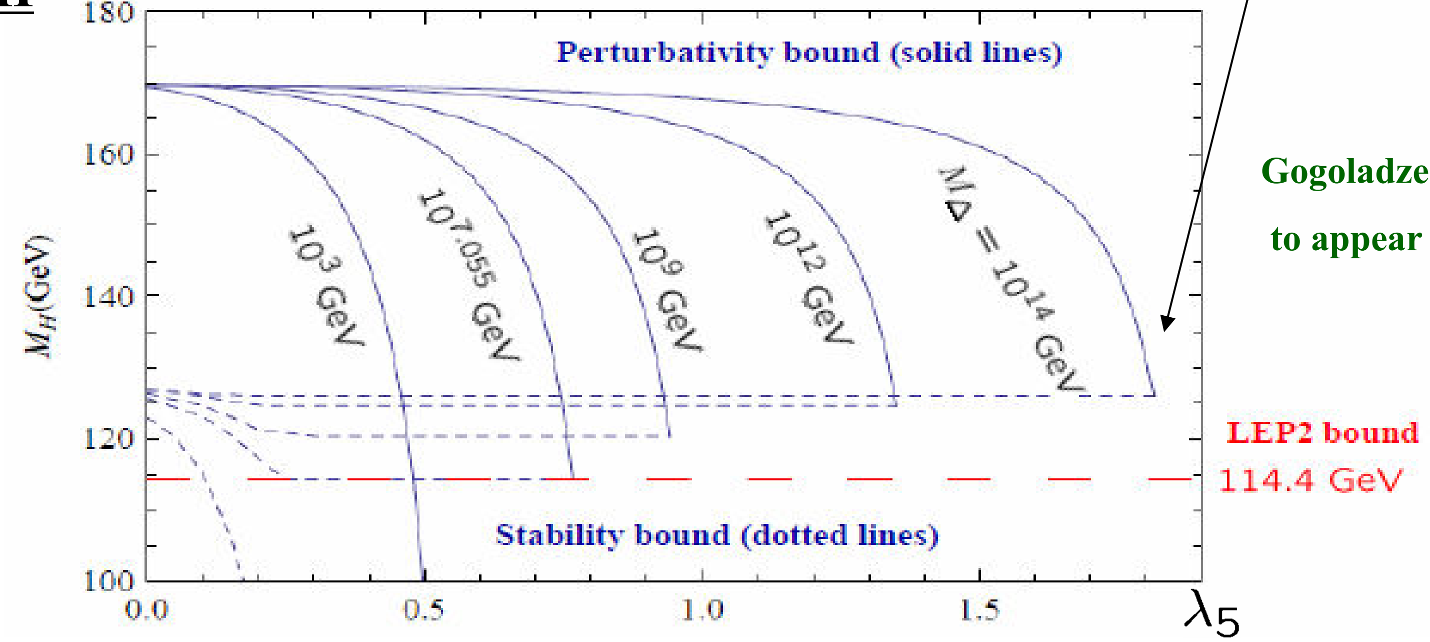
Type I

(Type III)



Higgs mass window is closed here

Type II



Gogoladze, N.O. & Shafi,

to appear PLB

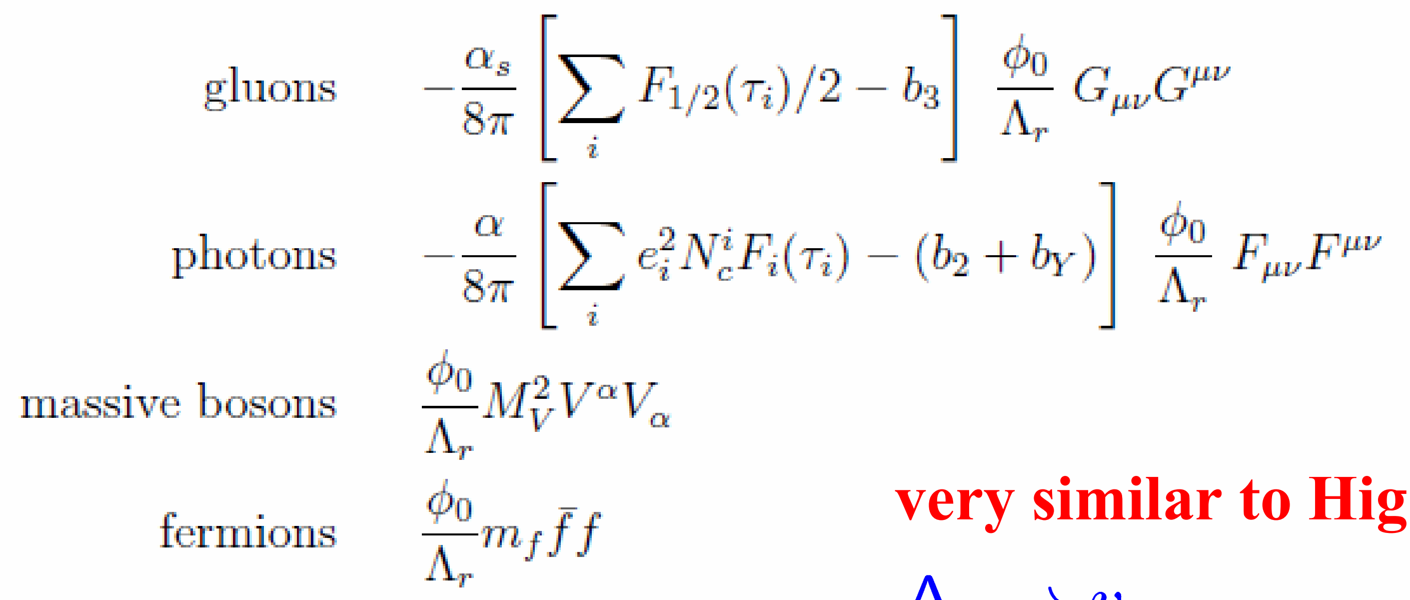
Higgs boson-like New Particle

A class of new physics models includes a neutral scalar

which behaves like SM Higgs boson

→ Higgs physics studies are **applicable to** such a new particle

Ex) Radion in the RS model



gluons	$-\frac{\alpha_s}{8\pi}\left[\sum_i F_{1/2}(\tau_i)/2 - b_3\right]\frac{\phi_0}{\Lambda_r}G_{\mu\nu}G^{\mu\nu}$
photons	$-\frac{\alpha}{8\pi}\left[\sum_i e_i^2 N_c^i F_i(\tau_i) - (b_2 + b_Y)\right]\frac{\phi_0}{\Lambda_r}F_{\mu\nu}F^{\mu\nu}$
massive bosons	$\frac{\phi_0}{\Lambda_r}M_V^2 V^\alpha V_\alpha$
fermions	$\frac{\phi_0}{\Lambda_r}m_f \bar{f} f$

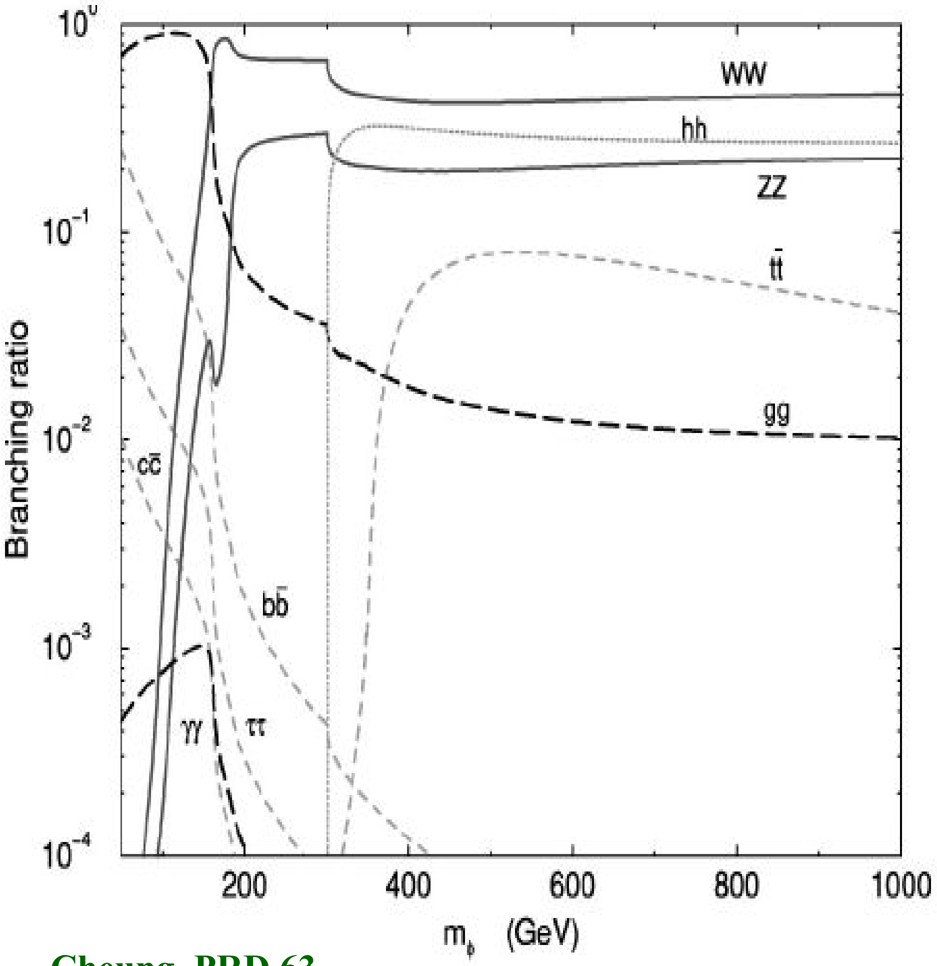
very similar to Higgs

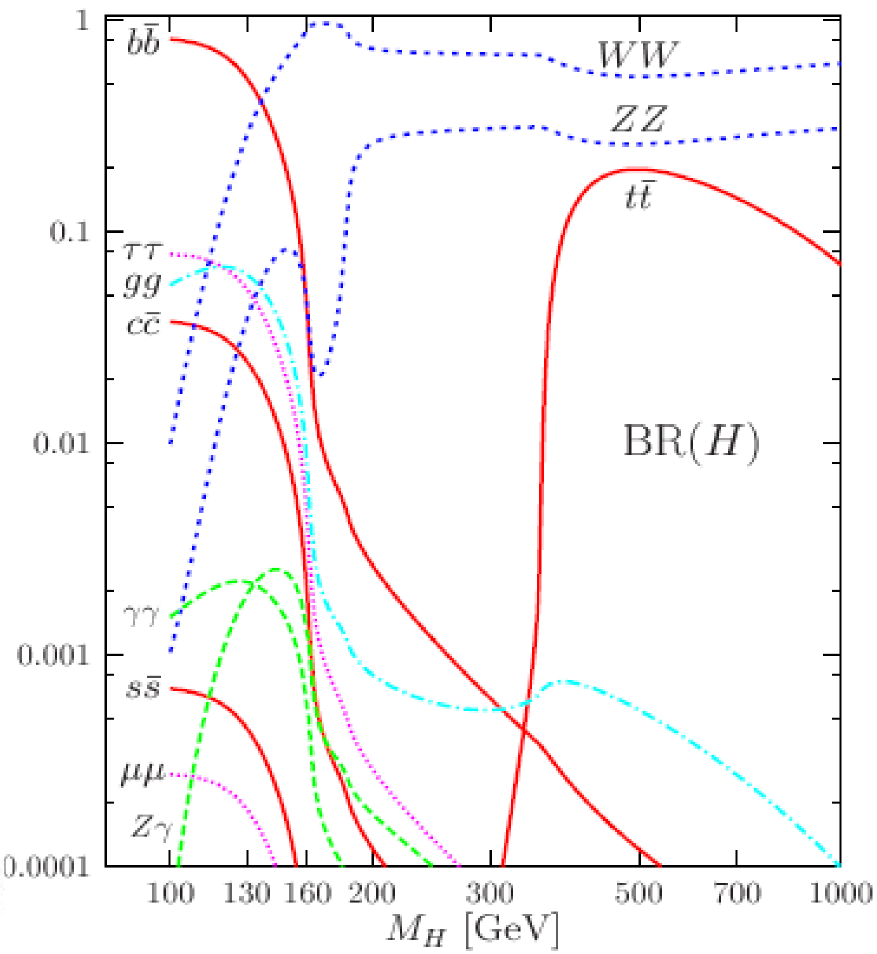
$\Lambda_r \to v$

Branching ratio

Radion

SM Higgs





Cheung, PRD 63, 056007 (2001)

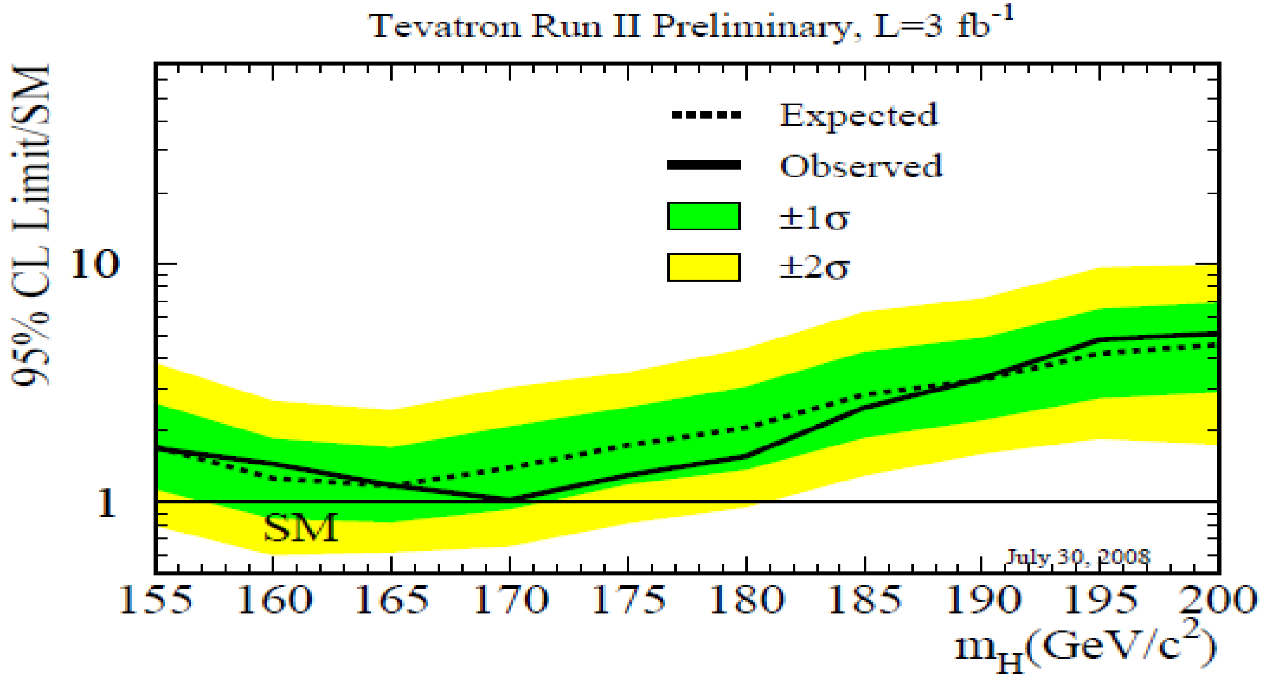
$$BR(\phi \to gg) > BR(h \to gg)$$

$$BR(\phi \to b\bar{b}) < B(h \to b\bar{b})$$

Higgs mass bounds from LEP2 &Tevatron are applicable to giving constraints on radion physics

Very recent combined CDF &D0 upper limits on SM Higgs production cross section with 3 fb^{-1}

$m_h \neq 170$ GeV @ 95% C.L.

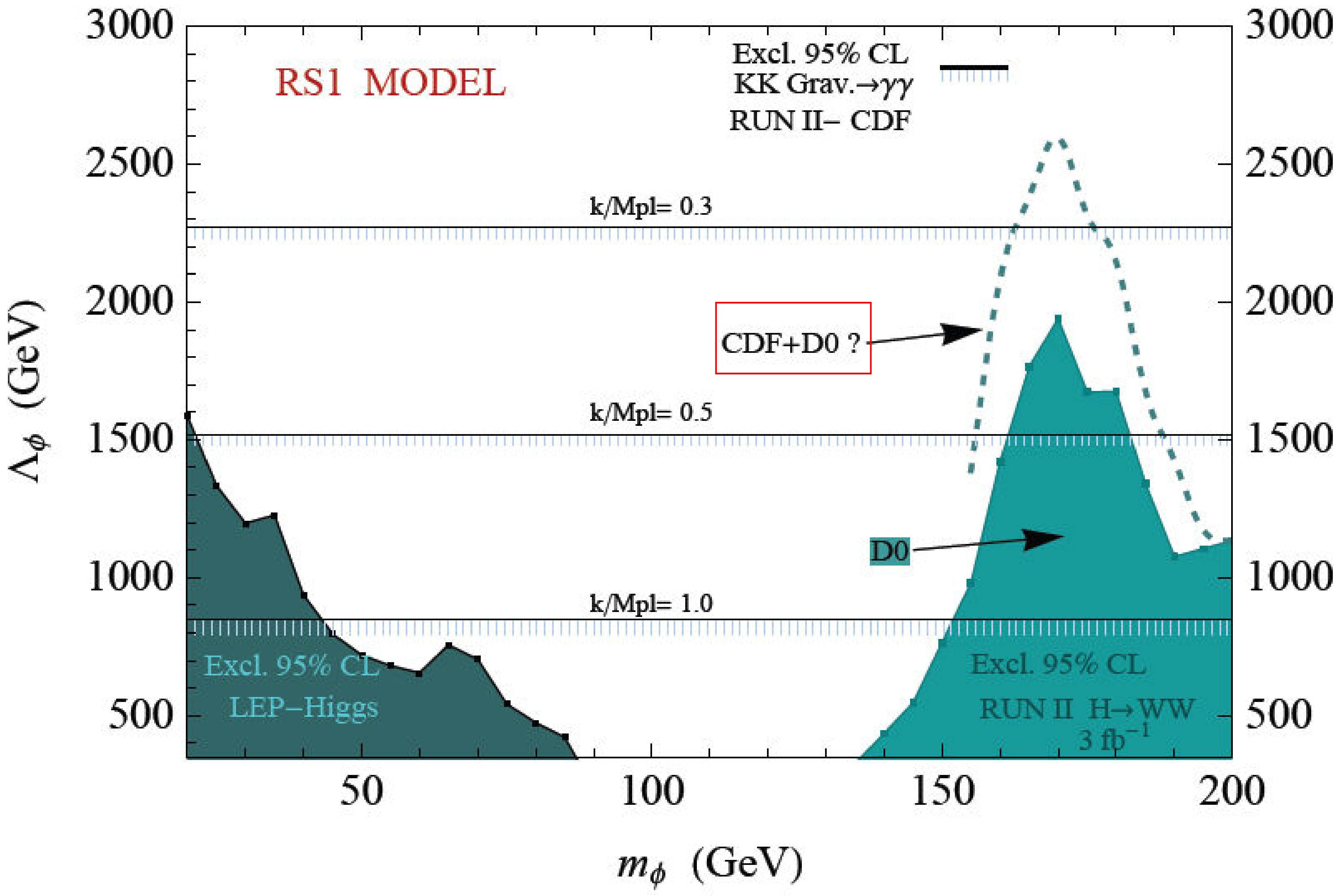


We interpret this bound to constraints on radion

Constraints on the parameters in radion physics

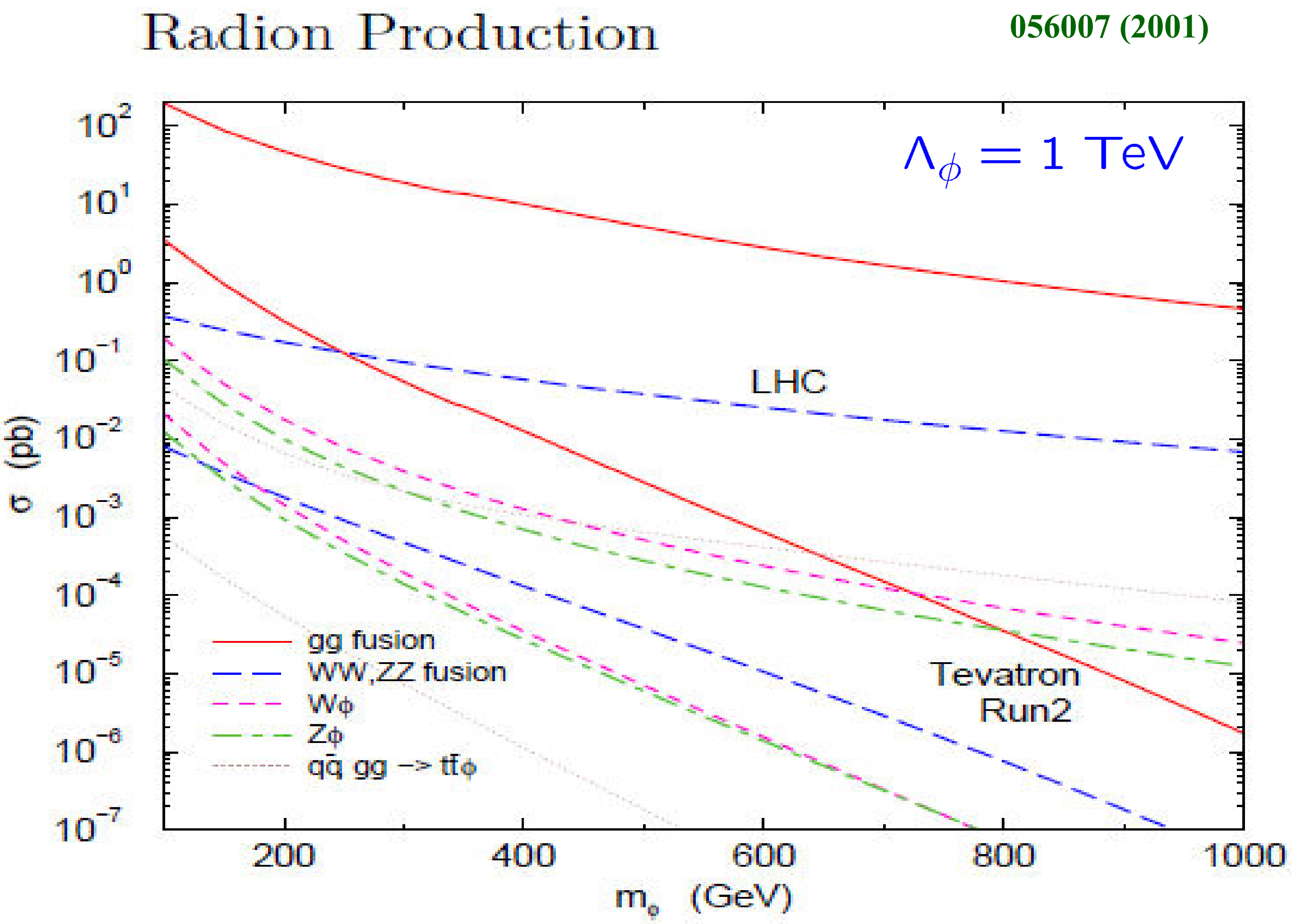
Manuel Toharia & N.O.

in preparation



What happens at LHC?

Cheung, PRD 63, 056007 (2001)



$\sigma \propto \Lambda_\phi^{-2}$ → **large production cross section for** $\Lambda_\phi = \mathcal{O}(1 \text{ TeV})$

Distinguishing a ``hidden scalar'' from Higgs boson

In a class of models, a singlet scalar appears and couples the weak gauge bosons through higher dim . OPs

$$\left.\begin{array}{l}\frac{X}{\Lambda}F_{\mu\nu}F^{\mu\nu}\\[2ex] \frac{X}{\Lambda}Z_{\mu\nu}F^{\mu\nu}\end{array}\right\}$$

→ **Higgs like**

$$\mathcal{L}_{\mathsf{SM}} \sim \frac{\alpha}{4\pi v}hF_{\mu\nu}F^{\mu\nu}$$

top loop

$$\mathcal{L}_{\mathsf{SM}} \sim \frac{eg}{16\pi^2 v}hZ_{\mu\nu}F^{\mu\nu}$$

W loop

$$\left.\begin{array}{l}\frac{X}{\Lambda}W^{+}_{\mu\nu}W^{-\mu\nu}\\[2ex] \frac{X}{\Lambda}Z_{\mu\nu}Z^{\mu\nu}\end{array}\right\}$$

→ **NOT like Higgs**

$$\mathcal{L}_{\mathsf{SM}} \sim 2\frac{m_W^2}{v}hW^{+}_{\mu}W^{-\mu}$$

$$\mathcal{L}_{\mathsf{SM}} \sim \frac{m_Z^2}{v}hZ_{\mu}Z^{\mu}$$

If $\Lambda \sim 1\ \mathsf{TeV}$ **X scalar can be produced at ILC**

in a similar way to SM Higgs boson production

$$e^+e^- \to Z^* \to ZX$$

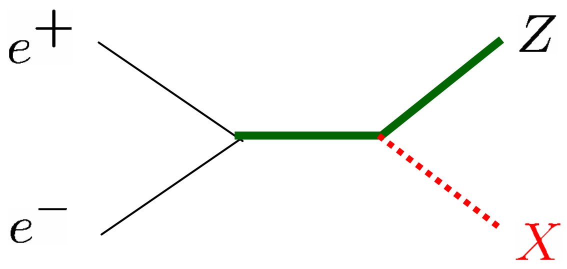
Crucial difference: X has nothing to do with EWSB

$\frac{X}{\Lambda} Z_{\mu\nu} Z^{\mu\nu}$ → **X mainly couples to transverse-mode of Z**

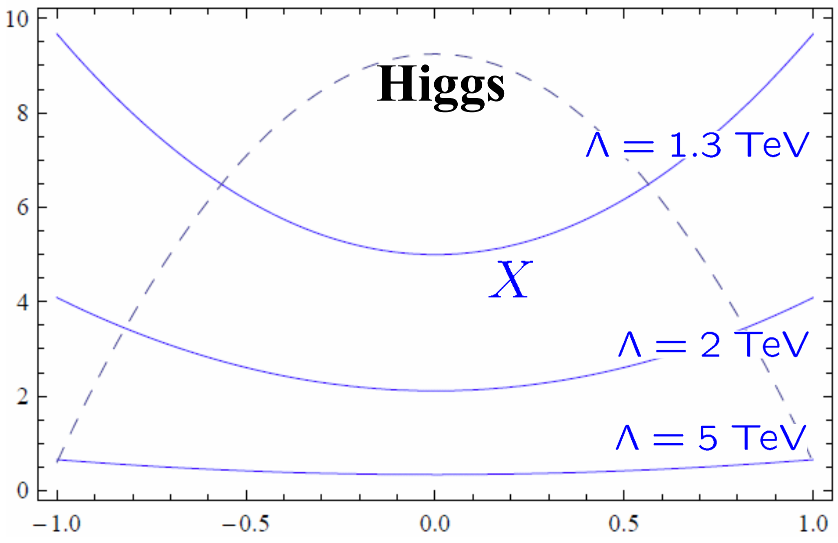
$\frac{m_Z^2}{v} h Z_{\mu} Z^{\mu}$ → **Higgs mainly couples to longitudinal-mode because of Higgs mechanism**

Can we distinguish this difference at ILC?

X or h productions @ ILC



$m_h = m_X = 120$ GeV, $\sqrt{s} = 1$ TeV

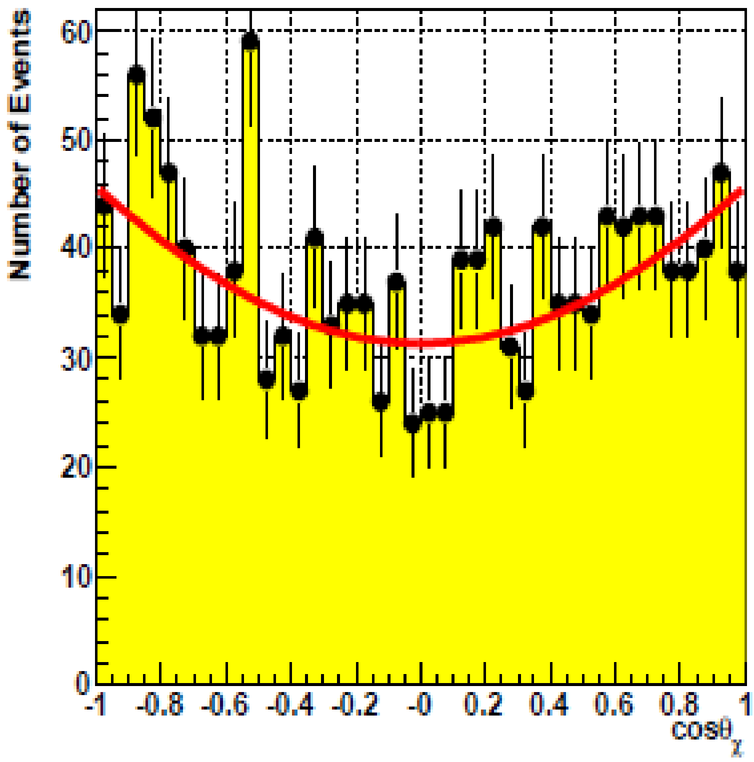


Simulation studies

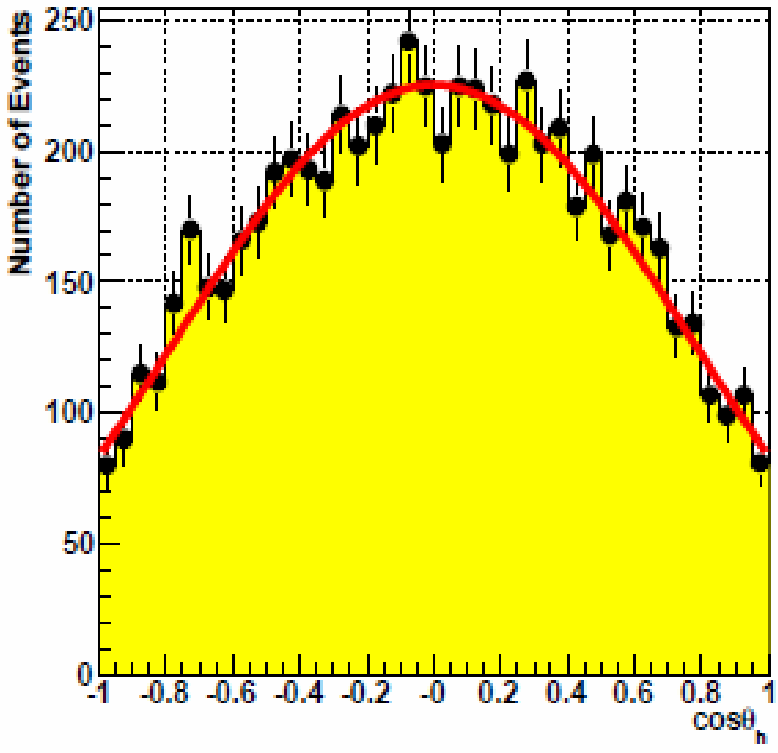
Fujii, Hano, Itoh, N.O., & Yoshioka,

PRD 78, 015008 (2008)

Angular dependence of the cross section



X production



Higgs production

4. Summary

Although the Standard Model is an excellent theory, there are some problems in the SM

The problems can be solved most likely by New Physics around 1 TeV

The TeV scale is accessible to future colliders

Many fruitful New Physics models have been proposed and their phenomenological aspects have been studied

It would be very possible for a certain New Physics to be discovered in the near future

Which New Physics models will be chosen or something else?

What will the future of particle physics be?

Who knows….. But, LHC has turned on!

LHC will tell us what is going on around TeV

Whatever happens or nothing happens, LHC results should be exciting and will tell us which direction we should take in the future.