Unified Modes and Collider Experiments

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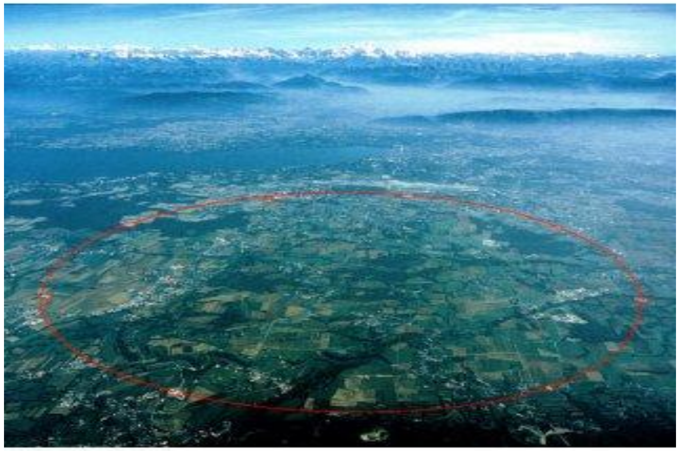
GUT07, Dec. 17, 2007 @ Ritsumeikan University

1. Introduction

Future colliders: hadron collider & lepton collider

Large Hadron Collider(LHC)

Coming soon! (2008)



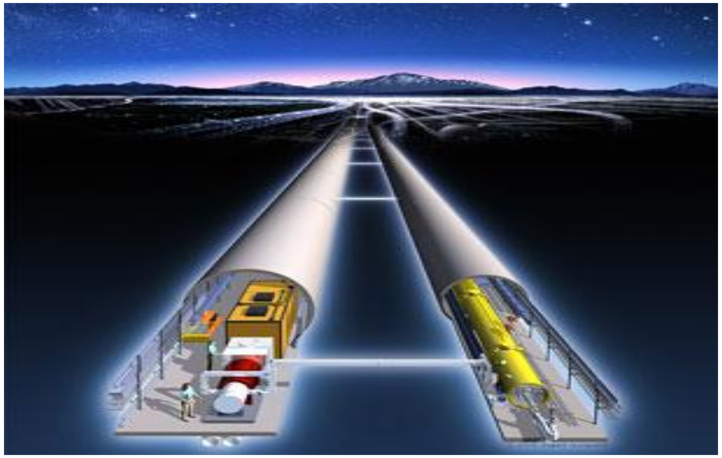
Hadron collider: pp

$\sqrt{s} = 14$ TeV

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

International Linear Collider (ILC)

from 2015 ?



Lepton collider: e^+e^-

$\sqrt{s} = 500$ GeV $-$ 1 TeV

Initial states e^+e^-

Purpose of future colliders

Discovery of Higgs boson ← the last particle in the SM to be observed

New Physics beyond the SM

Precise measurements of Higgs boson and New Physics properties

New couplings, masses, spins etc of new particles

LHC: high energy machine → high discovery potential,

can find Higgs boson and New Physics

ILC: precise measurement → discriminate New Physics Models

Well-motivated New Physics Model → appears around 1 TeV

→ accessible to LHC & ILC

Unified Model, in particular, GUT like unified model appears at M_{unify}

$1\ \mathrm{TeV} \ll M_{unify}$ → Very difficult to say something about Unification

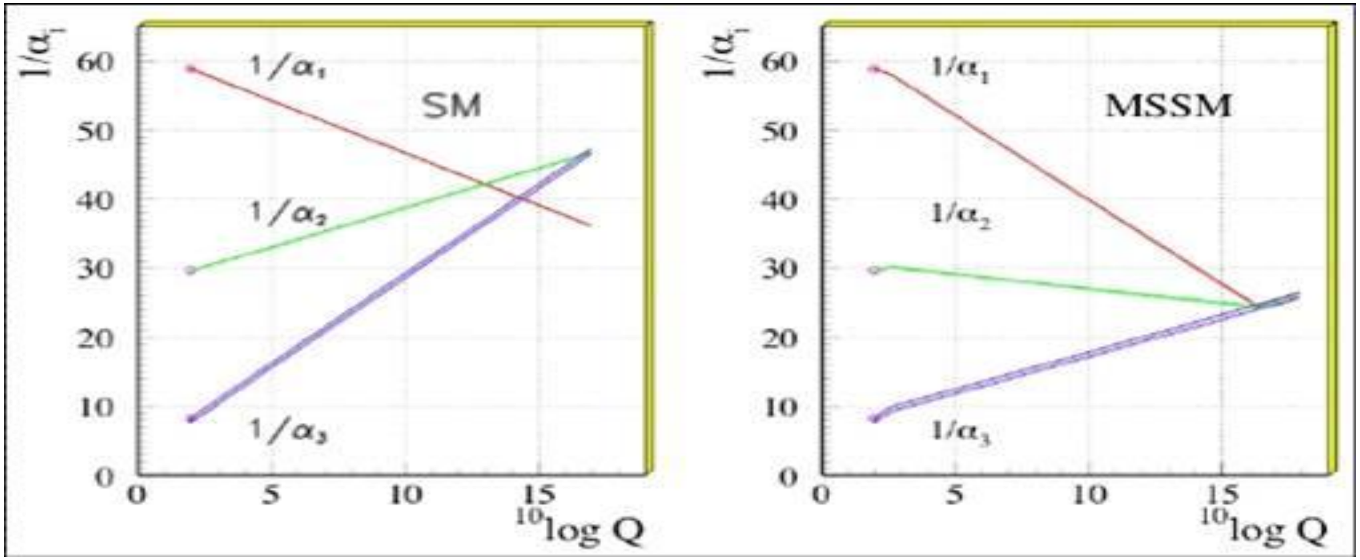
But..

Let us try to tell some information about Unified Models

For example, Grand Unification is suggested by current experiments

→ precise measurements of the SM gauge couplings

\+ weak scale SUSY



Even though collider energy << Unification Scale,

precise measurements of physics observables
their RGE extrapolation

can provide us some information about Unified Theories (UV theories)

Discovery of Higgs boson & New Particles

Indirect information

Higgs mass → solving RGEs toward high energy
→ some information of Unified Models
new particle masses → if the origin of masses lies at energies
higher than unified models, resultant masses
have some remnants of unified models

Direct information

some exotic particles with mass < O(1 TeV) predicted by some models

2. Indirect information

2.1 Discovery of SUSY and soft mass spectrum

Discovery of SUSY at LHC

Precise measurements of soft masses (LHC & ILC)

→ Information of SUSY breaking mediation

The mediation scale > Unified Model Scale

→ soft mass spectrum can carry information about Unified Model

Example 1: CMSSM-like model

SUSY breaking mediation happens at GUT scale

Gauge coupling unification → all the gauginos are in the same multiplet

→ gaugino masses are unified at GUT scale

Sfermion masses → (s)leptons and (s)quarks are unified into the same multiplets, but there is a model dependence

SO(10) GUT matter 16

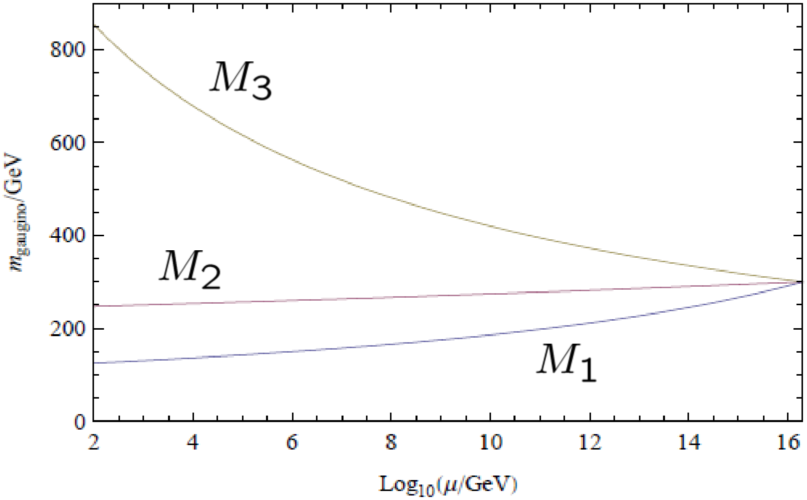
$$m_{\tilde{Q}} = m_{\tilde{U}} = m_{\tilde{D}} = m_{\tilde{L}} = m_{\tilde{E}}$$

SU(5) GUT matter 5* + 10 →

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

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)

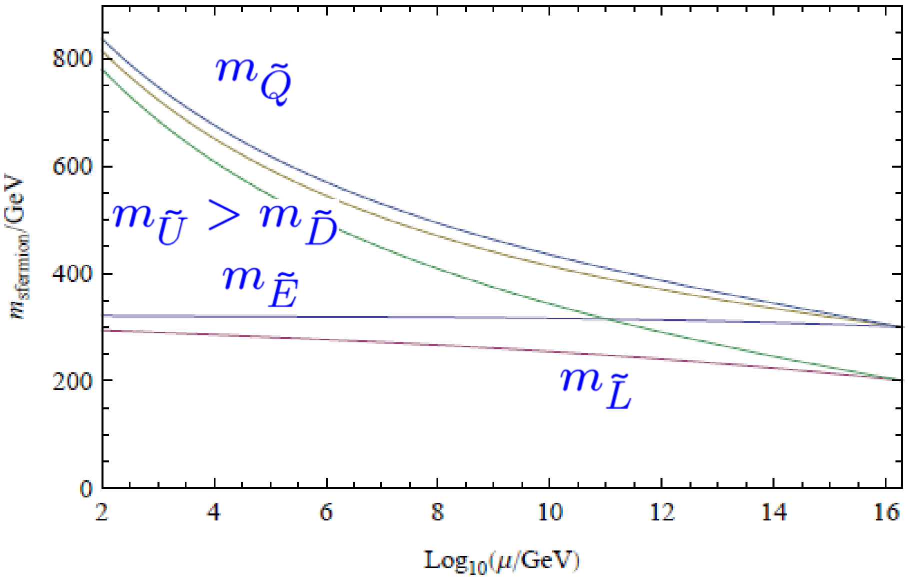
$m_{\tilde{D}} = m_{\tilde{L}} = 200$ GeV

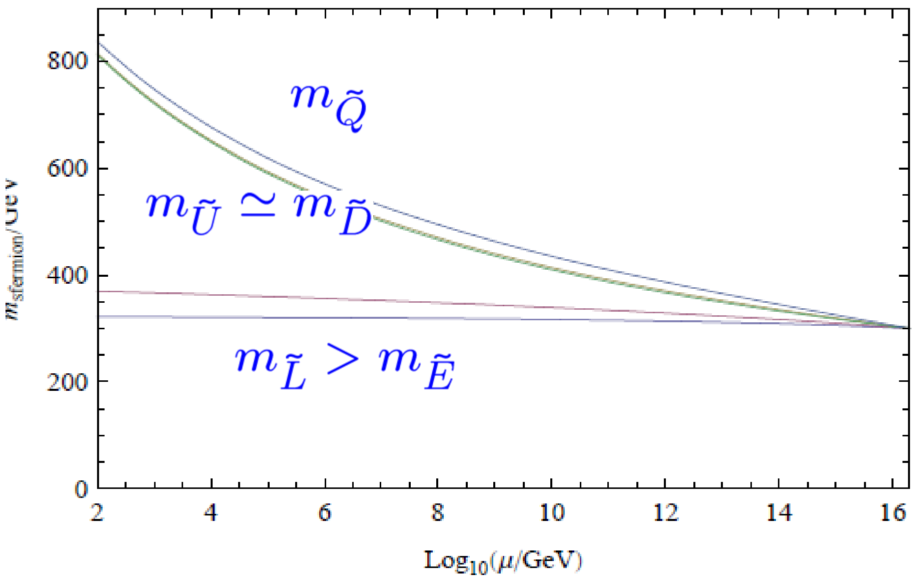
$m_{\tilde{Q}} = m_{\tilde{U}} = m_{\tilde{E}} = 300$ GeV

@ GUT

SO(10)

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





Example 2: discriminate seesaw modes

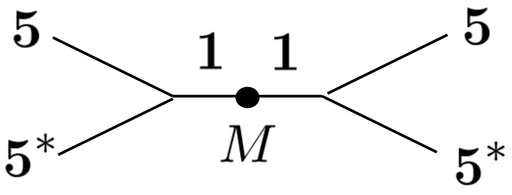
Buckley & Murayama

PRL 97, 231801 (2006)

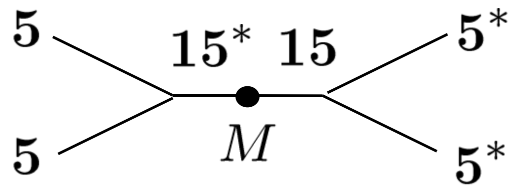
Seesaw models → natural explanation of tiny neutrino masses

SU(5) GUT + seesaw mechanism

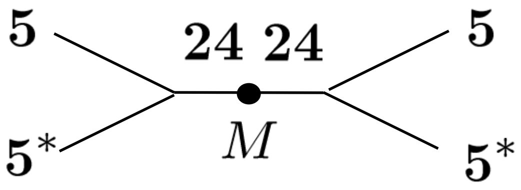
Type I: singlet



Type II: 15+15*



Type III: 24

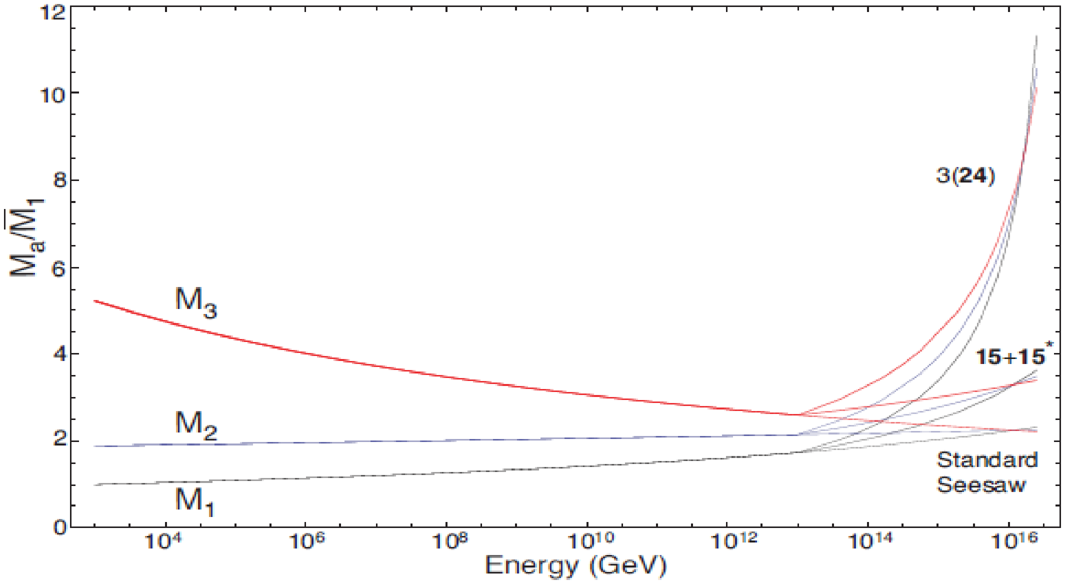


$M = 10^{12-14}\ \mathrm{GeV}$

$M = 10^{13}$ GeV

Gaugino masses

$$\overline{M}_1 = M_1(1\ \text{TeV})$$

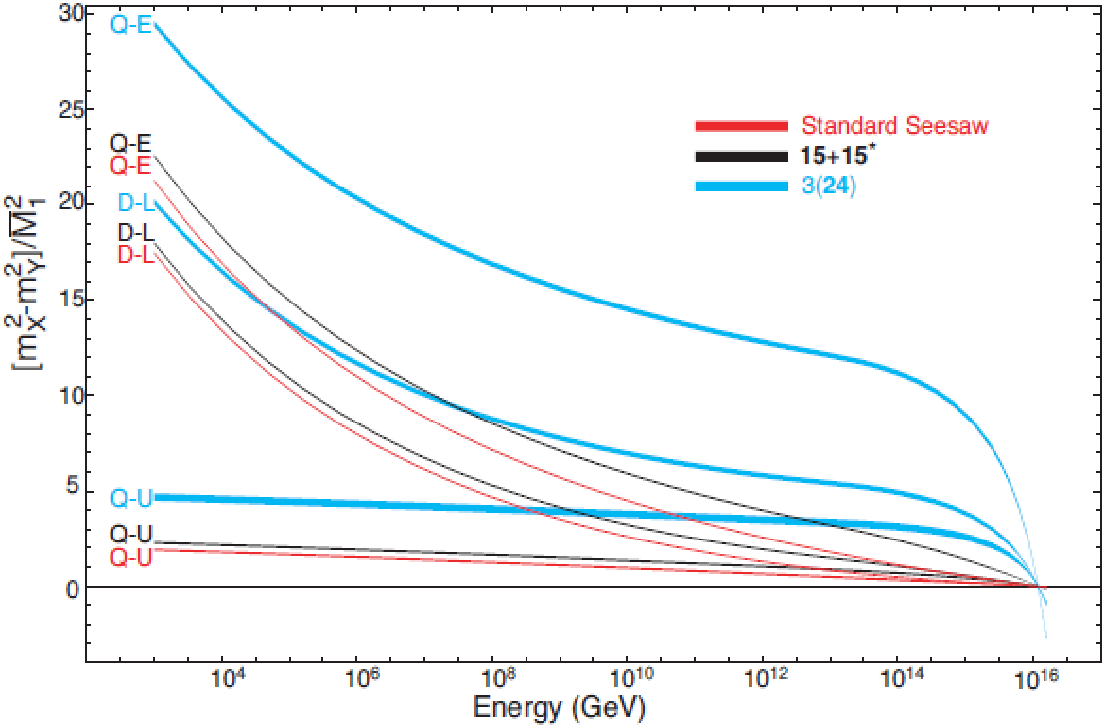


Sfermion masses

15+15* or 24 extra fields

contributes to RGE

→ changes sfermion masses



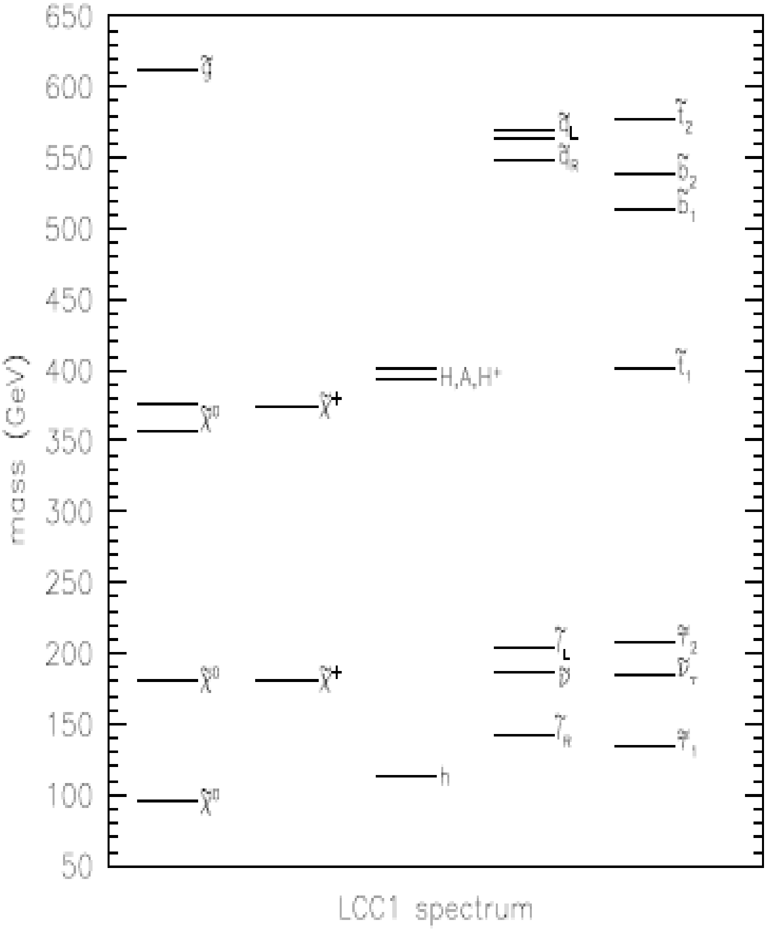
differences are

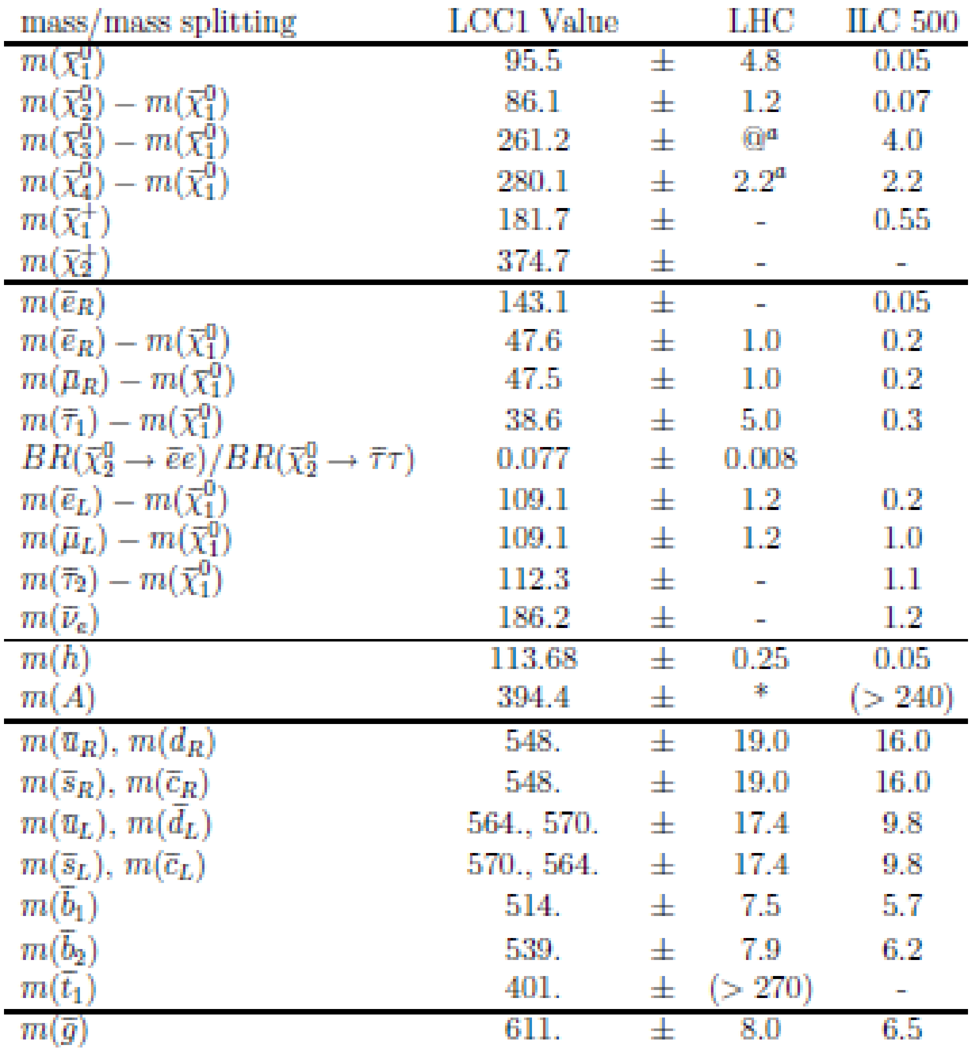
a few % at worst case

Precision measurements of sparticle mass spectrum @ LHC + ILC

highly depends on sparticel mass spectrum

An example





mass/mass splitting	LCC1 Value		LHC	ILC 500
$m(\tilde{\chi}_1^0)$	95.5	±	4.8	0.05
$m(\tilde{\chi}_2^0) - m(\tilde{\chi}_1^0)$	86.1	±	1.2	0.07
$m(\tilde{\chi}_3^0) - m(\tilde{\chi}_1^0)$	261.2	±	@^{a}	4.0
$m(\tilde{\chi}_4^0) - m(\tilde{\chi}_1^0)$	280.1	±	2.2^a	2.2
$m(\tilde{\chi}_1^+)$	181.7	±	-	0.55
$m(\tilde{\chi}_2^+)$	374.7	±	-	-
$m(\tilde{e}_R)$	143.1	±	-	0.05
$m(\tilde{e}_R) - m(\tilde{\chi}_1^0)$	47.6	±	1.0	0.2
$m(\tilde{\mu}_R) - m(\tilde{\chi}_1^0)$	47.5	±	1.0	0.2
$m(\tilde{\tau}_1) - m(\tilde{\chi}_1^0)$	38.6	±	5.0	0.3
$BR(\tilde{\chi}_2^0 \to \tilde{e}e)/BR(\tilde{\chi}_2^0 \to \tilde{\tau}\tau)$	0.077	±	0.008	
$m(\tilde{e}_L) - m(\tilde{\chi}_1^0)$	109.1	±	1.2	0.2
$m(\tilde{\mu}_L) - m(\tilde{\chi}_1^0)$	109.1	±	1.2	1.0
$m(\tilde{\tau}_2) - m(\tilde{\chi}_1^0)$	112.3	±	-	1.1
$m(\tilde{\nu}_e)$	186.2	±	-	1.2
$m(h)$	113.68	±	0.25	0.05
$m(A)$	394.4	±	*	(> 240)
$m(\tilde{u}_R)$, $m(\tilde{d}_R)$	548.	±	19.0	16.0
$m(\tilde{s}_R)$, $m(\tilde{c}_R)$	548.	±	19.0	16.0
$m(\tilde{u}_L)$, $m(\tilde{d}_L)$	564., 570.	±	17.4	9.8
$m(\tilde{s}_L)$, $m(\tilde{c}_L)$	570., 564.	±	17.4	9.8
$m(\tilde{b}_1)$	514.	±	7.5	5.7
$m(\tilde{b}_2)$	539.	±	7.9	6.2
$m(\tilde{t}_1)$	401.	±	(> 270)	-
$m(\tilde{g})$	611.	±	8.0	6.5

Example 3: discriminate seesaw modes in GMSB

Mohapatra, N.O. & Yu,
work in progress

Related work:
Mohapatra, Okada & Yu,
arXiv:0711.0956 [hep-ph]

SU(5) GUT + type II and III seesaw in GMSB scenario

Type II → 15*+15
Type III → 24s

These fields can be identified as the messenger fields in GMSB scenario

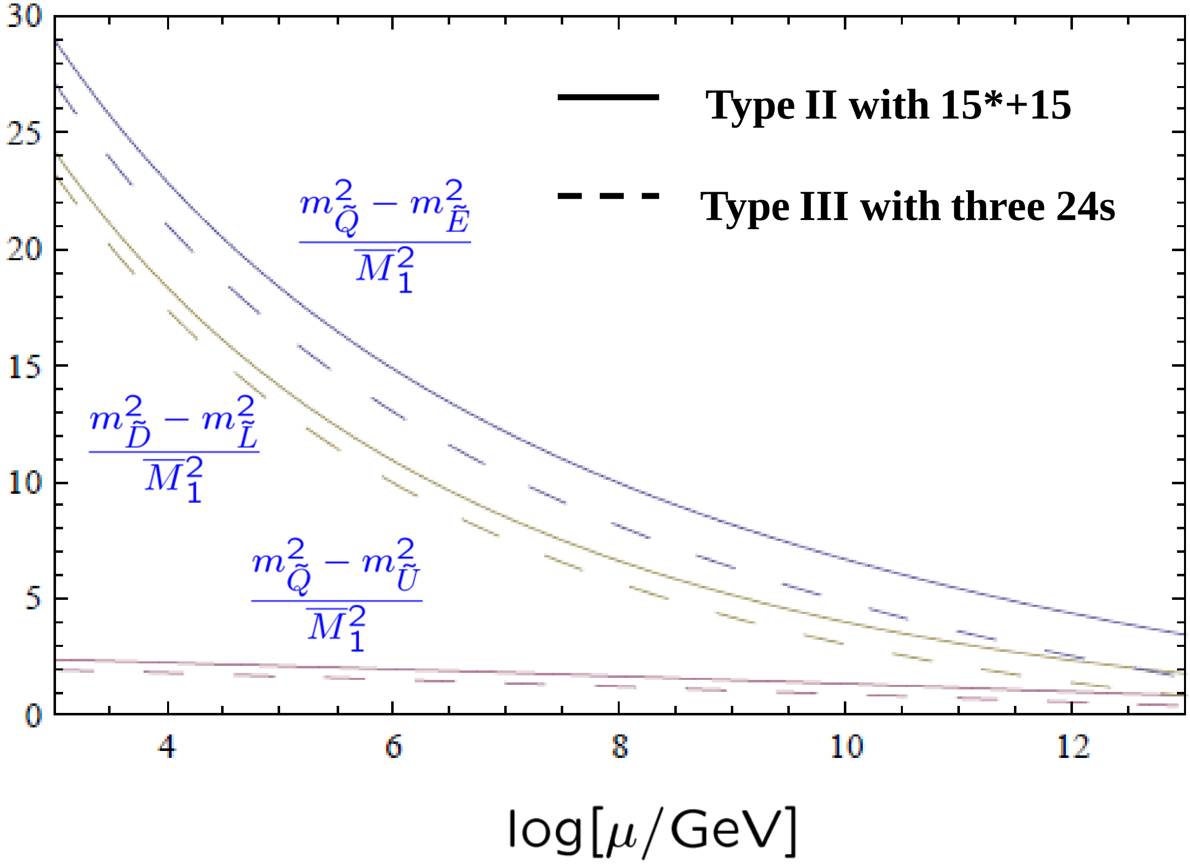
Messenger scale → Seesaw scale

Mass spectrum @ messenger (seesaw) scale

$$\left.\begin{array}{l} M_i(M) = \dfrac{\alpha_i(\mu)}{4\pi}\dfrac{F}{M} N_{mess} \\[2ex] \tilde{m}_i^2(M) = 2c_i \left(\dfrac{\alpha_i(\mu)}{4\pi}\right)^2 \left|\dfrac{F}{M}\right|^2 N_{mess} \end{array}\right\} \dfrac{\tilde{m}_i^2(M)}{M_i(M)^2} = \dfrac{c_i}{N_{mess}}$$

$$\left\{\begin{array}{l} \text{Type II} \rightarrow 15^*+15 \quad \rightarrow \quad N_{mess} = 7 \\ \text{Type III} \rightarrow \text{three } 24\text{s} \rightarrow \quad N_{mess} = 15 \end{array}\right.$$

→ difference in sfermion mass spectrum



Precision measurements in accuracy < O(a few %)

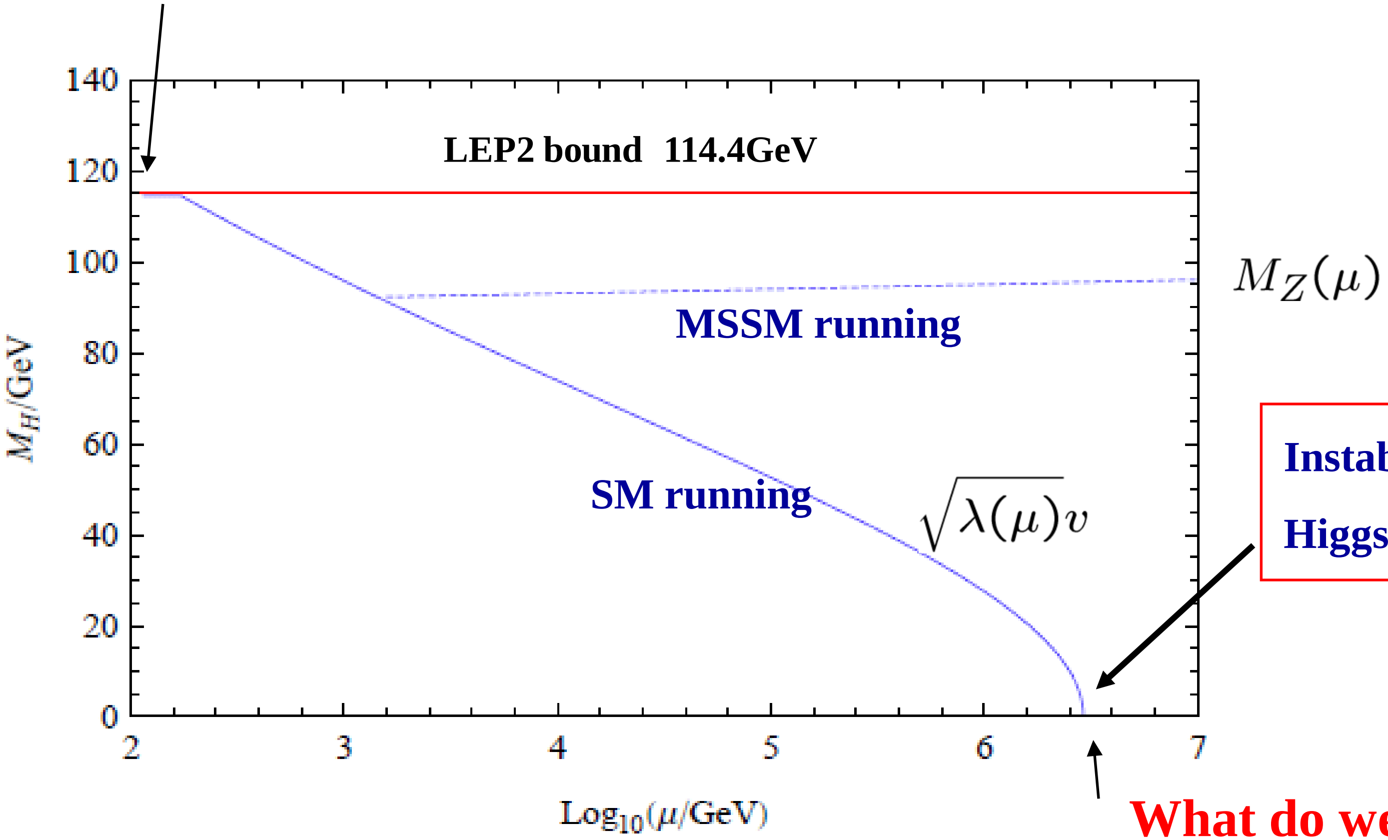
can discriminate between type II and type III seesaw

2-2: Higgs mass measurement and UV theory

Once Higgs boson is discovered and its mass is measured,

RGE running of Higgs mass (quartic Higgs coupling) tells us something.

Suppose $M_H \simeq 115$ GeV



Instability of Higgs potential

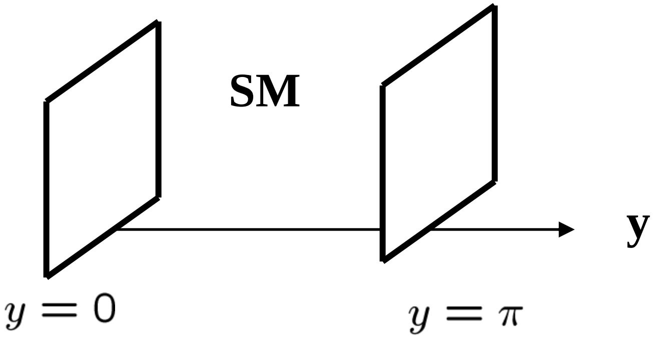
What do we thing of it?

What if UV theory is non-SUSY, what does the instability mean?

Gauge-Higgs Unification model?

Bulk Standard Model

5-dim. theory compactified on orbifold S^1/Z_2



All SM fields reside in the bulk

Higgs boson is unified into 5th component of gauge fields in higher dimension

Basic structure 5dim SU(3) gauge theory (toy model)

$$SU(3) \supset SU(2) \times U(1)$$

$$\textbf{SU(3) gauge} = \left(\begin{array}{c:c} \begin{matrix} SU(2) \\ \textbf{adj} \end{matrix} & \textbf{doublet} \\ \hdashline \textbf{doublet} & \textbf{singlet} \end{array}\right)$$

Impose non-trivial boundary conditions (parity assignment)

$$A_\mu = \left(\begin{array}{c|c} \enclose{circle}{W_\mu + B_\mu} & X_\mu \\ \hline X_\mu^\dagger & \enclose{circle}{B_\mu} \end{array}\right) \qquad A_5 = \left(\begin{array}{c|c} W_5 + B_5 & \enclose{circle}{H} \\ \hline \enclose{circle}{H^\dagger} & B_5 \end{array}\right)$$

○ **are Z2 even fields, others odd fields**

Zero modes for odd fields are project out,

So SU(3) is broken to SU(2) times U(1) by this parity assignment

5th component of 5dim gauge field → scalar in 4D theories

We identify ``H” as Higgs doublet in the SM → gauge-Higgs unification

$$\mathcal{L}_5^{gauge} = -\frac{1}{4}F^{aMN}F^a_{MN} = -\frac{1}{4}F^{a\mu\nu}F^a_{\mu\nu} + \frac{1}{2}F_5^{a\mu}F^a_{5\mu}$$

$$\frac{1}{2}F_5^{a\mu}F^a_{5\mu} \to (D_\mu H)^\dagger(D_\mu H)$$

$$H : (2, +1/2)$$

Kinetic term for Higgs is included as

5dim SU(3) gauge interaction

5 dimensional gauge symmetry → No mass and quartic coupling @ tree

Even at quantum level, there is no divergence

Phenomenologically interesting observation ``Gauge-Higgs Condition”

→ realization of gauge-Higgs unification at UV

is equivalent to imposing ``vanishing quartic Higgs couping”

at $\Lambda_{cut} = 1/(2\pi R)$

Haba, Matsumoto, N.O.&Yamashita,
JHEP 0602, 073 (2006)

Application of the guage-Higgs condition

UV completion of the SM by (5D) gauge-Higgs unification

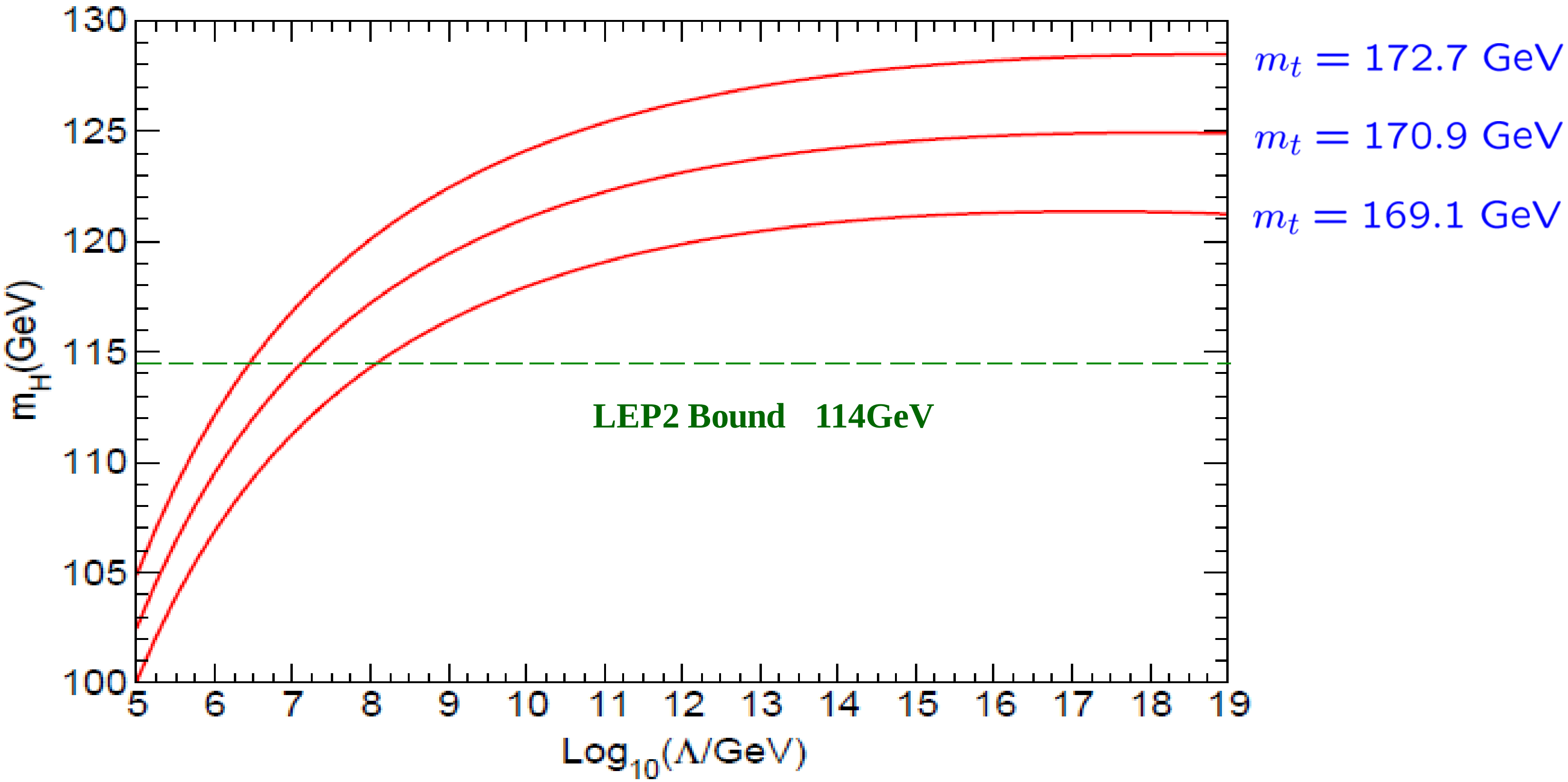
→Higgs boson mass prediction

as a function of the compactification scale

by imposing the condition $\lambda_H(\Lambda) = 0$

Gogoladze, N.O. & Shafi

Phys. Lett. B, 257 (2007)



2.3: new particle & impact on Higgs boson phenomenology at LHC

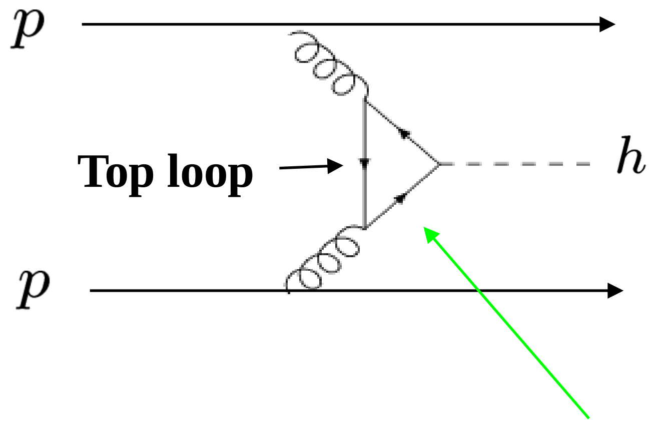
In Gauge-Higgs unification (GHU) and Universal Extra Dimension (UED)

KK excited states of SM particles

Top quark KK modes strongly couple to Higgs boson

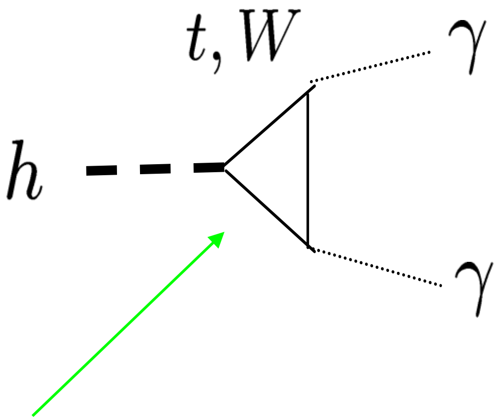
→ some impacts on Higgs boson phenomenology

Higgs production @ LHC



Top loop →

Primary discovery mode for $m_H < 2m_W$



New diagrams with new particles running in loops

Difference between GHU and UED

Maru & N.O.

e-Print: arXiv:0711.2589 [hep-ph]

UED & gauge-Higgs → KK modes of SM particles

Top quark KK modes → big effects in Higgs couplings

vertex

UED: **Two KK top with mass** $m_t^{(n)} = \sqrt{\left(\frac{n}{R}\right)^2 + m_t^2}$ $\quad -\frac{m_t}{v}\left(\frac{m_t}{m_t^{(n)}}\right)h$

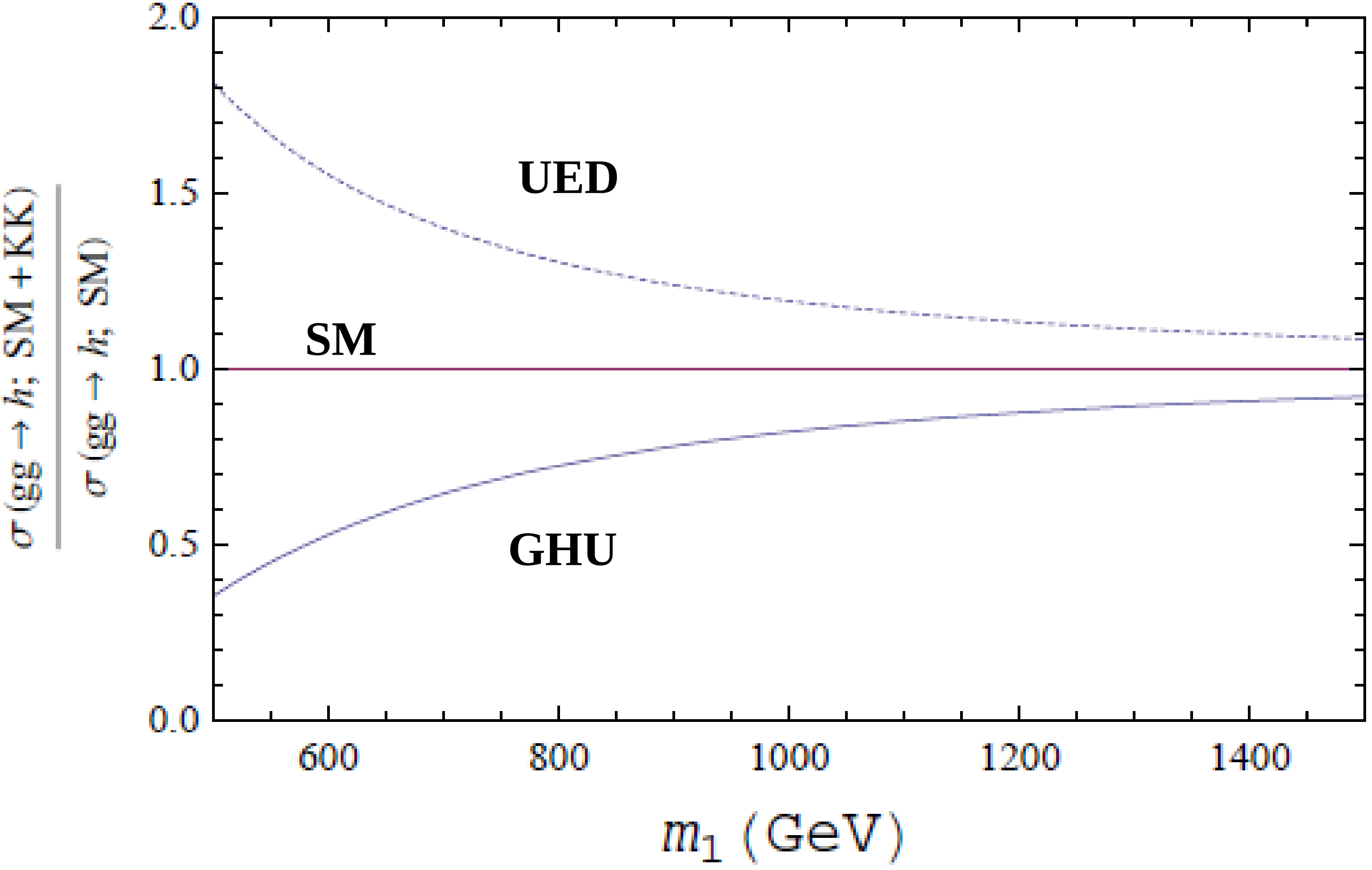
Gauge-Higgs: $m_{t+}^{(n)} = \frac{n}{R} + m_t$ $\quad -\frac{m_t}{v}h$

$m_{t-}^{(n)} = \frac{n}{R} - m_t$ $\quad +\frac{m_t}{v}h$

Difference of mass spectrum and coupling with Higgs boson

results in difference of Higgs effective coupling

Higgs boson production cross section through gluon fusion in UED and GHU



3. Direct information

Discovery of some new particle → evidence of some Unified Models

Example: Diquark Higgs production at LHC

Mohapatra, N.O. & Yu
e-Print: arXiv:0709.1486 [hep-ph]
to appear in PRD

A class of New Physics Models with B-L gauge symmetry

(Pati-Salam model, SO(10) GUT,…)

- See-saw mechanism → tiny neutrino mass
- associated with B-L symmetry → many exotic particles carrying B&L numbers

If exotic particles are light → production at LHC

New possibility: color sextet Higgs (diquark Higgs) boson
associated with B-L symmetry breaking

B-L breaking scale is the see-saw scale $\sim 10^{11-14}\ \mathrm{GeV}$,

so that exotic particles have mass around the see-saw scale

How can some exotic particle be light?

→ in a class of SUSY Pati-Salam Models, such particles can arise as

NG bosons through accidental global symmetry due to supersymmetry

Chacko & Mohapatra, PRD 59 055004 (1999)

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

Diquark Higgs

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

Brief overview of model

Gauge group: $\mathsf{SU}(2)_L \times \mathsf{SU}(2)_R \times \mathsf{SU}(4)_c$

Matter: $\psi : (\mathbf{2}, \mathbf{1}, \mathbf{4}) \oplus \psi^c : (\mathbf{1}, \mathbf{2}, \overline{\mathbf{4}})$

Higgs: $\phi_1 : (\mathbf{2}, \mathbf{2}, \mathbf{1}) \oplus \phi_{15} : (\mathbf{2}, \mathbf{2}, \mathbf{15})$ **for fermion masses**

$\Delta^c : (\mathbf{1}, \mathbf{3}, \mathbf{10}) \oplus \overline{\Delta}^c : (\mathbf{1}, \mathbf{3}, \overline{\mathbf{10}})$ **to break B-L symmetry**

$\Omega : (\mathbf{1}, \mathbf{3}, \mathbf{1})$ **to reduce too many global symmetries**

$S : (\mathbf{1}, \mathbf{1}, \mathbf{1})$

$$
\begin{aligned}
W_H &= \lambda_1 S(\Delta^c \overline{\Delta}^c - M_\Delta^2) + \mu_i \mathrm{Tr}\,(\phi_i \phi_i) + \lambda_C \Omega \Delta^c \overline{\Delta}^c \\
W_Y &= h_1 \psi \phi_1 \psi^c + h_{15} \psi \phi_{15} \psi^c + f \psi^c \Delta^c \psi^c.
\end{aligned}
$$

B-L symmetry breaking: $\langle \Delta^c \rangle, \ \langle \overline{\Delta}^c \rangle \neq 0$

$\mathrm{SU}(3)_c$

$\Delta^c : (\mathbf{1}, \mathbf{3}, \mathbf{10})$

6: $\Delta_{u^c u^c}, \ \Delta_{u^c d^c}, \ \Delta_{d^c d^c}$

3: $\Delta_{u^c \nu^c}, \ \Delta_{u^c e^c}, \ \Delta_{d^c \nu^c}, \ \Delta_{d^c e^c}$

1: $\langle \Delta_{\nu^c \nu^c} \rangle = v_{B-L}, \ \Delta_{\nu^c e^c} \ \Delta_{\nu^c \nu^c}$

$$\mathrm{SU}(2)_L \times \mathrm{SU}(2)_R \times \mathrm{SU}(4)_c \to G_{SM}$$

$W_Y \supset f \psi^c \Delta^c \psi^c \to f v_{B-L} \, \nu^c \nu^c$ **: right-handed neutrino mass**

Global symmetry in the Higgs superpotential

$\mathrm{U}(10, \mathrm{c}) \times \mathrm{SU}(2) \to \mathrm{U}(9, \mathrm{c}) \times \mathrm{U}(1)$ **: 21 NG modes**

9 eaten, leaving 12 d.o.f. → Diquark Higgs

$$W = \lambda_A \frac{(\Delta^c \overline{\Delta}^c)^2}{M_{P\ell}} + \lambda_B \frac{(\Delta^c \Delta^c)(\overline{\Delta}^c \overline{\Delta}^c)}{M_{P\ell}} + \lambda_C \Delta^c \overline{\Delta}^c \Omega + \lambda_D \frac{\mathrm{Tr}\,(\phi_1 \Delta^c \overline{\Delta}^c \phi_{15})}{M_{P\ell}}$$

→ $m_\Delta \sim \lambda_B \frac{v_{B-L}^2}{M_{P\ell}} = 100\ \mathrm{GeV} - 1\ \mathrm{TeV}$ **with** $v_{B-L} \sim 10^{11}\ \mathrm{GeV}$

Coupling between diquark and fermions

$$W_Y \supset f \psi^c \Delta^c \psi \rightarrow f_{ij} \Delta_{u^c u^c}\, u_i^c u_j^c$$

Diquark Higgs: couples to both up-type quarks

baryon number -2/3

color sextet

mass around 100GeV-1TeV

R-parity Even

Phenomenological constraints on Yukawa coupling

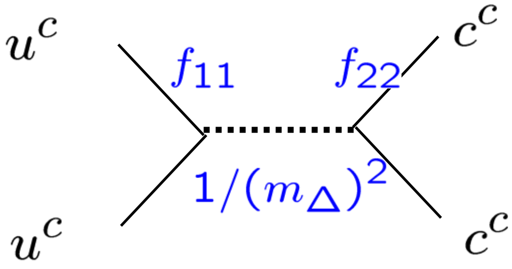
$$W_Y \supset f\psi^c\Delta^c\psi \to f_{ij}\Delta_{u^cu^c}\, u_i^c u_j^c$$

Only up-type quarks are involved

For $m_\Delta \sim \mathcal{O}(100\mathrm{GeV})$

Constraints by rare processes

$D^0 - \overline{D^0}$ **mixing**

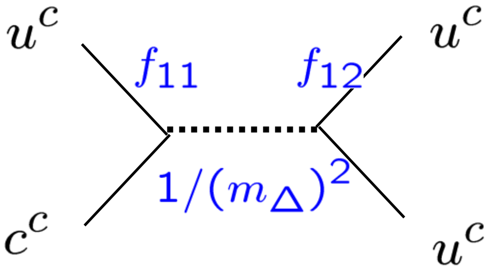


Severe

$$\boxed{f_{11}f_{22} \lesssim 4 \times 10^{-8}}$$

$f_{22} \to 0$

$D \to \pi\pi$



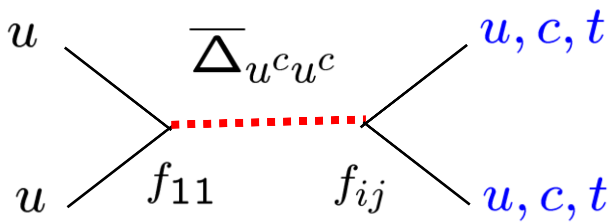
Mild

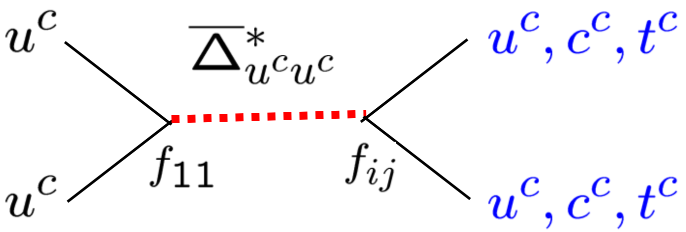
$$\boxed{f_{11}f_{12} \lesssim 4 \times 10^{-2}}$$

LHC phenomenology

It is possible to produce Diquark Higgs at hadron colliders

through uu or anti-u anti-u annihilations





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!

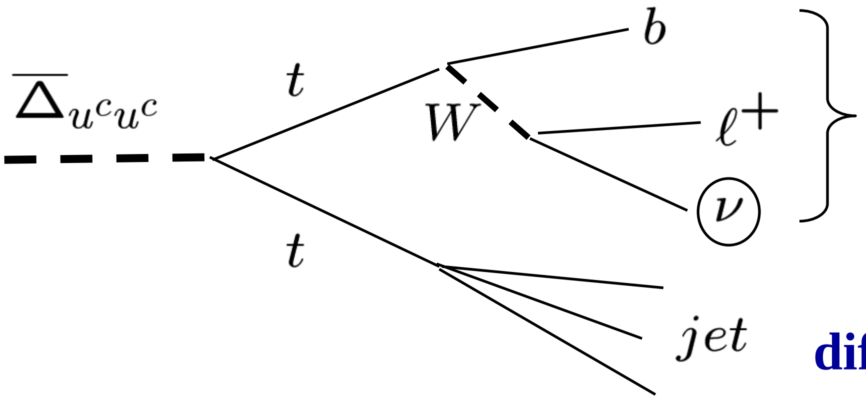
So, our target is

$$\begin{cases} uu \to \overline{\Delta}_{u^c u^c} \to tt \text{ or } t+\text{jet} \\ \bar{u}\bar{u} \to \overline{\Delta}^{*}_{u^c u^c} \to \bar{t}\bar{t} \text{ or } \bar{t}+\text{jet} \end{cases}$$

These processes have no Standard Model counterpart!

As a conservative studies, we consider $t\bar{t}$ pair production in the Standard Model as backgrounds

To measure diquark mass (final state invariant mass)



top quark identification

difficult to tell top or anti-top?

Basics formulas

$uu \to \overline{\Delta}_{u^c u^c} \to tt$ or $t + \text{jet}$ $\quad (\bar{u}\bar{u} \to \overline{\Delta}^*_{u^c u^c} \to \bar{t}\bar{t}$ or $\bar{t} + \text{jet})$

$$\frac{d\sigma(uu \to \overline{\Delta}_{u^c u^c} \to tt)}{d\cos\theta} = \frac{|f_{11}|^2\,|f_{33}|^2}{16\pi}\frac{\hat{s} - 2m_t^2}{(\hat{s} - m_\Delta^2)^2 + m_\Delta^2\Gamma_{\text{tot}}^2}\sqrt{1 - \frac{4m_t^2}{\hat{s}}}$$

$$\frac{d\sigma(uu \to \overline{\Delta}_{u^c u^c} \to t + \text{jet})}{d\cos\theta} = \frac{|f_{11}|^2\,(|f_{13}|^2 + |f_{23}|^2)}{8\pi\hat{s}}\frac{(\hat{s} - m_t^2)^2}{(\hat{s} - m_\Delta^2)^2 + m_\Delta^2\Gamma_{\text{tot}}^2}.$$

No angle dependence

with the total decay width as the sum if each partial decay width

$$\begin{aligned}
\Gamma(\overline{\Delta}_{u^c u^c} \to uu, cc) &= \frac{3}{16\pi}|f_{11,22}|^2\, m_\Delta, \\
\Gamma(\overline{\Delta}_{u^c u^c} \to tt) &= \frac{3}{16\pi}|f_{33}|^2\, m_\Delta\sqrt{1 - \frac{4m_t^2}{m_\Delta^2}}\left(1 - \frac{2m_t^2}{m_\Delta^2}\right) \\
\Gamma(\overline{\Delta}_{u^c u^c} \to uc) &= \frac{3}{8\pi}|f_{12}|^2\, m_\Delta, \\
\Gamma(\overline{\Delta}_{u^c u^c} \to ut, ct) &= \frac{3}{8\pi}|f_{13,23}|^2\, m_\Delta\left(1 - \frac{m_t^2}{m_\Delta^2}\right)^2.
\end{aligned}$$

At Tevatron:

$$\sigma(p\bar{p} \to u_i u_j) = \int dx_1 \int dx_2 \int d\cos\theta\, f_u(x_1, Q^2) f_{\bar{u}}(x_2, Q^2) \times \frac{d\sigma(uu \to \Delta_{u^c u^c} \to u_i u_j; \hat{s} = x_1 x_2 E_{\rm CMS}^2)}{d\cos\theta},$$

At LHC :

$$\sigma(pp \to u_i u_j) = \int dx_1 \int dx_2 \int d\cos\theta\, f_u(x_1, Q^2) f_u(x_2, Q^2) \times \frac{d\sigma(uu \to \Delta_{u^c u^c} \to u_i u_j; \hat{s} = x_1 x_2 E_{\rm CMS}^2)}{d\cos\theta},$$

$$\frac{d\sigma(pp\to u_i u_j)}{dM_{u_i u_j}} = \int d\cos\theta \int_{\frac{M_{u_i u_j}^2}{E_{\rm CMS}^2}}^{1} dx_1 \frac{2M_{u_i u_j}}{x_1 E_{\rm CMS}^2} \times f_u(x_1, Q^2) f_u\left(\frac{M_{u_i u_j}^2}{x_1 E_{\rm CMS}^2}, Q^2\right) \frac{d\sigma(uu \to \Delta_{u^c u^c} \to u_i u_j)}{d\cos\theta}$$

$$\frac{d\sigma(pp\to u_i u_j)}{d\cos\theta} = \int_{\boxed{M_{\rm cut}}}^{E_{\rm CMS}} dM_{u_i u_j} \int_{\frac{M_{u_i u_j}^2}{E_{\rm CMS}^2}}^{1} dx_1 \times \frac{2M_{u_i u_j}}{x_1 E_{\rm CMS}^2} f_u(x_1, Q^2) f_u\left(\frac{M_{u_i u_j}^2}{x_1 E_{\rm CMS}^2}, Q^2\right) \frac{d\sigma(uu \to \Delta_{u^c u^c} \to u_i u_j)}{d\cos\theta}$$

* **We employ CTEQ5M for the parton distribution functions (pdf)**

Analysis I

Example: $$f_{ij} = \begin{bmatrix} 0.3 & 0 & 0.3 \\ 0 & 0 & 0 \\ 0.3 & 0 & 0.3 \end{bmatrix}$$

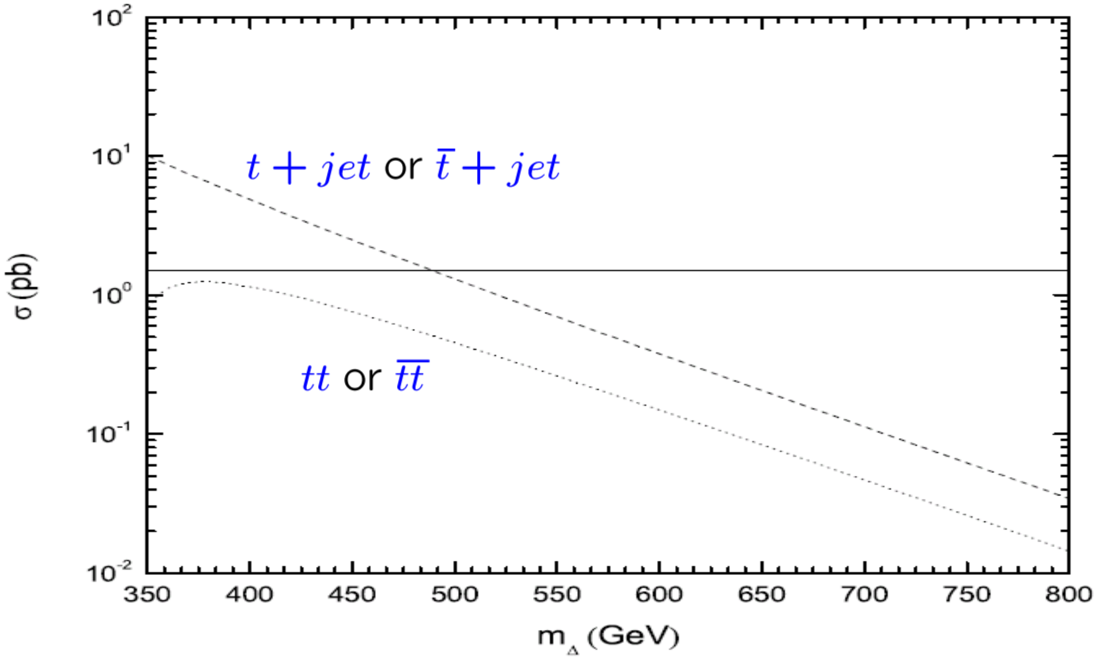
satisfies the constraints from rare decay process

Tevatron bound on Diquark Higgs mass

Top pair production cross section measured at Tevatron

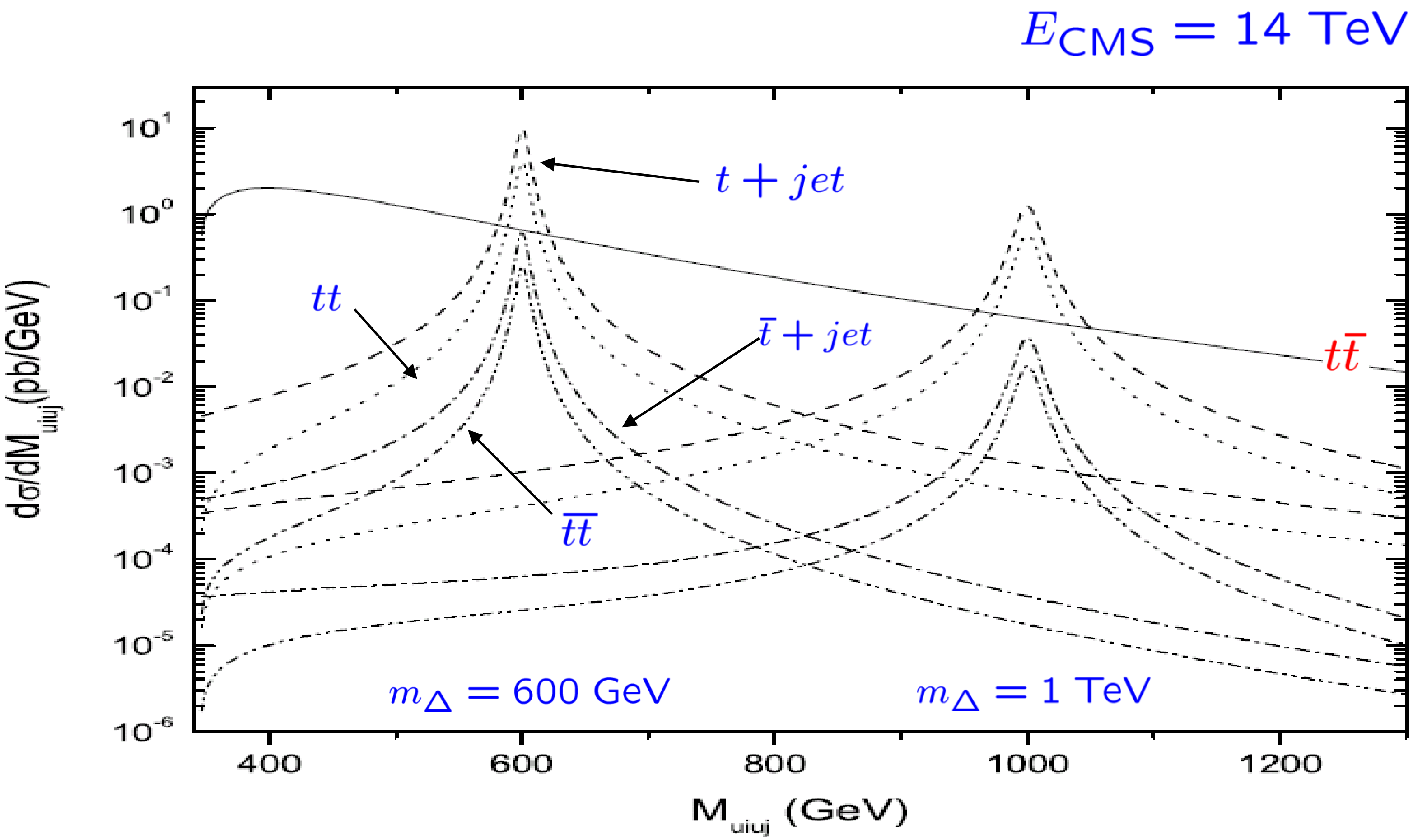
$$\boxed{\sigma(t\bar{t}) = 7.3 \pm 0.5(\mathrm{stat}) \pm 0.6(\mathrm{syst}) \pm 0.4(\mathrm{lum})\ \mathrm{pb}}$$

$$\to \sigma(p\bar{p} \to \overline{\Delta}_{u^c u^c} \to tt, ut) \lesssim 1.5\mathrm{pb}$$



$$m_\Delta \gtrsim 490\ \mathrm{GeV}$$

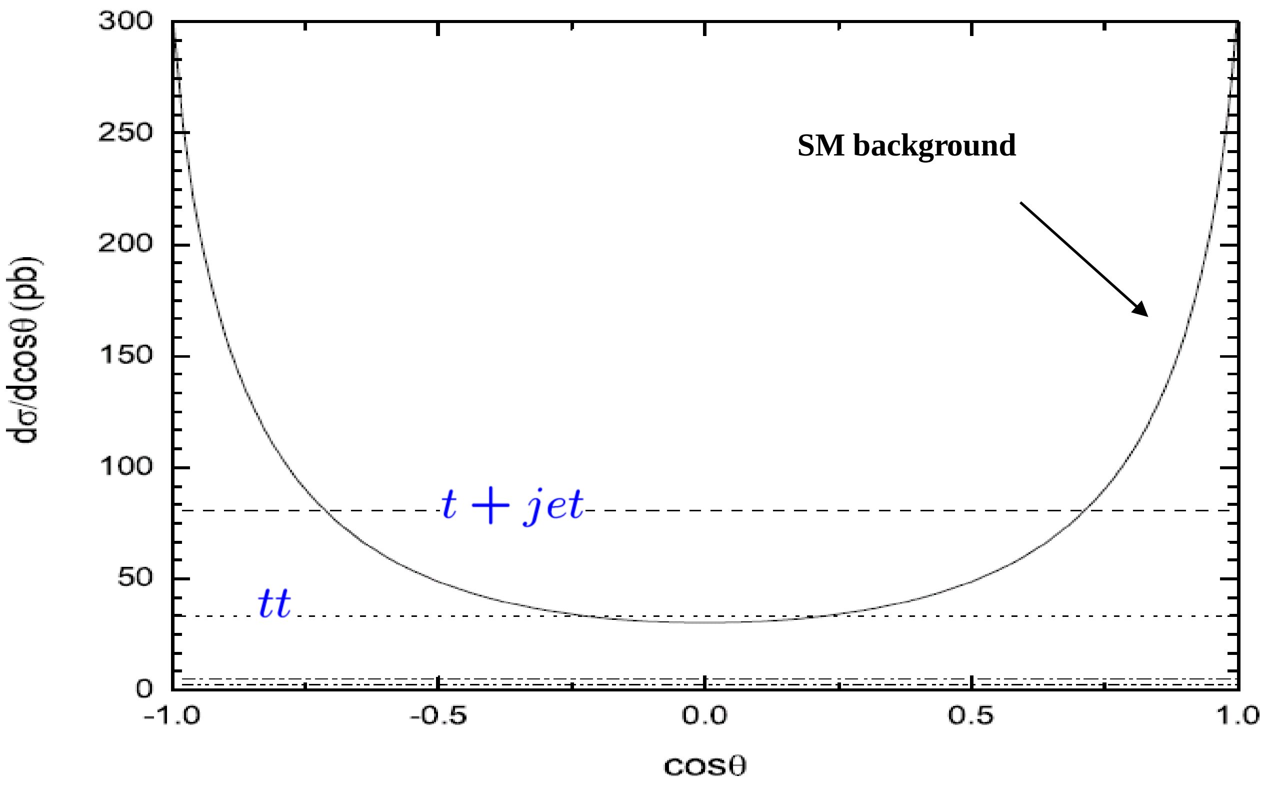
Differential cross section as a function of the invariant mass @ LHC



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

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

Angular distribution of the cross section @ LHC



$m_\Delta = 600$ GeV

$M_{\text{cut}} = 550$ GeV

Diquark is a scalar → No angular dependence

SM backgrounds→ gluon fusion → peak forward & backward region

Analysis II: type II see-saw dominant case

When we impose left-right symmetry on the model

→ Δ^c is accompanied by $\overline{\Delta}$: $(\mathbf{3},\mathbf{1},\overline{\mathbf{10}})$

$$W = f\psi\bar{\Delta}\psi \supset f\nu_L\Delta_T\nu_L$$

Assume type II see-saw dominance → $m_\nu = f v_T$

Direct relation between collider phenomenology and neutrino oscillation data!

Ex) $$f_{ij} = \begin{bmatrix} 0.27 & -0.48 & -0.47 \\ -0.48 & 0 & -0.38 \\ -0.47 & -0.38 & 0.2 \end{bmatrix}$$

This can fit the neutrino oscillation data

$$\Delta m^2_{12} = 8.9 \times 10^{-5}\ \mathrm{eV}^2, \quad \Delta m^2_{23} = 3 \times 10^{-3}\ \mathrm{eV}^2,$$
$$\sin^2\theta_{12} = 0.32, \quad \sin^2 2\theta_{23} = 0.99, \quad |U_{e3}| = 0.2,$$

$$v_T = 0.1\ \mathrm{eV}$$

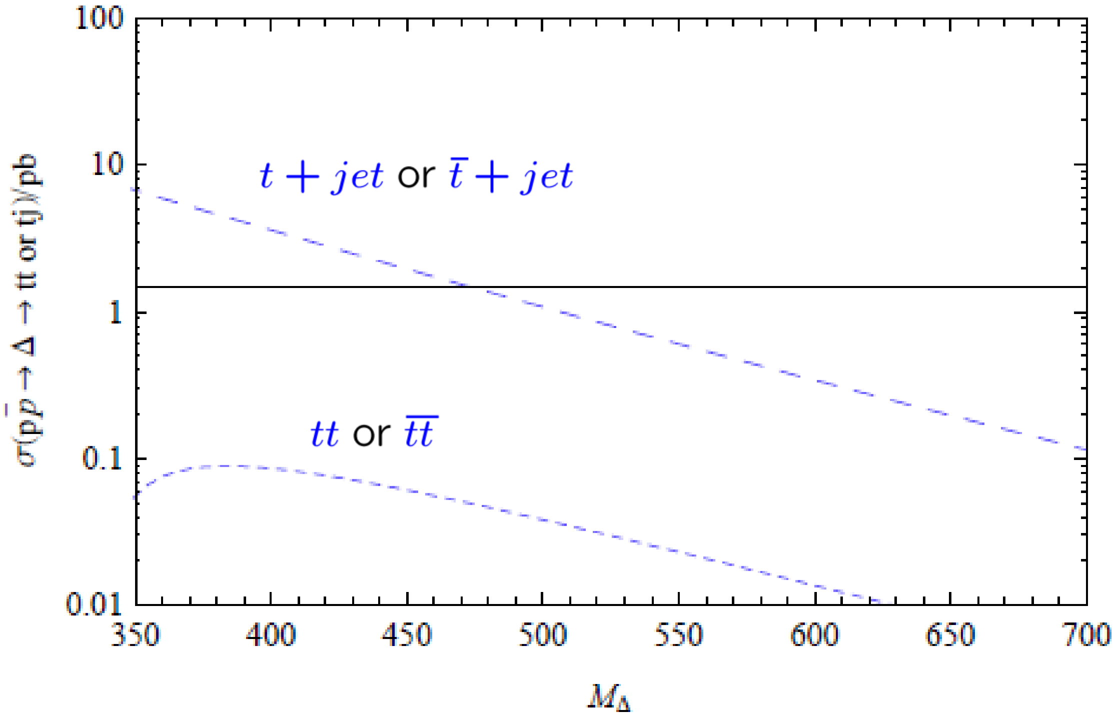
Only the inverted hierarchical case is possible

Tevatron bound on Diquark Higgs mass

Top pair production cross section at Tevatron

$$\boxed{\sigma(t\bar{t}) = 7.3 \pm 0.5(\text{stat}) \pm 0.6(\text{syst}) \pm 0.4(\text{lum})\ \text{pb}}$$

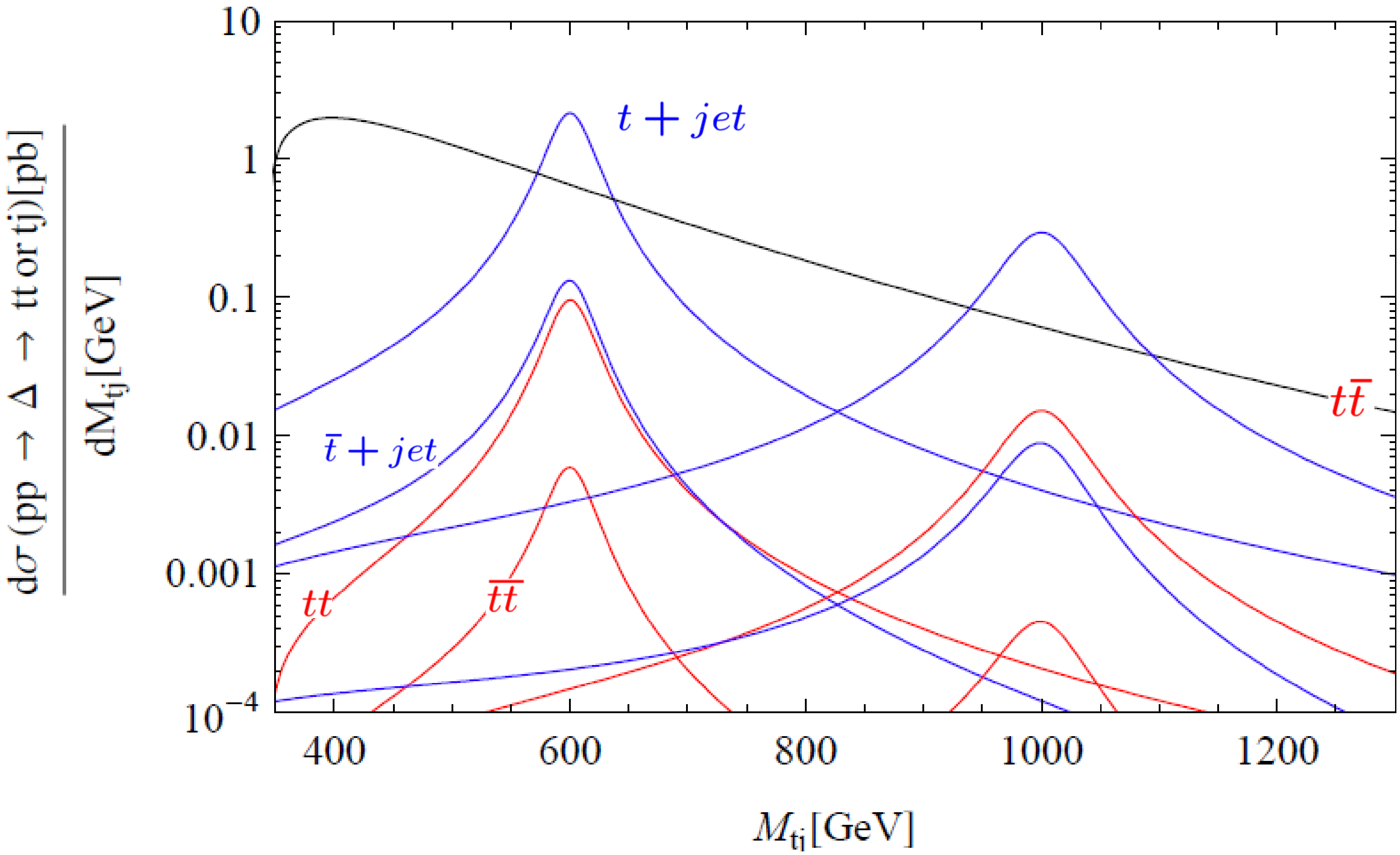
$$\rightarrow \sigma(p\bar{p} \rightarrow \overline{\Delta}_{u^c u^c} \rightarrow tt, ut) \lesssim 1.5\text{pb}$$



$$m_\Delta \gtrsim 470\ \text{GeV}$$

Differential cross section as a function of the invariant mass @LHC

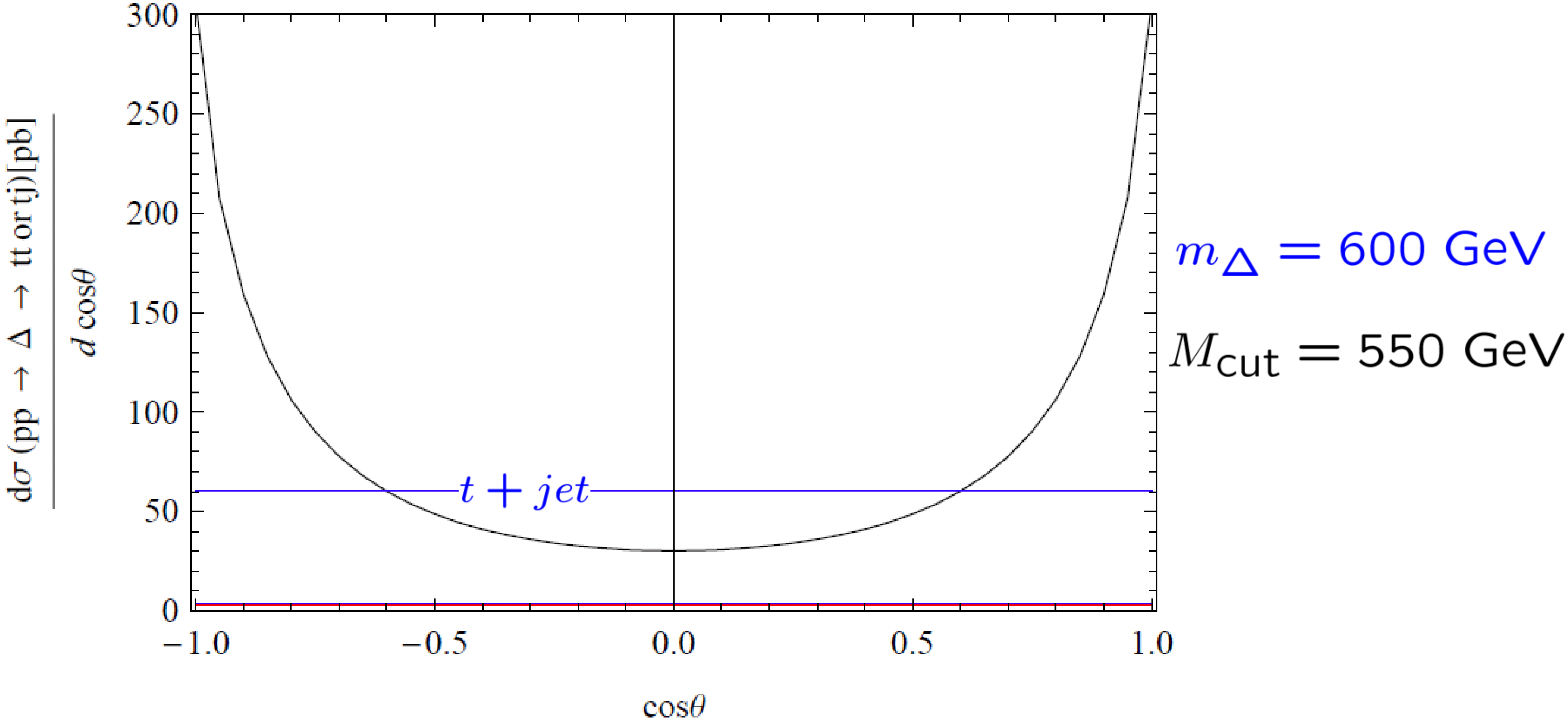
$E_{\mathrm{CMS}} = 14\ \mathrm{TeV}$



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

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

Angular distribution of the cross section



4. Summary

LHC is coming soon, followed by ILC

We are expecting the discovery of Higgs boson & New Physics

Precision measurements of masses, couplings etc @ LHC & ILC

→ ``indirectly" provide information of UV theory

Discovery of some exotic particle

→ ``directly" suggests a class of new physics models