Diquark Higgs production at LHC

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1. Introduction

LHC is coming soon!

We are expecting the evidence of New Physics (New Particles)

Ex) SUSY, Extra-dim, Little Higgs…

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)

associated with B-L symmetry breaking

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

Talk by R.N. Mohapatra

2. 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**

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

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

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

3. Phenomenological constraints on Yukawa coupling

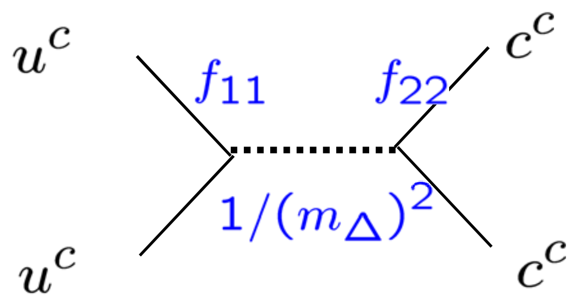
$$W_Y \supset f\psi^c\Delta^c\psi \to f_{ij}\Delta_{u^c u^c}\, u_i^c u_j^c$$

Only up-type quarks are involved

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

Constraints by rare processes

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

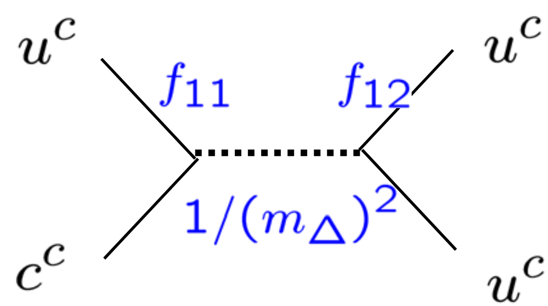


Severe

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

$\to f_{22} \to 0$

$D \to \pi\pi$



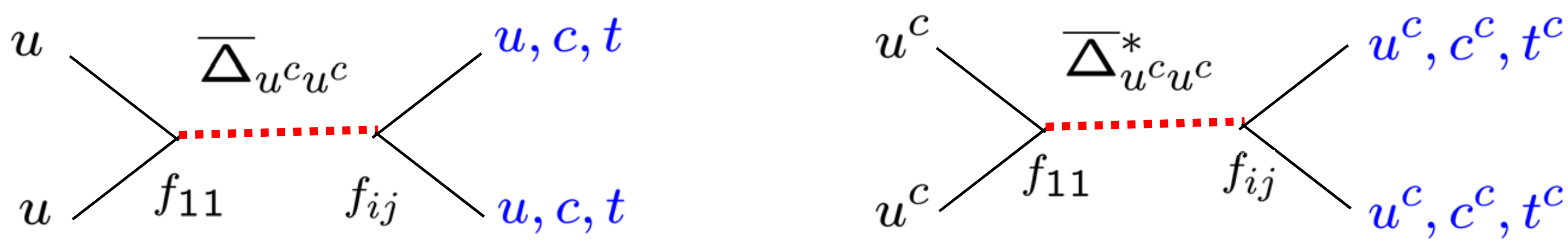
Mild

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

4. Collider 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 prove new physics!

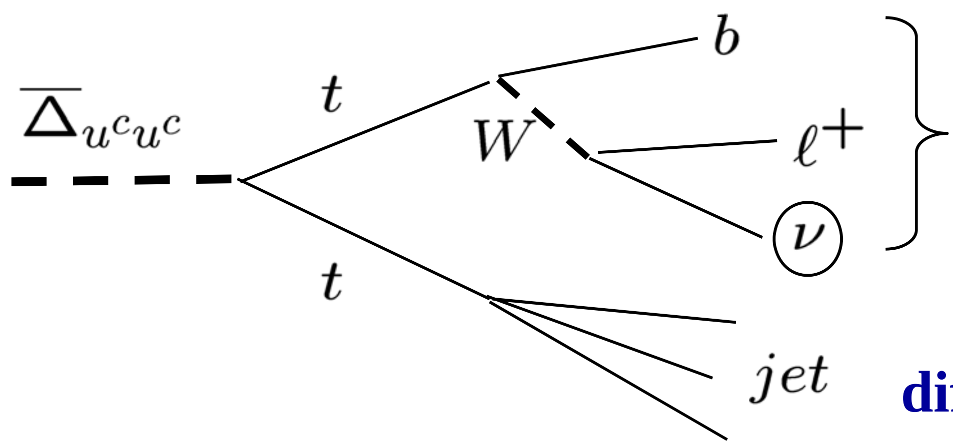
So, our target is

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

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

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

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

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

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:

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

At LHC :

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

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

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

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

Analysis I

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

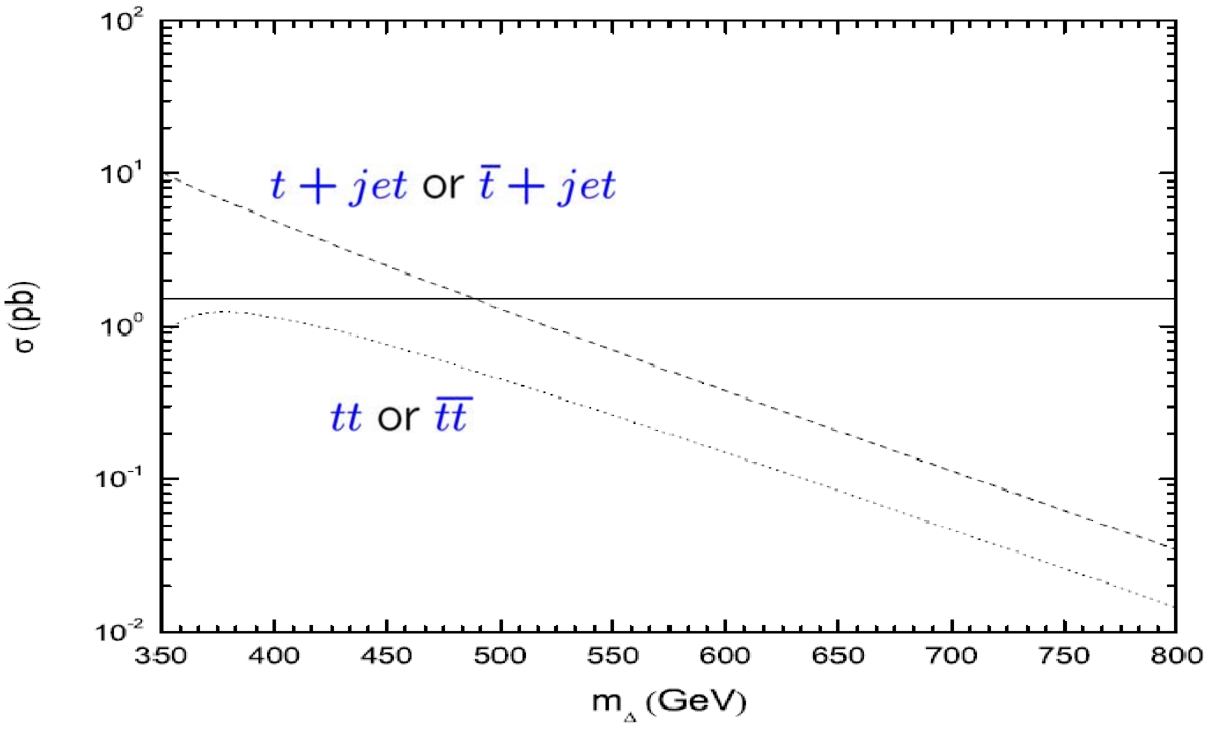
satisfies the constraints from rare decay process

Tevatron bound on Diquark Higgs mass

Top pair production cross section measured at Tevatron

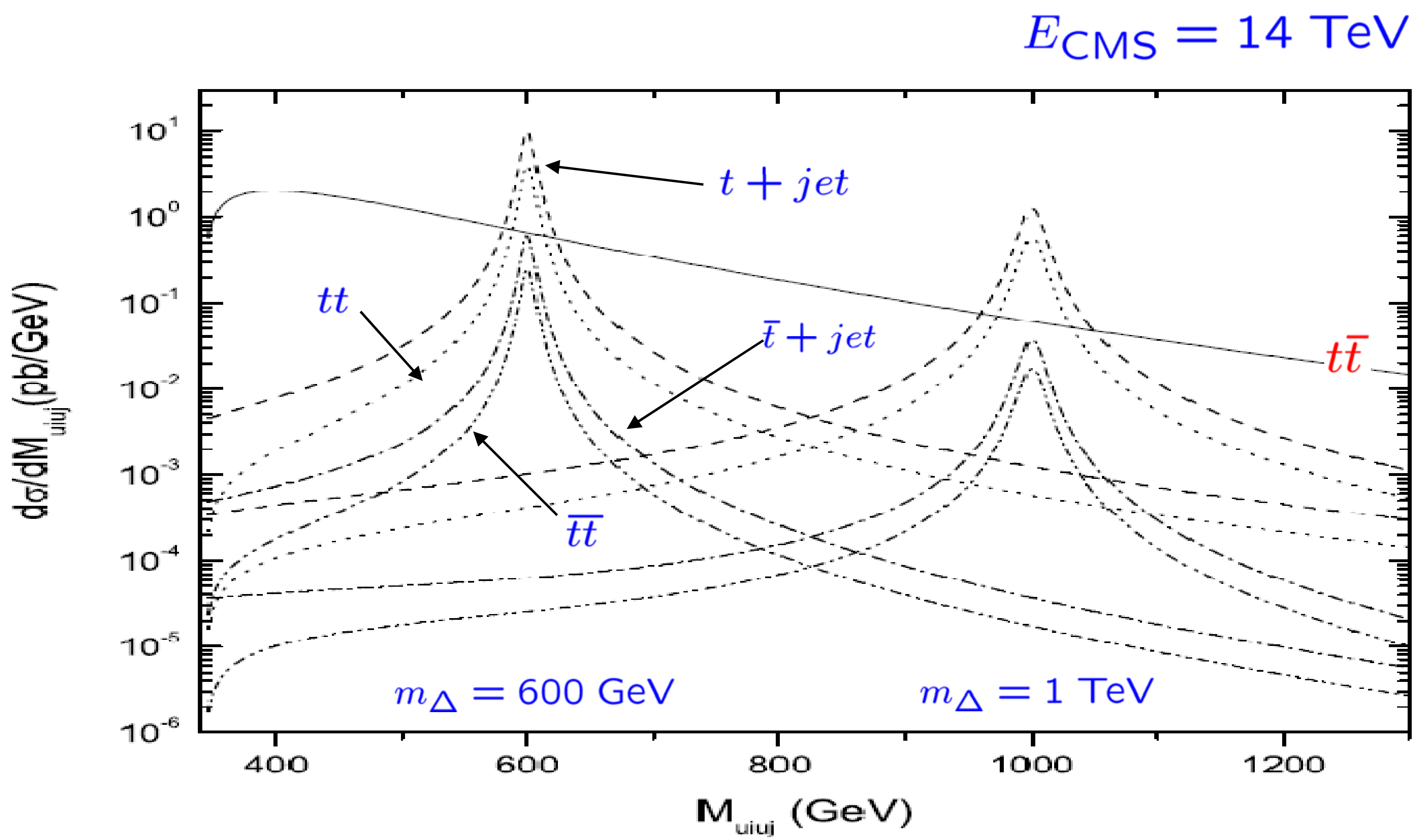
$$\sigma(t\bar{t}) = 7.3 \pm 0.5(\text{stat}) \pm 0.6(\text{syst}) \pm 0.4(\text{lum})\ \text{pb}$$

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



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

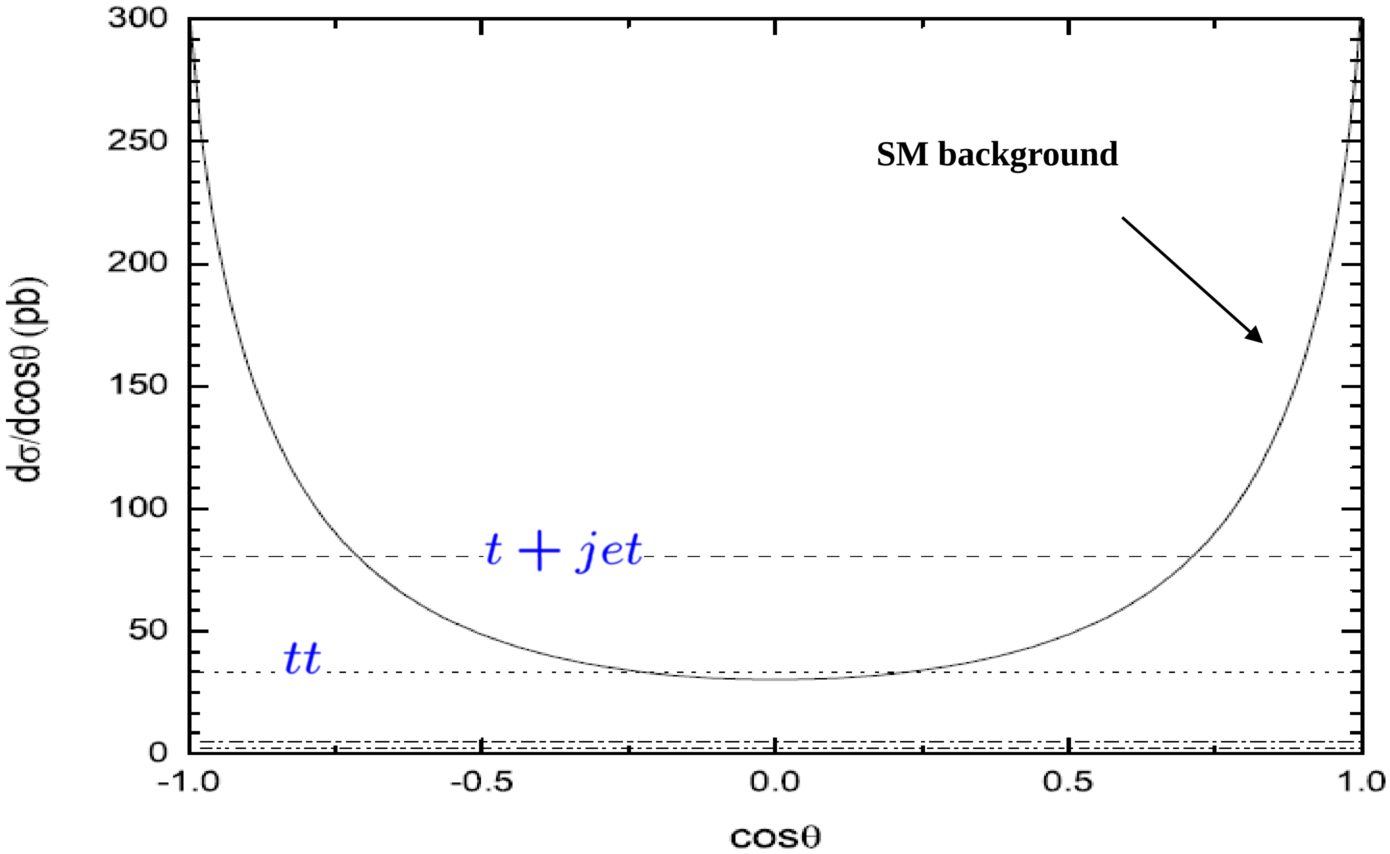
Differential cross section as a function of the invariant mass @ LHC



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

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

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

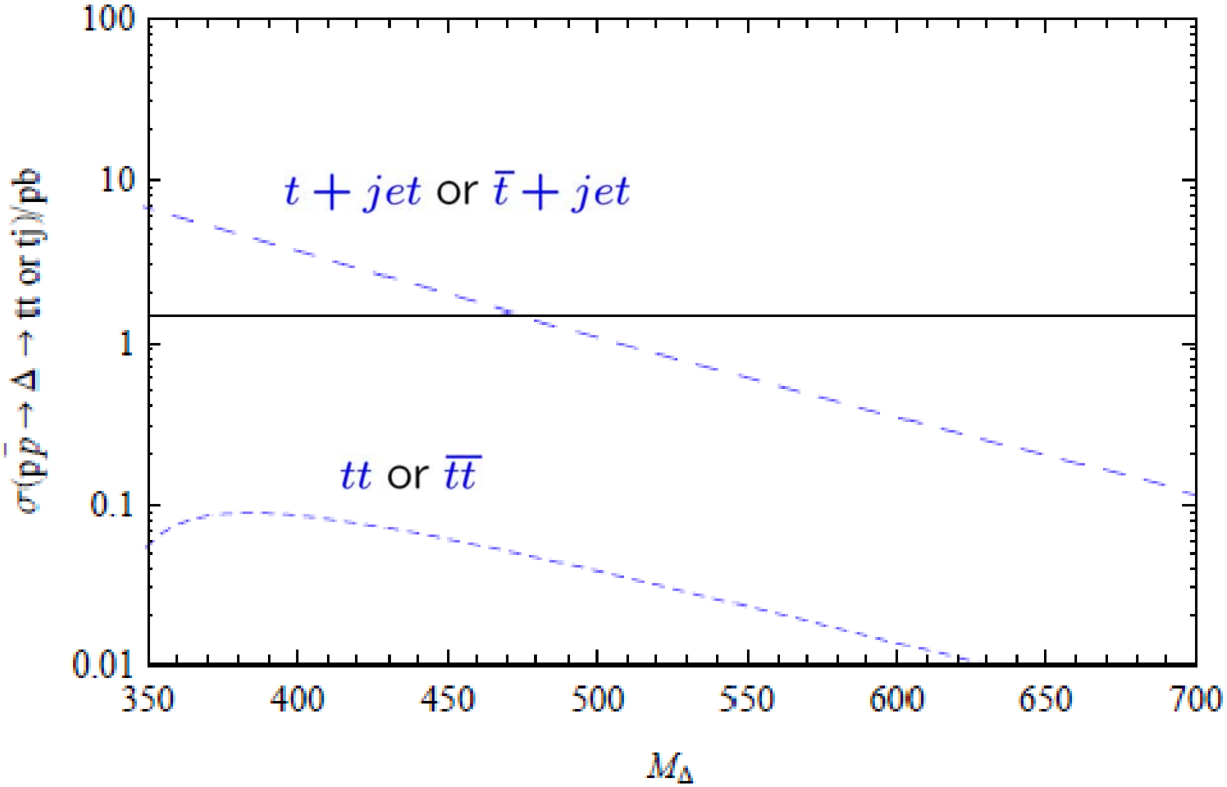
Only the inverted hierarchical case is possible

Tevatron bound on Diquark Higgs mass

Top pair production cross section at Tevatron

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

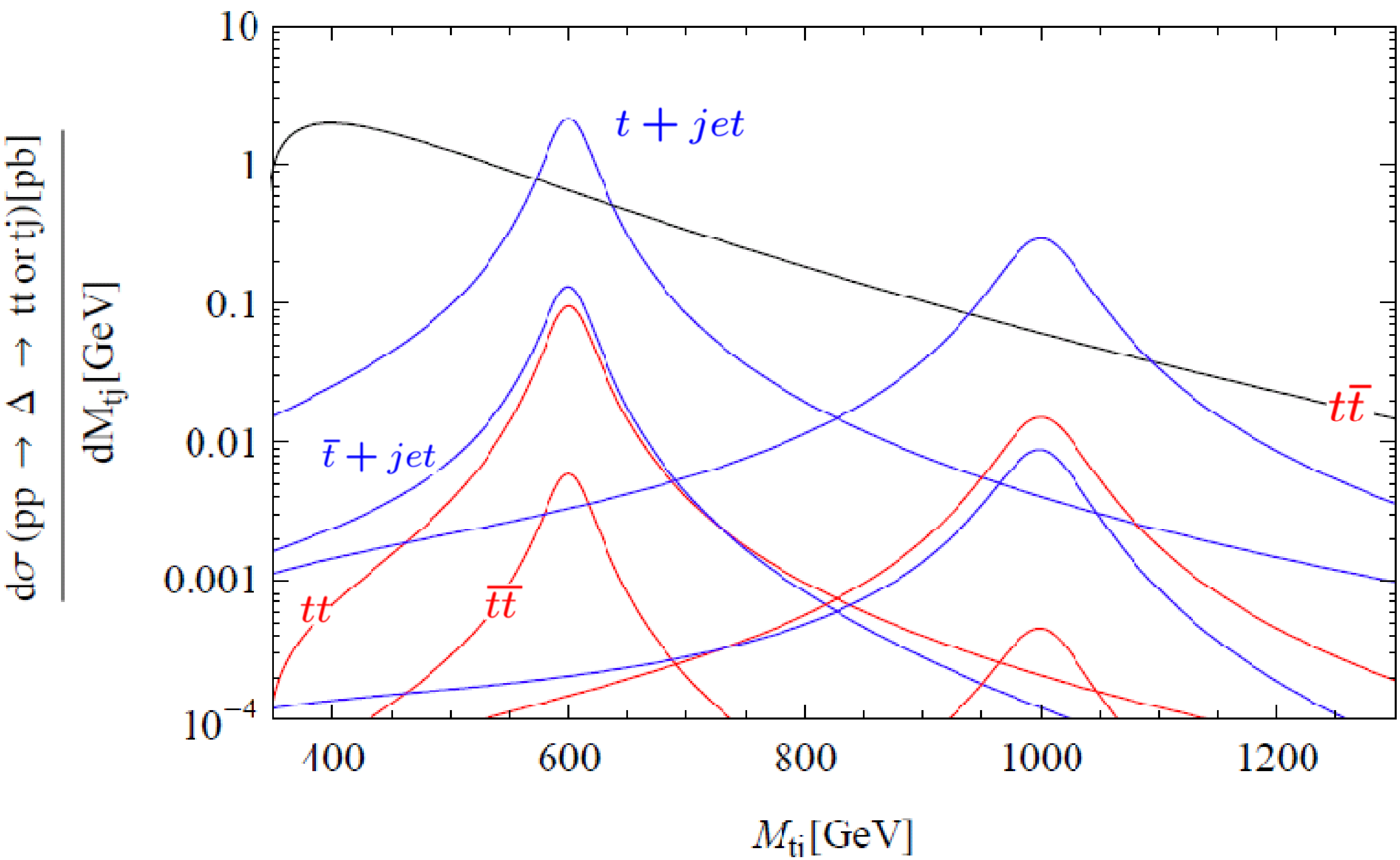
$$\rightarrow \sigma(p\bar{p} \rightarrow \overline{\Delta}_{u^c u^c} \rightarrow tt, ut) \lesssim 1.5\text{pb}$$



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

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

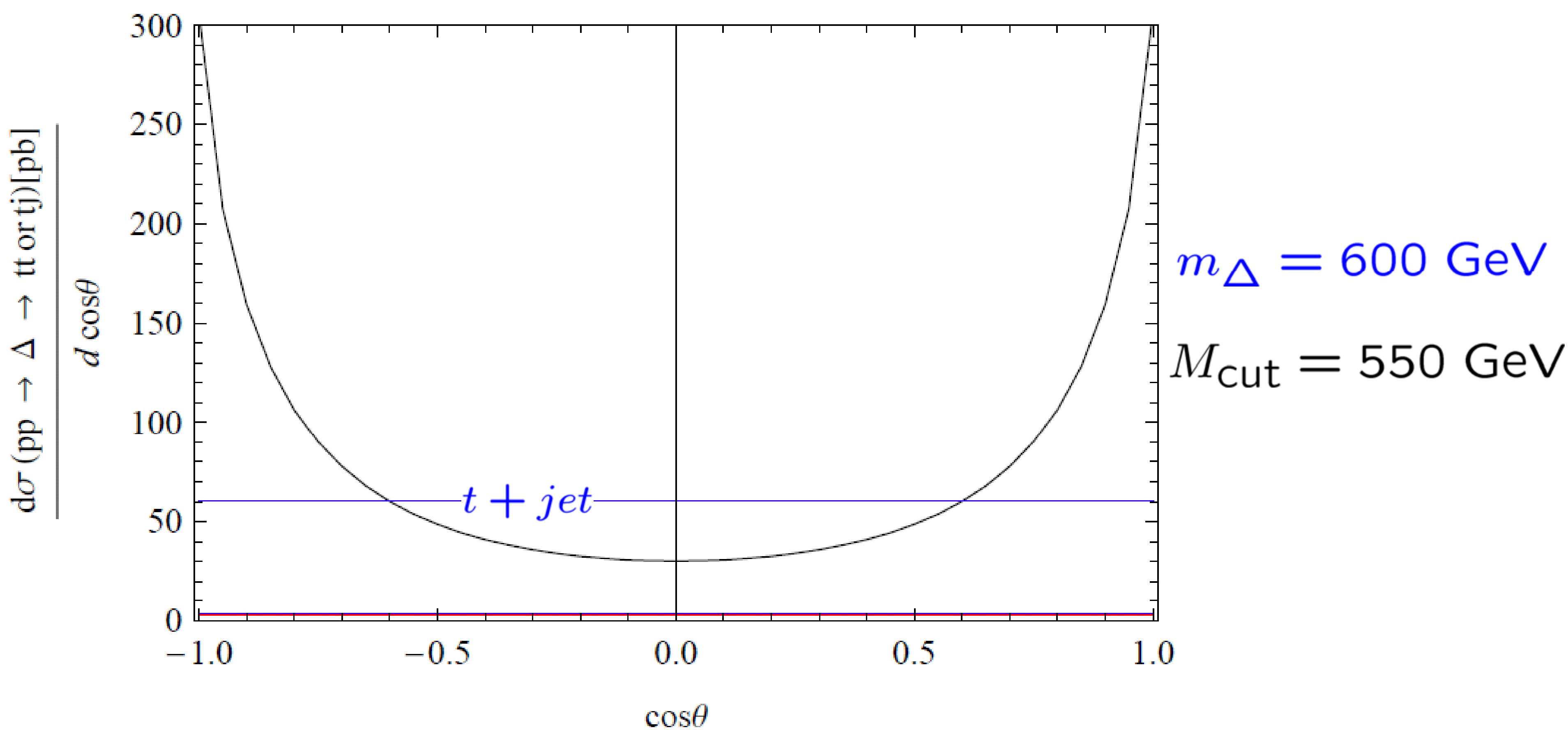
$E_{\mathrm{CMS}} = 14$ TeV



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

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

Angular distribution of the cross section



5. Summary

LHC is coming soon. We have been expecting the discovery of new particles (New Physics).

We have discussed a new kind of TeV mass Higgs boson (diquark Higgs) that arises in a class of Pati-Salam models with accidental global symmetries.

Several unique features:
- color sextet
- carrying baryon number
- couples to only (right-handed) up-type quarks
- R-parity even

We have studied the resonant diquark Higgs production at hadron collider

@LHC
- sizable deviations from the SM backgrounds
- asymmetry for top and anti-top production cross section
- no angular distribution
- only right-handed top couples to diquark Higgs