Lepton number violation at the LHC with Leptoquarks and Diquarks

Hiroaki SUGIYAMA
(Maskawa Inst., Kyoto Sangyo Univ.)

Contents

- Introduction, Motivation
- The Model - "colored Zee-Babu model" -
- Lepton Number Violation at the LHC
- Summary

based on 'M. Kohda, HS, K. Tsumura, PLB718, 1436 (2013)'

Introduction -Neutrino Oscillation-

Neutrino masses, mixings, and oscillations

Massive neutrinos can be mixed

$$\nu_\ell = \sum_i (U_{\rm MNS})_{\ell i}\, \nu_i$$

ν_ℓ : **flavor eigenstates (weak interaction)**

ν_i : **mass eigenstates (propagation)**

$U_{\rm MNS}$: **Maki-Nakagawa-Sakata matrix (mixing)**

(quark sector : Cabibbo-Kobayashi-Maskawa matrix)

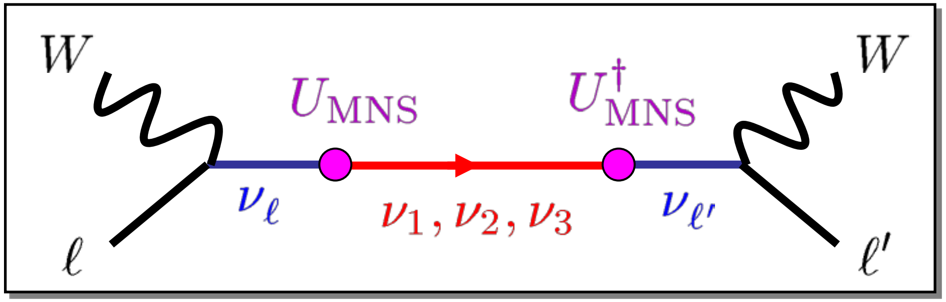
Flavor transitions (oscillations) are possible

$$P(\nu_\ell \to \nu_{\ell'}) = \left| \sum_i (U_{\rm MNS})_{\ell i}\ \exp\left(i \frac{m_i^2 L}{2E} \right) (U_{\rm MNS}^\dagger)_{i\ell'} \right|^2$$

m_i : **masses**

L : **distance**

E : **energy**

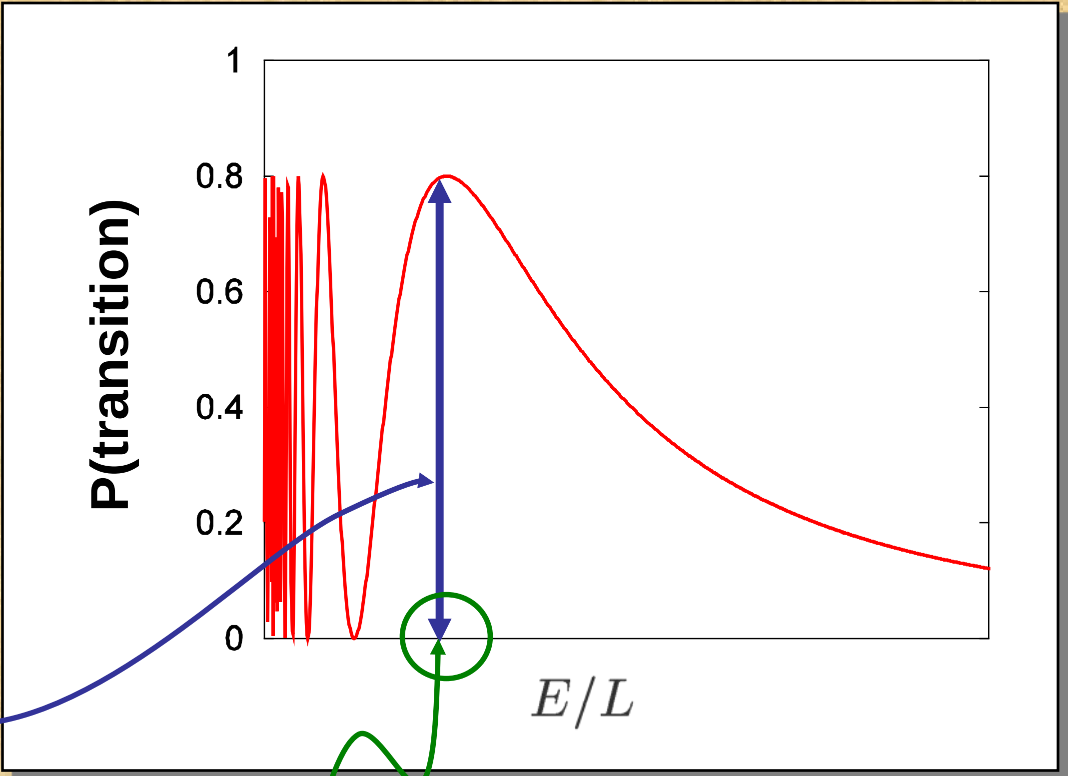


Two Neutrino Case (good approximation)

$$U_{\rm MNS} \equiv \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$$

$$P = \sin^2 2\theta \ \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

accuracy for P
$\simeq$ **accuracy for** $\sin^2 2\theta$



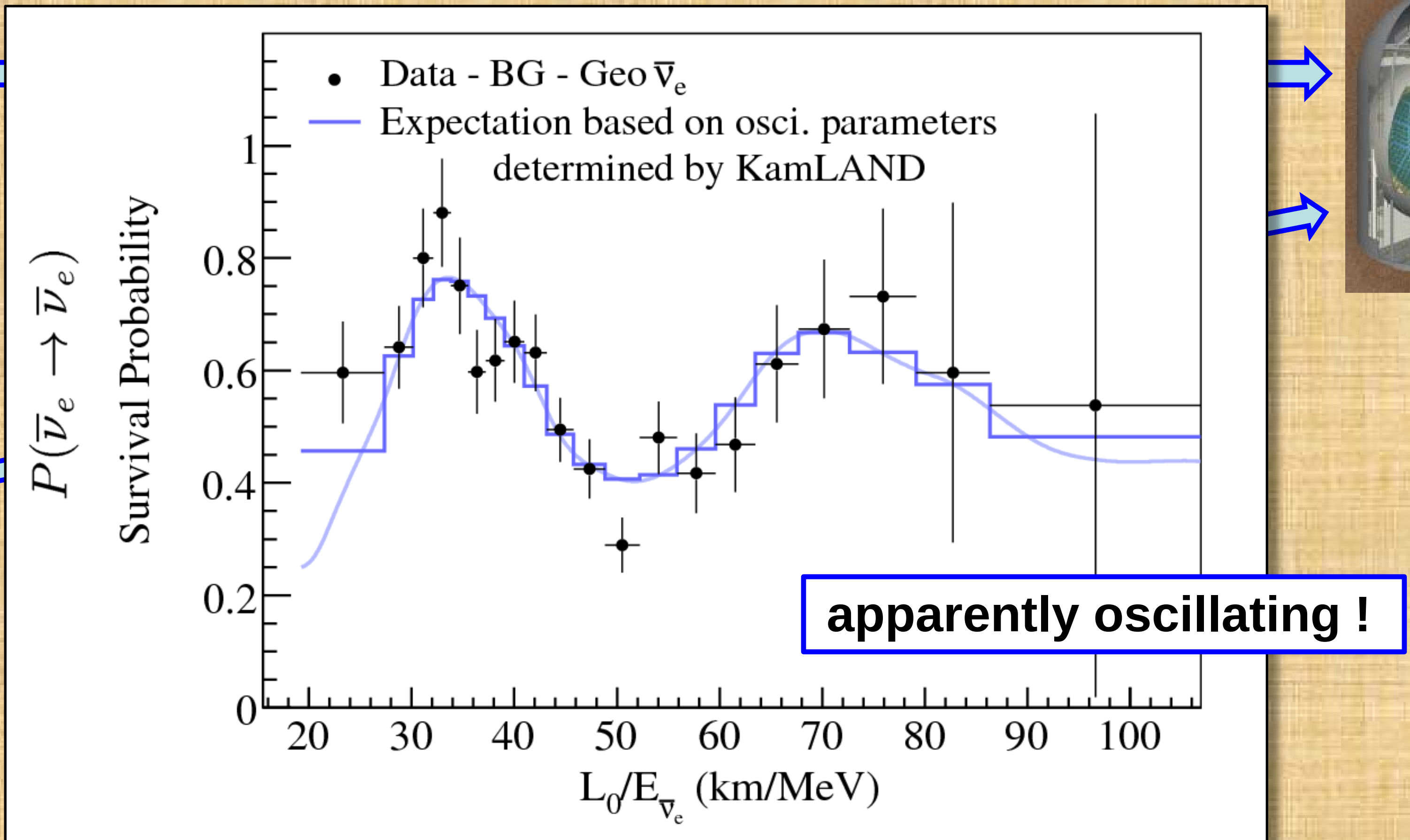
first oscillation maximum : $\dfrac{\Delta m^2 L}{4E} = \dfrac{\pi}{2}$

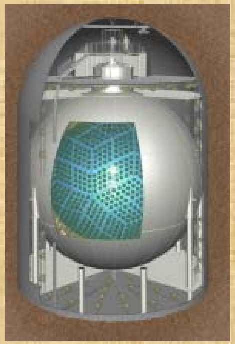
good set up (E, L) of experiments to obtain $\sin^2 2\theta$ **and** Δm^2

$$\frac{\Delta m^2 L}{4E} = 1.27 \ \frac{\Delta m^2({\rm eV}^2) \ L({\rm m})}{E({\rm MeV})}$$

e.g., Measurement in KamLAND experiment

55 Japanese nuclear power reactors $\xrightarrow{\overline{\nu}_e}$ **Kamioka mine**





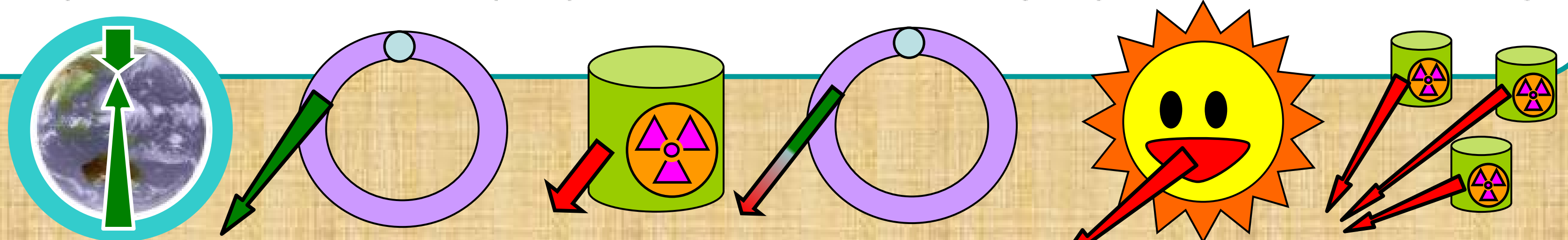
S. Abe *et al.*, PRL**100**, 221803

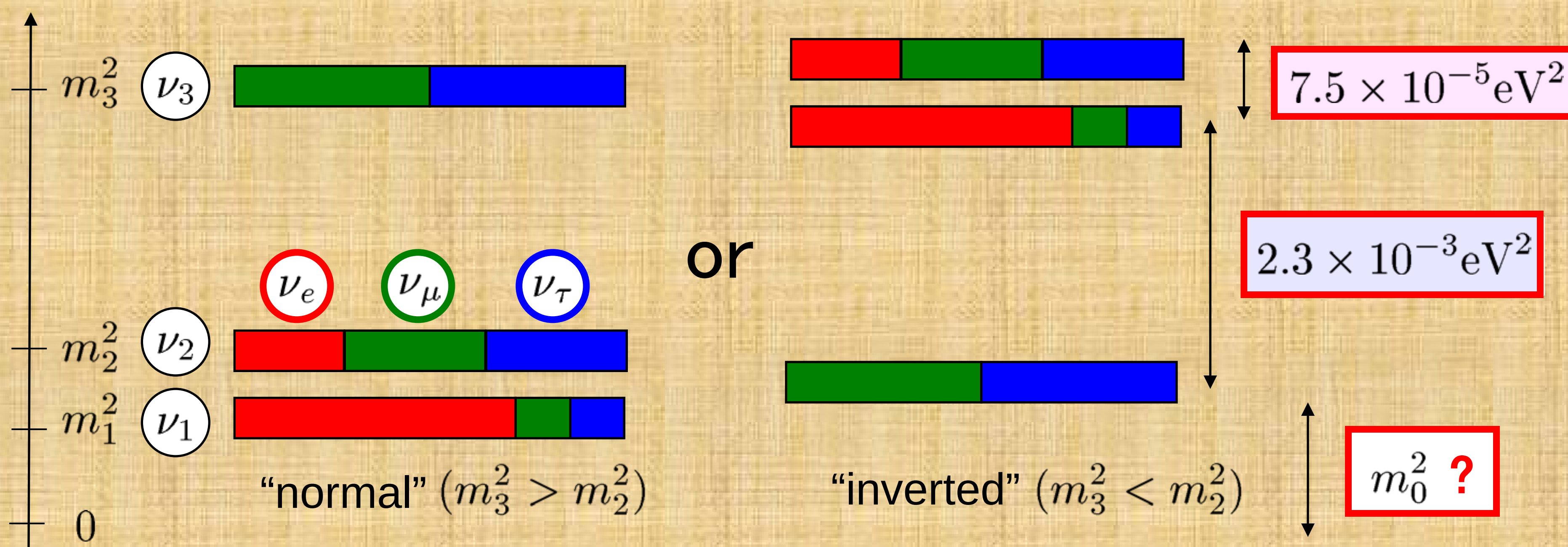
We have evidence of oscillations ⟶ **Neutrino masses are necessary**

Current knowledge on neutrino masses and mixings

$\theta_{23} \cong 45^\circ$ $\theta_{13} \simeq 9^\circ$ δ ? $\theta_{12} \simeq 33^\circ$

$$U_{\rm MNS} \simeq \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0.71 & 0.71 \\ 0 & -0.71 & 0.71 \end{pmatrix} \begin{pmatrix} 0.99 & 0 & 0.15 \\ 0 & 1 & 0 \\ 0.15 & 0 & 0.99 \end{pmatrix} \begin{pmatrix} 0.83 & 0.55 & 0 \\ -0.55 & 0.83 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

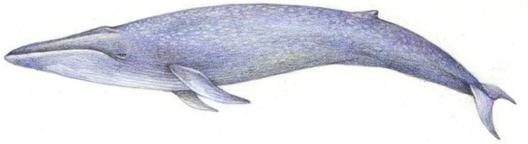




Introduction -Neutrino Mass-

Neutrino masses are extremely smaller than other fermion masses.

neutrino $\lesssim 1\,\mathrm{eV}$ electron $= 0.5\,\mathrm{MeV}$ tau $= 1.8\,\mathrm{GeV}$ top $= 172\,\mathrm{GeV}$

$1\,\mathrm{MeV}$ "$\simeq$" $1\,\mathrm{kg}$

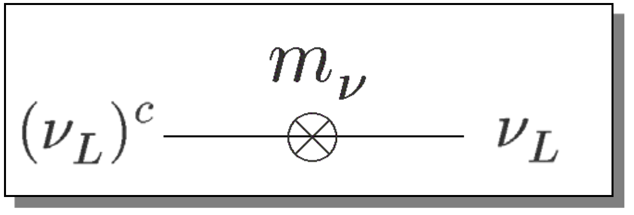
⟶ neutrino-specific mechanism to generate their masses ?

c.f. $m_\nu = y_\nu \frac{v_{\mathrm{SM}}}{\sqrt{2}} \Longrightarrow y_\nu \sim 10^{-12}$ **for** $m_\nu \sim 0.1\,\mathrm{eV}$

"Unnatural"

Neutrino-specific mass term

Majorana : $\frac{1}{2} m_\nu \overline{(\nu_L)^c}\, \nu_L$



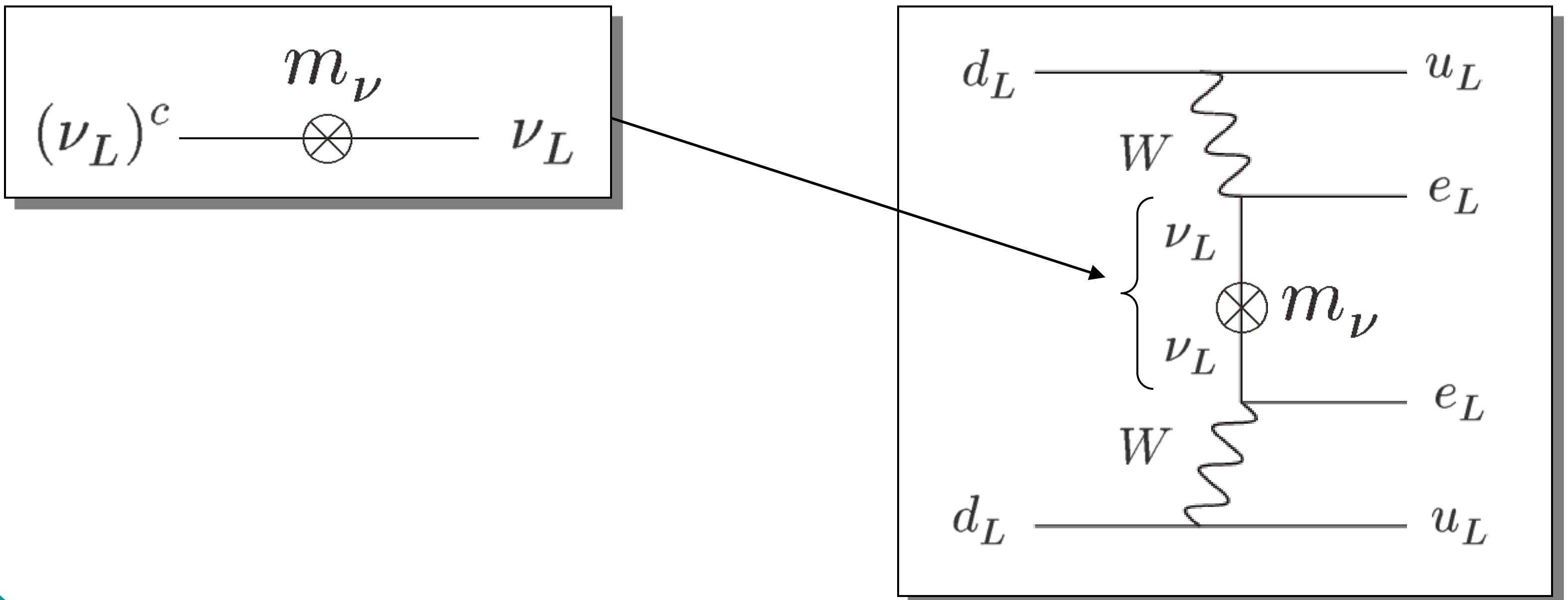
Q_{EM} : 0 + 0 = 0 **Allowed only for neutrinos**

$L\#$: 1 + 1 = 2 **Lepton number violation**

Majorana mass & L#V processes

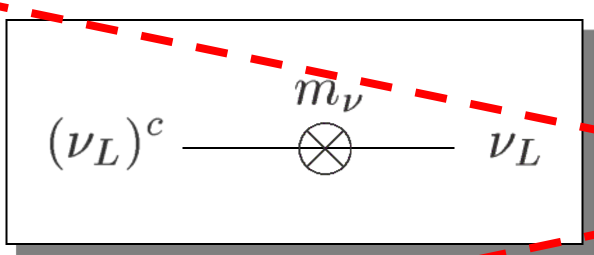
Majorana neutrino $\Rightarrow$ **L#V process**
(tiny mass) **(tiny rate)**

e.g., Neutrinoless double beta decay



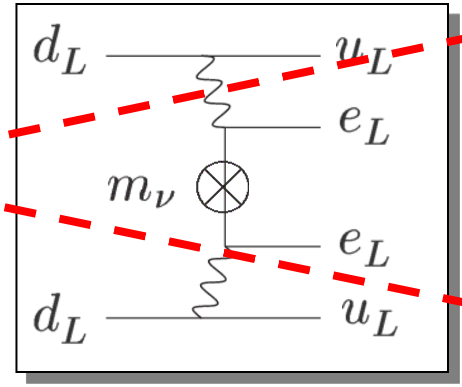
Motivation

Input : Small m_ν

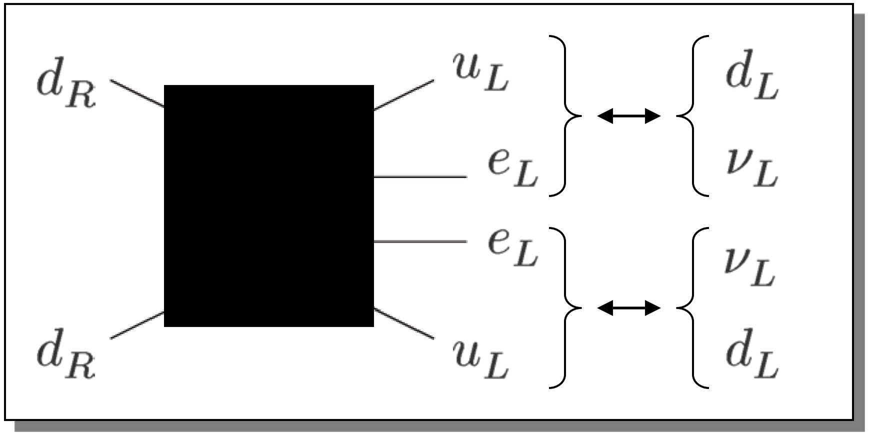


$\Rightarrow$

Output : Small rate of L#V



Input : Unsuppressed L#V

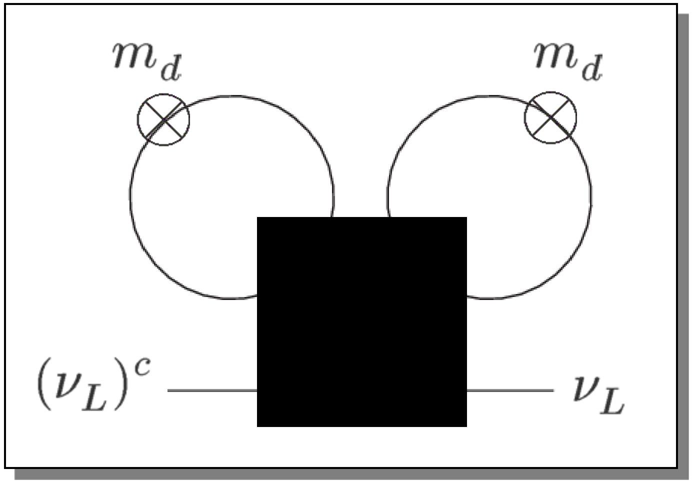


Black box : TeV-scale particles

No m_ν

$\Rightarrow$

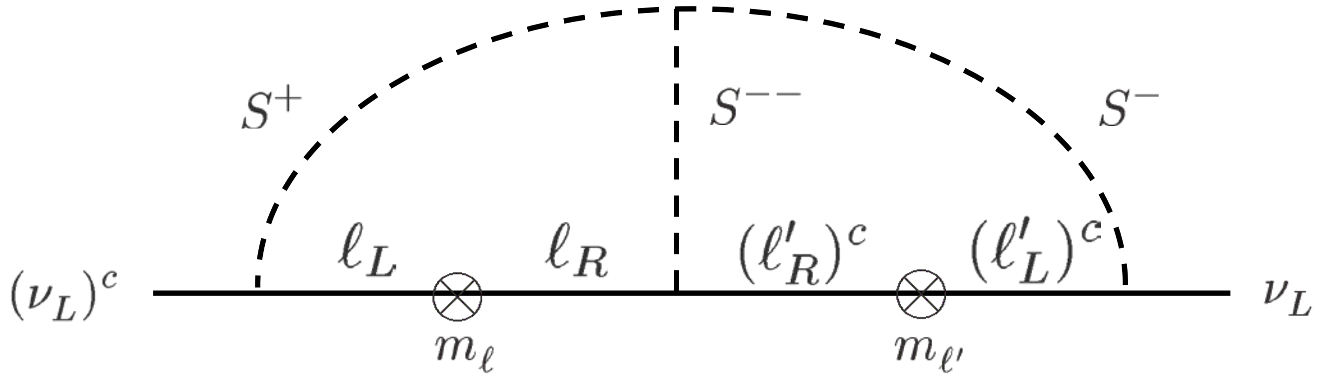
Output : Suppressed m_ν



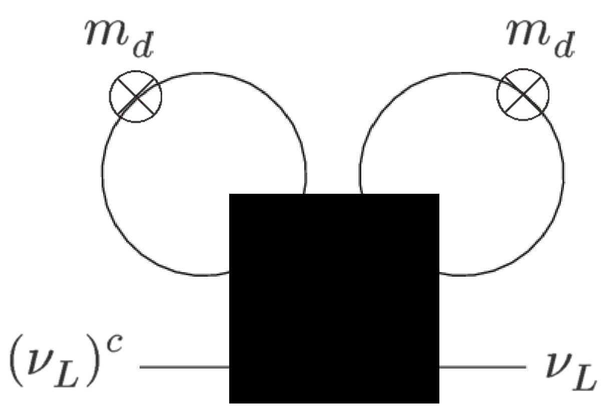
Two-Loop Neutrino Mass

Zee-Babu Model

A. Zee, NPB**264**, 99 (1986)
K.S. Babu, PLB**203**, 132 (1988)



colored version



two colored loops

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The Model - colored Zee-Babu Model -

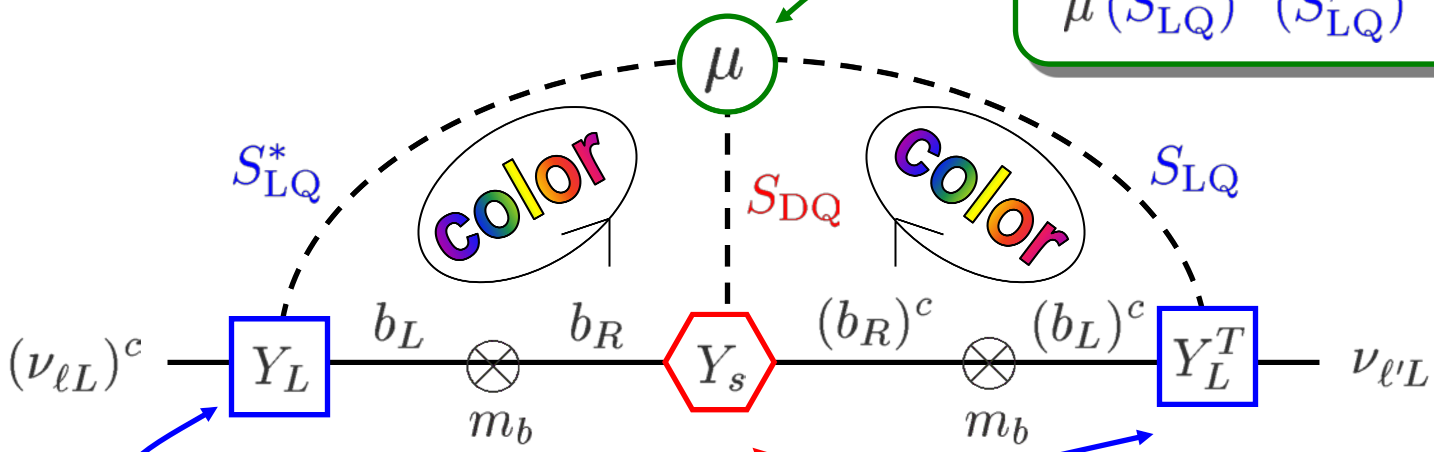
Briefly mentioned in 'K.S. Babu and C.N. Leung, NPB**619**, 667 (2001)'

		$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$B\#$	$L\#$
Scalar Leptoquark	S_{LQ}	$\underline{\mathbf{3}}$	$\underline{\mathbf{1}}$	$-1/3$	$1/3$	1
Scalar Diquark	S_{DQ}	$\underline{\mathbf{6}}$	$\underline{\mathbf{1}}$	$-2/3$	$2/3$	0

Two-loop neutrino mass

soft L#V term (no B#V)

$$\mu\,(S_{LQ}^{\alpha})^{*}\,(S_{LQ}^{\beta})^{*}\,S_{DQ}^{\alpha\beta}$$



$$(Y_L)_{\ell i}\left[\overline{L^c_\ell}\, i\,\sigma_2\, Q_i^\alpha\, (S_{LQ}^\alpha)^*\right] + \cdots$$

$$(Y_s)_{ij}\left[\overline{(d_{iR}^\alpha)^c}\, d_{jR}^\beta\, (S_{DQ}^{\alpha\beta})^*\right]$$

$$Y_s = Y_s^T$$

A Benchmark Point

LQ Yukawa :

$$Y_L = \begin{array}{c} \\ e(\nu_e) \\ \mu(\nu_\mu) \\ \tau(\nu_\tau) \end{array} \begin{array}{c} \begin{array}{ccc} u(d) & c(s) & t(b) \end{array} \\ \begin{pmatrix} 8.1\times10^{-5} & 3.5\times10^{-2} & -5.6\times10^{-3} \\ -4.9\times10^{-5} & 4.5\times10^{-2} & 3.5\times10^{-2} \\ 3.1\times10^{-5} & -1.9\times10^{-2} & 7.2\times10^{-2} \end{pmatrix} \end{array}$$

DQ Yukawa :

$$Y_s = \begin{array}{c} \\ d \\ s \\ b \end{array} \begin{array}{c} \begin{array}{ccc} d & s & b \end{array} \\ \begin{pmatrix} 1.0\times10^{-1} & 0 & 0 \\ 0 & 0 & -1.7\times10^{-2} \\ 0 & -1.7\times10^{-2} & -5.9\times10^{-4} \end{pmatrix} \end{array}$$

Scale : $\mu = 1\,\mathrm{TeV}$ $\quad m_{\mathrm{LQ}} = 1\,\mathrm{TeV}$ $\quad m_{\mathrm{DQ}} = 4\,\mathrm{TeV}$

$\Downarrow$ **satisfy constraints (couplings, masses)**

$\sin^2 2\theta_{23} = 1$ $\quad \sin^2 2\theta_{13} = 0.1$ $\quad \sin^2 2\theta_{12} = 0.87$

$\delta = 0$ $\quad \alpha_{21} = 0$ $\quad \alpha_{31} = \pi$

$m_1 \simeq 0$ $\quad \Delta m^2_{21} = 7.6\times10^{-5}\,\mathrm{eV}^2$ $\quad \Delta m^2_{31} = +2.4\times10^{-3}\,\mathrm{eV}^2$

agree with neutrino oscillation data

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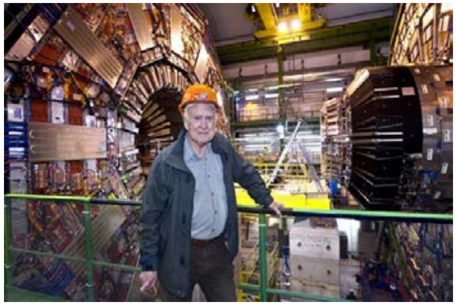
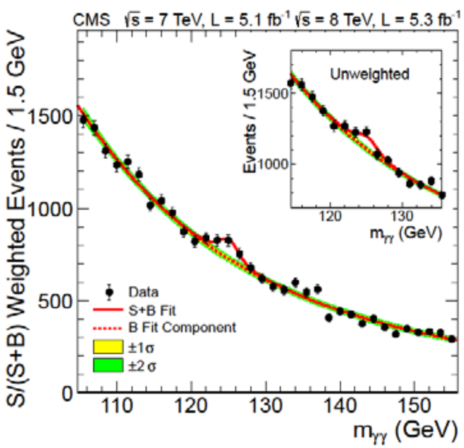
Large Hadron Collider

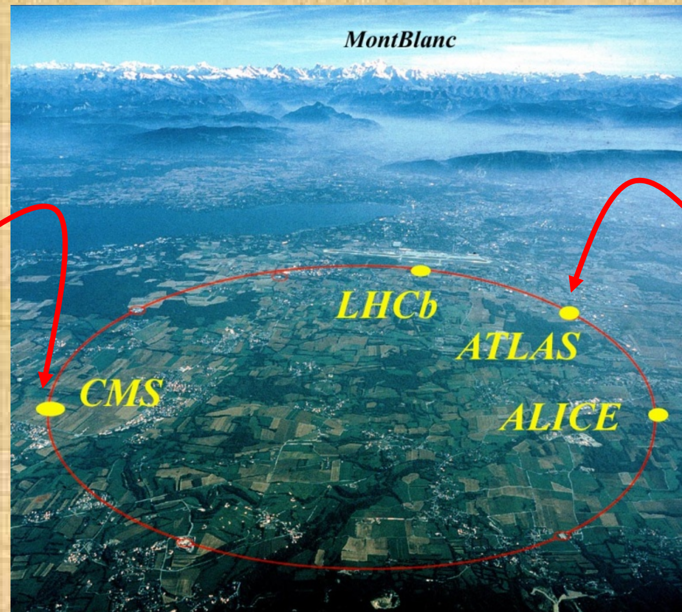
Higgs at CMS



4 Apr. 2008

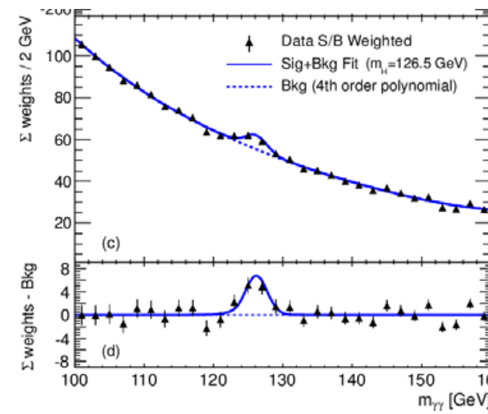


4 Jul. 2012



Higgs at ATLAS

4 Apr. 2008



4 Jul. 2012

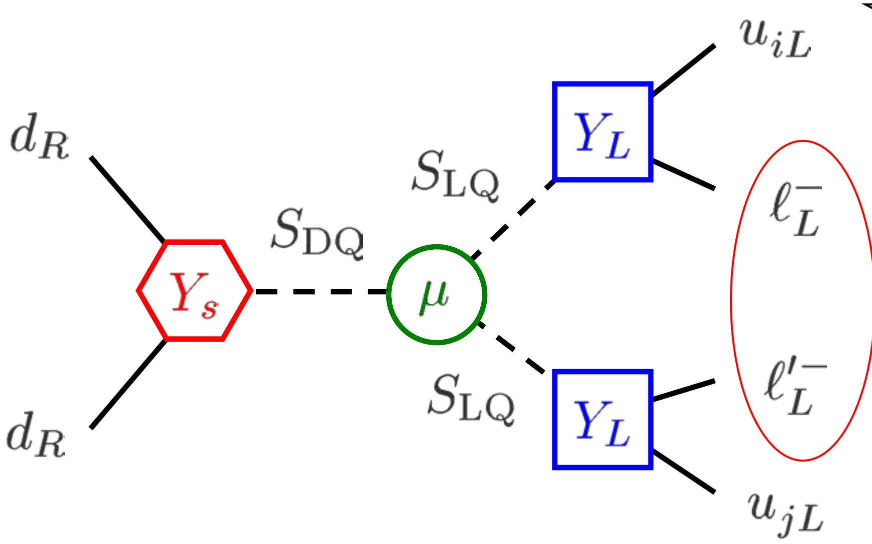
pp **collider at** $\sqrt{s} = 7,\ 8,\ 14\,\mathrm{TeV}$ **(cf. Tevatron:** $p\bar{p}$ **at** $\sqrt{s} = 1.96\,\mathrm{TeV}$**)**

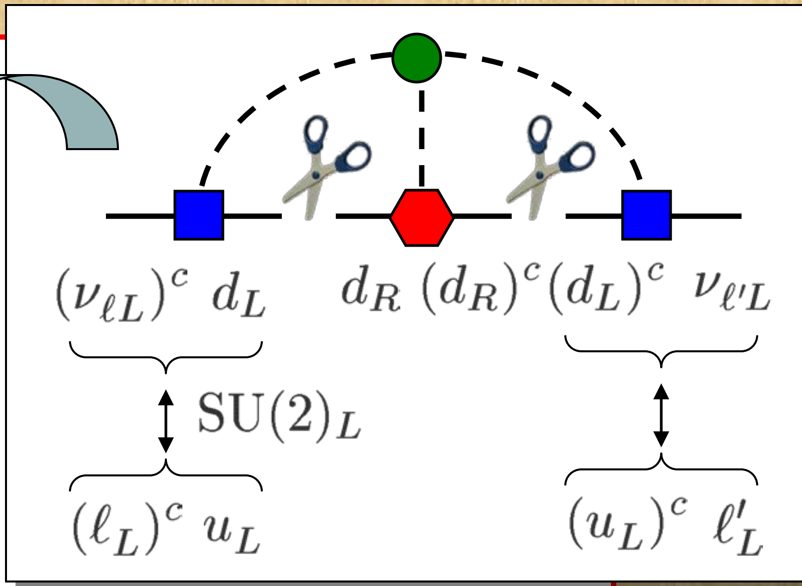
26.7km ring (cf. 26.4km loop subway in Nagoya, Japan)
(cf. 21.7km loop line in Osaka, Japan)


8.5 km
上京区
中京区
下京区
東山区
山科区
南区
北区役所
船岡山公園
北野白梅町
御室仁和寺
花園
山陰本線
京都市右京区役所
二条
四条通
丹波口
西五条通
阪急京都線
西京区役所
桂
陸上自衛隊桂駐屯地
西大路
京都
南区役所
山科区役所
山科
四宮
元田中
修学院
赤山禅院
比叡山口
八瀬
木野
二軒茶屋
沢山
銀閣寺
大文字山
岡崎公園
松尾

L#V Process at the LHC

$pp \to \ell^- \ell'^- jj$ **without missing**





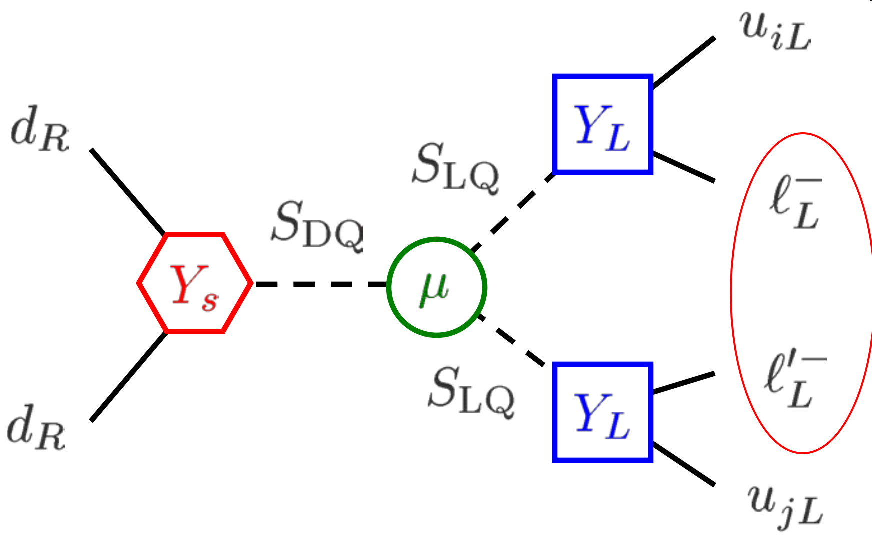
No missing energy $\Rightarrow$ **No missing L#** $(\nu, \overline{\nu}, \mathrm{DM}, \mathrm{etc.})$

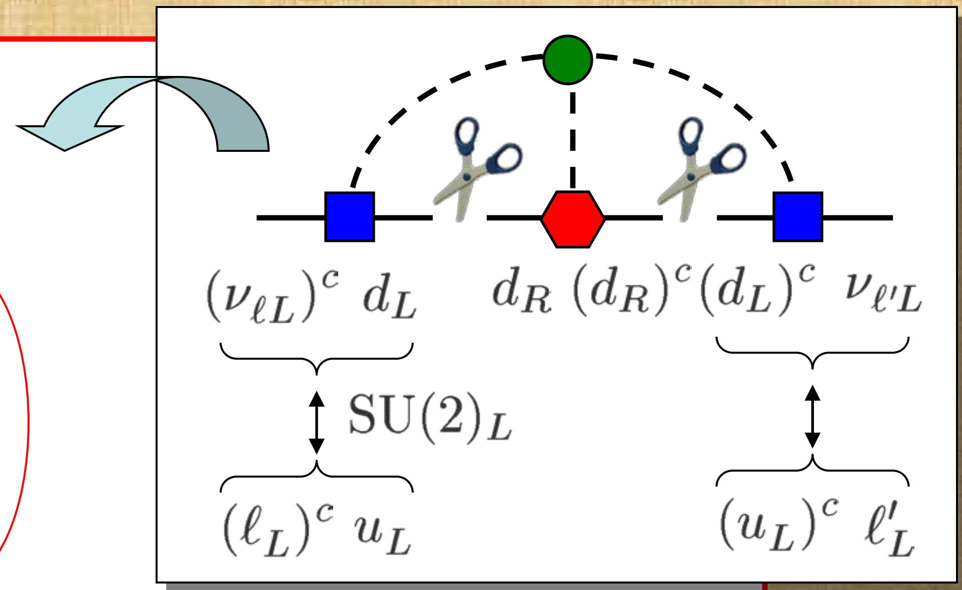
$\Rightarrow$ **Definite total L# of final states**

$\Downarrow$

Evidence for L#V

$pp \to \ell^- \ell'^- jj$ **without missing**



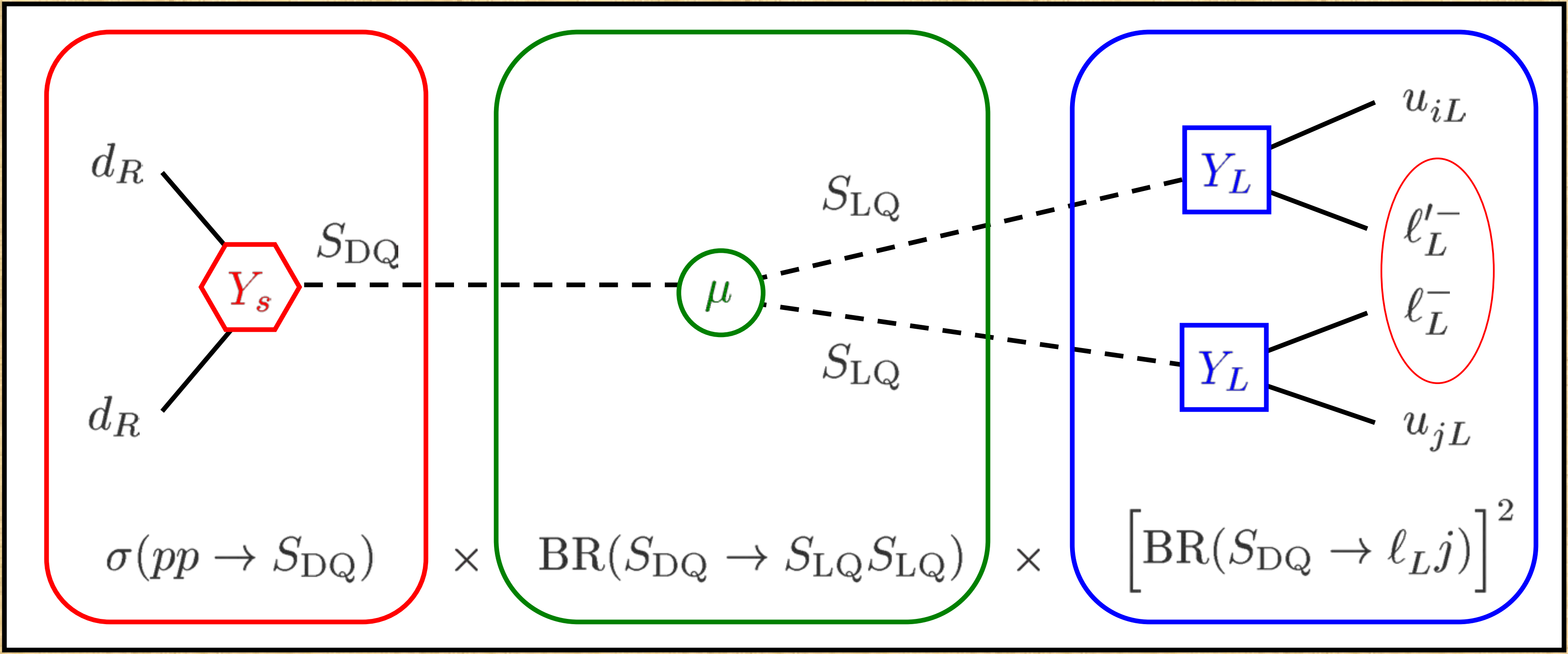


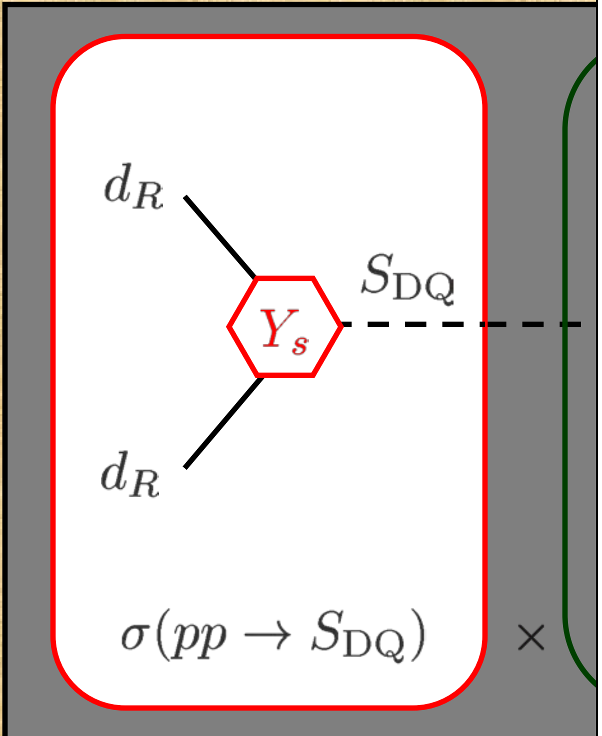
L#V $\Rightarrow$ **No SM process in principle**

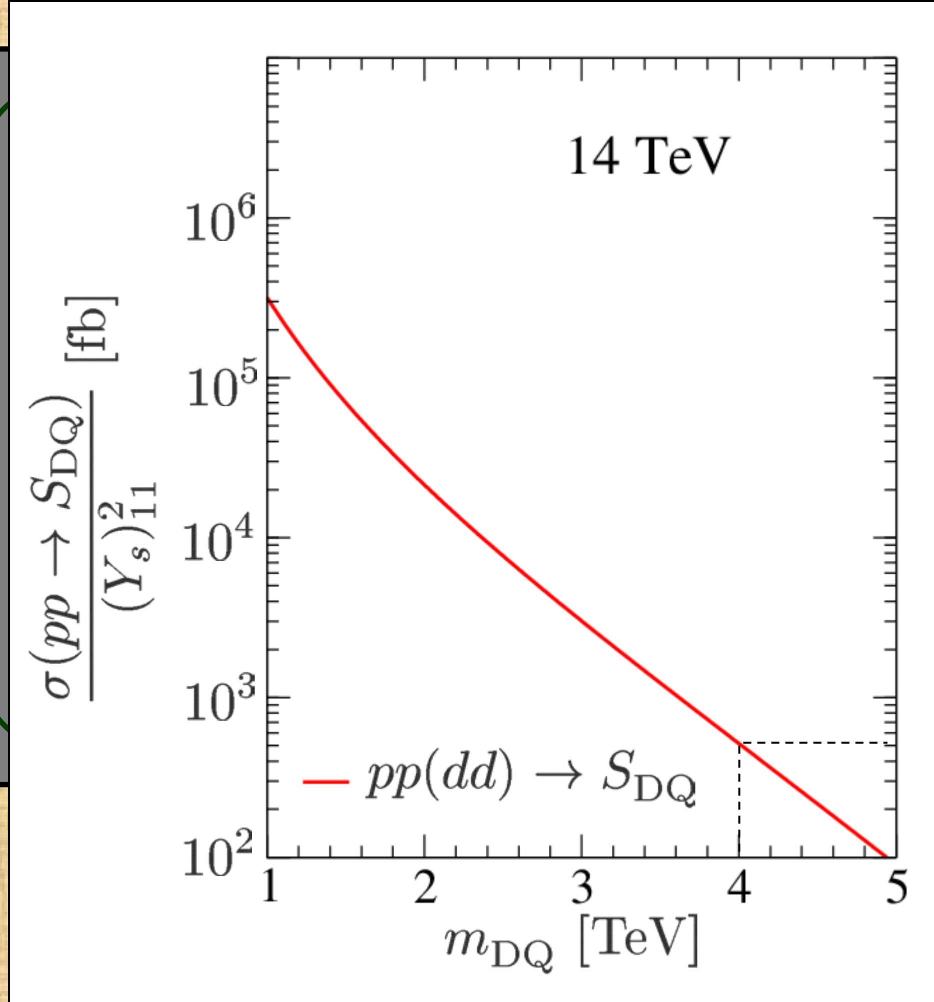
Hard ℓ_L^- $(\sim \text{TeV})$ $\Rightarrow$ **No mimic event in SM**

$\Downarrow$

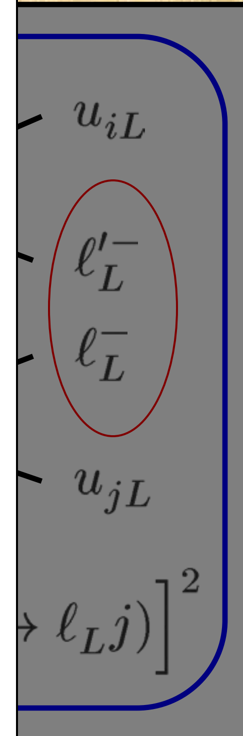
<u>Clear</u> evidence for L#V


d_R
d_R
Y_s
$S_{\rm DQ}$
μ
$S_{\rm LQ}$
$S_{\rm LQ}$
Y_L
Y_L
u_{iL}
ℓ'^-_L
ℓ^-_L
u_{jL}
$\sigma(pp \to S_{\rm DQ})$
$\times$
$\mathrm{BR}(S_{\rm DQ} \to S_{\rm LQ} S_{\rm LQ})$
$\times$
$\left[\mathrm{BR}(S_{\rm DQ} \to \ell_L j)\right]^2$



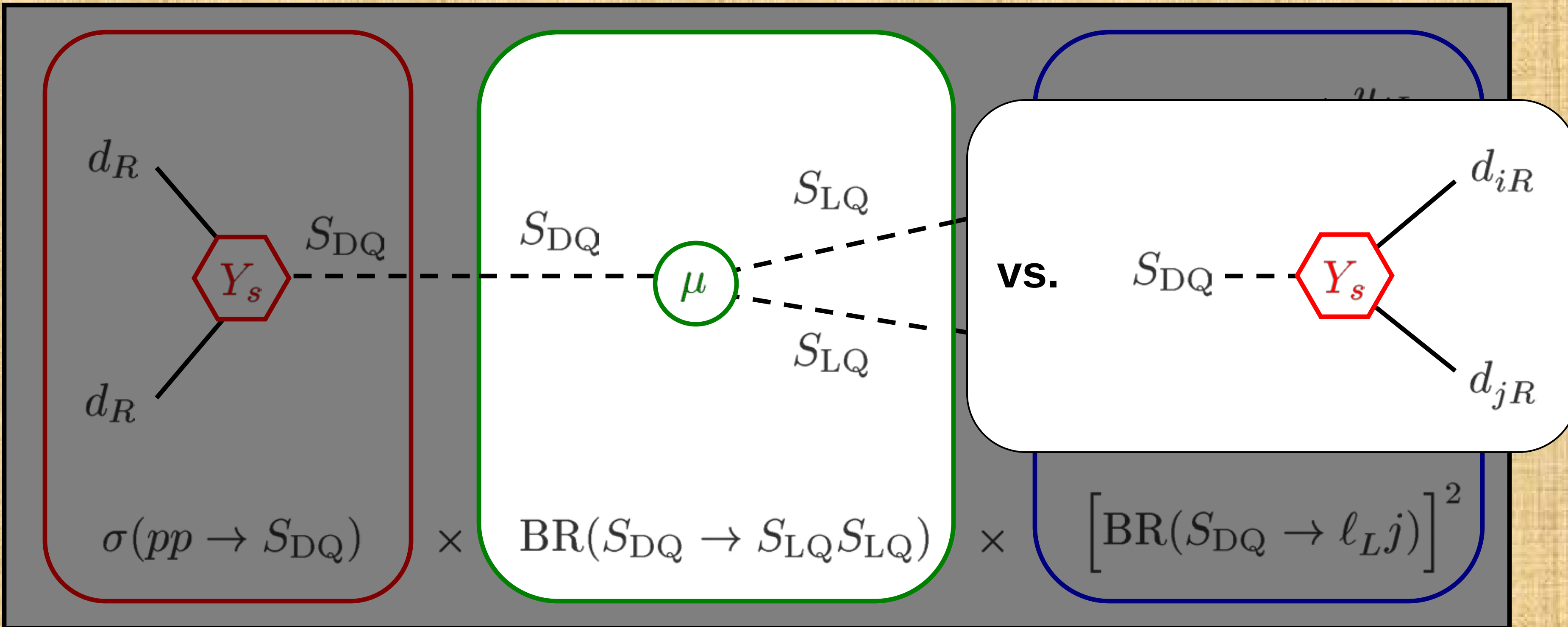


T. Han *et al.*, JHEP **1012**, 085 (2010)



$\sigma(pp \to S_{DQ}) \simeq 5\,\text{fb}$ **at** $\sqrt{s} = 14\,\text{TeV}$

for $(Y_s)_{11} = 0.1, m_{DQ} = 4\,\text{TeV}$



For fixed μ

- **Large** Y_s $\Longrightarrow$ **Good for** $\sigma(pp \to S_{\rm DQ})$ **&** **Bad for** ${\rm BR}(S_{\rm DQ} \to S_{\rm LQ} S_{\rm LQ})$
- **Small** Y_s $\Longrightarrow$ **Bad for** $\sigma(pp \to S_{\rm DQ})$ **&** **Good for** ${\rm BR}(S_{\rm DQ} \to S_{\rm LQ} S_{\rm LQ})$

$$\frac{\sum_{i,j} \Gamma(S_{\rm DQ} \to d_i d_j)}{\Gamma(S_{\rm DQ} \to S_{\rm LQ} S_{\rm LQ})} \simeq \frac{m_{\rm DQ}^2 {\rm tr}(Y_s Y_s^\dagger)}{\mu^2} = \mathcal{O}(0.1)\text{-}\mathcal{O}(1)$$ **is preferred**

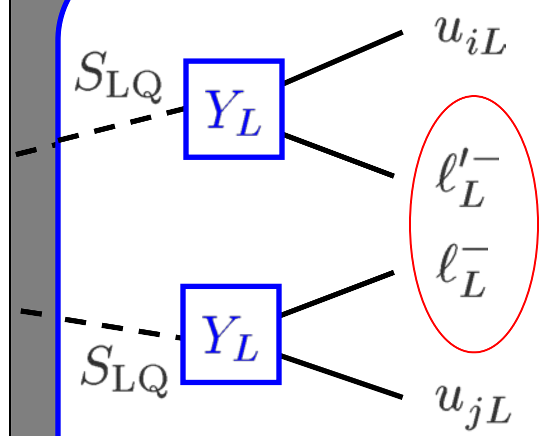
Benchmark point $\Longrightarrow$ 0.20 $\Longrightarrow$ ${\rm BR}(S_{\rm DQ} \to S_{\rm LQ} S_{\rm LQ}) = 84\,\%$

$\Gamma(S_{\rm LQ} \to \ell_L u_{iL}) \propto |(Y_L)_{\ell i}|^2$ **is small**

BUT $\Gamma_{\rm tot} \propto {\rm tr}(Y_L Y_L^\dagger)$ **is also small.**

$\Downarrow$

Sizable ${\rm BR}(S_{\rm DQ} \to \ell_L j)$



$\sigma(pp \to S_{\rm DQ}) \times {\rm BR}(S_{\rm DQ} \to S_{\rm LQ} S_{\rm LQ}) \times \left[{\rm BR}(S_{\rm DQ} \to \ell_L j)\right]^2$

@ Benchmark point

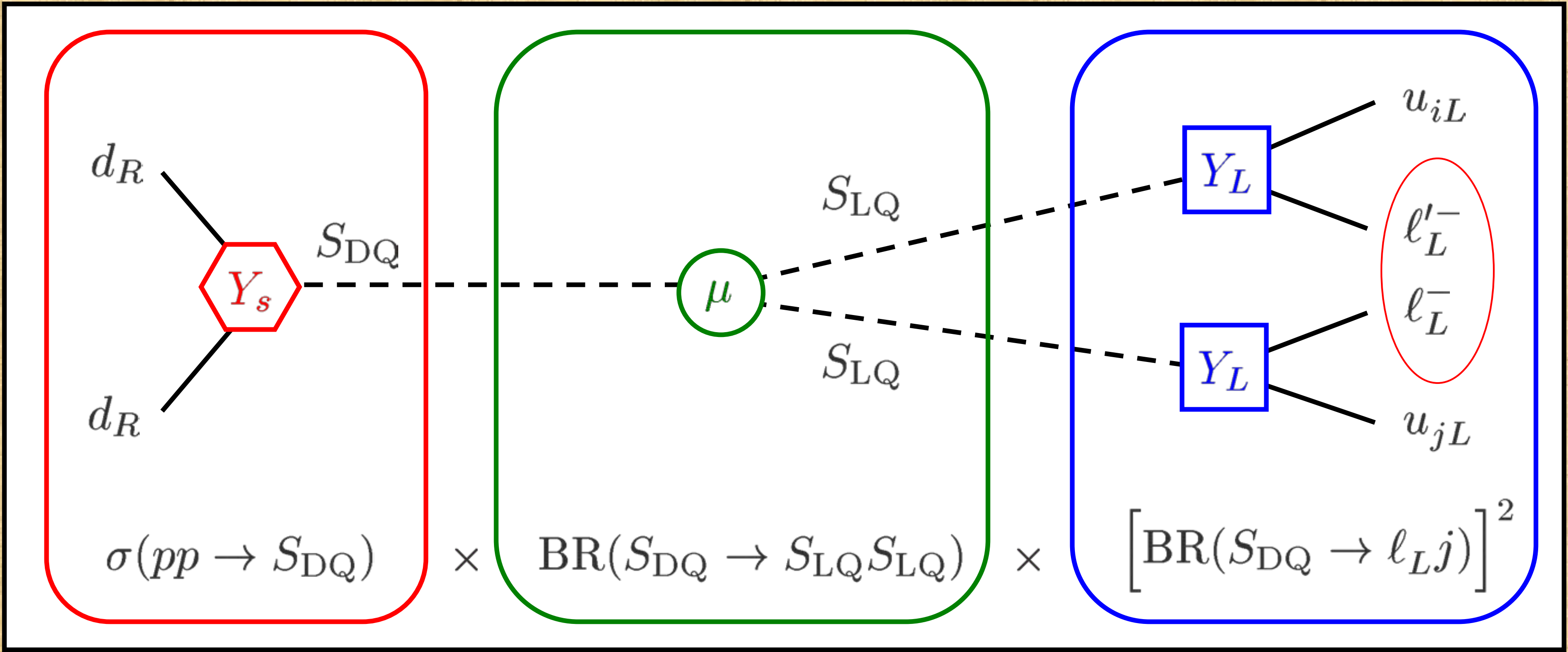
$$
{\rm BR} \simeq \begin{array}{c} e(\nu_e) \\ \mu(\nu_\mu) \\ \tau(\nu_\tau) \end{array}
\overset{\begin{array}{ccc} u(d) & c(s) & t(b) \end{array}}{\begin{pmatrix} 3.3\times10^{-7} & 6.0\times10^{-2} & 1.6\times10^{-3} \\ 1.2\times10^{-7} & 1.0\times10^{-1} & 6.2\times10^{-2} \\ 4.7\times10^{-6} & 1.9\times10^{-2} & 2.6\times10^{-1} \end{pmatrix}}
$$

$6\,\%\ t \longrightarrow \times 68\,\%\ bjj$ **w/o missing**

$16\,\%\ \ell j$ **w/o missing**

$28\,\%\ \tau$ **w/ missing**

($50\,\%\ \ell u_i + 50\,\%\ \nu_\ell d_i$ **)**



Benchmark point & LHC with $\sqrt{s} = 14\,\mathrm{TeV}$

$$\sigma(pp \to \ell^- \ell'^- + \mathrm{jets} + \textbf{no missing})$$

$$\simeq 5\,[\mathrm{fb}] \times 84\,\% \times (16\,\% + 6\,\% \times 68\,\%)^2 \simeq 0.17\,[\mathrm{fb}]$$

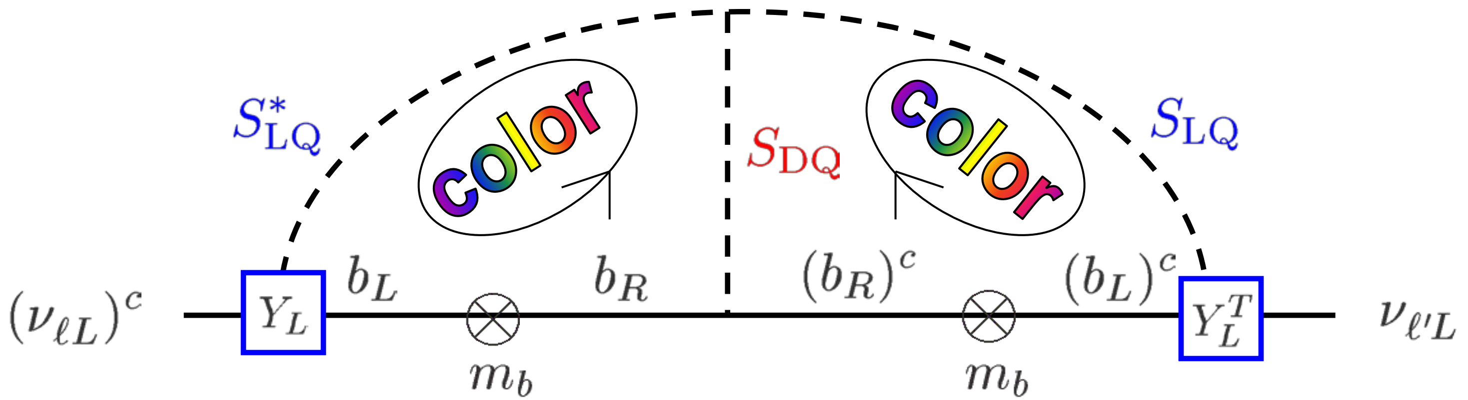
ℓj $\quad$ ℓbjj

$$\begin{cases} \ell\ell' jj \; (0.11\,[\mathrm{fb}]) \\ \ell\ell' bjjj \\ \ell\ell' bbjjjj \end{cases}$$

Summary

Colored Zee-Babu Model with Leptoquark and Diquark

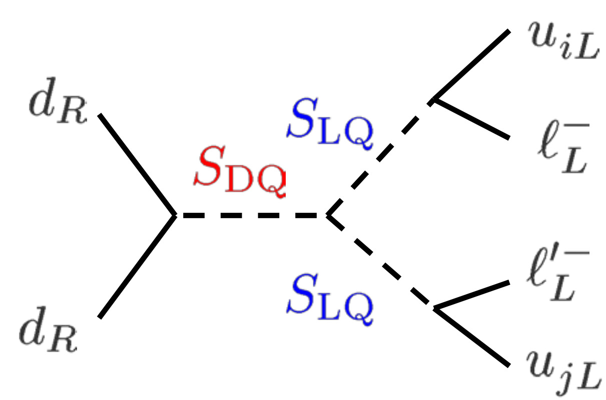
Suppressed neutrino mass (two-loop, $(m_b/m_{\rm DQ})^2$, Y_L^2)



Unsuppressed L#V process at the LHC

$pp \to \ell^- \ell'^- jj$ **without missing**

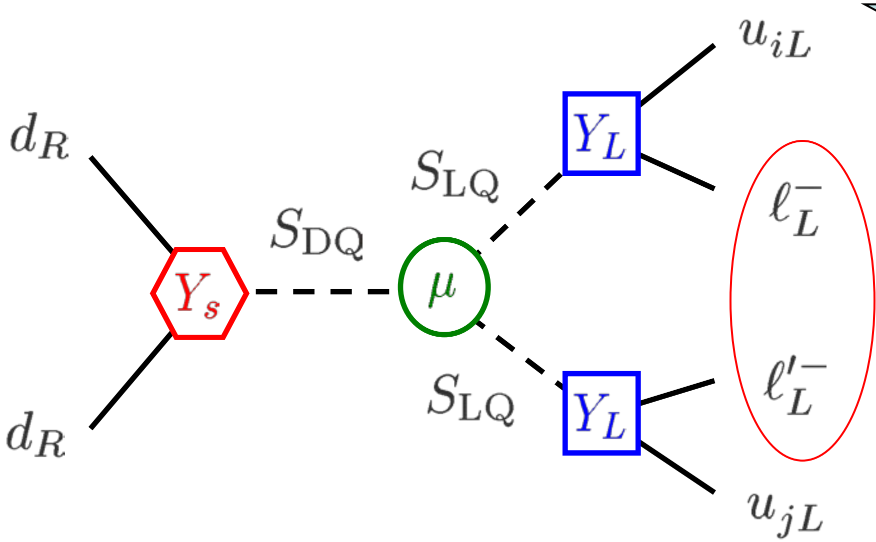
$$\sigma(pp \to S_{\rm DQ}) \times {\rm BR}(S_{\rm DQ} \to S_{\rm LQ} S_{\rm LQ}) \times \left[{\rm BR}(S_{\rm DQ} \to \ell_L j)\right]^2$$

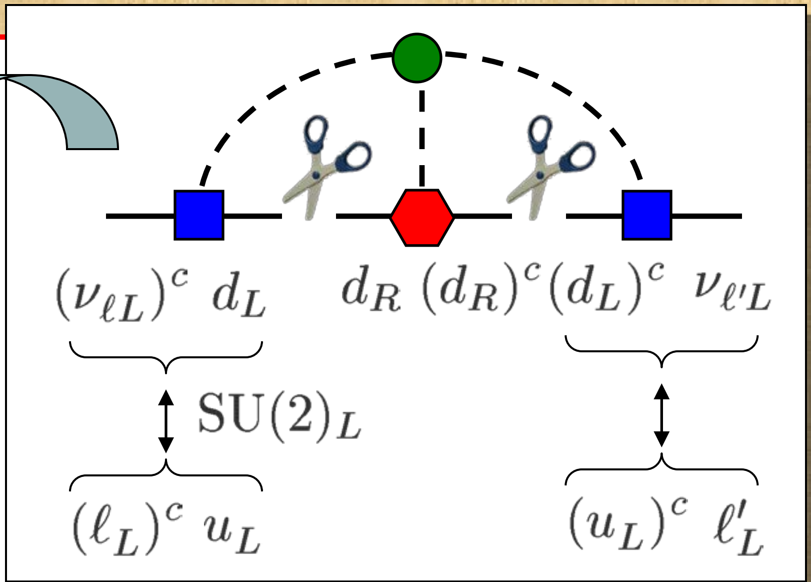


Backup

L#V Process at the LHC

$pp \to \ell^- \ell'^- jj$ **without missing**





$\sim 1\,\mathrm{fb}$ **at** $\sqrt{s} = 7\,\mathrm{TeV}$
for $Y_s \sim 0.1, m_{\rm DQ} \simeq 4\,\mathrm{TeV}$

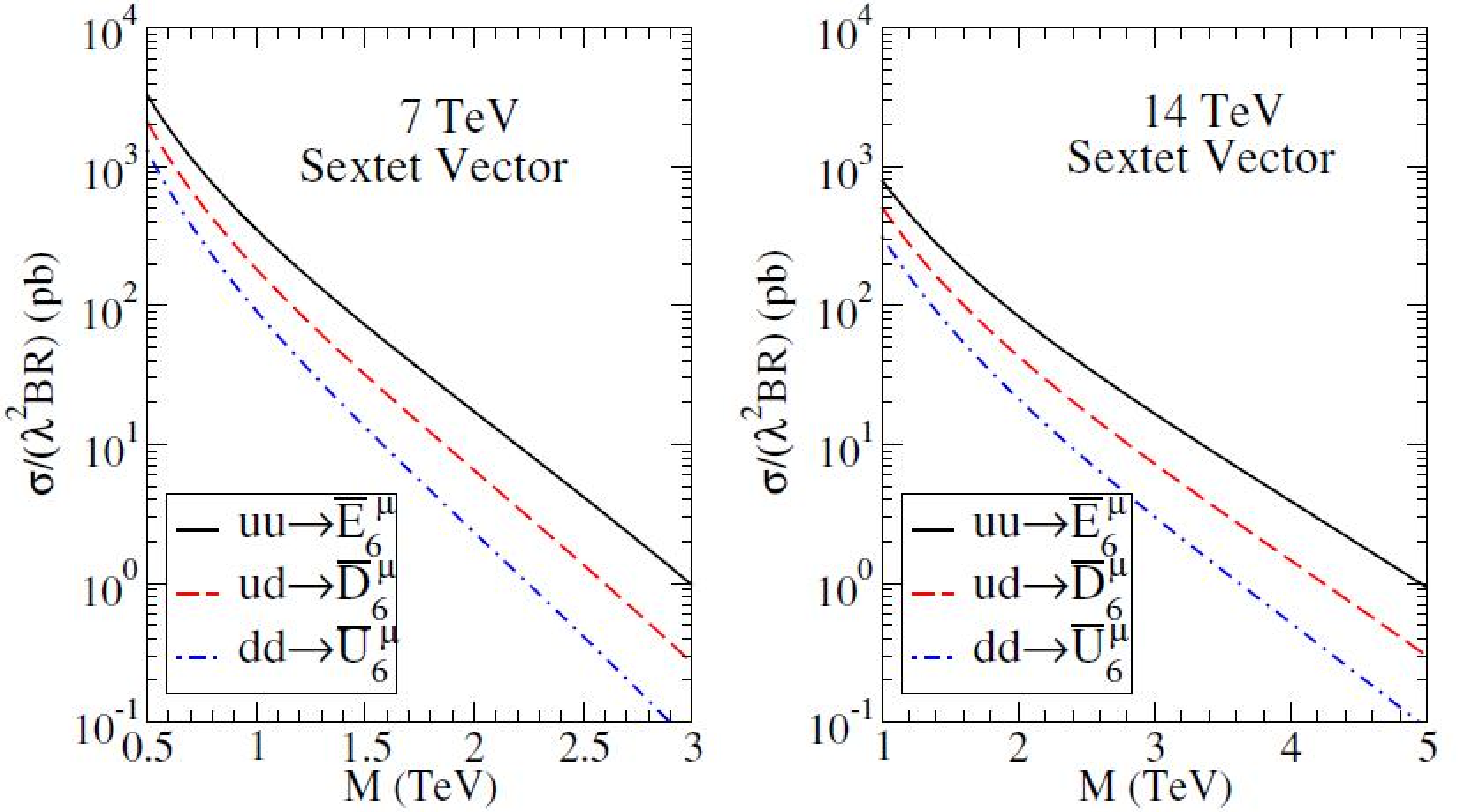
$\left[\mathcal{O}(0.1)\right]^2$ **even for** $Y_L \ll 1$

$$\sigma(pp \to S_{\rm DQ}) \times \mathrm{BR}(S_{\rm DQ} \to S_{\rm LQ} S_{\rm LQ}) \times \left[\mathrm{BR}(S_{\rm DQ} \to \ell_L j)\right]^2$$

$\mathcal{O}(1)$ **for** $\dfrac{\sum_{i,j} \Gamma(S_{\rm DQ} \to d_i d_j)}{\Gamma(S_{\rm DQ} \to S_{\rm LQ} S_{\rm LQ})} \simeq \dfrac{m_{\rm DQ}^2 \mathrm{tr}(Y_s Y_s^\dagger)}{\mu^2} \lesssim 1$

Production Cross Section

$$\sigma(\text{scalar}) = \frac{1}{2}\,\sigma(\text{vector})$$



T. Han, I. Lewis, and Z. Liu, JHEP **1012**, 085 (2010)

Bounds on Masses

Leptoquark mass (for $\mathrm{BR}(S_{\mathrm{LQ}} \to \ell u) = \mathrm{BR}(S_{\mathrm{LQ}} \to \nu d) = 50\,\%$)

CMS : $\sqrt{s} = 7\,\mathrm{TeV},\ 5.0\,\mathrm{fb}^{-1}$ PRD**86**, 052013 (2012)

$$pp \to S_{\mathrm{LQ}} S^*_{\mathrm{LQ}} \to e\bar{e}jj,\ e\bar{\nu}jj \ \Longrightarrow\ m_{\mathrm{LQ}} > 640\,\mathrm{GeV}(95\%\mathrm{CL})$$

$$pp \to S_{\mathrm{LQ}} S^*_{\mathrm{LQ}} \to \mu\bar{\mu}jj,\ \mu\bar{\nu}jj \ \Longrightarrow\ m_{\mathrm{LQ}} > 650\,\mathrm{GeV}(95\%\mathrm{CL})$$

ATLAS : $\sqrt{s} = 7\,\mathrm{TeV},\ 1.03\,\mathrm{fb}^{-1}$ PLB**709**, 158 (2012)

$$pp \to S_{\mathrm{LQ}} S^*_{\mathrm{LQ}} \to e\bar{e}jj,\ e\bar{\nu}jj \ \Longrightarrow\ m_{\mathrm{LQ}} > 607\,\mathrm{GeV}(95\%\mathrm{CL})$$

$\sqrt{s} = 7\,\mathrm{TeV},\ 1.03\,\mathrm{fb}^{-1}$ EPJC**72**, 2151 (2012)

$$pp \to S_{\mathrm{LQ}} S^*_{\mathrm{LQ}} \to \mu\bar{\mu}jj,\ \mu\bar{\nu}jj \ \Longrightarrow\ m_{\mathrm{LQ}} > 594\,\mathrm{GeV}(95\%\mathrm{CL})$$

Diquark mass

No analysis for $Y = -2/3\ (dd \to S_{\mathrm{DQ}})$

cf. CMS : $\sqrt{s} = 8\,\mathrm{TeV},\ 4.0\,\mathrm{fb}^{-1}$ arXiv:1302.4794

$$pp \to S_{\mathrm{DQ}} \to jj \ \Longrightarrow\ m_{\mathrm{DQ}} > 4.28\,\mathrm{TeV}(95\%\mathrm{CL})$$

$$(Y = 1/3,\ ud \to S_{\mathrm{DQ}})$$

Bounds on Masses

Leptoquark mass

CMS : $\sqrt{s} = 7\,\mathrm{TeV},\ 5.0\,\mathrm{fb}^{-1}$ PRD**86**, 052013 (2012)

$$pp \to S_{\mathrm{LQ}} S^*_{\mathrm{LQ}} \to e\bar{e}jj,\ e\bar{\nu}jj \implies m_{\mathrm{LQ}} > 640\,\mathrm{GeV}(95\%\mathrm{CL})$$
$$pp \to S_{\mathrm{LQ}} S^*_{\mathrm{LQ}} \to \mu\bar{\mu}jj,\ \mu\bar{\nu}jj \implies m_{\mathrm{LQ}} > 650\,\mathrm{GeV}(95\%\mathrm{CL})$$
$$(\mathrm{BR}(S_{\mathrm{LQ}} \to \ell u) = \mathrm{BR}(S_{\mathrm{LQ}} \to \nu d) = 50\,\%)$$

$$pp \to S_{\mathrm{LQ}} S^*_{\mathrm{LQ}} \to e\bar{e}jj \implies m_{\mathrm{LQ}} > 830\,\mathrm{GeV}(95\%\mathrm{CL})$$
$$pp \to S_{\mathrm{LQ}} S^*_{\mathrm{LQ}} \to \mu\bar{\mu}jj \implies m_{\mathrm{LQ}} > 840\,\mathrm{GeV}(95\%\mathrm{CL})$$
$$(\mathrm{BR}(S_{\mathrm{LQ}} \to \ell q) = 100\,\%)$$

$\sqrt{s} = 7\,\mathrm{TeV},\ 4.7\,\mathrm{fb}^{-1}$ JHEP**1212**, 055 (2012)

$$pp \to S_{\mathrm{LQ}} S^*_{\mathrm{LQ}} \to \nu\bar{\nu}j_b j_b \implies m_{\mathrm{LQ}} > 450\,\mathrm{GeV}(95\%\mathrm{CL})$$
$$(\mathrm{BR}(S_{\mathrm{LQ}} \to \nu b) = 100\,\%)$$

$\sqrt{s} = 7\,\mathrm{TeV},\ 4.8\,\mathrm{fb}^{-1}$ arXiv:1210.5629

$$pp \to S_{\mathrm{LQ}} S^*_{\mathrm{LQ}} \to \tau\bar{\tau}j_b j_b \implies m_{\mathrm{LQ}} > 525\,\mathrm{GeV}(95\%\mathrm{CL})$$
$$(Y = -4/3)$$

Bounds on Masses

Leptoquark mass

ATLAS : $\sqrt{s} = 7\,\mathrm{TeV},\ 1.03\,\mathrm{fb}^{-1}$ PLB**709**, 158 (2012)

$$pp \to S_{\mathrm{LQ}} S^*_{\mathrm{LQ}} \to e\bar{e}jj,\ e\bar{\nu}jj \quad \Longrightarrow m_{\mathrm{LQ}} > 607\,\mathrm{GeV}(95\%\mathrm{CL})$$

$$(\mathrm{BR}(S_{\mathrm{LQ}} \to eu) = \mathrm{BR}(S_{\mathrm{LQ}} \to \nu d) = 50\,\%)$$

$$\left[pp \to S_{\mathrm{LQ}} S^*_{\mathrm{LQ}} \to e\bar{e}jj \quad \Longrightarrow m_{\mathrm{LQ}} > 660\,\mathrm{GeV}(95\%\mathrm{CL}) \quad (\mathrm{BR}(S_{\mathrm{LQ}} \to eq) = 100\,\%) \right]$$

$\sqrt{s} = 7\,\mathrm{TeV},\ 1.03\,\mathrm{fb}^{-1}$ EPJC**72**, 2151 (2012)

$$pp \to S_{\mathrm{LQ}} S^*_{\mathrm{LQ}} \to \mu\bar{\mu}jj,\ \mu\bar{\nu}jj \quad \Longrightarrow m_{\mathrm{LQ}} > 594\,\mathrm{GeV}(95\%\mathrm{CL})$$

$$(\mathrm{BR}(S_{\mathrm{LQ}} \to \mu u) = \mathrm{BR}(S_{\mathrm{LQ}} \to \nu d) = 50\,\%)$$

$$\left[pp \to S_{\mathrm{LQ}} S^*_{\mathrm{LQ}} \to \mu\bar{\mu}jj \quad \Longrightarrow m_{\mathrm{LQ}} > 685\,\mathrm{GeV}(95\%\mathrm{CL}) \quad (\mathrm{BR}(S_{\mathrm{LQ}} \to \mu q) = 100\,\%) \right]$$

Bounds on Masses

Diquark mass

No analysis for $Y = -2/3 \ (dd \to S_{\rm DQ})$

cf. CMS : $\sqrt{s} = 8\,{\rm TeV},\ 4.0\,{\rm fb}^{-1}$ arXiv:1302.4794

$$pp \to S_{\rm DQ} \to jj \implies m_{\rm DQ} > 4.28\,{\rm TeV}(95\%{\rm CL})$$

$$(Y = 1/3,\ ud \to S_{\rm DQ})$$

Constraints on New Yukawa Couplings

LQ Yukawa

M. Carpenter and S. Davidson, EPJC**70**, 1071 (2010)

$$\frac{(Y_L)_{e1}(Y_L^*)_{\mu 1}}{4\sqrt{2}G_F m_{\rm LQ}^2} \times 2\sqrt{2}G_F(\overline{e_L}\gamma^\mu \mu_L)(\overline{u_L}\gamma_\mu u_L)$$

Constraint : $< 8.5 \times 10^{-7}$ (90 % C.L.) **(** μ - e **conversion)**

Benchmark : 1.2×10^{-10}

$$\frac{(Y_L)_{\ell 1}(Y_L^*)_{\ell' 2}}{4\sqrt{2}G_F m_{\rm LQ}^2} \times 2\sqrt{2}G_F(\overline{\nu_{\ell L}}\gamma^\mu \nu_{\ell' L})(\overline{d_L}\gamma_\mu s_L)$$

Constraint : $< 9.4 \times 10^{-6}$ (90 % C.L.) **(** K **meson decay)**

Benchmark : $\lesssim 10^{-7}$

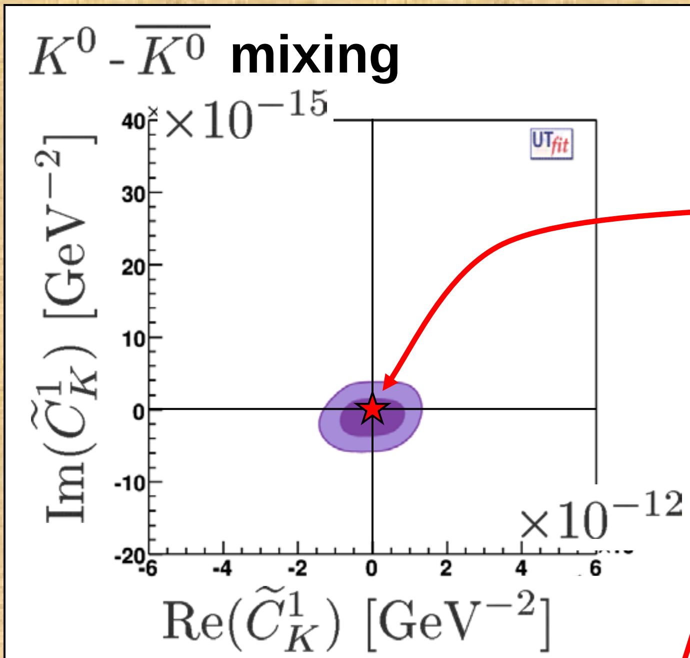
$$\mathrm{BR}(\mu \to e\gamma) = \frac{3\alpha_{\rm EM}}{256\pi G_F^2 m_{\rm LQ}^4}\left|(Y_L Y_L^\dagger)_{e\mu}\right|^2$$

Constraint : $< 2.4 \times 10^{-12}$ (90 % C.L.) MEG, PRL**107**, 171801 (2011)

$< 5.7 \times 10^{-13}$ (90 % C.L.) MEG, arXiv:1303.0754

Benchmark : 3.7×10^{-13}

DQ Yukawa   UTfit, JHEP**0803**, 049 (2008)

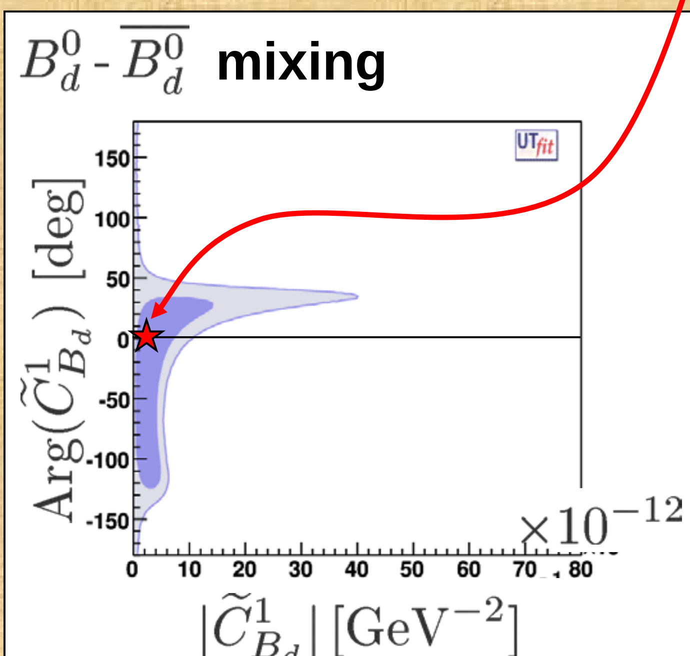


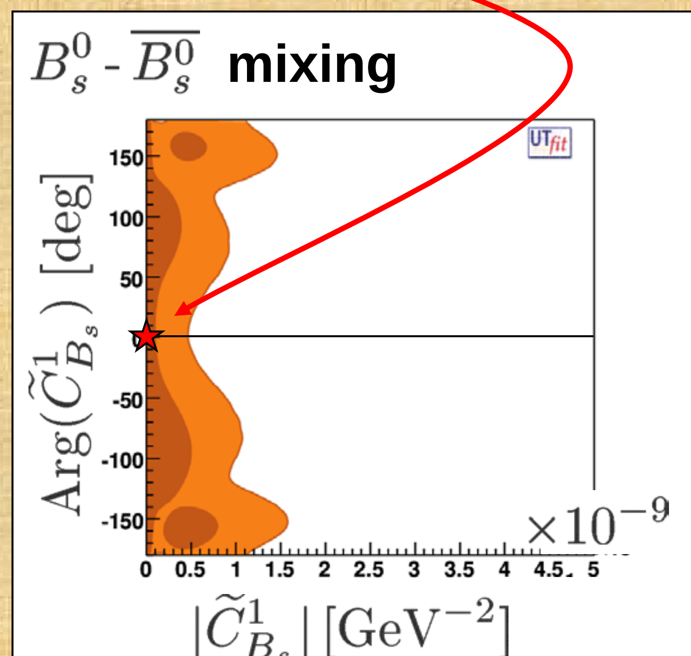
Benchmark point

$$\widetilde{C}_K^1 = -\frac{(Y_s^*)_{11}(Y_s)_{22}}{2m_{\mathrm{DQ}}^2} = 0$$

$$\widetilde{C}_{B_d}^1 = -\frac{(Y_s^*)_{11}(Y_s)_{33}}{2m_{\mathrm{DQ}}^2} = +1.9 \times 10^{-12}\,[\mathrm{GeV}^{-2}]$$

$$\widetilde{C}_{B_s}^1 = -\frac{(Y_s^*)_{22}(Y_s)_{33}}{2m_{\mathrm{DQ}}^2} = 0$$





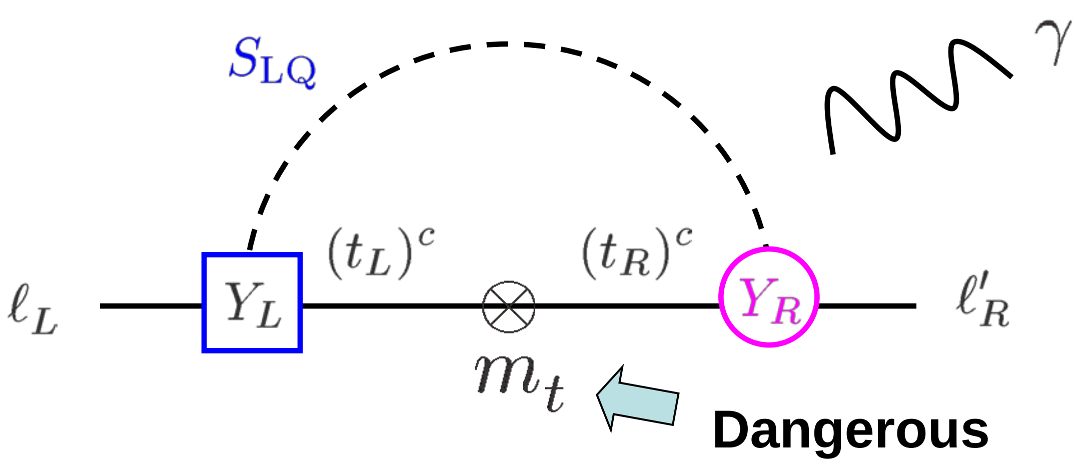
LFV

$$Q_i = \begin{pmatrix} u'_{iL} \\ d_{iL} \end{pmatrix} = \begin{pmatrix} [V^\dagger_{\rm CKM} u_L]_i \\ d_{iL} \end{pmatrix}$$

$$\mathcal{L}_{\rm Yukawa} = -\left\{ (Y_L)_{\ell i} \left[\overline{L^c_\ell}\, i\,\sigma_2\, Q^\alpha_i \right] + (Y_R)_{\ell i} \left[\overline{(\ell_R)^c}\, u'^{\alpha}_{iR} \right] \right\} (S^\alpha_{\rm LQ})^* - (Y_s)_{ij} \left[\overline{(d^\alpha_{iR})^c}\, d^\beta_{jR} (S^{\alpha\beta}_{\rm DQ})^* \right] + \text{H.c.}$$

We ignore Y_R .

No Y_R $\Longleftarrow$ Type-II or Type-X THDMs (u_{iR} or ℓ_R are Z_2- odd)
or $\mathrm{SU}(2)_L$- triplet Leptoquark



Neutrinoless Double Beta Decay

$$(M_\nu)_{ee} \equiv \left| m_1 (U_{\rm MNS})^2_{e1} + m_2 e^{i\alpha_{21}} (U_{\rm MNS})^2_{e2} + m_3 e^{i\alpha_{31}} (U_{\rm MNS})^2_{e3} \right|$$

$= 1.5 \times 10^{-3}\,\mathrm{eV}$ **@ Benchmark point**