Vector-like search at LHC using multi b-jet channel

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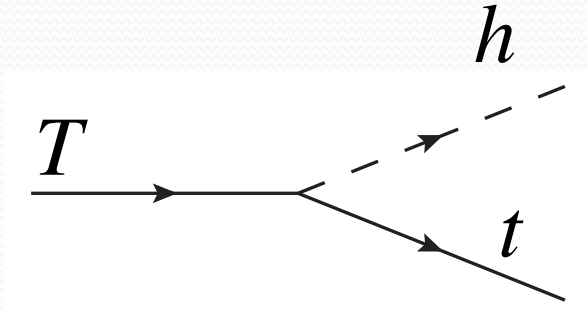
Abstract

Consider the vector-like quark T which mixes with top quark

(Top partner)

Decay mode 

is possible

Using multi-b channel, LHC's sensitivity is considerably improved!

Contents

1. Models including vector-like quark
2. Current status of the vector-like quark search
3. LHC prospect

1. Models including vector-like quark

Little Higgs model — Arkani-Hamed, Cohen, Georgi (2001)

MSSM+extra matter — Okada, Moroi (1992)
Kurosawa, Maru, Yanagida (2001)

Little Higgs model

Arkani-Hamed, Cohen, Georgi (2001)

How about dynamical EMSB?

Theory cut-off at scale Λ

Any operators should be generated

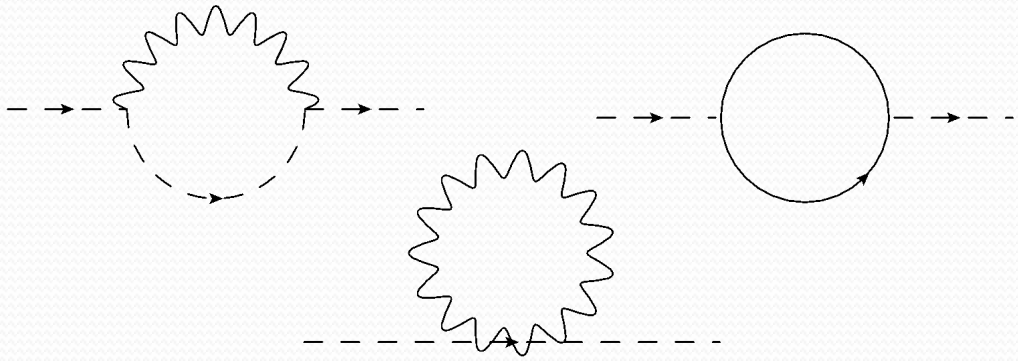
Note : operators like $\frac{1}{\Lambda^2}|H^\dagger D_\mu H|^2$ $\frac{1}{\Lambda^2}(H^\dagger \sigma^i H)W^i_{\mu\nu}B^{\mu\nu}$

conflict with the electroweak precise measurement

$\rightarrow$ $\Lambda > 9\ TeV$

Han, Skiba (2007)

Little hierarchy



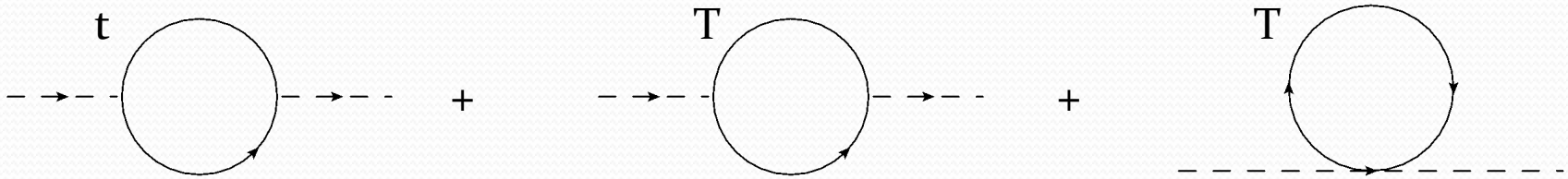
$$\propto \frac{\Lambda^2}{16\pi^2}$$

To avoid fine-tuning, $\Lambda \sim 4\pi m_Z \sim \mathrm{TeV}$

But $\Lambda > 9\ TeV$ Little Hierarchy problem

Solution: symmetry

Due to some symmetry, (depends on model)



$$= 0 \times \Lambda^2 + c_1 \times m_T^2 ln(\frac{\Lambda^2}{m_T^2})$$

(So do gauge sector)

MSSM+extra matter

Okada, Moroi (1992)
Kurosawa, Maru, Yanagida (2001)

MSSM

Super symmetric extension of 2HD Standard model

(later discovered) problem : Higgs is heavier than we thought!

$$m_{h^0} > 114.4\ \mathrm{GeV} > m_Z \quad \text{(LEP)}$$

Quantum correction can raise higgs mass

Raise SUSY breaking scale?

cf. $m_h = 124 - 126\mathrm{GeV}$?

Possible solution: extra matter

Some models contains
extra vector-like matter at low energy $U(3,2,\frac{1}{6}), Q(\bar{3},1,-\frac{2}{3}), \cdots$

$$W \supset yUQH_u$$

Enhance Higgs mass!

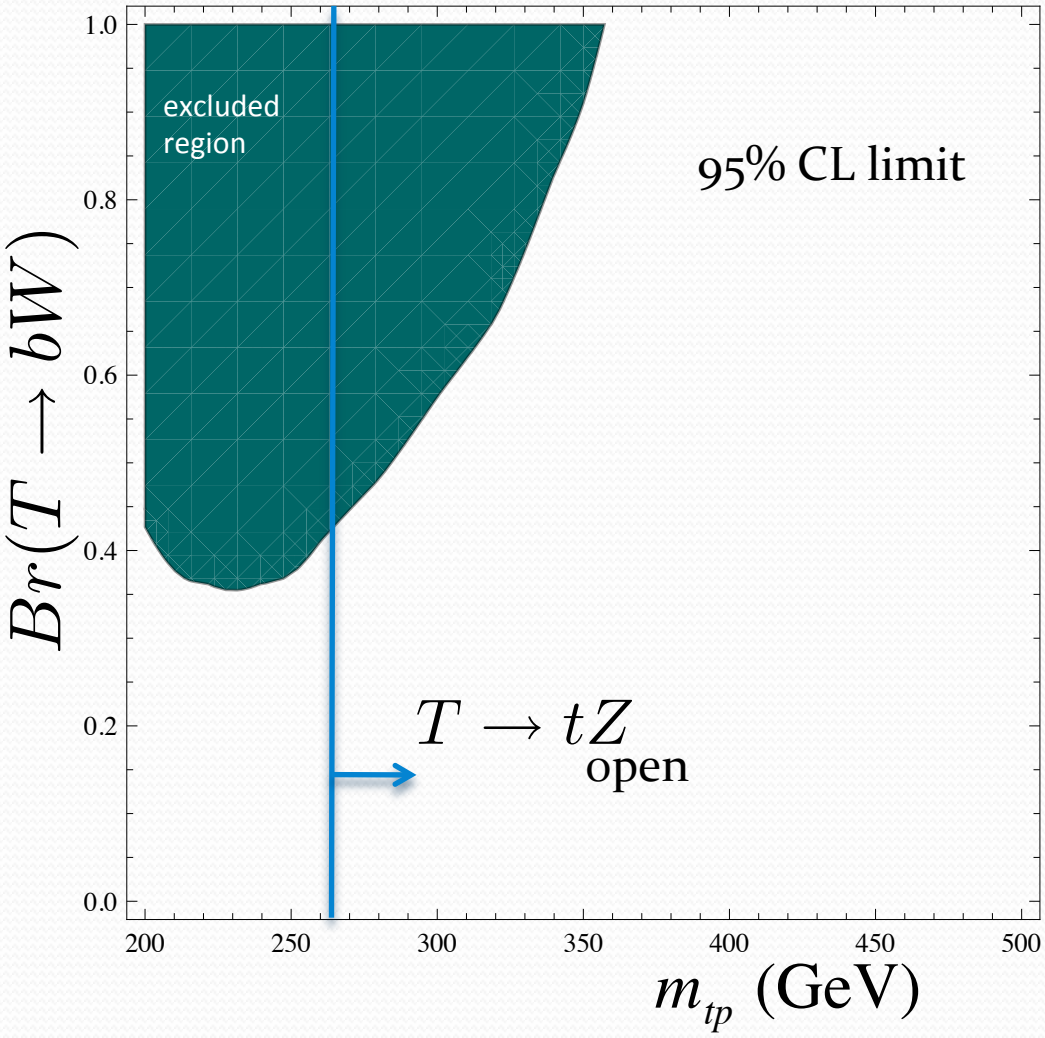
Added bonus : possible solution to muon $g-2$ even for $m_{h^0} = 125$ GeV

Endo, Hamaguchi, Iwamoto, Yokozaki (2011)

2. Current status of the vector-like quark search

Search for top partner mix with top quark

Constraints from CDF result



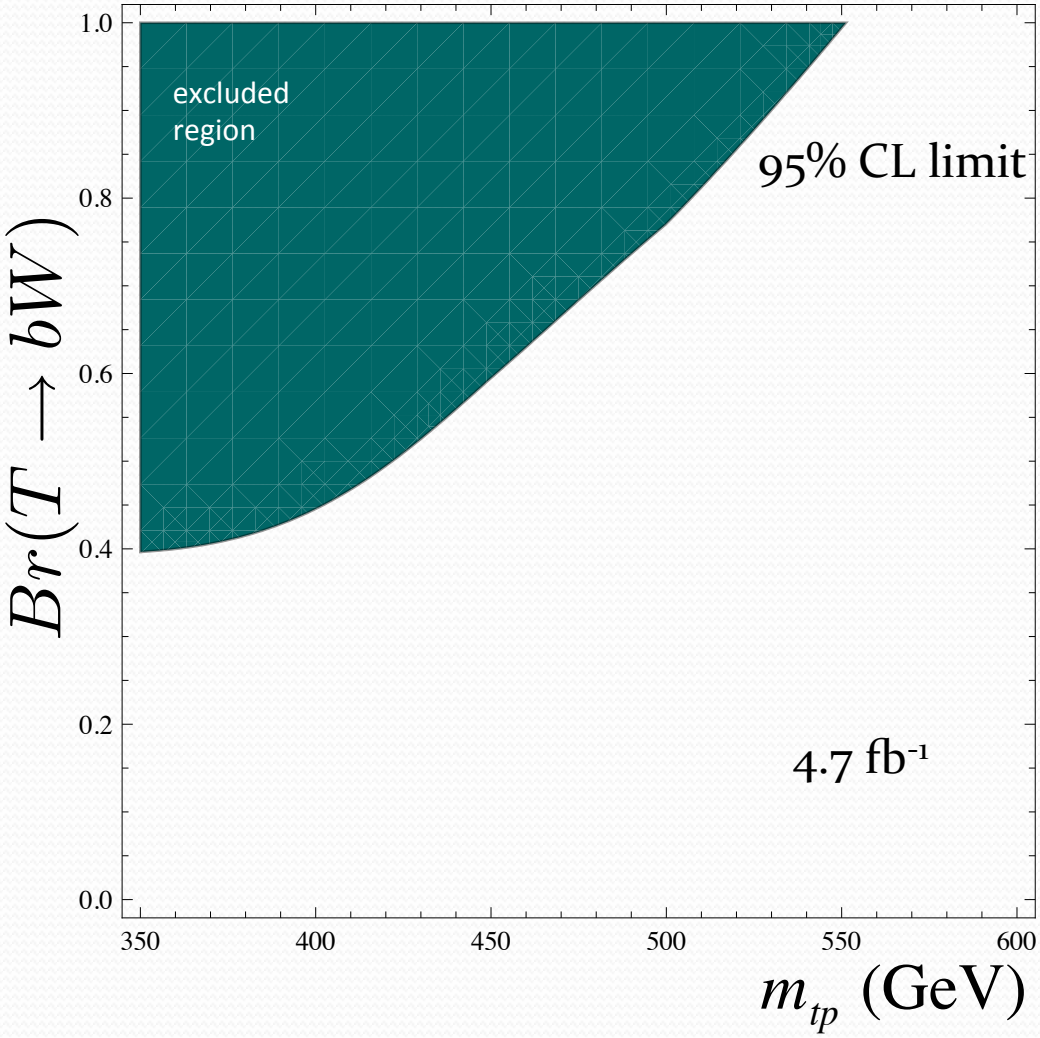
Assuming pair creation and

$$T \to bW$$

1-lepton, b-jet search

Picture: KH, Matsumoto, Nojiri, Tobioka(2012)

Constraints from CMS result



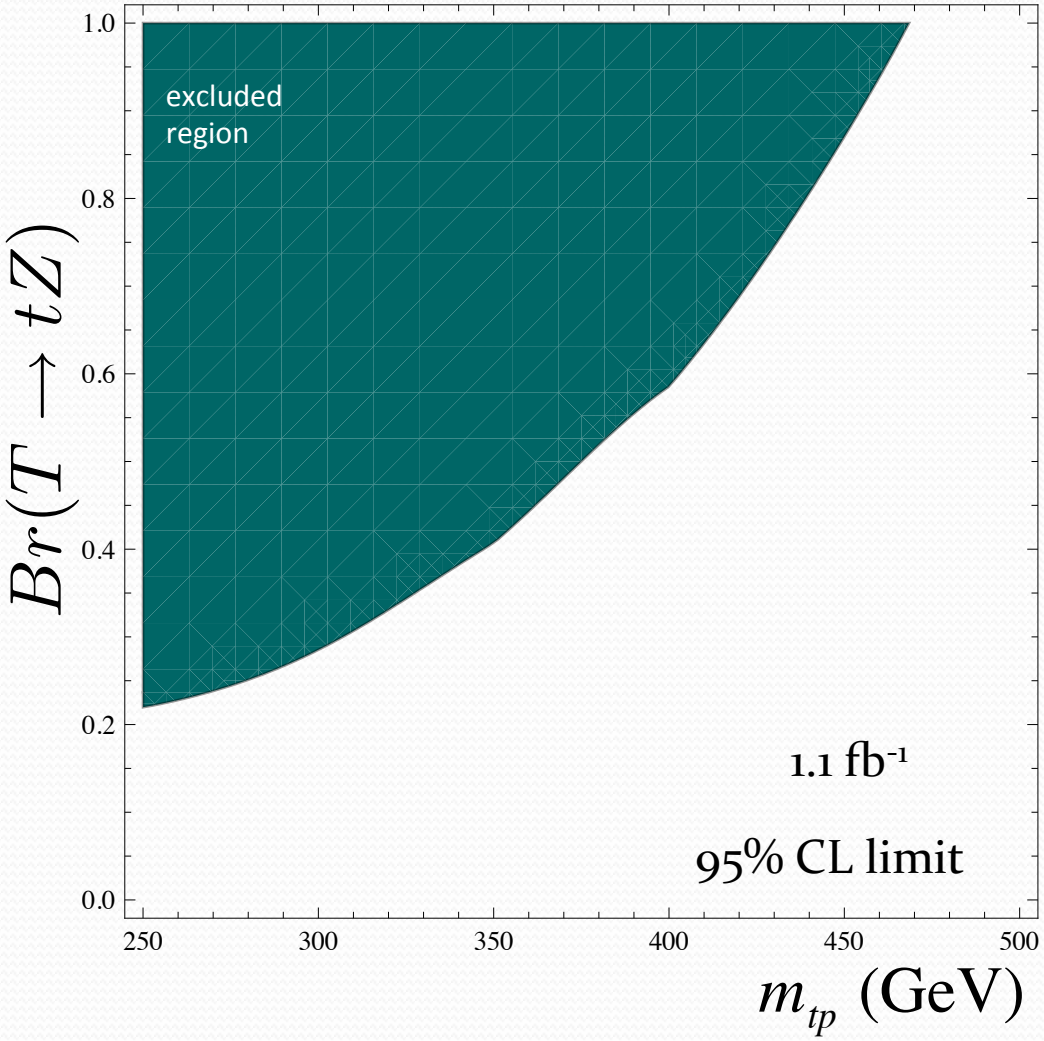
Assuming pair creation and

$$T \to bW$$

di-lepton

Picture: KH, Matsumoto, Nojiri, Tobioka(2012)

Constraints from CMS result



Assuming pair creation and

$$T \to tZ$$

$$Z \to l^+ l^-,$$

1 isolated lepton

Picture: KH, Matsumoto, Nojiri, Tobioka(2012)

3. LHC prospect

Concentrate on $bW,\ \ th$

Tools and assumptions

- Madgraph5
- Pythia
- Delphes
- ATLAS's object reconstruction method
- $m_h = 120$ GeV, $\sqrt{s} = 7$ TeV

For b-tagging,
SV050 method
b-tag efficiency ~ 0.6
mis-tag rate ~ 0.01
at high-pt

1-lepton + 1,2 b-jet

Imitating and modifying CMS's search

- Aim at $T\bar{T} \rightarrow bW^{+}\bar{b}W^{-}$
- Expect very hard b-jet
- W decay -> lepton, missing, jets
- Try to reconstruct the mass

$$\chi^2 = \left(\frac{m_{lv} - m_W}{\Delta m_{lv}}\right)^2 + \left(\frac{m_{jj} - m_W}{\Delta m_{jj}}\right)^2 + \left(\frac{m_{lvb} - m_{jjb}}{\sqrt{(\Delta m_{lvb})^2 + (\Delta m_{jjb})^2}}\right)^2$$

$$M_{fit} = min(m_{lvb}, m_{jjb})$$

Event selection

- Exactly 1 isolated lepton with pt > 30 GeV
- $\not{E}_T > 20$ GeV
- $\geqq 4$ isolated jets and 1 or 2 of them are b-jets
- The jets have pt > 80, 50, 30 GeV
- The leading b-jet has pt > 240 GeV
- $M_{fit} > 350$ GeV
- $M_{eff} > 950$ GeV

Cut flow

For 10 fb^{-1} data, $m_{tp} = 500$ GeV,

pt-jet > 70, 40 GeV, leptonic decay

	$t\bar{t}$ +jets	W + jets	$T\bar{T} \to bWbW$	$T\bar{T} \to bWth$	$T\bar{T} \to thth$
Generated	1624715	669280	60000	60000	60000
Normalized	1660000	2400000	3300	3300	3300
lepton, missing, 4jets, b-jets	149261	7394	571	527	410
jet pt	6912	2930	500	500	400
b-jet pt	1206	215	203	131	46
fitted mass	394	129	148	58	17
effective mass	216	61	113	41	14
acceptance	0.00013	0.000025	0.034	0.012	0.041

KH, Matsumoto, Nojiri, Tobioka(2012)

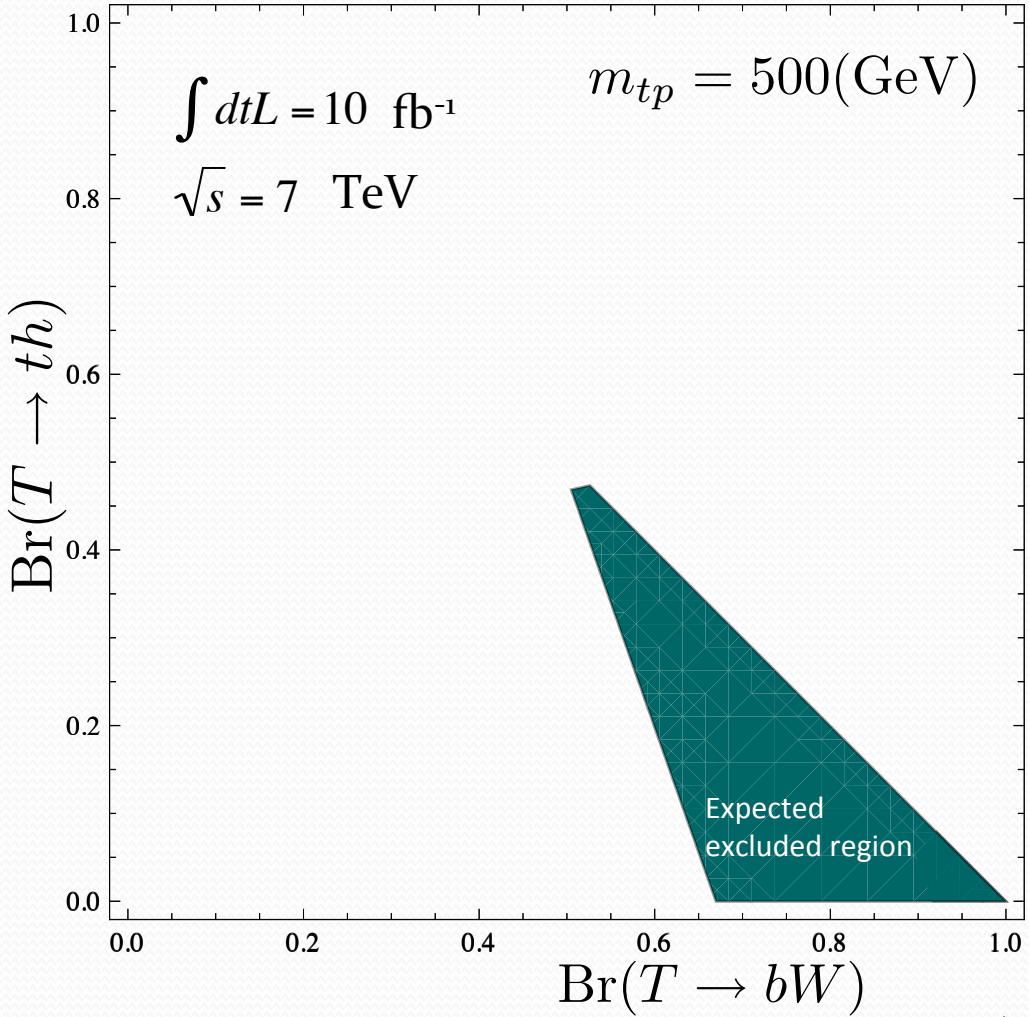
LHC's sensitivity

Expected 95 % CL excluded region if no excess

(cross section / pb)
×
(acceptance)

> 0.0050

0.0059(0.0094) when 10(20) % uncertainty
in $t\bar{t}$ background acceptance
times cross section



KH, Matsumoto, Nojiri, Tobioka(2012)

1-lepton + ≧3 b-jet

- Aim at $T\bar{T} \rightarrow bWth$ or $thth$
- Expect many hard b-jet
- W decay -> lepton, missing, jets

Event selection

- Exactly 1 isolated lepton with pt > 30 GeV
- $\not{E}_T > 20$ GeV
- $\geqq 5$ isolated jets and more than 2 of them are b-jets
- The b-jets have pt > 130, 70, 40 GeV
- $M_{eff} > 800$ GeV

Cut flow

For 10 fb^{-1} data, $m_{tp} = 500$ GeV,

ptb-jet > 20GeV

	$t\bar{t}$ +jets	$t\bar{t}b\bar{b}$	$T\bar{T} \to bWbW$	$T\bar{T} \to bWth$	$T\bar{T} \to thth$
generated	1624725	90000	60000	60000	60000
Normalized	1660000	9600	3300	3300	3300
lepton, missing, 5jets, b-jets	2949	233	31	178	302
b-jets pt	268	41	21	109	168
effective mass	60	9	18	83	102
acceptance	0.000036	0.00091	0.0054	0.025	0.031

KH, Matsumoto, Nojiri, Tobioka(2012)

W +jets, $Wb\bar{b}$ +jets : negligible

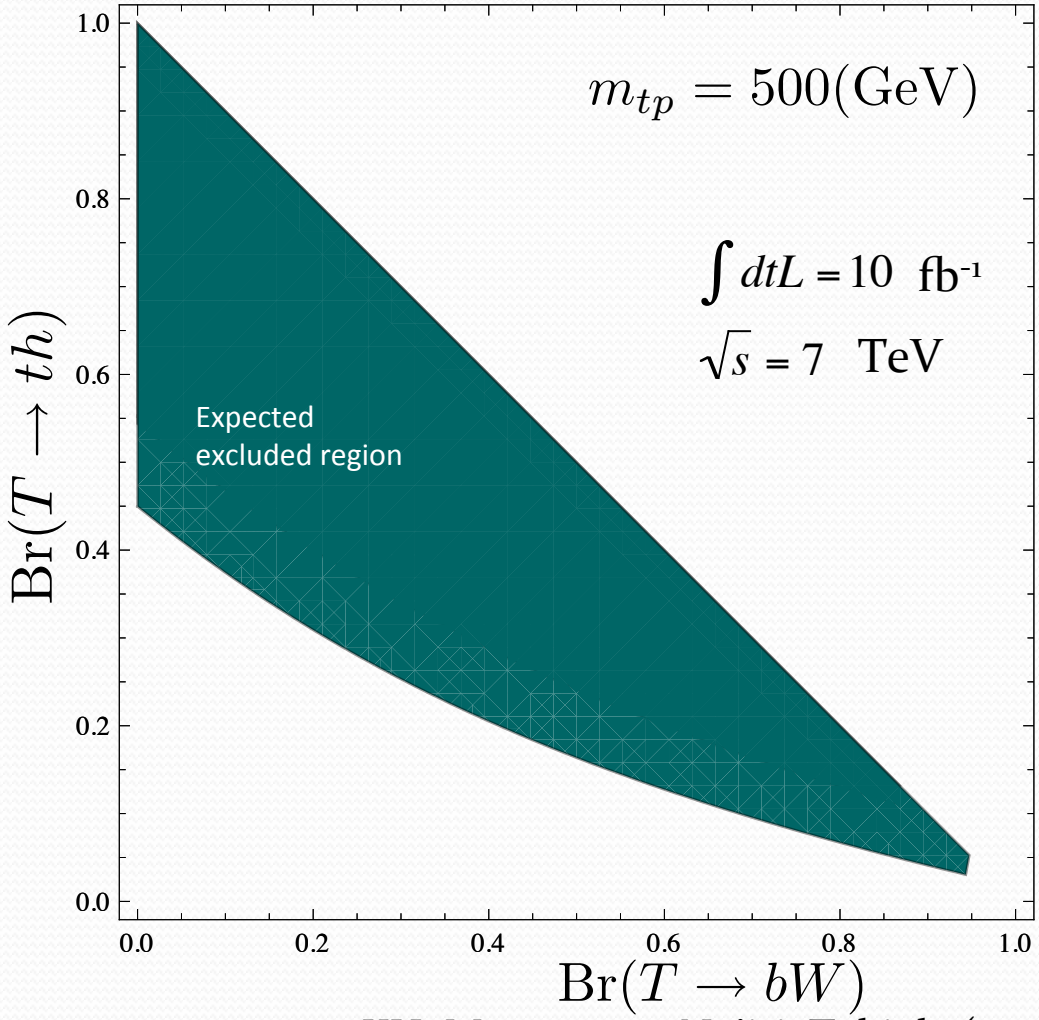
LHC's sensitivity

Expected 95 % CL excluded region if no excess with 10 fb^{-1} data

(cross section / pb)
×
(acceptance)

> 0.0021

0.0024(0.0030) when 12(20) %
Uncertainty in $t\bar{t}$ background
acceptance times cross section



KH, Matsumoto, Nojiri, Tobioka(2012)

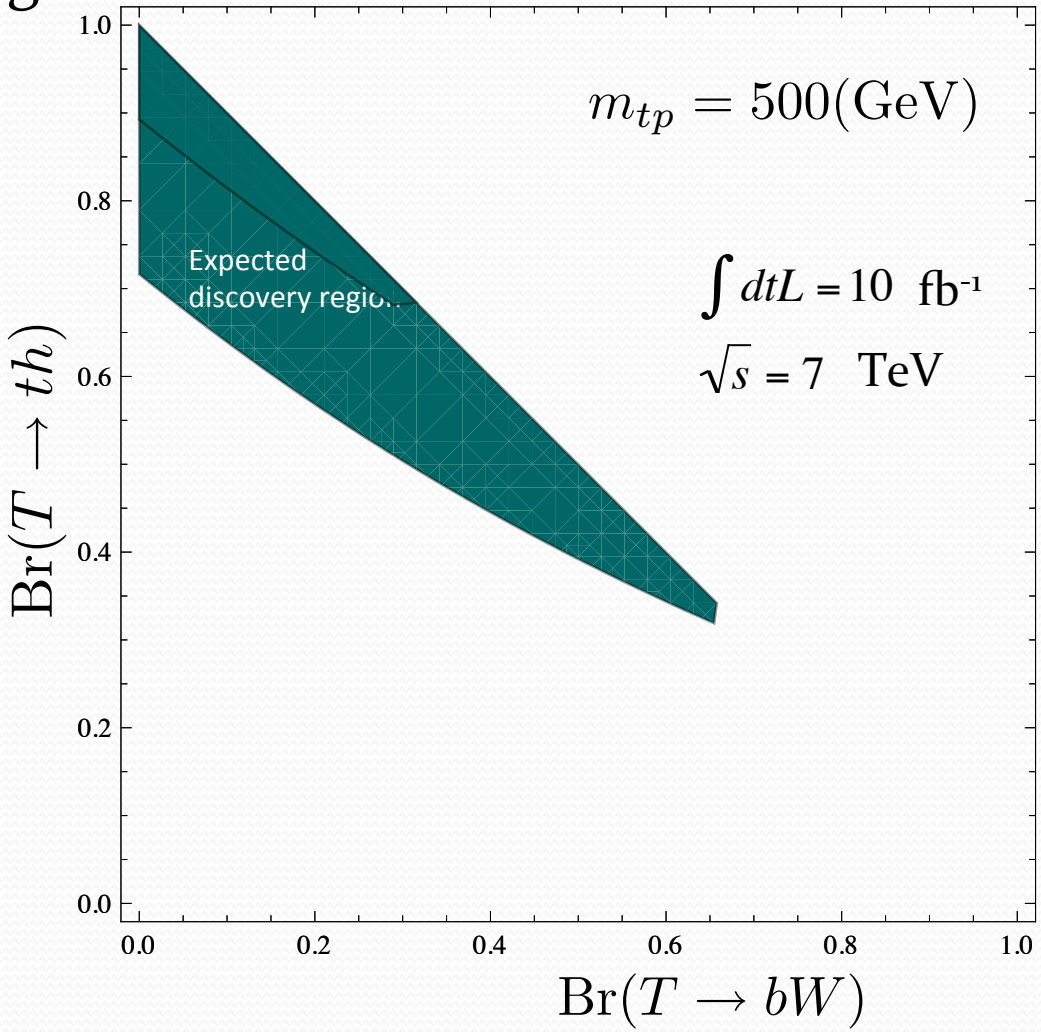
LHC's discovery potential

Expected 5 σ discovered region with 10 fb^{-1} data

(cross section / pb)
×
(acceptance)

> 0.0052

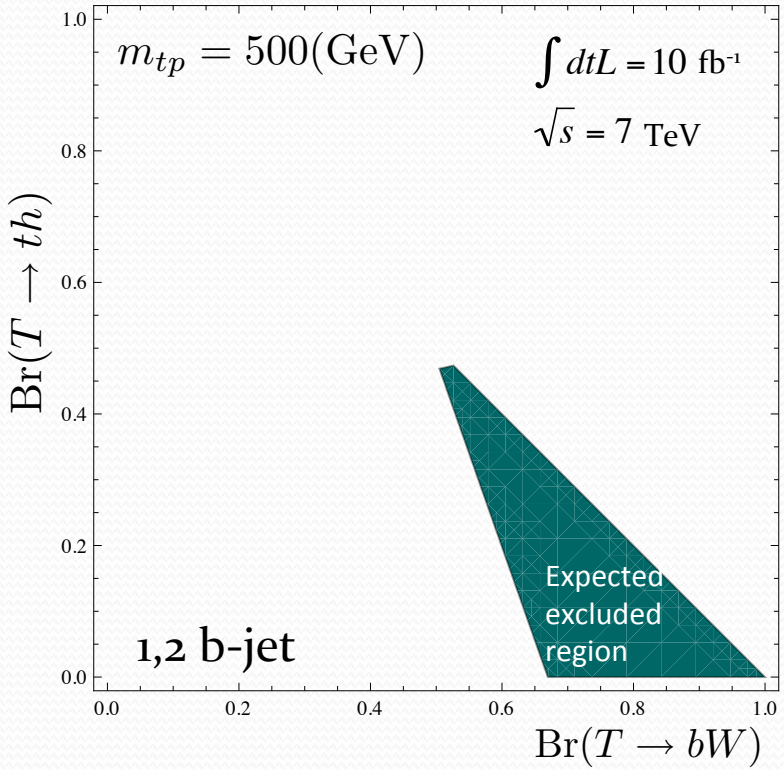
0.0062(0.0082) when 12(20) % uncertainty
in $t\bar{t}$ backgrond acceptance
times cross section

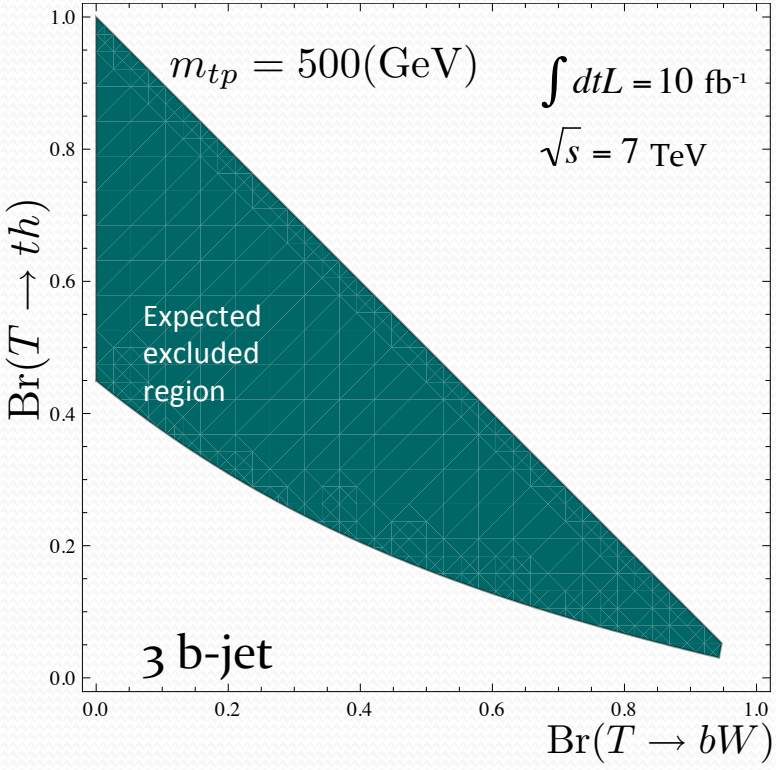


KH, Matsumoto, Nojiri, Tobioka(2012)

Summary

- Some models contain vector-like quark which mixes with up type quark
- Multi b- jet channel have grate sensitivity to the vector-like quark, especially for decay into top and higgs





Electro weak observables

parameter	value
α^{-1}	137.035999679(94)
G_F (GeV^{-2})	$1.16637(1)\times10^{-5}$
m_Z (GeV)	91.1876(21)
$\Delta\alpha_{lep}(m_Z^2)$	0.03150
$\Delta\alpha_h(m_Z^2)$	0.027626(138)
$\Delta\alpha_{top}(m_Z^2)$	-0.00007
m_W (GeV)	80.399(23)
m_t (GeV)	173.2(9)
$\bar{s}_l^2$	0.23153(16)
$\Gamma_{Z\to l^+l^-}$ (MeV)	83.984(86)
$\alpha_s(m_Z^2)$	0.1184(7)

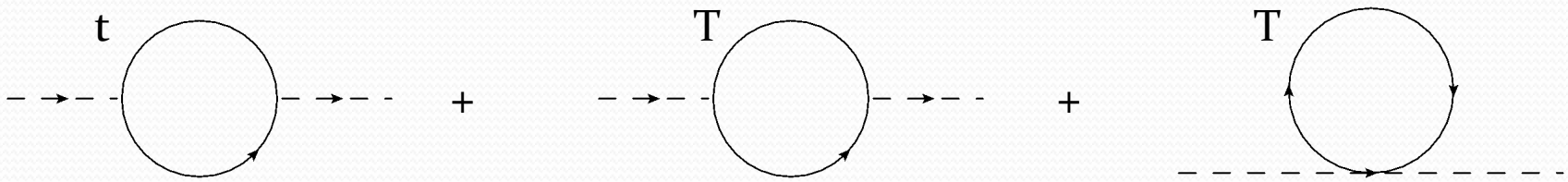
Little Higgs model

Suppose EWSB is generated by some mechanism

Cutoff $\Lambda > 10\ \mathrm{TeV}$ Han, Skiba (2007)

$$\frac{1}{\Lambda^2}(H^\dagger \sigma^i H) W^i_{\mu\nu} B^{\mu\nu}$$

Even if Higgs were pNGB, to avoid little hierarchy,



$$= 0 \times \Lambda^2 + c_1 \times m_T^2 ln(\frac{\Lambda^2}{m_T^2})$$

due to some symmetry. (depends on model)

Top see saw

Chivukula, Dobrescu, Georgi, Hill (1999)

Top quark condensate

$H \Leftrightarrow t_L^\dagger t_R$: same quantum number

How about top quark condensation like BCS theory?

Intrinsic energy scale provide dynamical scale
top quark Yukawa coupling is naturally large

Problem: top quark should be heavier

$$m_t \approx \frac{4\pi v}{\sqrt{N_c \ln \frac{\Lambda}{v}}}$$

Λ : cut off (=intrinsic energy scale)

N_c : Number of color

Solution: seesaw mechanism

Introduce vector-like quark T

$$m_t \approx \frac{4\pi v}{\sqrt{N_c \ln \frac{\Lambda}{v}}} \sin\theta$$

Suppressed by mixing angle

MSSM+extra matter

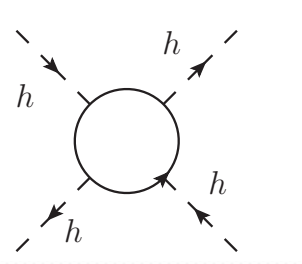
$$m_{h^0} > 114.4\ \mathrm{GeV} > m_Z \quad \text{(LEP)}$$

Raise stop mass and allow little hierarchy?

Possible solution : utilize vector-like extra matter $U(3,2,\frac{1}{6}), Q(\bar{3},1,-\frac{2}{3}), \cdots$

$$W \supset yUQH_u$$

Enhance Higgs mass!

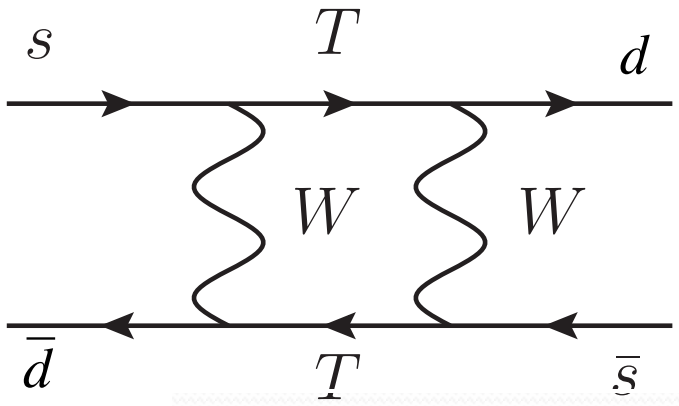


...

cf. $m_h = 124 - 126\mathrm{GeV}$?

Coupling with 1st, 2nd generations

ex.) $K\bar{K}$



$$\theta_{L1,2} \leq 10^{-3}$$

Systematic errors

- $t\bar{t}$ cross section: 166 ± 11 pb (CMS,2011)
- Integrated luminosity: 3.7% (ATLAS, 2011)
- b-tag efficiency and mis-tag rate

  : not accurately included

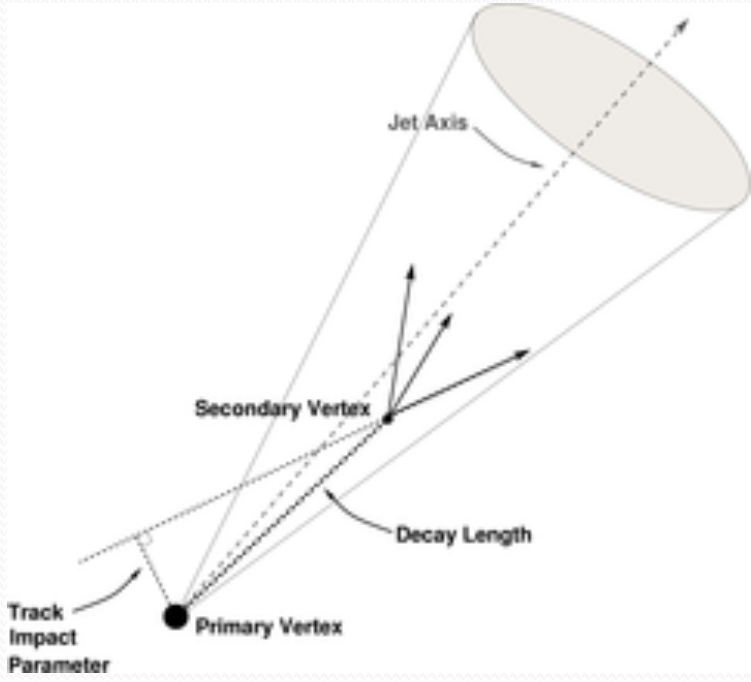
  (results with taking into the effect with rough estimate are also shown)

Uncertainties in b-tagging

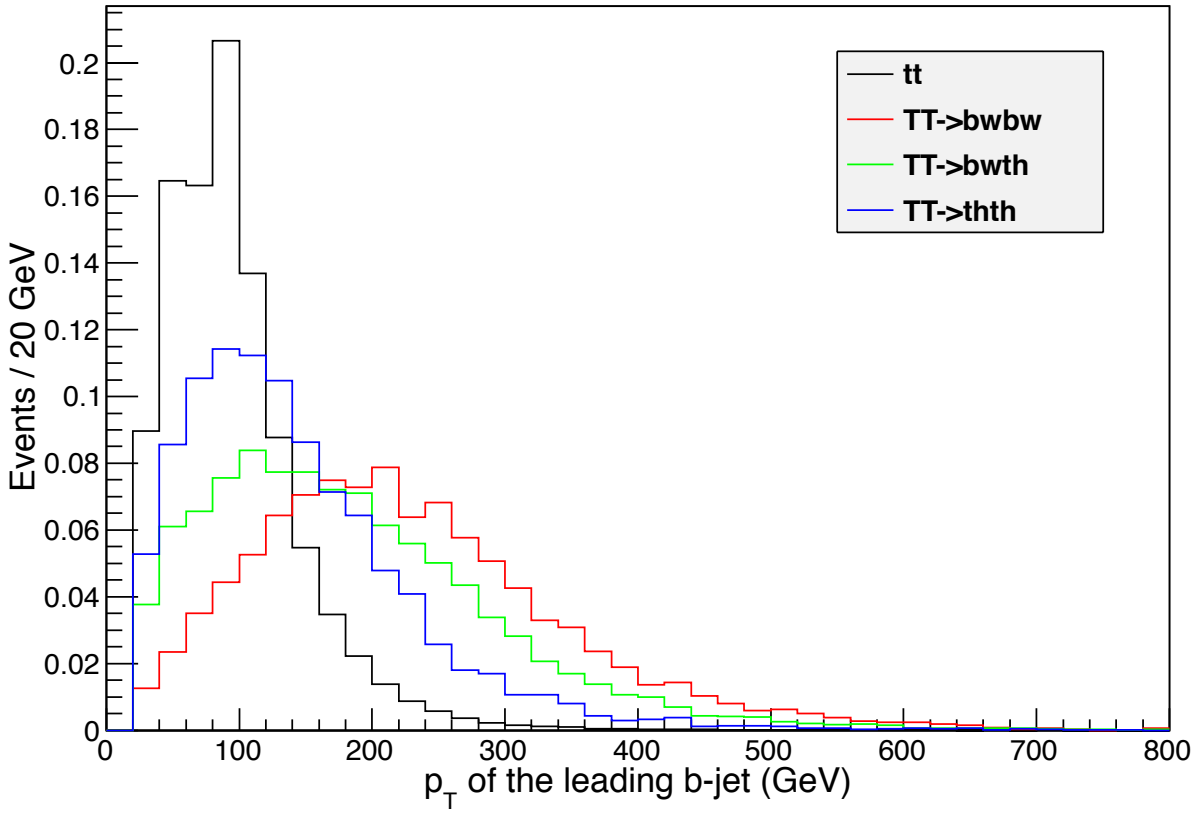
With 35 pb^{-1} data, for SVO50 method,

(ATLAS-CONF-2011-089)

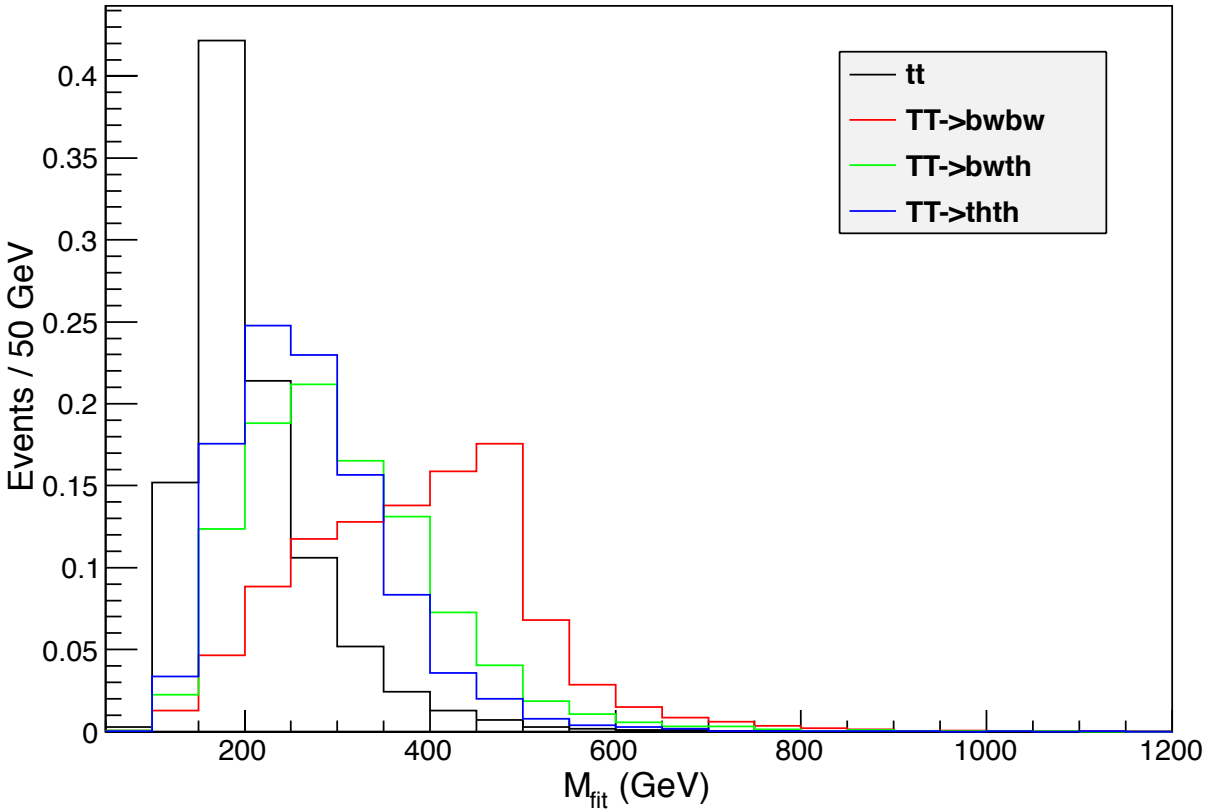
- b- tagging efficiency : ~ 5% (sys) 10% (stat)
- mis-tag rate for light jets : ~10% (stat)
- mis-tag rate for c-jets : not calibrated. ~0.14 (ATLAS TDR)



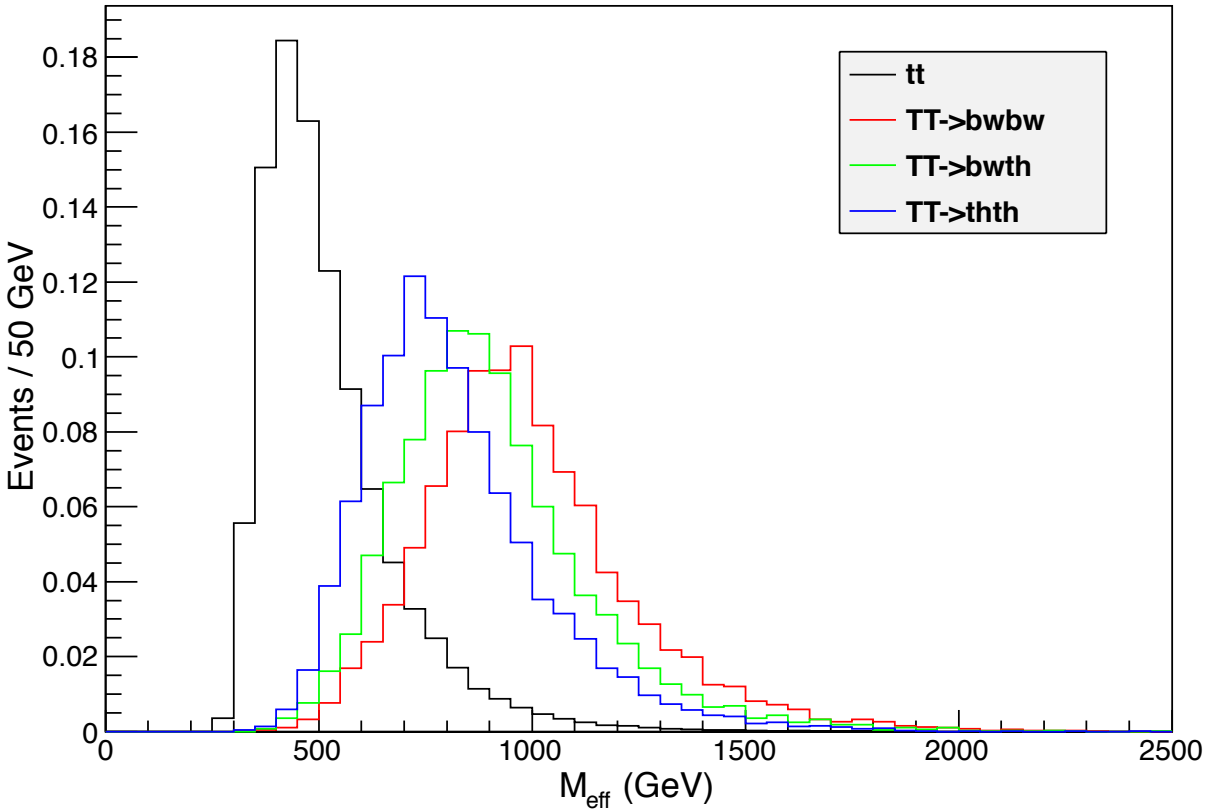
1 lepton + 1,2b-jets



1 lepton + 1,2b-jets



1 lepton + 1,2b-jets

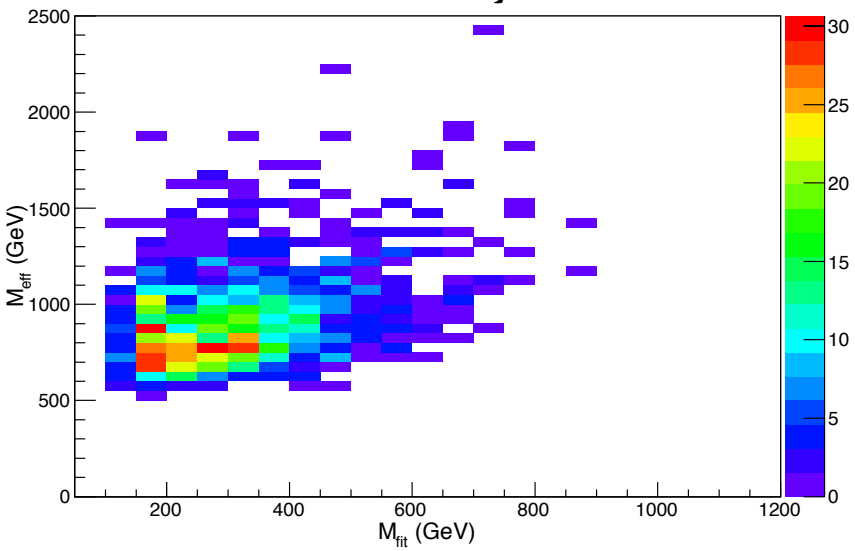


1 lepton + 1,2b-jets

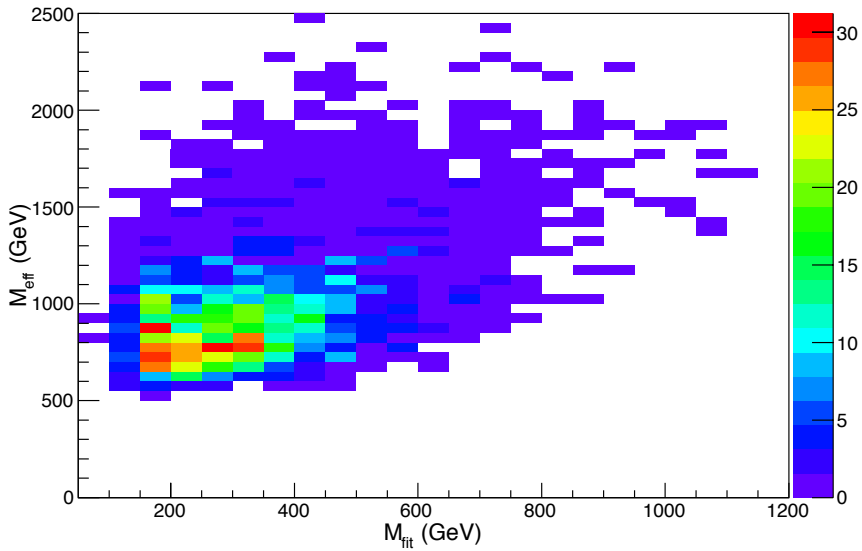
After hard b-jet cut,

$$m_{tp} = 500\ \text{GeV},\ \sin\theta_L = 0.1,\ \sin\theta_R = 0.03$$

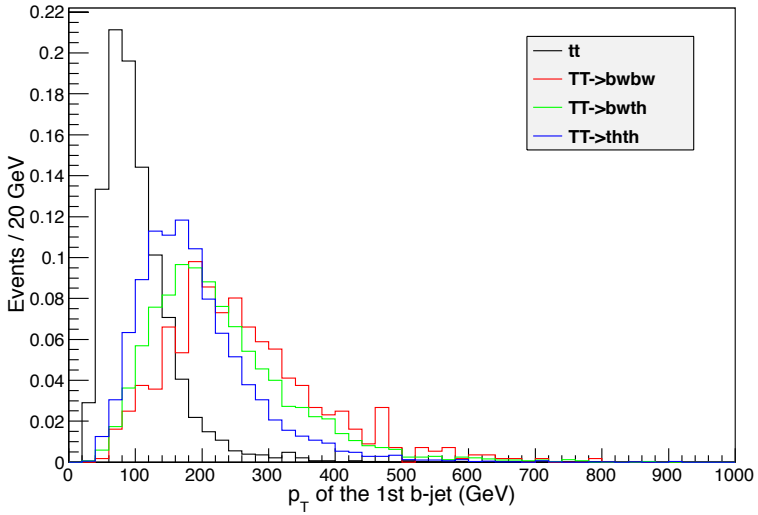
$t\bar{t}$ only

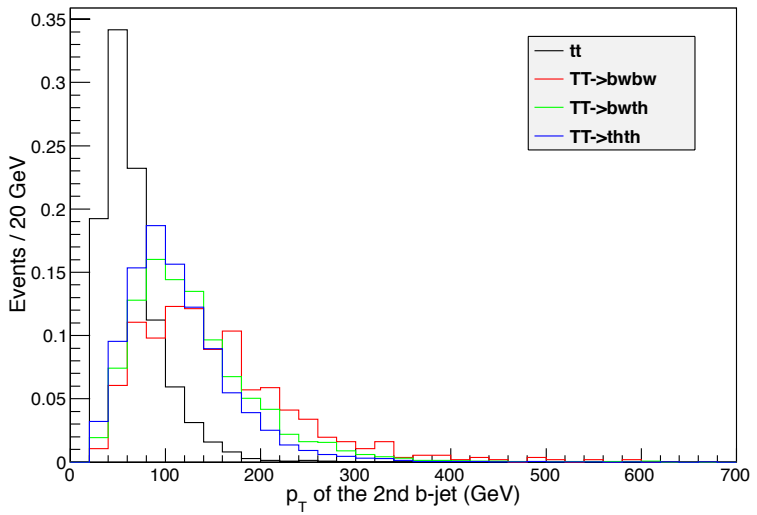


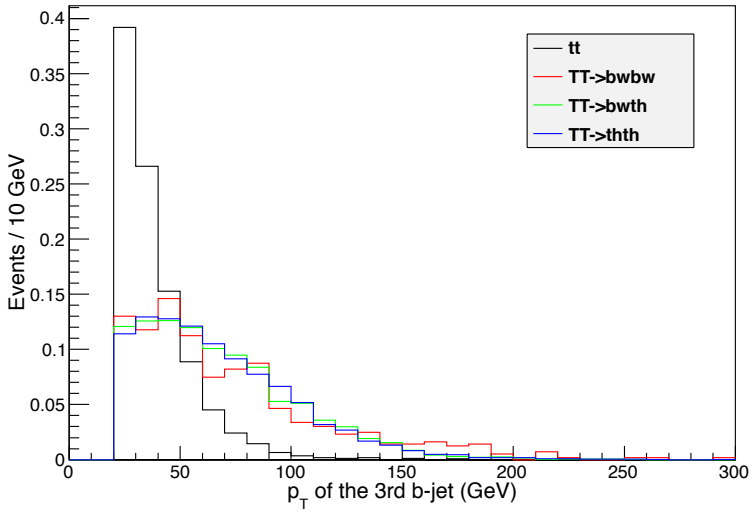
$t\bar{t}$ +signal



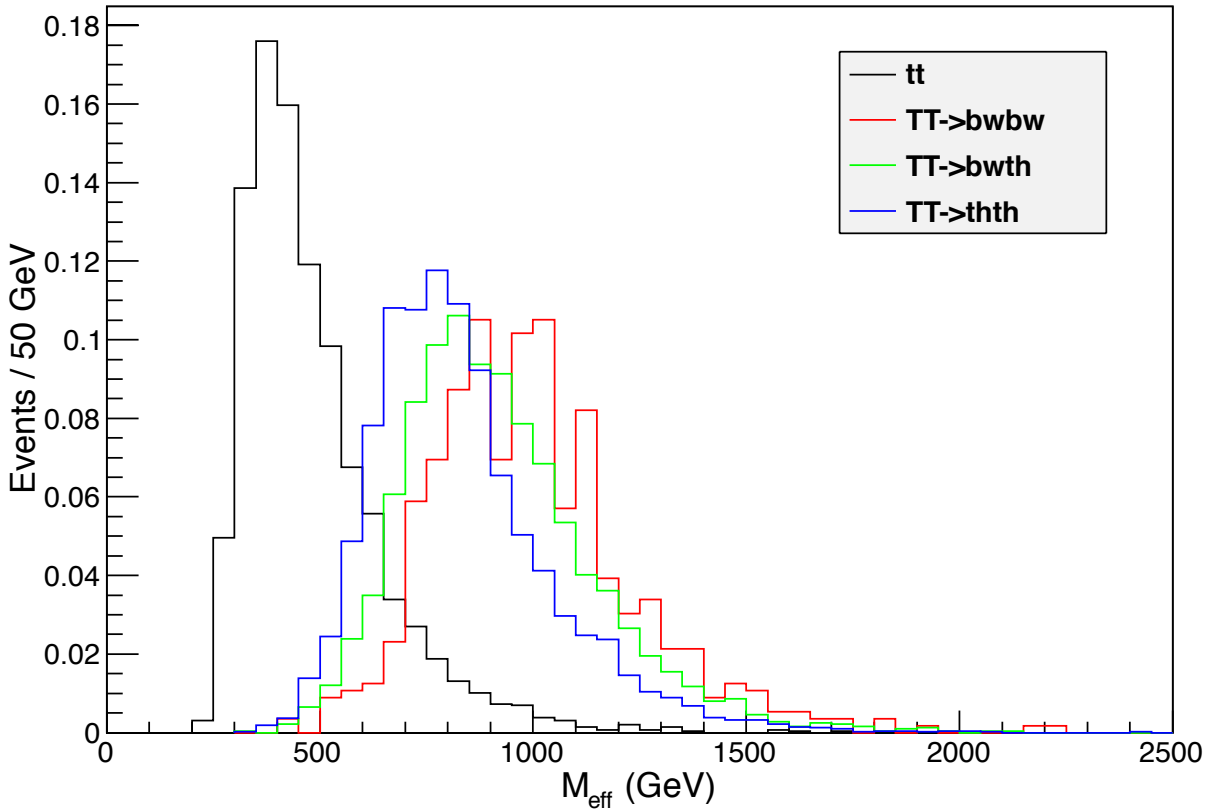
1 lepton + ≧3b-jets







1 lepton + ≧3b-jets



Possible terms

	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$
Q^3	3	2	1/6
$u^3{}_R$	3	1	2/3
U_L	3	1	2/3
U_R	3	1	2/3
H	1	2	1/2

$$-m_U U_L^\dagger U_R + h.c.$$

$$-y_3 Q^{3\dagger} H^c u_R^3 - y_U Q^{3\dagger} H^c U_R + h.c.$$

$$-\frac{\lambda}{m_U} U_L^\dagger u_{3R} |H|^2 + h.c.$$

Parameterization

To diagonalize mass,

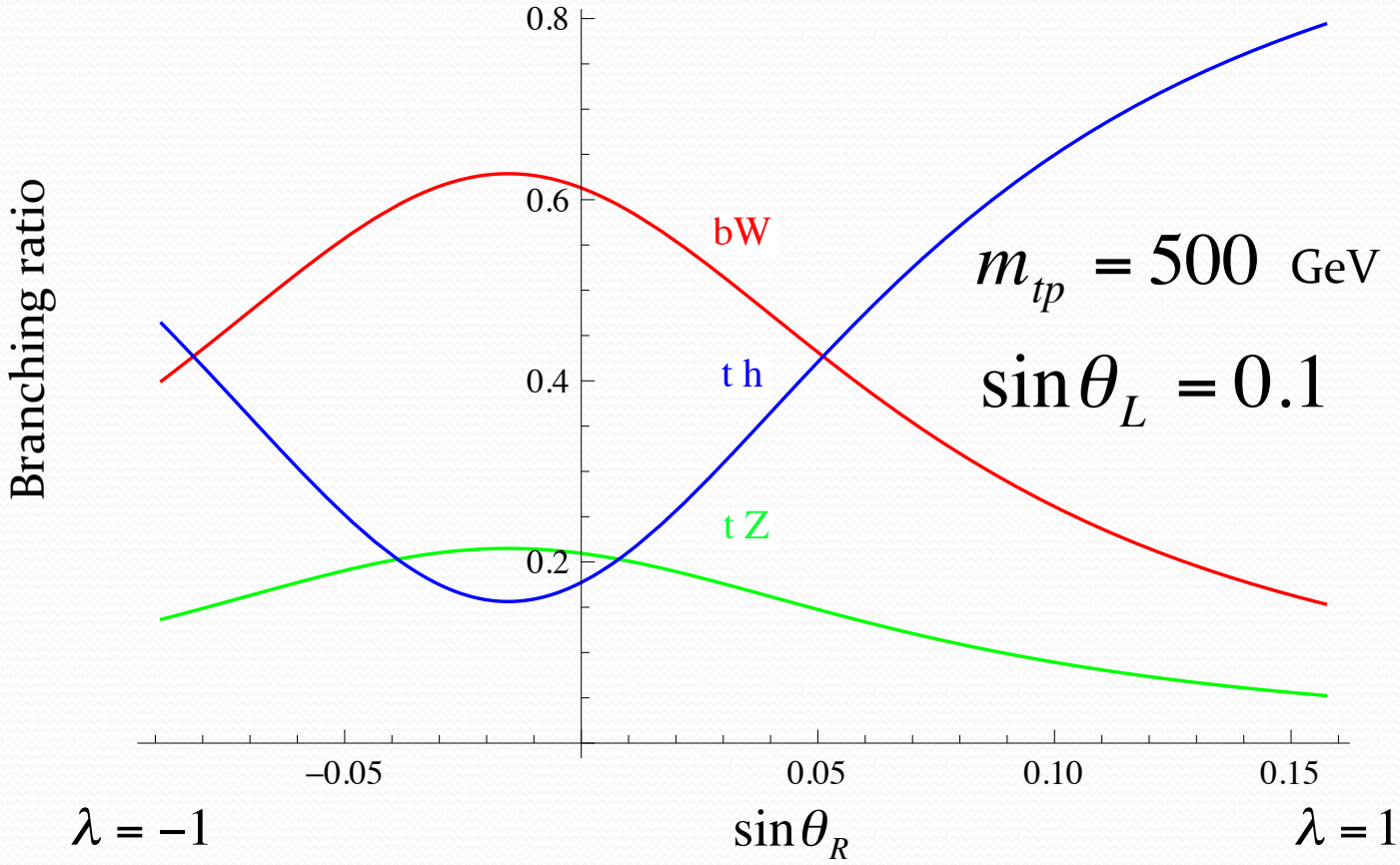
$$\begin{pmatrix} t_L \\ T_L \end{pmatrix} = \begin{pmatrix} \cos\theta_L & -\sin\theta_L \\ \sin\theta_L & \cos\theta_L \end{pmatrix} \begin{pmatrix} u_L^3 \\ U_L \end{pmatrix}$$

$$\begin{pmatrix} t_R \\ T_R \end{pmatrix} = \begin{pmatrix} \cos\theta_R & -\sin\theta_R \\ \sin\theta_R & \cos\theta_R \end{pmatrix} \begin{pmatrix} u_R^3 \\ U_R \end{pmatrix}$$

$$m_{tp}, \theta_L, \theta_R$$

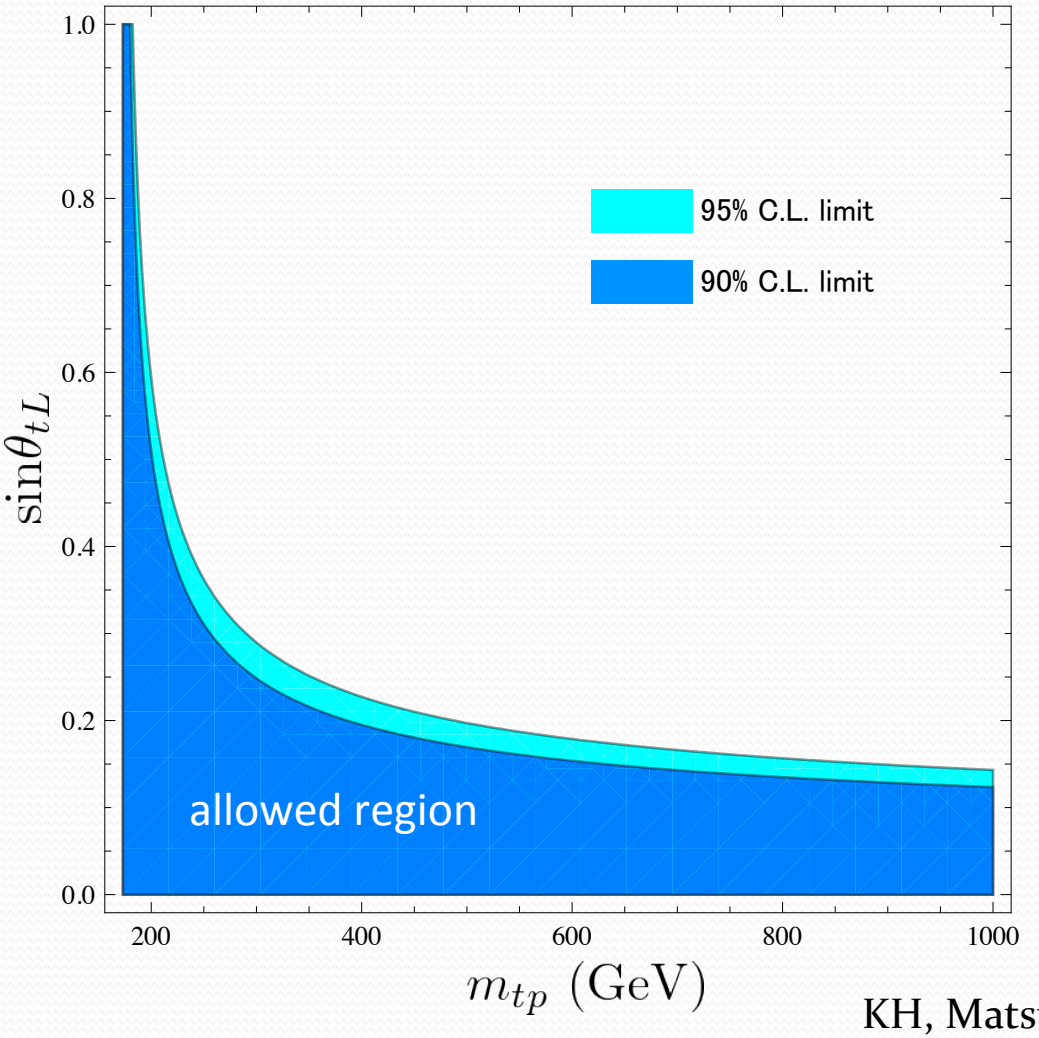
Branching ratio

Let's look at $\sin\theta_R$ dependence



KH (2012)

Constraint from EWPM



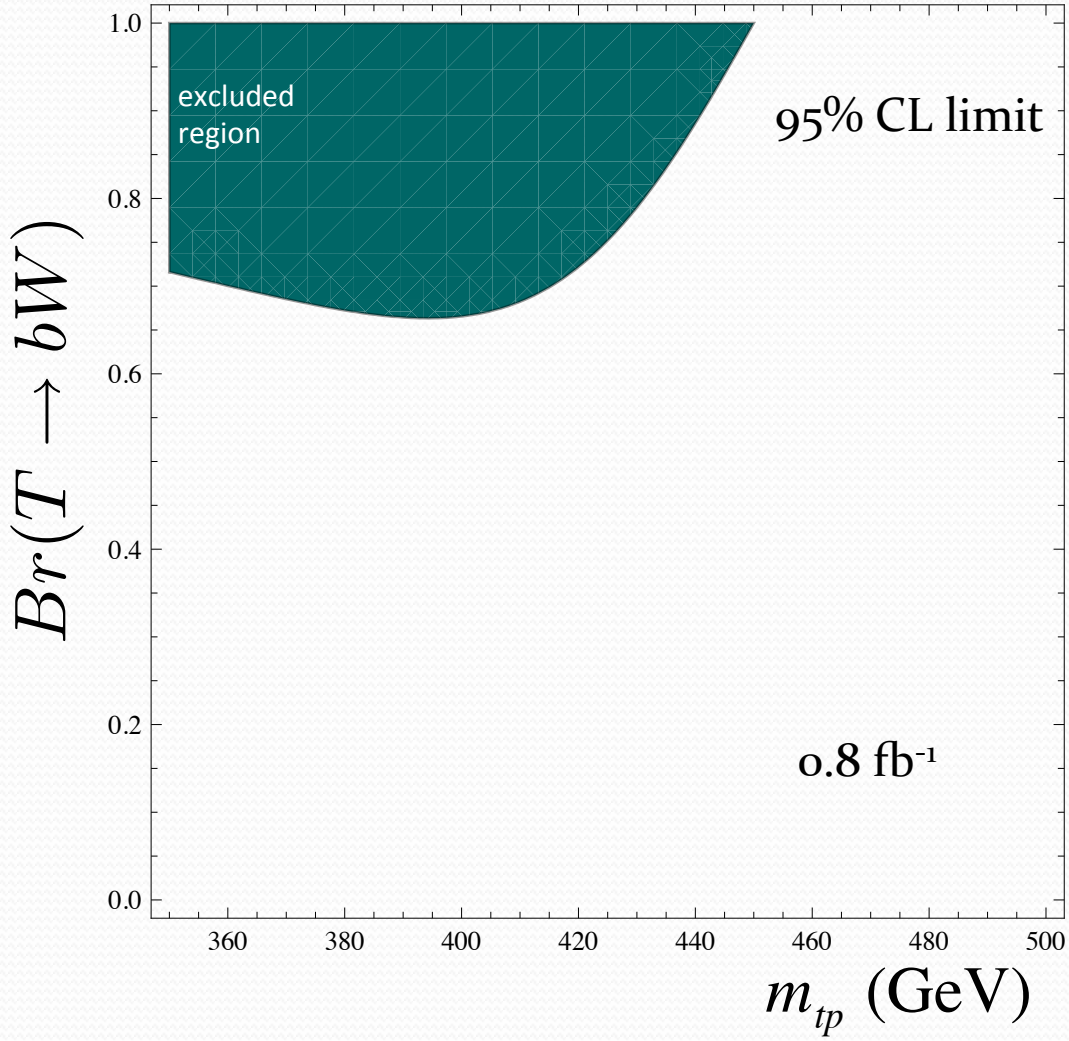
$m_h = 120$ GeV

S, T, U method with

$\sin^2\theta_{eff}^{lep}, \Gamma_{Z\to l^+l^-}, m_W$

KH, Matsumoto, Nojiri, Tobioka(2012)

Constraints from CMS result



Assuming pair creation and

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1-lepton, b-jet search

Picture: KH, Matsumoto, Nojiri, Tobioka(2012)