Composite Higgs Models and their Signatures

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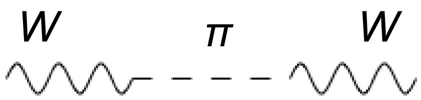
Higgs@Capri2025

The Composite Higgs Scenario

Georgi, Kaplan, 1984

- EWSB triggered by a new Strong Dynamics, composite at the TeV scale
- Higgs: composite + pGB of global invariance (G) of the strong sector

Inspired by QCD- (chiral symmetry)-EW phenomena



$$m_W^{(QCD)} = \frac{g}{2} f_\pi$$

Pion is the pGB of chiral symmetry breaking

$m_\pi << \Lambda_{QCD}$

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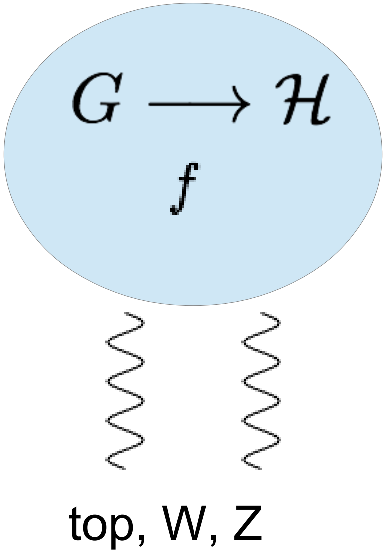
Physical cutoff set by the compositeness scale

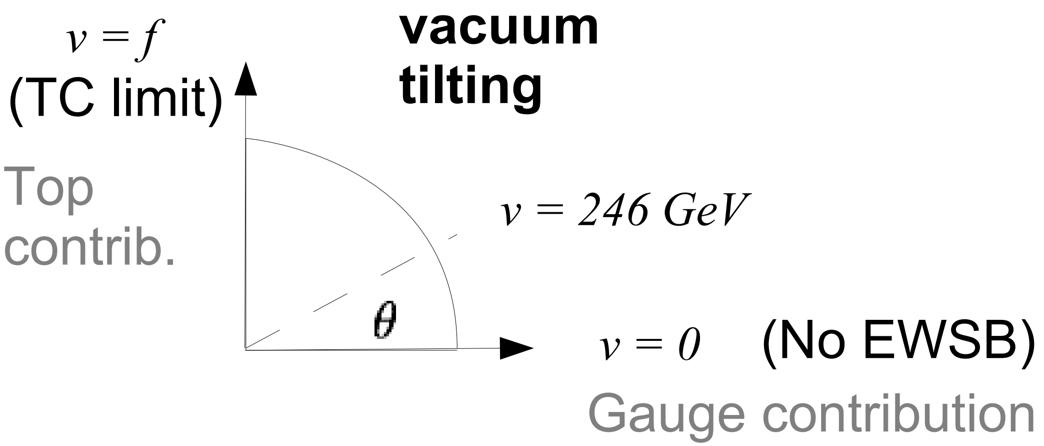
Higgs naturally light

$$\Delta m_h^2 \sim \Lambda^2$$

$$\Lambda \sim 4\,\pi\, f$$

$$m_h^2 \sim \left(\frac{v}{f}\right)^2 m_*^2 \frac{1}{16\pi^2}$$





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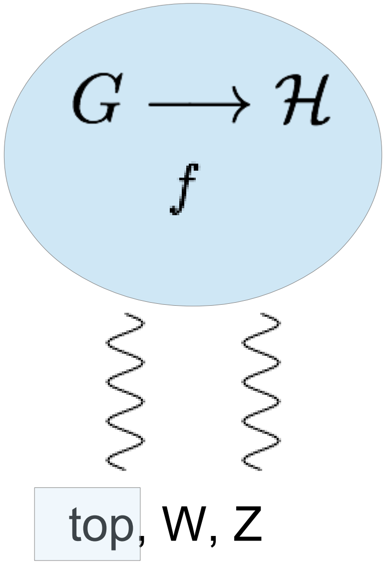

Interactions of the Strong sector with an “elementary” sector (≈ the SM) explicitly break G. V(h) is generated radiatively

$$V(h) \sim \frac{1}{16\pi^2}\left(-a\,h^2 + b\frac{h^4}{2f^2}\right)$$

$$v^2 = \frac{a}{b} f^2$$

but $a \sim b$

→ Fine-tuning of the order $(v/f)^2$ → $m_{t'} \lesssim 1\,\mathrm{TeV}$

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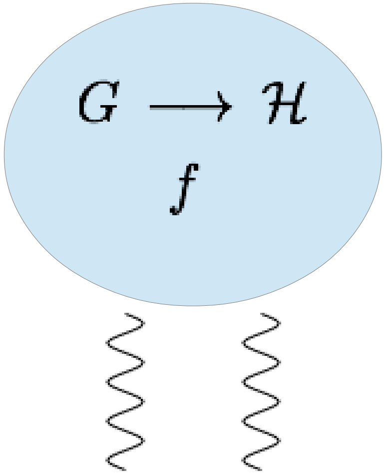


top, W, Z

MCHM Agashe, Contino, Pomarol, NPB 719 (2005)

$$SO(5) \to SO(4) \sim SU(2)_L \times SU(2)_R$$

$$4\text{GB} \,: h + W_L^{\pm}, Z_L$$

Minimal realization including custodial symmetry

LHC (and other experiments) are already testing the composite Higgs paradigm

directly

Limits on top-partners $m_{t'} \gtrsim 1.4\,\mathrm{TeV}$

and vector resonances $m_V \gtrsim 3-4\ \mathrm{TeV}$

$$(v/m_{t'})^2 \sim 3\%$$

indirectly

EWPD $\Delta S \sim (v/f)^2$

ATLAS + CMS, JHEP 08, 045 (2016)

Modification of Higgs couplings → diboson couplings $\sin\theta < 0.56$

ATLAS, JHEP 11, 206 (2015)

Including modification of the top coupling: $g_{htt} = \cos\theta\, g_{htt}^{SM}$ $\sin\theta < 0.35$

Flavor Physics

A new generation of quarks?

Data already tell us that new quarks are likely to be of vector-like type

↓

L-H and R-H components transform in the same way under the symmetry group of the theory

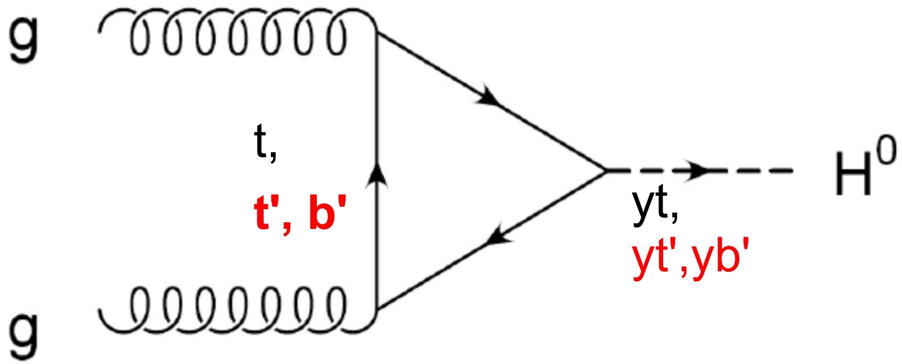
A chiral 4th family of quarks (and leptons) is excluded by LHC Higgs results

also dis-favored by electroweak precision data (S/T) and flavor observables

Chiral 4th generation

$\begin{pmatrix} t'_L \\ b'_L \end{pmatrix} \longrightarrow$ **2** of $SU(2)_L$ $\quad$ t'_R , $b'_R \longrightarrow$ **1** of $SU(2)_L$

$$\begin{array}{ll} \mathbf{y_{t'}\bar{t'}_L H t'_R} & \\ \mathbf{y_{b'}\bar{b'}_L H b'_R} & \end{array} \xcancel{\begin{array}{l} \mathbf{M_{t'}\bar{t'}_L t'_R} \\ \mathbf{M_{b'}\bar{b'}_L b'_R} \end{array}}$$



$$\boxed{\sigma_{\mathbf{SM}} \times \mathcal{O}(\mathbf{10})}$$

$$\sigma \sim \Big| \sum \frac{\mathbf{y_{ii}}}{\mathbf{M_i}} \mathbf{A}(\mathbf{m_h^2}/\mathbf{M_i^2}) \Big|^2 \sim \frac{\partial}{\partial \mathbf{v}} \ln(\det \mathcal{M})$$

+ *O*(100) suppression to h → γγ rate caused by the t',b' destructive interference with the W

Higgs measurements completely rule out a chiral 4th generation
[Kuflik *et al.* , .., PRL 110 (2013)]

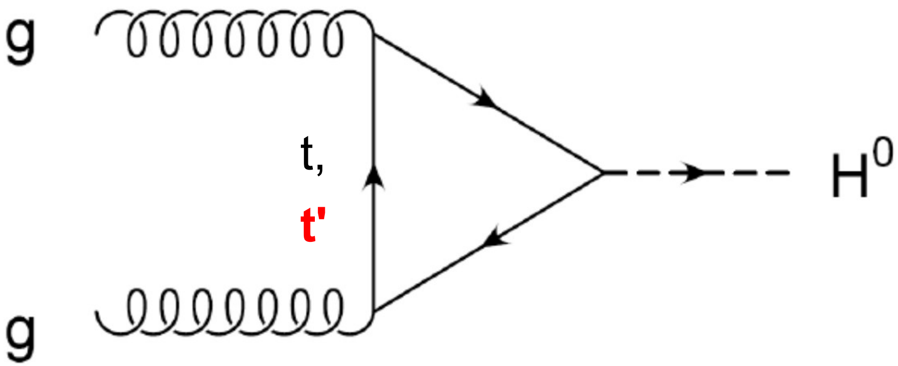
VLQ (t')

Example:
EW
doublet

t'_L , t'_R → **2** of $SU(2)_L$

$$\cancel{\mathbf{y_{t'}\bar{t'}_L H t'_R}}$$

$$\mathbf{M_{t'}\bar{t'}_L t'_R} \qquad \xi\ \mathbf{\bar{t'}_L H t_R}$$

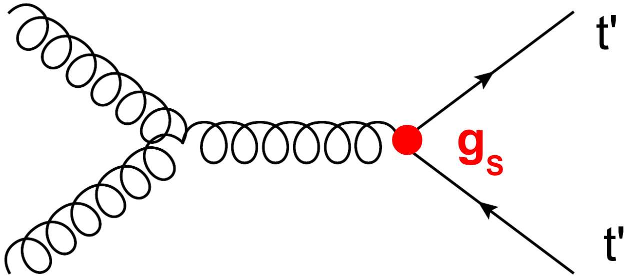


Mixing term gives off-diagonal contribution

$$\sigma \sim \Big|\sum \frac{\mathbf{y_{ii}}}{\mathbf{M_i}}\mathbf{A}(\mathbf{m_h^2}/\mathbf{M_i^2})\Big|^{\mathbf{2}} \sim \frac{\partial}{\partial \mathbf{v}}\ln(\det\mathcal{M}) \Rightarrow \sigma_{\mathbf{SM}} \times \big(\mathbf{1} + \boxed{\mathcal{O}(\mathbf{v^2}/\mathbf{f^2})}\big)$$

Indirect probes on vlqs from Higgs measurement and EW precision data

Direct search for VLQs: QCD pair production



→ Wb, Zt, ht

BRs dictated by t' EW quantum numbers, in minimal scenarios

but this can change significantly in more complex phenomenological scenarios: for example if new resonances in which t' can decay are sub-threshold

Model-independent production
(the coupling is g_S, it is determined by QCD gauge symmetry)

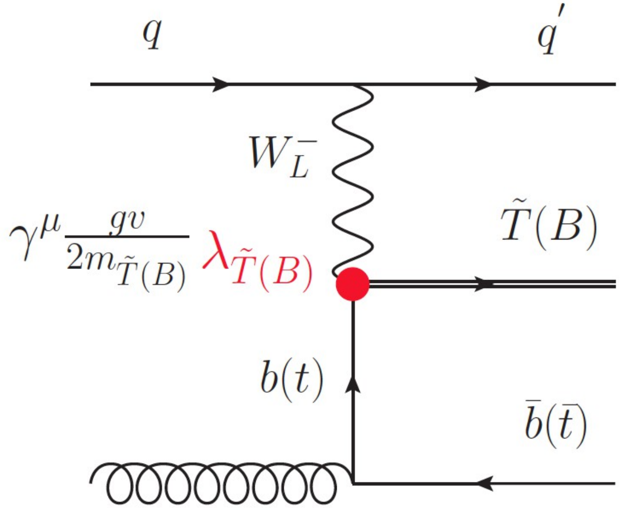
↓

Robust bounds on VLQs

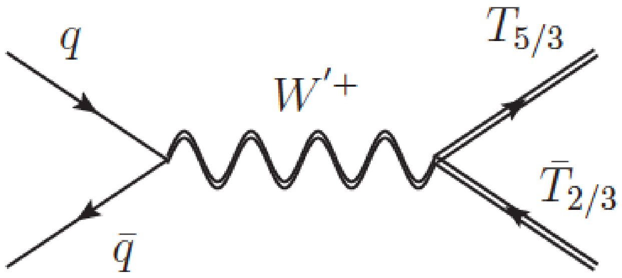
Direct search for VLQs: increasing the LHC reach

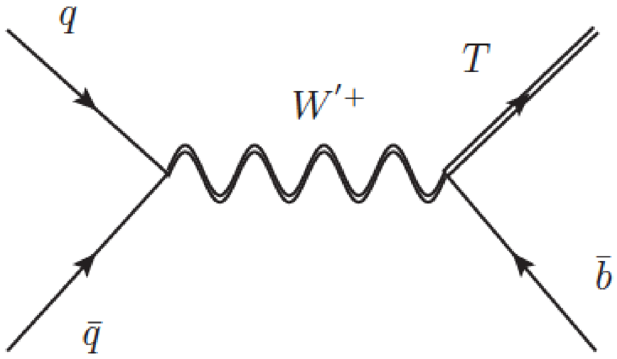
VLQ single production

NV, PRD 86 (2012) 075017;
JHEP 1207 (2012) 158



VLQ production through decays of vector resonances

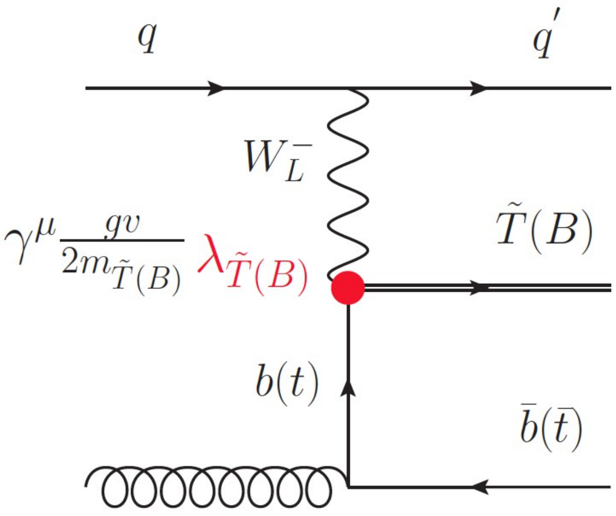




NV PRD 89 (2014) 9, 095027

EW single production

NP effects: Dirac mass terms, new fields with non-SM gauge charges (RH $SU(2)_L$ doublets) lead to EW interactions which are off-diagonal in the mass basis (even for neutral currents: there is no GIM protection) and mix VLQs with SM quarks



PROS

Typically higher cross section, compared to pair production, at high vlq mass

Peculiar topology

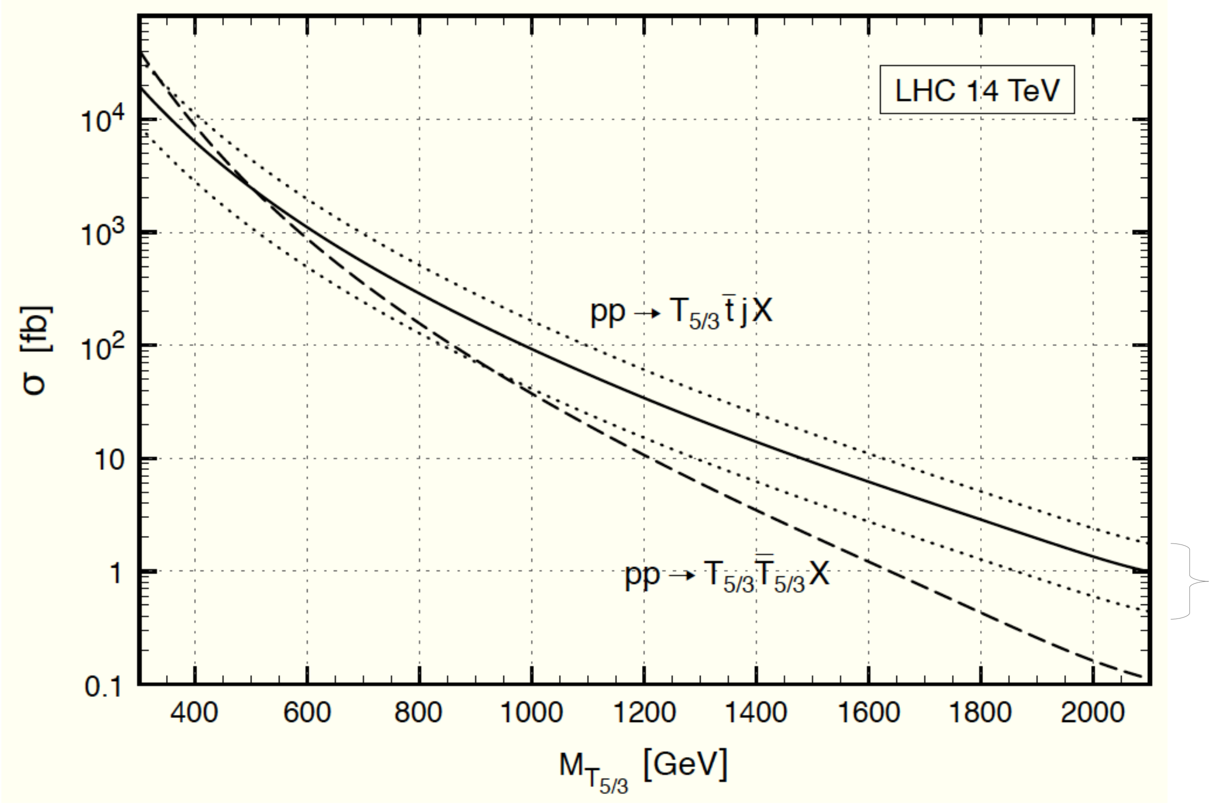
Possibility to measure the coupling → information on the EWSB sector

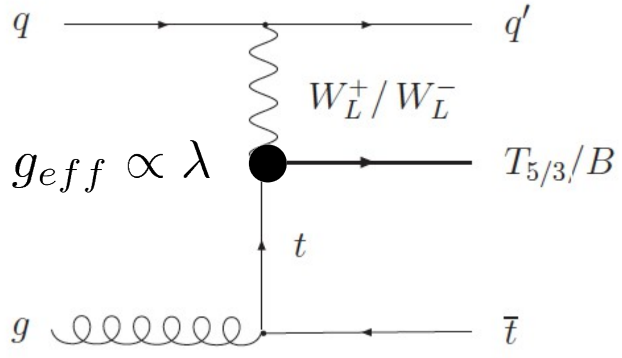
CONS

Model-dependent
(but “under control” in the high mass regime that will be explored at the LHC-13/14)

EW Single production *vs QCD pair production*

Plot from: R. Contino, G. Servant, arxiv: 0801.1679



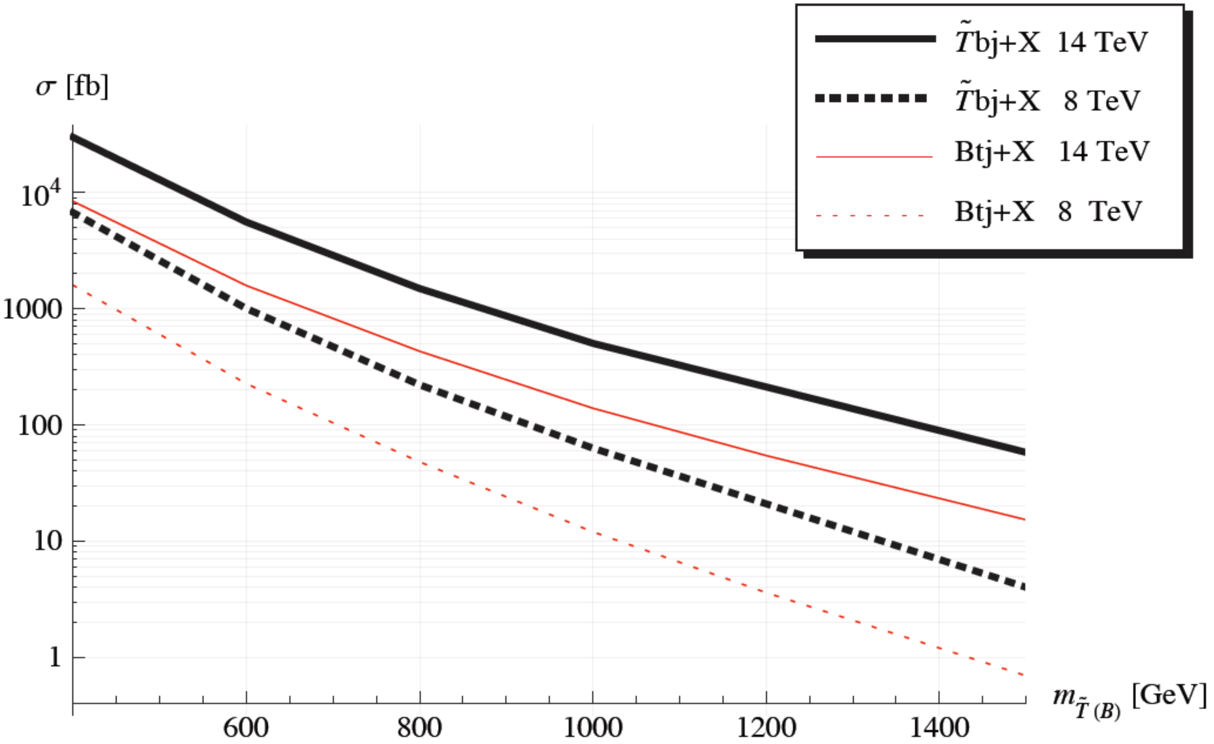


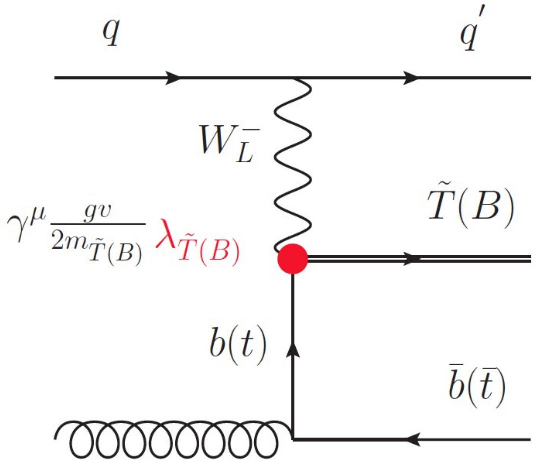
$\lambda \in [2, 4]$

Cross sections scale as ~ λ^2

t-channel enhancement of the cross-section at high mass

b-mediated vs t-mediated EW Single production





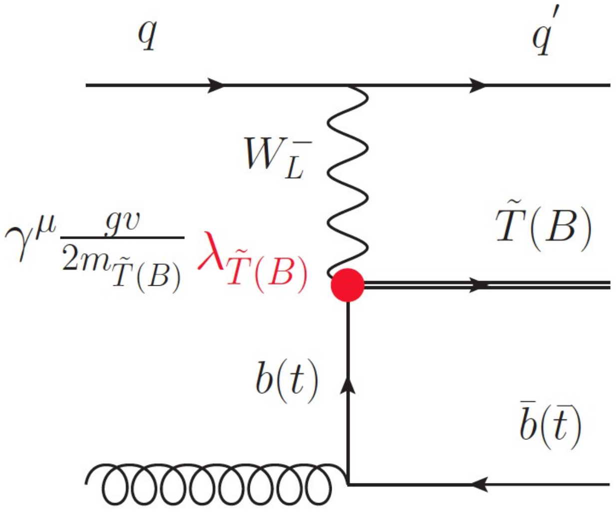
NV, PRD 86 (2012) 075017

About 4 times larger cross sections for t_R-partners
as an effect of the b (instead of top) intermediate exchange

EW single production kinematics

Same as Single-(SM)top

C.-P. Yuan '90
Stelzer, Sullivan, Willenbrock, '97



<u>Forward-jet tag</u>
(low-virtuality W leads to forward jet)

Possibility of <u>measuring the coupling</u>

Composite Higgs / RS Models

A simple Two-Site description

Contino et al. hep-ph/0612180

ELEMENTARY Sector

$\mathcal{G}_{SM} \equiv SU(2)_L \times U(1)_Y$

STRONG EWSB Sector

$\mathcal{G} \xrightarrow[\mathbf{H}]{} \mathcal{H}_1 \supset \mathcal{G}_{SM}$

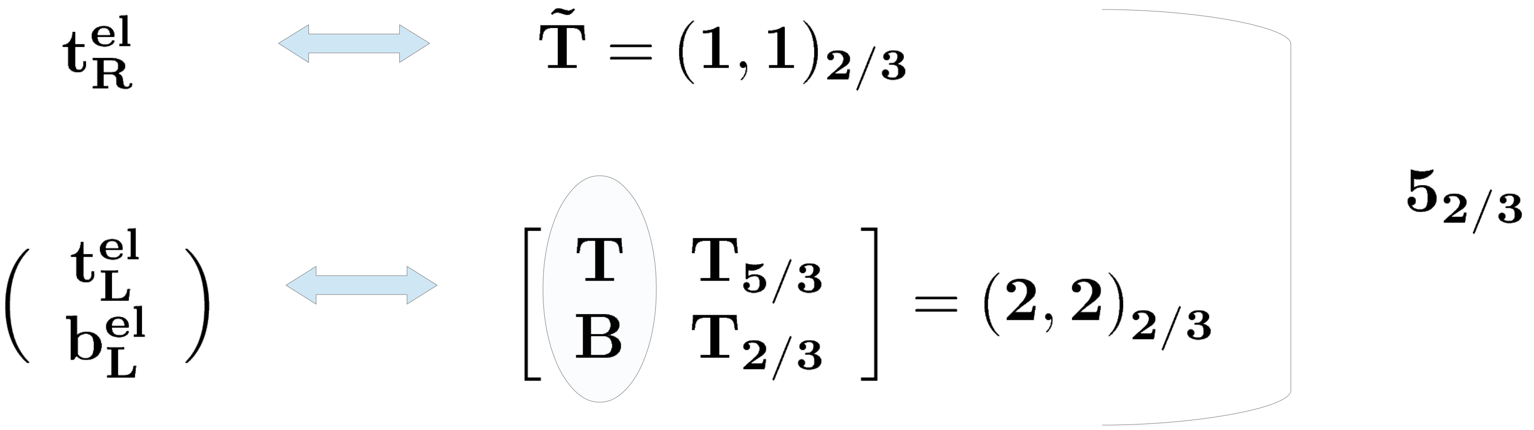
elementary/composite mixing

SM + NP

light SM particles + heavy resonances (Top-partners, W*, G*, ..)
[mainly elementary] [mainly composite]

top-partners in Composite Higgs / RS Models

Linear mass mixing terms [Kaplan '91]



$$\mathbf{t_R^{el}} \longleftrightarrow \mathbf{\tilde{T} = (1,1)_{2/3}}$$

$$\begin{pmatrix} \mathbf{t_L^{el}} \\ \mathbf{b_L^{el}} \end{pmatrix} \longleftrightarrow \begin{bmatrix} \mathbf{T} & \mathbf{T_{5/3}} \\ \mathbf{B} & \mathbf{T_{2/3}} \end{bmatrix} = \mathbf{(2,2)_{2/3}}$$

$$\mathbf{5_{2/3}}$$

PARTIAL COMPOSITENESS

Rotation
(Mixing angles: s_L, s_R)

$$\begin{cases} \mathbf{t_L = c_L t_L^{el} + s_L T_L} \\ \mathbf{t_R = c_R t_R^{el} + s_R \tilde{T}_R} \end{cases}$$

s_L / s_R are the t_L / t_R degree of compositeness

$$\mathbf{m_t \simeq Y_* s_L s_R \frac{v}{\sqrt{2}}}$$

Heavier particles have larger degrees of compositeness

EW VLQ Couplings

Yukawa interactions among composite states: Top partners – Higgs / W_L / Z_L

$$\mathcal{L}^{comp} \propto \mathcal{L}^{YUK} = Y_* \,\mathrm{Tr}\{\bar{\mathcal{Q}}\mathcal{H}\}\tilde{T}$$

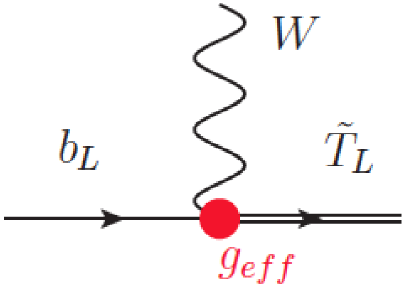
- Y_* is the Yuakawa coupling among composites, which is expected to be large $1 < Y_* \ll 4\pi$
- $\mathcal{H} = \begin{bmatrix} \phi_0^\dagger & \phi^+ \\ -\phi^- & \phi_0 \end{bmatrix}$ Higgs and would-be Goldstone bosons (W_L, Z_L) matrix
- $\mathcal{Q} = \begin{bmatrix} T & T_{5/3} \\ B & T_{2/3} \end{bmatrix}$ is the matrix of t_L partners (T, B) directly couple to (t_L, b_L); ($T_{5/3}$, $T_{2/3}$) are effects of the custodial symmetry in the composite sector
- $\tilde{T}$ is the EW singlet, partner of t_R

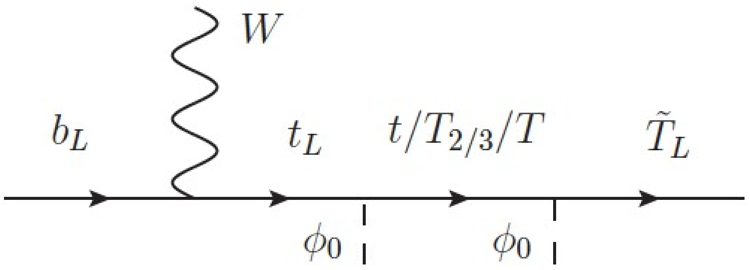
$$\boxed{\mathcal{L}^{YUK} = Y_* \, \mathrm{Tr}\{\bar{Q}\mathcal{H}\}\tilde{T}}$$

After elementary/composite mixing + EWSB:

Interactions among **SM quarks - h (W_L, Z_L) - Top partners**

$$\mathcal{L}^{\mathbf{YUK}} = +\mathbf{Y}_*\mathbf{s_L c_R}\left(\bar{\mathbf{t}}_\mathbf{L}\phi_\mathbf{0}^\dagger\tilde{\mathbf{T}}_\mathbf{R} - \bar{\mathbf{b}}_\mathbf{L}\phi^-\tilde{\mathbf{T}}_\mathbf{R}\right) + \ldots \qquad \lambda_{\tilde{\mathbf{T}}} = \mathbf{Y}_*\underbrace{\mathbf{s_L c_R}}_{\text{Ele-composite mixing}}$$





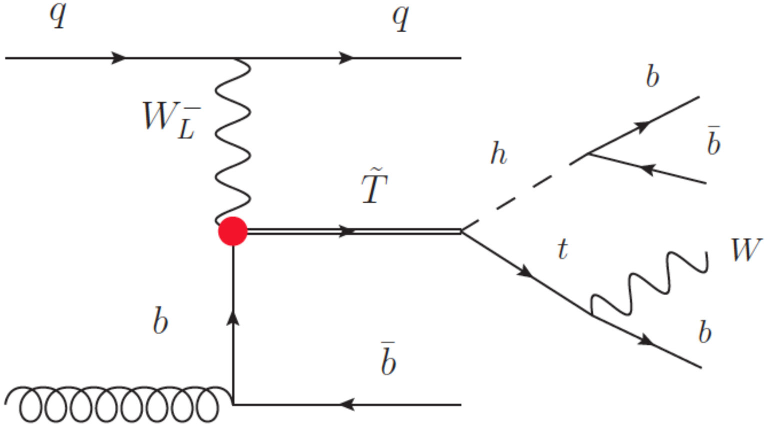
$$\mathbf{g_{eff}} = \frac{\mathbf{g}}{\sqrt{\mathbf{2}}}\underbrace{\sin\theta}$$

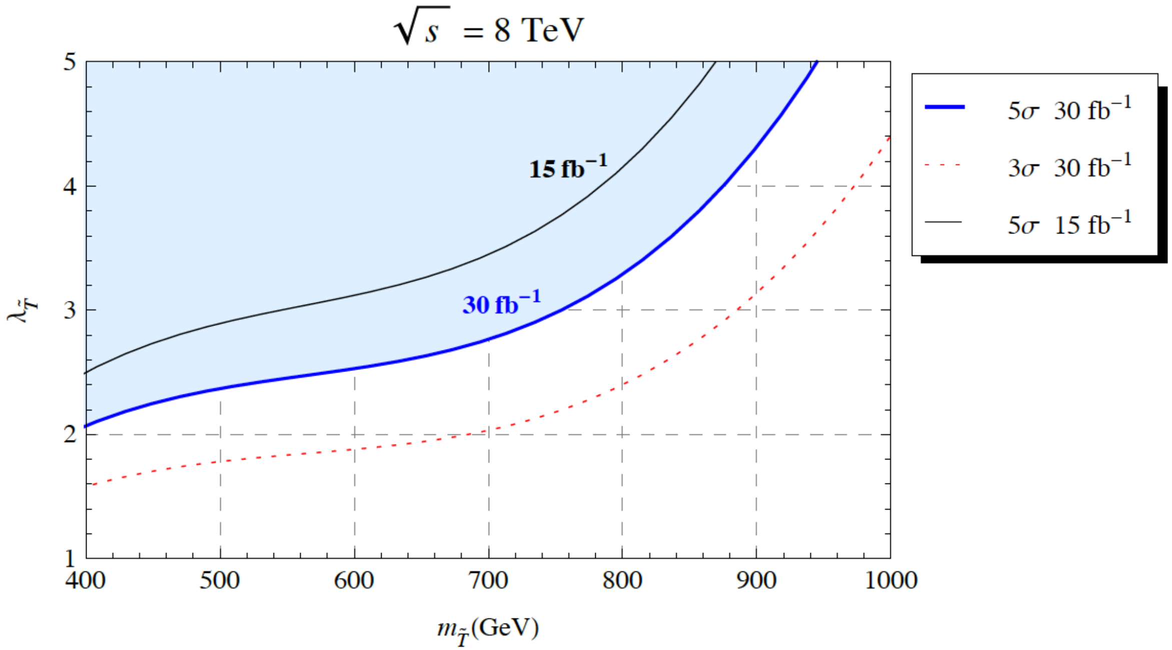
Is the superposition $\mathbf{t_L}$ - $\tilde{\mathbf{T}}_\mathbf{L}$:

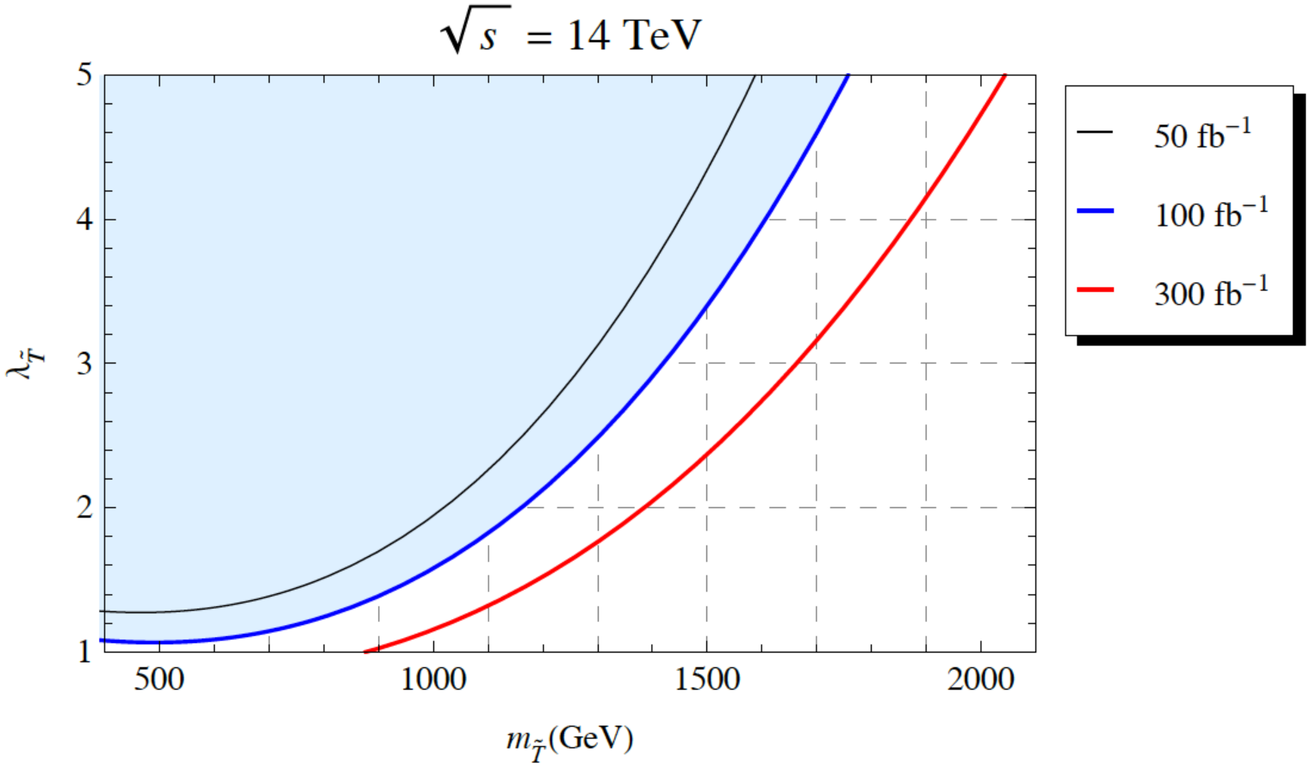
$$\sin\theta(\mathbf{LO}) = \frac{\lambda_{\tilde{\mathbf{T}}}\mathbf{v}}{\sqrt{\mathbf{2}}\mathbf{M}_{\tilde{\mathbf{T}}}}$$

Weak-mixing approximation

Reach on the plane mass-coupling

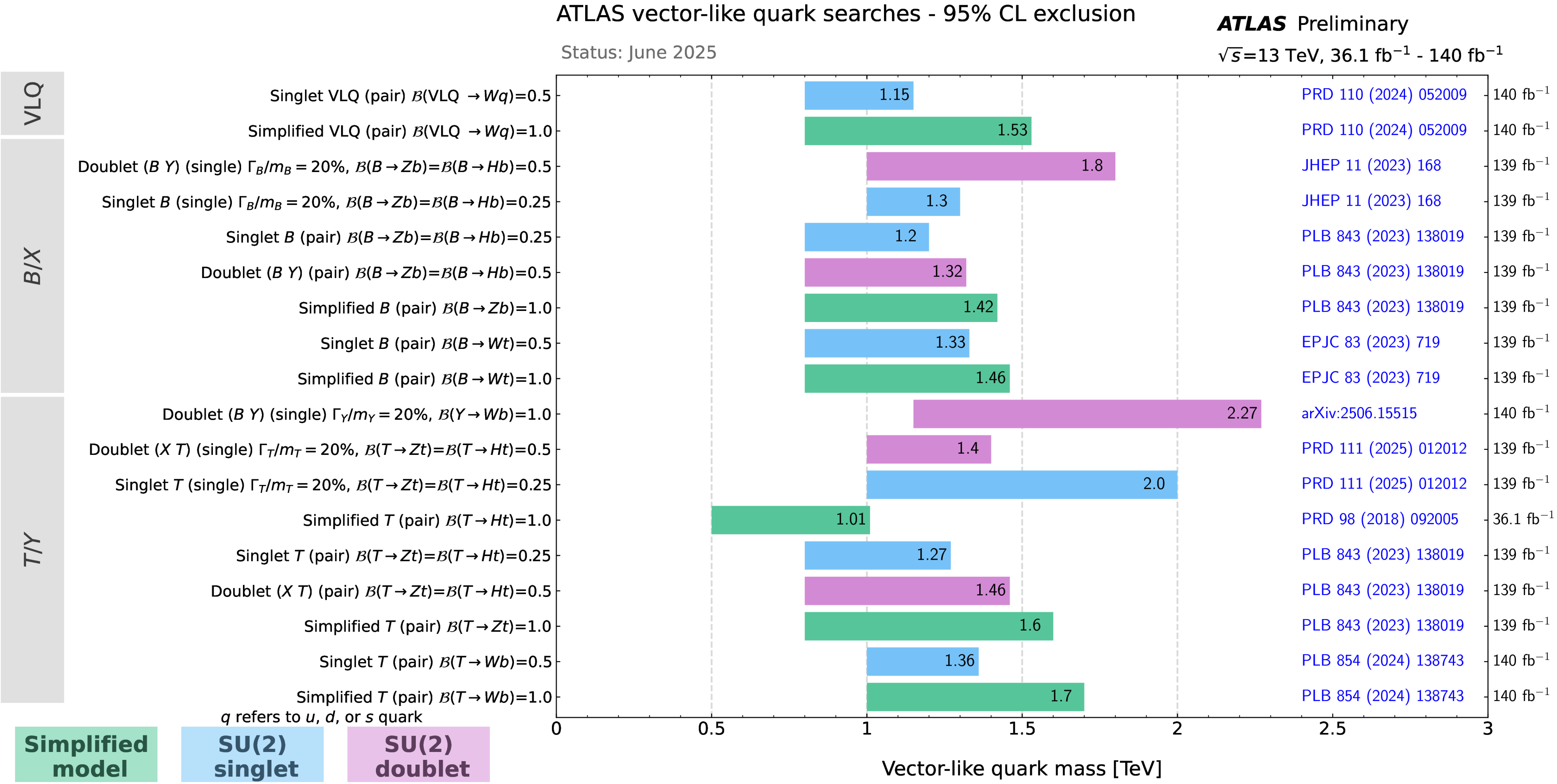






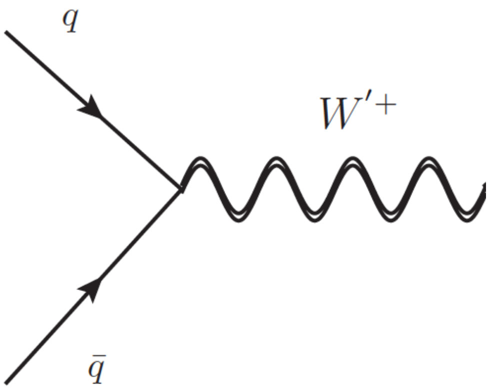
Estimated LHC-14 reach, from NV PRD86

Current LHC bounds on VLQs



Weaker constraints from EWPT (in models with custodial symmetry protection)

Searches for Vector Resonances



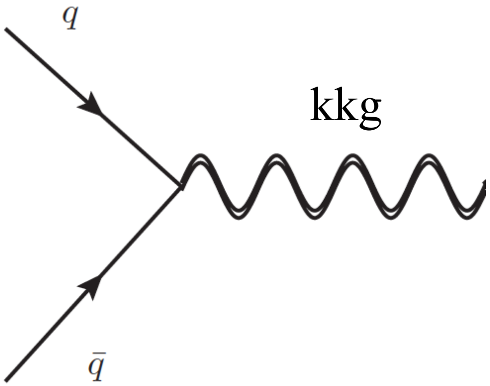
$\rightarrow l\nu$

$\rightarrow jj$

$\rightarrow WZ\,, Wh$

Benchmarks:

- SSM
- HVT
  (more appropriate for diboson channel)



$\rightarrow jj$

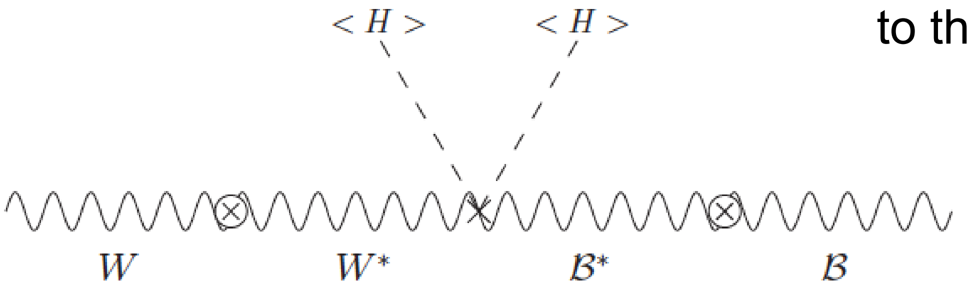
$\rightarrow t\bar{t}$

Benchmark:

RS
[Note that MCHM is dual to Warped Extra-Dimensional scenario]

Indirect Constraints on Vector Resonances

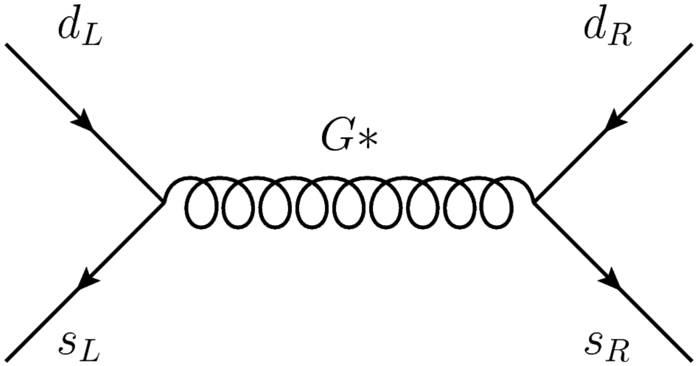
W', Z' ⟶ $\mathbf{m_V \gtrsim 2}\ \mathrm{TeV}$



Tree-level contribution to the S parameter

M. Ciuchini et al, [arXiv:1306.4644 [hep-ph]] ...

kkg ⟶ $\mathbf{m_{G^*} \gtrsim 3}\ \mathrm{TeV}$



Tree-level contribution to FV processes (K-Kbar mixing: ε_K)

In NMFV composite flavor structure

(Ex. Barbieri et al JHEP 1305 (2013) 069)

Data+Naturalness suggest to look at "cascade topologies"

naturalness *Top-partners control Higgs mass quantum corrections*

A ~125 GeV Composite Higgs implies *Top-partners below 1 TeV*

G. Panico, M. Redi, A. Tesi and A. Wulzer, [arXiv:1210.7114 [hep-ph]]

…….

EWPT
Flavor Obs.

V-prime above ~ 2 TeV
G above ~2-3 TeV*

In the "natural param. space" vector-resonances decay to vector-like top partners

A TS model for the W' pheno, including the decays to VLQs
[NV Phys.Rev. D89 (2014) 9]

W-prime in Composite Higgs / RS Models

$$\mathbf{SU(2)_L \times U(1)_Y}$$

$$\mathbf{g_2^{el} \simeq g_2}$$

(Small δT)

Custodial symmetry

$$\mathbf{SO(5) \rightarrow SO(4) \sim SU(2)_L \times SU(2)_R}$$

$$\mathbf{g_2^* > 1}$$

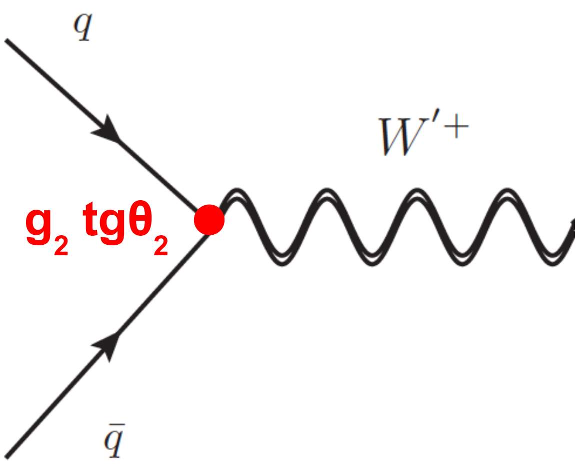
~ rho-photon mixing

$$\mathbf{W^a_{el} \in (3,1)} \longleftrightarrow \mathbf{W'^a_{com} \in (3,1)}$$

$$\cot\theta_2 = \frac{\mathbf{g_2^*}}{\mathbf{g_2^{el}}}$$

$$\mathbf{g_2} = \mathbf{g_2^{el}}\cos\theta_2 = \mathbf{g_2^*}\sin\theta_2$$

$$\mathbf{W'} = \cos\theta_2 \mathbf{W'_{com}} + \sin\theta_2 \mathbf{W_{el}}$$



Controls the strength of W' interactions

More strongly-coupled EW sectors correspond to larger cotθ$_2$

top-partners in Composite Higgs / RS Models

Linear mass mixing terms [Kaplan '91]

$$\mathbf{t_R^{el}} \Longleftrightarrow \mathbf{\tilde{T} = (1,1)_{2/3}}$$

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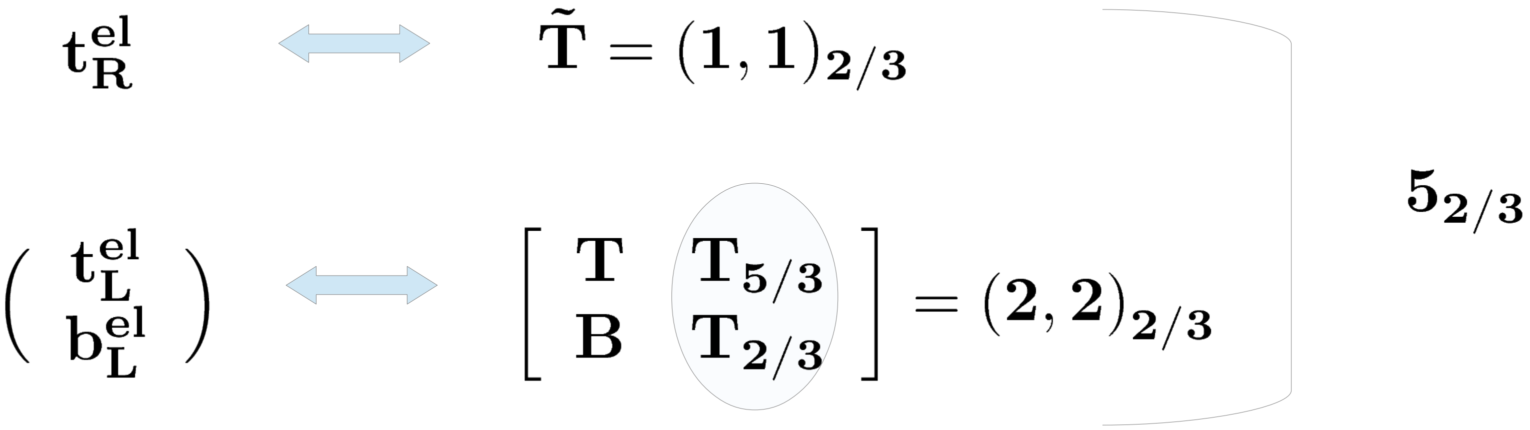

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$$\mathbf{5_{2/3}}$$

Custodial symmetry

[Carena *et al* Nucl.Phys. B759 (2006)]

Custodians

$$\mathbf{m_C = c_L m_T}$$

Custodians are expected to be lighter than the other VLQs,
Much lighter in the limit of large top degree of compositeness
($s_L \rightarrow 1$, $c_L \rightarrow 0$)

Model parameters: W' mass, ctθ_2 , (s_L)

ctθ_2 controls the production and BR

W' couplings to <u>composite</u> modes
(**$W_L h$, $W_L Z_L$, top-partners**)

$$\boxed{\propto g_2 \cot \theta_2}$$

W' couplings to <u>elementary</u> modes
(**lν, jj**)

$$\boxed{\propto g_2 \tan \theta_2}$$

Suppressed decays to leptons and di-jet for more strongly-interacting EW sectors

s_L dependence:

s_L mainly affects the relative importance of the decay channels:

W' → tb (larger s_L) W' → T b (smaller s_L)

Results could be presented in the W' mass *vs* coupling
($m_{W'}$, ctθ_2) param. space for some s_L values (i.e. 0.5, 0.9)

Comparison with “standard” benchmarks

Sequential-SM [Altarelli, Mele, Ruiz-Altaba '89] :
W' interactions with SM particles identical to those of the SM W

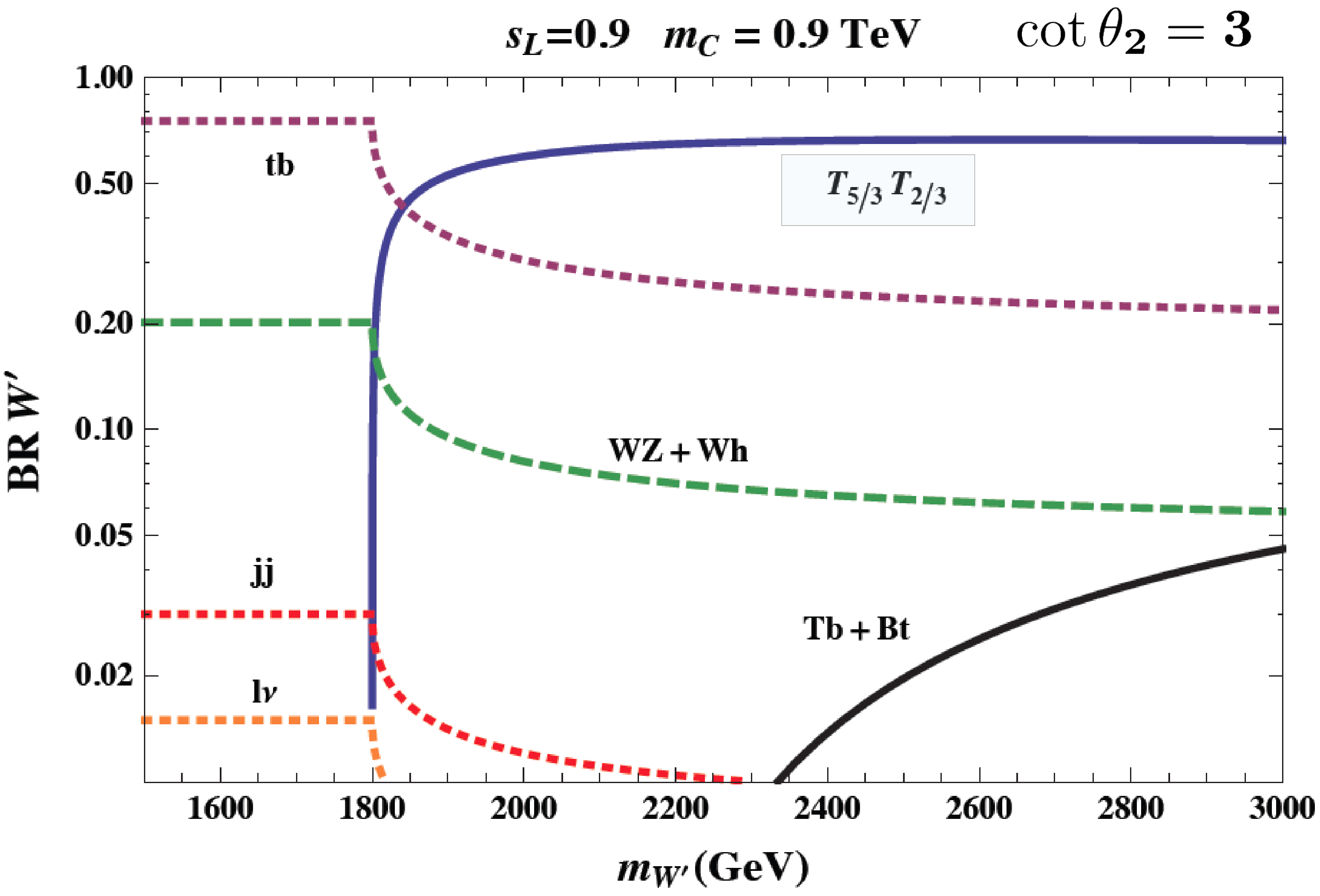
The SSM is obtained for:

- Decoupled top-partners
- $ct\theta_2 = 1$
- $s_L=0$

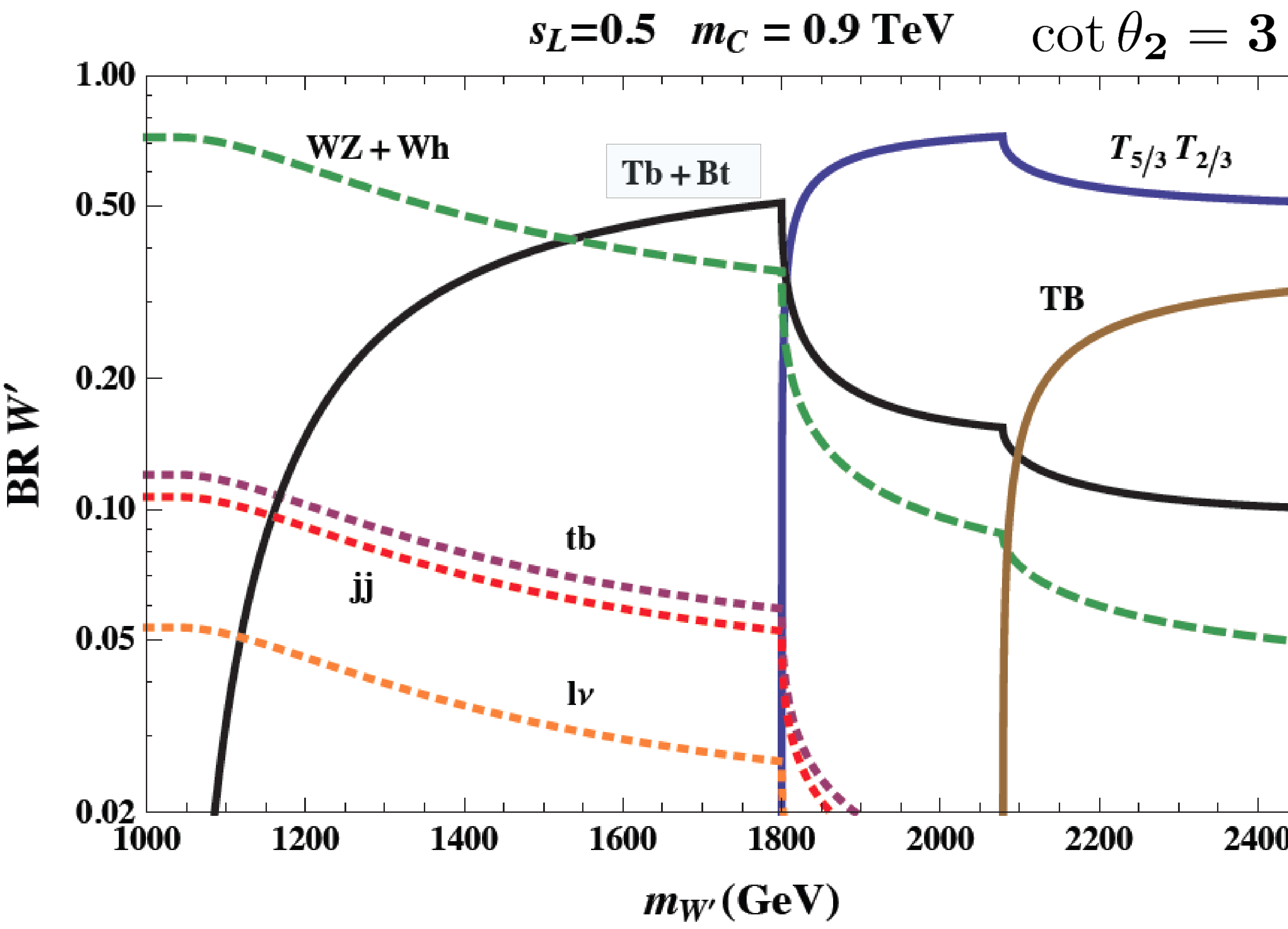
HVT Model B [Pappadopulo, Torre, Tham, Wulzer '14] :
MCHM with decoupled top-partners and universal couplings to fermions

- Decoupled top-partners
- $s_L=0$

W' BRs as functions of mW'



W' BRs as functions of mW'



Best W' Search Channels

- At high W' mass (the region favored by EWPT)

$$\mathbf{W' \rightarrow T_{5/3}\, T_{2/3}}$$

- For lighter W'

Larger $ct\theta_2$

(more natural param. space)

W' → tb (large s_L), **Tb** (intermediate s_L)

$W' \rightarrow W_L Z_L\ ,\ W_L\ h$

Small $ct\theta_2$

W' → ln

W' → jj

Channels suppressed in the scenario of strongly-interacting EW sector

LHC-8 LIMITS

Extracted from NV, PRD 89 (2014) 9, 095027

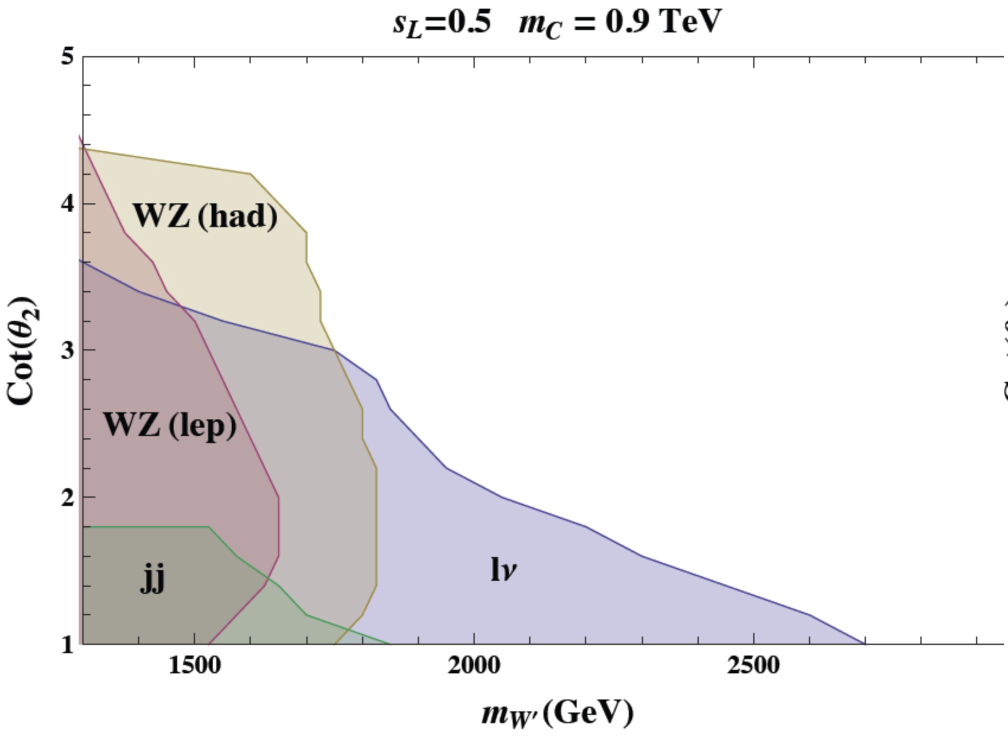
lν CMS-PAS-EXO-12-060; ATLAS-CONF-2014-017

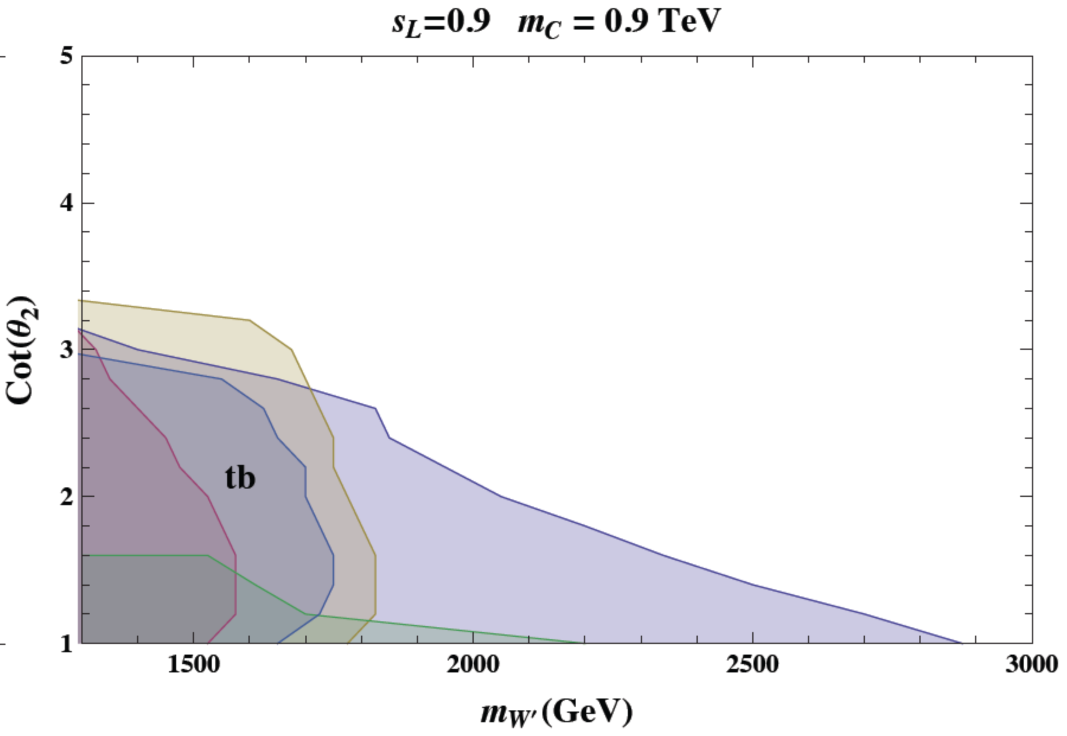
jj CMS-PAS-EXO-12-059; ATLAS-CONF-2012-148

WZ (fully had) CMS-PAS-EXO-12-024

tb CMS-PAS-B2G-12-010; ATLAS-CONF-2013-050

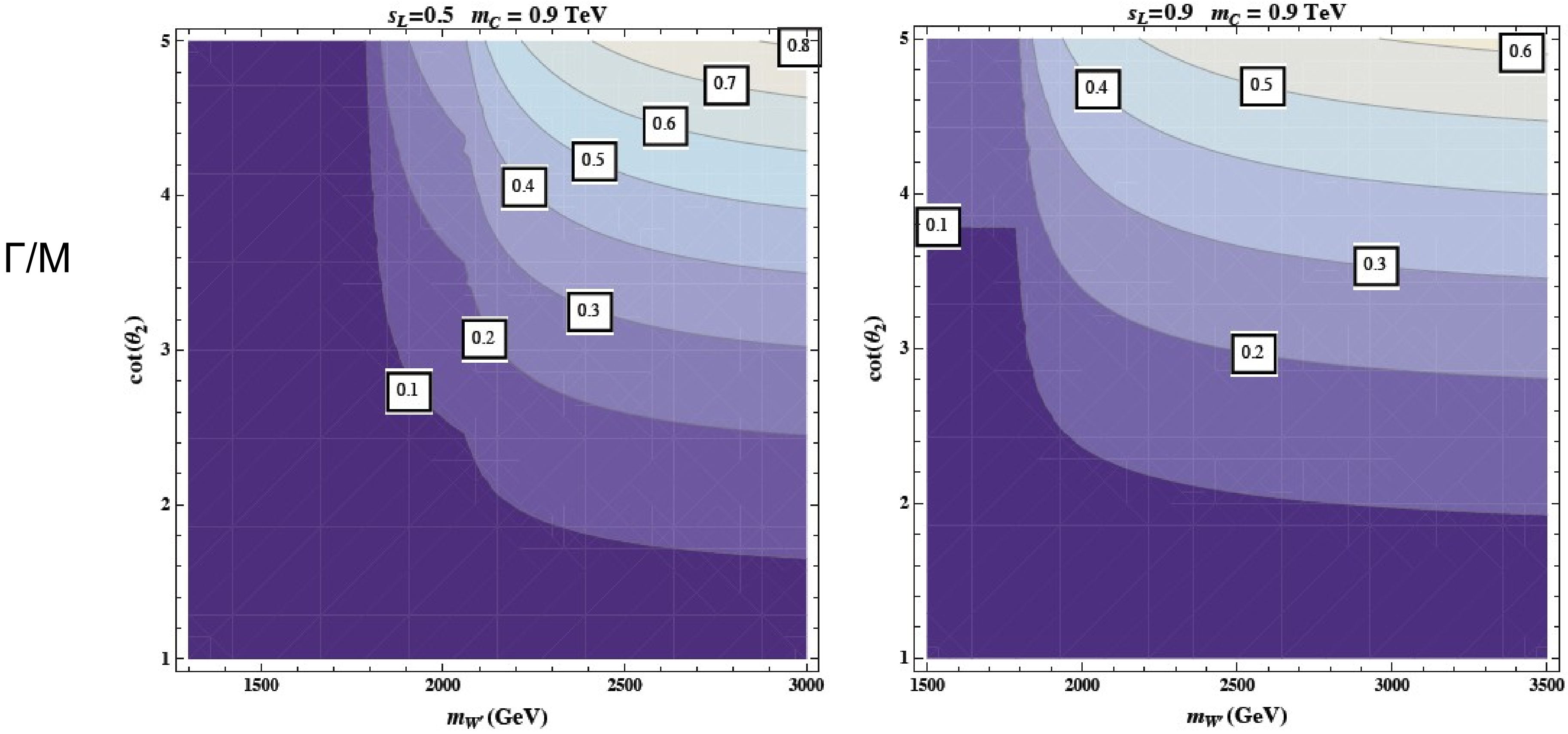
WZ (fully lep) CMS-PAS-EXO-12-025; ATLAS-CONF-2014-015





Limitation of the NWA

- Limits obtained with the NWA from ATLAS and CMS analyses which consider Sequential-Standard-Model cannot be directly applied to the CHM/RS scenario in the (Large Mass , Large coupling) parameter space

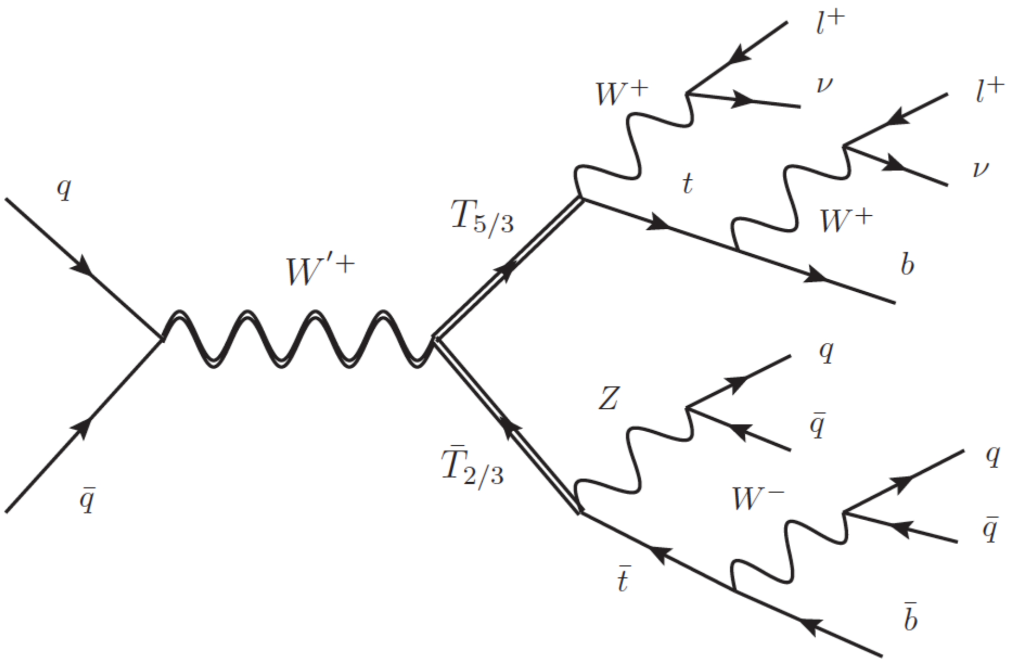


The custodian channel in the same-sign dilepton final state

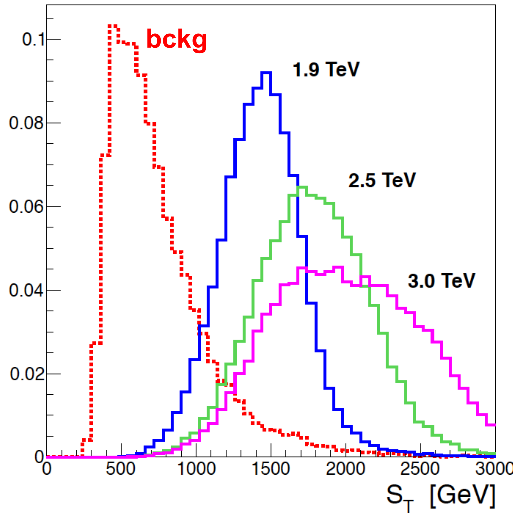
LHC-14

xsec(fb)

Same-Sign Dilep	acceptance
$m_{W'} = 1.9$ TeV	0.82
$m_{W'} = 2.2$ TeV	0.52
$m_{W'} = 2.5$ TeV	0.29
$m_{W'} = 3.0$ TeV	0.11
$m_{W'} = 3.5$ TeV	0.041
$W^+t\bar{t}$	4.1
W^+W^+	1.5
$W^+W^+W^-$	0.6
Total background	6.2



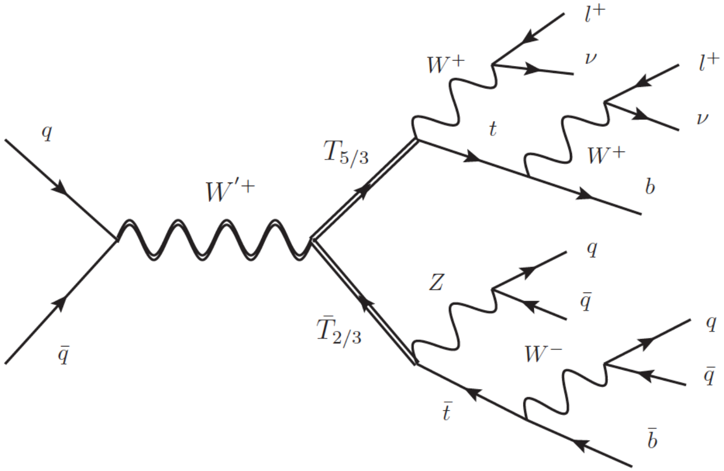
$+(h \to b\bar{b})\bar{t}$



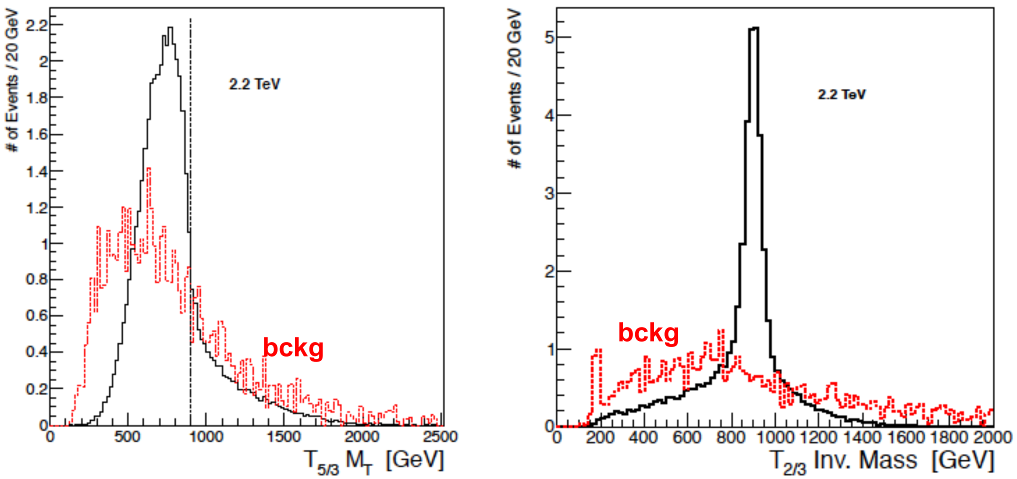
$$S_T \equiv H_T + \not{p}_T$$

	CUT-1	CUT-2
$p_T\ l(1)$	90	
$p_T\ l(2)$	30	
$p_T\ j(1)$	160	
$p_T\ j(2)$	100	
H_T	550	700
S_T	1100	1400

The custodian channel in the same-sign dilepton final state

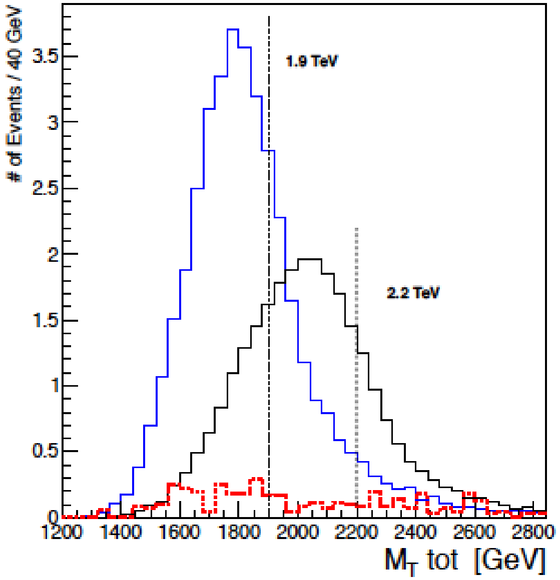


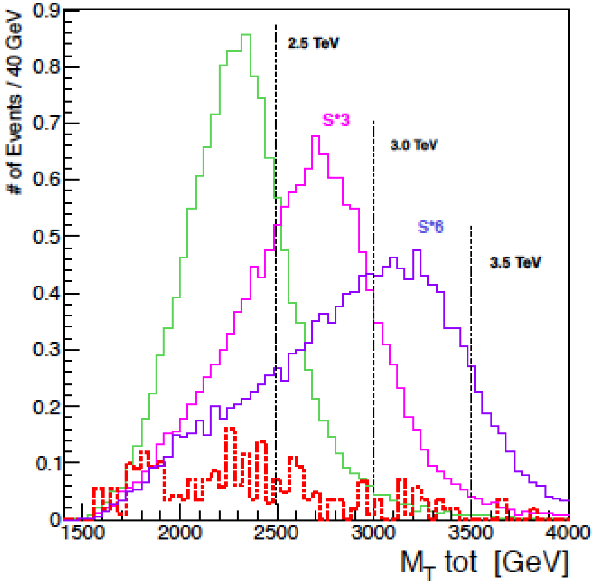
Custodians



Total transverse mass

(smearing in jet momentum included)



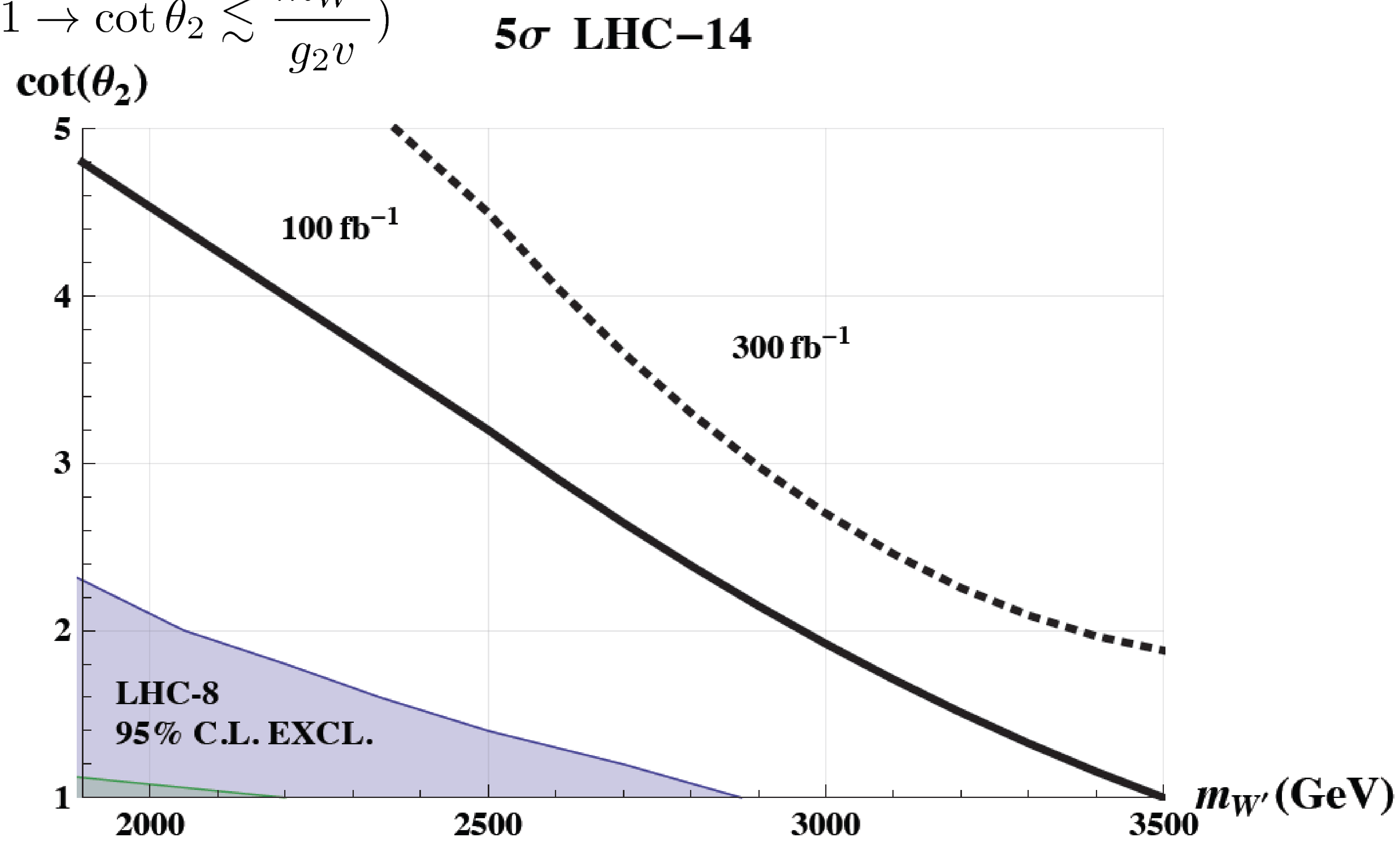


$M_T(T_{5/3}) > 400\ \mathrm{GeV}$

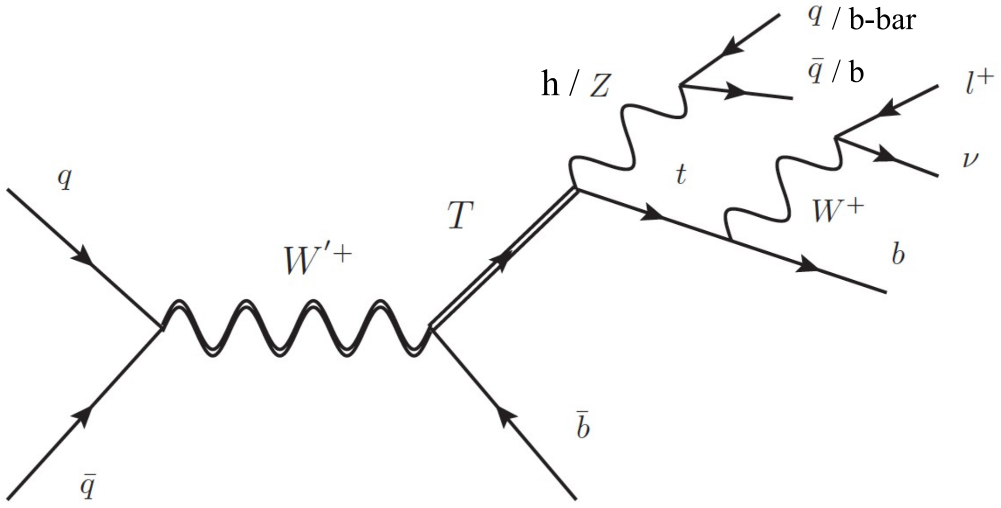
$M_{T_{2/3}} \in [0.8, 1.0]\ \mathrm{TeV}$

The custodian channel in the same-sign dilepton final state

$$(v/f < 1 \to \cot\theta_2 \lesssim \frac{m_{W'}}{g_2 v})$$



The heavy-light Tb channel, for s_L=0.5



$$pp \to l^+ + n\,\mathrm{jets} + \not{E}_T$$

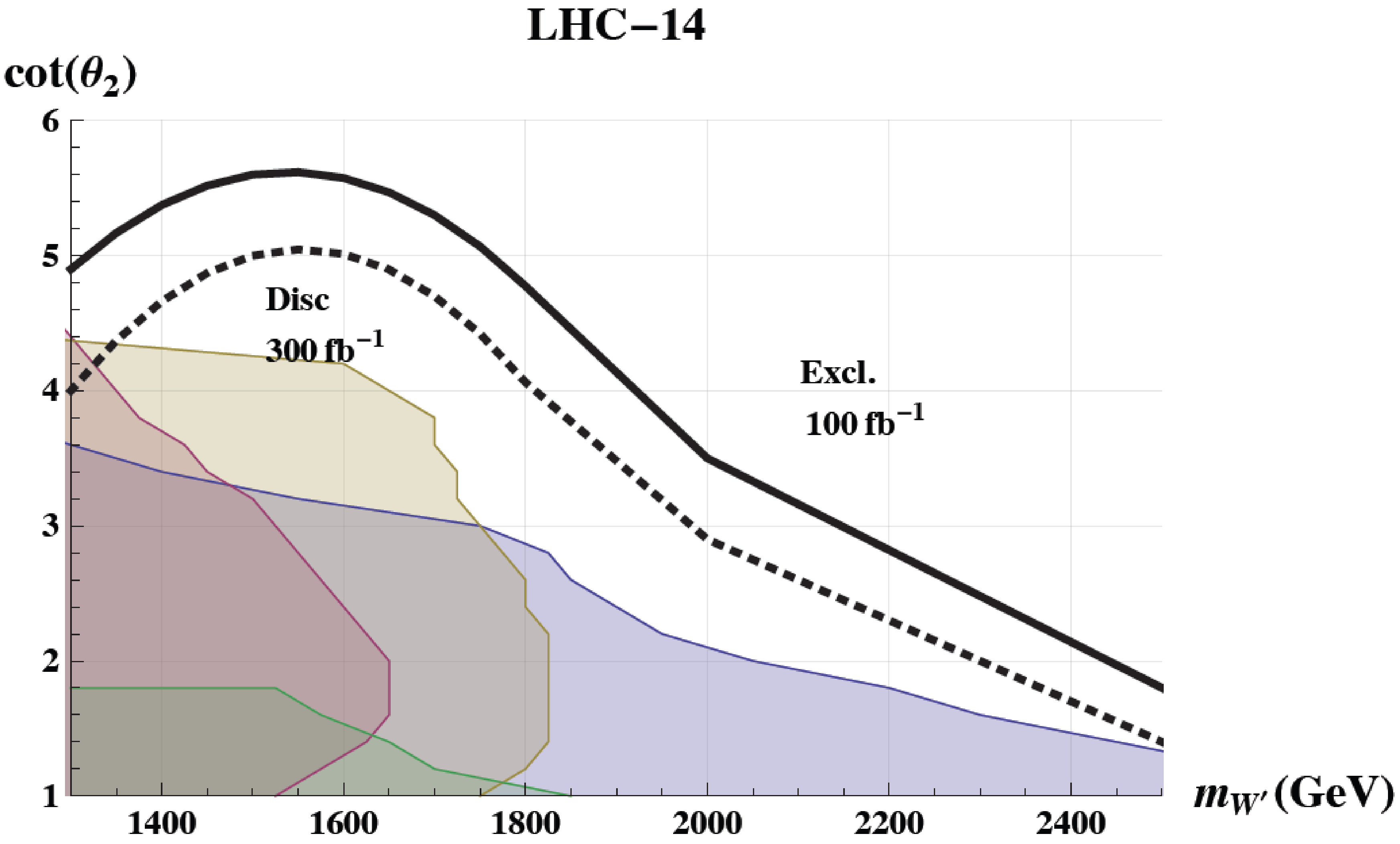
$$n \geq 3\,, \quad \text{at least 2 } b\text{-tag}$$

xsec(fb)

LHC-14	acceptance
$m_{W'} = 1.3$ TeV	9.1
$m_{W'} = 1.5$ TeV	7.5
$m_{W'} = 1.7$ TeV	5.0
$m_{W'} = 2.0$ TeV	0.70
$m_{W'} = 2.5$ TeV	0.11
$WWbb$	19000
$Wbb + jets$	1600
$W + jets$	560
Total background	21000

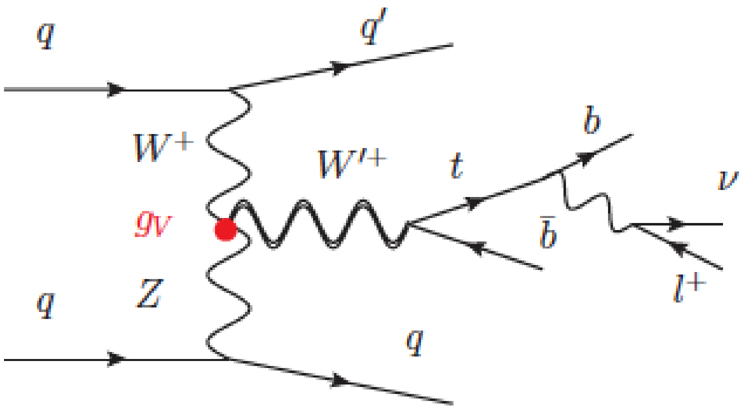
- Neutrino, top and T recostruction
- $S_T > 1.1\,\mathrm{TeV}$
$(t\,,\, b\,,\, Z/h\,,\, T\,)\, p_T > 150\,\mathrm{GeV}$
- T inv mass cut

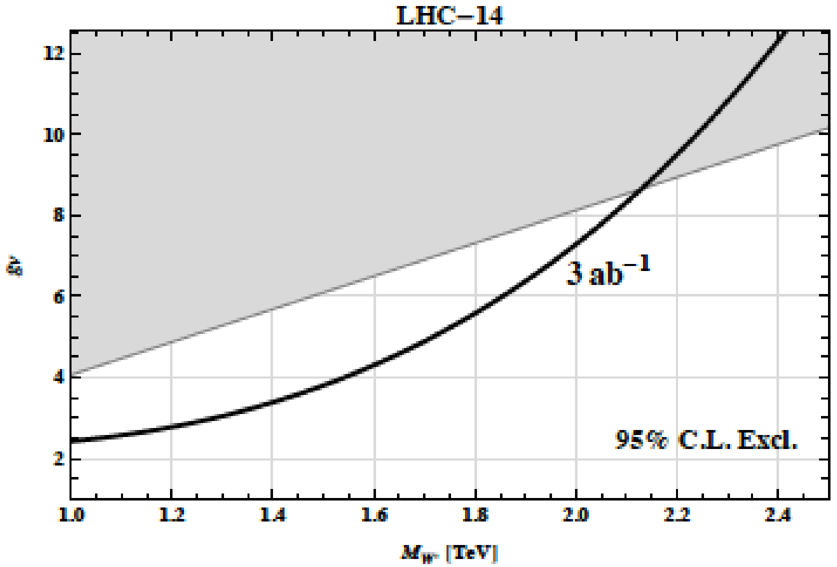
The heavy-light Tb channel, for s_L=0.5



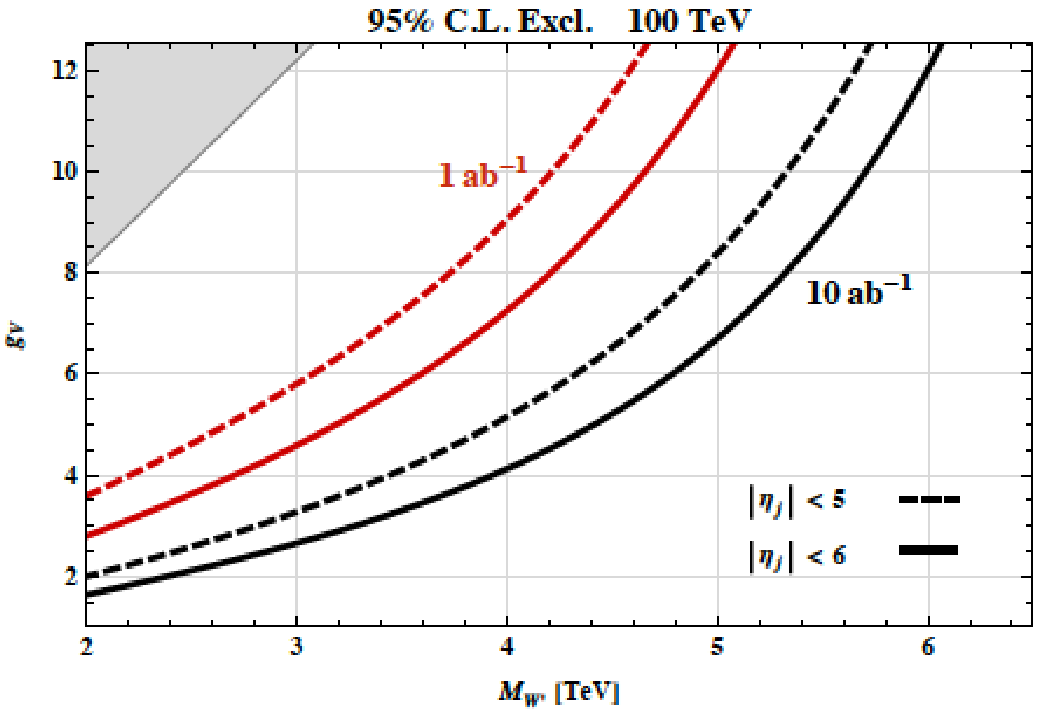
VBF production

Test the more strongly-coupled regime





$$g_V = g_2 \cot\theta_2$$



important to consider
at future colliders

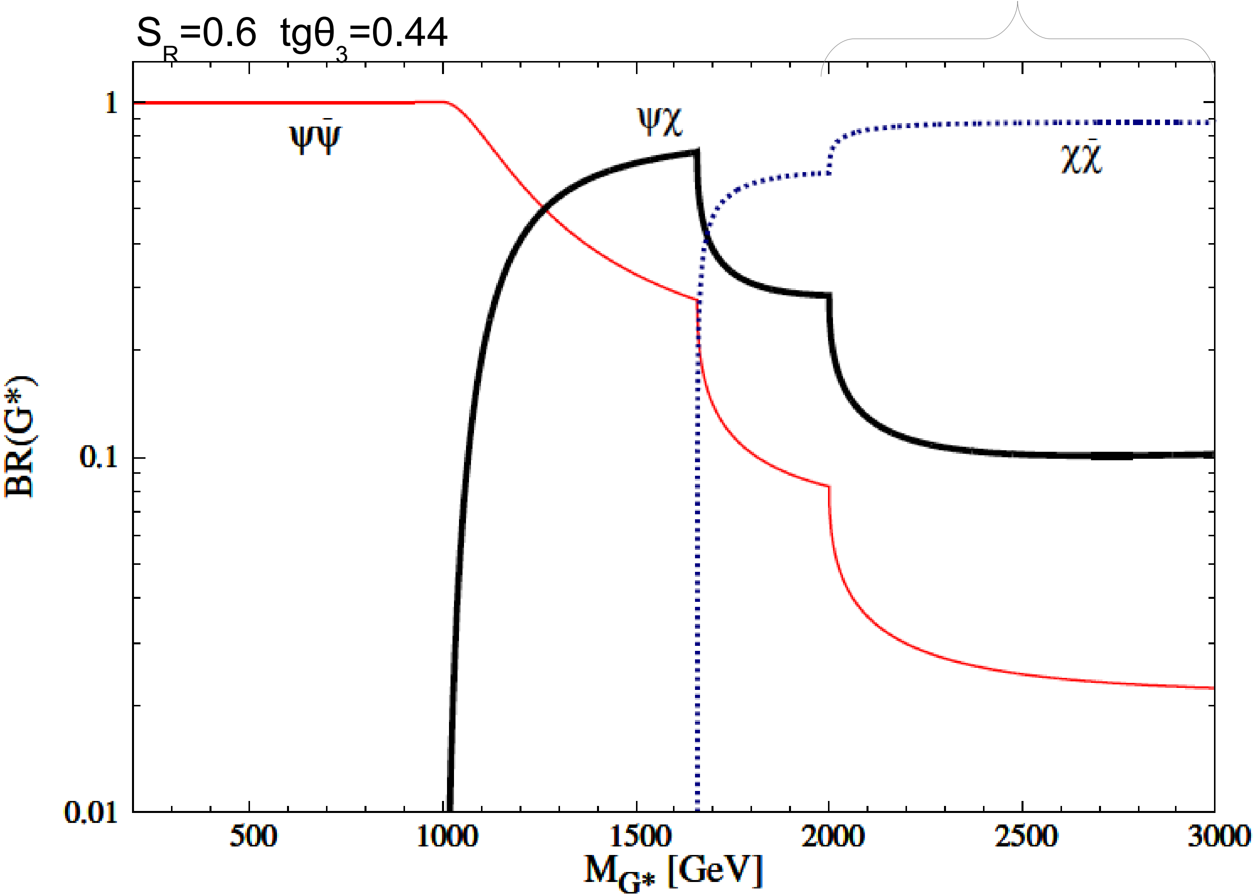
K. Mohan, NV
JHEP 1510 (2015) 031

Similar phenomenology for the G*

The only relevant difference with the W' is that G* could be broader, and thus ELUSIVE, in the heavy mass regime (above threshold for decays into pairs of VLQs)

Heavy-light Topologies
G* → Tt, Bb
→ Wtb, Ztt, Htt
[1110.6058]

S_R=0.6 tgθ_3=0.44

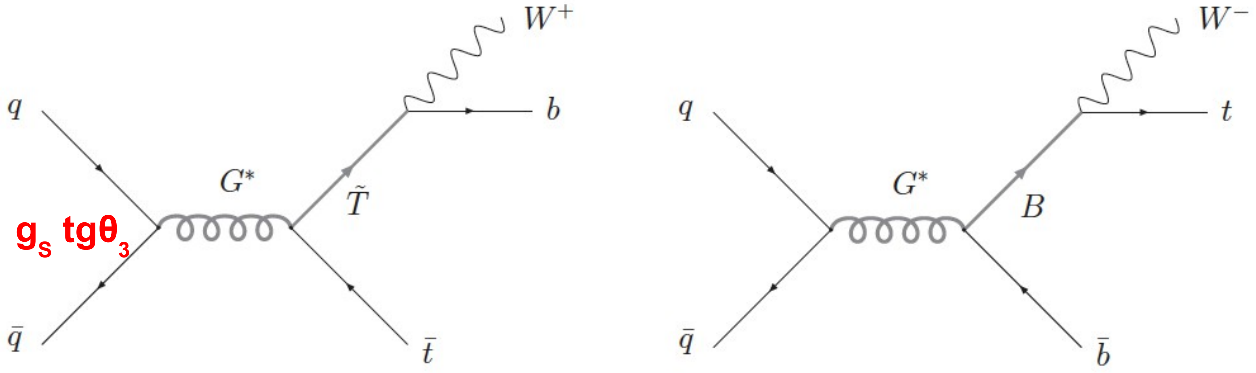


G* can be elusive (difficult to see a bump, but we could still measure indirect G* effects in VLQ pair production)
[1411.1771; 1505.01506]

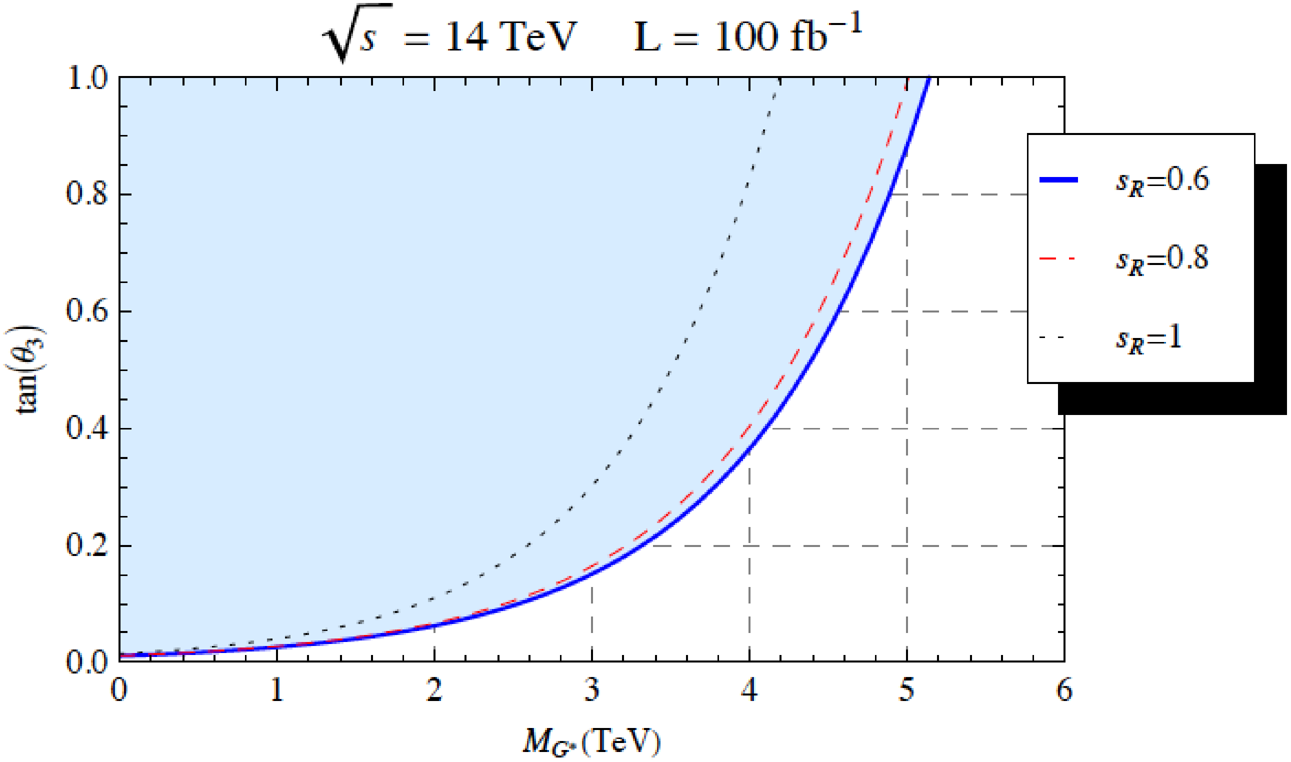
G* → custodians

The heavy-light decay channel

Bini, Contino, NV
JHEP 1201 (2012) 157



$g_s\ tg\theta_3$



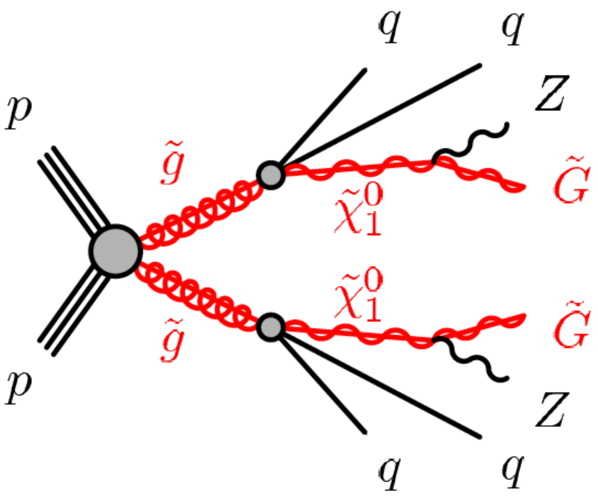
$$M_{G*}/m_{\tilde{T}} = 1.5$$

An example of the importance to consider vector resonance decays to VLQs

ATLAS 1503.03290 3 sigma excess in

Search for supersymmetry in events containing a same-flavour opposite-sign dilepton pair, jets, and large missing transverse momentum in $\sqrt{s} = 8$ TeV pp collisions with the ATLAS detector

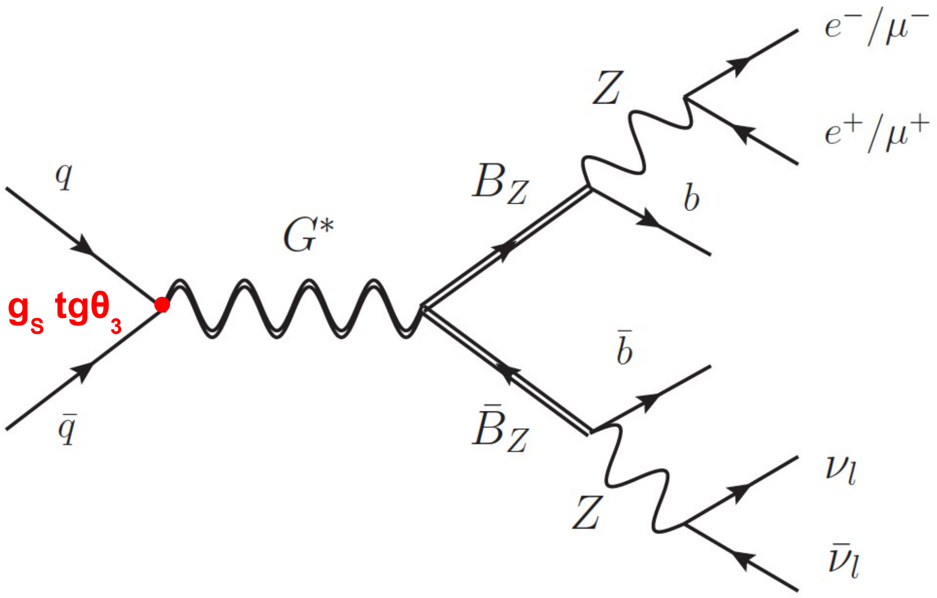
On-Z Region	E_T^{miss} [GeV]	H_T [GeV]	n_{jets}	$m_{\ell\ell}$ [GeV]	SF/DF	E_T^{miss} sig. [$\sqrt{\text{GeV}}$]	f_{ST}	$\Delta\phi(\text{jet}_{12}, E_T^{miss})$
Signal regions								
SR-Z	> 225	> 600	≥ 2	$81 < m_{\ell\ell} < 101$	SF	-	-	> 0.4



But a **non-susy** explanation is also possible (GGM does not fit well the observed jet multiplicity distribution)

An example of the importance to consider vector resonance decays to VLQs

NV, 1504.01768



G* decays to VLQs (bottom partners)

Bottom partners included to explain the bottom mass generation

$$Q' = \begin{pmatrix} B_{-1/3} & T' \\ B_{-4/3} & B' \end{pmatrix} = (\mathbf{3},\mathbf{2},\mathbf{2})_{-1/3}$$

Custodial symmetry leads to two kinds of peculiar bottom-partners

$$B_H = \frac{1}{\sqrt{2}}(B_{-1/3} + B')$$

100% decays to hb

$$B_Z = \frac{1}{\sqrt{2}}(B_{-1/3} - B')$$

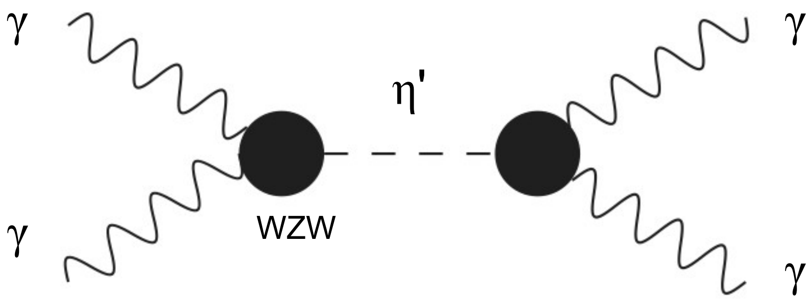
100% decays to Zb

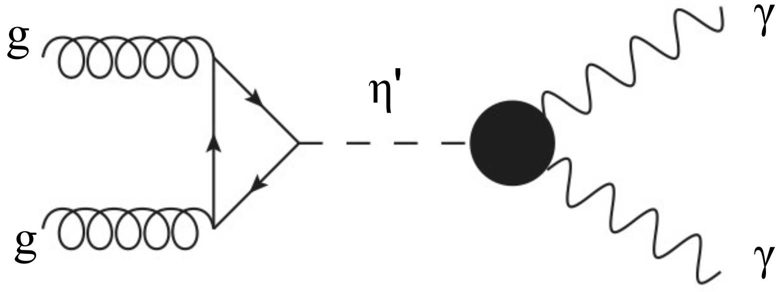
HIGH RATE for ZZbb hhbb final states

Composite Scalars and Topological Sectors

- η'-like states (related to U(1) axial anomaly)
- WZW anomalous couplings to EW gauge bosons, in particular to diphoton
- Diphoton channel very powerful to test strong dynamics

E. Molinaro, F. Sannino, NV
Mod. Phys. Lett. A 31 (2016) 26, 1650155
Nucl. Phys. B 911 (2016) 106-126





Minimal models

MCHM Agashe, Contino, Pomarol, NPB 719 (2005)

$$SO(5) \to SO(4) \sim SU(2)_L \times SU(2)_R$$

$$(2,2) \quad 4\mathrm{GB}\ : h + W_L^{\pm}, Z_L$$

Minimal realization including custodial symmetry

Cannot be realized by an underlying fundamental fermionic matter theory

$$SU(4)/Sp(4) \sim SO(6)/SO(5)$$

$$(2,2)+(1,1) \quad 5\,\mathrm{GB}\ : W_L^{\pm}, Z_L + h + \eta$$

Includes custodial symmetry

underlying fundamental fermionic matter theory

↓

N_f=2 techni-fermions in a Pseudo-Real of the underlying gauge dynamics.
Condensate in a 2-index antisymmetric rep. of SU(4)

Unveiling a new BSM strong dynamics via anomalous interactions

Molinaro, Sannino, Thomsen, NV, Phys. Rev. D 96 (2017) 7, 075040

ANOMALY: an invariance of the classical theory is no longer present after quantization

► Inspiration from QCD

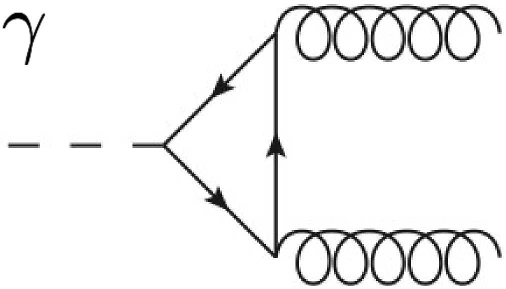
$$U(2)_L \times U(2)_R \sim SU(2)_V \times SU(2)_A \times U(1)_V \times U(1)_A$$

Broken (spontaneously) by the pion condensate and also by EM ANOMALY

Anomalous (instantons)

$m_{\eta'}$

$$\pi_0 \to \gamma\gamma$$



$$\partial_\mu J^\mu_A = \frac{e^2 N_C}{96\pi^2}\epsilon^{\mu\nu\rho\sigma}F_{\mu\nu}F_{\rho\sigma} \quad + \ldots$$

$$J^\mu_A = \frac{1}{2}\left(\bar{u}\gamma^\mu\gamma_5 u - \bar{d}\gamma^\mu\gamma_5 d\right)$$

SU(4)/Sp(4)

Sannino, Cacciapaglia,
JHEP 04 111

Minimal composite model with fermionic UV completion

4 Weyl fermions in $(1,2)_0 \oplus (1,1)_{-1/2} \oplus (1,1)_{+1/2}$ of $\mathrm{SU}(3)_c \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$

and in Pseudo-Real of **new strong gauge group** G_{TC}

No gauge anomalies

$$\mathcal{L}_{\mathrm{TC}} = -\frac{1}{4}\mathcal{G}^A_{\mu\nu}\mathcal{G}^{A,\mu\nu} + i\overline{\psi}_a\overline{\sigma}^\mu D_\mu\psi^a - \tfrac{1}{2}\left(\psi^a m_{ab}\epsilon_{\mathrm{TC}}\psi^b + \mathrm{h.c.}\right)$$

$\langle\psi^a\epsilon_{\mathrm{TC}}\psi^b\rangle = f^2\Lambda\,\Sigma_0^{ab}$ $\mathrm{SU}(4) \rightarrow \mathrm{Sp}(4)$ 5 NGB $W_L^\pm, Z_L + h + \eta$

For $m_{ab} \rightarrow 0$ Extra (anomalous) global U(1) symmetry, with associated particle η' (QCD analogy)

SU(4)/Sp(4)

Minimal composite model with fermionic UV completion

4 Weyl fermions in $(1,2)_0 \oplus (1,1)_{-1/2} \oplus (1,1)_{+1/2}$ of $\mathrm{SU}(3)_c \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$

and in Pseudo-Real of **new strong gauge group** G$_{\mathrm{TC}}$

No gauge anomalies

$$\mathcal{L}_{\mathrm{TC}} = -\frac{1}{4}\mathcal{G}^{A}_{\mu\nu}\mathcal{G}^{A,\mu\nu} + i\overline{\psi}_a\overline{\sigma}^{\mu}D_{\mu}\psi^a - \tfrac{1}{2}\left(\psi^a m_{ab}\epsilon_{\mathrm{TC}}\psi^b + \mathrm{h.c.}\right)$$

$\langle\psi^a\epsilon_{\mathrm{TC}}\psi^b\rangle = f^2\Lambda\,\Sigma_0^{ab}$ $\quad \mathrm{SU}(4) \to \mathrm{Sp}(4)$ $\quad$ 5 NGB $\quad W_L^{\pm}, Z_L + h + \eta$

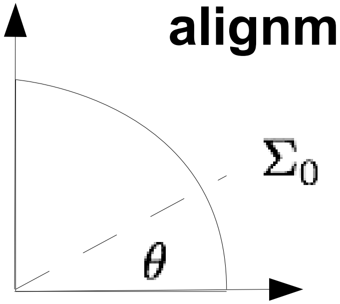
+ η'

$\sin\theta = 1$
(TC limit)

vacuum alignment

$$\boxed{v = 2\sqrt{2}f\sin\theta}$$

Top contrib.



$\sin\theta = 0$ (No EWSB)

Gauge contribution

$$\Sigma_0 = \cos\theta\,\Sigma_B + \sin\theta\,\Sigma_H$$

$$= \begin{pmatrix} i\,\sigma_2\cos\theta & \mathbf{1}\sin\theta \\ -\mathbf{1}\sin\theta & -i\,\sigma_2\cos\theta \end{pmatrix}$$

SU(4)/Sp(4)

Minimal composite model with fermionic UV completion

4 Weyl fermions in $(1,2)_0 \oplus (1,1)_{-1/2} \oplus (1,1)_{+1/2}$ of $\mathrm{SU}(3)_c \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$

and in Pseudo-Real of **new strong gauge group** G_{TC}

No gauge anomalies

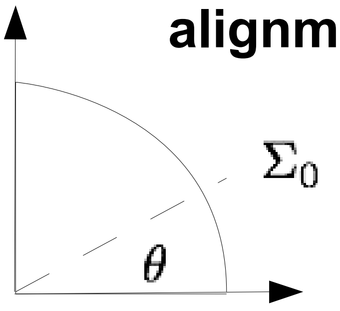
$$\mathcal{L}_{\mathrm{TC}} = -\frac{1}{4}\mathcal{G}^A_{\mu\nu}\mathcal{G}^{A,\mu\nu} + i\overline{\psi}_a\overline{\sigma}^\mu D_\mu \psi^a - \tfrac{1}{2}\left(\psi^a m_{ab}\epsilon_{\mathrm{TC}}\psi^b + \mathrm{h.c.}\right)$$

$\langle \psi^a \epsilon_{\mathrm{TC}} \psi^b \rangle = f^2 \Lambda \Sigma_0^{ab}$ $\mathrm{SU}(4) \to \mathrm{Sp}(4)$ 5 NGB $W_L^\pm, Z_L + h + \eta$

$+ \eta'$

$\sin\theta = 1$
(TC limit)

Top
contrib.



vacuum alignment

$$\boxed{v = 2\sqrt{2} f \sin\theta}$$

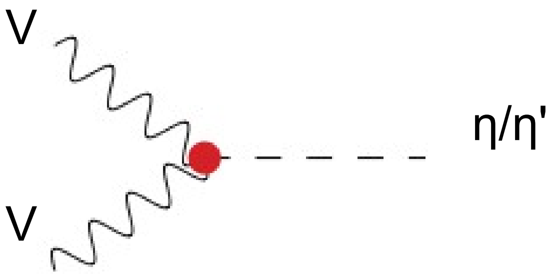
$\sin\theta = 0$ (No EWSB)

Gauge contribution

Fine-tuning ~ sinθ

In the CW potential,
in order to have EWSB
and a light Higgs

WZW terms



Couplings of the anomalous interactions are directly proportional to d(R), the dimension of the technifermion representation under G_{TC} (~ N)

large-N CHM especially interesting for studies of anomalous interactions at future colliders

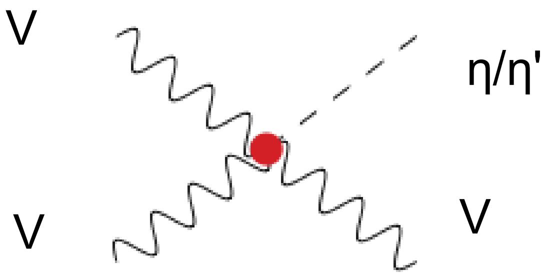
$$-\frac{\enclose{circle}{d(R)}\alpha_{\mathrm{EM}}\boxed{\cos\theta\sin\theta}}{32\pi v}\eta\left[\frac{2}{c_w s_w}A_{\mu\nu}\tilde{Z}^{\mu\nu}+\frac{c_w^2-s_w^2}{c_w^2 s_w^2}Z_{\mu\nu}\tilde{Z}^{\mu\nu}+\frac{2}{s_w^2}W^+_{\mu\nu}\tilde{W}^{-\mu\nu}\right]$$

$$-\frac{\enclose{circle}{d(R)}\alpha_{\mathrm{EM}}\boxed{\sin\theta}}{48\pi v}\eta'\left[3A_{\mu\nu}\tilde{A}^{\mu\nu}+3\frac{c_w^2-s_w^2}{c_w s_w}A_{\mu\nu}\tilde{Z}^{\mu\nu}+\frac{3-6c_w^2 s_w^2-\sin^2\theta}{2c_w^2 s_w^2}Z_{\mu\nu}\tilde{Z}^{\mu\nu}\right.$$

$$\left.+\frac{3-\sin^2\theta}{s_w^2}W^+_{\mu\nu}\tilde{W}^{-\mu\nu}\right]$$

Note: no EM anomaly for the η

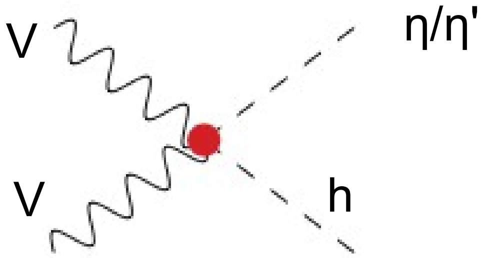
WZW terms



Gauged WZW action also generates η/η' interactions with 3 gauge bosons:

$$-i\frac{d(R)\alpha_{\mathrm{EM}}^{3/2}\cos\theta\sin\theta}{4\sqrt{\pi}v}\varepsilon^{\mu\nu\rho\sigma}\boxed{\partial_\mu\eta}\left[\frac{2}{s_w^2}A_\nu+\frac{2c_w^2-\sin^2\theta}{c_w s_w^3}Z_\nu\right]W_\rho^+W_\sigma^-$$

$$-i\frac{d(R)\alpha_{\mathrm{EM}}^{3/2}\sin\theta}{12\sqrt{\pi}v}\varepsilon^{\mu\nu\rho\sigma}\boxed{\partial_\mu\eta'}\left[\frac{6-2\sin^2\theta}{s_w^2}A_\nu+\frac{6c_w^2-(1+2c_w^2)\sin^2\theta}{c_w s_w^3}Z_\nu\right]W_\rho^+W_\sigma^-$$



... and with 2 gauge bosons and the Higgs

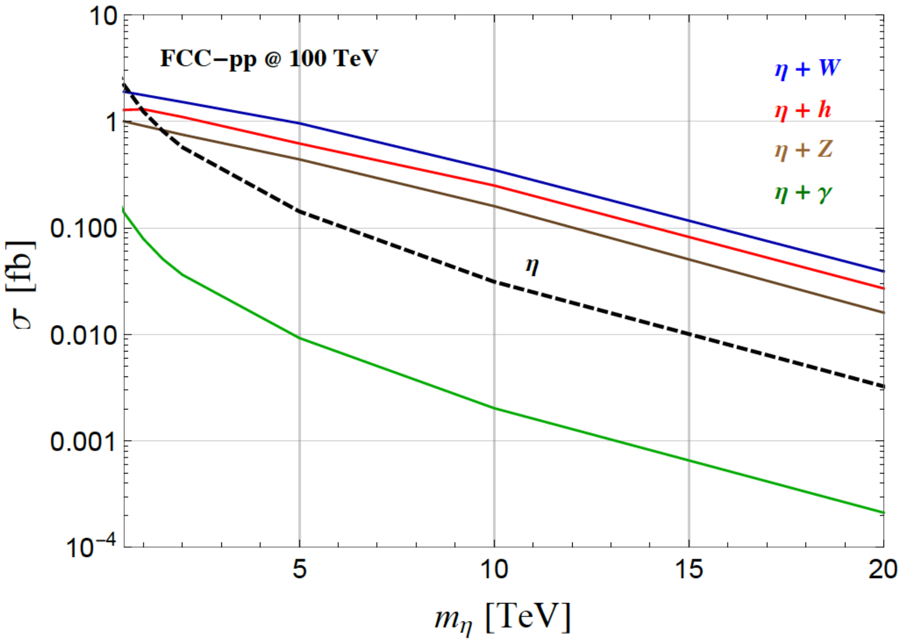
$$-\frac{d(R)\alpha_{\mathrm{EM}}\sin^3\theta}{16\pi v^2}\varepsilon^{\mu\nu\rho\sigma}\left[\frac{4}{c_w s_w}\partial_\mu h\partial_\nu\eta A_\rho Z_\sigma\right.$$

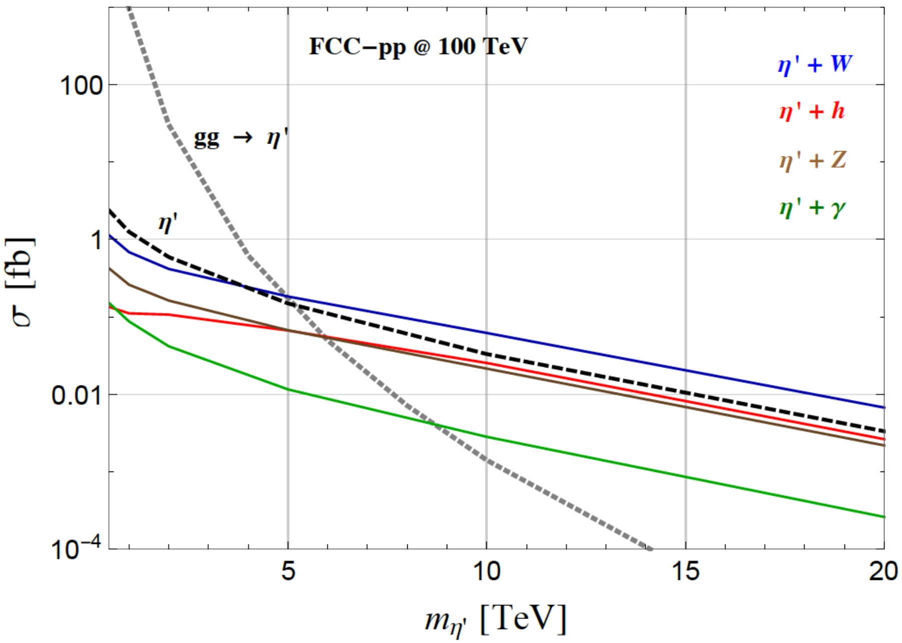
$$\left.+h\overleftrightarrow{\partial}_\mu\eta\left(\frac{c_w^2-s_w^2}{c_w^2s_w^2}Z_{\nu\rho}Z_\sigma+\frac{1}{s_w^2}\left(W^+_{\nu\rho}W^-_\sigma+W^-_{\nu\rho}W^+_\sigma\right)+\frac{1}{c_w s_w}\left(A_{\nu\rho}Z_\sigma+Z_{\nu\rho}A_\sigma\right)\right)\right]$$

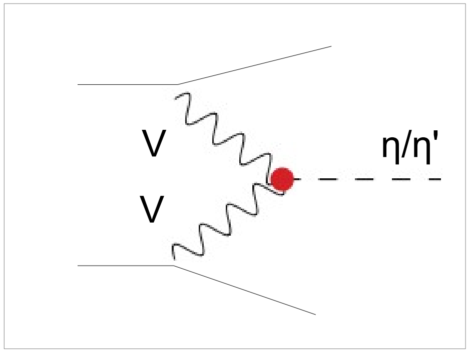
$$-\frac{d(R)\alpha_{\mathrm{EM}}\cos\theta\sin^3\theta}{24\pi v^2}\varepsilon^{\mu\nu\rho\sigma}h\partial_\mu\eta'\left[\frac{1}{c_w^2s_w^2}Z_{\nu\rho}Z_\sigma+\frac{1}{s_w^2}\left(W^+_{\nu\rho}W^-_\sigma+W^-_{\nu\rho}W^+_\sigma\right)\right]$$

Note: no anomalous triple- quartic-gauge couplings are generated

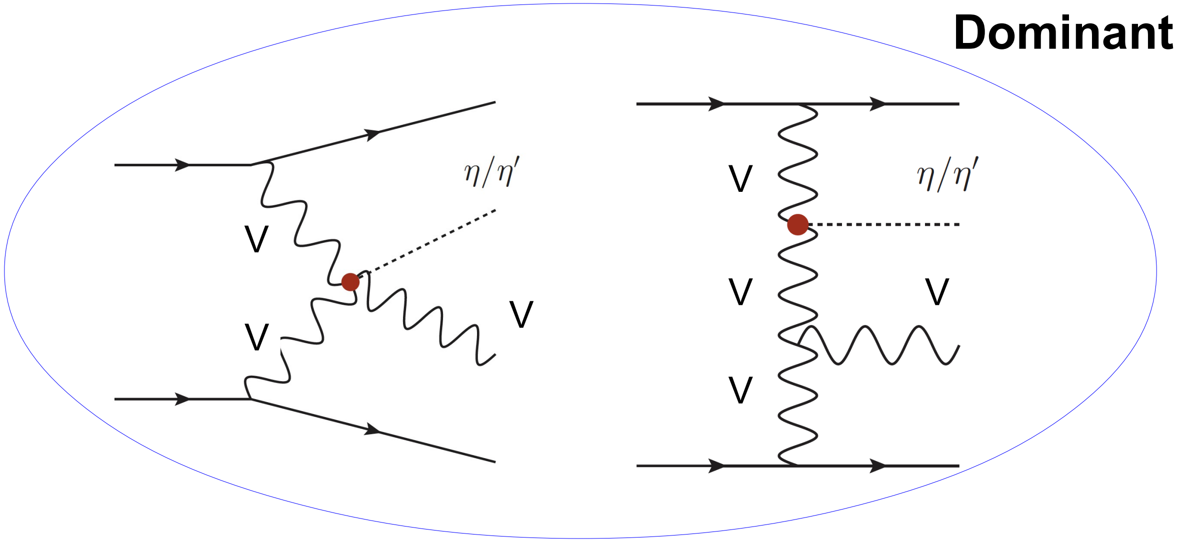
FCC-pp @ 100 TeV







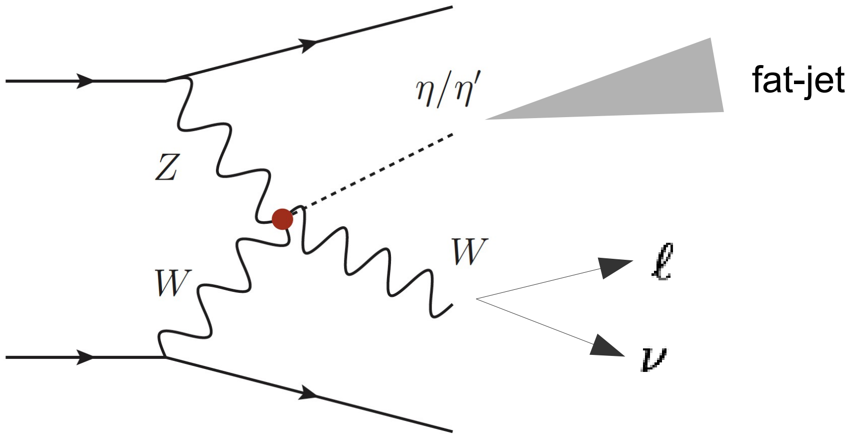
Dominant

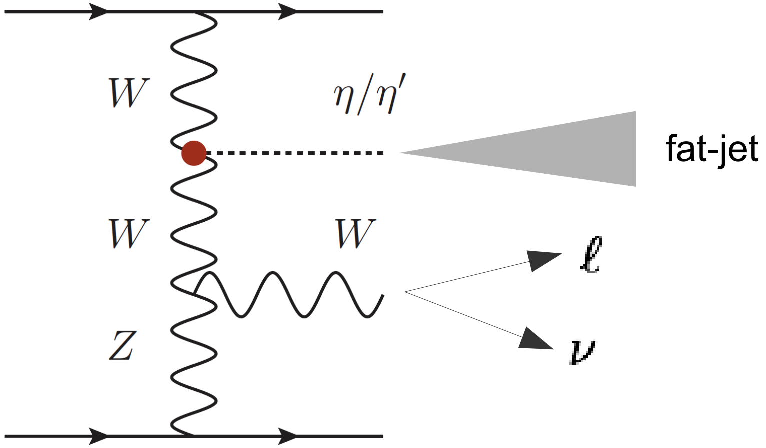


The signal (η/η' + W)

Production via topological interactions (interference between diagrams with 4 and 3 bosons interactions)

$$\eta \to VV \to \text{jets} \qquad \eta' \to t\bar{t} \to \text{jets}$$



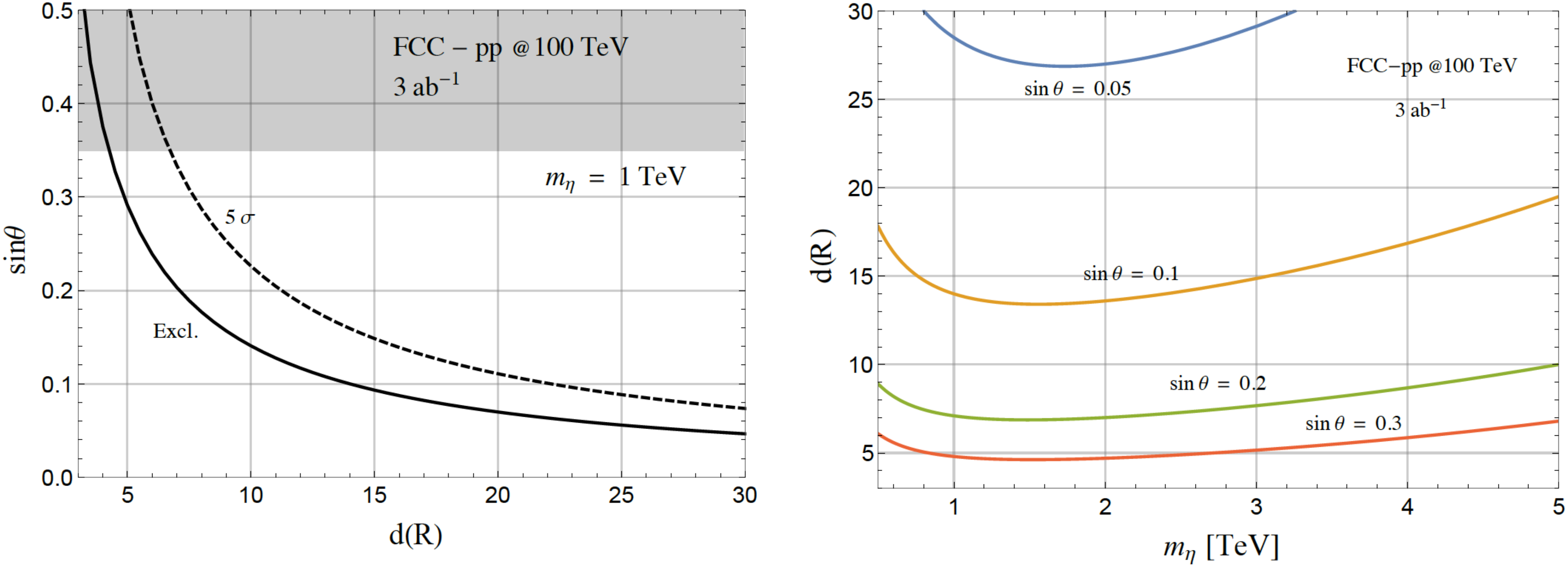


We reconstruct a single fat-jet from the hadronic decays of the η/η' (Jets clustered by FastJet with R=1.5)

$$\ell + n\,\text{jets} + \not{E}_T\,, \quad n \geq 3\,, \quad \ell \equiv e, \mu$$

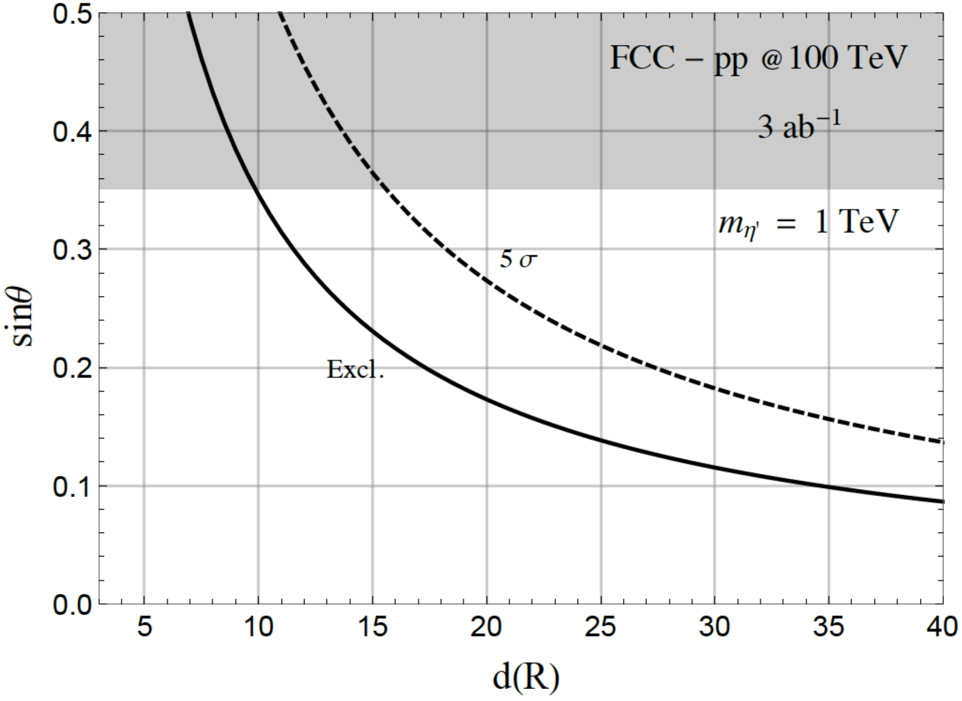
Dominant Background: W+jets

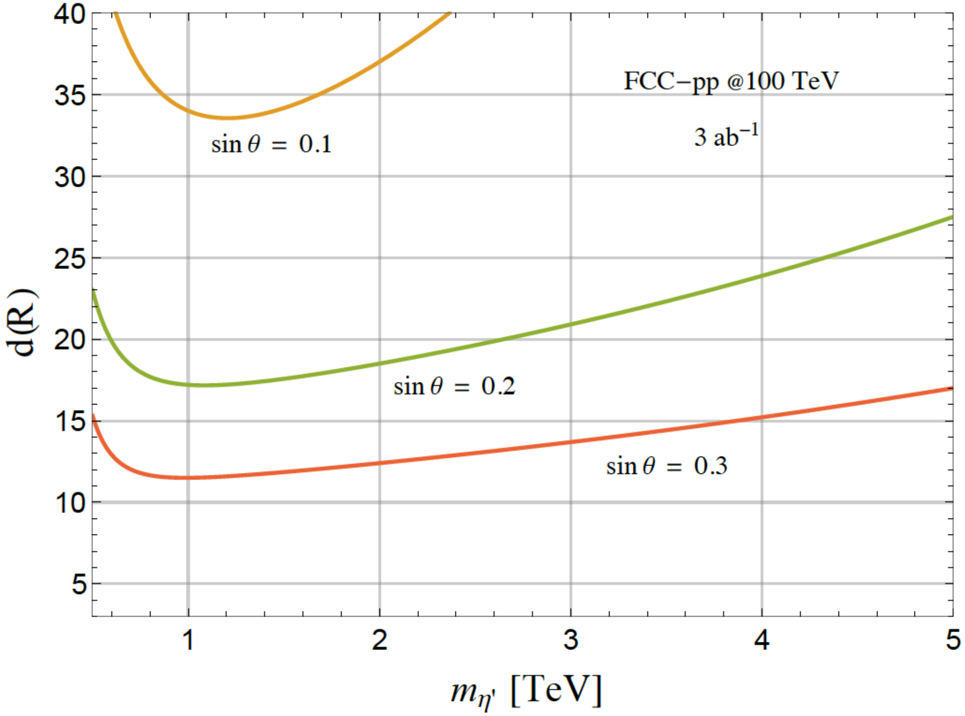
η signal



Wide FCC-pp reach on the fundamental parameters of the composite dynamics (d(R)) and the EWSB mechanism (sinθ)

η' signal


FCC – pp @ 100 TeV
3 ab^{-1}
$m_{\eta'}$ = 1 TeV
5 σ
Excl.
sinθ
0.0
0.1
0.2
0.3
0.4
0.5
d(R)
5
10
15
20
25
30
35
40


FCC−pp @100 TeV
3 ab^{-1}
sin θ = 0.1
sin θ = 0.2
sin θ = 0.3
d(R)
5
10
15
20
25
30
35
40
$m_{\eta'}$ [TeV]
1
2
3
4
5