One-family walking technicolor in light of LHC-Run II

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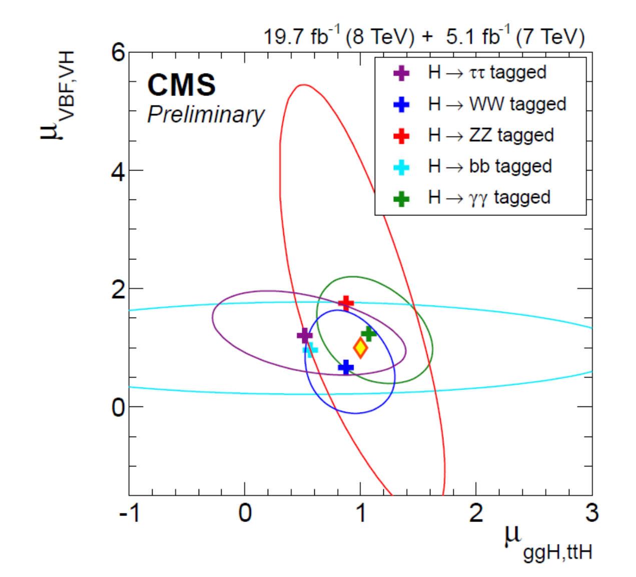
1. Introduction
2. Walking TC and Technidilaton (TD)
3. LHC Higgs v.s. TD in the one-family WTC w/ N_{TC}=4 and N_{TF}=8
4. Discovering technipion and technirhos at LHC
5. Summary

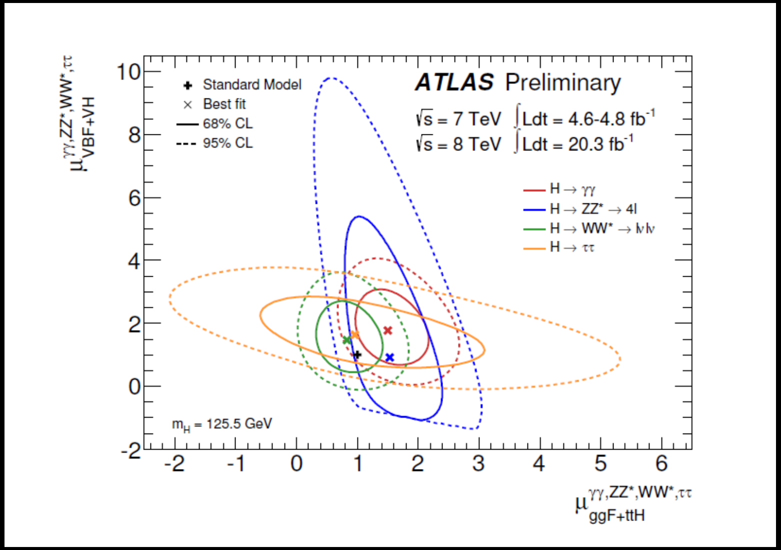
SCGT15@ Nagoya, Japan March 3 – 6, 2015

1. Introduction

* LHC discovered a Higgs boson

* measured coupling properties
consistent w/ the SM Higgs as of LHC-Run I



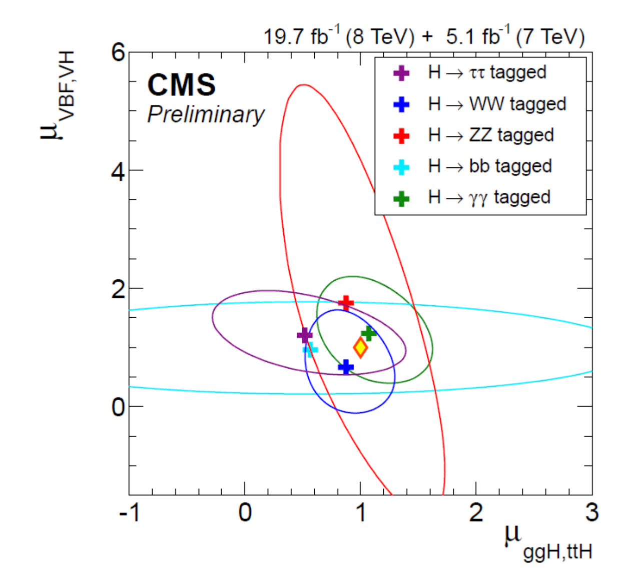


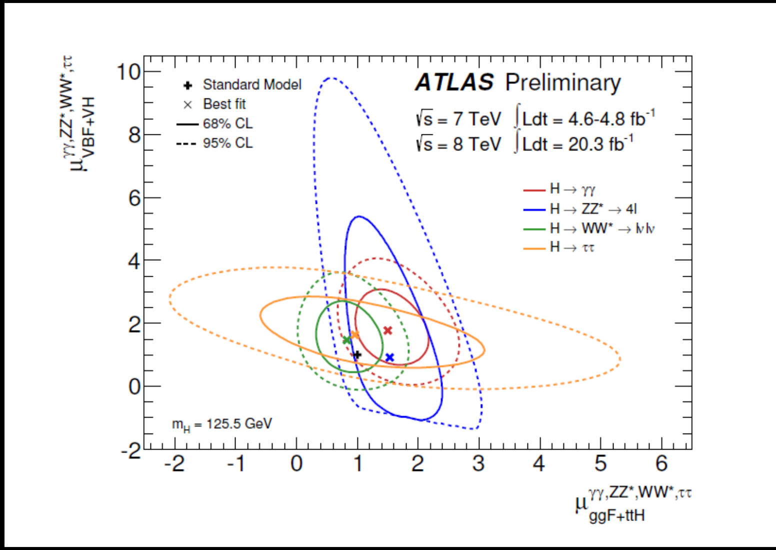
1. Introduction

* LHC discovered a Higgs boson

* measured coupling properties
  consistent w/ the SM Higgs as of LHC-Run I

* is it really the SM Higgs?
  --- origin of mass put in by hand?





It could be a composite scalar, "Technidilaton (TD)"

Yamawaki et al ('86); Bando et al ('86)

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giving dynamical origin of mass by technifermion condensate

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(approximate) scale symmetry
technifermion condensate

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-- lightness protected by the scale symmetry
~ 125 GeV.

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see later discussion

New observation!!

-- lightness protected by the scale symmetry & ***large Nf WTC***
~ 125 GeV.

M.Kurachi, S.M., R.Shrock and K.Yamawaki, in preparation

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-- lightness protected by the scale symmetry *& large Nf WTC*
~ 125 GeV.

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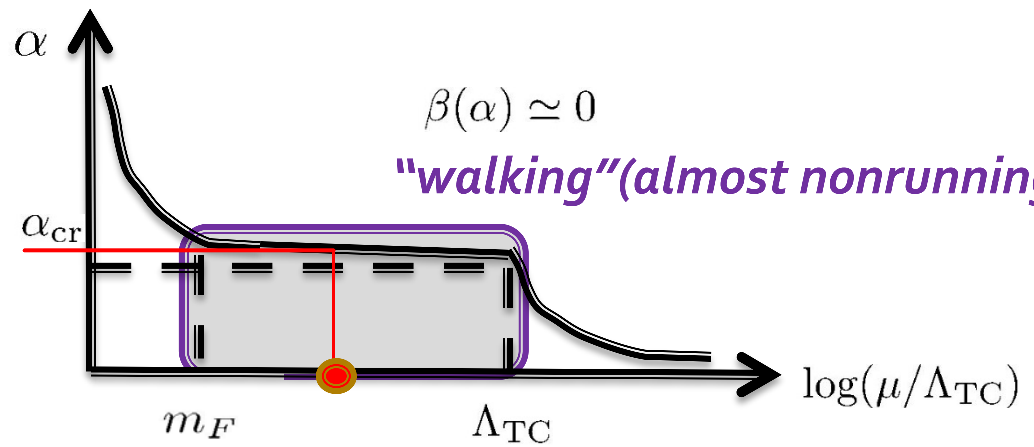
**** 125 GeV TD signatures, in one-family model w/ N_{TC}=4,***
are consistent with current LHC Higgs data

S.M. and K. Yamawaki, PRD85,86 ('12), PLB719 ('13); S.M. 1304.4882; talk at SCGT14mini ('14

2. Walking technicolor (WTC) and technidilaton (TD)

* Characteristic features of Walking Technicolor (WTC)



* **Dynamical EW/chiral SB by technifermion condensate**

$\langle \bar{F} F \rangle \neq 0$ **mass generation via Miransky scaling** $m_F \sim \Lambda_{\rm TC} e^{-\frac{\pi}{\sqrt{\alpha/\alpha_{\rm cr}-1}}}$ for $\alpha > \alpha_{\rm cr}$

Miransky ('85)

$$SU(N_{\rm TF})_L \times SU(N_{\rm TF})_R \to SU(N_{\rm TF})_V$$

Criticality leads to large scale hierarchy, in contrast to QCD $m_q^{\rm dynamical} \sim \Lambda_{\rm QCD}$

$$m_F/\Lambda_{\rm TC} \ll 1 \text{ as } \alpha \to \alpha_{\rm cr}$$

i.e. technihadron mass scale M_H

$$M_H = \mathcal{O}({\rm EW} \sim 1\,{\rm TeV}) \ll \Lambda_{\rm TC}(\sim 10^3\,{\rm TeV})$$

* Characteristic features of Walking Technicolor (WTC)

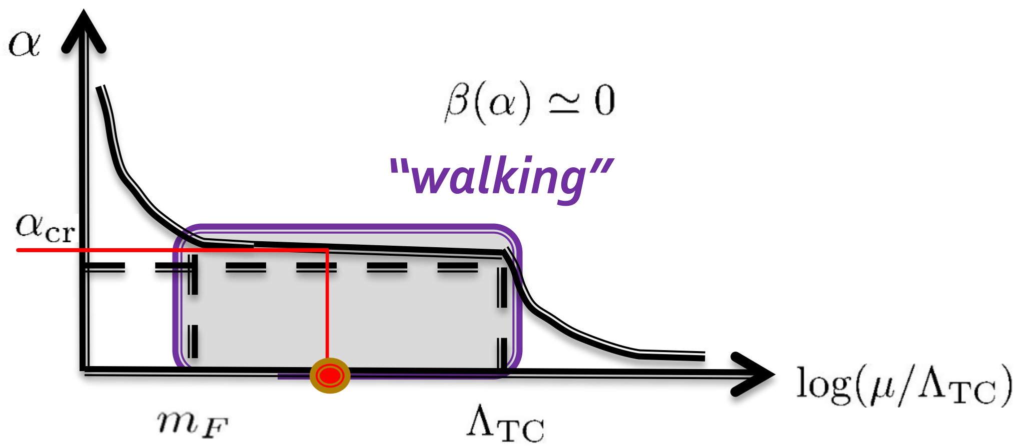
* "Walking" dynamics = almost scale inv.

$$\beta(\alpha) \simeq 0$$

nonzero chiral condensate

$$\langle \bar{F} F \rangle \neq 0$$

spontaneously breaks the approximate scale inv. as well as the chiral sym.



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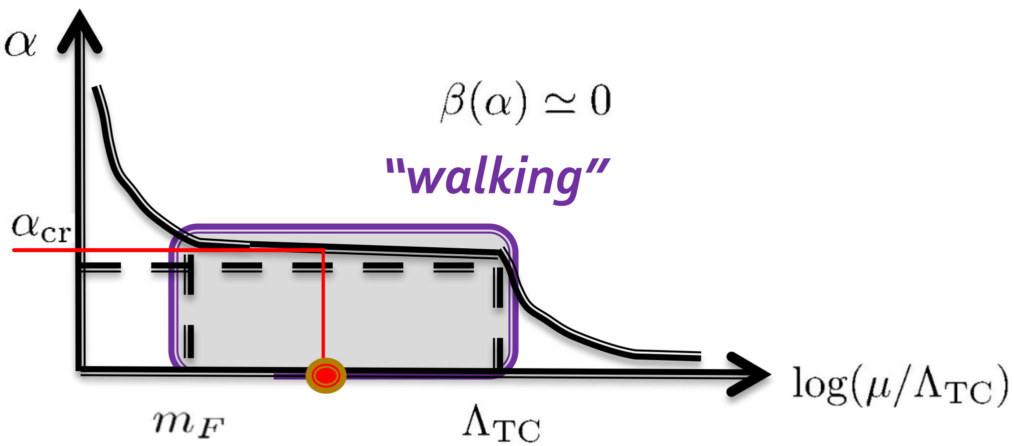
emergence of
- "chiral NG bosons": technipions (3 → eaten by W, Z)
- "scale-NG boson": **technidilaton (TD)**



* Characteristic features of Walking Technicolor (WTC)

$$m_F \sim \Lambda_{TC} e^{-\frac{\pi}{\sqrt{\alpha/\alpha_{cr}-1}}} \text{ for } \alpha > \alpha_{cr}$$

SSB of (approximate) scale sym.

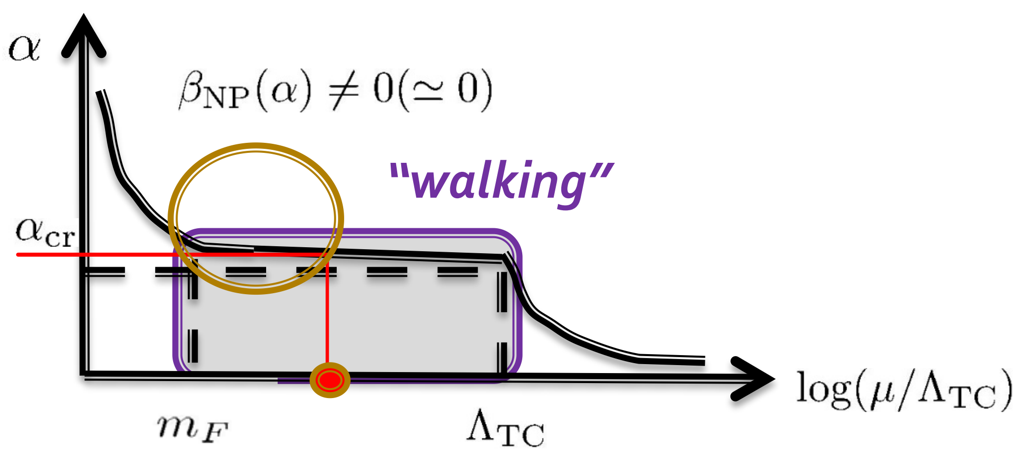
→ ***α starts "running" (walking) up to mF***

$$\beta_{NP}(\alpha) = \Lambda_{TC}\frac{\partial \alpha}{\partial \Lambda_{TC}} = -\frac{2\alpha_{cr}}{\pi}\left(\frac{\alpha}{\alpha_{cr}} - 1\right)^{3/2}$$

→ ***Nonpert. scale anomaly induced by mF itself***

$$\partial_\mu D^\mu = \frac{\beta_{NP}(\alpha)}{4\alpha^2}(\alpha G_{\mu\nu}^2) \neq 0 : \text{ explicitly broken by } m_F$$

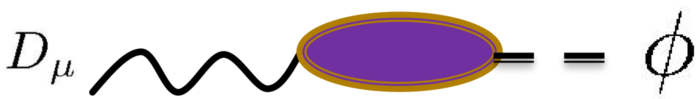
TD gets massive



* Characteristic features of Walking Technicolor (WTC)

* **TD =** 0^{++} composite scalar

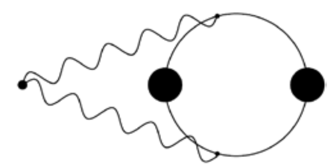
coupled to spontaneously broken TC dilatation current D_μ



$$\langle 0 | D_\mu(x) | \phi(p) \rangle = -i p_\mu F_\phi e^{-ipx} \text{ with the decay constnat } F_\phi$$

The TD mass can be evaluated by PCDC (partially conserved dilatation current) i.e. scale-Ward-Takahashi identity:

$$\langle 0 | \theta^\mu_\mu | 0 \rangle_{\rm NP} = -\frac{F_\phi^2 M_\phi^2}{4}$$



$$\langle \theta^\mu_\mu \rangle_{\rm NP} = \langle \partial^\mu D_\mu \rangle_{\rm NP} = \langle \frac{\beta_{\rm NP}(\alpha)}{4\alpha} G^2_{\mu\nu} \rangle_{\rm NP} \sim N_{\rm TC} N_{\rm TF} m_F^4$$

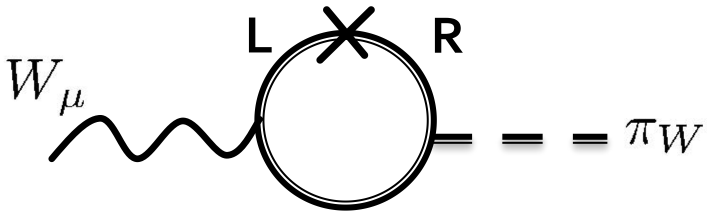
$$\longrightarrow \quad M_\phi \sim \sqrt{N_{\rm TF} N_{\rm TC}} \frac{m_F^2}{F_\phi}$$

* Characteristic features of Walking Technicolor (WTC)

* **TD = a composite Higgs** ($\bar{F}F$ **bound state, not glueball-like)**

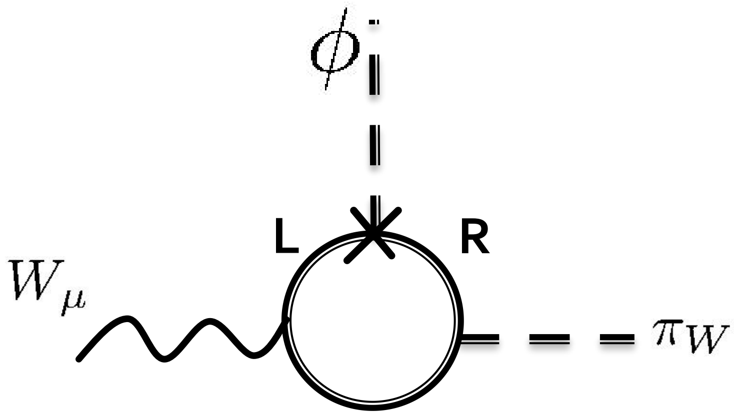
related to the mass generation of W and Z
(dynamical Higgs mechanism)

$\langle \bar{F}F \rangle \neq 0 \quad m_F \neq 0$



$$m_W^2 \sim g_W^2 N_D F_\pi^2 = g_W^2 v_{\rm EW}^2$$

N_D: # of techni-fermion EW doublets



$$\frac{m_W}{F_\phi} \phi W_\mu \partial^\mu \pi_W$$

TD coupling to W determined by spontaneously broken scale and chiral/EW invariance

→ See later discussion

A candidate for the walking gauge theory

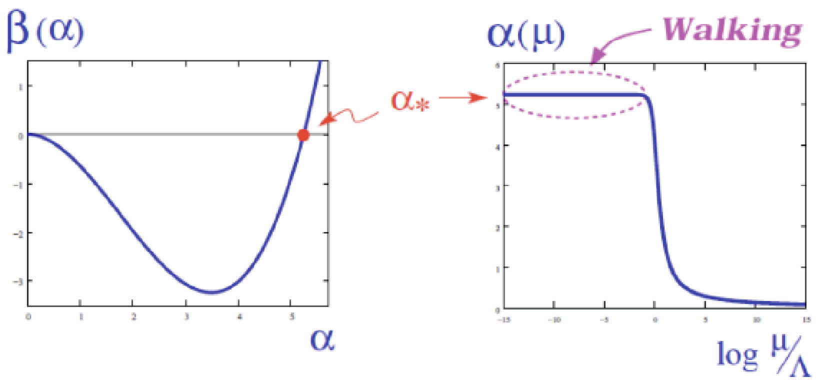
* QCD with many flavors (large Nf QCD)

Two-loop running coupling in the large N_f QCD

Caswell(1974)
Banks, Zaks(1982)

RGE $\mu \frac{d}{d\mu}\alpha(\mu) = -b\,\alpha^2(\mu) - c\,\alpha^3(\mu)$

$(N_c = 3)$	$N_f < 8.05$	$8.05 < N_f < 16.5$	$16.5 < N_f$
$b = \frac{1}{6\pi}(33 - 2N_f)$	+	+	−
$c = \frac{1}{12\pi^2}(153 - 19N_f)$	+	−	−



$(\alpha_* = -c/b)$ IR Fixed Point

Lattice simulation has observed large Nf walking signal & light 0++ scalar meson!

LatKMI collaboration, '13

* Parametrically light TD in Large Nf WTC
-- "Anti-Veneziano limit" --

M.Kurachi, S.M. , R.Shrock, and K.Yamawaki, in preparation

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PCDC:

$$M_\phi \sim \sqrt{N_{\rm TF} N_{\rm TC}} \frac{m_F^2}{F_\phi}$$

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consider ***"Anti-Veneziano limit":***

large $N_{\rm TC}$ and $N_{\rm TF}$ scaling with $r = N_{\rm TF}/N_{\rm TC} \gg 1$ fixed

$$m_F \sim \frac{F_\pi}{\sqrt{N_{\rm TC}}} \sim \frac{v_{\rm EW}}{\sqrt{N_{\rm TF} N_{\rm TC}}}$$ **e.g. via Pagels-Stokar**

$$F_\phi \sim \sqrt{N_{\rm TF} N_{\rm TC}} m_F \sim v_{\rm EW}$$

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e.g. via Pagels-Stokar

$$F_\phi \sim \sqrt{N_{\rm TF} N_{\rm TC}}\, m_F \sim v_{\rm EW}$$

In EW (and scale sym.) broken phase: $v_{\rm EW}$ = 246 GeV fixed

$$M_\phi \sim \frac{v_{\rm EW}}{\sqrt{N_{\rm TF} N_{\rm TC}}} = \frac{v_{\rm EW}}{\sqrt{r} \cdot N_{\rm TC}} \longrightarrow 0$$

as $N_{\rm TC} \to \infty$

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"Anti-Veneziano limit":

$$N_{\rm TC} \& N_{\rm TF} \to \infty \text{ with } \underline{r = N_{\rm TF}/N_{\rm TC} \gg 1} \text{ fixed}$$

Large Nf WTC

PCDC: $\dfrac{M_\phi}{v_{\rm EW}} \sim \dfrac{1}{\sqrt{r}} \cdot \dfrac{1}{N_{\rm TC}} \longrightarrow$ **0** $\quad$ as $N_{\rm TC} \to \infty$

analogous to η' in large N_c limit of QCD

Veneziano limit:

$$N_c \& N_f \to \infty \text{ with } \underline{r = N_f/N_c \ll 1} \text{ fixed}$$

Small Nf QCD

PCAC: $\dfrac{M_{\eta'}}{f_\pi} \sim \dfrac{\sqrt{N_f}}{N_c} = \sqrt{r} \cdot \dfrac{1}{\sqrt{N_c}} \longrightarrow$ **0** $\quad$ as $N_c \to \infty$

TD can be vanishingly light pNGB at the same level as eta' in QCD!!

* One-family WTC with $N_{TC}=4$ and $N_{TF}=8(N_D=4)$: $(r=N_{TF}/N_{TC}=2)$
--- “Walking on the Ladder” ---

M.Kurachi, S.M. , R.Shrock, and K.Yamawaki, in preparation

Based on Ladder Schwinger-Dyson gap equation for non-running gauge coupling

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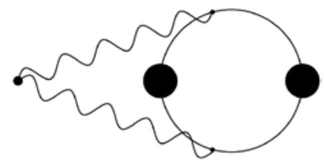
PCDC: $$M_\phi^2 F_\phi^2 = -4\langle\theta_\mu^\mu\rangle_{\rm NP}$$



$$\longrightarrow \quad M_\phi^2 F_\phi^2 \simeq \frac{16 N_{\rm TF} N_{\rm TC}}{\pi^4} m_F^4$$

Pagels-Stokar formula:

$$v_{\rm EW}^2 = N_D F_\pi^2 \simeq \frac{N_{\rm TF} N_{\rm TC}}{4\pi^2} m_F^2$$

$$\longrightarrow \quad m_F^2 \simeq v_{\rm EW}^2 \left(\frac{N_{\rm TF}}{8}\frac{N_{\rm TC}}{4}\right)^{-1}$$

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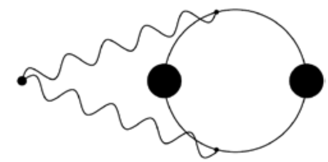

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$$\longrightarrow \quad m_F^2 \simeq v_{\rm EW}^2 \left(\frac{N_{\rm TF}}{8} \frac{N_{\rm TC}}{4} \right)^{-1}$$

$$\Rightarrow \quad M_\phi^2 \simeq \left(\frac{v_{\rm EW}}{2} \right)^2 \cdot \left(\frac{5 v_{\rm EW}}{F_\phi} \right)^2 \cdot \left(\frac{8}{N_{\rm TF}} \frac{4}{N_{\rm TC}} \right)$$

Ladder PCDC accommodates $M_\phi = 125$ GeV w/ $F_\phi = O(5\, v_{EW} \sim 1\,\text{TeV})$ for one-family WTC w/ $N_{TC}=4$ and $N_{TF}=8$!!

* One-family WTC with $N_{TC}=4$ and $N_{TF}=8(N_D=4)$: $(r=N_{TF}/N_{TC}=2)$
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for one-family WTC w/ $N_{TC}=4$ and $N_{TF}=8$

Note: $F_\phi \sim \sqrt{N_{\rm TF} N_{\rm TC}} m_F \simeq \sqrt{4 \times 8} v_{\rm EW} \sim 5\, v_{\rm EW}$

consistent w/ rough large Nf & Nc estimate!

→ Ladder PCDC naturally achieves the realistic point!!

$$M_\phi \simeq 125 \ {\rm GeV}, \ F_\phi \simeq 5\, v_{\rm EW}$$

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Amazingly,

**** The signal strengths of this TD are consistent with current LHC Higgs data!!***

See also later discussion

S.M. and K. Yamawaki, PRD85,86 ('12), PLB719 ('13); S.M. 1304.4882; talk at SCGT14mini ('14)

* Several supports for the light TD in large Nf WTC

i) Bethe-Salpeter eq. combined w/ SD eq. (Ladder approx.)

M.Kurachi and R.Shrock (' 06)

$$M_\phi / M_{\rho,a1} \sim 1/3 \qquad \text{for} \quad N_{\rm TF}/N_{\rm TC} \simeq 4 \; (N_{\rm TC}=3)$$

ii) Holographic analysis (non-ladder effects)

K.Haba, S.M and K.Yamawaki ('00); S.M. and K.Yamawaki ('12)

$$M_\phi / M_{\rho,a1} \to 0 \text{ as } G \sim \langle G_{\mu\nu}^2 \rangle / F_\pi^4 \sim \frac{N_{\rm TF}}{N_{\rm TC}} \to \infty$$

iii) Lattice simulation

LatKMI collaboration (' 14)

$$M_\phi / M_\pi \sim 1 \qquad \text{for} \quad N_{\rm TF}/N_{\rm TC} = 8/3 \; (N_{\rm TC}=3)$$

iii) Extended TC modeling

M.Kurachi, R.Shrock and K.Yamawaki, (' 15)

one-family model w/ $N_{\rm TF}=8, N_{\rm TC}=4$ (see Shrock's talk)

naturally embedded into ETC

3. LHC Higgs v.s. TD in the one-family (N_{TC}=4 & N_{TF}=8) WTC

* Effective model for the one-family WTC (N_{TC}=4, N_{TF}=8)

Nonlinear realization for scale & chiral $SU(8)_L$ x $SU(8)_R$ symmetries

"Scale-inv. ChPT" S.M. and K.Yamawaki ('14)

<u>* TD couplings to W, Z and fermions (compared to the SM Higgs)</u>

$$\frac{g_{\phi WW/ZZ}}{g_{h_{\rm SM}WW/ZZ}} = \frac{g_{\phi ff}}{g_{h_{\rm SM}ff}} \quad ({\rm for} \quad f = t, b, \tau)$$
$$= \frac{v_{\rm EW}}{F_\phi} .$$

Note the ladder PCDC result: $F_\phi \sim 5 v_{\rm EW}$

i.e. $v_{\rm EW}/F_\phi \sim 0.2$

<u>* TD couplings to photons and gluons</u>

$$\mathcal{L}_{\rm eff}^{\gamma\gamma, gg} = \frac{\phi}{F_\phi} \left\{ \frac{\beta_F(g_s)}{2 g_s} G_{\mu\nu}^2 + \frac{\beta_F(e)}{e} F_{\mu\nu}^2 \right\}$$

$$\beta_F(g_s) = \frac{g_s^3}{(4\pi)^2} \frac{4}{3} N_{\rm TC} , \quad \beta_F(e) = \frac{e^3}{(4\pi)^2} \frac{16}{9} N_{\rm TC}$$

one-family technifermion contributions at one-loop

S.M. and K. Yamawaki, PLB719 ('13); S.M. 1304.4882

** relevant production processes at LHC*

similar to SM Higgs:

ggF, VBF, VH, ttH

** relevant decay channels (for N_{TC}=4)*

		BR
$\Phi \to gg$	:	**~ 75%**
$\Phi \to bb$	:	~ 19 %
$\Phi \to WW$	:	~ 3.5%
$\Phi \to \tau\tau$	:	~ 1.1 %
$\Phi \to ZZ$	:	~ 0.4%
$\Phi \to \gamma\gamma$	:	~ 0.1%

enhanced by extra colored techni-quark contribution

Updated from S.M. and Yamawaki PLB719(2013)

The signal strength fit to the LHC-Run I full data

One-parameter fit (Fϕ)

$$\chi^2 = \sum_{i \in \text{events}} \left(\frac{\mu_i - \mu_i^{\text{exp}}}{\sigma_i} \right)^2$$

N_{TC}	$[v_{EW}/F_\phi]_{best}$	χ^2 min /d.o.f.
4	0.23	19/17 = 1.1

Compared w/ SM Higgs χ^2/d.o.f = 17/18 = 0.94

* Current LHC has favored TD in 1FM w/ N_{TC}=4 at almost the same level as the SM Higgs!

The signal strength fit to the LHC-Run I full data

Updated from S.M. and Yamawaki PLB719(2013)

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* Current LHC has favored TD in 1FM w/ N_{TC}=4 at almost the same level as the SM Higgs!

* best-fit v_{EW}/F_Φ ~ 0.2: F_Φ ~ 5 v_{EW} excellent agreement w/ ladder PCDC for 1FM w/ N_{TC}=4 !!

$$M_\phi^2 \simeq \left(\frac{v_{\rm EW}}{2}\right)^2 \cdot \left(\frac{5 v_{\rm EW}}{F_\phi}\right)^2 \cdot \left(\frac{8}{N_{\rm TF}} \frac{4}{N_{\rm TC}}\right)$$

The TD signal strengths (μ = σ x BR/SM Higgs) vs. the current data (i)

(i) ggF+ttH category

* Data as of ICHEP, July 2014

TD signal strength	ATLAS	CMS
$\mu_{\gamma\gamma}^{\rm ggF+ttH} \simeq 1.5$	1.6 ± 0.25	1.13 ± 0.35
$\mu_{ZZ}^{\rm ggF+ttH} \simeq 1.1$	1.8 ± 0.35	0.83 ± 0.28
$\mu_{WW}^{\rm ggF+ttH} \simeq 1.1$	0.82 ± 0.36	0.72 ± 0.37
$\mu_{\tau\tau}^{\rm ggF+ttH} \simeq 1.1$	1.1 ± 1.2	1.1 ± 0.46

Consistent!!

The TD signal strengths ($\mu = \sigma \times BR/SM$ Higgs) vs. the current data (ii)

(ii) VBF +VH category

* Data as of ICHEP, July 2014

TD signal strength	ATLAS	CMS
$\mu_{\gamma\gamma}^{\mathrm{VBF+VH}} \simeq 0.9$	1.7 ± 0.63	1.16 ± 0.59
$\mu_{ZZ}^{\mathrm{VBF+VH}} \simeq 0.7$	1.2 ± 1.3	1.45 ± 0.76
$\mu_{WW}^{\mathrm{VBF+VH}} \simeq 0.7$	1.7 ± 0.79	0.62 ± 0.53
$\mu_{\tau\tau}^{\mathrm{VBF+VH}} \simeq 0.7$	1.6 ± 0.75	0.94 ± 0.41
$\mu_{bb}^{\mathrm{VBF+VH}} \simeq 0.03$	0.20 ± 0.64	1.0 ± 0.50

* Consistent within about 1 sigma error
* VBF: ~ 30% contamination from ggF, compensating direct VBF coupling suppression:
  gg → Φ + gg highly enhanced, due to TQ loop, compared to SM Higgs case!

* Smaller VBF+VH signal (particularly, bb-channel), compared to the SM Higgs

SM Higgs, or TD?

-- Conclusive answer needs high statistic LHC-Run II !

What do we expect next to discovery of the "Higgs"?

SM Higgs, or TD?

-- Conclusive answer needs high statistic LHC-Run II !

What do we expect next to discovery of the "Higgs"?

= > Walking techni-pions

& techni-vector mesons

(technirho mesons) !

= smoking-gun of WTC

4. Discovering walking technipions and technirhos at LHC

Walking technipions and technirho mesons

* SSB pattern $SU(8)_L \times SU(8)_R \rightarrow SU(8)_V$
* 63 NGBs emerge: 3 = eaten by W,Z, 60 = *pseudos*, Technipions (TP)

techni-pion	color	isospin	current
θ_a^i	octet	triplet	$\frac{1}{\sqrt{2}}\bar{Q}\gamma_\mu\gamma_5\lambda_a\tau^i Q$
θ_a	octet	singlet	$\frac{1}{2\sqrt{2}}\bar{Q}\gamma_\mu\gamma_5\lambda_a Q$
T_c^i $(\bar{T}_c^i)$	triplet	triplet	$\frac{1}{\sqrt{2}}\bar{Q}_c\gamma_\mu\gamma_5\tau^i L$ (h.c.)
T_c $(\bar{T}_c)$	triplet	singlet	$\frac{1}{2\sqrt{2}}\bar{Q}_c\gamma_\mu\gamma_5 L$ (h.c.)
P^i	singlet	triplet	$\frac{1}{2\sqrt{3}}(\bar{Q}\gamma_\mu\gamma_5\tau^i Q - 3\bar{L}\gamma_\mu\gamma_5\tau^i L)$
P^0	singlet	singlet	$\frac{1}{4\sqrt{3}}(\bar{Q}\gamma_\mu\gamma_5 Q - 3\bar{L}\gamma_\mu\gamma_5 L)$

* TP masses are of O(a few TeV), due to the walking feature

J. Jia, S.M. and K. Yamawaki, PRD86 ('12)

TP	color	isospin	mass [TeV]
$\theta_a^{a,i}$	octet	singlet/triplet	$1.5 - 4.4$
$T_c^{0,i}$	triplet	singlet/triplet	$1.0 - 2.9$
P^i	singlet	triplet	$0.96 - 3.0$
P^0	singlet	singlet	$0.76 - 2.4$

* For N_{TC}= 4
  S parameter (S^{TC}) = 1.0 → 0.1

based on holographic estimate

M.Kurachi, S.M. and K. Yamawaki, PRD90('14)

* Current LHC limits on 60 technipions

* Coupling properties fixed by
  SU(8)L x SU(8)R /SU(8)V , scale-inv. chiral Lagrangian

J. Jia, S.M. and K. Yamawaki, PRD86 ('12); S.M. and K.Yamawaki, PRL90('14)

TPs predominantly decay to tt and gg,
so can be mainly produced via ggF at LHC

$$gg \to TP \to t\bar{t}/gg$$

* Most stringent constraints from
  pp → ggF → isosinglet technipions → tt
  (and scalar leptoquark search for color-triplet T_c)

exclude TPs w/ masses
- color-octet (θ_a) < 1.5—1.6 TeV
- color-triplet (T_c) < 1.0 – 1.1 TeV
- color-singlet (P) < 800 GeV

M.Kurachi, S.M. and K. Yamawaki, PRD90('14)

* Expect to discover TPs w/ higher masses at LHC-Run II

* Search for walking techni-rho mesons @ LHC

* 63 vector mesons in a way similar to TPs

Techni-rho meson	color	isopin
$\rho^i_{\theta_a}$	octet	triplet
$\rho^0_{\theta_a}$	octet	singlet
$\rho^i_{T_c}\,(\bar{\rho}^i_{T_c})$	triplet	triplet
$\rho^0_{T_c}\,(\bar{\rho}^0_{T_c})$	triplet	triplet
ρ^i_P	singlet	triplet
ρ^0_P	singlet	singlet
ρ^i_Π	singlet	triplet

* all masses are expected to be around a few TeV scale:

$$M_\rho \simeq 1 - 4\ \mathrm{TeV}$$

based on holographic estimate

S.M. and K. Yamawaki, PRD86 ('12);
M. Kurachi, S.M. and K.Yamawaki, PRD80('13)

* Coupling properties fixed by

[SU(8)L x SU(8)R x [SU(8)V]_HLS]/SU(8)V

scale-inv. Hidden Local Symmetry (HLS) Lagrangian

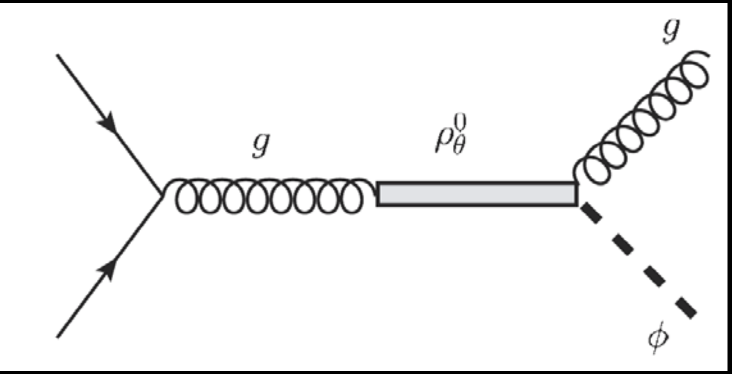
Refs. for HLS Bando, et al. PRL**54** ('85); Bando, et al, NP**B259** ('85);
Bando, et al, PTP**79** ('88); Bando, et al, PR**164** ('88)

* Relevant couplings: ρ – f-f, ρ – π –W/Z, ρ – W –W/Z
and interesting interactions involving TD (Higgs):

Of great interest is

Color-octet ρ

produced by DY process



vary

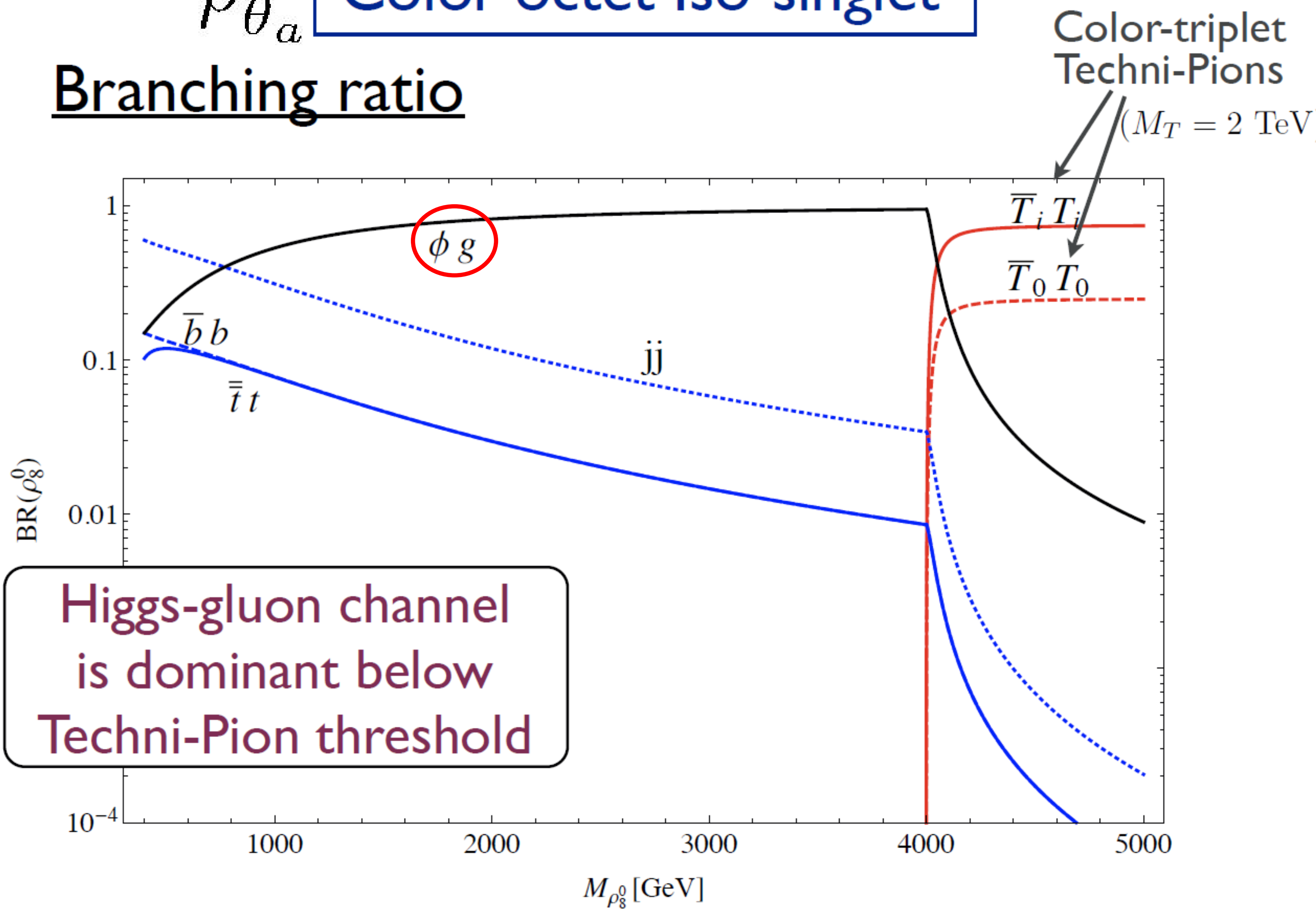
* 4 model parameters $F_\pi, F_\phi, M_\rho, F_\rho$ (w/ $M_\phi = 125$ GeV)

can be fixed: v_{EW}, 5 v_{EW}, VMD for TP

Slide from M.Kurachi's talk at SCGT14Mini, March 2014

$\rho^0_{\theta_a}$ **Color-octet Iso-singlet**

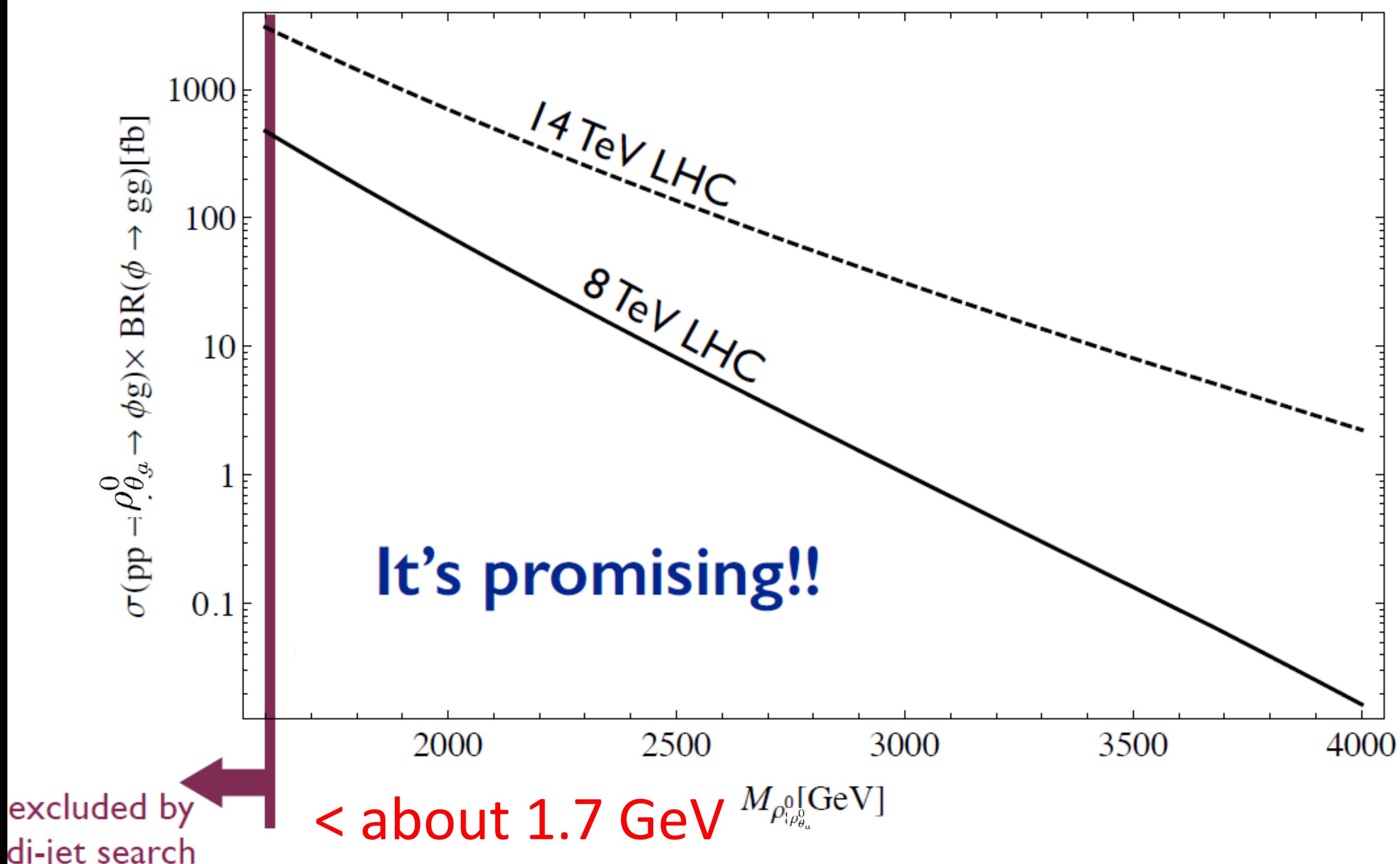
Branching ratio



Slide from M.Kurachi’s talk at SCGT14Mini, March 2014

$\rho^0_{\theta_a}$ Color-octet Iso-singlet

$$\sigma(pp \to \rho^0_{\theta_a} \to \phi\, g) \times \mathrm{BR}(\phi \to \underbrace{gg}_{\sim 75\%})$$

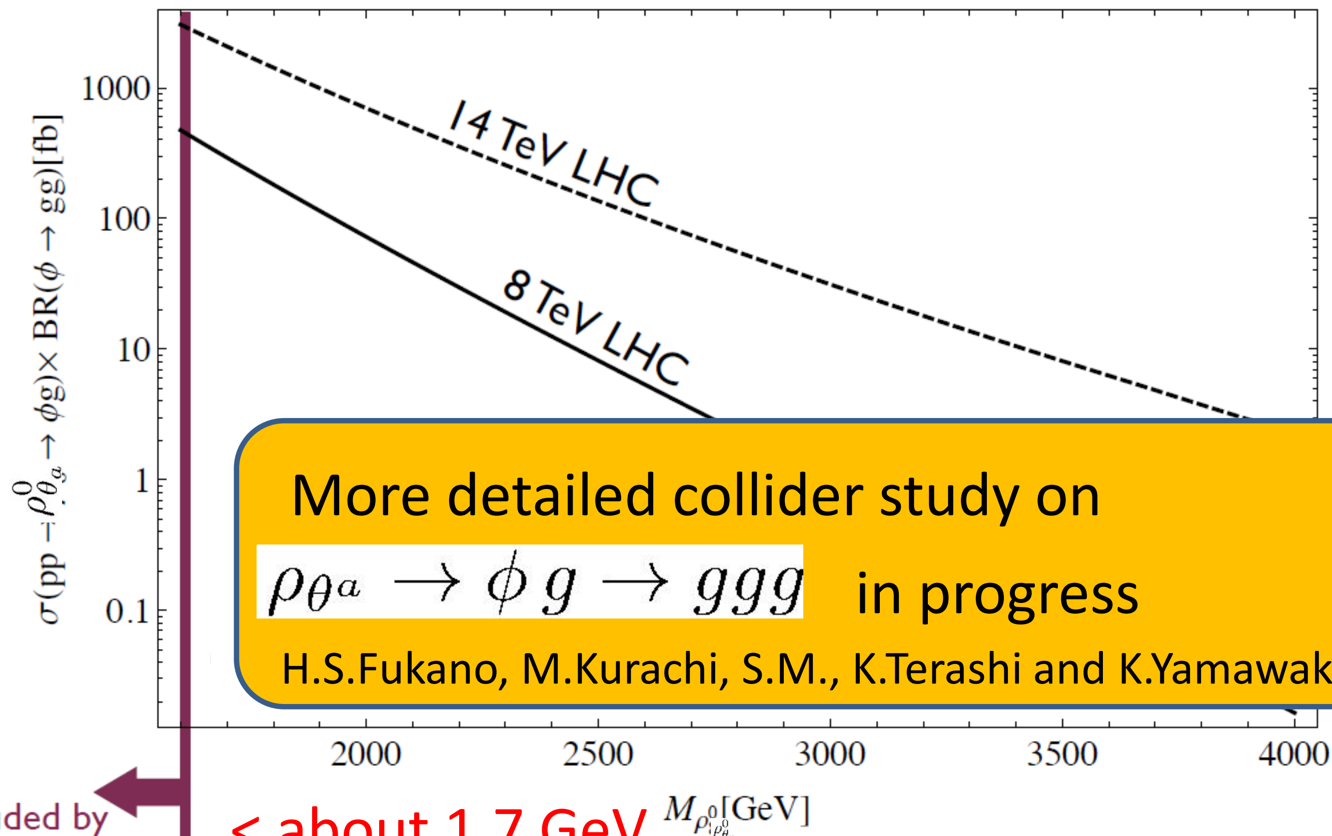


Slide from M.Kurachi's talk at SCGT14Mini, March 2014

$\rho^0_{\theta_a}$ Color-octet Iso-singlet

$$\sigma(pp \to \rho^0_{\theta_a} \to \phi\, g) \times \mathrm{BR}(\phi \to gg)$$

$\sim 75\%$



More detailed collider study on

$\rho_{\theta^a} \to \phi\, g \to ggg$ in progress

H.S.Fukano, M.Kurachi, S.M., K.Terashi and K.Yamawaki

excluded by di-jet search

< about 1.7 GeV

5. Summary

- Large Nf Walking TC is interesting candidate for BSM

- The one-family WTC w/ $N_{TC}=4$, $N_{TF}=8$
  -- naturally realizes 125 GeV Technidilaton
  with $F_\Phi \sim 5\, v_{EW}$, consistent with
  the LHC Higgs coupling property

  -- to be more precisely tested at the upcoming Run-II

- Probe the one-family WTC:
  -- the smoking-gun → technirhos and technipions

Viable benchmark:
One-family WTC w/
N_{TC}= 4 N_{TF}=8

for the S parameter
S^{TC} = 0.1 (0.3)

* Mass estimate is
based on holography

S.M. and K. Yamawaki, ('12);
M. Kurachi, S.M. and K.Yamawaki, ('13)

10 – 20 TeV — techniglueball

3 – 4 TeV — $\theta_a^{0,3,\pm}$ → tt/gg

2 – 3 TeV — $T_c^{0,3,\pm}$ leptoquark

1 – 2 TeV — $P^{0,3,\pm}$ → tt/gg

technirhos (#63) : e.g. $\rho_{\theta_a}^{0,3,\pm}$ → Φgg

125 GeV — Φ (TD) → bb

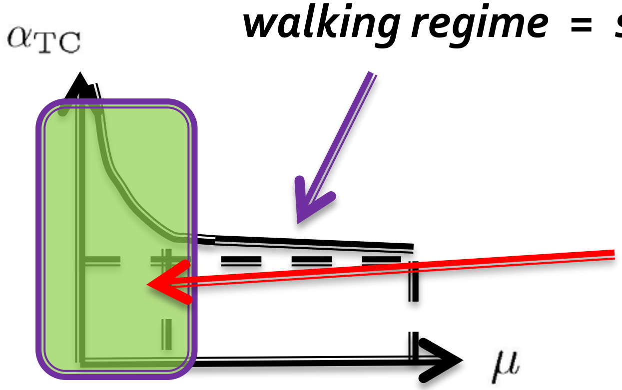
More on LHC pheno. for the technihadrons is in progress
Stay tune!!

Thank you very much!

Backup Slides

TD mass stability in the 1F-WTC w/ N_{TC}=4

walking regime = scale symm well protected
(natural enough)



$$\Lambda_\chi \sim \frac{4\pi F_\pi}{\sqrt{N_{TF}}}$$

Can TD mass be as small as 125GeV below Λ_χ?

→ **YES!!!**

Work on the eff. TD Lagrangian: $\mathcal{L} = \mathcal{L}_{\rm inv} + \mathcal{L}_S - V_\chi$

Dominant corrections come from top-loop (quadratic div.)

cutoff by $\Lambda_\chi \sim \frac{4\pi F_\pi}{\sqrt{N_{TF}}}\Big|_{N_{TF}=8}^{F_\pi=123\,{\rm GeV}} \sim 2.2\, v_{\rm EW}$ $\quad \delta M_\phi^2 \simeq -\frac{3}{4\pi^2}\frac{m_t^2}{F_\phi^2}\Lambda_\chi^2$

w/ $m_t^2 \simeq 2M_\phi^2$

$F_\phi \sim 5 v_{\rm EW}$

$$\left|\frac{\delta M_\phi}{M_\phi}\right| \simeq \frac{3}{4\pi^2}\left(\frac{2.2}{5}\right)^2 \simeq 0.01$$

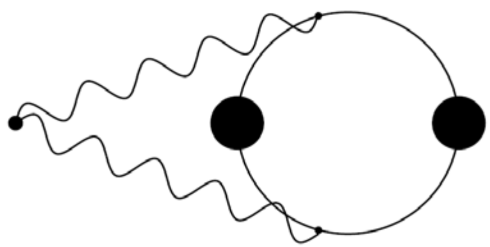
naturally light thanks to large F_Φ~ 5 v_{EW} (i.e. weak coupling)

* Characteristic features of Walking Technicolor (WTC)

*** technigluon condensate/vacuum energy induced from technifermion condensate**

$$\langle \bar{F}F \rangle \neq 0$$

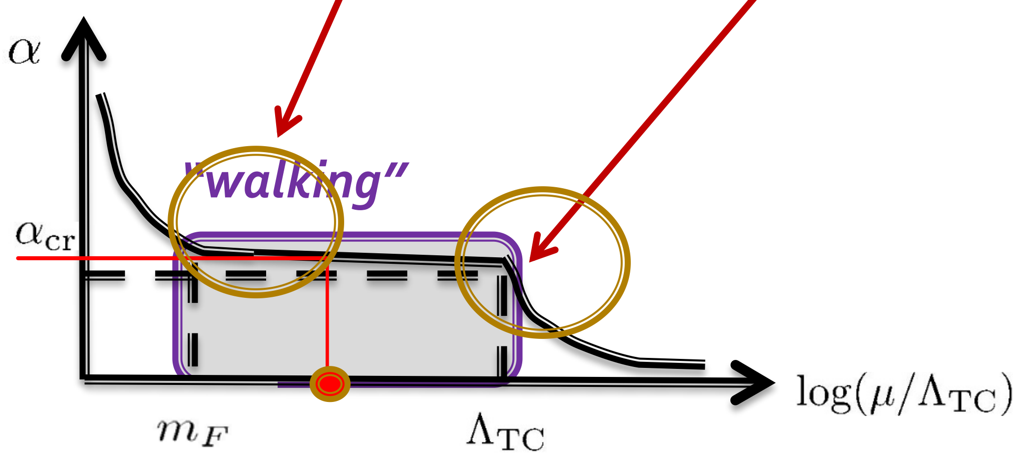
$$\langle \theta^\mu_\mu \rangle_{\rm NP} = \langle \partial^\mu D_\mu \rangle_{\rm NP} = \langle \frac{\beta_{\rm NP}(\alpha)}{4\alpha} G^2_{\mu\nu} \rangle_{\rm NP} \sim N_{\rm TC} N_{\rm TF} m_F^4$$



Scale sym. breaking by non-pert. walking dynamics

$$\langle \theta^\mu_\mu \rangle_{\rm NP} = \langle \theta^\mu_\mu \rangle_{\rm full} - \langle \theta^\mu_\mu \rangle_{\rm perturbation} (\Lambda^4_{\rm TC})$$

Miransky et al ('89)

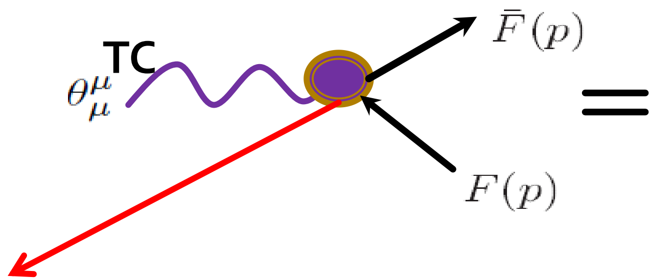


Direct consequences of Ward-Takahashi identities

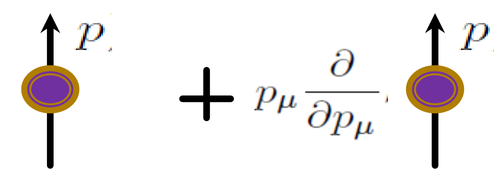
S.M. and K. Yamawaki, PRD86 (2012)

* Coupling to techni-fermions

$$\lim_{q_\mu \to 0} \int d^4y\, e^{iqy} \langle 0| T \partial^\mu D_\mu(y) F(x) \bar{F}(0) |0\rangle = i\delta_D \langle 0| T F(x) \bar{F}(0)|0\rangle$$
$$= i\left(2d_F + x^\nu \partial_\nu\right) \langle 0|T F(x) \bar{F}(0)|0\rangle$$



$=$



$$-S_F^{-1}(p) - i p_\mu \frac{\partial}{\partial p_\mu} S_F^{-1}(p)$$

Dilaton pole dominance

$$F_\phi \cdot \langle \phi(q=0)| T F(x) \bar{F}(0)|0\rangle = \delta_D \langle 0|T F(x) \bar{F}(0)|0\rangle$$

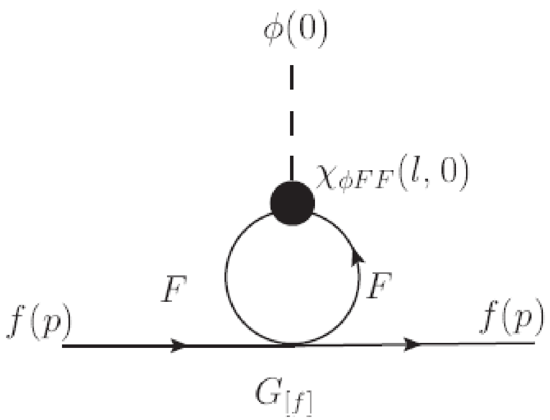
w/ TD decay constant Fphi

$$\langle 0| D_\mu(x) |\phi(q)\rangle = -iF_\phi q_\mu e^{-iqx}$$

Yukawa vertex func.

$$\chi_{\phi F F}(p, q=0) = \frac{1}{F_\phi} \delta_D S_F^{-1}(p) = \frac{1}{F_\phi}\left(1 - p_\mu \frac{\partial}{\partial p_\mu}\right) S_F^{-1}(p)$$

* Couplings to SM fermions



ETC induced 4-fermi

$$\mathcal{L}_{\rm ETC}^{\rm eff} = G_{[f]} \bar{F} F \bar{f} f$$

f-fermion mass:

$$m_f = -G_{[f]} \langle \bar{F} F \rangle$$

No direct coupling

TC

$$\langle f(p) | \theta_\mu^\mu(0) | f(p) \rangle = 0 \,.$$

~~transform~~

Techni-fermion loop induces

$$-\frac{iG_{[f]}}{F_\phi} \int \frac{d^4 l}{(2\pi)^4} {\rm Tr}[S_F(l) \cdot \delta_D S_F^{-1}(l) \cdot S_F(l)]$$

$$= \frac{iG_{[f]}}{F_\phi} \cdot \delta_D \int \frac{d^4 l}{(2\pi)^4} {\rm Tr}[S_F(l)]$$

$$= -i \frac{G_{[f]}}{F_\phi} \delta_D \langle \bar{F} F \rangle$$

$$\delta_D \langle \bar{F} F \rangle = (3 - \gamma_m) \langle \bar{F} F \rangle$$

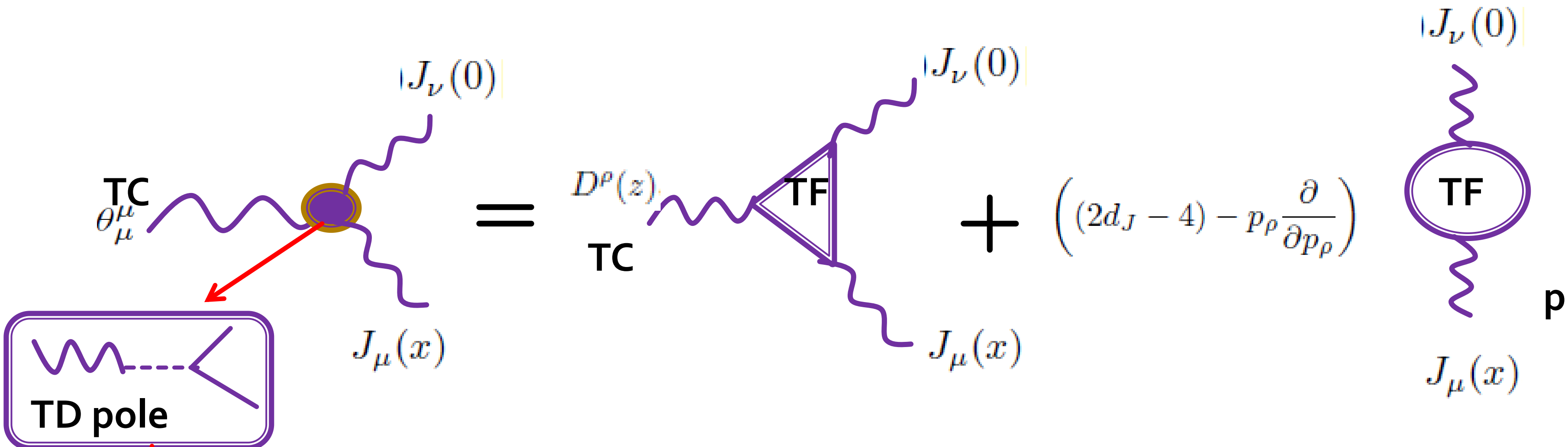
Yukawa coupling to SM-fermion

$$g_{\phi f f} = \frac{(3 - \gamma_m) m_f}{F_\phi}$$

* Couplings to SM gauge bosons

WT identity → scale anomaly term + anomaly-free term

$$\lim_{q_\rho \to 0} \int d^4z\, e^{iqz} \langle 0|T\partial_\rho D^\rho(z) J_\mu(x) J_\nu(0)|0\rangle = \lim_{q_\rho \to 0} \left(-iq_\rho \int d^4z\, e^{iqz} \langle 0|T D^\rho(z) J_\mu(x) J_\nu(0)|0\rangle \right) + i\delta_D \langle 0|T J_\mu(x) J_\nu(0)|0\rangle \,,$$



The loop integrals are actually saturated by IR contributions ($\gamma_m = 2$)

$$ig_W^2\, \mathrm{F.T.} \langle \phi(0)|T J_L^{\mu a}(x) J_L^{\nu b}(0)|0\rangle = \frac{2\beta_F(g)}{F_\phi\, g^3}(p^2 g_{\mu\nu} - p_\mu p_\nu) + \frac{2i}{F_\phi}\left(g_{\mu\nu} - \frac{p_\mu p_\nu}{p^2} \right) \left[\Pi_{LL}(0) + \mathcal{O}(p^4 \Pi''(0)) \right]$$

β_F: TF-loop contribution to beta function

β_F: TF-loop contribution to beta function

$$i g_W^2 \, \mathrm{F.T.} \langle \phi(0) | T J_L^{\mu a}(x) J_L^{\nu b}(0) | 0 \rangle = \frac{2\beta_F(g)}{F_\phi \, g^3} (p^2 g_{\mu\nu} - p_\mu p_\nu)$$

$$+ \frac{2i}{F_\phi} \left(g_{\mu\nu} - \frac{p_\mu p_\nu}{p^2} \right) [\Pi_{LL}(0) + \mathcal{O}(p^4 \Pi''(0))]$$

*** For SU(2)W gauge bosons: W –"broken" currents**

$$\Pi_{LL}(0) = N_D \frac{F_\pi^2}{4} = \frac{v_{\mathrm{EW}}^2}{4}$$

N_D = TF -EW-doublets

Coupling to W

$$\mathcal{L}_{\phi WW} = \frac{2m_W^2}{F_\phi} \phi W_\mu^a W^{\mu a}$$

*** For unbroken currents coupled to photon, gluon:**

$$\Pi(0) = 0.$$

Coupling to γγ & gluons

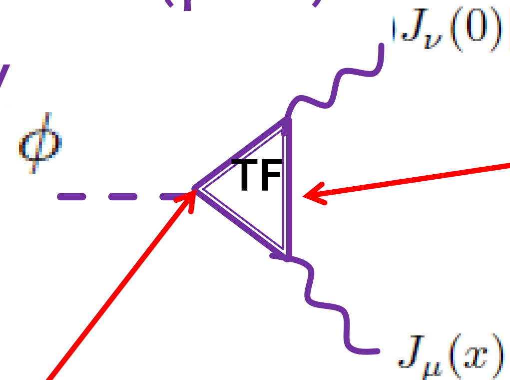
$$\mathcal{L}_{\phi\gamma\gamma, gg} = \frac{\phi}{F_\phi} \left[\frac{\beta_F(e)}{2e^3} F_{\mu\nu}^2 + \frac{\beta_F(g_s)}{2g_s^3} G_{\mu\nu}^2 \right]$$

* Calculation of beta functions

$$\mathcal{L}_{\phi\gamma\gamma,gg} = \frac{\phi}{F_\phi}\left[\frac{\beta_F(e)}{2e^3}F_{\mu\nu}^2 + \frac{\beta_F(g_s)}{2g_s^3}G_{\mu\nu}^2\right]$$

The loop is dominated at IR ($\gamma_m = 2$)

(well approximated by constant mass)



$$S_F(p) = \frac{1}{p - \Sigma(p)} \Rightarrow \boxed{\frac{1}{p - m_F}}$$

IR

Ladder approx.

Yukawa vertex

$$\chi_{\phi FF}(p, q=0) = \frac{1}{F_\phi}\delta_D S_F^{-1}(p) = \frac{1}{F_\phi}\left(1 - p_\mu \frac{\partial}{\partial p_\mu}\right) S_F^{-1}(p) \Rightarrow \frac{(3-\gamma_m)\Sigma(p^2)}{F_\phi} \Rightarrow \boxed{\frac{m_F}{F_\phi}}$$

IR

constant

The resultant betas coincide just one-loop perturbative expressions:

$$\beta_F(g_s) = \frac{g_s^3}{(4\pi)^2}\frac{4}{3}N_{\rm TC}$$

$$\beta_F(e) = \frac{e^3}{(4\pi)^2}\frac{16}{9}N_{\rm TC}$$

* TD couplings to SM fermions

$$-\frac{(3-\gamma_m)m_f}{F_\phi}\phi\bar{f}f$$

* $\gamma_m \simeq 1$

in WTC to get realitic masses w/o FCNC concerning 1st and 2nd generations

$$\frac{g_{\phi ff}}{g_{h_{\rm SM}ff}} = 2\frac{v_{\rm EW}}{F_\phi}$$

Miransky et al (1989); Matsumoto (1989); Appelquist et al (1989)

* $\gamma_m \simeq 2,$

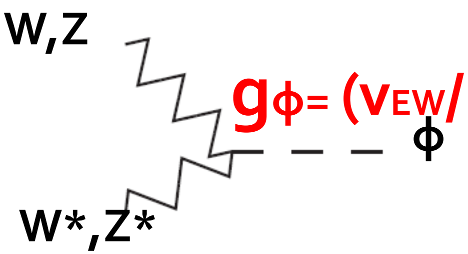
in Strong ETC to accommodate masses of the 3rd generations (t, b, tau)

$$\frac{g_{\phi ff}}{g_{h_{\rm SM}ff}} = 1\frac{v_{\rm EW}}{F_\phi}$$

Characteristic coupling property of 125 GeV TD in 1FM (w/ N_{TC}=4) at the LHC

v.s. SM Higgs

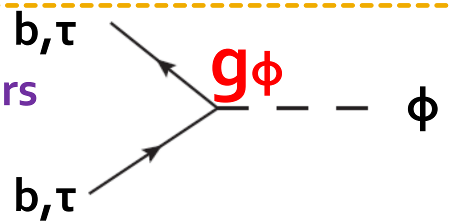
di-weak bosons



$g_\phi = (v_{EW}/F_\phi)\, g_H = 0.23\, g_H$

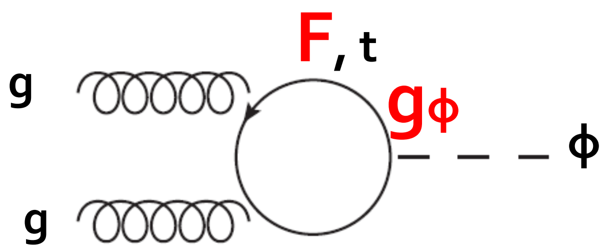
suppressed

quark, lepton pairs



suppressed

digluon

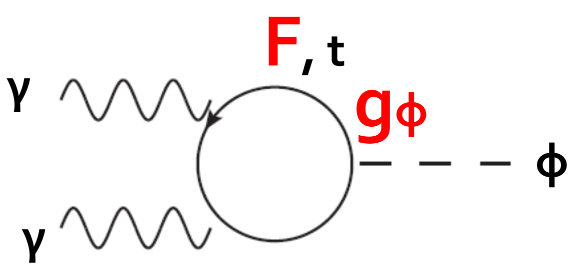


$\beta_F(g_s)$

moderately enhanced

QCD-colored TF contributions

diphoton



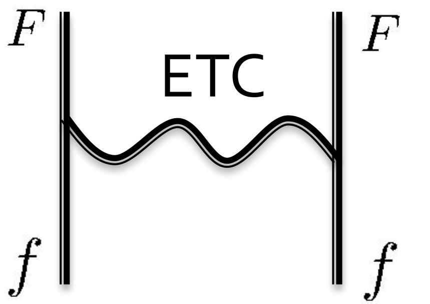
$\beta_F(e)$

moderately suppressed

EM-charged TF contributions

★ Technicolor should not be QCD-like at all

Extended TC: SM fermion mass generation



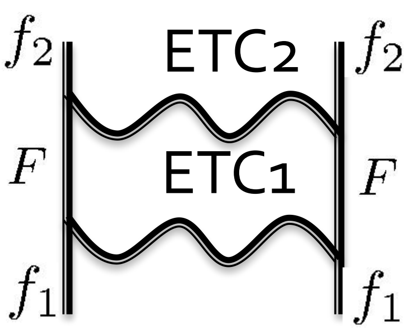
$M_{\rm ETC} = g_{\rm ETC}\Lambda_{\rm ETC}$

$$\xrightarrow{@\Lambda_{\rm ETC}} \frac{1}{\Lambda_{\rm ETC}^2}(\bar{F}_L F_R)(\bar{f}_R f_L) + \text{h.c.}$$

$$m_f \sim \frac{\langle \bar{F}F\rangle_{\Lambda_{\rm TC}}}{\Lambda_{\rm ETC}^2} \exp \int_{\Lambda_{\rm TC}}^{\Lambda_{\rm ETC}} \frac{d\mu}{\mu}\gamma_m(\mu)$$

RGE effect for $\bar{F}F$ operator w/ anomalous dim. γ_m

FCNC constraint



e.g.

$K_0 - \bar{K}_0$ mixing requires $\Lambda_{\rm ETC} > 10^3\,{\rm TeV}$

associated w/ strange quark mass

Naive scale-up of QCD $\gamma_m \simeq 0$: $m_s < 0.1\left(\frac{N_{\rm TC}}{3}\right)$ MeV

Needs enhancement by $\gamma_m \simeq 1$

Holdom (1981)

★ *Other pheno. issues in TC scenarios*

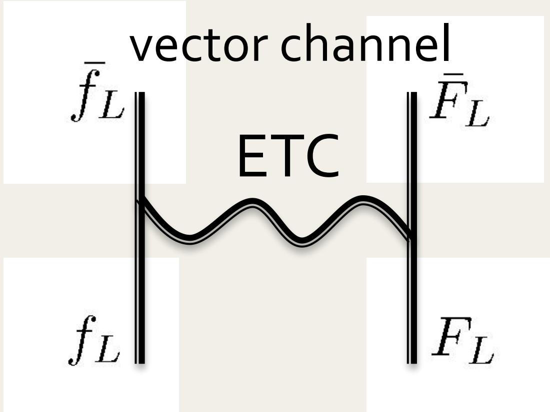
S parameter

$$S \approx N_D \cdot \frac{8\pi F_\pi^2}{M_\rho^2} \simeq \underline{0.3 \cdot N_D} \qquad \text{(for QCD-like)}$$

N_D : # EW doublets

too large!   Cf: S(exp) < 0.1   around T = 0

One resolution: ***ETC-induced "delocalization" operator***   Chivukula et al (2005)



$$-\frac{1}{\Lambda_{\rm ETC}^2} J^a_{\mu {\rm SM}_L} J^{\mu a}_{{\rm TC}_L}$$

in low-energy

$$J^{\mu a}_{{\rm TC}_L} \to {\rm Tr}[U^\dagger \tfrac{\sigma^a}{2} i D^\mu U]$$

w/ $U = e^{2i\pi_{\rm eaten}/v_{\rm EW}}$

$$\ni g_W W_\mu - g_Y B_\mu$$

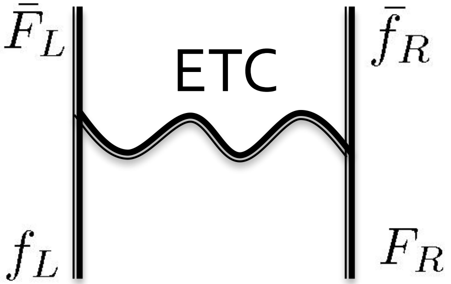
modifies SM f-couplings to W, Z

contributes to S "negatively"

$$\Delta S \sim -\frac{8\pi}{g_W^2}\left(\frac{v_{\rm EW}}{\Lambda_{\rm ETC}}\right)^2$$

$S_{\rm total} \to 0$ ("ideal delocalization")

Top quark mass generation



$$m_t \approx \frac{\langle \bar{U} U \rangle_{\rm ETC}}{\Lambda_{\rm ETC}^2} \approx \left(\frac{\Lambda_{\rm TC}}{\Lambda_{\rm ETC}} \right)^2 \Lambda_{\rm TC}$$

ETC scale associated w/ top mass

$$\rightarrow \quad \Lambda_{\rm ETC}^{\rm top} \approx 1{\rm TeV} \left(\frac{\Lambda_{\rm TC}}{1{\rm TeV}} \right)^{3/2} \left(\frac{172{\rm GeV}}{m_t} \right)^{1/2}$$

too small!

One resolution: ***Strong ETC*** Miransky et al (1989)

--- makes induced 4-fermi (tt UU) coupling large
enough to trigger chiral symm. breaking (almost by NJL dynamics)

$$\langle \bar{U} U \rangle_{\rm ETC} \approx \left(\frac{\Lambda_{\rm ETC}}{\Lambda_{\rm TC}} \right)^{\gamma_m} \langle \bar{U} U \rangle_{\rm TC} \qquad 1 < \gamma_m \leq 2$$

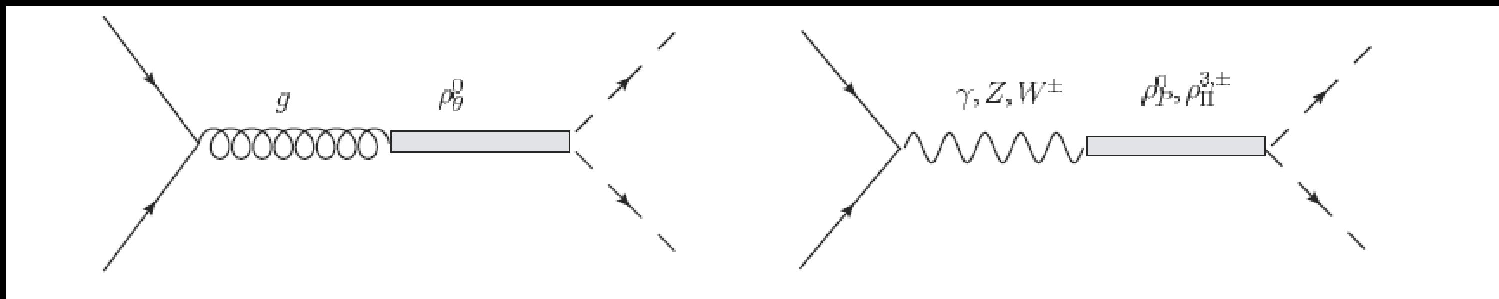
boost-up

$$\rightarrow \quad m_t \approx \left(\frac{\Lambda_{\rm TC}}{\Lambda_{\rm ETC}} \right)^{2-\gamma_m} \Lambda_{\rm TC} \leq \Lambda_{\rm TC} \sim 1{\rm TeV}$$

T parameter

(Strong) ETC generates large isospin breaking
→ highly model-dependent issue

* Dominant production process @ LHC = Drell-Yan (DY)

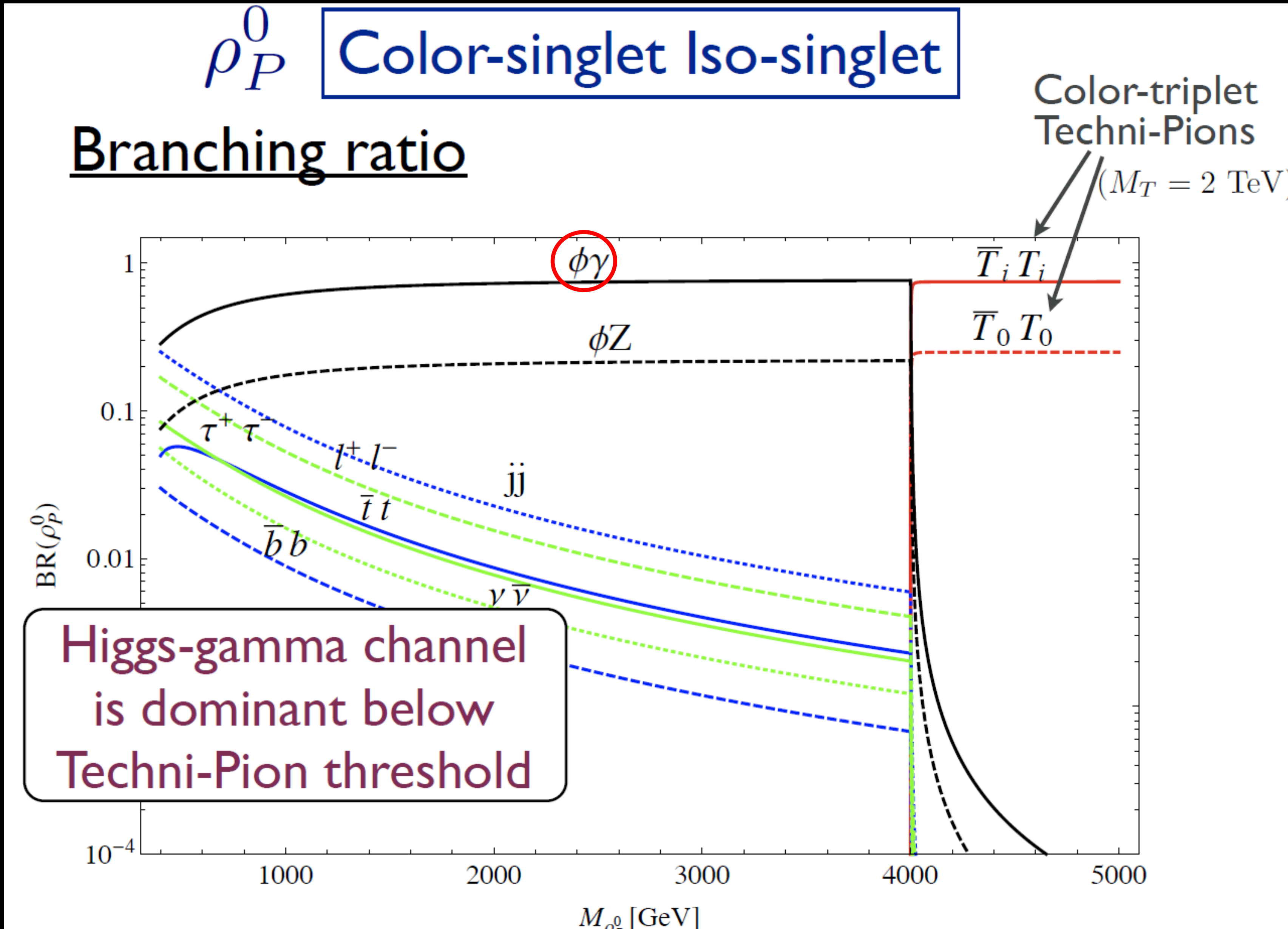


$$
\begin{aligned}
\mathcal{L}_{\mathcal{V}\rho} &= -2gF_\sigma^2 \mathrm{tr}[\mathcal{V}_\mu \rho^\mu] \\
&= -2gF_\sigma^2 \left[\frac{g_s}{\sqrt{2}} G_\mu^a \rho_\theta^{0a\mu} + eA_\mu \left\{ \rho_\Pi^{3\mu} + \frac{1}{\sqrt{3}} \rho_P^{0\mu} \right\} + \frac{e}{2sc} Z_\mu \left\{ (c^2 - s^2) \rho_\Pi^{3\mu} - \frac{2}{\sqrt{3}} s^2 \rho_P^{0\mu} \right\} + \frac{e}{2s} \{ W_\mu^- \rho_\Pi^{\mu+} + \mathrm{H.c.} \} \right]
\end{aligned}
$$

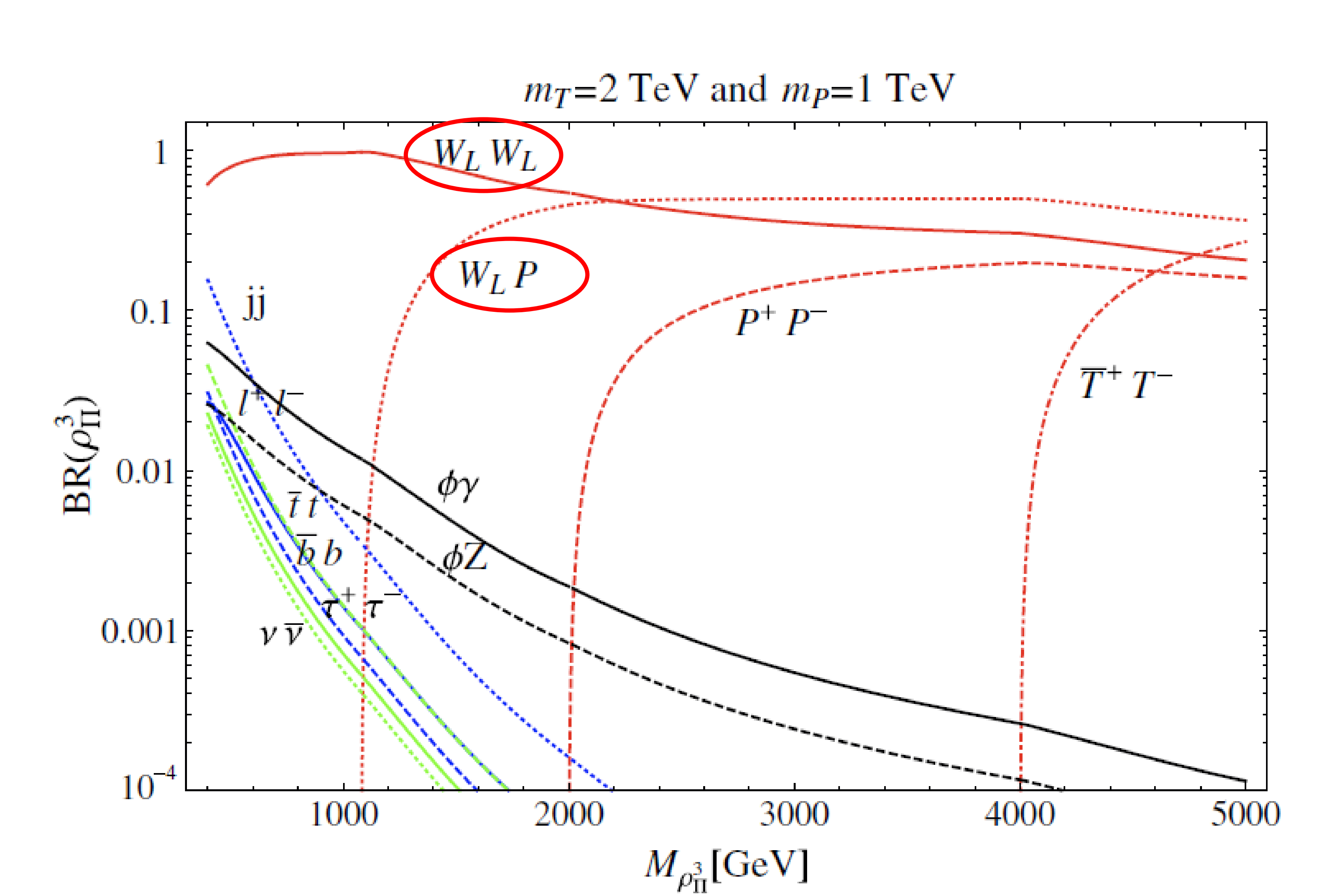
LHC cross section (LO): pp → qqbar → rho

$M_\rho = 2$ TeV	$\sigma_{\mathrm{DY}}(\sqrt{s} = 8\mathrm{TeV})$ [fb]	$\sigma_{\mathrm{DY}}(\sqrt{s} = 14\mathrm{TeV})$ [fb]
ρ_θ^0	100	1000
ρ_P^0	0.1	5
$\rho_\Pi^{\pm,3}$	1	10

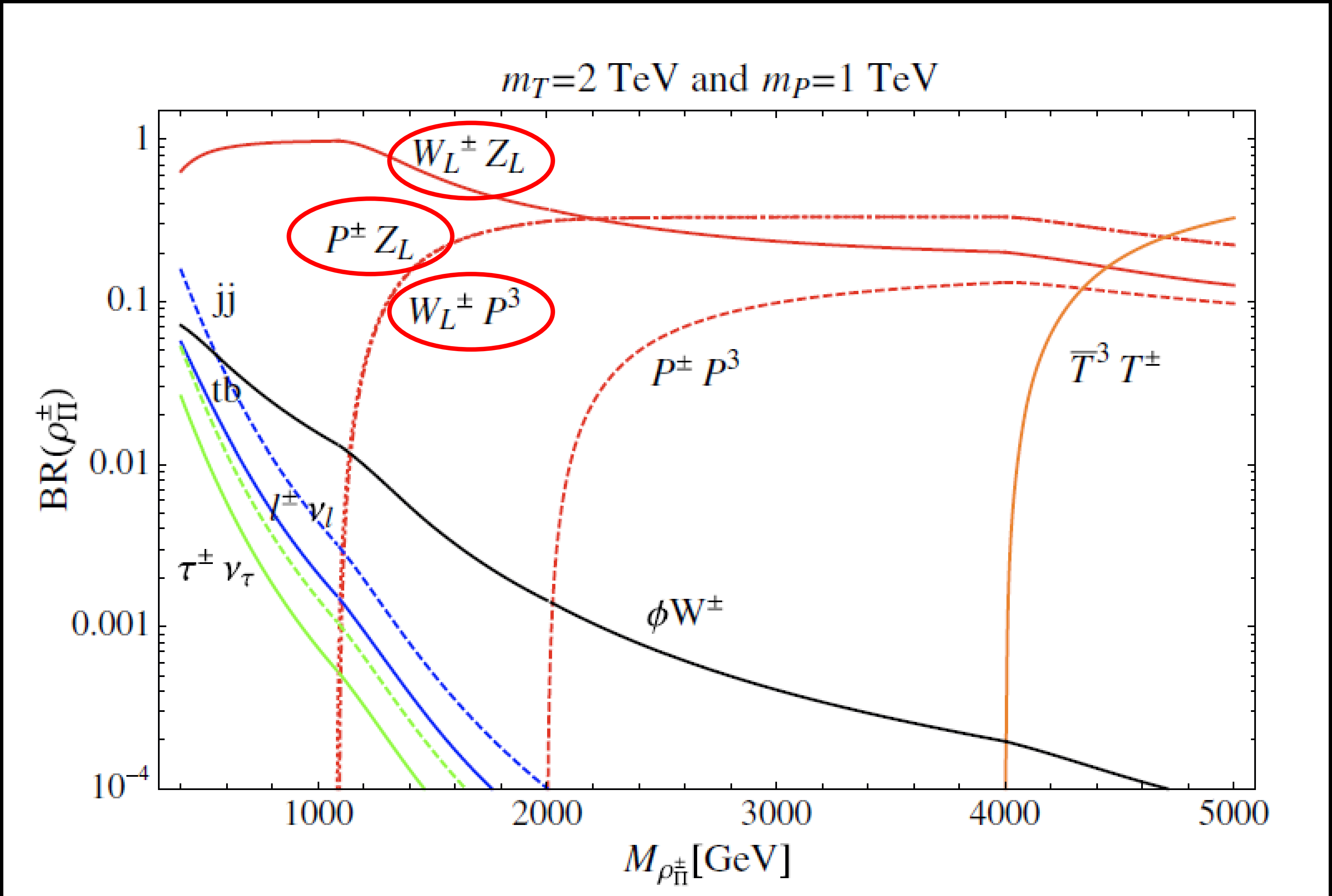
Slide from M.Kurachi's talk at SCGT14Mini, March 2014



Color-singlet iso-triplet (EM neutral)

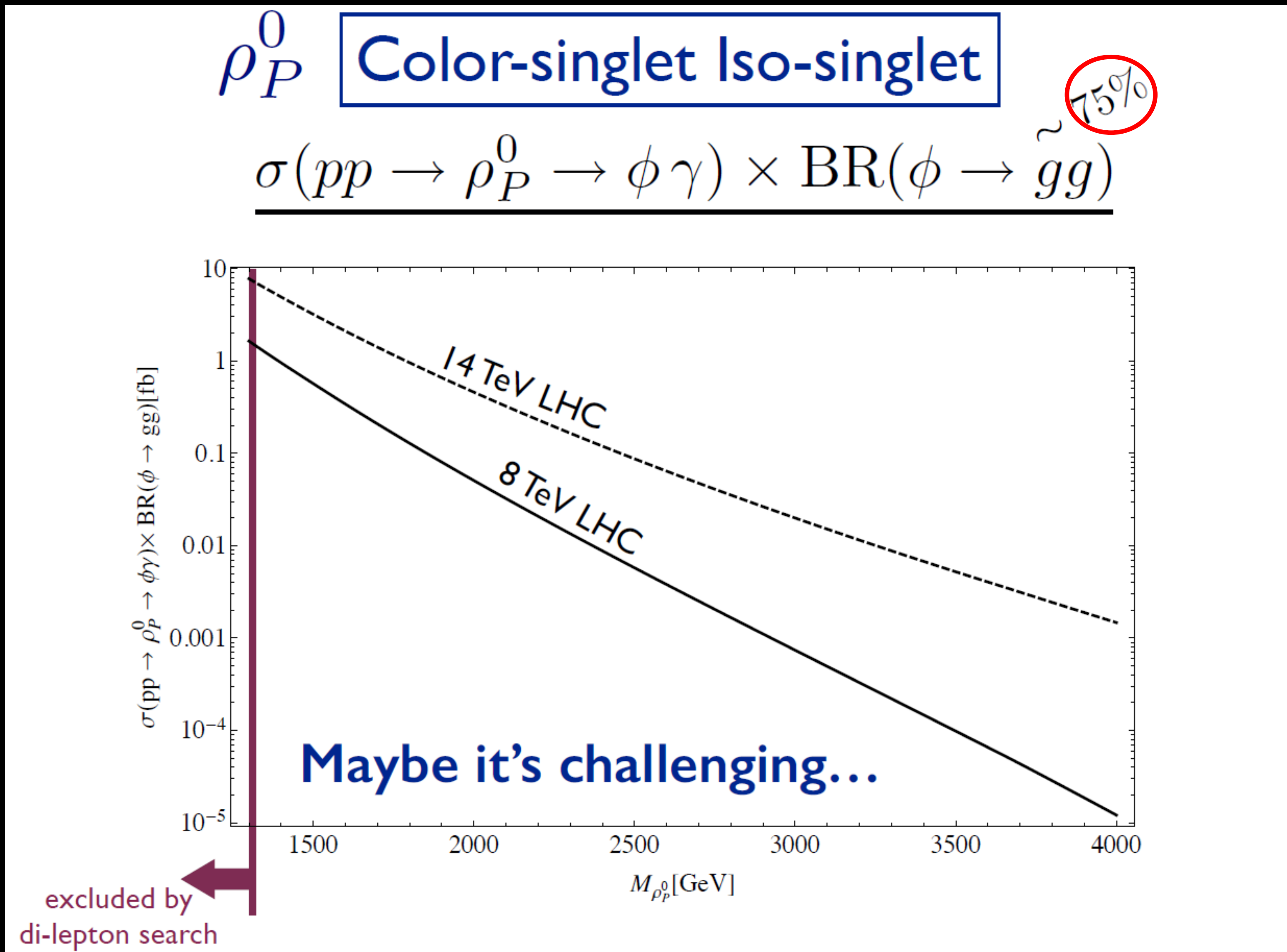


Color-singlet iso-triplet (EM charged)

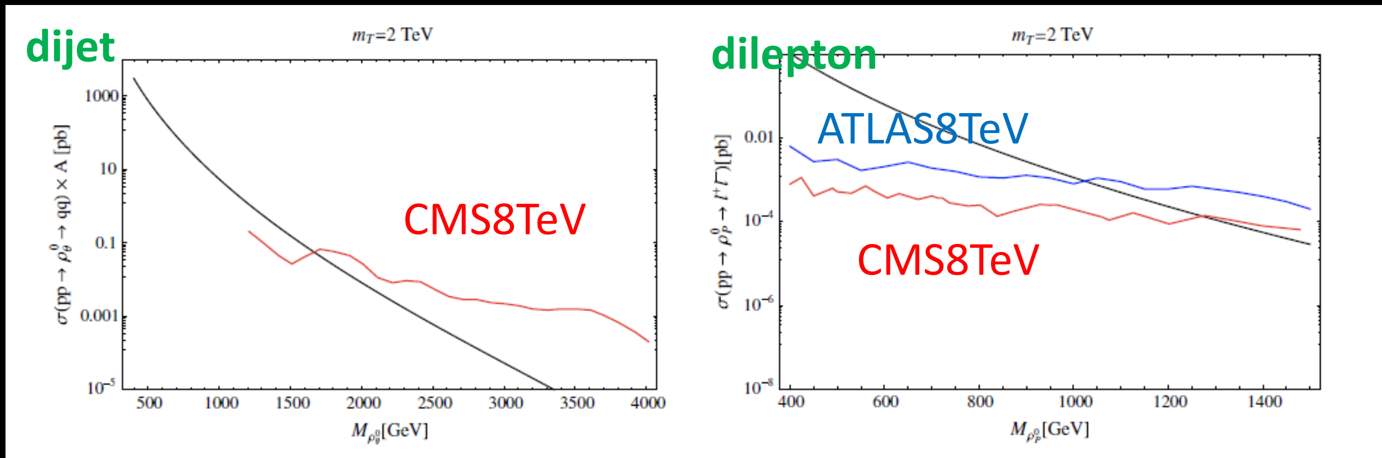


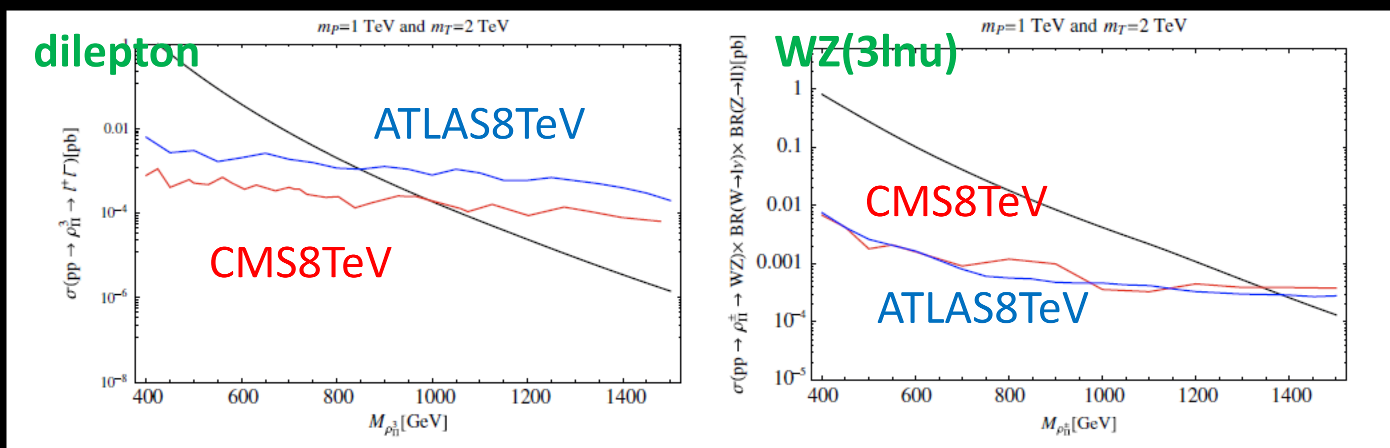
* Discovering technirho mesons associated w/ TD(Higgs)

Slide from M.Kurachi's talk at SCGT14Mini, March 2014



* Current LHC limits on 63 technirho mesons





constrains masses to be

$$M_{\rho^0_\theta} \gtrsim 1.7\ \text{TeV}, \qquad M_{\rho^0_P} \gtrsim 1.3\ \text{TeV},$$
$$M_{\rho^3_\Pi} \gtrsim 1.0\ \text{TeV}, \qquad M_{\rho^\pm_\Pi} \gtrsim 1.4\ \text{TeV}.$$

Slide from K.Terashi's talk at SCGT14Mini, March 2014
M.Kurachi, S.M., K.Terashi & K.Yamawaki, in progress

Color-Octet $\rho_8 \rightarrow g + \Phi$

$\sqrt{s}$ = 8 TeV

$m_{\rho 8}$ [TeV]	1.7	2.0	2.3
$\sigma \cdot$BR [fb]	~300	~70	~20

Color-octet technirho : $\rho_8 \rightarrow g + \Phi$ ($\Phi \rightarrow gg$)

$m_{\rho 8} \lesssim$ 1.6 TeV excluded by 8 TeV dijet resonance search

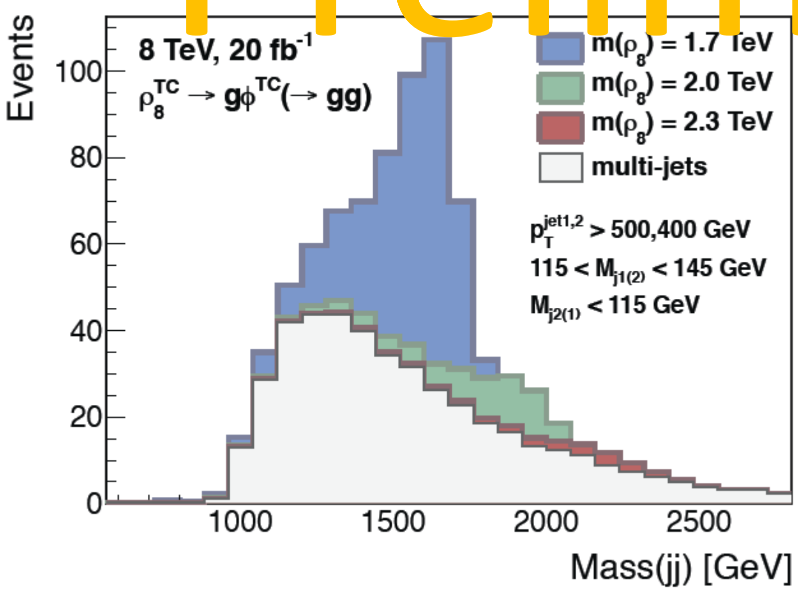
➡ $m_{\rho 8}$ = 1.7, 2.0 and 2.3 TeV chosen as benchmark points

Event Selection :
- $\geq$2 jets p_T >500,400 GeV
- Either one of them = 115 < m_{jet} < 145 GeV, other jet = m_{jet} < 115 GeV

Considered Backgrounds : multi-jets (PYTHIA)

Cut and count in a sliding M window

Preliminary



$\sqrt{s}$ = 8 TeV, 20 fb^{-1}

$m_{\rho 8}$ [TeV]	M_{jj} [TeV]	S	S/$\sqrt{B}$
2.0	1.7-2.0	45	5.3
2.3	2.1-2.3	8 (46)	1.5 (4.3)

($\sqrt{s}$ = 14 TeV, 10 fb^{-1})

➡ Promising channel to probe the model