Walking Technihadrons at the LHC

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References:
S.M. and K. Yamawaki, PRD85, 86, 86 ('12),
PRD87, PLB719, 1304.4882 ('13), 1403.0467, 1404.3048
and works in progress

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   and technidilaton (TD)
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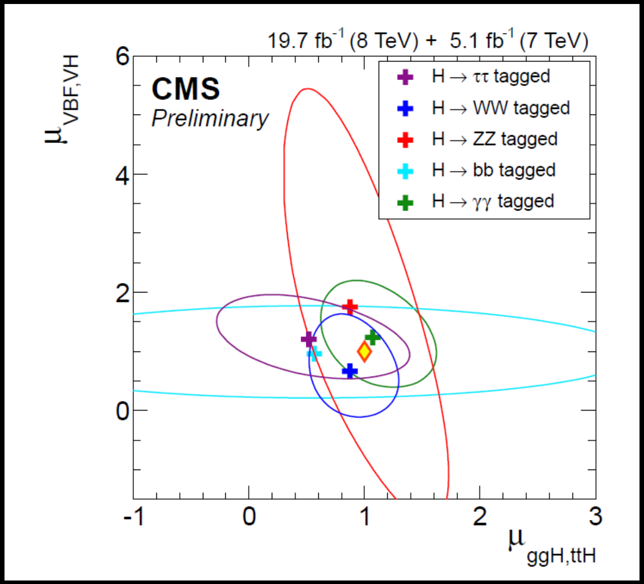
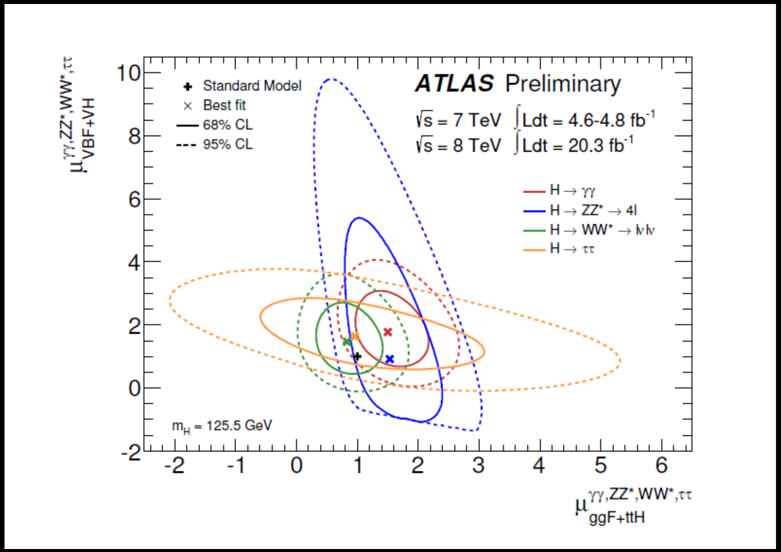
1. Introduction

Current status on 125 GeV Higgs discovered at LHC

CMS-PAS-HIG-14-009



ATLAS-CONF-2014-009



* measured coupling properties
consistent w/ the SM Higgs so far

* BUT, is it really the SM Higgs?

--- origin of mass put in by hand?

--- unnatural elementary Higgs?

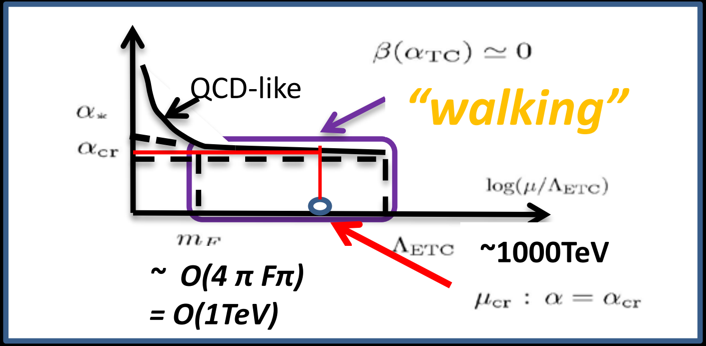
It could be a composite scalar, "Technidilaton (TD)"

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

* TD = a composite scalar:

-- predicted in walking technicolor (WTC)
giving dynamical origin of mass by technifermion condensate

-- arises as a pNGB for SSB of (approximate) scale symmetry technifermion condensate



-- lightness protected by the scale symmetry
and hence can be, say, ~ 125 GeV.

LatKMI Collaboration, PRD89('14)

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

** 125 GeV TD signatures at LHC are consistent with current data*

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

* Walking TC can be viable, solve problems by which QCD-like TC was killed:

- FCNC

  $m_{q,l} \ll m_{q,l}^{(\mathrm{exp})}$ ⇨ Walking TC $\gamma_m \simeq 1$

  Yamawaki,Bando, Matumoto ('86)

- S,T,U parameters

  $S/(N_{\mathrm{TC}} N_D) \sim S_{\mathrm{QCD}} \sim 0.3$

  $S^{(\mathrm{exp})} < 0.1$

  ⇨ (Holographic) Walking TC [or ETC effects]

  Haba, Matsuzaki, Yamawaki ('08,'10,)

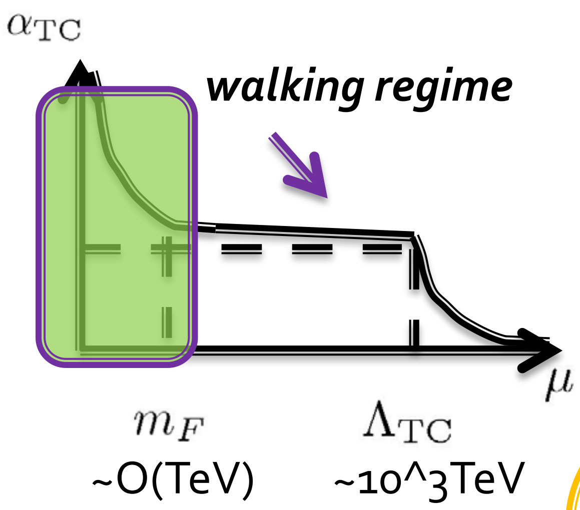
- 125 GeV Higgs

  $125\ \mathrm{GeV} \ll \Lambda_{\mathrm{TC}} = \mathcal{O}(\mathrm{TeV})$ ⇨ Walking TC scale inv.

  Matsuzaki, Yamawaki ('12,'13)

TD phenomenological Lagrangian

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



* effective theory below mF
  after TF decoupled/integrated out
  & confinement :
  governed by TD and other light TC hadrons (technipions, technirho)

* Nonlinear realization of scale and chiral symmetries

Nonlinear base χ for scale sym. w/ TD field Φ

$$\chi = e^{\phi/F_\phi}\,, \qquad \delta\chi = (1 + x^\nu \partial_\nu)\chi$$

TD decay constant FΦ

$$\delta\phi = F_\phi + x^\nu \partial_\nu \phi$$

Nonlinear base U for chiral sym. w/ TC pion field π

$$U = e^{2i\pi/F_\pi} \qquad \delta U = x^\nu \partial_\nu U$$

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

i) The scale anomaly-free part:

$$\mathcal{L}_{\rm inv} = \frac{F_\pi^2}{4}\chi^2 {\rm Tr}[\mathcal{D}_\mu U^\dagger \mathcal{D}^\mu U] + \frac{F_\phi^2}{2}\partial_\mu \chi \partial^\mu \chi$$

ii) The anomalous part (made invariant by including spurion field "S"):

$$\mathcal{L}_S = -m_f \left(\left(\frac{\chi}{S}\right)^{2-\gamma_m} \cdot \chi \right) \bar{f} f + \log\left(\frac{\chi}{S}\right) \left\{ \frac{\beta_F(g_s)}{2g_s} G_{\mu\nu}^2 + \frac{\beta_F(e)}{2e} F_{\mu\nu}^2 \right\} + \cdots$$

reflecting ETC-induced TF 4-fermi w/ (3-γ_m)

β_F: TF-loop contribution to beta function

iii) The scale anomaly part:

$$V_\chi = \frac{F_\phi^2 M_\phi^2}{4}\chi^4 \left(\log \chi - \frac{1}{4} \right)$$

which correctly reproduces the scale anomaly in the underlying WTC

$$\langle \theta_\mu^\mu \rangle = -\delta_D V_\chi \Big|_{\rm vacuum} = -\frac{F_\phi^2 M_\phi^2}{4} \langle \chi^4 \rangle \Big|_{\rm vacuum} = -\frac{F_\phi^2 M_\phi^2}{4}$$

TD couplings to the SM particles

* TD couplings to W/Z boson (from L_inv)

$$g_{\phi WW/ZZ} = \frac{2m_{W/Z}^2}{F_\phi}$$

The same form as SM Higgs couplings except F_Φ and betas

* TD couplings to γγ and gg (from L_S)

$$g_{\phi\gamma\gamma} = \frac{\beta_F(e)}{e}\frac{1}{F_\phi}$$

$$g_{\phi gg} = \frac{\beta_F(g_s)}{g_s}\frac{1}{F_\phi}$$

β_F: TF-loop contribution to beta function

* 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)

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

Thus , the TD couplings to SM particles essentially take the same form as those of the SM Higgs! :

Just a simple scaling from the SM Higgs:

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

But, note ϕ-gg, ϕ-γγ depending on particle contents of WTC models.

βF: TF-loop contribution to beta function

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

Thus , the TD couplings to SM particles essentially take the same form as those of the SM Higgs! :

Just a simple scaling from the SM Higgs:

$$\frac{g_{\phi WW/ZZ}}{g_{h_{\rm SM}WW/ZZ}} = \frac{v_{\rm EW}}{F_\phi}\,,$$

$$\frac{g_{\phi ff}}{g_{h_{\rm SM}ff}} = \frac{v_{\rm EW}}{F_\phi}\,, \qquad \text{for} \quad f = t, b, \tau\,.$$

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β_F: TF-loop contribution to beta function

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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

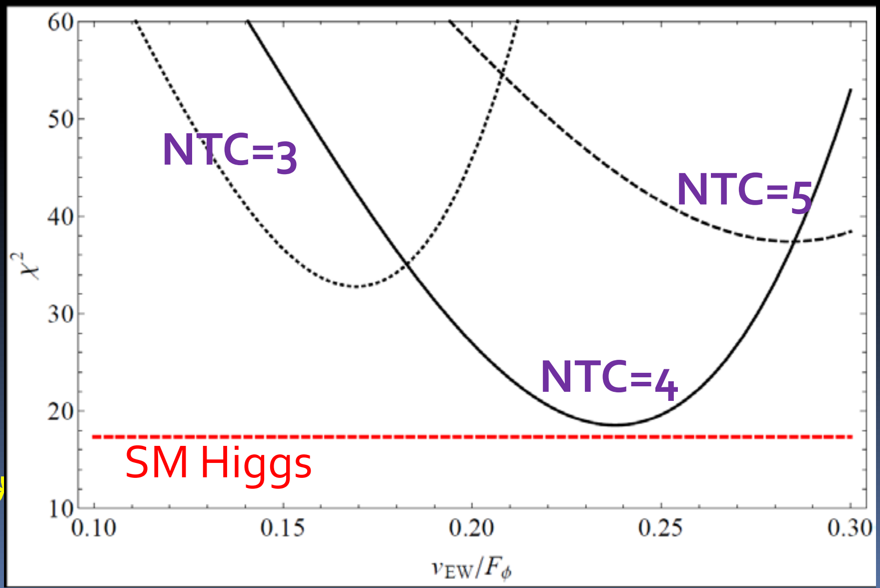
★ *The signal strength fit to the LHC-Run I full data*

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

One-parameter fit (F_ϕ)

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

N_{TC}	$[v_{EW}/F_\Phi]_{\text{best}}$	χ^2 min /d.o.f.
3	0.28	37/17 = 2.2
4	0.24	19/17 = 1.1
5	0.17	33/17 = 1.9



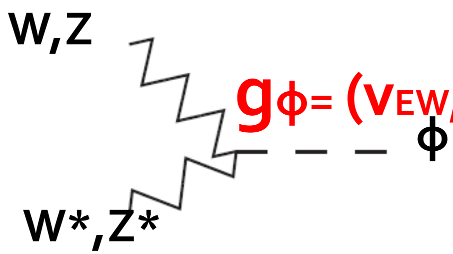
Compared w/ SM Higgs χ^2/d.o.f = 17/18 = 1.0

Current LHC has favored TD at almost the same level as SM Higgs!

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

v.s. SM Higgs

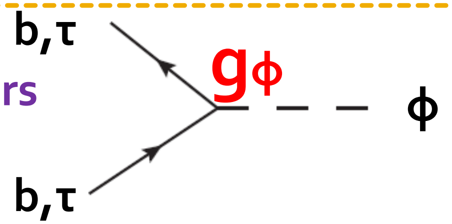
di-weak bosons



$g_\phi = (v_{EW}/F_\phi)\, g_H = 0.24\, g_H$

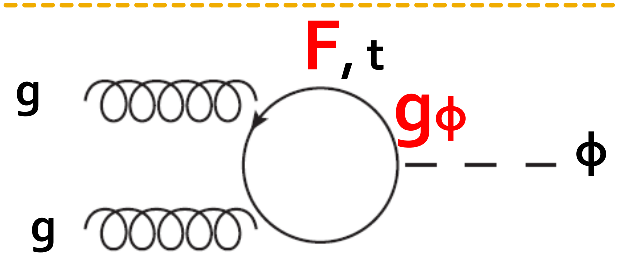
suppressed

quark, lepton pairs



suppressed

digluon

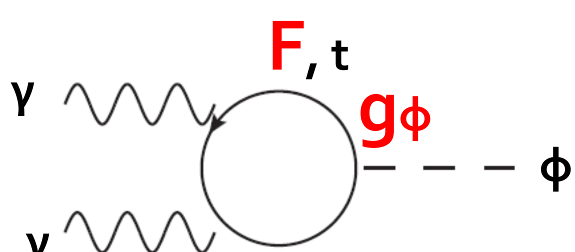


$\beta_F(g_s)$

moderately enhanced

QCD-colored TF contributions

diphoton



$\beta_F(e)$

moderately suppressed

EM-charged TF contributions

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

(i) ggF+ttH category

* Data as of ICHEP2014

TD signal strength	ATLAS	CMS
$\mu_{\gamma\gamma}^{\rm ggF+ttH} \simeq 1.6$	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

* one-family model w/ NTC=4, $v_{EW}/F_\phi = 0.24$

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

(ii) VBF +VH category

* Data as of ICHEP2014

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 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"?

New particles signaling the WTC as BSM

= > Walking techni-pions
& techni-vector mesons
(technirho mesons) !

= smoking-gun of WTC

3. Walking technipions and technirho mesons

* one-family (Farhi-Susskind) model w/ $SU(8)_L \times SU(8)_R \to SU(8)_V$

$TF_{\rm EW}$	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$
$Q_L = \begin{pmatrix} U \\ D \end{pmatrix}_L$	3	2	1/6
$L_L = \begin{pmatrix} N \\ E \end{pmatrix}_L$	1	2	-1/2
U_R	3	1	2/3
D_R	3	1	-1/3
N_R	1	1	0
E_R	1	1	-1

can be "walking" : suggested
by LatKMI collaboration ,
[PRD87 ('13), 1309.0711]
and can have a light TD [1403.500]

* By TF condensation, 63 NGBs emerge: 3 = eaten by W,Z
60 = *pseudos*, Technipions

Coupling properties fixed by
$SU(8)_L \times SU(8)_R / SU(8)_V$, scale-inv. chiral Lagrangian

Get masses
due to EW and ETC gauges

pNGB masses are of O(TeV), due to the walking feature

J. Jia, S.M. and K. Yamawaki, PRD86 ('12)
M.Kurachi, S.M. and K. Yamawaki, 1403.0467

* Current LHC limits on 60 technipions

M.Kurachi, S.M. and K. Yamawaki, 1403.0467

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	$\frac{1}{4\sqrt{3}}(\bar{Q}\gamma_\mu\gamma_5 Q - 3\bar{L}\gamma_\mu\gamma_5 L)$

Most stringent constraints from

pp → ggF → isosinglet technipions → tt

and scalar leptoquark search for color-triplet T_c

exclude TP 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

depending on # of Ntc and size of S^(TC) (for details, see 1403.0467)

* Search for walking techni-rho mesons @ LHC

M.Kurachi, S.M. and K. Yamawaki, 1404.3048
M.Kurachi, S.M., K.Terashi and K.Yamawaki, work in progress

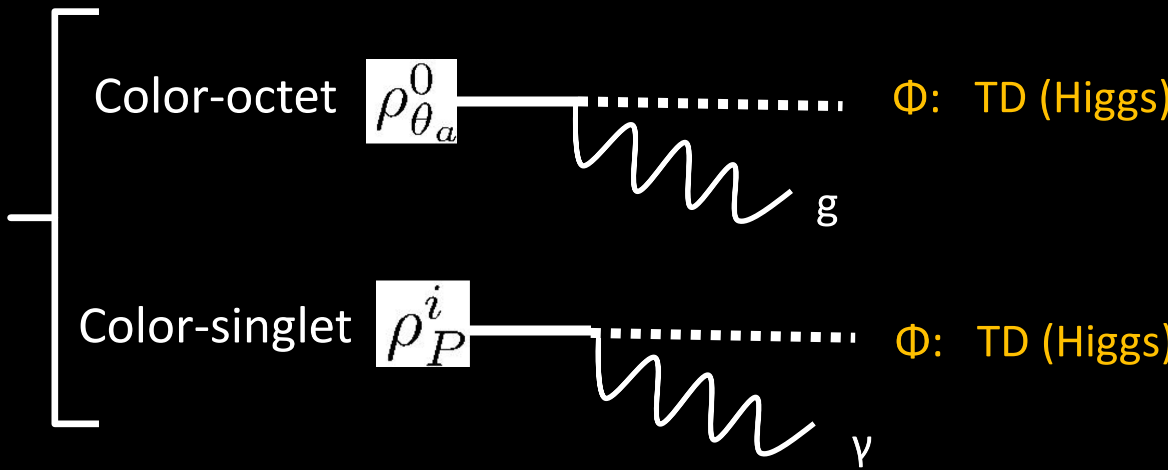
63 vector mesons in a way similar to TPs

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

Coupling properties fixed by
$[SU(8)_L \times SU(8)_R \;\; \times \;\; [SU(8)_V]\_HLS\;]/SU(8)_V$
scale-inv. Hidden Local Symmetry (HLS) Lagrangian

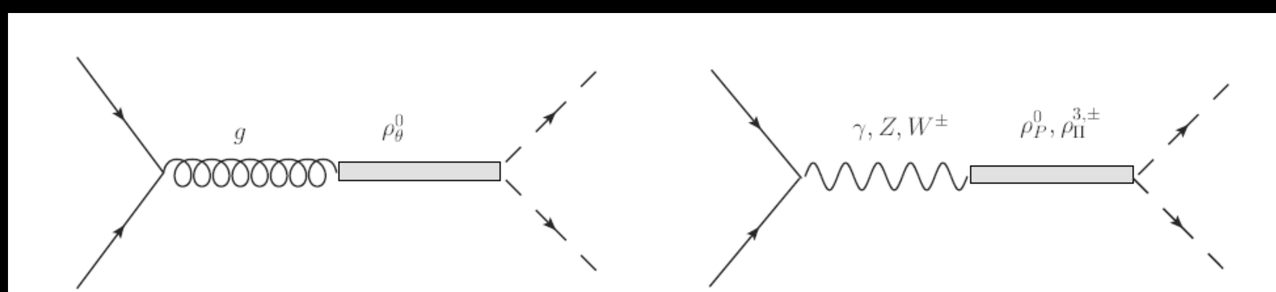
Refs. for HLS
Bando, et al. PRL**54** ('85);
Bando, et al, NP**B259** ('85);
Bando, et al, PTP**79** ('88);
Bando, et al, PR**164** ('88)

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



follows from
scale & ρ-gauge (HLS)
invariance

* Dominant production process @ LHC = > Drell-Yan



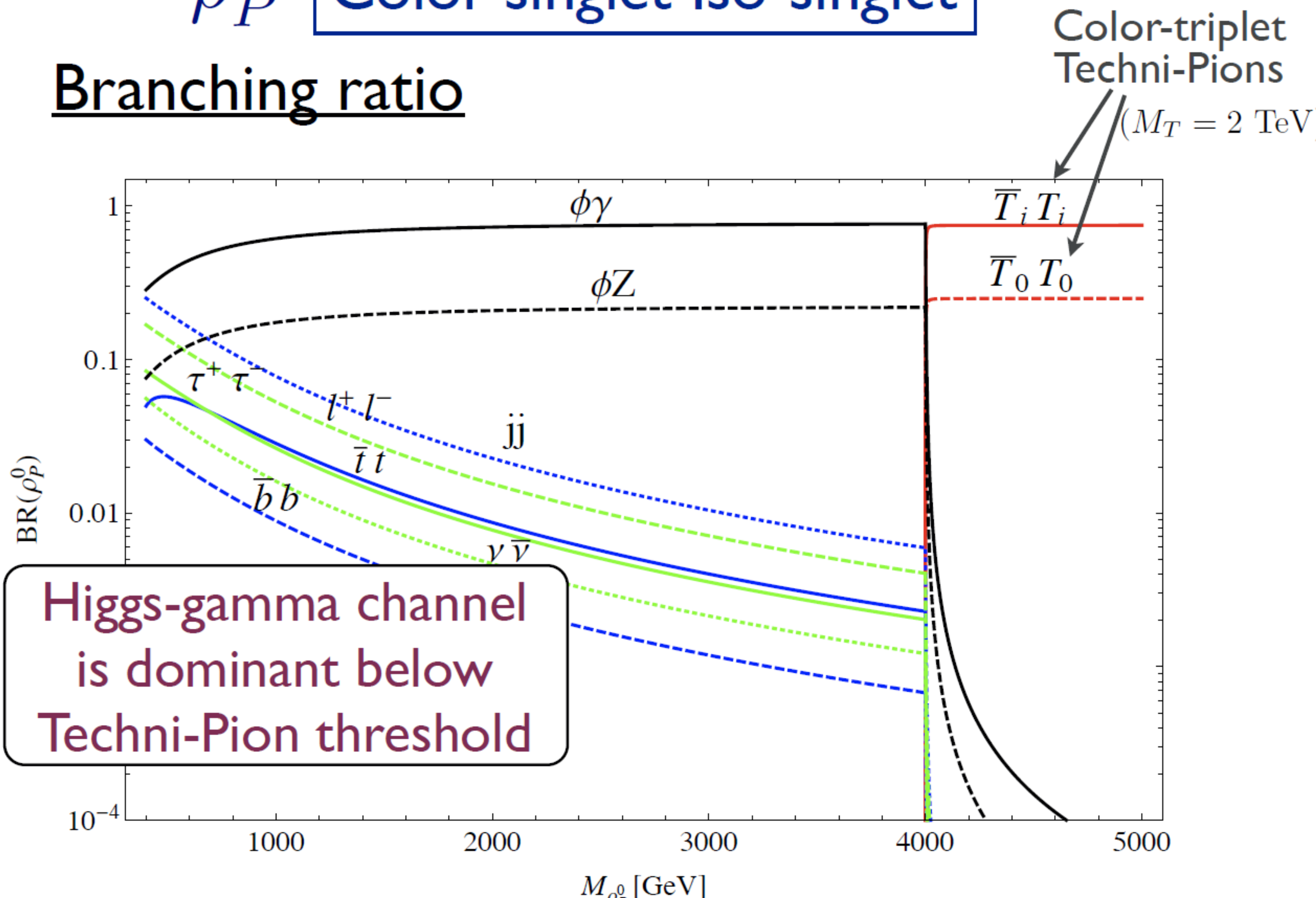
model parameters fixed:

VMD, $F_\pi = v_{EW}/2$, $F_\Phi \sim$ 1.1TeV (best-fit); varying M_ρ

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

ρ_P^0 Color-singlet Iso-singlet

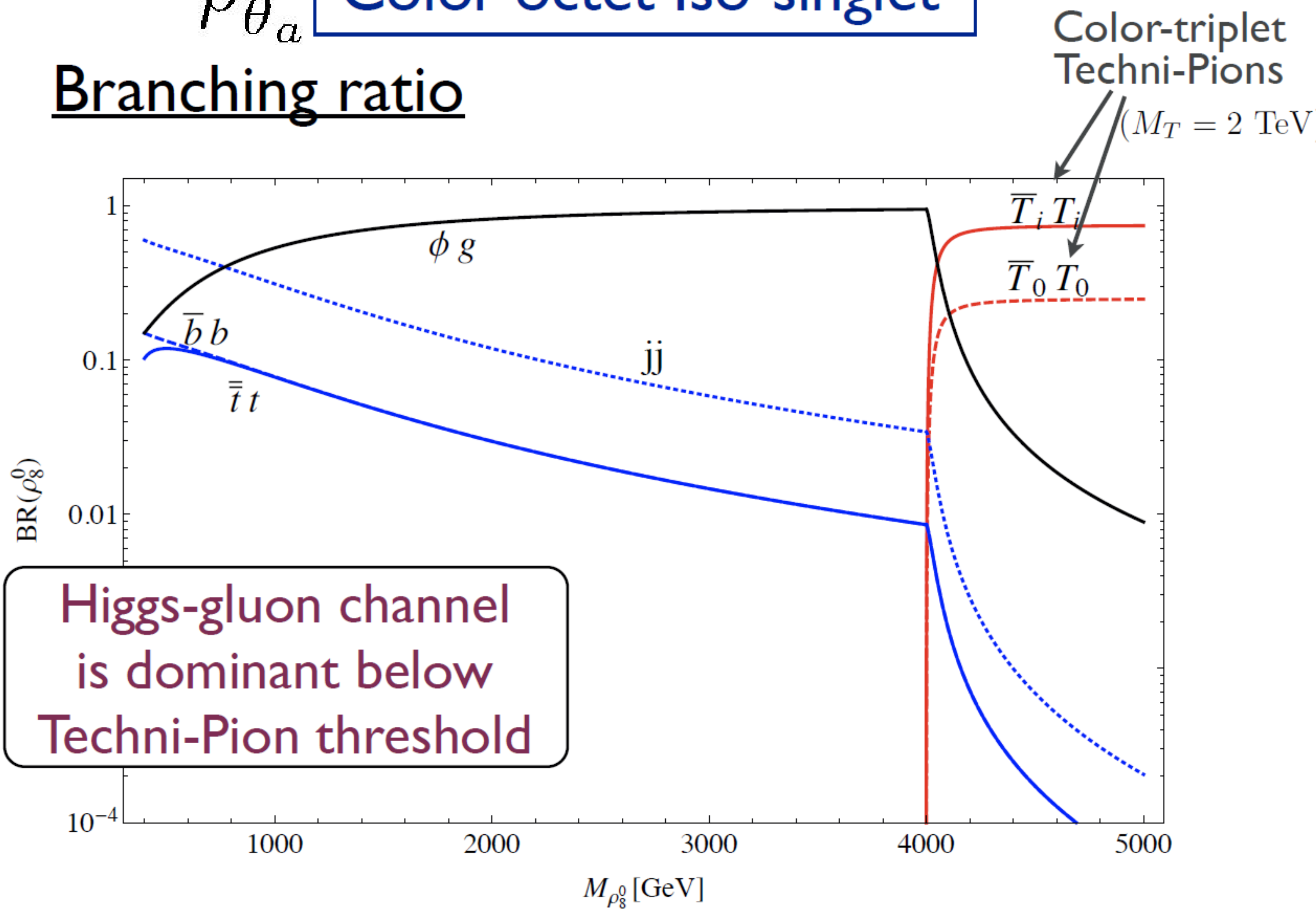
Branching ratio



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

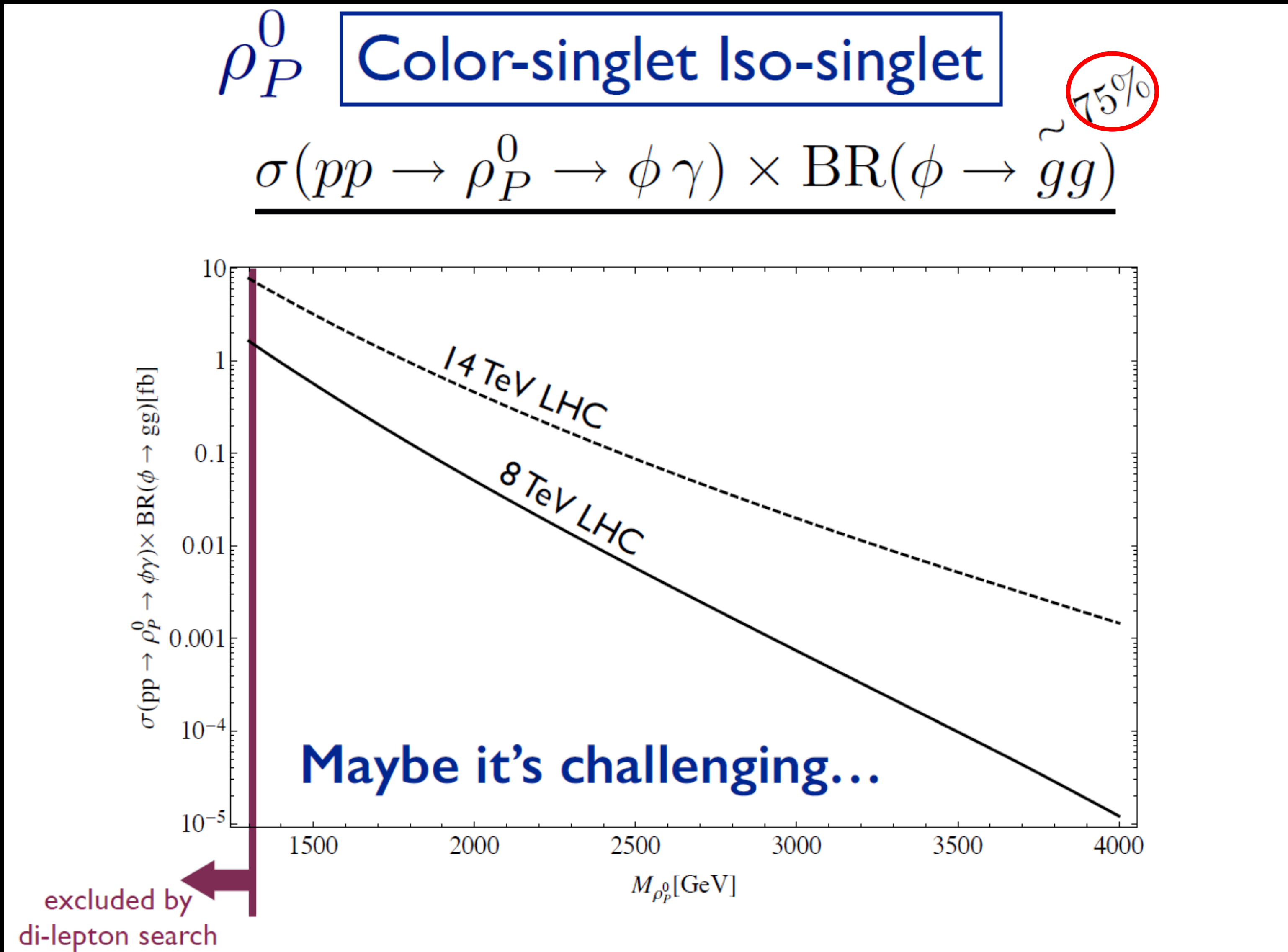
$\rho^0_{\theta_a}$ Color-octet Iso-singlet

Branching ratio



Higgs-gluon channel
is dominant below
Techni-Pion threshold

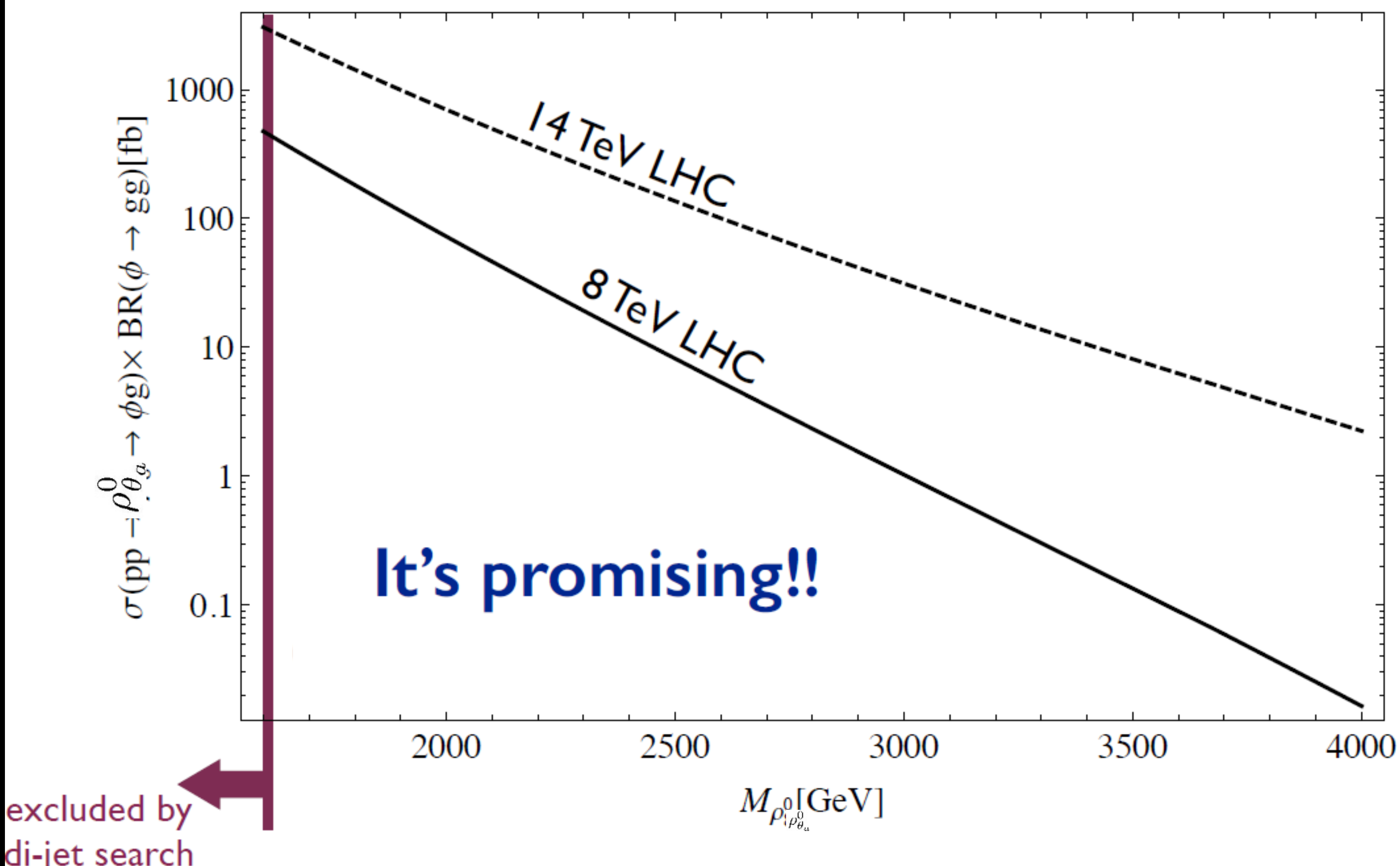
Slide from M.Kurachi's talk at SCGT14Mini, March 2014



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 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

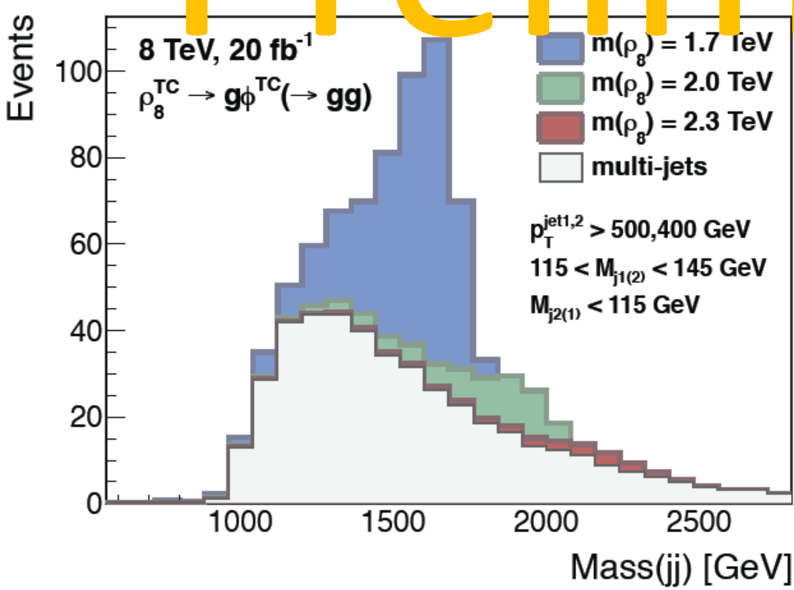
Color-octet technirho : $\rho_8 \rightarrow g + \Phi$ ($\Phi \rightarrow gg$)

$m_{\rho 8} \lesssim$ 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 :
- ≥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**

3. Summary

- Walking TC is viable for LHC-run II, in searching for BSM
- 125 GeV Higgs = could be the Technidilaton (→LHC Run II)
- Probing the WTC is argent task, promising via
  smoking-gun: technipion & techni-vectors,
  masses of order of just reach for upcoming Run II
  in particular, processes involving TD intrinsic to WTC!

Stay tune with WTC!!

Thank you very much!