LHC signatures inspired by Yukawa-bound mesons: Double resonant WW+jet

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based on T.Enkhbat, W.S.Hou, HY, Phys.Rev.D84.094013 (2011), and work in progress with J.Alwall, T.Enkhbat, W.S.Hou (NTU)

Outline:

1. Introduction
2. Yukawa-bound mesons
3. Study for collider signatures
4. Summary

1. Introduction

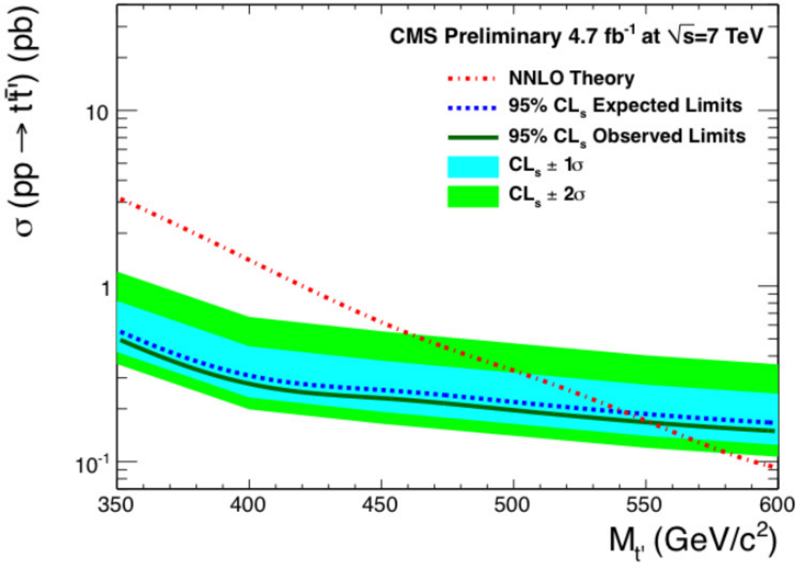
- 4^{th} generation model is a simple extension of the SM
  - The number of generation is a big mystery to us.
    We can always ask “ Why 3, Why not more ? ”.
  - Experimental observation can only tell us the truth.
    Theorists can help how that signal looks like, or what that means.
  - Lots of models with new heavy quarks for BSM physics.

- Direct search for heavy quarks :

Model-independent analysis by assuming the QCD production cross-section and 100% decay mode

CMS (4.7 fb^{-1}) : $m_T > 550$ GeV for $T \to bW$
$m_B > 600$ GeV for $B \to tW$
$m_T > 475$ GeV for $T \to tZ$

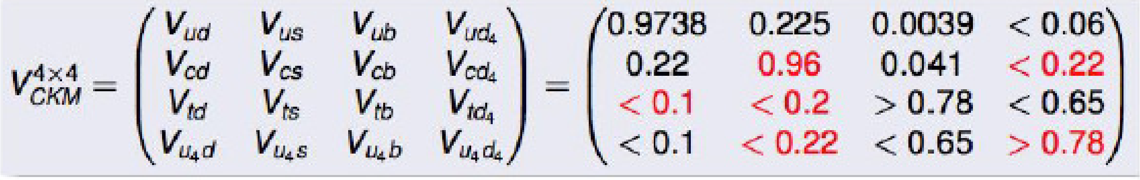
ATLAS (1 fb^{-1}) : $m_Q > 350$ GeV for $Q \to qW$



Unitarity bound for heavy chiral quarks

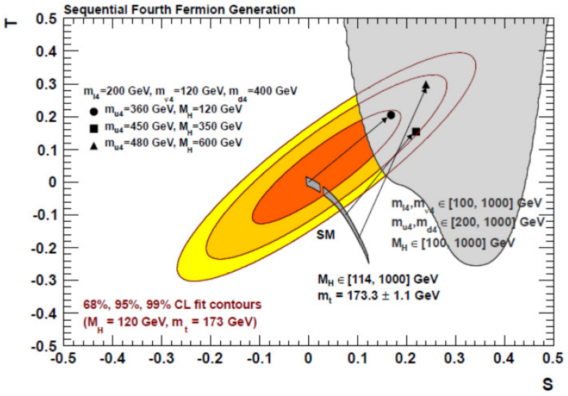
- Heavy quark search in a regime of the unitarity bound (UB)
  - Tree-level scattering amplitudes break unitarity condition, if $m_Q > 550\ \text{GeV}$
  - Beyond that we enter the non-perturbative regime. Chanowitz,Furman,Hincliffe 78,79
  - Then, what can be the heavy quark signature beyond the unitarity bound?

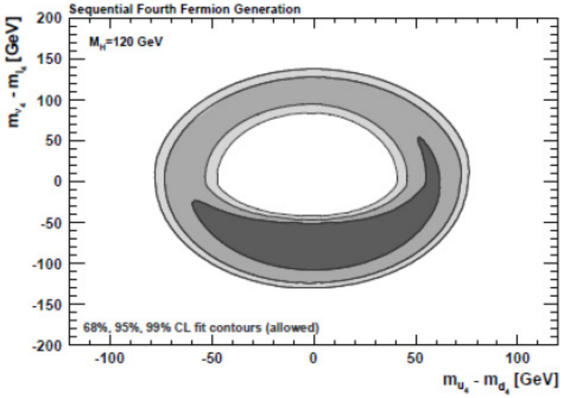
- Constraints from Flavors, EW precision tests
  - Heavy Higgs can be consistent with 4G. Kribs et. al. 07
  - Flavor data constrains CKM4 mixing matrix.
  - Parameter scan for SM4 e.g., GFitter, CKMFitter, Eberhardt et al,,,



$$V_{CKM}^{4\times 4} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} & V_{ud_4} \\ V_{cd} & V_{cs} & V_{cb} & V_{cd_4} \\ V_{td} & V_{ts} & V_{tb} & V_{td_4} \\ V_{u_4 d} & V_{u_4 s} & V_{u_4 b} & V_{u_4 d_4} \end{pmatrix} = \begin{pmatrix} 0.9738 & 0.225 & 0.0039 & < 0.06 \\ 0.22 & 0.96 & 0.041 & < 0.22 \\ < 0.1 & < 0.2 & > 0.78 & < 0.65 \\ < 0.1 & < 0.22 & < 0.65 & > 0.78 \end{pmatrix}$$

Yuan





2. Yukawa-bound mesons

- Our study:

We consider a possible bound-state phenomenology of the 4G scenario in a regime of the UB, and its collider signatures. Our set-up is following:

SM4 $\left\{ \right.$

- Chiral 4G quarks with degenerated mass: **$m_{t'} = m_{b'} > 500$ GeV**
- which is simply given by the Yukawa interactions.
- Higgs-boson is also heavy; $m_H > 600$ GeV
  (EW precision test, direct search, ggH cross-section)

- Yukawa-bound mesons:

Jain et. al. 92, 94, Ishiwata, Wise 11, Enkhbat, Hou, HY 11,,,

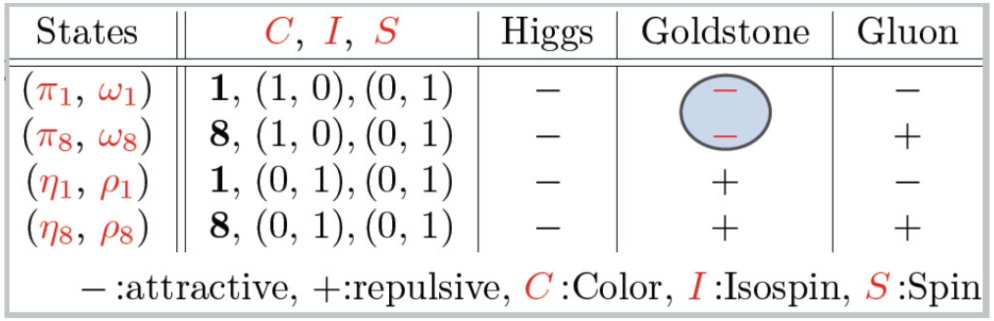
Large Yukawa couplings of the heavy chiral quarks provide a possibility to form bound-states by the Yukawa interaction rather than QCD.

$$\alpha_Y \simeq 1 > \alpha_s \simeq 0.1$$

Yukawa-bound heavy 4G mesons

- (Relativistic) Potentials for heavy chiral quarks
  - Higgs exchange contribution is suppressed by its mass and width.
  - Goldstone-boson exchange gives the dominant contributions.
    It is Isospin dependent, and pseudo-scalar exchange (relativistic).
  - Gluon exchange is subdominant, which gives singlet/octet splitting.

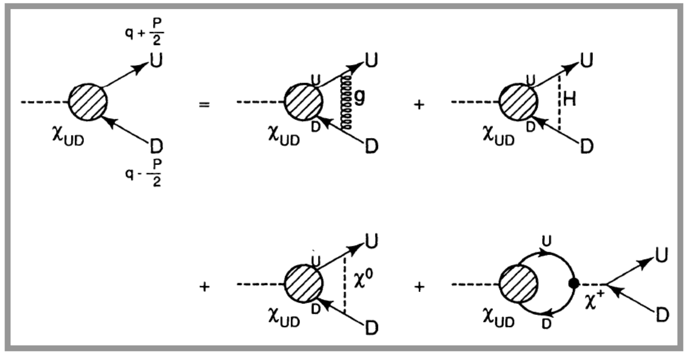
Potentials for B.S. equation



States	$C,\ I,\ S$	Higgs	Goldstone	Gluon
$(\pi_1,\ \omega_1)$	$\mathbf{1},\ (1,0),(0,1)$	$-$	$-$	$-$
$(\pi_8,\ \omega_8)$	$\mathbf{8},\ (1,0),(0,1)$	$-$	$-$	$+$
$(\eta_1,\ \rho_1)$	$\mathbf{1},\ (0,1),(0,1)$	$-$	$+$	$-$
$(\eta_8,\ \rho_8)$	$\mathbf{8},\ (0,1),(0,1)$	$-$	$+$	$+$

$-$:attractive, $+$:repulsive, C :Color, I :Isospin, S :Spin

diagrams for B.S. equation



- Relativistic Bethe-Salpeter equation describes the bound-state. Jain et.al. 92 94
- Relativistic expansion approach also showed that the binding energy could be O(100) GeV even for the color-octet state. Ishiwata, Wise 11

Yukawa-bound heavy 4G mesons

- The expected bound-states are :

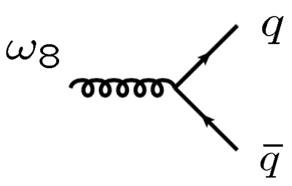
π_1, π_8 : Iso-triplet color- singlet/octet pseudoscalar $I^G(J^P)_C = 1^-(0^-)_{1,8}$

ω_1, ω_8 : Iso-singlet color- singlet/octet vector $I^G(J^P)_C = 0^-(1^-)_{1,8}$

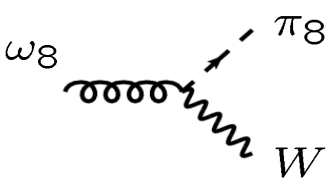
  - η, ρ states not bound (unlike the QCD-like models, e.g. Technicolor)
  - Expected mass spectrum is $m_{\pi_1} < m_{\pi_8} \simeq m_{\omega_1} < m_{\omega_8}$

- Parameterize the structures of mesons which are unknown to us
  - mesons mass splitting, decay constant, mixing angles
  - Interactions of the mesons :

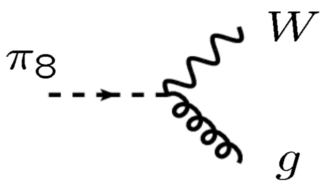
f : decay constant



$\sim g_s^2 f_\omega / m_\omega$



$\sim g_W$



$\sim g_W g_s f_\pi$

3. Study for Collider Signatures

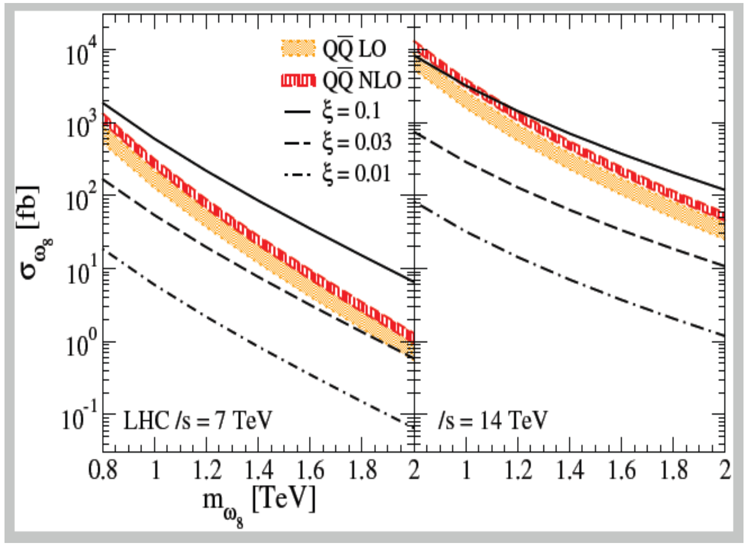
- Production mechanism :

$\pi_{1,8}$: Pair production due to Isospin conservation

ω_1 : Weak interaction

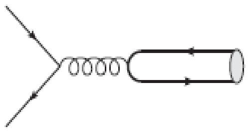
ω_8 : **Single production by strong interaction**
(via qqbar annihilation)

$pp \to \omega_8$ production cross-section



The cross-section depends on
an unknown decay constant.

$$\langle 0|V^{\mu,a}|\omega_8^b(p)\rangle = \frac{1}{\sqrt{2}}\delta^{ab} f_{\omega_8} m_{\omega_8} \varepsilon^\mu(p),$$



- Dominant decay of ω_8: under the assumption of the small mixing with 3G
(rather stable t' & b'. Mesons decay by annihilation)

Meson transition: $\omega_8 \to \pi_8 W$

and subsequently, $\pi_8 \to W g$

Annihilation decay: $\omega_8 \to q\bar{q},\ t\bar{t}$

The other modes can be

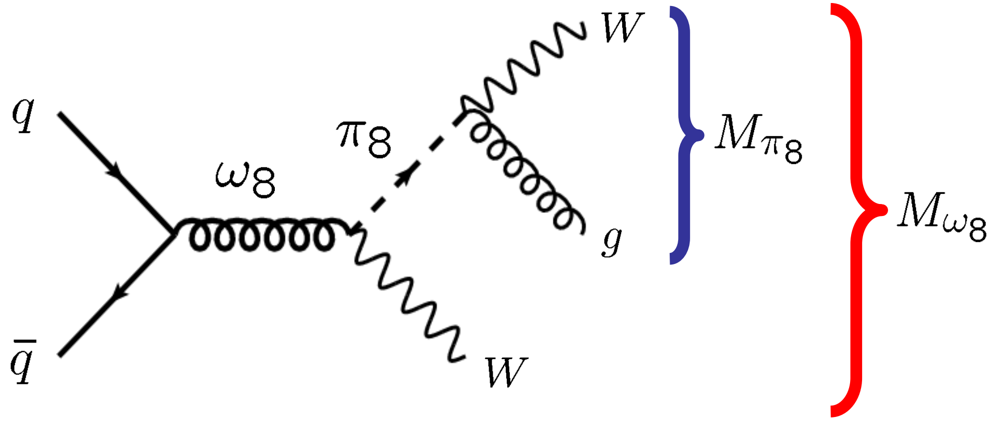
$\omega_8 \to \omega_1 g$

$\omega_8 \to t'\bar{b}W \to bW\bar{b}W,$

$\to b'\bar{t}W \to tW\bar{t}W,,,$

WW+jet signatures

- Thus the collider signatures are $pp \to \omega_8 \to W\pi_8 \to WWg$



A double resonant structure in the "soft W + hard W + hard gluon" final-state

Typical momentum of

soft W : $p_T^W \sim \mathcal{O}(m_{\omega_8} - m_{\pi_8})$

hard W : $p_T^W \sim m_{\pi_8}/2$

- Pattern of W's decay:

Semi-leptonic : $W\pi_8 \to W(Wg) \to (\ell\nu)((q\bar{q}')g)$ two collimated jets = "boosted W"

$W\pi_8 \to W(Wg) \to (q\bar{q}')((\ell\nu)g)$ high-p_T lepton + large missing E_T

Dilepton : $W\pi_8 \to W(Wg) \to (\ell\nu)((\ell'\nu)g)$

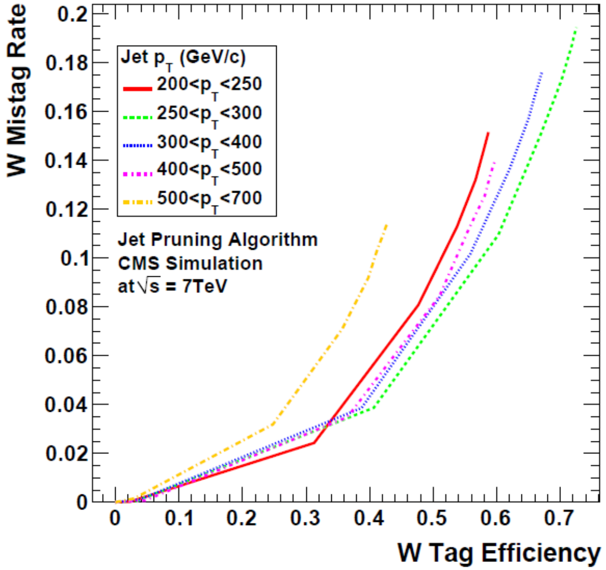
Z-boson case : $Z\pi_8 \to Z(Zg) \to (\ell\ell)((q\bar{q})g)$ "boosted Z" jet + dilepton

W-jet tagging method

Butterworth,Cox,Forshaw;Almeida,Lee,Perez,Sterman,Sung,Virzi;
Ellis,Vermilion.Walsh;Hackstein,Spannowsky;Katz,Son,Tweedie;
Thaler,Tilburg ,,,

- Find fat jets with a specific subjet structure

CMS PAS JME-10-013



CMS method : Pruning + Mass drop

1. Find jets by C/A algorithm with R=0.8
2. Pruning to remove soft and wide-angle radiation
3. Require two subjets, and find large inv-mass reduction

   of the hardest subjet; $M_1/M_j < 0.4$.

- Good significance for high-p_T jets can be achieved; $\epsilon_S \sim 30\%$ with $\epsilon_B \sim 2\%$

- Thus, the most promising signature could be $W(Wg) \to (\ell v)(j_W j)$
  where one of the jets is W-tagged.

- Dominant BG processes are W+2jets and tt~

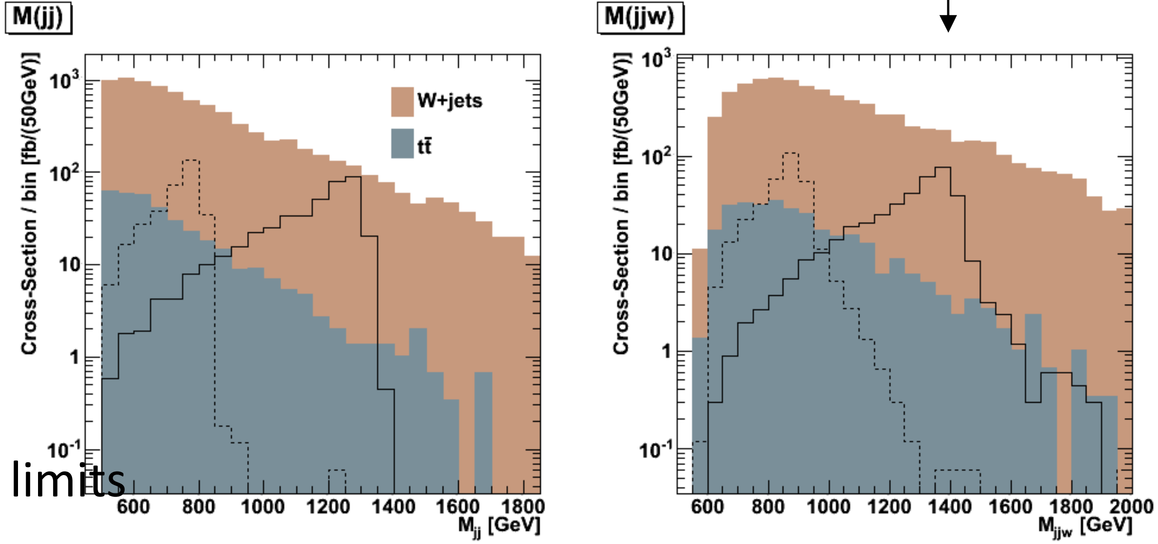
Simulation Results

$$pp \to \omega_8 \to W\pi_8 \to WWg \to (\ell\nu)j_w j$$

- Our simulation framework :
  - Event generation by MG5 + Pythia,
    matched up to one addional jet radiation.
  - Delphes detector simulation; W-tagging for CaloTower jets
- Selection cuts : (universal for any input signal masses)
  - Two high-p_T jets ($p_T > 200$ GeV, one is W-tagged)
  - One isolated lepton ($p_T > 20$ GeV) + missing $E_T > 20$ GeV.
  - Leptonic W momentum is reconstruction by on-shell W-boson condition.
  - $M_{jj} > 500$ GeV
- Reconstructed invariant-mass :
  - M_{jj} (left) and M_{jjw} (right)
  - Sharp peak in M_{jj} distribution

→ CLs analysis for the cross-section limits

signal events
with 1pb cross-section.



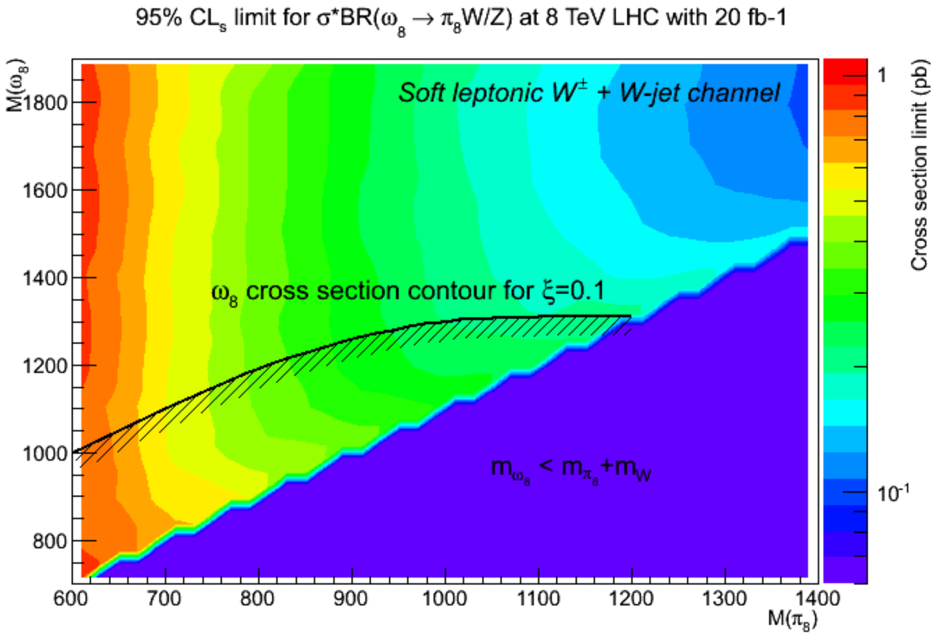
Constraints on the parameters

- Bump hunt from the continuum BG

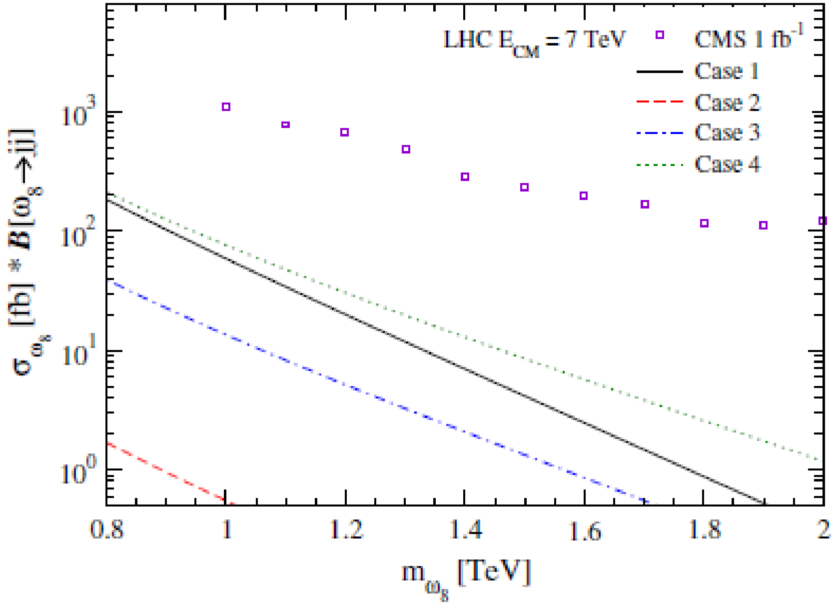
  → CLs analysis gives the upper limit of the cross-section.

  → Limit on the model parameter (decay constant) for given masses.

$$\xi = f_\omega / m_\omega$$



- Dijet signature (same as Z', G' search) also constrains the decay constant:
  - Large decay constant gives large branching ratio into di-jet.



4. Summary

- 4G quarks, if exist, can form relativistic bound-states by Yukawa int.

  Heavy Isospin and Goldstone-boson exchange force predict a characteristic spectrum of the 4G mesons ($\omega_{1,8}$, $\pi_{1,8}$ states).

- We study the collider signature of the 4G mesons.

  Single ω_8 is the most attractive production process,
  which would be followed by its decay into $W\pi_8$ and further into WWg.

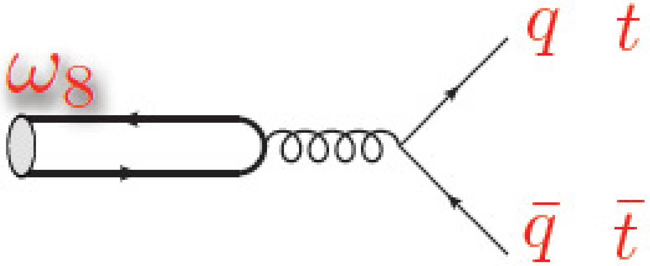
  Semi-leptonic decays of W's lead to a characteristic signature $W(Wg) > l\nu(j_W j)$ signature, where one of the hard jets is W-tagged.

- LHC early run (2011&2012) can search for it, and constrain parameters in the model (decay constant, meson masses).

Decay channels of ω_8

Three main decay mechanisms

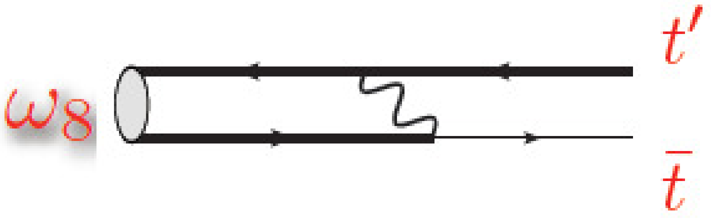
Annihilation decay $\omega_8 \to q\bar{q}, t\bar{t}, t'\bar{t}, b'\bar{b}$



$$\Gamma(\omega_8 \to q\bar{q}) = \xi^2 \frac{\pi\alpha_s^2}{3} m_{\omega_8} n_f$$

$$\Gamma(\omega_8 \to t\bar{t}) = \xi^2 \frac{\pi\alpha_s^2}{3} m_{\omega_8} \beta_t$$

$$\Gamma(\omega_8 \to t\bar{t}') = \xi^2 |V^*_{tb'} V_{t'b'}|^2 \frac{G_F^2 m_{\omega_8}^5}{192\pi} \quad E(\tilde{m}_{t'}, \tilde{m}_t)$$

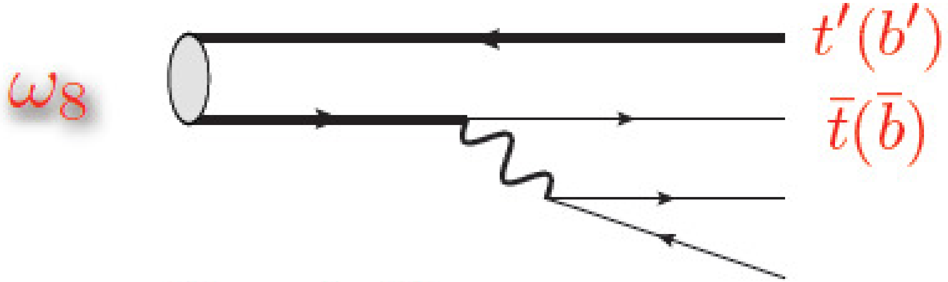


$V_{t'b}$ -4th & 3d generation mixing

$$E(x, x') = \frac{\lambda(1, x^2, x'^2)}{2(1 - 2x^2 - 2x'^2)^2} \times \Big[2 - 9x^2 + 15x^4 - 8x^6 - 9x'^2 + 18x^2x'^2 - 8x^4x'^2 - 16x^6x'^2 + 15x'^4 - 8x^2x'^4 + 32x^4x'^4 - 8x'^6 - 16x^2x'^6\Big].$$

Decay channels of ω_8 cont'd

Free quark decay $\omega_8 \to (t'\bar{t}' \to bW\bar{t}'), (b'\bar{b}' \to tW\bar{b}')$



$$\Gamma_{\text{free}} \simeq \Gamma_{t'} + \Gamma_{b'}$$

$$\Gamma_{t'} = |V_{t'b}|^2 \frac{G_F m_{t'}^3}{8\sqrt{2}\pi} F(\tilde{m}_W, \tilde{m}_b)$$

$$\tilde{m} = m/m_{t'}$$

$V_{t'b}$ -4th & 3d generation mixing

$$F(x,y) = (1 + x^2 - 2x^4 - 2y^2 + x^2y^2 + y^4)\,\lambda(1, x^2, y^2)$$

$$\lambda(a,b,c) = \sqrt{a^2 + b^2 + c^2 - 2(ab + bc + ca)}$$

Meson transition $\omega_8 \to \pi_8 W,\, \omega_1 g$

$$\Gamma(\omega_8 \to \pi_8 W) = \frac{G_F m_{\omega_8}^3}{32\sqrt{2}\pi} \frac{m_{\omega_8}}{m_{\pi_8}} W(\hat{m}_{\pi_8}, \hat{m}_W)$$

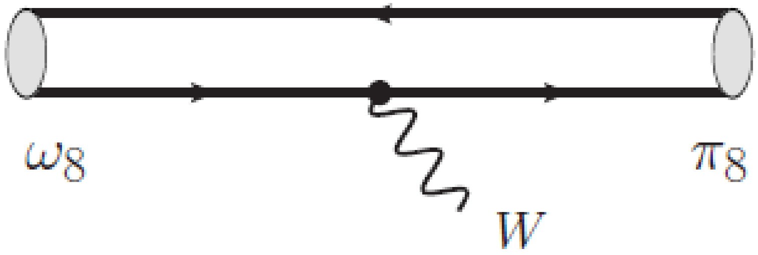
$$\Gamma(\omega_8 \to \omega_1 g) = \frac{\alpha_s}{18} \frac{m_{\omega_8}^2}{m_{\omega_1}} G(\hat{m}_{\omega_1})$$

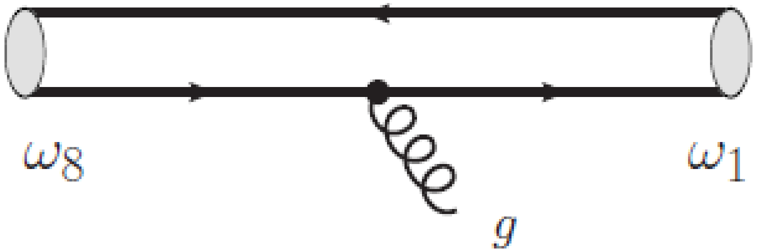
$$\Gamma(\omega_8 \to \pi_8 \gamma) \simeq \frac{\alpha}{3} \frac{(\Delta m)^3}{m_Q^2}$$

$$\hat{m} \equiv m / m_{\omega_8}$$

Here $\Delta m \equiv m_{\omega_8} - m_{\pi_8}$ due to Strong binding

$$W(x,y) \simeq (1 - 2x^2 + x^4 + 3y^2 + 2xy^2 + 3x^2y^2 - 4y^4) \\ \times (1 + 2x + x^2 - y^2)\,\lambda,$$





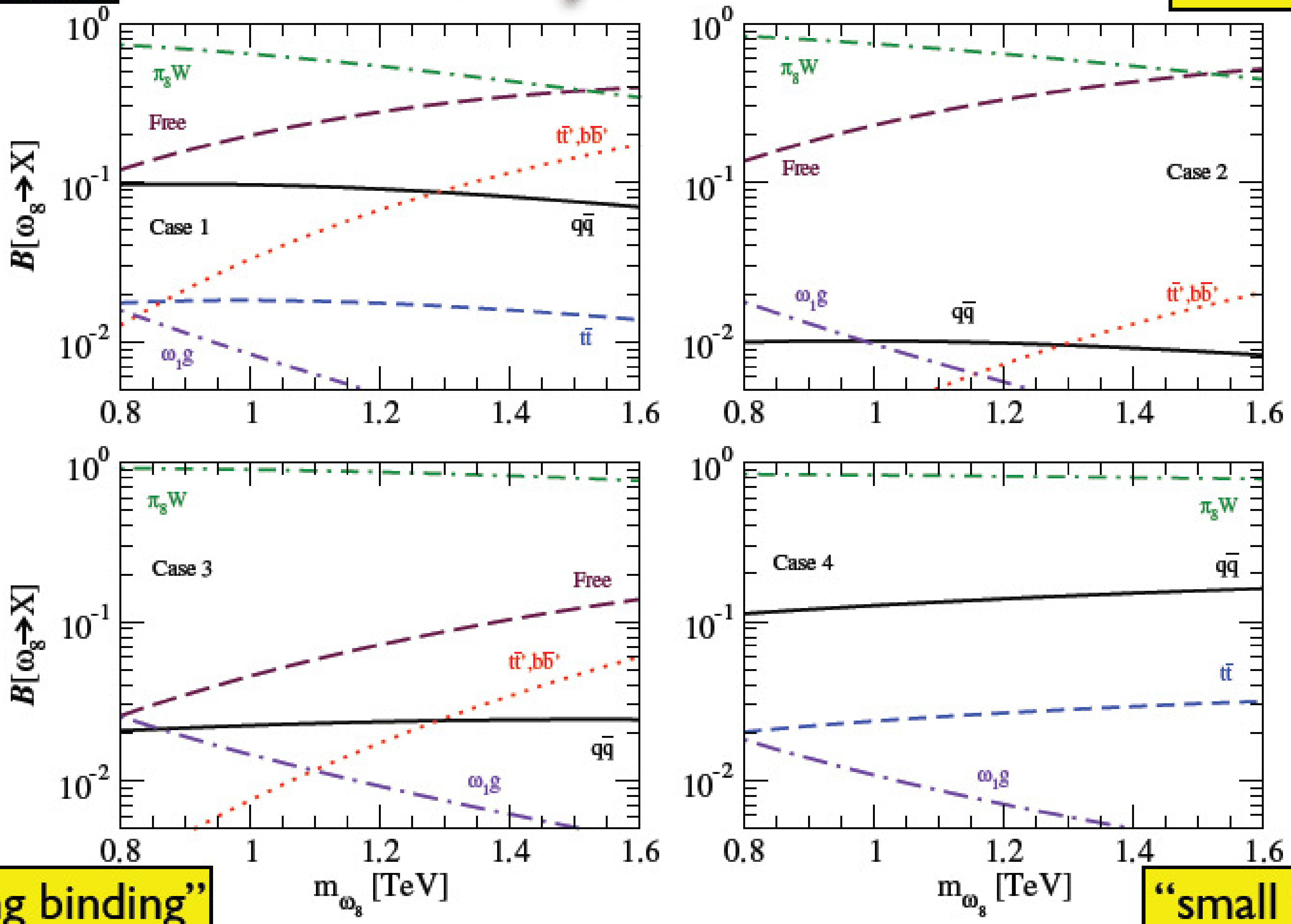
Four different choices for parameters for decay rate calculation

$$\xi \equiv \frac{f_{\omega_8}}{m_{\omega_8}}$$

$$\Delta m \equiv m_{\omega_8} - m_{\pi_8}$$

Case 1	$\xi = 0.1, \Delta m = 100\ GeV, V_{t'b} = 0.1$	"nominal"
Case 2	$\xi = 0.03, \Delta m = 100\ GeV, V_{t'b} = 0.1$	"small f_{ω_8} "
Case 3	$\xi = 0.1, \Delta m = 200\ GeV, V_{t'b} = 0.1$	"strong binding"
Case 4	$\xi = 0.1, \Delta m = 100\ GeV, V_{t'b} = 0.01$	"small mixing"

Decay rates of ω_8



"nominal"

"small f_{ω_8}"

"strong binding"

"small mixing"

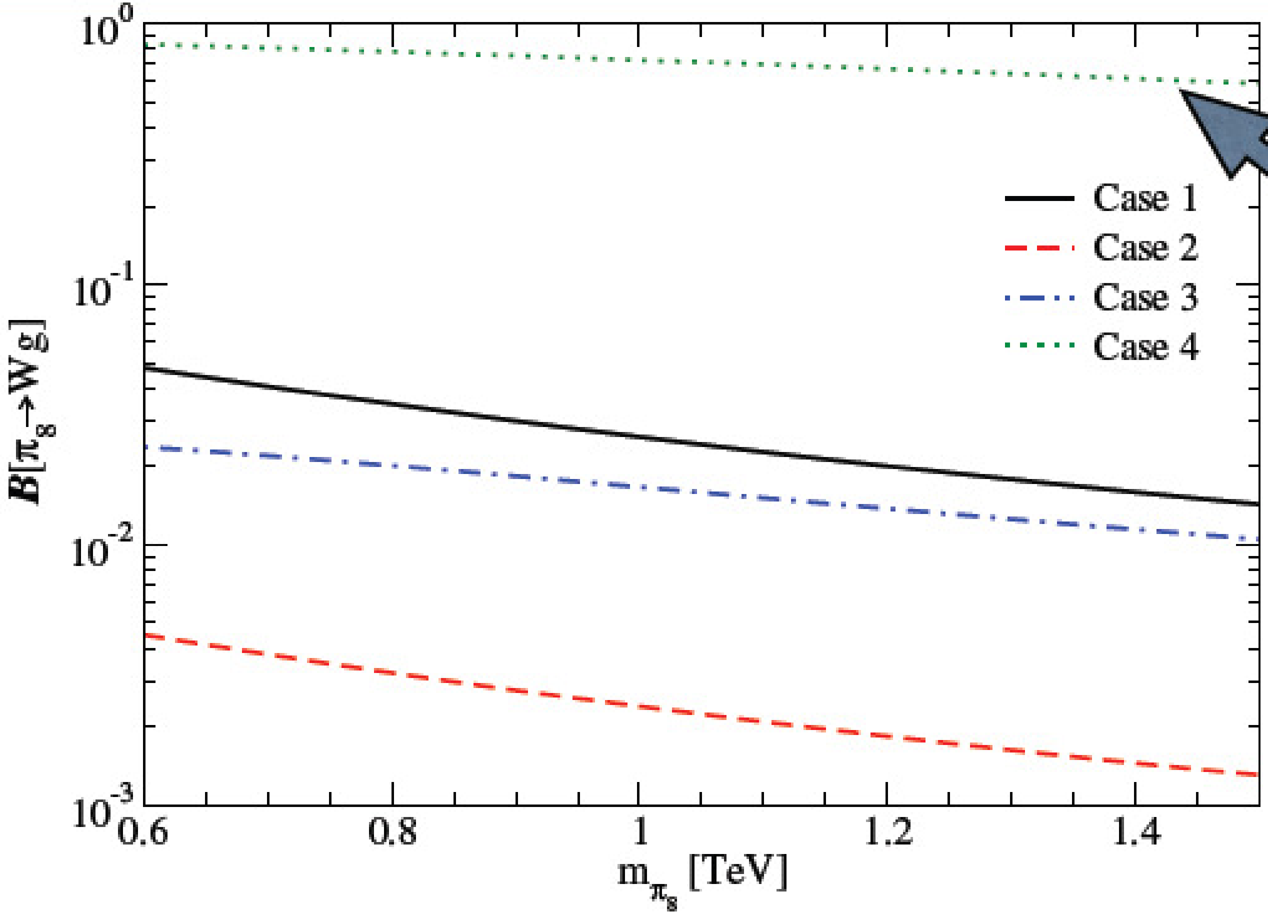
Meson transition $\omega_8 \to \pi_8 W$ dominates

If $\Delta m < M_W$, free or dijet are dominant

Branching ratio for of $\pi_8 \to W g$

Only free quark or $\pi_8 \to W g$ decays channels are present!

Annihilation s-channel or W-exch and $\pi_8 \to \pi_1 g$ are absent.



"small mixing"

For cases 1 to 3 the free quark decay dominates

For case 4, small mixing: $\pi_8 \to W g$ dominates