Doubly resonant WW+jet signatures at the LHC

Tsedenbaljir Enkhbat, NTU

VIII Rencontres du Vietnam,
Quy Nhon, Vietnam, December 16-22, 2012

Based on: J. Alwall, Ts. E, W-S. Hou & H. Yokoya,
PRD86 (2012) 074029,
Ts. E, W-S. Hou & H. Yokoya,
PRD84 (2011) 094013

Outline

- Introduction
- WW+jet signal
- Analysis method

  W-tagging

  CL_s method
- Numerical results
- Conclusions

Introduction

The Large Hadron Collider → Search for colored objects easier

Colored objects searched at the LHC

Diquarks, leptoquarks, excited quarks, squarks & gluino, colorons, axigluons, KK quarks & gluons, colored version of TC and other composite objects ....

CMS-PAS-EXO-12-016, [CMS collaboration] (2012)

- ✧ Most studies concentrate on individual resonances (Exception: SUSY & models with multiple resonances).
- ✧ Beyond SM theories usually predict not one but several resonances.
- ✧ Heavier ones often cascade decay to lighter ones.

Purpose of the Talk

Report a study of the LHC prospect for color-octet SU(2)-singlet vector resonance accompanied by lighter color-octet SU(2)-triplet (pseudo)scalar.

Possible origin of the phenomenon

Heavy colored fermions condensate → EWSB → Colored bound states

$v \sim < F\bar{F} >$

$W_L, \; Z_L \sim \pi_1$

(Colored counterparts)

$\pi_8, \rho_8, \omega_8 \sim (F\bar{F})_8$

Examples

✧ 4^{th} generation $\xrightarrow{\text{Yukawa bound states}}$ $\pi_8, \; \cancel{\rho_8}, \; \omega_8$

$\pi_1, \; \omega_1$

P. Jain et al, Phys.Rev. D49 (1994) 2514-2524,
K. Ishiwata & M. Wise, Phys.Rev. D83 (2011) 074015,
T.E, W-S Hou, H. Yokoyo, Phys.Rev. D84 (2011) 094013

Talks by Lin, Geller,
Hung, Hou at this conf

✧ Colored Technicolor $\xrightarrow{\text{Technimesons}}$ $\pi_8, \; \rho_8, \; \omega_8$

$\pi_1, \; \rho_1, \; \omega_1$

R.S. Chivukula et al hep-ph/9503202.

Spectrum

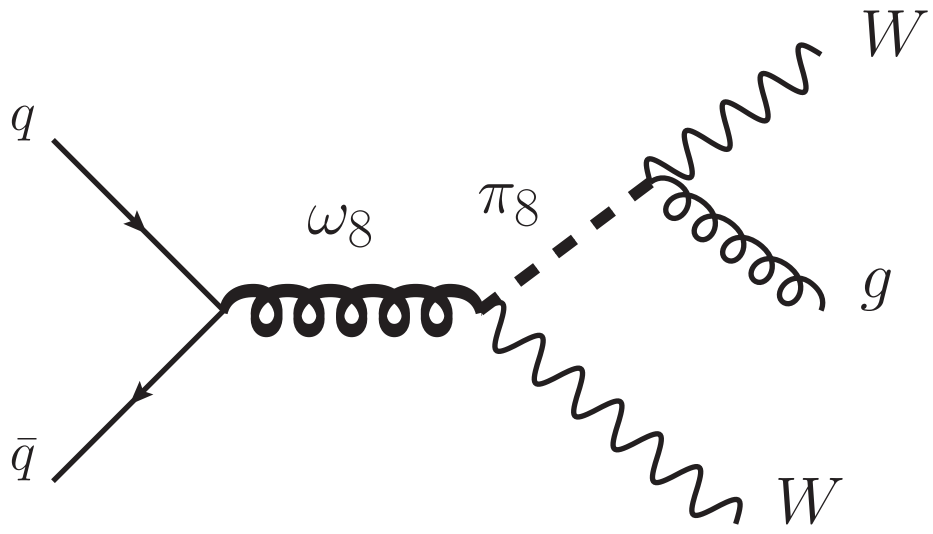
SU(2) singlet color-octet vector: ω_8

SU(2) triplet color-octet (pseudo)scalar: π_8

$$M_{\omega_8} > M_{\pi_8} + M_W$$

Appears in dynamical EWSB models: composite models colored version of technicolor, extra generation bound states

Process:



NOTE: Gluon fusion not available by Landau-Yang theorem

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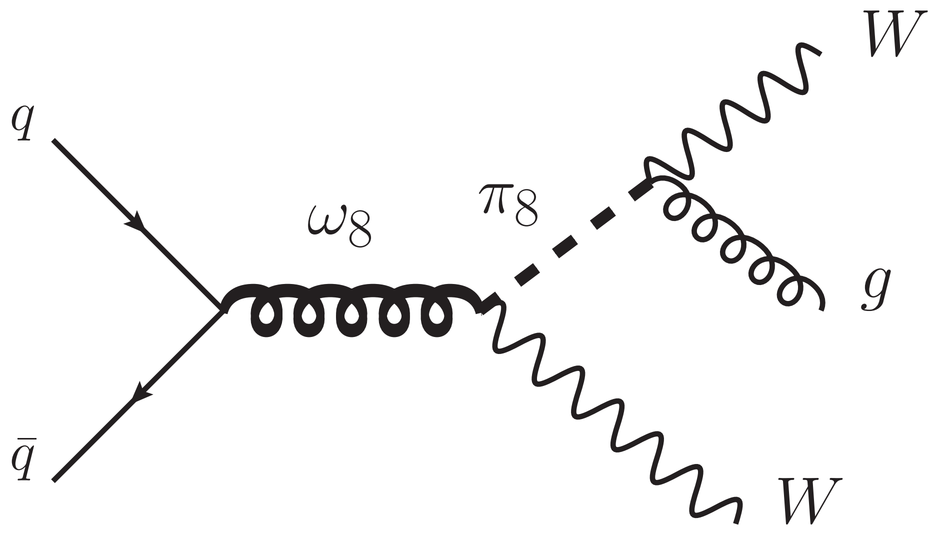
Process:

Hard if $M_{\pi_8} \sim O(\text{TeV})$



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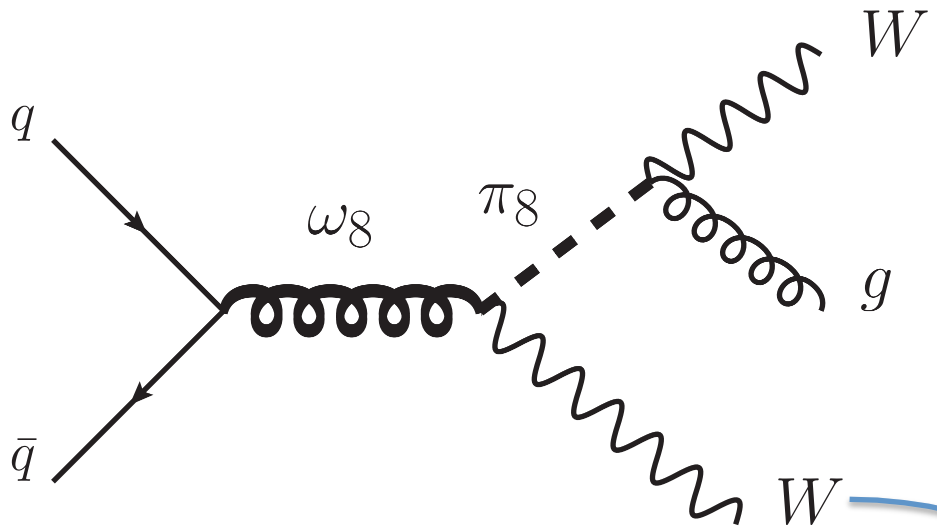

Hard if $M_{\pi_8} \sim O(\mathrm{TeV})$

“Soft”

NOTE: Gluon fusion not available by Landau-Yang theorem

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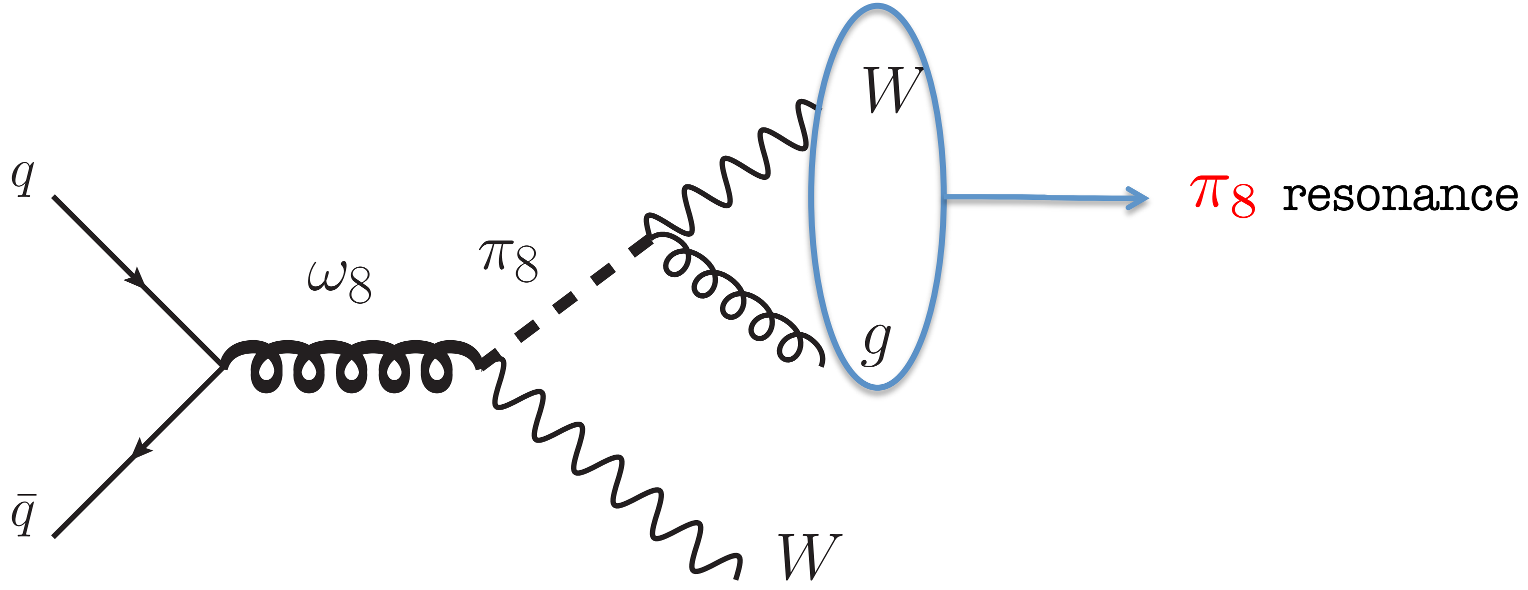

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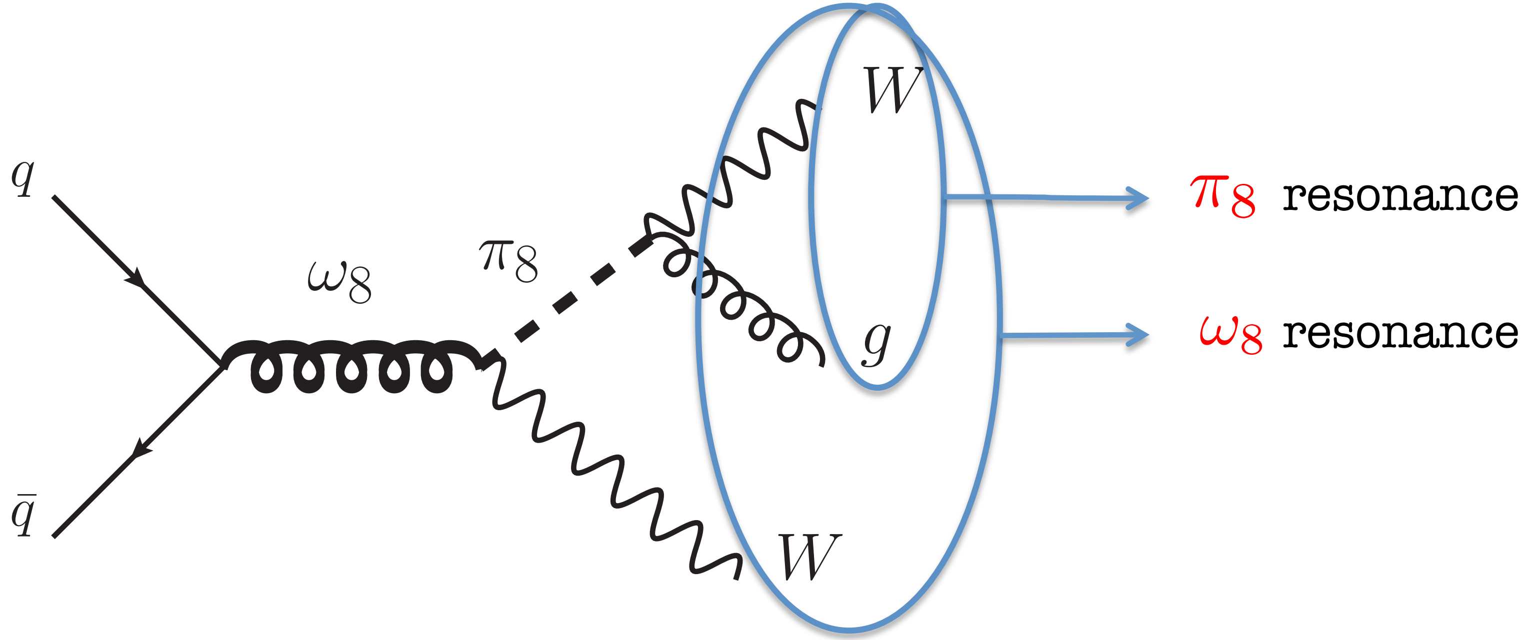

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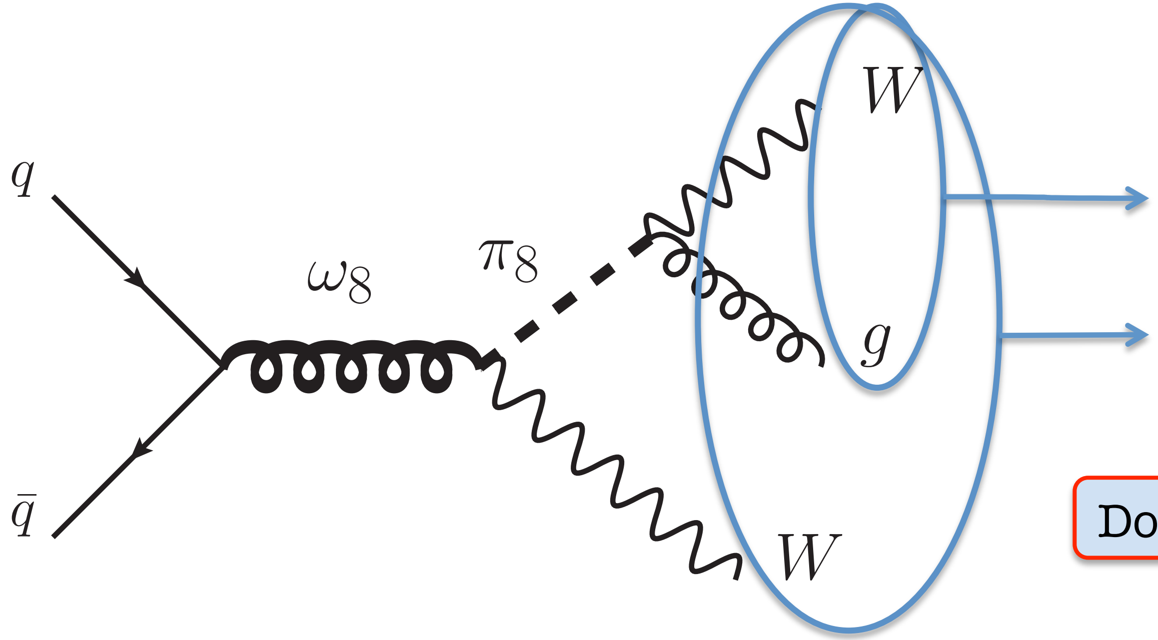


π_8 resonance

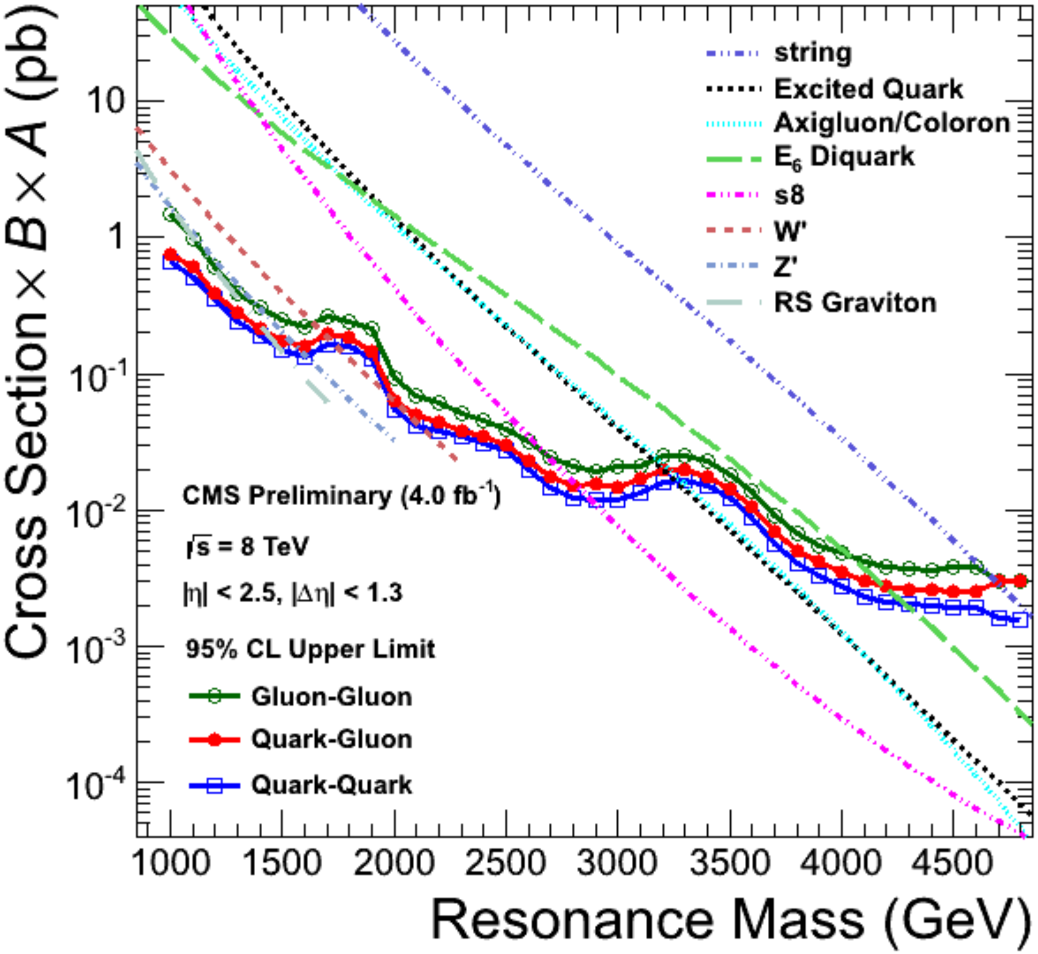
ω_8 resonance

Doubly resonant WW+jet

NOTE: Gluon fusion not available by Landau-Yang theorem

Constraint on color-octet from CMS Dijet search with 4fb^-1

CMS-PAS-EXO-12-016, [CMS collaboration] (2012)



✧ Dijet channel always present due to unitarity. Here A~0.6.

✧ For α_s coupling, the coloron is excluded up to 3.28 TeV.

Relevant terms for octet vector & scalar (V & S)

$$\mathcal{L}_{\omega_8\text{–decay}} = \xi\frac{g_s}{\sqrt{2}}\bar{q}_i\gamma_\mu(T^a)_{ij}q_jV_a^\mu + \frac{g_W}{\sqrt{m_Sm_V}}\Big[f_v\epsilon^{\mu\nu\rho\sigma}\left(\partial_\sigma S_a^\pm\partial_\rho W_\mu^\mp + \partial_\sigma S_a^0\partial_\rho Z_\mu\right)V_{a\nu}$$
$$+ S_a^\pm\left(f_{a_1}m_Sm_VV_a^\mu + f_{a_2}\partial^\mu V_{a\nu}\partial^\nu + f_{a_3}V_{a\nu}\partial^\mu\partial^\nu\right)W_\mu^\mp$$
$$+ S_a^0\left(f_{a_1}m_Sm_VV_a^\mu + f_{a_2}\partial^\mu V_{a\nu}\partial^\nu + f_{a_3}V_{a\nu}\partial^\mu\partial^\nu\right)Z_\mu\Big]$$

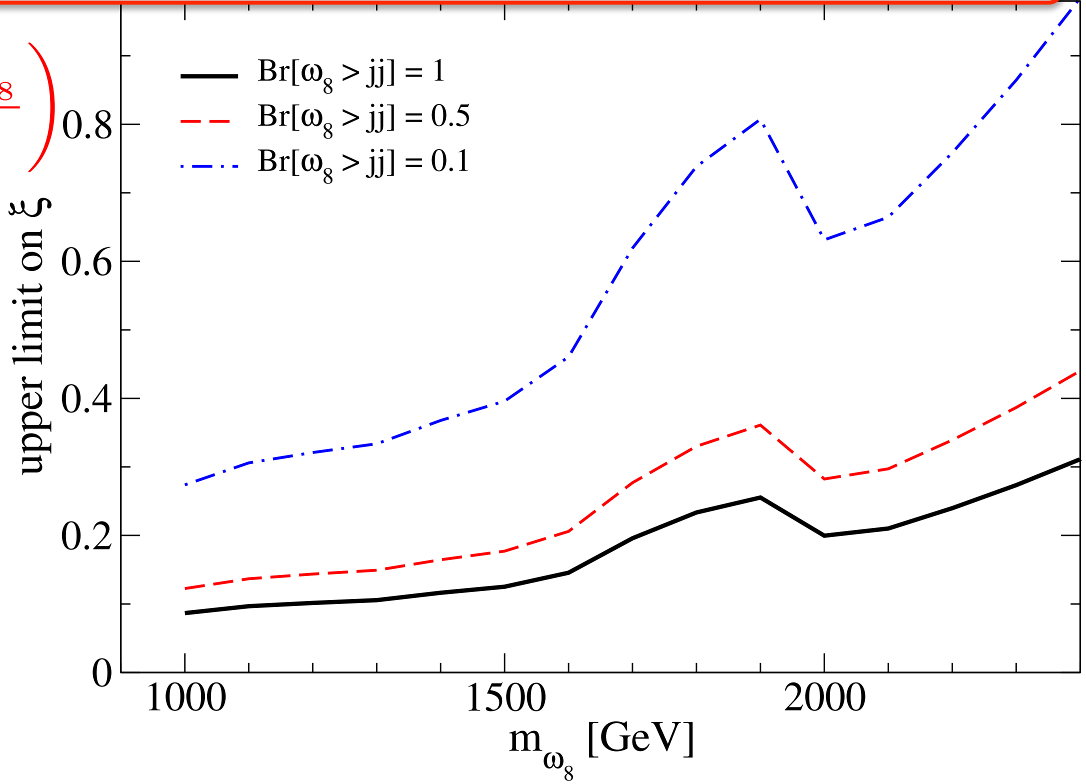
$$\hat{\sigma}_{q\bar{q}\to\omega_8}(\hat{s}) = \frac{32\pi^3\alpha_s^2}{9m_{\omega_8}^2}\xi^2\delta\left(1-\frac{m_{\omega_8}^2}{\hat{s}}\right)$$

Parton-level production xsec.

- ✧ f_{v,a_i} are assumed to be large: π_8W/Z is dominant.
- ✧ If dijet subdominant, constraint is relaxed.
- ✧ Used: CTEQ6L1 PDF with

$$\mu_F = m_{\omega_8}$$

Constraint from CMS Dijet search with 4fb^-1



CMS-PAS-EXO-12-016, [CMS collaboration] (2012)

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$$\hat{\sigma}_{q\bar{q}\to\omega_8}(\hat{s}) = \frac{32\pi^3\alpha_s^2}{9m_{\omega_8}^2}\xi^2\delta\left(1-\frac{m_{\omega_8}^2}{\hat{s}}\right)$$

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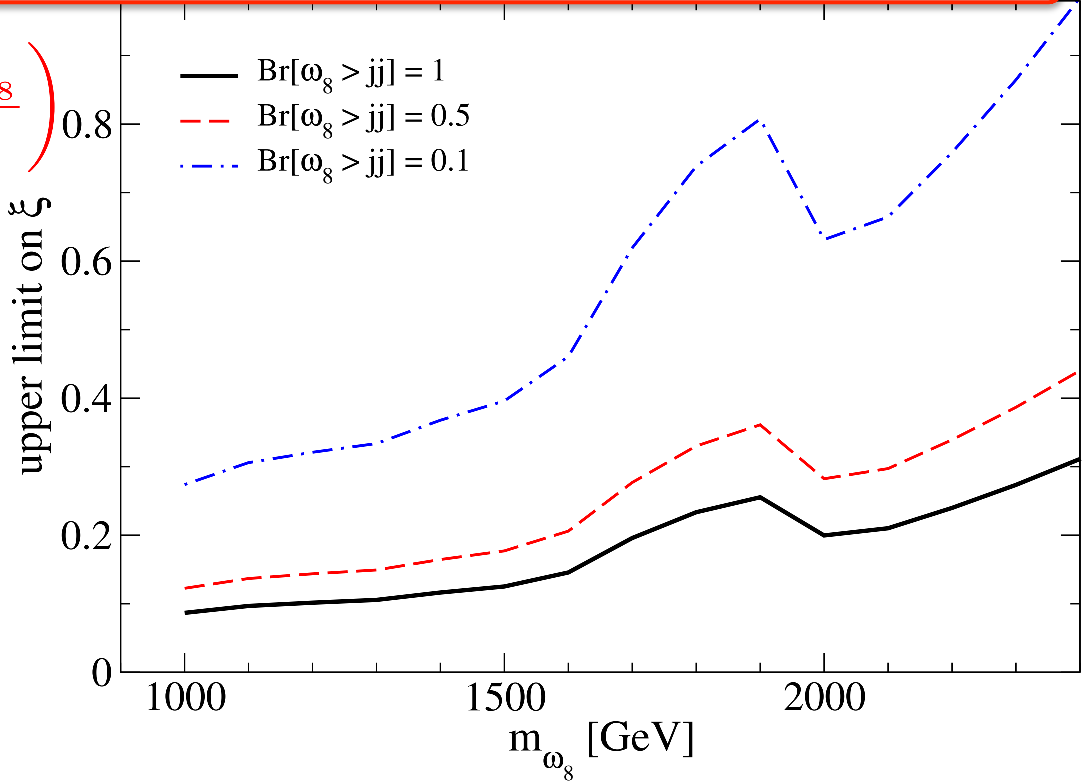

CMS-PAS-EXO-12-016, [CMS collaboration] (2012)

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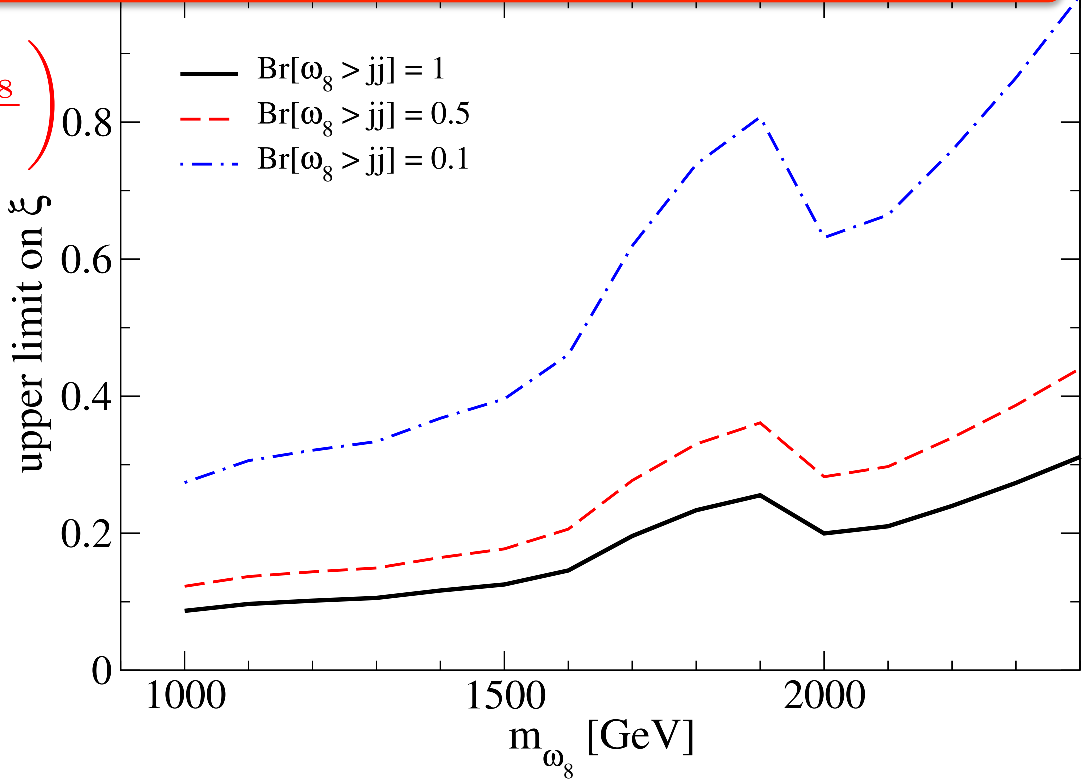


CMS-PAS-EXO-12-016, [CMS collaboration] (2012)

Situation when $\pi_8 \to Wg$ is dominant

✦ $q\bar{q} \to \pi_8 \quad \pi_8 \to q\bar{q},\ t\bar{t}$ are negligible.

π_8 is the color counter part of the Goldstones in dynamical models.

Top quark often need additional mechanism.

✦ $m_{\pi_8} \gtrsim 600\ \mathrm{GeV}$ where the pair production is inefficient.

The lighter case has been studied for pair production in TC context.

⬇

- ✧ The direct single production is suppressed.
- ✧ The doubly resonant signal can be used to access both ω_8 and π_8.
- ✧ This is the main point of the work : We show it is possible that both resonances are probed by the single process.

Collider signatures: Charged mode

$$B(\omega_8 \to \pi_8^{\pm} W^{\mp}) \simeq 2/3$$

$$\omega_8 \to \pi_8^{\pm} W^{\mp}_{(\mathrm{soft})} \to W^{\pm}_{(\mathrm{hard})} W^{\mp}_{(\mathrm{soft})} g$$

- Hadronic: both "hard" and "soft" W decay hadronically.
  Difficult to distinguish from multijet QCD background.
- Dileptonic: both W's decay leptonically.
  Branching ratio ~ only 5%,
  hard to reconstruct the final states.
- Semileptonic: More promising. Two cases:
  Hard leptonic W with hadronic soft W
  Hard W-tagged jet with leptonic soft W

Assumption

Neutral mode

$$B(\omega_8 \to \pi_8^{0} Z) \simeq 1/3$$

$$\omega_8 \to \pi_8^{0} Z_{(\mathrm{soft})} \to Z_{(\mathrm{hard})} Z_{(\mathrm{soft})} g$$

- Hard leptonic: highly collimated leptons-> only muon ch. useful

$$Z_{(\mathrm{hard})} Z_{(\mathrm{soft})} g \to (\ell^+ \ell^-)_{(\mathrm{hard})} (jj)_{(\mathrm{soft})} j$$

- Hard hadronic: collimated dijet-> hard W-tag method can be used

$$Z_{(\mathrm{hard})} Z_{(\mathrm{soft})} g \to (jj)_{(\mathrm{hard})} (\ell^+ \ell^-)_{(\mathrm{soft})} j$$

W -jet tagging

CMS PAS-JME-10-013, [CMS Collaboration]

- ✧ Find jets by the C/A algorithm with $R = 0.8$; keep the clustering history and momenta of clusters to be merged at each step.
- ✧ Pruning: Rerun the clustering: at each step, check if the two clusters *a* and *b* satisfy the following:

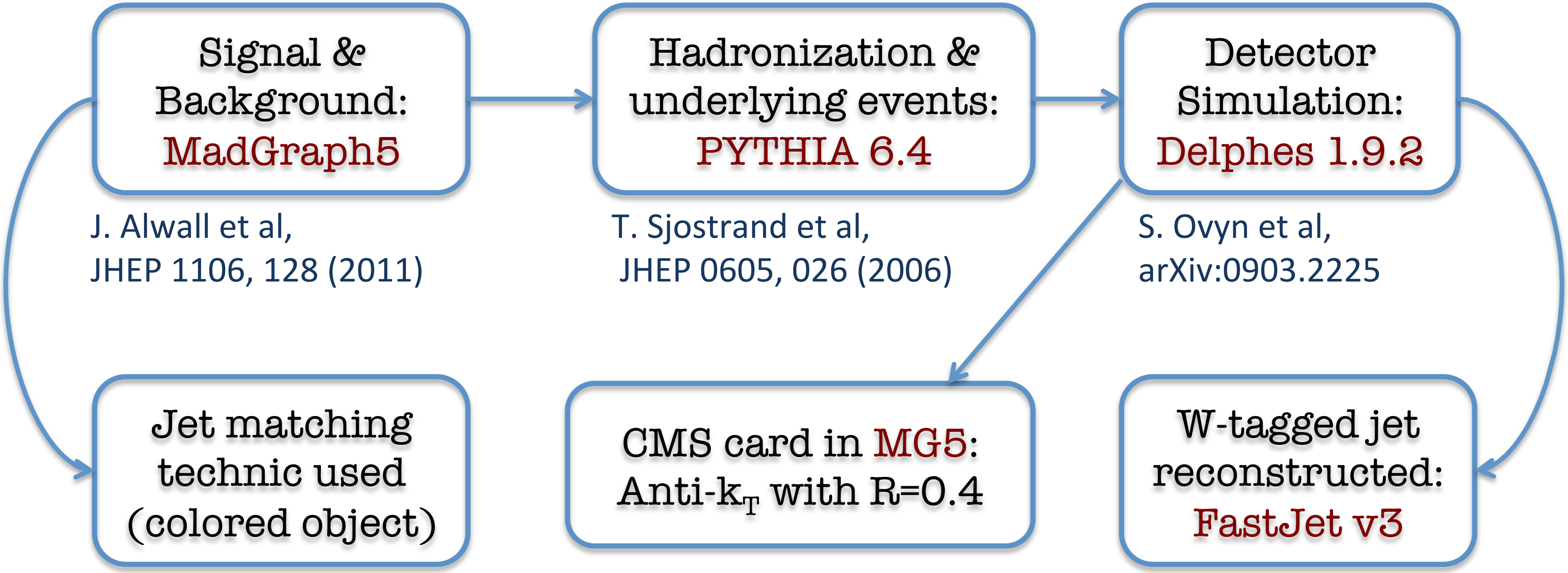
  1.
  $$z_{ab} \equiv \frac{\min(p_T^a, p_T^b)}{p_T^J} < z_{\rm cut} \qquad z_{\rm cut} = 0.1$$
  2.
  $$\Delta R_{ab} > D_{cut} \equiv \alpha \cdot \frac{M_J}{p_T^J} \qquad \alpha = 1$$

  if yes, the softer one is discarded. Here $\Delta R_{ab} = \sqrt{\Delta\eta_{ab}^2 + \Delta\phi_{ab}^2}$
- ✧ Mass drop tagging: Require the pruned jet mass to satisfy $60\ \text{GeV} < M_{\rm jet} < 100\ \text{GeV}$. The jet is tagged as a *W* candidate if there exists a mass drop

$$M_1/M_{\rm jet} < 0.4$$

M_1 is the mass of the hardest jet in the last step of the pruning.

Simulations



Signal & Background: MadGraph5

J. Alwall et al,
JHEP 1106, 128 (2011)

Hadronization & underlying events: PYTHIA 6.4

T. Sjostrand et al,
JHEP 0605, 026 (2006)

Detector Simulation: Delphes 1.9.2

S. Ovyn et al,
arXiv:0903.2225

Jet matching technic used (colored object)

J. Alwall et al,
JHEP 0902, 017 (2009)

CMS card in MG5: Anti-k_T with R=0.4

M. Cacciari et al,
JHEP 0804, 063 (2008)

W-tagged jet reconstructed: FastJet v3

M. Cacciari et al,
Eur. Phys. J. C 72, 1896 (2012)

Hard W-tagged jet with soft leptonic W

Most promising channel:

$\omega_8 \to \pi_8^{\pm} W^{\mp}_{(\mathrm{leptonic:}\mu,\mathrm{e})}$ followed by $\pi_8^{\pm} \to W^{\pm}_{(\mathrm{hadronic})} + \mathrm{jet}$

Backgrounds

Main SM backgrounds: $W + \mathrm{jets}$ and semileptonic $t\bar{t}$.
Irreducible background: $W^{\pm} + W/Z + \mathrm{jets}$ only few %.

Event selection cuts

✧ Exactly one isolated lepton (e or μ) with $p_{\perp}$ > 20 GeV.
✧ Missing $\mathrm{E_T}$ > 20 GeV.
✧ A W-tagged jet j_W with $p_{\perp}$ > 200 GeV.
✧ A jet j_1 with $p_{\perp}$ > 200 GeV.
✧ Invariant mass (reconstructed π_8 mass) $\mathrm{M}(j_W, j_1)$ > 500 GeV.

Hard W-tagged jet with soft leptonic W

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Lepton & E_{miss} trigger

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Lepton & $\mathrm{E}_{\mathrm{miss}}$ trigger

Studied as W-tagged jet

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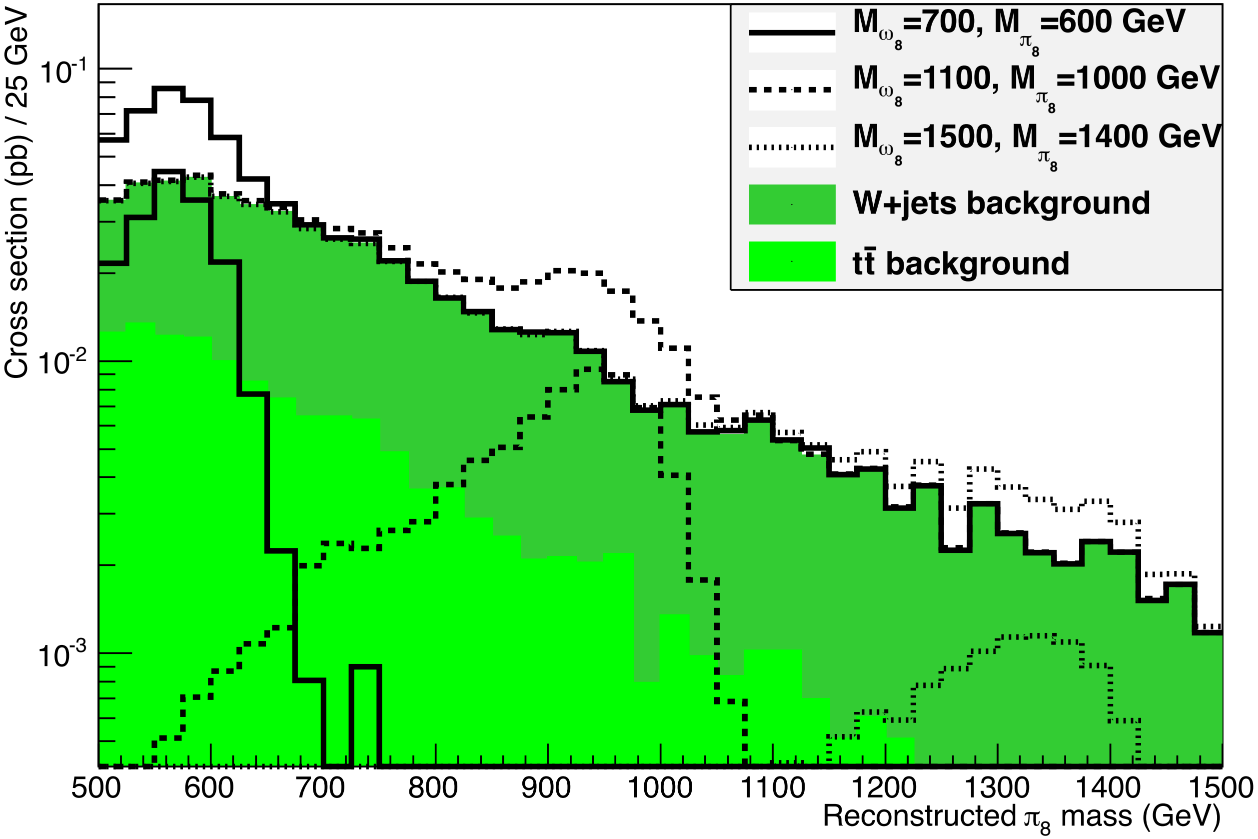
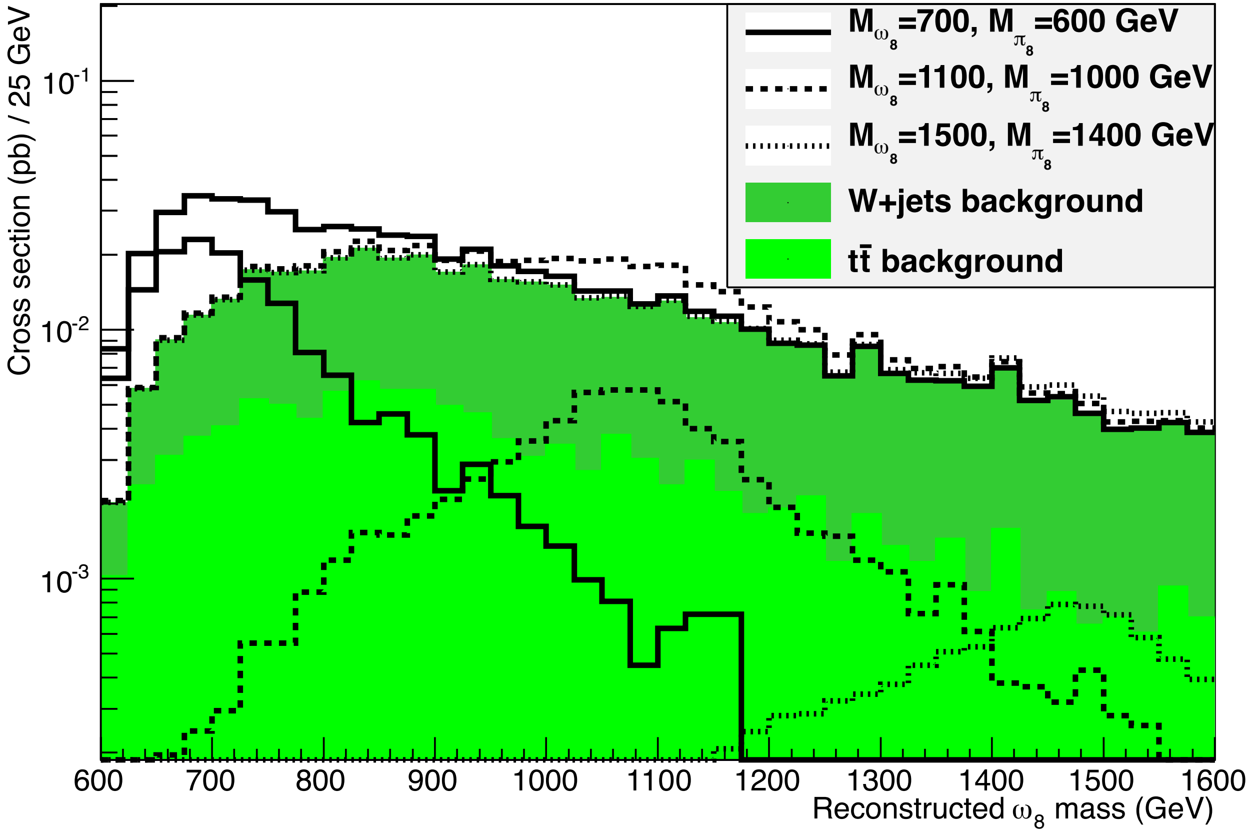
π_8 resonance mass in the hard W-tagged channel



- ✧ Here $\xi = 0.2$ case is shown. Assumed $B(\omega_8 \to \pi_8 W)$=100%.
- ✧ Energy scale uncertainties of W and gluon jets -> Relatively large width

ω_8 resonance mass in the hard W-tagged channel



- ✧ Leptonic W reconstruction needed for ω_8 mass reconstruction.
- ✧ If multiple solutions, the missing E_T with lowest p_z is chosen.
- ✧ if necessary adjust the magnitude of the missing E_T to bring the W mass back to the nominal value.

The $\mathrm{CL_s}$ method

- We have used for our exclusion and 5sig. discovery potential calc.
- Developed by LEP experiment & Standard method at the LHC. Used for the exclusion limits at the LHC.

Define:

$$CL_s \equiv P_{s+b}(Q \leq Q_{obs})/P_b(Q \leq Q_{obs})$$

P -probability of the chosen statistics Q less than the observed value.

Q -chosen to be the likelihood ratio which can be expressed as:

$$Q = e^{-s_{tot}} + \prod_{i=1}^{N_{chan}} \left(1 + \frac{s_i}{b_i}\right)^{n_i}$$

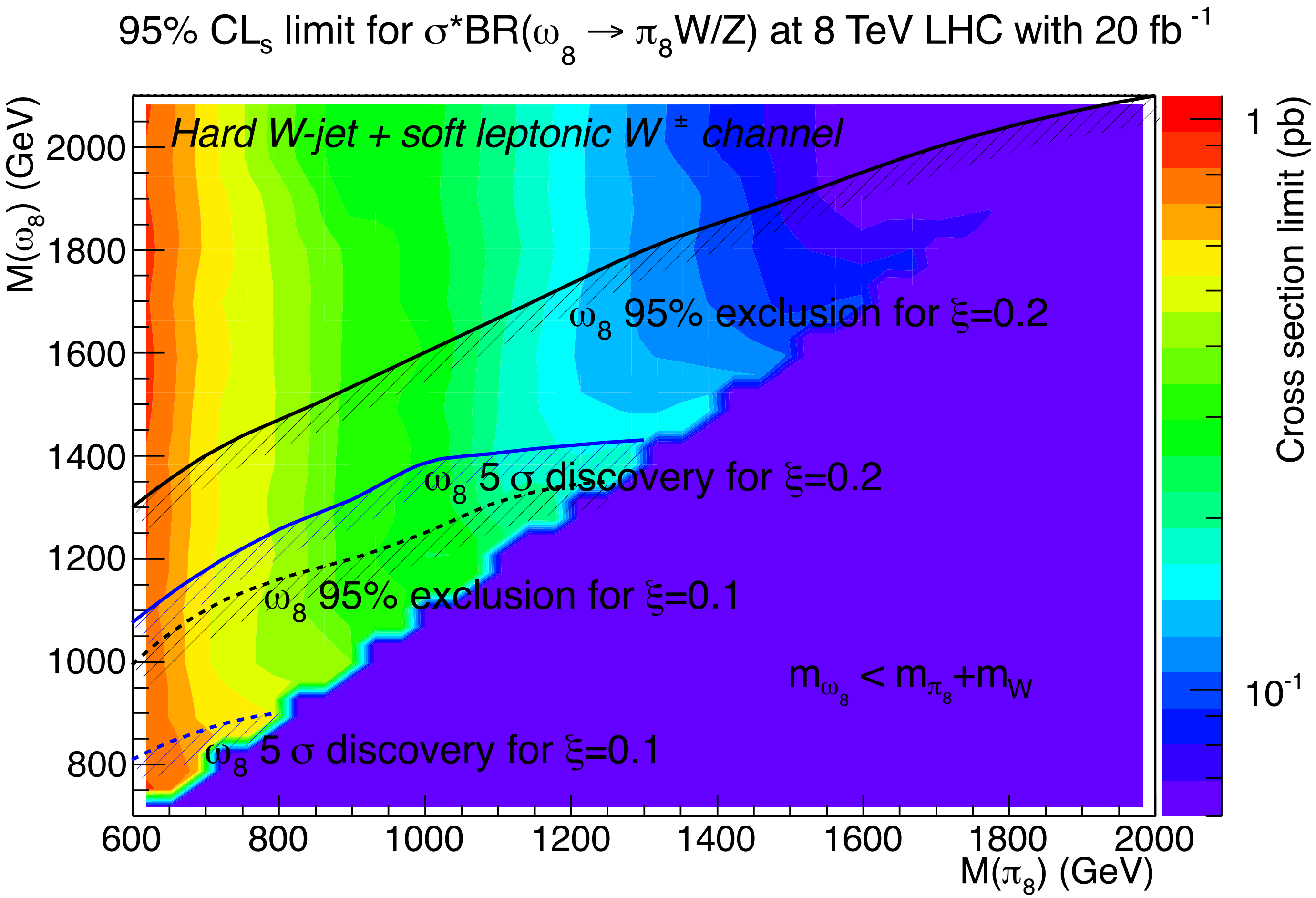
N_{chan} -total # of bin, s_{tot} -total signal rate

n_i -# of observed event in i-th bin

s_i b_i -signal & background rate in i-th bin

Given confidence level CL is reached when $CL \geq 1 - CL_s$

Used Roostat package



- Cross section exclusion limits in pb in the (ω_8, π_8) mass plane in the hard W-tagged jet channel.
- The exclusion regions for ω_8 with ξ set to 0.1 and 0.2 are indicated.
- Uncertainty=Statistic(MC+Event #) + ~20% syst. from background est.

The exclusion reach from hard *W*-jet channel

- ✧ The reconstructed π_8 bump is used as resolution is higher.
- ✧ For ω_8 and π_8 mass difference close to M_W, the LHC will be able to exclude ω_8 production at 95% CL up to

$$m_{\omega 8}=2100\ \mathrm{GeV}\ (1350\ \mathrm{GeV})$$

for $\xi = 0.2\ (0.1)$ with $20\mathrm{fb}^{-1}$ integrated luminosity for the 8 TeV LHC data.

The discovery reach

For the same mass splitting ω_8 and π_8, an ω_8 5σ discovery reach is possible for masses up to

$$m_{\omega 8}=1400\ \mathrm{GeV}\ (900\ \mathrm{GeV})$$

for $\xi = 0.2\ (0.1)$.

Hard leptonic W with soft W-jet

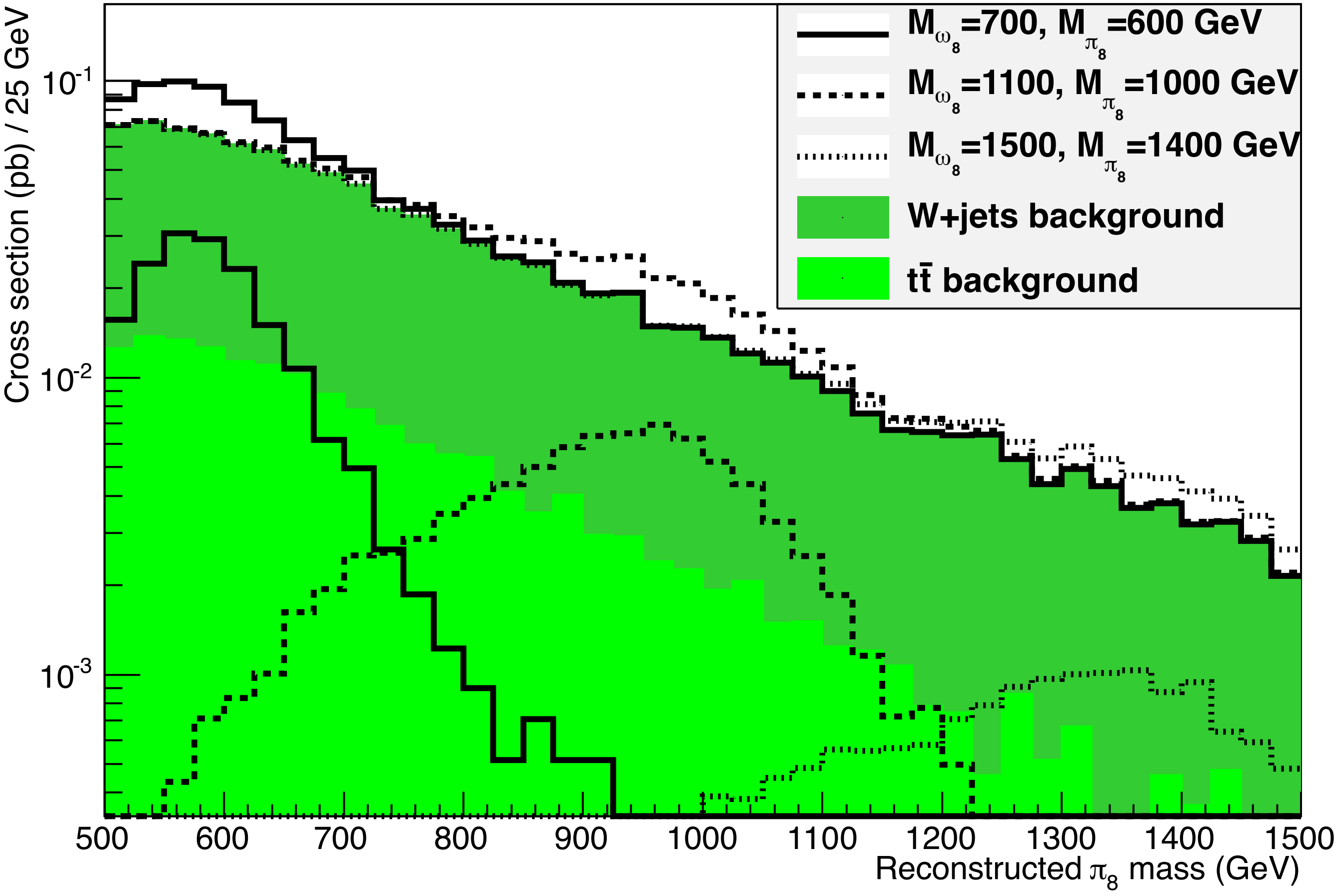
$\omega_8 \to \pi_8^{\pm} W^{\mp}_{(\mathrm{hadronic})}$ followed by $\pi_8^{\pm} \to W^{\pm}_{(\mathrm{leptonic}:\mu\,\mathrm{e})} + \mathrm{jet}$

- ✧ Unlike hard-W case, lacks energetic W-jet.
- ✧ Requires 2 jets from W ->significant reduction of the main backgrounds.
- ✧ Backgrounds are the same as the previous

Event selection cuts

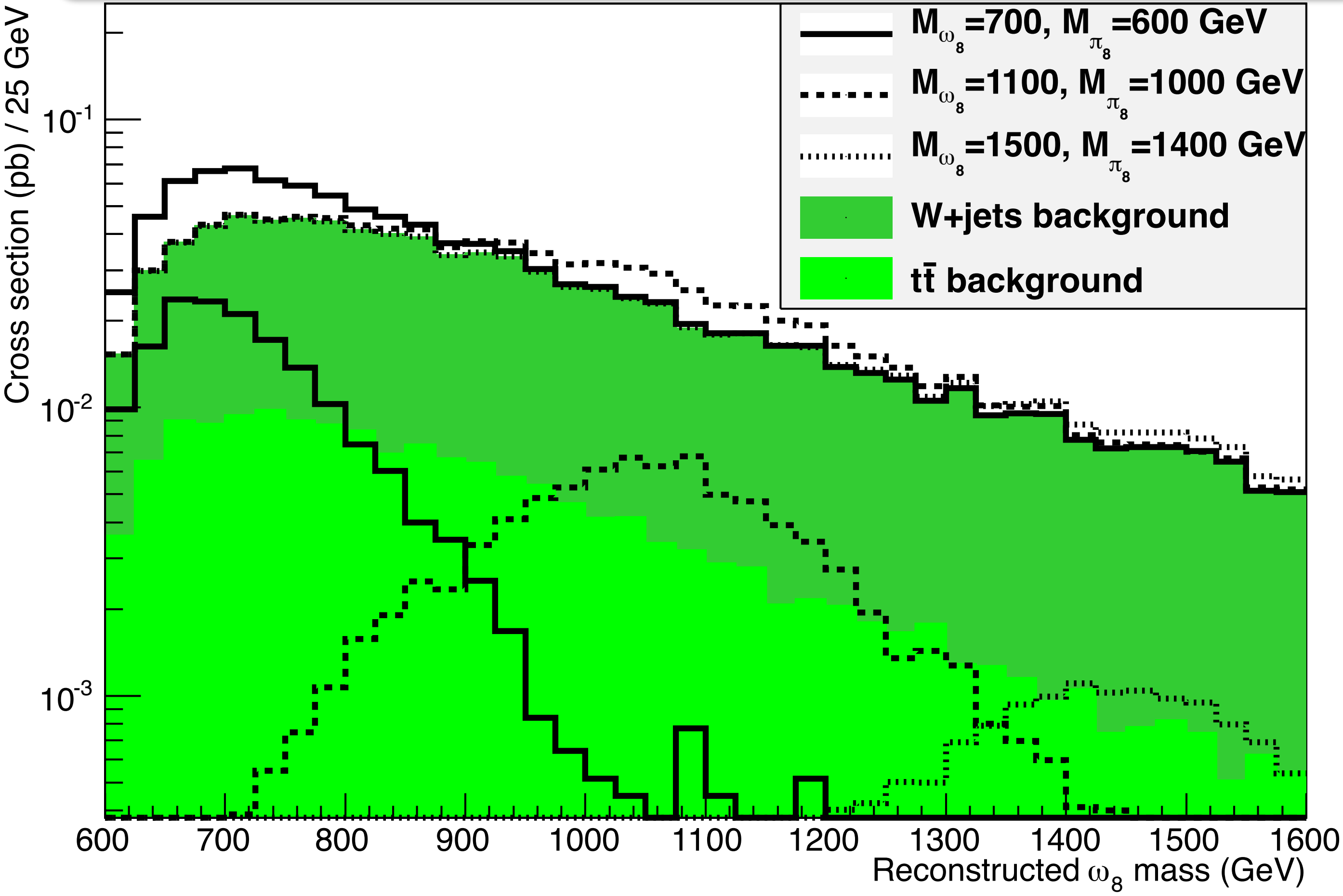
- ✧ Exactly one isolated lepton (e or μ) with $p_{\perp} > 50$ GeV.
- ✧ Missing $\mathrm{E_T} > 50$ GeV.
- ✧ A reconstructed $W_{(\mathrm{leptonic})}$ with $p_{\perp} > 200$ GeV.
- ✧ A jet j_1 with $p_{\perp} > 200$ GeV.
- ✧ Invariant mass (reconstructed π_8 mass) $\mathrm{M}(W_{\mathrm{lep}}, j_1) > 500$ GeV.
- ✧ A hadronic W reconstructed from two non-leading jets with $p_{\perp} > 20$ GeV & inv. mass between 50 and 110 GeV.

π_8 resonance mass in the hard leptonic $W^{\pm}$ channel

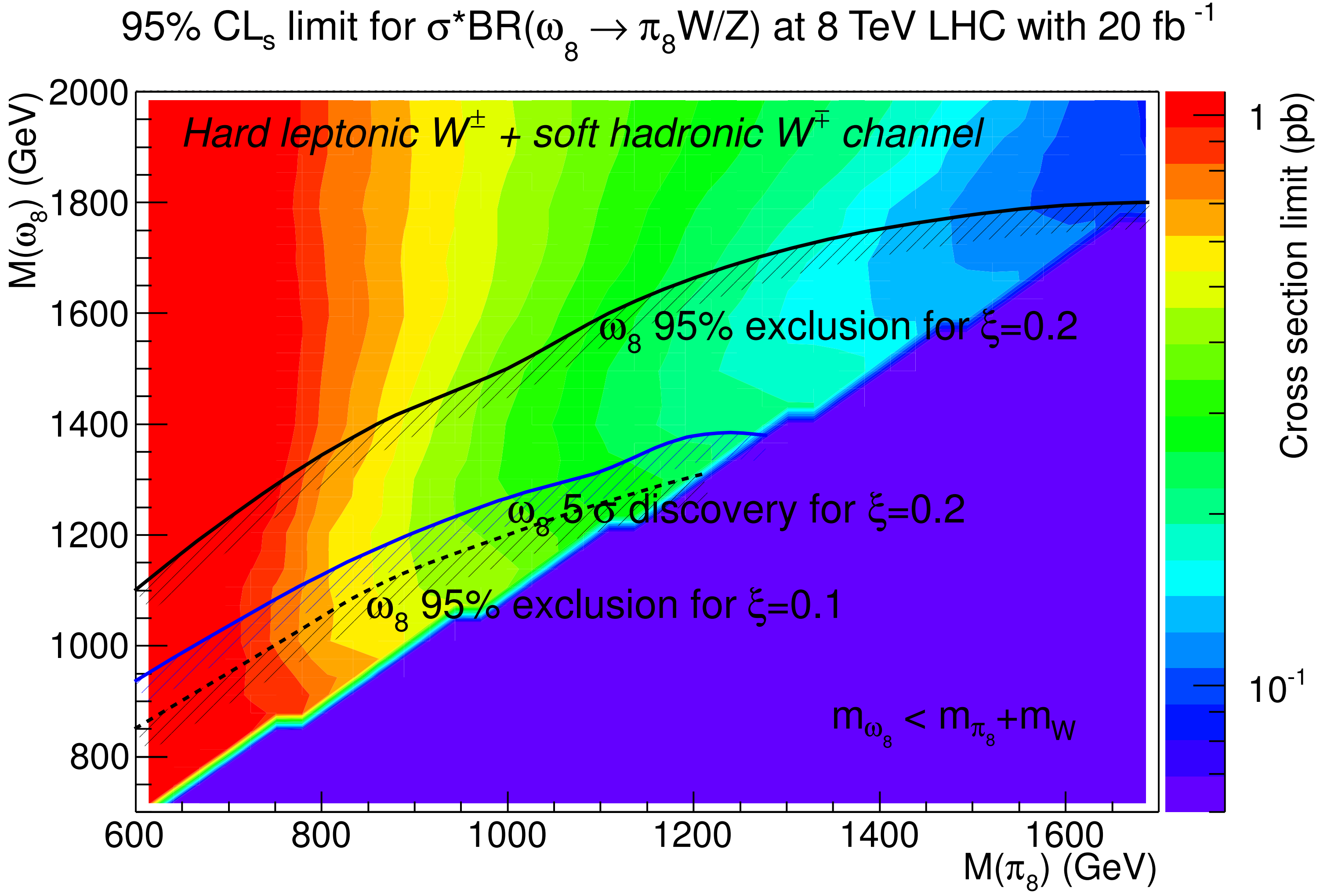


- ✧ Here $\xi = 0.2$ case is shown. Assumed $B(\omega_8 \text{->} \pi_8 W)=100\%$.
- ✧ The invariant mass width is larger than hard W-jet case

ω_8 resonance mass in the hard leptonic $W^\pm$ channel



- ✧ The energy of the hadronic W is rescaled to get the correct W mass, keeping η , ϕ and $p_\perp$ fixed.



- Cross section exclusion limits in pb in the (ω_8, π_8) mass plane in the hard leptonic W channel.
- The exclusion regions for ω_8 with ξ set to 0.1 and 0.2 are indicated.

The exclusion reach from hard leptonic W channel

For ω_8 and π_8 mass difference close to M_W, the LHC will be able to exclude ω_8 production at 95% CL up to

$$m_{\omega 8}=1800\ \text{GeV}\ (1300\ \text{GeV})$$

for $\xi = 0.2\ (0.1)$ with 20fb^{-1} integrated luminosity for the 8 TeV LHC data.

The discovery reach

For the same mass splitting ω_8 and π_8, an ω_8 5σ discovery reach is possible for masses up to

$$m_{\omega 8}=1300\ \text{GeV}$$

for $\xi = 0.2$.

For $\xi = 0.1$ no discovery is possible in the studied range.

Soft leptonic Z with hard Z jet

$\omega_8 \to \pi_8^0 Z_{(\mathrm{leptonic}:\mu\,\mathrm{e})}$ followed by $\pi_8^0 \to Z_{(\mathrm{hadronic})} + \mathrm{jet}$

- ✧ Promising: leptonic Z constructioncase lacks energetic W-jet
- ✧ $t\bar{t}$ is negligible if 2-lep inv. mass required to be close to Z mass.
- ✧ However: 3X smaller BR to leptons, 2X smaller total BR, worse cut efficiency.

Event selection cuts

- ✧ Exactly two isolated leptons of same flavor with opposite sign (e or μ) with $p_\perp > 20$ GeV and $|M(l^+l^-) - M_Z| < 15$ GeV.
- ✧ Missing $E_T < 50$ GeV.
- ✧ A W-tagged j_Z with $p_\perp > 200$ GeV.
- ✧ A jet j_1 with $p_\perp > 200$ GeV.
- ✧ Invariant mass (reconstructed π_8 mass) $M(j_Z\ , j_1) > 500$ GeV.

Conclusions

- Study of the LHC prospects for color-octet SU(2)-singlet vector accompanied by color-octet SU(2)-triplet (pseudo)scalar using jet tools is presented.
- Demonstrated both resonances ω_8 and π_8 can be searched upto $m_{\omega 8}$=1400 GeV (900 GeV) and exclude $m_{\omega 8}$=2100 GeV (1350 GeV) for $\xi = 0.2$ (0.1) for 20fb^{-1} integrated luminosity for the 8 TeV LHC data.
- The signal being doubly resonant is crucial for substantially reducing the main background.
- The most efficient channel is soft leptonic W and hard W-jet
- If π_8 is not accessible in direct production, due to its weak couplings to light generations, with sizable $\omega_8 \rightarrow \pi_8 W$, the doubly resonant signal opens possibility to both signal in a single stroke.