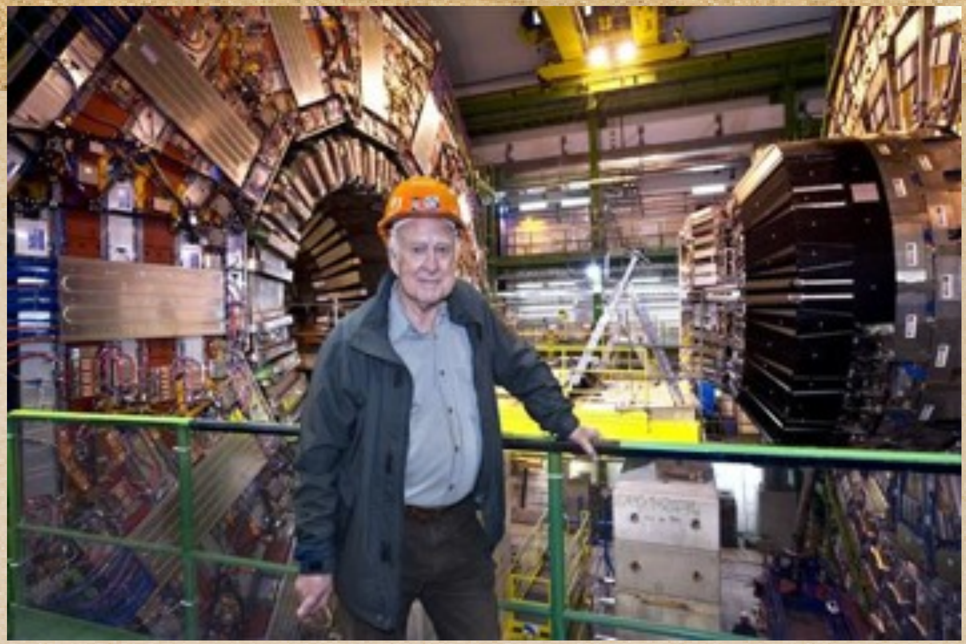

Higgs Amidst the LHC Detector

Prerit Jaiswal

Florida State University

BNL Forum 2013, Brookhaven National Lab

arXiv:1303.1181 : PJ, Karoline Köpp, Takemichi Okui

Post Higgs Discovery - Now what ?

- Look for deviations in (σ X Br) for Higgs decay to standard final states.
- Study non SM-like Higgs decays, for example : invisible Higgs decays, $h \to 2b2\tau$, etc
- New modes of Higgs production, for example : neutralino decays to Higgs + MET in SUSY.

Post Higgs Discovery - Now what ?

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- New modes of Higgs production, for example : neutralino decays to Higgs + MET in SUSY.

Are there more exotic Higgs production modes?

A Simple (toy) Model

- Minimal Extensions of SM ?
  - Flavor Constraints
  - Electroweak Precision Constraints
  - Anomaly-free
- Vector-like fermions :
  - Electroweak triplet $(1,3)_0$: ω (Dirac) and, singlet $(1,1)_0$: χ (massless Weyl)
  - An additional $U(1)_X$ symmetry

- Most general renormalizable Lagrangian

$$\mathcal{L}_{\rm ren} = \mathrm{i}\overline{\omega}\gamma^\mu \mathrm{D}_\mu \omega - m_\omega\, \overline{\omega}\omega + \mathrm{i}\chi^\dagger_{0\mathrm{L}}\overline{\sigma}^\mu \partial_\mu \chi_{0\mathrm{L}}$$

  - In electric-charge basis :

$$\omega_+ \equiv \frac{\omega^1 - \mathrm{i}\omega^2}{\sqrt{2}}\,, \quad \omega'_- \equiv \frac{\omega^1 + \mathrm{i}\omega^2}{\sqrt{2}}\,, \quad \omega_0 \equiv \omega^3$$

- Dimension-5 operators :

$$\mathcal{O}_5^{(1)} = H^\dagger H\, \omega^{a\dagger}_{\mathrm{R}} \omega^a_{\mathrm{L}} \qquad \mathcal{O}_5^{(4)} = g_1 B_{\mu\nu}\, \omega^{a\dagger}_{\mathrm{R}} \sigma^\mu \overline{\sigma}^\nu \omega^a_{\mathrm{L}}$$

$$\mathcal{O}_5^{(2)} = \mathrm{i}\epsilon^{abc} H^\dagger \sigma^a H\, \omega^{b\dagger}_{\mathrm{R}} \omega^c_{\mathrm{L}} \qquad \mathcal{O}_5^{(5)} = \mathrm{i}g_2\, \epsilon^{abc}\, W^a_{\mu\nu}\, \omega^{b\dagger}_{\mathrm{R}} \sigma^\mu \overline{\sigma}^\nu \omega^c_{\mathrm{L}}$$

$$\mathcal{O}_5^{(3)} = H^\dagger \sigma^a H\, \omega^{a\dagger}_{\mathrm{R}} \chi_{0\mathrm{L}} \qquad \mathcal{O}_5^{(6)} = g_2 W^a_{\mu\nu}\, \omega^{a\dagger}_{\mathrm{R}} \sigma^\mu \overline{\sigma}^\nu \chi_{0\mathrm{L}}$$

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$$\mathcal{O}_5^{(3)} = H^\dagger \sigma^a H\, \omega_{\mathrm{R}}^{a\dagger}\chi_{0\mathrm{L}} \qquad \mathcal{O}_5^{(6)} = g_2 W^a_{\mu\nu}\, \omega_{\mathrm{R}}^{a\dagger}\sigma^\mu\overline{\sigma}^\nu \chi_{0\mathrm{L}}$$

- Most general <u>renormalizable</u> Lagrangian

$$\mathcal{L}_{\text{ren}} = \mathrm{i}\overline{\omega}\gamma^\mu \mathrm{D}_\mu \omega - m_\omega \overline{\omega}\omega + \mathrm{i}\chi_{0\mathrm{L}}^\dagger \overline{\sigma}^\mu \partial_\mu \chi_{0\mathrm{L}}$$

  - In electric-charge basis :

$$\omega_+ \equiv \frac{\omega^1 - \mathrm{i}\omega^2}{\sqrt{2}}\,, \quad \omega'_- \equiv \frac{\omega^1 + \mathrm{i}\omega^2}{\sqrt{2}}\,, \quad \omega_0 \equiv \omega^3$$

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$$\mathcal{O}_5^{(1)} = H^\dagger H\, \omega_{\mathrm{R}}^{a\dagger}\omega_{\mathrm{L}}^a$$

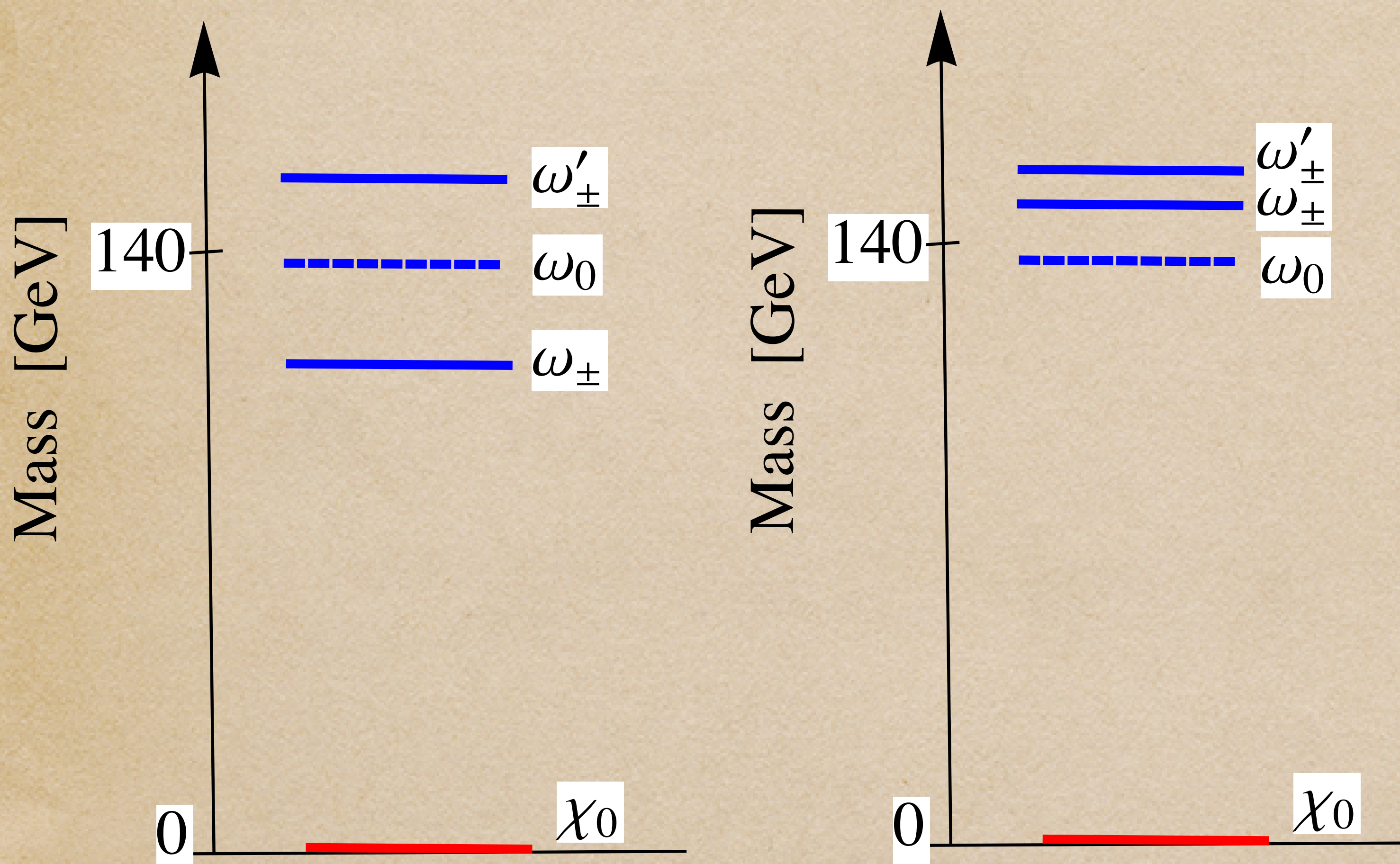
$$\boxed{\begin{aligned} \mathcal{O}_5^{(2)} &= \mathrm{i}\epsilon^{abc} H^\dagger \sigma^a H\, \omega_{\mathrm{R}}^{b\dagger}\omega_{\mathrm{L}}^c \\ \mathcal{O}_5^{(3)} &= H^\dagger \sigma^a H\, \omega_{\mathrm{R}}^{a\dagger}\chi_{0\mathrm{L}} \end{aligned}}$$

$$\cancel{\begin{aligned} \mathcal{O}_5^{(4)} &= g_1 B_{\mu\nu}\, \omega_{\mathrm{R}}^{a\dagger}\sigma^\mu\overline{\sigma}^\nu \omega_{\mathrm{L}}^a \\ \mathcal{O}_5^{(5)} &= \mathrm{i}g_2\, \epsilon^{abc} W_{\mu\nu}^a\, \omega_{\mathrm{R}}^{b\dagger}\sigma^\mu\overline{\sigma}^\nu \omega_{\mathrm{L}}^c \\ \mathcal{O}_5^{(6)} &= g_2 W_{\mu\nu}^a\, \omega_{\mathrm{R}}^{a\dagger}\sigma^\mu\overline{\sigma}^\nu \chi_{0\mathrm{L}} \end{aligned}}$$

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm ren} + \sum_n \frac{\mathcal{O}_5^{(n)}}{\Lambda_n}$$

$$\mathcal{O}_5^{(2)} = \mathrm{i}\epsilon^{abc} H^\dagger \sigma^a H\, \omega_{\rm R}^{b\dagger} \omega_{\rm L}^c$$
$$\mathcal{O}_5^{(3)} = H^\dagger \sigma^a H\, \omega_{\rm R}^{a\dagger} \chi_{0\rm L}$$

$\Lambda_2 \lesssim 200$ TeV $\qquad$ $\Lambda_2 \gtrsim 200$ TeV



$$m_{\omega_\pm} = m_\omega + \Delta m_\omega - \frac{v^2}{2\Lambda_2},$$

$$m_{\omega'_\mp} = m_\omega + \Delta m_\omega + \frac{v^2}{2\Lambda_2},$$

$$m_{\omega_0} = m_\omega + \frac{v^4}{8 m_\omega \Lambda_3^2}.$$

Quantum Mass-splitting :

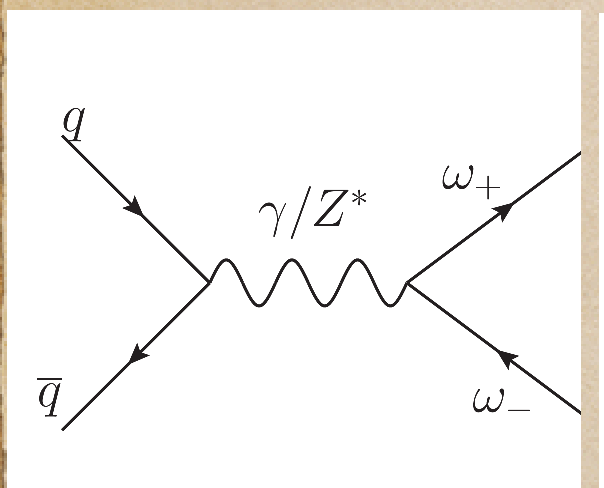
$$\Delta m_\omega \equiv m_{\omega_\pm} - m_{\omega_0} = m_{\omega'_\mp} - m_{\omega_0}$$
$$= \frac{\alpha_2}{4\pi} m_\omega \left[f\left(\frac{m_W}{m_\omega}\right) - f\left(\frac{m_Z}{m_\omega}\right) \cos^2\theta_{\rm W} \right]$$

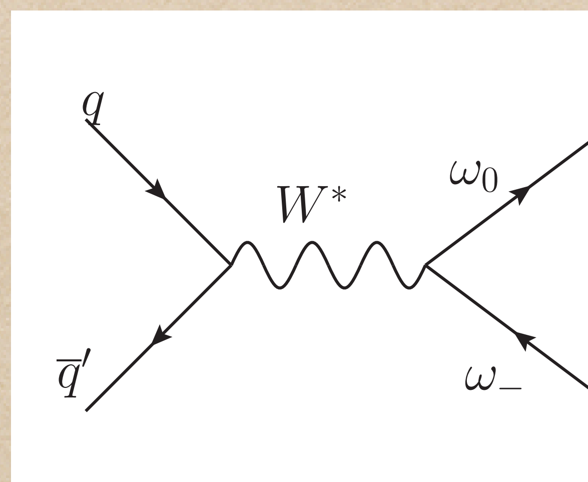
ω Production at the Colliders

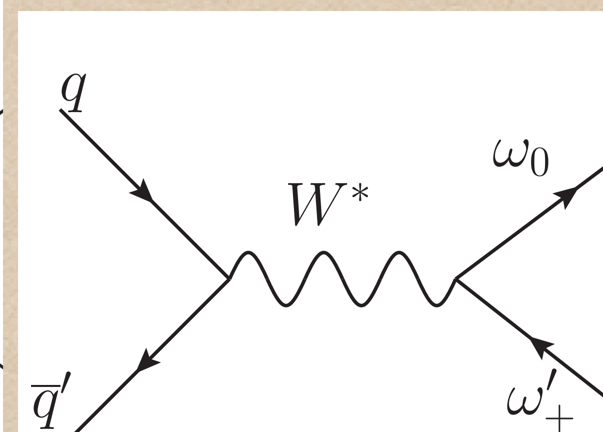
$$p\,p \to \gamma/Z^* \to \omega_+\,\omega_-\,, \quad p\,p \to \gamma/Z^* \to \omega'_-\,\omega'_+\,,$$

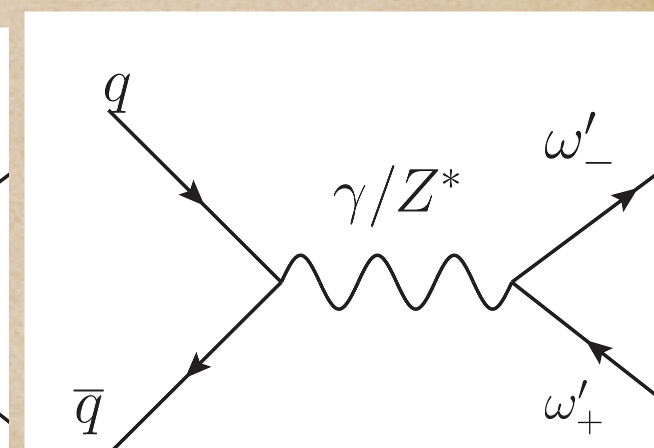
$$p\,p \to W^{+*} \to \omega_+\,\overline{\omega}_0\,, \quad p\,p \to W^{+*} \to \omega_0\,\omega'_+\,,$$

$$p\,p \to W^{-*} \to \omega_0\,\omega_-\,, \quad p\,p \to W^{-*} \to \omega'_-\,\overline{\omega}_0\,.$$



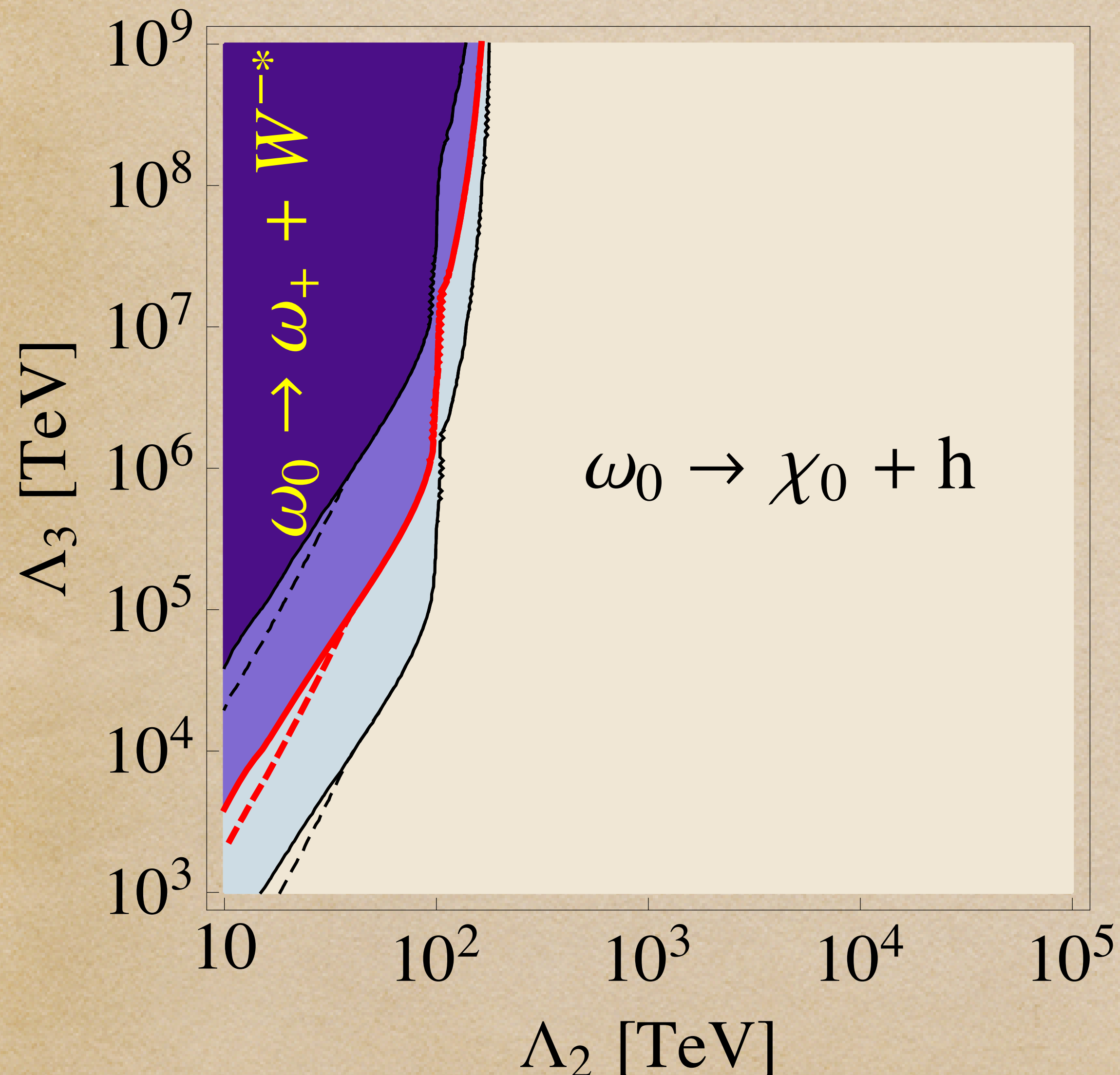


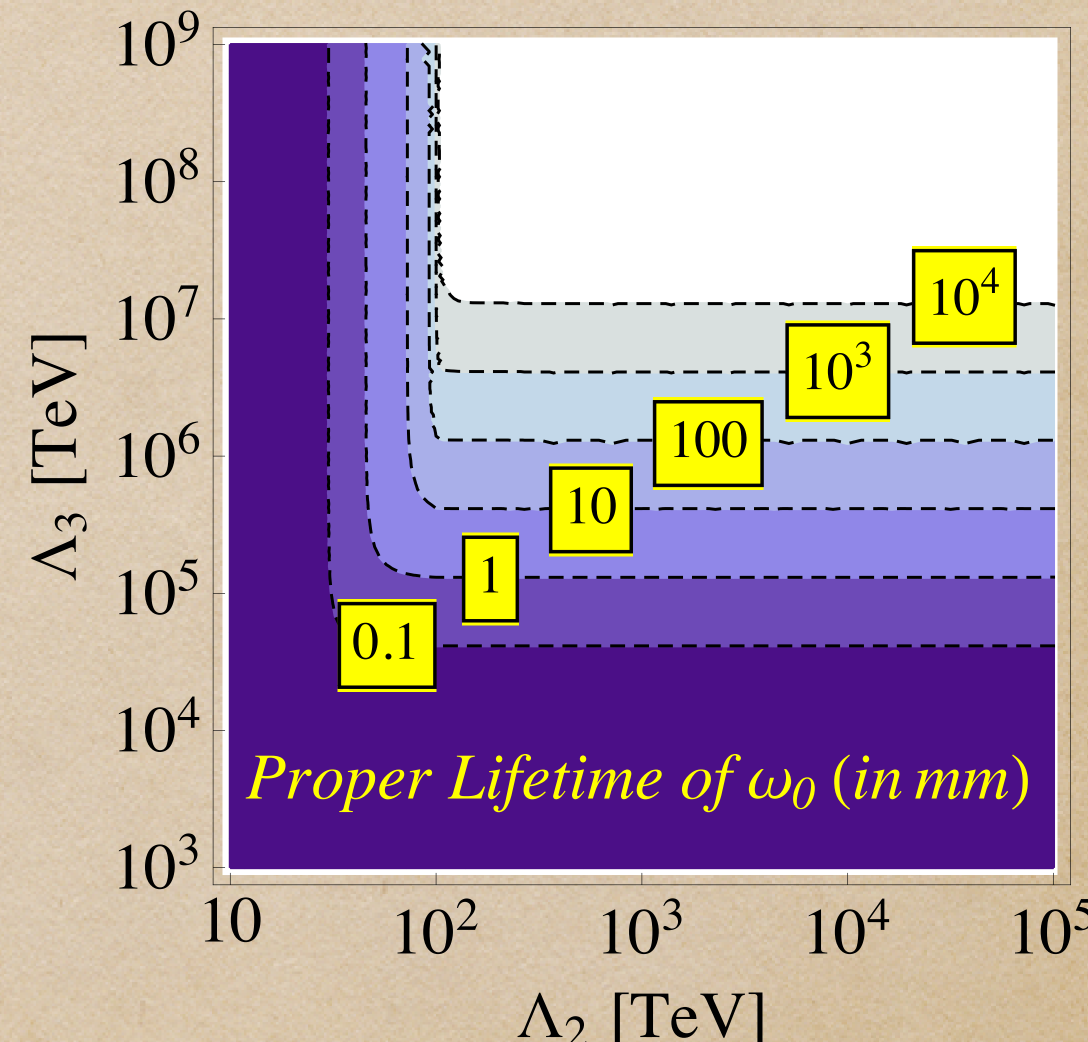




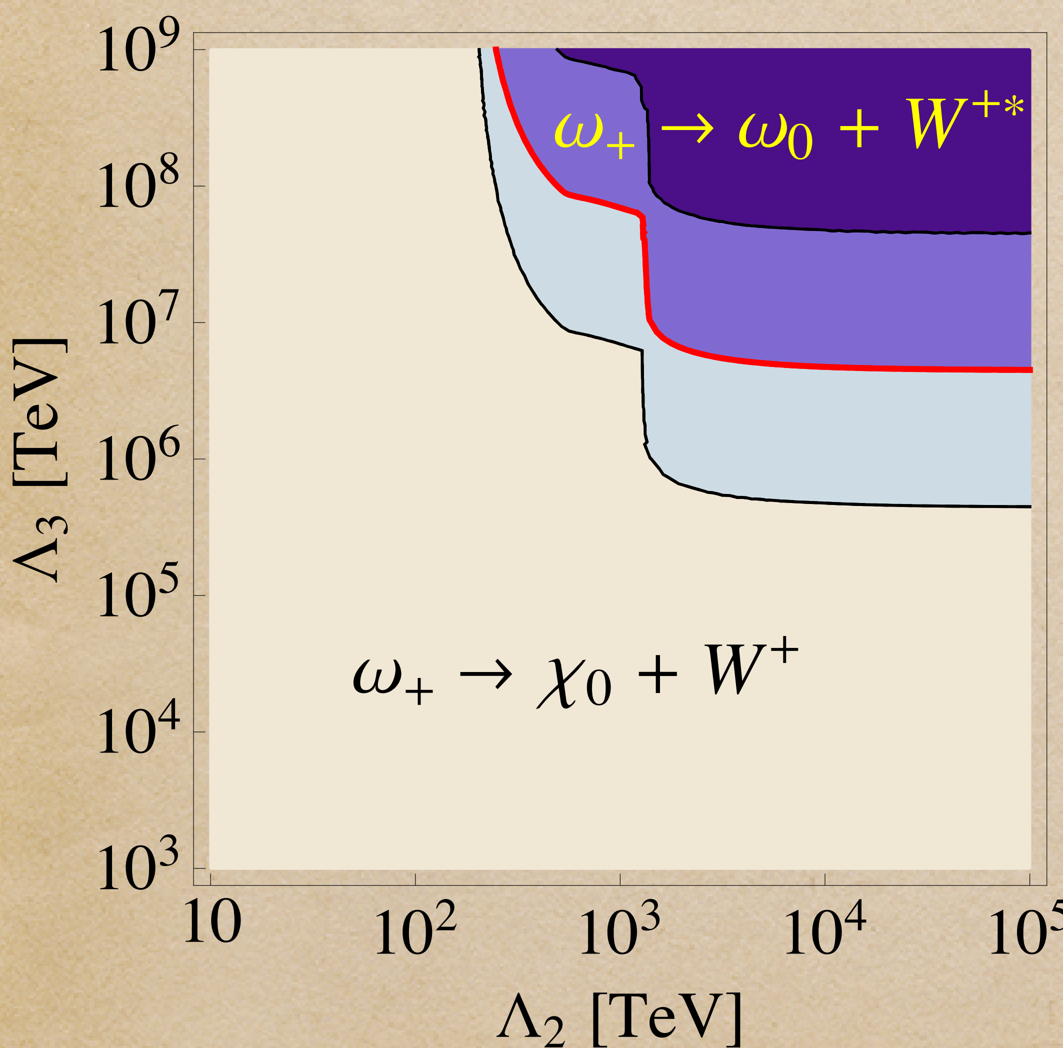
- Certain ω pairs forbidden by $U(1)_X$ symmetry.

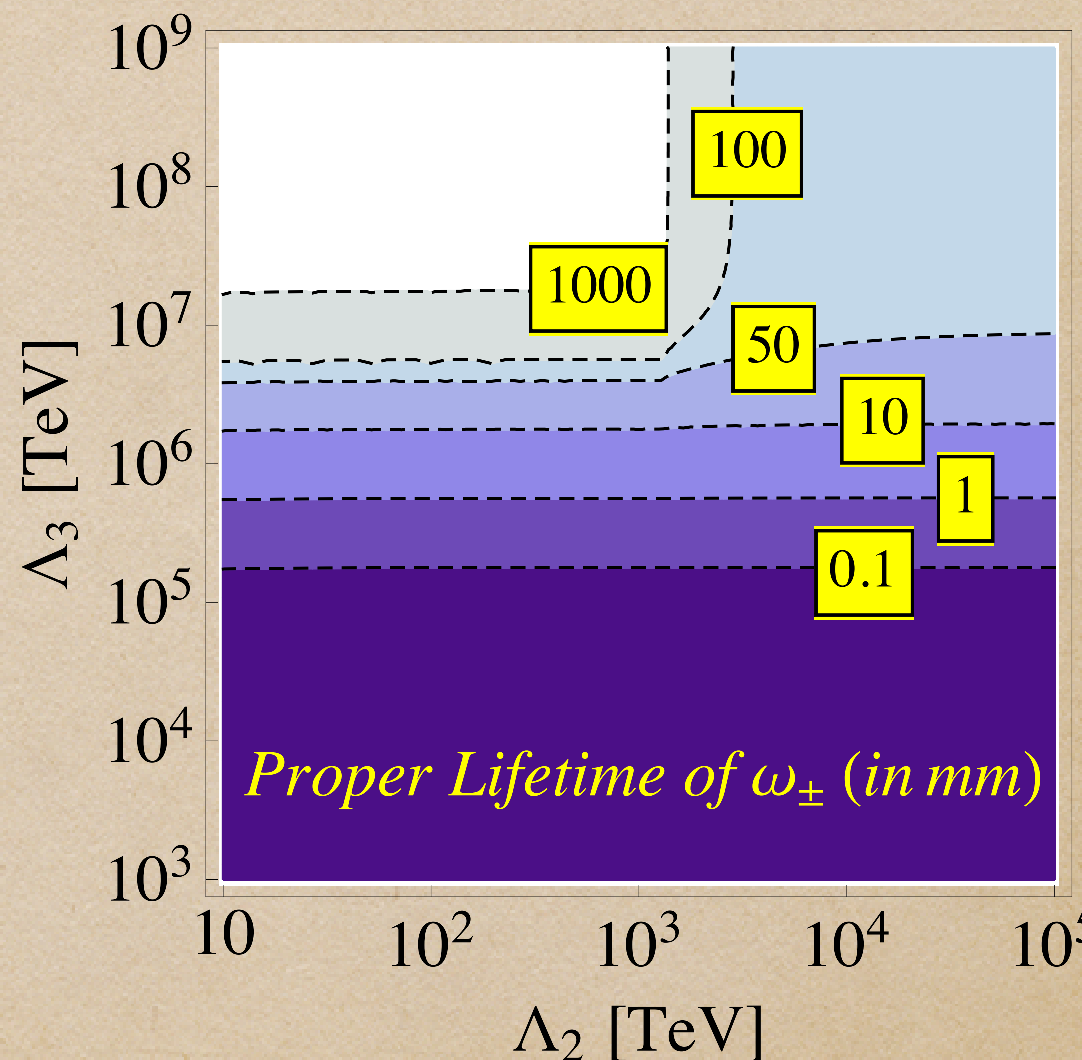
ω_0 Decays



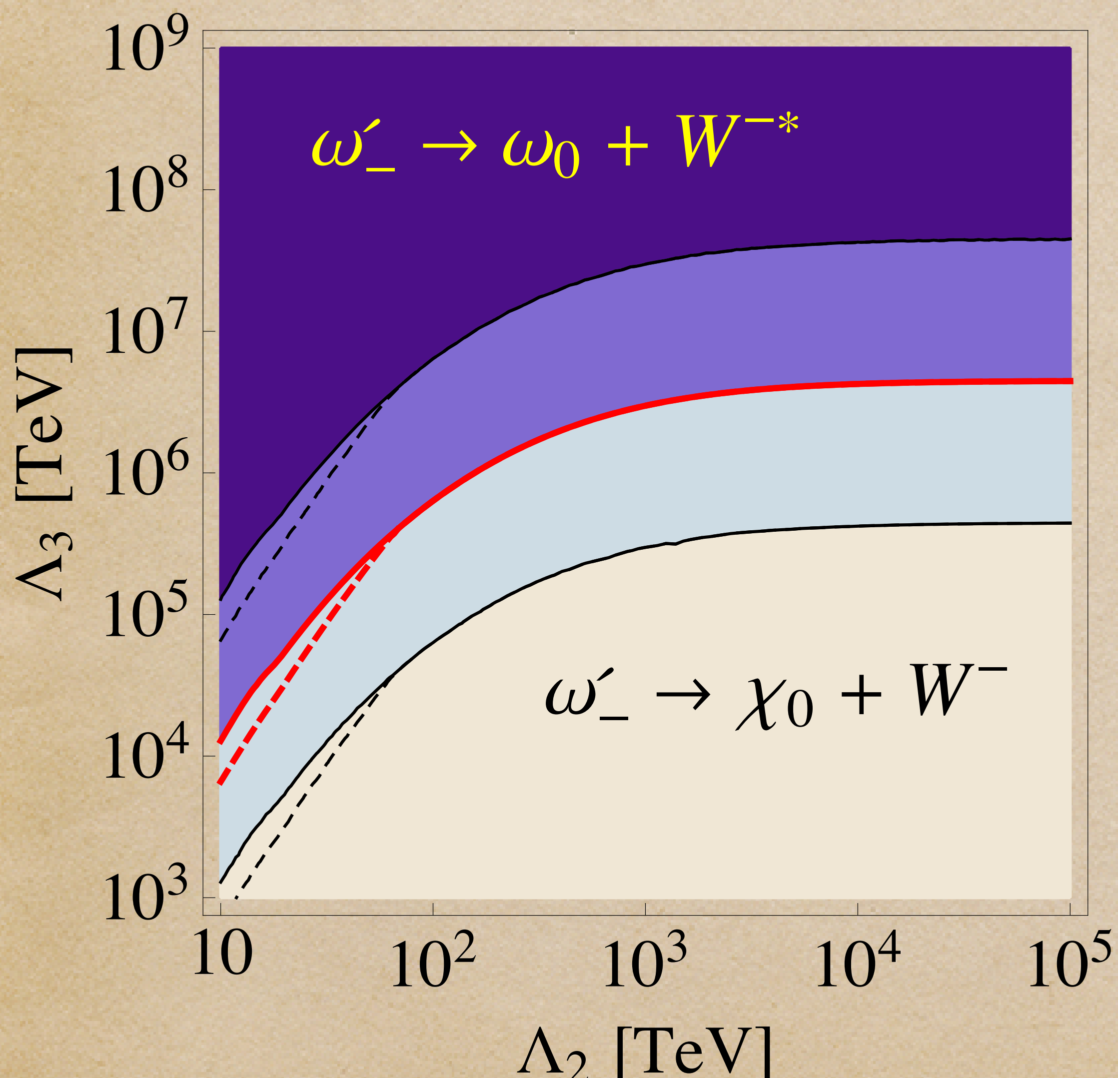


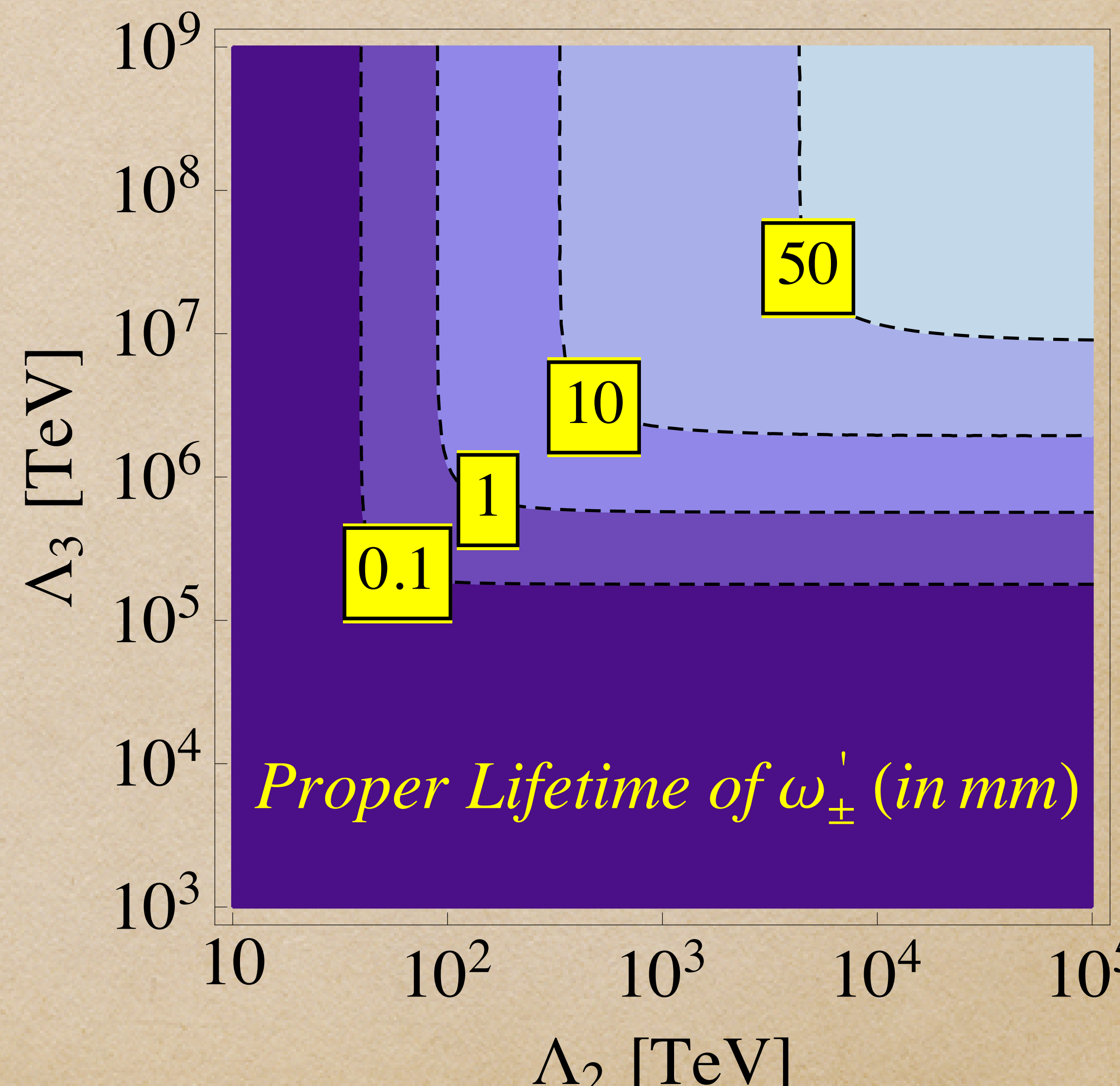
$\omega_{\pm}$ Decays





$\omega'_{\mp}$ Decays

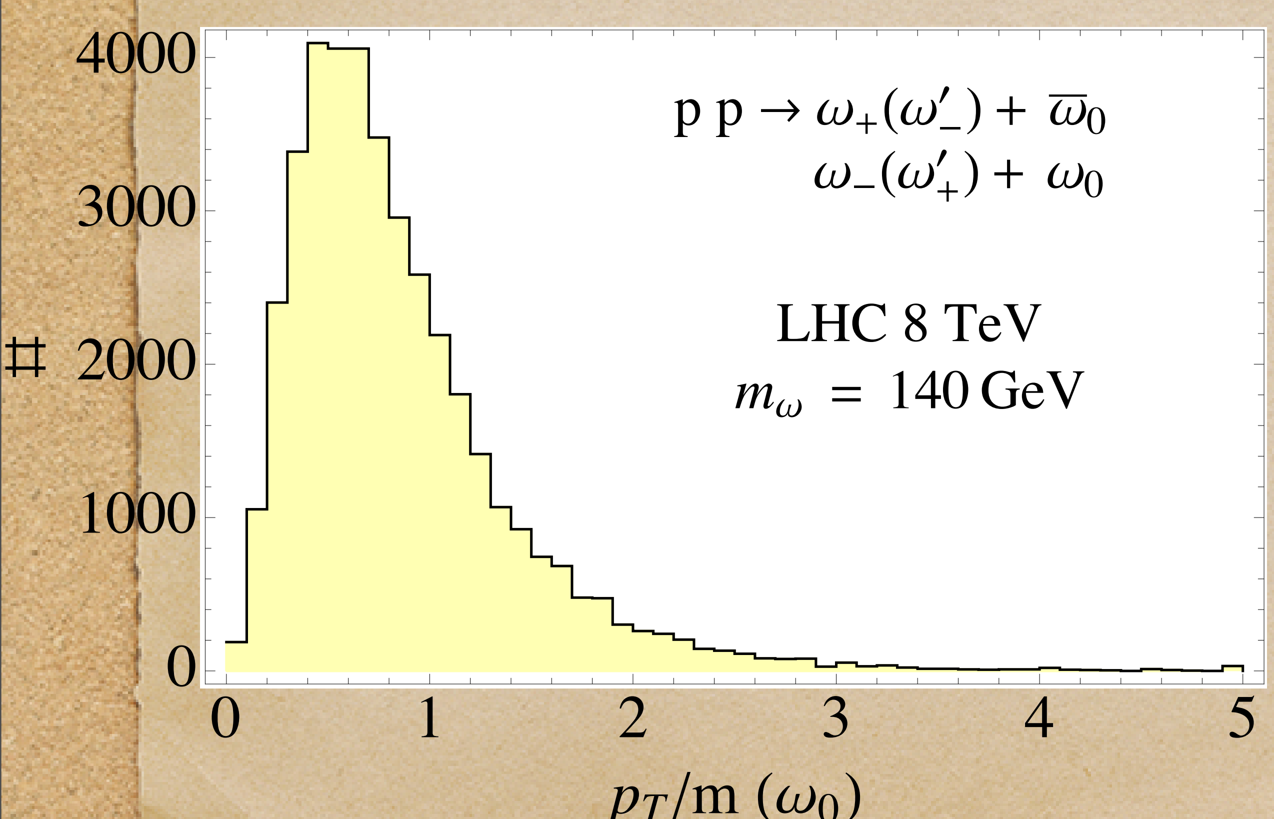




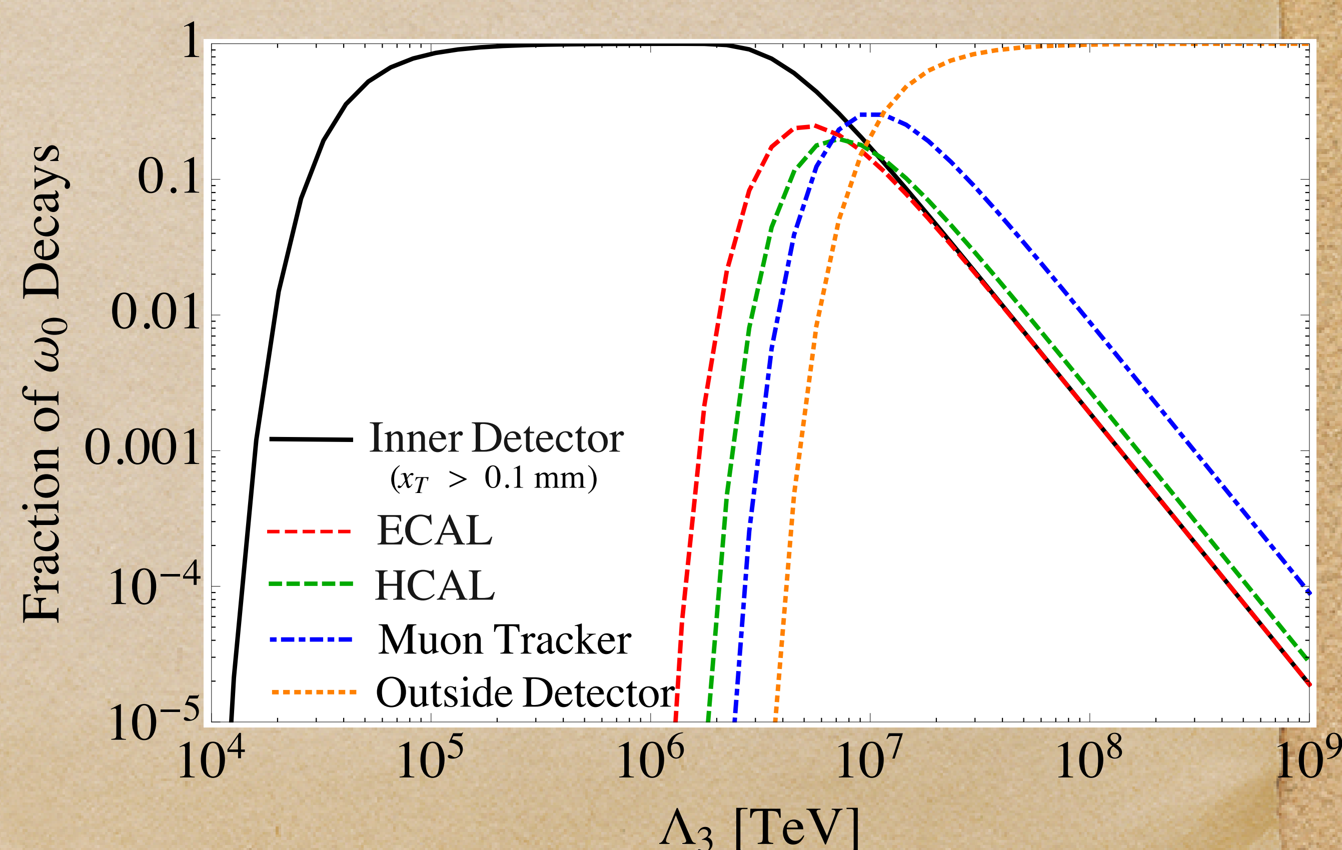
Simulation

- Lifetime in lab frame $\tau = \dfrac{\tau_0}{\sqrt{1-v^2}} \equiv \gamma\tau_0$
- Mean-transverse distance : $L_\mathrm{T} = \dfrac{p_\mathrm{T}}{m}\tau_0$

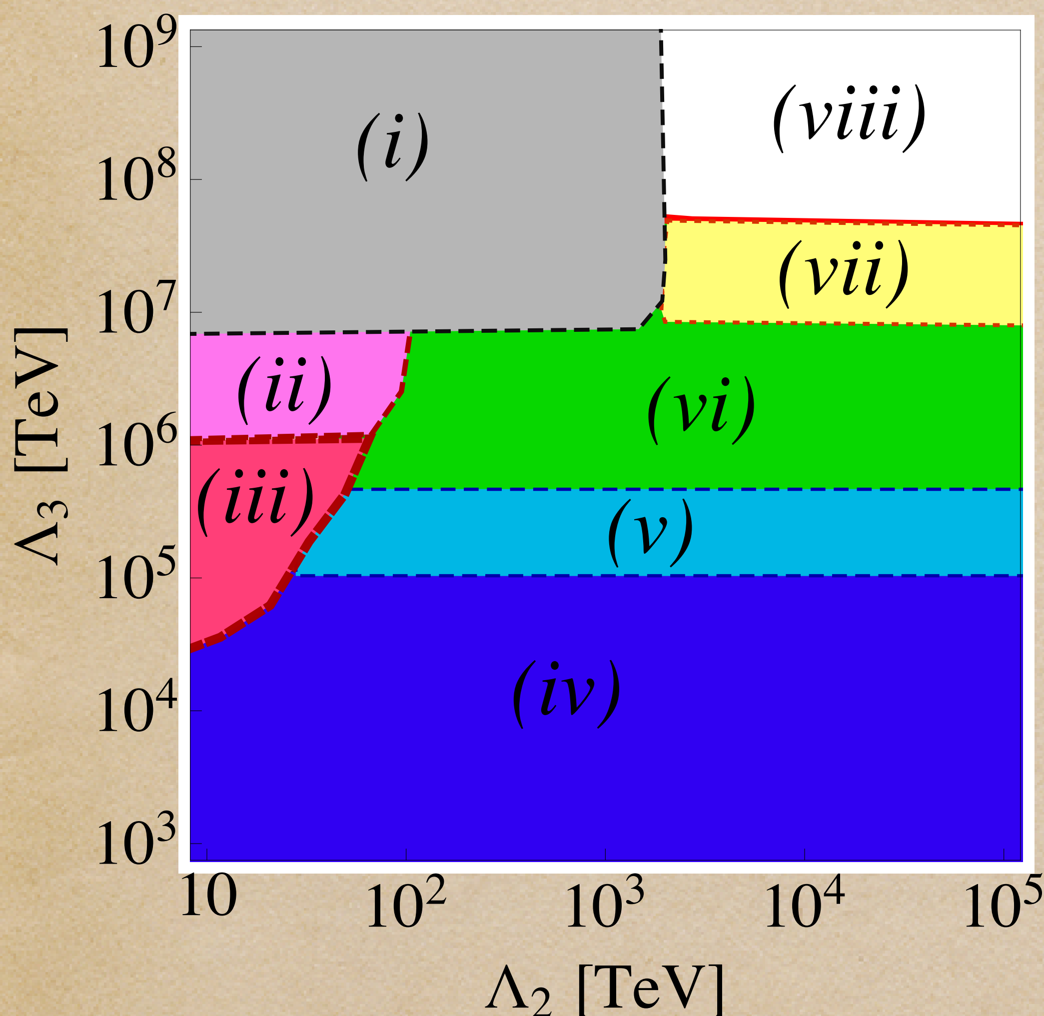
$$\boxed{N(x_\mathrm{T}) = \left(1 - \mathrm{e}^{-x_\mathrm{T}/L_\mathrm{T}}\right) N_0}$$



8 TeV LHC , $\Lambda_2 = 10^3$ TeV

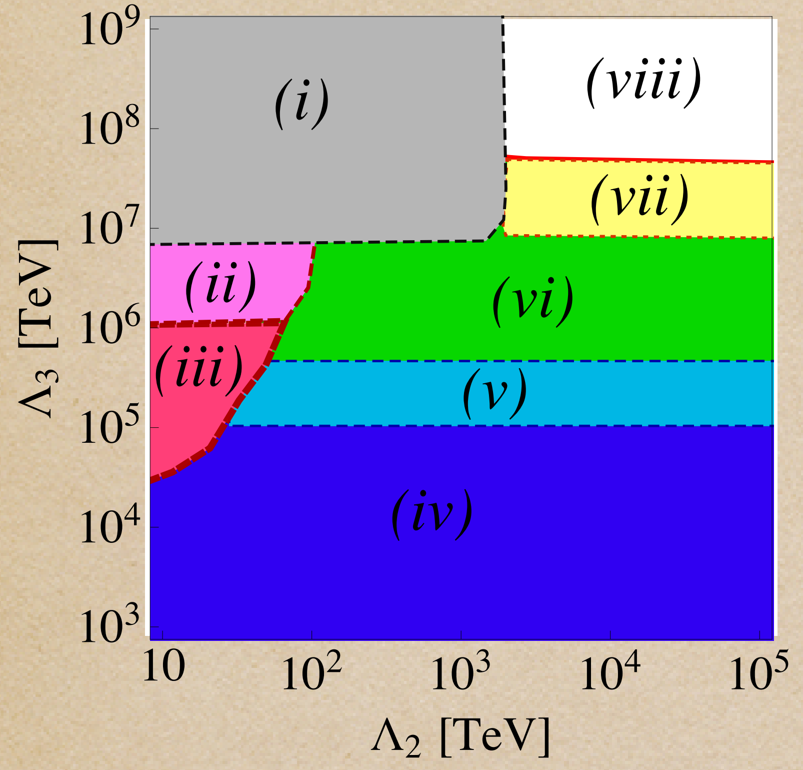


Collider Signatures

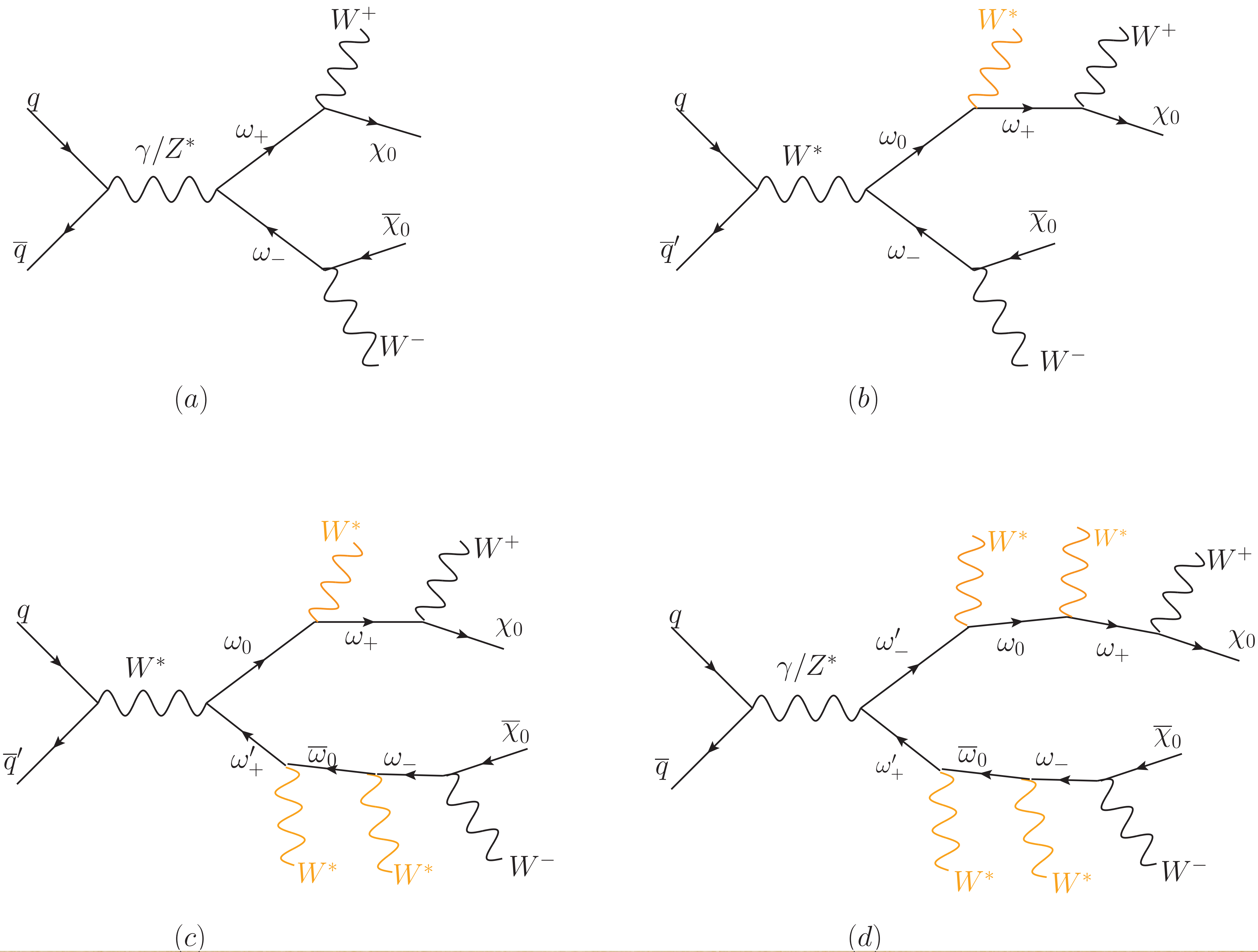


(i) Long-lived charged particles
(ii) Displaced WW + MET
(iii) Prompt WW + MET
(iv) Prompt W h + MET and Prompt WW + MET
(v) Displaced W h + MET and Prompt WW + MET
(vi) Displaced W h + MET and Displaced WW + MET
(vii) Displaced h h + MET
(viii) Pure MET

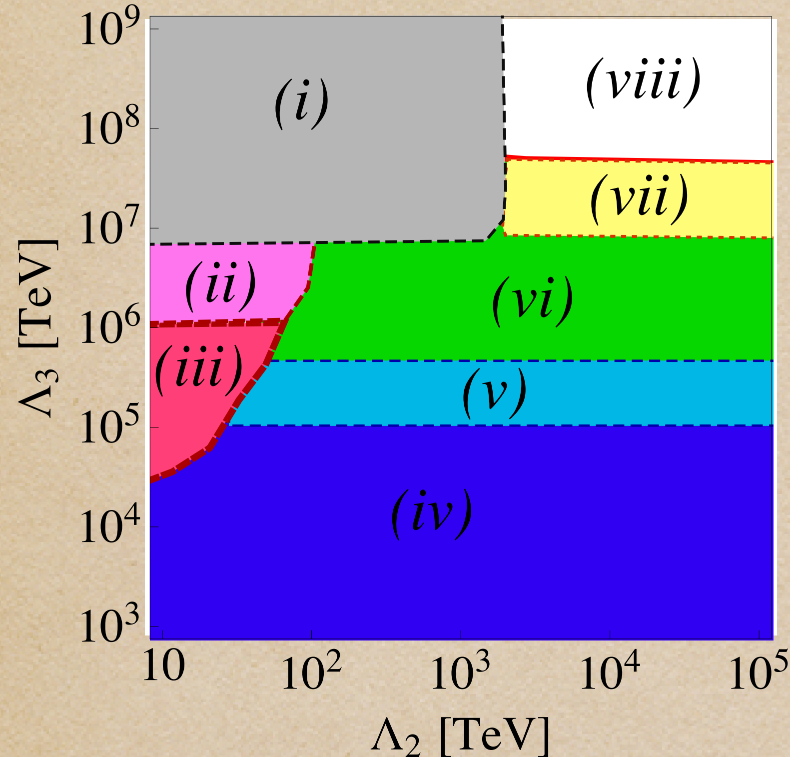
Region (iii) : Prompt WW + MET



- $\omega_\pm$ is the NLSP.
- $\omega_\pm$ decays promptly ($\tau_0 < 1$ mm).
- Visible Final States : Prompt WW
    - Dilepton signatures (always opposite sign)
    - mT2 searches
      arXiv:1208.2884 (ATLAS), arXiv:1301.0916(CMS)
    - Contribution to WW cross-section.


q
$\bar{q}$
γ/Z^*
ω_+
ω_-
W^+
χ_0
$\overline{\chi}_0$
W^-
(a)
q
$\bar{q}'$
W^*
ω_0
ω_+
ω_-
W^*
W^+
χ_0
$\overline{\chi}_0$
W^-
(b)
q
$\bar{q}'$
W^*
ω_0
ω_+
ω'_+
$\overline{\omega}_0$
ω_-
W^*
W^+
χ_0
$\overline{\chi}_0$
W^*
W^*
W^-
(c)
q
$\bar{q}$
γ/Z^*
ω'_-
ω_0
ω_+
ω'_+
$\overline{\omega}_0$
ω_-
W^*
W^*
W^+
χ_0
$\overline{\chi}_0$
W^*
W^*
W^-
(d)

Region (iii) : Prompt WW + MET



- $\omega_\pm$ is the NLSP.
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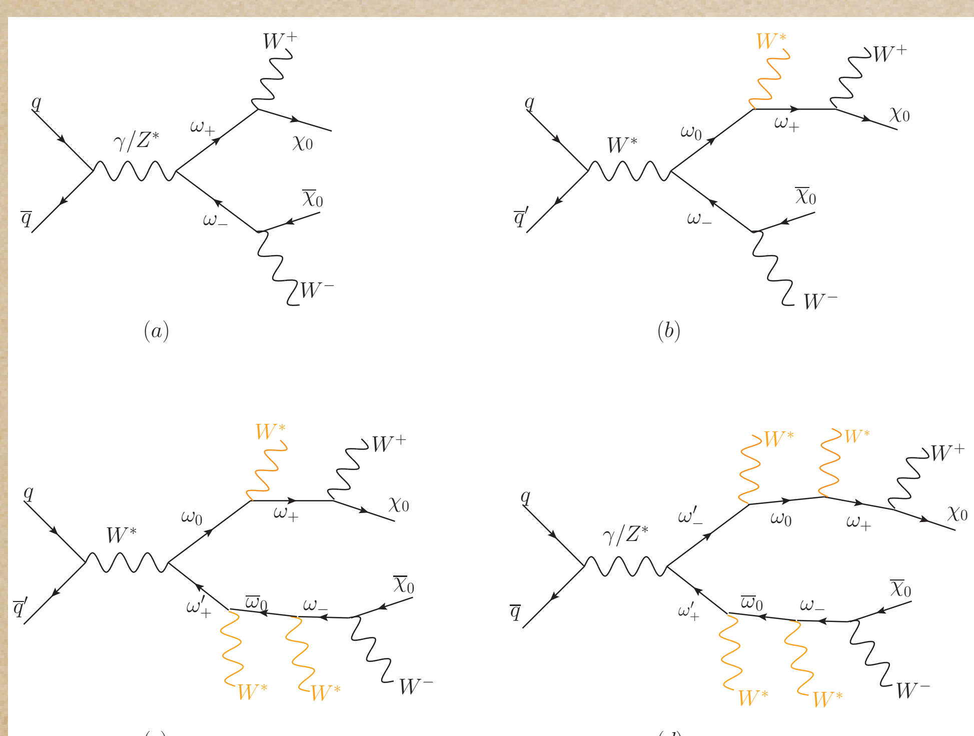
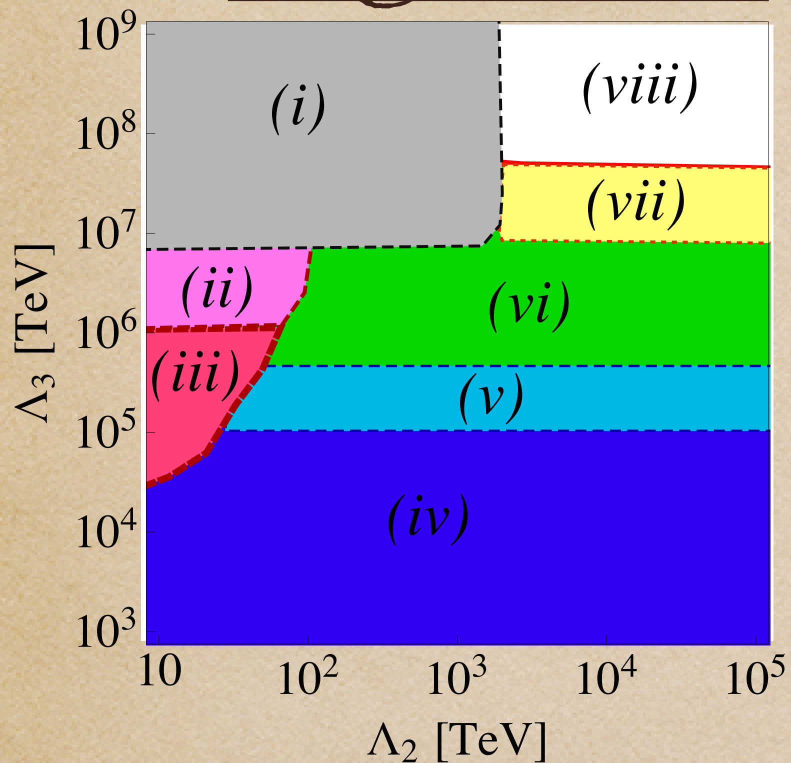


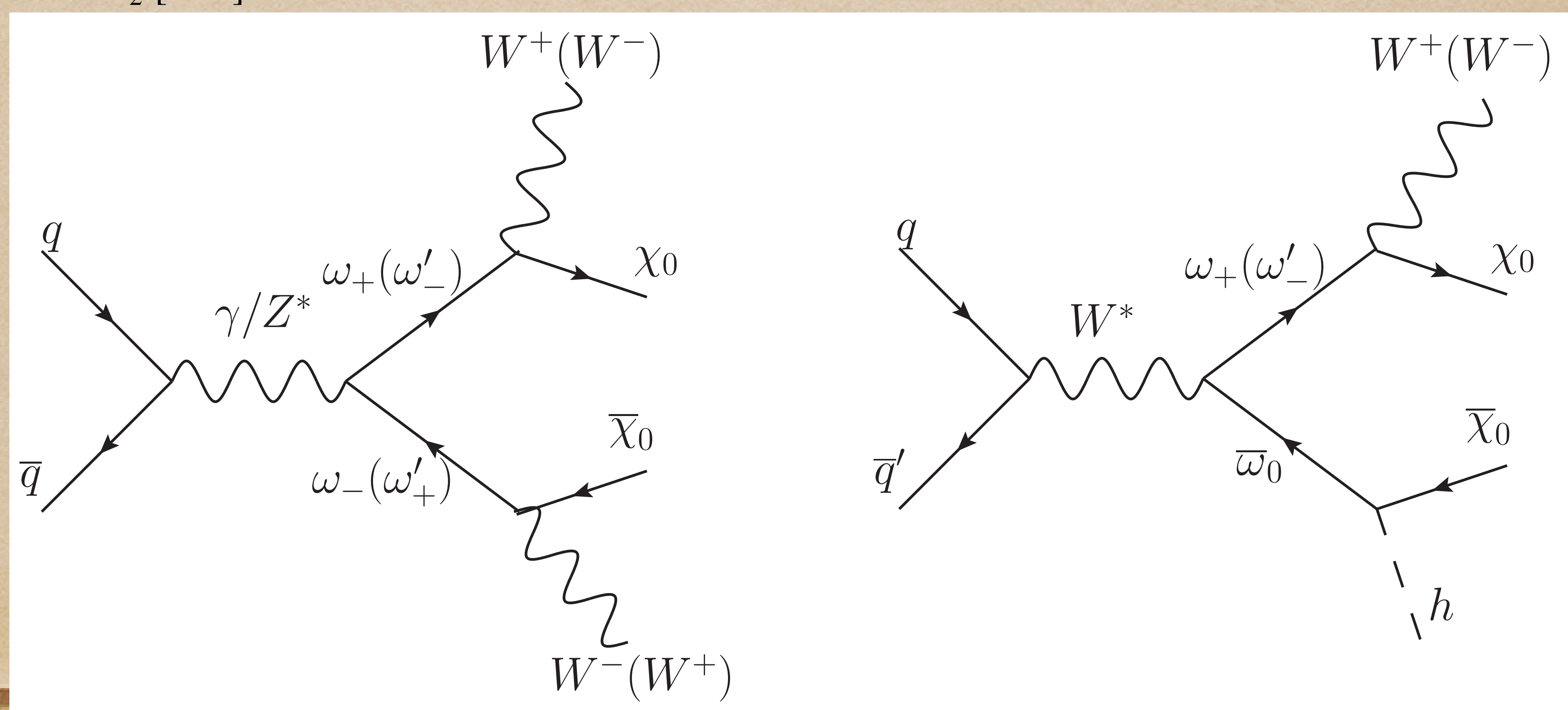
- Dilepton signatures (always opposite sign)
- mT2 searches

  arXiv:1208.2884 (ATLAS), arXiv:1301.0916(CMS)
- Contribution to WW cross-section.

Region (vi) : Displaced W h + MET
Displaced W W + MET



- All ω decay to χ_0 in a single step.
- Both ω_0 and $\omega_\pm$ are long-lived.
- Search for displaced Higgs.



Displaced Higgs (decays inside ID)

- $h \to b\bar{b}$: Highly displaced b-jets.
- $h \to n\,\text{jets} + X\ (n \geq 2)$: trackless jets : use triggers for hidden valley in ATLAS.

  $h \to gg,\ h \to b\bar{b},\ \ h \to WW^* \to 4\text{j or } \ell\nu 2\text{j},\ h \to ZZ^* \to 4j$
- $h \to n\ell + X\ (n \geq 2)$: Displaced Dilepton Resonance Searches [CMS : arXiv:1211.2472]
- $h \to \ell + n\,\text{jets} + X$: Displaced Lepton + Jets (RPV Searches) [ATLAS-CONF-2012-113]
- $h \to \gamma\gamma \text{ or } \gamma Z$: Displaced diphoton resonance

Displaced Higgs (decays inside CAL)

- ATLAS triggers for long-lived neutral particles that decay inside HCAL.

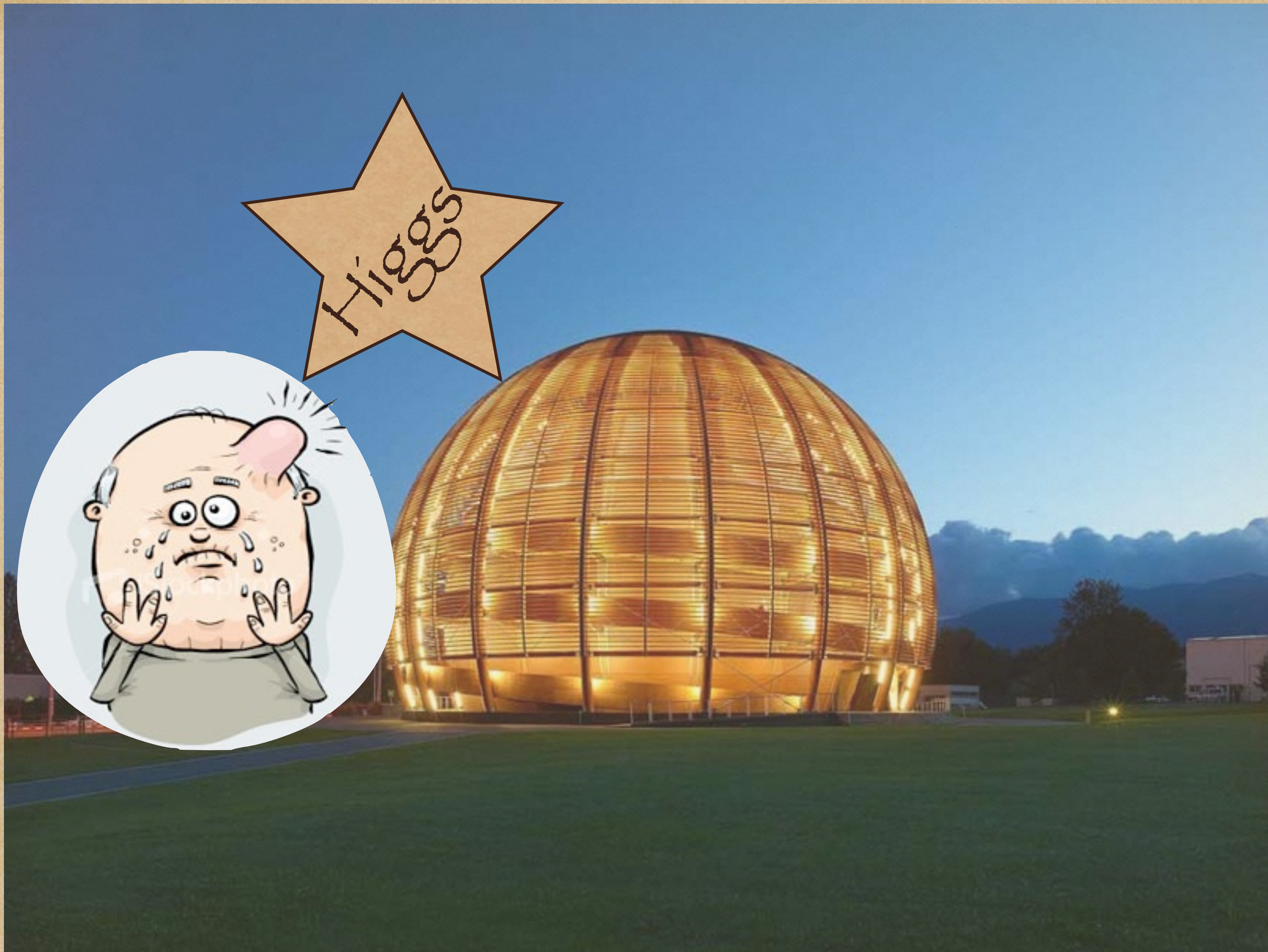
  [ATL-PHYS-PUB-2009-082]

Displaced Higgs (decays inside MS)

- Hidden valley searches : $h \rightarrow \pi_v \ \pi_v$

  [ATLAS : arXiv:1203.1303]

- Reduced signal efficiency due to wrong bunch crossing identification.


Higgs

Conclusion

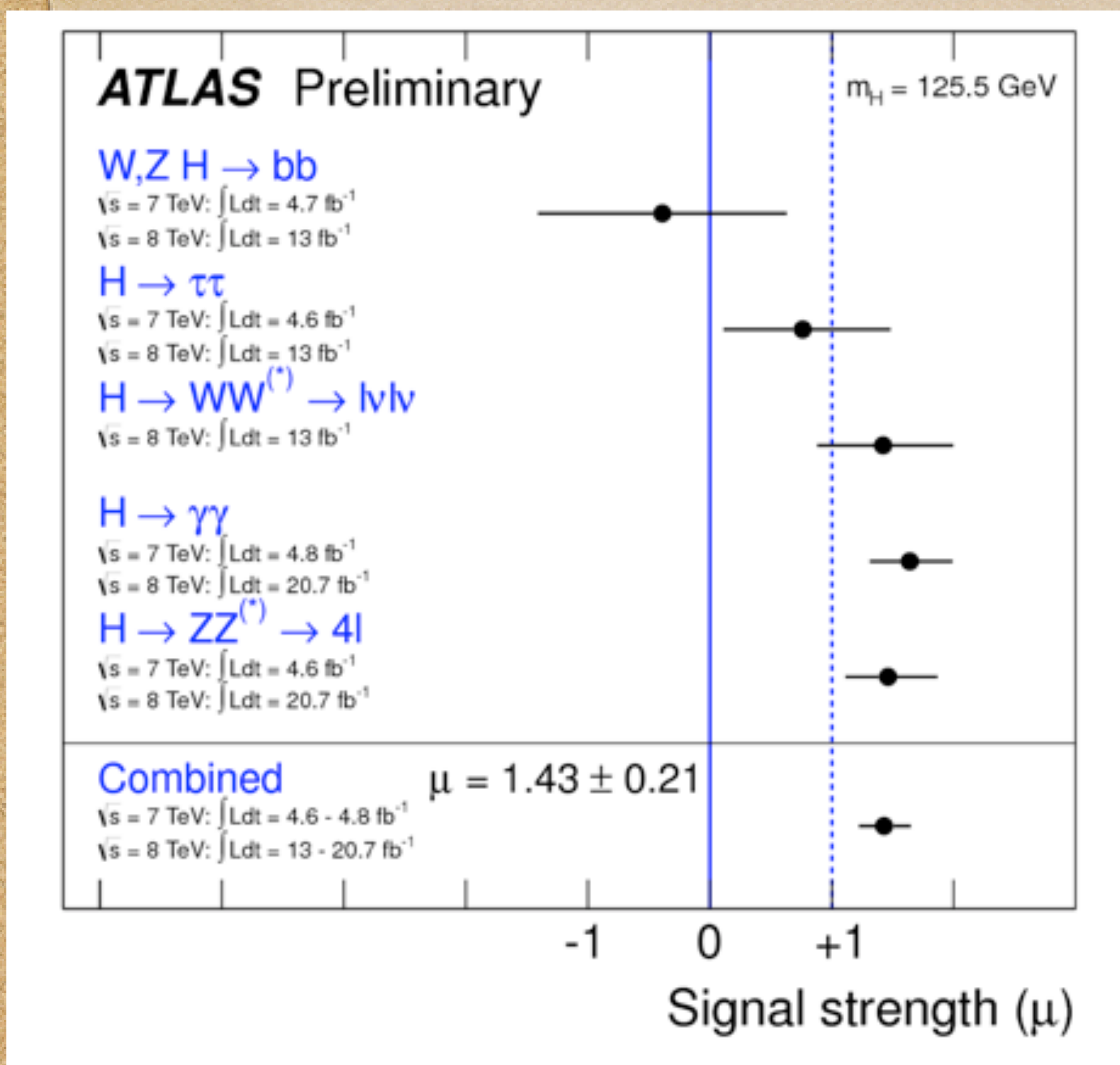
LHC should look for displaced Higgs ......

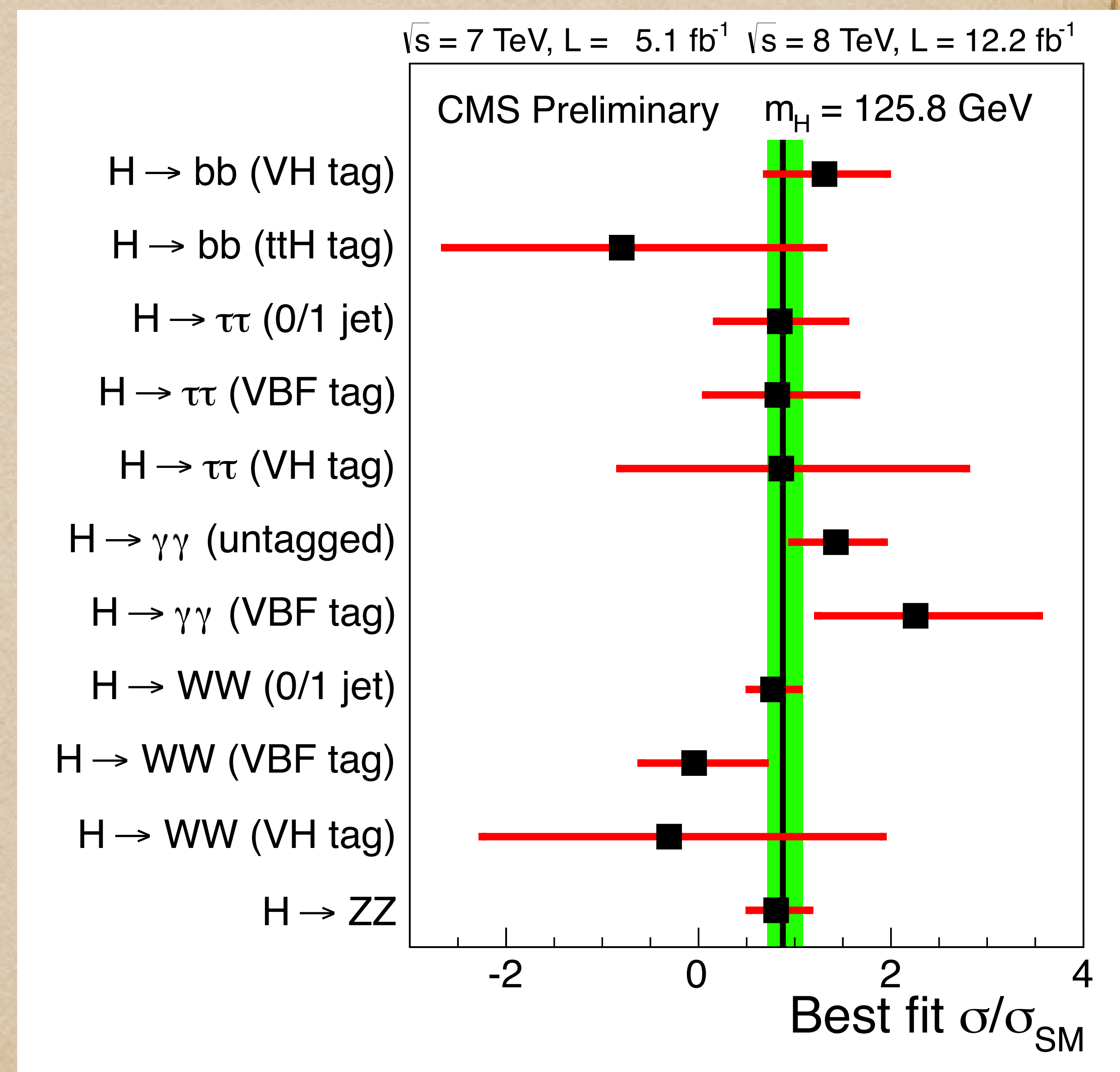
..... and it can.

Backup Slides

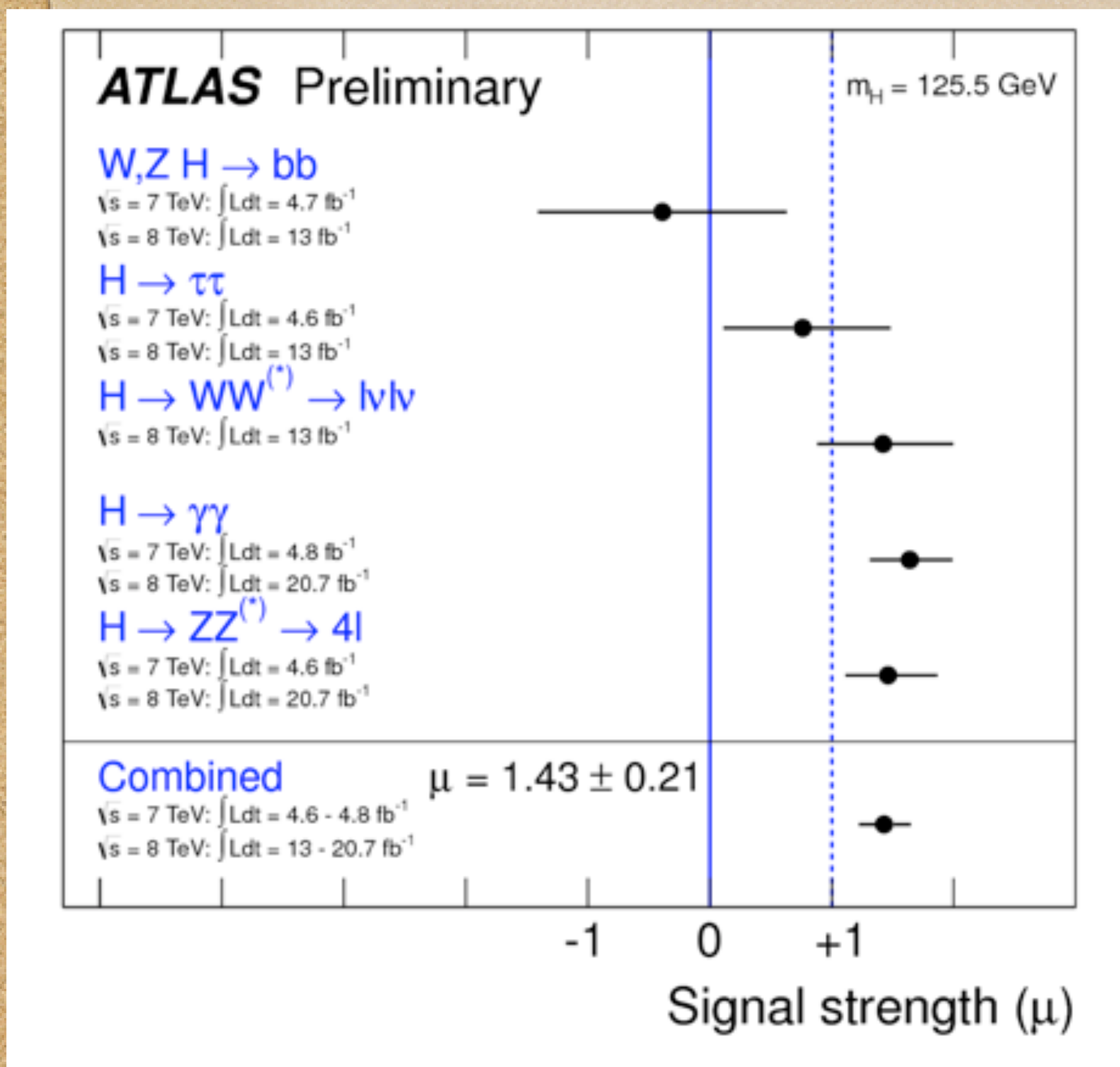
LHC has discovered 125 GeV Higgs

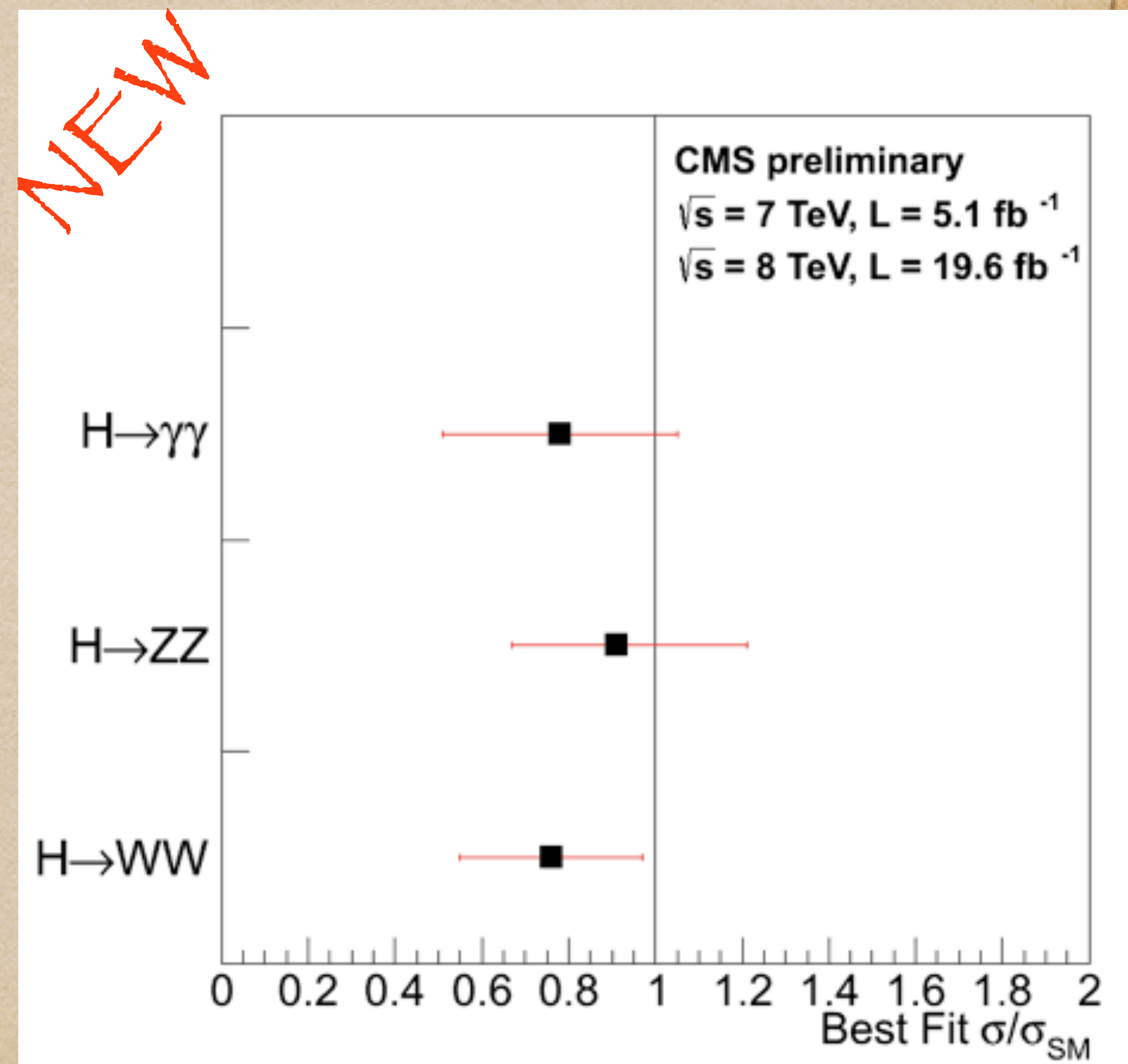
Looks increasingly SM-like.





- LHC has discovered 125 GeV Higgs
  - Looks increasingly SM-like.

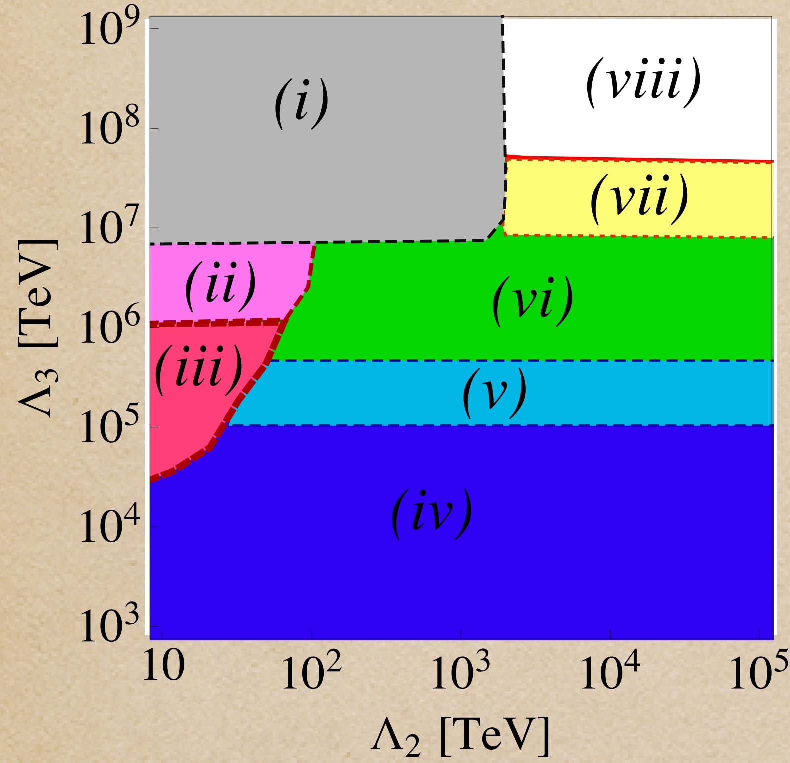




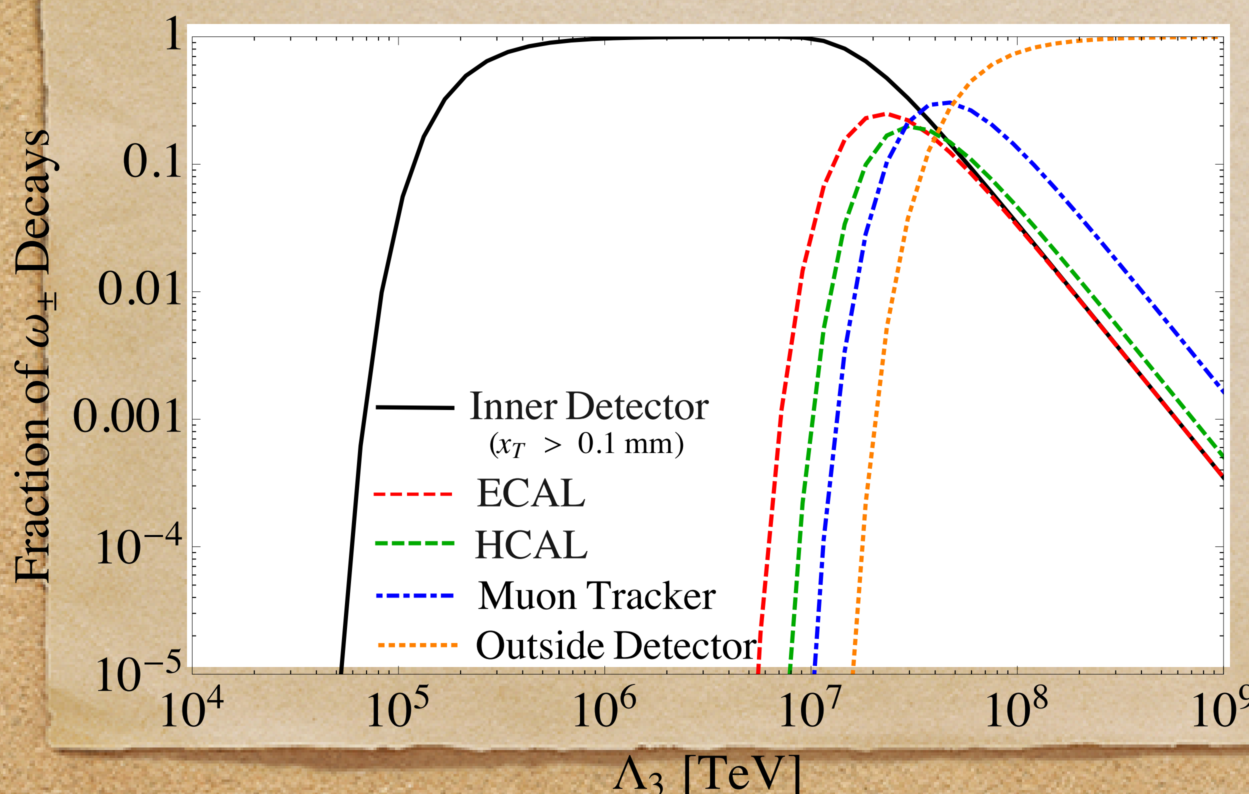
$m_\omega = 140$ GeV

	$\sqrt{s} = 1.96$ TeV Tevatron Run	$\sqrt{s} = 7$ TeV LHC Run	$\sqrt{s} = 8$ TeV LHC Run	$\sqrt{s} = 14$ TeV LHC Run
$p\,p(\overline{p}) \to \omega_0\,\omega_-$	0.16 pb	0.61 pb	0.78 pb	2.01 pb
$p\,p(\overline{p}) \to \overline{\omega}_0\,\omega_+$	0.16 pb	1.23 pb	1.52 pb	3.45 pb
$p\,p(\overline{p}) \to \omega_0\,\omega'_+$	0.16 pb	1.23 pb	1.52 pb	3.45 pb
$p\,p(\overline{p}) \to \overline{\omega}_0\,\omega'_-$	0.16 pb	0.61 pb	0.78 pb	2.01 pb
$p\,p(\overline{p}) \to \omega_+\,\omega_-$	0.22 pb	0.91 pb	1.14 pb	2.74 pb
$p\,p(\overline{p}) \to \omega'_+\,\omega'_-$	0.22 pb	0.91 pb	1.14 pb	2.74 pb

Region (i) : Long-lived charged particles

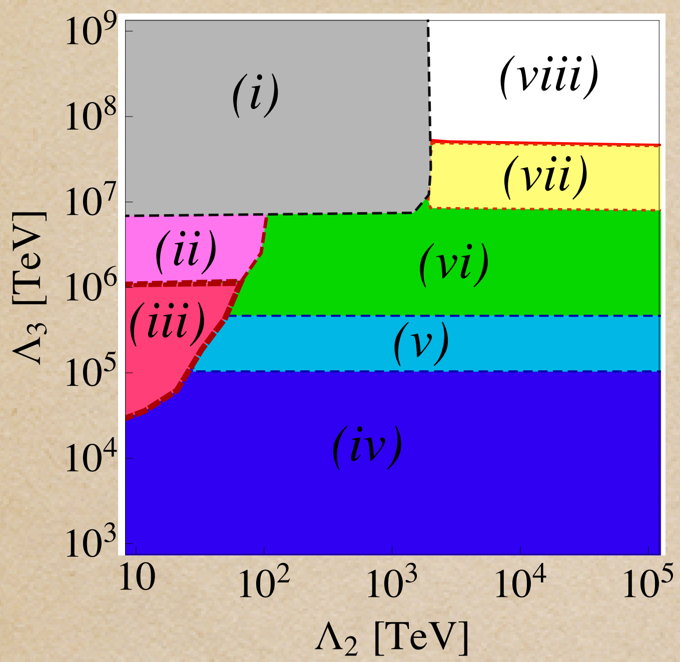


7 TeV LHC , Λ_2 = 100 TeV

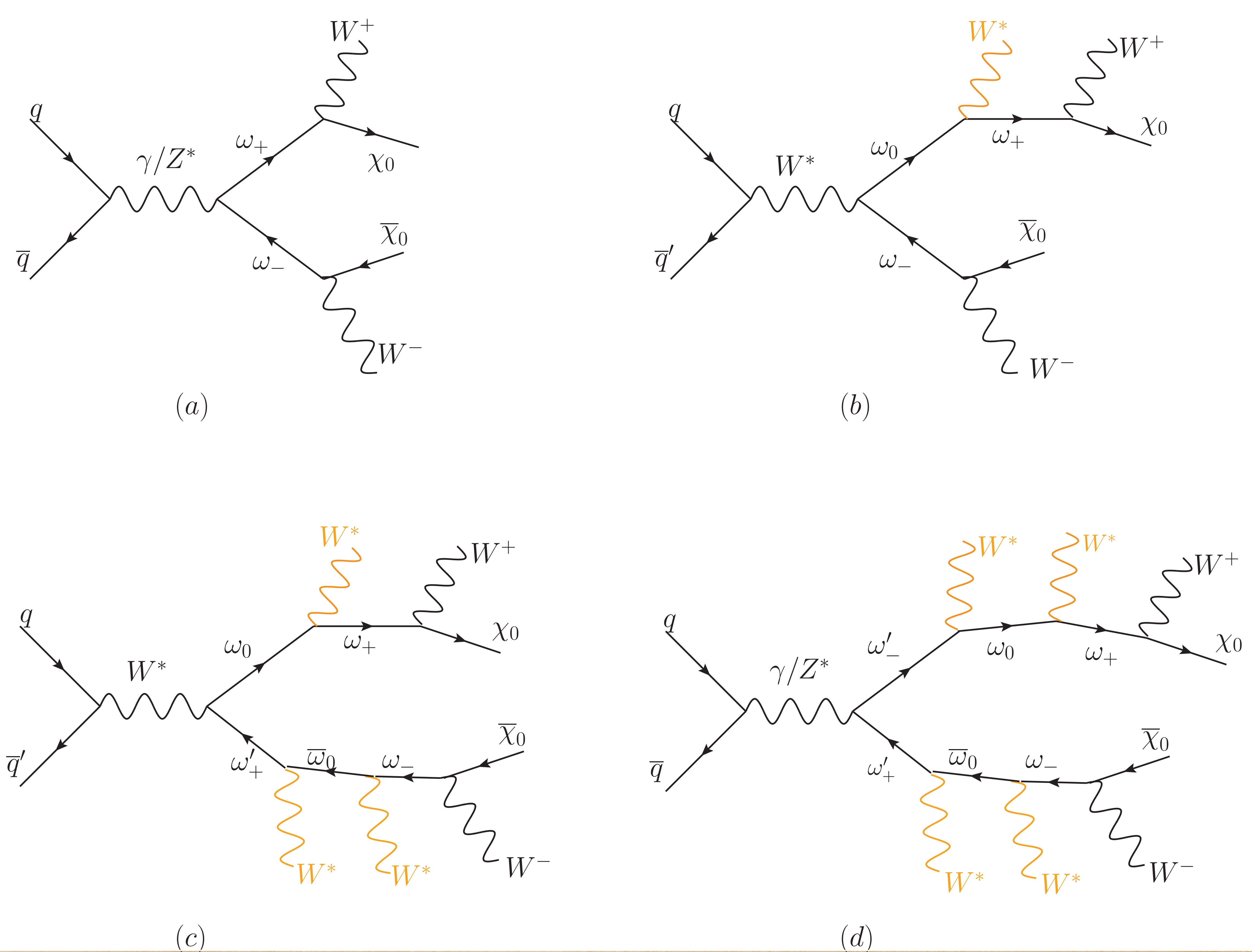


- $\omega_\pm$ is long-lived (τ_0 > 50 cm).
- $\omega_\pm$ is the NLSP (or co-NLSP).
- Searches for long-lived charged particles :
  - Decays inside muon tracker.
    arXiv:1211.1597 (ATLAS), arXiv:1205.0272(CMS)
  - Disappearing tracks.
    arXiv:1210.2852 (ATLAS)

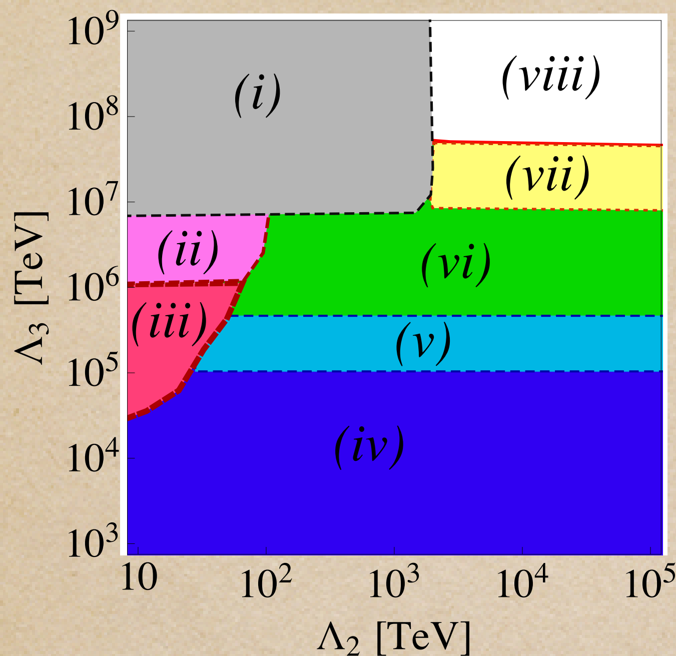
Region (ii) : Displaced WW + MET



- $\omega_\pm$ is the NLSP.
- $\omega_\pm$ is semi long-lived (τ_0 = 0.1- 50 cm).
- Visible Final States : Displaced WW
  - Possible signatures?
    - Displaced leptons/jets
    - Kinked tracks.


q
$\bar{q}$
γ/Z^*
ω_+
ω_-
W^+
χ_0
$\overline{\chi}_0$
W^-
(a)
q
$\bar{q}'$
W^*
ω_0
ω_+
ω_-
W^*
W^+
χ_0
$\overline{\chi}_0$
W^-
(b)
q
$\bar{q}'$
W^*
ω_0
ω_+
ω'_+
$\overline{\omega}_0$
ω_-
W^*
W^+
χ_0
$\overline{\chi}_0$
W^*
W^*
W^-
(c)
q
$\bar{q}$
γ/Z^*
ω'_-
ω_0
ω_+
ω'_+
$\overline{\omega}_0$
ω_-
W^*
W^*
W^+
χ_0
$\overline{\chi}_0$
W^*
W^*
W^-
(d)

Region (ii) : Displaced WW + MET



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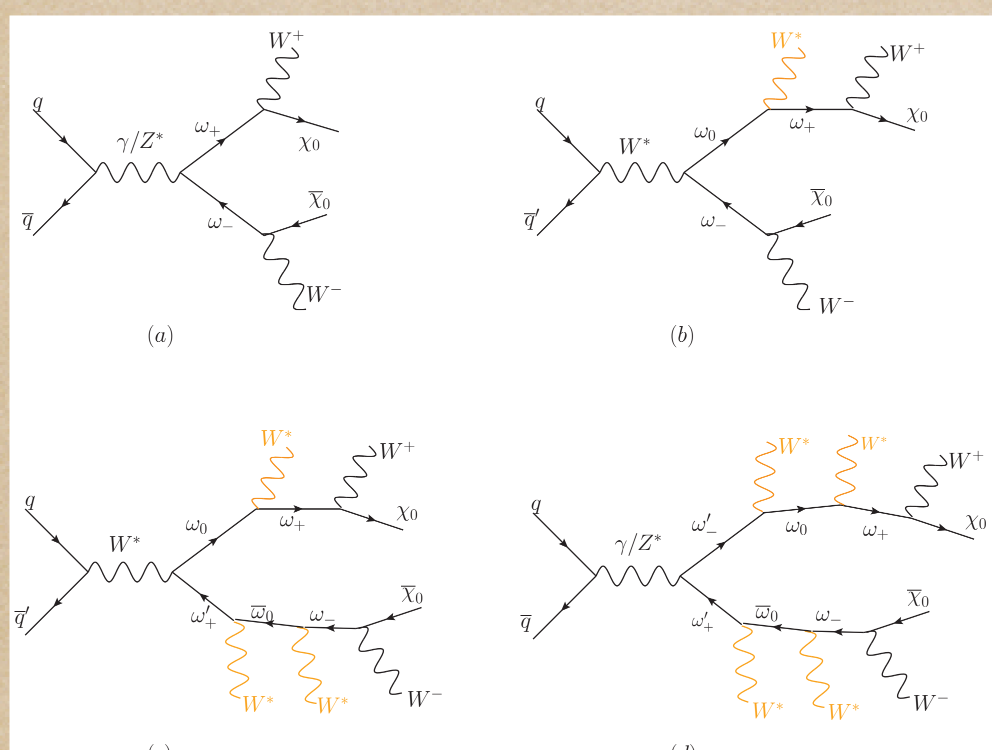
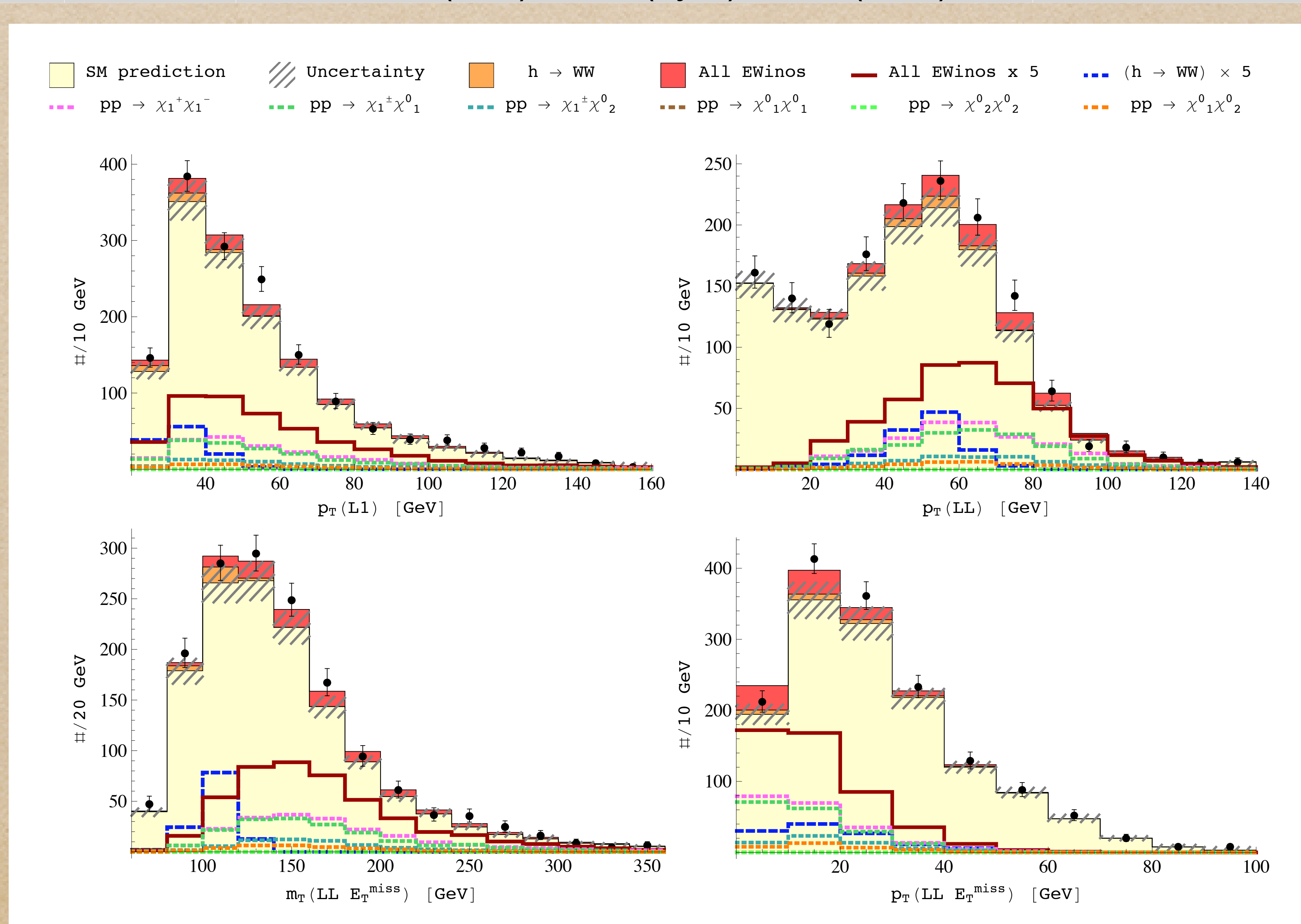


- Possible signatures?
  - Displaced leptons/jets
  - Kinked tracks.

SM W W Cross-section Measurement

		Measured (pb)	MCFM NLO (pb)
ATLAS	7 TeV	51.9 ± 2.0 (stat) ± 3.9 (syst) ± 2.0 (lumi)	$44.7^{+2.1}_{-1.9}$
CMS	7 TeV	52.4 ± 2.0 (stat) ± 4.5 (syst) ± 1.2 (lumi)	47.0 ± 2.0
CMS	8 TeV	69.9 ± 2.8 (stat) ± 5.6 (syst) ± 3.1 (lumi)	$57.3^{+2.4}_{-1.6}$



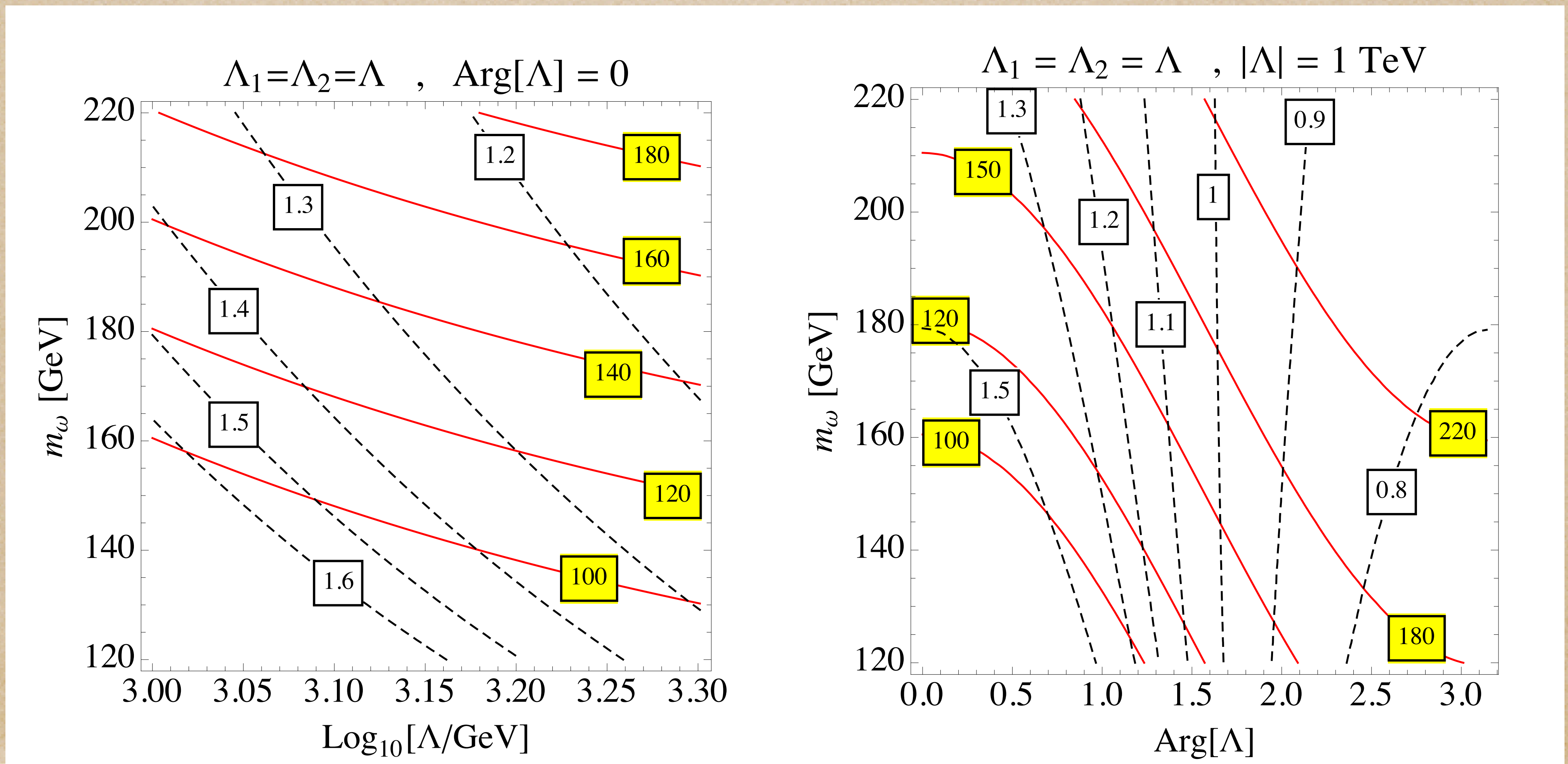
arXiv:1206.6888 : David Curtin, PJ, Patrick Meade

Diphoton Rate

$$\mathcal{O}_5^{(1)} = H^\dagger H\, \omega_{\rm R}^{a\dagger}\omega_{\rm L}^a \qquad \mathcal{O}_5^{(2)} = {\rm i}\epsilon^{abc} H^\dagger \sigma^a H\, \omega_{\rm R}^{b\dagger}\omega_{\rm L}^c$$

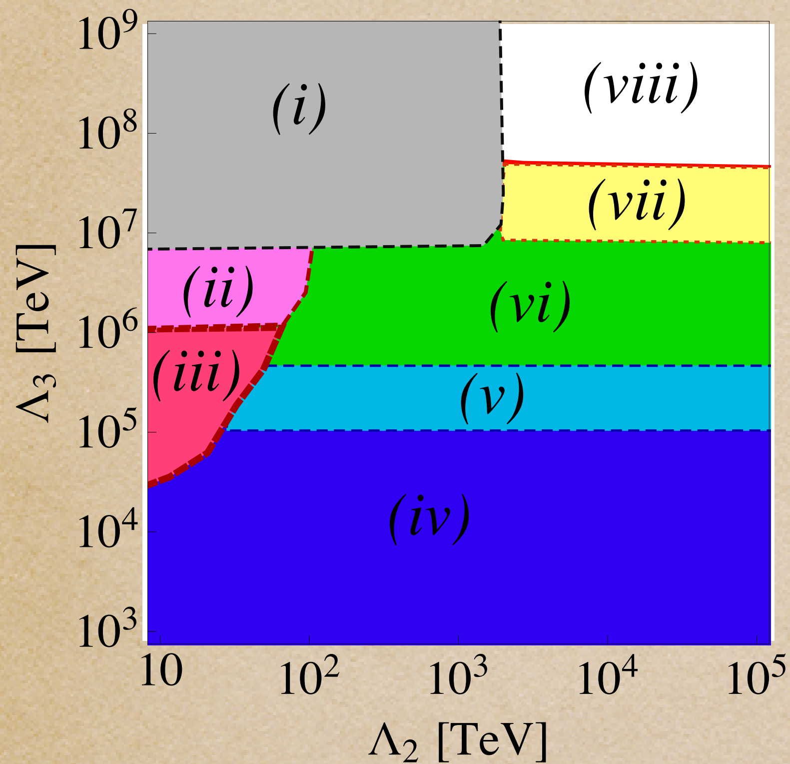
$$\Gamma(h\to\gamma\gamma) = \frac{\alpha_{\rm EM}^2\, G_{\rm F}\, m_h^3}{128\sqrt{2}\,\pi^3}\left| A_1^h(\tau_W) + \frac{4}{3}A_{1/2}^h(\tau_t) + \sum_{f=\omega,\,\omega'} g_{hf_+f_-}\frac{v}{m_{f_\pm}}A_{1/2}^h(\tau_{f_\pm})\right|^2$$

$$g_{h\omega_+\omega_-} = -\frac{v}{\Lambda_1} - \frac{v}{\Lambda_2}\,, \quad g_{h\omega'_+\omega'_-} = -\frac{v}{\Lambda_1} + \frac{v}{\Lambda_2}$$



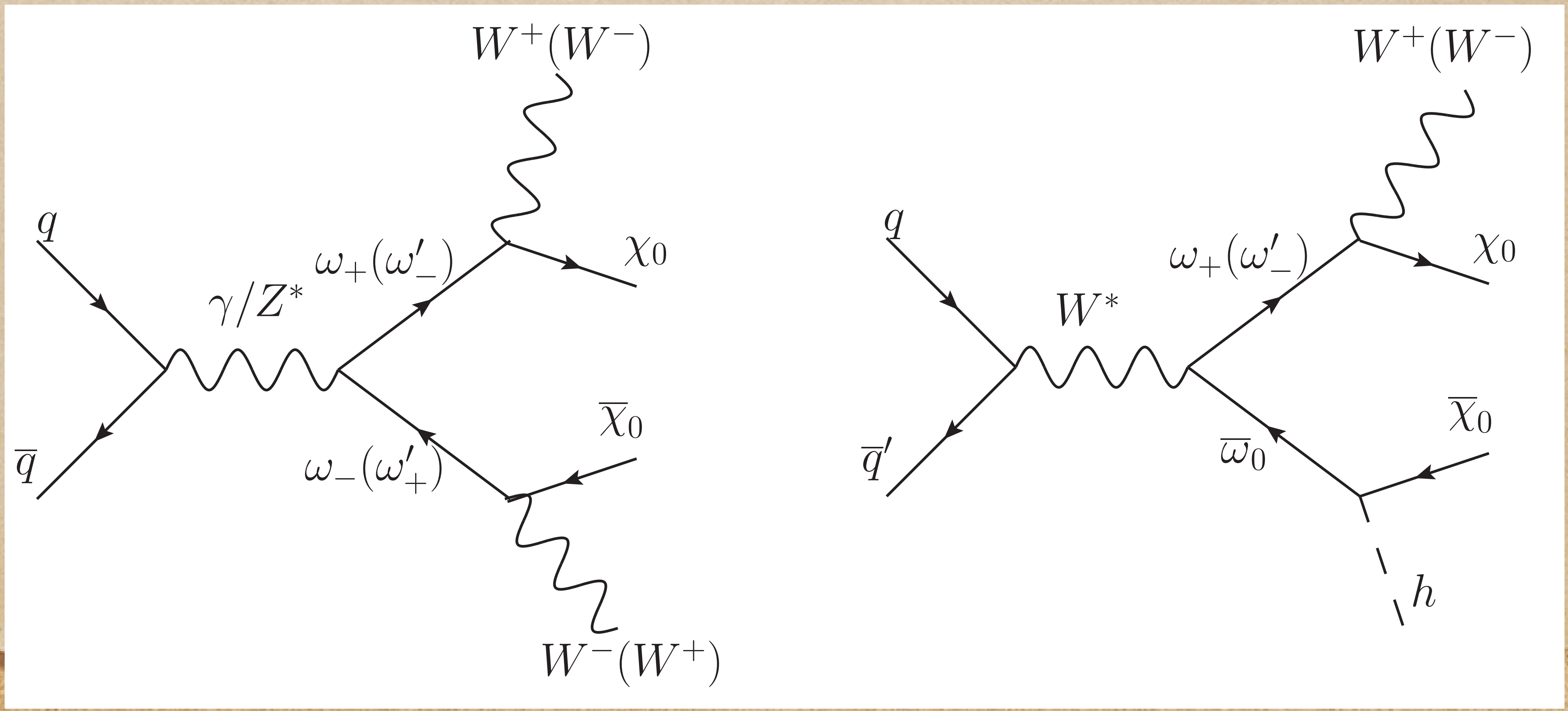
Region (iv) : Prompt W h + MET

Prompt W W + MET



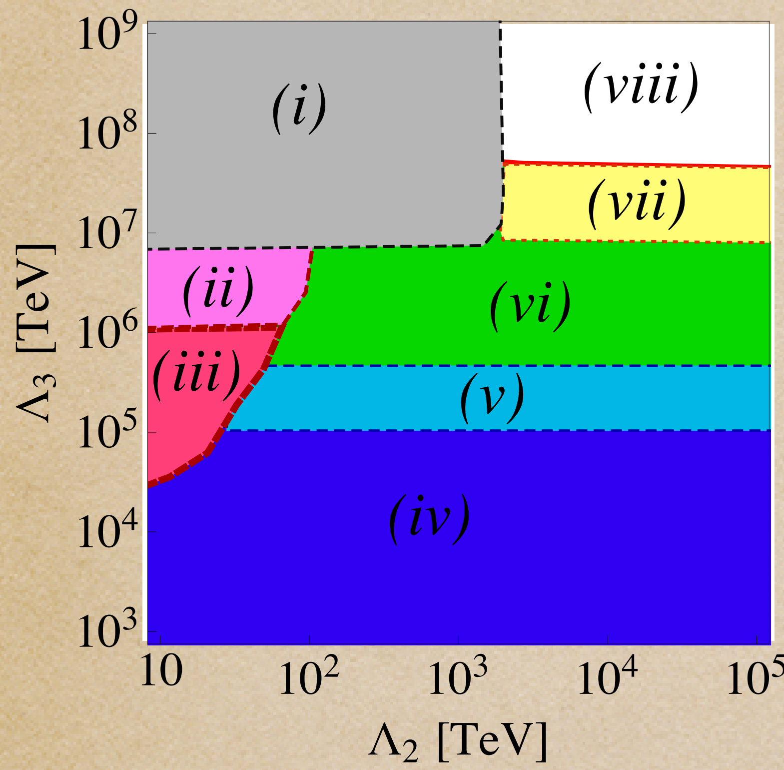
- All ω decay to χ_0 in a single step promptly.
- Collider bounds on W h production :

  2 X SM. [ATLAS-CONF-2012-161, CMS-PAS-HIG-12- 044]
- Exclusion : $m_\omega \lesssim 200$ GeV

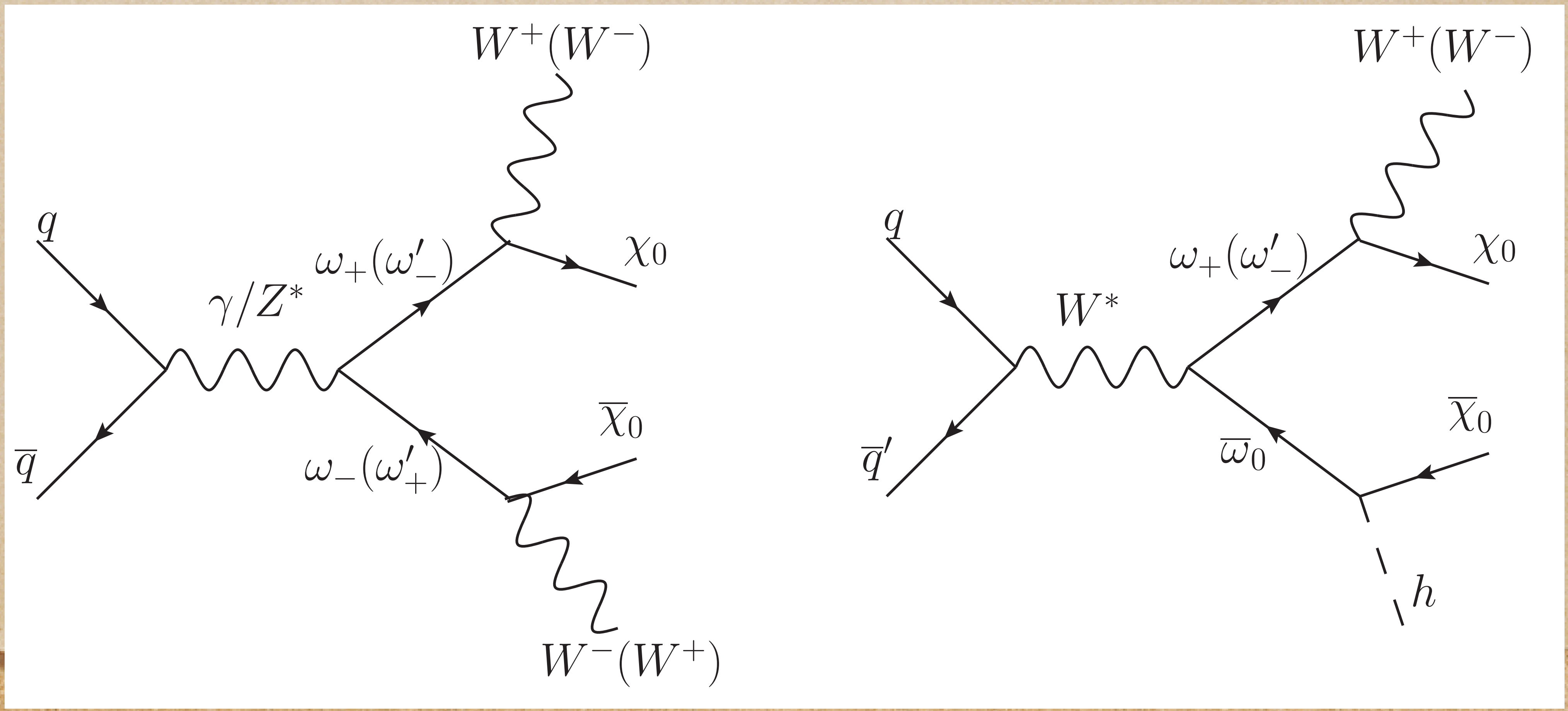


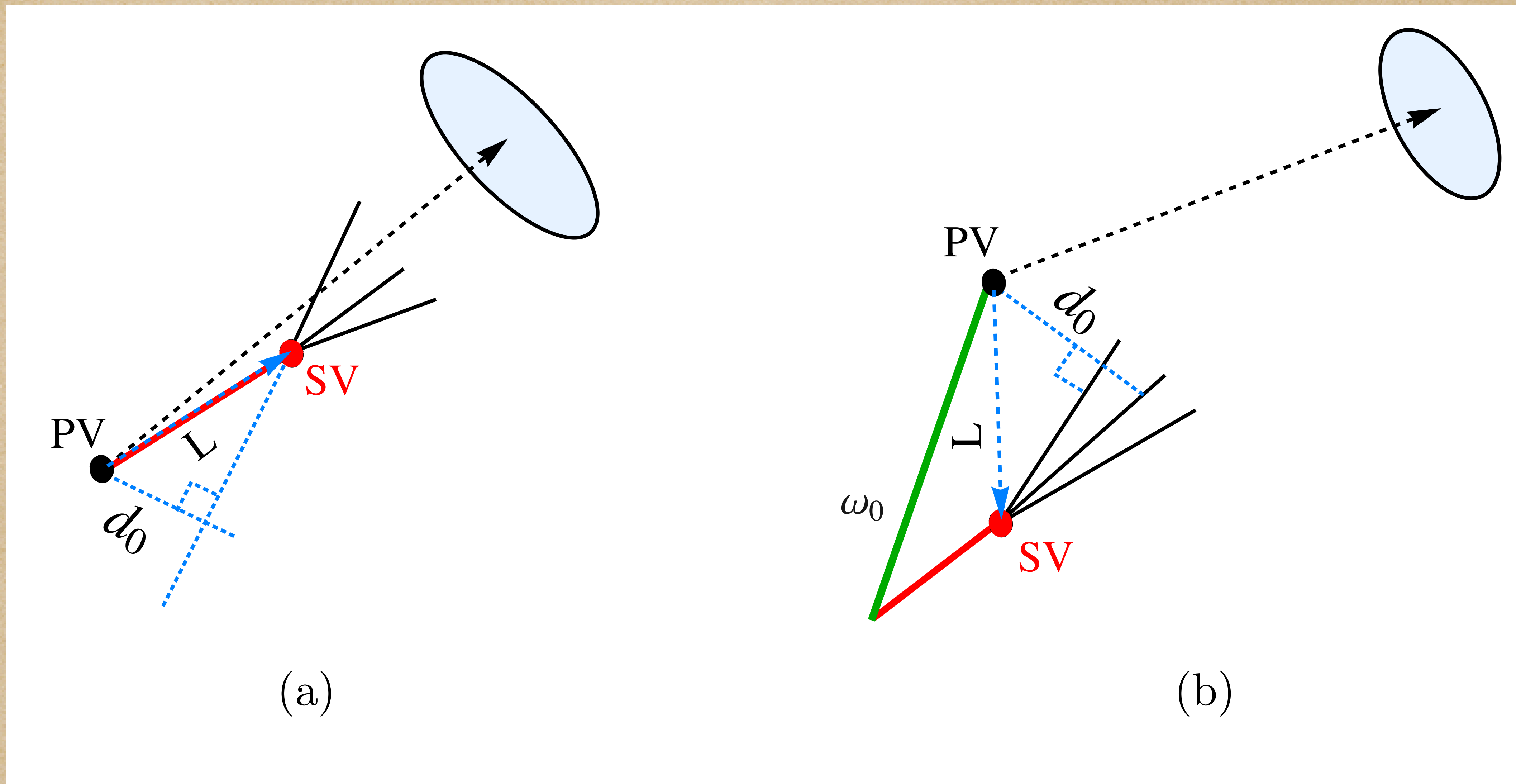
Region (v) : Displaced W h + MET

Prompt W W + MET



- All ω decay to χ_0 in a single step.
- ω_0 lifetime : 0.1-1 mm (phase space suppression) but $\omega_\pm$ prompt.
- Reduced b-tagging efficiency.

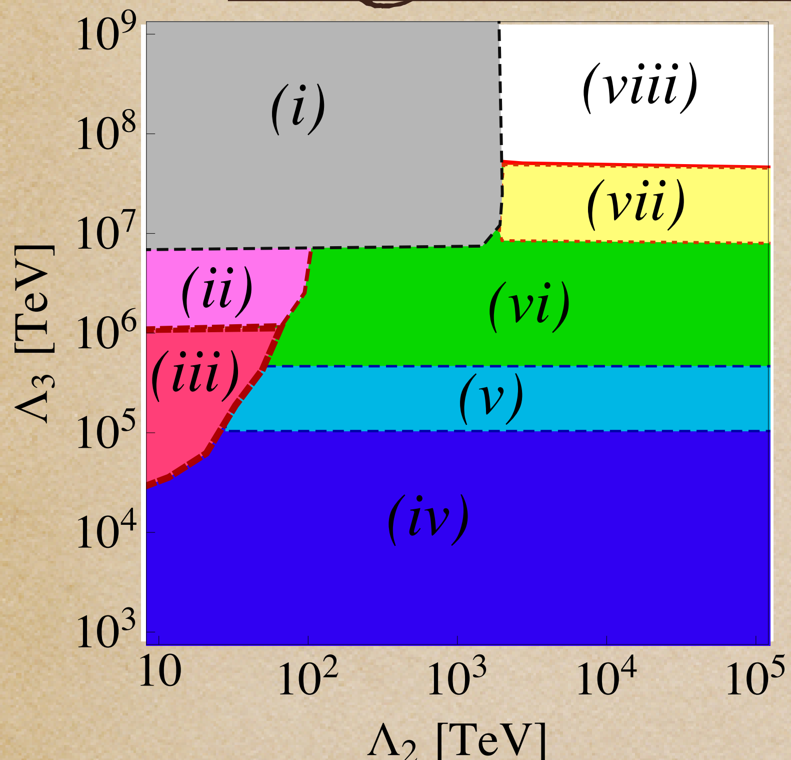




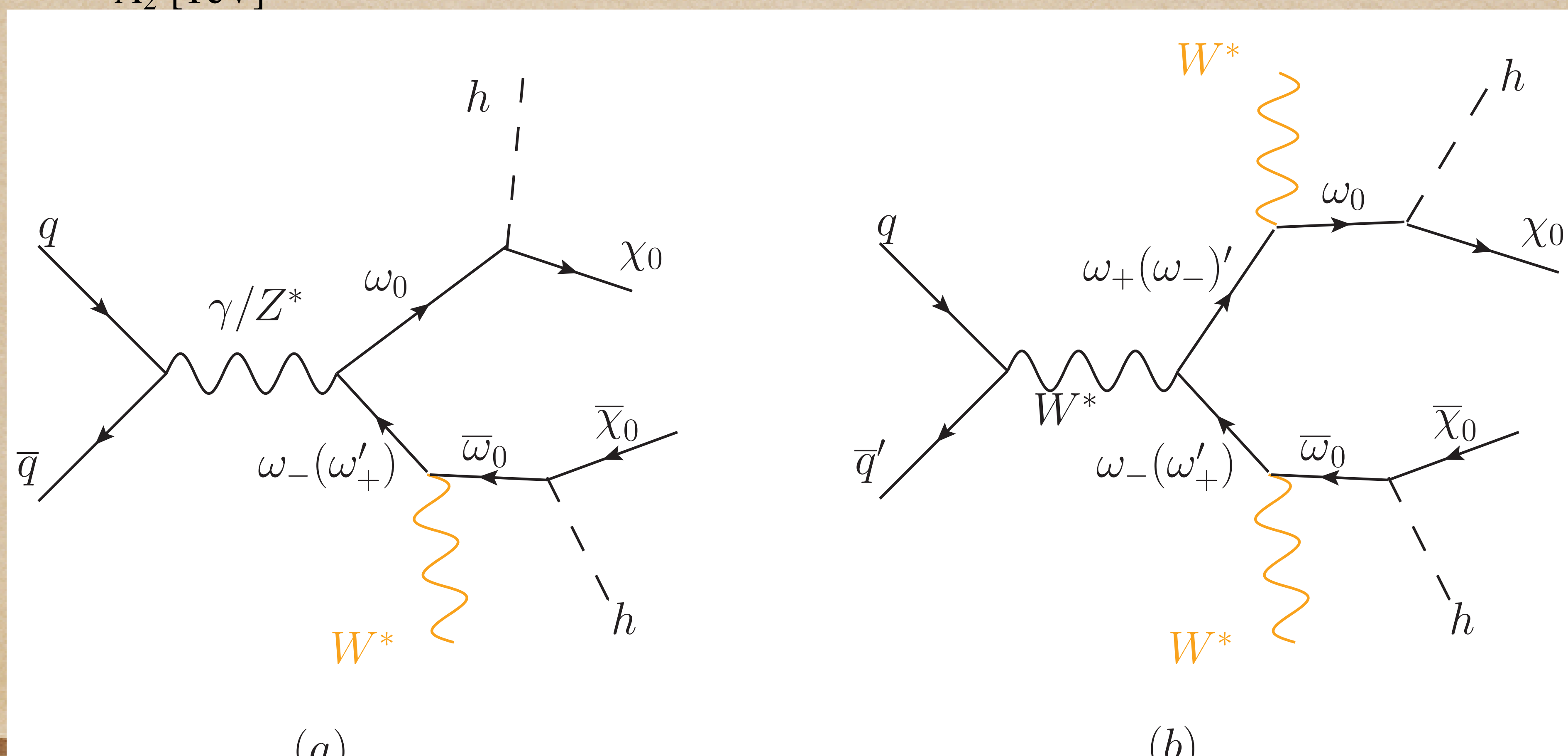
b-tagging for prompt Higgs production.

b-tagging for displaced Higgs production.

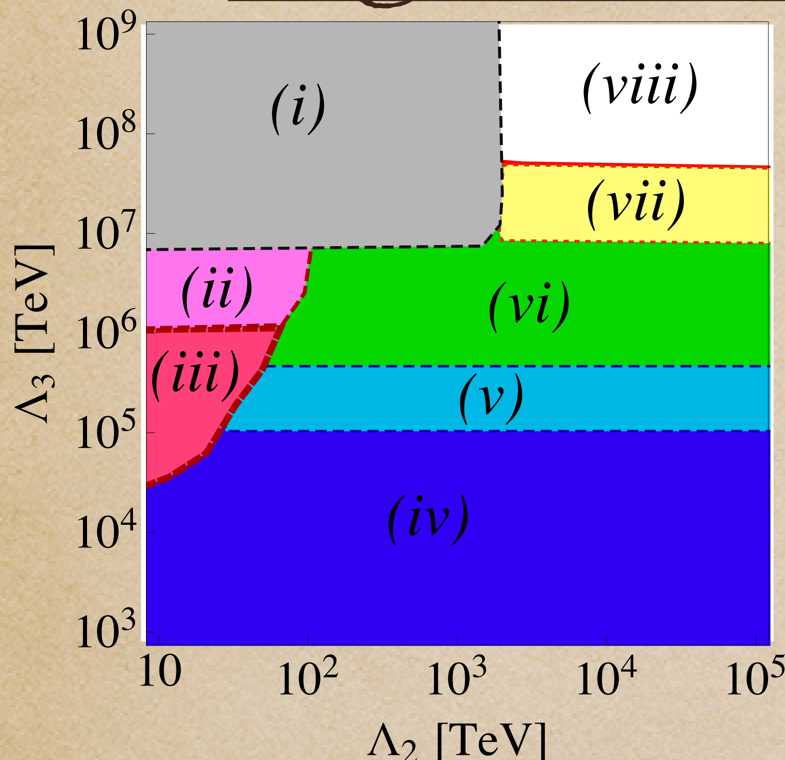
Region (vii) : Displaced h h + MET



- Charged ω decay to ω_0 instead of χ_0.
- Displaced di-Higgs production.



Region (viii) : Pure MET



- This region is sensitive to Monojet + MET, γ/Z/W + MET searches.
- Full 8 TeV data set may exclude this region.