Exotic Higgs decay into displaced heavy neutrinos

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A minimal Z' model

A very common scenario naturally accounting for heavy neutrinos

- Gauge sector

  $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)'$

  the gauged B-L is an appealing example

- Fermion sector

  SM-singlet right-handed neutrinos ν_R

  required by anomaly cancellation

- Scalar sector

  SM-singlet scalar χ

  required by SSB of U(1)'

  provides Majorana masses for ν_R

- New states: *Z' gauge boson, 3 heavy neutrinos, 1 real scalar*
- New parameters:

  $g'_1, \tilde{g}, M_{Z'}, \alpha, m_{H2}, m_{\nu_h}$

$$V(H,\chi) = m_1^2 H^\dagger H + m_2^2 \chi^\dagger \chi + \lambda_1 (H^\dagger H)^2 + \lambda_2 (\chi^\dagger \chi)^2 + \lambda_3 (H^\dagger H)(\chi^\dagger \chi)$$

Heavy neutrino interactions

$$-\mathcal{L} = \underbrace{Y_\nu^{ij}\, \bar{L}^i \tilde{H} \nu_R^j}_{\text{Dirac mass}} + \underbrace{Y_N^{ij} \overline{(\nu_R^i)^c}\, \nu_R^j \chi}_{\text{Majorana mass}} + z_{\nu_R} g'\, \bar{\nu}_R^i \gamma^\mu \nu_R^i\, B'_\mu + \dots$$

- Heavy neutrino interactions with the SM-like and Heavy Higgses

$$\mathcal{L} = -\frac{1}{\sqrt{2}} Y_N^k \left(\sin\alpha\, H_1 + \cos\alpha\, H_2\right) \bar{\nu}_{h_k} \nu_{h_k} \qquad Y_N^k \simeq m_{\nu_k}/(\sqrt{2}x)$$

the complex scalar acts as a portal for heavy neutrino interaction with the SM-like Higgs

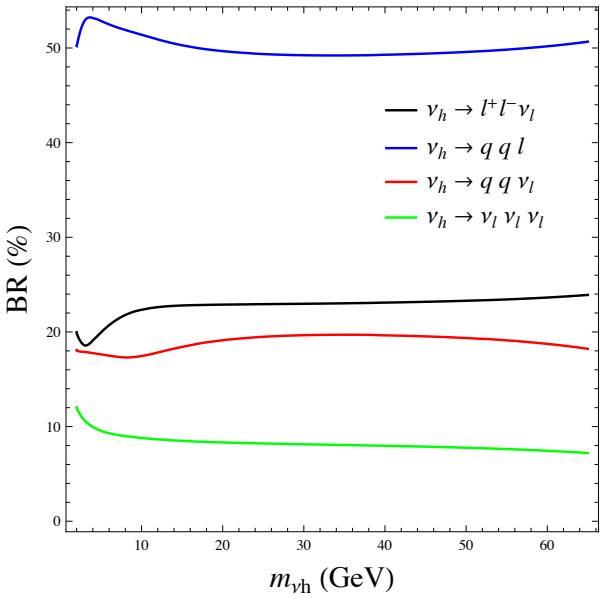
- Heavy neutrino interactions with the SM gauge bosons (typical of type-I seesaw)

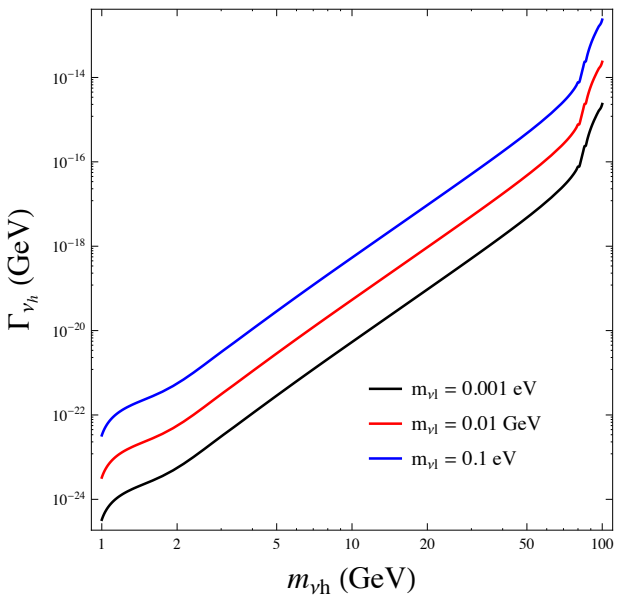
$$\mathcal{L} = \frac{g_2}{\sqrt{2}} V_{\alpha i}\, \bar{l}_\alpha \gamma^\mu P_L \nu_{h_i}\, W_\mu^- + \frac{g_Z}{2\cos\theta_W} V_{\alpha\beta} V_{\alpha i}^*\, \bar{\nu}_{h_i} \gamma^\mu P_L \nu_{l_\beta}\, Z_\mu$$

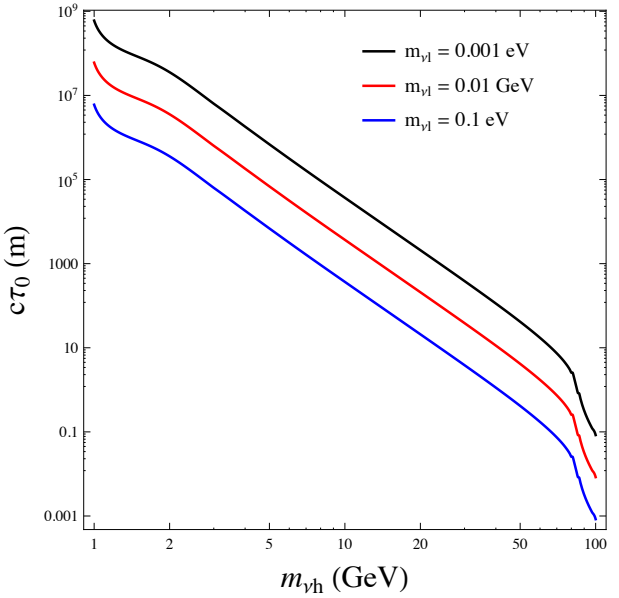
$$V_{\alpha i} \simeq m_D/M \simeq \sqrt{m_{\nu_l}/m_{\nu_h}}$$

- Heavy neutrino interactions with the *Z'* gauge boson

Heavy neutrino: proper decay length







Heavy neutrino (main) decay modes

$$\nu_h \to l^{\pm} W^{\mp *} \qquad \nu_h \to \nu_l Z^*$$

The total decay width can be extremely small due to the smallness of the (gauge) heavy neutrino interactions

$$\Gamma_{\nu_h} \sim |V_{\alpha i}|^2 \, m_{\nu_h}^5, \qquad |V_{\alpha i}|^2 = m_{\nu_l}/m_{\nu_h}$$

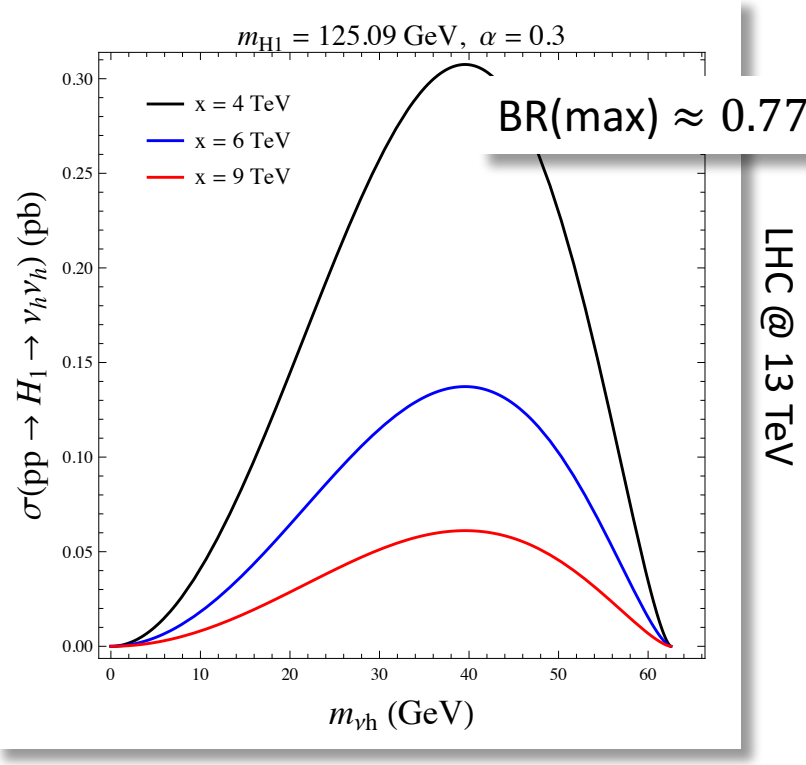
$$\Gamma \sim 10^{-24} - 10^{-14} \text{ GeV}$$

- Long Lived (LL) heavy neutrino for $m_{\nu_h} \lesssim M_Z$
  Displaced vertices appear in the detector (*almost background-free*)
- very LL heavy neutrinos ($m_{\nu_h} \lesssim 15 - 20$ GeV) may also decay outside the detector
- short lived heavy neutrinos for $m_{\nu_h} \gtrsim M_Z$

Heavy neutrinos from the *Exotic SM Higgs decay*

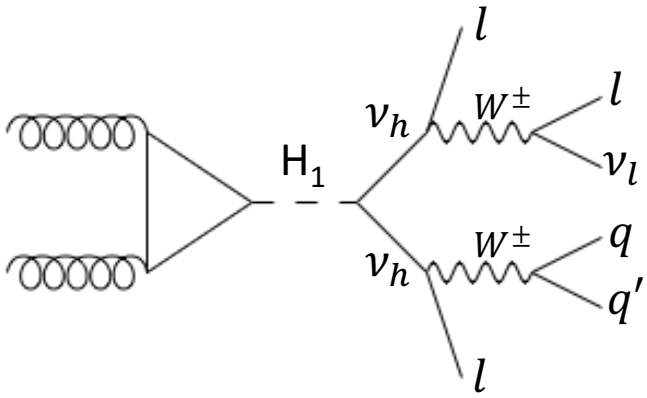
$$\sigma(pp \to H_1 \to \nu_h \nu_h) = \cos^2\alpha\, \sigma(pp \to H_1)_{\rm SM} \frac{\Gamma(H_1 \to \nu_h \nu_h)}{\cos^2\alpha\, \Gamma^{\rm tot}_{\rm SM} + \Gamma(H_1 \to \nu_h \nu_h)}$$

$$\Gamma(H_1 \to \nu_h \nu_h) = \frac{3}{2} \frac{m^2_{\nu_h}}{x^2} \sin^2\alpha \frac{m_{H_1}}{8\pi} \left(1 - \frac{4m^2_{\nu_h}}{m^2_{H_1}}\right)^{3/2}$$

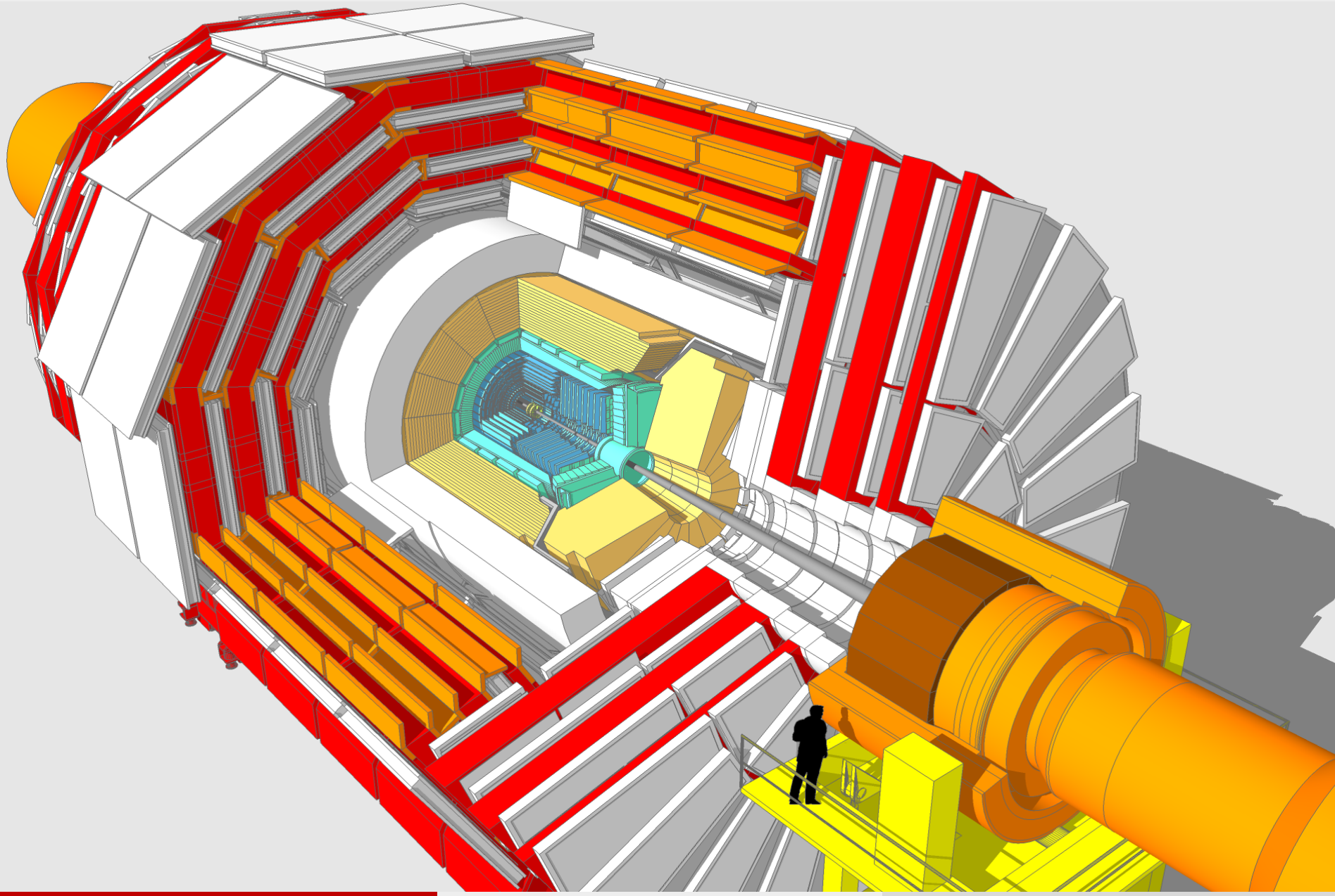


BR(max) ≈ 0.77%

LHC @ 13 TeV



What signatures can we observe?



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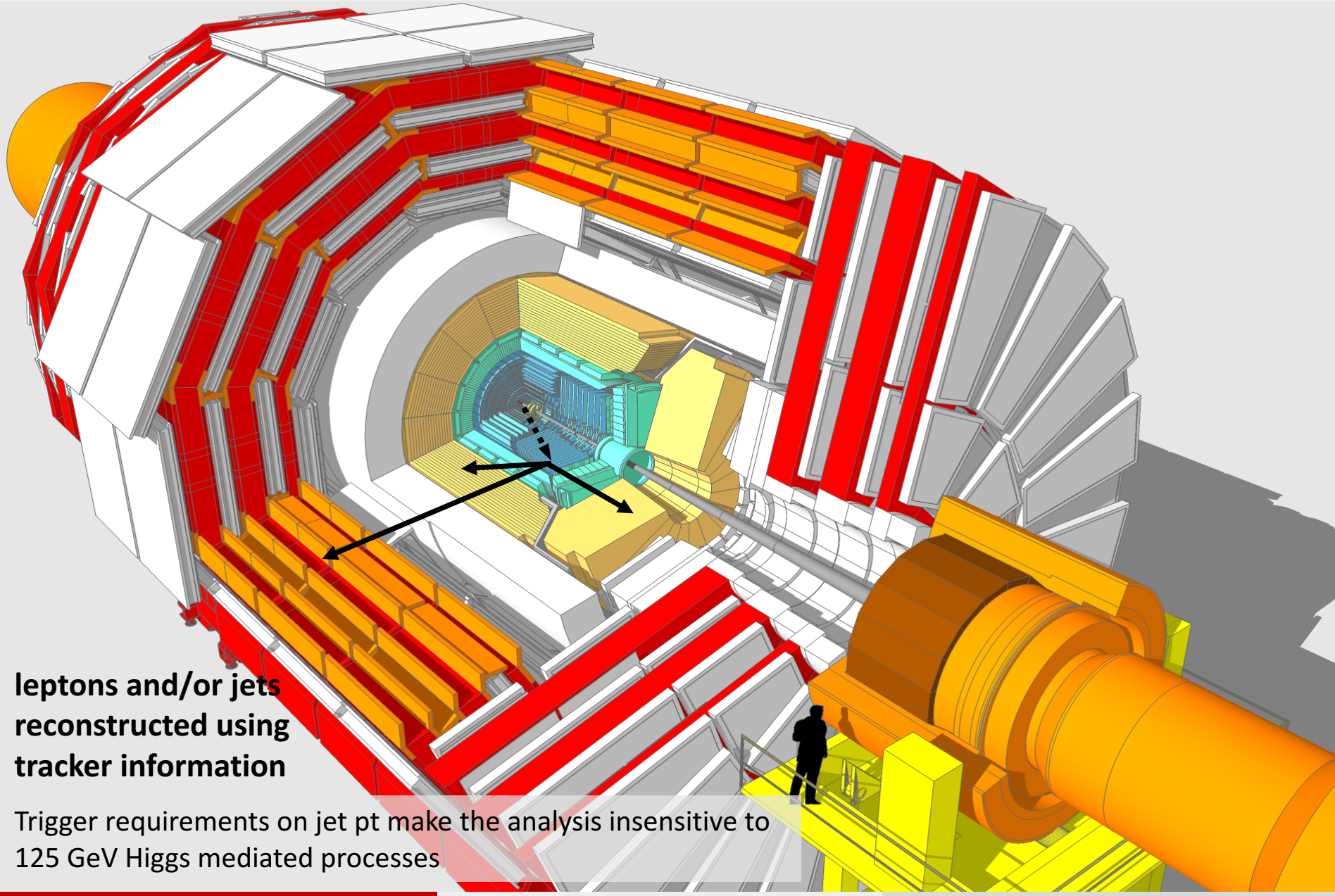
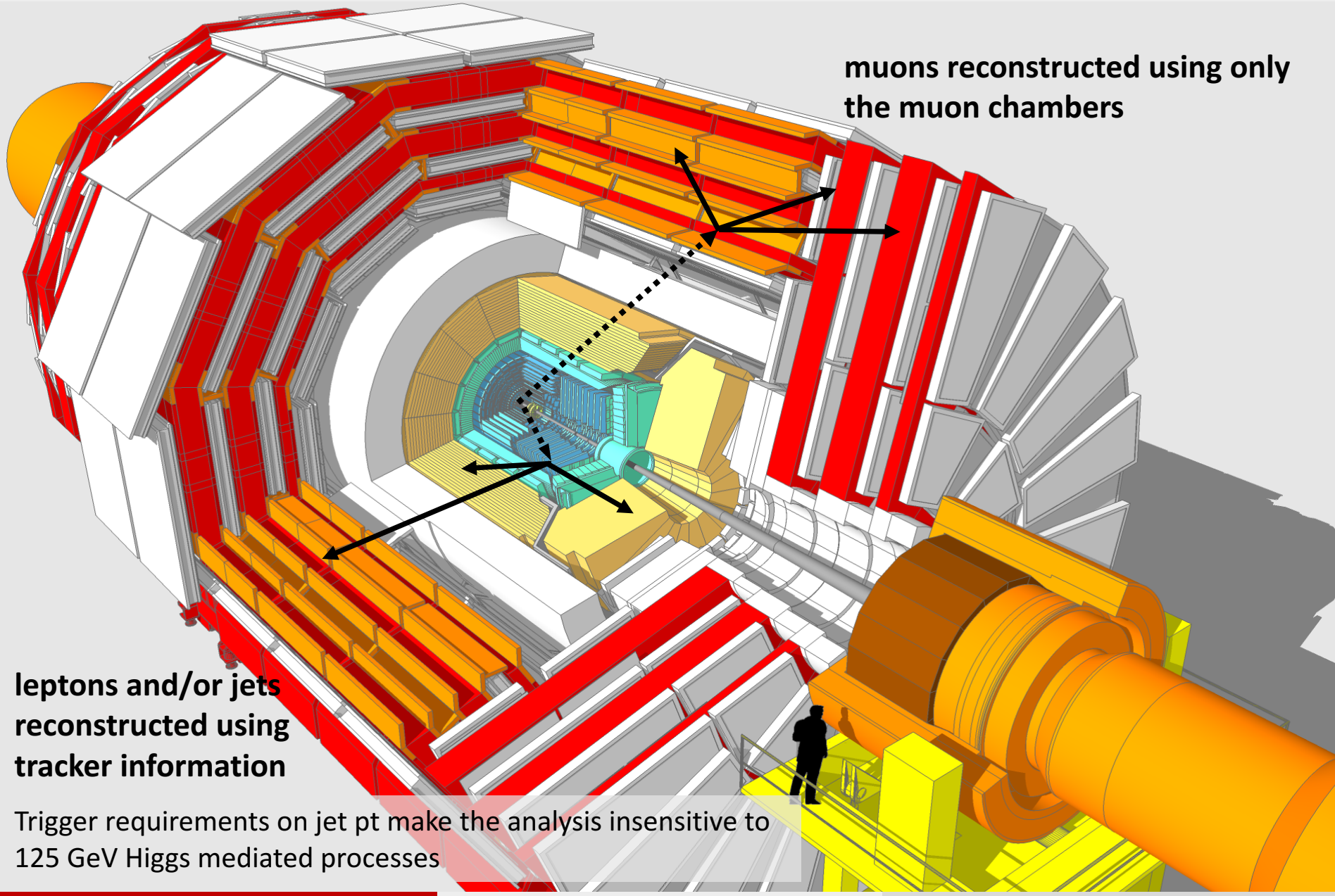


leptons and/or jets reconstructed using tracker information

Trigger requirements on jet pt make the analysis insensitive to 125 GeV Higgs mediated processes

What signatures can we observe?

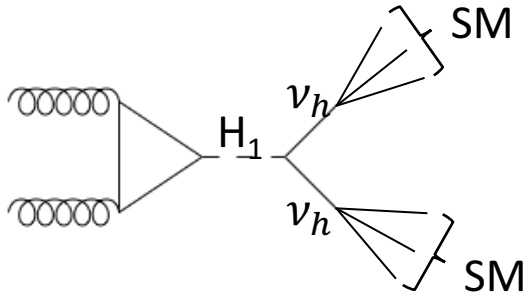


Trigger requirements on jet pt make the analysis insensitive to 125 GeV Higgs mediated processes

Exotic SM Higgs decay: benchmark points

Signatures:

- Displaced muons reconstructed using only the MC
- Displaced leptons reconstructed using the tracker



LO - MC parton level analysis at the LHC at 13 TeV and L = 100 fb^{-1}

	m_{ν_h} (GeV)	$c\tau_0$ (m)	$\sigma_{\nu_h\nu_h}$ (fb)
BP1	40	1.5	332.3
BP2	50	0.5	248.3

parameters comply with Higgs searches (HiggsBounds, HiggsSignals) and Drell-Yan analyses

cross section normalised with σ = 43.92 fb (LHCHXSWG)

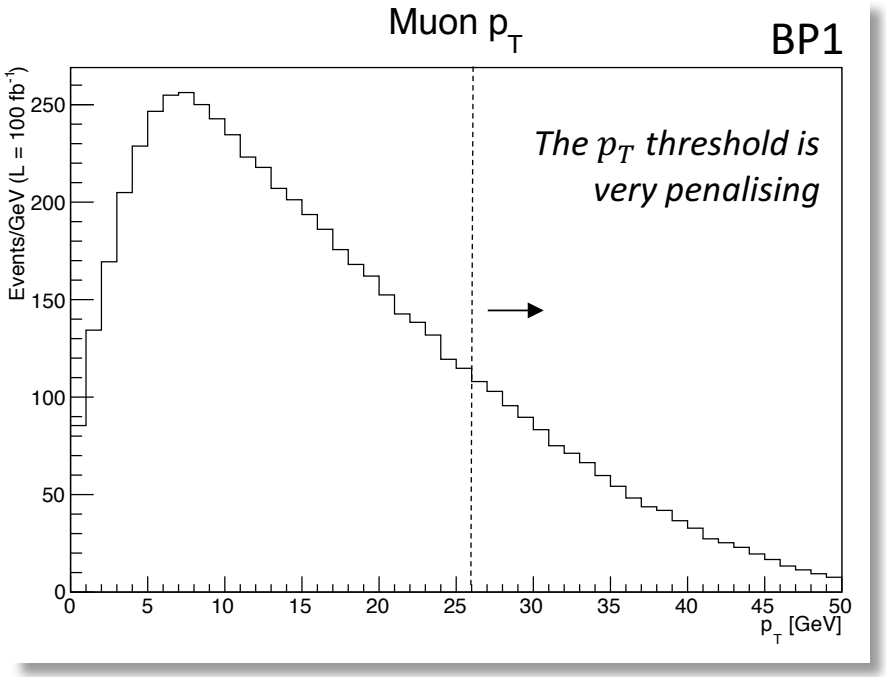
Simulation procedure:

1. generate events with CalcHEP or MadGraph
2. for each event compute the decay length in the lab. $c\tau$ for the two heavy neutrinos
3. randomly sample the distance *L* according to $e^{-x/c\tau}$ distribution
4. using the generated momentum, determine the position of the DV

Event selection – muons in the muon chambers

- $p_T > 26$ GeV for two leading muons, $p_T > 5$ GeV for all the others
- $|\eta| < 2$
- $\Delta R > 0.2$
- $L_{xy} < 5$ m, $L_{xy}/\sigma_{L_{xy}} > 12$ with $\sigma_{L_{xy}} \simeq 3$ cm
- $|d_0|/\sigma_d > 4$ with $\sigma_d \simeq 2$ cm
- $\cos\theta_{\mu\mu} > -0.75$

selection according to CMS PAS EXO-14-012



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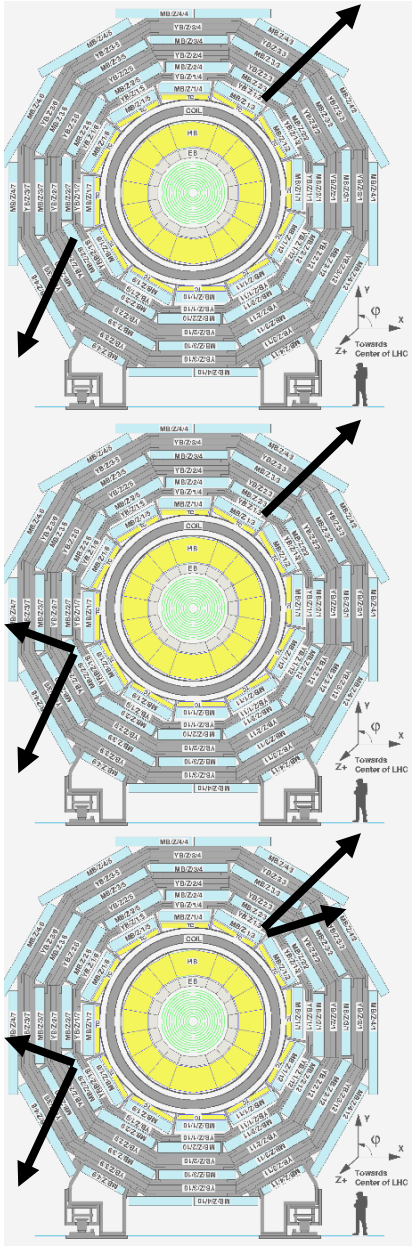
We define three inclusive and disjoint categories: 2μ, 3μ, 4μ

	2 μ	3 μ	4 μ
BP1 (ct_0 = 1.5 m)	29.53	3.91	0.18
BP2 (ct_0 = 0.5 m)	5.02	0.66	0.014

Displaced muons in the muon chambers
LHC 13 TeV L = 100 fb^{-1}



- The "Muon Chamber" analysis is particularly sensitive to bigger ct_0

Event selection and analysis – leptons in the inner tracker

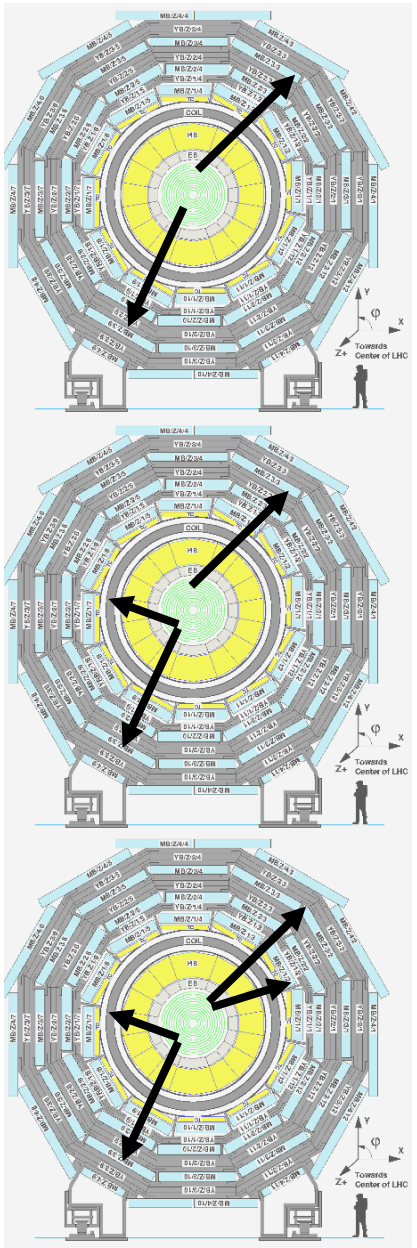
- $p_T > 26$ GeV for two leading muons, $p_T > 5$ GeV for all the others
- $|\eta| < 2$
- $\Delta R > 0.2$
- $0.1\,\mathrm{m} < L_{xy} < 0.5\,\mathrm{m}$
- $|d_0|/\sigma_d > 12$ with $\sigma_d \simeq 20\,\mu\mathrm{m}$
- $\cos\theta_{\mu\mu} > -0.75$

selection according to CMS-B2G-12-024

We define three inclusive and disjoint categories: $2l$, $3l$, $4l$

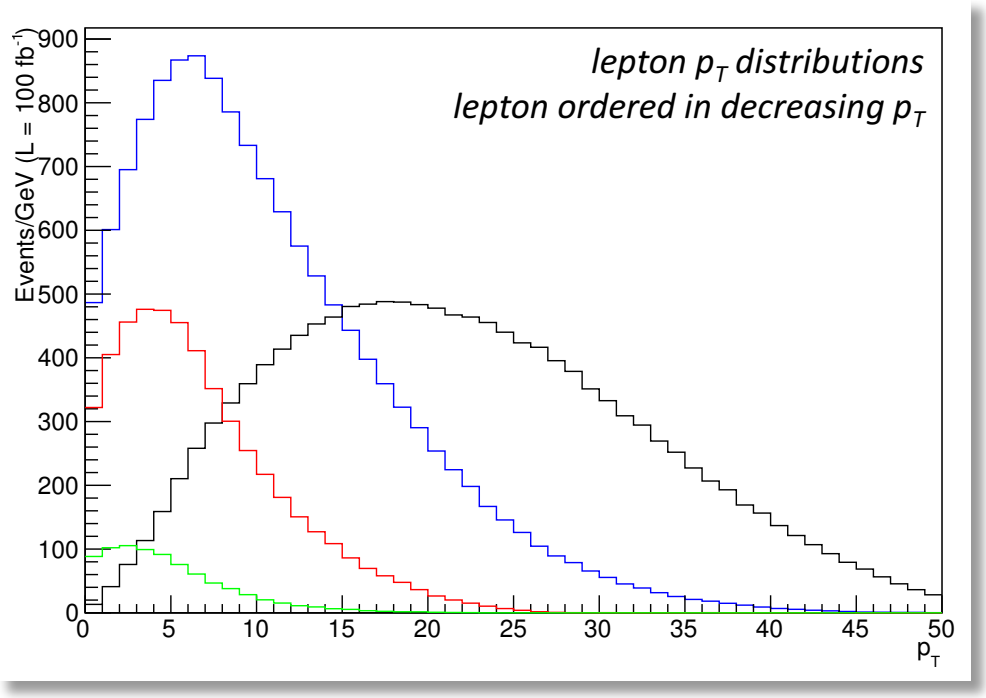
	$2\,l$	$3\,l$	$4\,l$
BP1 (ct_0 = 1.5 m)	9.65	4.64	0.79
BP2 (ct_0 = 0.5 m)	33.16	18.2	2.79

Displaced leptons in the inner tracker
LHC 13 TeV L = 100 fb^{-1}



- The "Inner Tracker" analysis is particularly sensitive to smaller ct_0
- The flavour composition can be easily scrutinised

Comments on tri-lepton triggers



The requirement of a least three leptons can allow for lower thresholds on the lepton transverse momenta

tri-lepton triggers have been extensively used in searches for supersymmetric particles but never employed in the study of displaced vertices

lepton trigger	BP1			BP2		
	$2\,l$	$3\,l$	$4\,l$			
$p_T > 26, 26$ GeV	9.65	4.64	0.79	33.16	18.2	2.79
$p_T > 20, 20, 10$ GeV	-	8.22	1.42	-	38.6	8.11
$p_T > 20, 15, 15$ GeV	-	5.31	1.31	-	27.3	6.94

$p_T > 5$ GeV for any subleading leptons

Conclusions

- *Displaced vertices and tracks are typical signatures of long-lived heavy neutrinos ($m_{\nu_h} \lesssim M_Z$) that can be observed in the (heavy) Higgs decay*

- *"Muon chambers" and "tracker" analyses are complementary and sensitive to different heavy neutrino lifetimes*

- New (soft) physics may be hidden by the trigger thresholds!
  it would be extremely important to develop dedicated triggers