Displaced heavy neutrinos from Higgs decay in abelian extensions of the Standard Model

Luigi Delle Rose

Rutherford Appleton Laboratory and University of Southampton

Higgs as a Probe of New Physics 2017

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E. Accomando, LDR, S. Moretti, E. Olaiya, C. Shepherd-Themistocleous

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The minimal Z′ model

- Z′ naturally arises from many GUT scenarios such as SO(10), E_6, L-R, string-theory constructions, KK theories, etc.
- Interesting phenomenology potentially accessible at colliders:
  Z′ usually accompanied by extra degrees of freedom (seesaw can be implemented)

➤ Gauge sector

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

➤ 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:

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

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

The fermion sector and the seesaw mechanism

$$\mathcal{L}_Y = \mathcal{L}_Y^{SM} - \underbrace{Y_\nu^{ij}\, \overline{L^i}\, \tilde{H}\, \nu_R^j}_{\textit{Dirac mass}} - \underbrace{Y_N^{ij}\, \overline{(\nu_R^i)^c}\, \nu_R^j\, \chi}_{\textit{Majorana mass}} + h.c.$$

The Majorana mass is dynamically generated through SSB

$$\mathcal{M} = \begin{pmatrix} 0 & m_D^T \\ m_D & M \end{pmatrix} \quad \rightarrow \quad \begin{aligned} m_{\nu_l} &\simeq -m_D^T M^{-1} m_D \\ m_{\nu_h} &\simeq M \end{aligned}$$

$$m_D = 1/\sqrt{2}\, v Y_\nu \quad M = \sqrt{2}\, x Y_N$$

Mass spectrum

O(1 TeV)	*Z'*
O(100 GeV)	H_2
125 GeV	H_1
O(10 GeV)	ν_h

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Dirac mass *Majorana mass*

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

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

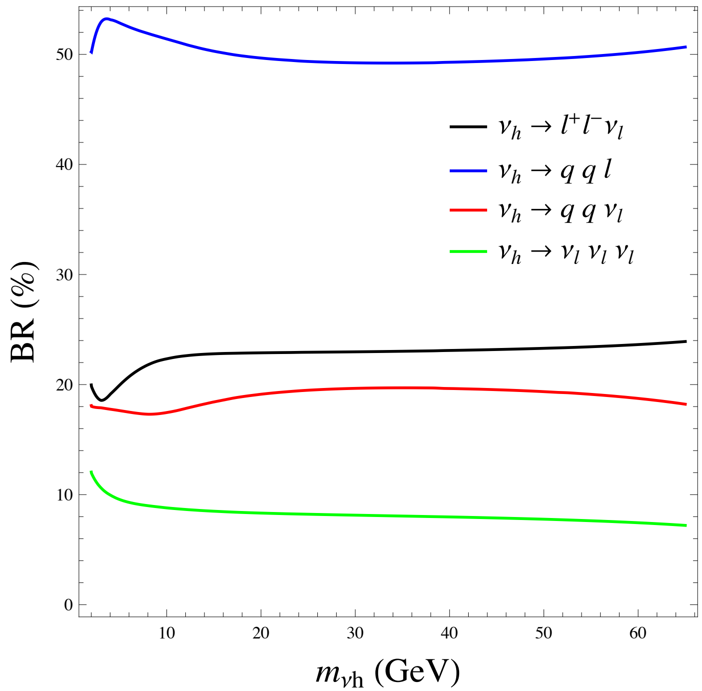
$$V_{\alpha i} \simeq m_D/M \simeq \sqrt{m_{\nu_l}/m_{\nu_h}}$$

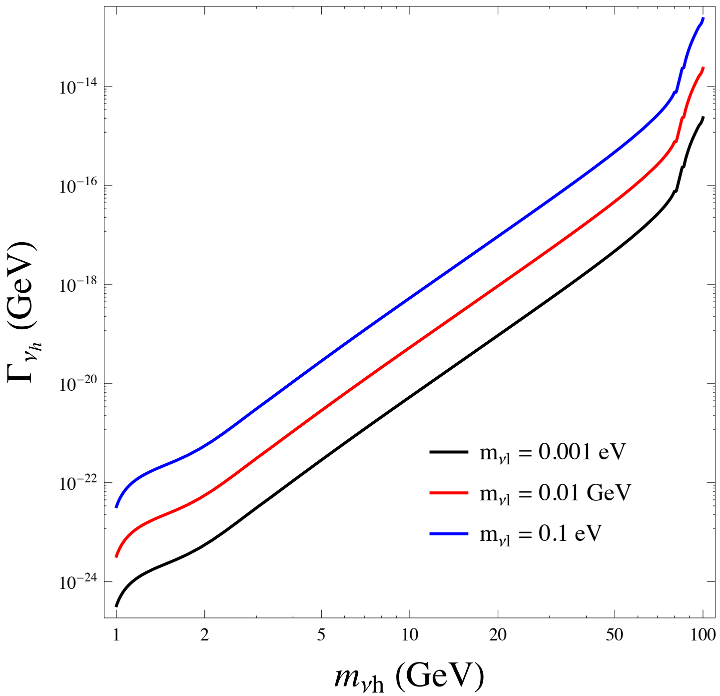
- Heavy neutrino interactions with the SM Higgs field

$$\mathcal{L} = -\frac{1}{\sqrt{2}} Y_N^k \sin\alpha\, H_1\, \bar{\nu}_{h_k} \nu_{h_k} = -g' \frac{m_{\nu_{h,k}}}{M_{Z'}} \sin\alpha\, H_1\, \bar{\nu}_{h_k} \nu_{h_k}$$

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

Heavy neutrino: total decay width and BRs





Heavy neutrino (main) decay modes

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

$$BR(qql) \sim 50\%$$

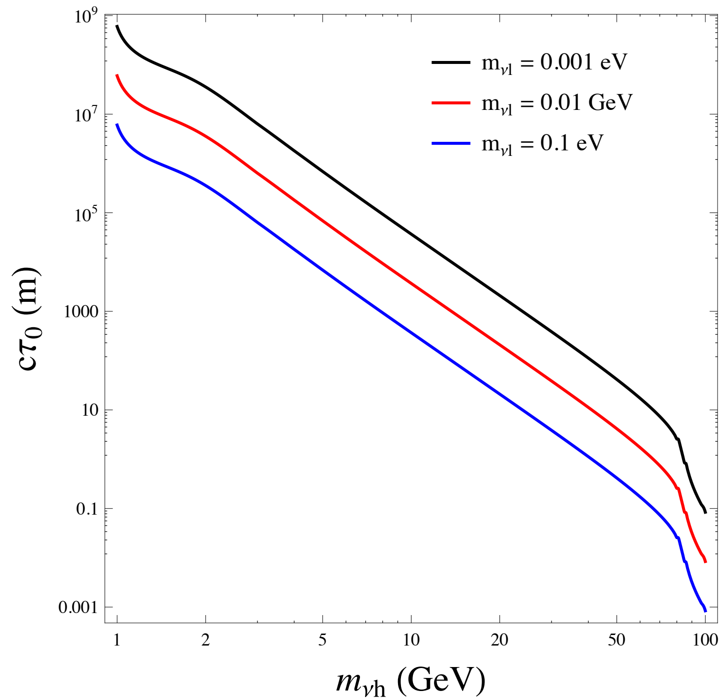
$$BR(ll\nu_l) \sim 21\%$$

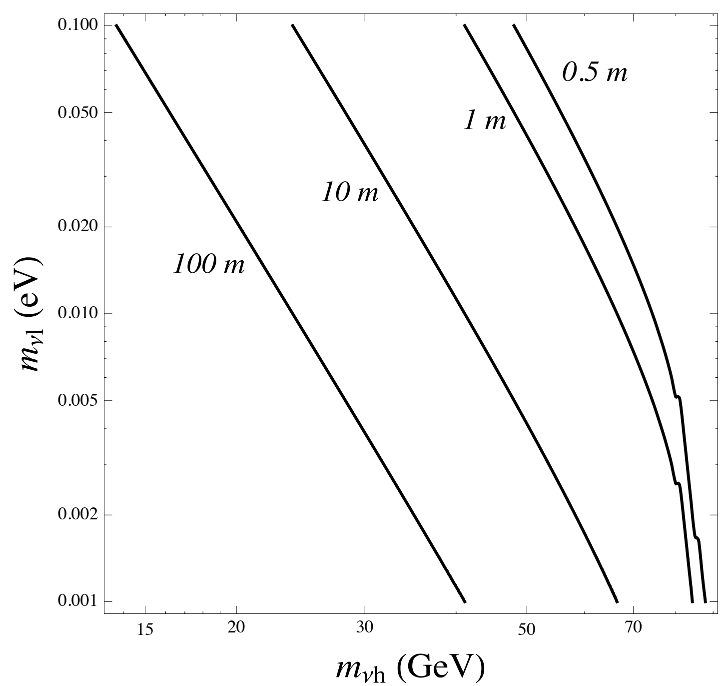
The total decay width can be extremely small due to the smallness of the (gauge) heavy neutrino interactions

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

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

Heavy neutrino: proper decay length





Long Lived (LL) heavy neutrino for $m_{\nu_h} \lesssim 100$ GeV

Displaced vertices appear in the detector

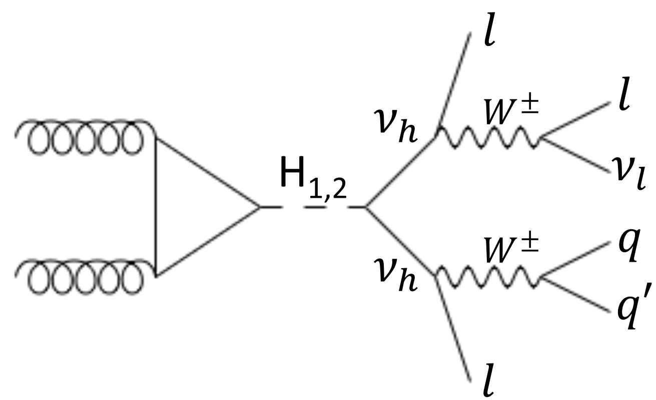
almost background-free

very LL heavy neutrinos ($m_{\nu_h} \lesssim 15 - 20$ GeV) may also decay outside the detector

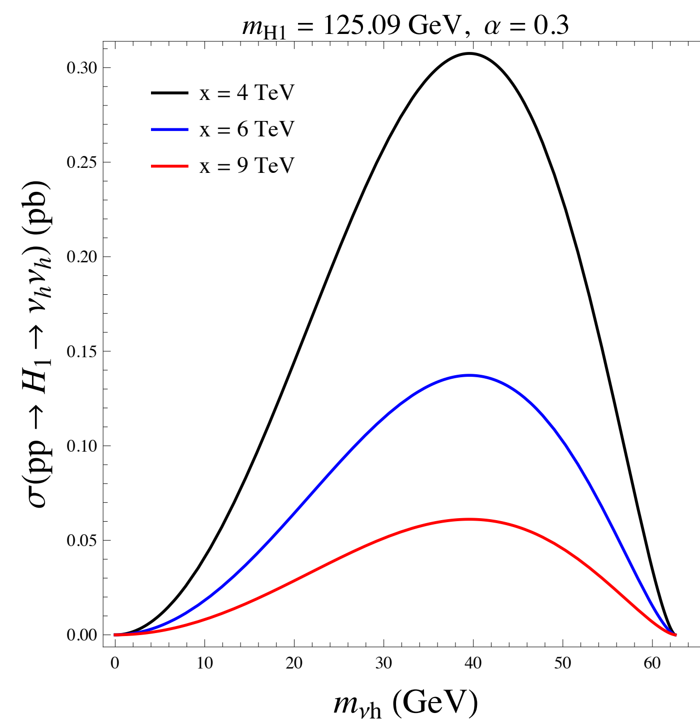
short lived heavy neutrinos for $m_{\nu_h} \gtrsim 100$ GeV

Heavy neutrino: production mechanisms

1. *Heavy neutrino production from the* ***SM-like Higgs***
2. *Heavy neutrino production from the* ***Heavy Higgs***
3. *Heavy neutrino production from the* ***Z'***



LHC @ 13 TeV

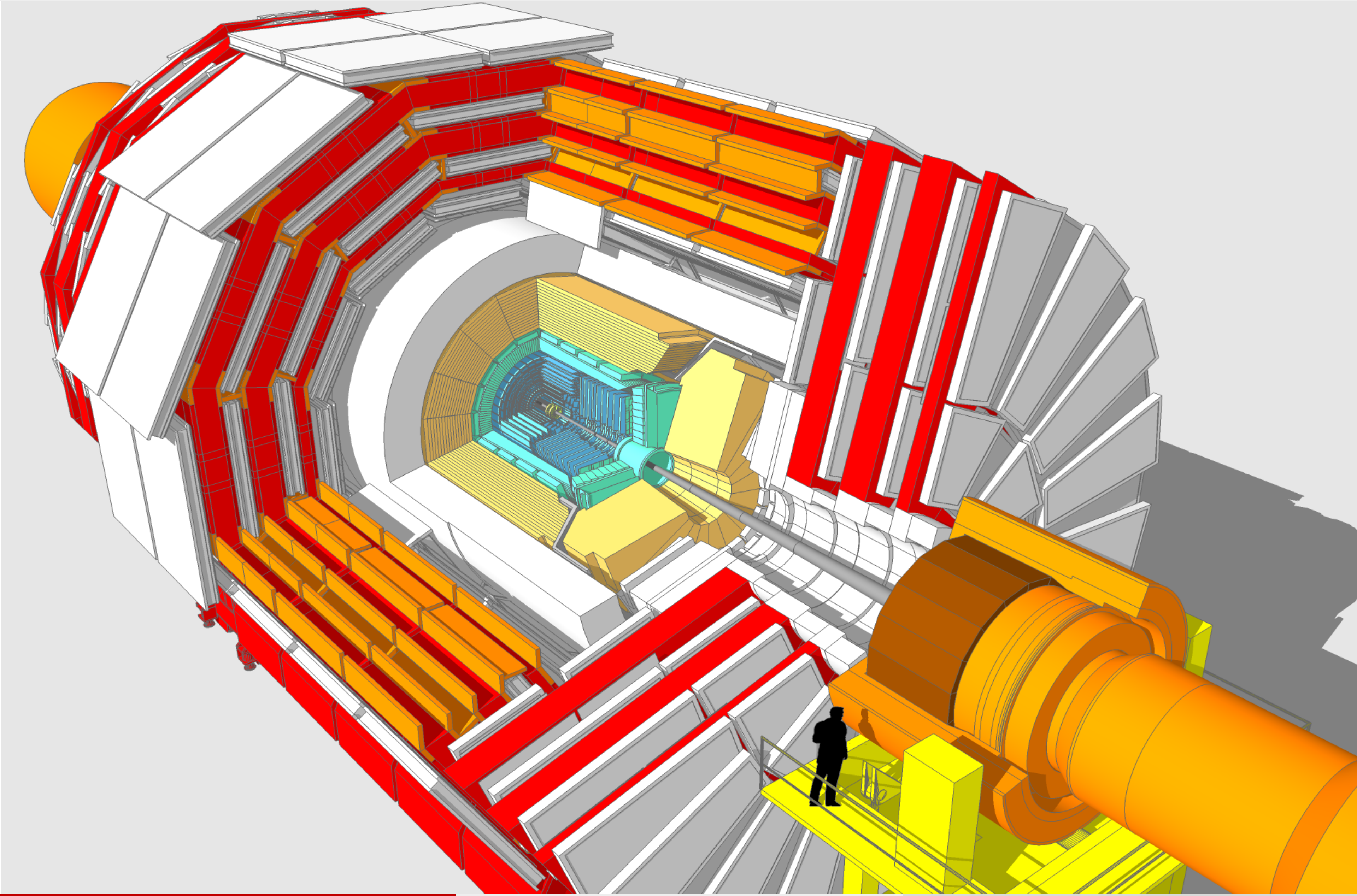


Heavy neutrino production cross section from the SM-like Higgs

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

$$\Gamma(H_1 \to \nu_h\nu_h) = \frac{3}{2}\frac{m^2_{\nu_h}}{x^2}\sin^2\alpha \frac{m_{h_1}}{8\pi}\left(1 - \frac{4 m^2_{\nu_h}}{m^2_{h_1}}\right)^{3/2} \qquad x = M_{Z'}/(2g')$$

What signatures can we observe?



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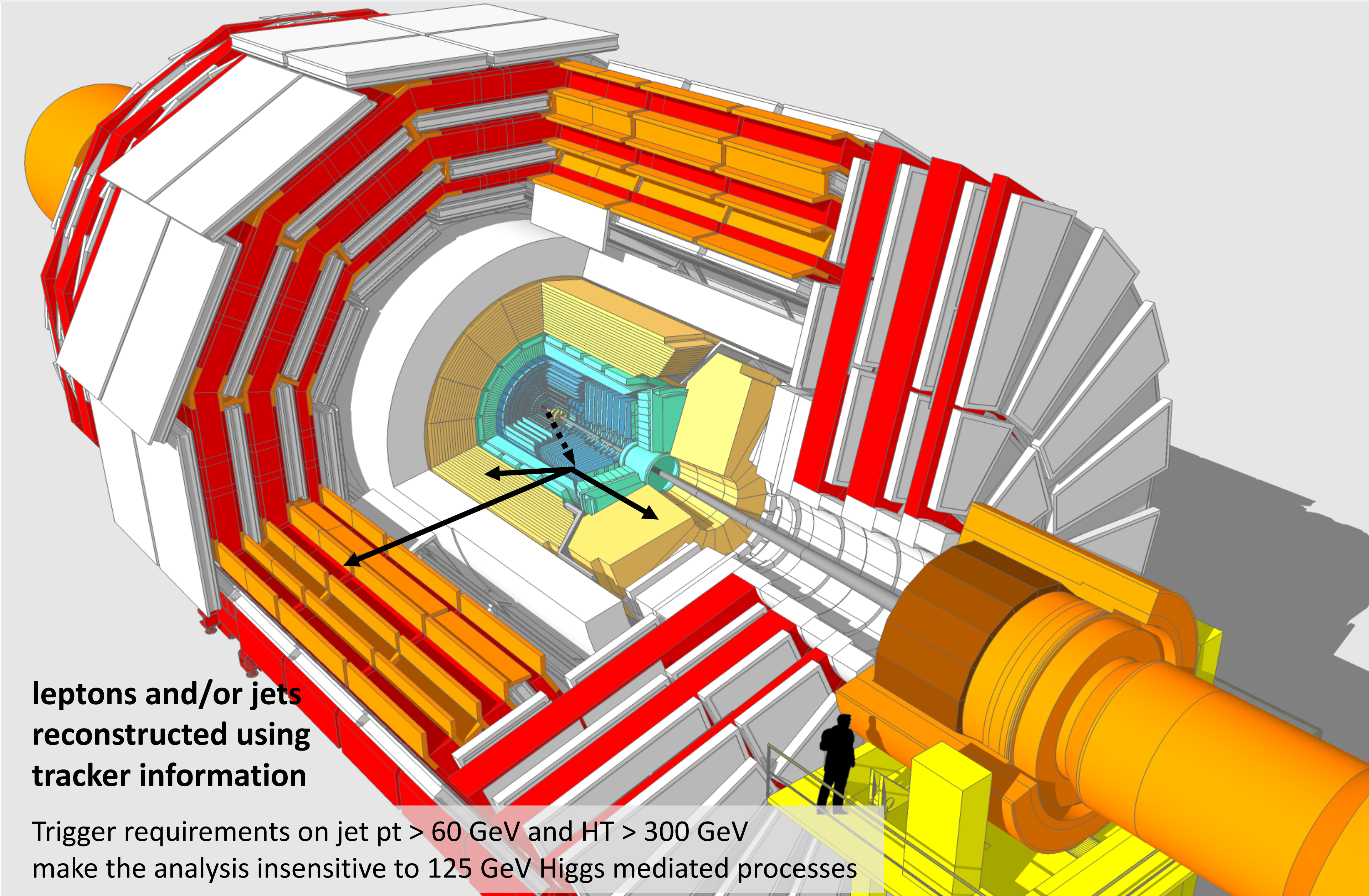

leptons and/or jets reconstructed using tracker information

Trigger requirements on jet pt > 60 GeV and HT > 300 GeV
make the analysis insensitive to 125 GeV Higgs mediated processes

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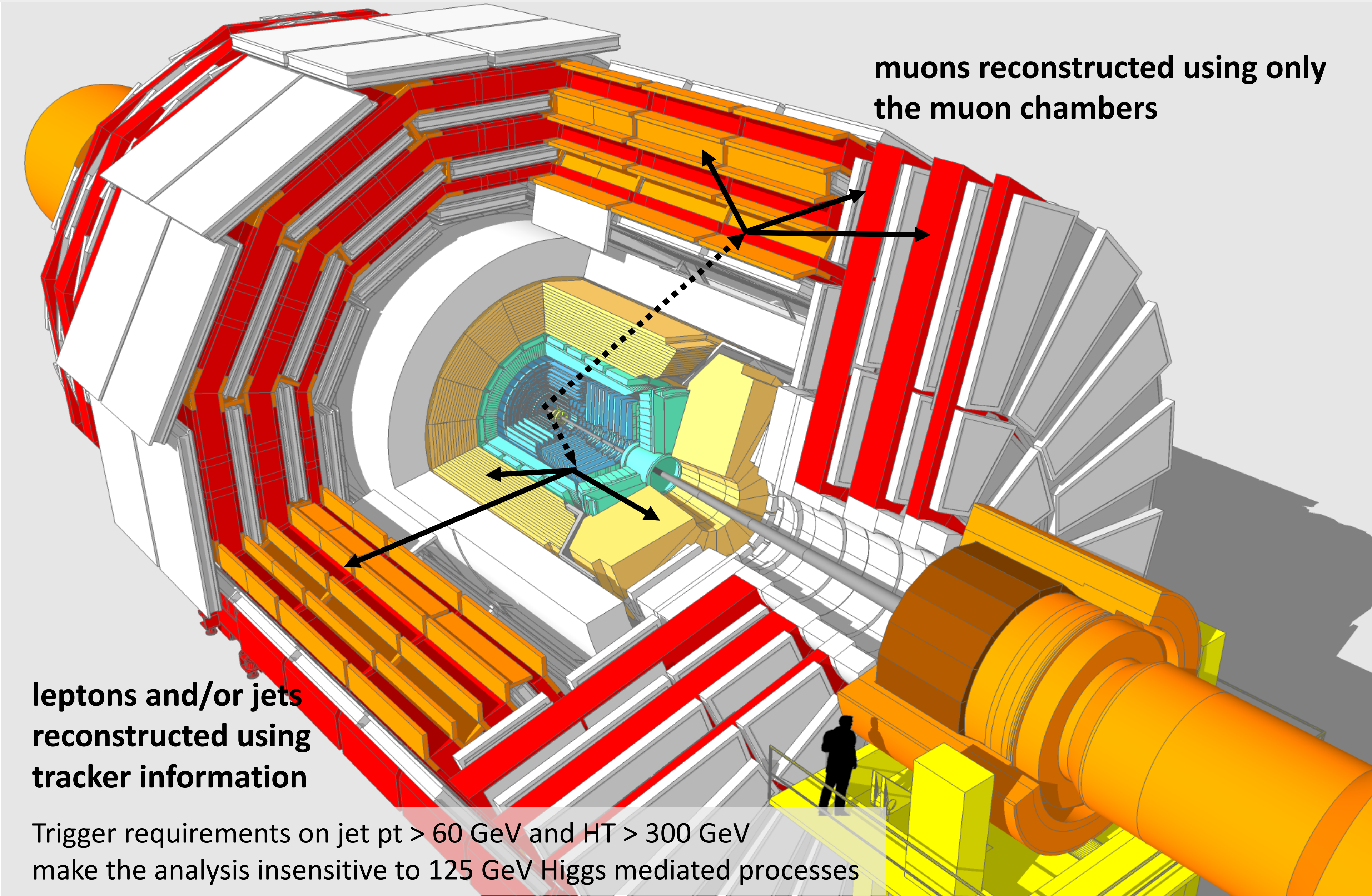

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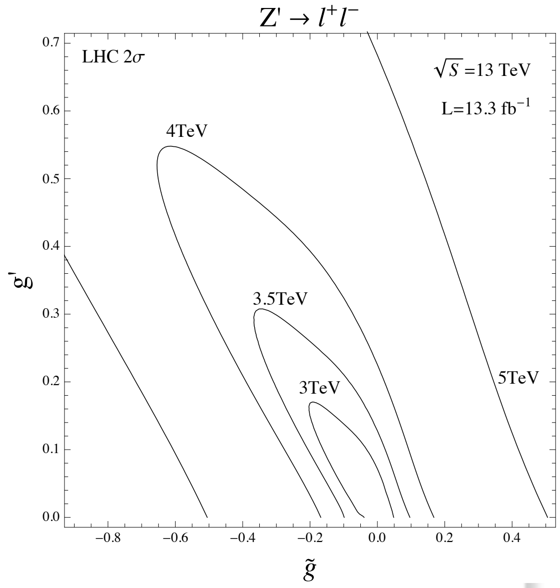
Benchmark points

Benchmark points characterised by long-lived heavy neutrinos

	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

Other parameters: $M_{Z'}$ = 5 TeV, g'_1 = 0.65 and α = 0.3

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



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

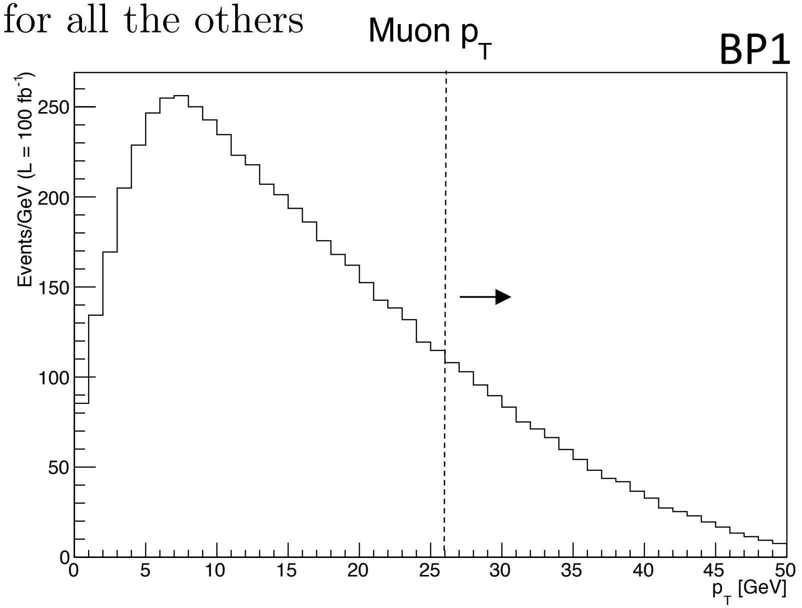
Signatures:

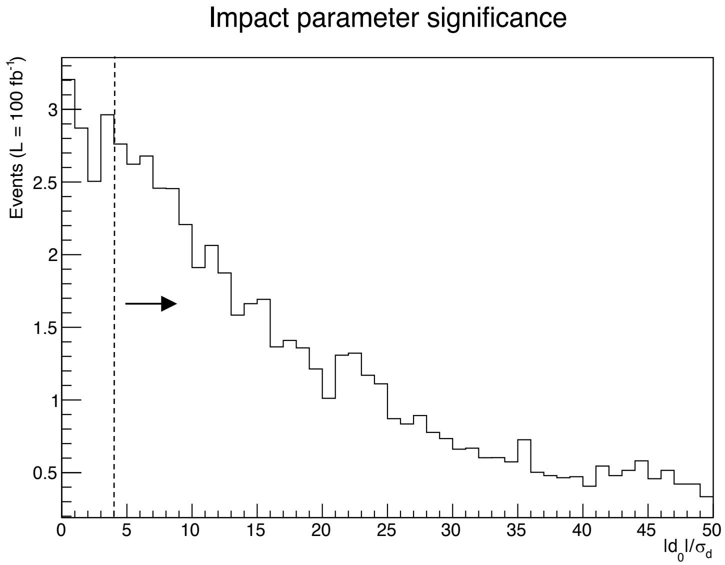
- Displaced muons reconstructed using only the muon chambers
- Displaced leptons reconstructed using the tracker information

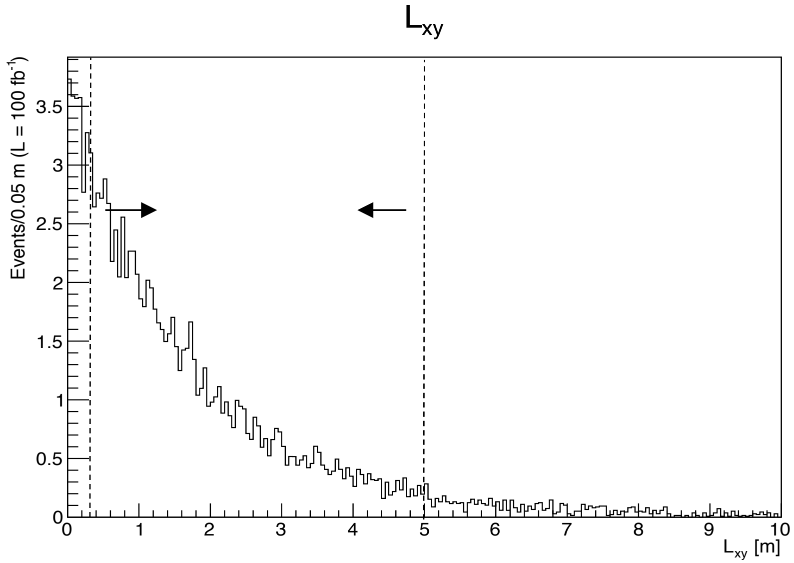
Event analysis – muons in the muon chambers

We require (according to CMS PAS EXO-14-012)

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







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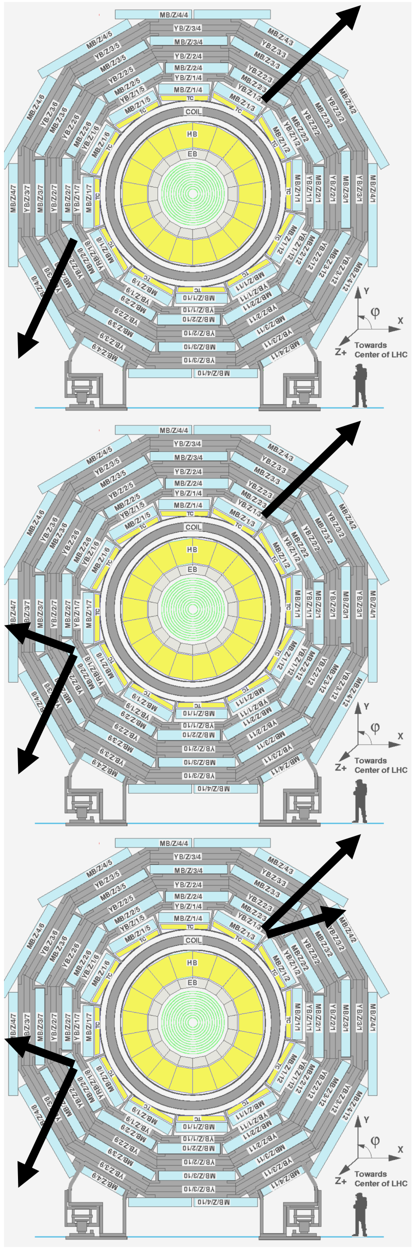
We define three inclusive and disjoint categories: 2μ, 3μ, 4μ

	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 analysis – leptons in the inner tracker

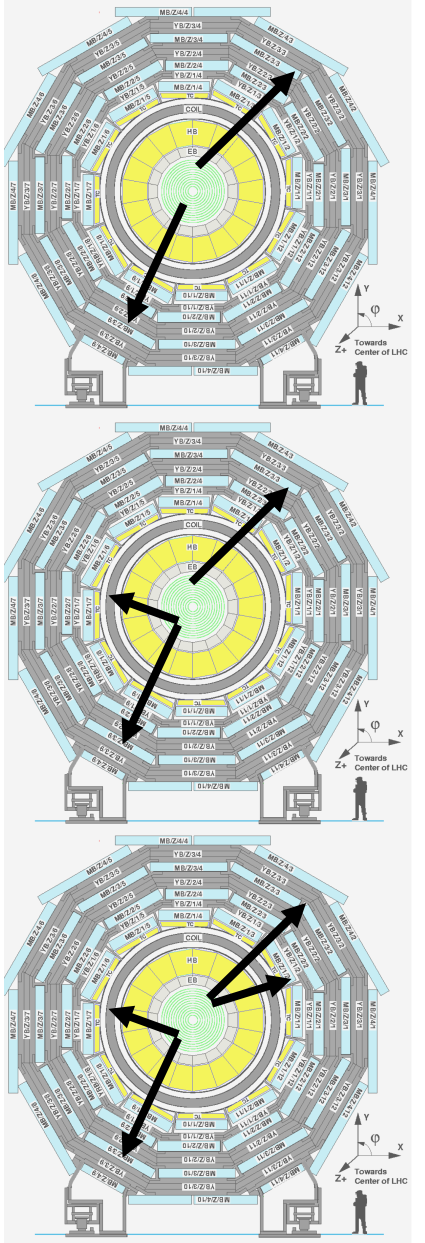
We require (according to CMS-B2G-12-024)

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

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

Conclusions

- Minimal Z’ extensions of the SM
  Z’ gauge boson, heavy scalar and long-lived heavy neutrinos

- The heavy scalar represents a portal to a sizeable heavy neutrino production through the 125 GeV Higgs

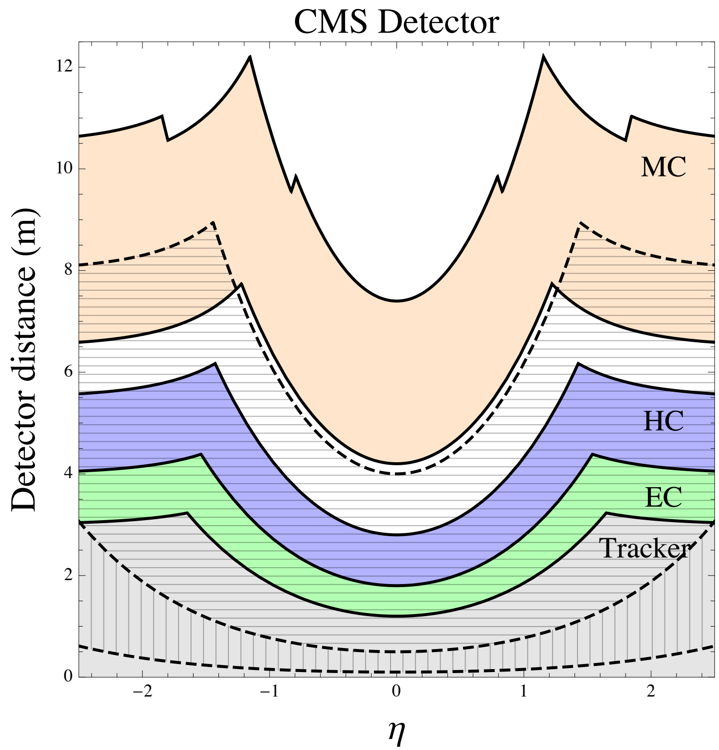
- Long-lived heavy neutrinos provide displaced tracks and vertices in the detectors

- ”Muon chambers” and “tracker” analyses are complementary and sensitive to different heavy neutrino lifetimes

BACKUP

Heavy neutrino: decay probability

Approximate description of the CMS detector



The horizontal (R1) and vertical (R2) hatched areas correspond to optimised regions for DV observations in the muon chambers and tracker respectively

Probability for the heavy neutrinos decaying in the annulus defined by the radial distances $d_1(\eta)$ and $d_2(\eta)$

$$P = \int_{d_1(\eta)}^{d_2(\eta)} dx \frac{1}{c\tau} \exp\left(-\frac{x}{c\tau}\right)$$

$$c\tau = \beta\gamma c\tau_0$$