Displaced vertices from heavy neutrinos in U(1)' models

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Outline

1. U(1)’ extensions and the seesaw

2. Anatomy of heavy neutrinos: decay and production mechanisms

3. Displaced vertices and tracks from heavy neutrinos

4. Results of a Monte Carlo simulation

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)
- Possibility to explain baryogenesis through resonant leptogenesis

➢ 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:

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

The fermion sector and the seesaw mechanism

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

The Majorana mass is dynamically generated through SSB

$$\mathcal{M} = \begin{pmatrix} 0 & m_D^T \\ m_D & M \end{pmatrix}$$

$$m_D = 1/\sqrt{2}\,vY_\nu \quad M = \sqrt{2}\,xY_N$$

$$m_{\nu_l} \simeq -m_D^T M^{-1} m_D$$

$$m_{\nu_h} \simeq M$$

Mass spectrum

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

The fermion sector and the seesaw mechanism

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

Dirac mass *Majorana mass*

The Majorana mass is dynamically generated through SSB

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

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

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

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

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

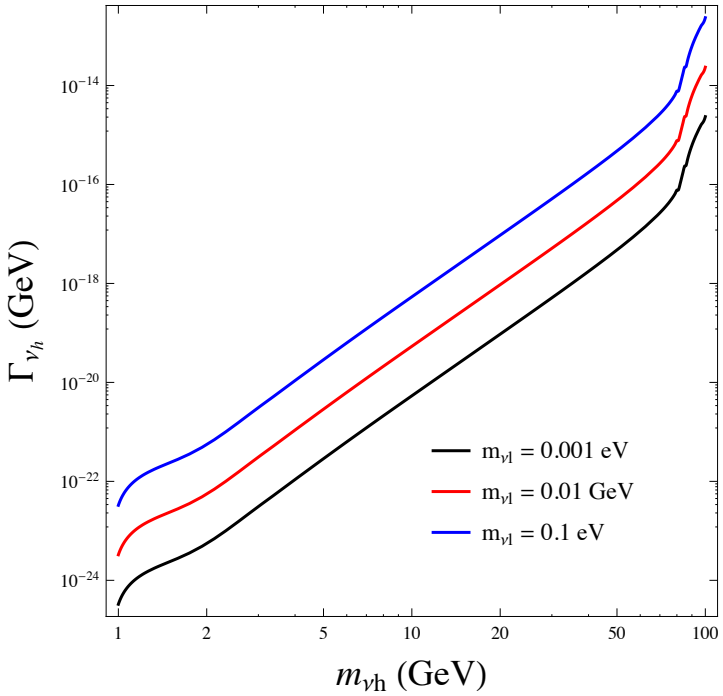
Heavy neutrino interactions with the SM Higgs field

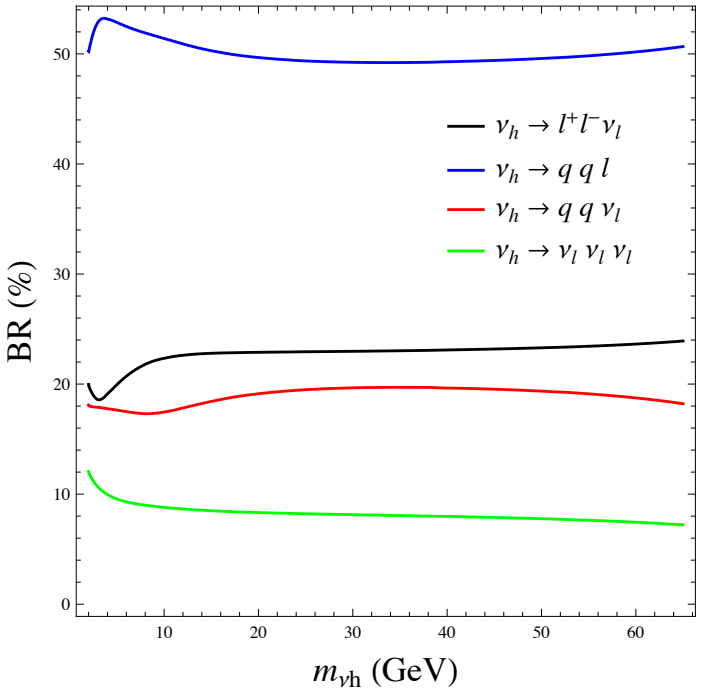
$$\mathcal{L} = -\frac{1}{\sqrt{2}} Y_N^k \sin\alpha\, H_1\, \bar{\nu}_{h_k} \nu_{h_k} = -g' \frac{m_{\nu_{h,k}}}{M_{Z'}} \sin\alpha\, H_1\, \bar{\nu}_{h_k} \nu_{h_k}$$

Mass spectrum

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

Heavy neutrino: total decay width and BRs





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

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

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

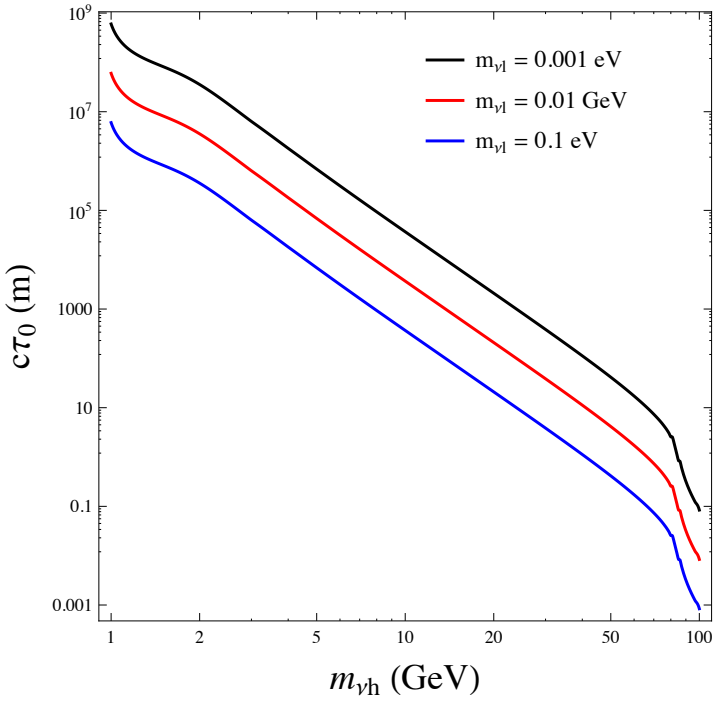
Heavy neutrino (main) decay modes

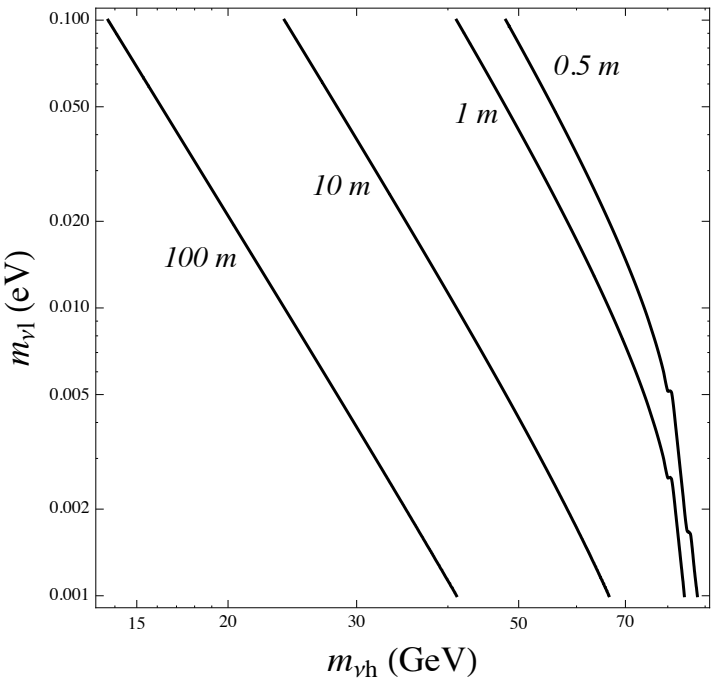
$$\nu_h \to l^{\pm} W^{\mp *} \qquad \nu_h \to \nu_l Z^*$$

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

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

Heavy neutrino: proper decay length





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

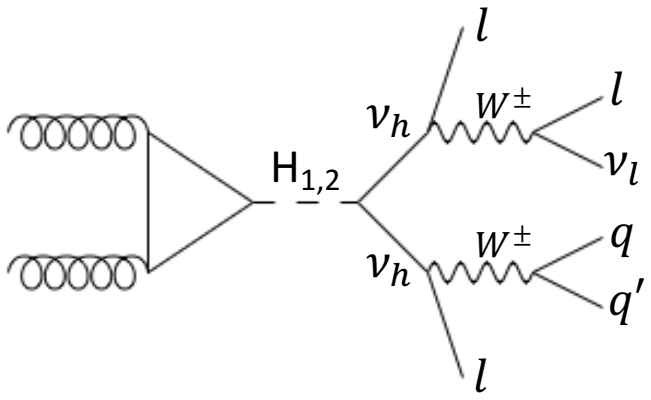
Displaced vertices appear in the detector

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 Higgs
2. Heavy neutrino production from the Heavy Higgs

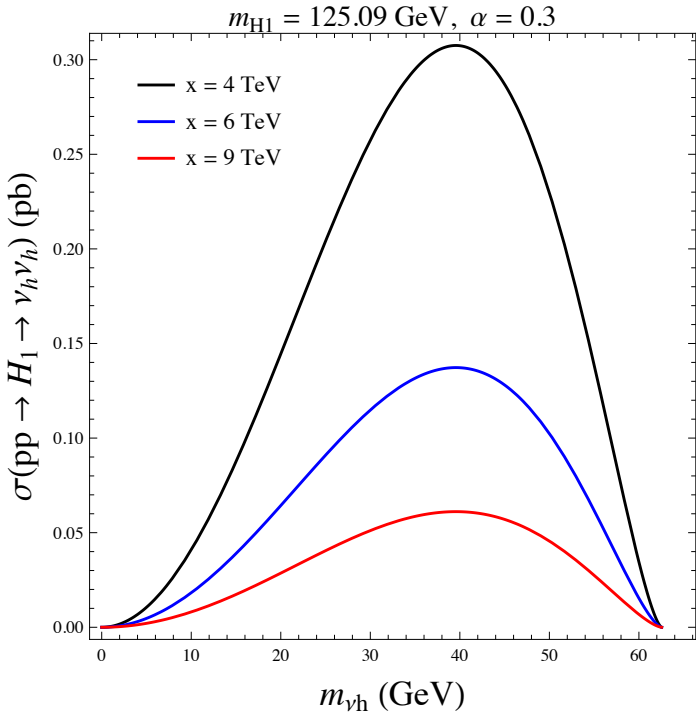


LHC @ 13 TeV

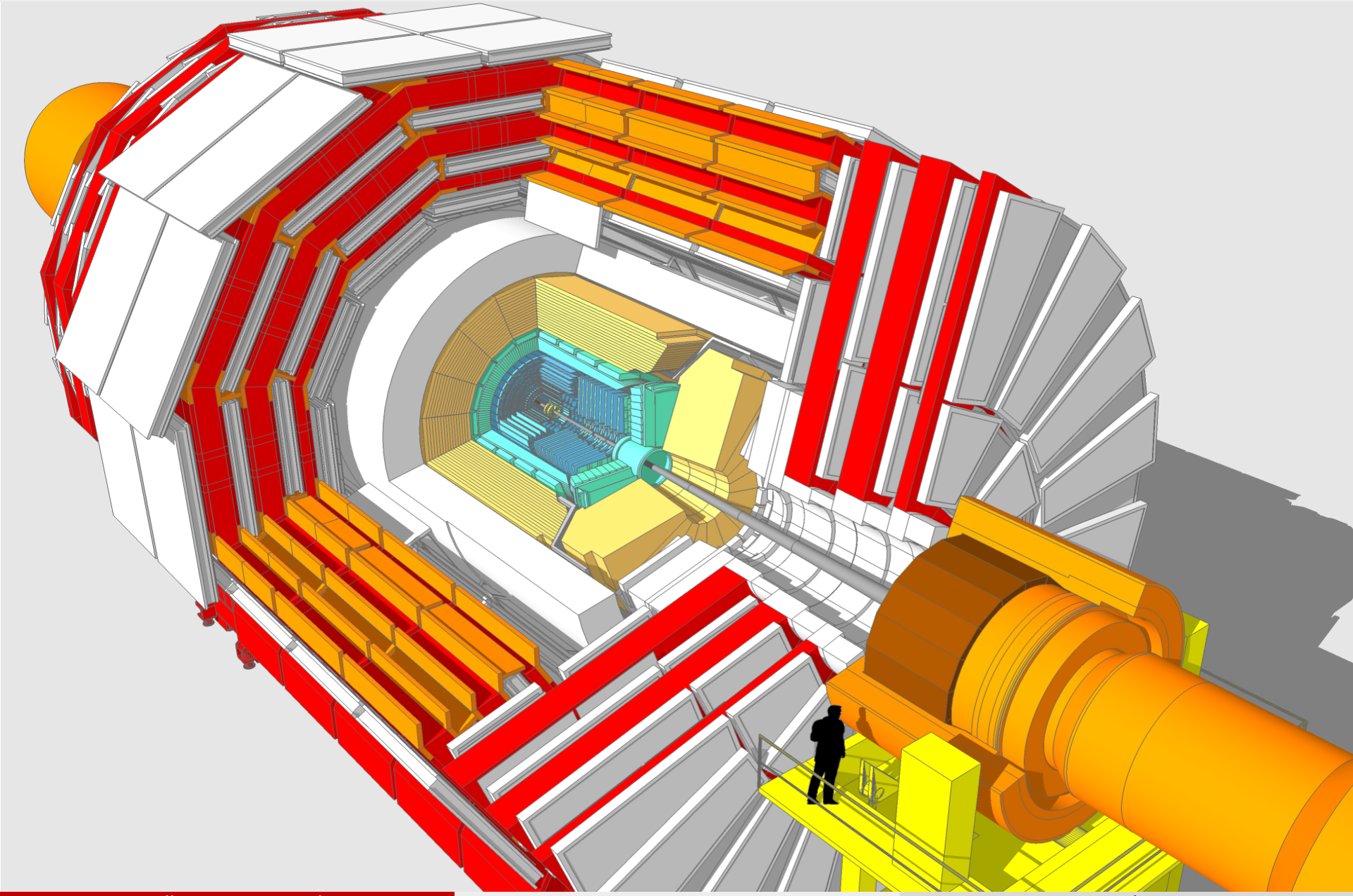
Heavy neutrino production cross section from the SM Higgs

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

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



What signatures can we observe?



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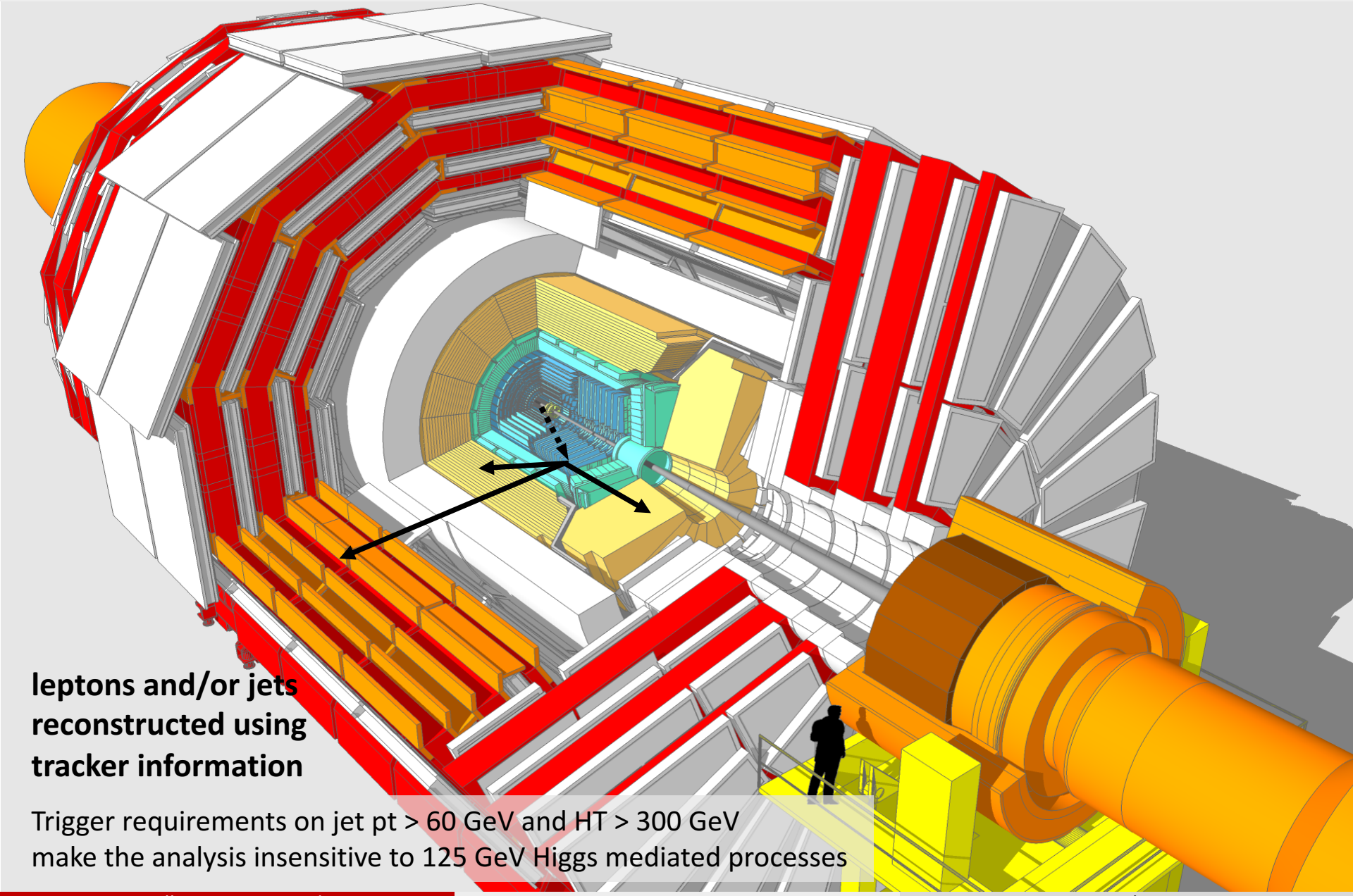
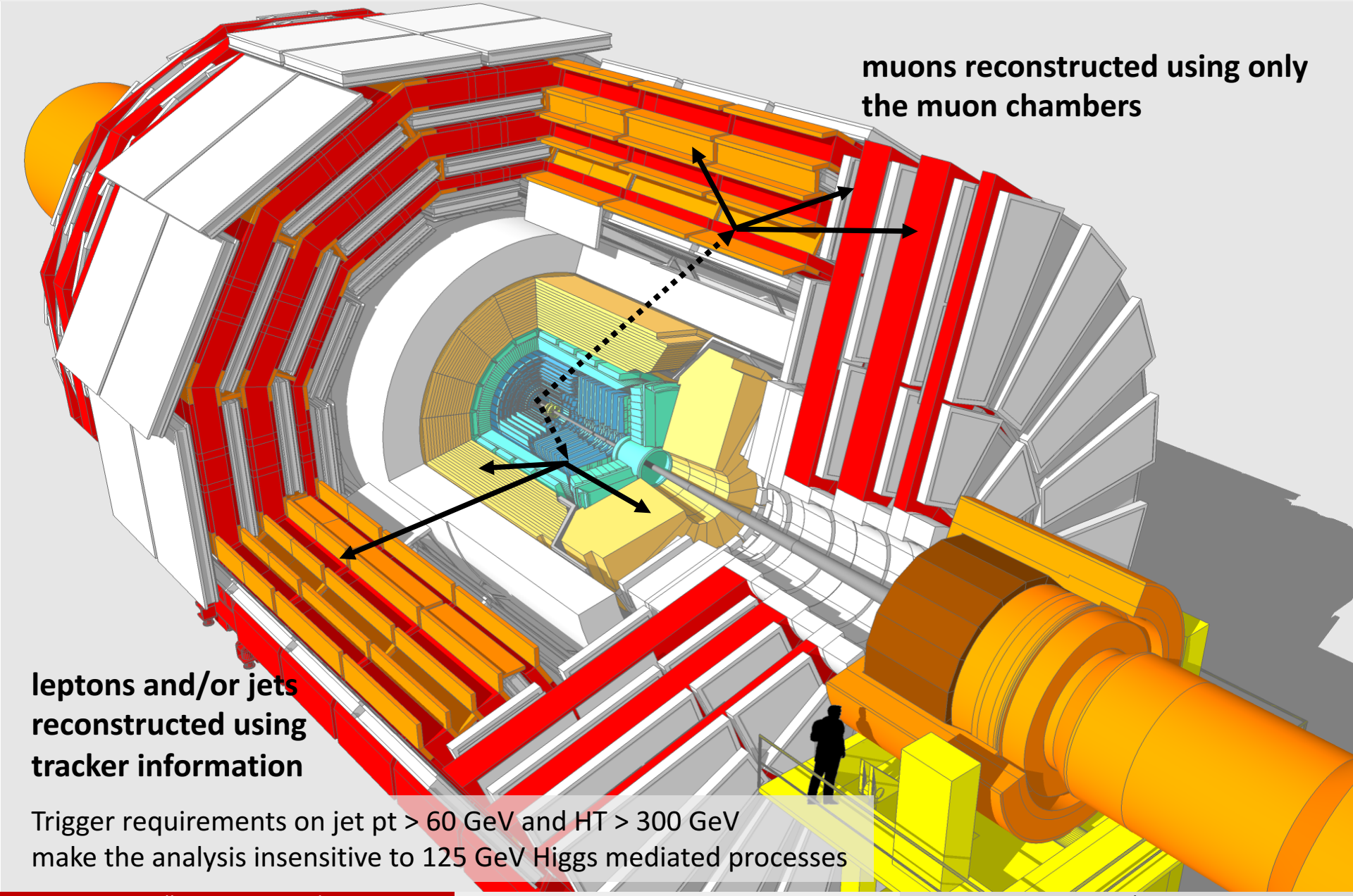


leptons and/or jets reconstructed using tracker information

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

What signatures can we observe?



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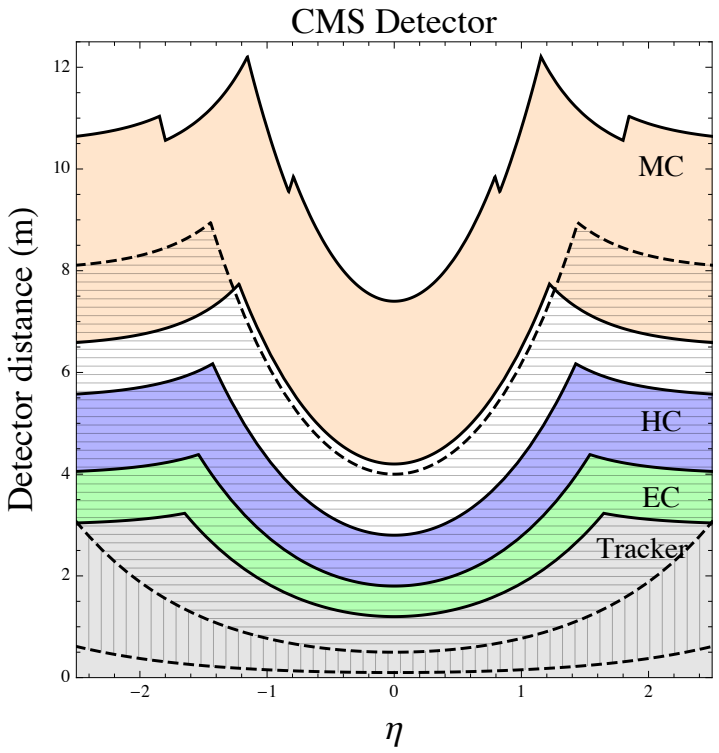
Heavy neutrino: decay probability

Approximate description of the CMS detector

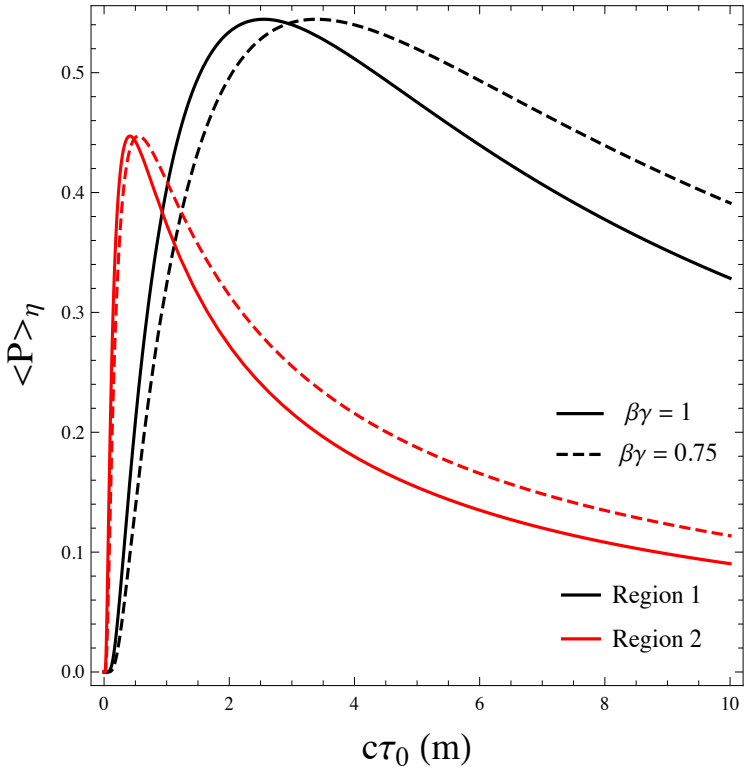


The horizontal (R1) and vertical (R2) hatched areas correspond to optimised regions for DV observations in the muon chambers and tracker respectively

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

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

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



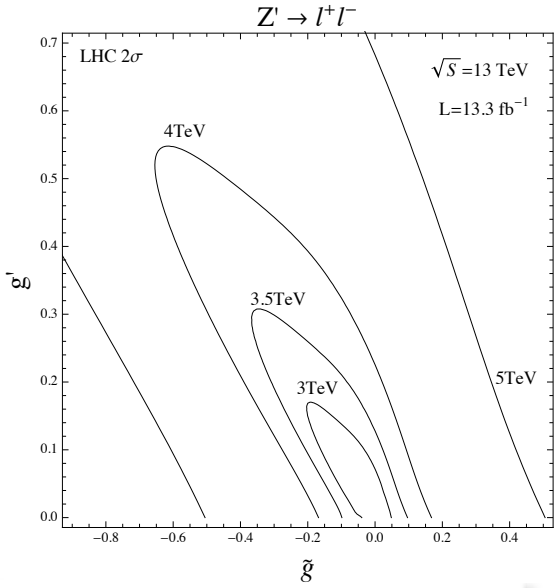
Benchmark points

Benchmark points characterised by long-lived heavy neutrinos

	m_{ν_h} (GeV)	m_{ν_l} (eV)	$c\tau_0$ (m)	$\sigma_{\nu_h\nu_h}$ (fb)
BP1	40	0.075	1.5	332.3
BP2	50	0.082	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 muon chambers

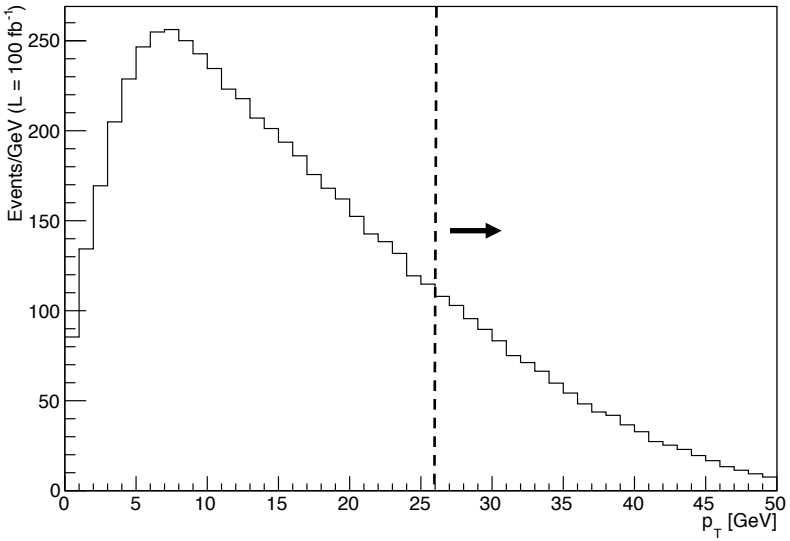
We require (according to CMS PAS EXO-14-012)

- $p_T > 26$ 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
- $L_{xy}/\sigma_{L_{xy}} > 12$
- $|d_0|/\sigma_d > 4$

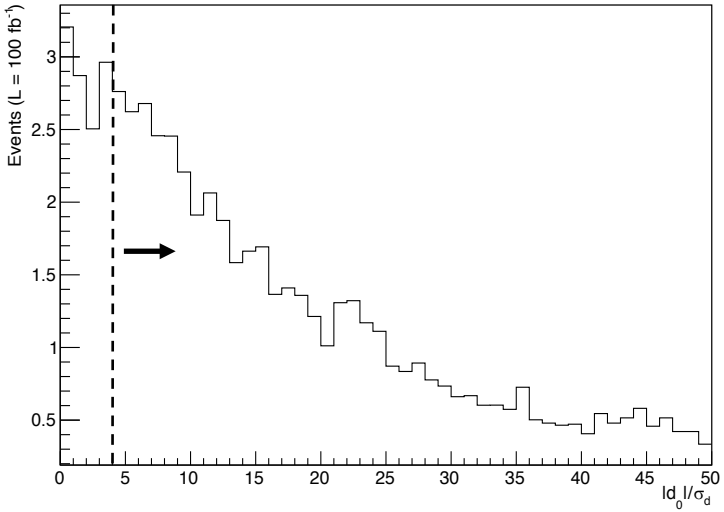
$\sigma_{L_{xy}} \simeq 3\,\text{cm}$

$\sigma_d \simeq 2\,\text{cm}$

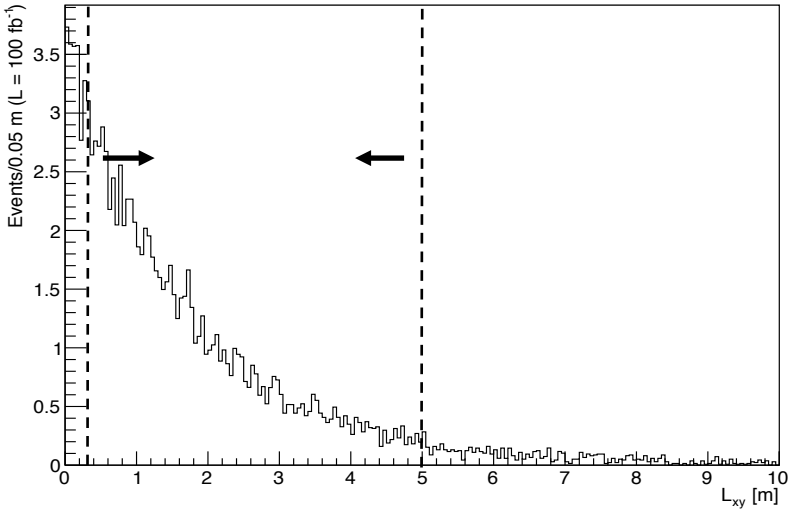
Muon p_T BP1



Impact parameter significance



L_{xy}



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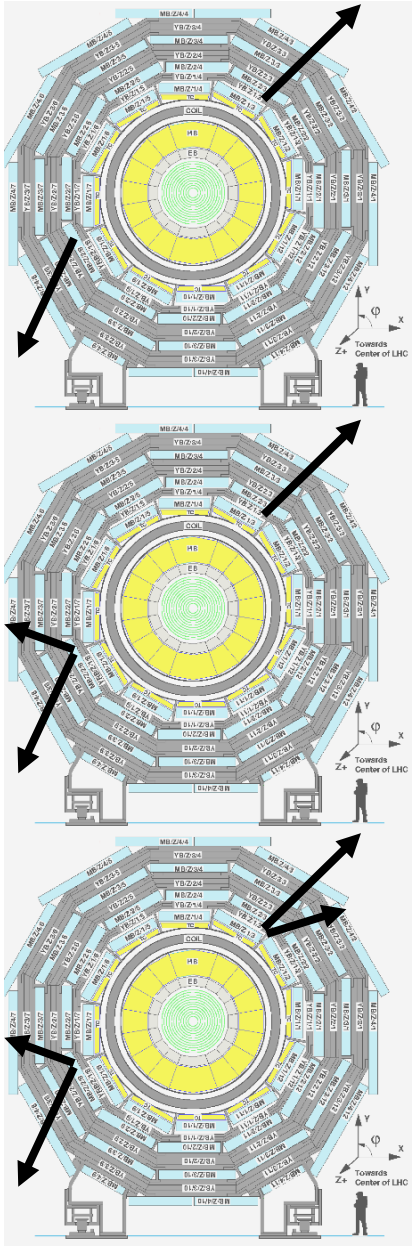
- $L_{xy} < 5$ m
- $L_{xy}/\sigma_{L_{xy}} > 12$ $\quad \sigma_{L_{xy}} \simeq 3\,\mathrm{cm}$
- $|d_0|/\sigma_d > 4$ $\quad \sigma_d \simeq 2\,\mathrm{cm}$

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

	2 μ	3 μ	4 μ
BP1 (ct_0 = 1.5 m)	39.55	6.12	0.23
BP2 (ct_0 = 0.5 m)	5.57	1.03	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

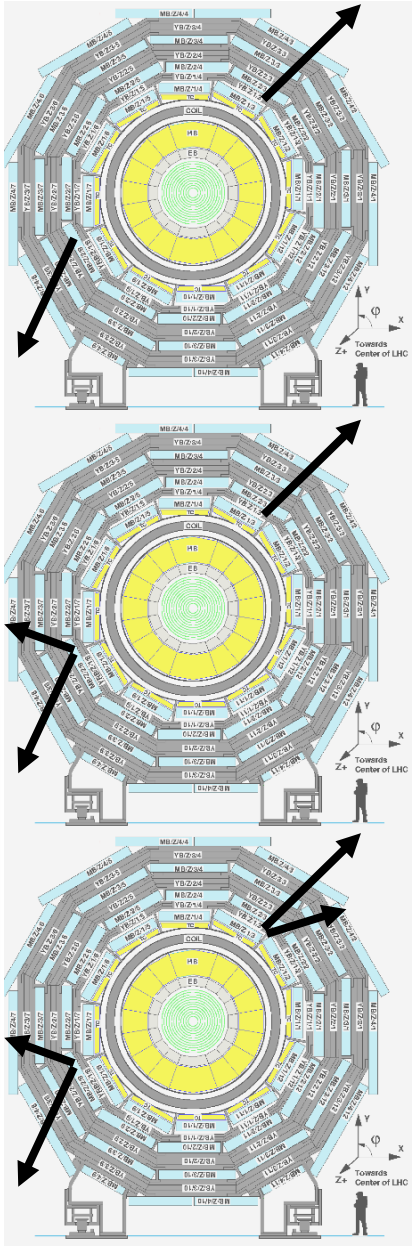
We require (according to CMS-B2G-12-024)

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

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

	$2\,l$	$3\,l$	$4\,l$
BP1 (ct_0 = 1.5 m)	10.32	4.82	0.72
BP2 (ct_0 = 0.5 m)	37.39	22.03	3.28

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 RH neutrinos

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

- LL Heavy neutrinos provide displaced tracks and vertices in the detectors

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