Displaced vertices from heavy neutrinos at the LHC

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arXiv:1612.05977, arXiv:1708.03650

Outline

- Heavy neutrino decay and production modes
  - Model realisations
  - BR and cross section estimates
- Signatures at the LHC
  - Displaced vertices
- Conclusions

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:

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

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

The (type-I) seesaw mechanism

The observation of neutrino oscillations has provided a clear evidence for BSM

but neither the details of this new physics nor its scale are known

the simplest and minimal way to account for neutrino masses is

the (type-I) seesaw mechanism

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

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

$$m_D = 1/\sqrt{2}\, v Y_\nu$$

if the seesaw scale is in the TeV range we could have the opportunity

to disclose its dynamics at the LHC

Heavy neutrino interactions

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

- 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 SM-like and Heavy Higgses

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

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

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

Others scenarios

- Different seesaw realisations
- Left-right symmetric models, GUT inspired models, ….
- Scalar + RH neutrino extended models (*no need of extra gauge symmetry*)
- Model independent approaches using effective field theory

RH neutrinos allow for a new d=5 operator, besides the well-known Weinberg operator, inducing exotic Higgs decay

$$\mathcal{O}_{\nu_R \Phi} = \frac{(\alpha_{\nu_R \Phi})_{ij}}{\Lambda} \overline{(\nu_R^i)^c} \, \nu_R^j \, \Phi^\dagger \Phi + \mathrm{h.c.}$$

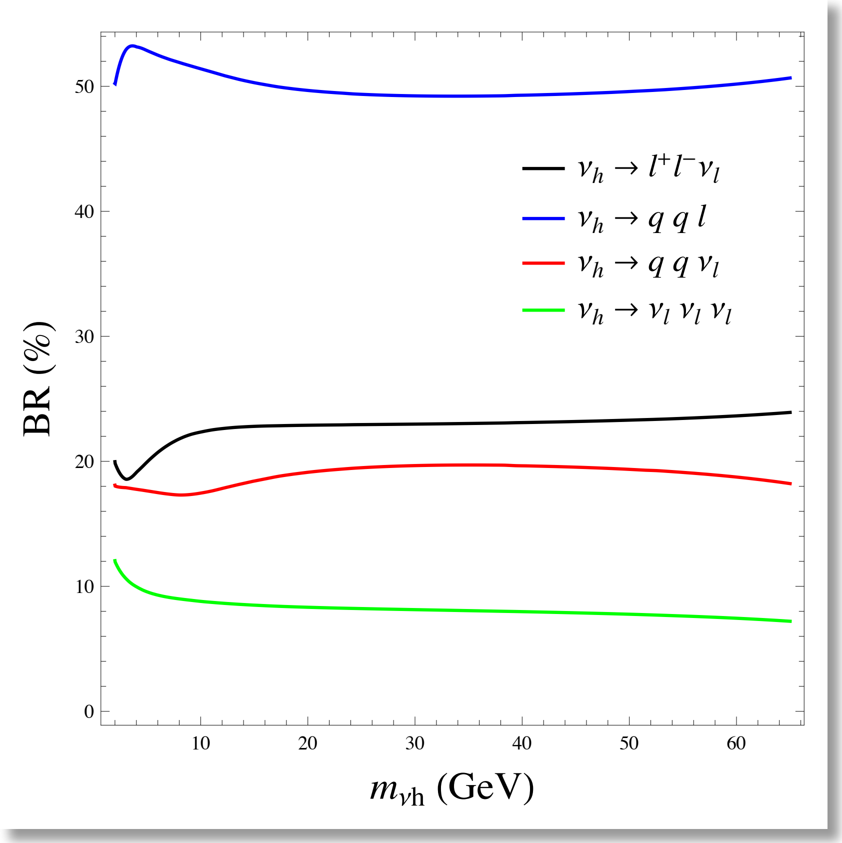
arXiv:1704.08721

Heavy neutrino: decay modes

Heavy neutrino (main) decay modes

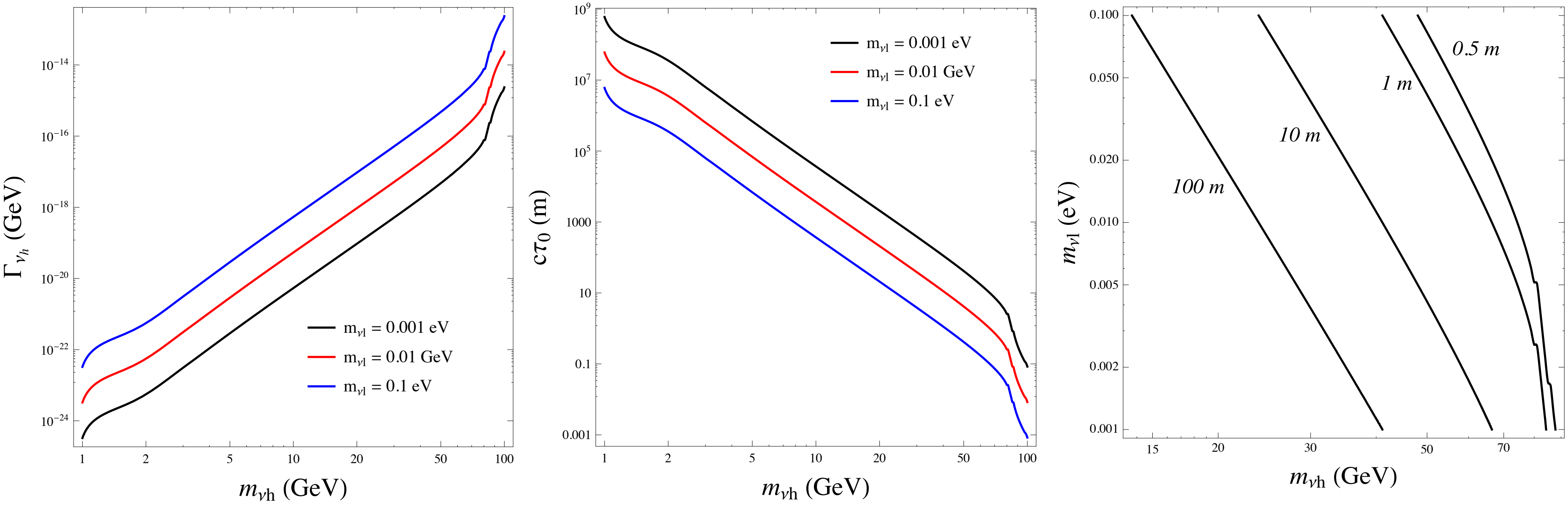
$$\nu_h \to l^\pm W^{\mp *} \qquad \nu_h \to \nu_l Z^*$$

- $\nu_h \to l^\mp W^\pm \to l^\mp l'^\pm \nu_{l'}$
- $\nu_h \to l^\mp W^\pm \to l^\mp q\bar{q}'$
- $\nu_h \to \nu_{l'} Z \to \nu_{l'} l^+ l^-$
- $\nu_h \to \nu_{l'} Z \to \nu_{l'} q\bar{q}$
- $\nu_h \to \nu_{l'} Z \to \nu_{l'} \nu_l \nu_l$



$BR(qql) \sim 50\%$ $\qquad BR(ll\nu_l) \sim 21\%$

Heavy neutrino: proper decay length



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

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

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

- Long Lived (LL) heavy neutrino for $m_{\nu_h} \lesssim M_Z$

  Displaced vertices appear in the detector

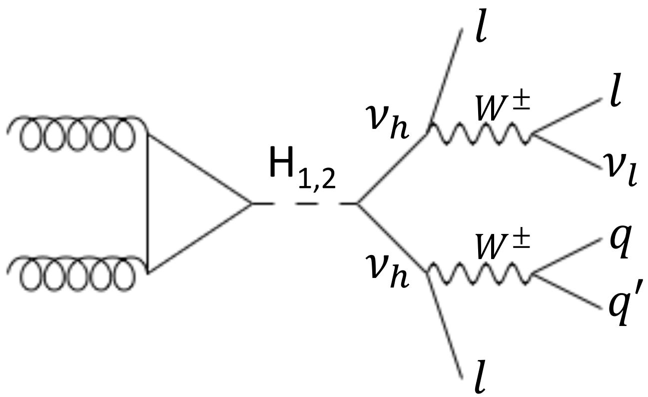
  (*almost background-free*)

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

- short lived heavy neutrinos for $m_{\nu_h} \gtrsim M_Z$

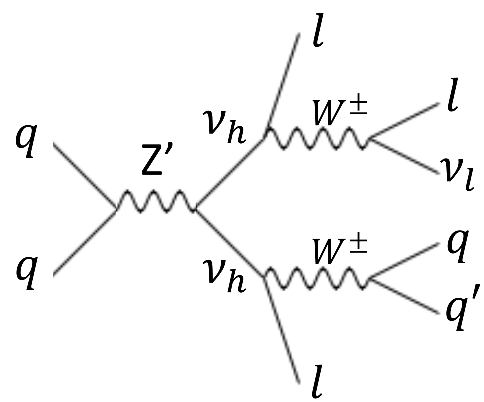
Heavy neutrino: production mechanisms

1. *Heavy neutrino production from the* **SM-like Higgs**



2. *Heavy neutrino production from the* **Heavy Higgs**

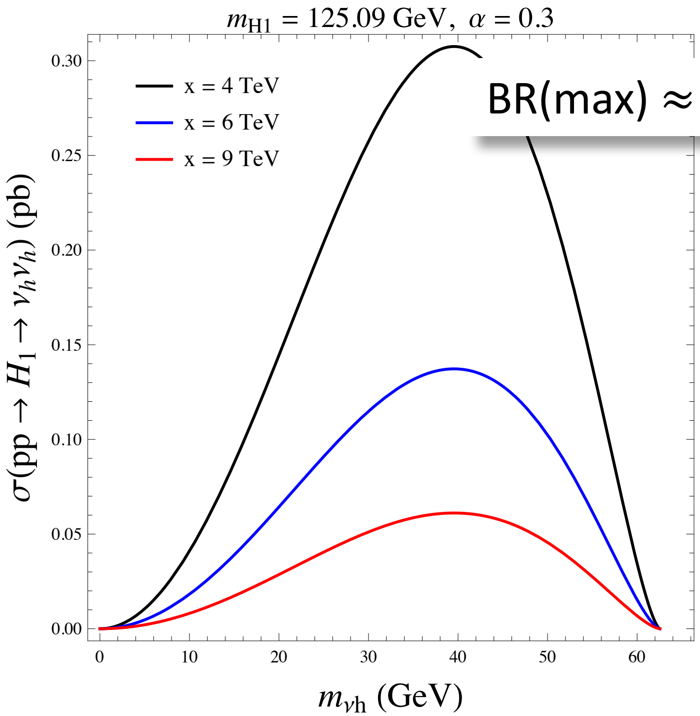
3. *Heavy neutrino production from the* **Z’**



Heavy neutrinos from the *Exotic SM Higgs decay*

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

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



BR(max) ≈ 0.77%

LHC @ 13 TeV

the small BR is compensated by the large Higgs production σ

in an abelian extension of the SM, the vev x is fixed by the Z' mass

$$x = M_{Z'}/(2g')$$

in other scenarios x is a free parameter and larger BR can be obtained

Heavy neutrino: signatures

Typical mass hierarchy:

M_Z m_{H_1} m_{H_2} $M_{Z'}$

m_{ν_h}

Long-lived neutrinos

Short-lived neutrinos

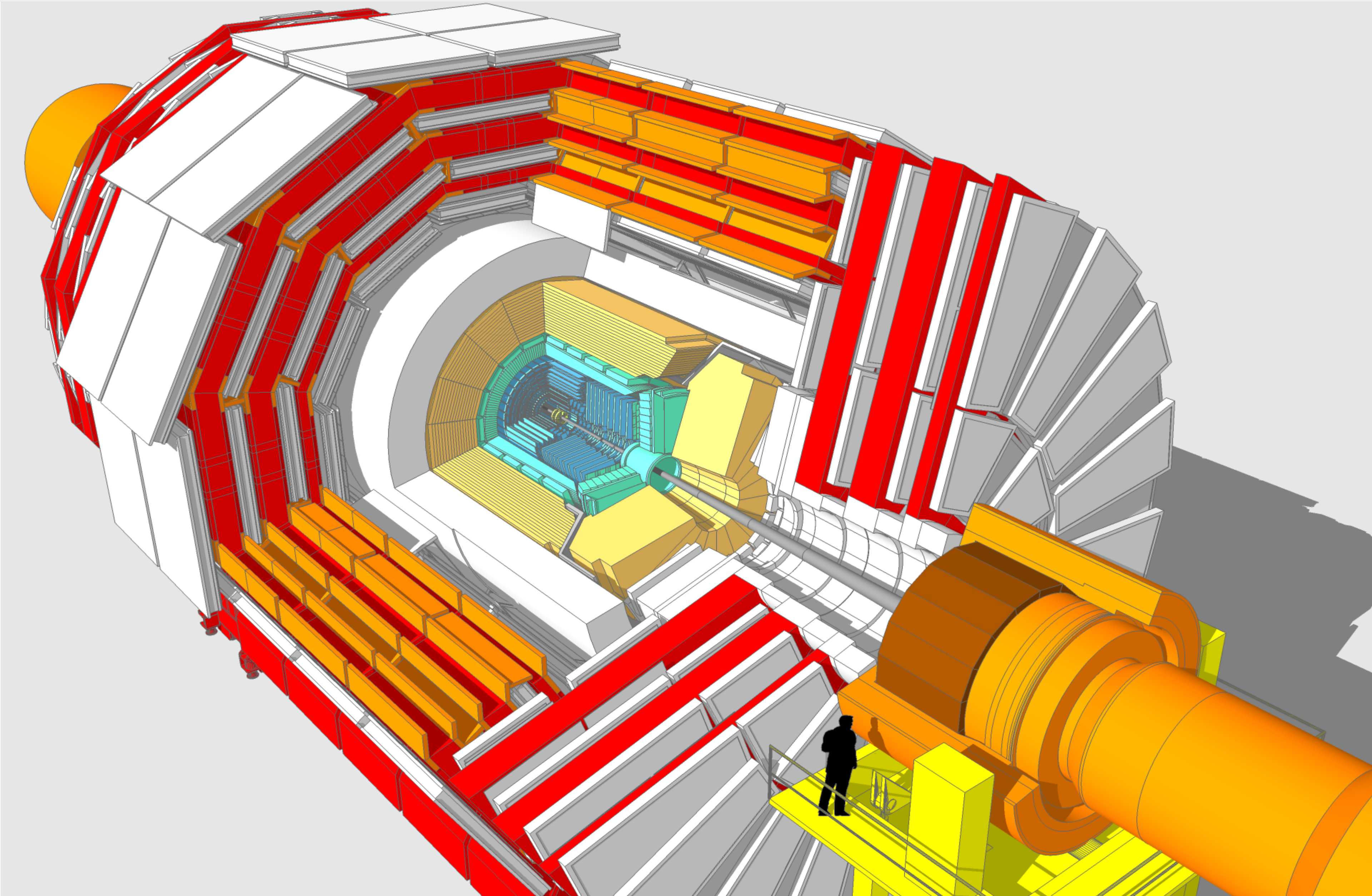
Typical signatures

displaced vertices

prompt decays with standard leptonic or semi-leptonic signatures

boosted final states, fat jets

What signatures can we observe?



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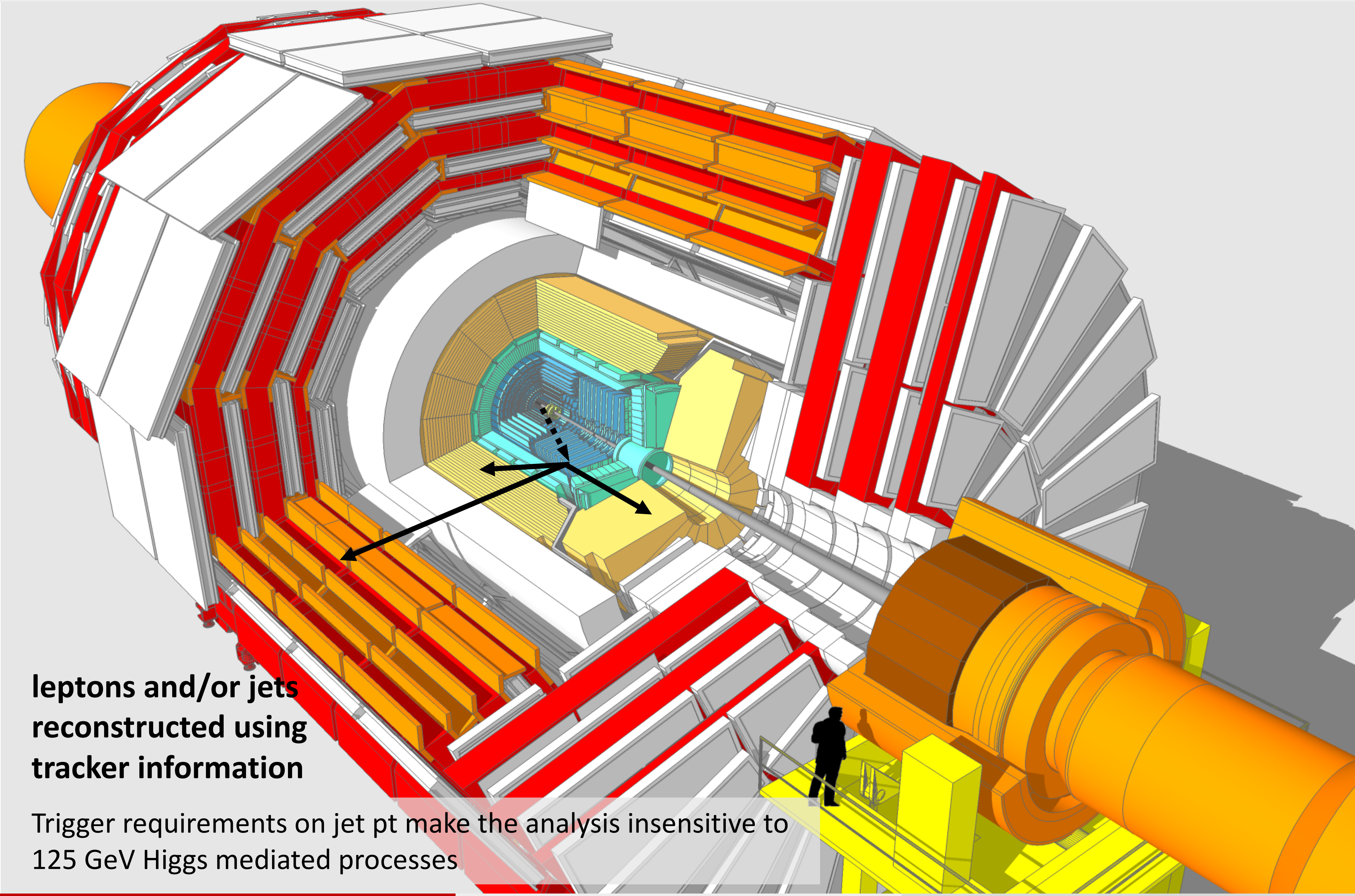

leptons and/or jets reconstructed using tracker information

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

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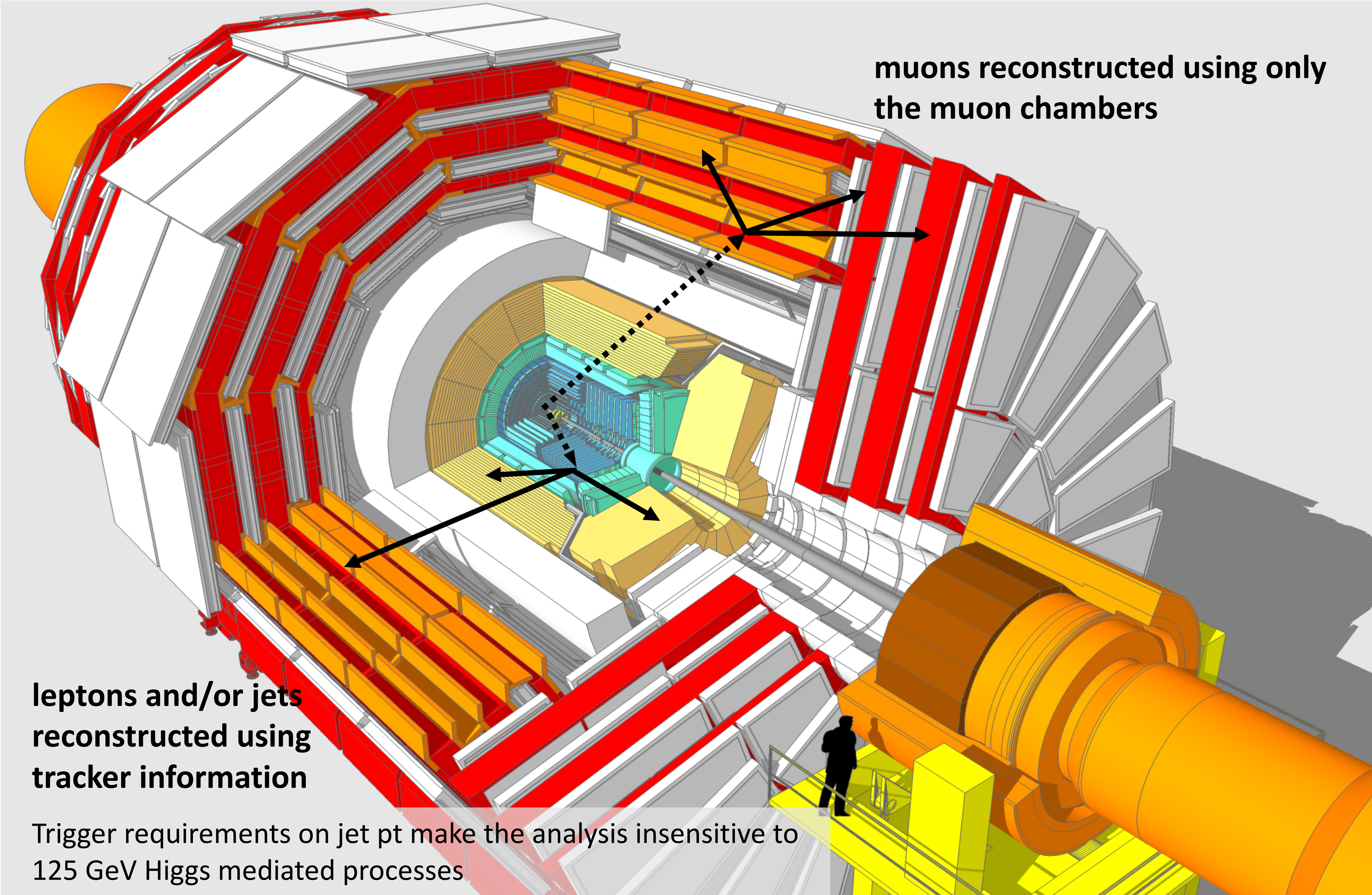
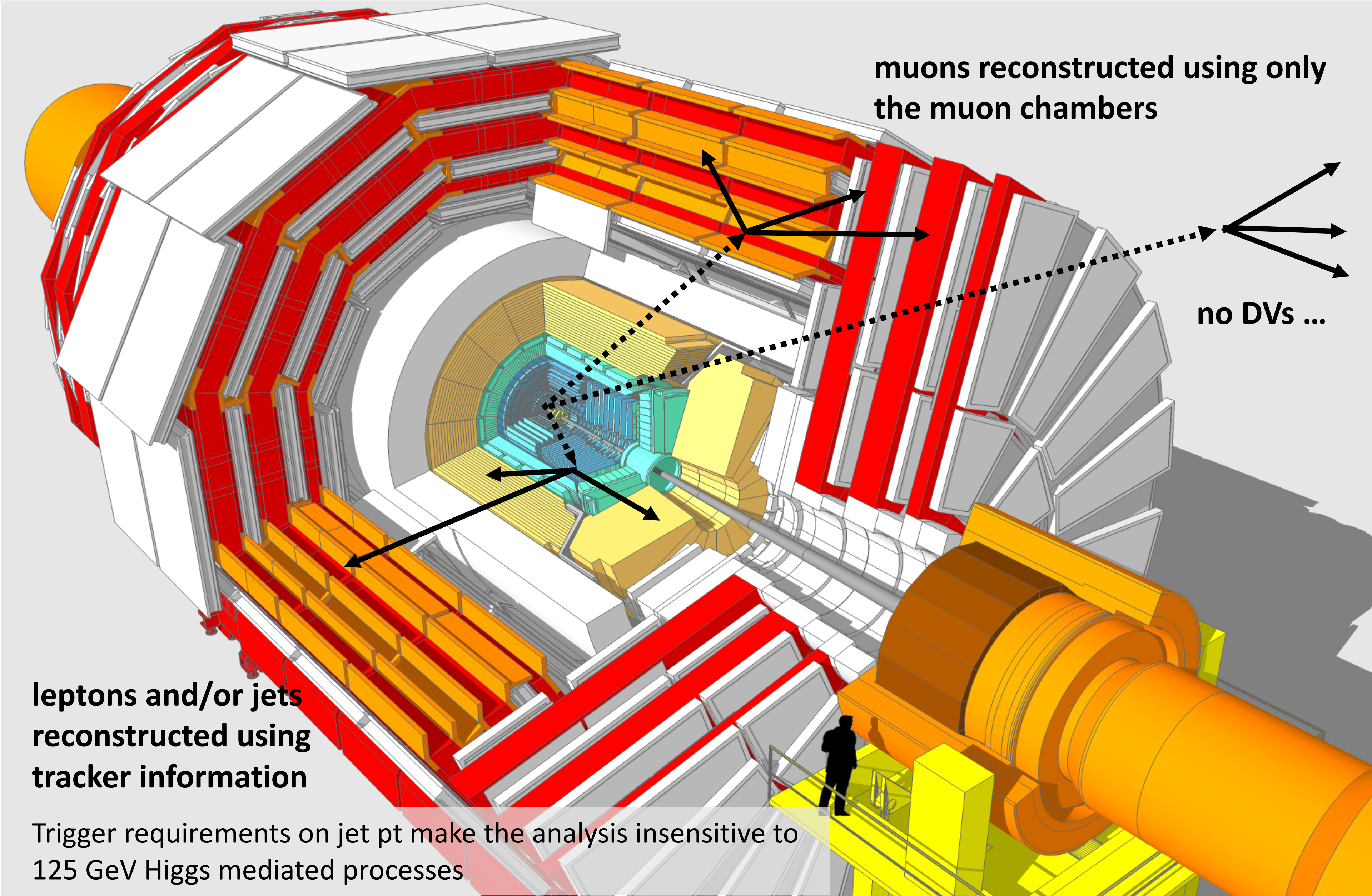


muons reconstructed using only the muon chambers

leptons and/or jets reconstructed using tracker information

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

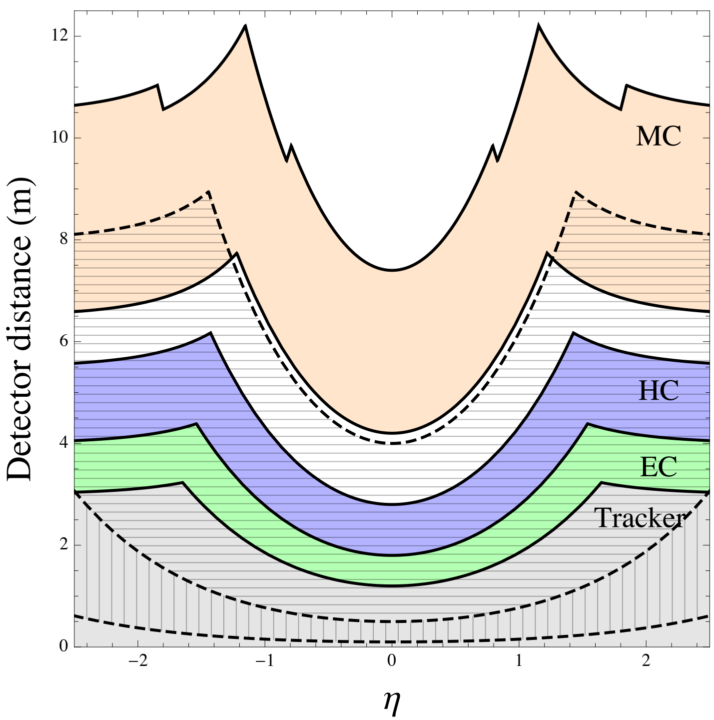
What signatures can we observe?

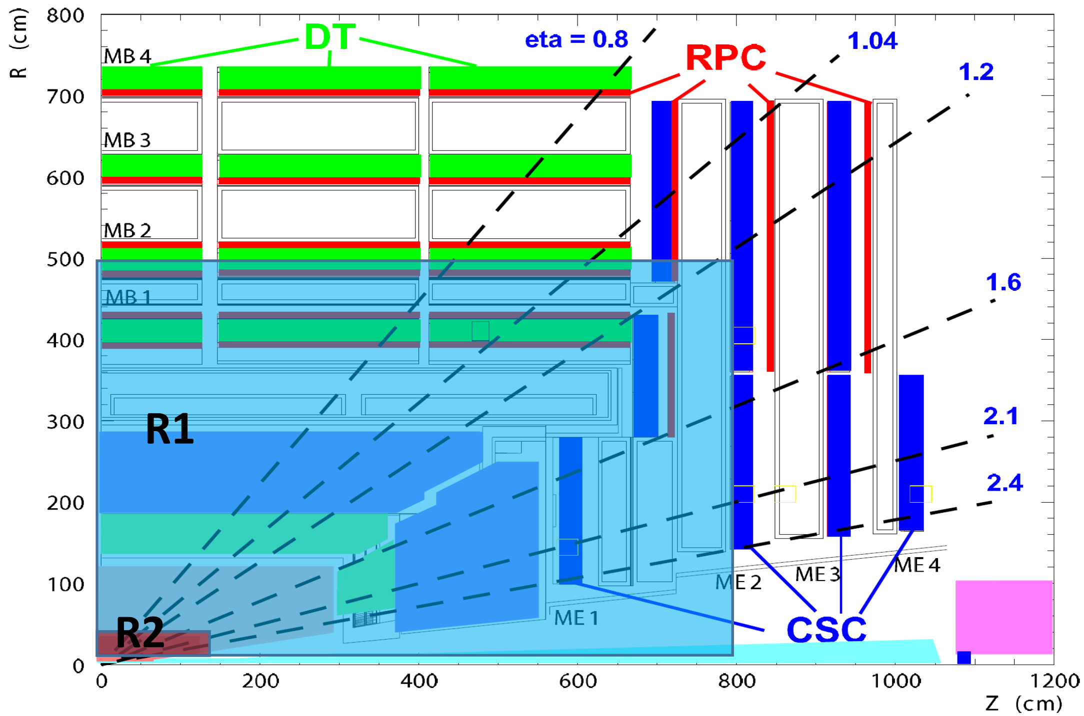


Trigger requirements on jet pt make the analysis insensitive to 125 GeV Higgs mediated processes

CMS detector geometry

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

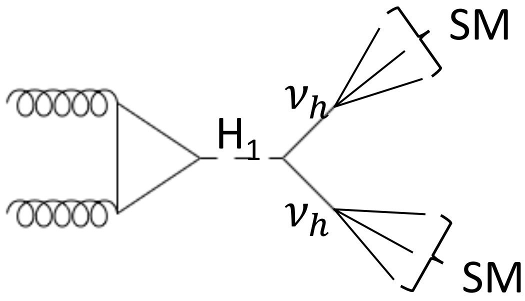
$R_2^{min} = 0.1\ m$ $\quad R_2^{max} = 0.5\ m$ $\quad |z_2| < 1.4\ m$

$R_1^{min} = 0.5\ m$ $\quad R_1^{max} = 5.0\ m$ $\quad |z_1| < 8.0\ m$

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)

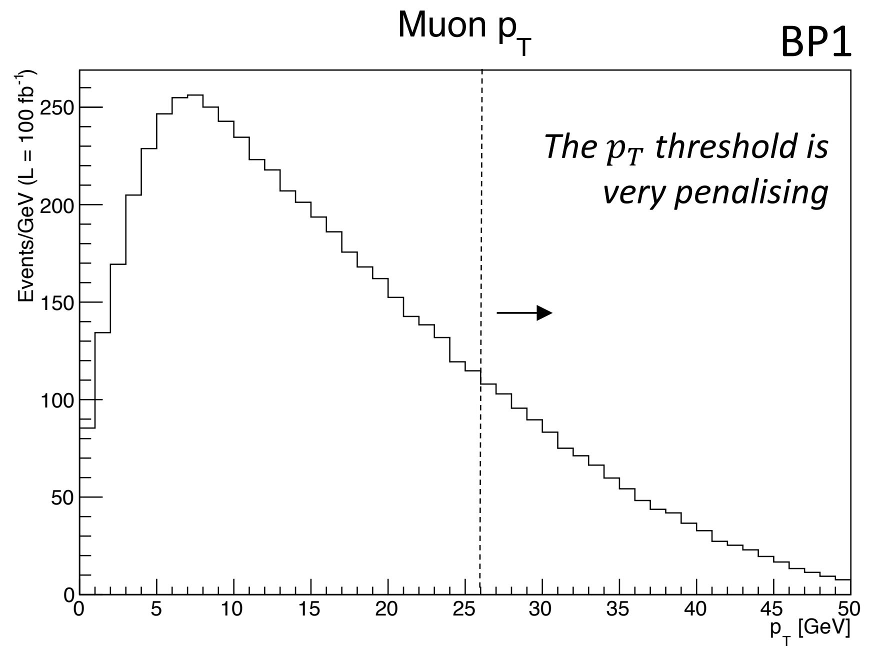
Simulation procedure:

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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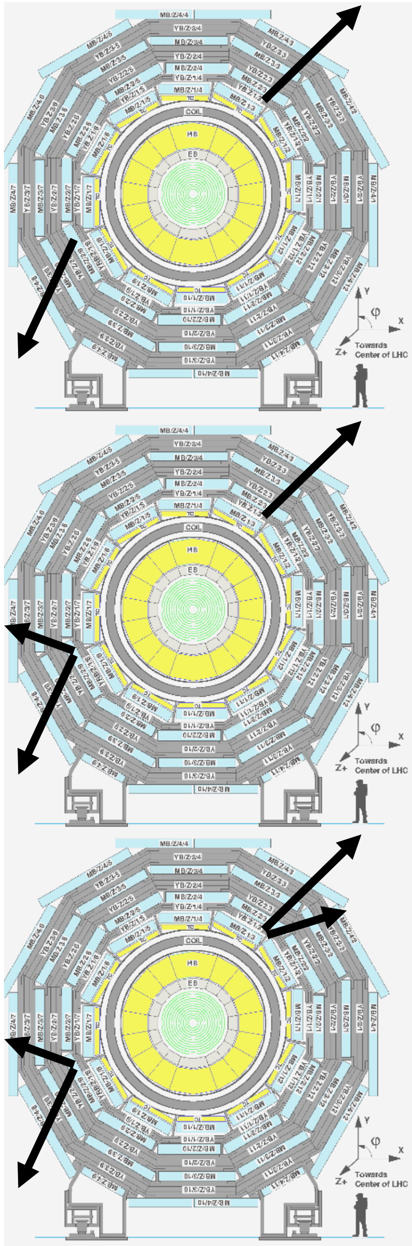
selection according to CMS PAS EXO-14-012

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

	$2\ \mu$	$3\ \mu$	$4\ \mu$
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 $\sigma_d \simeq 20\,\mu\mathrm{m}$
- $\cos\theta_{\mu\mu} > -0.75$

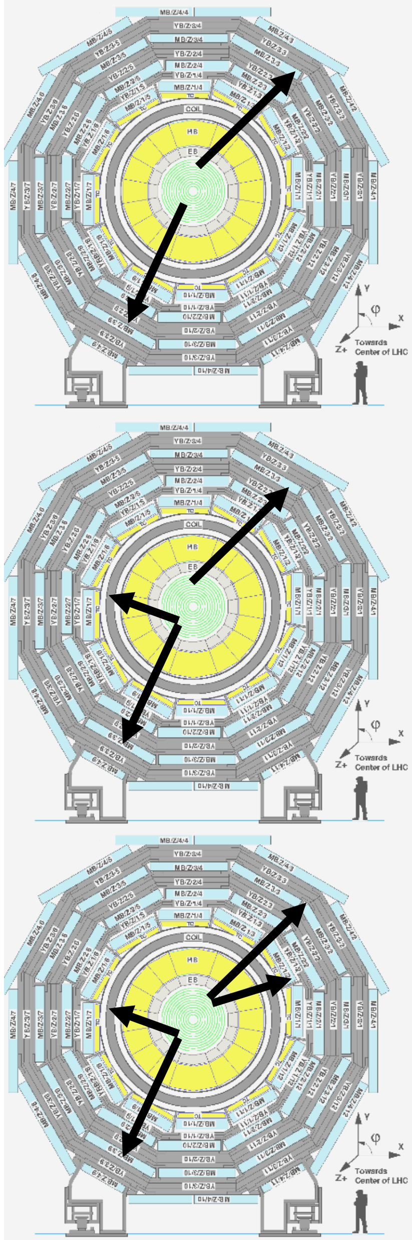
selection according to CMS-B2G-12-024

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

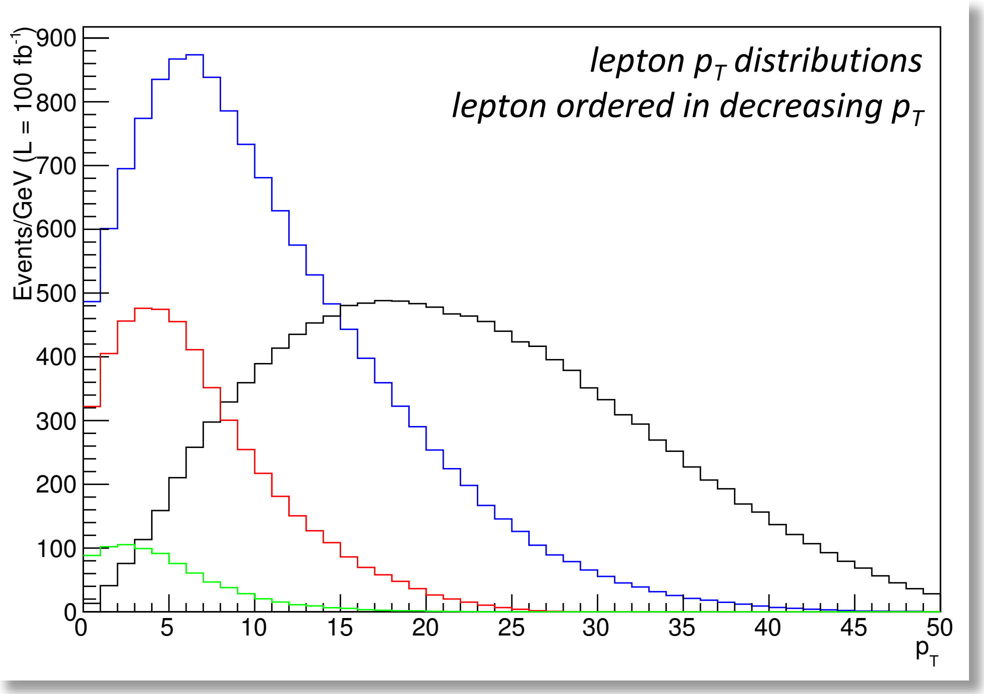
	$2\,l$	$3\,l$	$4\,l$
BP1 (ct_0 = 1.5 m)	9.65	4.64	0.79
BP2 (ct_0 = 0.5 m)	33.16	18.2	2.79

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

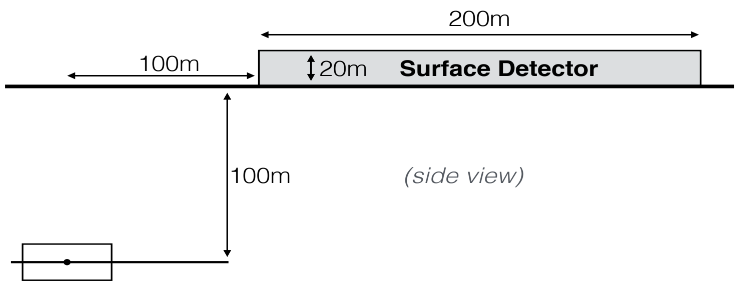
lepton trigger	BP1			BP2		
	$2\,l$	$3\,l$	$4\,l$			
$p_T > 26, 26$ GeV	9.65	4.64	0.79	33.16	18.2	2.79
$p_T > 20, 20, 10$ GeV	-	8.22	1.42	-	38.6	8.11
$p_T > 20, 15, 15$ GeV	-	5.31	1.31	-	27.3	6.94

$p_T > 5$ GeV for any subleading leptons

Long-lived particles: future prospects

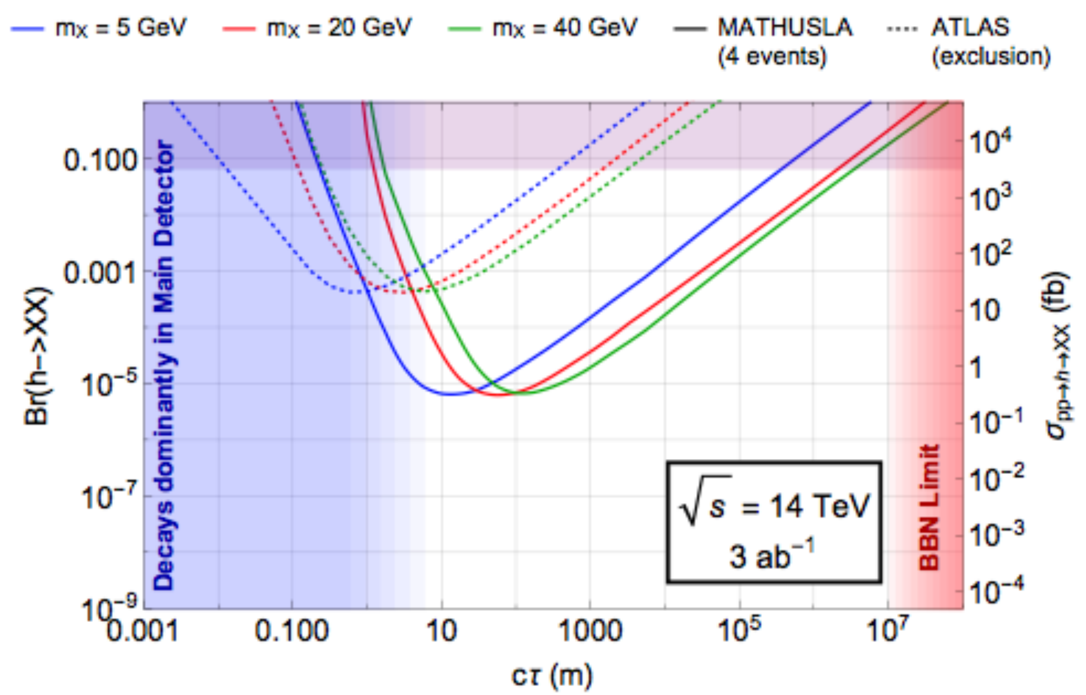
<u>MATHUSLA</u> - M*assive* T*iming* H*odoscope for* U*ltra* S*table neutra*L pA*rticles*

arXiv:1606.06298



Possible geometric configuration for the MATHUSLA surface detector at the HL-LHC

Sensitivity projection



Conclusions

- Heavy neutrinos offer a variety of signatures that can be explored at the LHC: *displaced vertices, boosted objects and fat jets, …*
- *Displaced vertices and tracks are typical signatures of long-lived heavy neutrinos (*$m_{\nu_h} \lesssim M_Z$*)*
- *"Muon chambers" and "tracker" analyses are complementary and sensitive to different heavy neutrino lifetimes*
- Displaced vertices characterise long-lived heavy neutrinos with relative small mass (*new experiments will probe very long lifetime*)
- New (soft) physics may be hidden by the trigger thresholds!
  it would be extremely important to develop dedicated triggers

Backup slides

The minimal Z' model: *a comment on the kinetic mixing*

- The most general Lagrangian allowed by gauge invariance admits a *kinetic mixing* between the two abelian field strengths

$$\mathcal{L} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} - \frac{1}{4}F'^{\mu\nu}F'_{\mu\nu} - \frac{\kappa}{2}F^{\mu\nu}F'_{\mu\nu}$$

even if absent at tree-level it can be reintroduced by radiative corrections

- The kinetic Lagrangian can be recast into a diagonal form thus introducing a non-diagonal covariant derivative

$$\mathcal{D}_\mu = \partial_\mu + i g_1 Y B_\mu + i(\tilde{g}\, Y + g_1'\, Y_{B-L}) B'_\mu + \ldots$$

induced Z-Z' mixing

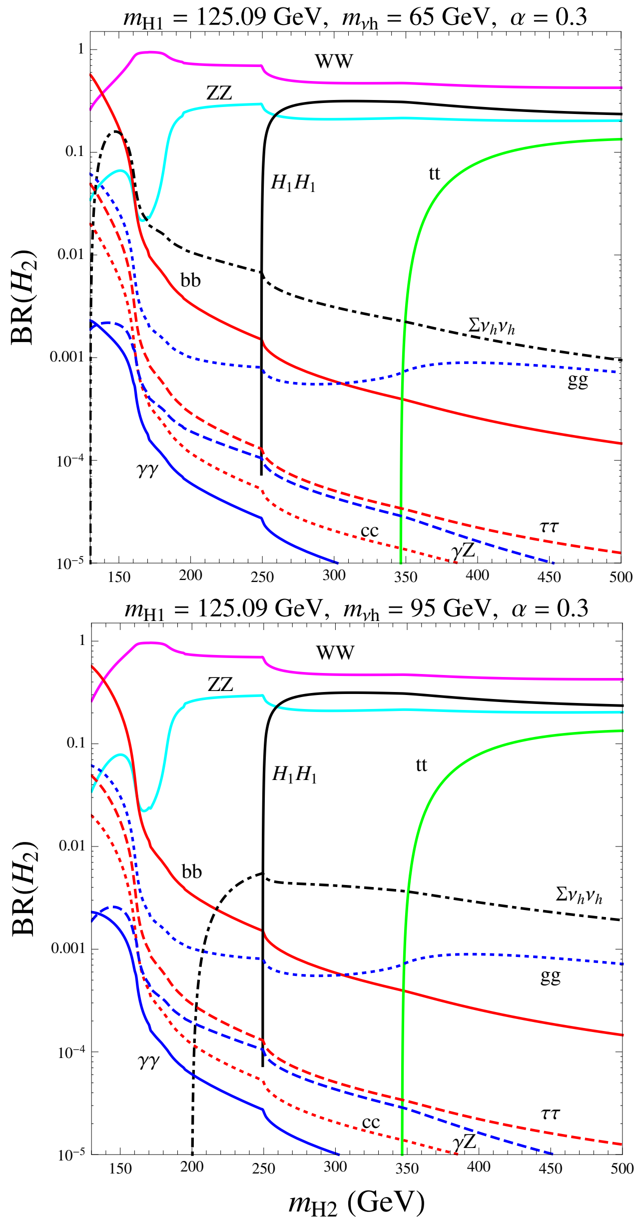
$$\theta' \simeq \tilde{g} \frac{M_Z\, v/2}{M_{Z'}^2 - M_Z^2}$$

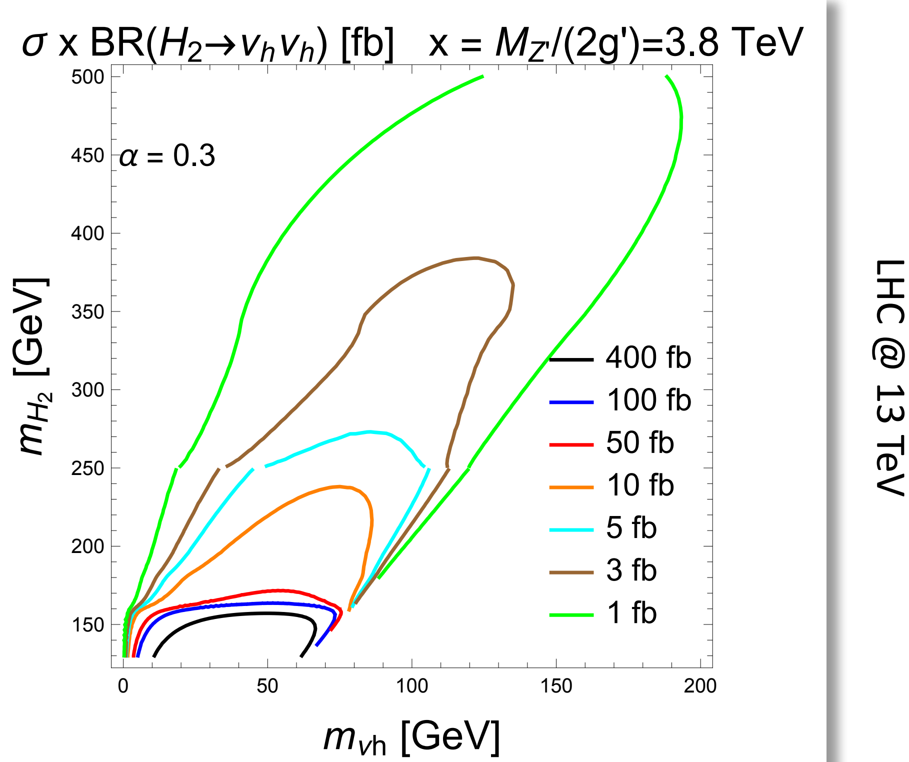
an additional abelian gauge factor can always be described by a linear combination of the hypercharge and of the B-L quantum number

- We can explore an entire class of minimal Abelian models through the ratio of the gauge couplings $\tilde{g}/g'_1$

- Typical benchmark models:
  - $g'_1 = 0$: sequential SM
  - $\tilde{g} = 0$: pure B-L
  - $\tilde{g} = -2g'_1$: $U(1)_R$
  - $\tilde{g} = -4/5 g'_1$: $U(1)_X$ from SO(10)

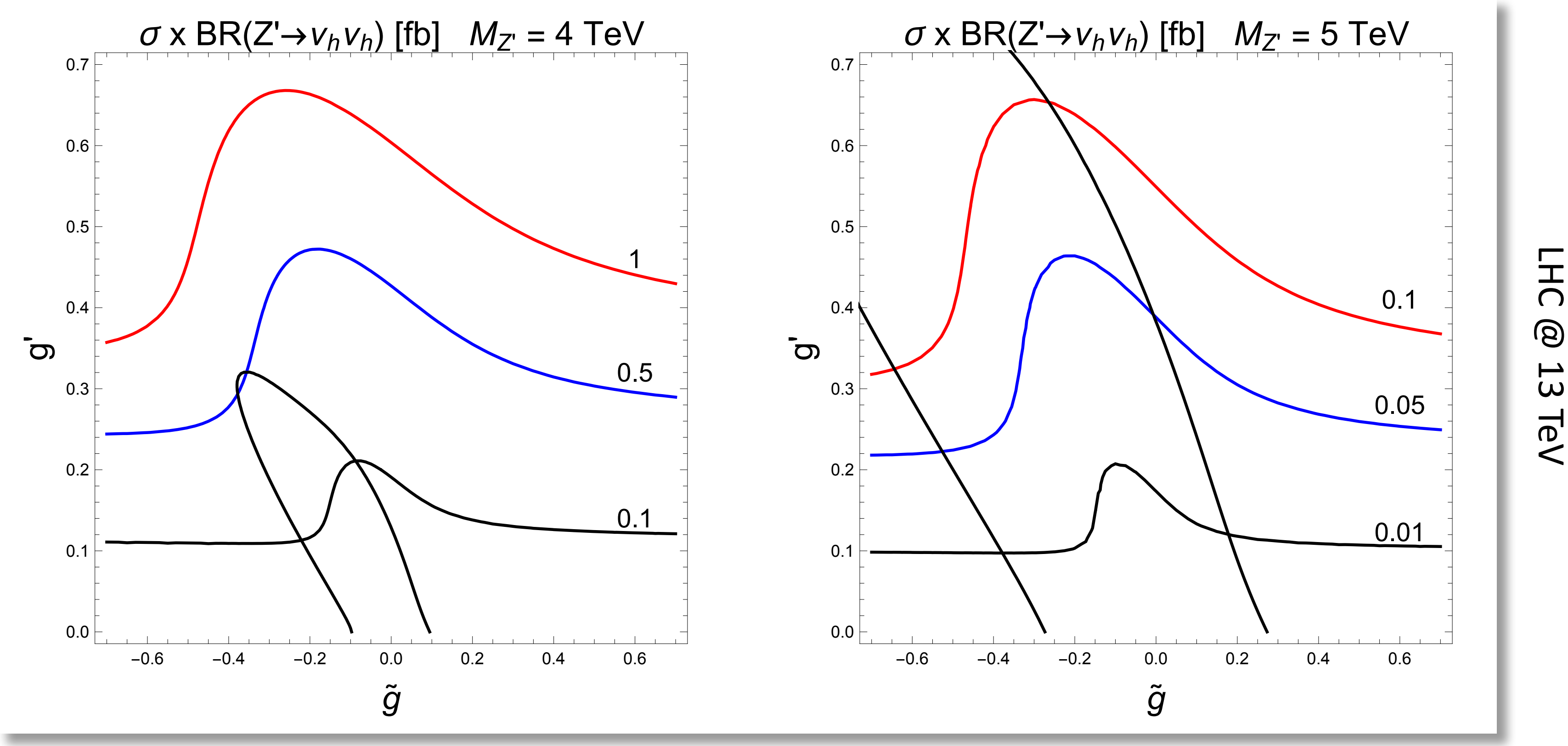
Heavy neutrinos from the *Heavy Higgs decay*





For $m_{H_2} < 160$ GeV ($m_{\nu_h} < 80$ GeV) the $H_2 \rightarrow WW$ channel is closed and the $\sigma(\nu_h \nu_h)$ can reach 400 fb

Heavy neutrinos from the *Z' gauge boson*



This channel can be competitive to the scalar mediated mode only for $m_{\nu_h} \gtrsim 200$ GeV

For $\alpha \approx 0$, the Z' production mode remains the main accessible channel despite its low σ

Heavy neutrino: decay probability

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

$$P = \int_{d_1(\eta)}^{d_2(\eta)} dx \frac{1}{c\tau} \exp\left(-\frac{x}{c\tau}\right) \qquad c\tau = \beta\gamma c\tau_0$$