Long-Lived Particles at the LHC

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Long-Lived states

LLP are produced with sizeable production rate and suppressed decay (tiny couplings, approximate symmetries, etc.)

There are many theories yielding displaced signatures

Main options:

(i) LLP carry SM quantum numbers: SUSY realizations

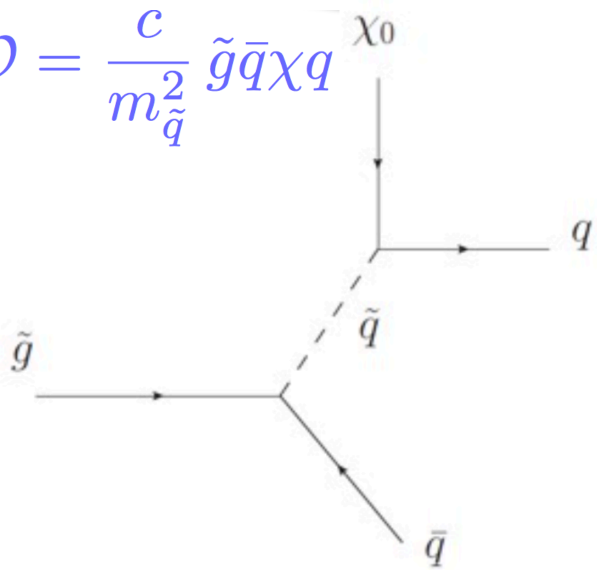
(ii) LLP are SM singlets: Higgs decays etc.

Susy I: Split-Susy

High-scale sfermions and low-scale inos: $m_{ino} << m_{sfermion}$

Consequence: there might exist fermions, like the gluinos, potentially accessible at the LHC, that can be pair-produced but cannot decay except via higher-order operators.

$$\mathcal{O} = \frac{c}{m_{\tilde{q}}^2}\,\tilde{g}\bar{q}\chi q$$



The lifetime depends on the splitting to the power four

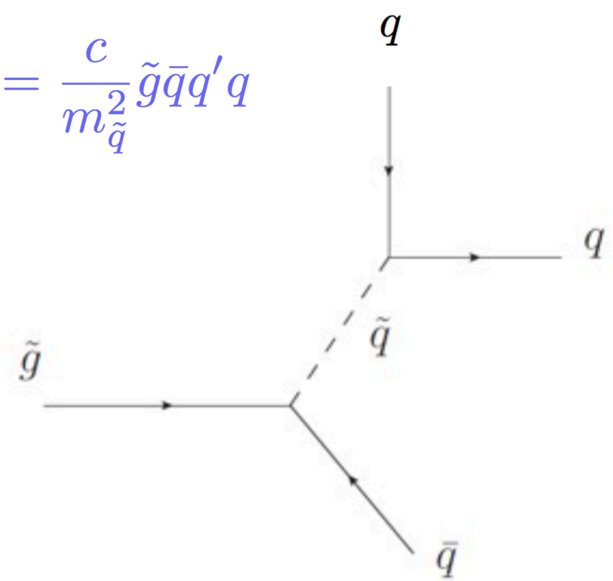
$$c\tau \approx 100\mu m \times \left(\frac{m_{\tilde{q}}}{1000\mathrm{TeV}}\right)^4 \left(\frac{\mathrm{TeV}}{m_{\tilde{g}}}\right)^5$$

Susy II: RPV

R-parity violating couplings can be included or not by hand.

The proton decay constrains combinations of RPV couplings to be small. But, the individual RPV couplings can be a priori large.

$$\mathcal{O} = \frac{c}{m_{\tilde{q}}^2} \tilde{g}\bar{\tilde{q}}q' q$$



Consequence: all the familiar prompt RPV decays can be made displaced if small couplings are introduced by hand.

Hidden sector(s)

New SM singlet degrees of freedom, X, at the weak scale.

There are only a few production options, basically the direct resonant pair-production of X via:

- the Higgs(es)
- the Z boson
- some BSM particle, e.g. a Z′-boson (likely to be heavy)

Displaced decays

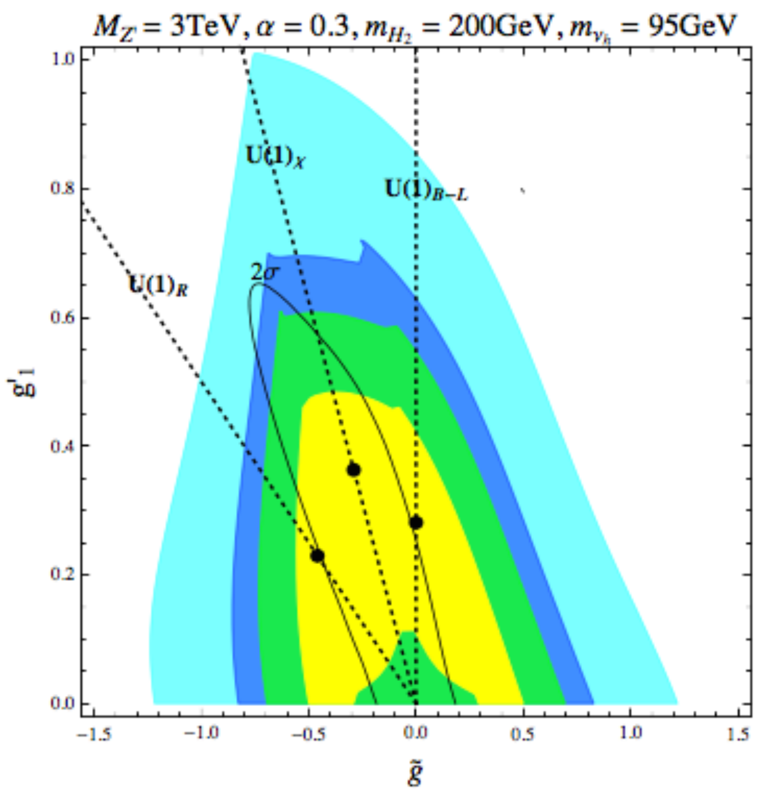
The focus has been initially on theories giving two displaced vertices per event, for sake of simplicity.

The lifetime is treated as a free parameter.

LLP signatures can be quite challenging at the LHC, we discuss an example in the following.

The minimal $U(1)_{B\_L}$ model

[EA, Delle Rose, Coriano', Moretti, Shepherd-Themistocleous, arXiv:1612.05977, arXiv:1605.02910]



$SU(2) \times U(1)_Y \times U(1)_{B-L}$

$D_\mu = \delta_\mu + ig_1 Y B_\mu + i(g{\sim}Y + g'_1 Y_{B-L}) B'_\mu$

Scalar potential $V(h, H_2)$

with α the scalar mixing between the two d.o.f.

$L_Y = L_Y^{SM} + L_Y(\nu, \nu_h)$

ν_h being the right-handed heavy neutrinos

The minimal $U(1)_{B\_L}$ model

Particle content

1 extra heavy Z′-boson

with M > 2.5 TeV for a viable leptogenesis, so-called the friendly setup [Mohapatra, Blanchet 2010]

3 heavy Right-Handed neutrinos ν_h

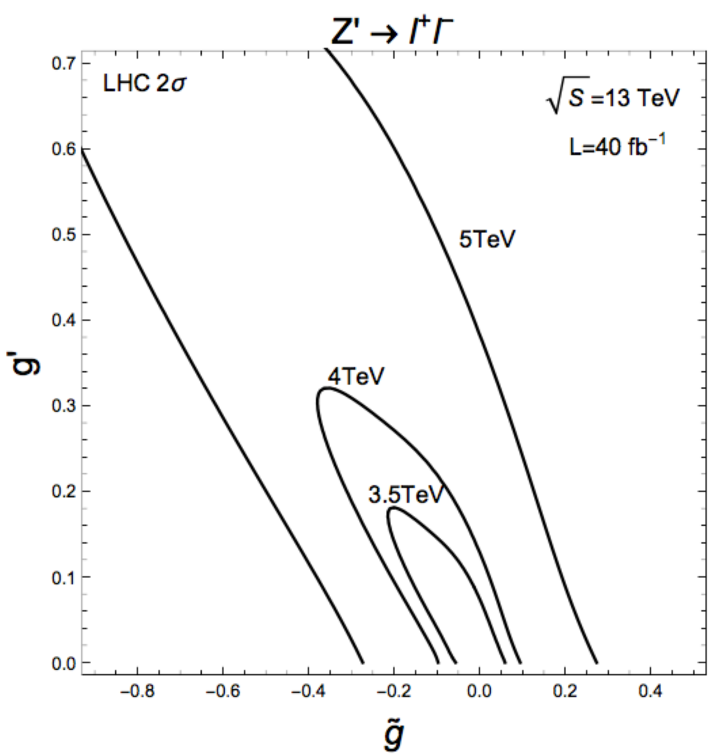
they acquire a Majorana mass and naturally implement the Type I seesaw mechanism. If close to degeneracy, they can give rise to resonant leptogenesis, explaining the matter-antimatter asymmetry.

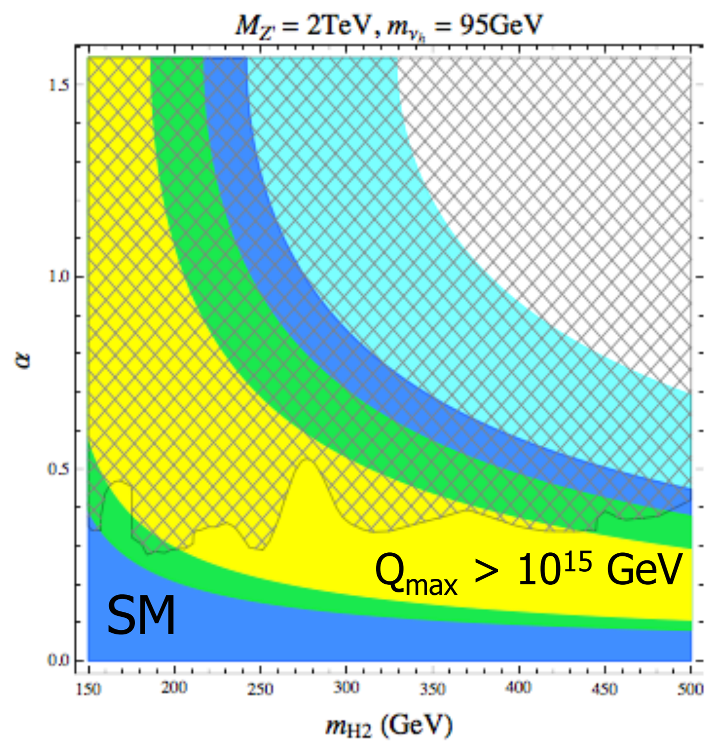
1 extra Higgs singlet H_2

giving mass to Z′ and ν_h

The minimal $U(1)_{B\_L}$ model

Recent limits on masses, couplings and mixing





The minimal $U(1)_{B\_L}$ model

Striking signatures: pp -> h, H_2, Z′ -> heavy neutrinos

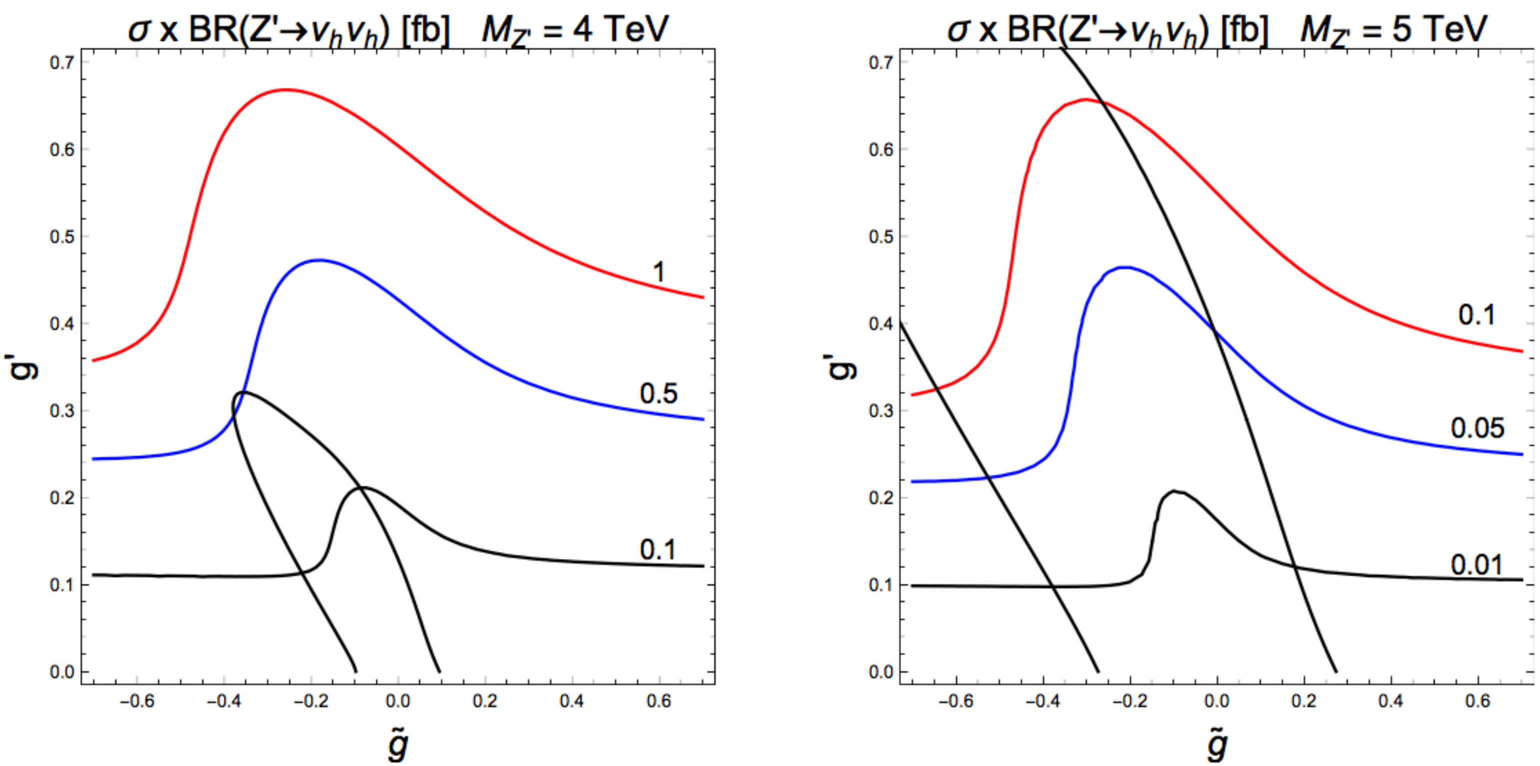
4 possible scenarios

- **h and H_2 are almost decoupled, $\alpha = 0$**
  the Z′ mode is the only accessible channel
- **$m_{\nu h} < m_h/2$ and $m_{H2} > 2M_w$**
  heavy neutrinos are produced by the SM-like Higgs
- **$m_{\nu h} > m_h/2$ and $2m_{\nu h} < m_{H2} < 2M_w$**
  heavy neutrinos are produced by the heavy Higgs
- **$m_{\nu h} < m_h/2$ and $2m_{\nu h} < m_{H2} < 2M_w$**
  heavy neutrinos are produced by both h and H2

The minimal $U(1)_{B\_L}$ model

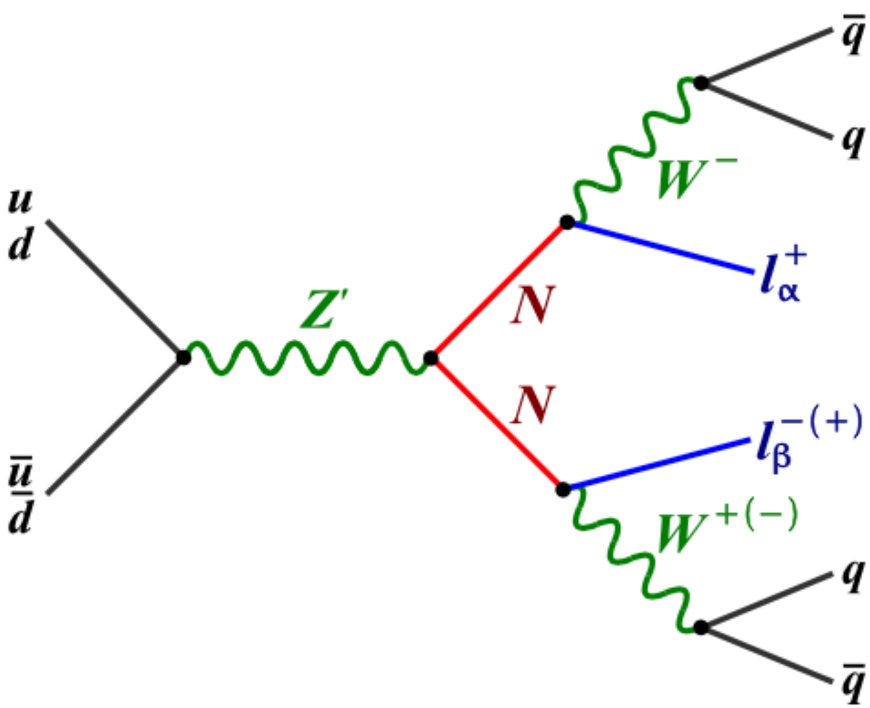
Striking signatures: pp -> Z' -> heavy neutrinos

This friendly channel advocated by Mohapatra et al. does not seem viable



The minimal $U(1)_{B\_L}$ model

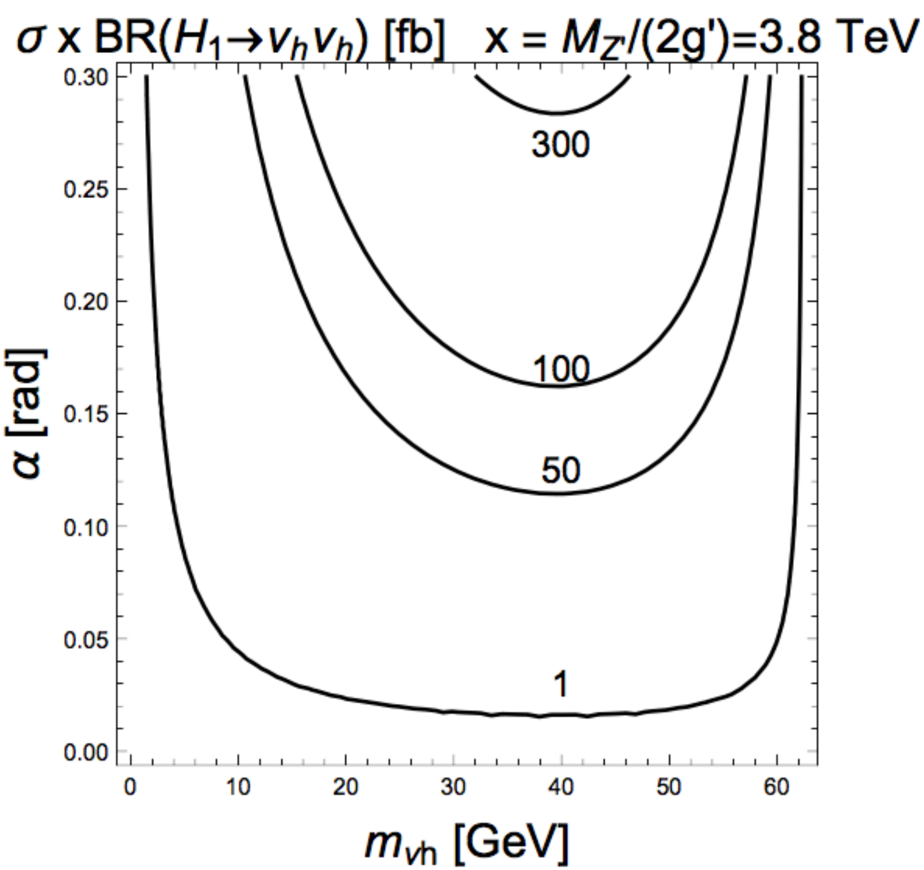
Striking signatures: pp -> Z' -> heavy neutrinos

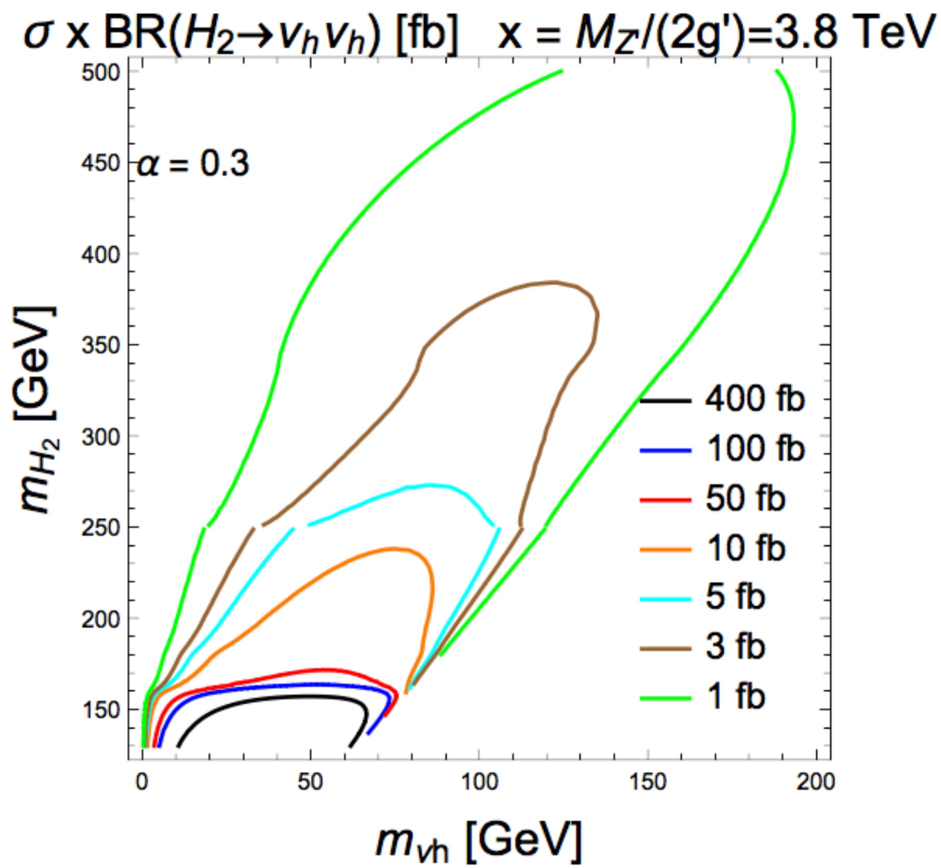


Exploring fat jet and jet substructure to enhance S/B [EA, Delle Rose, Moretti, Oleiya, Shepherd-Themistocleous 2017]

The minimal $U(1)_{B\_L}$ model

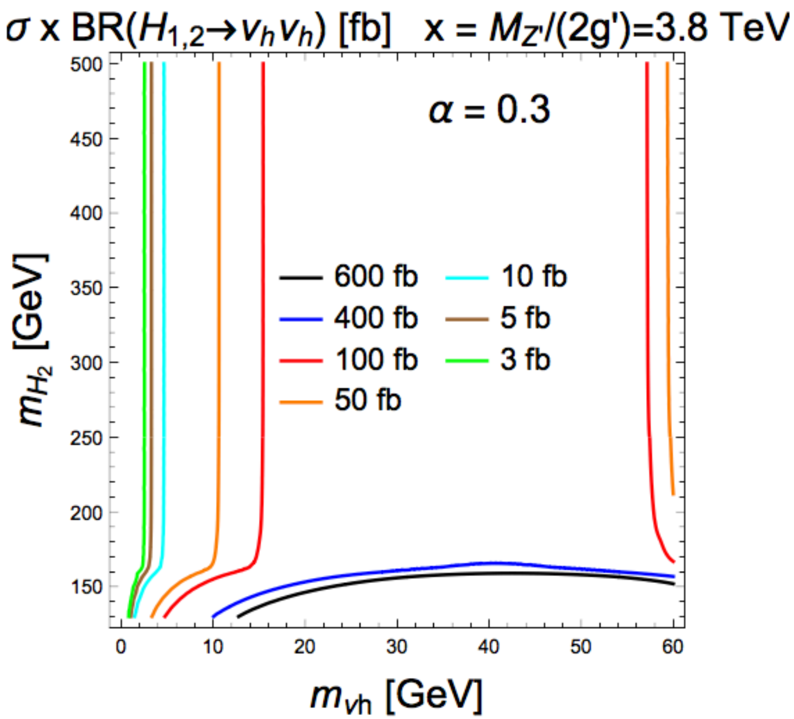
Striking signatures: pp -> h, H_2 -> heavy neutrinos

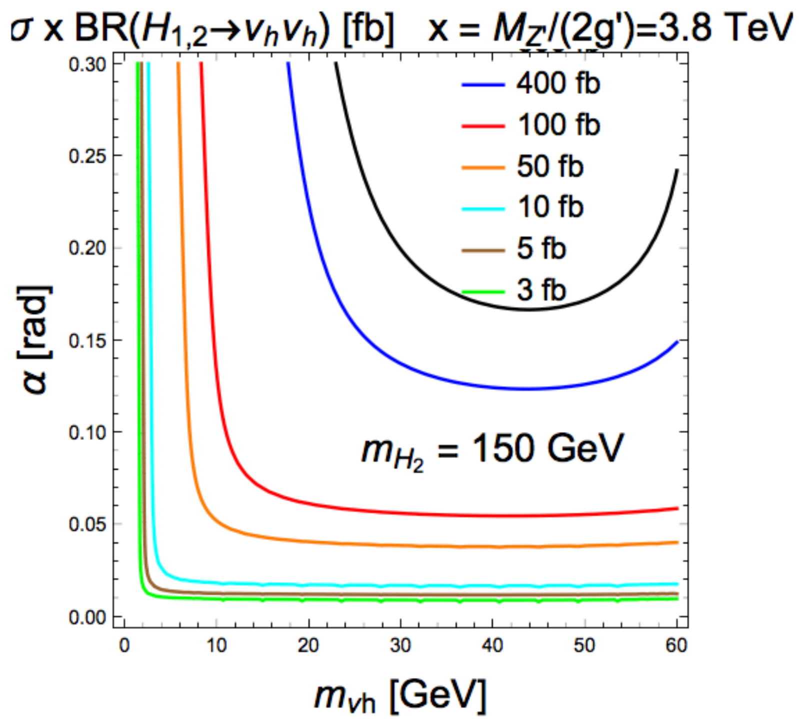




The minimal $U(1)_{B\_L}$ model

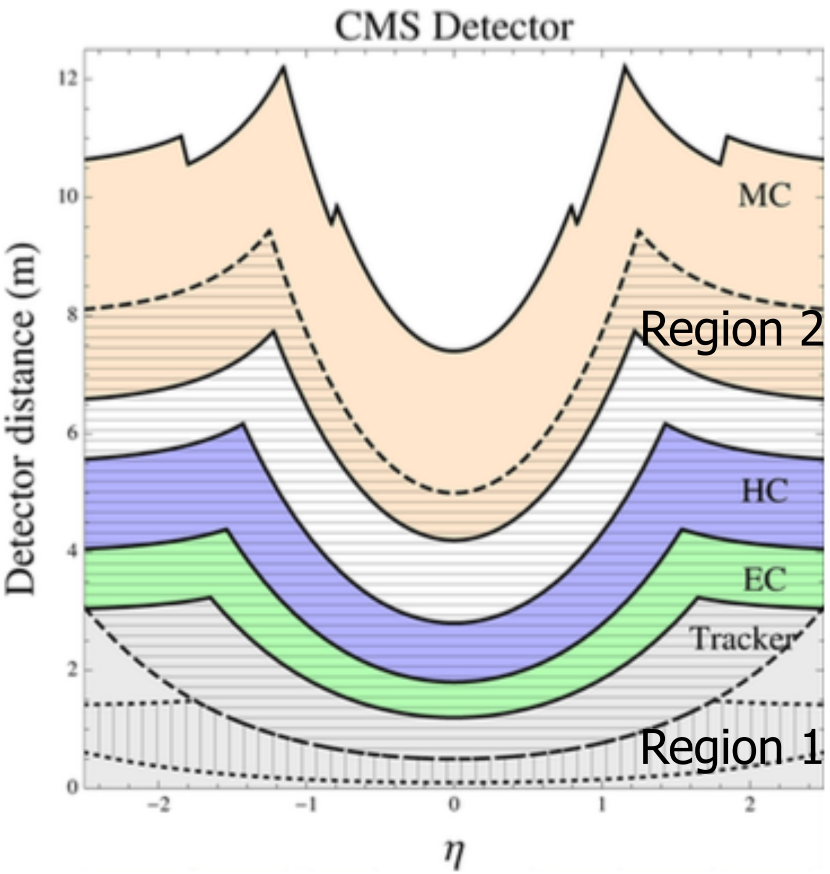
Striking signatures: pp -> h, H_2 -> heavy neutrinos





The minimal $U(1)_{B\_L}$ model

heavy neutrinos decay length and apparatus

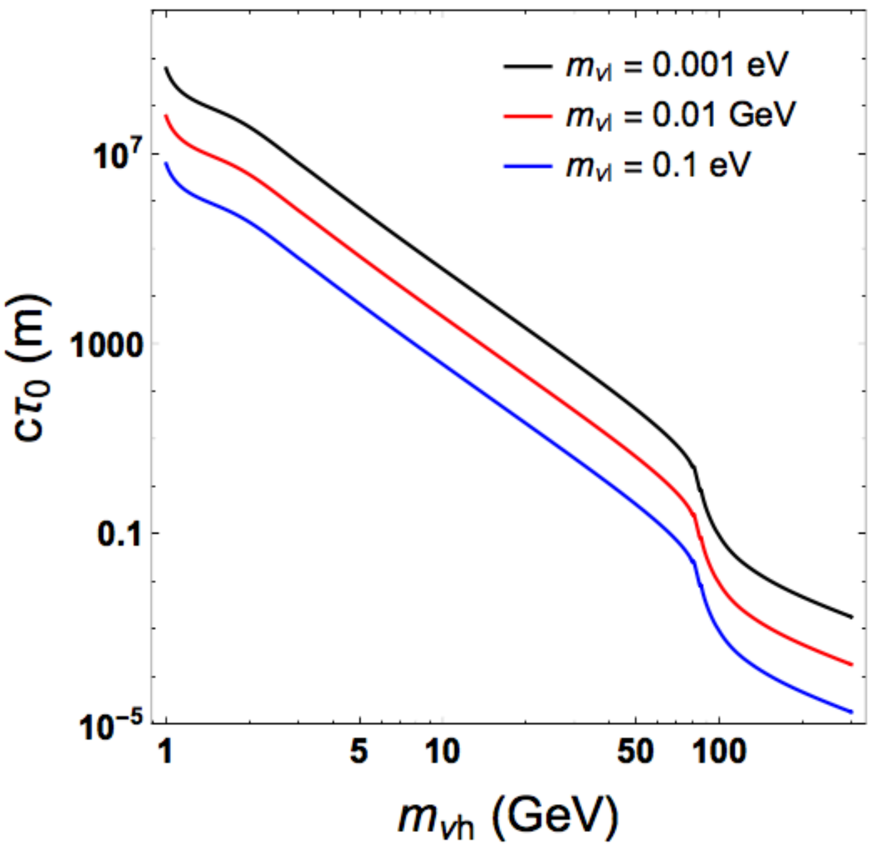


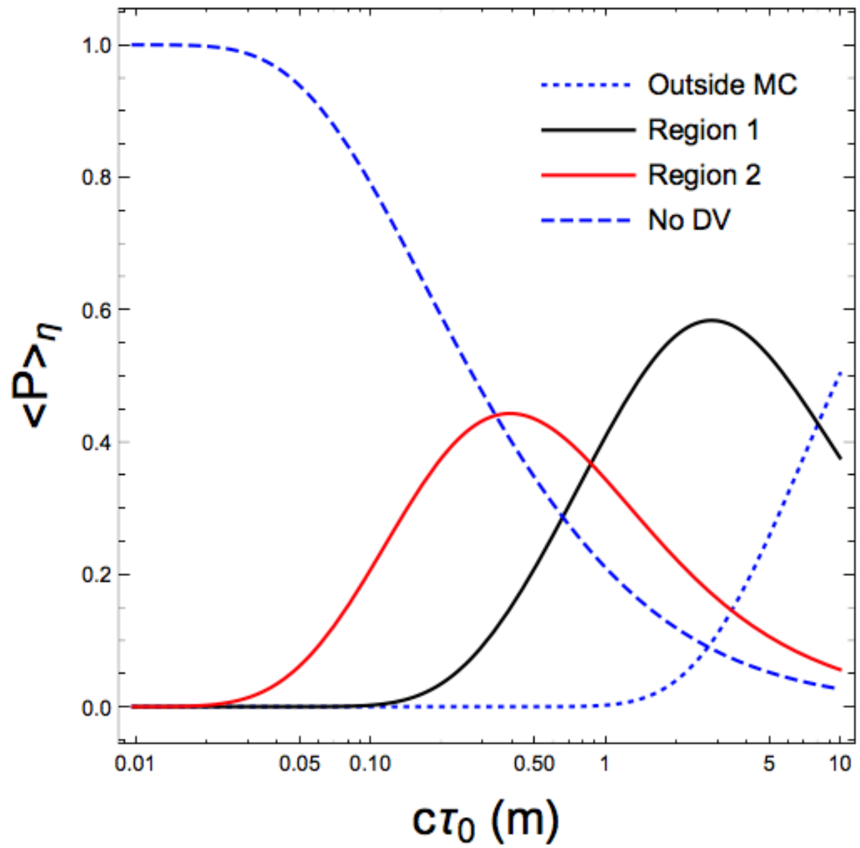
The probability that ν_h would decay in the annulus defined by the radial distances $d_1(\eta)$ and $d_2(\eta)$ is

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

The minimal $U(1)_{B\_L}$ model

heavy neutrinos decay length and apparatus





The minimal U(1)$_{B\_L}$ model

Heavy neutrinos decays

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

Same-sign events
ν_h reconstruction is possible

The minimal $U(1)_{B\_L}$ model

Long lived heavy neutrinos in the muon chamber

pp -> h -> $\nu_h \nu_h$ -> 2l+X, 3l+X or 4l+X (l=e, μ)

	BP1		
	2μ	3μ	4μ
Ev. before cuts	5016	960.2	57.57
p_T cuts	206.7	47.37	3.084
$\|\eta\| < 2$	149.4	32.59	1.965
$\Delta R > 0.2$	147.8	28.42	1.542
$\cos\theta_{\mu\mu} > -0.75$	114	19.33	0.9453
$L_{xy} < 5$ m	100.7	17.59	0.8279
$L_{xy}/\sigma_{L_{xy}} > 12$	63.19	10.62	0.6247
$\|L_z\| < 8$ m	53.97	8.717	0.5086
$\|d_0\|/\sigma_d > 4$	36.46	5.363	0.2764
rec. eff.	29.53	3.909	0.1813

BP1: $m_{\nu h}$=40 GeV, $c\tau_o$=1.5 m

P_T > 26 GeV for the two most energetic muons and P_T > 5 GeV for all the others.

L = 100 fb^{-1}

3 event categories:

2μ-> 2 separated tracks
3μ -> 1 DV + 1 separated track
4μ -> 2 DVs

The minimal $U(1)_{B\_L}$ model

Long lived heavy neutrinos in the inner tracker

pp -> h -> $\nu_h \nu_h$ -> 2l+X, 3l+X or 4l+X (l=e, μ)

	BP4		
	$2l$	$3l$	$4l$
Ev. before cuts	6645	3285	645.2
p_T cuts	206.7	145.5	26.87
$\lvert\eta\rvert < 2$	153.8	99.68	17.51
$\Delta R > 0.2$	148.5	86.45	13.98
$\cos\theta_{\mu\mu} > -0.75$	135	78.52	12.22
$10 < \lvert L_{xy}\rvert < 50$ cm	46.41	27.35	4.474
$\lvert L_z\rvert < 1.4$	41.51	25.17	4.29
$\lvert d_0\rvert/\sigma_d > 12$	40.94	24.96	4.247
rec. eff.	33.16	18.2	2.786

BP4: $m_{\nu h}$=50 GeV, $c\tau_o$=0.5 m

P_T > 26 GeV for the two most energetic muons and P_T > 5 GeV for all the others.

L = 100 fb^{-1}

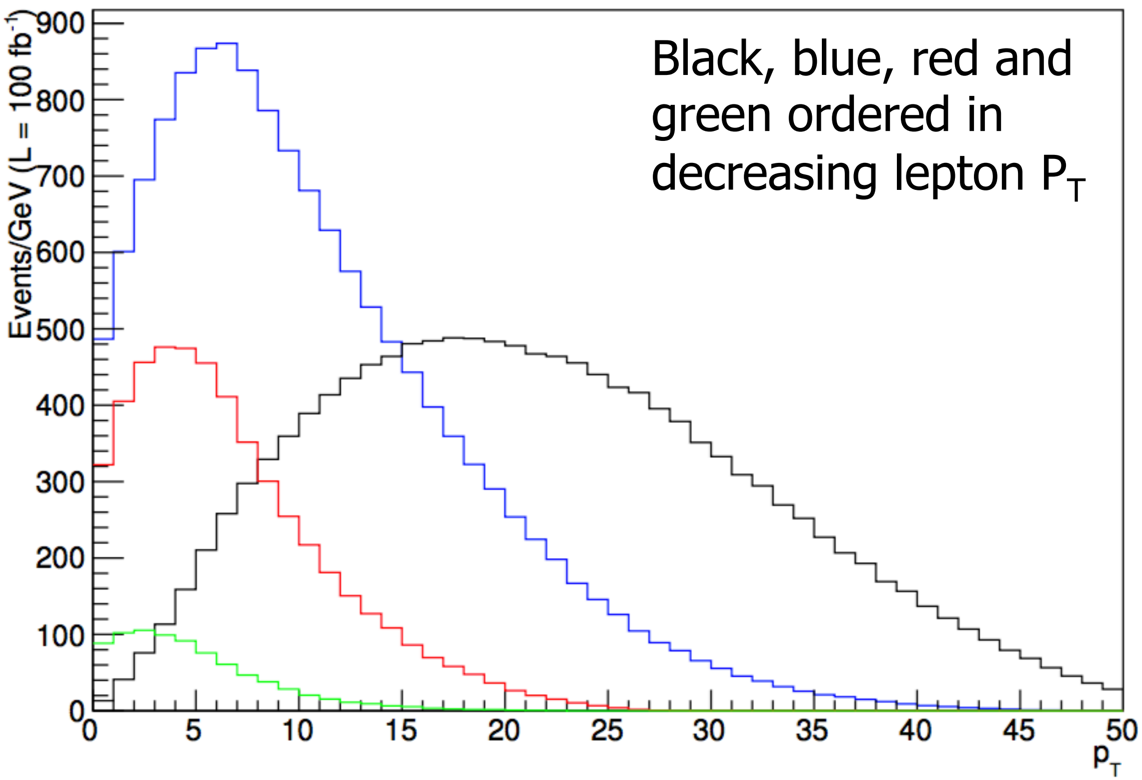
3 event categories:

2l-> 2 separated tracks
3l -> 1 DV + 1 separated track
4l -> 2 DVs

The minimal $U(1)_{B\_L}$ model

Light long lived RH neutrinos ($m_{\nu h} < M_h/2$) and P_T^l

pp -> h -> $\nu_h \nu_h$ -> 2l+X, 3l+X or 4l+X (l=e, μ)



Black, blue, red and green ordered in decreasing lepton P_T

The analysis is very sensitive to trigger thresholds.

The investigation of new displaced tri-lepton triggers is quite worth.

The minimal $U(1)_{B\_L}$ model

Light long lived RH neutrinos ($m_{\nu h} < M_h/2$) and P_T^l

pp -> h -> $\nu_h\nu_h$ -> 2l+X, 3l+X or 4l+X (l=e, μ)

$p_T^{(1)}$/GeV \ $p_T^{(2)}$/GeV	0	1	3	5	7	9	11	13	15	17	19	21	23	25	26
0	100														
1	96.53	94.31													
3	87.26	85.41	79.77												
5	75.78	74.3	69.75	63.69											
7	63.35	62.2	58.66	53.92	48.47										
9	51.75	50.87	48.17	44.52	40.32	36.27									
11	41.65	40.97	38.9	36.12	32.93	29.83	26.92								
13	33.05	32.53	30.95	28.83	26.42	24.11	21.9	19.85							
15	25.83	25.43	24.23	22.61	20.8	19.07	17.44	15.89	14.44						
17	19.82	19.51	18.6	17.4	16.07	14.8	13.59	12.46	11.39	10.44					
19	14.95	14.72	14.04	13.14	12.18	11.25	10.36	9.534	8.754	8.079	7.454				
21	11.06	10.89	10.38	9.731	9.028	8.352	7.721	7.126	6.577	6.108	5.672	5.304			
23	8.039	7.914	7.538	7.068	6.553	6.066	5.616	5.195	4.807	4.485	4.193	3.956	3.756		
25	5.808	5.719	5.442	5.095	4.721	4.37	4.046	3.75	3.483	3.264	3.069	2.922	2.796	2.709	
26	4.907	4.83	4.591	4.289	3.973	3.677	3.406	3.161	2.942	2.764	2.605	2.487	2.389	2.327	2.304

The minimal $U(1)_{B\_L}$ model

Short lived heavy neutrinos ($M\nu_h$ > 100 GeV)

[EA, Delle Rose, Moretti, Oleiya, Shepherd-Themistocleous, preliminary]

pp -> H_2 -> $\nu_h\nu_h$ -> 3l+2j + ETmiss

	BP1	Eff. %	$WZjj$	Eff. %	$t\bar{t}l\nu$	Eff. %	$t\bar{t}$	Eff. %	$S/\sqrt{B}$
No cuts.	148.959	100	75561.3	100	497.759	100	56562.5	100	0.409035
η	109.627	73.6	38495.8	50.95	351.134	70.54	43538.9	76.97	0.381938
p^T	25.1557	22.95	16437.2	42.7	254.054	72.35	12882.5	29.59	0.146279
ΔR	20.8808	83.01	14309.7	87.06	216.271	85.13	0	0	0.17325
$\|M_{jj} - M_W\| < 20$ GeV	20.7898	99.56	1719.47	12.02	29.8004	13.78	0	100	0.497076
$\|M_{l^+l^-} - M_Z\| > 20$ GeV	18.3081	88.06	105.085	6.111	22.7111	76.21	0	100	1.61951
$\|M^T_{vis} - m_{H_2}\| < 50$ GeV	17.9312	97.94	13.5729	12.92	0.952433	4.194	0	100	4.70486
$\|M_{all} - m_{H_2}\| < 50$ GeV	13.8772	75.8	5.59708	5.326	0.304386	1.34	0	100	5.71245

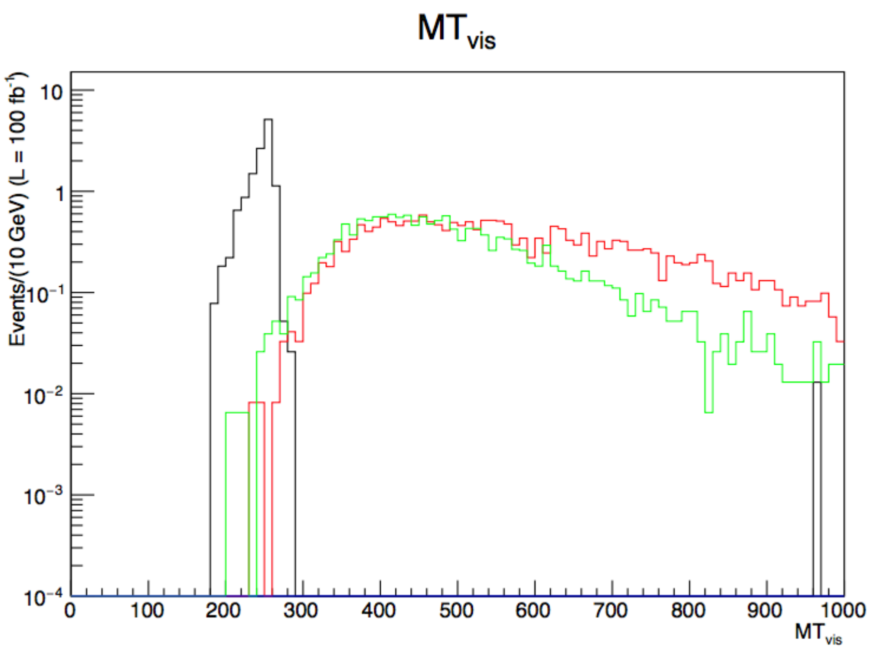
Table 1. Luminosity $\mathcal{L} = 100$ fb^{-1}. basic cuts $= |\eta_l| < 2.5$, $|\eta_j| < 3$, $p^T_{j_{1,2}} > 30$ GeV, $p^T_{l_1} > 30$ GeV and $p^T_{l_{2,3}} > 5$ GeV. ΔR cuts $\equiv \Delta R_{jj} > 0.4 + \Delta R_{lj} > 0.4 + \Delta R_{ll} > 0.3$

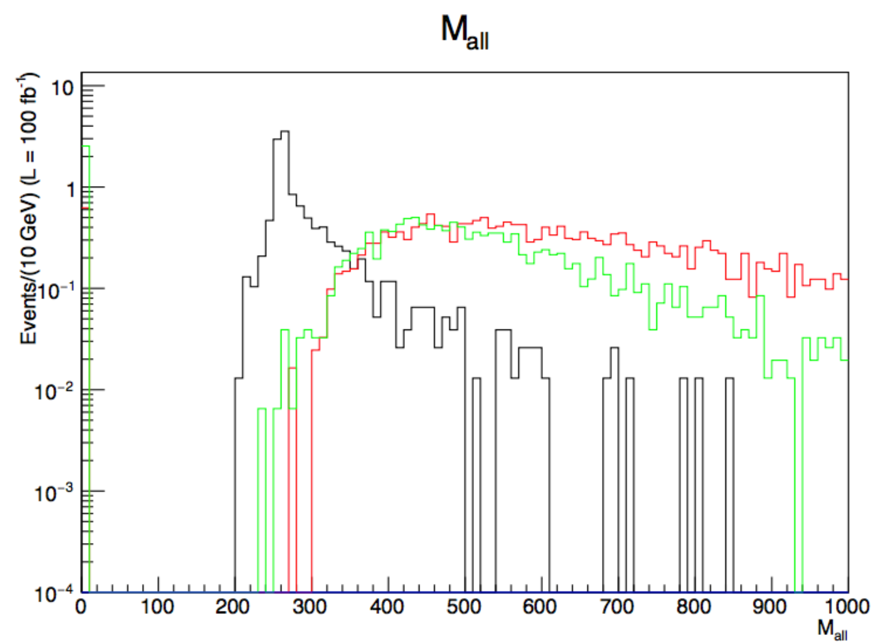
The minimal $U(1)_{B\_L}$ model

Reconstructing the heavy Higgs

pp -> H_2 -> $\nu_h \nu_h$ -> 3l+2j + ETmiss

[m_{H2}=250 GeV, $m_{\nu h}$ = 100 GeV, α = 0.3, $M_{Z'}$ = 5 TeV, g'=0.65]



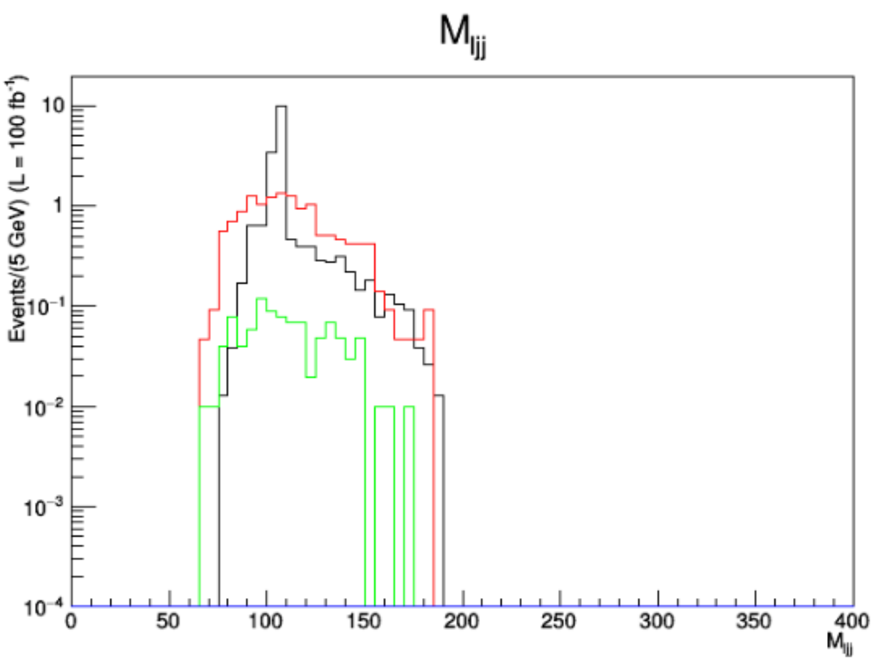


The minimal $U(1)_{B\_L}$ model

Reconstructing the heavy neutrino

pp -> H_2 -> $\nu_h \nu_h$ -> 3l+2j+ETmiss

[m_{H2}=250 GeV, $m_{\nu h}$ = 100 GeV, α = 0.3, $M_{Z'}$ = 5 TeV, g'=0.65]



After applying the cut

$|M^T_{vis} - M_{H2}| < 100$ GeV

Conclusions

Long-Lived particles is a rich framework for BSM searches

- A heavy LLPs naturally appear in a variety of theories
- Within the $U_{B-L}(1)$, the discovery of LL heavy right-handed neutrinos would have important cosmological implications (probe the type of seesaw mechanism, test of leptogenesis, …)
- Generally, striking signatures aside, at times involved, i.e. new experimental challenges ahead especially on trigger thresholds.

Always a step forward