High mass resonances: extra gauge bosons, and/or other exotics.

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Outlook

- **Z′ Physics**

  Z′-bosons: LHC data interpretation and mass limits
- **W′ Physics**

  W′-bosons: interference effects and LHC data analysis
- **and/or other particles**

  A class of minimal and anomaly-free Z′ models with

  - extended Higgs sector and long lived RH neutrinos

  - striking signatures and experimental challenges

  - cosmological implications

Z′ physics

Single and multiple Z′-bosons are a natural product of many BSM theories [Langacker, arXiv:0801.1345]

Single Z′

(i) Extra U(1): E6, Left-Right models, B-L motivated

(ii) Extra SU(2): 2HDM, SSM

Multiple Z′

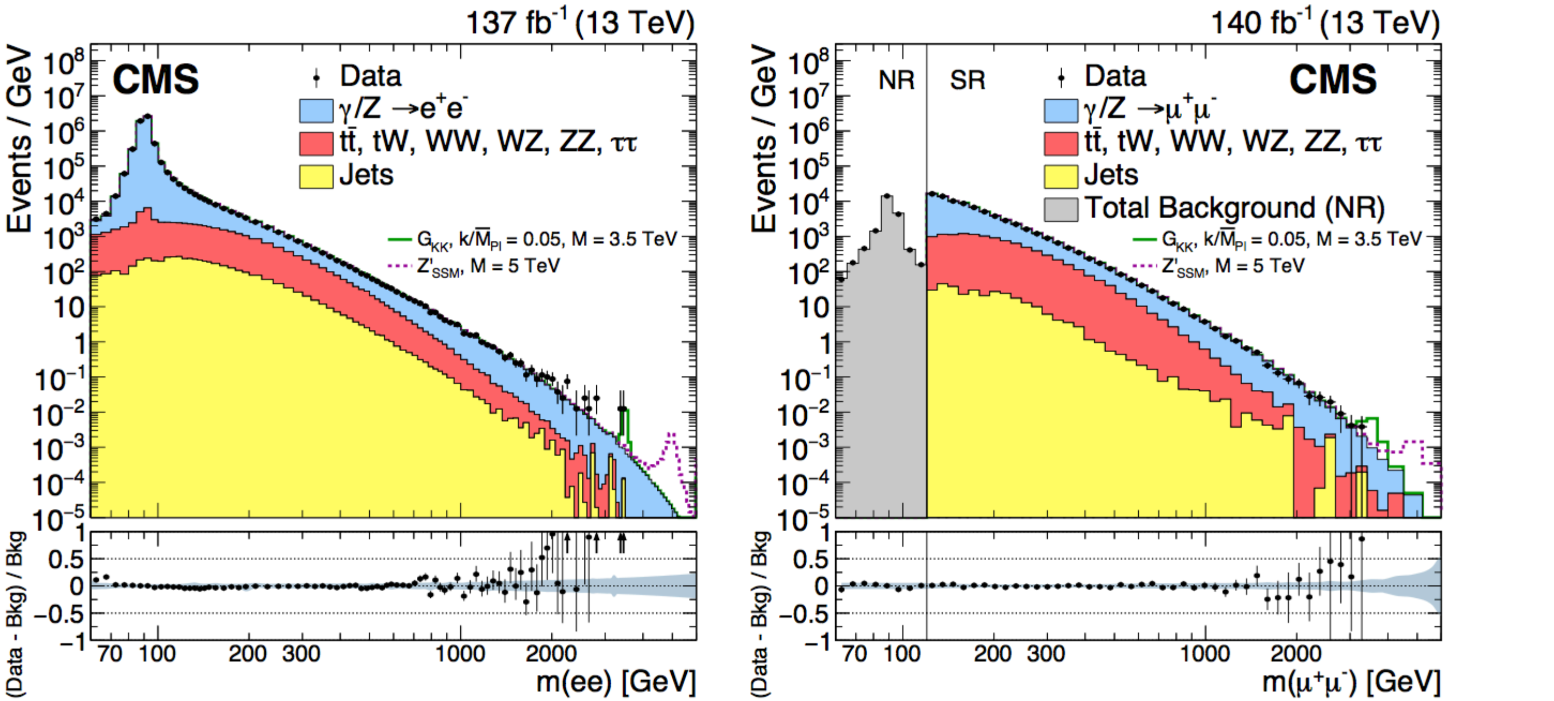
(i) Technicolor [the CP^3 school]

(ii) Extra Dimensions [UED and NUED]

(iii) Composite Higgs models

Z'-boson search strategy

The Drell-Yan channel: pp -> γ, Z, Z' -> l^+l^-



CMS – arXiv:2103.02708

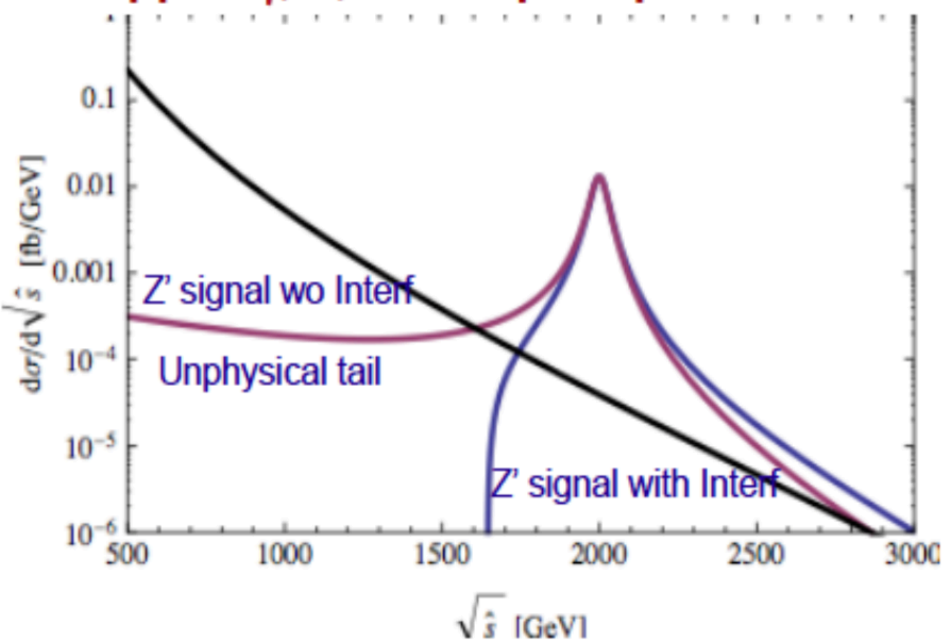
Signal: Breit-Wigner convoluted with a Gaussian Resolution function.

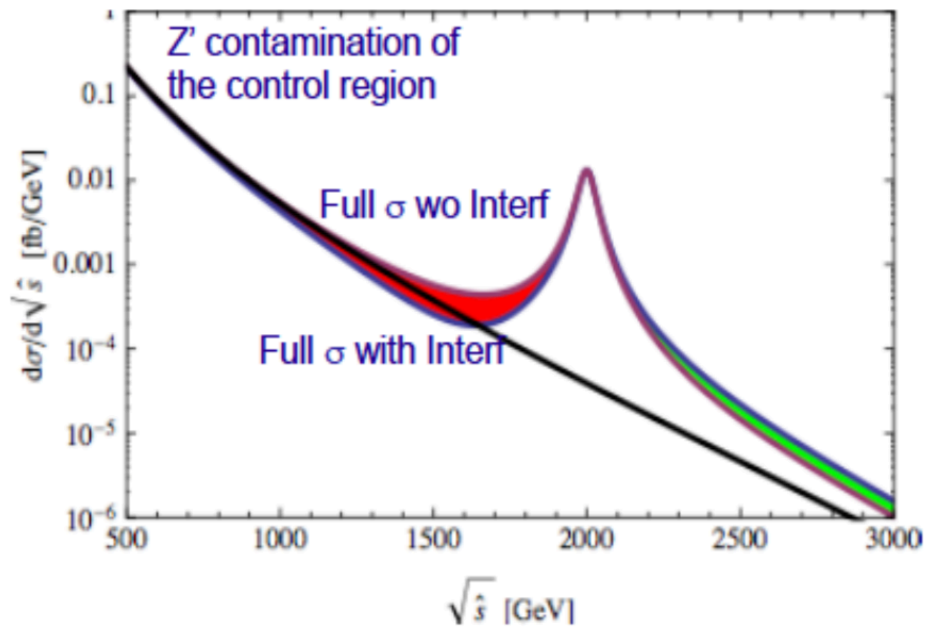
SM Backg.: Data, MCEG and functional form $m^{-k}e^{-\alpha m}$

Z’-boson search strategy

EA, Becciolini, Belyaev, Moretti, Shepherd-Themistocleus – arXiv:1304.6700

pp → γ, Z, Z’ → lepton pair

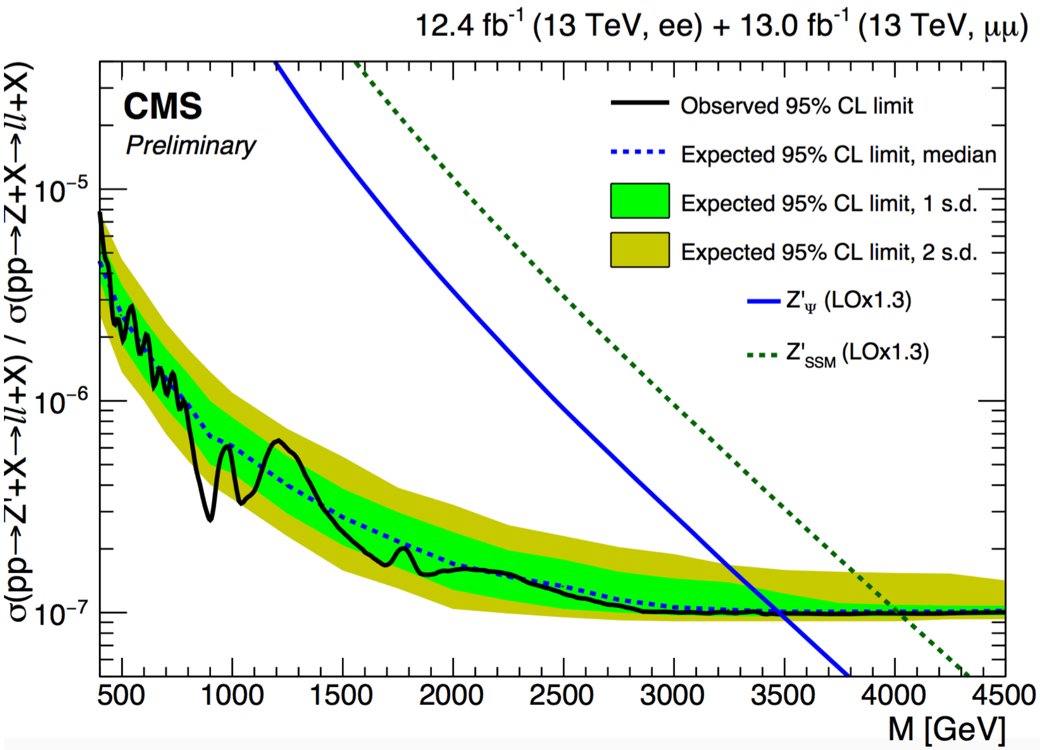




Interference effects are sizeable and model dependent. The optimal cut |M(ll)-MZ’| < 5% E_{LHC} reduces them to O(10%) for all single narrow Z’s thus allowing for model-independent analyses.

From 2014, implemented in all di-lepton analyses within CMS.

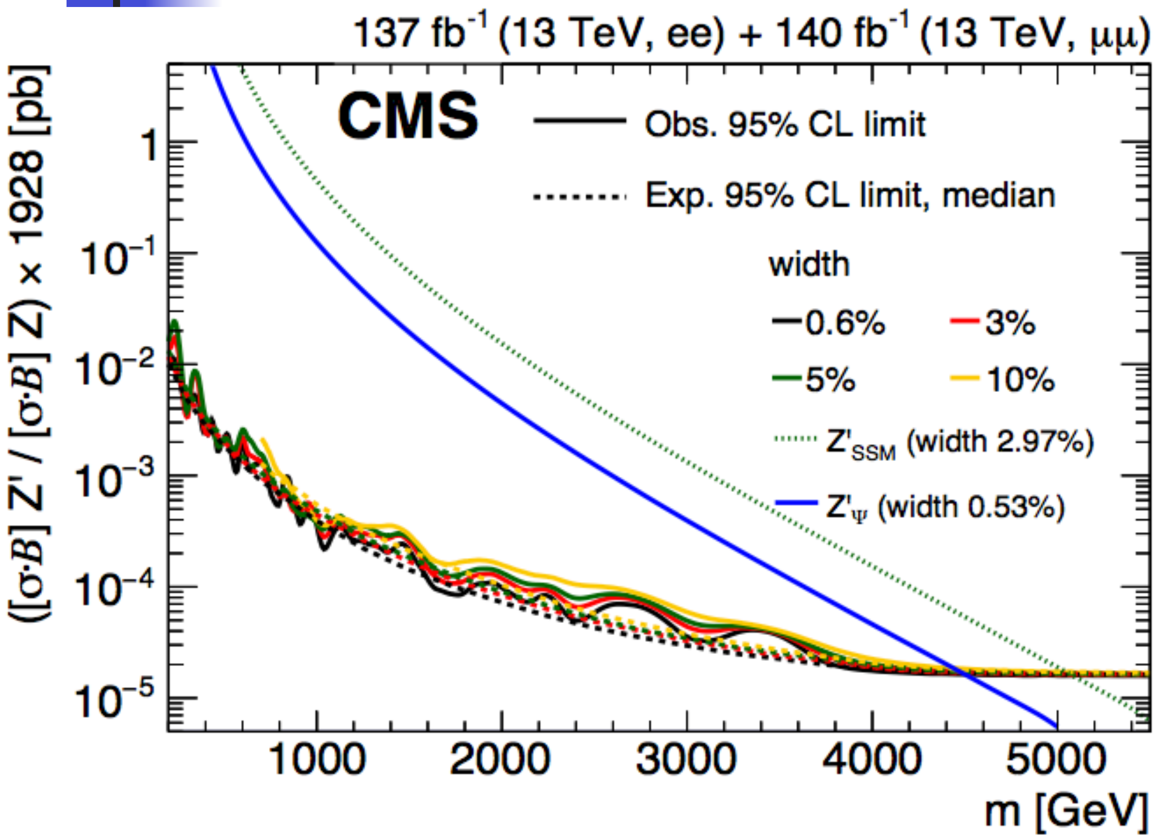
95% C.L. Exclusion Limits



Model independent searches for heavy narrow spin-1 resonances decaying into lepton pairs via the Drell-Yan channel pp -> l^+l^- (l=e, μ) in 2014.

Based on EA, Becciolini, Belyaev, Moretti, Shepherd-Themistocleous arXiv:1304.6700.

95% C.L. Exclusion Limits

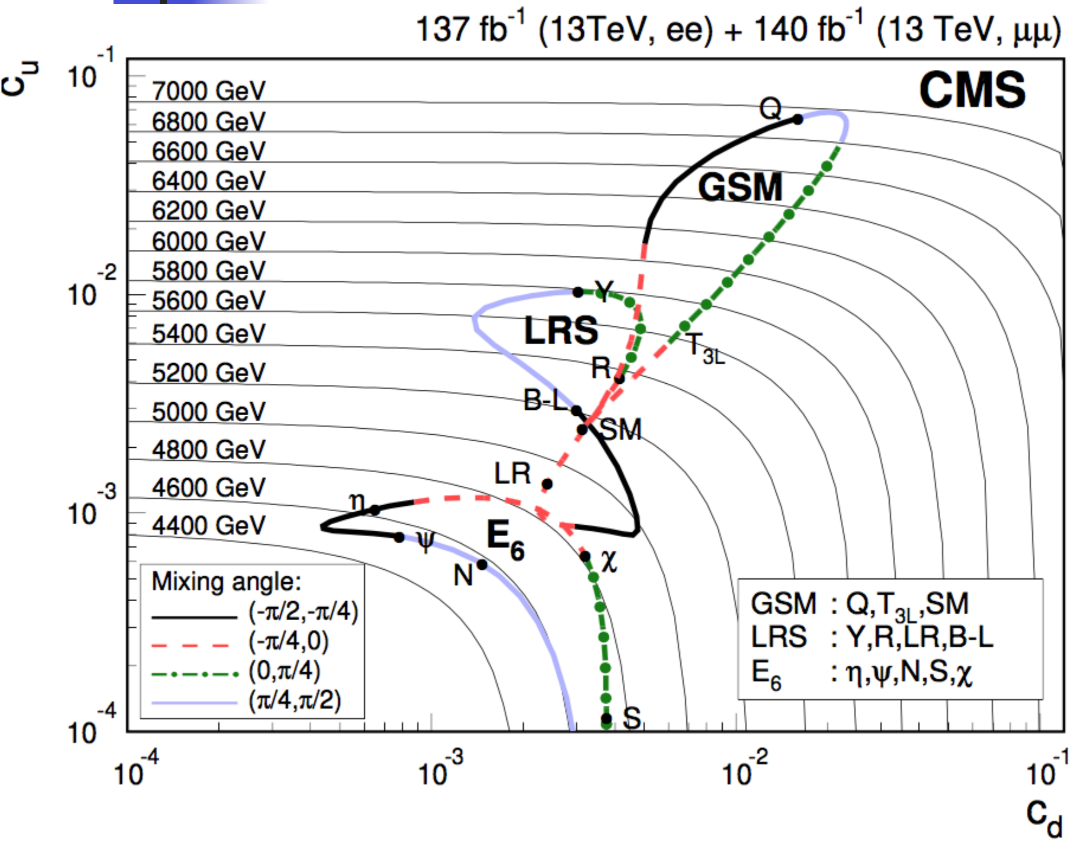


Model independent searches for heavy narrow spin-1 resonances decaying into lepton pairs via the Drell-Yan channel pp -> l^+l^- (l=e, μ) in 2021.

[CMS – arXiv:2103.02708]

An increase of a factor of 10 in luminosity has extended the Z′ mass bounds by ~1 TeV. Now we are at **$M_{Z'}$ > 4.5 TeV**.

95% C.L. Exclusion Limits



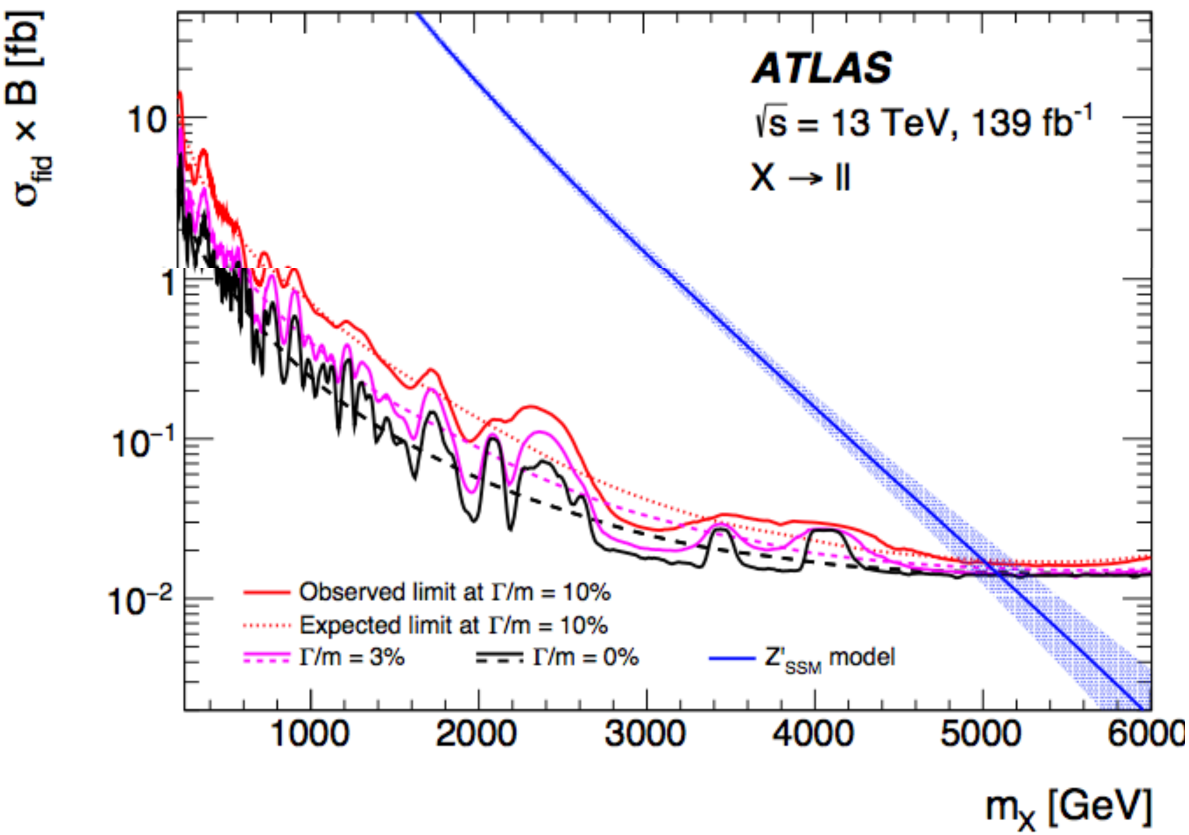
High invariant mass di-lepton search in the Drell-Yan channel pp -> l^+l^- (l=e, μ).

[CMS – arXiv:2103.02708]

The cu-cd parametrization was proposed in 2011 by EA, Belyaev, Fedeli and King [arXiv:1010.6058] and has been used in CMS since then.

L~140 fb^{-1} pushes the mass limits towards Z_{ψ} > 4.5 TeV and Z_Q >7 TeV.

95% C.L. Exclusion limits

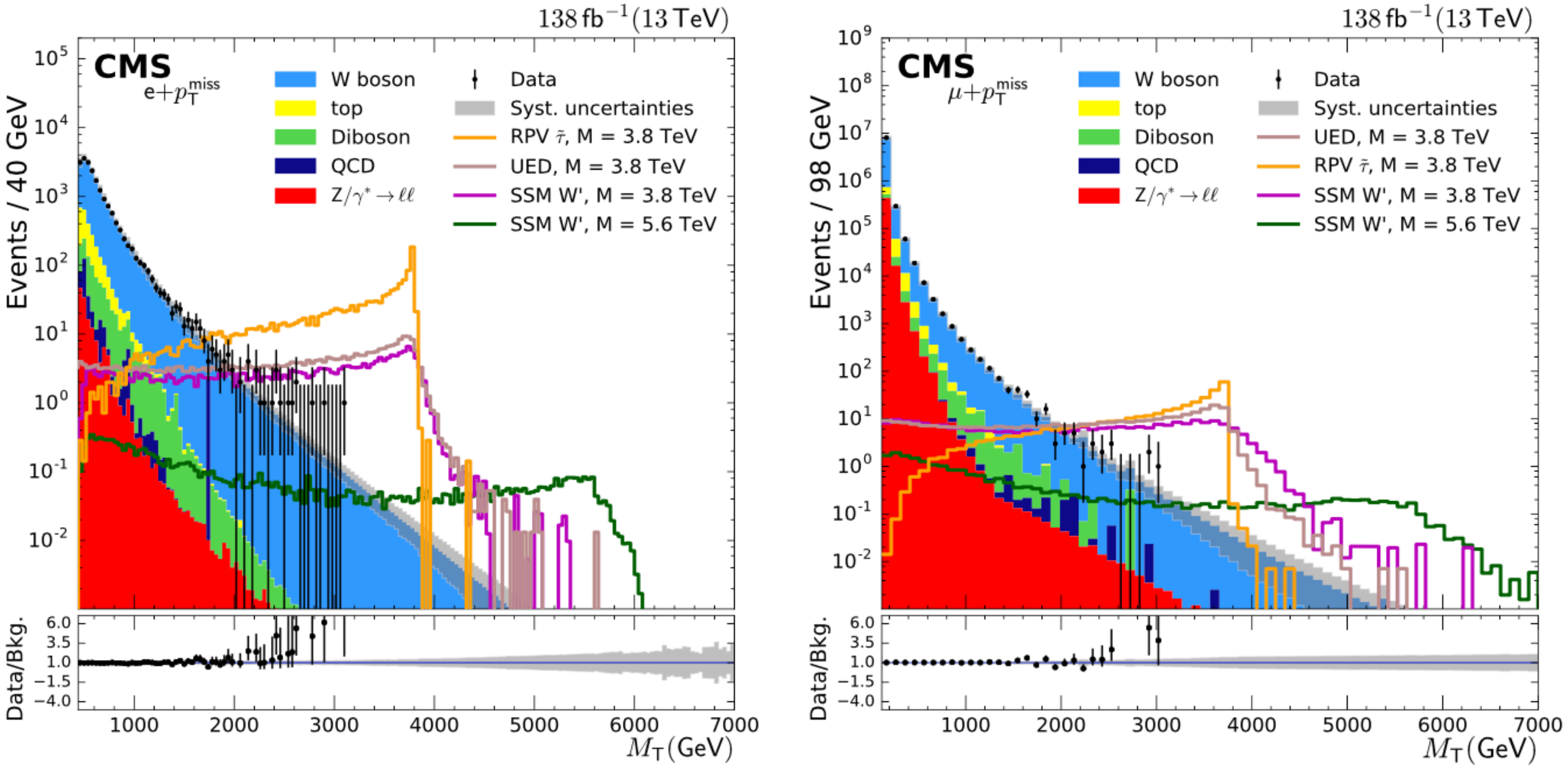


ATLAS has implemented a similar search strategy and signal modelling with $M_{ll} > M_x - 2\Gamma_x$.

[arXiv:1903.06248]

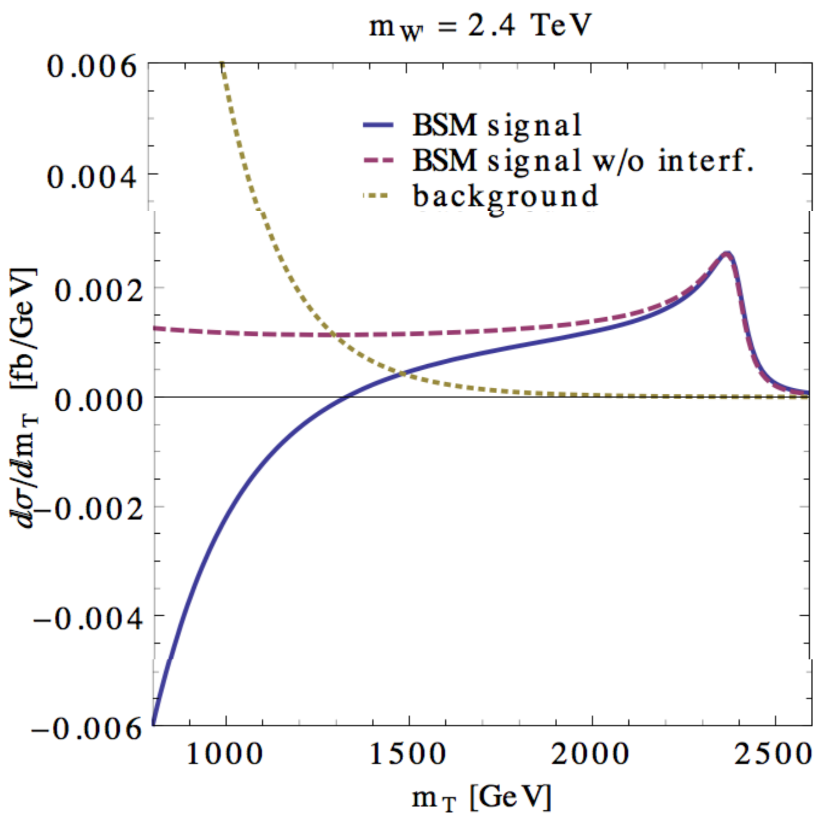
W'-boson search strategy

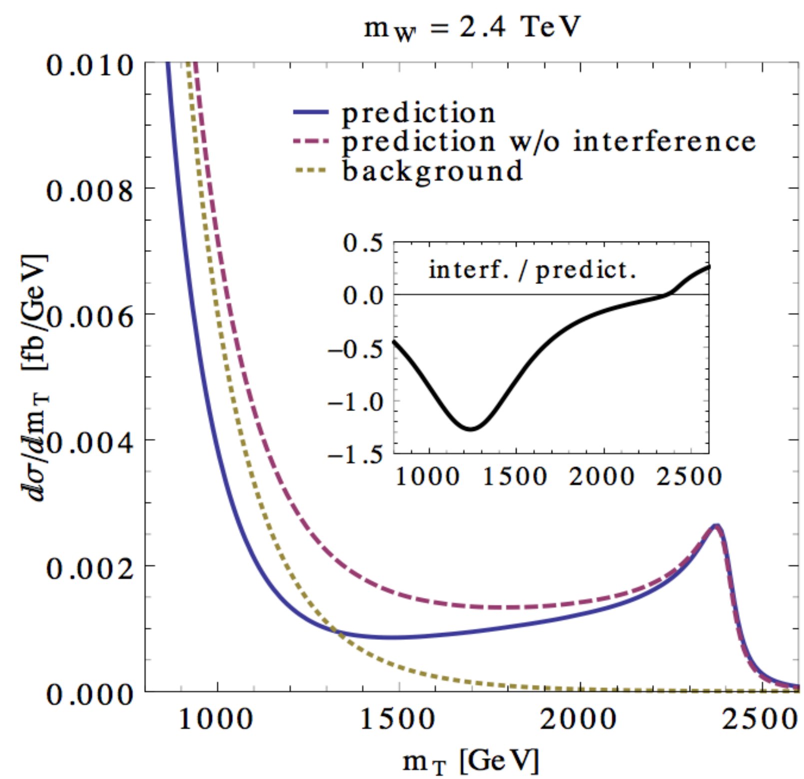
The Drell-Yan channel: pp -> W, W' -> lν_l



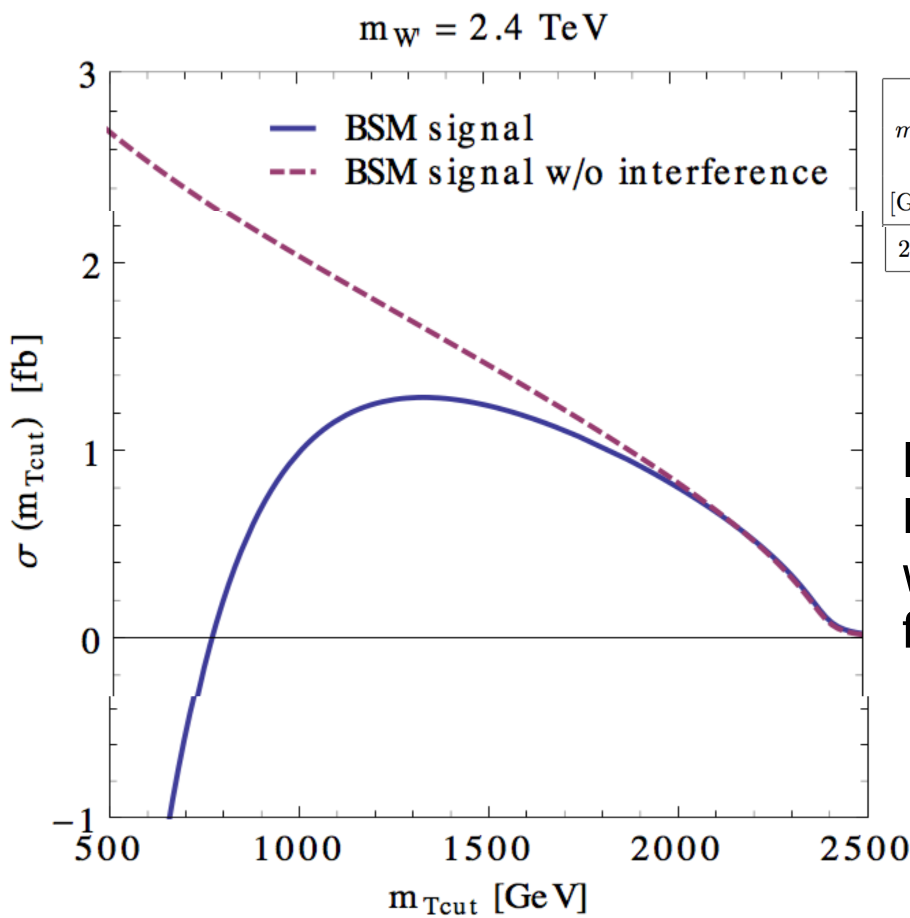
CMS – JHEP07 (2022) 067

W’-boson signal shape





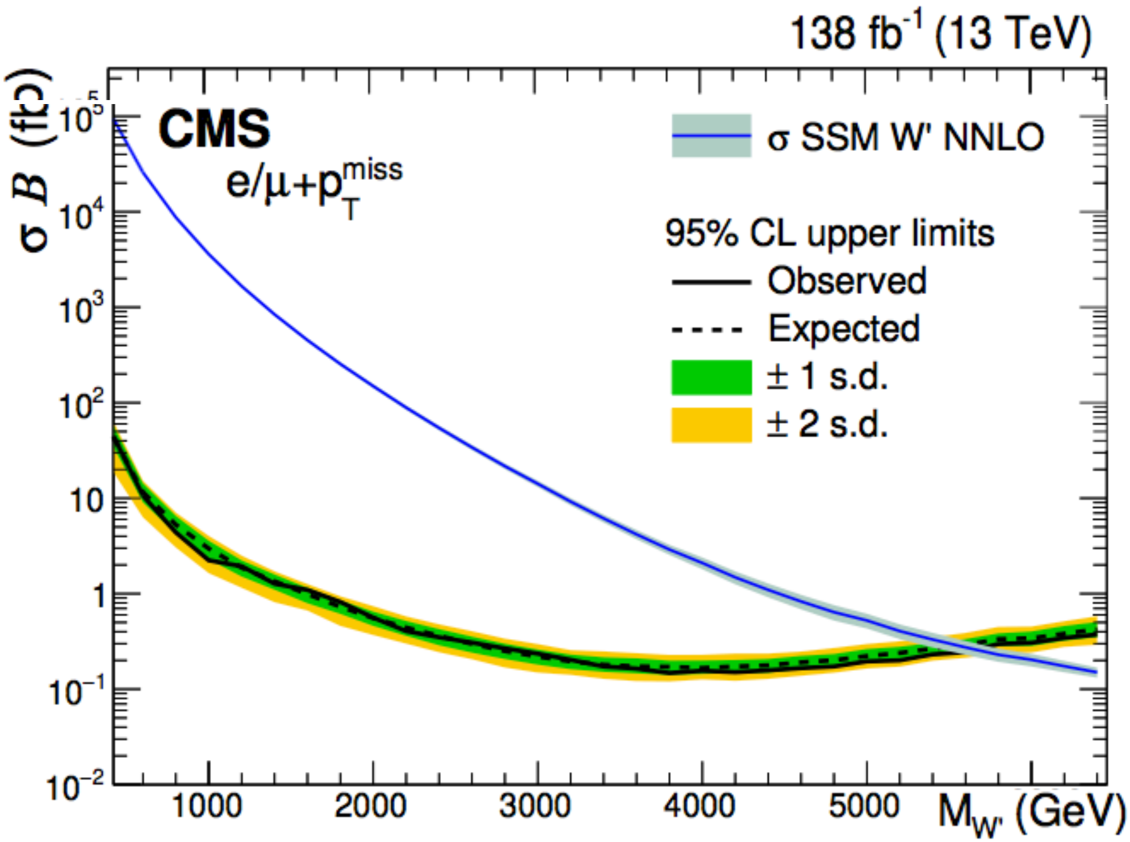
Expected cross-section: interference and M_T cuts



$m_{W'}$ [GeV]	$m_{T\text{cut}}$ [GeV]	σ ($m_{T\text{cut}}$) [fb] signal no interf.	signal with interf.	diff. in %	SM backgr.	σ total [fb] signal no interf.	signal with interf.
2400	1100	1.9	1.2	64	0.6	3.7	−45.6

Presenting the exp. results with a M_{Tcut} is essential to interpret the data within a more general theoretical framework.

95% C.L. upper bound on the SSM W'-boson

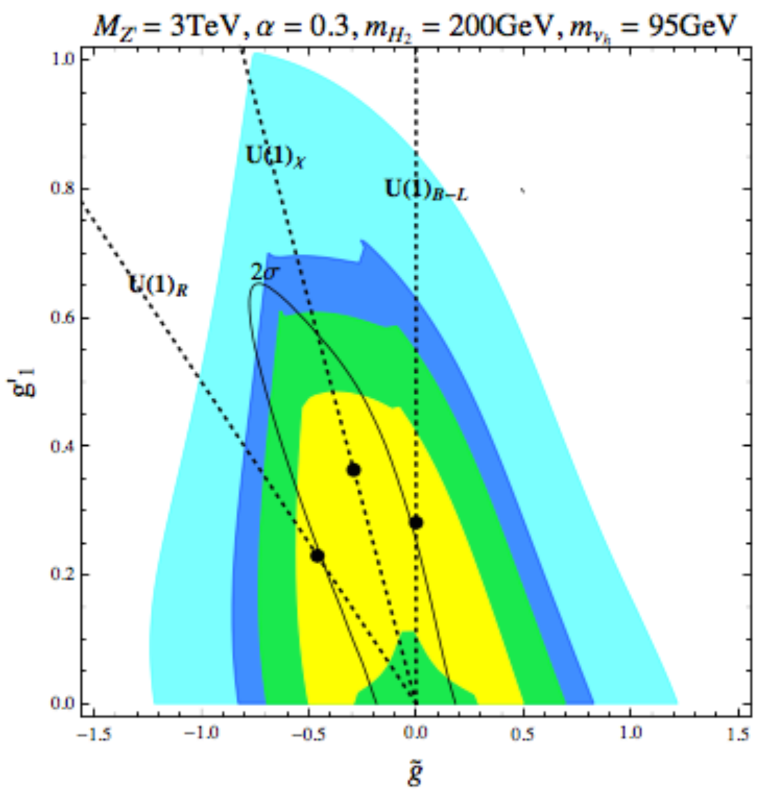


This is strictly valid only for a W'_R-boson uniquely interacting with right-handed leptons so that the interference with the SM W-boson is null.

In a standard SSM the signal cross section would be 6 times smaller pushing back the limit by ~1TeV.

The minimal $U(1)_{B\_L}$ model: Z', extra Higgs and LLPs

[EA, Delle Rose, Coriano', Moretti, Shepherd-Themistocleous, 1612.05977, 1605.02910, 1708.03650, 1806.07396]



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

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

A generalized theory where different combinations of couplings can recover the benchmark Z' models.

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

Rich phenomenology and cosmological implications

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

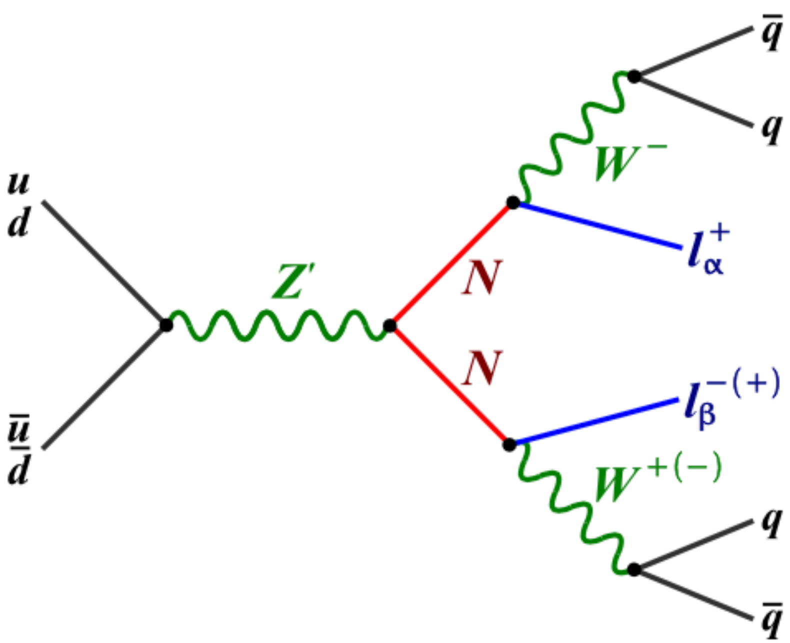
they acquire a Majorana mass and naturally implement the Type I seesaw mechanism. If close to degeneracy, they can give rise to a low-scale resonant leptogenesis, explaining the matter-antimatter asymmetry (talk by Juraj Klaric).

1 extra Higgs singlet H_2

that gives mass to Z′ and $\nu_{h,}$ and generates an exotic heavy neutrino coupling to the SM-like Higgs via the α mixing between the two Higgses.

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

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



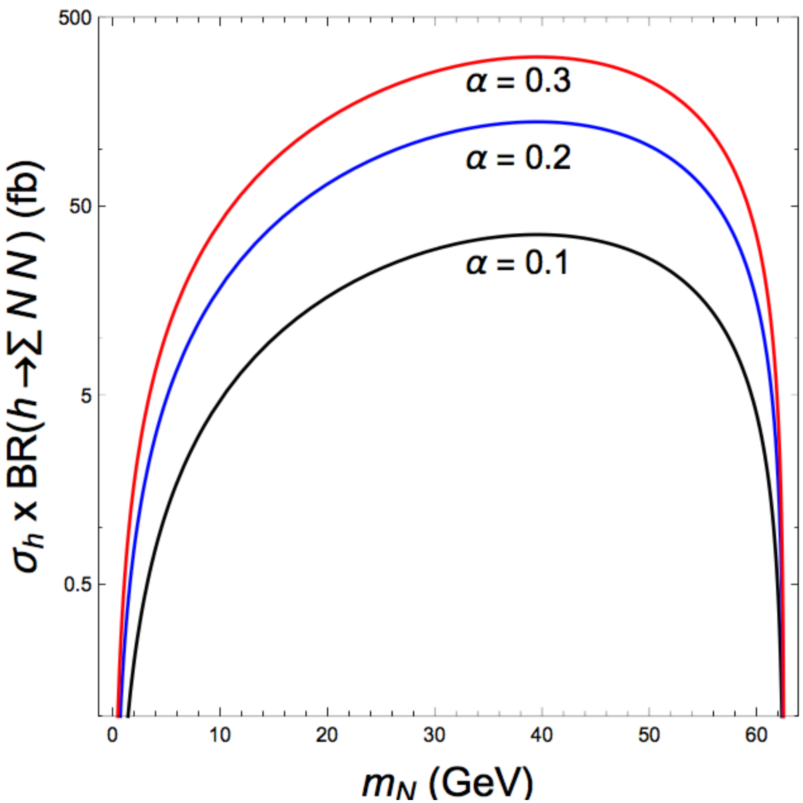
Cross section of order 1 fb for $M_{Z'} < 5$ TeV.

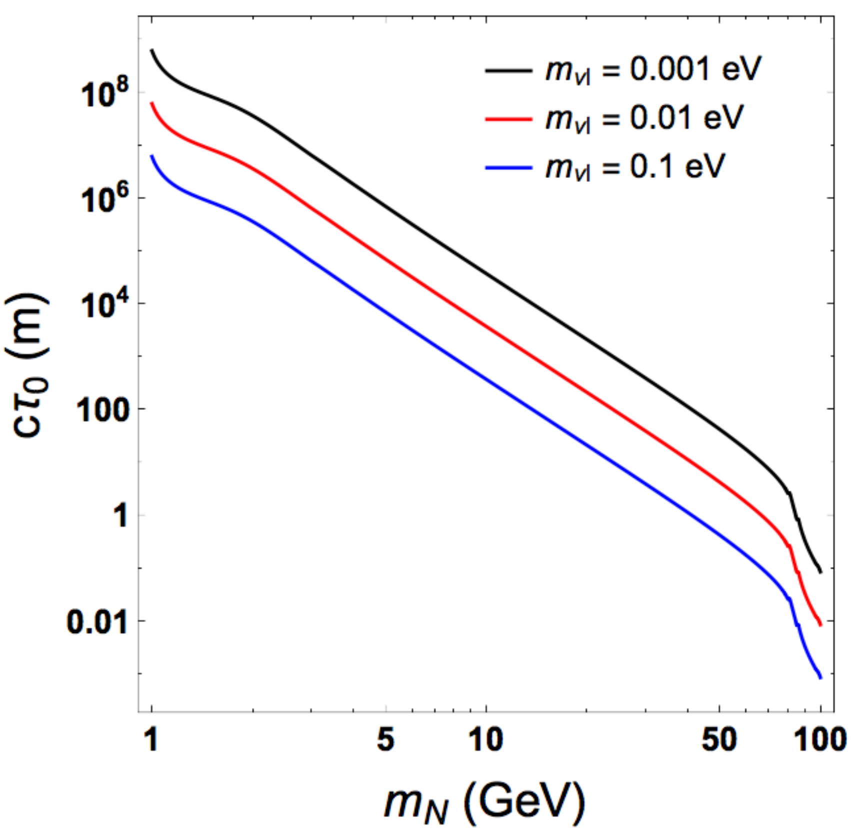
Exploring fat jet and jet substructure to enhance S/B
[EA, Delle Rose, Moretti, Oleiya, Shepherd-Themistocleous]

The RH neutrino decay is proportional to the neutrino mixing $V_{\alpha i}^2 \sim m_\nu/m_N$. So, the RH neutrinos can be Long-Lived Particles (LLP).

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

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





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
$\lvert\eta\rvert < 2$	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
$\lvert L_z\rvert < 8$ m	53.97	8.717	0.5086
$\lvert d_0\rvert/\sigma_d > 4$	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, L = 100 fb^{-1}

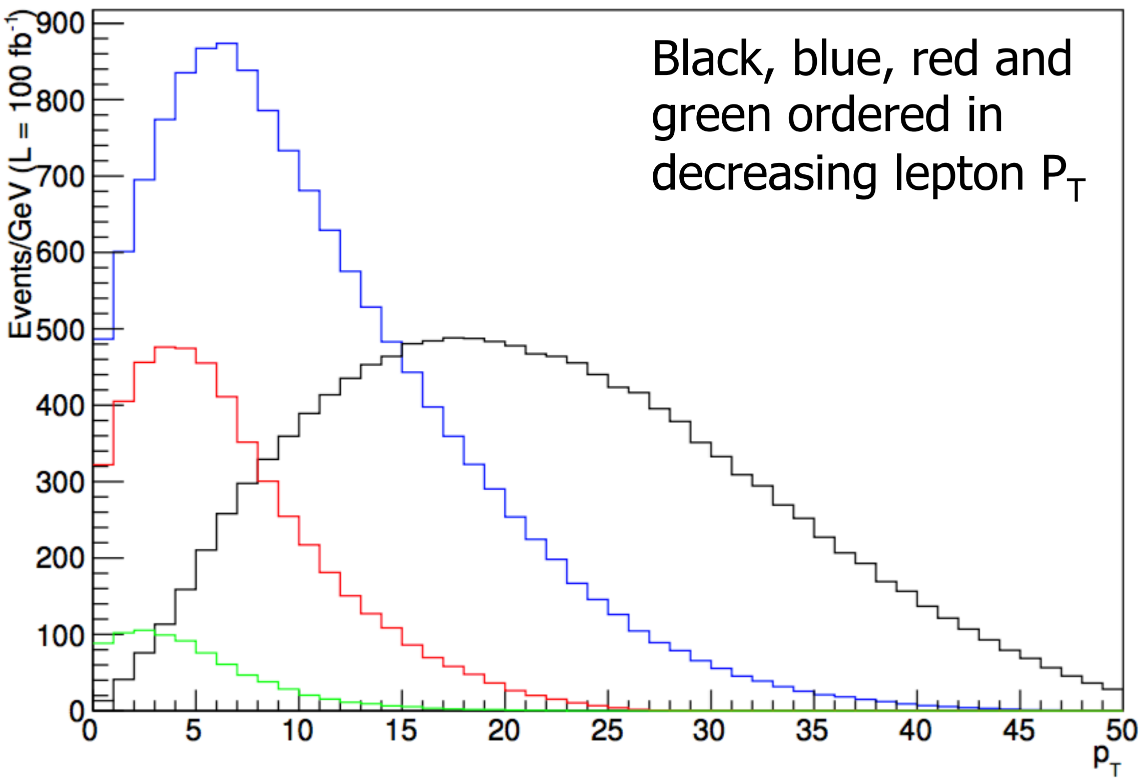
3 event categories:
2μ-> 2 separated tracks
3μ -> 1 DV + 1 separated track
4μ -> 2 DVs

Trigger thresholds:
P_T > 26 GeV for the two most energetic muons and P_T > 5 GeV for all the others has an efficiency of 4%.

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)



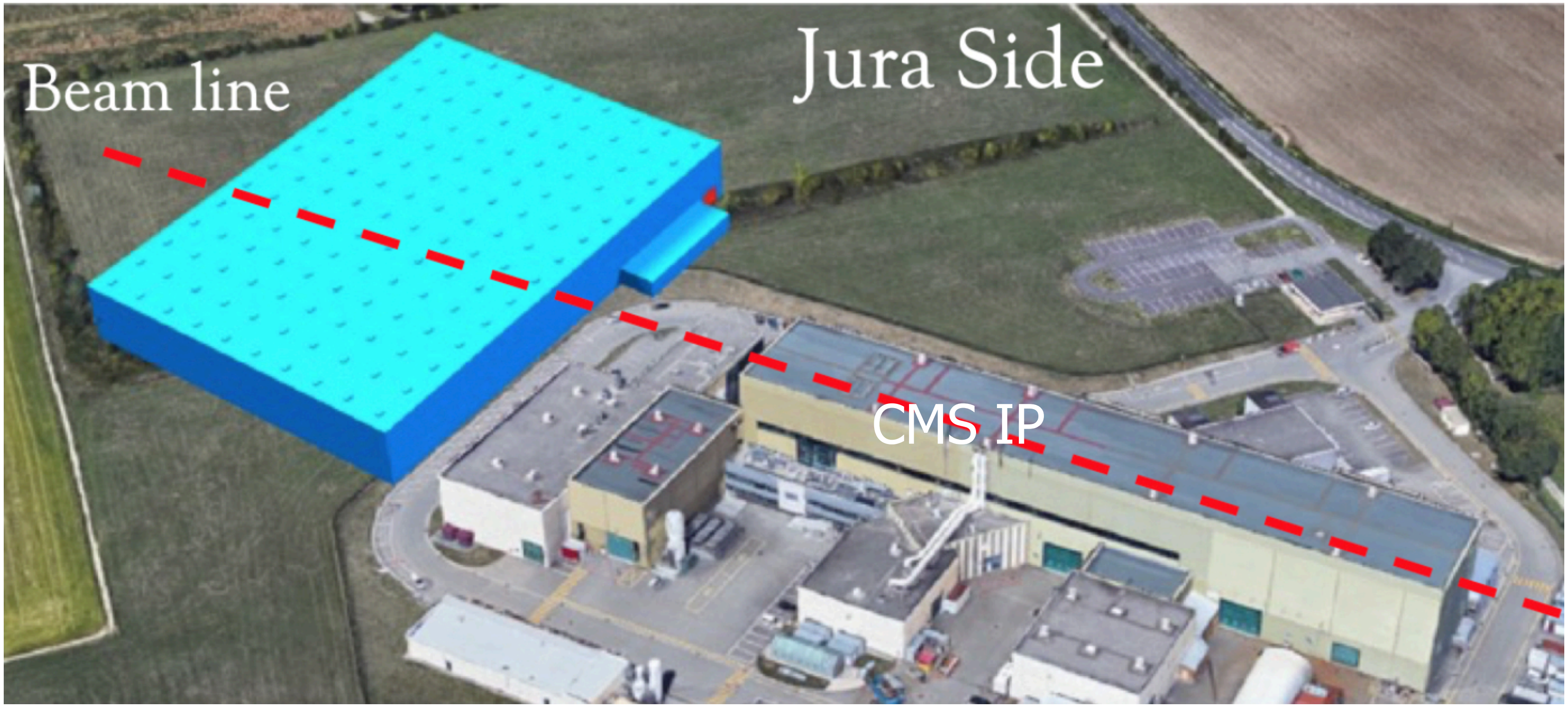
The analysis is very sensitive to trigger thresholds.

The investigation of a new search strategy with novel displaced tri-lepton triggers is worth consideration.

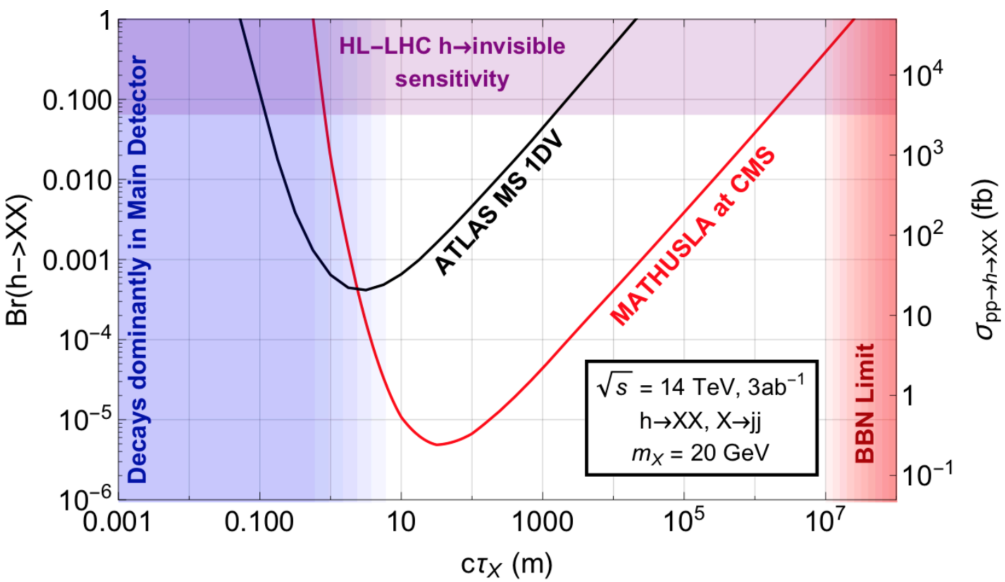
But, despite the efforts, the 4 main LHC detectors, ALICE, ATLAS, LHCb and CMS, are not built to detect soft neutral LLPs.

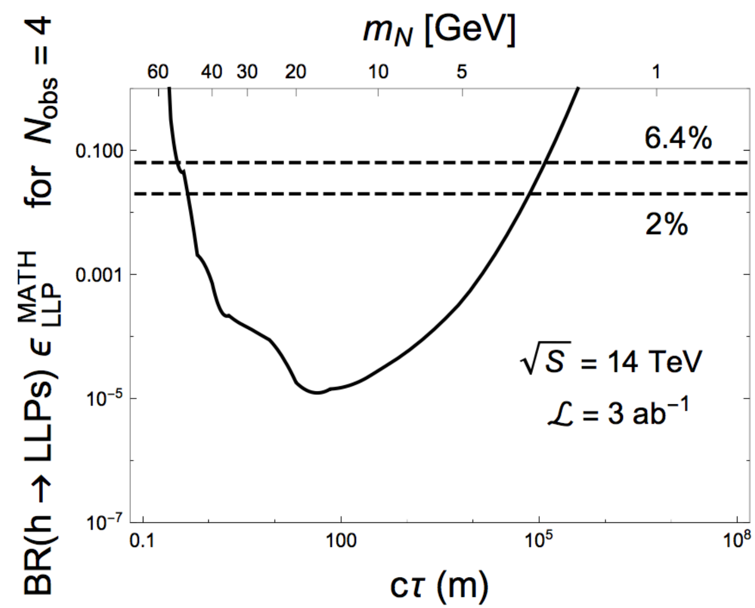
Future prospects (Exp)

- **Mathusla** – the large-volume detector for the HL-LHC (2025) nearly background free and with no trigger limitations would be ideal for light neutral LLPs decaying into leptons and jets with low transverse momentum.



Future prospects (Exp-Ph)





Sensitivity to a hidden sector model with a SM-like Higgs decaying into two neutral scalar LLPs.

Sensitivity to the $U(1)_{B-L}$ model from the process pp -> h -> ΣNN.

Conclusions

Z′ physics is a rich framework for BSM searches

- An heavy extra Z′-boson naturally appears in a variety of GUT theories (E_6, GLR, GSM, B-L, Technicolor, Composite Higgs, …)
- Its discovery would have important cosmological implications (probe the type of seesaw mechanism, test of leptogenesis, …)
- Striking signatures are ready for the present LHC Run3 and the HL-LHC upgrade in DY and LLPs channels. The new and proposed detectors for Forward Physics are highly wanted.

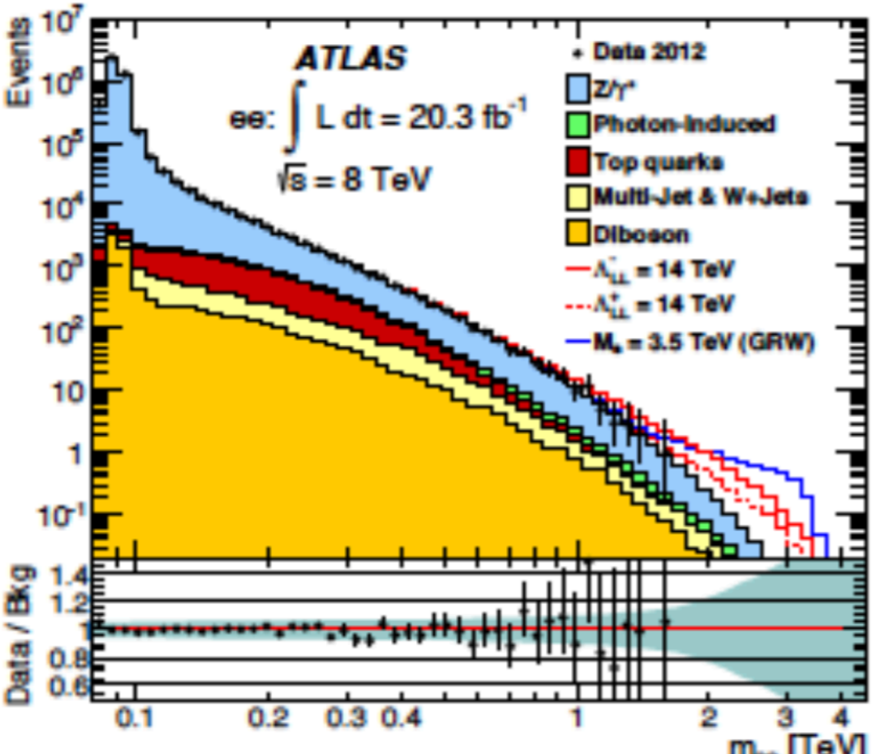
W′ physics is equally important but the data analysis should be extended to help interpreting the results.

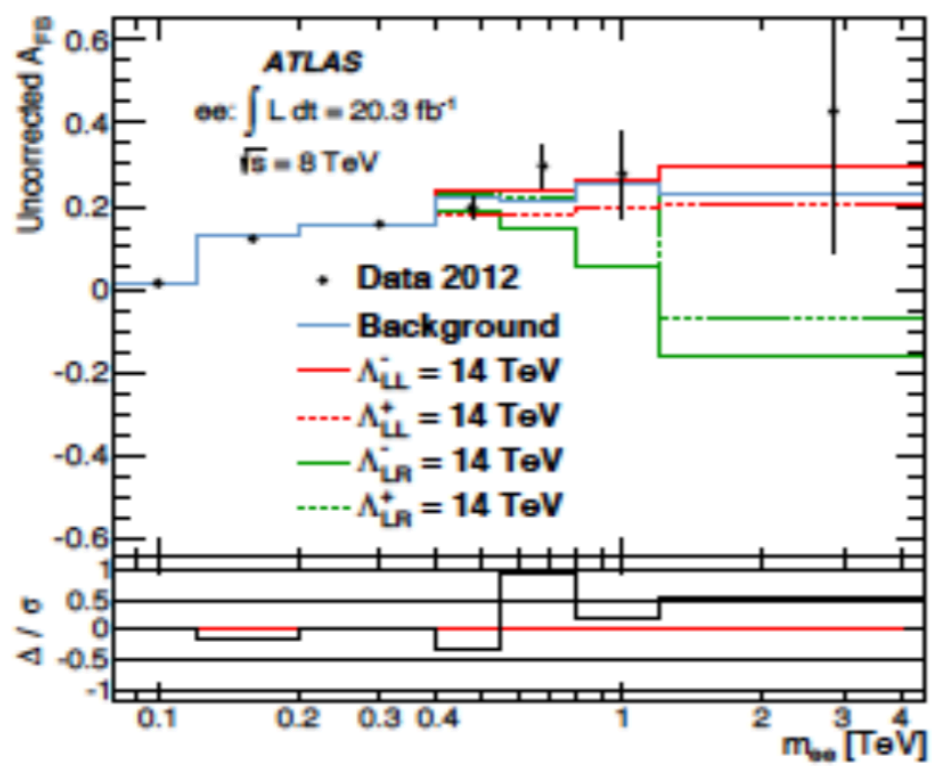
Always a step forward

Wide Z' resonance

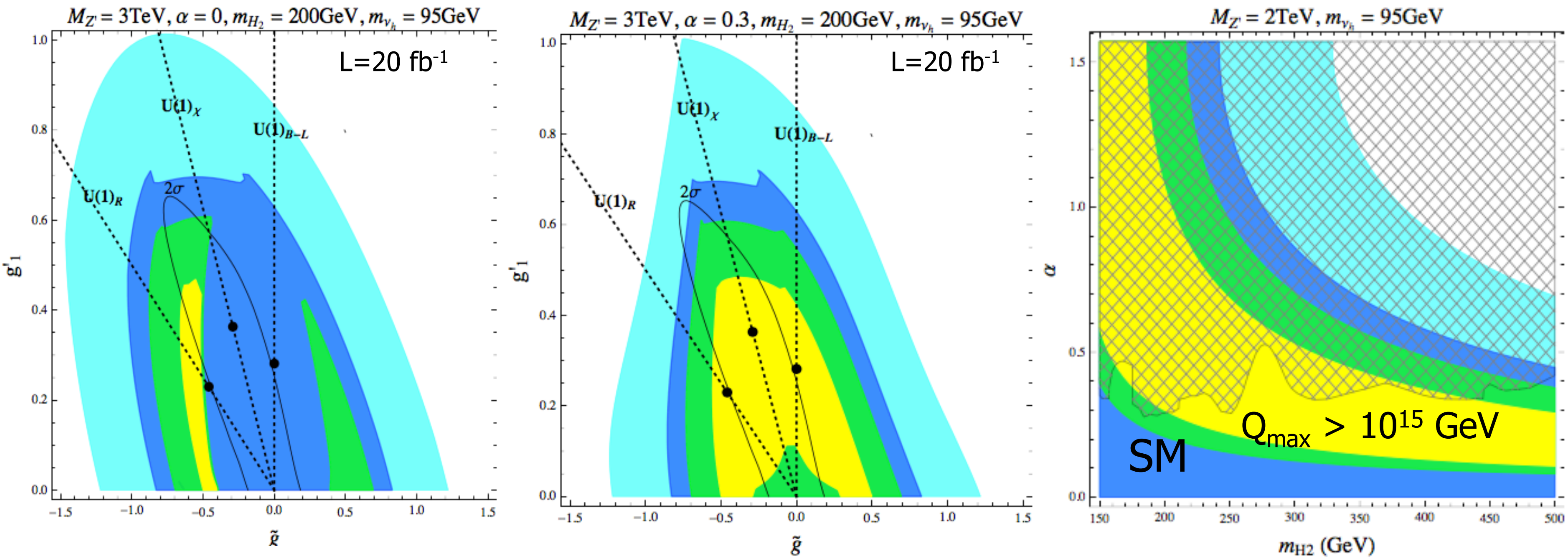
Might have escaped detection. One needs combined observables to optimize the searches. [ATLAS 1407.2410; EA, Belyaev, Fiaschi, Mimasu, Moretti,1503.02672; +xFitter 1907.07727]

Cross section vs FB-asymmetry





Limits on masses, couplings and mixing



LHC measurements could open a window onto the high energy behaviour of the theory up to the scale where stability and perturbativity are guaranteed.

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

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

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 $m_{H2} > 2M_w$**
  novel signal: heavy neutrinos are produced by the SM-like Higgs

- **$m_{\nu h} > m_h/2$ and $2m_{\nu h} < m_{H2} < 2M_w$**
  hallmark of U(1)′ : heavy neutrinos are produced by the heavy Higgs

- **$m_{\nu h} < m_h/2$ and $2m_{\nu h} < m_{H2} < 2M_w$**
  hallmark of U(1)′ : heavy neutrinos are produced by both h and H2

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

RH heavy neutrinos can be long-lived (LLP) and decay into

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

Width and BRs are computed with CalcHEP + HEPMDB [Belyaev et al.]

Same-sign events and Displaced Vertices (DV) are a powerful signature with small background.

ν_h reconstruction is possible via visible charged lepton and jet identification.

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

Heavy neutrinos in the inner tracker and trigger thresholds

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:

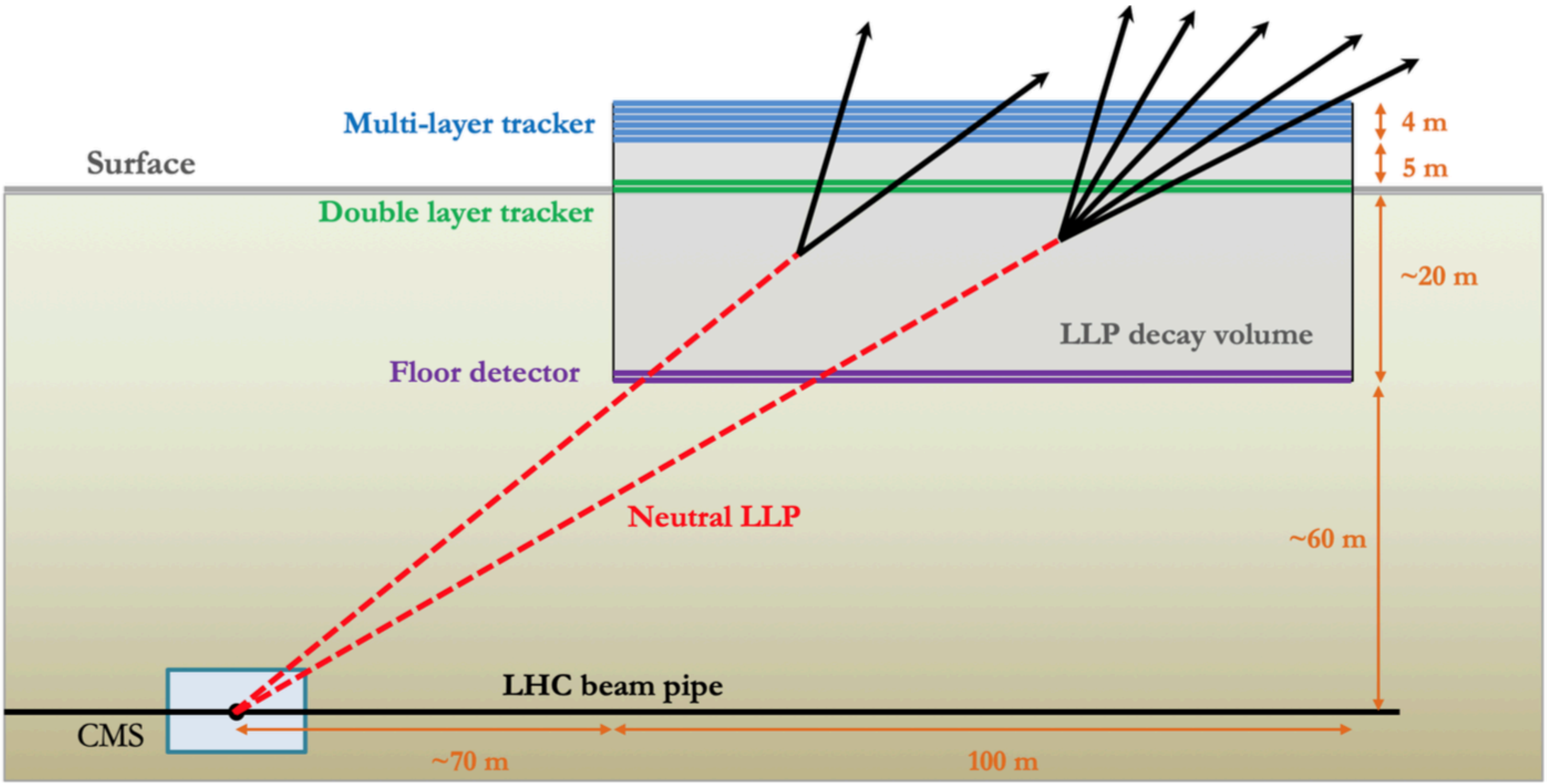
2l-> 2 separated tracks
3l -> 1 DV + 1 separated track
4l -> 2 DVs

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

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

$p_T^{(2)}$/GeV \ $p_T^{(1)}$/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

Future prospects (Exp)



Future prospects (Th & Cosmology)

Within the presented U(1)'B-L model, the 3 RH heavy neutrinos are flavour universal and exactly degenerate. The model could be extended towards a non-universal scenario where the mass degeneracy is slightly lifted.

A low scale resonant leptogenesis could be achieved where the CP asymmetry responsible for the matter-antimatter unbalance is generated by the decay of nearly-degenerate RH neutrinos with TeV-scale mass

$$\epsilon_i = \frac{1}{(\lambda^\dagger\lambda)_{ii}} \frac{\mathrm{Im}[(\lambda^\dagger\lambda)^2_{21}]}{8\pi} \frac{M_1 M_2 (M_2^2 - M_1^2)}{(M_2^2 - M_1^2)^2 + A^2}$$

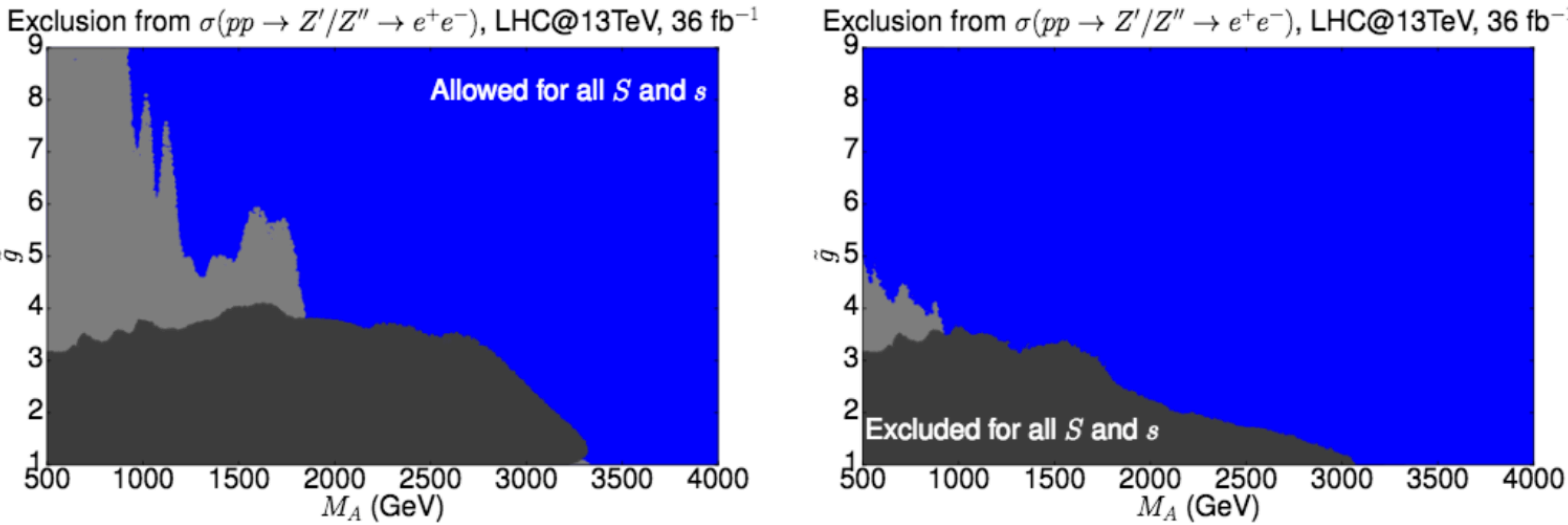
Walking Technicolor Model

[Belyaev, Coupe, Evans, Locke, Scott: arXiv:1812.09052;
Belyaev, Coupe, Frandsen, Olaiya, Shepherd-Themistocleous: arXiv:1805.10867]

- The model provides a rich phenomenology of composite spin-0 and spin-1 resonances: the vector Z′ and the axial-vector Z″.
- For multiple Z′ spectra, search strategies are not yet optimized at the LHC.
- First exclusion limits in DY channel via a phenomenological analysis in the 4D parameter space.

Walking Technicolor Model in DY channel

pp -> Z′, Z″, γ, Z ->l^+l^-



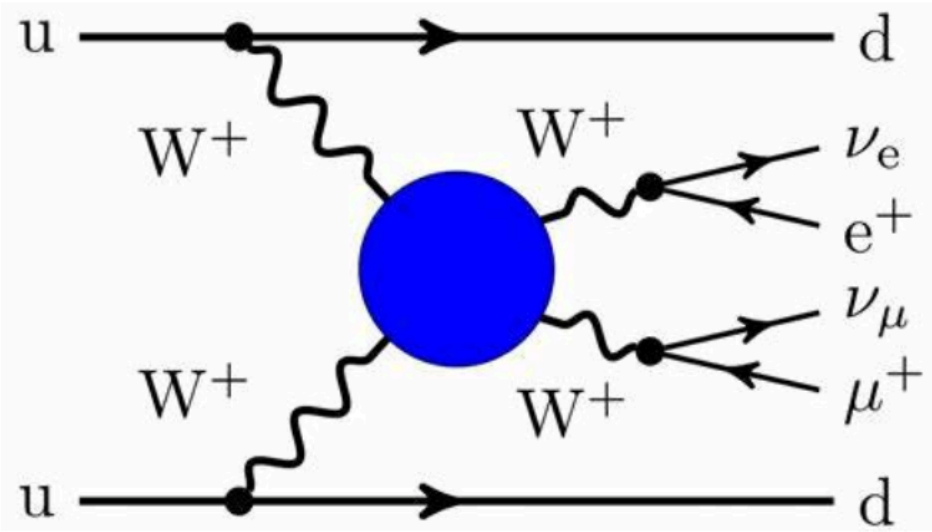
The two exclusion regions in the 2D parameter space from Z′ and Z″ searches are complementary and set the mass limit at $M_{Z'}$>3.1 TeV.

Future prospects
WTC and Vector Boson Scattering (VBS)

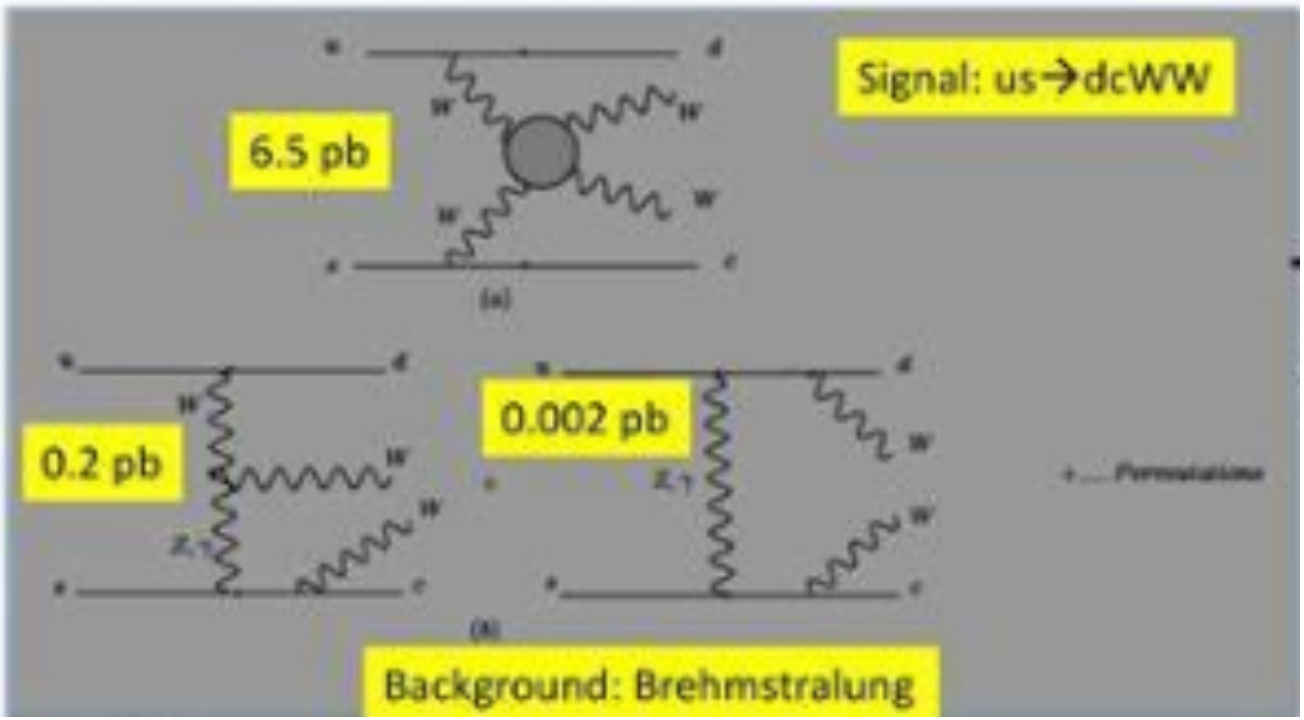
Walking Technicolor Model in the VBS channel

pp -> Z′, Z″, γ, Z -> VV, VH (V=W,Z)

This is a novel channel that could cover the high g~ region of the parameter space, thus complementing the DY channel search.



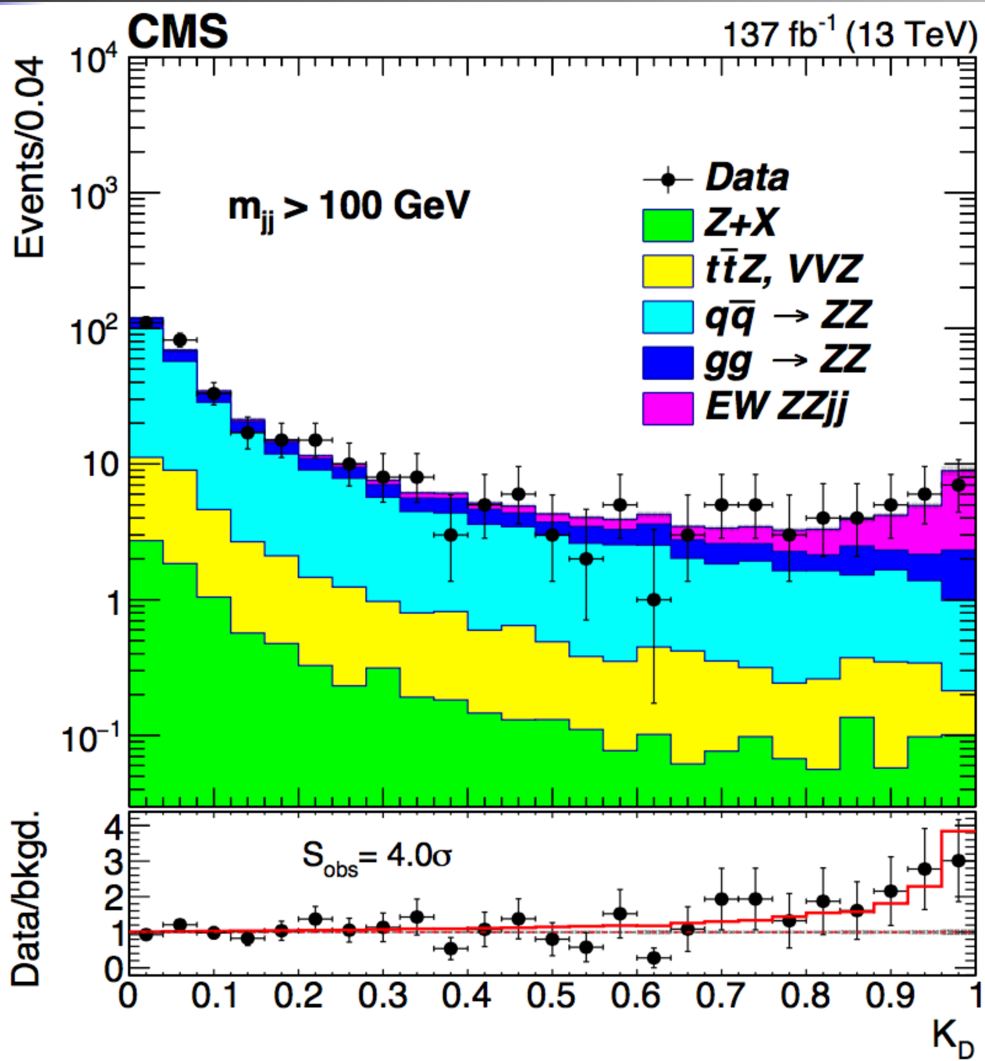
VBS and gauge invariance



σ(WW->WW)=6.5 fb

Owing to the strong gauge cancellations of O(10^3) between signal and irreducible background, the VBS process must be computed completely and accurately.

VBS at the LHC

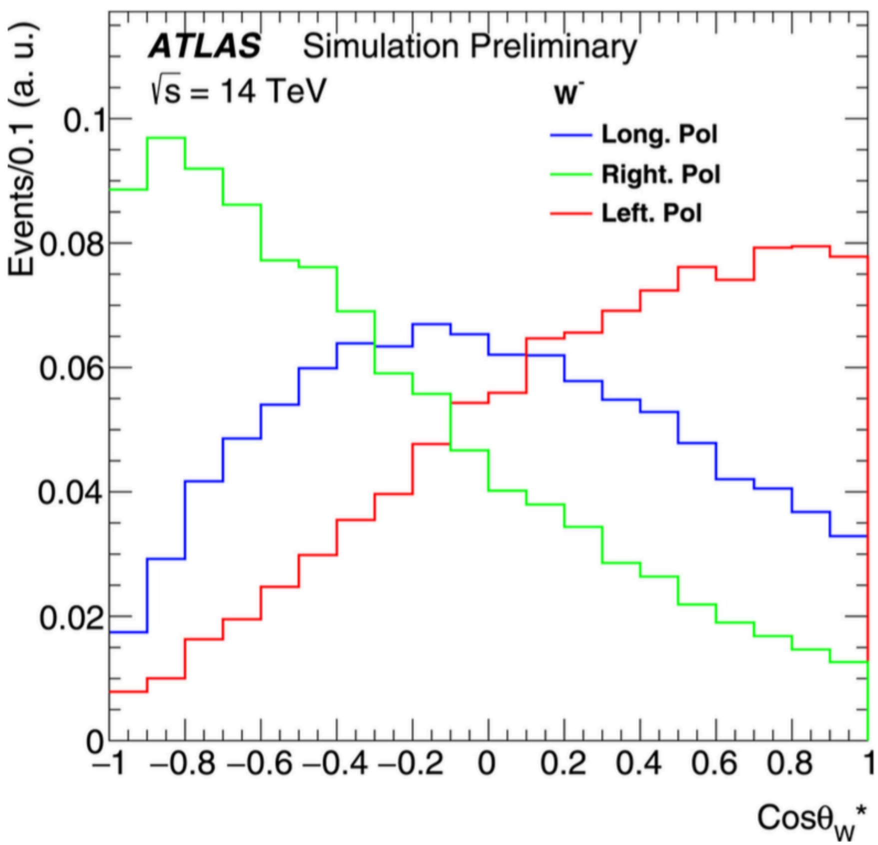


The present Run3 will have sensitivity to this channel.

An observed significance greater than 5 standard deviations is expected.

VBS at the LHC

Also the polarized VBS is under investigation at the LHC with very positive preliminary results.



The MCEG Phase/Phantom can simulate the six-fermion final state in a complete way, also giving access to the polarizations. [E.A., Ballestrero, Maina, hep-ph:0504009; Ballestrero, Belhouari, Bevilacqua, Kashkan, Maina, arXiv: 0801.3359].

The WTC analysis is now timely.

Conclusions

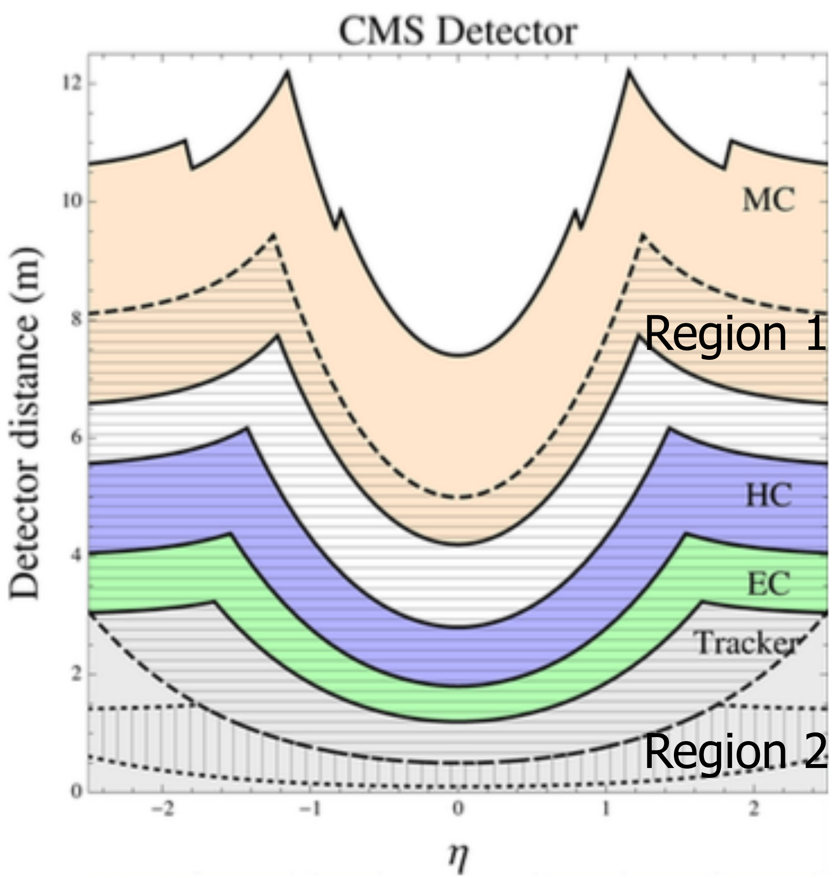
Z′ physics is a rich framework for BSM searches

- An heavy extra Z′-boson naturally appears in a variety of GUT theories (E_6, GLR, GSM, B-L, Technicolor, Composite Higgs, …)
- Its discovery would have important cosmological implications (probe the type of seesaw mechanism, test of leptogenesis, …)
- Striking signatures are ready for the present LHC Run3 and the HL-LHC upgrade in DY, VBS and LLPs channels.
- Even a null result from ATLAS and CMS can shed light on our theories: big data and smart tools can help us

Always a step forward

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

RH heavy neutrinos decay length and CMS detector



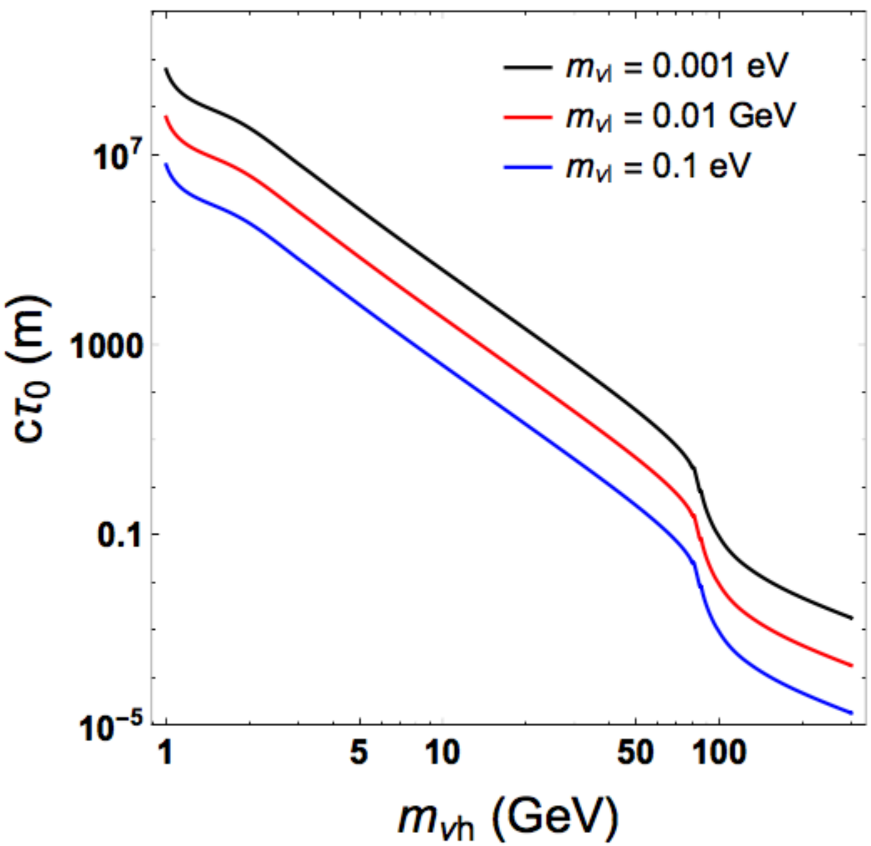
The probability that ν_h would decay in the annulus defined by the radial distances $d_1(\eta)$ and $d_2(\eta)$ is

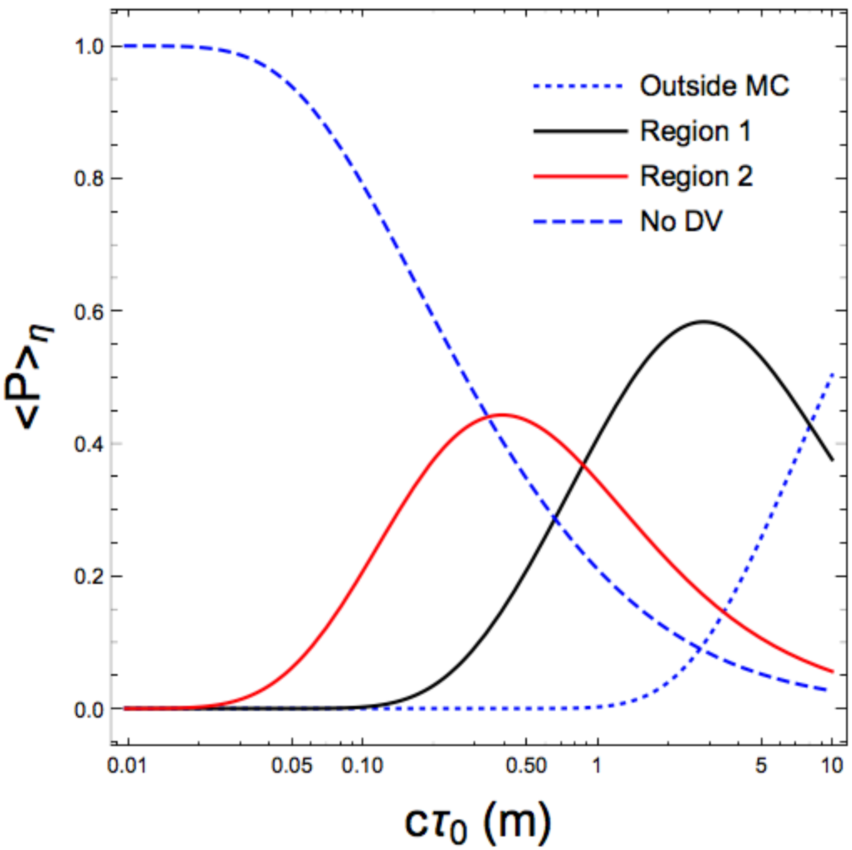
$$P = \int_{d_1(\eta)}^{d_2(\eta)} dx \frac{1}{c\tau} \exp\left(-\frac{x}{c\tau}\right)$$

[E.A. Delle Rose, Moretti, Olaiya, Shepherd-Themistocleous: 1612.05977]

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

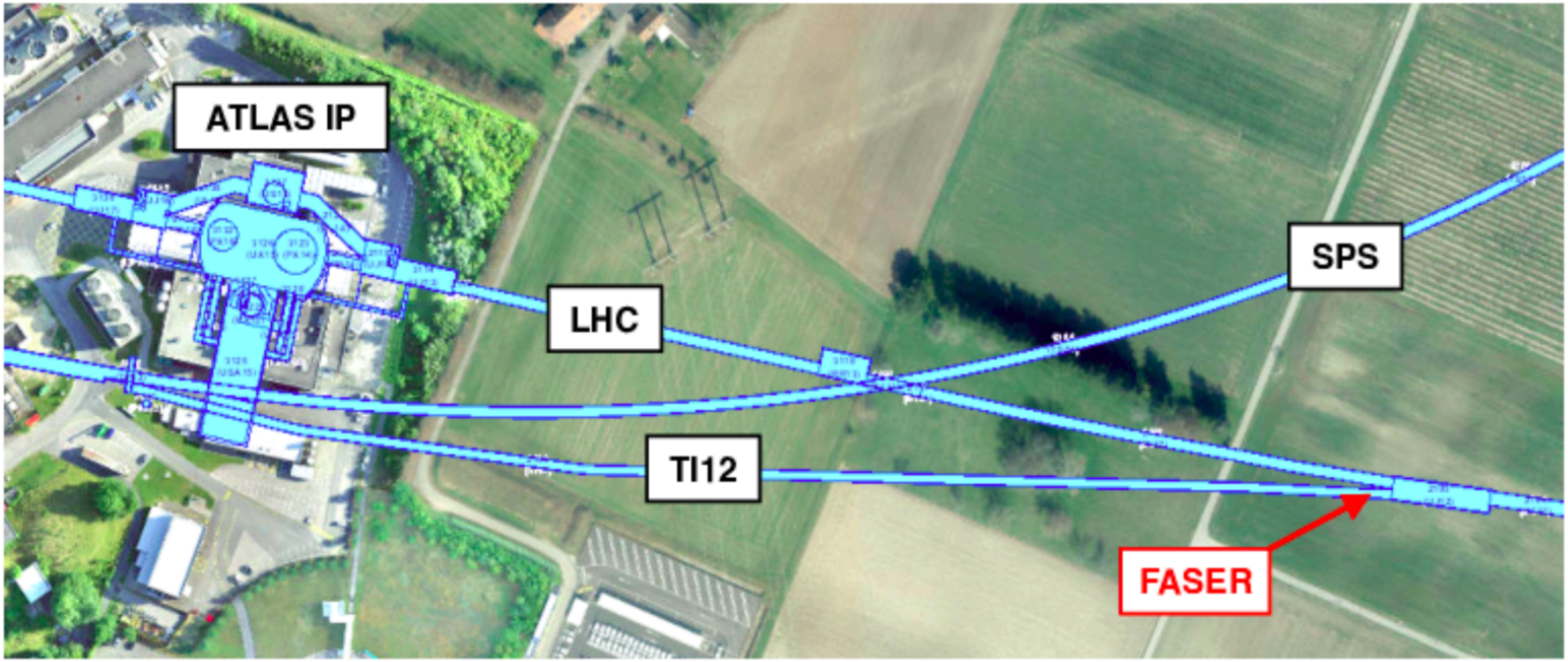
RH heavy neutrinos can be long-lived (LLP)





Future prospects (Exp)

- **Faser – the ATLAS twin:** the detector, designed to search for light and weakly interacting particles, will start taking data during Run3. **pp -> LLP+X, LLP travels 480 m, LLP -> charged tracks +X**



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

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
$\lvert M_{jj} - M_W \rvert < 20$ GeV	20.7898	99.56	1719.47	12.02	29.8004	13.78	0	100	0.497076
$\lvert M_{l^+l^-} - M_Z \rvert > 20$ GeV	18.3081	88.06	105.085	6.111	22.7111	76.21	0	100	1.61951
$\lvert M^T_{vis} - m_{H_2} \rvert < 50$ GeV	17.9312	97.94	13.5729	12.92	0.952433	4.194	0	100	4.70486
$\lvert M_{all} - m_{H_2} \rvert < 50$ 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

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

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

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