國立臺灣大學
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LHC physics with displaced vertices

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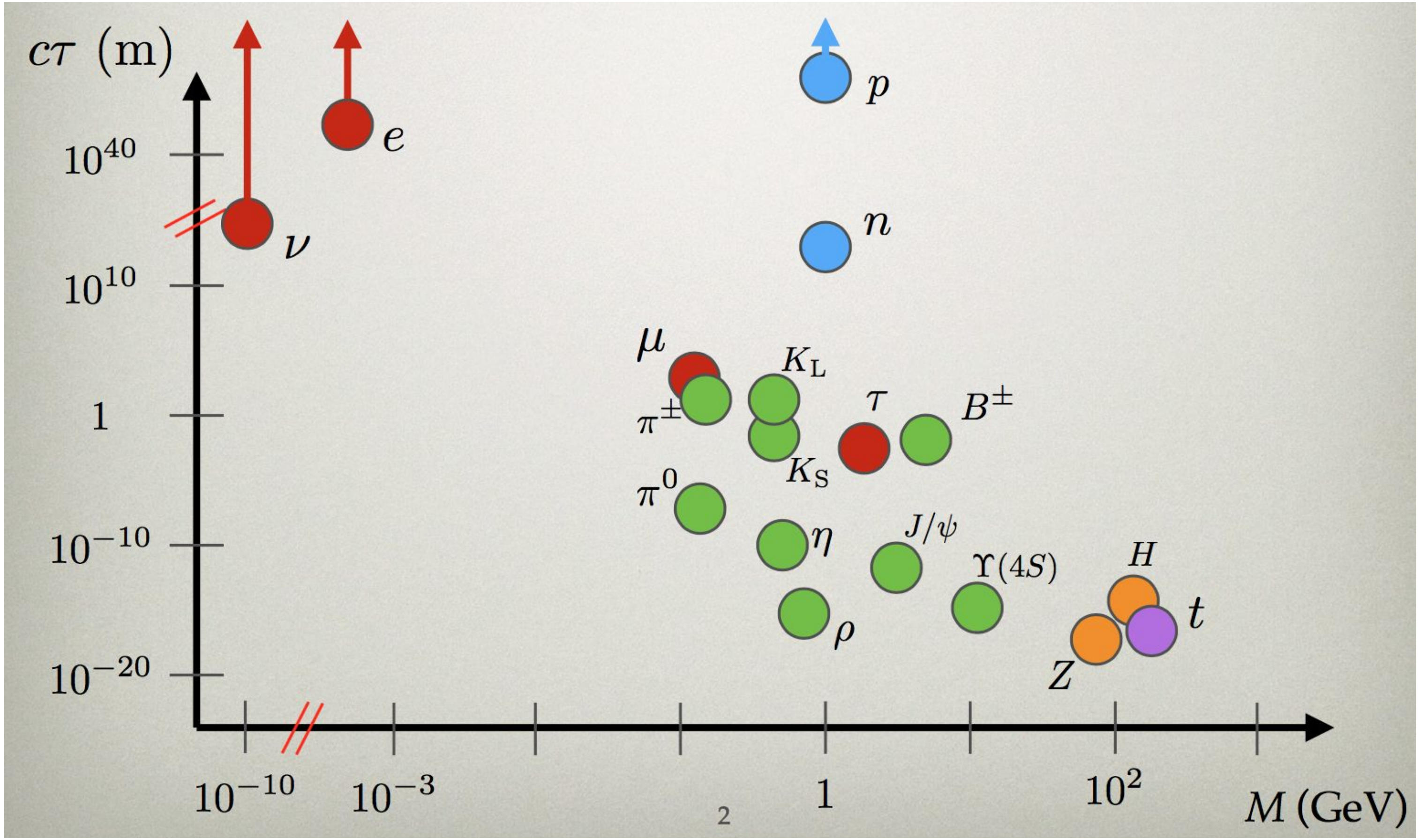
The world is full of long-lived particles



Their presence comes from conserved symmetries, small couplings or heavy mediators.

Source: B.Shuve @ LHC-LLP workshop, CERN

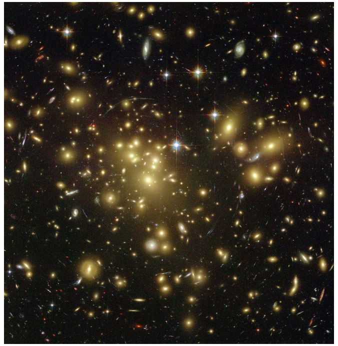
Why shouldn't an exotic/dark sector have the same structure?

Many BSM models predict LLPs, including RPV/split SUSY, GMSB, LR symmetric models, hidden sectors/portals

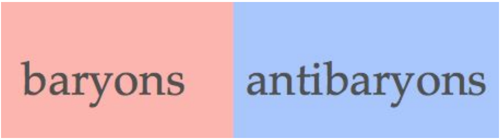
Explain baryogenesis, dark matter and neutrinos: same old strong motivations to invest in a dedicated long-lived particle (LLP) program at colliders

See for example:

Shuve, Cui JHEP 1502 (2015) 049
Strassler, Zurek PRD 94 (2016) no.1, 011504
Co, D'Eramo, Hall, Pappadopulo JCAP 1512 (2015) no.12, 024
Chacko, Curtin, Verhaaren PLB 651 (2007) 374-379

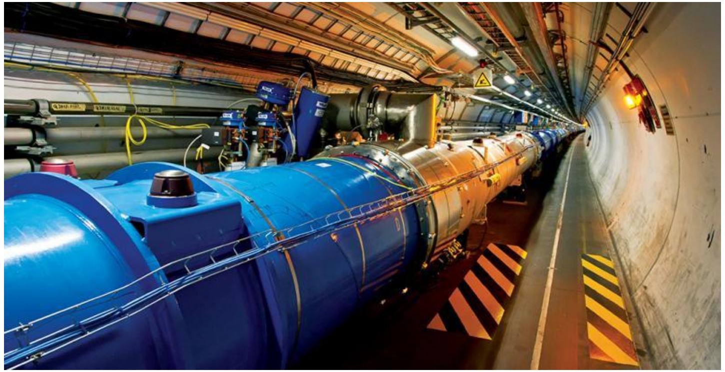


Source: wikipedia.org

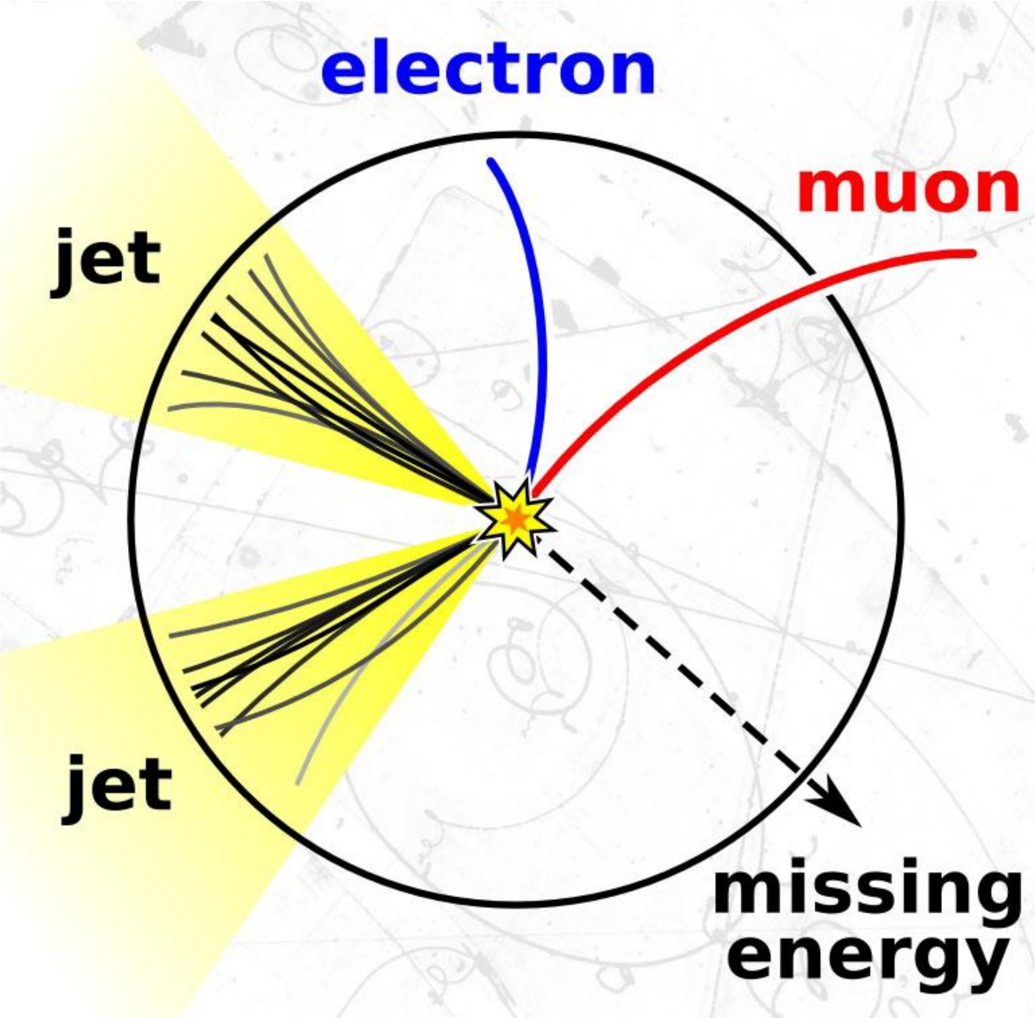


Source: nobelprize.org

Standard Signatures @ LHC detectors



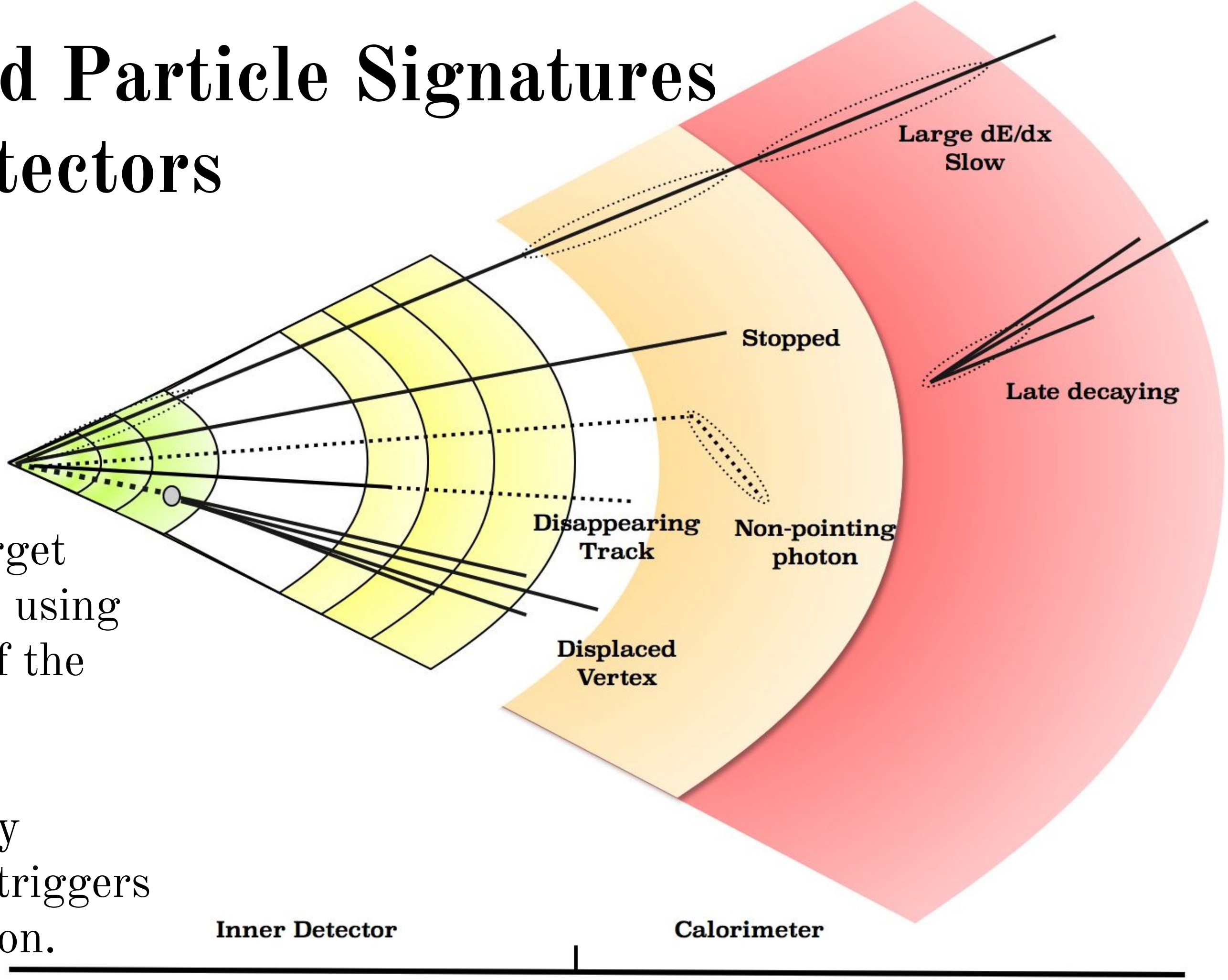
Source: CERN https://home.cern/topics/large-hadron-collider



Source : http://www.fnal.gov/pub/today/images/images11/CMSResult042211figure1.jpg

Long-Lived Particle Signatures @ LHC detectors

Source: G. Cottin

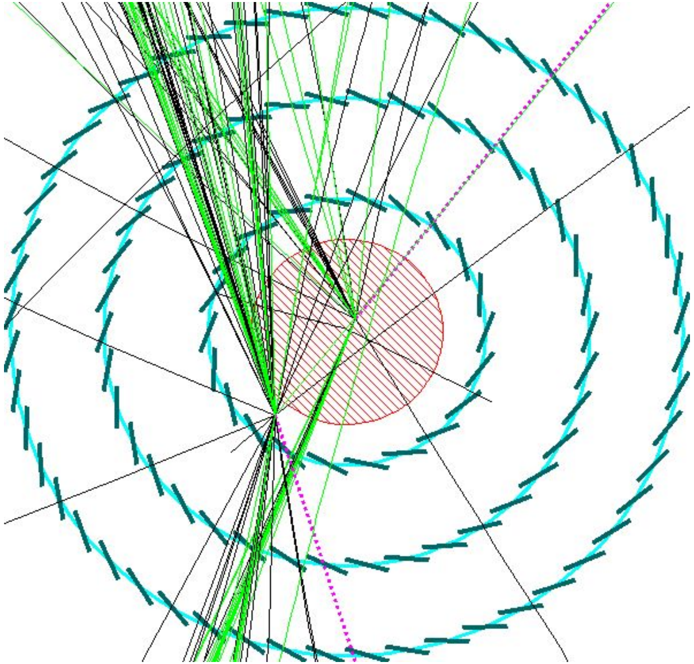


Searches can target specific lifetimes using different parts of the detector.

Detection usually requires special triggers and reconstruction.

The lifetime frontier is theoretically and *also* experimentally well motivated

Displaced Vertex signatures @ LHC detectors
Source: G. Cottin



The lack of evidence of any new physics at the LHC motivates unconventional searches, such as displaced vertices arising from the decay of a LLP

The null results at the LHC may point that the new physics is so feebly coupled to our SM that its signatures may have been overlooked or misidentified by searches not dedicated to LLPs

Using Displaced Vertices @ LHC to search for New Physics

How? Two studies in this talk (neutrinos and dark matter):

1) Reinterpreting current displaced searches in the context of a left-right symmetric model with a long-lived sterile neutrino

2) Proposing a mass reconstruction method that uses information on displaced vertices to find the masses of neutral daughters (i.e dark matter) and their parents

1) Recasting Displaced Searches @ LHC. Looking for a light, long-lived sterile neutrino

Based on

arXiv:1801.02734, G. Cottin, J.C. Helo, M. Hirsch

Left-Right Symmetric Models

J. C. Pati and A. Salam, Phys. Rev. D10, 275 (1974)
R. N. Mohapatra and J. C. Pati, Phys. Rev. D11, 2558 (1975)
R. N. Mohapatra and G. Senjanovic, Phys. Rev. D23, 165 (1981)

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

Neutrino masses explained by the so-called see-saw mechanism, introducing the existence of massive, right-handed (sterile) neutrinos.

Sterile neutrinos with Majorana masses covering various mass ranges.

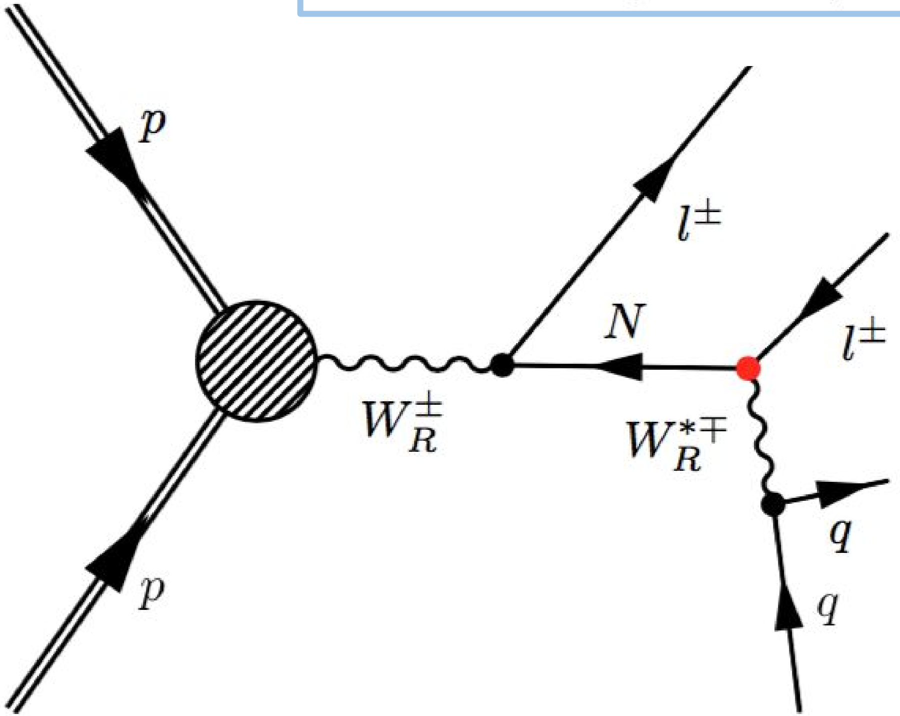
Production and decay of the sterile neutrino depends mostly on the unknown mass of the new, heavy right-handed gauge boson, WR.

Source: nobelprize.org

LHC Phenomenology

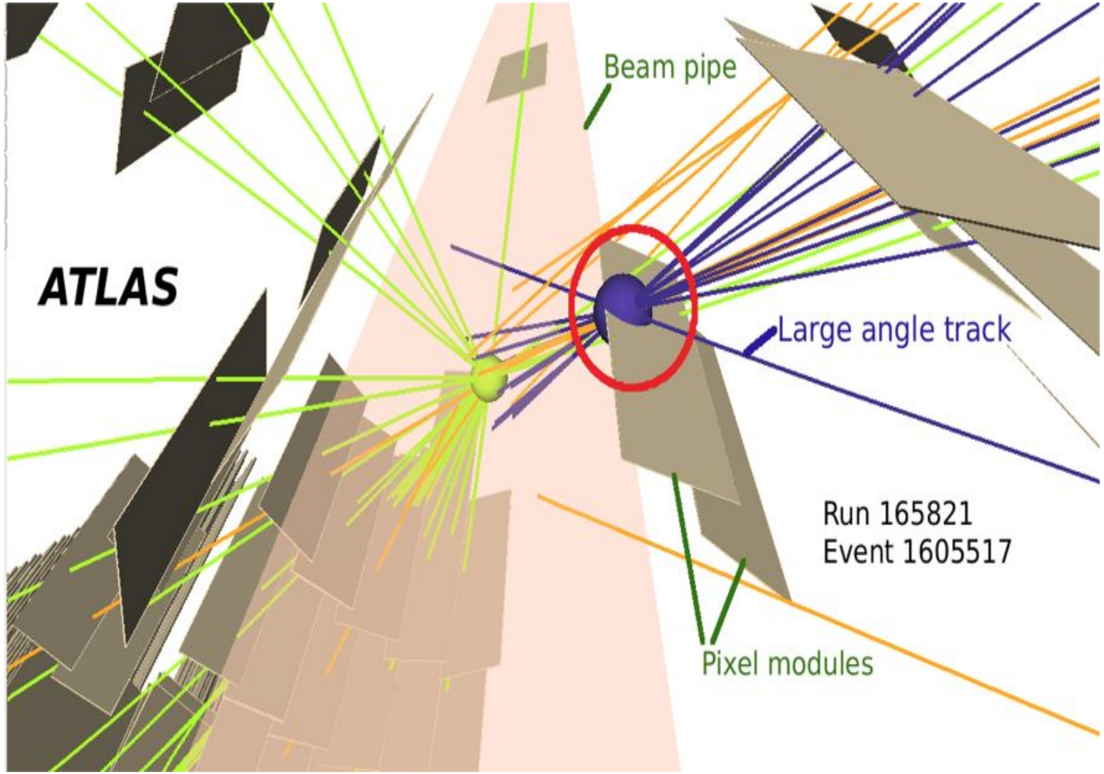
$$m_N \ll m_{W_R}, m_N < m_W$$

$$c\tau_N \sim 0.12 \left(\frac{10\ \text{GeV}}{m_N}\right)^5 \left(\frac{m_{W_R}}{1000\ \text{GeV}}\right)^4 \ [\text{mm}]$$



Displaced Searches @ the ATLAS detector. Multitrack DV 13 TeV search

Signatures inside inner tracker (lifetimes of order picosecond to a nanosecond)



Source: ATLAS Event Display arXiv:1109.2242

Analysis strategy:

* Look for high-mass and track multiplicity DVs in inner tracker mDV>10 GeV, nTrk>5

* Standard ATLAS tracking is run again with looser cuts to gain efficiency for high-d0 tracks

* Veto vertices in material layers (dominant background vertices) with a 3D material. After this, ZERO background search

Source: http://arxiv.org/abs/1710.04901
PRD92 (2015) 7, 072004

Event Simulation and Selections

Source: CERN https://atlas.cern/discover

We generate events in MadGraph and interphace with Pythia 8.
Detector response to physics objects modeled inside Pythia.

Original analysis triggers on missing transverse momenta.
We propose to trigger on the prompt lepton. We require:

- electron with pT>25 GeV
- One “trackless jet” (a jet with sum_pT of tracks less than 5 GeV) with pT>70 GeV or two trackless jet with pT>25 GeV

At least one DV with:

- Distance between interaction point and decay position > 4 mm
- Decays within rDV and |zDV|<300 mm
- At least 5 charged decay products with pT>1 GeV and |d0|>2mm
- Invariant mass of DV > 10 GeV, under charged pion mass hypothesis for tracks

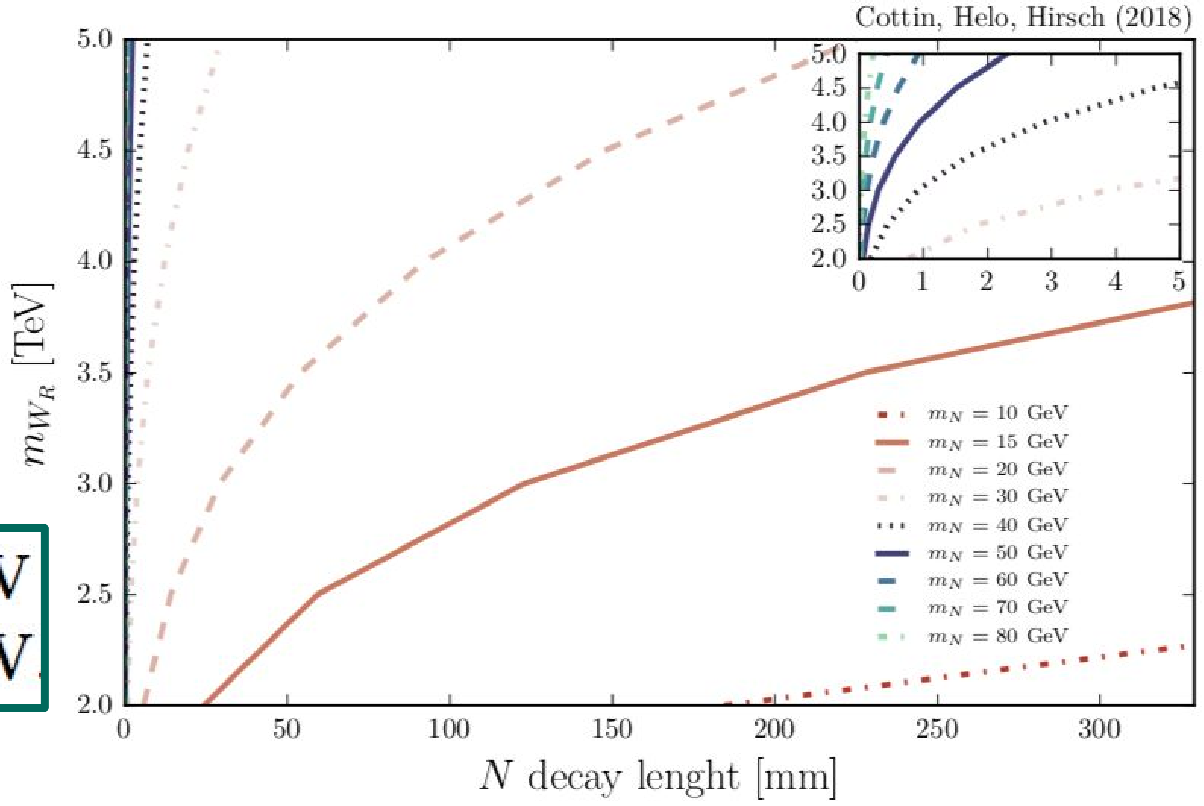
Acceptance

We scan:

$$m_N = [10-80]\ \text{GeV}$$
$$m_{W_R} = [2-5]\ \text{TeV}$$

Optimal acceptance region:

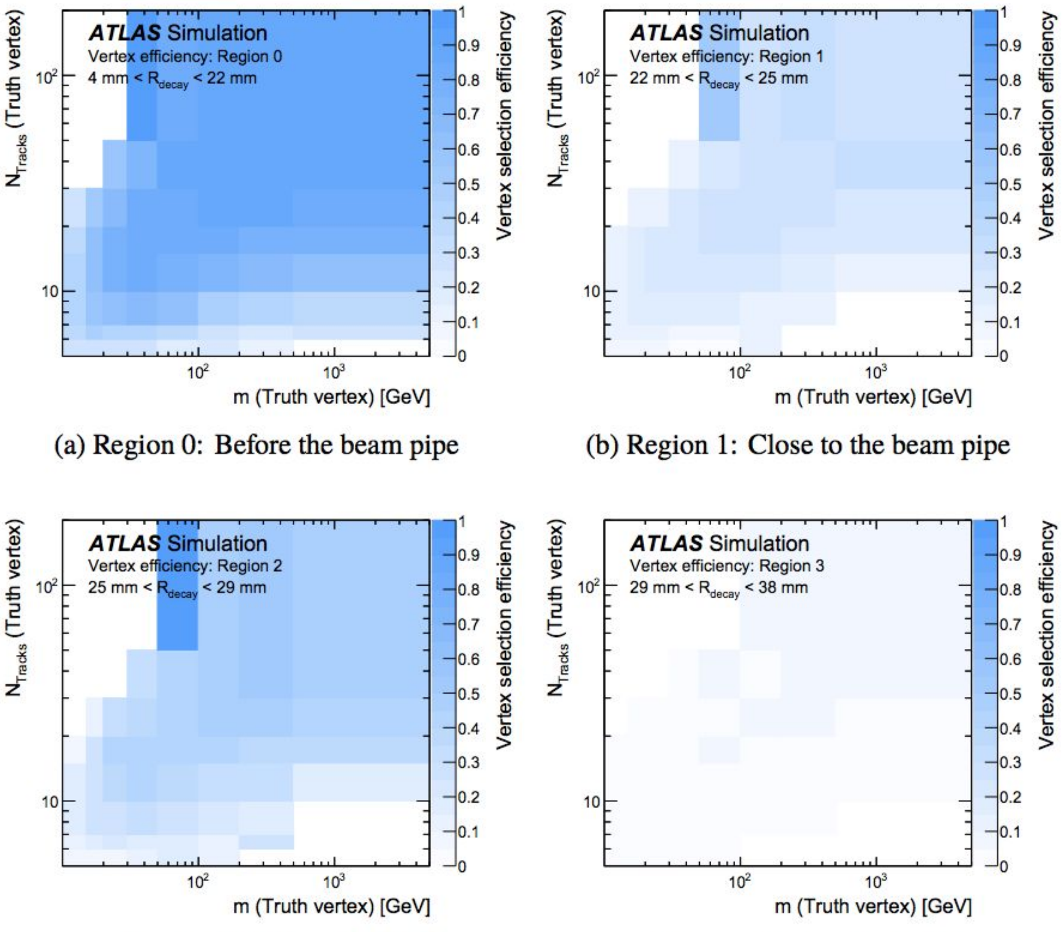
$$10\ \text{GeV} < m_N < 40\ \text{GeV}$$
$$2\ \text{TeV} < m_{W_R} < 5\ \text{TeV}$$



Efficiency

Often a difficulty in recasting LLP analysis lies in the lack of object level efficiencies (i.e how to select DVs in a model independent way?)

Public ATLAS efficiency grids to model detector response to DVs.
Can be applied to truth-level MC (nTrk, mDV, rDV)



(a) Region 0: Before the beam pipe
(b) Region 1: Close to the beam pipe
(c) Region 2: Before the IBL
(d) Region 3: Close to the IBL

Source: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/SUSY-2016-08/hepdata_info.pdf

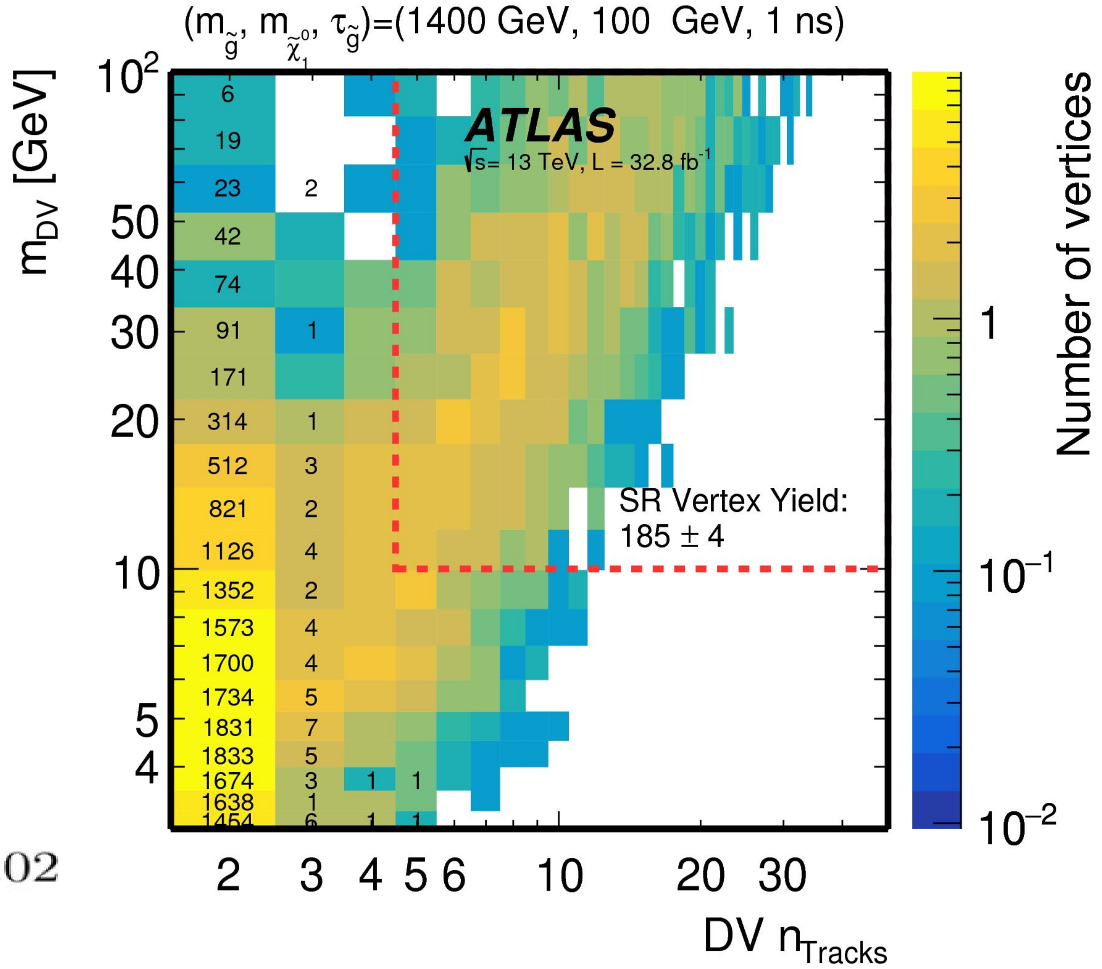
We find LOW sensitivity to the LR model

$\sqrt{s} = 13$ TeV

$m_N = 20$ GeV, $m_{W_R} = 4$ TeV and $c\tau_N = 1.3$ mm

	N	Rel. ϵ [%]	Ov. ϵ [%]
All events	10000	100	100
Prompt electron	8721	87.2	87.2
Trackless jet	8704	99.8	87.0
DV fiducial	7615	87.5	76.1
DV N_{trk}	528	6.9	5.3
DV m_{DV}	89	16.9	0.9
DV efficiency	6	6.7	0.06

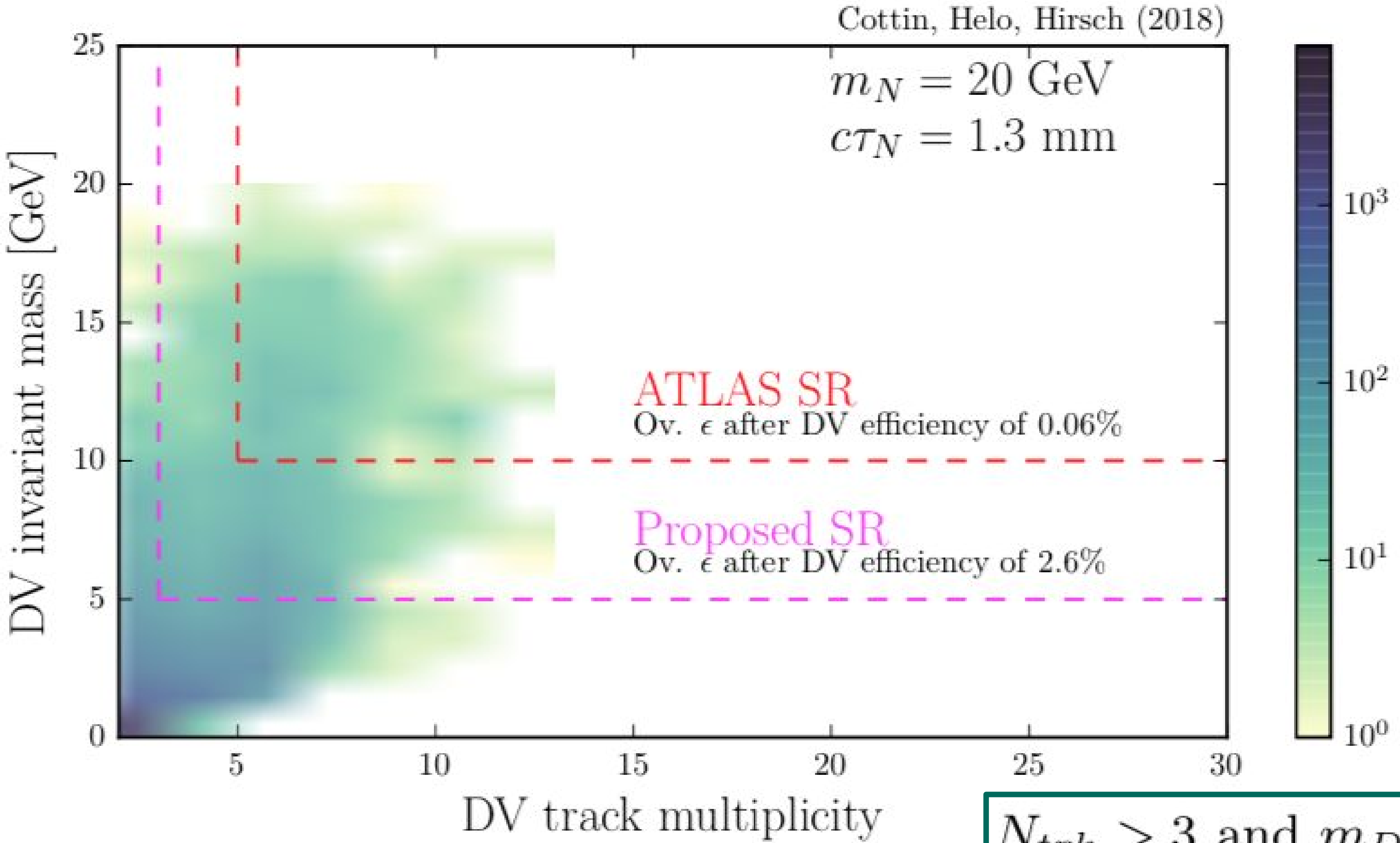
ATLAS yields



$$N_{DV}^{BG} = 0.02 \pm 0.02$$

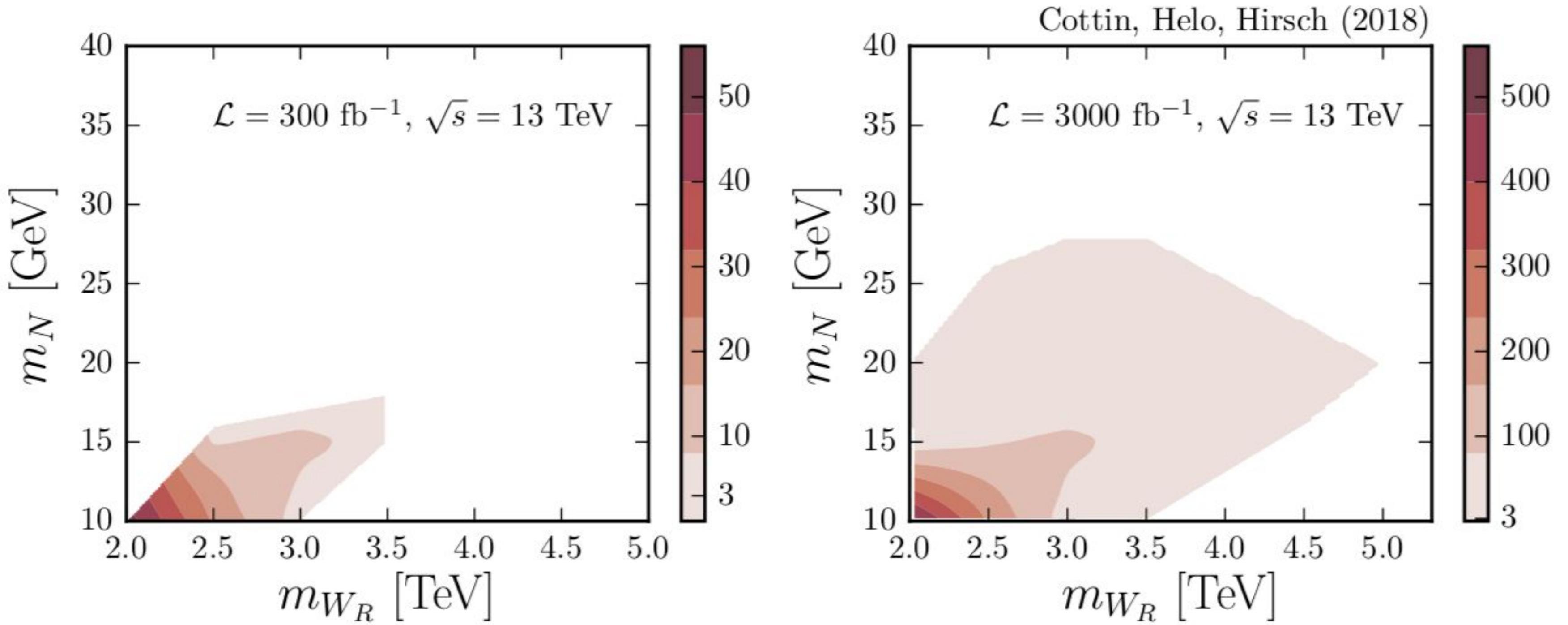
Source: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/SUSY-2016-08/

So we propose a new strategy, relaxing DV cuts



$N_{trk} > 3$ and $m_{DV} \geq 5$ GeV

With our proposed "prompt lepton+loose DV" search, we can reach up to 30 GeV sterile neutrinos with 3000 fb-1 at 13 TeV



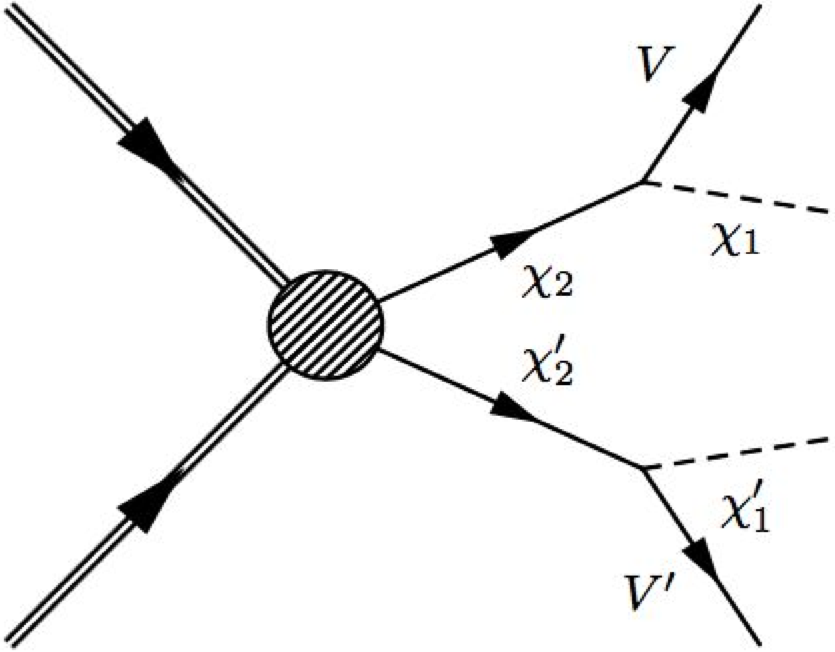
This motivates the experimental collaborations to perform dedicated DV searches to target light sterile neutrinos !

2) What else could be measured at colliders (and what could thus be inferred about the nature of dark matter) given a displaced vertex signal?

Work in progress

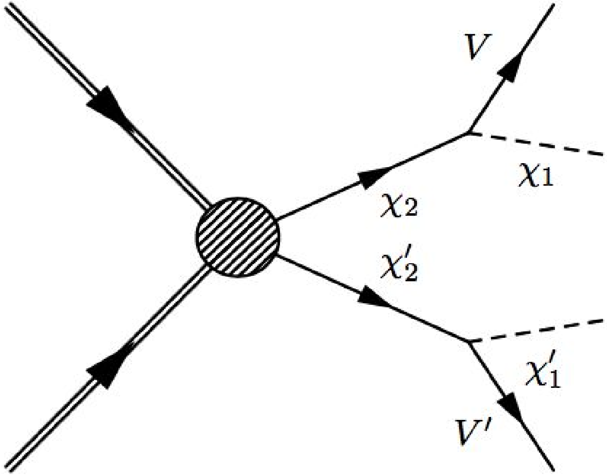
G. Cottin, C. Lester

Construction of a kinematic mass variable that takes into account the displaced vertex information, starting with the following hypothesis



Work in collaboration with Chris Lester (**in preparation**)

Our displaced case



$$m_{\chi_1}^2 = p_{\chi_1}^2 = p_{\chi_1'}^2$$

$$m_{\chi_2}^2 = (p_V + p_{\chi_1})^2 = (p_{V'} + p_{\chi_1'})^2$$

Including information on the displaced vertex positions **r**, we get extra knowledge on the direction of the momentum of the parent

$$p_{\chi_1}^x + p_{\chi_1'}^x = p_x^{\text{miss}}$$

$$p_{\chi_1}^y + p_{\chi_1'}^y = p_y^{\text{miss}}$$

$$\boldsymbol{p}_{\chi_2} = |\boldsymbol{p}_{\chi_2}| \frac{\boldsymbol{r}}{r} = |\boldsymbol{p}_{\chi_2}| \hat{\boldsymbol{r}}$$

$$m_{\chi_2}^2 = m_{\chi_1}^2 + m_V^2 + 2E_V\sqrt{m_{\chi_1}^2 + |\mathbf{p}_{\chi_1}|^2} - 2\mathbf{p}_V \cdot \mathbf{p}_{\chi_1}$$

$$m_{\chi_2}^2 = m_{\chi_1}^2 + m_{V'}^2 + 2E_{V'}\sqrt{m_{\chi_1}^2 + |\mathbf{p}_{\chi_1'}|^2} - 2\mathbf{p}_{V'} \cdot \mathbf{p}_{\chi_1'}$$

Unknowns

Define projections of three momenta of daughter and visible along the directions of the parent to help solve the system

$$(\mathbf{p}_{\chi_1})_{\parallel\chi_2} = (\mathbf{p}_{\chi_1} \cdot \hat{\mathbf{r}})\hat{\mathbf{r}}$$

$$(\mathbf{p}_V)_{\parallel\chi_2} = (\mathbf{p}_V \cdot \hat{\mathbf{r}})\hat{\mathbf{r}}$$

$$(\mathbf{p}_{\chi_1})_{\perp\chi_2} = \mathbf{p}_{\chi_1} - (\mathbf{p}_{\chi_1} \cdot \hat{\mathbf{r}})\hat{\mathbf{r}}$$

$$(\mathbf{p}_V)_{\perp\chi_2} = \mathbf{p}_V - (\mathbf{p}_V \cdot \hat{\mathbf{r}})\hat{\mathbf{r}}.$$

$$(\mathbf{p}_{\chi_1})_{\perp\chi_2} = -(\mathbf{p}_V)_{\perp\chi_2}$$

$$\boldsymbol{p}_{\chi_1} = (A+B)\hat{\boldsymbol{r}} - \boldsymbol{p}_{\boldsymbol{V}}$$

$$\boldsymbol{p}_{\chi_1'} = (C+D)\hat{\boldsymbol{r}}' - \boldsymbol{p}_{\boldsymbol{V}'}$$

$$A \equiv (\boldsymbol{p}_{\chi_1} \cdot \hat{\boldsymbol{r}})$$

$$B \equiv (\boldsymbol{p}_{\boldsymbol{V}} \cdot \hat{\boldsymbol{r}})$$

$$C \equiv (\boldsymbol{p}_{\chi_1'} \cdot \hat{\boldsymbol{r}}')$$

$$D \equiv (\boldsymbol{p}_{\boldsymbol{V}'} \cdot \hat{\boldsymbol{r}}')$$

Assuming missing transverse momenta comes only from daughters

$$\boldsymbol{p}_T^{\mathrm{miss}} = [(A+B)\hat{\boldsymbol{r}} - \boldsymbol{p}_{\boldsymbol{V}} + (C+D)\hat{\boldsymbol{r}'} - \boldsymbol{p}_{\boldsymbol{V}'}]_\perp$$

We can solve for A and C

$$A = A(p_X^{miss}, p_Y^{miss}, \hat{\boldsymbol{r}}, \hat{\boldsymbol{r}}', \boldsymbol{p}_{\boldsymbol{V}}, \boldsymbol{p}_{\boldsymbol{V}'})$$

$$C = C(p_X^{miss}, p_Y^{miss}, \hat{\boldsymbol{r}}, \hat{\boldsymbol{r}}', \boldsymbol{p}_{\boldsymbol{V}}, \boldsymbol{p}_{\boldsymbol{V}'})$$

We can rewrite the system as

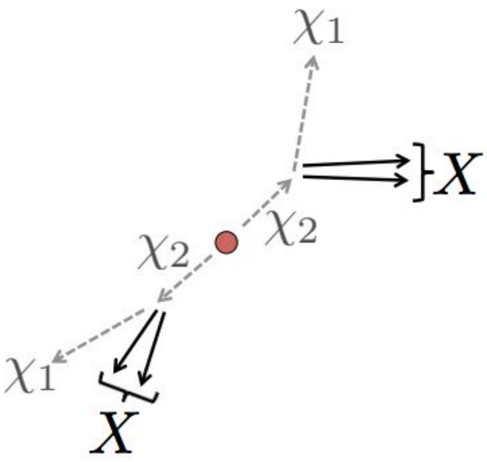
$$m_{\chi_2}^2 = m_{\chi_1}^2 + \alpha\sqrt{m_{\chi_1}^2 + \beta} + \gamma$$
$$m_{\chi_2}^2 = m_{\chi_1}^2 + \delta\sqrt{m_{\chi_1}^2 + \epsilon} + \zeta$$

$$\alpha \equiv 2E_V$$
$$\delta \equiv 2E_{V'}$$
$$\beta \equiv A^2 - B^2 + |\boldsymbol{p}_V|^2$$
$$\epsilon \equiv C^2 - D^2 + |\boldsymbol{p}_{V'}|^2$$
$$\gamma \equiv m_V^2 - 2(A+B)B + 2|\boldsymbol{p}_V|^2$$
$$\zeta \equiv m_{V'}^2 - 2(C+D)D + 2|\boldsymbol{p}_{V'}|^2$$

So we can solve event-by-event, the system is fully constrained.

In principle we have 8 solutions for the pair (m_{χ_1}, m_{χ_2})
But we are interested in the two requiring positive masses. We will see zero, one or sometimes two solutions per event.

Displaced Dark Matter Simplified Model



We use for our study the simplified displaced dark matter model
JHEP 1709 (2017) 076 (Buchmueller, De Roeck, Hahn, McCullough, Schwaller, Sung,Yu)

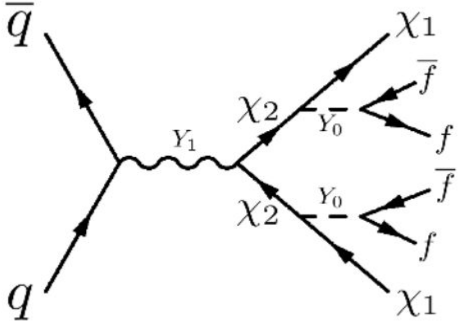


Figure 3. A representative diagram from the DisplacedDM model that produces displaced verticies plus $\not{E}_T$. The subscripts on Y indicate the spin of the mediator.

Simulation

$q\bar{q} \to Y_1 \to \chi_2\bar{\chi}_2 \to \chi_1 Y_0 \chi_1 Y_0 \to \chi_1 f\bar{f}\chi_1 f\bar{f}.$

$c\tau \sim 20$ mm $\quad \Gamma_{\chi_2} = 1 \times 10^{-14}$

$m_{Y_1} = 1$ TeV $\quad m_{Y_0} = 40$ GeV

We first study events at truth level

Event input

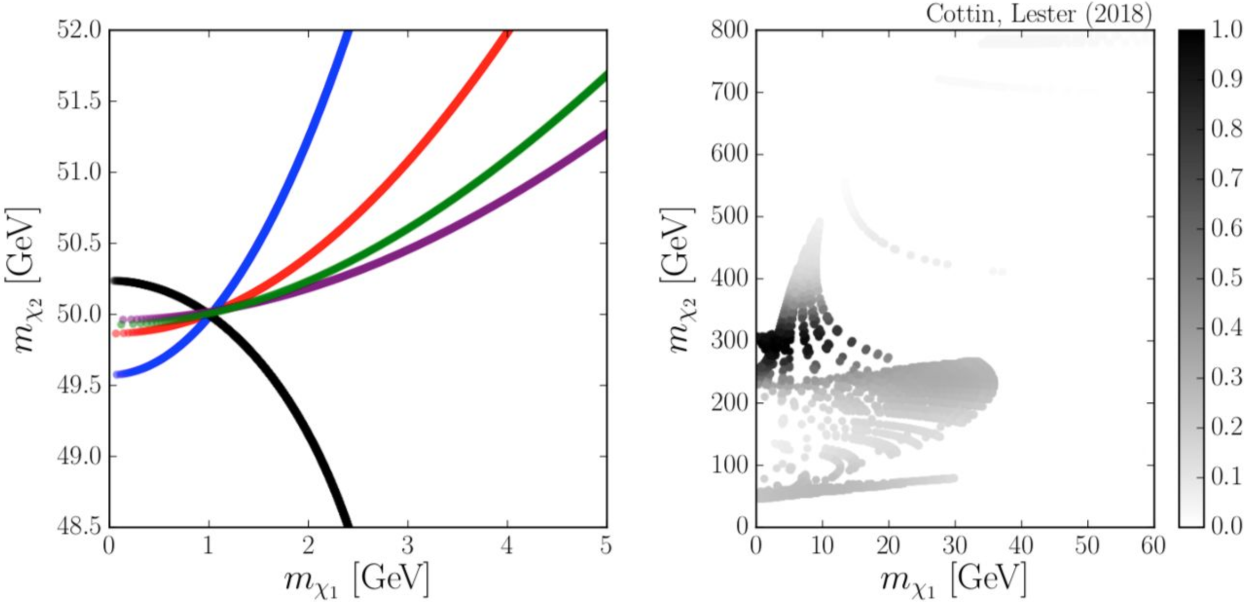
$$(\boldsymbol{r}, \boldsymbol{r}', \boldsymbol{p_V}, \boldsymbol{p_{V'}}, p_x^{\text{miss}}, p_y^{\text{miss}})$$

$$\boldsymbol{r} \longrightarrow \boldsymbol{r} + \theta \boldsymbol{p_V}$$

$$\theta = [-0.1, 0.1]$$

$$\boldsymbol{r} \longrightarrow \boldsymbol{r} + \theta_1 \boldsymbol{p_V}$$

$$\boldsymbol{r}' \longrightarrow \boldsymbol{r}' + \theta_2 \boldsymbol{p_{V'}}$$

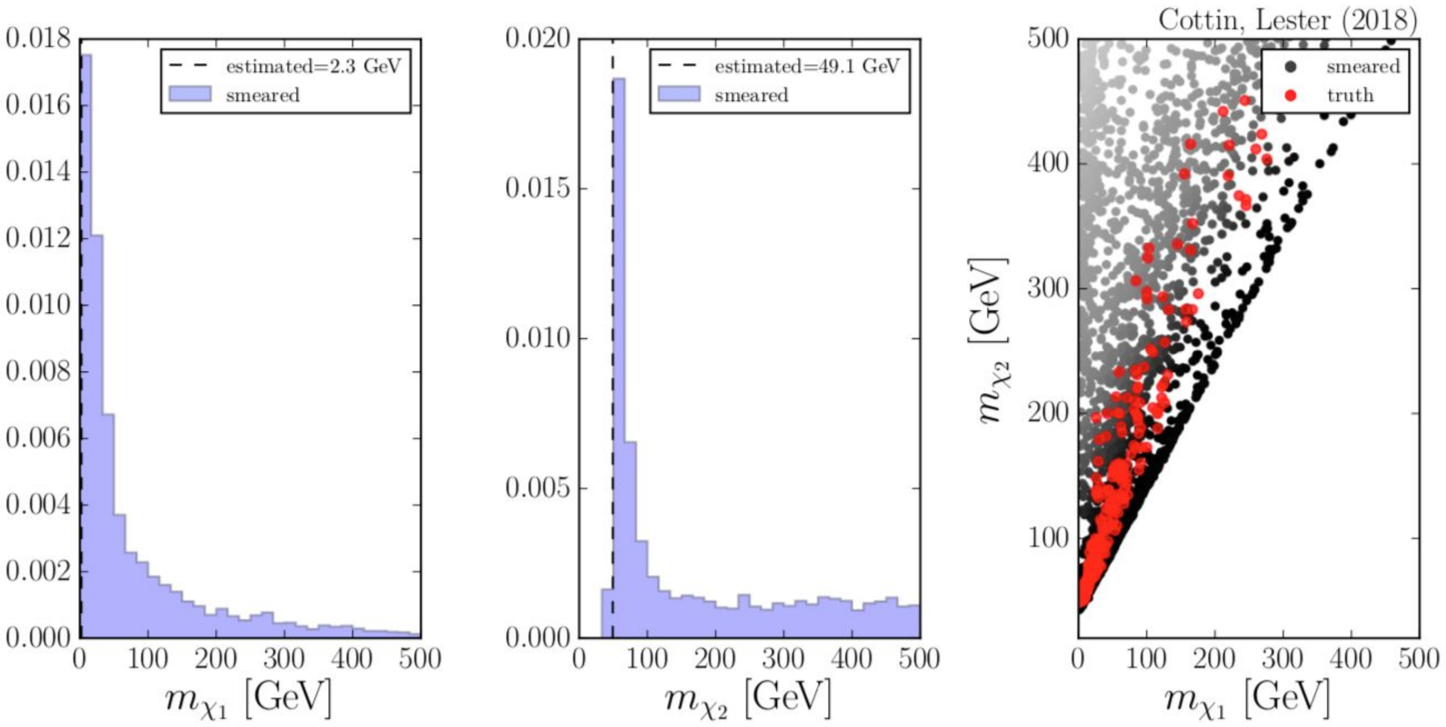


θ_1 and θ_2 are sampled from two different Normal distributions

We do a detector simulation and generate the smeared quantities to solve the system again

Smeared quantities $(\boldsymbol{r}, \boldsymbol{r'}, \boldsymbol{p_V}, \boldsymbol{p_{V'}}, p_x^{\text{miss}}, p_y^{\text{miss}})$

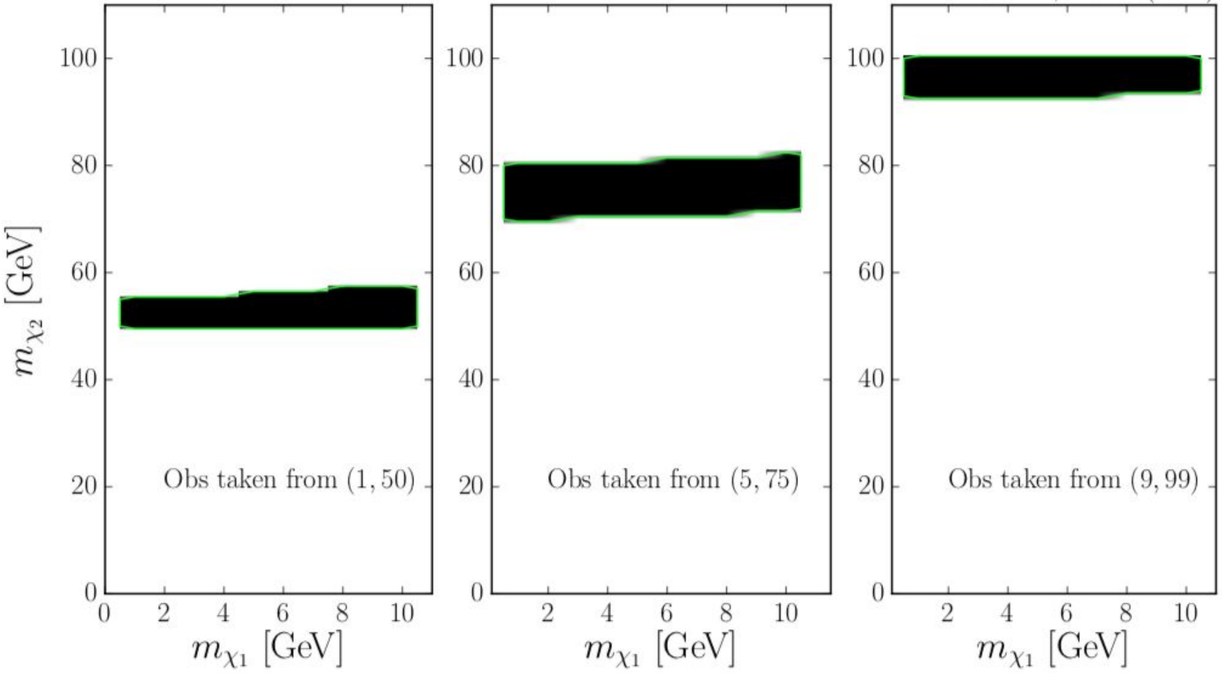
Mass Estimation based on the 1st percentile : i.e (2.3, 49.1) for truth masses (1,50)



Our goal is to be able to extract both masses from the data. Construction of a confidence region based on our mass estimates

We draw 5 points in our estimation space to be used as “observations”, and construct 95% CR. The real masses will lie in these regions at least 95% of the time.

Cottin, Lester (2018)



To take home

- We have found low sensitivity for discovering a light sterile neutrino with current displaced LHC searches. We need dedicated searches if sterile neutrinos are ~ 20 GeV !

- We proposed a method to reconstruct the mass of a (invisible, dark matter) particle and its long-lived parent. If displaced events are seen at the LHC, the method can be applied, shedding light on the mass scale for dark matter

We need a dedicated program to systematize LLP searches, to ensure coverage and to make sure LLP analysis are optimal for recasting. New methods/ideas are coming from both theoretical and experimental fronts (LHC-LLP Community White paper in preparation).

The lifetime frontier is the cutting edge of LHC physics !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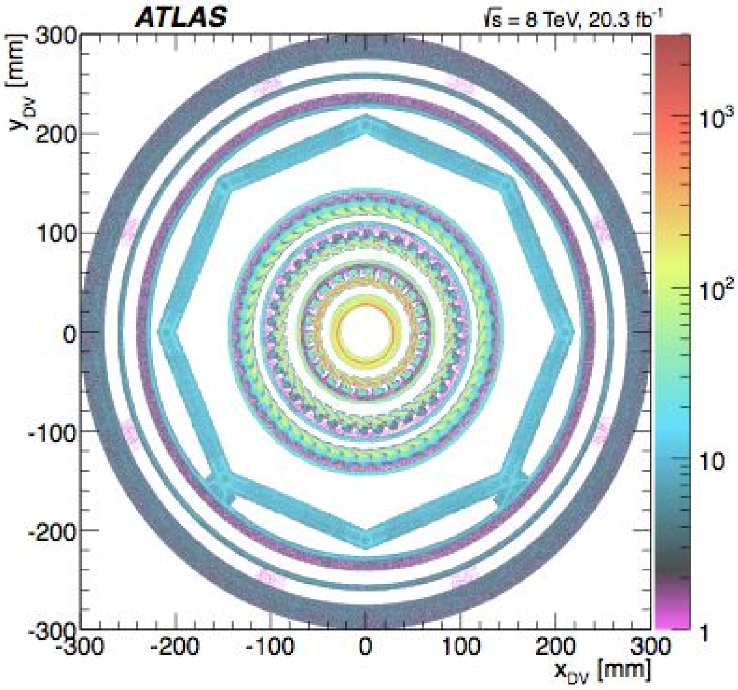
Backup

ATLAS DV analysis strategy

* Look for high-mass, high-track multiplicity displaced vertices in inner tracker with mass>10 GeV and at least 5 tracks

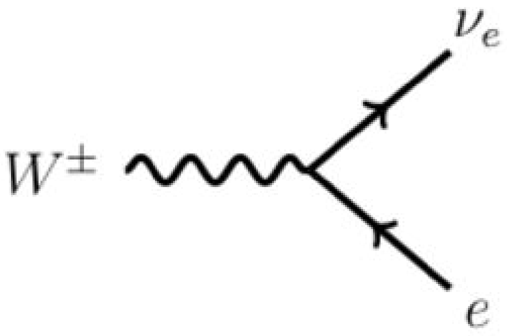
* Standard ATLAS tracking algorithms are re-run with looser cuts to gain efficiency for high-d0 tracks

* Veto vertices in material layers (dominant background vertices) with a 3D material. After this, almost zero background search



Source: PRD92 (2015) 7, 072004

Historic example of a kinematic mass variable, the transverse mass



$$m_W^2 = m_e^2 + m_\nu^2 + 2(E_e E_\nu - 2\vec{p}_e \cdot \vec{p}_\nu)$$

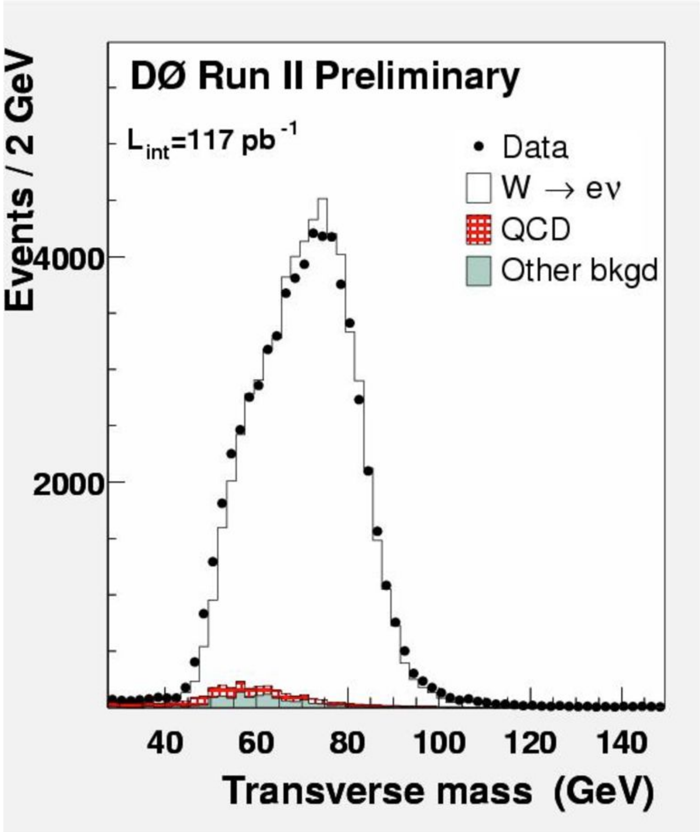
$$m_e^2 = E_e^2 - p_e^2$$
$$m_\nu^2 = E_\nu^2 - p_\nu^2$$
$$p_T \equiv (p_x, p_y)$$

$$m_W^2 = (E_e + E_\nu)^2 - (\vec{p}_{Te} + \vec{p}_{T\nu})^2 - (p_{ze} + p_{z\nu})^2$$

$$m_T^2 \equiv (E_e + E_\nu)^2 - (\vec{p}_{Te} + \vec{p}_{T\nu})^2$$

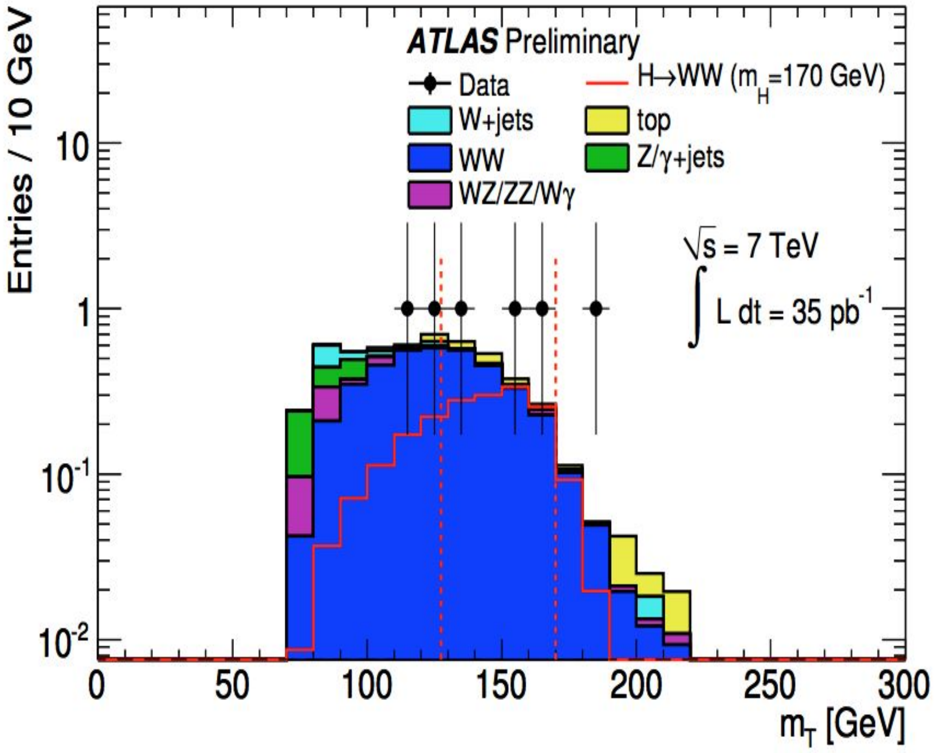
$$m_T^2 \equiv m_e^2 + m_\nu^2 + 2(E_e E_\nu - \vec{p}_{Te} \cdot \vec{p}_{T\nu})$$

Can not directly compute W mass from the lepton and neutrino. But can know a lower limit as $m_T^2 \leq m_W^2$



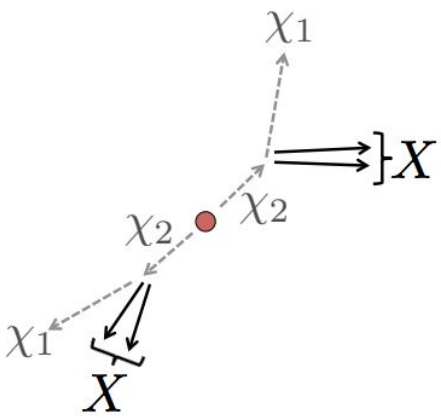
Source: d0.fnal.gov

Cuts on this variable also had a big role in LHC Higgs searches



Source: ATLAS-CONF-2011-005

Displaced Dark Matter Simplified Model



We use for our study the simplified displaced dark matter model in
JHEP 1709 (2017) 076 (Buchmueller, De Roeck, Hahn, McCullough, Schwaller, Sung, Yu)

Simplified DM models		
Variables	DM candidate	Interaction
m_ϕ	Dirac	Vector
m_1	Majorana	Axial-Vector
g_χ	Scalar-real	Scalar
g_ϕ	Scalar-complex	Pseudoscalar
Displaced signature extension		
τ, m_2	Decay of $\chi_2 \to \chi_1 X$	

Table 1. Overview of the different building blocks that form simplified DM models. The lower part of this table lists the kinematic variables, lifetime (τ) and mass (m_2) of the excited state χ_2 and its decay $\chi_2 \to \chi_1 X$, which are required to add the displaced signature to the standard simplified DM models.

Source: JHEP 1709 (2017) 076

$\not{E}_T$ plus displaced X system					
dMETs	dMET$_{jj}$	dMET$_{e^+e^-}$	dMET$_{\mu^+\mu^-}$	dMET$_{\tau^+\tau^-}$	dMET$_\gamma$
X	*jet*-pair	e-pair	μ-pair	τ-pair	γ

Table 4. Minimal set of dMETs searches for neutral displaced SM particles. To facilitate the trigger acceptance for these topologies, especially for soft X systems, the dMETs can be combined with an ISR signature, such as an additional hard jet or hard γ. A list of basic operators that would give rise to such topologies is shown in table 2.

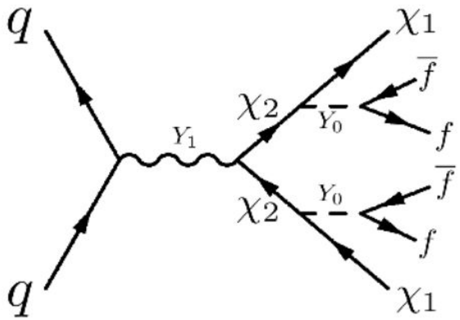
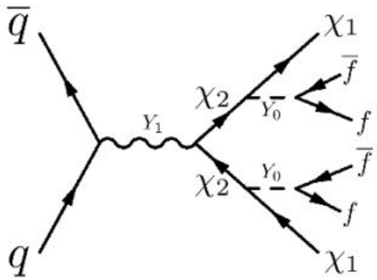


Figure 3. A representative diagram from the `DisplacedDM` model that produces displaced verticies plus $\not{E}_T$. The subscripts on Y indicate the spin of the mediator.

Simulation



$$q\bar{q} \to Y_1 \to \chi_2\bar{\chi}_2 \to \chi_1 Y_0 \chi_1 Y_0 \to \chi_1 f \bar{f} \chi_1 f \bar{f}.$$

Simulation is done in two stages. We use the UFO model provided by the authors and simulate with MadGraph5

$$pp \to Y_1 \to \chi_2\bar{\chi}_2 \text{ at } \sqrt{s} = 13 \text{ TeV}$$

The output corresponds to events in LHE format that includes the lifetime of the LLP. The LHE events are passed to Pythia8 to compute the decays

$$\chi_2 \to \chi_1 f \bar{f}$$

The Pythia output is saved to be further processes with python routines to solve the system of equations

$$A = \frac{(r_x r'_y - r_y r'_x)(p_V^x r_x + p_V^y r_y + p_V^z r_z) + [(p_V^y + p_{V'}^y + p_y^{\text{miss}}) r'_x - (p_V^x + p_{V'}^x + p_x^{\text{miss}}) r'_y](r_x^2 + r_y^2 + r_z^2)}{(r_y r'_x - r_x r'_y)\sqrt{r_x^2 + r_y^2 + r_z^2}} \tag{2.19}$$

$$C = \frac{(r_x r'_y - r_y r'_x)(p_{V'}^x r'_x + p_{V'}^y r'_y + p_{V'}^z r'_z) + [(p_V^x + p_{V'}^x + p_x^{\text{miss}}) r_y - (p_V^y + p_{V'}^y + p_y^{\text{miss}}) r_x](r_x'^2 + r_y'^2 + r_z'^2)}{(r_y r'_x - r_x r'_y)\sqrt{r_x'^2 + r_y'^2 + r_z'^2}} \tag{2.20}$$

with $\boldsymbol{r} = (r_x, r_y, r_z)$, $\boldsymbol{r'} = (r'_x, r'_y, r'_z)$, $\boldsymbol{p_V} = (p_V^x, p_V^y, p_V^z)$ and $\boldsymbol{p_{V'}} = (p_{V'}^x, p_{V'}^y, p_{V'}^z)$.

```
evt :  0  mChiarr :  [49.982221462459556]  mBarr :  [399.9957020056687]
evt :  1  mChiarr :  [49.997847802846437]  mBarr :  [399.99975823914735]
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evt :  5  mChiarr :  [49.997122013410426]  mBarr :  [399.99826691166845]
evt :  6  mChiarr :  [50.014707822323942]  mBarr :  [400.00453952926358]
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evt :  9  mChiarr :  [49.992738898517388]  mBarr :  [399.99698845905823]
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evt :  12  mChiarr :  [49.992303389461341]  mBarr :  [399.999283417041]
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evt :  18  mChiarr :  [49.998777778621744]  mBarr :  [399.99790453719328]
evt :  19  mChiarr :  [49.986317180114575]  mBarr :  [399.99608835930223]
evt :  20  mChiarr :  [50.010826027572556, 929.1353116641712]  mBarr :  [400.0018834655807, 1189.0032178162496]
```

Final state X	$\mathcal{O}_F$	$\mathcal{O}_S$
γ/γ^*	$\frac{1}{\Lambda}\overline{\chi}_2\sigma_{\mu\nu}\chi_1 F^{\mu\nu}$	$\frac{1}{\Lambda^2}(\partial_\mu\phi_2\partial_\nu\phi_1)F^{\mu\nu}$
Z	$\frac{1}{\Lambda}\overline{\chi}_2\sigma_{\mu\nu}\chi_1 Z^{\mu\nu}$	$\frac{1}{\Lambda^2}(\partial_\mu\phi_2\partial_\nu\phi_1)Z^{\mu\nu}$
h	$\overline{\chi}_2\chi_1 h$	$\Lambda\phi_2\phi_1 h$
jj	$\frac{1}{\Lambda^3}\overline{\chi}_2\chi_1\,\mathrm{Tr}[G^{\mu\nu}G_{\mu\nu}]$	$\frac{1}{\Lambda^2}\phi_2\phi_1\,\mathrm{Tr}[G^{\mu\nu}G_{\mu\nu}]$
$\bar{l}l$	$\frac{1}{\Lambda^2}\bar{l}l\overline{\chi}_2\chi_1$	$\frac{1}{\Lambda}\phi_2\phi_1\bar{l}l$
$\bar{b}b$	$\frac{1}{\Lambda^2}\bar{b}b\overline{\chi}_2\chi_1$	$\frac{1}{\Lambda}\phi_2\phi_1\bar{b}b$
$\bar{t}t$	$\frac{1}{\Lambda^2}\bar{t}t\overline{\chi}_2\chi_1$	$\frac{1}{\Lambda}\phi_2\phi_1\bar{t}t$

Table 2. List of example effective operators for the decay $\chi_2 \to \chi_1 X$ for fermionic (middle column) and scalar (right column) DM particles. Each of these operators corresponds to different final state X (left column). Note that this is not an exhaustive list. For example, one could also have diboson final states. Furthermore, the scalar charge radius operator gives decays only to off-shell photons, $\gamma^* \to \overline{f}f$, W^+W^-.

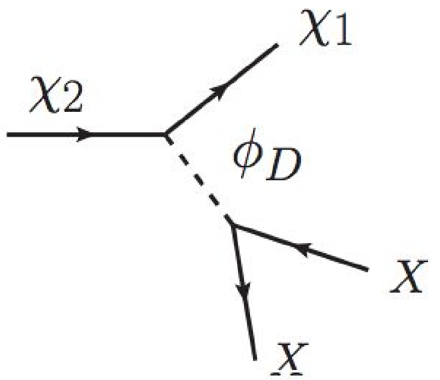
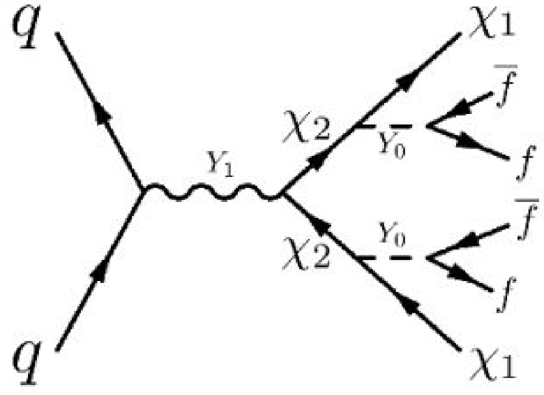


Figure 2. Topology for the decay of χ_2 into χ_1 and SM particles (X) through a light mediator ϕ_D.

Final state	$\mathcal{O}_{\rm DM} + \mathcal{O}_{\rm SM}$
$\overline{f}f$	$-g_{12}\phi^{\mu}_{D}\overline{\chi}_1\gamma_\mu\chi_2 - g_q\phi^{\mu}_{D}\overline{q}\gamma_\mu q$ $-g_{12}\phi^{\mu}_{D}\overline{\chi}_1\gamma_\mu\gamma_5\chi_2 - g_q\phi^{\mu}_{D}\overline{q}\gamma_\mu\gamma_5 q$ $-g_{12}\phi_D\overline{\chi}_1\chi_2 - g_q\phi_D\overline{q}q$ $-ig_{12}\phi_D\overline{\chi}_1\gamma^5\chi_2 - g_q\phi_D\overline{q}\gamma^5 q$

Table 3. A small sample list of example vector, axial-vector, scalar, and pseudo-scalar decay mediator couplings for fermionic DM particles. Similar models may also be constructed for bosons.



$$\mathcal{L'}^{Y_0}_{\rm DM} = \bar{\chi_2}(g^S_\chi + i g^P_\chi \gamma_5)\chi_1 Y_0 + \text{h.c.}\,.$$

$$\mathcal{L}^{Y_0}_{\rm SM} = \sum_{i,j}\left[\bar{d}_i \frac{y^d_{i,j}}{\sqrt{2}}(g^S_{d_{ij}} + i g^P_{d_{ij}}\gamma_5)d_j + \bar{u}_i \frac{y^u_{i,j}}{\sqrt{2}}(g^S_{u_{ij}} + i g^P_{u_{ij}}\gamma_5)u_j\right] Y_0\,,$$

$$\mathcal{L}^{Y_1}_{\rm SM} = \sum_{i,j}[\bar{d}_i\gamma_\mu(g^V_{d_{ij}} + g^A_{d_{ij}}\gamma_5)d_j + \bar{u}_i\gamma_\mu(g^V_{u_{ij}} + g^A_{u_{ij}}\gamma_5)u_j] Y^\mu_1,$$

$$\mathcal{L}^{Y_1}_{\rm DM} = \bar{\chi}\gamma_\mu(g^V_\chi + g^A_\chi\gamma_5)\chi Y^\mu_1.$$

Smearings inside the detector simulation in Pythia8 goes like this:

Jet energy resolution: Use 20% for jets at 50 GeV, falling linearly to 10% at 100 GeV, then flat 10%.

Jet energy scale: For jets with $|eta| > 2$, use 3% flat, for jets with $|eta| < 2$, use 1% flat (I am assuming the jets are above 20-30 GeV by which point this is probably quite accurate)

Electron resolution: use 2% at 10 GeV, falling linearly to 1% at 100GeV, and then 1% flat. Electron scale is effectively 0 so we can forget it.

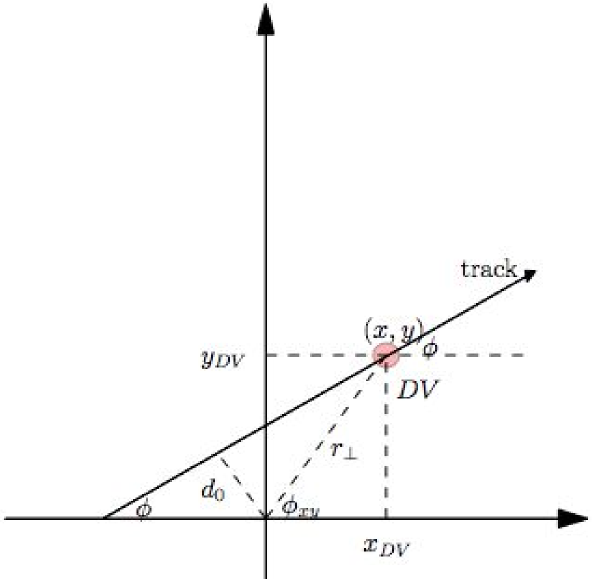
For displaced mass method we require:

- At least 4 electrons in each event
- Each electron has to be truth matched to a displaced track with deltaR in (η, ϕ) to be less than 0.1
- $|d_0| > 2$ mm and $p_T > 1$ GeV

$$r_\perp = \sqrt{x^2 + y^2}$$

$$\tan\phi = p_y / p_x$$

$$d_0 = r_\perp \times \sin(\phi_{xy} - \phi)$$



Source: **EPJ C76 (2016)**

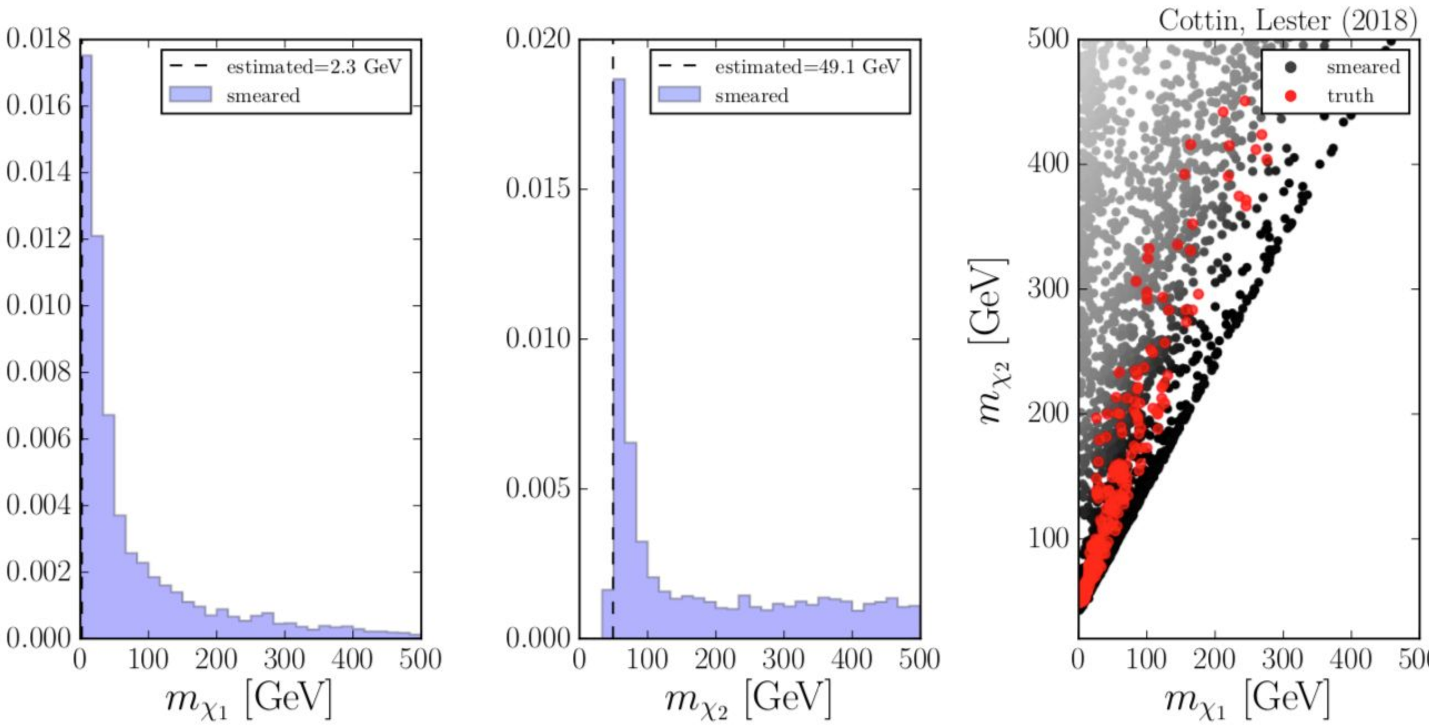
We do a detector simulation and generate the smeared quantities to solve the system again

Smeared quantities $(\boldsymbol{r}, \boldsymbol{r'}, \boldsymbol{p_V}, \boldsymbol{p_{V'}}, p_x^{\text{miss}}, p_y^{\text{miss}})$

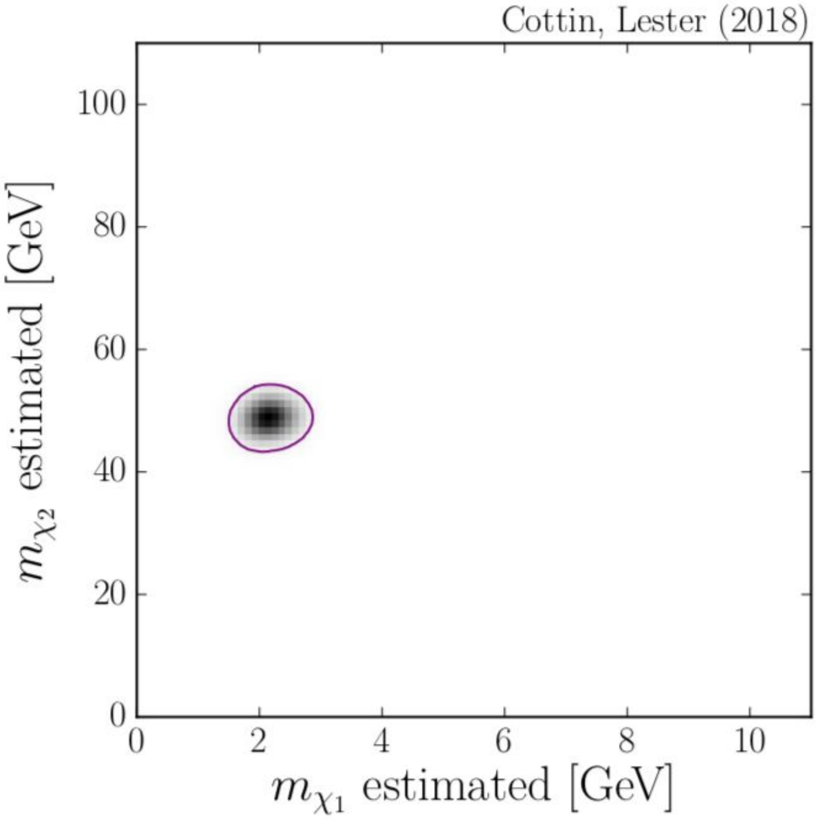
Mass Estimation based on the 1st percentile

Smearings for jets and leptons include energy scales/resolutions.
DV resolution of sigma=0.3 mm

At least 4 electrons in each event
Each electron has to be truth matched to a displaced track with deltaR less than 0.1



Our goal is to be able to extract both masses from the data. Estimated region for *every truth mass* pair that gets estimated



Estimated mass plane from truth mass pair (1,50)

Construct a confidence region based on our maps in estimation space (we have 510 of them, one per each grid point), to guarantee that, given an observation, the real masses will lie in the region at least some fixed fraction of the time (e.g. 95%)

Obs. A (m_{χ_1}, m_{χ_2})	Obs. B (m_{χ_1}, m_{χ_2})	Obs. C (m_{χ_1}, m_{χ_2})
(2.2, 49.0)	(5.2, 73.0)	(7.9, 96.2)
(1.9, 49.1)	(4.7, 73.0)	(6.9, 95.2)
(2.0, 48.6)	(4.6, 73.2)	(7.1, 95.9)
(2.2, 49.1)	(5.2, 73.4)	(7.3, 96.8)
(2.3, 49.0)	(5.5, 73.8)	(7.5, 96.1)

Table 1. Sets of 5 observations for the mass pair (m_{χ_1}, m_{χ_2}). These were randomly selected before creating the estimation maps to construct the median 95% confidence regions in Figure 5.