A novel signature for LLP at the LHC

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- A slow particle while decaying sprays particles in all directions.

- A novel signature of LLP decay that arises from this For heavy long lived particles (LLP) this would mean the objects which emerge from the decay of LLP could even give rise to backward moving objects (BMO's) from the secondary vertex.

Based on a revised version of 1706.07407.

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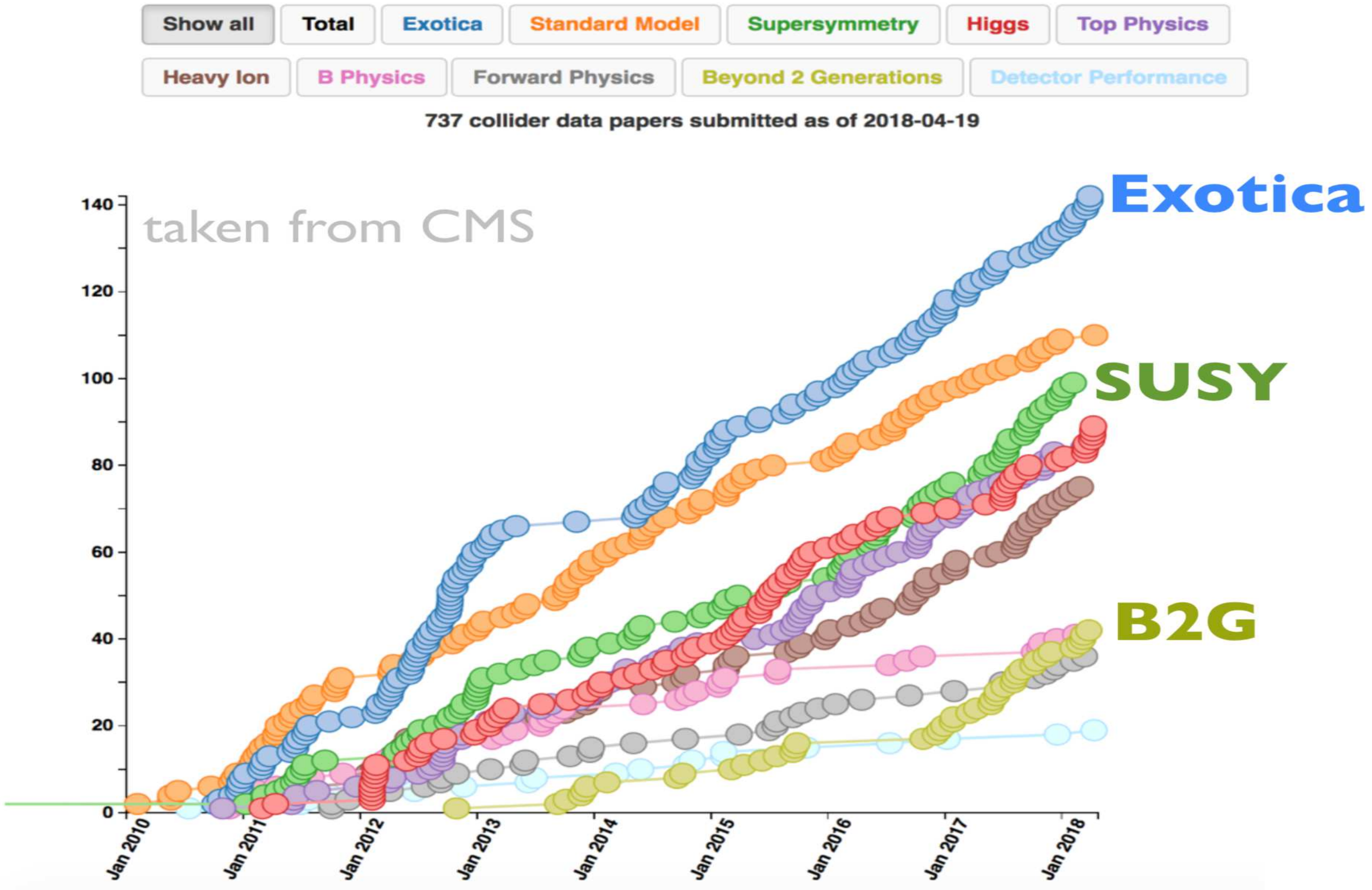
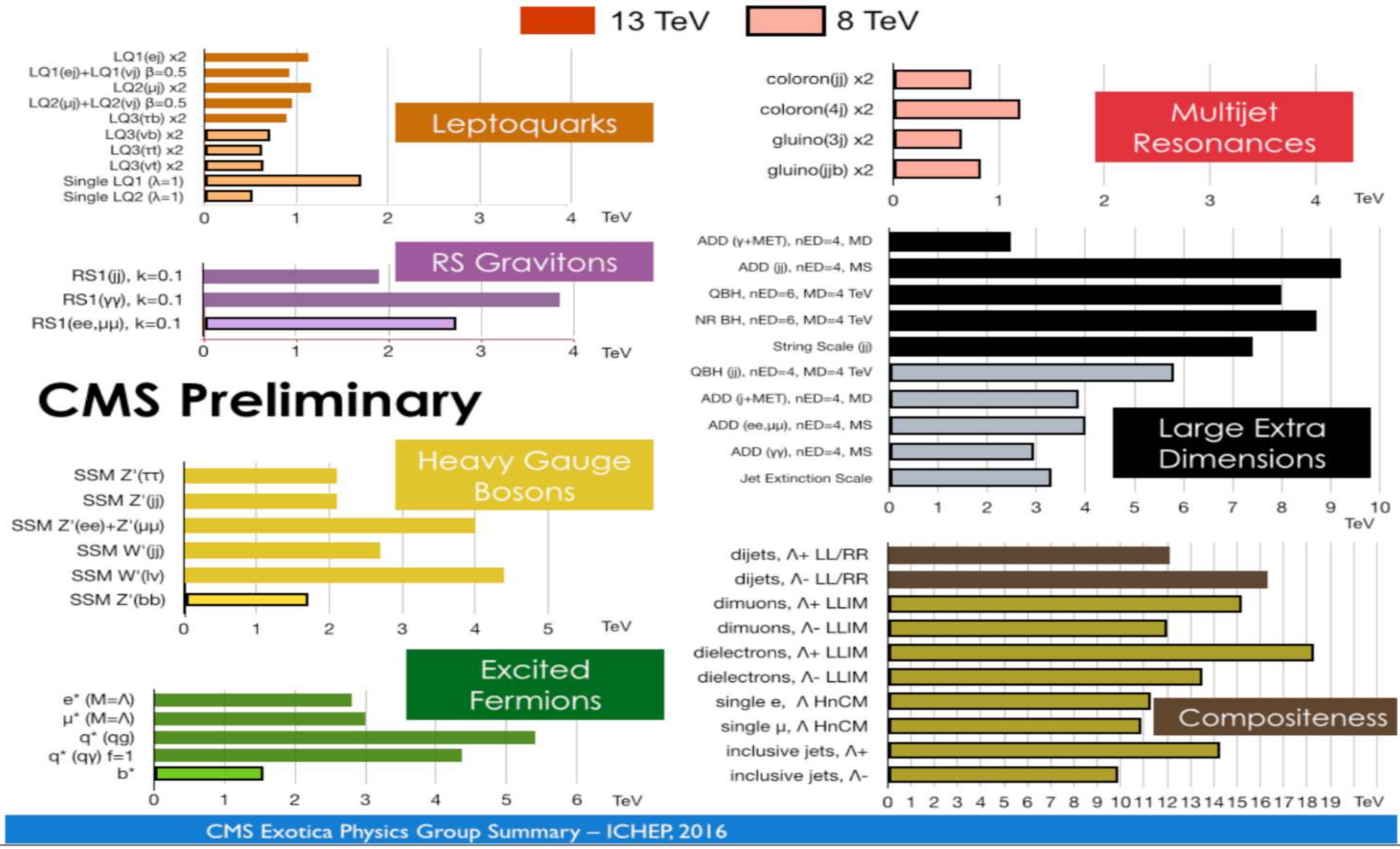
Theory: B. Bhattacharjee, S. Banerjee, F. Boudjema and G. Belanger.

Incredible number of searches for New Physics



Incredible number of searches for New Physics

in many different channels,
using various physics interpretations



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Quite a few long-lived signatures are also searched for

But null results so far...

Where is new physics hiding?

Very exotic, unconventional signature

- not yet searched for?
- experimentally challenging?

Long Lived Particles (LLP's) are part of this new landscape that is being explored.

All these models always had regions in parameter space which would give rise to long lived neutral or charged particles. There are a lot of examples in the models. One which we will use to simulate are SUSY decays either in R parity conserving theories or in R parity violating theories.

We need to search in all possible places..The search for LLP's has been on.

Mainly as displaced vertices, emerging jets, OR dark showers.

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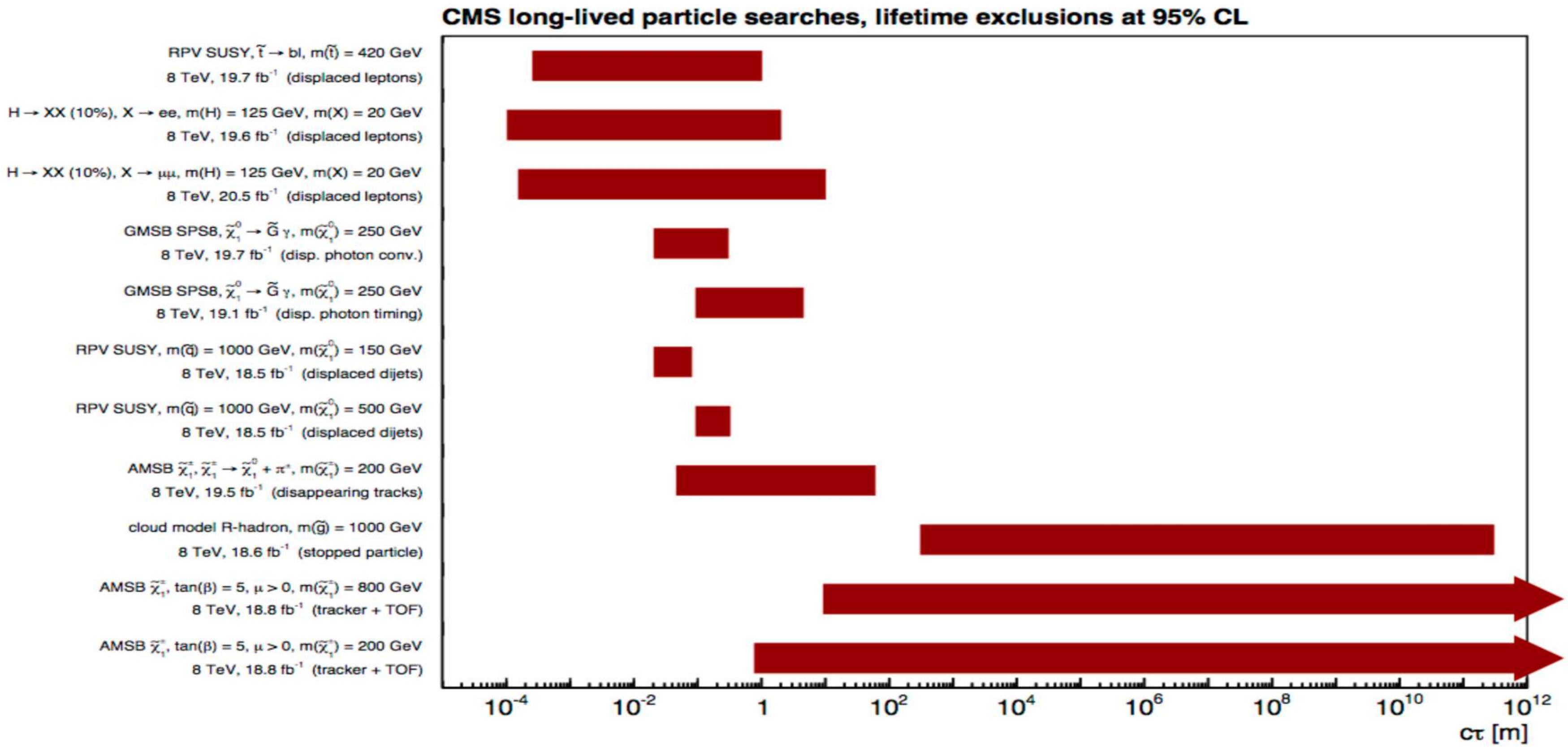
Quite a few long-lived signatures are also searched for



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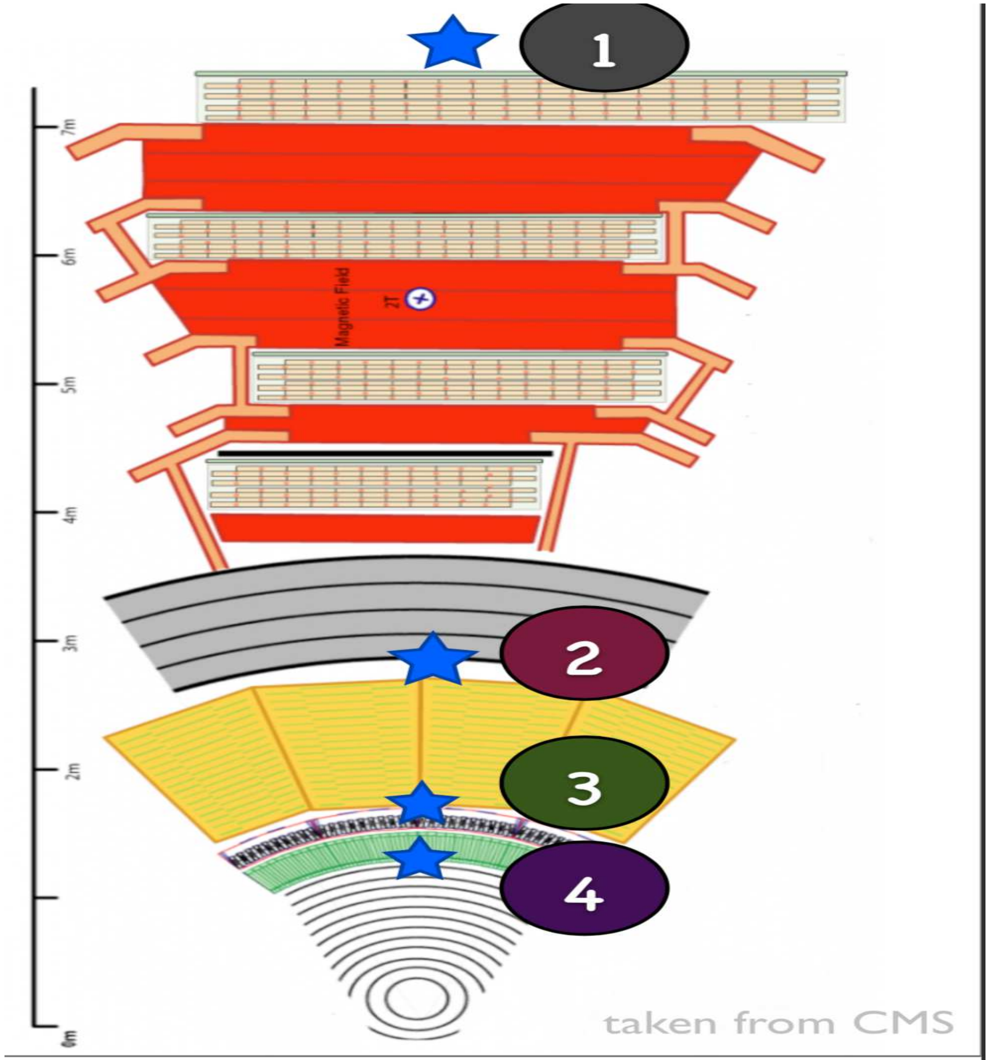
All these searches use what one can call inside -out . Ordered sequence of events going from the inner detector layers to outer layers. I.e interaction point to layers in tracker, the ECAL then HCAL and finally the muon chamber.

Heavy particle is produced and then decays and the decay products are followed through the detectors layers.



What we want to suggest is a new signature which will arise from the decay of LLP travelling inside-out, away from the beam but some portion of the decay products emitted in a direction opposite to the LLP direction, will seem to be moving inward and hence outside-in ins some layers or sublayers

If decay products are jets then these jets coming from a displaced vertex will be deviated compared to prompt jets coming from the interaction point. These jets will hit multi-towers of HCAL. These will be a bit like non pointing photons!

So one can have 'Backward moving objects' (BMO's) or 'Distorted Objects (DO)'

First let me show an example pictorially for one of the cases:

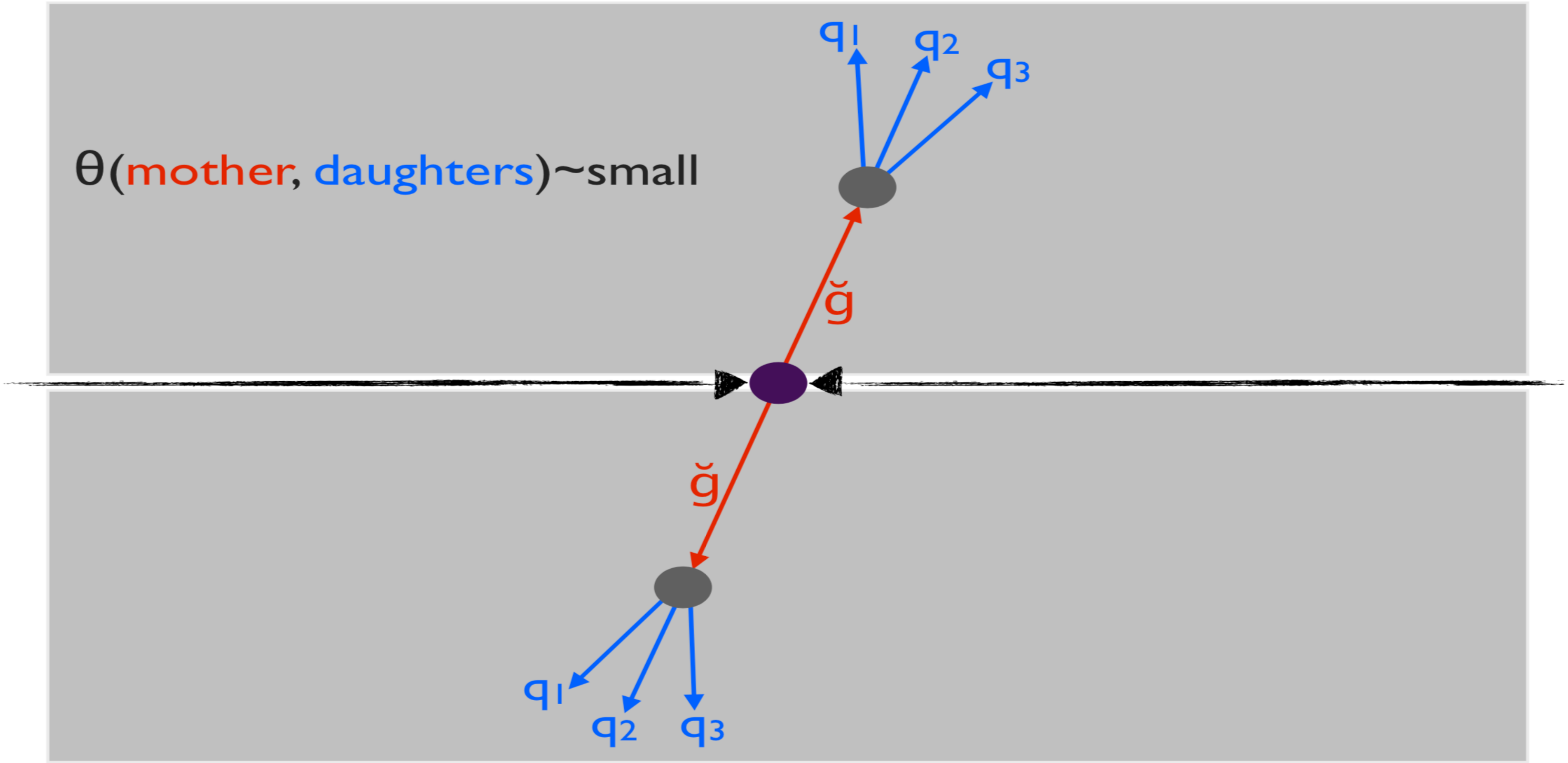
Consider the case of a gluino decaying via RPV couplings:

$\tilde{g} \to q_1 q_2 q_3$.

So one is considering $pp \to \tilde{g}\tilde{g}$ followed by the decay through RPV couplings. (R-hadrons)

The life time and the place where particle will decay will depend on the details of the theory.

Usual 'displaced vertices' ,'displaced jets' signature

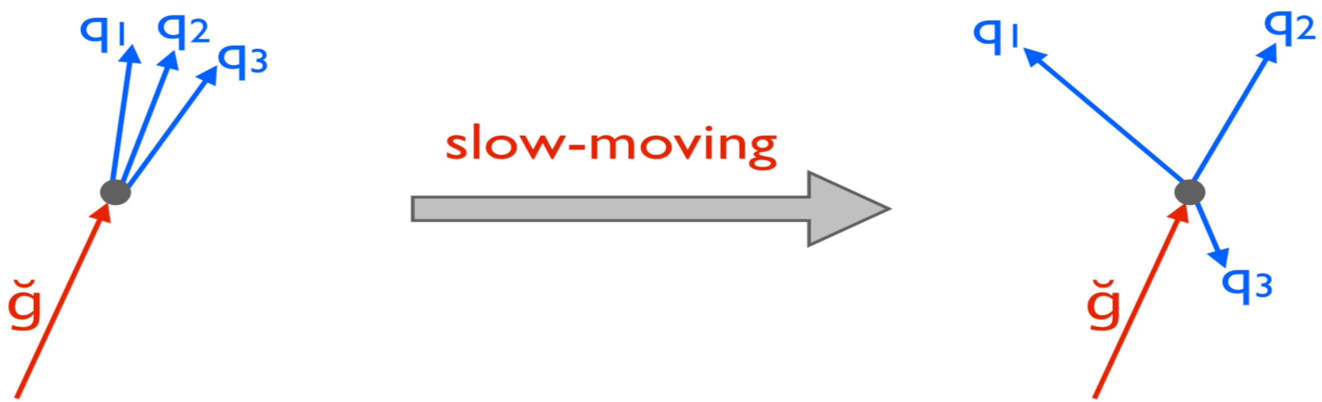


If ğ heavy → slow-moving

$\beta(=p/E) < 1$

Decay products not collimated anymore

θ(mother, daughters) can be big



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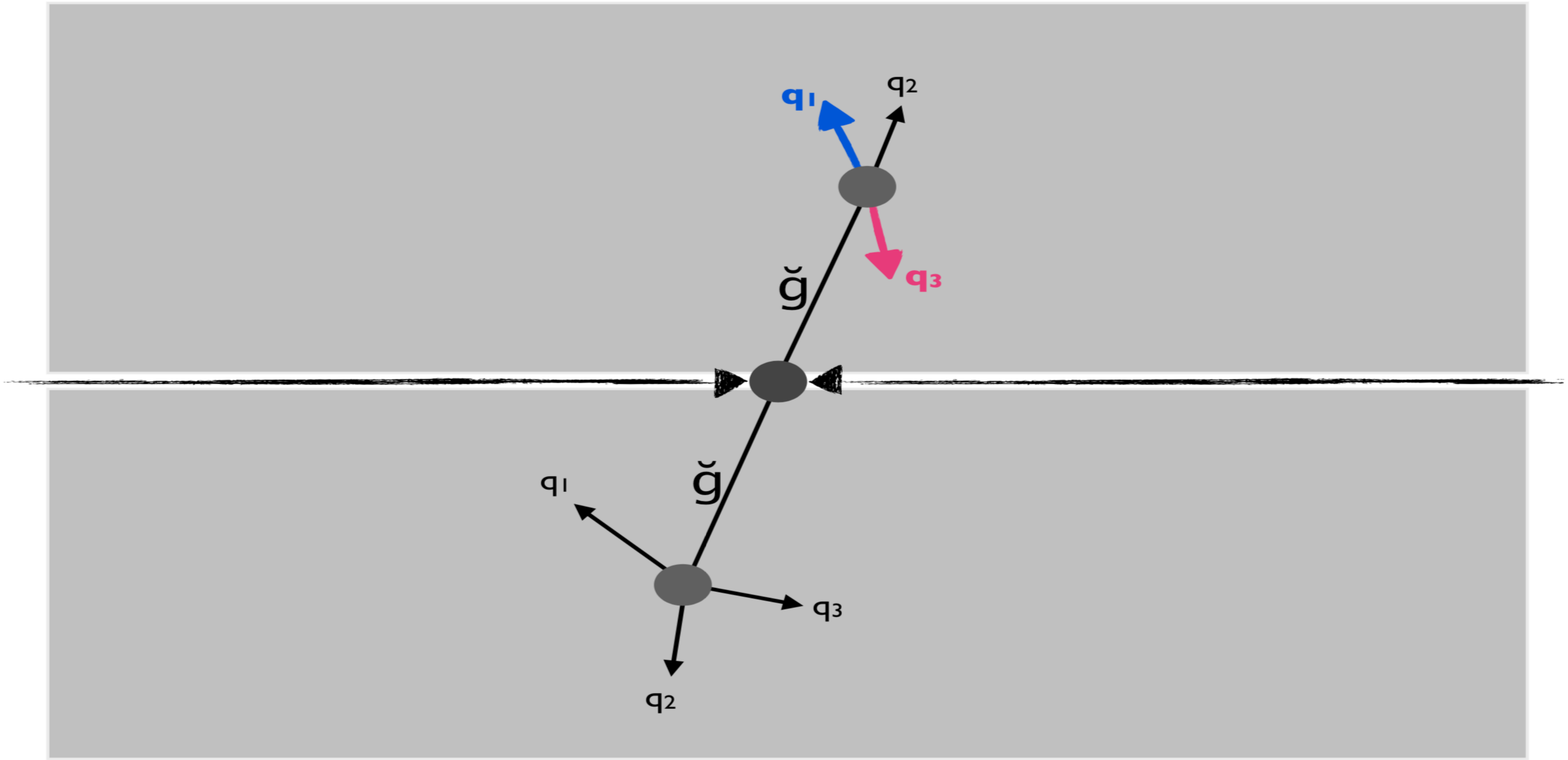
Non-pointing or even backward-moving particles



Before discussion implications of these for LLP searches let us first understand what does the fraction of daughter particles moving at large angles to the mother LLP depend on.

After that the discussion will depend on where the LLP will decay.

We demonstrate that the effect is largely kinemtical and is not affected by spins of the particles involved. Also dont seem to depend on the production mode s-channel vs t-channel etc. Model independent way. Ie. we are not looking at any one particular model with some parameter space which will give rise to the LLP etc.

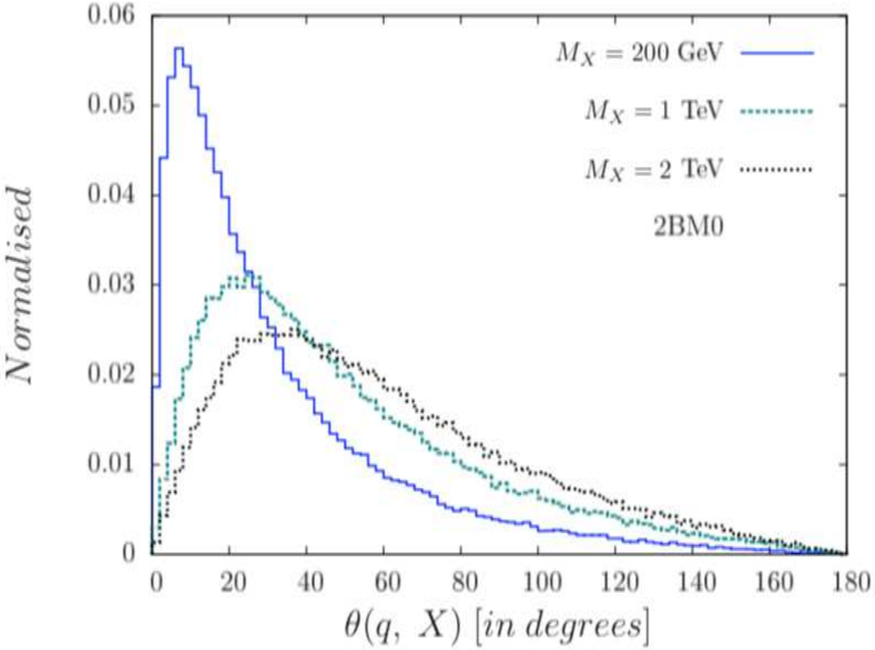
We consider four different cases, which differ in the kinematics, production mechanisms , spins of the particles involved, number of decay particles as well as the masses of the decay particles.

i] 2BM0: Two body decay mode with massless daughters: $X \to qq$ For example RPV decay $\tilde{q} \to qq$ (involves baryonic RPV and hence LLP) OR RPV decay $\tilde{l} \to qq$. Production mode quark initiated.

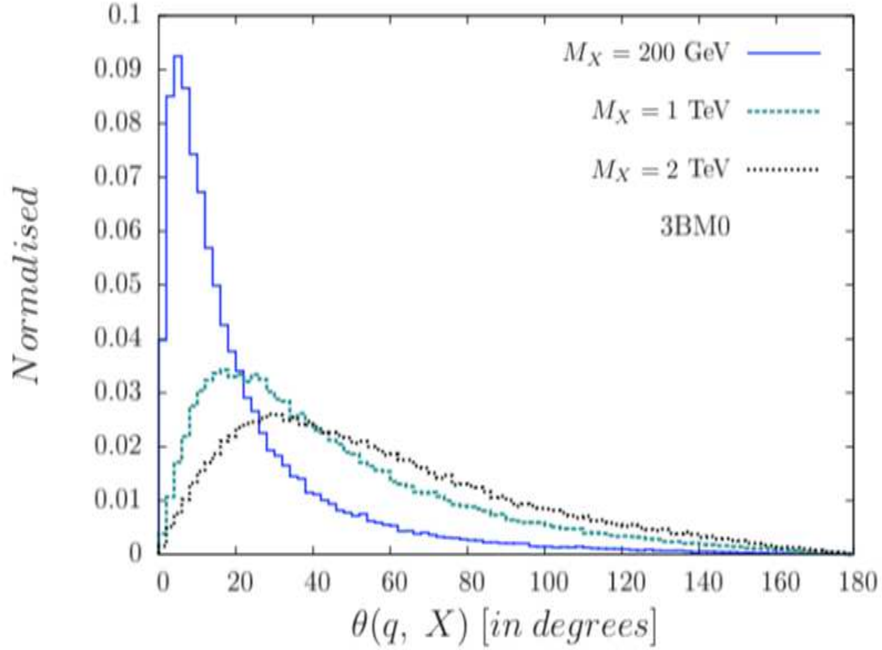
II] 3BM0: Three body decays with massless daughters, $X \to qqq$. For example RPV decay of $\tilde{\chi}_1^0 \to qqq$ OR a decaying $\tilde{g}$ (or R-hadron) . Production can be both quark and gluon initiated.

III] 2BM: 2 body massive daughter, $X \to q + DM$. Example R-parity conserving case , $\tilde{q} \to q + \tilde{\chi}_1^0$ The particle can be a LLP because of compressed mass spectra. Production dominantly gluon initiated.

IV] 3BM: Three body decay with massive daughters : $X \to DMqq$. An example is the RPC scenario with $\tilde{g} \to q\bar{q}\tilde{\chi}_1^0$. We chose gluon dominated production.

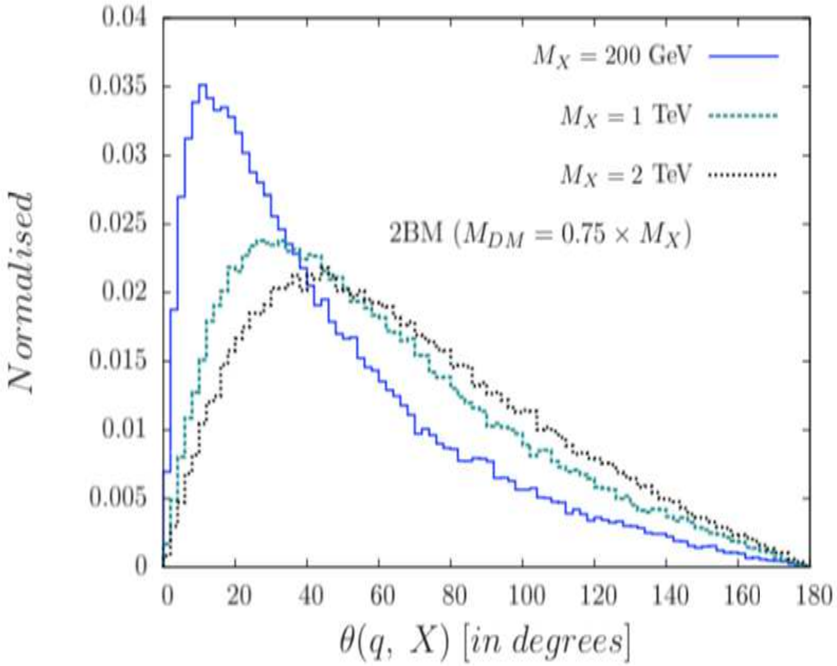


(a)

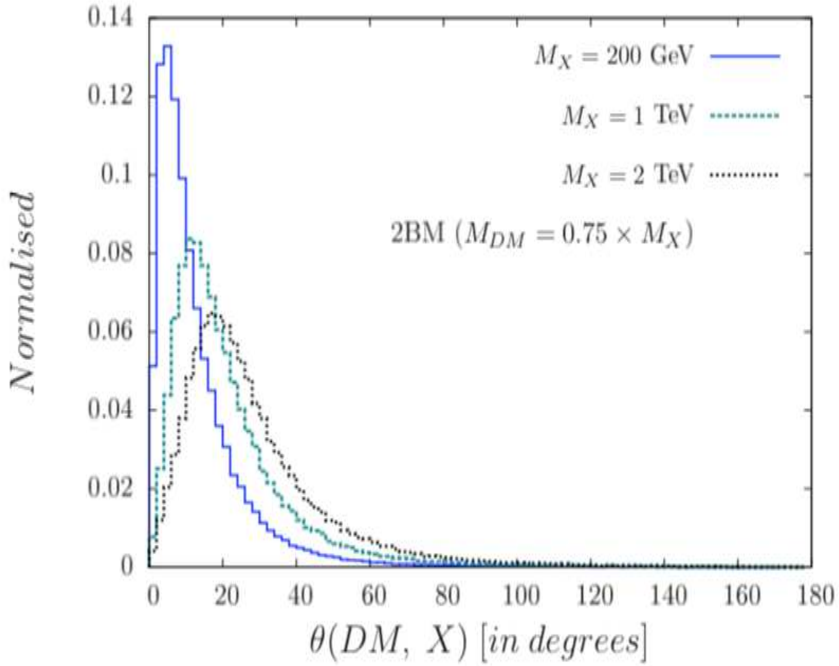


(b)

Angular separation is larger for larger masses of parent X for both 2BM0 and 3BM0

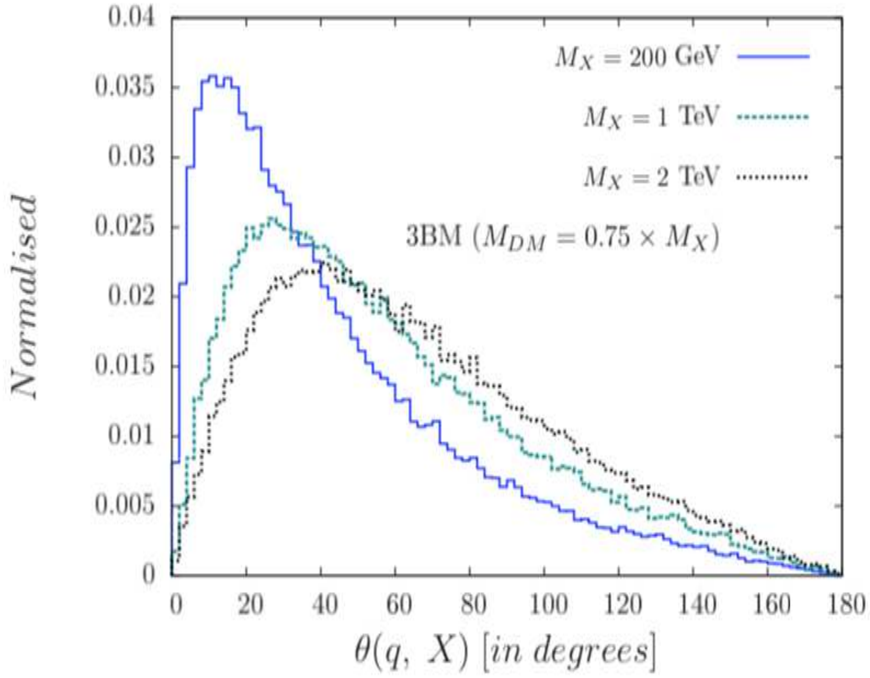


(c)

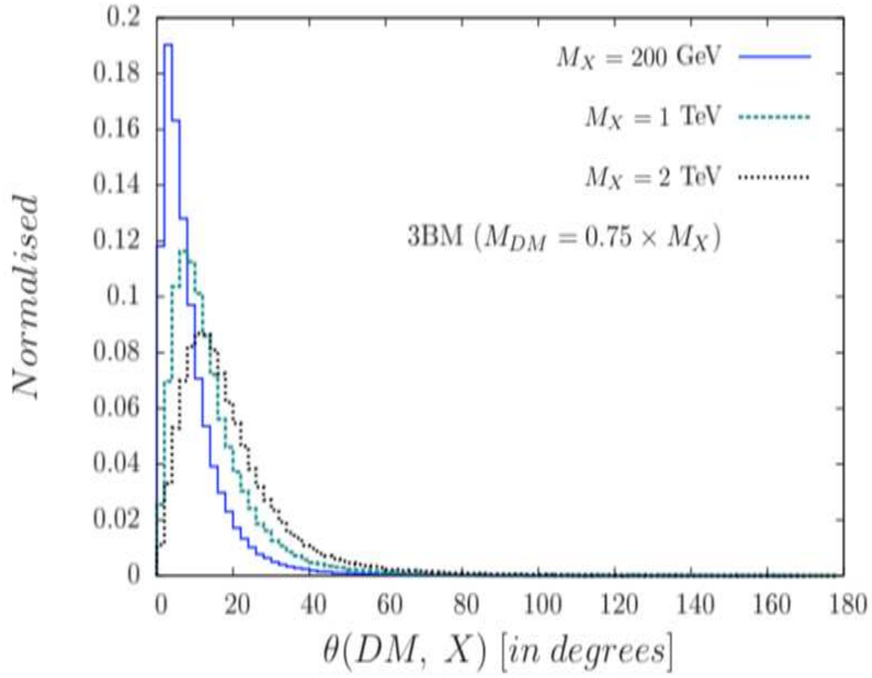


(d)

Angular separation is larger for larger masses of parent X even with the massive daughter. The right hand plot for angle between X and the massive daughter. Even in the second case the angular separation is substantial.



(e)



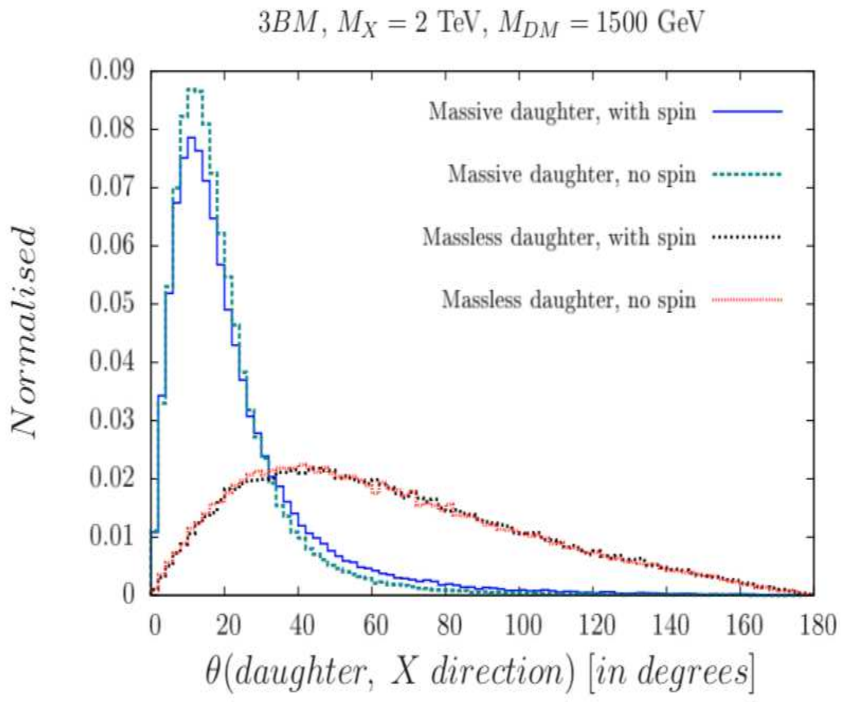
(f)

Angular separation is larger for larger masses of parent X even with the massive daughter. The right hand plot for angle between X and the massive daughter. Even in the second case the angular separation is reduced further.

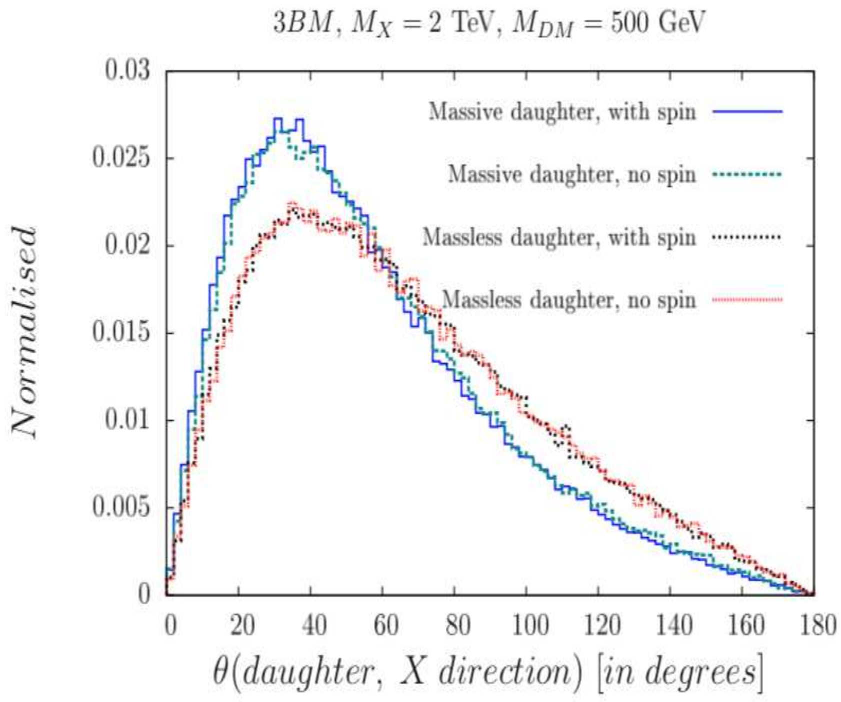
Case	M_X [TeV]	$M_{\rm DM}$ [TeV]	β (mean, RMS)	$\theta > 22.5^\circ$	$\theta > 45^\circ$	$\theta > 90^\circ$	$\theta > 135^\circ$
2BM0	0.2	-	0.75, 0.23	0.85	0.62	0.25	0.05
			0.87, 0.13	*0.78*	*0.46*	*0.13*	*0.03*
	0.5	-	0.66, 0.24	0.96	0.78	0.33	0.07
			0.81, 0.14	*0.94*	*0.65*	*0.19*	*0.04*
	1	-	0.58, 0.23	0.99	0.90	0.42	0.09
			0.72, 0.15	*0.99*	*0.83*	*0.28*	*0.06*
	2	-	0.46, 0.20	1.00	0.98	0.54	0.13
			0.60, 0.14	*1.00*	*0.97*	*0.40*	*0.08*

Table 1. Mean value and dispersion (rms) of the velocity of the mother particle (X) and fraction of events with angle θ made by at least one of the lightest daughter particles with the direction of X, for the four scenarios. For each M_X (and M_{DM}), we also give the $\mathcal{M} = 1$ (kinematics only) case (first row). The row just below (in *italics*) is for the the model-dependent scenarios.

			0.62, 0.15	*1.00*	*0.98*	*0.92*	*0.12*
3BM	0.2	0.05	0.67, 0.24	0.91	0.70	0.31	0.07
			0.76, 0.19	*0.86*	*0.60*	*0.22*	*0.05*
	0.2	0.15	0.67, 0.24	0.89	0.67	0.30	0.07
			0.77, 0.19	*0.84*	*0.58*	*0.21*	*0.05*
	0.5	0.125	0.60, 0.23	0.96	0.79	0.37	0.09
			0.69, 0.19	*0.94*	*0.73*	*0.29*	*0.06*
	0.5	0.375	0.60, 0.23	0.94	0.76	0.36	0.09
			0.69, 0.19	*0.92*	*0.70*	*0.28*	*0.06*
	1	0.25	0.53, 0.22	0.98	0.86	0.43	0.11
			0.61, 0.18	*0.97*	*0.82*	*0.36*	*0.08*
	1	0.75	0.52, 0.22	0.97	0.83	0.42	0.10
			0.61, 0.18	*0.96*	*0.79*	*0.35*	*0.08*
	2	0.50	0.42, 0.19	0.99	0.93	0.52	0.13
			0.50, 0.16	*0.99*	*0.90*	*0.46*	*0.11*
	2	1.50	0.42, 0.19	0.99	0.90	0.49	0.13
			0.50, 0.16	*0.98*	*0.87*	*0.44*	*0.11*



(a)



(b)

Spin effects do not affect our results.

For larger M_X β is smaller and hence fraction of decay products at large angles increases.

Usually for quark induced processes β values are a little larger but cross-sections are smaller. The two may compensate.

For pair production decays of the other X will also come inwords

Fractions of backward particles is at least 10% to as much as 68%. Thus fraction of particles moving outside in can be large. Extreme scenario: Stopped R-hadron $\beta = 0$. We can thus have BMO's, backward moving objects.

Depending on where the LLP decays it will have different implications for the LLP searches.

Say the particle reverses into the tracker. Compute then the ratio of visible (hadronised BMO's) E_{in} to E_{LLP}. We think this observable can be a proxy for the proportion of the backward moving, outside in objects. We consider a very simple geometry.

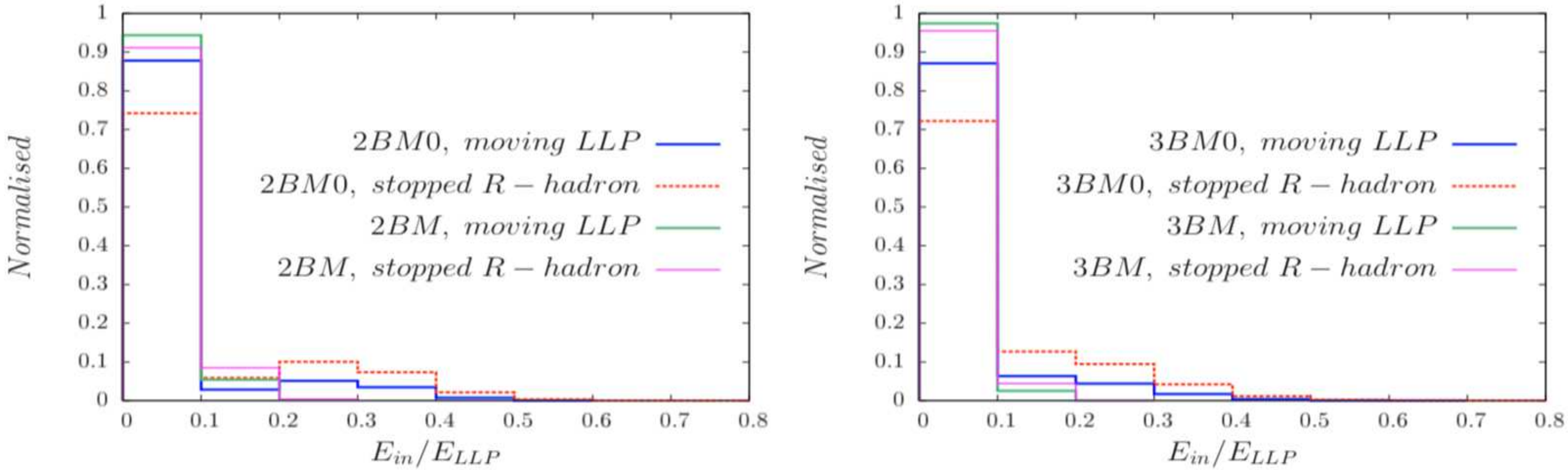


Figure 3. Normalised distribution of $E_{\rm in}/E_{\rm LLP}$, the energy fraction of visible daughter particles to the mother LLP shown for $M_{LLP} = 2$ TeV and $M_{\rm DM} = 0.75 \times M_{\rm LLP} = 1.5$ TeV. For the definition of the 2BM/3BM decays, see the text. In the first bin ($E_{\rm in}/E_{\rm LLP} < 0.1$) $E_{\rm in} = 0$. It should be interpreted as the case where no *BMO* has registered.

Lowest bin means this fraction did not make it to the tracker.

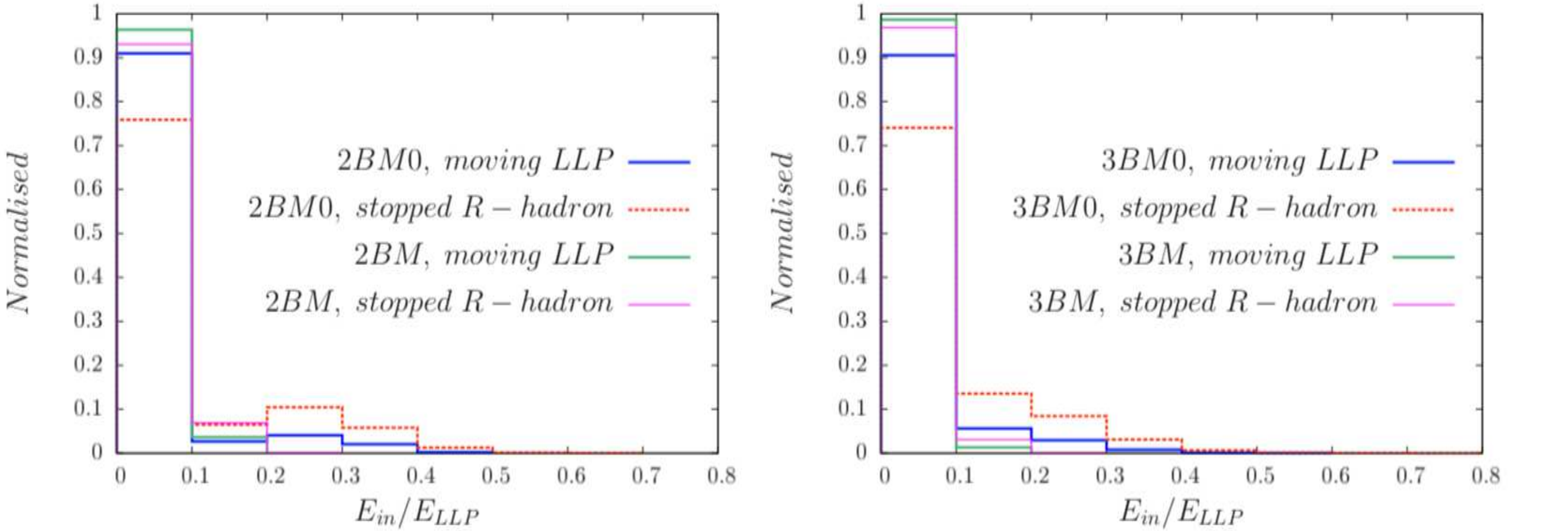


Figure 4. As in Fig. 3 but for the case of the muon chamber with dimensions as specified in the text.

Lowest bin means this fraction did not make it to the tracker.

If the particle decays outside the muon chamber the BMO's can provide a way to still catch them in the detector.

For stopped R-hadrons fraction of energy traversing inside is as much as 22.5%, for moving LLP it is 12.2 % For the three body case the numbers are even higher.

If one of the daughters is massive situation changes. for the R-hadron these fractions are now 8.2% and 4.6%.

But these signatures have no SM background to speak of. Hence even if the fraction of these particles is small it will be still interesting

One will need to figure out how to distinguish between a hadron in a muon chamber from a cosmic muon.

Also how will shower shape variables in ECAL and HCAL change for inward moving objects , ie. our BMO's?

Possible to have timing information for muon chamber?

BMO's will have large angular separation from the primary vertex. will they be caught by jet reconstruction algorithms? Can one use data scouting for this?

Lots of questions..but basically BMO's can be a very interesting signature for heavy LLP's