Triggering long-lived particles in HL-LHC and and the challenges in the first stage of the trigger system

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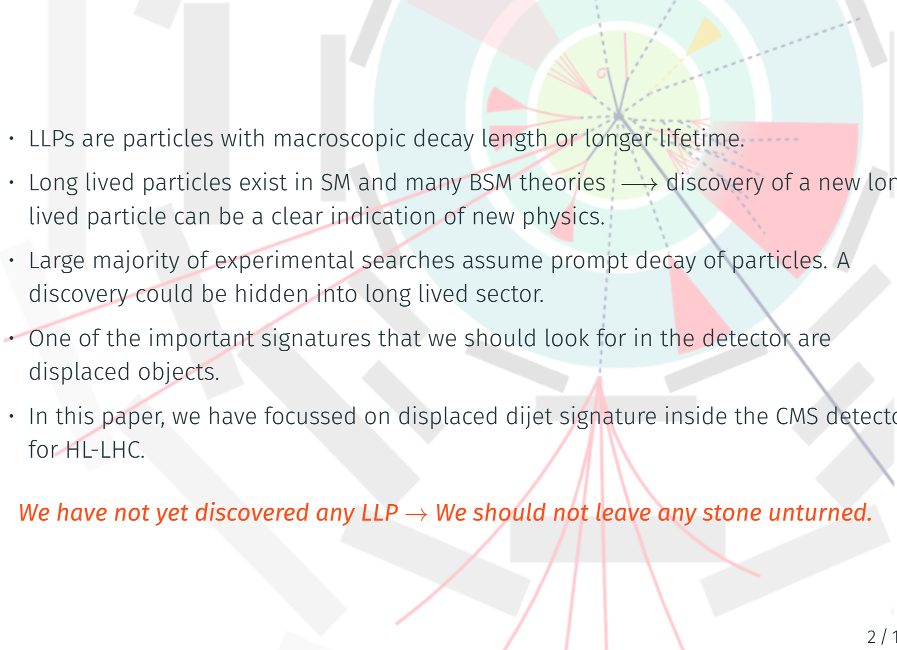
Based on- JHEP 08 (2020) 141, e-Print: 2003.03943 [hep-ph] with B. Bhattacherjee, S. Mukherjee and R. Sengupta

Introduction



- LLPs are particles with macroscopic decay length or longer lifetime.
- Long lived particles exist in SM and many BSM theories ⟶ discovery of a new long lived particle can be a clear indication of new physics.
- Large majority of experimental searches assume prompt decay of particles. A discovery could be hidden into long lived sector.
- One of the important signatures that we should look for in the detector are displaced objects.
- In this paper, we have focussed on displaced dijet signature inside the CMS detector for HL-LHC.

We have not yet discovered any LLP → We should not leave any stone unturned.

L1 trigger

Triggering is one of the crucial parts of an analysis where interesting events are stored for further analysis and rest are discarded forever. → Can't afford to lose interesting LLP events at the first stage of the analysis.

- Existing triggers employed for LLP searches with displaced jet signatures are highly PU sensitive → Won't be effective at HL-LHC with PU interactions reaching 200.
- Several detector upgrades concerning tracker and faster FPGAs will make the collection of tracks available at L1.
- FPGA upgrade will enable faster processing at L1 and will open possibility of deployment of light machine learning techniques at L1.

We can approach this challenge of triggering LLP events in two ways

- Use existing triggers but with tightened trigger cuts and constraints to control rate.
- Use dedicated LLP triggers harnessing the tracking and faster processing capability of upgraded detectors.

Wise choice will be to use dedicated triggers to keep rate under control and select events efficiently.

Why do we need dedicated LLP triggers?

Standard jet triggers like

- Single jet (atleast 1 jet with p_T > 173 GeV)
- Di-jet (atleast 2 jets with same vertex and p_T > 136 GeV)
- Quad jet (atleast 4 jets with same vertex and p_T > 72 GeV)

will be helpful in triggering events where

- LLP is really massive and decays to quarks or gluons ($pp \to AA, A \to XX$ or $pp \to XX$).

Standard triggers will not be helpful in cases where

- LLPs are not massive enough to deposit enough energy in the calorimeters after decay.
- Decay length is large such that same vertex condition is not satisfied and decay happens after tracker.
- Very light LLPs (few GeVs) which will always require some prompt particles or ISR to trigger the event.

Simulation

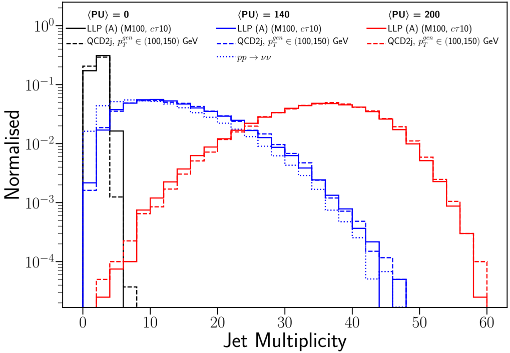
In this work, we have focused on triggering moderately massive LLPs with moderate decay length.

- Pair produced LLPs decaying to Jets ($pp \to XX, X \to jj$) as signal with $M_X \in \{50, 100, 200\}$ GeV and $c\tau \in \{10, 100\}$ cm.
- QCD dijets ($pp \to jj$) as the background.

- We use Delphes-3.4.1 for detector simulation in our work with some modification pertaining to displaced particles.
- Displaced stable particles deposit energy in the η and ϕ bins corresponding to the detector segmentation rather than their actual η and ϕ.

Effect of PU

Jet Multiplicity for 0, 140 and 200PU for R = 0.4 Jets with $p_T > 60$ GeV

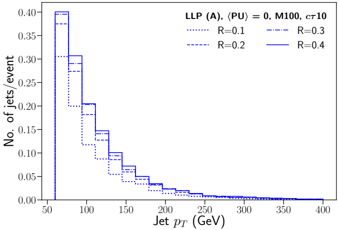


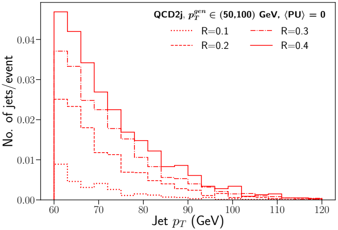
Effect of PU is dominant for both LLP signal and QCD background.

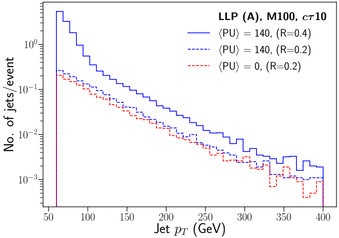
Since, PU is proportional to jet area, can narrow jets help?

Narrow jets

Since, PU is uniformly distributed, reducing the jet cone size can decrease the PU contribution given that it contains most of the hadronic activity of signal



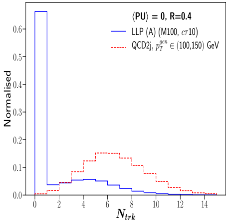




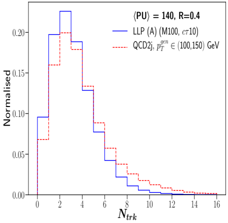
- LLP jets deposit energy in smaller area and are narrow.
  arxiv:1706.07407, Biplob B. et. al.
  arxiv:1904.04811, Biplob B. et. al.
- R = 0.2 jets with 140 PU matches fairly with the hard process without PU → PU contribution is drastically reduced.

L1 tracking

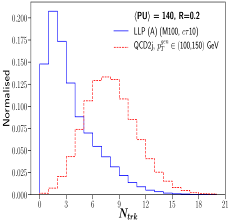
Trackless LLP jets



PU Dominates



R = 0.2 Jets

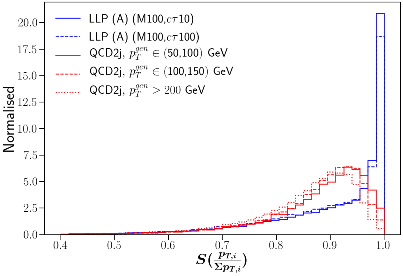


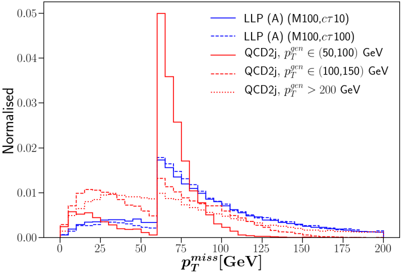
- At L1, we can reconstruct tracks originating from vertex within radial distance of < 1 cm and having $p_T > 2$ GeV.
- LLP decaying after 1 cm radial distance will have no reconstructed tracks at L1 unlike QCD.
- We can use this information to make a new trigger which makes use of *tracklessness* of these jets.

BDT training using tracking variables

BDT Variables

$\sum \mathbf{p_T}$, $\mathbf{z}_{\text{j\_vtx}}$, $\Delta z_{\text{j\_vtx}}$, $\mathbf{p}_{\mathbf{T}\text{(vtx)}}^{\text{miss}}$, $\mathbf{n}_{\mathbf{z}_{\text{trk\_max}}}$, $\Delta\mathbf{z}_{\text{trk\_max}}$, $\sum \mathbf{p}_{\mathbf{T}}^{\mathbf{z}_{\text{trk\_max}}}$, $\sum \mathbf{p}_{\mathbf{T}}^{\mathbf{z_a} \neq \mathbf{z}_{\text{trk\_max}}}$, $\frac{\sum \mathbf{p}_{\mathbf{T}}^{\mathbf{z}_{\text{trk\_max}}}}{\sum \mathbf{p_T}}$, $S(z_i)$, $S(p_{T,i})$, All variables with tracks within 0.2, $\mathbf{N}_{\text{trk}}/\mathbf{N}_{\text{trk}}^{(\mathbf{0.2})}$, $\sum p_T / \sum p_T^{(0.2)}$



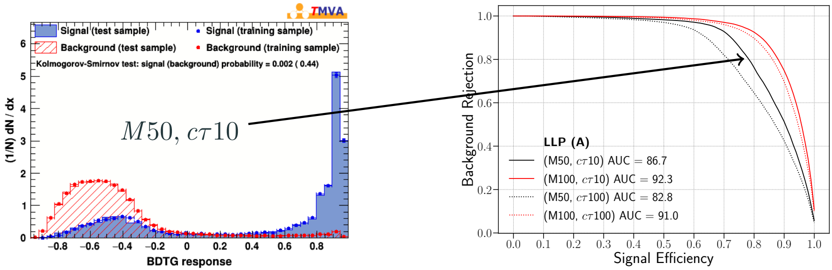


$$S\left(\frac{p_{T,i}}{\Sigma p_T^1}\right) = -\sum_{i=1}^{N_{\text{trk}}} P\left(\frac{p_{T,i}}{\Sigma p_T^1}\right) \log_{N_{\text{trk}}} P\left(\frac{p_{T,i}}{\Sigma p_T^1}\right)$$

$$p_{T\text{(vtx)}}^{\text{miss}} = \sqrt{\left(\sum_n p_x^i\right)^2 + \left(\sum_n p_y^i\right)^2}$$

Performance

We have trained the BDT classifier using total of 32 tracking variables in the TMVA framework.



- There might be jets with $p_T > 60\ \mathrm{GeV}$ which come from the PU in the LLP events. These jets are similar to prompt QCD jet.
- Classifier performance degrades with decreasing mass and increasing decay length as less and less jets with $p_T > 60$ GeV become available and PU starts dominating.

Triggers based on the BDT training using tracking variables

Triggers

- $\mathbf{T_1}$: at least one $R = 0.2$ jet with $p_T > 60$ GeV;
- $\mathbf{T_2^a}$: T_1 + that jet passes the BDT threshold corresponding to a background rejection of 98% ($a = 0$), 90% ($a = 1$) and 70% ($a = 2$);
- $\mathbf{T_3^a}$: No other jet from the same z-vertex (i.e., Δz with all other jets is greater than 1 cm) + T_2^a;

T3→ Bkg rejection ↓	Rate (KHz) QCD2j $p_T^{gen} \in \{50, 100\}$GeV	Efficiency (%) LLP (M50 $c\tau 10$)	Efficiency (%) LLP (M100, c$\tau 10$)
98 %	1046 →14	13	60
70 %	1046 →190	19	73

For 70% background rejection, we will get signal efficiency of $\approx 13\%$ for LLP of mass 50 GeV and decay length 10 cm from standard jet triggers with an overlap of 5% taking total efficiency to ≈ 27% .

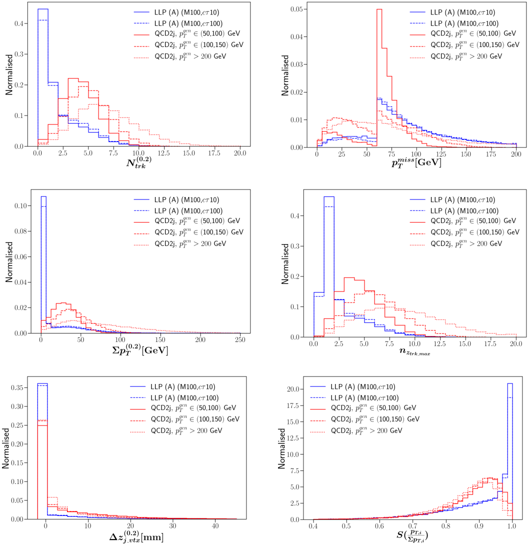
Conclusion

- Unique signatures of LLPs offer staggering scope for discovery of physics beyond the standard model in the LHC experiments.
- We need dedicated trigger strategies so that we do not miss rare LLP events in the first level (L1).
- Standard triggers targeting prompt particles will be inefficient of some LLP searches in high PU conditions.
- High PU being an issue at L1 can be managed by reducing the cone size of jets used in the trigger.
- We can use MVA instead of cut based analysis at L1 due to improvement of front end electronics.
- We have trained BDT classifier using tracking variables making use of tracklessness of jets and relatively large decay time of LLP.
- Triggers developed with BDT classification based on L1 track variables improve signal efficiency at moderate rates.

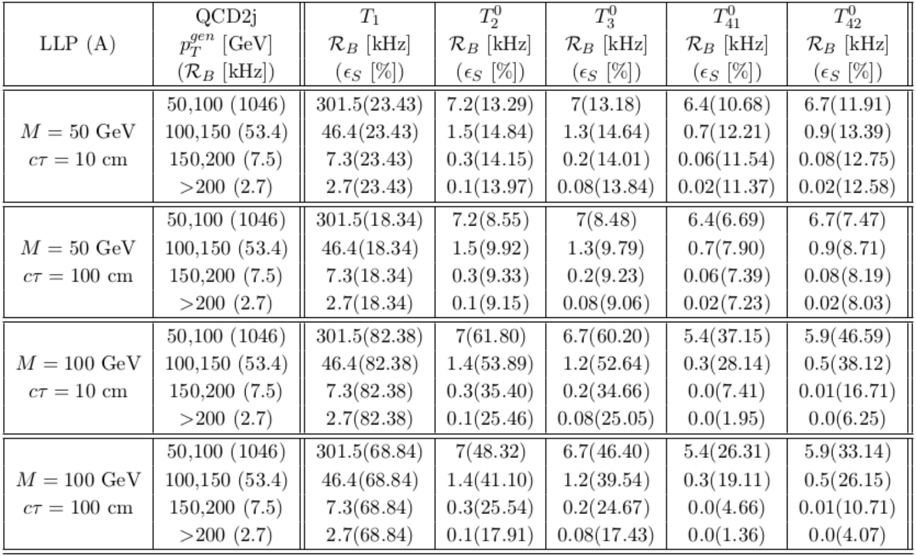
For further details please have a look at
B. Bhattacherjee, S. Mukherjee, RS, and P. Solanki, JHEP 08 (2020) 141, e-Print: 2003.03943 [hep-ph]

Thank you

Backup: Track distributions

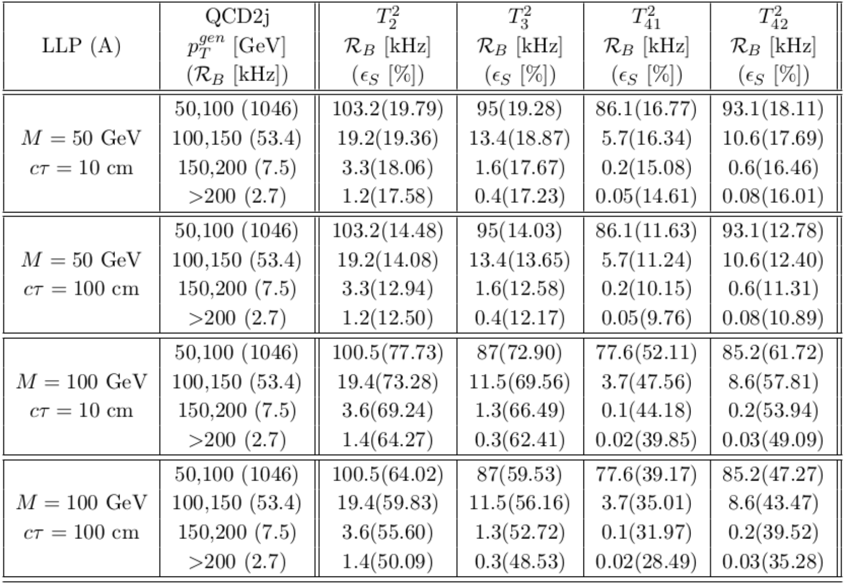


Backup: Trigger performance (98% BR)



LLP (A)	QCD2j p_T^{gen} [GeV] ($\mathcal{R}_B$ [kHz])	T_1 $\mathcal{R}_B$ [kHz] (ϵ_S [%])	T_2^0 $\mathcal{R}_B$ [kHz] (ϵ_S [%])	T_3^0 $\mathcal{R}_B$ [kHz] (ϵ_S [%])	T_{41}^0 $\mathcal{R}_B$ [kHz] (ϵ_S [%])	T_{42}^0 $\mathcal{R}_B$ [kHz] (ϵ_S [%])
$M = 50$ GeV $c\tau = 10$ cm	50,100 (1046)	301.5(23.43)	7.2(13.29)	7(13.18)	6.4(10.68)	6.7(11.91)
	100,150 (53.4)	46.4(23.43)	1.5(14.84)	1.3(14.64)	0.7(12.21)	0.9(13.39)
	150,200 (7.5)	7.3(23.43)	0.3(14.15)	0.2(14.01)	0.06(11.54)	0.08(12.75)
	>200 (2.7)	2.7(23.43)	0.1(13.97)	0.08(13.84)	0.02(11.37)	0.02(12.58)
$M = 50$ GeV $c\tau = 100$ cm	50,100 (1046)	301.5(18.34)	7.2(8.55)	7(8.48)	6.4(6.69)	6.7(7.47)
	100,150 (53.4)	46.4(18.34)	1.5(9.92)	1.3(9.79)	0.7(7.90)	0.9(8.71)
	150,200 (7.5)	7.3(18.34)	0.3(9.33)	0.2(9.23)	0.06(7.39)	0.08(8.19)
	>200 (2.7)	2.7(18.34)	0.1(9.15)	0.08(9.06)	0.02(7.23)	0.02(8.03)
$M = 100$ GeV $c\tau = 10$ cm	50,100 (1046)	301.5(82.38)	7(61.80)	6.7(60.20)	5.4(37.15)	5.9(46.59)
	100,150 (53.4)	46.4(82.38)	1.4(53.89)	1.2(52.64)	0.3(28.14)	0.5(38.12)
	150,200 (7.5)	7.3(82.38)	0.3(35.40)	0.2(34.66)	0.0(7.41)	0.01(16.71)
	>200 (2.7)	2.7(82.38)	0.1(25.46)	0.08(25.05)	0.0(1.95)	0.0(6.25)
$M = 100$ GeV $c\tau = 100$ cm	50,100 (1046)	301.5(68.84)	7(48.32)	6.7(46.40)	5.4(26.31)	5.9(33.14)
	100,150 (53.4)	46.4(68.84)	1.4(41.10)	1.2(39.54)	0.3(19.11)	0.5(26.15)
	150,200 (7.5)	7.3(68.84)	0.3(25.54)	0.2(24.67)	0.0(4.66)	0.01(10.71)
	>200 (2.7)	2.7(68.84)	0.1(17.91)	0.08(17.43)	0.0(1.36)	0.0(4.07)

Backup: Trigger performance (70% BR)



LLP (A)	QCD2j p_T^{gen} [GeV] ($\mathcal{R}_B$ [kHz])	T_2^2 $\mathcal{R}_B$ [kHz] (ϵ_S [%])	T_3^2 $\mathcal{R}_B$ [kHz] (ϵ_S [%])	T_{41}^2 $\mathcal{R}_B$ [kHz] (ϵ_S [%])	T_{42}^2 $\mathcal{R}_B$ [kHz] (ϵ_S [%])
$M = 50$ GeV $c\tau = 10$ cm	50,100 (1046)	103.2(19.79)	95(19.28)	86.1(16.77)	93.1(18.11)
	100,150 (53.4)	19.2(19.36)	13.4(18.87)	5.7(16.34)	10.6(17.69)
	150,200 (7.5)	3.3(18.06)	1.6(17.67)	0.2(15.08)	0.6(16.46)
	>200 (2.7)	1.2(17.58)	0.4(17.23)	0.05(14.61)	0.08(16.01)
$M = 50$ GeV $c\tau = 100$ cm	50,100 (1046)	103.2(14.48)	95(14.03)	86.1(11.63)	93.1(12.78)
	100,150 (53.4)	19.2(14.08)	13.4(13.65)	5.7(11.24)	10.6(12.40)
	150,200 (7.5)	3.3(12.94)	1.6(12.58)	0.2(10.15)	0.6(11.31)
	>200 (2.7)	1.2(12.50)	0.4(12.17)	0.05(9.76)	0.08(10.89)
$M = 100$ GeV $c\tau = 10$ cm	50,100 (1046)	100.5(77.73)	87(72.90)	77.6(52.11)	85.2(61.72)
	100,150 (53.4)	19.4(73.28)	11.5(69.56)	3.7(47.56)	8.6(57.81)
	150,200 (7.5)	3.6(69.24)	1.3(66.49)	0.1(44.18)	0.2(53.94)
	>200 (2.7)	1.4(64.27)	0.3(62.41)	0.02(39.85)	0.03(49.09)
$M = 100$ GeV $c\tau = 100$ cm	50,100 (1046)	100.5(64.02)	87(59.53)	77.6(39.17)	85.2(47.27)
	100,150 (53.4)	19.4(59.83)	11.5(56.16)	3.7(35.01)	8.6(43.47)
	150,200 (7.5)	3.6(55.60)	1.3(52.72)	0.1(31.97)	0.2(39.52)
	>200 (2.7)	1.4(50.09)	0.3(48.53)	0.02(28.49)	0.03(35.28)