Searching for long-lived particles at the LHC: Seventh workshop of the LHC LLP Community

Triggering long-lived particles in HL-LHC at level-1

Based on
arXiv:2003.03943 [hep-ph]
with Biplob Bhattacherjee, Swagata Mukherjee and Prabhat Solanki

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- Proper triggering at the first level of the trigger system (L1 for CMS) is an integral part of any BSM search at LHC.
- LLP signatures depend on decay products as well as decay length − need dedicated triggers.
- Novel ideas by experimental collaborations − trackless jet, CalRatio, anomalous activity in muon spectrometer, when LLP decays to jets.

  ATLAS, 1305.2284; ATLAS, 1811.07370
- HL-LHC: high PU $\sim$ 140-200 compared to $\sim$ 60 in Run 3 − trackless jet and CalRatio triggers might get affected.

Search for LLP triggers for HL-LHC continue...

- **Tracker update:** read out hits left by tracks with $p_T > 2$ GeV, $|\eta| < 2.5$, $L_{xy} < 1$ cm, $|z_0| < 30$ cm at 40 MHz to the hardware-based L1 trigger system.

  T. James, CERN-THESIS-2018-241
- **Regional use of MIP timing detector (MTD):** Timing of charged particles with $p_T > 0.7$ GeV upto $|\eta| = 1.5$; $p > 0.7$ GeV for $1.5 < |\eta| < 3.0$ with 30 ps resolution.

  CMS Technical Proposal, LHCC-P-009
- **FPGAs** at L1 trigger hardware: able to handle small scale ML applications, like BDT classification.

  J. Duarte *et al.*, 1804.06913; S. Summers *et al.*, 2002.02534

Can we use these to develop any L1 trigger suitable for LLPs in the HL-LHC environment?

The L1 trigger menu for HL-LHC

L1 Calo jets:

- Towers (0.1×0.1 in η-ϕ) up to $|\eta| = 2.5$ with $E_T > 2$ GeV clustered using sliding windows of size 9×9 around seed tower with the maximum $E_T > 4$ GeV.
- Similar to anti-k_T with $R = 0.4$

A. Zabi *et al.*, JINST 11, no. 02, C02008 (2016)

Same z-vertex condition:

- Δz within all objects < 1 cm
- z_{vtx} for jets: $\frac{\sum_i p_T^i \times z_i}{\sum_i p_T^i}$; sum runs over all tracks associated with a jet

CMS Technical Proposal, LHCC-P-008

V. Rekovic "CMS Trigger @ HL LHC", TDII-2018

Trigger Algorithm	Threshold [GeV]	Rate w/ L1 tracks [kHz]	Rate w/o L1 tracks [kHz]
Single Jet	173	42	–
Double Jet	2@136	26	52
Quad Jet	4@72	12	185

Same z-vertex condition helps control huge rates from PU – more effect for triggers with lesser p_T thresholds.

Effect of the same z-vertex condition on LLPs

Modified `Delphes` *to correct the η-ϕ of towers for displaced particles.*

$$pp \to XX, X \to q\bar{q}, \quad X\text{: LLP}$$

Table for standard trigger efficiency

The signal efficiencies are quite low for LLPs with mass less than 200 GeV.

- **PU contribution help the jets pass the p_T threshold of standard triggers.**

  $M_X = 100$ GeV, $c\tau = 10$ cm: single jet trigger – 11.39% (w/o PU) to 27.43% (w/ 140 PU)

- **Same z-vertex condition reduces signal efficiency for LLPs in the multijet triggers.**

  $M_X = 100$ GeV, $c\tau = 10$ cm: dijet trigger – 28% (w/o trk) to 5.8% (w/ trk)

- **The LLP event gets triggered mostly by PU jets with the standard multijet triggers.**

  $M_X = 50$ GeV: quad jet trigger (w/ trk) – 10.99% ($c\tau = 10$ cm) to 10.57% ($c\tau = 100$ cm)

  Trigger efficiency almost independent of decay length.

Challenges of triggering LLPs at L1 of HL-LHC

- The same z-vertex condition imposed to control PU for prompt processes at HL-LHC adversely affects many LLP scenarios while triggering.

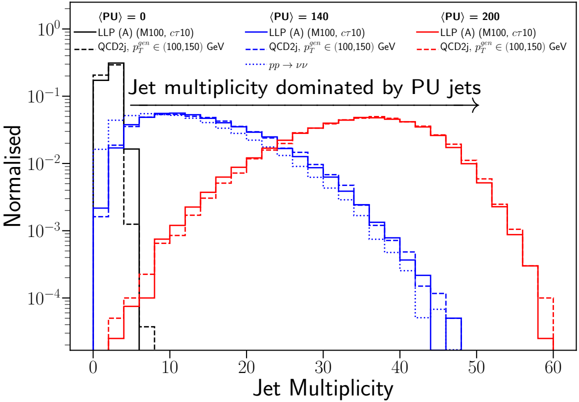
- Higher p_T thresholds will have less PU contamination, but lose sensitivity to light LLPs.

LLP scenarios in increasing order of the difficulty to trigger them at L1 –

- LLPs with associated hard and prompt particles,
  $pp \to AA$, $A \to q\bar{q}X$, LLPs from decay of h produced though VBF
  J. Jones-Prez *et al.*, 1912.08206
- LLPs without associated hard and prompt particles
  - massive LLPs decaying to jets – pass single jet trigger
  - LLPs decaying to electrons, photons, muons – cleaner channels
  - LLPs decaying to jets just before muon spectrometer – lesser PU
  - This work: LLPs decaying to jets within tracker or calorimeters

Effect of high PU

Number of R=0.4 jets with $p_T > 60$ GeV for QCD dijet and LLP processes



- **Both QCD and LLP jet distributions dominated by PU jets.**
- **PU $\propto$ Jet area**

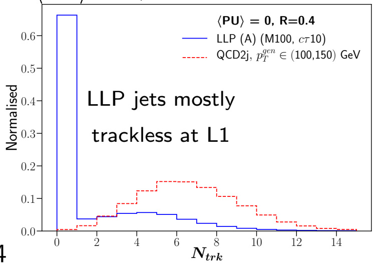
Can narrower jets help?

Dedicated triggers: L1 tracks

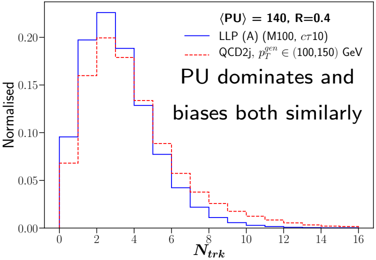
L1 tracking

N_{trk}: number of tracks within $\Delta R = 0.4$ of the jet axis

$\langle \text{PU} \rangle = 0,\ R = 0.4$

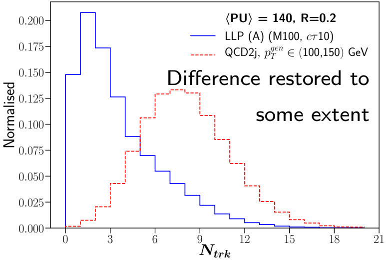


$\langle \text{PU} \rangle = 140,\ R = 0.4$



Reduce → **cone-size**

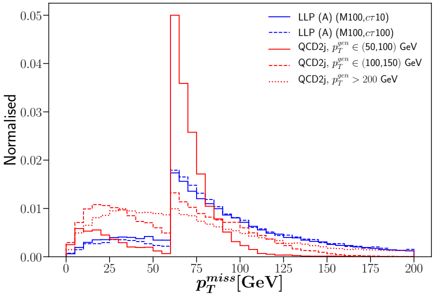
$\langle \text{PU} \rangle = 140,\ R = 0.2$



Narrow jets reduce PU contribution.

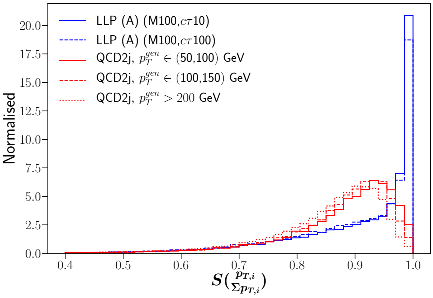
Some variables constructed out of L1 tracking

$\mathbf{p_{T(vtx)}^{miss}}$



- Missing transverse momentum at the z-vertex of a jet
- $p_{T(\text{vtx})}^{\text{miss}} = \sqrt{(\sum_n p_x^i)^2 + (\sum_n p_y^i)^2}$, where n jets come from the same z vertex

Entropy variables



- Shannon entropy of the p_T

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

- Pure set: entropy $\rightarrow 0$;

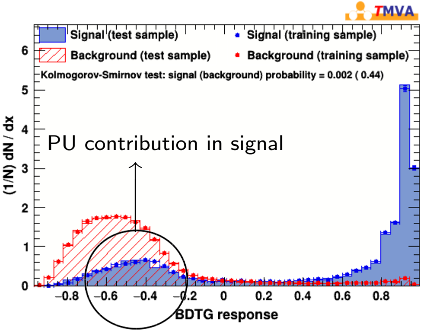
  Mixed set: entropy $\rightarrow 1$

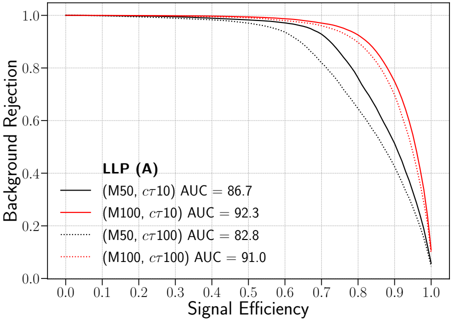
BDT classification based on track variables

$$N_{\text{trk}},\ \sum p_T,\ z_{\text{j\_vtx}},\ \Delta z_{\text{j\_vtx}},\ p_{T(\text{vtx})}^{\text{miss}},\ n_{z_{\text{trk\_max}}},\ \Delta z_{\text{trk\_max}},\ \sum p_T^{z_{\text{trk\_max}}},\ \sum p_T^{z_a \neq z_{\text{trk\_max}}},$$

$$\frac{\sum p_T^{z_{\text{trk\_max}}}}{\sum p_T},\ S\left(\frac{|z_i|}{\sum |z_i|}\right),\ S(z_i + 301),\ S\left(\frac{z_i+301}{\sum(z_i+301)}\right),\ S(p_{T,i}),\ S\left(\frac{p_{T,i}}{\sum p_{T,i}}\right)$$

All variables with tracks within 0.2, $\frac{N_{\text{trk}}}{N_{\text{trk}}^{(0.2)}}$, $\frac{\sum p_T}{\sum p_T^{(0.2)}}$





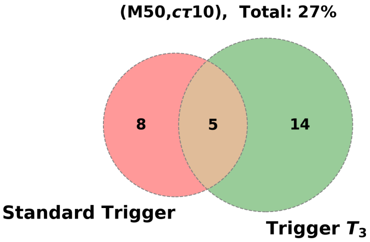
Performance degrades with decreasing LLP mass and increasing $c\tau$: lesser jets with $p_T > 60$ GeV and more PU contamination.

Triggers based on classification achieved using track variables

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

$T_3 \rightarrow$ Bkg rejection $\downarrow$	QCD2j $p_T^{gen} \in (50, 100)$ GeV rate (kHz)	LLP (M50,$c\tau$10) efficiency (%)	LLP (M100,$c\tau$10) efficiency (%)
98% Table	$1046 \rightarrow 14$	13	60
70% Table	$1046 \rightarrow 190$	19	73

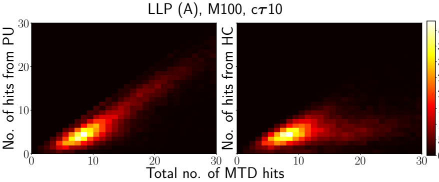
We can choose the ROC point depending on the trigger bandwidth constraints.

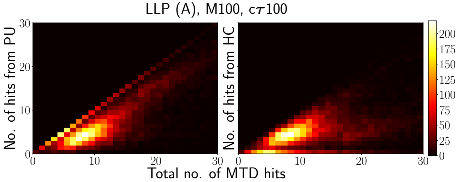


- **Provides high signal efficiency for higher mass LLPs with reasonable rates.**
- **Mostly exclusive to standard triggers – improves signal efficiency for lower mass LLPs as well.**

Dedicated triggers: Regional use of MTD at L1

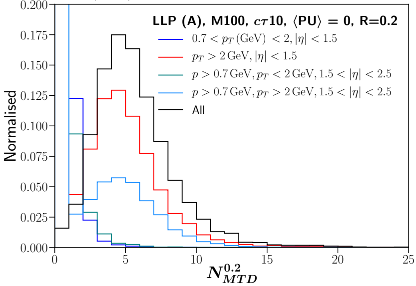
PU contamination in MTD hits associated with a jet



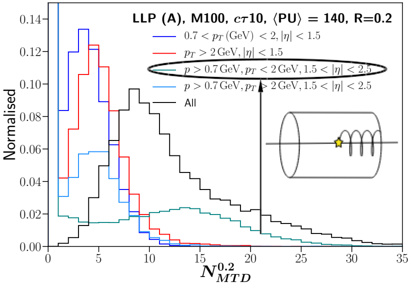


MTD hits from PU dominate in a jet: effect more for higher $c\tau$

$\langle \text{PU} \rangle = 0$



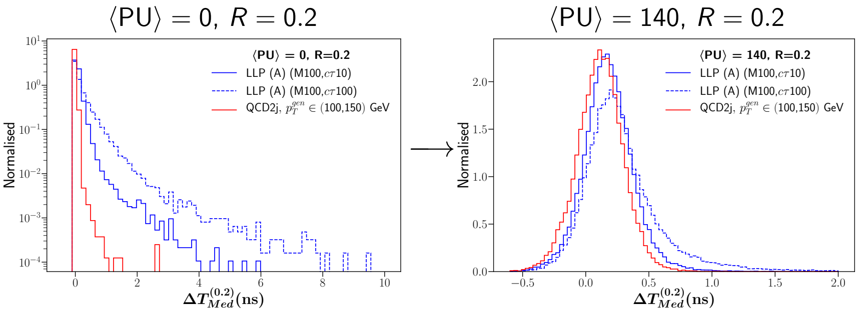
$\langle \text{PU} \rangle = 140$



Mostly these hits have $p_T < 2$ GeV – smaller radius of curvature – longer path length – larger time to reach MTD

Distributions of timing variables

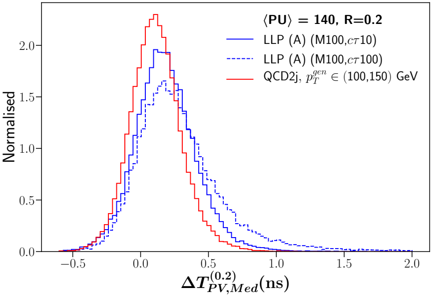
- Timing of a jet is a statistical measure: usually median time of all hits used.
- Timing of PU hits will bias the jet timing for both prompt and displaced jets.



The difference in the $\Delta T_{Med}^{(0.2)}$ distributions of signal and background reduces drastically with PU.

Finding the Primary Vertex (PV)

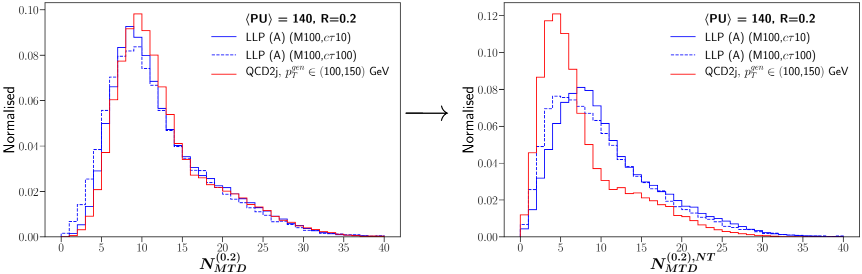
Mass [GeV], Decay Length [cm]	$\max(\sum p_T^2/n_{z_a})$ is PV
50, 10	36.1%
50, 100	32.3%
100, 10	51.0%
100, 100	43.8%



- **PV identification not so efficient for LLP processes.**
- **Time difference w.r.t PV does not improve separation between signal and background.**

Remove MTD hits associated with L1 tracks

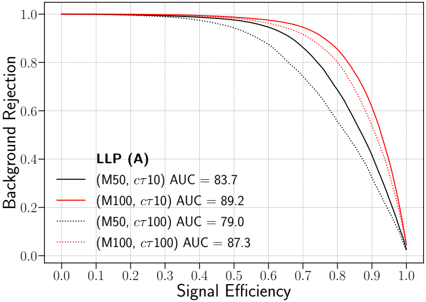
Before removing hits with tracks — After removing hits with tracks



- **Most MTD hits in QCD have L1 tracks: $N_{MTD}^{(0.2)}$ shifts to lower values.**
- **QCD prompt jets now dominated by low p_T PU hits: $\Delta T_{Med}^{(0.2)}$ shifts to higher values.**
- **Correlation between $N_{MTD}^{(0.2)}$ before and after removal of hits with associated L1 tracks different for signal and background.** Correlation matrices

BDT classification based on timing variables

p_T, η, $N^{(0.2)}_{\text{MTD}}$, $T^{(0.2)}_{\text{Med}}$, $\Delta T^{(0.2)}_{\text{Med, PV}}$, $N^{(0.2),\text{NT}}_{\text{MTD}}$, $\Delta T^{(0.2),\text{NT}}_{\text{Med, PV}}$



- Regional timing can be used as a separate trigger.
- Can be used in combination with the trigger based on L1 tracking: an extra factor of background rejection for similar signal efficiency.
- Applying timing BDT on events passing the tracking BDT score corresponding to 70% bkg rej. (T_2), we can reduce the background rate by a factor of 4 with little loss in the signal efficiency.

Conclusions

- Dedicated L1 triggers for LLPs required at HL-LHC to ensure we don't miss them at the very beginning.
- Same z-vertex condition of standard L1 multijet triggers adversely affect LLP triggering.
- Jet distributions dominated by PU, reduces discrimination between displaced and prompt jets – narrow jets of $R = 0.2$ help reduce PU contamination.
- Triggers developed with BDT classification based on L1 track variables and regional timing improve signal efficiency at moderate rates.
- MET triggers won't be efficient in LLP scenarios with missing particles in final state as the $\not{E}_T$ distribution, constructed with tracks from PV, falls off with increasing decay lengths – our triggers work reasonably well.
- LLPs from h decay: ISR jet might help trigger events or improve PV efficiency, however, suffers from lower signal cross section as p_T of the ISR increases.

Other LLP scenarios

For further details please have a look at

B. Bhattacherjee, S. Mukherjee, RS, and P. Solanki, arXiv:2003.03943 [hep-ph]

Thank you.

Backup Slides

Effect of the same z-vertex condition on LLPs

$$pp \to XX, X \to q\bar{q}$$

Number of ⟨PU⟩	Mass [GeV], Decay Length [cm]	Single jet	Dijet	Dijet (trk)	Quad jet	Quad jet (trk)
$\langle PU \rangle = 0$	50, 10	0.92%	0.83%	0.03%	0.01%	0.00%
	50, 100	0.50%	0.17%	0.02%	0.00%	0.00%
	100, 10	11.39%	10.20%	0.83%	1.24%	0.05%
	100, 100	8.26%	3.44%	0.53%	0.18%	0.03%
	200, 10	54.40%	47.73%	7.08%	13.40%	0.67%
	200, 100	43.73%	25.72%	4.36%	3.99%	0.28%
$\langle PU \rangle = 140$	50, 10	2.72%	2.81%	0.47%	59.65%	10.99%
	50, 100	1.78%	0.94%	0.25%	55.94%	10.57%
	100, 10	27.43%	28.03%	5.83%	75.85%	14.21%
	100, 100	20.48%	12.59%	2.93%	66.94%	12.26%
	200, 10	81.04%	77.71%	23.68%	89.19%	18.23%
	200, 100	67.98%	50.11%	13.98%	77.18%	14.86%

Same z-vertex condition reduces signal efficiency for LLPs in the multijet triggers.

Back

Effect of the same z-vertex condition on LLPs

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PU contribution help the jets pass the p_T threshold of standard triggers.

Back

Effect of the same z-vertex condition on LLPs

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	200, 100	67.98%	50.11%	13.98%	77.18%	14.86%

The LLP event gets triggered mostly by PU jets with the standard multijet triggers.

Back

98% background rejection

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)

70% background rejection

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)

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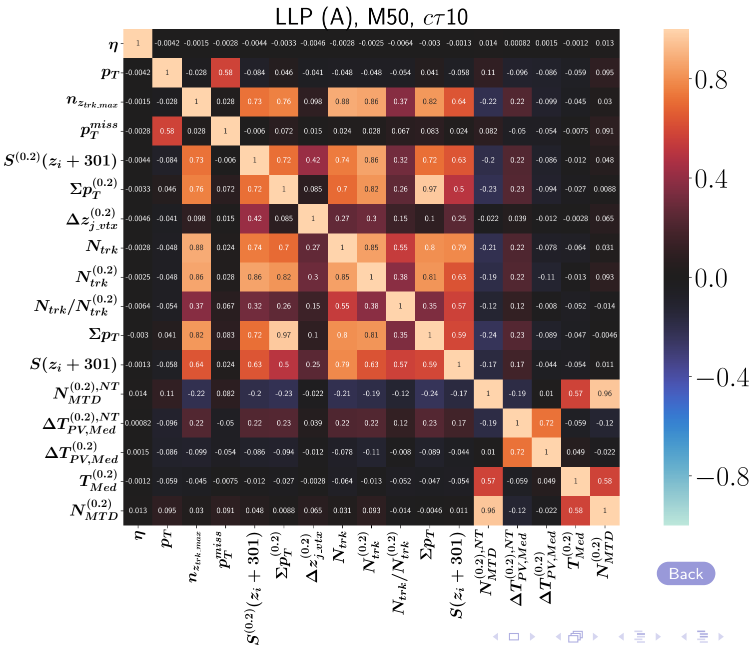
Correlation matrix for signal



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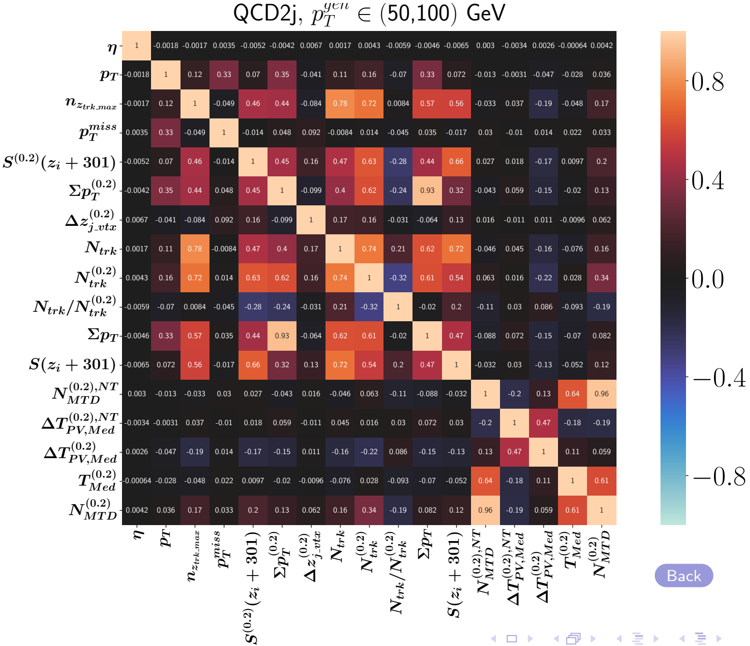
Correlation matrix for background



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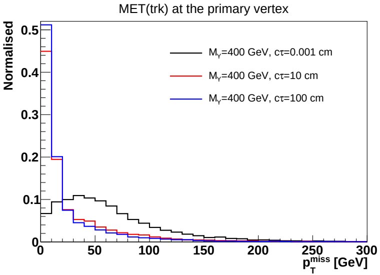
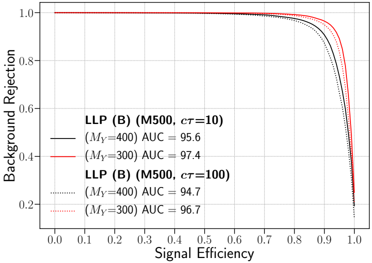
Comments on some other LLP scenarios

LLPs with missing particles in the final state

$$pp \to XX, X \to q\bar{q}Y,\ Y\text{: invisible}$$





- p_T^{miss} distribution gets affected due to displaced decay of particles
- MET triggers won't be efficient
- Track and timing based triggers perform reasonably well.

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Comments on some other LLP scenarios

Effect of an ISR jet

$$gg \to h, j \to XX, X \to q\bar{q}$$

	$\max(\sum p_T^2/n_{z_a})$ corresponds to hard collision	$\frac{\sigma(gg\to h+1j)}{\sigma(gg\to h)}$
$+0j$	14.14%	–
$+1j,\ p_T^j > 50$ GeV	68.26%	25.73%
$+1j,\ p_T^j > 100$ GeV	84.82%	8.81%
$+1j,\ p_T^j > 150$ GeV	93.54%	3.76%

- LLPs from h decays have lesser boost and therefore, their decay products have low p_T.
- Presence of ISR increases chances of triggering from standard single jet trigger and also improves PV identification.
- However, as p_T of ISR increases, the signal cross section decreases.
- Triggers based on track and timing variables could be useful.

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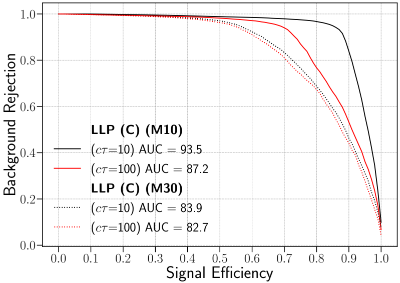
Comments on some other LLP scenarios

Effect of an ISR jet

$$gg \to h, j \to XX, X \to q\bar{q}$$



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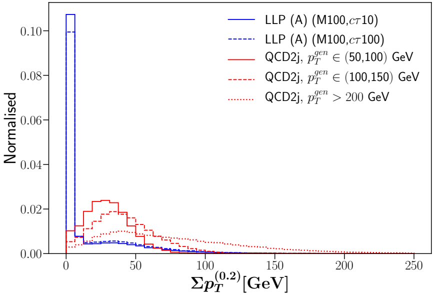
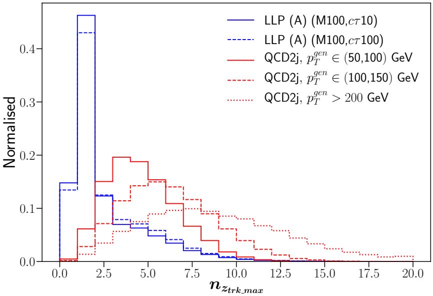
Some variables constructed out of L1 tracking

$\sum p_T^{(0.2)}$



Sum of p_T of all the tracks associated with the jet.

$n_{z_{trk\_max}}$



For each jet, the maximum number of tracks coming from the same z-position.

The High Luminosity LHC

	Peak instantaneous luminosity ($\mathrm{cm}^{-2}\mathrm{s}^{-1}$)	$\langle$PU$\rangle$
LHC Run 3	$\sim 2.2 \times 10^{34}$	60
HL-LHC start	$\sim 5.6 \times 10^{34}$	140
HL-LHC end	$\sim 7.5 \times 10^{34}$	200

Spread of z positions and timings of 140 average PU vertices for 10,000 events

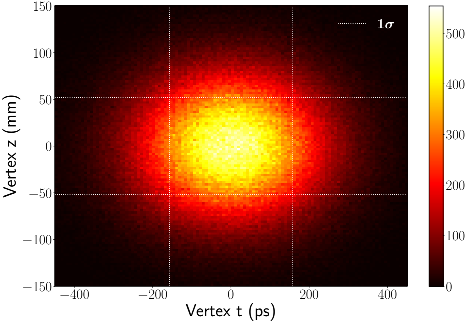
2D Gaussian:

$\mu_z = 0$ cm,

$\sigma_z = 5.3$ cm;

$\mu_t = 0$ ps,

$\sigma_t = 160$ ps

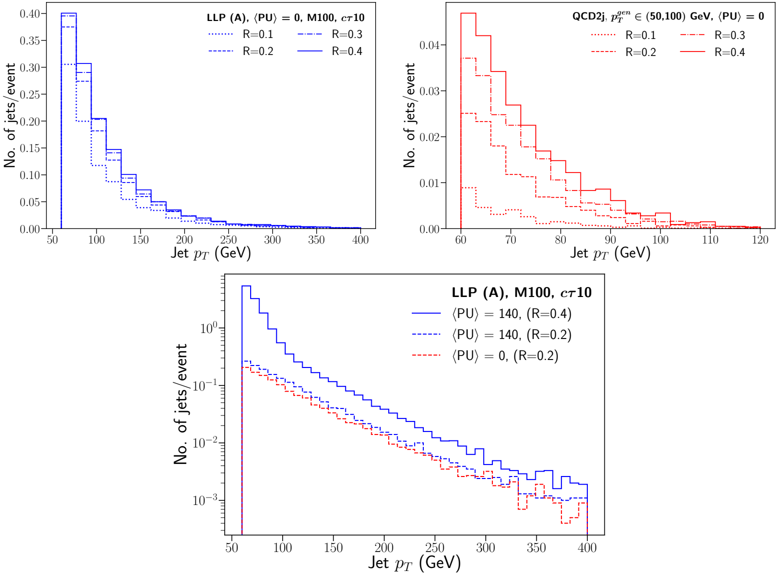


Total spread in:

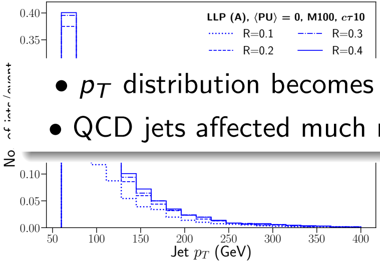
$z-$ 25 cm;

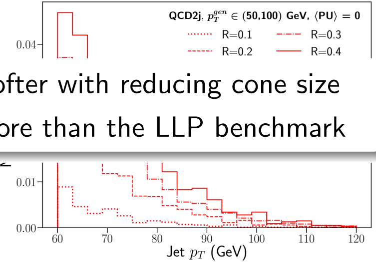
$t-$ 800 ps

Towards narrow jets...

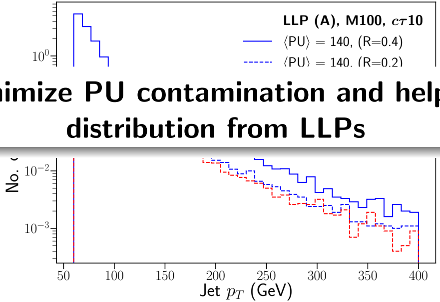


Towards narrow jets...





- p_T distribution becomes softer with reducing cone size
- QCD jets affected much more than the LLP benchmark



$R = 0.2$ jets minimize PU contamination and help restore jet p_T distribution from LLPs