Triggering long-lived particles (LLPs) at HL-LHC

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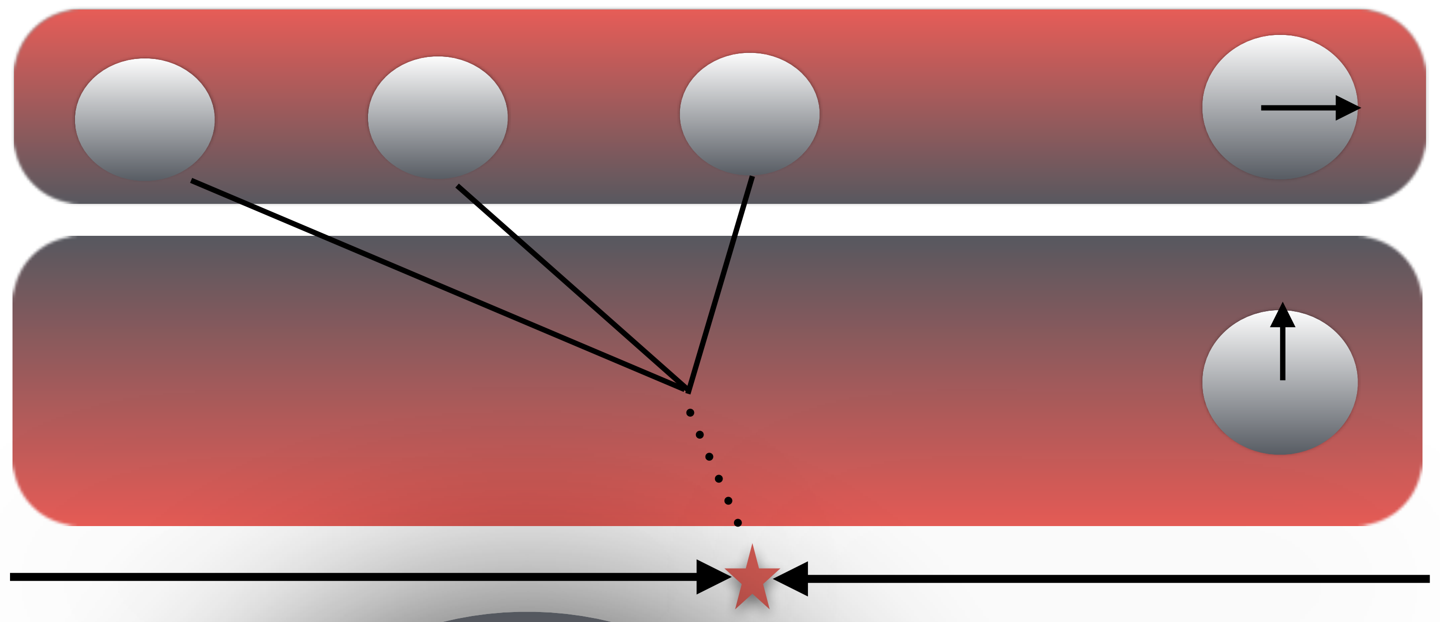
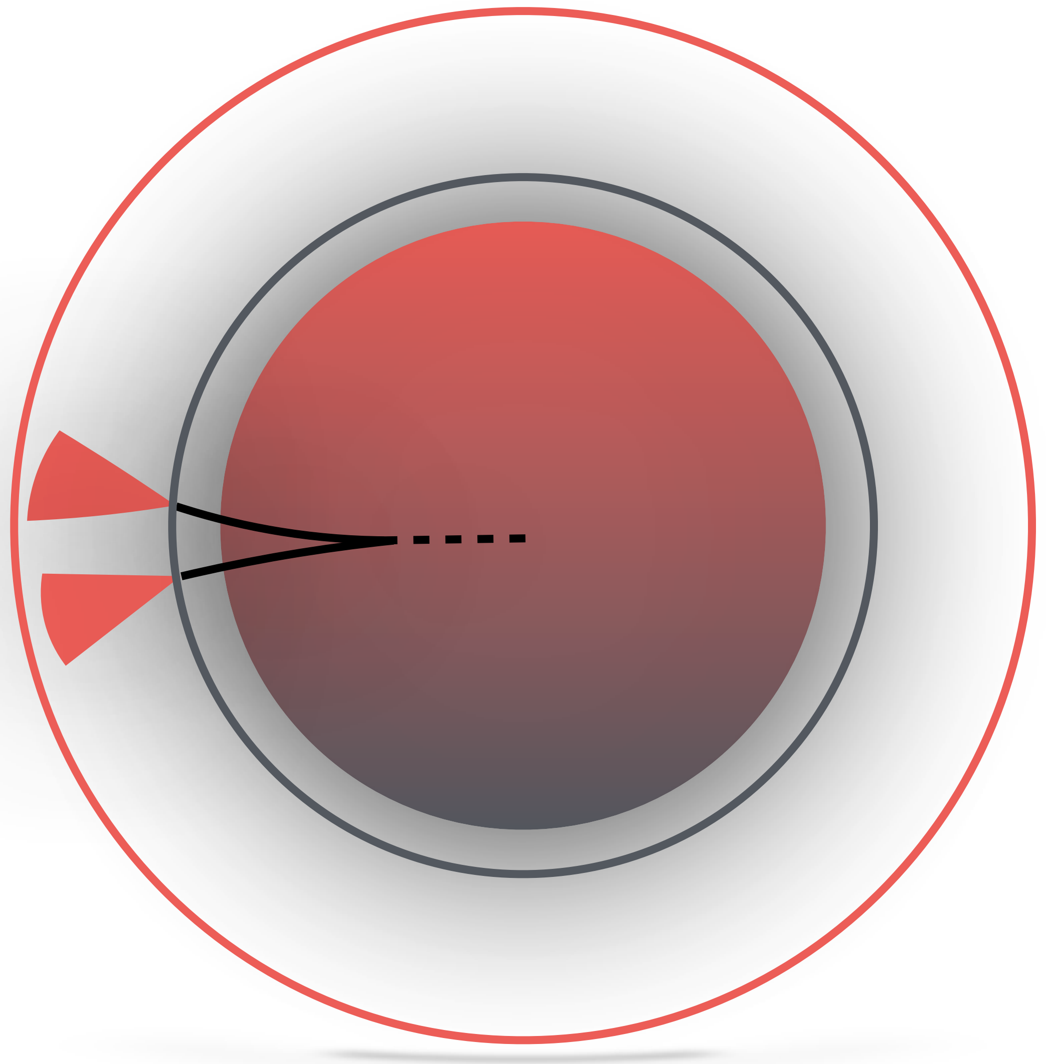
Long Lived Particles

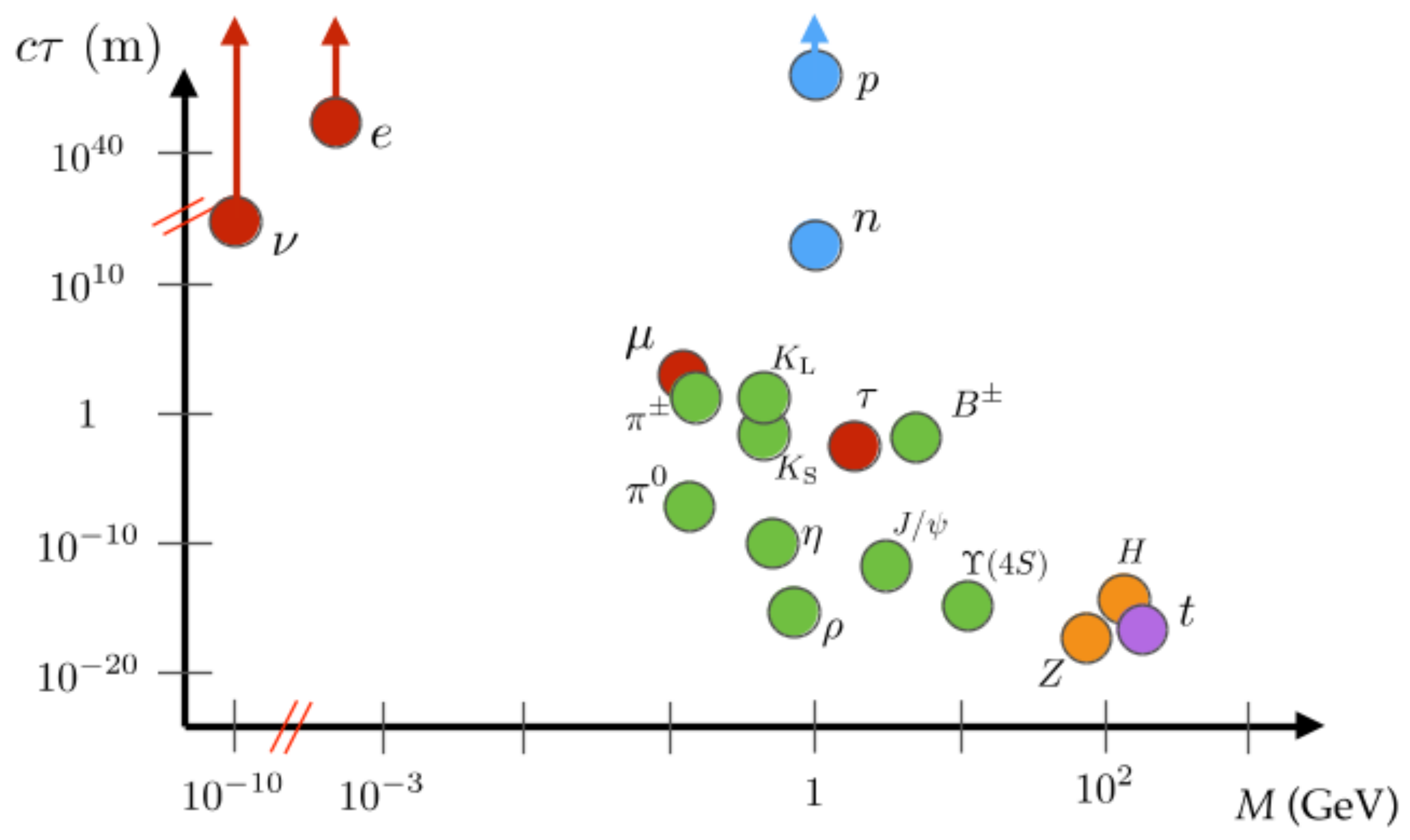
Decays at a reconstructable distance from the primary collision or is quasi-stable on the scale of the detector



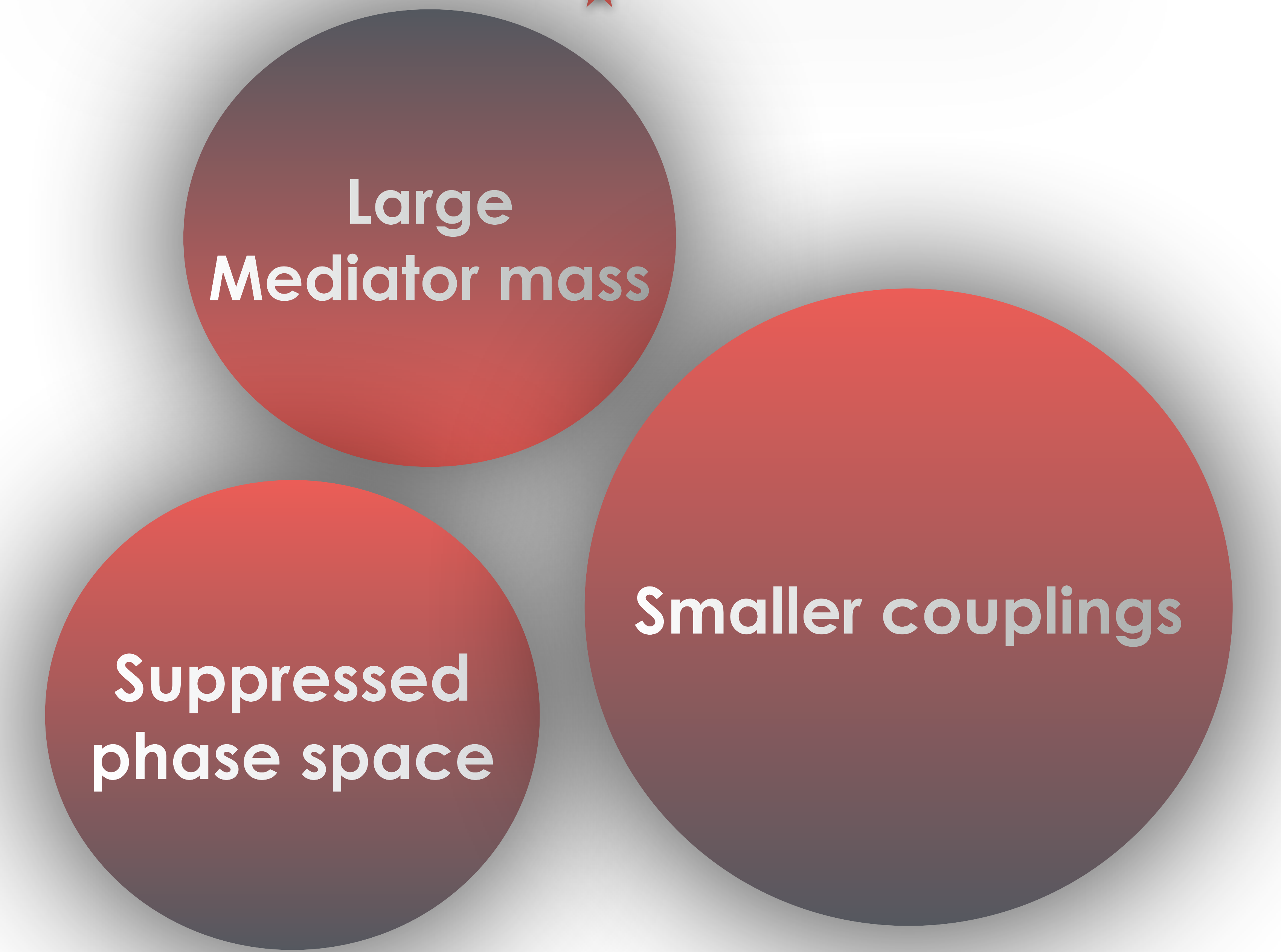


Decay Products are delayed!

We already have LLPs in SM



Shuve, 2019

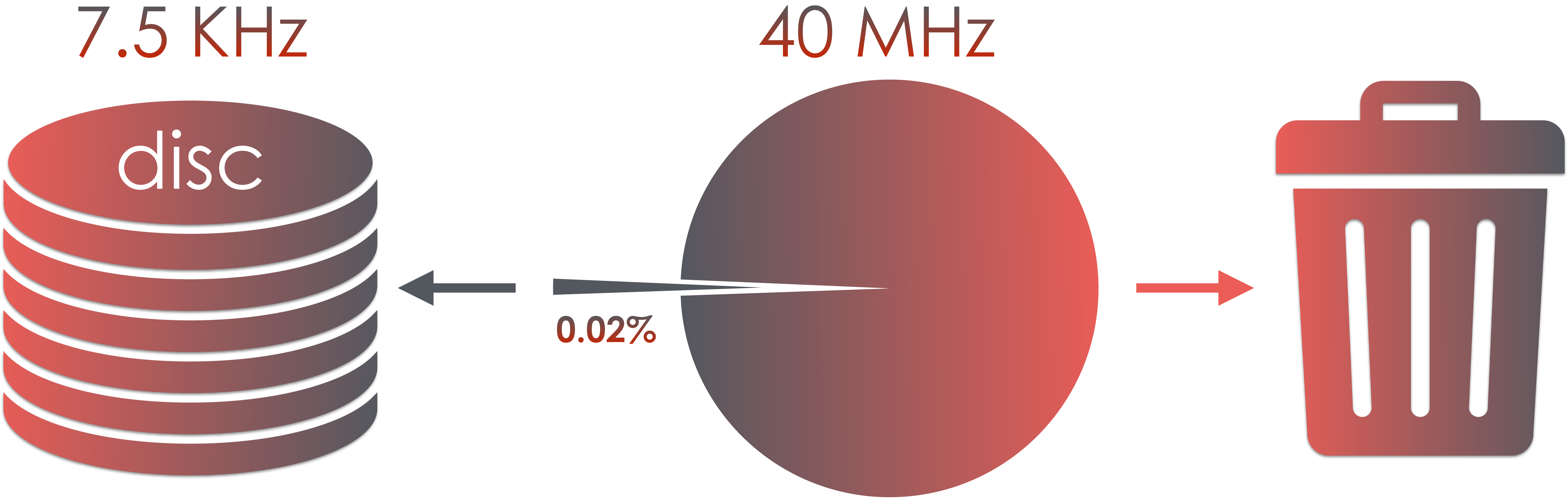


- A new long-lived particle would be a clear sign of new physics but often overlooked.
- Long-lived particles appear in many BSM scenarios.
- But challenging (exciting)! We need to push analysis techniques to the limit.

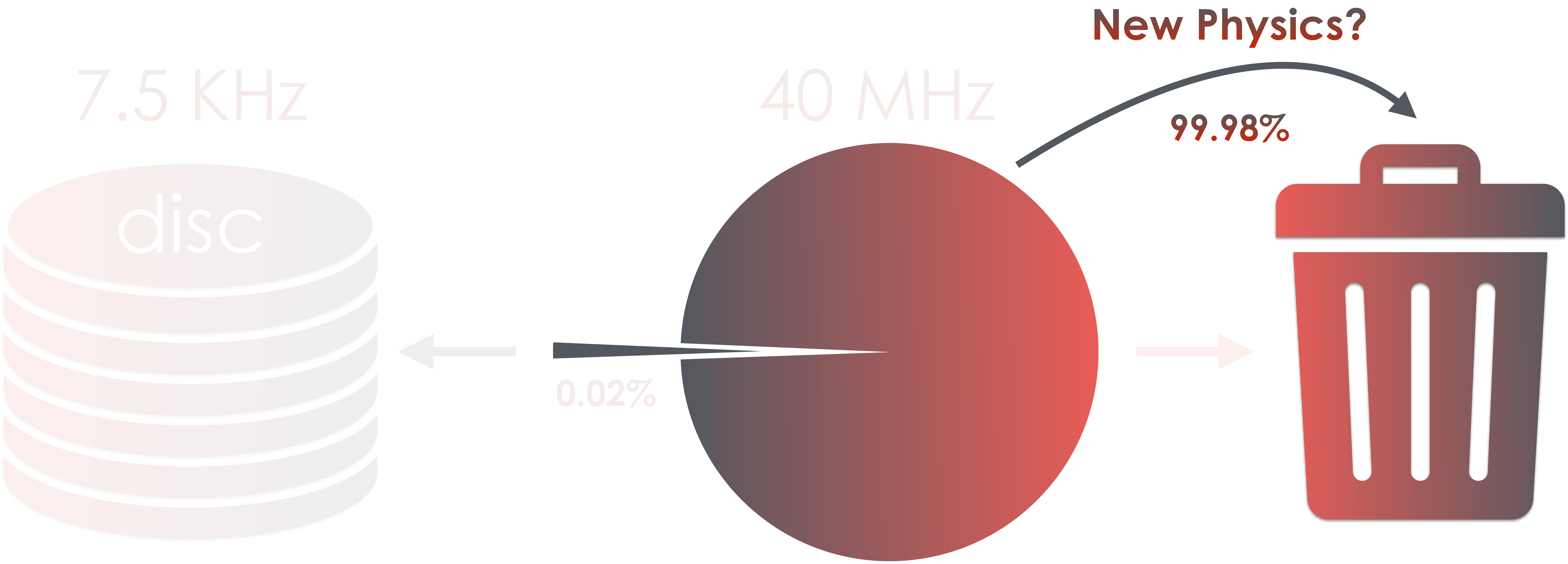
Motivation

One of the major challenges - Triggering displaced events at online stage

Motivation



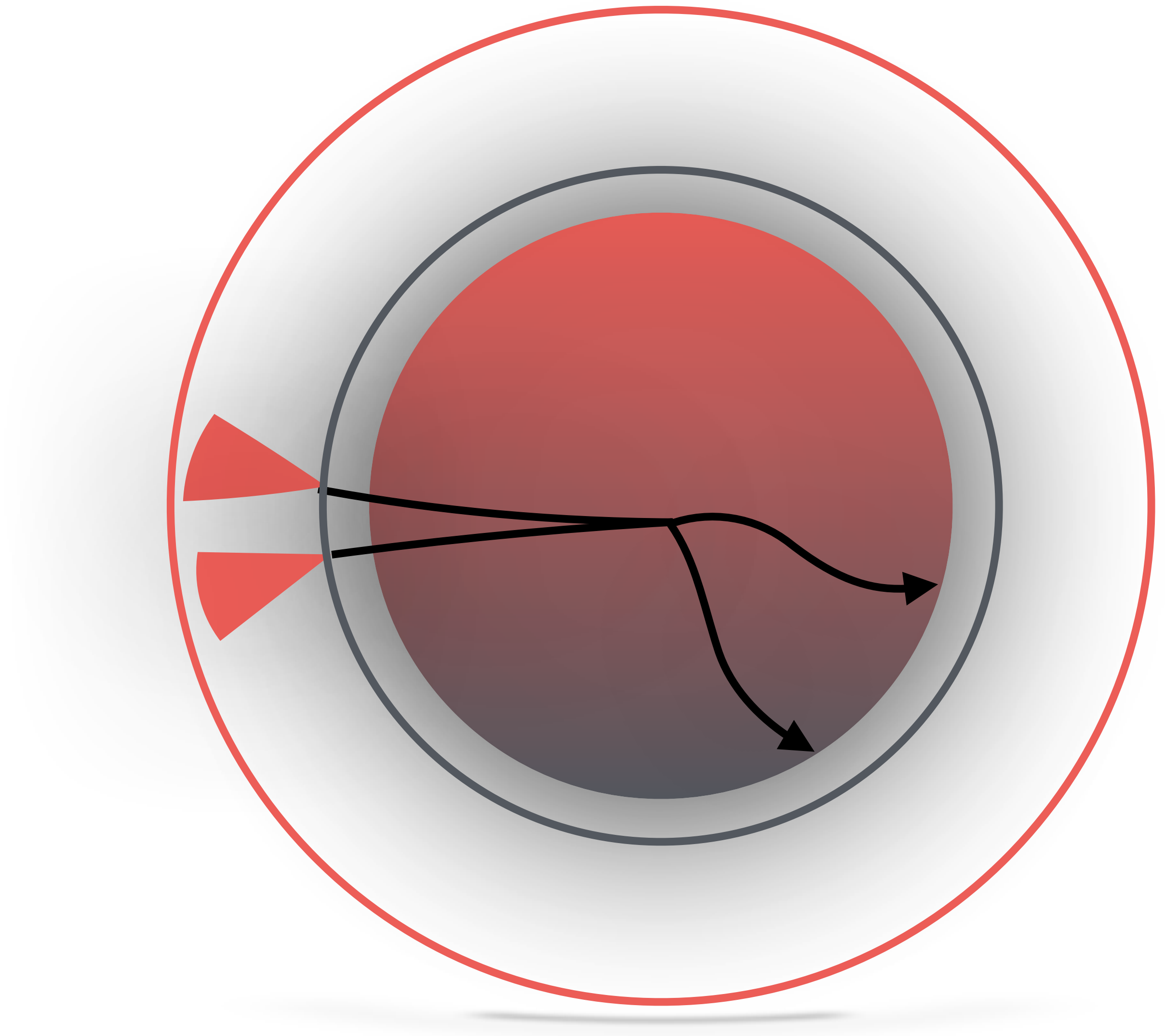
Motivation



Phase-II

Triggers optimised for

This

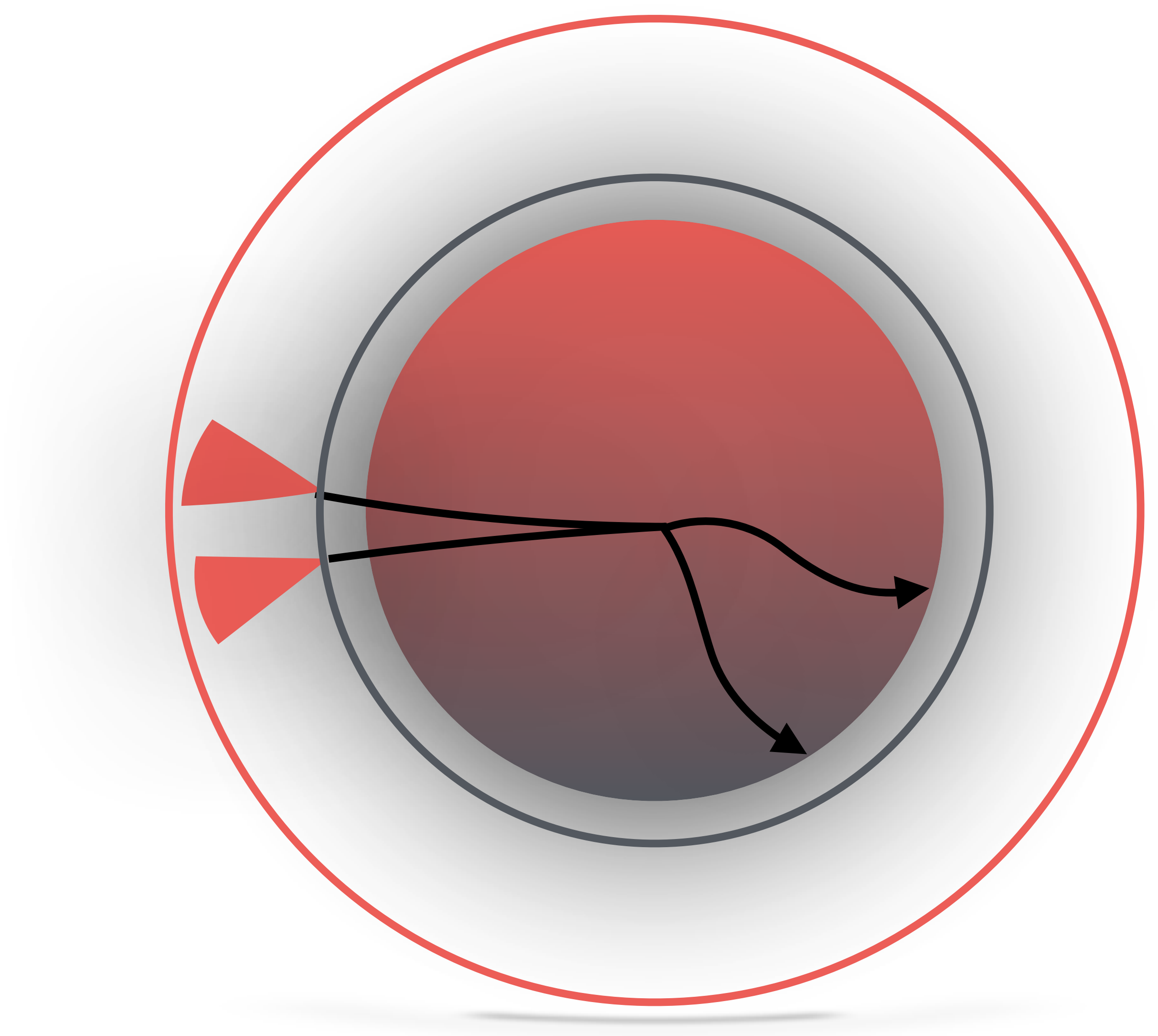


Prompt Signatures

Challenges

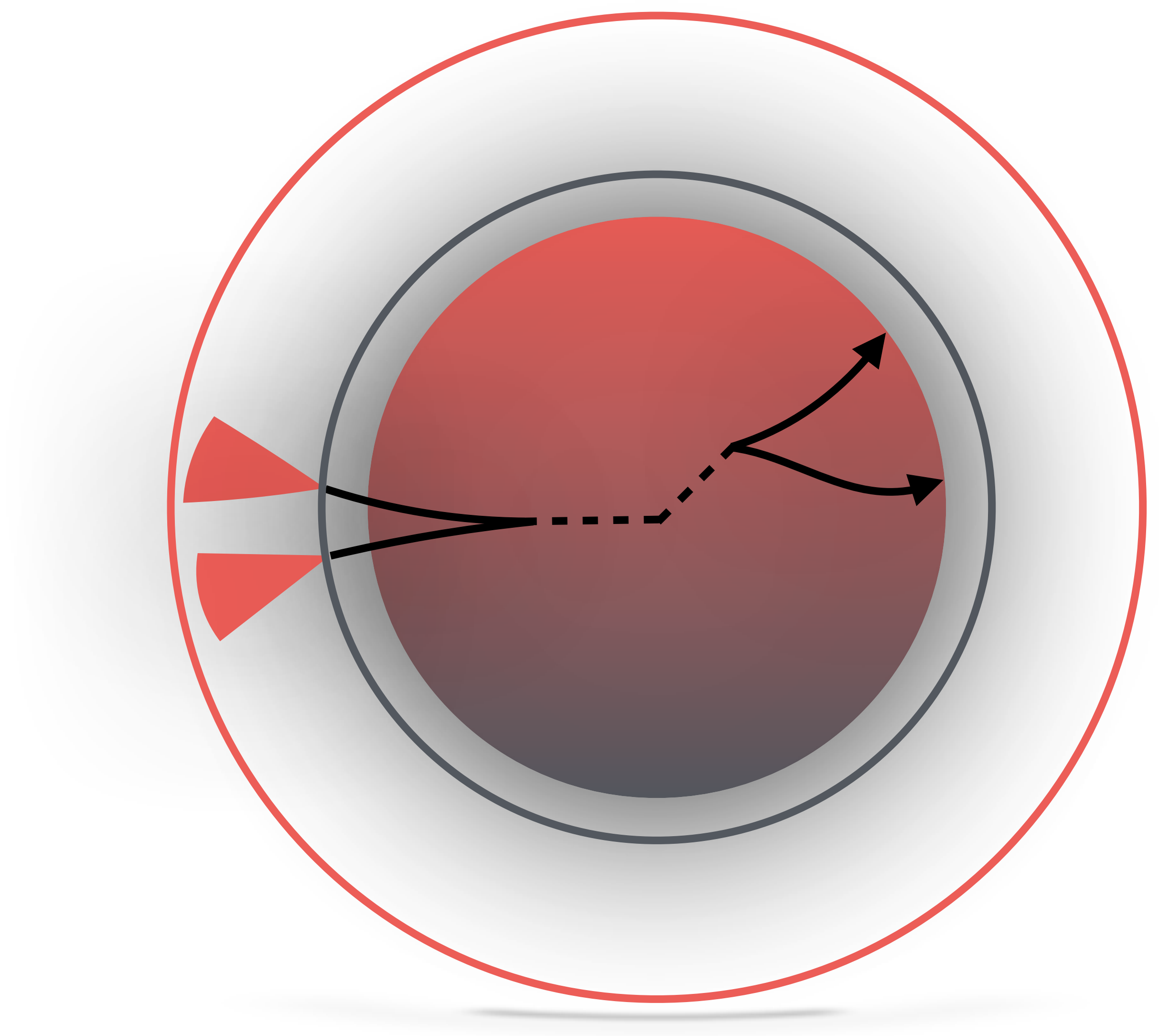
Triggers optimised for

This



Prompt Signatures

Not this



Displaced Signatures

Challenges

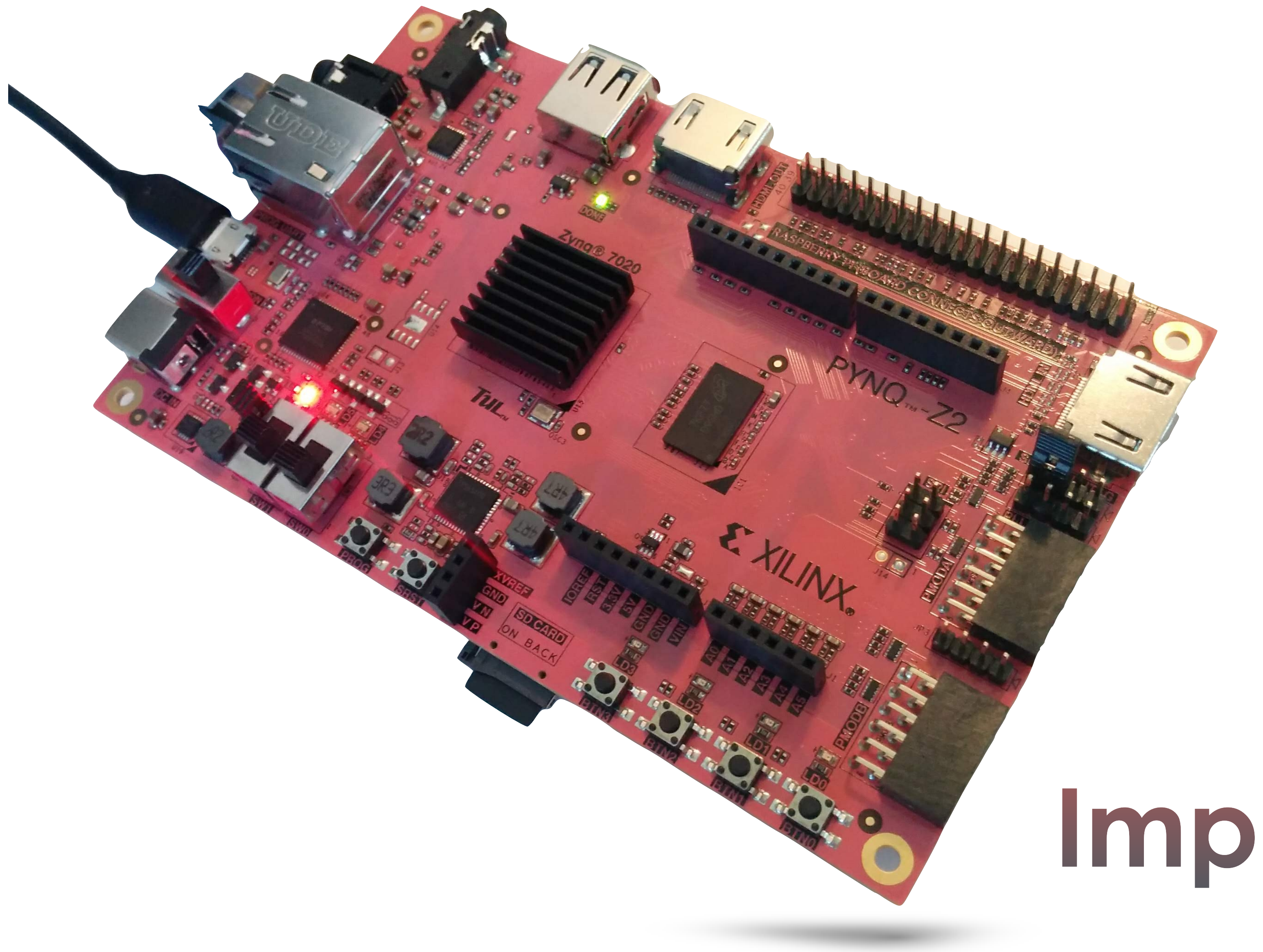
40 MHz

→

Level-1 Trigger
(750 KHz), FPGAs

Low latency

L1: 12 μs



FPGA Implementation

Challenges

40 MHz → **Level-1 Trigger**
(750 KHz), FPGAs

Low latency

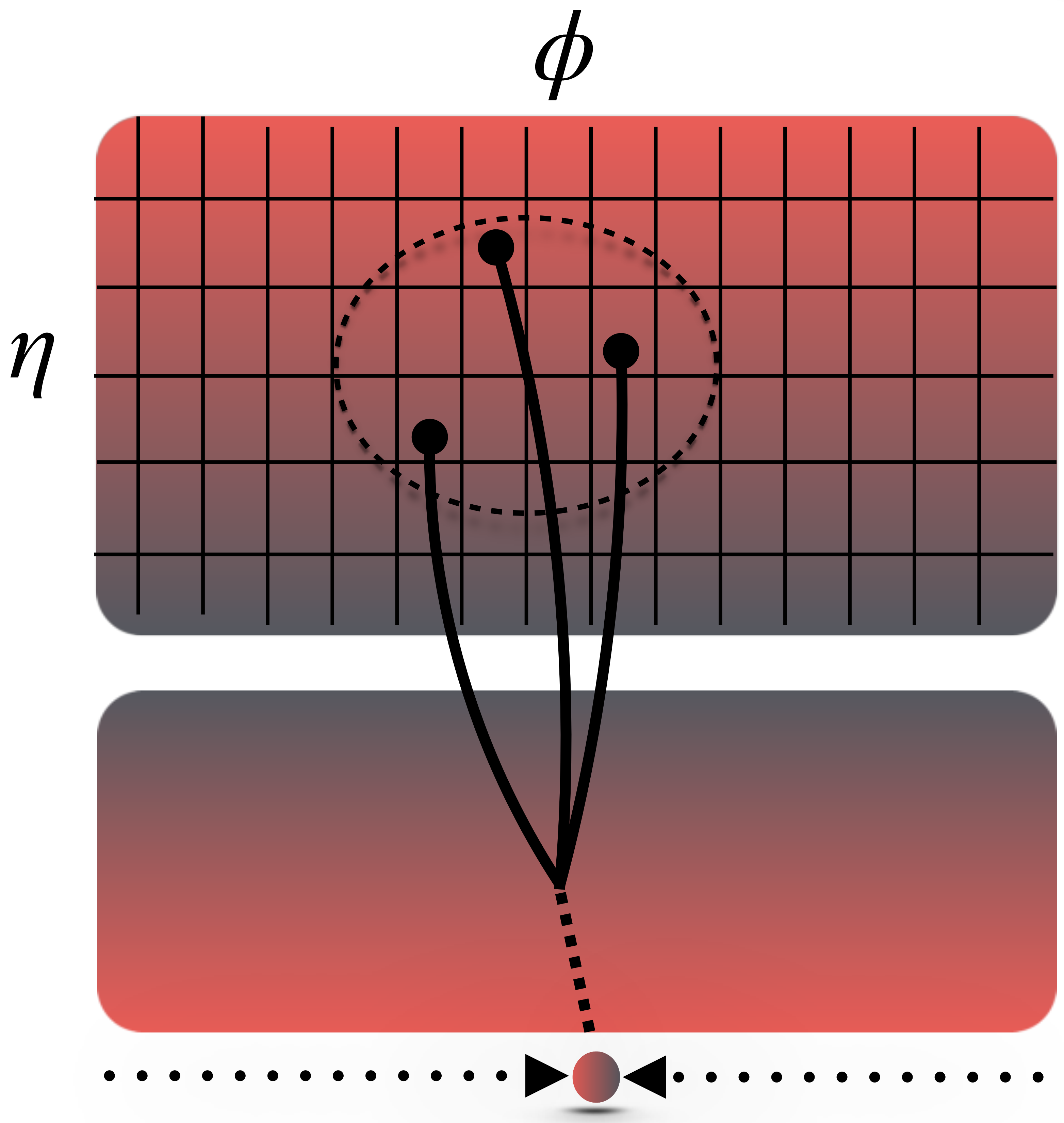
L1: 12 μs

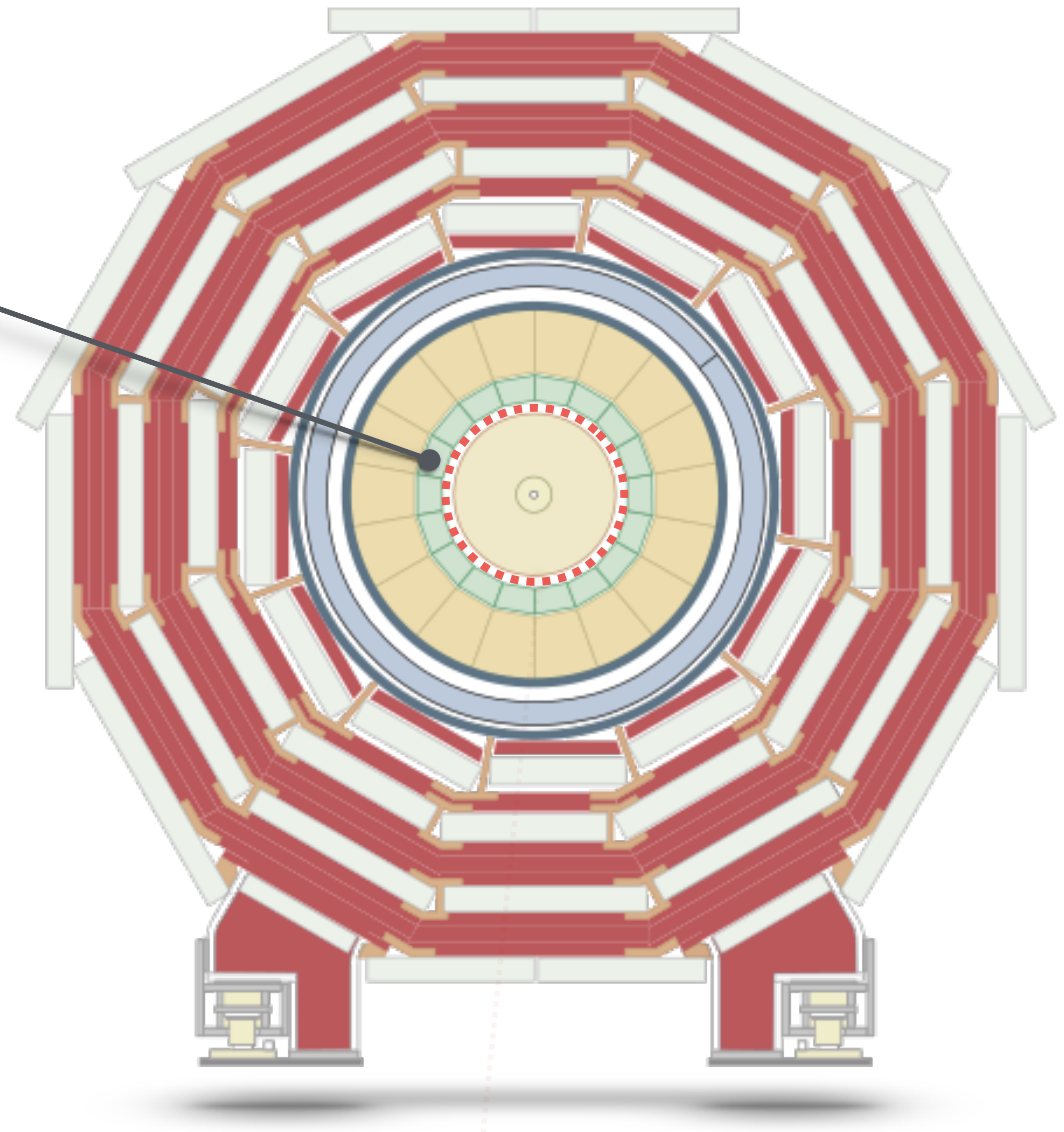
FPGA Implementation

Solution and future upgrades

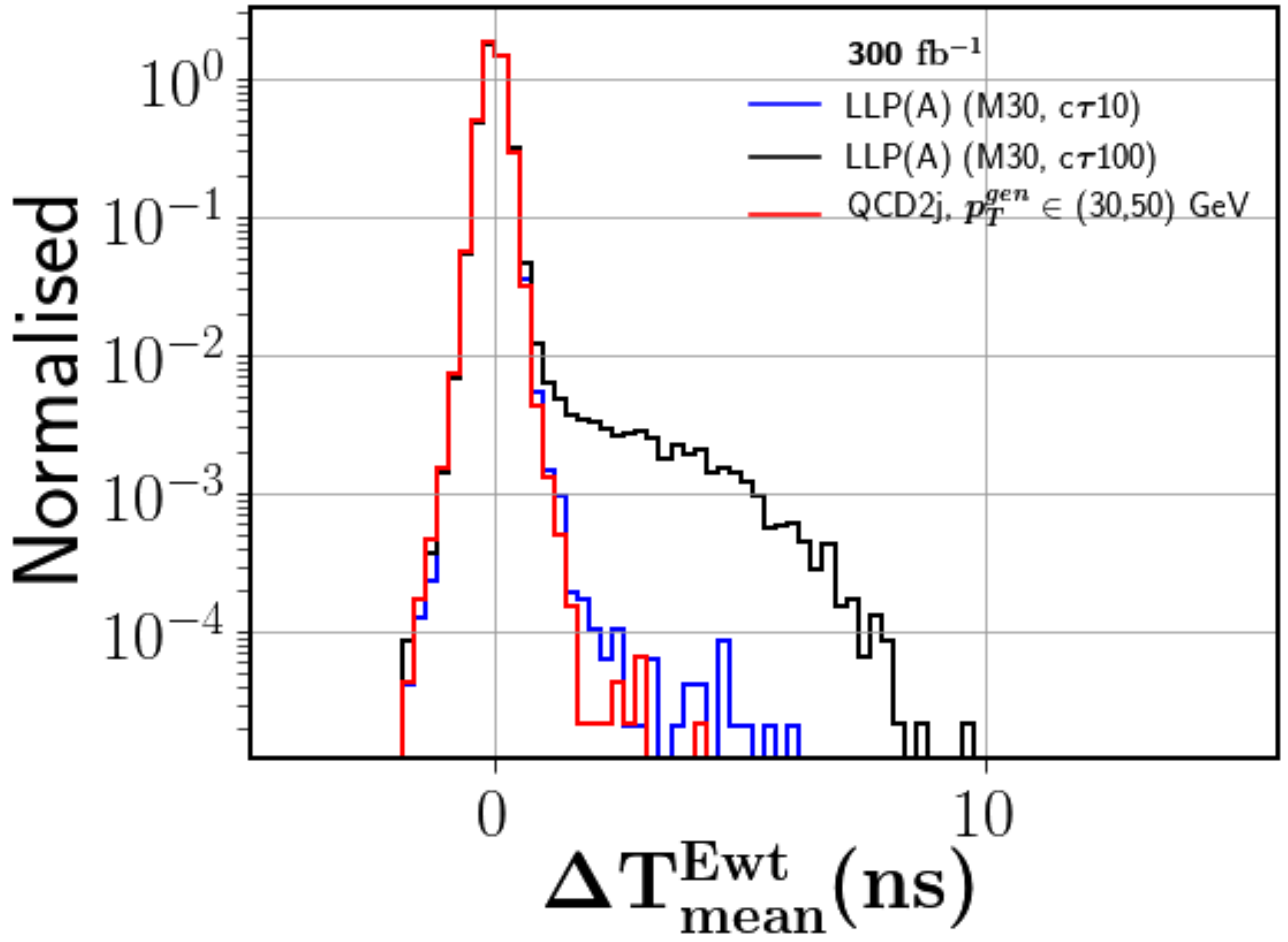
Dedicated triggers optimised for displaced searches in High PU environment

ECAL timing at L1





Cut based



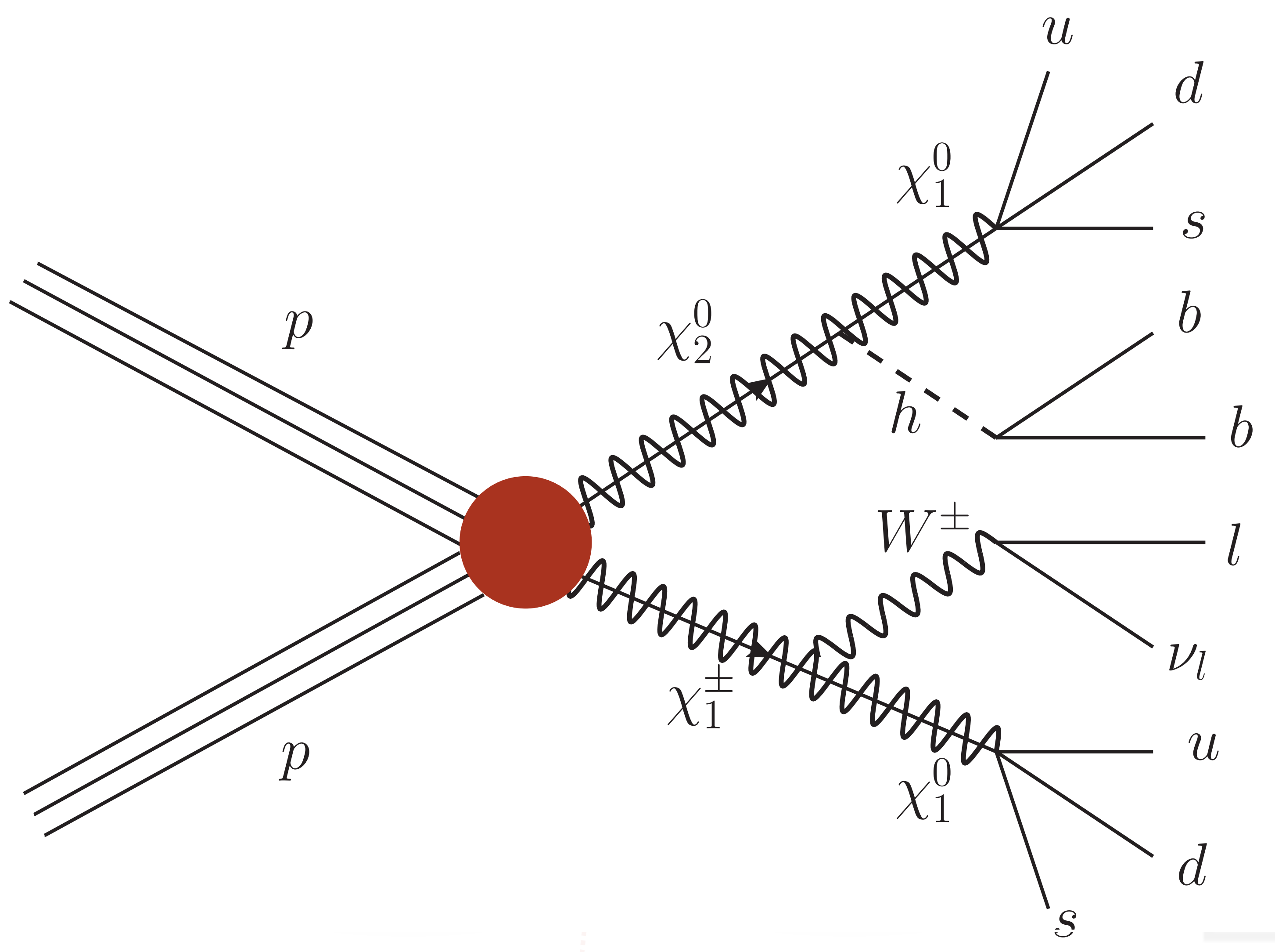
Dedicated Triggers for Displaced Jets using Timing Information from Electromagnetic Calorimeter at HL-LHC, B. Bhattacherjee, T. Ghosh, R.Sengupta, PS, *JHEP* 08 (2022) 254

Solution and future upgrades

Dedicated triggers optimised for displaced searches in High PU environment

ECAL timing at L1

Cut based



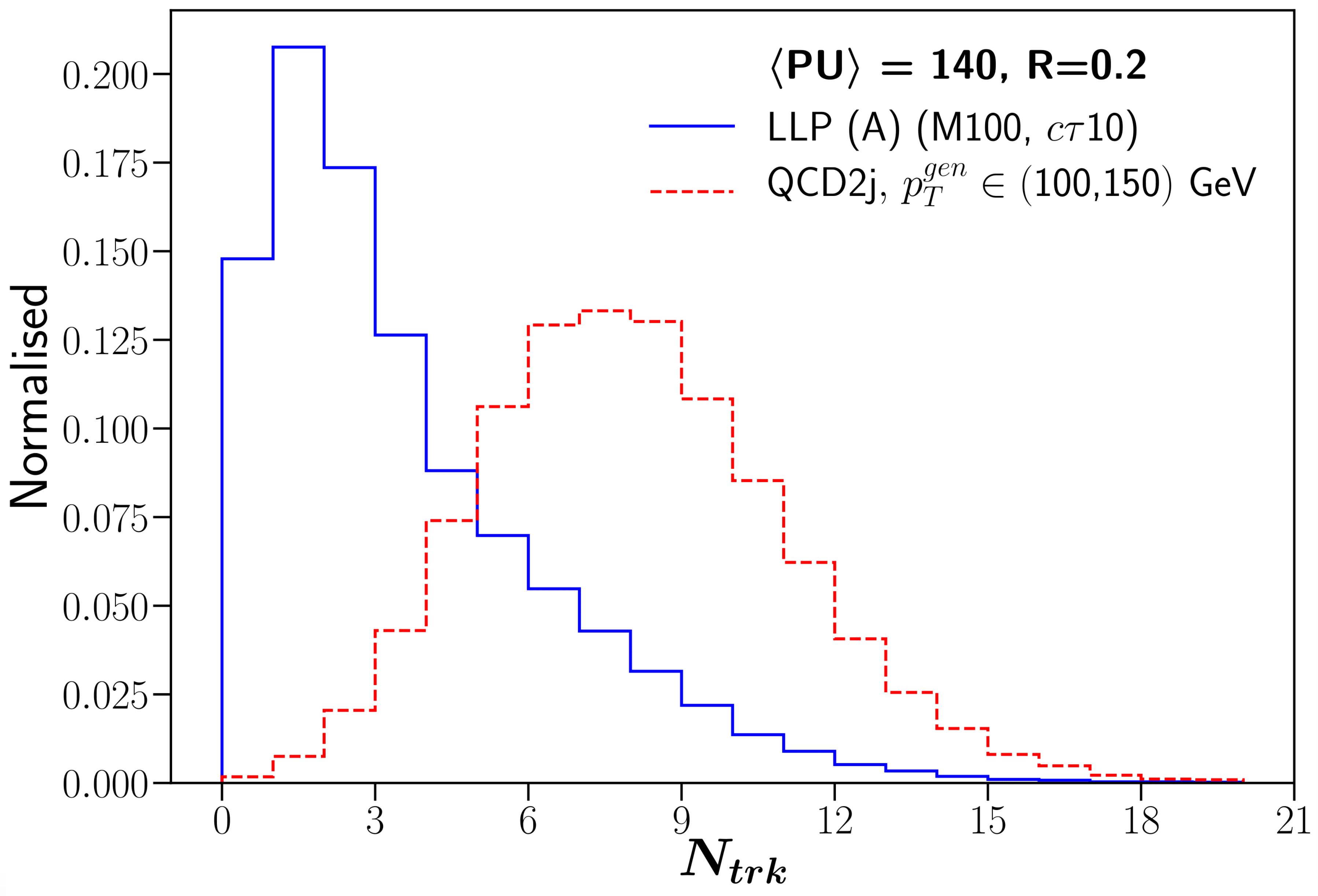
Search for Electroweakinos in R-Parity Violating SUSY with Long-Lived Particles at HL-LHC
B. Bhattacherjee, PS, 2308.05804

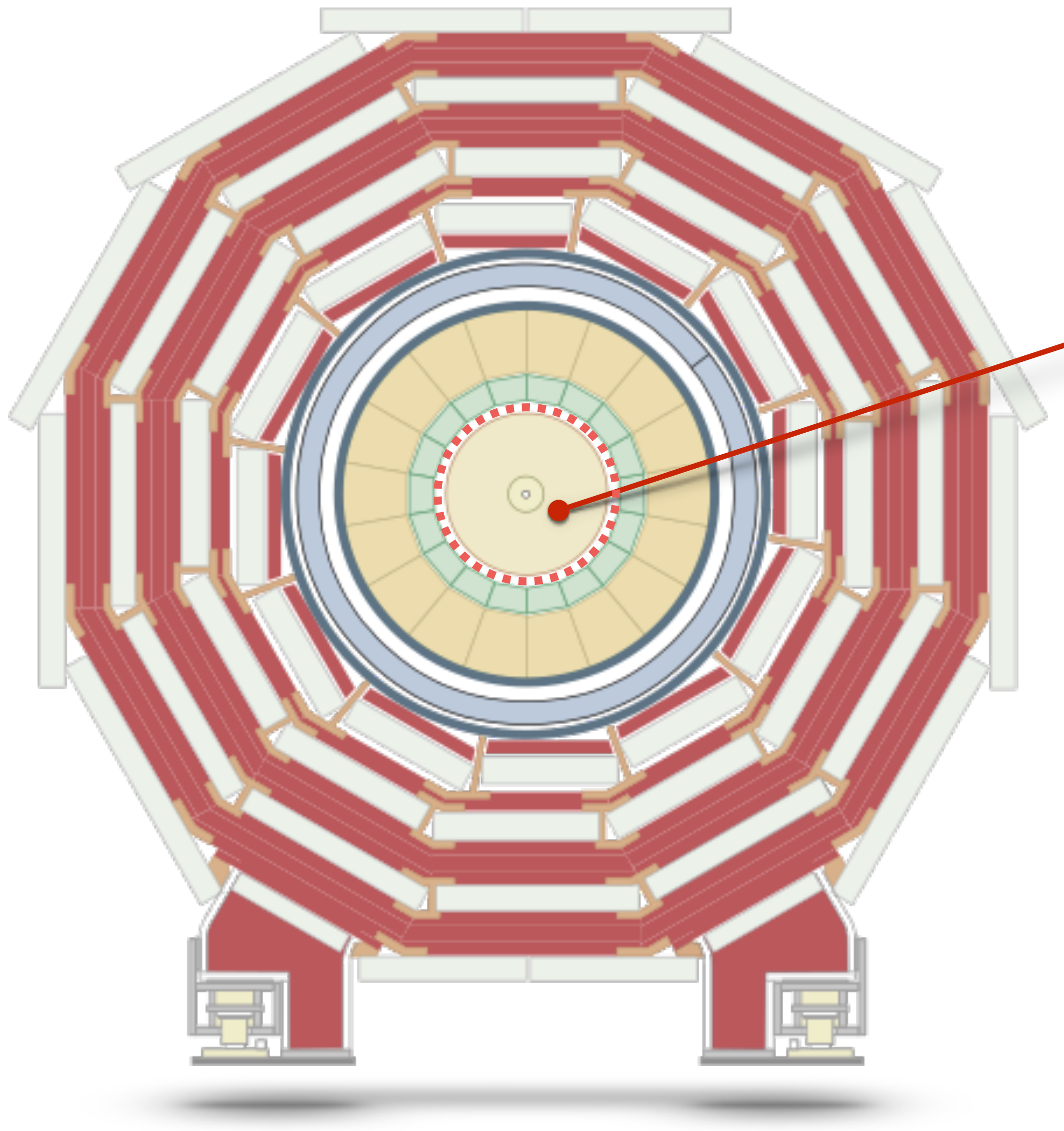
Dedicated Triggers for Displaced Jets using Timing Information from Electromagnetic Calorimeter at HL-LHC, B. Bhattacherjee, T. Ghosh, R.Sengupta, P. Solanki, *JHEP* 08 (2022) 254

Solution and future upgrades

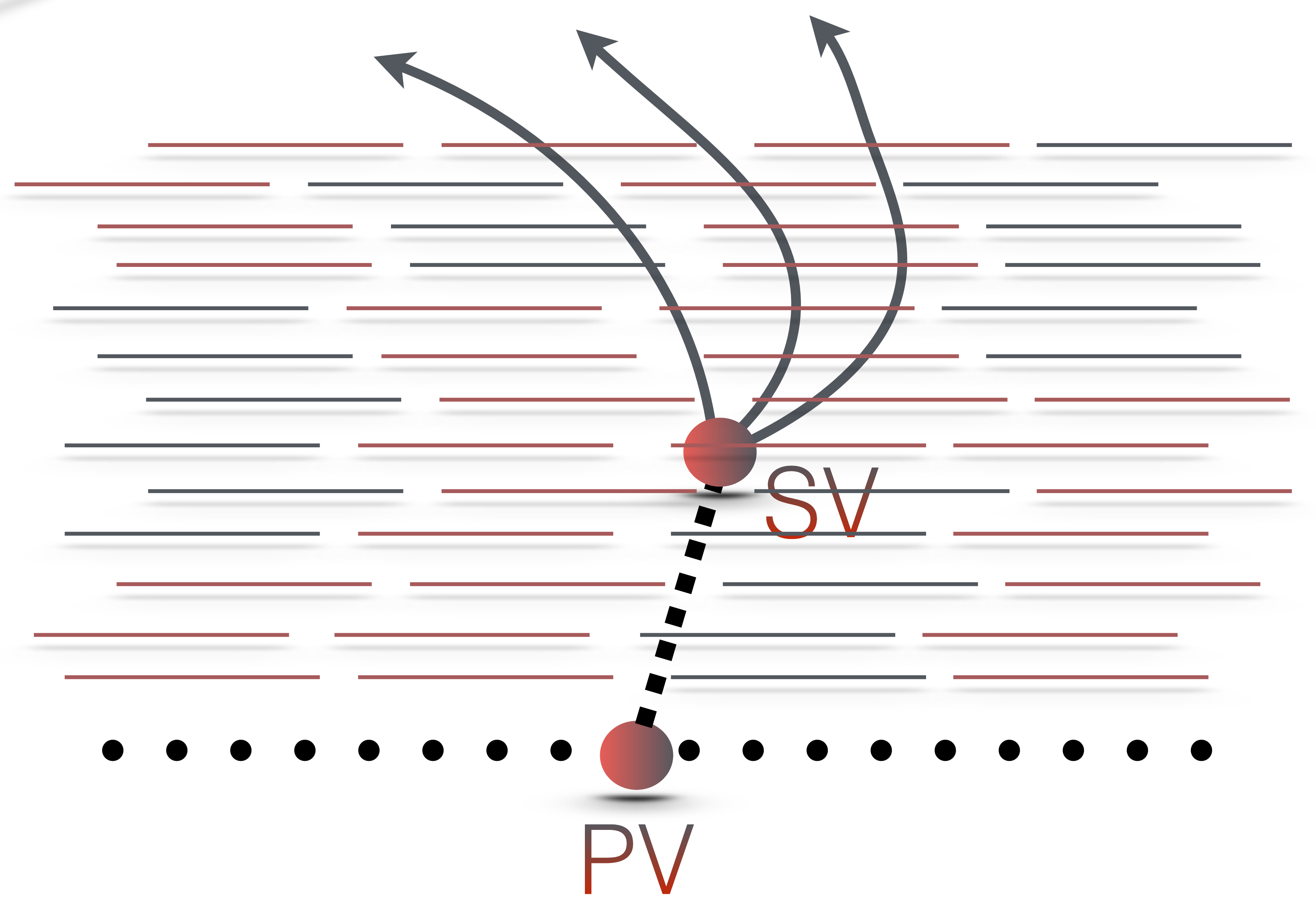
Dedicated triggers optimised for long lived particles in High PU environment

BDT Based





Extended tracking at L1

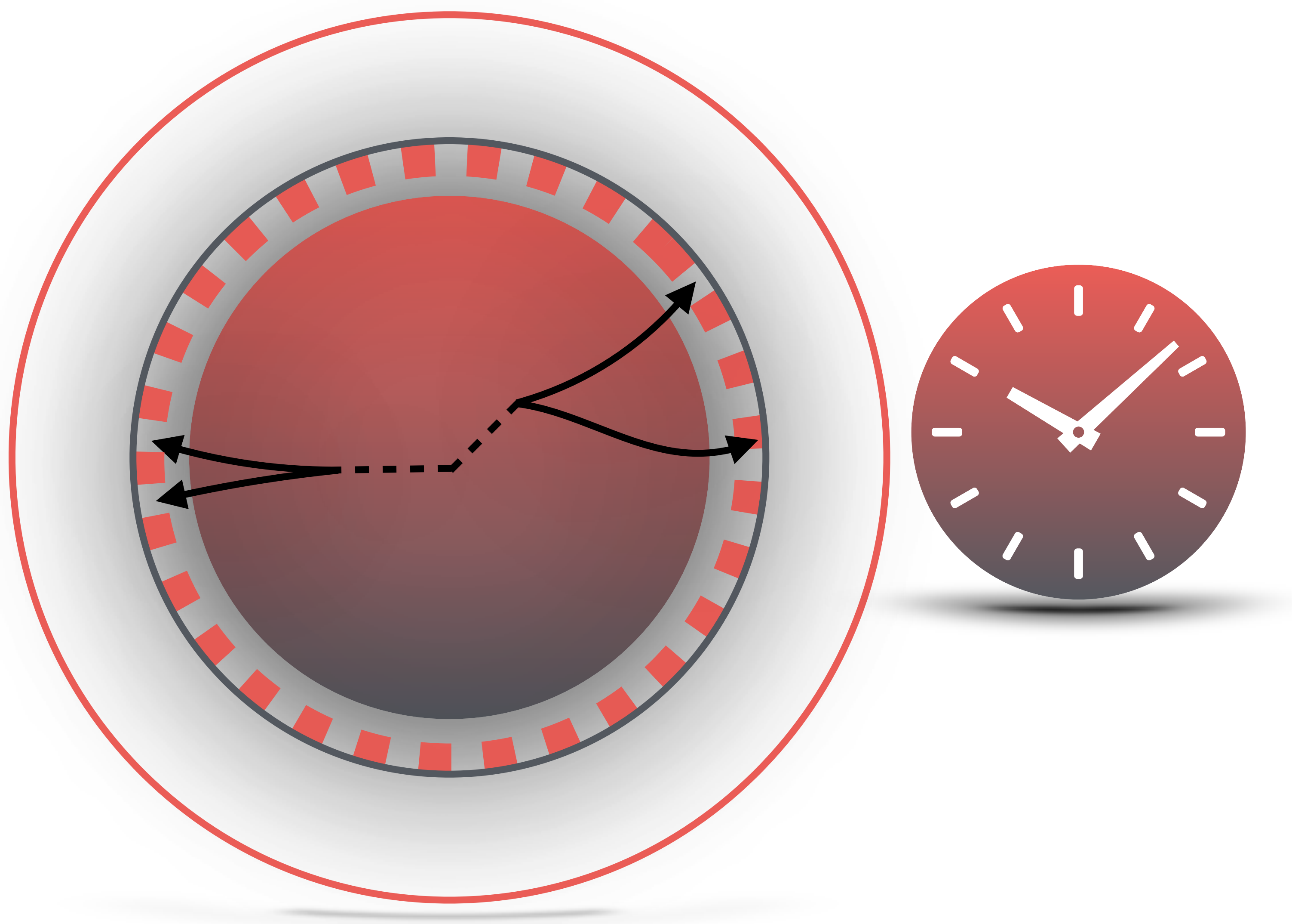


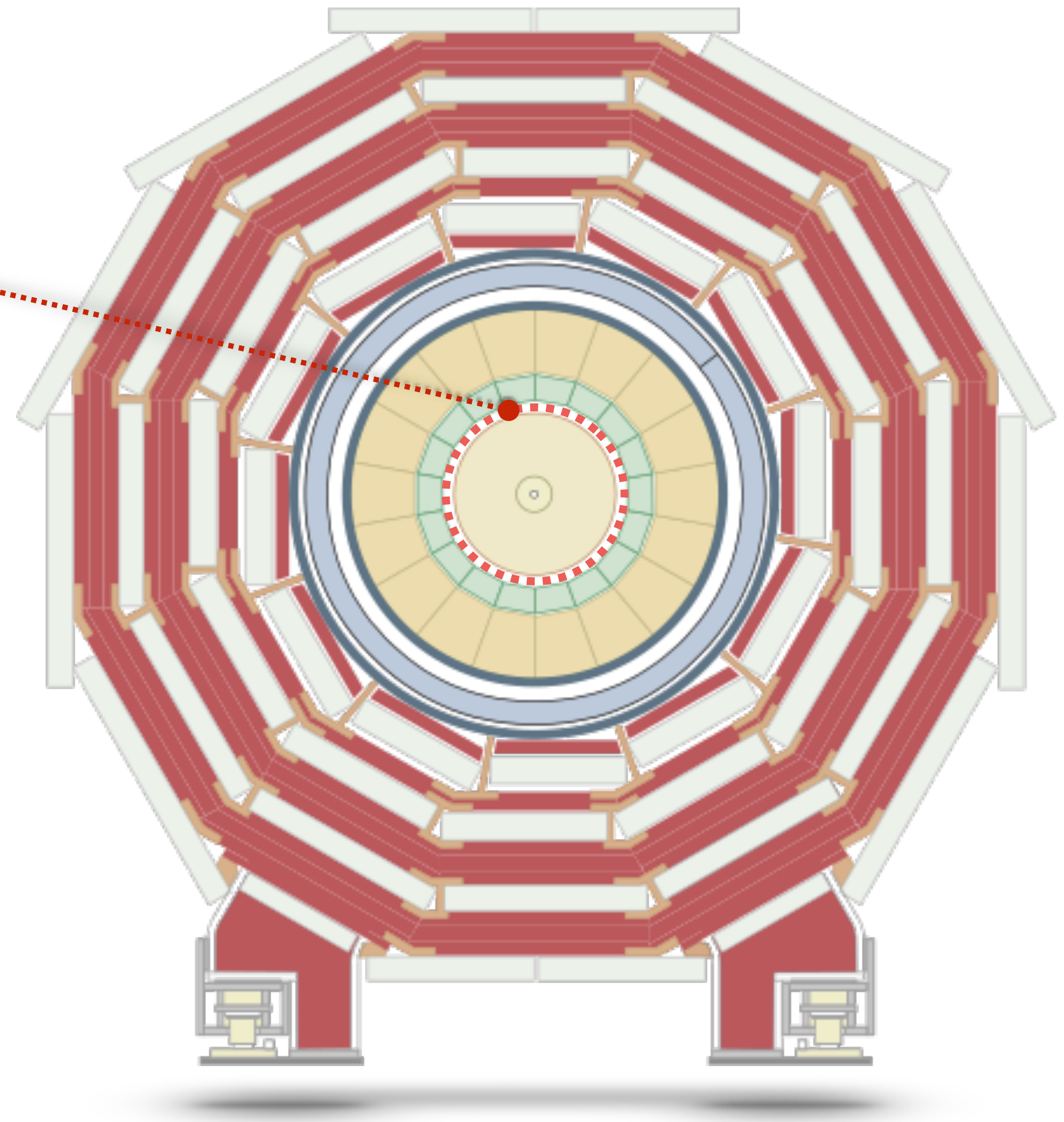
Triggering long-lived particles in HL-LHC and the challenges in the first stage of the trigger system, B. Bhattacherjee, S. Mukherjee, R. Sengupta, PS, *JHEP* 08 (2020) 141

Solution and future upgrades

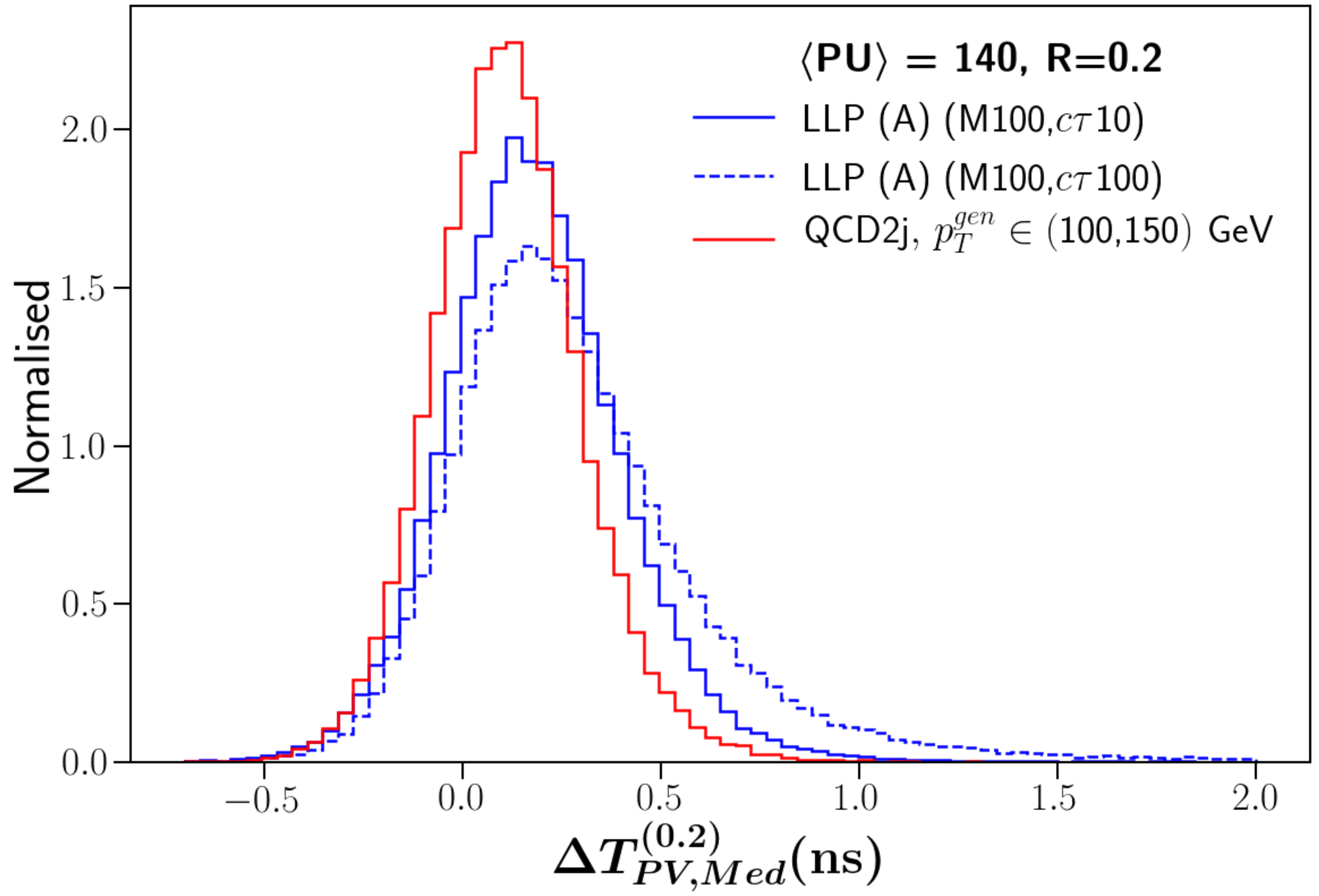
Dedicated triggers optimised for long lived particles in High PU environment

MIP timing detector (MTD)





BDT Based



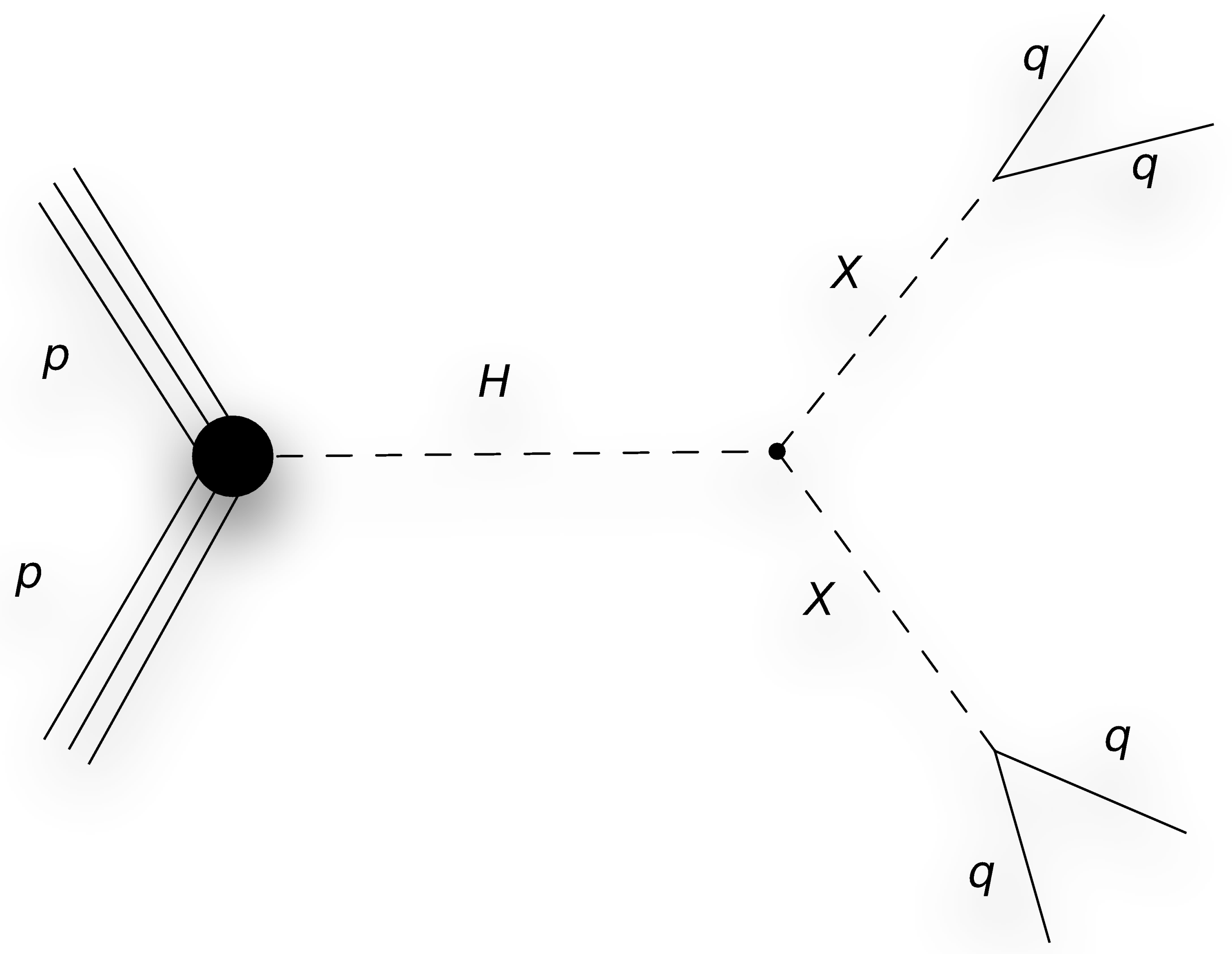
Triggering long-lived particles in HL-LHC and the challenges in the first stage of the trigger system, B. Bhattacherjee, S. Mukherjee, R. Sengupta, PS, *JHEP* 08 (2020) 141

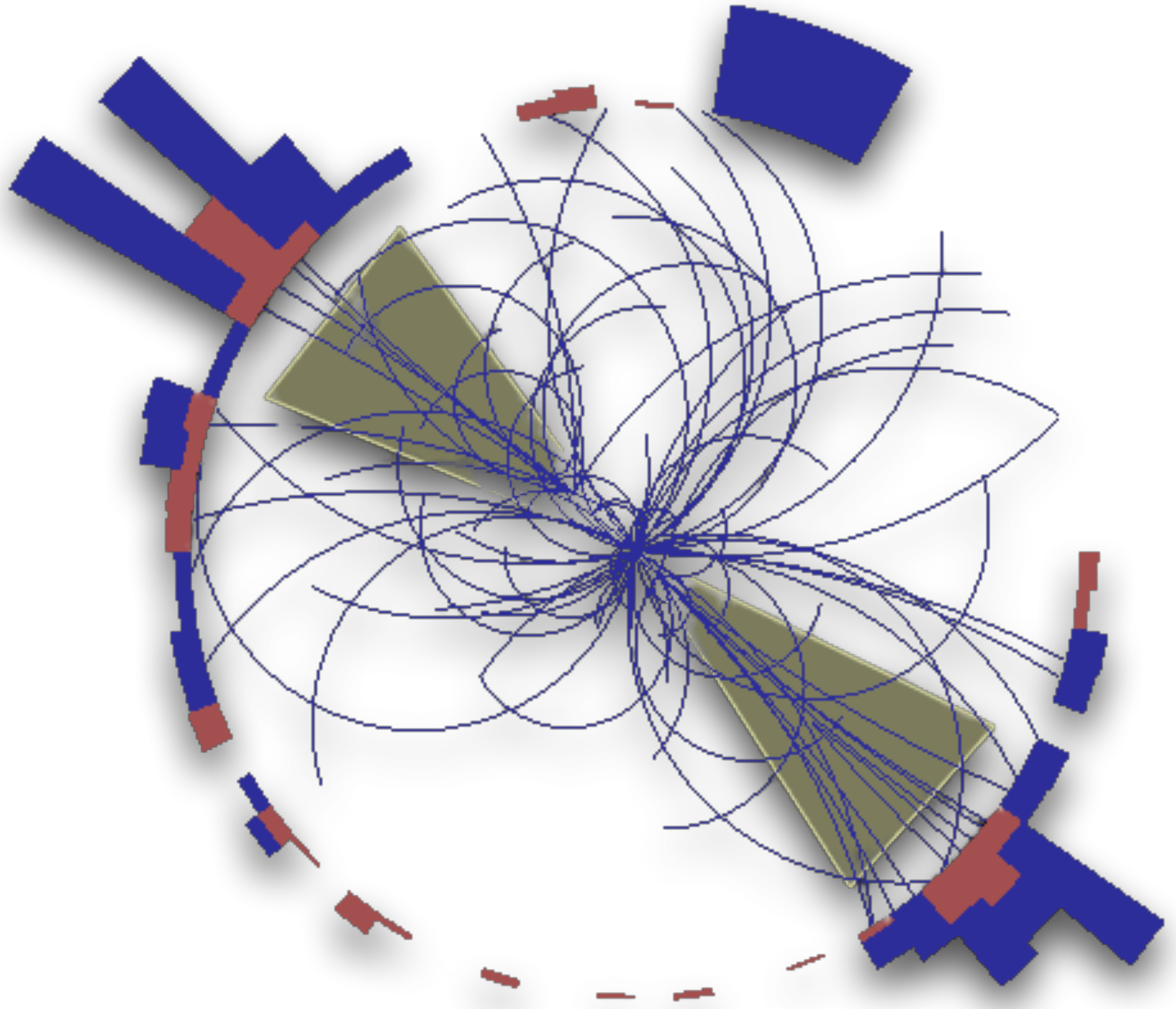
Searching for light LLPs at L1 using ML

Unsupervised anomaly detection using message passing GNN

LLPNet: Graph Autoencoder for Triggering Light Long-Lived Particles at HL-LHC,
B. Bhattacharjee, P. Konar, V. S. Ngairangbam, PS, 2308.13611

Signal



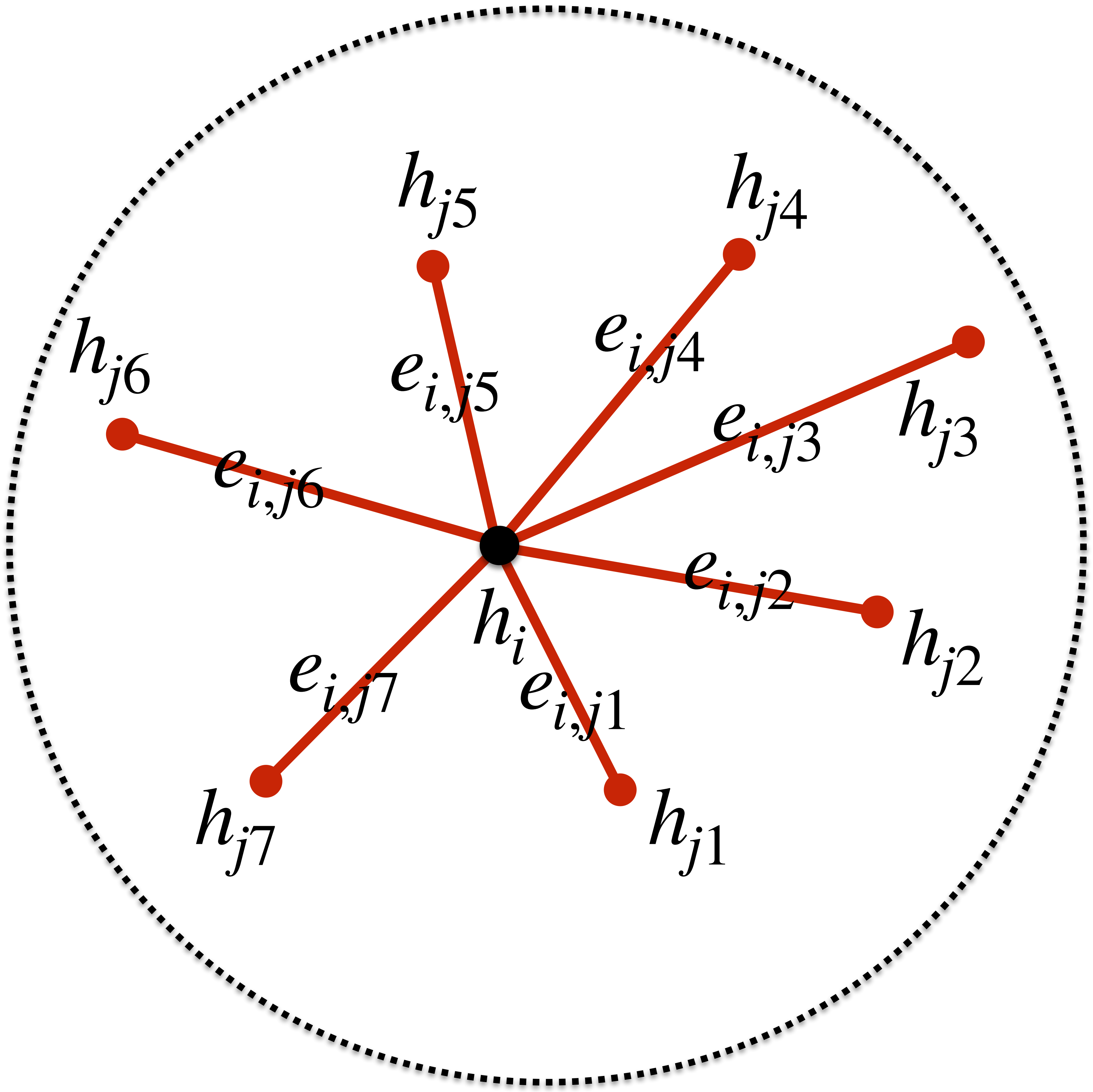


- LLPs produced through decay of 125 GeV Higgs boson
- We study LLP masses in range (10-50 GeV) with decay length (1-100 cm)

Background- Minimum bias (80 mb) and QCD jets

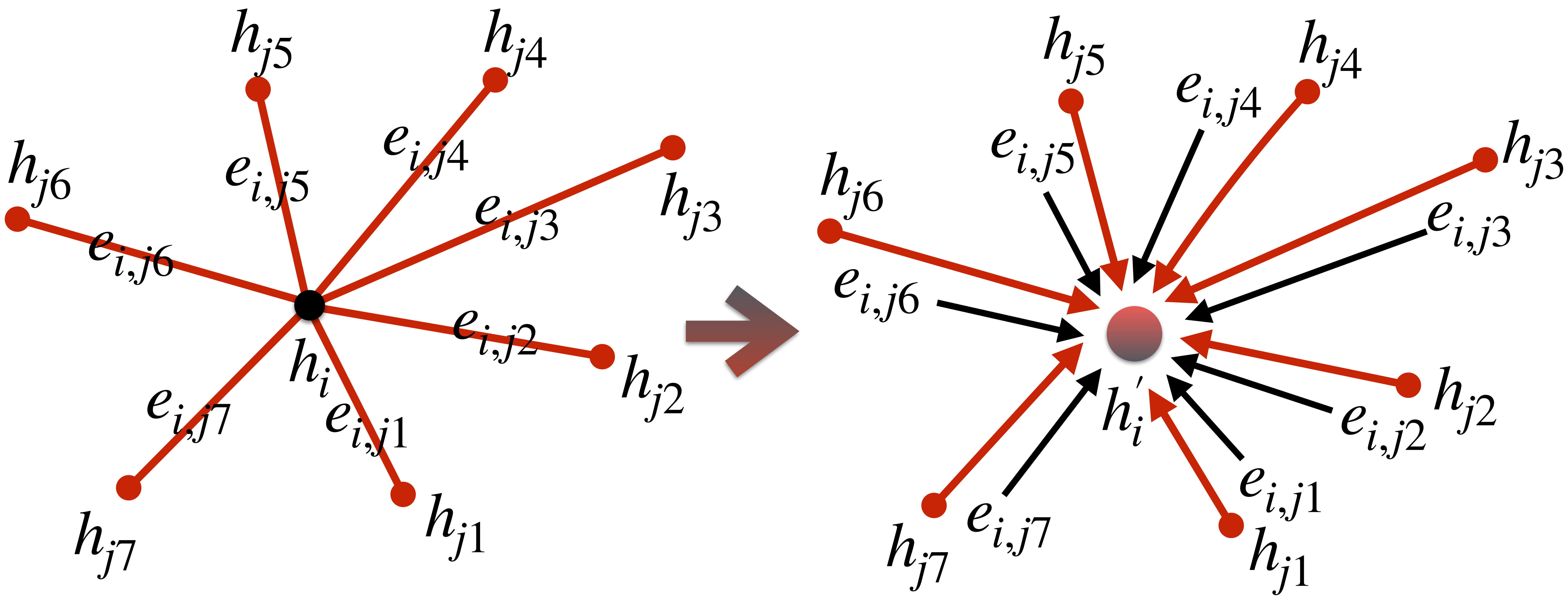
Graph formation

- Graph is constructed using extended L1 tracks with reconstruction efficiency varying with impact parameter.
- For each event, neighbours are selected within a certain radius (r).
- To calculate r, we take into account initial position of tracks in the spatial dimensions.
- Each node is associated with track parameters.
- Each edge is associated with following edge features- Spatial separation, momentum and transverse momentum ratio.



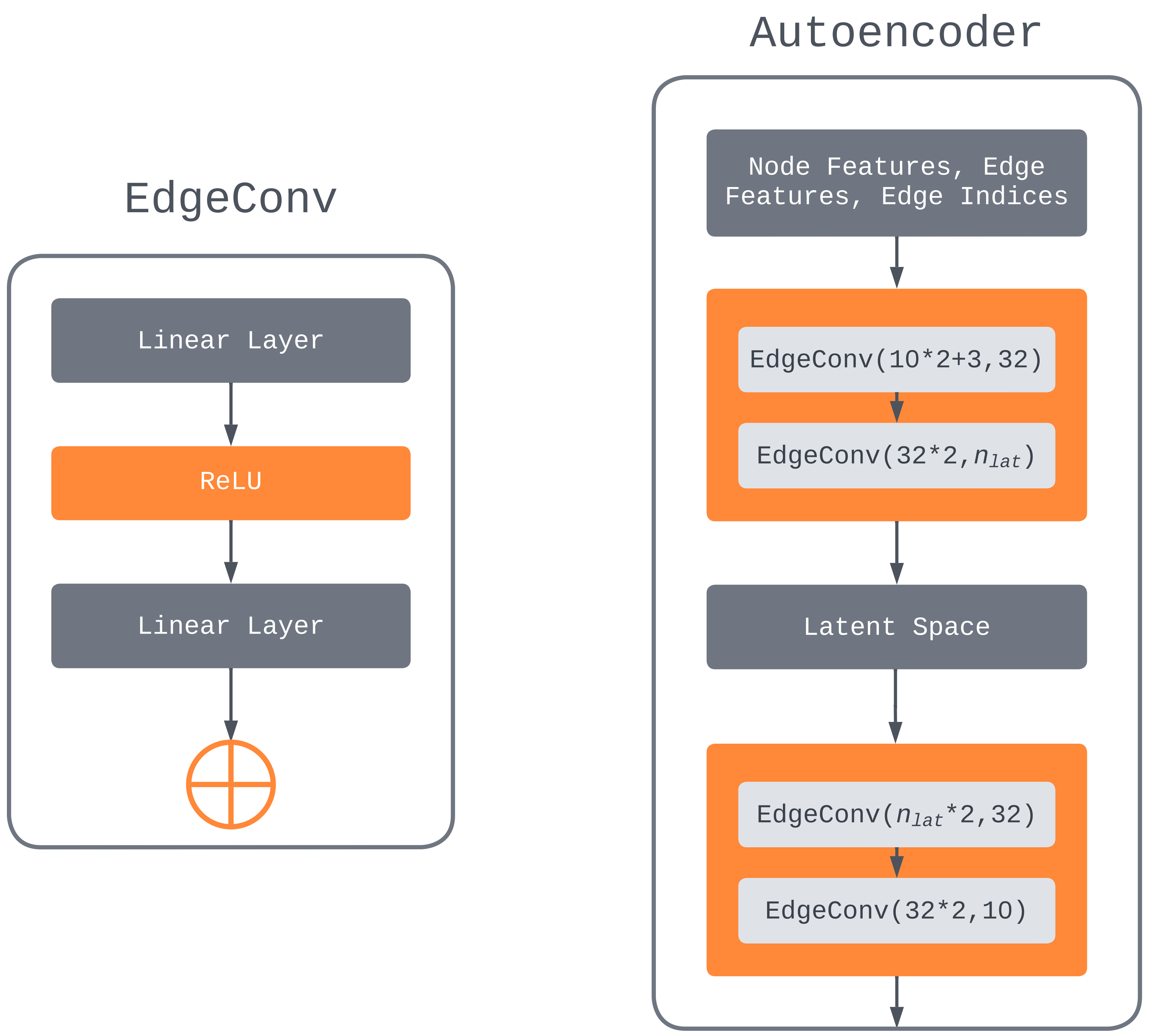
Edge Convolution

$$\mathbf{h}_i^{(l+1)} = \Delta_{j \in \mathcal{N}(i)} \Theta^{(l)} \cdot (\mathbf{h}_i^{(l)}, \mathbf{h}_j^{(l)} - \mathbf{h}_i^{(l)}, \mathbf{e}_{ij}^{(l)})$$



DGCNN, 1801.07829

Autoencoder



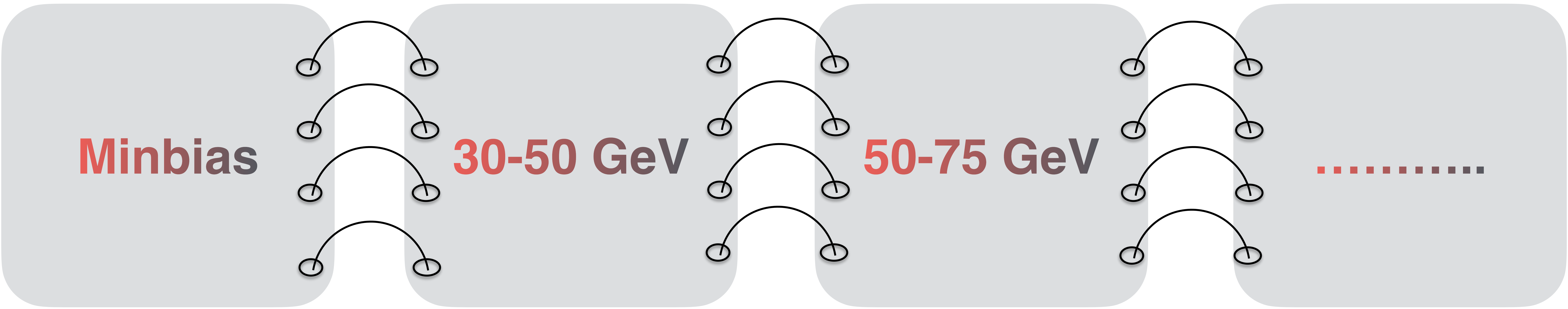
MSE score as anomaly score

~ 6000 trainable parameters

Hyperparameter tuning done on HPC for radius and latent space dimension which led to three WPs in [R, L]: [0.9,6], [1,10],[0.6,8]

Rate calculation

- Not so straight forward as there can be overlap in phase space between different backgrounds.
- We "stitch" together minbias samples with QCD samples (which is divided in various bins based on gen level momentum)[1]



[1] Stitching Monte Carlo samples by Karl Ehataht and Christian Veelken, 2106.04360.

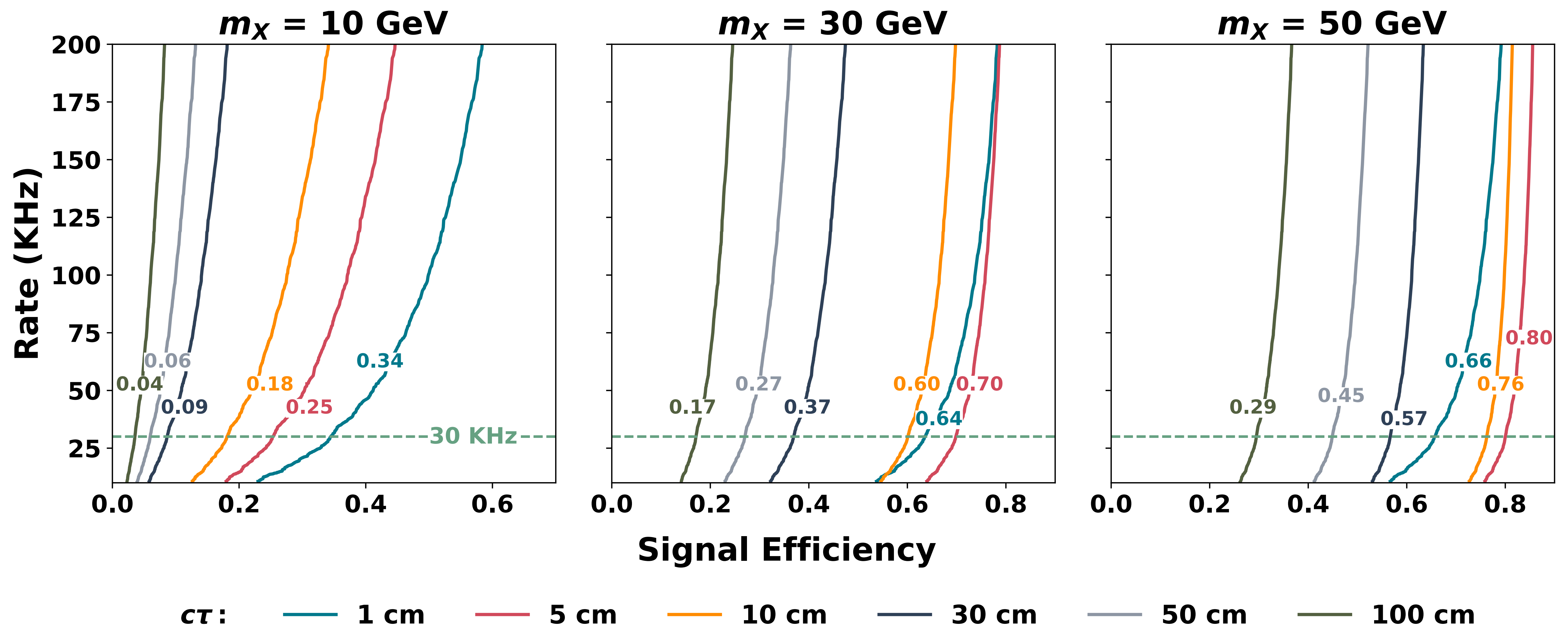
Rate calculation

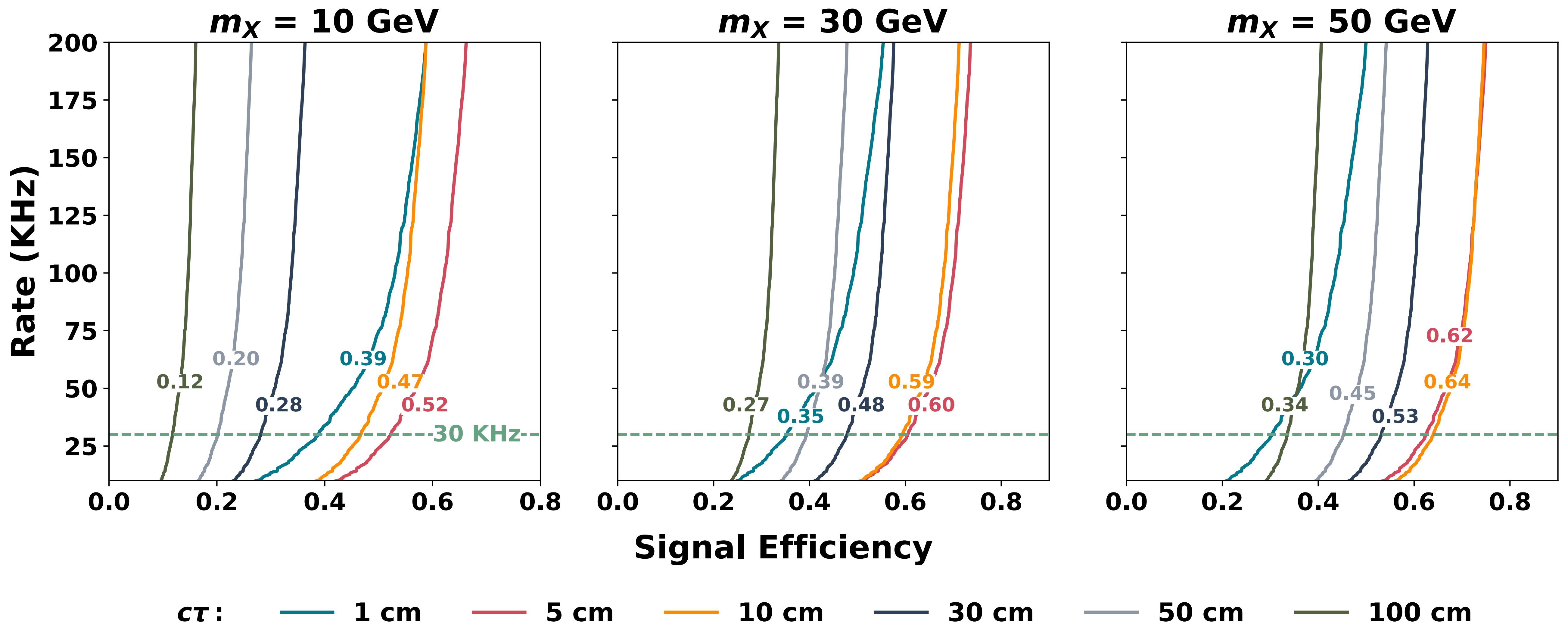
- Weight of each event is then calculated using following formula-

$$w^I = \frac{F}{N_{incl} + \sum_j N_j \times \frac{n_j}{(N_{PU}+1) \times p_j}}$$

- *F* is the *pp* collision frequency.
- N_{incl} refers to the total number of events with $N_{PU}+1$ minbias events, where N_{PU} is the average PU events in a collision.
- N_j is the event count for the j^{th} p_T^{gen} bin, and n_j is the number of inelastic *pp* interactions in that bin.
- p_j is the probability of a single inelastic collision in the j^{th} p_T^{gen} bin, determined by comparing the cross-section for that bin to the cross-section without any p_T^{gen} conditions.

Results



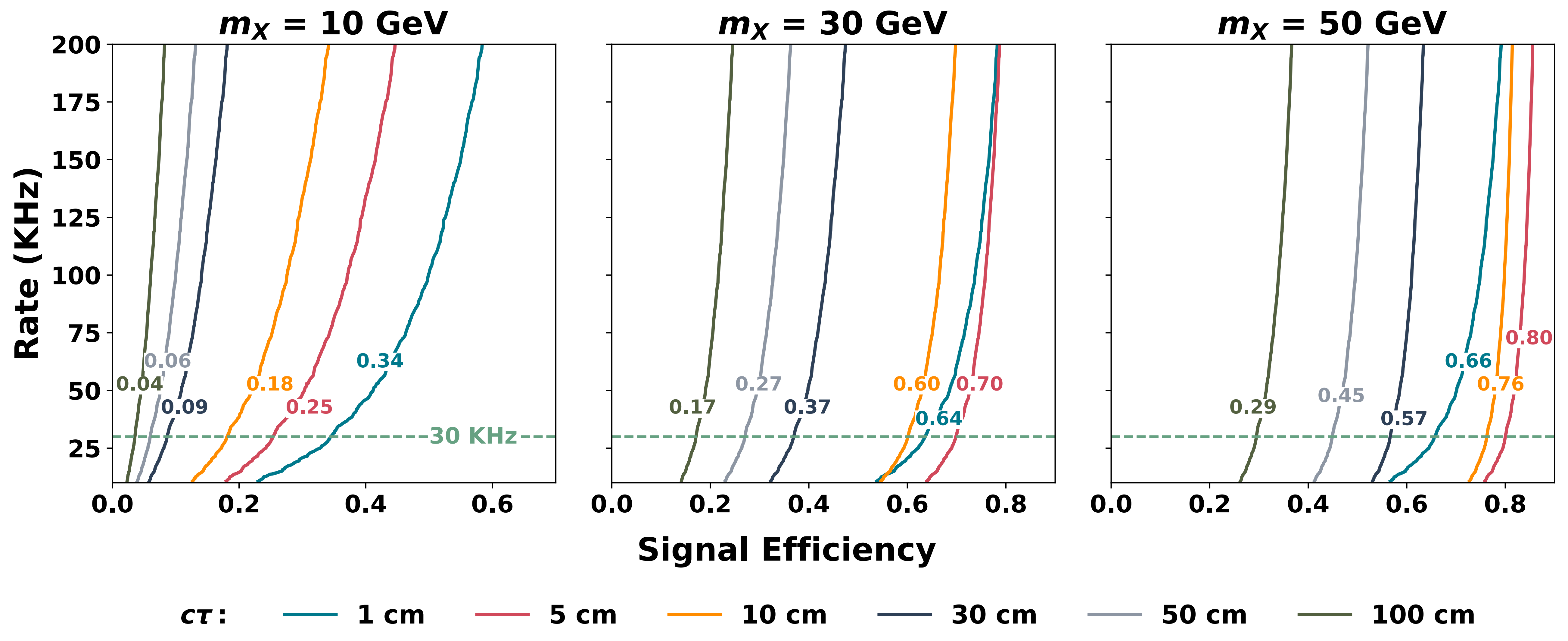


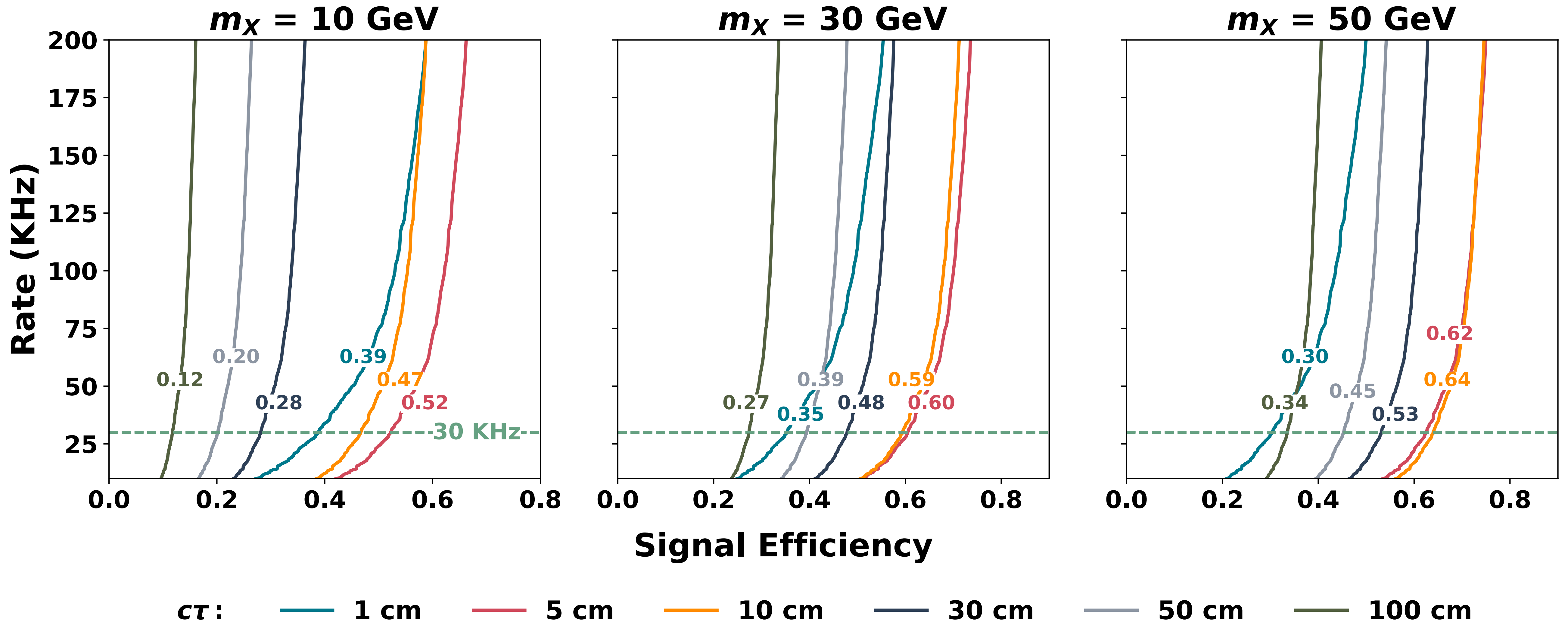
m_X (GeV)	$c\tau$ (cm)					
	1	5	10	30	50	100
WP-1						
10	0.40	0.33	0.24	0.12	0.08	0.05
30	0.63	0.70	0.60	0.37	0.27	0.17
50	0.64	0.80	0.76	0.56	0.44	0.29
WP-2						
10	0.39	0.52	0.47	0.28	0.20	0.12
30	0.35	0.60	0.59	0.48	0.39	0.27
50	0.30	0.62	0.64	0.53	0.45	0.34
WP-3						
10	0.34	0.25	0.18	0.09	0.06	0.04
30	0.64	0.70	0.60	0.37	0.27	0.17
50	0.66	0.80	0.76	0.57	0.45	0.29

CMS: 30 GeV, 5 cm: **8%**
50 GeV, 100 cm: **20%**

Results

Room for improvement: Include timing information





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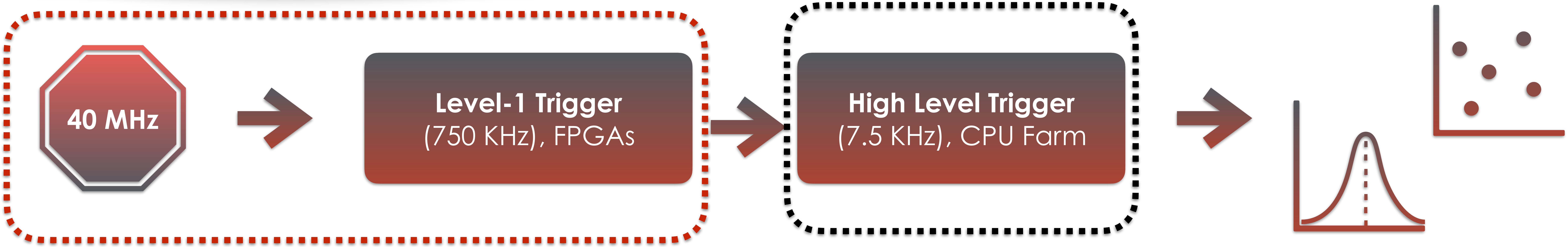
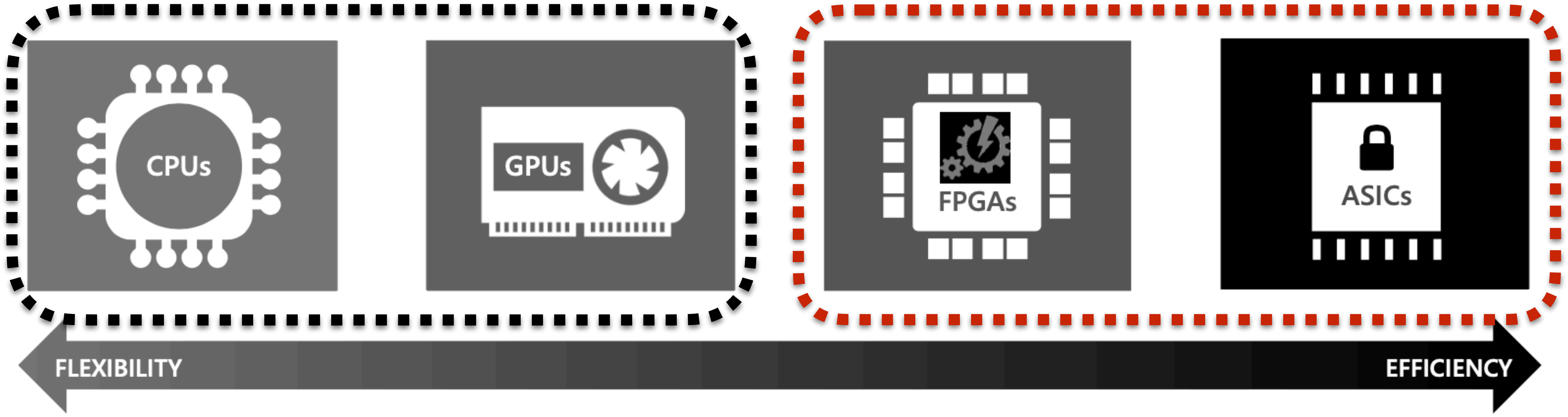
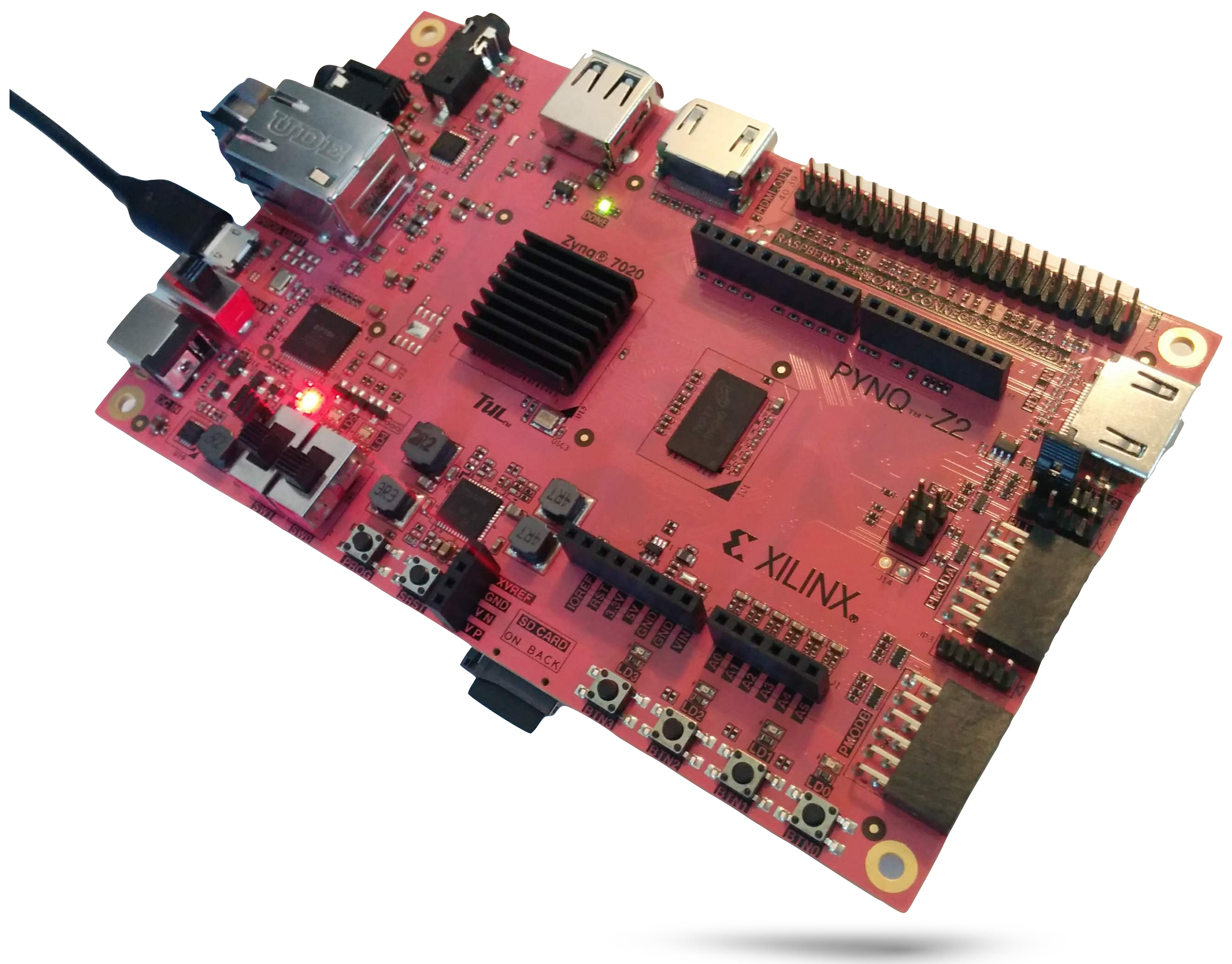
Future plans: ML on FPGAs



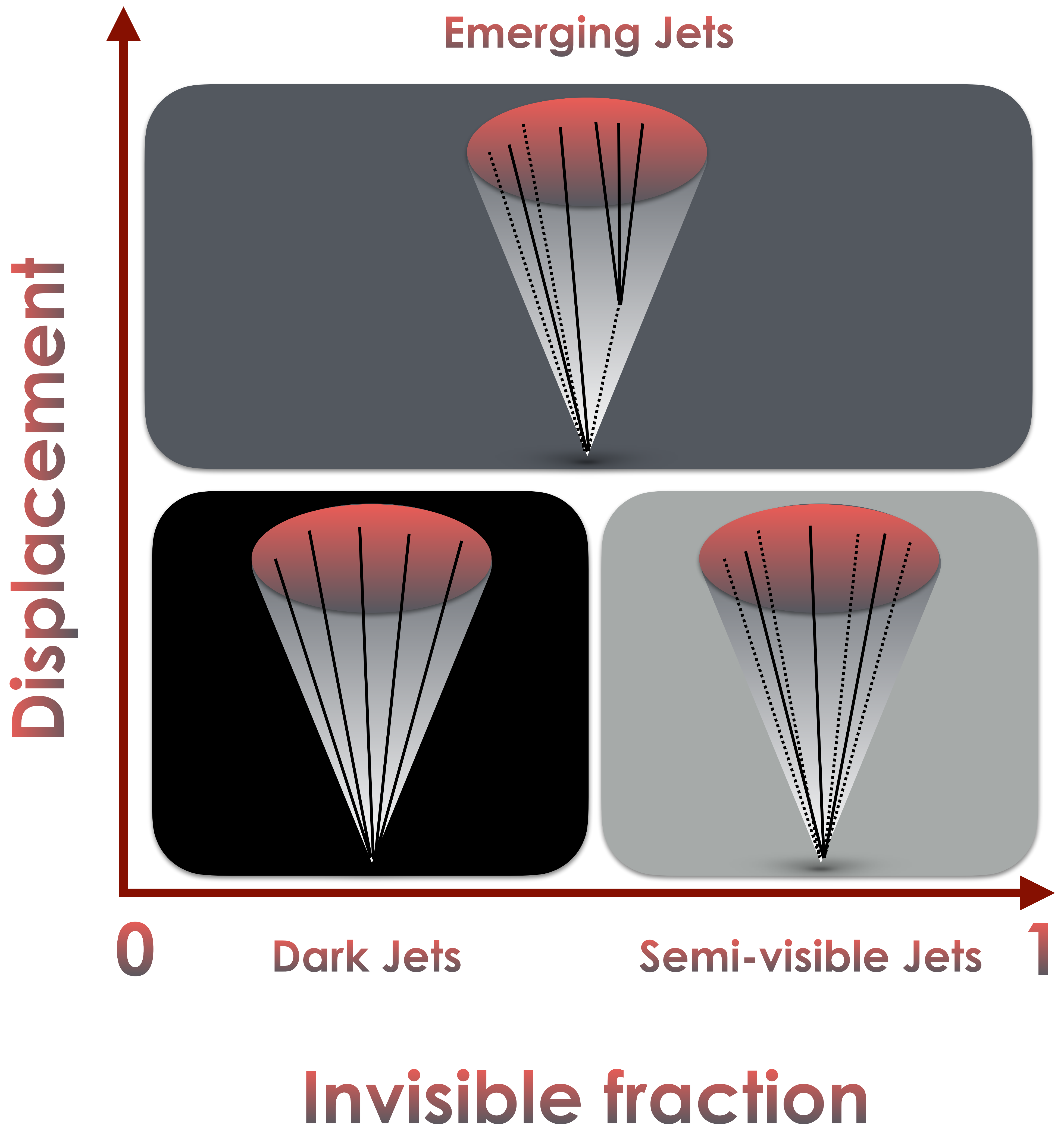
Trigger decisions to be made in 12 μs



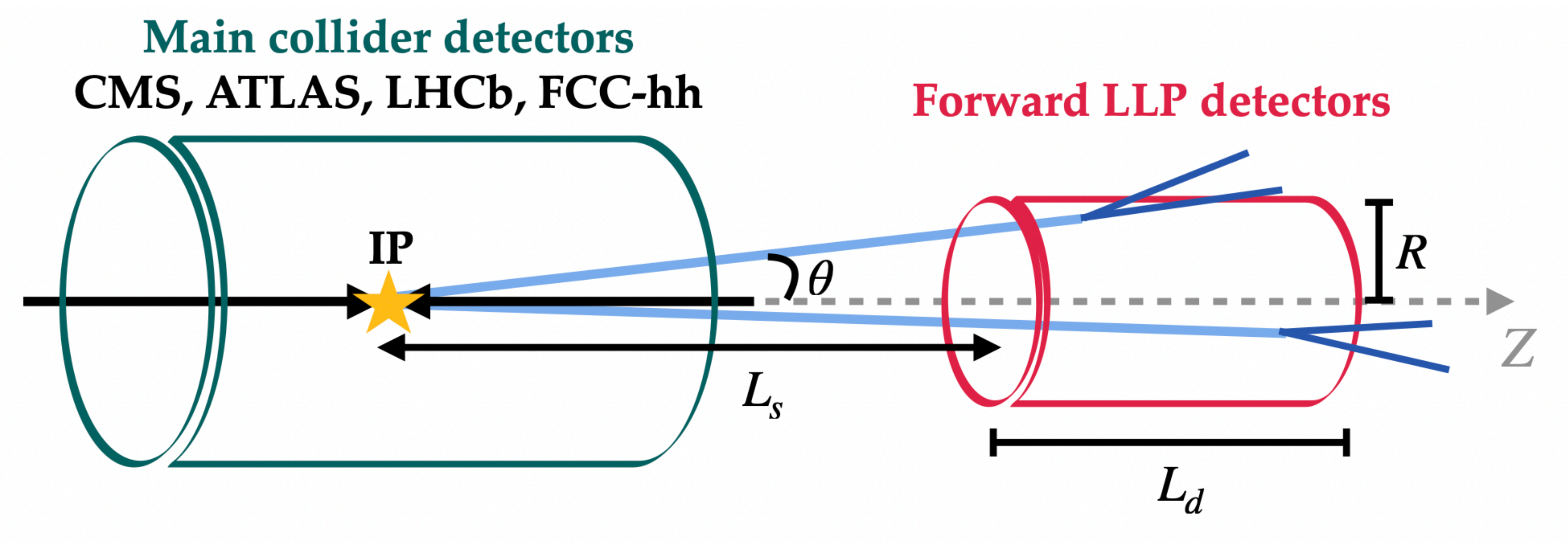


K + TensorFlow PYTORCH ONNX → hls4ml → Vivado™ HLS

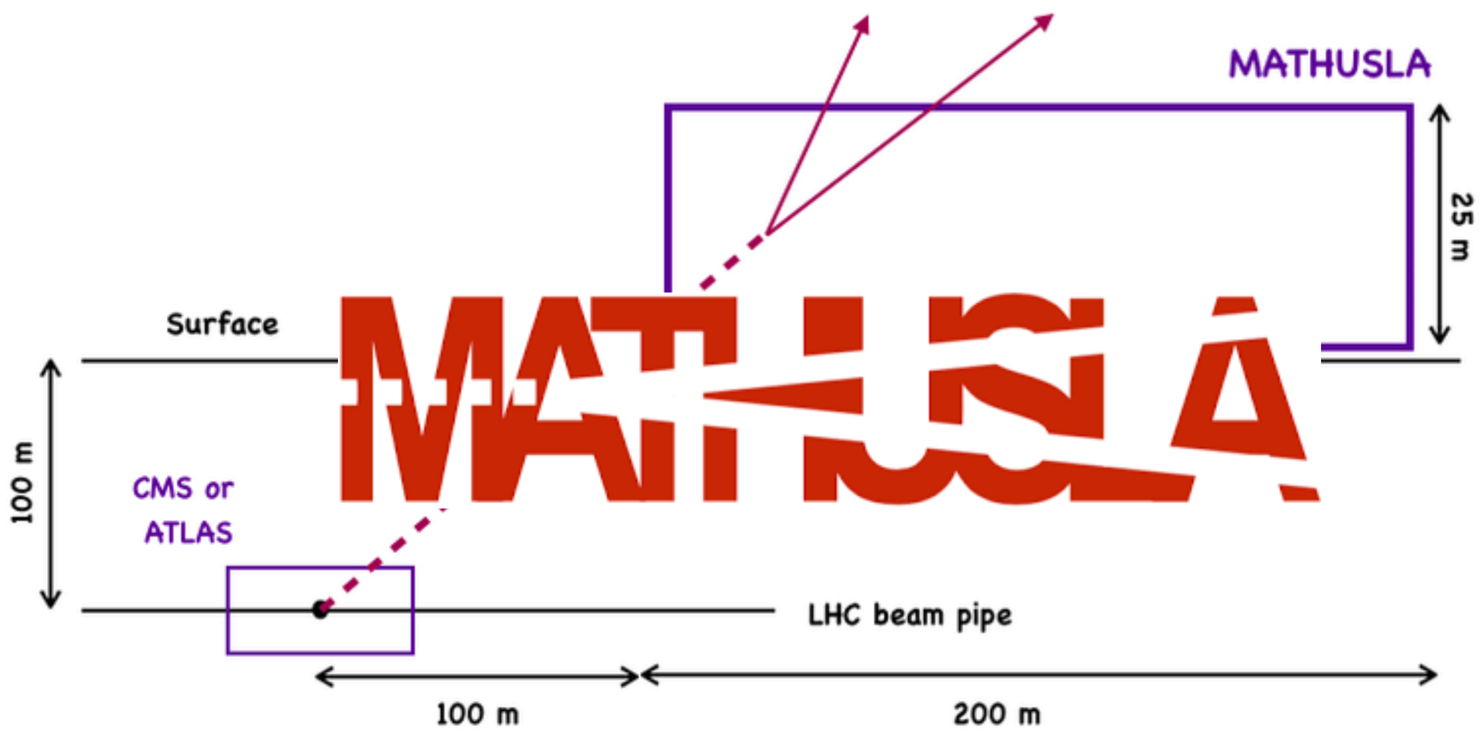
Future plans: ML for dark sector



Future plans: ML @ future LLP detectors



FOREHUNT, B. Bhattacherjee, H. K. Dreiner, N. Ghosh, S. Matsumoto, R. Sengupta, PS, 2306.11803



FASER

CODEX-b

SHiP
Search for Hidden Particles

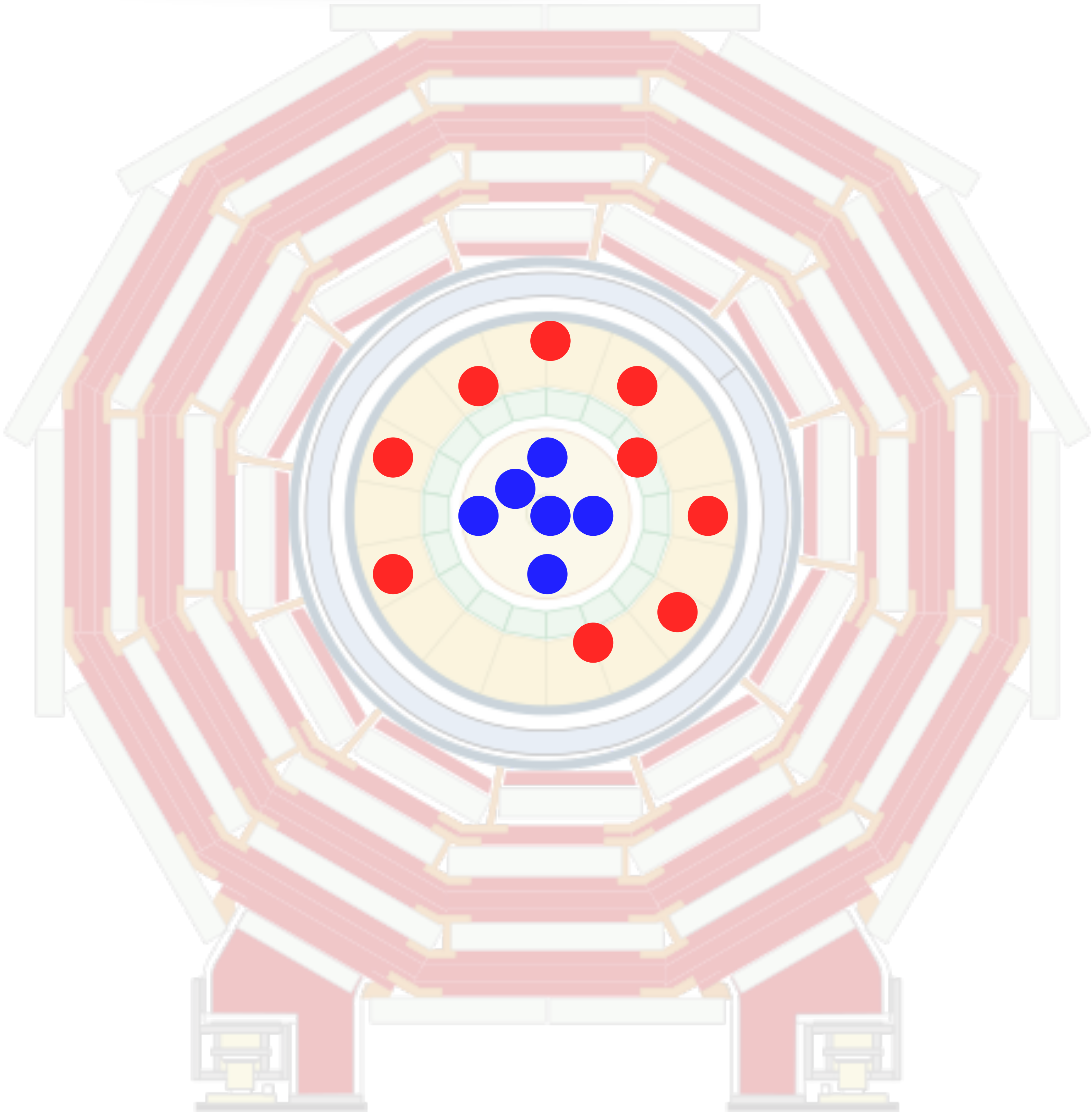
ANUBIS

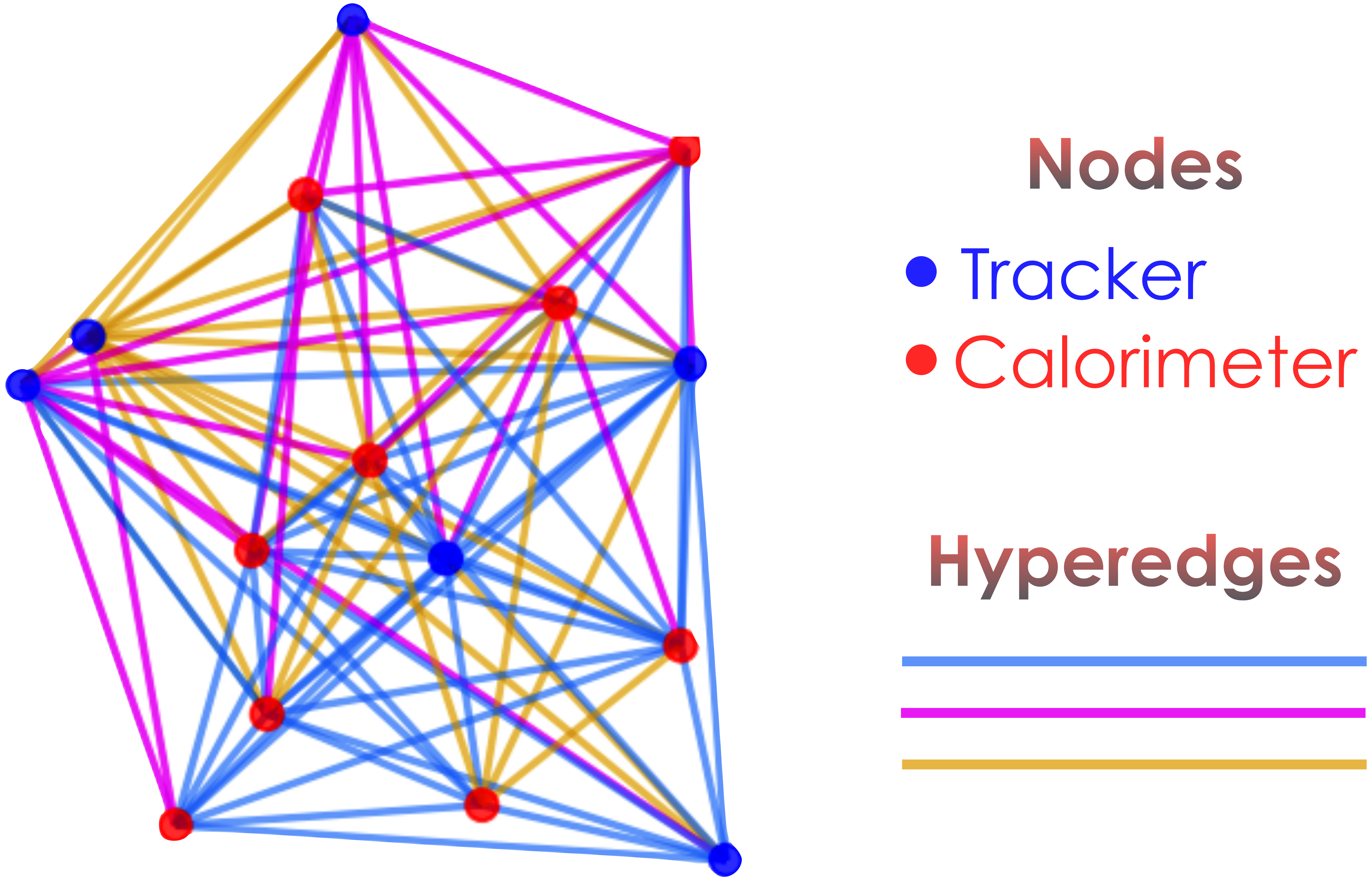
Conclusion

- Future upgrades at phase-2 for L1 will open many avenues for BSM searches especially for displaced physics.
- ML can offer efficient ways to utilise the information available at L1 to trigger such events.
- We studied prospect of using ML based L1 trigger to select LLP events at L1 by using a simple auto-encoder and constraining the background rate.
- Further studies concerning FPGA implementation are imminent!

BACK UP

Heterogenous Hypergraphs



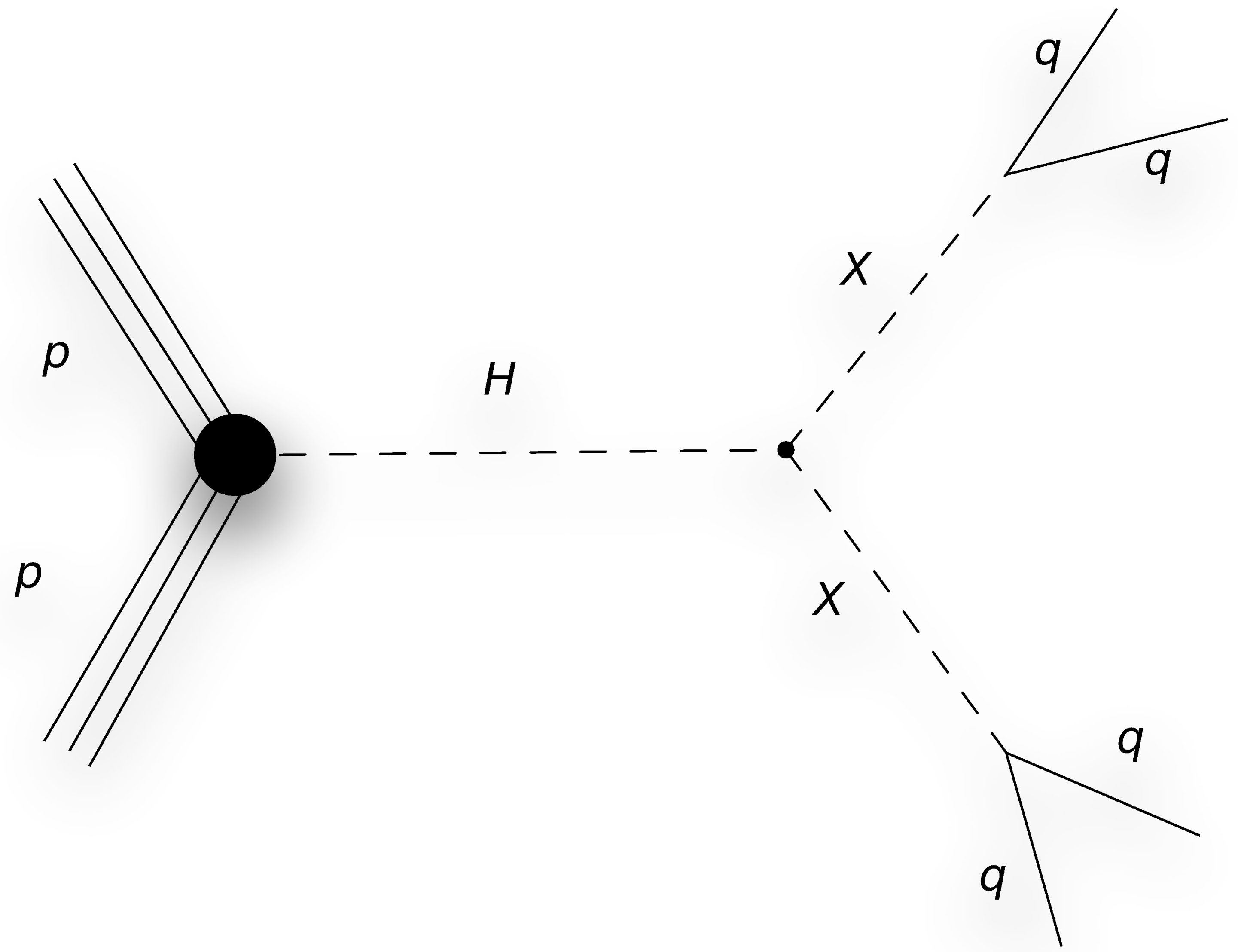


- Better representations of event structure
- Combining information from various sub-detectors to efficiently search for BSM physics (e.g. MTD can provide valuable inputs for displaced searches and PU mitigation)

Signal

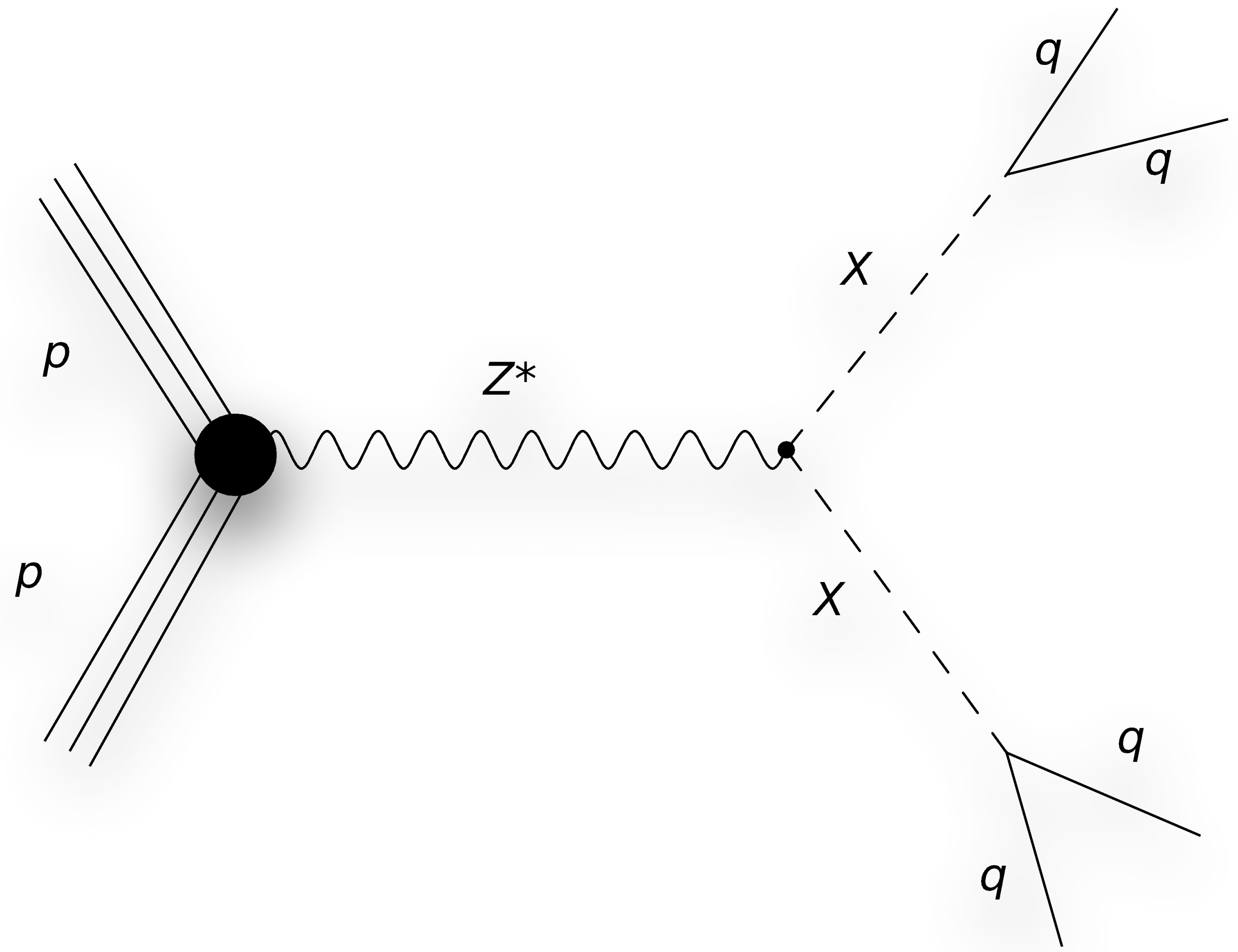
Signature based and model independent study - Final state contains **displaced jets**

Scenario-A



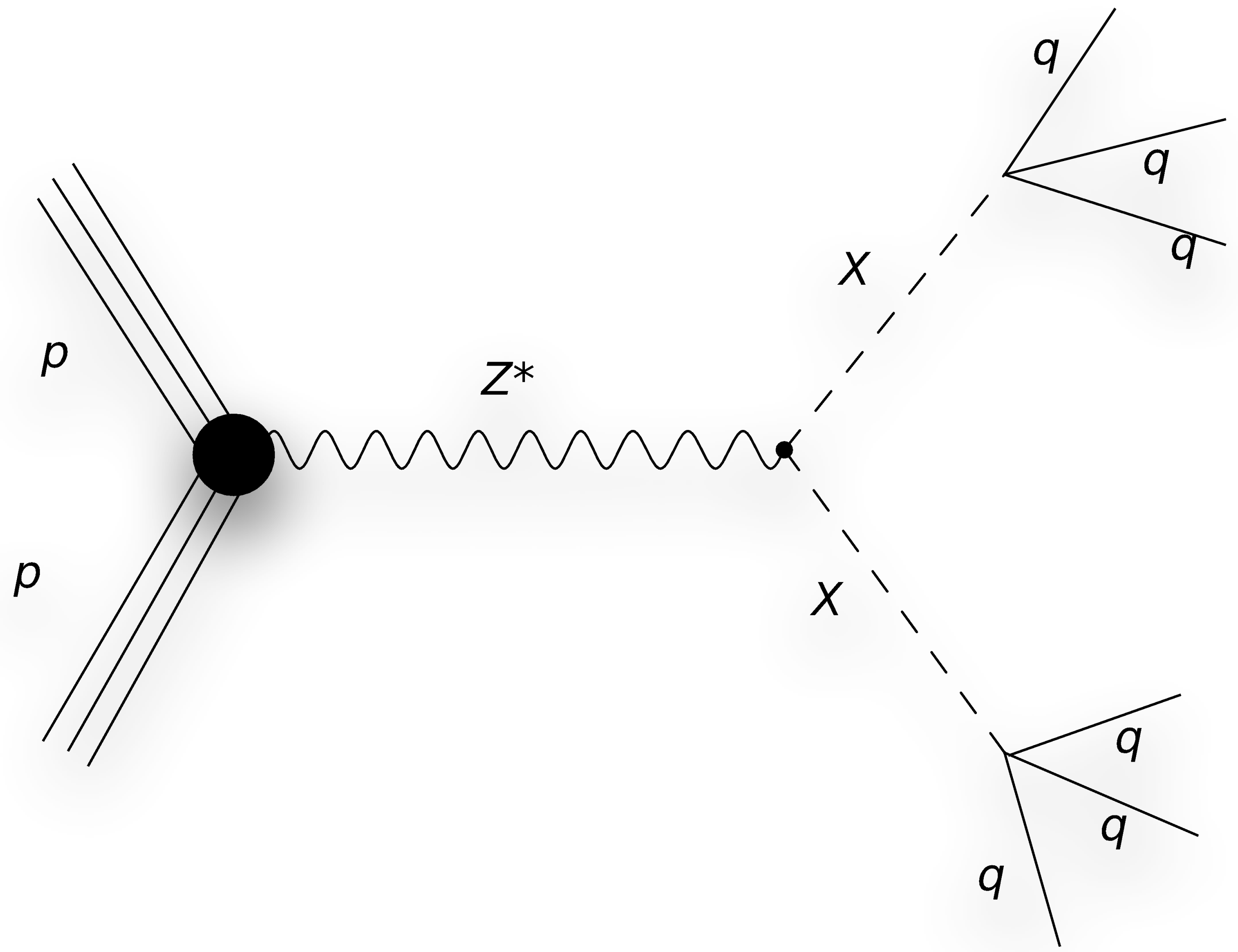
- LLPs produced through decay of 125 GeV Higgs boson
- We study LLP masses in range (10-50 GeV) with decay length (1-500 cm)

Scenario-B



- Direct pair production of LLPs decaying to two quarks each

Scenario-C



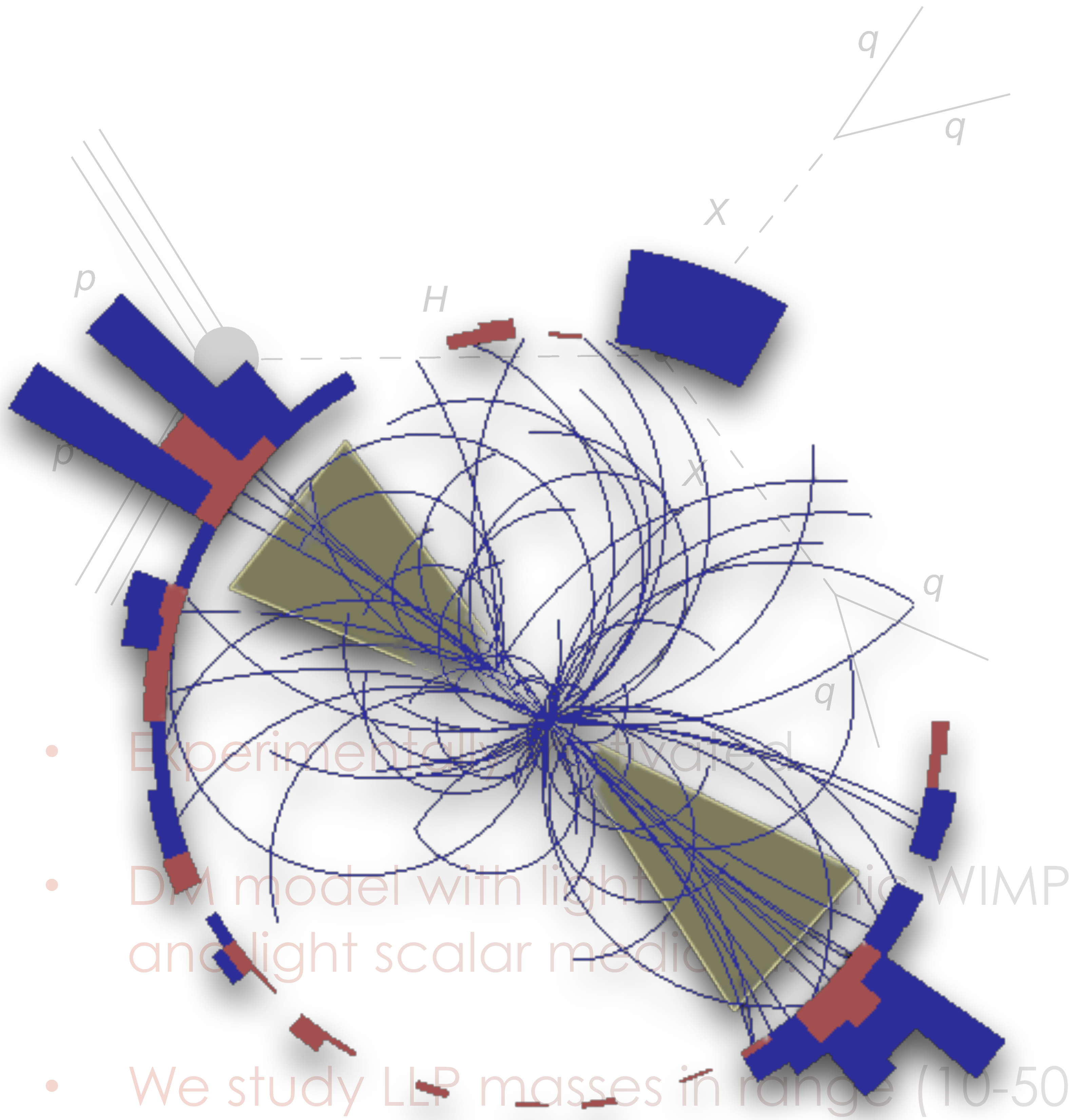
- Direct pair production of LLPs where LLP decays to three quarks

We study LLP masses in range (100-500 GeV) with decay length (1-500 cm) for scenario-B and C.

Signal

Signature based and model independent study - Final state contains displaced jets

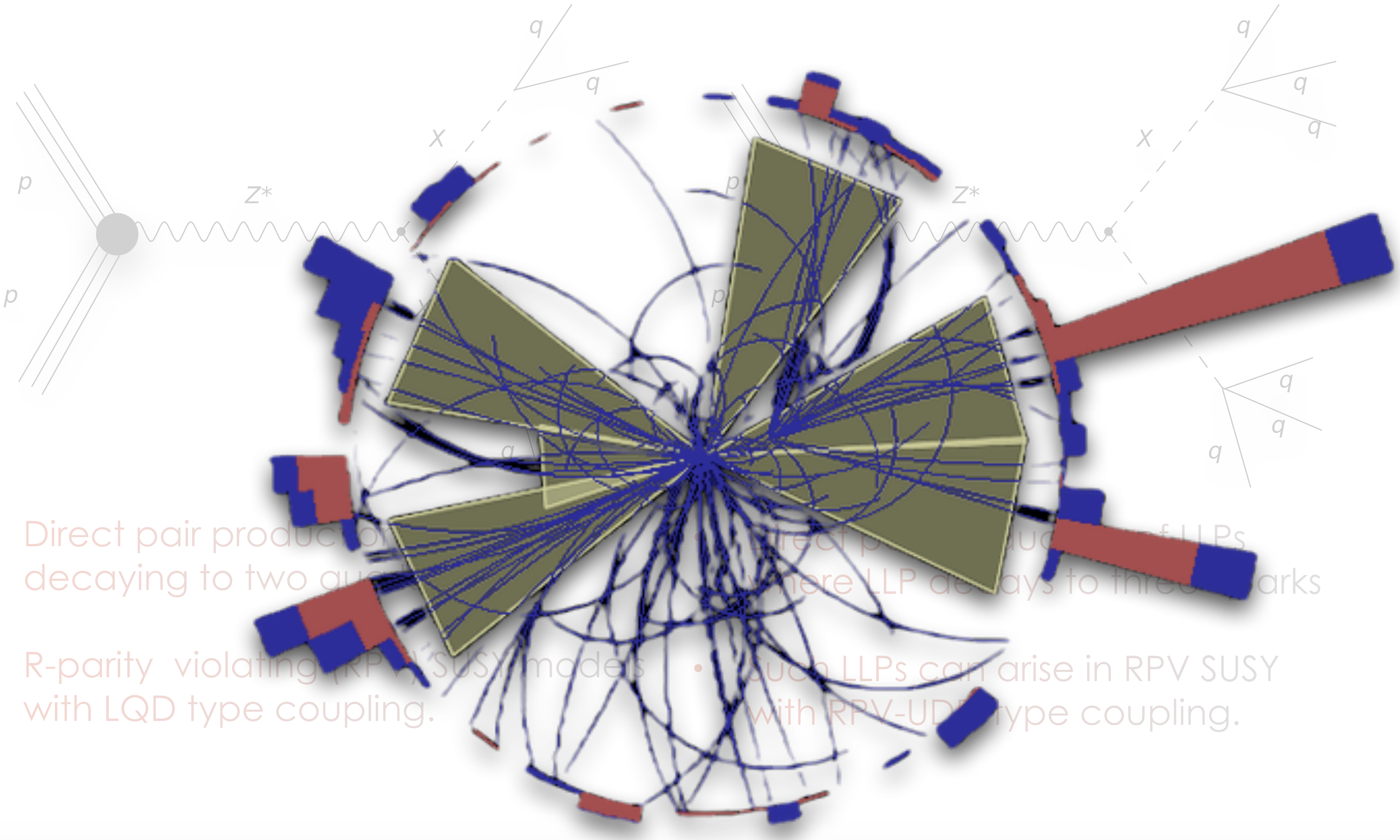
Scenario-A



- We study LLP masses in range (10-50 GeV) with decay length (1-500 cm)

Scenario-B

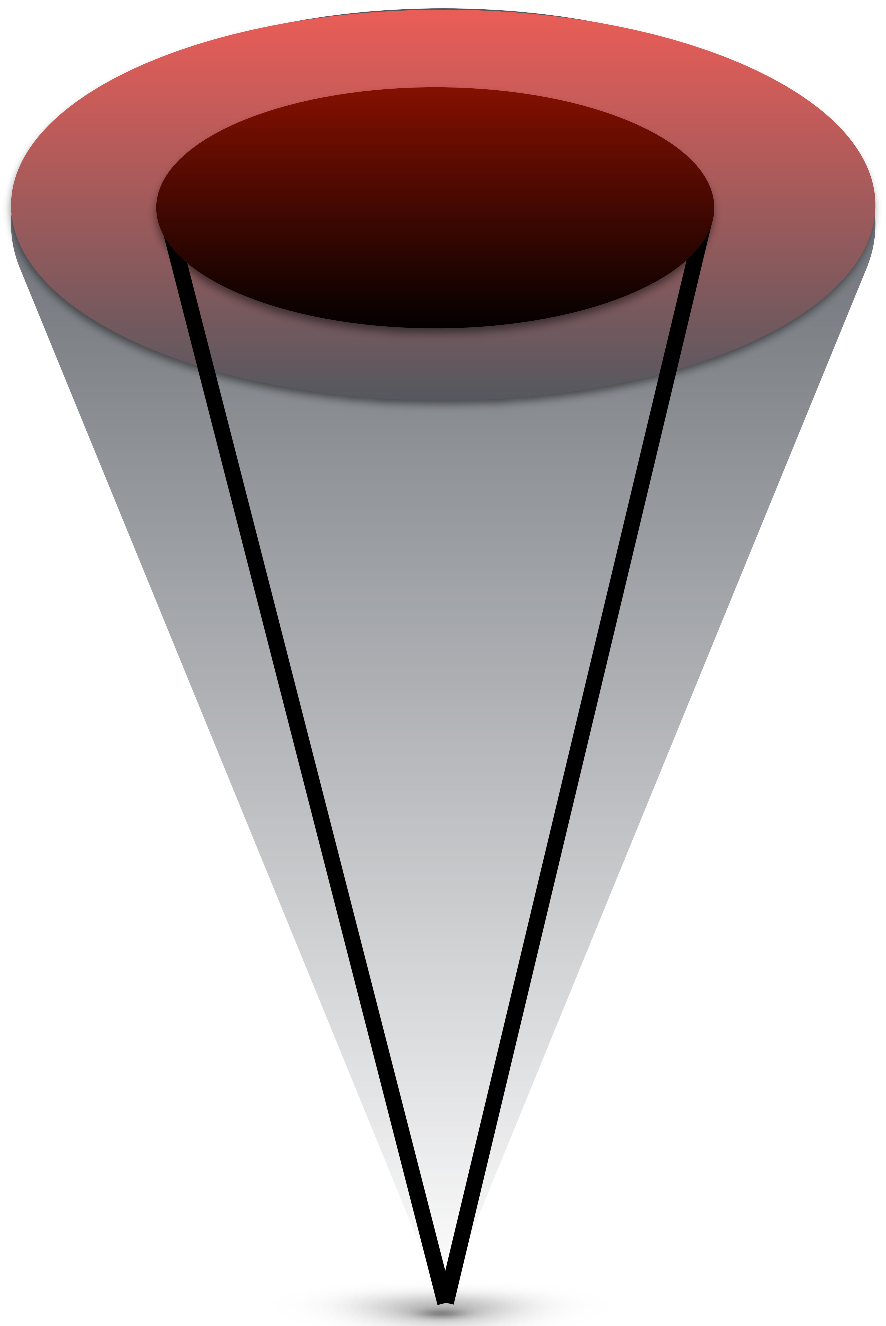
Scenario-C



- R-parity violating (RPV) SUSY models with LQD type coupling.
- Such LLPs can arise in RPV SUSY with RPV-UDD type coupling.

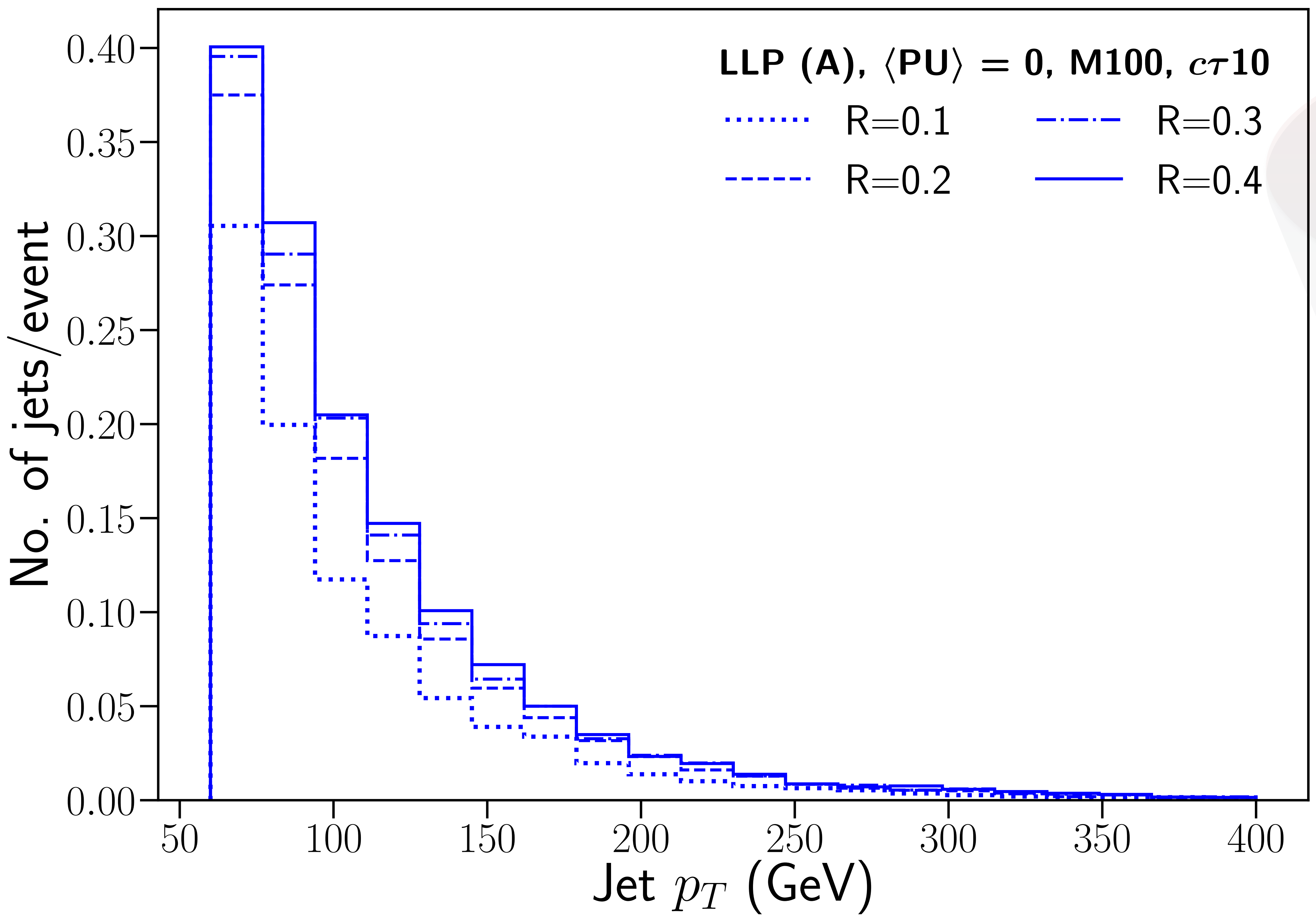
We study LLP masses in range (100-500 GeV) with decay length (1-500 cm) for scenario-B and C.

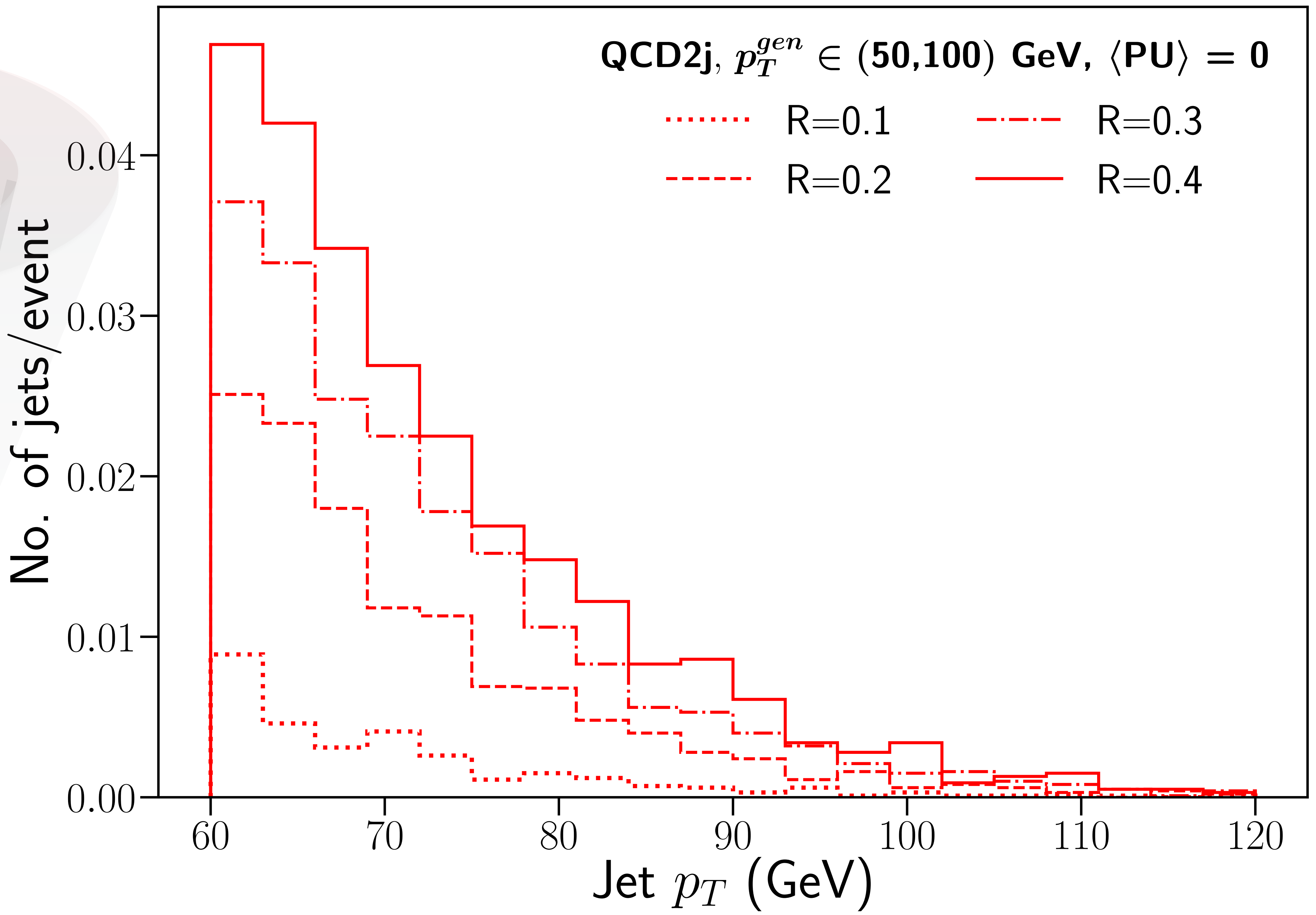
PU and Narrow Jets



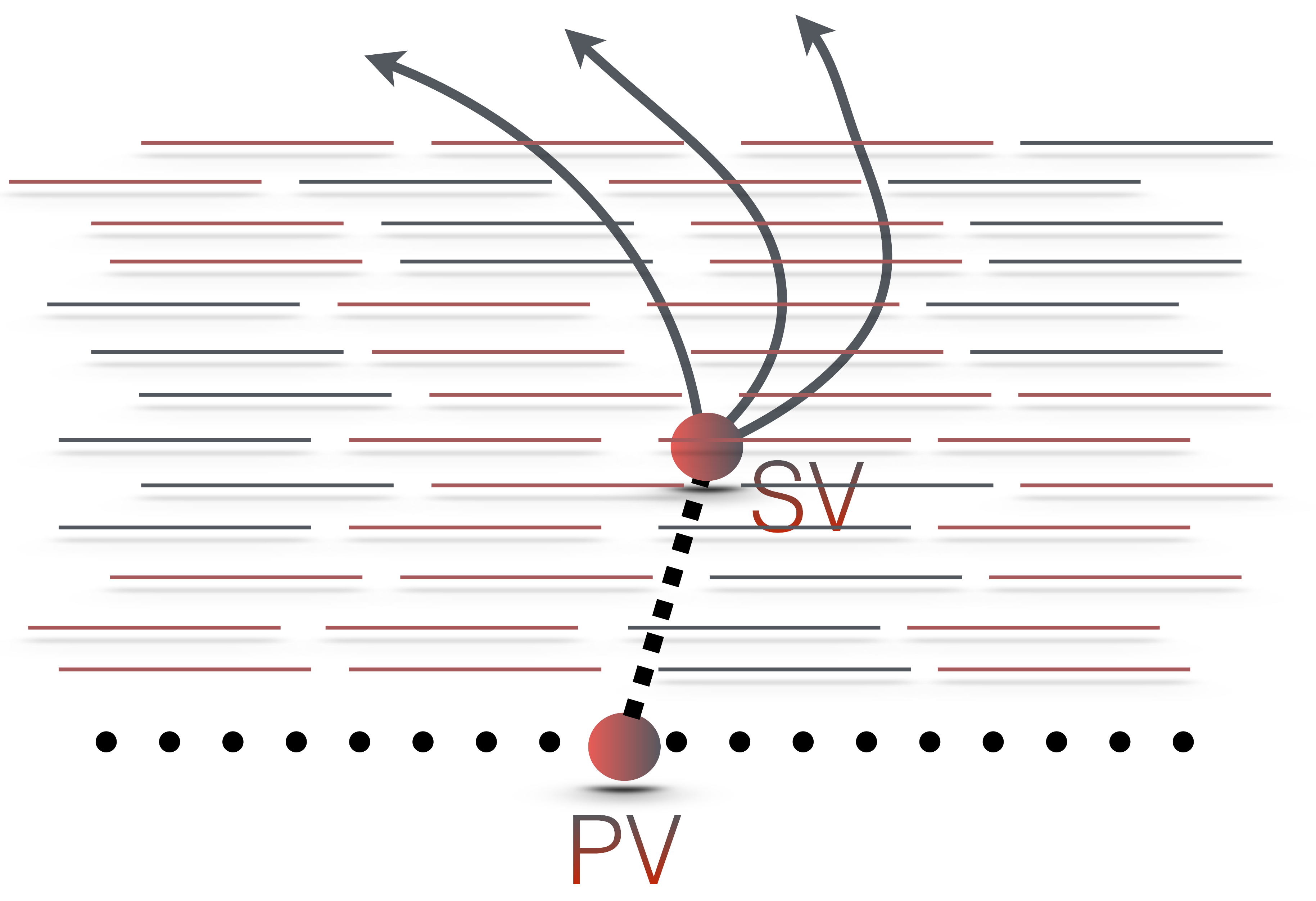
PU is uniformly distributed, Reducing the jet cone size can decrease the PU contribution given that it contains most of the hadronic activity of signal

Narrow Jets

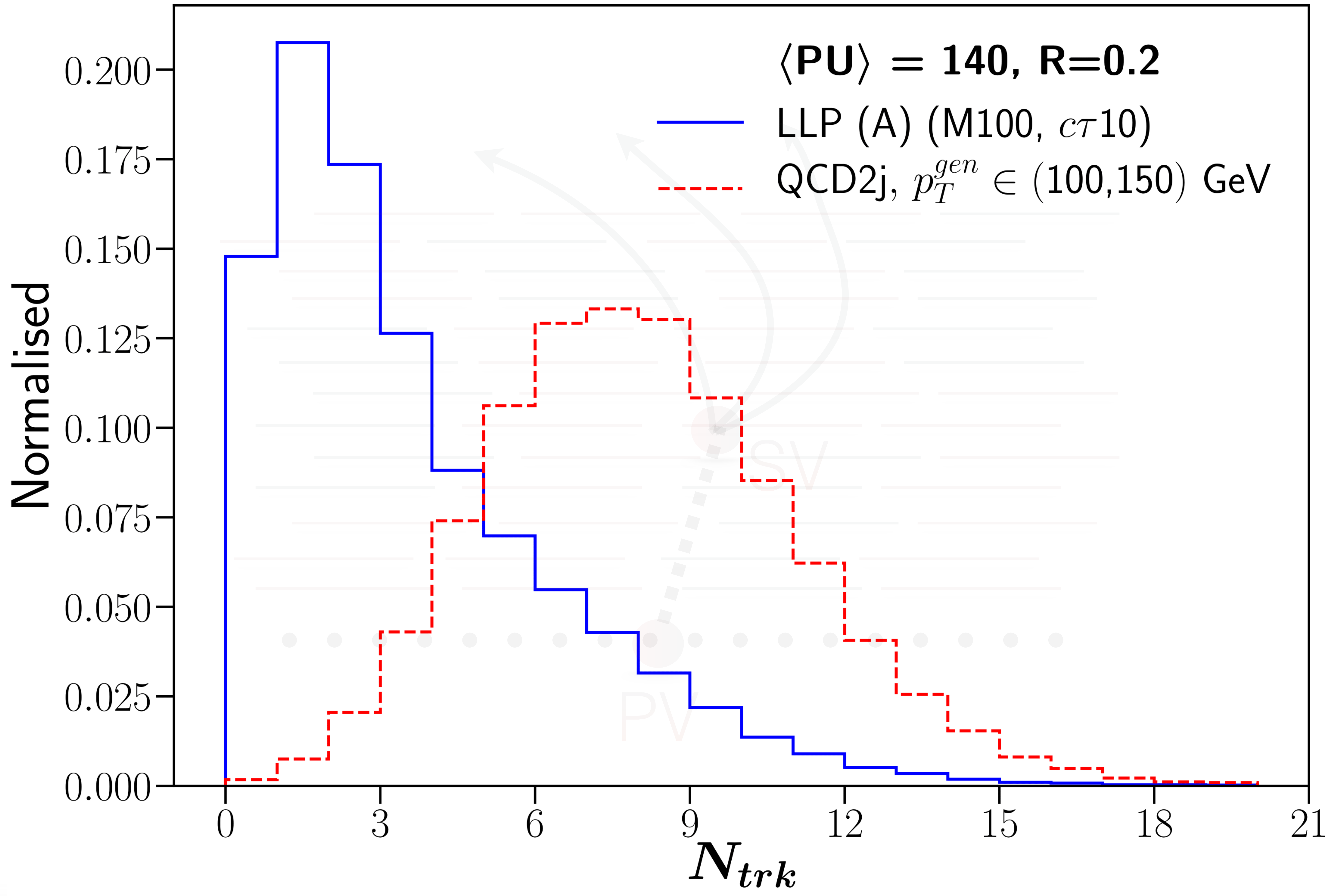

LLP (A), ⟨PU⟩ = 0, M100, cτ10
R=0.1
R=0.2
R=0.3
R=0.4
No. of jets/event
Jet p_T (GeV)
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
50
100
150
200
250
300
350
400


QCD2j, $p_T^{gen} \in$ (50,100) GeV, ⟨PU⟩ = 0
R=0.1
R=0.2
R=0.3
R=0.4
No. of jets/event
Jet p_T (GeV)
0.00
0.01
0.02
0.03
0.04
60
70
80
90
100
110
120

Tracklessness

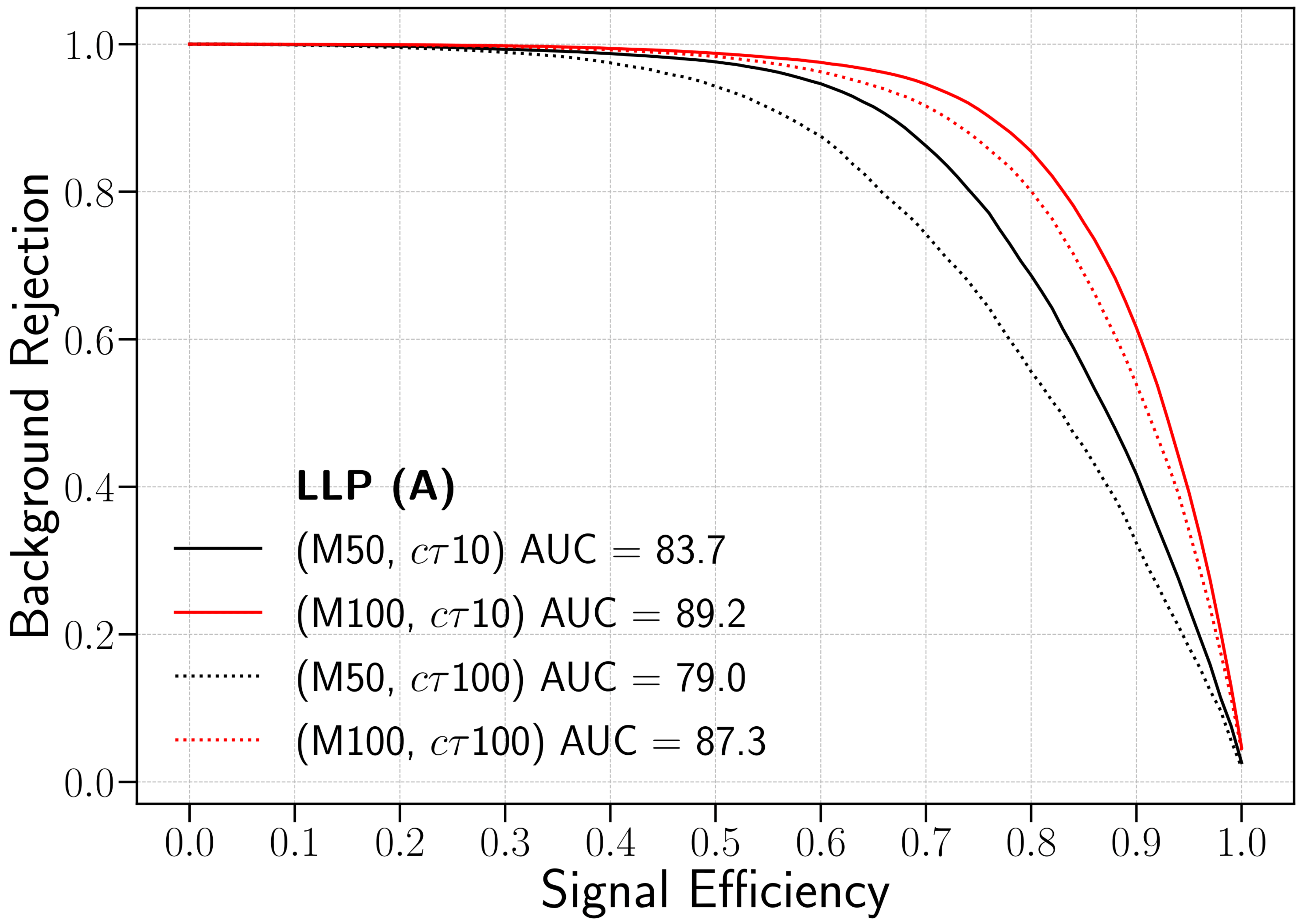


Tracklessness

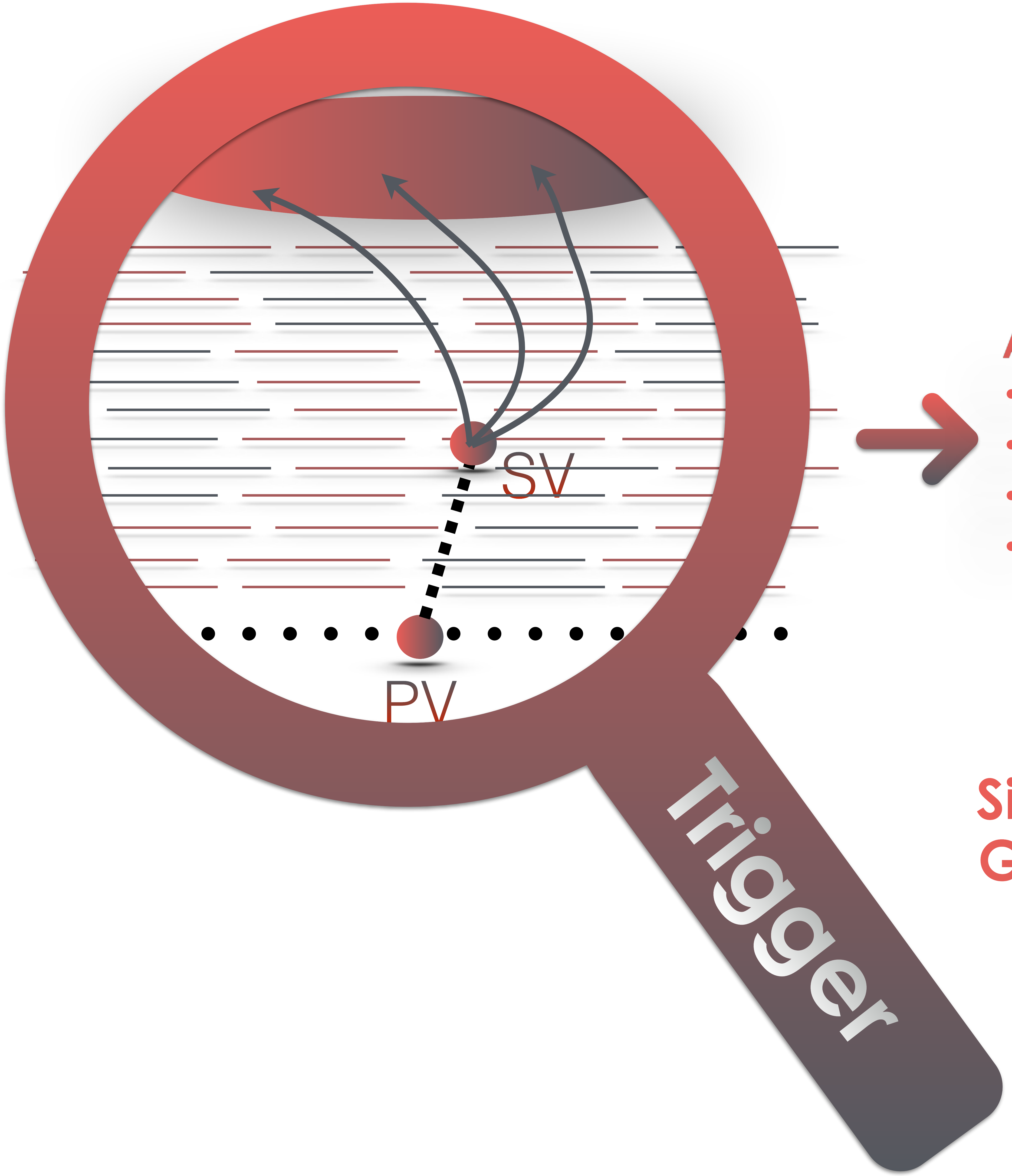


Tracklessness

$$\Sigma p_T^{0.2},\ N_{trk}^{0.2},\ n_{z_{trk\_max}},\ p_{T,vtx}^{miss}$$



Trackless jet trigger

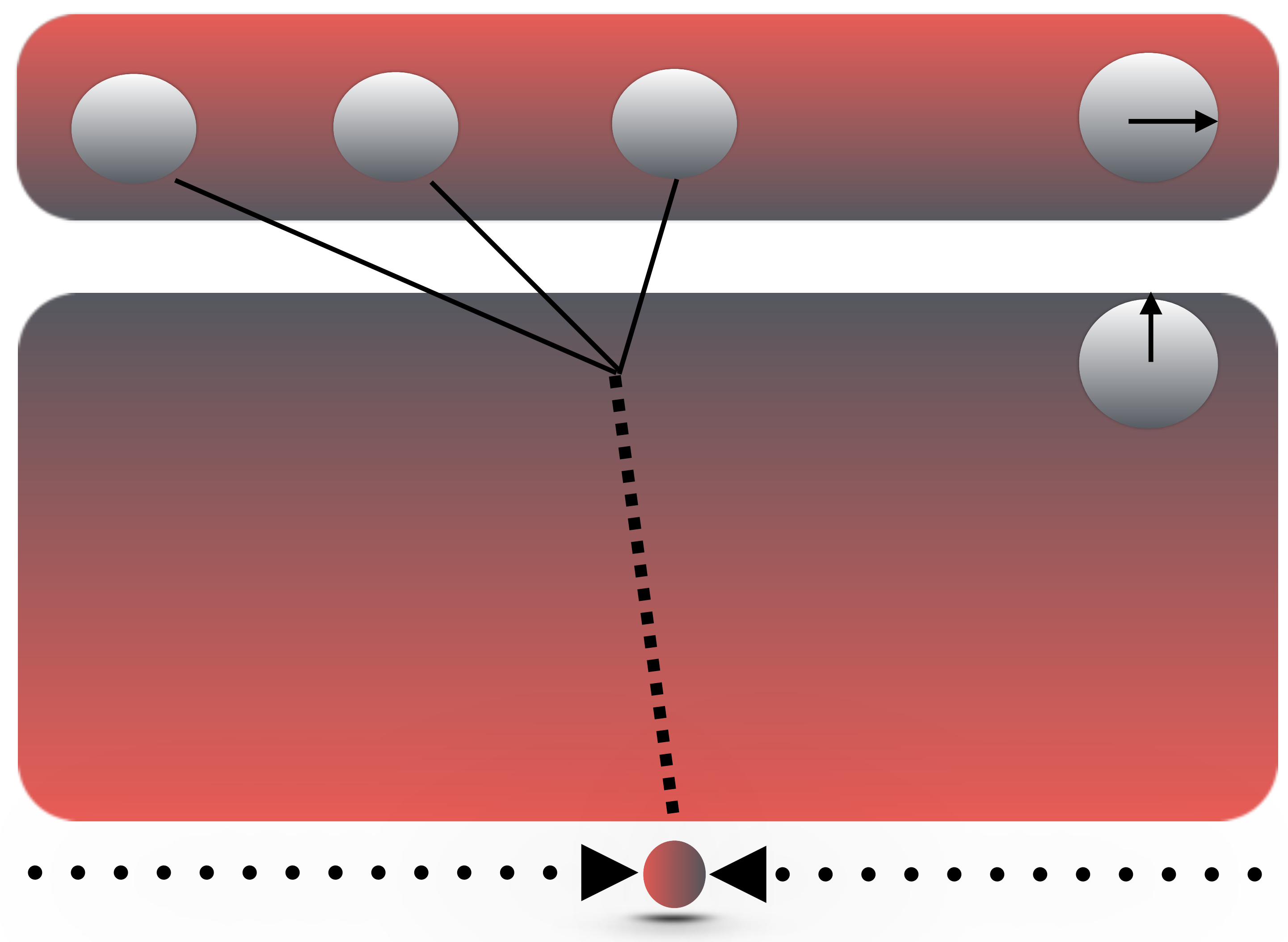


At-least one jet with-

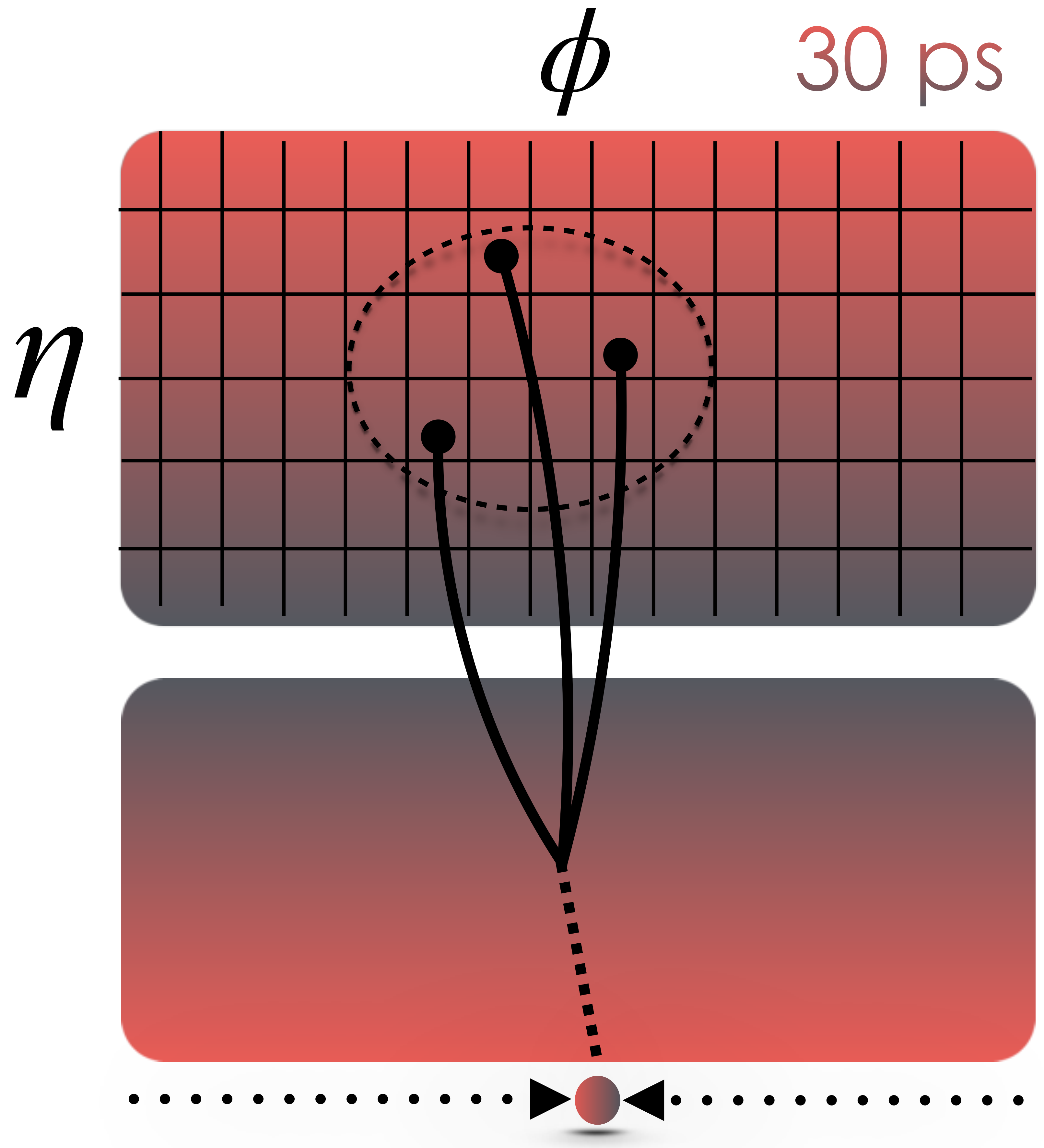
- R = 0.2
- PT = 60 GeV
- BDT score corresponding to a background rejection of 98%
- No other jet from the same z-vertex

Signal efficiency of ≈ 60% for LLP with mass 100 GeV and 10 cm decay length with permissible background rates.

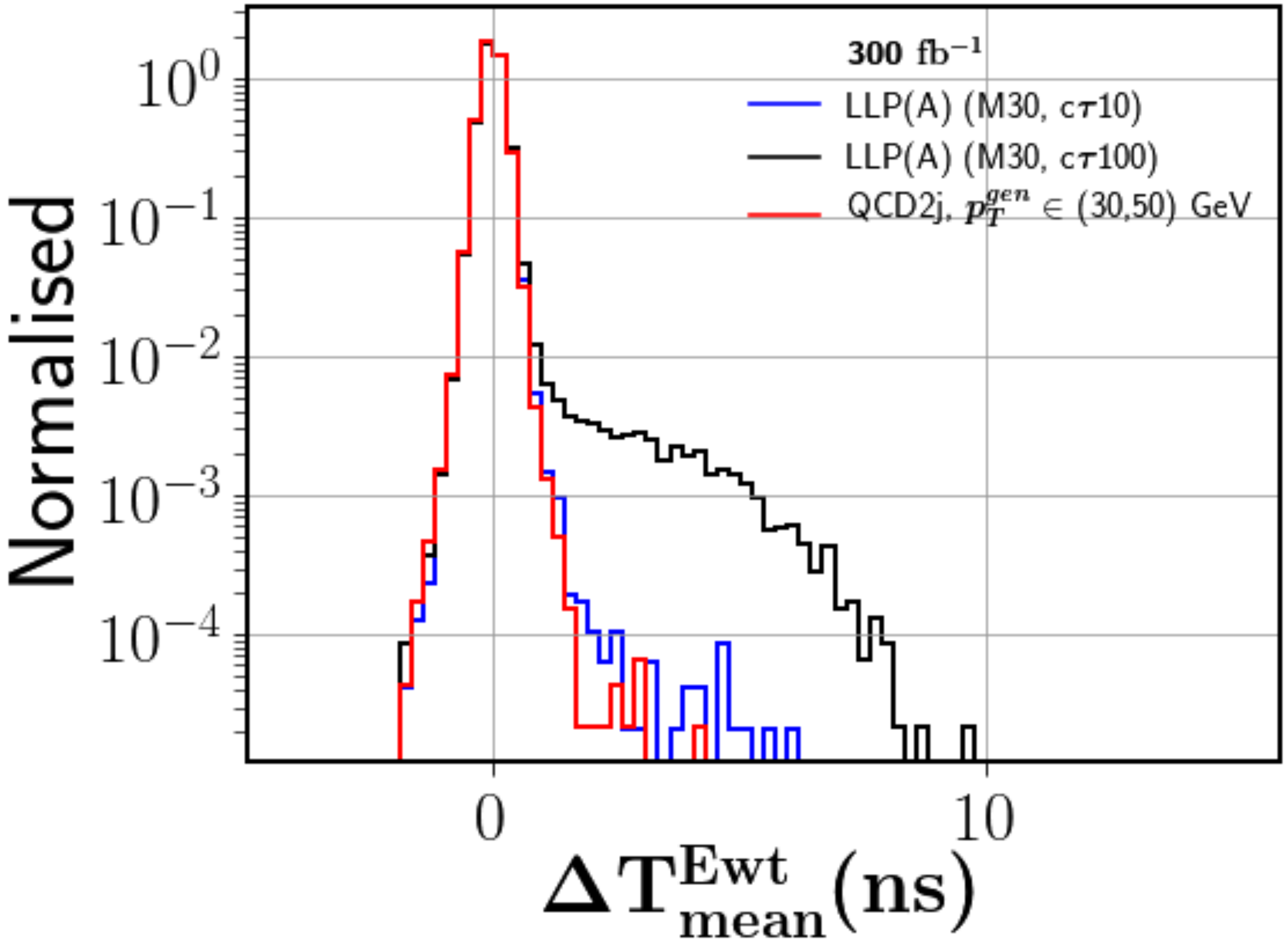
ECAL Timing



ECAL Timing

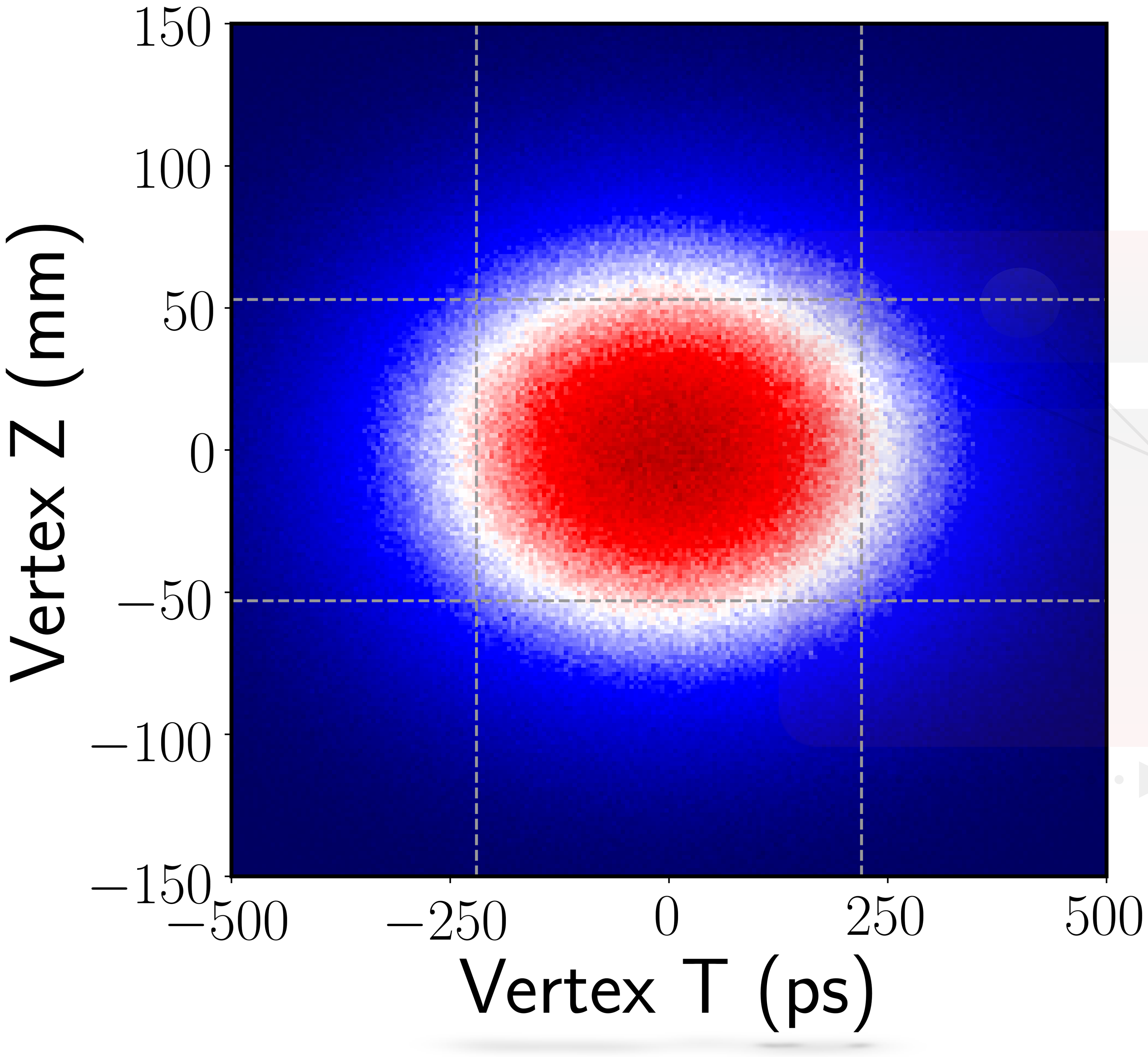


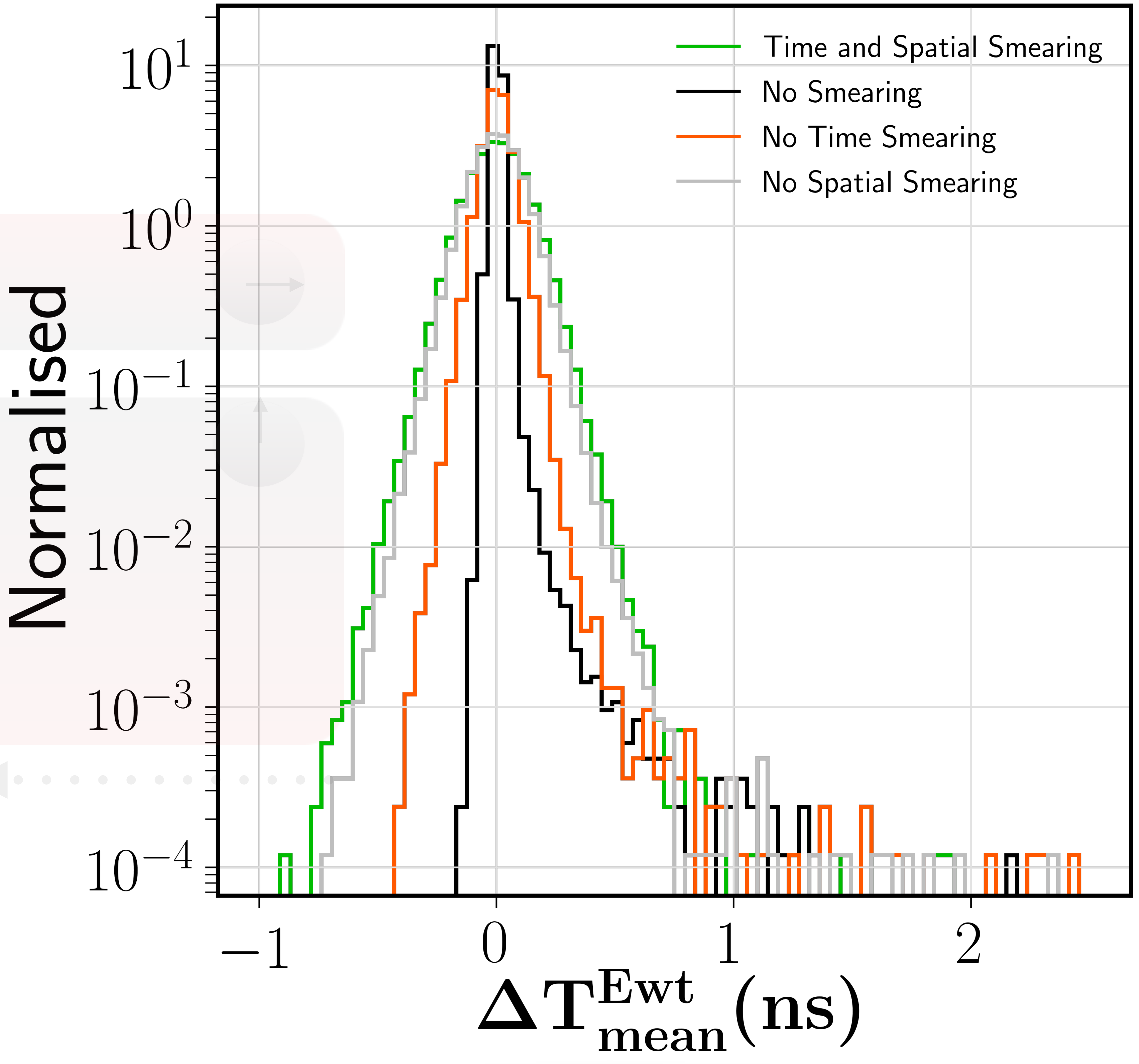
ϕ
30 ps
η



300 fb^{-1}
LLP(A) (M30, cτ10)
LLP(A) (M30, cτ100)
QCD2j, $p_T^{gen} \in$ (30,50) GeV
Normalised
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0
10
ΔT^{Ewt}_{mean}(ns)

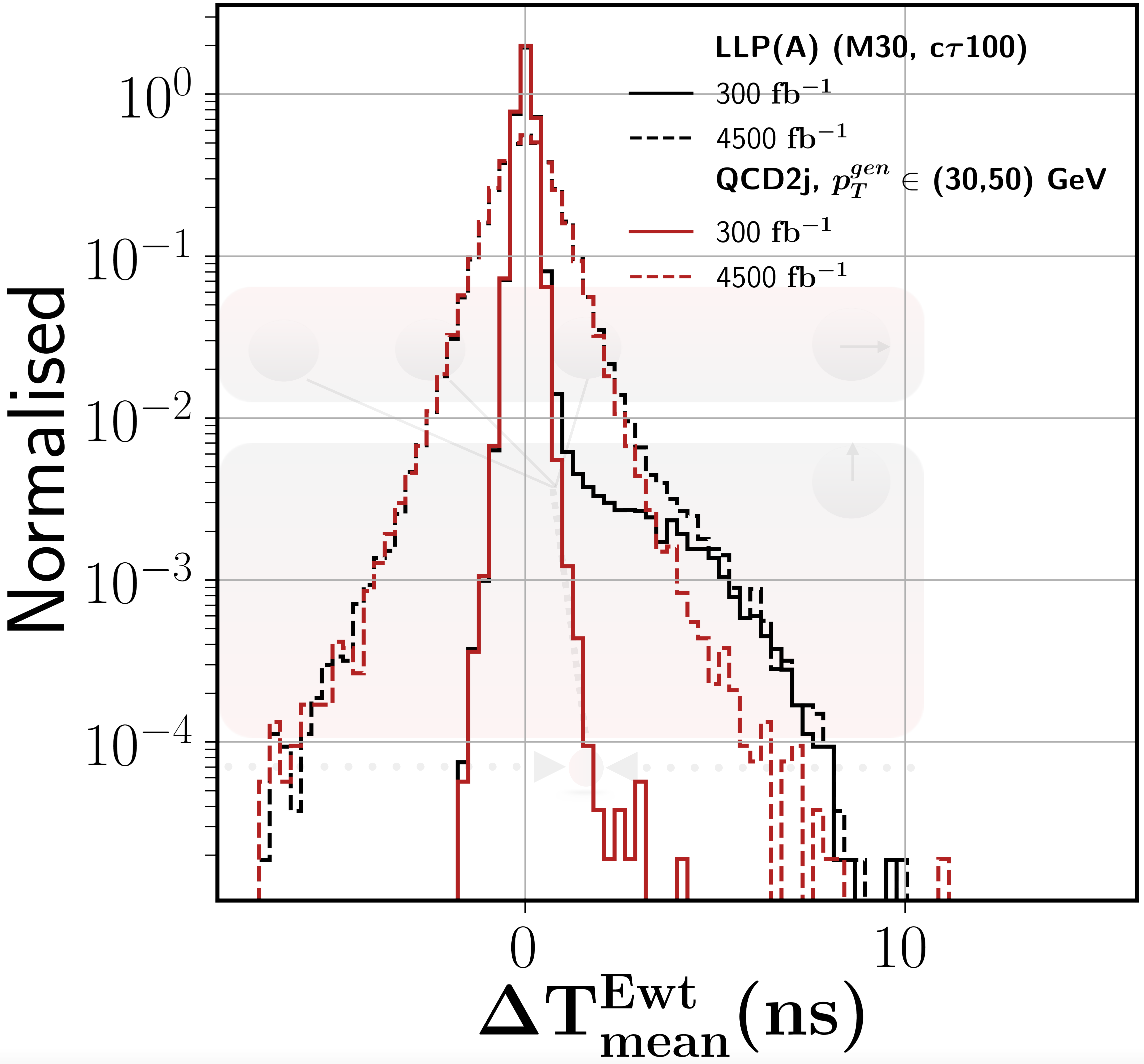
Beamspot





Timing of jets will dominated by the beamspot spread in t-z plane.

Timing resolution



ECAL Timing resolution will degrade over time as we collect more and more data.

Background rate

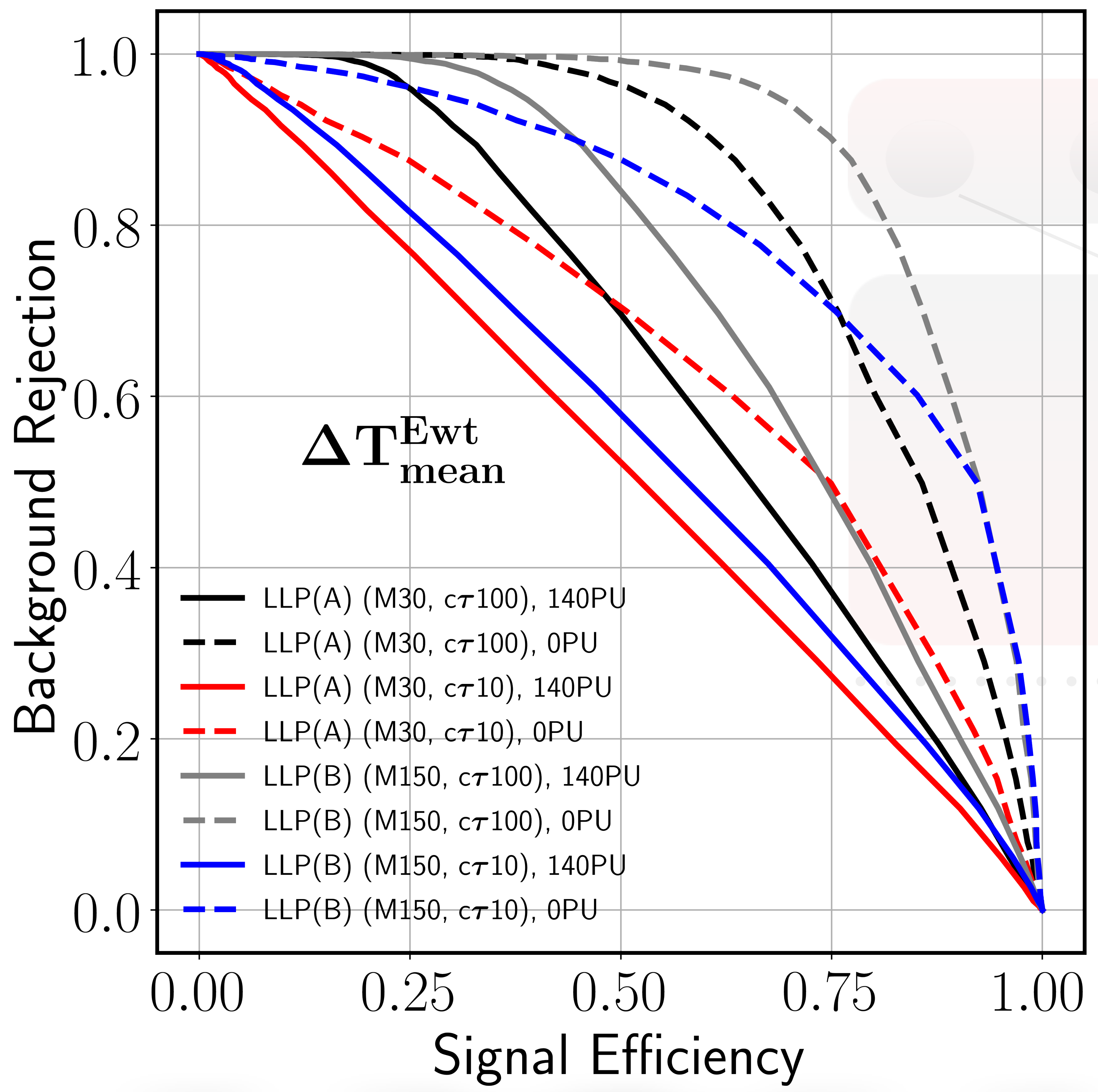
Background event rate can be calculated as: $\mathscr{R}_B = \sigma(\text{nb}) \times \mathscr{L}(\text{nb}^{-1}\text{s}^{-1}) \times \epsilon_b$

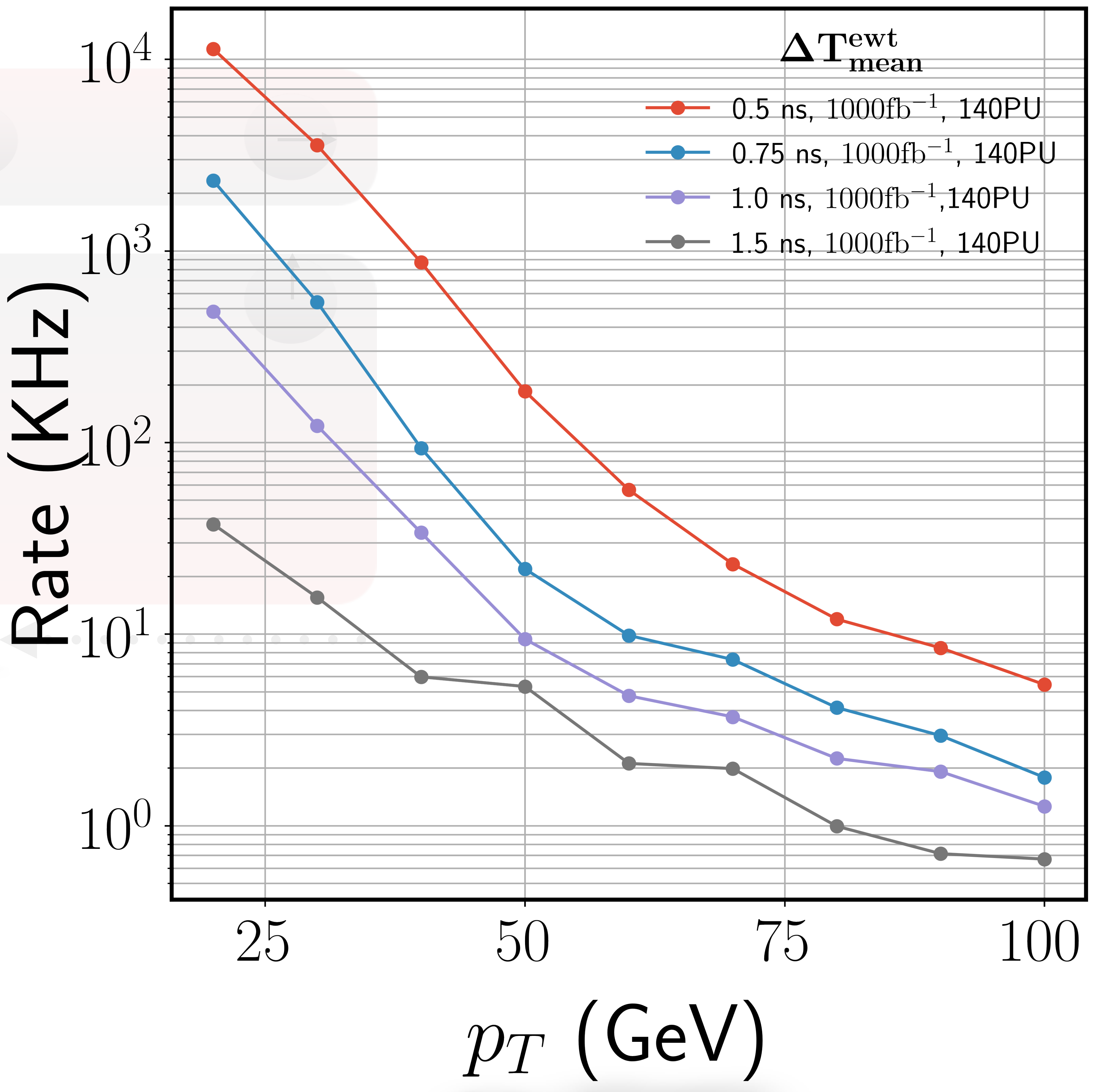
For displaced L1 triggers, we have fixed trigger rate not to exceed ~30 KHz.

For more accurate calculation of background rate, look at: Stitching Monte Carlo samples by Karl Ehataht and Christian Veelken, 2106.04360.

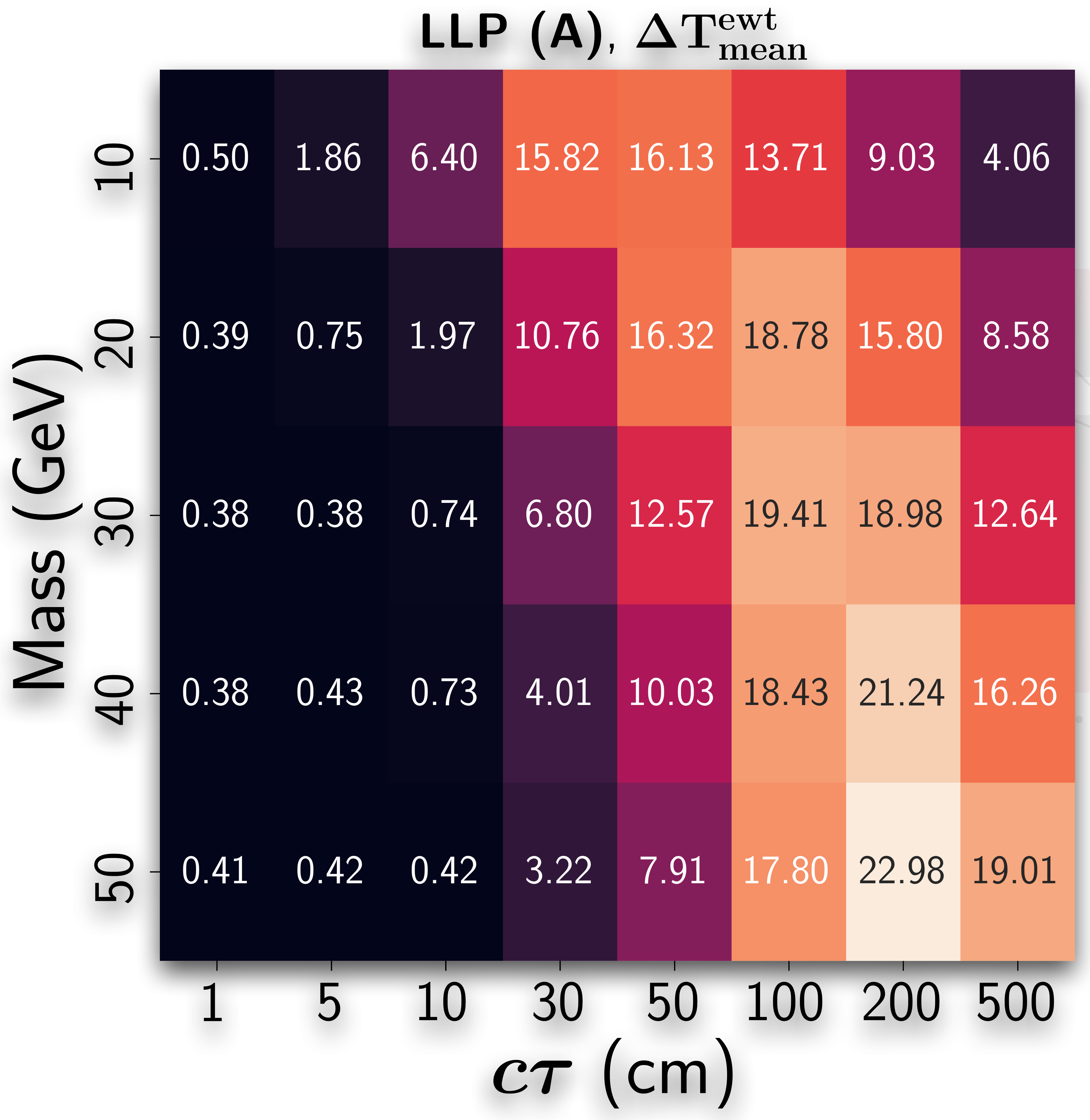
Timing variables and background rate

$$\Delta T_{mean}, \Delta T_{median}, \Delta T_{RMS}, \Delta T^{Ewt}_{mean}, \Delta T^{ETwt}_{mean}, \Delta T^{Max5}_{mean}, (\Delta T \times E)^{Max5}_{mean}, \Delta T^{Max10}_{mean}, (\Delta T \times E)^{Max10}_{mean}, \sum \Delta T$$





Signal efficiency

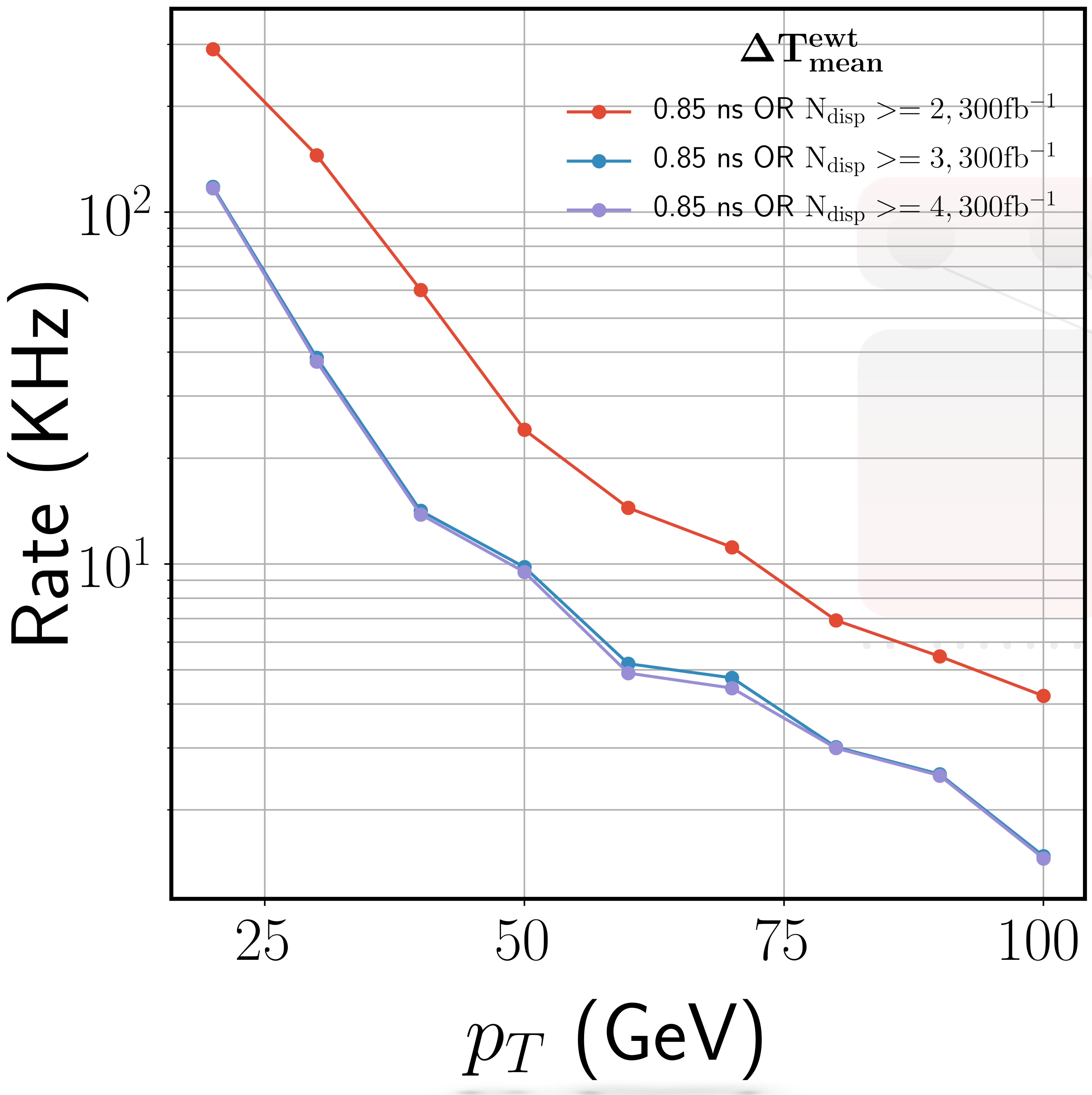


$\mathrm{Br}(h \to XX) \lesssim 6.2 \times 10^{-6}$ for $M_X = 10\,\mathrm{GeV}$, $c\tau = 50\,\mathrm{cm}$

$\mathrm{Br}(h \to XX) \lesssim 5.1 \times 10^{-6}$ for $M_X = 30\,\mathrm{GeV}$, $c\tau = 100\,\mathrm{cm}$

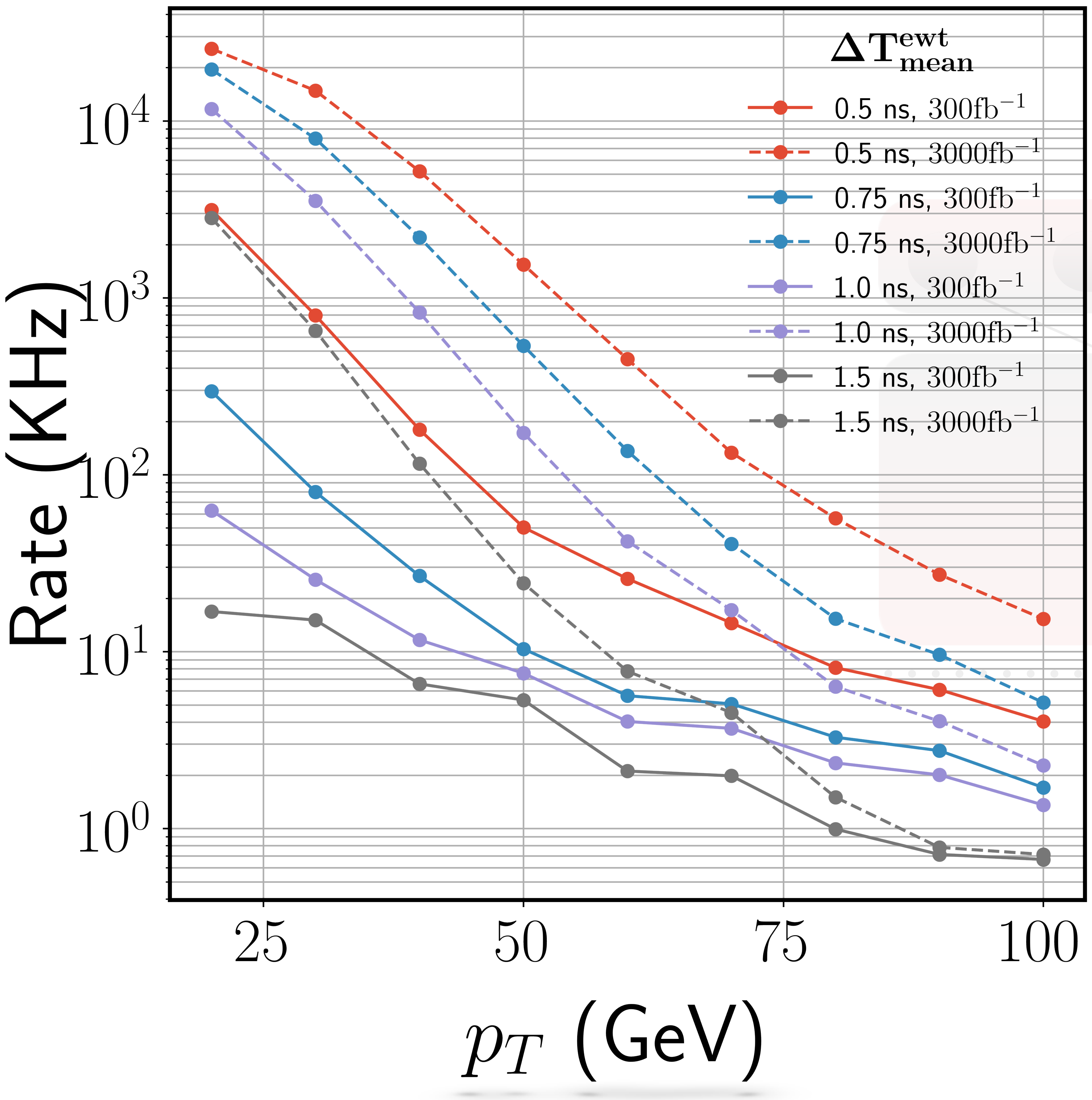
$\mathrm{Br}(h \to XX) \lesssim 4.3 \times 10^{-6}$ for $M_X = 50\,\mathrm{GeV}$, $c\tau = 200\,\mathrm{cm}$

Inclusion of displaced tracks information



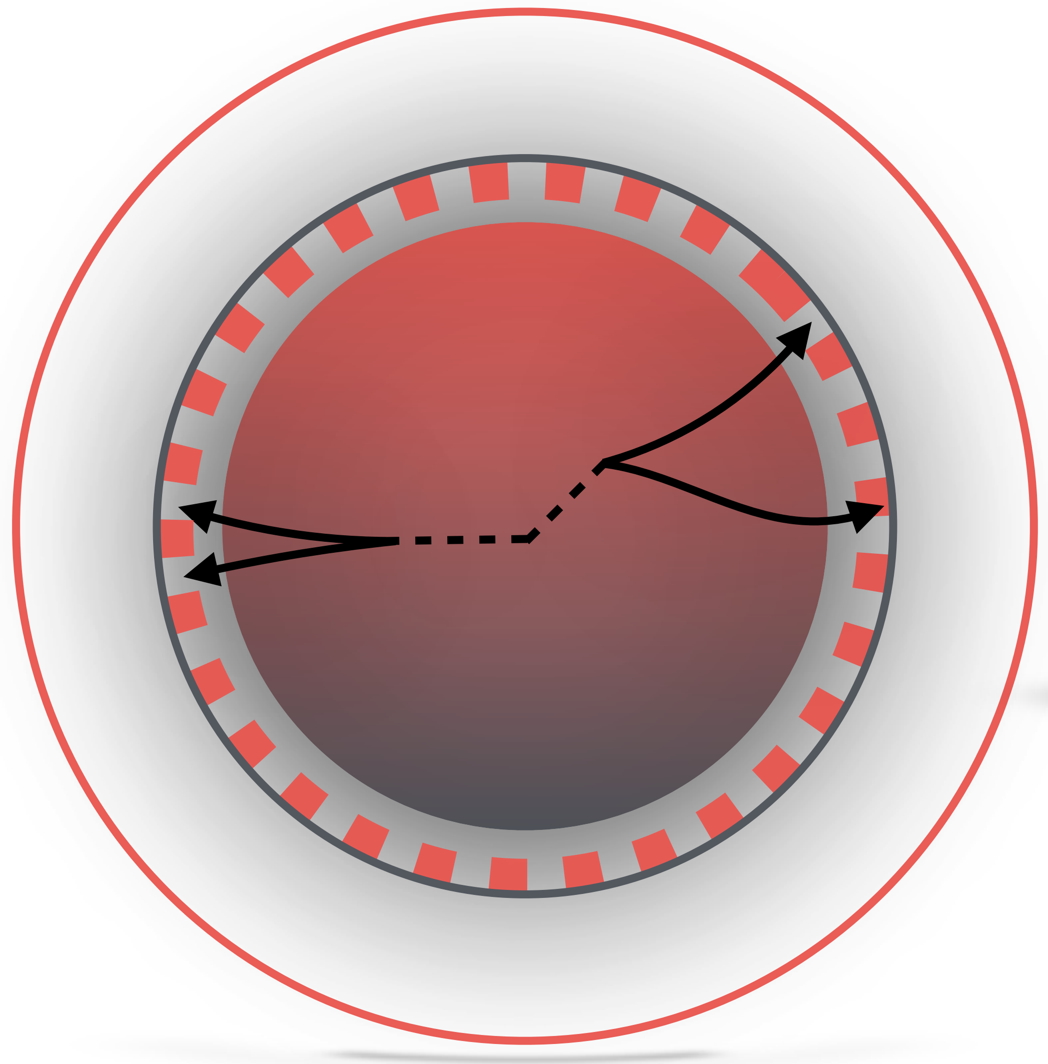
Improves signal efficiency for LLPs with smaller decay length by a factor of 6

Early runs



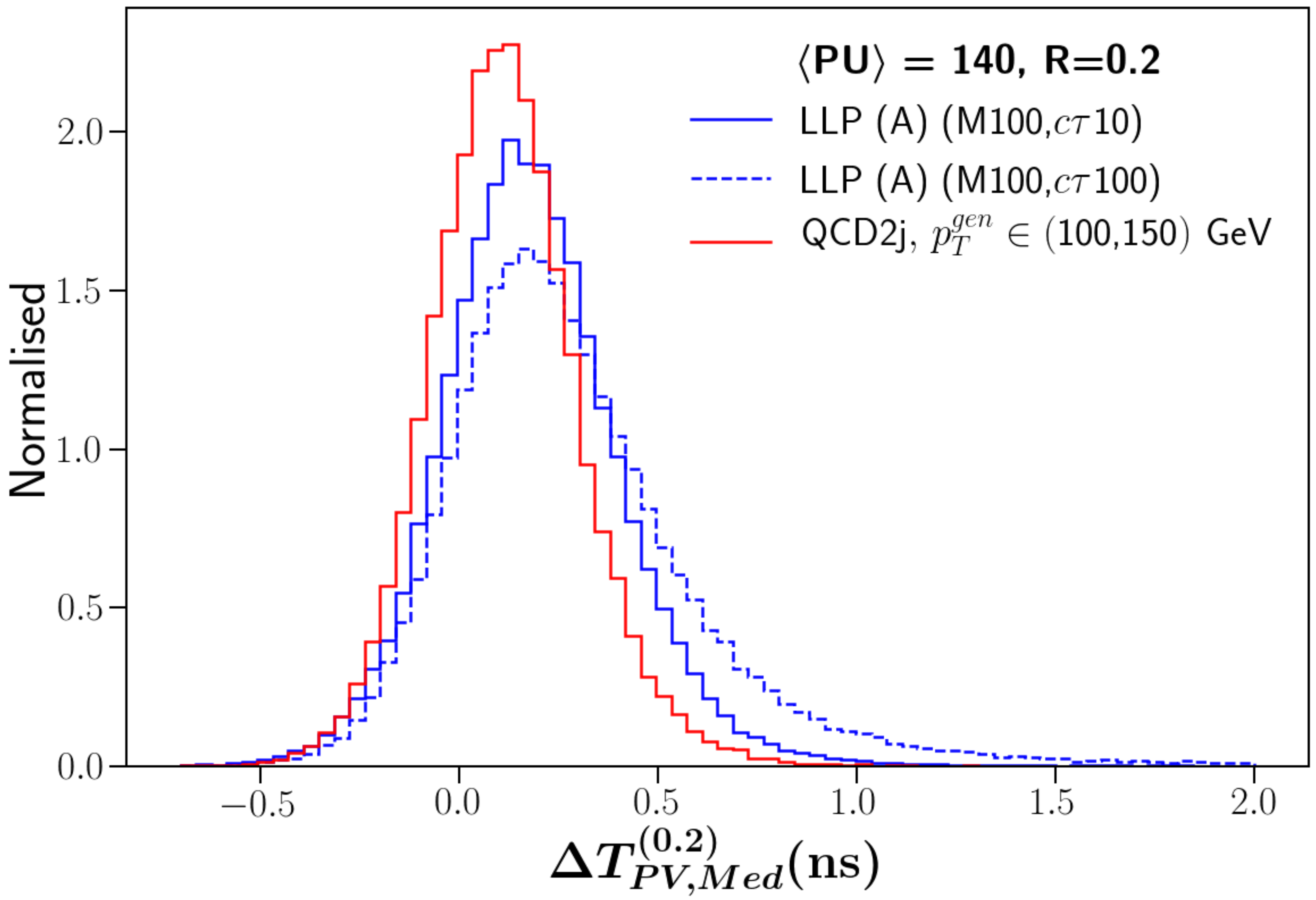
Early runs at HL-LHC might be crucial in search of LLPs using timing information

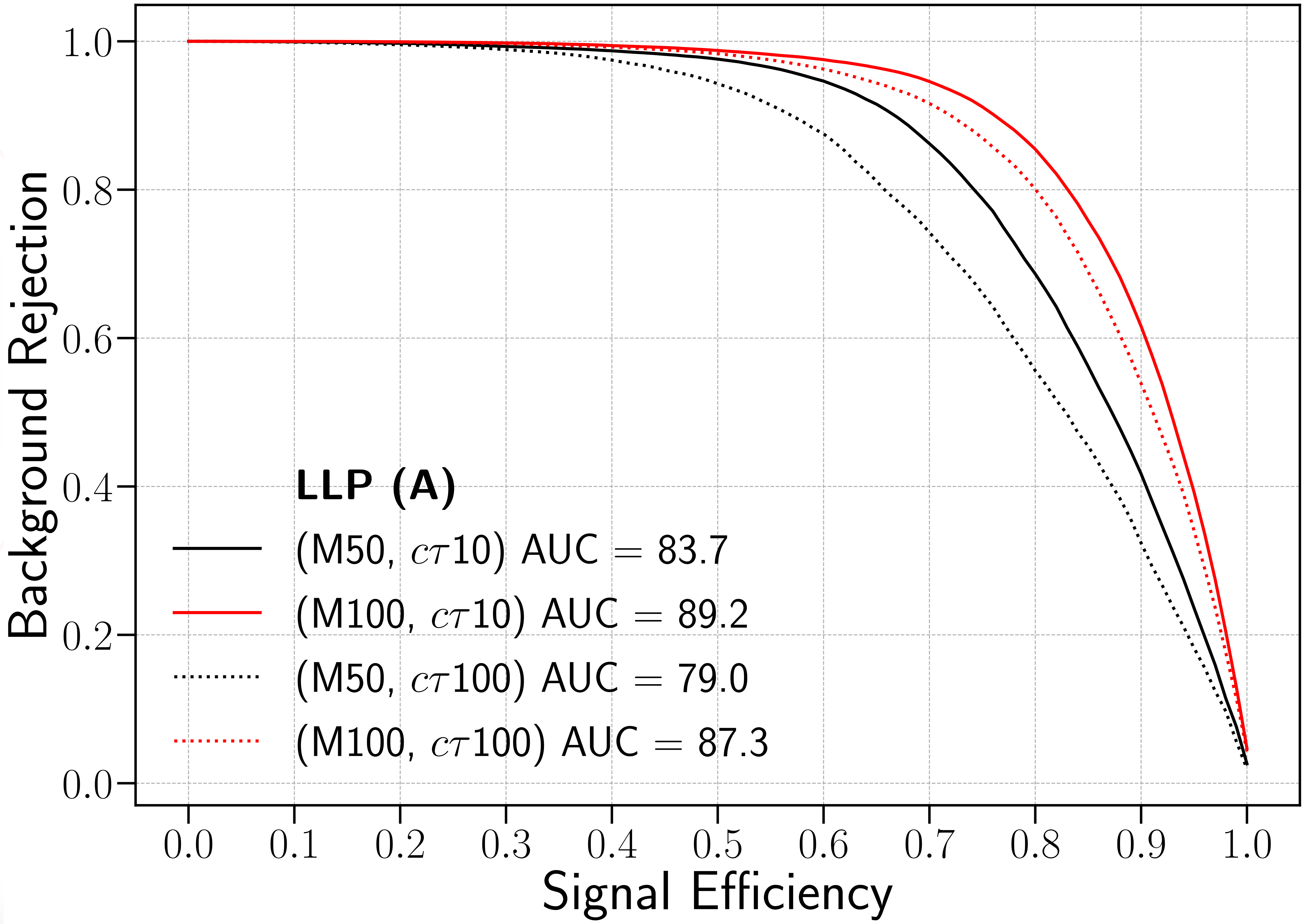
MTD



MTD

$N_{MTD}^{(0.2)}, T_{Med}^{(0.2)}, \Delta T_{Med,PV}^{(0.2)}, N_{MTD}^{(0.2),NT}, \Delta T_{Med,PV}^{(0.2),NT}$





Similar performance as the trackless jet trigger.

Summary

- At HL-LHC, high PU will have adverse effect on the timing of the displaced jets. Effect of the PU can be reduced by considering "**narrow jets**".
- BDT based triggers constructed using tracking and timing variables can select LLP events efficiently keeping background rate within permission range.
- Timing resolution will play a very important role constructing triggers based on L1 ECAL timing.
- We find two efficient timing variables to be used at L1 for constructing timing of the jet using ECAL inputs which are more PU resistant.
- Background rate coming from QCD jets is accurately calculated using "**stitching method**".
- Signal efficiency for three LLP scenarios with various mass and decay length is calculated keeping background rate under 30 KHz.
- Timing based triggers will work best during initial runs of HL-LHC when ECAL has better timing resolution.
- Performance of timing based triggers can be improved by including displaced track information where both will compliment each other.

For detailed study, kindly have a look at:

- Triggering long-lived particles in HL-LHC and the challenges in the first stage of the trigger system, B. Bhattacherjee, S. Mukherjee, R. Sengupta, P. Solanki, *JHEP* 08 (2020) 141
- Dedicated Triggers for Displaced Jets using Timing Information from Electromagnetic Calorimeter at HL-LHC, B. Bhattacherjee, T. Ghosh, R.Sengupta, P. Solanki, *JHEP* 08 (2022) 254