Long-lived particles at present and future circular colliders

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Long-Lived Particles

Particles with suppressed decay widths $\Rightarrow$ long lifetimes

$c\tau \gtrsim \mathcal{O}(\text{mm})$
$\tau \gtrsim \mathcal{O}(10\,\text{ps})$

Small couplings

e.g., c and b quarks (SM)

RPV SUSY (BSM)

Heavy scales, $\Gamma \sim \dfrac{m^5}{M^4}$

e.g., muon (SM)

gluino in Split-SUSY (BSM)

Kinematic squeezing

e.g., neutron (SM)

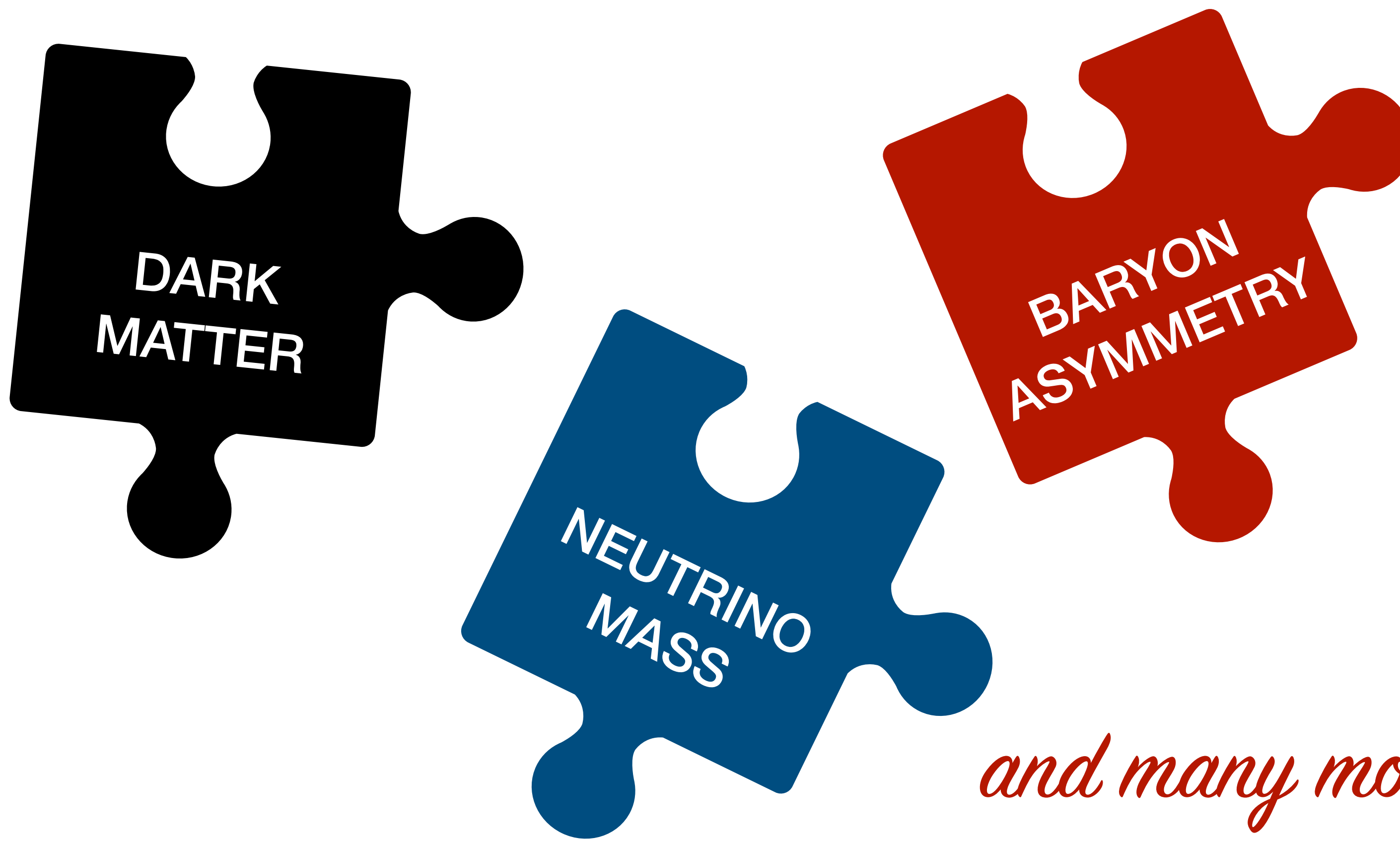
compressed SUSY scenarios (BSM)

LLP White Paper: arXiv:1903.04497

Why LLPs?

Standard Model of particle physics (**SM**) *successfully explains many fundamental phenomena of particles*

Still many pieces **missing from the SM**, like



and many more...

We need to look beyond the SM (BSM)

Experiments provide exhaustive bounds on where new physics cannot be and precise measurements of the SM

Where is new physics?

Experiments are putting **stronger constraints on the nature of new physics, especially for the conventional scenarios**

1

New physics appears at a scale beyond LHC or HL-LHC's reach

Extend mass reach by increasing centre of mass energy or with higher precision

2

Scale is within LHC's reach, but the process is very rare or have large backgrounds

Increase luminosity or more sophisticated analyses to reduce backgrounds

3

Their signatures are so unusual that they are overlooked in the present searches

More inclusive or smarter trigger and search strategies

Where is new physics?

3

Their signatures are so unusual that they are overlooked in the present searches

More inclusive or smarter trigger and search strategies

Are we covering the full phase-space of new physics? Or are we missing something?

What if we have long-lived BSM particles?

LLP

Credit: Gemini

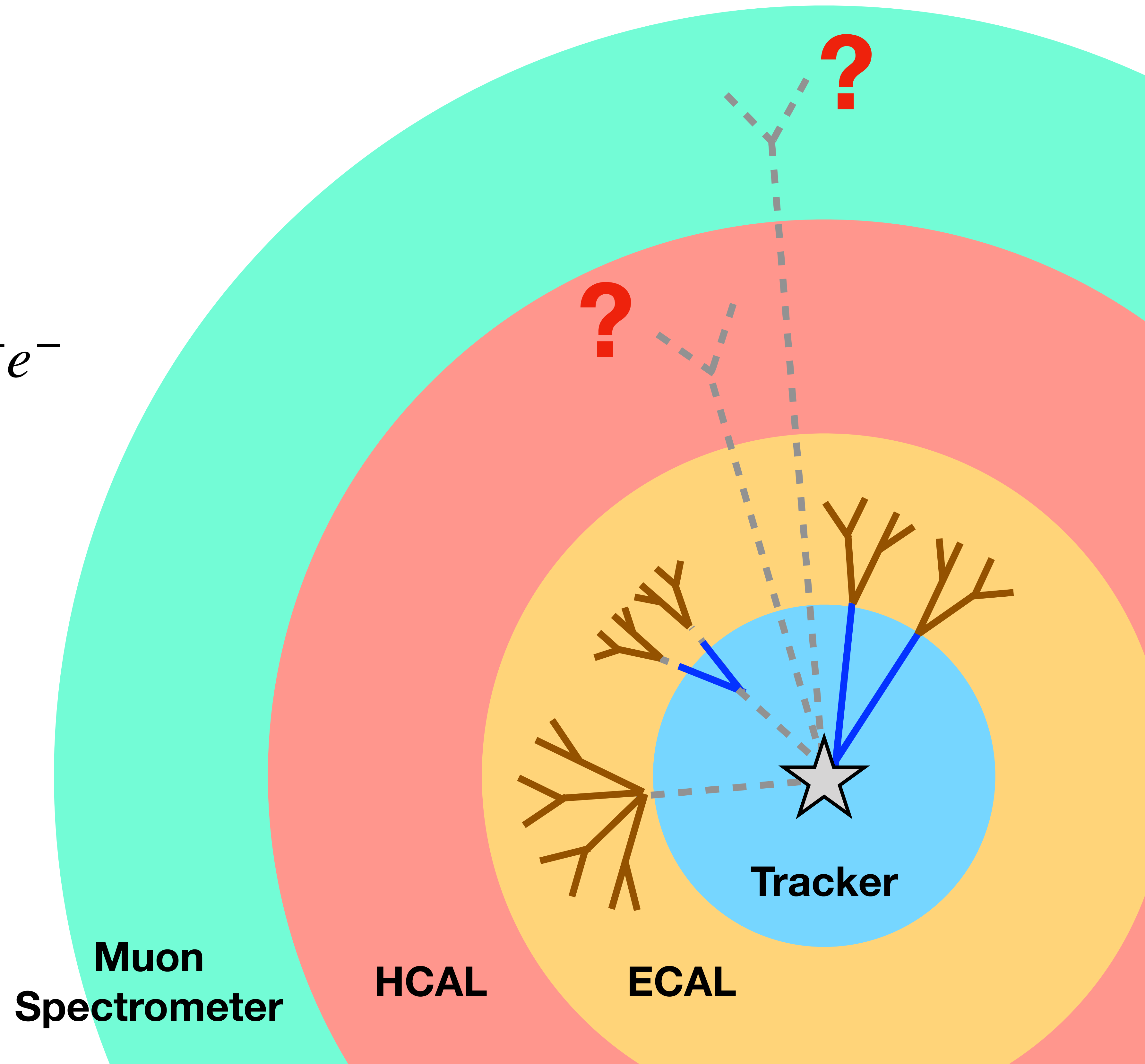
Both theoretically motivated and experimentally interesting!

LLPs and their unusual signatures...

depends on

- what it decays into
- where it decays

For e.g., say, $X \rightarrow e^{+}e^{-}$



LLPs and their unusual signatures...

depends on

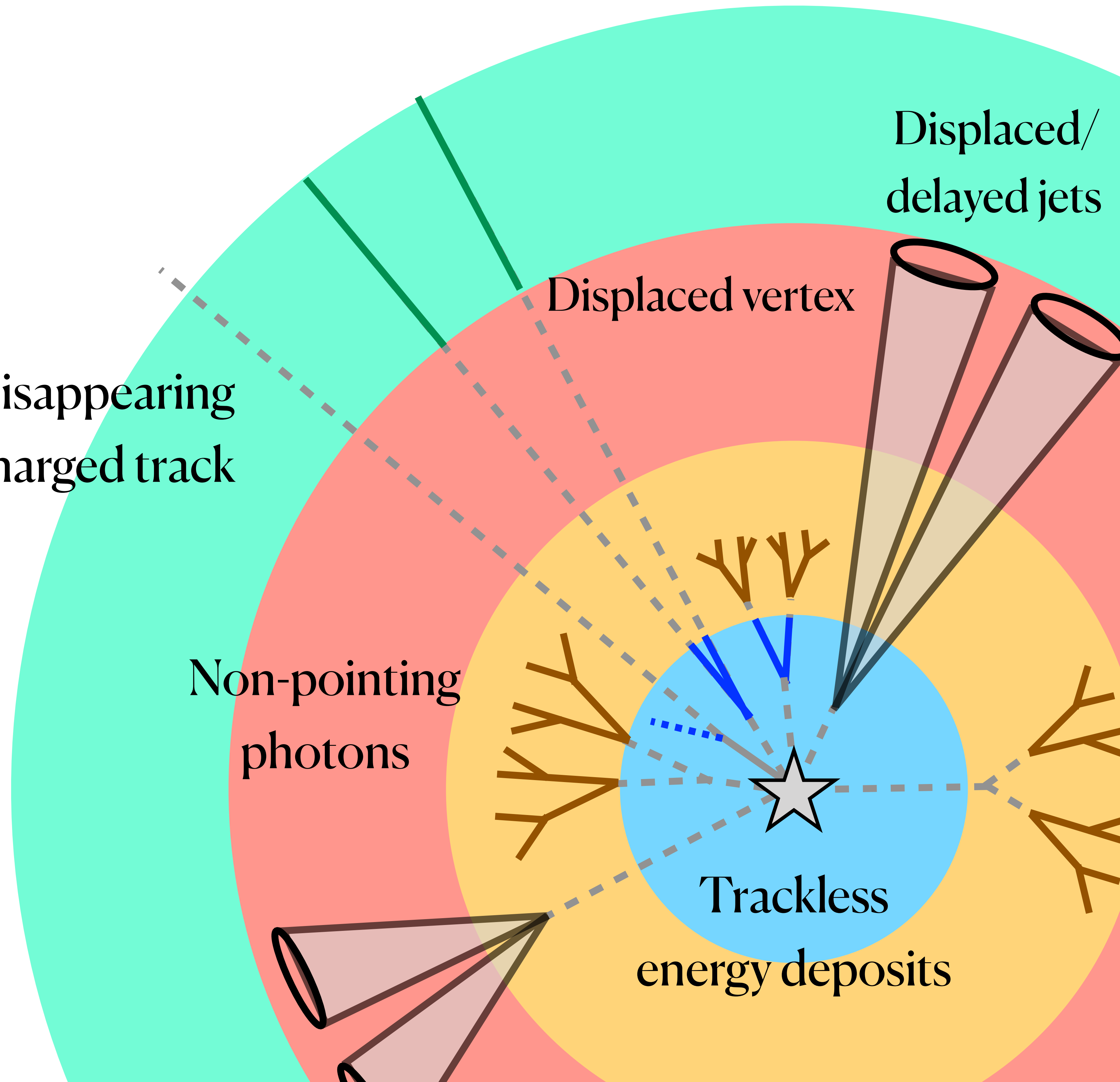
- what it decays into
- where it decays

Displaced leptons

Disappearing charged track

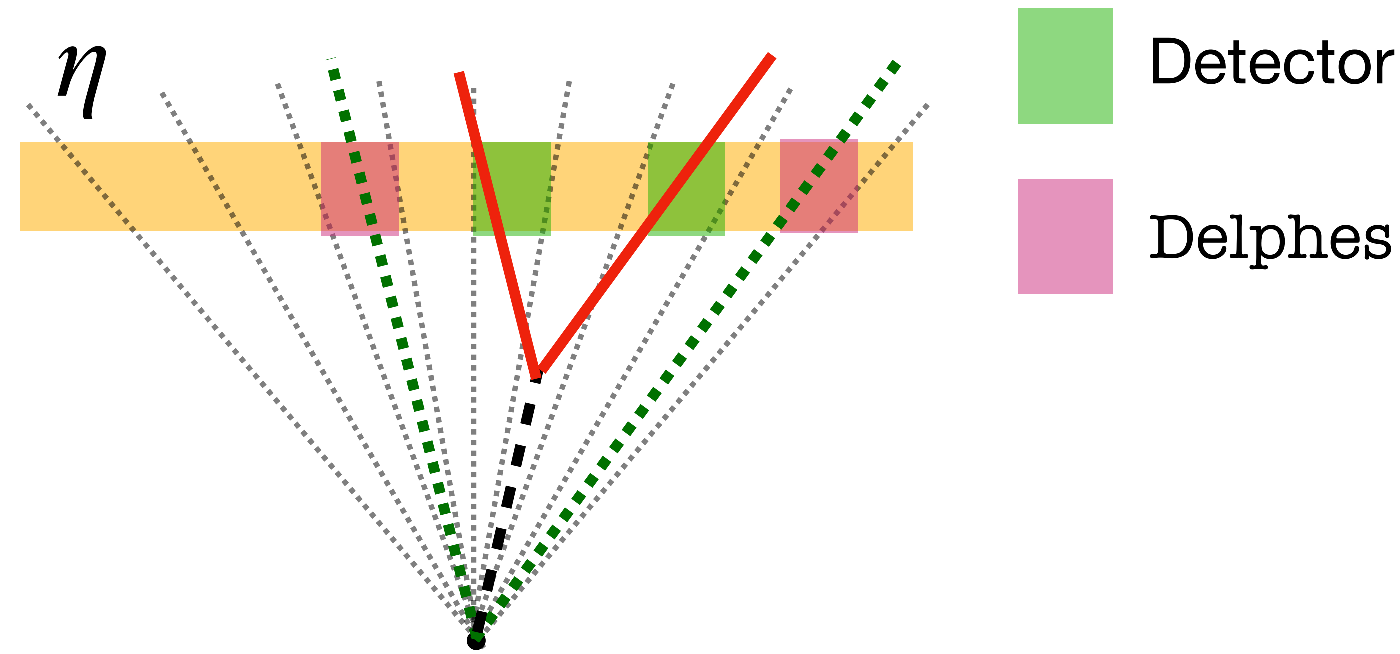
HSCP track, large $\frac{dE}{dx}$

Muon Spectrometer clusters

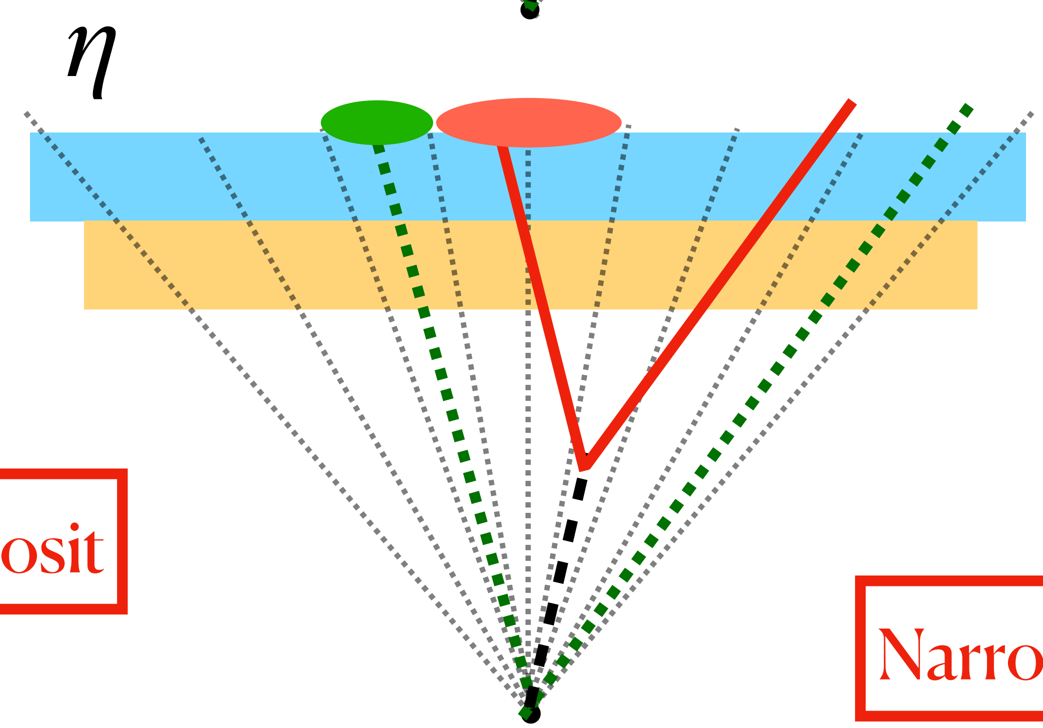


Pattern of energy deposits *unusual signatures contd.*

Mismatch of displaced particle's η-ϕ direction with η-ϕ segmentation of the detector

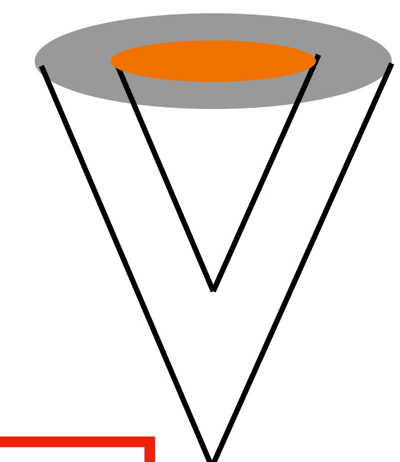


To understand the mismatch, layered structure/ depth segmentation needed



Absent in fast detector simulations (eg. **Delphes**)

Elongated energy deposit



Narrow jets

Can be used to discriminate from prompt jets using CNN

B. Bhattacherjee, S. Mukherjee, RS, JHEP 11 (2019) 156

Non-pointing photon search by CMS/ATLAS Collaborations

CNN for identifying long-lived particles in HGCAL

J. Alimena, Y. Iiyama and J. Kieseler, JINST 15 (2020) 12, P12006

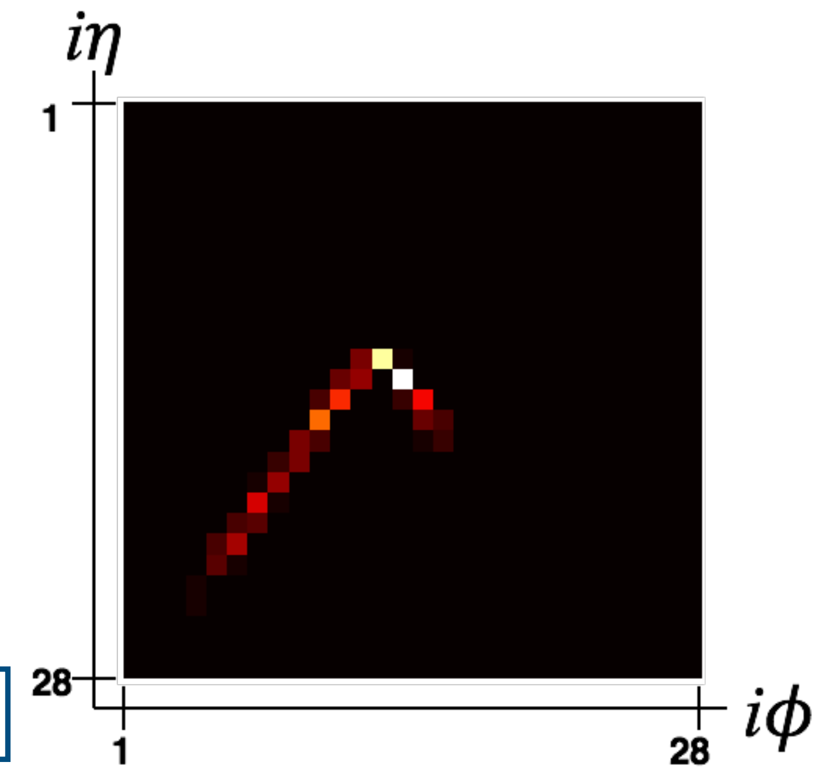
Stopped *R*-hadrons

unusual signatures contd.

- $\Gamma_{\tilde{g}} < \Lambda_{QCD} \Rightarrow$ hadronizes before decaying "***R*-hadrons**"
- loses energy via ionization while traversing the detector $\Rightarrow$ **stops before decaying**

Decays at rest $\Rightarrow$ maximal mismatch of η-ϕ

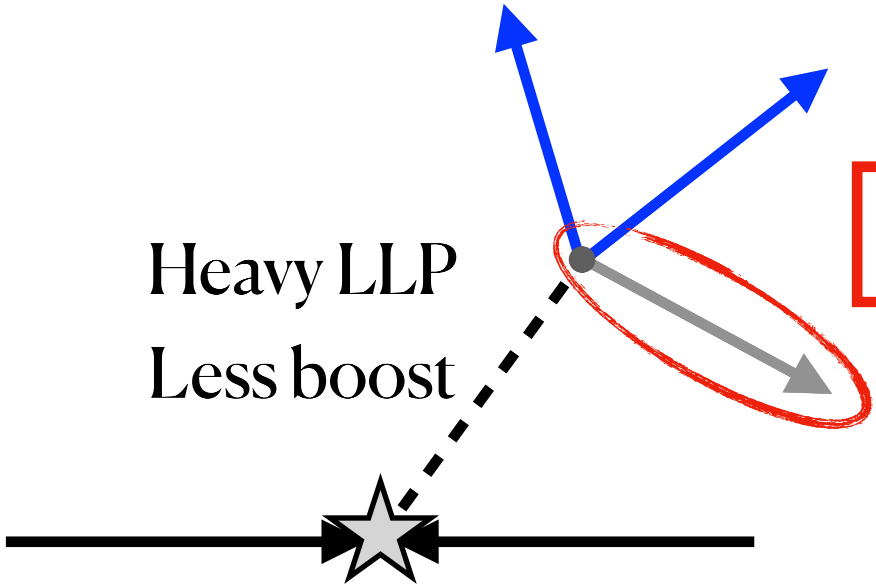
B. Bhattacherjee, S. Mukherjee, RS, JHEP 11 (2019) 156



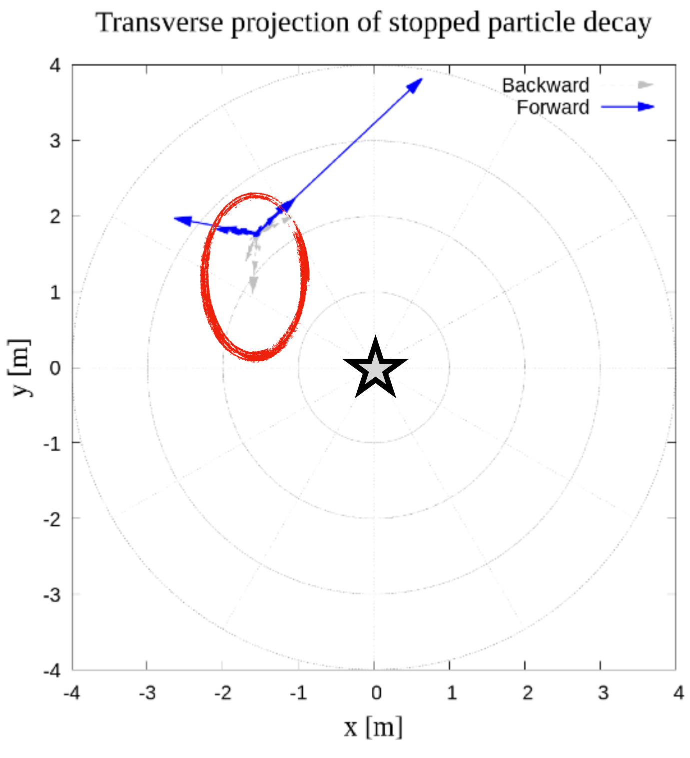
Backward moving particles

unusual signatures contd.

S. Banerjee, G. Bélanger, B. Bhattacherjee, F. Boudjema, R. M. Godbole, and S. Mukherjee, PRD 98, 115026 (2019)



Backward moving particles



General difficulties in LLP searches

SM background - mostly prompt - difficult to
mimic the exotic signatures of LLPs

- SM long-lived particles like b-hadrons, c-hadrons, K_S, K_L or Λ
  Difficult for BSM scenarios having similar mass range and final states

- Real Particles Produced via Interactions with the Detector
  Material maps

- Real Particles Originating from Outside the Detector
  Cosmic muons

- Fake signatures

  Detector noise
  Randomly merged vertices
  random tracks crossing each other

- Detector simulation of unusual signatures not phenomenologically straightforward

Chances to miss real signal unless carefully searched
Proper triggering required

Non-standard and unusual backgrounds
Simulation very technical

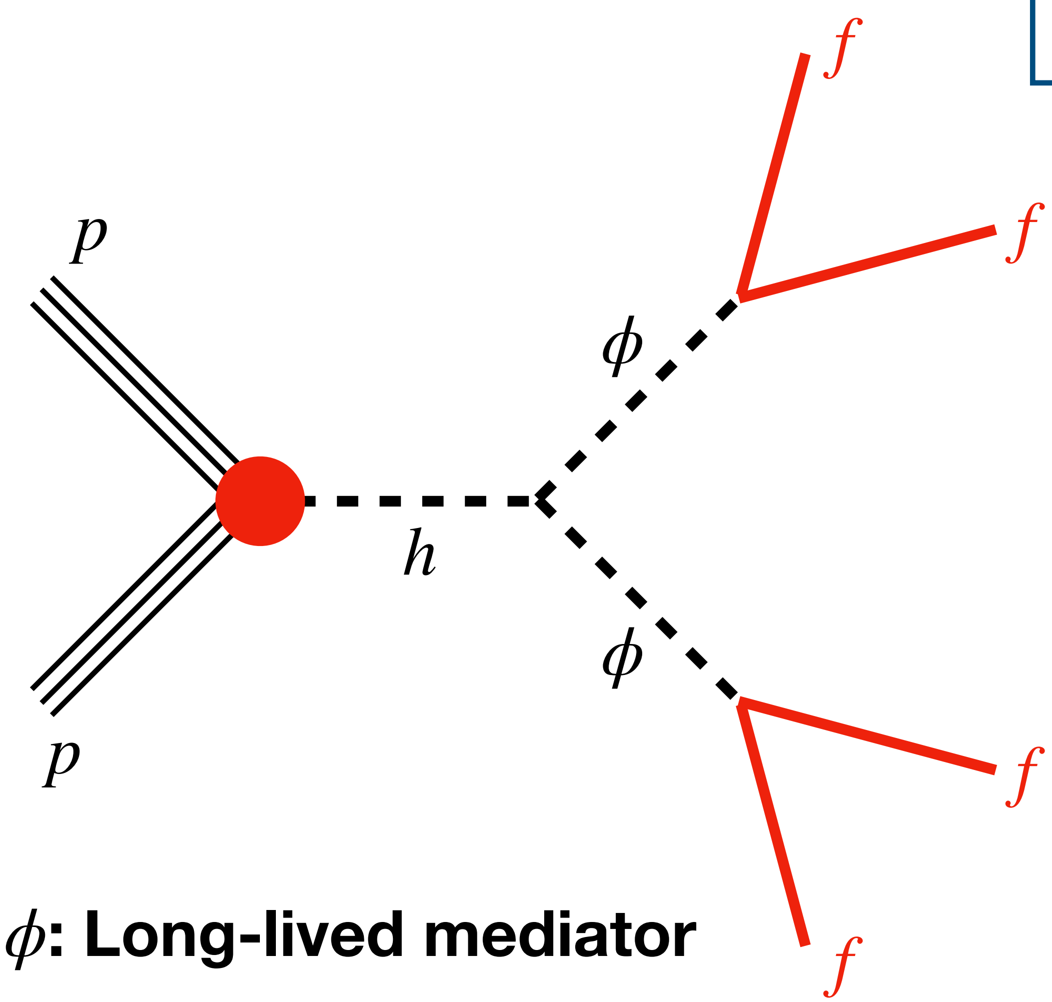
Long-Lived Particles: an example

$$\mathcal{L} \subset -m_\phi^2\phi^2 - \sin\theta\,\frac{m_f}{v}\phi\bar{f}f - \lambda_{h\phi\phi}\,h\phi\phi + \ldots$$

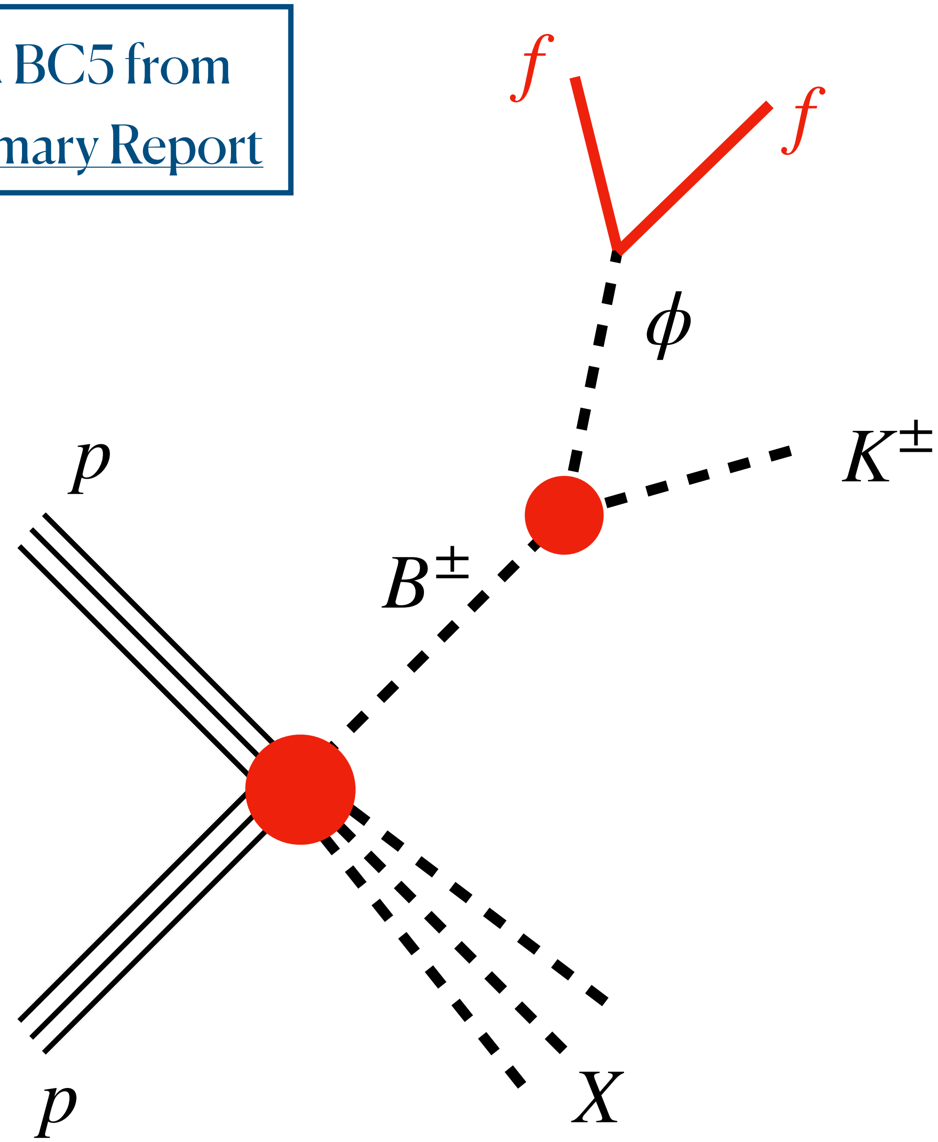
Mixing highly constrained

Not severely constrained so far

BC4 and BC5 from PBC Summary Report



ϕ: **Long-lived mediator**



Outline

- Dedicated triggers
- Leveraging Pile-up
- Searches in the Muon Spectrometer
- Role of FCC-ee
- Upgrading ZDCs for LLPs
- Optimised dedicated LLP detectors

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- ❑ **Dedicated triggers**
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- ❑ Optimised dedicated LLP detectors

Triggering: What, Why, How?

Selecting interesting events from the many *pp* interactions and storing them for further analysis

pp collisions rate at LHC: 40 MHz, event size ~ 1 MB ⇒ 40000 GB/sec

Not feasible

40 MHz

Level-1 trigger

- Need to be quick
- Detector read at course granularity
- Tracker information not available till Run-3

100 kHz

High Level Trigger (HLT)

- More time available - not as much as offline
- Full detector read at full granularity
- Full event information stored for offline analyses

1 kHz

Stored for offline analyses

1kHz x 1 MB ~ 1 GB/sec

Dedicated L1 Triggers important for LLPs

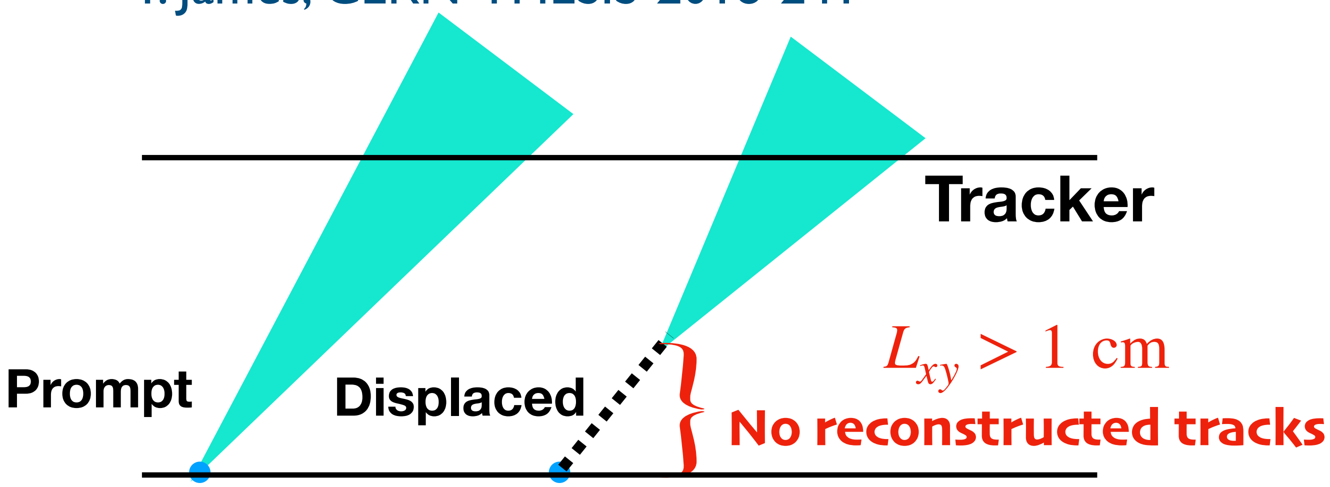
L1 Tracking

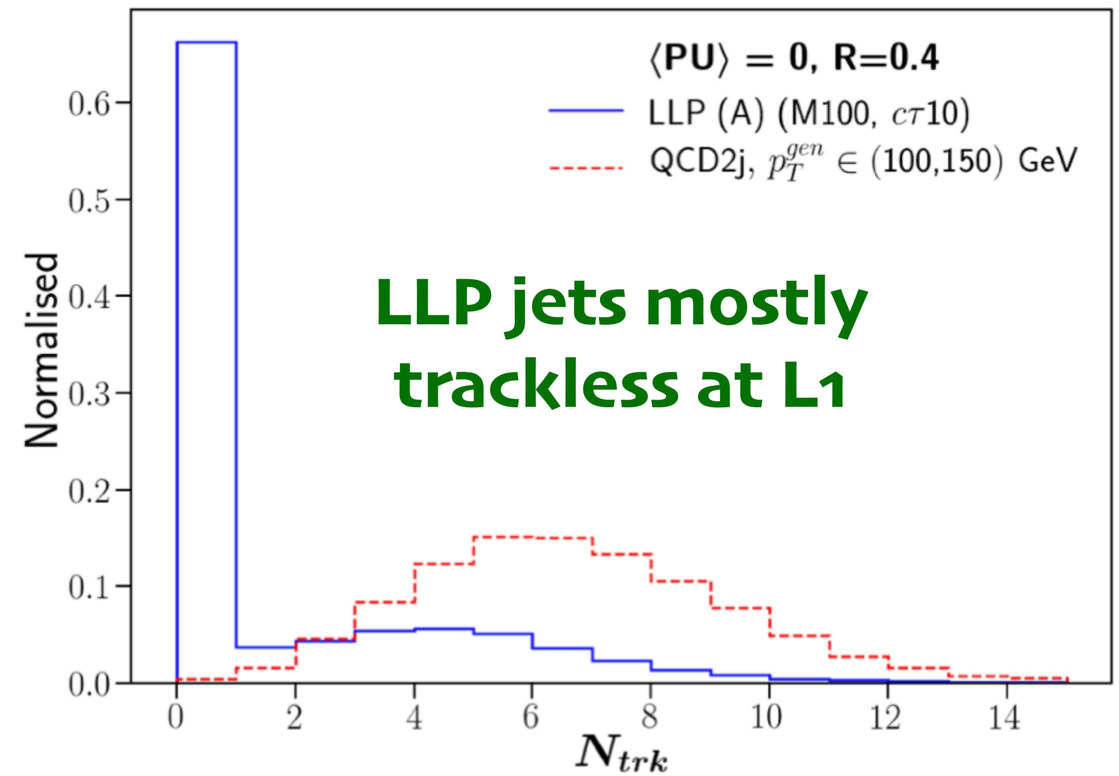
Dedicated triggers contd.

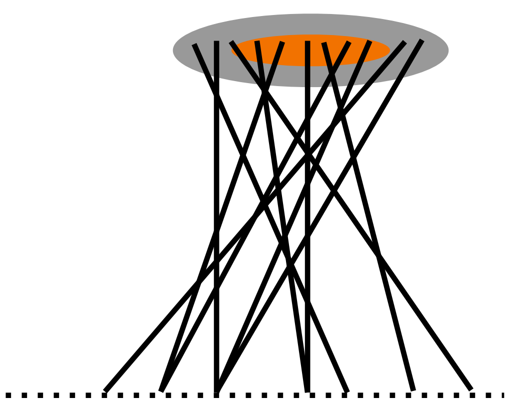
L1 track:

$p_T > 2$ GeV, $|\eta| < 2.5$,
$L_{xy} < 1$ cm, $|z_0| < 30$ cm

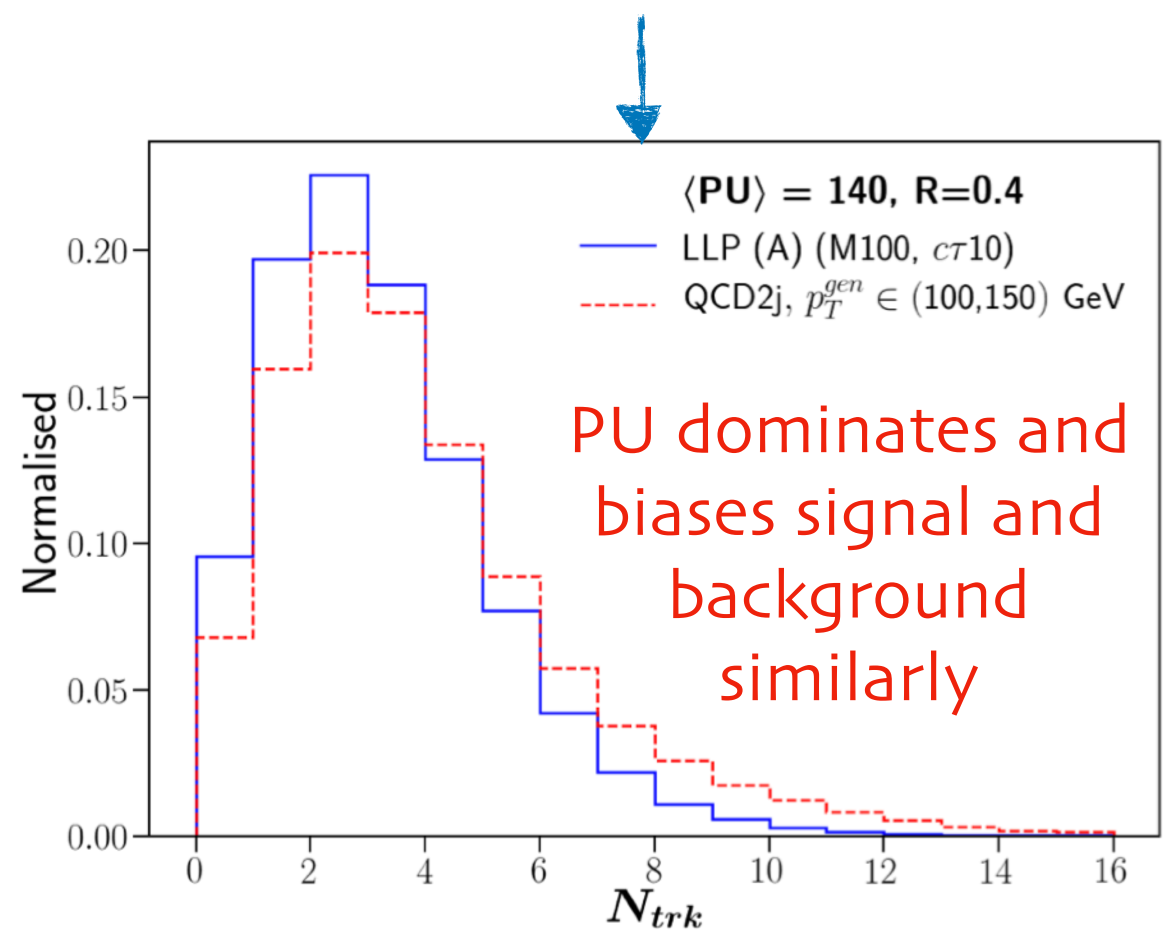
T. James, CERN-THESIS-2018-241

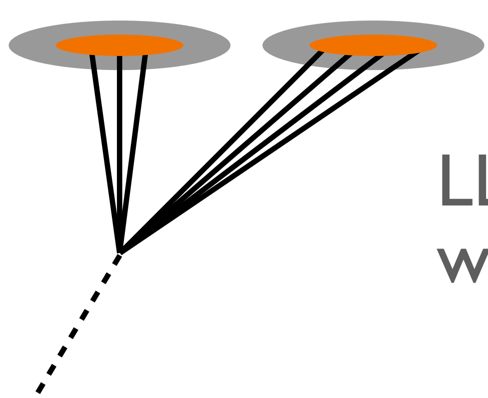






PU contribution, being more uniform, reduces with reduced cone-size





LLP signals not affected with reduced cone-size

L1 Tracking

Dedicated triggers contd.

<u>L1 track:</u>

$p_T > 2$ GeV, $|\eta| < 2.5$,
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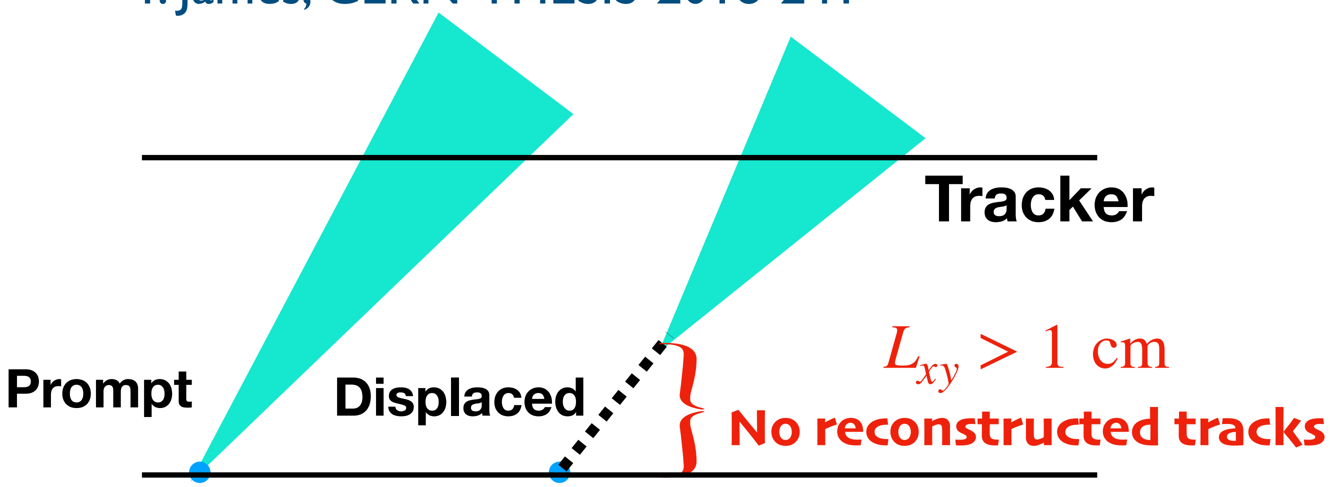
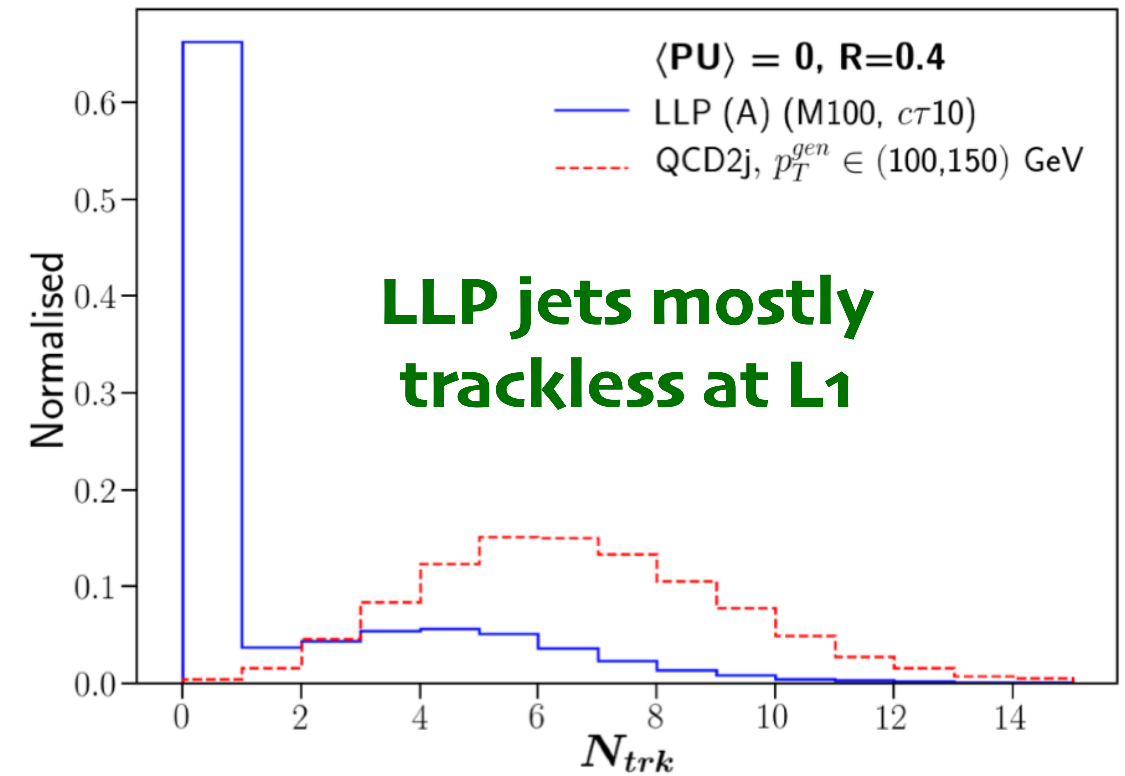
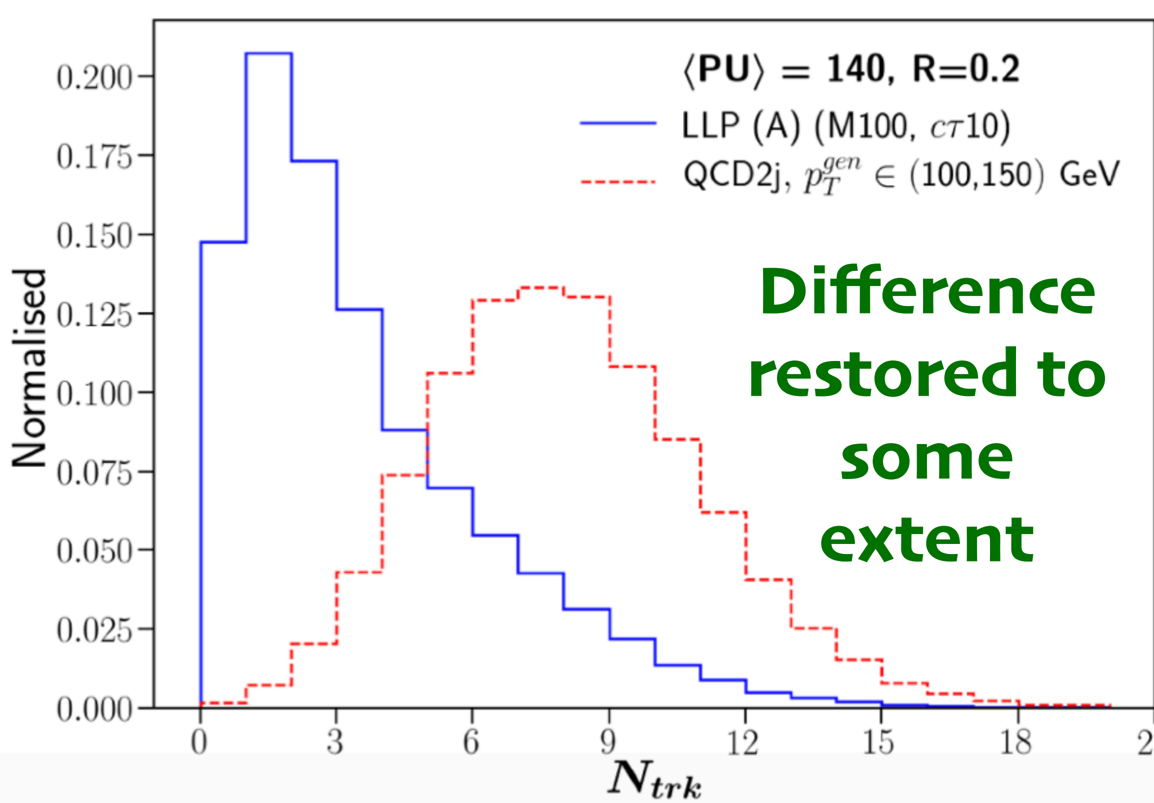
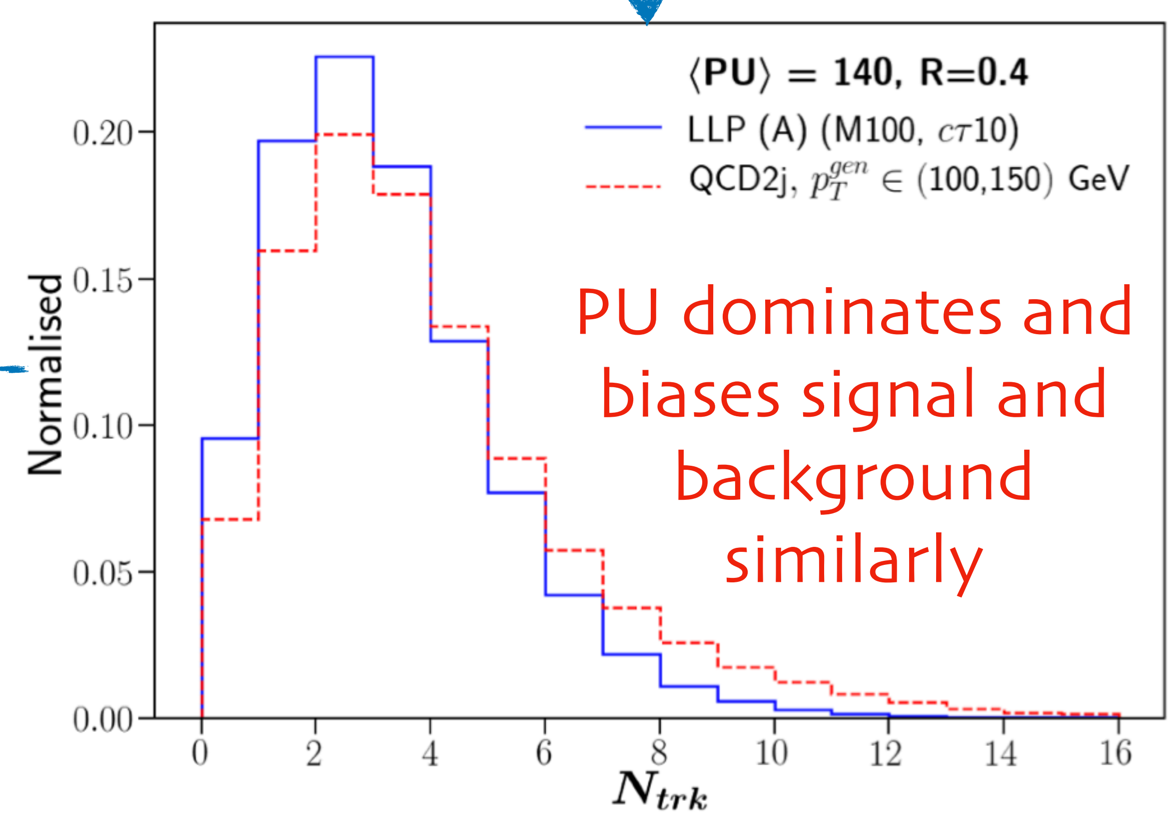




Reduce cone-size from $R = 0.4 \rightarrow R = 0.2$





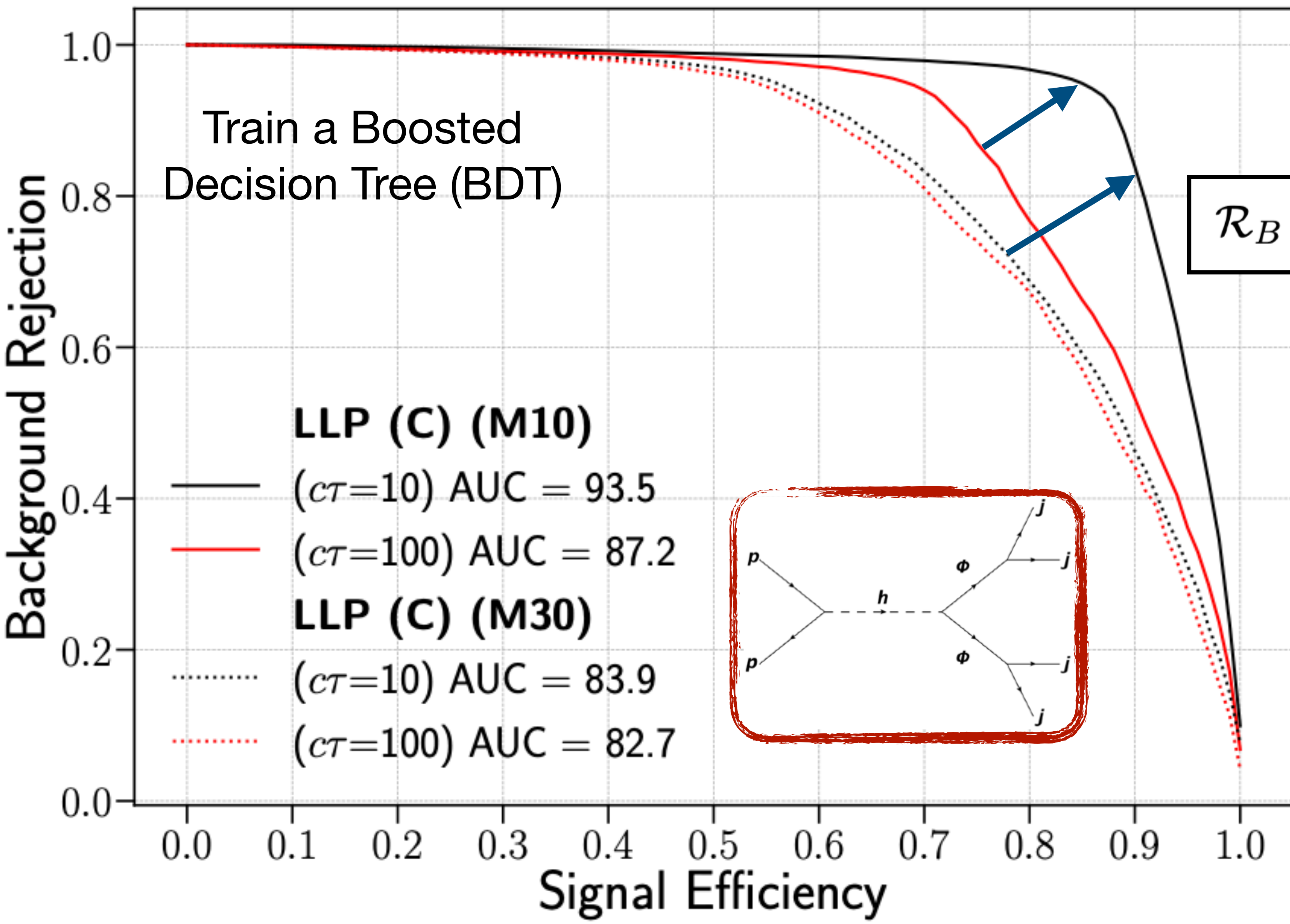
L1 Tracking

Dedicated triggers contd.

Bhattacherjee, Mukherjee, RS, Solanki, JHEP 08 (2020) 141

Tracking variables:

$N_{\rm trk}$ | $\sum p_T$ | $z_{\rm j\_vtx}$ | $\Delta z_{\rm j\_vtx}$ | $p_{T(\rm vtx)}^{\rm miss}$|$n_{z_{\rm trk\_max}}$ | $\Delta z_{\rm trk\_max}$ | $\sum p_T^{z_{\rm trk\_max}}$| $\sum p_T^{z_a \neq z_{\rm trk\_max}}$| $\frac{\sum p_T^{z_{\rm trk\_max}}}{\sum p_T}$| $S(\frac{|z_i|}{\sum |z_i|})$ |
$S(z_i + 301)$ | $S(\frac{z_i+301}{\sum (z_i+301)})$ | $S(p_{T,i})$ | $S(\frac{p_{T,i}}{\sum p_{T,i}})$ | Same vars with trks within $\Delta R = 0.2$ | $\frac{N_{\rm trk}}{N_{\rm trk}^{(0.2)}}$ | $\frac{\sum p_T}{\sum p_T^{(0.2)}}$



$$\mathcal{R}_B = \sigma\ (\text{nb}) \times \mathcal{L}\ (\text{nb}^{-1}\text{Hz}) \times \epsilon_B$$

QCD dijet background rate suppressed to 14 kHz for considerable signal efficiency.

Timing @ MTD

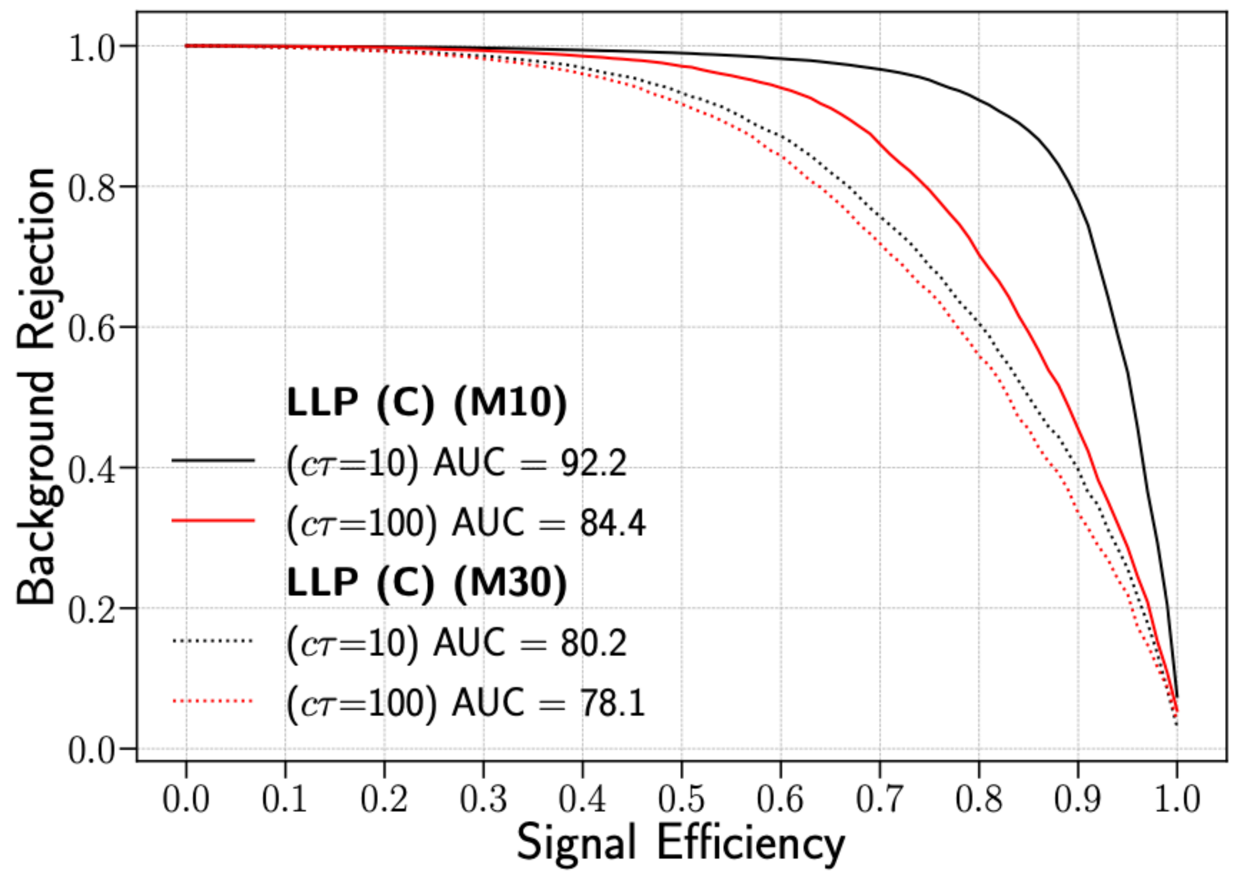
Dedicated triggers contd.

MIP Timing Detector

MTD: Timing of charged particles with $p_T > 0.7$ GeV up to $|\eta| = 1.5; p > 0.7$ GeV for $1.5 < |\eta| < 3.0$ with 30 ps resolution

Timing:

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



Bhattacherjee, Mukherjee, RS, Solanki, JHEP 08 (2020) 141

Jets - many particles - timing?

Median of the time differences of all particles associated with the jet (within $\Delta R = 0.2$ of the jet axis) w.r.t to photons starting from the reconstructed Primary Vertex (PV)

Timing @ ECAL

Dedicated triggers contd.

$\Delta T_{Mean}, \Delta T_{Median}, \Delta T_{RMS}, \Delta T^{Ewt}_{Mean}, \Delta T^{ETwt}_{Mean}, \Delta T^{Max5}_{Mean},$

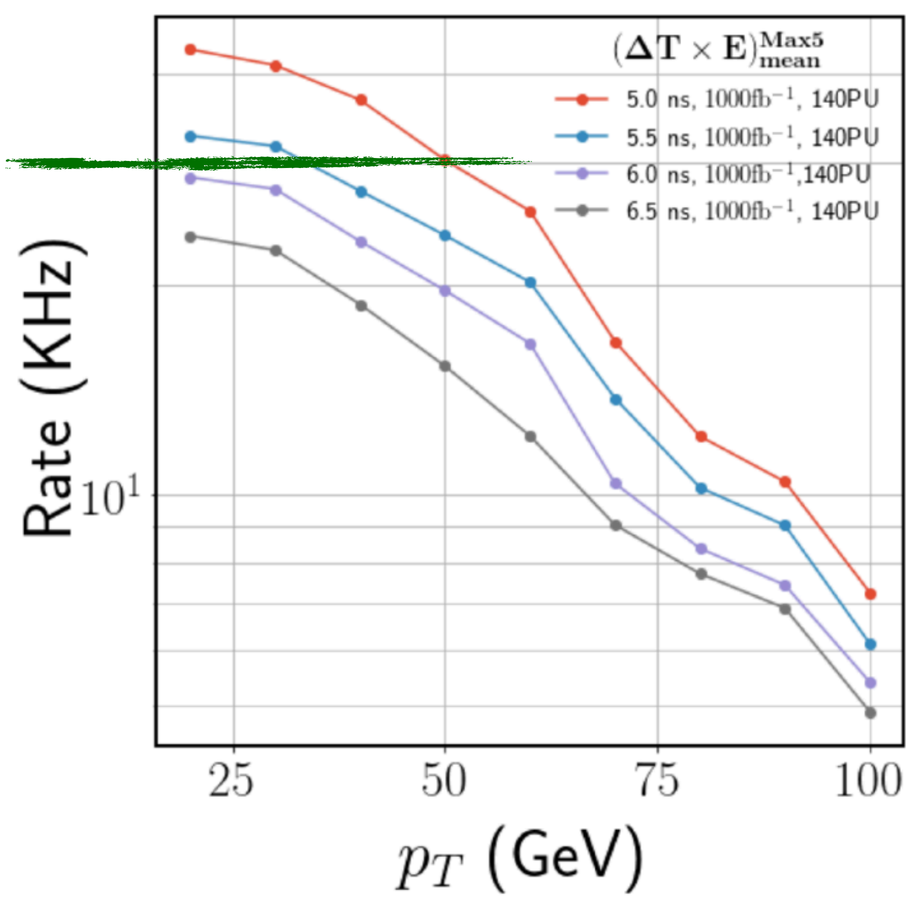
$(\Delta T \times E)^{Max5}_{Mean}, \Delta T^{Max10}_{Mean}, (\Delta T \times E)^{Max10}_{Mean}, \sum \Delta T$

Degrading resolution with increasing luminosity

Spread of vertices in the z and t directions

LLPs in SM

Bhattacherjee, Ghosh, RS, Solanki, JHEP 08 (2022) 254

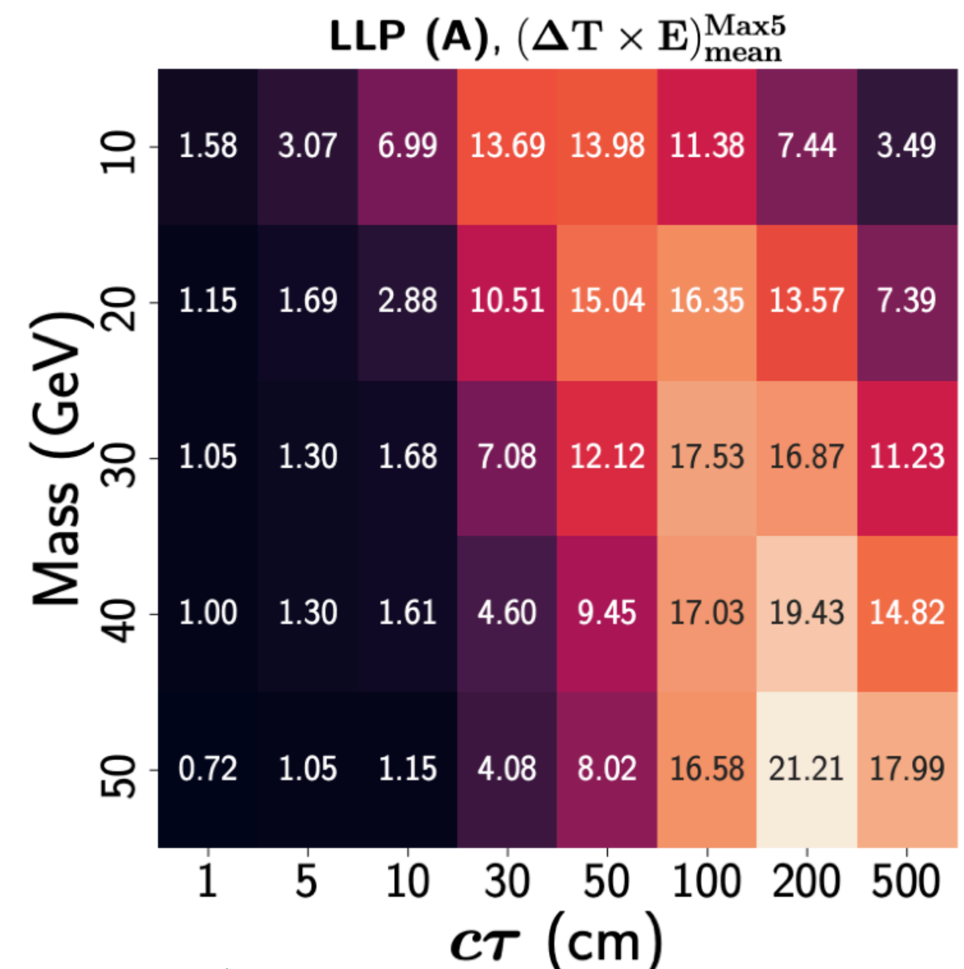


Select cuts that maintain **30 kHz rate**

$(\Delta T \times E)^{Max5}_{Mean}$

Average timing of the 5 ECAL crystals having maximum value of $\Delta T \times E$

Signal efficiency grid demanding at least one jet with $p_T > 35$ GeV and $(\Delta T \times E)^{Max5}_{Mean} > 5.5$ ns



Outline

- [x] Dedicated triggers
- [ ] **Leveraging Pile-up**
- [ ] Searches in the Muon Spectrometer
- [ ] Role of FCC-ee
- [ ] Upgrading ZDCs for LLPs
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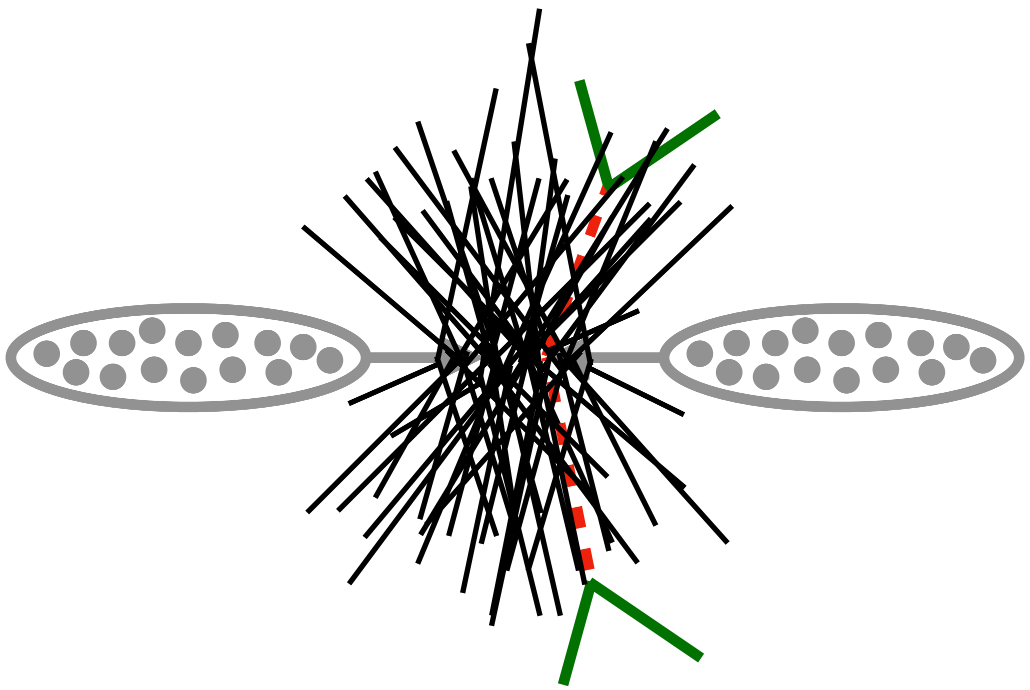
Leveraging the high pile-up environment

Future hadron colliders are high luminosity machines

High instantaneous luminosity = high pile-up environment

Issue of pile-up (PU)

to increase luminosity, number of protons per bunch increased



busy environment to dig out interesting new physics

Adversely impacts resolutions of experimentally measured observables used to distinguish BSM signals

Effect even more for light new physics!

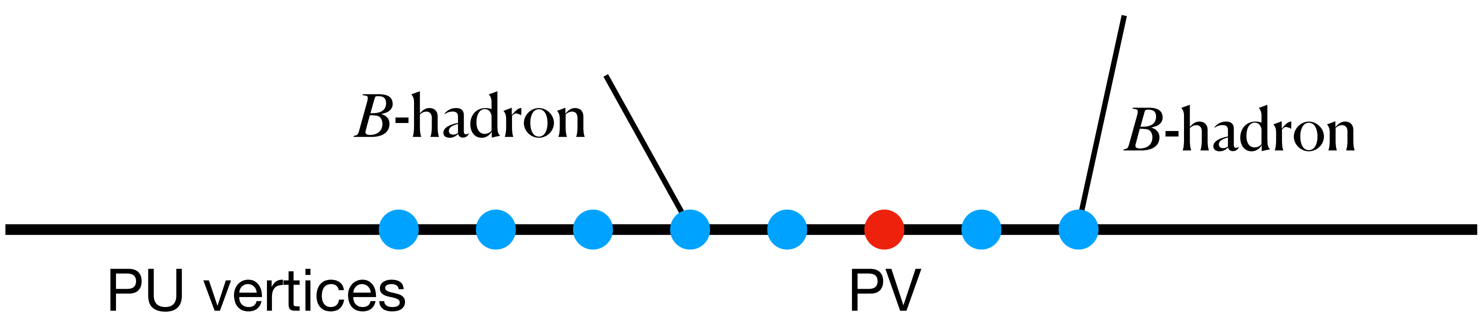
Leveraging the high pile-up environment

What about light new particles coming from meson decays?

Collider	$\sqrt{s}$ [TeV]	Number of pile-up vertices	Number of B hadrons produced per bunch-crossing in pileup	Number of D hadrons produced per bunch-crossing in pileup
HL-LHC	14	200	2-4	~40
FCC-hh	100	500	~40	~200

Increases the production of LLPs from *B* and *D* meson decays per bunch-crossing

Biplob Bhattacherjee, Abhinav Kumar, Swagata Mukherjee, RS, Anand Sharma, e-Print: 2503.11760



Thereby, increasing the efficiency of detecting LLPs in various detectors per bunch-crossing

Look for light new physics coupled to *D*-hadrons in *B*-parking dataset!

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Why the muon spectrometer?

- Least affected by PU - farthest detector from the IP
- Large decay volume - compensates for its distance from the IP
- Sensitive to multiple decay modes

How do particles other than muons look in the MS?

ATLAS	CMS

displaced vertices in the MS

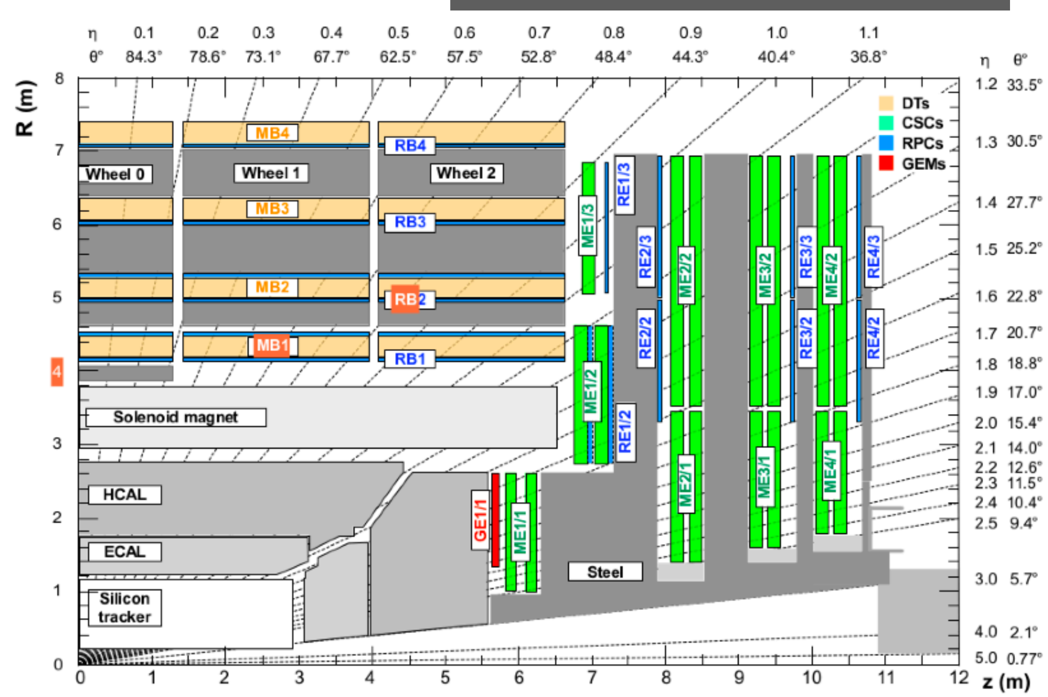
ATLAS, *PRD* 99 no. 5, (2019) 052005

ATLAS, *PRD* 101 no. 5, (2020) 052013

ATLAS, ATL-PHYS-PUB-2019-002

$e^{\pm}, \gamma,$ hadrons

iron yokes



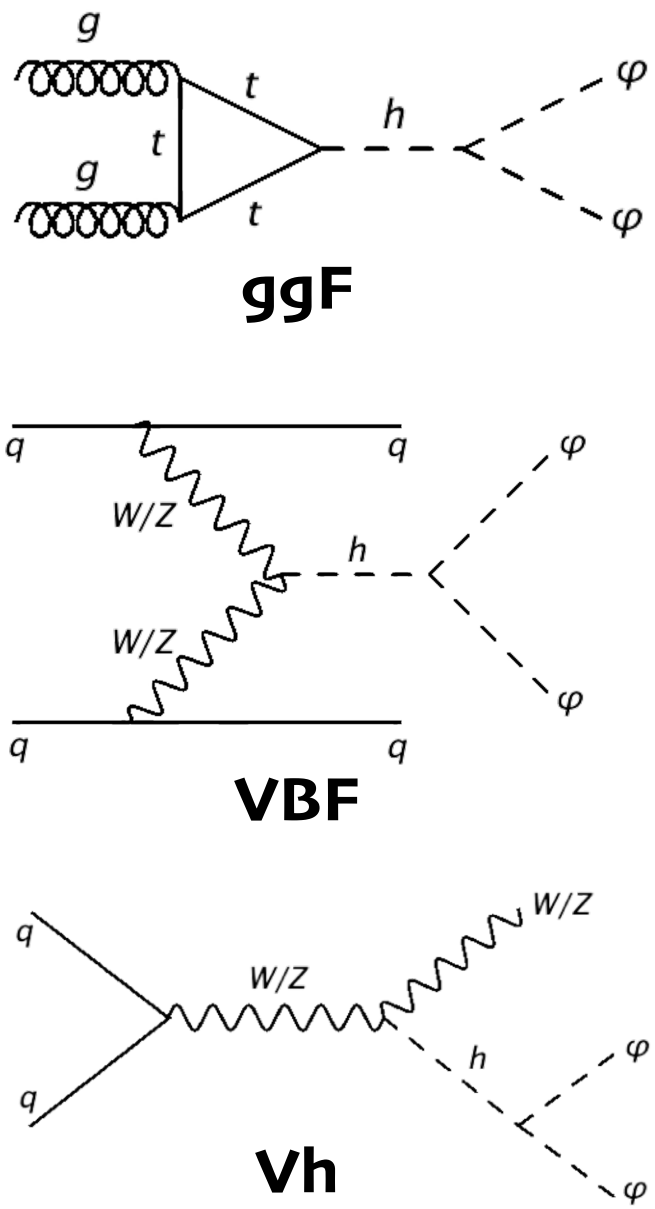
cluster of hits in the MS

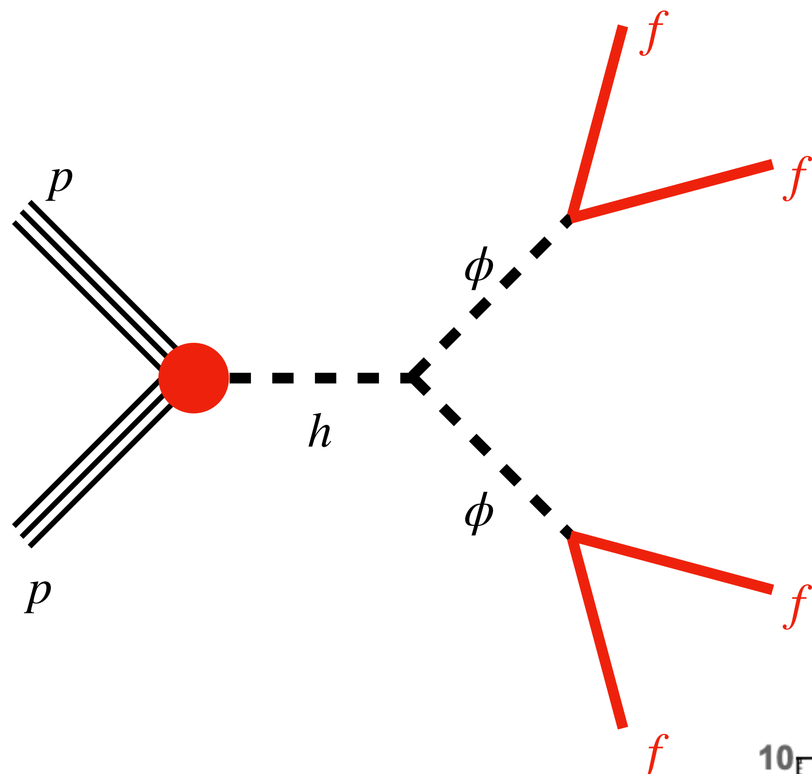
CMS, *PRL* 127 (2021) 26, 261804

CMS, *PRD* 110 no. 3, (2024) 032007

Analysis Strategy

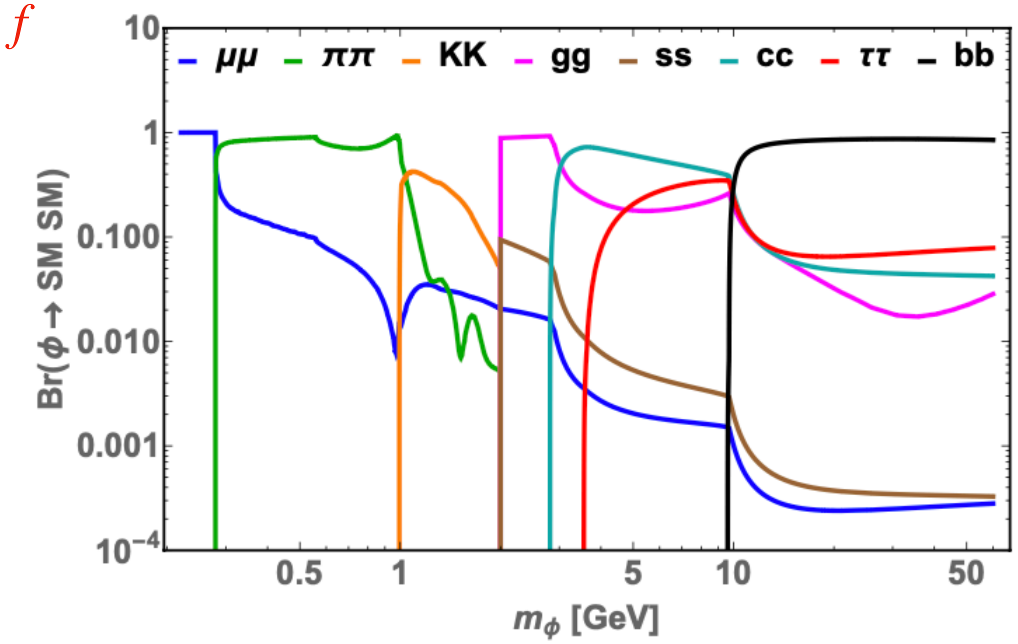
Production





Decay

$\mu^+\mu^-$	$s\bar{s}$
$\pi^+\pi^-$	$c\bar{c}$
K^+K^-	$\tau^+\tau^-$
gg	$b\bar{b}$



Prompt objects associated with production

Displaced objects from the LLP decay

Results

Combination of cuts using hard and soft selections on prompt and displaced objects

$P^H \times D^S$
$(\geq 1\text{vtx})$

harder set of cuts on the prompt objects
allows to relax cuts on displaced objects

Biplob Bhattacherjee, Shigeki Matsumoto, RS,
e-Print: 2111.02437, PRD 2022

CMS MS @ HL-LHC

Observation of 50 events required

$\mathrm{Br}(h \to \phi\phi) \times \mathrm{Br}(\phi \to \mu^+\mu^-) < 1.1 \times 10^{-5}$ for $m_\phi = 50\,\mathrm{GeV}, c\tau = 0.5\,\mathrm{m}$

$\mathrm{Br}(h \to \phi\phi) \times \mathrm{Br}(\phi \to b\bar{b}) < 6.7 \times 10^{-5}$ for $m_\phi = 50\,\mathrm{GeV}, c\tau = 5\,\mathrm{m}$

Muon Spectrometer only analysis - sensitive to higher decay lengths

FCC-hh MS

Observation of 50 events required

$\mathrm{Br}(h \to \phi\phi) \times \mathrm{Br}(\phi \to \mu^+\mu^-) < 4.1 \times 10^{-8}$ for $m_\phi = 50\,\mathrm{GeV}, c\tau = 0.5\,\mathrm{m}$

$\mathrm{Br}(h \to \phi\phi) \times \mathrm{Br}(\phi \to b\bar{b}) < 3.4 \times 10^{-7}$ for $m_\phi = 50\,\mathrm{GeV}, c\tau = 5\,\mathrm{m}$

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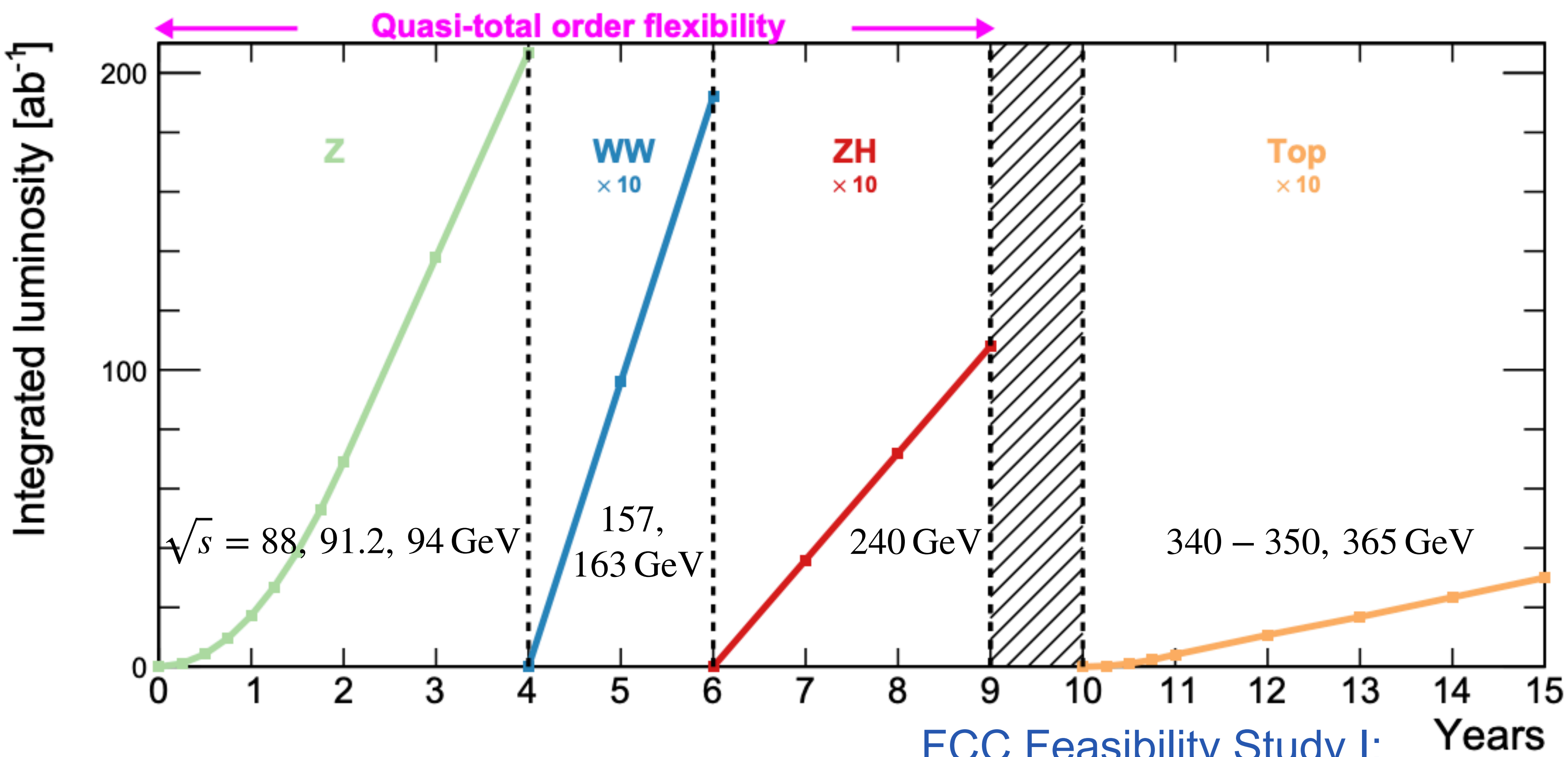
The FCC program at CERN

FCC-ee



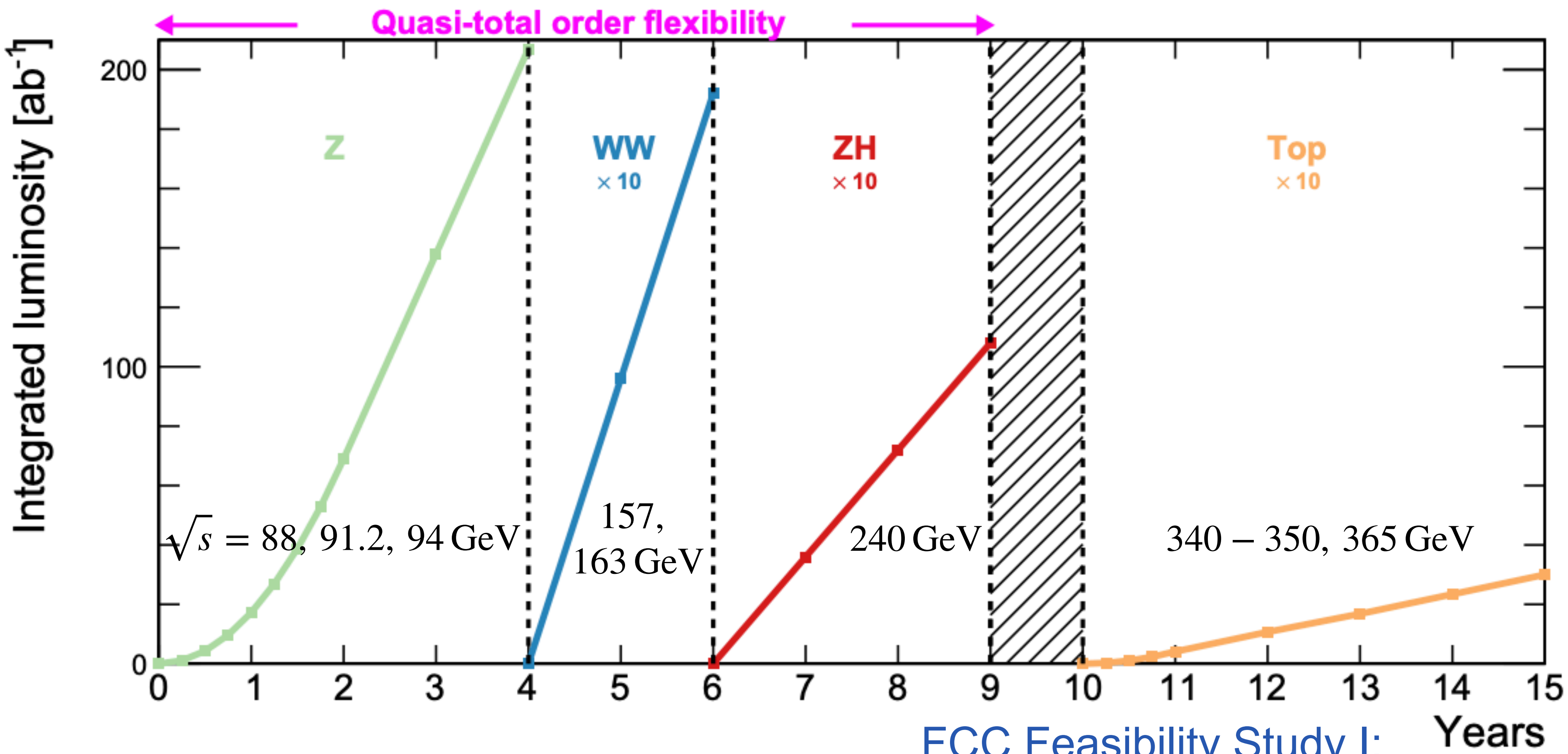
FCC Feasibility Study I:
arXiv:2505.00272

FCC-hh

The FCC-ee 100 km tunnel is designed to host subsequently a future circular hadron collider (FCC-hh) of a centre-of-mass energy of 100 TeV, and an integrated luminosity of 30 ab^{-1}.

The FCC program at CERN

FCC-ee



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FCC-hh

The FCC-ee 100 km tunnel is designed to host subsequently a future circular hadron collider (FCC-hh) of a centre-of-mass energy of 100 TeV, and an integrated luminosity of 30 ab^{-1}.

Role of FCC-ee?

We don't find a signal!

- Does it improve sensitivity to any region of the parameter space that lies outside the coverage of the currently running/proposed experiment?
- Does the particle identification capabilities of the FCC-ee increase sensitivity to mediator masses where it dominantly decays to mesons, like pions and kaons?

We observe a signal in one (or more) of these experiments!

- Does it help in identifying the underlying model - observe other interactions and measure model parameters?

Light scalar LLPs in the Higgs portal

$$\mathcal{L} \subset -m_\phi^2\phi^2 - \sin\theta\,\frac{m_f}{v}\phi\bar{f}f - \lambda_{h\phi\phi}h\phi\phi + \ldots$$

Mixing highly constrained

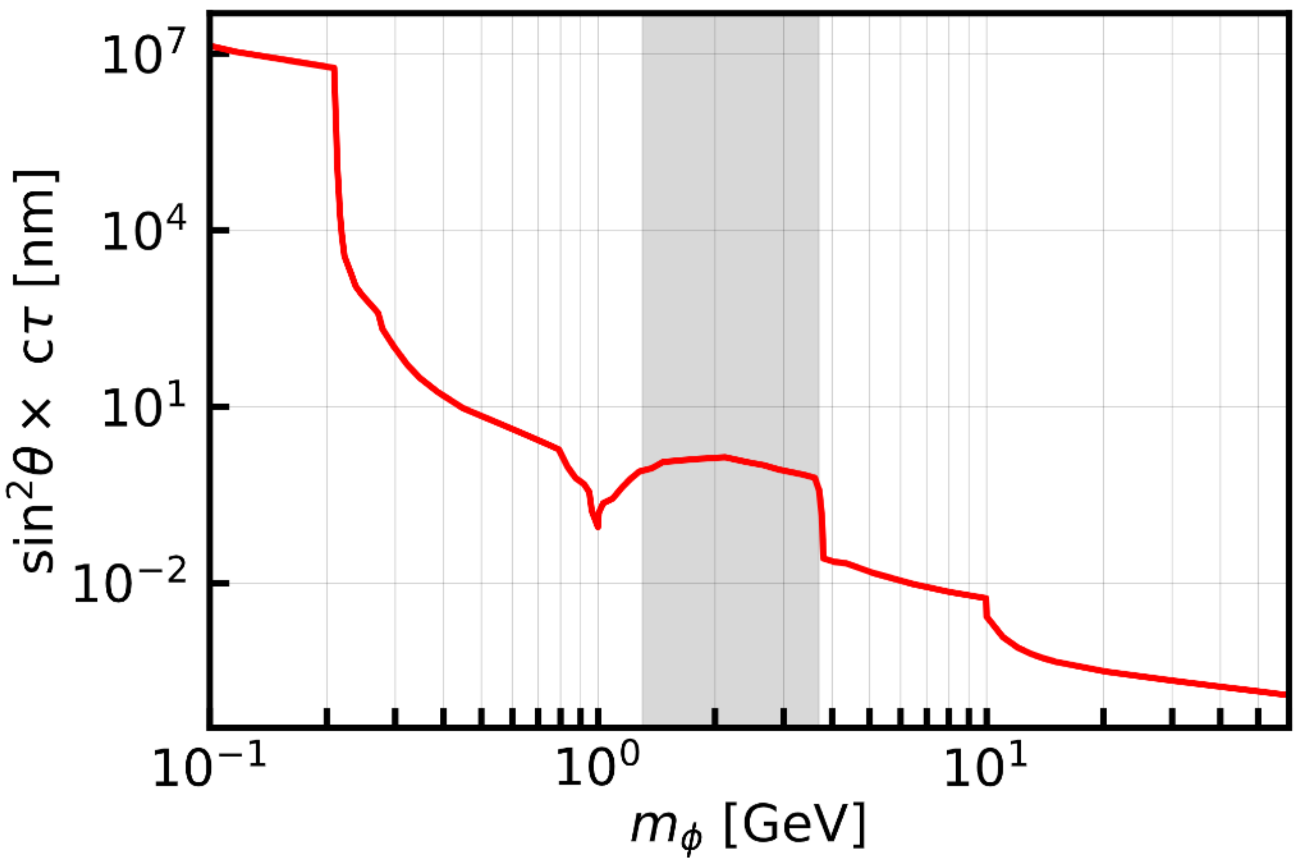
Not severely constrained so far

A $e^-e^+ \to Z \to b\bar{b},$
$B \to X_s\phi$

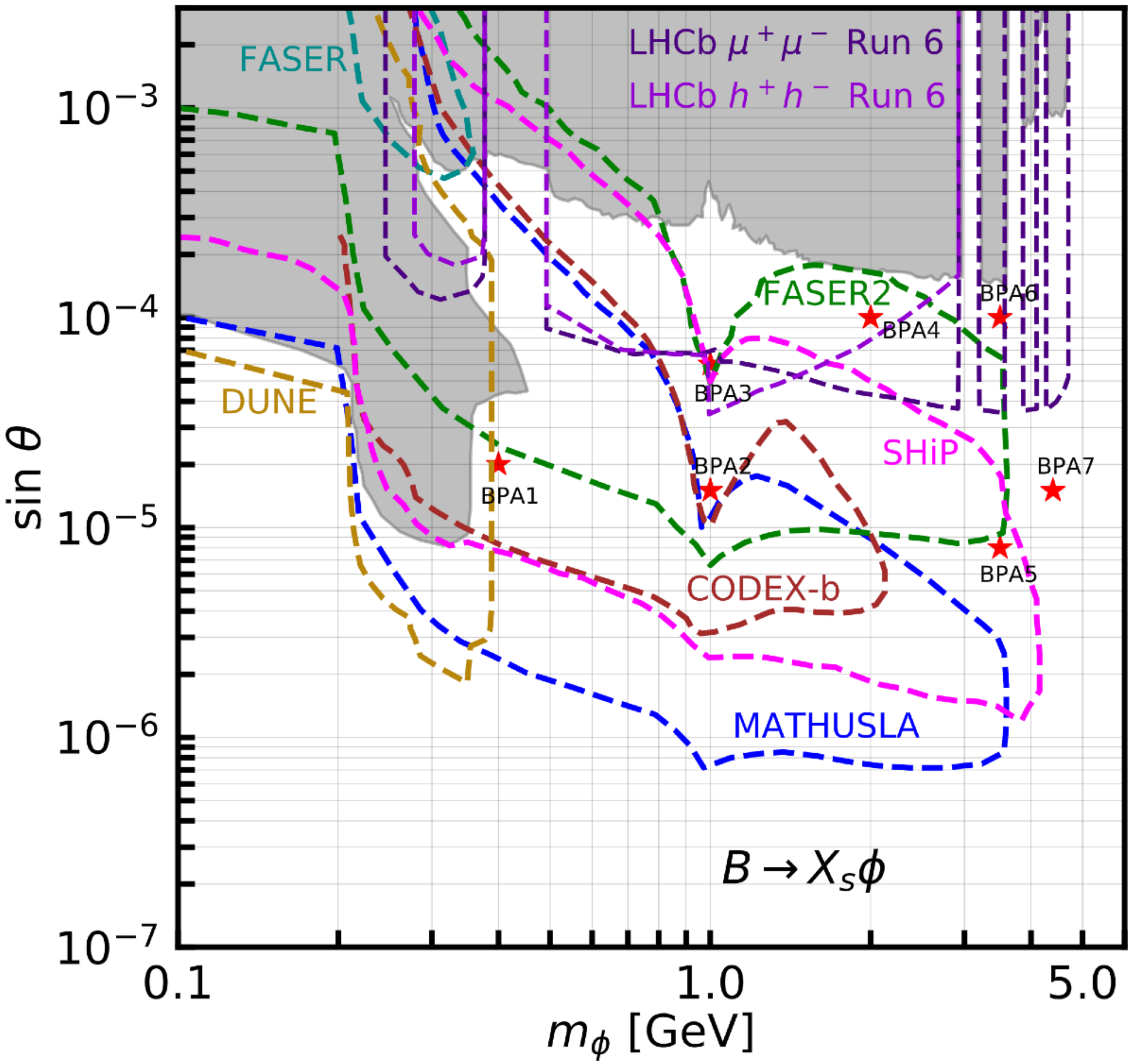
@ Z-pole of FCC-ee

B $e^-e^+ \to Zh,\ h \to \phi\phi$

@ ZH production peak of FCC-ee



Benchmarks for FCC-ee: $B \to X_s \phi$



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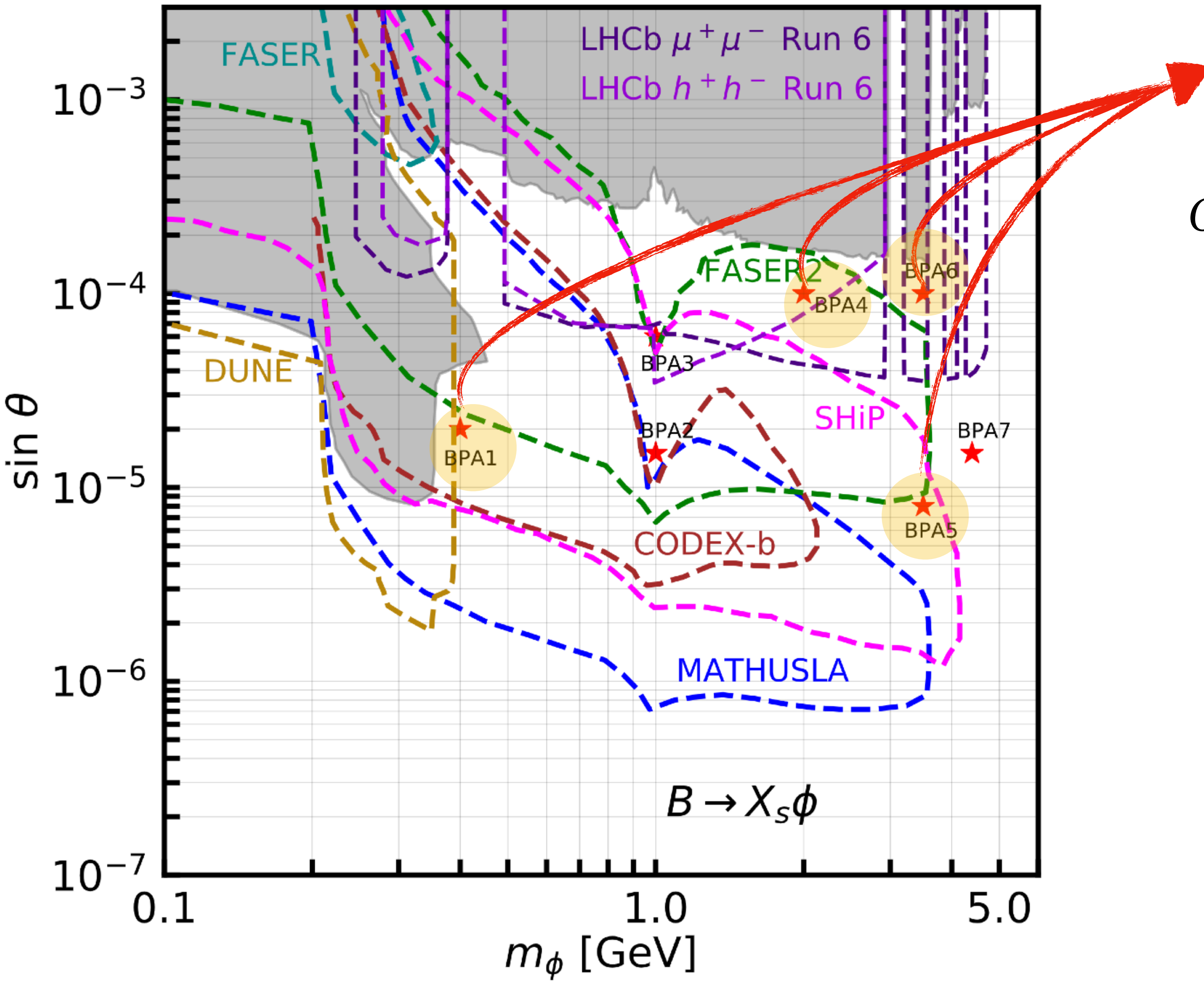
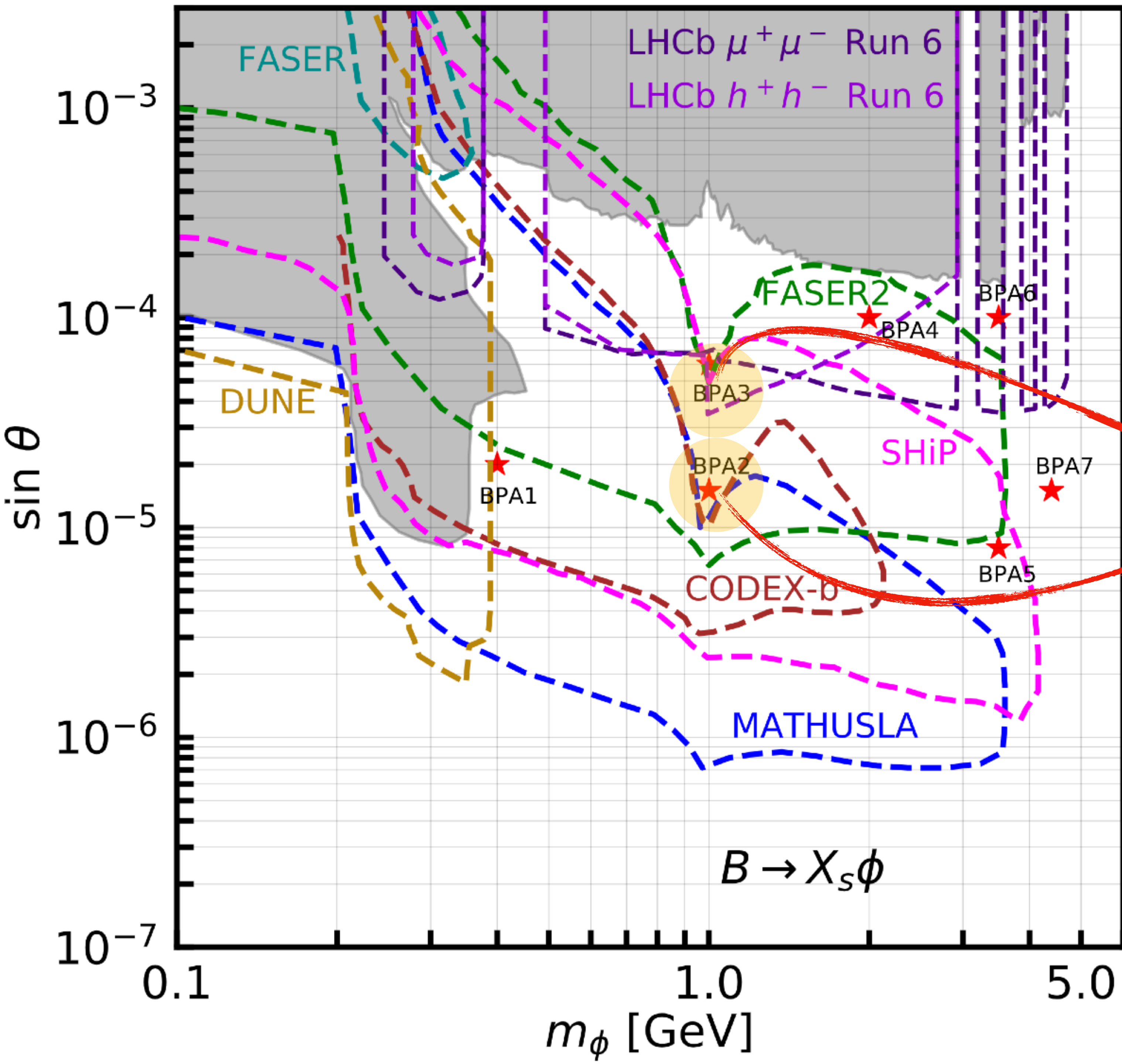


lies at corners of various future projections —

Can FCC-ee tell more?

BPA1, BPA4, BPA5, BPA6

Benchmarks for FCC-ee: $B \to X_s\phi$



lies at corners of various future projections —

Can FCC-ee tell more?

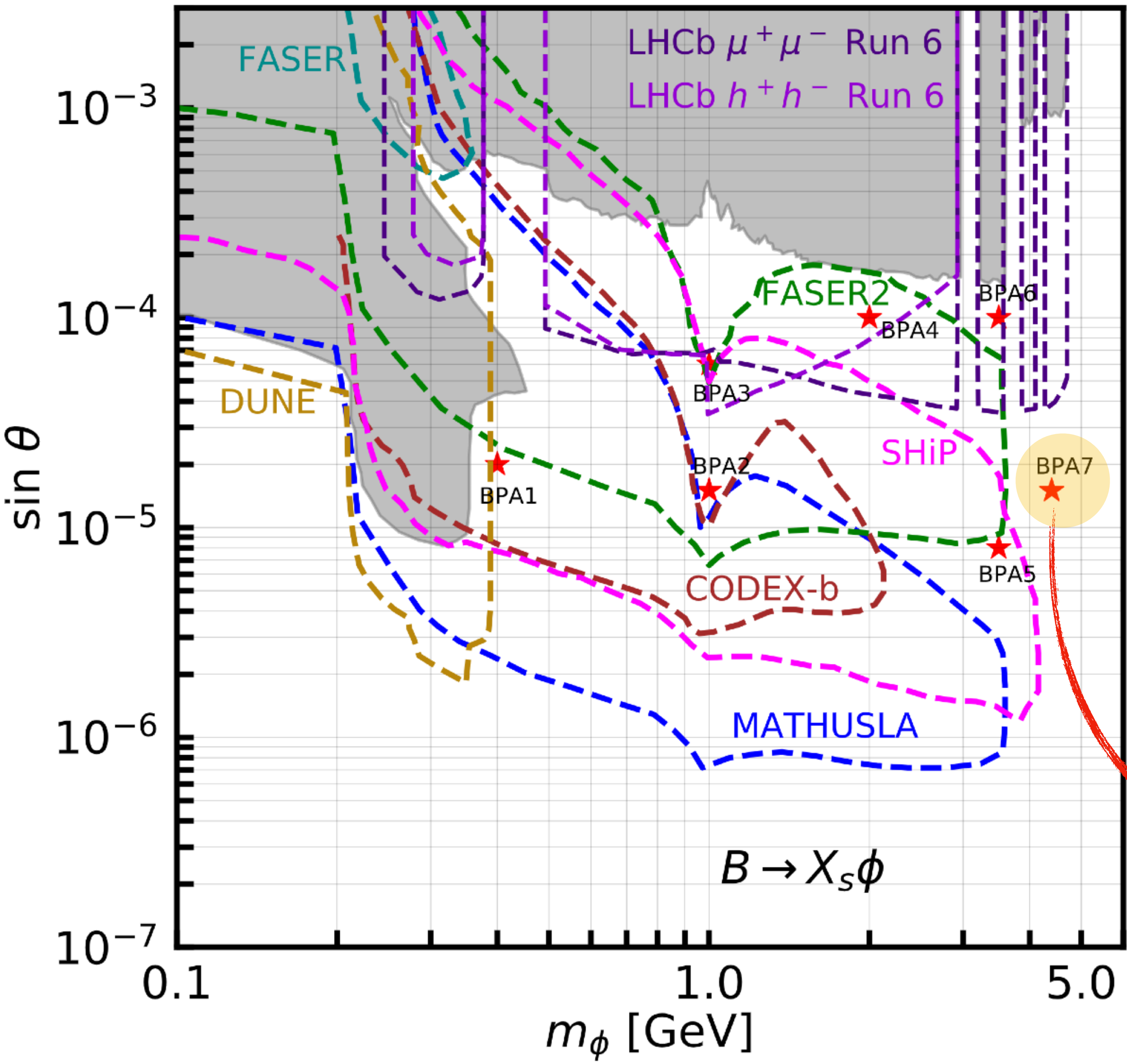
BPA1, BPA4, BPA5, BPA6

dominant decay to mesons —

Use the particle identification at FCC-ee!

BPA2, BPA3

Benchmarks for FCC-ee: $B \to X_s \phi$



lies at corners of various future projections —

Can FCC-ee tell more?

BPA1, BPA4, BPA5, BPA6

dominant decay to mesons —

Use the particle identification at FCC-ee!

BPA2, BPA3

outside the projected coverage —

Sensitivity at FCC-ee?

BPA7

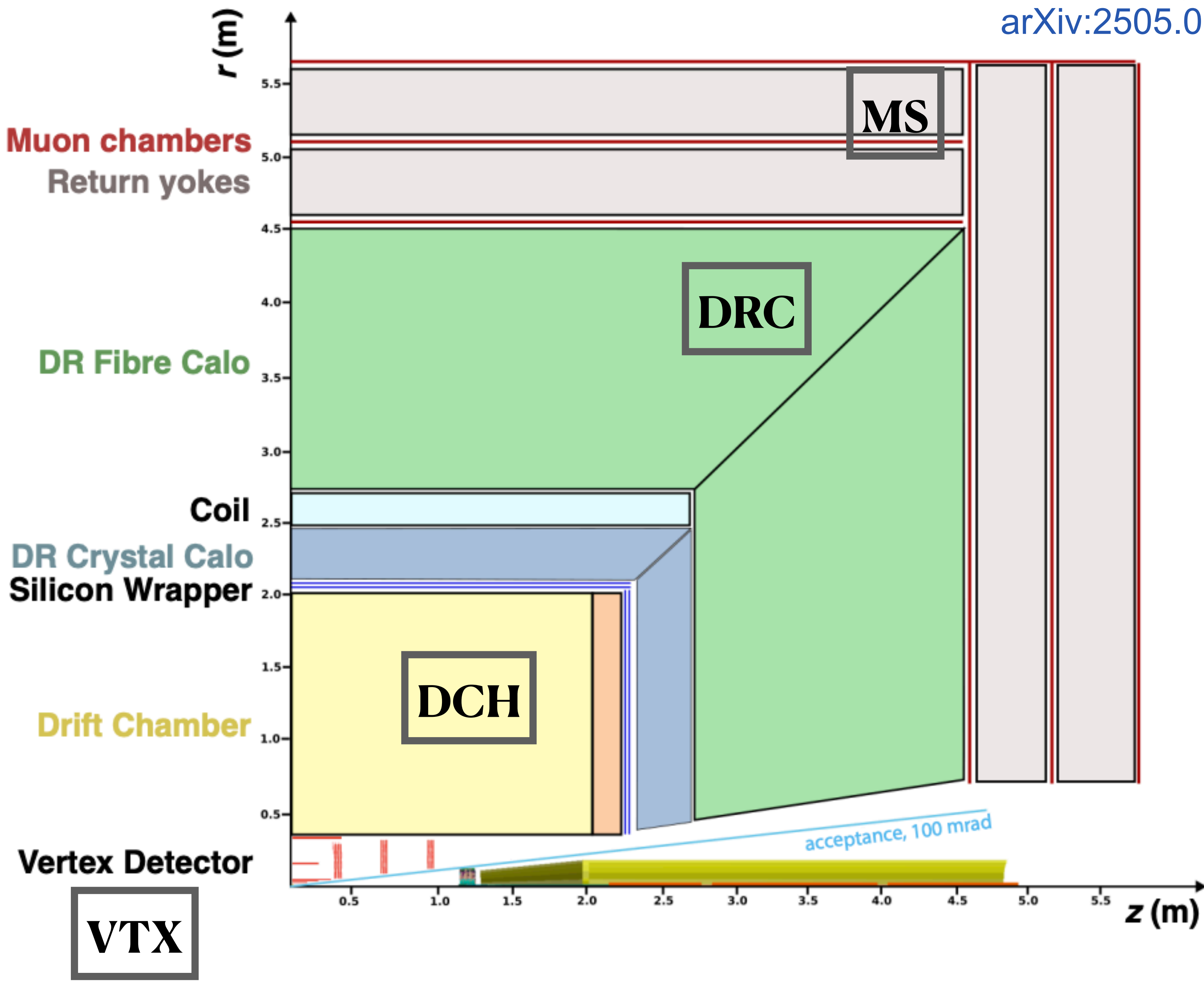
Benchmarks for FCC-ee: $B \to X_s \phi$

Benchmark	m_ϕ (GeV)	$\sin\theta$	$c\tau$ (mm)	Dominant decay modes	Potential experiments to probe			
					FASER2	LHCb (projected)	MATHUSLA	SHIP
BPA1	0.4	2.0×10^{-5}	39666.6	$\pi^+\pi^-$: 76% $\mu^+\mu^-$: 10%	×	×	✓	✓
BPA2	1.0	1.5×10^{-5}	554.3	$\pi^+\pi^-$: 50% K^+K^- : 50%	✓	×	×	✓
BPA3	1.0	6×10^{-5}	34.6	$\pi^+\pi^-$: 50% K^+K^- : 50%	×	×	×	×
BPA4	2.0	10^{-4}	135.2	$\pi^+\pi^-$: 41% K^+K^- : 41% $\mu^+\mu^-$: 12%	✓	✓	×	×
BPA5	3.5	8×10^{-6}	10285.4	$\pi^+\pi^-$: 53% K^+K^- : 21% $\mu^+\mu^-$: 5%	×	×	×	✓
BPA6	3.5	10^{-4}	65.8	$\pi^+\pi^-$: 53% K^+K^- : 21% $\mu^+\mu^-$: 5%	×	✓	×	×
BPA7	4.4	1.5×10^{-5}	95.0	$c\bar{c}$: 65% $\tau^+\tau^-$: 20%	×	×	×	×

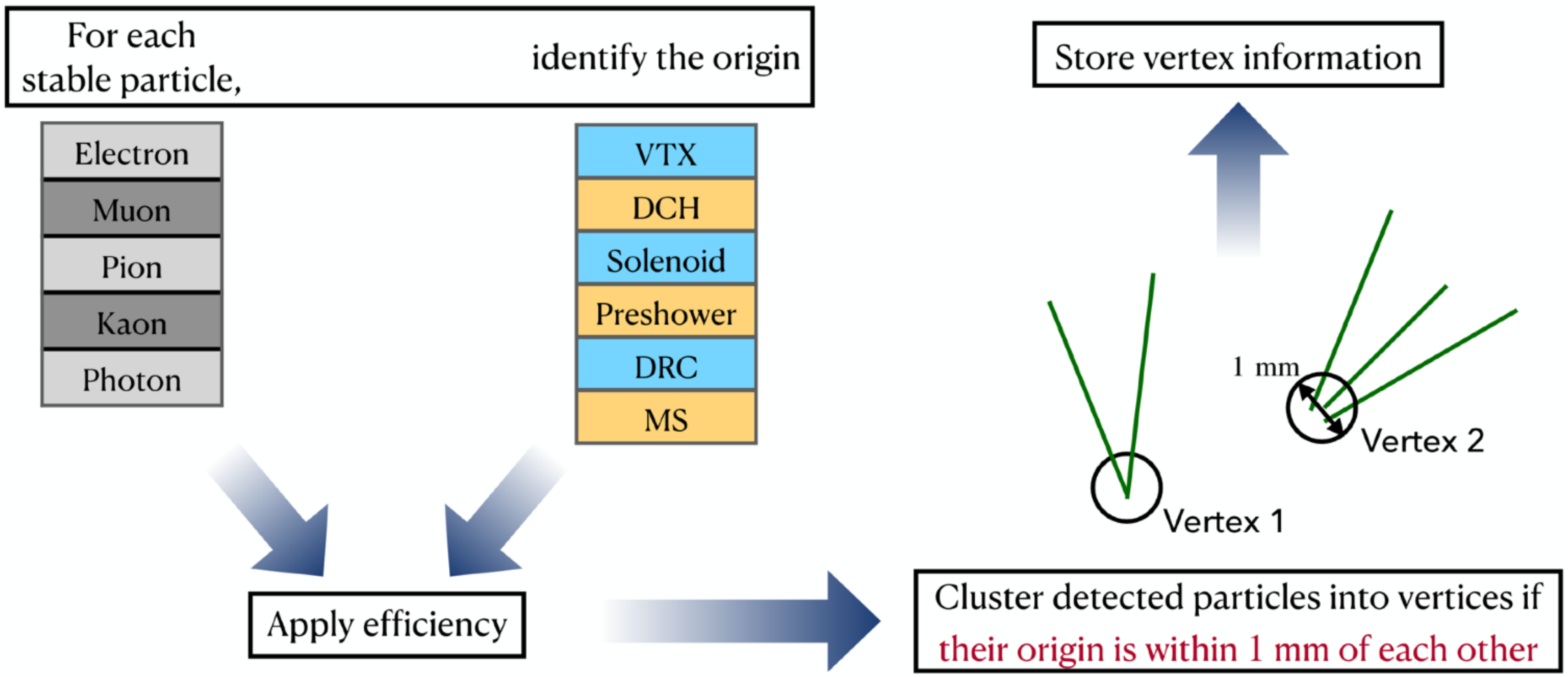
The IDEA detector

Innovative **D**etector for an **E**lectron-Positron **A**ccelerator

FCC Feasibility Study I:
arXiv:2505.00272



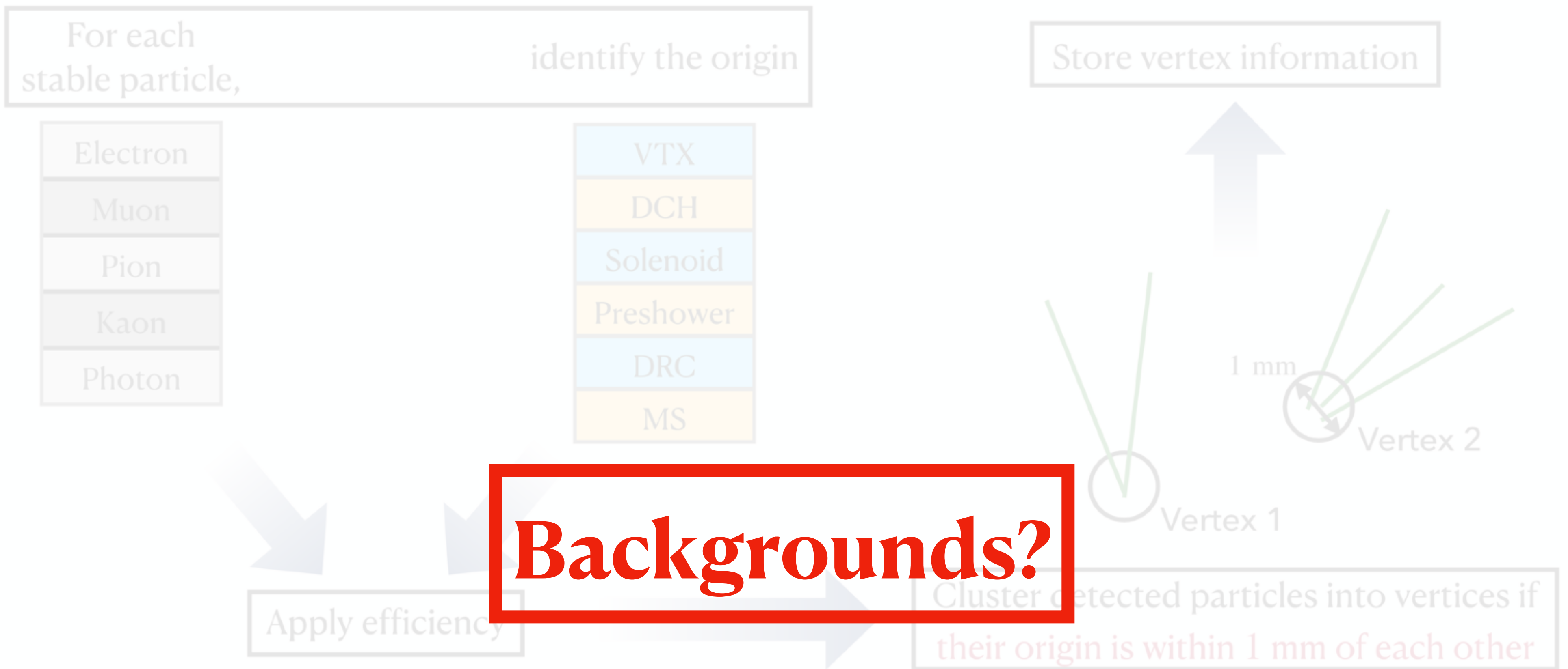
Analysis strategy



Variables:

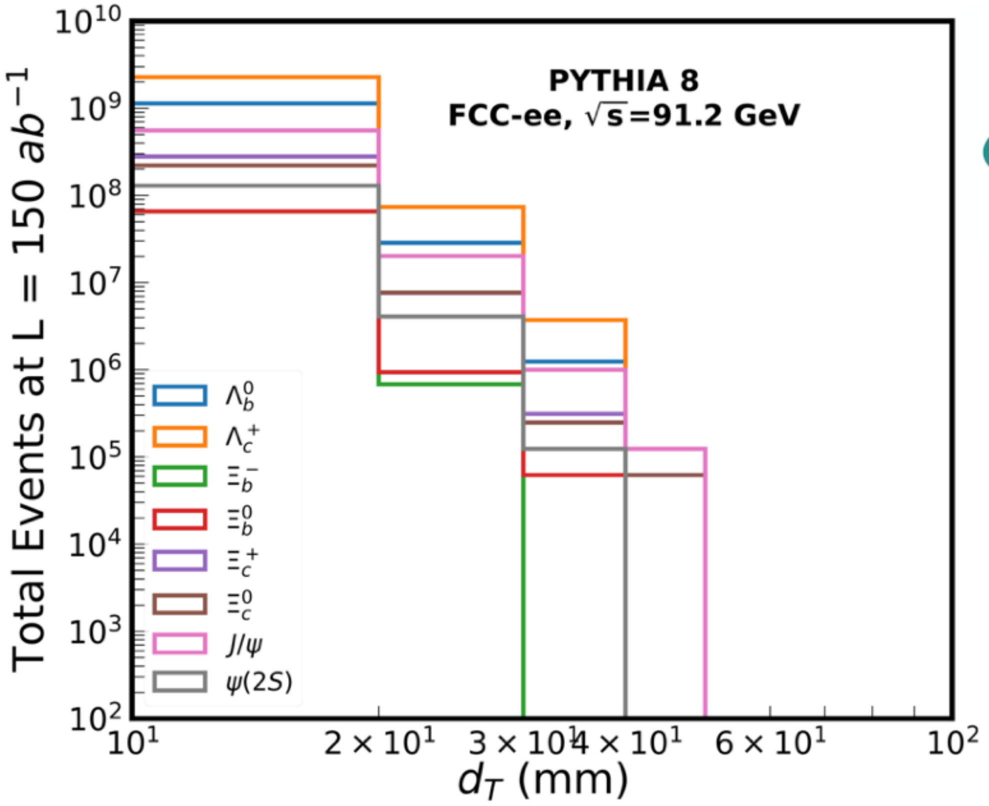
- detector element based on the location of the vertex, D_{vtx}
- number of charged particles (N_{ch}), muons (N_μ), pions (N_π), kaons (N_K), and electrons (N_e) originating at the vertex
- total energy of the particles produced at the vertex, E
- transverse displacement of the vertex from the origin, d_T
- invariant mass of the final state particles associated with the vertex, m_{vtx}
- the impact parameter of the vertex, d_0

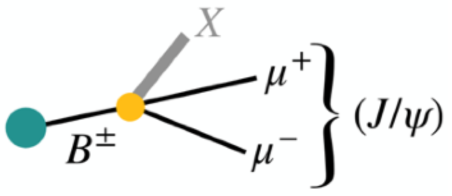
Analysis strategy



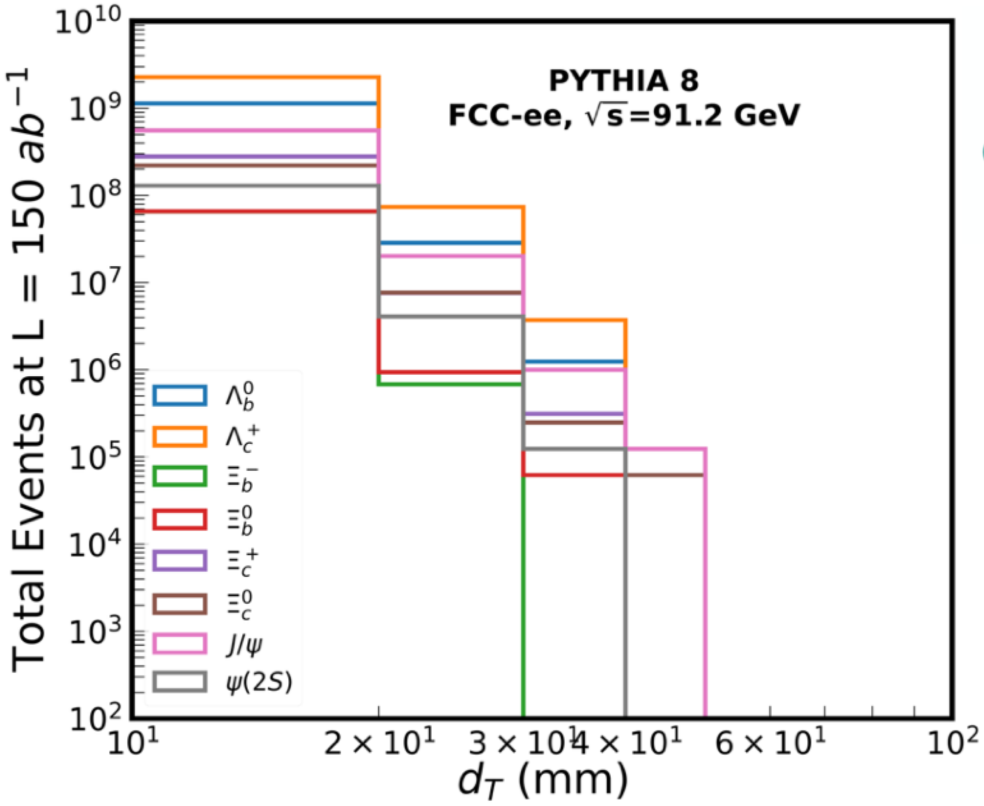
Backgrounds?

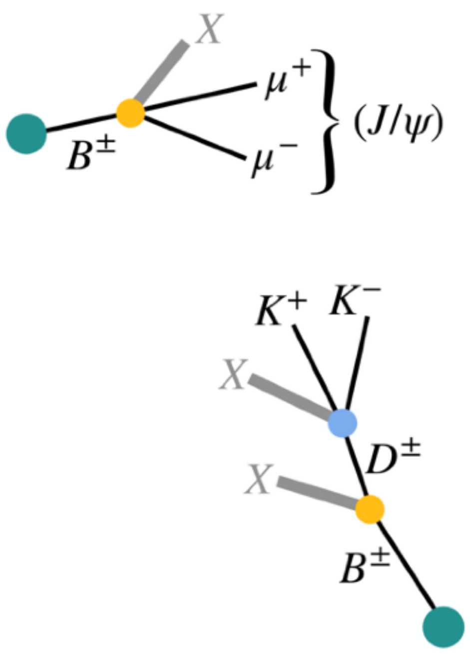
SM LLP backgrounds

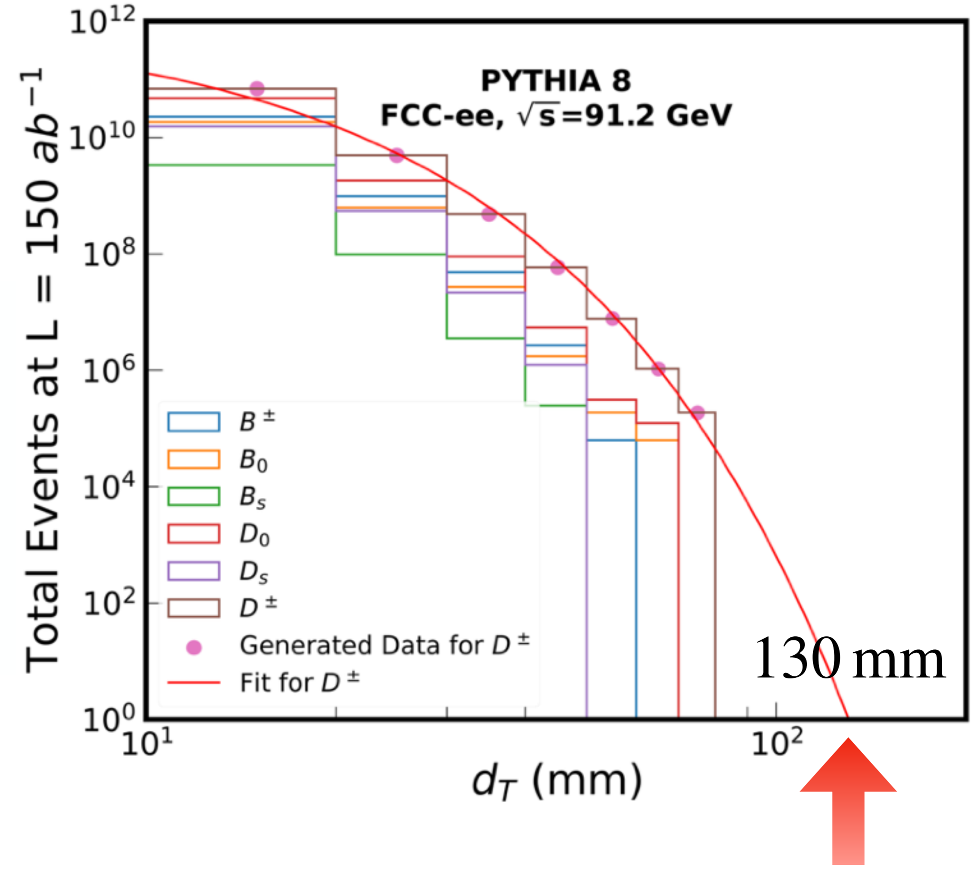




SM LLP backgrounds

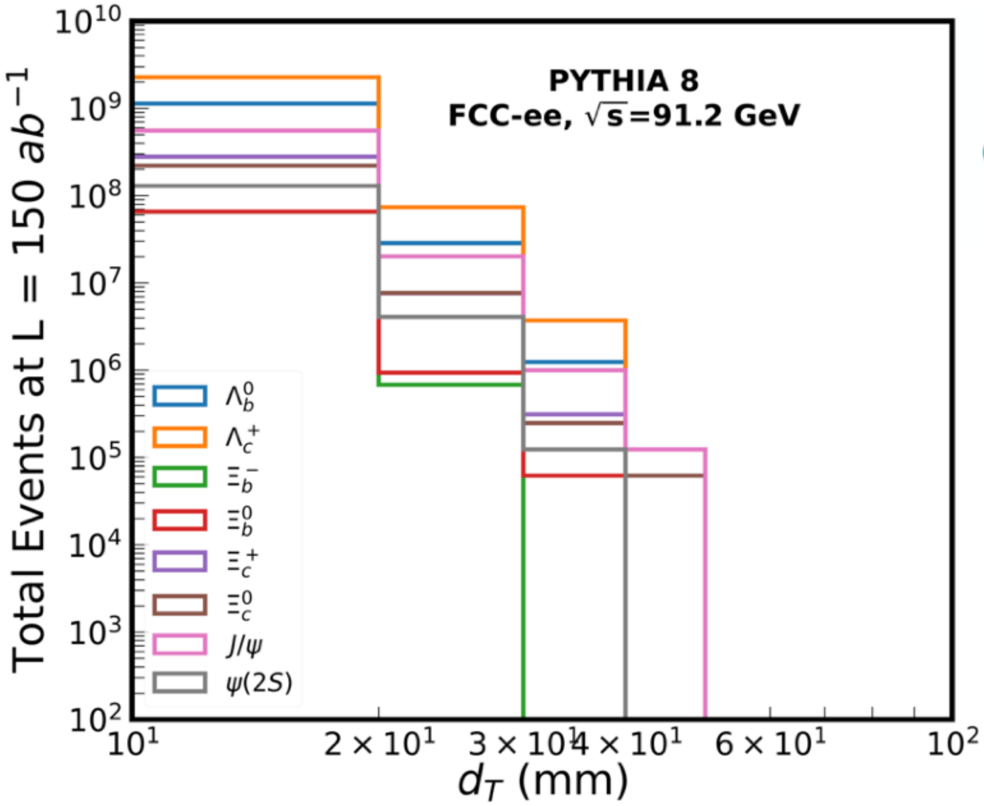


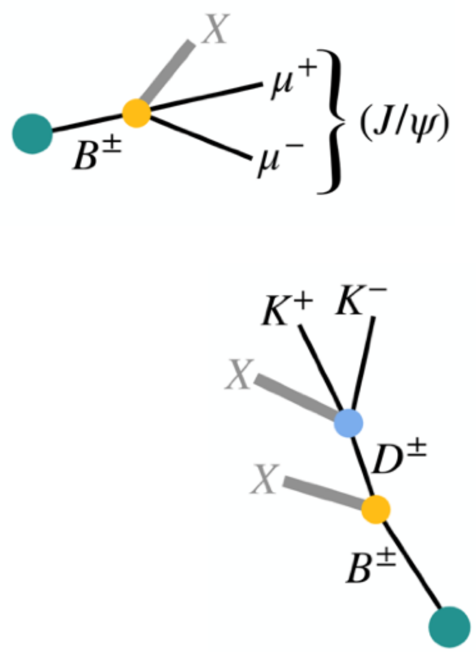


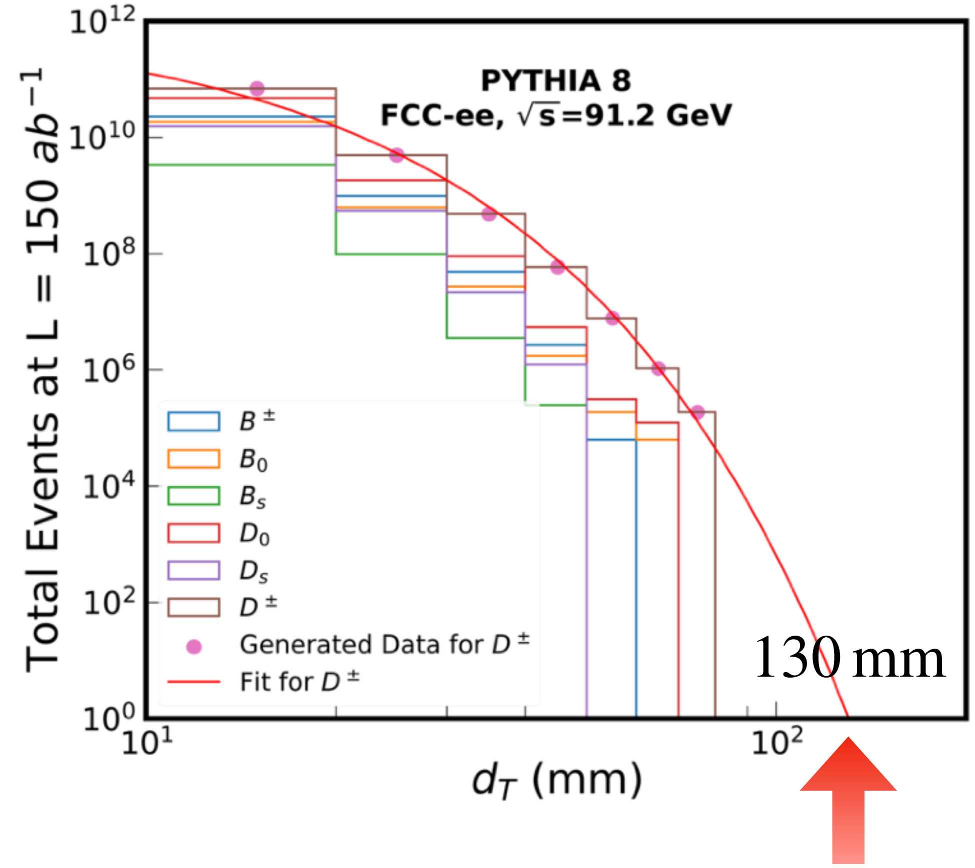


Extrapolated the d_T distribution to find the maximum extent of SM LLP backgrounds

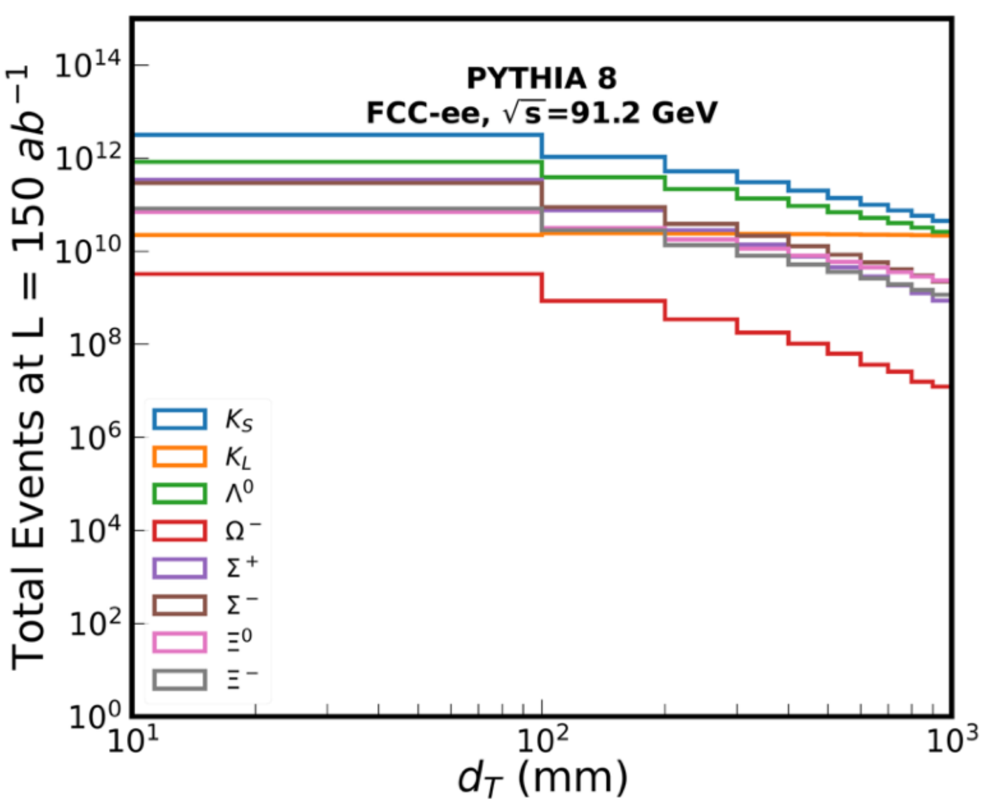
SM LLP backgrounds

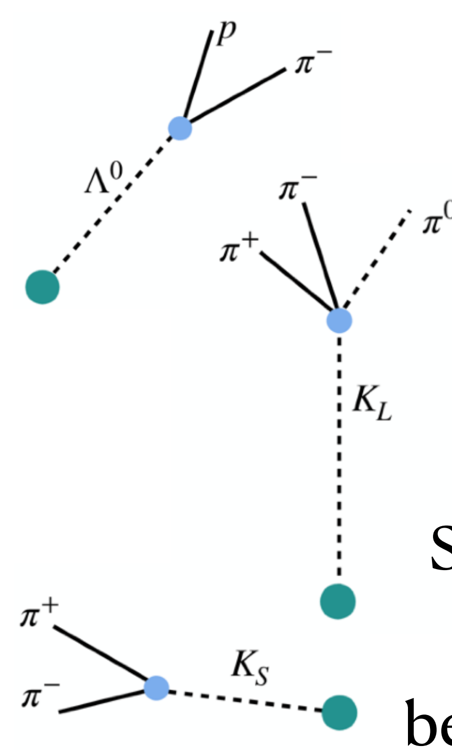






Extrapolated the d_T distribution to find the maximum extent of SM LLP backgrounds

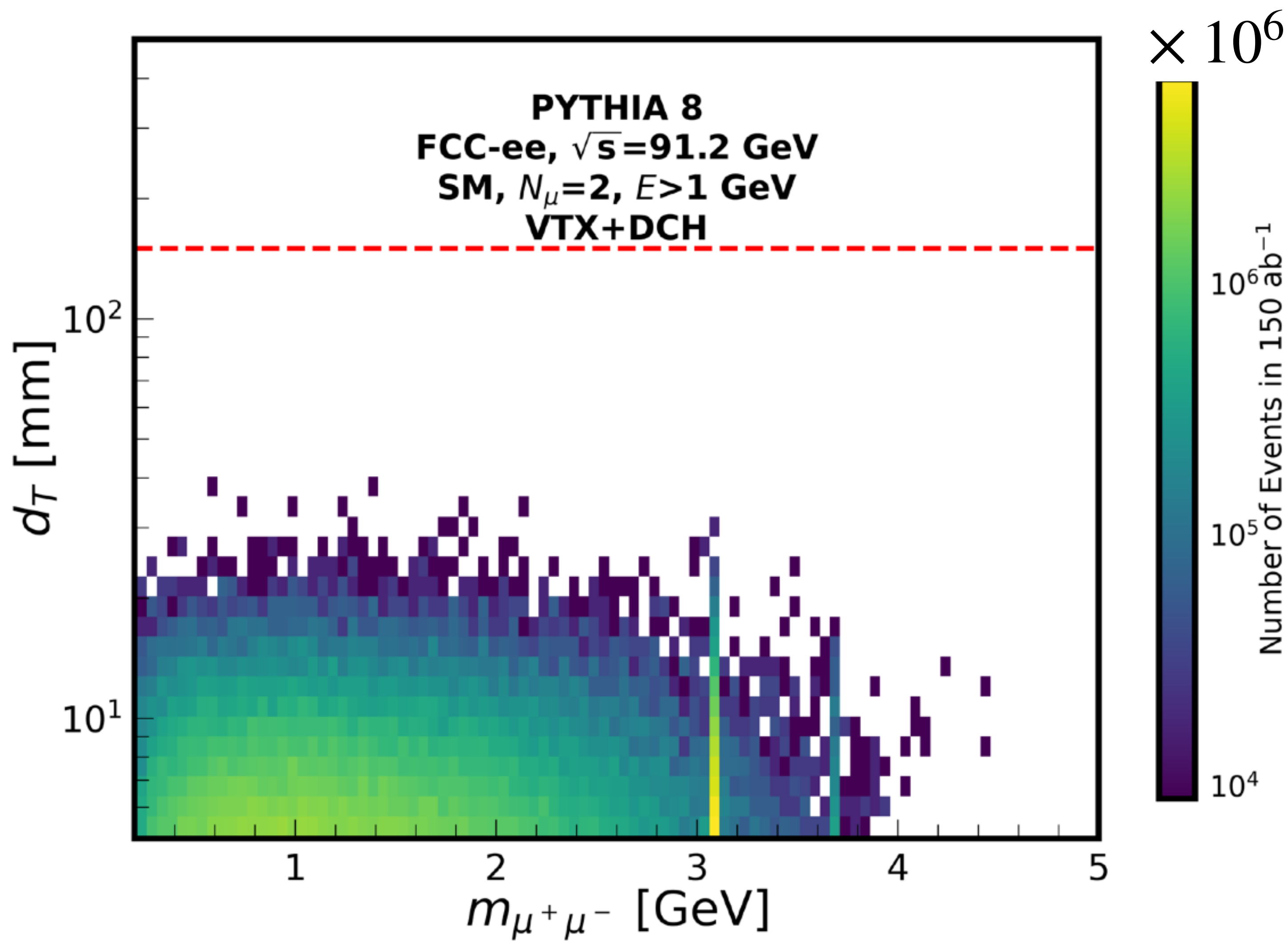




SM LLPs with highly displaced decays — travel till the DRC before decaying — MS searches?

$B \to X_s \phi, \quad \phi \to \mu^+\mu^-$

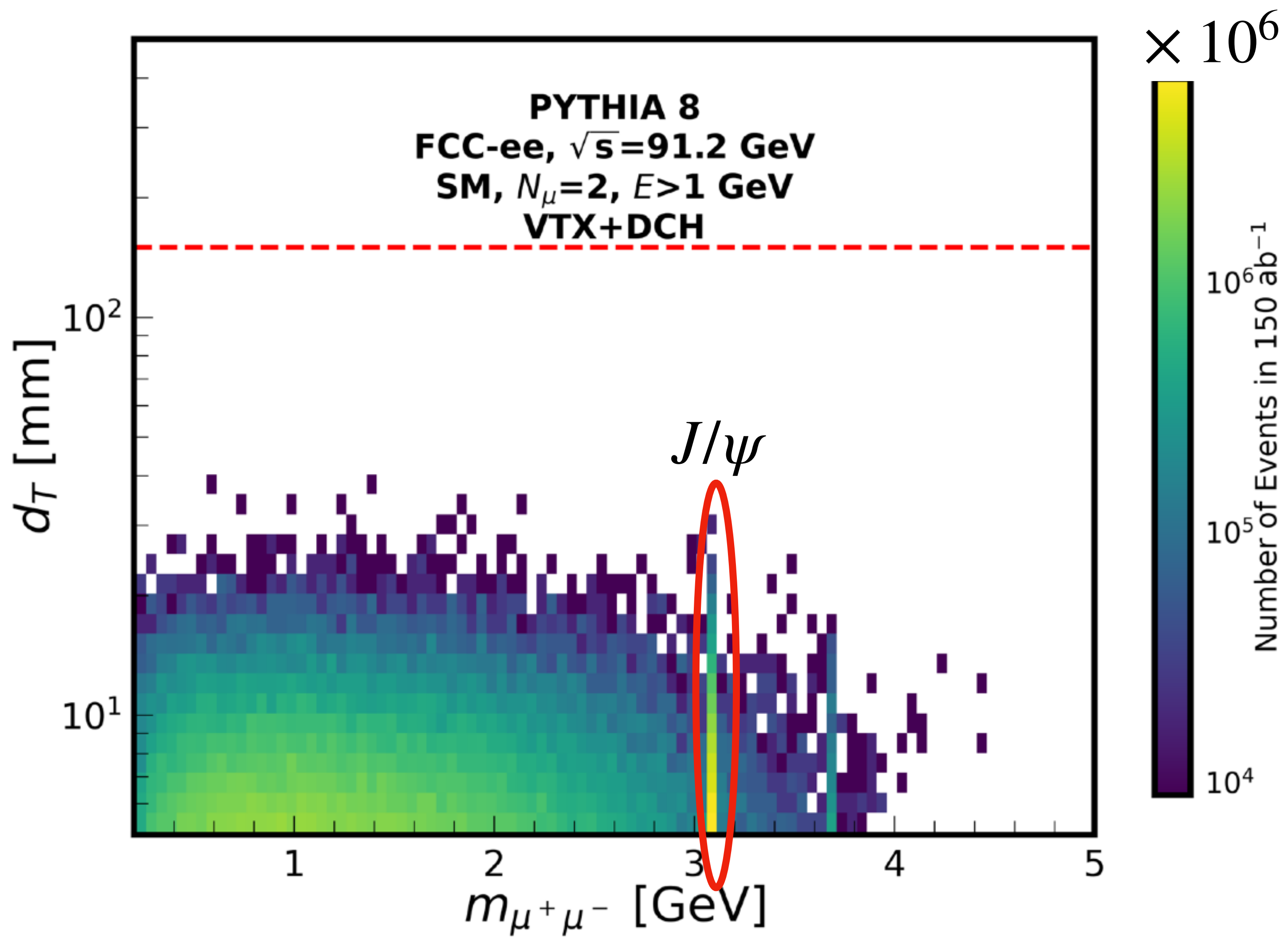
$\sim 5 \times 10^{12}$ Z bosons @ FCC-ee, we simulate $\sim 10^9$ events at the Z pole



Number of events in 150 ab^{-1}

$B \to X_s\phi, \quad \phi \to \mu^+\mu^-$

$\sim 5 \times 10^{12}$ Z bosons @ FCC-ee, we simulate $\sim 10^9$ events at the Z pole



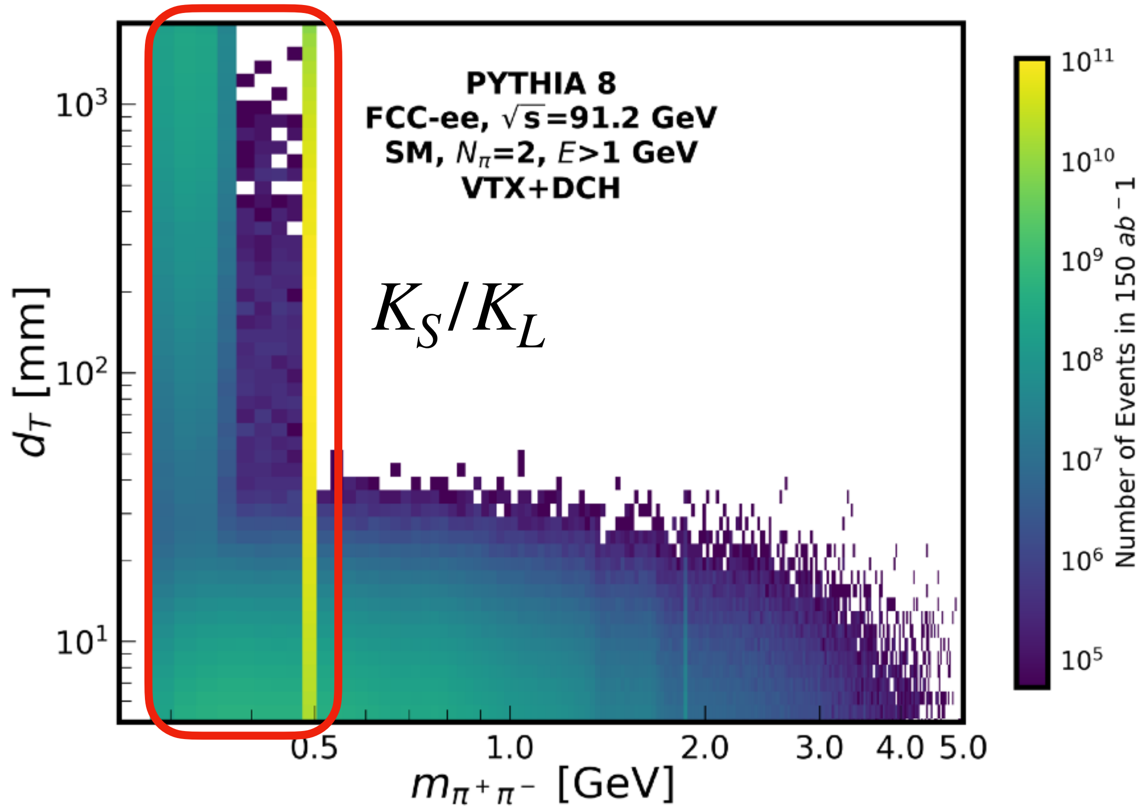
Final cuts for the dimuon final state
$D_{\text{vtx}} \equiv$ out to the MS
$N_{\text{chg}} = 2$
$N_\mu = 2$
$E > 2\,\text{GeV}$
$d_T > 150\,\text{mm}$

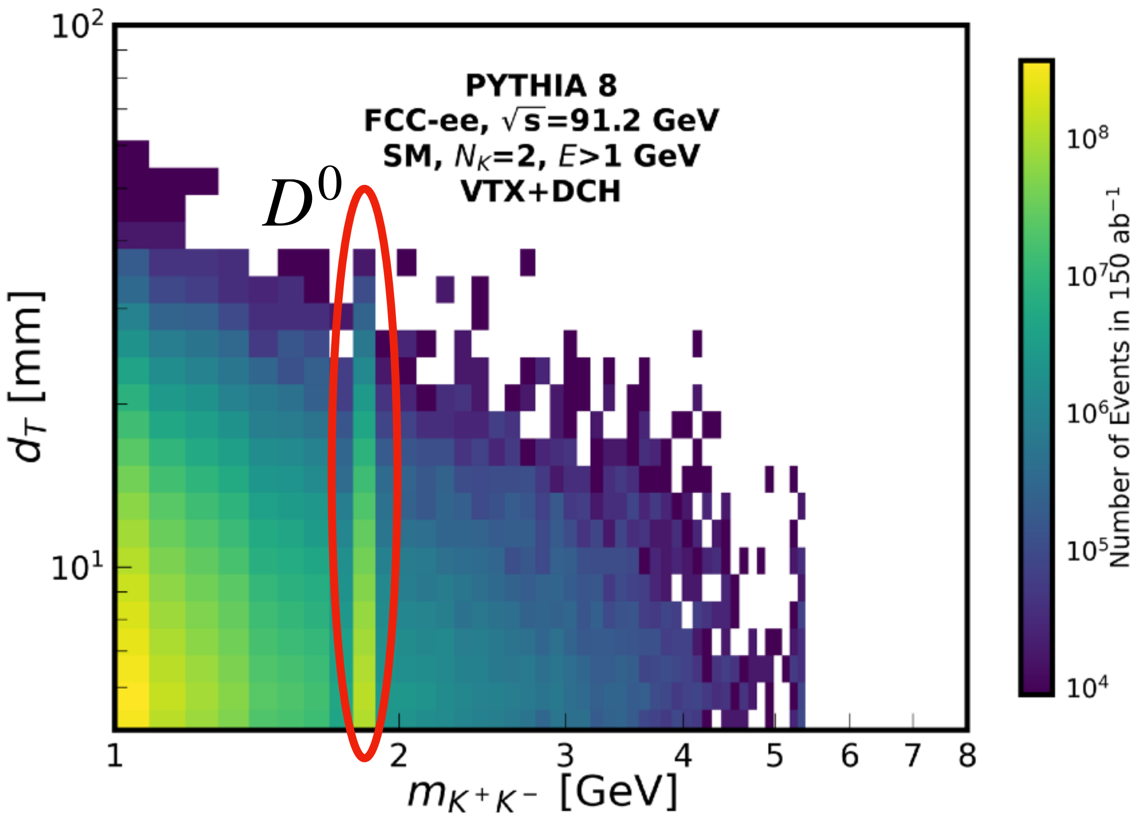
d_T threshold obtained from extrapolating the d_T distribution of $D^\pm$

Achieve zero SM LLP background after these cuts!

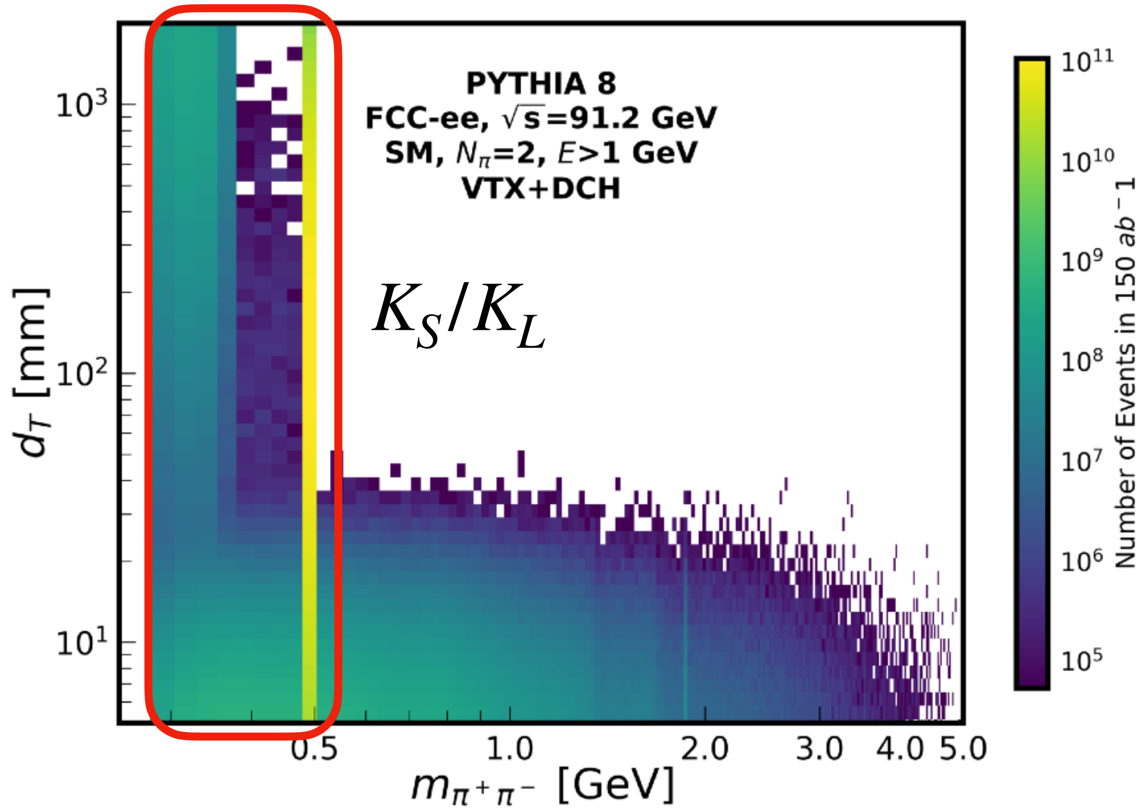
based on the extrapolation!

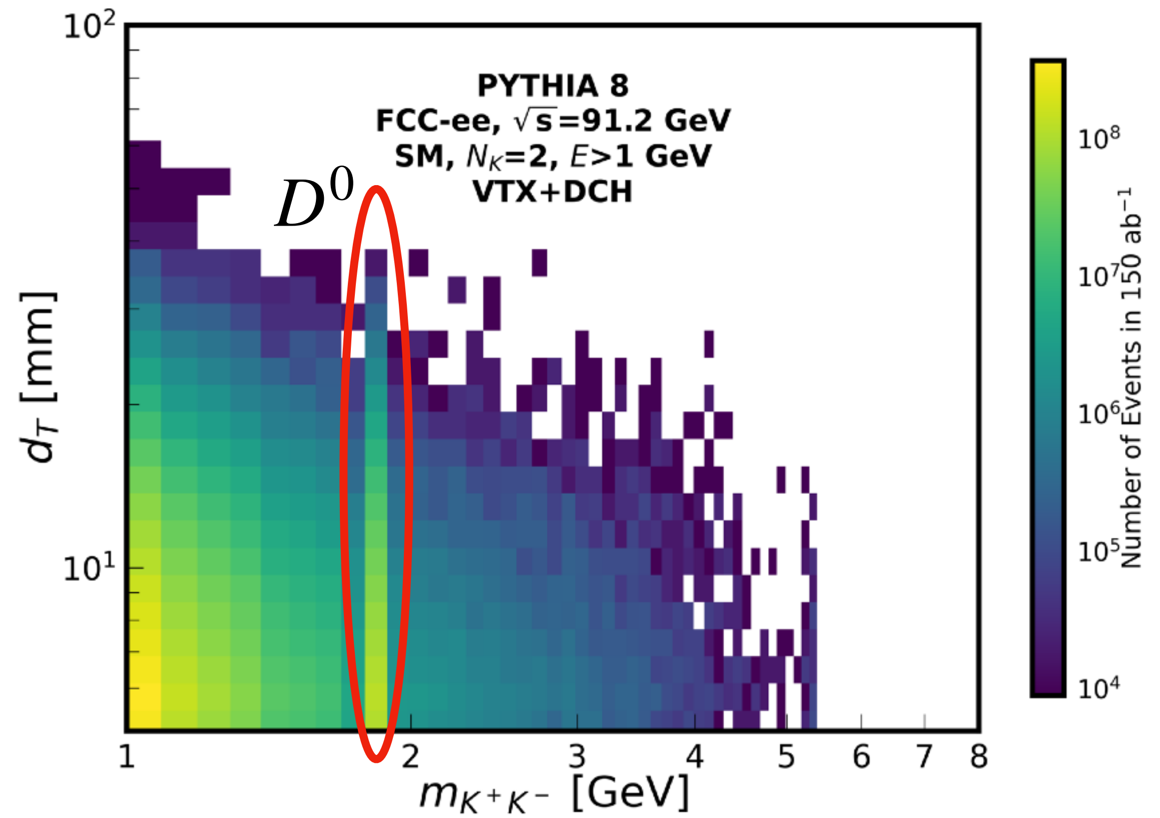
$B \to X_s\phi, \ \ \phi \to \pi^+\pi^-/K^+K^-$

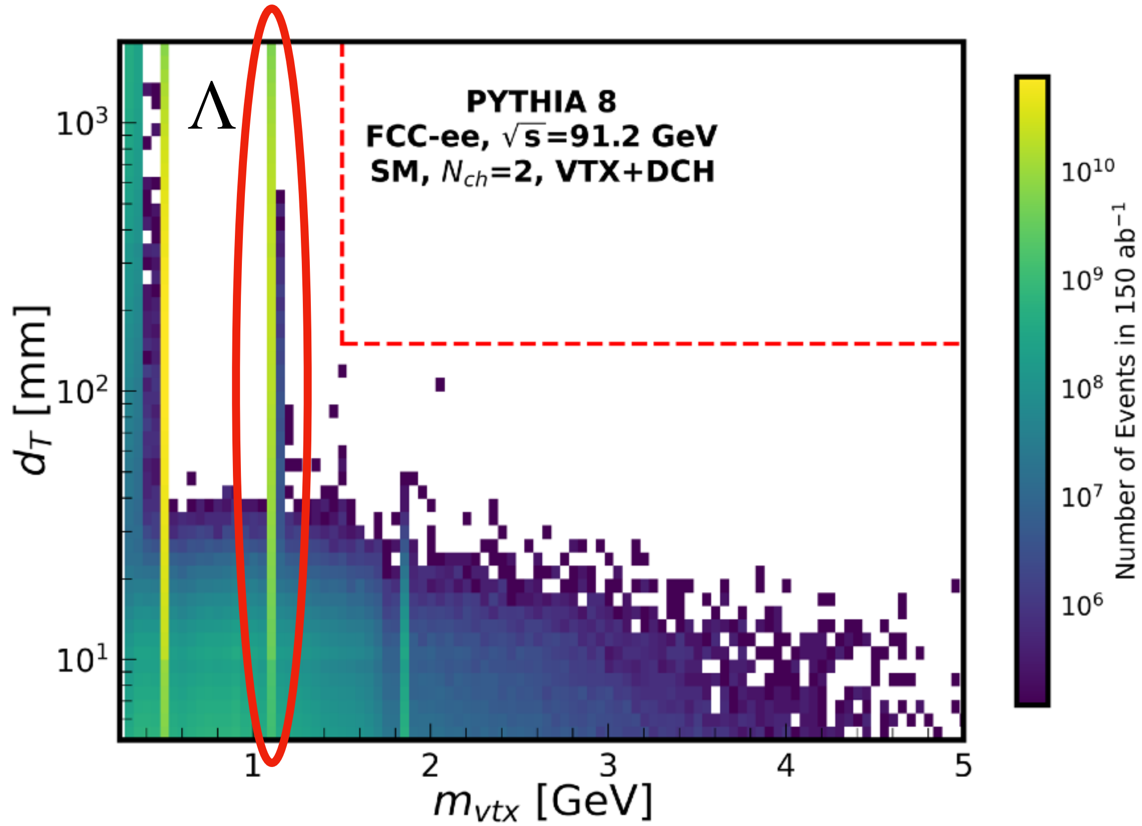




$B \to X_s\phi, \quad \phi \to \pi^+\pi^-/K^+K^-$

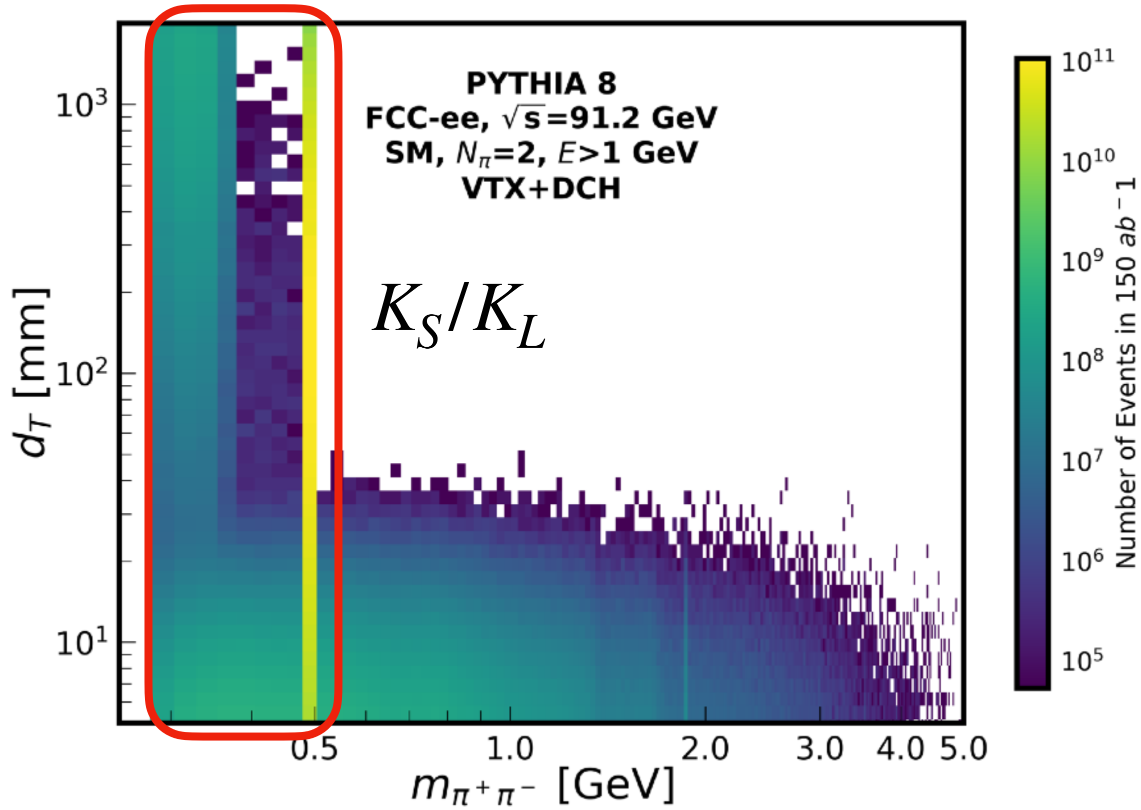


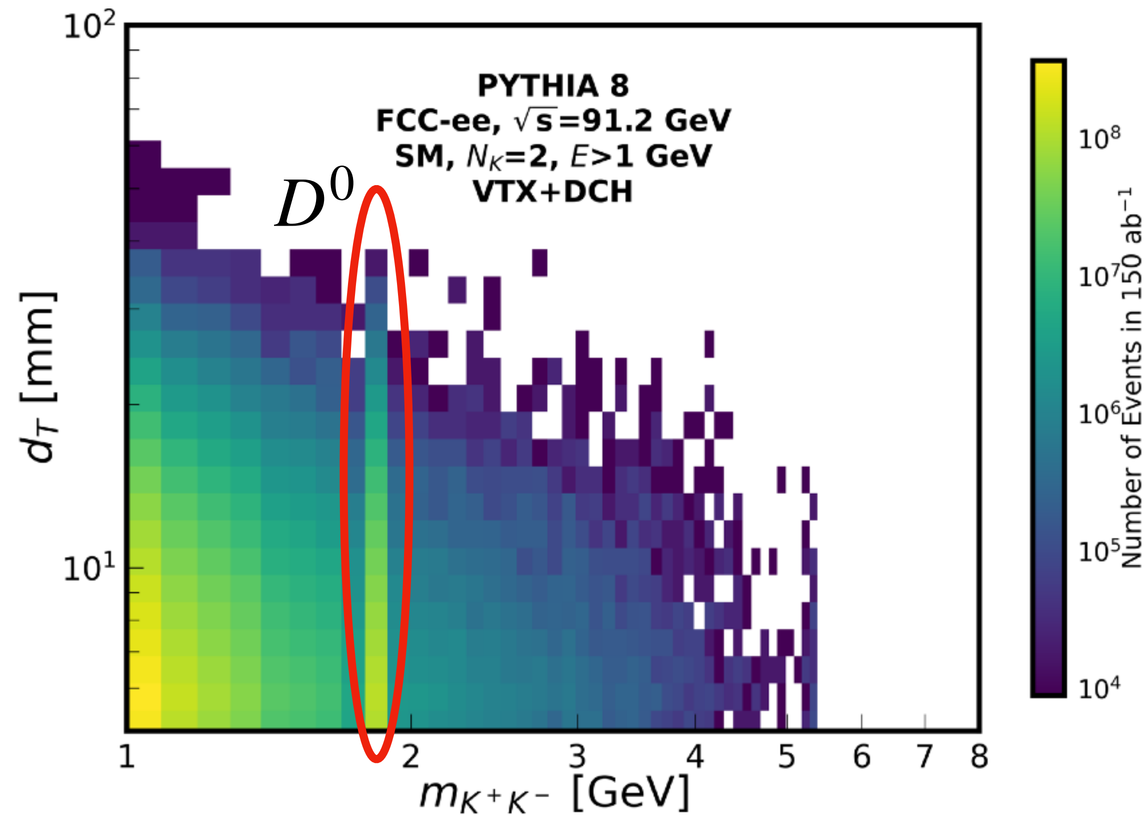


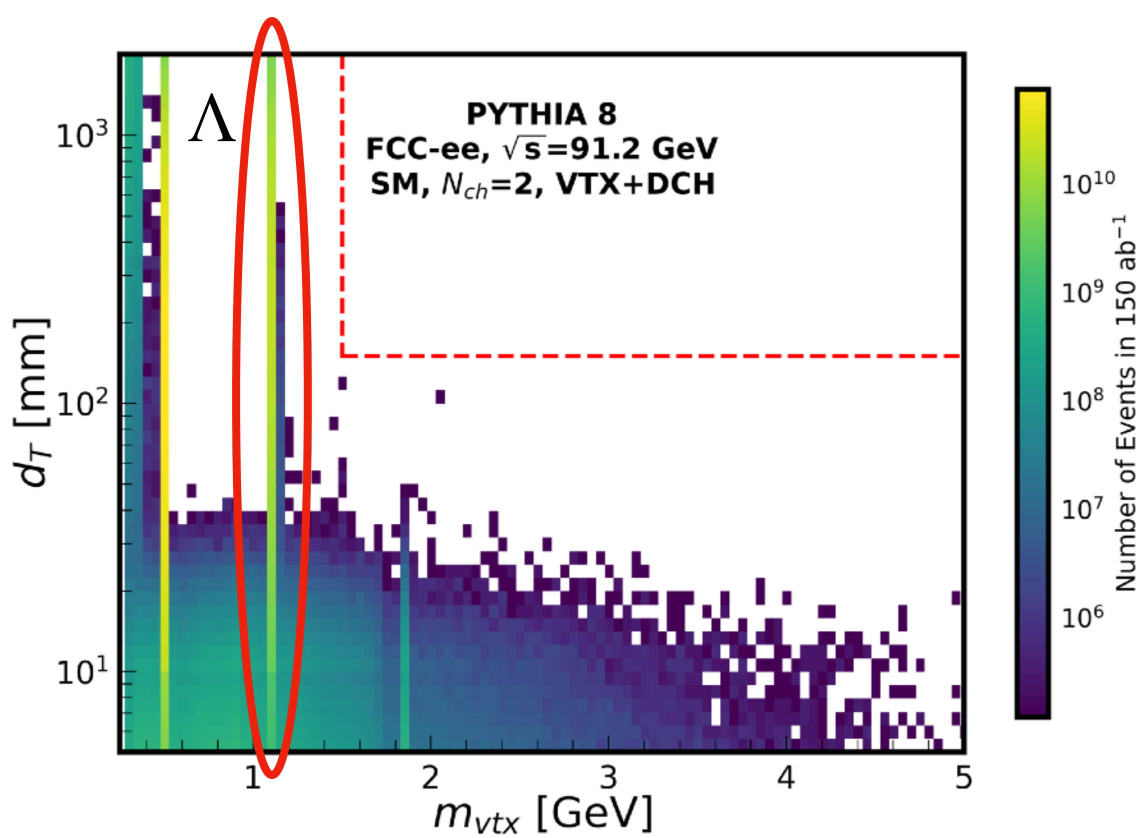


Protons misidentified as pions/kaons!

$B \to X_s\phi, \quad \phi \to \pi^+\pi^-/K^+K^-$



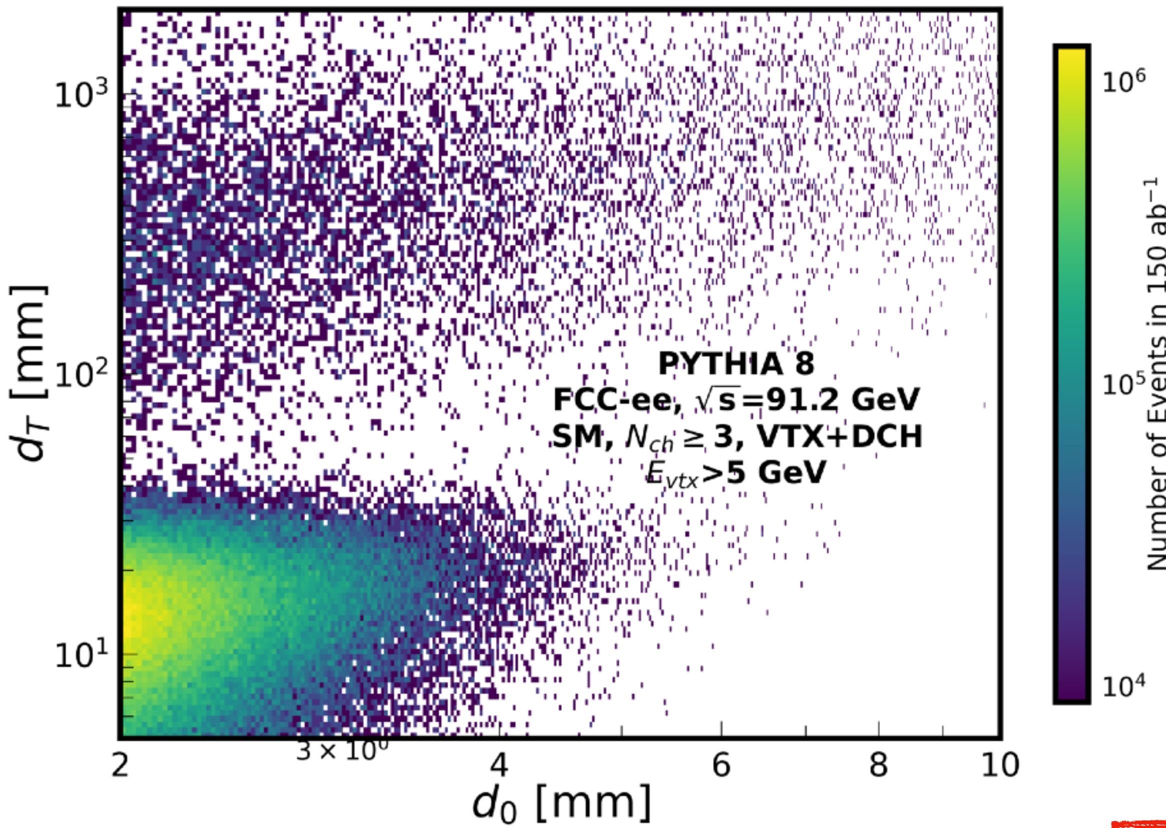


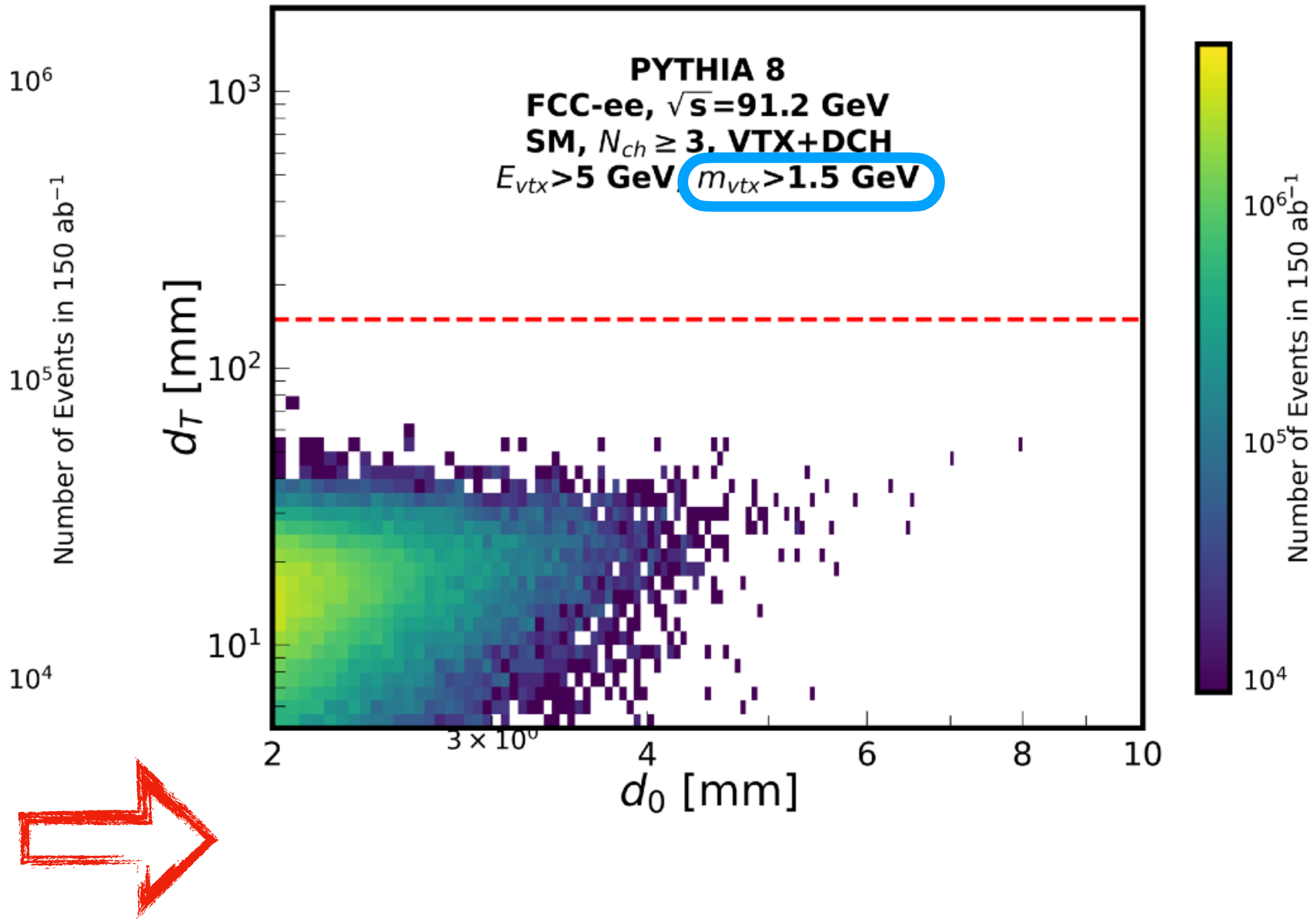


Protons misidentified as pions/kaons!

Final cuts for the di-pion/di-kaon final state	
$m_\phi \gtrsim 1.5\,\mathrm{GeV}$	All benchmarks
$D_{\rm vtx} \in$ VTX or DCH $N_{\rm ch} = 2$ $N_{\pi/K} = 2$ $E > 1\,\mathrm{GeV}$ $d_T > 150\,\mathrm{mm}$	$D_{\rm vtx} \in$ MS $N_{\rm ch} = 2$ $E > 5\,\mathrm{GeV}$

$B \to X_s\phi, \ \ \phi \to c\bar{c}$





Most of the highly displaced SM LLP backgrounds gone after the mass cut

$D_{vtx} \in$ VTX or DCH, $N_{ch} \geq 3$, $E > 5\,\text{GeV}$, $m_{vtx} > 1.5\,\text{GeV}$, $d_T > 150\,\text{mm}$, $|d_0| > 10\,\text{mm}$

$D_{vtx} \in$ MS, $N_{ch} \geq 3$, $E > 5\,\text{GeV}$

Results from $B \to X_s \phi$

outside the projected coverage —
Sensitivity at FCC-ee?
BPA7

Expect around 6 events in FCC-ee VTX+DCH

Dominant backgrounds from K_S, K_L, Λ

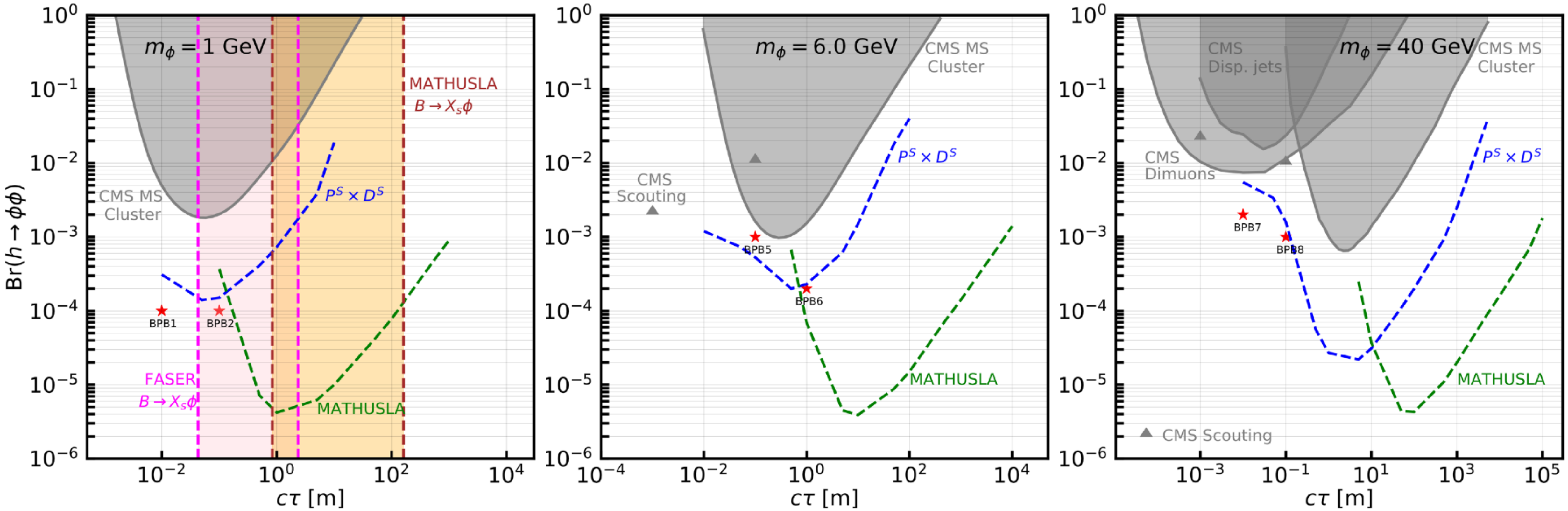
dominant decay to mesons —
Use the particle identification at FCC-ee!
BPA2, BPA3

Expect around 200 (70) events in FCC-ee MS

lies at corners of various future projections —
Can FCC-ee tell more?
BPA1, BPA4, BPA5, BPA6

e.g.,
BPA1: 3 (di-muon) + 4 (di-meson, MS) → Dedicated detectors?
BPA4: 9352 (di-muon) + 26202 (di-pion, VTX+DCH) + 26970 (di-kaon, VTX+DCH) + 1515 (di-meson, MS)

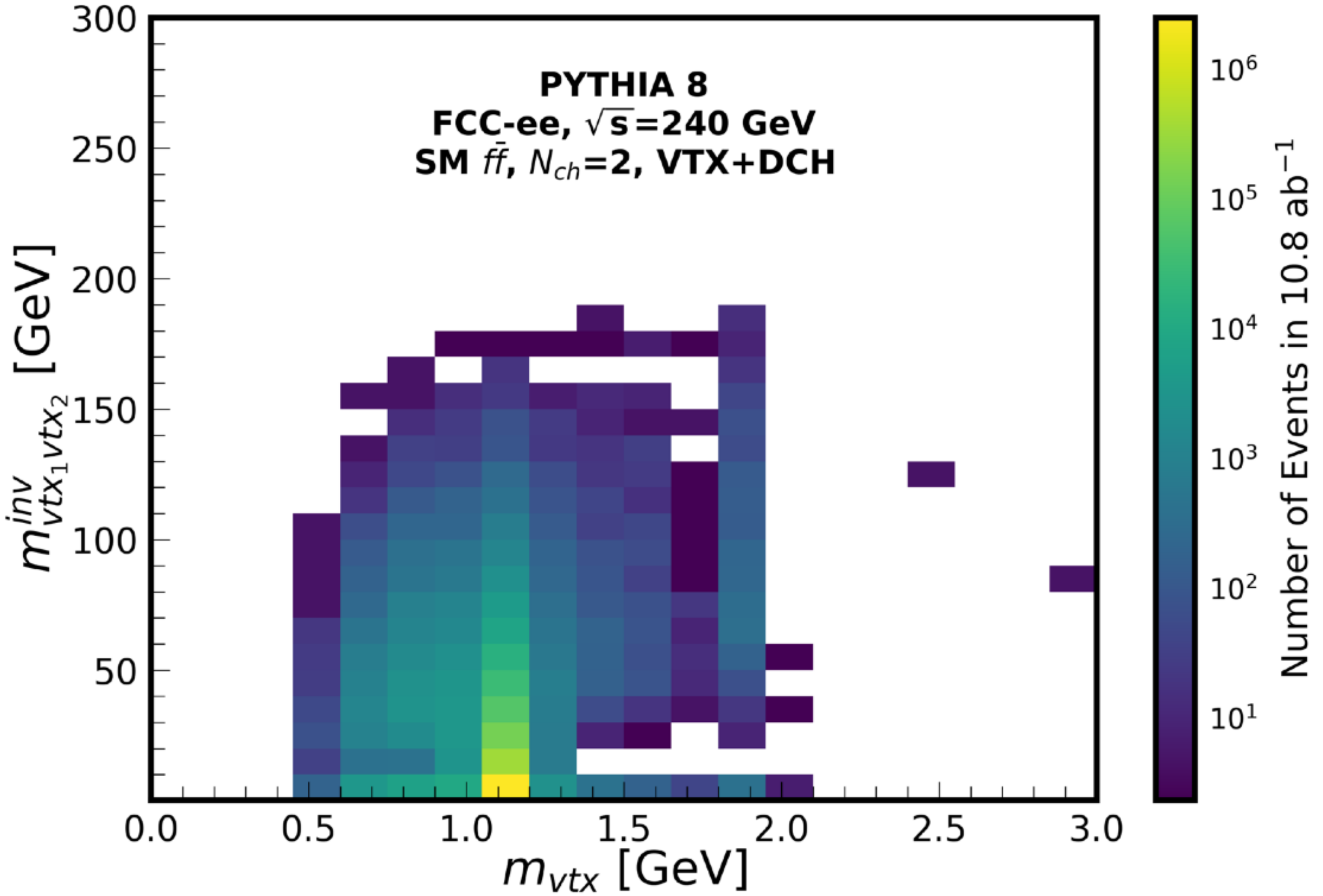
Benchmarks for FCC-ee: $h \to \phi\phi$



Benchmark	m_ϕ (GeV)	$\sin\theta$	$c\tau$ (mm)	$\mathrm{Br}(h \to \phi\phi)$	Dominant decay modes	Potential experiments to probe		
						HL-LHC	FASER	MATHUSLA
BPB1	1.0	1.1×10^{-4}	10	10^{-4}	$\pi^+\pi^-$: 50% K^+K^- : 50%	×	×	×
BPB2	1.0	3.5×10^{-5}	100	10^{-4}	$\pi^+\pi^-$: 50% K^+K^- : 50%	×	✓	×
BPB3	4.4	4.6×10^{-5}	10	10^{-2}	$c\bar{c}$: 65% $\tau^+\tau^-$: 20%	✓	×	×
BPB4	4.4	1.5×10^{-5}	100	5×10^{-4}	$c\bar{c}$: 65% $\tau^+\tau^-$: 20%	×	×	×
BPB5	6.0	1.1×10^{-5}	100	10^{-3}	$c\bar{c}$: 49% $\tau^+\tau^-$: 30%	✓	×	×
BPB6	6.0	3.4×10^{-6}	1000	2×10^{-4}	$c\bar{c}$: 49% $\tau^+\tau^-$: 30%	×	×	✓
BPB7	40.0	4.2×10^{-6}	10	2×10^{-3}	$b\bar{b}$: 100%	×	×	×
BPB8	40.0	1.3×10^{-6}	100	10^{-3}	$b\bar{b}$: 100%	×	×	×

$h \to \phi\phi, \;\; \phi \to \pi^+\pi^-/K^+K^-$

SM Backgrounds	Cross-section (pb)	Expected number of events
$e^+e^- \to f\bar{f}$	21.43	2.3×10^8
$e^+e^- \to W^+W^-$	16.84	1.8×10^8
$e^+e^- \to ZZ$	1.4	1.5×10^7
$e^+e^- \to Zh$	0.237	2.5×10^6



$D_{\rm vtx} \in$ VTX or DCH,

$N_{\rm ch} = 2, E > 1$ GeV,

$N_{\rm vtx} = 2$,

$m_{{\rm vtx}_{1/2}} > 0.5$ GeV,

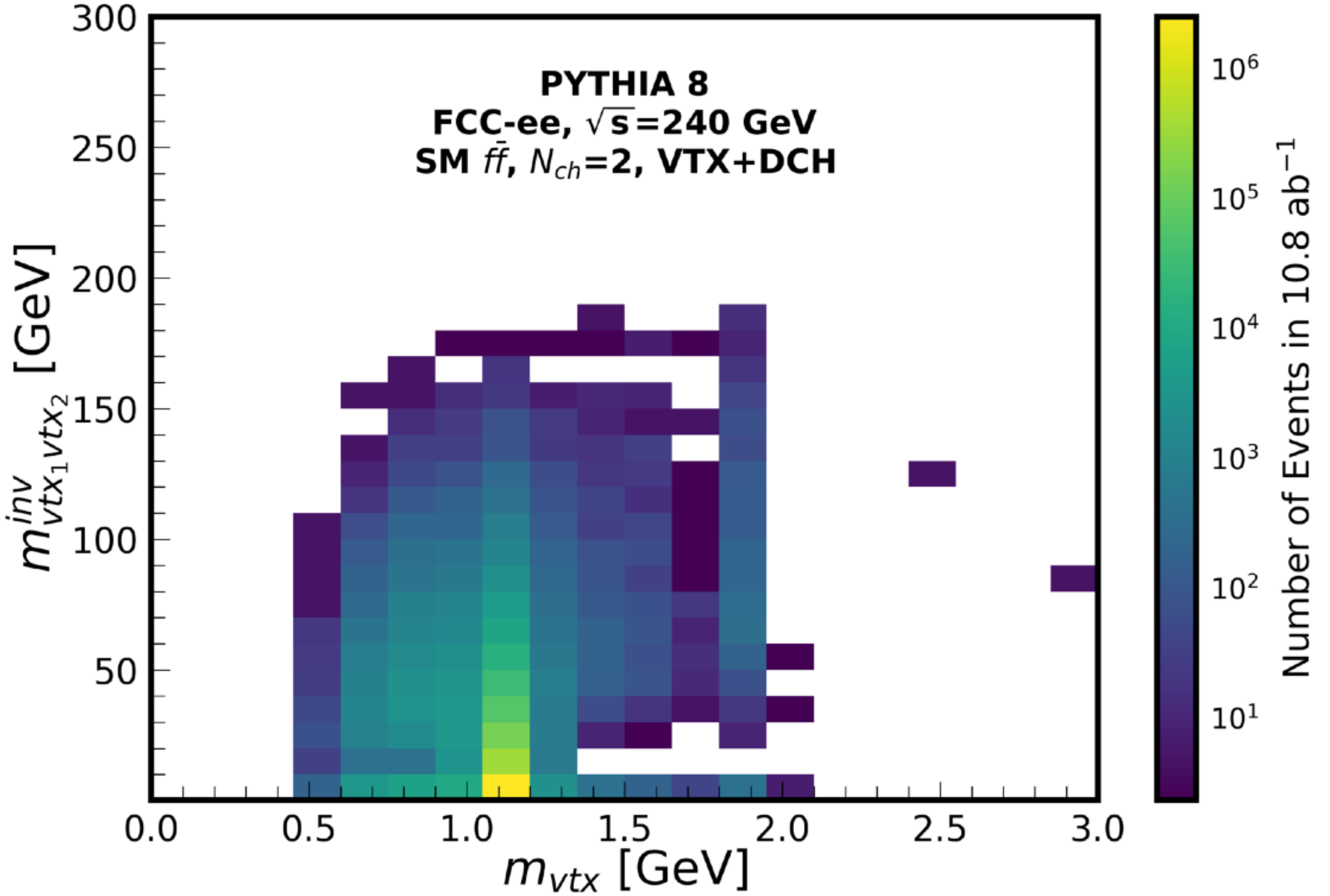
$|m_{{\rm vtx}_1} - m_{{\rm vtx}_2}| < 0.1$ GeV

Distributions for other backgrounds in the backup

$h \to \phi\phi, \;\; \phi \to \pi^+\pi^- / K^+K^-$

SM Backgrounds	Cross-section (pb)	Expected number of events
$e^+e^- \to f\bar{f}$	21.43	2.3×10^8
$e^+e^- \to W^+W^-$	16.84	1.8×10^8
$e^+e^- \to ZZ$	1.4	1.5×10^7
$e^+e^- \to Zh$	0.237	2.5×10^6

Our analysis relies on finding two displaced vertices: leptonic decay of Z not used!



Distributions for other backgrounds in the backup

$D_{\mathrm{vtx}} \in$ VTX or DCH,

$N_{\mathrm{ch}} = 2, E > 1$ GeV,

$N_{\mathrm{vtx}} = 2,$

$m_{\mathrm{vtx}_{1/2}} > 0.5$ GeV,

$|m_{\mathrm{vtx}_1} - m_{\mathrm{vtx}_2}| < 0.1$ GeV

Two displaced vertices

$h \to \phi\phi, \quad \phi \to \pi^+\pi^-/K^+K^-$

SM Backgrounds	Cross-section (pb)	Expected number of events
$e^+e^- \to f\bar{f}$	21.43	2.3×10^8
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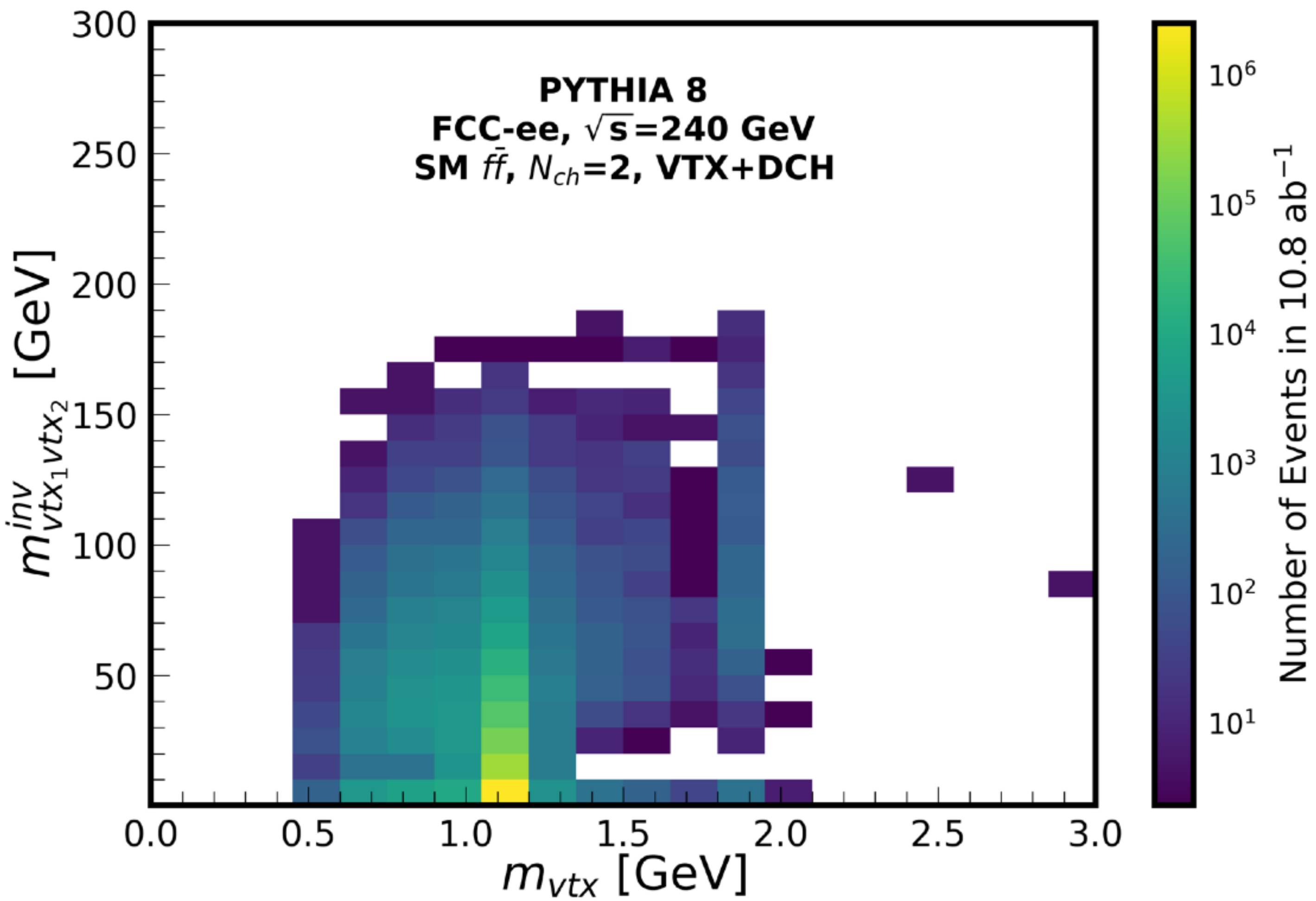

Distributions for other backgrounds in the backup

$D_{vtx} \in$ VTX or DCH,

$N_{ch} = 2, E > 1$ GeV,

$N_{vtx} = 2$,

$m_{vtx_{1/2}} > 0.5$ GeV,

$|m_{vtx_1} - m_{vtx_2}| < 0.1$ GeV

Signal has two identical LLPs

$h \to \phi\phi, \quad \phi \to \pi^+\pi^- / K^+K^-$

SM Backgrounds	Cross-section (pb)	Expected number of events
$e^+e^- \to f\bar{f}$	21.43	2.3×10^8
$e^+e^- \to W^+W^-$	16.84	1.8×10^8
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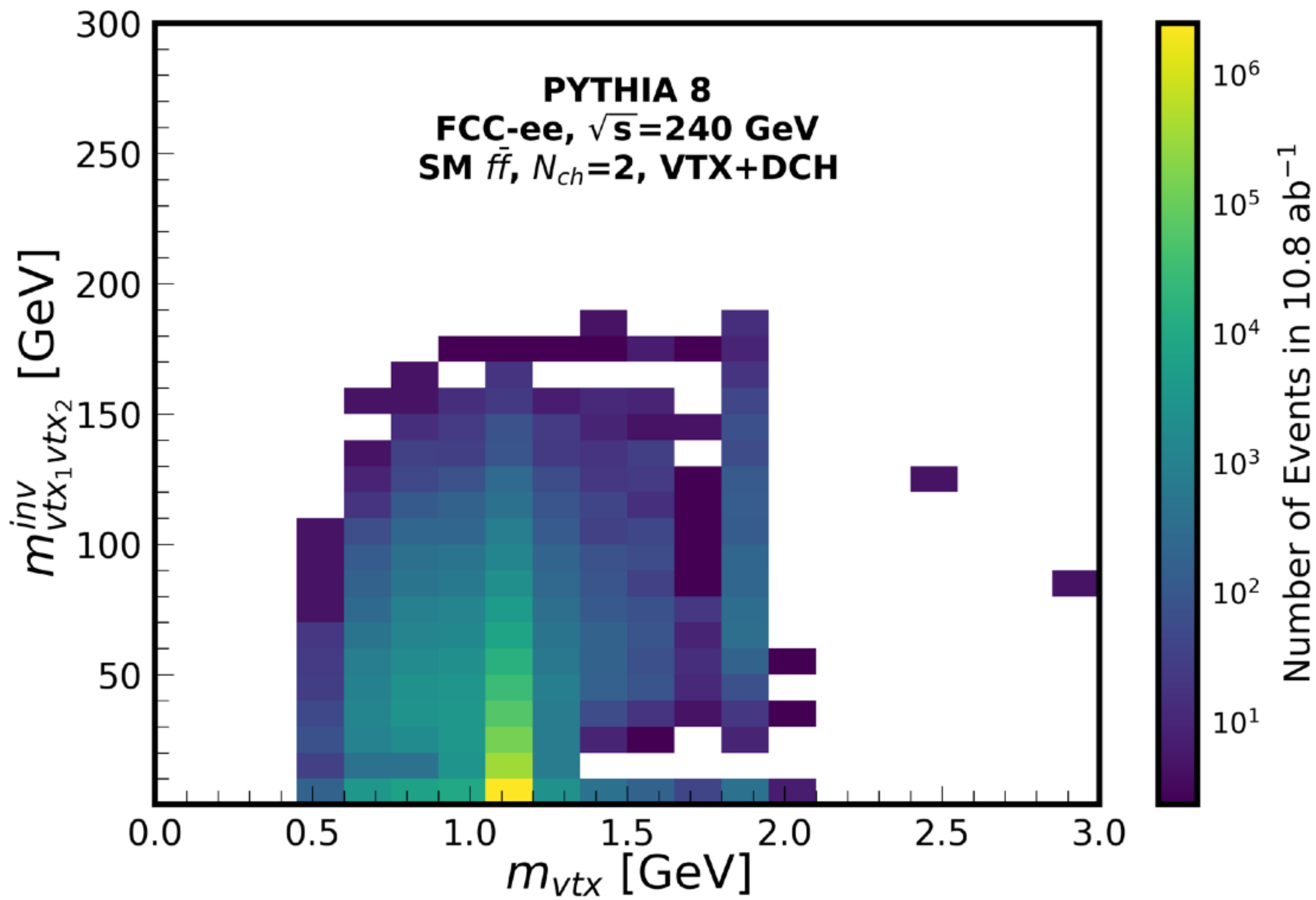


Distributions for other backgrounds in the backup

$D_{\text{vtx}} \in \text{VTX or DCH},$

$N_{\text{ch}} = 2, E > 1\,\text{GeV},$

$N_{\text{vtx}} = 2,$

$m_{\text{vtx}_{1/2}} > 0.5\,\text{GeV},$

$|m_{\text{vtx}_1} - m_{\text{vtx}_2}| < 0.1\,\text{GeV},$

$122\,\text{GeV} < m^{\text{inv}}_{\text{vtx}_1\text{vtx}_2} < 128\,\text{GeV},$

$N_p = 0, N_{K^\pm} = 2, N_{\pi^\pm} = 2,$

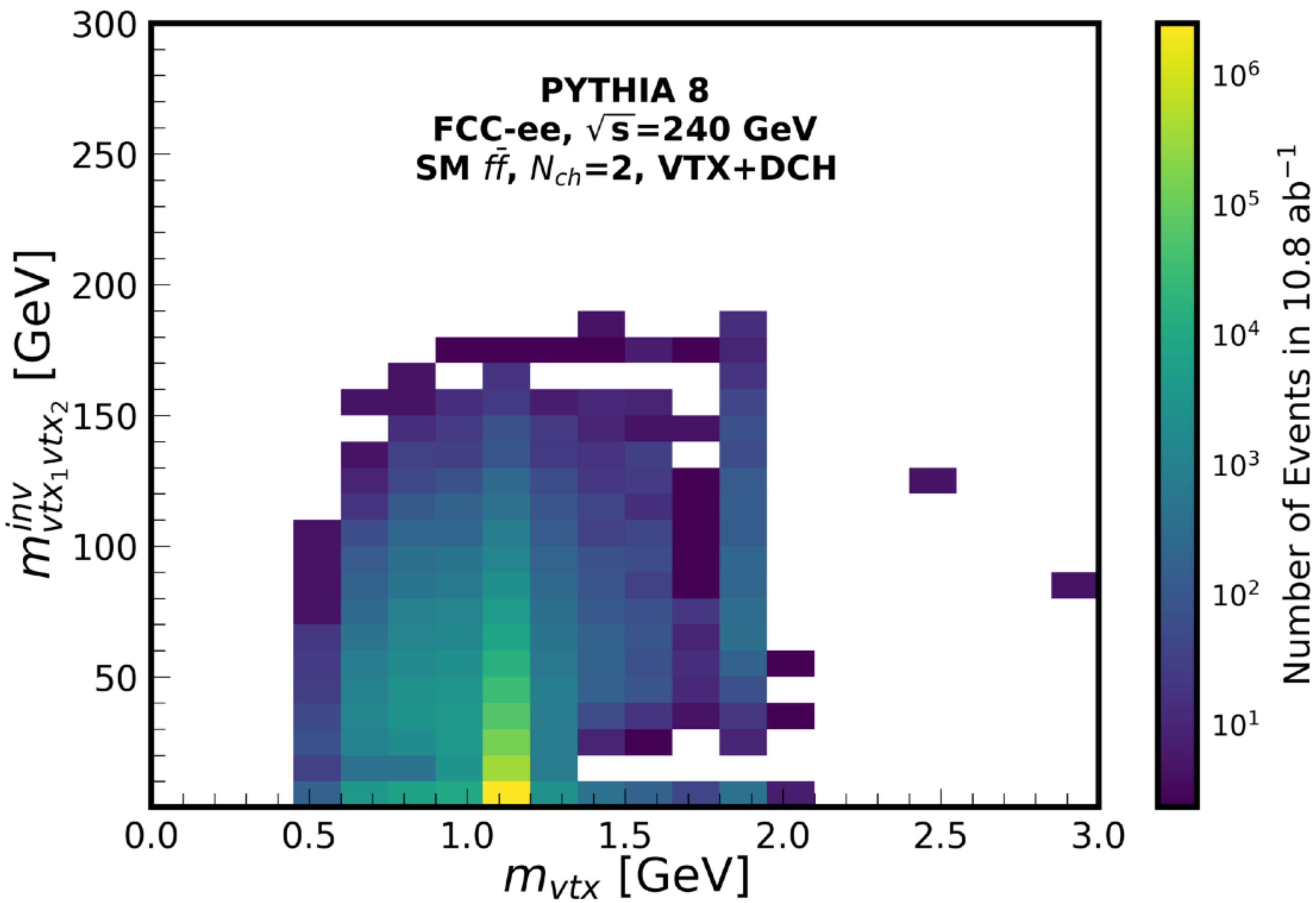
$d_T > 100\,\text{mm}$

The two vertices come from Higgs decay

$h \to \phi\phi, \quad \phi \to \pi^+\pi^-/K^+K^-$

SM Backgrounds	Cross-section (pb)	Expected number of events
$e^+e^- \to f\bar{f}$	21.43	2.3×10^8
$e^+e^- \to W^+W^-$	16.84	1.8×10^8
$e^+e^- \to ZZ$	1.4	1.5×10^7
$e^+e^- \to Zh$	0.237	2.5×10^6

Our analysis relies on finding two displaced vertices: leptonic decay of Z not used!



Distributions for other backgrounds in the backup

$D_{\rm vtx} \in$ VTX or DCH,

$N_{\rm ch} = 2, E > 1\,{\rm GeV}$,

$N_{\rm vtx} = 2$,

$m_{{\rm vtx}_{1/2}} > 0.5\,{\rm GeV}$,

$|m_{{\rm vtx}_1} - m_{{\rm vtx}_2}| < 0.1\,{\rm GeV}$,

$122\,{\rm GeV} < m^{\rm inv}_{{\rm vtx}_1{\rm vtx}_2} < 128\,{\rm GeV}$,

$N_p = 0, N_{K^\pm} = 2, N_{\pi^\pm} = 2$,

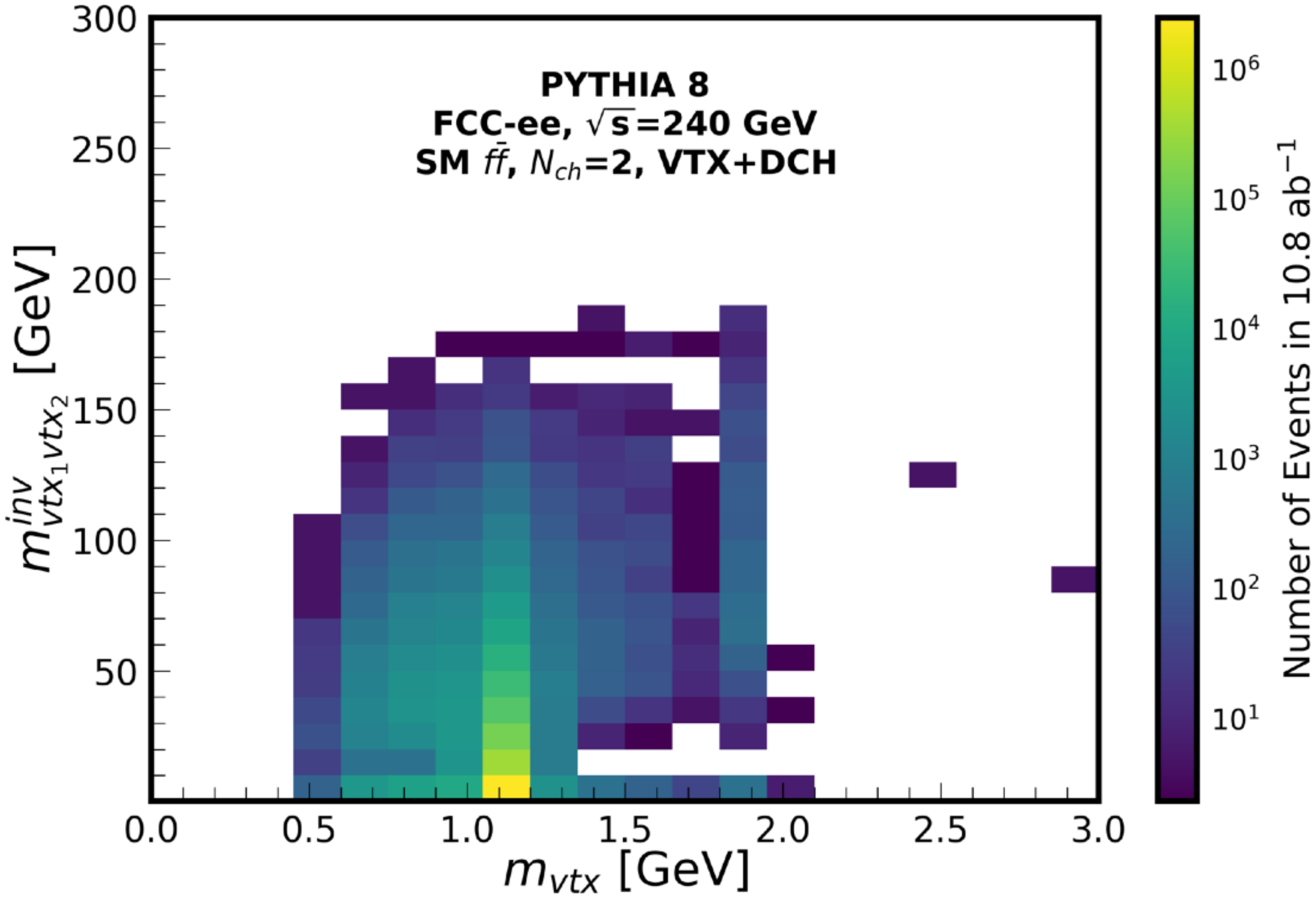
$d_T > 100\,{\rm mm}$

Proton veto

$h \to \phi\phi, \;\; \phi \to \pi^+\pi^- / K^+K^-$

SM Backgrounds	Cross-section (pb)	Expected number of events
$e^+e^- \to f\bar{f}$	21.43	2.3×10^8
$e^+e^- \to W^+W^-$	16.84	1.8×10^8
$e^+e^- \to ZZ$	1.4	1.5×10^7
$e^+e^- \to Zh$	0.237	2.5×10^6

Our analysis relies on finding two displaced vertices: leptonic decay of Z not used!



Distributions for other backgrounds in the backup

$D_{\text{vtx}} \in \text{VTX or DCH},$

$N_{\text{ch}} = 2, E > 1\,\text{GeV},$

$N_{\text{vtx}} = 2,$

$m_{\text{vtx}_{1/2}} > 0.5\,\text{GeV},$

$|m_{\text{vtx}_1} - m_{\text{vtx}_2}| < 0.1\,\text{GeV},$

$122\,\text{GeV} < m^{\text{inv}}_{\text{vtx}_1\text{vtx}_2} < 128\,\text{GeV},$

$N_p = 0, N_{K^\pm} = 2, N_{\pi^\pm} = 2,$

$d_T > 100\,\text{mm}$

Achieve zero SM LLP background after these cuts!

Results from $h \to \phi\phi$

Analyses for $\phi \to c\bar{c}$ and $\phi \to b\bar{b}$ are detailed in the backup

Benchmark	m_ϕ (GeV)	$\sin\theta$	$c\tau$ (mm)	$\mathrm{Br}(h \to \phi\phi)$	Dominant decay modes	Potential experiments to probe			FCC-ee VTX+DCH
						HL-LHC	FASER	MATHUSLA	
BPB1	1.0	1.1×10^{-4}	10	10^{-4}	$\pi^+\pi^-$: 50% K^+K^- : 50%	×	×	×	143
BPB2	1.0	3.5×10^{-5}	100	10^{-4}	$\pi^+\pi^-$: 50% K^+K^- : 50%	×	✓	×	18

Results from $h \to \phi\phi$

Analyses for $\phi \to c\bar{c}$ and $\phi \to b\bar{b}$ are detailed in the backup

Benchmark	m_ϕ (GeV)	$\sin\theta$	$c\tau$ (mm)	$\mathrm{Br}(h \to \phi\phi)$	Dominant decay modes	Potential experiments to probe			FCC-ee VTX+DCH
						HL-LHC	FASER	MATHUSLA	
BPB1	1.0	1.1×10^{-4}	10	10^{-4}	$\pi^+\pi^-$: 50% K^+K^- : 50%	×	×	×	143
BPB2	1.0	3.5×10^{-5}	100	10^{-4}	$\pi^+\pi^-$: 50% K^+K^- : 50%	×	✓	×	18

Much lower branching fractions can be probed for 3 observed events

Results from $h \to \phi\phi$

Analyses for $\phi \to c\bar{c}$ and $\phi \to b\bar{b}$ are detailed in the backup

Benchmark	m_ϕ (GeV)	$\sin\theta$	$c\tau$ (mm)	$\mathrm{Br}(h \to \phi\phi)$	Dominant decay modes	Potential experiments to probe			FCC-ee VTX+DCH
						HL-LHC	FASER	MATHUSLA	
BPB1	1.0	1.1×10^{-4}	10	10^{-4}	$\pi^+\pi^-$: 50% K^+K^- : 50%	×	×	×	143
BPB2	1.0	3.5×10^{-5}	100	10^{-4}	$\pi^+\pi^-$: 50% K^+K^- : 50%	×	✓	×	18

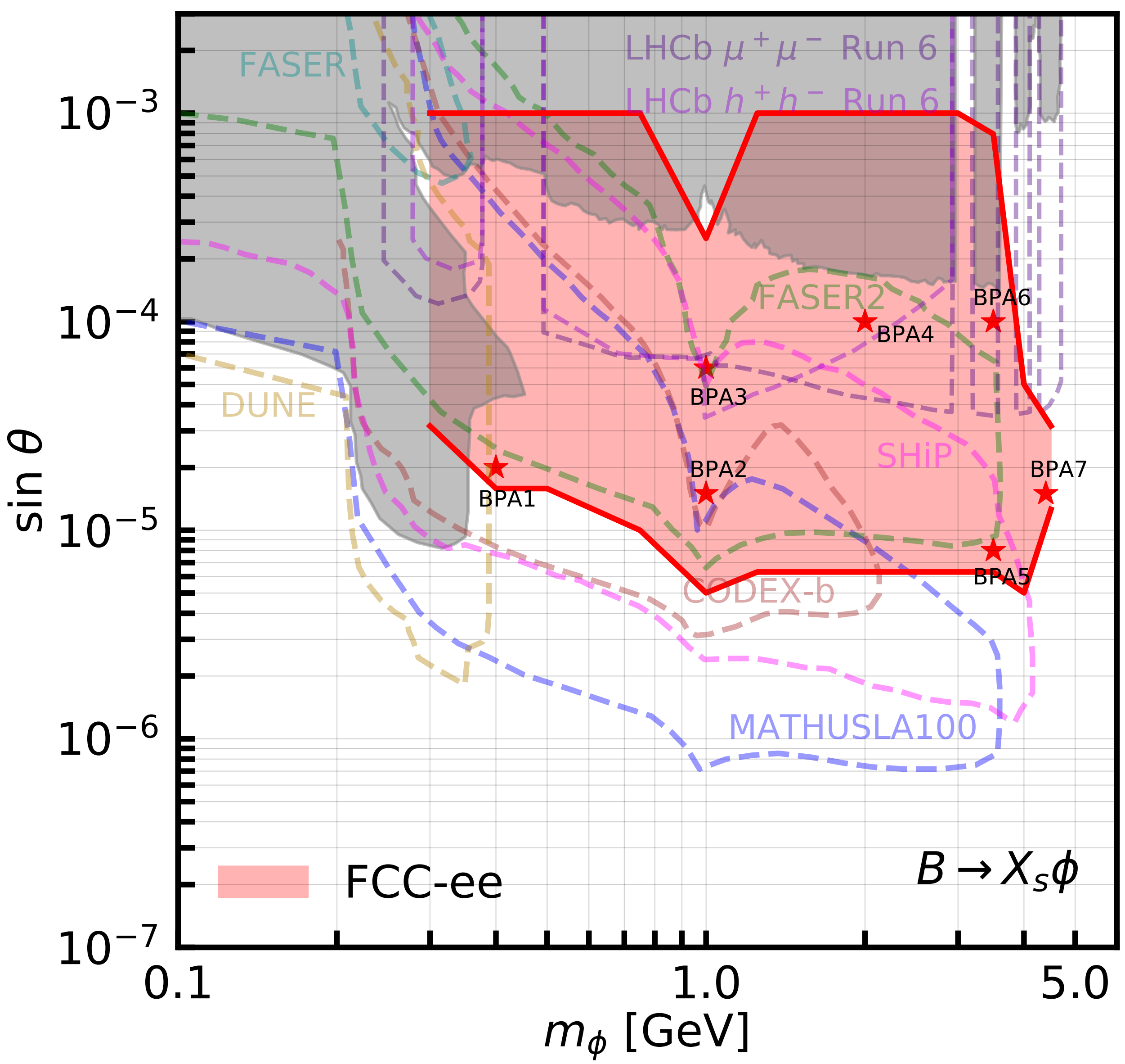
Much lower branching fractions can be probed for 3 observed events

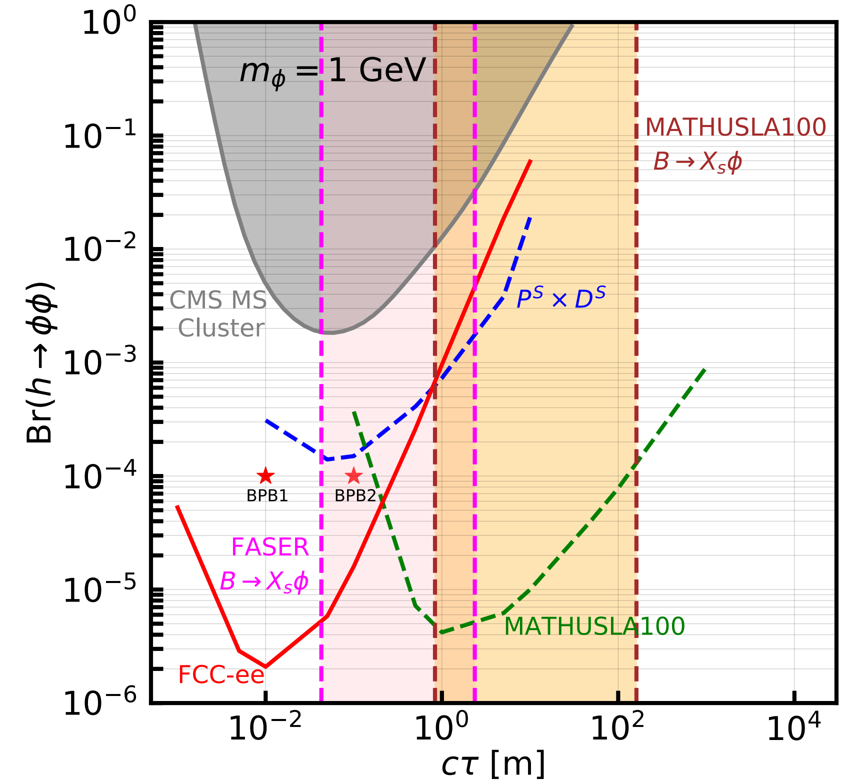
!

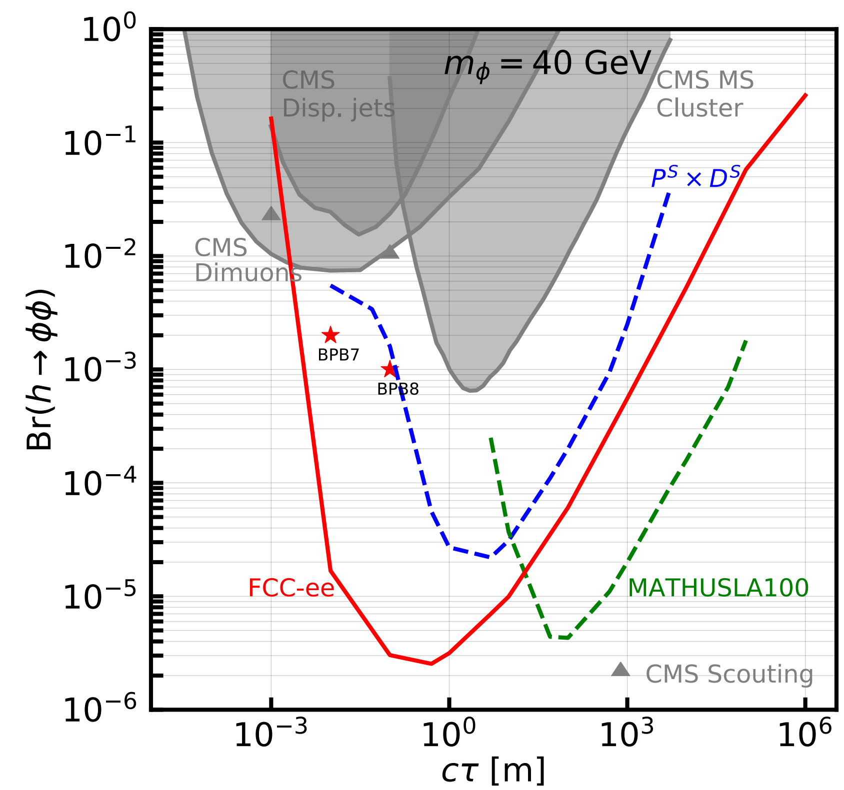
If we observe a signal for $B \to X_s\phi$ in experiments like SHiP or FASER2,

FCC-ee will be important to analyse whether the $h \to \phi\phi$ coupling exists!

Performance for BC4 and BC5







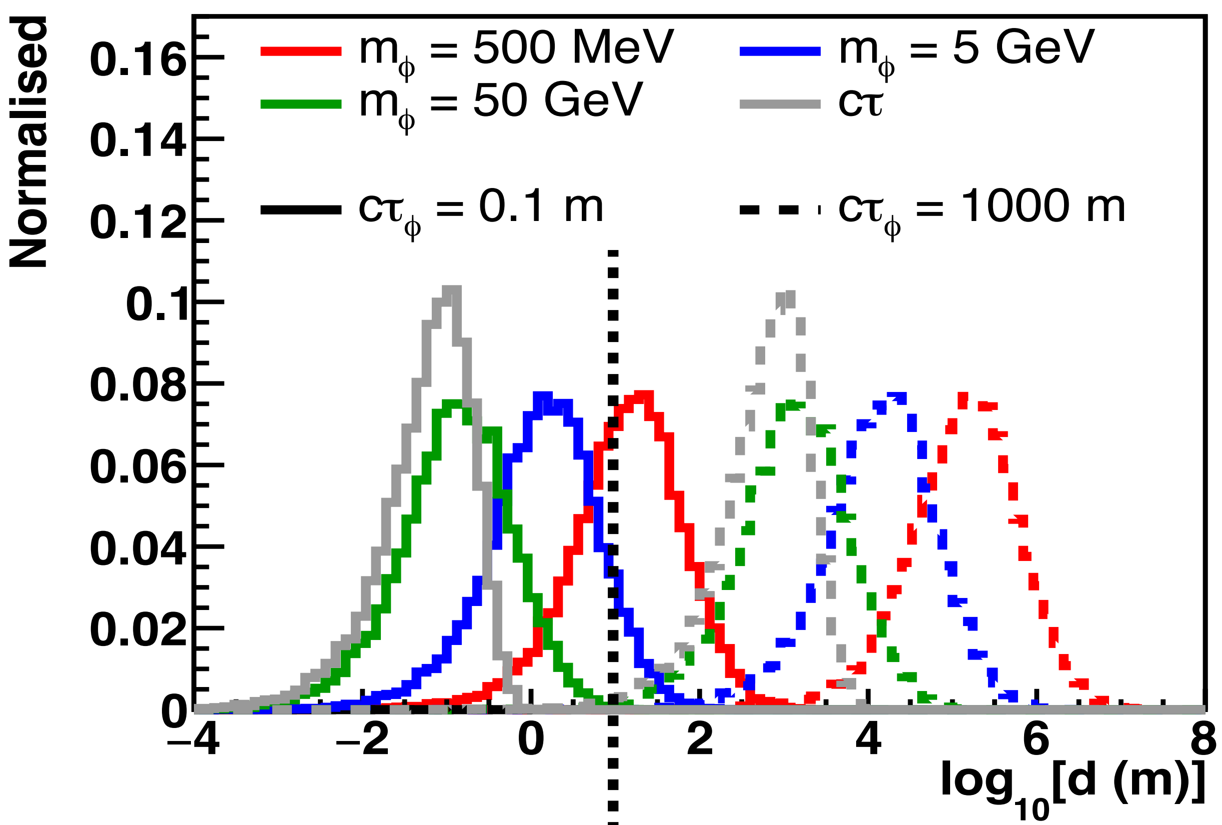
Sensitivity to new regions
of parameter space!

Outline

- ☑ Dedicated triggers
- ☑ Leveraging Pile-up
- ☑ Searches in the Muon Spectrometer
- ☑ Role of FCC-ee
- ☐ **Upgrading ZDCs for LLPs**
- ☐ Optimised dedicated LLP detectors

Dedicated detectors for LLPs

Distribution of decay length in the lab frame, $d = \beta\gamma c\tau$



ATLAS and CMS main detectors can probe

after $\mathcal{O}(10)$ m, ATLAS and CMS main detectors lose sensitivity

HL-LHC:

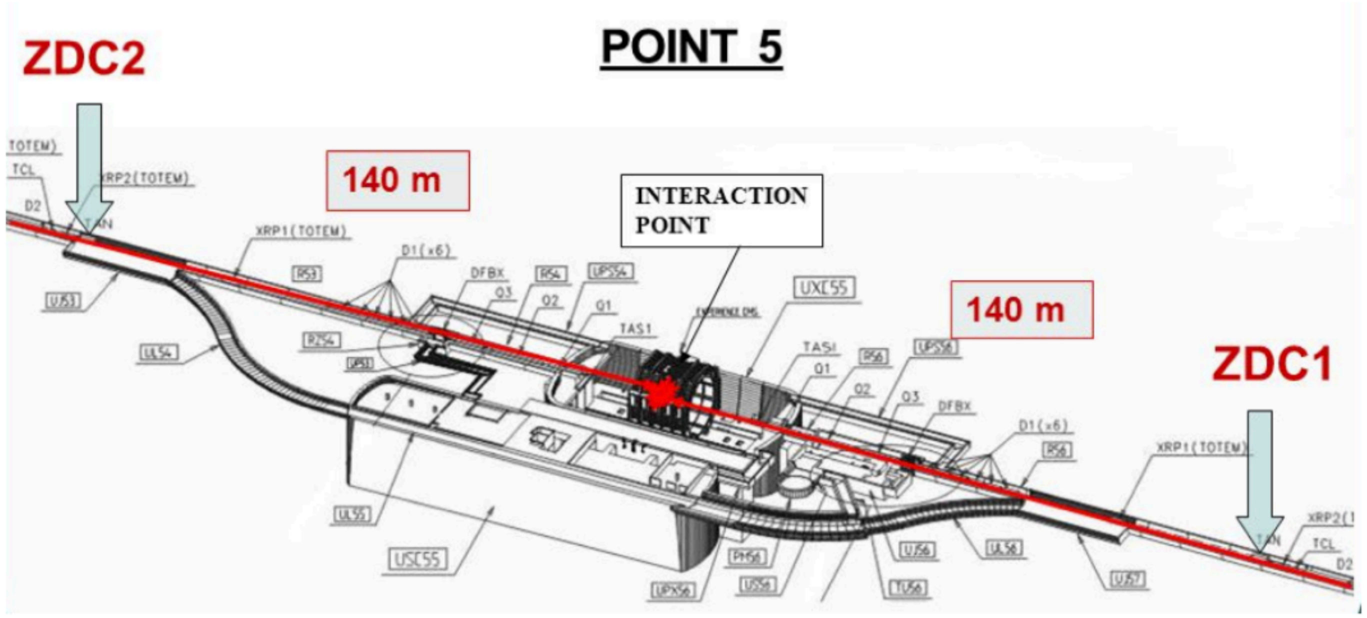
FASER	1811.12522
FACET	2201.00019
MATHUSLA	1901.04040
CODEX-b	1911.00481
ANUBIS	1909.13022
AL3X	1810.03636

BELLE-II: GAZELLE

2105.12962

Existing facility at HL-LHC

For example, let us look at the CMS Zero Degree Calorimeters (ZDC)

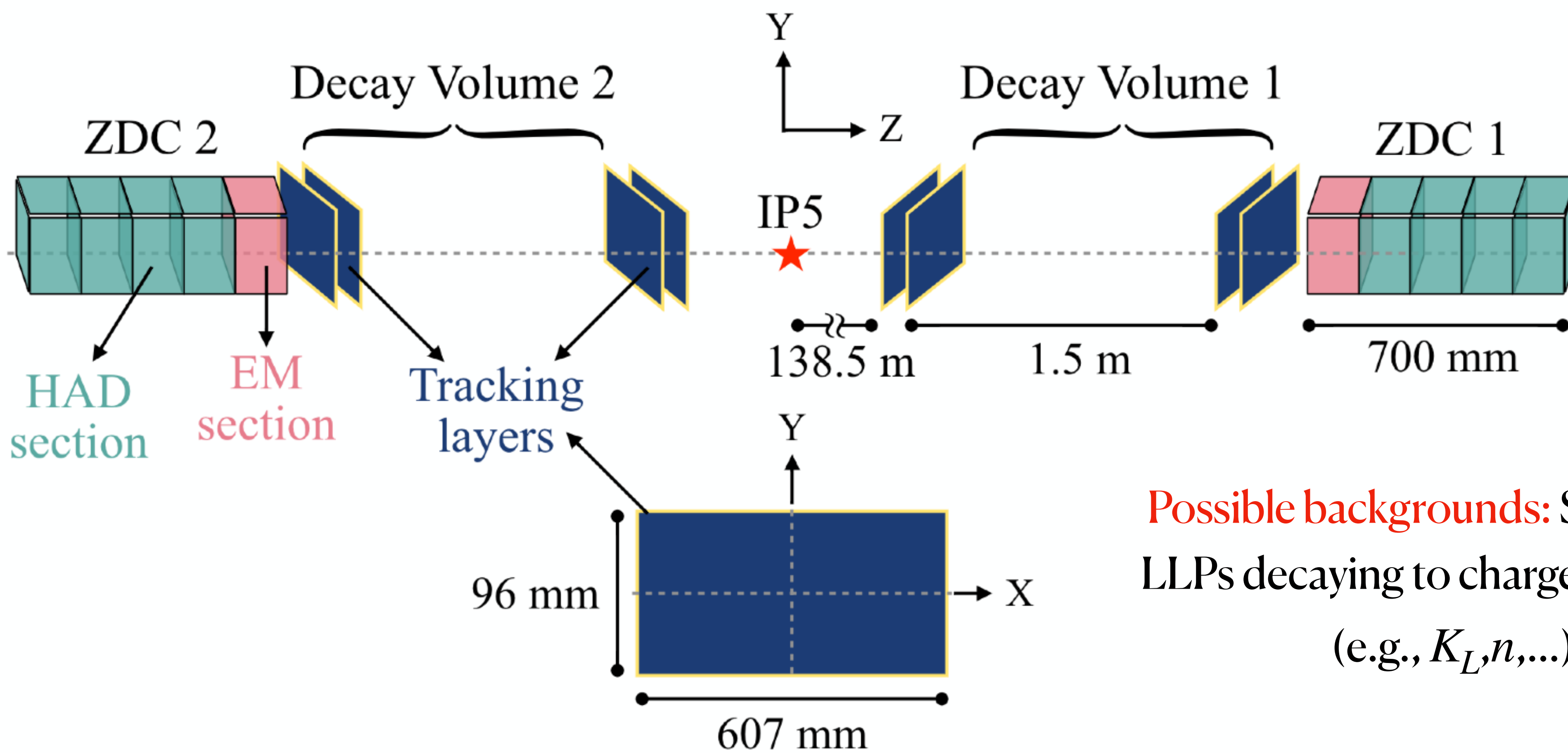


- Located ±140 meters from the IP - on both sides of the IP.
- Detects neutral particles at pseudorapidity $|\eta| > 8.3$.
- Each ZDC consists of electromagnetic (19 radiation lengths and hadronic (5.6 interaction lengths) sections, designed to measure forward neutral particles like neutrons and photons.
- Charged particles are typically deflected away by magnets before reaching the ZDCs.

Existing facility at HL-LHC

ZDC for LLPs: our proposal for HL-LHC

Forward Dedicated LLP detector in front of ZDC at CMS



Possible backgrounds: SM neutral LLPs decaying to charged particles (e.g., K_L,n,...)

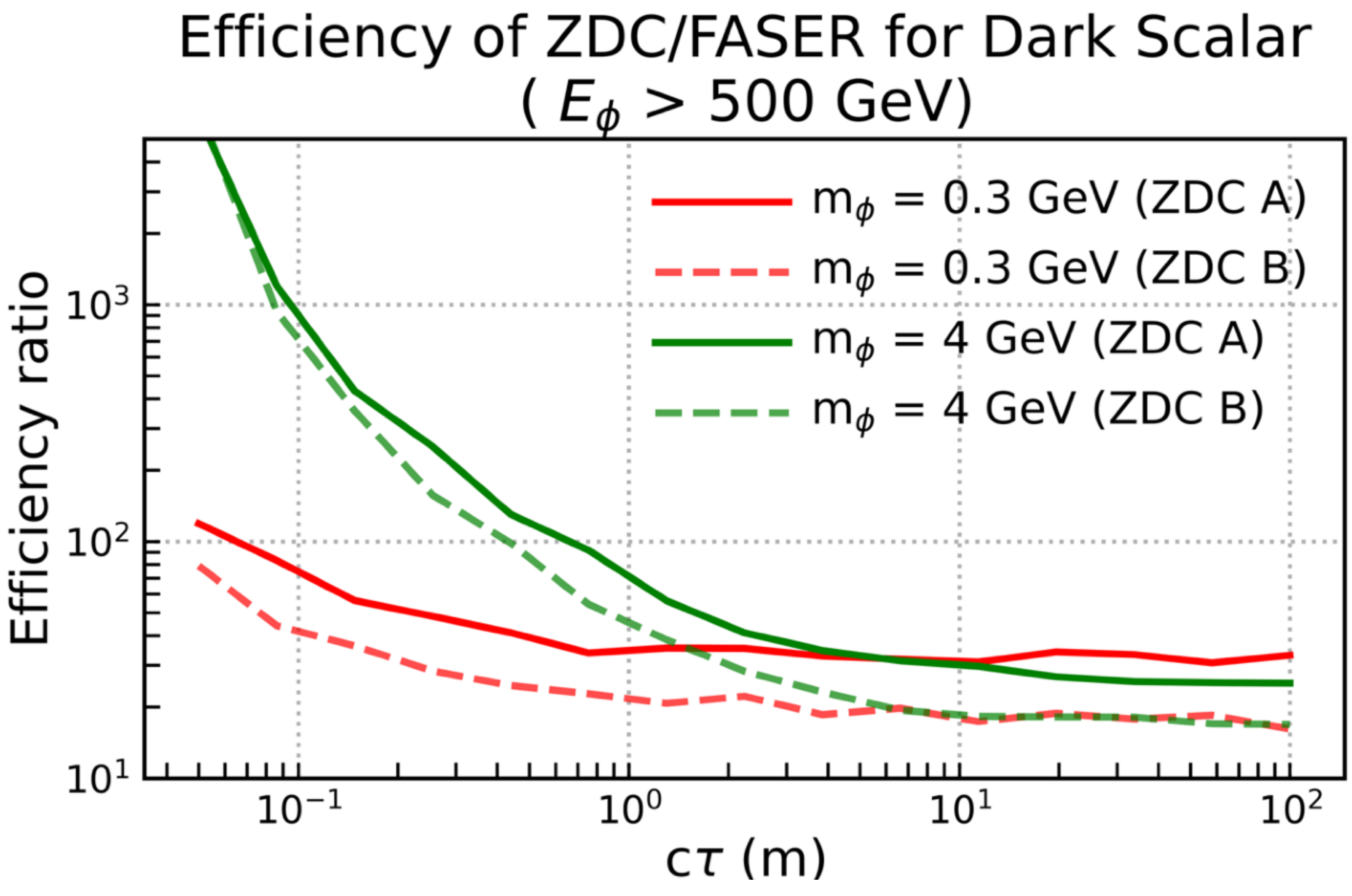
Biplob Bhattacherjee, Abhinav Kumar, Swagata Mukherjee, RS, Anand Sharma, e-Print: 2503.11760

We have contacted and shared this proposal with the ZDC members to receive their feedback!

Feasibility discussions ongoing...

Existing facility at HL-LHC

ZDC for LLPs: our proposal for HL-LHC



ZDC B: same decay volume as FASER

Improvement in performance with respect to FASER

- especially for heavy LLPs with low $c\tau$

Biplob Bhattacherjee, Abhinav Kumar, Swagata Mukherjee, RS, Anand Sharma, e-Print: 2503.11760

Outline

- ☑ Dedicated triggers
- ☑ Leveraging Pile-up
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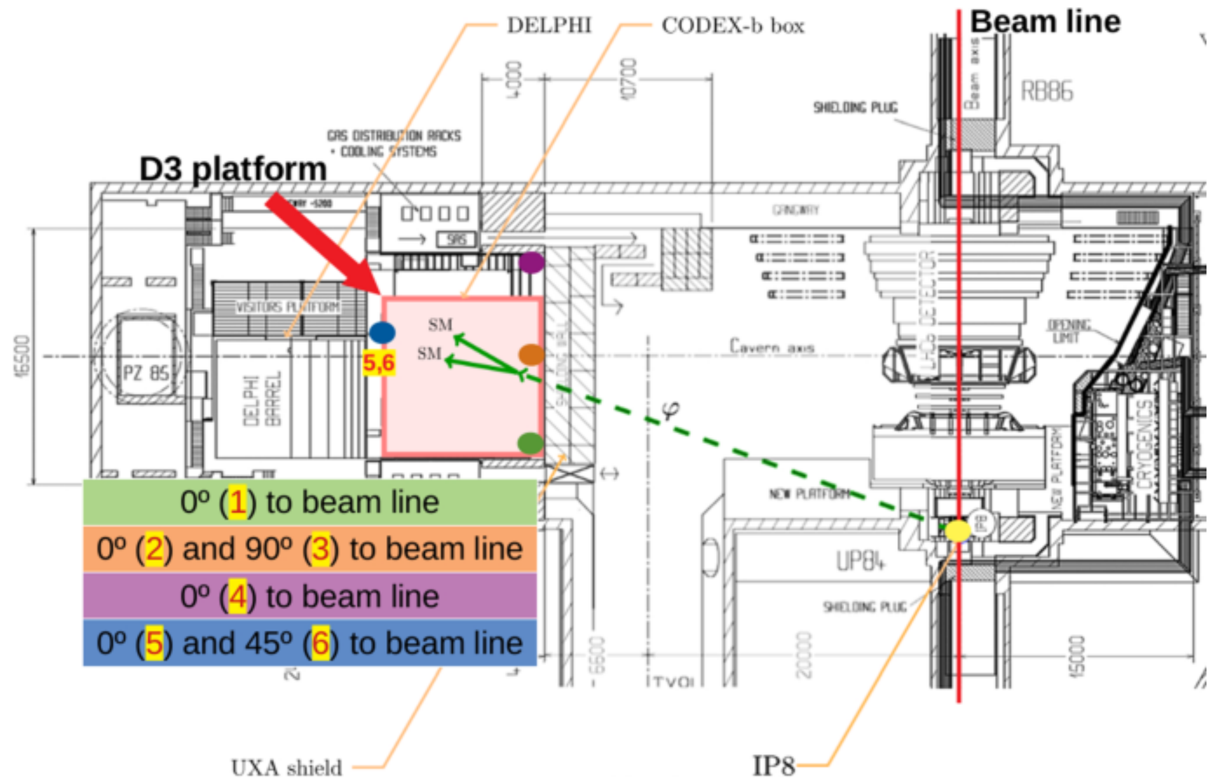
- ☑ Upgrading ZDCs for LLPs
- ☐ **Optimised dedicated LLP detectors**

Optimisation of dedicated detectors

For LHC or HL-LHC, the dedicated detectors are accommodated in empty shafts or available halls around the main detectors

For example, see for CODEX-b



EPJC 80, 1177 (2020)

But this might not be optimal for the LLP models beyond the SM

The Future Colliders are in their conceptual design phase now

Optimise and integrate dedicated LLP detectors with the main detector design

---

HECATE — EPJC (2021)
near and far detectors — PRD (2020), PRD (2023)
DELIGHT — PRD (2022)

Dedicated detectors @ FCC-hh — JHEP (2023)
FOREHUNT — PRD (2024)
LAYCAST — arXiv:2406.05770
FPF@FCC — JHEP (2025)

Optimisation of dedicated detectors

Our proposals for FCC-hh

(A) Transverse detector:

DELIGHT

Detector for **l**ong-**li**ved particles at hi**gh** energy of 100 **T**eV

Biplob Bhattacherjee, Shigeki Matsumoto, RS, e-Print: 2111.02437, PRD 2022

(B) Forward detector:

FOREHUNT

Forward **E**xperiment for **Hun**dred **T**eV

Biplob Bhattacherjee, Herbi Dreiner, Nivedita Ghosh, Shigeki Matsumoto, RS, Prabhat Solanki, e-Print: 2306.11803, PRD 2024

Their performance for FCC-ee is also studied

Biplob Bhattacherjee, Camellia Bose, Herbi Dreiner, Nivedita Ghosh, Shigeki Matsumoto, RS, e-Print: 2503.08780

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Performance? Optimisation?

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Biplob Bhattacherjee, Camellia Bose, Herbi Dreiner, Nivedita Ghosh, Shigeki Matsumoto, RS, e-Print: 2503.08780

(B) Forward detector:

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Forward **E**xperiment for **Hun**dred **T**eV

Biplob Bhattacherjee, Herbi Dreiner, Nivedita Ghosh, Shigeki Matsumoto, RS, Prabhat Solanki, e-Print: 2306.11803, PRD 2024

Optimisation with respect to FASER in backup

Optimisation of dedicated detectors

Our proposals for FCC-hh

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Biplob Bhattacherjee, Shigeki Matsumoto, RS, e-Print: 2111.02437, PRD 2022

(B) Forward detector:

FOREHUNT

Forward **E**xperiment for **Hun**dred **T**eV

Biplob Bhattacherjee, Herbi Dreiner, Nivedita Ghosh, Shigeki Matsumoto, RS, Prabhat Solanki, e-Print: 2306.11803, PRD 2024

Performance?
Optimisation?

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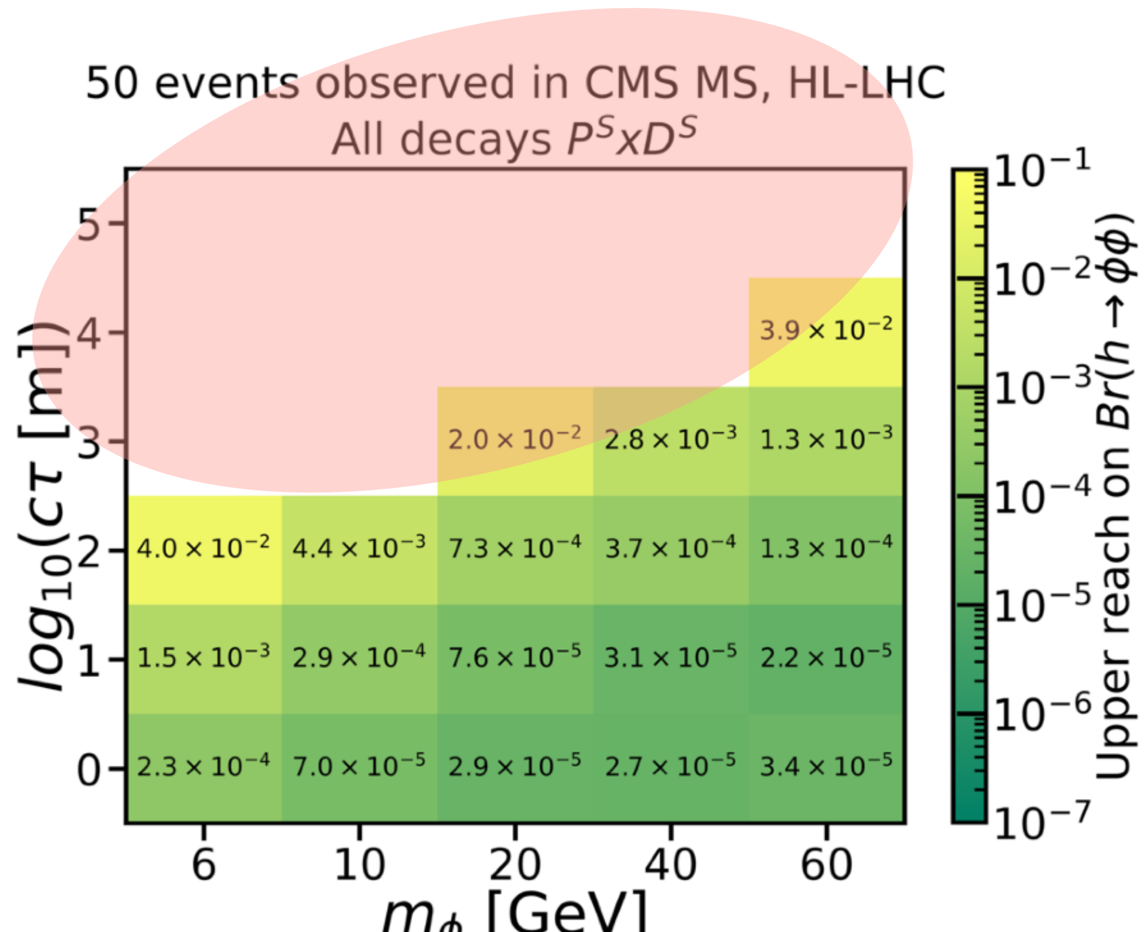
HL-LHC



Optimisation of dedicated detectors

Our proposals for FCC-hh

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Biplob Bhattacherjee, Shigeki Matsumoto, RS, e-Print: 2111.02437, PRD 2022

(B) Forward detector:

FOREHUNT

Forward **E**xperiment for **Hun**dred **T**eV

Biplob Bhattacherjee, Herbi Dreiner, Nivedita Ghosh, Shigeki Matsumoto, RS, Prabhat Solanki, e-Print: 2306.11803, PRD 2024

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Optimisation?

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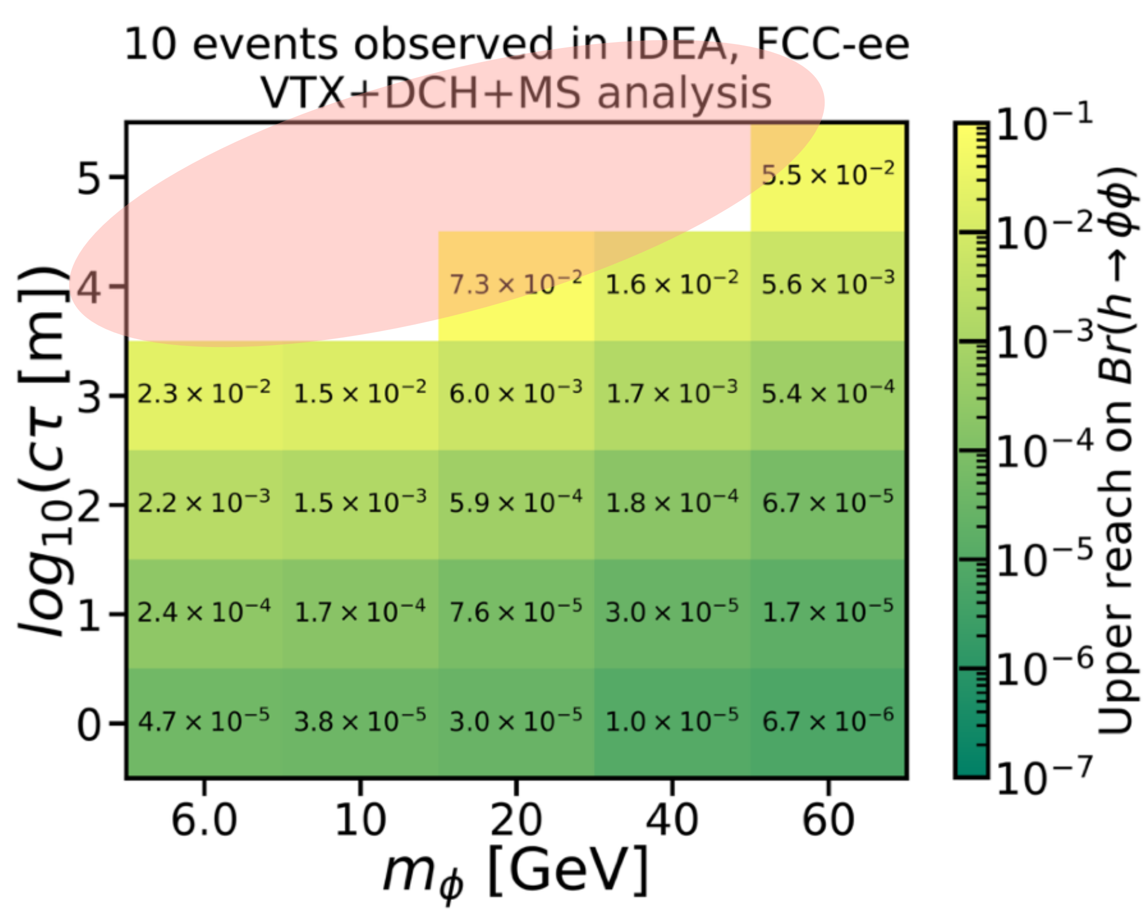
Biplob Bhattacherjee, Camellia Bose, Herbi Dreiner, Nivedita Ghosh, Shigeki Matsumoto, RS, e-Print: 2503.08780

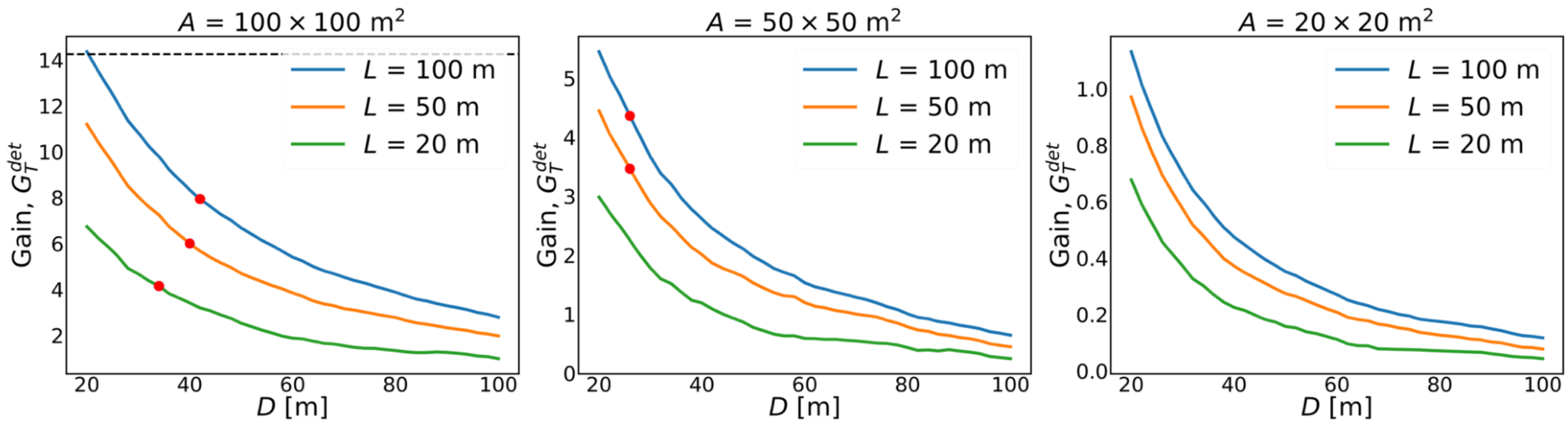
FCC-ee
IDEA



Economical, yet useful?

$$G_T^{\rm det} = \frac{1}{9} \sum_{\rm benchmarks} \frac{\epsilon_{\rm det}}{\epsilon_{\rm IDEA}}$$

Benchmarks:
(6 GeV, 10 m), (6 GeV, 10^3 m), (6 GeV, 10^5 m),
(20 GeV, 10 m), (20 GeV, 10^3 m), (20 GeV, 10^5 m),
(60 GeV, 100 m), (60 GeV, 10^3 m), (60 GeV, 10^5 m)



EPPSU input

Biplob Bhattacherjee, Camellia Bose, Herbi Dreiner, Nivedita Ghosh, Shigeki Matsumoto, Swagata Mukherjee, RS, Anand Sharma, e-Print: 2503.21875

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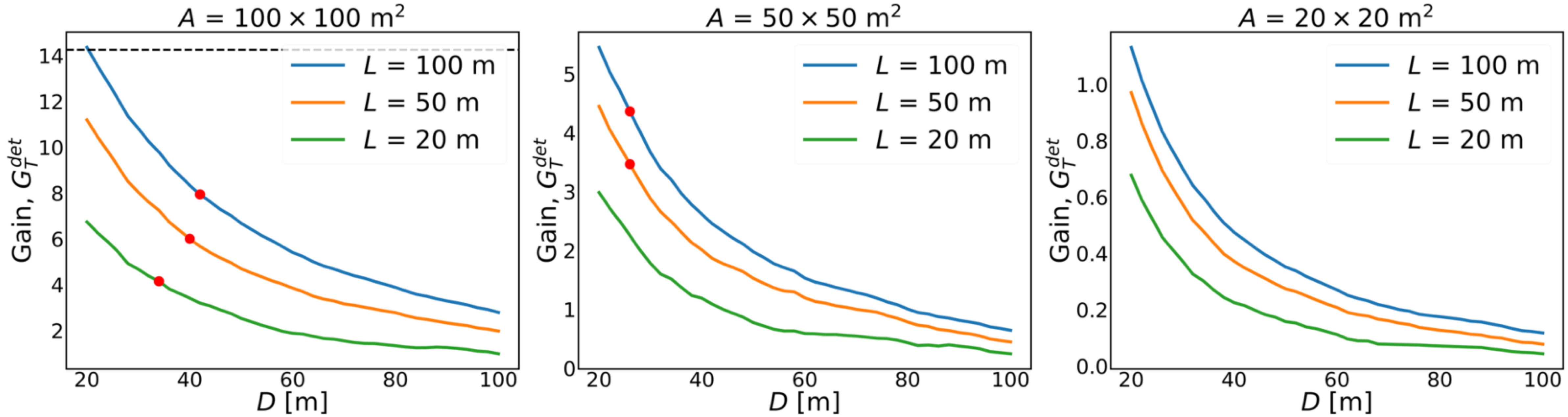
(60 GeV, 100 m), (60 GeV, 10^3 m), (60 GeV, 10^5 m)



What is the minimal design to have at least the same efficiency as the IDEA main detector?

EPPSU input

Biplob Bhattacherjee, Camellia Bose, Herbi Dreiner, Nivedita Ghosh, Shigeki Matsumoto, Swagata Mukherjee, RS, Anand Sharma, e-Print: 2503.21875

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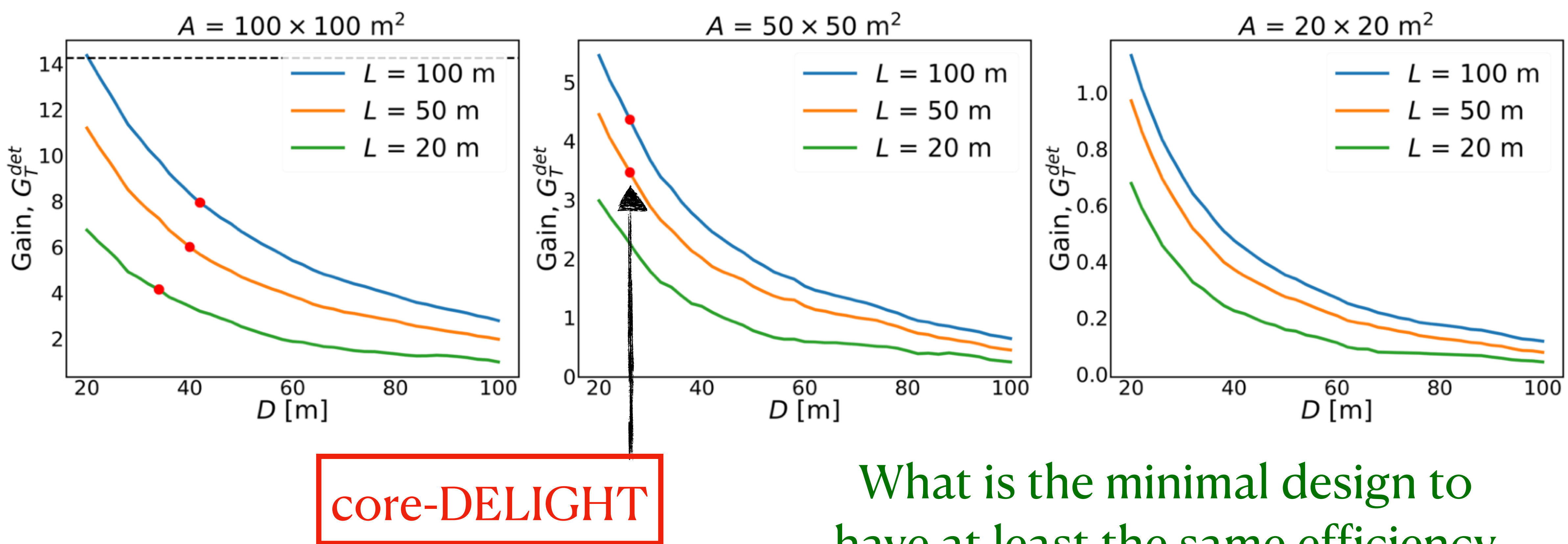
(60 GeV, 100 m), (60 GeV, 10^3 m), (60 GeV, 10^5 m)



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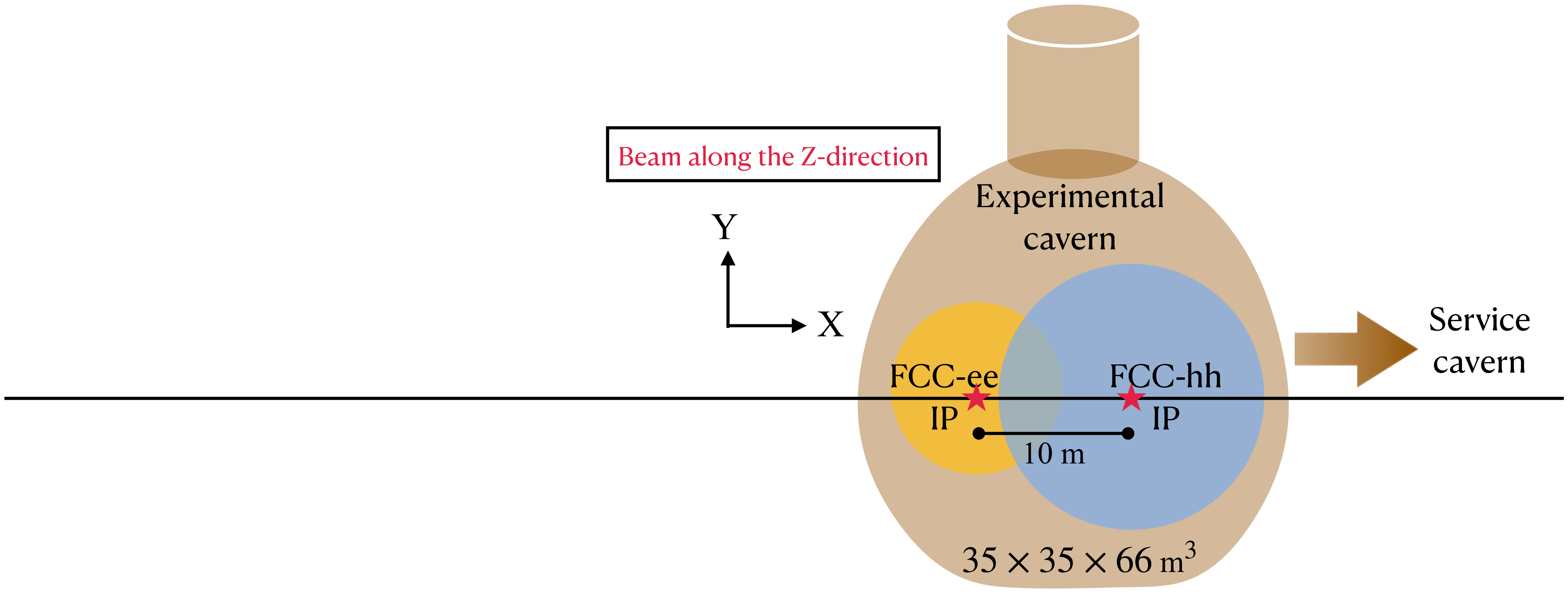
EPPSU input

Biplob Bhattacherjee, Camellia Bose, Herbi Dreiner, Nivedita Ghosh, Shigeki Matsumoto, Swagata Mukherjee, RS, Anand Sharma, e-Print: 2503.21875

A shared transverse detector?

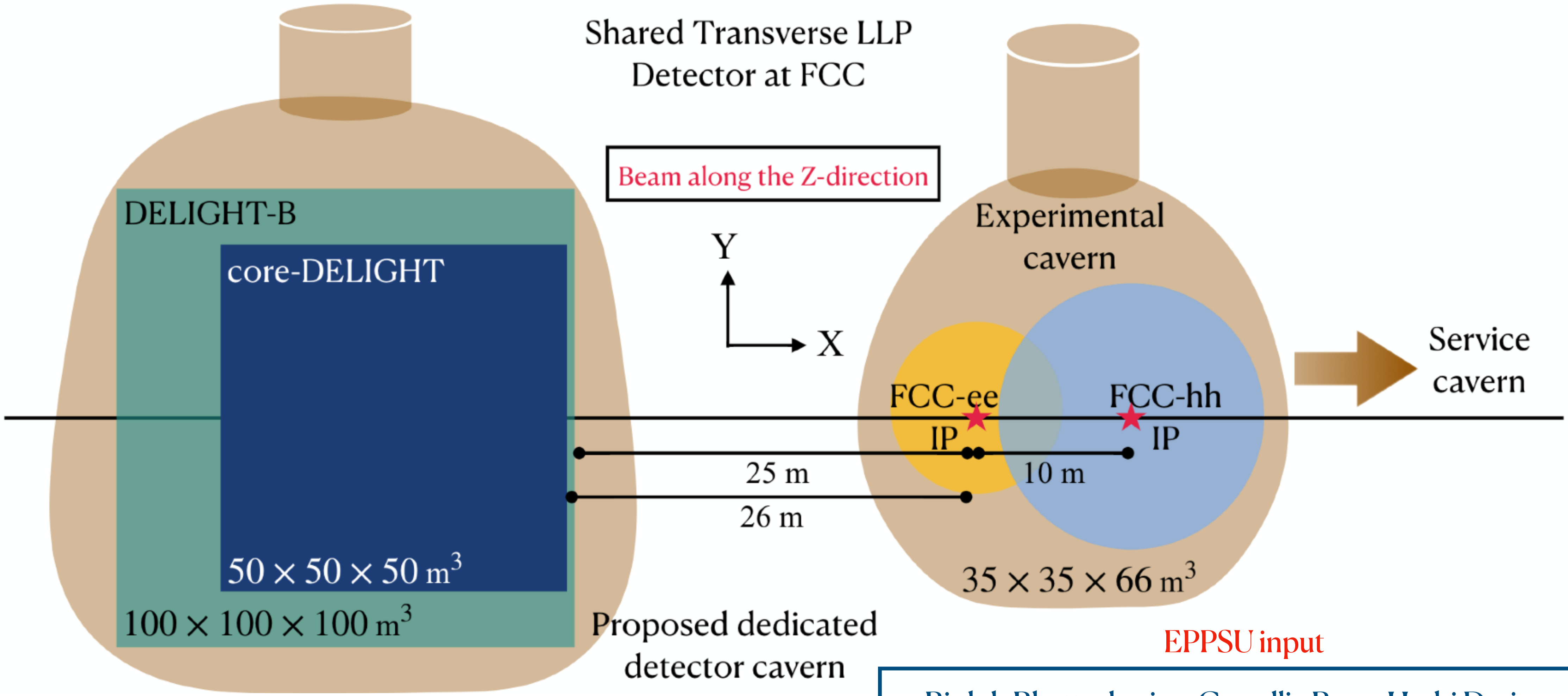
FCC-ee: The Lepton Collider CDR
EPJST **228**, 261–623 (2019)



Can we use the transverse detector
DELIGHT at both FCC-ee and FCC-hh?

A shared transverse detector? DELIGHT

Can we use the transverse detector
DELIGHT at both FCC-ee and FCC-hh?

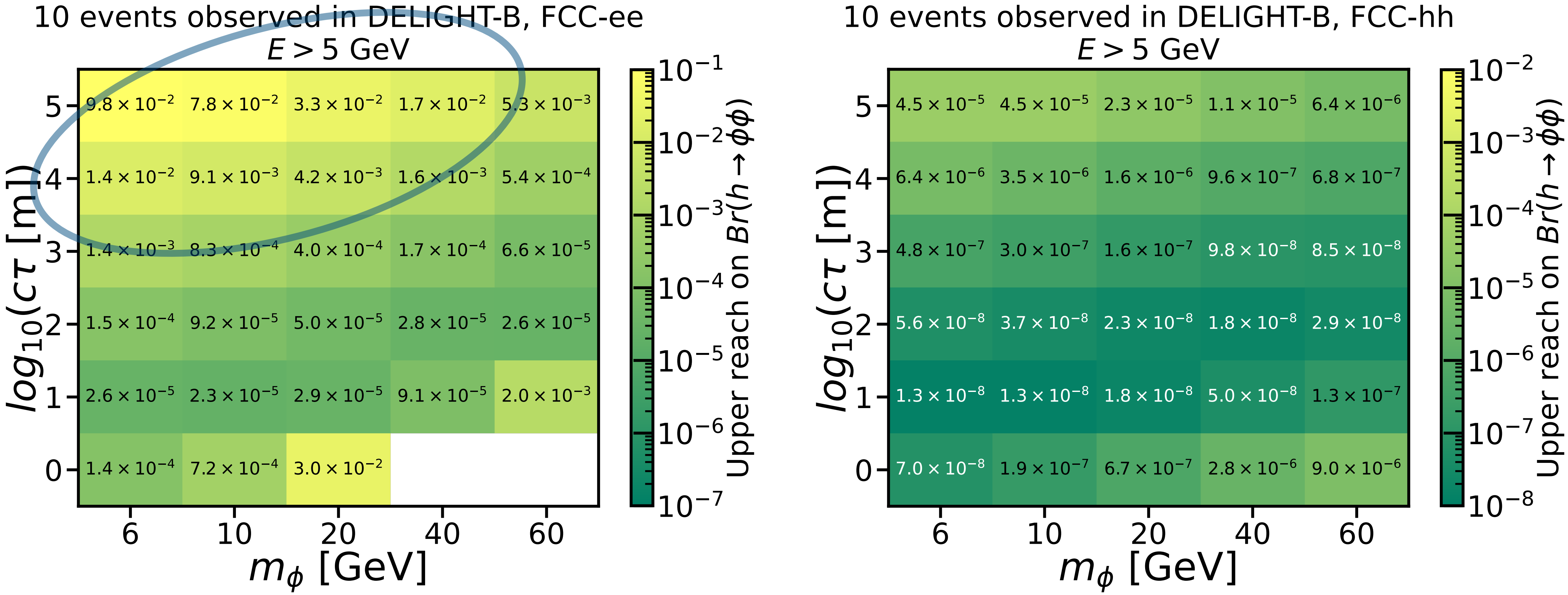


EPPSU input

Biplob Bhattacherjee, Camellia Bose, Herbi Dreiner,
Nivedita Ghosh, Shigeki Matsumoto, Swagata Mukherjee,
RS, Anand Sharma, e-Print: 2503.21875

The opportunity to reuse an entire dedicated detector at FCC!
Maximises resource utilisation.

The shared transverse detector: DELIGHT



FCC-ee:

$log_{10}(c\tau$ [m])	6	10	20	40	60
5	9.8×10^{-2}	7.8×10^{-2}	3.3×10^{-2}	1.7×10^{-2}	5.3×10^{-3}
4	1.4×10^{-2}	9.1×10^{-3}	4.2×10^{-3}	1.6×10^{-3}	5.4×10^{-4}
3	1.4×10^{-3}	8.3×10^{-4}	4.0×10^{-4}	1.7×10^{-4}	6.6×10^{-5}
2	1.5×10^{-4}	9.2×10^{-5}	5.0×10^{-5}	2.8×10^{-5}	2.6×10^{-5}
1	2.6×10^{-5}	2.3×10^{-5}	2.9×10^{-5}	9.1×10^{-5}	2.0×10^{-3}
0	1.4×10^{-4}	7.2×10^{-4}	3.0×10^{-2}		

FCC-hh:

$log_{10}(c\tau$ [m])	6	10	20	40	60
5	4.5×10^{-5}	4.5×10^{-5}	2.3×10^{-5}	1.1×10^{-5}	6.4×10^{-6}
4	6.4×10^{-6}	3.5×10^{-6}	1.6×10^{-6}	9.6×10^{-7}	6.8×10^{-7}
3	4.8×10^{-7}	3.0×10^{-7}	1.6×10^{-7}	9.8×10^{-8}	8.5×10^{-8}
2	5.6×10^{-8}	3.7×10^{-8}	2.3×10^{-8}	1.8×10^{-8}	2.9×10^{-8}
1	1.3×10^{-8}	1.3×10^{-8}	1.8×10^{-8}	5.0×10^{-8}	1.3×10^{-7}
0	7.0×10^{-8}	1.9×10^{-7}	6.7×10^{-7}	2.8×10^{-6}	9.0×10^{-6}

EPPSU input

Biplob Bhattacherjee, Camellia Bose, Herbi Dreiner, Nivedita Ghosh, Shigeki Matsumoto, Swagata Mukherjee, RS, Anand Sharma, e-Print: 2503.08780

Improvement in performance from both FCC-ee and FCC-hh

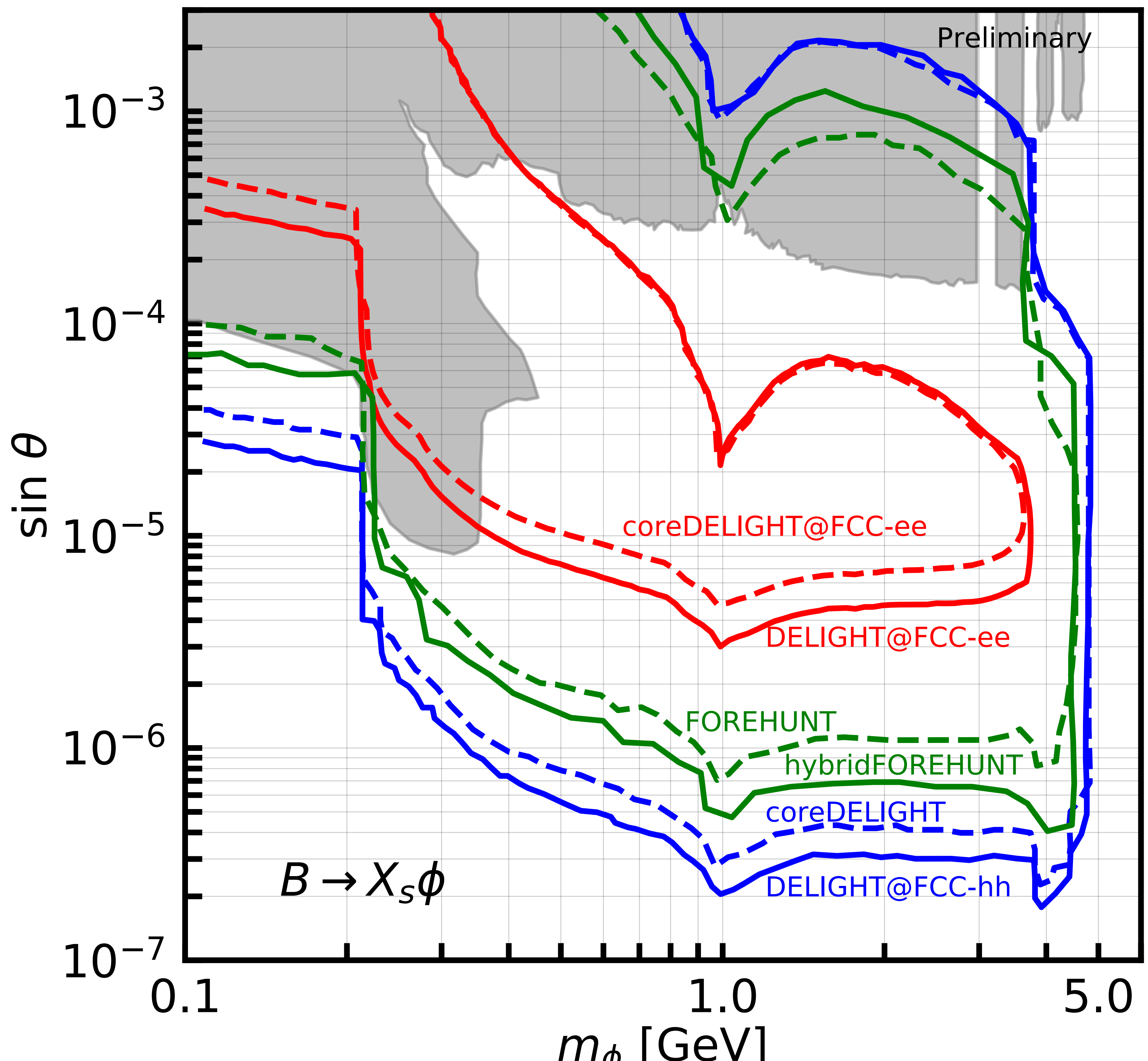
Increased sensitivity to light and displaced new physics!

Performance for BC4

Exotic decay of B meson

Preliminary

By Anand Sharma



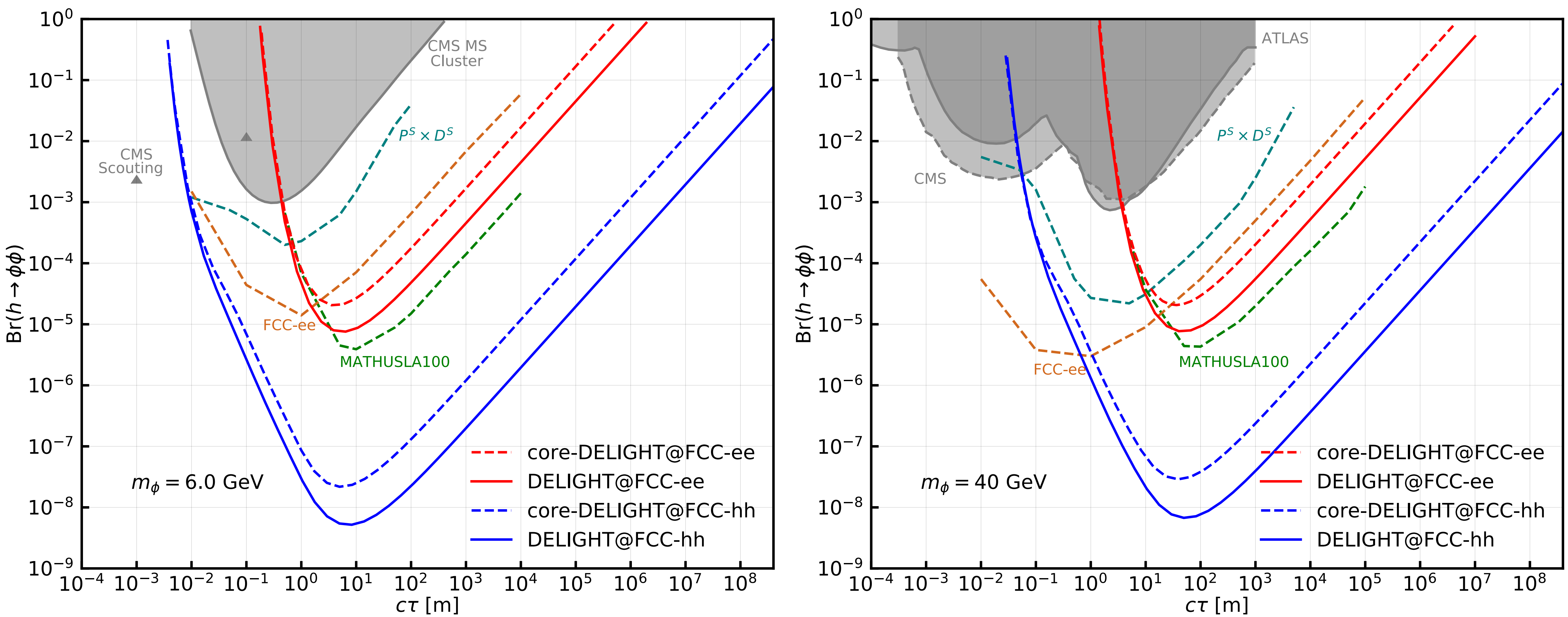
Ongoing: Proper background simulation

Performance for BC5

Exotic decay of Higgs boson

Preliminary

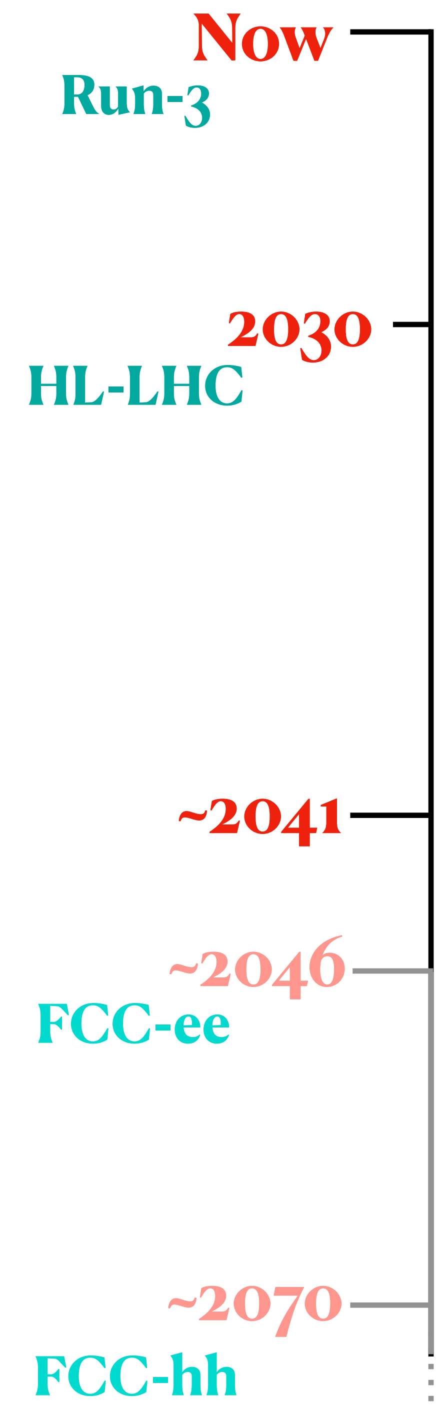
By Anand Sharma



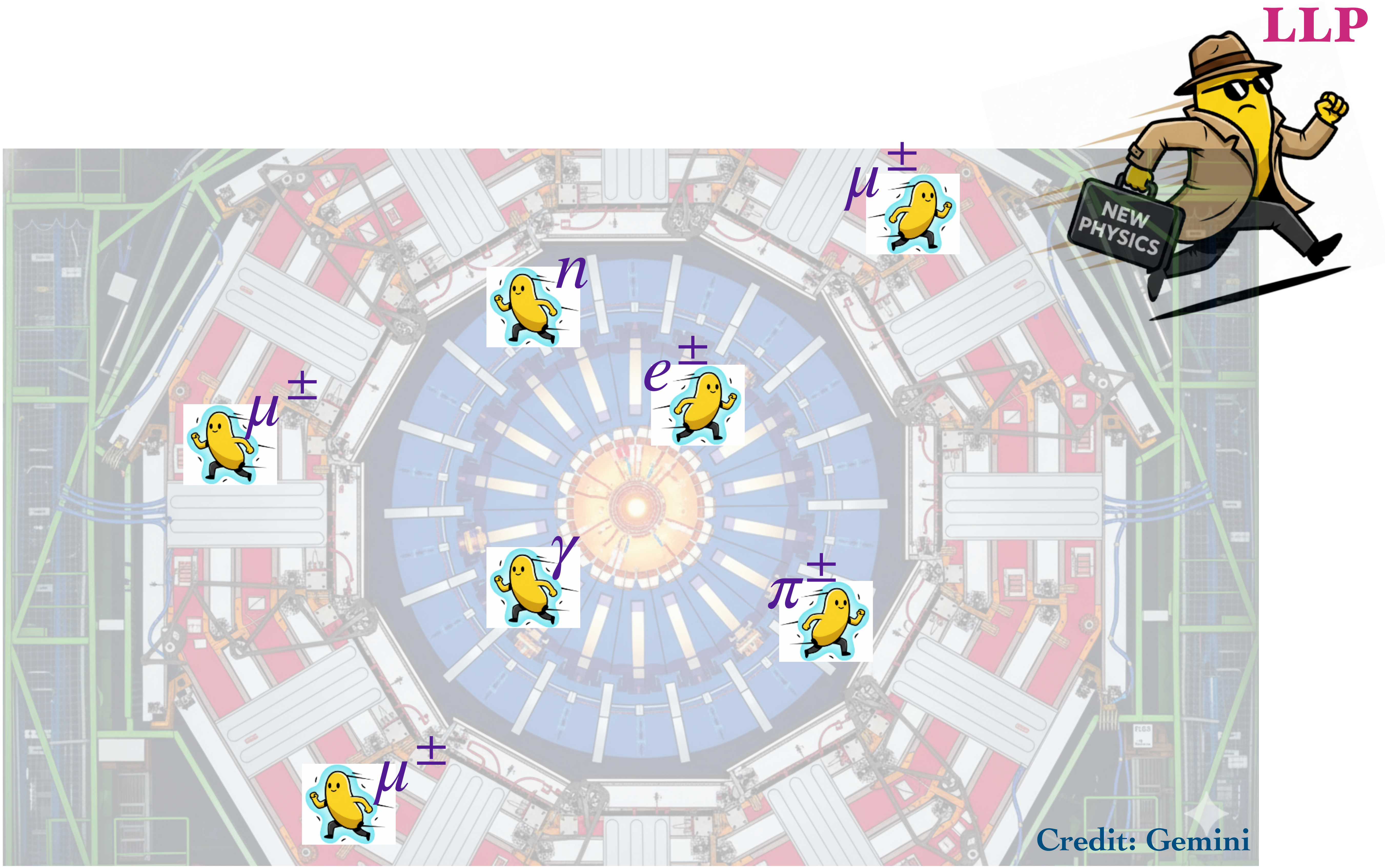
Ongoing: Proper background simulation

Summary

- Long-lived particles ⇒ unusual collider signatures interesting and important avenues of new physics
- Presented some ways to look for them in present and future collider programs — from triggering to collider analyses to optimised dedicated LLP detectors
- Proposal to study the feasibility of upgrading the ZDCs to LLP detectors.
- Detailed SM LLP background analysis for light LLPs at FCC-ee.
- Discussed the role of optimised dedicated LLP detectors at FCC.
  - A shared detector for FCC-ee and FCC-hh — DELIGHT
  - A forward detector for FCC-hh — FOREHUNT



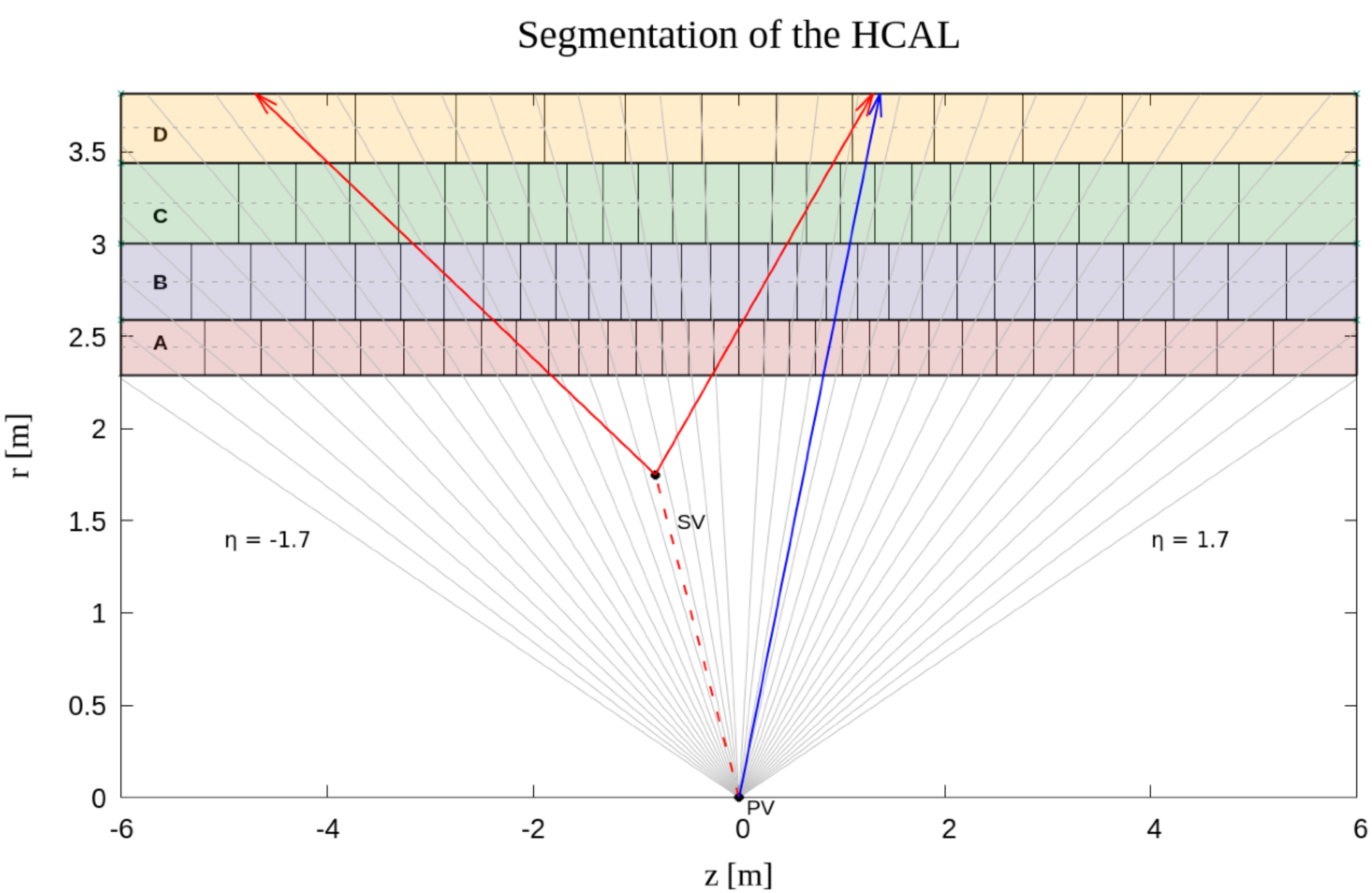
Keep looking out for new possibilities!



Thank you for your attention!

Backup Slides

Displaced Jet Images



$X(\mathrm{LLP}) \to Z(\mathrm{SM}) + Y(\mathrm{Invisible})$

$Z \to jj, \quad [m_X = 800 \text{ GeV}]$

Displaced Z boson

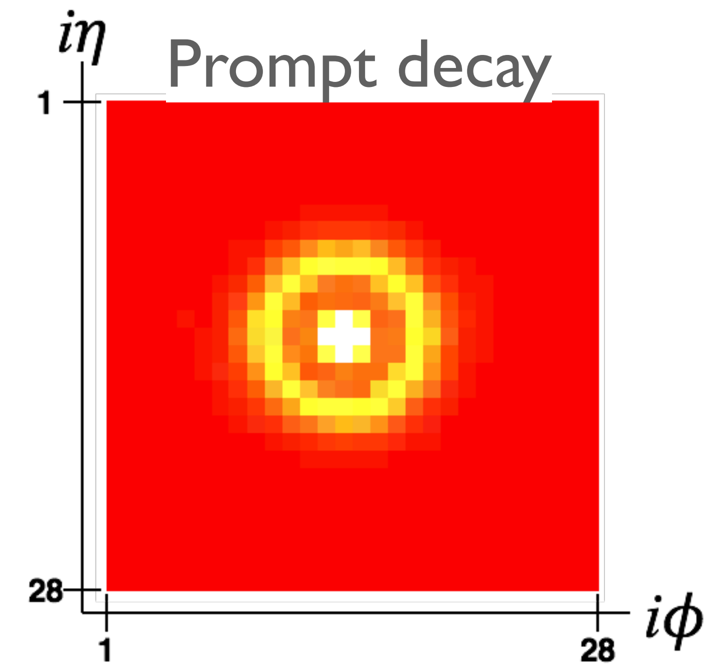
GMSB SUSY

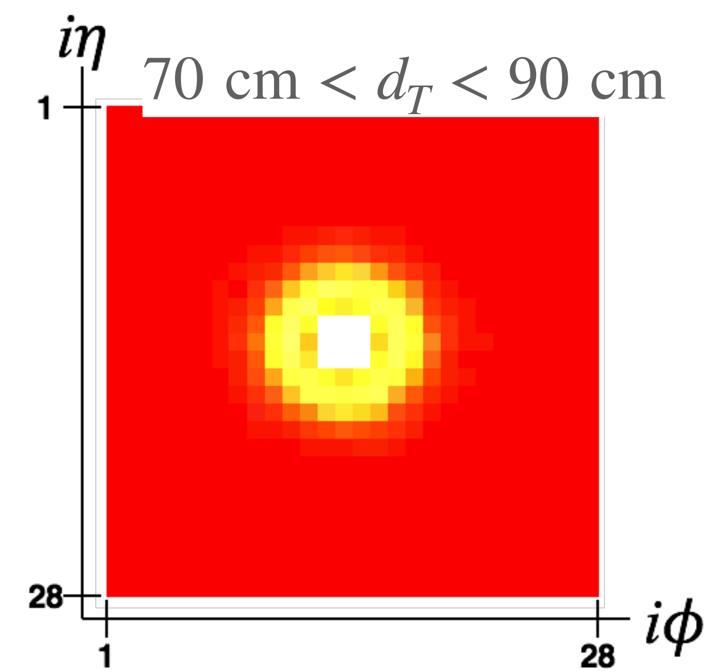
$\tilde{\chi}_1^0 \to Z\tilde{G}$

Neutralino width suppressed by SUSY breaking scale

$$\Delta R \sim \frac{2m_Z}{p_T^Z}$$

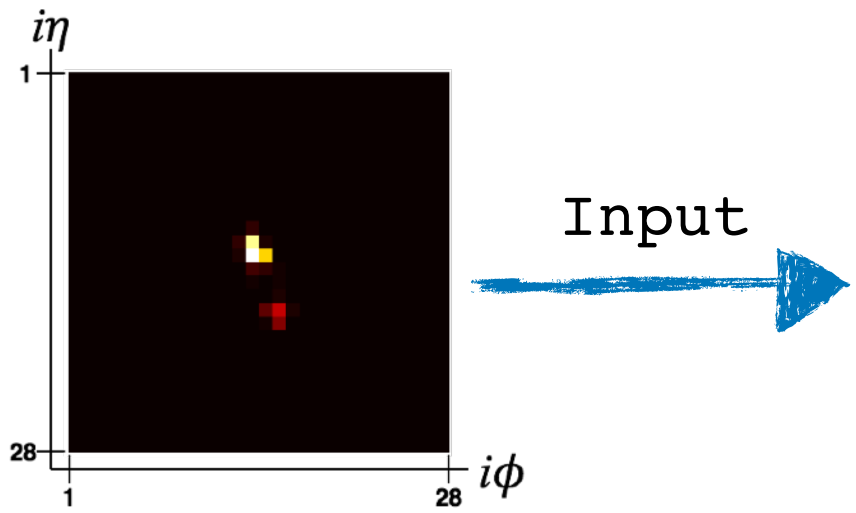
p_T^Z almost fixed due to window cut on $\sum E$

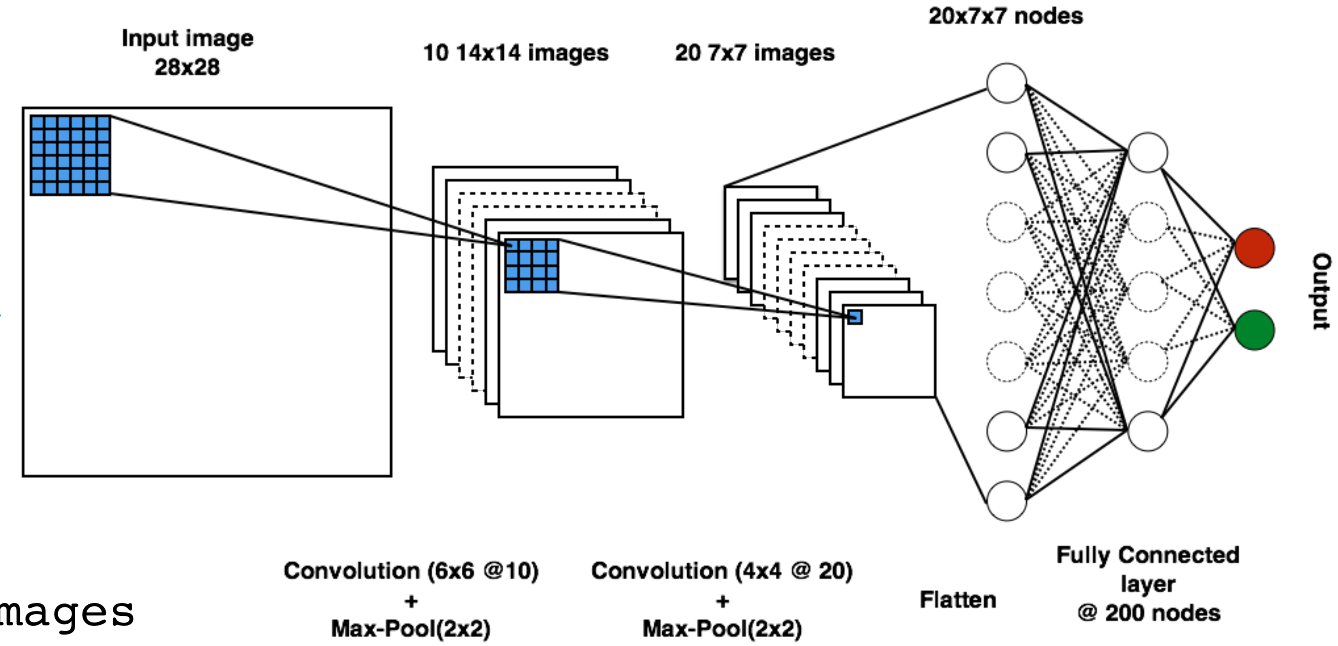




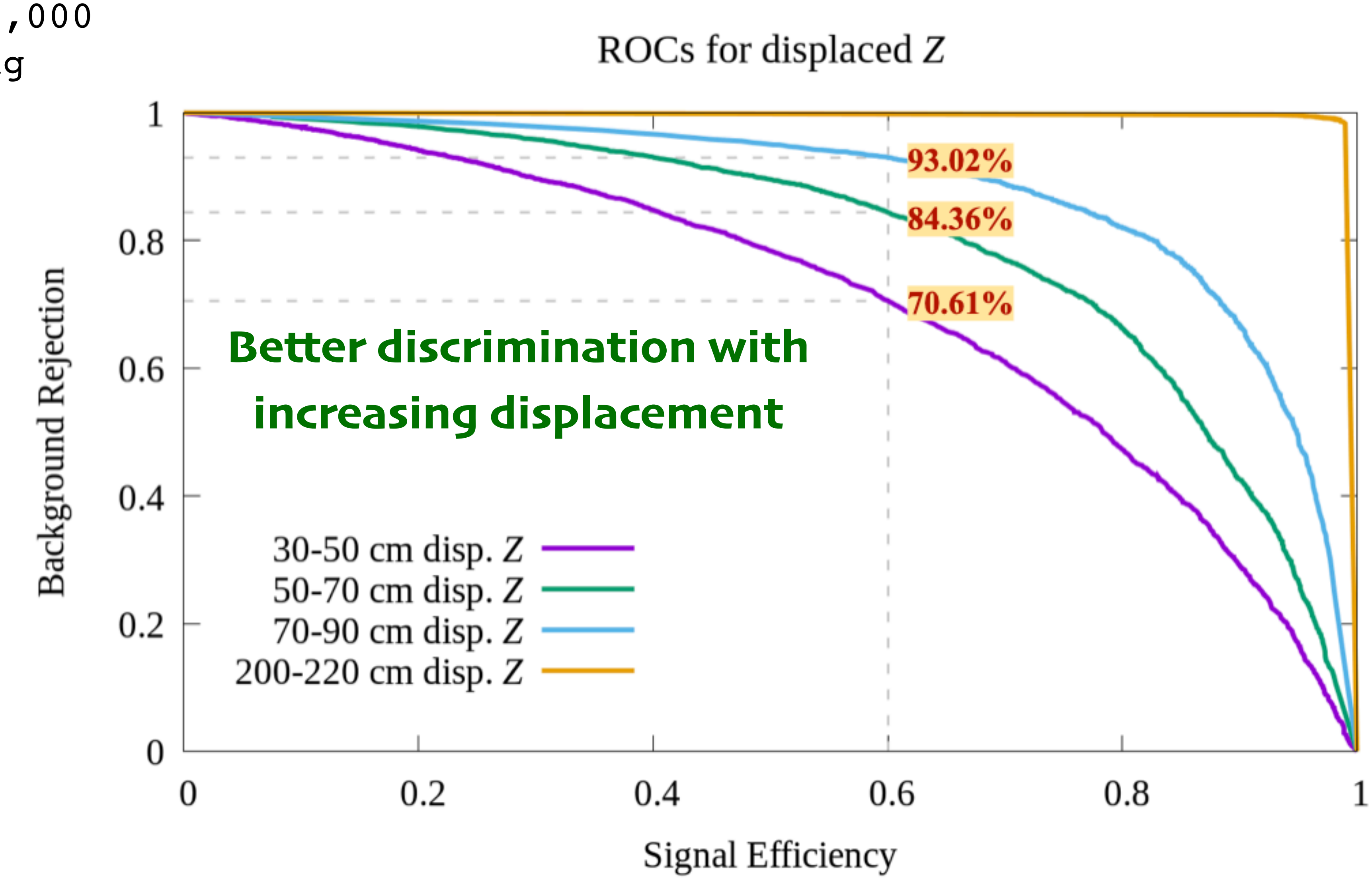
Average over 50 000 images

Displaced Jet Images





- Minimal preprocessing of images
- 60,000 images for training, 20,000 each for validation and testing
- Batch size: 200
- Adam Optimizer
- Activation by RELU
- Learning rate: 0.001
- Dropout: 50%
- Training stopped at the epoch with minimum validation loss



Triggers using L1 Tracking

Max L1 trigger bandwidth for HL-LHC: 750 kHz

- **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;

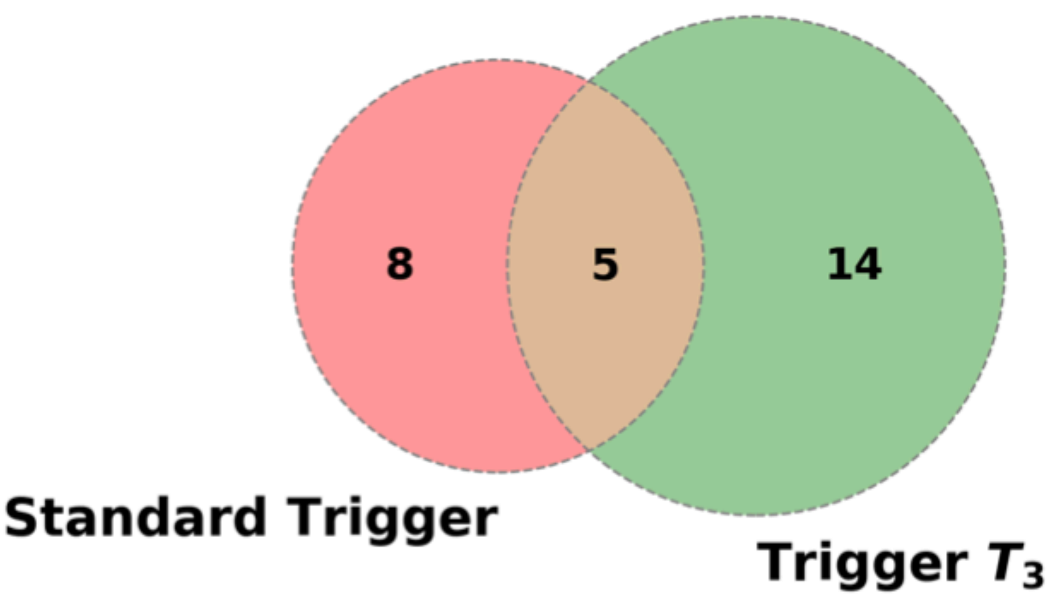
For direct production of LLPs

$T_3 \rightarrow$ 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.

$$\mathcal{R}_B = \sigma \text{ (nb)} \times \mathcal{L} \text{ (nb}^{-1}\text{Hz)} \times \epsilon_B$$

(M50,$c\tau$10), Total: 27%



- **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.**

HL-LHC L1 triggers

CMS Level-1 Trigger TDR, CMS-TDR-021

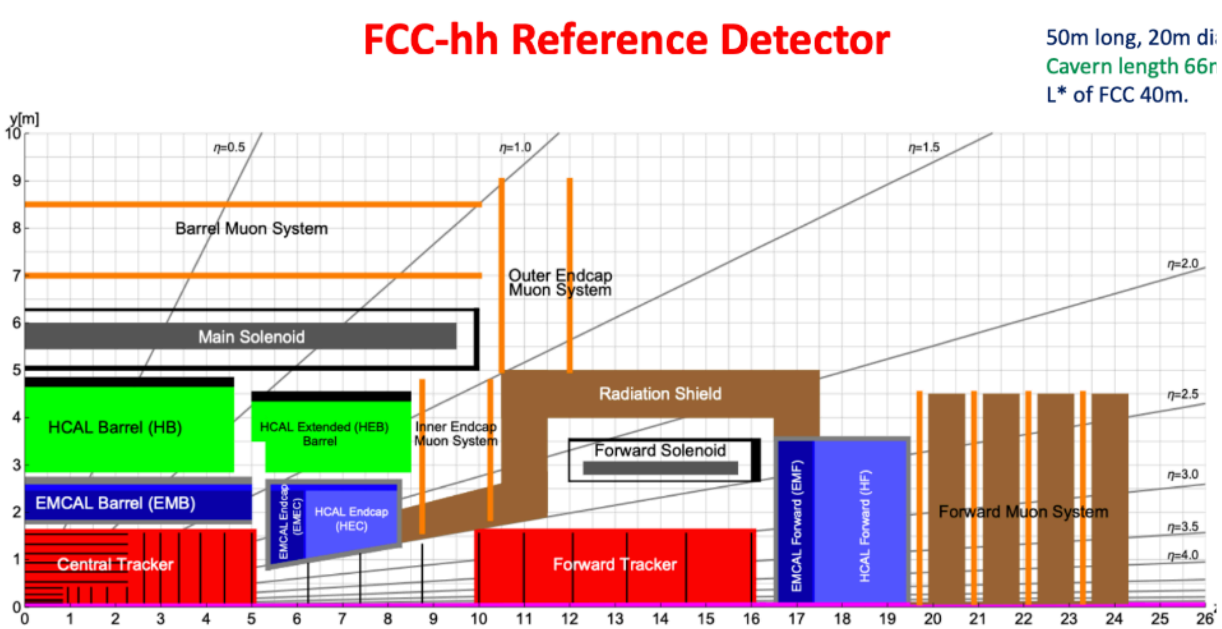
Will MTD be available at L1?

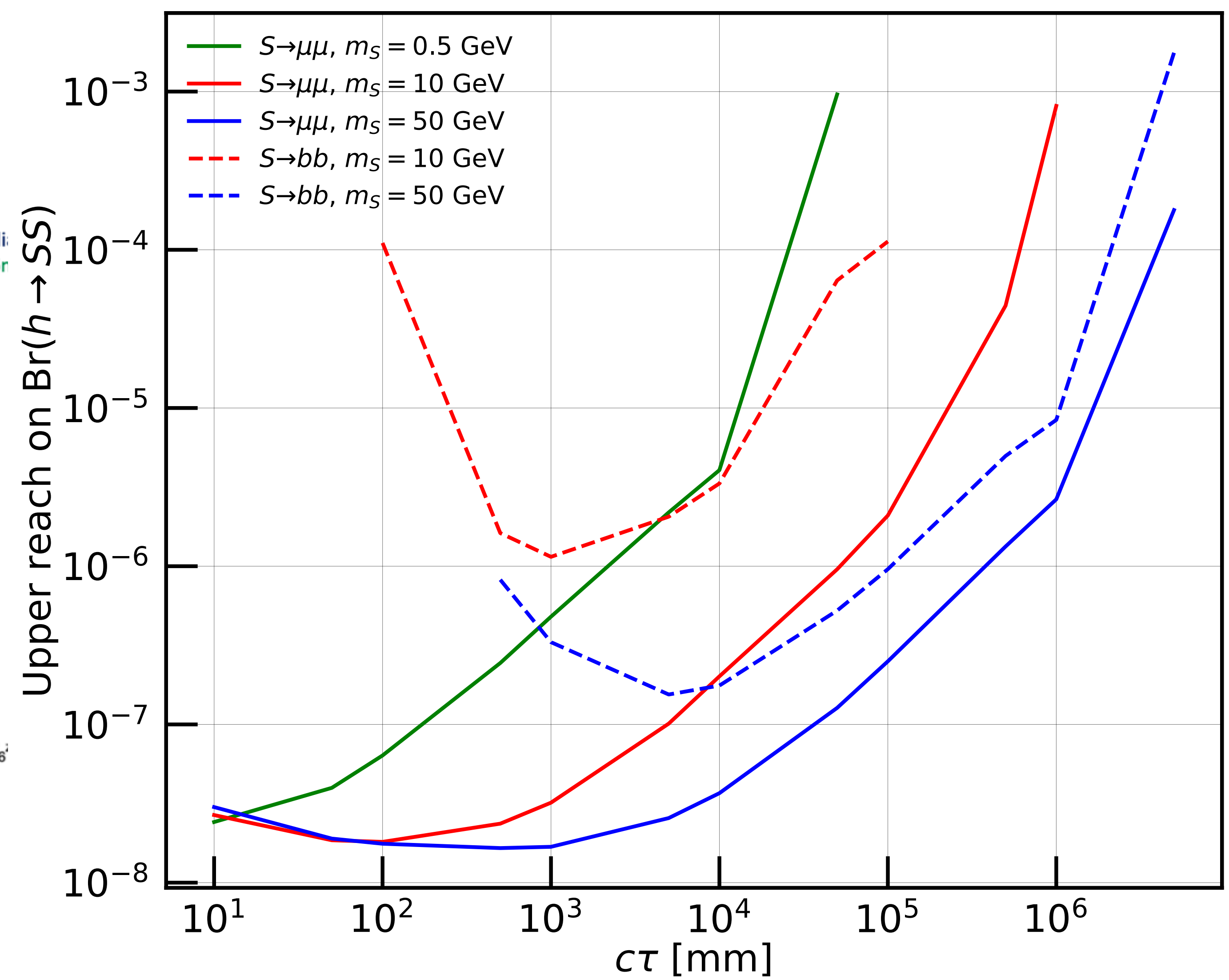
Regional timing - separately or in combination with L1 track trigger

Applying timing BDT on events passing the tracking BDT score corresponding to 70% bkg rej., we can reduce the **background rate by a factor of 4 with little loss in the signal efficiency**.

Inclusion of L1 **displaced tracking** (efficient till $d_0 < 8$ cm) increases sensitivity for low lifetimes

FCC-hh MS search

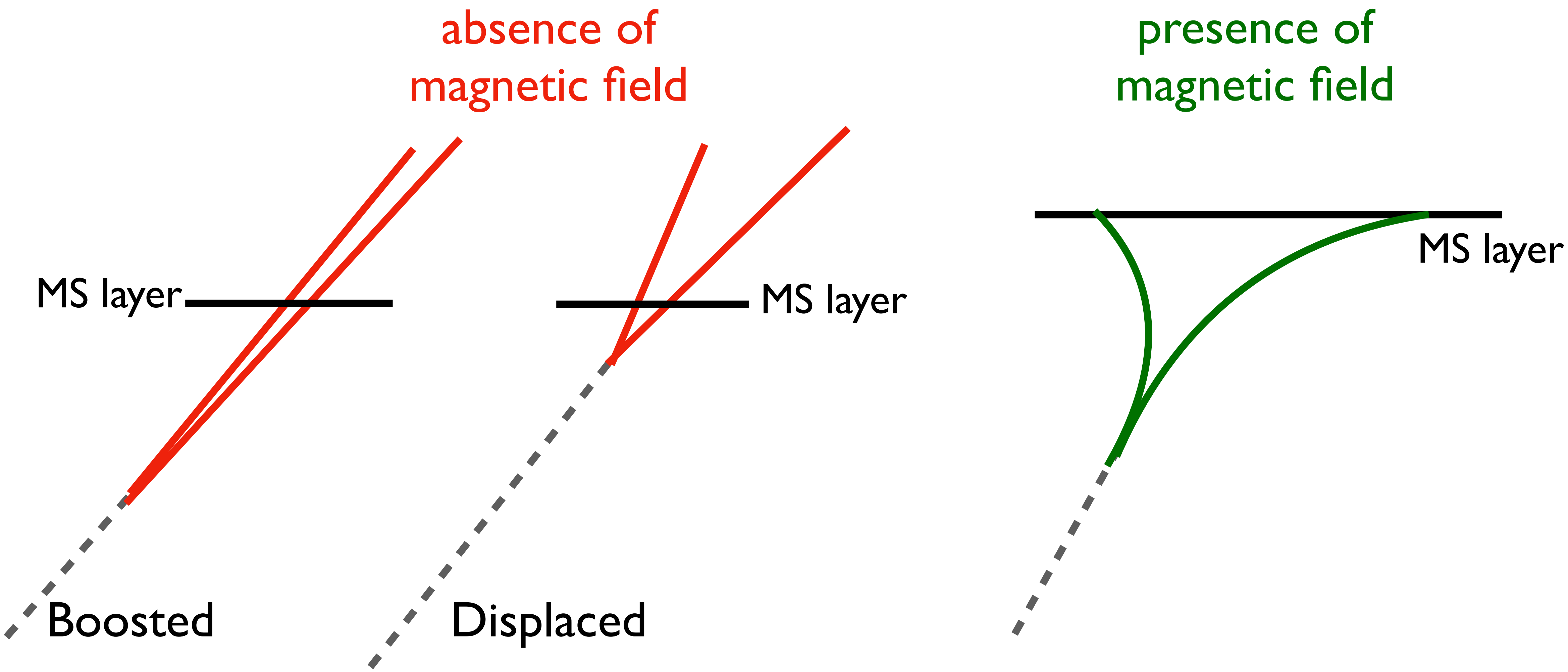




Analysis Strategy

CMS: Magnetic field till MS (changes sign after HCAL and reduced in magnitude from 3.8 T to 0.5 T)

Delphes (fast detector simulation): Magnetic field till Tracker



Implemented magnetic field till muon spectrometer in Delphes for correct $\Delta\phi$ – important in boosted and displaced cases

List of SM LLPs

Mesons	m (GeV)	$c\tau$ (mm)	Baryons	m (GeV)	$c\tau$ (mm)
K_L	0.498	15330	Ξ^0	1.315	87.1
K_S	0.498	26.84	Λ	1.116	78.9
$B^\pm$	5.279	0.491	Ξ^-	1.322	49.1
B^0	5.279	0.459	Σ^-	1.197	44.34
B_S^0	5.367	0.439	Ω^-	1.672	24.61
$D^\pm$	1.869	0.312	Σ^+	1.189	24.04
$D_S^\pm$	1.968	0.150	Λ_b^0	5.619	0.369
D^0	1.865	0.123	Ξ_b^-	5.791	0.364
			Ξ_b^0	5.788	0.364
			Ξ_c^+	2.468	0.132
			Λ_c^+	2.286	0.06
			Ξ_c^0	2.471	0.0336

IDEA efficiencies

Detector component	Particles	Energy threshold (GeV)	Efficiency
Vertex detector (VTX) Drift Chamber (DCH)	charged particles	$0.1 < E < 0.3$ $0.3 < E < 0.5$ $E > 0.5$	0.06 0.65 0.997
Solenoid Preshower	$e^\pm$, $\mu^\pm$, charged hadrons γ	$E > 0.5$ $E > 0.10$	0.98
DR calorimeter		$E > 0.5$	0.98
Muon system	$\mu^\pm$	$E > 0.10$	0.98

Number of events at FCC-ee for the various benchmarks

Benchmark	Number of LLP decays for $\mathcal{L} = 150\,\text{ab}^{-1}$						
	VTX	DCH	Solenoid	Preshower	DRC	MS	Outside
BPA1	5	17	1	1	21	13	6175
BPA2	315	720	31	28	485	228	1348
BPA3	32750	16977	184	134	1014	84	50
BPA4	42924	47166	861	834	8534	1937	1611
BPA5	2	6	0	0	8	5	188
BPA6	22573	10029	32	24	124	4	0
BPA7	42	28	0	0	1	0	0

Benchmark	Number of LLP decays for $\mathcal{L} = 10.8\,\text{ab}^{-1}$						
	VTX	DCH	Solenoid	Preshower	DRC	MS	Outside
BPB1	194	179	2	2	9	1	0
BPB2	38	106	6	5	87	43	155
BPB3	25487	3356	0	0	0	0	0
BPB4	610	961	32	29	281	54	51
BPB5	1487	1932	53	44	345	47	25
BPB6	49	150	9	9	144	79	403
BPB7	5119	0	0	0	0	0	0
BPB8	2555	248	0	0	0	0	0

Case A results

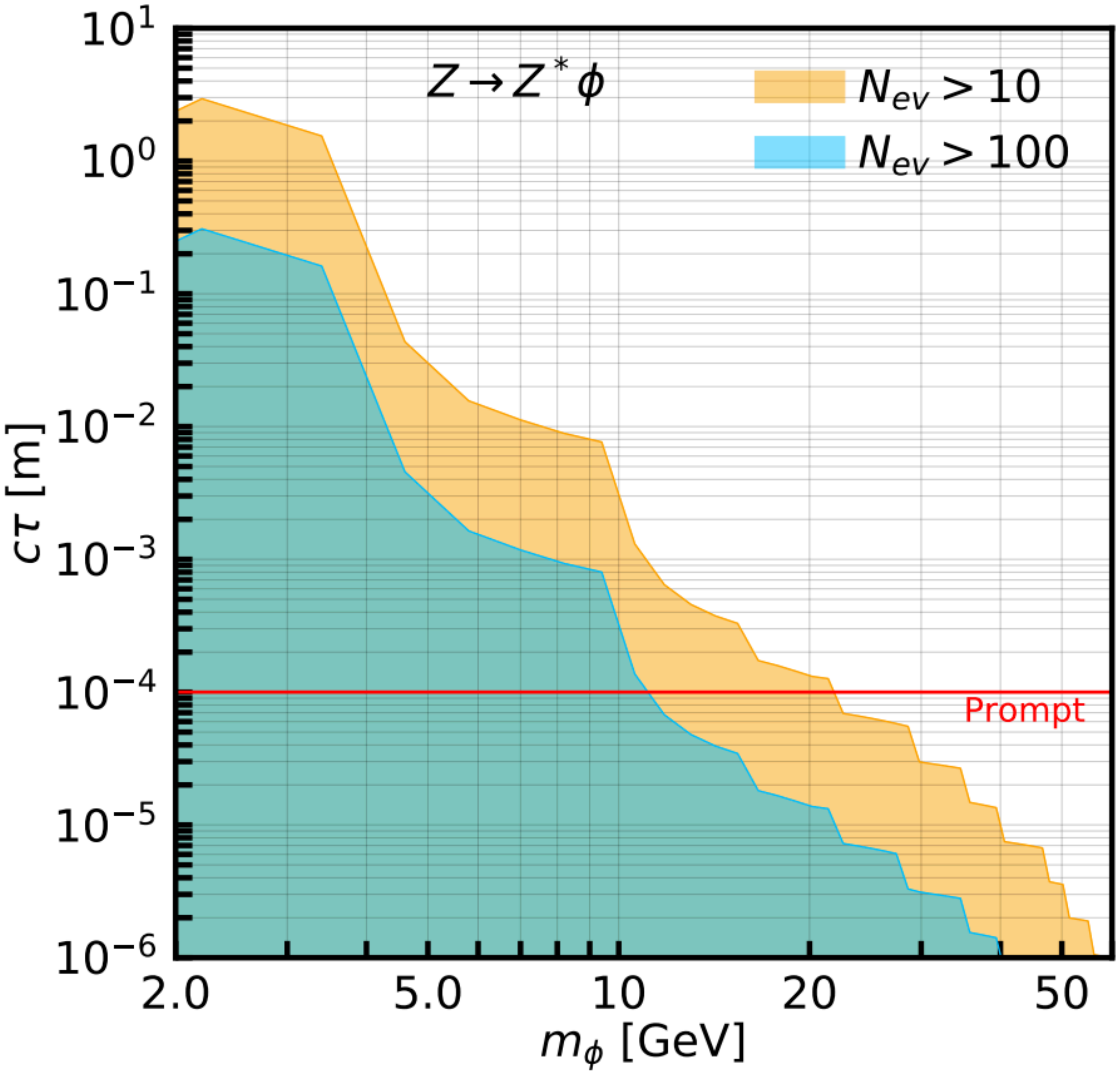
Benchmarks	Dimuon analysis for decays out to the MS		
	m_ϕ (GeV)	$c\tau$ (mm)	Number of events
BPA1	0.4	39666.6	3
BPA4	2.0	135.2	9352
BPA5	3.5	10285.4	1
BPA6	3.5	65.8	915

Benchmarks	VTX + DCH analysis			
	m_ϕ (GeV)	$c\tau$ (mm)	Number of events	
			$\phi \to \pi^+\pi^-$	$\phi \to K^+K^-$
BPA4	2.0	135.2	26202	26970
BPA5	3.5	10385.4	4	2
BPA6	3.5	65.8	9495	3822

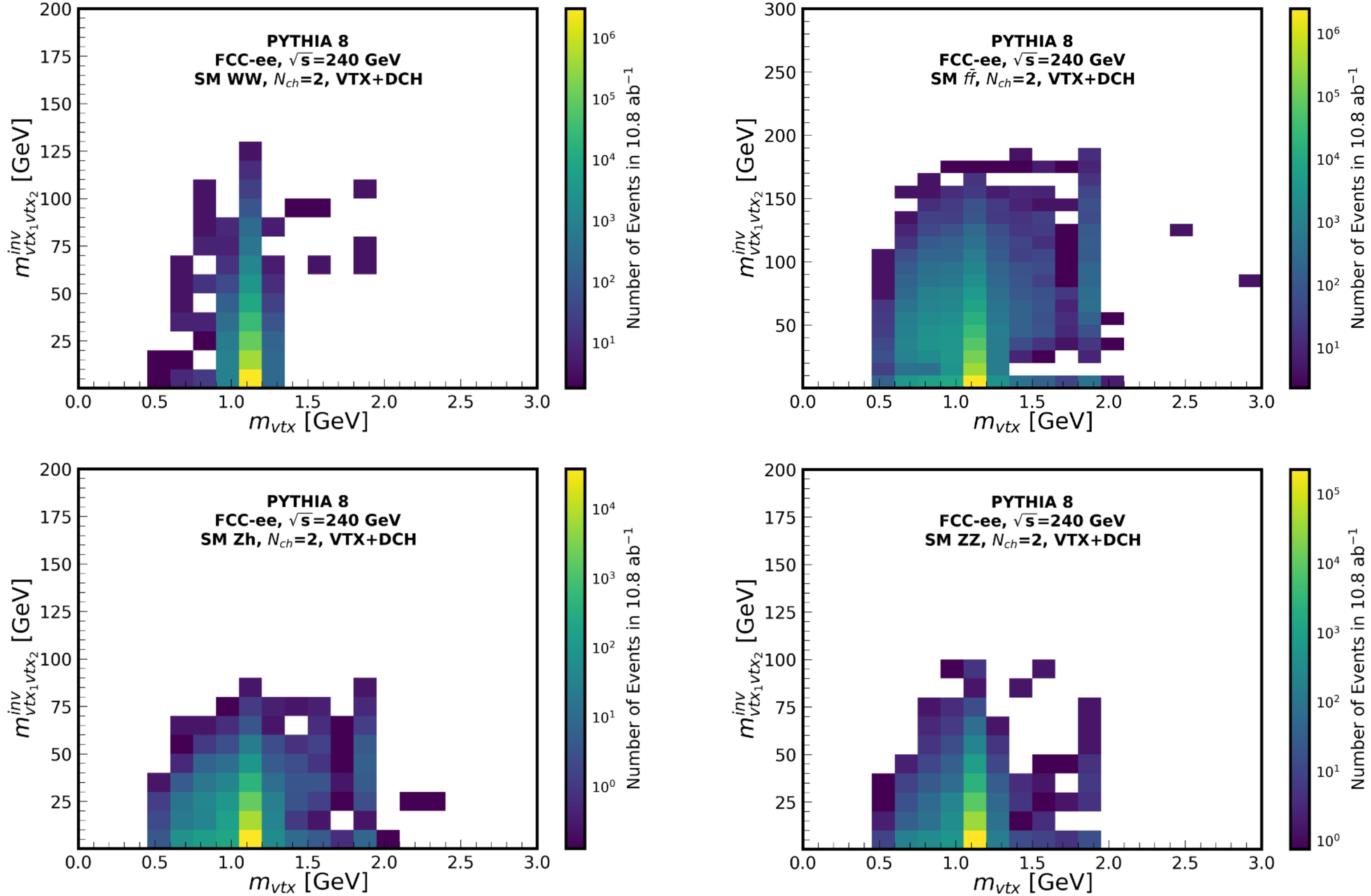
Benchmarks	Muon Spectrometer analysis		
	m_ϕ (GeV)	$c\tau$ (mm)	Number of events
BPA1	0.4	39666.6	4
BPA2	1.0	554.3	206
BPA3	1.0	34.6	78
BPA4	2.0	135.2	1515
BPA5	3.5	10285.4	4
BPA6	3.5	65.8	3

Benchmark		m_ϕ (GeV)	$c\tau$ (mm)
BPA7		4.4	95.0
Final cuts for the $c\bar{c}$ final state		Number of events	
$D_{\text{vtx}} \in$ VTX or DCH, $N_{\text{ch}} \geq 3$, $E > 5\,\text{GeV}$, $m_{\text{vtx}} > 1.5\,\text{GeV}$ +	$d_T > 100\,\text{mm},\ d_0 > 10\,\text{mm}$	6	
	$d_T > 150\,\text{mm},\ d_0 > 10\,\text{mm}$	6	
	$d_T > 250\,\text{mm},\ d_0 > 20\,\text{mm}$	3	

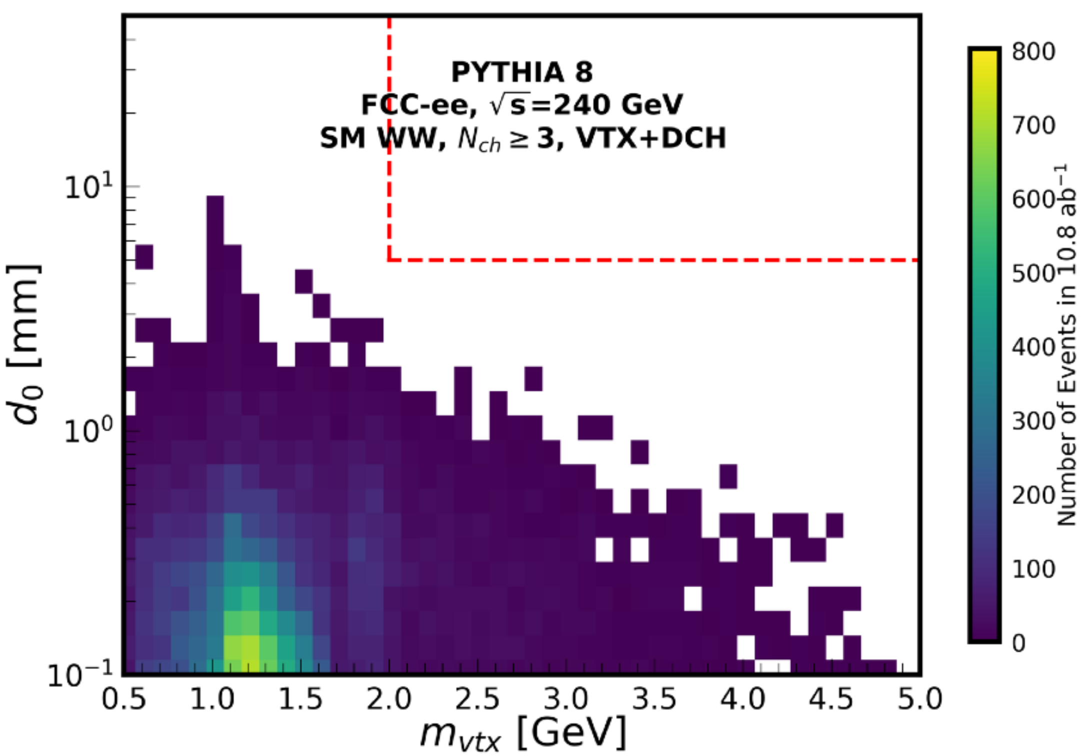
Production mode: $Z \to Z^* \phi$

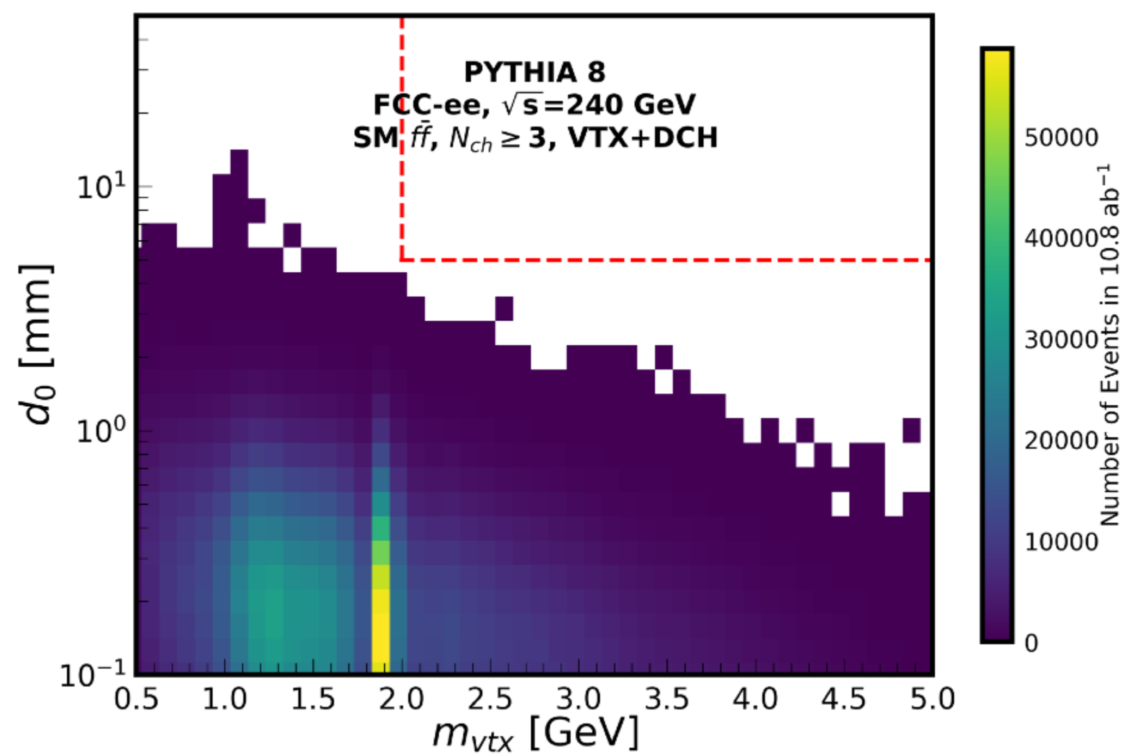


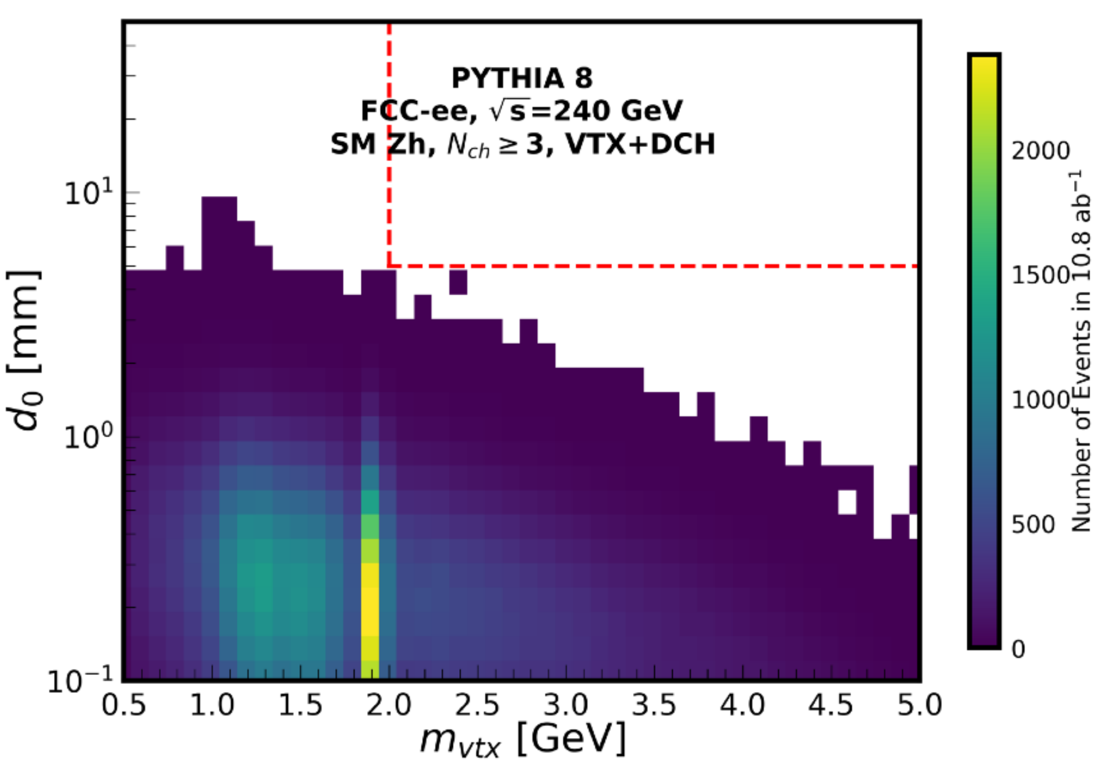
$h \to \phi\phi, \;\; \phi \to \pi^+\pi^- / K^+K^-$

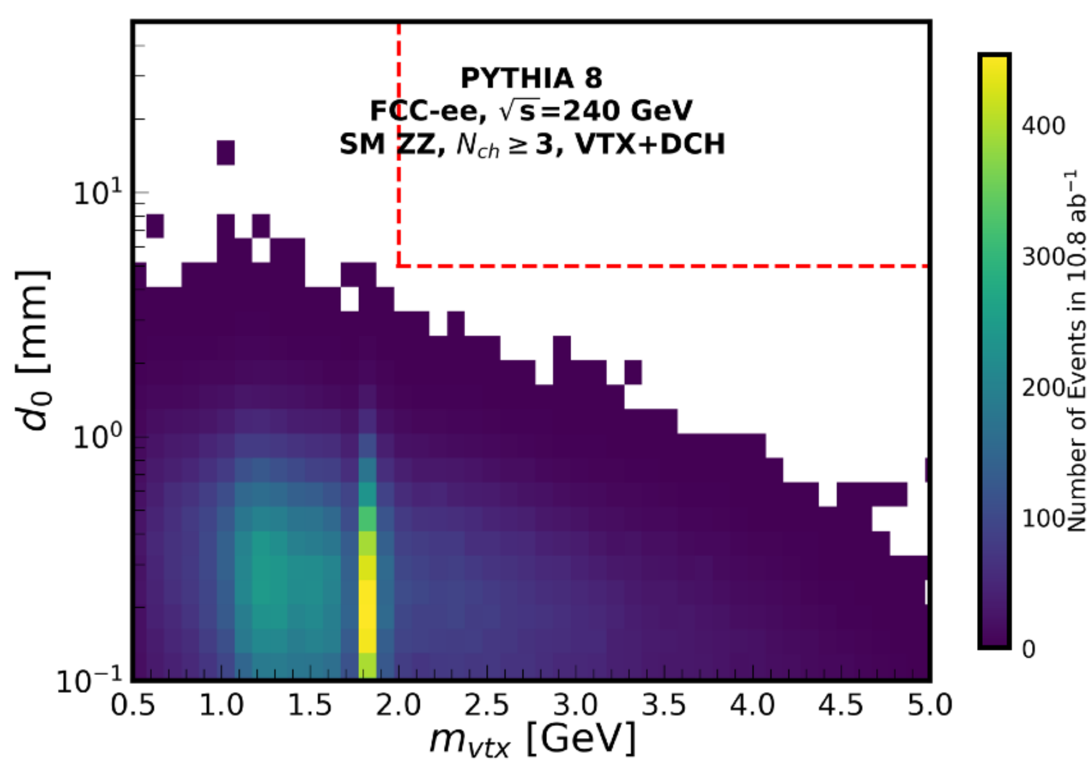


$h \to \phi\phi, \;\; \phi \to c\bar{c}/b\bar{b}$







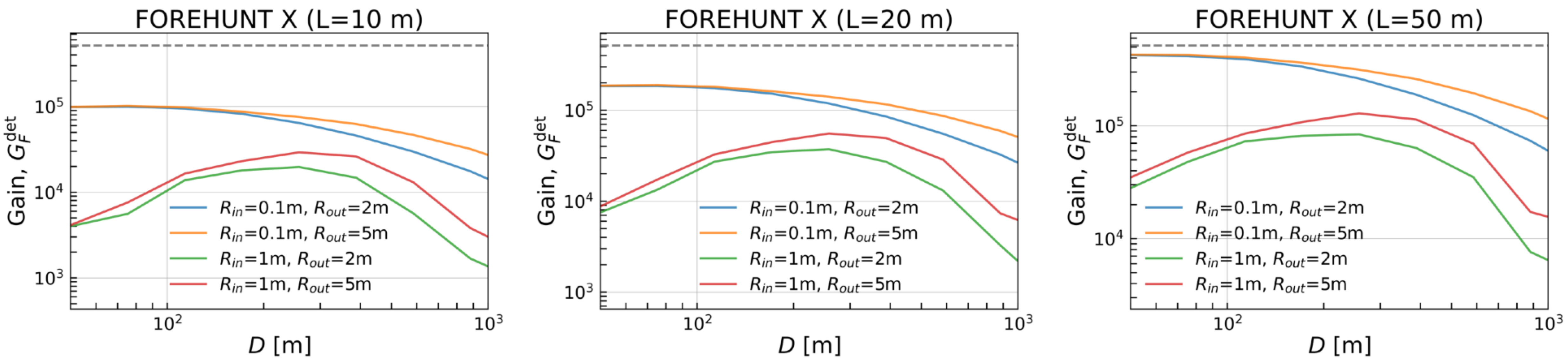


Case B results

Benchmarks	m_ϕ (GeV)		$c\tau$ (mm)			
BPB1	1		10			
BPB2	1		100			
Cuts	Number of events					
	Signal		Backgrounds			
	BPB1	BPB2	$f\bar{f}$	WW	ZZ	Zh
122 GeV $< m^{\text{inv}}_{\text{vtx}_1\text{vtx}_2} <$ 128 GeV	222	21	215	24	0	0
In each vertex, $N_p = 0$	222	21	125	4	0	0
In each vertex, $N_{\pi^\pm} = 2$ or $N_{K^\pm} = 2$	222	21	14	0	0	0
$d_T >$ 100 mm	143	18	0	0	0	0

Benchmarks	m_ϕ (GeV)	$c\tau$ (mm)	Number of signal events	
			Criterion 1	*Criterion 2*
BPB3	4.4	10	32	3
BPB4	4.4	100	8	1
BPB5	6.0	100	71	18
BPB6	6.0	1000	<1	~ 0
BPB7	40	10	562	320
BPB8	40	100	1747	887

Optimisation of FOREHUNT



Gain estimated with respect to the FASER detector @ LHC