

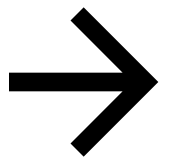
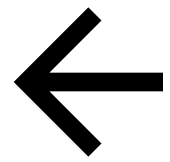


The model: A theory of dark pions

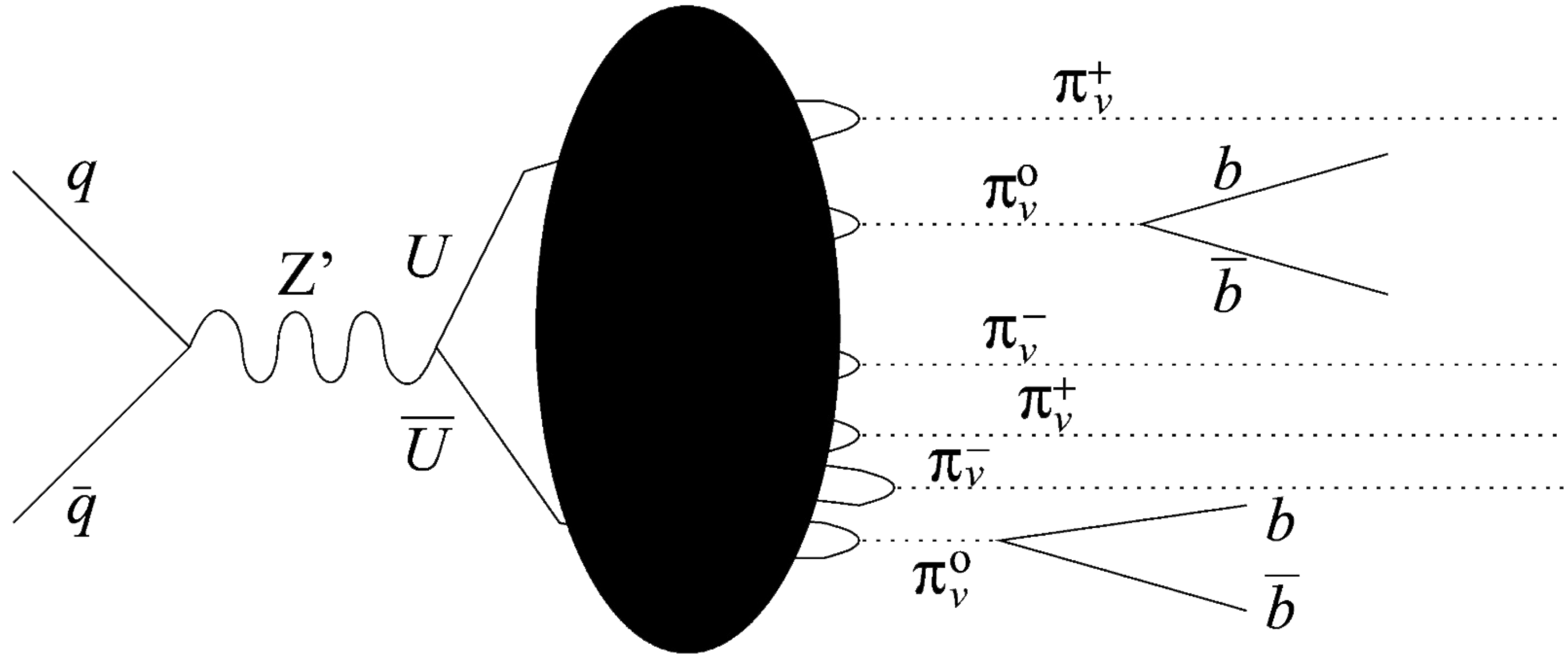
- Hidden Valley (HV) models
- Dark QCD-like force
- Arbitrary number of flavours and colours within approximate confinement $N < 4N_d$
- Lightest dark hadron: "dark pion" Long-lived-particle (LLP)
- Higgs Portal

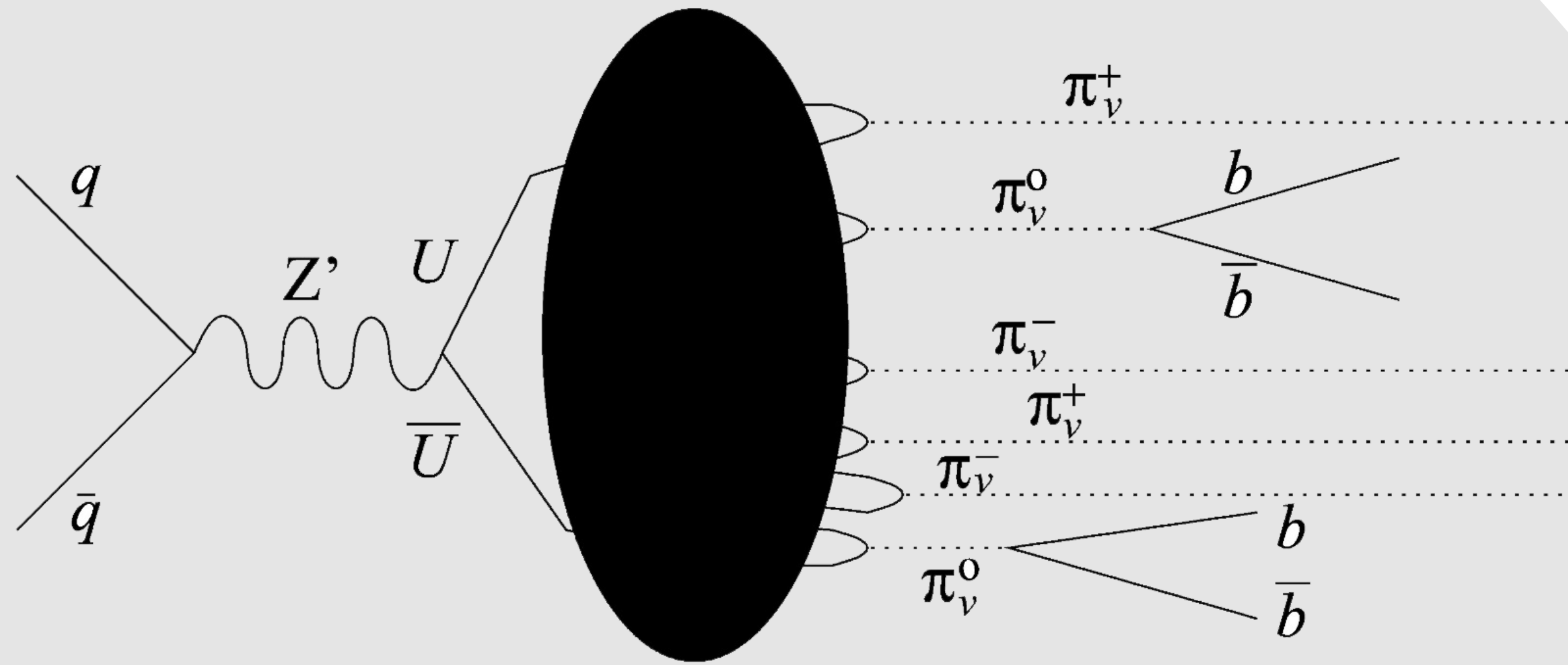
$$\hat{\pi} \rightarrow K_s^0 + K^- + \pi^-$$

$$K_s^0 \rightarrow \pi^+ + \pi^-$$

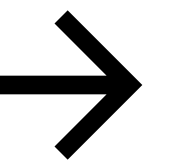


6.9% BR $\hat{\pi} \rightarrow K_s^0 K^+ \pi^+$
 $K_s^0 \rightarrow \pi^+ \pi^-$





A sensitivity study for dark pions at the LHCb





Contents

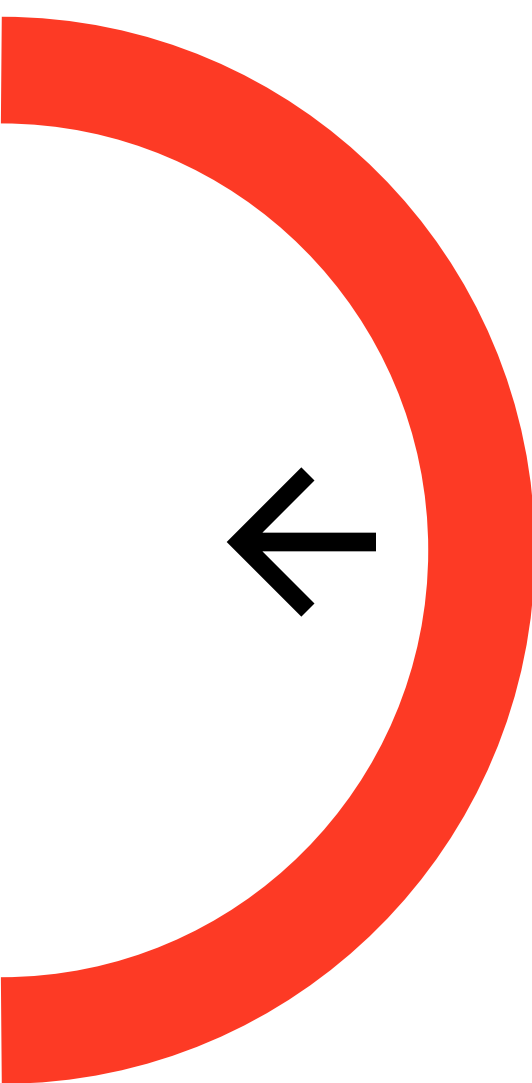
**The model: A theory of dark pions
Higgs bosons in Run 2**

**Simulation studies generator level & complete
detector**

**Multivariate Analysis (MVA)
with gradient boosted decision tree (BDT)**

Estimated significance

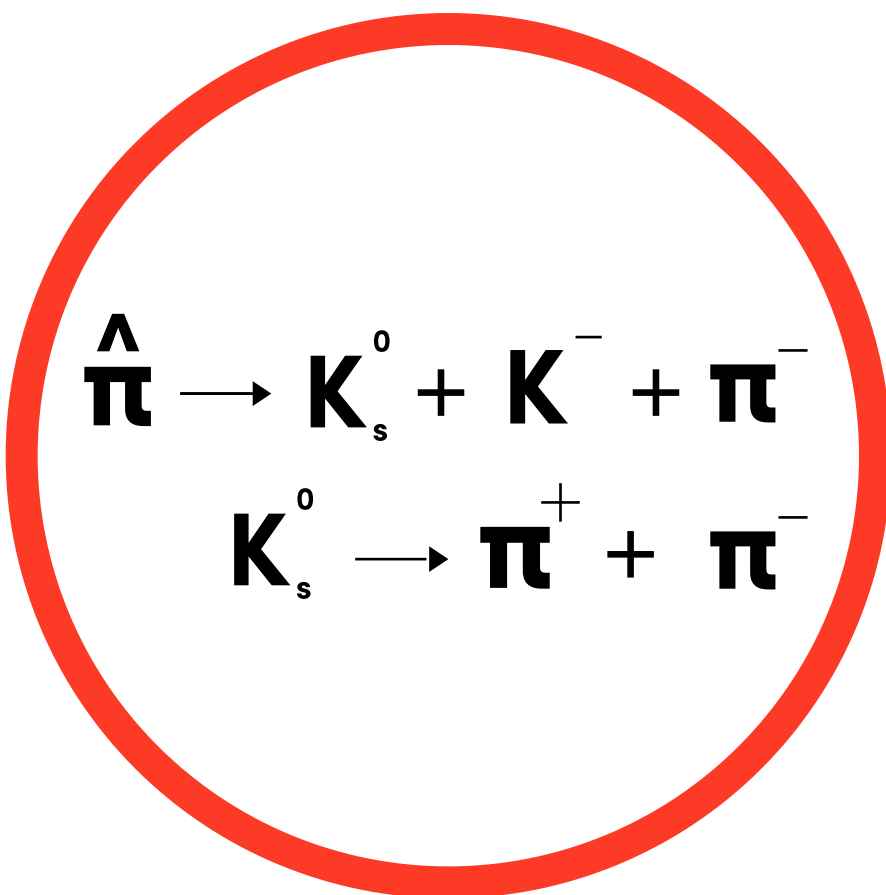
Results and conclusions





The model: A theory of dark pions

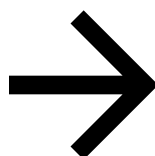
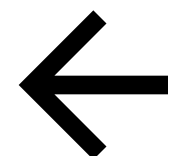
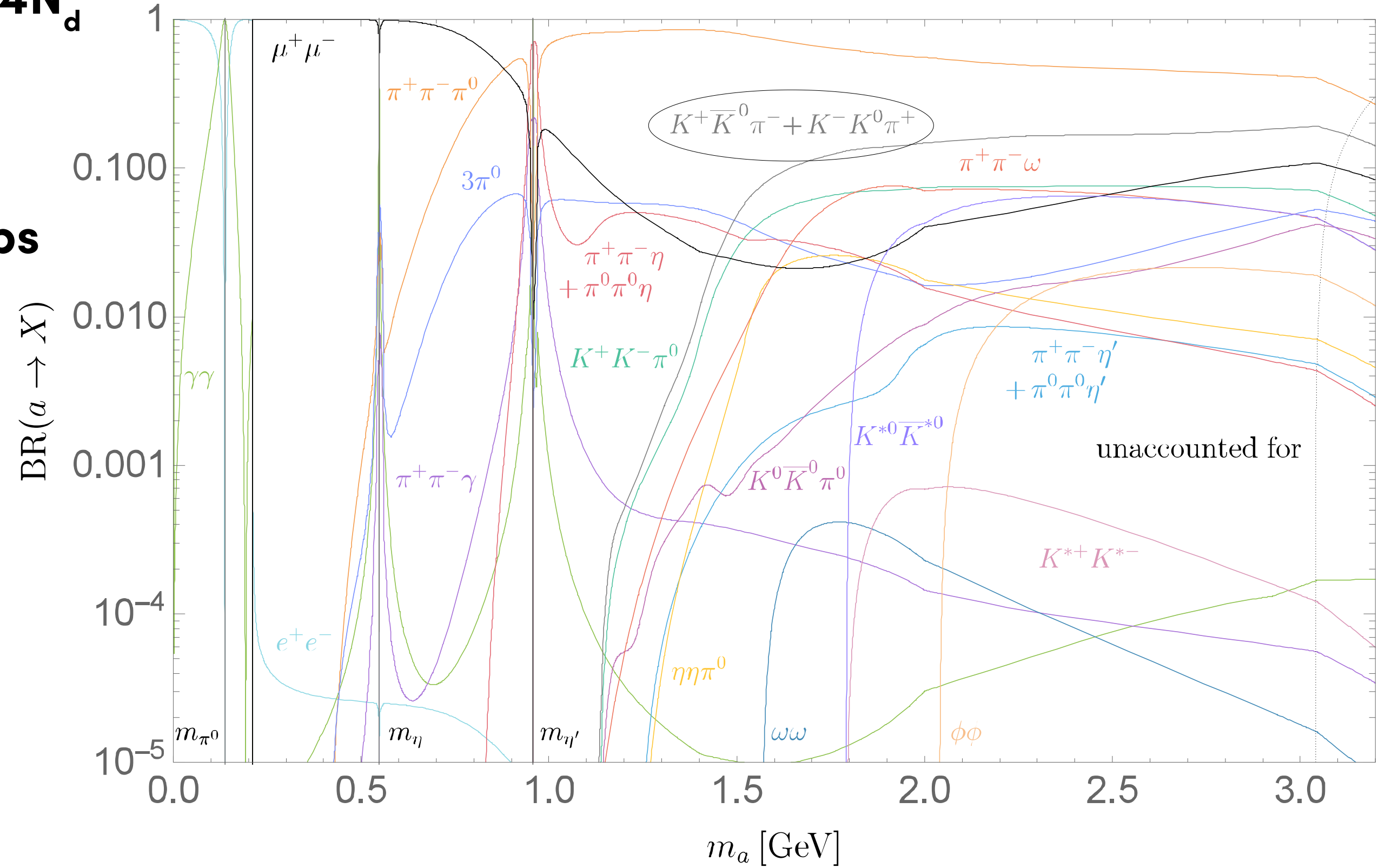
- Hidden Valley (HV) models
- Dark QCD-like force
- Arbitrary number of flavours and colours within approximate confinement $N < 4N_d$



- Lightest dark hadron: "dark pion" Long-Lived-Particle (LLP)
- Investigated lifetime range: 5 to 100 ps

- Higgs Portal
6.9% total BR $\hat{\pi} \rightarrow K_s^0 K^+ \pi^+$
 $K_s^0 \rightarrow \pi^+ \pi^-$

- Mass region: $1.2 < M < 3 \text{ GeV}$





Higgs bosons in Run 2

- Higgs boson 13 TeV cross section: $56.9 \text{ pb} = 56.9 \cdot 10^{-12} \text{ b}$

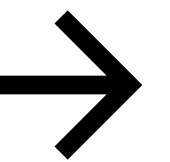
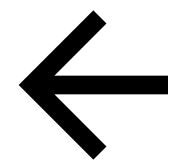
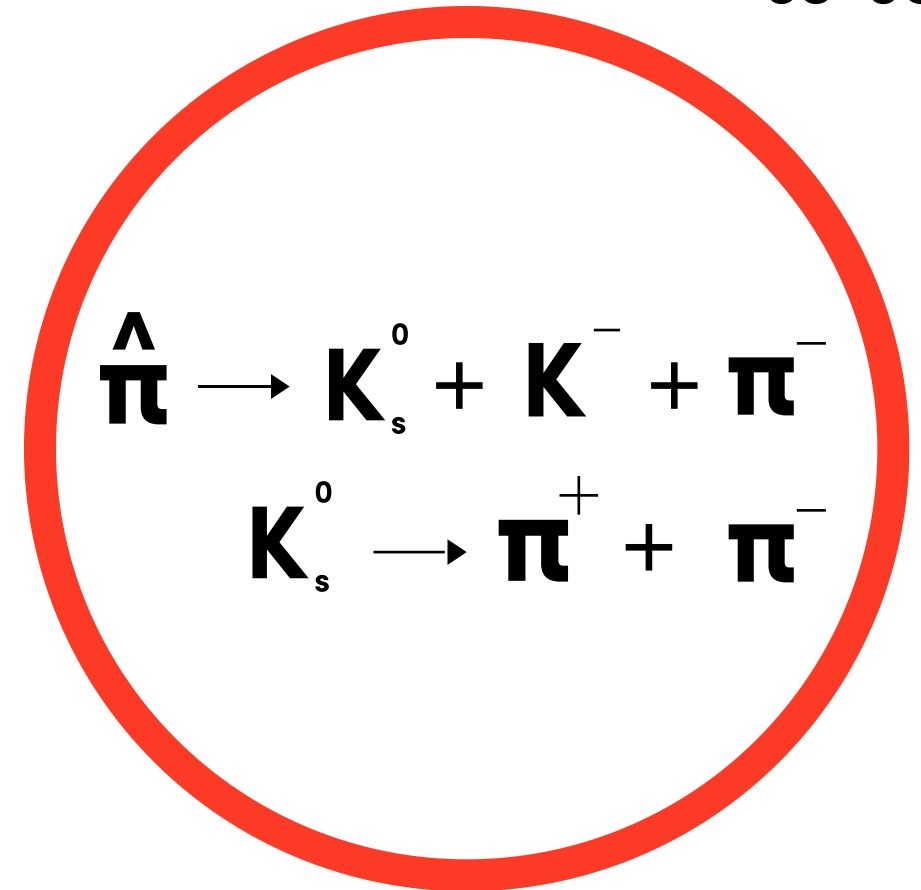
- LHCb Run 2 luminosity: $5.7 \text{ fb}^{-1} = 5.7 \cdot 10^{15} \text{ b}^{-1}$

- Higgs bosons LHCb Run 2: $56.9 \cdot 5.7 \cdot 10^3 = 324330$

- CMS 2022: $\text{BR}(h \rightarrow \text{invisible}) < 18\%$

- Best case scenario dark Higgs bosons run 2:

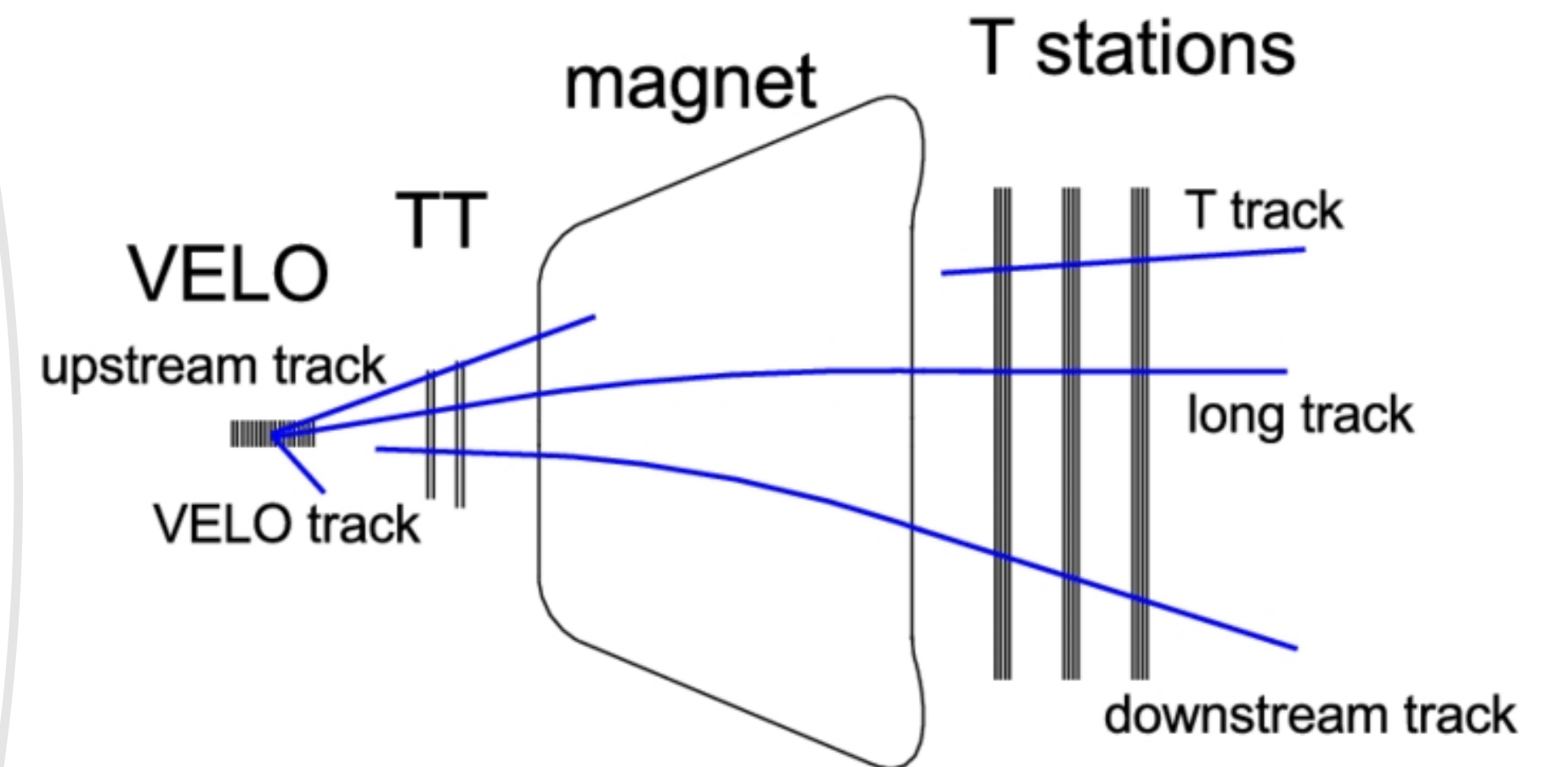
$$324330 \cdot 0.18 = 58379$$





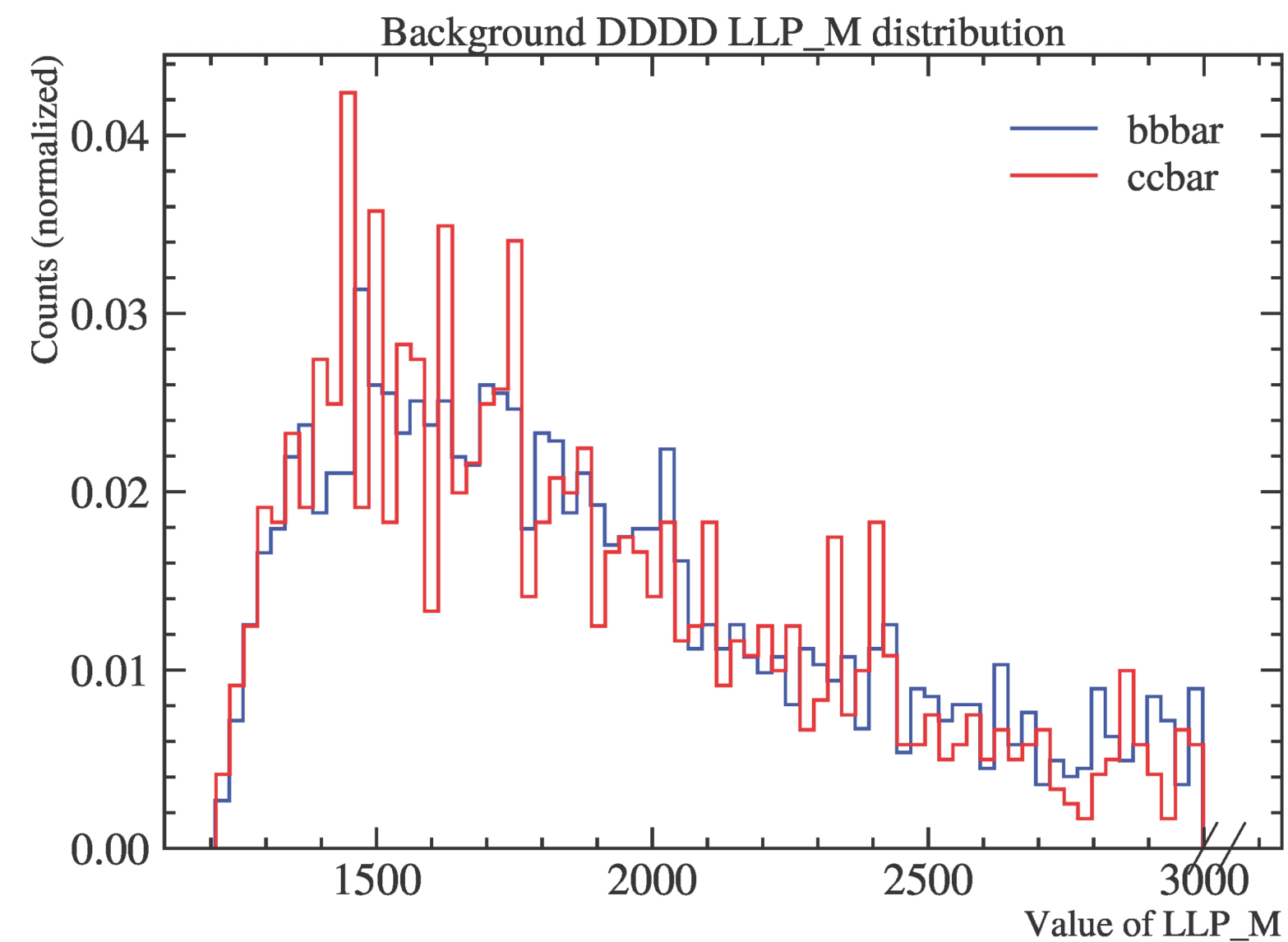
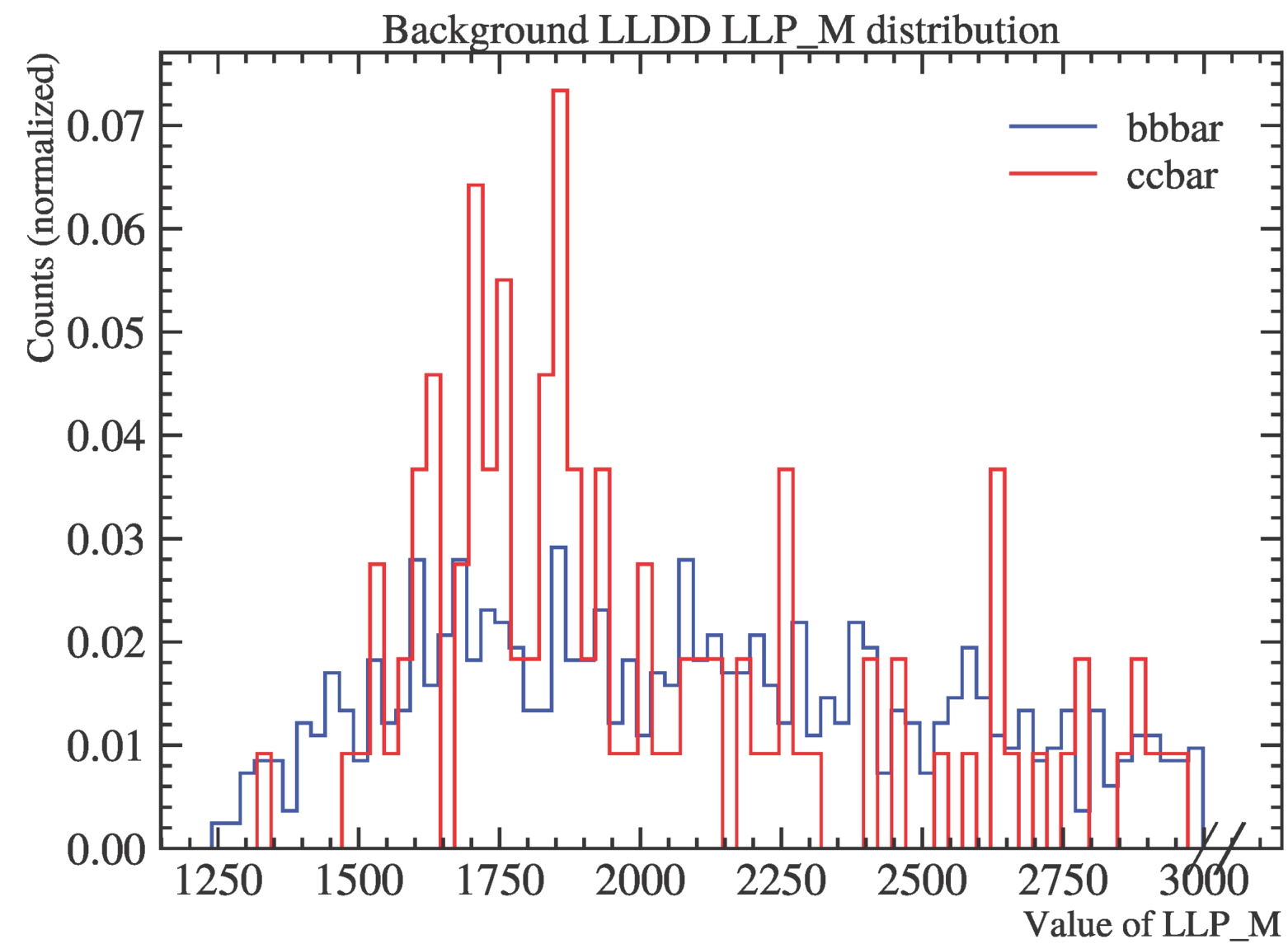
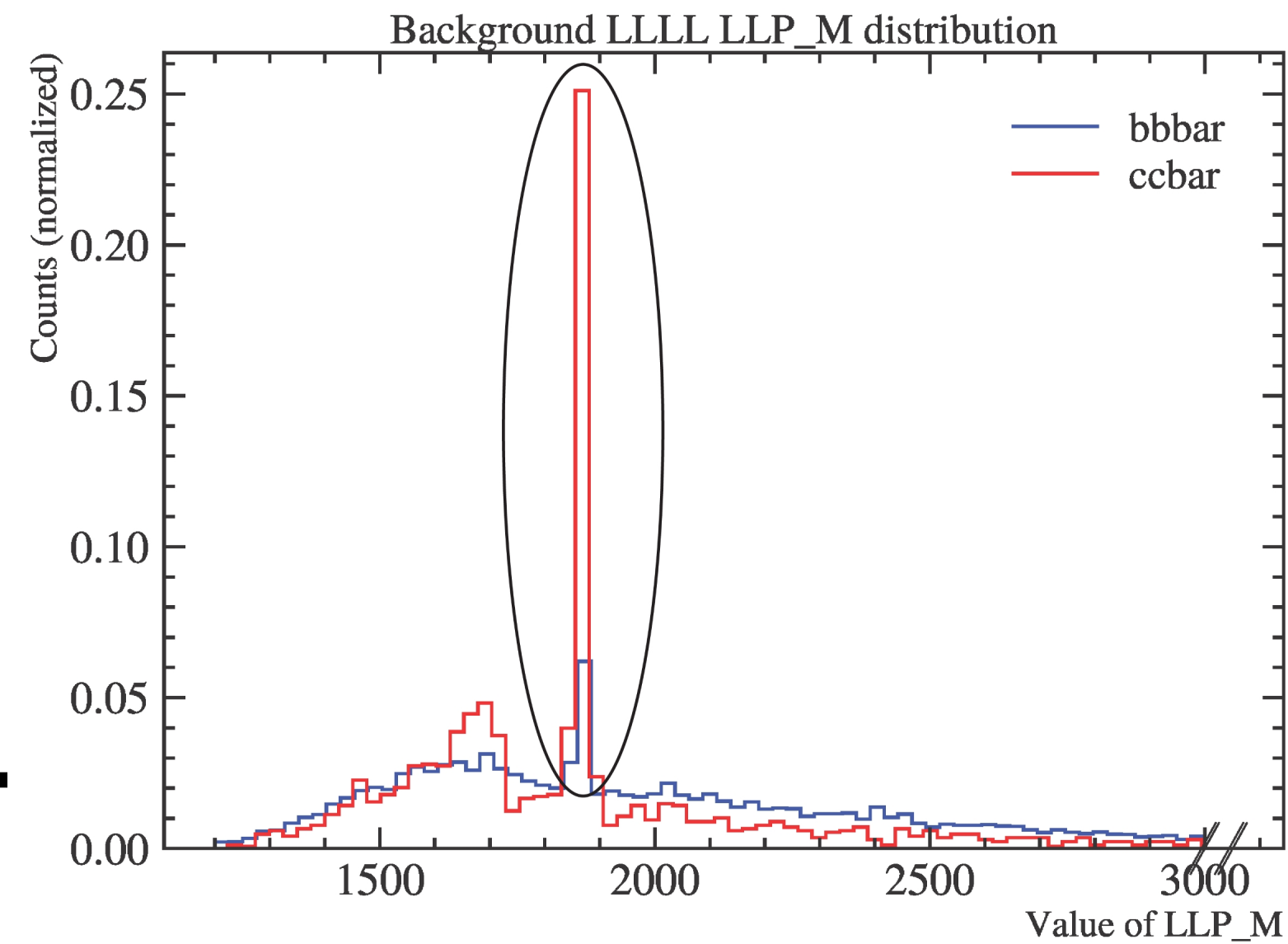
Simulation

- Generator level 5, 10 & 100 ps: 10K events
- Complete detector 10 ps: $\approx 1M$ events
- 200M background events each, $b\bar{b}$ and $c\bar{c}$
- Three analysis categories for long and downstream tracks: LLLL, LLDD, DDDD
- LLLL: Long track reconstruction of $\hat{\pi}$ and K_s^0
- LLDD: Long track reconstruction of $\hat{\pi}$
Downstream track reconstruction of K_s^0
- DDDD: Downstream track reconstruction of $\hat{\pi}$ and K_s^0





Background simulation

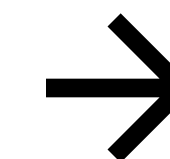
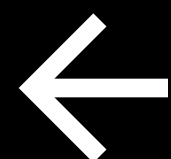
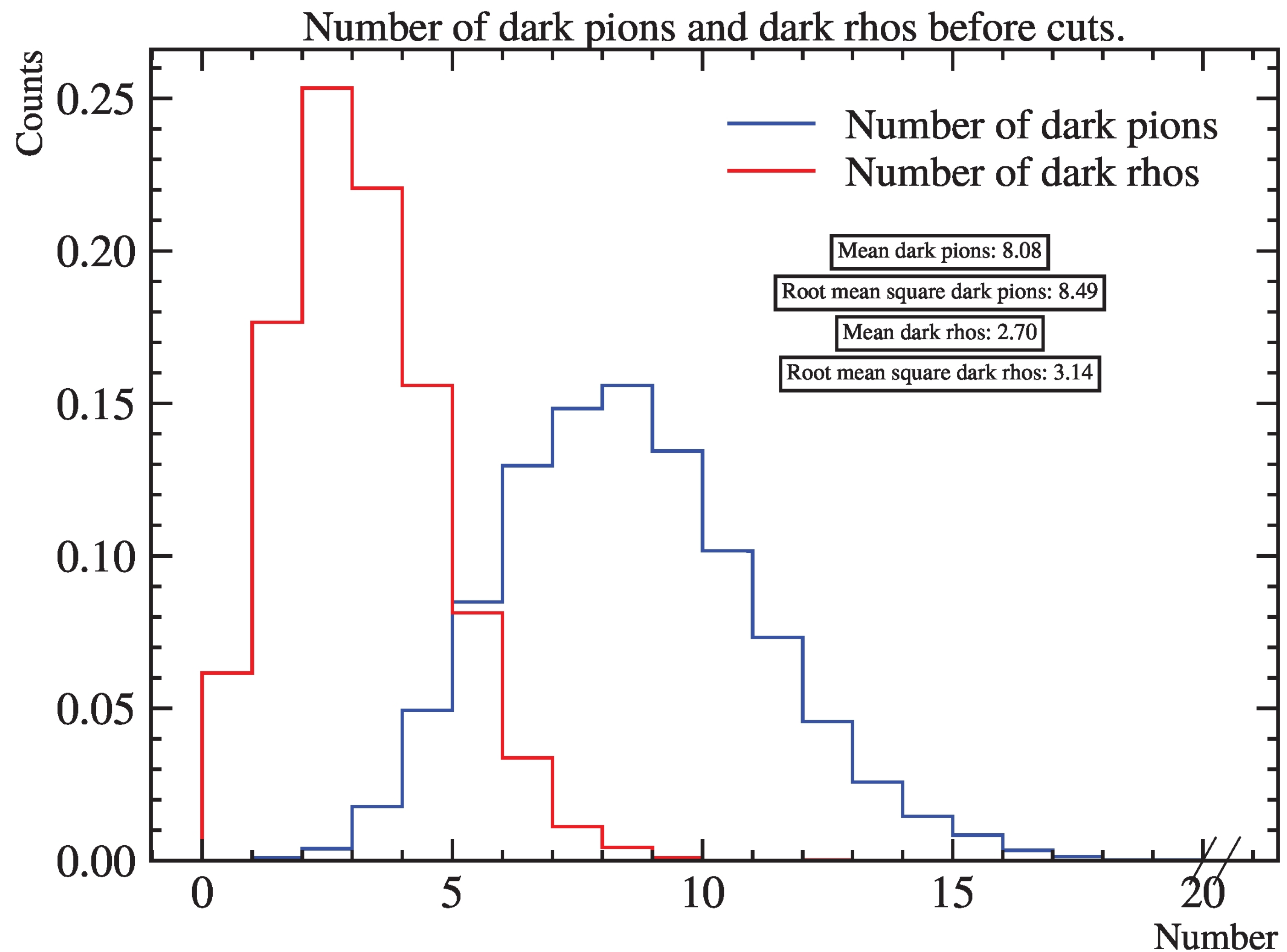


- Major background: D^0 meson (≈ 1865 MeV)
 - $5.74 \cdot 10^{-3}$ BR $D^0 \rightarrow K_s^0 K^+ \pi^-$
- And 55.5% BR $B^0 \rightarrow D^0 X$



Generator level studies

Dark pions per Higgs

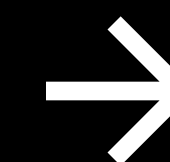
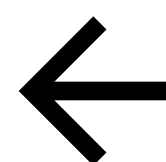
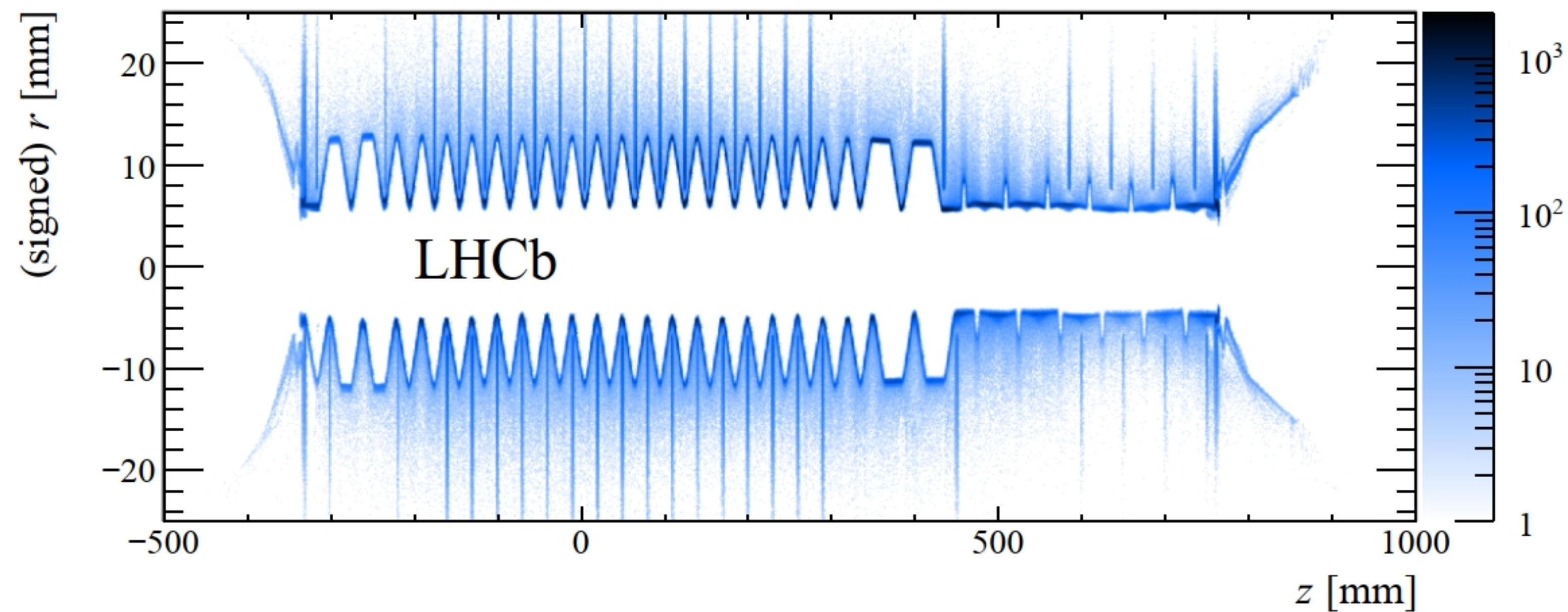




Generator level studies

Acceptance efficiencies

- For long tracks:
 - Distance from beamline: < 30 mm
 - z-coordinate cut: $-100 < z < 600$ for VELO



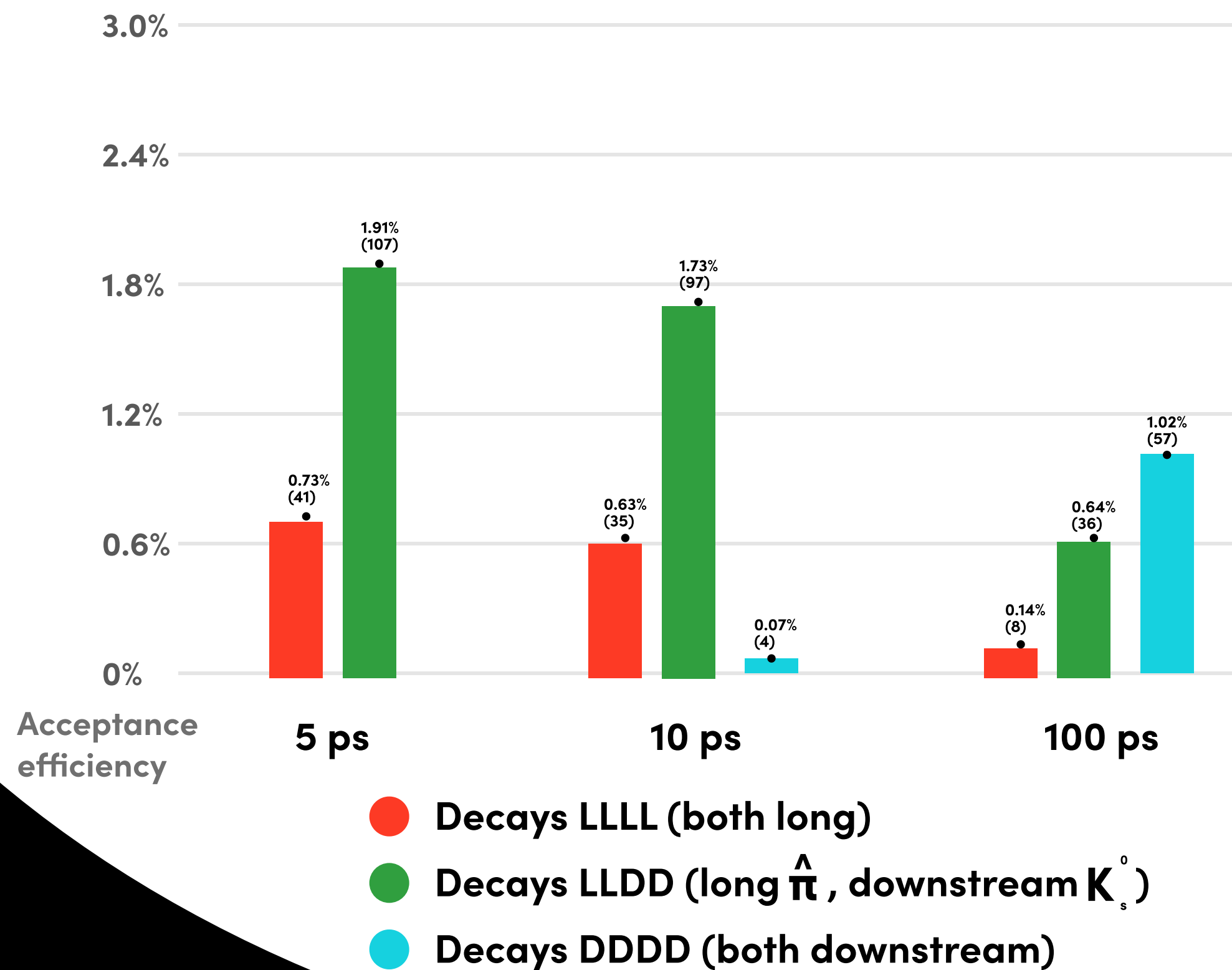


Generator level studies

Acceptance efficiencies

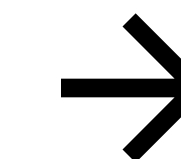
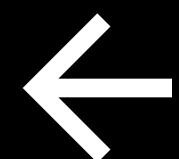
Generator level cuts

- Pseudorapidity $2 < \eta < 5$
- Total momentum $> 2 \text{ GeV}$
- Distance from beamline: $< 30 \text{ mm}$ for long tracks
- z-coordinate: $-100 < z < 600$ for long tracks, $600 < z < 2200$ for downstream tracks



Best performing categories

- 5 ps: LLDD (1.91%)
 - 618 reconstructible decays in Run 2
- 10 ps: LLDD (1.73%)
 - 554 reconstructible decays in Run 2
- 100 ps: DDDD (1.02%)
 - 327 reconstructible decays in Run 2

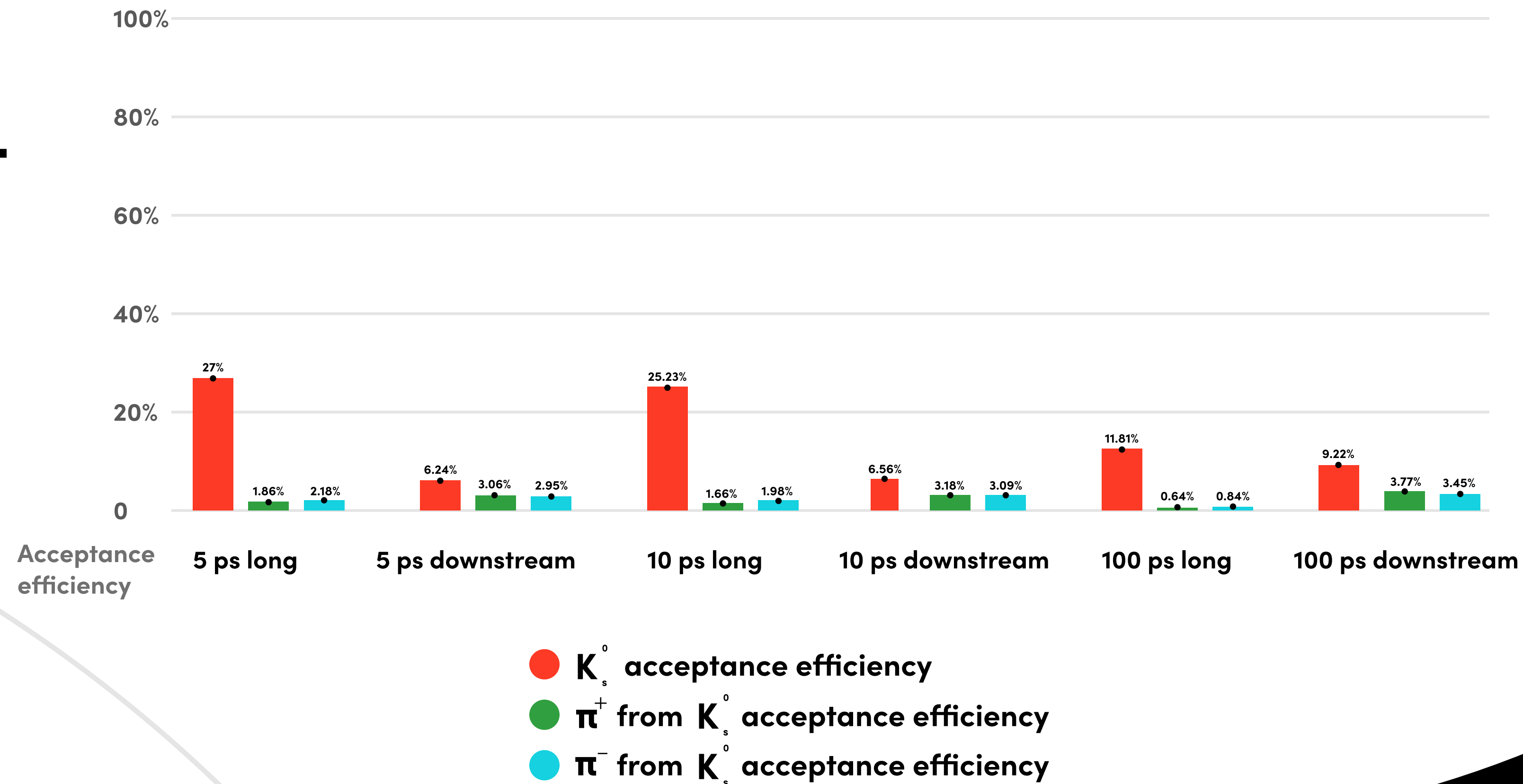




Generator level studies

Acceptance efficiencies

- In 5 and 10 ps, despite much lower K_s^0 acceptance downstream
 - Daughter pions have similar acceptance, highest in downstream
- In 100 ps, similar acceptance K_s^0
 - Daughter pions have higher acceptance in downstream track, larger difference

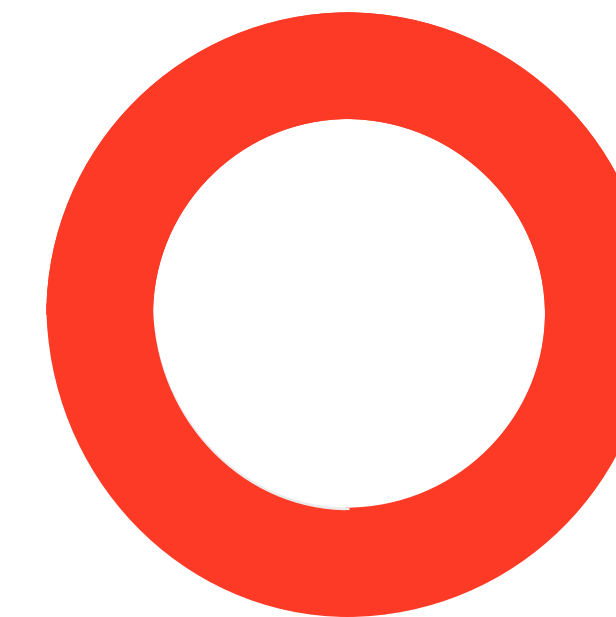




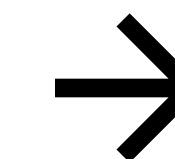
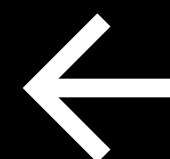
Generator level studies

Run 2 predictions

- After cuts, 1 dark pion per dark Higgs
- Recall: 58379 dark Higgs bosons in Run 2
- Using the acceptance efficiencies, predict Run 2 reconstructible decays



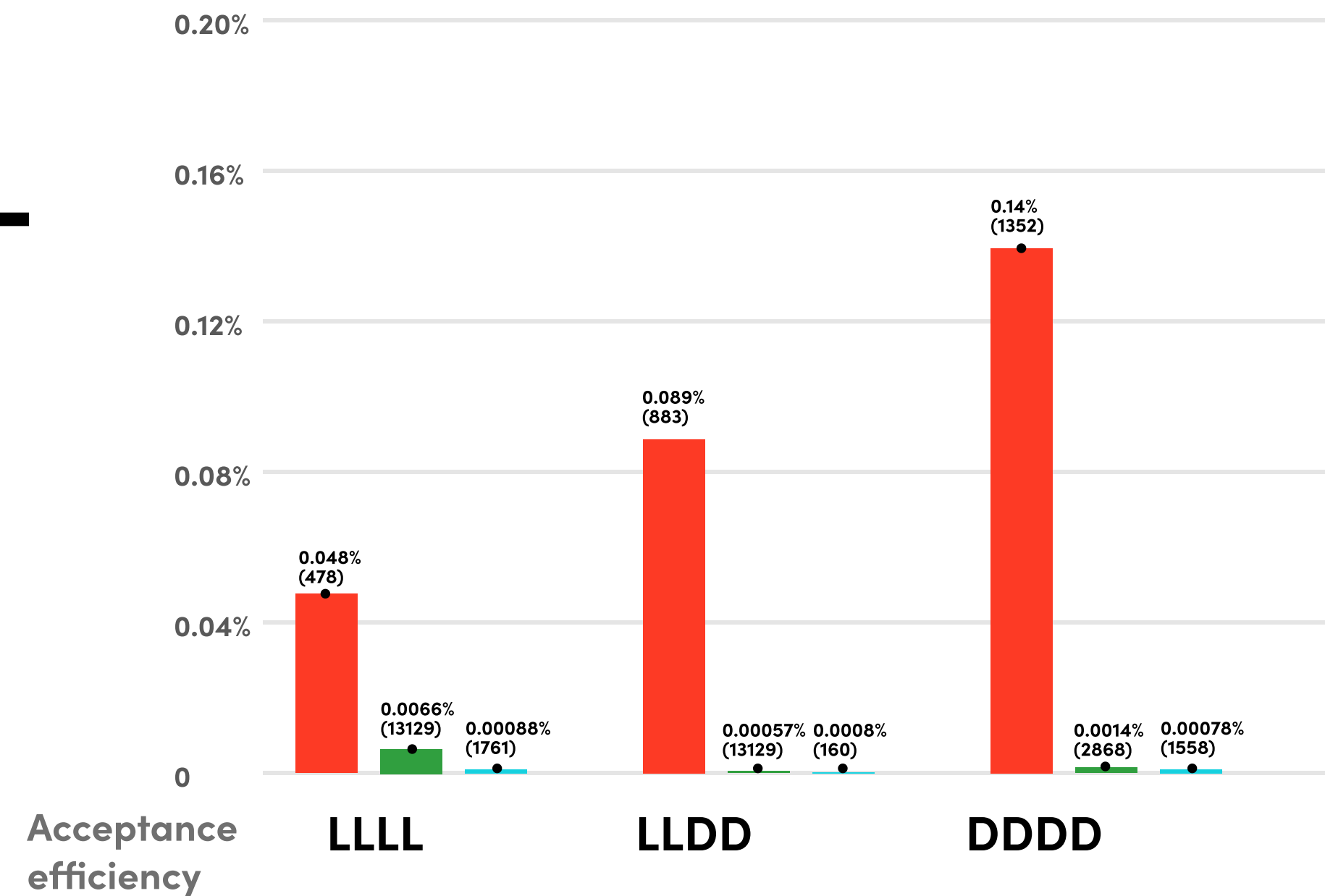
	5 ps	10 ps	100 ps
LLLL	239	204	47
LLDD	618	554	204
DDDD	0	23	327





Complete detector simulation

Stripping selection



- Recall: 1M signal events
- 200M background events
- Run 2 LHCb stripping selection for LLP's
- Despite higher cross section of cc , acceptance efficiency is lower
- Recall generator level acceptance efficiencies:
 - LLLL: 0.63%
 - LLDD: 1.73%
 - DDDD: 0.07%

- Signal events acceptance efficiency
- $b\bar{b}$ background events acceptance efficiency

- $c\bar{c}$ background events acceptance efficiency

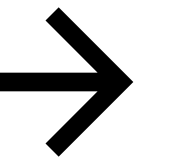
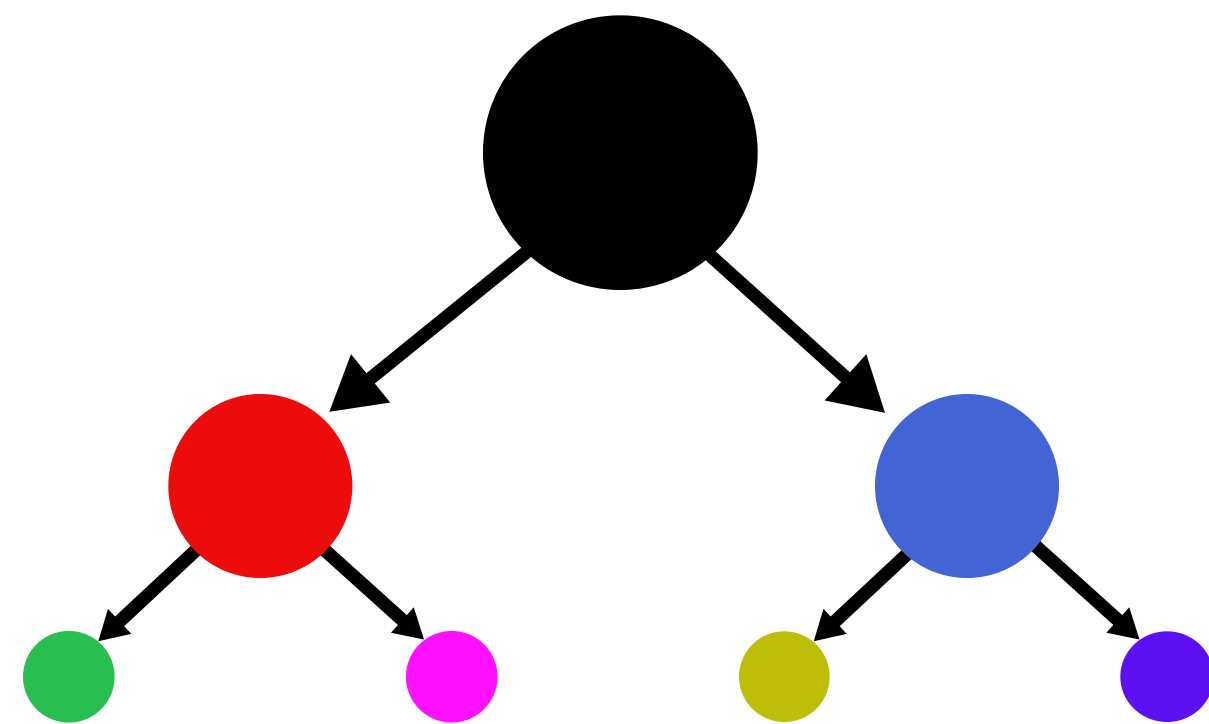
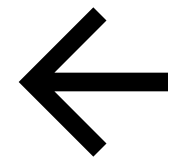


MVA: Gradient BDT



• Hyperparameters:

- Learning rate: 0.15
- Number of estimators: 100
- Maximum depth: 4
- Subsample: 0.5



• Simple BDT

- Training weak learners based on prediction of negative gradient of loss function, for minimization of loss function

• Train features:

- Transverse momentum ; for LLP, Ks, KM, PiP

- PID variables ProbNNk and ProbNNpi ; for KM, PiP

- Impact parameter χ^2 w.r.t own primary vertex (pv) ; for LLP, Ks, KM, PiP

- Flight distance χ^2 w.r.t origin vertex ; for LLP & Ks

- Vertex isolation: smallest $\Delta\chi^2$ when adding one track ; for LLP

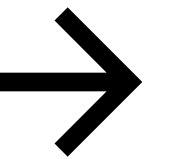
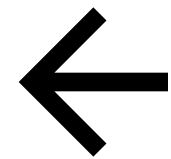
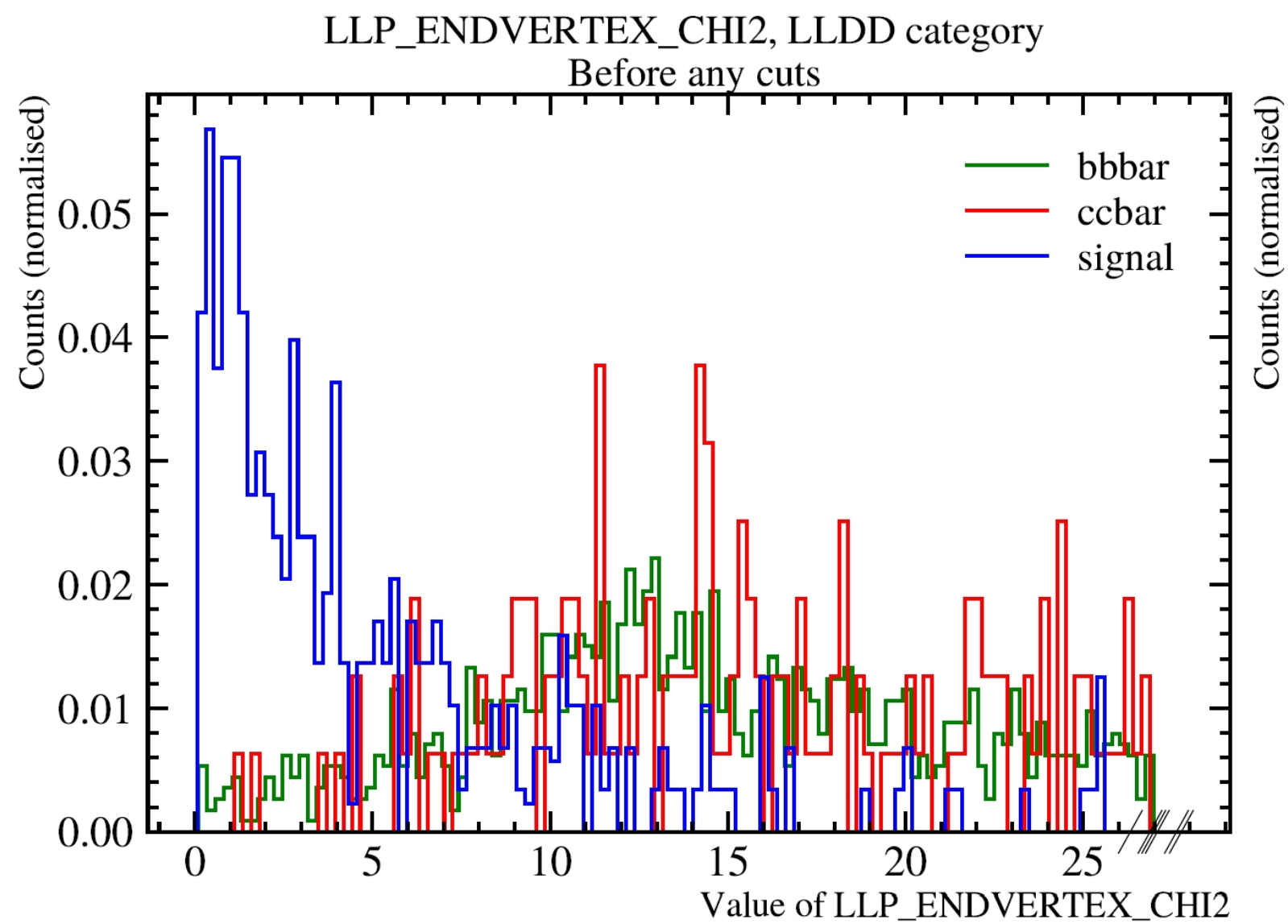
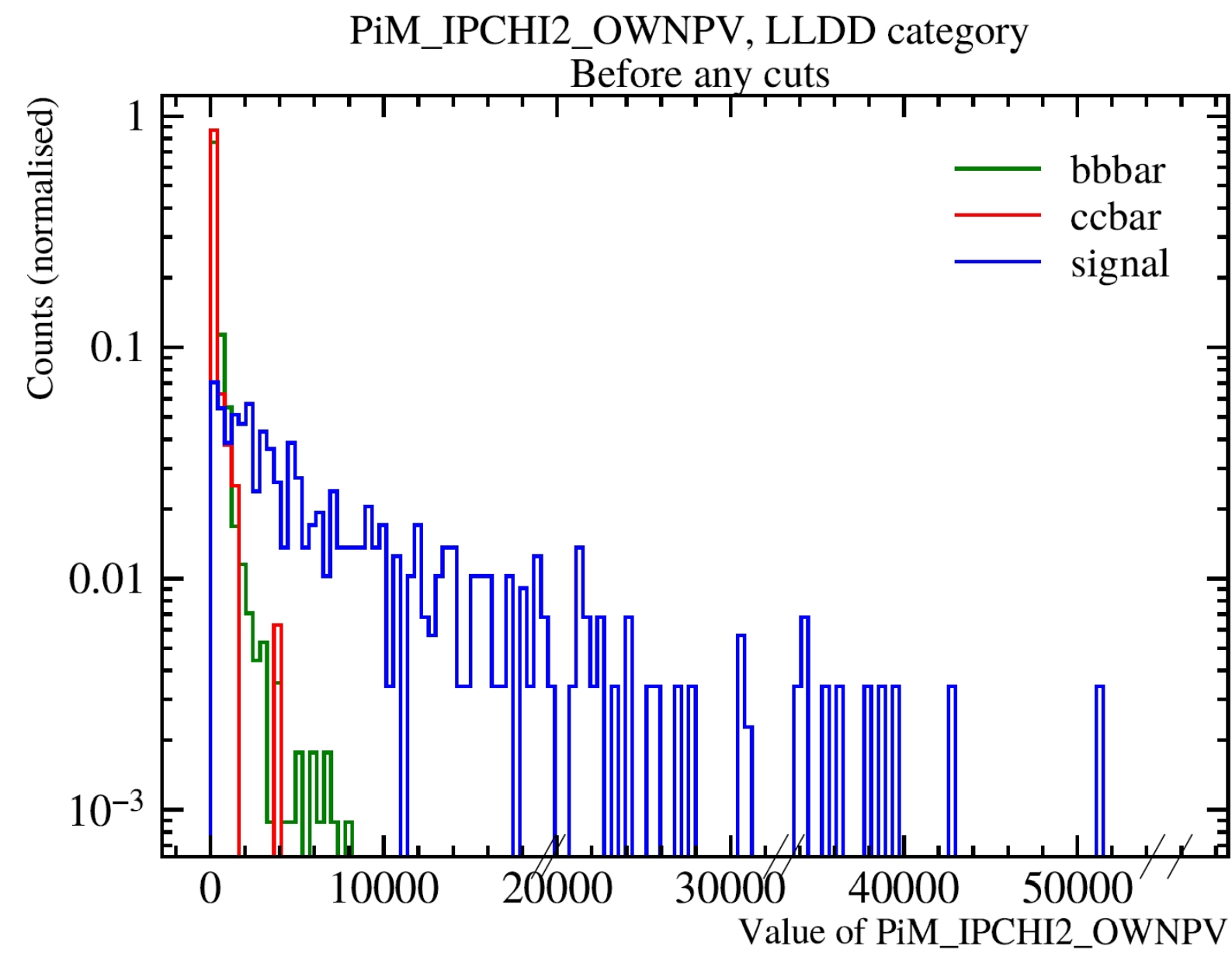
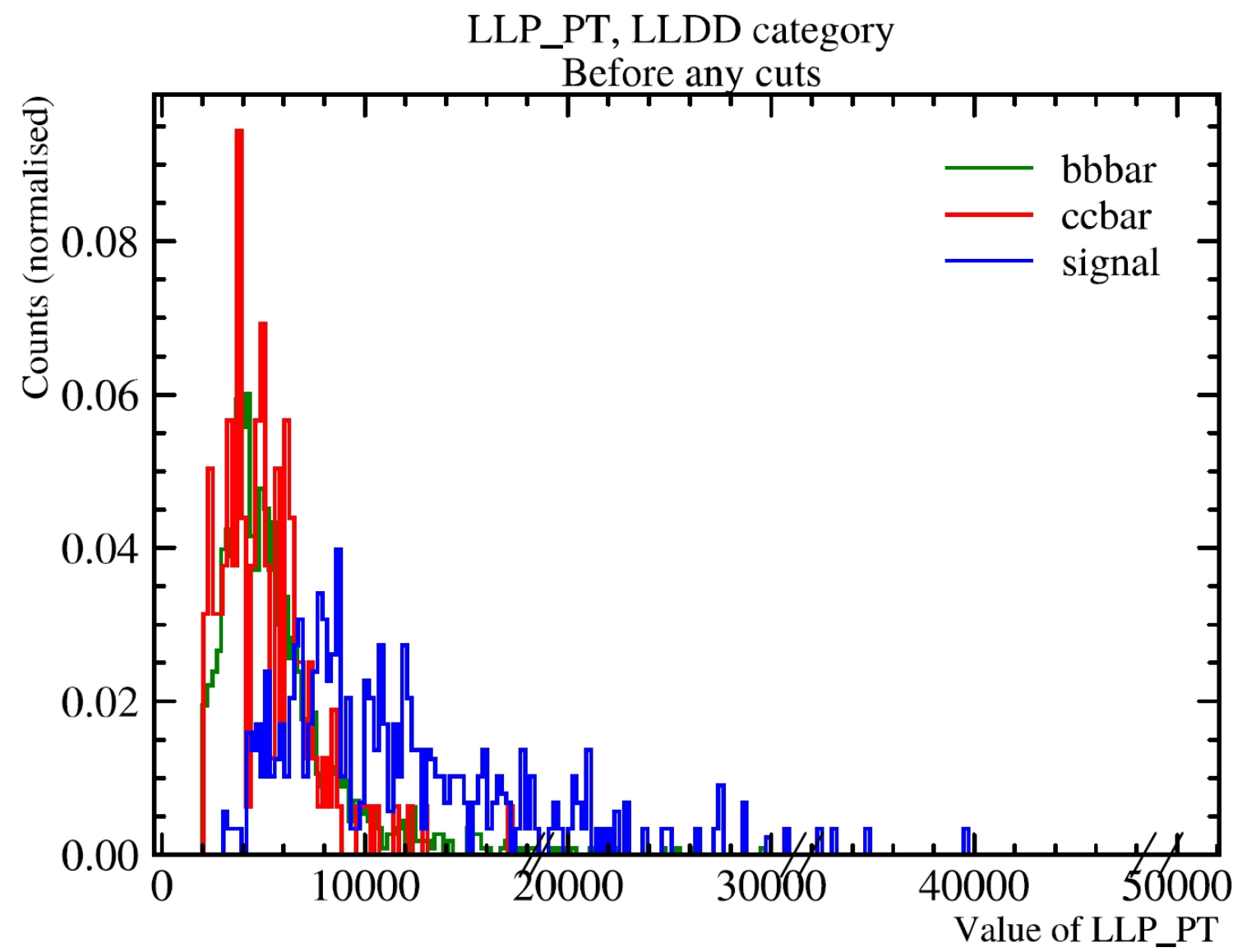
- Isolation variable 0.40nc_mult (neutral particles in 0.40 mrad cone); for LLP

- Isolation variable 0.40nc_sPT (sum transverse momentum neutral particles in cone); for LLP

- End vertex χ^2 ; for LLP



MVA: Gradient BDT





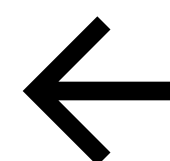
MVA: Number of events



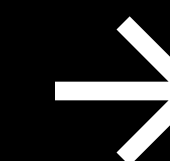
- $b\bar{b}$ LHCb acceptance cross section at 13 TeV: $144 \mu\text{b}$
- $c\bar{c}$ LHCb acceptance cross section at 13 TeV: $2369 \mu\text{b}$
- bb events: $8.21 \cdot 10^{11}$
- cc events: $1.35 \cdot 10^{13}$
- Recall 58379 dark Higgs bosons

- Recall acceptance efficiencies

	LLLL	LLDD	DDDD
Signal	0.048%	0.089%	0.14%
$b\bar{b}$	0.0066%	0.00057%	0.0014%
$c\bar{c}$	0.00088%	0.0008%	0.00078%



- Recall the much broader mass window in DDDD
 - Because of this, computed for both small 60 MeV ($2470 < M < 2530$) window and complete range $1.2 < M < 3 \text{ GeV}$
 - Future research needs to fit width per category
- **Extrapolation to Run 2 in mass ranges, using estimated number of events.**
Remarkably accurate background extrapolation for LLDD (150k from data vs. 170k extrapolated)



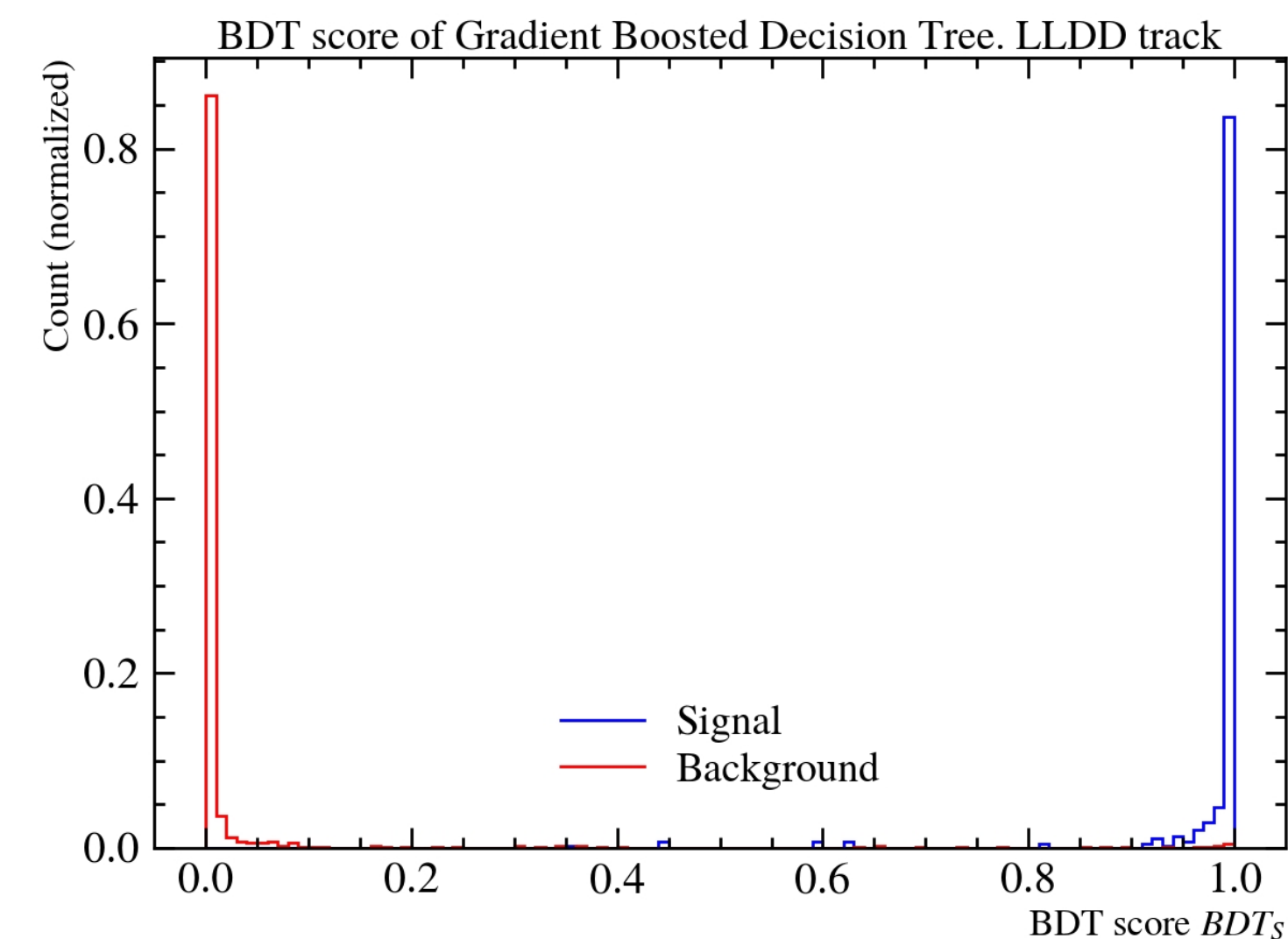
Event type	Category		
	LLLL	LLDD	DDDD
Run 2 signal events in mass window	1.67	3.03	1.10
Run 2 signal events in total mass range	2.80	5.14	7.52
Run 2 $b\bar{b}$ background events in mass window	965260.80	91108.80	160056
Run 2 $c\bar{c}$ background events in mass window	1377336.60	81019.80	1134277.20



MVA: Background suppression

Estimated significance

- Need more data for more natural distribution
- High signal retainment (> 90%)
- Recall from generator level:
 - 10 ps estimated Run 2 DDDD reconstructible decays: 23
 - 100ps estimated Run 2 DDDD reconstructible decays: 327



	Category		
	LLL	LLDD	DDDD
Signal events cut efficiency	91.9%	99.1%	100%
Background events cut efficiency	1.33%	2.44%	4.24%
Signal events left in mass window	1.53	3.00	1.10
Signal events left in total mass range	2.57	5.10	7.52
Estimated significance, with signal events in mass window	0.009	0.046	0.005
Estimated significance, with signal events in total mass range	0.015	0.079	0.032

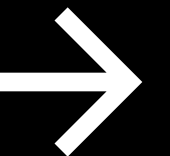
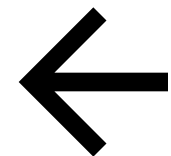
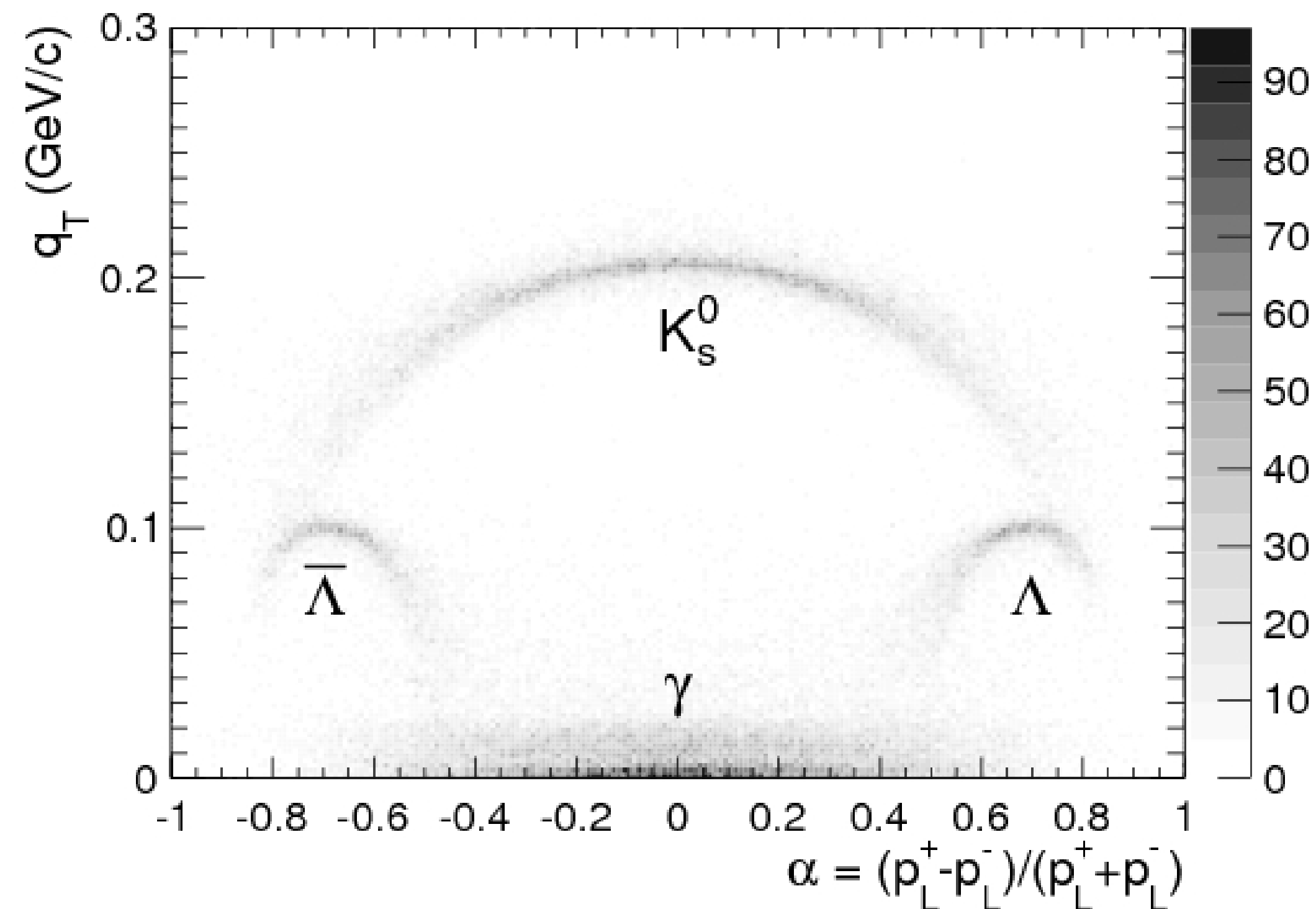


MVA: Improvements



- Improvement opportunities:

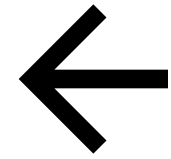
- LHCb Run 3 trigger: factor 10
- Kinematic cuts with Armenteros-Podolanski plot: factor 10
Symmetric momentum distribution of equal mass pions;
plot shows transverse momentum w.r.t mother vs.
longitudinal momentum assymetry
- Other: Flight distance in mm ; additional isolation variables

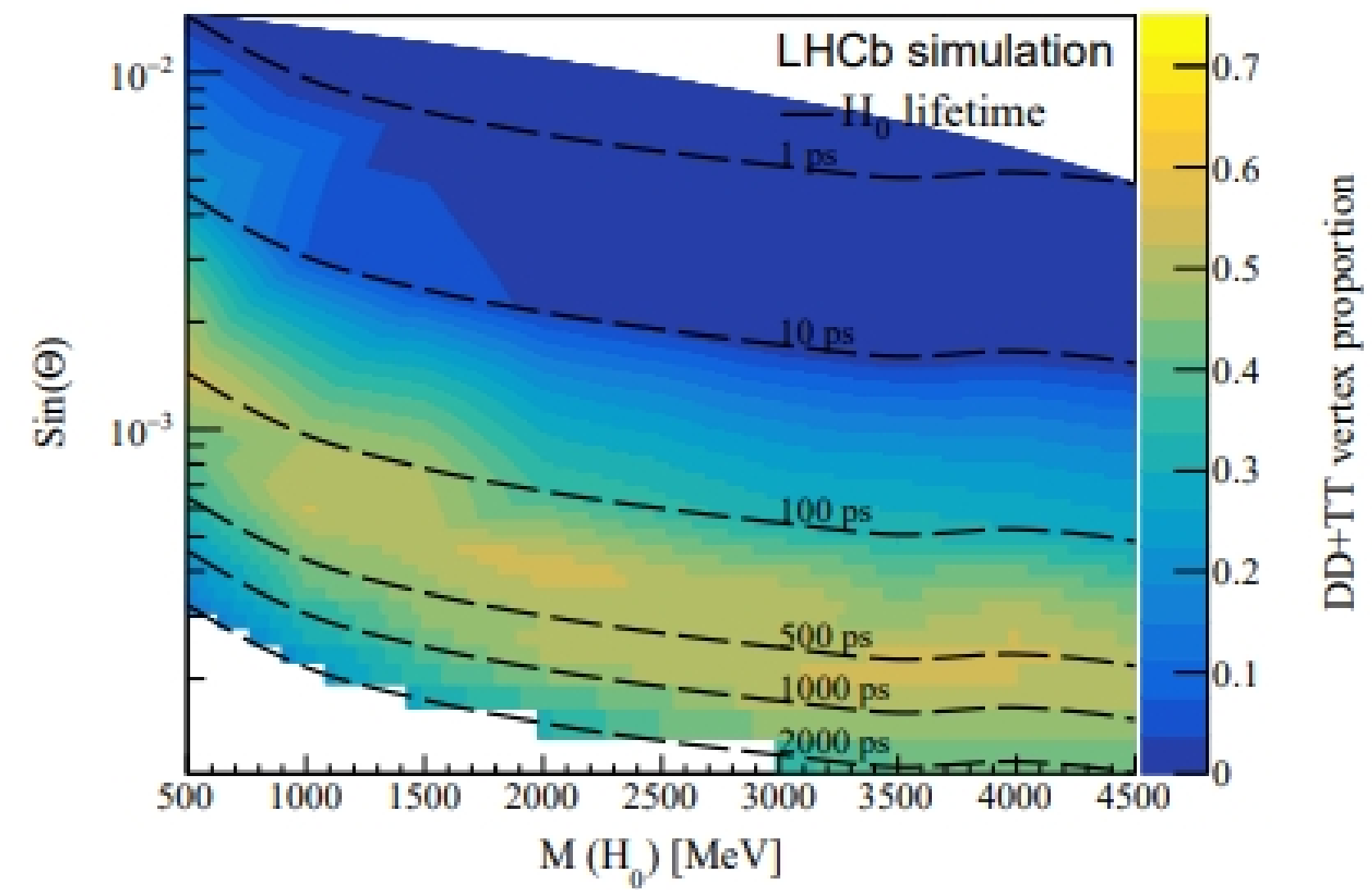
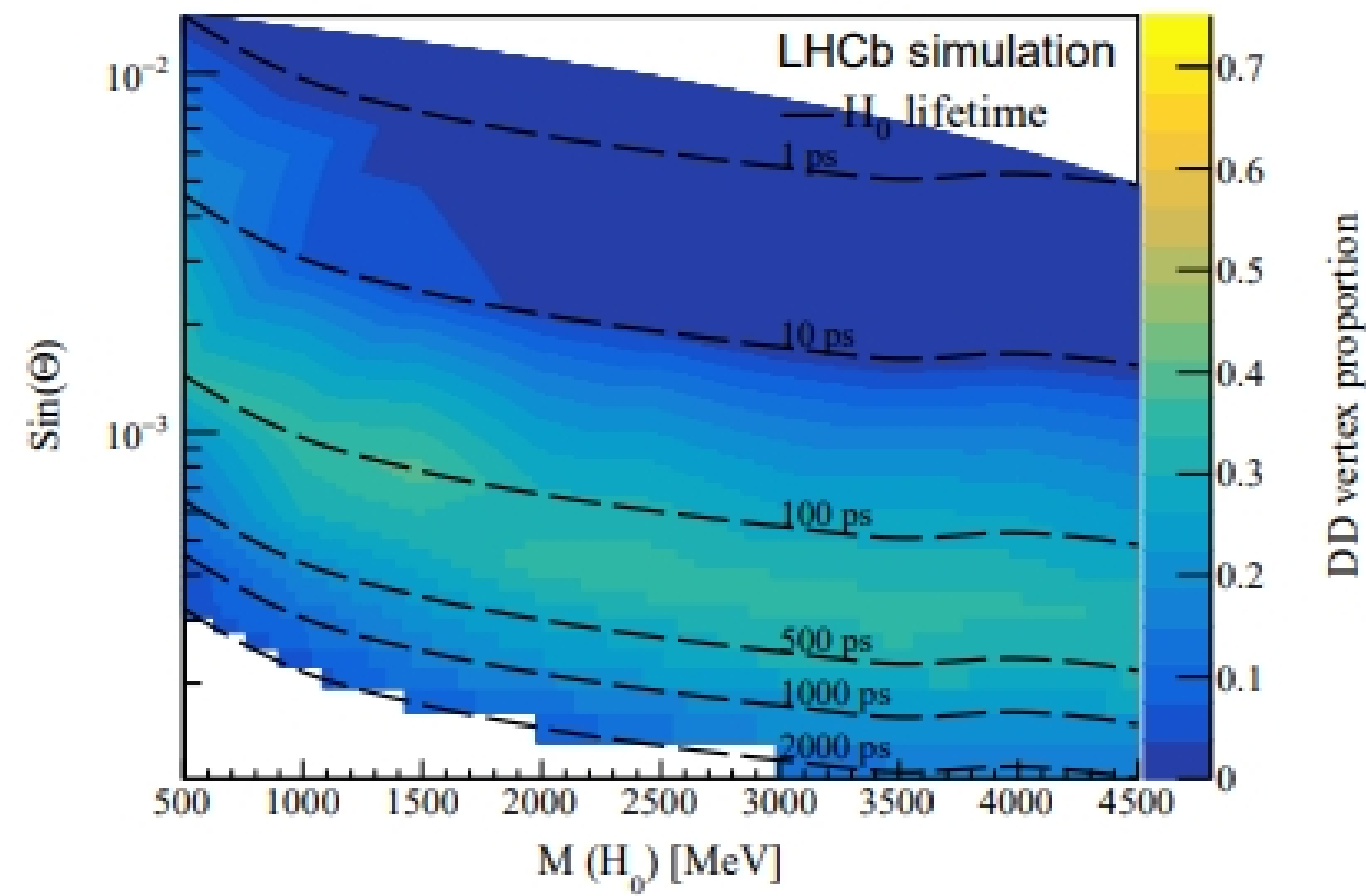
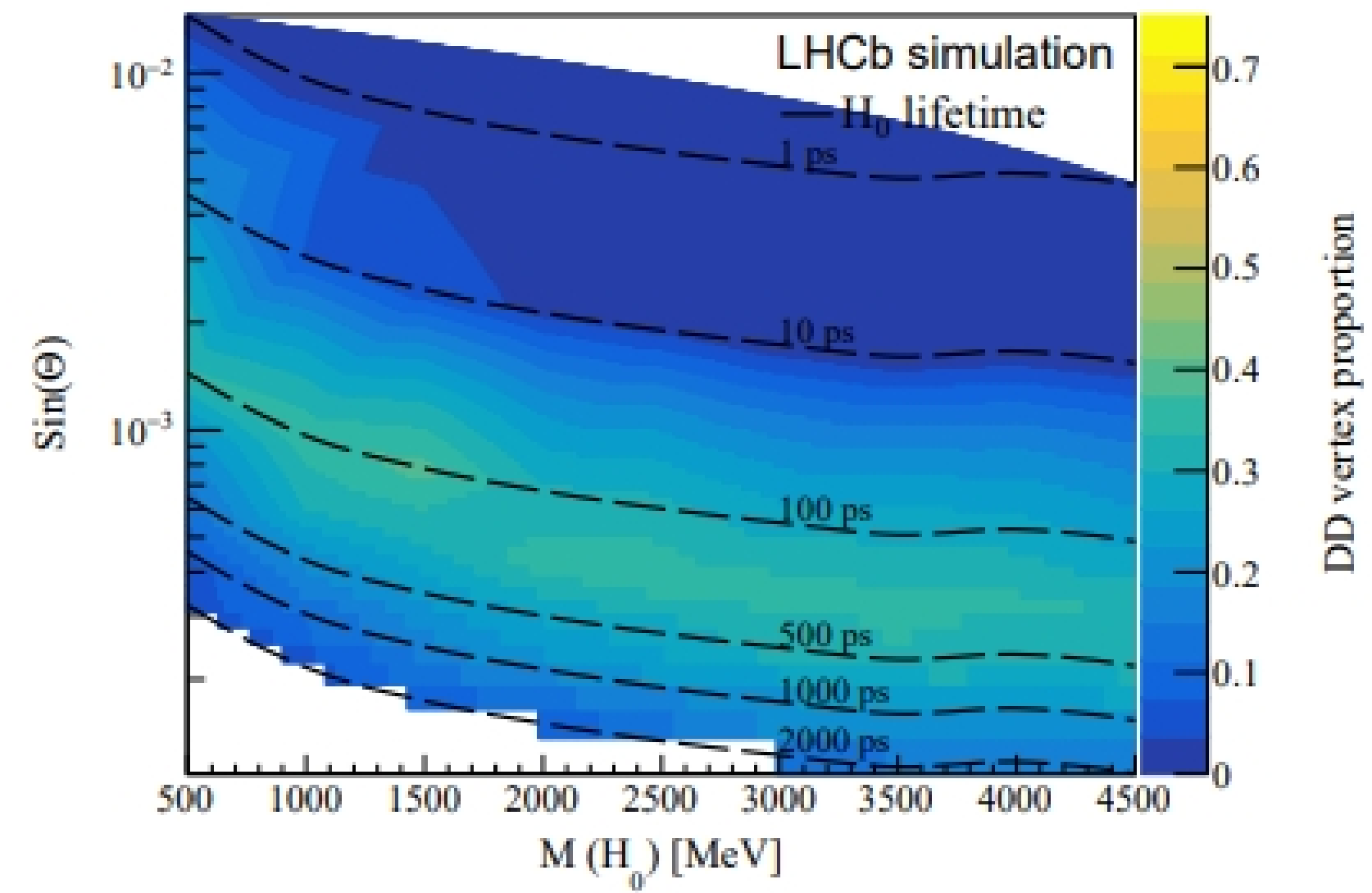
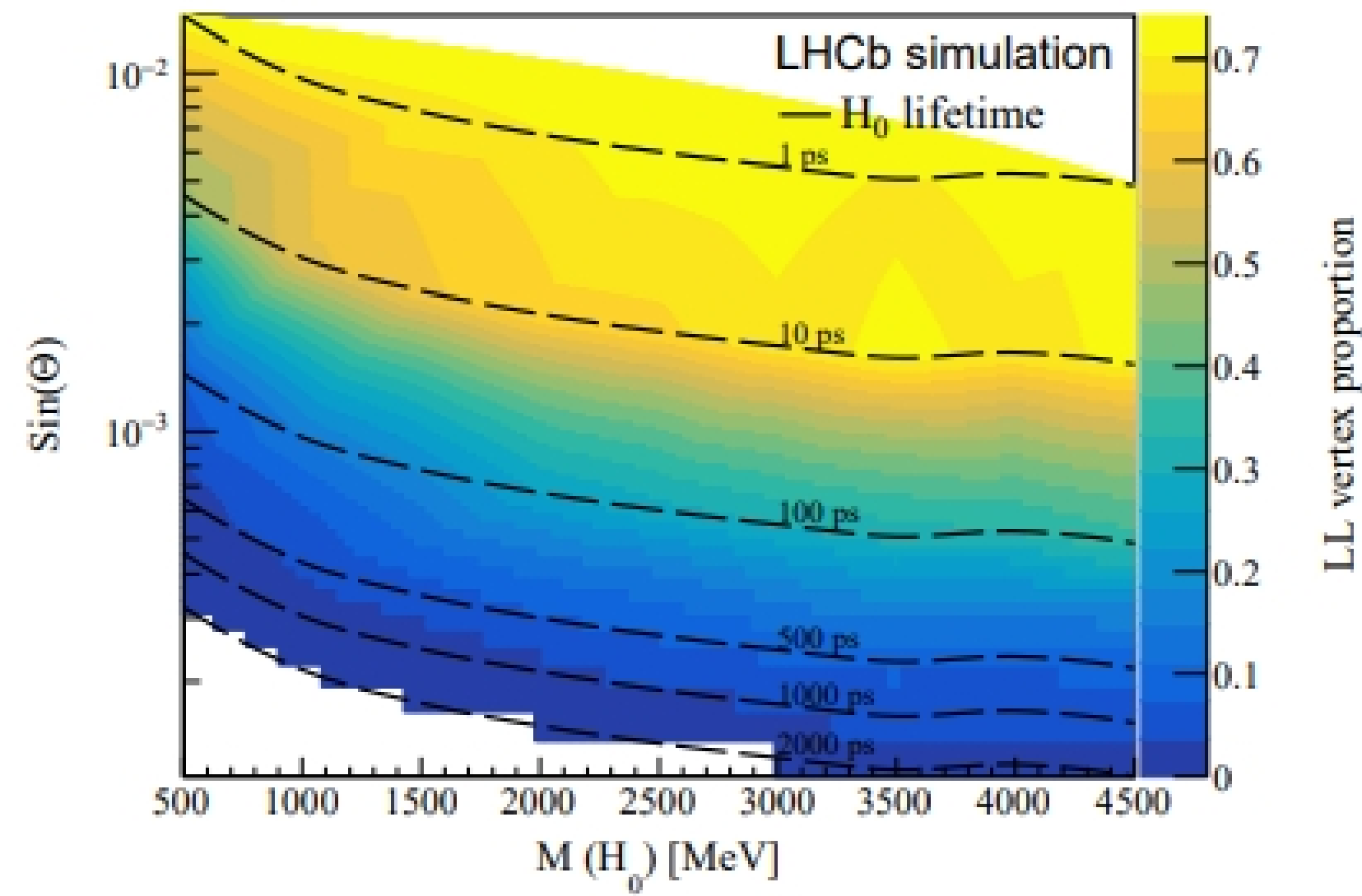




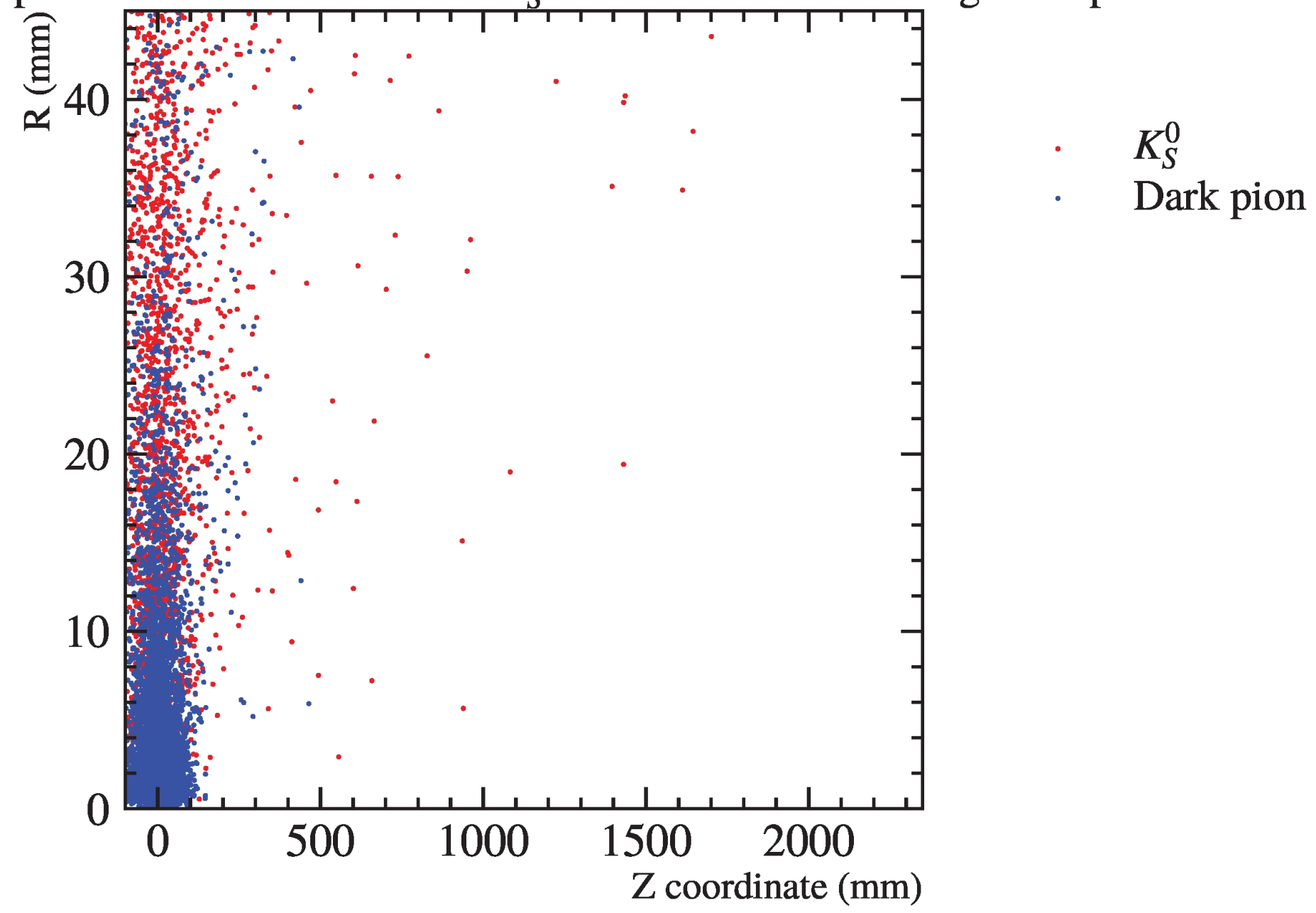
Conclusions

- **Cautious optimism**
- **Run 3 LHCb**
- **BDT improvement**

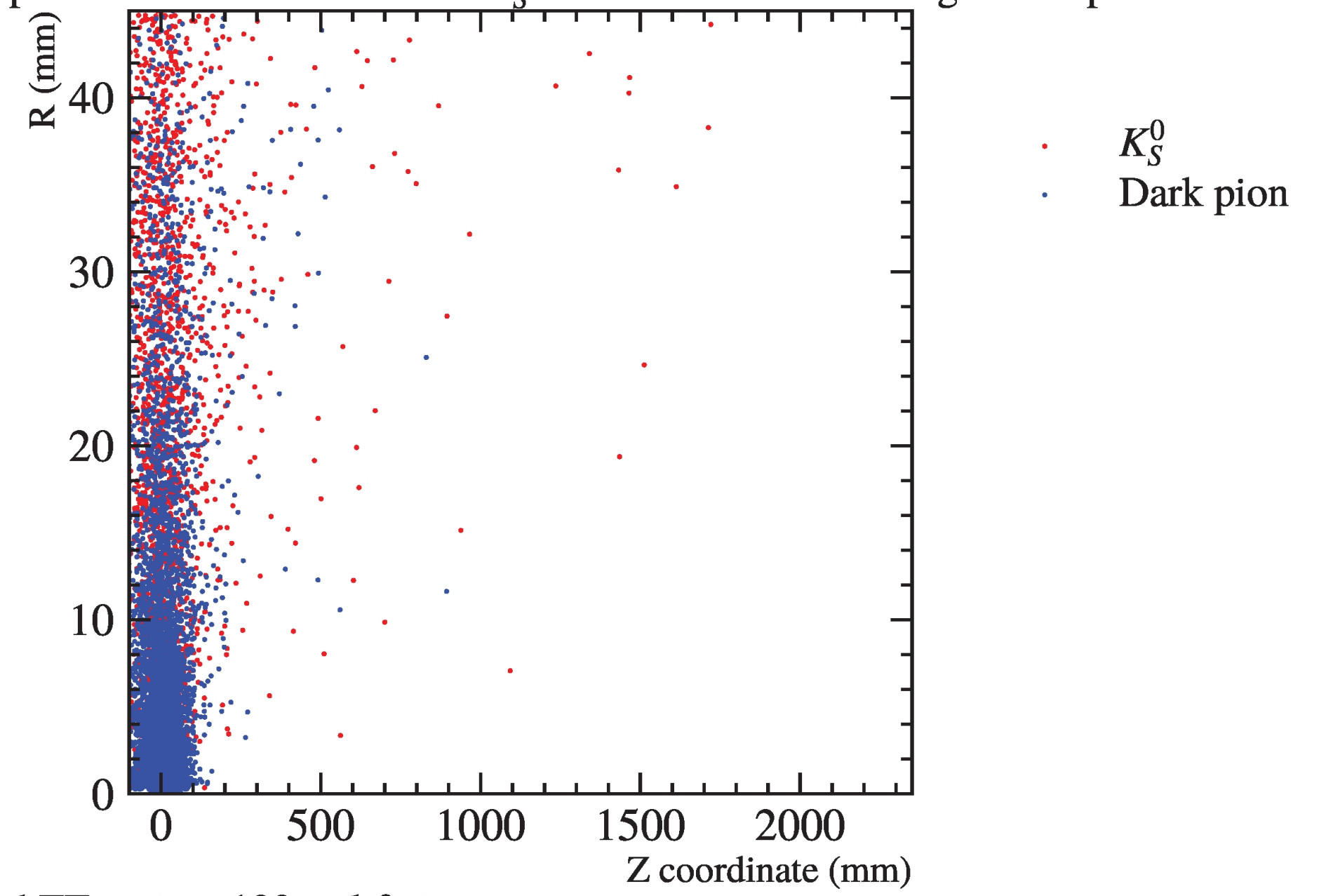




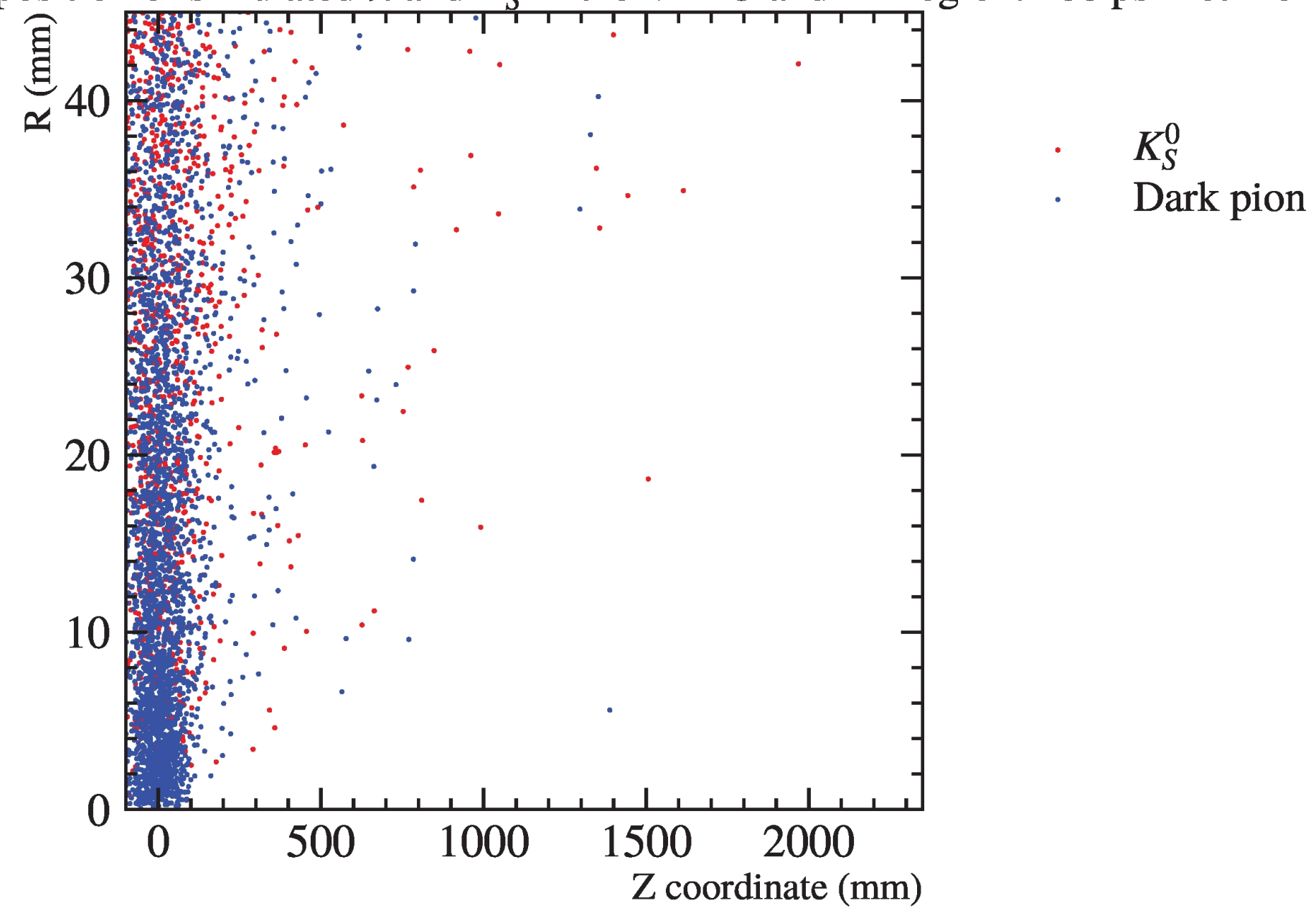
Decay vertex position of simulated $\hat{\pi}$ and K_S^0 in the VELO and TT region. 5 ps lifetime

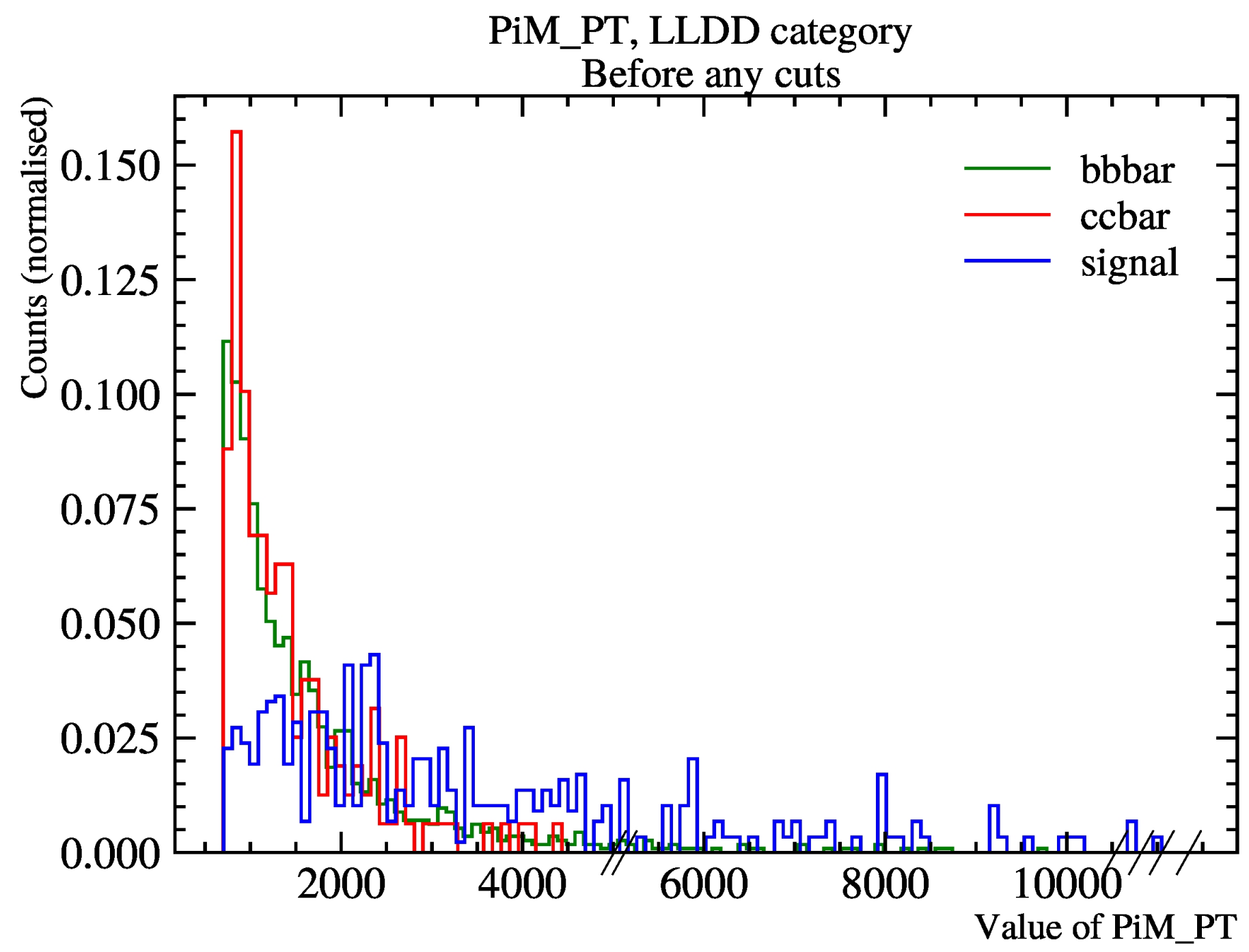
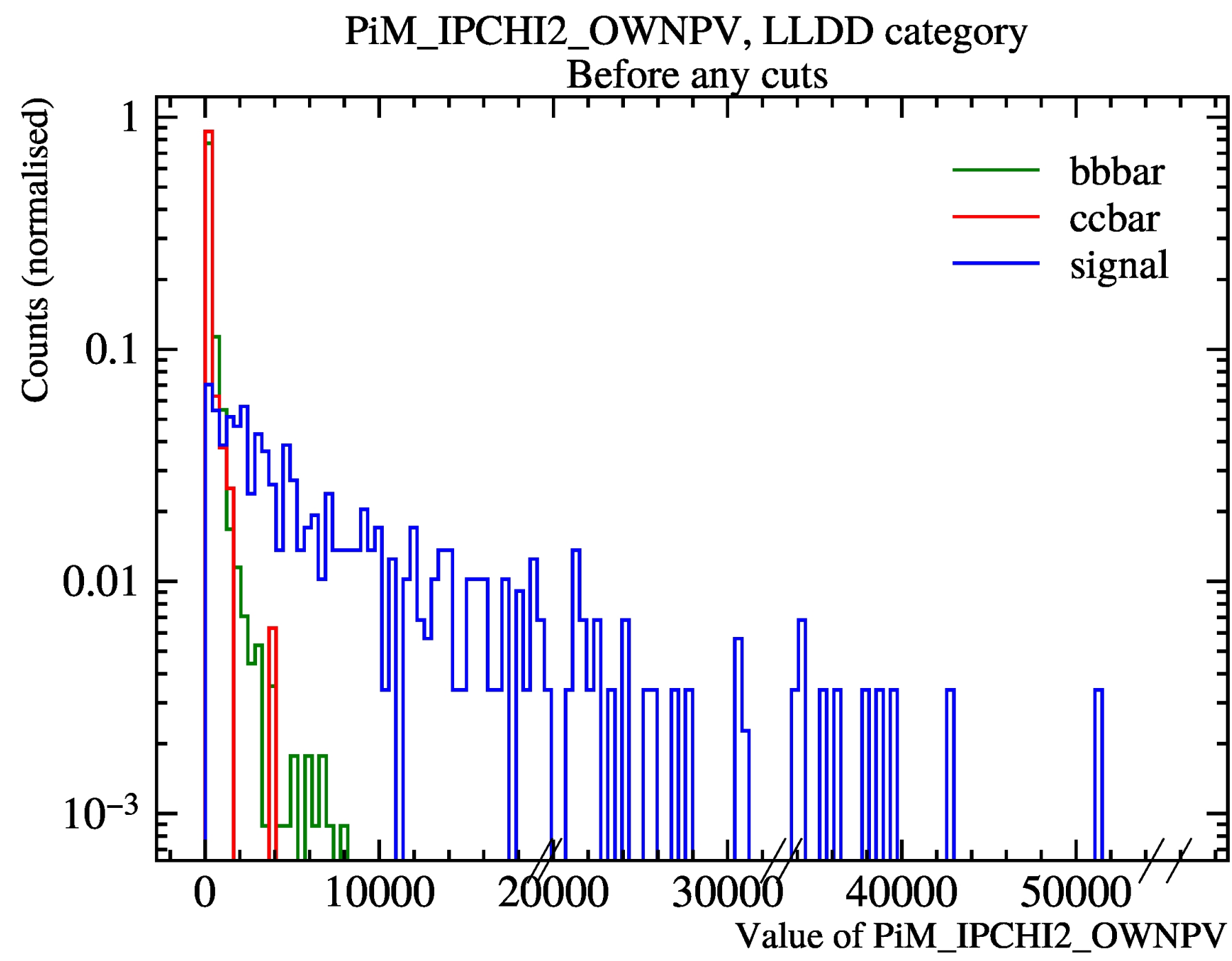
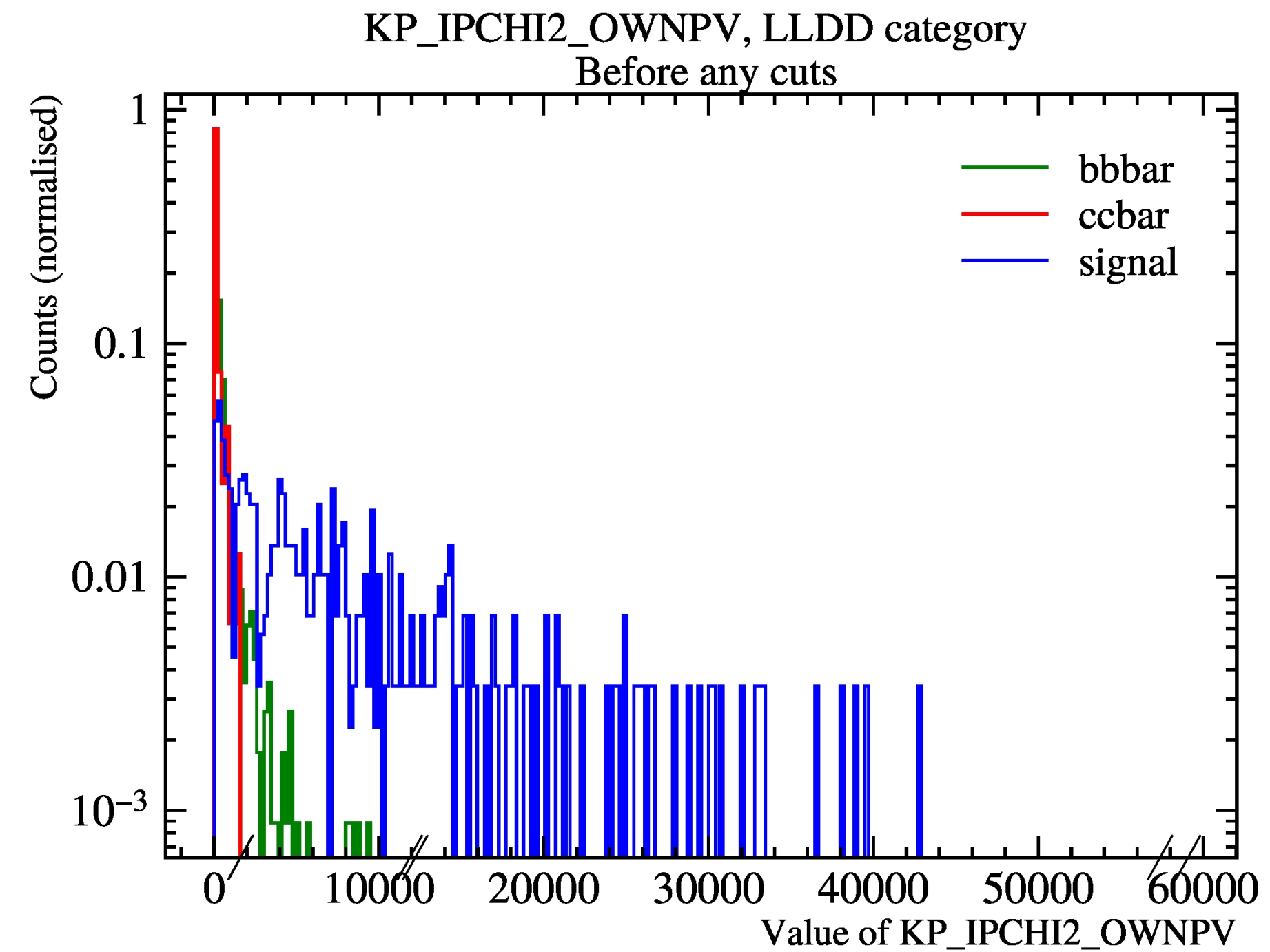
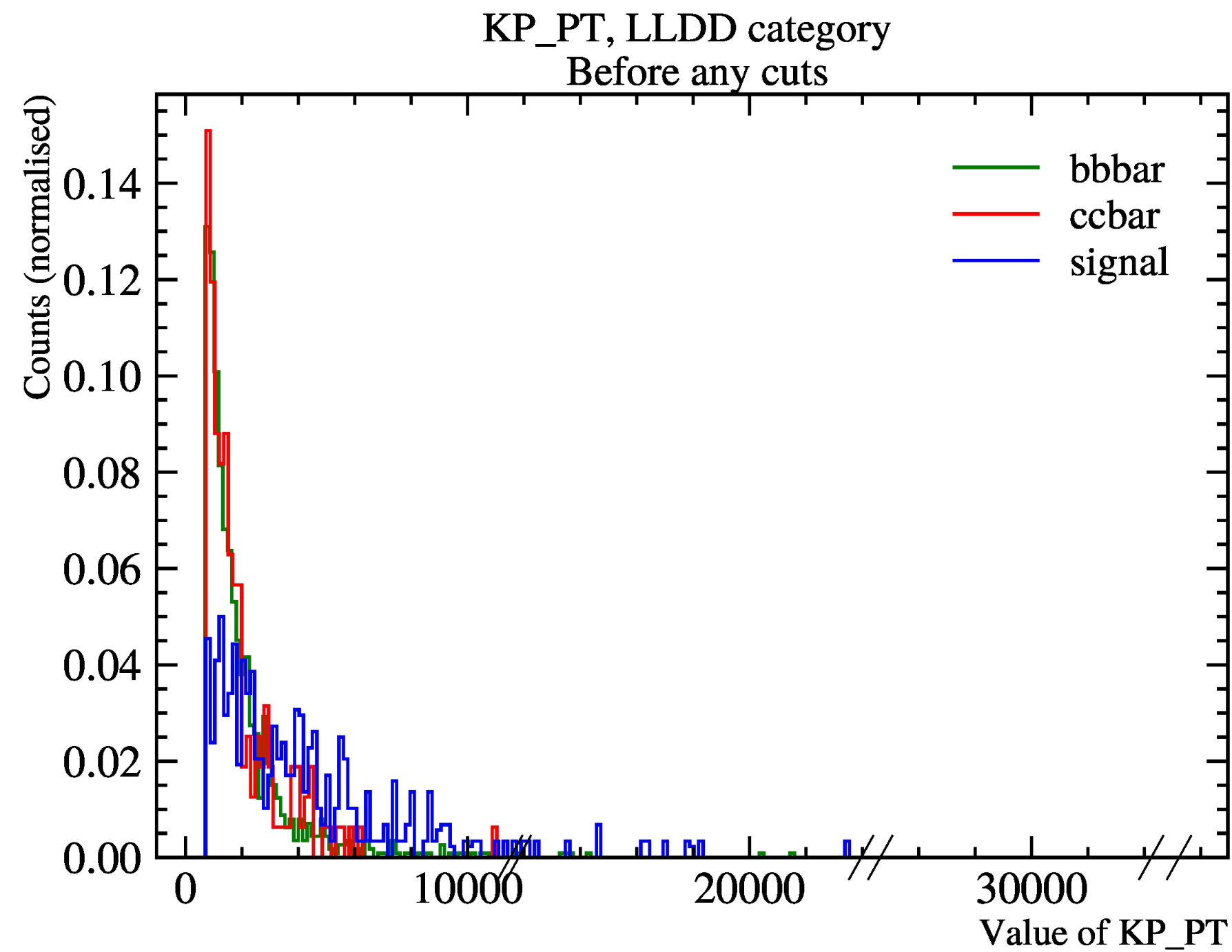


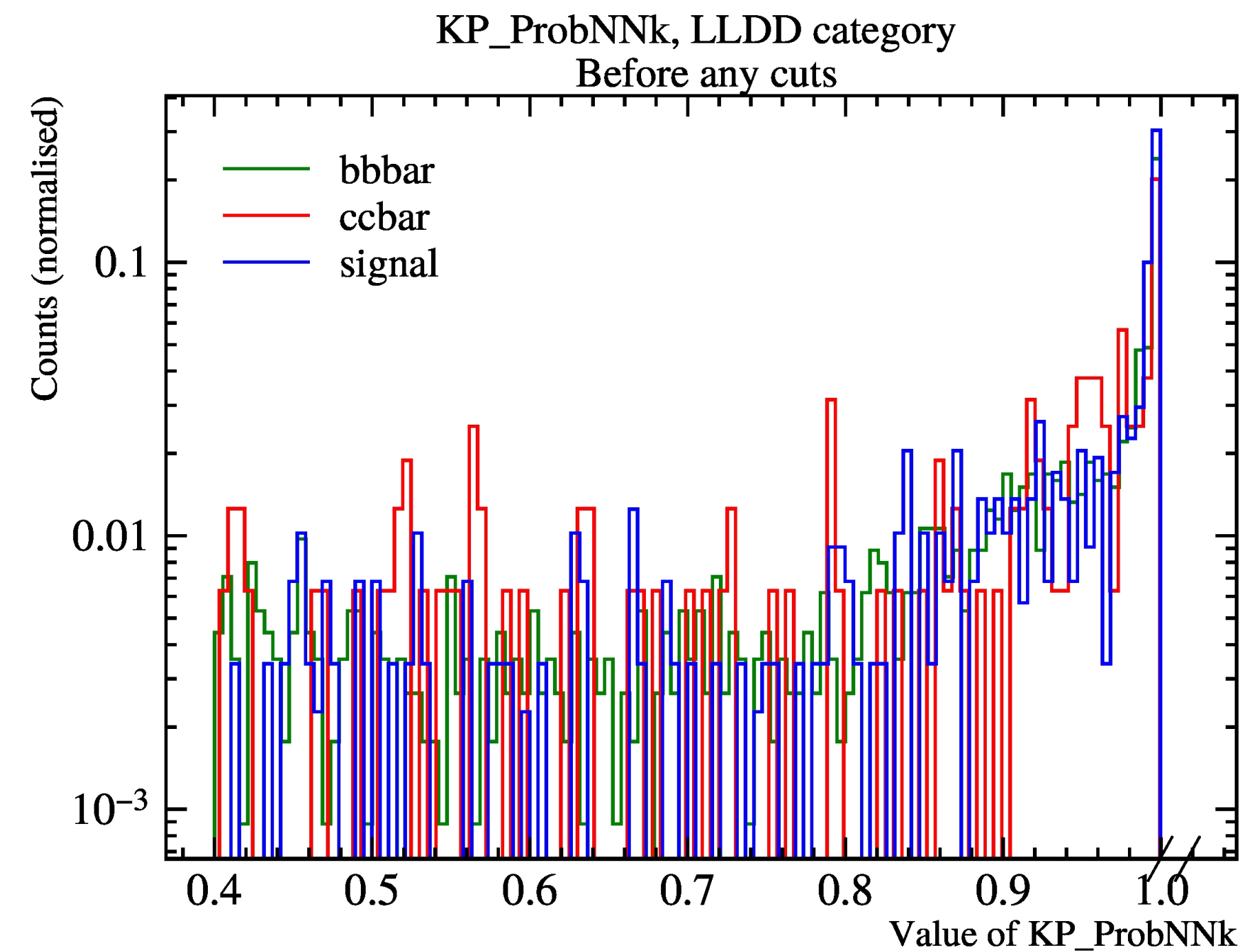
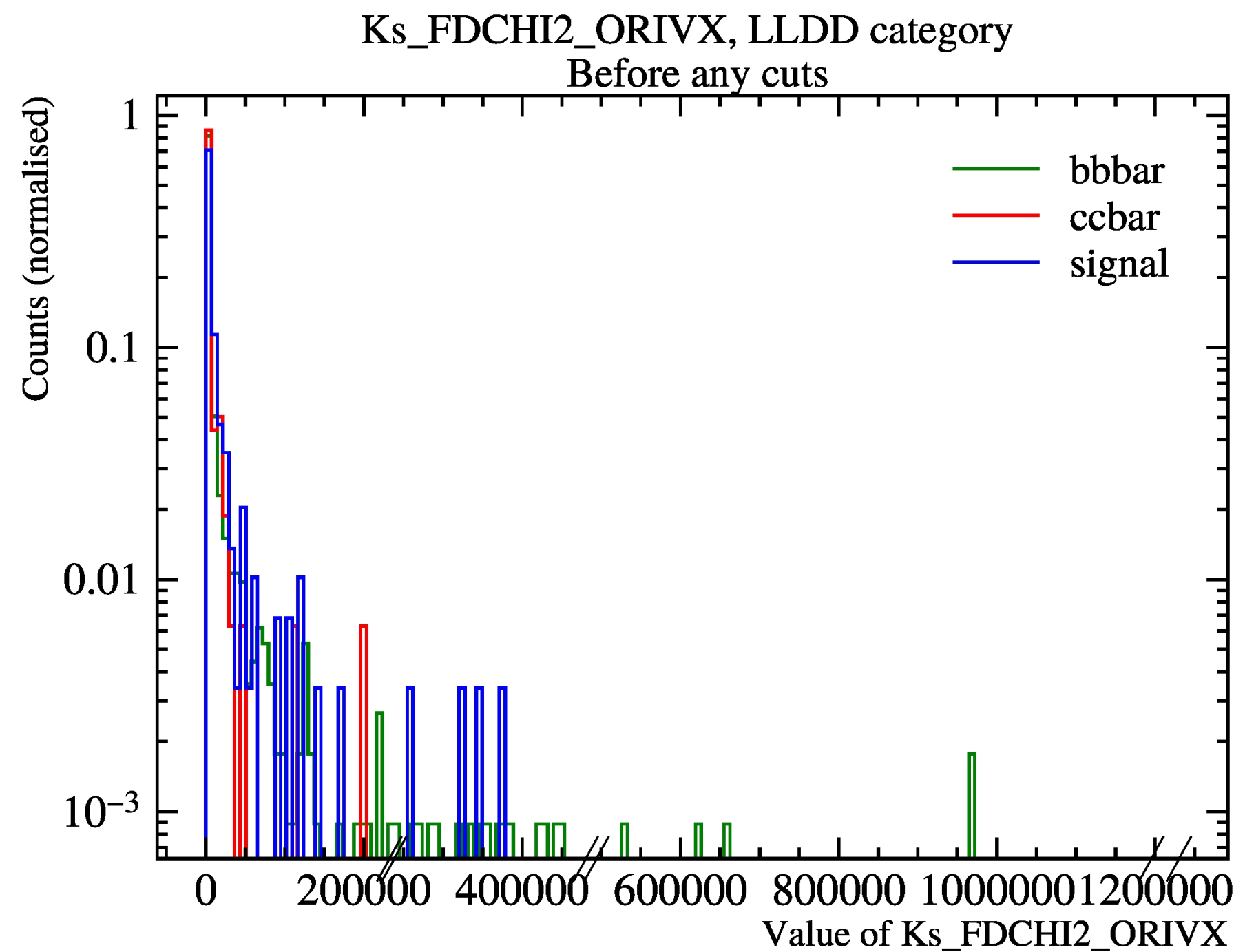
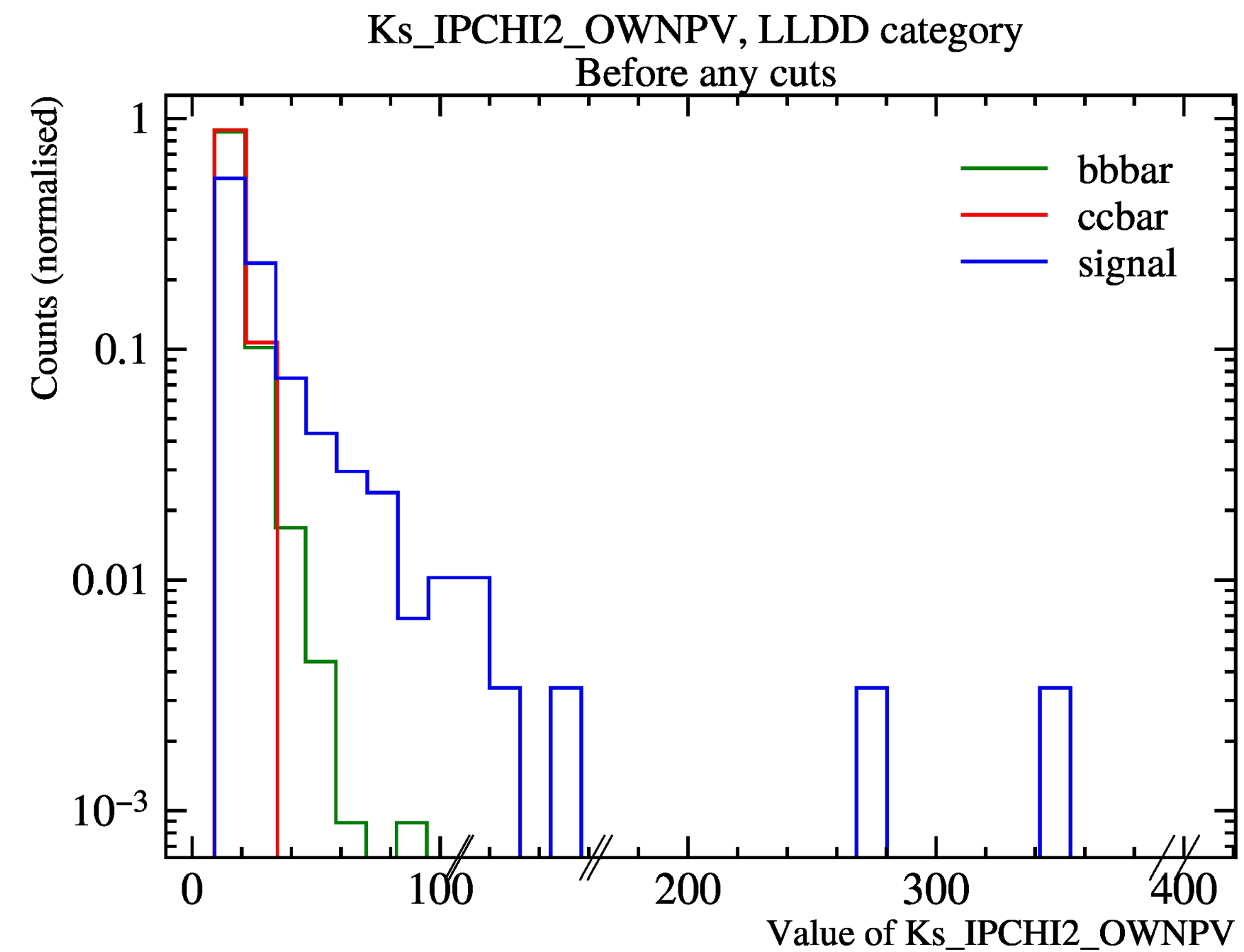
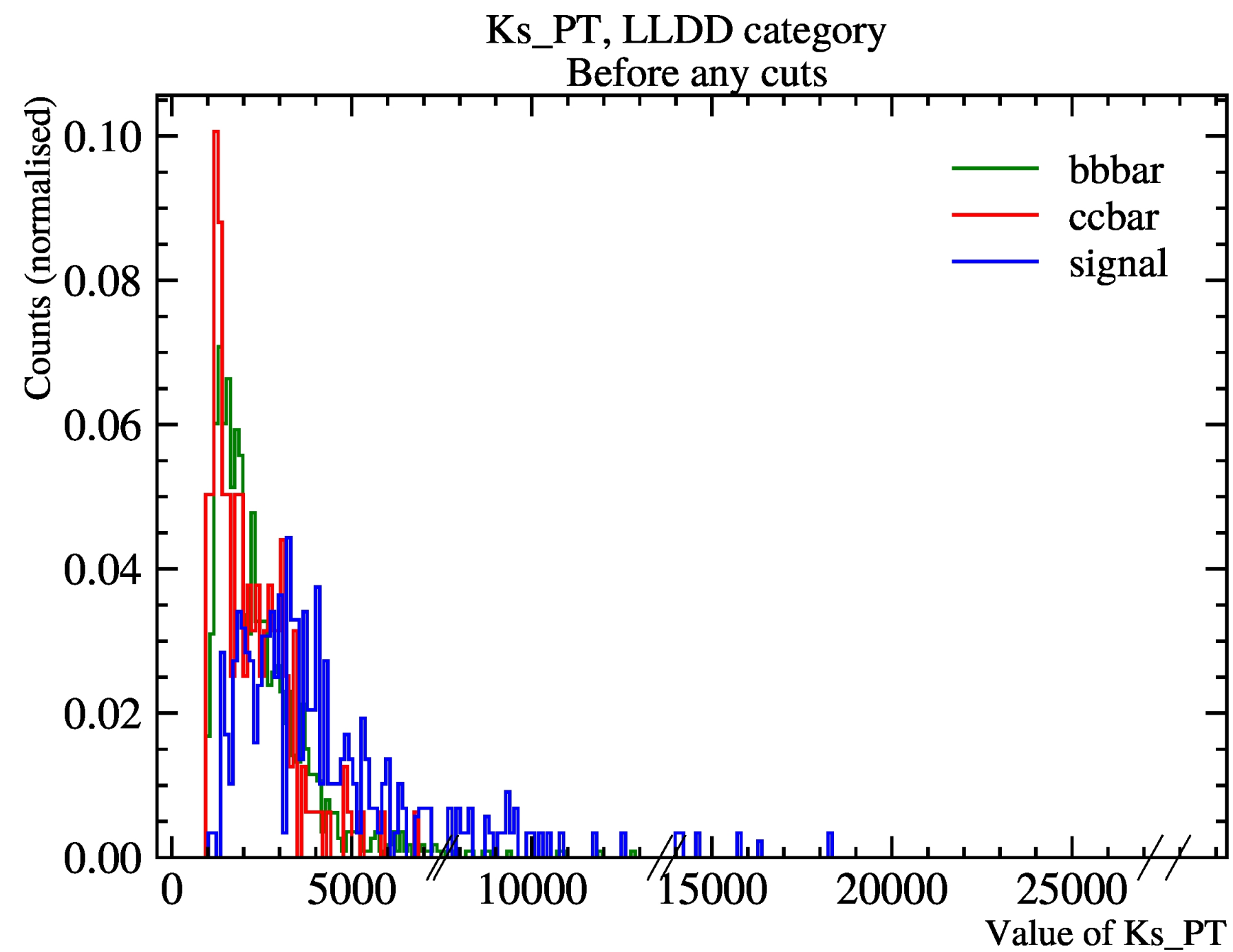
Decay vertex position of simulated $\hat{\pi}$ and K_S^0 in the VELO and TT region. 10 ps lifetime

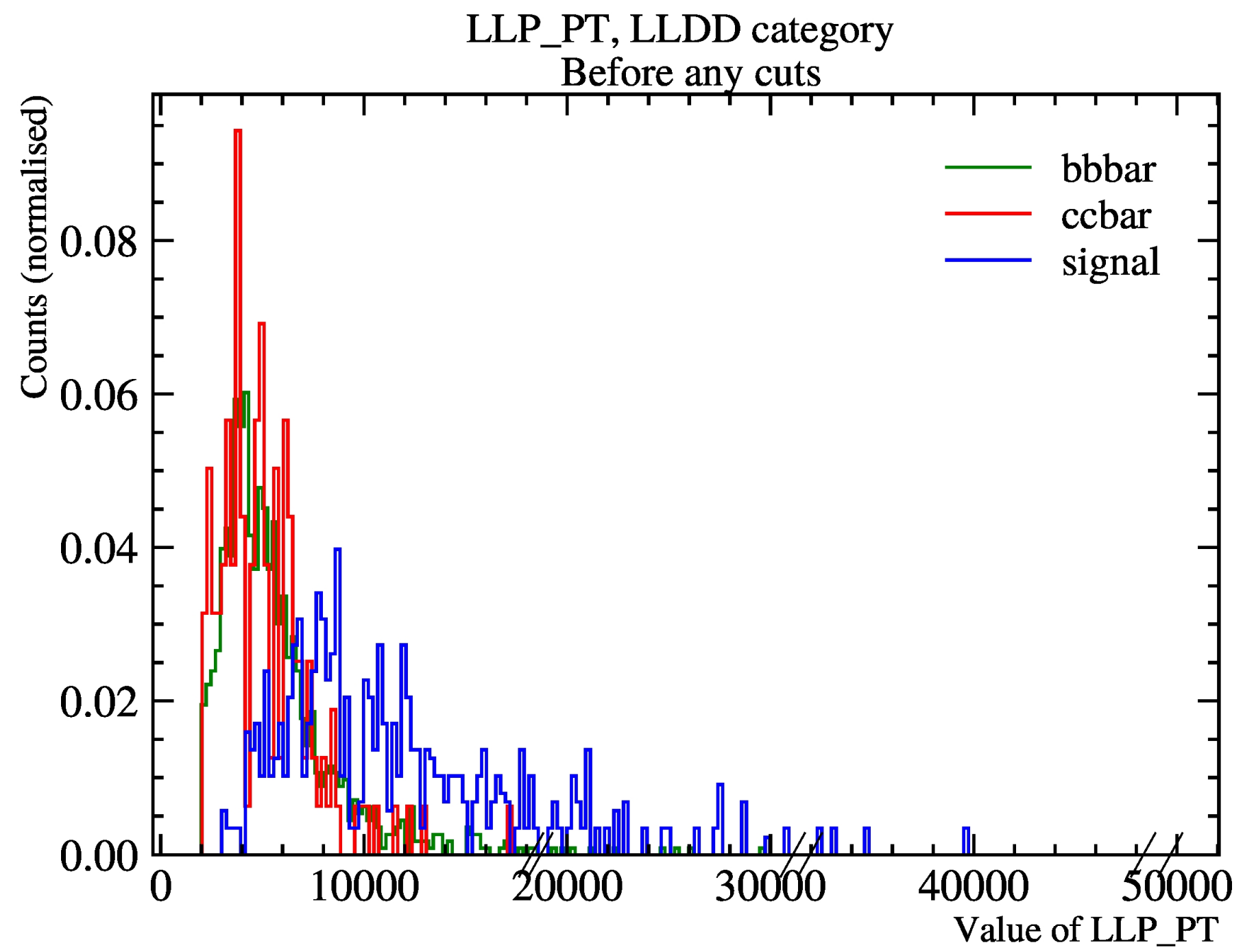
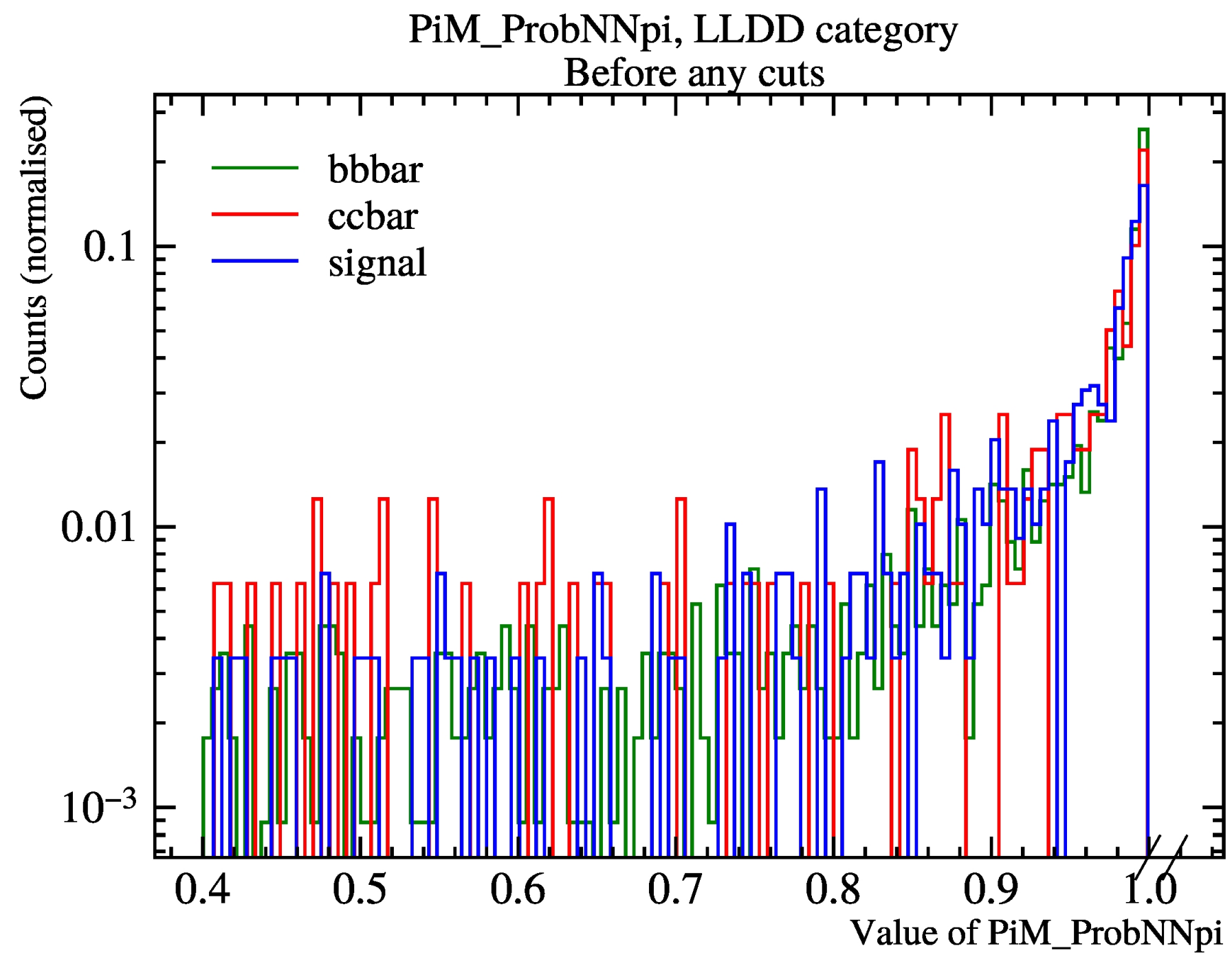


Decay vertex position of simulated $\hat{\pi}$ and K_S^0 in the VELO and TT region. 100 ps lifetime



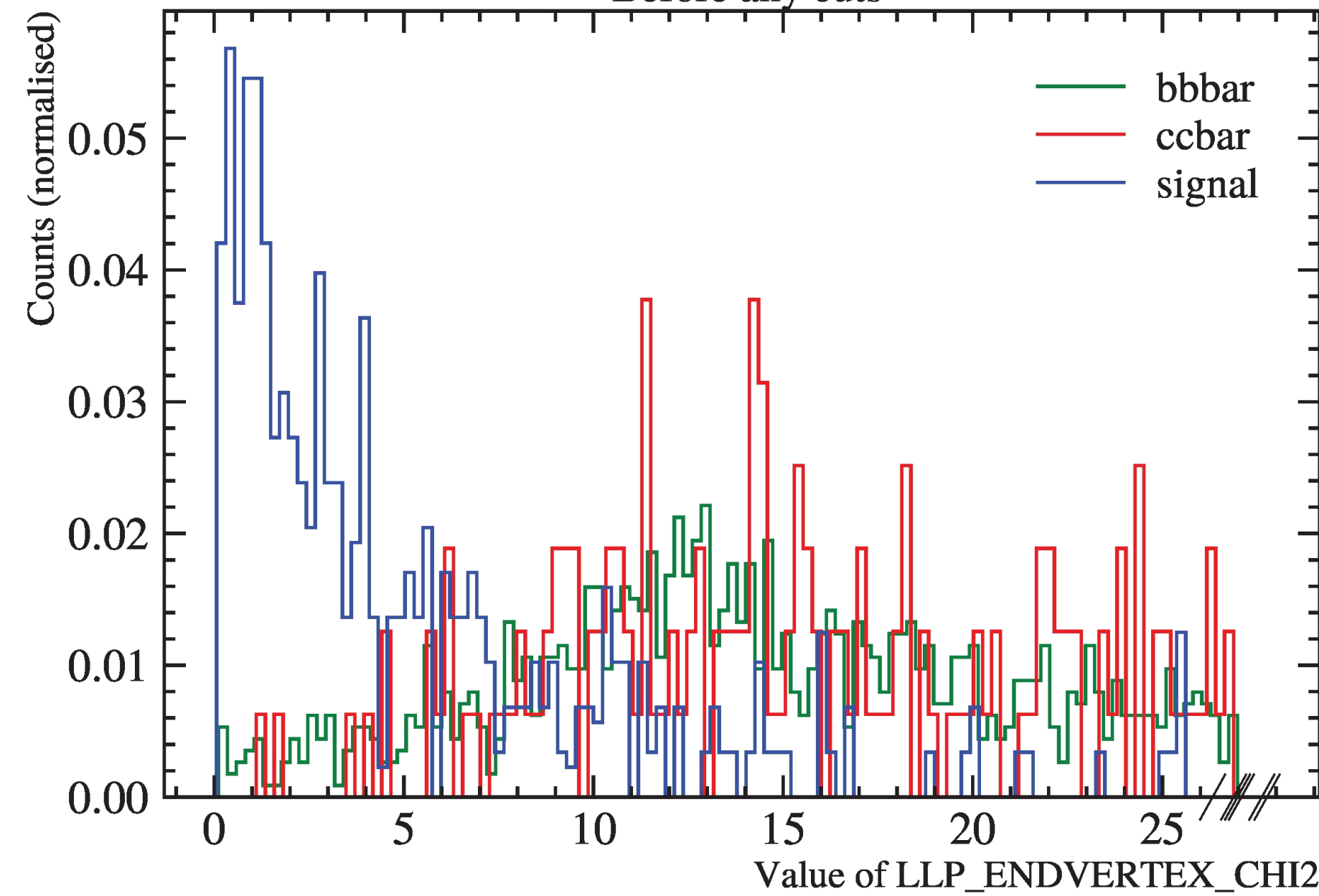






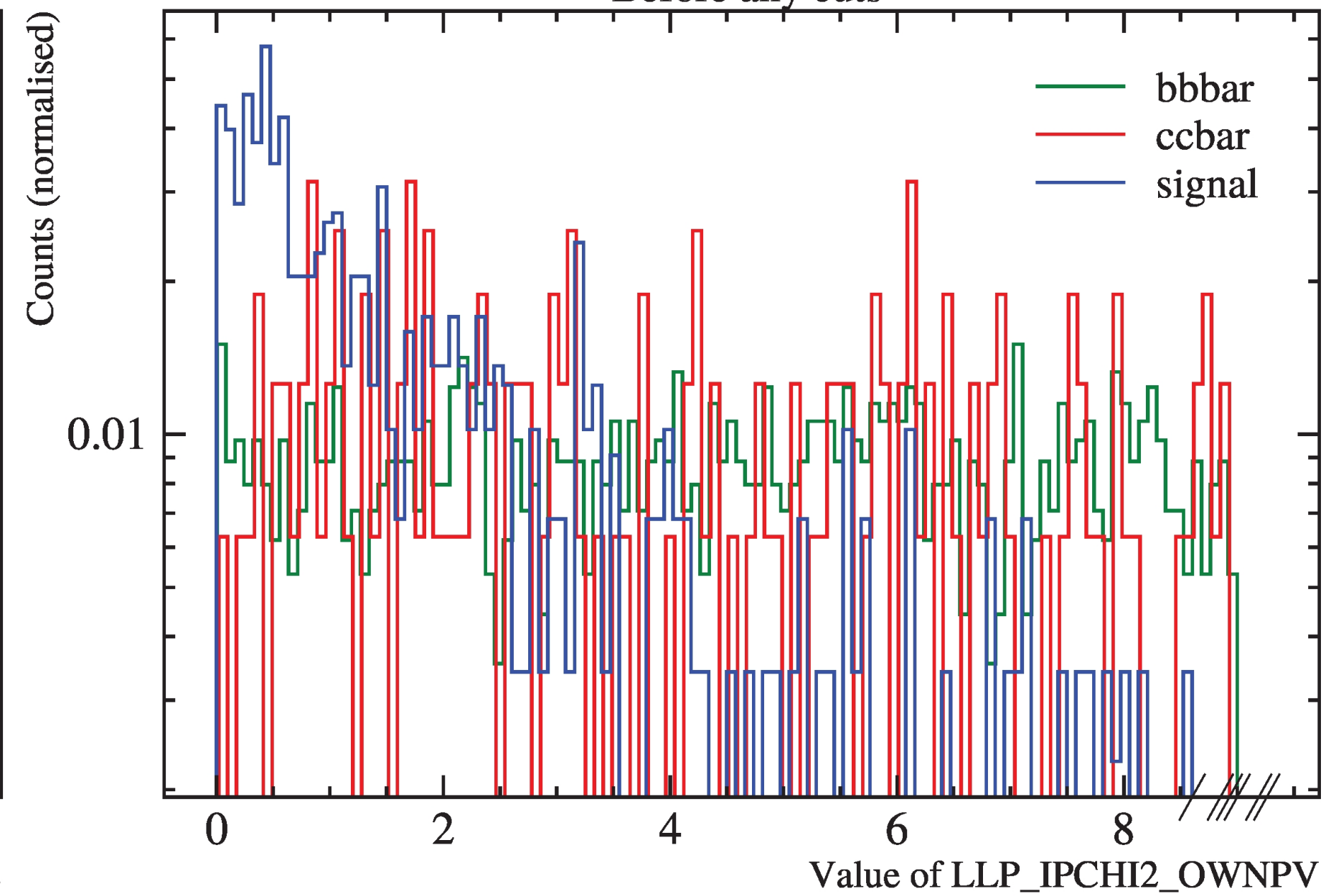
LLP_ENDVERTEX_CHI2, LLDD category

Before any cuts



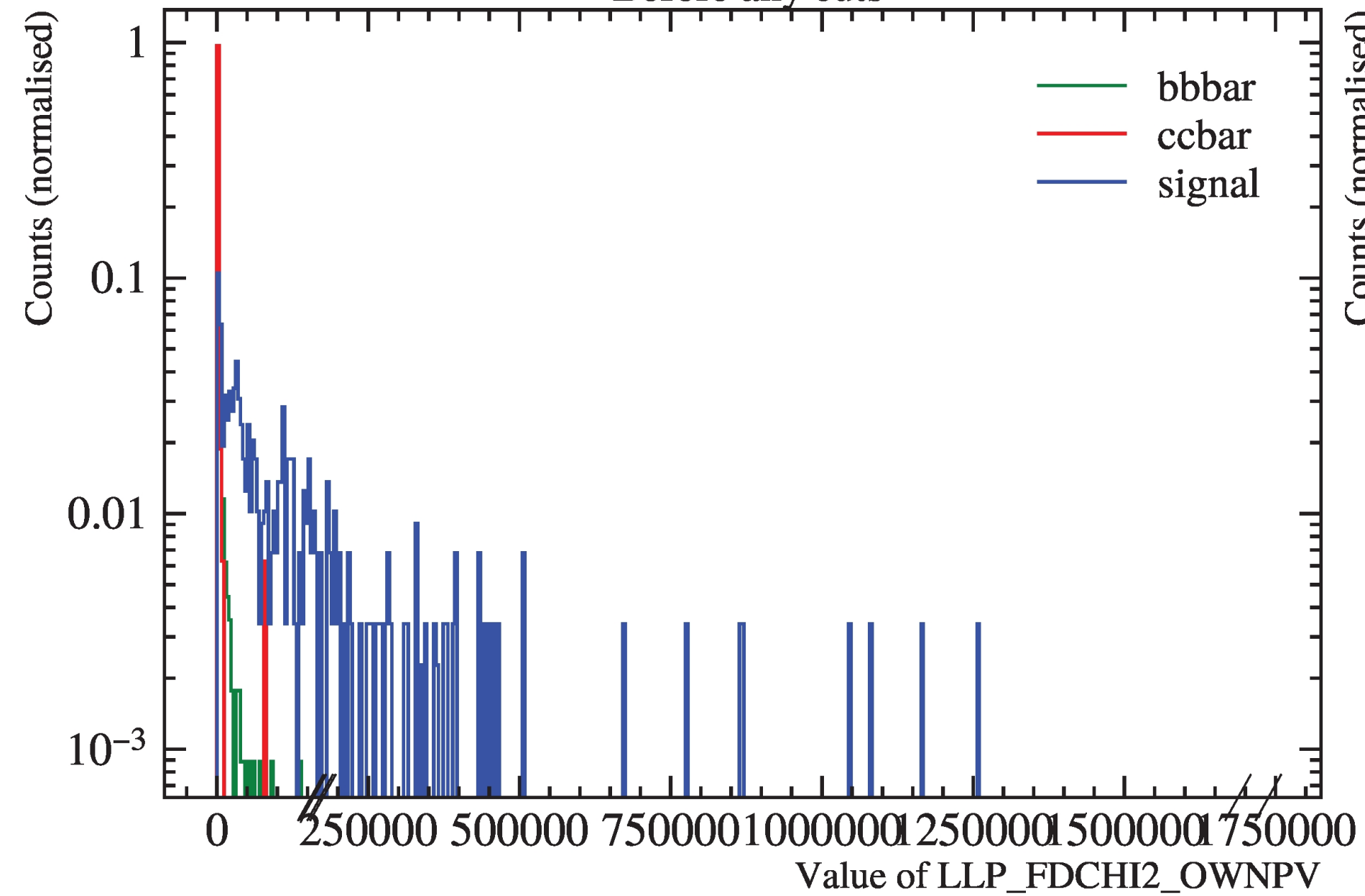
LLP_IPCHI2_OWNPV, LLDD category

Before any cuts



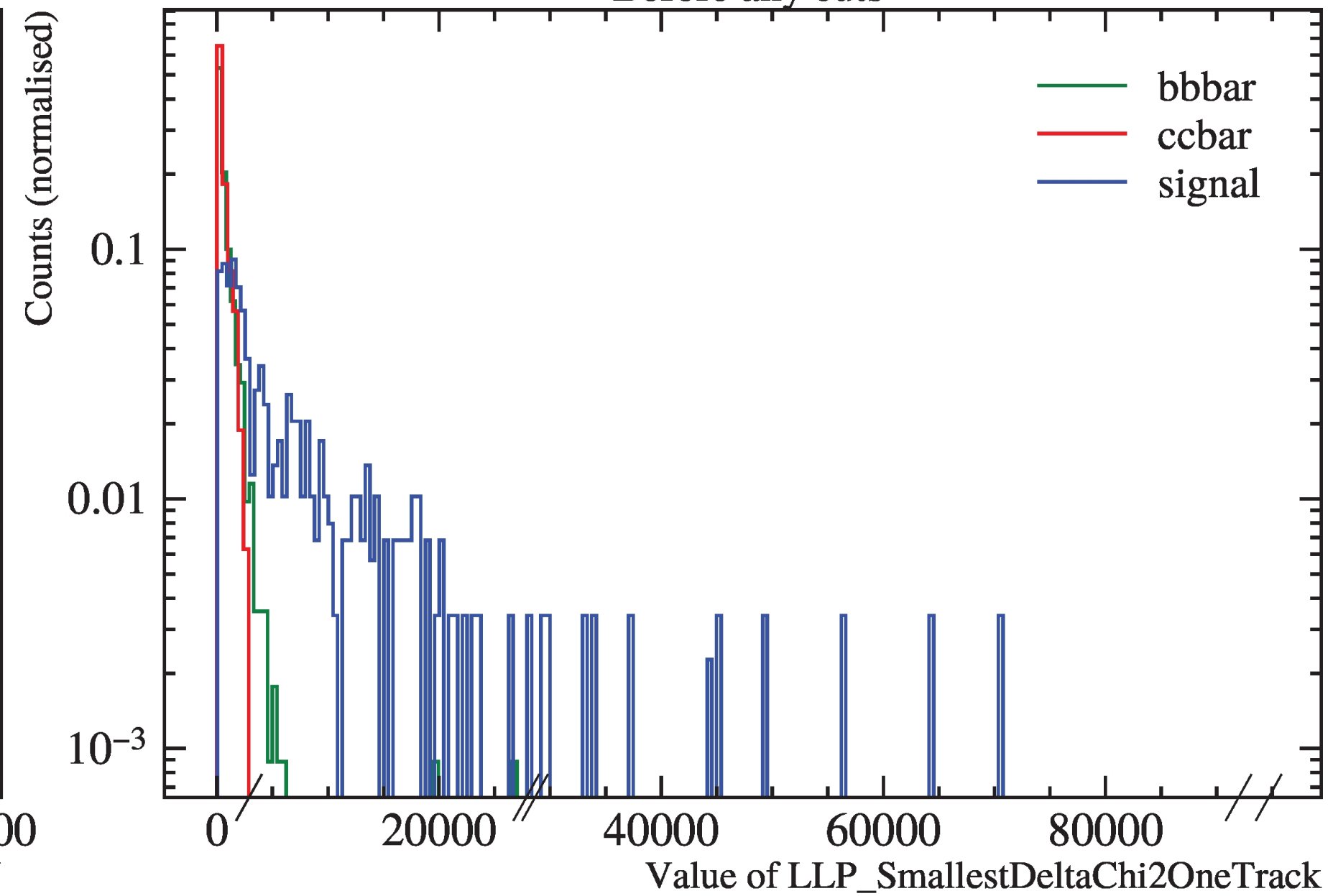
LLP_FDCHI2_OWNPV, LLDD category

Before any cuts

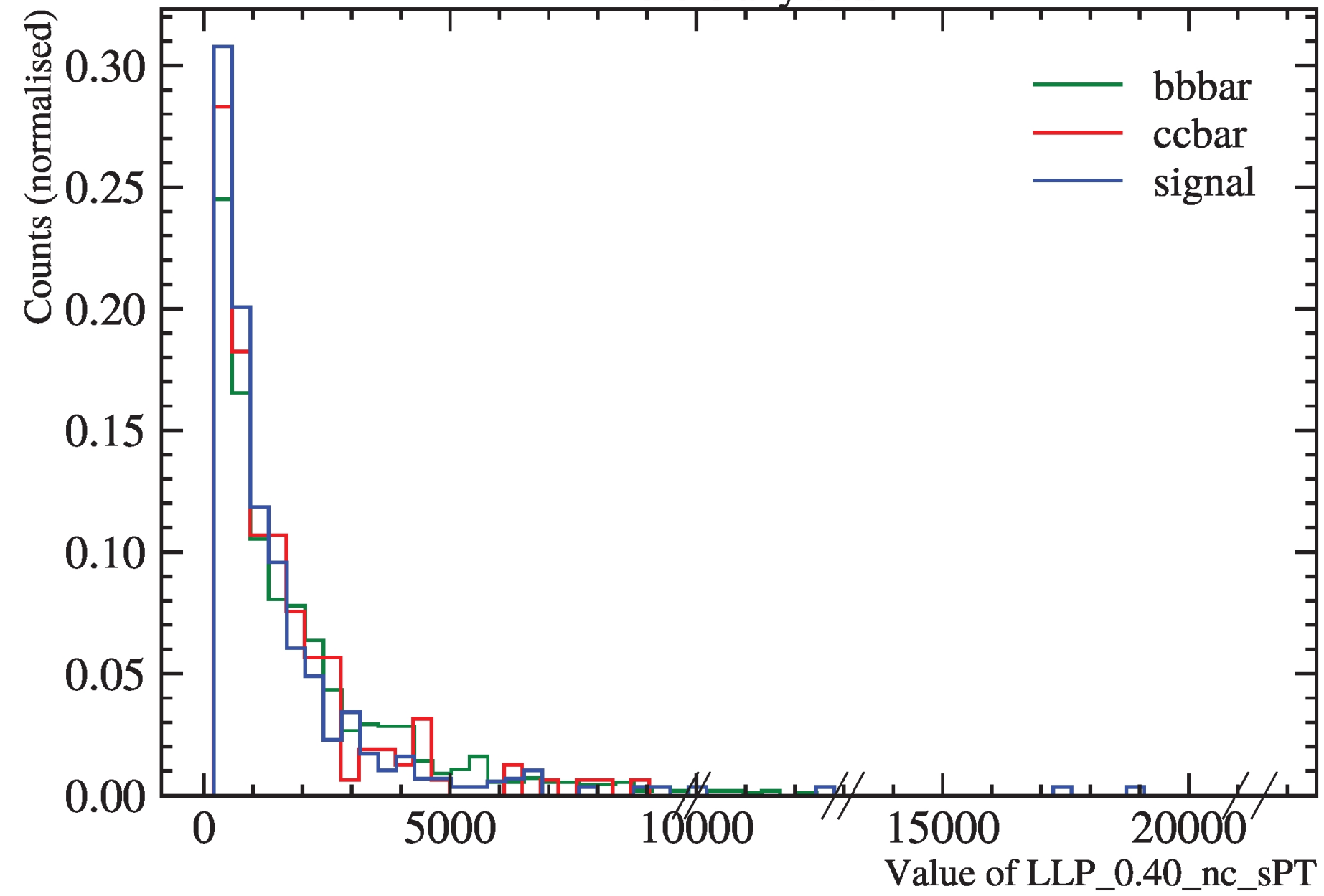


LLP_SmallestDeltaChi2OneTrack, LLDD category

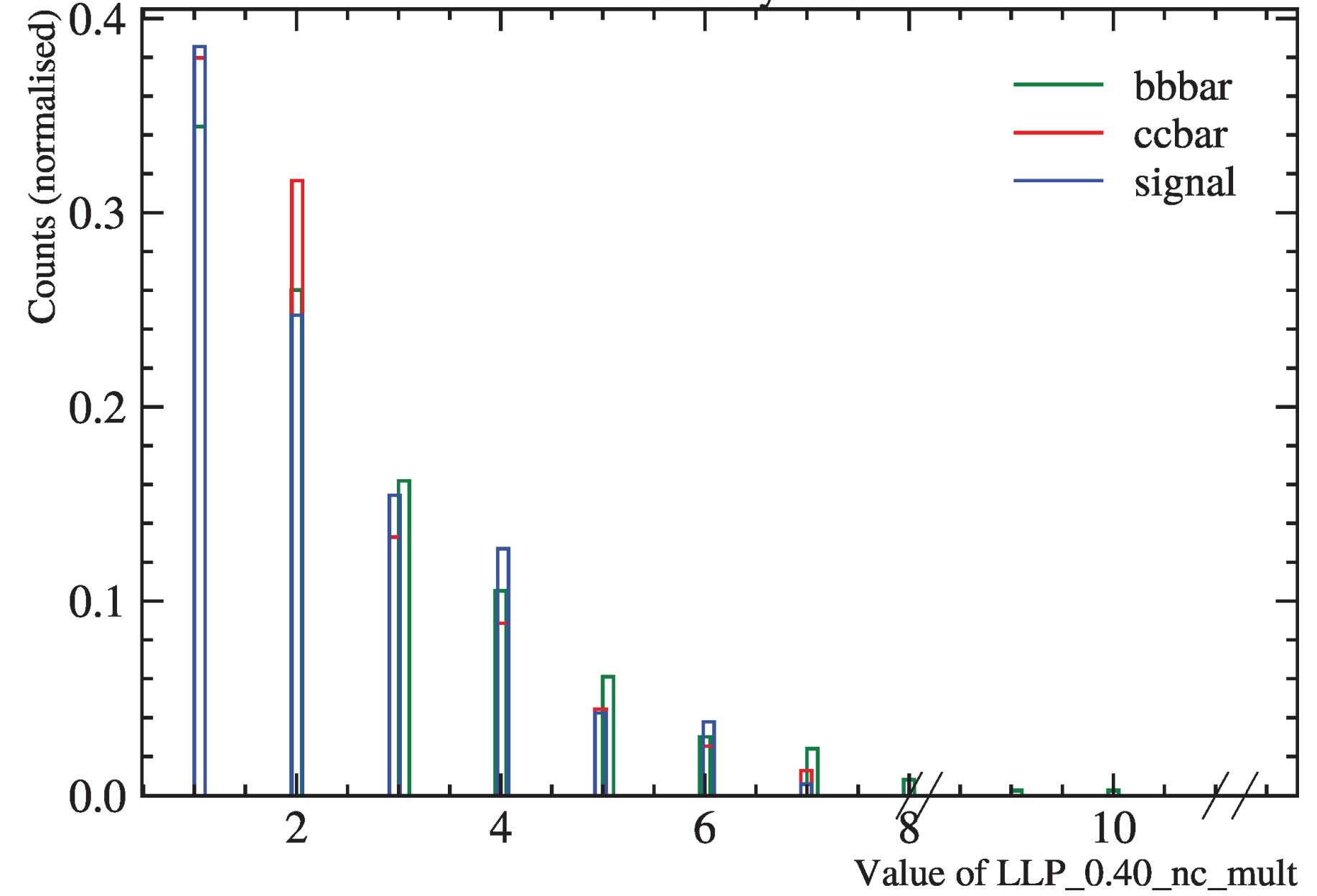
Before any cuts



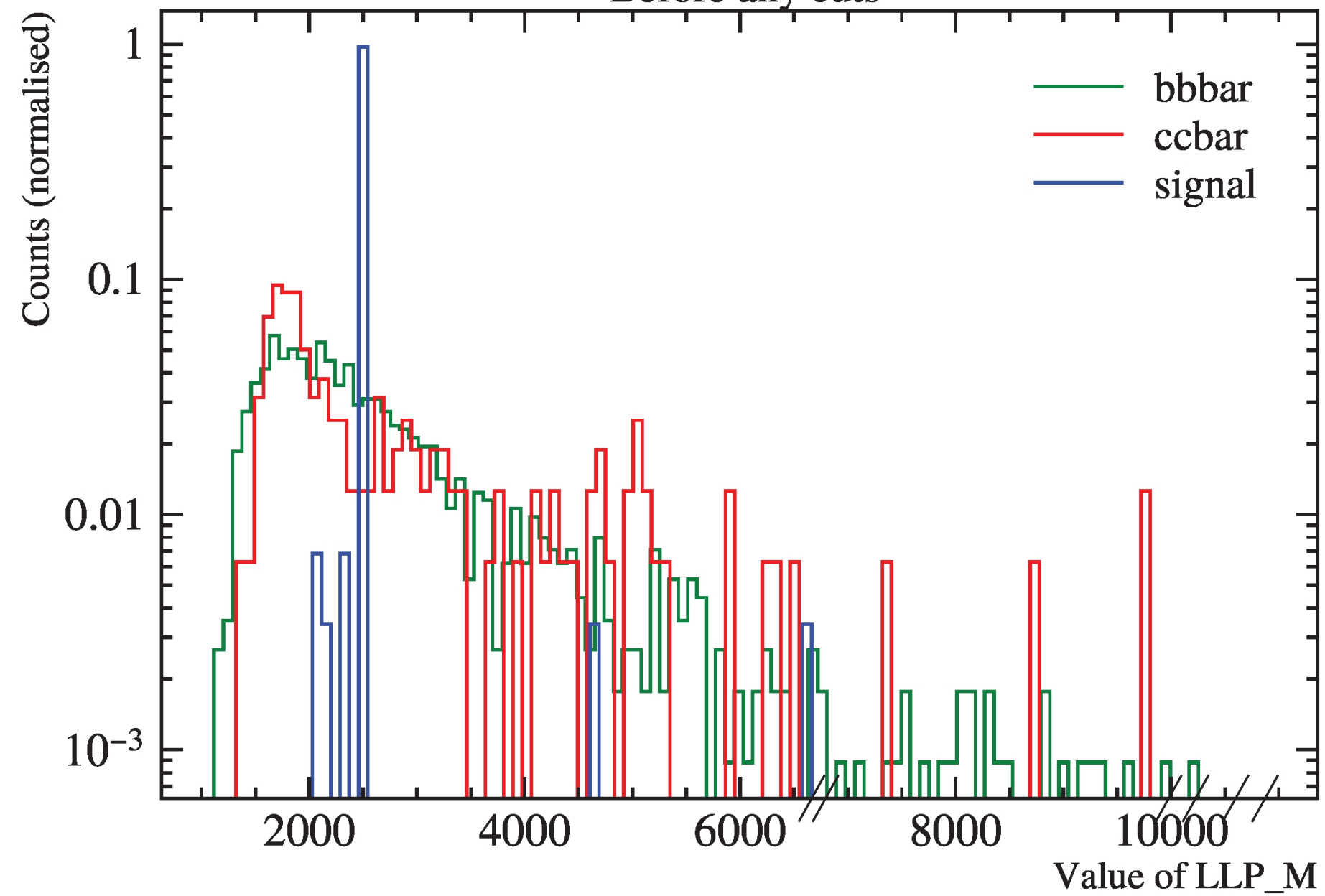
LLP_0.40_nc_sPT, LLDD category
Before any cuts



LLP_0.40_nc_mult, LLDD category
Before any cuts



LLP_M, LLDD category
Before any cuts



Ks_M, LLDD category
Before any cuts

