

Analysis of $D^0 \rightarrow K_S^0 \pi^+ \pi^-$ decays in Run 3

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Overview

Introduction

- Mixing and CPV
- Status of the art
- $D^0 \rightarrow K_S^0 \pi^+ \pi^-$ channel
- Bin-flip method
- LHCb experiment

Run 3 analysis

- HLT1 Selection
- Datasets and Selection
- Signal extraction
- Efficiency Maps

Conclusions

Neutral meson mixing

A quantum mechanical phenomenon in which neutral mesons can oscillate between their particle and anti-particle state

The D^0 system has the lowest frequency of oscillations

This is due to the D^0 system having a very small mass difference between the mass eigenstates D_1 and D_2

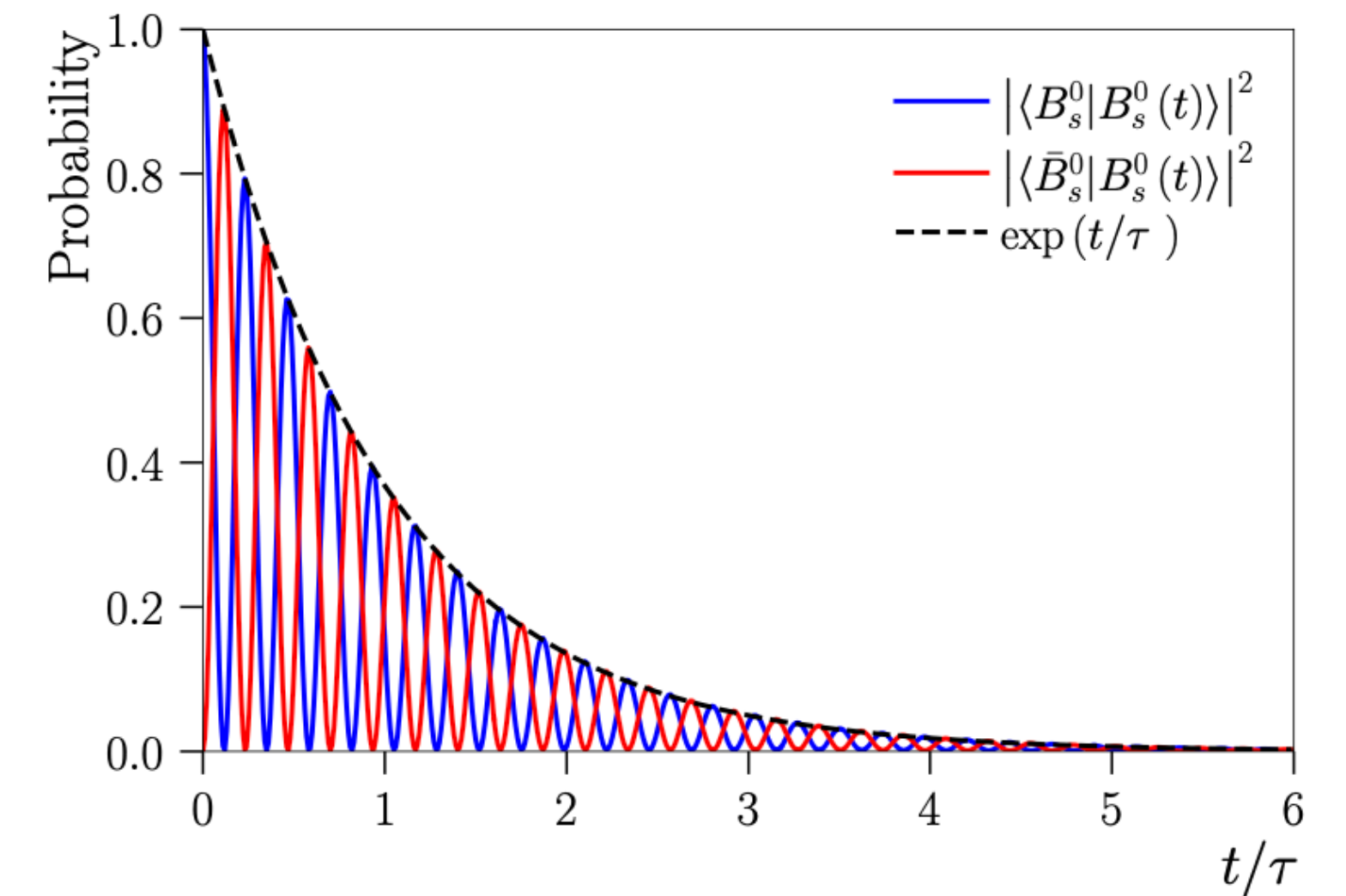
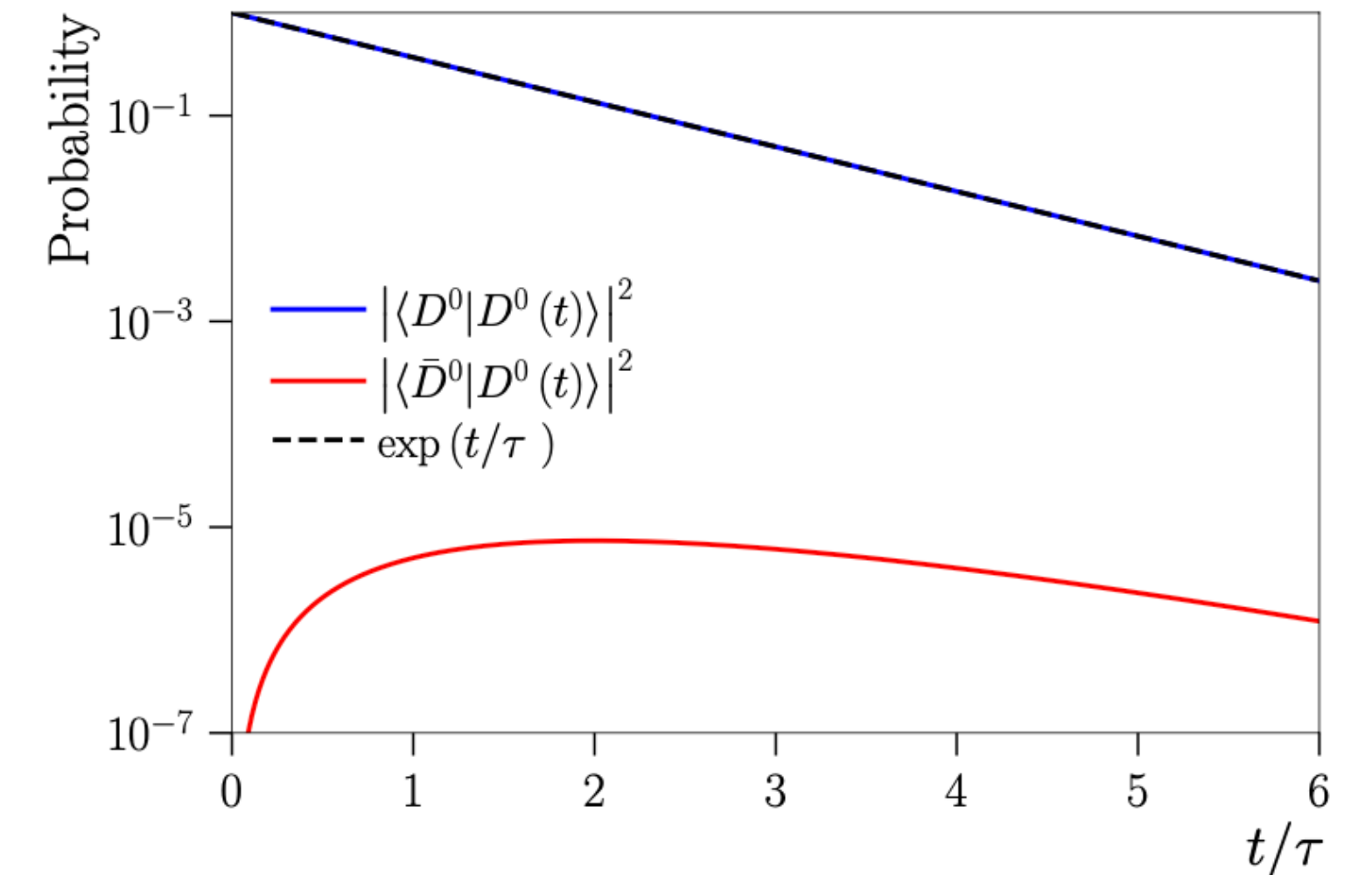
Their mass eigenstates, related to the flavor eigenstates, are:

$$|D_{1,2}\rangle = p|D^0\rangle \pm q|\bar{D}^0\rangle \quad \text{with } |p|^2 + |q|^2 = 1$$

In the limit of CP symmetry, $q = p$ and the oscillations are characterized by two dimensionless parameters:

$$x \equiv \frac{\Delta m}{\Gamma} = \frac{2(m_1 - m_2)}{\Gamma_1 + \Gamma_2}, \quad y \equiv \frac{\Delta\Gamma}{2\Gamma} = \frac{\Gamma_1 - \Gamma_2}{\Gamma_1 + \Gamma_2}$$

where $m_{1,2}$ and $\Gamma_{1,2}$ are the mass and decay width of the CP-even/odd eigenstate $D_{1,2}$ and Γ is the average decay width



Types of $\mathcal{CP}$

CPV in mixing:

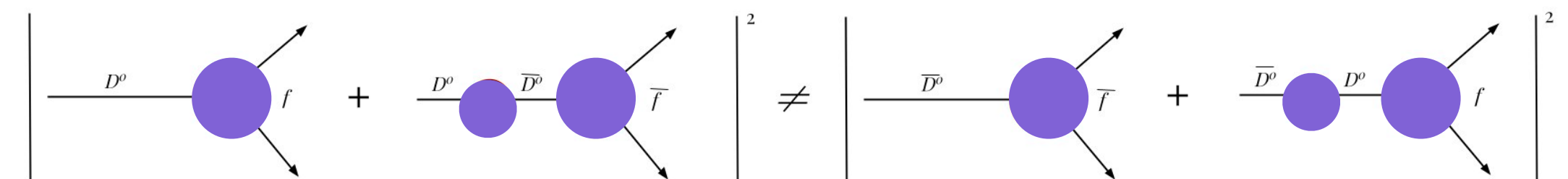
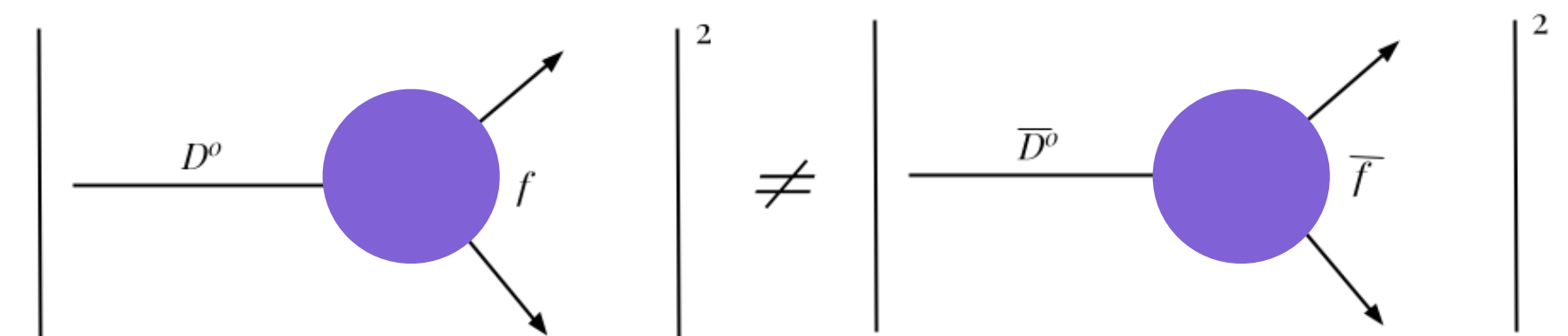
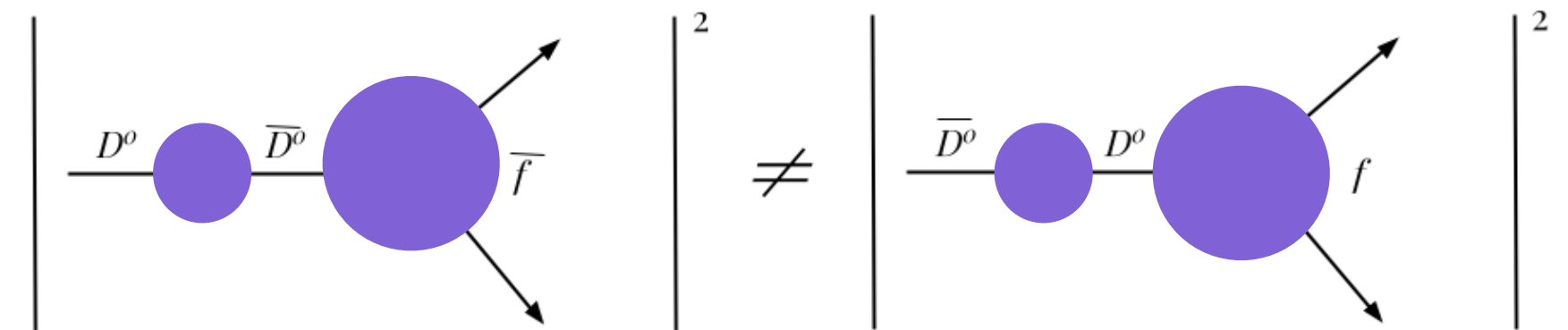
- Different probabilities for $D^0 \leftrightarrow \bar{D}^0$ oscillations

CPV in decay:

- Difference between decay rates $D^0 \rightarrow f$ and $\bar{D}^0 \rightarrow \bar{f}$

CPV in interference (mixing–decay):

- When D^0 and $\bar{D}^0$ decay to the same final state, amplitudes interfere



Note that decay channels have different sensitivities to the variables $x = \frac{\Delta m}{\Gamma}$ and $y = \frac{\Delta \Gamma}{2\Gamma}$

Multibody States (e.g. $D^0 \rightarrow K_S^0 \pi^+ \pi^-$):

- Dalitz plot $\Rightarrow$ access to **local variation** of **decay amplitudes** and **strong phases** vs phase space
- Sensitive to strong-phase differences across bins $\Rightarrow$ requires an **amplitude model** or **external inputs**

$\Rightarrow x, \Delta x, y, \Delta y$

$\Rightarrow x, \Delta x$

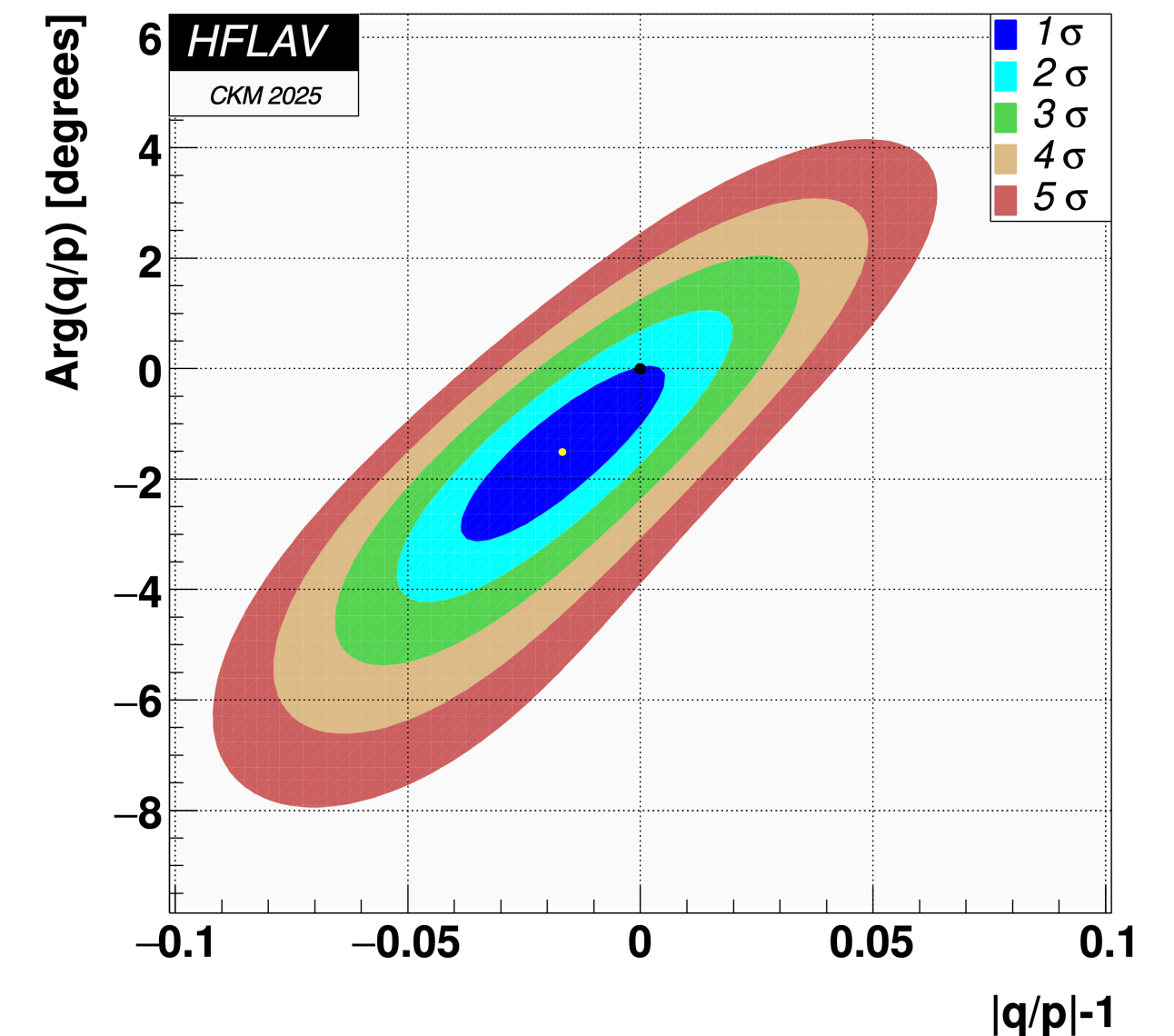
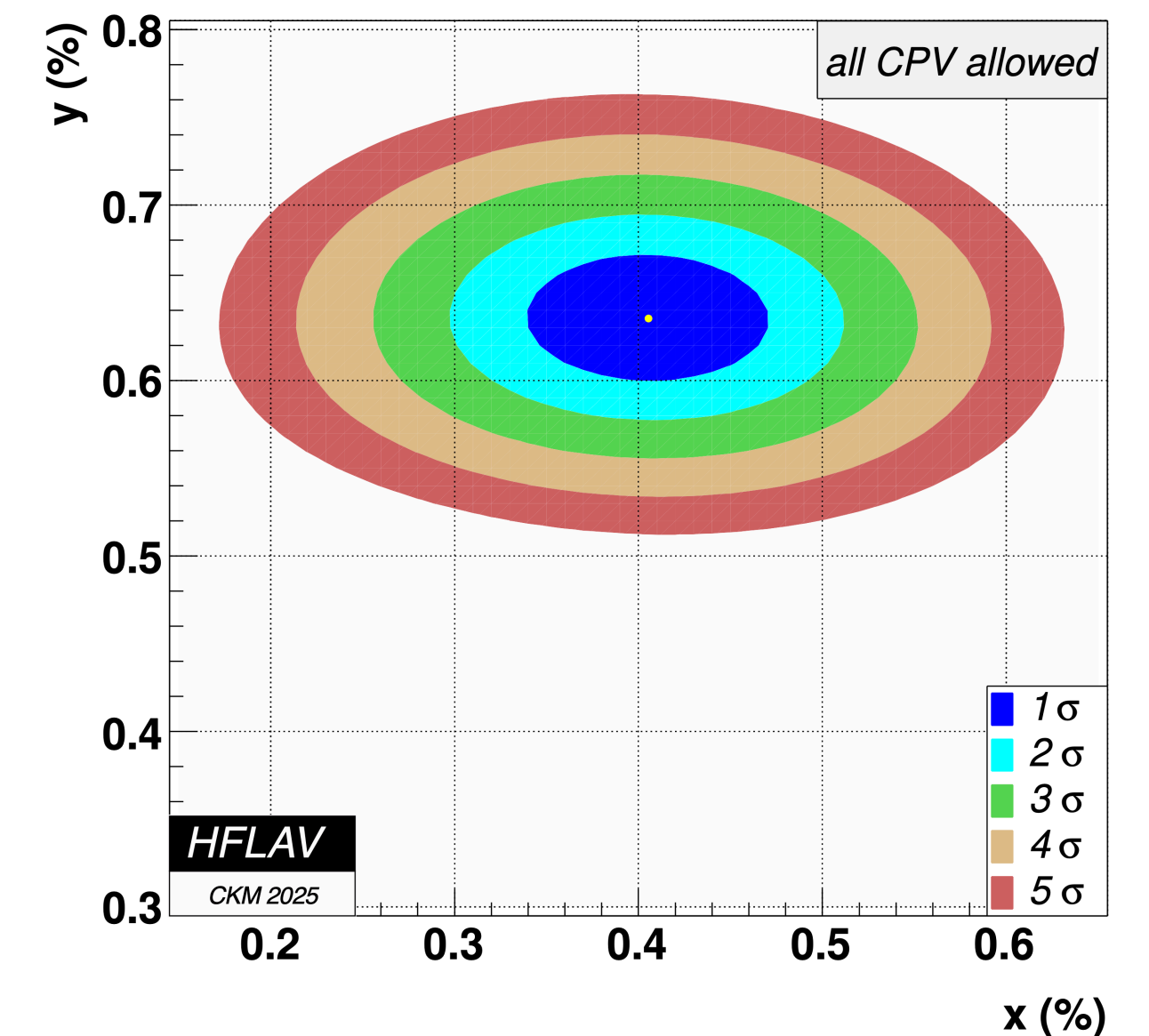
Status of the Art

LHCb:

- $D^0 \rightarrow K_S^0 \pi^+ \pi^-$ in 2021 (PRL127,111801)
 - $x = (3.98^{+0.56}_{-0.54}) \times 10^{-3}$
 - $y = (4.6^{+1.5}_{-1.4}) \times 10^{-3}$
 - first observation of $\Delta m \neq 0$ in D^0 system (significance exceeding 7σ)

Belle & BelleII:

- $D^0 \rightarrow K_S^0 \pi^+ \pi^-$ in 2025 (PRD111,112011)
 - Assuming no CPV:
 - $x = (4.0 \pm 1.7 \pm 0.4) \times 10^{-3}$
 - $y = (2.9 \pm 1.4 \pm 0.3) \times 10^{-3}$
 - Results are consistent with previous determinations (PRD 89, 091103(R))
 - **20%** and **14% improvement** compared to previous model-dependent determinations (PRD 89, 091103(R))



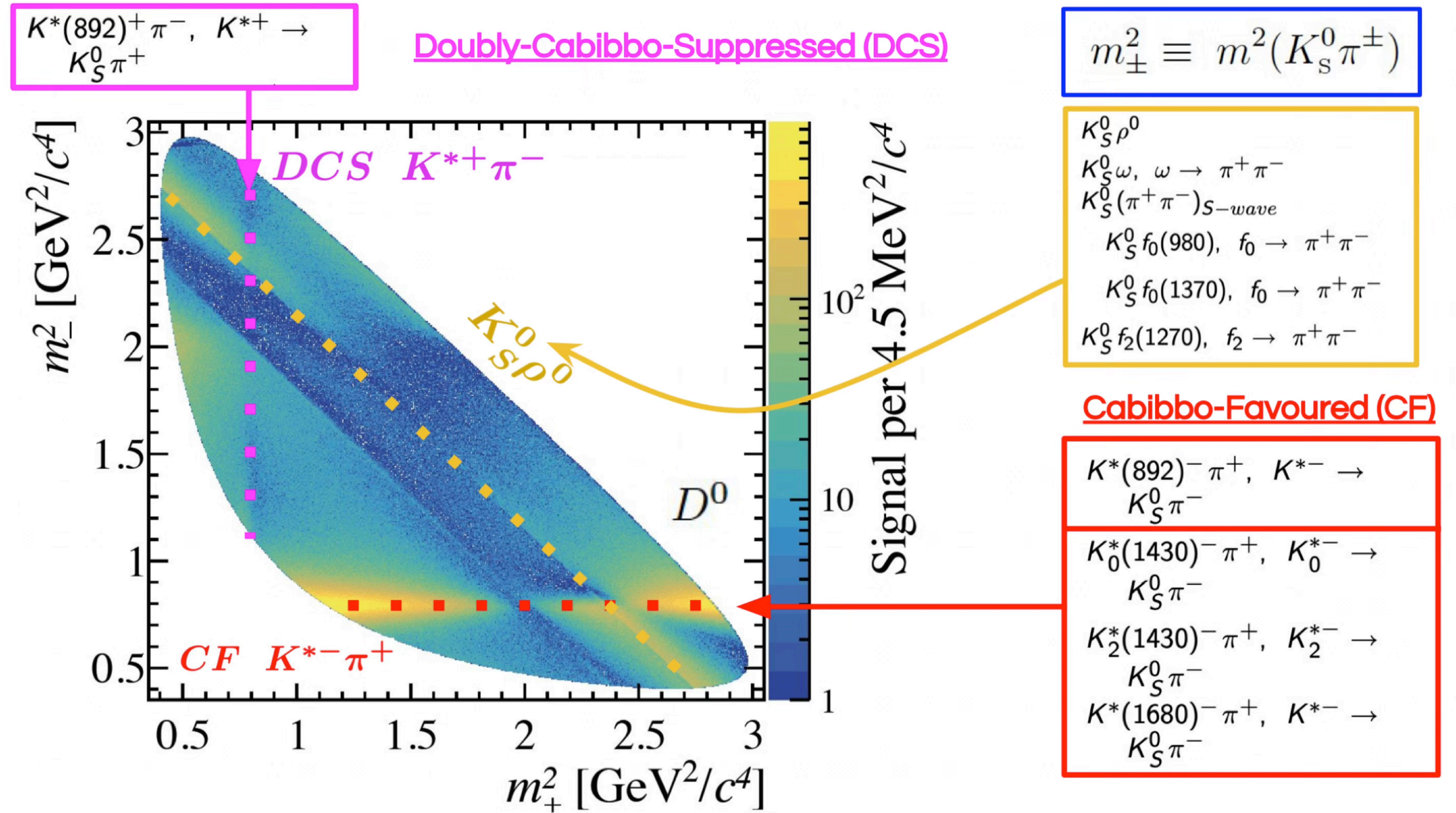
$D^0 \rightarrow K_S^0 \pi^+ \pi^-$ channel

- Since Run 3, with the removal of LO hardware trigger, the selection efficiency of $D^0 \rightarrow K_S^0 \pi^+ \pi^-$ decays improved
- Run 2 trigger-induced decay-time/Dalitz correlations
 - main source of systematics
- Removal of LO allows us to consider a single selection stage
 - which is easier to simulate compared to the hardware one
 - reduced trigger-related systematics and improved control of trigger effects

Bin-flip method (I)

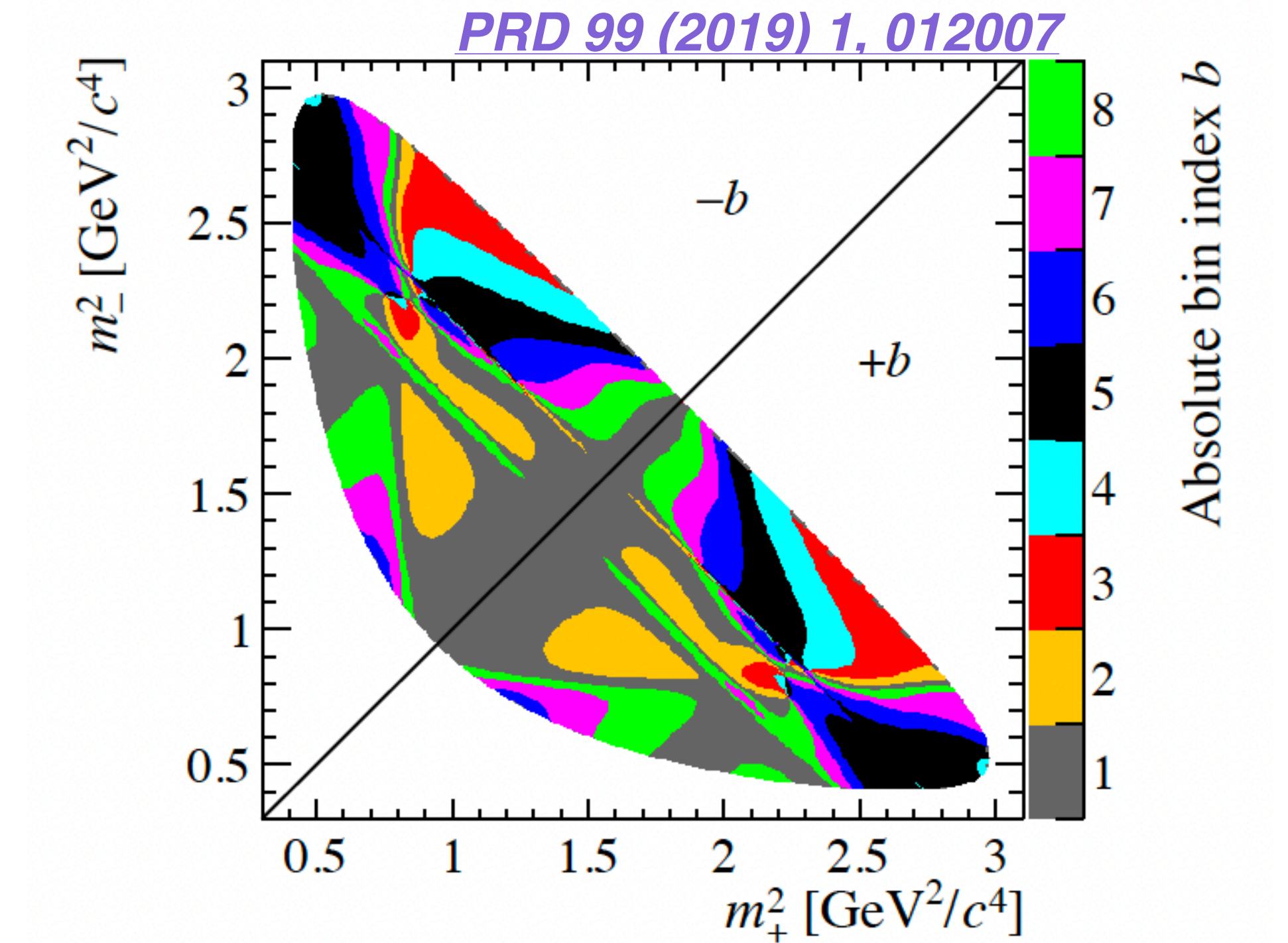
- $D^0 \rightarrow K_S^0 \pi^+ \pi^-$ allows to calculate mixing and CP violating parameters
- This decay receives contributions from the **CF** and **DCS** decays:

$$m_{\pm}^2 \equiv \begin{cases} m^2(K_S^0 \pi^\pm) & \text{for } D^0 \rightarrow K_S^0 \pi^\pm \pi^\mp \\ m^2(K_S^0 \pi^\mp) & \text{for } \bar{D}^0 \rightarrow K_S^0 \pi^\mp \pi^\pm \end{cases}$$



Bin-flip method (II)

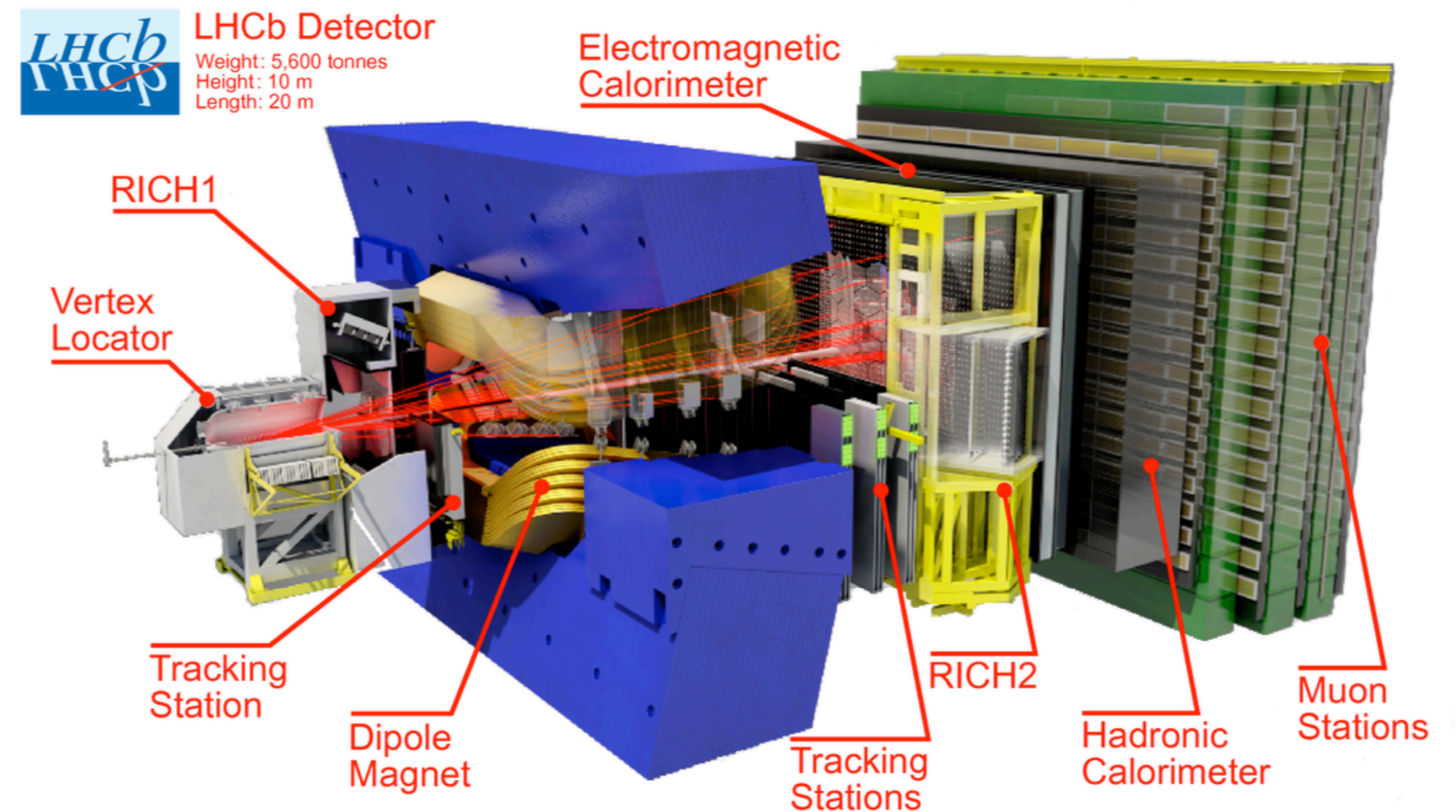
- Model-independent method
- Data are partitioned into bins of the Dalitz plot
 - defined to preserve nearly constant strong phase differences $\delta(m_-^2, m_+^2)$ between the D^0 and $\bar{D}^0$ amplitudes within each bin: subscript b
- Dalitz plane divided into two regions:
 - $m_+^2 > m_-^2$: contribution from CF: $+b$
 - $m_+^2 < m_-^2$: contribution from DCS: $-b$
- At first order, it is not affected by uncertainties due to time acceptance effects



LHCb detector

LHCb (Ref1, Ref2)

- LHC: pp collision
- A single-arm forward spectrometer designed for the study of particles containing b or c quarks
- Pseudorapidity range: $2 < \eta < 5$
- Highly efficient PID
- Very good momentum and IP resolution
- Excellent primary and secondary vertex reconstruction

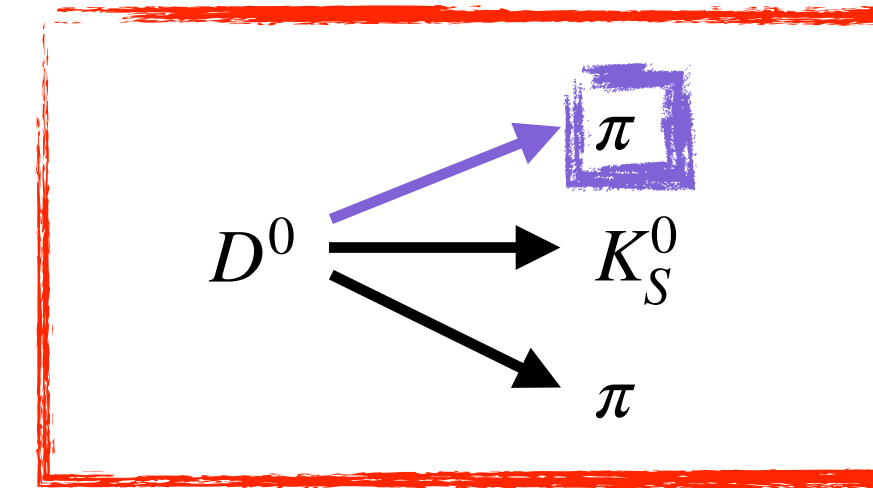


HLT1 Selection

- LHCb Run3 $\Rightarrow$ removal of hardware trigger for the HLT1 software one

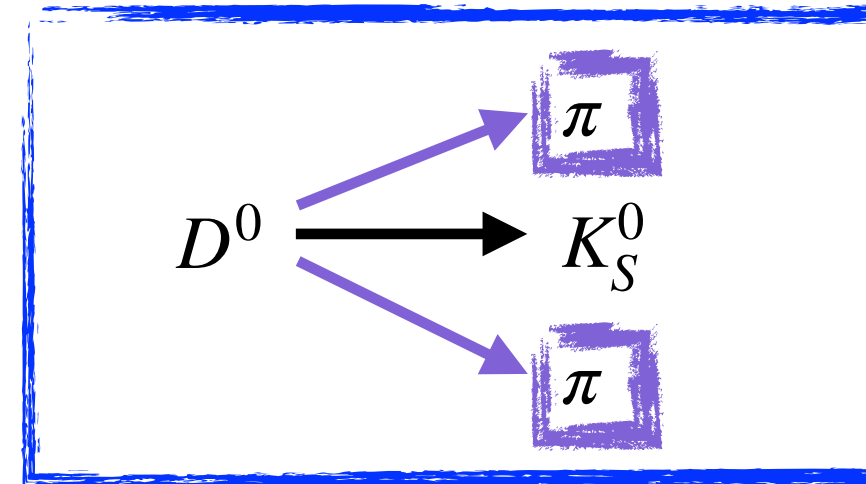
One Track:

- Uses one pion for selection
- MVA cuts based on PT, IPChi2



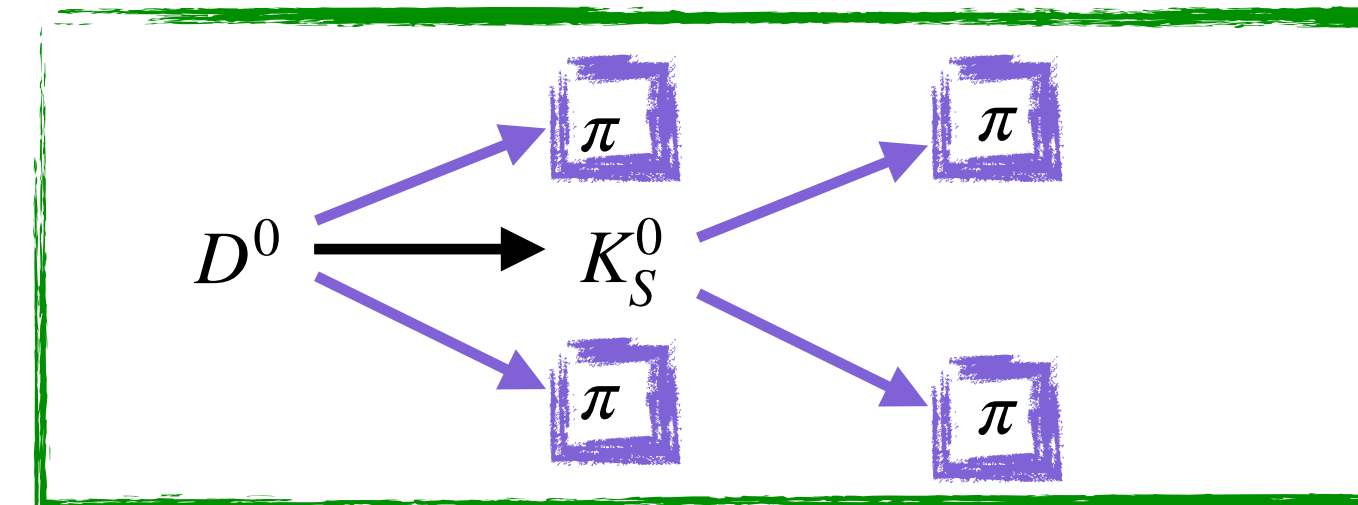
Two Tracks:

- Uses the two pions for selection
- MVA cuts based on PT(hh) and IPCHI2(hh)



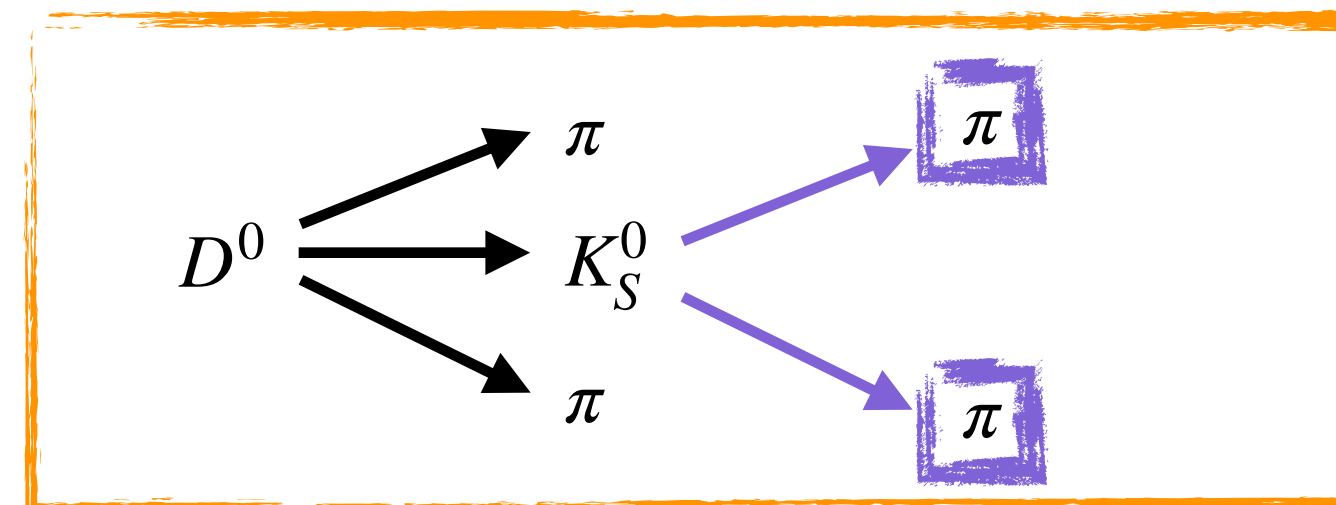
D2Kshh:

- Uses the 4 tracks
- Selection on the masses of K_S^0 and D^0 , PT and IP



KS:

- Uses the K_S^0 daughters
- Selection on the mass of K_S^0 , PT and IP



TIS:

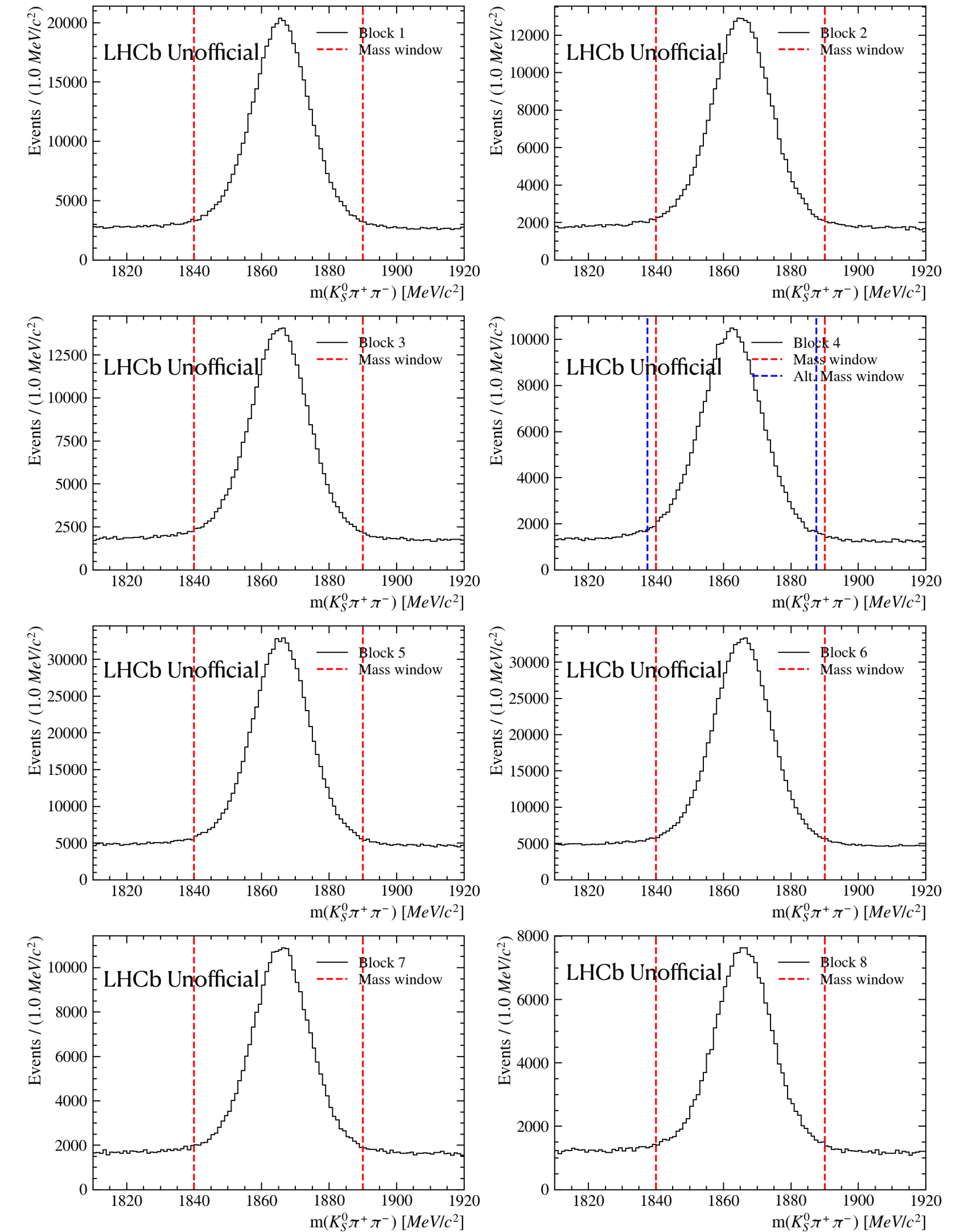
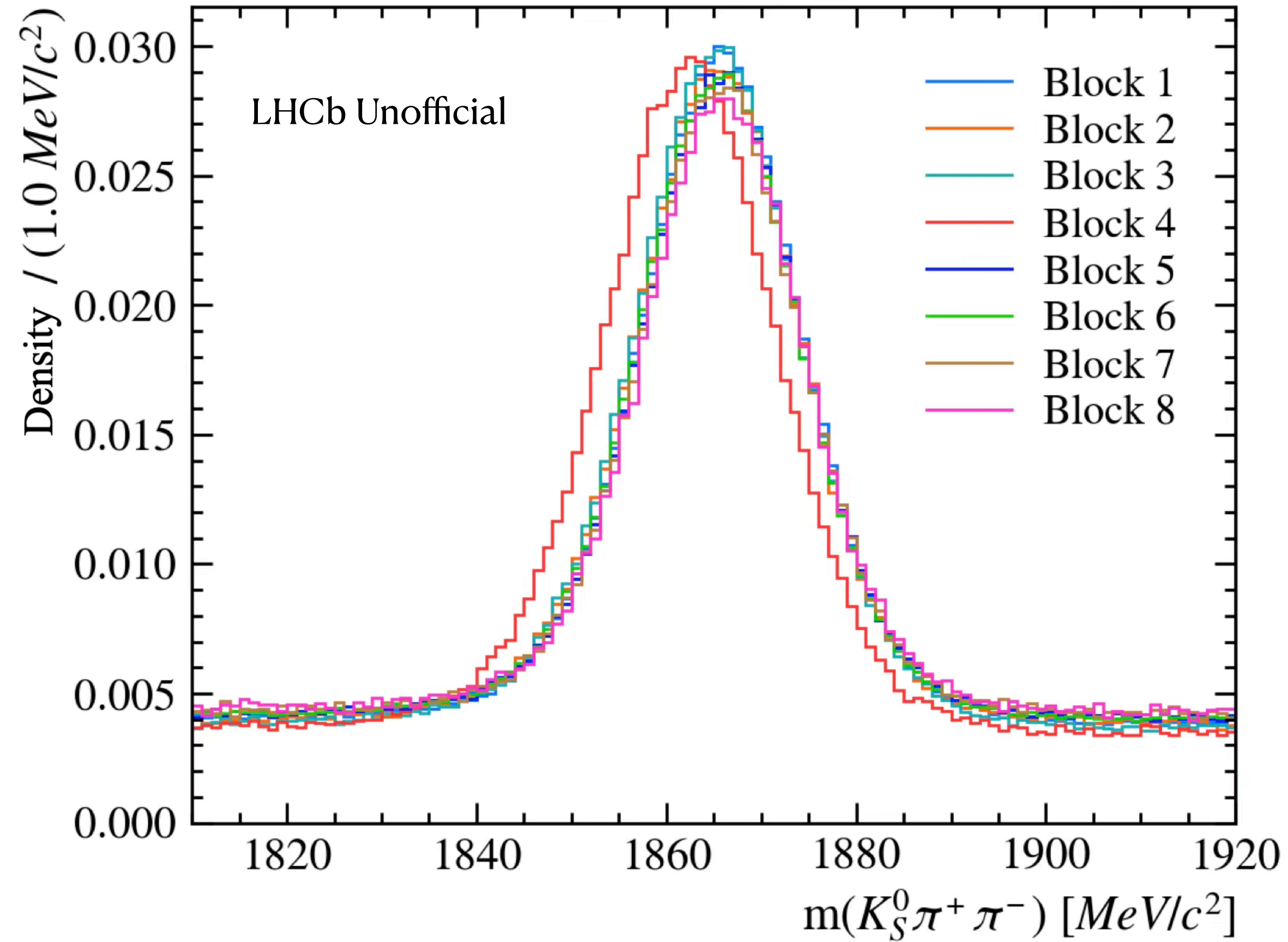
- No selected track participates in the HLT1 selections

Dataset & Selection

- Data
 - 2024 data mag **up** and **down** (9/fb)
 - Both long (**LL**) and downstream (**DD**) tracks
 - Data divided by **Blocks**
- Selection:
 - $p_T(D^0)$ different for each trigger line
 - $\log(\chi_{IP}^2(D^0)) < 2.2$ to remove secondaries
 - $DOCA(\pi\pi) < 0.14$ mm
 - $z_{V_{tx}}(K_S^0) - z_{V_{tx}}(D^0) > 10$ mm
 - m_{D^0} in $[1840, 1890]$ MeV/c²
 - Introduced a shift of 2.5 MeV in block 4 due to data reconstructed with preliminary alignment $\Rightarrow$ will be updated
 - Different modes to select those candidates at trigger level
 - offer different acceptances

Hlt	$P_T(D^0) >$
OneTrack	4000
TwoTrack	2500
TIS	3750
D2Kshh	2500
KS	4500

Selection: $m(D^0)$

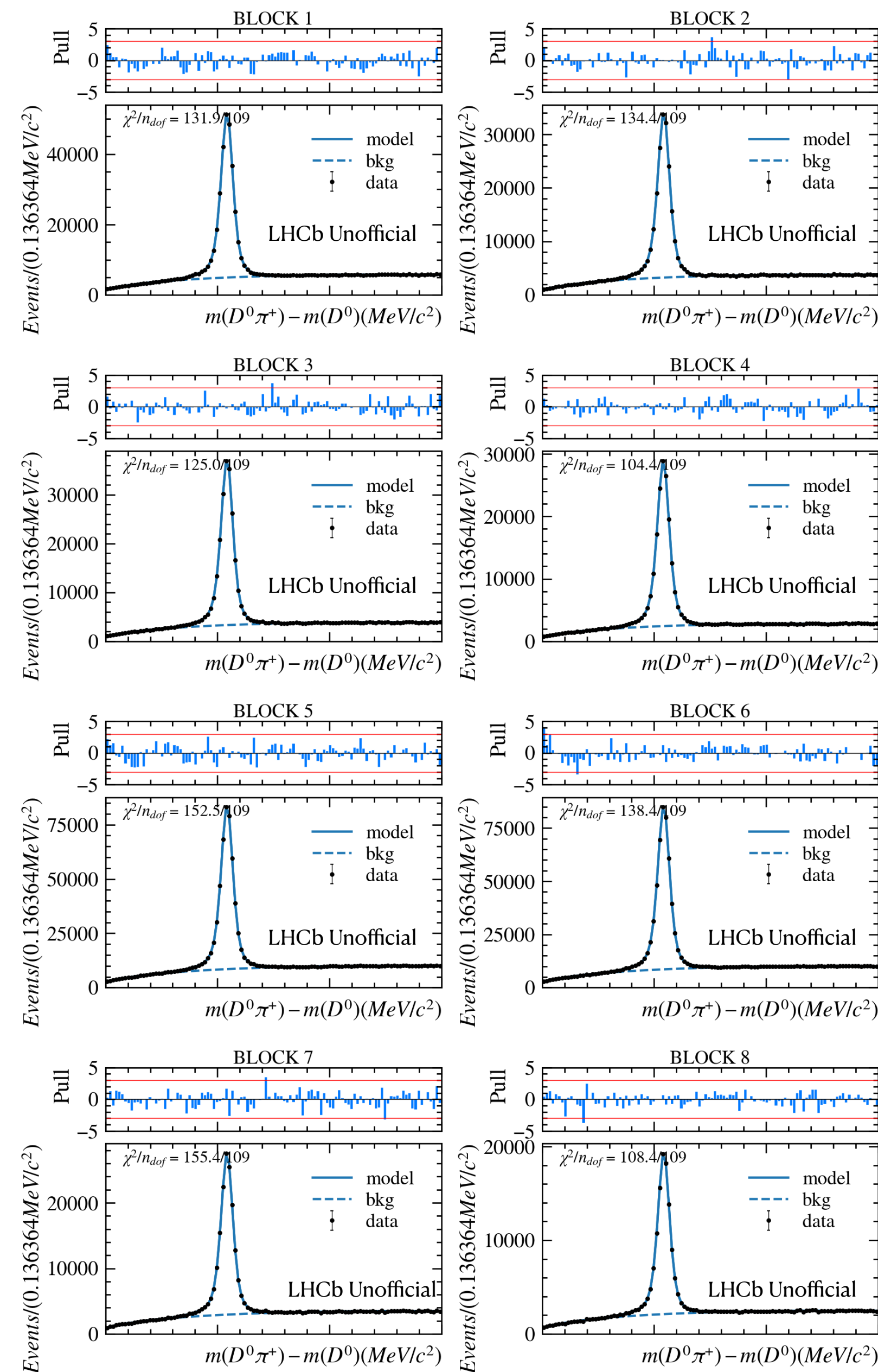
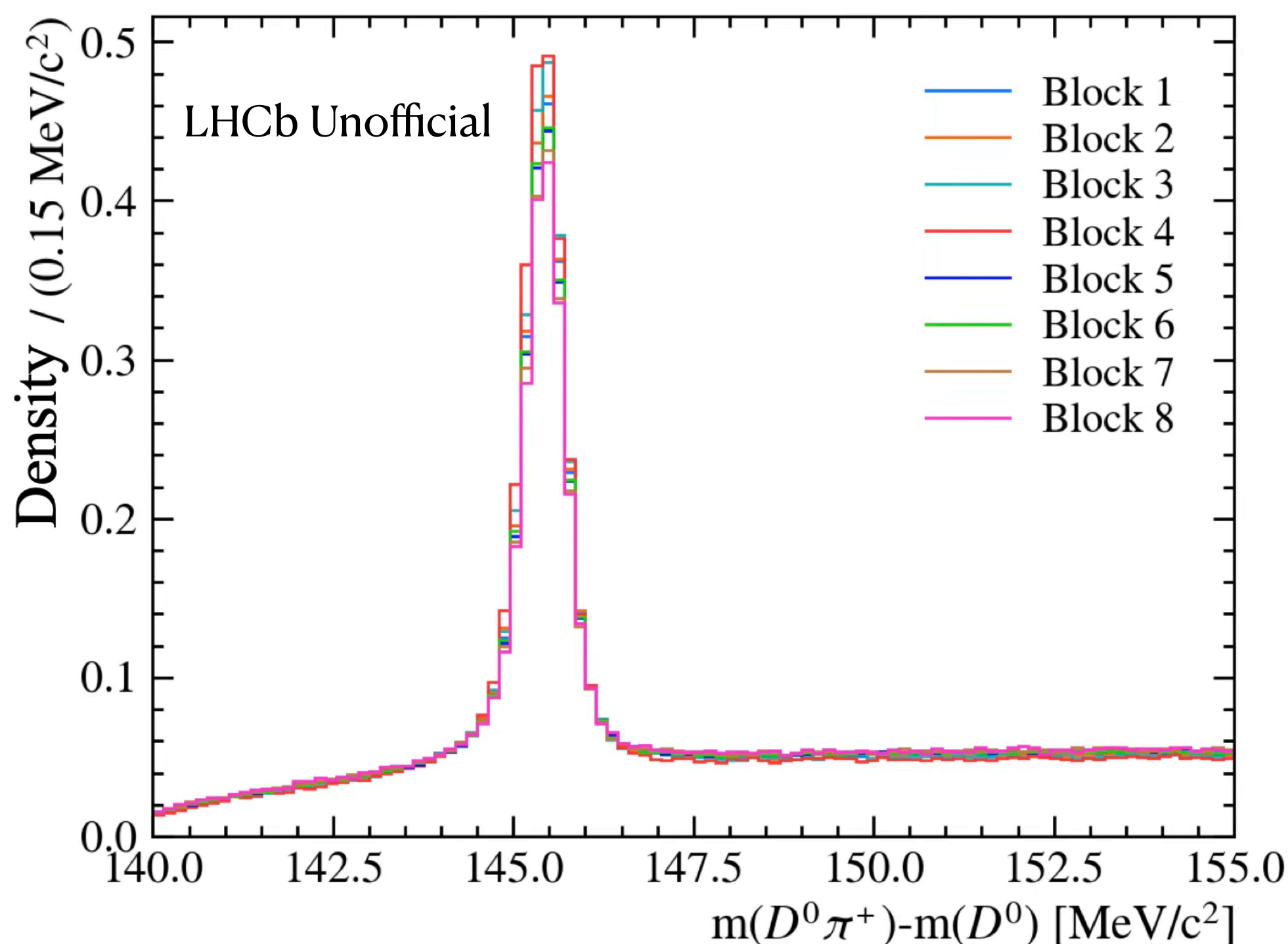


Signal extraction: Δm

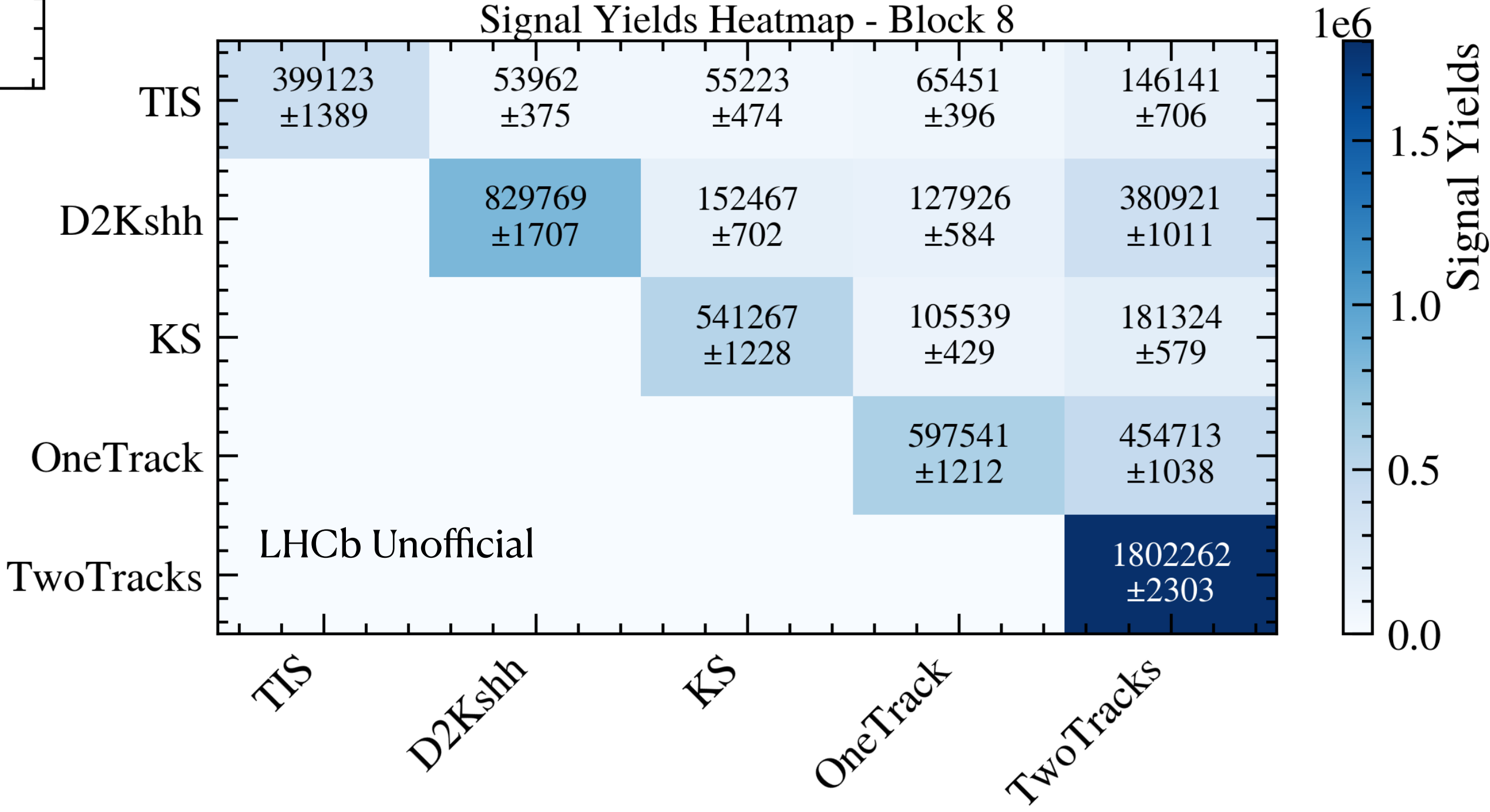
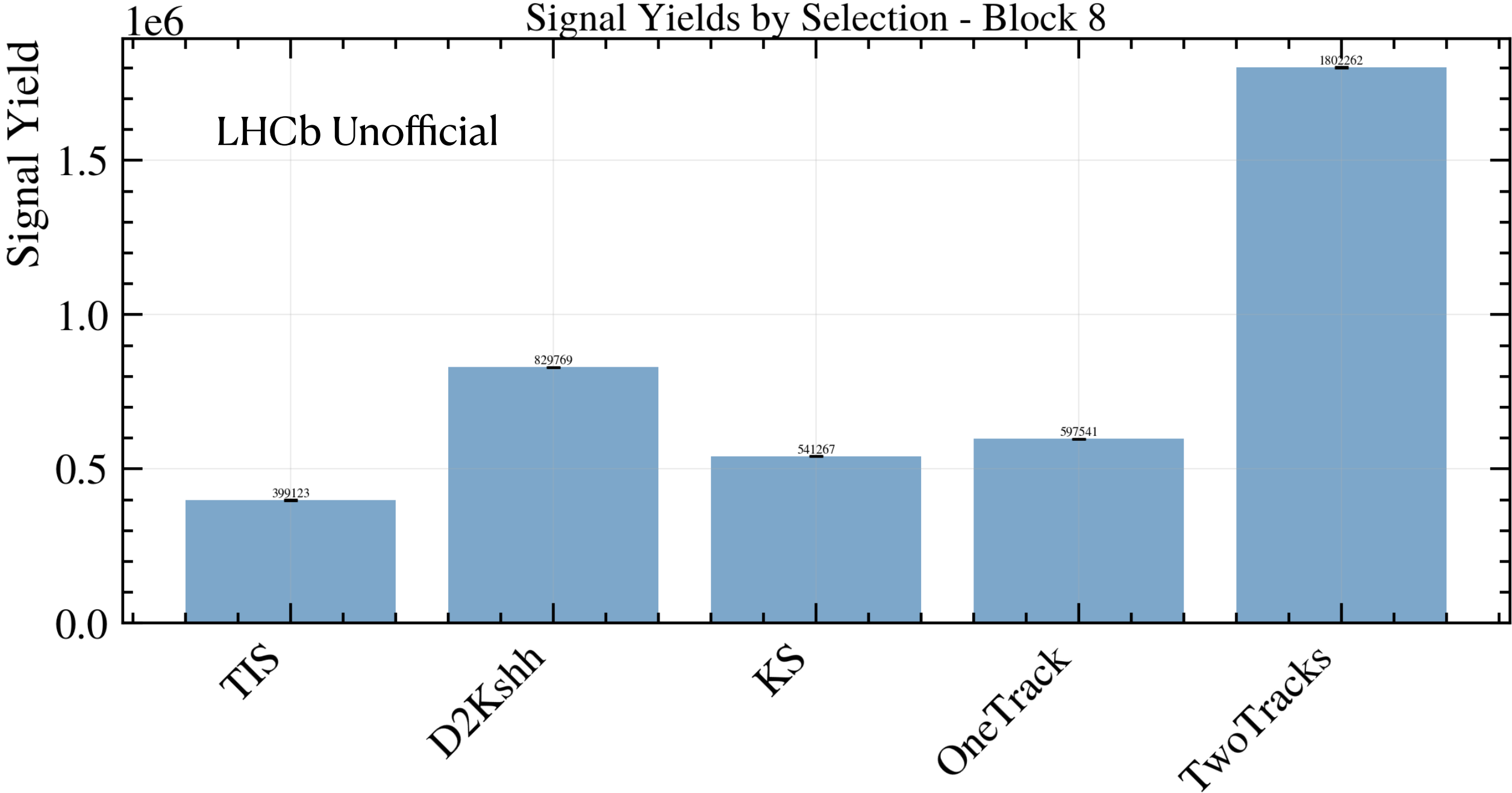
- To fit the Δm distribution:
 - for signal: a Johnson SU + Gaussian
 - for background: Threshold function

$$\text{DmModel}(x) = f_{\text{sig}} \left(f_{\text{JSU}} \cdot \text{JSU}(x) + (1 - f_{\text{JSU}}) \cdot (w_1 \cdot G_1(x)) \right) + (1 - f_{\text{sig}}) \cdot \text{RooThresholdDAcp}(x; \theta, a, b)$$

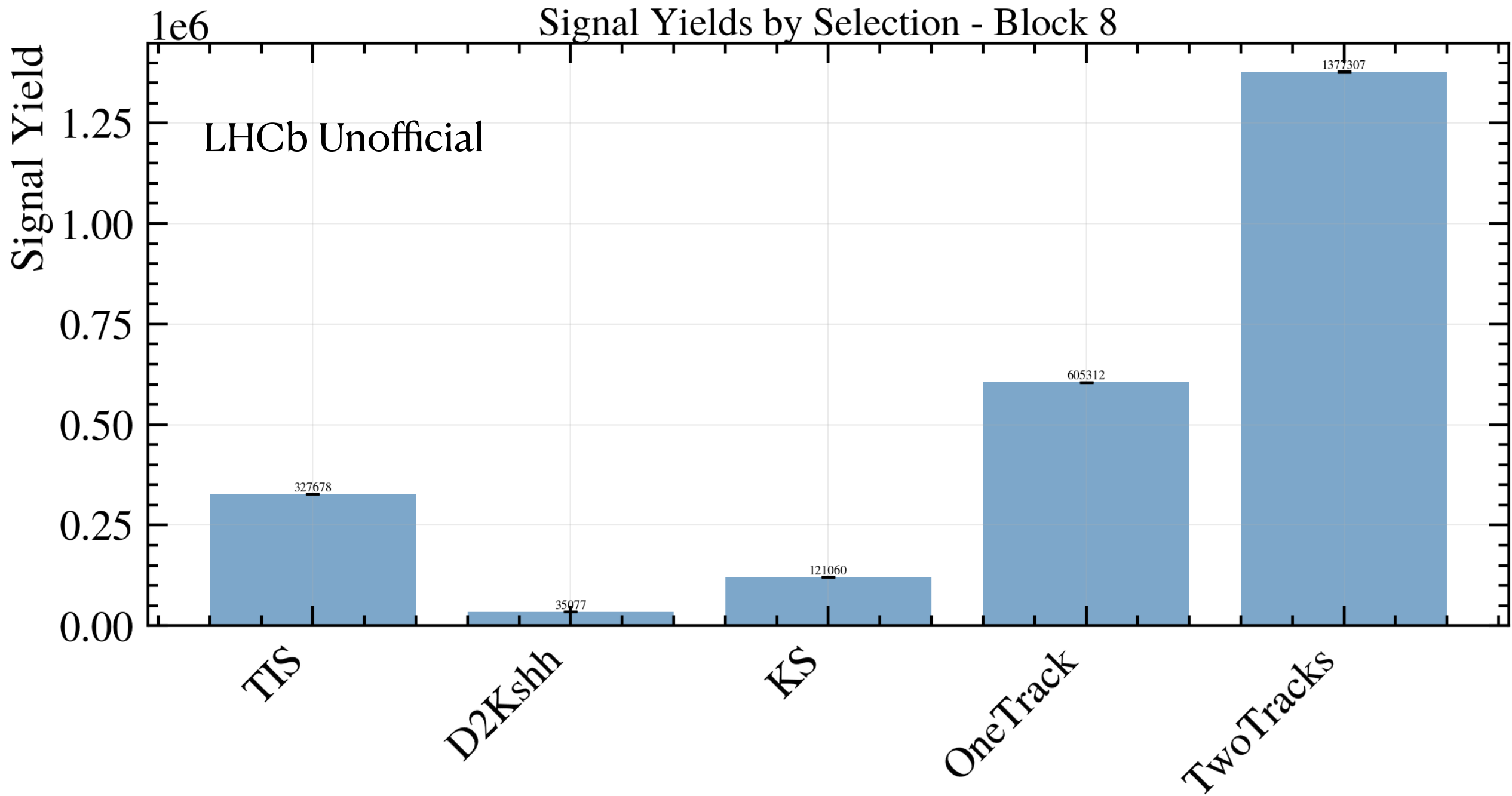
$$\text{with } \text{RooThresholdDAcp}(x; \theta, a, b) = \Theta(x - x_{\text{th}})(x - x_0)^a e^{-b(x-x_0)}$$



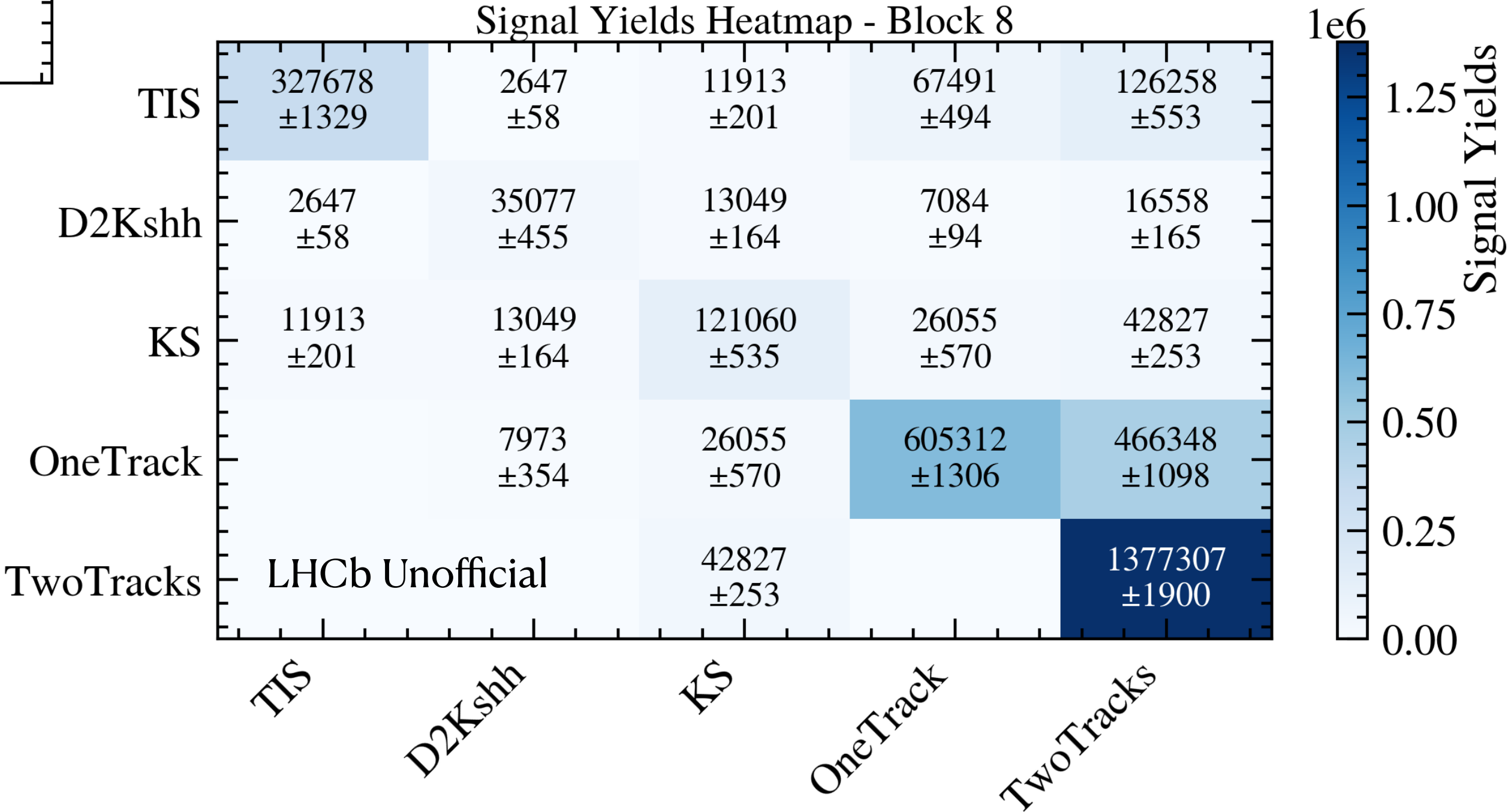
Signal Yields by Selection - LL



Signal Yields by Selection - DD



- Downstream tracks reconstruction in HLT1 introduced later during 2024
 - Not optimised yet



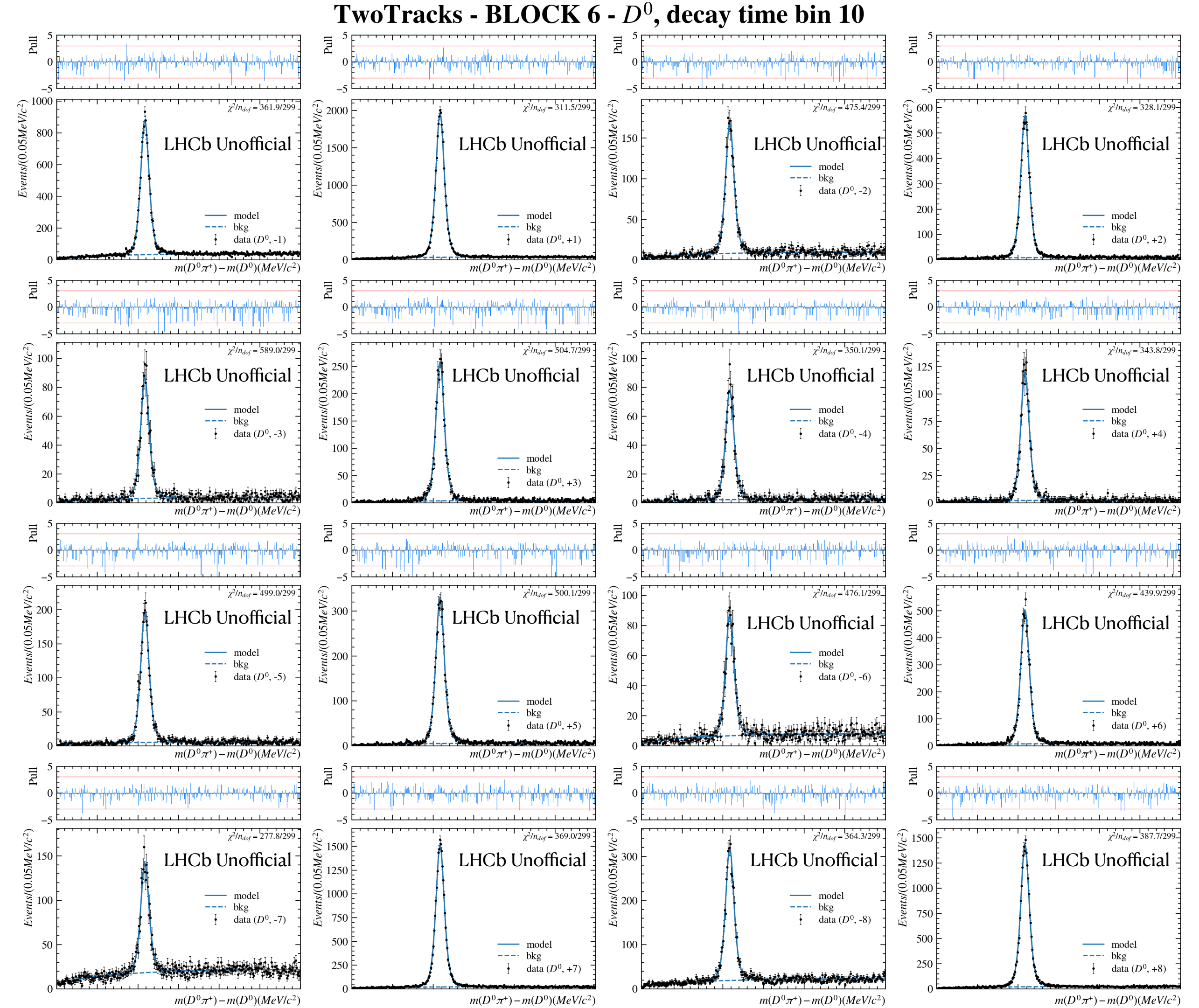
Run 3 2024 data divided per dataset

▫ Yields obtained through a fit of the Δm variable ($\Delta m = m(D^{*+}) - m(D^0)$)

Data	Lumi (MU+MD) [pb ⁻¹]	Yield/lumi	
		LL	DD
Run2	5400	1826.4 ± 1.2	3837.31 ± 1.66
Block 4 [9808, 9910]	1131.8	4912.04 ± 3.04	2854.37 ± 2.24
Block 3 [9911, 9943]	670.4	5509.18 ± 4.32	3377.92 ± 3.27
Block 2 [9945, 9978]	601	6510.27 ± 4.94	3919.64 ± 3.74
Block 1 [9982, 10056]	1161.1	6407.83 ± 3.60	3823.57 ± 2.61
Block 5 [10059, 10102]	1125.8	6651.64 ± 3.72	4797.59 ± 3.02
Block 6 [10104, 101381]	949.1	6537.33 ± 4.06	4674.80 ± 3.18
Block 7 [10197, 10213]	717.6	5810.06 ± 4.28	4019.62 ± 3.42
Block 8 [10214, 10232]	417.6	5787.06 ± 5.65	3979.94 ± 4.45
Run3	6774.4	6020.6 ± 1.4	3913.7 ± 1.1

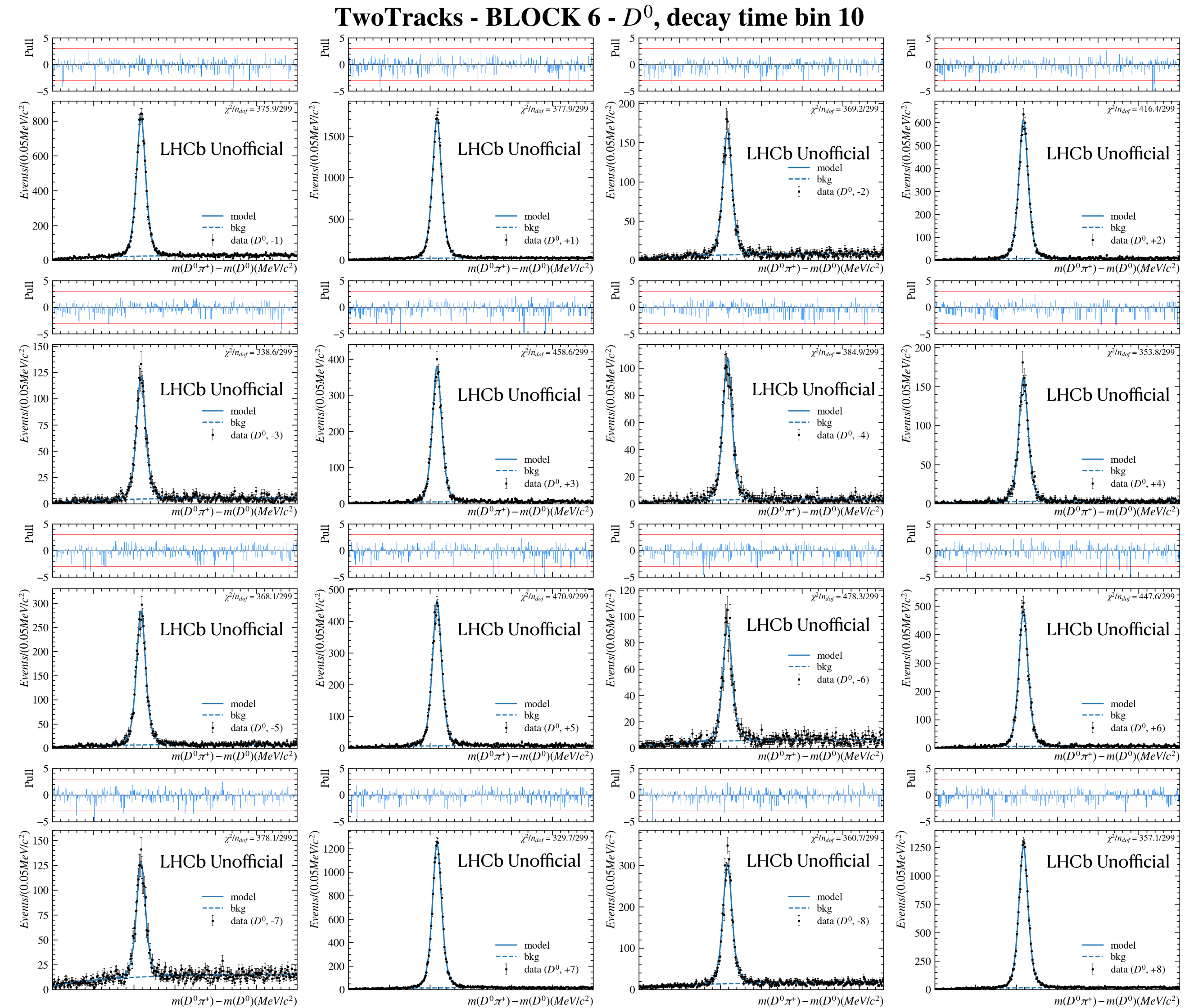
Simultaneous fits - LL

- Simultaneous fits in phase-space bins per lifetime bins
 - To directly extract from the fit the R_b ratios in each bin



Simultaneous fits - DD

- Simultaneous fits in phase-space bins per lifetime bins
 - To directly extract from the fit the R_b ratios in each bin



Efficiency Maps - Two Tracks

Initial Problem

- Correct data by removing experimentally induced correlations between decay time and phase-space coordinates
- Full correction would require knowledge of the 3D (phase-space + decay time) efficiency variation

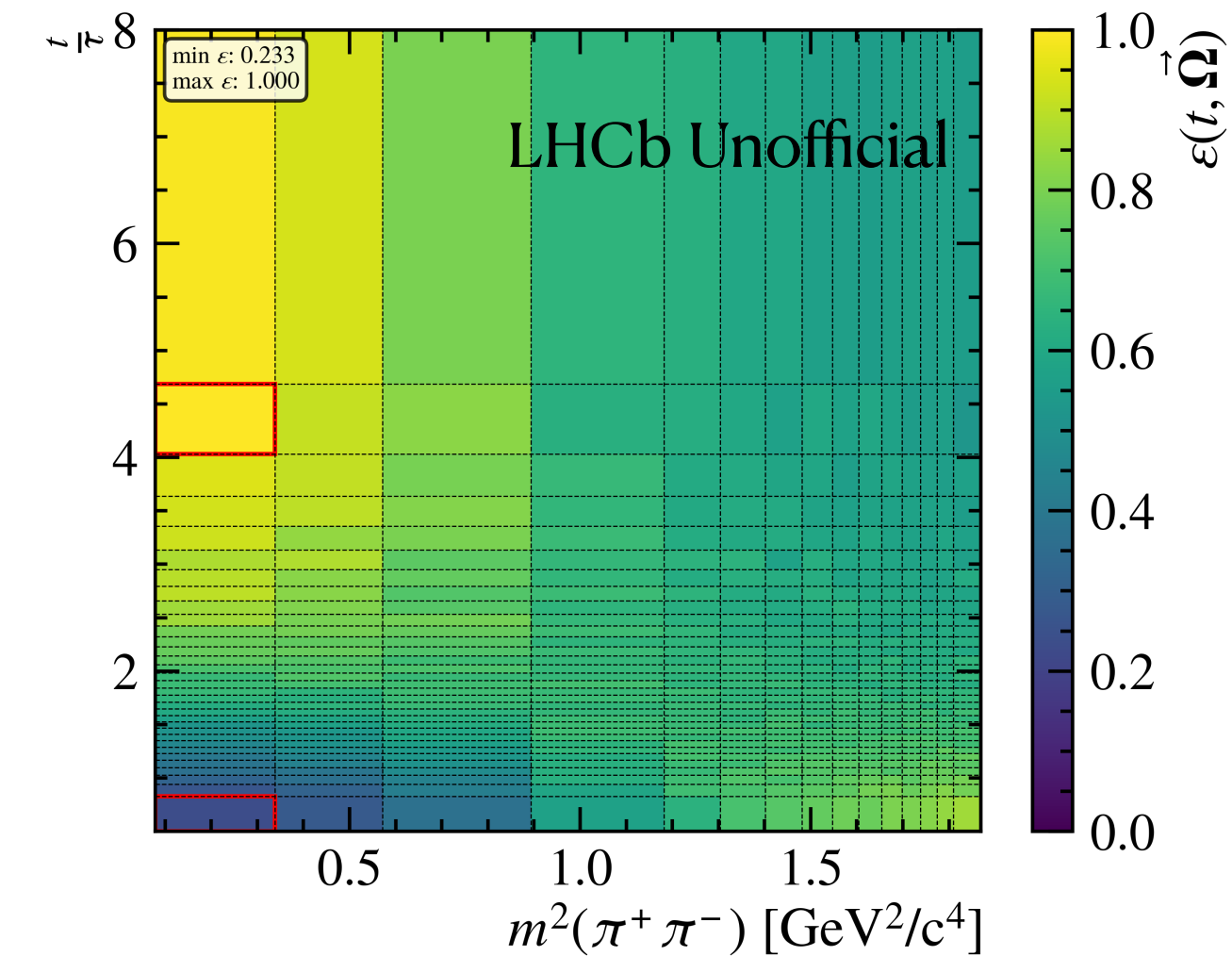
Adopted Approach

- No need to correct for overall efficiency variation
 - *bin-flip* method handles independent variations of decay time and phase-space
- Sufficient to make decay-time acceptance uniform across the phase space

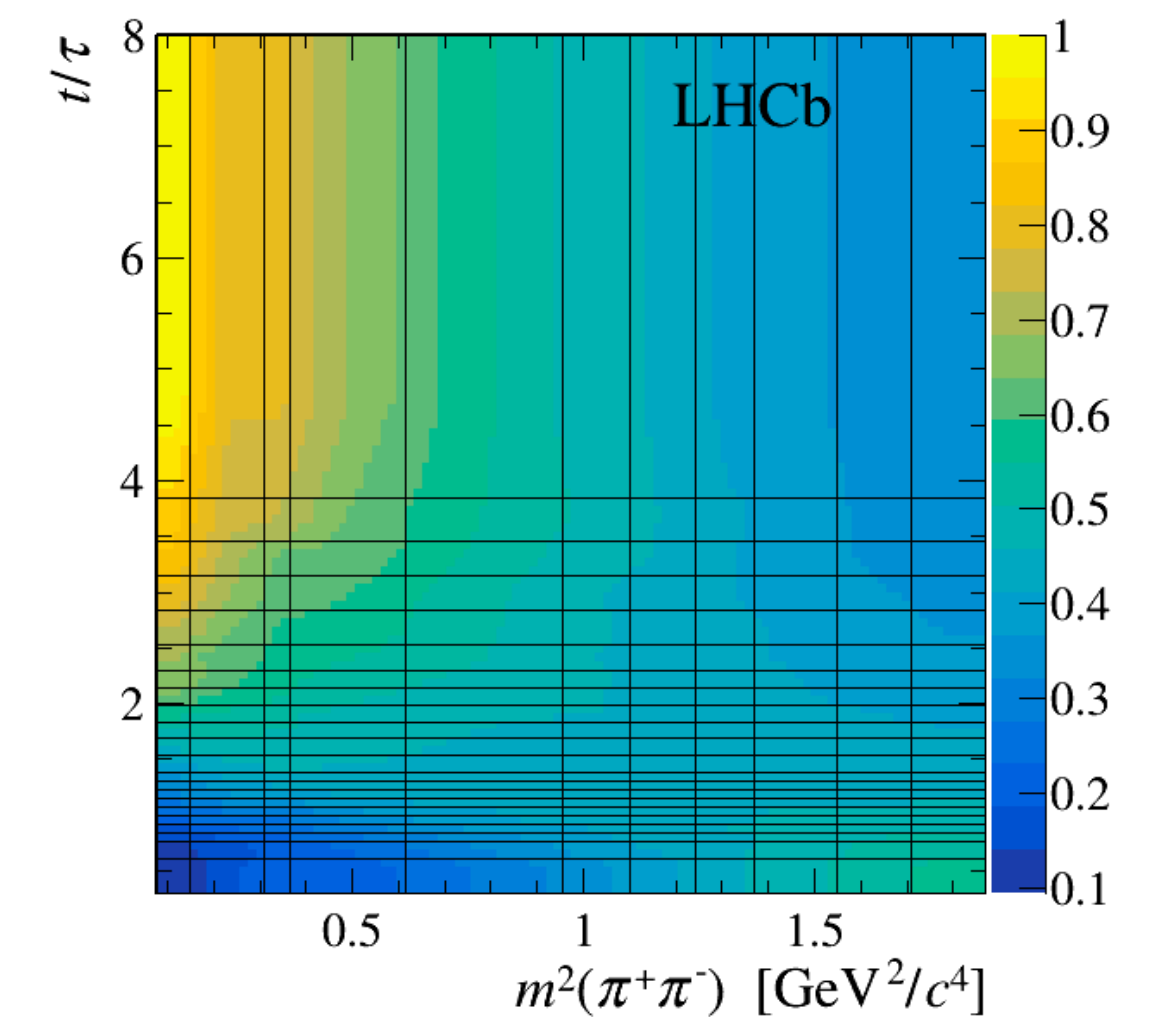
Estimation of Relative Efficiency

- Efficiency estimated **directly from data** using background subtraction via *sWeights*
 - Decay-time differences across phase space attributed only to efficiency variations
 - D^0 and $\bar{D}^0$ without charge conjugation, assuming negligible direct CPV in bin-flip ratios
-
- Run 3 maps have higher minimum values $\Rightarrow$ smaller efficiency variation

Run3
Block 8 - LL



Run2



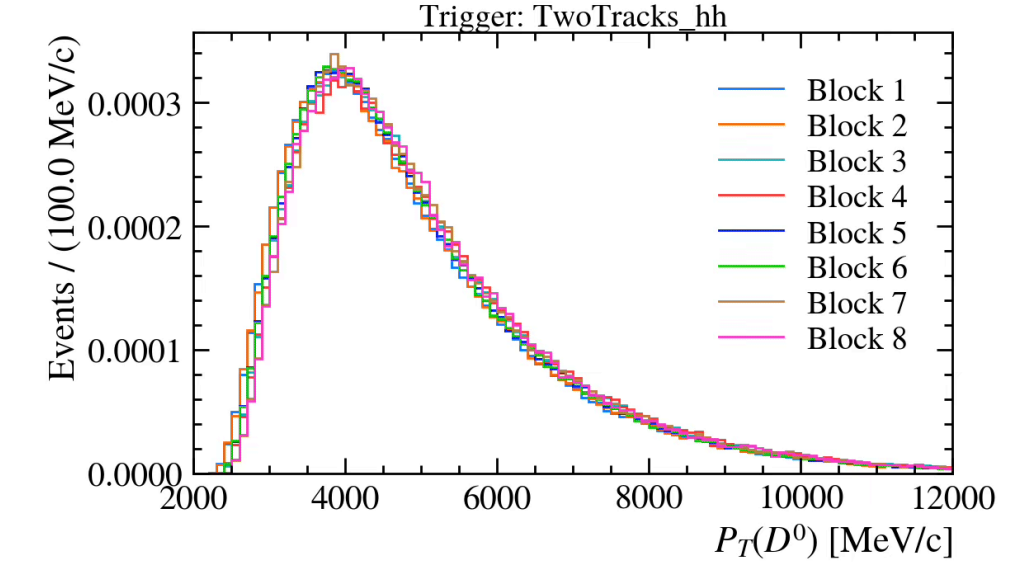
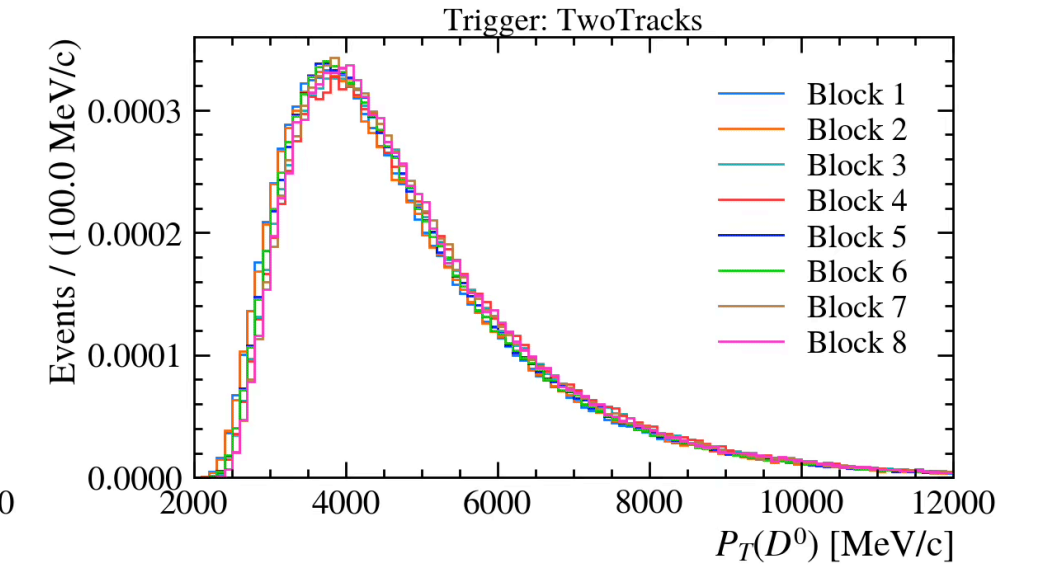
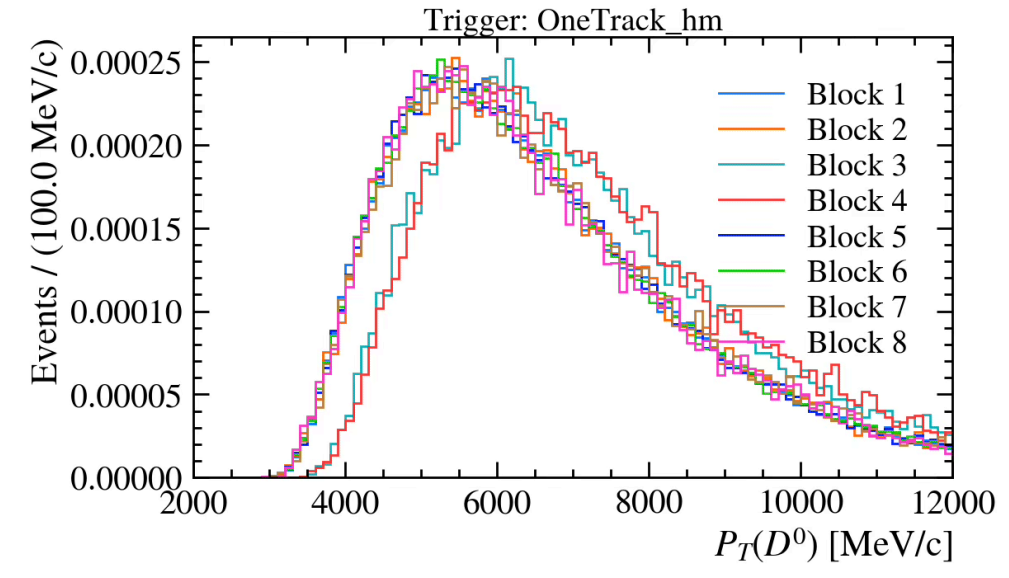
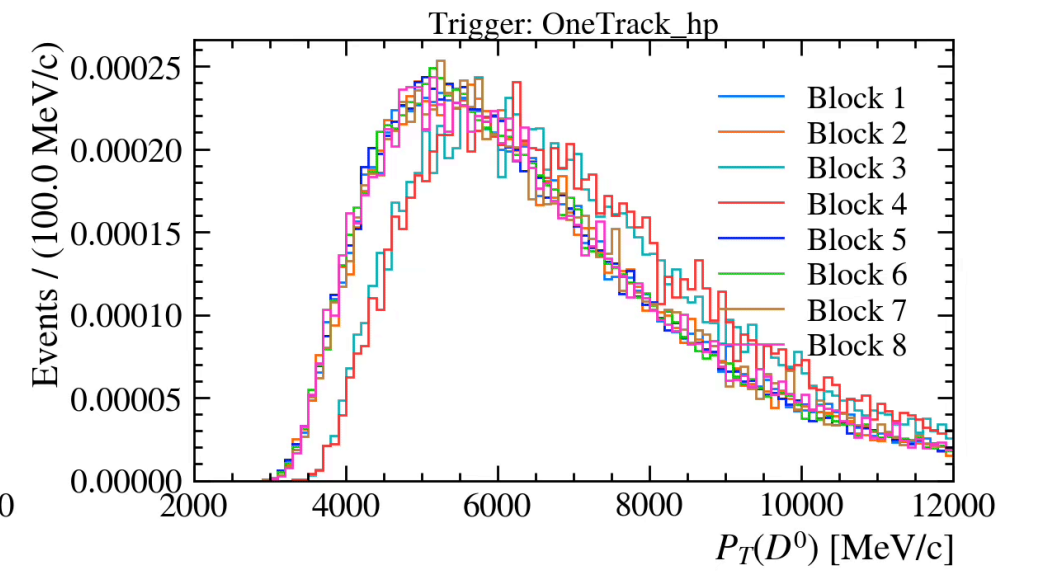
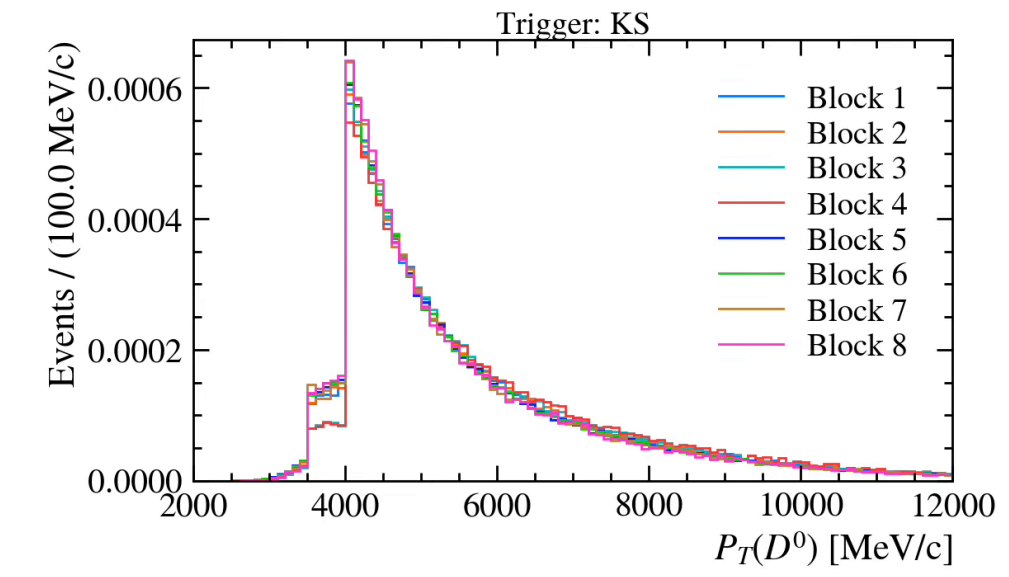
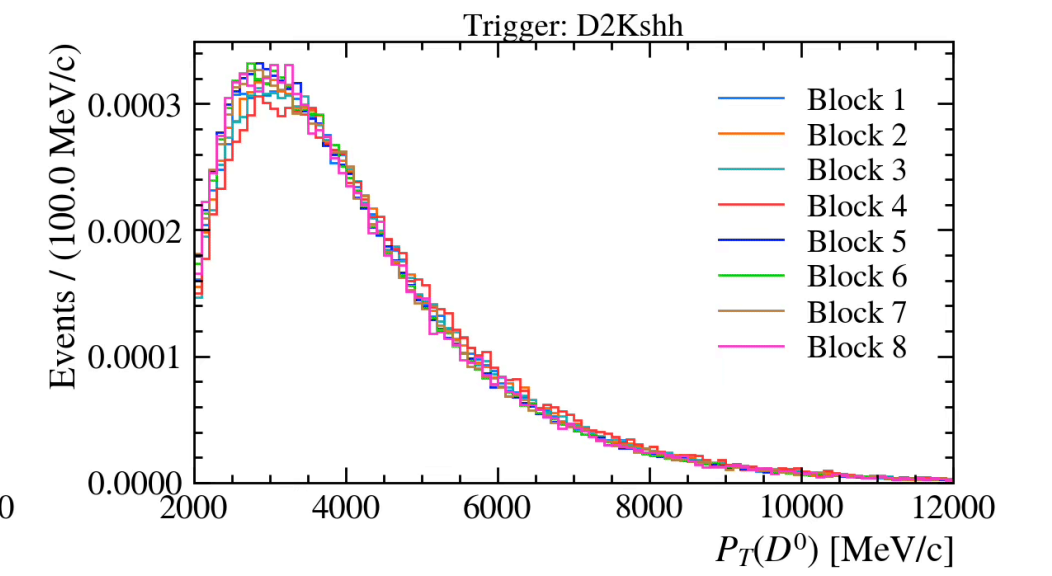
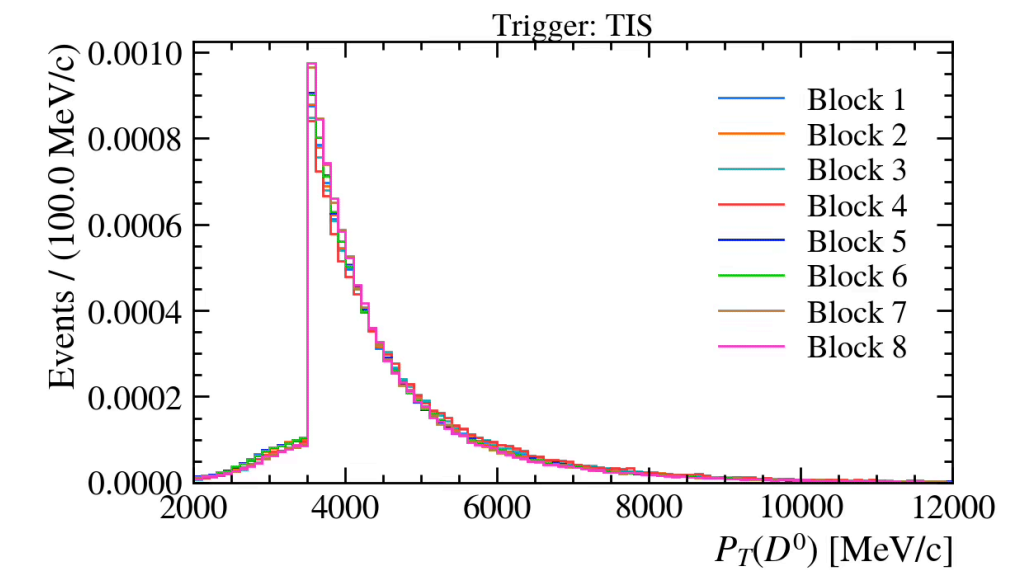
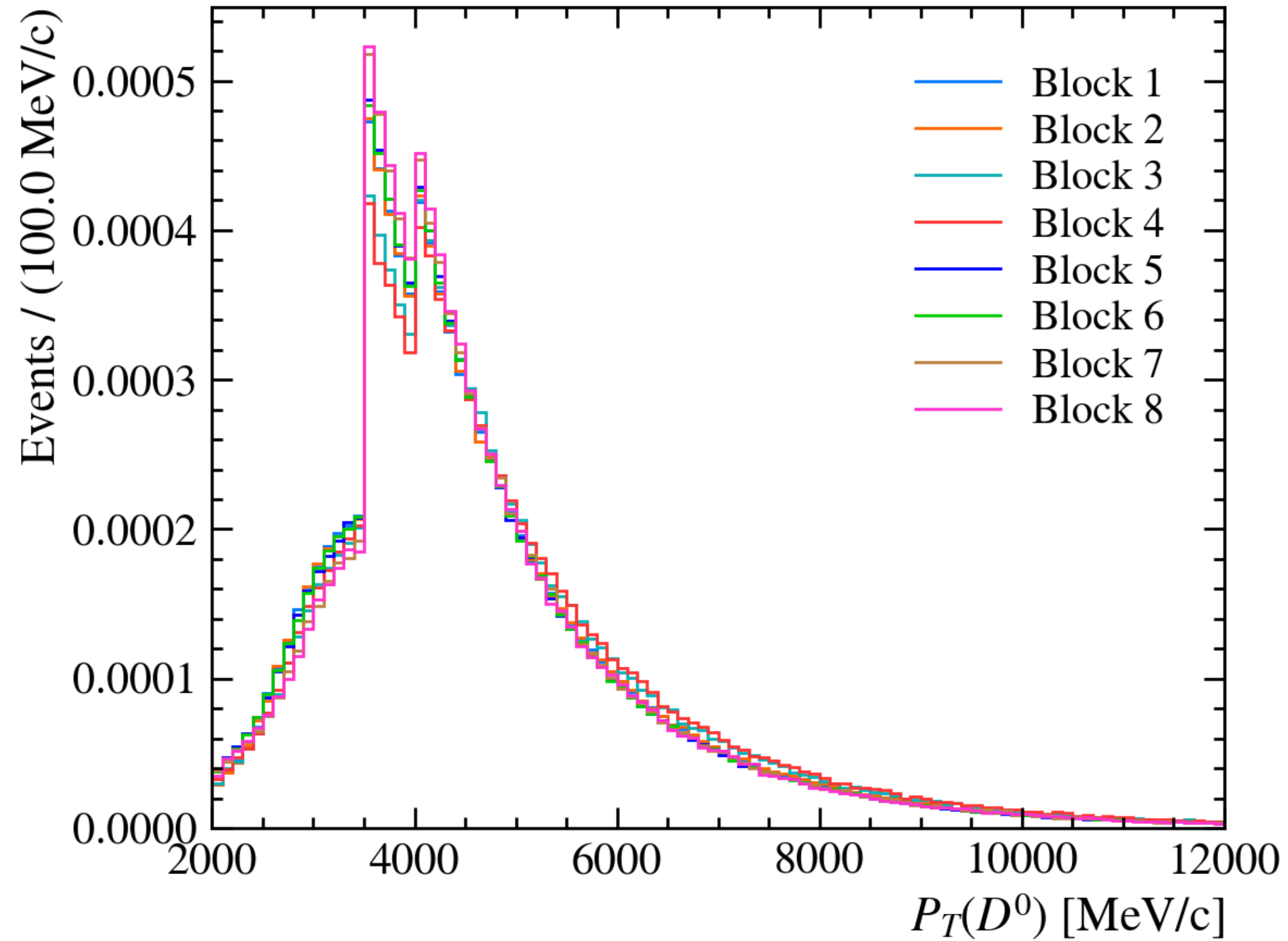
Conclusions

- With OneTrack and TwoTracks datasets $\Rightarrow$ threefold increase in signal yields in Run 3 2024 with respect to Run 2
- Aim for publication by 2026 with the 2024 dataset

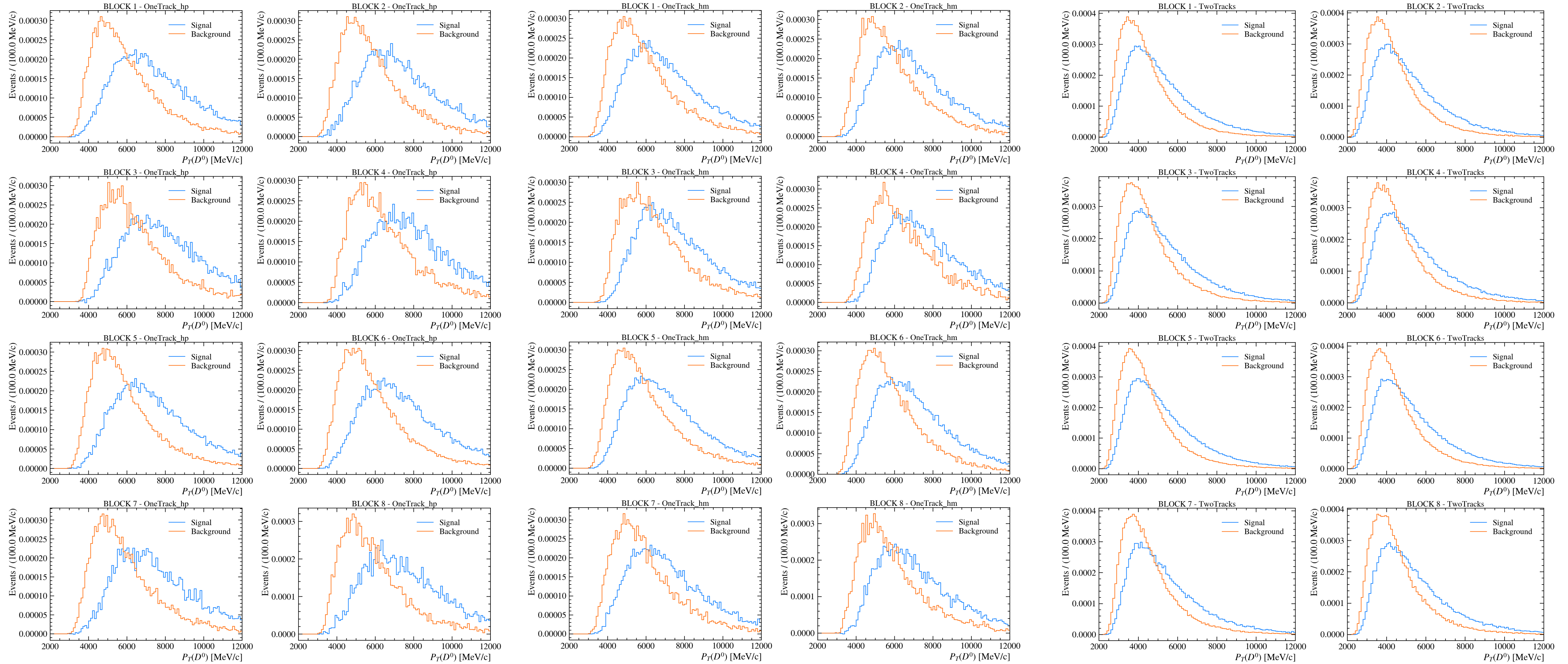
Thank you for your attention

Backup

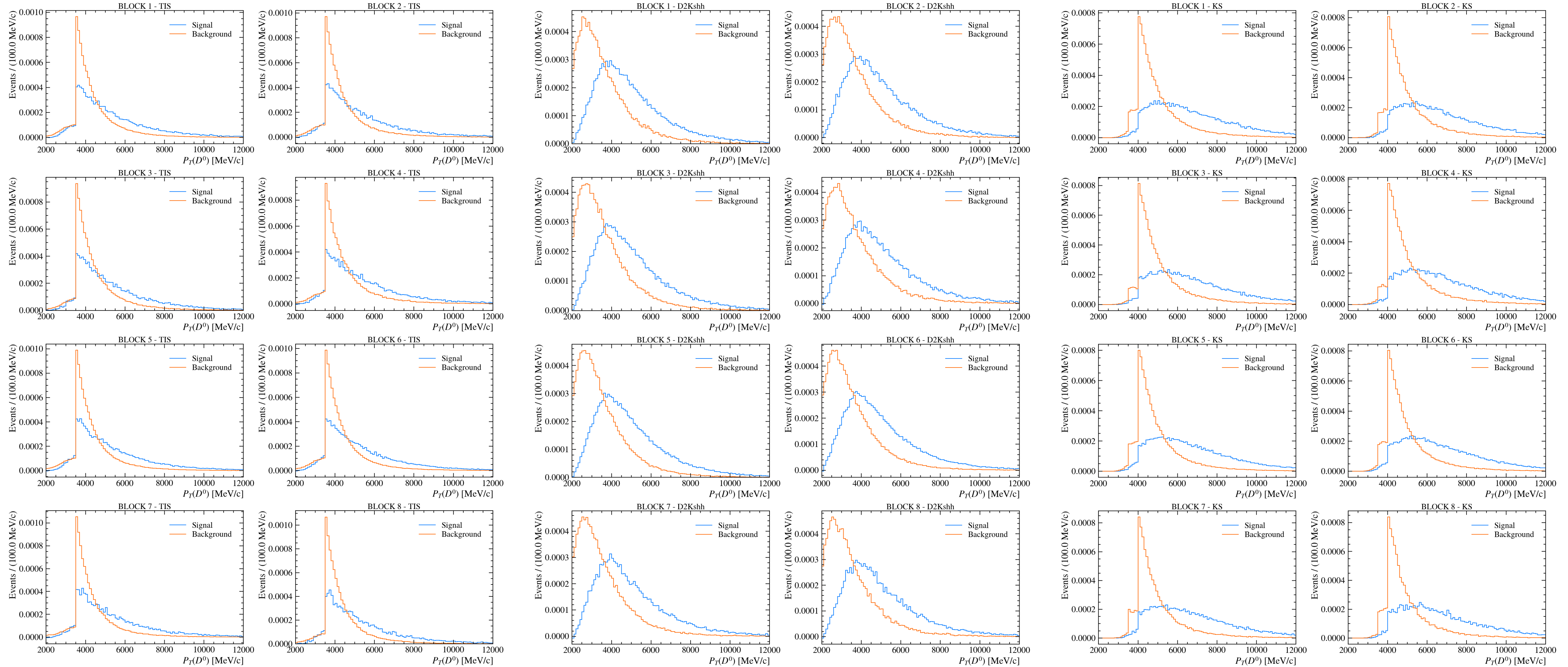
$p_T(D^0)$



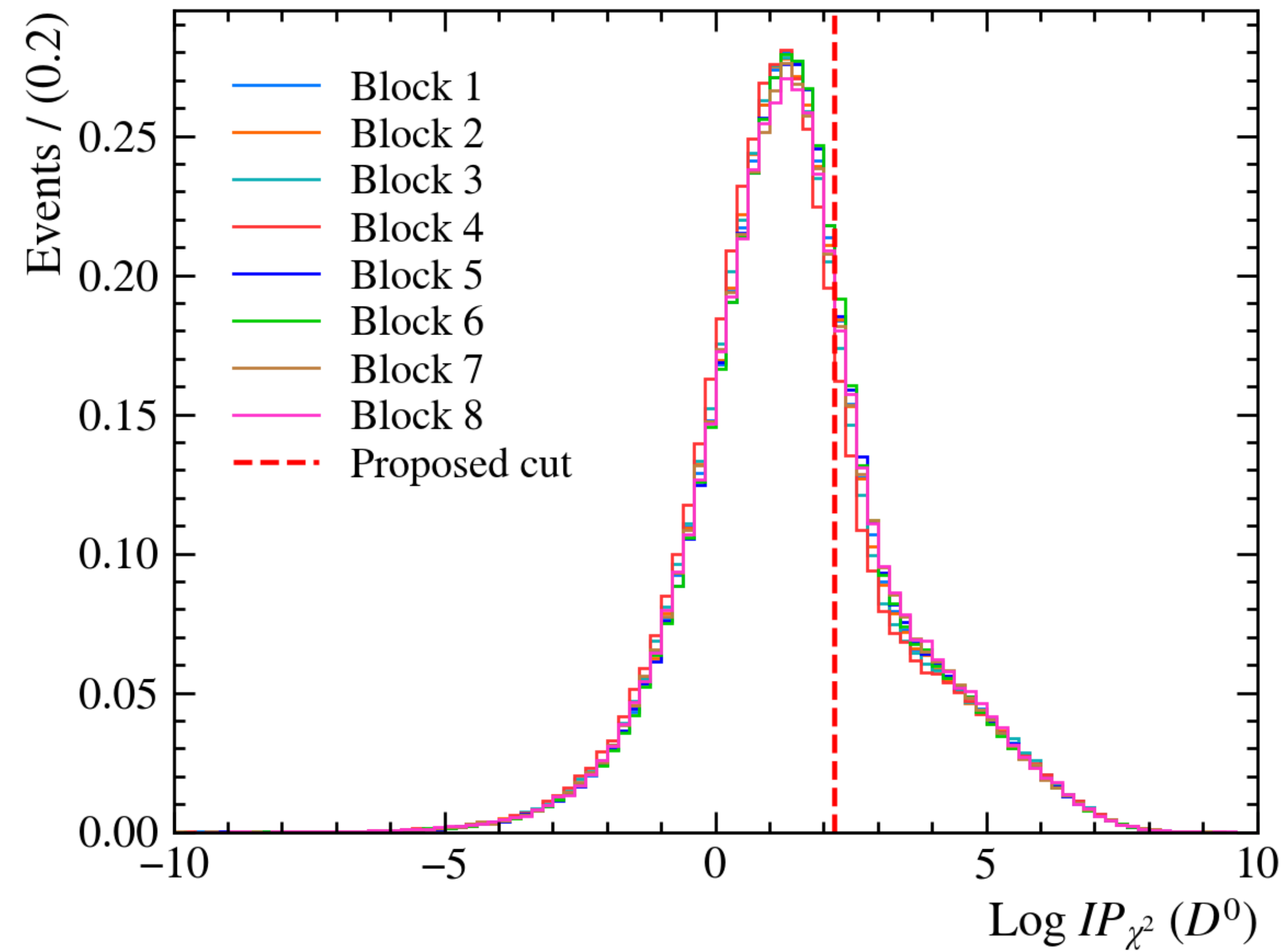
$p_T(D^0)$



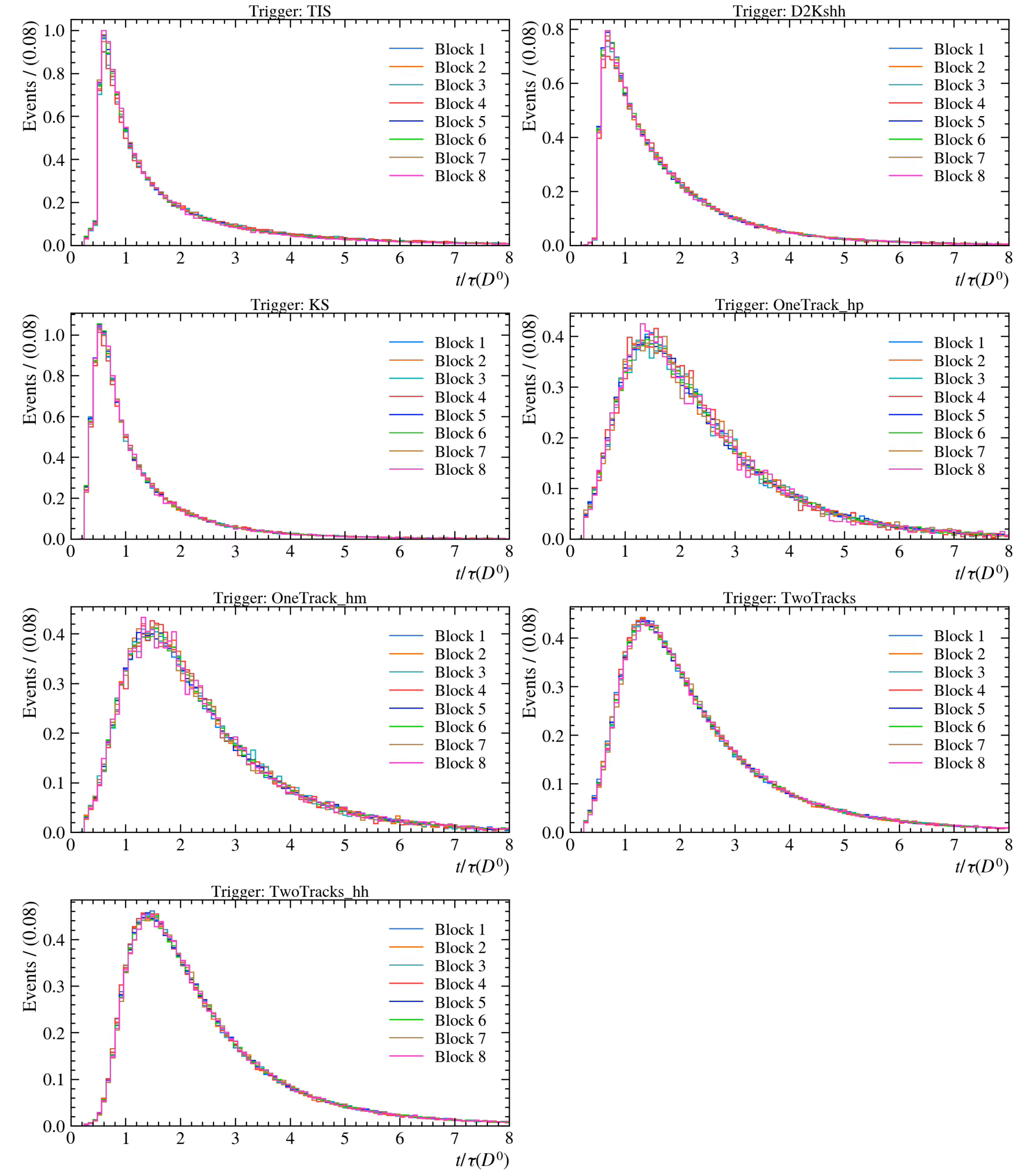
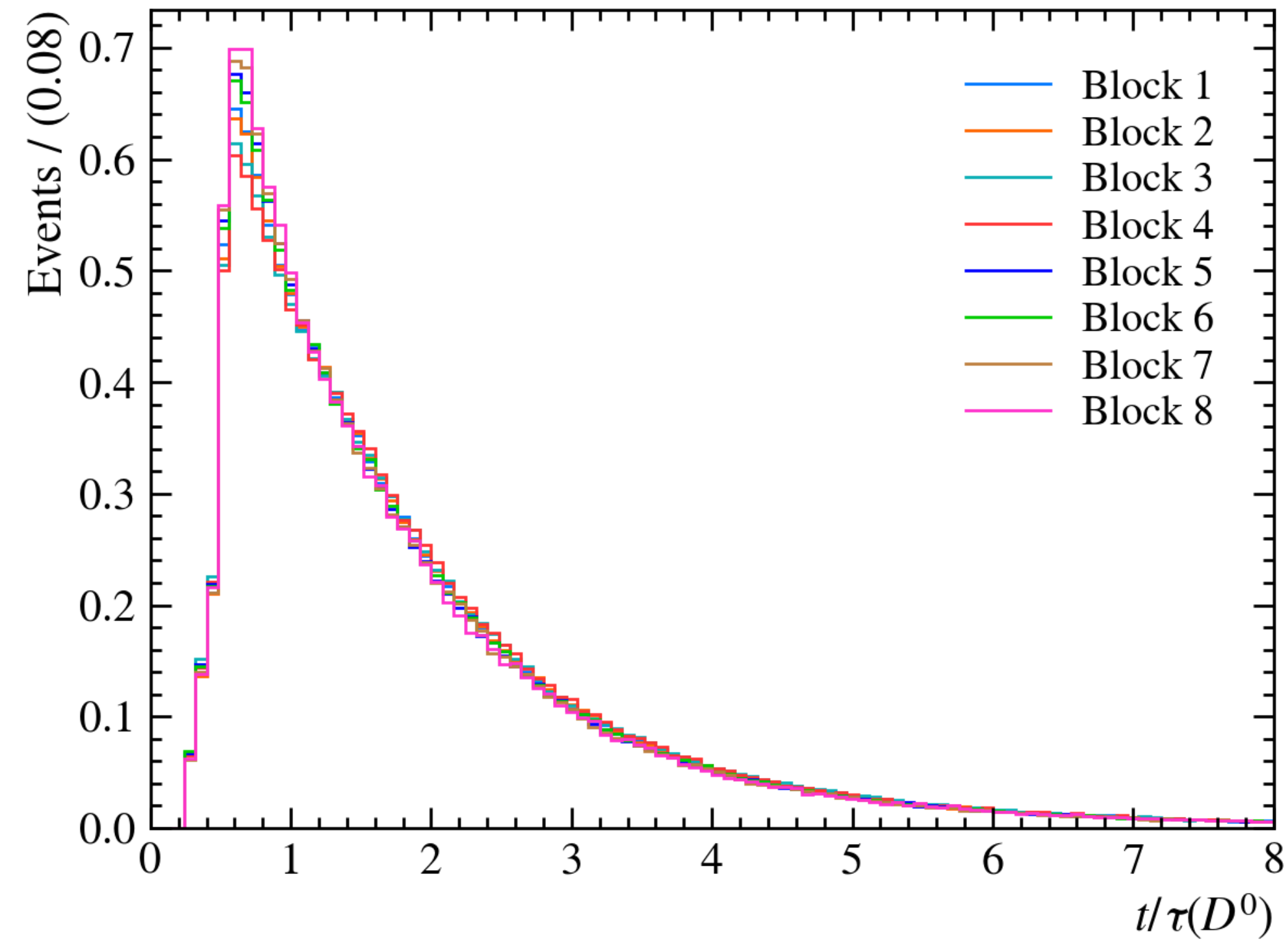
$p_T(D^0)$



$\log(IP\chi^2(D^0))$



$$t/\tau$$



Efficiency Maps (II)

Practical Implementation

- Data binned in $(\vec{\Omega}, t)$ with variable bin widths
- Finer bins at low decay times to capture rapid efficiency changes

$$\epsilon_{ijk} = \frac{\frac{n_{ijk}}{\sum_l n_{ijl}}}{\frac{\sum_{l,m} n_{lmk}}{\sum_{l,m,n} n_{lmn}}}$$

- i, j, k bins of $m_{\pi^+\pi^-}^2$, $|\cos\theta_{\pi^+\pi^-}|$, decay-time
- l, m, n indicate summation over the entire $m_{\pi^+\pi^-}^2$, $|\cos\theta_{\pi^+\pi^-}|$ and t range
- Then corrected to that accounts for mixing, assuming specific values of y and strong phases δ : $\epsilon_{y,\delta}(t | \vec{\Omega})$

Efficiency Maps (III)

- To properly account for mixing, it is necessary to **remove the effect of mixing** when building the weights
- This is achieved by correcting the data using the ratio: $\frac{\varepsilon_{\text{data}}(t | \vec{\Omega})}{f_{y,\delta}(t | \vec{\Omega})}$
- Repeating the original calculation $\epsilon_{ijk} = \frac{\frac{n_{ijk}}{\sum_l n_{ijl}}}{\frac{\sum_{l,m} n_{lmk}}{\sum_{l,m,n} n_{lmn}}}$ with entries weighted by: $\frac{1}{f_{y,\delta}(t | \vec{\Omega})}$
- The result is a **correction function** that accounts for mixing, assuming specific values of y and strong phases δ : $\varepsilon_{y,\delta}(t | \vec{\Omega})$
- These $\varepsilon_{y,\delta}(t | \vec{\Omega})$ are used to construct correction factors for the ratios of fitted yields in each Dalitz and decay-time bin

2025 vs 2024

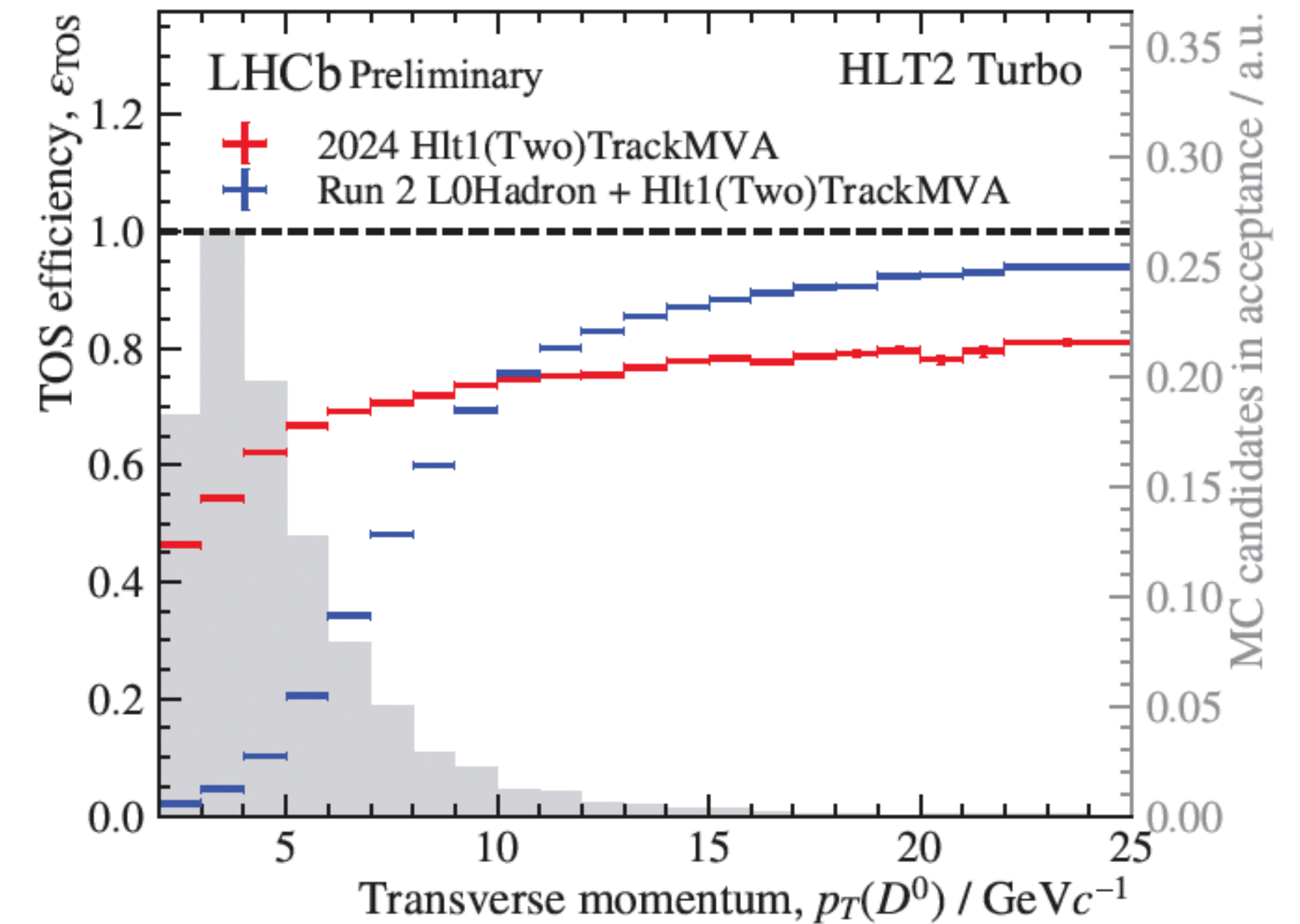
- Comparing 2025 data from s25c1 with 2024 data from s24c4, since they have the same $\mu \sim 5.3$

Data	Lumi (pb ⁻¹)		OneTrackMVA	TwoTracksMVA	D2Kshh	KS	TIS
MD	s25c1 359	LL	827254 ± 1405	1865682 ± 2072	855762 ± 1474	662107 ± 1304	461950 ± 1365
			1523058 ± 1931	3660205 ± 2810	1510928 ± 1834	1236102 ± 1765	897573 ± 1925
	s24c4 717.7	DD	1056735 ± 1400	2182209 ± 2135	22569 ± 198	17682 ± 196	540685 ± 976
			1171289 ± 1500	2606830 ± 2337	34060 ± 211	114126 ± 538	644636 ± 1533
MU	s25c1 658	LL	1532064 ± 1990	3446050 ± 2860	1541683 ± 1910	1249487 ± 1781	891057 ± 2008
			878312 ± 1403	2121200 ± 2173	868819 ± 1362	713746 ± 1335	526476 ± 1478
	s24c4 417.6	DD	1939167 ± 1967	3985785 ± 2863	38150 ± 253	31162 ± 261	1054181 ± 2073
			673808 ± 1168	1500036 ± 1752	20090 ± 215	64553 ± 481	373641 ± 1268

Run 3 LHCb Prospects

LHCb-FIGURE-2024-030

- Combined HLT1 (Two) TrackMVA TOS efficiencies in D decays to light hadrons, computed in bins of B transverse momentum in 2024 data
- For comparison, the combined TOS efficiencies of L0Hadron and HLT1TrackMVA / HLT1TwoTrackMVA calculated in Run 2 (from [2019 JINST 14 P04013](#))
- Generator-level distributions of $p_T(D)$ for MC events within the LHCb acceptance in grey
- At lower $p_T(D)$ efficiencies in 2024 data are significantly higher than those of Run 2, whilst at higher $p_T(D)$ the reverse is true
- The latter is driven by differences in tracking algorithms between HLT1 and HLT2 in 2024, wherein higher proportions of tracks found in HLT2 are not found in HLT1 at higher $p_T(D)$
- In Run1+Run2, efficiency at low momentum was gained by triggering on tracks not belonging to the signal candidate



TOS efficiencies in $D^0 \rightarrow K^- \pi^+$