Time-dependent amplitude-model analysis of $D^0 \to K_S^0 \pi^+ \pi^-$ at LHCb

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Outline

- > Motivation
- > The LHCb experiment
- > Analysis strategy
- > Amplitude model
- > GPU fitting
- > Selection
- > Conclusion and outlook

Motivation

Decay-time dependent amplitude-model analysis of self-conjugate $D^0 \to K_S^0 \pi^+ \pi^-$ decays:

> Access to charm mixing parameters x_D and y_D

> Measure indirect CP violation via $|q/p|$ and $\phi = arg(p, q)$

> Expected sensitivities at $\mathcal{L}_{\text{int}} = 3\,\text{fb}^{-1}$ (2011 and 2012 data set)

- 0.23% for x_D and 0.17% for y_D [LHCb2013]
- 0.2 for $|q/p|$ and 11.7° for ϕ [LHCb2013]

BaBar results for $\mathcal{L} = 468.5\,\mathrm{fb}^{-1}$ [BaBar2010]

> $D^0 \to K_S^0\pi^+\pi^-$ from prompt $D^{*+} \to D^0\pi^+ \; + \; cc$ decays

> Yield ~541k, purity 98.5%

> Amplitude model

- P- and D-wave (8 resonances): relativistic Breit-Wigner
- $\pi^+\pi^-$ S-wave: K-matrix
- $K_S^0\pi^\pm$ S-wave: LASS

> Combined with $D^0 \to K_S^0K^+K^-$: yield: ~80k, purity: 99.2%

$D^0 \to K_S^0\pi^+\pi^-$

$$x_D = (0.26 \pm 0.24)\,\%$$

$$y_D = (0.60 \pm 0.21)\,\%$$

$D^0 \to K_S^0K^+K^-$

$$x_D = (-1.36 \pm 0.92)\,\%$$

$$y_D = (0.44 \pm 0.57)\,\%$$

Combined

$$x_D = (0.16 \pm 0.23 \pm 0.12 \pm 0.08)\,\%$$

$$y_D = (0.57 \pm 0.20 \pm 0.13 \pm 0.07)\,\%$$

Belle results for $\mathcal{L} = 921\,\mathrm{fb}^{-1}$ [Belle2013]

> $D^0 \to K_S^0 \pi^+ \pi^-$ from prompt $D^{*+} \to D^0 \pi^+ + cc$ decays

> Yield ~1.23M, purity 95.6%

> Amplitude model

- P- and D-wave (12 resonances): relativistic Breit-Wigner
- $\pi^+\pi^-$ S-wave: K-matrix
- $K_S^0 \pi^\pm$ S-wave: LASS

Preliminary results

No CP violation

$$x_D = (0.56 \pm 0.19 \,^{+0.03}_{-0.09} \,^{+0.06}_{-0.09})\,\%$$

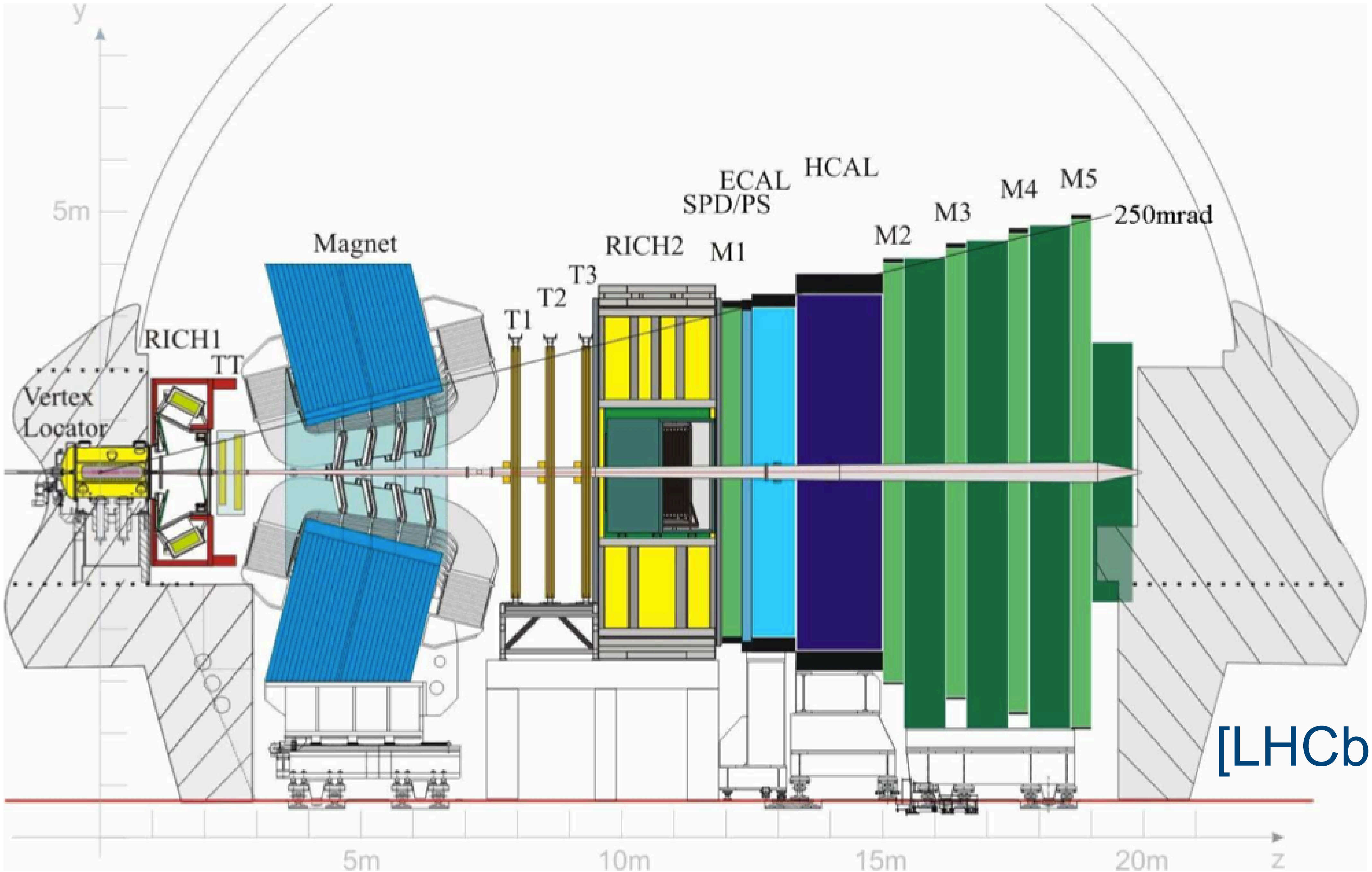
$$y_D = (0.30 \pm 0.15 \,^{+0.04}_{-0.05} \,^{+0.03}_{-0.06})\,\%$$

No direct CP violation

$$|q/p| = (0.90 \,^{+0.16}_{-0.15} \,^{+0.05}_{-0.04} \,^{+0.06}_{-0.05})$$

$$\phi = arg(p,q) = (-6 \pm 11 \,^{+3}_{-3} \,^{+3}_{-4})^\circ$$

The LHCb experiment: Detector



[LHCb2008]

> K_S^0-meson decays

- inside Vertex Locator: long tracks $\rightarrow K_S^0\,(\mathrm{LL})$
- outside Vertex Locator: downstream track $\rightarrow K_S^0\,(\mathrm{DD})$

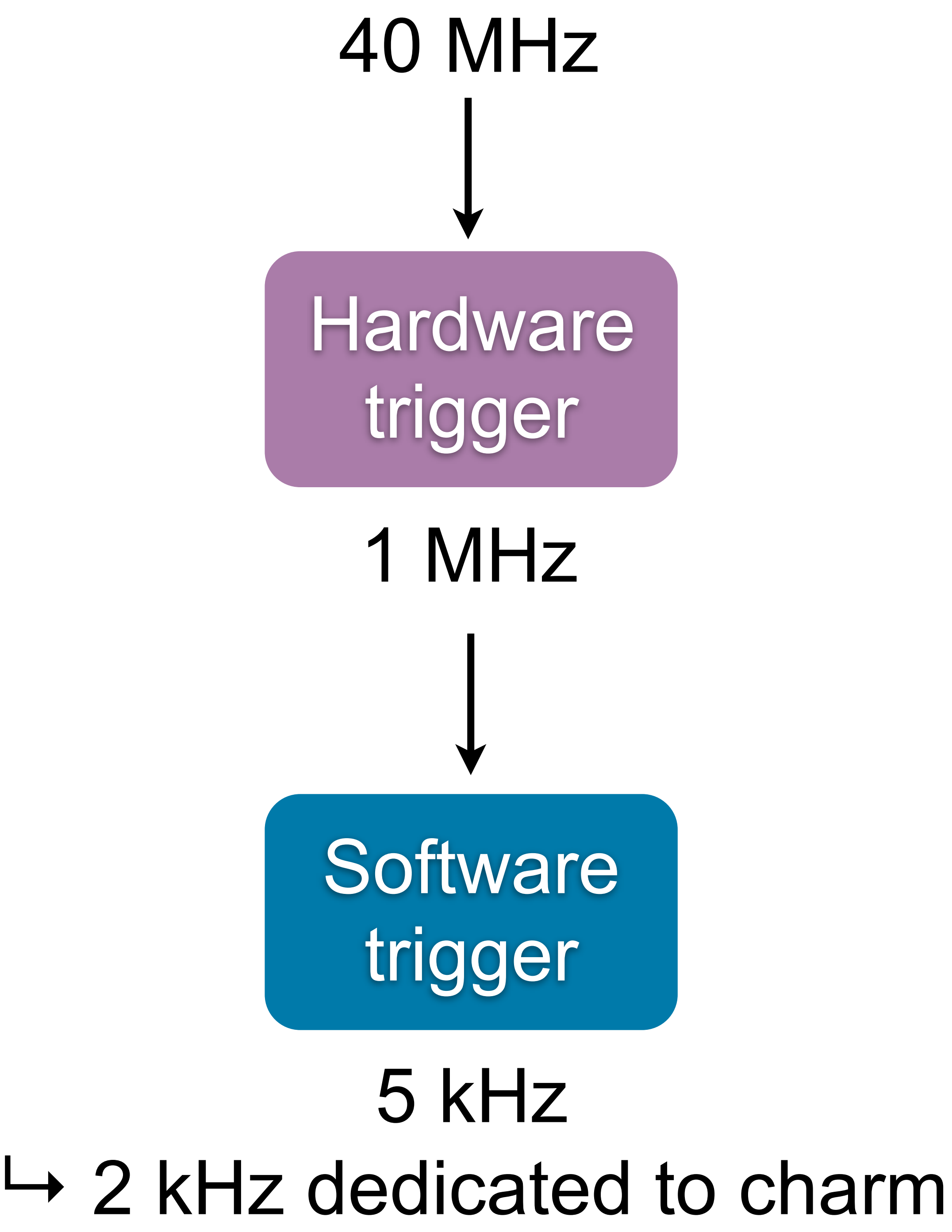
The LHCb experiment: Trigger

> Hardware trigger

- Muon and Dimuon: transverse momentum
- Hadron, Photon, Electron: transverse energy

> Software-based trigger

- Momentum
- Transverse momentum
- Track fit χ^2/dof
- Impact parameter
- ...

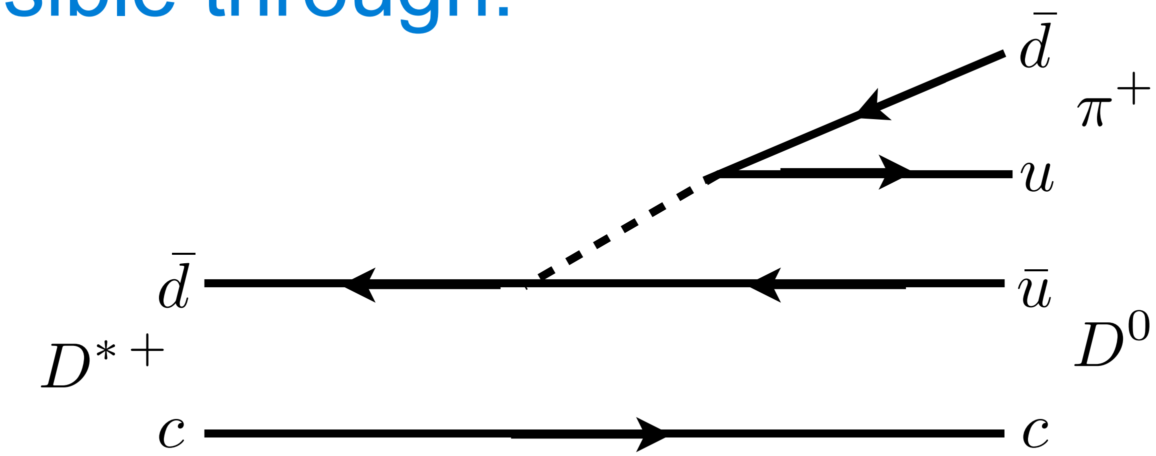


Analysis strategy

$D^0 \to K_S^0\pi^+\pi^-$ accessible through:

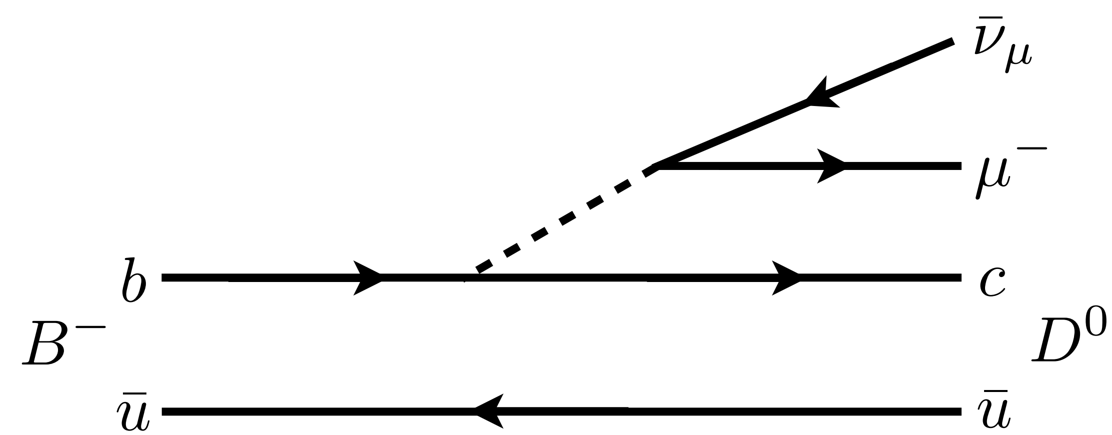
> Prompt $D^{*+} \to D^0\pi^+ + cc$

- High yield
- Access only to high D^0 decay times



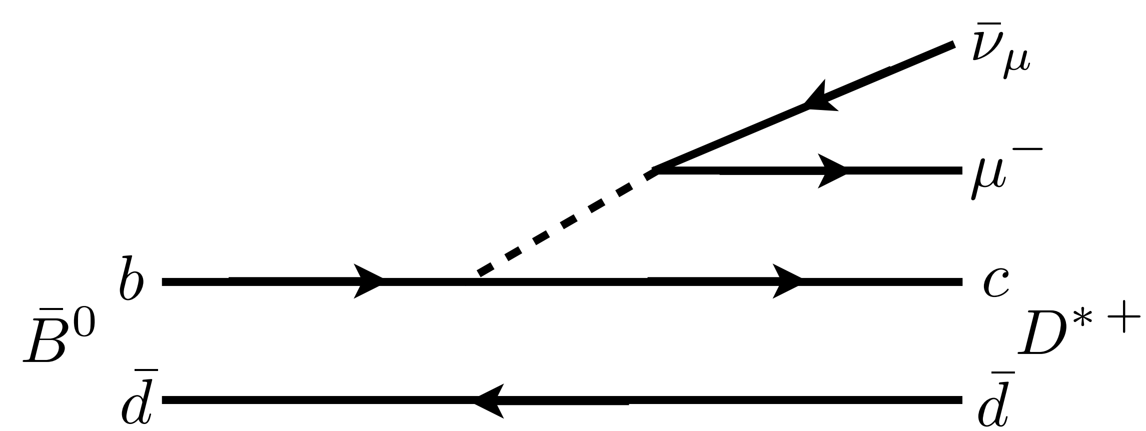
> Semileptonic $B^- \to D^0\mu^-\bar{\nu}_\mu + cc$

- High trigger efficiency
- Access to all D^0 decay times



> Semileptonic $\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu + cc$

- High trigger efficiency
- Clean signature
- Access to all D^0 decay times



Analysis strategy

> Prompt $D^{*+} \to D^0\pi^+ + cc$

> Semileptonic $B^- \to D^0\mu^-\bar{\nu}_\mu + cc$ $\leftarrow$ this talk

> Semileptonic $\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu + cc$

$\Rightarrow$ Fit to all sub samples for combined 2011 and 2012 data set corresponding to $\mathcal{L} = 3\,\mathrm{fb}^{-1}$

$\Rightarrow$ Mixing and indirect CP violation parameters

Analysis strategy

Analysis in progress
→ only LHCb simulation shown

> Prompt $D^{*+} \to D^0\pi^+ + cc$

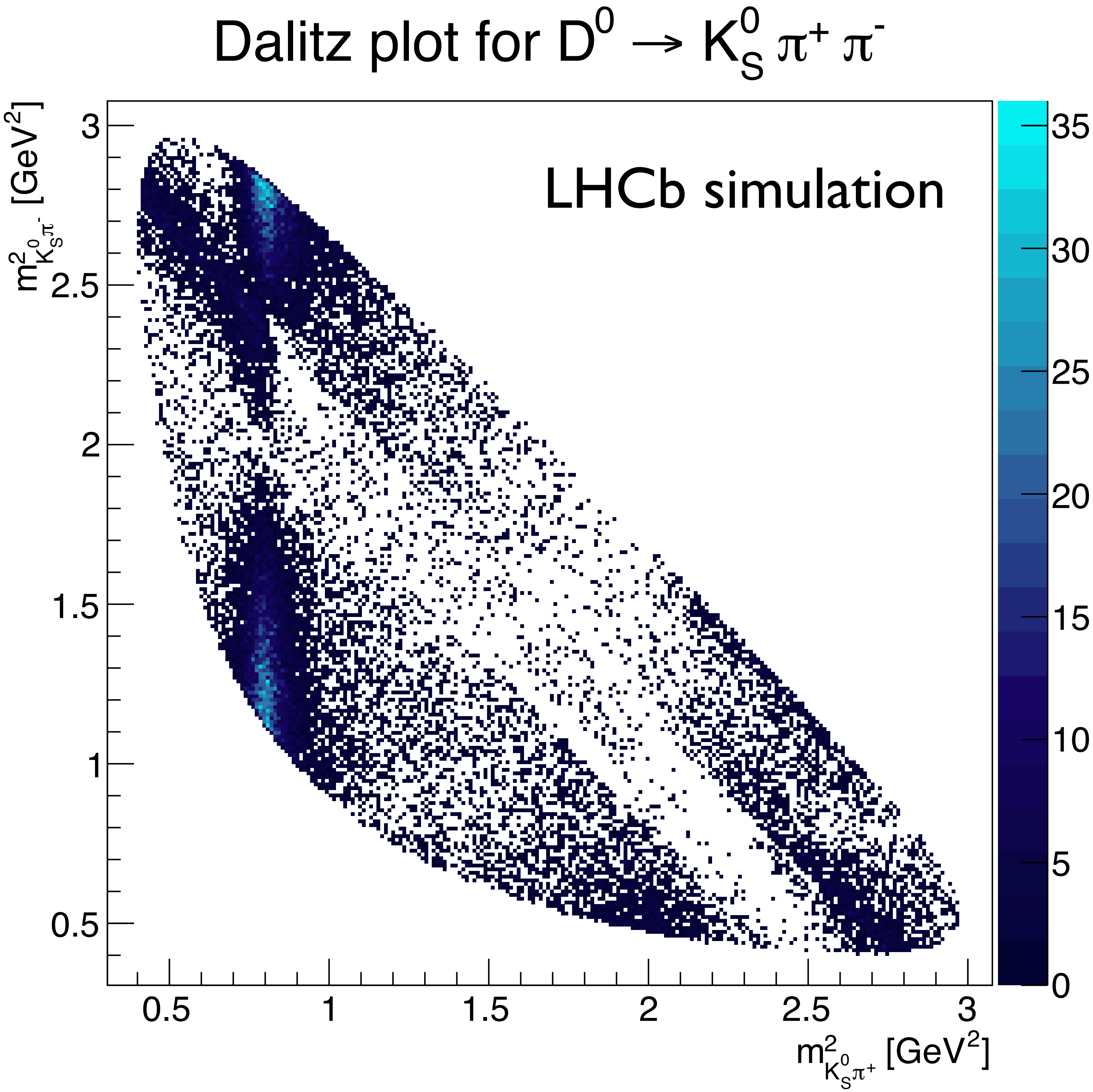
> Semileptonic $B^- \to D^0\mu^-\bar{\nu}_\mu + cc$ ← this talk

> Semileptonic $\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu + cc$

⇒ Fit to all sub samples for combined 2011 and 2012 data set corresponding to $\mathcal{L} = 3\,\mathrm{fb}^{-1}$

⇒ Mixing and indirect CP violation parameters

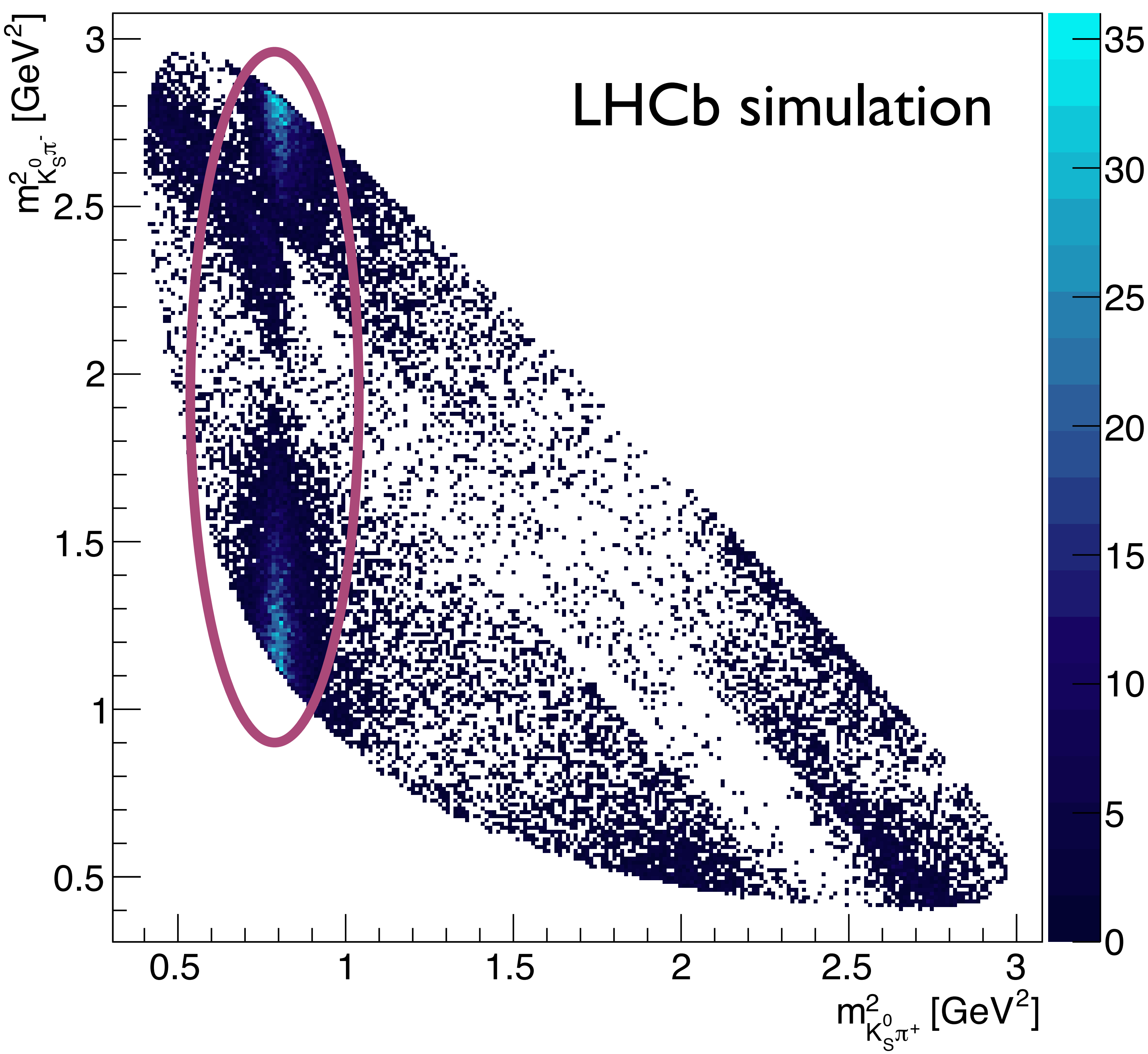
Amplitude model



Generator-level Monte-Carlo

Amplitude model

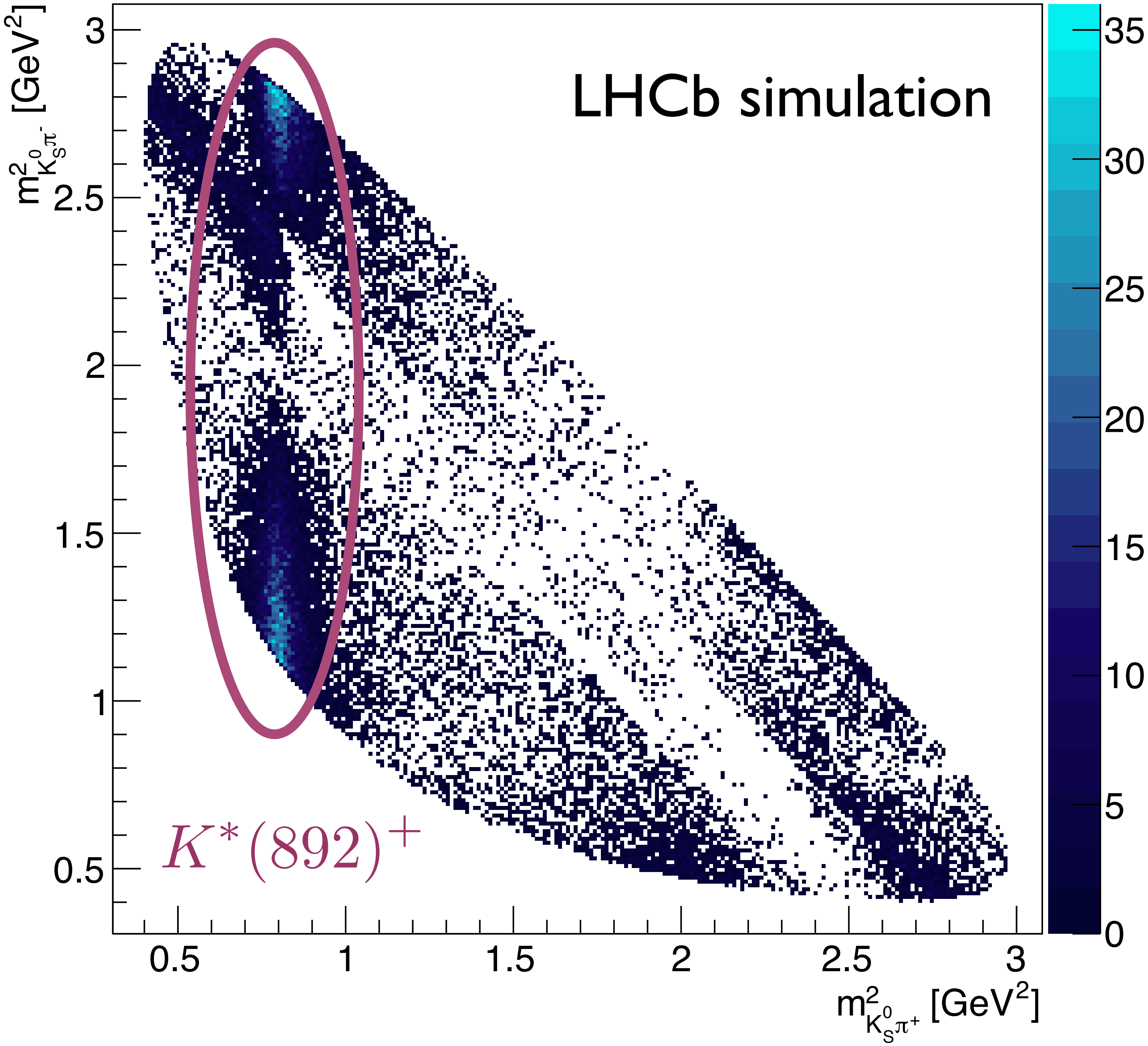
Dalitz plot for $D^0 \to K^0_S \pi^+ \pi^-$



Generator-level Monte-Carlo

Amplitude model

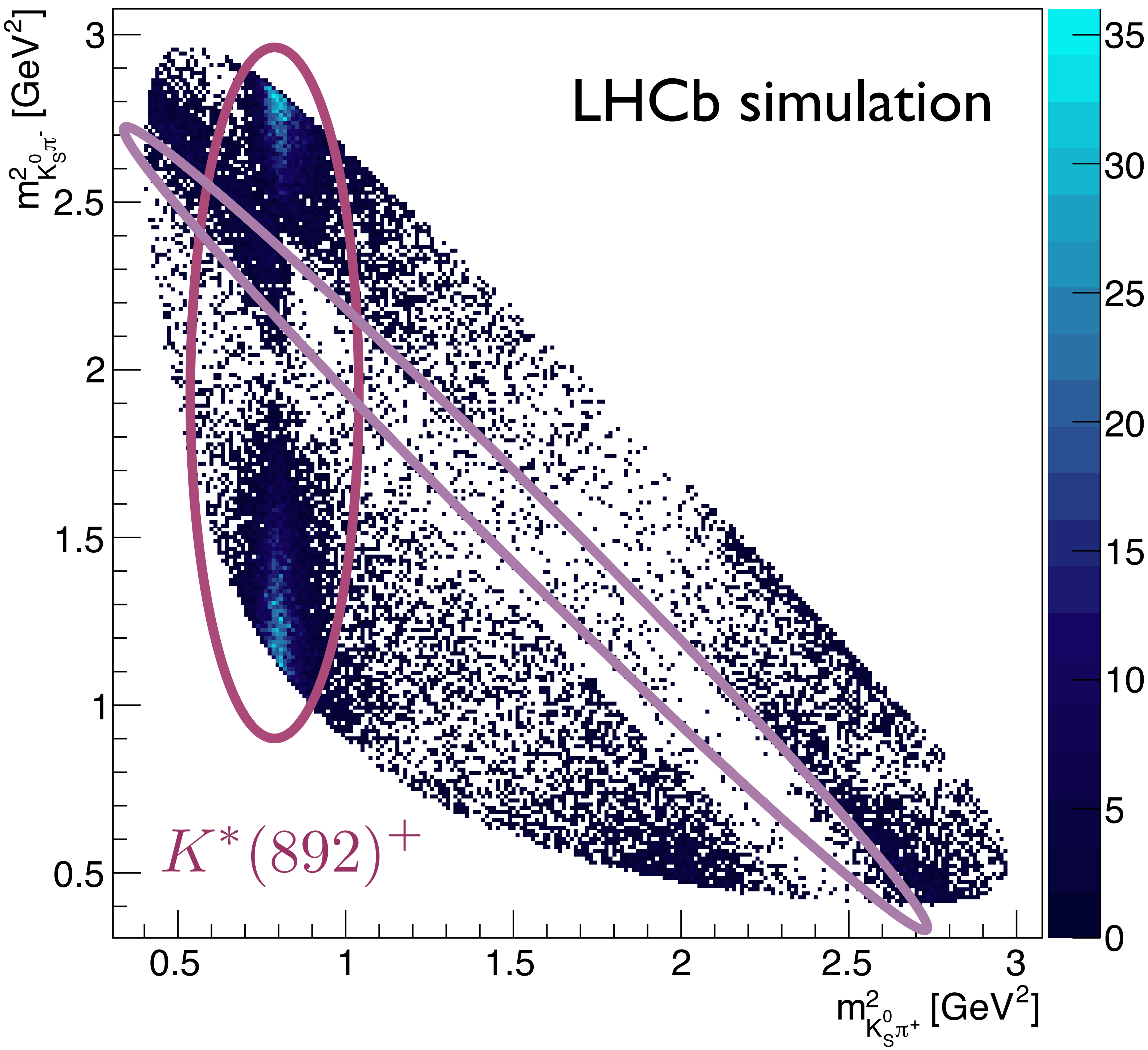
Dalitz plot for $D^0 \to K^0_S \pi^+ \pi^-$



Generator-level Monte-Carlo

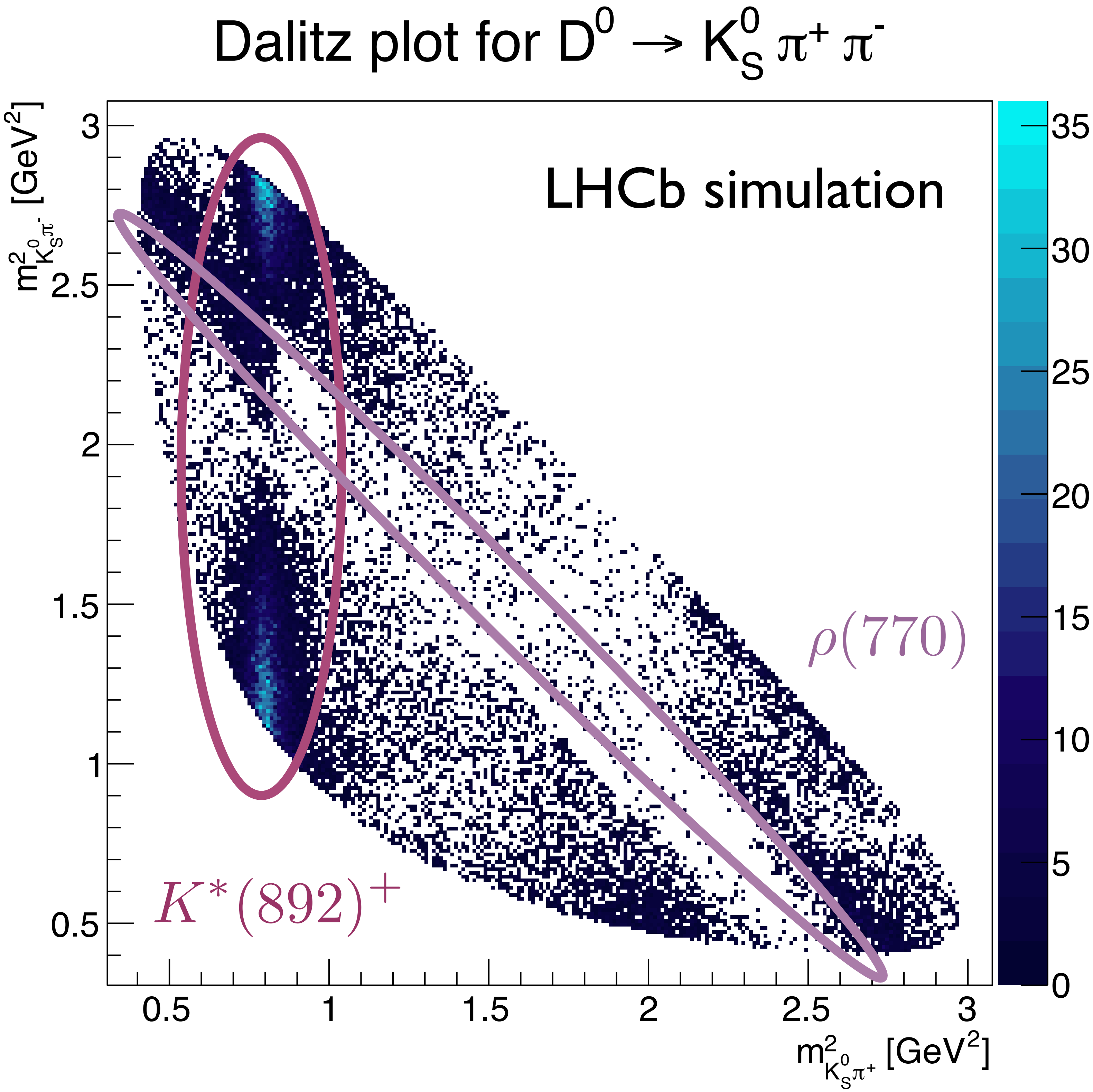
Amplitude model

Dalitz plot for $D^0 \rightarrow K^0_S \pi^+ \pi^-$



Generator-level Monte-Carlo

Amplitude model



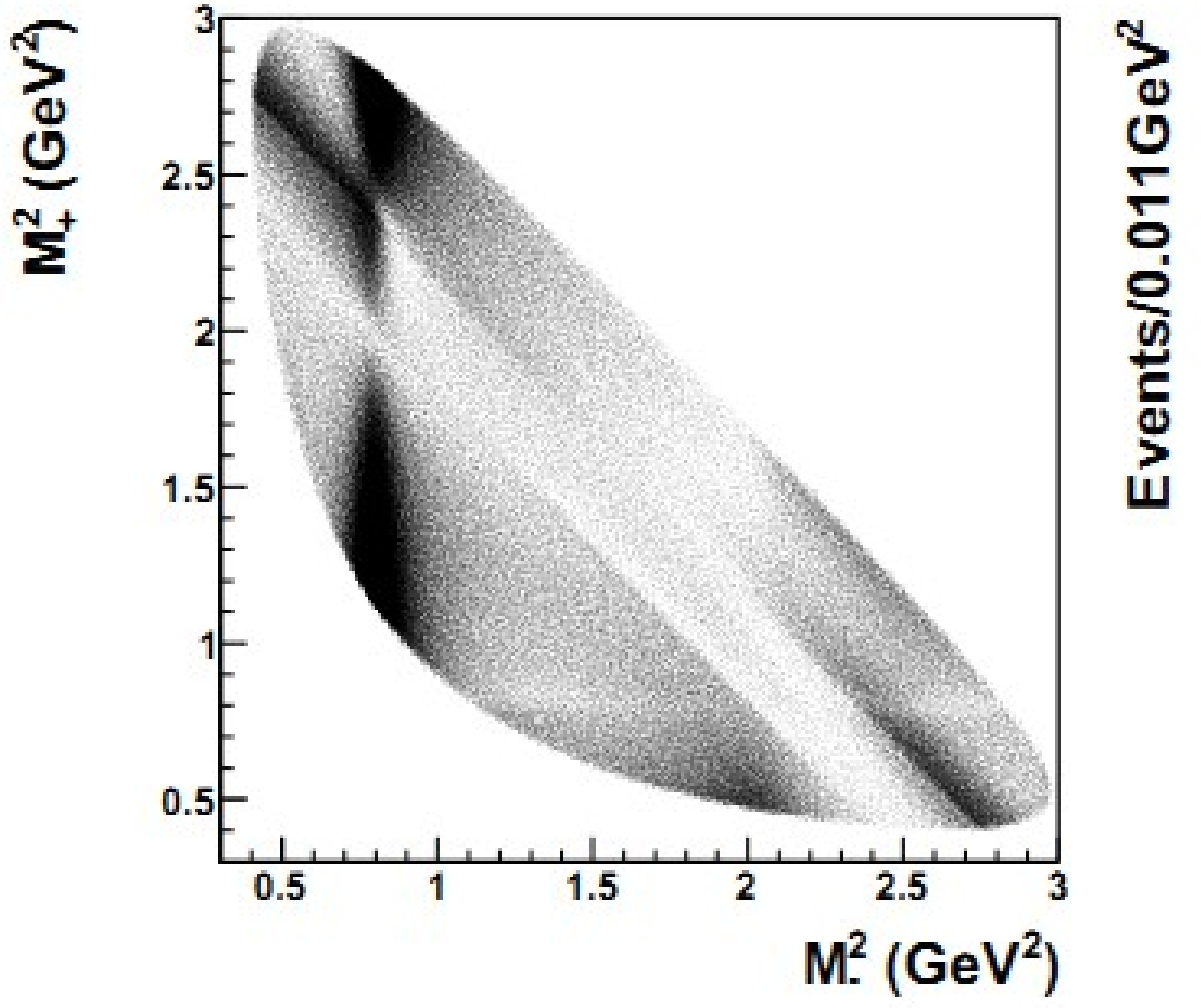
Generator-level Monte-Carlo

Amplitude model

Resonance	Mass [GeV/c^2]	Width [GeV/c^2]	Spin	Parametrisation
		$\pi^+\pi^-$		
$\rho(770)$	0.775	0.480	1	Gounaris-Sakurai
$\pi^+\pi^-$ S-wave			0	K-matrix
$f_2(1270)$	1.275	0.270	2	Relativistic Breit-Wigner
$\omega(782)$	0.783	0.180	1	Relativistic Breit-Wigner
		$K_S^0\pi^-$		
$K^*(892)^-$	0.892	0.230	1	Relativistic Breit-Wigner
$K_0^*(1430)^-$	1.430	0.600	0	LASS
$K_2^*(1430)^-$	1.426	0.700	2	Relativistic Breit-Wigner
$K^*(1680)^-$	1.717	0.700	1	Relativistic Breit-Wigner
		$K_S^0\pi^+$		
$K^*(892)^+$	0.892	0.230	1	Relativistic Breit-Wigner
$K_0^*(1430)^+$	1.430	0.600	0	LASS
$K_2^*(1430)^+$	1.426	0.700	2	Relativistic Breit-Wigner
		Non-resonant $K_S^0\pi^+\pi^-$		

Masses and widths taken from LHCb data base, Model [Babar2010]

Amplitude model



[Belle2013]

> Possible further resonances to be included [Belle2013]

- $\pi^+\pi^-$: $\rho(1450)$
- $K^0_S\pi^-$: $K^*(1410)^-$
- $K^0_S\pi^+$: $K^*(1410)^+$, $K^*(1680)^+$

> Introduction of artificial structure in non-resonant contribution

GPU fitting

> GPUs provide significant speed-up compared to CPUs

- Speed-up of factor 100-150 realistic

> Parallel fitting framework GooFit [GooFit] implemented in CUDA

- Maximum likelihood fits
- Time-dependent amplitude-model analyses

> Amplitude models available in GooFit (excerpt)

- Relativistic Breit-Wigner
- Gounaris-Sakurai
- LASS parametrisation
- Ongoing work on implementation of K-matrix

Selection

1. Trigger

2. LHCb wide preselection

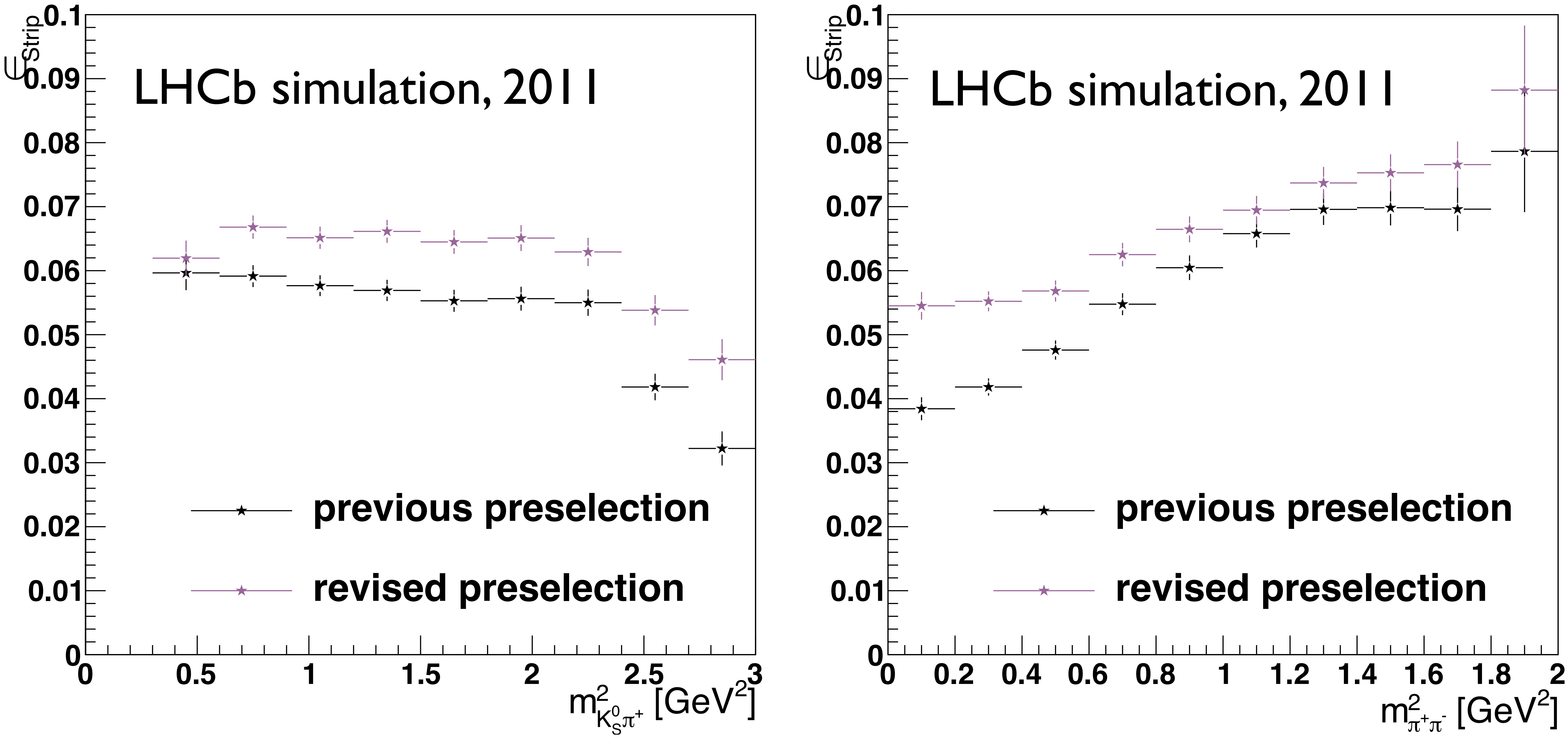
3. Cut-based offline selection

4. Multivariate classifier relying on data
   - NeuroBayes
   - Boosted Decision Tree in TMVA
     ⇒ Similar performance but implementation of BDT simpler

     ⇒ BDT chosen

Selection: Preselection efficiency

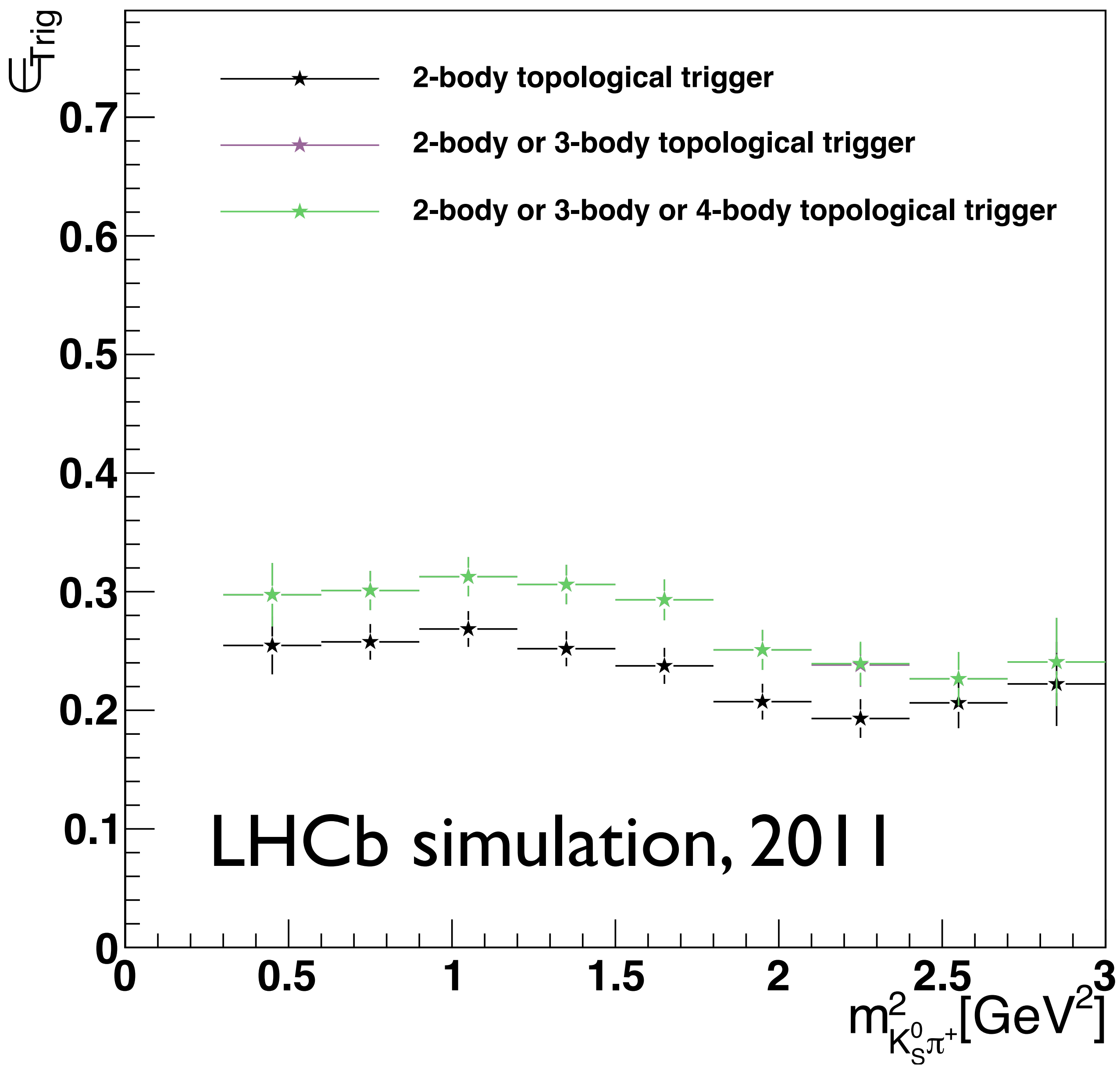
$$D^0 \to K_S^0\,(\mathrm{DD})\,\pi^+\pi^-$$

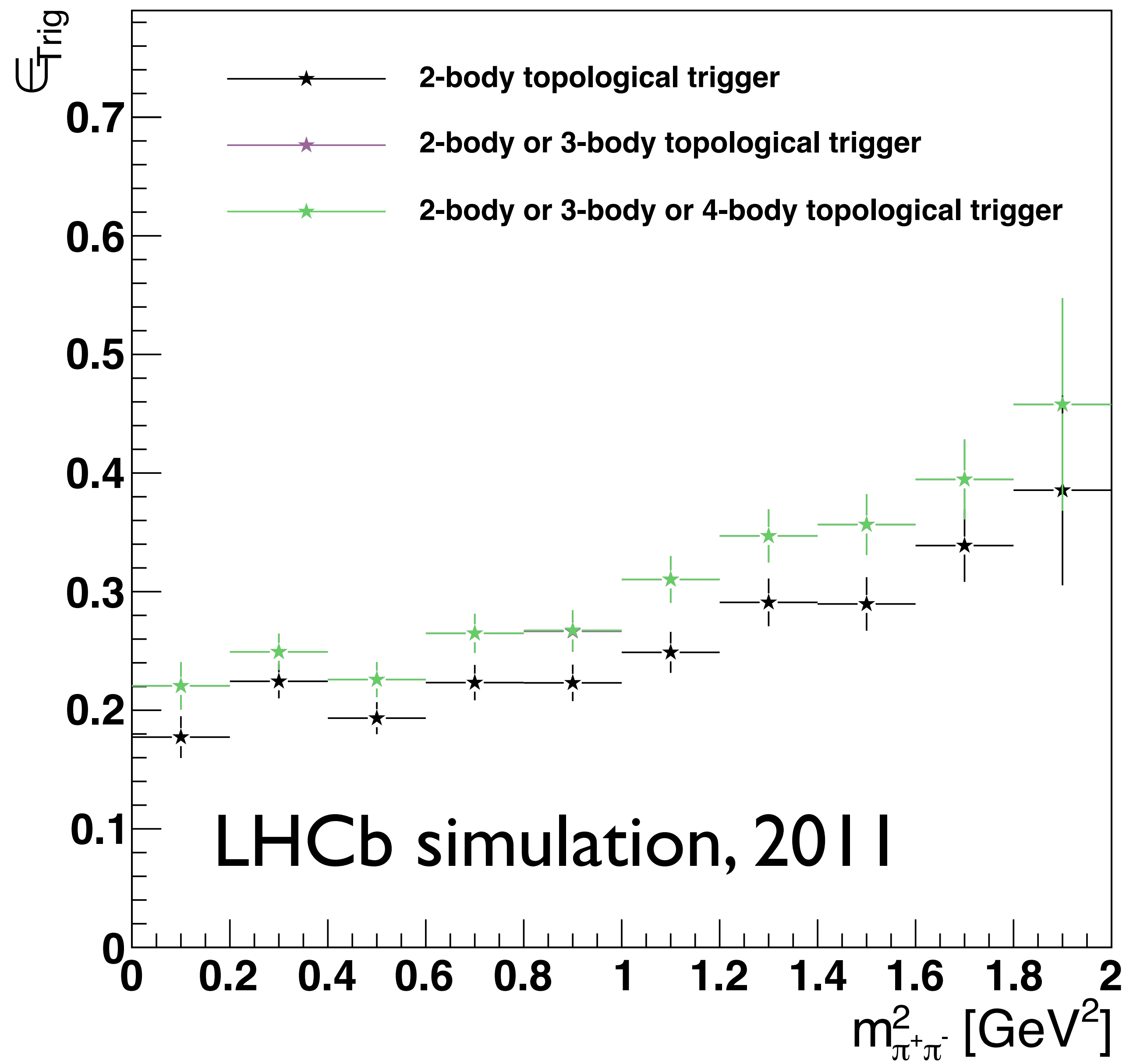


Effect of efficiencies on acceptance correction?

Selection: Relative trigger efficiency

$$D^0 \to K_S^0\,(\mathrm{DD})\,\pi^+\pi^-$$





Variation in efficiencies ⇒ large acceptance corrections

Conclusion and outlook

> Analysis of $D^0 \to K_S^0\pi^+\pi^-$ decays to measure $x_D, y_D, |q/p|, \phi$
- current world-averages from HFAG allowing CP violation [HFAG]

- $x_D = (0.49^{+0.17}_{-0.18})\,\%$ and $y_D = (0.74 \pm 0.09)\,\%$
- $|q/p| = 0.69^{+0.17}_{-0.14}$ and $\phi = (-29.6^{+8.9}_{-7.5})\,^\circ$

> Selection of $D^0 \to K_S^0\pi^+\pi^-$ from $B^- \to D^0\mu^-\bar{\nu}_\mu + cc$ finalised

> Next steps:

- Acceptance studies
- Fitting Toy Monte-Carlo → validate fitter

> Also perform analysis for $D^0 \to K_S^0 K^+ K^-$

Thank you.

Literature

[LHCb2008] The LHCb detector at the LHC, The LHCb collaboration, J. Instrum. 3 S08005 (2008)

[Belle2013] $D^0 - \bar{D}^0$ mixing and CP violation in $D^0 \to K_S hh$ measurements, L. Li on behalf of the Belle collaboration, Charm 2013, https://indico.hep.manchester.ac.uk/contributionDisplay.py?sessionId=19&contribId=24&confId=4022

[Babar2010] Measurement of $D^0 - \bar{D}^0$ mixing parameters using $D^0 \to K_S^0 \pi^+ \pi^-$ and $D^0 \to K_S^0 K^+ K^-$ decays, The Babar collaboration, Phys. Rev. Lett.105 (2010)

[LHCb2013] Implications of LHCb measurements and future prospects, The LHCb collaboration, EPJ C 73 (2013) 2373

[HFAG] http://www.slac.stanford.edu/xorg/hfag/charm/April13/results_mix+cpv.html

Backup

sPlot formalism

> sPlot formalism relies on maximisation of extended log-likelihood

$$\mathcal{L} = \sum_{e=1}^{N} \ln \left\{ \sum_{i=1}^{N_s} N_i f_i(y_e) \right\} - \sum_{i=1}^{N_s} N_i$$

- N - total number of events in data set
- N_s - number of species of events in the given data set
- N_i - average number of events expected for the i^{th} species
- $f_i(y_e)$ - value of the probability density function for the i^{th} species f_i at a set of discriminating variables y_e for event e

sPlot formalism

> Maximisation of extended log-likelihood

> sWeight for each event and each species

$$ {}_s\mathcal{P}_n(y_e) = \frac{\sum_{j=1}^{N_s} V_{nj} f_j(y_e)}{\sum_{k=1}^{N_s} N_k f_k(y_e)} \quad \text{with} \quad V_{nj}^{-1} = \frac{-\partial^2 \mathcal{L}}{\partial N_n \partial N_j} $$

> Reweighting signal + background distribution with

- signal sWeight $\rightarrow$ signal distribution
- background sWeight $\rightarrow$ background distribution

> See: M. Pvik, F. R. le Diberder. sPlot: a statistical tool to unfold data distributions. Nucl. Instrum. Meth. A 555, 2005.

sPlot formalism

> Signal + background distribution with prominent signal feature, e.g. mass distribution

> PDFs for signal and background → input in sWeights calculation

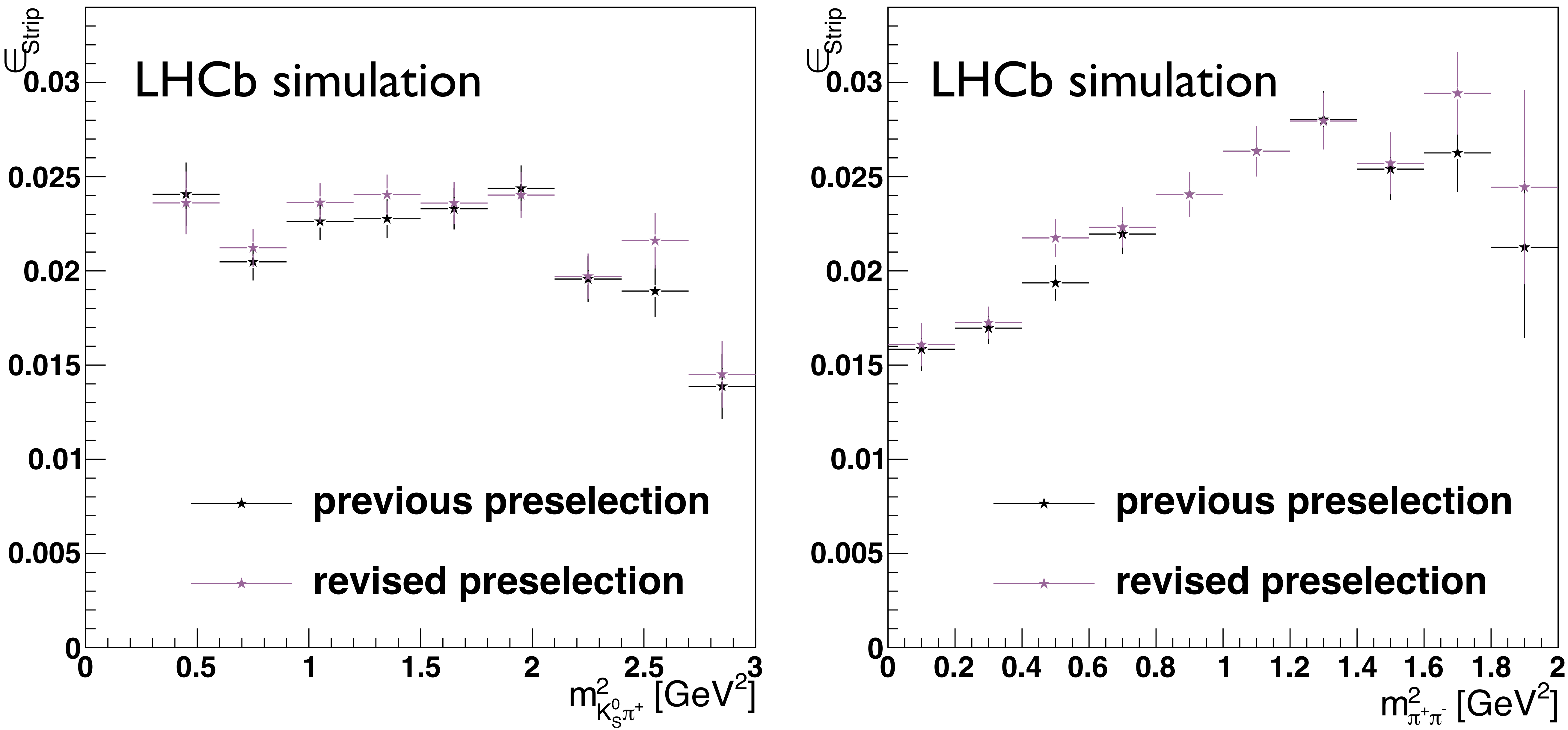
> Perform extended maximum likelihood fit to extract expected event yields for species → input in sWeights calculation

> Tools in ROOT and RooFit available to calculate sWeights

> Be careful with MVAs → sWeights might be negative

Selection: Preselection efficiency

$$D^0 \to K_S^0\,(\mathrm{LL})\,\pi^+\pi^-$$



Selection: Relative trigger efficiency

$$D^0 \to K_S^0\,(\mathrm{LL})\,\pi^+\pi^-$$