Discovering matter-antimatter asymmetries with GPUs

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on behalf of the LHCb collaboration

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LHCb

Outline

> Introduction and motivation

> Energy test for $D^0 \to \pi^+\pi^-\pi^0$ using CUDA and Thrust libraries

> Time-dependent amplitude analysis of $D^0 \to K_S^0\pi^+\pi^-$ with GooFit

> Summary

Introduction: Neutral meson mixing

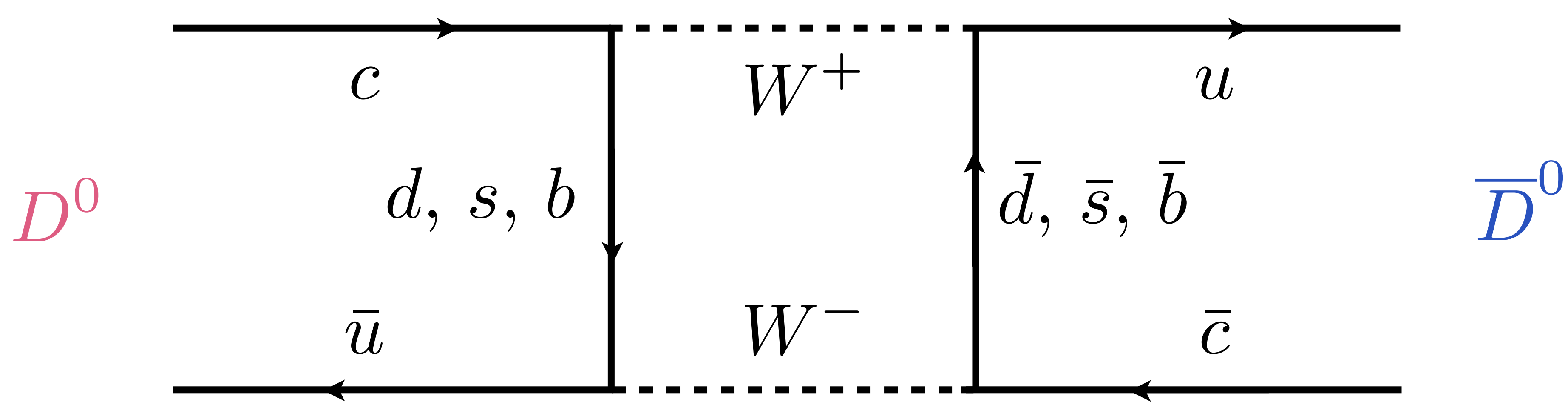
> Mass eigenstates of neutral charm meson system $|D_{1,2}\rangle$ have mass $m_{1,2}$ and width $\Gamma_{1,2}$

> $|D_{1,2}\rangle$ are linear combination of flavour eigenstates $|D^0\rangle$ and $|\overline{D}^0\rangle$

$$|D_{1,2}\rangle = p|D^0\rangle \pm q|\overline{D}^0\rangle$$

with $q, p \in \mathbb{C}$ satisfying $|q|^2 + |p|^2 = 1$

> $|D^0\rangle$ and $|\overline{D}^0\rangle$ subject to matter-antimatter transitions (mixing)

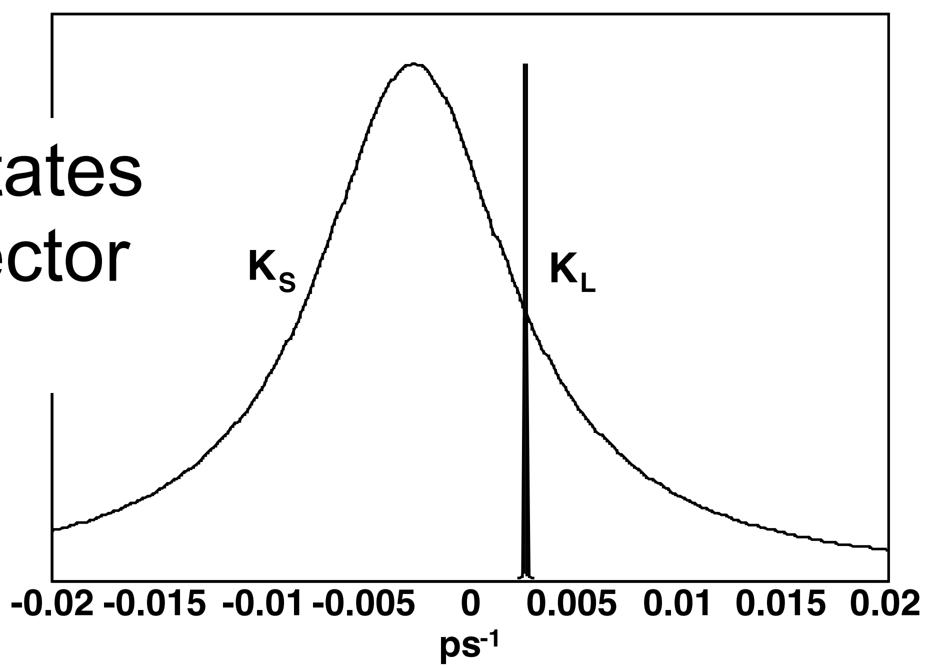


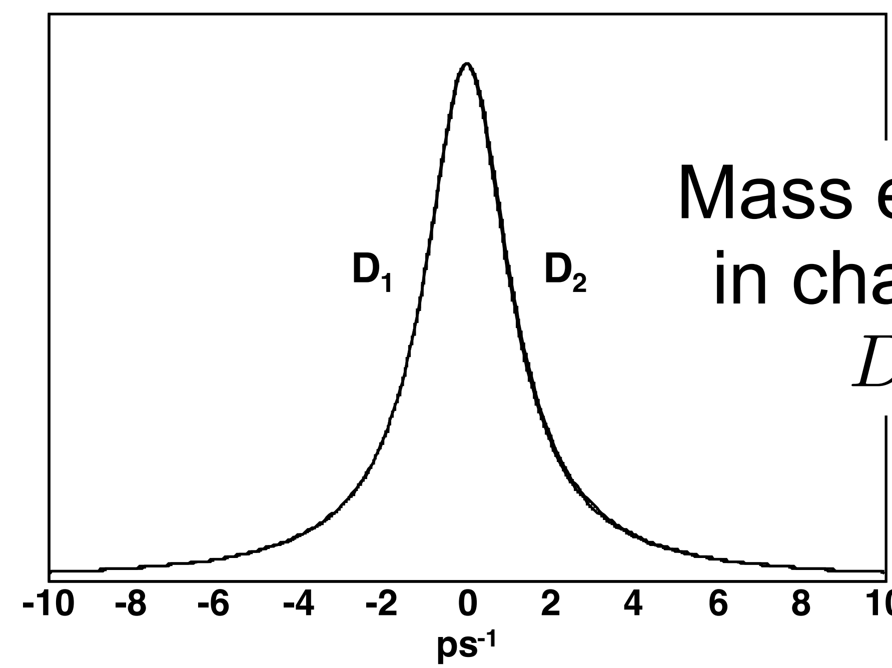
Introduction: Neutral meson mixing

$$|D_{1,2}\rangle = p|D^0\rangle \pm q|\overline{D}^0\rangle$$

- Mass difference $\Delta m \equiv m_2 - m_1$
- Width difference $\Delta\Gamma \equiv \Gamma_2 - \Gamma_1$
- Mixing parameters $x \equiv \Delta m/\Gamma$ and $y \equiv \Delta\Gamma/(2\Gamma)$

Mass eigenstates in strange sector $K_S,\ K_L$





Mass eigenstates in charm sector $D_1,\ D_2$

- Charm sector: Mass and width differences small ⇒ mixing small

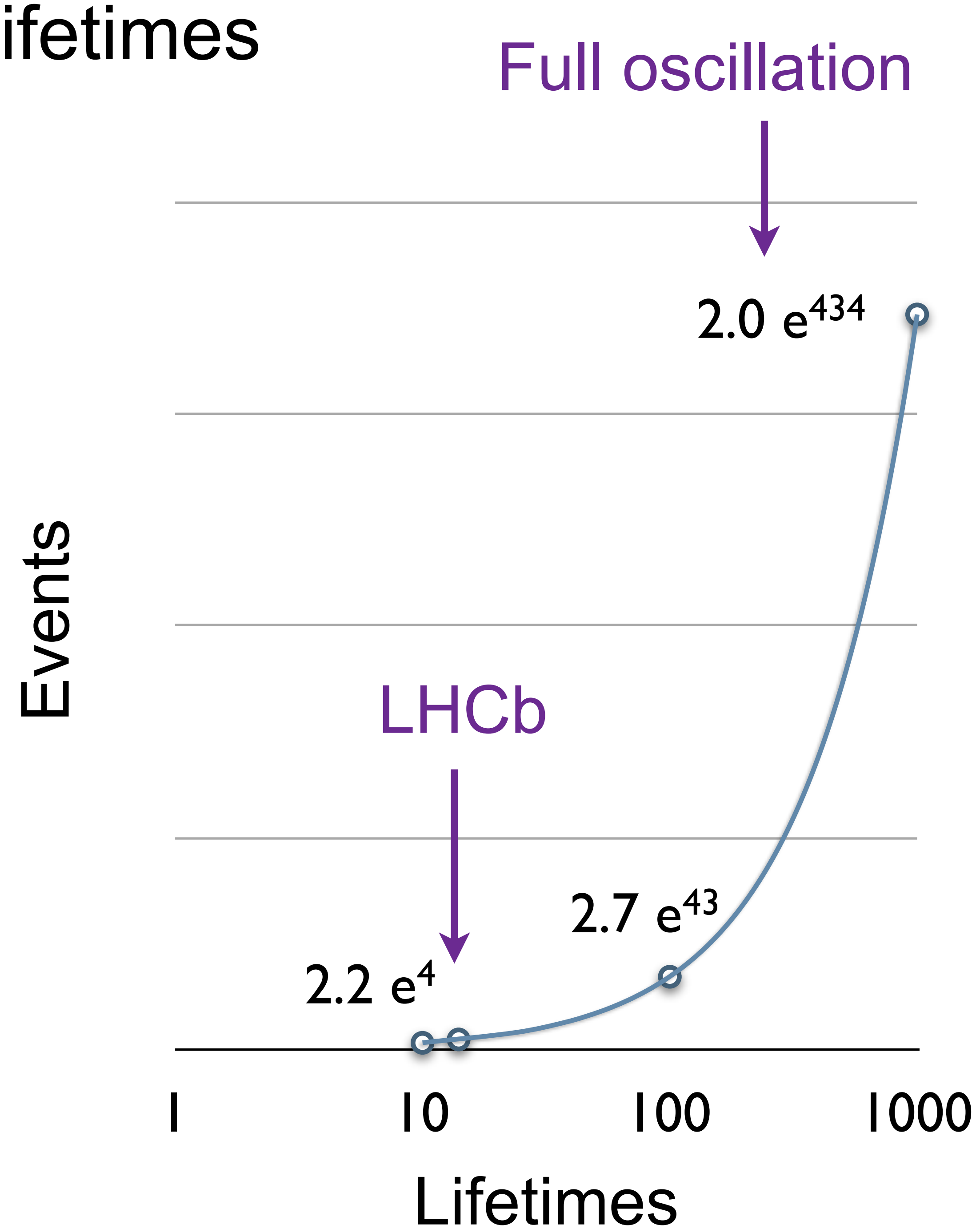
Plots taken from: Brief review of charm physics, M. Gersabeck, arXiv: 1207.2195 [hep-ex]

Introduction: Neutral meson mixing

> Charm mixing parameters small $\sim \mathcal{O}(10^{-3})$
  ↪ Full oscillation takes around 1000 lifetimes
  ↪ Large datasets required

> Datasets covering 1000 lifetimes
  e^{1000} events

> LHCb datasets for mixing and CPV analyses typically around 10^6 - 10^7 events
  - sufficient to determine mixing parameters



Introduction: CP violation

$$|D_{1,2}\rangle = p|D^0\rangle \pm q|\overline{D}^0\rangle$$

> $|D_{1,2}\rangle$ are CP eigenstates if $\mathcal{CP}|D_{1,2}\rangle = \pm|D_{1,2}\rangle$

> If $q \neq \pm p$, mass eigenstates are not CP eigenstates
↪ CP violation in mixing (indirect CPV)

> If amplitudes for $D^0 \to f$ and charge-conjugate $\overline{D}^0 \to \bar{f}$ differ
↪ CP violation in decay (direct CPV)

> Interference of CPV in mixing and decay possible

> No evidence for CP violation in charm sector[1].

[1]Averages of b-hadron, c-hadron, and tau-lepton properties as of early 2012, Y. Amhis et al., arXiv:1207.1158 and online update at http://www.slac.stanford.edu/xorg/hfag/

Motivation

> Searches for CPV in charm can be CPU-expensive and are performed on large datasets

- Energy test relies on evaluation of distances between events
- Time-dependent amplitude analysis uses minimisation of negative log-likelihood function

> Computation is the same for each event out of millions of events

↪ Parallelisable

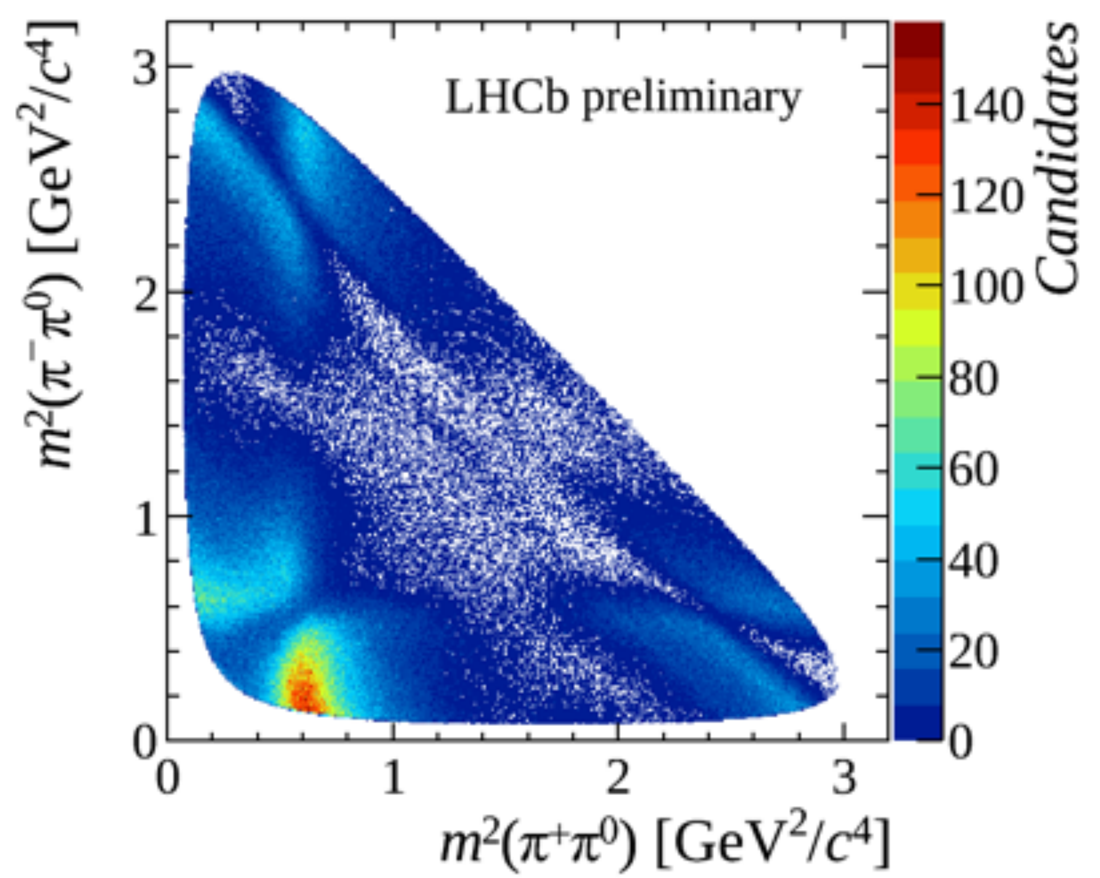
Massive parallelisation on GPUs renders analysis feasible

The analyses presented here use Nvidia GPUs at Ohio Supercomputer Centre and at Manchester University.

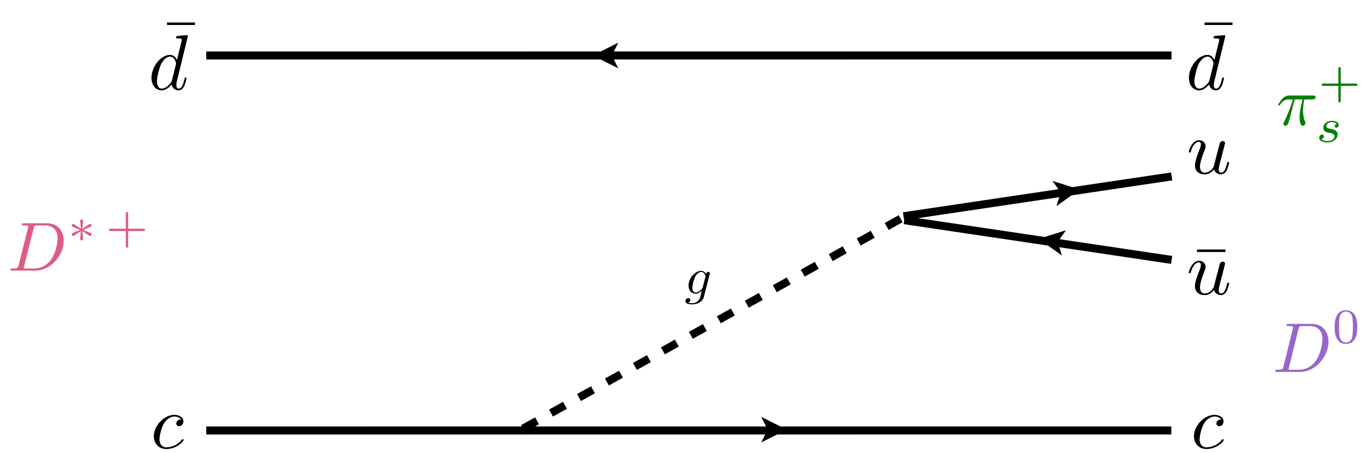
Energy test for $D^0 \rightarrow \pi^+\pi^-\pi^0$ using CUDA and Thrust libraries

Energy test: Method

LHCb-PAPER-2014-054



- Unbinned model-independent statistical method to search for time-integrated CPV in $D^0 \to \pi^+\pi^-\pi^0$ decays[1]
- Sensitive to local CP asymmetries across phase-space
- Comparsion of $D^0, \overline{D}^0$ samples of size $n, \bar{n}$
- Flavour samples are obtained by determining charge of soft pion π_s^+ of a $D^{*+} \to D^0\pi_s^+$ decay with $D^0 \to \pi^+\pi^-\pi^0$



[1]Observing CP Violation in Many-Body Decays, M. Williams, Phys. Rev. D84, 054015 (2011)

Energy test: Method

> Test statistic for two flavour samples of size $n, \bar{n}$ defined as

$$T \approx \sum_{i}^{n} \sum_{j>i}^{n} \frac{\psi(\Delta\vec{x}_{ij})}{n^2 - n} + \sum_{i}^{\bar{n}} \sum_{j>i}^{\bar{n}} \frac{\psi(\Delta\vec{x}_{ij})}{\bar{n}^2 - \bar{n}} - \sum_{i}^{n} \sum_{j}^{\bar{n}} \frac{\psi(\Delta\vec{x}_{ij})}{n\bar{n}}$$

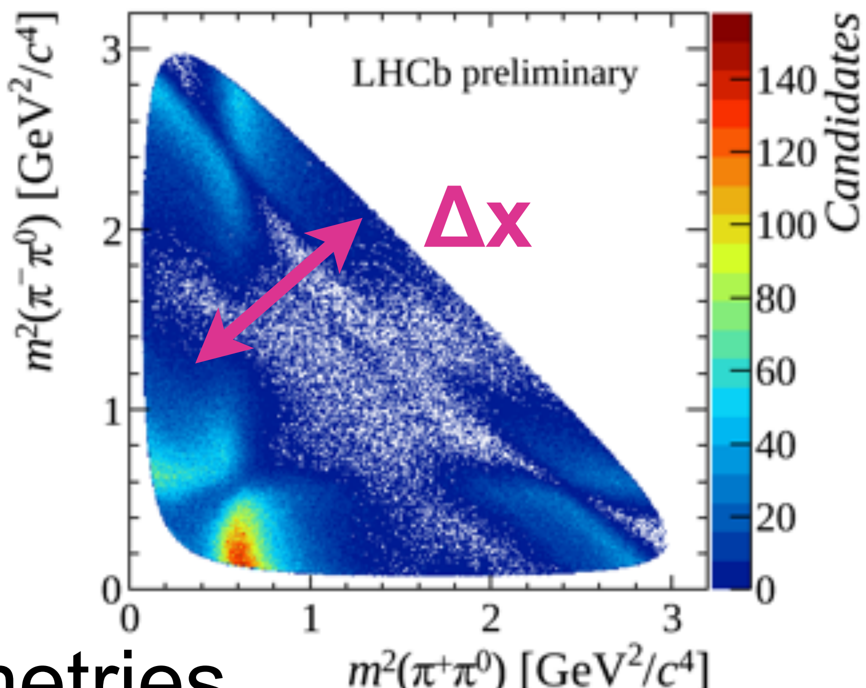
average distance in D^0 sample

average distance in $\overline{D}^0$ sample

average distance in mixed sample

$$\psi(\Delta\vec{x}_{ij}) = e^{-\Delta\vec{x}_{ij}{}^2/2\sigma^2}$$ - Gaussian metric function, σ tunable

$$\Delta\vec{x}_{ij} = |\vec{x}_i - \vec{x}_j|$$ - distance between two events i, j



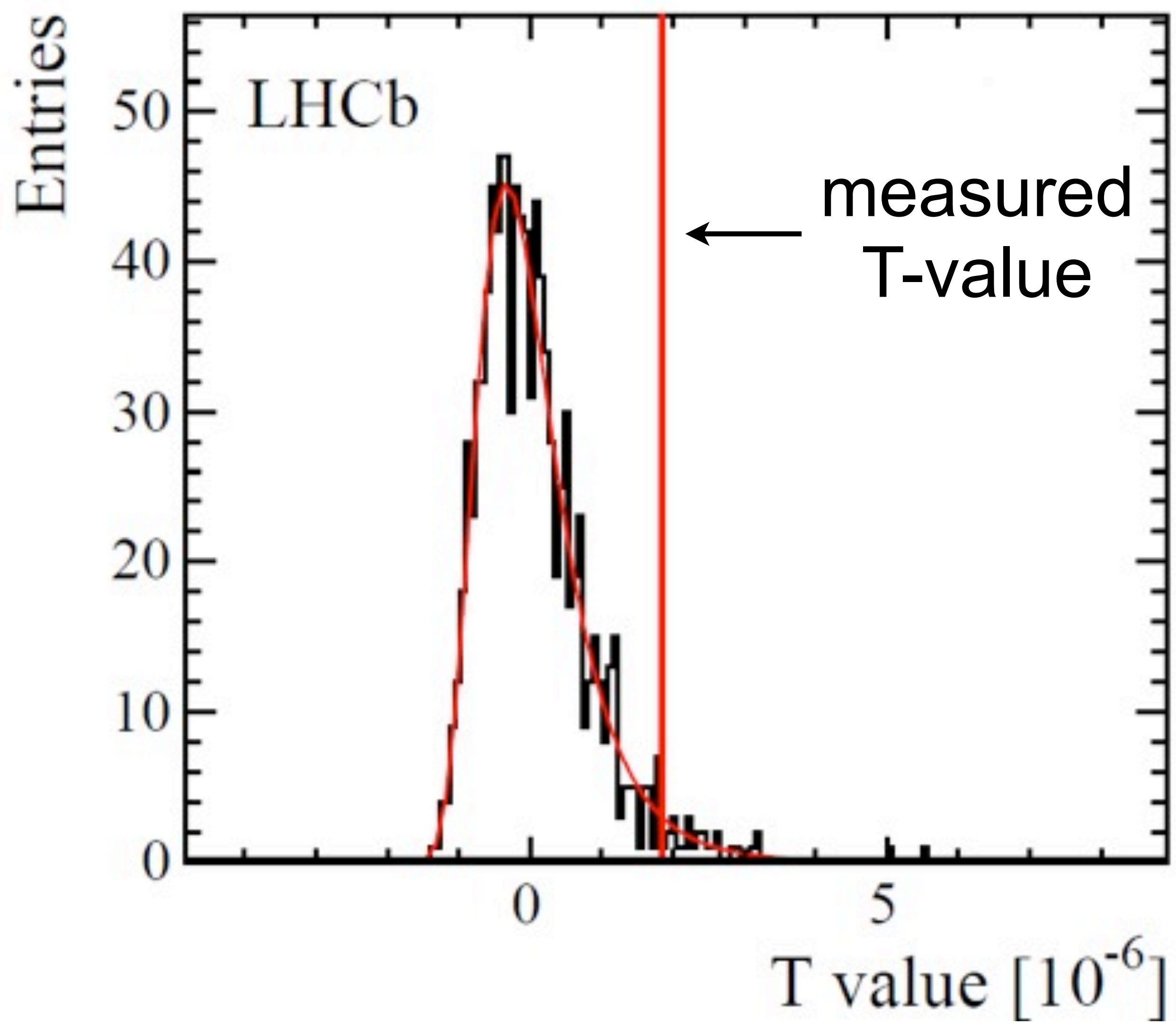
> T-value increases in case of large CP asymmetries

Energy test: Method

> Generation of permutation samples where the flavour of each event has been reassigned randomly
  ↪ no CPV samples

> Obtain distribution of T-values from permutation samples

> p-value for no CPV hypothesis is fraction of permutation T-values greater than measured T-value



Measured T-value (red vertical line) and T-value distribution of permutation samples for $\sigma = 0.3$ from LHCb-PAPER-2014-054

Energy test: Implementation

$$T \approx \sum_{i}^{n} \sum_{j>i}^{n} \frac{\psi\left(\Delta\vec{x}_{ij}\right)}{n^2 - n} + \sum_{i}^{\bar{n}} \sum_{j>i}^{\bar{n}} \frac{\psi\left(\Delta\vec{x}_{ij}\right)}{\bar{n}^2 - \bar{n}} - \sum_{i}^{n} \sum_{j}^{\bar{n}} \frac{\psi\left(\Delta\vec{x}_{ij}\right)}{n\bar{n}}$$

> Definition of unary function to compute Gaussian distance functor

$\psi\left(\Delta\vec{x}_{ij}\right) = e^{-\Delta\vec{x}_{ij}{}^2/2\sigma^2}$ where $\Delta\vec{x}_{ij} = |\vec{x}_i - \vec{x}_j|$

initialised with position of event i

> Sum over all events i of D^0 sample of size n:

- For each event i compute

$\sum_{j>i}^{n} \frac{\psi\left(\Delta\vec{x}_{ij}\right)}{n-1}$ and $\sum_{j}^{\bar{n}} \frac{\psi\left(\Delta\vec{x}_{ij}\right)}{\bar{n}}$ via thrust::transform_reduce

Energy test: Implementation

$$T \approx \sum_{i}^{n}\sum_{j>i}^{n}\frac{\psi\left(\Delta\vec{x}_{ij}\right)}{n^2-n}+\sum_{i}^{\bar{n}}\sum_{j>i}^{\bar{n}}\frac{\psi\left(\Delta\vec{x}_{ij}\right)}{\bar{n}^2-\bar{n}}-\sum_{i}^{n}\sum_{j}^{\bar{n}}\frac{\psi\left(\Delta\vec{x}_{ij}\right)}{n\bar{n}}$$

> Sum over all events i of $\overline{D}^0$ sample of size $\bar{n}$:

- For each event i compute

  $$\sum_{j>i}^{\bar{n}}\frac{\psi\left(\Delta\vec{x}_{ij}\right)}{\bar{n}-1}$$

  via thrust::transform_reduce(dev_data_d0bar->begin(), dev_data_d0bar->end(), gd, (double) 0., plus<double>())

Energy test: Performance

> Energy test over a sample of 700,000 events with a single permutation: ~10 hours of CPU time

> Around 1000 permutations required
↪ Not feasible on a CPU

> Energy test over a sample of 700,000 events with a single permutation: ~11 minutes on a GPU

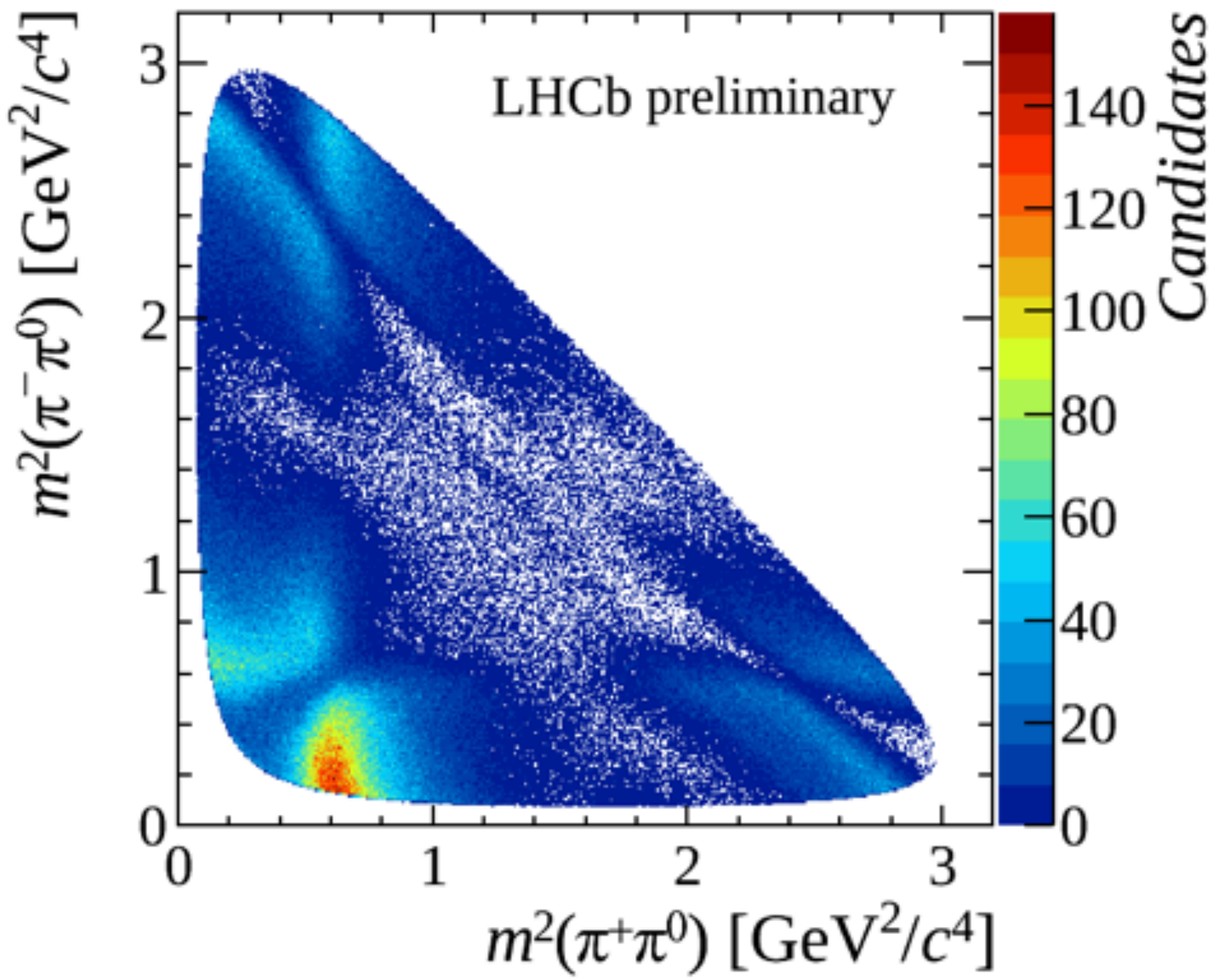
↪ 1000 permutations not a problem on a GPU!

Energy test: Analysis

> Data set of $\mathcal{L}_{\text{int}} = 2\,\text{fb}^{-1}$ recorded with the LHCb detector in 2012 at $\sqrt{s} = 8\,\text{TeV}$

> $D^0 \to \pi^+\pi^-\pi^0$ sample

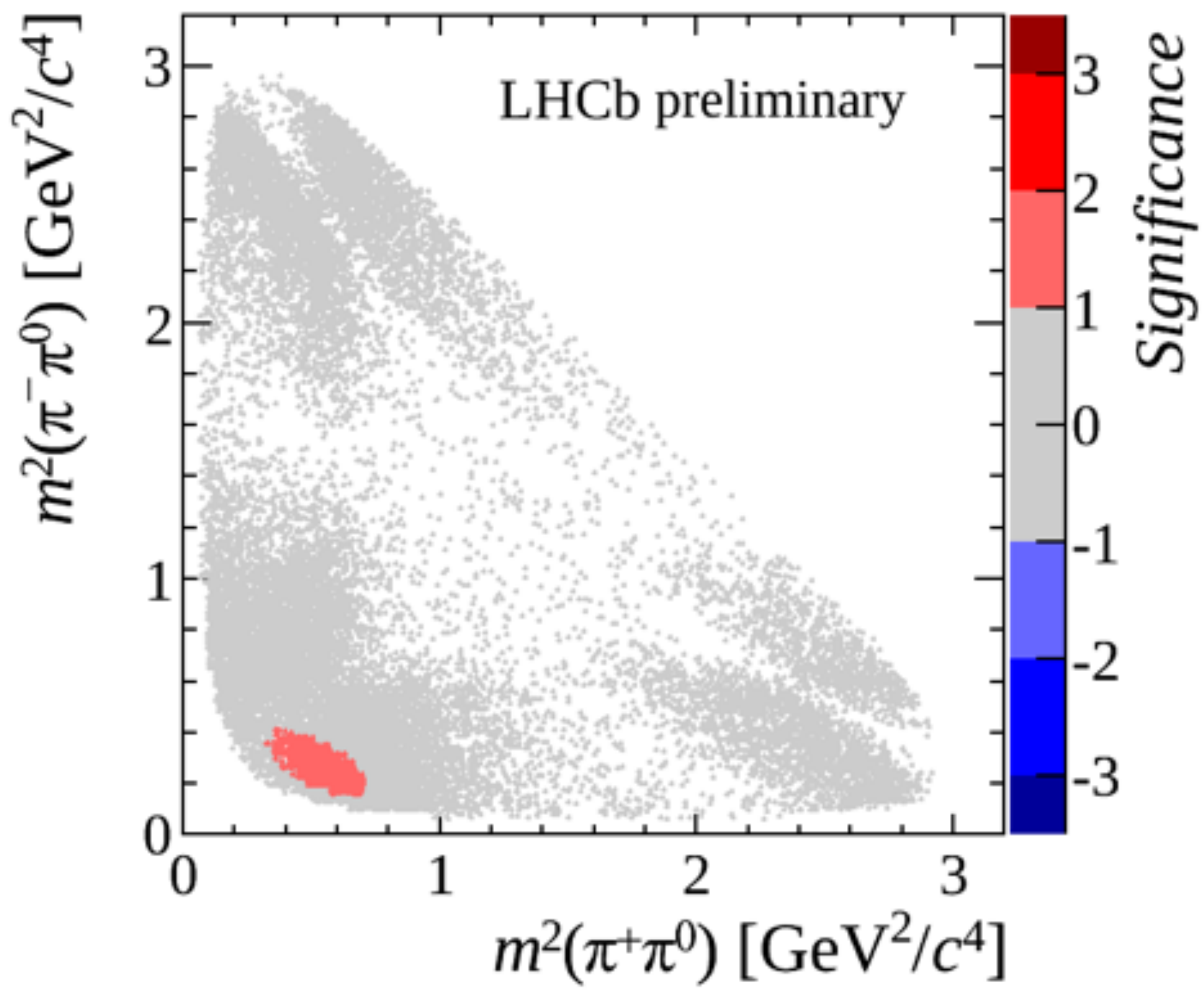
- 663k candidates
- Purity ~ 85%



Dalitz plot for $D^0 \to \pi^+\pi^-\pi^0$ samples taken from LHCb-PAPER-2014-054

Energy test: Preliminary results

σ	p-value
0.2	$(4.2 \pm 0.6)\times10^{-2}$
0.3	$(2.6 \pm 0.5)\times10^{-2}$
0.4	$(1.7 \pm 0.4)\times10^{-2}$
0.5	$(2.1 \pm 0.5)\times10^{-2}$



Data found to be consistent with a no CPV hypothesis at a probability of (2.6 ± 0.5) % (LHCb-PAPER-2014-054)

Visualisation of local asymmetry significances for $\sigma = 0.3$ from LHCb-PAPER-2014-054

Time-dependent amplitude analysis of $D^0 \to K_S^0\pi^+\pi^-$ with GooFit

Amplitude analysis: Method

> Time-dependent amplitude-analysis of $D^0 \to K_S^0\pi^+\pi^-$

- direct access to mixing parameters x, y
- search for indirect CPV by measuring $|q/p|, \varphi = arg(q,p)$

> D^0 flavour determined by muon of a $B^- \to D^0\mu^-\bar{\nu}_\mu$ decay

> 3-body decay $D^0 \to a\,b\,c$ treated as 2-body decay $D^0 \to R\,c$ through an intermediate resonance $R \to a\,b$

> Model-dependence through choice of resonances and line-shapes

- $R \to K_S^0\pi^\pm : K^*(892)^\pm,\ K_0^*(1430)^\pm,\ K_2^*(1430)^\pm,\ ...$
- $R \to \pi^+\pi^- : \rho(770),\ \omega(782),\ f_0(980),\ ...$
- Line-shapes, e.g. Gounaris-Sakurai, relativistic Breit-Wigner

Amplitude analysis: Implementation

> Parallel fitting framework GooFit[1] implemented in CUDA and using Thrust libraries (see talk by M. Sokoloff on 12/09/2014)

> A few resonance models available in GooFit::ResonancePdf

- Relativistic Breit-Wigner
- Gounaris-Sakurai
- LASS-like parametrisation
- Implementation of K-matrix ongoing

> Framework for time-dependent amplitude analysis available in GooFit::TddpPdf

[1] https://github.com/GooFit/GooFit/

Amplitude analysis: Implementation

> TddpPdf requires the following input variables

- m^2_{ab} , e.g. $m^2_{K^0_S\pi^+}$
- m^2_{ac} , e.g $m^2_{K^0_S\pi^-}$
- D^0 decay time t
- D^0 decay time error σ_t
- Event number

> Amplitude model and fit parameters configurable in steering file

> Features of the fit

- background components
- efficiency (parametrisation or histogram) and resolution
- veto regions in phase-space
- blinding of results

Amplitude analysis: Implementation

```
DecayInfo* dtop0pp = new DecayInfo();
dtop0pp->motherMass  = 1.86486;
dtop0pp->daug1Mass  = 0.497614;
dtop0pp->daug2Mass  = 0.13957018;
dtop0pp->daug3Mass  = 0.13957018;
dtop0pp->meson_radius  = 1.5;
```

Decay info

```
dtop0pp->_tau = new Variable("tau", 0.4101, 0.001, 0.300, 0.500);
dtop0pp->_xmixing = new Variable("xmixing", 0.005, 0.0001, 0, 0);
dtop0pp->_ymixing = new Variable("ymixing", 0.005, 0.0001, 0, 0);

ptr_to_xmix = dtop0pp->_xmixing;
ptr_to_ymix = dtop0pp->_ymixing;
ptr_to_dtau = dtop0pp->_tau;
ptr_to_xmix->fixed = false;
ptr_to_ymix->fixed = false;
```

Mixing parameters

```
// Amplitudes and phases relative to rho(770)
ResonancePdf* rho_770;
ResonancePdf* f0_980;
ResonancePdf* f0_1370;
```

Resonance model

Amplitude analysis: Implementation

```
// GS - initialisation: name, ar, ai, sp, mass, width, cyc
rho_770  = new ResonancePdf("rho_770",
                            new Variable("rho0_amp_real", 1),
                            new Variable("rho0_amp_imag", 0),
                            1,
                            new Variable("rho0_mass", 0.7758),
                            new Variable("rho0_width", 0.1464),
                            PAIR_23);
```

$\rho(770) \to \pi^+\pi^-$

```
// RBW - initialisation: name, ar, ai, mass, width, sp, cyc
Kstarm_892  = new ResonancePdf("Kstarm_892",
                               new Variable("Kstarm_amp_real", -1.16356,
                                     0.001, 0, 0),
                               new Variable("Kstarm_amp_imag", 1.19933,
                                     0.1, 0, 0),
                               new Variable("Kstarm_mass", 0.893606),
                               new Variable("Kstarm_width", 0.0463407),
                               1,
                               PAIR_13);
```

$K^*(892)^- \to K^0_S\pi^-$

Amplitude analysis: Implementation

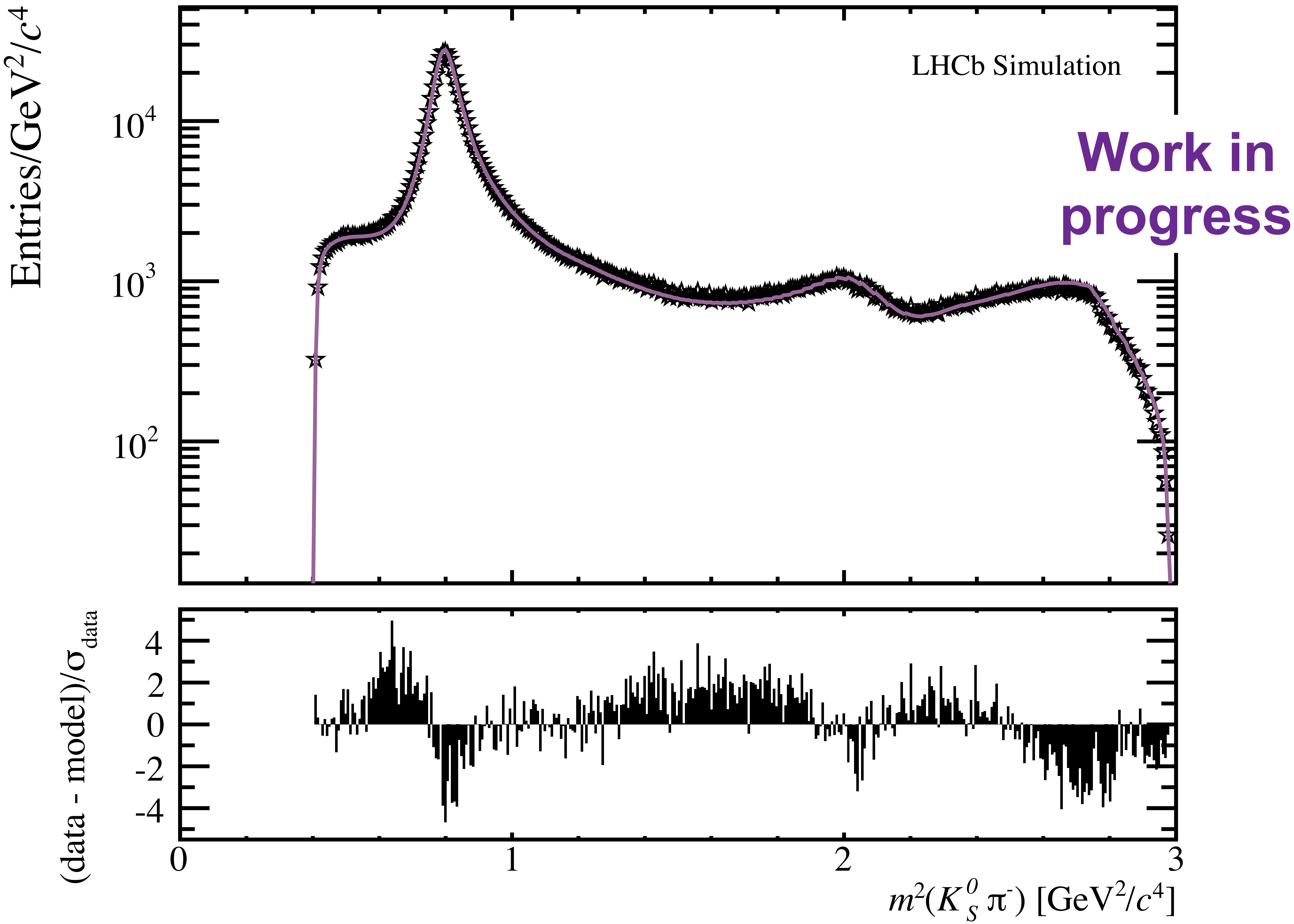
```
// Resolution
TruthResolution* res = new TruthResolution();
// Efficiency
vector<Variable*> off;
off.push_back(Zero); off.push_back(Zero);
vector<Variable*> obs;
obs.push_back(m12); obs.push_back(m13);
vector<Variable*> coeff;
coeff.push_back(One); coeff.push_back(One);

GooPdf *eff = new PolynomialPdf("constantEff", obs, coeff, off, 0);
// TddpPdf
TddpPdf* signal = new TddpPdf("signal", dtime, sigma, m12, m13,
                              eventNumber, dtop0pp, res, eff, wBkg);

signal->setDataSize(data->getNumEvents());
signal->setData(data);
FitManager datapdf(signal);
// Fit
datapdf.fit();
```

Resolution

Efficiency

Fit

Amplitude analysis: Toy fit with efficiency



Projection of the time-dependent fit of a $D^0 \to K^0_S\pi^+\pi^-$ sample including an efficiency parametrisation $\varepsilon(m^2(K^0_S\pi^+), m^2(K^0_S\pi^-))$

Summary

> Measurements of mixing and search for CP violation in charm sector on large data sets benefit from usage of GPUs

> Implementation of energy test in CUDA with Thrust libraries renders analysis feasible

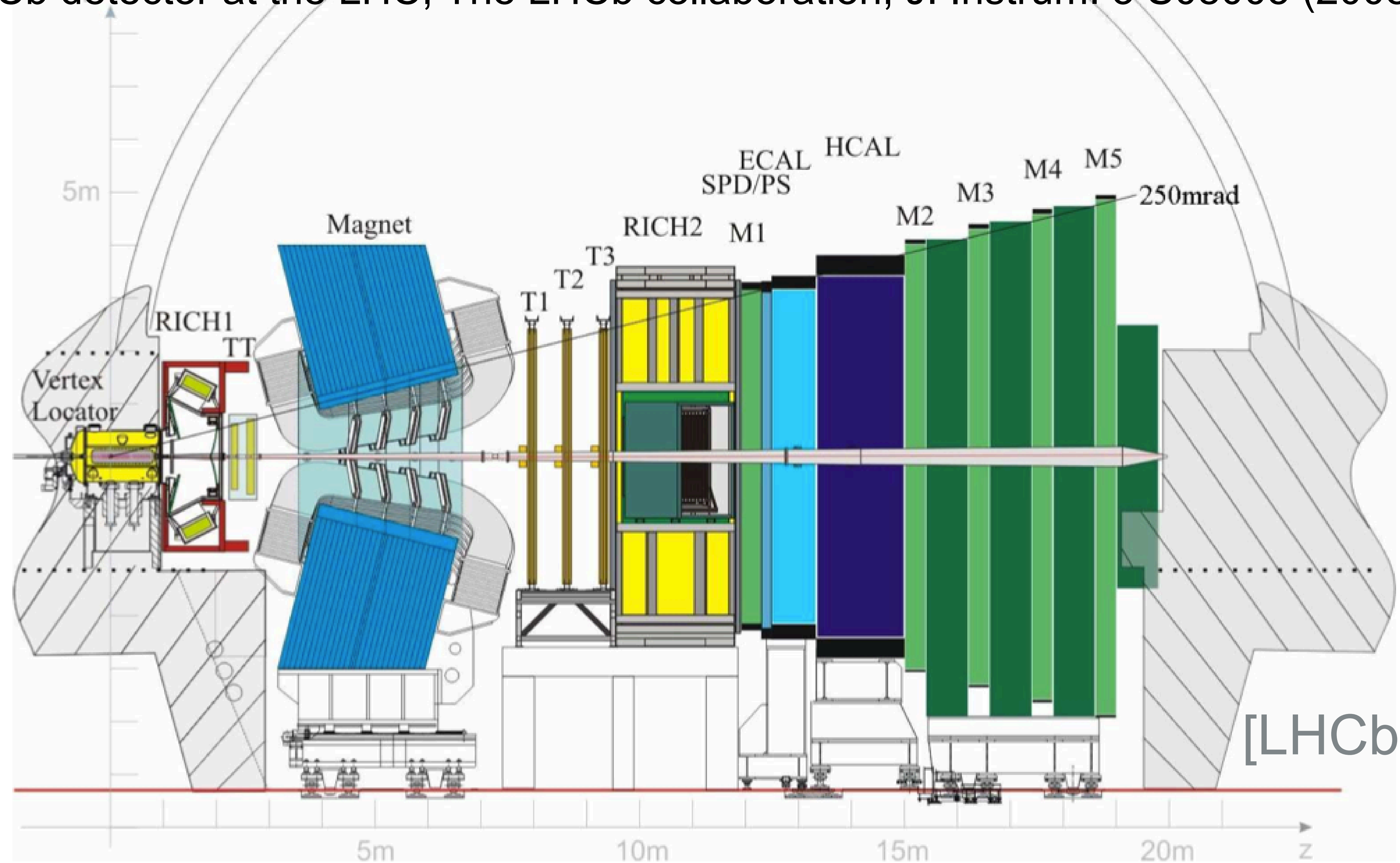
> GooFit provides everything for time-dependent and model-dependent amplitude-analysis with significant speed-up

Thank you.

Backup

The LHCb experiment: Detector

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



[LHCb2008]

> K_S^0-meson decays

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

Introduction: CP violation

> No evidence for CP violation in charm sector.

> CP violation (CPV) occurs if $\lambda_f \neq 1$, λ_f being defined as

$$\lambda_f \equiv \frac{q\bar{A}_{\bar{f}}}{pA_f} = -\left|\frac{q}{p}\right| \left|\frac{\bar{A}_{\bar{f}}}{A_f}\right| e^{i\phi}$$

A_f $(\bar{A}_{\bar{f}})$ - amplitude of a D^0 $(\overline{D}^0)$ decaying into a final state f $(\bar{f})$,
ϕ - CP violating relative phase

> CP violation

- in decay if $|\bar{A}_{\bar{f}}/A_f| \neq 1$ (direct CPV)
- in mixing if $|q/p| \neq 1$ (indirect CPV)
- in interference between decay and mixing if $\phi \neq 0$

Energy test: Selection

> Pre-selection

- Resolved π^0: $|m_{\gamma\gamma} - m_{\pi^0}^{\mathrm{PDG}}| < 15\,\mathrm{MeV}$
- Particle identification requirements on $\pi^\pm$ (reduce mis-identification rate)
- $|m_{\pi^-\pi^+\pi^0} - m_{D^0}^{\mathrm{PDG}}| < 40\,(60)\,\mathrm{MeV}$ for the resolved (merged) sample
- Decay chain of D^{*+} refitted where $\chi^2 < 35$. Refit requires
  - D^{*+} from primary vertex
  - π^0 and D^0 masses correspond to nominal masses

> Boosted Decision Tree (BDT) trained separately for merged and resolved samples with highly discriminating variables, e.g.

- $p_T(\pi_s),\ p_T(D^0),\ p_T(\pi^0)$ for resolved sample
- $p_T(\pi_s),\ p_T(D^0),\ \chi^2_{IP}(D^0)$ for merged sample
- Cut on BDT output and on $|\Delta m - 145.4| < 1.8\,\mathrm{MeV}$

Energy test: Mass fits

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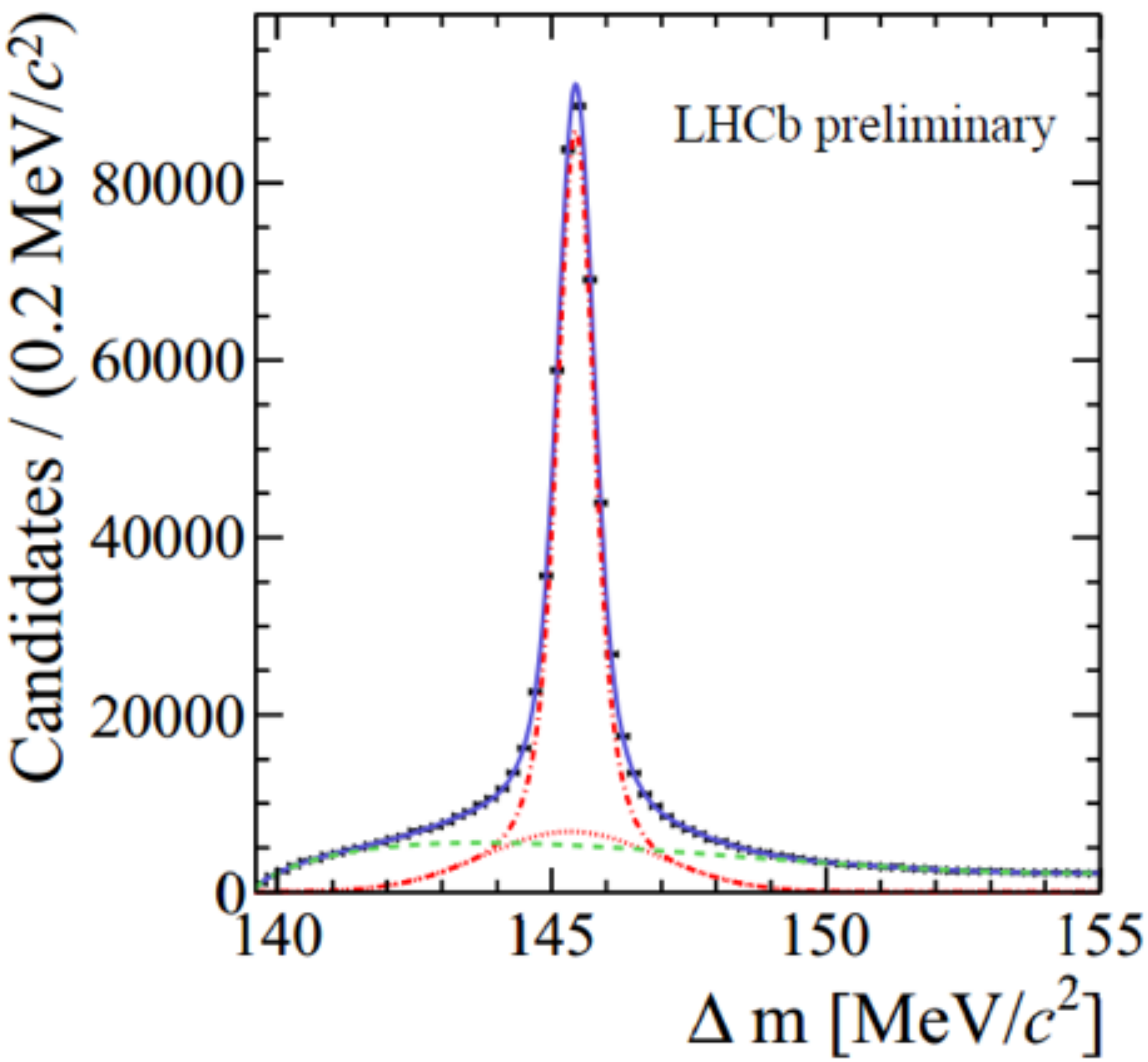
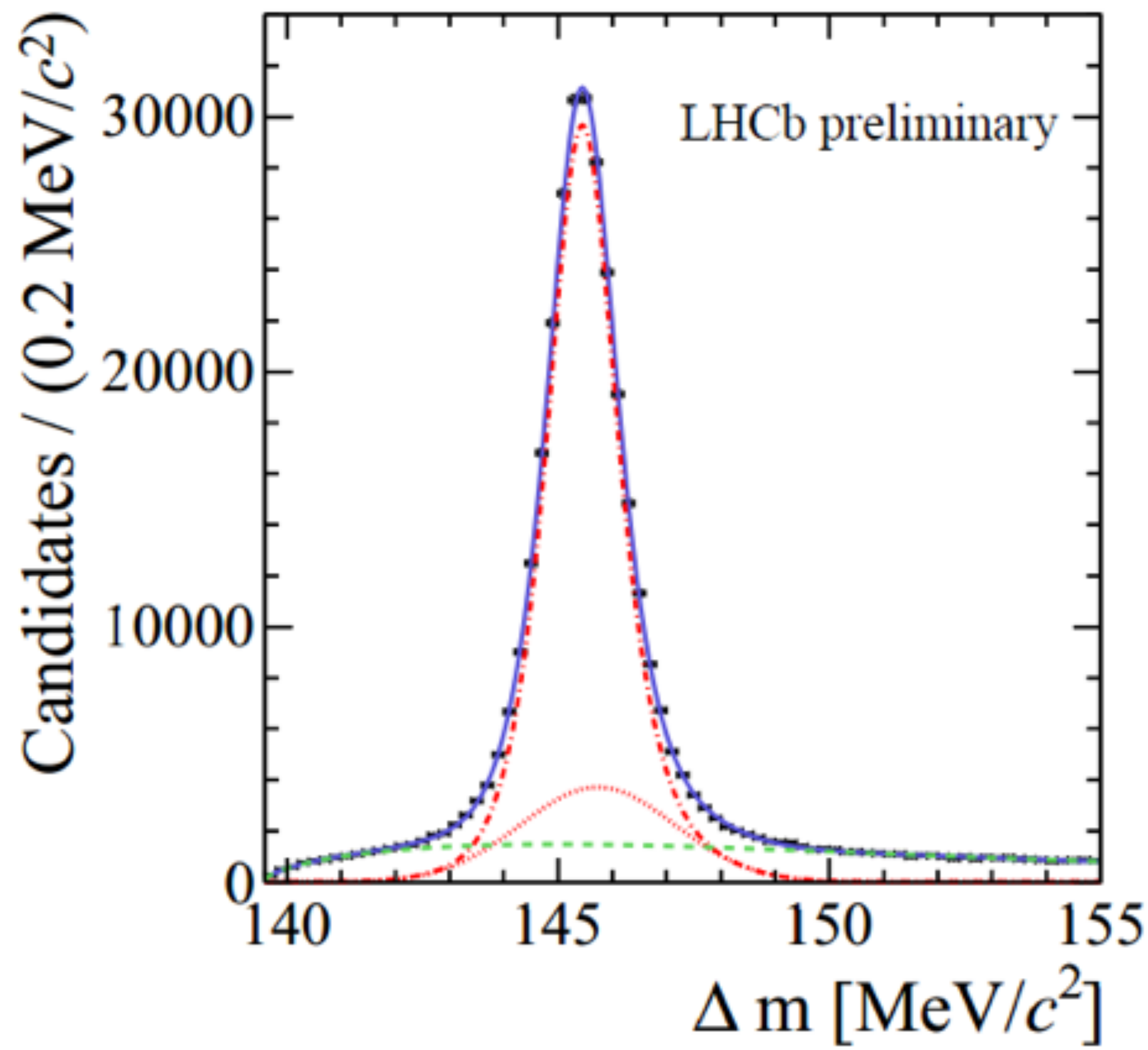


resolved π^0 sample



merged π^0 sample

Energy test: Efficiency

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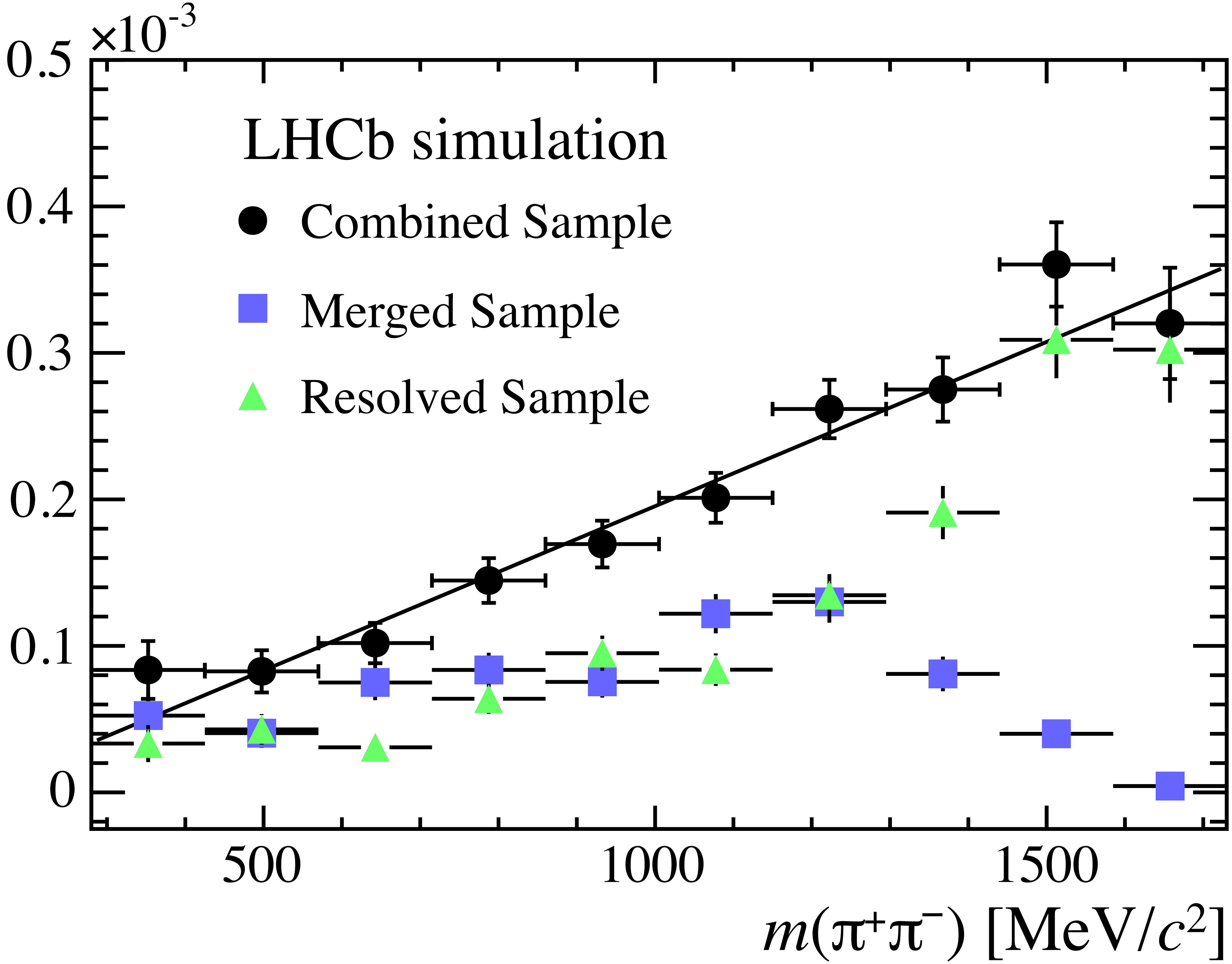

Energy test: p-value fit function

- In case of large CP violating effects, the nominal T-value might lie outside the range of the T-value distribution obtained from the permutation samples
- Fit T-value distribution with a generalised extreme value function

$$f(x;\mu,\sigma,\xi) = N\left[1+\xi\left(\frac{x-\mu}{\sigma}\right)\right]^{(-1/\xi)-1}\exp\left\{-\left[1+\xi\left(\frac{x-\mu}{\sigma}\right)\right]^{-1/\xi}\right\}$$

  with N - normalisation, μ - location, σ - scale, ξ - shape parameter

- p-value defined as fraction of the integral of $f(x;\mu,\sigma,\xi)$ above the nominal T-value
- Uncertainty on p-value obtained through propagation of uncertainties on fit parameters

Amplitude analysis: Method

> Isobar model as coherent sum of matrix elements[1]

- $R \to K_S^0\pi^+$: $K^*(892)^+,\ K_0^*(1430)^+,\ K_2^*(1430)^+$
- $R \to K_S^0\pi^-$: $K^*(892)^-,\ K_0^*(1430)^-,\ K_2^*(1430)^-,\ K^*(1680)^-$
- $R \to \pi^+\pi^-$: $\rho(770),\ \omega(782),\ f_0(980),\ f_0(1370),\ f_2(1270),\ \sigma_1,\ \sigma_2$
- non-resonant $D^0 \to K_S^0\pi^+\pi^-$
- relativistic Breit-Wigner (BW) except Gounaris-Sakurai (GS) for $\rho(770)$

> Alternative model[1]

- $R \to K_S^0\pi^\pm$ S-wave: LASS-like parametrisation
- $R \to K_S^0\pi^+$: $K^*(892)^+,\ K_2^*(1430)^+$ (BW)
- $R \to K_S^0\pi^-$: $K^*(892)^-,\ K_2^*(1430)^-,\ K^*(1680)^-$ (BW)
- $R \to \pi^+\pi^-$ S-wave: K-matrix
- $R \to \pi^+\pi^-$: $\rho(770),\ \omega(782),\ f_2(1270)$ (BW except GS for $\rho(770)$)

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