Search for matter-antimatter asymmetries in multi-body decays with GPUs

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Introduction

Energy test

- Statistical method
- Sensitive to local asymmetry of two distributions
- Search for matter-antimatter asymmetries (CP violation) in phase space

Implementation with GPUs

- Applied with CUDA platform of NVIDIA GPUs
- Applied with both local and Grid GPUs
- Reduce large amount of computation time

Application in 3 body decays

- Studied with $D^0 \to \pi^-\pi^+\pi^0$ decay
- World's best sensitivity in this decay channel
- Result consistent with no CP violation hypothesis

Energy test

- Method to search for CP violation in phase-space distribution of 3-body decays (Dalitz plot) based on unbinned sample comparison.
- Test statistic T used to compare average weighted distances of two flavour samples [1]:

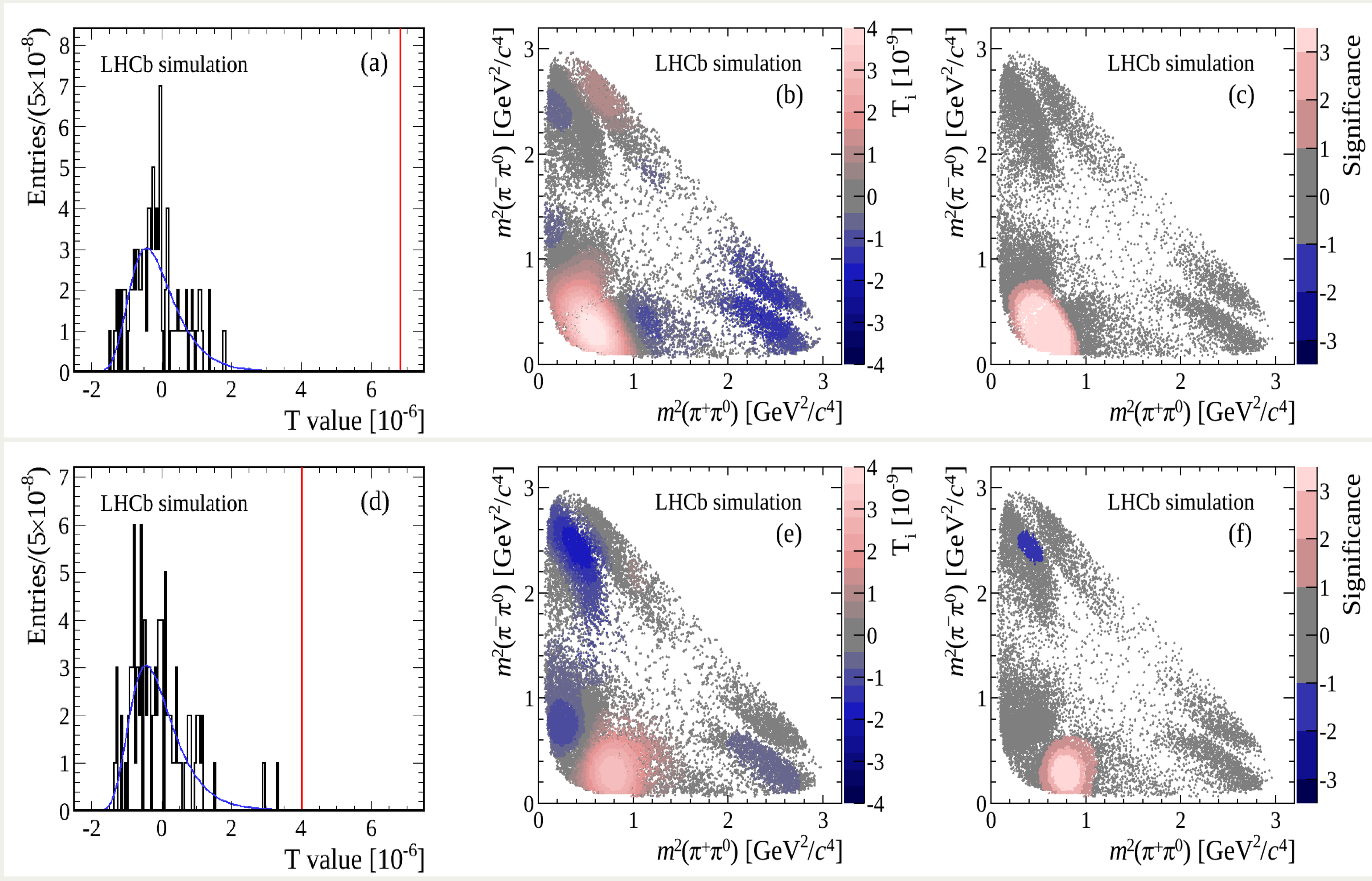
$$T = \sum_{i,j>i}^{n} \frac{\psi_{ij}}{n^2 - n} + \sum_{i,j>i}^{\overline{n}} \frac{\psi_{ij}}{\overline{n}^2 - \overline{n}} - \sum_{i,j}^{n,\overline{n}} \frac{\psi_{ij}}{n\overline{n}}, \quad (1)$$

where $\psi_{ij} \equiv \psi(\Delta\vec{x}_{ij}) = e^{-\Delta\vec{x}_{ij}^2/2\sigma^2}$, with a tunable parameter σ, here using $\sigma = 0.3$ GeV$^2/c^4$.

- Compare to T values from no CP violation samples from randomly retagging flavour of events (permutation T values).
- p-value for no CP violation hypothesis is fraction of permutation T values larger than nominal T value.
- Can either get fraction from counting or from fitting with generalised extreme value function [2].
- Contribution to T from each event is given as

$$T_i = \frac{1}{2n\,(n-1)} \sum_{j\neq i}^{n} \psi_{ij} - \frac{1}{2n\overline{n}} \sum_{j}^{\overline{n}} \psi_{ij}, \quad (2)$$

- T_i distribution indicates local asymmetries.
- Assign local asymmetry significances by comparing T_i to largest/smallest T_i from each of the permutations.

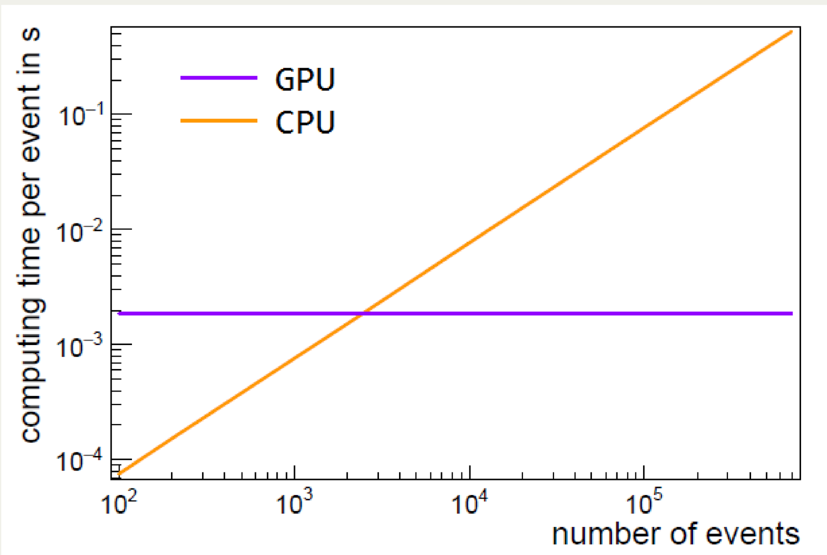


- CP violation simulation examples with (top) 2% amplitude and (bottom) 1° phase asymmetry of ρ^+ resonance.
- (Left) T value distribution, (centre) T_i value distribution, and (right) T_i value significance.

Energy test with GPUs

Feasible with GPUs

- The modern graphics processing unit (GPU) is not only a powerful graphics engine but also a highly parallel programmable processor, the graphic pipeline is well suited for parallelism and the large memory bandwidth allows rapid data exchange [3]
- Energy test considers distances between every two events, which will lead to $\sim$(Number of events)^2/2 calculations $\to$ prohibitively long calculation time on CPU for large datasets
- Parallel architecture of GPU makes it possible to dramatically reduce computation time for datasets with 10^4 to 10^6 events on GPU
- Computation time on CPU is quadratic to data size, while on GPU is linear for samples with less than $\sim 10^6$ events, but become quadratic again for larger samples



Computation time per event is constant on GPU (purple) while increases with sample size on CPU (orange) for data samples with less than $\sim 10^6$ events

Implementation with NVIDIA GPUs

- Applied with CUDA computing platform of NVIDIA GPUs
- Implemented with Thrust, a C++ template library for CUDA
- For each event i compute $\sum_j^n \frac{\psi_{ij}}{n-1}$ via

```
thrust::transform_reduce( dev_data_d0->begin(), dev_data_d0->end(),
gaussian_distance, (double) 0., plus<double>() )
```

- Ran with NVIDIA Tesla M2070 GPUs (Ohio Supercomputer Center computer farm "Oakley") and NVIDIA Tesla K40c GPUs (Manchester HEP GPU cluster)

GPUs on Grid

- 4 NVIDIA Tesla K40c GPUs were installed in Manchester Tier2 Grid, which is part of the UK NorthGrid
- Energy test Implemented with UK NorthGrid GPUs
- Grid jobs submitted by Job Description Language (JDL) commands
- Similar time performance as on local GPUs

Application in $D^0 \to \pi^-\pi^+\pi^0$ decay

Dataset

- Data collected by LHCb experiment
- Yields 663×10^3 candidates
- Phase space dominated by interfering $\rho^+\pi^-$, $\rho^-\pi^+$, $\rho^0\pi^0$ resonances

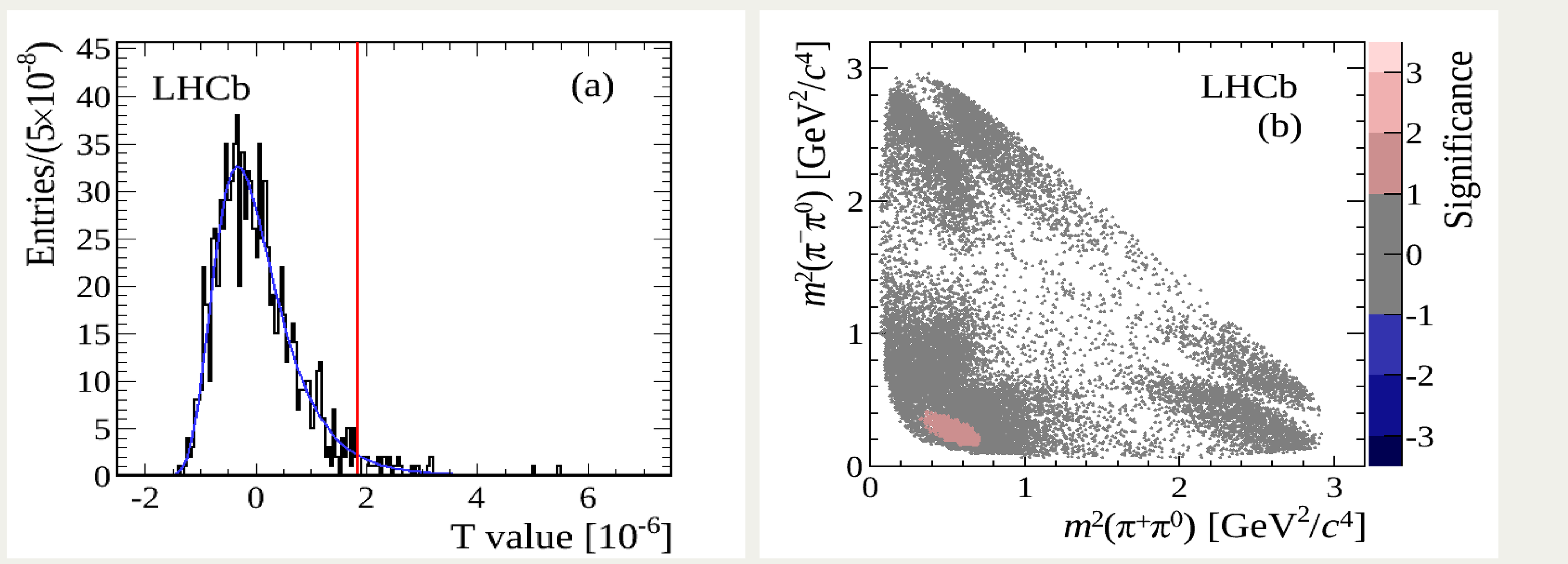
Sensitivity

CP violation examples with p-value and 90% CL upper limit on p-value.

Resonance (A,ϕ)	p-value (fit)	upper limit
ρ^0 (+3%,+0°)	$1.1^{+2.4}_{-1.1} \times 10^{-2}$	4.0×10^{-2}
ρ^0 (+0%,+3°)	$1.5^{+1.7}_{-1.4} \times 10^{-3}$	3.8×10^{-3}
ρ^+ (+2%,+0°)	$5.0^{+8.8}_{-3.8} \times 10^{-6}$	1.8×10^{-5}
ρ^+ (+0%,+1°)	$6.3^{+5.5}_{-3.3} \times 10^{-4}$	1.4×10^{-3}
ρ^- (+2%,+0°)	$2.0^{+1.3}_{-0.9} \times 10^{-3}$	3.9×10^{-3}
ρ^- (+0%,+1.5°)	$8.9^{+22}_{-6.7} \times 10^{-7}$	4.2×10^{-6}

Results

- implementation of GPUs reduces computation time from $\sim$ 10 hours per permutation on CPUs to $\sim$ 10 minutes per permutation
- p-value for no CP violation hypothesis is $(2.6 \pm 0.5) \times 10^{-2}$ [4].



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References

[1] M. Williams, "Observing CP Violation in Many-Body Decays" PRD 84, 054015 (2011).
[2] G. Zech, B. Aslan, "A new test for the multivariate two-sample problem based on the concept of minimum energy" arXiv:math/0309164.
[3] J. D. Owens et al, "GPU Computing" Procceding of the IEEE, vol. 96, May, 2008.
[4] R. Aaij et al. (LHCb collaboration), "Search for CP violation in $D^0 \to \pi^-\pi^+\pi^0$ decays with the energy test" PLB 740(2015) 158-167.