Charm mixing and CP violation at LHCb

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Charm at LHCb

- Charm is unique: up-type quark system where mixing and CPV can occur
- Mass eigenstates vs flavour eigenstates

  $|D_{1,2}\rangle = p|D^0\rangle \pm q|\overline{D}^0\rangle$ q=p if no CPV

  - mixing well established (>10σ) **PRL 111 (2013) 251801**
  - CPV in charm not yet observed
- Cross section for $c\overline{c}$ in LHCb acceptance

  $$\sigma(c\overline{c})_{p_T<8\,\mathrm{GeV}/c,\,2.0<y<4.5} = 1419 \pm 12\,(\mathrm{stat}) \pm 116\,(\mathrm{syst}) \pm 65\,(\mathrm{frag})\,\mu\mathrm{b}$$

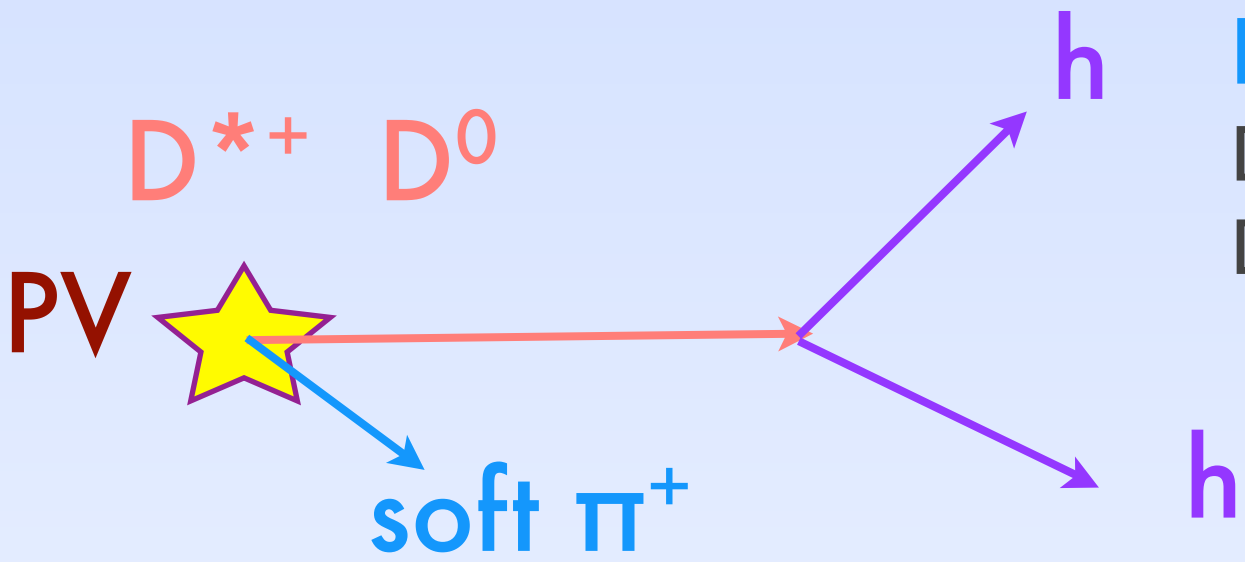
  Nucl.Phys. B871 (2013) 1-20

  @ 7TeV

  ➡ ~ 5×10^{12} D^0 candidates produced in LHCb acceptance in run1
- Huge amount of charm decays collected and reconstructed

  ➡ World's best sensitivity to charm CPV
- Heavily boosted quarks, high rapidities: ideal for studying time-dependent effects

D^0 flavour tagging: prompt and secondary charm

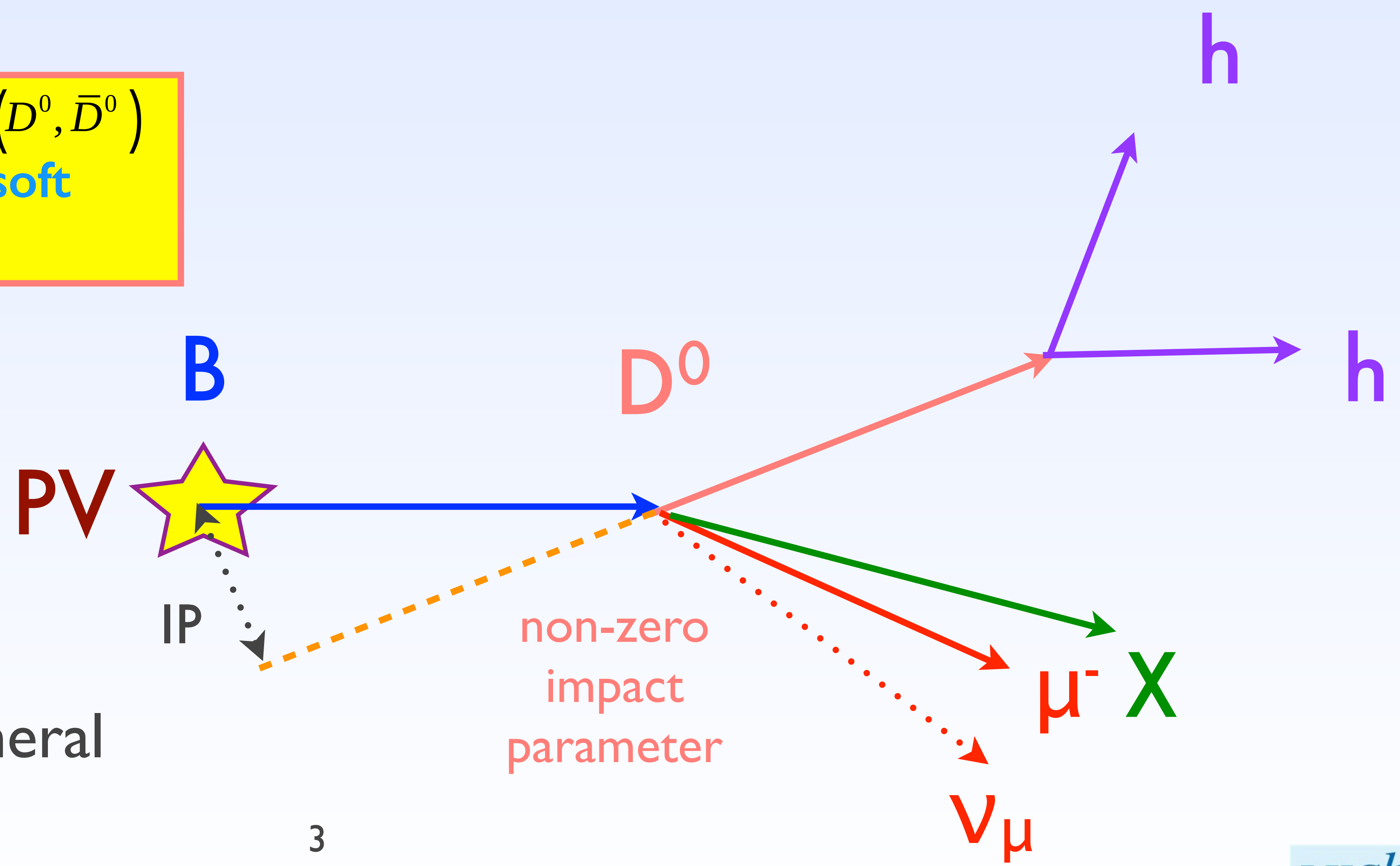


Prompt charm:

D points to primary vertex

Daughters of D don't in general

The flavour of the initial state $(D^0, \bar{D}^0)$ is tagged by the charge of the soft pion or the muon



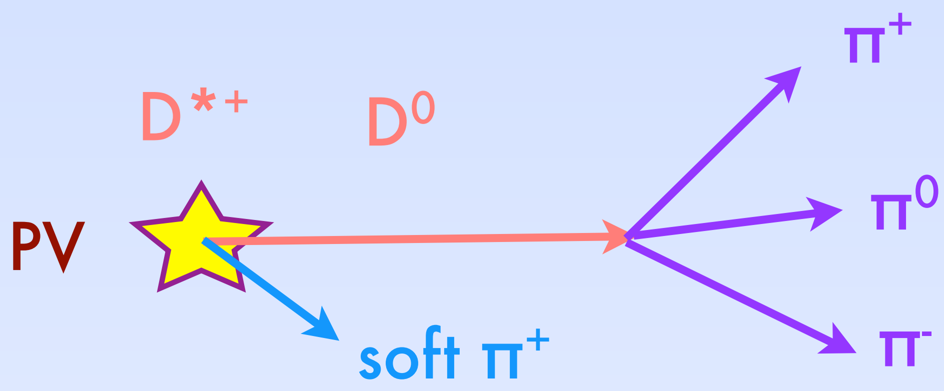
Secondary charm:

D doesn't point to PV in general

Direct CPV searches in multibody decays $D^0 \to \pi^- \pi^+ \pi^0$

- Depends on decay mode $|\bar{A}_{\bar{f}}/A_f| \neq 1$
- Time integrated
- Sensitive to local asymmetries

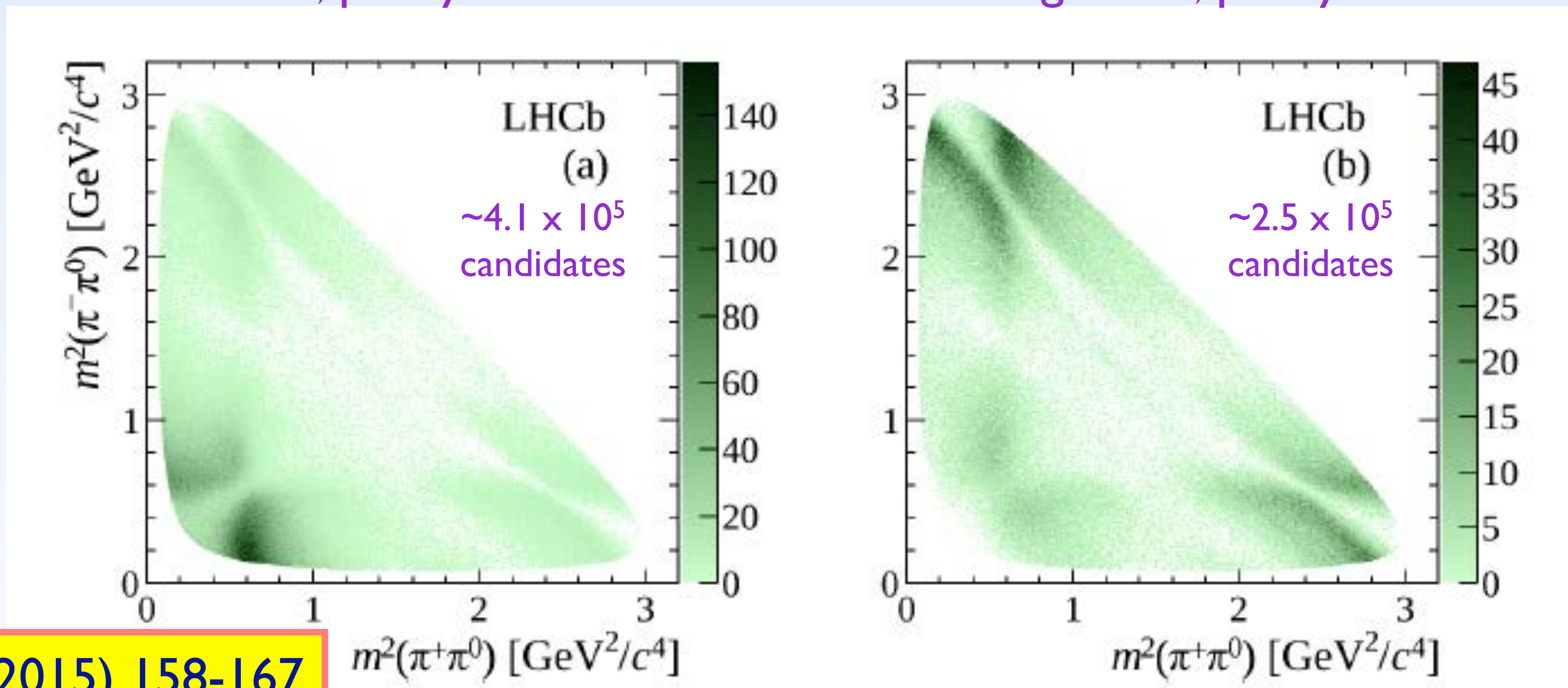
Time integrated search for CPV in $D^0 \to \pi^-\pi^+\pi^0$ decays



~ 660 k $D^0 \to \pi^-\pi^+\pi^0$ decays using 2012 data (2 fb^{-1}), prompt charm

Resolved π^0 :
both γ were detected separately,
low P_T, purity 82%

Merged π^0 :
both γ form 1 cluster,
higher P_T, purity 91%



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Decay dominated by ρ(770) resonances: $\rho^0\pi^0$, $\rho^+\pi^-$, $\rho^-\pi^+$

Local asymmetry search techniques

- Many ways to reach multibody final states through intermediate resonances
- Resonances interfere and can carry different strong phases: Superb playground for CP violation

Local asymmetries

- potentially larger than the phase space integrated ones
- may change sign across the Dalitz plot
- additional information about the dynamics

Local asymmetries searches techniques

- Model-dependent:
  Fit all contributing amplitudes and look for differences in fit parameters

- Model-independent:
  Look for asymmetries in regions of phase space by "counting"
  - binned (χ^2 difference method)
  - unbinned (Energy test, kNN)

Phys.Lett. B728 (2014) 585–595,
Phys.Lett. B726 (2013) 623–633

Stat. Comp. Simul. 75, Issue 2 109-119 (2004),
Nucl. Instrum. Methods A537, 626-636 (2005),
Phys.Rev. D84 (2011) 054015.

Energy test: unbinned sample comparison used to assign p-value for hypothesis of identical distributions (= no CPV)

First application of the method for a CPV search

Analysis method: Energy test

- Compare average pair-wise distance in Dalitz plot between:
  - ➡ all D^0 events
  - ➡ all $\overline{D}^0$ events
  - ➡ all D^0 to $\overline{D}^0$ events
- Test statistics
  - no CP violation
    - ➡ all average distances equal $\rightarrow T \approx 0$
  - CP asymmetry
    - ➡ average distance btw. D^0 and $\overline{D}^0$ events larger $\rightarrow T > 0$

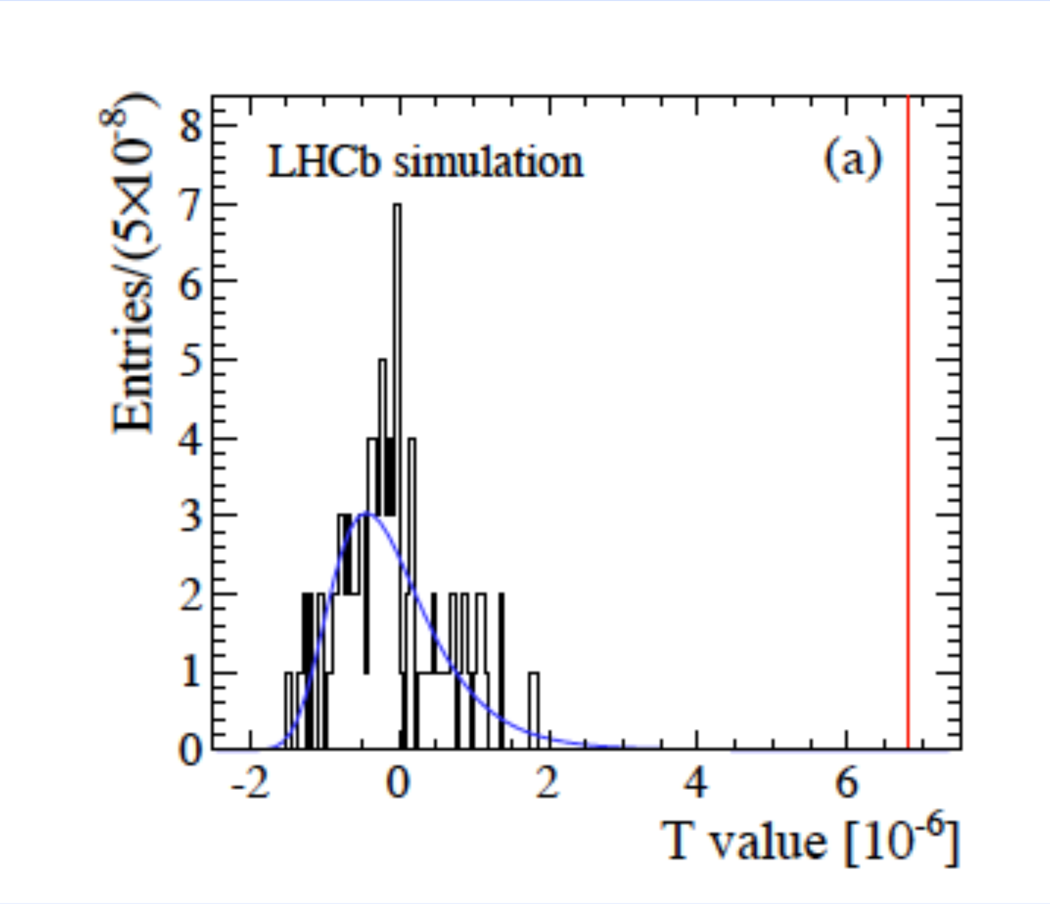
P-values & sensitivity

Compare nominal T-value to T-values for no CPV:

distribution obtained by randomly assigning flavour tags to events thus creating no CPV permutations

Calculate p-value for no CPV hypothesis:

fraction of elements above the nominal T-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}
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ρ^- $(+0\%, +1.5°)$	$8.9^{+22}_{-6.7} \times 10^{-7}$	4.2×10^{-6}

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Best sensitivity in general,

similar to BaBar PRD 78 (2008) 051102

for CPV in ρ^0 amplitude

Results

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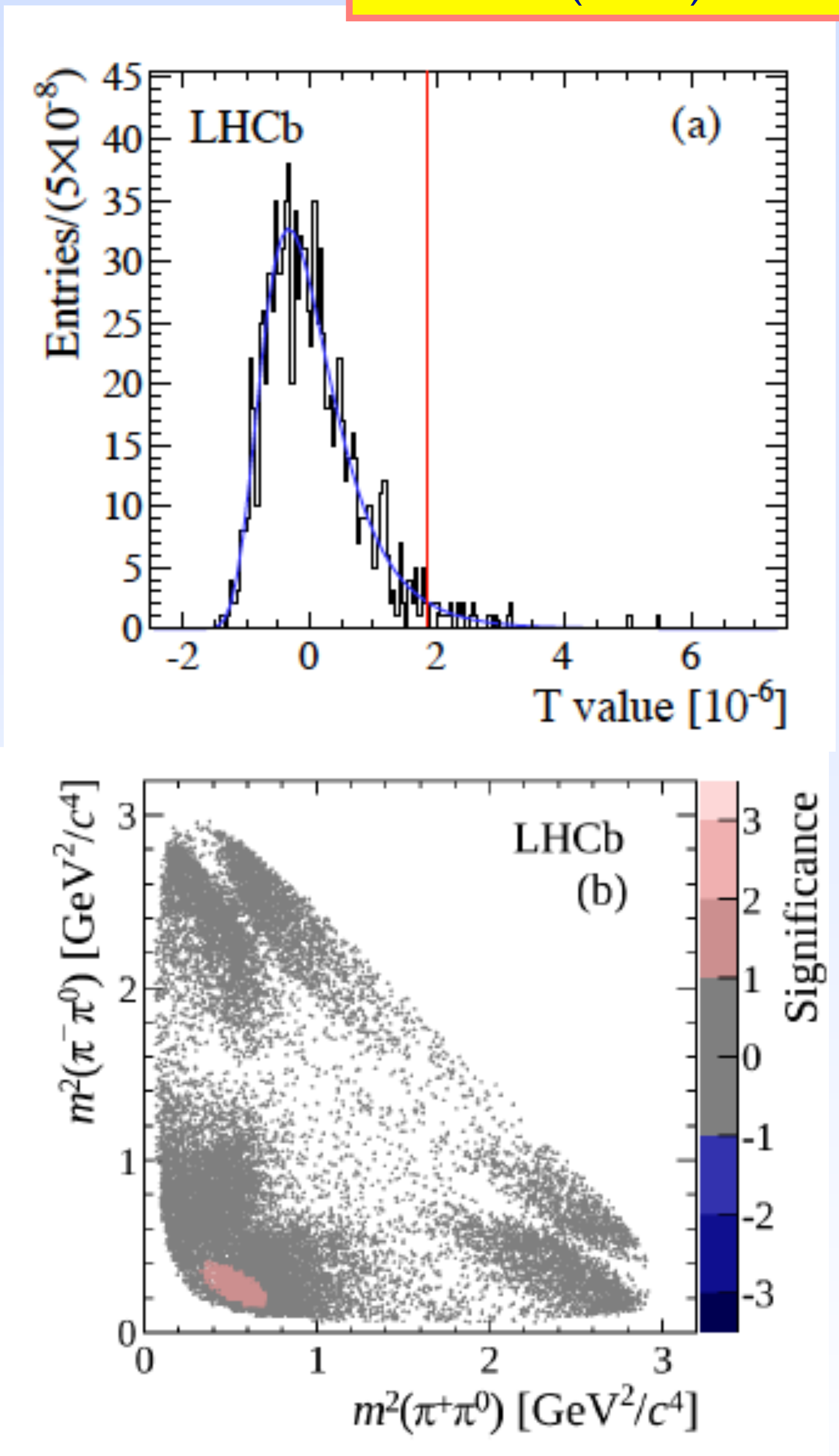
- With1000 permutations
- For no-CPV hypothesis:
  - p-value = (2.6±0.5)%

Method allows visualisation of local asymmetry significances

World's best sensitivity for CPV in $D^0 \rightarrow \pi^- \pi^+ \pi^0$

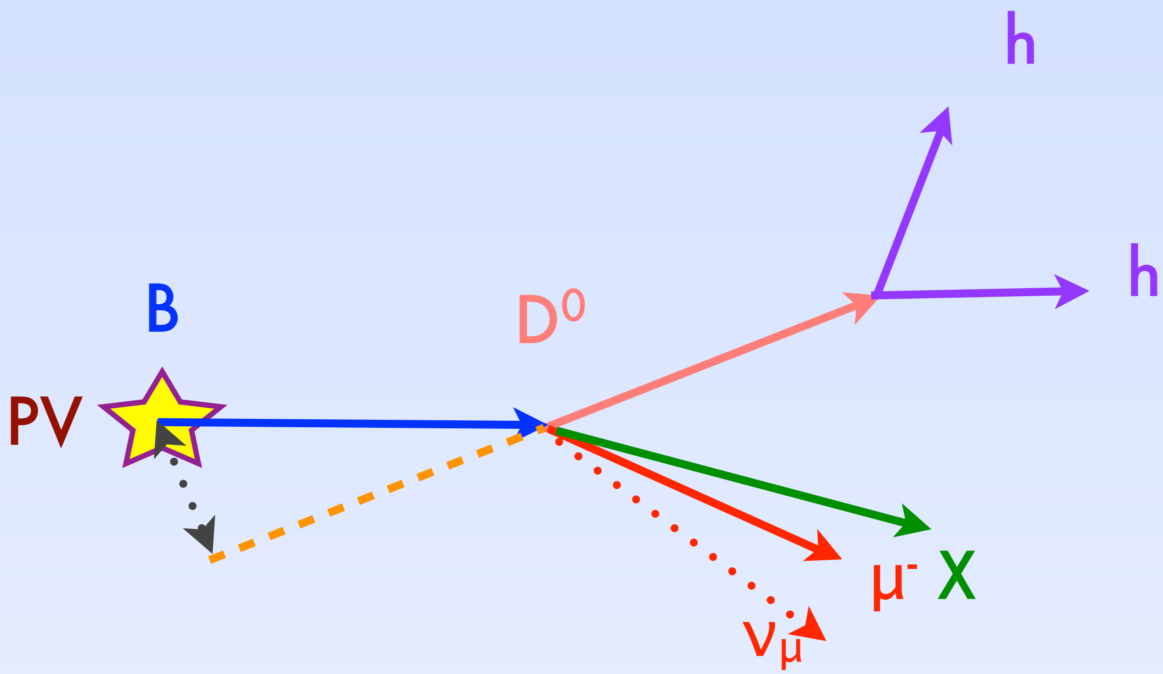
Result consistent with no CP violation



Indirect CPV in charm: A_Γ from muon tagged $D^0 \rightarrow h^+h^-$ decays

- CPV in mixing $|q/p| \neq 1$
- Interference of direct CPV and mixing
  $\varphi = \arg |q/p\ \bar{A}_{\bar{f}}/A_f| \neq 0, \pi$;
- Time dependent

Indirect CPV in muon tagged $D^0 \to h^+h^-$ decays



Measure asymmetries of effective lifetimes of decays to CP eigenstates:

$$A_\Gamma = \frac{\tau^- - \tau^+}{\tau^- + \tau^+}$$

$A_\Gamma \approx A_M\, y \cos\phi + x \sin\phi \equiv -a_{CP}^{ind}$

(Neglecting direct CPV: $A_d\, y \cos\phi$)

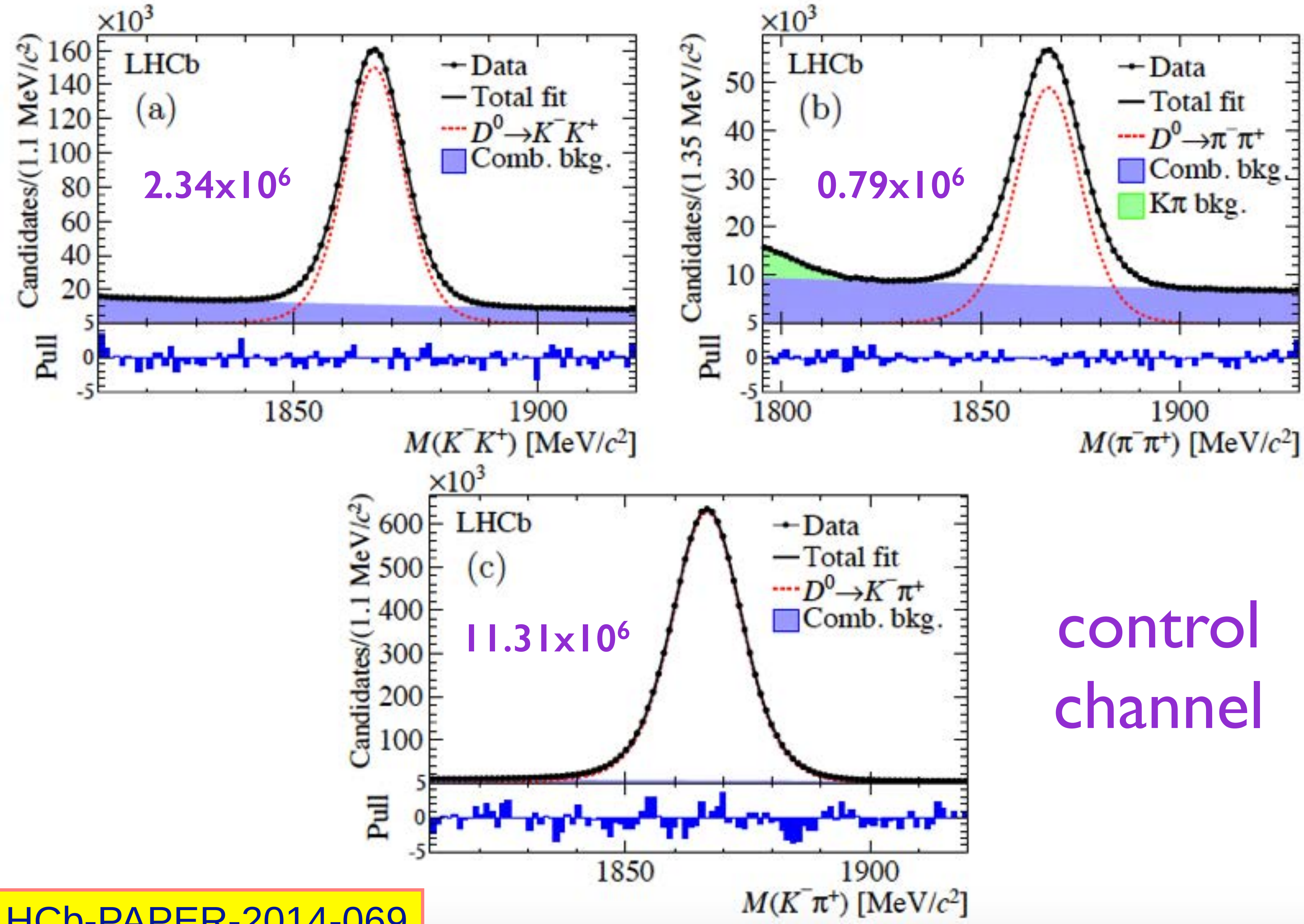
$$A_M = \frac{|q/p|^2 - |p/q|^2}{|q/p|^2 + |p/q|^2}$$

- CP asymmetry

$$A_{CP}(t) \equiv \frac{\Gamma(D^0 \to f;t) - \Gamma(\overline{D}^0 \to f;t)}{\Gamma(D^0 \to f;t) + \Gamma(\overline{D}^0 \to f;t)}$$

- 50 bins of the D^0 decay time
- Using fits to the invariant mass of D^0 and $\overline{D^0}$

Mass fits & yields with 3 fb^{-1}



control channel

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Submitted to JHEP

Raw CP asymmetry as a function of D^0 proper time

Fit the time dependent asymmetry to extract A_Γ

$$A_{CP}(t) \approx A_{CP}^{\rm dir} - A_\Gamma \frac{t}{\tau}$$

LHCb-PAPER-2014-069
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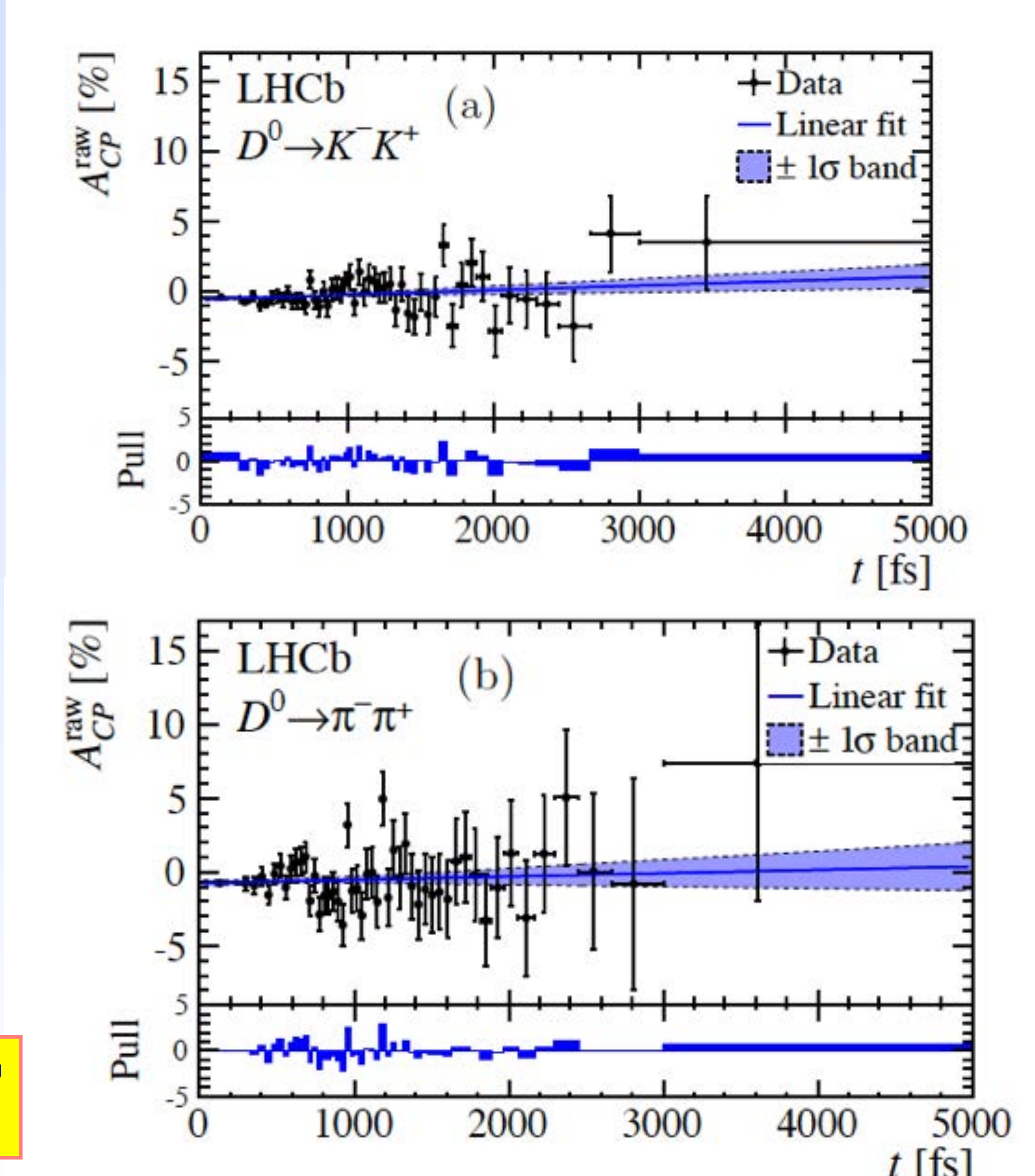

Results

A_Γ has been measured using the full sample of muon tagged D^0 corresponding to 3 fb^{-1} run1 data set

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NEW

$$A_\Gamma(KK) = (-0.134 \pm 0.077\ ^{+0.026}_{-0.034})\%$$

$$A_\Gamma(\pi\pi) = (-0.092 \pm 0.145\ ^{+0.025}_{-0.033})\%$$

Statistically dominated uncertainty
Largest systematic contribution coming from the mistag asymmetry

SM predicts $A_\Gamma \sim O(10^{-4})$

Phys.Rev. D80 **(2009) 076008,**
JHEP 1106 (2011) 089

Enhancements up to 1 order of magnitude are possible in BSM models

Results

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$A_\Gamma(\pi\pi) = (-0.092 \pm 0.145\ ^{+0.025}_{-0.033})\%$

In agreement with the most precise measurement to date by LHCb using prompt $D^0 \rightarrow K^-K^+$ and $D^0 \rightarrow \pi^-\pi^+$ decays (1 fb^{-1})

PRL 112 (2014) 041801

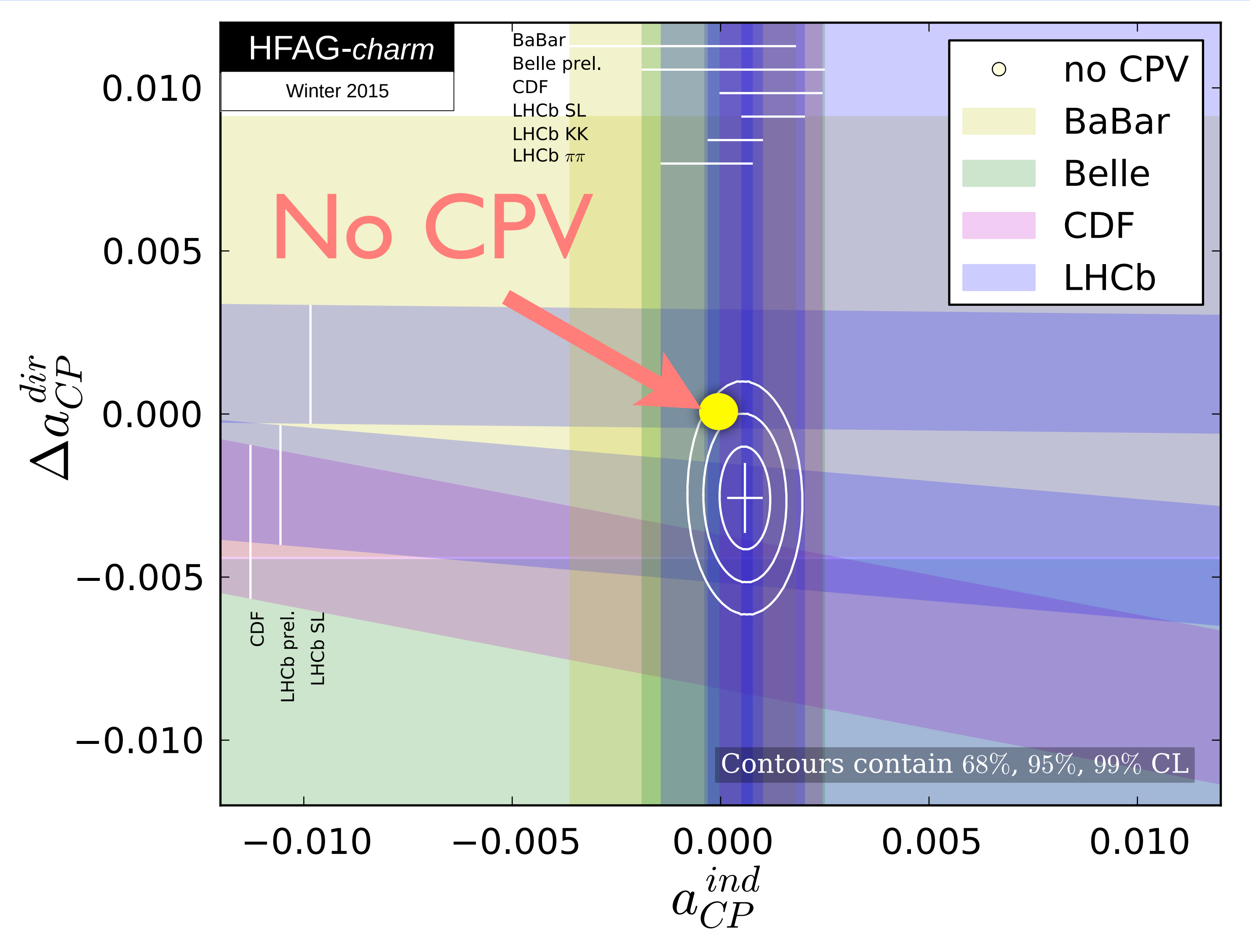
$A_\Gamma(KK) = (-0.35 \pm 0.62 \pm 0.12) \times 10^{-3}$

$A_\Gamma(\pi\pi) = (0.33 \pm 1.06 \pm 0.14) \times 10^{-3}$

Most precise measurement of charm CP asymmetries, update with 3 fb^{-1} ongoing

Prompt and secondary charm results are uncorrelated
Using both tagging techniques improves decay time coverage

HFAG averages including the latest A_Γ results



$a_{CP}^{ind} = 0.00058 \pm 0.00040$

$\Delta a_{CP}^{dir} = -0.00257 \pm 0.00104$

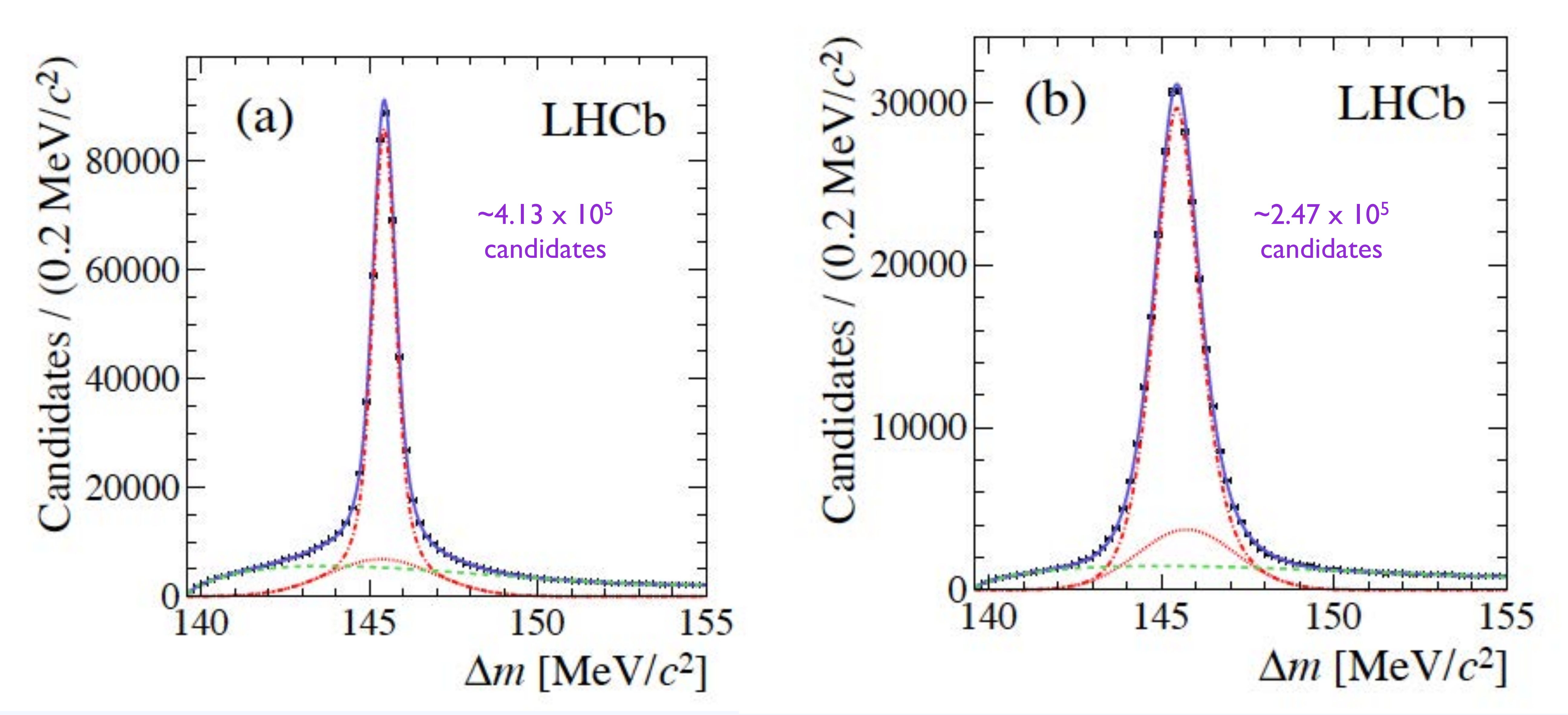
No evidence for CPV in the charm sector at 1.8% CL

Conclusions

- Precision CPV measurements in the charm sector at LHCb
- First application of the energy test for direct CPV searches in the multibody decays $D^0 \rightarrow \pi^- \pi^+ \pi^0$ (2 fb^{-1})
- First CPV measurement using π^0's at LHCb
- Measurement of A_Γ using muon tagged D^0 decays corresponding the full Run 1 data sample (3 fb^{-1})
- All searches consistent with no direct or indirect CPV
- Still several LHCb Run 1 analysis ongoing

BACKUP SLIDES

Yields



$\Delta m = m(\pi^{+}\pi^{-}\pi^{0}\pi_{s}^{+}) - m(\pi^{+}\pi^{-}\pi^{0})$

Analysis method: Energy test

Distance metric for the discrete distributions:

test statistic
$$T \approx \frac{1}{n(n-1)} \sum_{i,j>i}^{n} \psi(\Delta\vec{x}_{ij}) + \frac{1}{\bar{n}(\bar{n}-1)} \sum_{i,j>i}^{\bar{n}} \psi(\Delta\vec{x}_{ij}) - \frac{1}{n\bar{n}} \sum_{i,j}^{n,\bar{n}} \psi(\Delta\vec{x}_{ij}).$$

average ψ of D^0 events w.r.t. each other

average ψ of $\bar{D}^0$ events w.r.t. each other

average ψ of D^0 to $\bar{D}^0$ events

Method sensitive to local CP asymmetries but not to global asymmetries

$$\vec{x} \equiv (M_{ab}^2, M_{bc}^2, M_{ca}^2)$$

Point in phase space, all 3 invariant masses used

$$\psi(\Delta\vec{x}) = e^{-\Delta\vec{x}^2/2\sigma^2}.$$

Gaussian metric function

- no CP violation
  - ➡ all average distances equal → T≈0
- CP asymmetry
  - ➡ average distance btw. D^0 and $\bar{D}^0$ events larger
  - ➡ average ψ btw. D^0 and $\bar{D}^0$ events smaller
  - ➡ T > 0

σ -tunable parameter: effectively, radius in the phase space in which a local asymmetry is measured

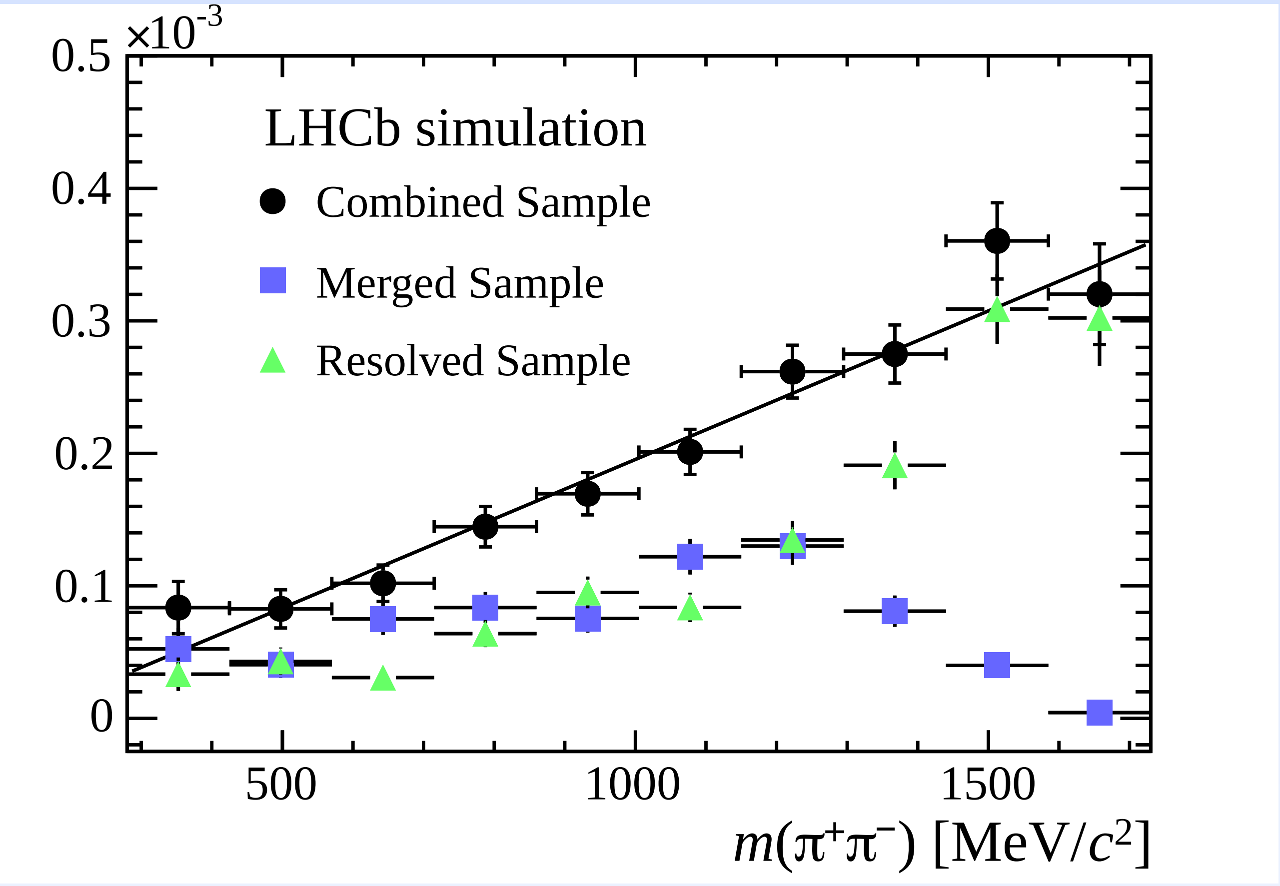
P-values

- Calculate p-value for no CPV hypothesis
- Can obtain p-value from counting permutation T values (used for final result)
- For small p-values from fitting distribution and calculating fractional integral (used for sensitivity studies)
    - Fit using generalised extreme value function

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

Sensitivity

- The selection efficiency obtained using full LHCb MC
- The sensitivity studies use generator package: Laura++ to model signal decays
- Background events modelled according to sideband distributions



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Better sensitivity than BaBar in general, but comparable for ρ^0 amplitude CPV

PLB 740 (2015) 158-167

Results

- With1000 permutations
- For no-CPV hypothesis:
  - p-value = (2.6±0.5)%
- Other metric parameters
  - σ = 0.2: p = (4.6±0.6)%
  - σ = 0.4: p = (1.7±0.4)%
  - σ = 0.5: p = (2.1±0.5)%

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Visualisation

- Split T value in 2 parts

$$T = \sum_i T_i + \sum_i \bar{T}_i.$$

- Obtain "contribution" of each event

$$T_i = \frac{1}{2n\,(n-1)} \sum_{j \neq i}^{n} \psi\left(\Delta\vec{x}_{ij}\right) - \frac{1}{2n\bar{n}} \sum_{j}^{\bar{n}} \psi\left(\Delta\vec{x}_{ij}\right).$$

$$\bar{T}_i = \frac{1}{2\bar{n}\,(\bar{n}-1)} \sum_{j \neq i}^{\bar{n}} \psi\left(\Delta\vec{x}_{ij}\right) - \frac{1}{2n\bar{n}} \sum_{j}^{n} \psi\left(\Delta\vec{x}_{ij}\right).$$

same sign events   cc events

- Calculate permutation T_i values
- Take smallest and largest T_i of each permutation

➡ Calculate T_i significance for being larger than T_i^{max} or smaller than T_i^{min} distribution

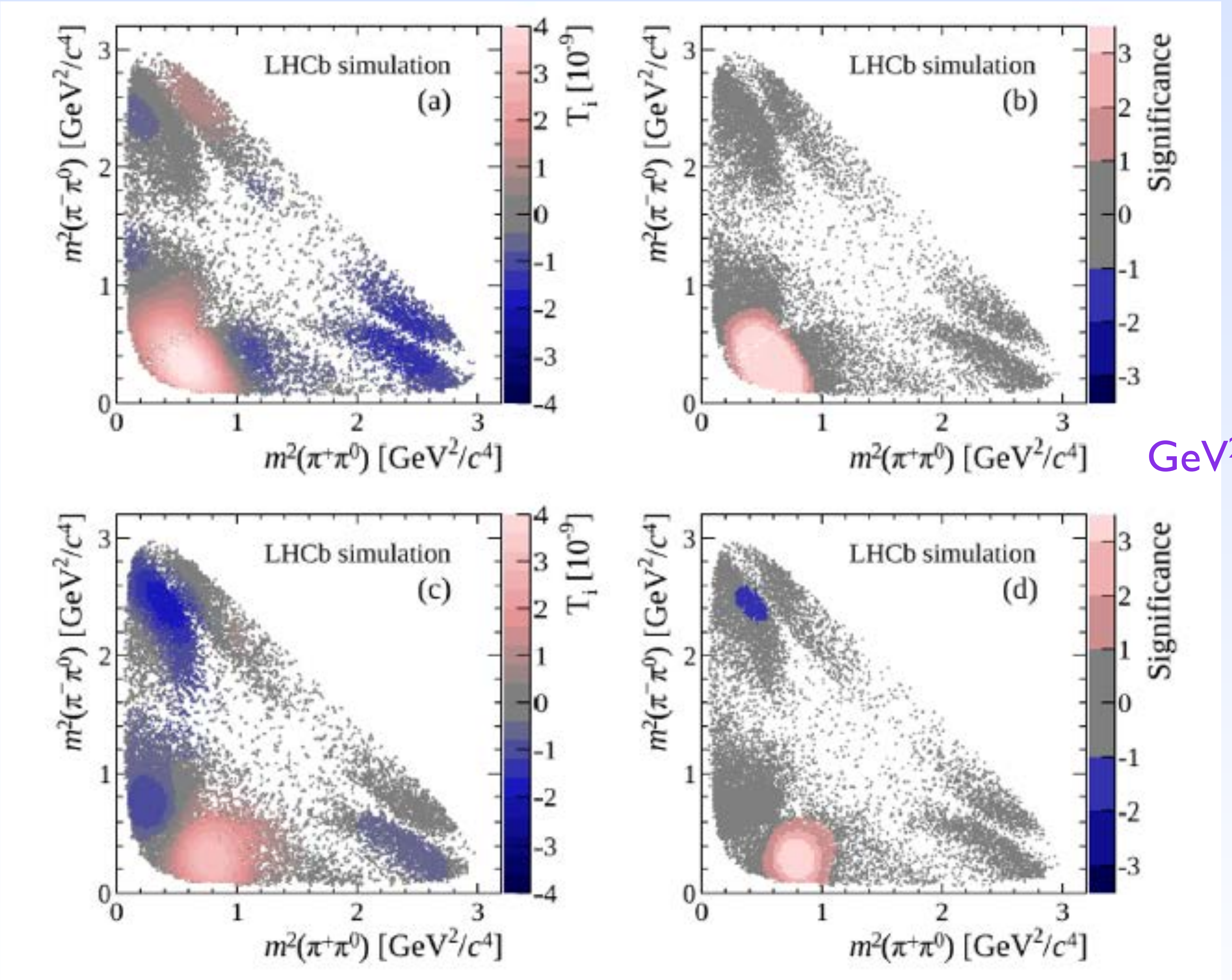
➡ Can plot significance of positive or negative asymmetry for each event

Visualisation

$$\psi(\Delta\vec{x}) = e^{-\Delta\vec{x}^2/2\sigma^2}.$$

ρ$^+$ amplitude CPV

ρ$^+$ phase CPV



GeV^2/c^4

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Cross checks

Two major sources of asymmetries that may bias the result:

- Asymmetries from background events
  - Apply energy test to the upper sideband of Δm
  - Generating toys for D^0 and $\overline{D}^0$ sidebands
- Detection asymmetries
  - Use the Cabibbo-favoured $D^0 \to K^- \pi^+ \pi^0$ mode (conservative test because of the larger kaon detection asymmetry)
  - Split the sample in 8 subsamples
  - Split the sample by polarity

No indication of background or detector related asymmetries

Crosscheck with a binned method yields consistent results

Systematics

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Submitted to JHEP

Source of uncertainty	$D^0 \to K^- K^+$		$D^0 \to \pi^- \pi^+$	
	constant	scale	constant	scale
Mistag probability	0.006%	0.05	0.008%	0.05
Mistag asymmetry	0.016%		0.016%	
Time-dependent efficiency	0.010%		0.010%	
Detection and production asymmetries	0.010%		0.010%	
D^0 mass fit model	0.011%		0.007%	
D^0 decay-time resolution		0.09		0.07
B^0–$\overline{B}^0$ mixing	0.007%		0.007%	
Quadratic sum	0.026%	0.10	0.025%	0.09