Mixing and CP violation in charm at LHCb

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for the LHCb Collaboration

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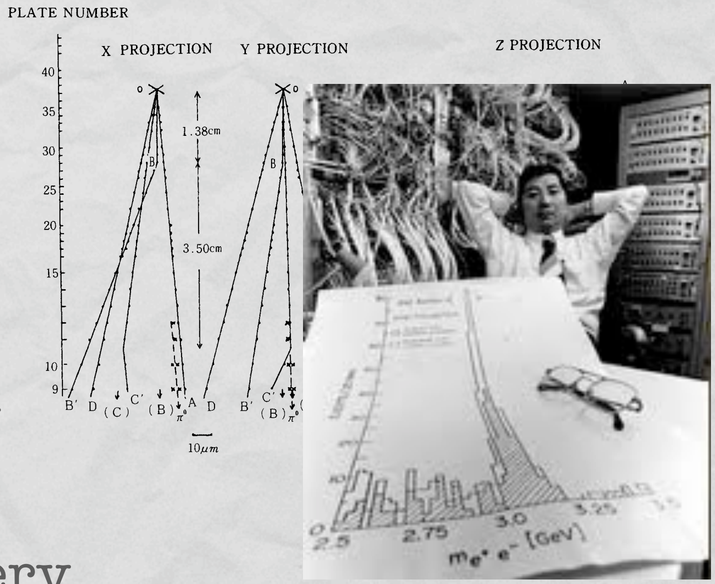
Why charm (again)

Unique probe. Supplements B and K.

Charm quark is up-type. D sensitive to (right-handed) up-type BSM.

Effects are $<10^{-3}$ due to CKM/GIM suppressions: calls for O(>1M) yields and control over systematics.

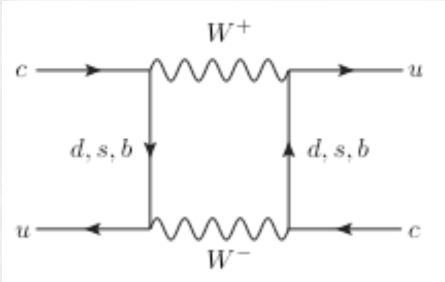


Predictions are hard -- charm is a discovery tool not a precision probe. CP violation in

Mixing $|D_{1,2}\rangle = p|D^0\rangle + q|\overline{D}^0\rangle,\ x = \dfrac{m_2 - m_1}{\Gamma},\ y = \dfrac{\Gamma_2 - \Gamma_1}{2\Gamma}$

Decay $|\mathcal{A}(\overline{D}^0 \to \bar{f})| \neq |\mathcal{A}(D^0 \to f)|$

Both $\lambda_f = \left|\dfrac{q}{p}\right| \left|\dfrac{\mathcal{A}(\overline{D}^0 \to f)}{\mathcal{A}(D^0 \to f)}\right| e^{i(\phi+\delta_f)}$



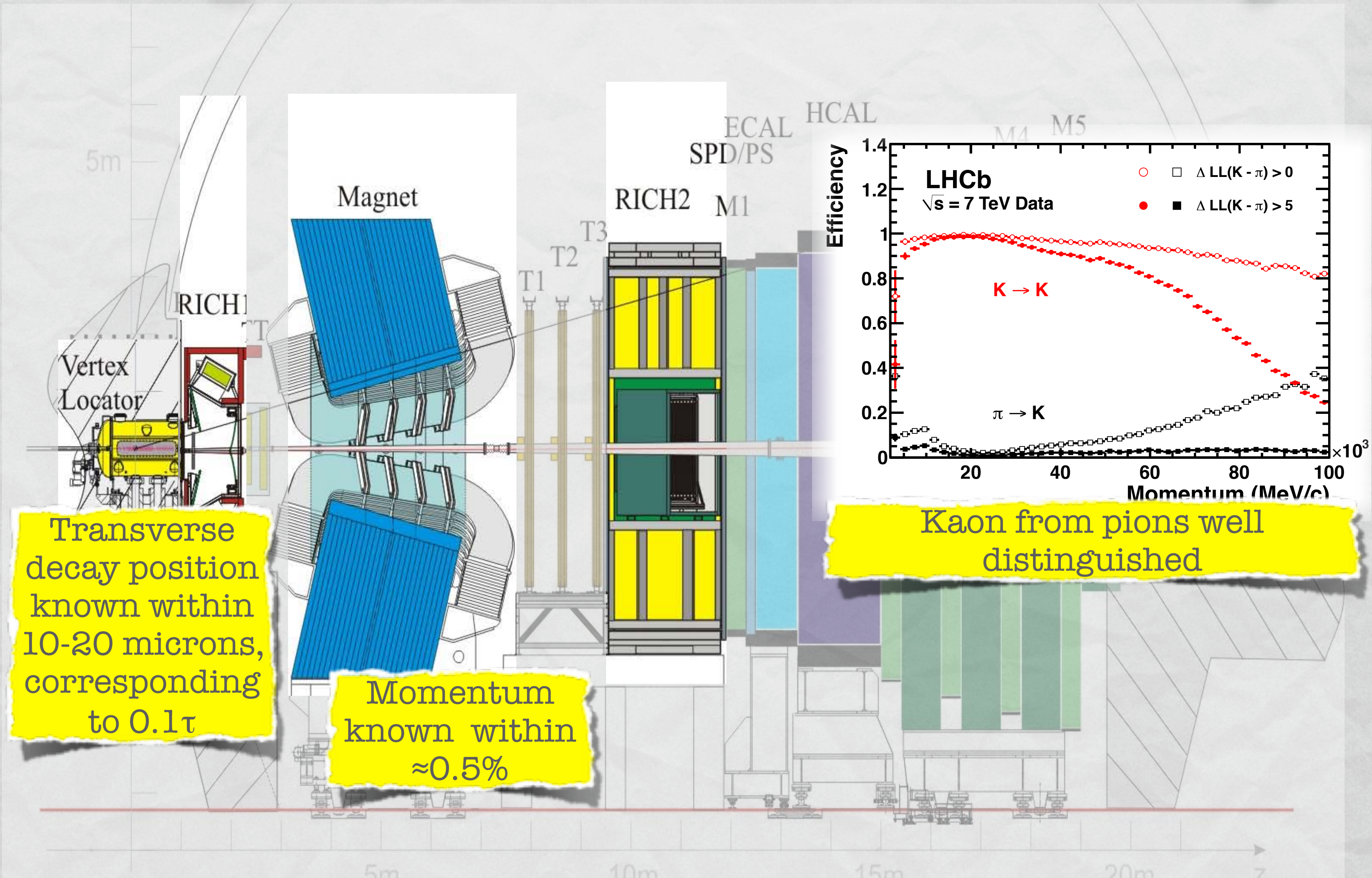
Only recently reached sensitivity to discern SM from non-SM effects

Charm at LHCb

- >2 years of 7-8 TeV proton-proton collisions.
- 5-10% of collisions yield D pairs: $O(10^5)$/s of which $O(10^4)$ are reconstructable and interesting.
- Store 10-20% of them using E_T, p_T, and displacement online. Displacement criterion biases time-evolution.

Today: recent CPV and mixing results based on 1-3 fb^{-1} data set

Large Hadron Collider beauty



Transverse decay position known within 10-20 microns, corresponding to 0.1τ

Momentum known within ≈0.5%

Kaon from pions well distinguished

Measurements of local, time-integrated CP violation in multibody decays

Direct CPV in $D \to$ multibody

$$A_{CP} = \frac{\Gamma(D \to f) - \Gamma(\bar{D} \to \bar{f})}{\Gamma(D \to f) + \Gamma(\bar{D} \to \bar{f})}$$

To be nonzero, needs >1 amplitude: use Cabibbo suppressed, fully reconstructed decays into charged final-state particles $D^0 \to \pi\pi\pi\pi$, $KK\pi\pi$ and $D^+ \to \pi\pi\pi$ (1 fb^{-1} of 2011 data).

Use p_T and displacement online to isolate pure signal samples.

Residual background suppressed offline with PID and D pointing.

Equalize kinematics and data-taking conditions of D and $\bar{D}$ samples. Yields determined from fits to mass distributions.

Exploit $D \to$ n-body dynamics to seek enhancements of CPV that cluster in subregions of the phase space. Could go unnoticed in measurements of global asymmetries.

Gettin' local

Separate D from $\bar{D}$ using final-state charge or D*-tag.

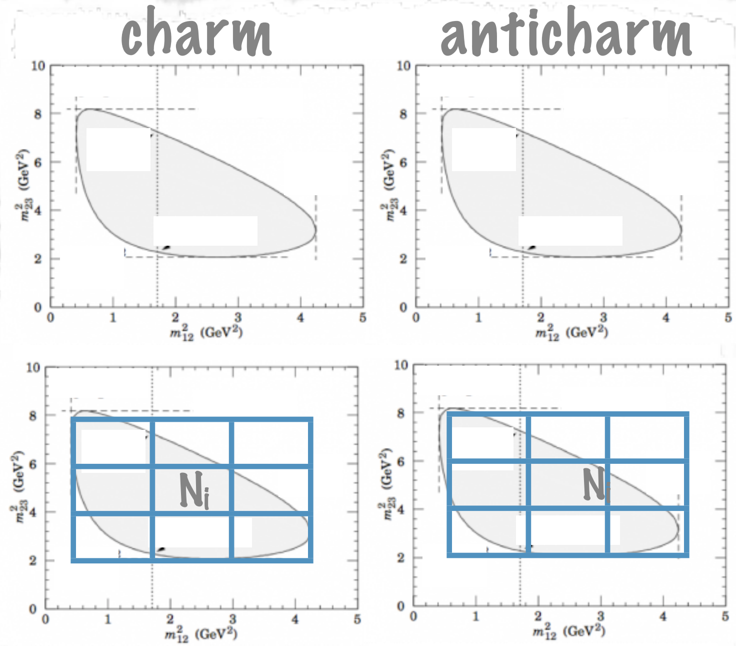
Divide phase-space into regions.

Seek differences in relative density between D and $\bar{D}$ in each region by constructing a pull-like variable, S.

S sensitive to CPV and provides χ^2-like quantity to test consistency with CP symmetry. No measurement or limit.

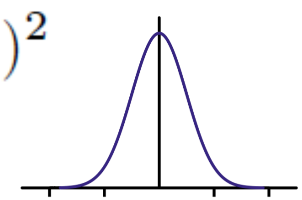
Insensitive to global asymmetries (from physics or spurious).

With 1 fb^{-1} sensitive to 1°-10° differences in phase and 1-10% in magnitude



$$S^i_{CP} = \frac{N_i(D^0) - \alpha N_i(\overline{D}^0)}{\sqrt{\alpha\left(\sigma_i^2(D^0) + \sigma_i^2(\overline{D}^0)\right)}}$$

$$\chi^2 = \sum_i (S^i_{CP})^2$$

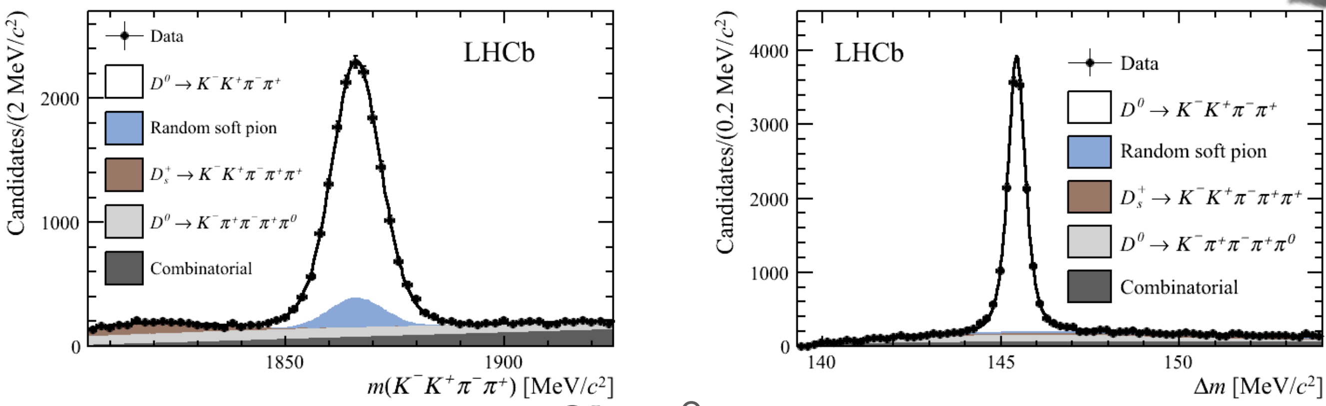


4-body

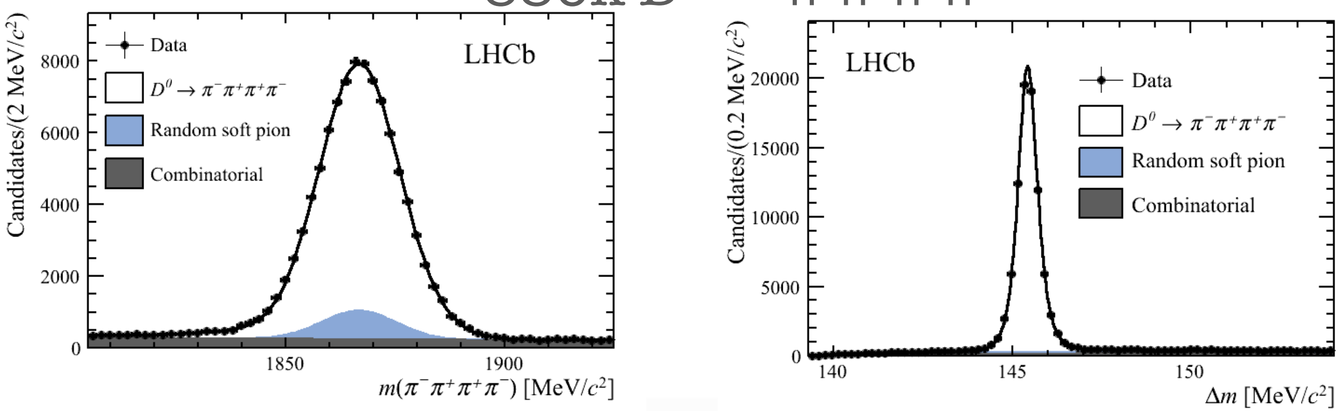
PLB 726, 623 (2013)

1 fb^{-1}

57k $D^0 \to K^+K^-\pi^+\pi^-$



330k $D^0 \to \pi^+\pi^-\pi^+\pi^-$



Simultaneous Δm-m(D) fit. Subtract background and compare the 5-dimensional phase space.

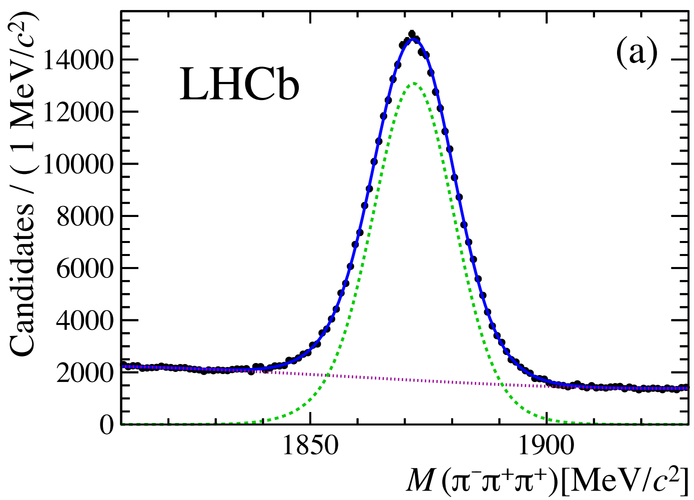
Validate analysis on 2.9M Cabibbo-favored D→Kπππ decays.

3-body

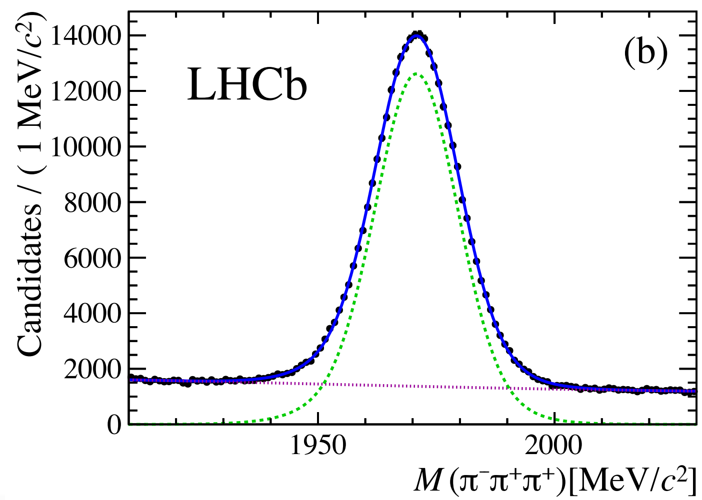
1 fb^{-1}

arXiv:1310.7593

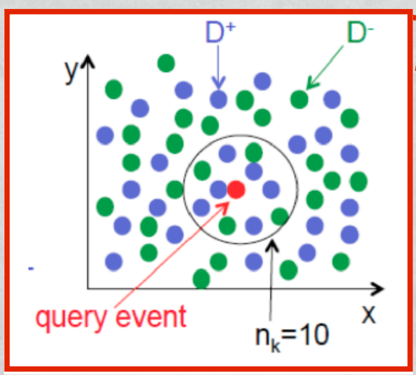
2.7M D^+ signal

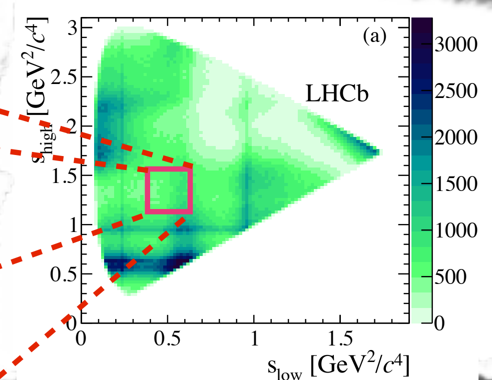


2.7M D^+_s control



Unbinned approach based on recurrence of same-flavor vs opposite-flavor neighbors in an arbitrary radius of the Dalitz space.





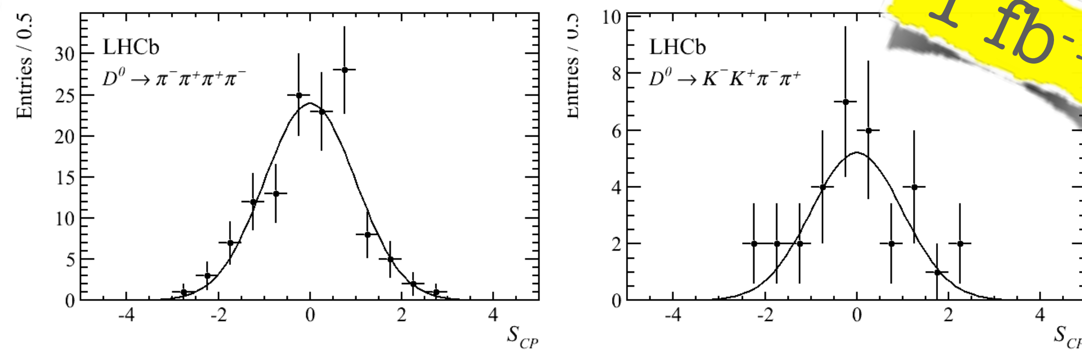
Binned method used too.

Local CPV results

1 fb^{-1}

4 body

PLB 726, 623 (2013)

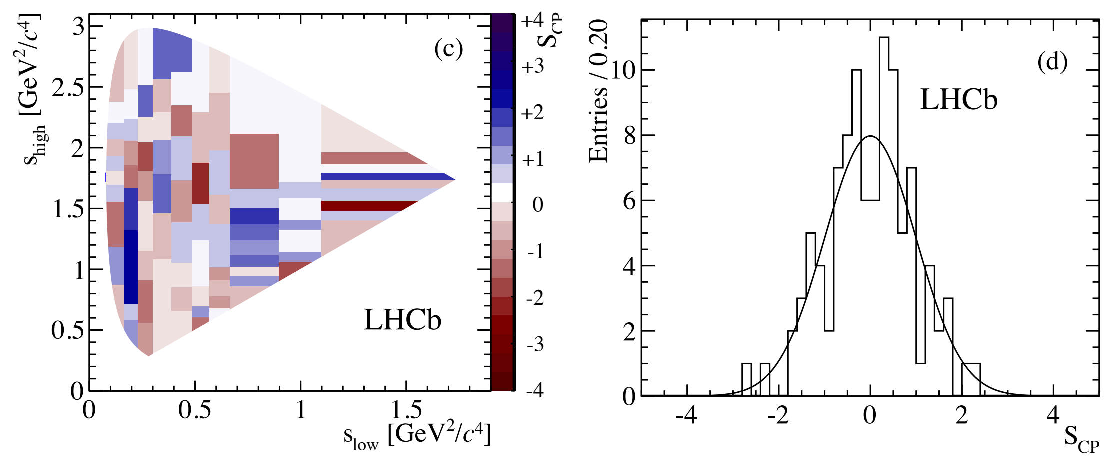


p-value = 41%

p-value = 9%

3 body

arXiv:1310.7593

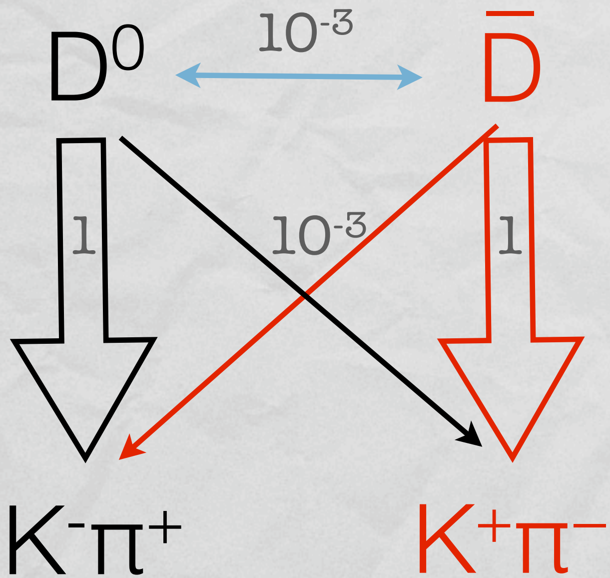


p-value = 75%

No evidence for local CP violation

Measurements of mixing and decay-time-dependent CP violation

Wrong-sign mixing



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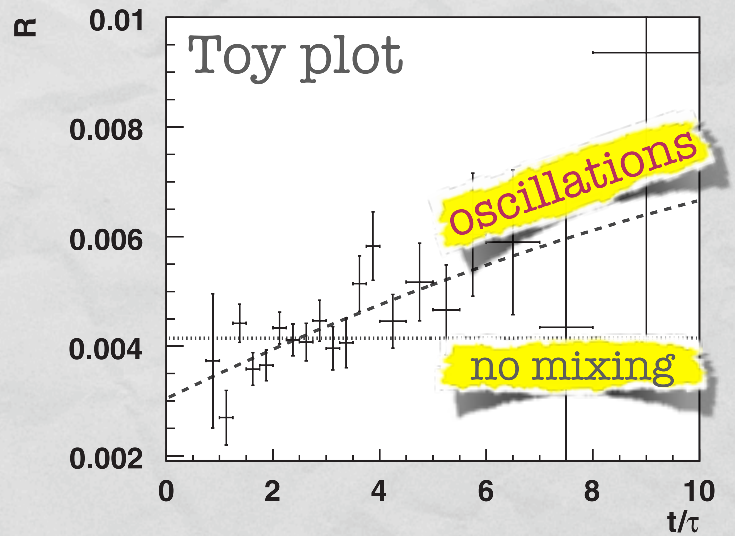


$$R(t) = \frac{N_{WS}(t)}{N_{RS}(t)} = R_D + \sqrt{R_D}y't + \frac{x'^2 + y'^2}{4}t^2$$

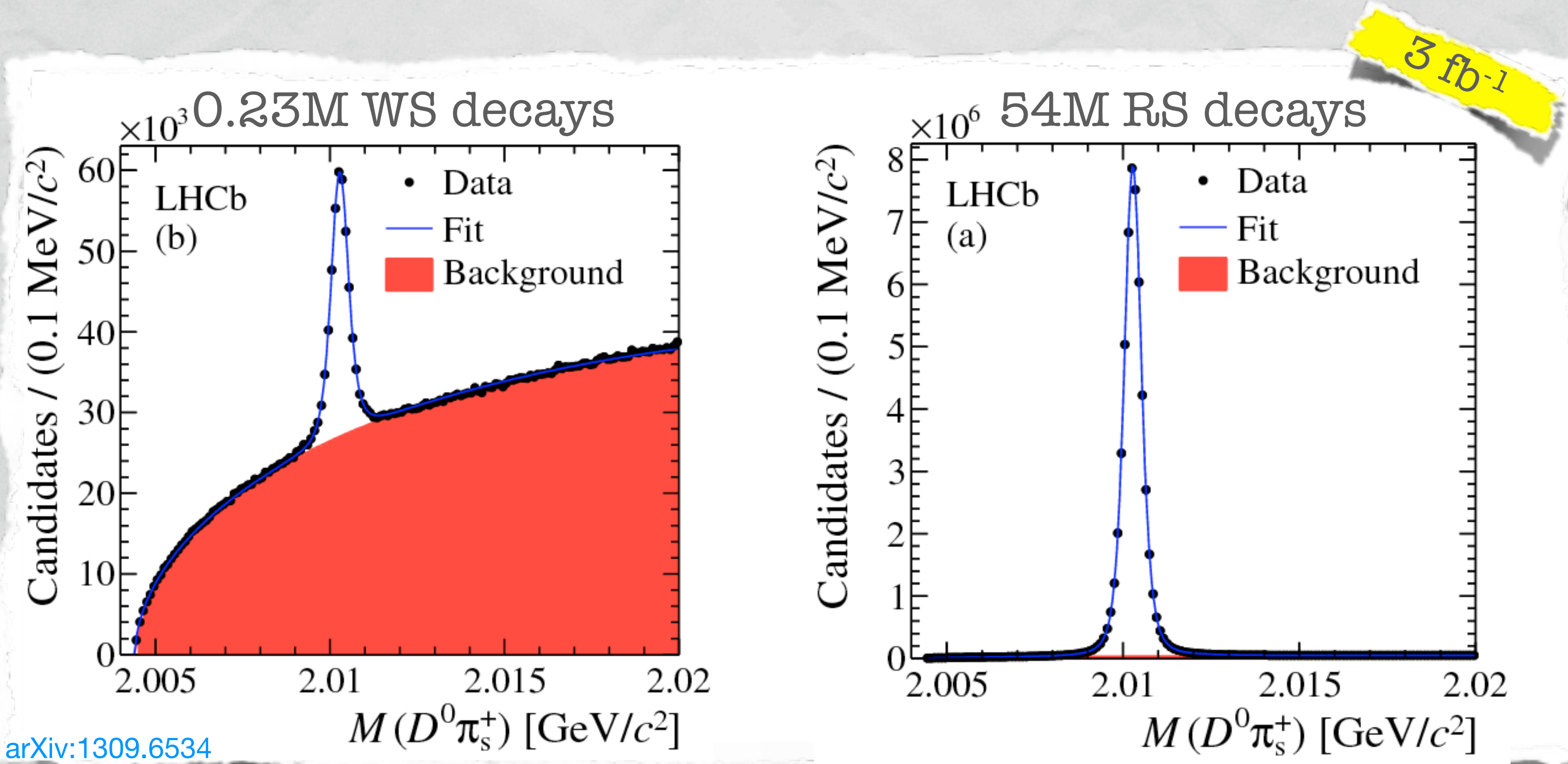
i) Reconstruct neutral D signals in $K^{\mp}\pi^{\pm}$ final states.

ii) Classify as WS or RS using $D^{*\pm}$ to identify flavor at production.

iii) WS/RS ratio vs time separates suppressed decay from oscillation.

vi) Fit D^0 and $\bar{D}^0$ time evolution independently in search for CPV.

Full LHCb data set



arXiv:1309.6534

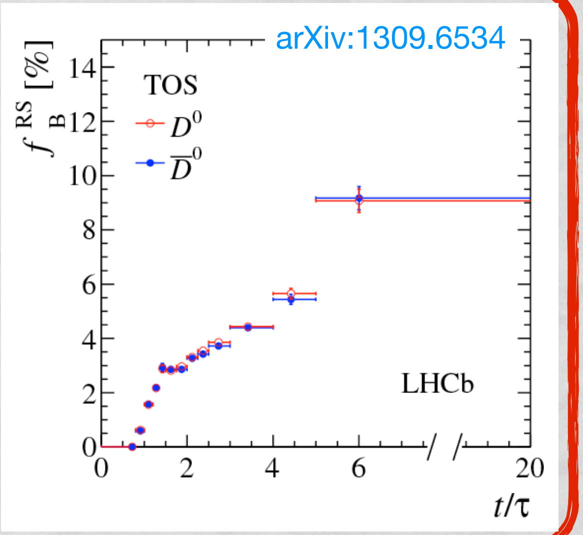
Cut tight on M(D) and PID. Fit the yield using M(Dπ) mass.

Fit yields in bins covering the 0-20τ range. WS and RS signal shapes constrained to be the same. All the rest independent.

Systematic effects

Assume maximum bias due to 3% residual contamination of D from B.

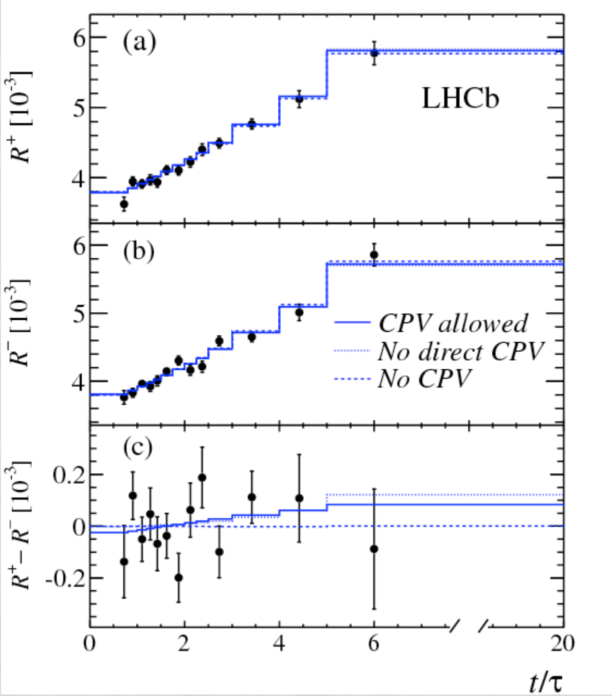
Fraction determined by fits of the D impact parameter and checked to be charge-symmetric

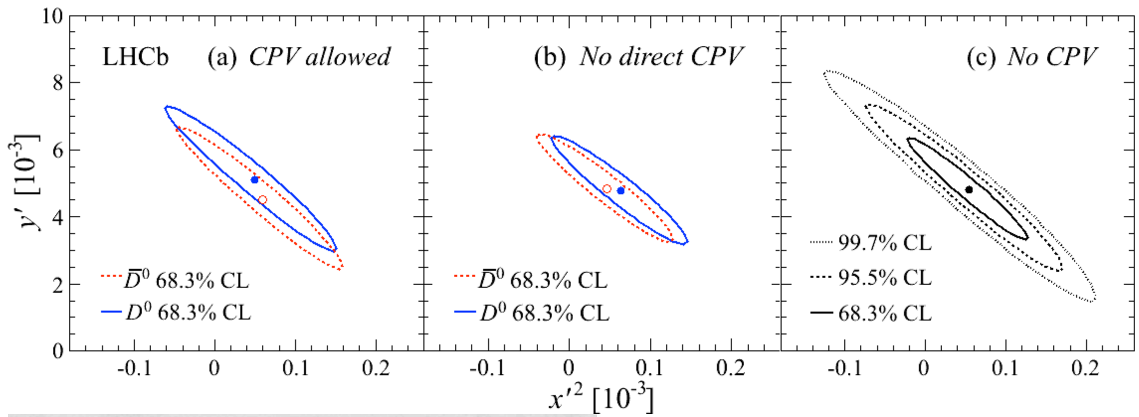


Instrumental bias from differing reconstruction efficiency between $K^+\pi^-$ and $K^-\pi^+$ final state constrained to be (1.0 ± 0.2)% from charged D decays into $K_S{}^0\pi$ and $K\pi\pi$

Systematic uncertainties smaller than statistical ones. Included as Gaussian constraints in the final fit.

CPV in wrong-sign mixing





Full LHCb 3 fb^{-1} data set

Direct and indirect *CP* violation		
R_D^+	$[10^{-3}]$	$3.545 \pm 0.082 \pm 0.048$
y'^+	$[10^{-3}]$	$5.1 \pm 1.2 \pm 0.7$
x'^{2+}	$[10^{-5}]$	$4.9 \pm 6.0 \pm 3.6$
R_D^-	$[10^{-3}]$	$3.591 \pm 0.081 \pm 0.048$
y'^-	$[10^{-3}]$	$4.5 \pm 1.2 \pm 0.7$
x'^{2-}	$[10^{-5}]$	$6.0 \pm 5.8 \pm 3.6$
χ^2/ndf		85.9/98
No direct *CP* violation		
R_D	$[10^{-3}]$	$3.568 \pm 0.058 \pm 0.033$
y'^+	$[10^{-3}]$	$4.8 \pm 0.9 \pm 0.6$
x'^{2+}	$[10^{-5}]$	$6.4 \pm 4.7 \pm 3.0$
y'^-	$[10^{-3}]$	$4.8 \pm 0.9 \pm 0.6$
x'^{2-}	$[10^{-5}]$	$4.6 \pm 4.6 \pm 3.0$
χ^2/ndf		86.0/99
No *CP* violation		
R_D	$[10^{-3}]$	$3.568 \pm 0.058 \pm 0.033$
y'	$[10^{-3}]$	$4.8 \pm 0.8 \pm 0.5$
x'^2	$[10^{-5}]$	$5.5 \pm 4.2 \pm 2.6$
χ^2/ndf		86.4/101

$0.75 < |q/p| < 1.24$ at the 68% CL

$A_D = (-0.7 \pm 1.9)\%$

No evidence for CP violation. Best determination of mixing parameters

arXiv:1309.6534

Effective-lifetime asymmetry

$$A_\Gamma = \frac{\hat{\tau}(\overline{D}^0) - \hat{\tau}(D^0)}{\hat{\tau}(\overline{D}^0) + \hat{\tau}(D^0)} \approx \frac{1}{2}\left[\left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right) y\cos\phi - \left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right) x\sin\phi\right]$$

Nonzero if CPV in mixing occurs. Dominated by B-factories with 0.2% uncertainty. Update of early LHCb measurement using 1 fb^{-1} of 2011 data.

Use p_T, displacement, and PID to select >90% pure samples of 3M $D^0 \to KK$ and 1M $D^0 \to \pi\pi$ decays.

D^* to tag D flavor at production and measure D and $\bar{D}$ yields as a function of decay time.

Validate analysis on $D^0 \to K\pi$ decays.

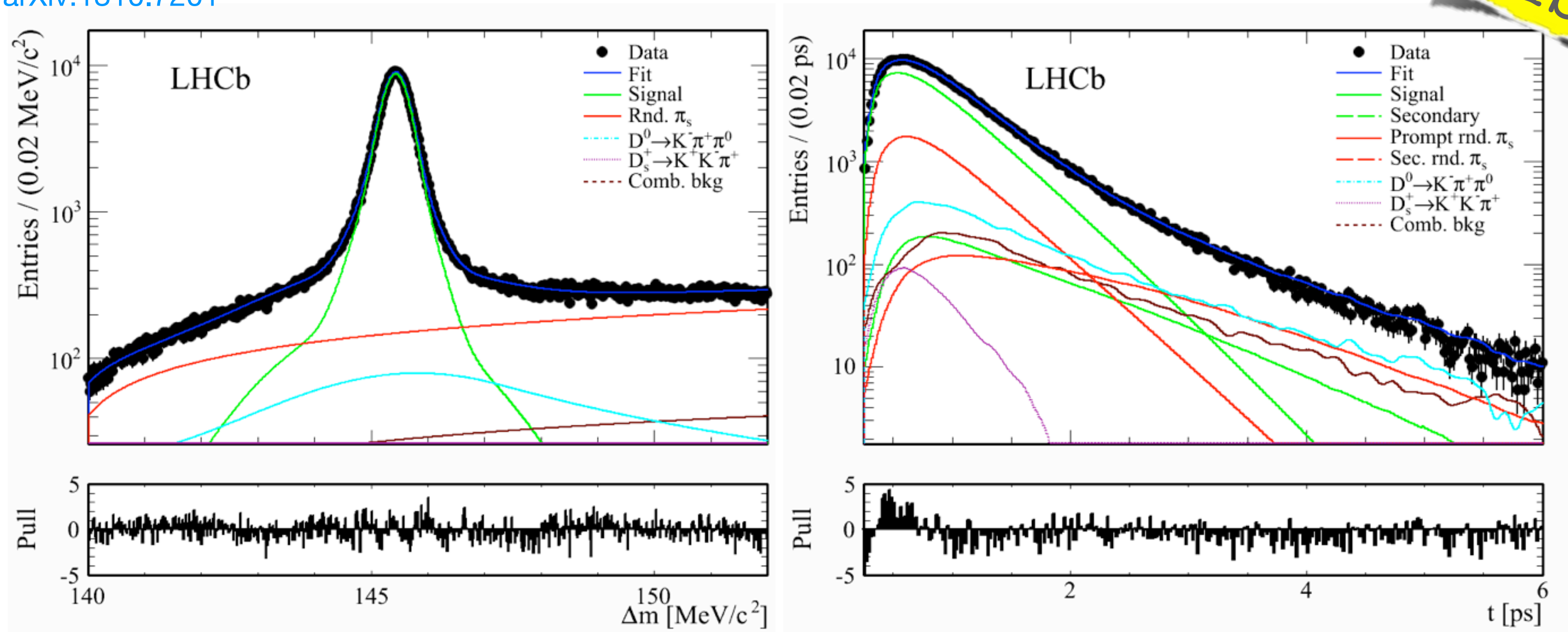
Acceptance vs decay-time for each candidate taken from data.

Slide each decay along the D flight path to determine the sequence of accepted/rejected times for that decay.

Effective lifetime fit

1 fb^{-1}

arXiv:1310.7201



1. Joint Δm-m(D) fit separates signal from background and determines charm and anticharm yields.

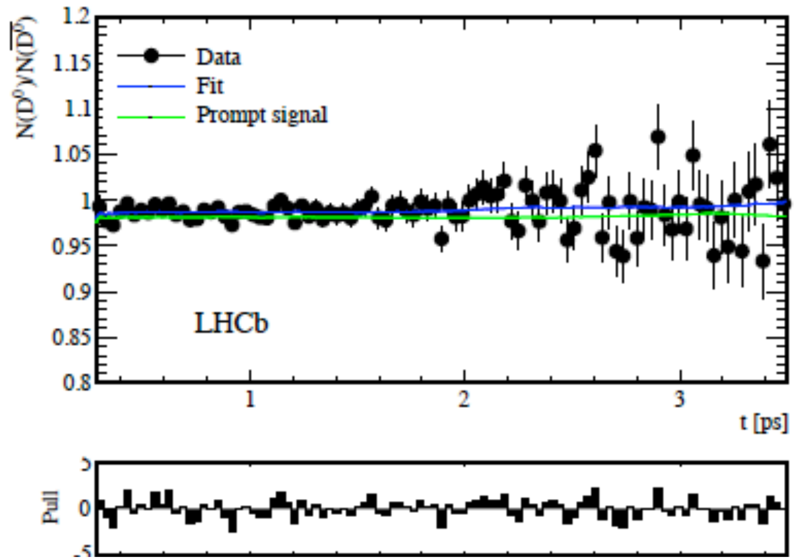
2. Joint ct and D-pointing fit determines the time evolution separating primary D from a small fraction of B→D decays.

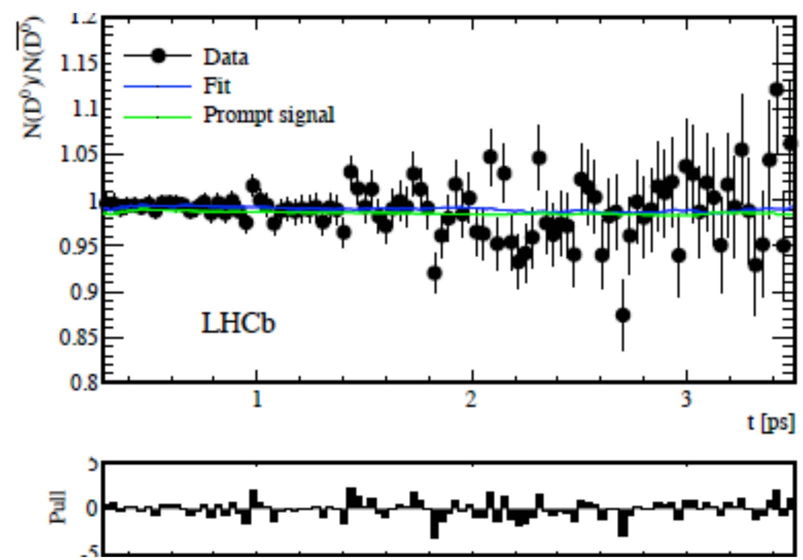
Lifetime-asymmetry results

1 fb^{-1}

arXiv:1310.7201

Source	$A_\Gamma(K^+K^-)$	$A_\Gamma(\pi^+\pi^-)$
Partially reconstructed backgrounds	± 0.02	± 0.00
Charm from b decays	± 0.07	± 0.07
Other backgrounds	± 0.02	± 0.04
Acceptance function	± 0.09	± 0.11
Total syst. uncertainty	± 0.12	± 0.14





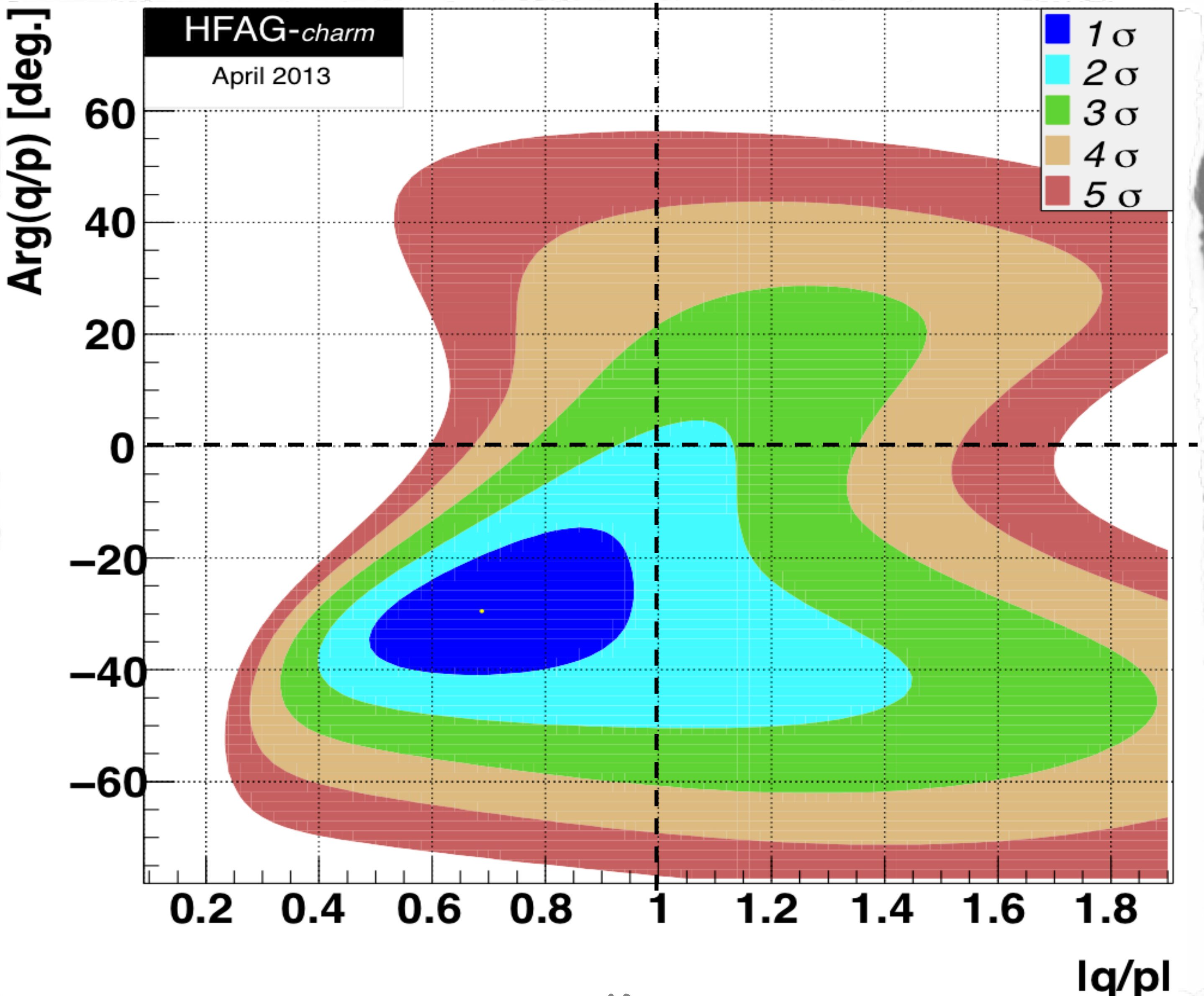
$A_\Gamma(K^+K^-) = (-0.35 \pm 0.62 \pm 0.12) \times 10^{-3}$

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

No evidence for indirect CPV within 0.1%

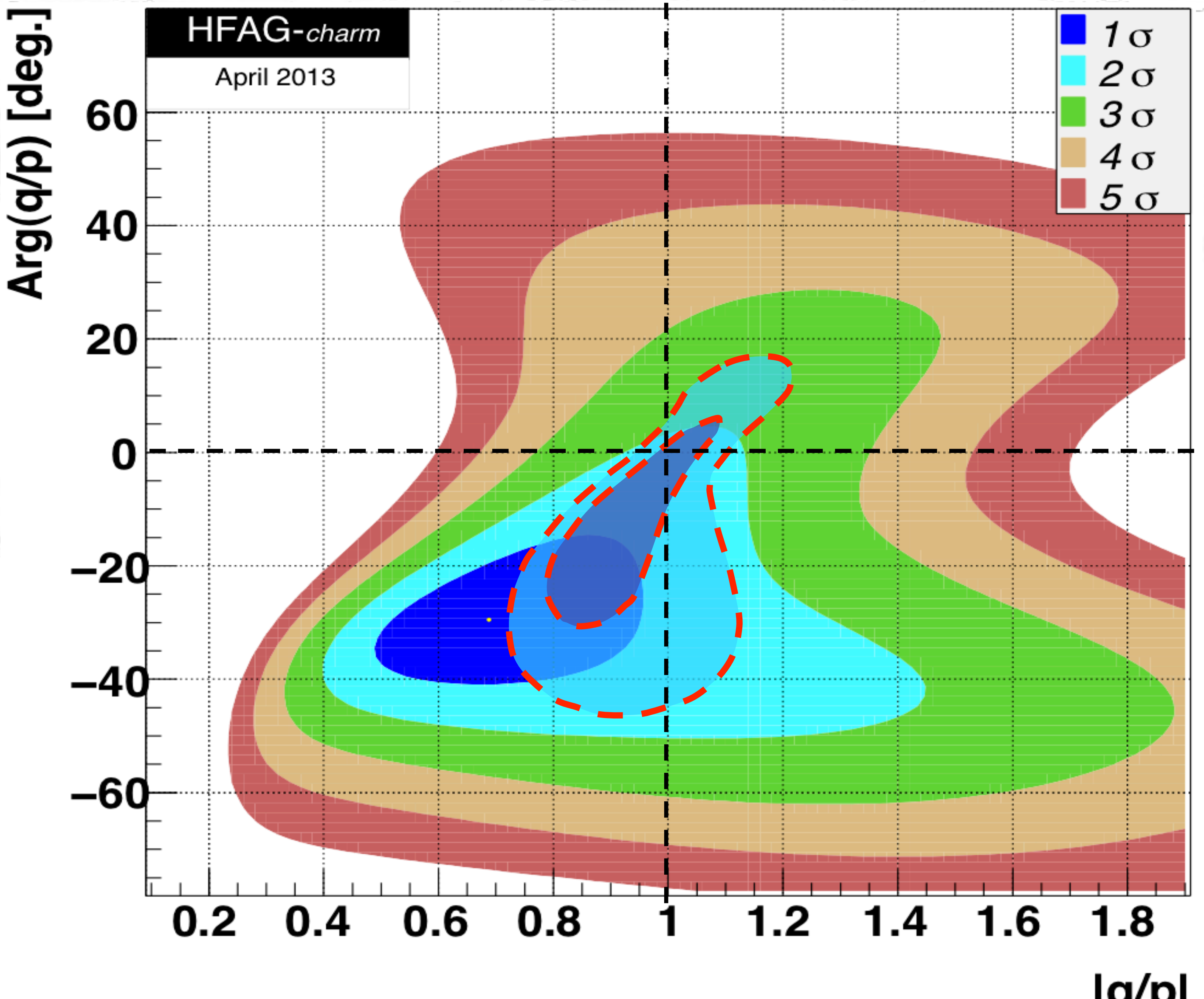
World's best result with only 1/3 of currently available data.

Impact



HFAG-charm
April 2013
1 σ
2 σ
3 σ
4 σ
5 σ
Arg(q/p) [deg.]
60
40
20
0
−20
−40
−60
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
Iq/pI

Impact



HFAG-charm
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1 σ
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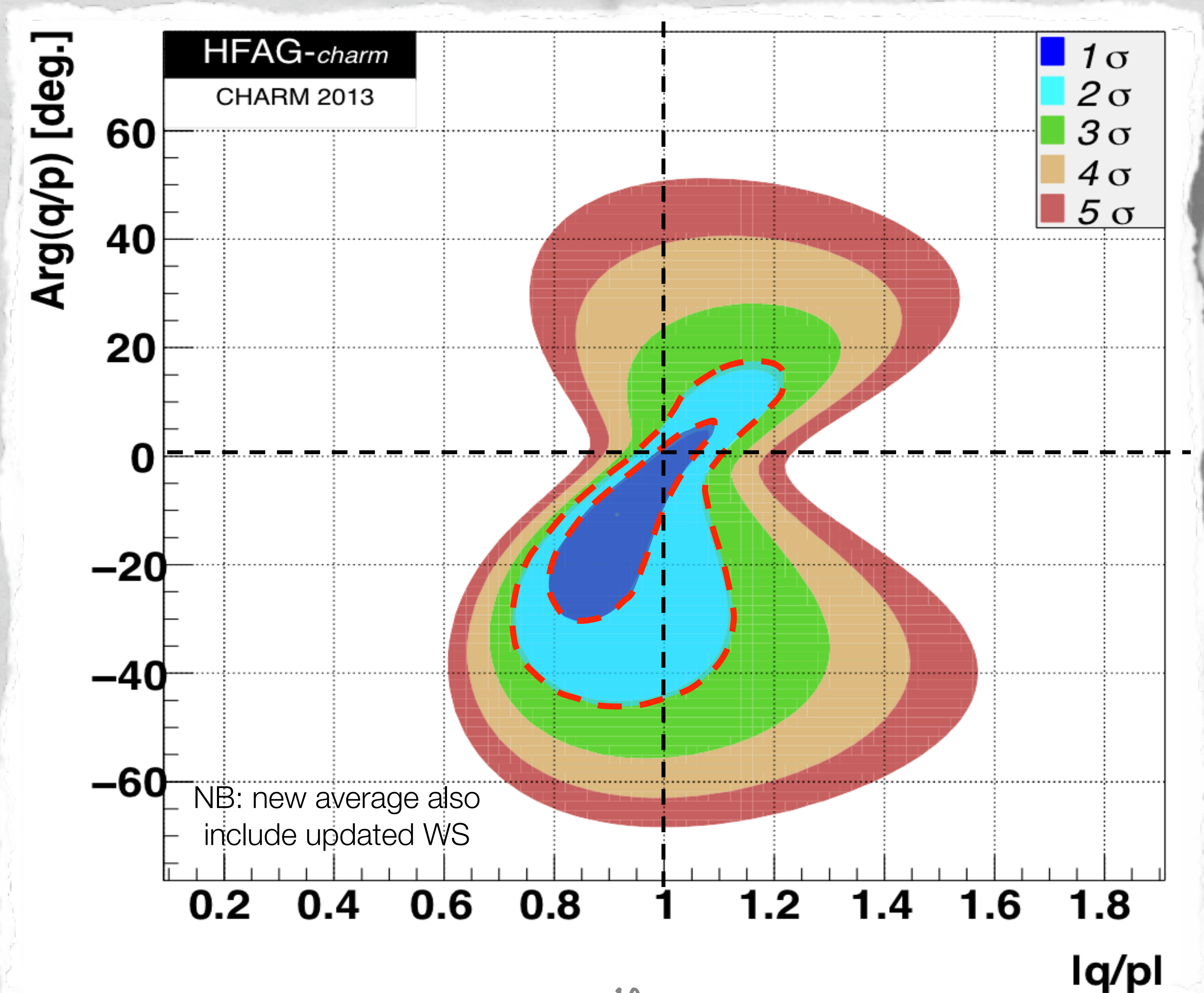
Arg(q/p) [deg.]
60
40
20
0
−20
−40
−60
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
lq/pl

Impact



HFAG-charm
CHARM 2013
1 σ
2 σ
3 σ
4 σ
5 σ
Arg(q/p) [deg.]
60
40
20
0
–20
–40
–60
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
Iq/pI
NB: new average also
include updated WS

Summary

- CPV and mixing in charm -- among the best games in town to probe the multiTeV scale.
- Only recently enough sensitivity to probe SM from nonSM.
- Exploration led by LHCb: low-background samples with $O(10^6)$ decays. Sample decay times with $\approx 20\tau$ lever arm and 0.1τ resolution.
  - No CPV in wrong-sign $K\pi$ mixing using the full sample.
  - No CPV in KK and $\pi\pi$ lifetime asymmetries within 0.1%.
  - No CPV in the phase-space of multibody D^+ and D^0 decays
- All are world best measurements -- sit back and relax; many others are coming.

the end


CHARM QUARK
c
charm quark
Heavier than a strange quark, but not as heavy as a bottom quark, the CHARM QUARK was discovered in 1974. Particles that contain charm and anticharm quarks are called "charmed matter."
Acrylic felt/fleece with a mix of poly beads and gravel for medium-heavy mass.
$9.75 PLUS SHIPPING
LIGHT
HEAVY
CHARM QUARK
The PARTICLE ZOO

Difference of DCPV

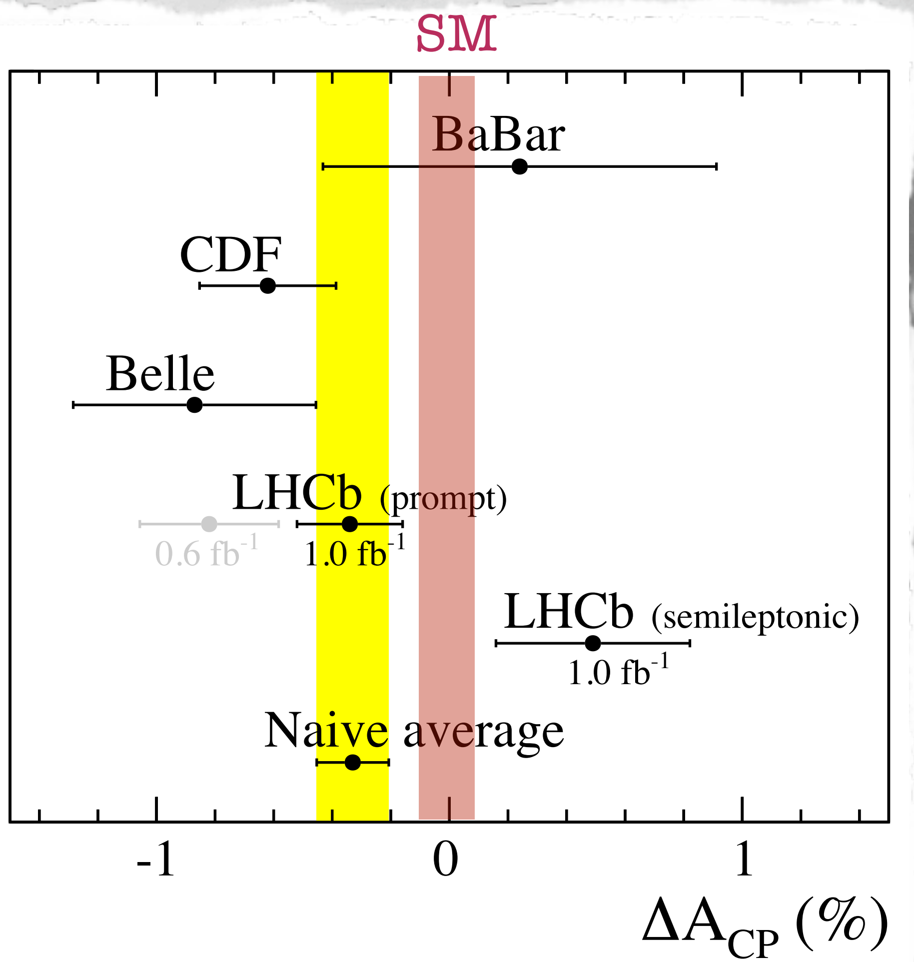
Intriguingly large difference between the decay rate of charm matter and antimatter in pairs of pions and kaons.

At odds with expectations

Experimental and theoretical picture is still blurry

Wrong expectations?
Wrong measurements?
Both?
Something new sneaking in?

Measurement with full LHCb data set in progress



PRL 108 (2012) 111602, PRL 109 (2012) 111801, arXiv:1212.1975, PRL 100 (2008) 061803, LHCb-CONF-2013-003, arXiv:1303.2614