Incontri di Fisica delle Alte Energie (IFAE)
Laboratori Nazionali del Gran Sasso
Gran Sasso Science Institute
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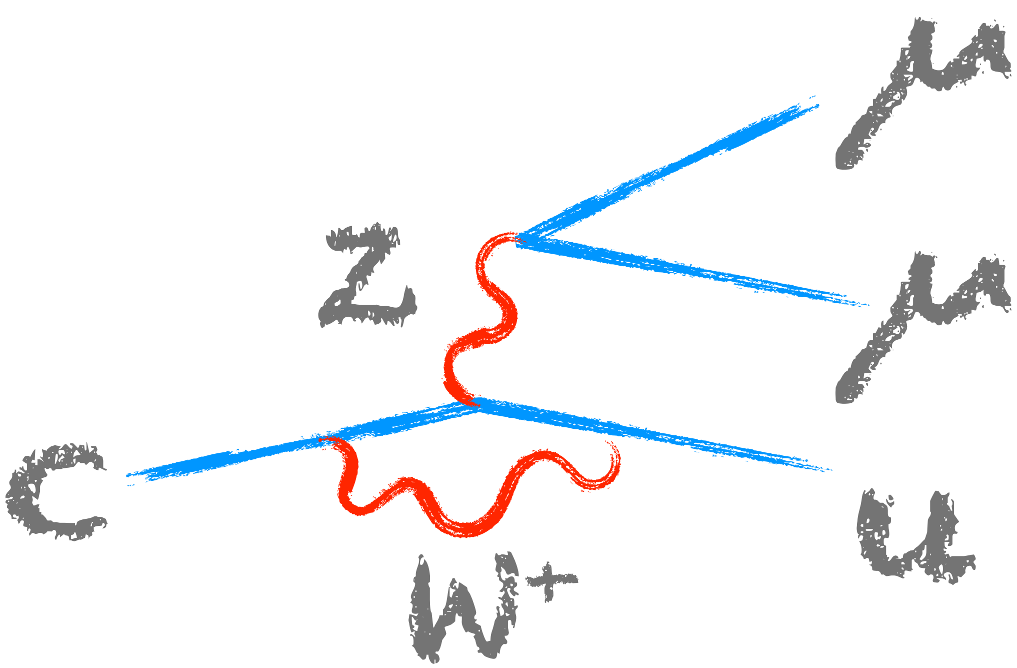
Charm physics at LHCb

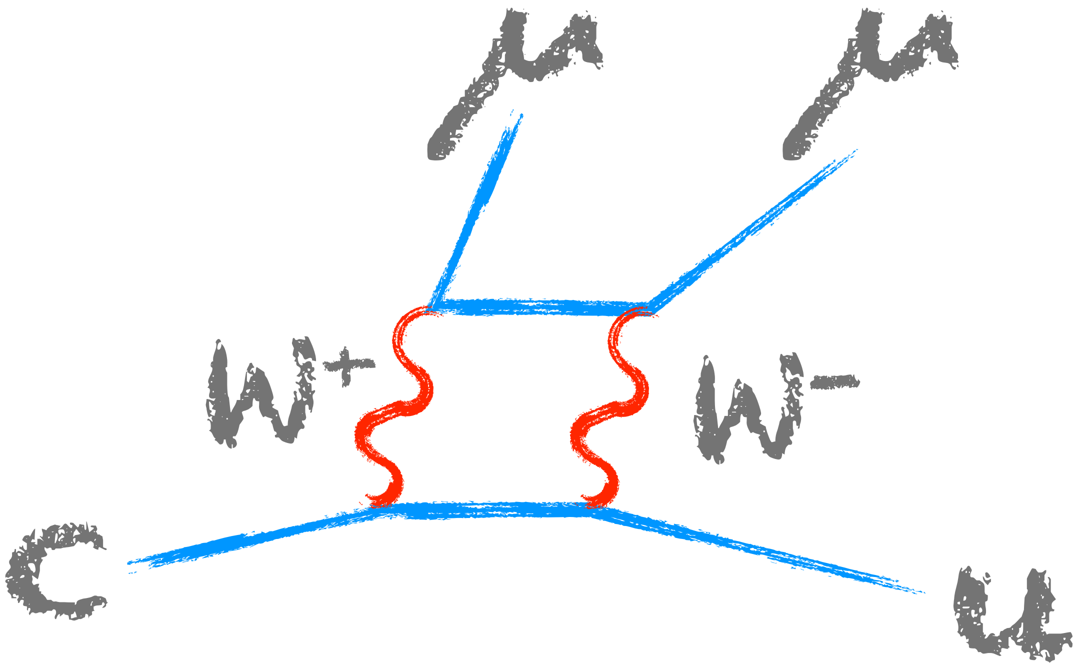
Angelo Di Canto (CERN) on behalf of LHCb

Why is charm charming?

- Unique and powerful probe of BSM flavor effects
- Charm quark is up-type: complements searches done in K and B systems, interplays with high-p_T (top physics) and low-energy (EDMs) probes
- SM 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
- Only recently reached sensitivity to possible BSM physics

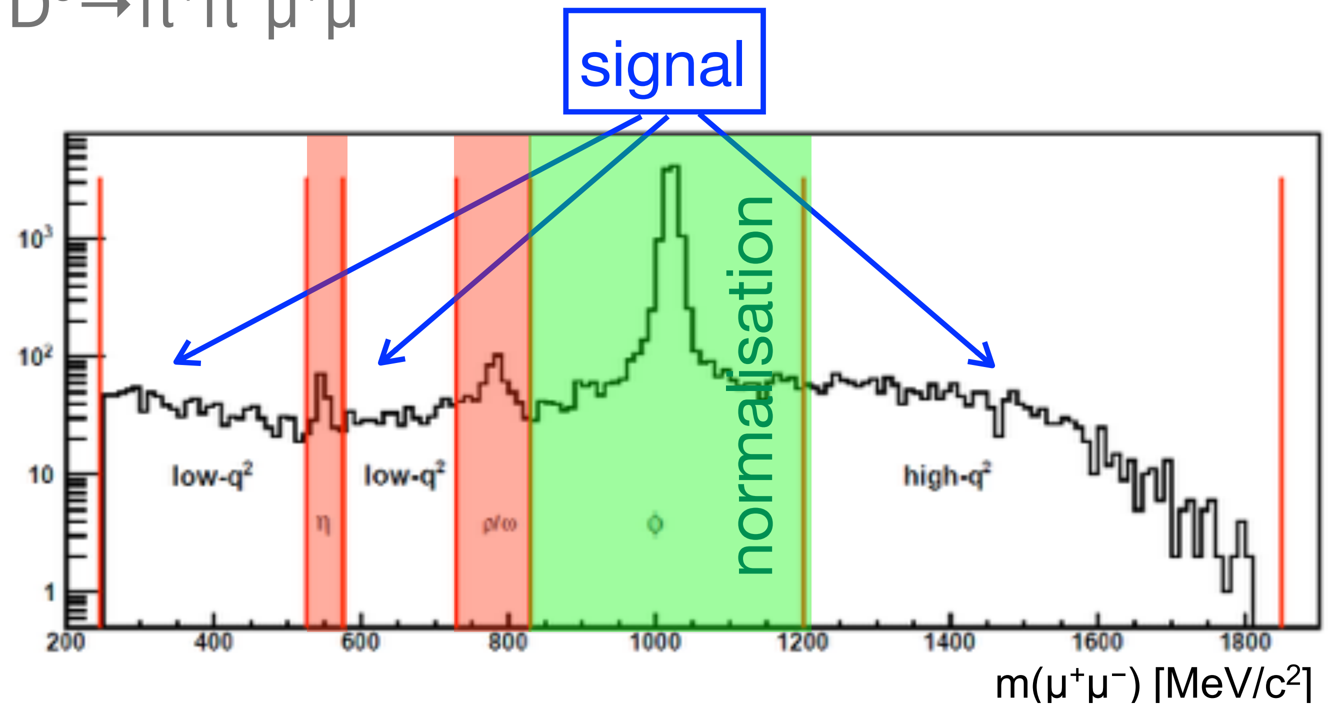
Flavor changing neutral currents





Charm FCNC decays

- Short-distance rate ≲10^{-9}, but rates dominated by long-distance dynamics
- Multibody decays such as $D^+ \to \pi^+\mu^+\mu^-$ or $D^0 \to \pi^+\pi^-\mu^+\mu^-$
  - Long-distance effects alleviated by avoiding μμ resonances (convenient as rate normalisation and control sample)
  - Angular observables/asymmetries are theoretically clean and increase sensitivity to BSM physics

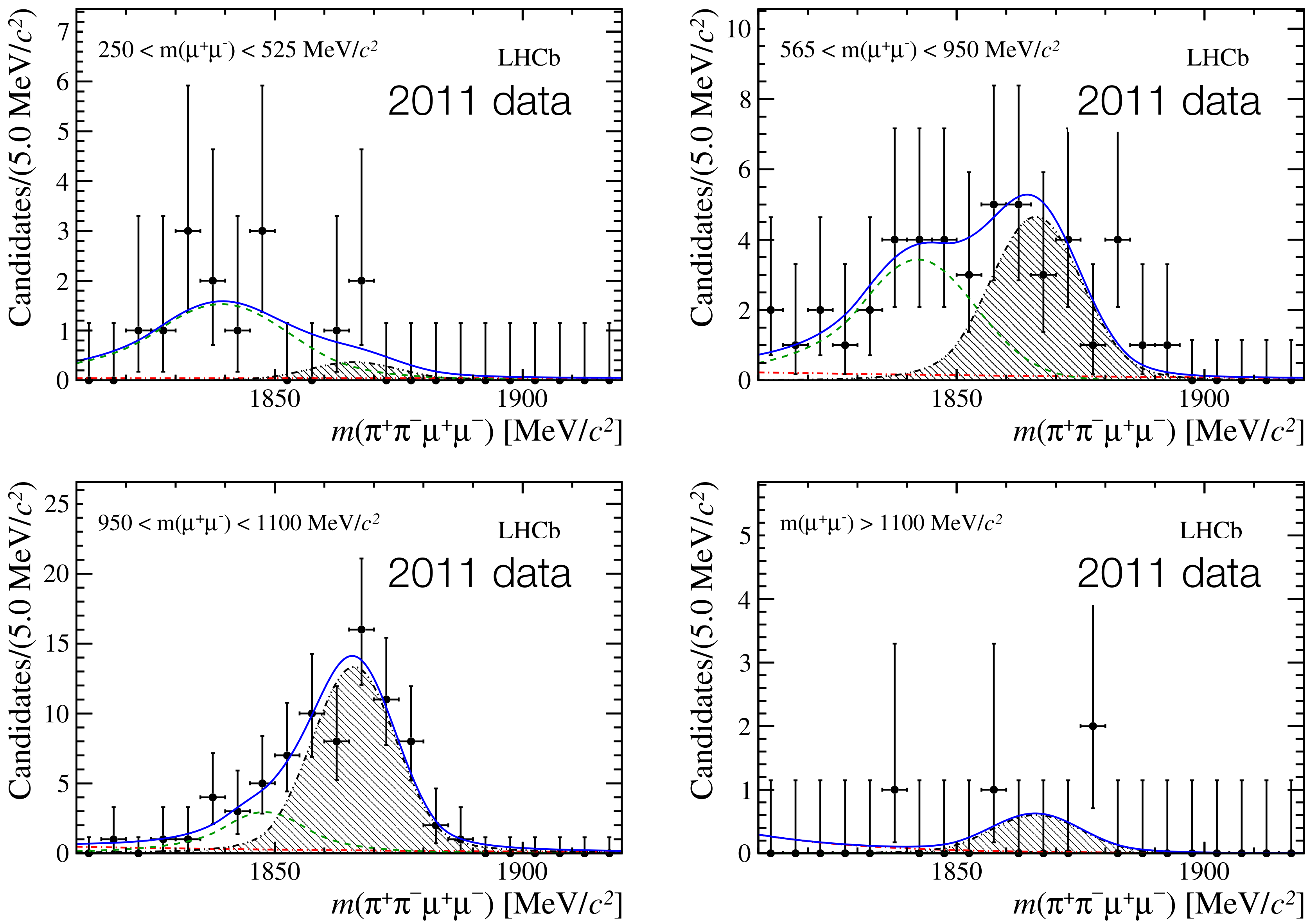


- Experimentally: keep efficiency high and strongly suppress background
  - PID against misidentified hadronic decays (10^6 larger)
  - For neutral mesons, use D^0 from $D^{*+} \to D^0\pi^+$ decays to beat huge combinatorics

Search for $D^0 \to \pi^+\pi^-\mu^+\mu^-$ — Results

signal region (low q^2)

ρ/ω region



ϕ region

signal region (high q^2)

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$D^0 \to \pi\pi\mu\mu$

$D^0 \to 4\pi$

comb bkg

$$\mathcal{B} < 5.5(6.7) \times 10^{-7}$$

$$@\ 90(95)\%\ \mathrm{CL}$$

World's best upper bound (100× better than previous results)

Direct CP violation

CP asymmetries in charm decays

- Define CP asymmetry as

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

  - To be nonzero, needs two or more interfering amplitudes with different weak and strong phases: look only at Cabibbo-suppressed decays such as $D^0 \to \pi^+\pi^-$, $D^0 \to K^+K^-$, $D^0 \to K^+K^-\pi^+\pi^-$, $D^0 \to \pi^+\pi^-\pi^0$, $D^+ \to \pi^+\pi^+\pi^-$, $D_s^+ \to K_S\pi^+$, $D^+ \to K_S K^+$, …

  - For neutral mesons, tag flavor at production time with D^0 from flavor-conserving $D^{*+} \to D^0\pi^+$ or flavour-specific $B \to D^0\mu^- X$ decays

- Develop fully data-driven methods to control spurious/unwanted asymmetries

Experimental method

- Observed (raw) asymmetries suffer from instrumental and production effects

$$\frac{N(D^0 \to h^+h^-) - N(\bar{D}^0 \to h^+h^-)}{N(D^0 \to h^+h^-) + N(\bar{D}^0 \to h^+h^-)}$$

$$A(h^+h^-) = A_{CP}(h^+h^-) + A_D + A_P$$

The CP asymmetry you want to measure

Detection asymmetry of tagging track (π^+ or μ^-)

Production asymmetry of parent hadron (D* or B)

- Difference of raw asymmetries to cancel unwanted effect and is robust against systematic uncertainties

$$\Delta A_{CP} = A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-) = A(K^+K^-) - A(\pi^+\pi^-)$$

- Similar strategy for most of other CP asymmetry measurements

First evidence of direct CPV in charm?

- Available measurements point to an intriguingly large value of ΔA_{CP}

$$\Delta A_{CP}(h^+h^-) = (-0.68 \pm 0.15)\%$$

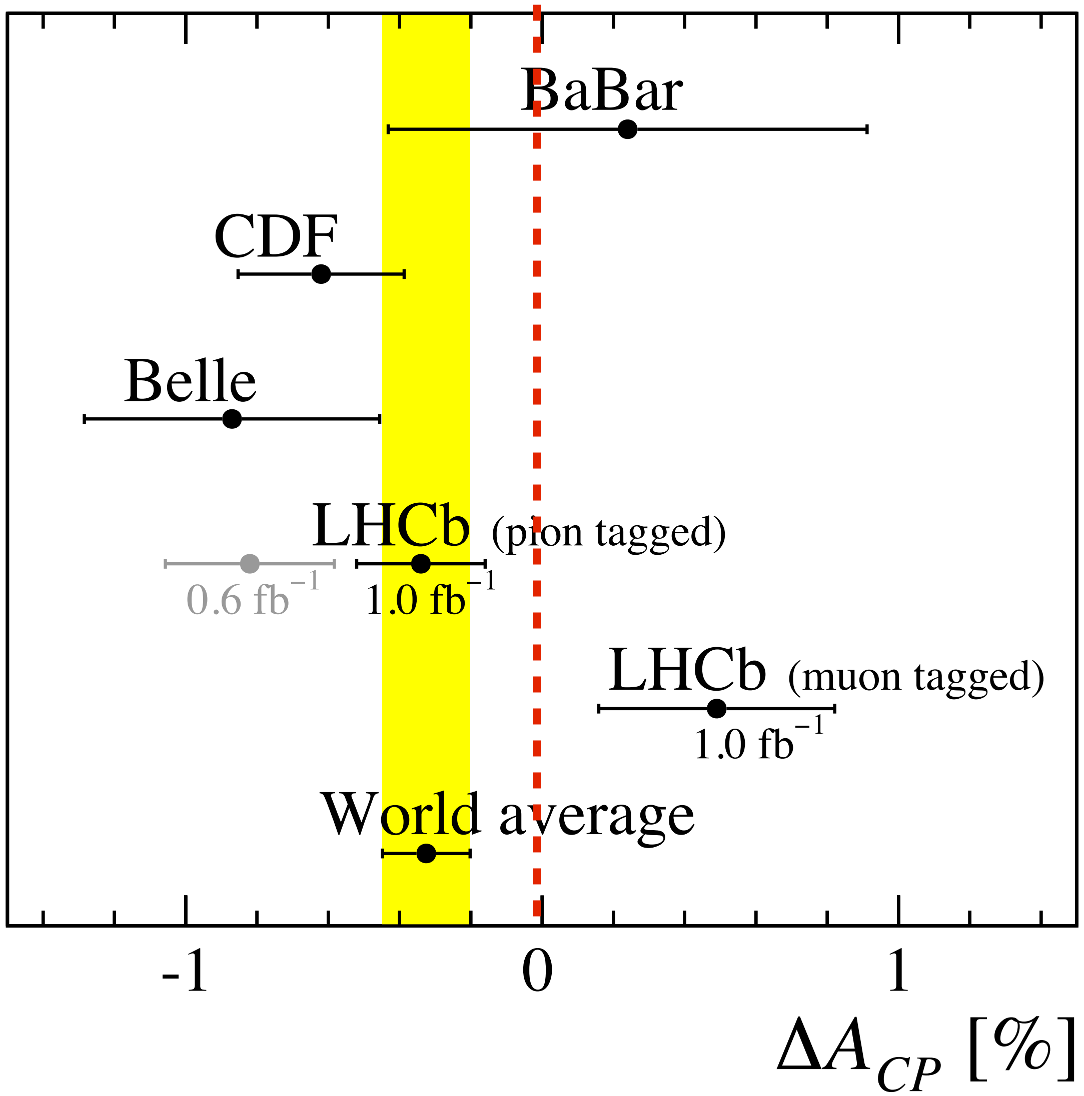
[HFAG ICHEP '12]

$$\Delta A_{CP}(h^+h^-) = (-0.33 \pm 0.12)\%$$

[HFAG March '13]

- At odds with expectations… but picture is still blurry
- Stimulated an interesting discussion: wrong expectations? wrong measurements? both? something new sneaking in?

PRL 100 (2008) 061803, PRL 109 (2012) 111801, arXiv:1212.1975, PRL 108 (2012) 111602, LHCb-CONF-2013-003, PLB 723 (2013) 33



Update with full Run I dataset in progress

Search for CPV in multibody decays

- Exploit enriched dynamics of multi-body decays to seek enhancements of CPV in subregions of the phase space. Could go unnoticed in measurements of global asymmetries
- Insensitive to global asymmetries (physical or spurious)
- Study phase-space-dependent production/detection asymmetries with CF decays (in the SM, direct CPV can only occur in SCS decays)

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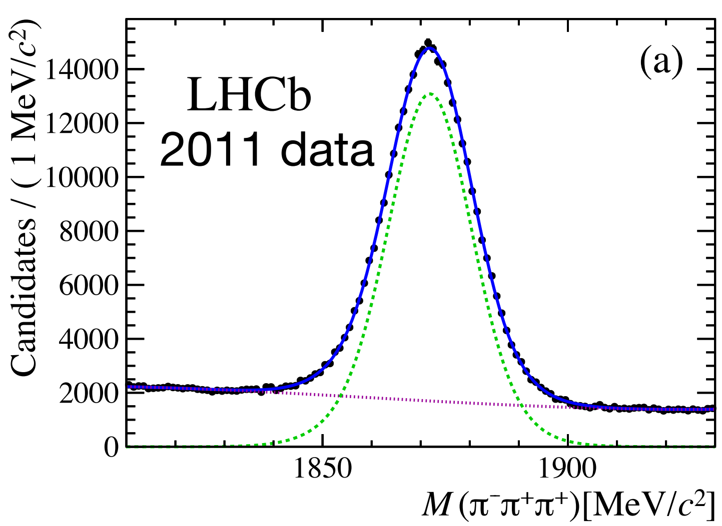
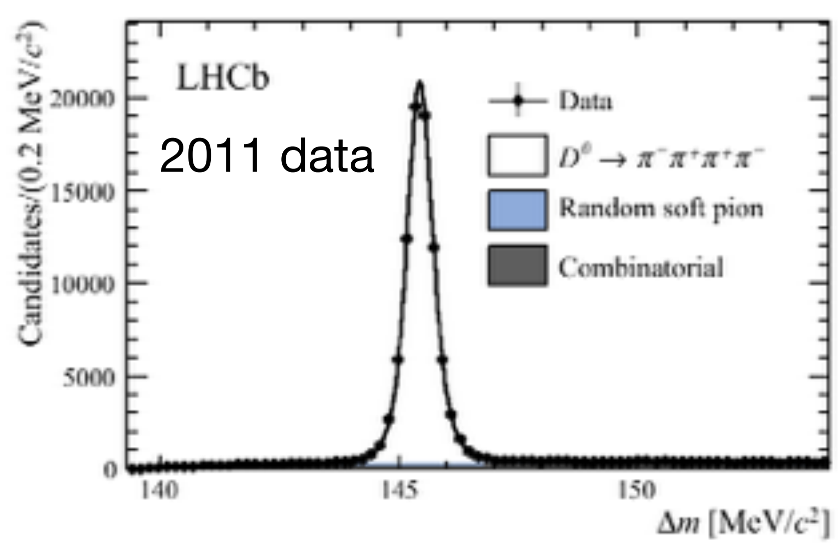
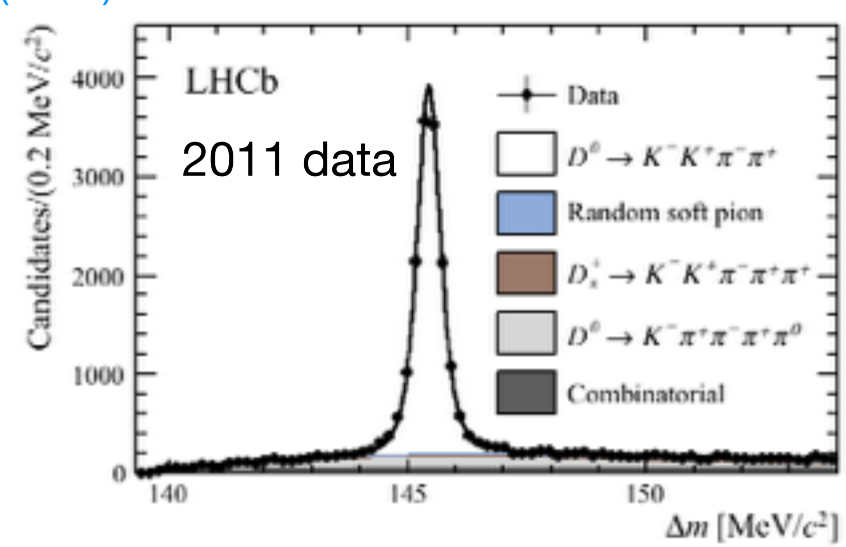


PLB 726 (2013) 623



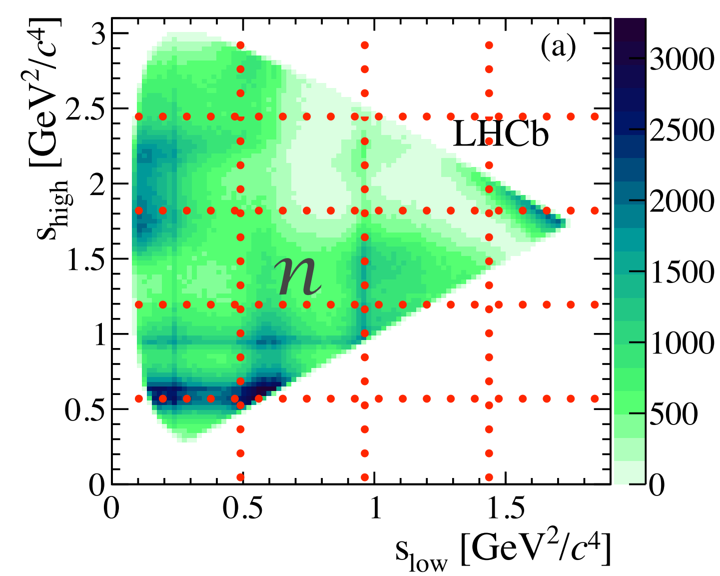


~3M $D^+ \to 3\pi$ ~300k $D^0 \to 4\pi$ ~57k $D^0 \to 2K2\pi$

Search for local CPV across Dalitz plot

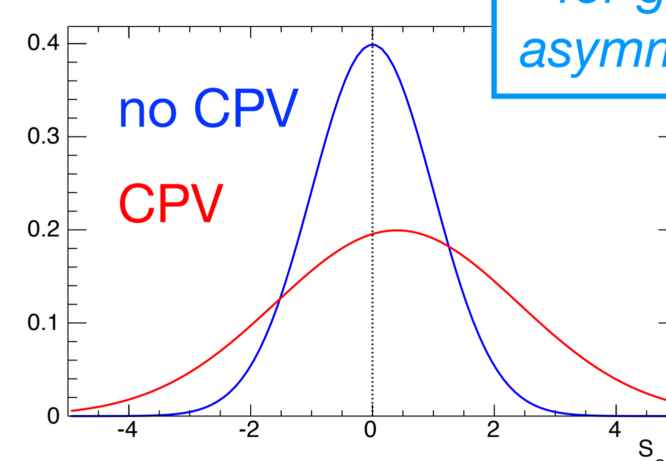
- Compute local CP asymmetry in different bins of the Dalitz plot
- No CPV means that distribution of local asymmetry is gaussian with zero mean and unit sigma
- Get p-value from $\chi^2 = \sum_i \left(S^i_{\mathrm{CP}}\right)^2$
- Test several binning schemes (same number of events/same strong phase)
- With 2011 data sensitive to 1º-10º differences in phase and 1-10% in magnitude

Binned (a.k.a. Miranda) method

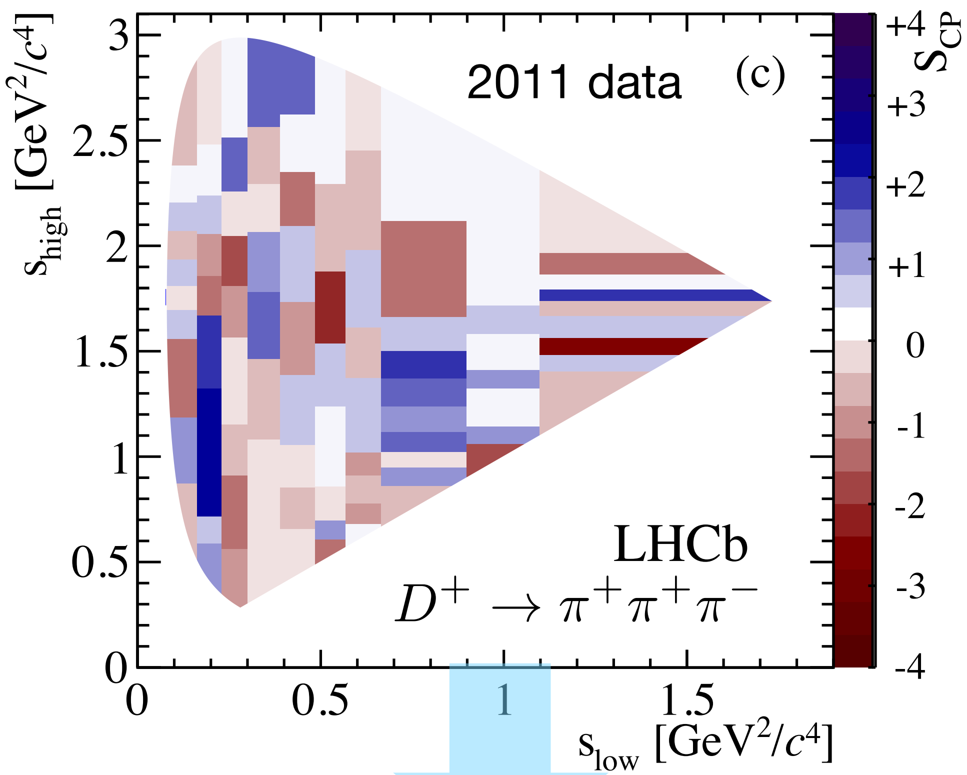


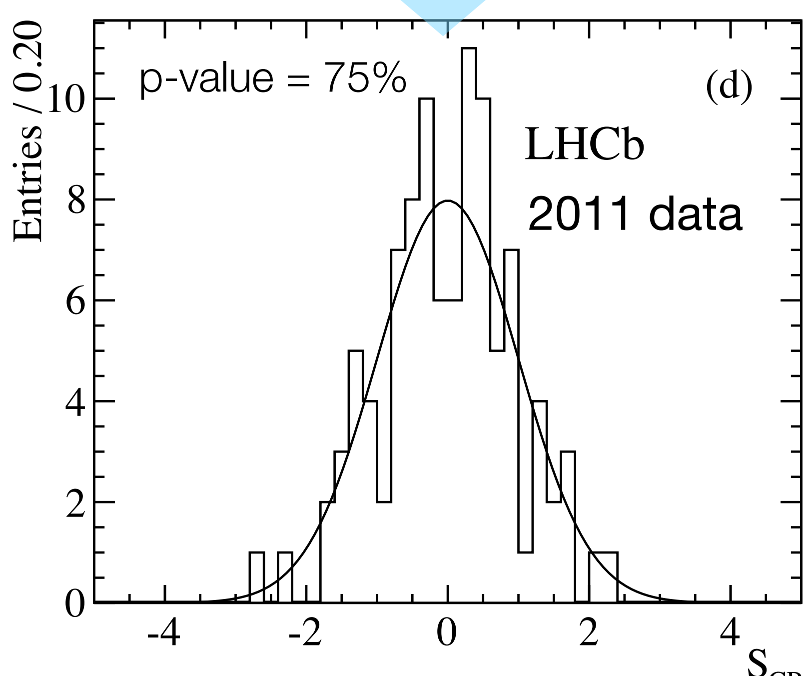
$$S^i_{\mathrm{CP}} = \frac{n^i(D^+) - \alpha n^i(D^-)}{\sqrt{n^i(D^+) + \alpha n^i(D^-)}}$$

to account for global asymmetries $\alpha = \dfrac{N(D^+)}{N(D^-)}$



Local CPV in multibody decays — Results





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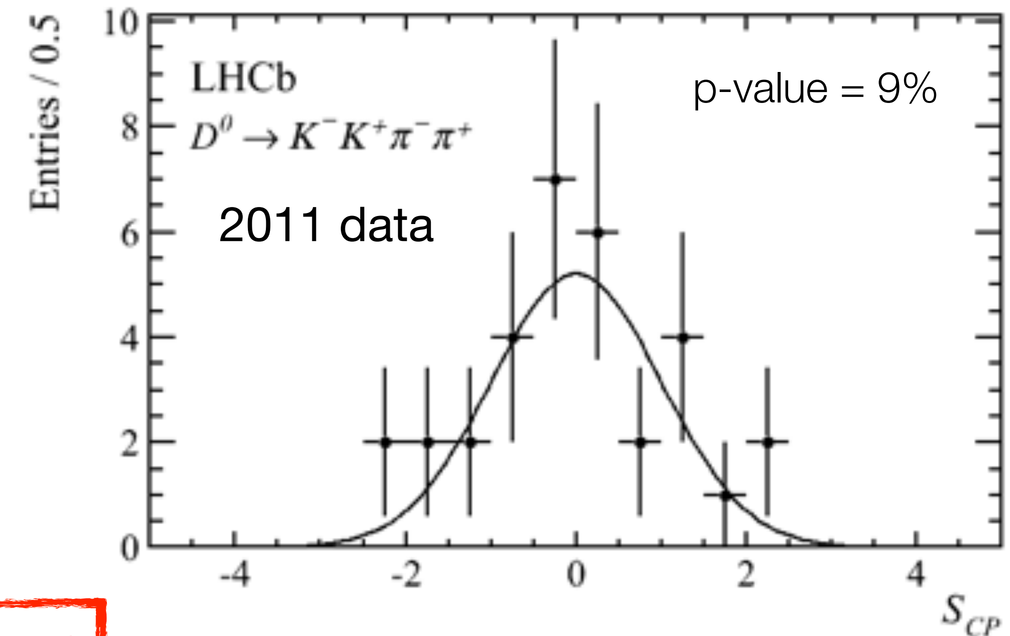
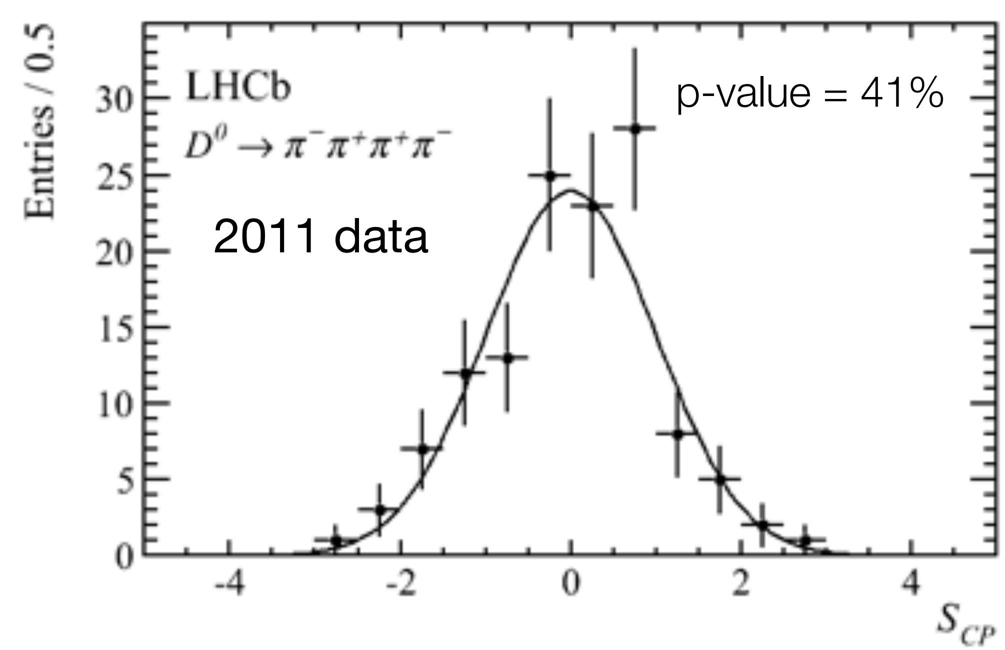
No evidence of local CPV





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

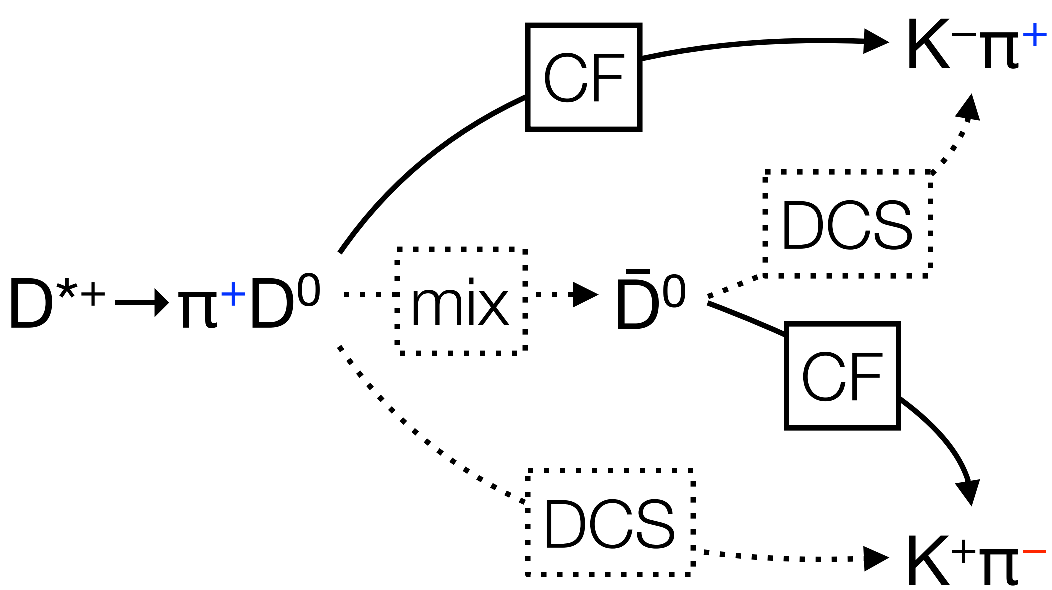
$$x = (m_1 - m_2)/\Gamma$$

$$y = (\Gamma_1 - \Gamma_2)/2\Gamma$$

Mixing and indirect CP violation

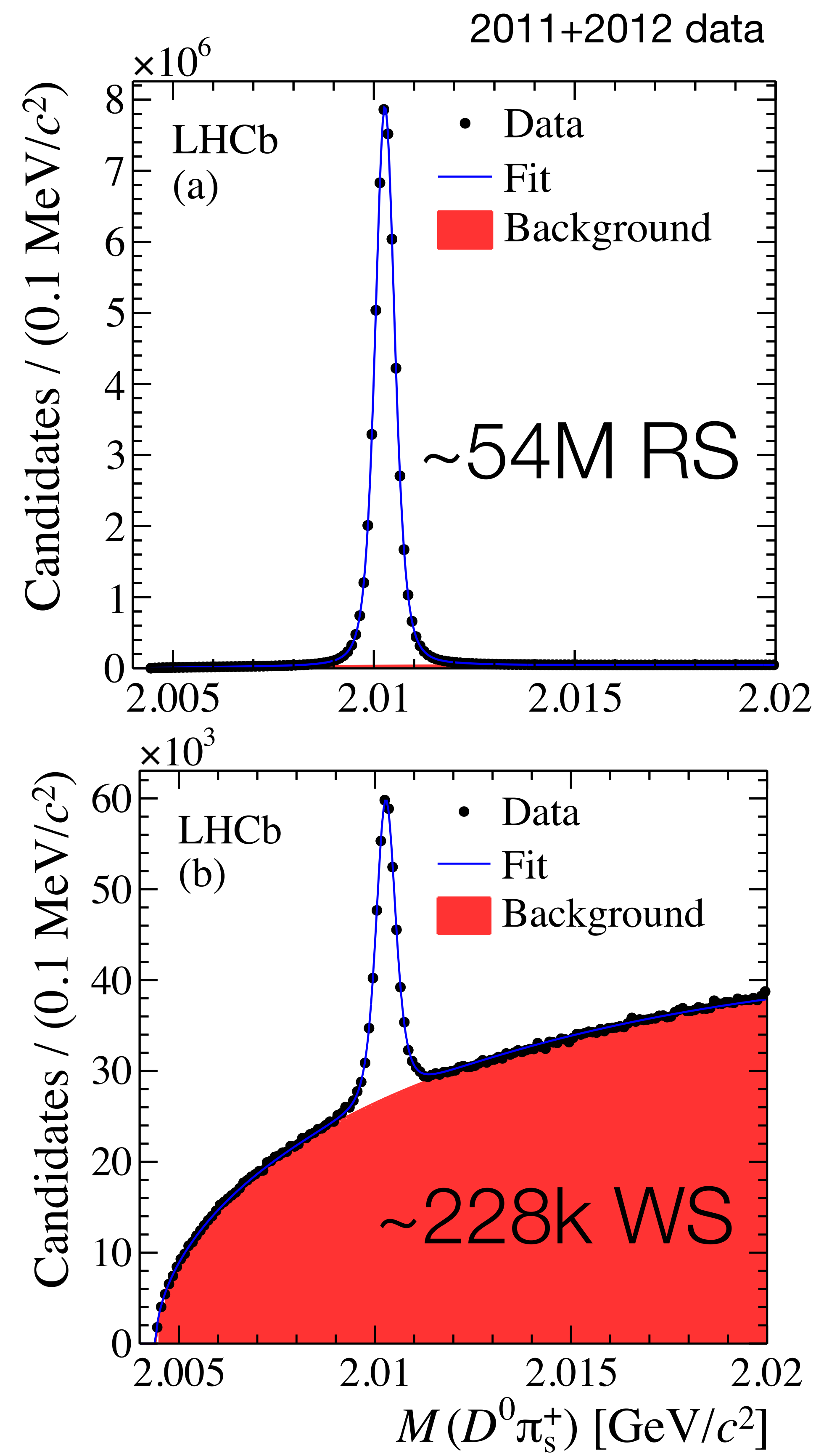
Mixing and CPV with $D^0 \to K^+\pi^-$

- Built upon previous iteration of the analysis [PRL 110 (2013) 101802] with full Run I dataset
- Reconstruct RS and WS decays using D^* to identify flavor at production



- Fit ratio of WS/RS yields in bins of decay time to separate mixing from DCS contribution
- Fit D^{*+} and D^{*-} independently to search for CPV ($K^\pm\pi^\mp$ asymmetry from CF D^+ decays)

PRL 111 (2013) 251801



Mixing and CPV with $D^0 \to K^+\pi^-$ — Results

- Time-dependent WS/RS ratio:

$$R^{\pm} \approx R_D^{\pm} + \sqrt{R_D^{\pm}}\, y'^{\pm} \left(\frac{t}{\tau}\right) + \frac{x^2+y^2}{4} |q/p|^{\pm 2} \left(\frac{t}{\tau}\right)^2$$

$$y'^{\pm} = |q/p|^{\pm 1} \left[y \cos(\delta \pm \phi) \mp \sin(\delta \pm \phi)\right]$$

$$R_D^{\pm} = R_D(1 \pm A_D)$$

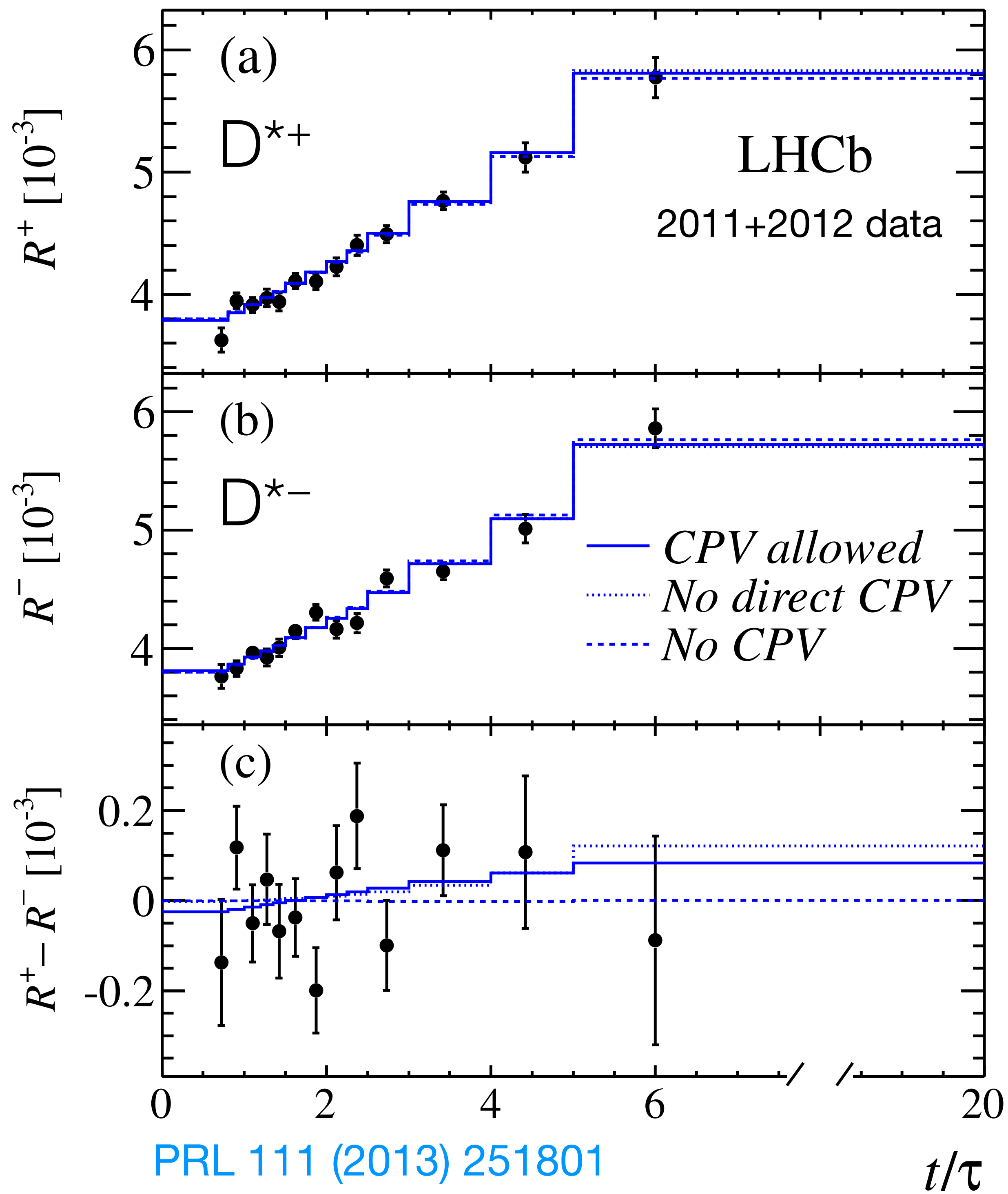
- Indirect CPV ($|q/p| \neq 1$ or $\phi \neq 0$) if difference between ratios varies vs time:

$$0.75 < |q/p| < 1.24 \text{ @ } 68.3\% \text{ CL}$$

- Direct CPV in DCS decay if nonzero intercept:

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

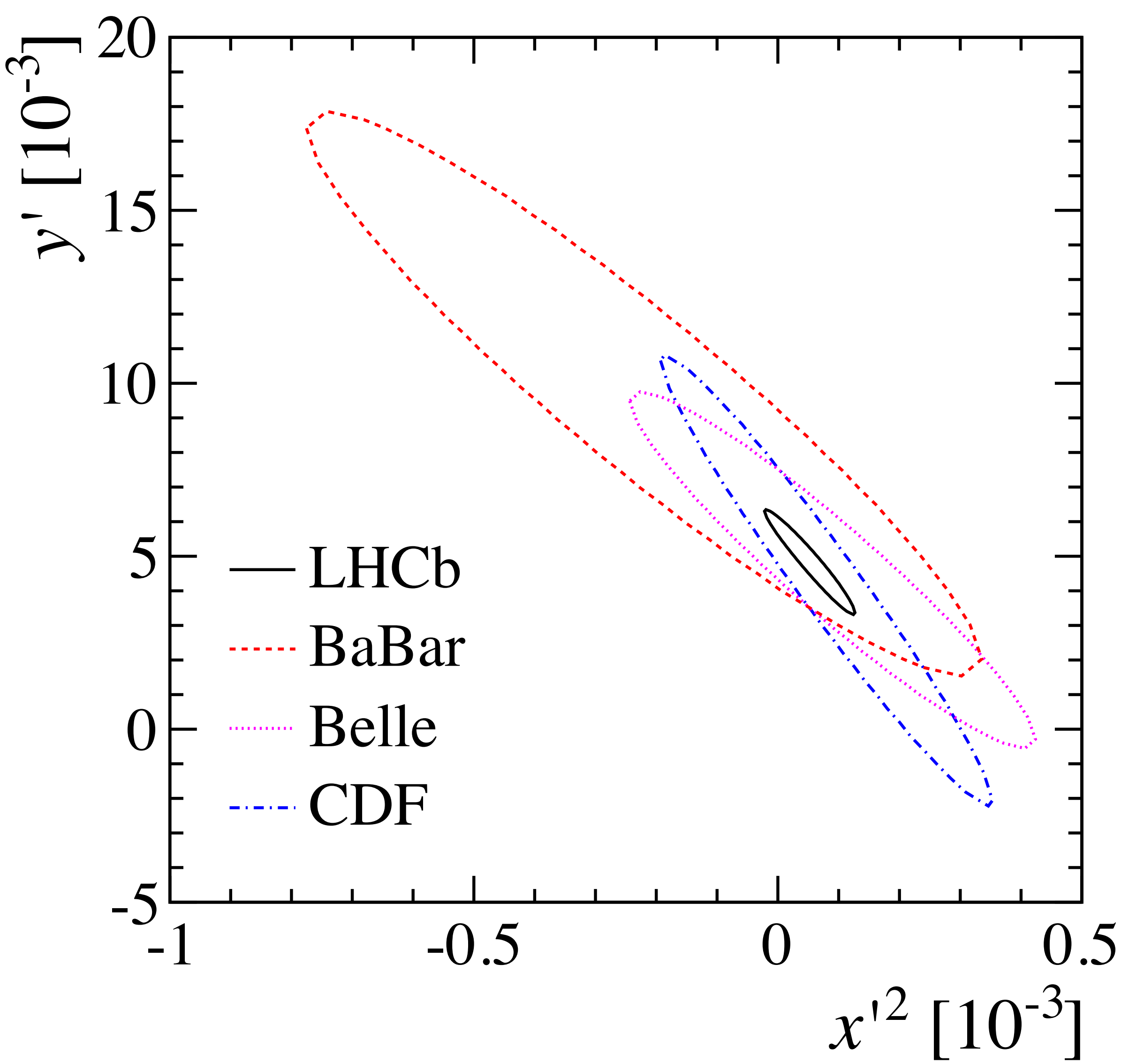
World's best bound on CPV in charm mixing and in DCS decays



PRL 111 (2013) 251801

Mixing with $D^0 \to K^+\pi^-$ — Results

Precision on mixing parameters improved by 2.5× wrt our previous result [PRL 110 (2013) 101802]



	R_D (10^{-3})	y' (10^{-3})	x'^2 (10^{-3})
LHCb	3.568 ± 0.066	4.8 ± 1.0	0.055 ± 0.049
BaBar	3.03 ± 0.19	9.7 ± 5.4	-0.22 ± 0.37
Belle	3.53 ± 0.13	4.6 ± 3.4	0.09 ± 0.22
CDF	3.51 ± 0.35	4.3 ± 4.3	0.08 ± 0.18

★ LHCb: PRL 111 (2013) 251801

BaBar: PRL 98 (2007) 211802

★ Belle: PRL 112 (2014) 111801

★ CDF: PRL 111 (2013) 231802

★ = mixing probability > 5σ

PRL 112 (2014) 041801

Effective-lifetime asymmetry

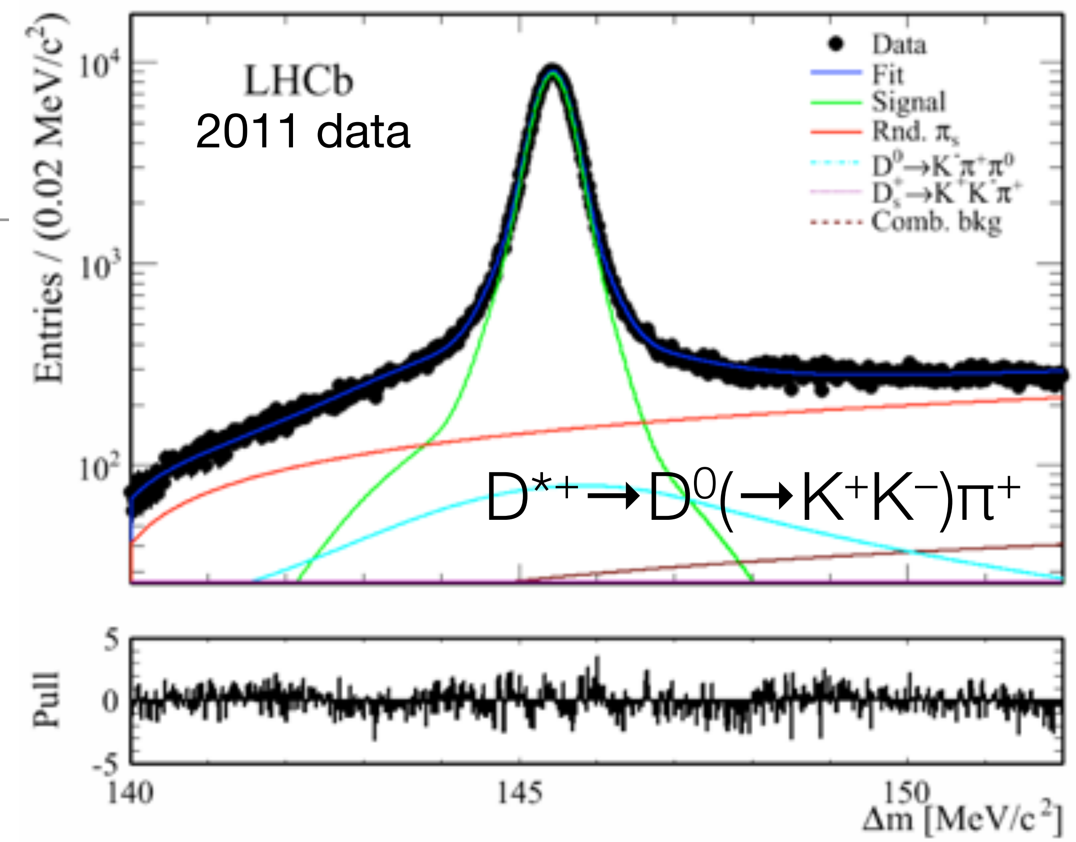
- Measure asymmetry between effective lifetimes of SCS D*-tagged $D^0 \to K^+K^-$ (~3M) and $D^0 \to \pi^+\pi^-$ (~1M) decays

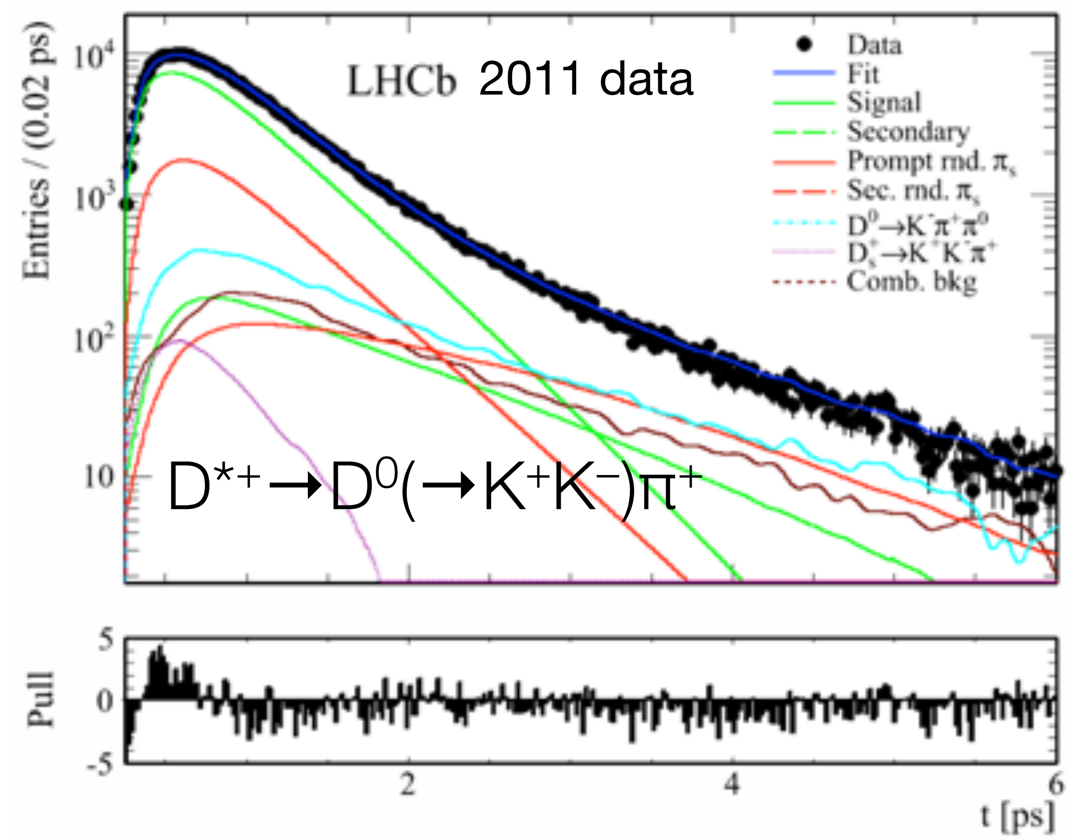
$$A_\Gamma = \frac{\hat{\tau}(\overline{D}^0) - \hat{\tau}(D^0)}{\hat{\tau}(\overline{D}^0) + \hat{\tau}(D^0)}$$
$$\approx \frac{1}{2}\left[\left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right) y\cos\phi - \left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right) x\sin\phi\right]$$

- Nonzero if indirect CPV ($|q/p| \neq 1$ or $\phi \neq 0$) occurs

- Evaluate acceptance vs decay-time for each candidate using only data

- Validate analysis on larger sample of CF $D^0 \to K^-\pi^+$ decays



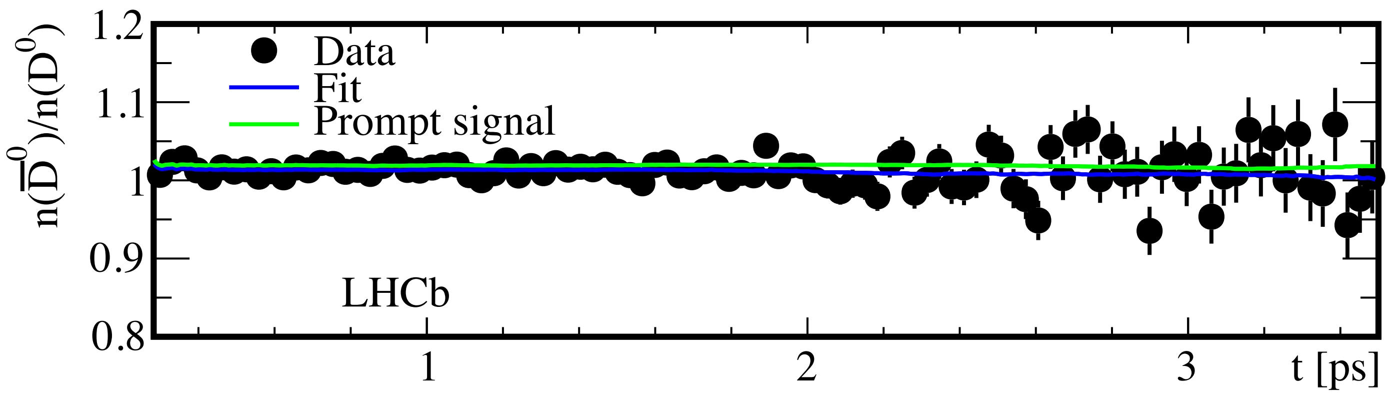


Effective-lifetime asymmetry — Results

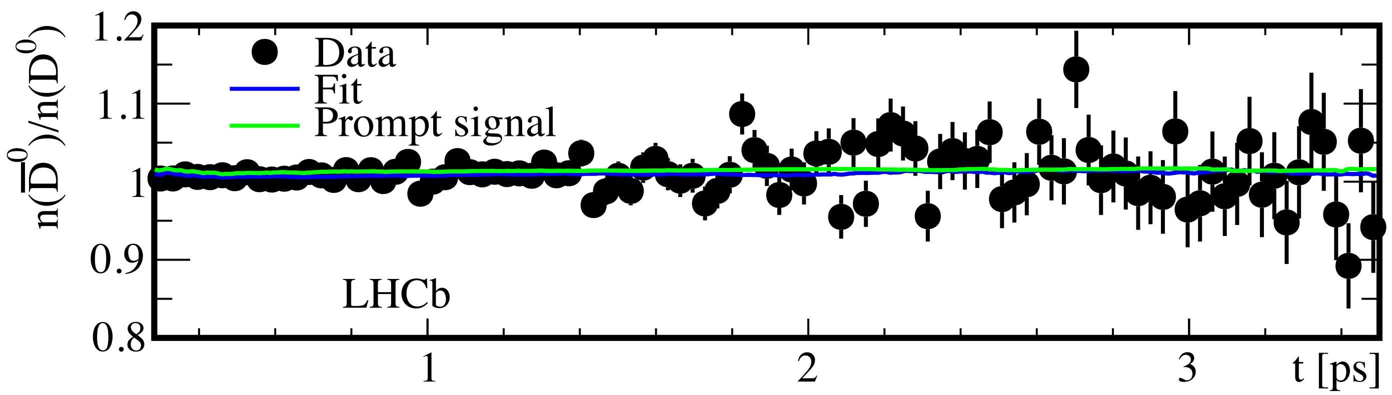
- No signs of indirect CP violation at 0.1% level

PRL 112 (2014) 041801

2011 data

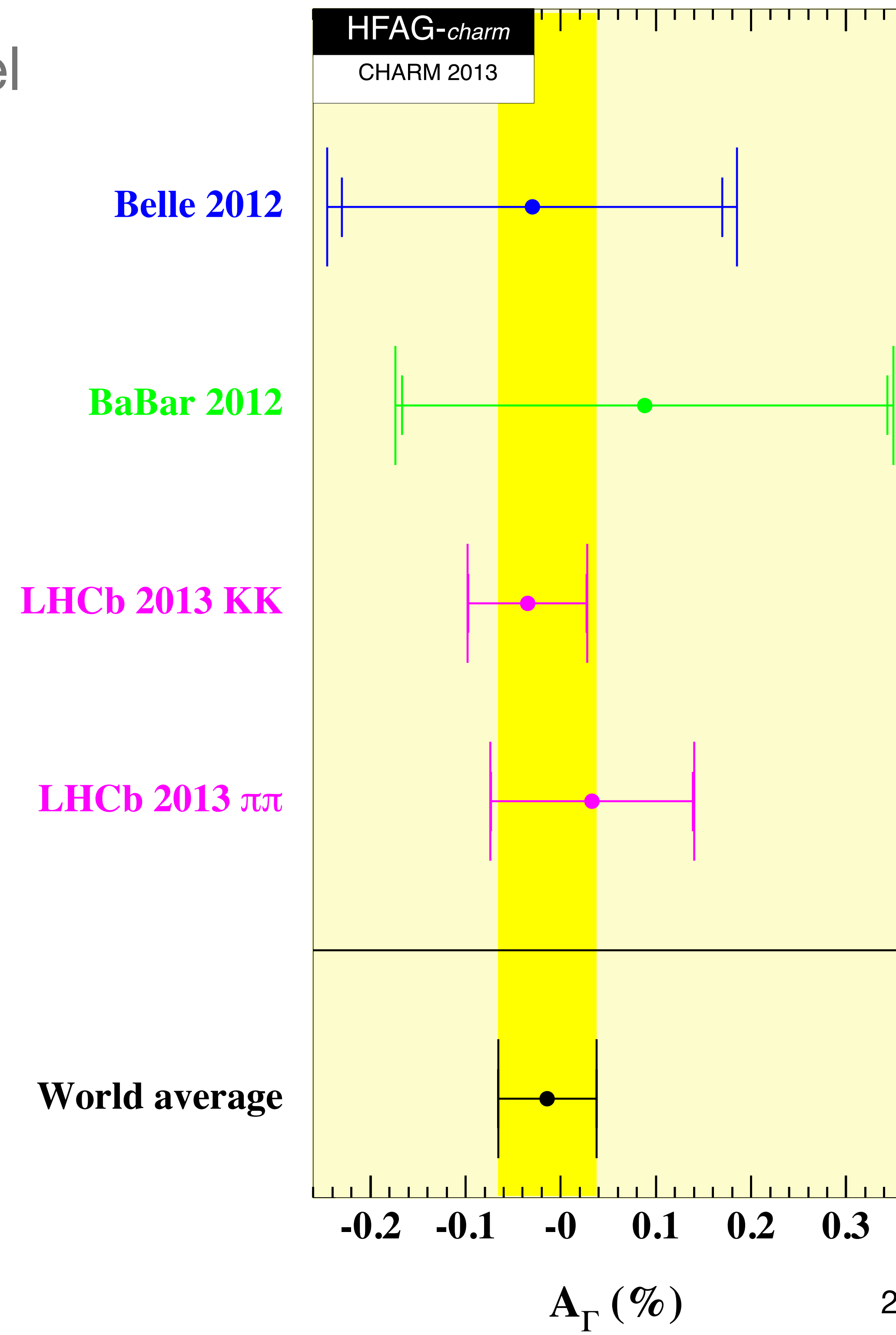


$$A_\Gamma(K^+K^-) = (-0.35 \pm 0.62 \pm 0.12) \times 10^{-3}$$

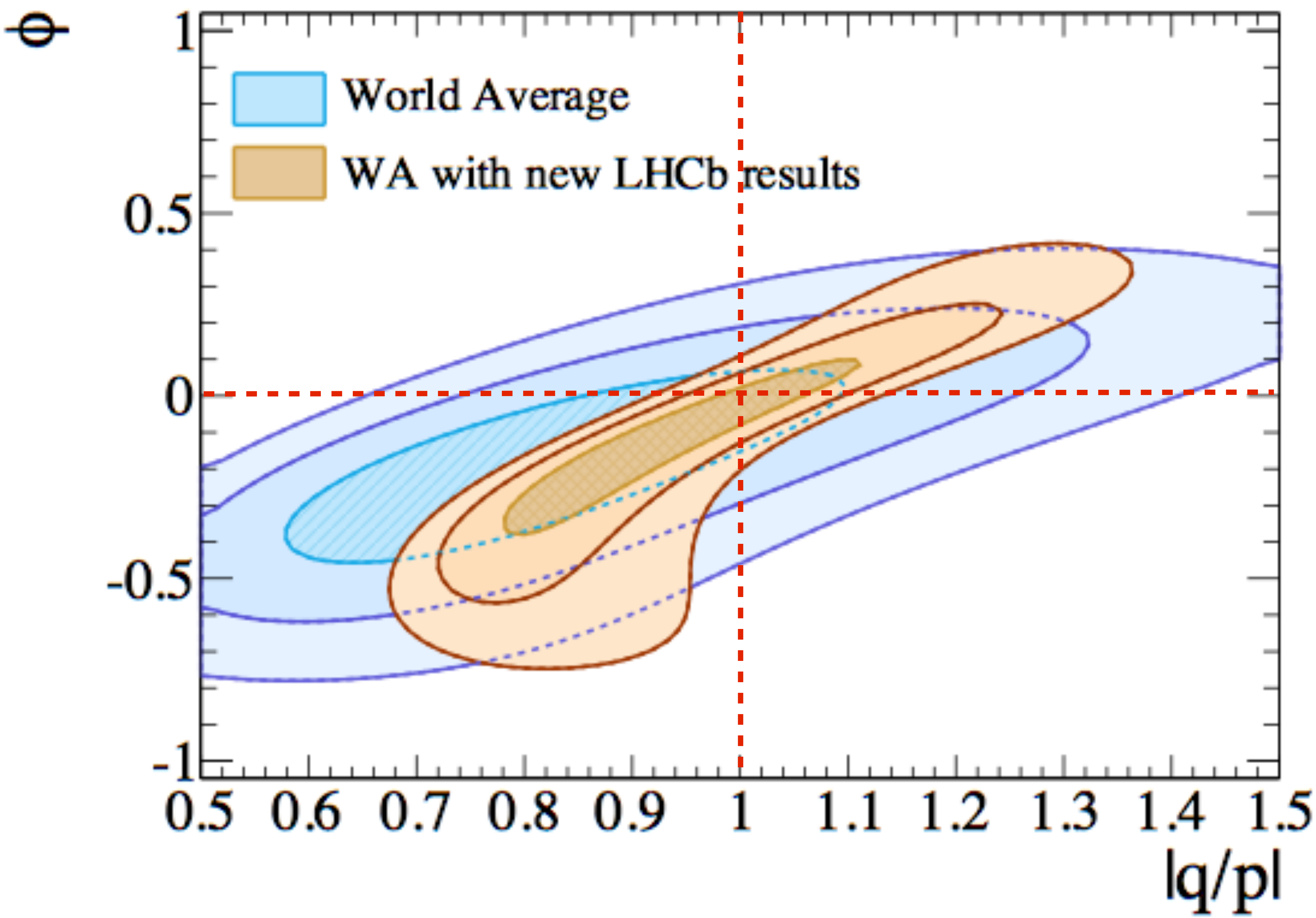


$$A_\Gamma(\pi^+\pi^-) = (0.33 \pm 1.06 \pm 0.14) \times 10^{-3}$$

World's best results with only ~1/3 of currently available data



Impact on world average



Conclusions

- Charm is a unique probe of BSM couplings to up-quark sector
- LHCb leads thanks to O(1M) charm decays collected:
    - world's best bounds on FCNC c→uμμ transitions
    - world's best determination of mixing and bounds on CPV
- Charm papers are ~10% of total LHCb output… but often among top cited
- Much more to come as Run I dataset still being analysed