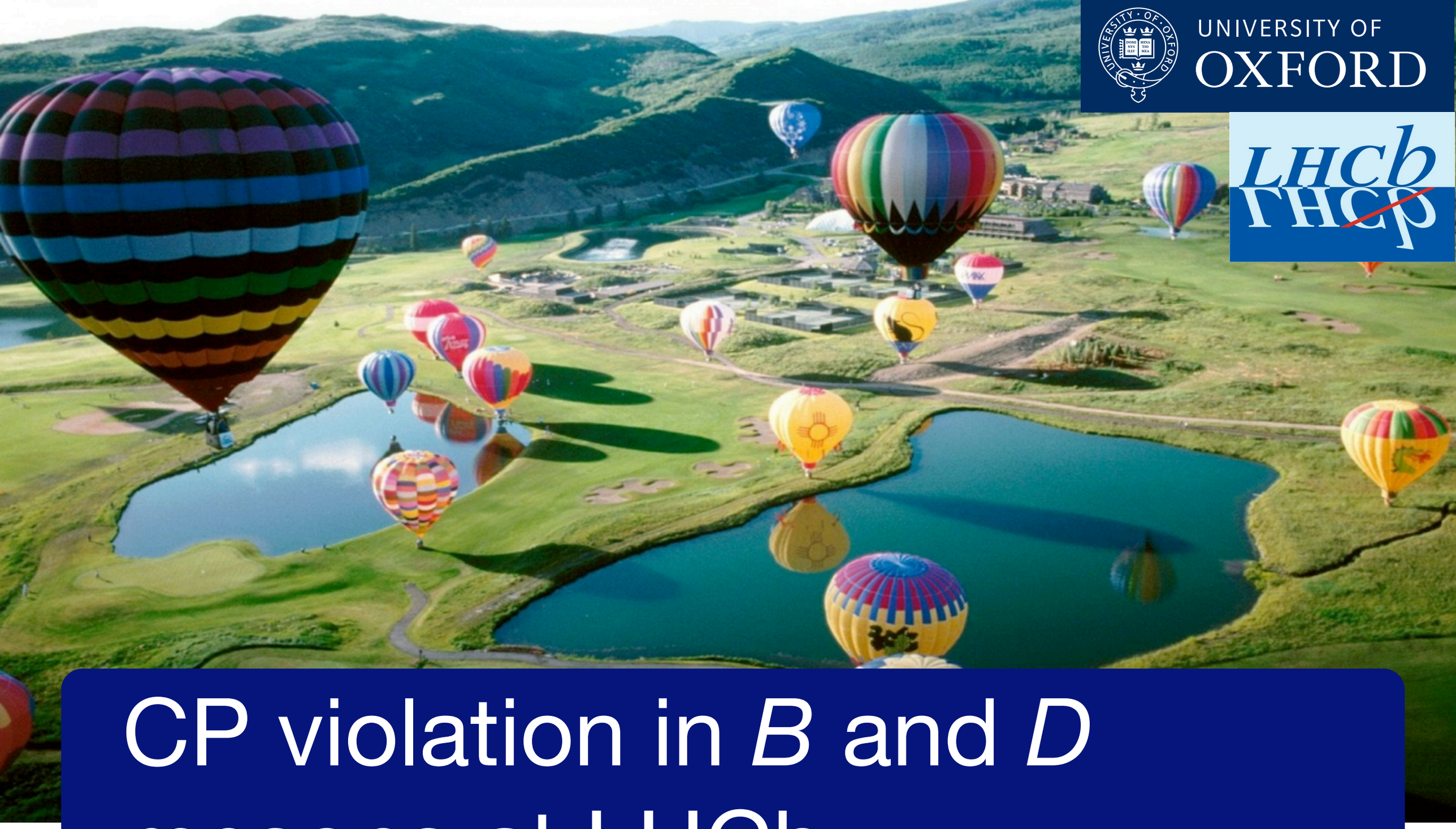


CP violation in *B* and *D* mesons at LHCb

Dan Johnson, on behalf of the LHCb collaboration

...with many thanks to the organisers

Outline

- The LHCb detector

- Standard Model CP violation and the CKM phase γ
- Measuring γ in $B^{\pm}$ meson decays

- Searches for CP violation in the charm sector

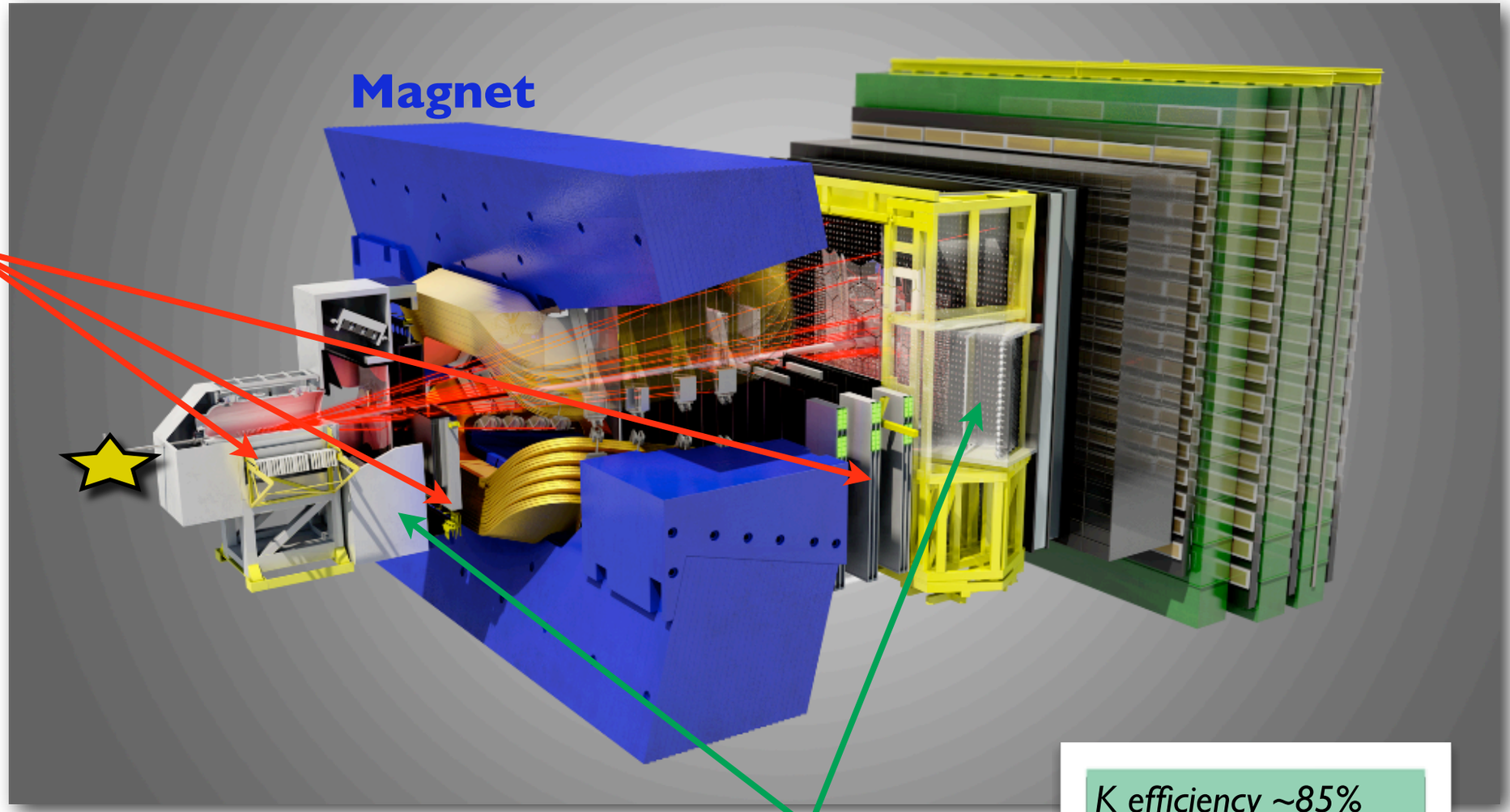
- Conclusions

The LHCb detector

- $2<\eta<5$ pseudorapidity acceptance; 4% of solid angle; 40% of heavy quarks
- Trigger reduces rate from 40MHz → 5kHz
- 3 fb^{-1} data set collected during 2011-2012

Vertex Locator and tracking system:
B and D vertex positions and track momenta

IP resolution: 20μm
Δp/p: 0.4-0.6 %



RICH detectors:
K/π separation

K efficiency ~85%
π→K mis-ID ~3%

Life at tree-level: $B^{\pm} \to D^0 K^{\pm}$

Introducing γ

- SM CP violation parameterised by complex phases in CKM matrix
- γ is the least well known

$$\gamma = -\arg\left(\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$

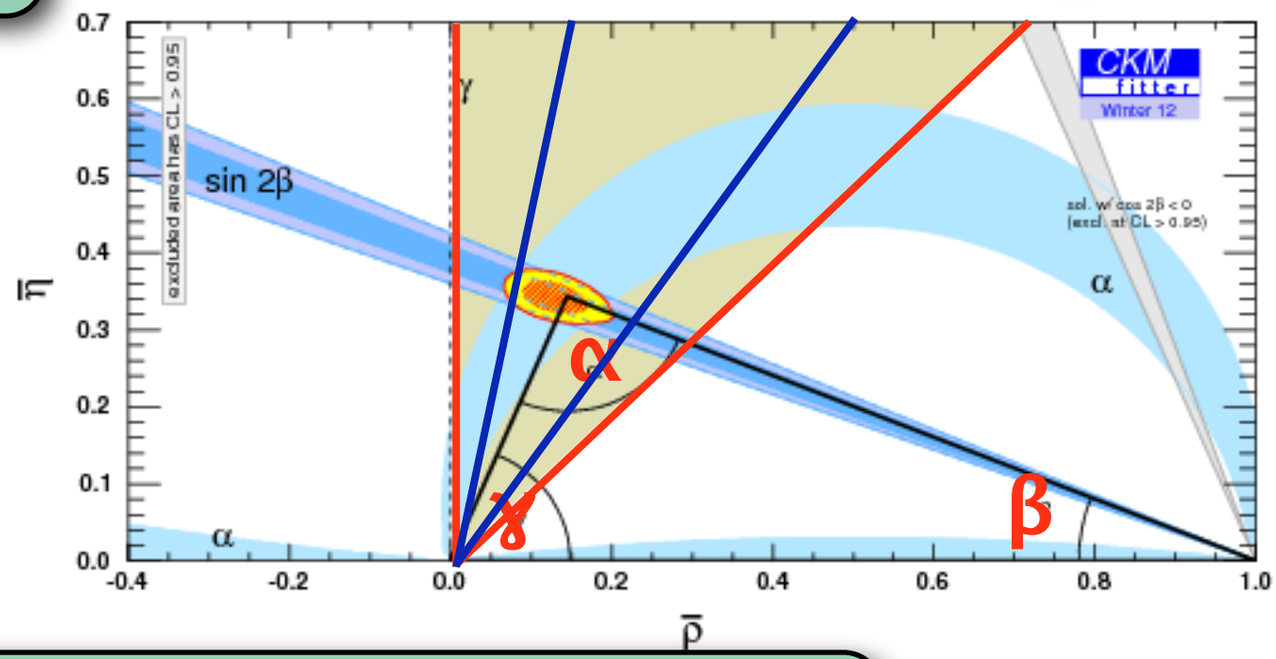
Before LHCb (ICHEP '12):

$$\gamma = (66 \pm 12)^\circ$$

Including LHCb 1fb^{-1} (FPCP '13):

$$\gamma = (68^{+8.0}_{-8.5})^\circ$$

(direct measurements, CKMfitter)

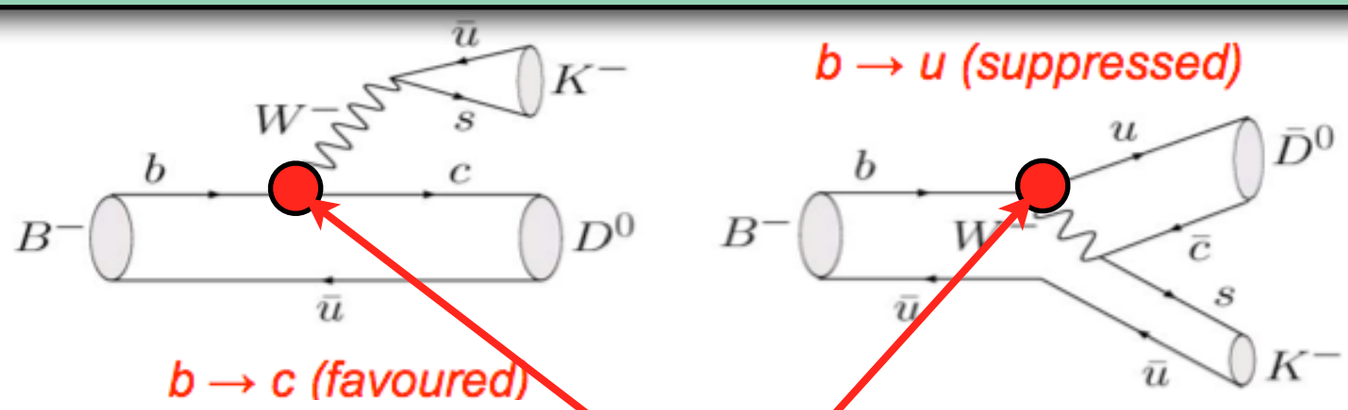


At LHCb:

- Improved precision in theoretically clean tree-level decays to over-constrain the unitarity triangle ⇒ **α+β+γ = 180°?**
- Only angle where measurement possible in tree- *and* loop- level processes ⇒ **potential NP sensitivity**

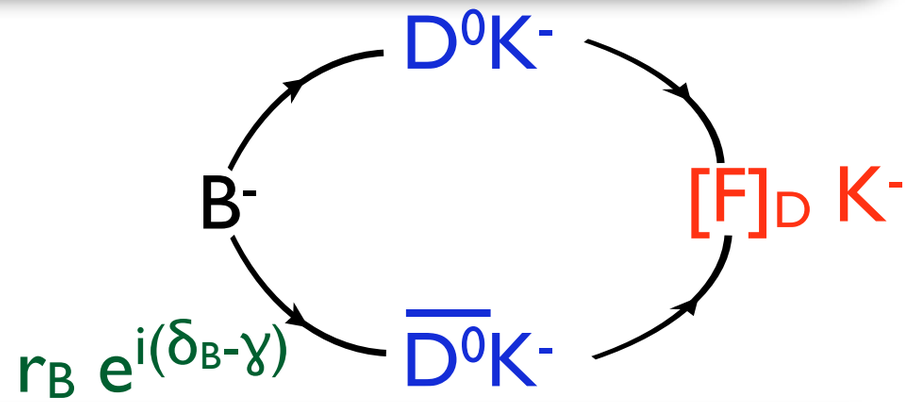
$B^{\pm} \to D^0 K^{\pm}$

- Sensitive to γ through interference between $B^{\pm} \to D^0 K^{\pm}$ and $B^{\pm} \to \overline{D}^0 K^{\pm}$



$$\gamma = -\arg\left(\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$

- Reconstruct D in final state F (e.g. KK)
- Interference between $B^{\pm} \to F_{D0} K^{\pm}$ and $B^{\pm} \to F_{D0} K^{\pm}$



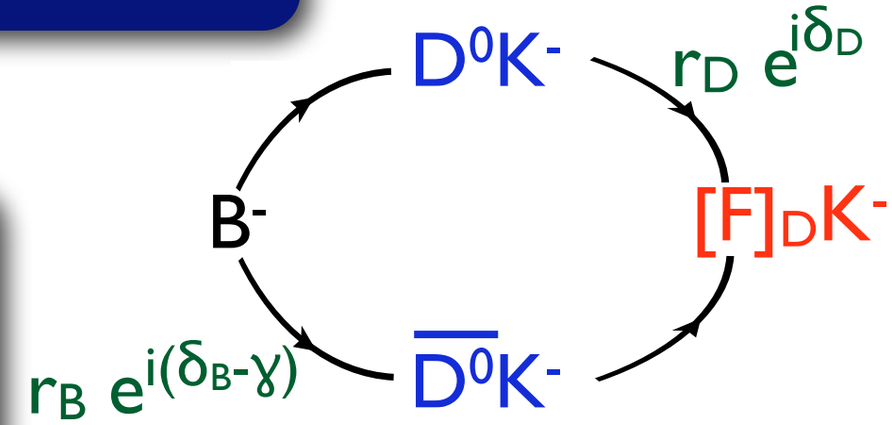
- Tree-level process: very low theoretical uncertainties
- Exploit many D^0 final states F

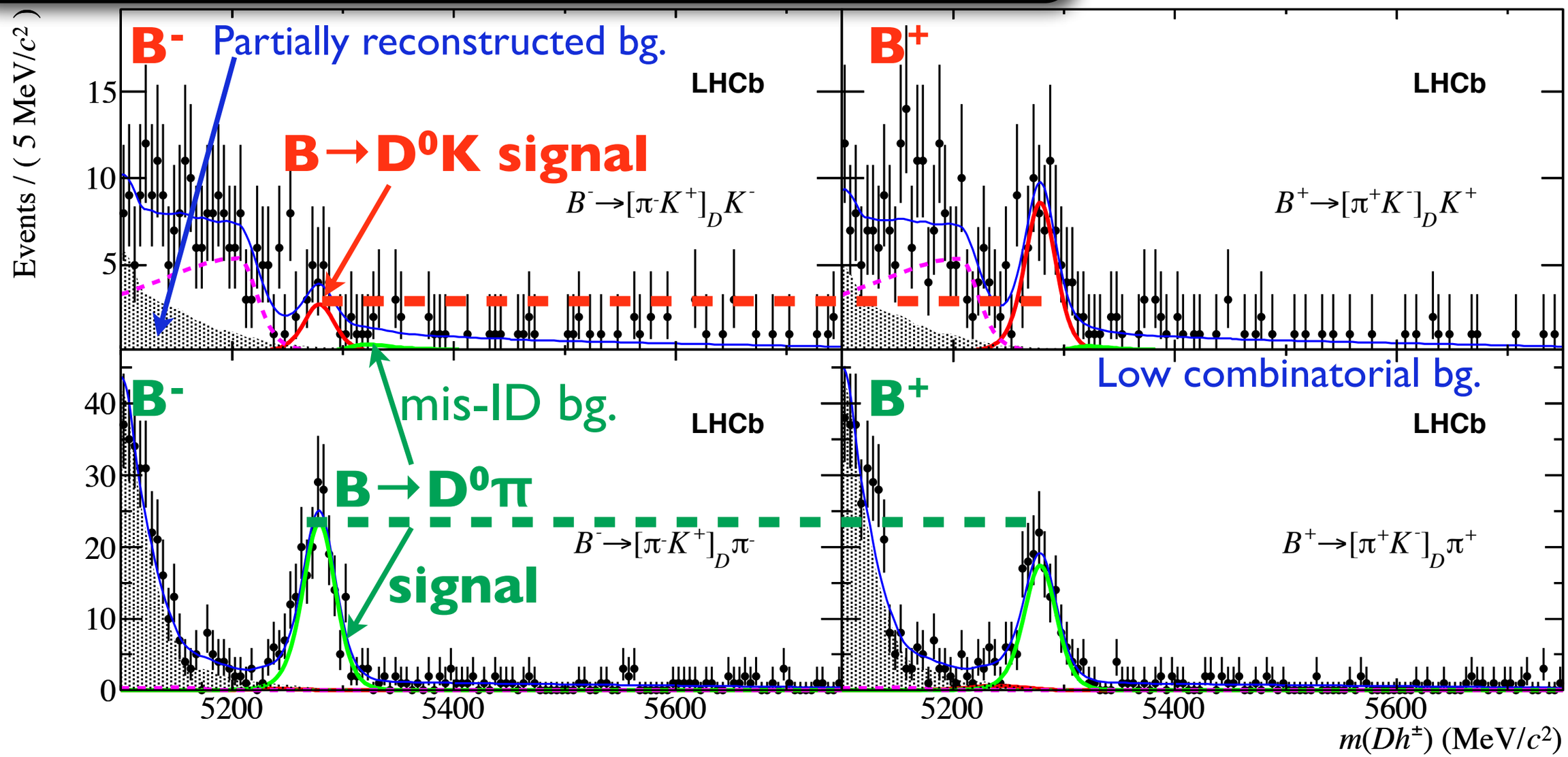
Latest LHCb γ: 1fb^{-1}

PLB 726 (2013) 151

F = KK,ππ (GLW), Kπ (ADS) 1fb^{-1} PLB 712 (2012) 203

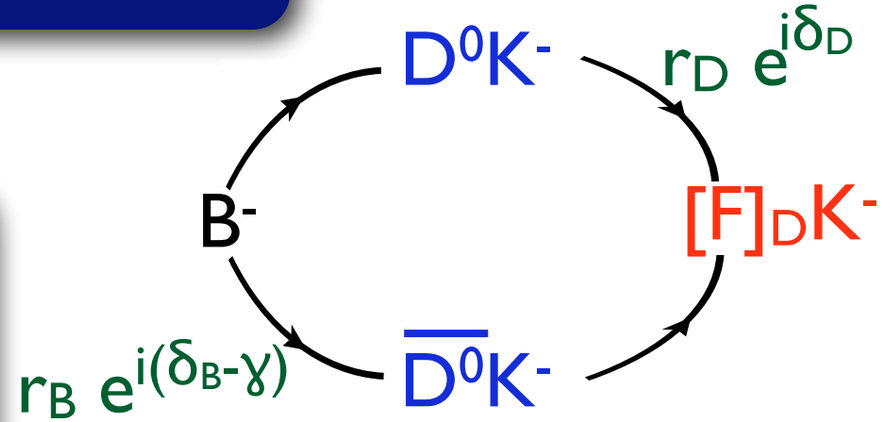
- Employ CP-eigenstates and CF/DCS decays
- Largest interference in $B^{\pm}\to[\pi^{\pm}K^{\mp}]\,K^{\pm}$
- Interference lower in $B^{\pm}\to D\pi^{\pm}$ ($r_B^{\pi}\sim 0.1 \times r_B$)
- $B^{\pm}\to D\pi^{\pm}$ used to drive aspects of $B^{\pm}\to DK^{\pm}$ fit





Latest LHCb γ: 1fb^{-1}

PLB 726 (2013) 151



F = KK,ππ (GLW), Kπ (ADS) 1fb^{-1}

PLB 712 (2012) 203

- Employ CP-eigenstates and CF/DCS decays
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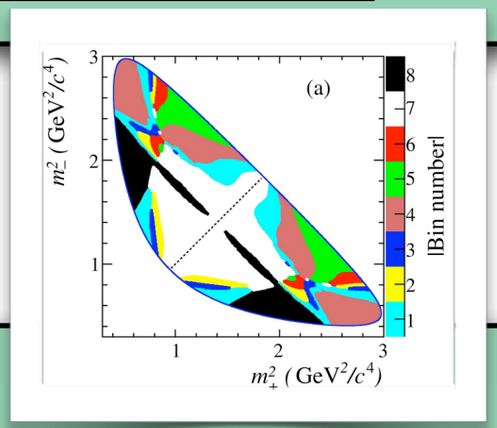
- $B^{\pm}\to D\pi^{\pm}$ used to drive aspects of $B^{\pm}\to DK^{\pm}$ fit

F = Kπππ (ADS) 1fb^{-1}

PLB 723 (2012) 44

- Analogous to two-body analysis
- 4-body final state ⇒ use CLEO coherence factor & avg. δ_D (0.33 ± 0.25)

PRD 80 (2009) 031105



F = K_S^0ππ / K_S^0KK (GGSZ) 1fb^{-1}

PLB 718 (2012) 43

- Dalitz analysis of final state in 16 (4) regions of D^0 phase space
- 3-body final state: use CLEO average strong phases
- Acceptance taken from $B^{\pm}\to D\pi^{\pm}$, neglecting interference

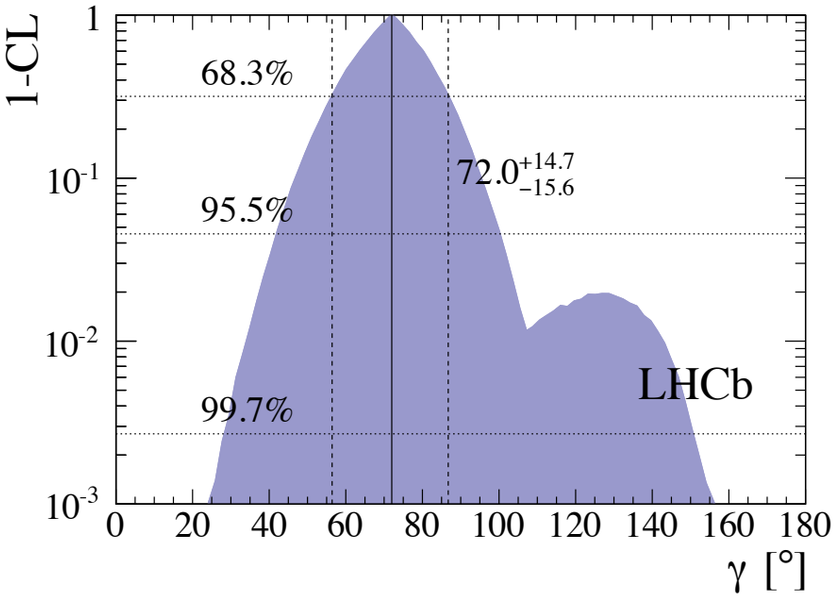
Latest LHCb γ: $1\,fb^{-1}$

- Best-fit values of γ (,$r_B^{(\pi)}$, $\delta_B^{(\pi)}$) are extracted from the combined measurements, adding stat. and syst. errors in quadrature.
- Confidence intervals in the parameters are determined using a frequentist statistical treatment

Results for measurements in the $B^{\pm} \to DK^{\pm}$ system:

LHCb $\gamma = 72.0^{+14.7}_{-15.6}\,^{\circ}$

PLB 726 (2013) 151



Belle $\gamma = 68^{+15}_{-14}\,^{\circ}$

BaBar $\gamma = 69^{+17}_{-16}\,^{\circ}$

- [Preliminary] Including latest $3\,fb^{-1}$ measurements: $\gamma = 67.2^{+11.9}_{-12.1}\,^{\circ}$

LHCb-CONF-2013-006

- Essential to exploit new D decay modes (new result follows)

$B^{\pm} \to D^0(\to K_S K\pi)\, K^{\pm}$

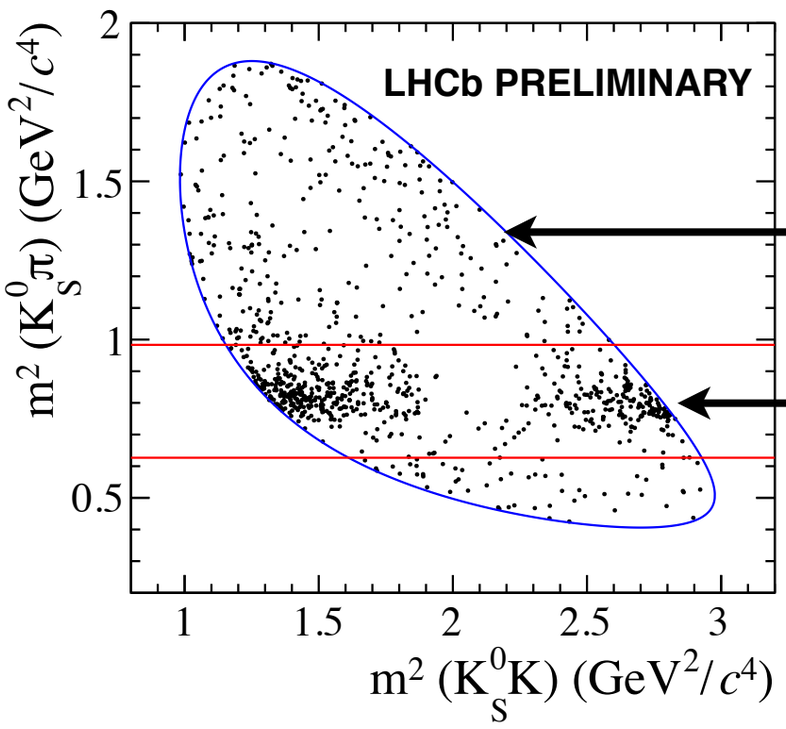
Preliminary: LHCb-PAPER-2013-068 in preparation

NEW

- Addition of D final states: increased γ sensitivity
- First analysis of $D^0 \to K_S^0 K^{\mp}\pi^{\pm}$ mode for γ
- First use of SCS modes in an ADS-like measurement

- As for $D^0 \to K3\pi$, use CLEO coherence factor and avg. δ_D
- Perform analysis in:
  (i) Whole D^0 Dalitz plot
  (ii) Region around $K^*(892)$ resonance (greater interference and γ sensitivity)

PRD 85 (2012) 092016



Coherence factor: 0.73±0.08

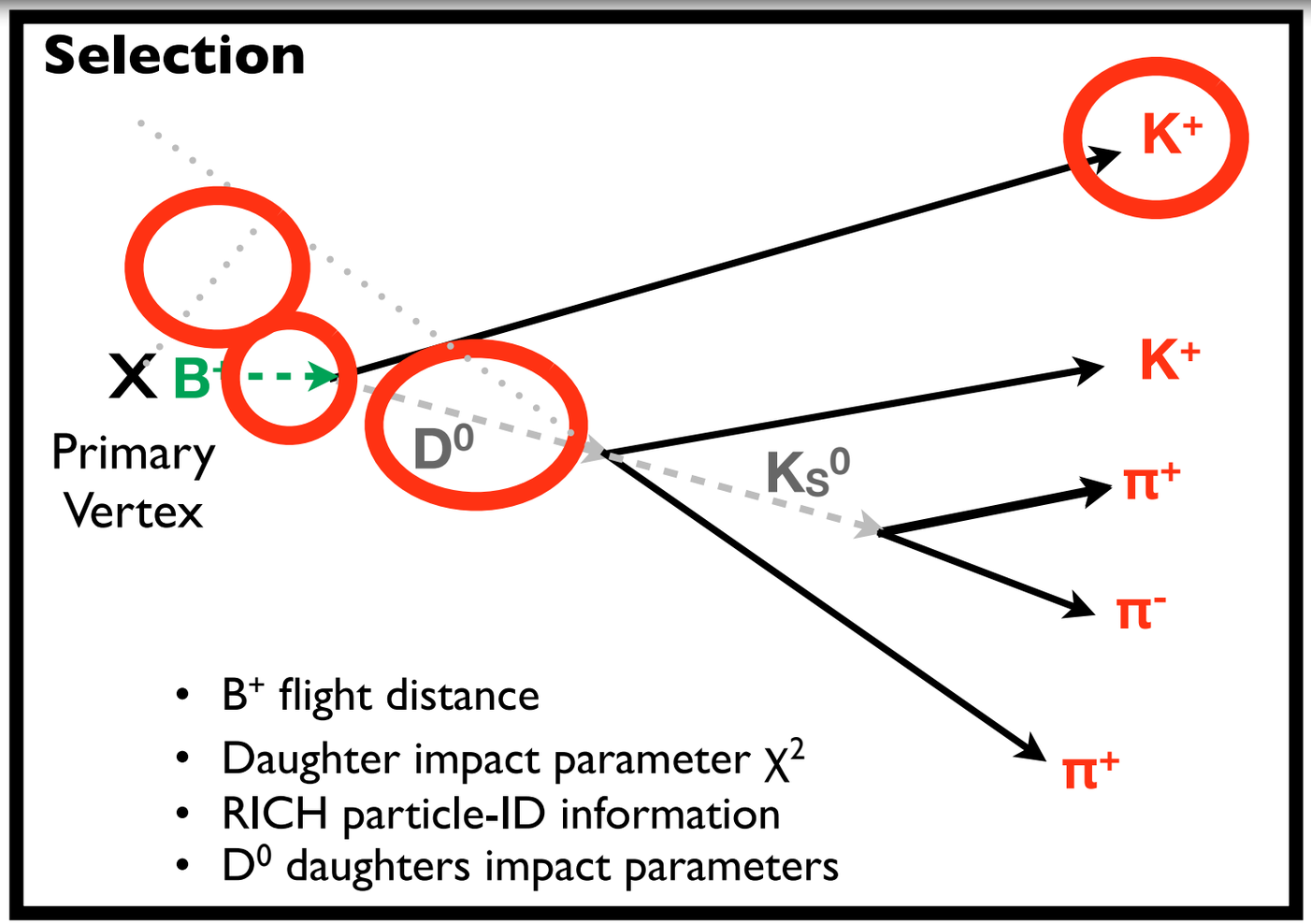
Coherence factor: 1.00±0.16

Candidate selection

Preliminary:
LHCb-PAPER-2013-068
in preparation

NEW

- BDT trained for $B^{\pm} \to [K_S^0 hh] K^{\pm}$ using signal MC and data sidebands



Suppress:

- Charmless background by requiring D^0 lifetime > 0.2ps
- $D^0 \to K\pi\pi\pi$ background with cut on K_S^0 flight distance
- $D^0 \to K_S^0 hh$ mis-ID background using RICH PID

$B^{\pm} \to D^0(\to K_S K\pi)\, K^{\pm}$

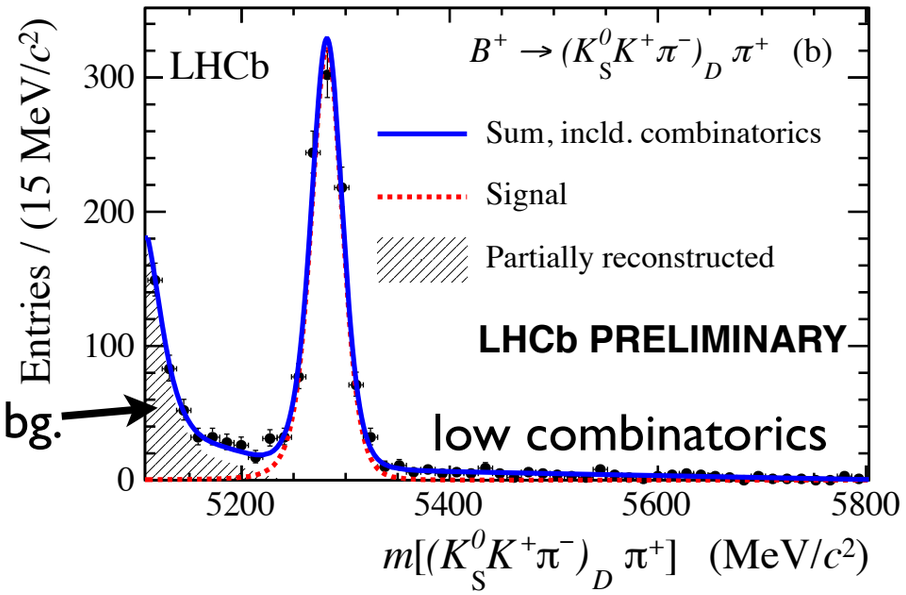
Preliminary: LHCb-PAPER-2013-068 in preparation

NEW

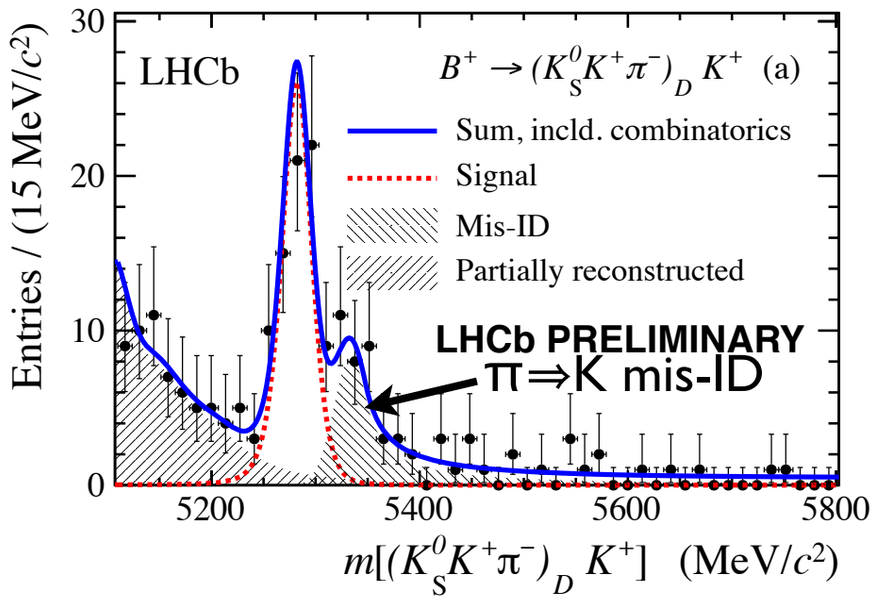
- Measure charge-separated $B^{\pm} \to [K_S^0 K^{\pm}\pi^{\mp}]_D K^{\pm}$ and $B^{\pm} \to [K_S^0 K^{\mp}\pi^{\pm}]_D K^{\pm}$ yields
- Find charge-summed signal yields of ~150 and 70 candidates, respectively

e.g.

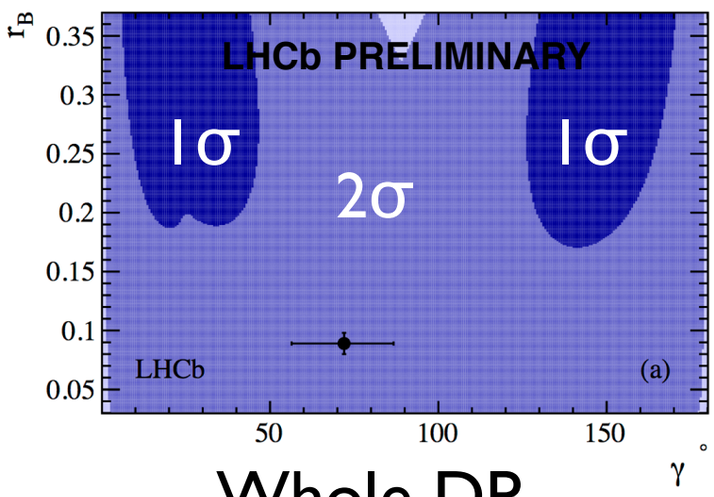
$B^+ \to [K_S^0 K^+\pi^+]_D \pi^+$



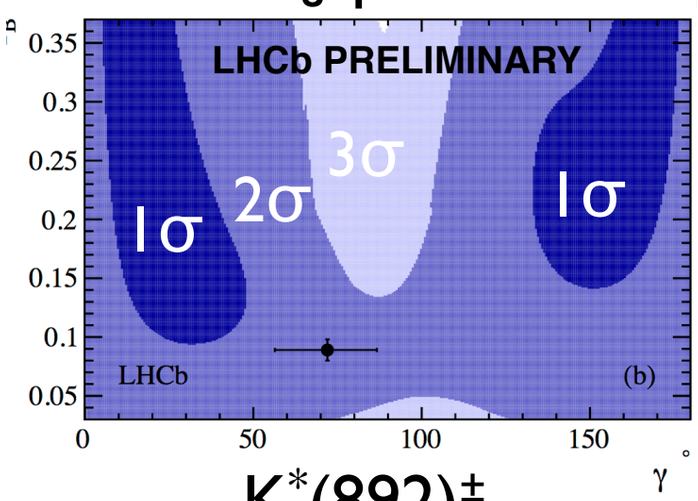
$B^+ \to [K_S^0 K^+\pi^+]_D K^+$



- Profile likelihood scan of r_B– γ parameter space



Whole DP



$K^*(892)^{\pm}$

- **Statistically** limited
- **$K^*(892)^{\pm}$ region well-motivated** in future analysis
- Main **systematic** due to different acceptance for $B^{\pm} \to [K_S^0 K^{\pm}\pi^{\mp}]_D K^{\pm}$ and $B^{\pm} \to [K_S^0 K^{\mp}\pi^{\pm}]_D K^{\pm}$

Beauty...

... ~~the beast~~ CPV in charm

CP violation in charm

Reminder:

- Theory calculations difficult in charm (npQCD); CPV very low within the SM.
- 2011: LHCb sees >3σ CPV in prompt $D^0 \to hh$ (0.6 fb^{-1}):
  - $\Delta A_{CP} = [-0.82 \pm 0.24]\%$
- Result accommodated by theoretical predictions.
- 2012: LHCb repeats analysis using charm from semileptonic B decays (1 fb^{-1})
  - $\Delta A_{CP} = [+0.49 \pm 0.33]\%$
- 2013: LHCb updates prompt $D^0 \to hh$ search to 1 fb^{-1}:
  - $\Delta A_{CP} = [-0.34 \pm 0.18]\%$ ... enticing hint disappears
- With analysis of full LHCb data set, approaching SM level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15 November 2011 Last updated at 12:18

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LHC reveals hints of 'new physics' in particle decays

By Jason Palmer
Science and technology reporter, BBC News

LHC-beauty, or LHCb, is an enormous detector designed to examine CP violation

Large Hadron Collider researchers have shown off what may be the facility's first "new physics" outside our current understanding of the Universe.

Related Stories

PRL 108 (2012) 111602

PLB 723 (2013) 33

LHCb-CONF-2013-003

Today:

- $3fb^{-1}$ study of mixing and CPV in $D^0 \to K\pi$
- $1fb^{-1}$ study of $D^0 \to KK, \pi\pi$ decays

PRL 111(2013) 251801

arXiv:1310.7201

I) Mixing in WS $D^0 \to K^+\pi^-$

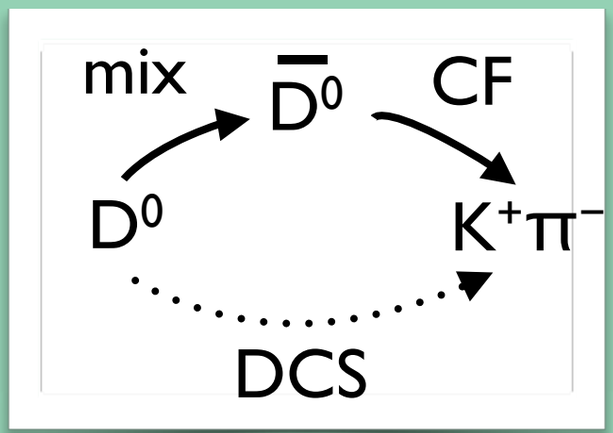
PRL 111(2013) 251801

- D^0-$\bar{D}^0$ mixing due to misaligned mass-flavour eigenstates:

$$|D_{1,2}> \equiv p|D^0> \pm q|\bar{D}^0>, |q|^2 + |p|^2 \equiv 1$$

  - Indirect CP conservation: $\left|\frac{q}{p}\right| = 1, \phi = \arg\left(\frac{q\bar{A}_f}{pA_f}\right) = 0$

- Most evident in WS decay:



Analysis:

- Uses full $3fb^{-1}$ data set
- Uses prompt $D^{*\pm} \to D^0\pi^\pm$
- Measure time-dependent ratio of WS/RS decay rates

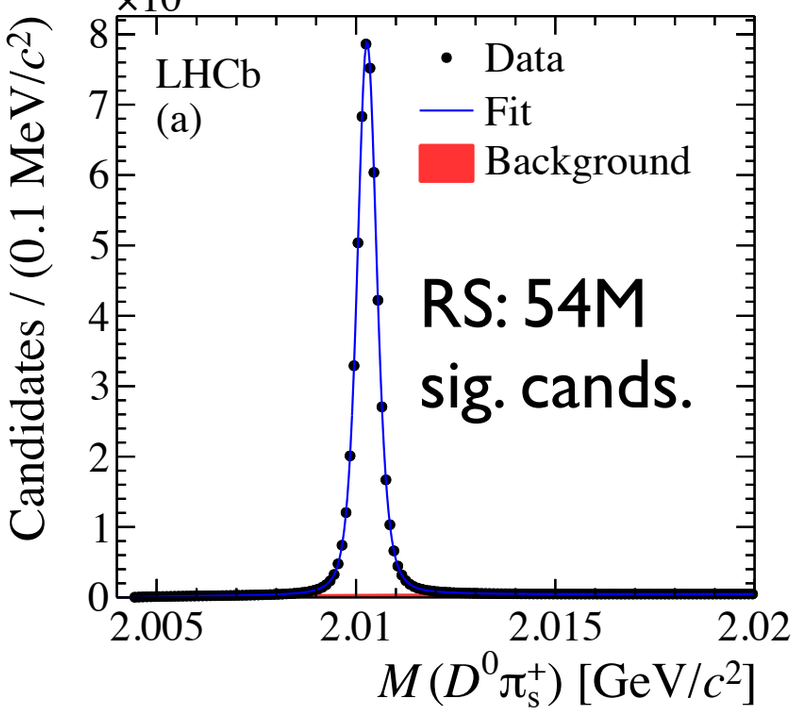
I) Mixing in WS $D^0 \to K^+\pi^-$

PRL 111(2013) 251801

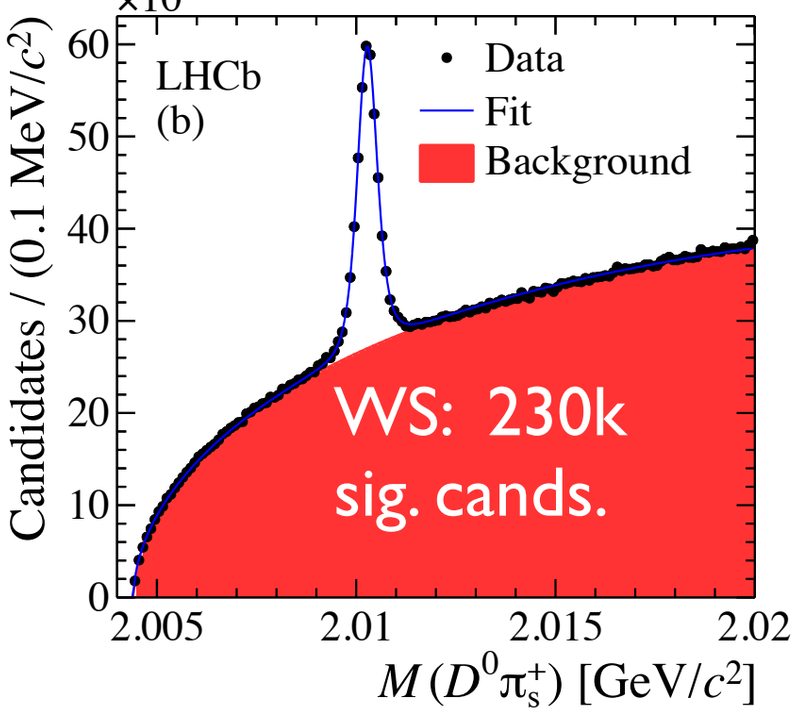
Selection:

- p_T and p of D^0, daughters and π_s
- D^0, π_s χ^2(IP) suppress secondaries
- RICH used to suppress mis-ID
- Mass-vetoes suppress KK,ππ

$D^0 \to K^-\pi^+$ fit to $m(D^0\pi_s)$



$D^0 \to K^+\pi^-$ fit to $m(D^0\pi_s)$



- Measure $R^{\pm}(t) \approx R_D^{\pm} + \sqrt{R_D^{\pm}}y'^{\pm}\frac{t}{\tau} + \frac{x'^{2\pm}+y'^{2\pm}}{4}\left(\frac{t}{\tau}\right)^2$

I) Mixing in WS $D^0 \to K^+\pi^-$

PRL 111(2013) 251801

- Measure $R^{\pm}(t) \approx R_D^{\pm} + \sqrt{R_D^{\pm}} y'^{\pm} \frac{t}{\tau} + \frac{x'^{2\pm} + y'^{2\pm}}{4} \left(\frac{t}{\tau}\right)^2$

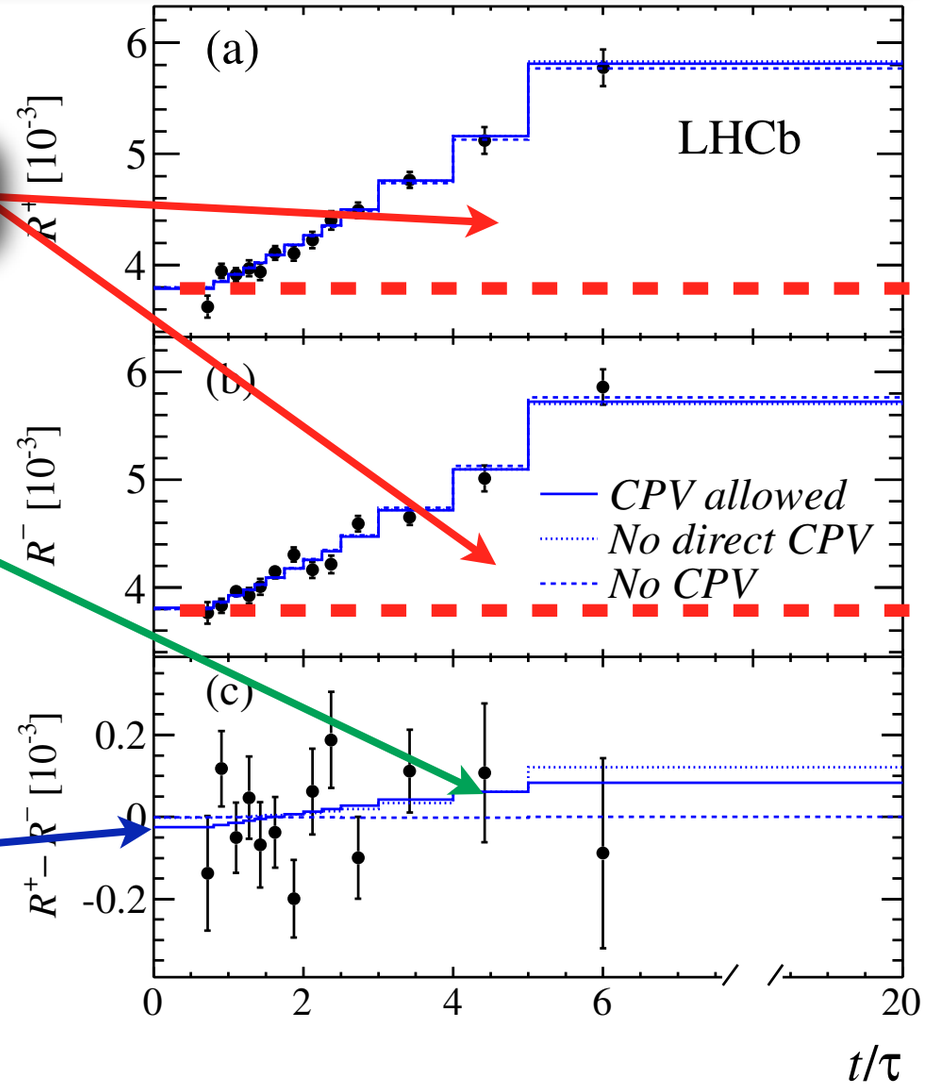
Clear mixing effect:

No signif. CP violation in x', y':

$$0.75 < \left|\frac{q}{p}\right| < 1.24 \text{ (68\% CL)}$$

No signif. direct CPV:

$$A_D \equiv \frac{(R_D^+ - R_D^-)}{(R_D^+ + R_D^-)} = (-0.7 \pm 1.9)\%$$



- Main systematic uncertainties:
  - Backgrounds from secondaries or double mis-ID decays
  - Uncertainty on instrumental asymmetry

2) $D^0 \to KK, \pi\pi$

arXiv:1310.7201

Introduction:

- Time dependent analysis of $D^0 \to hh$ (h=K,π)
- Measure effective lifetime asymmetry, A_Γ

$$A_\Gamma \equiv \frac{\hat{\Gamma} - \hat{\bar{\Gamma}}}{\hat{\Gamma} + \hat{\bar{\Gamma}}} \approx \eta_{CP} \left(\frac{A_m + A_d}{2} y \cos\phi - x \sin\phi \right)$$

- Sensitive to indirect CPV (effect of 1% A_d beyond analysis precision
- ϕ is final-state independent (in SM) and =0 if no CPV

Data set:

- $1 fb^{-1}$ data set
- Similar selection to WS $D^0 \to K\pi$ analysis
- D^0 flavour tagged by slow pion ($D^* \to D^0 \pi_s$)

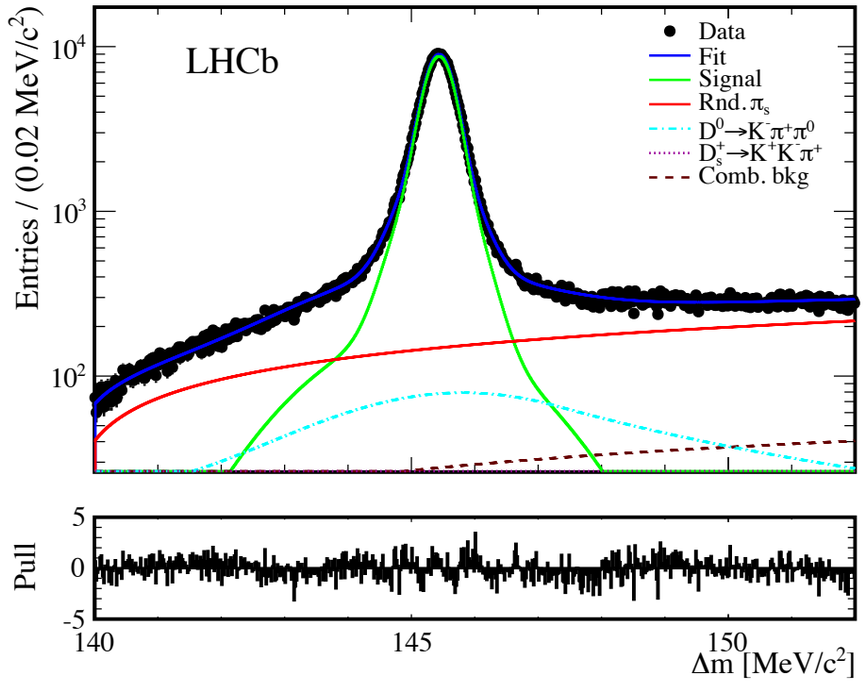
2) $D^0 \to KK, \pi\pi$

arXiv:1310.7201

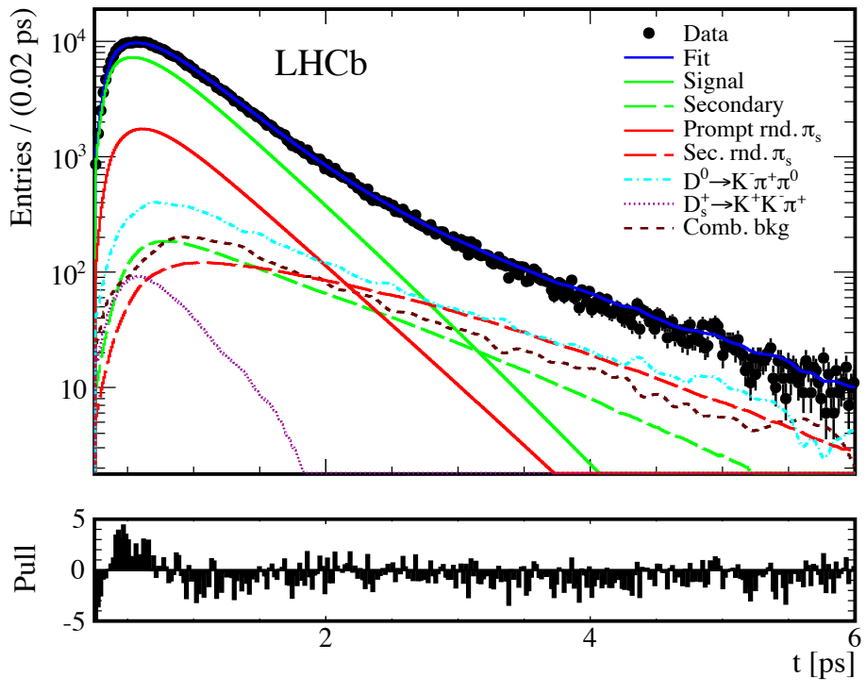
Fits:

1) Fit m(hh) and Δm spectra to determine signal yield
   - Distinguish signal, random π_s and combinatorial bg.
   - Model $D^0 \to K^-\pi^+\pi^0$ and $D_s^+ \to K^-\pi^+\pi^-$

⇒ 3M $D^0 \to KK$ and 1M $D^0 \to \pi\pi$



2) Fit decay time and $\ln[\chi^2(IP)]$ to determine effective lifetime
   - Allows identification of secondary charm contributions
   - Account for 50fs detector resolution (determined using $B \to J/\psi X$)
   - Cross-check with binned fit in decay time

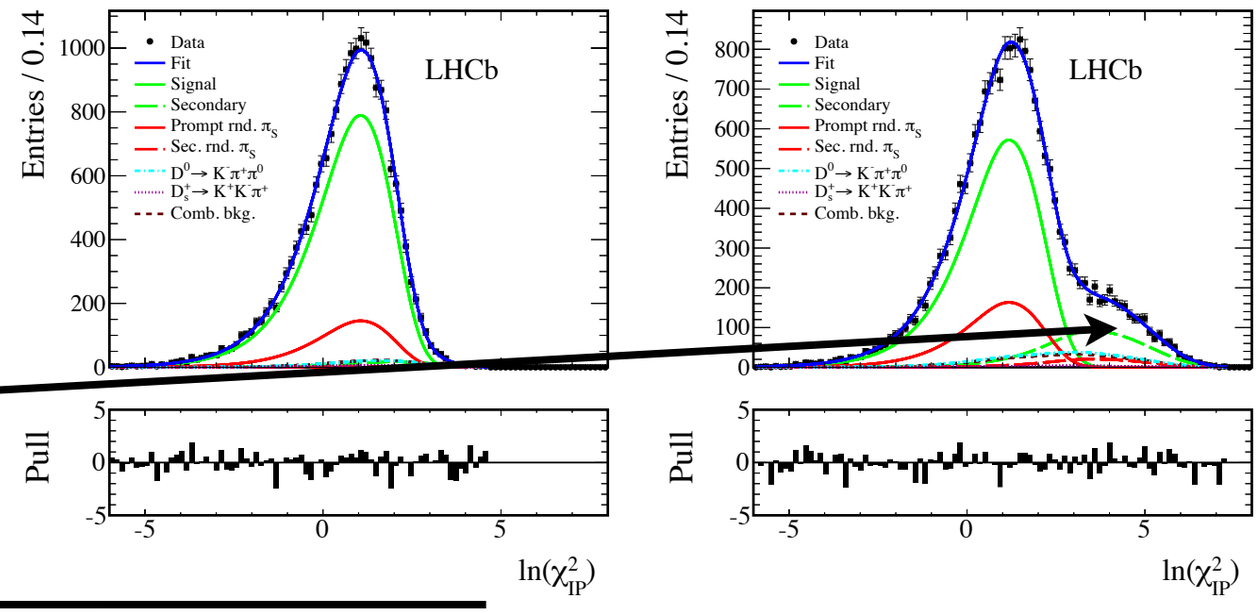


2) $D^0 \to KK, \pi\pi$

arXiv:1310.7201

2 (cont.) Fits to $\ln[\chi^2(IP)]$ in decay time
0.25→0.37ps (L) and 1.55→1.80ps

Secondary charm:



Results:

$$A_\Gamma(KK) = (-0.35 \pm 0.62 \pm 0.12) \times 10^{-3},$$
$$A_\Gamma(\pi\pi) = (0.33 \pm 1.06 \pm 0.14) \times 10^{-3}$$

- Dominant systematic uncertainties due to:
  - Sensitivity to artificial biases in the per-event acceptance function
  - Descriptions of secondary, partially reconstructed and signal backgrounds

- World's best measurement of $A_\Gamma(KK, \pi\pi)$
- No final state difference.
- No indication of indirect CPV

Conclusions

CP violation in B mesons

- Considerable precision attained for γ with low theoretical uncertainty
  - LHCb-only measurement attains ~12° precision
- Extending analyses to 2012 data set; employing additional D final states
- LHCb set to make γ measurement in loop-processes ($B \to hh$) shortly

CP violation in D mesons

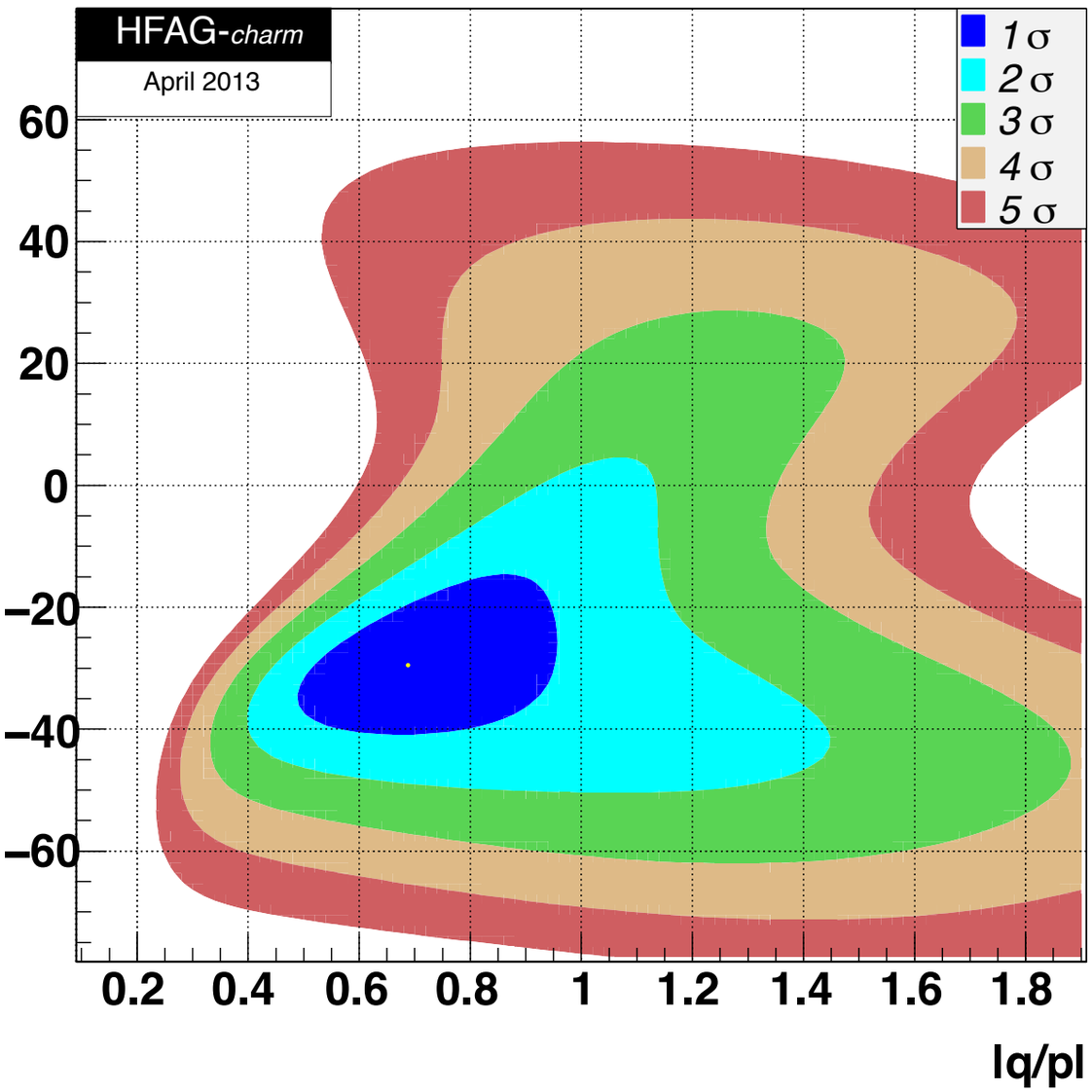
- Early, intriguing, hint of CPV in charm diminished
- LHCb now approaching a precision comparable to expected SM CPV
  - $3fb^{-1}$ analysis of CPV in $D^0 \to K^+\pi^-$ decays
  - $1fb^{-1}$ analysis of CPV in $D^0 \to KK, \pi\pi$ decays
- $3fb^{-1}$ $D^0 \to hh$ and many other searches in 3+ body D^0 decays ongoing

LHCb restarts data-taking in Spring 2015, anticipating $10fb^{-1}$ data set

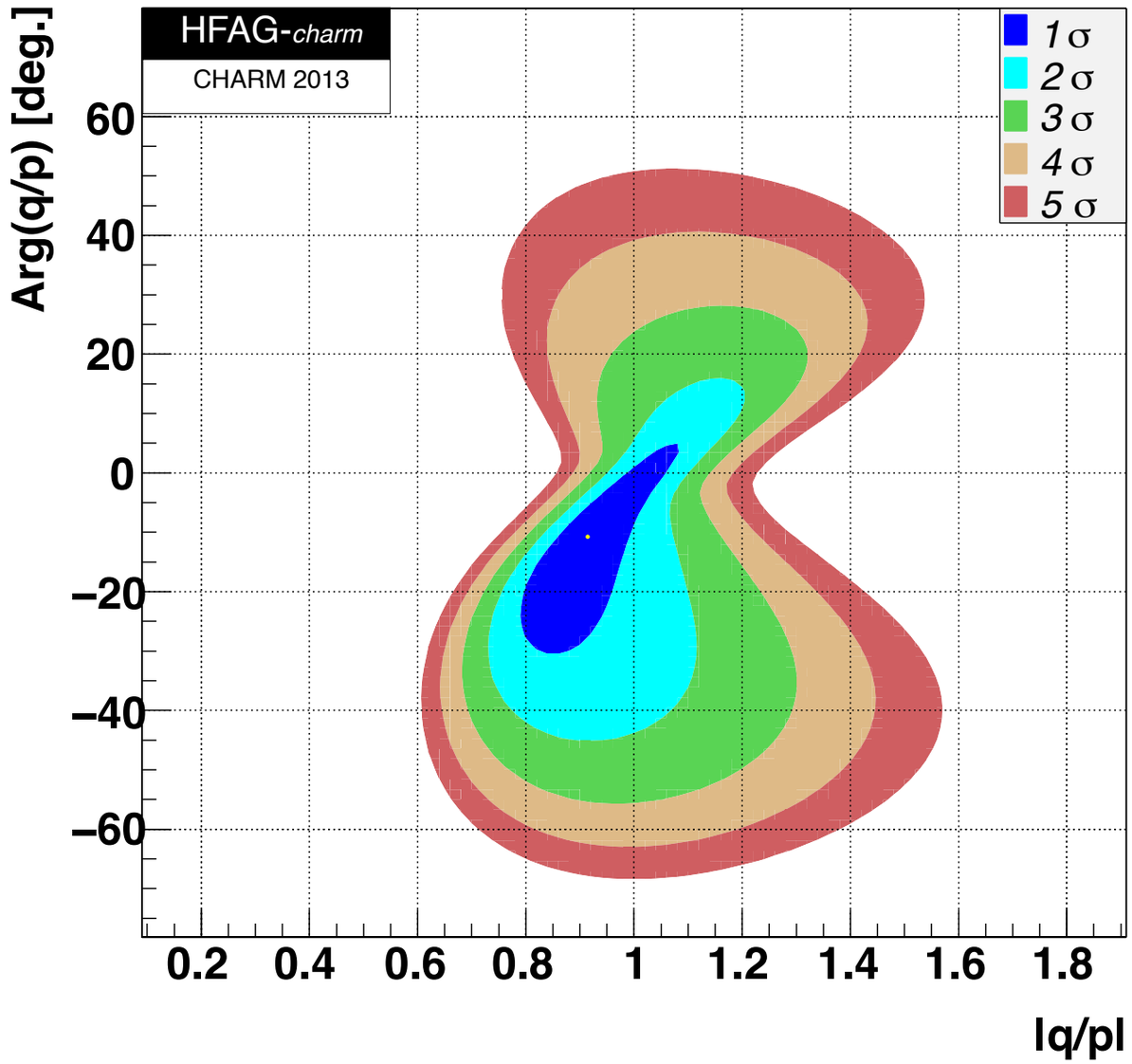
Backup

- Effect of LHCb WS result on HFAG CPV-allowed averages:

April 2013



September 2013



- No-mixing hypothesis excluded at 12σ