Hadronic B Decays

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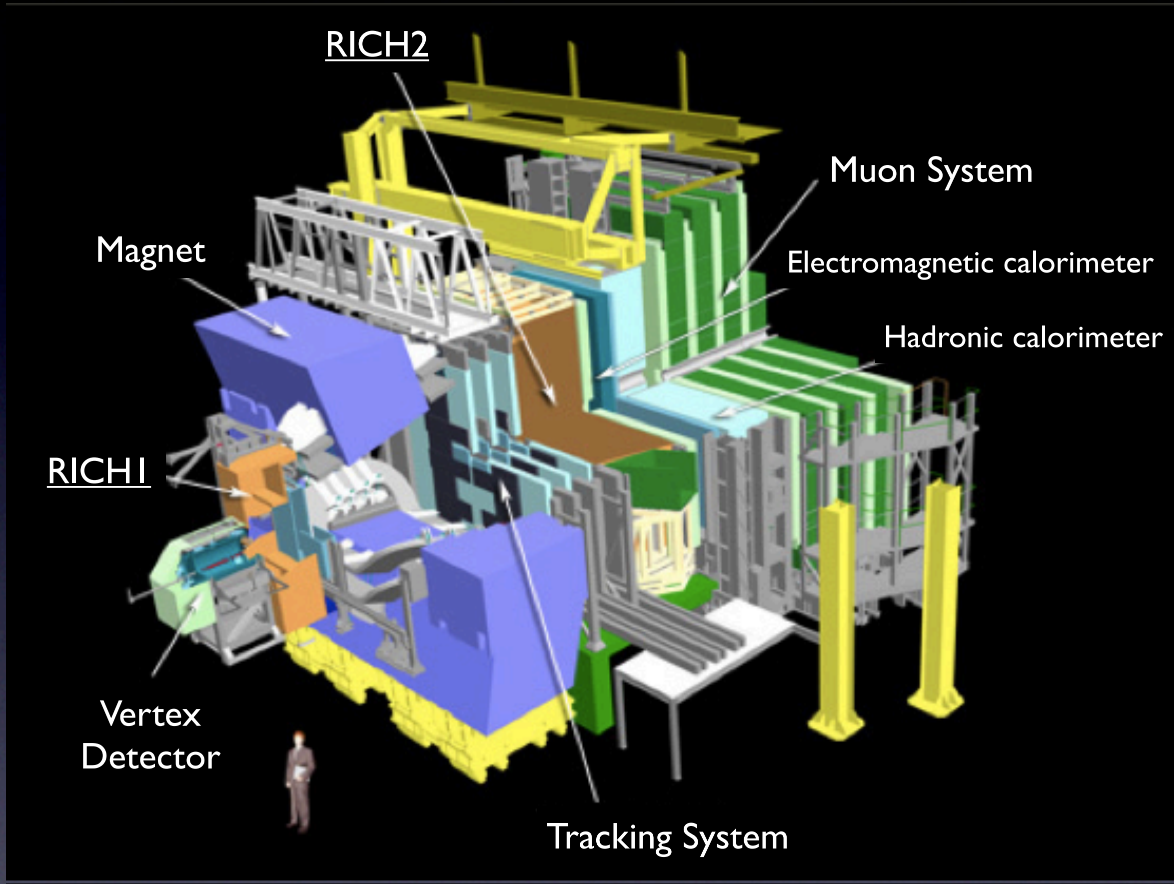
on behalf of the LHCb Collaboration

Moriond QCD 2012

Hadronic B Decays @ LHCb

- Single Arm Spectrometer
  - Excellent vertex resolution
  - Precise Tracking with Dipole Magnet
  - Hadronic PID over ~2-100 GeV/c using two RICH detectors
  - Calorimeters and Muon Detectors
  - Efficient Multi-Level Trigger



- New or updated LHCb results using **1.0 fb^{-1} from 2011**
  - $B \to DD'$ LHCb-CONF-2012-009
  - $B \to DK$ LHCb-PAPER-2012-001
  - $B^0_s \to \phi\phi$ LHCb-PAPER-2012-004

$B \to DD'$

LHCb-CONF-2012-009

$B \to DD'$ Decays

- Interesting avenue for studies of new physics beyond the Standard Model
  - $\sin(2\beta)$ from $\overline{B^0} \to D^+D^-$ Complementary to e.g. $\overline{B^0} \to (c\bar{c})K^0_s$
  - ϕ_s from $B^0_s \to D^+_s D^-_s$
  - Weak phase γ (assuming U-spin symmetry)

- Present here :
  - Branching ratio measurement for $B^0_s \to D^+_s D^-_s$
  - ***First observations*** and branching ratio measurements of $B^0_s \to D^+D^-$, $B^0_s \to D^+D^-_s$ and $B^0_s \to D^0\overline{D^0}$

[pdg.org] PDG $\mathcal{B}$ Values in 10^{-4}

	D^+D^-	$D_s D$	$D_s D_s$	$D^0 \bar{D}^0$
B^0	2.11 ± 0.31	72 ± 8	<0.36	<0.43
B_s	–	–	104 ± 29	–

B→DD' Analysis

- Generic D Selection :
  - Multi-variate selection of D→(hh,hhh) decays (h=K,π) trained on $B_{u,d,s}$→$D_{u,d,s}$π *from data*
  - K/π cross feed suppressed, with PID, kinematic isolation and $|m_{KK}-m_{\phi}|$ cuts
  - Efficiencies determined from *independent* B→Dπ data sample

$$\frac{\mathcal{B}(\overline{B}{}^0_s \to D^+D^-)}{\mathcal{B}(\overline{B}{}^0 \to D^+D^-)} = \frac{f_d}{f_s} \cdot \frac{N_{\overline{B}{}^0_s \to D^+D^-}}{N_{\overline{B}{}^0 \to D^+D^-}}$$

$$\frac{\mathcal{B}(\overline{B}{}^0_s \to D^+D^-_s)}{\mathcal{B}(\overline{B}{}^0 \to D^+D^-_s)} = \frac{f_d}{f_s} \cdot \frac{N_{\overline{B}{}^0_s \to D^+D^-_s}}{N_{\overline{B}{}^0 \to D^+D^-_s}}$$

$$\frac{\mathcal{B}(\overline{B}{}^0_s \to D^+_sD^-_s)}{\mathcal{B}(\overline{B}{}^0 \to D^+D^-_s)} = \frac{f_d}{f_s} \cdot R_{B^0/B^0_s} \cdot \frac{\mathcal{B}(D^+ \to K^-\pi^+\pi^+)}{\mathcal{B}(D^+_s \to K^+K^-\pi^+)} \frac{N_{\overline{B}{}^0_s \to D^+_sD^-_s}}{N_{\overline{B}{}^0 \to D^+D^-_s}}$$

$$\frac{\mathcal{B}(\overline{B}{}^0_s \to D^0\overline{D}{}^0)}{\mathcal{B}(B^- \to D^0D^-_s)} = \frac{f_d}{f_s} \cdot R_{B^-/B^0_s} \cdot \frac{\mathcal{B}(D^+_s \to K^+K^-\pi^+)}{\mathcal{B}(D^0 \to K^-\pi^+)} \frac{N_{\overline{B}{}^0_s \to D^0\overline{D}{}^0}}{N_{B^- \to D^0D^-_s}},$$

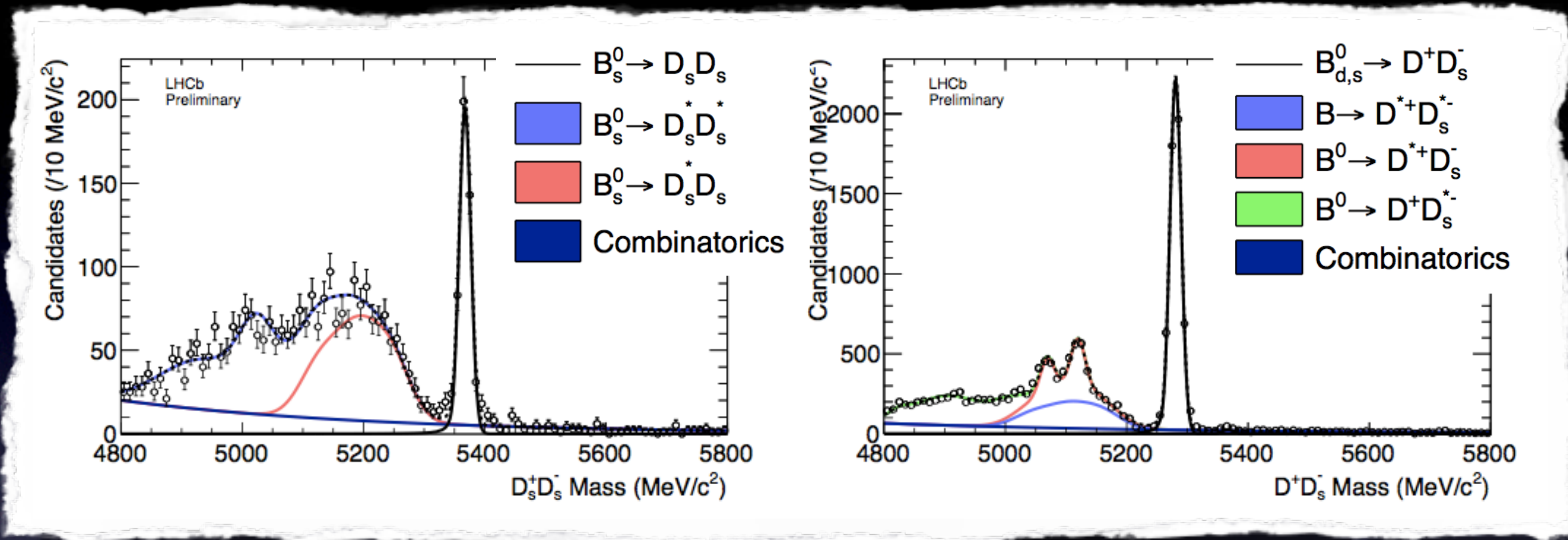
- Systematics :
  - Largely cancel for same final states.
    - f_s/f_d and B lifetime differences
  - For different final states, other factors including selection efficiencies, fit model, f_s/f_d, D branching ratios considered.

$$f_s/f_d = 0.267^{+0.021}_{-0.020}$$

LHCB-PAPER-2011-018
(See talk by A.Kozlinskiy)

Relative efficiencies $R_{B^0/B^0_s}, R_{B^-/B^0_s}$ extracted from MC

$B_s \to D^+_s D^-_s$ / $B_d \to DD_s$

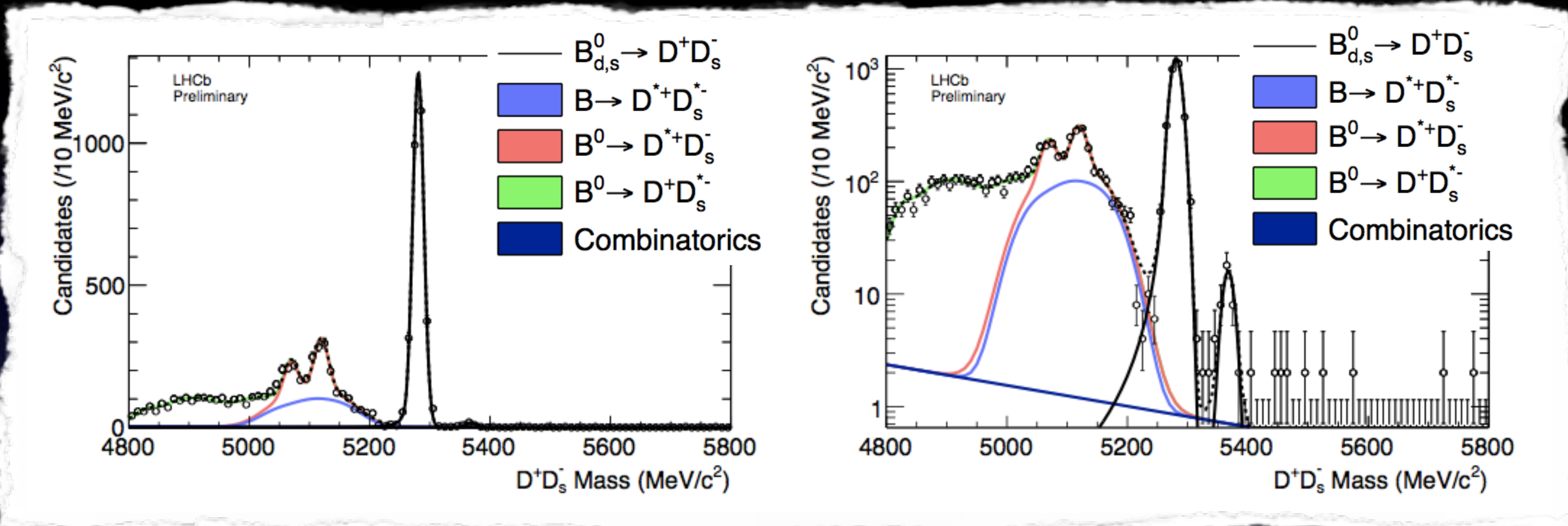


$\mathcal{B}(B_s \to D^+_s D^-_s)/\mathcal{B}(B_d \to DD_s) = 0.508 \pm 0.026(\mathrm{stat}) \pm 0.043(\mathrm{syst})$

Preliminary

- PDG : $\mathcal{B}(B_s \to D^+_s D^-_s)/\mathcal{B}(B_d \to DD_s) = 1.44 \pm 0.44$
- New CDF Result (Lake Louise 2012)
  $\mathcal{B}(B_s \to D^+_s D^-_s)/\mathcal{B}(B_d \to DD_s) = 0.183 \pm 0.021 \pm 0.017 \; * \; (f_d/f_s)$
  $= 0.685 \pm 0.079 \pm 0.075$

First Observation of $B_s \to D^-_s D^+$

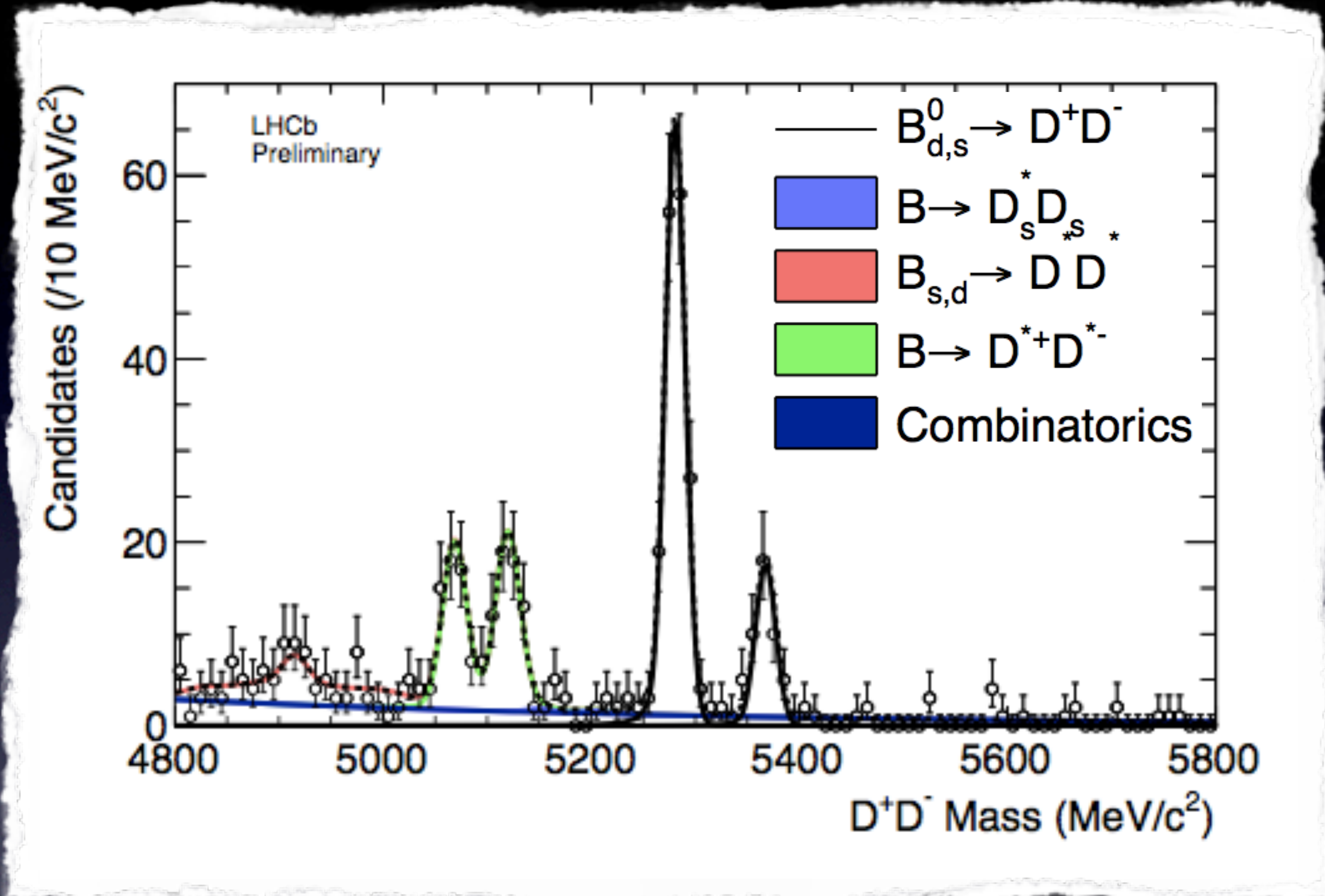


$\mathcal{B}(B_s \to D_s D)/\mathcal{B}(B_d \to D_s D) = 0.048 \pm 0.008(\text{stat}) \pm 0.004(\text{syst})$

Preliminary

- Expect $\mathcal{B}(B_s \to D_s D)/\mathcal{B}(B_d \to D_s D) \approx |V_{cd}|^2/|V_{cs}|^2 \approx 0.051$
- 10.1σ signal significance

First Observation of $B_s \rightarrow D^+D^-$

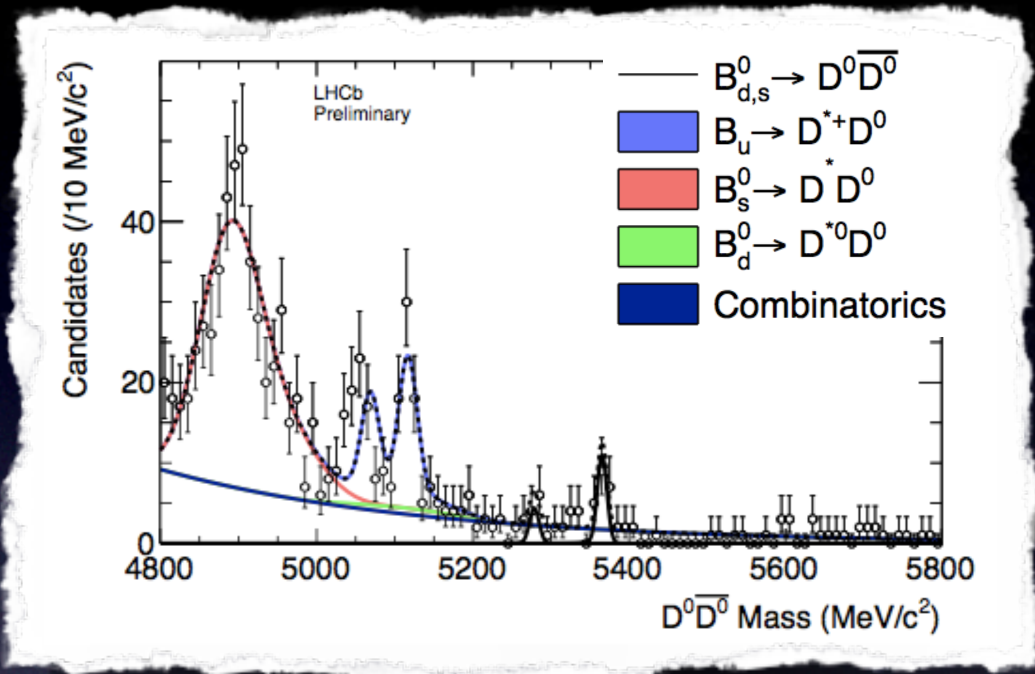


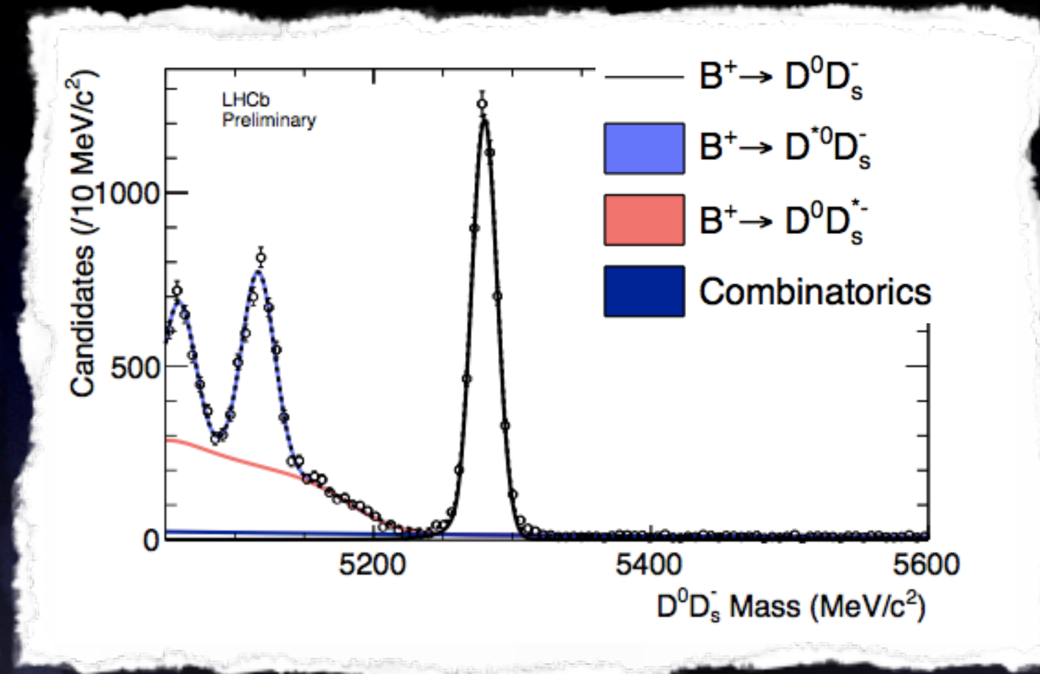
$\mathcal{B}(B_s \rightarrow D^+D^-)/\mathcal{B}(B_d \rightarrow D^+D^-) = 1.00 \pm 0.18(\text{stat}) \pm 0.09(\text{syst})$

Preliminary

Signal Significance 10.7σ

First Observation of $B_s \rightarrow D^0\overline{D}^0$





$$\mathcal{B}(B_s \rightarrow D^0\overline{D}^0)/\mathcal{B}(B^- \rightarrow D^0D^-_s) = 0.015 \pm 0.004(\text{stat}) \pm 0.002(\text{syst})$$

Preliminary

$B_s \rightarrow D^0\overline{D}^0$ signal significance 5.4σ

$B_d \rightarrow D^0\overline{D}^0$ significance 2.1σ

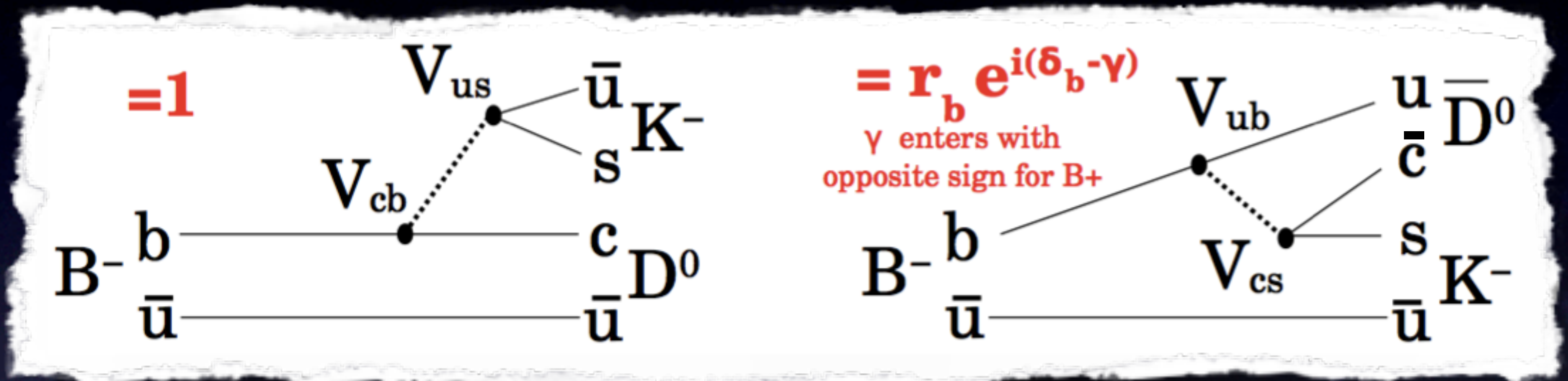
$\mathcal{B}(B_s \rightarrow D^0\overline{D}^0) \sim 2\text{x}10^{-7}$ Unprecedented reach

B→DK

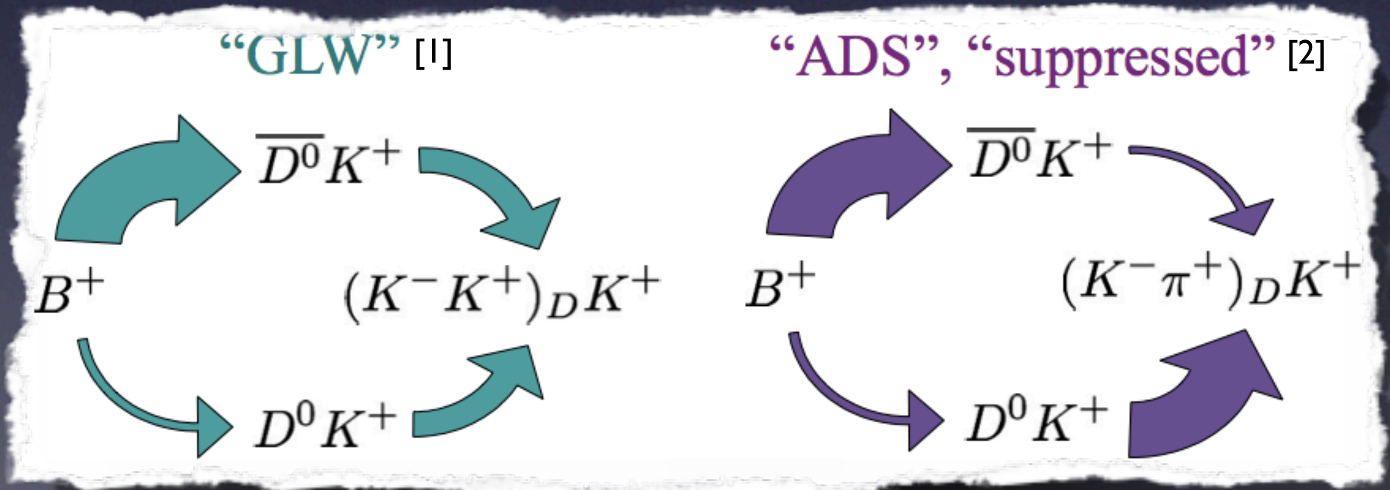
LHCb-PAPER-2012-001

B→DK Decays

- Established mode to measure weak phase γ
- Complementary to B→hh (See talk by J.Tilburg)
- Penguin free, theoretically clean



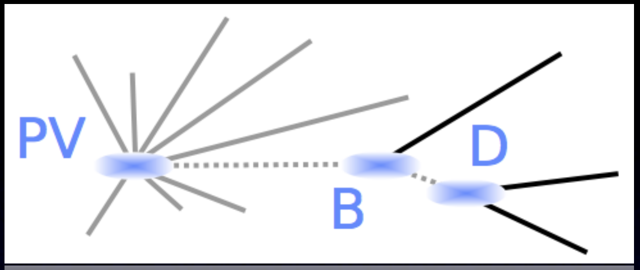
- If same D final state accessible to both, interference gives sensitivity to γ and may exhibit direct CP violation



[1] Phys Lett. B253 (1991) 483 [2] Phys. Rev. D63 (2001) 036005

B→DK Analysis

- Reconstruct all B→$[hh]_D h$ mass combinations (h=π,K)
- Multi-variate B selection designed to suppress combinatorial backgrounds



- Extract ratios and asymmetries from simultaneous fit with 13 observables :

$$
\begin{aligned}
R_{CP+} &\approx \; < R^{KK}_{K/\pi}, R^{\pi\pi}_{K/\pi} > / R^{K\pi}_{K/\pi} \\
A_{CP+} &= \; < A^{KK}_{K}, A^{\pi\pi}_{K} > \\
R_{ADS(K)} &= (R^-_K + R^+_K)/2 \\
A_{ADS(K)} &= (R^-_K - R^+_K)/(R^-_K + R^+_K)
\end{aligned}
$$

3 partial width ratios (f = KK, ππ, Kπ)

$$R^f_{K/\pi} = \frac{\Gamma(B^- \to [f]_D K^-) + \Gamma(B^+ \to [f]_D K^+)}{\Gamma(B^- \to [f]_D \pi^-) + \Gamma(B^+ \to [f]_D \pi^+)},$$

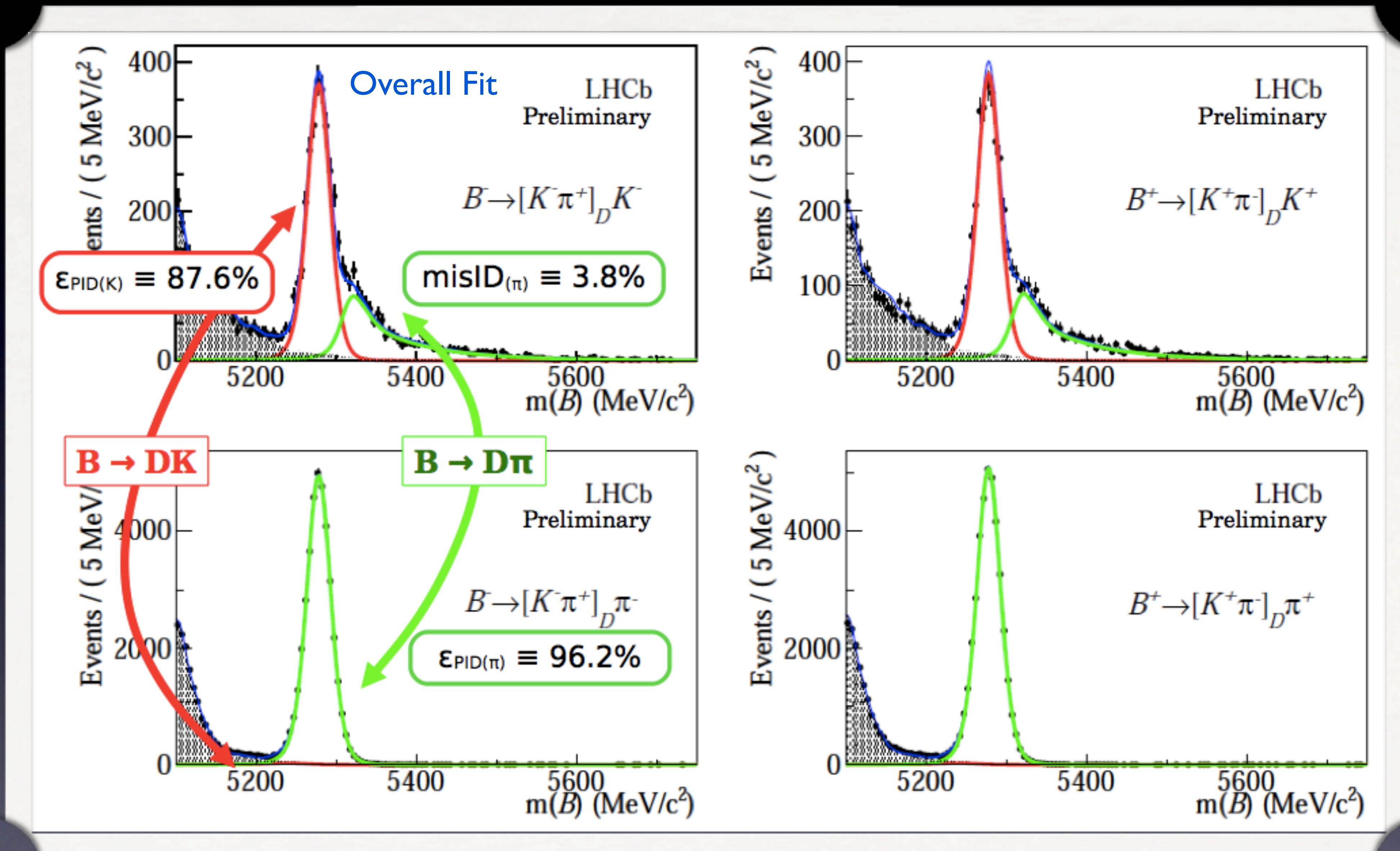
6 CP asymmetries (h = K,π)

$$A^f_h = \frac{\Gamma(B^- \to [f]_D h^-) - \Gamma(B^+ \to [f]_D h^+)}{\Gamma(B^- \to [f]_D h^-) + \Gamma(B^+ \to [f]_D h^+)},$$

4 charged separated partial widths of ADS(suppressed) to favoured mode

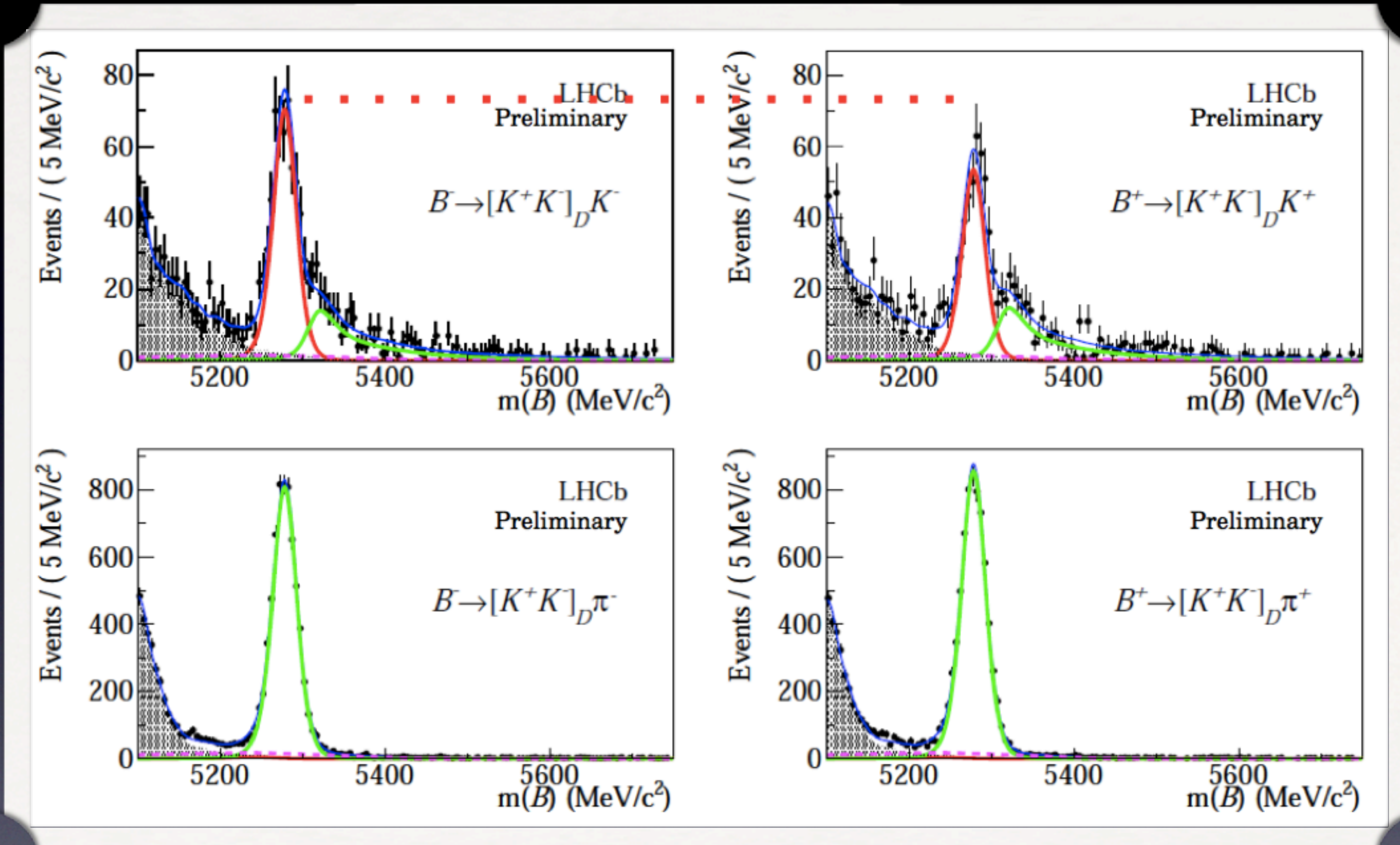
$$R^\pm_h = \frac{\Gamma(B^\pm \to [\pi^\pm K^\mp]_D h^\pm)}{\Gamma(B^\pm \to [K^\pm \pi^\mp]_D h^\pm)}.$$

$B^{\pm} \to D(K\pi)h^{\pm}$



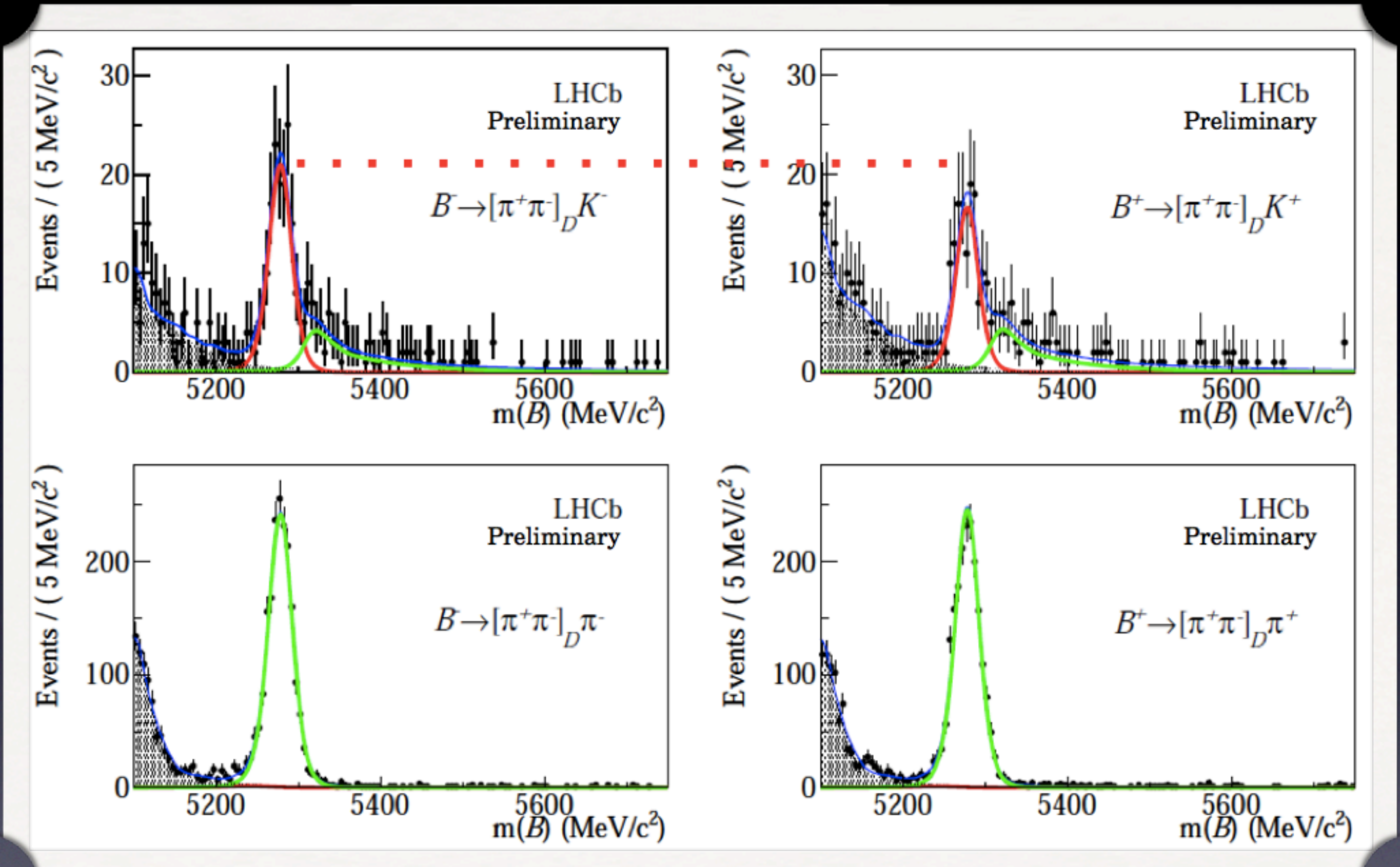
- Favoured ADS modes. Little asymmetry expected

$B^{\pm} \to D(K^+K^-)h^{\pm}$



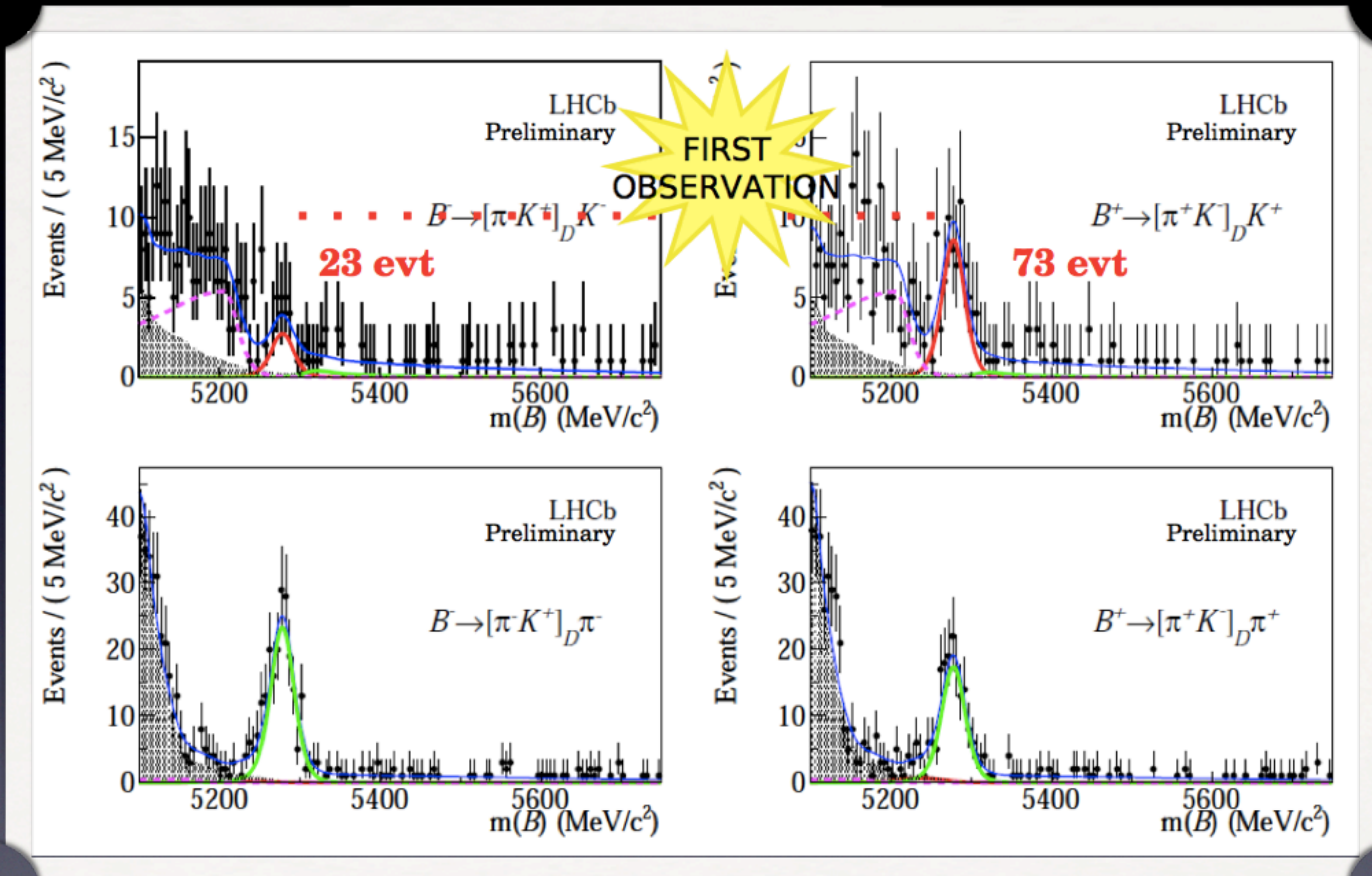
- GLW CP+ mode.
- B→DK shows clear asymmetry. No asymmetry in B→Dπ (as expected)

$B^{\pm} \to D(\pi^+\pi^-)h^{\pm}$



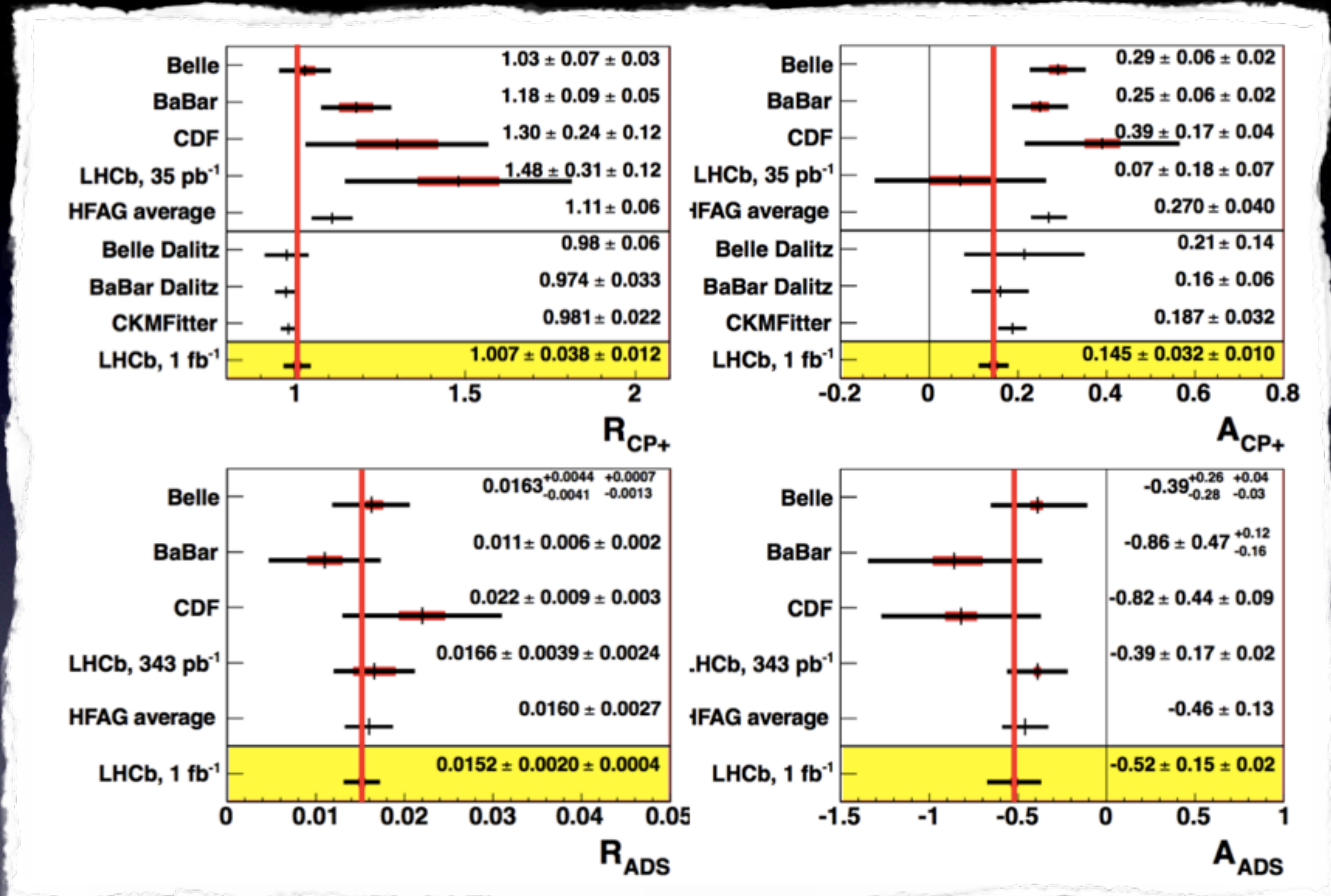
- GLW CP+ mode.
- B→DK shows clear asymmetry   No asymmetry in B→Dπ (as expected)

B± → D(πK)h±



- Suppressed ADS mode (wrong sign kaons)

B→DK Results

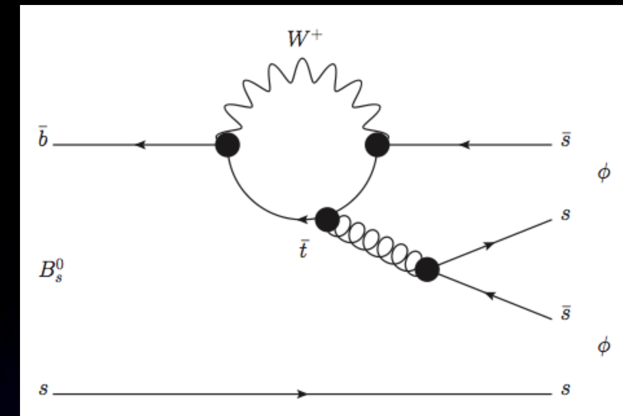


Updated CKFitter results imminent

$B^0_s \to \phi\phi$

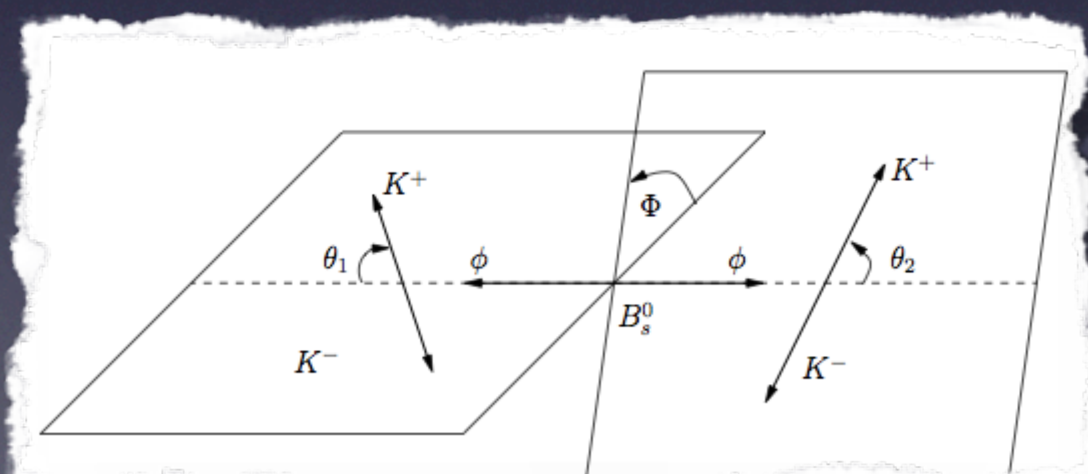
LHCb-PAPER-2012-004

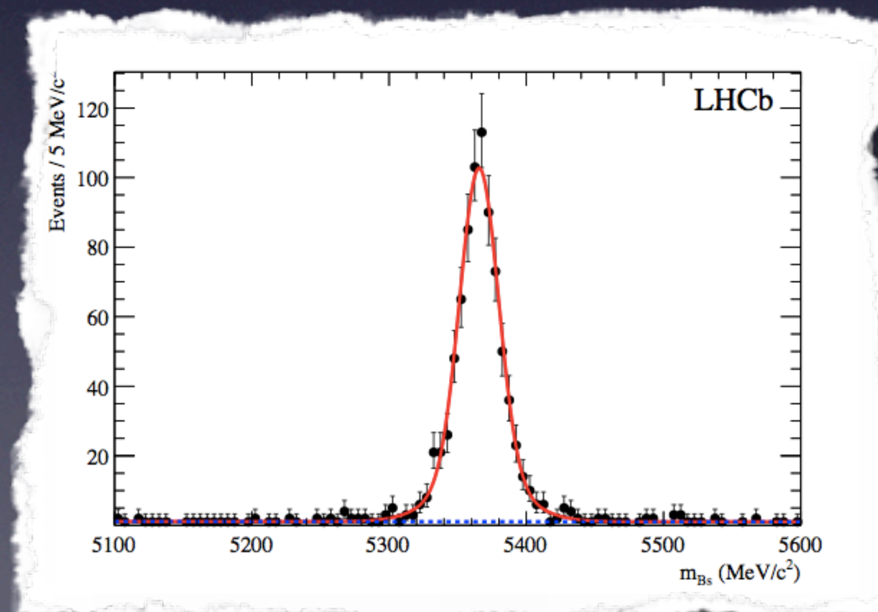
$B^0_s \to \phi\phi$



- Decay proceeds via a Flavour Changing Neutral Current
- Arena for NP searches, due to possible CPV from decay and mixing
  - SM CPV expected to be very small (LHCb-PUB-2009-025)
- Full angular analysis is required
  - Three possible spin configurations. H_{+1}, H_{-1} H_0
  - Rewrite as polarisation amplitudes $A_0, A_\perp, A_\parallel$ of definite CP

$$A_0 = H_0$$
$$A_\perp = \frac{H_{+1} - H_{-1}}{\sqrt{2}}$$
$$A_\parallel = \frac{H_{+1} + H_{-1}}{\sqrt{2}}.$$

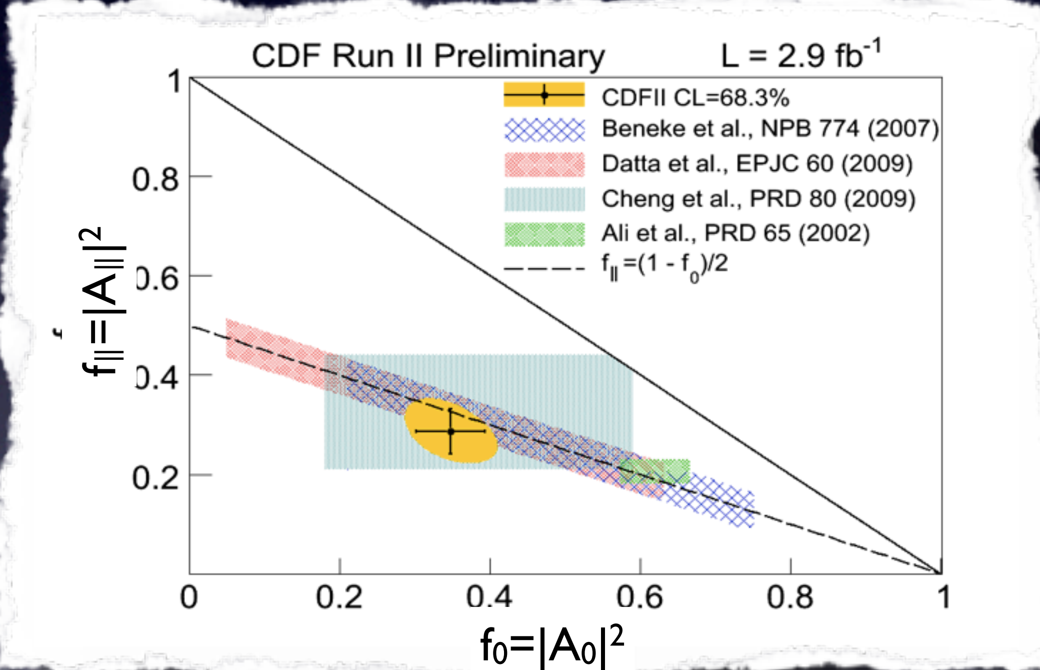




"Polarisation Puzzle"

- Expect $f_L \gg f_T$ due to V-A nature of the weak interaction
- Confirmed at B-factories in tree processes (e.g. $B^+ \to \rho^+ \rho^0$)
- However, in $B^0 \to \phi K^*$ ($b \to s$ penguin) found $f_L \approx f_T$
- Various explanations proposed, such as penguin annihilation effects, final state interactions, or New Physics.
- More recent theoretical predictions, adjusting phenomenological parameters to match the data, give $f_L (= f_0) \sim 0.4$ to 0.7

$$f_L = \frac{|A_0|^2}{|A_0|^2 + |A_\perp|^2 + |A_\parallel|^2}, \; f_T = \frac{|A_\perp|^2 + |A_\parallel|^2}{|A_0|^2 + |A_\perp|^2 + |A_\parallel|^2}.$$



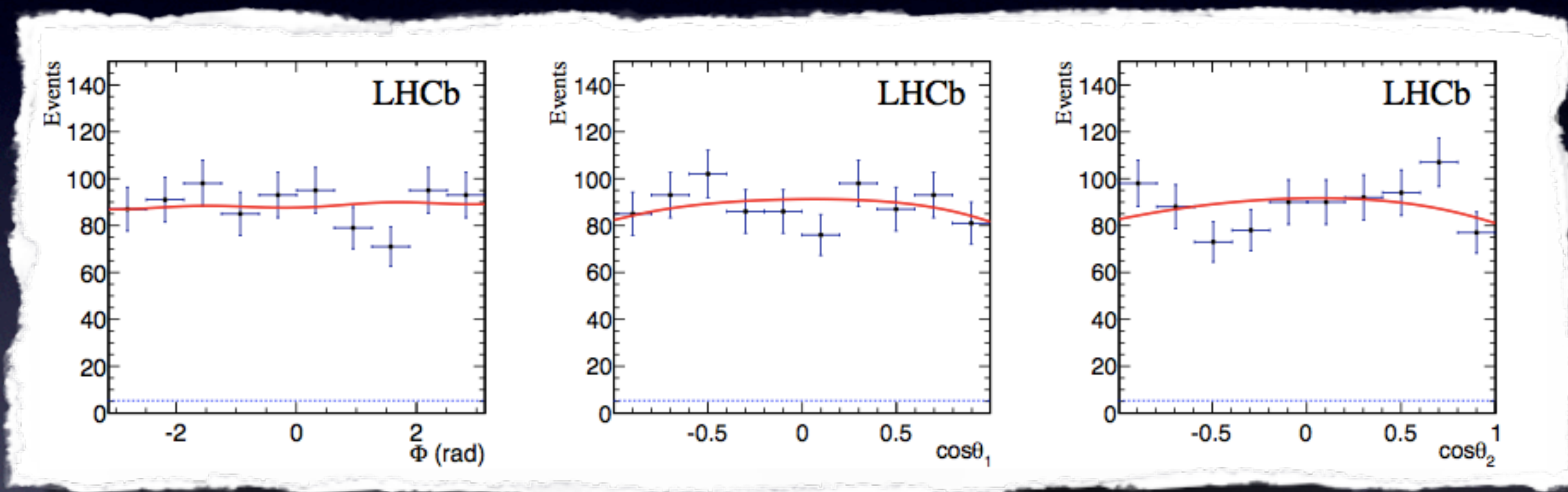
http://www-cdf.fnal.gov/physics/new/bottom/110331.blessed-BsphiphiCPV/

$B^0_s \rightarrow \phi\phi$ Polarisation Amplitudes

- Time integrated fit to PDF
- Angular distributions and fit projections for signal and background

$$\frac{d^3\Gamma}{d\vec{\omega}} \propto \tau_{\mathrm{L}}\left(|A_0|^2 f_1(\vec{\omega}) + |A_\parallel|^2 f_2(\vec{\omega}) + \right. \\ \left. + |A_0||A_\parallel|\cos\delta_\parallel f_5(\vec{\omega})\right) + \tau_{\mathrm{H}}|A_\perp|^2 f_3(\vec{\omega}),$$

Note that the PDF assumes $\phi_s^{\phi\phi} = 0$



$|A_0|^2 = 0.365 \pm 0.022(\mathrm{stat}) \pm 0.012(\mathrm{syst})$

$|A_\perp|^2 = 0.291 \pm 0.024(\mathrm{stat}) \pm 0.010(\mathrm{syst})$

$|A_\parallel|^2 = 0.344 \pm 0.024(\mathrm{stat}) \pm 0.014(\mathrm{syst})$

$\cos(\delta_\parallel) = -0.844 \pm 0.068(\mathrm{stat}) \pm 0.029(\mathrm{syst})$ ($\delta_\parallel = \mathit{arg}(A_\parallel/A_0)$)

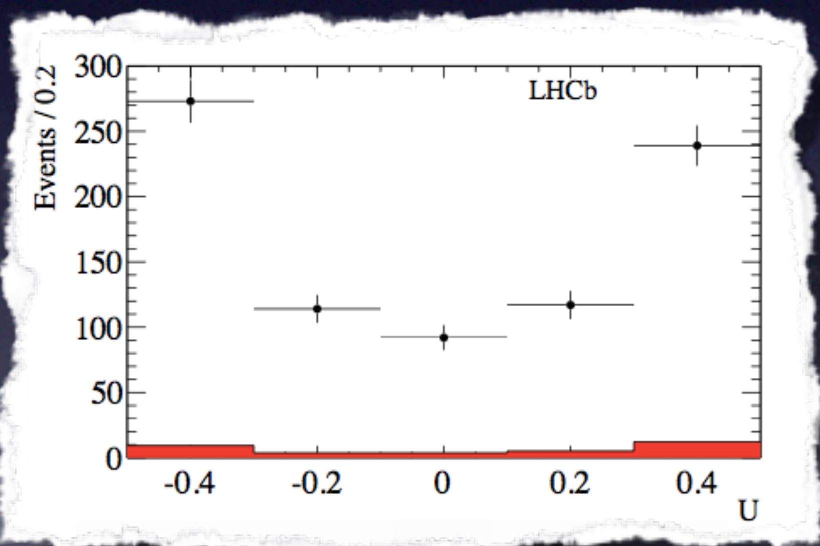
$B^0_s \to \phi\phi$ Triple Products

- Scalar triple products of momentum or spin vectors odd under time reversal
- $A_u, A_v \sim \sin(\phi_{weak}) \times \cos(\delta_{strong}) \sim 0$ in SM
- $A_u, A_v \neq 0$ implies CP violation (assuming CPT conservation), due to difference in weak phase for CP even/odd amplitudes. *Sign of New Physics.*

We define our triple products as:

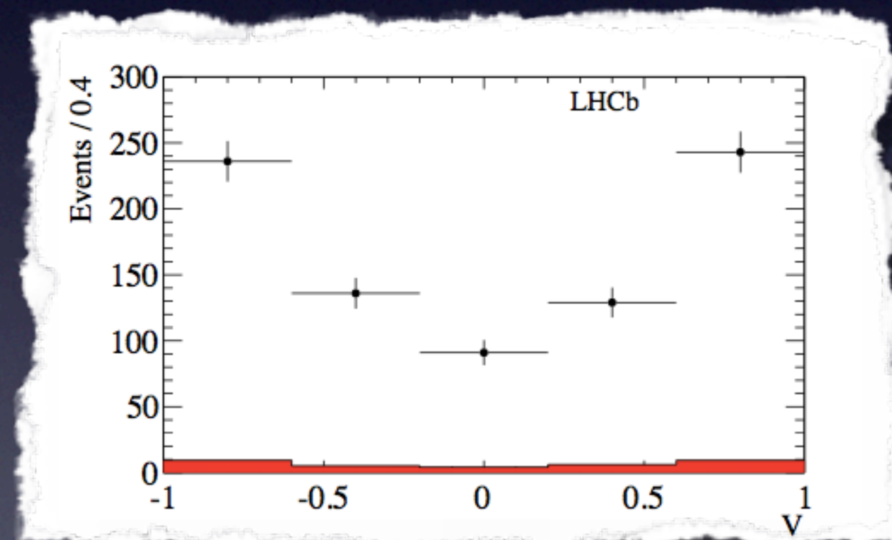
$$U = \sin(2\Phi)$$
$$V = \sin(\pm\Phi)$$
$$A_u \equiv \frac{\Gamma(\sin 2\Phi > 0) - \Gamma(\sin 2\Phi < 0)}{\Gamma(\sin 2\Phi > 0) + \Gamma(\sin 2\Phi < 0)}.$$
$$A_v \equiv \frac{\Gamma(\sin(\pm\Phi) > 0) - \Gamma(\sin(\pm\Phi) < 0)}{\Gamma(\sin(\pm\Phi) > 0) + \Gamma(\sin(\pm\Phi) < 0)}.$$

Where positive sign in $\sin(\pm\Phi)$ is taken if $\cos\theta_1 \cos\theta_2 \geq 0$.



U and V distributions for signal(black) and background

Background taken from sidebands and normalised to the signal



$$A_u = -0.055 \pm 0.036(\text{stat}) \pm 0.018(\text{syst})$$
$$A_v = 0.010 \pm 0.036(\text{stat}) \pm 0.018(\text{syst})$$

Compatible with previous LHCb result (LHCb-CONF-2011-052) and CDF (FERMILAB-PUB-11-345-E)

Conclusions

- **2011 was an excellent year for LHCb, collecting 1.0 fb^{-1}**
- **$B \rightarrow DD$** **LHCb-CONF-2012-009**
  - ***First observations*** of $B_s \rightarrow D^+D^-_s$, $B_s \rightarrow D^+D^-$ and $B_s \rightarrow D^0\bar{D}^0$
  - ***Current World Best*** $\mathcal{B}(B_s \rightarrow D^+_s D^-_s)$ measurement
- **$B \rightarrow DK$** **LHCb-PAPER-2012-001**
  - ***Precise measurements*** of R_{CP}, A_{CP}, R_{ADS}, A_{ADS}
  - ***5.8σ First Observation*** of CPV in $B^{\pm}$
  - Closer to a measurement of CKM angle γ
- **$B_s \rightarrow \phi\phi$** **LHCb-PAPER-2012-004**
  - ***Currently most precise*** measurements of polarisation amplitudes, triple products and strong phase.

... and plenty more to come in 2012

Backups

Generic D→(hh,hhh) Decay Selection

- Multi-Variate D→X selection (Boosted Decision Tree)
  - Trained on real data from $B_{u,d,s} \rightarrow D_{u,d,s}\pi$ decays.
    - sWeighted signal and D side-bands as background
  - D and D daughter kinematical quantities
  - Track Quality and PID variables
- Efficiencies determined from independent sub-set of B→Dπ data

Measurement	$\mathrm{BDT}^{\mathrm{opt}}_{\mathrm{D_1 \times D_2}}$ cut value	Cut Efficiency
$\overline{B}{}^0_s \rightarrow D_s^+ D_s^-$	0.03	97.5%
$\overline{B}{}^0 \rightarrow D^+ D_s^-$ for $\mathcal{B}(\overline{B}{}^0_s \rightarrow D_s^+ D_s^-)$	0.02	100%
$\overline{B}{}^0 \rightarrow D^+ D_s^-$ for $\mathcal{B}(\overline{B}{}^0_s \rightarrow D^+ D_s^-)$	0.47	53.2%
$\overline{B}{}^0, \overline{B}{}^0_s \rightarrow D^+ D^-$	0.67	49.9%
$\overline{B}{}^0_s \rightarrow D^0 \overline{D}{}^0$	0.86	60.4%

- Cross feed, when $D_{(s)}$ candidates fall in both D→Kππ and D_s→KKπ mass windows, suppressed using :-
  - Tighten PID criteria on ambiguous K/π
  - Cut on $|m_{KK}-m_{\phi}|$ to select/reject compatible KK combinations

B→DD' Analysis

- B Selection :-
  - Apply ambiguous D rejection
  - Cut on product of the two D BDT values.
  - Require B candidates $p(\chi^2_{IP}+\chi^2_{vert}) > 0.3\%$
  - Require for each D $\chi^2_{FD\text{-}from\text{-}B} > 2$ to suppress prompt backgrounds
- Mass Fit :-
  - Signal described a single crystal ball
  - Gaussian parameterisations of background shapes (e.g. excited D meson decays) extracted from MC
  - Exponential combinatoric background
- Systematics :-
  - Largely cancel for same final states, only f_s/f_d and lifetime differences (O(10%)).
  - For different final states, selection efficiencies, fit model, f_s/f_d, D branching ratios considered.

$$\frac{\mathcal{B}(\bar{B}^0_s \to D^+D^-)}{\mathcal{B}(\bar{B}^0 \to D^+D^-)} = \frac{f_d}{f_s} \cdot \frac{N_{\bar{B}^0_s \to D^+D^-}}{N_{\bar{B}^0 \to D^+D^-}}$$

$$\frac{\mathcal{B}(\bar{B}^0_s \to D^+D^-_s)}{\mathcal{B}(\bar{B}^0 \to D^+D^-_s)} = \frac{f_d}{f_s} \cdot \frac{N_{\bar{B}^0_s \to D^+D^-_s}}{N_{\bar{B}^0 \to D^+D^-_s}}$$

$$\frac{\mathcal{B}(\bar{B}^0_s \to D^+_sD^-_s)}{\mathcal{B}(\bar{B}^0 \to D^+D^-_s)} = \frac{f_d}{f_s} \cdot R_{B^0/B^0_s} \cdot \frac{\mathcal{B}(D^+ \to K^-\pi^+\pi^+)}{\mathcal{B}(D^+_s \to K^+K^-\pi^+)} \frac{N_{\bar{B}^0_s \to D^+_sD^-_s}}{N_{\bar{B}^0 \to D^+D^-_s}}$$

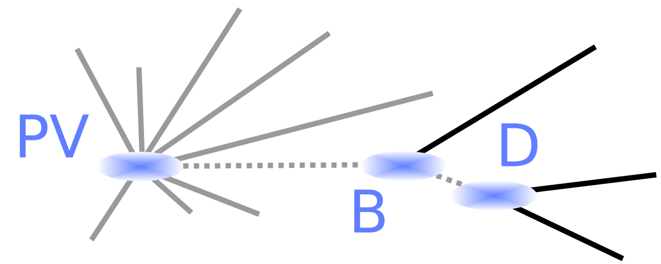
$$\frac{\mathcal{B}(\bar{B}^0_s \to D^0\bar{D}^0)}{\mathcal{B}(B^- \to D^0D^-_s)} = \frac{f_d}{f_s} \cdot R_{B^-/B^0_s} \cdot \frac{\mathcal{B}(D^+_s \to K^+K^-\pi^+)}{\mathcal{B}(D^0 \to K^-\pi^+)} \frac{N_{\bar{B}^0_s \to D^0\bar{D}^0}}{N_{B^- \to D^0D^-_s}},$$

$$f_s/f_d = 0.267^{+0.021}_{-0.020}$$

LHCb : arXiv:1111.2357

Relative efficiencies $R_{B^0/B^0_s}, R_{B^-/B^0_s}$ extracted from MC

Selection



- Most background from combinatoric
- Use MVA method: **BDT with 20 variables**
- Train on **Signal MC** *vs* **2010 Sidebands** (35 pb^{-1} independent sample)

- Partially reconstructed background
- Peaking backgrounds (from charmless B decays & internal **cross feed btw modes)**
- Exploit forward boost in LHCb and cut on D flight distance

e.g. $B^{\pm}\to[\pi\pi]_D K^{\pm}$ suffers from:

$B^{\pm}\to K\pi\pi^{\pm}$ Charmless

$B^{\pm}\to[K\pi]_D\pi^{\pm}$ Cross feed

$B^{\pm}\to[\pi\pi\pi^0]_D\pi^{\pm}$ Part. reco. cross feed