Measuring γ at LHCb

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(On behalf of the LHCb collaboration)

Heavy Quarks and Leptons 2012
Prague, Czech Republic

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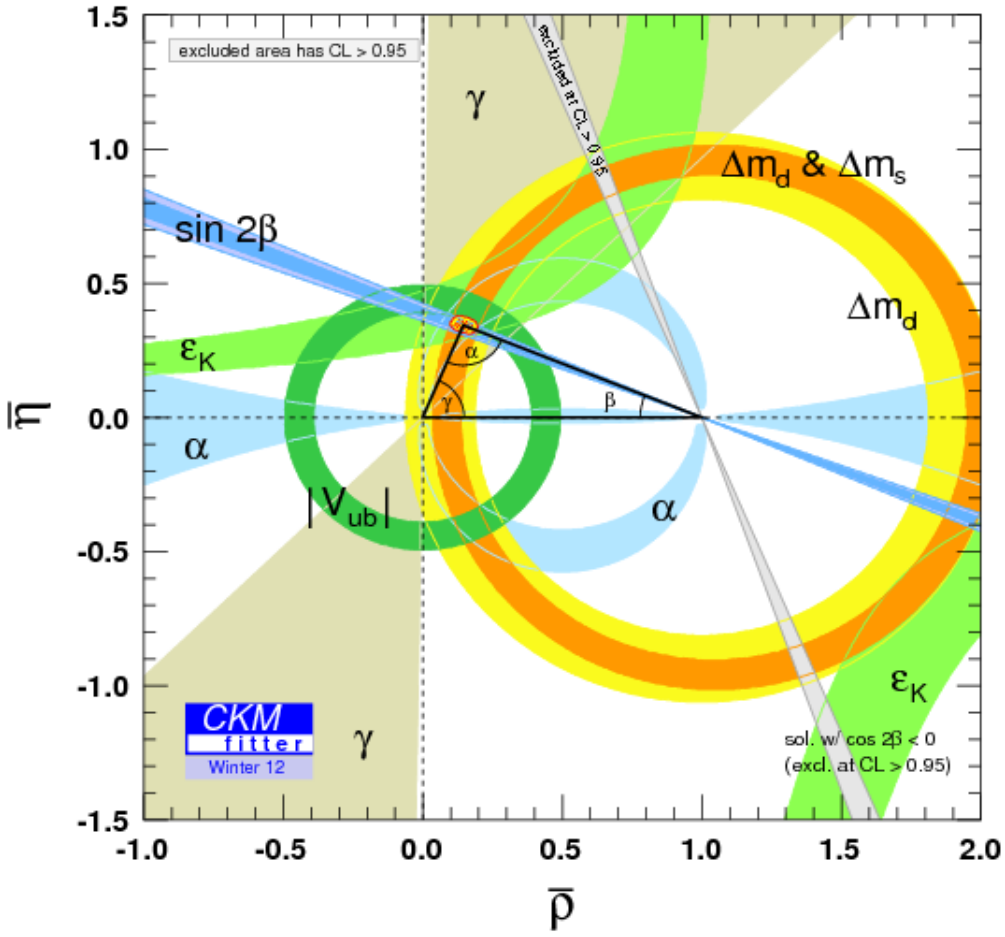
LHCb

Introduction to LHCb γ program

- Two groups of γ measurements at LHCb
  - Tree level processes discussed here
  - Loop processes
    - See following talk by Denis Derkach

- Strengths of LHCb for γ
  - High $b\bar{b}$ production rate
    - Combat low rates of b → u transitions
  - Excellent PID from 2 RICHs
    - Separate K and π
  - Excellent proper time resolution
    - Required for time dependent analyses

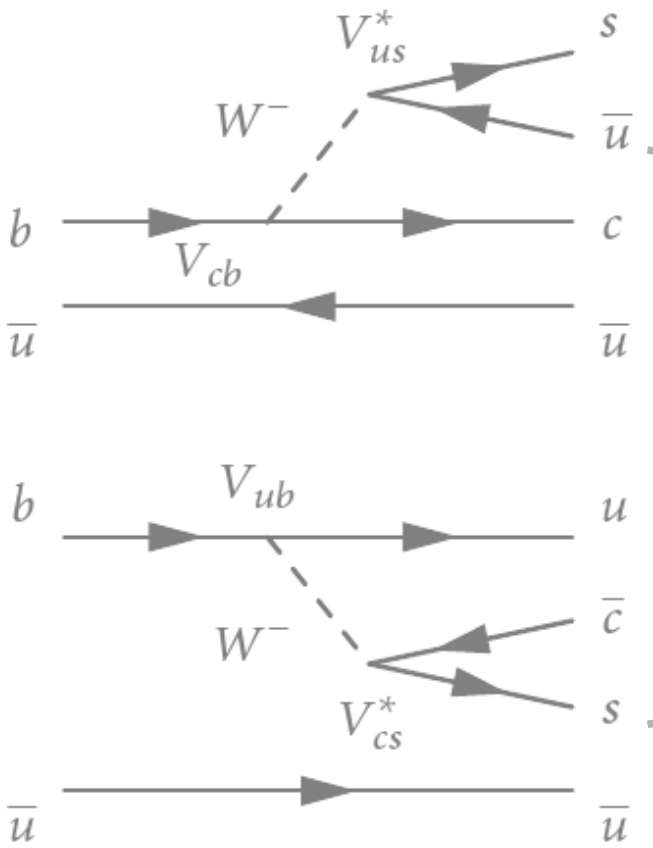


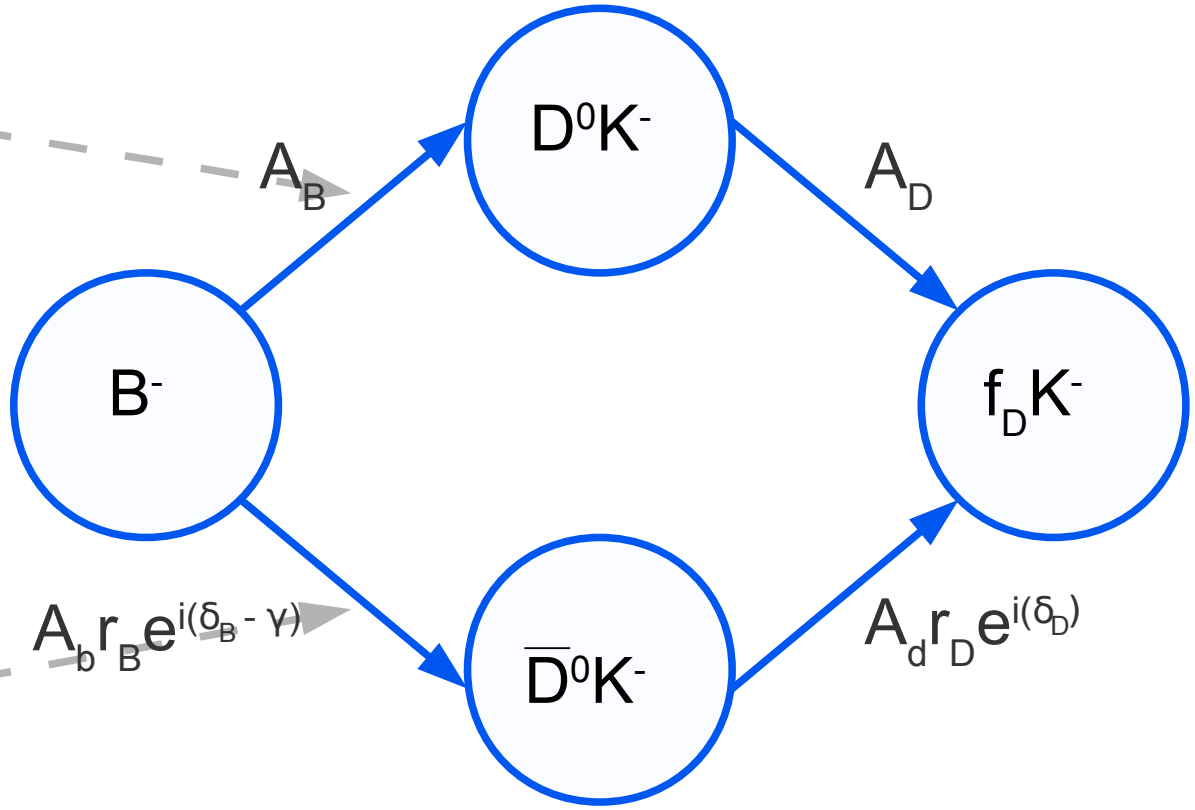
γ = 66 ± 12° (CKMfitter Winter 2012)

γ from trees - principle

- Interference of b → u and b → c amplitudes
  - Theoretically clean → γ the only weak phase

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



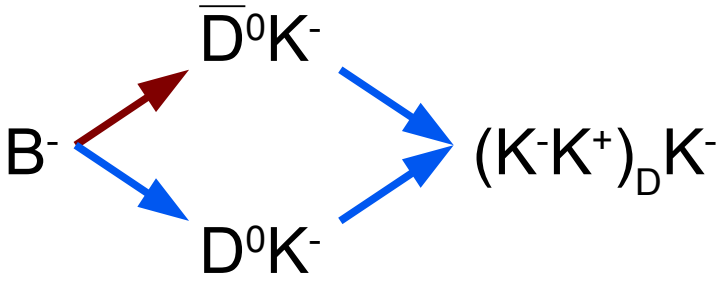


A_B, A_D: Amplitudes r_B, r_D: Suppression factors δ_B, δ_D: Strong phase difference

Time independent methods

Time independent - GLW

- GLW method [Phys. Lett. B 253, 483 (1991), Phys. Lett. B 265, 172 (1991)]
  - Previously used at B-factories and Tevatron
  - For D decays to CP eigenstates
    - For example K^+K^- and $\pi^+\pi^-$



  - Two observables

$$A_{CP\pm} = \frac{\Gamma(B^- \to D_{CP\pm}K^-) - \Gamma(B^+ \to D_{CP\pm}K^+)}{\Gamma(B^- \to D_{CP\pm}K^-) + \Gamma(B^+ \to D_{CP\pm}K^+)} = \frac{\pm 2r_B \sin\delta_B \sin\gamma}{1 + r_B^2 \pm 2r_B \cos\delta_B \cos\gamma}$$

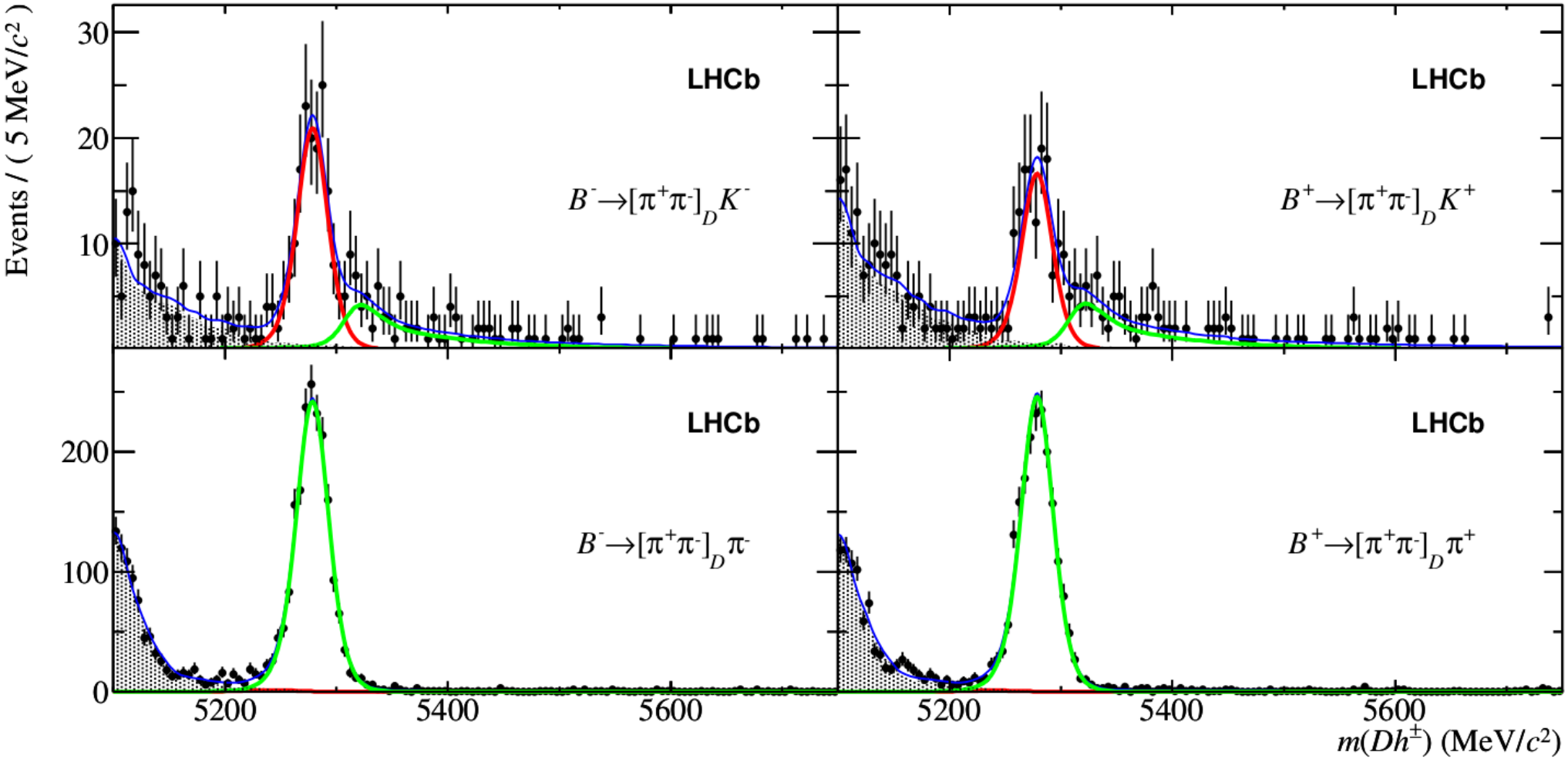
$$R_{CP\pm} = \frac{\Gamma\left(B^- \to D_{CP\pm}K^-\right) + \Gamma\left(B^+ \to D_{CP\pm}K^+\right)}{\Gamma\left(B^- \to D^0K^-\right) + \Gamma\left(B^+ \to \overline{D}^0K^+\right)} = 1 + r_B^2 \pm 2r_B \cos\delta_B \cos\gamma$$

  - 3 “unknowns” r_B δ_B and γ

Time independent – GLW @ LHCb

- $B^- \rightarrow D(\pi^+\pi^-)h^-$ [Physics Letters B 712 (2012), pp. 203-212]
  - Where h = K or π

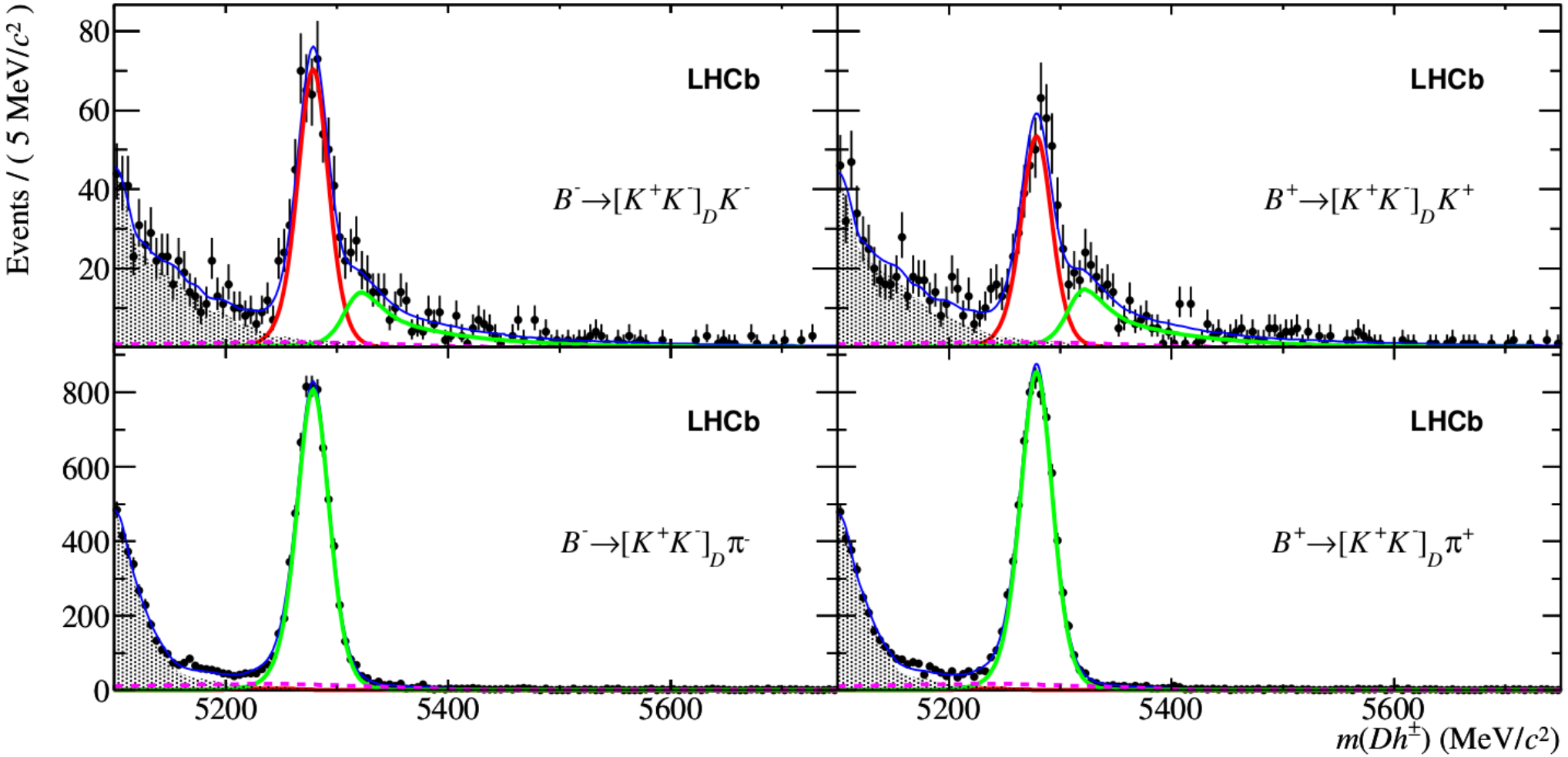
B → DK, B → Dπ, partially reconstructed decays and the full fit



Time independent – GLW @ LHCb

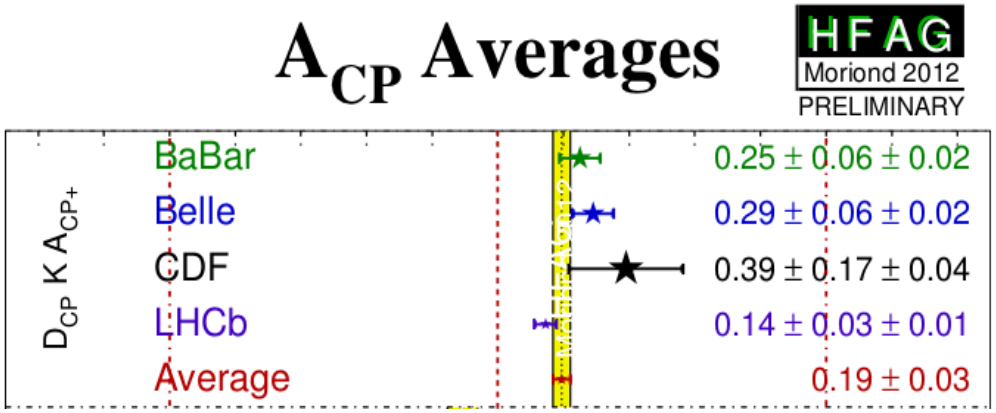
- $B^- \to D(K^+K^-)h^-$ [Physics Letters B 712 (2012), pp. 203-212]
  - Where h = K or π

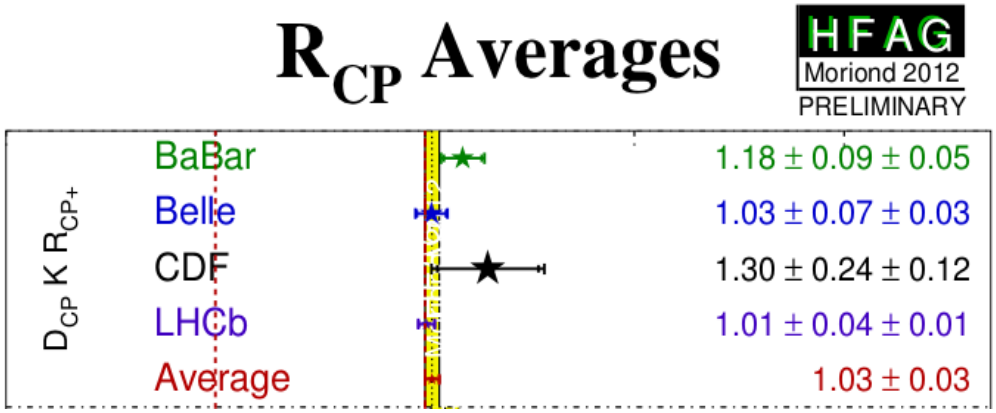
B → DK, B → Dπ, dashed $\Lambda_b \to \Lambda_c h$, partially reconstructed decays and the full fit



Time independent – GLW @ LHCb

- $B^- \to D(h^+h^-)h^-$ GLW summary
  - World's most precise measurements of A_{CP+} and R_{CP+}

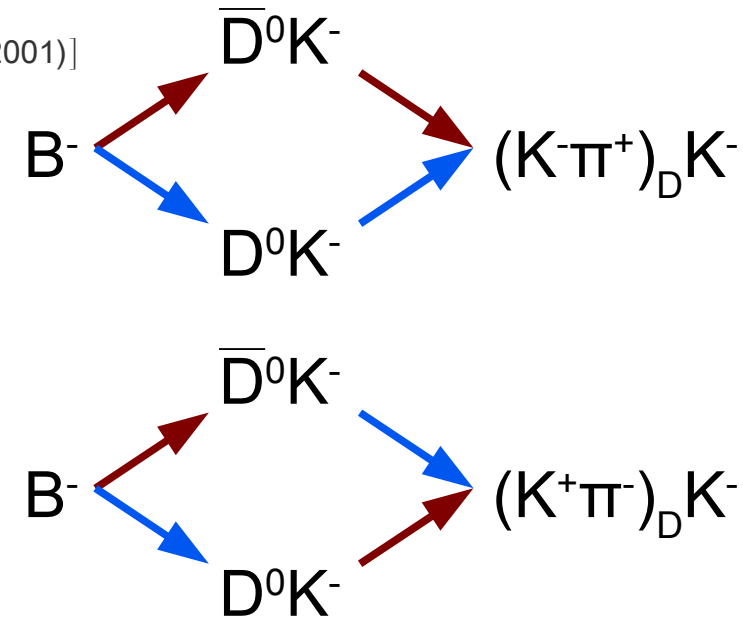




- B factories still dominating the other GLW modes
  - Look out for future results from LHCb:
    - $B^0 \to DK^{*0}$

Time independent - ADS

- ADS method [Phys. Rev. Lett. 78, 3257 (1997), Phys. Rev. D 63, 036005 (2001)]
  - Previously used at B-factories and Tevatron
  - For D decays to flavour specific states
    - For example Kπ:
    - $D^0 \to K^-\pi^+$ (CF) and $D^0 \to K^+\pi^-$ (DCS)
    - Suppressed B decay balanced by DCS D decay



Two observables

$$A_{ADS} = \frac{2r_B r_D \sin(\delta_D + \delta_B)\sin(\gamma)}{r_D^2 + r_B^2 + 2r_B r_D \cos(\delta_D + \delta_B)\cos(\gamma)}$$

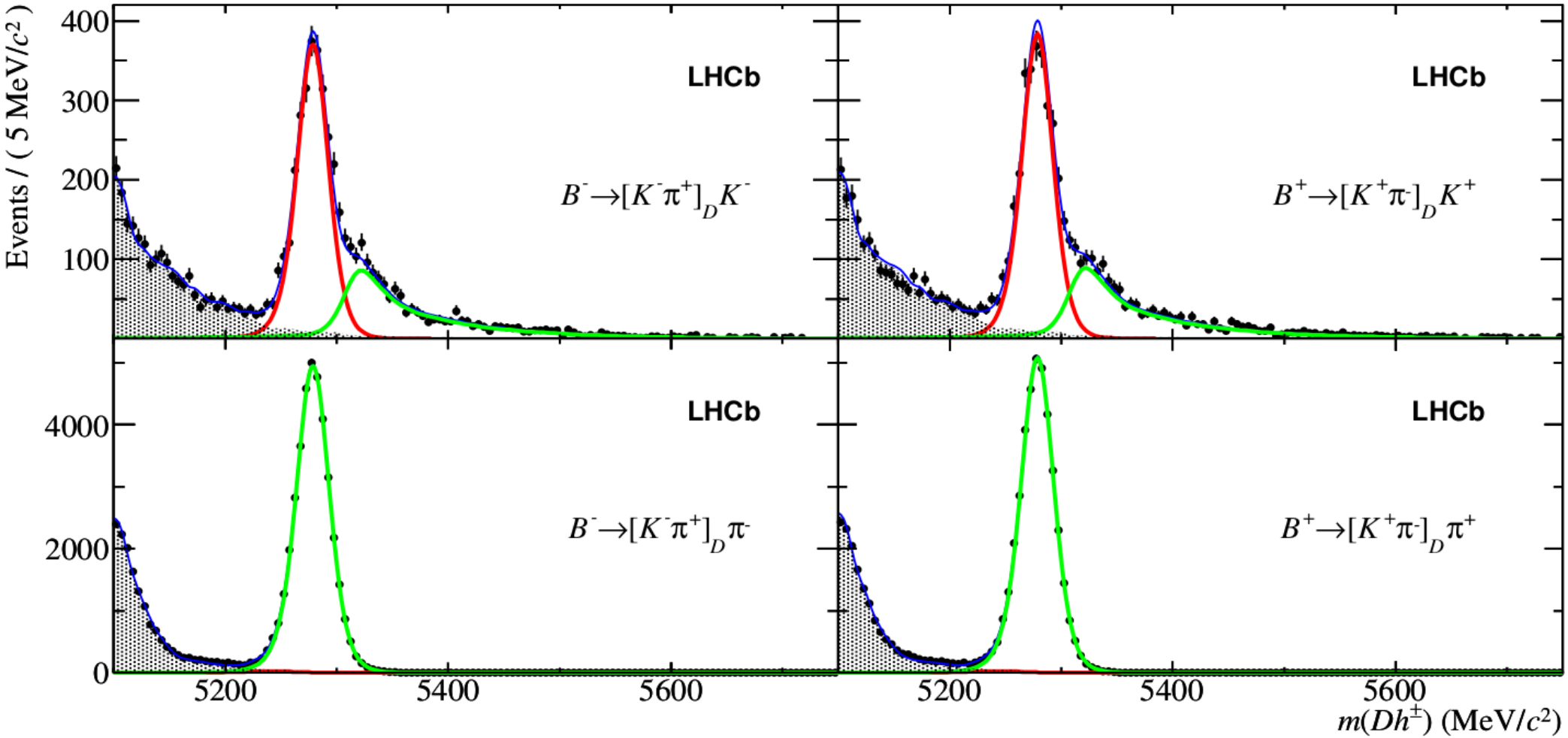
$$R_{ADS} = r_D^2 + r_B^2 + 2r_B r_D \cos(\delta_D + \delta_B)\cos(\gamma)$$

- Same 3 "unknowns" r_B δ_B and γ plus 2 more: r_D and δ_D
  - 2 extras are known from CLEO-c experiment [arXiv:1101.4855]

Time independent – ADS @ LHCb

- $B^- \to D(K\pi)h^-$ [Physics Letters B 712 (2012), pp. 203-212]
  - Where h = K or π

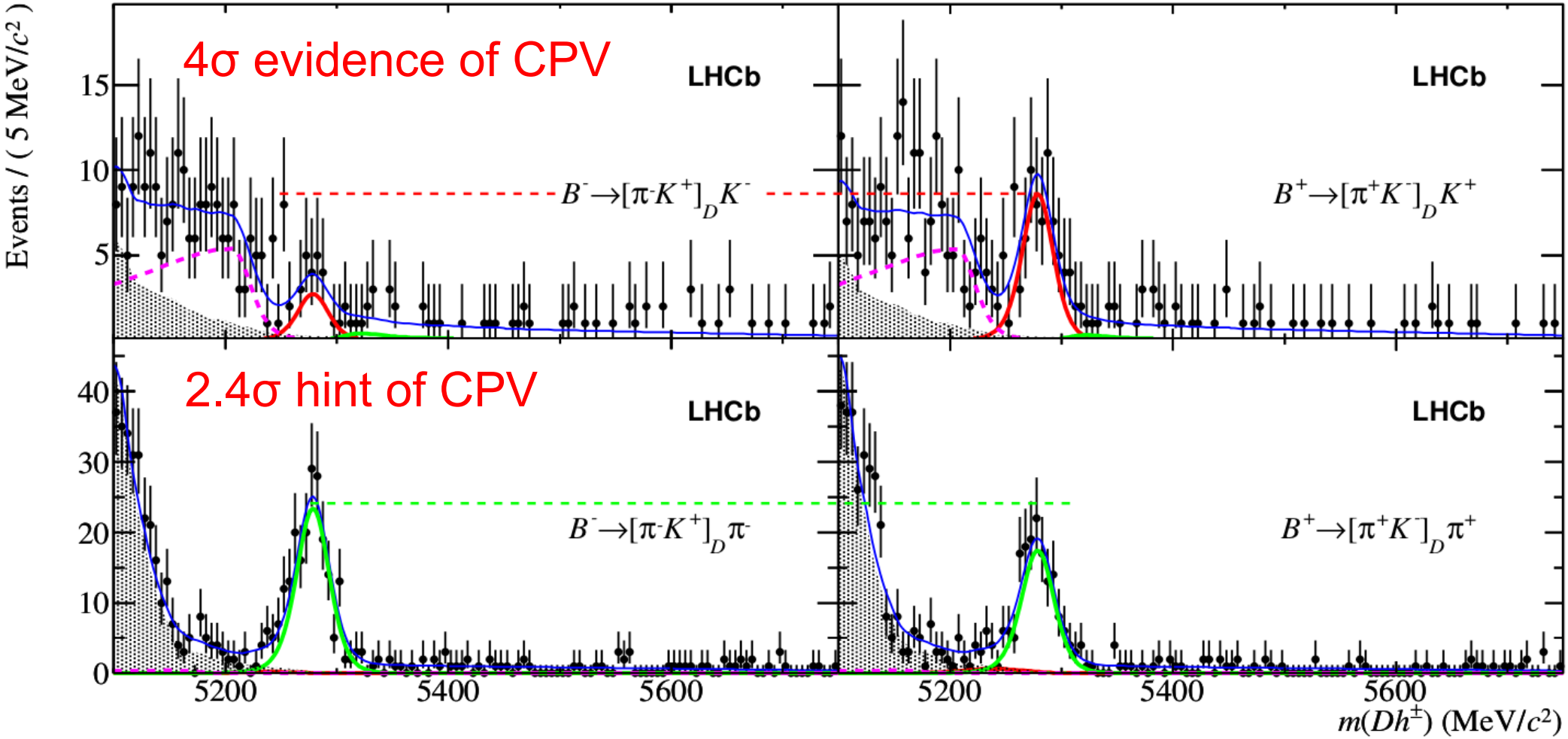
B → DK, B → Dπ, partially reconstructed decays and the full fit



Time independent – ADS @ LHCb

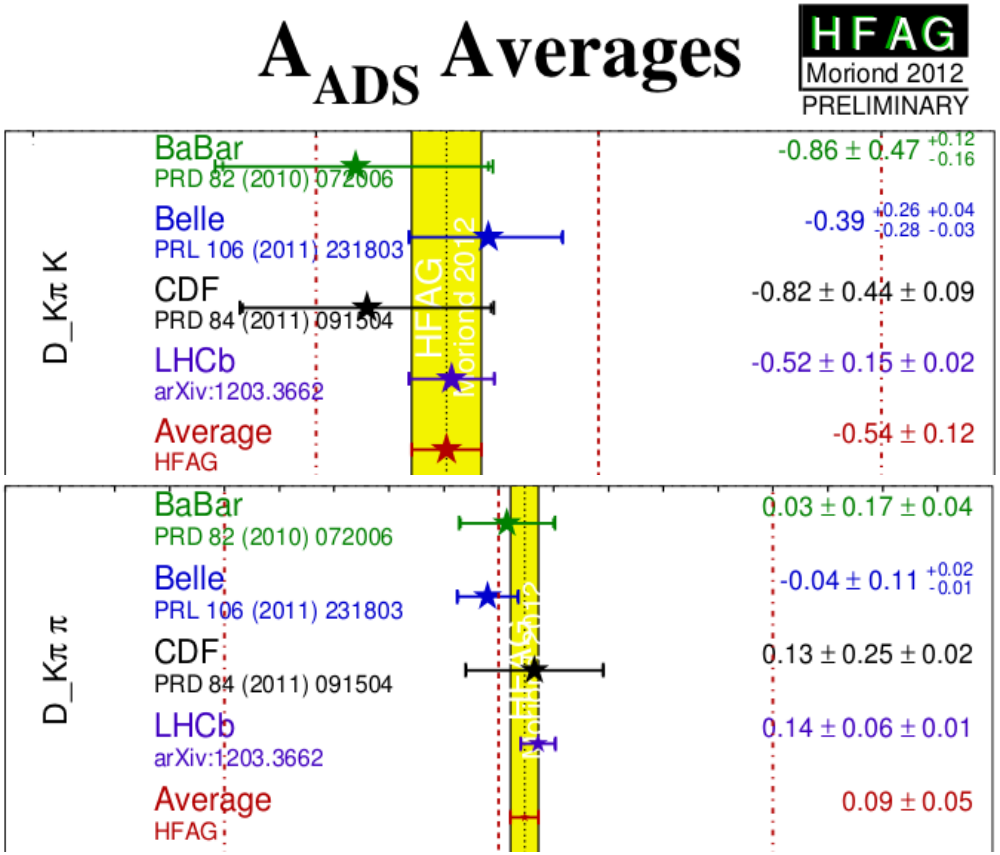
- $B^- \to D(K\pi)h^-$ [Physics Letters B 712 (2012), pp. 203-212]
  - Where h = K or π

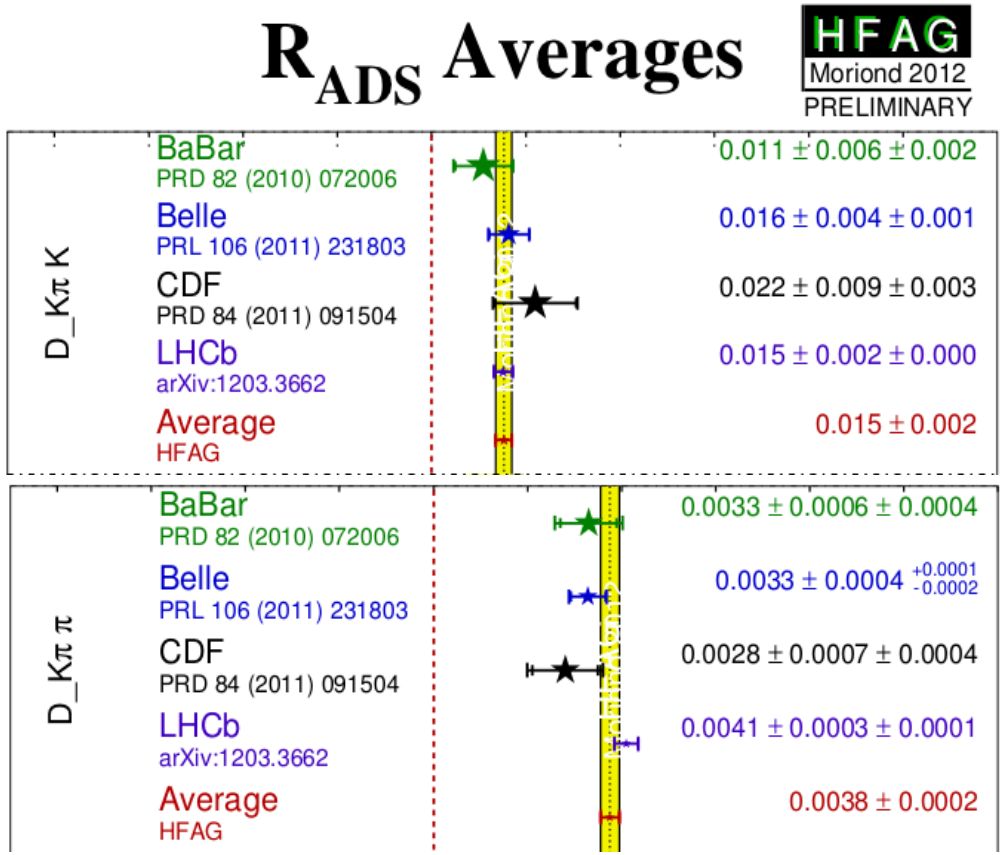
B → DK, B → Dπ, partially reconstructed decays (dashed $B_s \to DK\pi$) and the full fit



Time independent – ADS @ LHCb

- $B^- \to D(K\pi)h^-$ ADS summary
  - World's most precise measurements of A_{ADS} and R_{ADS}

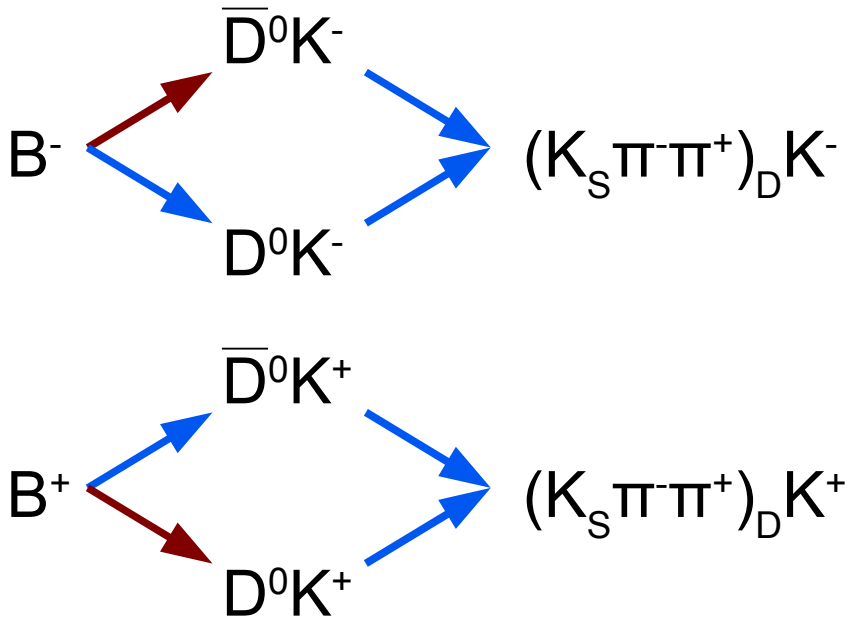




- B factories still dominating the other ADS modes

Time independent – GGSZ

- GGSZ (Dalitz) method
  - Exploit different interference patterns in D-Dalitz plots for B^+ and B^-
    - For example $K_s\pi^+\pi^-$
  - Model independent approach
    - Binned fit with δ_D input from CLEO-C
  - Model dependent approach
    - Unbinned fit with D decay model



  - Two observables to fit for

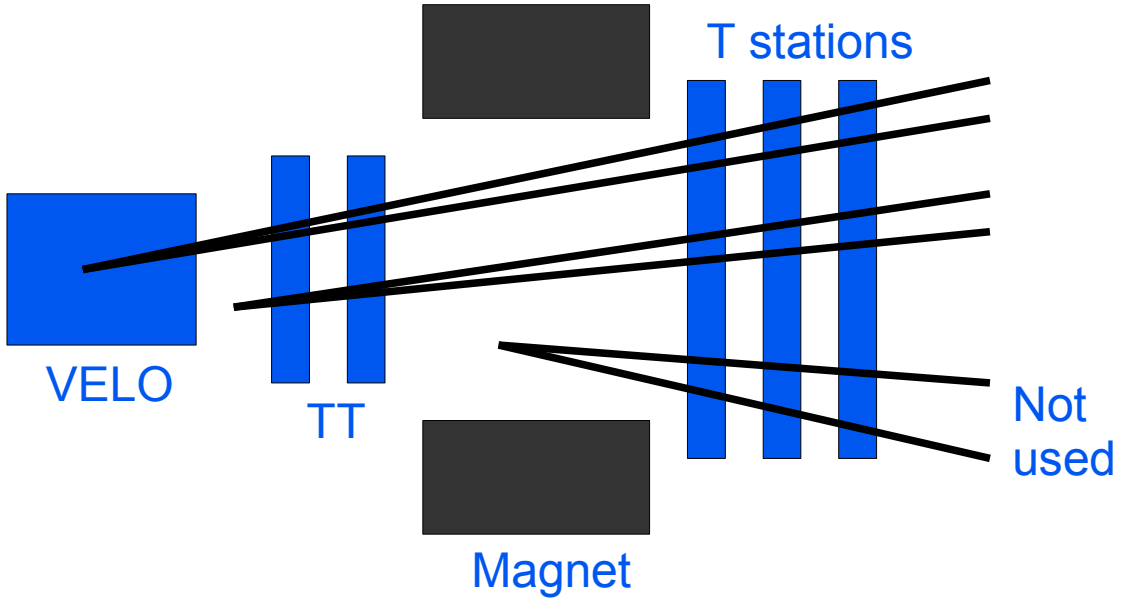
$$x_\pm = r_B \cos(\gamma \pm \delta_B)$$

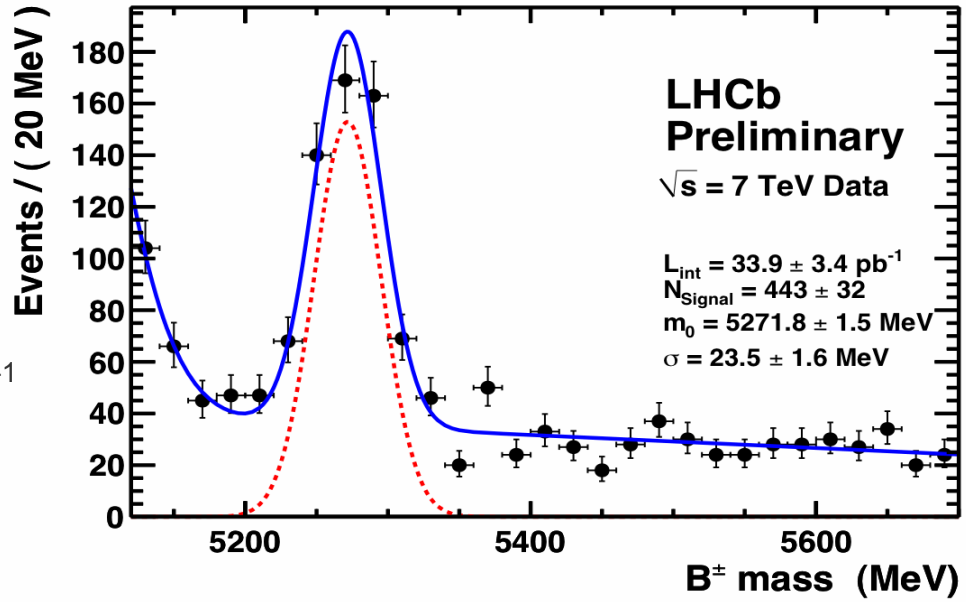
$$y_\pm = r_B \sin(\gamma \pm \delta_B)$$

  - Used by B-factories to make the most accurate measurements of γ

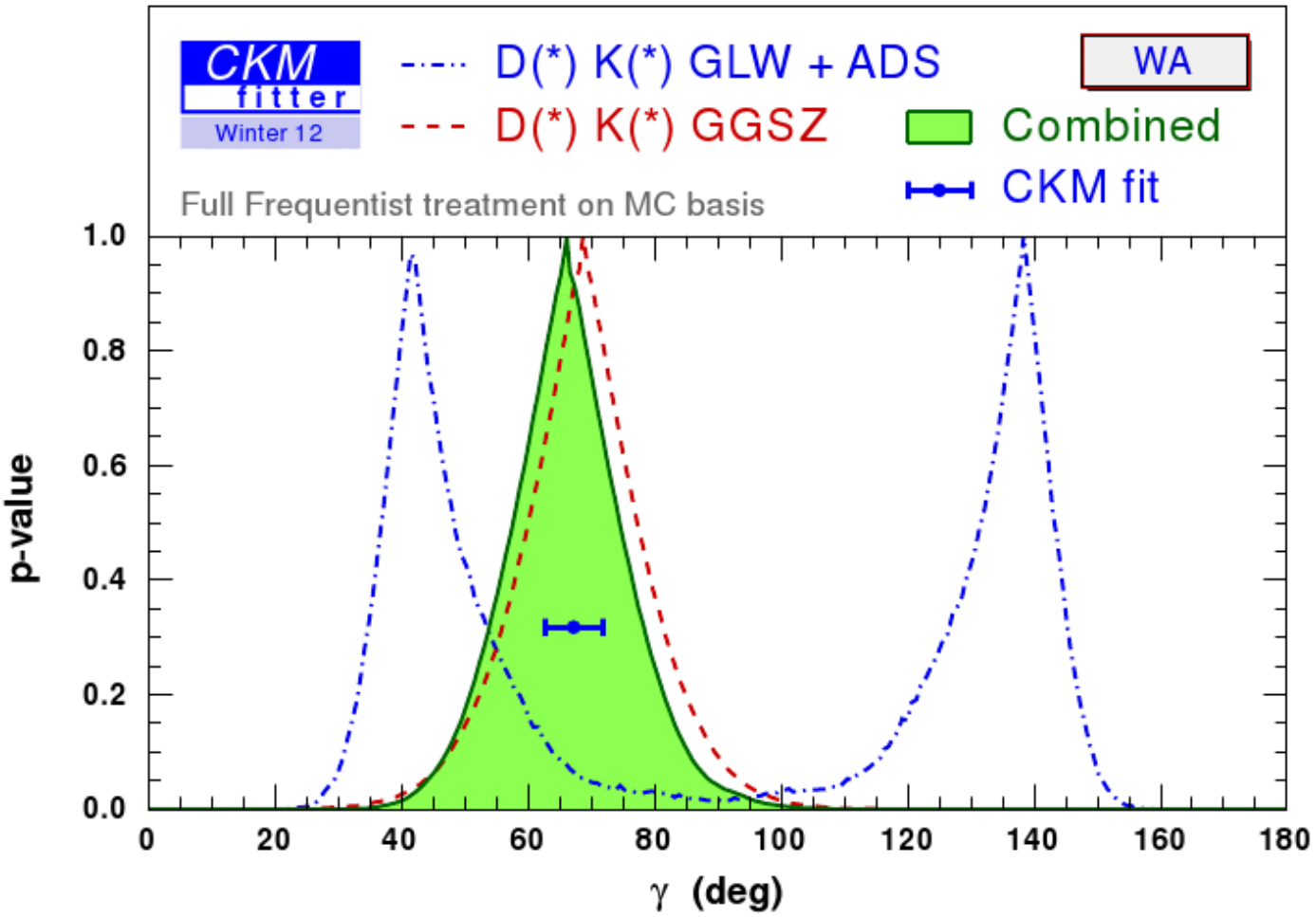
Time independent – GGSZ @ LHCb

- $B^- \to D(K_S\pi^-\pi^+)K^-$
  - K_S reconstruction a challenge
    - 2/3 decay downstream of the VELO
  - Two parallel analyses
    - Binned model independent
    - Unbinned model dependent
  - Control mode observed
    - $B^- \to D(K_S\pi^-\pi^+)\pi^-$
    - ~ 400 events in $36pb^{-1}$
  - Analysis in progress
    - Expect ~600 $B^- \to D(K_S\pi^-\pi^+)K^-$ events in $1fb^{-1}$
    - 0.5 x Belle dataset





Time independent – Summary



- GLW/ADS improvements are important, but not enough
  - Two solutions are resolved by other method(s) (GGSZ)

Time dependent method

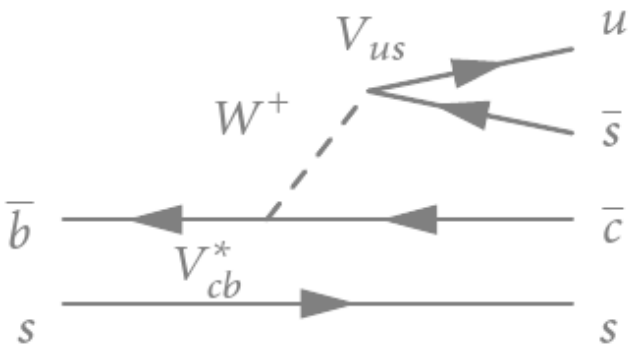
Time dependent studies @ LHCb

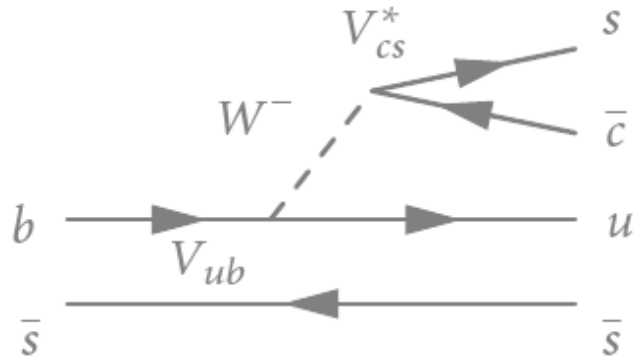
- Mixing induced interference in $B_s \rightarrow D_s^{\mp} K^{\pm}$
  - Particle and anti-particle decay to the same final state
    - Four decay rates to measure

$$\Gamma(B_S^0 \longrightarrow D_S^- K^+) \quad \Gamma(B_S^0 \longrightarrow D_S^+ K^-)$$

$$\Gamma(\overline{B_S^0} \longrightarrow D_S^- K^+) \quad \Gamma(\overline{B_S^0} \longrightarrow D_S^+ K^-)$$

  - Sensitive to $\gamma + \varphi_s$
    - Can measure φ_s from other channels

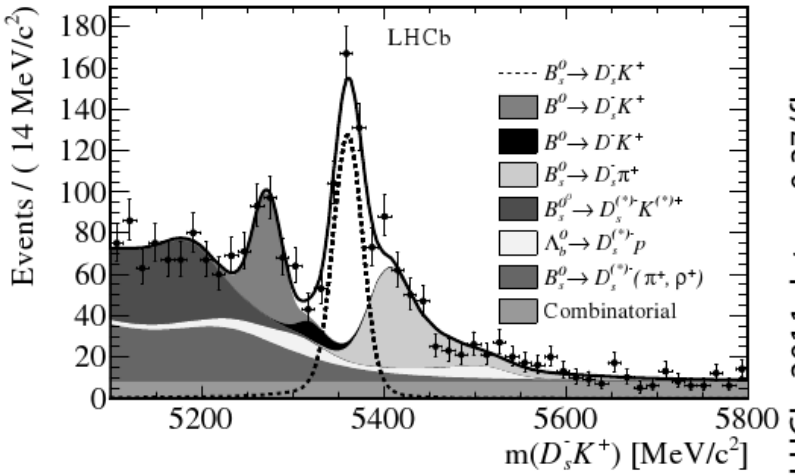




  - No colour suppression
    - Increased interference between channels

Time dependent studies @ LHCb

- $B_s \rightarrow D_s^{\mp} K^{\pm}$
  - Excellent proper time resolution required
    - ~50 fs to resolve B_s oscillations
  - Flavour tagging vital [arXiv:1204.1237]
    - Opposite side tagger: 3.2 ± 0.8 %
    - Extra power from same-side tagger

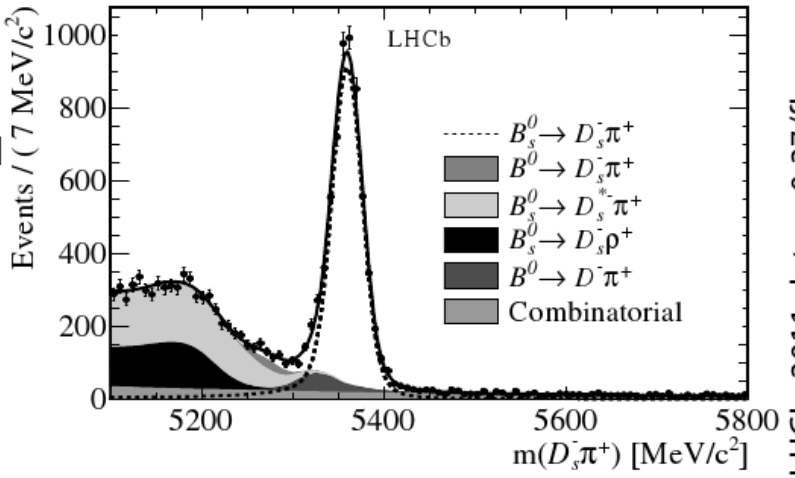


- Progress towards γ
  - Oscillation frequency [Phys.Lett. B709(2012)177-184]

$$\Delta m_s = 17.63 \pm 0.11 \pm 0.02 \text{ ps}^{-1}$$

stat syst

  - $B_s \rightarrow D_s^{\mp} K^{\pm}$ branching fraction [arXiv:1204.1237]



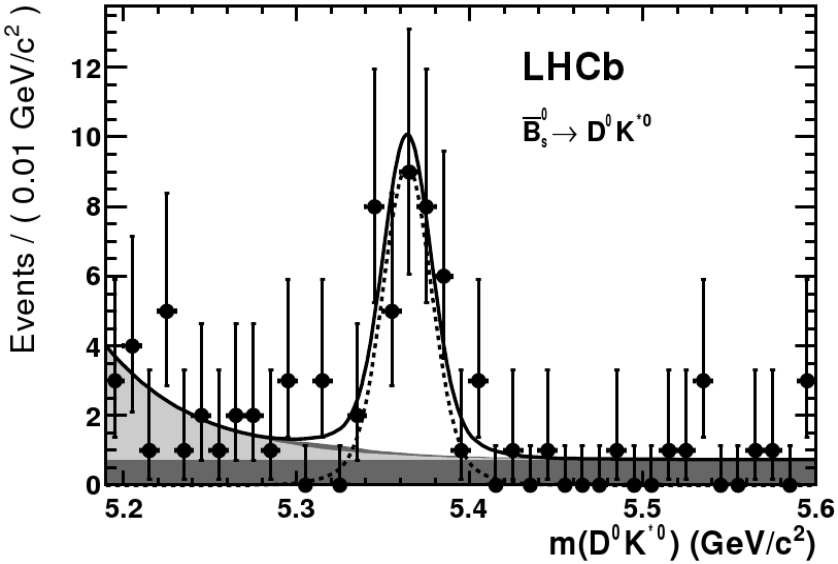
$$\mathcal{B}(B_s^0 \to D_s^{\mp} K^{\pm}) = (1.90 \pm 0.12 \pm 0.13^{+0.12}_{-0.14}) \times 10^{-4}$$

stat syst fs/fd

Other measurements

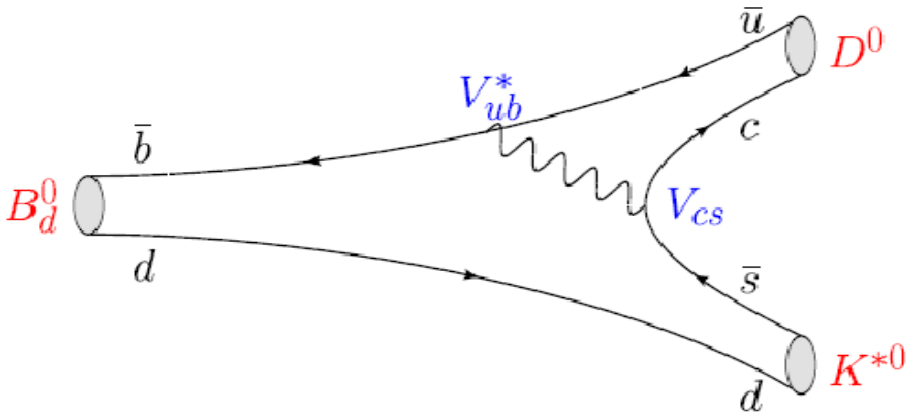
Other modes – $B^0 \to DK^{*0}$

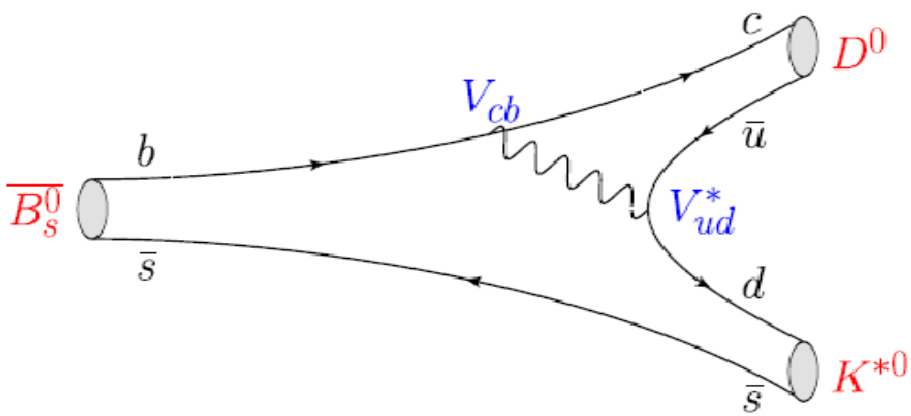
- GLW / ADS analysis similar to $B^- \to DK^-$
  - Interfering diagrams both colour suppressed
    - Low rates
    - Enhanced interference
  - Suppressed B^0 decay shares final state with B_s
    - B_s mode ~ 20x the rate
    - First observation of B_s decay [Phys.Lett. B706 (2011) 32-39]



$$\mathcal{B}\left(\overline{B}{}^0_s \to D^0 K^{*0}\right) = (4.72 \pm 1.07 \pm 0.48 \pm 0.37 \pm 0.74) \times 10^{-4}$$

stat syst fs/fd $B(B \to D\rho^0)$





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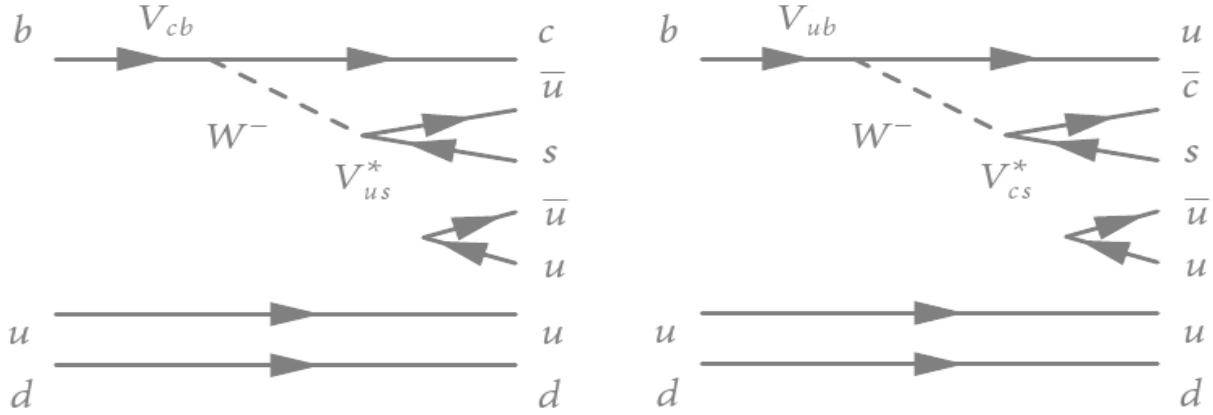
Other modes – $\Lambda_b \rightarrow DpK$

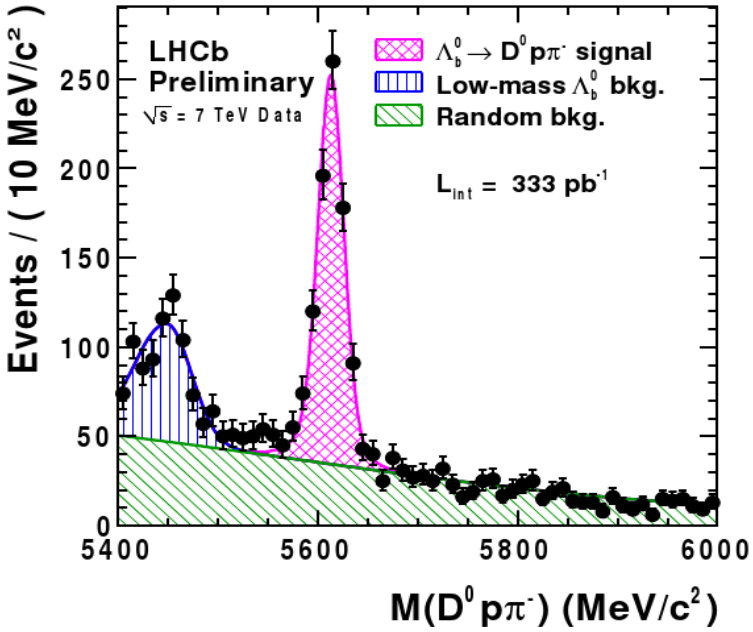
- $\Lambda_b \rightarrow DpK$
  - Sensitivity to γ analogous to $B \rightarrow DK^{*0}$

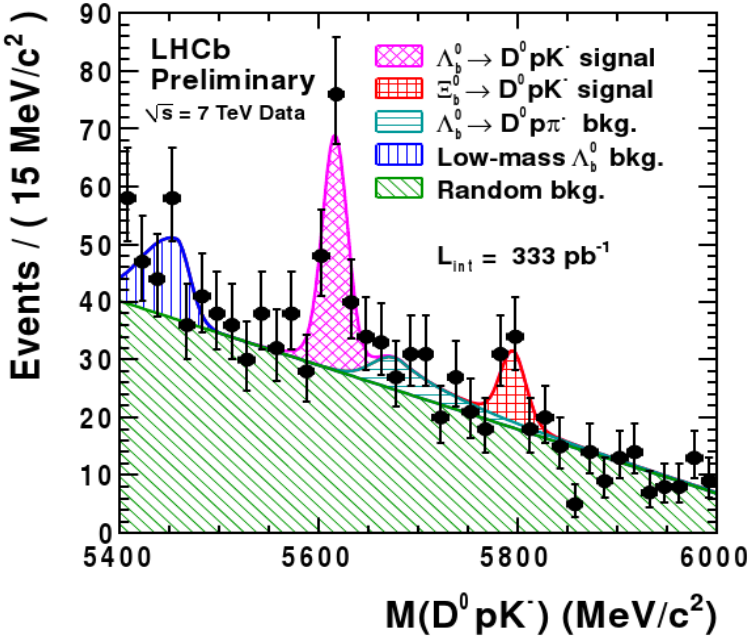


  - Well suited to LHCb
    - All final state particles are charged
  - Exploit the full phase space
    - Dalitz plot analysis
  - Branching fraction ratio 6.3σ [LHCb-CONF-2011-036]

$$\frac{\mathcal{B}(\Lambda_b^0 \rightarrow D^0 p K^-)}{\mathcal{B}(\Lambda_b^0 \rightarrow D^0 p \pi^-)} = 0.112 \pm 0.019 \,{}^{+0.011}_{-0.014}$$

stat syst





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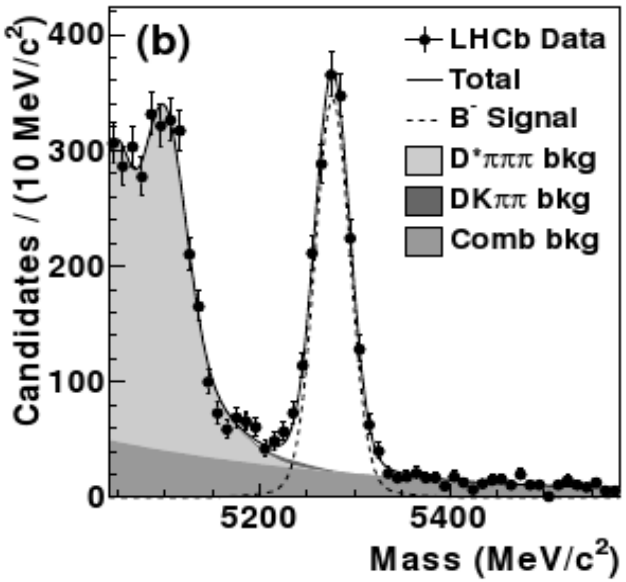
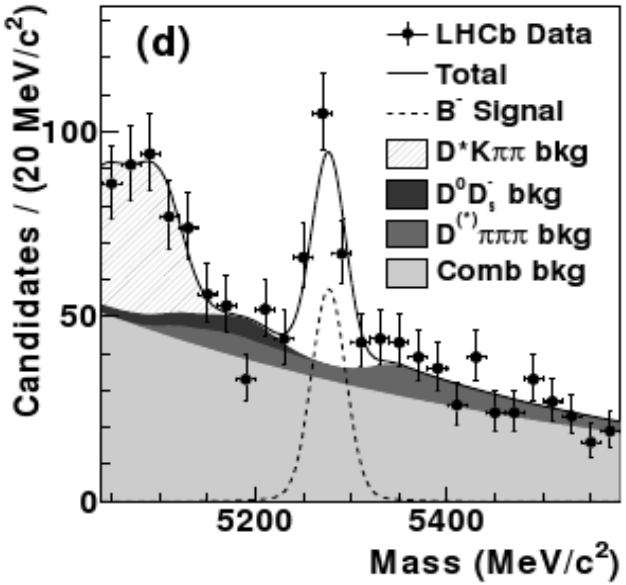
Other modes – $B^- \to D^0 K^- \pi^+ \pi^-$

- Several methods to extract γ
  - Quasi-two body
    - Modified GLW/ADS method
    - Potential dilution from intermediate resonances
  - Amplitude analysis
- Using $D^0 \to K^- \pi^+$ [arXiv:1201.4402]
  - Favoured ADS mode observed (9σ)
    - ~130 events in 36pb^{-1} from 2010 data
    - Expect ~1/3 of $B^- \to DK^-$ in 2011 data

$$\frac{\mathcal{B}(B^- \to D^0 K^- \pi^+ \pi^-)}{\mathcal{B}(B^- \to D^0 \pi^- \pi^+ \pi^-)} = (9.4 \pm 1.3 \pm 0.9) \times 10^{-2}$$

stat syst





Other modes

- Many other options available
  - $B_s \to D\varphi$
    - First step is a first observation
  - $B_s \to \overline{D}^0 K^+ K^-$
    - First step to observe both B^0 and B_s to DKK final state
  - $B^0 \to \overline{D}^0 K^+ \pi^-$
    - Enhanced sensitivity to γ using the whole phase space w.r.t. $B^0 \to DK^{*0}$
    - First step to measure branching fraction ratios for B^0 and B_s
  - Additional D decays in $B^- \to DK^-$
    - $D^0 \to K^-\pi^+\pi^-\pi^+$
    - $D^0 \to K^-\pi^+\pi^0$
    - $D^0 \to K^-K^+\pi^-\pi^+$
    - $D^0 \to \pi^-\pi^+\pi^-\pi^+$
  - Further multi-body modes

Summary

- New era of γ measurements beginning at LHCb
  - World's most precise GLW/ADS measurements of $B^- \to DK^-$
    - ~10σ observation of the suppressed $B^- \to D(K^+\pi^-)K^-$ decay
    - 5.8σ observation of CPV in $B^- \to DK^-$ decays (combined)
  - Other modes are well under way
    - $B^0 \to DK^{*0}$
    - $B^0 \to Dhhh$
    - $B_s \to D_s^{\mp}K^{\pm}$
    - Stay tuned!
- Different modes and techniques are complimentary
  - No one approach dominates sensitivity
  - Combination of many measurements required

Back up

Back up

$B^- \to DK^-\pi^+\pi^-$

Variation of B hadronic parameters over phase-space
$\Rightarrow$ **different approaches for extracting γ :**

- **Quasi-two body:** Modified ADS, GLW observables; needs "coherence factor"

$$e.g., R_{ADS} = r_s^2 + r_D^2 + 2r_s r_D \kappa \cos(\delta_s + \delta_D)\cos\gamma$$

$$\kappa \in [0,1]$$

$$\kappa e^{i\delta_s} = \frac{\int \left|\overline{A}\right| |A| e^{i(\arg(\overline{A}) - \arg(A))} dPS}{\sqrt{\int \left|\overline{A}\right|^2 dPS} \sqrt{\int |A|^2 dPS}}$$

Potential dilution of interference due to different intermediate resonances with different strong-phases contributing to final state, e.g. $B^- \to DK_1(1270)$

$\kappa = 1$ in the two-body limit – one single resonance contributing

[PLB 557 198 (2003)]

- **Amplitude analysis**
- **Binned:** Quasi-two body approach in high-coherent bins of the 4-body phase-space