Measurements of $\mathbf{B \to DK^{(*)}}$ decays to constrain the CKM unitarity triangle angle γ at LHCb

Andrew Powell (University of Oxford)

On behalf of the LHCb Collaboration

36th ICHEP Conference, Melbourne, Australia - July 2012

Hadronic B Decays for Accessing γ

- **γ is unique: only CPV parameter accessible via**
  - Tree Process: γ_{SM}
  - Loop Process: $\gamma_{SM} + \gamma_{NP}$
- **Comparison of measurements sensitive to NP**

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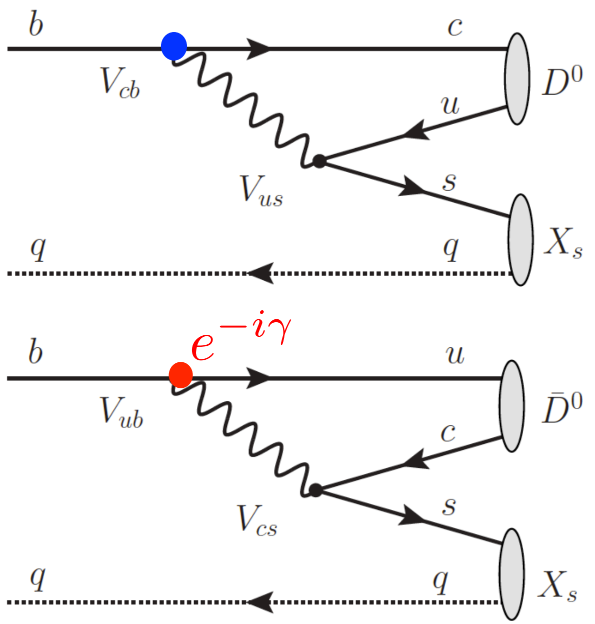

- Tree-level b→c and b→u transitions
  - For q = u:
    - $B^{\pm} \rightarrow DX_s$ where $X_s = \{K^{\pm}, K^{\pm}\pi\pi, K^{*\pm},\ldots\}$
    - Colour favoured diagrams possible
  - For q = d:
    - $B^0 \rightarrow DX_s$ where $X_s = K^{*0}$
  - $D/\overline{D}$ decay to common final state

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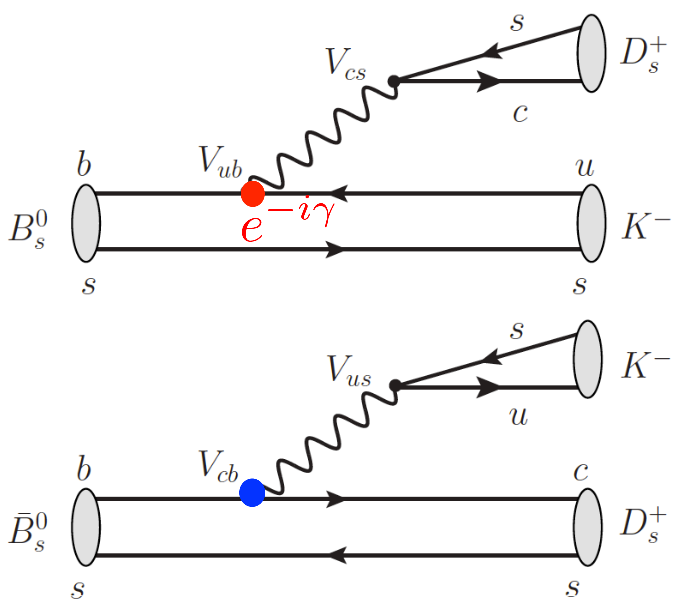

- Tree-level **b→c** and **b→u** transitions
  - For q = s (colour favoured decays)
    - $B_s^0 \rightarrow D_s^{\mp}K^{\pm}$
  - Interference from $B_s^0 \Leftrightarrow \overline{B}_s^0$ mixing

Hadronic B Decays for Accessing γ

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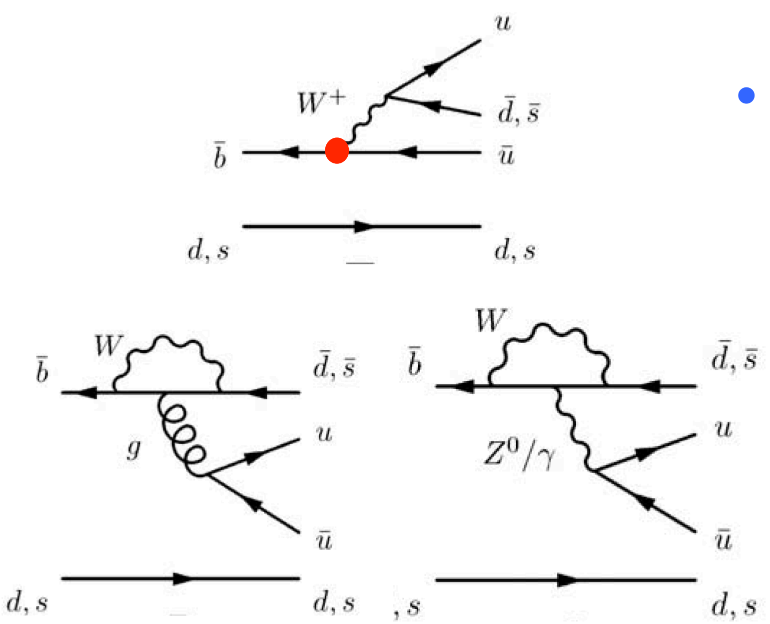
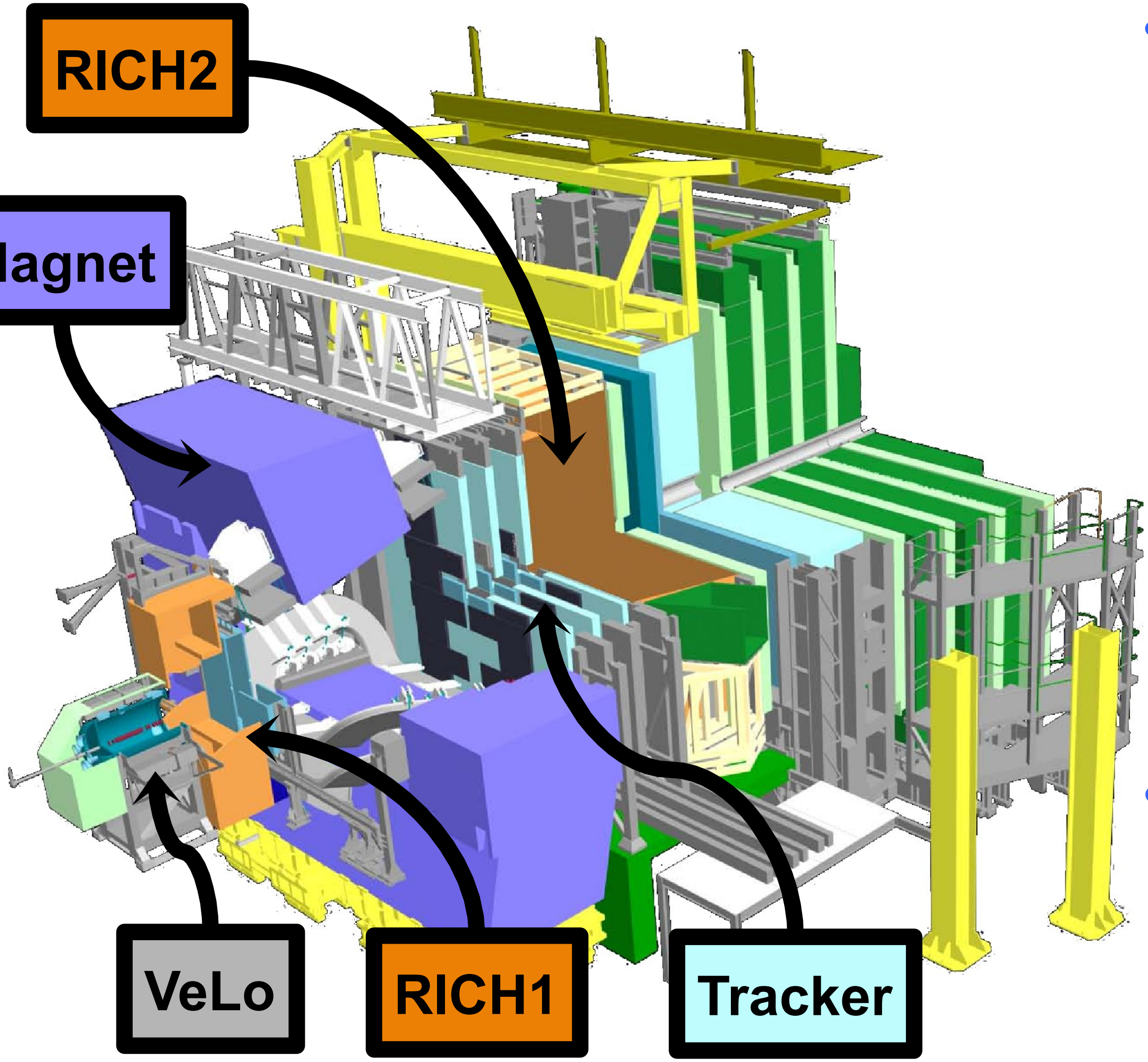
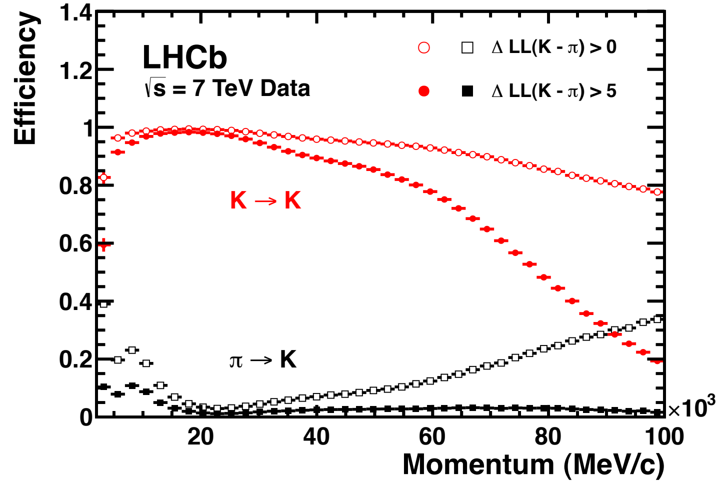


- Loop-level via $B \rightarrow h^- h^{+\prime}$ family
  - Sensitive to:
    - γ, ϕ_d, ϕ_s
  - See talk by Paul Soler in this session

LHCb – Optimised for B & D Physics



- All γ analyses at LHCb benefit greatly from dedicated PID



- Data acquired to date:
  - 2010 : 37 pb^{-1}
  - 2011 : 1 fb^{-1}
  - 2012 : 0.6 fb^{-1} so far
    - Aiming for 1.5 fb^{-1}

LHCb Results Shown Today

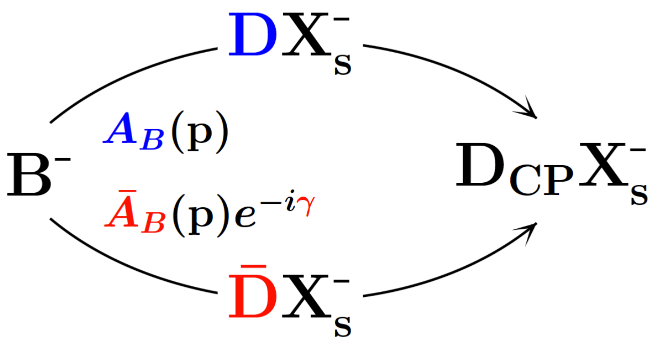
- **$B^{\pm} \longrightarrow D^0 X_s^{\pm}$ (1 fb^{-1} 2011 data)**
  - 'GLW' parameters A_{CP+} & R_{CP+} using $D^0 \longrightarrow \{\pi\pi, KK\}$
    - $X_s = K$ [Phys. Lett. B 712 (203)]
    - $X_s = K\pi\pi$ [LHCb-CONF-2012-021] New!
  - 'ADS' parameters A_{ADS} & R_{ADS} using $D^0 \longrightarrow K\pi$
    - $X_s = K$ [Phys. Lett. B 712 (203)]
- **$B^0 \longrightarrow D^0 K^{*0}$ (1 fb^{-1} 2011 data)** New!
  - 'GLW' parameters A_{CP+} & R_{CP+} using $D^0 \longrightarrow KK$
    - [LHCb-CONF-2012-024]
- **$B_s^0 \longrightarrow D_s^{\mp} K^{\pm}$ (0.37 fb^{-1} 2011 data)**
  - Branching ratio measurements
    - $\mathcal{B}(B_s \longrightarrow D_s K)$ [JHEP 06 (2012) 115]
    - $\mathcal{B}(B_s \longrightarrow D_s \pi)$ [JHEP 06 (2012) 115]

$B^{\pm} \longrightarrow D^0 X_s^{\pm}$: GLW

$B^{\pm} \rightarrow D^0 X_s^{\pm}$: 'GLW' Analyses

Phys. Lett. B 253 (483)
Phys. Lett. B 265 (172)
Phys. Lett. B 557 (198)

- **X_s : final state with same quantum numbers as $K^{\pm}$**
  - Two LHCb analyses: $X_s^{\pm} = \{K^{\pm}, K^{\pm}\pi^{\mp}\pi^{\pm}\}$ with $X_d^{\pm} = \{\pi^{\pm}, \pi^{\pm}\pi^{\mp}\pi^{\pm}\}$
- **Exploit interference of $D^0/\bar{D}^0$ decaying to CP-eigenstate**



- $A(\mathbf{p}) = A_B(\mathbf{p}) + \bar{A}_B(\mathbf{p})e^{-i\gamma}$
- **p : position in multi-body B phase space**
- **Total rate** $\longrightarrow \int A_{(\mathbf{p})} d\mathbf{p}$

$B^{\pm} \longrightarrow D^0 X_s^{\pm}$: 'GLW' Analyses

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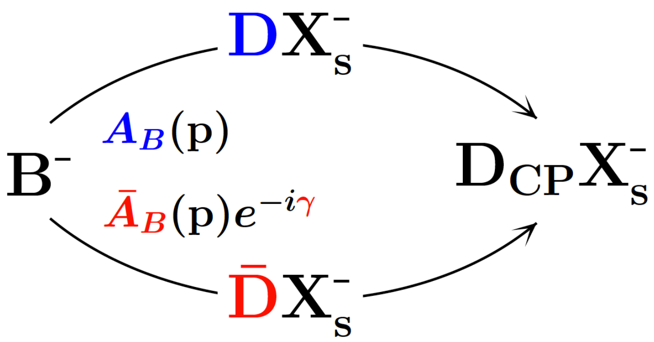

- $A(\mathbf{p}) = A_B(\mathbf{p}) + \bar{A}_B(\mathbf{p})e^{-i\gamma}$
- p : position in multi-body B phase space
- Total rate $\longrightarrow \int A_{(\mathbf{p})} d\mathbf{p}$

- Two CP observables:

$$R_{CP+} \equiv 2\frac{\Gamma(B^- \to D_{CP+}K^-) + \Gamma(B^+ \to D_{CP+}K^+)}{\Gamma(B^- \to D^0 K^-) + \Gamma(B^+ \to \bar{D}^0 K^+)}$$

Av. Partial Rate

$$A_{CP+} \equiv \frac{\Gamma(B^- \to D_{CP+}K^-) - \Gamma(B^+ \to D_{CP+}K^+)}{\Gamma(B^- \to D_{CP+}K^-) + \Gamma(B^+ \to D_{CP+}K^+)}$$

CP Asymmetry

$B^{\pm} \rightarrow D^0 X_s^{\pm}$: 'GLW' Analyses

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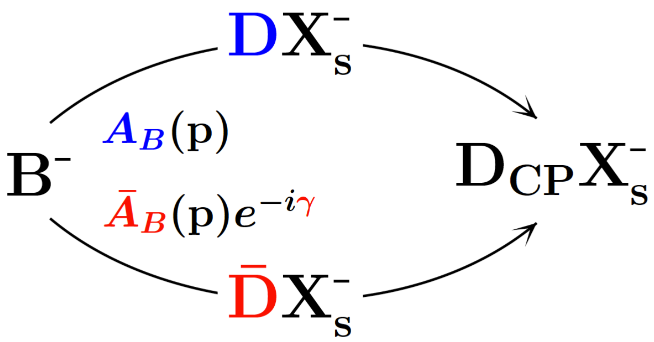


- $A(\mathbf{p}) = A_B(\mathbf{p}) + \bar{A}_B(\mathbf{p})e^{-i\gamma}$
- p : position in multi-body B phase space
- Total rate $\longrightarrow \int A_{(\mathbf{p})} d\mathbf{p}$

- Two CP observables:

$$R_{CP+} = 1 + r_B{}^2 + 2\kappa r_B \cos\delta_B \cos\gamma$$

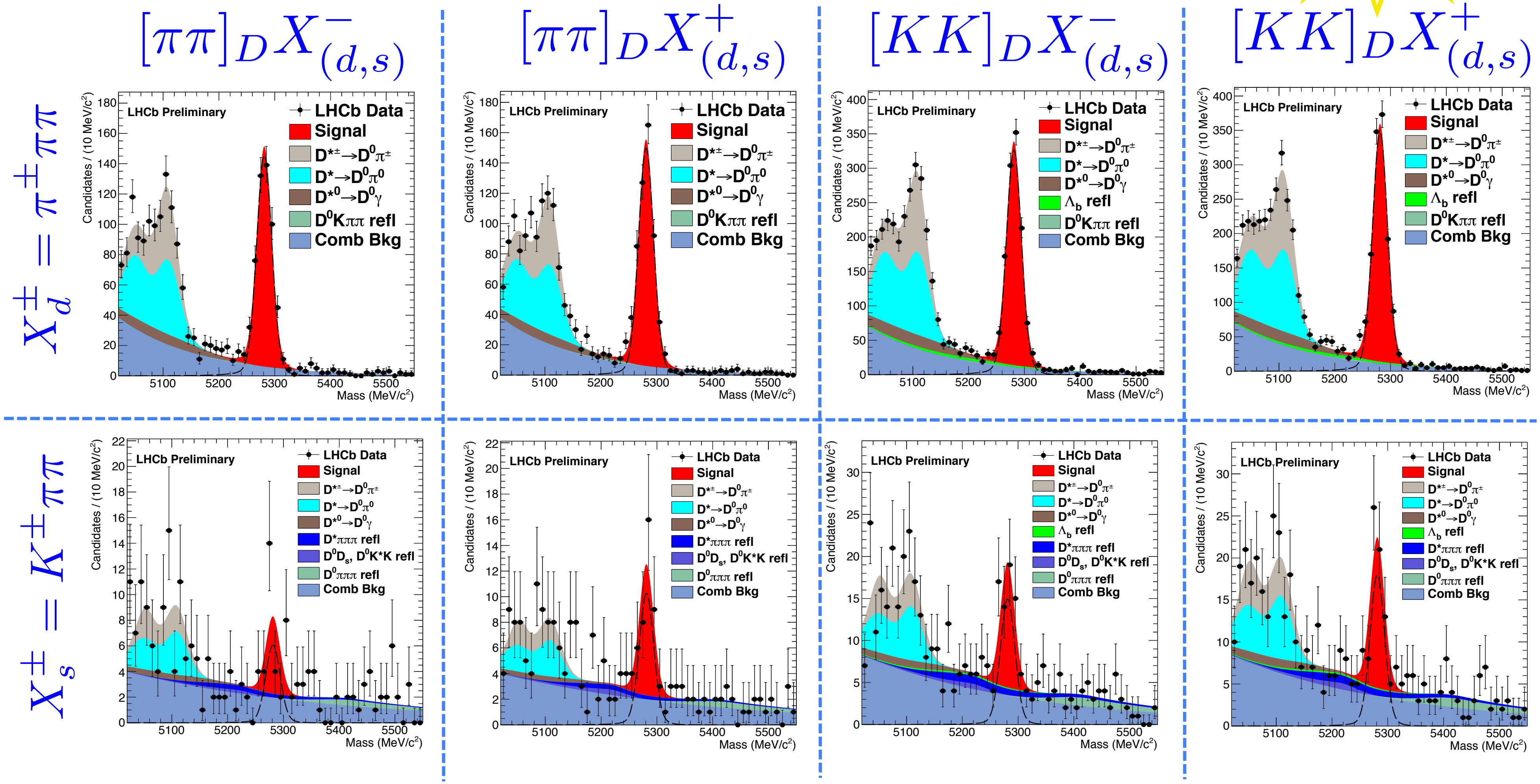
$$A_{CP+} = \frac{2\kappa r_B \sin\delta_B \sin\gamma}{R_{CP+}}$$

- r_B : ratio decay amplitudes A and $\bar{A}$
- δ_B : strong phase difference within B decays
- κ : coherence factor $\{0 \leq \kappa \leq 1\}$

LHCb-CONF-2012-021

$B \to D^0X$, $D^0 \to \{\pi\pi, KK\}$, $X=3h$

NEW Preliminary



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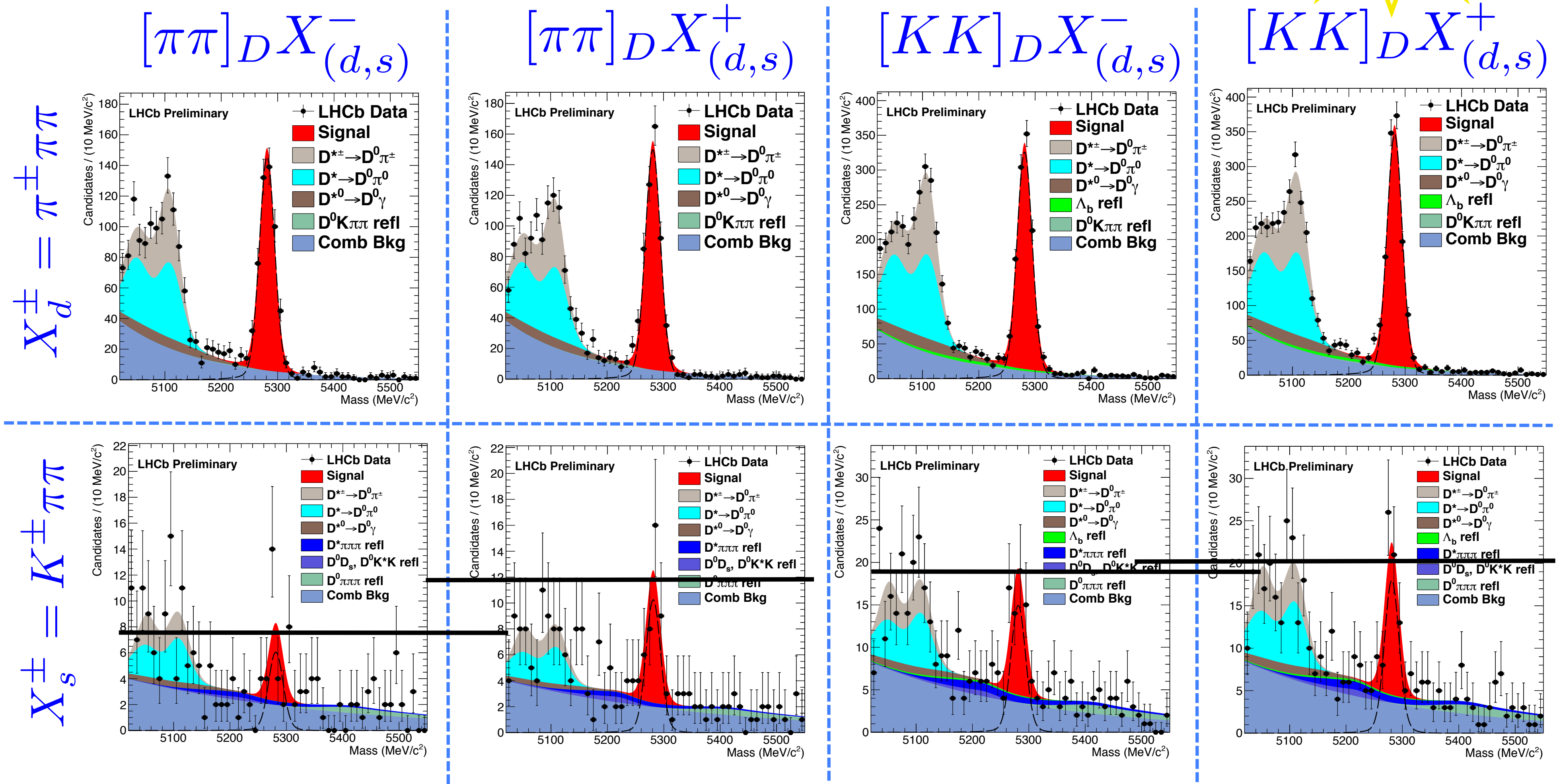
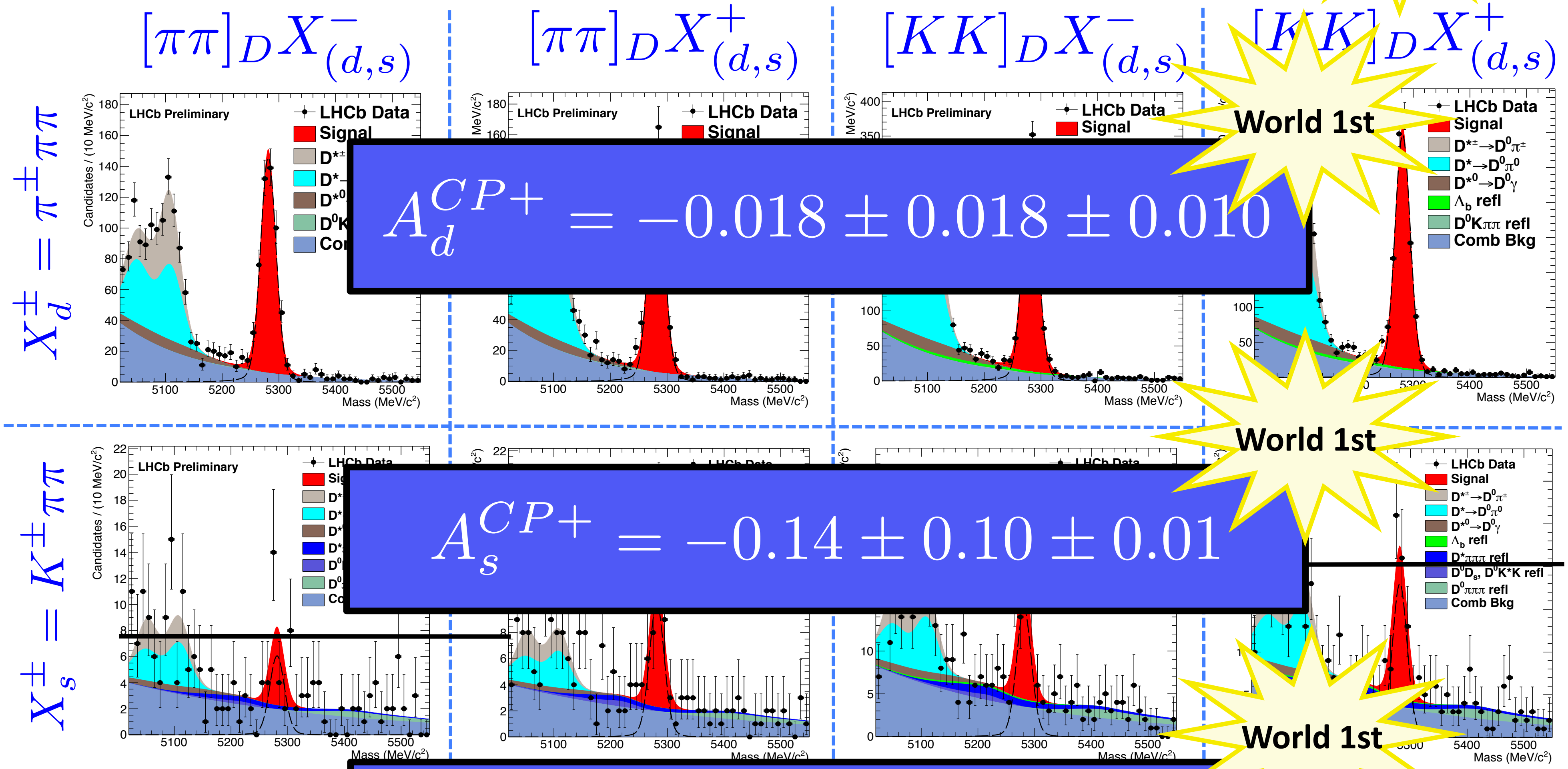


- Raw asymmetries visible in Cabibbo Suppressed (X_s) final states
- Require corrections for production & detection asymmetries (from data)

LHCb-CONF-2012-021

$B \to D^0X, D^0 \to \{\pi\pi, KK\}, X=3h$

NEW Preliminary



$$A_d^{CP+} = -0.018 \pm 0.018 \pm 0.010$$

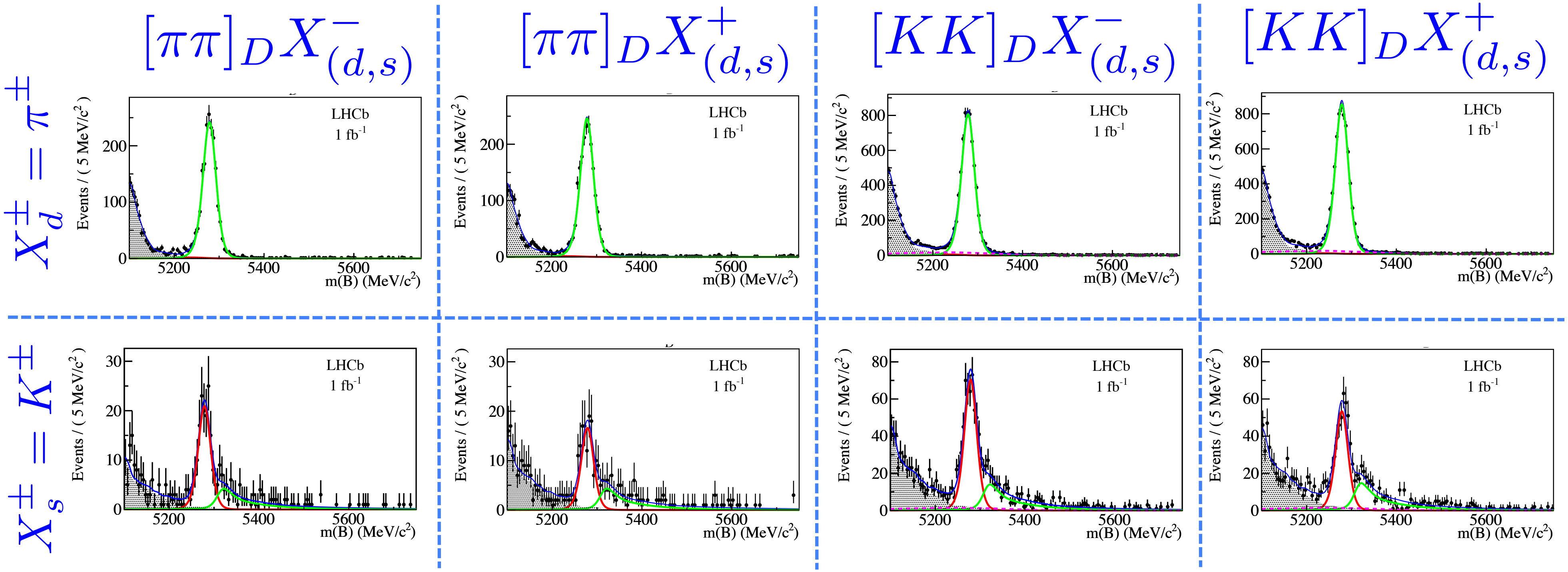
$$A_s^{CP+} = -0.14 \pm 0.10 \pm 0.01$$

$$R_{CP+} = 0.95 \pm 0.11 \pm 0.02$$

- Raw asymm
- Require cor

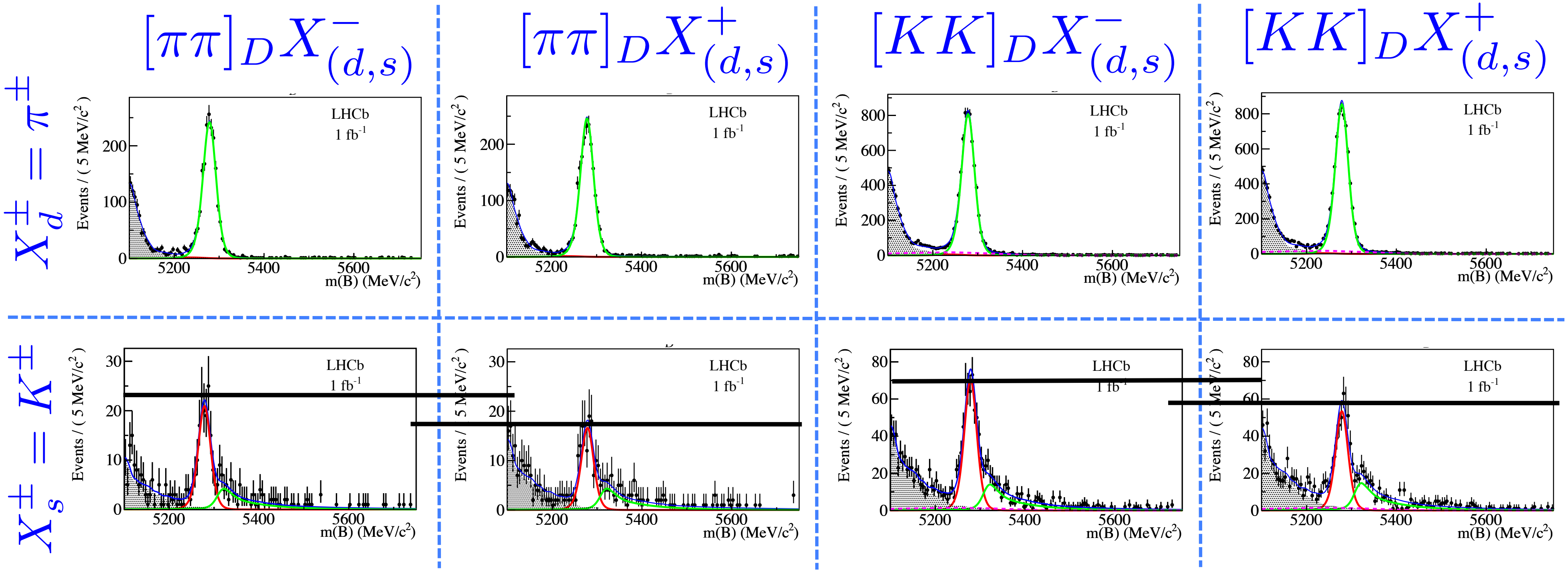
Phys. Lett. B 712 (203)

B → D^0X, D^0 → {ππ,KK}, X=h



Phys. Lett. B 712 (203)

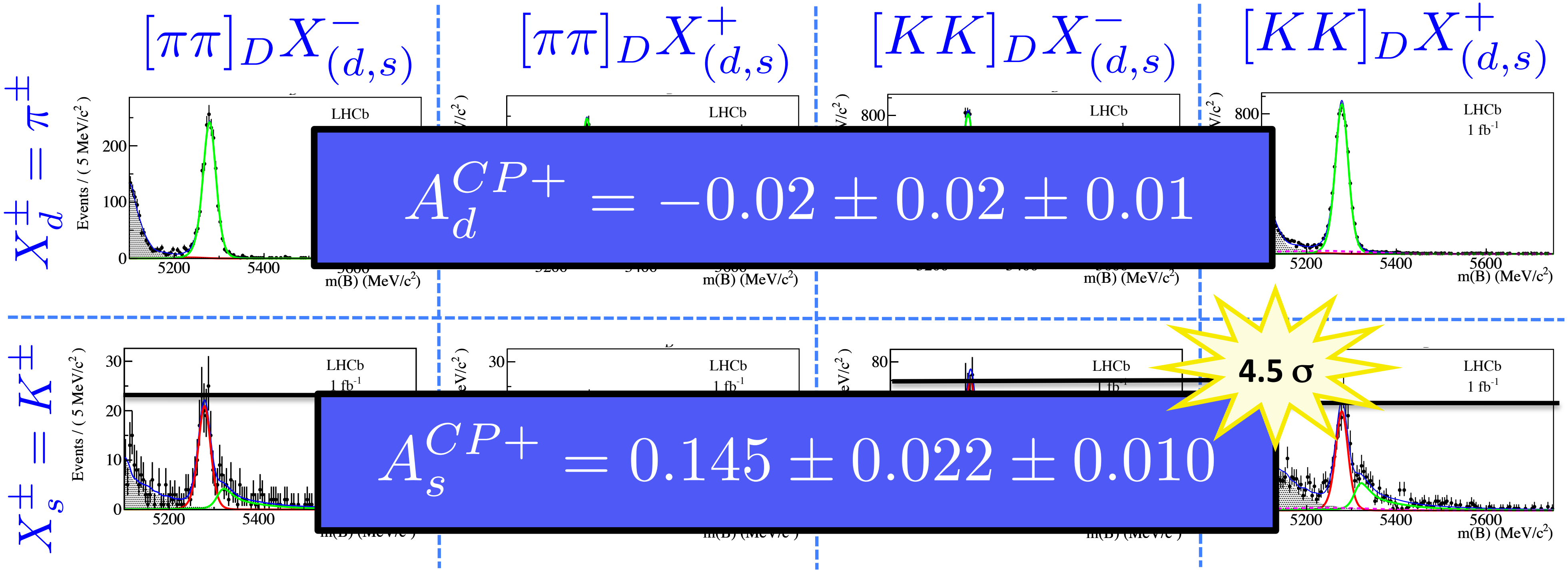
$B \to D^0X$, $D^0 \to \{\pi\pi, KK\}$, X=h



- Again, raw asymmetries visible in the Cabibbo Suppressed mode

Phys. Lett. B 712 (203)

$B \rightarrow D^0X,\ D^0 \rightarrow \{\pi\pi, KK\},\ X=h$



$$A_d^{CP+} = -0.02 \pm 0.02 \pm 0.01$$

$$A_s^{CP+} = 0.145 \pm 0.022 \pm 0.010$$

- Again, raw asymmetries visible in the Cabibbo Suppressed mode

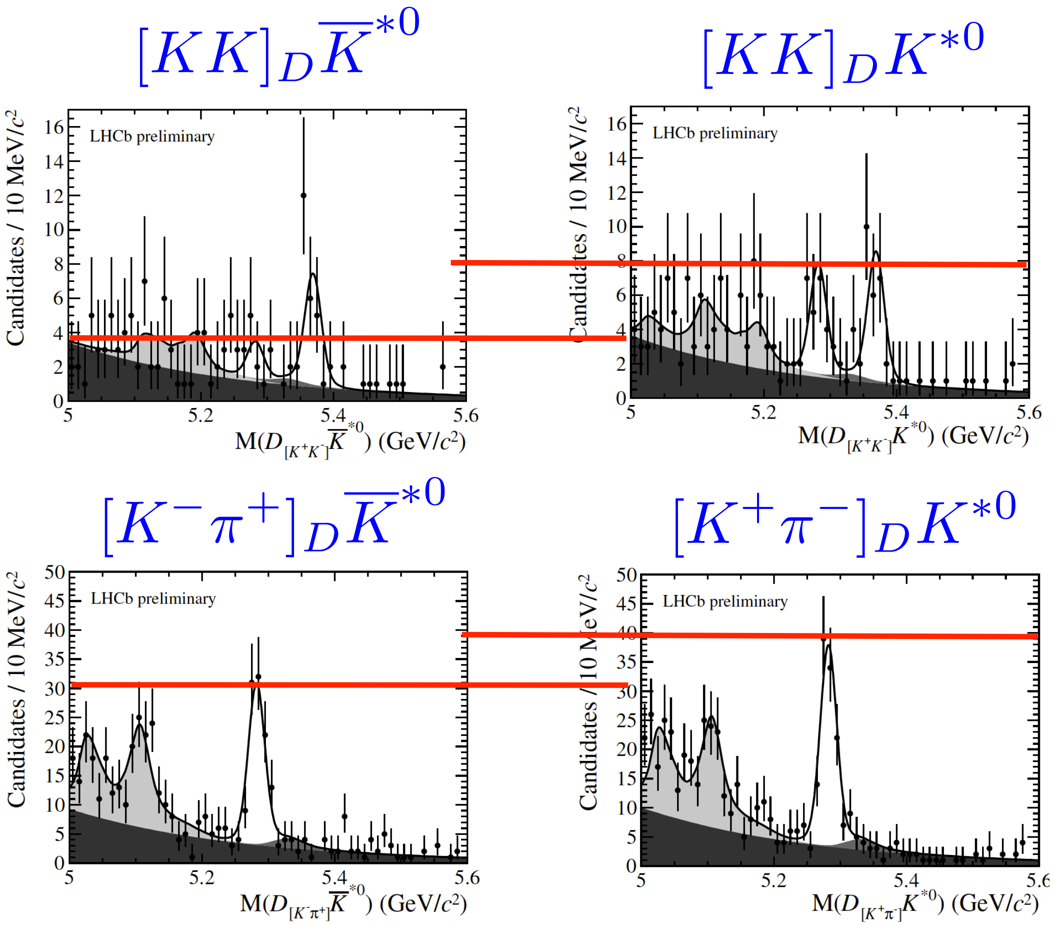
$$R_{CP+} = 1.007 \pm 0.038 \pm 0.012$$

LHCb-CONF-2012-024

$B^0 \rightarrow D^0K^{*0}, D^0 \rightarrow KK$

NEW Preliminary

- **World 1st A_{CP} measurements in $B^0 \rightarrow DK^{*0}$**
  - See talk by Alexandra Martín Sánchez earlier today



LHCb-CONF-2012-024

$B^0 \to D^0K^{*0}, D^0 \to KK$

NEW Preliminary

- **World 1st A_{CP} measurements in $B^0 \to DK^{*0}$**
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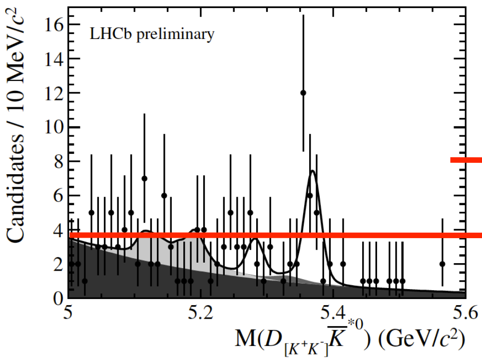
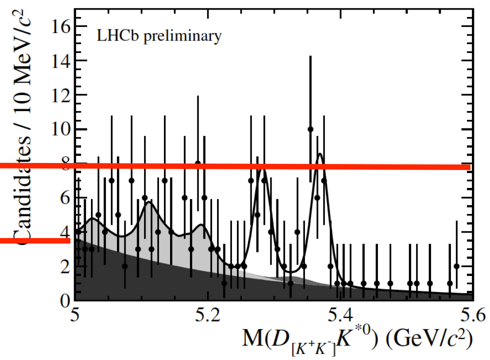
5.1 σ
$B^0 \to [KK]_D K^{*0}$

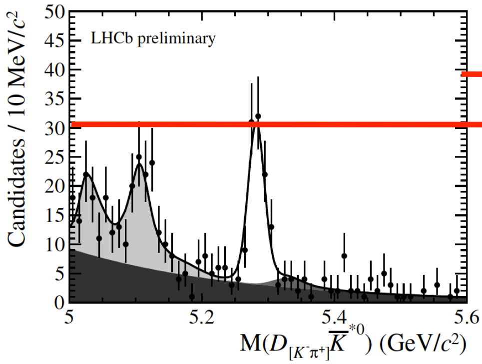
$[KK]_D\overline{K}^{*0}$



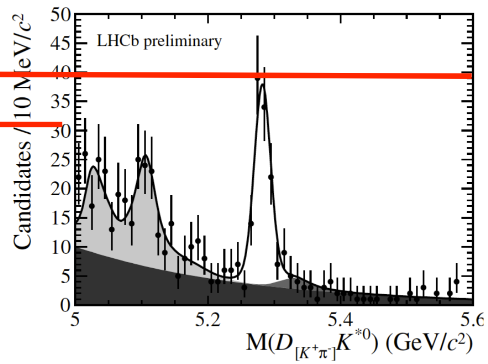
$[KK]_D K^{*0}$



$[K^-\pi^+]_D\overline{K}^{*0}$



$[K^+\pi^-]_D K^{*0}$



$$A^{KK}(B_d) = -0.47^{+0.24}_{-0.25} \pm 0.02$$

$$A^{KK}(B_s) = 0.04 \pm 0.17 \pm 0.01$$

$$R^{KK}(B_d) = 1.42^{+0.41}_{-0.35} \pm 0.07$$

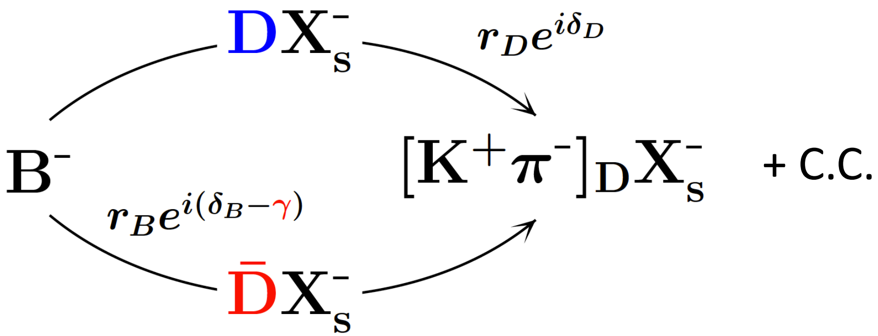
$$A^{K\pi}(B_d) = -0.08 \pm 0.08 \pm 0.01$$

$$B^{\pm} \longrightarrow D^{0} X_{s}^{\pm} : ADS$$

$B^{\pm} \to DX_s^{\pm}$: 'ADS' Analysis

Phys. Rev. Lett. 78 (3257)
Phys. Rev. D 68 (033003)

- Particular sensitivity to γ from suppressed ADS modes where interference is large:



- 'Rare' ($\mathcal{B} \sim 2 \times 10^{-7}$)
- + 2 favoured modes (SS kaons)
- $B \to DX_d$ control modes

- $$\mathcal{R}_s^{\pm} \equiv \frac{\Gamma([K^{\mp}\pi^{\pm}]_D X_s^{\pm})}{\Gamma([K^{\pm}\pi^{\mp}]_D X_s^{\pm})}$$
  - $$\mathcal{R}_s^{ADS} \equiv \frac{1}{2}(\mathcal{R}_s^{+} + \mathcal{R}_s^{-})$$
  - $$\mathcal{A}_s^{ADS} \equiv \frac{\mathcal{R}_s^{-} - \mathcal{R}_s^{+}}{\mathcal{R}_s^{-} + \mathcal{R}_s^{+}}$$

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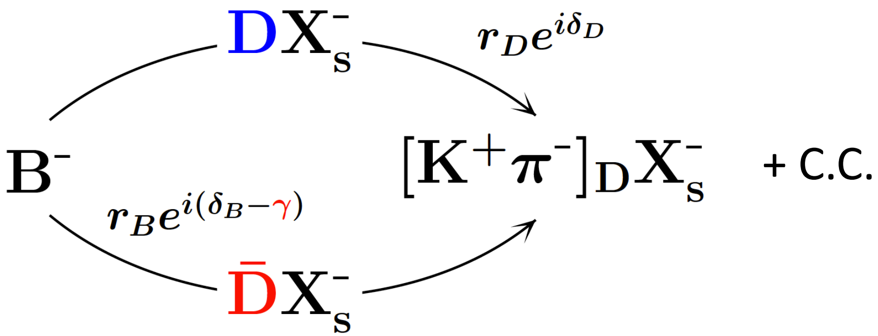


- 'Rare' ($\mathcal{B}$ ~ 2 x 10^{-7})
- + 2 favoured modes (SS kaons)
- $B\rightarrow DX_d$ control modes

- $r_{B(D)}$: ratio of B(D) decay amplitudes
- $\delta_{B(D)}$: strong phase difference within B(D) decays
- κ : coherence factor

- $$\mathcal{R}_s^{\pm} \equiv \frac{\Gamma([K^{\mp}\pi^{\pm}]_D X_s^{\pm})}{\Gamma([K^{\pm}\pi^{\mp}]_D X_s^{\pm})}$$

  – $$\mathcal{R}_s^{ADS} = {r_B}^2 + {r_D}^2 + 2\kappa r_B r_D \cos(\delta_B + \delta_D)\cos\gamma$$

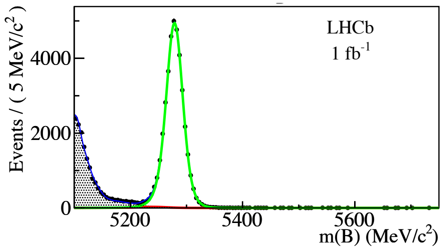
  – $$\mathcal{A}_s^{ADS} = 2\kappa r_B r \sin(\delta_B + \delta_D)\sin\gamma / \mathcal{R}_s^{ADS}$$

Phys. Lett. B 712 (203)

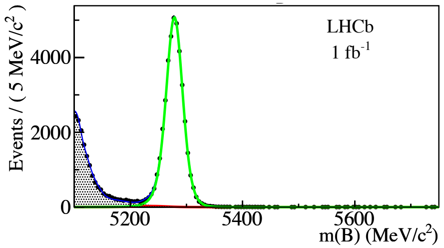
$B \rightarrow D^0X, D^0 \rightarrow K\pi, X=h$

[Fav.]

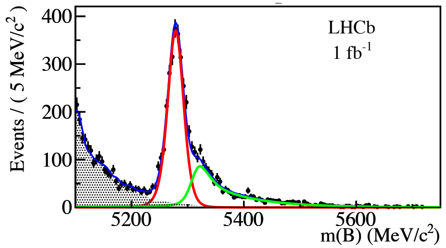
$[K\pi]_D\pi^-$



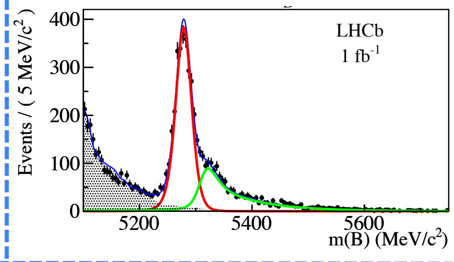
$[K\pi]_D\pi^+$



$[K\pi]_DK^-$

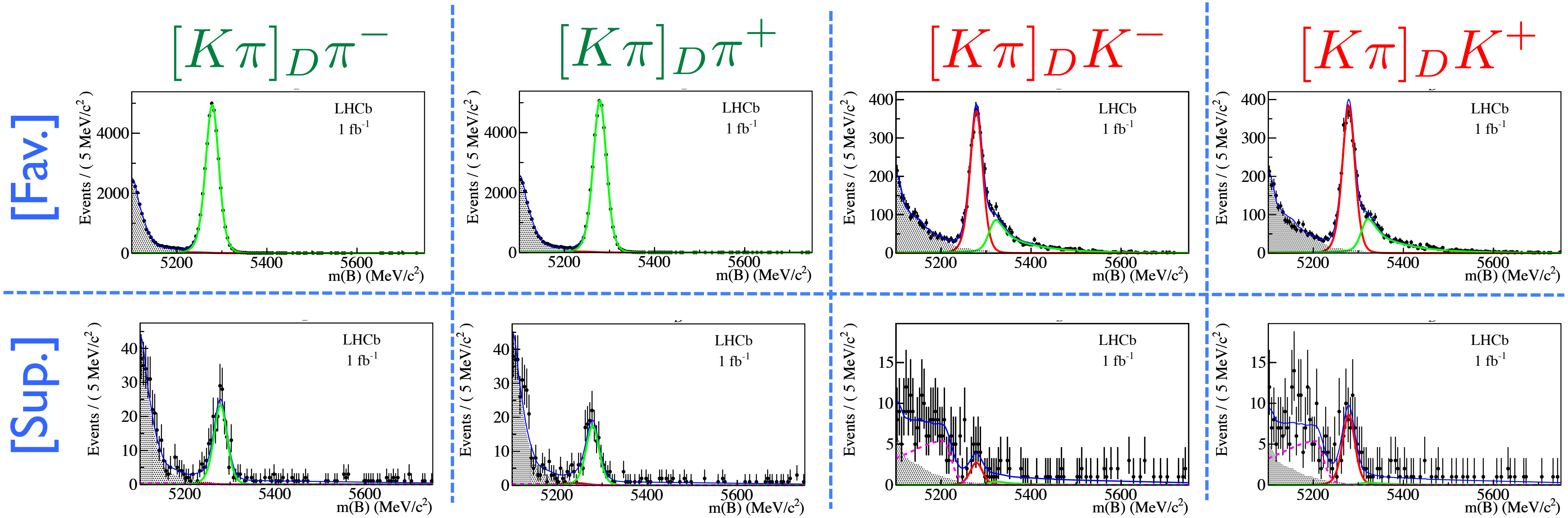


$[K\pi]_DK^+$



Phys. Lett. B 712 (203)

$B \to D^0 X, D^0 \to K\pi, X = h$



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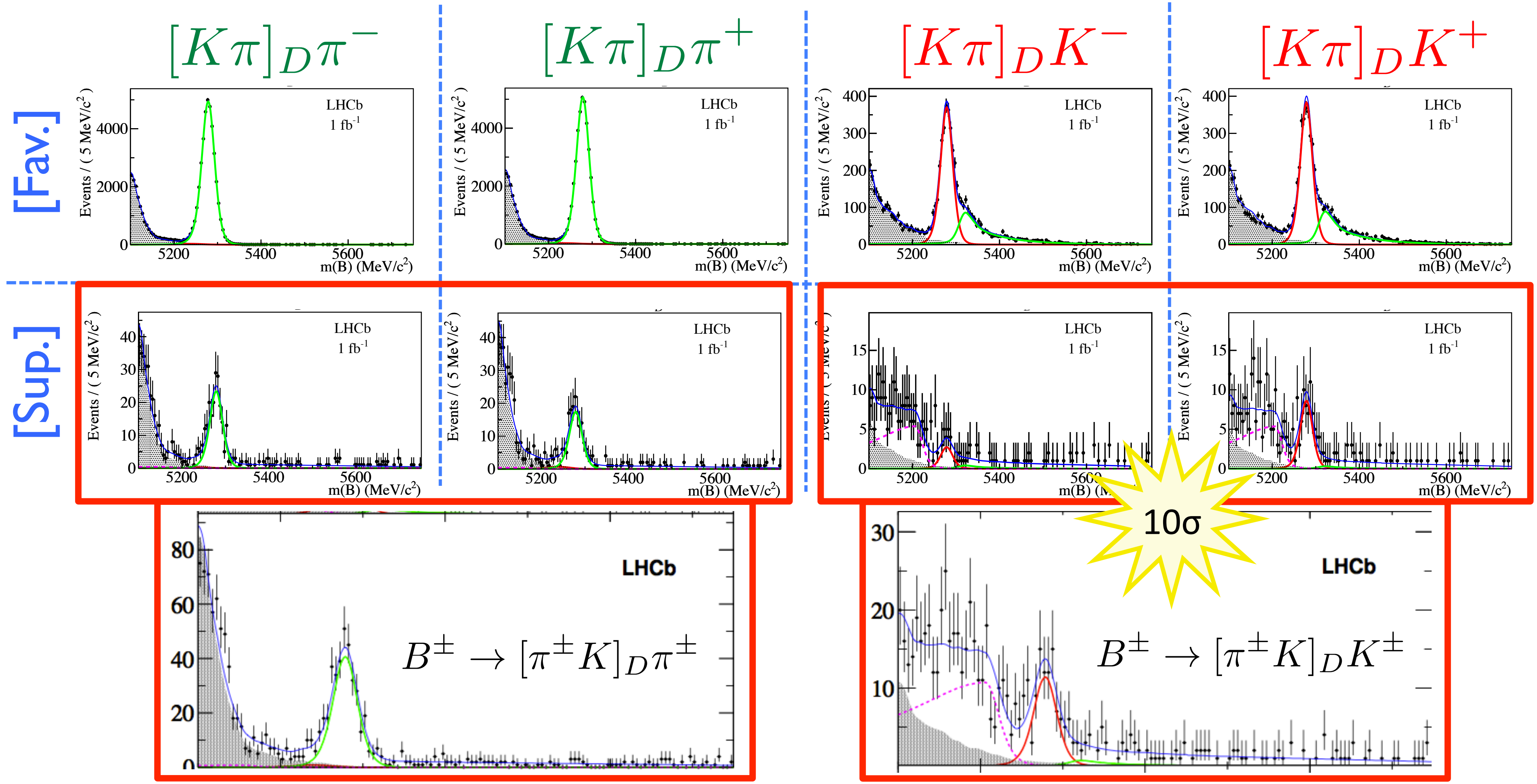
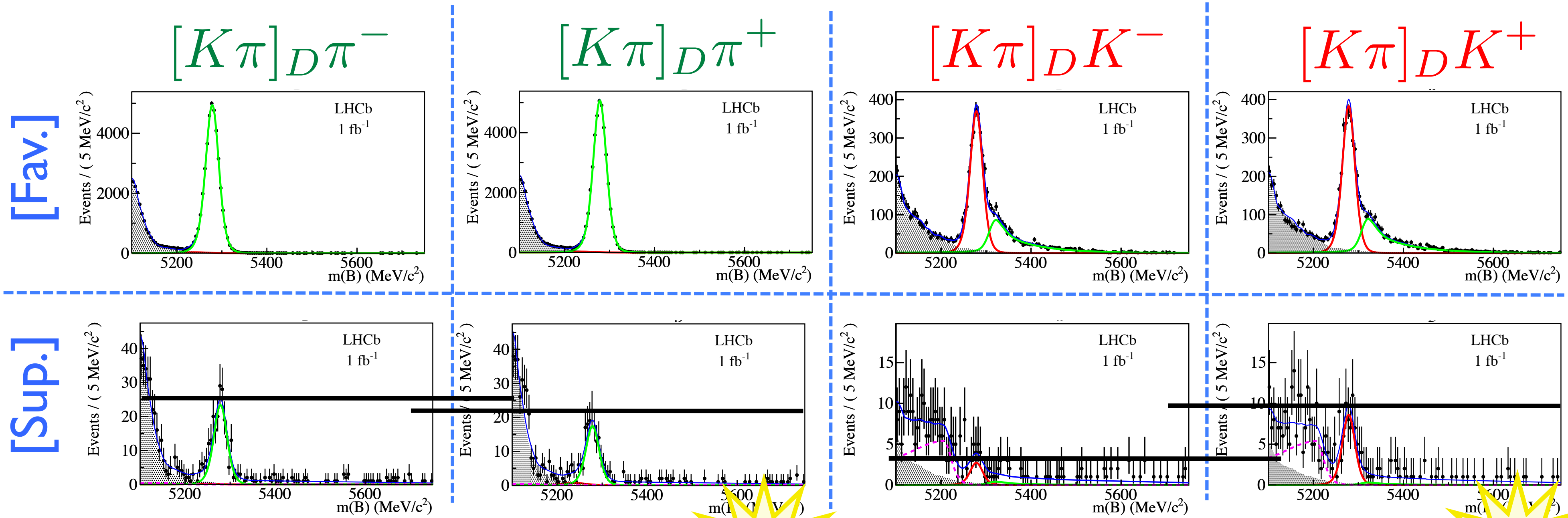


$$R_d^{ADS} = (0.410 \pm 0.025 \pm 0.005)\%$$

$$R_s^{ADS} = (1.52 \pm 0.20 \pm 0.04)\%$$

Phys. Lett. B 712 (203)

$B \to D^0 X, D^0 \to K\pi, X=h$



2.4σ

$$A_d^{ADS} = (14.3 \pm 6.2 \pm 1.1)\%$$

4.0σ

$$A_s^{ADS} = (-52 \pm 15 \pm 2)\%$$

- First 'hint' of CPV in this decay
- Combining with KK/ππ this is the 1st single analysis to observe (5.8 σ) CPV in $B^\pm \to DK^\pm$

γ from $B_s \to D_s^{\mp} K^{\pm}$

JHEP 06 (2012) 115

$B_s \to D_s^{\mp}K^{\pm}$

R. Fleischer
Nucl. Phys. B 671 (459)

- **Large interference effects expected**
  - Two interfering tree-level processes of similar strength
- **Time dependent analysis sensitive to ($\gamma + \phi_s$)**
  - Requires excellent proper time resolution + statistics
  - Analysis method unique to LHCb!
- **Measurement of $\mathcal{B}(B_s \to D_s^{\mp}K^{\pm})$ an important stepping stone to accessing γ with this mode:**
  - Determine $\frac{\mathcal{B}(B_s^0 \to D_s^{\mp}K^{\pm})}{\mathcal{B}(B_s^0 \to D_s^-\pi^+)}$ and $\frac{\mathcal{B}(B_s^0 \to D_s^-\pi^+)}{\mathcal{B}(B^0 \to D^-\pi^+)}$
  - Use LHCb's measurement of f_s/f_d @ $\sqrt{s} = 7$ TeV

Phys. Rev. D 85 (032008)

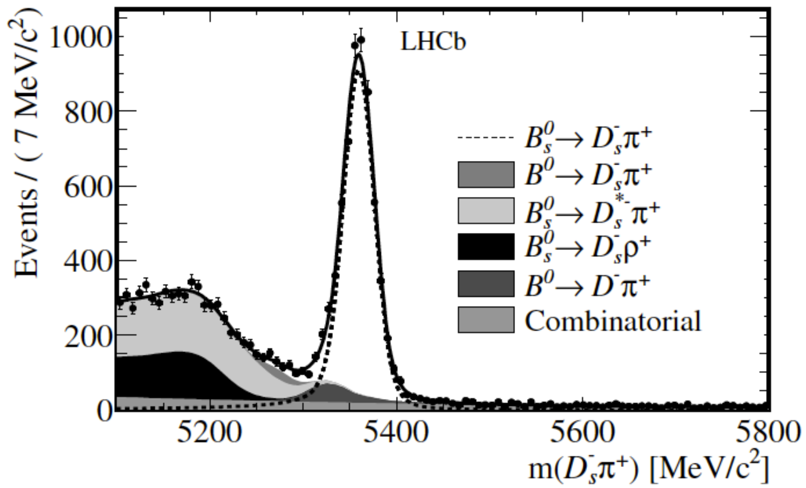
$$\mathcal{B}(B_s^0 \to D_s^{\mp}K^{\pm}) = (1.90 \pm 0.12 \pm 0.13^{+0.12}_{-0.14}) \times 10^{-4}$$
$$\mathcal{B}(B_s^0 \to D_s^-\pi^+) = (2.95 \pm 0.05 \pm 0.17^{+0.12}_{-0.14}) \times 10^{-3}$$

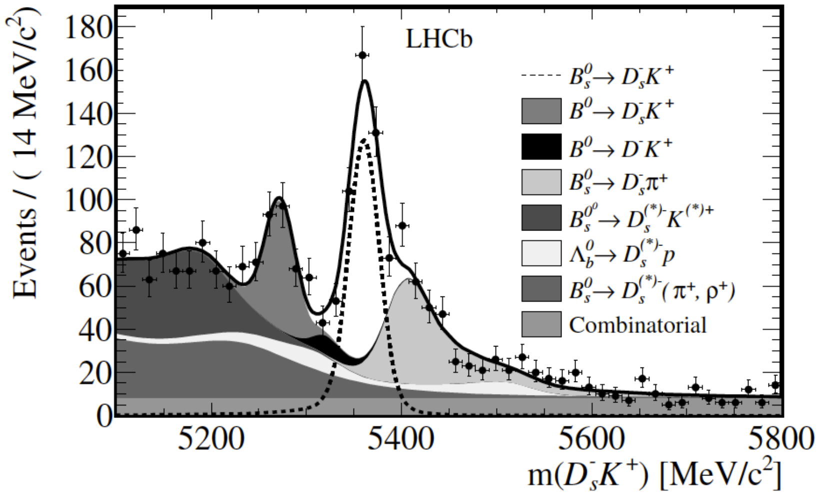
World Best

JHEP 06 (2012) 115

$B_s \rightarrow D_s^{\mp}K^{\pm}$: Towards γ

- **Proper time studied**
  - 45 fs resolution ($D_s\pi$)
- **Tagging understood**
  - $\varepsilon D^2 = (3.2 \pm 0.8)\%$ OS
  - Additional power from SS
  - See talk by S. Vecchi earlier today
- **Milestone measurements:**
  - $\Delta m_s = (17.725 \pm 0.041 \pm 0.026)\,\mathrm{ps}^{-1}$
    - LHCb-CONF-2011-050
  - $\mathcal{B}(B_s^0 \rightarrow D_s^{\mp}K^{\pm})$
- **All necessary ingredients are there**
  - Just awaiting the statisitics





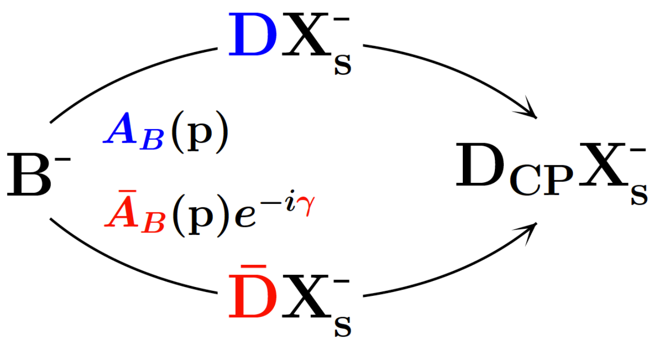
Summary

- $B \rightarrow DK$ decays provide an extensive set of channels in order to measure the CKM angle γ
- Results are now coming in from several of them:
  - $B^{\pm} \rightarrow D^{o}X_{s}^{\pm}$: GWL + ADS
  - $B^{o} \rightarrow D^{o}K^{*}$ (see talk by A. Martín Sánchez earlier today)
  - $B_{s}^{o} \rightarrow D_{s}^{\mp}K^{\pm}$
- …and many are on their way:
  - $B^{\pm} \rightarrow D^{o}X_{s}^{\pm}$, $D^{o} \rightarrow K_{S}\pi\pi$: GGSZ + Dalitz
  - $B^{\pm} \rightarrow D^{o}X_{s}^{\pm}$, $D^{o} \rightarrow \{K3\pi, K\pi\pi^{o}\}$
- Lots of exciting results in the pipeline – stay tuned!

Backup

$B^{-} \rightarrow D^0 X^{-}_s$: 'GLW' Analyses

- X_s : final state with same quantum no.'s as $K^{\pm}$
  - Two LHCb analyses: $X_s = \{K^{\pm}, K^{\pm}\pi^{\mp}\pi^{\pm}\}$
- Exploit interference of $D^0/\bar{D}^0$ decaying to CP-eigenstate



- $A(\mathbf{p}) = A_B(\mathbf{p}) + \bar{A}_B(\mathbf{p})e^{-i\gamma}$
- p : position in multi-body B phase space
- Total rate $\longrightarrow \int A_{(\mathbf{p})}\, d\mathbf{p}$

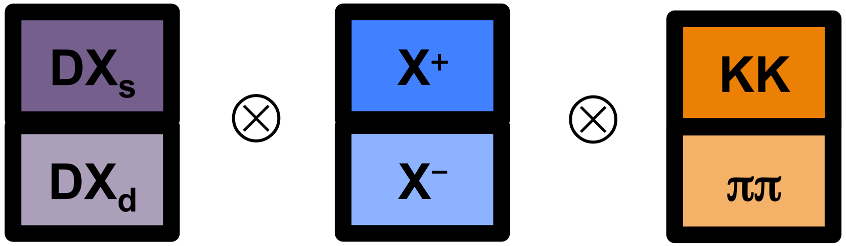
- For R_{CP+}, experimentally we actually measure:

$$R_{+} \equiv \frac{R^{CP+}_{s/d}}{R^{K\pi}_{s/d}} \quad \text{where} \quad R^{f}_{s/d} = \frac{\Gamma(B^{\pm} \rightarrow D_f X^{\pm}_{s})}{\Gamma(B^{\pm} \rightarrow D_f X^{\pm}_{d})}$$

- Equivalent to within a theoretical uncertainty of $\mathcal{O}(1\%)$

Analysis Strategy

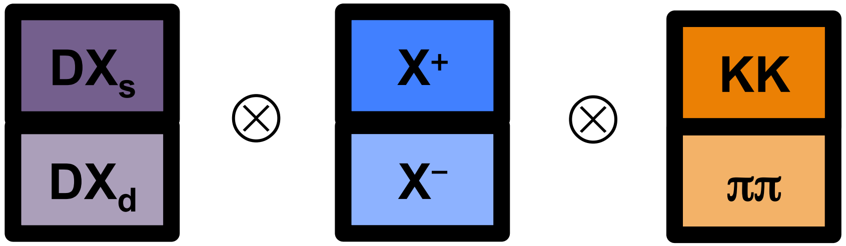
- **$B^{\pm} \rightarrow DX^{\pm}$ selected using MVA algorithm**
  - X = h : TMVA BDT
  - X = 3h : NeuroBayes Neural Network
- **Compose 8 mutually exclusive sub-samples:**



- **Use PID to:**
  - isolate DX_s/DX_d enhanced samples
  - Distinguish KK and $\pi\pi$
- **Employ data-driven method to determine PID cut efficiency**

Analysis Strategy

- $B^{\pm} \rightarrow DX^{\pm}$ selected using MVA algorithm
  - X = h : TMVA BDT
  - X = 3h : NeuroBayes Neural Network
- Compose 8 mutually exclusive sub-samples:



- Use PID to:
  - isolate DX_s/DX_d enhanced samples
  - Distinguish KK and $\pi\pi$
- Employ data-driven method to determine PID cut efficiency

- Peaking Backgrounds
  - Charmless backgrounds
    - Suppressed with D^0 flight significance cut and PID cuts on D^0 daughter tracks
  - Non-prompt X = 3h backgrounds (e.g. $B \rightarrow D^0 D_s^+$)
    - Apply a mass veto about the D_s^+ mass
  - Fully reconstructed $B \rightarrow DX$ decays (e.g. $B \rightarrow D(K\pi)a_1(KK\pi)$)
    - Assess in D^0 mass sidebands

- Simultaneous, maximum-likelihood fits to all $B^{\pm}$ mass distributions
  - Fit for Cabibbo Favoured yields + physics asymmetries
  - Detection and production asymmetries accounted for

$B^0 \to D K^{*0}$ analysis

- Based on 2011 LHCb data sample: 1.0 fb^{-1}.
- Cut-based selection: kinematics, vertex quality, PID ($DLL_{K-\pi}$).
- Background from charmless decays (such as $B^0 \to K^- \pi^+ K^{*0}$, etc.) removed by D meson flight distance significance cut.
- $D_{(s)}^- h^+$ contributions vetoed.
- $D^{*0} K^{*0}$ partially reconstructed background ($D^{*0} \to D^0 \pi^0/\gamma$) and $D^0 \rho^0$ cross-feed (π misidentified as K) modeled in the fit to the invariant mass.
- Unbinned maximum likelihood fit to the invariant mass distribution.
  - Signal and background shapes modeled from simulation.
  - Dominant systematic uncertainty comes from the fit model.

$D \to K^+ K^-, K^- \pi^+$

$$\mathcal{A}_d^{KK} = \frac{\Gamma(\overline{B}^0 \to D_{[K^+K^-]}\overline{K}^{*0}) - \Gamma(B^0 \to D_{[K^+K^-]}K^{*0})}{\Gamma(\overline{B}^0 \to D_{[K^+K^-]}\overline{K}^{*0}) + \Gamma(B^0 \to D_{[K^+K^-]}K^{*0})}$$

$$\mathcal{R}_d^{KK} = \frac{\Gamma(\overline{B}^0 \to D_{[K^+K^-]}\overline{K}^{*0}) + \Gamma(B^0 \to D_{[K^+K^-]}K^{*0})}{\Gamma(\overline{B}^0 \to D_{[K^-\pi^+]}\overline{K}^{*0}) + \Gamma(B^0 \to D_{[K^+\pi^-]}K^{*0})}$$

$$\mathcal{A}^{\text{fav}} = \frac{\Gamma(\overline{B}^0 \to D_{[K^-\pi^+]}\overline{K}^{*0}) - \Gamma(B^0 \to D_{[K^+\pi^-]}K^{*0})}{\Gamma(\overline{B}^0 \to D_{[K^-\pi^+]}\overline{K}^{*0}) + \Gamma(B^0 \to D_{[K^+\pi^-]}K^{*0})}$$

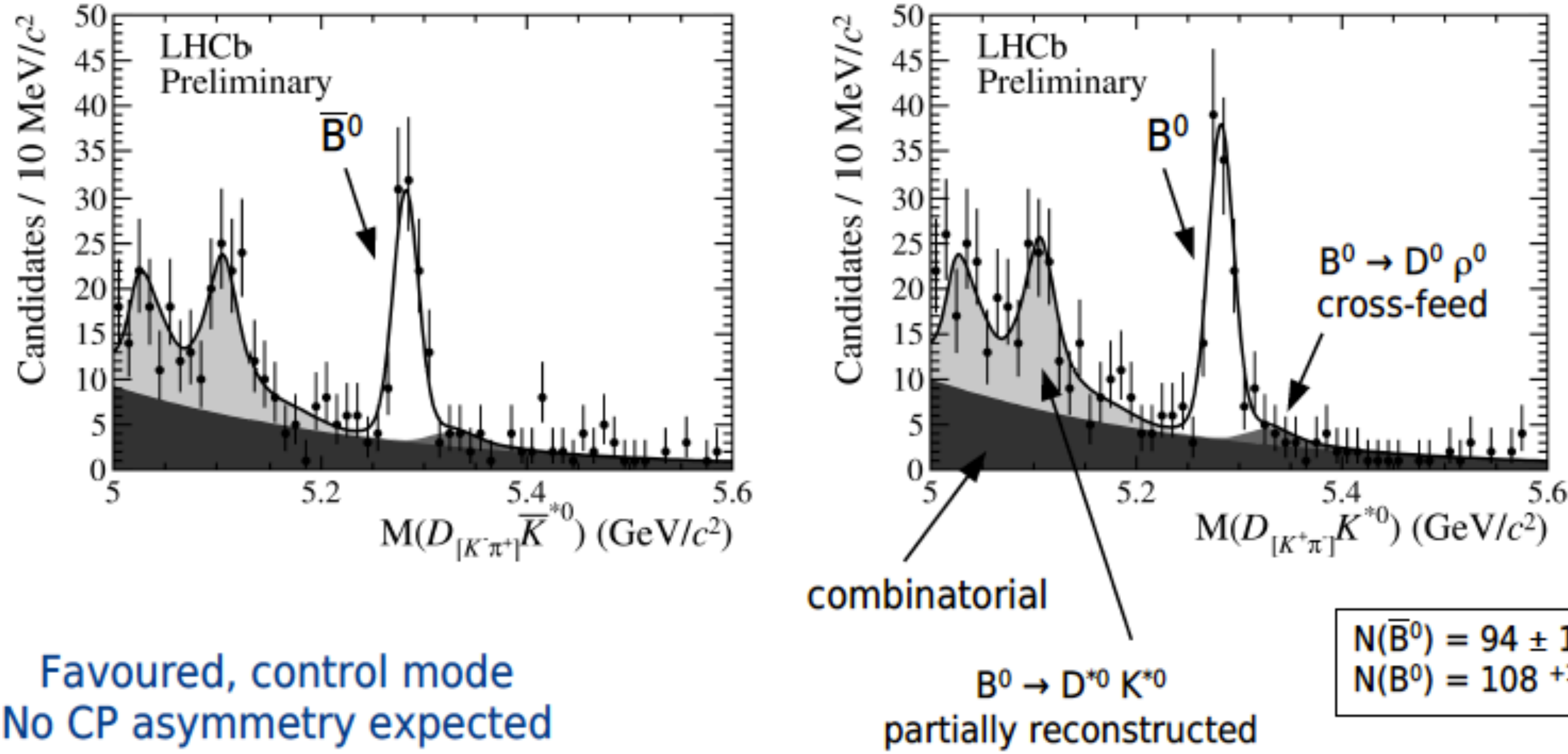
$$\mathcal{A}_s^{KK} = \frac{\Gamma(\overline{B}_s^0 \to D_{[K^+K^-]}K^{*0}) - \Gamma(B_s^0 \to D_{[K^+K^-]}\overline{K}^{*0})}{\Gamma(\overline{B}_s^0 \to D_{[K^-\pi^+]}K^{*0}) + \Gamma(B_s^0 \to D_{[K^+\pi^-]}\overline{K}^{*0})}$$

new LHCb result

Preliminary

LHCb-CONF-2012-024

$B^0 \to D K^{*0}$, $D^0 \to K^- \pi^+$



$N(\overline{B}^0) = 94 \pm 11$
$N(B^0) = 108\,^{+12}_{-11}$

Favoured, control mode
No CP asymmetry expected

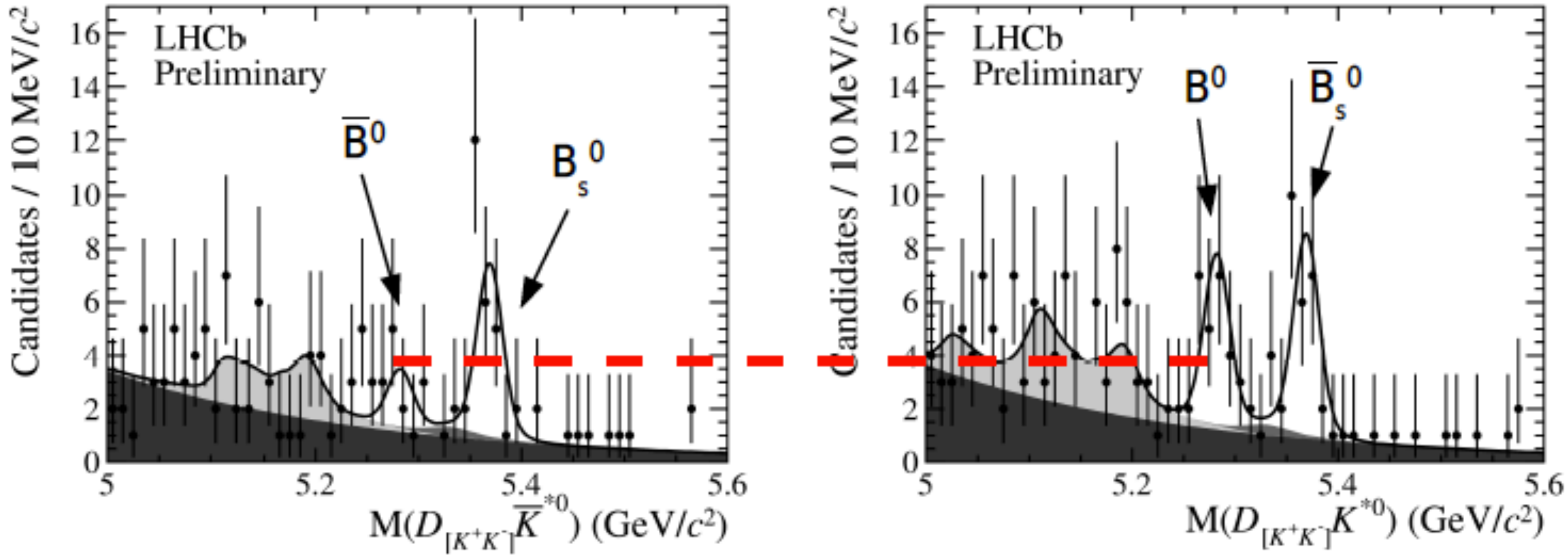
$$\mathcal{A}_d^{\mathrm{fav}} = -0.08 \pm 0.08\ (\mathrm{stat}) \pm 0.01\ (\mathrm{syst})$$

new LHCb result

Preliminary

LHCb-CONF-2012-024

$B^0 \to D K^{*0}$, $D^0 \to K^- K^+$



$$\mathcal{A}_d^{KK} = -0.47^{+0.24}_{-0.25}\ (\text{stat}) \pm 0.02\ (\text{syst})$$

$$\mathcal{A}_s^{KK} = 0.04 \pm 0.17\ (\text{stat}) \pm 0.01\ (\text{syst})$$

$$\mathcal{R}_d^{KK} = 1.42^{+0.41}_{-0.35}\ (\text{stat}) \pm 0.07\ (\text{syst})$$

5.1 σ B^0 signal ($B^0 + \overline{B}^0$)

$N(\overline{B}^0) = 7 \pm 4$
$N(B^0) = 20\ ^{+6}_{-5}$
$N(B_s^0) = 22\ ^{+6}_{-5}$
$N(\overline{B}_s^0) = 24\ ^{+6}_{-5}$

1st measurement in the $B^0 \to D(K^+K^-)K^{*0}$ system