$D^0 \rightarrow K\pi\pi\pi$ decays at LHCb

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  - $D^{*+} \rightarrow D^0(K^-\pi^+\pi^-\pi^+)\pi^+$ (+c.c.)
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- Conclusions

Introduction

- $D^0 \to K\pi\pi\pi$ ($D^0 \to K3\pi$) decays have many interesting physics applications at LHCb:
  - $D^0 \to K^- 3\pi$ and $D^{*+} \to (D^0 \to K^- 3\pi)\pi^+$:
    - D^0 and D^{*+} charm cross-section measurements
  - $D^{*+} \to (D^0 \to K^+ 3\pi)\pi^+$:
    - Amplitude model of $D^0 \to K^+ 3\pi$
    - Indirect CP violation and mixing
  - $B^+ \to (K^+ 3\pi)_D K^+$ and $B^+ \to (K^+ 3\pi)_D \pi^+$:
    - Measurement of $B(B^+ \to DK^+)/ B(B^+ \to D\pi^+)$
  - $B^+ \to (K^- 3\pi)_D K^+$:
    - Tree-level measurement of the CKM angle γ

Charm physics at LHCb

- Same aspects of LHCb that make us good for b-physics also aids charm physics
  - Low pileup
  - Great K-π discrimination
  - Excellent PV resolution
  - Good tracking and momentum resolution
- $c\bar{c}$ cross-section ~20x larger than $b\bar{b}$ cross-section
  - Can do many competitive analyses in charm sector with early data
- Crucial to charm physics at LHCb is the measurement of the open charm production cross-section

Measuring the open charm cross-section at LHCb

- Test predictions of QCD
- Input to sensitivity estimates for mixing, CP violation (CPV) and rare decays in the charm sector
- Ensure production cross-sections well described by MC
- Key features of LHCb cross-section measurements:
  - Measure transverse momentum (p_T) of the D hadron down to zero
  - Have access to all charm hadron species
- Preliminary cross-sections results produced for **D^0**, **D^{*+}**, D^+ and D_s^+ with first 1.8nb^{-1} of $\sqrt{s}$=7TeV LHCb collision data

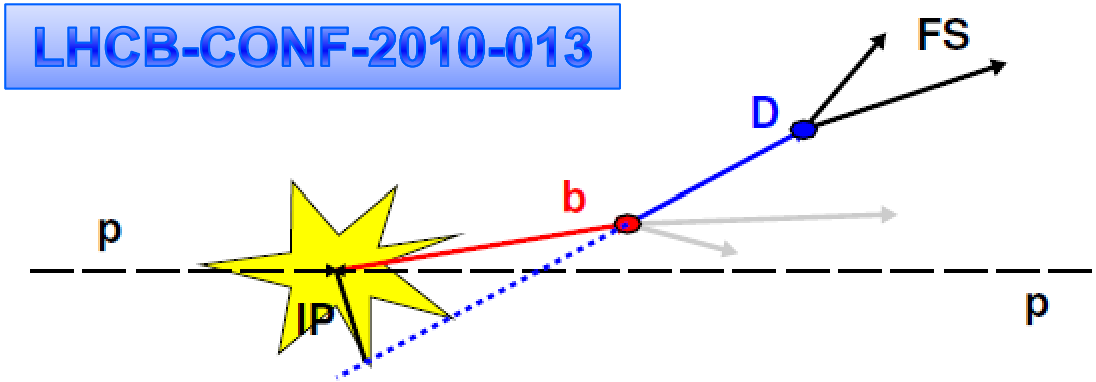
Measurement strategy

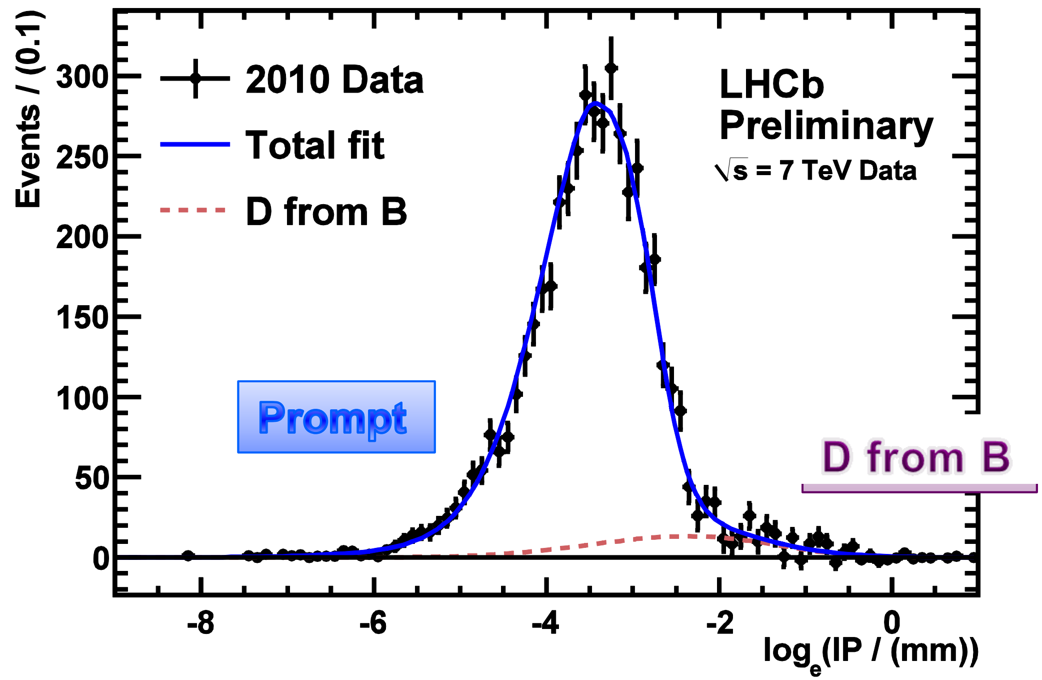
- $\sigma(\mathcal{L}_{int}; p_T, y) = \frac{N_{sig}(p_T, y)}{\varepsilon_{tot}(p_T, y) \cdot BR \cdot \mathcal{L}_{int}}$
  - Raw signal yields determined in 2D bins of y, p_T
    - Signal separated from background
    - Contamination from secondary charm determined from fit to D IP in data
  - Selection efficiencies ε_{tot} determined from MC
    - Extensive cross-checks on data
    - PID cut efficiency determined separately using data
  - Branching ratios from Particle Data Group (PDG) 2010
  - Integrated luminosity measured by LHCb

Prompt-secondary separation

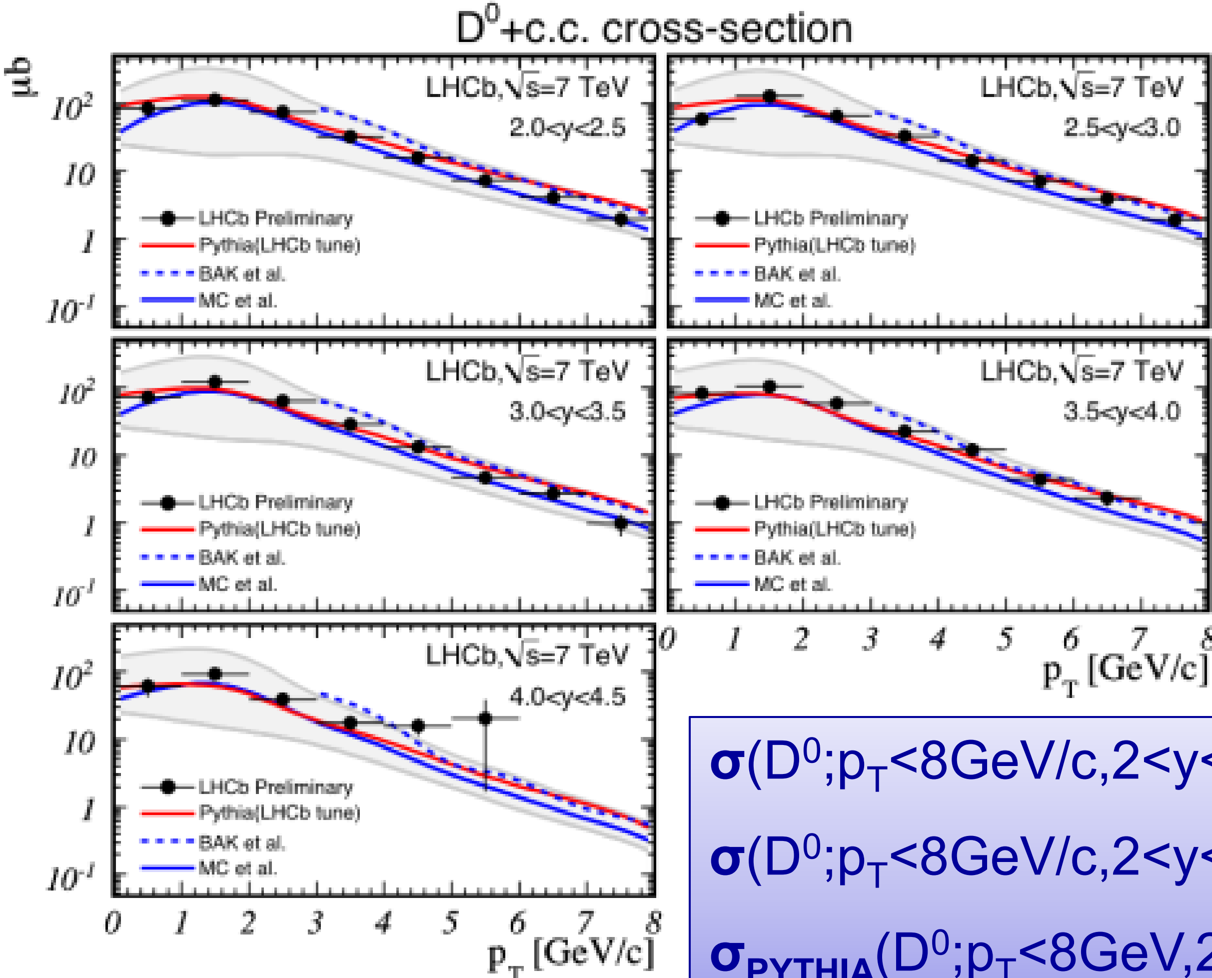
- After background subtraction, the remaining background primarily comes from decays of long-lived particles – **secondary charm**
- Measure secondary fraction from the D impact parameter (IP) distribution

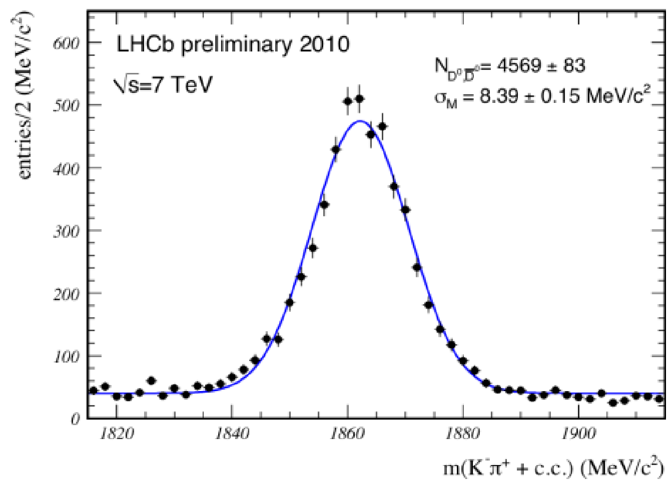
LHCB-CONF-2010-013





Cross-section results: D^0





$D^0 \to K^- \pi^+$

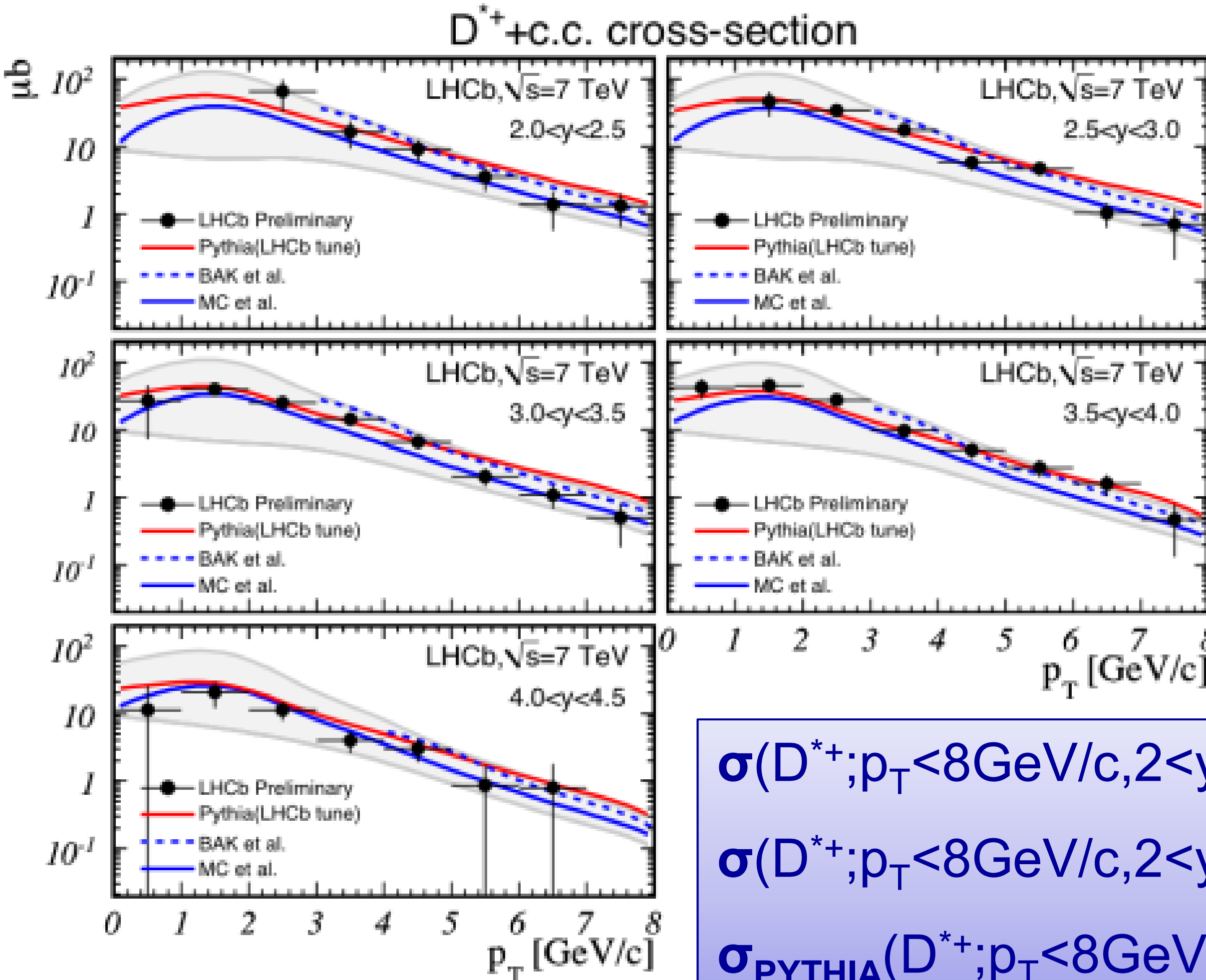
$\sigma(D^0;p_T<8\text{GeV/c},2<y<4.5)=$ **$1488\pm41\pm34\pm174$ μb**

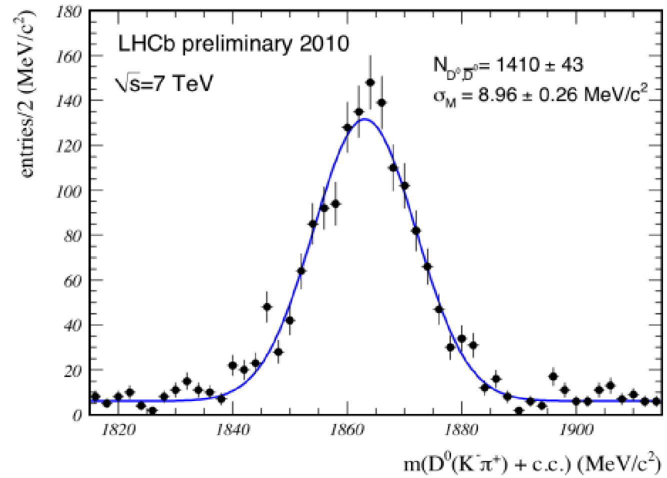
$\sigma(D^0;p_T<8\text{GeV/c},2<y<4.5)=$ **1488 ± 182 μb**

$\sigma_{PYTHIA}(D^0;p_T<8\text{GeV},2<y<4.5)=$ **1402 ± 2 μb**

---- B.A. Kniehl, G. Kramer, I. Schienbein, and H. Spiesberger
—— M. Cacciari, S. Frixione, M. Mangano, P. Nason, and G. Ridolfi

Cross-section results: D^{*+}





$D^{*+} \rightarrow D^0(K^-\pi^+)\pi^+$

$\sigma(D^{*+};p_T<8GeV/c,2<y<4.5)=$**$676 \pm 64 \pm 21 \pm 119$ μb**

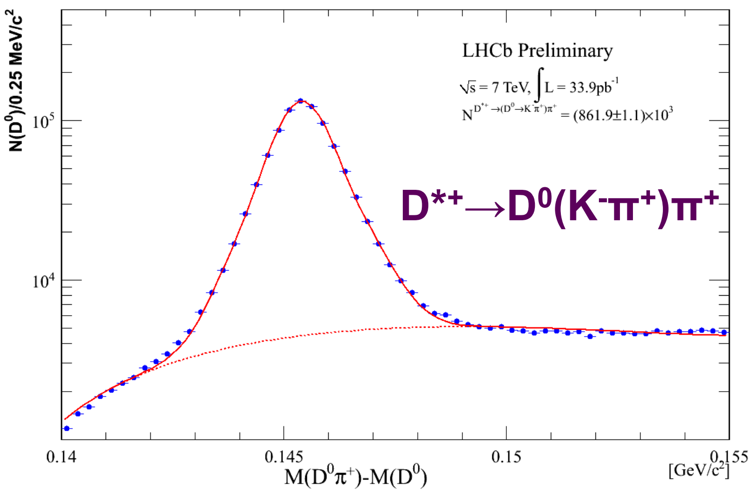
$\sigma(D^{*+};p_T<8GeV/c,2<y<4.5)=$**$676 \pm 137$ μb**

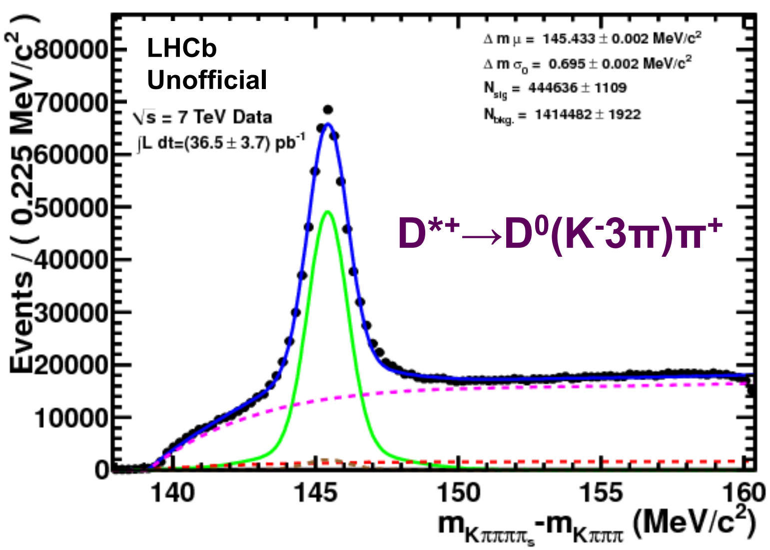
$\sigma_{PYTHIA}(D^{*+};p_T<8GeV,2<y<4.5)=$**$653 \pm 1$ μb**

Including $D^0 \rightarrow K3\pi$ decays in the cross-section measurement

- Work is on-going to produce a public note for the cross-section measurements with increased statistics
- For the D^0 and D^{*+} cross-section measurements, only $D^0 \rightarrow K^-\pi^+$ decays have been considered so far
- We also plan to include $D^0 \rightarrow K^-3\pi$ decays in the final result
  - Consistent results between the two- and four-body measurements is important to show that we understand our tracking efficiencies

$D^{*+} \rightarrow D^0(K^-3\pi)\pi^+$ in 2010 data

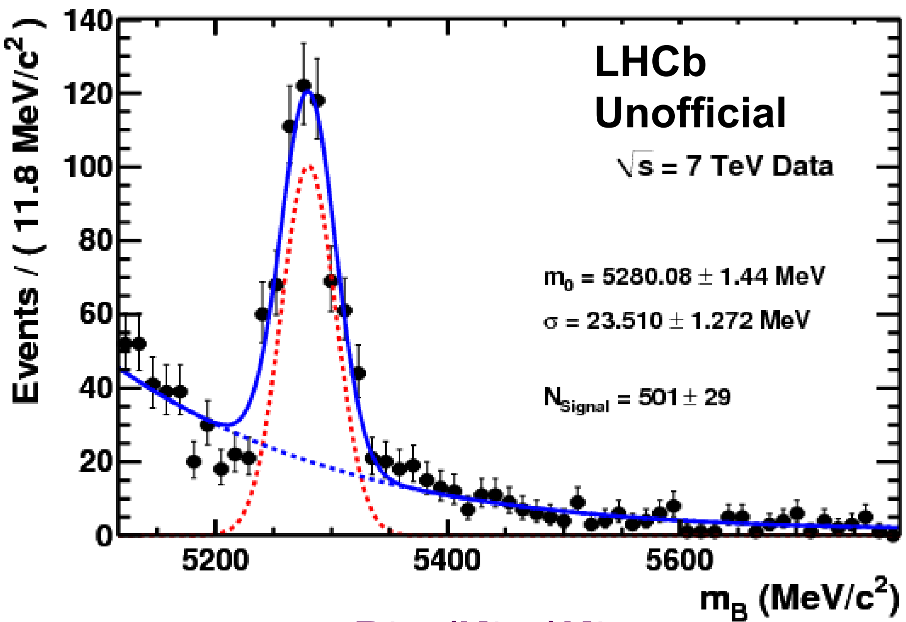




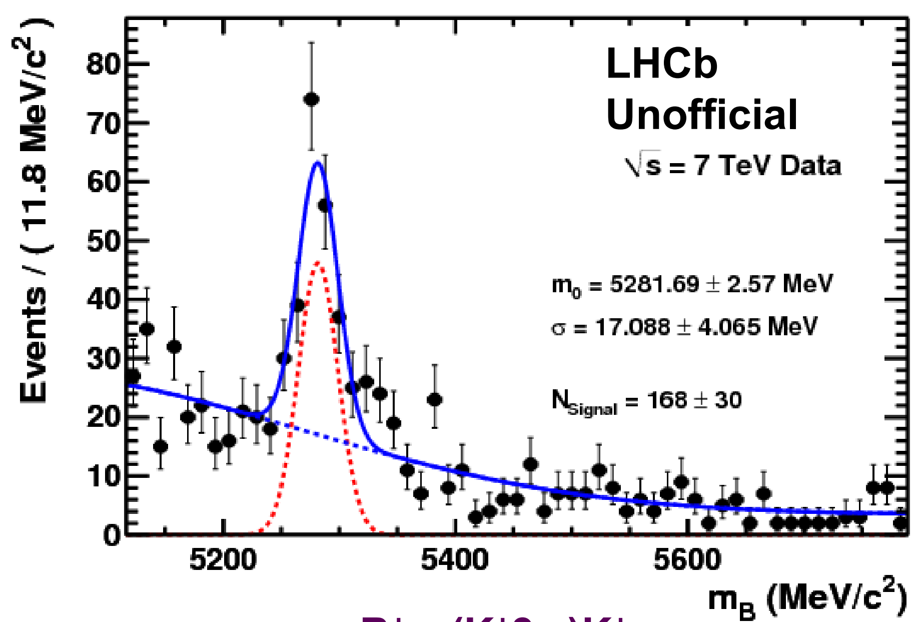
- Reconstructing and selecting $D^0 \rightarrow K^-3\pi$ events in 2010 was hard work:
  - Pileup and track multiplicity much higher than LHCb design
    - As we approach nominal luminosity in 2011, LHCb can run with pileup closer to design
  - No dedicated four-body charm software trigger line in 2010
    - New trigger line commissioned for 2011 to handle four-body charm decays
- Despite these problems, we managed to reconstruct O(½M) events in 2010!

$B^+ \to (K^+ 3\pi)_D K^+$ in 2010 data

- Even with a fraction of a nominal year of LHCb data, we can already see the first multi-body $B^+ \to DK^+$ events



$B^+ \to (K^+\pi^-)K^+$



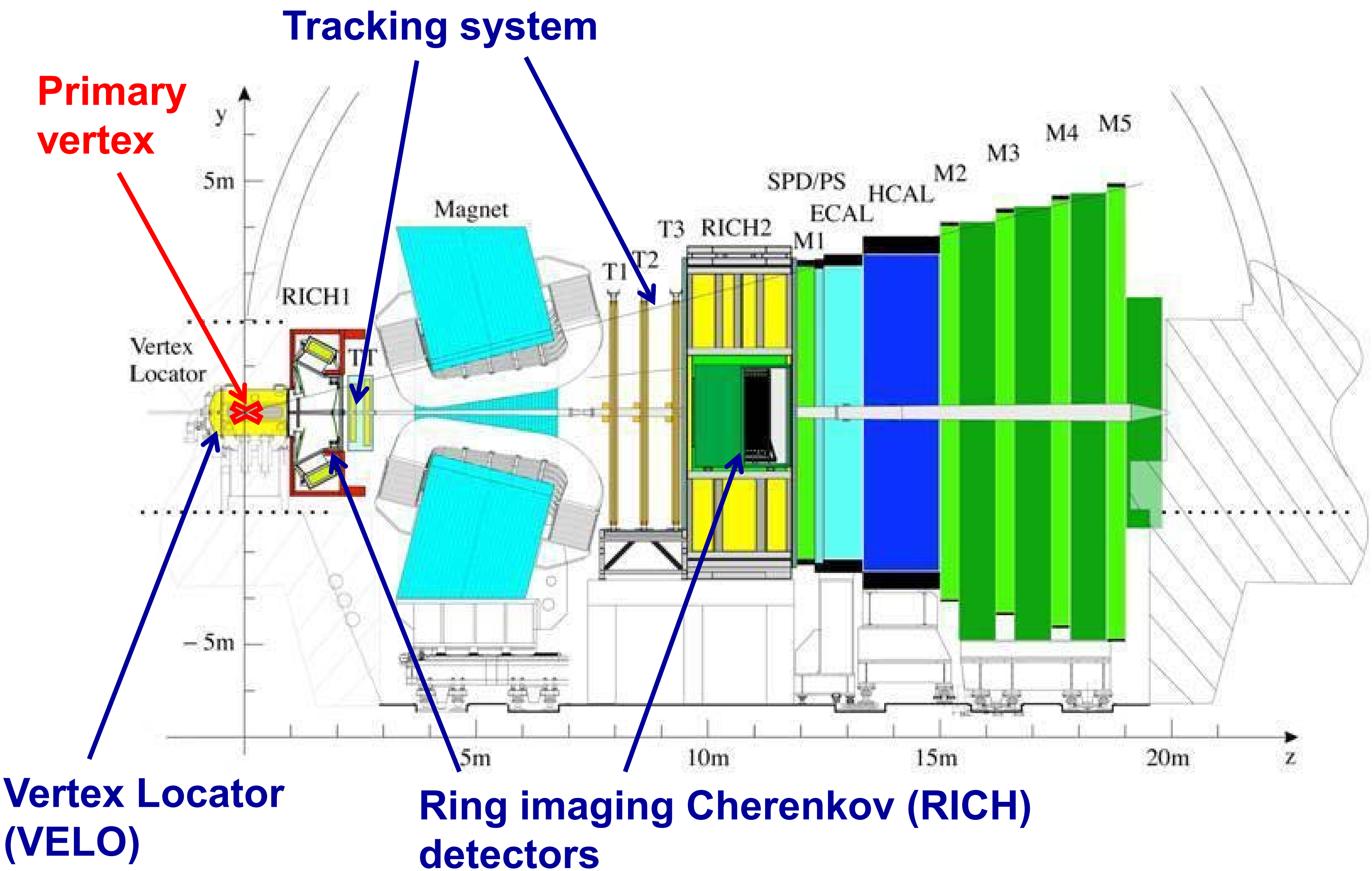
$B^+ \to (K^+ 3\pi)K^+$

Conclusions

- $D^0 \to K\pi\pi\pi$ decays have many physics applications at LHCb in the charm and beauty sectors
- Current open charm cross-section results show good consistency with MC
  - The inclusion of $D^0 \to K\pi\pi\pi$ decays in the final results will give important corroboration of our tracking efficiencies
- Even with the less than ideal 2010 detector conditions, LHCb has proved that multi-body decays can be reconstructed at a hadron collider
- First physics results with $D^0 \to K\pi\pi\pi$ decays very soon

Backup

Overview of LHCb



The CKM matrix

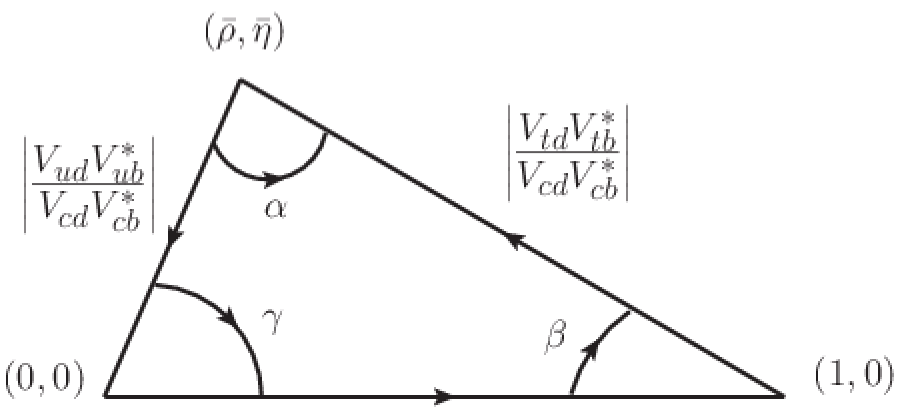
- The Cabibbo–Kobayashi–Maskawa (CKM) matrix quantifies the mixing between the different flavours of quarks in weak force interactions

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

- The CKM matrix can be fully describes by three mixing angles and one complex phase
  - CP violation (CPV) is generated in the Standard Model (SM) by this complex phase

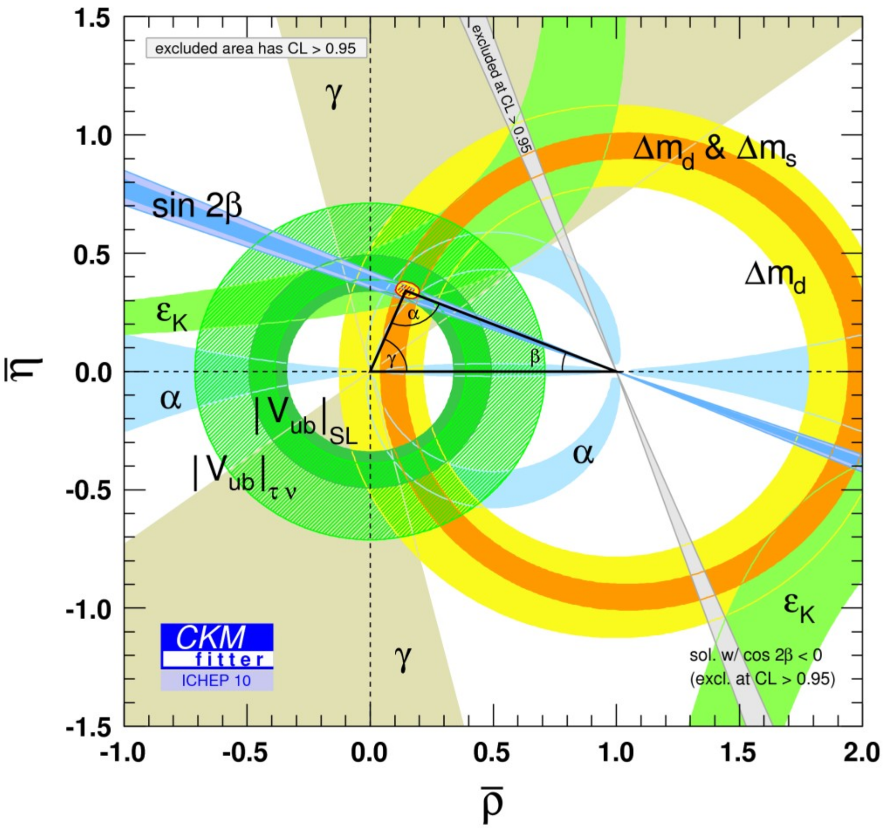
Unitarity of the CKM matrix

- Invoking unitarity gives a series of relations between the elements of the CKM matrix V_{ij}:
  - $\sum_k V_{ik} V^*_{jk} = \delta_{ij}$; $\sum_k V_{ik} V^*_{kj} = \delta_{ij}$.
- When i=j, we have the constraint that the couplings of an up-type quark (u,c,t) to the down-type quarks (d,s,b) are the same for all generations (**universality**)
- The six remaining relations (when i≠j), can be represented as triangles in a complex plane, known as a **unitarity triangle**



The CKM angle γ

- Of the three standard CKM angles, γ is by far the least constrained
- One of LHCb's primary objectives is to reduce the uncertainty on γ to a few %



CKMFitter Summer 2010 global fit results (from direct measurement):

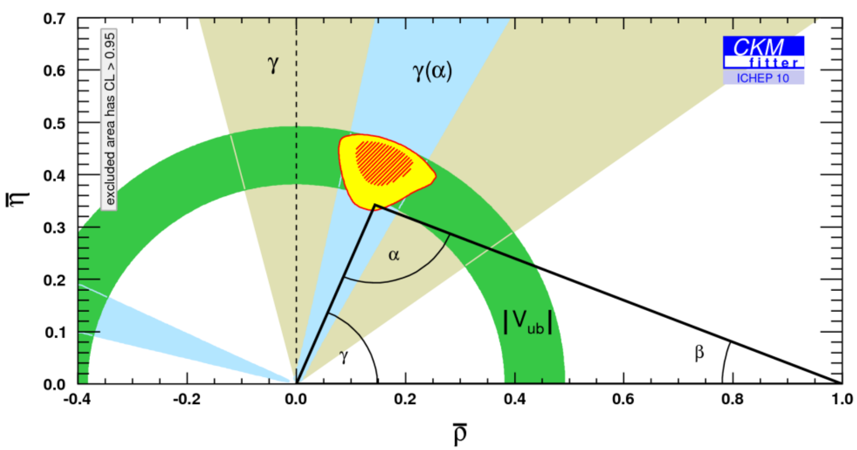
$\alpha = (89.0^{+4.4}_{-4.2})°$

$\beta = (21.15^{+0.90}_{-0.88})°$

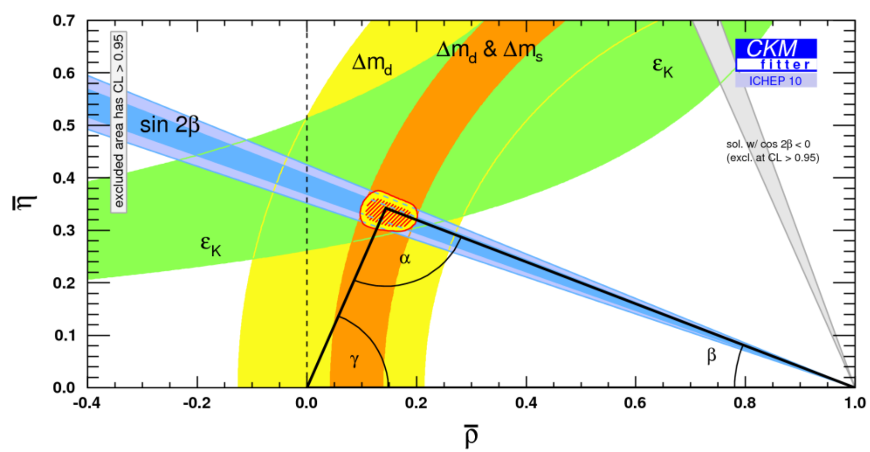
$\gamma = (71^{+21}_{-25})°$

Measuring γ from tree-level processes

- Decays with internal loops in the Standard Model (SM) are sensitive to new physics (NP) processes
  - NP can distort the angles of the unitary triangle
- Measuring γ from "tree-level" processes gives a SM benchmark, since they are much less sensitive to NP



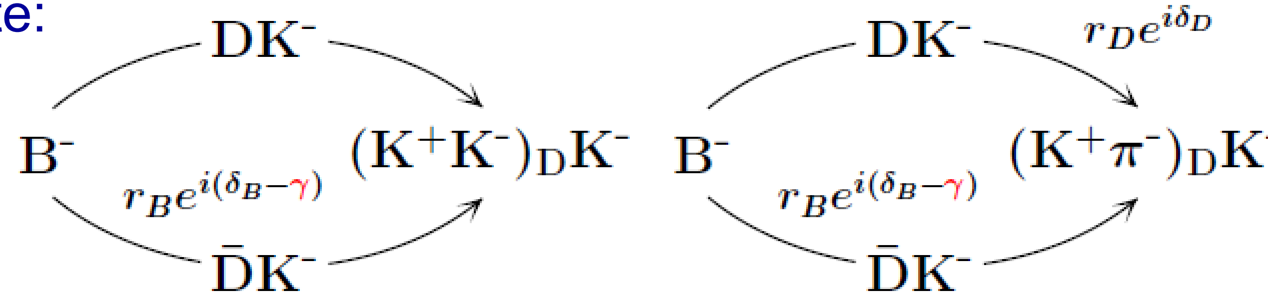
Constraints from trees



Constraints from loops

Measuring γ from interference between $B^+ \to D^0 K^+$ and $B^+ \to \bar{D}^0 K^+$

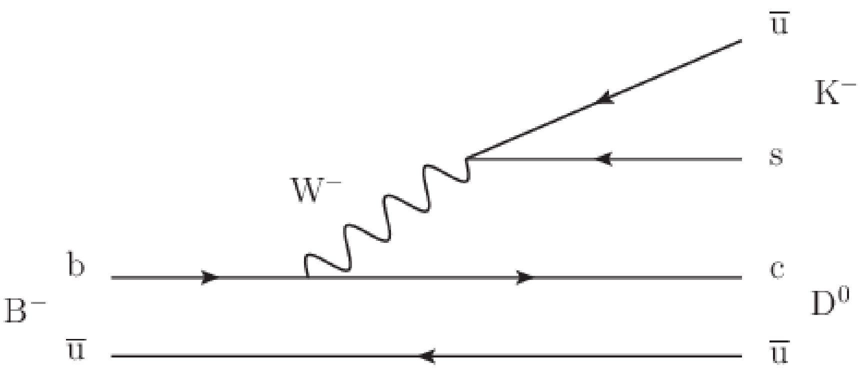
- γ can be determined from tree-level processes by exploiting the interference of $B^+ \to D^0 K^+$ and $B^+ \to \bar{D}^0 K^+$ when decaying to the same final state:



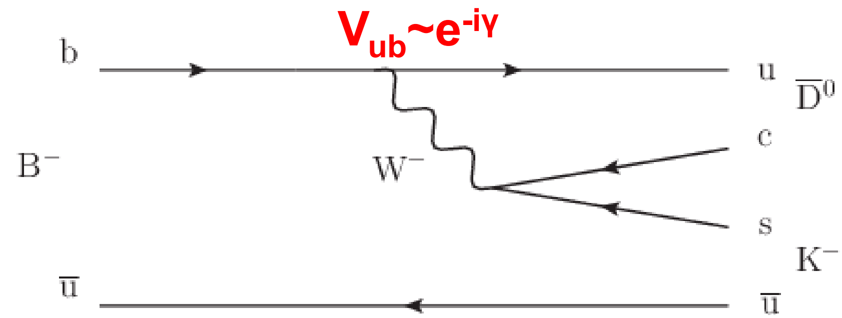
- Gronau-London-Wyler (GLW) method (left):
  - D decays to a CP eigenstate, e.g. K^+K^-
  - Since r_B is relatively small (~0.1), the upper process dominates, so low γ sensitivity
- Atwood-Dunietz-Soni (ADS) method (right):
  - D decays to non-CP eigenstate, e.g. $K^+\pi^-$
  - Since the upper process is supressed, the interference is large, so maximal γ sensitivity
  - State-specific amplitudes r_D well-measured from charm decays for many modes
  - **At least one other final-state (e.g. $K^+3\pi$) needed to constrain all parameters**

Feynman diagrams for $B^- \to D^0 K^-$ and $B^- \to \overline{D}^0 K^-$

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



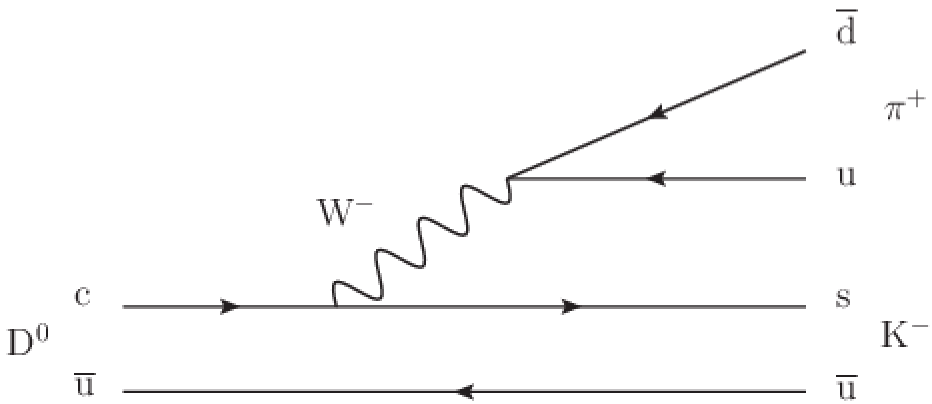
Colour favoured



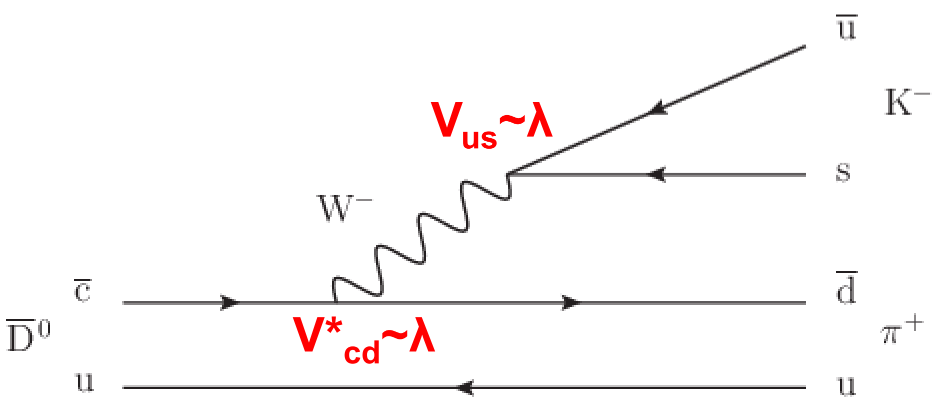
Colour suppressed

Feynman diagrams for $D^0 \to K^- \pi^+$ and $\overline{D}^0 \to K^- \pi^+$

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$



Cabibbo Favoured (CF)



Doubly Cabibbo Supressed (DCS)

|λ|~0.2

Using ADS method for multi-body modes

- The ADS method can be applied to multi-body final states such as $D^0 \rightarrow K^+\pi^-\pi^0$ and $D^0 \rightarrow K^+\pi^-\pi^+\pi^-$ ($D^0 \rightarrow K^+3\pi$)
- However, these are complicated by the fact that the D^0 or D^0 can decay to the final state via several short-lived intermediate resonances
  - These resonances can interfere with one another, so the amplitude ratio and strong phase difference can vary over the phase space
- There are two ways to account for this:
  - "Pseudo-two-body" (**coherence factor**) method
  - Amplitude model

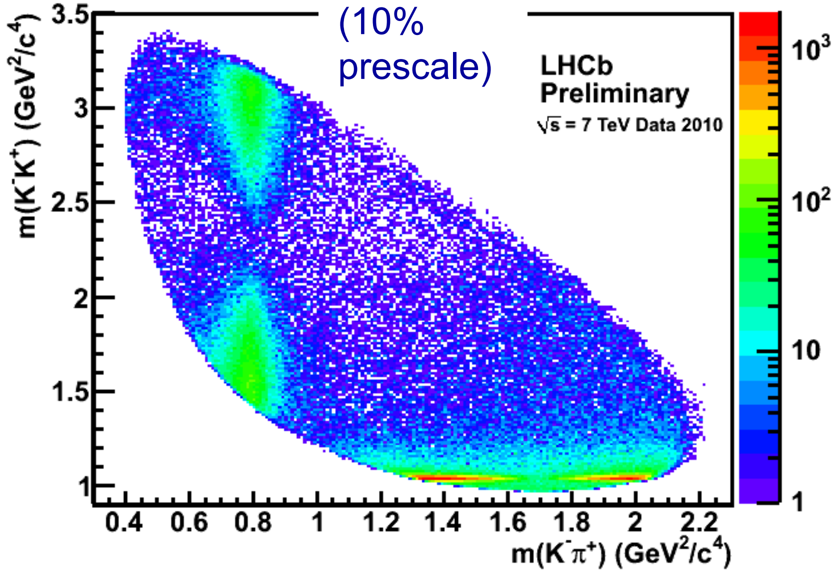
Coherence Factor

- An additional parameter is introduced into the two-body amplitude equations called a **coherence factor**, which quantifies the interference between the resonances:
  - $R_{K3\pi} e^{-i\delta_D^{K3\pi}} = \dfrac{\int A_{K^-3\pi}(\vec{x}) A_{K^+3\pi}(\vec{x}) d\vec{x}}{\int |A_{K^-3\pi}(\vec{x})|^2 d\vec{x} \int |A_{K^+3\pi}(\vec{x})|^2 d\vec{x}}$
    - Can take any value in range 0-1
    - Low coherence factor means the resonances are largely incoherent => low γ sensitivity
  - The coherence factors for $D^0 \rightarrow K\pi\pi^0$ and $D^0 \rightarrow K\pi\pi\pi$ have been measured by the CLEO-c collaboration (Phys.Rev.D80,(2009)031105)
  - For $K\pi\pi\pi$, the central value is quite small, albeit with very large errors ($0.33^{+0.26}_{-0.23}$)
  - Reduction in γ sensitivity, but heightened sensitivity to r_B ($0.103^{+0.015}_{-0.024}$) [CKMFitter, ICHEP 2010]

Amplitude model

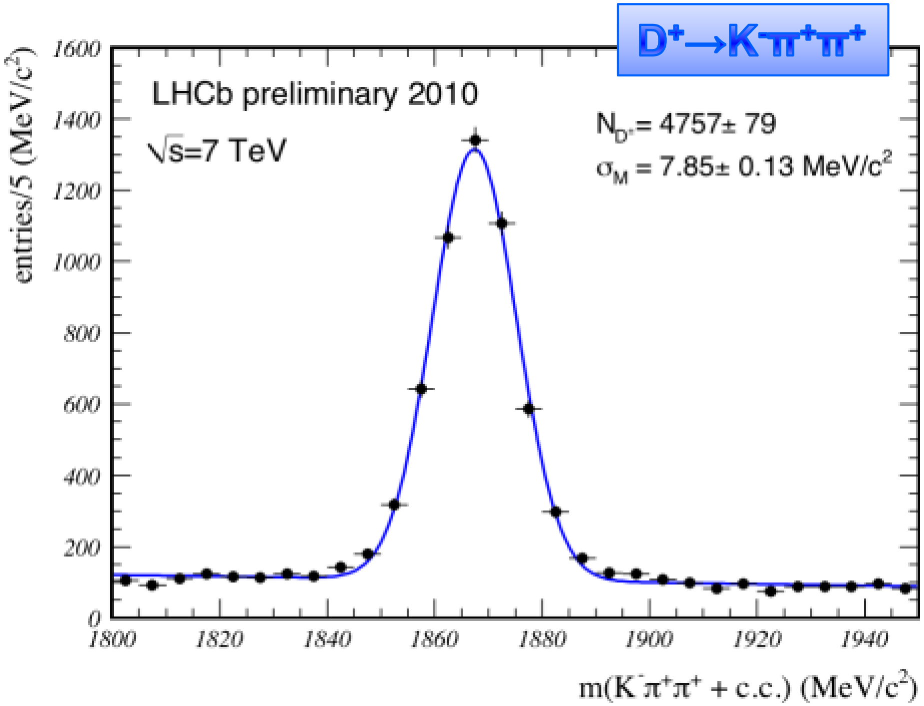
- Dalitz plots are commonly used to investigate the resonant structure of three-body decays (e.g. $D_s^+ \rightarrow K^-K^+\pi^+$, shown right)
- Such plots can be used to fit for the amplitudes and phases of the resonances
- Things are more complicated for decays with four final-state tracks. e.g. $D^0 \rightarrow K^+3\pi$, as we have to deal with a 5D Dalitz space

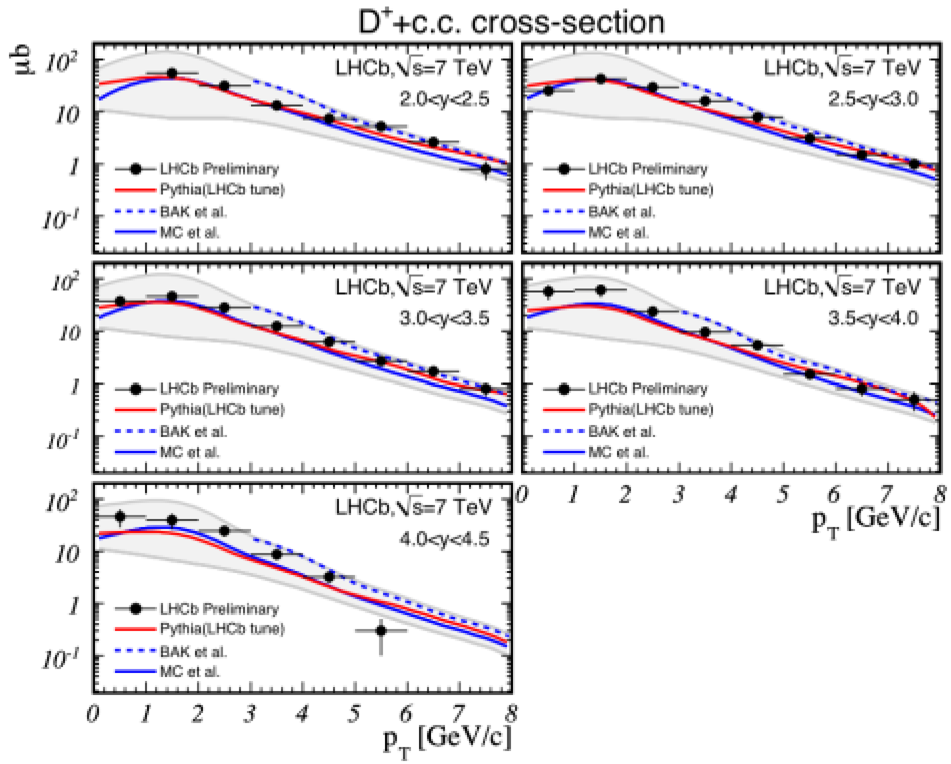
~10pb^{-1} (10% prescale)



- For neutral D decays, it is necessary to consider events in which the D comes from a $D^{*\pm}$ decay, since the charge of the pion tells us whether a D^0 or $\bar{D}^0$ decayed
- A full amplitude model already exists for the Cabibbo favoured (CF) $D^0 \rightarrow K^-3\pi$, and we are working on incorporating the model into the LHCb framework
- There is no amplitude model yet for the doubly Cabibbo suppressed (DCS) $D^0 \rightarrow K^+3\pi$. We plan to exploit the vast number of charm events that LHCb will generate to determine the first amplitude model for this decay channel

Cross-section results: D^+



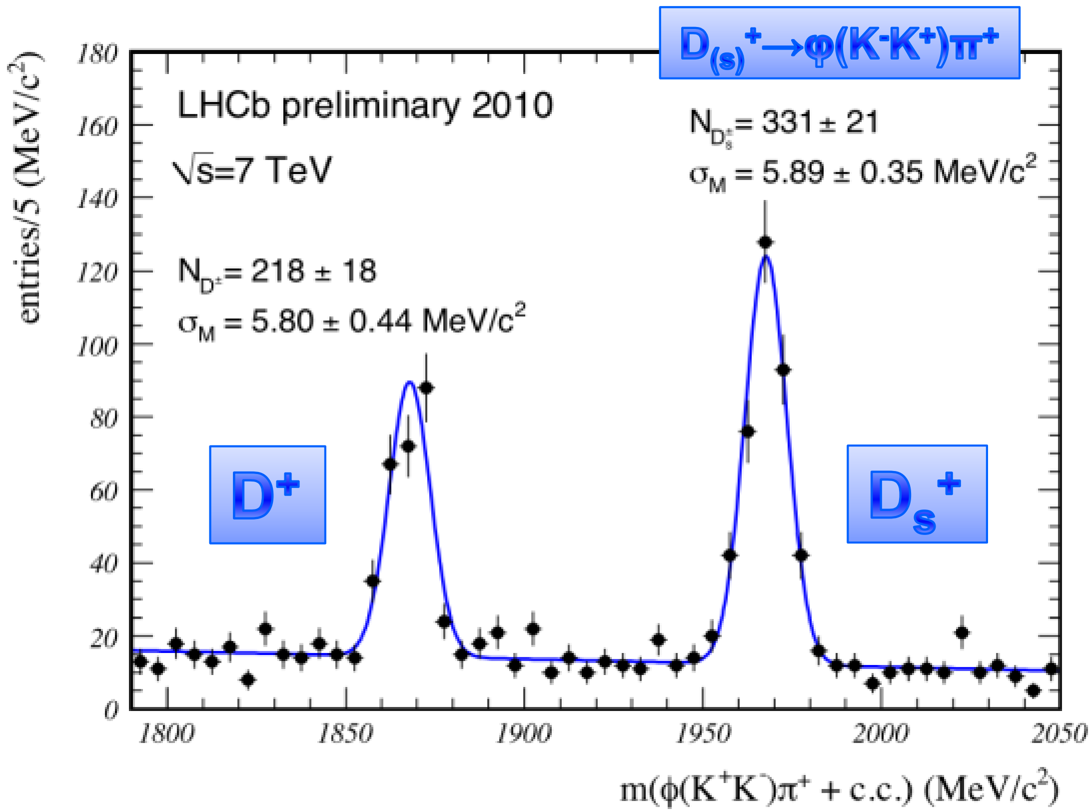


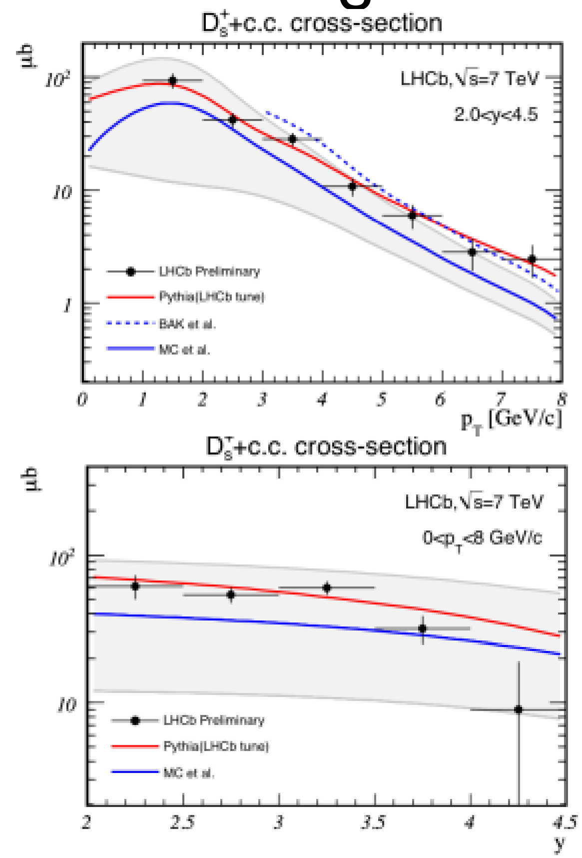
$\sigma(D^+;p_T<8\text{GeV/c},2<y<4.5)$=**717±39(stat.) ±26(uncorr.) ±98(corr.) μb**

$\sigma(D^+;p_T<8\text{GeV/c},2<y<4.5)$=**717±109μb**

PYTHIA prediction: $\sigma(D^+;p_T<8\text{GeV},2<y<4.5)$=**509±1 μb**

Cross-section results: D_s^+





$\sigma(D_s^+;p_T<8\text{GeV/c},2<y<4.5)=$**194±23(stat.) ±16(uncorr.) ±26 (corr.) μb**

$\sigma(D_s^+;p_T<8\text{GeV/c},2<y<4.5)=$**194±38μb**

PYTHIA prediction: $\sigma(D_s^+;p_T<8\text{GeV},2<y<4.5)=$**255±1 μb**

Cross-section results

- Cross-sections results in agreement with MC and theory predictions
- Calculating open charm cross-section for each analysis (in fitted pt and y range), and performing a least-squares fit to a constant:
  - $\sigma(pp\rightarrow H_c X, 2<y<4.5, p_T<8\,\mathrm{GeV}/c)=$**1.23±0.19mb**, $\chi^2/\mathrm{ndf}=$**2.28/3**
- Using PYTHIA to extrapolate to 4π, we obtain the following (preliminary) total open charm cross-section:
  - $\sigma(pp\rightarrow c\bar{c})=$**6.10±0.93mb**

$D^{*+} \rightarrow D^0(K^-3\pi)\pi^+$ selection cuts

- $-7.5 < \Delta m - (\Delta m)_{PDG} < 15 MeV/c^2$
- $|m_{D0} - m_{PDG}| < 75 MeV/c^2$
- D^* DOCA < 0.45mm
- D^0 DOCA < 0.5mm
- D^0 daughter p_T > 300MeV/c
- D^0 daughter p > 3GeV/c
- D^*/D^0 p_T > 3GeV/c
- Bachelor π p_T > 70MeV/c
- D^* vertex χ^2/d.o.f. < 20
- D^0 vertex χ^2/d.o.f. < 10
- D^0 daughter IP χ^2 > 1.7
- D^0 daughter max(IP χ^2) > 30
- D^0 FD χ^2 > 48
- D^0 IP χ^2 > 30
- D^0 DIRA > 0.9998
- Track χ^2/d.o.f. < 5
- Kaon Δln L(K-π) > 0
- Pion Δln L(π-K) > -3*

* No PID cut applied to bachelor π

$B^+ \to (K^+ 3\pi)_D K^+$ stripping cuts

Cut variable	B2DXWithDhh	B2DXWithD2hhhh
$B^{\pm}$ mass window	$\pm 500\ \mathrm{MeV}/c^2$	$\pm 500\ \mathrm{MeV}/c^2$
D^0 mass window	$\pm 100\ \mathrm{MeV}/c^2$	$\pm 100\ \mathrm{MeV}/c^2$
D^0 p_T	$> 1\,\mathrm{GeV}/c$	$> 2\,\mathrm{GeV}/c$
D^0 daughter $K^{\pm}$ p_T	$> 250\,\mathrm{MeV}/c$	$> 250\,\mathrm{MeV}/c$
D^0 daughter $\pi^{\pm}$ p_T	$> 250\,\mathrm{MeV}/c$	$> 150\,\mathrm{MeV}/c$
D^0 daughter π^0 p_T	—	—
Bachelor p_T	$> 500\,\mathrm{MeV}/c$	$> 500\,\mathrm{MeV}/c$
D^0 daughter $K^{\pm}$ $\lvert\vec{p}\rvert$	$> 2\,\mathrm{GeV}/c$	$> 3\,\mathrm{GeV}/c$
D^0 daughter $\pi^{\pm}$ $\lvert\vec{p}\rvert$	$> 2\,\mathrm{GeV}/c$	$> 2\,\mathrm{GeV}/c$
		—
Bachelor $\lvert\vec{p}\rvert$	$> 5\,\mathrm{GeV}/c$	$> 5\,\mathrm{GeV}/c$
$B^{\pm}$ IP χ^2	< 25	< 25
D^0 daughter $K^{\pm}$, $\pi^{\pm}$ sIP χ^2	> 4	> 4
max(D^0 daughter $K^{\pm}$, $\pi^{\pm}$ sIP χ^2)	> 40	> 40
Bachelor sIP χ^2	> 16	> 16
D^0 FD χ^2	> 36	> 36
$B^{\pm}$ DOCA	$< 1.5\,\mathrm{mm}$	$< 1.5\,\mathrm{mm}$
D^0 max(DOCA)	$< 1.5\,\mathrm{mm}$	$< 1.5\,\mathrm{mm}$
$B^{\pm}$ DIRA	> 0.9998	> 0.9998
D^0 DIRA	> 0.9	> 0.9
$B^{\pm}$ lifetime	$> 0.2\,\mathrm{ps}$	$> 0.2\,\mathrm{ps}$
$B^{\pm}$ vertex χ^2 / d.o.f.	< 12	< 12
D^0 vertex χ^2 / d.o.f.	< 12	< 10
D^0 daughter $K^{\pm}$, $\pi^{\pm}$ track χ^2 / d.o.f.	< 5	< 5
Bachelor track χ^2 / d.o.f.	< 5	< 5

$B^+ \to (K^+ 3\pi)_D K^+$

$B^+ \to (K^+ \pi^-)_D K^+$

$B^+ \to (K^+ 3\pi)_D K^+$ offline cuts

Cut name
Preselected candidates
$\geq$ 3 D^0 daughters with p_T > 240 MeV/c
$\geq$ 2 D^0 daughters with p_T > 400 MeV/c
≥ 3 D^0 daughters with sIP $\chi^2 > 16$
≥ 2 D^0 daughters with sIP $\chi^2 > 30$
$B^\pm$ IP $\chi^2 < 9$
Bachelor K sIP $\chi^2 > 28$
D^0 max(DOCA) < 0.3 mm
$B^\pm$ DOCA < 0.1 mm
$B^\pm$ FD $\chi^2 > 76$
D^0 FD $\chi^2 > 252$
$B^\pm$ DIRA > 0.99995
D^0 DIRA > 0.992
D^0 vertex $\chi^2/d.o.f. < 6$
D^0 daughter K $\Delta \ln L\,(K-\pi) > 0$
D^0 daughter π $\Delta \ln L\,(K-\pi) < 10$
Bachelor K $\Delta \ln L\,(K-\pi) > -2$
D^0 mass window = $\{-40, +30\}$ MeV/c^2

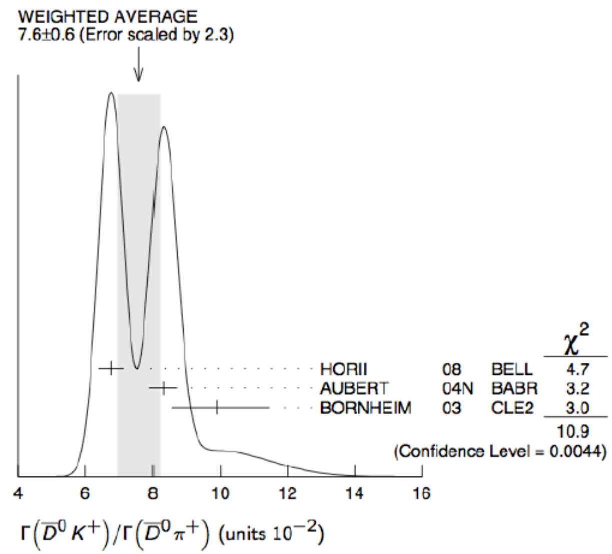
$B^+ \to (K^+ 3\pi)_D K^+$

Cut name
Preselected candidates
D^0 daughter $p_T > 330$ MeV/c
D^0 daughter sIP $\chi^2 > 21$
$B^\pm$ IP $\chi^2 < 9$
Bachelor K sIP $\chi^2 > 28$
D^0 max(DOCA) < 0.3 mm
$B^\pm$ DOCA < 0.1 mm
$B^\pm$ FD $\chi^2 > 76$
D^0 FD $\chi^2 > 252$
$B^\pm$ DIRA > 0.99995
D^0 DIRA > 0.992
D^0 vertex χ^2 / d.o.f. < 6
D^0 daughter K $\Delta \ln L\,(K-\pi) > 0$
D^0 daughter π $\Delta \ln L\,(K-\pi) < 10$
Bachelor K $\Delta \ln L\,(K-\pi) > -2$
D^0 mass window = $\{-40, +30\}$ MeV/c^2

$B^+ \to (K^+ \pi)_D K^+$

Measuring $B(B^- \to D^0 K^-)/B(B^- \to D^0 \pi^-)$

- Well measured by BaBar and Belle
- Ratio (approx.) the same for all final states
  - Currently considering Kπ, KK, ππ and K3π
- Can do a lot of the groundwork for measuring γ using channels with low sensitivity to the key parameters
  - Much work done to understand and fit our backgrounds
  - Fitter code blinded to γ, r_B and δ_B
- Currently finalising the results and determining systematic errors



PDG 2010:
K. Nakamura *et al.* (Particle Data Group), J. Phys. G **37**, 075021 (2010)