LHCb status of CKM γ from tree-level decays

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On behalf of the LHCb Collaboration

- The first LHCb results
- What's coming up
- Some promising approaches for the future

Discussing merits and challenges for each method

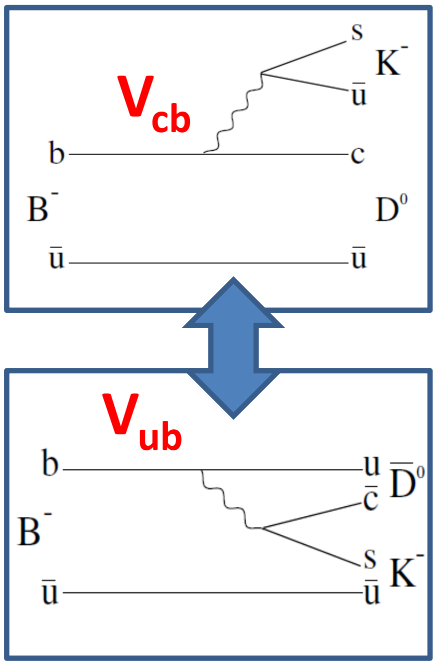
Implications of LHCb measurements and future prospects (CERN, April 16-18, 2012)

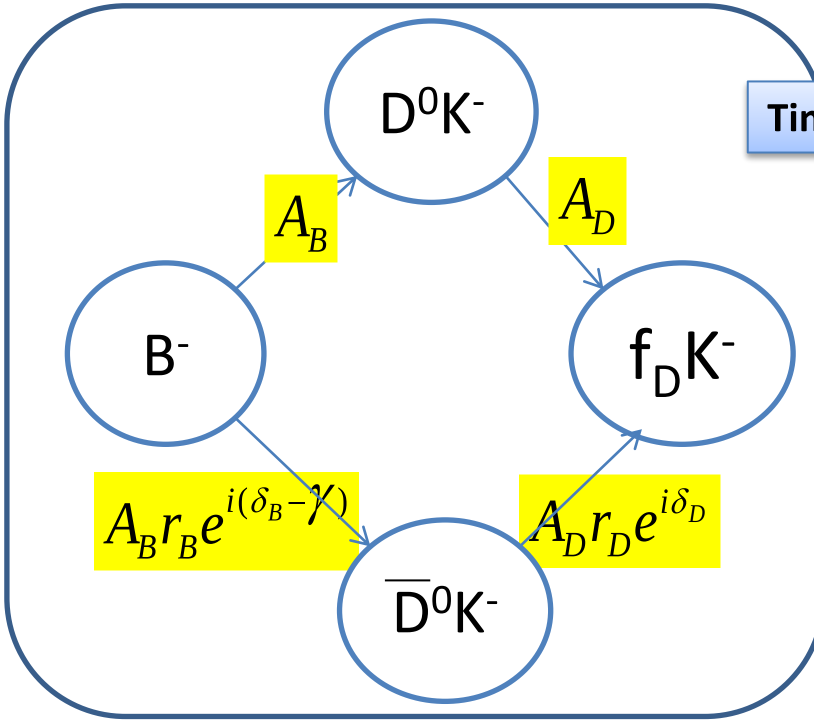
γ from trees: the principle

Interference between b→ c and b →u amplitudes in decays such as
$B^- \to D^0 K^-$ and $B^- \to \overline{D}^0 K^-$ when D^0 and $\overline{D}^0$ decay to common final state, f_D

- tree-level amplitudes only
- no penguin pollution, only one weak phase: γ

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





Time-Integrated (TI) methods

Other B and D hadronic parameters in play

r_B = relative magnitude of suppressed B-decay amplitude over favoured one

δ_B = *B*-decay strong phase difference

r_D and δ_D similarly defined

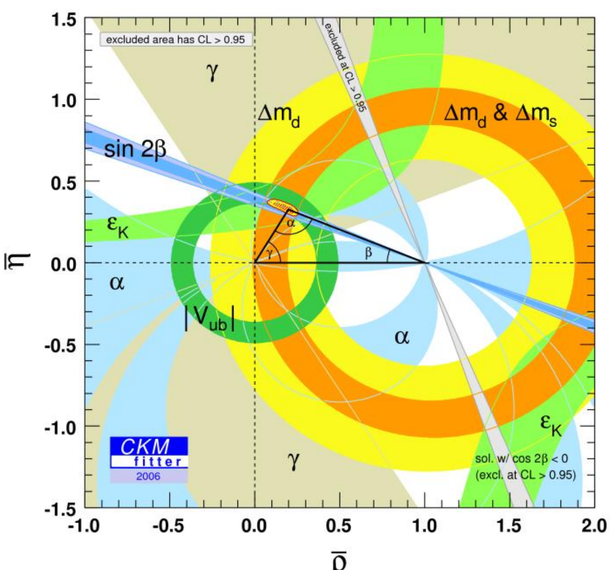
Several methods to extract γ and other hadronic parameters from data (both TI and Time-Dependent)

- Hence, in principle, no theoretical uncertainties
- In practice, γ extraction benefits from external measurements and/or model for the charm parameters

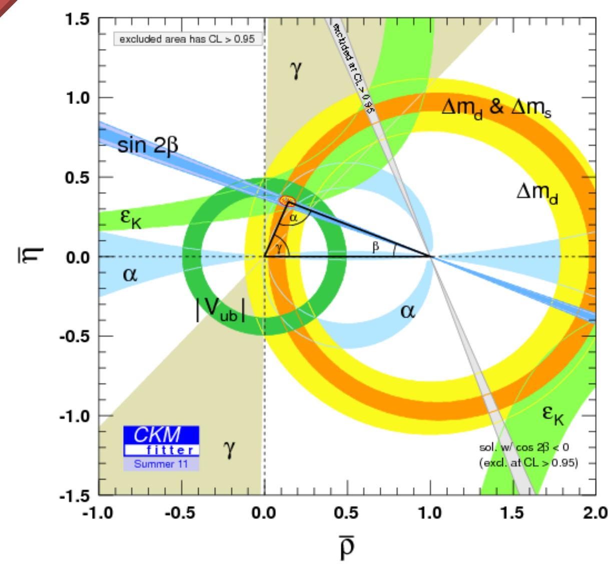
γ before the *LHCb era*

- Impressive achievements from B-factories, well beyond design:
  - thanks to excellent experimental performance, but also to introduction of new powerful methods and to progress in understanding of the charm system
- CDF has set the first constraints on γ at hadron collider, demonstrating the capability of making measurements with fully hadronic processes in a harsh environment

2006



2011



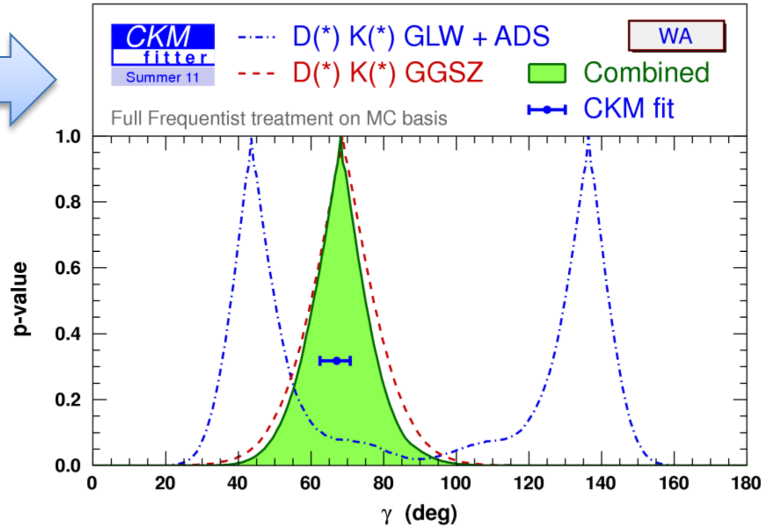
Huge progress over past five years

The case for γ from trees is unchanged and increasingly compelling

- Still a most-wanted SM reference required to unravel *increasingly subtle* NP effects
  - Tree-level determination largely insensitive to New Physics
- Still the most poorly measured angle of the UT $\gamma=68^{+10}_{-11}{}^\circ$ (CKMFitter, 2011)

Smallest theoretical uncertainty but largest experimental error among all UT constraints!

Precision dominated by $B^+ \to D(K_S h^+ h^-)K^+$ GGSZ measurements



GGSZ: D to 3-body decays

Giri, Grossman, Soffer, & Zupan, PRD 68, 054018 (2003)

Bondar, PRD 70, 072003 (2004)

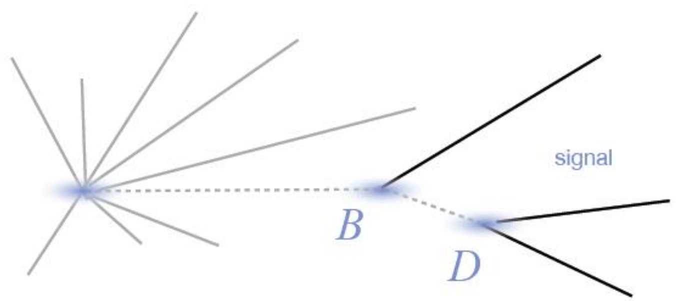
One phase, many trees, many methods for extracting γ

- Many additional methods at LHCb
  - **Large data sample** size opens up possibilities with other rarer but very sensitive modes where large asymmetries are expected (such as $B^0 \to DK^{0*}$)
  - **Excellent proper time-resolution** allows time-dependent analyses with fast oscillating B_s modes (e.g., $B_s \text{->} D_s K^+$)
  - **All b-hadrons species** are produced at LHC, including baryons, which will also contribute (e.g., $\Lambda_b \to D^0 \Lambda$)
- No method expected to dominate the sensitivity
  Redundancy will protect LHCb against malign choices of Nature (e.g., unlucky strong-phases).
- Final precision likely to be given by the combination of several methods

GLW : D to CP eigenstates
Gronau & London, PLB 253, 483 (1991);
Gronau & Wyler, PLB 265, 172 (1991)
ADS: D to CF and DCS quasi-flavour eigenstates
Atwood, Dunietz, & Soni, PRL 78, 3257 (1997),
Atwood, Dunietz, & Soni, PRD 63, 036005 (2001)

The dawn of the new era arXiv:1203.3662 sub. to PLB

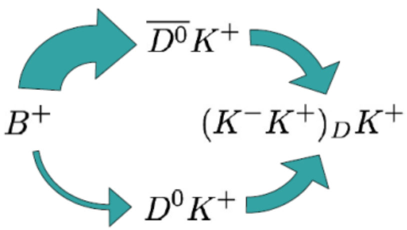
ADS/GLW results for $B^+ \to D(hh)K^+$



- **Main challenge:** Very small branching fractions of the sensitive modes (10^{-7})
- **Main merits**:
  - easiest topology $\Rightarrow$large efficiency
  - Time-Integrated methods: exploit full statistical power of large $b\bar{b}$ cross-section at LHC

GLW Observables

GLW: A_{CP+} and R_{CP+}



LHCb uses only D_CP+ eigenstates (K^+K^-, π^+,π^-)
2 observables:

CP asymmetry

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

Ratio
of partial widths

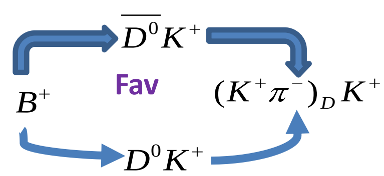
$$R_{CP+} = 2\frac{\Gamma(B^- \to D_{CP+}K^-) + \Gamma(B^+ \to D_{CP+}K^+)}{\Gamma(B^- \to D^0K^-) + \Gamma(B^+ \to \overline{D}^0K^+)} = 1 + r_B^2 + 2r_B\cos\delta_B\cos\gamma$$

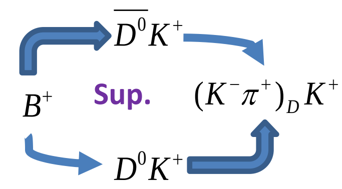
3 "unknowns": r_B, δ_B, and γ
$\Rightarrow$ Has to be combined with ADS method

ADS observables

ADS: A_{ADS} and R_{ADS}

LHCb uses $D^0 \to K^-\pi^+$ (CF) and $D^0 \to K^+\pi^-$ (DCS).
2 final states for each B charge





CP asymmetry for sup.

$$A_{ADS} = \frac{\Gamma(B^- \to D(K^+\pi^-)K^-) - \Gamma(B^+ \to D(K^-\pi^+)K^+)}{\Gamma(B^- \to D(K^+\pi^-)K^-) + \Gamma(B^+ \to D(K^-\pi^+)K^+)} = \frac{+2r_B r_D \sin(\delta_B + \delta_D)\sin\gamma}{r_B^2 + r_D^2 + 2r_B r_D \cos(\delta_B + \delta_D)\cos\gamma}$$

Ratio
of partial widths

$$R_{ADS} = \frac{\Gamma(B^- \to D(K^+\pi^-)K^-) + \Gamma(B^+ \to D(K^-\pi^+)K^+)}{\Gamma(B^- \to D(K^-\pi^+)K^-) + \Gamma(B^+ \to D(K^+\pi^-)K^+)} = r_B^2 + r_D^2 + 2r_B r_D \cos(\delta_B + \delta_D)\cos\gamma$$

Same 3 unknowns as GLW: r_B, δ_B, and γ
+ r_D and δ_D . Have to use external measurements:

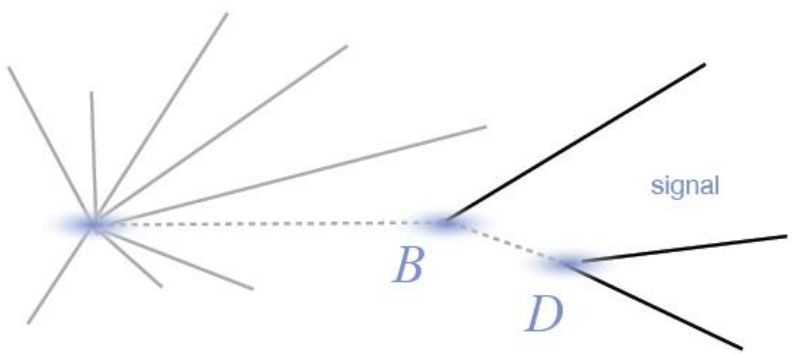
r_D ($K\pi$) = 0.0575 ± 0.0007
δ_D ($K\pi$)= 202.0 ± 11.2°

(HFAG averages)

$B^\pm \to Dh^\pm$ ($h=K,\pi$) analysis in brief

More details in recent CERN-EP seminar by M. John [https://indico.cern.ch/conferenceDisplay.py?confId=180554]

- $B^\pm \to DK^\pm$ ADS and GLW analyses simultaneously performed
- $B^\pm \to D\pi^\pm$ also included [yield 10x , much smaller interference]
- Select on bachelor PID (K/π) to separate $B^\pm \to DK^\pm$ from $B^\pm \to D\pi^\pm$

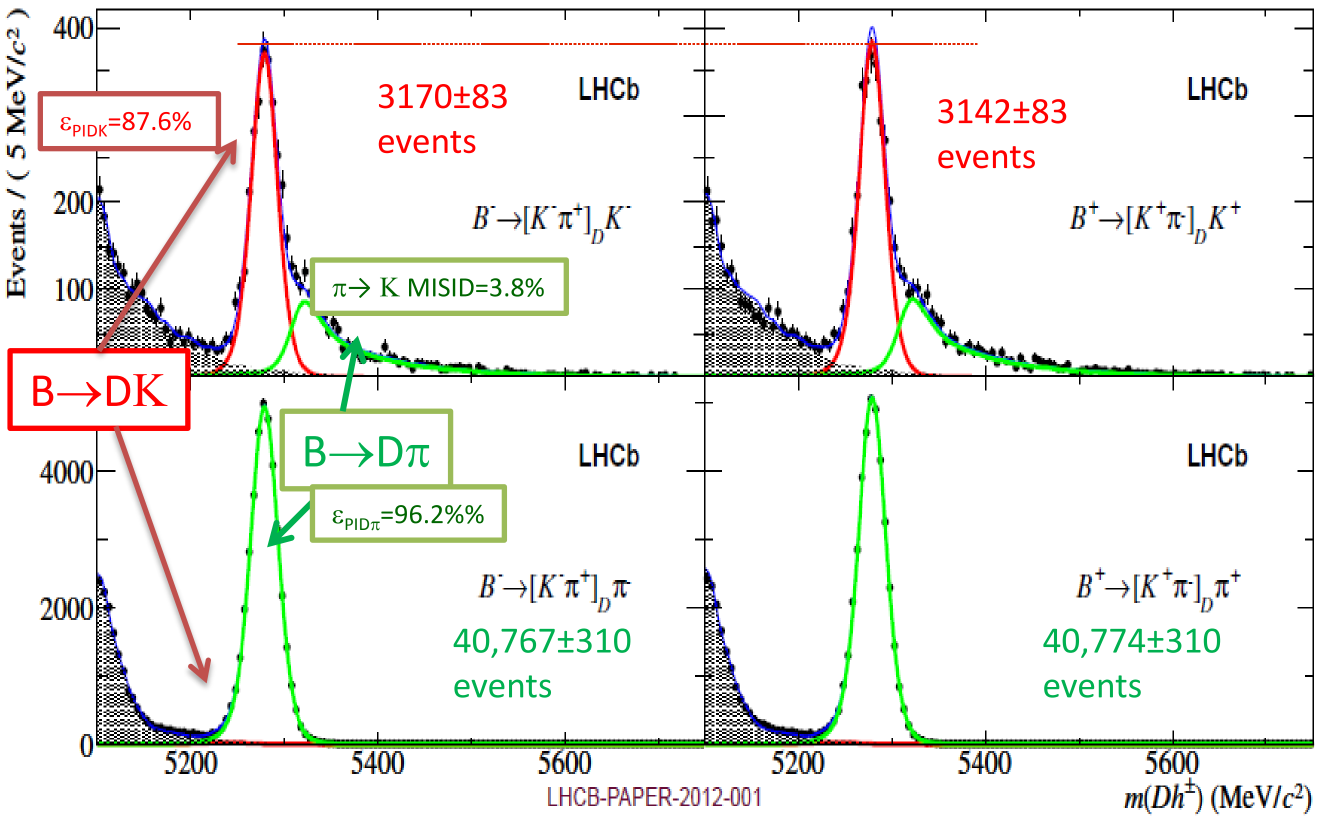


Crucial ingredients:
I. PID
II. Tracking and vertexing

- Simultaneous fit **16** independent data samples:
  = **2** (B charge, +/-)
  x **2** (bachelor ID, K/π)
  x **4** (D decays: $K\pi$ fav, $K\pi$ suppressed, KK, $\pi\pi$)

[~1/fb^{-1} , 2011 data]

$B^{\pm} \rightarrow D(K^{\pm}\pi^{-})h^{\pm}$ (favoured mode)



High signal yields

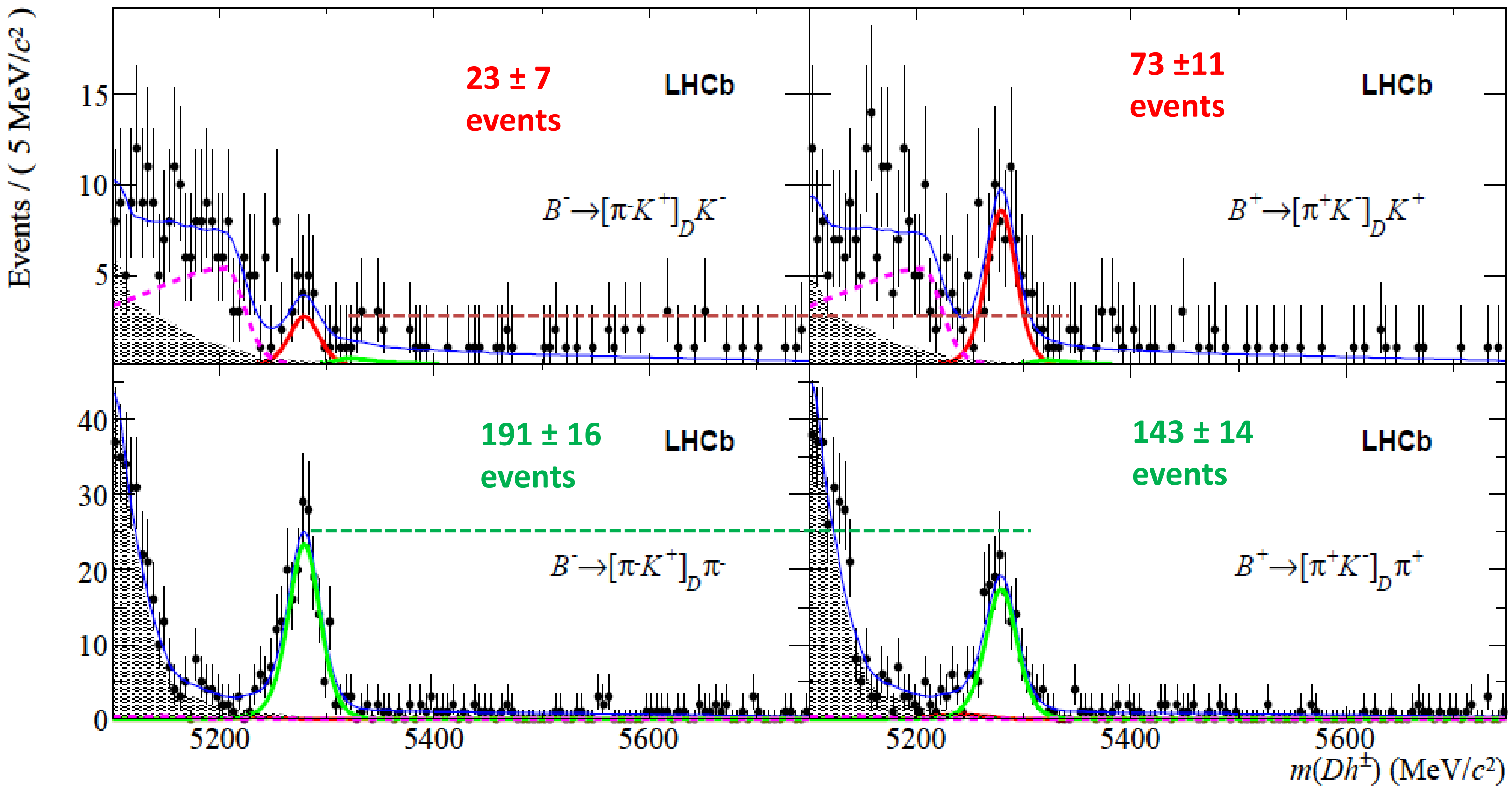
Low combinatorial level

Partially reconstructed decays contribute to low mass

Data-driven estimation of mis-ID component

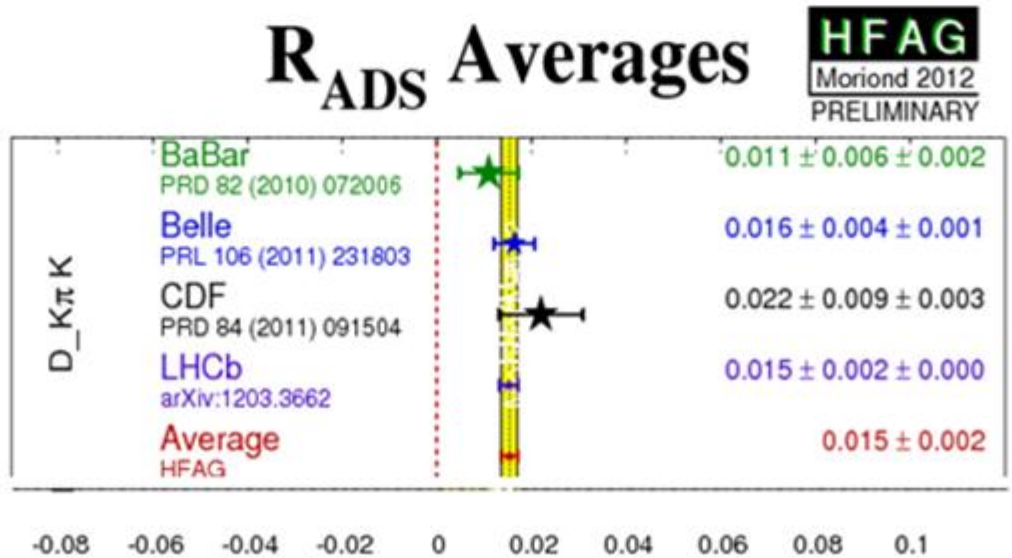
[~1 fb^{-1} , 2011 data]

$B^{\pm} \rightarrow D(K^{\mp}\pi^{+})h^{\pm}$ (suppressed mode)



Large negative asymmetry in DK: A_{ADS} (K)= (-52 ± 15 ± 2)% [4σ]

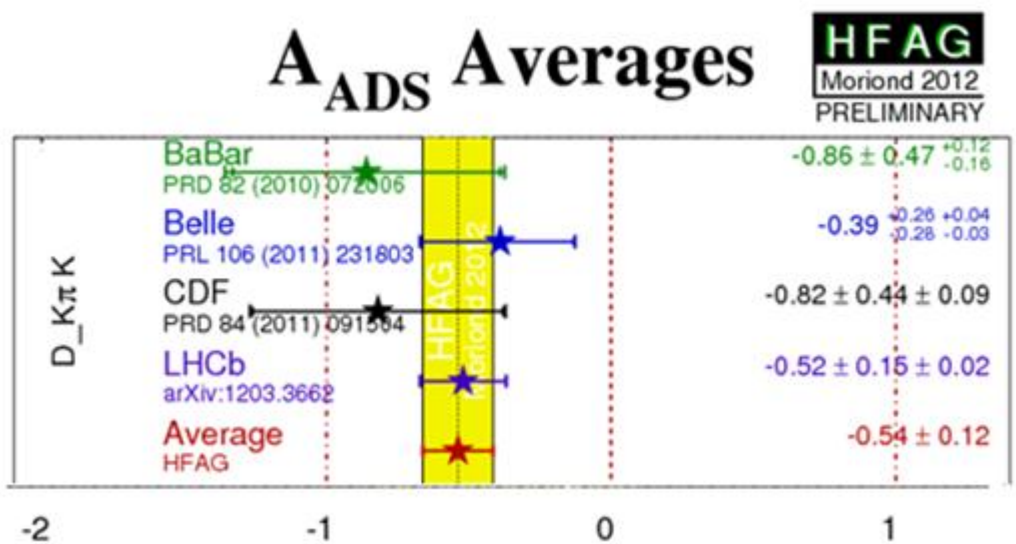
Hint of positive asymmetry in Dπ: A_{ADS} (π)= (14.3 ± 6.2 ± 1.1)% [2.4σ]



10σ

⇒ **Important to constrain r_B**

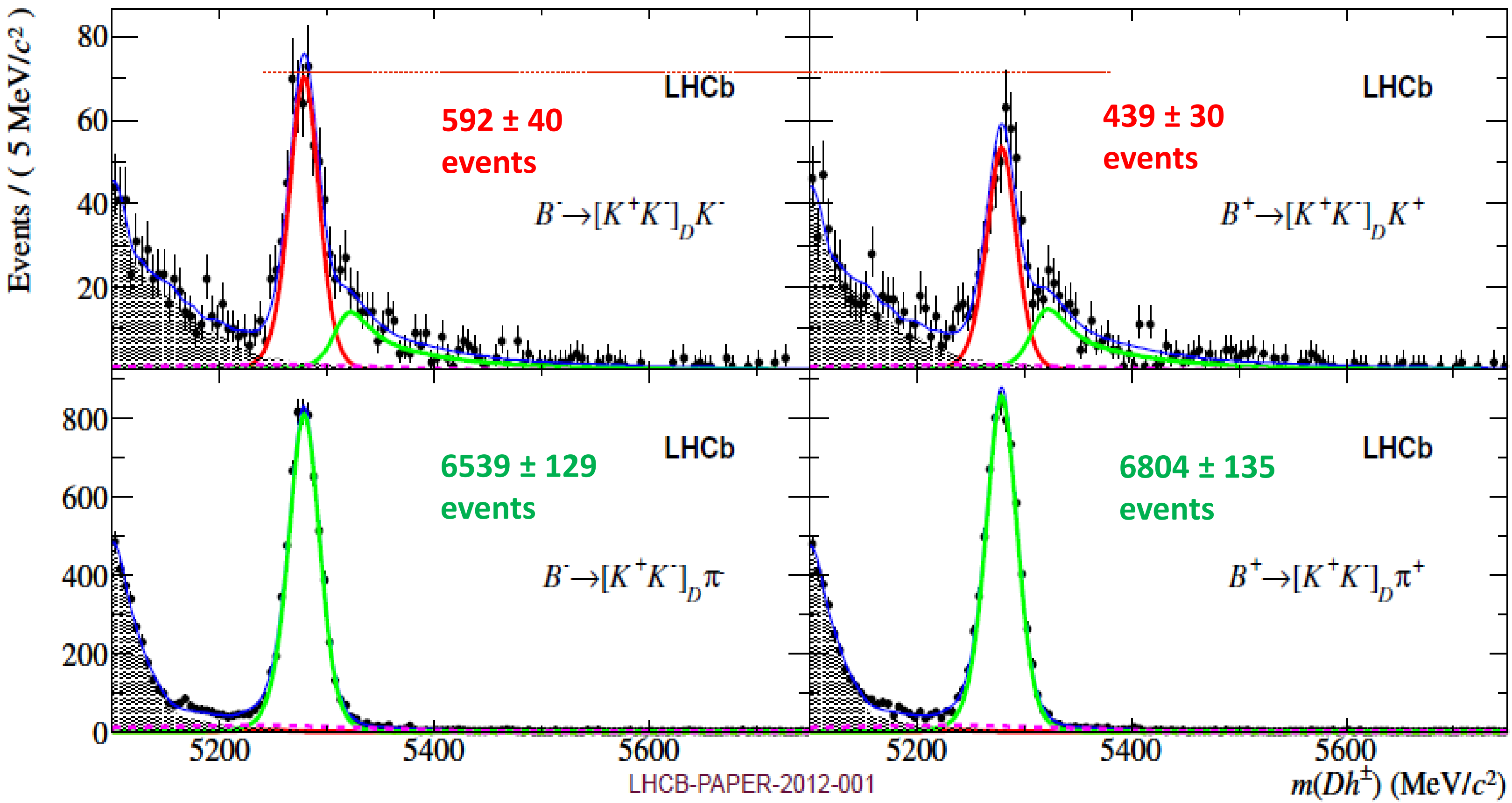
$$R_{ADS} = r_B^2 + r_D^2 + 2 r_B r_D \cos(\delta_B + \delta_D) \cos\gamma$$



4σ

[~1 fb^{-1} , 2011 data]

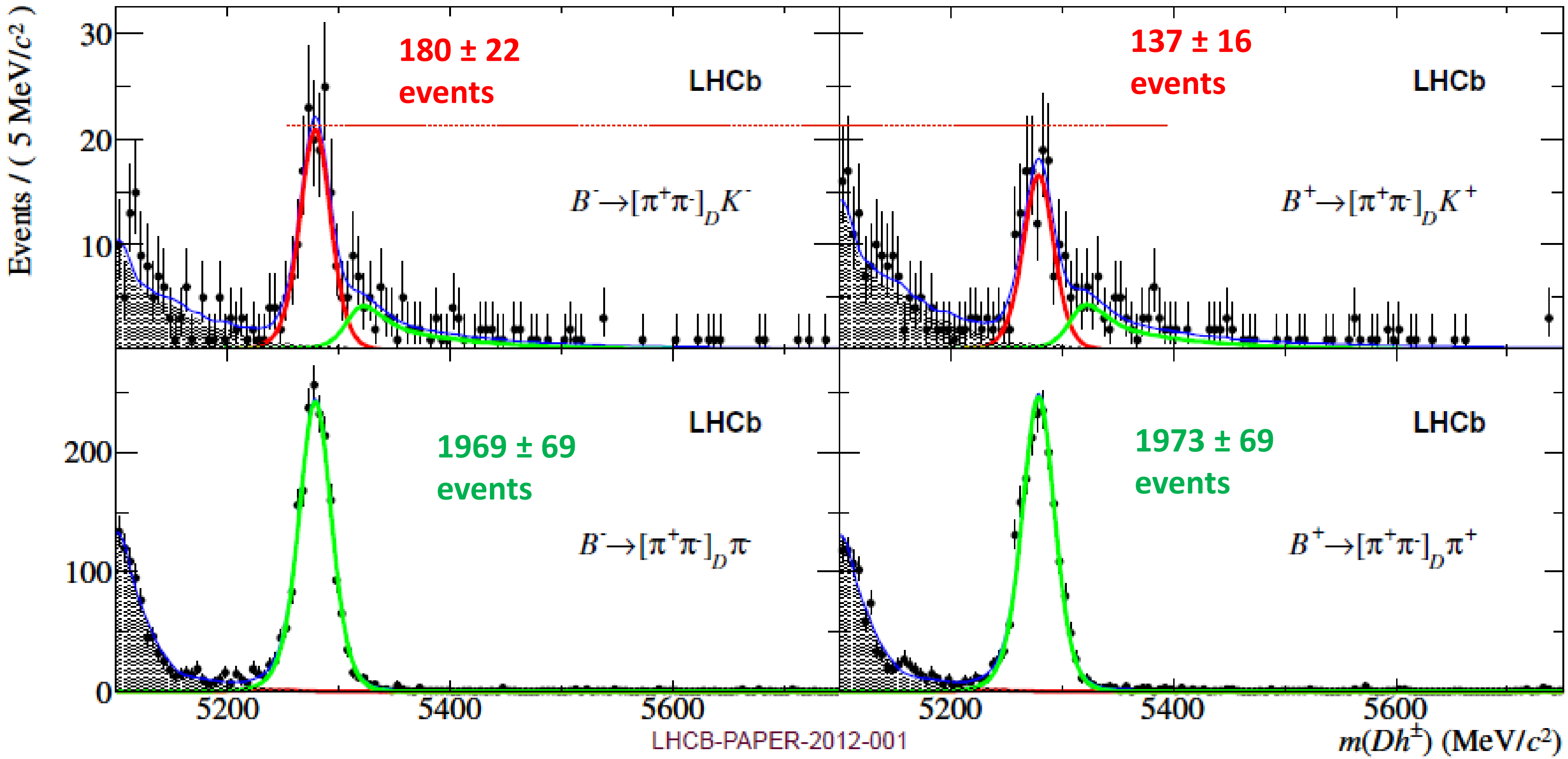
$B^{\pm} \rightarrow D(K^{+}K^{-})h^{\pm}$



A_{CP+} (KK)= (-14.8 ± 3.7 ± 1.0)%

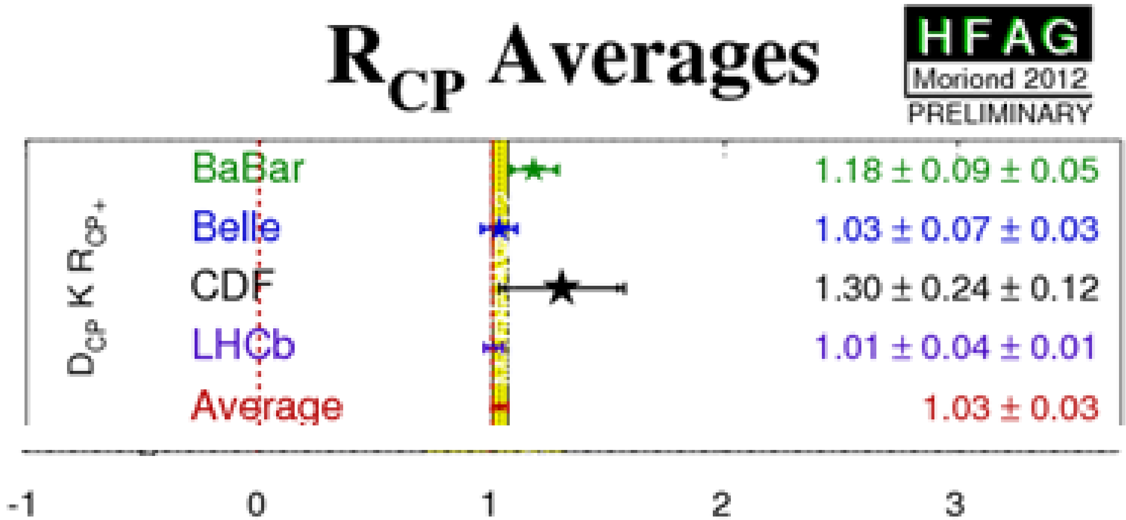
[~1 fb^{-1} , 2011 data]

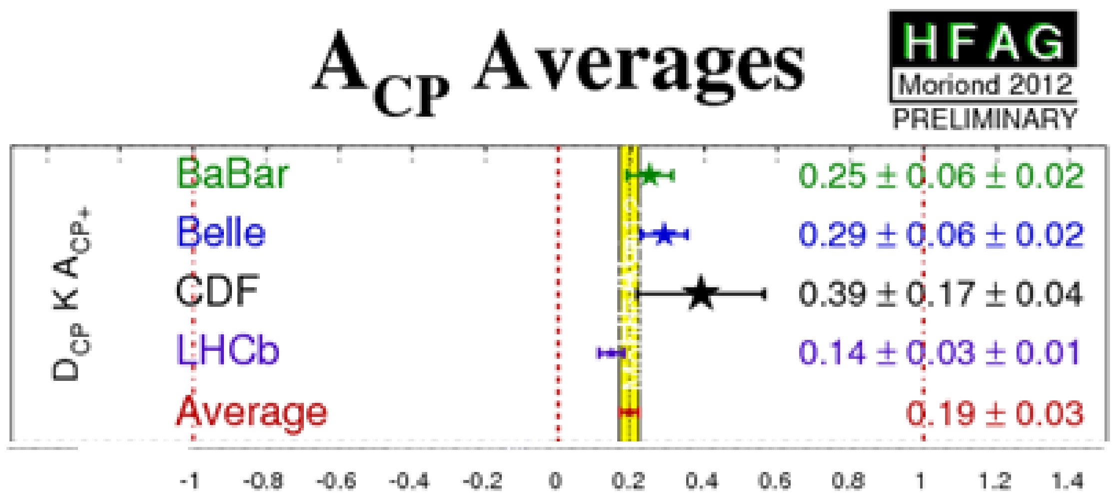
$B^{\pm} \rightarrow D(\pi^+\pi^-)h^{\pm}$



A_{CP+} $(\pi\pi)$= (-13.5 ± 6.6 ± 1.0)%

GLW Results



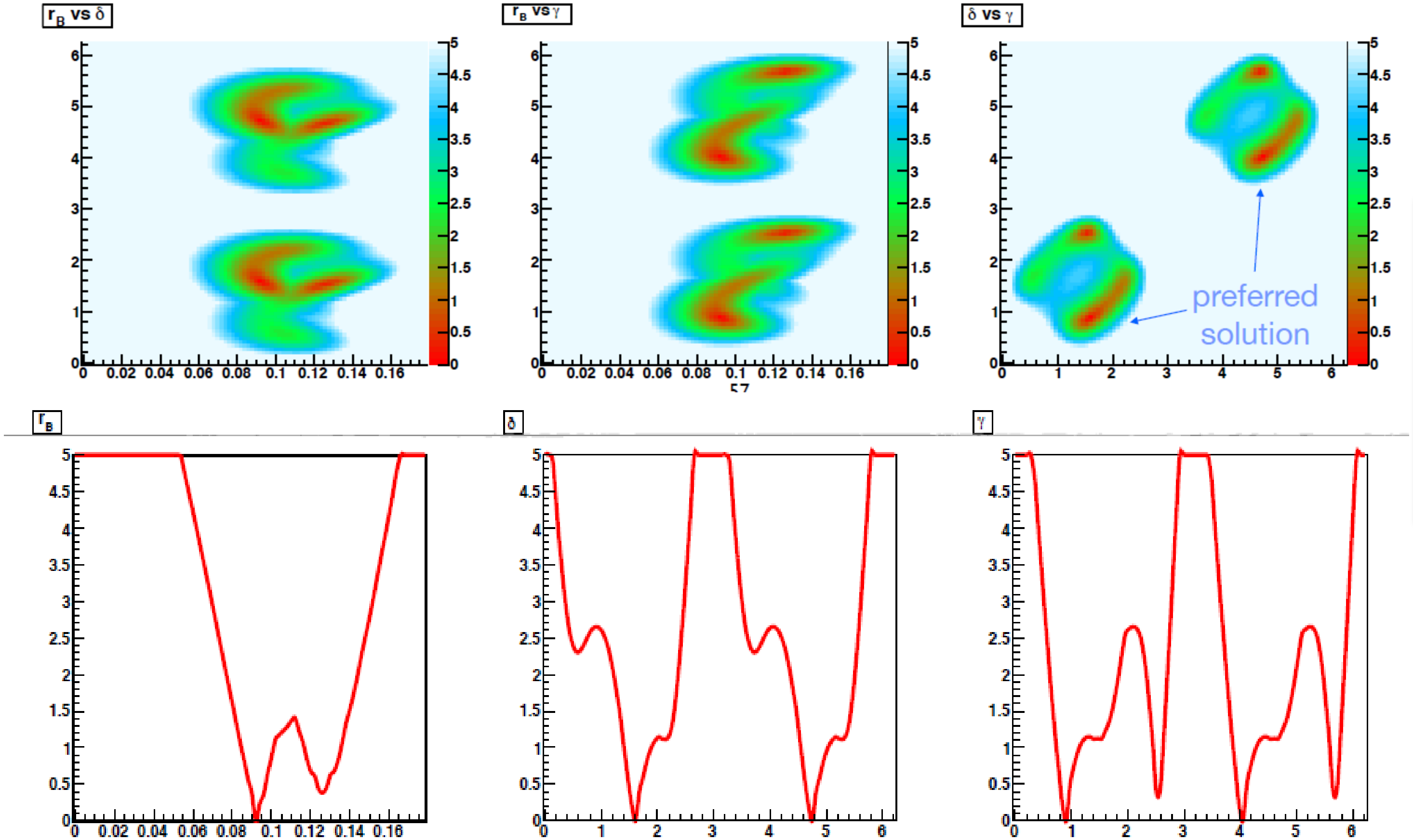


KK and ππ combined

4.5σ

What about γ?

Multiple ambiguities in the extraction of all unknowns=> most stringent constraints on ADS/GLW parameters do not translate immediately in the most stringent constraints on gamma



For illustration purposes only:
- Correlations not taken into account;
- Uncertainty on δ_D ignored

Nice constraint on r_B

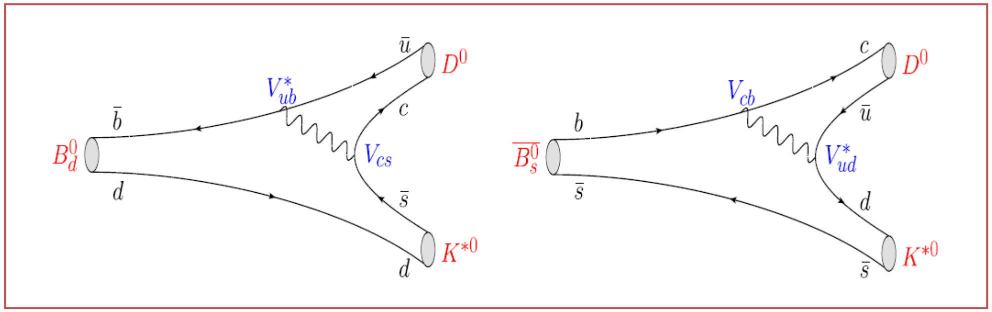
Coming soon..

ADDITIONAL MEASUREMENTS FROM "CLASSIC" METHODS

Towards a ADS/GLW measurement with $B^0 \to D^0(hh)K^{*0}$

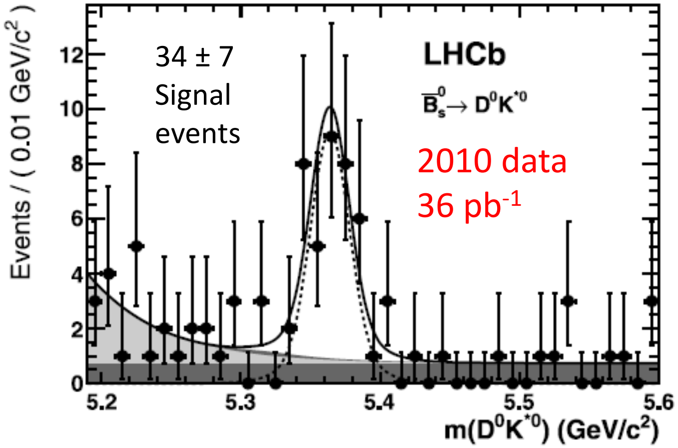
Self-tagged . TI analysis similar to $B^+ \to D(hh)K^+$. Larger r_B (3x) $\Rightarrow$ larger interference effects
Interfering diagrams both colour suppressed $\Rightarrow$ Low yields

$B_d \to D^0K^{*0}$ **$B_s \to D^0K^{*0}$**



First step: measurement of $B_s \to DK^{*0}$ B.F.

Favoured B_s ADS mode and sensitive suppressed B_d mode share same final state :
B_s fav. yield ~ 20 X B_d sup.
Merit: small $r_B(B_s)$, no interference,
good as control sample and normalisation
Challenge: background,
In addition $B_s \to D^{*0}K^{*0}$ (main challenge!)



LHCb, PLB 706 (2011) 32, arXiv:1110.3676

$$\mathcal{B}(\overline{B}_s^0 \to D^0K^{*0}) = (4.72 \pm \underset{stat.}{1.07} \pm \underset{syst.}{0.48} \pm \underset{f_s/f_d}{0.37} \pm \underset{\text{From B.F. } B\to D\rho}{0.74}) \times 10^{-4}$$

- Mode can be efficiently reconstructed
- Good B_d/B_s separation, low combinatorial
- Progressing towards GLW/ADS analysis with 2011 data
- Expect ~300 events from B_d favoured ADS decay in 1fb^{-1}

GGSZ: γ from $B^+ \to D(K_S h^+ h^-)K^+$

Exploit different interference pattern over *D-Dalitz* plots from B^+ and B^- decays:

requires an amplitude fit and a model for D decay

or external input on δ_D over the Dalitz plane (available from CLEO-c) for a model-independent approach

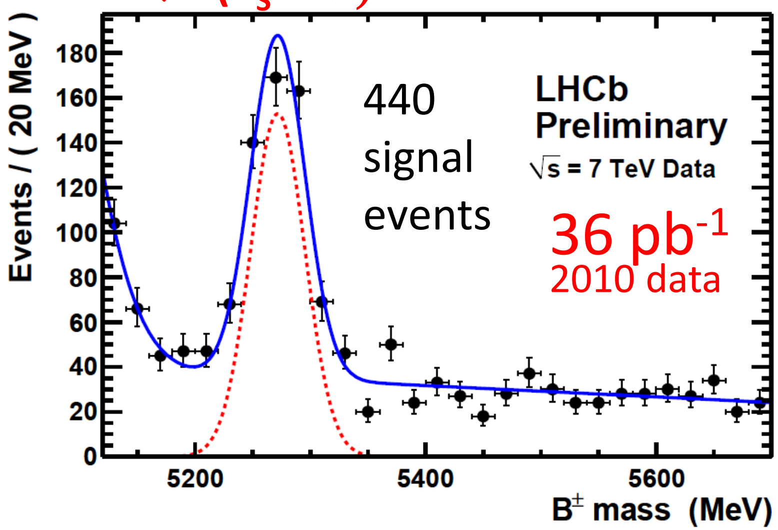
Two approaches: unbinned model-dependent and binned model-independent pursued in parallel at LHCb

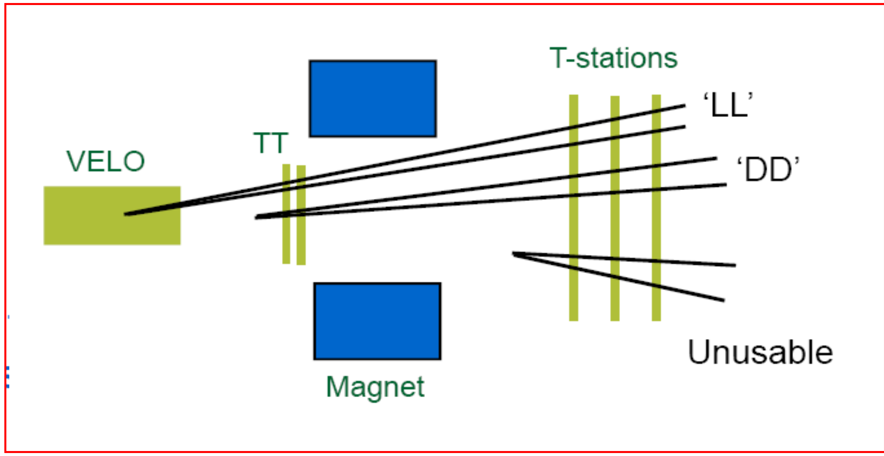
Specific LHCb challenge for this decays :

K_s reconstruction

2/3 decay downstream (DD) of vertex detector
(but have hits in downstream tracker stations)

$B^+ \to D(K_S \pi^+ \pi^-)\pi^+$





$B^+ \to D(K_S h^+ h^-)K^+$

Expect ~600 events in 1/fb

(roughly half size wrt Belle)

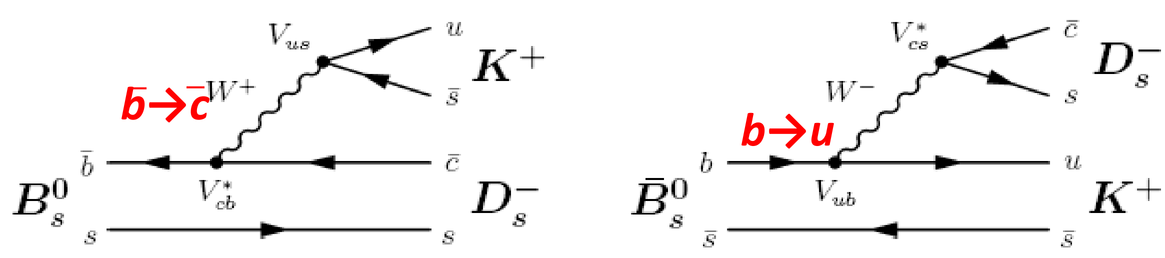
First CP results in the summer

Stefania Ricciardi
CLEO-c input to gamma

$B_s \to D_s K$: time-dependent analysis

Sensitive to $\gamma + \phi_s$

Both colour allowed transition: large interference expected



- 4 time-dependent rates:
  - $B_s \to D_s^+ K^-$
  - $\bar{B}_s \to D_s^+ K^-$
  - $B_s \to D_s^- K^+$
  - $\bar{B}_s \to D_s^- K^+$
- 2 CP-asymmetries

Crucial:

-**proper time resolution** ~50 fs

adequate to resolve fast Bs oscillation

-**Tagging power:** LHCB-CONF-2011-050

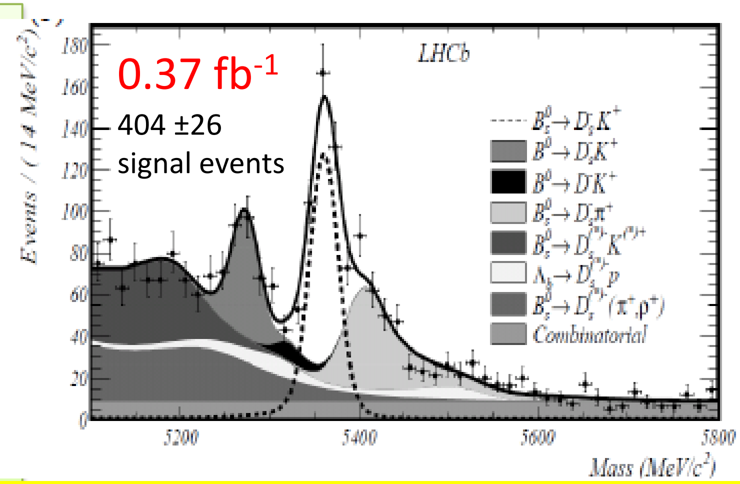
-opposite side tagger $\varepsilon D^2 = 3.2 \pm 0.8\%$

-additional power from same- side tagger

First step: PLB 709 (2012) 177, arXiv: 1112.4311 (36 pb^{-1})

precise determination of Δm_s from $B_s \to D_s \pi$

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



NEW measurement of the branching fraction (arXiv 1204.1237)

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

Stat. Syst. From f_s/f_d

$$B^- \to D^0 K^-$$

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

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

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

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

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

$$B_s \to D_s^{\mp} K^{\pm} \pi^+ \pi^-$$

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

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

Not exhaustive list

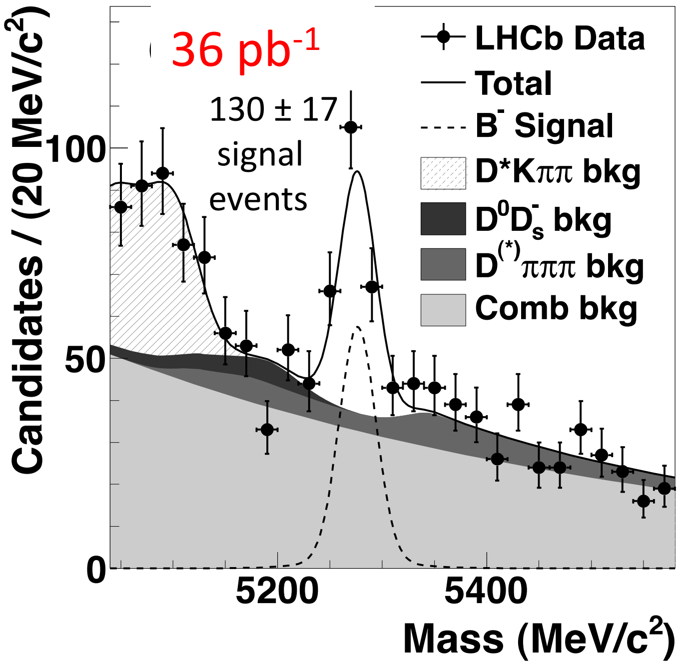
$$\Lambda_b \to D^0 p K^-$$

Longer term

MORE MULTI-BODY MODES

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

Efficient reconstruction in high track-multiplicity modes



First observation (9σ) of Favoured “ADS” mode

arXiv:1201.4402

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

Expect ~2k signal events
in 2011 data 1 fb^{-1}
[~1/3 of $B^- \to D(K^-\pi^+)K^-$]

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

Variation of B hadronic parameters over phase-space

$\Rightarrow$ **different approaches for extracting γ :**

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

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

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

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

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

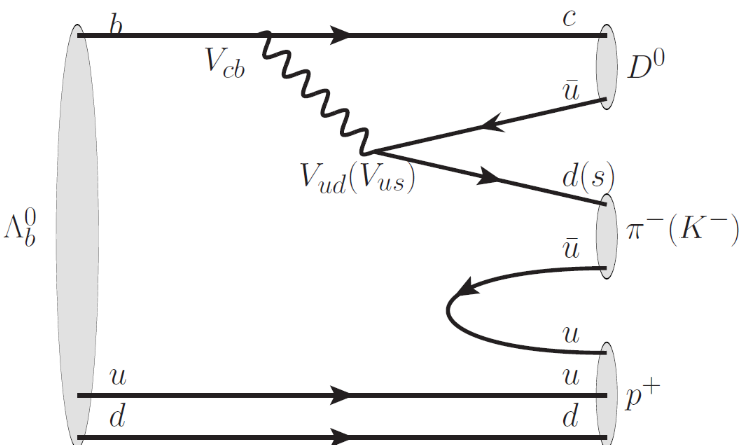
κ =1 in the two-body limit – one single resonance contributing

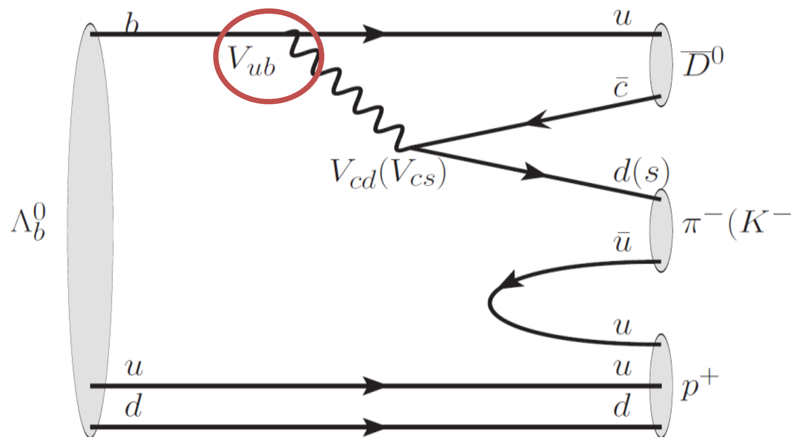
[PLB 557 198 (2003)]

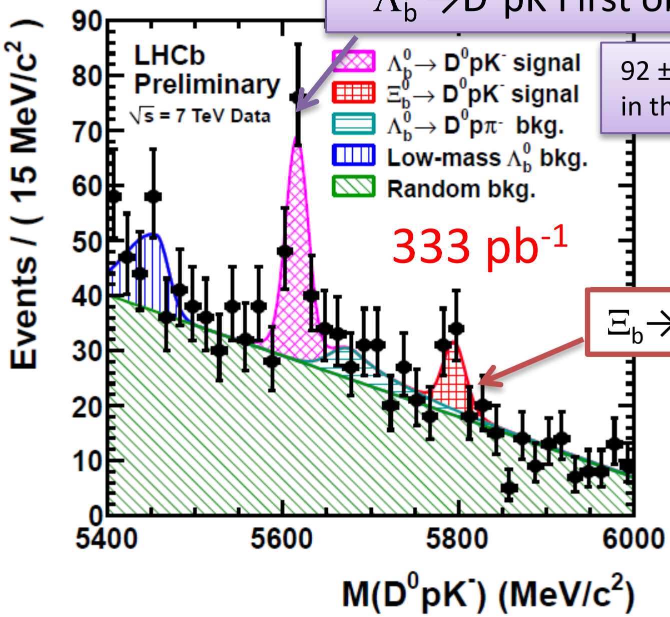
- **Amplitude analysis**
- **Binned:** Quasi-two body approach in high-coherent bins of the 4-body phase-space

$\Lambda_b \rightarrow D^0 p h^-$ ($h=\pi,K$)

[LHCb-CONF-2011-036]







$\Lambda_b \rightarrow D^0pK$ First observation (6σ)

92 ± 15 signal events in the favoured $D^0(K\pi)$

$\Xi_b \rightarrow D^0pK$: 2.6σ

$\Lambda_b \rightarrow D^0 pK$

Enhances sensitivity of $\Lambda_b \rightarrow D^0\Lambda$ originally proposed by I.Dunietz Z.Phys C56(1992) 129

- No long-lived V^0
- Exploit full 3-body phase space

Dalitz plot analysis to extract γ without ambiguities

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

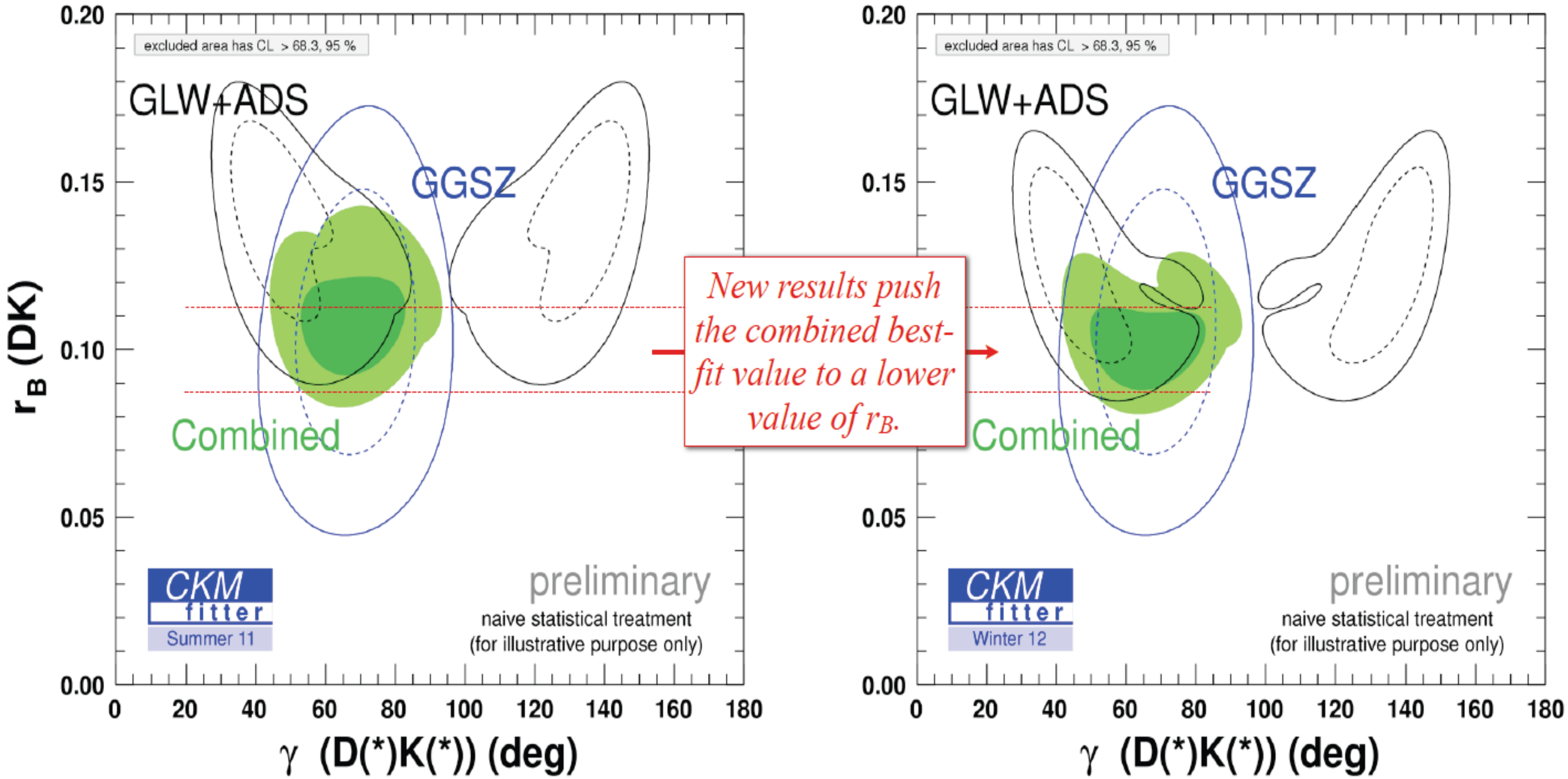
Conclusions

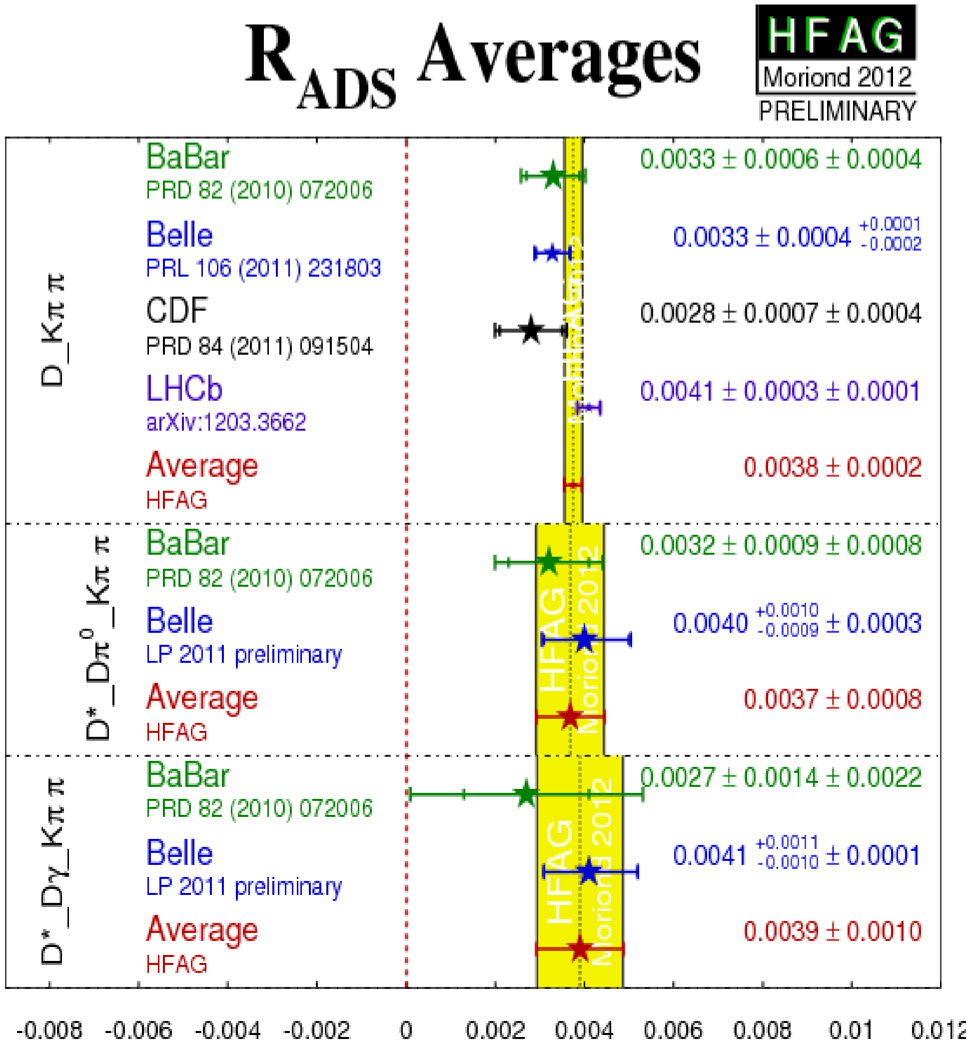
A new era for γ has just started at LHCb!

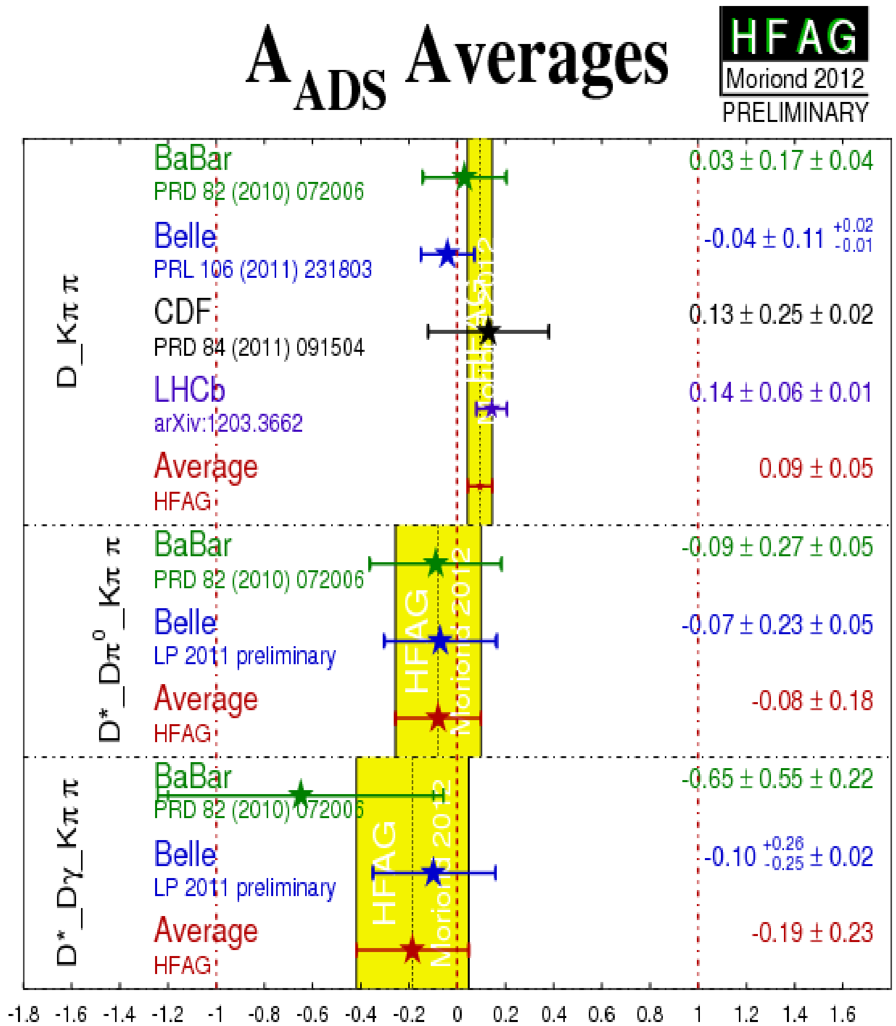
- Recent results from simultaneous GLW/ADS analysis with $B^+ \rightarrow DK^+$
  - Observation of ADS sensitive mode firmly established (10 σ)
  - First observation of direct CPV in GLW and ADS (5.8 σ, combined)

  Important milestone towards a precise determination of γ at LHCb
- Analyses for many other promising decay modes under way. First step: results on branching ratios.
- High reconstruction efficiency and high purity even for modes with high track multiplicity.
- No single method dominates sensitivities. Precision from combination of several modes.
- Expect LHCb to improve on B-factory precision with 2011+2012 data-set.

ADDITIONAL MATERIAL


excluded area has CL > 68.3, 95 %
GLW+ADS
GGSZ
Combined
CKM fitter
Summer 11
preliminary
naive statistical treatment
(for illustrative purpose only)
r_B (DK)
γ (D(*)K(*)) (deg)
New results push the combined best-fit value to a lower value of r_B.
excluded area has CL > 68.3, 95 %
GLW+ADS
GGSZ
Combined
CKM fitter
Winter 12
preliminary
naive statistical treatment
(for illustrative purpose only)
γ (D(*)K(*)) (deg)


R_ADS Averages
HFAG
Moriond 2012
PRELIMINARY
D_Kπ π
BaBar
PRD 82 (2010) 072006
0.0033 ± 0.0006 ± 0.0004
Belle
PRL 106 (2011) 231803
0.0033 ± 0.0004 +0.0001 -0.0002
CDF
PRD 84 (2011) 091504
0.0028 ± 0.0007 ± 0.0004
LHCb
arXiv:1203.3662
0.0041 ± 0.0003 ± 0.0001
Average
HFAG
0.0038 ± 0.0002
D*_Dπ0_Kπ π
BaBar
PRD 82 (2010) 072006
0.0032 ± 0.0009 ± 0.0008
Belle
LP 2011 preliminary
0.0040 +0.0010 -0.0009 ± 0.0003
Average
HFAG
0.0037 ± 0.0008
D*_Dγ_Kπ π
BaBar
PRD 82 (2010) 072006
0.0027 ± 0.0014 ± 0.0022
Belle
LP 2011 preliminary
0.0041 +0.0011 -0.0010 ± 0.0001
Average
HFAG
0.0039 ± 0.0010
-0.008 -0.006 -0.004 -0.002 0 0.002 0.004 0.006 0.008 0.01 0.012


A_ADS Averages
HFAG
Moriond 2012
PRELIMINARY
D_Kπ π
BaBar
PRD 82 (2010) 072006
0.03 ± 0.17 ± 0.04
Belle
PRL 106 (2011) 231803
-0.04 ± 0.11 +0.02 -0.01
CDF
PRD 84 (2011) 091504
0.13 ± 0.25 ± 0.02
LHCb
arXiv:1203.3662
0.14 ± 0.06 ± 0.01
Average
HFAG
0.09 ± 0.05
D*_Dπ0_Kπ π
BaBar
PRD 82 (2010) 072006
-0.09 ± 0.27 ± 0.05
Belle
LP 2011 preliminary
-0.07 ± 0.23 ± 0.05
Average
HFAG
-0.08 ± 0.18
D*_Dγ_Kπ π
BaBar
PRD 82 (2010) 072006
-0.65 ± 0.55 ± 0.22
Belle
LP 2011 preliminary
-0.10 +0.26 -0.25 ± 0.02
Average
HFAG
-0.19 ± 0.23
-1.8 -1.6 -1.4 -1.2 -1 -0.8 -0.6 -0.4 -0.2 0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6