γ at hadronic machines

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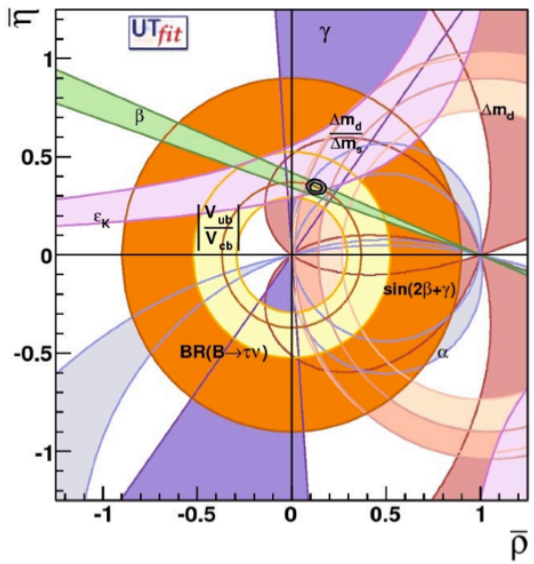
INFN Bologna

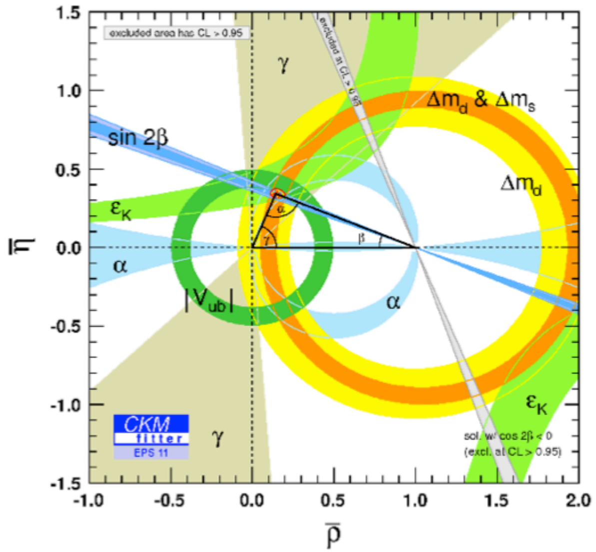
8th meeting on B physics
Genova, 6 February 2012

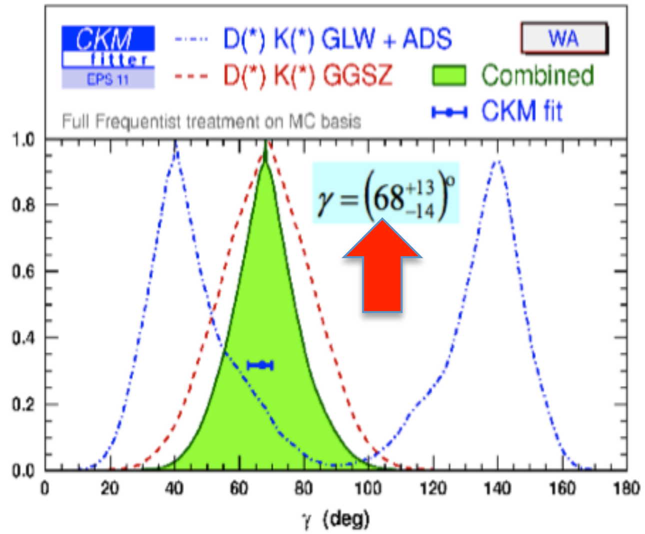
Outline

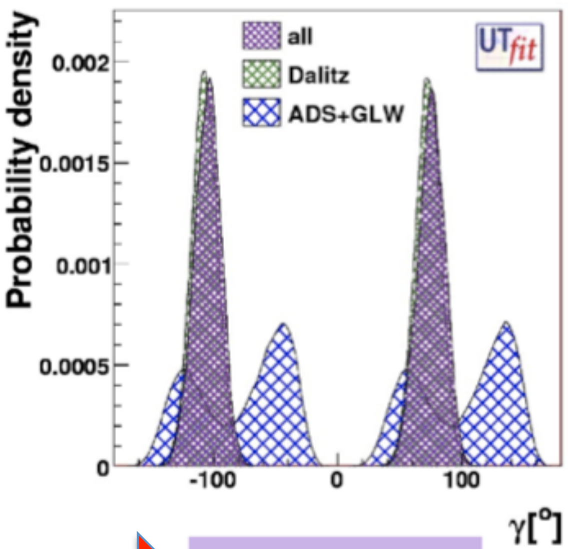
- Why γ at hadron colliders?
- Various paths to the quest of γ
  - time-integrated tree level: ADS, GLW, GGSZ
  - time-dependent tree level: $B_s \rightarrow D_s K$
  - time-dependent with penguins: $B^0 \rightarrow \pi^+\pi^-$, $B_s \rightarrow K^+K^-$
- Will basically cover γ at LHCb
  - for CDF see Michael Morello's talk
- A look into the future

Why γ?









$\gamma = (76 \pm 11)^o$

- **Experimental uncertainty on γ still large**
  - → **less constrained amongst the UT angles**
- **Tree level allows for a NP-free determination**
  - → **building block for any UT fit beyond the SM**

Note that today UTfit and CKMfitter roughly agree on the size of the overall experimental uncertainty

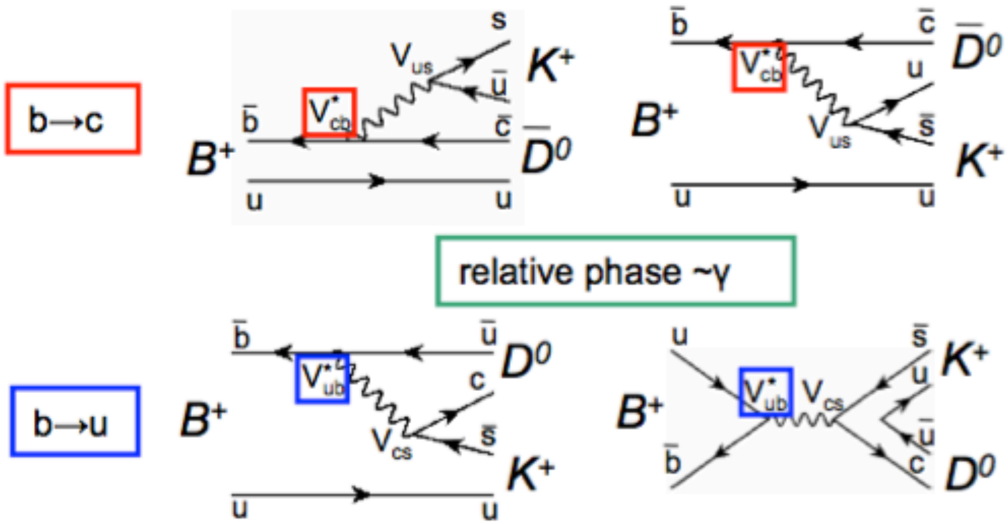
And why at hadron colliders?

- Measurements from B factories limited by statistics
  - dominated by GGSZ analysis
- No tagging required for time-integrated analyses
  - Full power of large beauty cross section in hadronic collisions can be exploited!
  - Ideal measurement for hadronic machines, provided that signals with good purity can be triggered and reconstructed
- Hadron colliders also give exclusive access to time-dependent study of $B_s \to D_s K$ decays

	$\sigma(b\bar{b})$	$\sigma(\text{inel})/\sigma(bb)$	$\int L dt$
CDF	~ 100 mb	1000	~10fb^{-1}
LHCb	~290 mb	~300	~1fb^{-1} (end of 2011)
BaBar BELLE	~1 nb	~4	425 fb^{-1} (BaBar) 700 fb^{-1} (BELLE)

γ from B→D$^{(*)}$K$^{(*)}$

Interference between b→u and b→c transistions



Favoured

$$A(B^- \to D^0 K^-) = A_B$$

$$A(B^+ \to \overline{D}^0 K^+) = A_B$$

Suppressed

$$A(B^- \to \overline{D}^0 K^-) = A_B r_B e^{i(\delta_B - \gamma)}$$

A_B strong amplitude

$$\delta_B = \delta_1 - \delta_2$$

strong phase difference between V_{ub} and V_{cb} mediated transitions

Related variables (depend on the *B* meson decay channel):

$$r_B = \frac{|A_{b\to u}|}{|A_{b\to c}|}$$

- $r_B \sim 0.1$ For charged *B* mesons
- $r_B \sim 0.3$ For neutral *B* mesons

δ_B strong phase (*CP* conserving)

r_B is a crucial parameter - the sensitivity on γ depends on it

Gronau-London-Wyler (GLW)

- In the GLW method the D meson is reconstructed into a CP eigenstate $D^0, \overline{D}^0 \to K^+K^-, \pi^+\pi^-, K_S^0\pi^0, K_S^0\omega, K_S^0\phi$

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

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

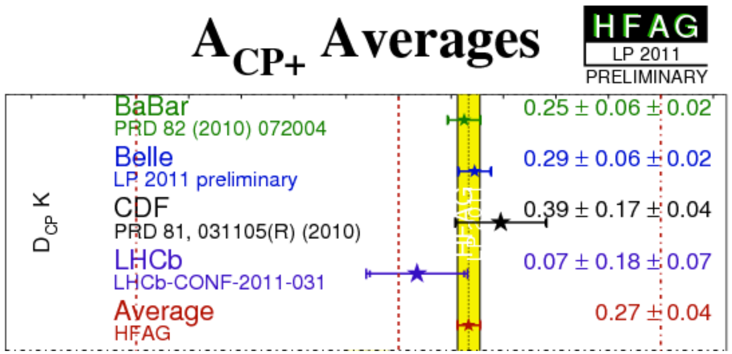
M.Gronau,D.London,D.Wyler,PLB253,483(1991);PLB 265,172(1991)

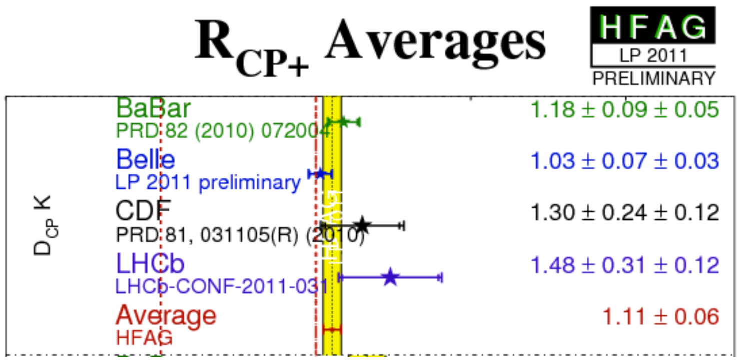
- Neutral modes challenging at hadron colliders
  - BaBar, Belle, CDF and LHCb all use the CP even D decays to K^+K^- and $\pi^+\pi^-$, while BaBar and Belle also study the CP odd D decays to $K_S\pi^0$, $K_S\omega$ and $K_S\phi$
- Can also be done with $B^0 \to D_{CP\pm}K^{*0}$

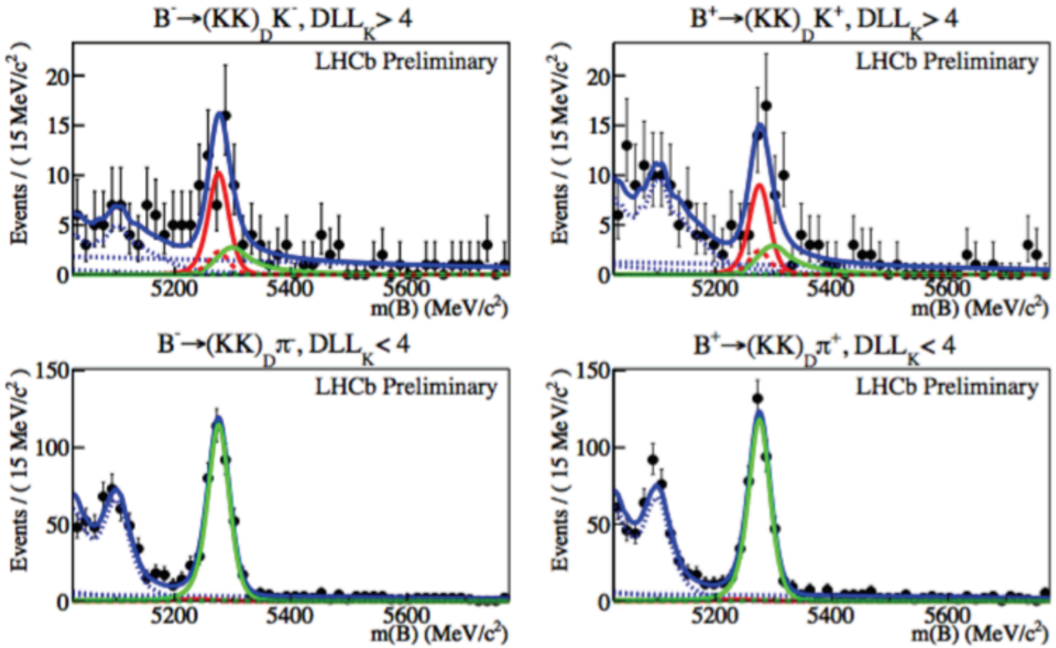
GLW at LHCb

- Preliminary results with 2010 data only (L=36 pb^{-1})
  - work in progress for 2011 update
- Not yet competitive with B factories, but LHCb will soon dominate with 1 fb^{-1}

LHCb-CONF-2011-031







$$R_{CP+} = 1.48 \pm 0.31 \pm 0.12$$

$$\mathcal{A}^{DK}_{CP+} = 0.07 \pm 0.18 \pm 0.07$$

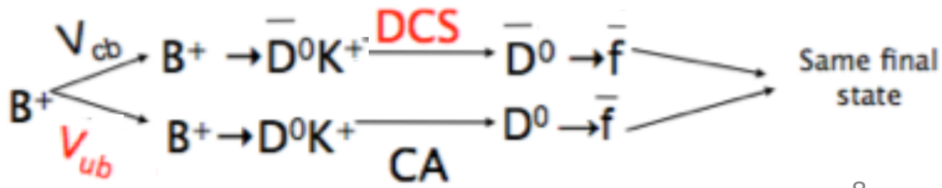
Atwood-Dunietz-Soni (ADS)

- The ADS method uses the interference between the $B^- \to D^0 K^-$ followed by the doubly Cabibbo-suppressed $D^0 \to K^+\pi^-$ and the suppressed $B^- \to \overline{D}^0 K^-$ followed by the Cabibbo-allowed $\overline{D}^0 \to K^+\pi^-$
  - Can be made with other modes involving a π^0 or a photon in the final state, but only $K\pi$ mode competitive at hadronic machines

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

$$A_{ADS} = \frac{\Gamma(B^- \to [K^+\pi^-]_D K^-) - \Gamma(B^+ \to [K^-\pi^+]_D K^+)}{\Gamma(B^- \to [K^+\pi^-]_D K^-) + \Gamma(B^+ \to [K^-\pi^+]_D K^+)} = 2 r_B r_D \sin\gamma \sin(\delta_B + \delta_D) \Big/ R_{ADS}$$

$$r_D = \frac{|A(D^0 \to K^+\pi^-)|}{|A(D^0 \to K^-\pi^+)|} = 0.0613 \pm 0.0010$$



D.Atwood,I.Dunietz,A.Soni,PRL78,3357(1997)

ADS at LHCb

- Measurement performed with 0.34 fb^{-1}

$$R_{ADS} = (1.66 \pm 0.39 \pm 0.24) \times 10^{-2}$$
$$A_{ADS} = -0.39 \pm 0.17 \pm 0.02$$

Still large room for improvement already with full 2011 data set

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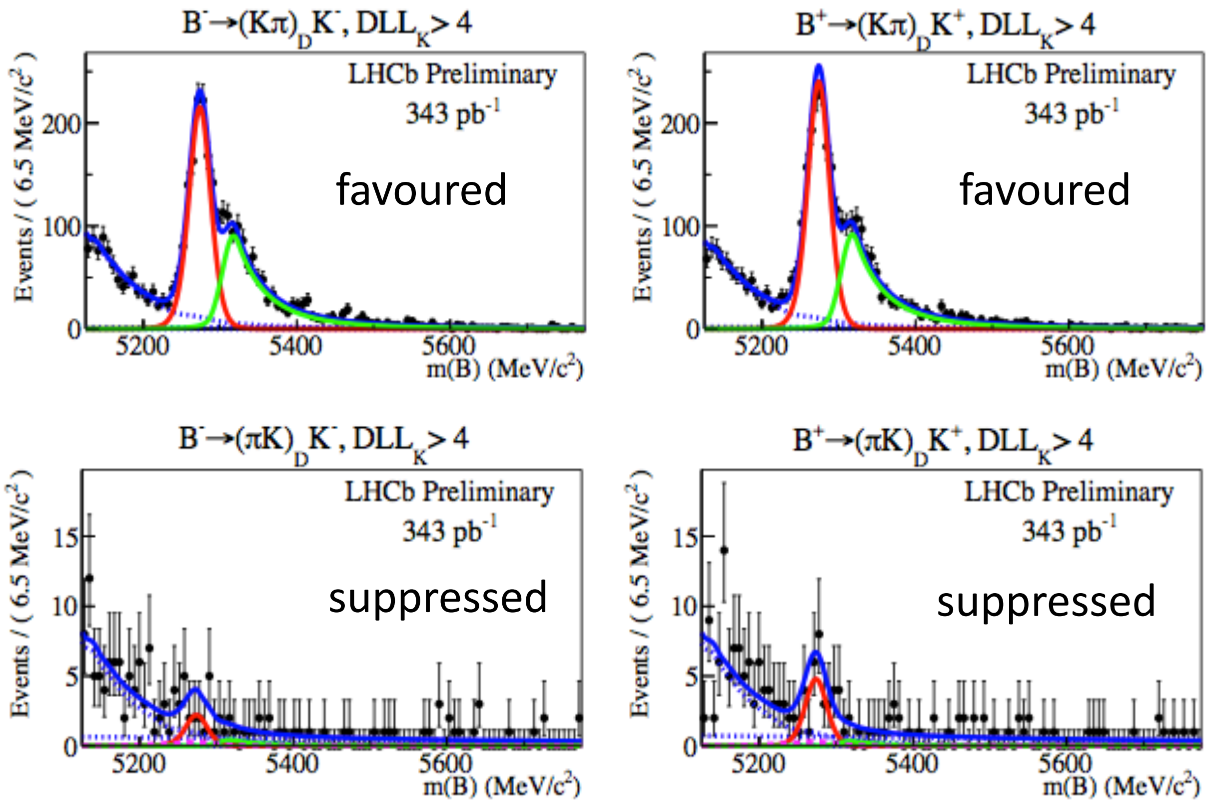
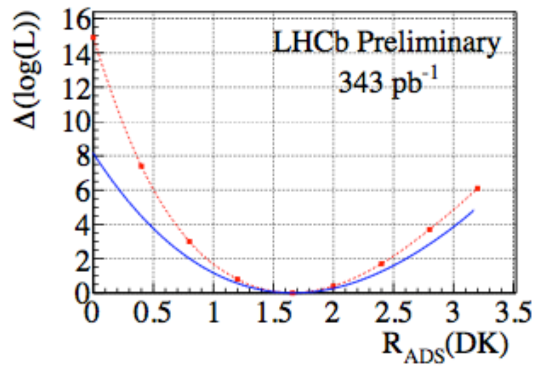


4σ evidence for the suppressed decay



ADS at LHCb

- Sizeable asymmetries may be found also using $B^- \to D\pi^-$ decays, although $r_B \approx 0.01$ in this case

$$R^{D\pi}_{ADS} = (4.13 \pm 0.41 \pm 0.40) \times 10^{-3}$$
$$A^{D\pi}_{ADS} = 0.09 \pm 0.10 \pm 0.01.$$

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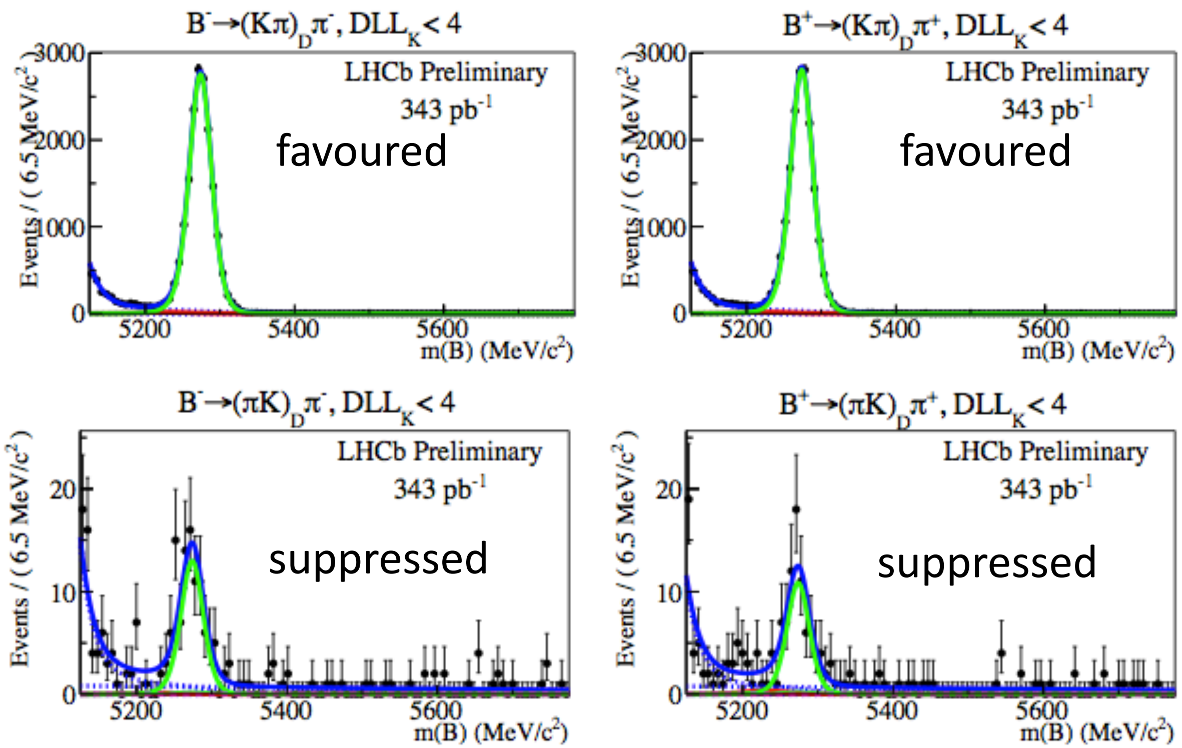
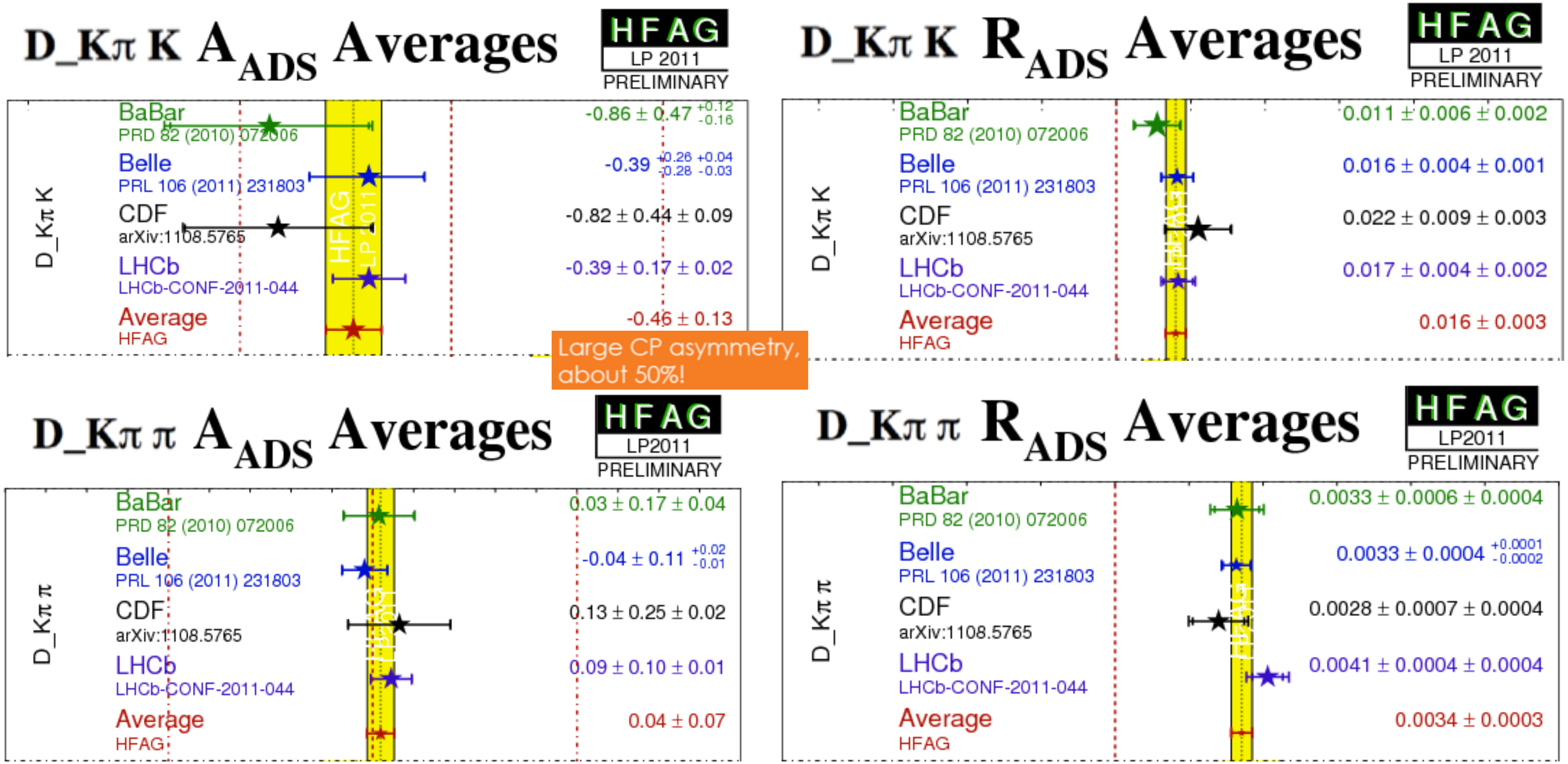
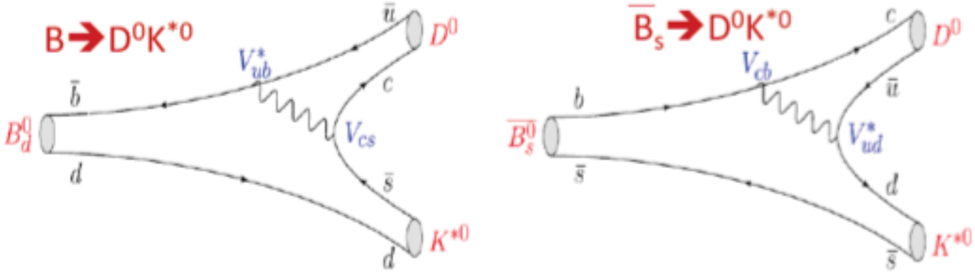


Impact of LHCb for ADS

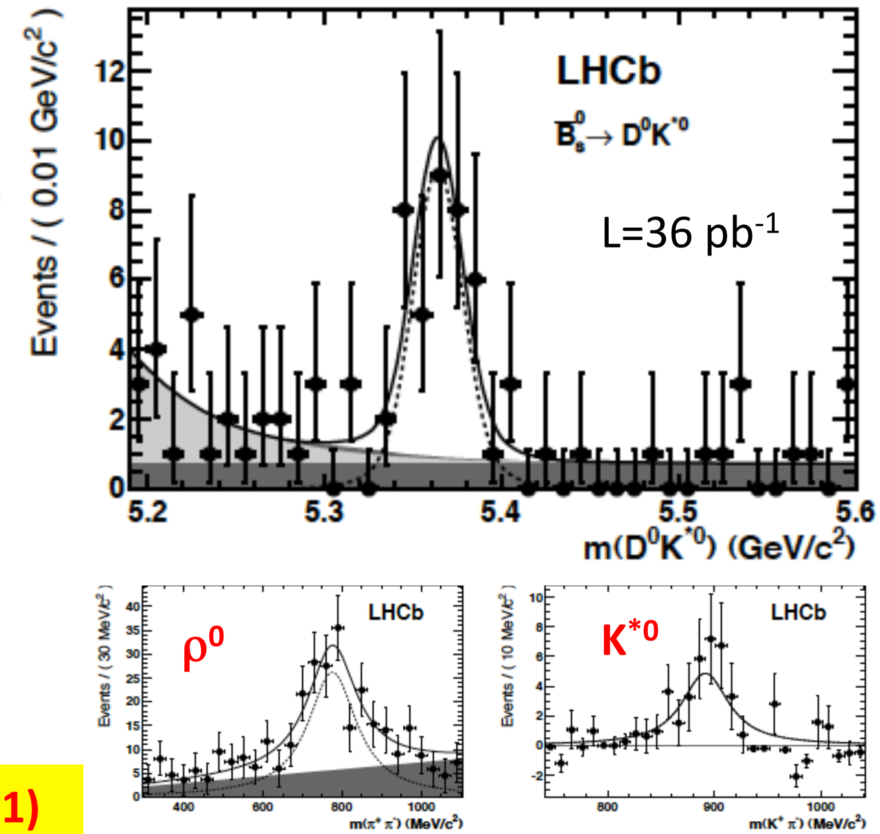


- LHCb already very competitive with 1/3 of 2011 statistics
  - Good agreement with existing measurements
- Will dominate the sector soon

Towards B→DK*: first measurement of $\overline{B}_s \to D^0K^{*0}$



- Very large branching fraction
  - dangerous background for Cabibbo-suppressed $B^0 \to D^0K^{*0}$
- Seen with a significance of 9σ
- Branching fraction measured relative to $B^0 \to D^0\rho^0$



Phys. Lett. B706 (2011)

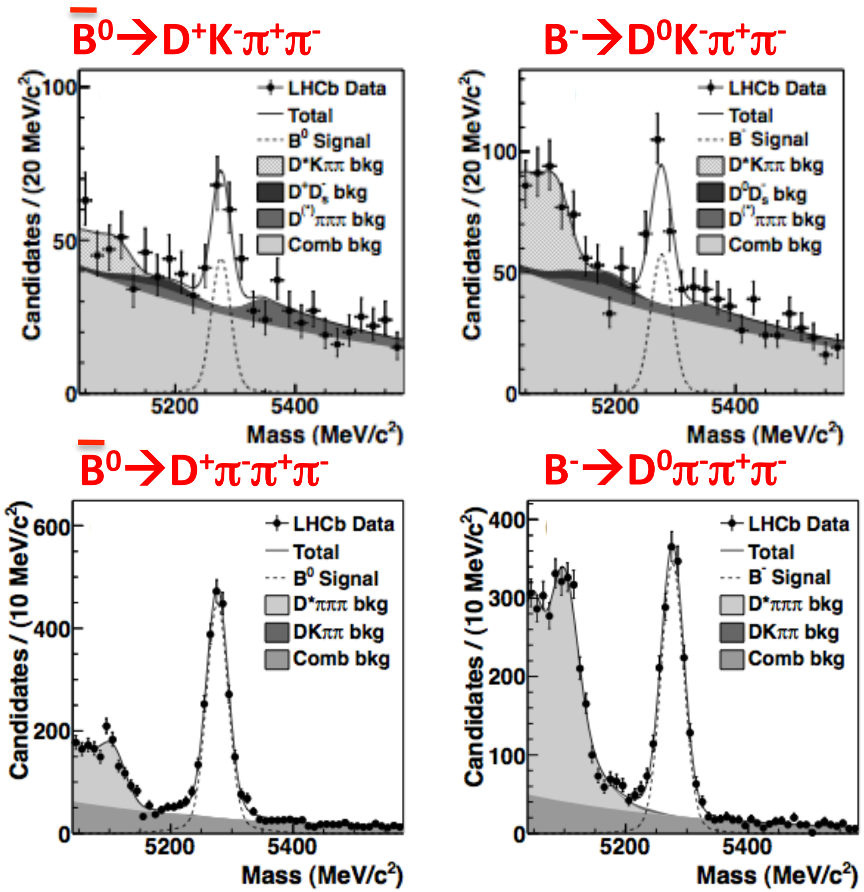
$$\frac{\mathcal{B}\left(\overline{B}^0_s \to D^0K^{*0}\right)}{\mathcal{B}\left(\overline{B}^0 \to D^0\rho^0\right)} = 1.48 \pm 0.34 \pm 0.15 \pm 0.12$$

f_d/f_s

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

Measurement of Cabibbo-suppressed $\bar{B}^0 \to D^+K^-\pi^+\pi^-$ e $B^- \to D^0K^-\pi^+\pi^-$

- $B^0 \to DK\pi\pi$ yield is 40% wrt that of $B^0 \to DK$, and $B^- \to DK\pi\pi$ is 25% less than $B^- \to DK$
  - Significant contribution to γ is expected
- Expect to observe $B_s \to D_sK\pi\pi$ decay very soon, to be used for time-dependent γ



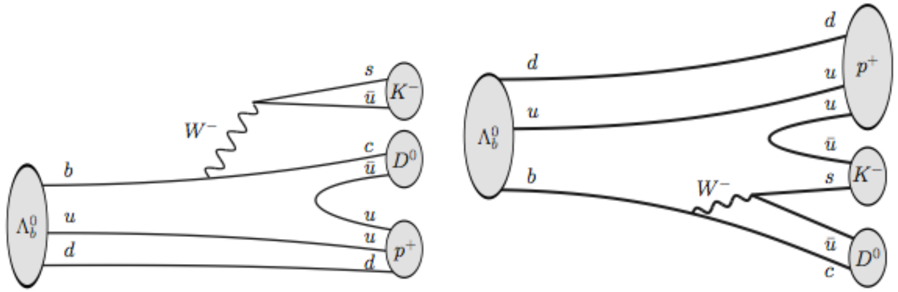
$$\frac{\mathcal{B}(\bar{B}^0 \to D^+K^-\pi^+\pi^-)}{\mathcal{B}(\bar{B}^0 \to D^+\pi^-\pi^+\pi^-)} = (5.9 \pm 1.1 \pm 0.5) \times 10^{-2}$$

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

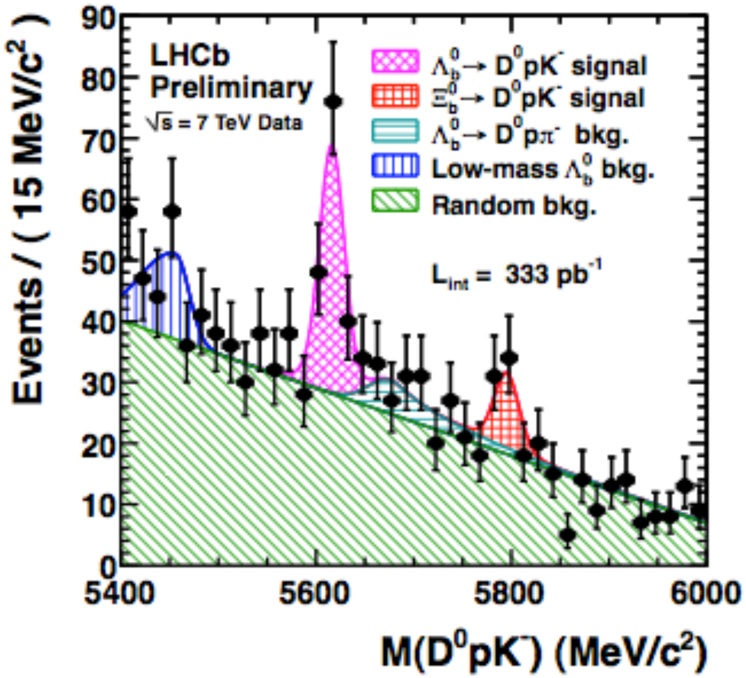
arXiv:1201.4402v1

L=35 pb^{-1}

First observation of Cabibbo-suppressed $\Lambda_b \rightarrow D^0 p K^-$ decays



- Seen with 6σ significance
- Also b-baryon decays can play a role in the quest for γ



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

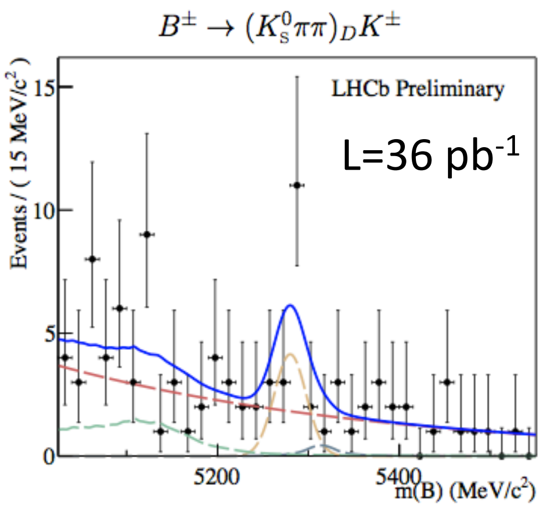
LHCb-CONF-2011-036

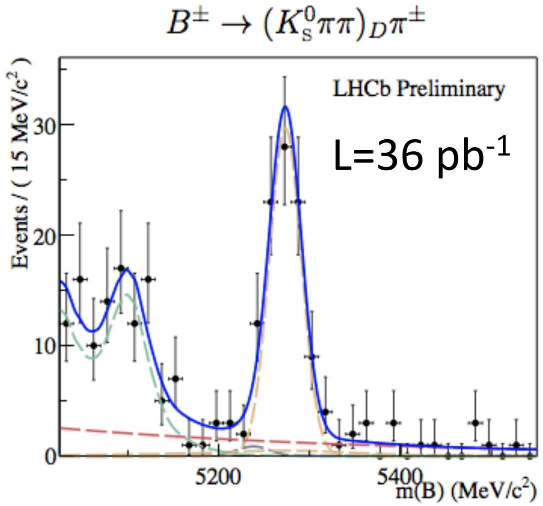
$L = 0.33\ fb^{-1}$

Towards γ from GGSZ at LHCb

- Multibody D decays like $D^0 \rightarrow K_S\pi\pi$ can also be used to extract γ from the interference between $B^- \rightarrow D^{(*)0}K^-$ and $B^- \rightarrow \overline{D}^{(*)0}K^-$
  - Dalitz plot analysis allows simultaneous determination of the weak phase difference γ, the strong phase difference δ_B and the ratio of the amplitudes r_B

A. Giri, Yu. Grossman, A Soffer and J. Zupan, Phys. Rev. D 68, 054018 (2003)
A. Bondar, Proceedings of BINP Special Analysis Meeting on Dalitz Analysis



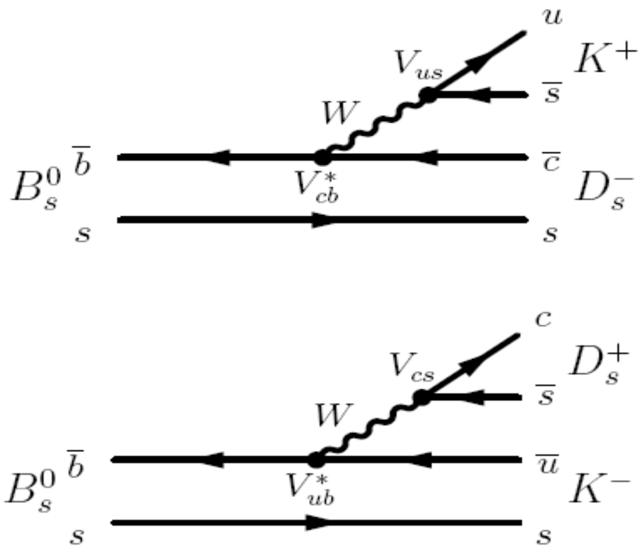


Preliminary study made only with 2010 data
Still unable to make precise estimates, but O(500-1000) $B \rightarrow (K_S\pi\pi)_D K$ events seems feasible with 2011 data set

LHCb-CONF-2011-031

Time-dependent γ

- Tree-level γ also accessible via $B_s \rightarrow D_s K$ and $B^0 \rightarrow D^{\pm}\pi$
- $B_s \rightarrow D_s K$ unique opportunity at hadronic machines
  - characterized by large interference
    - Both $b \rightarrow u$ and $b \rightarrow c$ diagrams are colour allowed
  - time-dependent analysis sensitive to γ-ϕ_s
    - can determine γ in conjunction with other measurements of the B_s mixing phase ϕ_s



  - Requires tagging, but also untagged analysis sensitive to γ owing to $\Delta\Gamma_s \neq 0$
  - First step now is to observe the signal and measure the branching ratio
    - Δm_s already precisely measured

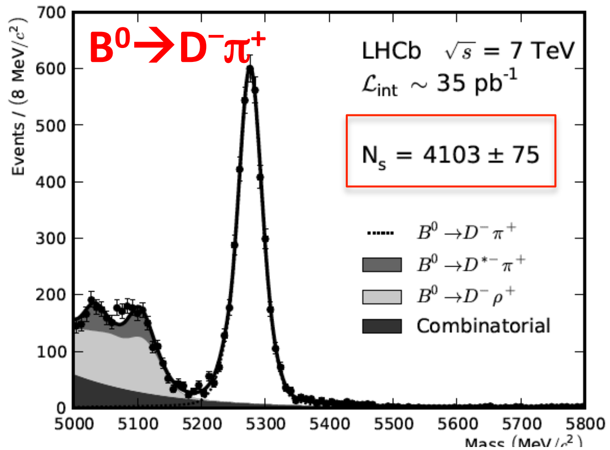
arXiv:1112.4311

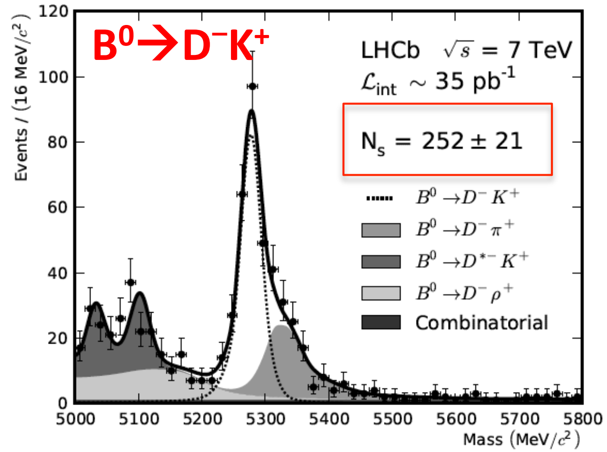
$$\Delta m_s = 17.63 \pm 0.11\ (\text{stat}) \pm 0.02\ (\text{syst})\ \text{ps}^{-1}$$

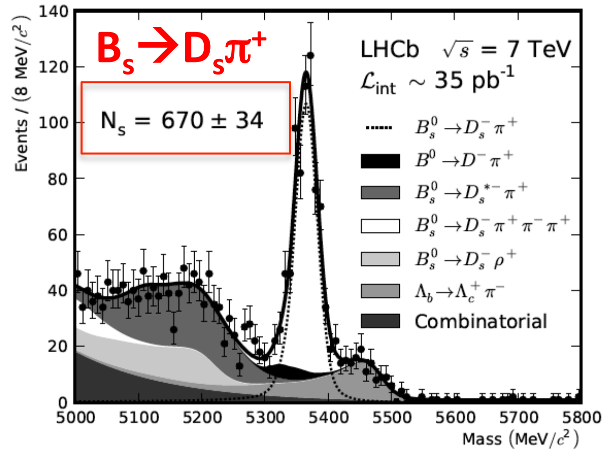
R. Aleskan, I. Dunietz and B. Kayser, Z. Phys. C 54, 653 (1992)

On the road to time-dependent γ : f_s/f_d

- Relevant measurement as this is a basic ingredient for relative B_s branching ratio measurements
- Performed by determining the relative yields of $B^0 \to D^-\pi^+$, $B^0 \to D^-K^+$, $B_s \to D_s\pi^+$
  - As a by-product of the analysis, also the branching fraction of $B^0 \to D^-K^+$ has been measured







Phys. Rev. Lett. 107 (2011)

L=35 pb^{-1}

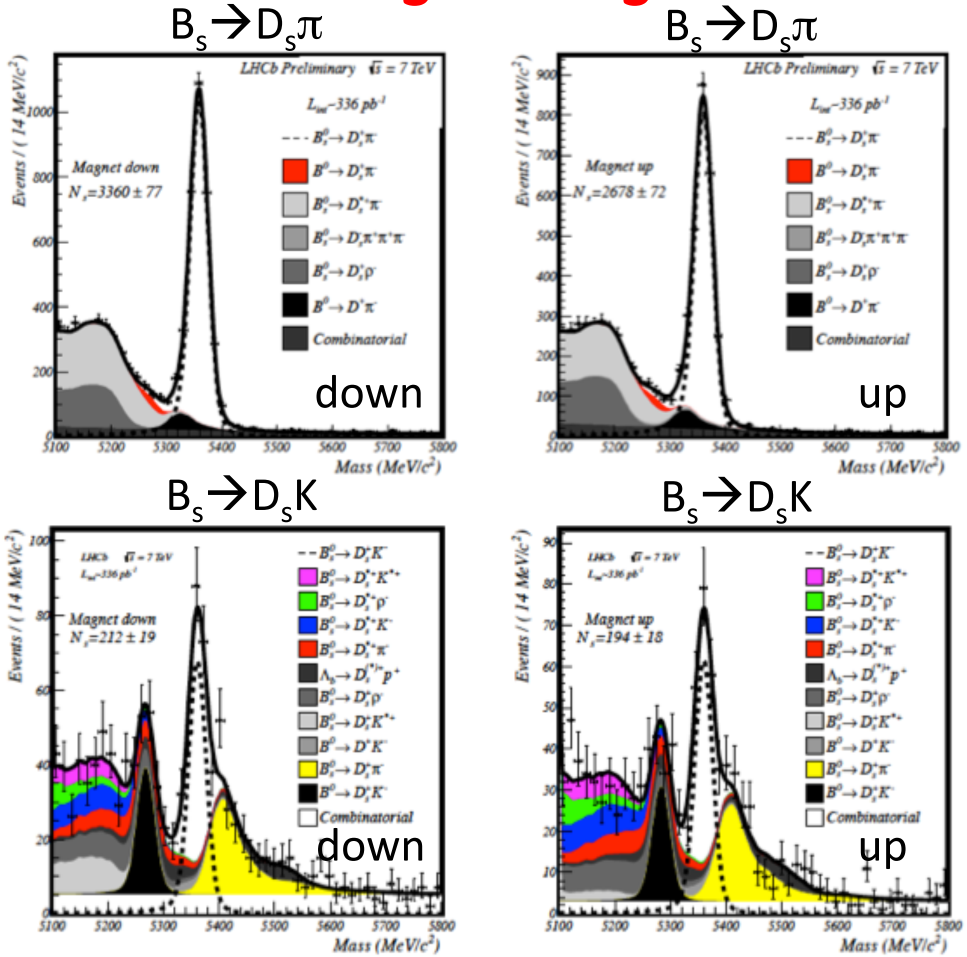
$$f_s/f_d = 0.253 \pm 0.017^{\text{stat}} \pm 0.017^{\text{syst}} \pm 0.020^{\text{theor}}$$

$$\mathcal{B}\left(B^0 \to D^- K^+\right) = (2.01 \pm 0.18 \pm 0.14) \times 10^{-4}$$

Branching ratio of $B_s \rightarrow D_s K$

$L = 0.34\ fb^{-1}$

- First observation of $B_s \rightarrow D_s K$ at LHCb
- World's best measurement of $B_s \rightarrow D_s h$ branching fractions
- With full 2011 data set ($1\ fb^{-1}$) LHCb expects to reconstruct 1300-1500 events
- First results for time-dependent CP violation expected for spring/ summer 2012



$$\frac{B(B_s^0 \to D_s^{\mp} K^{\pm})}{B(B_s^0 \to D_s^- \pi^+)} = 0.0647 \pm 0.0044(stat.)^{+0.0039}_{-0.0043}(syst.)$$

$$B(B_s^0 \to D_s^- \pi^+) = (3.04 \pm 0.19(stat.) \pm 0.23(syst.)^{+0.18}_{-0.16}(f_s/f_d))x10^{-3}$$

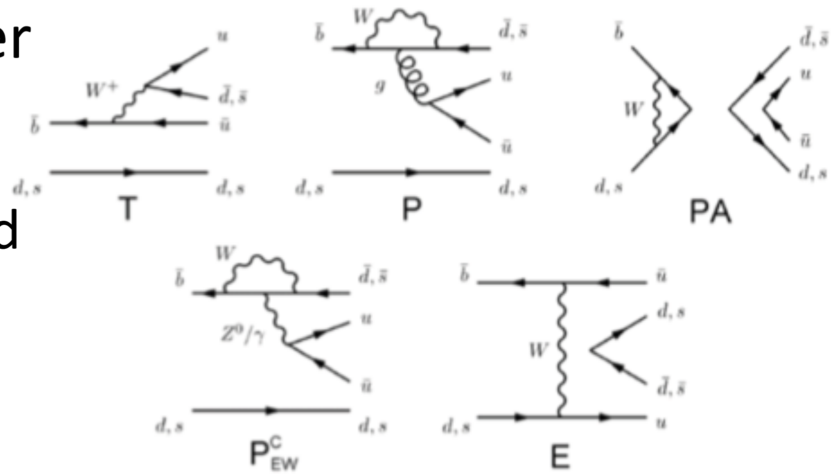
$$B(B_s^0 \to D_s^{\mp} K^{\pm}) = (1.97 \pm 0.18(stat.)^{+0.19}_{-0.20}(syst.)^{+0.11}_{-0.10}(f_s/f_d))x10^{-4}$$

LHCb-CONF-2011-057

γ from penguins

- $B \rightarrow h^+h'^-$ decays provide yet another path to γ
  - The direct and mixing-induced CP asymmetry terms of $B^0 \rightarrow \pi^+\pi^-$ and $B_s \rightarrow K^+K^-$ are sensitive to γ

$$\mathcal{A}_f^{CP}(t) = \frac{\mathcal{A}_f^{dir}\cos(\Delta m\, t) + \mathcal{A}_f^{mix}\sin(\Delta m\, t)}{\cosh\left(\frac{\Delta\Gamma}{2}t\right) - \mathcal{A}_f^{\Delta}\sinh\left(\frac{\Delta\Gamma}{2}t\right)}$$



- 4 equations but too many unknowns
  - $B^0 \rightarrow \pi^+\pi^-$ and $B_s \rightarrow K^+K^-$ decay diagrams related by d-s quark exchange (U-spin symmetry)
    - Making use of the U-spin symmetry and other measurements of the mixing phases ϕ_d and ϕ_s, γ can be extracted
  - Other $B \rightarrow h^+h'^-$ modes useful to check and constrain U-spin validity

$$\mathcal{A}^{dir}_{K^+K^-} = -\frac{2\tilde{d}'\sin(\vartheta')\sin(\gamma)}{1 + 2\tilde{d}'\cos(\vartheta')\cos(\gamma) + \tilde{d}'^2}$$

$$\mathcal{A}^{dir}_{\pi^+\pi^-} = \frac{2d\sin(\vartheta)\sin(\gamma)}{1 - 2d\cos(\vartheta)\cos(\gamma) + d^2}$$

$$\mathcal{A}^{mix}_{\pi^+\pi^-} = -\frac{\sin(\phi_d + 2\gamma) - 2d\cos(\vartheta)\sin(\phi_d + \gamma) + d^2\sin(\phi_d)}{1 - 2d\cos(\vartheta)\cos(\gamma) + d^2}$$

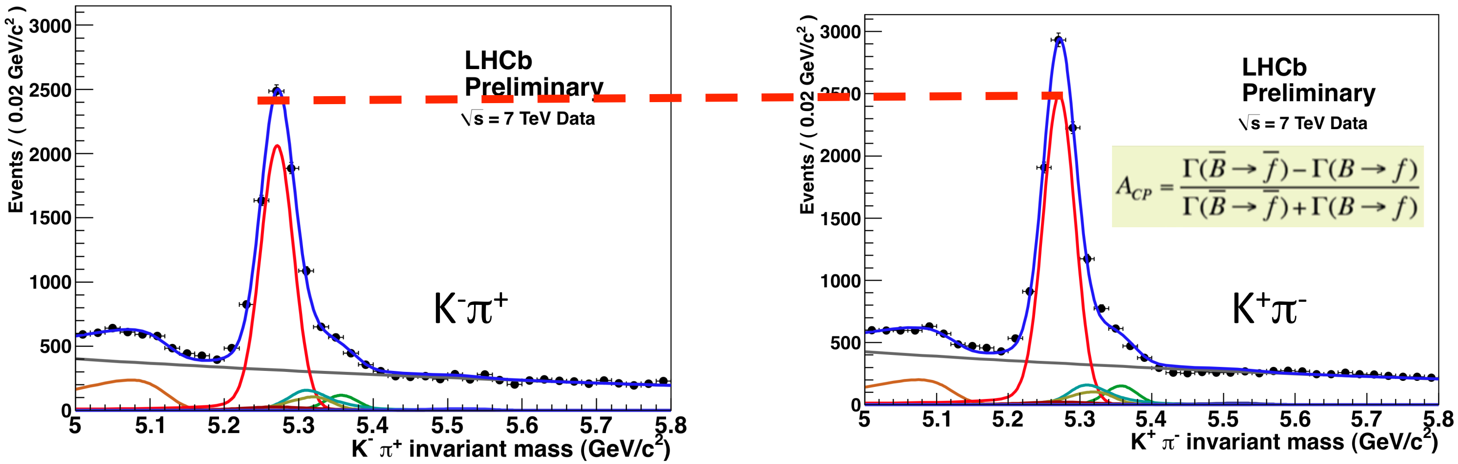
$$\mathcal{A}^{mix}_{K^+K^-} = -\frac{\sin(\phi_s + 2\gamma) + 2\tilde{d}'\cos(\vartheta')\sin(\phi_s + \gamma) + \tilde{d}'^2\sin(\phi_s)}{1 + 2\tilde{d}'\cos(\vartheta')\cos(\gamma) + \tilde{d}'^2}$$

R.Fleischer PLB 459 (1999) 306
R. Fleischer and R. Knegjens EPJ c71 (2011)1532

Direct CP asymmetries in B→Kπ

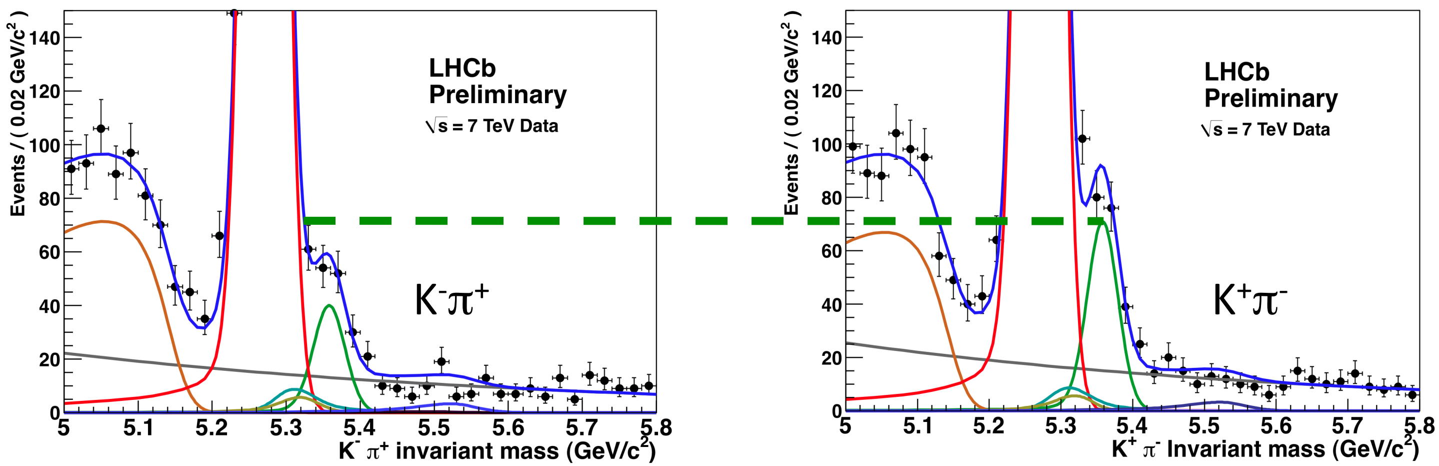
Raw CP asymmetry in $B^0 \to K\pi$: -0.095 ± 0.011

L=0.35 fb^{-1}



Selection optimized for $A_{CP}(B^0 \to K\pi)$

Raw CP asymmetry in $B^0_s \to \pi K$: 0.28 ±0.08



Raw CP asymmetry clearly visible from the plots

Selection optimized for $A_{CP}(B^0_s \to \pi K)$

The raw asymmetries measured in data must be corrected for detector-induced $K^+\pi^-$ /π^-K^+ charge asymmetries and B production asymmetry

LHCb-CONF-2011-042

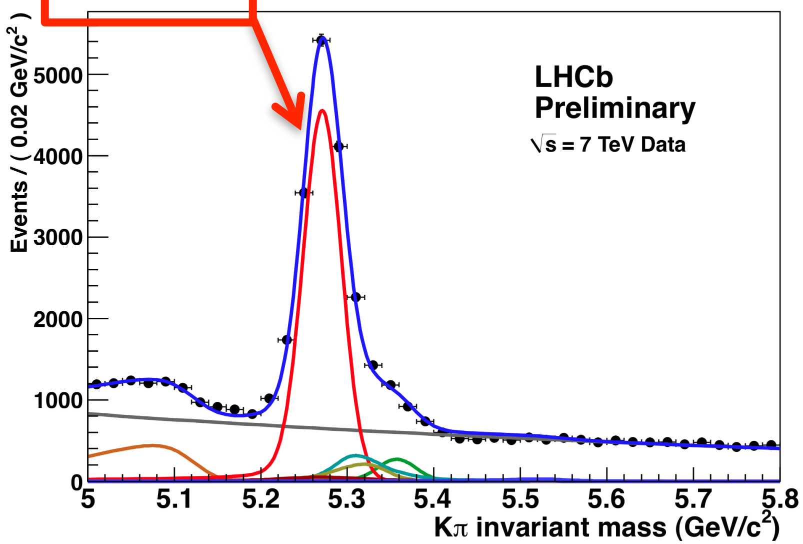
Direct CP asymmetries in B→Kπ

$B^o \to K\pi$

Kπ mass spectra

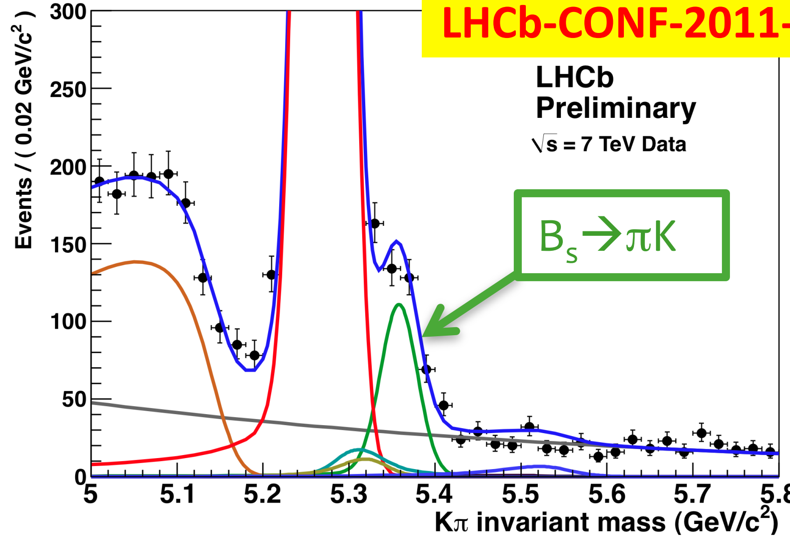
L=0.35 fb^{-1}

LHCb-CONF-2011-042



Selection optimized for $A_{CP}(B^0 \to K\pi)$

$N(B^0 \to K\pi) = 13245 \pm 151$



$B_s \to \pi K$

Selection optimized for $A_{CP}(B^0_s \to \pi K)$

$N(B^0_s \to \pi K) = 314 \pm 27$

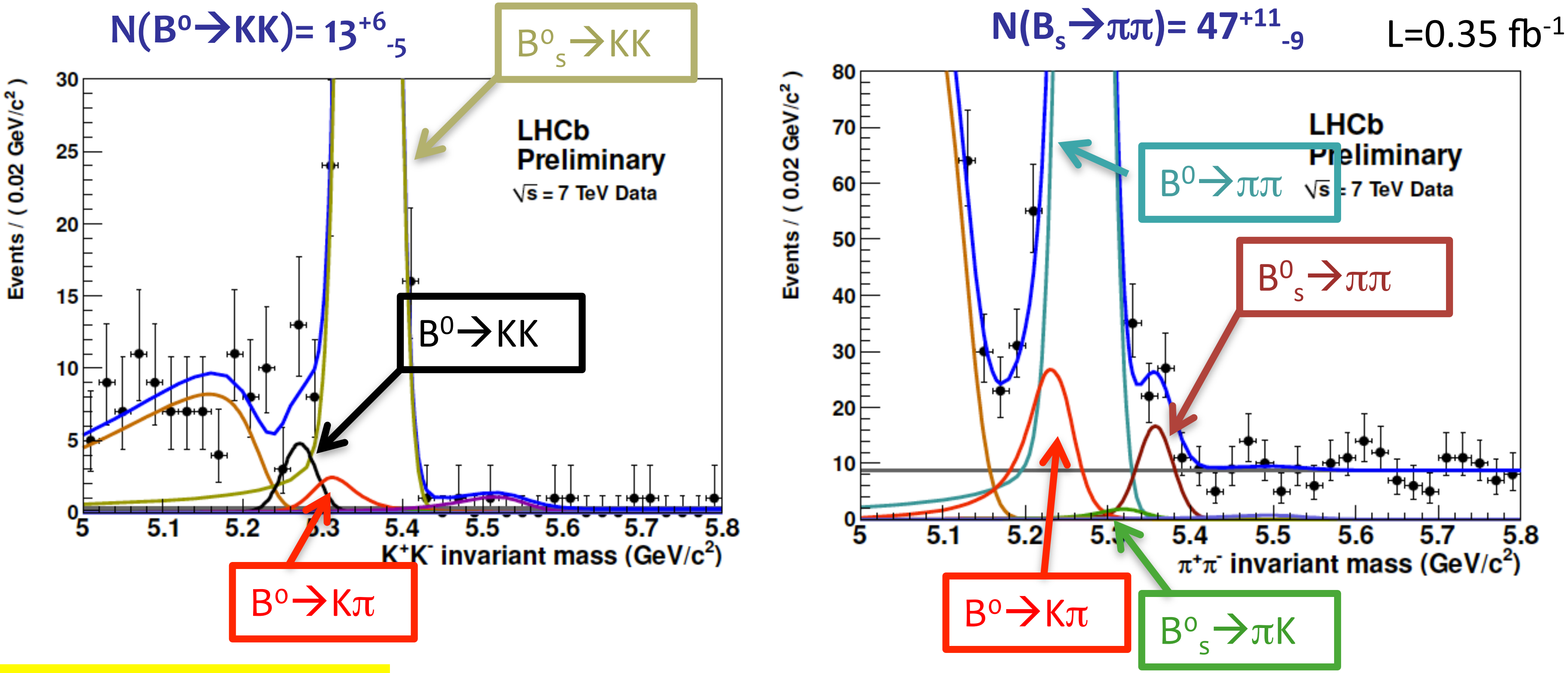
$$A_{CP}(B^0 \to K^+\pi^-) = -0.088 \pm 0.011(\text{stat}) \pm 0.008(\text{syst})$$

World's best and first observation of CP violation in the B system at a hadron collider

$$A_{CP}(B^0_s \to \pi^+ K^-) = 0.27 \pm 0.08(\text{stat}) \pm 0.02(\text{syst})$$

First evidence of CP violation in B_s decays

Searching for rare decays



LHCb-CONF-2011-042

$$\mathcal{BR}(B^0 \to K^+K^-) = (0.13^{+0.06}_{-0.05}(\text{stat}) \pm 0.07(\text{syst})) \times 10^{-6}$$

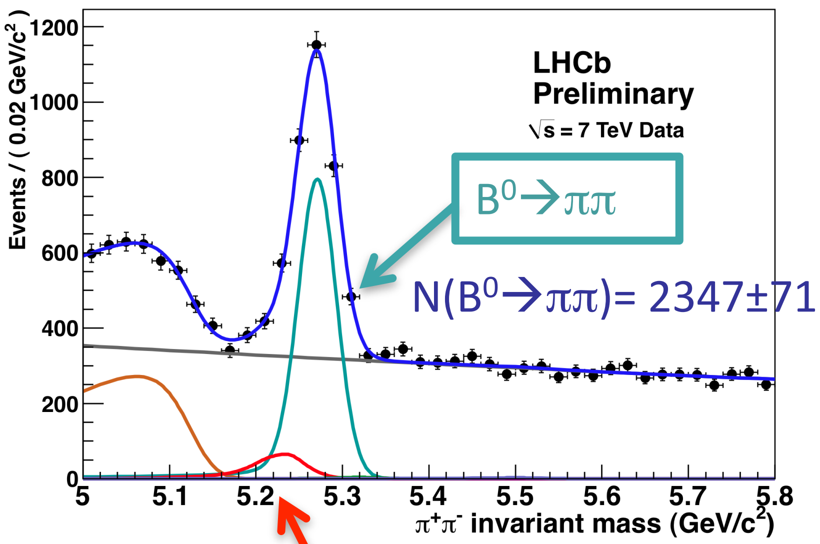
$$\mathcal{BR}(B_s^0 \to \pi^+\pi^-) = (0.98^{+0.23}_{-0.19}(\text{stat}) \pm 0.11(\text{syst})) \times 10^{-6}$$

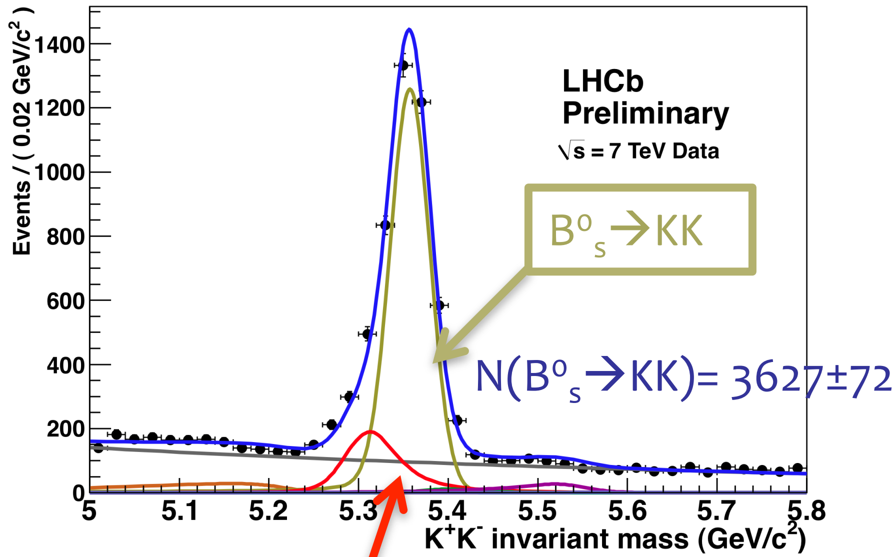
first observation of $B^0_s \to \pi\pi$ with a significance of 5.3 σ

Towards time-dependent asymmetries in $B^0 \to \pi^+\pi^-$ and $B^0_s \to K^+K^-$

- Large samples of $B^0 \to \pi^+\pi^-$ and $B_s \to K^+K^-$ already observed with 1/3 of 2011 statistics
- Measurement of all $B \to h^+h'^-$ branching fractions and first measurement of time-dependent CP asymmetries are being finalized

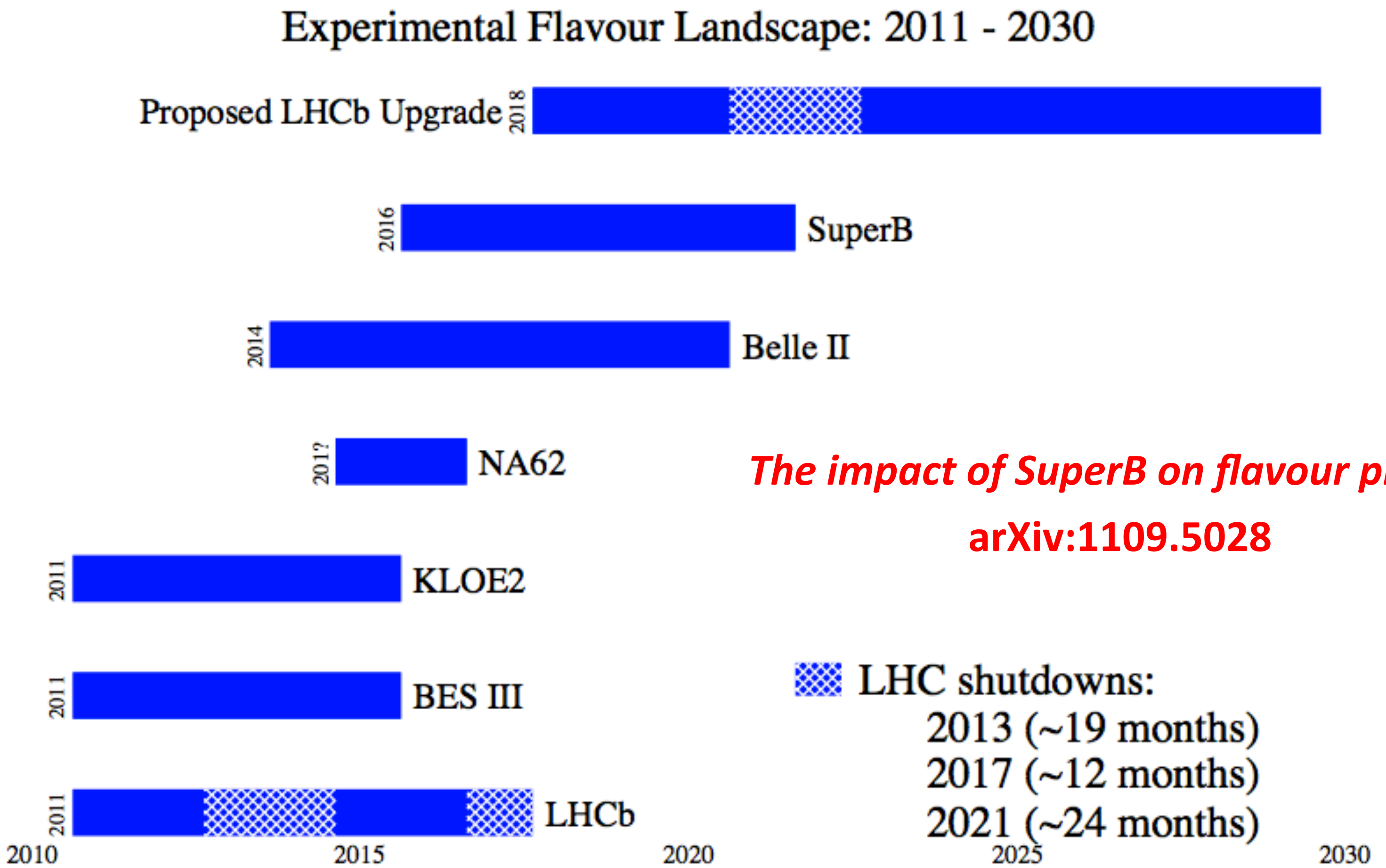
L=0.35 fb^{-1}





Cross feed background from $B^0 \to K\pi$ decays

A look into the future of flavour physics



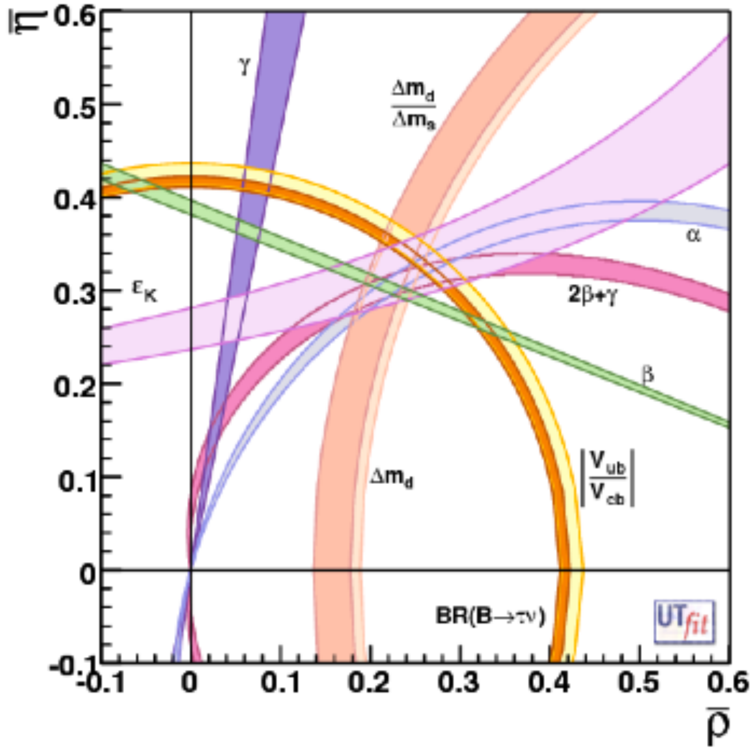
The impact of SuperB on flavour physics

arXiv:1109.5028

Prospects for γ at Super (LHC)B factories

- The ultimate precision on γ for both the LHCb upgrade and Super B factories are comparable at the level of ~1° for any given channel
- According to the present schedule and target physics performance, the Super B factories can achieve such a result some years in advance with respect to a Super LHCb

Dream scenario for a SuperB at 75 ab^{-1}



Observable/mode	Current now	LHCb (2017)	Super$B$ (2021)	Belle II (2021)	LHCb upgrade (10 years of running)	theory now
		5 fb^{-1}	75 ab^{-1}	50 ab^{-1}	50 fb^{-1}	
γ from $B \to DK$	11°	$\sim 4^\circ$	1°	1.5°	0.9°	clean

Conclusions

- First results from LHCb (up to ~0.3 fb^{-1}) have already an impact on the world average for γ
- In the course of 2012, exploiting the full 2011 dataset and even more, LHCb results will start dominating
  - Many modes in the pipeline
  - Naïve extrapolation to ~1 fb^{-1} of 7 TeV collisions gives $\sigma(\gamma) \approx 7^o$
- Access to γ via time-dependent measurements unique opportunity at hadronic machines
  - In 2012 the first measurements using $B_s \rightarrow D_s K$ and $B \rightarrow hh$ will be unveiled
- Expected sensitivity for ~5 fb^{-1} at 14 TeV is $\sigma(\gamma) \approx 2\text{-}3^o$
- LHCb upgrade will benefit from significantly improved trigger efficiency
  - Sub-degree precision possible with 50 fb^{-1} (CERN-LHCC-2011-001)
- Nice competition with Super B factory projects which aim to similar precision with 50-75 ab^{-1}