$B_{s,d} \rightarrow h^+h'^-$ @ LHCb

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$B \to h^+h'^-$ modes: CKM phases and NP

- Since the original CLEO measurement [$BR(B_d \rightarrow K^+\pi^-) \sim 4\ BR(B_d \rightarrow \pi^+\pi^-)$], it is well known that penguin diagrams cannot be neglected in the two-body B-decay amplitudes
  - This fact complicates considerably the extraction of CKM phases from these decays
  - However, a possibility to eliminate unknown hadronic quantities relies in exploiting flavour symmetries, e.g. combining the measurements from U-spin related decay modes
- The presence of penguins can be viewed as an opportunity rather than a problem
  - New Physics contributions might show up inside the loops of the penguin diagrams, and CKM quantities extracted from these modes can differ from the ones calculated from tree-level modes

U-spin symmetries

$B_d \to \pi^+\pi^-$ $T+P+P^C_{EW}+PA+E$	⟺	$B_s \to K^+K^-$ $T+P+P^C_{EW}+PA+E$
$B_d \to \pi^+\pi^-$ $T+P+P^C_{EW}+PA+E$	⟺	$B_s \to \pi^+K^-$ $T+P+P^C_{EW}$
$B_s \to K^+K^-$ $T+P+P^C_{EW}+PA+E$	⟺	$B_d \to K^+\pi^-$ $T+P+P^C_{EW}$

T: tree
P: penguin
P^C_{EW}: colour suppressed electroweak penguin
PA: penguin annihilation
E: exchange

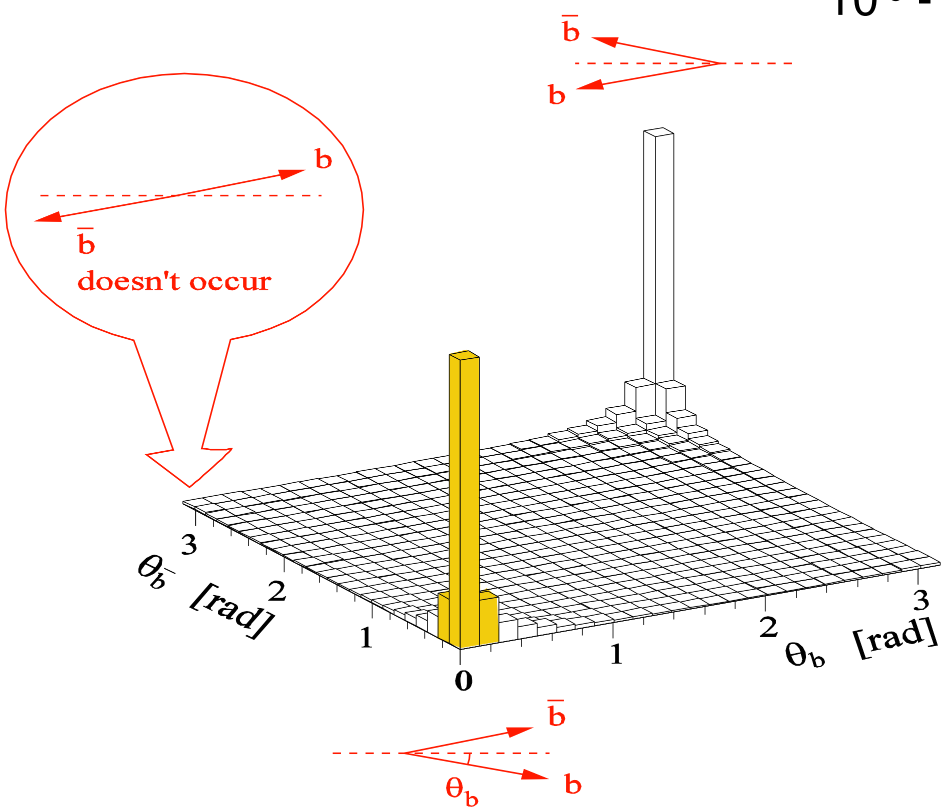
- Not all exactly U-spin symmetric, E and PA contributions missing from flavour specific decays
- E and PA contributions expected to be relatively small, and can be experimentally probed by measuring the still unobserved $B_s \to \pi^+\pi^-$ and $B_d \to K^+K^-$ branching ratios BR~$O(10^{-8})$

$B \to h^+h'^-$ events @ LHCb

Details on LHCb detector can be found in F. Muheim's talk

- Large beauty production cross section expected at 14 TeV p-p collisions: all b-hadron species produced ($B^\pm$, B^0_d, B^0_s, B_c, Λ_b.... $\to$ 40%,40%,10%,10%)
- B hadrons are produced very likely with a small relative angle and in the very forward (backward) region: LHCb uses just the forward direction $1.8 < \eta < 4.9$

@ nominal luminosity ($L=2\bullet10^{32}$ $cm^{-2}s^{-1}$) about 10^{12} $b\bar{b}$ events in 10^7 s



- $B \to h^+h'^-$ channels have typical branching ratios in the range 10^{-5} - 10^{-6}
  - Millions of such events produced per year!

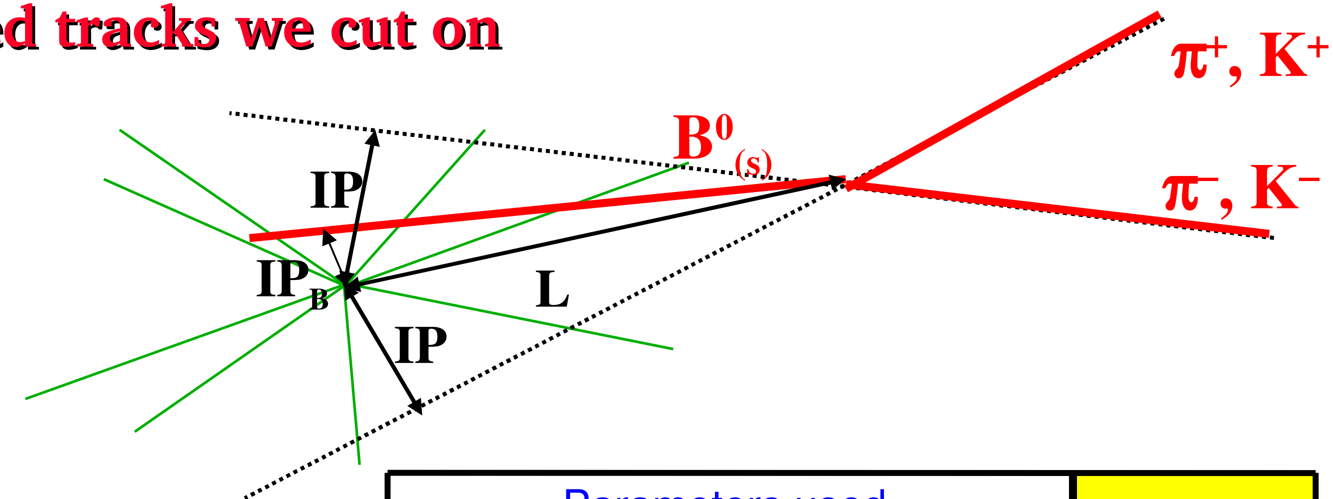
$\sigma_{bb} = 500\mu b$; $\sigma_{inel}=80mb$; $\sigma_{bb}/\sigma_{inel} \sim 6‰$

– Too many min bias MC events needed to asses S/B: assumption that main bkg comes from b events reduces the events by factor 100

For this study about 300k signal events and 27M inclusive beauty events have been used

$B \to h^+h'^-$ selection cuts

- **For each pair of charged tracks we cut on**
  - max (p_{T1}, p_{T2})
  - min (p_{T1}, p_{T2})
  - max $(IP1/\sigma_{IP1}, IP2/\sigma_{IP2})$
  - min $(IP1/\sigma_{IP1}, IP2/\sigma_{IP2})$
  - χ^2 of common vertex



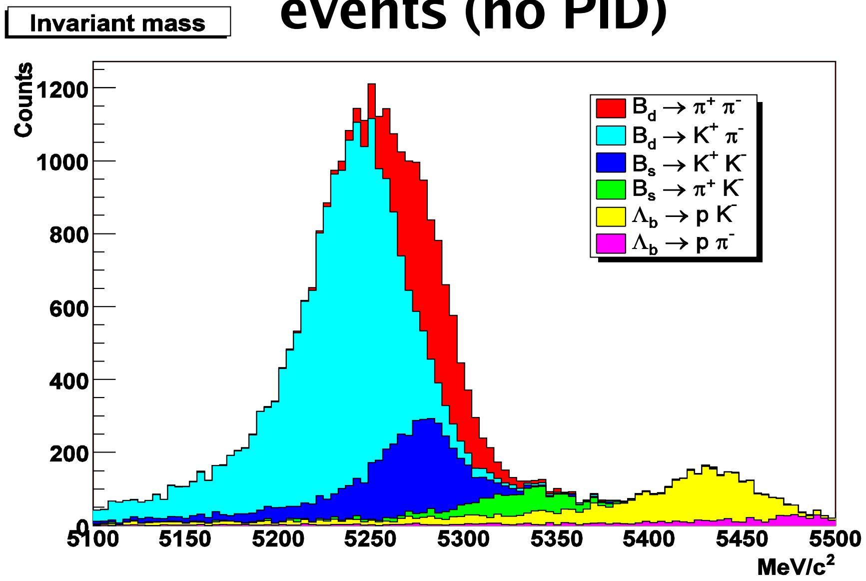
- **Then, the B candidate is selected with cuts on**
  - p_T
  - IP/σ_{IP}
  - L/σ_L

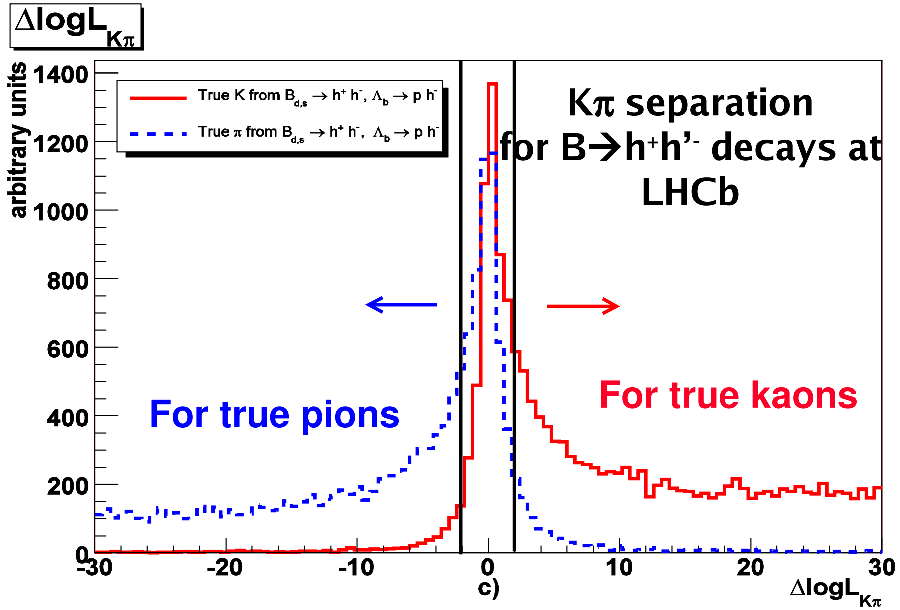
Parameters used for selection			
h,h	Smallest p_t	GeV/c	> 1
h,h	largest p_t	GeV/c	> 3
h,h	smallest IP/σ_{IP}		> 6
h,h	largest IP/σ_{IP}		> 12
h, h	vertex fit χ^2		< 5
B	p_t	GeV/c	> 1
B	IP/σ_{IP}		< 2.5
B	L/σ_L		> 18

Particle identification

- PID discriminants built as difference between log likelihoods of particle hypotheses

Invariant mass of selected events (no PID)

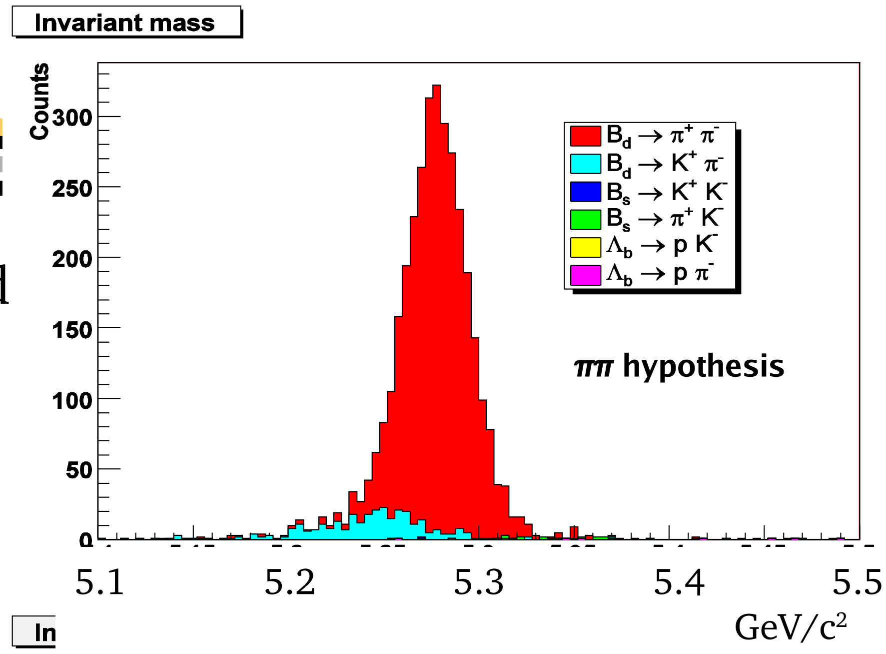


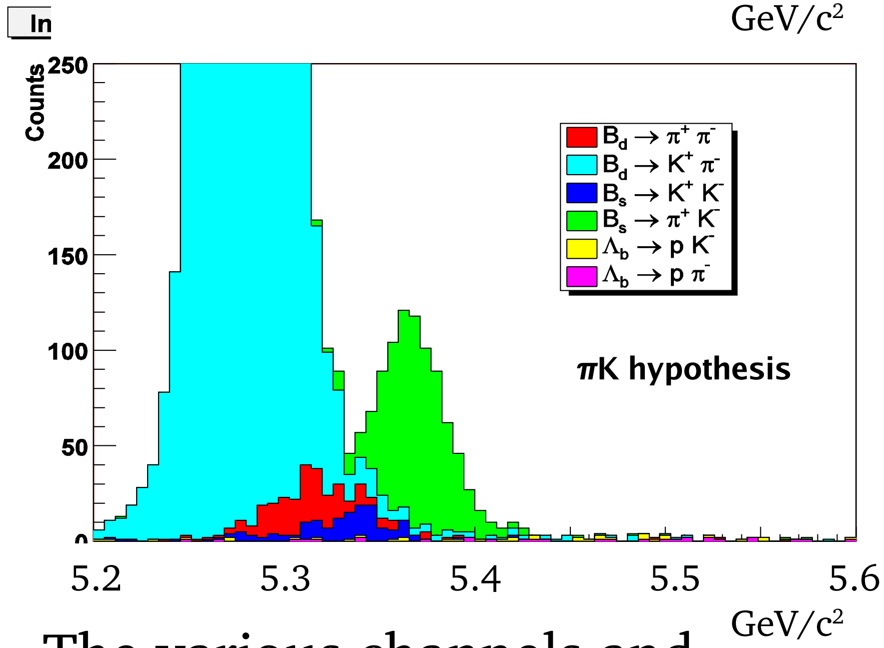


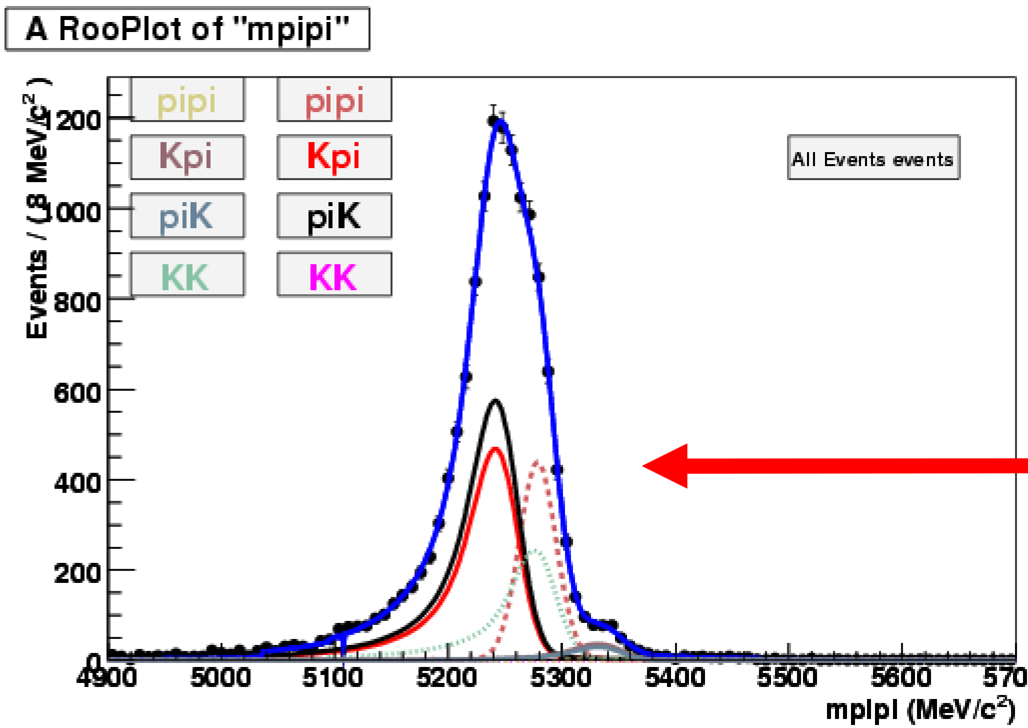
- Efficient hadron PID crucial for the $B \to h^+h'^-$ channels
  - Invariant masses one on top of the other → kinematic separation possible but weak
- Calibration of K/π PID on data will be performed using the $D^{*+} \to D^0\pi^+$, $D^0 \to K^+\pi^-$ decay chain
  - Large "PID unbiased" samples of such D* decays will be acquired with dedicated D* trigger chain (300 Hz bandwidth)

Using PID information

- Every h⁺h'⁻ channel is potentially a background for the other channels:
  - The impressive performance of RICH systems allows to select very clean samples cutting on PID information
  - To ease the evaluation of systematics a simultaneous Likelihood fit has been used



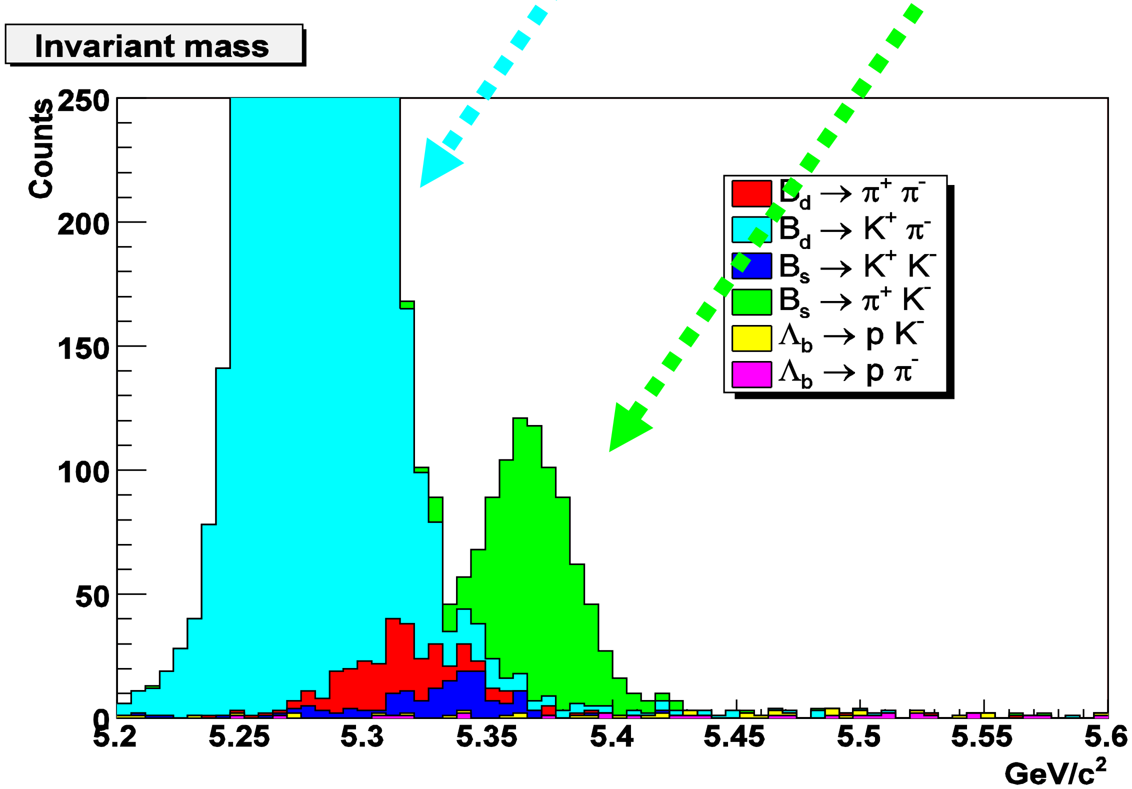




The various channels and background are separated in the fit by means of the particle ID observables and invariant mass

Mass resolution

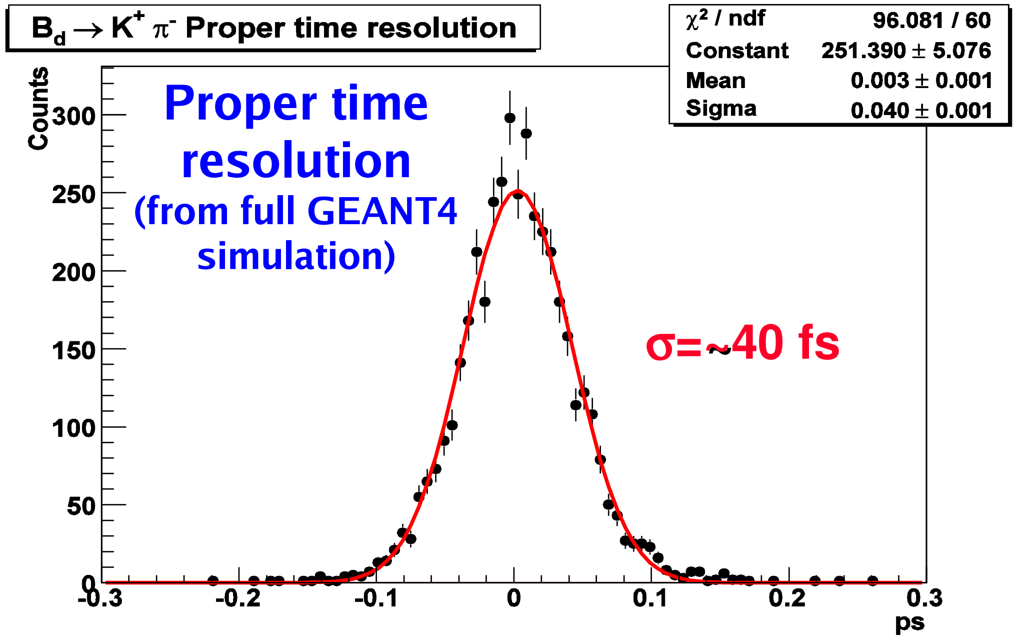
- Discrimination of $B_d \to K^- \pi^+$ from $B_s \to \pi^+ K^-$ must rely on mass resolution only since they share exactly the same signature
  - $B_d \to K^- \pi^+$ about 16 times more abundant (4 times larger branching fraction, 4 times larger hadronization fraction)

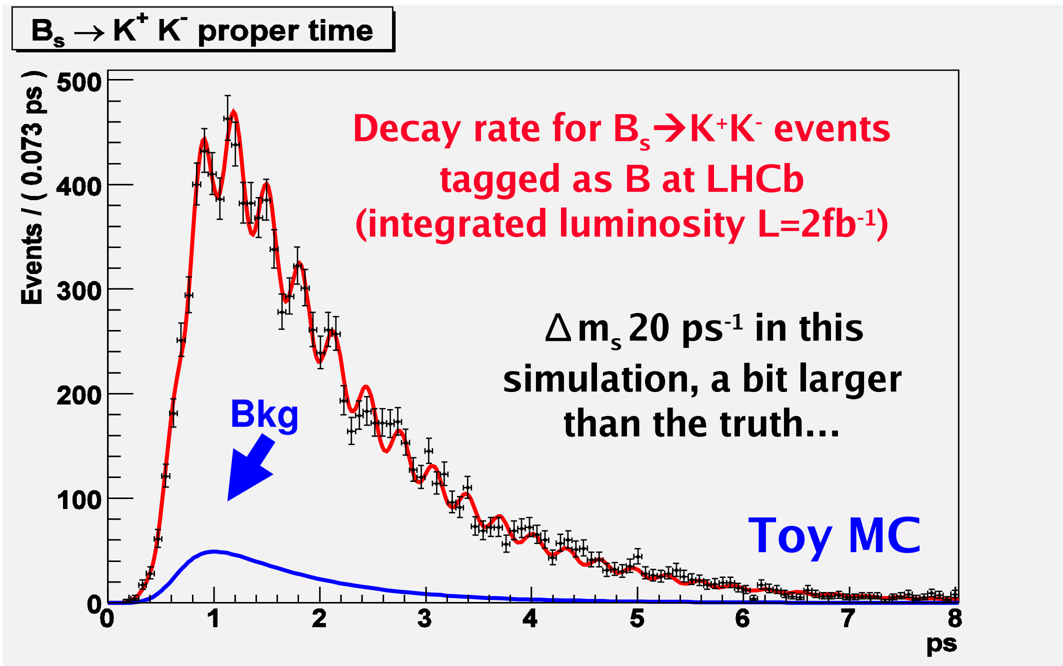


Nominal mass resolution of σ=16 MeV/c^2 allows for a clean separation between the two signals

Proper time resolution

- Excellent proper time resolution allows to perfectly resolve the fast B_s oscillations
  - σ_t = ~40 fs (10 times less than the oscillation period actually)
- Calibration of proper time resolution on data is crucial!
  - will be done in LHCb by disentangling prompt $J/\psi \rightarrow \mu^+\mu^-$ from non-prompt component from B decays
  - The prompt component is affected just by the intrinsic resolution of the detector, hence can be used for calibration
  - "Lifetime unbiased" prompt J/ψ events will be acquired with dedicated high-mass di-muon trigger (600 Hz bandwidth)

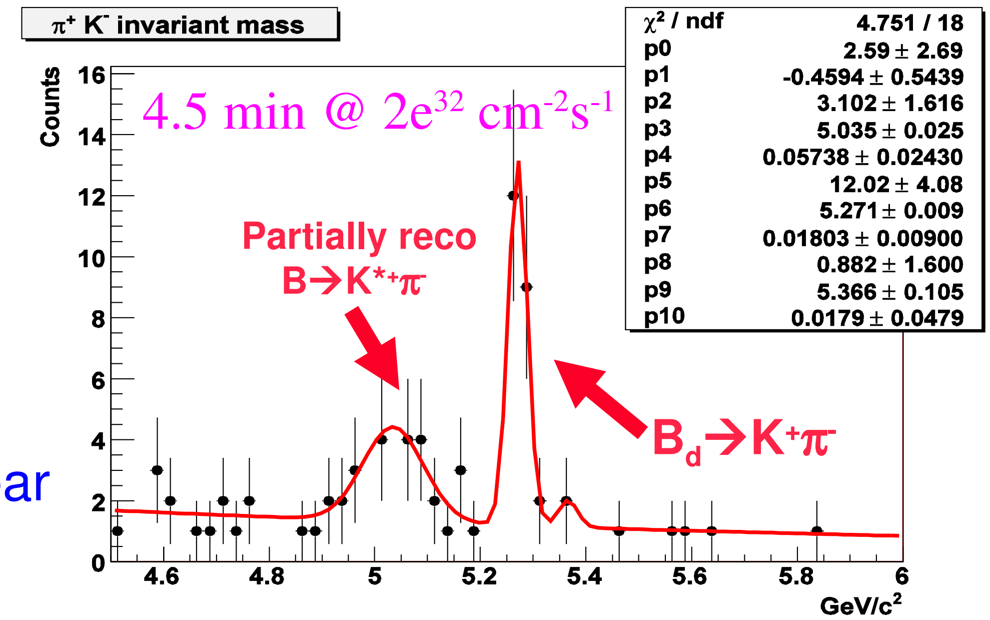




Selection performance

- Yields are calculated for an integrated luminosity of 2 fb^{-1}
  - 10^7 seconds at nominal LHCb luminosity
- Limited background-to-signal ratios
  - Both combinatorial and from the other $B \to h^+h'^-$ modes (due to wrong particle ID
- Hundreds of thousands of $B \to h^+h'^-$ decays triggered, reconstructed and selected per year of running with high degree of purity!

πK spectrum selected from a sample of 27M $b\bar{b}$ MC events



	$\epsilon_{tot} = \epsilon_{gen} \times \epsilon_{sel/gen} \times \epsilon_{trg/sel}$				BR 10^{-6}	Yield	B/S bb	B/S spec
	ϵ_{gen}	$\epsilon_{sel/gen}$	$\epsilon_{trg/sel}$	ϵ_{tot}				
$B_d^0 \to \pi^+\pi^-$	34.9 ± 0.3	7.36 ± 0.13	36.3 ± 1.1	0.93 ± 0.03	4.8	35700	0.46	0.08
$B_d^0 \to K^+\pi^-$	34.9 ± 0.3	7.21 ± 0.07	36.8 ± 0.6	0.93 ± 0.02	18.5	137600	0.14	0.02
$B_s^0 \to \pi^+K^-$	34.8 ± 0.3	7.25 ± 0.30	40.6 ± 2.3	1.02 ± 0.06	4.8	9800	1.92	0.54
$B_s^0 \to K^+K^-$	34.8 ± 0.3	7.11 ± 0.13	39.3 ± 1.2	0.97 ± 0.03	18.5	35900	< 0.06	0.08
$\Lambda_b \to p\pi^-$	34.6 ± 0.3	7.20 ± 0.26	38.3 ± 2.3	0.95 ± 0.06	4.8	9100	1.66	0.11
$\Lambda_b \to pK^-$	34.6 ± 0.3	6.80 ± 0.13	36.0 ± 1.1	0.86 ± 0.03	18.5	31800	< 0.08	0.02

Flavour Tagging

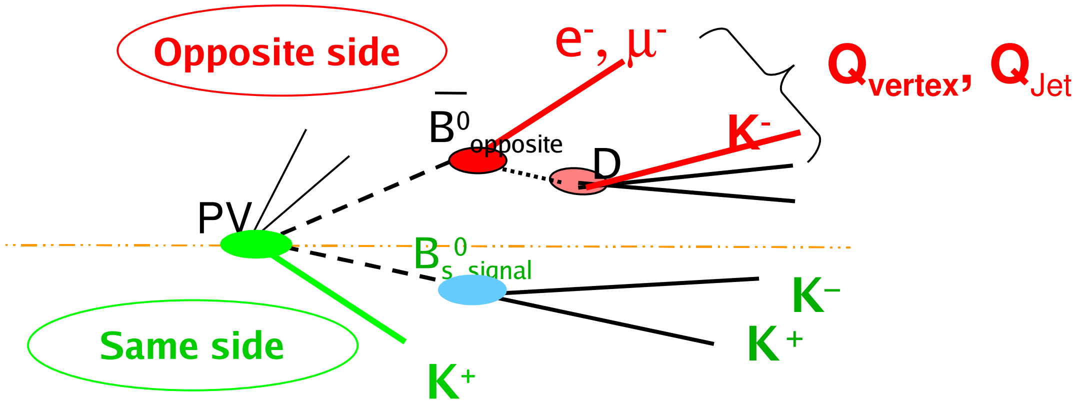
Opposite side
- High p_T leptons
- $K^{\pm}$ from $b \to c \to s$
- Vertex charge
- Jet charge

Same side
- Fragmentation $K^{\pm}$ accompanying B_s
- $\pi^{\pm}$ from $B^{**} \to B^{(*)}\pi^{\pm}$

$\varepsilon D^2 = \varepsilon(1-2\omega)^2$: tagging power

ε: tagging efficiency

ω: mistag probability



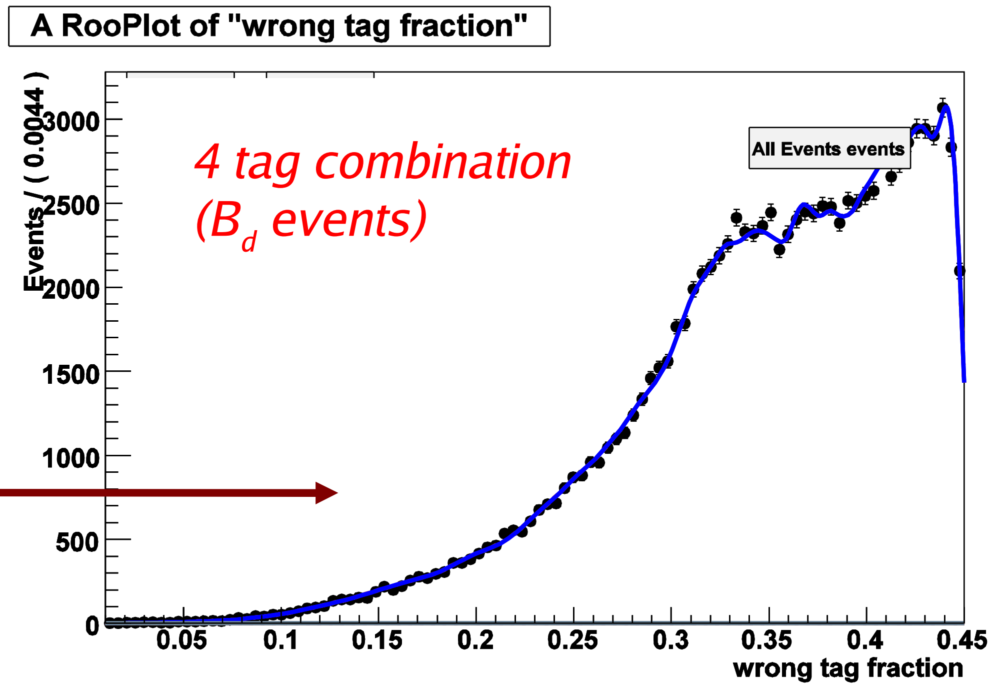
Tagging power in %

Tag	B_d	B_s
Muon	1.1	1.5
Electron	0.39	0.69
Kaon opp.side	2.1	2.3
Jet/ Vertex Charge	1.0	0.97
Same side π / K	0.73 (π)	3.5 (K)
Combined (NNET)	5.05	9.5

Work in continuous progress.

Flavour Tagging (II)

- Strategy I:
  - Define N different tagging categories and use various fixed ω_N
- Strategy II:
  - Extract from kinematic variables the per event ω : $P(\omega) = P(\omega|p,\ldots)P(p)$



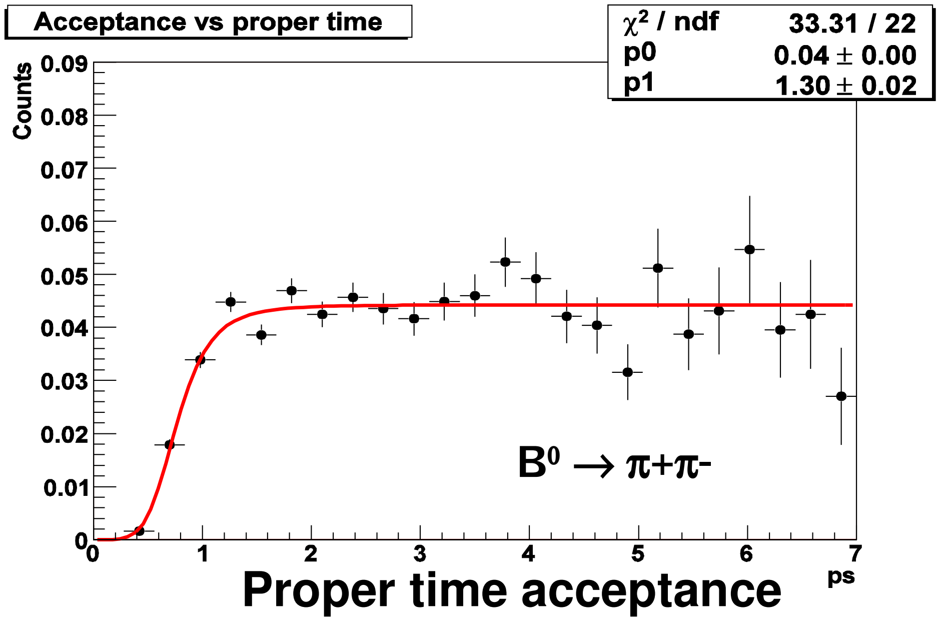
In both cases, control samples are needed in order to evaluate ω

$\omega_{(N)}$ can be extracted from data using B^+ (ex. $B^+ \to J/\psi K^+$, $B^+ \to D^0 \mu\nu$) or B^0 flavour-specific ($B^0 \to K^+\pi^-$, $B^0 \to J/\psi K^{*0}$, $B^0 \to D^{*-}\mu^+\nu$) decays

For the K_{ss}, BR($B_s \to \pi K$) is too low. ω_{ss} can be fixed to the value extracted from $B_s \to D_s\pi$ or $B_s \to D_s\mu\nu$ events.

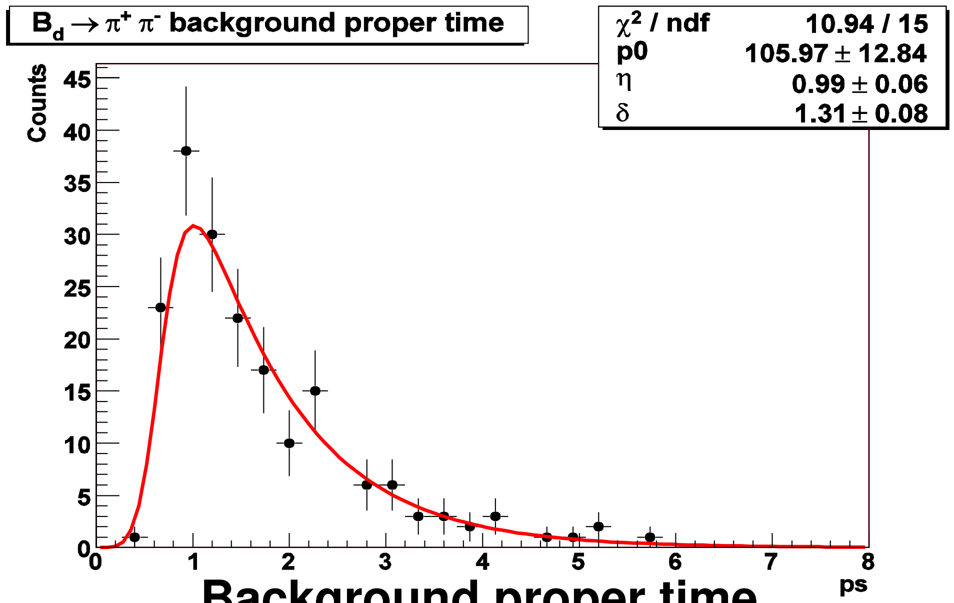
Toy MC generation

- A toy MC is used in order to generate large samples of signal and background events for estimating sensitivities on CP parameters from time dependent decay rate fits
- Signal samples generated simulating CP violation, proper time acceptance, proper time resolution and tagging
  - For each event the toy MC generates mass, proper time, tagging response, PID response according to the results from the full GEANT4 simulations
- Background mass and proper time spectra generated according to result from the full simulation



Proper time acceptance

will be calibrated on real data using event by event acceptance functions – studies going on in LHCb



Background proper time

will be well known from real data using mass sidebands

Sensitivity on CP asymmetries

- CP sensitivities are then estimated with an extended unbinned maximum likelihood fit to the toy MC sample
- The likelihood fit is performed simultaneously to all the B→hh' channels, including tagged and untagged samples
- C and S coefficients for $B_d \to \pi^+\pi^-$ and $B_s \to K^+K^-$ events tagged as B (q=+1) or $\overline{B}$ (q=–1) are given by

$$\lambda_f = \frac{q}{p}\frac{\overline{A}_f}{A_f}; \quad f = \pi^+\pi^-, K^+K^-; \quad C_f = \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2}; \quad S_f = \frac{2Im\lambda_f}{1+|\lambda_f|^2}$$

LHCb can reach a sensitivity, on B_d modes, about 3 times better than the current world average in 10^7 s of running at nominal luminosity

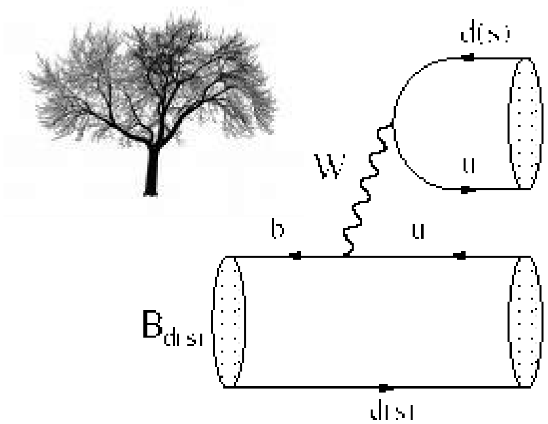
Fit results corresponding to Int. L=2fb^{-1} (10^7 seconds at nominal LHCb luminosity)

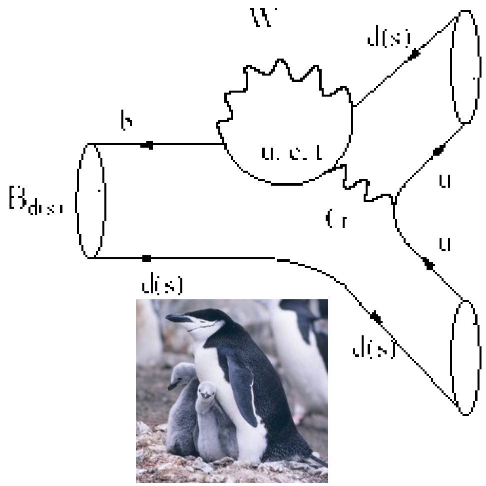
	$B_d \to \pi^+\pi^-$	$B_s \to K^+K^-$
σ(C)	0.043 (0.10*)	0.042
σ(S)	0.037 (0.12*)	0.044

	$B_d \to K^+\pi^-$	$B_s \to \pi^+K^-$
$\sigma(A_{CP})$	0.003 (0.015*)	0.02

***Current world average**

Trees, penguins and gamma





Sensitivity to γ from the interference of T and P amplitudes

- d, d': penguin-to-tree ratios
- θ, θ': penguin-tree strong phase differences

$$A(B^0 \to \pi^+\pi^-) = K(e^{i\gamma} - de^{i\theta})$$

$$A(B_s^0 \to K^+K^-) = \frac{\lambda}{1-\lambda^2/2} K'(e^{i\gamma} + \frac{1-\lambda^2}{\lambda^2} d' e^{i\theta'})$$

Sensitivity to γ doubly Cabibbo suppressed in this mode ☹

Using U-spin symmetry one gets d=d' and θ=θ'

Method and parametrization from
R. Fleischer, PLB 459 (1999) 306

Extraction of gamma

$$C(B_d^0 \to \pi^+\pi^-) = f_1(d,\theta,\gamma)$$

$$S(B_d^0 \to \pi^+\pi^-) = f_2(d,\theta,\gamma,\phi_d)$$

$$C(B_s^0 \to K^+K^-) = f_3(d',\theta',\gamma)$$

$$S(B_s^0 \to K^+K^-) = f_4(d',\theta',\gamma,\phi_s)$$

$$A_{CP}^{th}(\tau) = \frac{C \cdot cos(\Delta M \cdot \tau) - S \cdot sin(\Delta M \cdot \tau)}{cosh(\frac{\Delta\Gamma}{2} \cdot \tau) - A_{\Delta\Gamma} \cdot sinh(\frac{\Delta\Gamma}{2} \cdot \tau)}$$

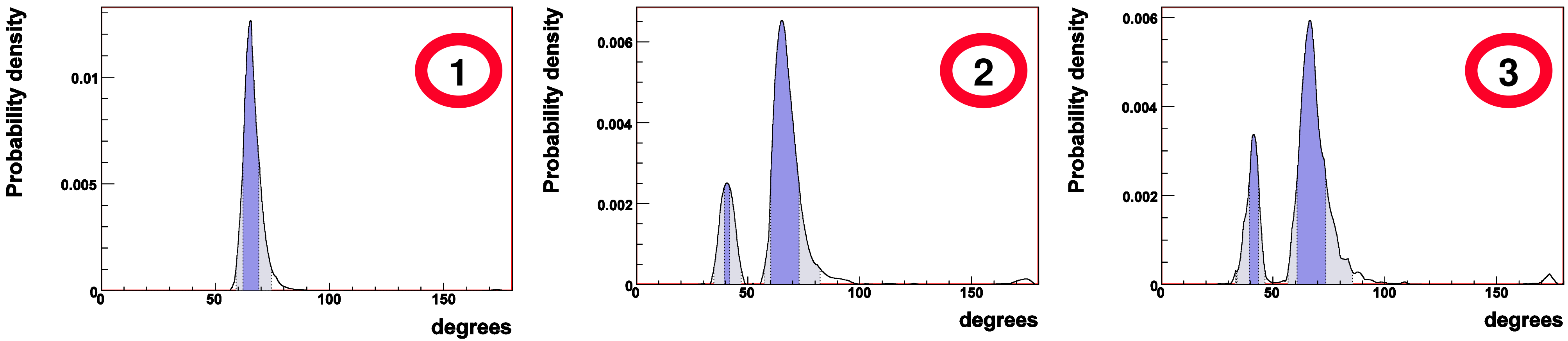
Once the direct and mixing-induced CP-violating terms are measured, one has a system of 7 unknowns and 4 equations

However, the mixing phase ϕ_d (ϕ_s) is (will be) measured from $B_d \to J/\psi K_S$ ($B_s \to J/\psi\phi$) → 5 unknowns

Relying on U-spin symmetry one eliminates two further unknowns → 3 unknowns, system over-constrained, γ can be extracted unambiguously

Sensitivity on gamma ($L=2fb^{-1}$)

- Extraction of γ performed with a Bayesian approach in 3 different scenarios (in this exercise $\gamma=65^o$ is assumed)
  - (1) Perfect U-spin symmetry
    - i.e. using the constraints $d=d'$; $\theta = \theta'$
  - (2) Weaker assumption: perfect U-spin symmetry just for d, d'
    - $d=d'$; no constraint on θ, θ'
  - (3) Even weaker: given U-spin breaking for d, d'
    - $\xi = d'/d = [0.8, 1.2]$; no constraint on θ, θ'



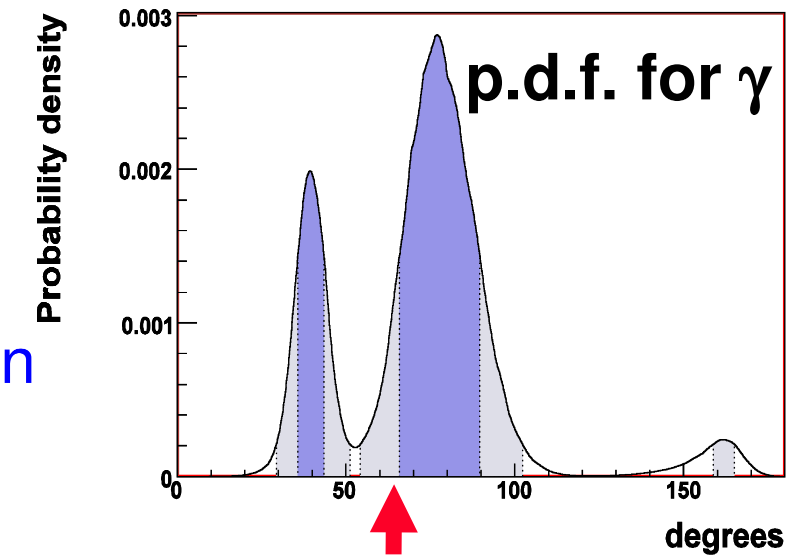
Sensitivity ranging from ~4° in case of perfect U-spin assumed, to 7°-10° partially releasing U-spin assumptions (but a secondary fake solution appears)

Exercise: using world averages

(not using LHCb results)

- Instead of using the $B_s \rightarrow K^+K^-$ one can make use of the $B_d \rightarrow K^+\pi^-$
  - It just differs for the spectator quark, but neglecting penguin annihilation and exchange diagrams which are not present in $B_d \rightarrow K^+\pi^-$
  - Assuming U-spin symmetry the cosine term of the time dependent asymmetry of $B_s \rightarrow K^+K^-$ is equal to the charge asymmetry of $B_d \rightarrow K^+\pi^-$, thus we can replace C_{KK} with $A_{K\pi}$
  - One observable is missing (S_{KK}), but still can solve system of contraints for γ

- Current world averages from HFAG
  - $C_{\pi\pi}$ = -0.37 ± 0.10 (BaBar/Belle)
  - $S_{\pi\pi}$ = -0.50 ± 0.12 (BaBar/Belle)
  - $A_{K\pi}$ = -0.093 ± 0.015 (BaBar/Belle/CLEO/CDF)
- p.d.f. for γ obtained allowing for a U-spin breaking
  - $\Delta\theta = \theta' - \theta = \pm 20^o$
  - $\xi = d'/d = [0.8, 1.2]$



Conclusions

- LHCb will collect large samples of $B \to h^+h'^-$ decays
  - Its excellent vertexing and PID capabilities will allow to collect several hundreds of thousands of $B\to h^+h'^-$ events with very high purity
- The CP sensitivity reachable on B_d modes (10^7 s of data taking, L = $2\cdot10^{32}$ cm^{-2}s^{-1}) is ~3 times better than the current world averages (B factories, Tevatron)
- Besides the general interest of measuring CP violation for these channels, especially for the still unmeasured B_s decays, the $B \to h^+h'^-$ modes can provide useful information to constrain the CKM angle
  - By relating the B_d and B_s decay modes by means of the U-spin flavour symmetry (even allowing a symmetry breaking to some extent it is still possible to extract useful information)
- The extraction of γ from these decays can reveal contributions from NP
  - γ obtained from these decay modes might thus be different from γ from tree level modes, such as $B \to DK$