$B^0_{(s)} \to h^+h'^-$ prospects at LHCb

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Outline

- $B \rightarrow h^+h'^-$ channels and U-spin symmetric modes
- Event selection
- Sensitivity on direct and mixing induced CP violation parameters
- Extraction of the γ angle of the unitarity triangle
- Conclusions

Why $B \to h^+ h'^-$ decays interesting?

- **Since the original CLEO measurement that $BR(B_d \to K^+\pi^-)$ is ~4 times larger than $BR(B_d \to \pi^+\pi^-)$, 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**
- **This way, the presence of penguins can be transformed from a problem to an opportunity**
  - **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, which are basically unaffected from NP**

U-spin (d←→s quark exchange) symmetric modes

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

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~10^{-8})

B→$h^+h'^-$ events produced at LHCb

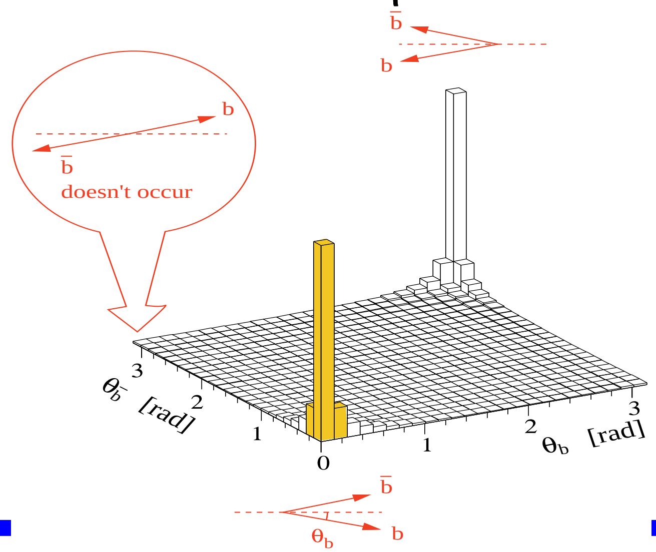
- **Large beauty production cross section expected at 14 TeV p-p collisions**
  - All b-hadron species produced
- **B hadrons are produced very likely with a small relative angle and in the very forward (backward) region**
  - LHCb uses just the forward direction 1.8 < η < 4.9

$$B^+, B_d^0, B_s^0, B_c, \Lambda_b, ...$$

~40% ~40% ~10% ~10%

$$\sigma_{b\bar{b}} \approx 500\ \mu b \qquad \frac{\sigma_{b\bar{b}}}{\sigma_{inelastic}} \approx 0.006$$

$$\sigma_{inelastic} \approx 80\ mb$$

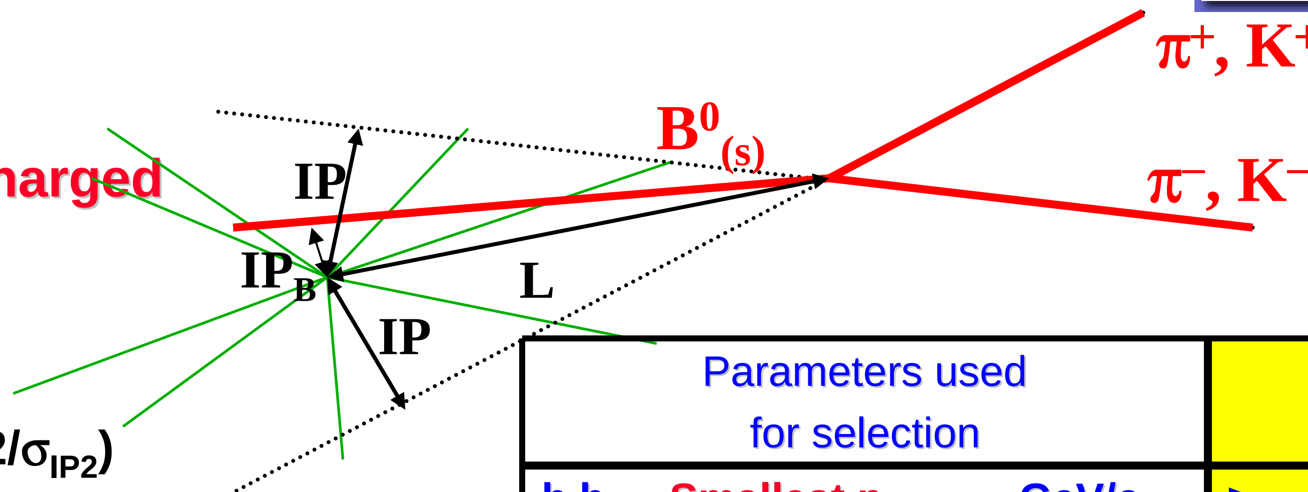


- **At the nominal LHCb luminosity $\mathcal{L}$=2x10^{32} cm^{-2}s^{-1} about 10^{12} B events are produced in 10^7 s**
  - B→$h^+h'^-$ channels have typical branching ratios in the range 10^{-5} - 10^{-6}
    - Millions of such events produced per year!

Event simulation

- **Event generation using Pythia 6.3 with dedicated LHCb tuning**
- **Full GEANT4 simulation and Pattern Recognition**
- **Problem: how to estimate combinatorial background-to-signal ratios before data comes?**
  - **Expected beauty production cross section is about 100 times less than visible cross section in the detector (~0.5 mb vs ~65 mb), and branching ratios of interest at 10^{-5}-10^{-6}**
  - **The number of minimum bias events equivalent to signal events necessary to be generated and processed through GEANT4 is out of reach**
- **In order to study the combinatorial background we make the reasonable assumption that the dominant source comes from beauty events, thus reducing by a factor 100 the number of simulated events**
  - **Still a computing challenge, but affordable with currently available resources on the LCG**
- **For this study about 300k signal events and 27M inclusive beauty events have been used**

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

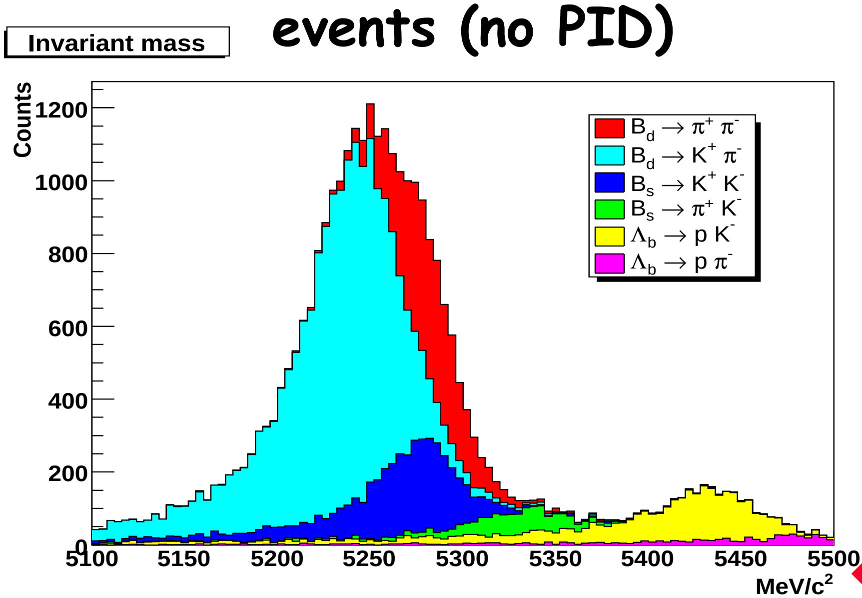


- **For each pair of charged tracks we cut on**
  - max (p_{T1}, p_{T2})
  - min (p_{T1}, p_{T2})
  - max ($IP1/\sigma_{IP1}$, $IP2/\sigma_{IP2}$)
  - min ($IP1/\sigma_{IP1}$, $IP2/\sigma_{IP2}$)
  - χ^2 of common vertex
- **Then, the B candidate is selected with cuts on**
  - p_T
  - IP/σ_{IP}
  - L/σ_L

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

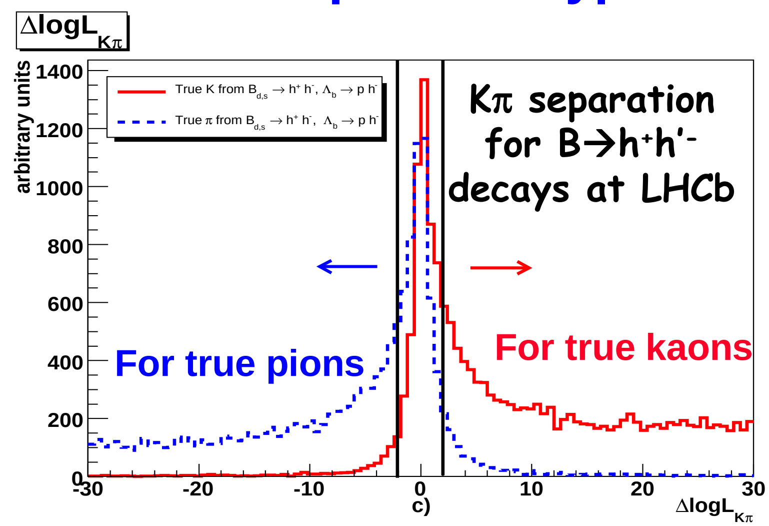
Particle identification p/K/π

Invariant mass of selected events (no PID)



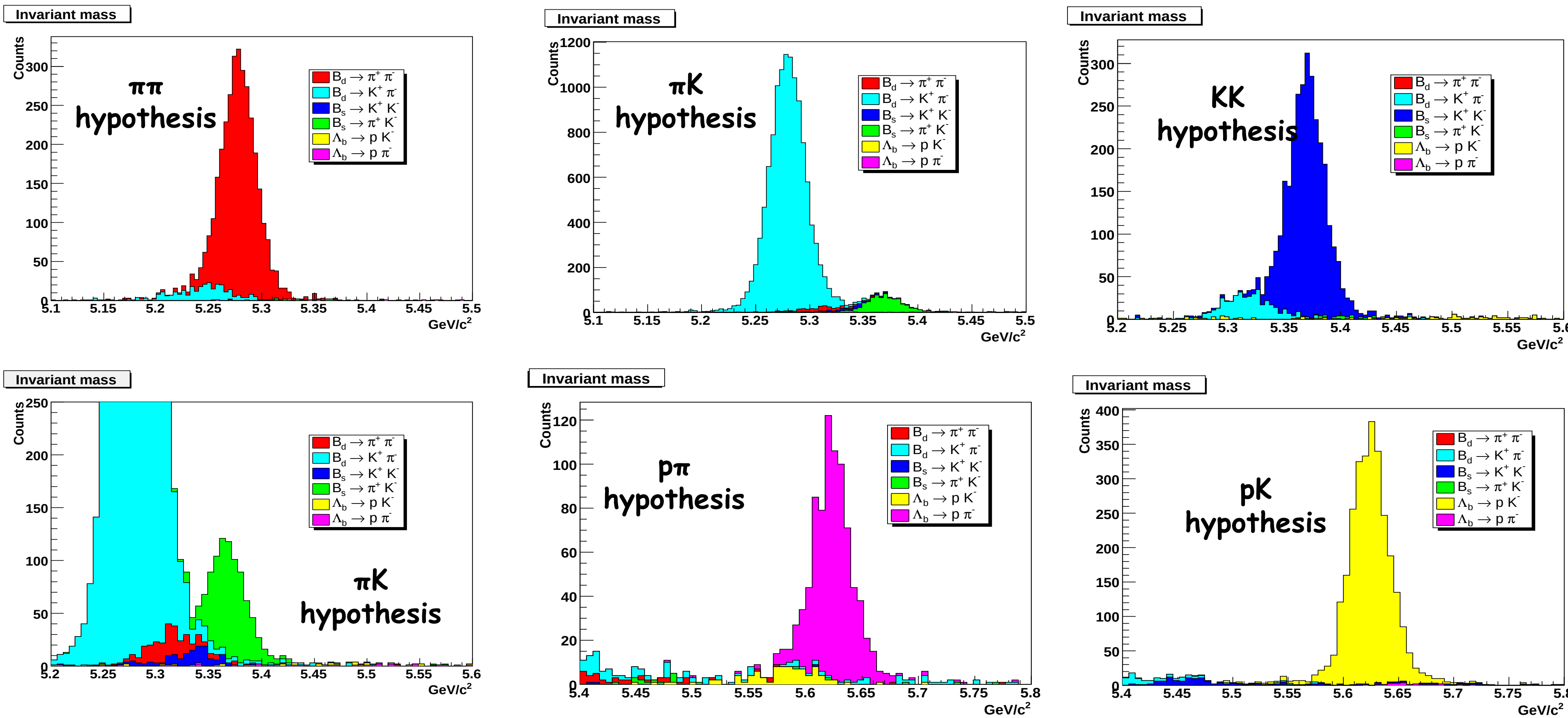
Channel	BR $\times 10^6$	
$B^0 \to \pi^+ \pi^-$	4.8	measured
$B^0 \to K^+ \pi^-$	18.5	measured
$B^0_s \to \pi^+ K^-$	4.8	assumed
$B^0_s \to K^+ K^-$	18.5	assumed
$\Lambda_b \to \pi^- p$	4.8	assumed
$\Lambda_b \to K^- p$	18.5	assumed

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



- **Efficient hadron PID crucial for the B→$h^+h'^-$ 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) - see talk by Raluca Muresan

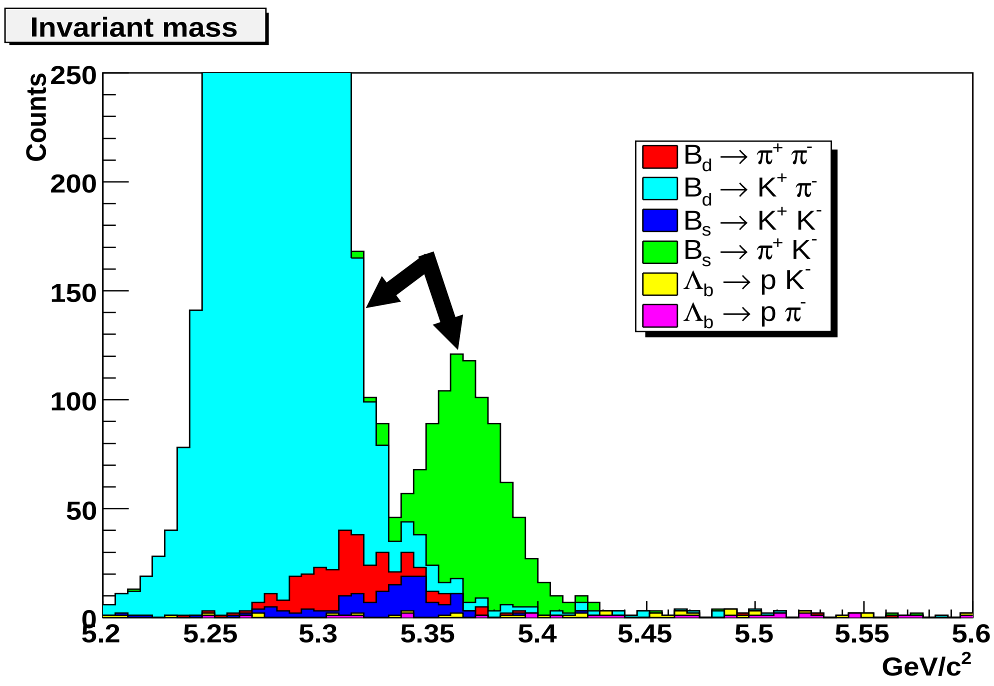
Performance of hadron PID: invariant mass spectra



- Every $h^+h'^-$ channel is potentially a background for the other channels…
- …but impressive performance of RICH systems allows to select very clean samples

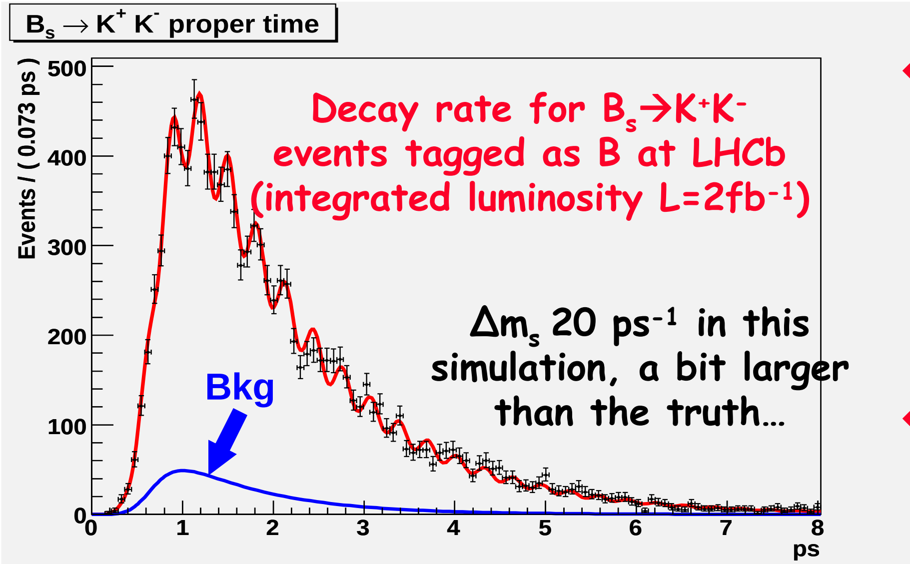
Importance of good mass resolution

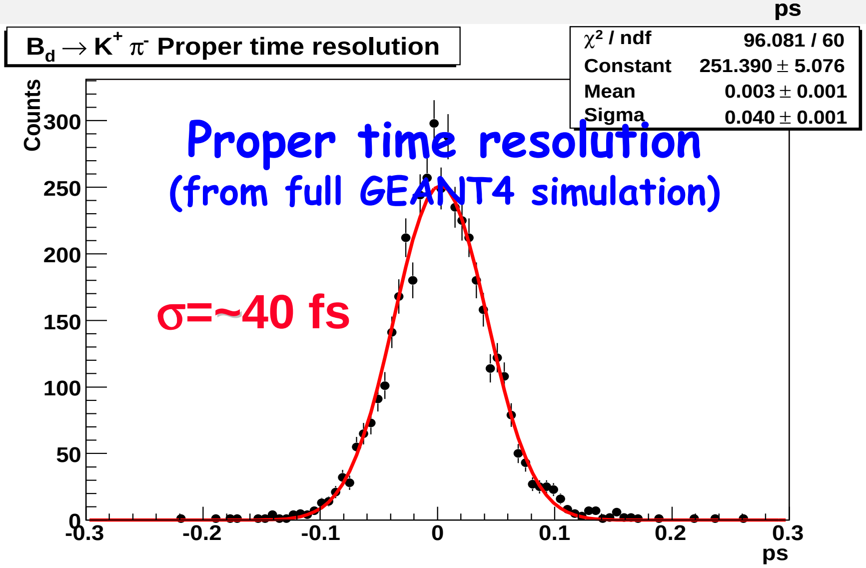
- Discrimination of $B_s \to \pi^+ K^-$ from $B_d \to K^- \pi^+$ must rely on mass resolution only since they share exactly the same signature
  - $B_d \to K^- \pi^+$ about 16 more abundant
    - 4 times larger branching fraction, 4 times large hadronization fraction



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

Proper time resolution





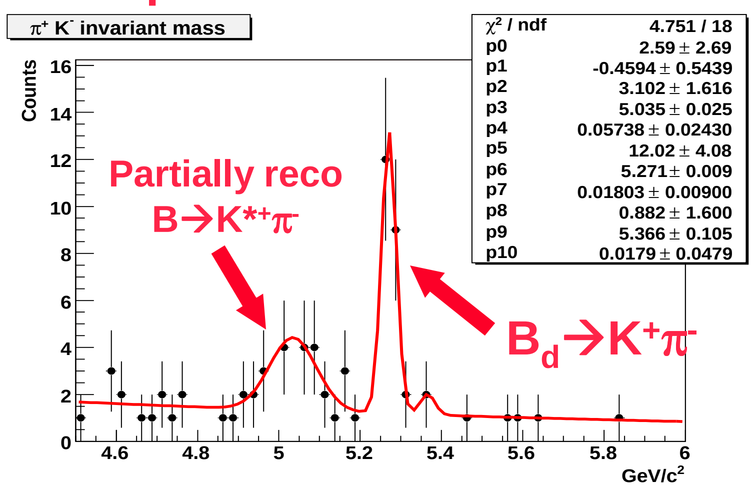
- **Excellent proper time resolution allows to perfectly resolve the fast B_s oscillations**
  - σ_t = ~40 fs
    - almost 10 times less than the oscillation period actually
- **Calibration of proper time resolution on data very important to achieve in order not to be dependent on MC imperfections**
  - will be done in LHCb by disentangling prompt $J/\psi \to \mu^+\mu^-$ 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 summary

	$\epsilon_{tot} = \epsilon_{gen} \times \epsilon_{sel/gen} \times \epsilon_{trg/sel}$				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

- **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!**

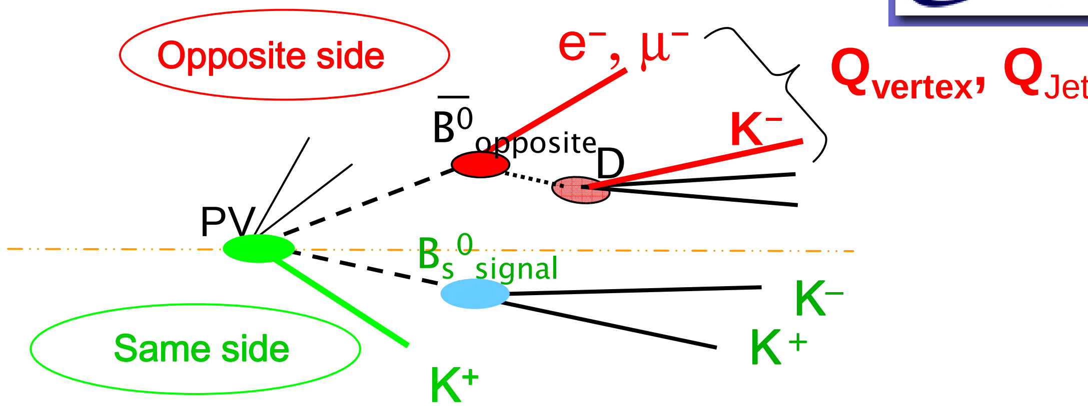
πK spectrum selected from a sample of 27M $b\bar{b}$ MC events



Flavour tagging

Opposite side

- **High p_T leptons**
- **$K^\pm$ from $b \rightarrow c \rightarrow s$**
- **Vertex charge**
- **Jet charge**



Same side

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

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

ε: tagging efficiency

ω: mistag probability

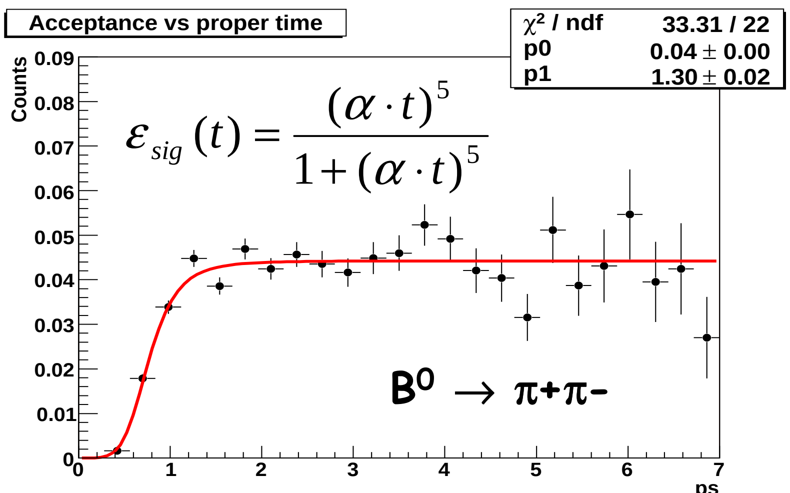
Tagging power in %

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	5.05	9.5

Work in continuous progress.
See talk on LHCb tagging by Hugo Ruiz

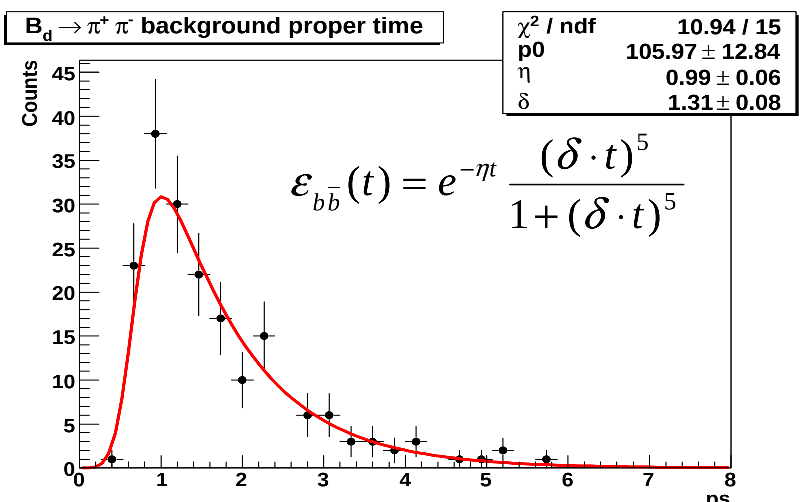
Toy MC generation for CP sensitivity studies

- 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

Maximum likelihood fit

- 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
  - The various channels and background are then separated each-other in the fit by means of the particle ID observables and invariant mass
- In particular, the decay rate for $B_d \to \pi^+\pi^-$ and $B_s \to K^+K^-$ events tagged as B (q=+1) or $\bar{B}$ (q=-1) entering the likelihood is given by

$$F(t,q) = \left(1+|\lambda_f|^2\right)\cosh\frac{\Delta\Gamma}{2}t - 2\Re e(\lambda_f)\sinh\frac{\Delta\Gamma}{2}t + q\cdot(1-2\omega)\cdot\left[\left(1-|\lambda_f|^2\right)\cos\Delta m t - 2\Im m(\lambda_f)\sin\Delta m t\right]$$

$$\lambda_f = \frac{q}{p}\frac{\bar{A}_f}{A_f} \qquad f = \pi^+\pi^-, K^+K^-$$

- The usual C and S coefficients are related to λ_f by

$$C_f = \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2} \qquad S_f = \frac{2\Im m\lambda_f}{1+|\lambda_f|^2}$$

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

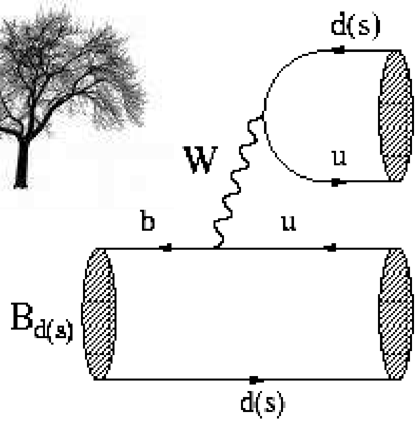
Fit results corresponding to Int. L=2fb^{-1} (10^7 seconds at nominal LHCb luminosity)

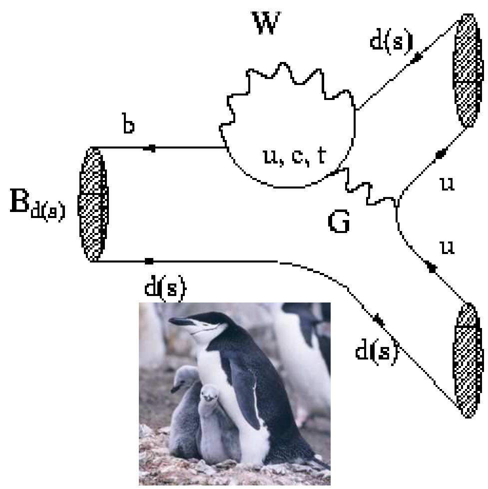
	$B_d \to \pi^+\pi^-$	$B_s \to K^+K^-$
σ(C)	0.043 (0.10*)	0.042
σ(S)	0.037 (0.12*)	0.044

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

*Current world average

Tree, penguins and… γ





- **Sensitivity to γ from the interference of T and P amplitudes**
  - **d, d': penguin-to-tree ratios**
  - **θ, θ': penguin-tree strong phase differences**

$$A\left(B^0 \to \pi^+\pi^-\right) = K\left(e^{i\gamma} - d e^{i\vartheta}\right)$$

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

Sensitivity to γ doubly Cabibbo suppressed in this mode ☹

- **Relating by the U-spin symmetry the two amplitudes one gets d=d' and θ=θ'**

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

Extraction of γ

$$C(B_d^0 \to \pi^+\pi^-) = f_1(d,\vartheta,\gamma)$$
$$S(B_d^0 \to \pi^+\pi^-) = f_2(d,\vartheta,\gamma,\phi_d)$$
$$C(B_s^0 \to K^+K^-) = f_3(d',\vartheta',\gamma)$$
$$S(B_s^0 \to K^+K^-) = f_4(d',\vartheta',\gamma,\phi_s)$$

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

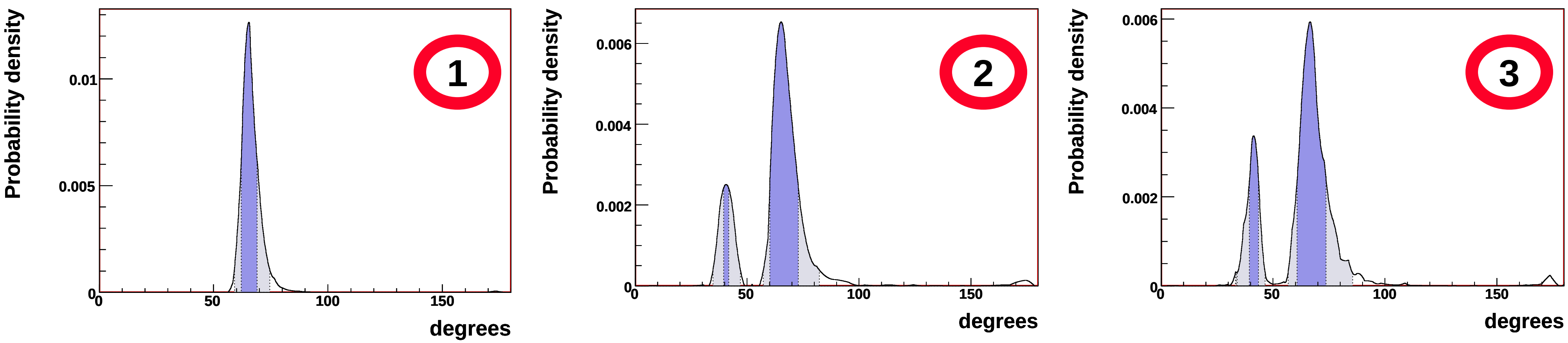
Once the direct and mixing-induced CP-violating terms are measured, one has a system of 7 unknowns and 4 equations

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

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

Sensitivity on γ (for L=2fb^{-1})

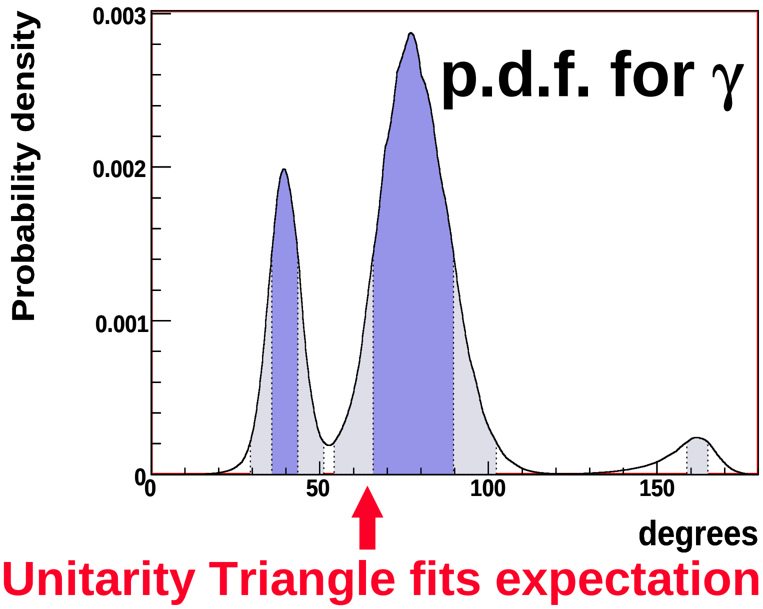
- **Extraction of γ performed with a Bayesian approach in 3 different scenarios (in this exercise γ=65^{o} is assumed)**
  - **(1) Perfect U-spin symmetry**
    - **i.e. using the constraints d=d' - $\theta = \theta'$**
  - **(2) Weaker assumption: perfect U-spin symmetry just for d, d'**
    - **d=d'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



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

An exercise: using current world averages of $B_d \to \pi^+\pi^-$ and $B_d \to K^+\pi^-$
(not using LHCb results)

- **Instead of using the $B_s \to K^+K^-$ one can make use of the $B_d \to K^+\pi^-$**
  - It just differs for the spectator quark, but neglecting penguin annihilation and exchange diagrams which are not present in $B_d \to K^+\pi^-$
  - Assuming U-spin symmetry the cosine term of the time dependent asymmetry of $B_s \to K^+K^-$ is equal to the charge asymmetry of $B_d \to K^+\pi^-$, thus we can replace C_{KK} with $A_{K\pi}$
  - However one observable is missing, since S_{KK} is unaccessible, but still can solve system of contraints for γ
- **Current world averages from HFAG**
  - $C_{\pi\pi} = -0.37 \pm 0.10$ (BaBar/Belle)
  - $S_{\pi\pi} = -0.50 \pm 0.12$ (BaBar/Belle)
  - $A_{K\pi} = -0.093 \pm 0.015$ (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 $B \rightarrow h^+h'^-$ decays**
  - Its excellent vertexing and PID capabilities will allow to collect several hundreds of thousands of $B \rightarrow h^+h'^-$ events with very high purity
- **The CP sensitivity reachable in 10^7 s of data taking at the nominal LHCb luminosity of $2 \cdot 10^{32}$ cm^{-2}s^{-1} is estimated to be about 3 times better than the current world averages from the beauty factories and the Tevatron**
- **Besides the general interest of measuring CP violation for these channels, especially for the still unmeasured B_s decays, the $B \rightarrow h^+h'^-$ modes can provide useful information to constrain the CKM angle γ**
  - This is accomplished by relating the B_d and B_s decay modes by means of the U-spin flavour symmetry
  - Even if the U-spin symmetry will result to be broken to some extent, we have shown how it is still possibile to extract useful information on γ in scenarios where the U-spin breaking is taken into account
- **The extraction of γ from these decays can reveal contributions from New Physics inside the loops of the penguin diagrams, which contribute significantly to the $B \rightarrow h^+h'^-$ modes**
  - γ obtained from these decay modes might thus be different from γ from tree level modes, such as $B \rightarrow DK$, which can be assumed to be basically free of New Physics contributions