# LHCb sensitivity to $\gamma$ with $B \rightarrow h^+h^-$ and U-spin Symmetry

**Laura Fabbri**
on behalf of the LHCb collaboration

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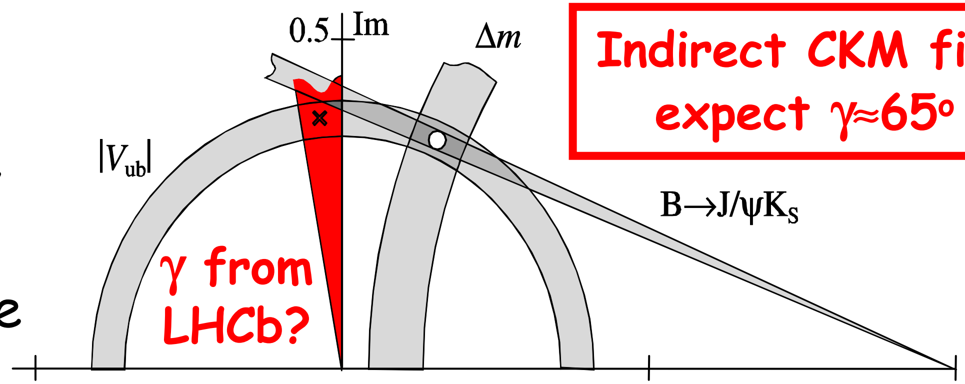
# Outline

- Physics motivation
  - Extraction of the weak phase $\gamma$ from the $B_d \rightarrow \pi^+\pi^-$ and $B_s \rightarrow K^+K^-$ decays
- $B_{d(s)} \rightarrow h^+h^-$ event selection
  - Strategy, event yields and background-to-signal ratios
- CP sensitivity
  - Bayesian determination of $\gamma$
- Conclusions

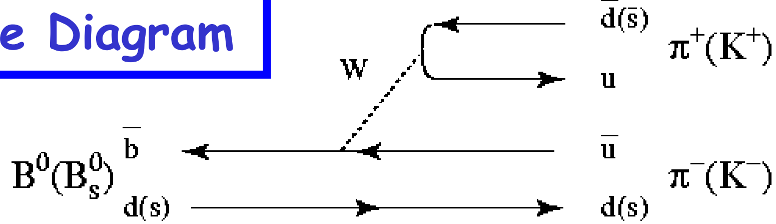
# CKM (new?) physics

- When LHCb starts taking data in 2007, sin2β will be already known with very good accuracy
- To isolate signals of new physics, it is crucial to measure the other two angles of the Unitarity Triangle, as γ ($\equiv -\arg V_{ub}$)
- In case of new physics, more complementary measurements of γ will help to understand where the new contributions come from
  - $B \to h^+ h^-$ have sizeable contribution from penguin graphs which may evidence new physics in loops

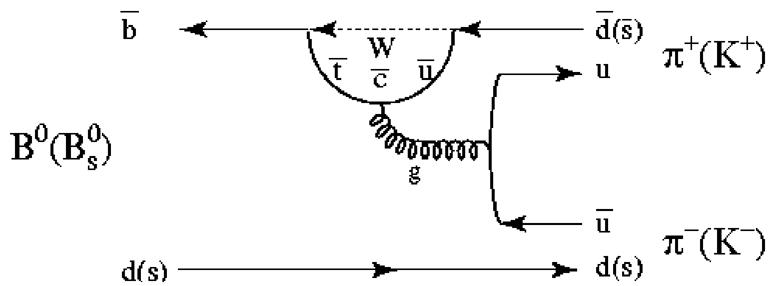
**Indirect CKM fits expect γ≈65°**




**Tree Diagram**




**Penguin Diagram**



# Extracting $\gamma$ from $B_d \to \pi^+\pi^-$ and $B_s \to K^+K^-$

$$A_{CP}(t) = \frac{\Gamma(\bar{B}^0_{(s)}(t) \to f) - \Gamma(B^0_{(s)}(t) \to f)}{\Gamma(\bar{B}^0_{(s)}(t) \to f) + \Gamma(B^0_{(s)}(t) \to f)} = \frac{A_{CP}^{dir} \cos \Delta m \cdot t + A_{CP}^{mix} \sin \Delta m \cdot t}{\cosh \frac{\Delta\Gamma}{2} \cdot t - A_{CP}^{\Delta\Gamma} \sinh \frac{\Delta\Gamma}{2} \cdot t}$$

$$A_{CP}^{dir}(B_d^0 \to \pi^+\pi^-) = f_1(d, \vartheta, \gamma)$$
$$A_{CP}^{mix}(B_d^0 \to \pi^+\pi^-) = f_2(d, \vartheta, \gamma, \phi_d)$$
$$A_{CP}^{dir}(B_s^0 \to K^+K^-) = f_3(d', \vartheta', \gamma)$$
$$A_{CP}^{mix}(B_s^0 \to K^+K^-) = f_4(d', \vartheta', \gamma, \phi_s)$$

$$de^{i\vartheta} = \frac{1}{R_b}\left(\frac{A_P^c - A_P^t}{A_T^u + A_P^u - A_P^t}\right) \sim \frac{P}{T}$$

$$R_b \equiv \frac{1}{\lambda}\left(1 - \frac{\lambda^2}{2}\right)\left|\frac{V_{ub}}{V_{cb}}\right|$$

$\phi_d = 2\beta$ $B_d$-$\bar{B}_d$ mixing phase (measured with $B_d \to J/\psi K_s$)

$\phi_s = -2\lambda^2\eta$ $B_s$-$\bar{B}_s$ mixing phase (can be probed with $B_s \to J/\psi\phi$)

4 equations and 5 unknowns: $d$, $\vartheta$, $d'$, $\vartheta'$ (hadronic parameters) and $\gamma$

**One needs other inputs to solve for $\gamma$**

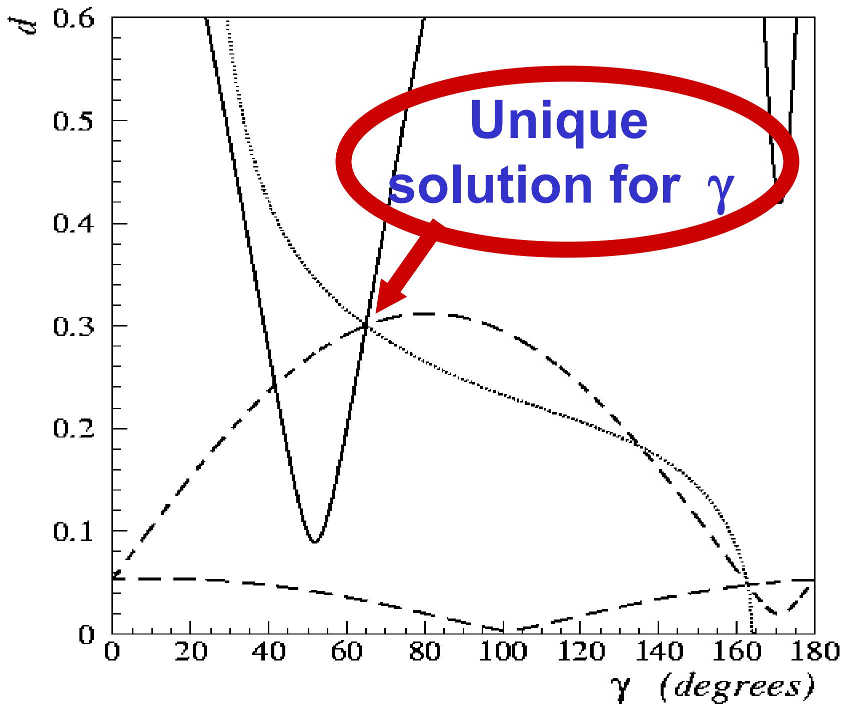
[R.Fleischer, Phys. Lett. B459 (1999)]

# Using U-spin Symmetry

$B_d \to \pi^+\pi^-$ ← U-spin (d,s quark exchange) → $B_s \to K^+K^-$

U-spin symmetry $\Rightarrow \begin{cases} d = d' \\ \vartheta = \vartheta' \end{cases}$ ➡

**6 eqs. and 5 unknowns**
**the system can be solved unambiguously**




—— $(A_{CP}^{dir}, A_{CP}^{mix})$ from $B^0 \to \pi^+\pi^-$

- - - $(A_{CP}^{dir}, A_{CP}^{mix})$ from $B_s^0 \to K^+K^-$

........ $A_{CP}^{dir}$ from $B^0 \to \pi^+\pi^-$ and $(A_{CP}^{dir}, A_{CP}^{mix})$ from $B_s^0 \to K^+K^-$

**In this example**

$\phi_d = 55^o,\ \phi_s = 0^o,\ d = d' = 0.3,$

$\vartheta = \vartheta' = 160^o,\ \gamma = 65^o$

# $B_{d(s)} \rightarrow h^+h^-$ event selection

- Selection cuts are simultaneously optimized in order to maximize $S / \sqrt{S + B}$
- Two major sources of backgrounds taken into account
  - **Combinatorial background from bb inclusive events**
    - Due to the huge minimum bias MC statistics required for a detailed study of combinatorial background, we make the plausible assumption that most of the combinatorial background will come from beauty events (presence of high $p_T$ and large IP tracks from B)
  - **Specific background from B decays with same two-track topology**
    - e.g. $B_d \rightarrow K^+\pi^-$, $B_s \rightarrow K^+K^-$, $B_s \rightarrow \pi^+K^-$ as backgrounds for $B_d \rightarrow \pi^+\pi^-$
- After event selection, tagging and trigger algorithms are tuned on selected events

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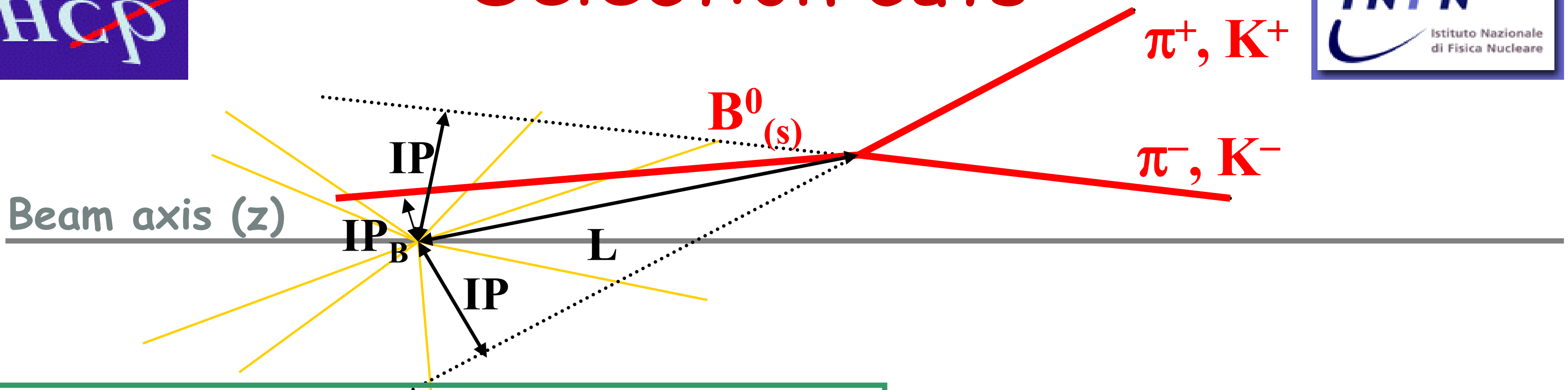
# Selection cuts



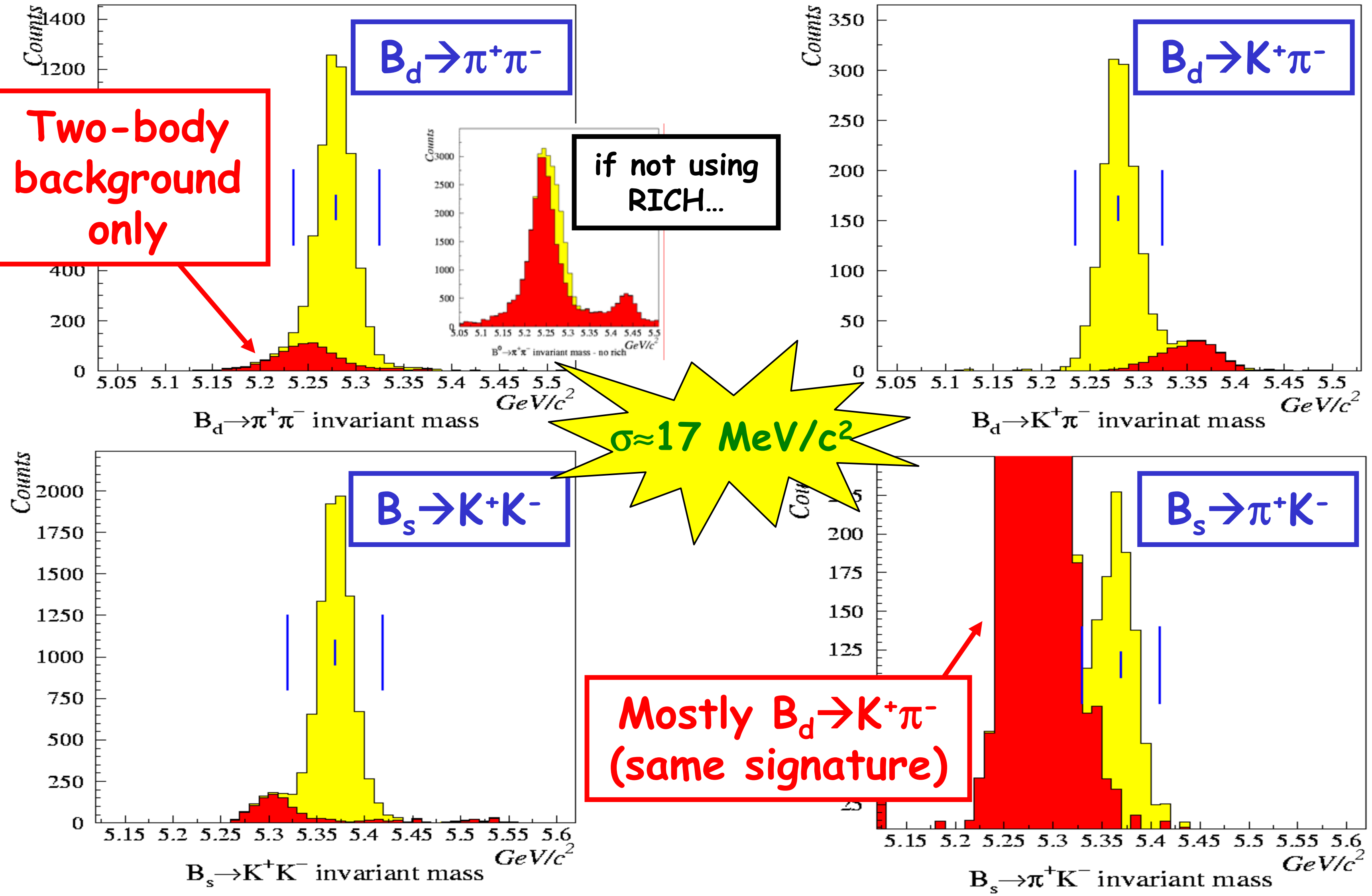

- Reconstruction and Particle ID
  - Each charged track identified as a Pion or Kaon using the Particle ID detectors (RICHs in particular)

- Selection cuts on identified tracks
  - p
  - $Max[p_T(h^+), p_T(h^-)]$
  - $Min[p_T(h^+), p_T(h^-)]$
  - $Max[IP/\sigma_{IP}(h^+), IP/\sigma_{IP}(h^-)]$
  - $Min[IP/\sigma_{IP}(h^+), IP/\sigma_{IP}(h^-)]$
  - $\chi^2$ of common vertex

- Selection cuts on the candidate B
  - $p_T$
  - $IP/\sigma_{IP}$
  - $L/\sigma_L$
  - Invariant mass

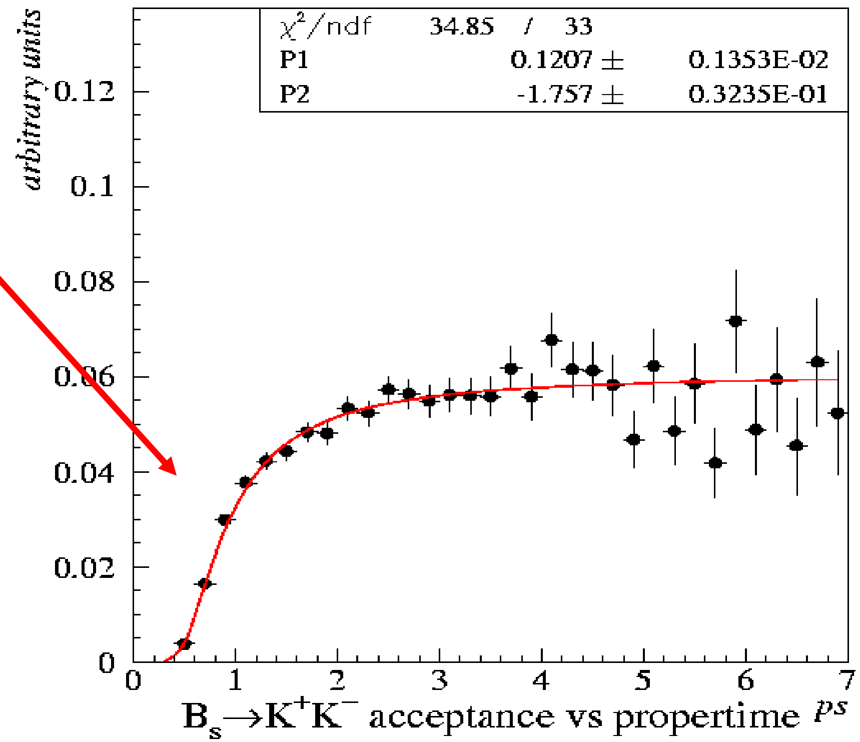
# Mass spectra

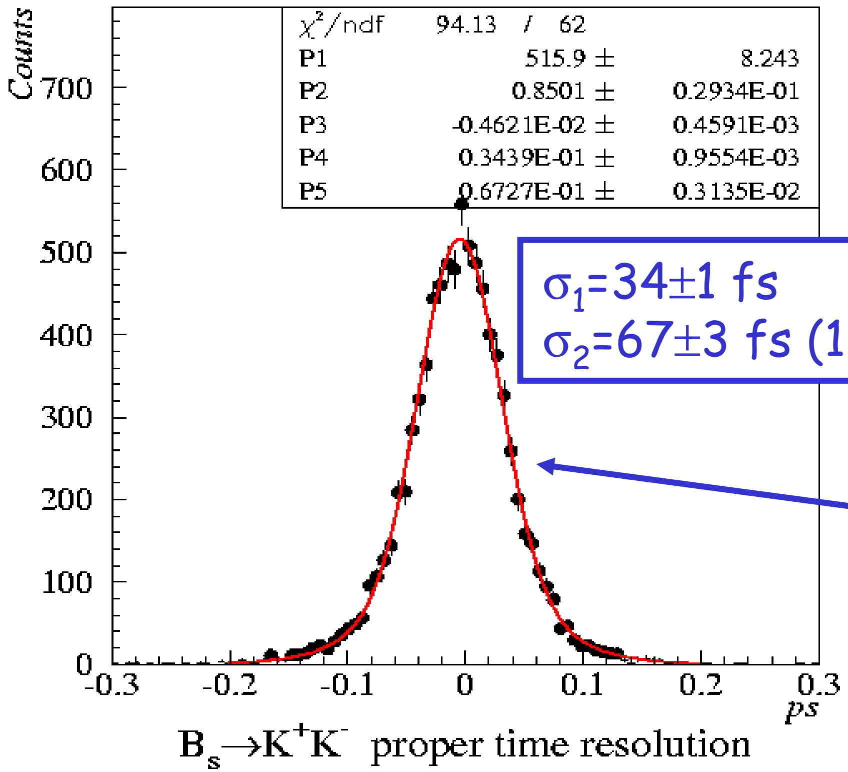
## signals + specific backgrounds only



# Proper time acceptance and resolution

**Acceptance suppression at low proper time due to cuts on IPs and distance of flight**




$\sigma_1$=34±1 fs
$\sigma_2$=67±3 fs (15%)

**Resolution on proper time fitted with double Gaussian (single Gaussian σ≈40 fs)**

# Signal yields and background-to-signal ratios

| Event type | Assumed BR ($\times 10^{-6}$) | $B_{b\bar{b}}/S$ | Untagged annual yield | $\varepsilon D^2$ |
|---|---|---|---|---|
| $B_d \to \pi^+\pi^-$ | 4.8 | 0.42 | 26000 | 4% |
| $B_d \to K^+\pi^-$ | 18.5 | 0.16 | 135000 | 4% |
| $B_s \to K^+K^-$ | 18.5 | 0.31 | 37000 | 6% |
| $B_s \to \pi^+K^-$ | 4.8 | 0.67 | 5300 | 6% |

- Annual yields after L0+L1 triggers and offline selection (assumed $\sigma_{b\bar{b}}$ = 0.5 mb and L = 2 $fb^{-1}$/yr)

# CP sensitivity studies Fast Monte Carlo Simulation

- In order to study the sensitivity on the $\gamma$ angle we generated many data samples, each corresponding to different settings of the relevant unknown parameters:
  - $\Delta M_{s,}$, $\Delta\Gamma_s$, d, $\vartheta$, etc.
- The Fast Monte Carlo produces proper time and invariant mass distributions $\{(t, m)_k; k=1, N\}$ of tagged B decays (combinatorial background included).
- The $\{(t, m)_k; k=1, N\}$ distributions are parameterized according to the proper time acceptance, resolution and invariant mass distributions obtained from the full GEANT simulation, which takes into account realistic pattern recognition, trigger and offline selection.

# Likelihood Fit

- In order to extract CP asymmetries and mistag fraction simultaneously from data we perform a combined extended unbinned maximum likelihood fit of $B_d \to \pi^+ \pi^-$ and $B_d \to K^+ \pi^-$ ($B_s \to K^+ K^-$ and $B_s \to \pi^+ K^-$) event samples (plus background)
  - $B_d \to K^+ \pi^-$ ($B_s \to \pi^+ K^-$) is a flavour specific decay and is used as control channel
    - $B_d \to \pi^+ \pi^-$ ($B_s \to K^+ K^-$ ) and $B_d \to K^+ \pi^-$ ($B_s \to \pi^+ K^-$) have the same two-track topology (same tagging power)
  - extract the wrong tag probability from data itself
  - The fit is performed against 17 parameters describing the shape of the decay rate and invariant mass distributions
- In particular we obtain the joint p.d.f. for the CP asymmetry coefficients $A^{dir}$ and $A^{mix}$
  - Bivariate gaussians $G_{\pi\pi}(A^{dir}, A^{mix})$ for the $B_d \to \pi^+ \pi^-$ and $G_{KK}(A^{dir}, A^{mix})$ for the $B_s \to K^+ K^-$

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# Bayesian approach to determine the γ p.d.f.

- To propagate the experimental joint p.d.f. for $A^{dir}$, $A^{mix}$, the weak mixing phases $\phi_d$ and $\phi_s$ to a joint p.d.f. for d, θ and γ the Bayesian approach is used:

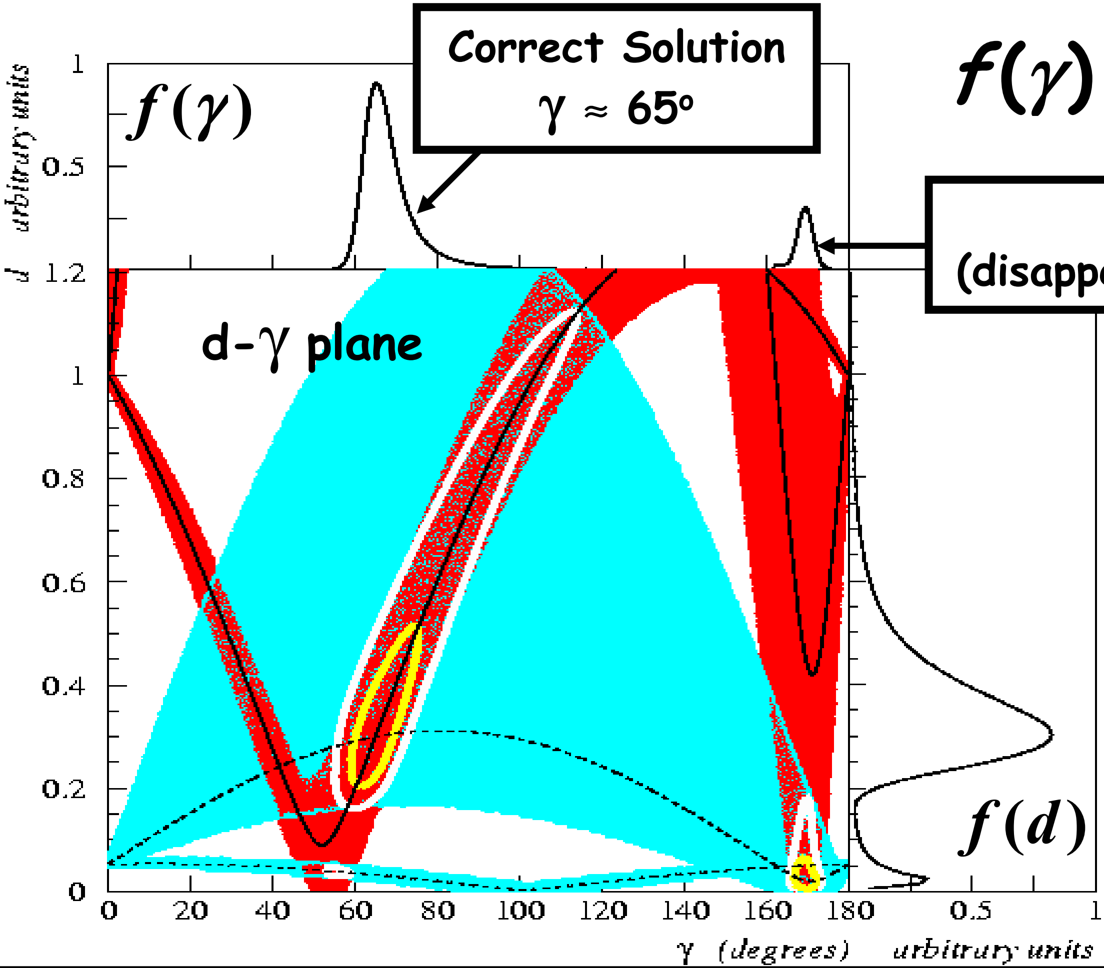
$$F(d,\vartheta,\gamma) = \iint G_{\pi\pi}\left(A_{\pi\pi}^{dir}(d,\vartheta,\gamma), A_{\pi\pi}^{mix}(d,\vartheta,\gamma,\phi_d)\right) \times$$
$$\times G_{KK}\left(A_{KK}^{dir}(d,\vartheta,\gamma), A_{KK}^{mix}(d,\vartheta,\gamma,\phi_s)\right) \times$$
$$\times g_0^d(\phi_d) \times g_0^s(\phi_s)\, d\phi_d d\phi_s$$

Exp. joint p.d.f. (bivariate gaussian) for $(A_{\pi\pi}^{dir}, A_{\pi\pi}^{mix})$ & $(A_{KK}^{dir}, A_{KK}^{mix})$

Gaussian priors for the weak mixing phases (from LHCb $B_d \to J/\psi K_S$ and $B_s \to J/\psi\phi$)

# Sensitivity on $\gamma$ from $B_d \to \pi^+\pi^-$ and $B_s \to K^+K^-$ (1 year)

$$f(\gamma) = \iint F(d, \vartheta, \gamma)\, \mathrm{d}d\, \mathrm{d}\vartheta$$




95% confidence region from $B_d \to \pi^+\pi^-$ only

95% confidence region from $B_s \to K^+K^-$ only

**Perfect U-spin**

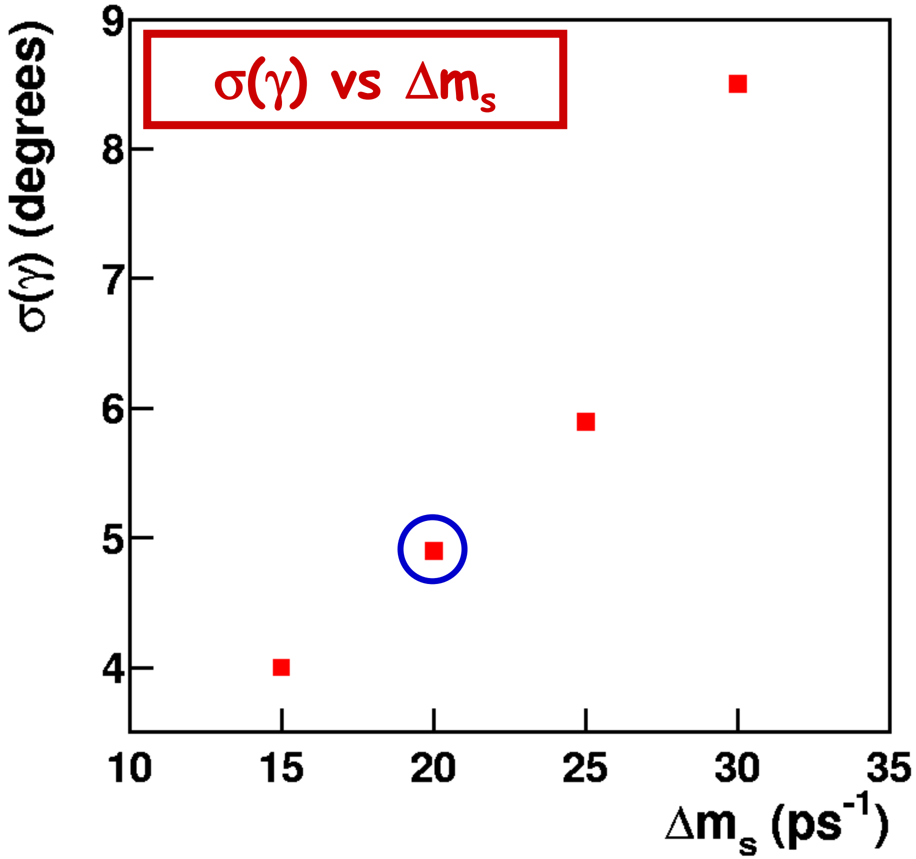
$\sigma(\gamma) \approx 5^o$

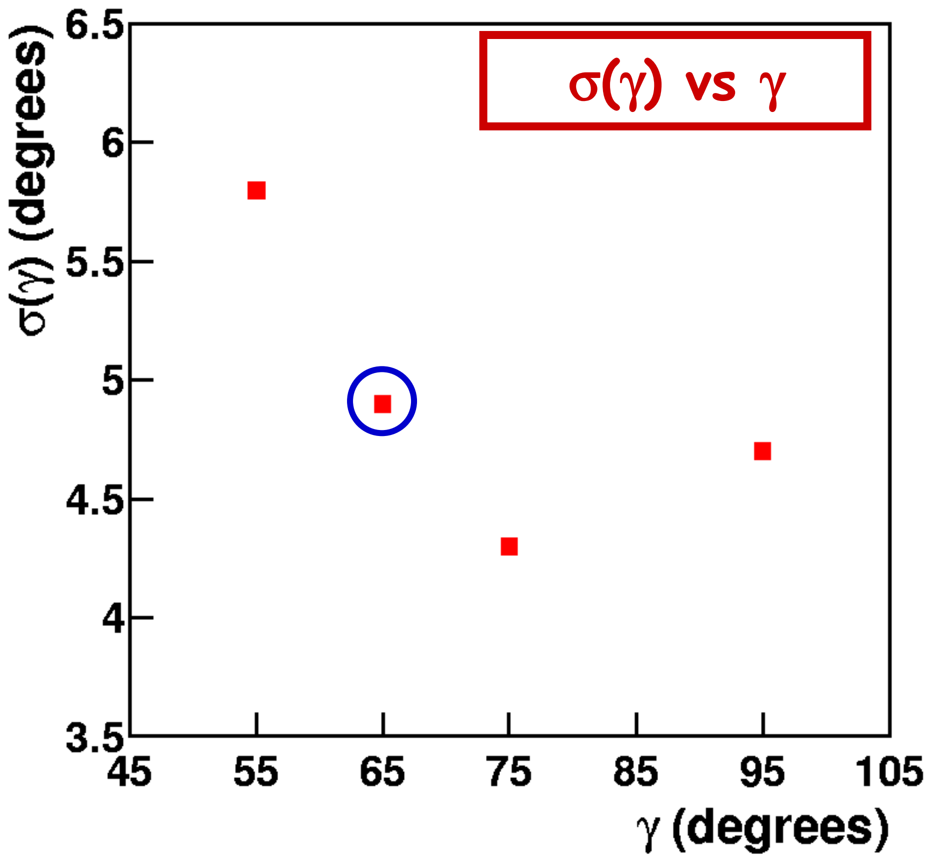
O(20%) U-spin breaking would induce only a few degrees shift on $\gamma$

*Yellow* and *White* contours: 68% and 95% confidence regions using all the information

# Sensitivity scan

d=0.3, θ= 160°, γ=65°,
$\phi_s$=-0.04°, $\Delta\Gamma_s/\Gamma_s$=0.1



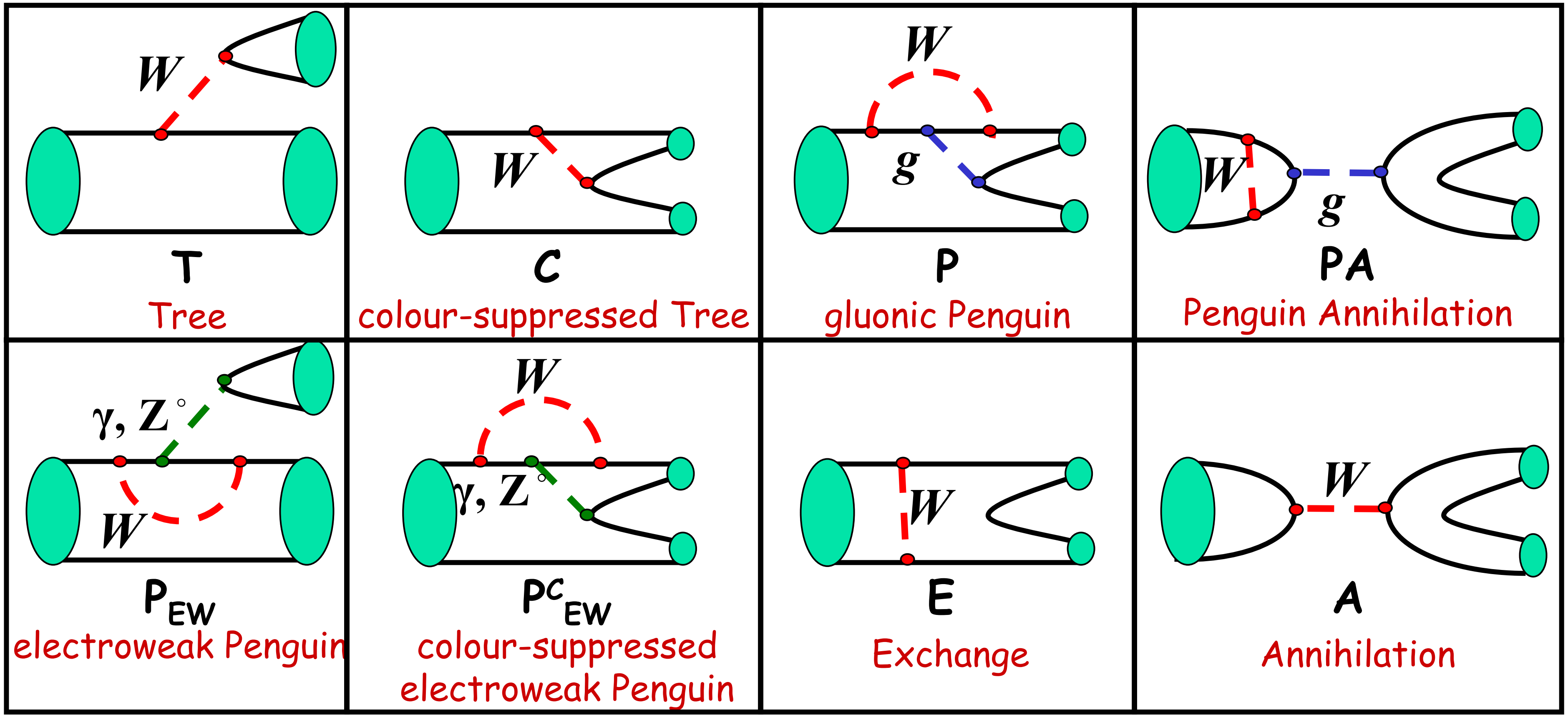

d=0.3, θ= 160°, $\phi_s$=-0.04°,
$\Delta\Gamma_s/\Gamma_s$=0.1, $\Delta m_s$=20 ps$^{-1}$

# Conclusions

- The LHCb experiment will select and tag very large samples of $B_d$ ($B_s$) charmless two-body decays
- By combining the measurements of the $B_d \rightarrow \pi^+\pi^-$ and $B_s \rightarrow K^+K^-$ asymmetry coefficients LHCb can measure $\gamma$ with a 5° statistical uncertainty, in one year, assuming U-spin symmetry and Standard Model
- This strategy could disclose new physics effects in penguin diagrams providing a different measurement of $\gamma$ with respect to e.g. $B_s^0 \rightarrow D_s^{\mp} K^{\pm}$ and $B^0 \rightarrow D^0 K^*$
  - see LHCb talks by Eduardo Rodrigues and Sandra Amato

# Backup slides

# Charmless two-body decays of B mesons: diagrams




Gronau, Hernandez, London and Rosner, Phys. Rev. D50 (1994) 4529

# $B_d \rightarrow \pi^+\pi^-$ and $B_s \rightarrow K^+K^-$ decay amplitudes

## $B_d \rightarrow \pi^+\pi^-$

$$A\left(B_d^0 \rightarrow p^+ p^-\right) = V_{ub}^* V_{ud} A_T^u + V_{ub}^* V_{ud} A_P^u + V_{cb}^* V_{cd} A_P^c + V_{tb}^* V_{td} A_P^t$$

$$\boxed{A\left(B_d^0 \rightarrow \pi^+\pi^-\right) = C\left(e^{i\gamma} - d e^{i\vartheta}\right)}$$

$$C \equiv \lambda^3 A R_b \left(A_T^u + A_P^u - A_P^t\right)$$

$$d e^{i\vartheta} \equiv \frac{1}{R_b}\left(\frac{A_P^c - A_P^t}{A_T^u + A_P^u - A_P^t}\right)$$

## $B_s \rightarrow K^+K^-$

$$A\left(B_s^0 \rightarrow K^+K^-\right) = V_{ub}^* V_{us} A_T'^u + V_{ub}^* V_{us} A_P'^u + V_{cb}^* V_{cs} A_P'^c + V_{tb}^* V_{ts} A_P'^t$$

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

$$C' \equiv \lambda^3 A R_b \left(A_T'^u + A_P'^u - A_P'^t\right),$$

$$R_b \equiv \frac{1}{\lambda}\left(1 - \frac{\lambda^2}{2}\right)\left|\frac{V_{ub}}{V_{cb}}\right|$$

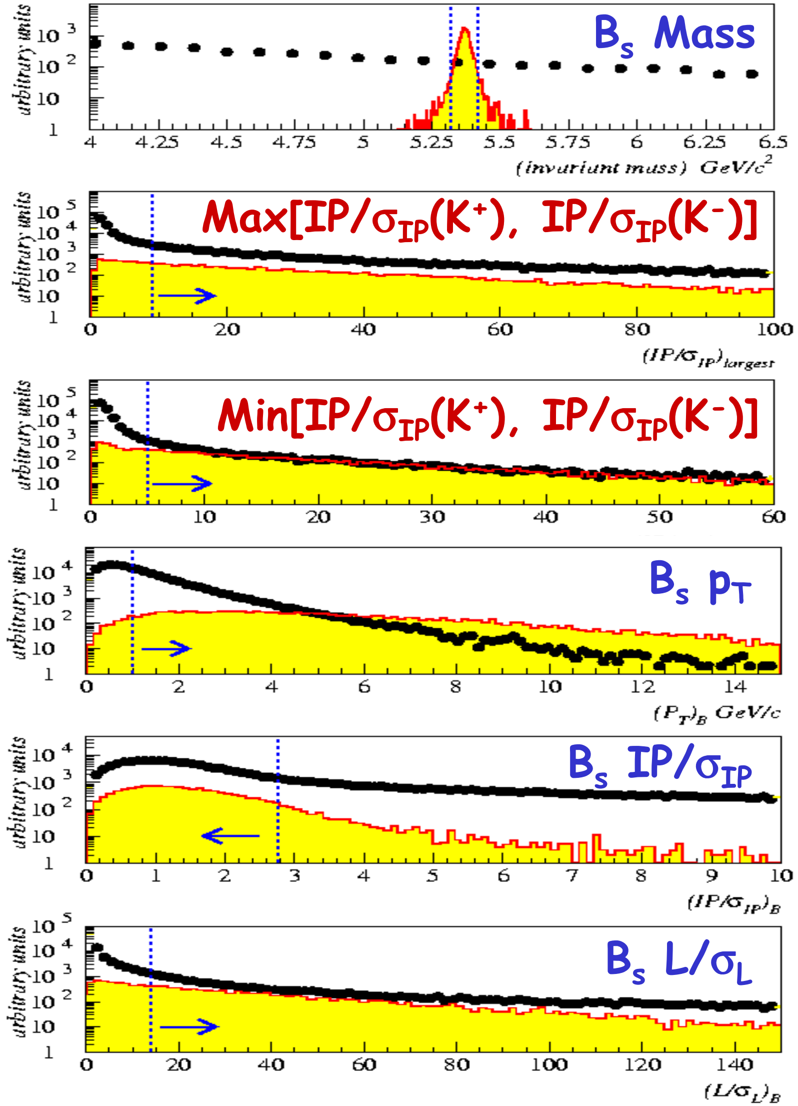
$$d' e^{i\vartheta'} \equiv \frac{1}{R_b}\left(\frac{A_P'^c - A_P'^t}{A_T'^u + A_P'^u - A_P'^t}\right)$$

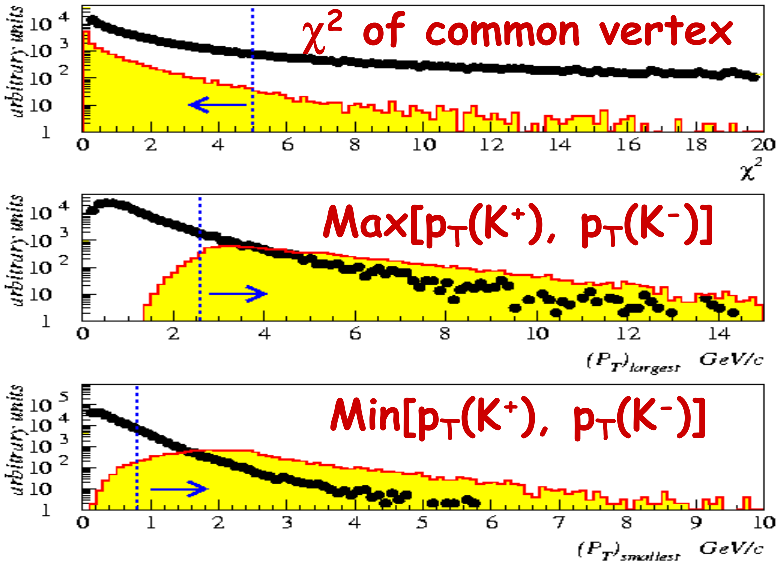
# Distributions of selection variables for $B_s \to K^+K^-$ and combinatorial bb background

bb background

signal

cut value and accepted region



# Selection cuts

| | Channel: | $B_d \to \pi^+ \pi^-$ | $B_d \to K^+ \pi^-$ | $B_s \to K^+ K^-$ | $B_s \to \pi^+ K^-$ |
|---|---|---|---|---|---|
| Identified tracks | $P_{min}$ (GeV/c) | 2.50 | 2.75 | 2.75 | 2.75 |
| Identified tracks | $P_{max}$ (GeV/c) | 100 | 200 | 125 | 100 |
| Identified tracks | $(P_T)_{each}$ (GeV/c) | 1.2 | 1.2 | 0.8 | 1.4 |
| Identified tracks | $(P_T)_{one}$ (GeV/c) | 3.2 | 3.0 | 2.6 | 3.4 |
| Identified tracks | $(IP/\sigma_{IP})_{each}$ | 6 | 6 | 5 | 7 |
| Identified tracks | $(IP/\sigma_{IP})_{one}$ | 12 | 11 | 9 | 14 |
| Identified tracks | $\chi^2_{max}$ | 4 | 5 | 5 | 4 |
| candidate B | $(P_T)_{min}$ (GeV/c) | 1.6 | 1.4 | 1.0 | 1.6 |
| candidate B | $(IP/\sigma_{IP})_{max}$ | 2.25 | 2.50 | 2.75 | 2.25 |
| candidate B | $(L/\sigma_L)_{min}$ | 19 | 17 | 14 | 20 |
| candidate B | $\delta m$ (MeV/$c^2$) | 50 | 50 | 50 | 40 |

# Fast MC input values

| Nominal parameters: | $B_d \rightarrow \pi^+\pi^-$, $B_d \rightarrow K^+\pi^-$ | $B_s \rightarrow K^+K^-$, $B_s \rightarrow \pi^+K^-$ |
|---|---|---|
| tagging efficiency | 42% | 50% |
| wrong tagging fraction | 35% | 33% |
| $\Delta M$ | 0.5 $ps^{-1}$ | 20 $ps^{-1}$ |
| $\Gamma$ | 1/1.54 $ps^{-1}$ | 1/1.46 $ps^{-1}$ |
| $\Delta\Gamma/\Gamma$ | 0 | 0.1 |
| d | 0.3 | 0.3 |
| $\vartheta$ | 160° | 160° |
| $\gamma$ | 65° | 65° |
| weak mixing phase | 0.82 | -0.04 |

**Sensitivity scan: parameters are varied one at a time**

| | | | | | | |
|---|---|---|---|---|---|---|
| d: | 0.1 | 0.2 | (0.3) | 0.4 | | |
| $\vartheta$: | 120° | 140° | (160°) | 180° | 200° | |
| $\gamma$: | 55° | (65°) | 75° | 85° | 95° | 105° |
| $\phi_s$: | 0 | (-0.04) | -0.1 | -0.2 | | |
| $\Delta M_s$ ($ps^{-1}$) | 15 | (20) | 25 | 30 | | |
| $\Delta\Gamma_s/\Gamma_s$: | 0 | (0.1) | 0.2 | | | |

# Sensitivity on $\gamma$

| | | | | | | |
|---|---|---|---|---|---|---|
| $d$ | 0.1 | 0.2 | (0.3) | 0.4 | | |
| $\sigma(\gamma)$ | 1.8° | 2.7° | 4.9° | 9.0° | | |
| $\vartheta$ | 120° | 140° | (160°) | 180° | 200° | |
| $\sigma(\gamma)$ | 3.8° | 3.8° | 4.9° | 6.7° | 5.2° | |
| $\gamma$ | 55° | (65°) | 75° | 85° | 95° | 105° |
| $\sigma(\gamma)$ | 5.8° | 4.9° | 4.3° | 4.7° | 4.7° | 4.7° |
| $\phi_s$ | 0 | (-0.04) | -0.1 | -0.2 | | |
| $\sigma(\gamma)$ | 4.9° | 4.9° | 4.9° | 5.4° | | |
| $\Delta\Gamma_s / \Gamma_s$ | 0 | (0.1) | 0.2 | | | |
| $\sigma(\gamma)$ | 5.2° | 4.9° | 4.5° | | | |
| $\Delta M_s$ | 15 $ps^{-1}$ | (20 $ps^{-1}$) | 25 $ps^{-1}$ | 30 $ps^{-1}$ | | |
| $\sigma(\gamma)$ | 4.0° | 4.9° | 5.9° | 8.5° | | |

Resolution computed as half the 68% confidence interval

# U-spin Symmetry
# How much rely on it?

- U-spin symmetry in the relations d=d' and $\vartheta=\vartheta'$ is not broken within naïve factorization approximation (Fleischer, Phys. Lett. B459, 1999)
- Fleischer and Matias (hep-ph/0204101) allow for a SU(3) violation of 20%: $d'/d \approx 0.8 \div 1.2$
- Matias (hep-ph/0311042) claims that a SU(3) breaking of 20% would induce only a $5^o$ shift on $\gamma$; a phase difference $\Delta\vartheta=\vartheta'-\vartheta$ as large as $40^o$ induces only a shift on $\gamma$ of $1^o$
- Beneke (hep-ph/0308040) estimates through QCD factorization a possible SU(3) violation at 30% level: $d'/d \approx 0.85 \div 1.3$, $\Delta\vartheta \approx \pm 15^o$
- A better understanding of SU(3) breaking would be desirable, but a O(20%) breaking does not spoil the measurement

# Mass spectra

## signals + combinatorial beauty background only