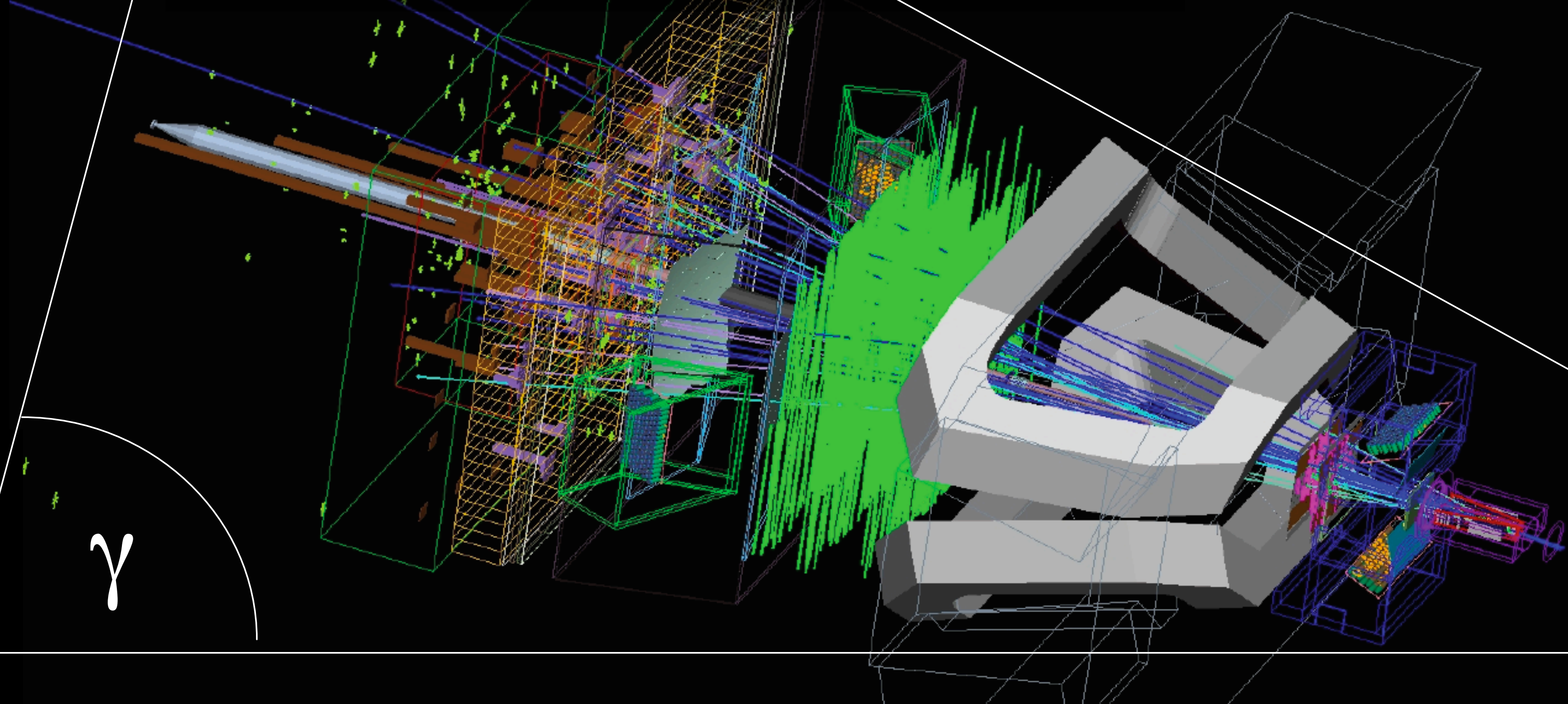
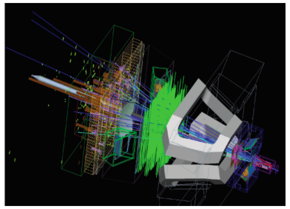
Géraldine Conti (EPFL)
On Behalf of the LHCb Collaboration

Prospects for CP Violation at LHCb

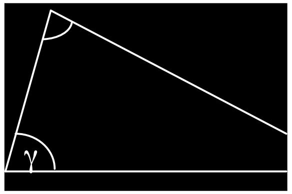


Outline

1. The LHCb Detector



2. CP Violation Studies at LHCb :



   - Mixing-induced CP-Violation in $B_s \to J/\psi\phi$
   - Determination of the CKM angle γ

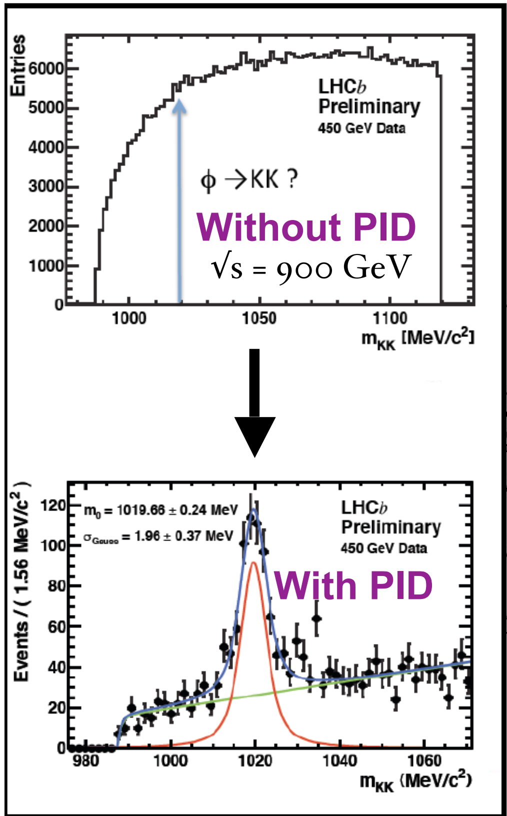
3. Conclusions

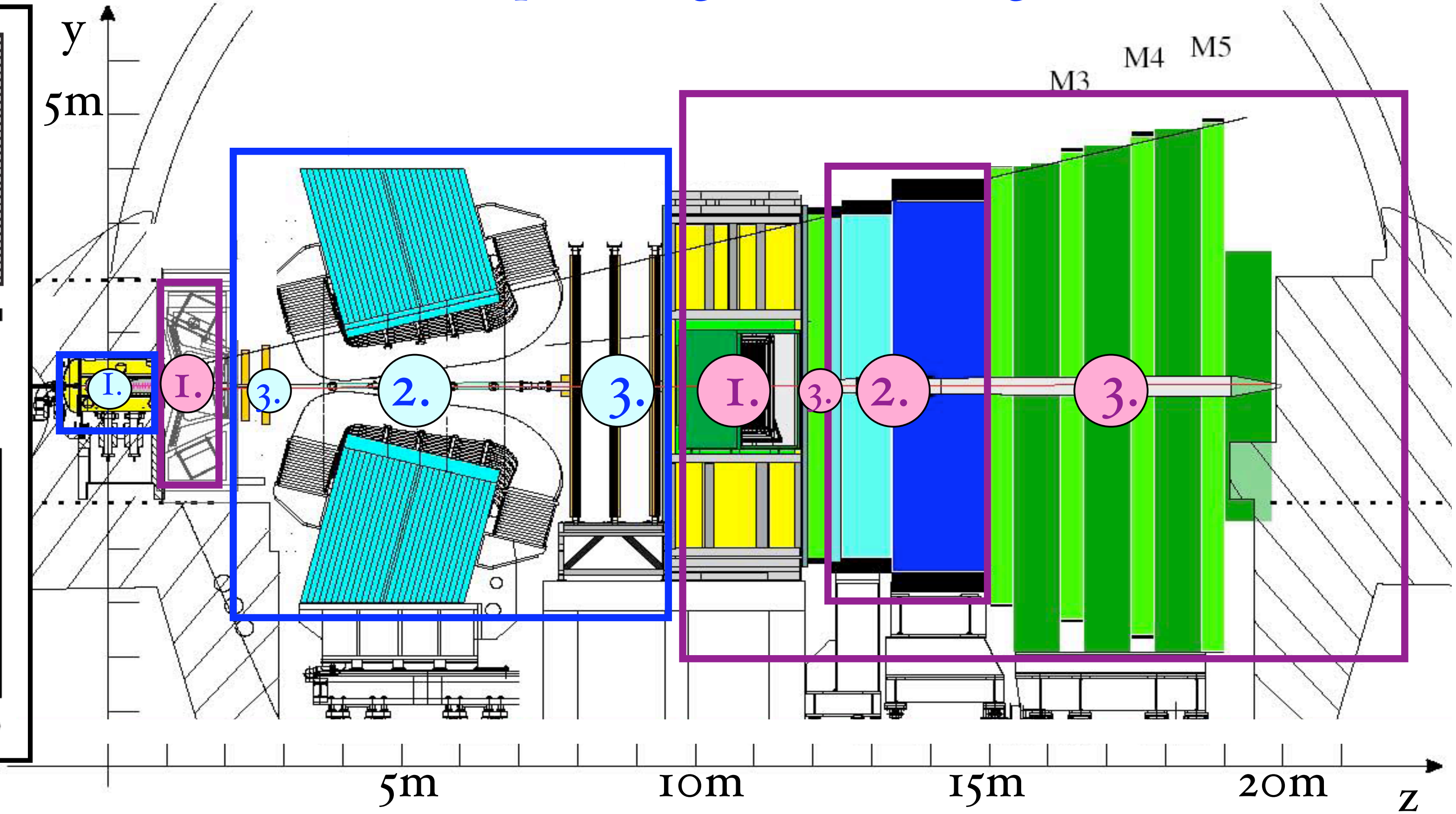
The LHCb Detector

See talk of Andrei Golutvin
See talk of Dirk Wiedner

Tracking System : See talk of Florin Maciuc

1. VErtex LOcator 2. Dipole Magnet 3. Tracking Stations (TT,T1-3)



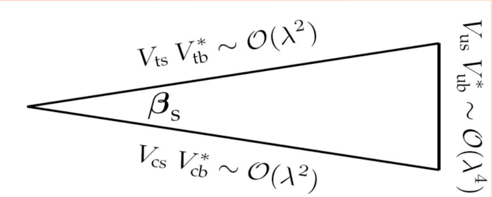


Particle Identification System : See talk of Philip Xing

1. Cherenkovs 2. Calorimeters 3. Muon Chambers

CP Violation Studies at LHCb

The CKM matrix can be parameterized using four independent phases. A useful parameterization is given in terms of **four** (rephasing invariant) **angles** :

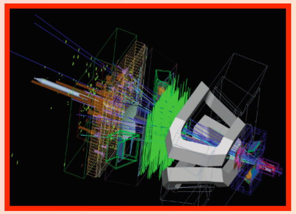


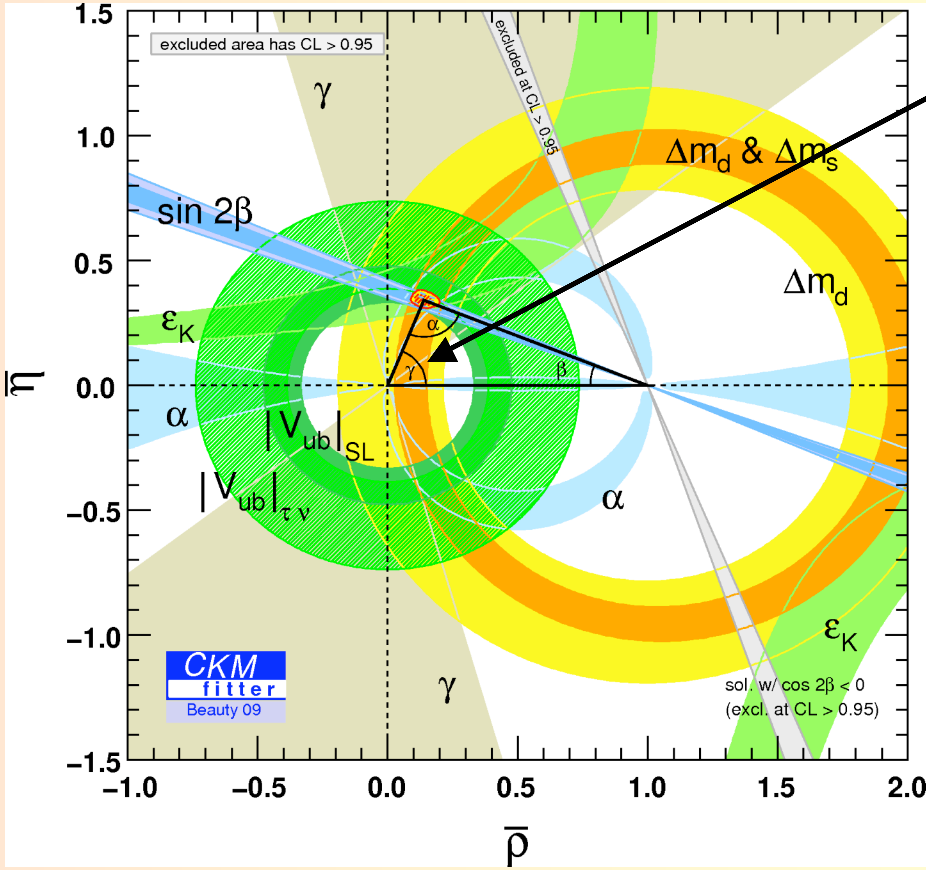
“b-s” triangle of the CKM matrix

$$\beta_s = arg\left[-\frac{V_{cb}V_{cs}^*}{V_{tb}V_{ts}^*}\right]$$

$\beta_s = 0.018 \pm 0.002$ rad

1. Mixing-induced CP violation in $B_s \to J/\psi\phi$





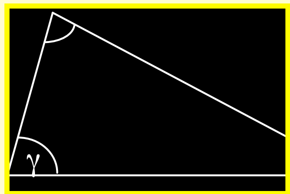
$$\gamma = arg\left[-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right]$$

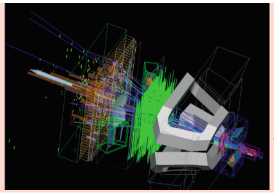
γ is the least well determined angle :

$\gamma = 73^{\circ}{}^{+22}_{-25}$

CKM Fitter

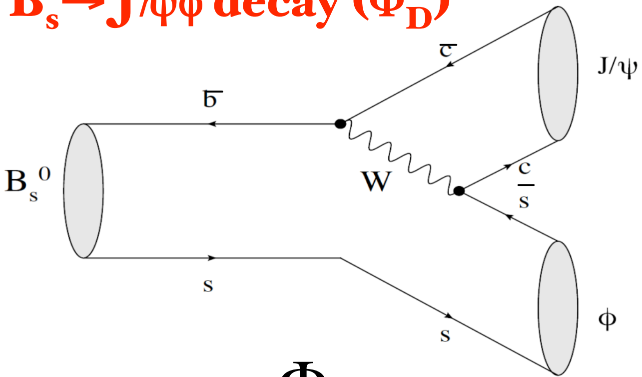
2. The CKM angle γ

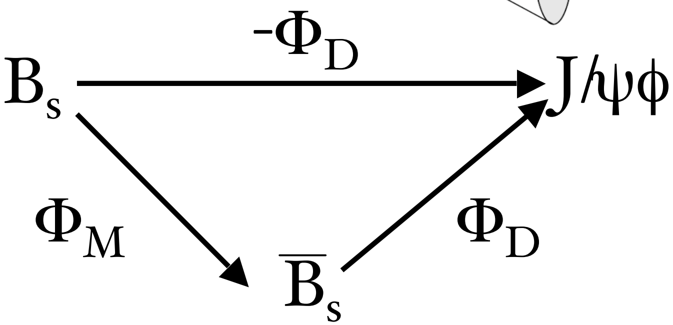


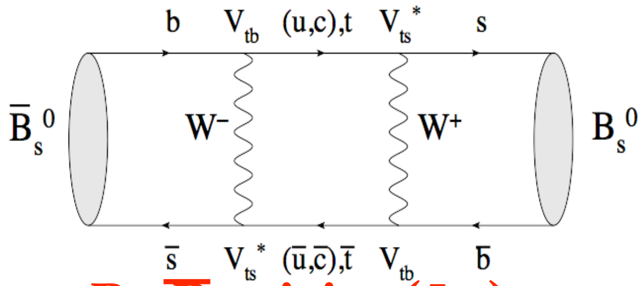


Mixing-induced CP violation in $B_s \to J/\psi\phi$

$B_s \to J/\psi\phi$ decay (Φ_D)







B_s-$\bar{B}_s$ mixing (Φ_M)

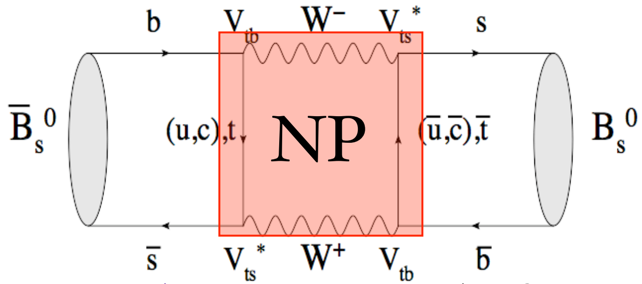
Interference between the different paths to $J/\psi\phi$

CP-violating phase : $\Phi^{J/\psi\phi} = \Phi_M - 2\Phi_D$

Standard Model prediction : $\Phi^{J/\psi\phi}(SM) = -2 \cdot \beta_s$ Very small !

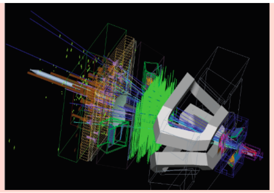
$\beta_s = 0.018 \pm 0.002$ rad

New particles could contribute to the B_s-$\bar{B}_s$ box diagram and modify $\Phi^{J/\psi\varphi}$:



See talk of Iain Bertram for Do results (this session)

→ **Indirect** search for New Physics !



How to measure $\Phi_{J/\psi\phi}$: Angular Analysis

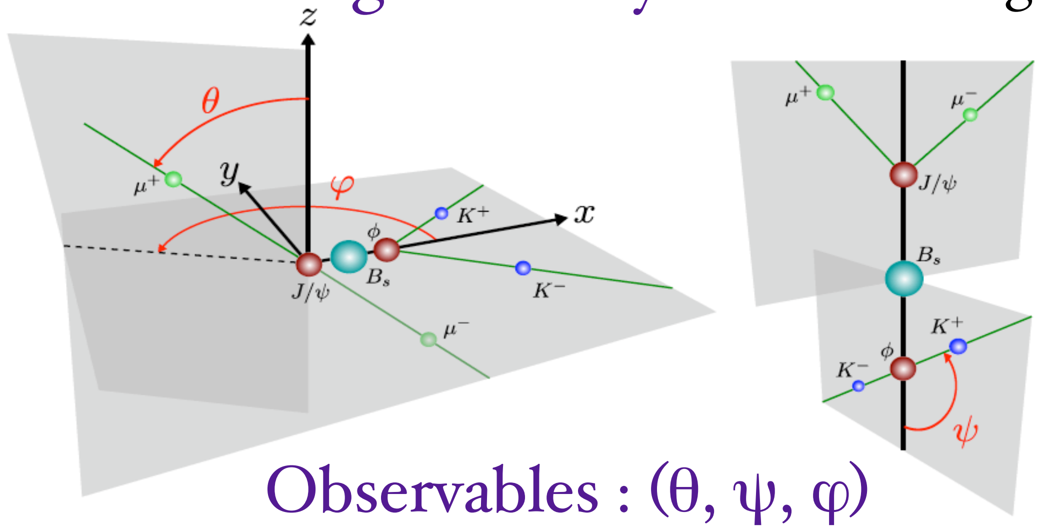
Pseudo-Scalar to Vector-Vector decay : $\underbrace{B_s}_{S=0} \rightarrow \underbrace{J/\psi}_{S=1}(\rightarrow\mu^+\mu^-) \quad \underbrace{\phi}_{S=1}(\rightarrow K^+K^-)$

CP eigenvalues of the final state : Admixture of CP-odd and CP-even states

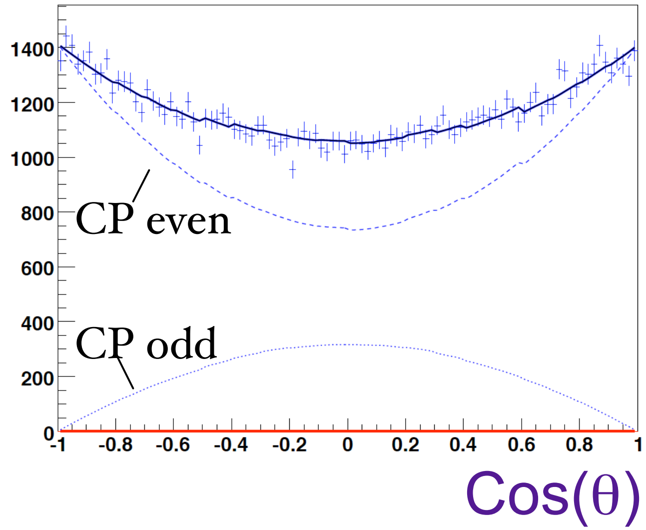
CP eigenvalue of the final state = $CP(J/\psi)\cdot CP(\phi)\cdot(-1)^L$, with L=0,1,2

→ Decomposition of the decay amplitudes in terms of linear polarization of the J/ψ and ϕ.

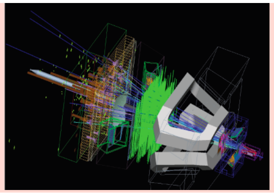
Need for an Angular Analysis to disentangle statistically the CP states :



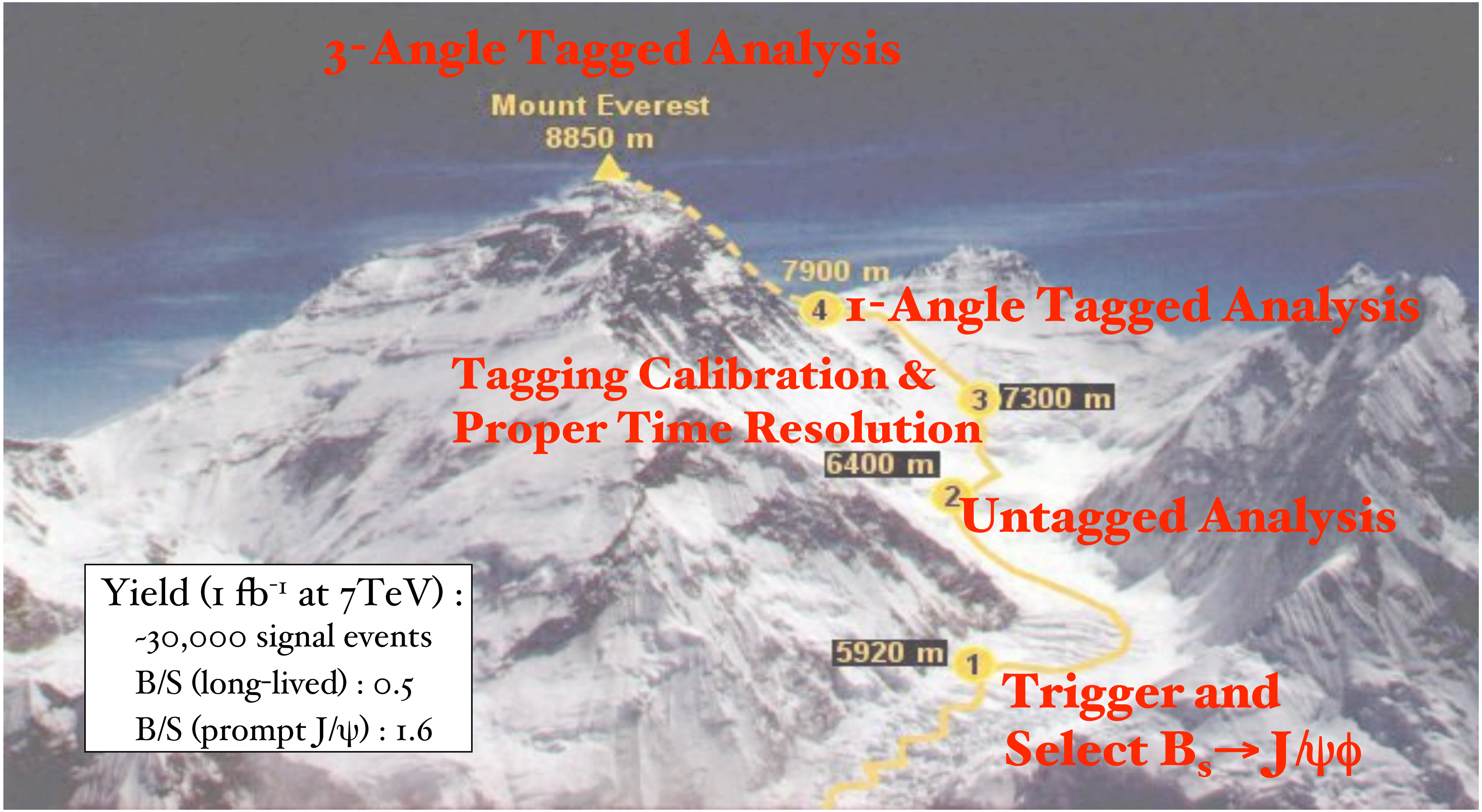
Observables : (θ, ψ, φ)



→ $\Phi^{J/\Psi\phi}$ depends on the fractions of CP-odd and even components ($|A_0(0)|^2$, $|A_\perp(0)|^2$).



Steps towards $\Phi^{J/\psi\phi}$



3-Angle Tagged Analysis

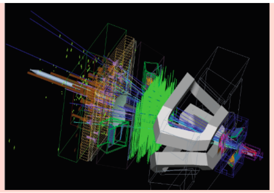
1-Angle Tagged Analysis

Tagging Calibration & Proper Time Resolution

Untagged Analysis

Trigger and Select $B_s \to J/\psi\phi$

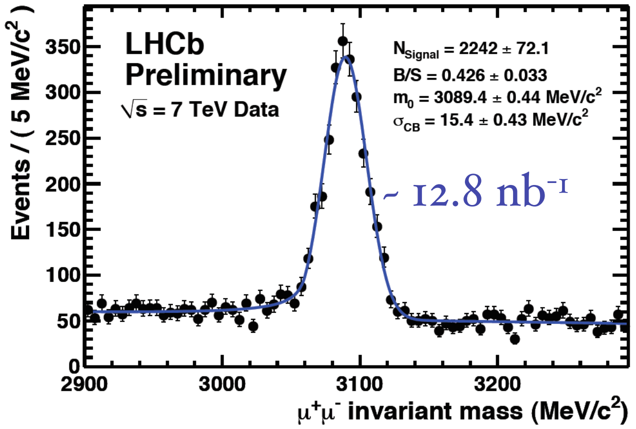
Yield (1 fb^{-1} at 7TeV) :
~30,000 signal events
B/S (long-lived) : 0.5
B/S (prompt J/ψ) : 1.6

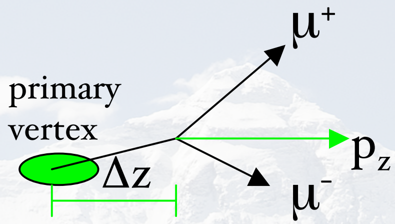


Very First Steps towards $\Phi_{J/\psi\phi}$

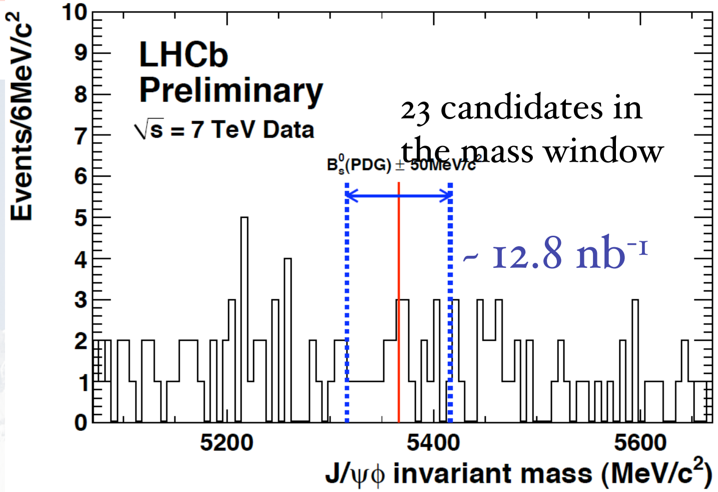
See talk of Olivier Schneider

See talk of Julien Cogan

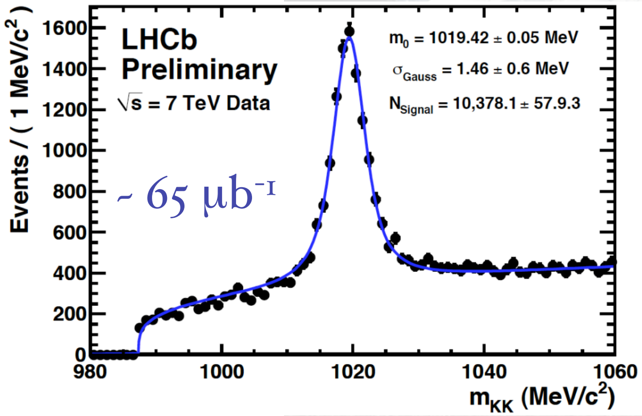


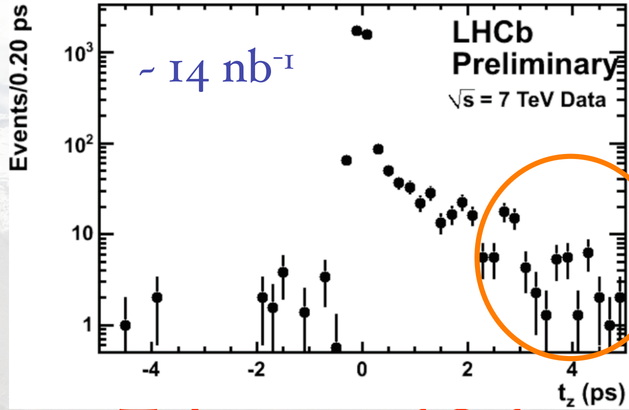


$t_z = (\Delta z/p_z)\cdot m(J/\psi)$



See talk of Walter Bonivento





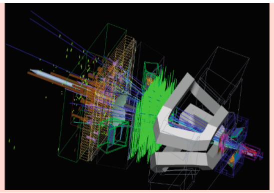
J/ψ from B…

Trigger and Select $B_s \to J/\psi\phi$

1

Trigger and Select $J/\psi \to \mu\mu$

Trigger and Select $\phi \to KK$



The Control Channels

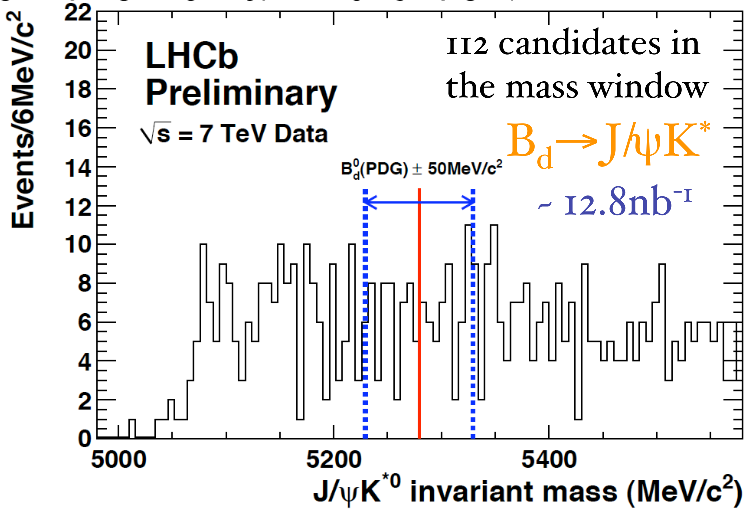
The $B_d \to J/\psi K^*$ and $B_u \to J/\psi K^+$ are used as control channels to :

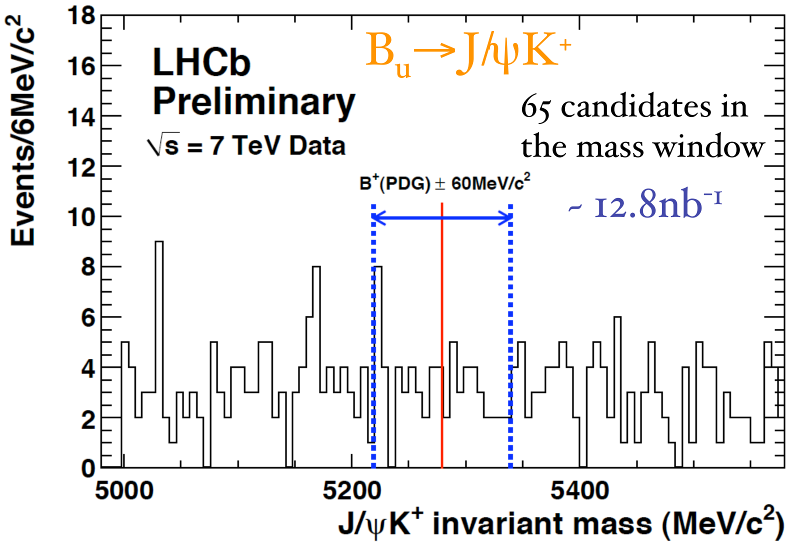
1. Check the **angular acceptance** description (B_d) :

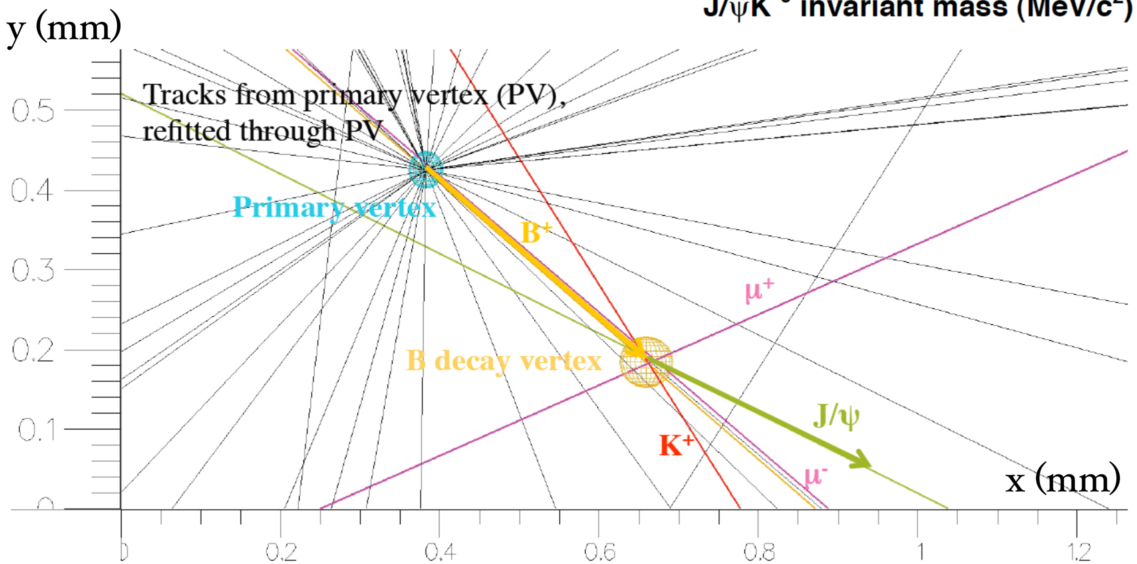
   ~8% distortion expected for the angular distributions

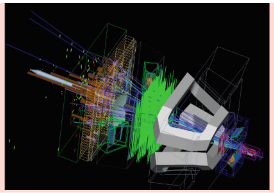
2. **Flavour tagging** calibration of the initial B_s flavour

3. Check the **proper time resolution**





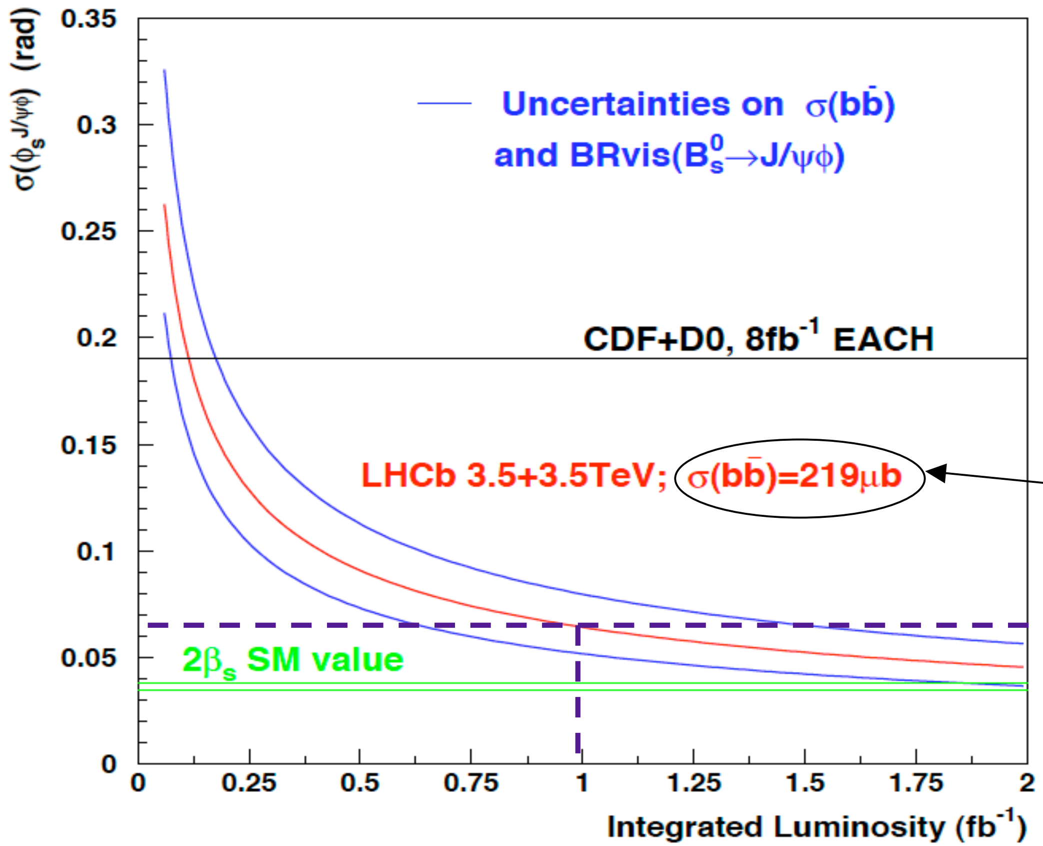




LHCb Sensitivity to $\Phi^{J/\psi\phi}$ for 7 TeV

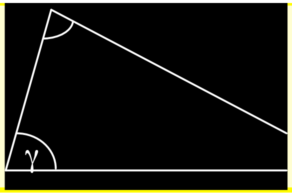
3-angle tagged analysis :

See talk of Elisa Pueschel for latest CDF result with 5.2 fb^{-1} (this session)



rather conservative
(latest Pythia quotes a σ(bb̄)=0.457 μb (2x))

With 1 fb^{-1} (7 TeV) : $\sigma(\Phi^{J/\psi\phi})$ ~ 0.07



The CKM angle γ

Measurement of the CKM angle γ at tree or loop levels :

Insensitive to New Physics

$$\gamma = 73^{+22}_{-25}\ \mathrm{deg}$$

Direct observation

B→DK

2-body decay
(multi-body)

flavour specific

ADS*

$B^{-/+} \to D(K\pi)K^{-/+}$
$B^{o} \to D(K\pi)K^{*o}$
$(B^{-/+} \to D(K\pi\pi\pi)K^{-/+})$

CP eigenstates

GLW*

$B^{-/+} \to D(\pi\pi/KK)K^{-/+}$
$B^{o} \to D(\pi\pi/KK)K^{*o}$

3-body decay

GGSZ** (Dalitz)

$B^{-} \to D^{o}(K_s\pi\pi)K^{-}$

Time-dependent

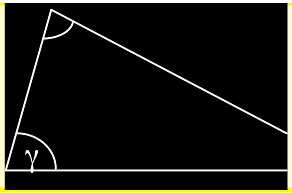
$B_s \to D_s^{\pm}K$ **$B_d \to D^{\pm}\pi^{\mp}$**

Sensitive to New Physics

B→hh (h=K,π)

...

* Atwood, Dunietz, Soni / Gronau, London, Wyler
** Giri, Grossman, Soffer, Zupan



Tree-Level Measurements

ADS/GLW

$B^\pm \rightarrow D^0 K^\pm$; $D^0 K^\pm \xrightarrow{r_D e^{i(\delta_D)}} f_D K^\pm$

$B^\pm \xrightarrow{r_B e^{i(\delta_B \pm \gamma)}} \overline{D}^0 K^\pm \rightarrow f_D K^\pm$

- **ADS** : flavour eigenstates ($f_D = K^+\pi^-$, $K^-\pi^+$)
- **GLW** : CP eigenstates ($f_D = K^+K^-$, $\pi^-\pi^+$)

→ combined measurement

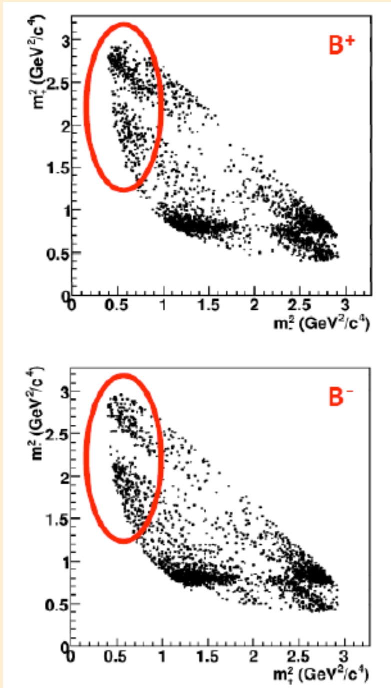
Similar measurement for B^0
(higher sensitivity, lower signal yield)

Interference between the amplitudes is sensitive to γ

GGSZ

$B^- \rightarrow D\,K^-$
$B^+ \rightarrow D\,K^+$

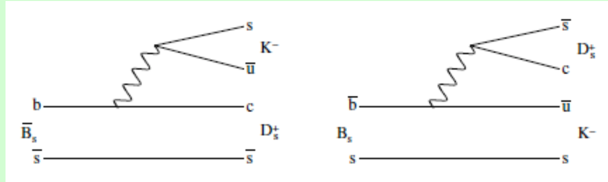
with :
$D \rightarrow K_s\pi\pi$



Differences in Dalitz plots for B^+ and B^- sensitive to γ

Time-Dependent

$B_s \rightarrow D_s^\pm K^\mp$ $B_d \rightarrow D^\pm \pi^\mp$



$B_s \rightarrow D_s^\pm K^\mp$

$B_s \xrightarrow{\Phi_M} \overline{B}_s \rightarrow D_s^\pm K^\mp$

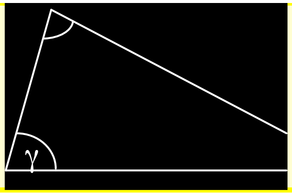
measured from $B_s \rightarrow J/\psi\phi$

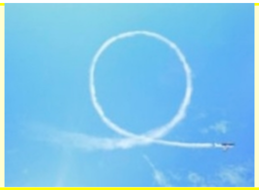
Interference between the two paths to $D_s^\pm K$ sensitive to $\gamma - \Phi_M$

Global fit to all the tree measurements to obtain the best sensitivity to γ :

~7° for 1 fb^{-1} at 7 TeV

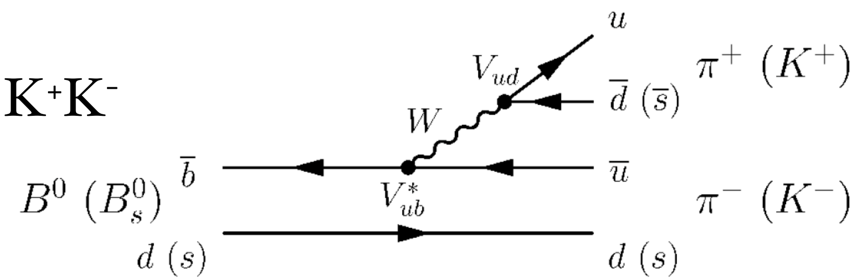
With only 100 pb^{-1}, LHCb can improve some B-factory measurements





Loop-Level Measurements

Combined measurement of $B_d \to \pi^+\pi^-$ and $B_s \to K^+K^-$



The sensitivity to γ arises from interferences between tree and penguin diagrams :

$$\mathcal{A}_{CP}(t) = \frac{\Gamma(\overline{B^0}_{d/s}(t) \to f) - \Gamma(B^0_{d/s}(t) \to f)}{\Gamma(\overline{B^0}_{d/s}(t) \to f) + \Gamma(B^0_{d/s}(t) \to f)} = \frac{-C_{CP}\cos\Delta mt + S_{CP}\sin\Delta mt}{\cosh\frac{\Delta\Gamma}{2}t - A^{\Delta\Gamma}_{CP}\sinh\frac{\Delta\Gamma}{2}t}$$

CP-eigenstate

Depend on γ, d (d') and θ (θ')

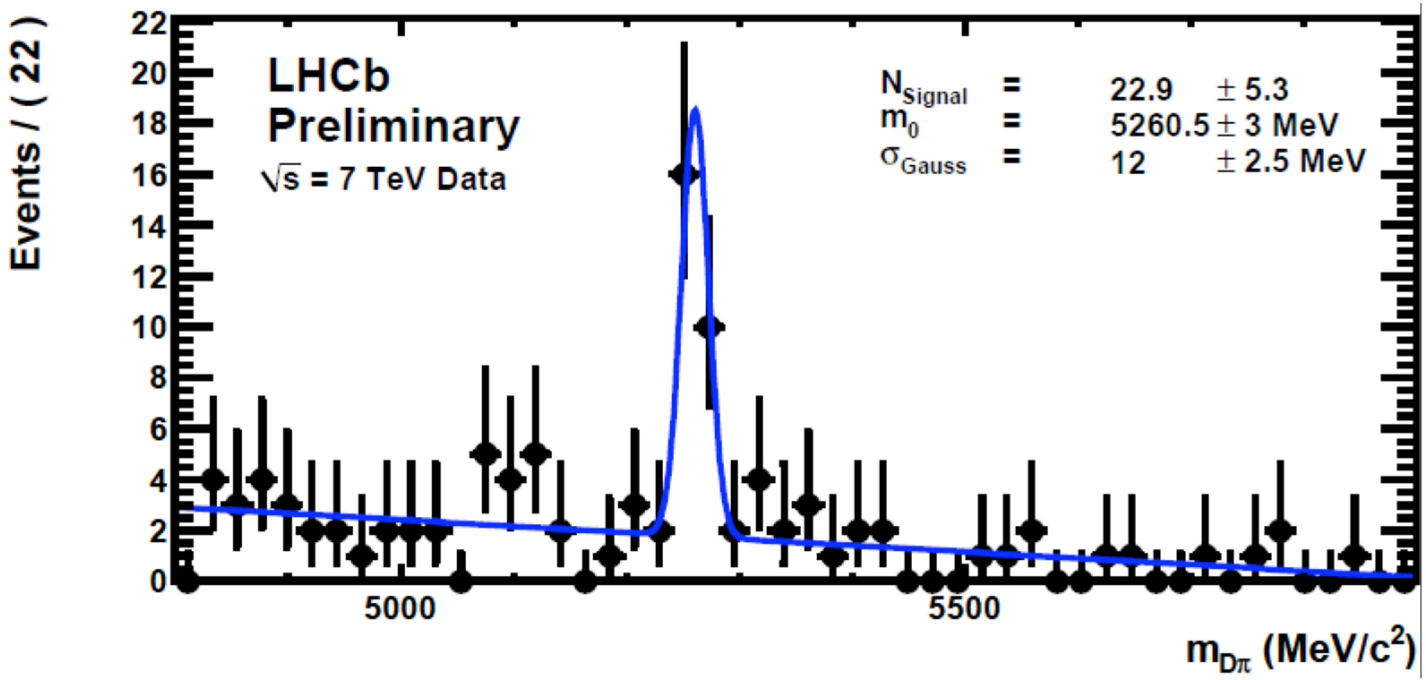
Magnitude and phase of the penguin-to-tree amplitude ratio

\+ U-spin symmetry (invariance of the strong interaction under the d and s quarks exchange) → d=d' and θ=θ'

Sensitivities to γ (2 fb^{-1} at 14 TeV) ~7-10° (depending on U-spin scenarios)

On the way to γ...

$B^\circ \to D^+\pi^-$ + $B^+ \to D^\circ\pi^+$



Conclusions

The journey has started for the LHCb collaboration towards the measurements of the CP-violating weak phases $\Phi^{J/\psi\phi}$ and γ...

With 1 fb^{-1} (at 7 TeV) :

$\sigma(\Phi^{J/\psi\phi}) \sim 0.07$
$\sigma(\gamma) \sim 7°$

(N.B. : from MC studies assuming some selection & trigger efficiencies)

Both measurements made at LHCb will improve a lot the knowledge we have about CP-violation due to their high sensitivities. They could also potentially lead to an indirect discovery of New Physics !

Thank you for your attention

N.B. : The list of routes mentioned in this talk towards $\Phi^{J/\psi\phi}$ and γ is not exhaustive, thanks to the richness of the LHCb physics program.

Bibliography

All measurements cited in this talk : http://arxiv.org/abs/0912.4179

Other promising routes to Φ :

Bs→J/ψf° : http://arxiv.org/abs/0812.2832 , LHCb-2009-037

Bs→ϕ ϕ : LHCb-PUB-2009-025

Measurement of the γ angle at tree-level :

GLW/ADS method : LHCb-2006-066, LHCb-2008-011, LHCb-2009-011

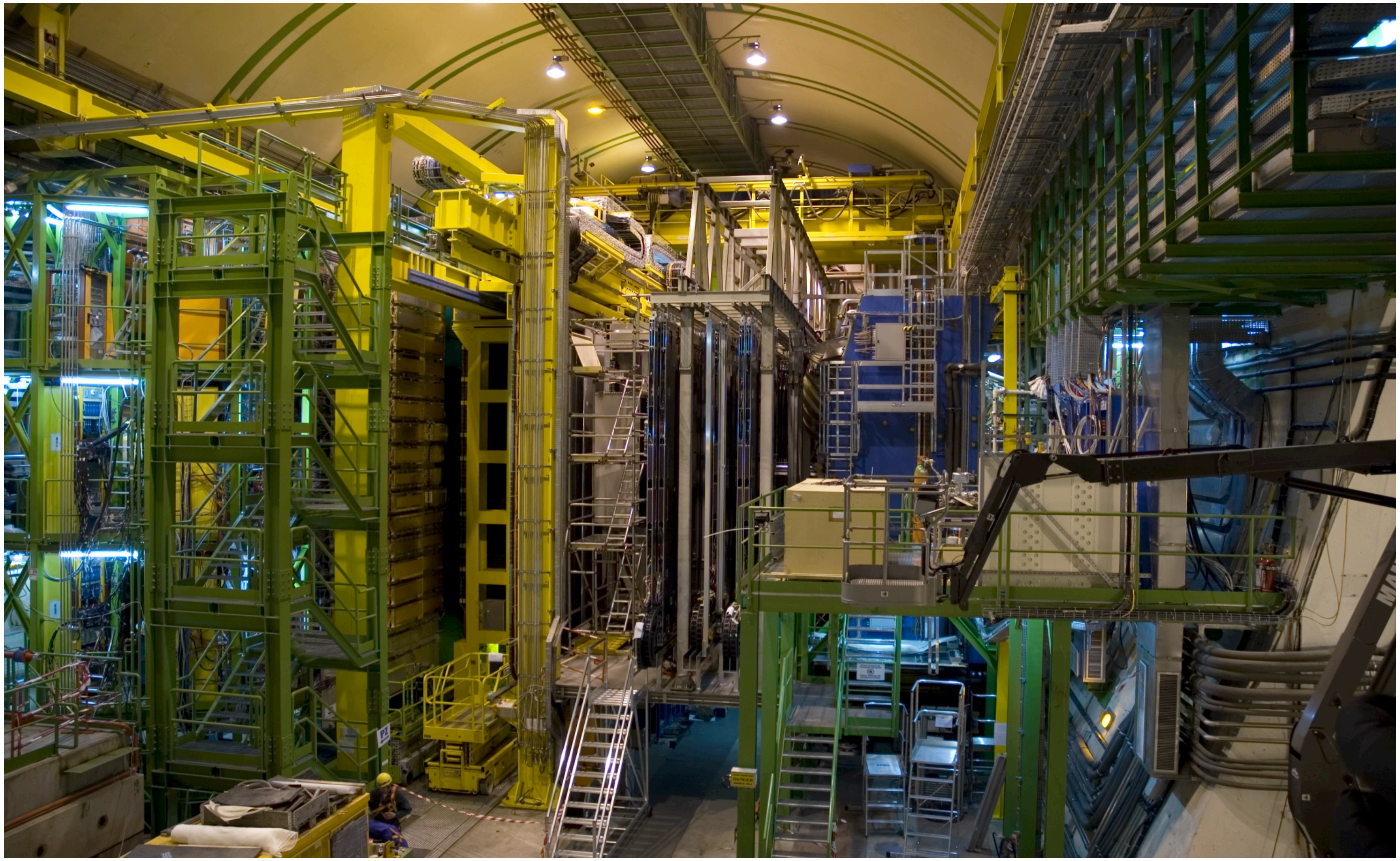
GGSZ method : LHCb-2007-048, LHCb-2007-141, LHCb-2007-142, LHCb-2008-028

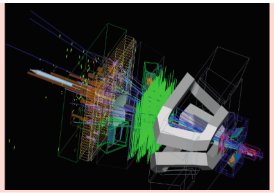
ADS extended to multi-body decays : LHCb-2007-098, LHCb-2009-002

GLW/ADS to neutral B : LHCb-2007-050, LHCb-2008-038

Time-dependent : LHCb-2008-035, LHCb-PUB-2009-003, LHCb-PUB-2010-009 …

Back-Up Slides





Differential Decay Rate

$$\frac{d^4\Gamma[B_s \to (\mu^+\mu^-)_{J/\psi}(K^+K^-)_\phi]}{dcos\theta\; d\varphi\; dcos\psi\; dt} = \frac{9}{32\pi}\{$$

$$\text{Quadratic terms :}\begin{cases} |A_0(t)|^2 \; 2\,cos^2\psi \cdot (1 - sin^2\theta \cdot cos^2\varphi) \\ +|A_{||}(t)|^2 \; sin^2\psi \cdot (1 - sin^2\theta \cdot sin^2\varphi) \\ +|A_\perp(t)|^2 \cdot \; sin^2\psi \cdot sin^2\theta \end{cases}$$

$$\text{Interfering terms :}\begin{cases} -\Im\{A_{||}^*(t)A_\perp(t)\} \cdot sin^2\psi \cdot sin(2\theta) \cdot sin\varphi \\ +\Re\{A_0^*(t)A_{||}(t)\} \cdot \frac{1}{\sqrt{2}} sin(2\psi) \cdot sin^2\theta \cdot sin(2\varphi) \\ +\Im\{A_0^*(t)A_\perp(t)\} \cdot \frac{1}{\sqrt{2}} sin(2\psi) \cdot sin(2\theta) \cdot cos\varphi \end{cases}$$

$$\}$$

Observables :

Proper-time

Mass

3 basis angles

Tagging factor
(q=+1,0,-1)

Physics Parameters :

Weak Phase : Φ = 0.0368 rad (SM) ; 0.6 rad (NP)

2 amplitudes : $|A_0|^2 = 0.556$, $|A_\perp|^2 = 0.233$
($|A_{||}|^2 = 1 - |A_0|^2 - |A_\perp|^2$)

2 strong phases : $\delta_{||}$ = -2.93 rad, $\delta_\perp$ = 2.91 rad
($\delta_{||} = \arg(A_{||})$, $\delta_\perp = \arg(A_\perp)$)

Average Width : $\Gamma_s = 0.5(\Gamma_L+\Gamma_H)$=0.68 ps^{-1}

Width Difference : $\Delta\Gamma_s = \Gamma_L-\Gamma_H$=0.049 ps^{-1}

Mass Difference : $\Delta m_s = m_H - m_L$=17.77 ps^{-1}

+ Detector Parameters...

Time-Dependent Amplitudes

$$|A_0(t)|^2 = |A_0(0)|^2 e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) - \cos\Phi \sinh\left(\frac{\Delta\Gamma_s t}{2}\right) + \sin\Phi\sin(\Delta m_s t)\right]$$

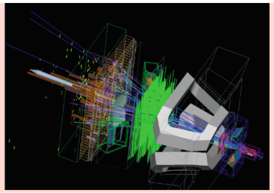
$$|A_{||}(t)|^2 = |A_{||}(0)|^2 e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) - \cos\Phi \sinh\left(\frac{\Delta\Gamma_s t}{2}\right) + \sin\Phi\sin(\Delta m_s t)\right]$$

$$|A_\perp(t)|^2 = |A_\perp(0)|^2 e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) + \cos\Phi \sinh\left(\frac{\Delta\Gamma_s t}{2}\right) - \sin\Phi\sin(\Delta m_s t)\right]$$

$$\Im\{A_{||}^*(t)A_\perp(t)\} = |A_{||}(0)||A_\perp(0)|e^{-\Gamma_s t}\left[-\cos(\delta_\perp - \delta_{||})\sin\Phi\sinh\left(\frac{\Delta\Gamma_s t}{2}\right) + \sin(\delta_\perp - \delta_{||})\cos(\Delta m_s t) - \cos(\delta_\perp - \delta_{||})\cos\Phi\sin(\Delta m_s t)\right],$$

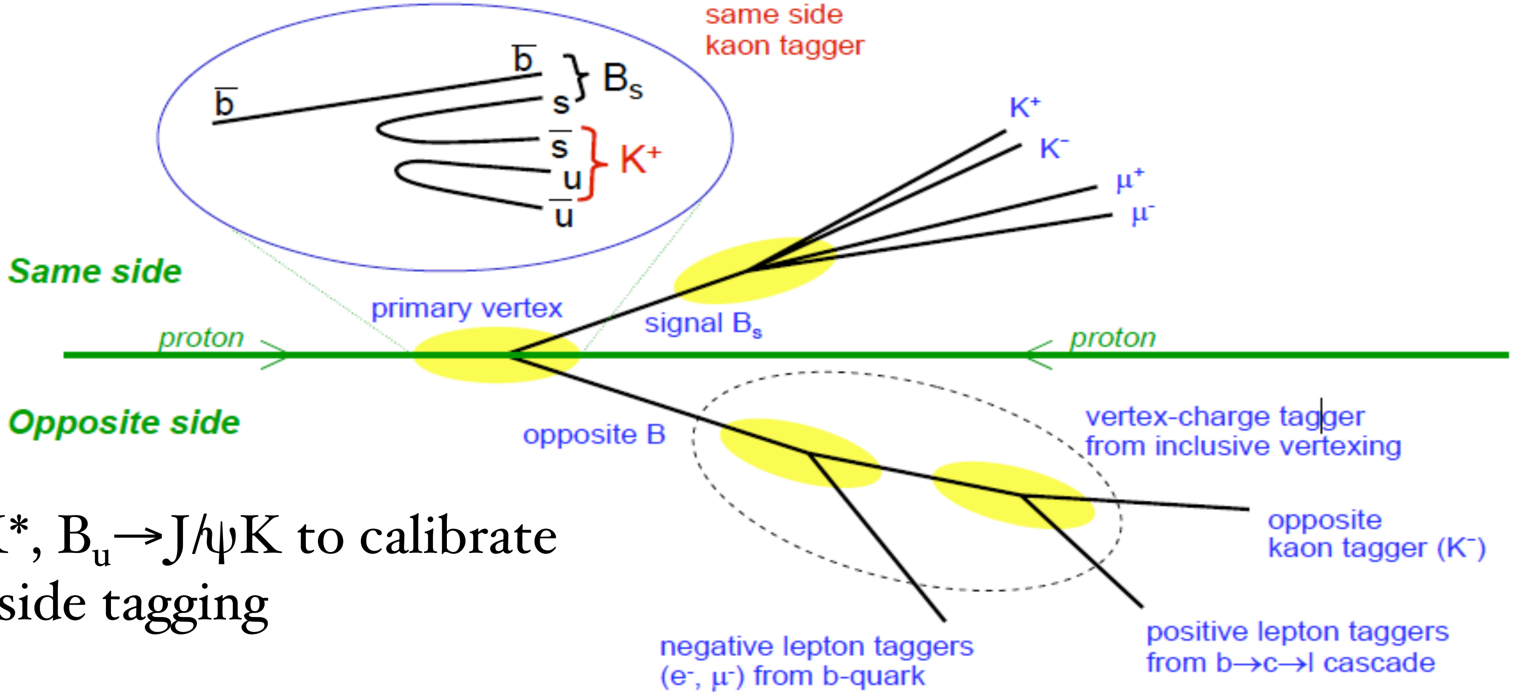
$$\Re\{A_0^*(t)A_{||}(t)\} = |A_0(0)||A_{||}(0)|e^{-\Gamma_s t}\cos\delta_{||}\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) - \cos\Phi\sinh\left(\frac{\Delta\Gamma_s t}{2}\right) + \sin\Phi\sin(\Delta m_s t)\right] \text{ and}$$

$$\Im\{A_0^*(t)A_\perp(t)\} = |A_0(0)||A_\perp(0)|e^{-\Gamma_s t}\left[-\cos\delta_\perp\sin\Phi\sinh\left(\frac{\Delta\Gamma_s t}{2}\right) + \sin\delta_\perp\cos(\Delta m_s t) - \cos\delta_\perp\cos\Phi\sin(\Delta m_s t)\right].$$



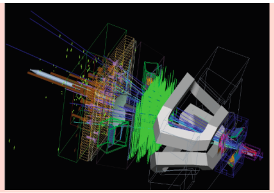
Flavour Tagging

$B_s \to D_s\pi$, $B_s \to D_s\mu\upsilon$ to calibrate same side tagging



$B_d \to J/\psi K^*$, $B_u \to J/\psi K$ to calibrate opposite side tagging

$B_s \to J/\psi\phi$ Tagging Efficiency = *57%*
Mistag rate ~ *33%*



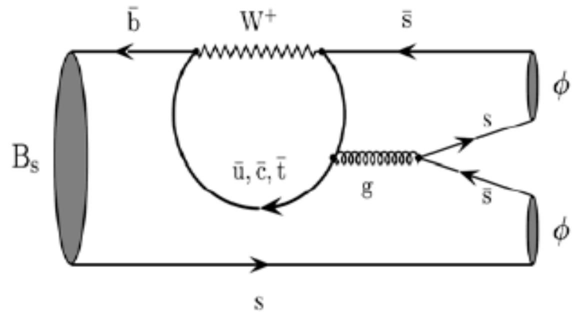
Others ways to Φ...

$B_s \to \phi\phi$ is dominated by a penguin :

New Physics could enter in the penguin and/or in the box diagram.

$\Phi_{\phi\phi}$=0 in SM ; $\Phi_{\phi\phi} = \Phi_M - 2\Phi_D$ in NP

$\sigma(\Phi_{\phi\phi})$=0.06 (10fb^{-1})



$B_s \to J/\psi(ee)\phi$, ...

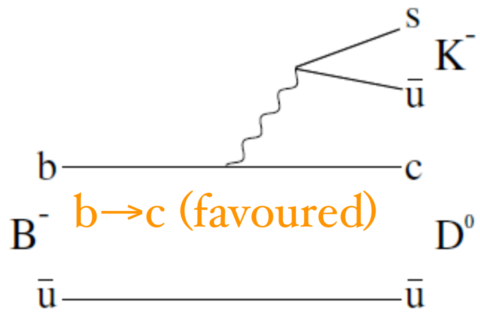
Pure CP eigenstates	Yield (10³/2 fb^{-1})	σ(Φs)
$B_s \to \eta_c(h^-h^+h^-h^+)\phi(K^+K^-)$	**3**	~0.11
$B_s \to J/\psi(\mu^-\mu^+)\,\eta(\gamma\gamma)$	**8.5**	~0.11
$B_s \to D_s(K^+K^-\pi^-)\,D_s(K^+K^-\pi^+)$	**4.0**	~0.13

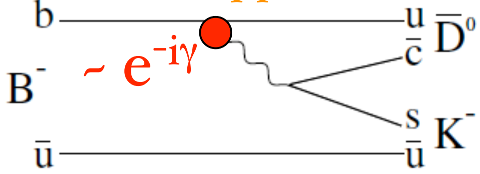
Higher background than $B_s \to J/\psi(\mu^-\mu^+)\phi(K^+K^-)$

$B_s \to J/\psi f_0(\pi\pi)$,...

ADS / GLW measurements for $B^{\pm}$

If D^0 and $\bar{D}^0$ decay to a common final state → Interference





ADS: 4 final states (2 x B^- and 2 x B^+)

5 parameters : γ, r_B, δ_B, δ_D, $N_{K\pi}$

r_D = 0.060 ± 0.003 well-measured

flavour eigenstates ($K^+\pi^-$) → 4 constraints

δ_B=strong phase difference between the B^+ and B^- decays
δ_D=strong phase difference between the two D-decays (measured at CLEO-c or can be determined from global fit to D mixing parameters)
r_B=relative magnitude of the suppressed B-decay amplitude
$N_{K\pi}$ = normalization factor

GLW: **CP-even** eigenstates ($\pi^+\pi^-$ or K^+K^-) considered together in D→hh (same dependence on unknown parameters)

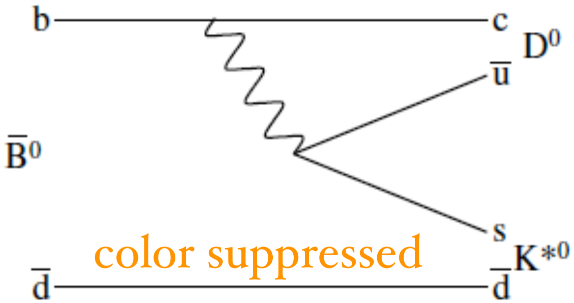
2 constraints from B^+ and B^- rates
1 additional parameter N_{hh}

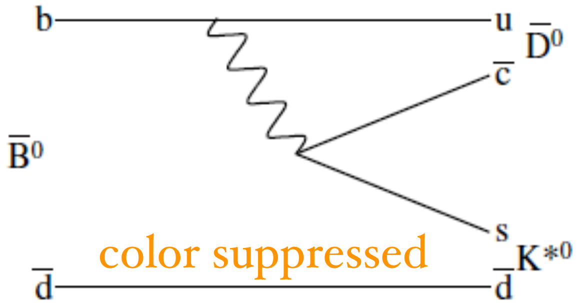
N_{hh} = normalization factor

only one normalization factor left → over-constrained system (6dof:5param)

ADS / GLW measurements for B°

Analysis very similar to ADS/GLW for B±...





r_B governs the size of the asymmetry → hence the sensitivity to γ

$$r_B \sim f_c \cdot \frac{|V_{ub}V_{cs}|}{|V_{cb}V_{us}|}$$

= ~ 0.3

f_C = colour suppression factor

- f_C = 1/3 for B±
- f_C = 1 for B° more sensitive to γ !

However, lower signal yields...

The sensitivity can be enhanced by making a Dalitz plot analysis of $B^0 \to D\pi^- K^+$:

arXiv:0810.2706, Phys.Rev.D79:051301,2009

Status for the other parameters :

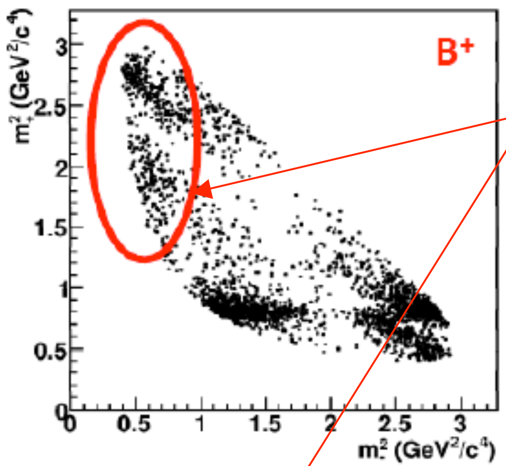
$r_B(B^\pm)$=0.096 (+ 0.019) (- 0.016) % (CKMfitter)
$r_B(B^0)$=0.27 ± 0.18 (BABAR-PUB-07/072, 2009)
$\delta_B(B^\pm)$= 114° (+ 20) (- 24) ° (CKMfitter, 2009)
$\delta_B(B^0)$ unknown
δ_D=22° (+11+9) (-12-11) ° (Phys. Rev. D 78, 012001 (2008))

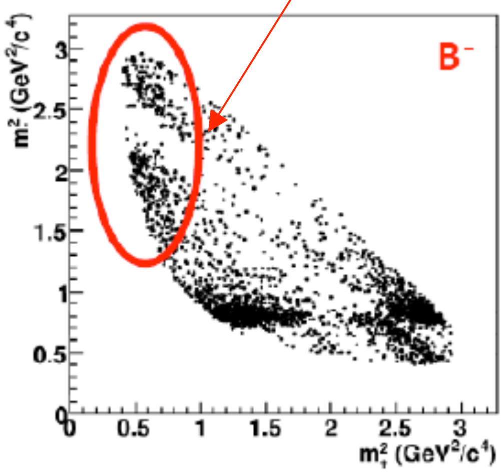
GGSZ Method

Differences in Dalitz plots for $B^+ \to DK^+$ and $B^- \to DK^-$ decays

(with $D=\{D^0,\bar{D}^0\}$ and $D \to K_s\pi^+\pi^-$)

Yield (1 fb^{-1}) :
1,700 signal events
B/S < 1.1 at 90% CL





γ sensitivity ~ difference in the density of events between the two plots

$$A(B^\pm \to D(K_s\pi\pi)K^\pm) \propto f(m_\mp, m_\pm) + r_B e^{i(\delta_B \pm \gamma)} f(m_\pm, m_\mp)$$

δ_B=strong phase difference between B^+ and B^-
r_B=ratio between the suppressed and the favoured B-decay amplitudse

complex D-decay amplitude **f** wit $m_\pm = m^2(K_s\pi^\pm)$ depending on δ_D

Strong phase difference between D^0 and $\bar{D}^0$ decays

f is needed to obtain γ

Methods	Unbinned fit	Binned fit
Requirements	Need for a **model** of **f** systematics : 6° - 15°	**Knowledge** of δ_D (CLEO-c) systematics ~ 2°

Parameter	Belle	BABAR
γ	$(78^{+11}_{-12} \pm 4 \pm 9)^\circ$	$(76 \pm 22 \pm 5 \pm 5)^\circ$