$B \rightarrow X_s\gamma$ and $B \rightarrow X_s l^+ l^-$ decays at LHCb

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September 7, 2010

1. Introduction: LHC*b* and rare decays

2. $B \to X_s\gamma$
   - Introduction, measurements
   - Photon polarization using $B \to f^{CP}\gamma$
   - Experimental prerequisites
   - Photon polarization using $B_d \to K^*e^+e^-$
   - Outlook

3. $B \to X_s l^+ l^-$
   - Introduction and status
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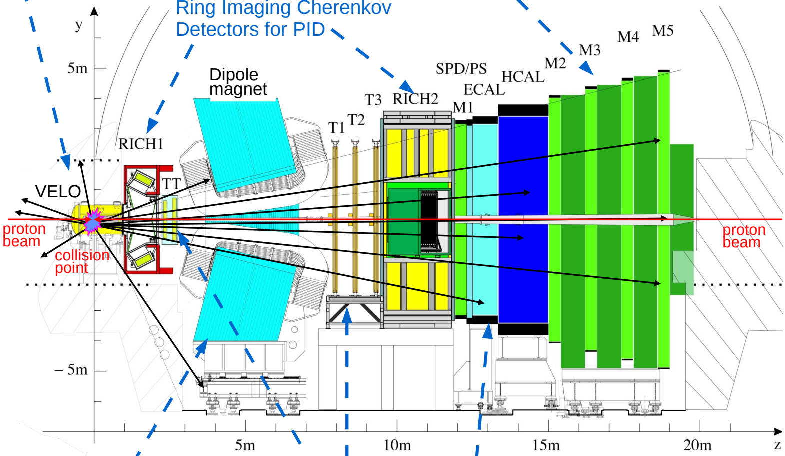
LHC*b* detector overview



Vertex Locator around the IP

Ring Imaging Cherenkov Detectors for PID

Muon systems

Provides bending for momentum determination

Tracking stations

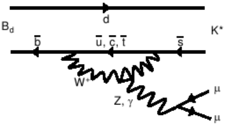
Calorimeter systems

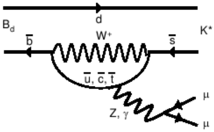
LHC*b* Rare decays physics

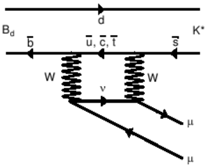
A diverse and interesting program, but this talk will focus on

$B \to X_s\gamma$ and $B \to X_s l^+ l^-$

- Are flavour changing neutral currents
- In the SM, are allowed through loop diagram only
- So are sensitive to NP contribution, and can test the
  1. Mass scale of NP
  2. Coupling strength of NP particles
  3. V-A structure of NP particles







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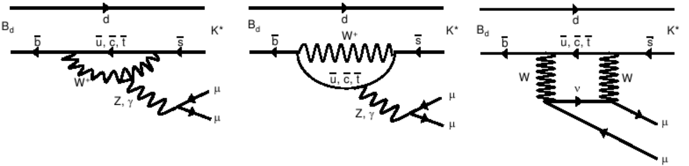

⟶ Will talk separately about the planned measurements and challenges

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Motivation to measure $B \rightarrow X_s\gamma$

$\star$ $BR_{incl} B \rightarrow X\gamma$ in agreement with theory

- $B_{incl,exp}(B \rightarrow X_s\gamma) = 3.56 \pm 0.26 \times 10^{-4}$ [1] [2]
- $B_{incl,th}(B \rightarrow X_s\gamma) = 3.15 \pm 0.23 \times 10^{-4}$ [3]

which can put limits on NP models

Also note that the BR is not sensitive to the coupling structure of NP

$\star$ Measure direct CP asymmetry

(inclusive and exclusive measurement measurements by Belle and Babar [11][10])

Motivation to measure $B \rightarrow X_s\gamma$

$\star$ Can also probe the structure of NP operators [5] by measuring the polarization of the photon in $B \rightarrow X_s\gamma$

→ Photon emitted in $\bar{B} \rightarrow X_s\gamma$ is predominantly left handed because

$$\frac{F_R}{F_L} \approx \frac{m_s}{m_b}$$

where F_L and F_R are amplitudes for left and right polarized photons in a b decay ($\bar{B}$ meson)

→ Ratio of "wrong" helicity photons in predicted to be ~ 0.4% in the SM
→ Can be up to 10% in some NP models
→ e.g.LR symmetric model and unconstrained MSSM, this ratio can be large without affecting the BR

How to measure the photon polarization

Several methods proposed in literature [9]

- CP asymmetry in $B \to f^{CP}\gamma$ (f^{CP} is a CP eigenstate)

  Time dependent decay rate

- Angular distribution in $B \to K^*(\to K\pi)e^+e^-$

  Angle between the $K\pi$ and e^+e^- plane

- Forward backward asymmetry in $\Lambda_b \to \Lambda(\to p\pi)\gamma$

  Forward backward asymmetry of the proton flight direction wrt the Λ_b, in the Λ rest frame

- Angular distribution in $B \to K\pi\pi\gamma$

  Only K(1400) has sensitivity, need to separate from other resonances

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Initially use the first two approaches at LHC*b*

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1. Measuring photon polarization in $B \to f^{CP}\gamma$

In decays of type $B \to f^{CP}\gamma$, the time dependent decay rate

$$\Gamma_{\mathrm{B}(\bar{\mathrm{B}})\to f^{\mathcal{CP}}\gamma}(\mathrm{t}) = |\mathrm{A}|^2\,\mathrm{e}^{-\Gamma\mathrm{t}}\Big(\cosh\frac{\Delta\Gamma\mathrm{t}}{2} \;-\; \mathcal{A}^{\Delta}\sinh\frac{\Delta\Gamma\mathrm{t}}{2} \\ +(-)\,\mathcal{C}\cos\Delta\mathrm{mt} \;-(+)\,\mathcal{S}\sin\Delta\mathrm{mt}\Big)$$

contains the parameters

$$\mathcal{S} \approx \sin 2\psi \sin\varphi_{\mathrm{s}} \quad \textit{and} \quad \mathcal{A}^{\Delta} \approx \sin 2\psi \cos\varphi_{\mathrm{s}}$$

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contains the parameters (possibility of an untagged analysis due to large $\Delta\Gamma$ is B_s [15])

$$\mathcal{S} \approx \sin 2\psi \sin\varphi_{\mathrm{s}} \quad \textit{and} \quad \mathcal{A}^{\Delta} \approx \sin 2\psi \cos\varphi_{\mathrm{s}}$$

which contain the "wrong" photon polarization fraction

$$\tan\psi \equiv \frac{\mathcal{A}\left(\bar{\mathrm{B}}_{\mathrm{s}} \to f^{\mathcal{CP}}\gamma_{\mathrm{R}}\right)}{\mathcal{A}\left(\bar{\mathrm{B}}_{\mathrm{s}} \to f^{\mathcal{CP}}\gamma_{\mathrm{L}}\right)}$$

Current sensitivity and LHC*b* prospects

Current status

Results from B factories using $B \rightarrow K^*(\rightarrow K_s^0\pi^0)\gamma$ [8]

$$sin2\psi = 0.28 \pm 0.44$$

LHC*b* reach

At LHC*b*, we will use $B_s \rightarrow \phi\gamma$ for this measurement.
In a nominal LHC*b* year, 11k events with a B/S of <0.55 expected

→ With a tagged analysis,

$$\sigma_{sin2\psi} \sim 0.2$$

→ And with an untagged analysis,

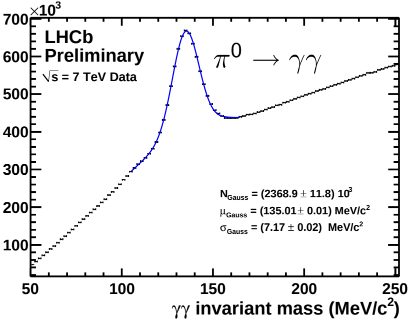
$$\sigma_{sin2\psi} \sim 0.22$$

⇒ focus on the untagged analysis of $B_s \rightarrow \phi\gamma$, to measure $\mathcal{A}^{\Delta}$

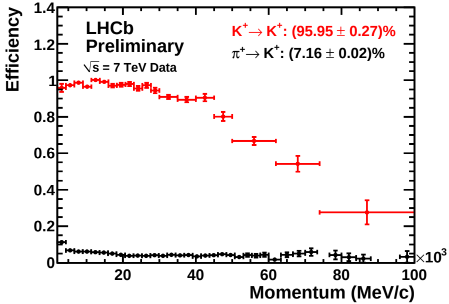
Experimental requirements | Detector

- Trigger:dedicated trigger lines making use of the high PT photons

- Good ECAL calibration



- Good PID performance
  (to identify kaons from $\phi \to K^+K^-$
  and $K^{*0} \to K^+\pi^-$)

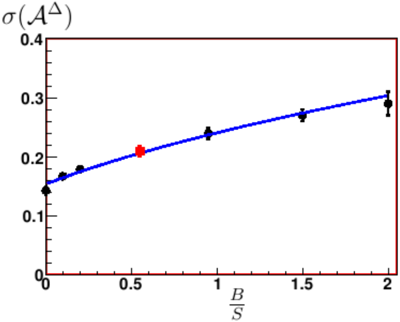


⇒These results look encouraging, further improvements expected with more data

Experimental requirements | Analysis

- Good control over background

  From MC studies, $\frac{B}{S}$ estimated to be < 0.55 @ 90% CL [16]



- However, key systematics are the proper time reconstruction bias and the proper time acceptance

Proper time reconstruction

The proper time acceptance function and any bias in its reconstruction need to be understood to a few percent level

The observable is extremely sensitive to these because:

$$\Gamma_{\mathrm{B}(\bar{\mathrm{B}})\to f^{\mathcal{CP}}\gamma}(\mathrm{t}) = |\mathrm{A}|^2\,\mathrm{e}^{-\Gamma \mathrm{t}}\Big(\cosh\frac{\Delta\Gamma \mathrm{t}}{2} - \mathcal{A}^{\Delta}\sinh\frac{\Delta\Gamma \mathrm{t}}{2} + (-)\,\mathcal{C}\cos\Delta \mathrm{mt} - (+)\,\mathcal{S}\sin\Delta \mathrm{mt}\Big)$$

For small $\mathcal{A}^{\Delta}$, one can write

$$\Gamma_{\mathrm{B}(\bar{\mathrm{B}})\to f^{\mathcal{CP}}\gamma}(\mathrm{t}) \approx |\mathrm{A}|^2\,\mathrm{e}^{-\Gamma \mathrm{t}}\left(1 - \frac{\mathcal{A}^{\Delta}\Delta\Gamma \mathrm{t}}{2} + \frac{1}{2}\Big(\frac{\Delta\Gamma \mathrm{t}}{2}\Big)^2 + ...\right) \approx |\mathrm{A}|^2\,\mathrm{e}^{-\Gamma_{B_s\to\phi\gamma}\mathrm{t}}$$

where $\Gamma_{B_s\to\phi\gamma} = \Gamma + \frac{\mathcal{A}^{\Delta}\Delta\Gamma}{2}$

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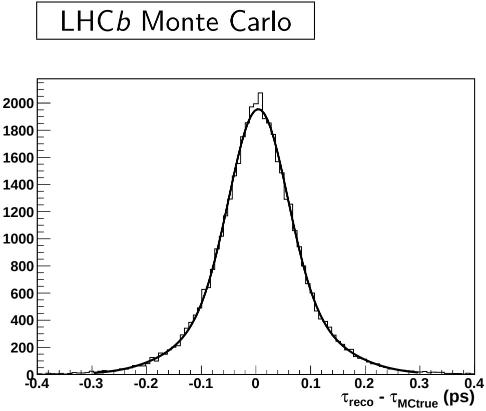
The measurement of $\mathcal{A}^{\Delta}$ is actually a measurement of the difference in the life time in $B_s \to \phi\gamma$ and another channel, e.g. $B_s \to J/\psi\phi$

⇒Show an MC study (on Monte Carlo) to understand proper time reconstruction bias

Proper time bias ($B_s \to \phi\gamma$ MC)



Proper time resolution model fitted with double gaussian

$$\textit{Fraction of core gaussian} = 71\%$$
$$\textit{Mean of core gaussian} = 4.2 \pm 0.5\ fs$$
$$\textit{Width of core gaussian} = 52 \pm 1\ fs$$
$$\textit{Mean of wide gaussian} = 5.4 \pm 1\ fs$$
$$\textit{Width of wide gaussian} = 109 \pm 2\ fs$$

→ A 5 fs bias in proper time results in a systematic uncertainty about 30% of the statistical one

Sources of proper time bias

The B_s proper time is calculated from,

$$\tau = \frac{m \times \vec{p}.(SV - PV)}{\mid \vec{p} \mid^2}$$

therefore, the measurements needed are:

1. B_s momentum
2. B_s mass
3. B_s decay vertex (SV)
4. Primary vertex (PV)

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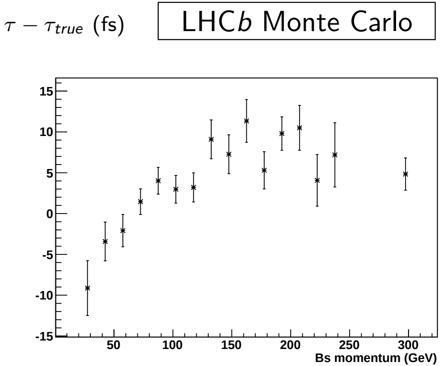
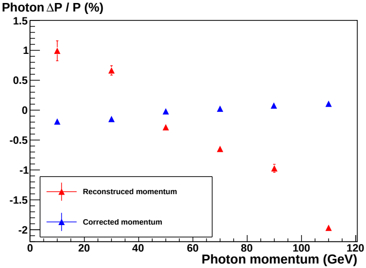


- The photon and phi momenta are correlated to the B_s momentum
- The reconstruction of the momenta and vertex (of the phi) has momentum dependance

→ A potential bias in the photon momentum reconstruction is the biggest effect

Correction of the Photon momentum (MC study)

Constrain the B_s mass and calculate the "correct" photon momentum



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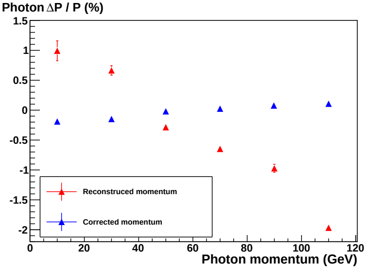

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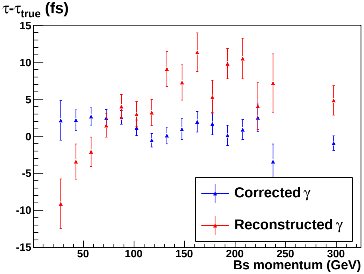
Using this "correct" photon to reconstruct the B_s candidate



→ The proper time reconstruction is now much flatter in the B_s momentum

Correction of the Photon momentum (MC study)

→A bias of order 1% in photon momentum
⇒ ∼ 15 fs in the B_s proper time
⇒ $\sigma_{\mathcal{A}^\Delta,syst} = \sigma_{\mathcal{A}^\Delta,stat}$

→Can be corrected to order 0.2%
⇒ ∼ 5 fs in the B_s proper time
⇒ $\sigma_{\mathcal{A}^\Delta,syst} = 1/3\,\sigma_{\mathcal{A}^\Delta,stat}$

The proper time reconstruction and acceptance function are expected to be understood to desirable levels using control channels $B_d \to K^*\gamma$ and $B_s \to J/\psi\phi$

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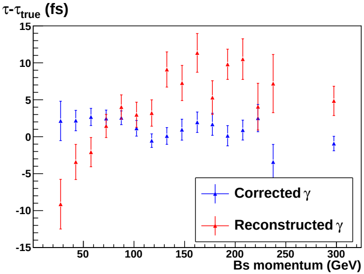

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2. Angular analysis of $B_d \longrightarrow K^* e^+ e^-$ decay products [13]

- The observable $A_T^{(2)}$ is constructed from amplitudes $A_\perp$ and $A_\parallel$
- Transforming to helicity amplitudes, and for small (real) values of $\frac{A_R}{A_L}$

(where A_R and A_L, are the amplitudes for the "right handed" and "left handed" polarization of the photon)

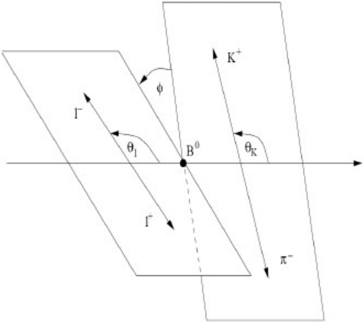
$$A_T^{(2)} \sim -2\frac{A_R}{A_L}$$

Extracting the Photon polarization observable

→ $A_T^{(2)}$ will be extracted from a 2D fit, integrating over θ_l, or a full 3D fit.

→ It has been shown that the sensitivity on $A_T^{(2)}$ is the same for both fits

→ Also, the analysis is not very sensitive to the angular acceptance, hence, systematic uncertainties are expected to be small [12]

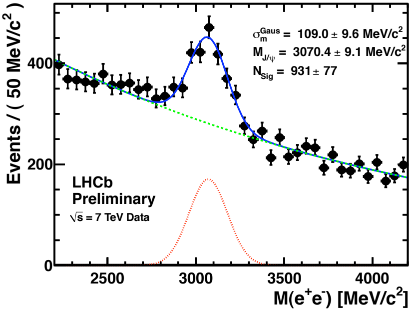


Sensitivity and expected performance of detector

- Expected yield: 200-250 events per 2 fb^{-1}

- Expected S/B: ~ 1

Background levels can be checked with 2 pb^{-1}



From the $B_d \to K^* e^+ e^-$ analysis, for 2 fb^{-1}, expect [12]

$$\sigma_{A_T^{(2)}} \sim 0.2 \Rightarrow \sigma_{\frac{A_R}{A_L}} \sim 0.1 \text{ to } 0.12 \text{ (statistical only)}$$

$B \rightarrow X_s\gamma$ Outlook

- Competitive measurement of photon polarization with $2\,\text{fb}^{-1}$
- Key systematics in $B_s \rightarrow \phi\gamma$ are being understood, and studies suggest they can be controlled at desired levels
  → Further input from control channels $B_s \rightarrow J/\psi\phi$ and $B_d \rightarrow K^*\gamma$
- With $B_d \rightarrow K^*e^+e^-$ analysis, expect to get a factor 2 better statistical precision with $2\,\text{fb}^{-1}$. Systematic studies ongoing

With only $100\,\text{pb}^{-1}$, a competitive measurement of the Direct CP asymmetry in $B_d \rightarrow K^*\gamma$ can be made at LHC*b* [14]

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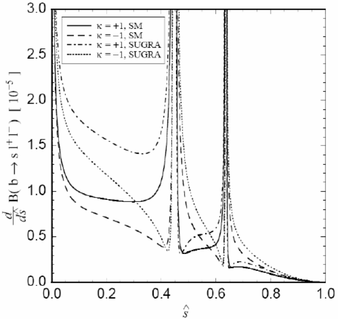
Motivation to measure $B \longrightarrow X_s l^+ l^-$

- b to s ll are interesting because of the BR vs q^2 predictions (enhanced by factor 2 in some NP models)

  Figure from [6]

- Inclusive decays are hard to access in hadron environment
- Exclusive decays, suffer from hadronic uncertainties



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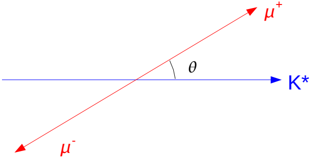


$\rightarrow$ Use observables where these uncertainties cancel, like the forward backward asymmtery A_{FB}

defined as the difference between the number of positive and negative leptons going in the same direction as the K* in the dilepton restframe

$\Rightarrow$ will talk about the measurement of A_{FB} with $B_d \to K^* \mu\mu$, at LHC*b*

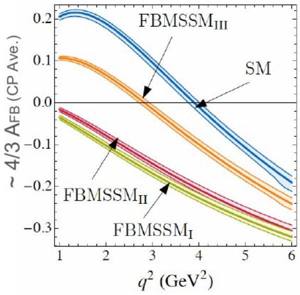
A_{FB} in $B_d \longrightarrow K^* \mu\mu$

- Measurement of the shape of the asymmetry can help to distinguish between different new physics models(Figure from [7])

- The zero crossing point (s_0) of the asymmetry corresponds to the ratio of wilson coefficients

$$s_0 = \frac{-2C_7^{Eff}}{C_9^{Eff}(s_0)}$$

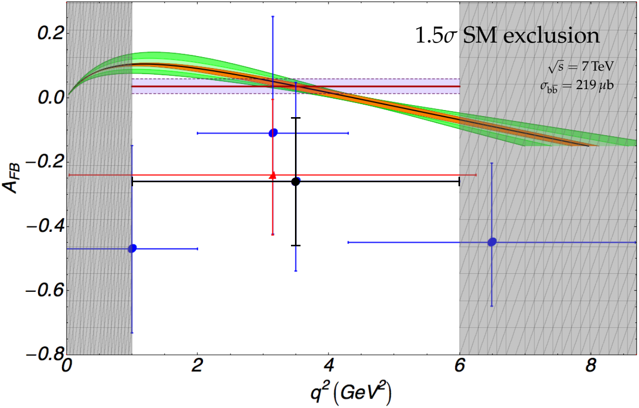
- Theoretically clean measurement



Current status and LHC*b* prospects[1]

BaBar, Belle and LHC*b* with 100 pb^{-1}

(Theory Errors, $\frac{\Lambda}{m_b}$ corrections at 10% level, average of theory curve)



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[1] assuming the central from Belle, error on LHC*b* point is purely statistical

Current status and LHC*b* prospects[2]

BaBar, Belle and LHC*b* with 2 fb^{-1}

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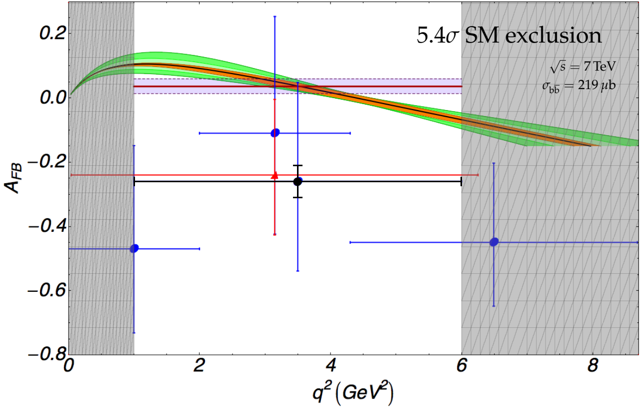

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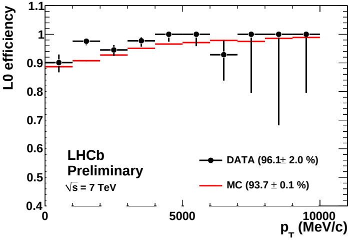
Experimental requirements | Detector

⇒ Efficient trigger: dedicated lines triggering on high PT muons



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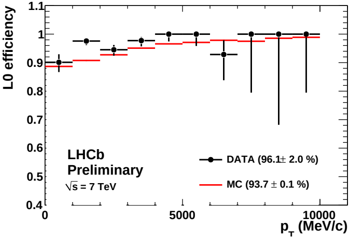
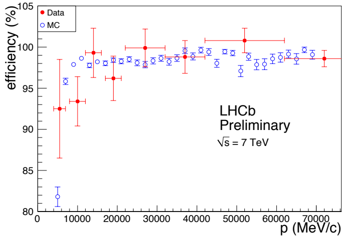


⇒ Positive identification of muons



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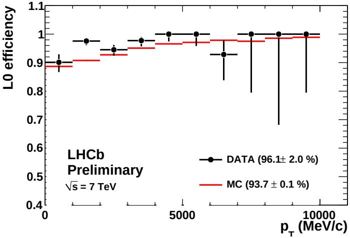

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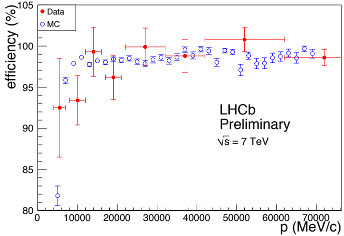
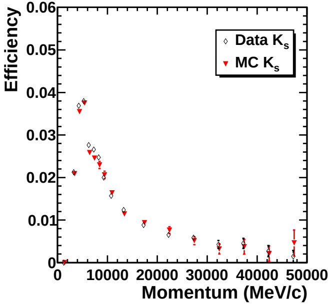


⇒ Low muon mis id rate

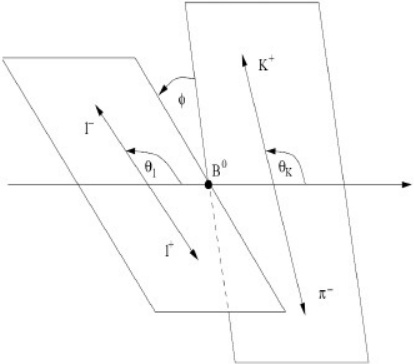


⇒ And efficient particle identification for kaons from $K^* \to K\pi$

Experimental requirements | Analysis

⇒ Measurement of A_{FB} is a counting experiment

⇒ With angular analysis, extract A_{FB} and other variables



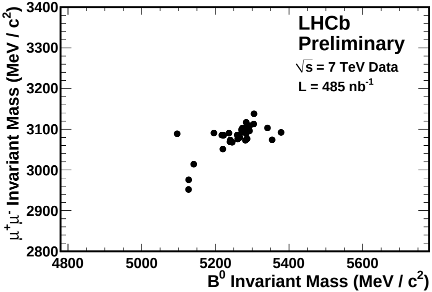
This requires correction of angular distributions for bias introduced by the detector acceptance, trigger and selection requirements [14]

Use $B_d \rightarrow K^* J/\psi$ and $D \rightarrow K\pi\pi\pi$ to understand many of these aspects.

Validation using $B_d \to K^* J/\psi$

This decay has the same final state particles as $B_d \to K^* \mu^+ \mu^-$, and is an excellent way to test the trigger and selection criteria

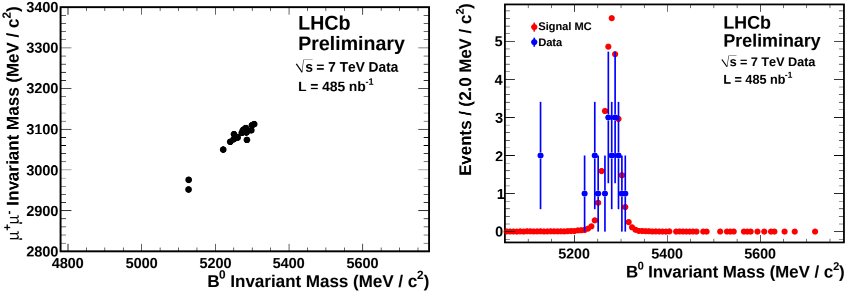
Applying loose preselection



Validation using $B_d \to K^* J/\psi$

This decay has the same final state particles as $B_d \to K^*\mu^+\mu^-$, and is an excellent way to test the trigger and selection criteria

Applying all the $B_d \to K^*\mu^+\mu^-$ selection cuts



Clear signal of $B_d \to K^* J/\psi$ with $B_d \to K^*\mu^+\mu^-$ cuts

⇒The data and MC are normalized to the measured $\sigma_{b\bar{b}}$

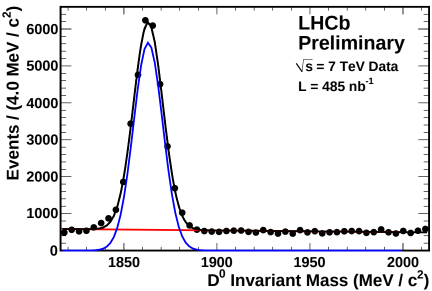
⇒Efficiency estimates from MC are reliable

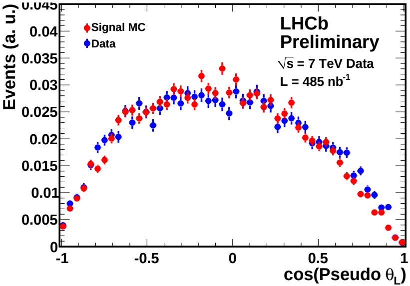
Validation using $D \to K\pi\pi\pi$

Has the same topology and is much more abundent.

Test the trigger and selection criteria, and look at angular distributions

Applying all the $B_d \to K^*\mu^+\mu^-$ selection cuts (barring the μ ID)





$B_d \to K^*\mu^+\mu^-$ like angular distributions made with final state particles

⇒Good agreement between data and MC

⇒The angular biases predicted by MC are reliable

$B \rightarrow X_s l^+ l^-$ Outlook

- A competitive measurement of A_{FB} with early data at LHC*b*
- Further improvements with the understanding of the detector and more data will enable an angular fit to extract complete information from $B_d \rightarrow K^* \mu^+ \mu^-$
- Work started with the data collected with year, to validate the selection chain for $B_d \rightarrow K^* \mu^+ \mu^-$, preliminary results look promising

In summary...

LHC*b* is well positioned to make measurements with relatively small amounts of intergated luminosity ($\sim 100\,\mathrm{pb}^{-1}$)

At that stage, the sensitivities of the measurements in $B \rightarrow X_s l^+ l^-$ and $B \rightarrow X_s \gamma$ are projected to be comparable to existing measurements

With data sets corresponding to $2\,\mathrm{fb}^{-1}$, LHC*b* has the potential to discover NP or at least exclude SM at 5σ level

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Backup slides

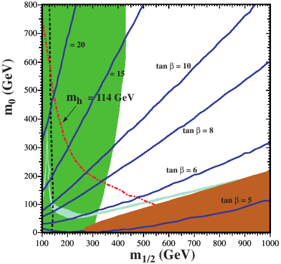
Motivation to measure $B \rightarrow X_s\gamma$

⋆ $BR_{incl} B \rightarrow X\gamma$ in agreement with theory

- $B_{incl,exp}(B \rightarrow X_s\gamma) = 3.56 \pm 0.26 \times 10^{-4}$ [1] [2]
- $B_{incl,th}(B \rightarrow X_s\gamma) = 3.15 \pm 0.23 \times 10^{-4}$ [3]

which can put limits on NP models

Exclusion areas in parameter space of a CMSSM model. constraints from $b \rightarrow s\gamma$, constraints from LSP, and area favoured by WMAP [4]

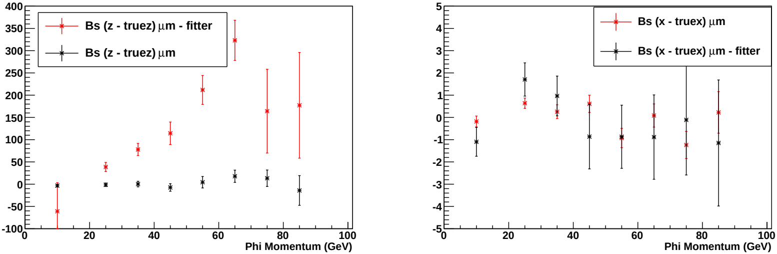


⋆ Measure direct CP asymmetry

(inclusive and exclusive measurement measurements by Belle and Babar [11][10])

Contribution of the vertex reconstruction

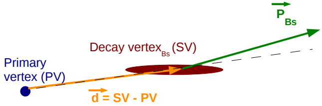
mean(μm) of the core gaussian component of



B_s vertex(z) - true vertex(z)

B_s vertex(x) - true vertex(x)

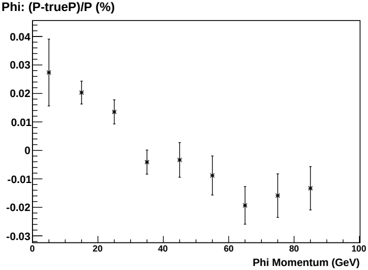
The proper time fitter uses the pointing constraint to find the best position of the B_s vertex and momentum (within errors)

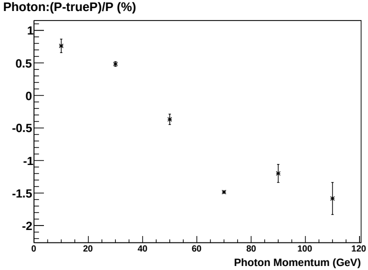


→ Seems to be doing a good job at finding the vertex position

Contribution of the momentum reconstruction

Notice scale on y axes



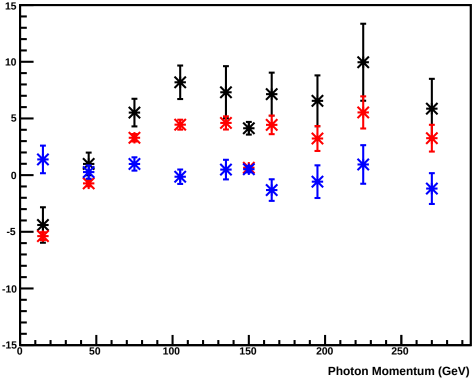


→ The γ momentum exhibits a much bigger effect than the ϕ momentum

Detailed study on Monte Carlo, using the MC true momenta and vertex, but using the errors from reconstruction

Bias in proper time as function of Photon momentum

Bias in the proper time ($\tau - \tau_{true}$, in fs) as a function of the photon momentum for the three cases where

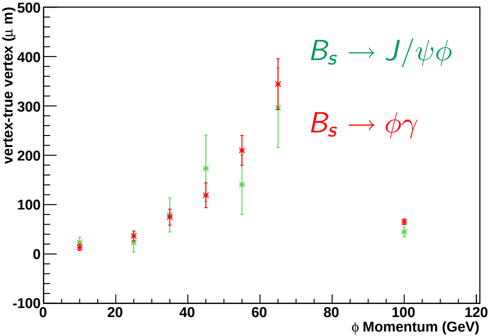


both phi and photon had "reconstructed" momenta and vertex,
only the ϕ was reconstructed while photon had the "true" momentum,

only the photon was reconstructed while the ϕ had the "true" momentum and vertex

ϕ vertex reconstruction

Good agreement between the ϕ vertex bias from $B_s \rightarrow \phi\gamma$ and control channel, after the events from the control channel have been selected to mimic the kinematics of the ϕ in $B_s \rightarrow \phi\gamma$



$b \longrightarrow s\gamma$

The current measurement of $\mathcal{S}$, combining results from the B Factories, is

$$\mathcal{S} = -0.19 \pm 0.23$$

Using $sin2\beta = 0.678 \pm 0.025$ ($2\beta \approx \varphi_s$) and $\mathcal{S} = sin2\beta sin2\psi$

$$sin2\psi = 0.28 \pm 0.44$$

→ In a nominal LHC*b* year, $\sigma_{\mathcal{S}} = 0.1$ (tagged analysis), and $\sigma_{sin2\psi} \sim 0.2$

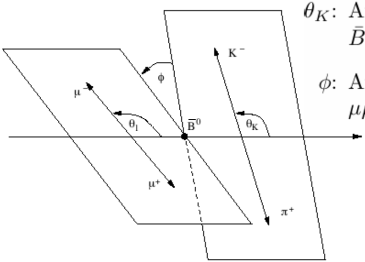
It is also worth noting that the sensitivity of the tagged analyais depends on the size of φ_s

→ By measuring A^{Δ} ($\mathcal{A}^{\Delta} \approx \sin 2\psi$), we get roughly the same sensitivity to $sin2\psi$ without tagging

$$\sigma_{A^{\Delta}} = 0.22$$

$b \longrightarrow sll$

Decay Kinematics



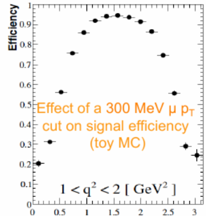
θ_l: Angle between μ^- and $\bar{B}$ in $\mu\mu$ rest frame

θ_K: Angle between K^- and the $\bar{B}$ in the $\bar{K}^{*0}$ rest frame

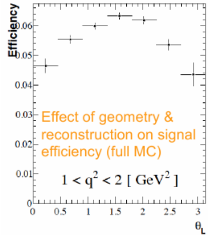
ϕ: Angle between the $\bar{K}^{*0}$ and $\mu\mu$ decay planes

$b \to sll$ Analysis issues

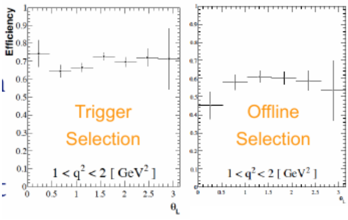
Biases introduced due to geometric acceptance of the detector, trigger requirements


Effect of a 300 MeV μ p_T cut on signal efficiency (toy MC)

$1 < q^2 < 2$ [GeV^2]


Effect of geometry & reconstruction on signal efficiency (full MC)

$1 < q^2 < 2$ [GeV^2]


Trigger Selection

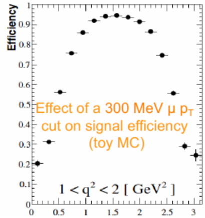
$1 < q^2 < 2$ [GeV^2]

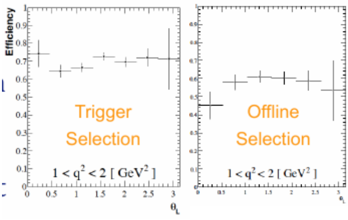
Offline Selection

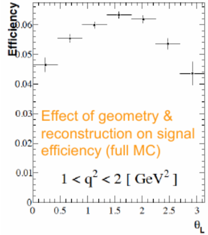
$1 < q^2 < 2$ [GeV^2]

$b \longrightarrow sll$ Analysis issues

Biases introduced due to geometric acceptance of the detector, trigger requirements







Peaking background sources such as $B_d \longrightarrow K^* J/\psi$ (due to mis ID of muon and pion) or $B_s \longrightarrow \phi\mu\mu$ (mis id of kaon as pion) can be reduced by reversing mass hypothesis on the tracks and veto on the ϕ and B_s mass

Trigger, resolutions

- Increased lumi per bunch due to β^* 3.5 m instead of 10
- Higher no of pp interactions per visible event (1.5 instead of 1.2)
- CPU increases dramatically
  → 1 in 100 visible events has a $b\overline{b}$
  → BF of interesting decays $< 10^{-3}$

- Velo: 20 micron IP resolution (at high PT)
- pp vertex resolution: 15 micron in x, y and 100 in z (15 tracks)