Study of the decay $B_s \to J/\psi\phi$ with the CMS detector

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Outline

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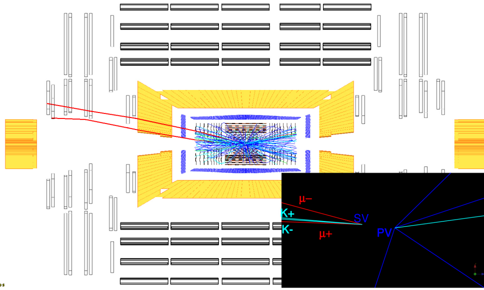
The $B_s \to J/\psi\phi$ decay

$$B_s \to J/\psi\phi \to \mu^+\mu^- K^+ K^-$$

fully reconstructed decay
two muons used for triggering



Parameters

extractable without tagging:
$|A_0|, |A_{||}|, |A_\perp|, \delta_1, \delta_2$
$\Delta\Gamma/\Gamma \approx 10 - 20\%$ (theory)
$\phi_{CKM} = 2\lambda^2\eta \approx -0.04$
with tagging: Δm

First measurements

$\Delta\Gamma/\Gamma(\text{CDF}) = (65^{+25}_{-33} \pm 1)\%$, $\Delta\Gamma/\Gamma(\text{DO}) = (25^{+14}_{-15})\%$

Outline

Trigger selection 1

Level 1: hardware trigger

- di-muon trigger: $p_\perp(\mu) > 3\mathrm{GeV}$
- opposite charge of the 2 muons required

$\Rightarrow$ 900Hz output rate (total L1 output rate: 100kHz)

High Level Trigger 1

J/ψ search (1st part)

- primary vertex reconstruction with pixel detector (use the 3 most probable vertices)
- partial track reconstruction of L1 muons
- cuts on transverse momentum of muons
- $|M(\mu\mu) - M(J/\psi)| < 150\mathrm{MeV}$

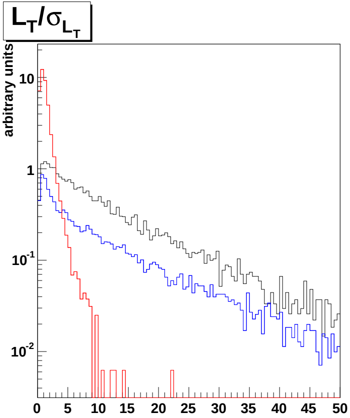
Trigger selection 2

High Level Trigger 2

J/ψ search (2nd part)

- vertex fit for track pairs: $\chi^2 < 20$
- (decay length)$/\sigma_{\text{(decay length)}} > 3$
- cos(p, decay length) > 0.9

$\Rightarrow$ 15Hz output rate
80% from b decays



Trigger selection 3

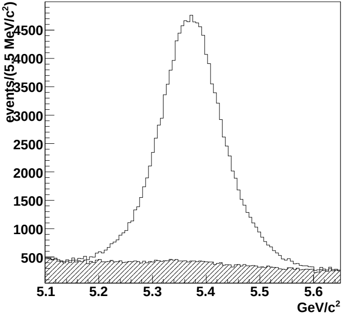
High Level Trigger 3

ϕ and B_s search

- transverse momentum cuts
- $|M(KK) - M(\phi)| < 20\mathrm{MeV}$
- $|M(\mu\mu KK) - M(B_s)| < 200\mathrm{MeV}$
- vertex reconstruction with similar cuts

$\Rightarrow$ 0.1Hz output rate
total HLT output rate: 150Hz

B_s mass at trigger level with combinatorial background



$\sigma = 65\mathrm{MeV}$

Offline selection and reconstuction

muon reconstruction

- full reconstruction using tracker and muon chambers
- transverse momentum cuts

track reconstruction

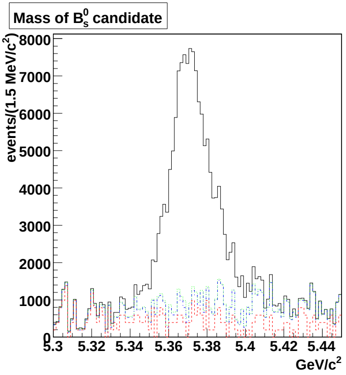
- combinatorial track finder
- transverse momentum cuts

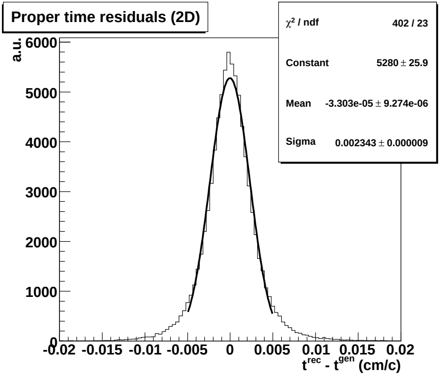
Kinematic fit

- vertex constaint
- J/ψ mass constraint
- $P(\chi^2) > 1 \cdot 10^{-3}$(7 dof)
- cos(p, decay length) > 0.98
- mass cut on ϕ

	$B_s \rightarrow J/\psi\phi$	$b \rightarrow J/\psi$ incl.	$B_d \rightarrow J/\psi K^*$
$\sigma \cdot Br$ (nb)	0.074	3.2	0.366
ϵ (%)	14.7	0.113	0.202
Events per 10 fb^{-1}	109'000	36'200	7'400

Resolution after full reconstruction





Invariant B_s mass

$\sigma(m_{B_s}) = 14\text{MeV}$

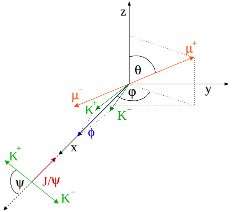
Resolution

transverse decay length: 77 μm
poper decay time: 23 μm/c

Outline

The likelihood function

$$B_S \rightarrow J/\psi\phi \rightarrow \mu^+\mu^- K^+ K^-$$

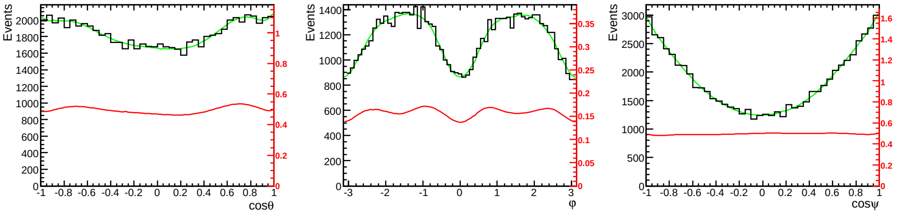


decay can be described by the following differential decay rate:

$$\frac{d^4\Gamma(B_s(t))}{d\cos\theta d\varphi d\cos\psi dt} = f(\Theta,\alpha,t) = \sum_{i=1}^{6} O^{(i)}(\alpha,t)\cdot g^{(i)}(\Theta)$$

- observables O_i only depend on lifetime and parameters like Γ, $\Delta\Gamma$, Δm(in case of tagging), not on angles
- MINUIT fit of full differential decay rate (3 angles + lifetime): $\mathcal{P} = \epsilon(t)\cdot\epsilon(\Theta)\cdot f(\Theta,\alpha,t) + f(\text{background})$
- error on proper decay length free parameter

Angular distributions



projections of

- angular efficiency
- $\epsilon(\Theta) \cdot f(\Theta)$
- MC events

Angular efficiencies

- expand efficiency the following way (from BaBar):

$$\epsilon(\Theta) = \sum_{LRM} T^{\epsilon}_{LRM} \cdot \mathcal{Y}_{LRM}(\Theta) \quad M \leq L, R$$

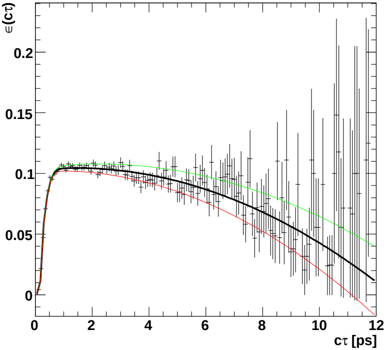
$$\text{with} \quad \mathcal{Y}_{LRM}(\Theta) = \sqrt{2\pi} \cdot Y_{LM}(\theta, \varphi) \cdot Y_{RM}(\psi, 0)$$

- scalar $\rightarrow$ vector decay can be described in terms of these functions
- the coefficients can be determined easily:

$$\Rightarrow T^{\epsilon}_{LRM} = \int \epsilon(\Theta) \cdot \mathcal{Y}^{*}_{LRM}(\Theta) d\Theta$$

$$\approx \frac{1}{N_{gen}} \sum_{i=1}^{N_{obs}} \frac{1}{f(\Theta_i)} \mathcal{Y}_{LRM}(\Theta_i)$$

Efficiency of proper time



proper time efficiency

turn-on with plateau, then deficit

- proper decay length cut
- due to cut on tracking region $\Rightarrow$ implicit cut on proper decay time

try to calibrate with $B_d \rightarrow J/\psi K^{*0}$

$$\epsilon(t) = \begin{cases} c \cdot \left(1 + \tanh\left(\frac{t-t_0}{\Delta t_1}\right)\right) & \text{for } t < t_0 \\ (at^2 + bt + c) \cdot \left(1 + \tanh\left(\frac{t-t_0}{\Delta t_2}\right)\right) & \text{for } t \geq t_0 \end{cases}$$

Background

$B^0 \to J/\psi\, K^{*0} \to \mu^+\mu^- K^+\pi^-$

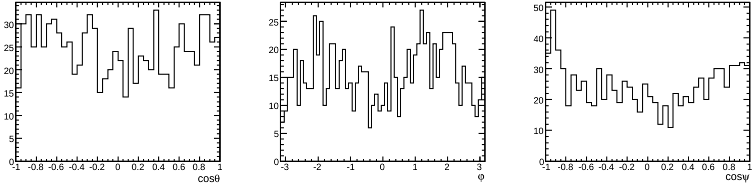
- missidentified π as K
- similar angular distribution as signal but distorted by misidentification of the π
- proper time distribution can be modelled by exponential decay

$b \to J/\psi\, X$, prompt J/ψ

- flat distribution in angles
- fast and slow exponential in proper time

	$B_s \to J/\psi\phi$	$b \to J/\psi$ incl.	$B_d \to J/\psi K^*$
$\sigma \cdot Br$ (nb)	0.074	3.2	0.366
ϵ (%)	14.7	0.113	0.202
Events per 10 fb^{-1}	109'000	36'200	7'400
Events processed	507888	154000	486000
Corresp. Lumi.	$6.8\mathrm{fb}^{-1}$	48 pb^{-1}	$1.3\mathrm{fb}^{-1}$
Events selected	74662	175	981

The maximum likelihood function



probability density function including background

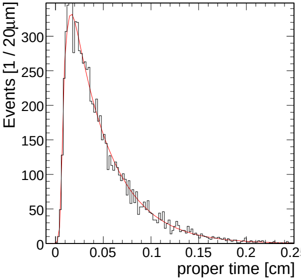
$$\mathcal{P} = \epsilon(t)\cdot\epsilon(\Theta)\cdot f(\Theta,\alpha,t)\cdot(1-b_d-b_c)\cdot G_s(m;m_s,\sigma_s)$$
$$+b_d\cdot f_d(\Theta)\cdot\epsilon(t)\cdot G_d(m;m_d,\sigma_d)\cdot\frac{1}{\tau_d}e^{-t/\tau_d}$$
$$+b_c\cdot\epsilon(t)\cdot\left(\frac{1}{\tau_{cl}}e^{-t/\tau_{cs}}+\frac{1}{\tau_{cl}}e^{-t/\tau_{cl}}\right)\cdot L(m)$$

too low bg statistics → only added to signal, not in fit

Results from the likelihood fit for 1.3 fb^{-1}

Parameter	Input value	Result	Stat. error	Sys. error	Total error	Rel. error
$\|A_0(0)\|^2$	0.57	0.5823	0.0061	0.0152	0.0163	2.8%
$\|A_{\|\|}(0)\|^2$	0.217	0.2130	0.0077	0.0063	0.0099	4.6%
$\|A_\perp(0)\|^2$	0.213	0.2047	0.0065	0.0099	0.0118	5.8%
Γ	0.712ps^{-1}	0.7060ps^{-1}	0.0080ps^{-1}	0.0227ps^{-1}	0.0240ps^{-1}	3.4%
$\Delta\Gamma$	0.142ps^{-1}	0.1437ps^{-1}	0.0255ps^{-1}	0.0113ps^{-1}	0.0279ps^{-1}	19%
$\Delta\Gamma/\Gamma$	0.2	0.2036	0.0374	0.0173	0.0412	20%

- for 10 fb^{-1}(1year of LHC): statistical error on $\Delta\Gamma/\Gamma$: 0.011 syst. error starts to dominate
- stat. error on $\Delta\Gamma/\Gamma$ and ϕ_{CKM} stays approx. const. for different values (from toy-MC)



Systematics and detector effects

Systematic uncertainties on $\Delta\Gamma/\Gamma$

- proper time efficiency uncertainty: 0.0140
- influence of background distribution: 0.0059
- S/B ratio: 0.0055
- resolution: 0.0045
- alignment: 0.0014
- angular efficiency uncertainty: 0.0010

$\Rightarrow$ total systematic uncertainty: 0.0173

Outline

Summary

Conclusion

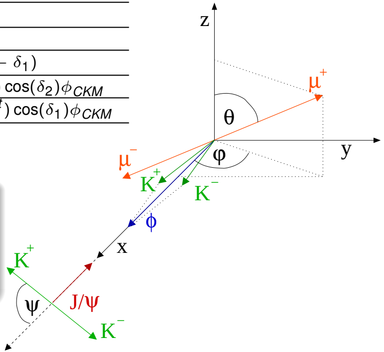
- Angular analysis for $B_s \rightarrow J/\psi\phi$ tested and performed on 1.3 fb
- This would already give better measurement than the currently available:
  - accuracy on $\Delta\Gamma/\Gamma$: 0.04
  - expected statistical error on 10 fb^{-1}: 0.01
- ϕ_{CKM} measurable for large non SM values

Outlook

- Flavour tagging to distiguish B_s and $\bar{B}_s$ in order to measure Δm_s

Backup: Parameters of interest

i	$g^{(i)}(\Theta)$	$O^{(i)}(\alpha, t)$
1	$2\cos^2\psi(1-\sin^2\theta\cos^2\varphi)$	$\lvert A_0\rvert^2 e^{-\Gamma_L t}$
2	$\sin^2\psi(1-\sin^2\theta\sin^2\varphi)$	$\lvert A_\parallel\rvert^2 e^{-\Gamma_L t}$
3	$\sin^2\psi\sin^2\theta$	$\lvert A_\perp\rvert^2 e^{-\Gamma_H t}$
4	$1/\sqrt{2}\sin 2\psi\sin^2\theta\sin 2\varphi$	$\lvert A_0\rvert\lvert A_\parallel\rvert e^{-\Gamma_L t}\cos(\delta_2-\delta_1)$
5	$1/\sqrt{2}\sin 2\psi\sin 2\theta\cos\varphi$	$\lvert A_0\rvert\lvert A_\perp\rvert(1/2)(e^{-\Gamma_H t}-e^{-\Gamma_L t})\cos(\delta_2)\phi_{CKM}$
6	$\sin^2\psi\sin 2\theta\sin\varphi$	$-\lvert A_\parallel\rvert\lvert A_\perp\rvert(1/2)(e^{-\Gamma_H t}-e^{-\Gamma_L t})\cos(\delta_1)\phi_{CKM}$



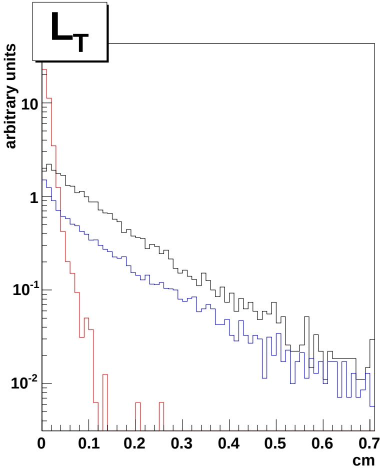
parameters

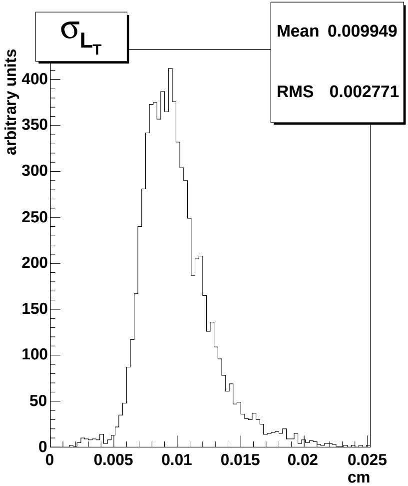
$|A_0|, |A_\parallel|, |A_\perp|, \Gamma_L, \Gamma_H, \delta_1, \delta_2$ and $\phi_{CKM} = 2\lambda^2\eta$
sample is untagged $\Rightarrow \Delta m_s$ cannot be fitted

Backup trigger and DAQ

- Two level trigger architecture:
    - Level 1 trigger based on muon & calorimeters ($40\mathrm{MHz} \rightarrow 100\mathrm{kHz}$)
    - High Level trigger (HLT) using simmilar reconstruction algorithms as offline ($\mathrm{kHz} \rightarrow 150\mathrm{Hz}$)
- Triggers for *B* physics:
    - Level 1: single-muon or dimuon trigger:
        - single-muon: $p_T > 14\mathrm{GeV}$
        - dimuon: $p_T > 3\mathrm{GeV}$
    - HLT:
        - inclusive b,c trigger through b-tagging: $\sim 5\mathrm{Hz}$
        - exclusive *B* decays - under study: consider partial reconstruction of decay products in the tracker in Region of Interest around the muons
          special interest in the initial low-luminosity period

Backup HLT resolution





Backup efficiencies & log-likelihood cont.

- Maximum Likelihood:

$$\sum_{j\text{events}} -\ln f_j' = \sum_{j\text{events}} \left(+\ln N - \ln\left[\epsilon_j(\Theta)\cdot\epsilon_j(t)\right] - \ln f_j\right)$$
$$= \#\text{events}\cdot\ln N - \text{const.} - \sum_{j\text{events}} \ln f_j$$

- constants do not matter if finding a maximum
-

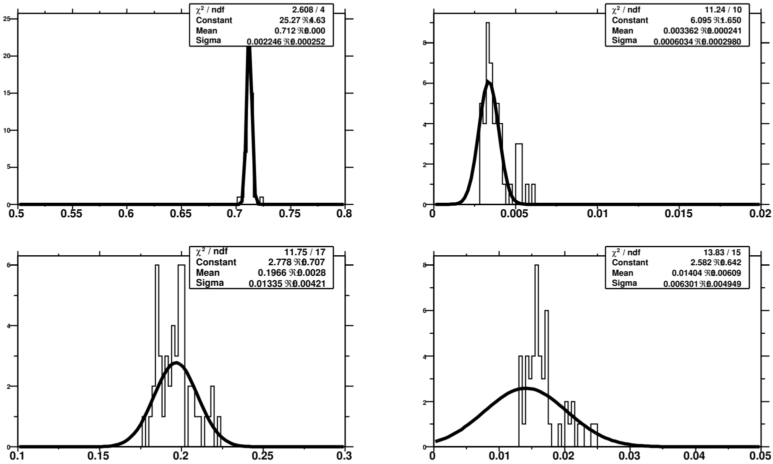
$$N = \int \epsilon(\Theta)\cdot\epsilon(t)\cdot f(\Theta,\alpha,t)\sum_{i=1}^{6} O^{(i)}(\alpha,t)\cdot g^{(i)}(\Theta)\mathrm{d}\Theta\mathrm{d}t$$
$$= \sum_{i=1}^{6}\cdot\left[\int\epsilon(t)O^{(i)}(\alpha,t)\mathrm{d}t\cdot\underbrace{\int\epsilon(\Theta)g^{(i)}(\Theta)\mathrm{d}\Theta}_{canbedeterminedinadvance}\right]$$

Backup validation of likelihood fit

Results of a single generation and likelihood fit on 100'000 events produced with the toy Monte Carlo

Parameter	Input value	Result	Stat.error	Rel.error
$\|A_0(0)\|^2$	0.57	0.5711	0.0023	0.4%
$\|A_{\|\|}(0)\|^2$	0.217	0.2141	0.0036	1.7%
$\|A_\perp(0)\|^2$	0.213	0.2148	0.0030	1.4%
Γ	$0.712\mathrm{ps}^{-1}$	$0.7132\mathrm{ps}^{-1}$	$0.0032\mathrm{ps}^{-1}$	0.5%
$\Delta\Gamma$	$0.142\mathrm{ps}^{-1}$	$0.1338\ \mathrm{ps}^{-1}$	$0.0100\mathrm{ps}^{-1}$	7.4%
$\Delta\Gamma/\Gamma$	0.2	0.188	0.015	8.0%
δ_1	π	2.93	0.61	
δ_2	0	-0.09	0.63	
ϕ_s	-0.04	-0.042	0.072	
$\sigma(\tau)$	$0.1\mathrm{ps}^{-1}$	$0.1006\mathrm{ps}^{-1}$	$0.0039\mathrm{ps}^{-1}$	3.9%

Backup validation of the errors returned by the fit



Backup: Systematic errors

Source	$\|A_0\|^2$	$\|A_{\|\|}\|^2$	$\|A_\perp\|^2$	$\Gamma[\mathrm{ps}^{-1}]$	$\Delta\Gamma/\Gamma$
Bckg. distrib.	0.0034	0.0011	0.0045	0.0043	0.0059
S/B ratio	0.0037	0.0001	0.0024	0.0025	0.0055
Resolution	-	-	-	0.00060	0.0045
Ang. distortion	0.0143	0.0061	0.0082	0.00083	0.0010
$c\tau$ distortion	0.0016	0.00073	0.0023	0.0221	0.0146
Alignment	0.00012	0.00042	0.00055	0.00040	0.0014
Total	0.0152	0.0063	0.0099	0.0227	0.0173