Search for new physics in the $b \rightarrow c\bar{c}s$ decays with LHCb detector at LHC

Morgan MARTIN*

Supervisor: Jibo HE*

Student Session

* *European Organisation for Nuclear Research (CERN), Geneva Switzerland*

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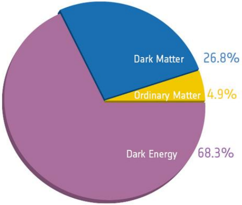
Beyond Standard Model



CP-Violation → Asymmetry

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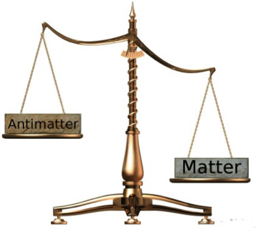
Prediction in Standard Model is too small

⇓

There must be New physics!



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Indirect search:

- Sensitive process of virtual particles (LHCb)

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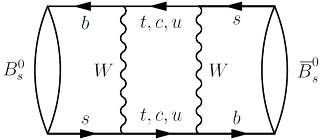
Direct search:

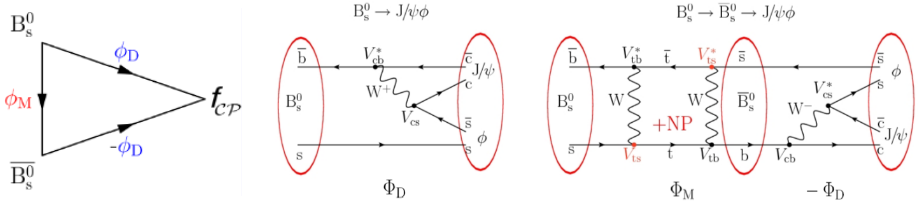
- New particles with high energy (ATLAS, CMS, ...)



Constrain → CKM Matrix

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

Mixing induced CP violation in B_s^0: ϕ_s



- We want to measure $\phi_s \equiv \phi_M - 2\phi_D = -2\beta_s + \delta^{NP}$

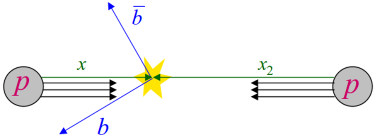
$$\beta_s \equiv \arg\left(-\frac{V_{ts}V_{tb}^\star}{V_{cs}V_{cb}^\star}\right) \quad ; \quad \phi_M = 2\arg(V_{ts}V_{tb}^*) \quad ; \quad \phi_D = \arg(V_{cs}V_{cb}^*)$$

- $\mathcal{A}_{CP}(t) = \frac{\Gamma[\overline{B_s^0}(t)\to f_{\mathcal{CP}}]-\Gamma[B_s^0(t)\to f_{\mathcal{CP}}]}{\Gamma[\overline{B_s^0}(t)\to f_{\mathcal{CP}}]+\Gamma[B_s^0(t)\to f_{\mathcal{CP}}]} \propto sin(\phi_s)sin(\Delta m_s t)$

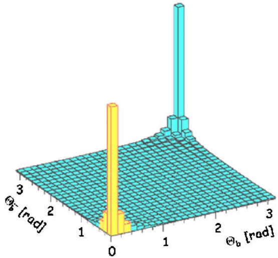
- $\phi_s = -0.0364 \pm 0.0017$ rad (SM global fit)
- $\phi_s = \;\; 0.07 \pm \mathbf{0.09} \pm 0.01$ rad (LHCb latest result)

b quark production at LHC

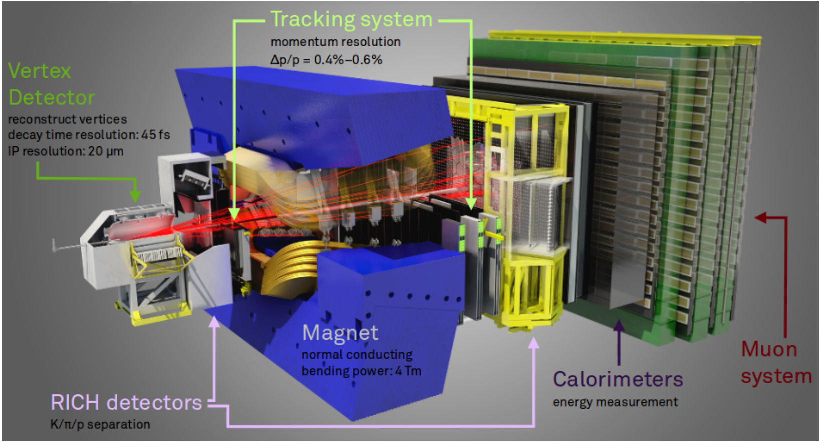
pp collider at high energy ($\sqrt{s} \sim 8\,\mathrm{TeV}$)
σ_{pp} ~60 mb
$\downarrow$
$q\bar{q}$ cross section improve with energy:
$\sigma(pp \to b\bar{b}\,X) \sim 0.3$ mb at $\sqrt{s} \sim 8\,\mathrm{TeV}$
$\sigma(e^+e^- \to b\bar{b}) \sim 1$ nb at $\Upsilon(4S)$
$\Downarrow$
LHC is flavour factory,
Most of background



- In high energy collisions, $b\bar{b}$ pairs are produced predominantly in forward or backward directions



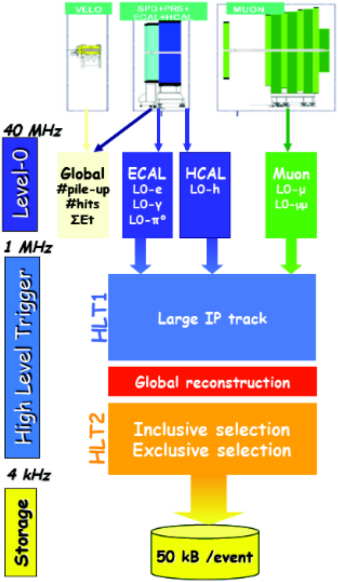
LHCb detector: single-arm forward spectrometer



- 2011 $\sqrt{s} \sim 7$ TeV 1 fb^{-1} and 2012 $\sqrt{s} \sim 8$ TeV 2 fb^{-1}

LHCb work flow

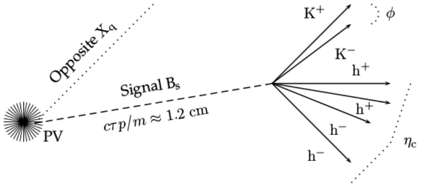
- **Trigger:** Select interesting events
  - L0 trigger (hardware):
    High transverse momentum
  - HLT (software):
    Full reconstruction
- **Stripping:** Central pre-selection of decays under study

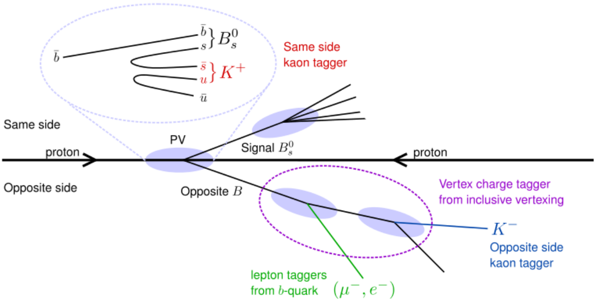


Analysis methodology to ϕ_s

$$\mathcal{A}_{CP}(t) = \frac{\Gamma[\overline{B}^0_s(t)\rightarrow f_{\mathcal{CP}}]-\Gamma[B^0_s(t)\rightarrow f_{\mathcal{CP}}]}{\Gamma[\overline{B}^0_s(t)\rightarrow f_{\mathcal{CP}}]+\Gamma[B^0_s(t)\rightarrow f_{\mathcal{CP}}]} \propto sin(\phi_s)sin(\Delta m_s t)$$

- Trigger and select candidates
    - long lifetime
    - high transverse momentum (P_T)
- Tag initial flavour (B^0_s or $\overline{B}^0_s$?)
- Measure their decay time $t = \frac{\ell \times m}{p}$
- Angular analysis (optional)





$B_s^0 \to \eta_c \phi$

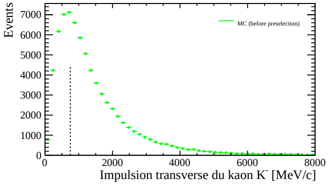
- Goal:
  - reduce the statistical uncertainty on ϕ_s
    $\Rightarrow$ add a new decay mode
  - Never studied before
- Branching Ratio
  - $\mathcal{B}(B_s^0 \to J/\psi\ (\mu^+\mu^-)\ \phi\ (KK)) \simeq 3.2 \times 10^{-5}$
  - $\mathcal{B}(B_s^0 \to \eta_c\ (4h)\ \phi\ (KK)) \simeq 2.3 \times 10^{-5}$ (estimate)
- Challenge
  - $J/\psi\ (\mu^+\mu^-)\ \phi\ (KK)$: easy to select
  - η_c (4h) $\phi\ (KK)$: 6 hadrons in the final state
    $\Rightarrow$ Harder to select
- Angular analysis?
  - $B_s^0 \to J/\psi\, \phi$: Mixing CP-even/odd $\Rightarrow$ Angular analysis
  - $B_s^0 \to \eta_c \phi$: CP-even $\Rightarrow$ No angular analysis

Selection efficiency

- MC samples were generated: $B_s^0 \to \eta_c$ (4h) ϕ (KK)
- Signal reconstruct $B_s^0 \to \eta_c$ ($KK\pi\pi$) ϕ (KK): Current Stripping Line
  - $\epsilon_{\text{Strip}} = (8.63 \pm 0.13) \times 10^{-2}$

Some efficiency of Stripping Line cut

K^+ P$_T$ [MeV]	>	750.0	% 79.57	±	0.18
K^- P$_T$ [MeV]	>	750.0	% 79.45	±	0.19
π^+ P$_T$ [MeV]	>	750.0	% 66.05	±	0.23
π^- P$_T$ [MeV]	>	750.0	% 65.79	±	0.23
η_c ΣP$_T$ (K^+, K^-, π^+, π^-) [MeV]	>	4000.0	% 77.45	±	0.20
DOCA	<	0.1	65.02	±	0.23

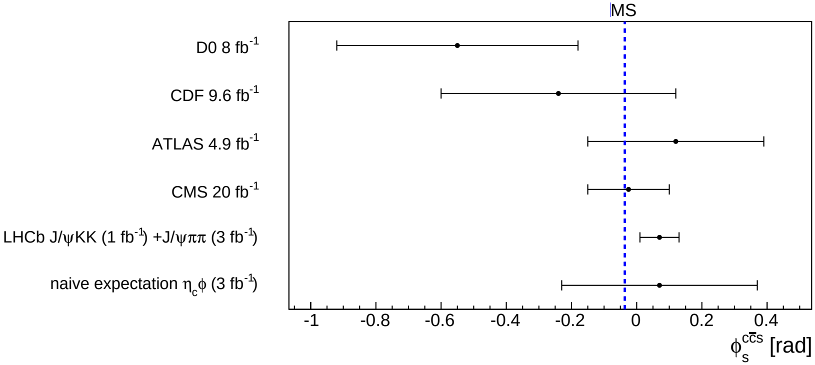


The to-do-list

- More familiar with LHCb software
- Develop new Stripping Line
  1) Use cut-based pre-selection to reduce number of combinations and save CPU
  2) Use MVA for final selection, to fit into the bandwidth budget
  3) Add channel $\eta_c \rightarrow KKKK$ and $\eta_c \rightarrow \pi\pi\pi\pi$
- Signal $\rightarrow$ MC
- Background $\rightarrow$ Real data: Upper Side Band

Conclusions and prospects (Preliminary)

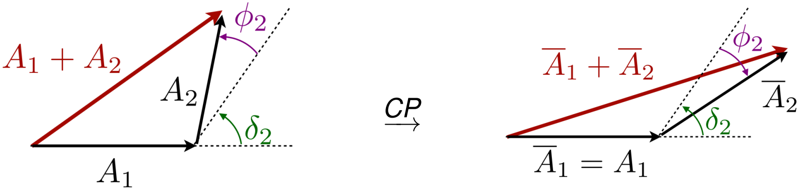
- $B_s^0 \to \eta_c(4h)\phi(KK)$ selection:
  - re-optimize Stripping Line
  - perform full ϕ_s analysis
    $\Rightarrow$ naive estimate $\sigma(\phi_s) < 0.3$ rad



Backup

CP violation observation

- A single amplitude cannot give an observable CP violation
- Must have a sum of amplitudes $\Rightarrow$ contribution from few processes



- ϕ_2 weak phase: CP-violating
- δ_2 strong phase: CP-conserving

Two amplitudes with one phase changing under CP and one CP-conserving $\rightarrow$ CP asymmetry:

$$\mathcal{A}_{CP} = \frac{\Gamma[\overline{B}\to\bar{f}]-\Gamma[B\to f]}{\Gamma[\overline{B}\to\bar{f}]+\Gamma[B\to f]}$$

Estimation of $\mathcal{B}(B_s^0 \to \eta_c(4h)\phi(KK))$

$$\begin{aligned}\mathcal{B}(B_s^0 \to \eta_c(4h)\phi(KK)) &= \mathcal{B}(B_s^0 \to \eta_c\phi) \times \mathcal{B}(\eta_c \to 4h) \times \mathcal{B}(\phi \to KK) \\ &\simeq 2.3 \times 10^{-5}\end{aligned}$$

- $\mathcal{B}(B_s^0 \to \eta_c\phi)$:
  - $d = s$ hypothesis

$\rightarrow \frac{\mathcal{B}(B_s^0 \to \eta_c\phi)}{\mathcal{B}(B_s^0 \to J/\psi\,\phi)} = \frac{\mathcal{B}(B_d \to \eta_c K^0)}{\mathcal{B}(B_d \to J/\psi\,K^0)}$

- $\mathcal{B}(\eta_c \to K^+K^-\pi^+\pi^-) \sim 53\%$
  - $\mathcal{B}(\eta_c \to K^+K^-\pi^+\pi^-)$ NR
  - $\mathcal{B}(\eta_c \to K_0^* K^-\pi^+)$
  - $\mathcal{B}(\eta_c \to K_0^* \overline{K}_0^*)$
  - $\mathcal{B}(\eta_c \to f_2(1270)f_2'(1525))$
  - $\mathcal{B}(\eta_c \to f_2(1270)f_2(1270))$
- $\mathcal{B}(\eta_c \to \pi^+\pi^-\pi^+\pi^-) \sim 40\%$
  - $\mathcal{B}(\eta_c \to \pi^+\pi^-\pi^+\pi^-)$ NR
  - $\mathcal{B}(\eta_c \to \rho_0\rho_0)$
  - $\mathcal{B}(\eta_c \to f_2(1270)f_2(1270))$
- $\mathcal{B}(\eta_c \to K^+K^-K^+K^-) \sim 7\%$
  - $\mathcal{B}(\eta_c \to K^+K^-K^+K^-)$ NR
  - $\mathcal{B}(\eta_c \to \phi K^+K^-)$
  - $\mathcal{B}(\eta_c \to \phi\phi)$

Angular analysis

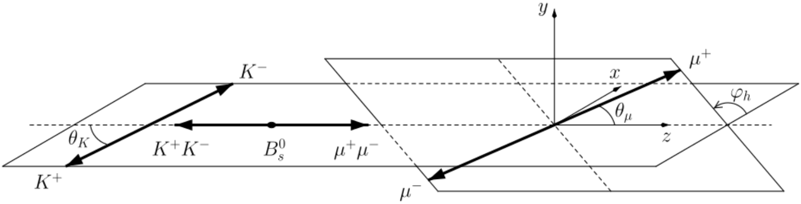
B_s^0 pseudo-scalar particle and ϕ vector particle

- J/ψ vector particle
  $\Rightarrow B_s^0 \to J/\psi\ \phi$ mixing CP-even/odd

  $\downarrow$

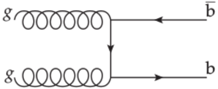
  3 Strong phases $\delta_{\parallel}$,$\delta_{\perp}$ and δ_0
  $\to -30\%$ of stat

- η_c pseudo-scalar particle
  $\Rightarrow B_s^0 \to \eta_c\ \phi$ CP-even



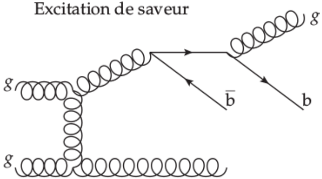
Production of pair $b\overline{b}$

Fusion de gluons

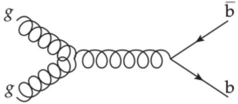


Annihilation $q\bar{q}$

Excitation de saveur



Separation de gluons



- 57% flavor exciting
- 27% gluons separation
- 16% pair creation

Decay modes (1/5)

Mode	$\mathcal{B}$	$\sigma_{\mathcal{B}}$
$\rho_0 \to \pi^+\pi^-$	1.00	0.00
$f_2(1270) \to \pi\pi$	8.48×10^{-1}	2.40×10^{-2}
$f_2(1270) \to \pi^+\pi^-$	5.65×10^{-1}	1.60×10^{-2}
$f_2(1270) \to K\overline{K}$	4.60×10^{-2}	4.00×10^{-3}
$f_2(1270) \to K^+K^-$	3.07×10^{-2}	2.67×10^{-3}
$f_2'(1525) \to \pi\pi$	8.20×10^{-3}	1.50×10^{-3}
$f_2'(1525) \to \pi^+\pi^-$	5.47×10^{-3}	1.00×10^{-3}
$f_2'(1525) \to K\overline{K}$	8.87×10^{-1}	2.20×10^{-2}
$f_2'(1525) \to K^+K^-$	5.91×10^{-1}	1.47×10^{-2}
$K_0^* \to K^+\pi^-$	6.67×10^{-1}	0.00
$\phi \to K^+K^-$	4.89×10^{-1}	5.00×10^{-3}

Decay modes (2/5)

Mode	$\mathcal{B}$	$\sigma_{\mathcal{B}}$
$\eta_c \to K^+K^-K^+K^-$ (non résonant)	1.34×10^{-3}	3.20×10^{-4}
$\eta_c \to \phi K^+K^-$	2.90×10^{-3}	1.40×10^{-3}
$\eta_c \to \phi(K^+K^-)K^+K^-$	1.42×10^{-3}	6.85×10^{-4}
$\eta_c \to \phi\phi$	1.94×10^{-3}	3.00×10^{-4}
$\eta_c \to \phi(K^+K^-)\phi(K^+K^-)$	4.64×10^{-4}	7.20×10^{-5}
$\eta_c \to K^+K^-K^+K^-$	3.22×10^{-3}	7.59×10^{-4}

Decay modes (3/5)

$\eta_c \to K^+K^-\pi^+\pi^-$ (non résonant)	6.10×10^{-3}	1.20×10^{-3}
$\eta_c \to K_0^* K^-\pi^+$	2.00×10^{-2}	7.00×10^{-3}
$\eta_c \to K_0^*(K^+\pi^-)K^-\pi^+$	1.33×10^{-2}	4.67×10^{-3}
$\eta_c \to K^*\overline{K}^*$	6.80×10^{-3}	1.30×10^{-3}
$\eta_c \to K_0^*\overline{K}_0^*$	2.27×10^{-3}	4.33×10^{-4}
$\eta_c \to K_0^*(K^+\pi^-)\overline{K}_0^*(K^-\pi^+)$	1.01×10^{-3}	1.93×10^{-4}
$\eta_c \to f_2(1270)f_2'(1525)$	9.30×10^{-3}	3.10×10^{-3}
$\eta_c \to f_2(1270)(\pi^+\pi^-)f_2'(1525)(K^+K^-)$	3.11×10^{-3}	1.04×10^{-3}
$\eta_c \to f_2(1270)(K^+K^-)f_2'(1525)(\pi^+\pi^-)$	1.56×10^{-6}	6.08×10^{-7}
$\eta_c \to f_2(1270)f_2(1270)$	9.70×10^{-3}	2.50×10^{-3}
$\eta_c \to f_2(1270)(\pi^+\pi^-)f_2(1270)(K^+K^-)$	1.68×10^{-4}	4.60×10^{-5}
$\eta_c \to f_2(1270)(K^+K^-)f_2(1270)(\pi^+\pi^-)$	1.68×10^{-4}	4.60×10^{-5}
$\eta_c \to K^+K^-\pi^+\pi^-$	2.39×10^{-2}	4.93×10^{-3}

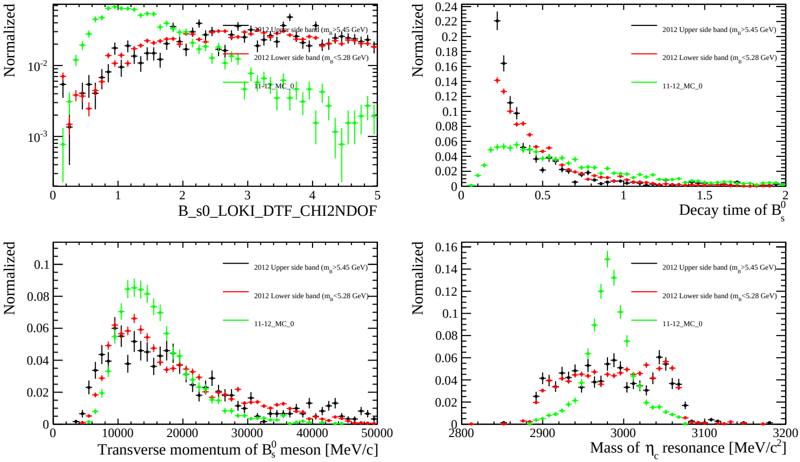
Decay modes (4/5)

$\eta_c \to \pi^+\pi^-\pi^+\pi^-$ (non résonant)	8.60×10^{-3}	1.30×10^{-3}
$\eta_c \to \rho\rho$	1.80×10^{-2}	5.00×10^{-3}
$\eta_c \to \rho_0\rho_0$	6.00×10^{-3}	1.67×10^{-3}
$\eta_c \to \rho_0(\pi^+\pi^-)\rho_0(\pi^+\pi^-)$	6.00×10^{-3}	1.67×10^{-3}
$\eta_c \to f_2(1270)f_2(1270)$	9.70×10^{-3}	2.50×10^{-3}
$\eta_c \to f_2(1270)(\pi^+\pi^-)f_2(1270)(\pi^+\pi^-)$	3.10×10^{-3}	8.09×10^{-4}
$\eta_c \to \pi^+\pi^-\pi^+\pi^-$	1.77×10^{-2}	2.26×10^{-3}
$\eta_c \to (4h)$	4.48×10^{-2}	5.48×10^{-3}

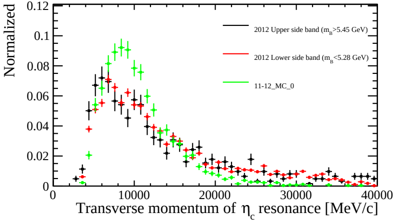
Decay modes (5/5)

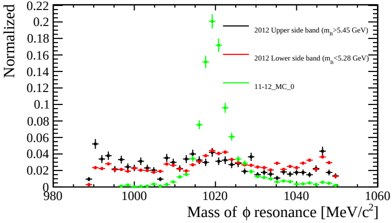
Mode	$\mathcal{B}$	$\sigma_{\mathcal{B}}$
$J/\psi \to \mu^+\mu^-$	5.93×10^{-2}	6.00×10^{-4}
$B_s^0 \to J/\psi\phi$	1.09×10^{-3}	2.60×10^{-4}
$B_s^0 \to J/\psi(\mu^+\mu^-)\phi(K^+K^-)$	3.16×10^{-5}	7.55×10^{-6}
$B_s^0 \to \eta_c\phi$	1.04×10^{-3}	2.91×10^{-4}
$B_s^0 \to \eta_c(4h)\phi(K^+K^-)$	2.27×10^{-5}	6.96×10^{-6}
$B_s^0 \to \eta_c(K^+K^-K^+K^-)\phi(K^+K^-)$	1.63×10^{-6}	5.99×10^{-7}
$B_s^0 \to \eta_c(\pi^+\pi^-\pi^+\pi^-)\phi(K^+K^-)$	8.96×10^{-6}	2.77×10^{-6}
$B_s^0 \to \eta_c(K^+K^-\pi^+\pi^-)\phi(K^+K^-)$	1.21×10^{-5}	4.22×10^{-6}

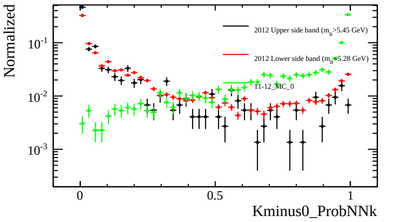
Descriminating variable (1/3)

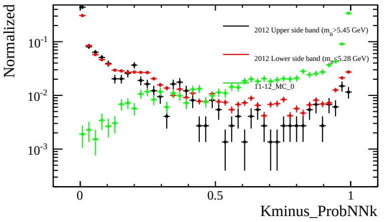


Descriminating variable (2/3)

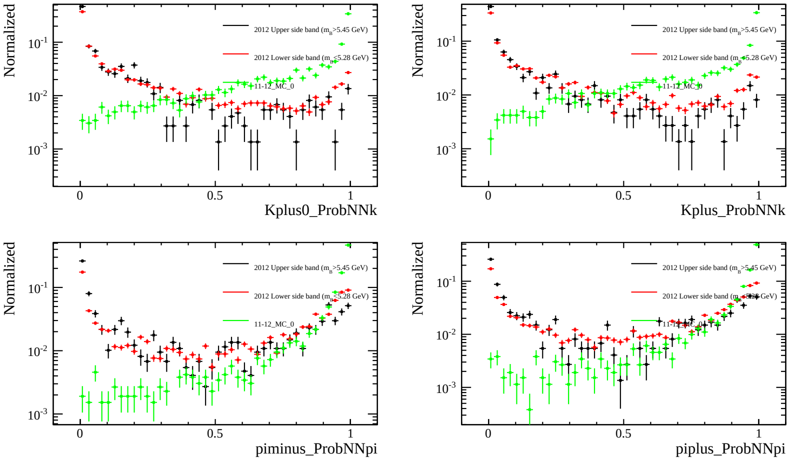








Descriminating variable (3/3)



Software in LHCb

online:

- Particles productions and decays:
  - PYTHIA: proton-proton collision
  - Photos: photon emission
  - EvtGen: hadron-*b* decays
- Interaction with LHCb detecteur
  - GEANT4: Interaction between matter and particles
  - Boole: Digitisation

offline:

- Brunel: event reconstruction
- DaVinci: Decay analysis
- Stripping Line: preselection code
- MINUIT: likelihood minimisation algorithm

Measurement of ϕ_s in $B_s \to \eta_c \phi$

- $\eta_c \phi$ purely even-CP eigenstate$\Rightarrow$no angular dependence

$$\frac{d\Gamma(B_s^0 \to \eta_c \phi)}{dt} \propto e^{-\Gamma_s t}\left[\sin(\phi_s)\sin(\Delta m_s t) + \cosh(\tfrac{1}{2}\Delta\Gamma_s t) - \cos(\phi_s)\sinh(\tfrac{1}{2}\Delta\Gamma_s t)\right]$$

$$\frac{d\Gamma(\bar{B}_s^0 \to \eta_c \phi)}{dt} \propto e^{-\Gamma_s t}\left[-\sin(\phi_s)\sin(\Delta m_s t) + \cosh(\tfrac{1}{2}\Delta\Gamma_s t) - \cos(\phi_s)\sinh(\tfrac{1}{2}\Delta\Gamma_s t)\right]$$

with $\Delta\Gamma_s \equiv \Gamma_H - \Gamma_L$ and $\Delta m_s \equiv M_H - M_L$

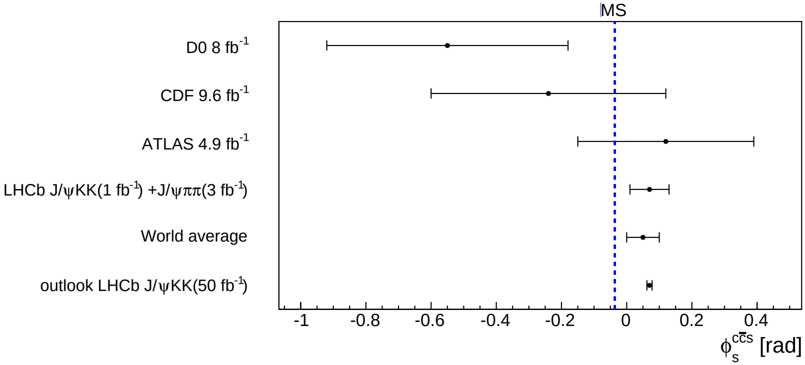
- $\mathcal{A}_{CP}(t) = \frac{\Gamma[\overline{B}_s(t)\to\eta_c\phi]-\Gamma[B_s(t)\to\eta_c\phi]}{\Gamma[\overline{B}_s(t)\to\eta_c\phi]+\Gamma[B_s(t)\to\eta_c\phi]} \propto sin(\phi_s)sin(\Delta m_s t)$

Background

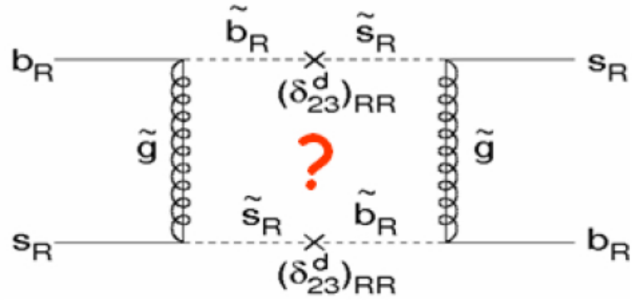
- $\eta_c \to KK\pi\pi$
  - $B_s^0 \to D_s D_s$
    where $D_s \to \phi\pi$ or $D_s \to KK\pi$
  - $B_s^0 \to \phi\, 4h$
  - $B_s^0 \to \phi\phi\phi$
- $\eta_c \to \pi\pi\pi\pi$
  - $B_s^0 \to D_s\pi\pi\pi$

Step	# MC evts of signal	Efficiency		Error
$\epsilon_{rec/gen}$	178 842	4.50×10^{-2}	$\pm$	0.10×10^{-2}
$\epsilon_{strip/rec}$	15 434	8.63×10^{-2}	$\pm$	0.13×10^{-2}
$\epsilon_{trig/strip}$	3 725	2.28×10^{-1}	$\pm$	0.30×10^{-1}

Expected sensitivity in 2028



Example of NP



Systematics

Source	Γ_s [ps^{-1}]	$\Delta\Gamma_s$ [ps^{-1}]	$\|A_\perp(t)\|^2$	$\|A_0(t)\|^2$	$\delta_\parallel$ [rad]	$\delta_\perp$ [rad]	ϕ_s [rad]	$\|\lambda\|$
Stat. uncertainty	0.0048	0.016	0.0086	0.0061	$^{+0.13}_{-0.21}$	0.22	0.091	0.031
Background subtraction	0.0041	0.002	–	0.0031	0.03	0.02	0.003	0.003
$B^0 \to J/\psi K^{*0}$ background	–	0.001	0.0030	0.0001	0.01	0.02	0.004	0.005
Ang. acc. reweighting	0.0007	–	0.0052	0.0091	0.07	0.05	0.003	0.020
Ang. acc. statistical	0.0002	–	0.0020	0.0010	0.03	0.04	0.007	0.006
Lower decay time acc. model	0.0023	0.002	–	–	–	–	–	–
Upper decay time acc. model	0.0040	–	–	–	–	–	–	–
Length and mom. scales	0.0002	–	–	–	–	–	–	–
Fit bias	–	–	0.0010	–	–	–	–	–
Quadratic sum of syst.	0.0063	0.003	0.0064	0.0097	0.08	0.07	0.009	0.022
Total uncertainties	0.0079	0.016	0.0107	0.0114	$^{+0.15}_{-0.23}$	0.23	0.091	0.038

CP and CKM

- Definition: CP transformation (not conserved)

- Charge Conjugation C:
$$C|\psi(\vec{p},h)\rangle = \eta_C|\overline{\psi}(\vec{p},h)\rangle$$

- Parity P:
$$P|\psi(\vec{p},h)\rangle = \eta_P|\psi(-\vec{p},-h)\rangle$$

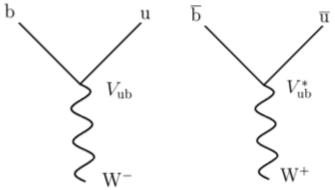
- Product CP:
$$CP|\psi(\vec{p},h)\rangle = \eta_{CP}|\overline{\psi}(-\vec{p},-h)\rangle$$

- CKM Matrix and Wolfenstein parametrization

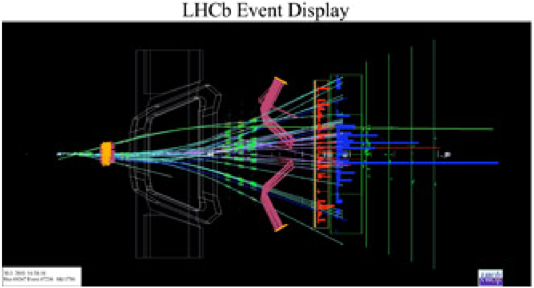
$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

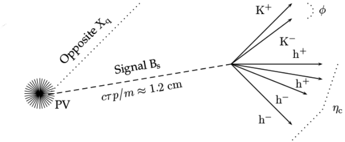
- CP violation is described by an irreducible phase: $\eta \neq 0$ in the SM

- CKM phase: $V_{ub} \neq V_{ub}^*$



Combinatorial background and preselection





- $\sim$100 tracks per event
  - 80% are low p_T kaons and pions from the primary vertex
    $\longrightarrow$ source of combinatorial background
    $\longrightarrow$ difficult to select the 6 hadrons of our final state
- Preselection: reduce number of events
  - Kinematic cuts (p, p_T, χ^2 vertex, mass)
  - Particle-identification cuts

Expected number of signal candidates (S)

$$S = \mathcal{L}_{\text{int}} \times \sigma_{b\bar{b}} \times f_{B_s^0} \times 2 \times \mathcal{B}(B_s^0 \to \eta_c(4h)\phi(KK)) \times \epsilon_{\text{tot}}$$
$$\epsilon_{\text{tot}} = \epsilon_{\text{acceptance}} \times \epsilon_{\text{reconstruction}} \times \epsilon_{\text{trigger}} \times \epsilon_{\text{preselection}}$$

- First estimation of S with a Monte Carlo based study (2006) $\longrightarrow \sim$ 4300 events
  (LHCb has 95 000 $B_s^0 \to J/\psi(\mu^+\mu^-)\phi(KK)$ events)

- $\mathcal{L}_{\text{int}}$ total luminosity (3 fb^{-1})
- $\sigma_{b\bar{b}}$ cross section of $b\bar{b}$ production ($\sim$250 μb at 7 TeV)
- $f_{B_s^0}$ fraction of b quark giving a B_s^0 meson ($\sim$10%)

- We need to estimate:
  - $\mathcal{B}(B_s^0 \to \eta_c(4h)\phi(KK))$
  - ϵ_{tot} (and intermediate efficiencies)