Measurement of CP violation phase in B_s mixing from (pseudo)scalar-vector decays in LHCb experiment

Expected results from Monte Carlo study

On behalf of LHCb collaboration

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Outline

1. **Part I**
   - CP violation in B_s mesons decays
   - Current state of the measurements
   - Measurements of weak mixing phase in LHCb experiment

2. **Part II**
   - $B_s^0 \longrightarrow \chi_c^0 \, \phi$ event selection in LHCb experiment

3. **Summary**

PART I

CKM matrix and weak mixing phase

- Cabibbo-Kobayashi-Maskawa) matrix - transitions between quark families:

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

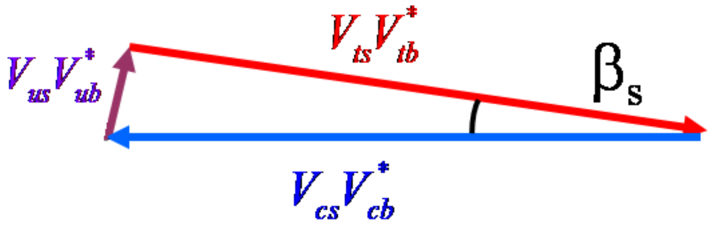
Parameters depend on three (real) mixing angles and one complex phase which is the only source of CP violation in the SM

$$\begin{array}{cc} & \begin{array}{ccc} d & s & b \end{array} \\ \begin{array}{c} u \\ c \\ t \end{array} & \begin{pmatrix} 1 & 1 & e^{-i\gamma} \\ 1 & 1 & 1 \\ e^{-i\beta} & -e^{-i\beta_s} & 1 \end{pmatrix} \end{array}$$

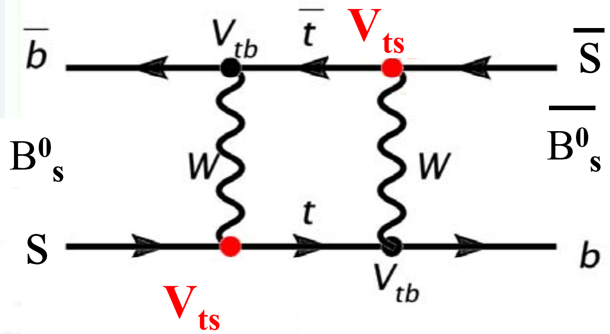
- CKM unitarity → unitary triangles

$$\boxed{V_{us}V_{ub}^{*} + V_{cs}V_{cb}^{*} + V_{ts}V_{tb}^{*} = 0}$$

$$\beta_s = \arg(-V_{ts}V_{tb}^{*} / V_{cs}V_{cb}^{*})$$



In B_s^0-B_s^0 mixing diagra V_{ts} occurs twice



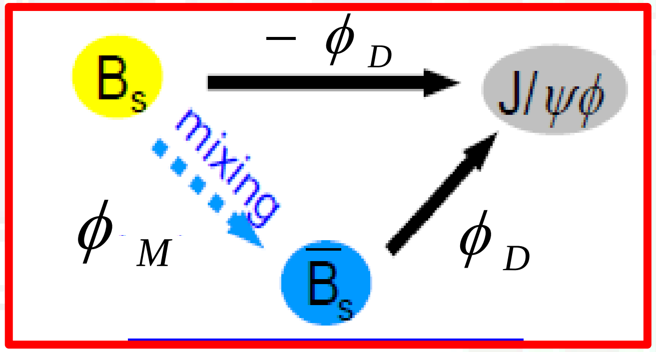
✓ In the Standard Model weak mixing phase $\phi_S = -2\ \beta_S$ is related with B^0_s oscillations

✓ In the same way B^0_d mixing generates $\phi = -2\ \beta$

~~CP~~ in B_s decays: b→ccs quark-level process

- Very rare penguin decays: → ~~CP~~ in decays neglected
- No ~~CP~~ in mixing: $\left|\frac{q}{p}\right| = 1, \ \frac{q}{p} = e^{-i\phi_M}$
- ~~CP~~ in the interference between decays to the same final state either directly or via mixing:

$$\boxed{\phi_s = \phi_M - 2\phi_D}$$

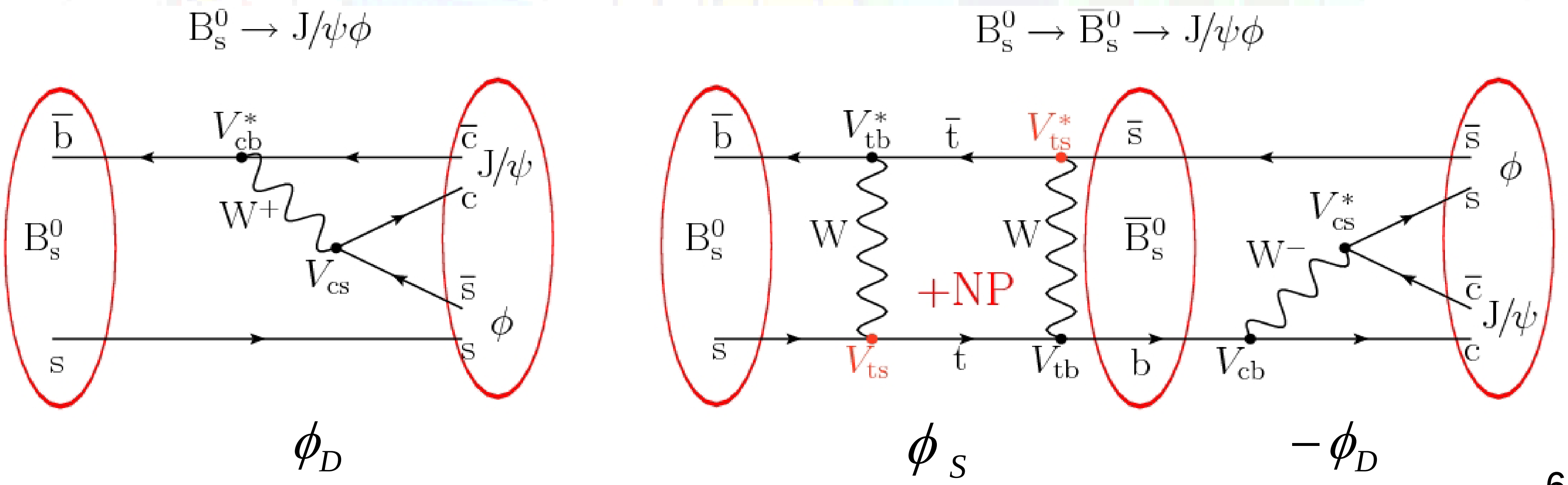


- ϕ_s accessible directly from CP asymmetry:

$$A_{CP}(t) = \frac{\Gamma(B_s^0(t) \to f) - \Gamma(\overline{B_s^0}(t) \to f)}{\Gamma(B_s^0(t) \to f) + \Gamma(\overline{B_s^0}(t) \to f)} = \frac{-\sin(\phi_s)\sin(\Delta m_s t)}{\cosh(\frac{\Delta\Gamma_s t}{2}) - \cos(\phi_s)\sinh(\frac{\Delta\Gamma_s t}{2})}$$

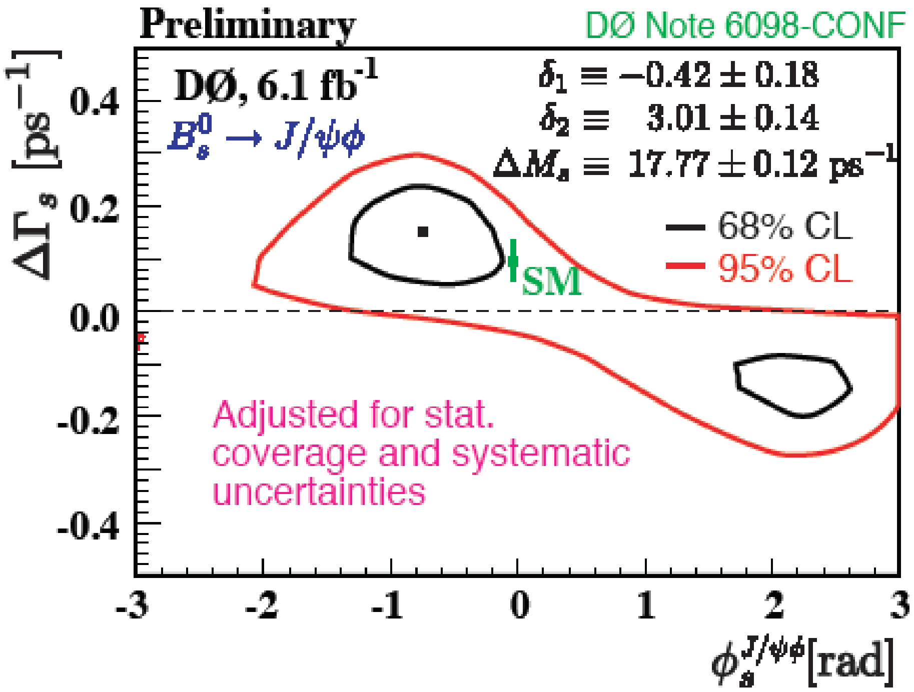
- ϕ_s **is accessible via B_s decays:**
  - to CP eigenstates: $B_s^0 \to J/\psi\eta, B_s^0 \to J/\psi\eta', B_s^0 \to \eta_c\phi, B_s^0 \to \chi_c\phi, B_s^0 \to J/\psi f_o, B_s^0 \to D_s^+ D_s^-$
  - to the superposition of CP eigenstates: $B_s^0 \to J/\psi\phi$ - golden channel for ϕ_S

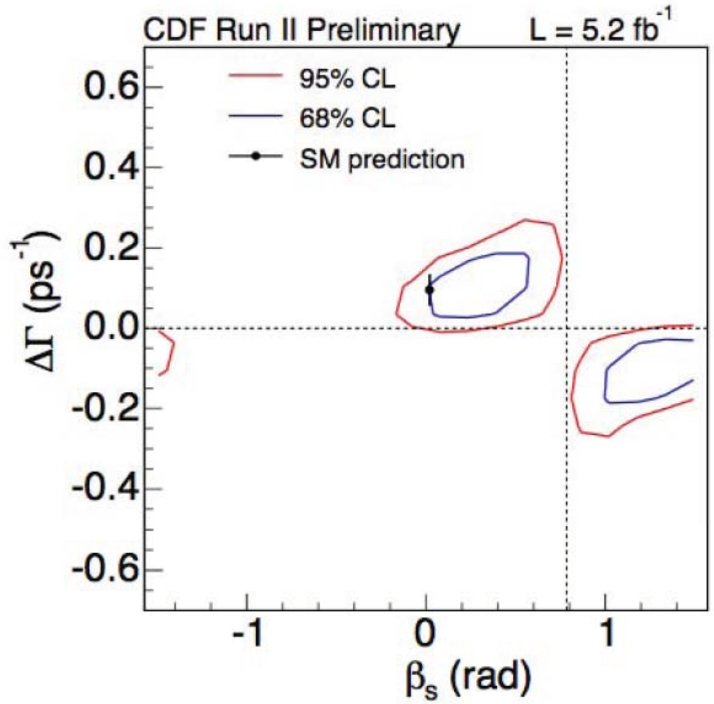
- ϕ_s **is the sensitive probe of New Physics:**
  - ϕ_s very small in the SM: $\phi_{s(SM)} = -0.037 \pm 0.002$ rad
  - Small theoretical uncertainty $\rightarrow$ well predicted in the SM
  - New particles can contribute to the B_s-B_s box diagrams and significantly modify the SM prediction



Present state of the measurements

ϕ_s value obtained by CDF and D0 from $B_s \to J/\psi\phi$ analysis shifted from the SM prediction



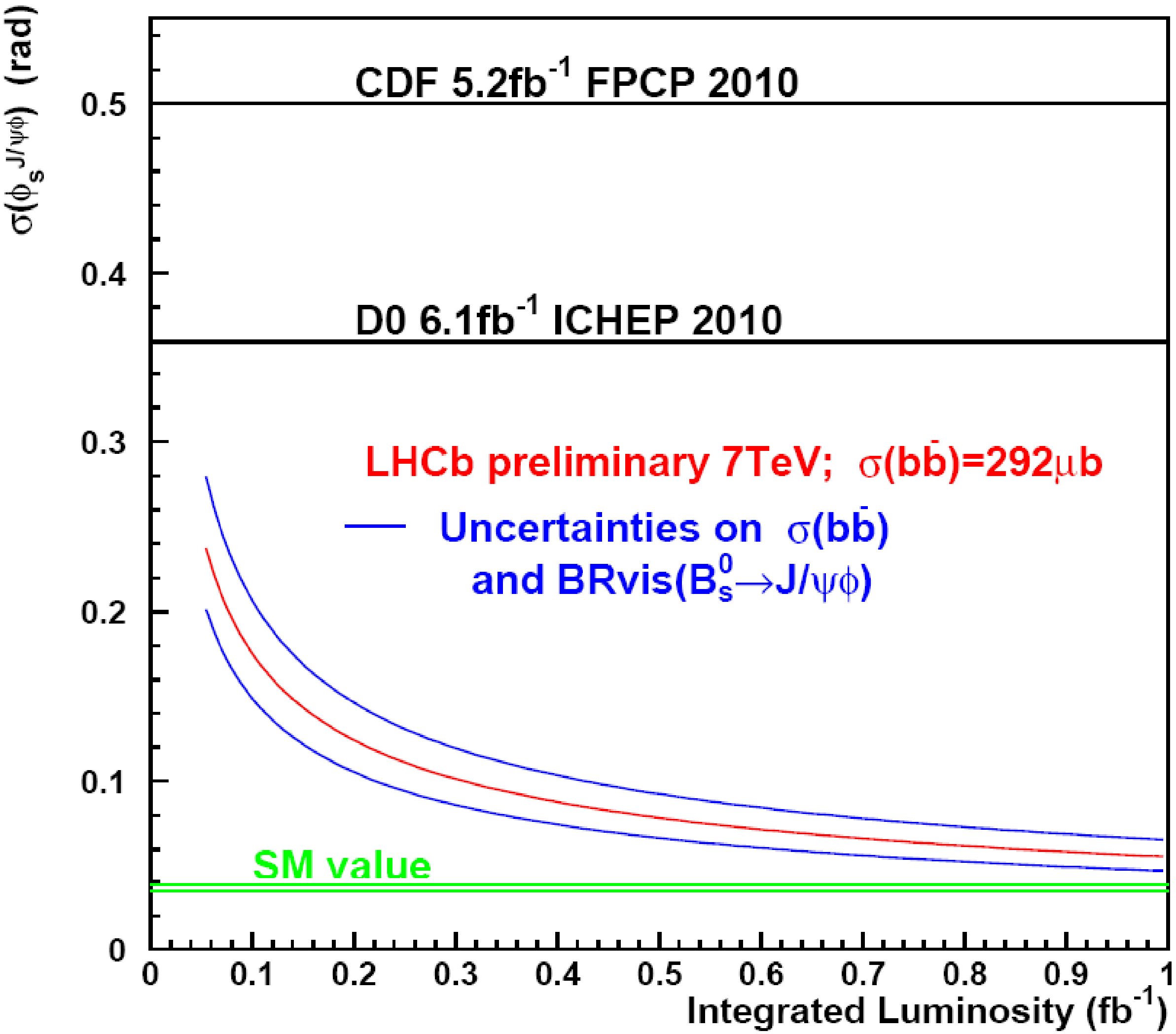


$$\bar{\tau}_s = 1.45 \pm 0.04 \pm 0.01 \text{ ps}$$
$$\Delta\Gamma_s = 0.15 \pm 0.06 \pm 0.01 \text{ ps}^{-1}$$
$$\phi_s^{J/\psi\phi} = -0.76^{+0.38}_{-0.36} \pm 0.02$$

Rick Van Kooten, ICHEP 2010

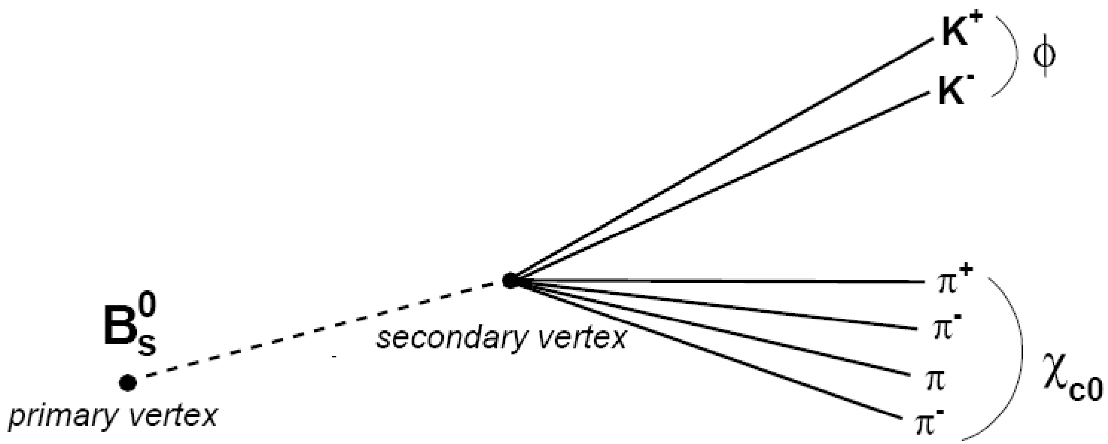
Louise Oakes, FPCP 2010

Expected ϕ_s sensitivity from $B_s^0 \to J/\psi\ \phi$ in LHCb experiment



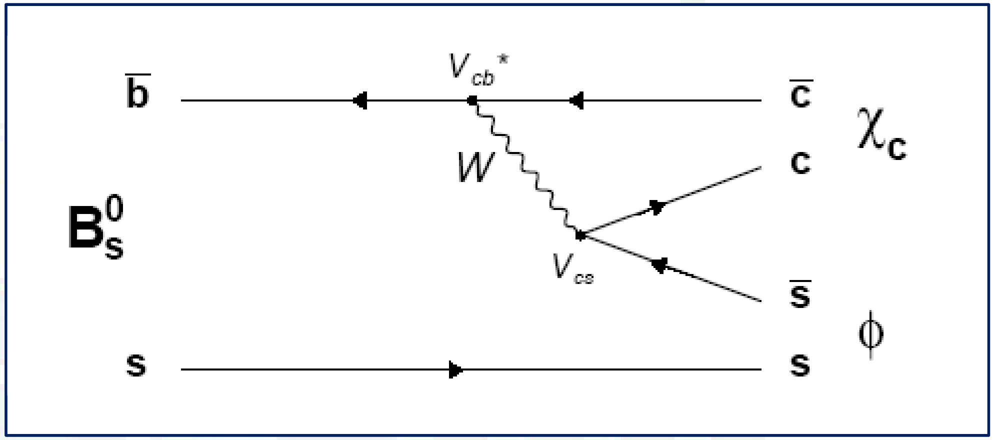
$B_s \to J/\psi\phi$, 1 fb^{-1}:
$\sigma(\phi_s)_{stat}$ ~0.07 rad

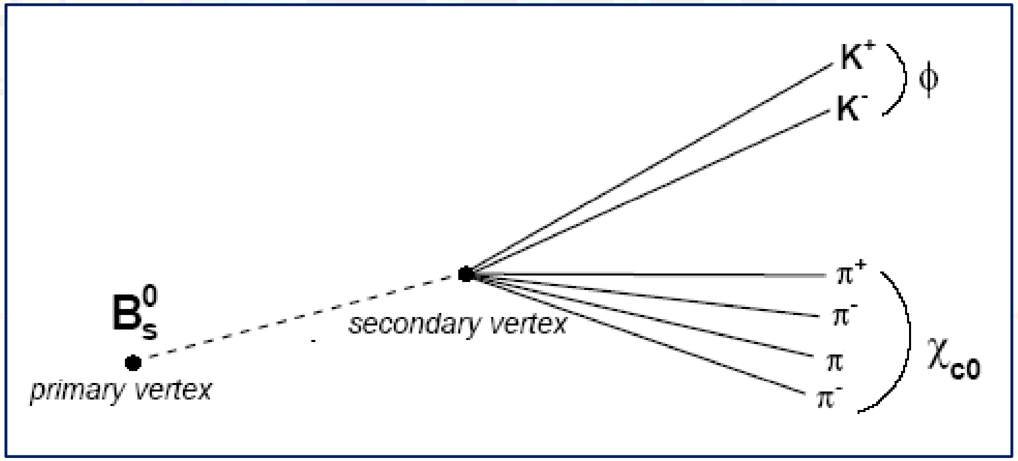
PART II



Reconstruction of $B_s^0 \rightarrow \chi_c \phi$ decay

- The estimated branching fraction for $B_s^0 \rightarrow \chi_c \phi$: $1.19 \cdot 10^{-4}$
- The branching fraction of the full decay chain: $1.85 \cdot 10^{-6}$
- The total number of $B_s^0 \rightarrow \chi_c \phi$ decays produced at nominal LHCb luminosity in one year: 336.8k
  (L_{int}=2fb^{-1}, E_{CM}=5+5 TeV, $\sigma_{b\bar{b}}$=434 μb)





Event selection

- To tune the selection criteria, the following Monte Carlo samples were used:
  1. Signal: $B_s^0 \to \chi_c \phi$
  2. Background: $b\bar{b}$ inclusive

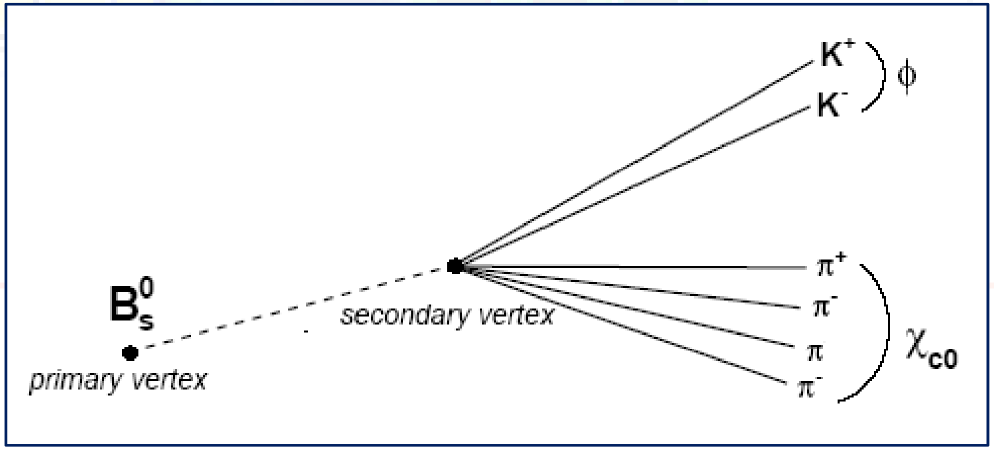
- The idea of selection: two-step procedure:
  1. Cut-based selection to reject most background events & keep a relatively high efficiency for signal events
  2. Multivariate analysis (Fisher discrimination) in order to obtain best S/B ratio
     - Proper choice of discriminating variables sufficient to obtain the best performance

TMVA

Cut-based selection

- Simple, rectangular cuts applied to signal and background samples:
  - to keep only signal-like events in background sample
  - to obtain a relatively high efficiency for signal events

- Typical cuts used:
  - pions/kaons identification cuts
  - transverse momenta
    - for ϕ, χ_c decay products >~ 0.4 GeV/c
    - for ϕ, χ_c >~ 1 GeV/c
  - impact parameters
  - B_s pointing angle
  - χ^2 of vertices
  - invariant mass cuts



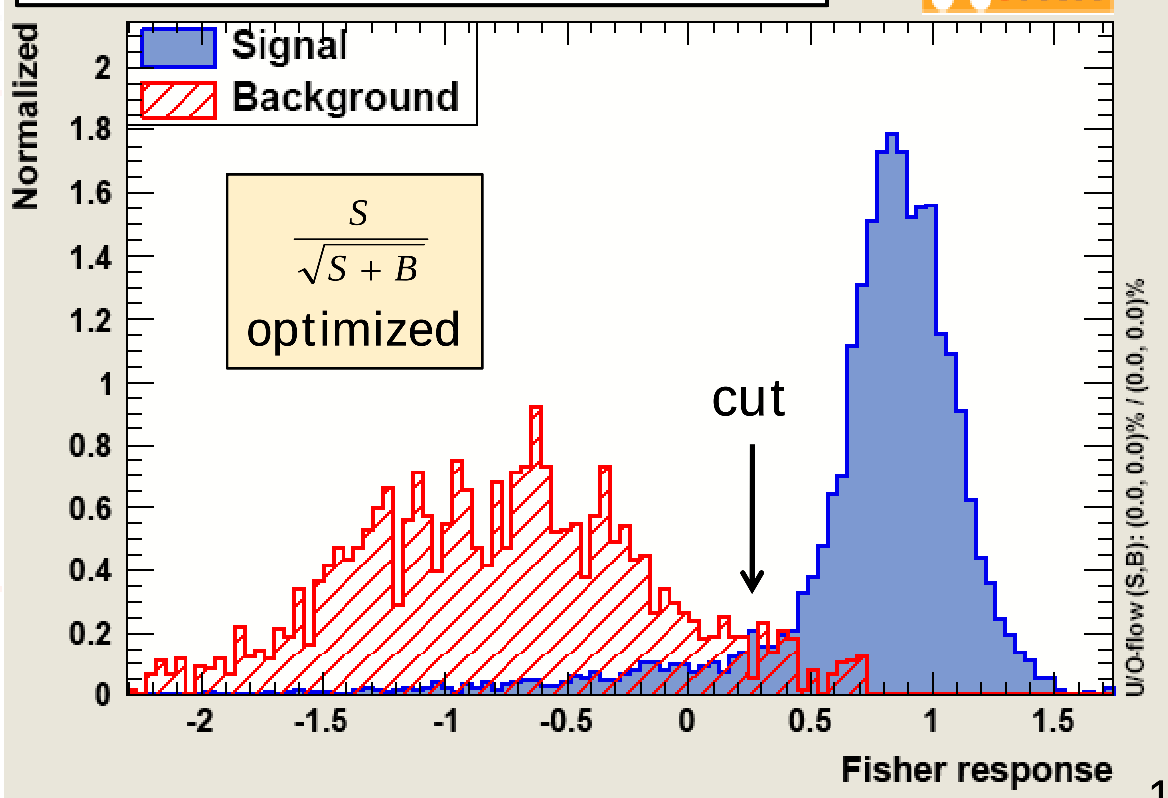
Fisher performance

- After cut-based selection the signal and background samples splitted randomly in half for training and testing
- Several best discriminating variables chosen for Fisher discrimination
  - transverse momentum, flight distance, pointing angle, vertex χ^2 of B_s
  - impact parameters of ϕ, χ_c
  - kaon identification

Mass windows tightened after the discrimination

- φ : ± 20 MeV/c²
- χ_c : ± 70 MeV/c²
- B_s^0 : ± 50 MeV/c²

distribution for loose mass cuts



Selection efficiencies

MC study

- The **total signal efficiency** - number of reconstructed, selected and triggered signal events in 400mrad acceptance divided by the number of generated signal events:

The **total signal efficiency** consists of:

geometrical factor	selection/geo efficiency	trigger/sel efficiency		total efficiency
33.10 %	16.10 %	19.68 %	→	1.05 %

- The **resulting number of $B_s^0 \rightarrow \chi_c \phi$ events** expected to be selected in the LHCb experiment in one year of data taking with the nominal LHCb luminosity: **3538**

- The corresponding **signal to background ratio** after selection (without ε_{trg}) > **1.51 at 90% CL**

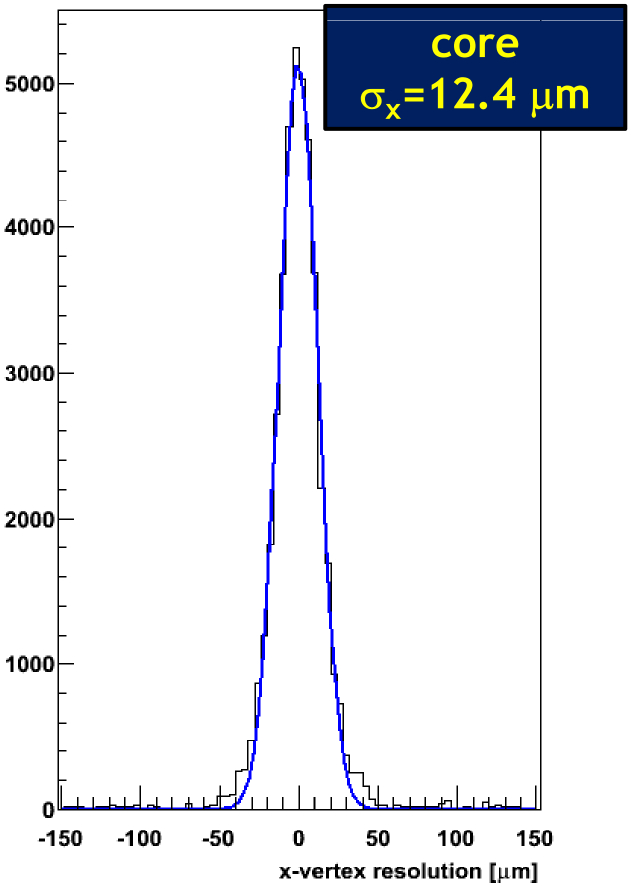
Secondary vertex resolutions

Vertex resolution - difference between the reconstructed vertex position and the true position of the MC generated vertex

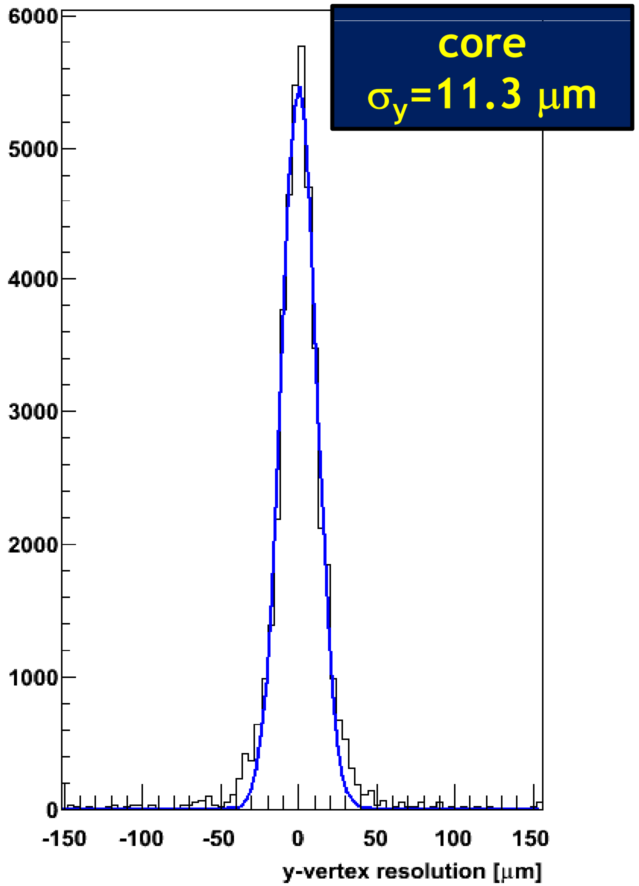
for events passing selection criteria, TMVA optimization and tight mass cuts

MC study

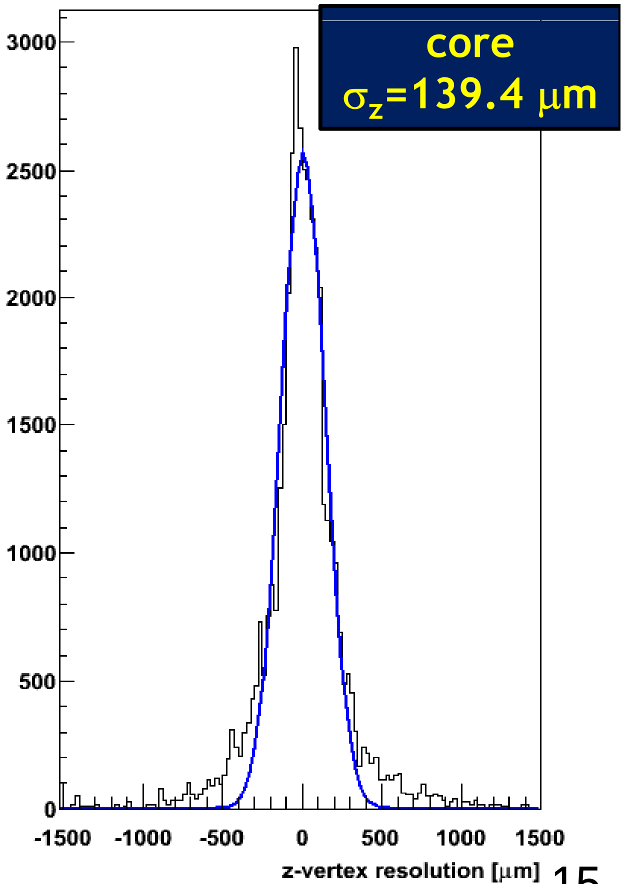
x-resolution of B_s^0 decay vertex



y-resolution of B_s^0 decay vertex



z-resolution of B_s^0 decay vertex

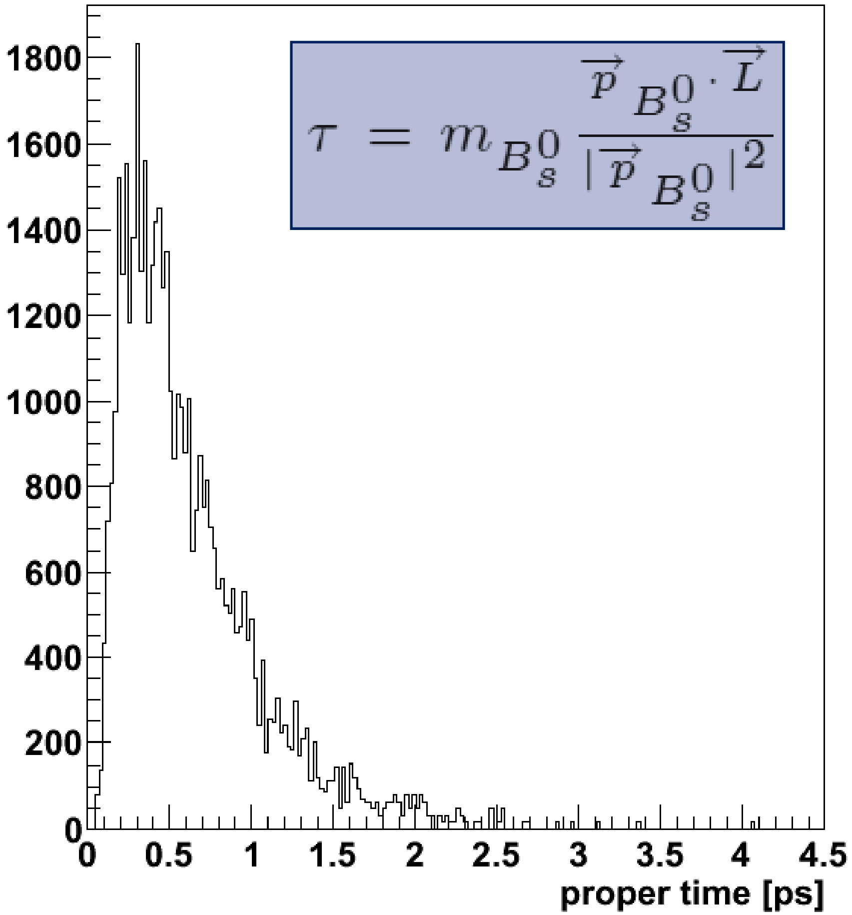


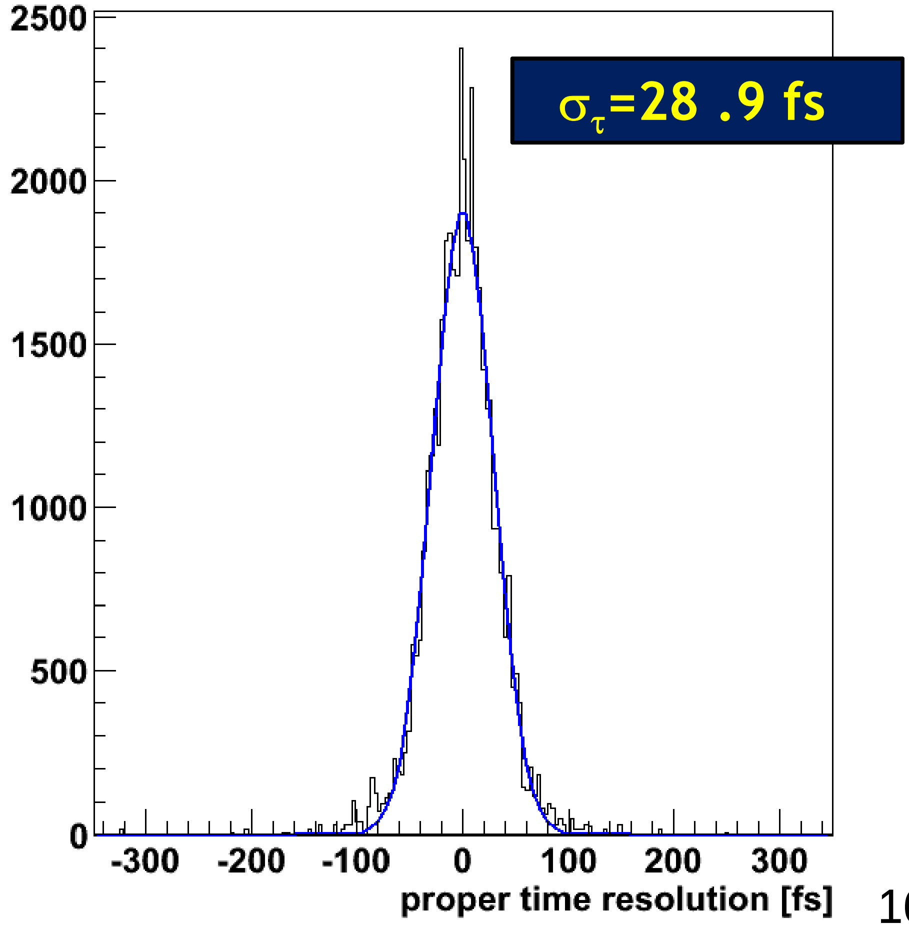
Proper time studies

Proper time resolution - difference between the reconstructed and true proper time

for events passing selection criteria, TMVA optimization and tight mass cuts

MC study





Now it's time to look at data…

what do expect to see at LHCb:

- **So far (in 2010 data):**
  - L_{int}=0.038 fb^{-1}, E_{CM}=3.5+3.5 TeV, $\sigma_{b\bar{b}}$=284 μb
  - the number of $B_s^0 \to \chi_c \phi$ decays expected to be **produced** so far in LHCb: **4193**
  - the resulting number of $B_s^0 \to \chi_c \phi$ events expected to be **selected** in LHCb: **44**
- **Next year - in 2011 data:**
  - L_{int}=1fb^{-1}, E_{CM}=3.5+3.5 TeV, $\sigma_{b\bar{b}}$=284 μb
  - the number of $B_s^0 \to \chi_c \phi$ decays expected to be **produced** in LHCb: **110 k**
  - the resulting number of $B_s^0 \to \chi_c \phi$ events expected to be **selected** in the LHCb experiment: **1159**

SUMMARY

Summary

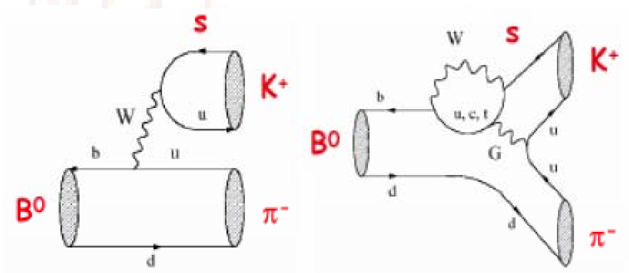
- Potential for New Physics discovery in B_s^0 decays
- CDF/D0: ϕ_s shifted from SM prediction (~1σ)
- ϕ_s sensitivity from $B_s^0 \to J/\psi\phi$: $\sigma(\phi_s)$~0.07 rad with 1fb^{-1}
- B_s^0 decays to pure CP eigenstates can improve ϕ_s sensitivity
- $B_s^0 \to \chi_c\phi$ seems to be a promising channel to improve ϕ_s sensitivity
  - ~1.16k events expected in 2011 data
  - ~3.5k events expected in one year at nominal LHCb luminosity
- $B_s^0 \to \chi_c\phi$ has never been observed
- Event selection based on Fisher discriminant → good purity of signal decay (S/B > 1.51)

BACKUP

3 types of CP symmetry violation:

1. In decays (direct):
   - Difference in the decay rates for the process and its CP conjugation
   - Requires at least two amplitudes for the same process

$$\Gamma(B \to f) \neq \Gamma(\bar{B} \to \bar{f})$$

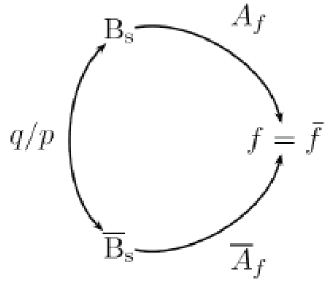


2. In oscillations (indirect):
   - Mass eigenstates differs from CP eigenstates
   - $X^0 \to \underline{X}^0$ and $X^0 \to \underline{X}^0$ oscillations frequencies are not the same

$$|X_1\rangle = p|X^0\rangle + q|\bar{X}^0\rangle$$
$$|X_2\rangle = p|X^0\rangle - q|\bar{X}^0\rangle$$
$$|p|^2 + |q|^2 = 1$$
$$\left|\frac{q}{p}\right| \neq 1$$

3. In the interference between decays and oscillations
   - Occurs when both the neutral meson and its antipartner decay to the same final state

$$\lambda = \frac{q}{p}\frac{\bar{A}_f}{A_f}$$
$$|\lambda| \neq 1$$
$$\mathrm{Im}\{\lambda\} \neq 0$$

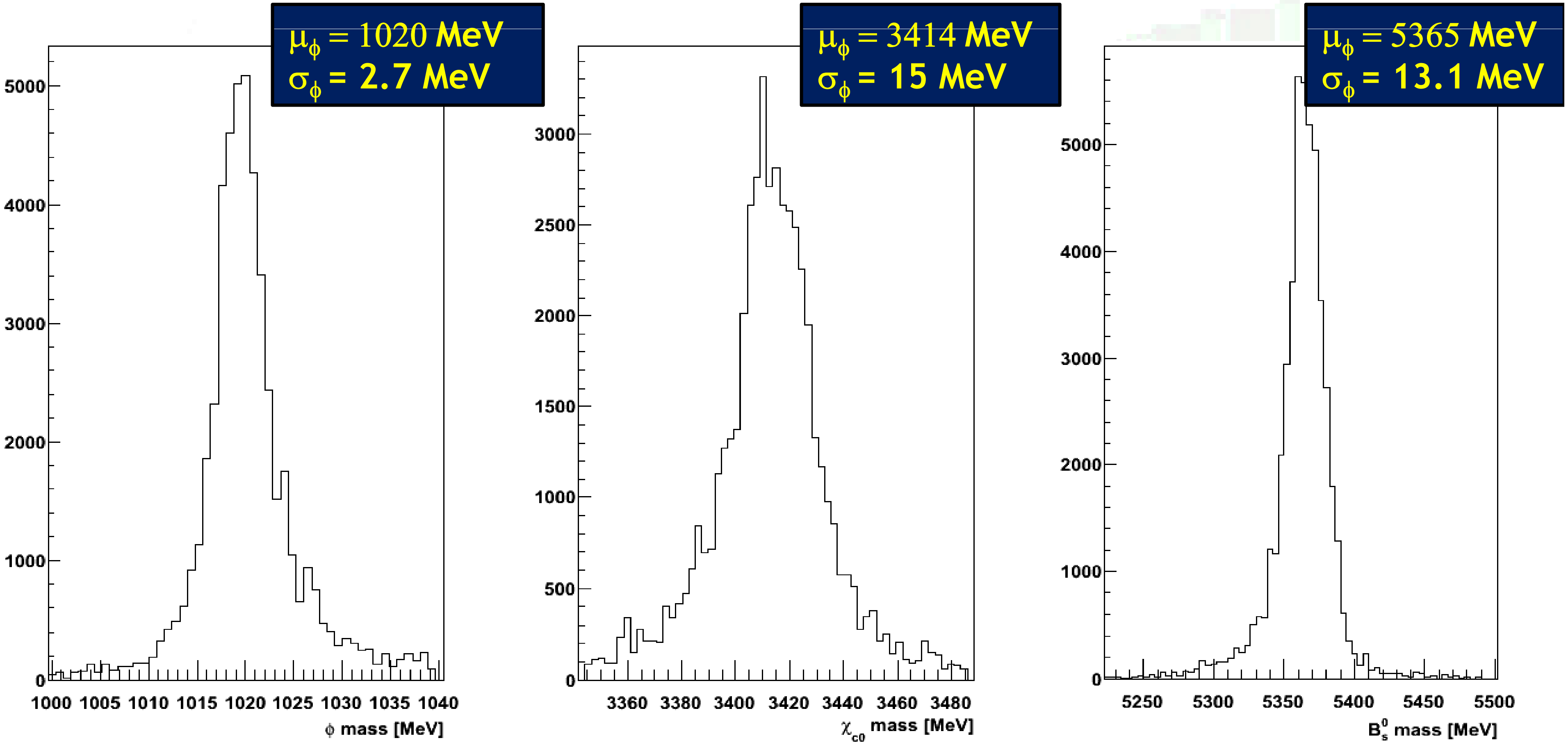


Mass distributions

MC study

Invariant mass distributions for the reconstructed ϕ, χ_c and B_s^0 mesons

for events passing selection criteria, TMVA optimization and tight mass cuts for ϕ and χ_c



The obtained results are consistent with the generated particle masses:

$$m_\phi = 1019.46\ \mathrm{MeV}/c^2,\ m_{\chi_{c0}} = 3414.75\ \mathrm{MeV}/c^2,\ m_{B_s^0} = 5366.3\ \mathrm{MeV}/c^2$$