# Study of CP violation with $B_s \to \phi\phi \to K^+K^-K^+K^-$ at FCC

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FCC workshop Liverpool
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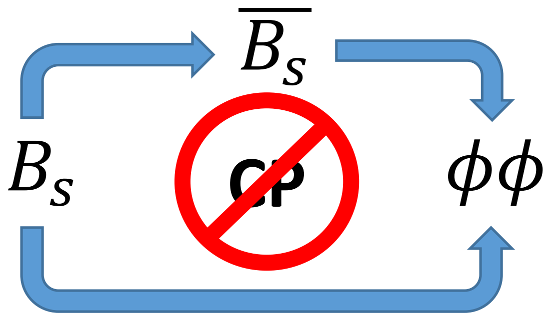
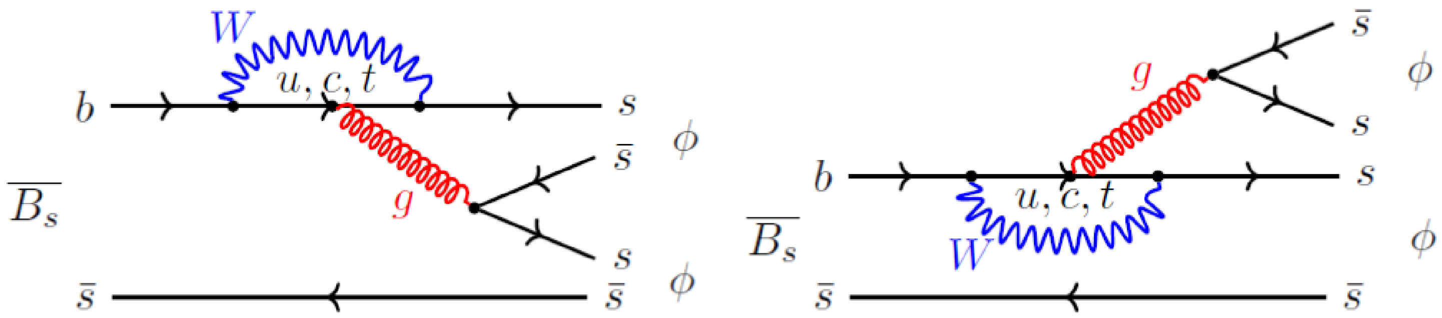
Based on work done with L.Oliver
arXiv paper to appear very soon




- Theoretical background and Motivation
- Theoretical issues
- Experimental study and sensitivities af FCC
- Detector requirements
- Conclusions

# Theoretical background and motivation

$\bar{B}_s \to \phi\phi$ is a pure penguin decay




In the Naive Factorization (**NF**) Scheme (i.e. with top-dominance in mixing and decay)

$$\mathcal{A}(\bar{B}_s \to \phi\phi) \propto V_{tb}V_{ts}^{*}|\bar{M}|$$

$$\mathcal{A}(\bar{B}_s \to B_s) \times \mathcal{A}(B_s \to \phi\phi) \propto (V_{tb}V_{ts}^{*})^2 V_{ts}V_{tb}^{*}|M|$$

$$\mathcal{J} \propto (V_{tb}V_{ts}^{*})(V_{ts}V_{tb}^{*}) \propto |V_{tb}V_{ts}^{*}|^2$$

$$|\lambda^{NF}| = 1$$
$$\phi_{CKM}^{NF} = 0$$

➪ Very good for probing BSM Physics

In order to search for BSM physics, one need to evaluate the effect of charmed and up penguins

But to which extend can we rely on **NF** scheme (in particular with penguin modes) ?

# Theoretical Issues (1/2)

In fact we <u>cannot rely</u> on NF:
$\phi\phi$ is a Vector-Vector decay
⇨ polarized final states

| PDG | | | NF |
| --- | --- | --- | --- |
| $f_L = \Gamma_L/\Gamma$ | $\mathbf{0.378 \pm 0.013}$ | CP (η=+1) | $\approx \mathbf{0.92}$ |
| $f_\parallel = \Gamma_\parallel/\Gamma$ | $0.330 \pm 0.016$ | CP (η=+1) | $\approx \mathbf{0.04}$ |
| $f_\perp = \Gamma_\perp/\Gamma$ | $0.292 \pm 0.009$ | CP (η=−1) | $\approx \mathbf{0.04}$ |

$$A_L = A[B \to V_1(0)V_2(0)]$$
$$A_\pm = A[B \to V_1(\pm)V_2(\pm)]$$

$$A_\parallel = \frac{1}{\sqrt{2}}(A_+ + A_-)$$
$$A_\perp = \frac{1}{\sqrt{2}}(A_+ - A_-)$$

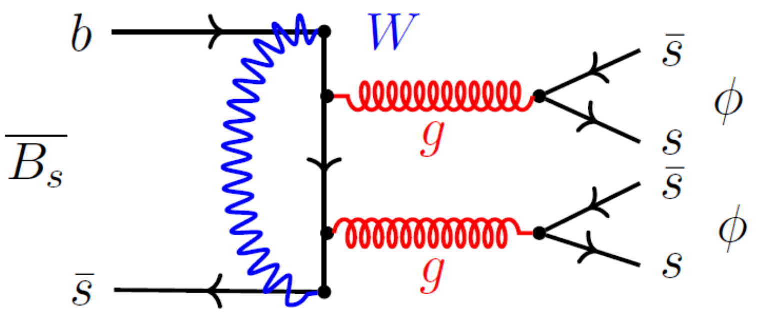
Due to V-A , $A_L : A_- : A_+ = 1 : \frac{\Lambda_{QCD}}{m_b} : \left(\frac{\Lambda_{QCD}}{m_b}\right)^2$ ⇨ $f_\parallel \approx f_\perp \ll f_L$

**But very off for $f_L$**

# Theoretical Issues (2/2)

Instead we use the **QCD Factorization** scheme which takes proper account of penguins

- More complete treatment of penguins, in particular for the Weak annihilation processes with helicity dependent corrections
- includes NLO vertex, Hard scattering, penguins corrections …
- Coefficients $a_i^{p,h}$ (combination of Wilson coeff. $C_i$) depend on the helicity




| PDG | | | QCDF |
|---|---|---|---|
| $f_L = \Gamma_L/\Gamma$ | $\mathbf{0.378 \pm 0.013}$ | CP (η=+1) | $\approx \mathbf{0.370}$ |
| $f_\parallel = \Gamma_\parallel/\Gamma$ | $0.330 \pm 0.016$ | CP (η=+1) | $\approx \mathbf{0.315}$ |
| $f_\perp = \Gamma_\perp/\Gamma$ | $0.292 \pm 0.009$ | CP (η=−1) | $\approx \mathbf{0.315}$ |
| Br | $(1.87 \pm 0.15)10^{-5}$ | | $\mathbf{2.1\ 10^{-5}}$ |

$$\left|\lambda_{\phi\phi}^{L,QCDF}\right| \approx 1.01$$
$$\phi_{\phi\phi}^{L,QCDF} \approx -0.5°$$

$$\left|\lambda_{\phi\phi}^{\parallel,QCDF}\right| = \left|\lambda_{\phi\phi}^{\perp,QCDF}\right| \approx 1.004$$
$$\phi_{\phi\phi}^{\parallel,QCDF} = \phi_{\phi\phi}^{\perp,QCDF} \approx 0.05°$$

CKM phases **depend on polarization** but all remain very small

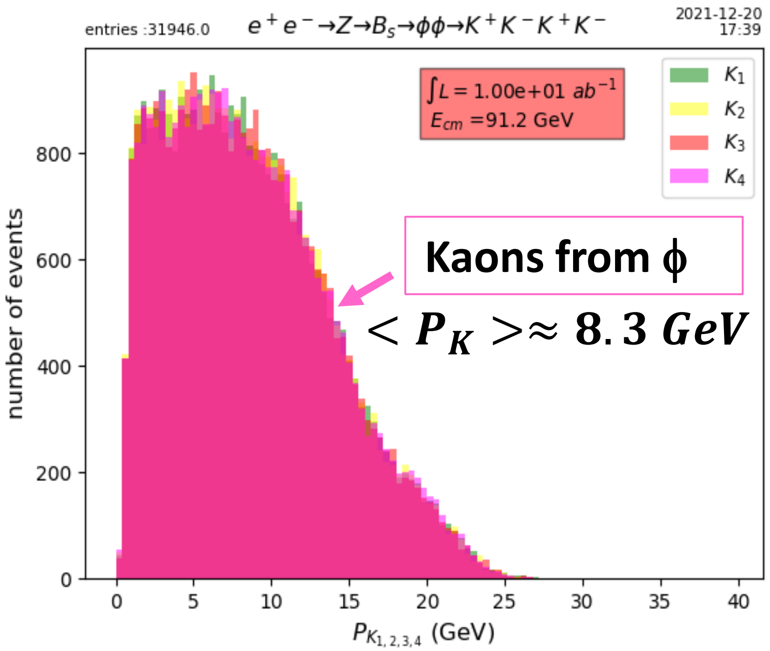
# Detector response is parametrized

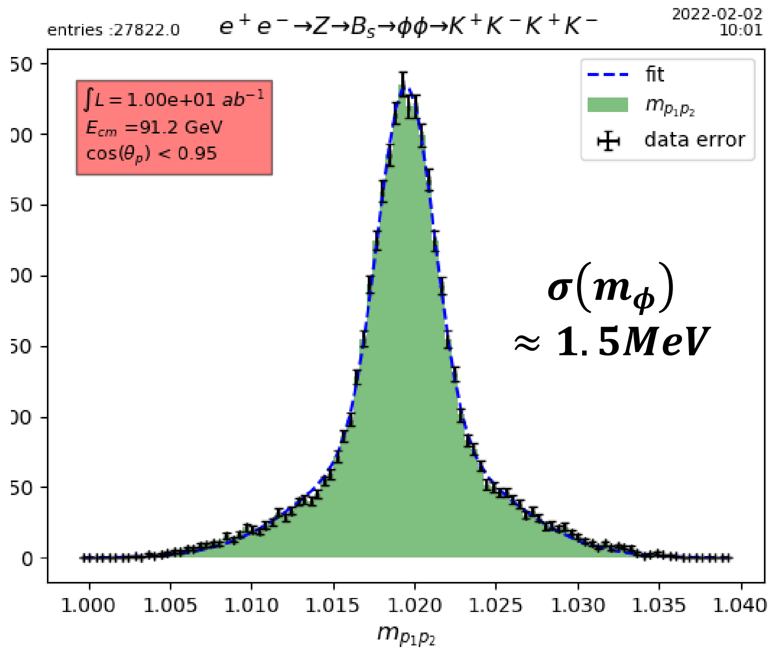
| | | | |
|---|---|---|---|
| Acceptance : | $\vert\cos\theta\vert$ | $<$ | $0.95$ |
| Track $p_T$ resolution : | $\frac{\sigma(p_T)}{p_T^2}$ | $=$ | $2.\times 10^{-5} \oplus \frac{1.2\times10^{-3}}{p_T \sin\theta}$ |
| Track $\phi,\theta$ resolution : | $\sigma(\phi,\theta)\ \mu\text{rad}$ | $=$ | $18 \oplus \frac{1.5\times10^{3}}{p_T \sqrt[3]{\sin\theta}}$ |
| Vertex resolution : | $\sigma(\mathrm{d_{Im}})\ \mu m$ | $=$ | $1.8 \oplus \frac{5.4\times10^{1}}{p_T \sqrt{\sin\theta}}$ |
| Vertex resolution : | $<\sigma(\mathrm{d_{Im}})>$ | $\simeq$ | $10\ \mu m$ |
| Calorimeter resolution : | $\frac{\sigma(E)}{E}$ | $=$ | $\frac{5\times10^{-2}}{\sqrt{E}} \oplus 5\times10^{-3}$ |

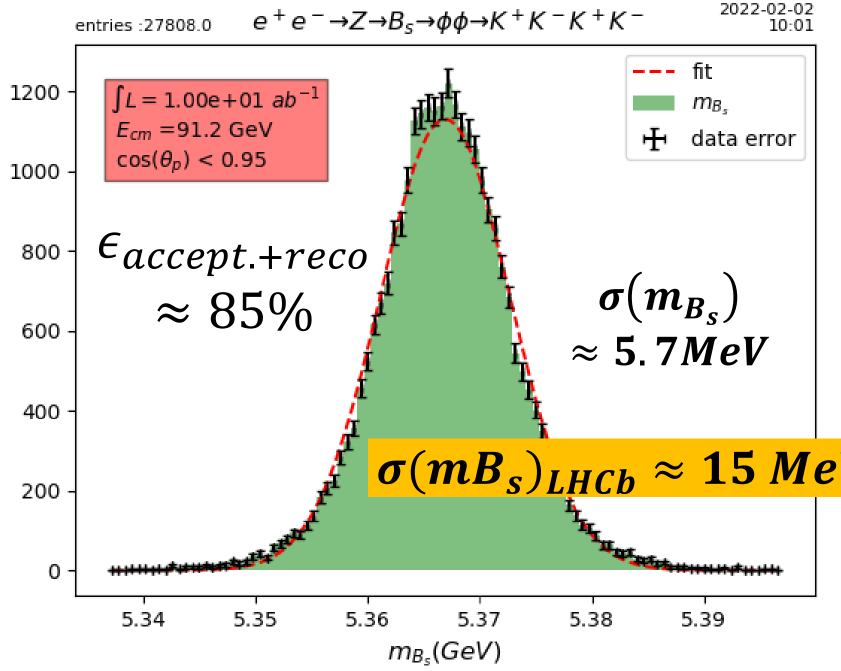
| | unit | value |
|---|---|---|
| acceptance | % | 86 |
| $\sigma(m_\phi)$ | MeV | ~1.5 |
| $\sigma(m_{B_s})$ | MeV | ~5.7 |
| $\sigma(d_{B_s}^{flight})$ | µm | ~20. |

see https://arxiv.org/abs/2107.02002

Essentially no combinatorial background if excellent PID (see LHCb) else good PID + excellent momemtum resolution



# Time dependent analysis

$$\Gamma(\overline{B}_s \to \phi\phi) = | < \phi\phi|B_s > |^2 \times e^{-\Gamma t}\{\cosh\frac{\Delta\Gamma}{2} - (1-2\omega)A_{CP}^{dir}\cos\Delta m t$$
$$+ A_{\Delta\Gamma}\sinh\frac{\Delta\Gamma}{2} - (1-2\omega)A_{CP}^{mix}\sin\Delta m t\}$$
$$\Gamma(B_s \to \phi\phi) = | < \phi\phi|B_s > |^2 \times e^{-\Gamma t}\{\cosh\frac{\Delta\Gamma}{2} + (1-2\omega)A_{CP}^{dir}\cos\Delta m t$$
$$+ A_{\Delta\Gamma}\sinh\frac{\Delta\Gamma}{2} + (1-2\omega)A_{CP}^{mix}\sin\Delta m t\}$$

$$A_{CP}^{dir} = \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2}, \quad A_{CP}^{mix} = -\frac{2Im\lambda_f}{1+|\lambda_f|^2}, \quad A_{\Delta\Gamma} = -\frac{2Re\lambda_f}{1+|\lambda_f|^2}$$

$$\lambda_{\phi\phi}^{(k)} = \left(\frac{q}{p}\right)_{B_s}\frac{A(\overline{B}_s \to \phi\phi, k)}{A(B_s \to \phi\phi, k)} = \eta_k \mid \lambda_{\phi\phi}^{(k)} \mid e^{-i\phi_{\phi\phi}^{(k)}}$$

$$A_{CP}^{mix} \approx -\eta_{\phi\phi}^{eff}\sin\phi_{\phi\phi}$$

$\omega = wrong\ tagging = 0.25$

| | LEP | BaBar | LHCb |
|---|---|---|---|
| $\epsilon(1-2\omega)^2$ | 25-30% | 30% | 6% |

Can be obtained very precisely from $B_s \to D_S^- \pi^+$ see https://arxiv.org/abs/2107.02002

$$\boldsymbol{\delta(\omega)_{stat} = 1.4 \times 10^{-4}}$$

If no angular analysis reduced sensitivity since $\eta_{\phi\phi}^{eff} = 1 - 2f_\perp \approx 0.416$

If angular analysis (tbd) the sensitivity is improved by factor ~2

# Study of CP violation with $B_s \to \phi\phi \to K^+K^-K^+K^-$

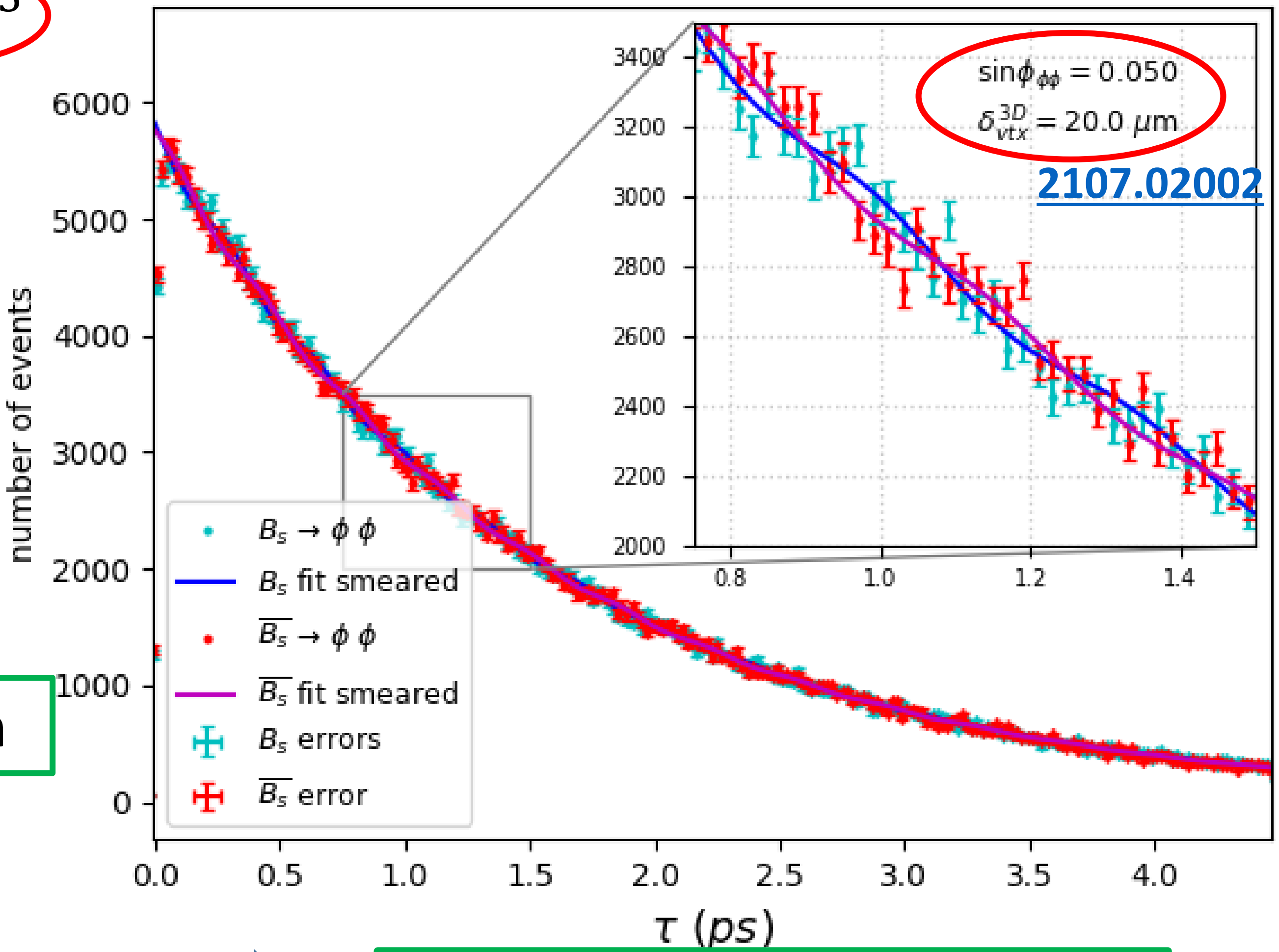
Generated : $|\lambda_{\phi\phi}| = 1.$ $\sin\phi_{\phi\phi} = 0.05$

Large number of events expected @FCCee

$$N[(B_s + \bar{B}_s) \to \phi\phi \to K^+K^-K^+K^-] \approx 9.4\ 10^5$$

| $E_{cm} = 91.2$ GeV and $\int L = 150ab^{-1}$ | | | |
|---|---|---|---|
| $\sigma(e^+e^- \to Z)$ nb | number of Z | $f(Z \to \bar{B}_s)$ | Number of produced $\bar{B}_s$ |
| $\sim 42.9$ | $\sim 6.4\ 10^{12}$ | 0.0159 | $\sim 1\ 10^{11}$ |
| $\bar{B}_s$ decay Mode | Decay Mode | Final State | Number of $\bar{B}_s$ decays |
| $\phi\phi$ | $\phi \to K^+K^-$ | $K^+K^-K^+K^-$ | $\sim 4.7\ 10^5$ |

5 $10^3$ experiments generated with 8.2 $10^5$ each




2107.02002

$\delta(|\lambda^{FCC}_{\phi\phi}|) \approx 0.004$

$\delta(\sin\phi^{FCC}_{\phi\phi}) \approx 9 \times 10^{-3}$ rad

$\cong \delta(\phi^{FCC}_{\phi\phi}) \approx 0.5° (stat.)$

$\delta(\Delta\Gamma^{FCC}_{s,\phi\phi}) \approx 0.004$

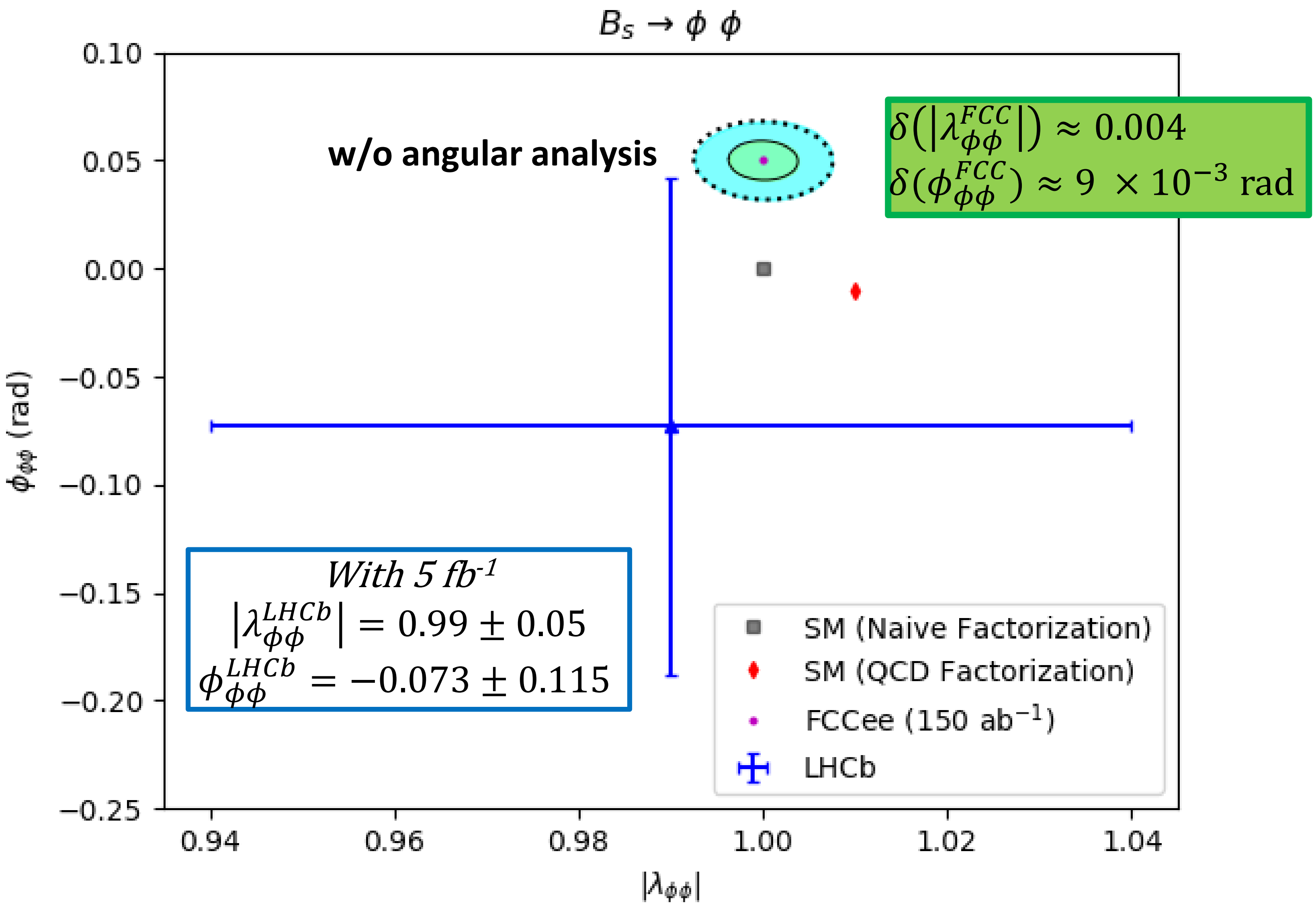
Angular analysis

$\delta(\sin\phi_{\phi\phi}) \approx 4.5 \times 10^{-3}$ rad

$\cong \delta(\phi^{FCC}_{\phi\phi}) \approx 0.25° (stat.)$

# Study of CP violation with $B_s \to \phi\phi \to K^+K^-K^+K^-$

simulation generated with $\lambda_{\phi\phi} = 1$ and $\phi_{\phi\phi} = 0.05$rad




If indeed : $|\lambda_{\phi\phi}| = 1. \pm 0.004$
$\sin\phi_{\phi\phi} = 0.05 \pm 0.009$ rad.

is measured @ FCCee

5σ deviation from SM

**If angular analysis**

>~10 σ deviation from SM potentially possible

# Bounds on New Physics

New Physics is included in the Mixing with complex parameter $\Delta_s$ $(\boldsymbol{SM \Rightarrow \Delta_s = (1,0)})$

$$M_{12}^s = M_{12}^{SM,s}\Delta_s = M_{12}^{SM,s}\left(\mathrm{Re}\ \Delta_s + i\mathrm{Im}\ \Delta_s\right) = M_{12}^{SM,s}\,|\,\Delta_s\,|\,e^{i\phi_s^\Delta}$$

$$\lambda_{\phi\phi}^{exp} = \lambda_{\phi\phi}^{QCDF}\sqrt{\frac{\Delta_s^*}{\Delta_s}}$$

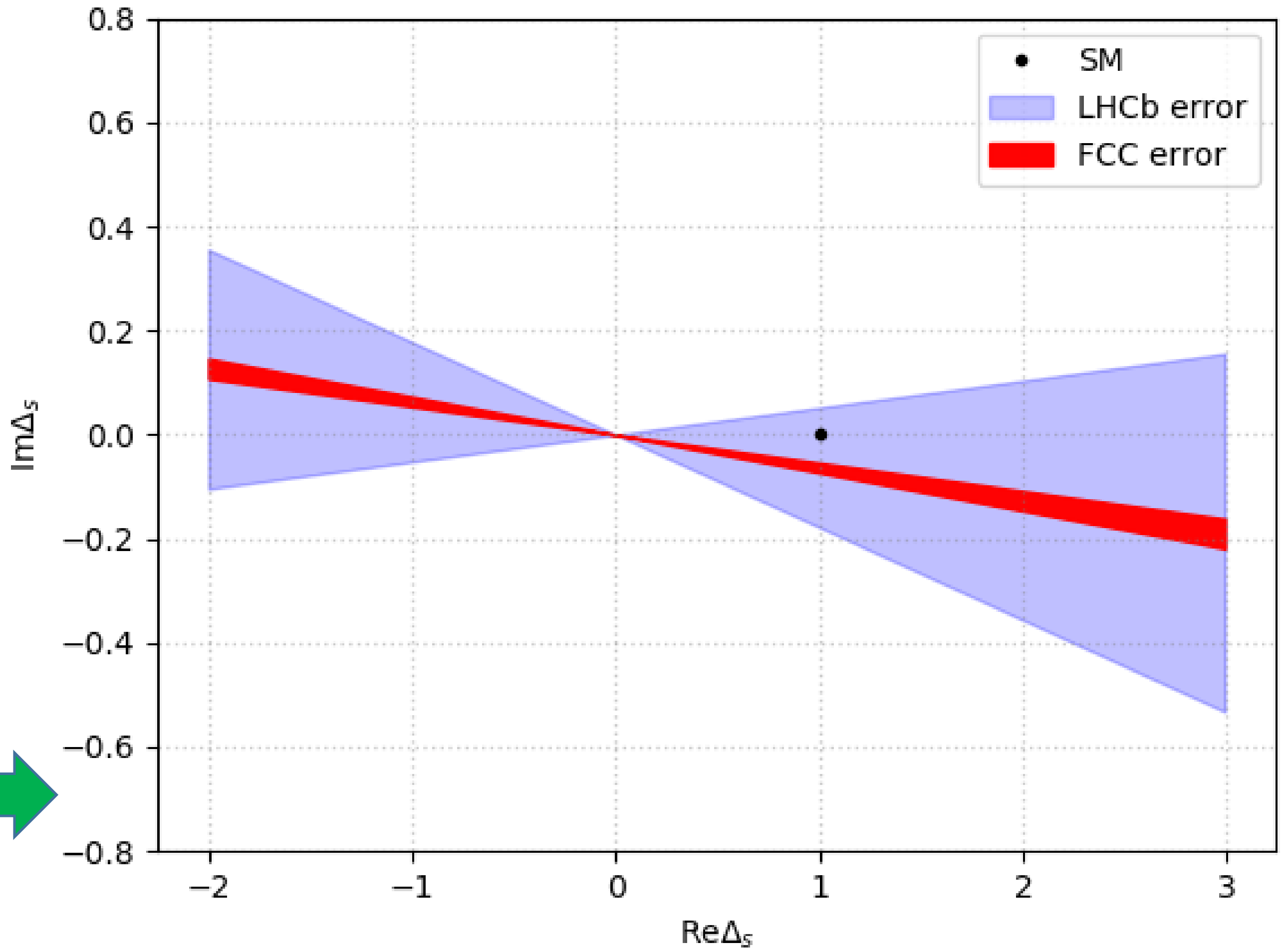
$$\phi_{\phi\phi}^{exp} - \phi_{\phi\phi}^{QCDF} \approx \phi_{\phi\phi}^{\Delta} \approx \frac{Im\Delta_s}{Re\Delta_s}$$

With $5fb^{-1}$

$$\lambda_{\phi\phi}^{LHCb} = 0.99 \pm 0.05$$

$$\phi_{\phi\phi}^{LHCb} = -0.073 \pm 0.115$$

Assuming FCC measures the same central value as LHCb



# Considerations on detectors requirements

| Parameters | Errors scaling |
| --- | --- |
| $\phi_{\phi\phi}$ | $\frac{1}{\eta_{\phi\phi}(1-2\omega)\sqrt{N}}$ |
| $\lvert\lambda_{\phi\phi}\rvert$ | $\frac{1}{(1-2\omega)\sqrt{N}}$ |
| $\Delta\Gamma$ | $\frac{1}{\eta_{\phi\phi}\sqrt{N}}$ |

$\sqrt{N}$ : increase statistics

- **Increase Instant. Lumi**
- **Increase $\int Ldt \Rightarrow$ 4 IP, more time @Z-pole**
- **Increase acceptance and recons. Efficiency**
  - **Large tracking volume with many meas. points**
    - ⇨ **SVD + gaseous tracking detector**
- **Excellent momentum resolution**
  - **Very good point resolution but even more important**
  - **Very low material budget**
    - ⇨ **gaseous tracking detector**

$(1-2\omega)$ : decrease wrong tagging fraction ω

- **Excellent vertex resolution**
  - **to identify secondary + tertiary vertices**
  - **Also mandatory to study $B_s$ time dependence**
    - ⇨ **state-of-the-art pixelized vertex detector**
- **Excellent overall Part. Ident. (at least for e,μ,K) up to al least 25 GeV**
  - **Ideally specific PID system (but difficult to cover large p range**
  - **Alternative is de/dx with cluster counting + ToF**
    - ⇨ **gaseous tracking detector**

$\eta_{\phi\phi}$ : disentangling the polarizations (gain of factor 2 in sensitivity)

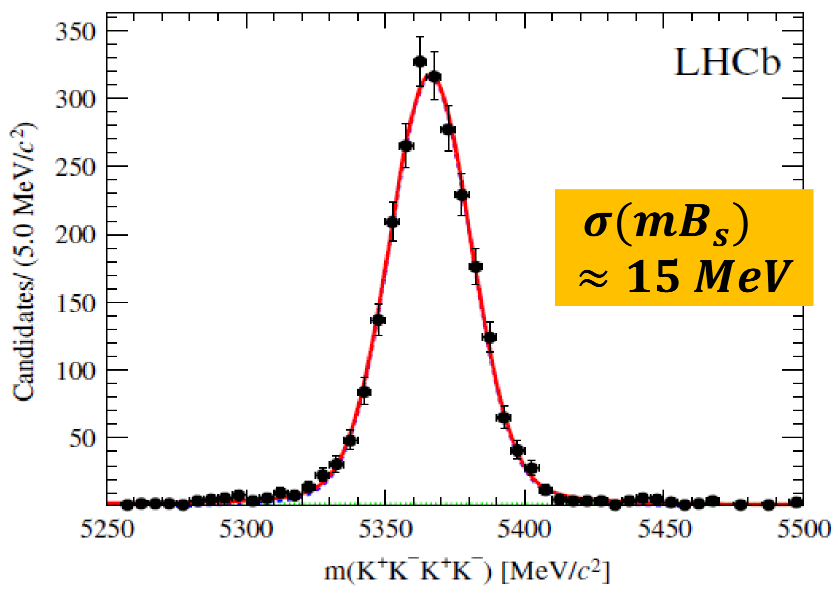
- **Angular dependent analysis needed**
  - **Test of QCD Factorization with precise measurement of $f_L$, $f_\parallel$, $f_\perp$**
  - **Polarization dependent CP violating phases ⇒ deeper test of CP sector (unprecedented) and better sensitivity to BSM physics**
    - ⇨ **Good angular resolution of tracking**

# Conclusions

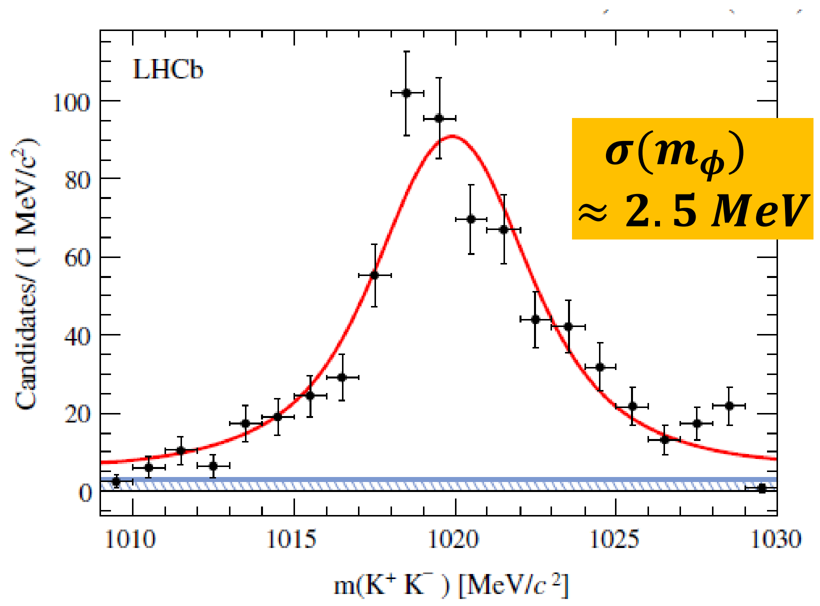
- The mode $B_s \to \phi\phi$ very interesting
  - To test QCD Factorization
  - To test the CP sector with unprecedented precision
  - to search for New Physics
- QCD Factorization predicts $\left|\lambda_{\phi\phi}^{L}\right| \left(\left|\lambda_{\phi\phi}^{\parallel,\perp}\right|\right) \approx 1.01(1.004)$

  $\phi_{\phi\phi}^{L}\left(\left|\phi_{\phi\phi}^{\parallel,\perp}\right|\right) \approx -0.01 \text{ rad } (-0.001 \text{ rad})$
- FCC can measure the CP parameters very precisely
  - $\delta A_{CP}^{dir} \Rightarrow \delta\left|\lambda_{\phi\phi}\right| \pm 0.004$ and $\delta\phi_{\phi\phi} = \pm 0.009$ rad ($\approx 0.005$ rad) if angular analysis is carried out
- The study of this mode establishes important constraints on the detectors
- Higher integrated Luminosity (x 5-10)would be extremely useful

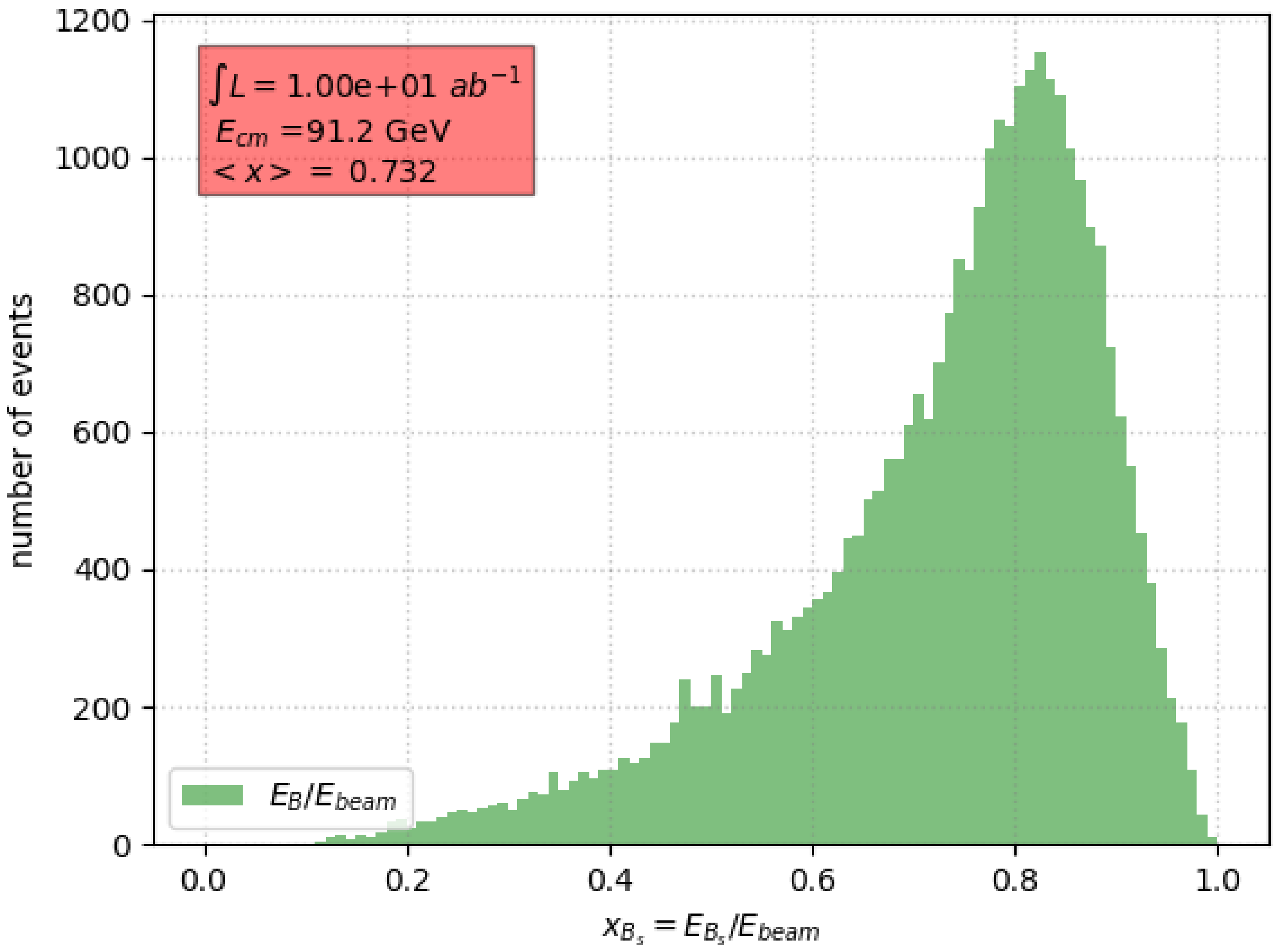
# Additional Slides



LHCb
Candidates/ (5.0 MeV/c²)
m(K⁺K⁻K⁺K⁻) [MeV/c²]
$\sigma(mB_s)$
$\approx 15\ MeV$

LHCb
Candidates/ (1 MeV/c²)
m(K⁺ K⁻) [MeV/c²]
$\sigma(m_\phi)$
$\approx 2.5\ MeV$

$\int L = 1.00e+01\ ab^{-1}$
$E_{cm}$ =91.2 GeV
$< x > = 0.732$
$E_B/E_{beam}$
number of events
$x_{B_s} = E_{B_s}/E_{beam}$