$B_{d,s} \rightarrow K^{*0}\overline{K^{*0}} \rightarrow K^{+}\pi^{-}K^{-}\pi^{+}$: a serious problem for the SM

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FCC workshop Annecy
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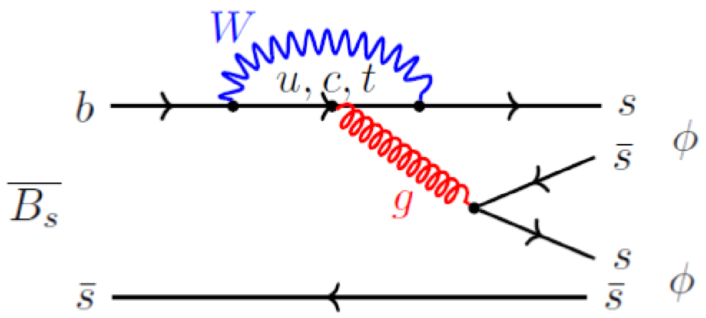
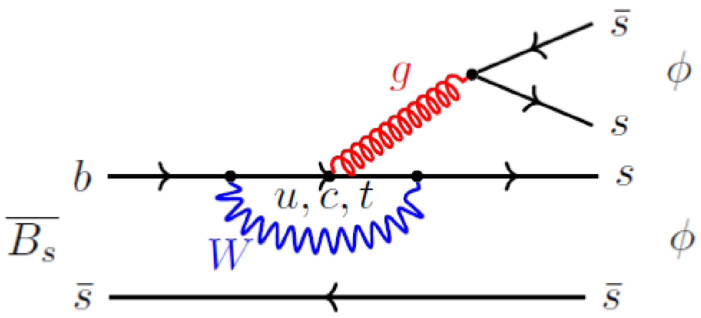
Based on work done with L. Oliver
arXiv 2312.07198

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

Theoretical background and motivation

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





R.A. , L. Oliver
[arXiv 2205.07823]

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

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

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

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

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

⇨ No ~~CP~~

⇨ Very good for probing BSM Physics

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

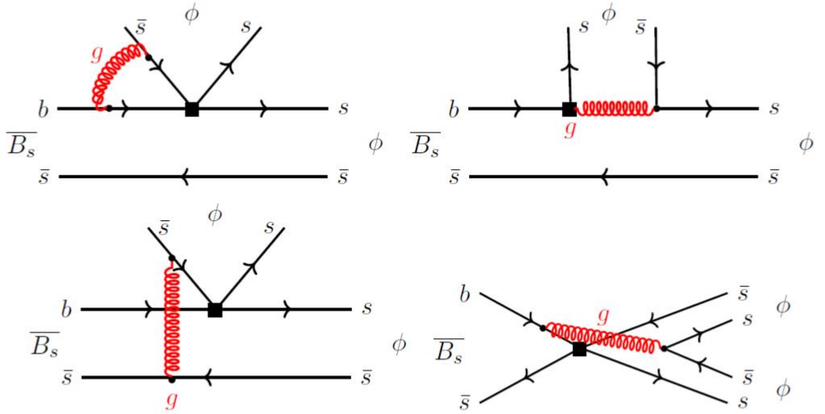
	PDG		NF	QCDF
$f_L = \Gamma_L/\Gamma$	$\mathbf{0.378 \pm 0.013}$	CP (η=+1)	$\approx \mathbf{0.92}$	$\approx \mathbf{0.38 \pm 0.08}$
$f_\parallel = \Gamma_\parallel/\Gamma$	0.330 ± 0.016	CP (η=+1)	$\approx \mathbf{0.04}$	$\approx \mathbf{0.31 \pm 0.04}$
$f_\perp = \Gamma_\perp/\Gamma$	0.292 ± 0.009	CP (η=−1)	$\approx \mathbf{0.04}$	$\approx \mathbf{0.31 \pm 0.04}$

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

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

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

QCD Factorization adds many helicity dependent corrections



Theoretical Issues (2/2)

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

$$|\lambda^{NF}| = 1$$
$$\phi^{NF}_{CKM} = \pi$$

$$\left|\lambda^{L,QCDF}_{\phi\phi}\right| \approx 1.013^{+0.005}_{-0.003}$$
$$\phi^{L,QCDF}_{\phi\phi} \approx 180.17^{+0.36}_{-027}\ \text{deg}$$

$$\left|\lambda^{\parallel,QCDF}_{\phi\phi}\right| = \left|\lambda^{\perp,QCDF}_{\phi\phi}\right| \approx 1.004^{+0.001}_{-0.001}$$
$$\phi^{\parallel,QCDF}_{\phi\phi} = \phi^{\perp,QCDF}_{\phi\phi} \approx 180.09^{+0.10}_{-0.11}\ \text{deg}$$

	unit	value
acceptance	%	86
$\sigma(m_\phi)$	MeV	$\sim$1.5
$\sigma(m_{B_s})$	MeV	$\sim$7.
$\sigma(d^{flight}_{B_S})$	µm	$\sim$20.

FCC sensitivity with time dependent fit

$$\delta\left(\Delta\Gamma^{FCC}_{s,\phi\phi}\right) \approx 0.004$$
$$\delta\left(\phi^{FCC}_{\phi\phi}\right) \approx 0.5^\circ\ (stat.)$$

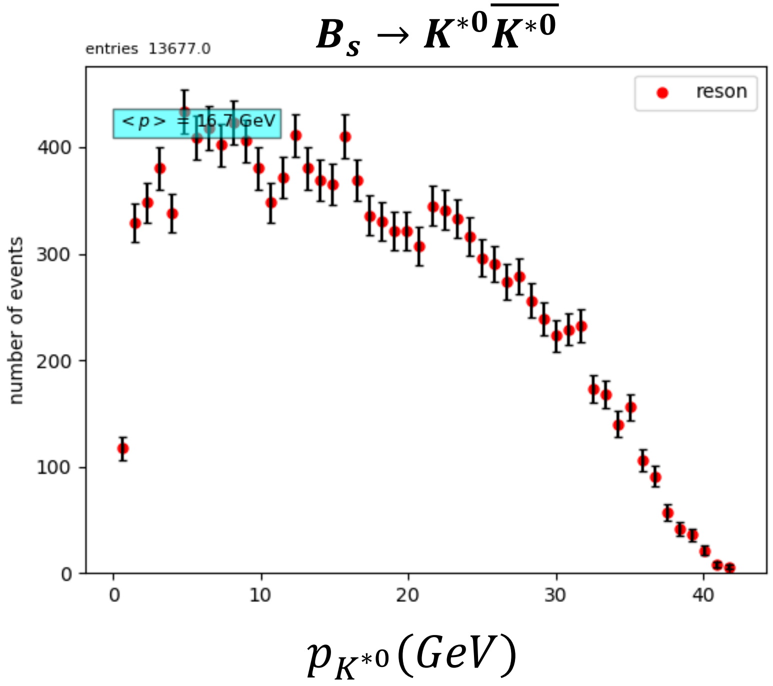
Detector response is parametrized

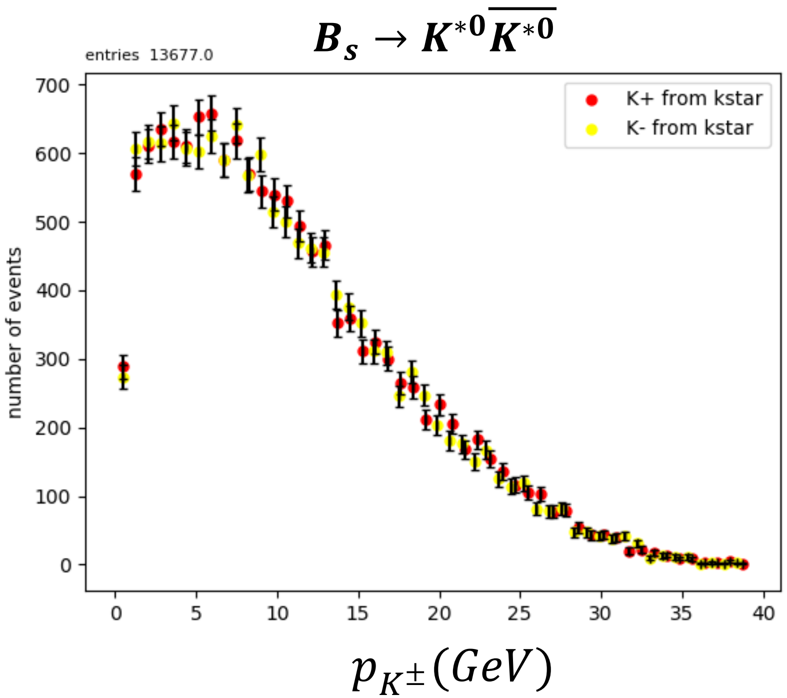
(See backup slides)

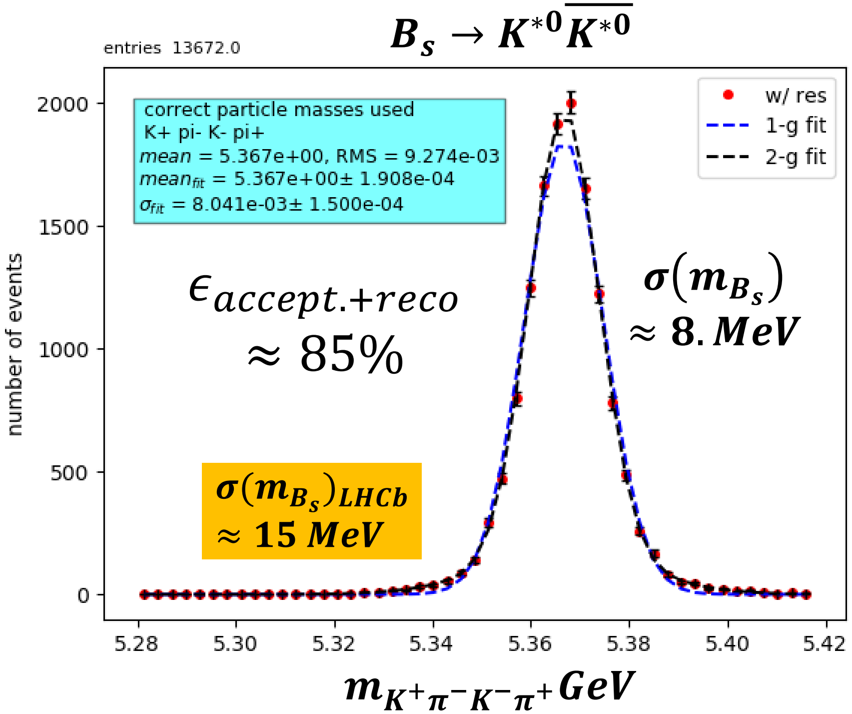
Acceptance :	$\lvert\cos\theta\rvert$	$<$	0.95
Track p_T resolution :	$\frac{\sigma(p_T)}{p_T^2}$	$=$	$2. \times 10^{-5} \oplus \frac{1.2\times 10^{-3}}{p_T \sin\theta}$
Track ϕ, θ resolution :	$\sigma(\phi,\theta)\ \mu\mathrm{rad}$	$=$	$18 \oplus \frac{1.5\times 10^{3}}{p_T \sqrt[3]{\sin\theta}}$
Vertex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

	unit	value
acceptance	%	85
$\sigma(m_{B_s})$	MeV	~8.
$\sigma(d_{B_s}^{flight})$	μm	~20.

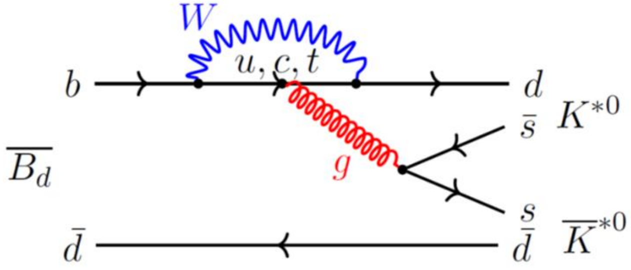
Essentially no combinatorial background if excellent PID (see LHCb) else good PID + excellent momemtum resolution

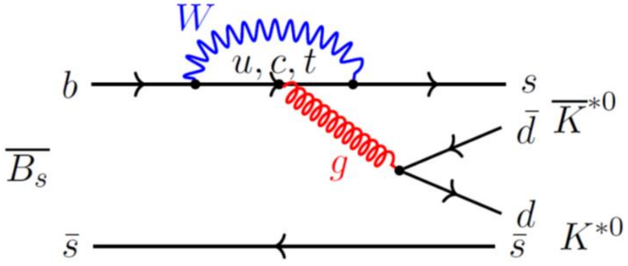






$B_{d,s} \to K^{*0}\overline{K^{*0}} \to K^+\pi^-K^-\pi^+$ leads to the same results





$|\lambda^{NF}| = 1$

$\phi^{NF}_{CKM} = \pi$

$$\left|\lambda^{L,QCDF}_{B_d\to K^{*0}\overline{K^{*0}}}\right| \approx 0.797^{+0.019}_{-0.024}$$

$$\phi^{L,QCDF}_{B_d\to K^{*0}\overline{K^{*0}}} \approx \mathbf{175.00^{+4.77}_{-3.92}\ deg}$$

$$\left|\lambda^{\parallel,QCDF}_{B_d\to K^{*0}\overline{K^{*0}}}\right| = \left|\lambda^{\perp,QCDF}_{B_d\to K^{*0}\overline{K^{*0}}}\right| \approx 0.906^{+0.020}_{-0.027}$$

$$\phi^{\parallel,QCDF}_{B_d\to K^{*0}\overline{K^{*0}}} = \phi^{\perp,QCDF}_{B_d\to K^{*0}\overline{K^{*0}}} \approx \mathbf{177.68^{+2.35}_{-1.88}\ deg}$$

$$\left|\lambda^{L,QCDF}_{B_s\to K^{*0}\overline{K^{*0}}}\right| \approx 1.010^{+0.002}_{-0.002}$$

$$\phi^{L,QCDF}_{B_s\to K^{*0}\overline{K^{*0}}} \approx \mathbf{180.12^{+0.19}_{-0.21}\ deg}$$

$$\left|\lambda^{\parallel,QCDF}_{B_s\to K^{*0}\overline{K^{*0}}}\right| = \left|\lambda^{\perp,QCDF}_{B_s\to K^{*0}\overline{K^{*0}}}\right| \approx 1.003^{+0.001}_{-0.001}$$

$$\phi^{\parallel,QCDF}_{B_s\to K^{*0}\overline{K^{*0}}} = \phi^{\perp,QCDF}_{B_s\to K^{*0}\overline{K^{*0}}} \approx \mathbf{180.09^{+0.09}_{-0.10}\ deg}$$

QCDF

$\overline{B}_s \to K^{*0}\overline{K}^{*0}$	$K^+\pi^-$	$K^+\pi^-K^-\pi^+$	$\sim 4.9\ 10^5$
$\overline{B}_d \to K^{*0}\overline{K}^{*0}$	$K^+\pi^-$	$K^+\pi^-K^-\pi^+$	$\sim 1.4\ 10^5$

FCC sensitivity with time dependent fit

$$\delta\left(\Delta\Gamma^{FCC}_{s,K^{*0}\overline{K^{*0}}}\right) \approx 0.004$$

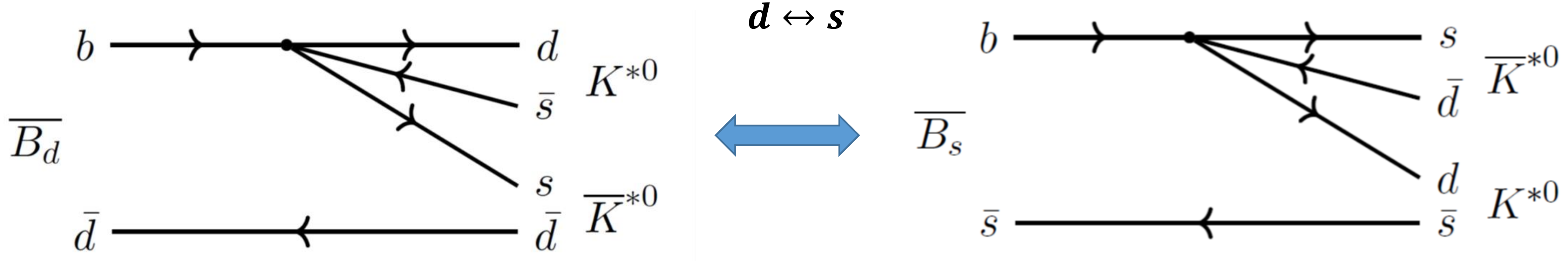
$$\delta\left(\phi^{FCC}_{K^{*0}\overline{K^{*0}}}\right) \approx 0.5^\circ\ (stat.)$$

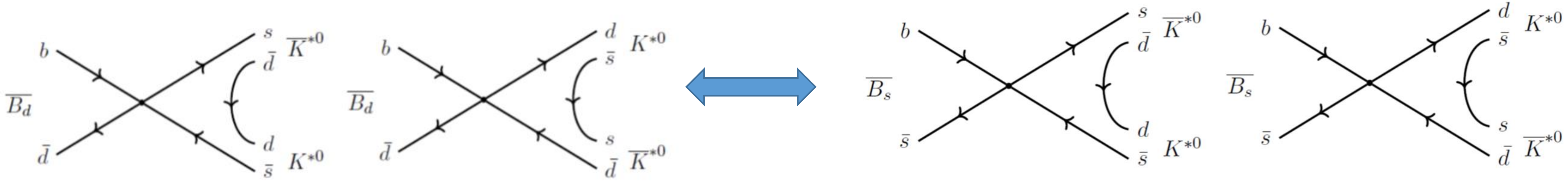
⇨ Very good for probing BSM Physics (as good as $\overline{B}_s \to \phi\phi$)

Special properties for $B_{d,s} \to K^{*0}\overline{K^{*0}} \to K^+\pi^-K^-\pi^+$

U-spin symmetry

$d \leftrightarrow s$





One expects the same values for $f_L, f_\parallel$ and $f_\perp$ in $B_d \to K^{*0}\overline{K^{*0}}$ and $B_s \to K^{*0}\overline{K^{*0}}$ modulo SU(3) breaking

Note : We have also calculated $Br, f_L, f_\parallel, f_\perp$ and A_{CP} for numbers of B-mesons to light Vector-Vector meson and compared with existing data (paper to come soon) . FCCee will make a real breakthrough in $B \to V_1^{\text{light}} V_2^{\text{light}}$ decays

Comparing data and QCDF (1/3)

modes		LHCb	QCDF
$B_d \to K^{*0}\overline{K^{*0}}$	$f_L = \Gamma_L/\Gamma$	$\mathbf{0.724 \pm 0.053}$	0.498 ± 0.086
	$f_\parallel = \Gamma_\parallel/\Gamma$	0.116 ± 0.035	0.251 ± 0.043
	$f_\perp = \Gamma_\perp/\Gamma$	0.160 ± 0.046	0.251 ± 0.043
$B_s \to K^{*0}\overline{K^{*0}}$	$f_L = \Gamma_L/\Gamma$	$\mathbf{0.240 \pm 0.040}$	0.429 ± 0.088
	$f_\parallel = \Gamma_\parallel/\Gamma$	0.234 ± 0.027	0.286 ± 0.044
	$f_\perp = \Gamma_\perp/\Gamma$	$\mathbf{0.526 \pm 0.037}$	0.286 ± 0.044

LHCb

$$f_L^{B_d \to K^{*0}\overline{K^{*0}}} \gg f_L^{B_s \to K^{*0}\overline{K^{*0}}}$$

$$f_\perp^{B_s \to K^{*0}\overline{K^{*0}}} \gg f_\parallel^{B_s \to K^{*0}\overline{K^{*0}}}$$

while

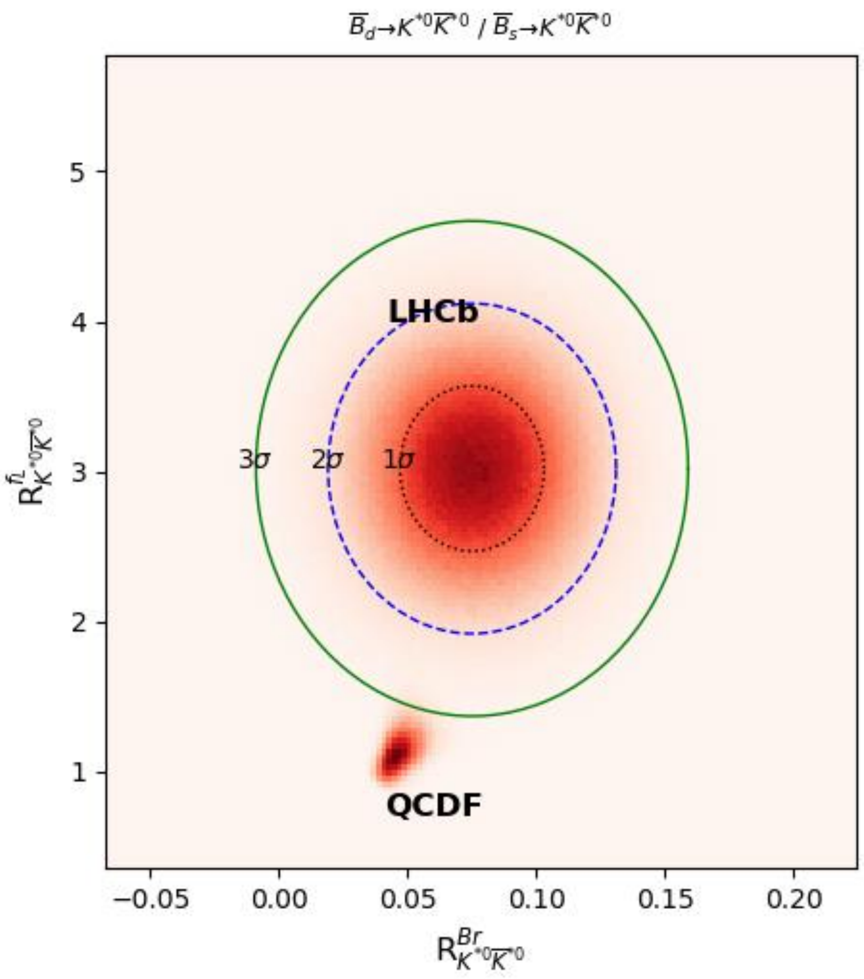
QCDF

$$f_L^{B_d \to K^{*0}\overline{K^{*0}}} \approx f_L^{B_s \to K^{*0}\overline{K^{*0}}}$$

$$f_\perp^{B_s \to K^{*0}\overline{K^{*0}}} \approx f_\parallel^{B_s \to K^{*0}\overline{K^{*0}}}$$

Comparing data and QCDF (2/3)

$$R^{f_L}_{K^{*0}\overline{K^{*0}}} = \frac{f_L(B_d \to K^{*0}\overline{K^{*0}})}{f_L(B_s \to K^{*0}\overline{K^{*0}})}$$

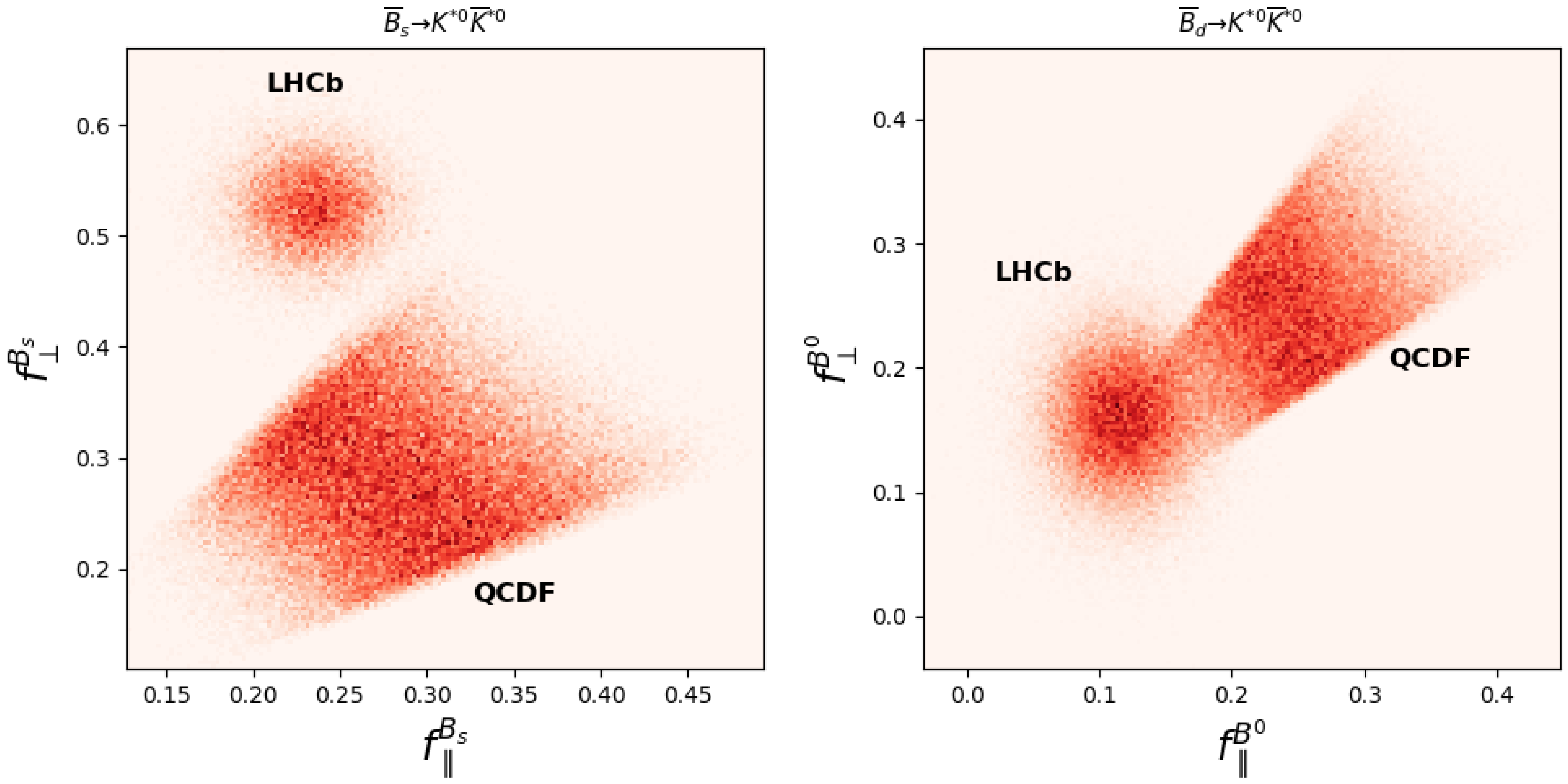


While the measured ratio of the Branching Fractions is compatible with the expectations from QCDF , the ratio of the longitudinal is $> 3\,\sigma$ away from the predictions.

$$R^{Br}_{K^{*0}\overline{K^{*0}}} = \frac{Br(B_d \to K^{*0}\overline{K^{*0}})}{Br(B_s \to K^{*0}\overline{K^{*0}})}$$

Comparing data and QCDF (3/3)

Similarly the measured parallel polarization and the perpendicular one are significantly different from the expectations from QCDF, in particular for the $B_s \rightarrow K^{*0}\overline{K^{*0}}$ decay ($> 3\,\sigma$) away from the predictions) .

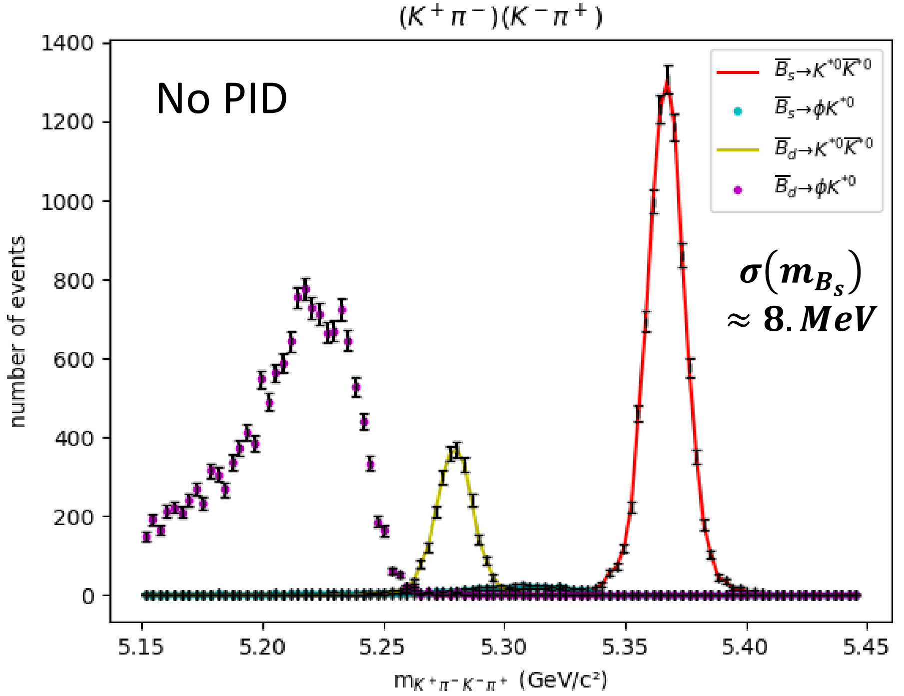


Summary

One needs to improve both
- the uncertainties of the theory
- the precision of the measurement (in particular for Bs; a factor 2 reduction of errors would lead to the significance exceeding 5σ)

@FCC , large number of $B_{d,s} \rightarrow K^{*0}\overline{K^{*0}}$ decays : very good to search for BSM physics
- In CP violation studies (as discussed earlier no CP violation expected)
- But also in polarization measurements

$E_{cm} = m_Z$ and $\int L = 150ab^{-1}$			
$\sigma(e^+e^- \rightarrow Z)$ nb	number of Z	$f(Z \rightarrow \overline{B}_s)$	Number of produced $\overline{B}$
~ 42.9	$\sim 6.4\ 10^{12}$	0.0159	$\sim 1\ 10^{11}\overline{B}_s$
~ 42.9	$\sim 6.4\ 10^{12}$	0.0608	$\sim 3.9\ 10^{11}\overline{B}_d$
$\overline{B}$ decay Mode	K^{*0} Decay Mode	Final State	Number of $\overline{B}$ decays
$\overline{B}_s \rightarrow K^{*0}\overline{K}^{*0}$	$K^+\pi^-$	$K^+\pi^-K^-\pi^+$	$\sim 4.9\ 10^5$
$\overline{B}_d \rightarrow K^{*0}\overline{K}^{*0}$	$K^+\pi^-$	$K^+\pi^-K^-\pi^+$	$\sim 1.4\ 10^5$



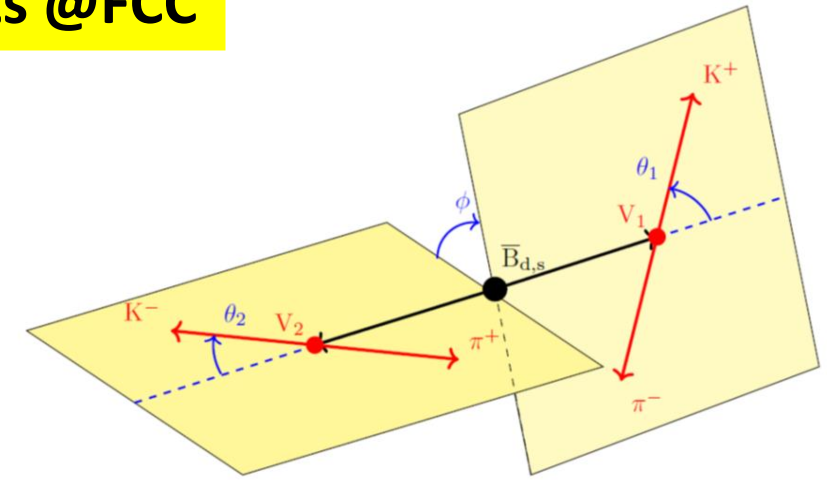
Very small combinatorial background is expected if excellent PID (cf. LHCb) : to be verified @FCCee

Polarization measurements @FCC

$$\frac{d\Gamma(\overline{B}_{d,s}\to K^{*0}\overline{K}^{*0})}{d\cos\theta_1\, d\cos\theta_2\, d\phi} \propto |\overline{A}_0|^2\cos^2\theta_1\cos^2\theta_2 + \frac{|\overline{A}_+|^2+|\overline{A}_-|^2}{4}\sin^2\theta_1\sin^2\theta_2$$

$$-[\Re(e^{-i\phi}\overline{A}_0\overline{A}_+^*) + \Re(e^{i\phi}\overline{A}_0\overline{A}_-^*)]\cos\theta_1\sin\theta_1\cos\theta_2\sin\theta_2$$

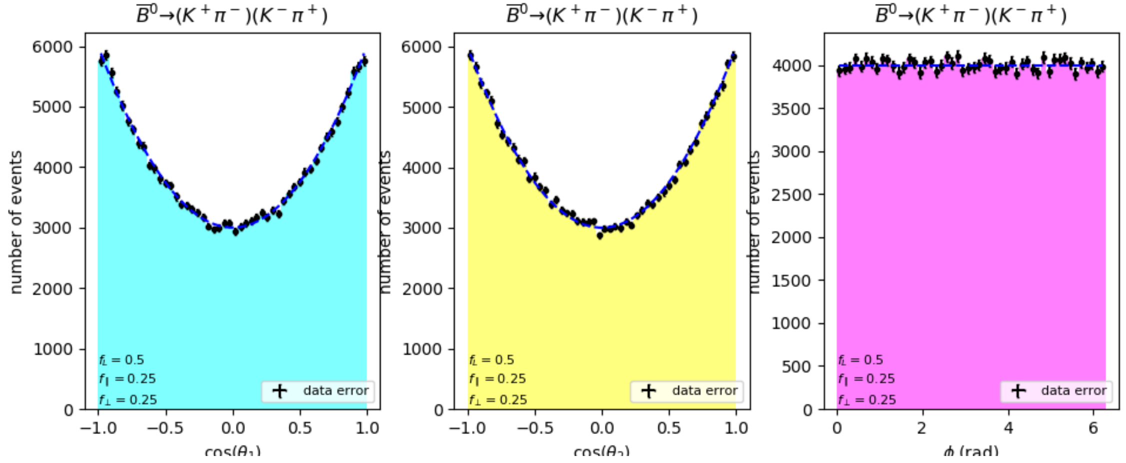
$$+\frac{\Re(e^{2i\phi}\overline{A}_+\overline{A}_-^*)}{2}\sin^2\theta_1\sin^2\theta_2$$

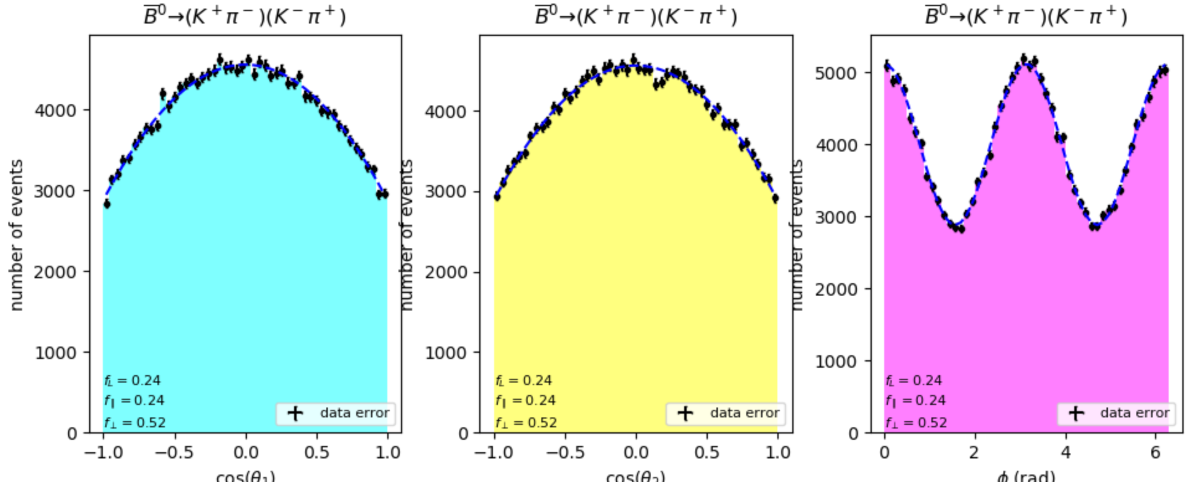


$$f_{L,\parallel,\perp}^{(B_d\to K^{*0}\overline{K^{*0}})} \approx 0.004$$
$$f_{L,\parallel,\perp}^{(B_s\to K^{*0}\overline{K^{*0}})} \approx 0.002$$

QCDF $\Longrightarrow f_L : f_\perp : f_\parallel = 0.5 : 0.25 : 0.25$

LHCb $\Rightarrow f_L : f_\perp : f_\parallel = 0.25 : 0.25 : 0.5$





Conclusions

$B_{d,s} \rightarrow K^{*0}\overline{K^{*0}}$ decays : excellent candidates to search for BSM physics :

- With CP violation studies (as good as $B_s \rightarrow \phi\phi$)
- With measurements of polarizations
  - where there is ***evidence for anomaly in the present data***

FCC-ee would enable ultra precise measurements for search of new physics

- With CP violation measurements
  - at the ***sub-degree level for the CP phase***
  - at the ***sub % level for direct CP measurement***
- for measurements of polarizations
  - at the ***sub % level***

To achieve these figures :

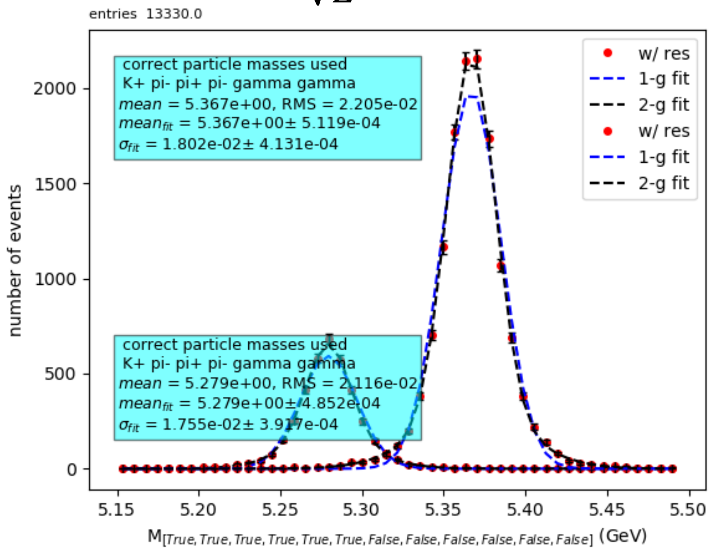
- Excellent momentum resolution is necessary
- Excellent PID is mandatory

Still to be done : study of combinatoric backgound to verify that it is small.

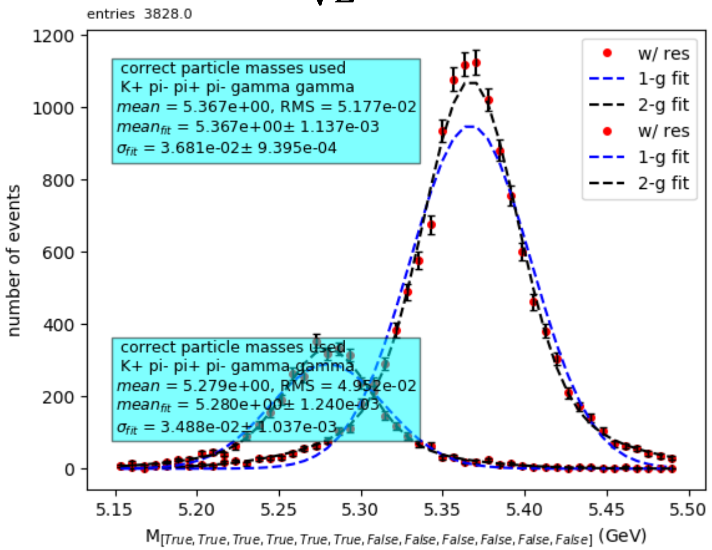
Conclusions (addendum)

One could increase the statistics (+30%) using $K^{*0} \to K^0\pi^0$ for one of the K^{*0} (useful for polarization measurement)
… but strong constraint on Electromagnetic calorimeter

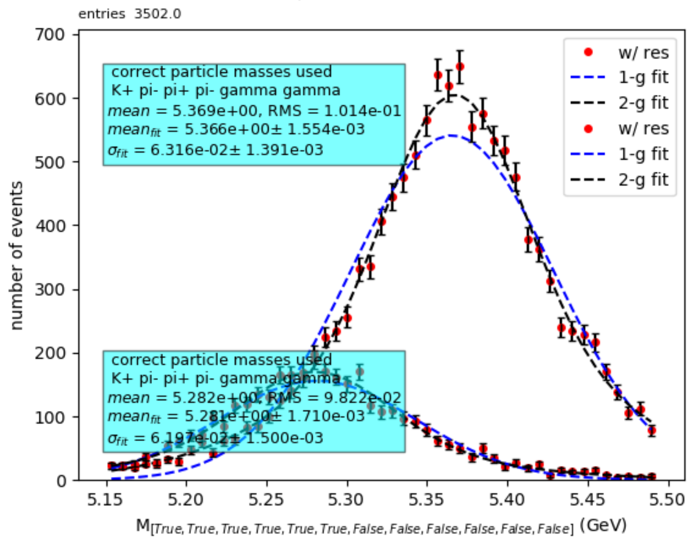
$$\frac{\delta E}{E} = \frac{0.03}{\sqrt{E}} + 0.005 + \frac{0.001}{E}$$



$$\frac{\delta E}{E} = \frac{0.08}{\sqrt{E}} + 0.005 + \frac{0.005}{E}$$



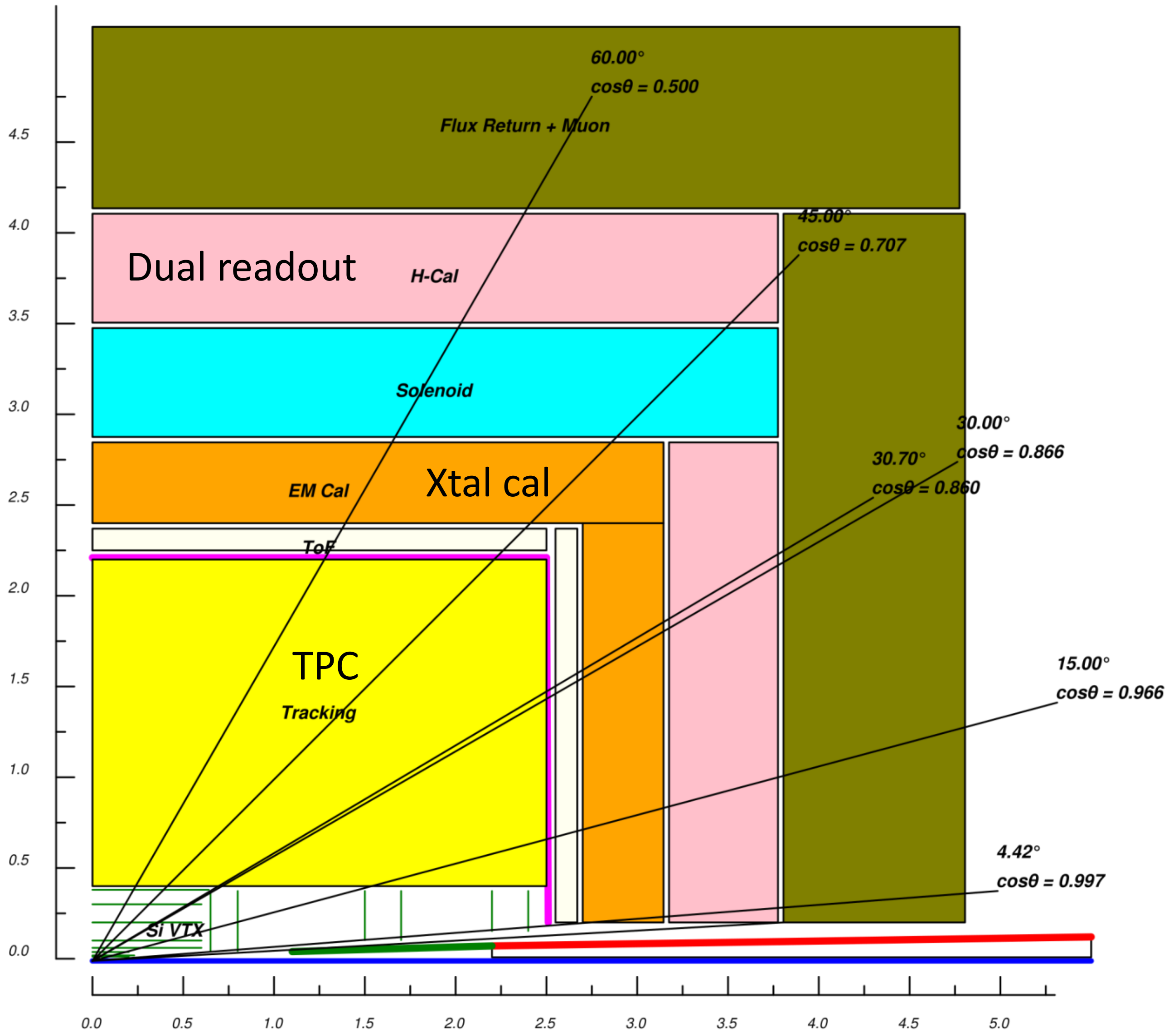
$$\frac{\delta E}{E} = \frac{0.15}{\sqrt{E}} + 0.005 + \frac{0.03}{E}$$



Note : In this case, combinatoric background needs definitely to be studied

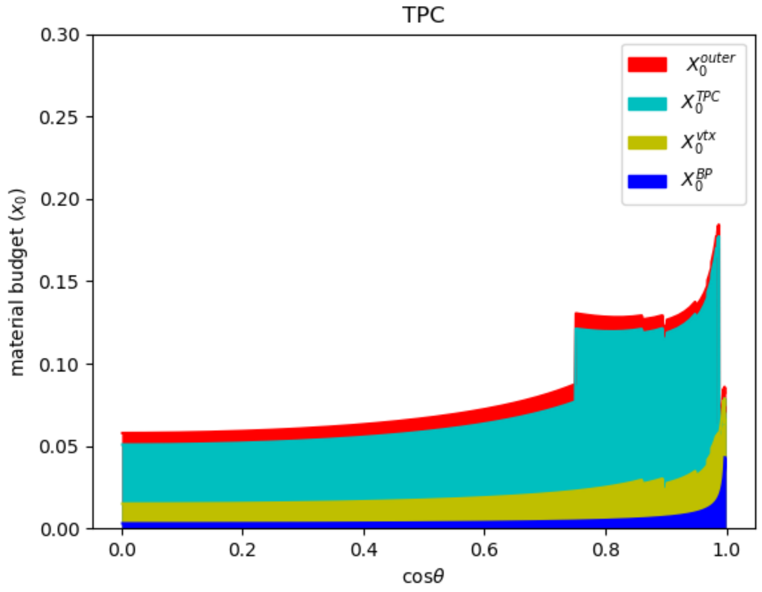
Additional Slides

Simulated detector



Tracking is completely simulated including

- Multiple scattering with all material
- Track fitting and then parametrization



Time dependent analysis

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

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

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

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

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

$\omega = wrong\ tagging = 0.25$

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

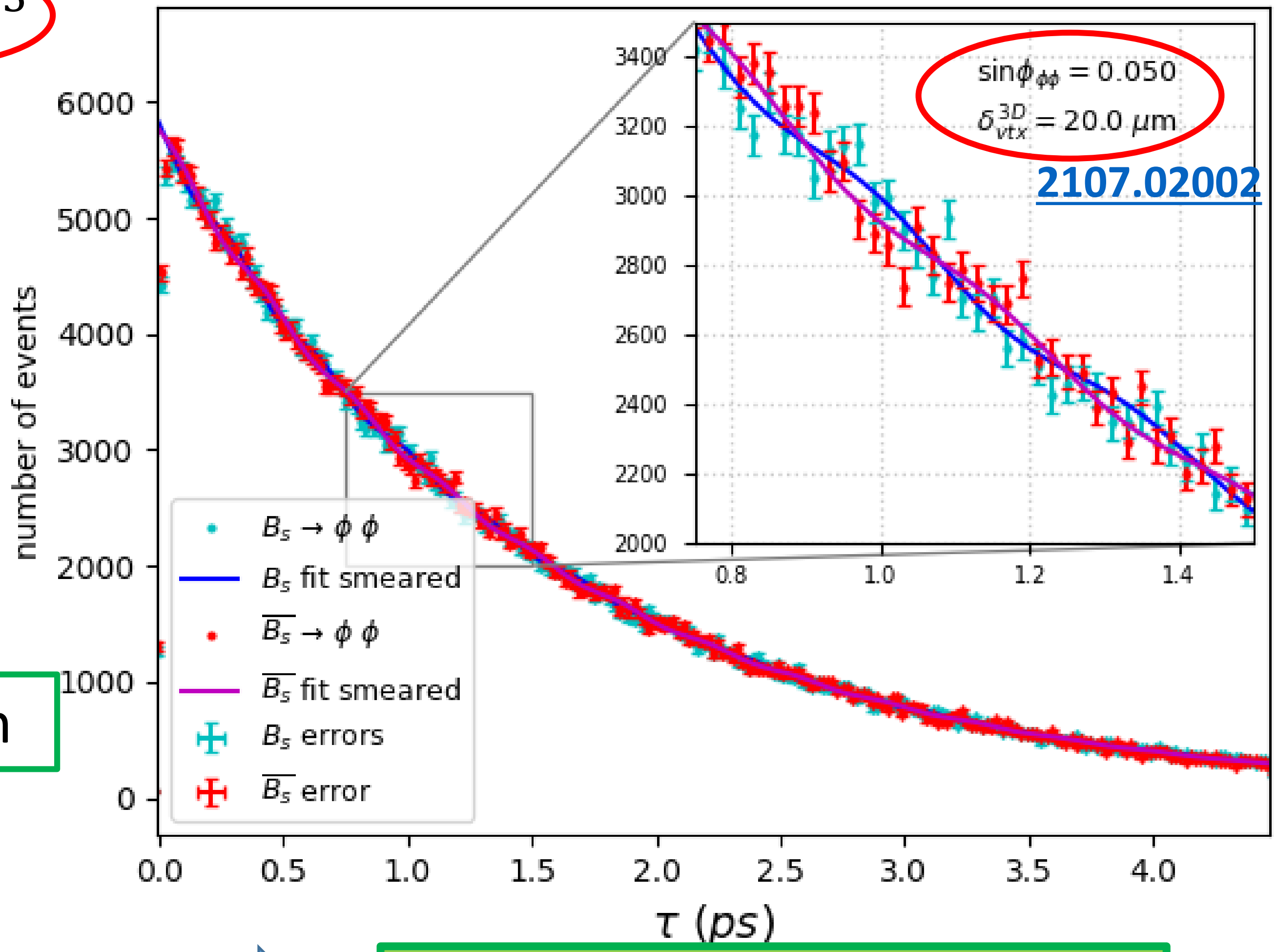
Large number of events expected @FCCee

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

$E_{cm} = 91.2$ GeV and $\int L = 150 ab^{-1}$

$\sigma(e^+e^- \to Z)$ nb	number of Z	$f(Z \to \overline{B}_s)$	Number of produced $\overline{B}_s$
~ 42.9	$\sim 6.4\ 10^{12}$	0.0159	$\sim 1\ 10^{11}$

$\overline{B}_s$ decay Mode	Decay Mode	Final State	Number of $\overline{B}_s$ 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

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

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

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

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

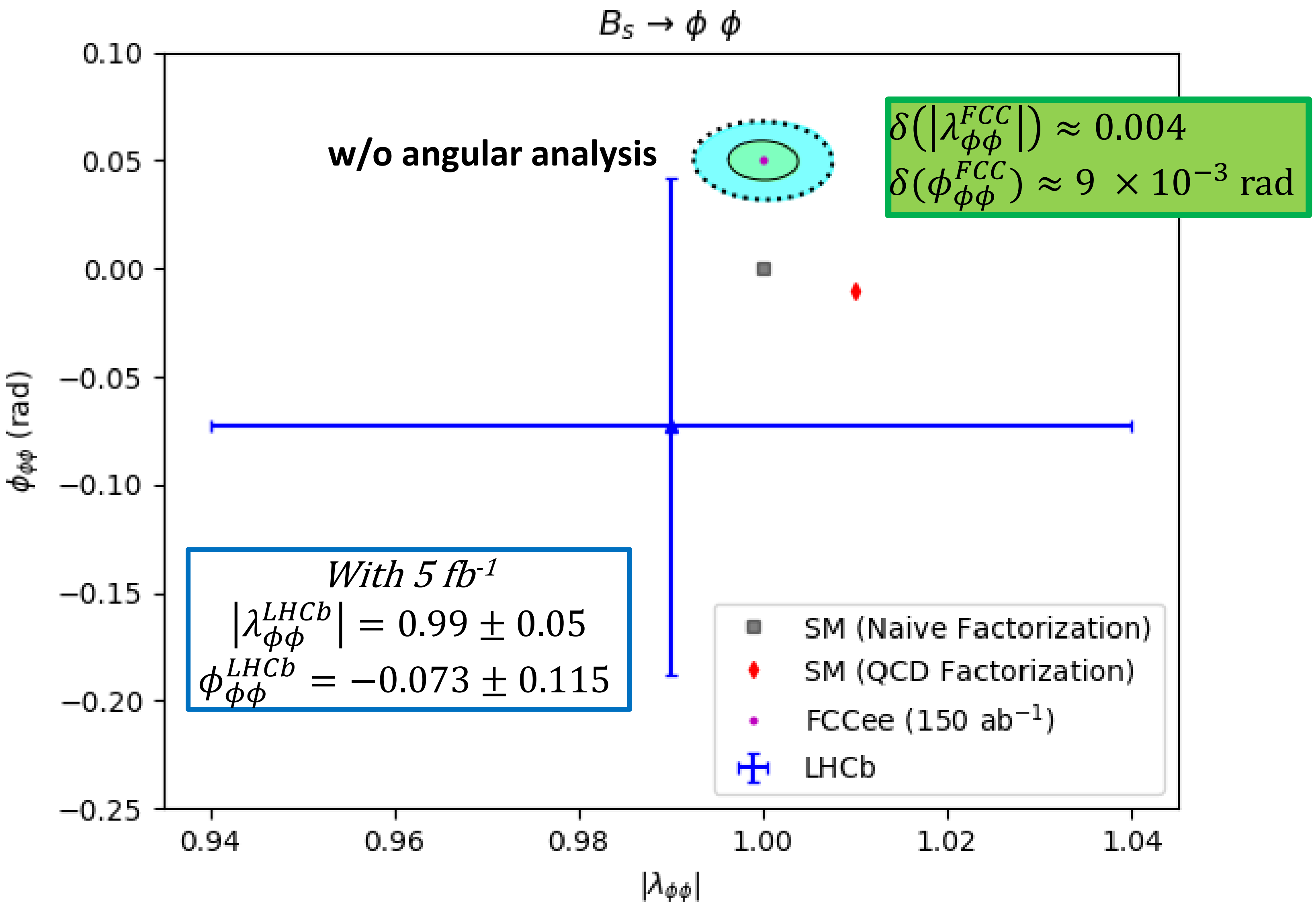
Angular analysis →

$\delta(\sin\phi_{\phi\phi}) \approx 4.5 \times 10^{-3}$ 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 $\phi_{\phi\phi} = 0.05\text{rad}$

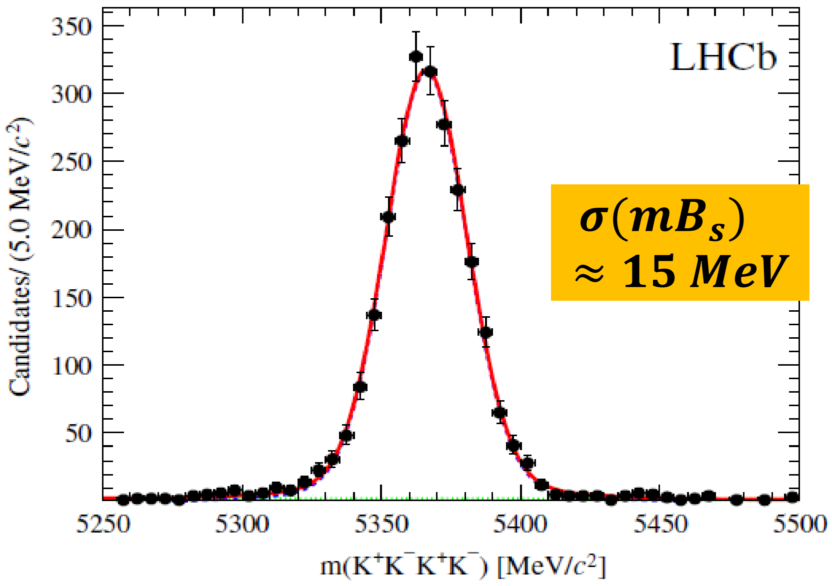


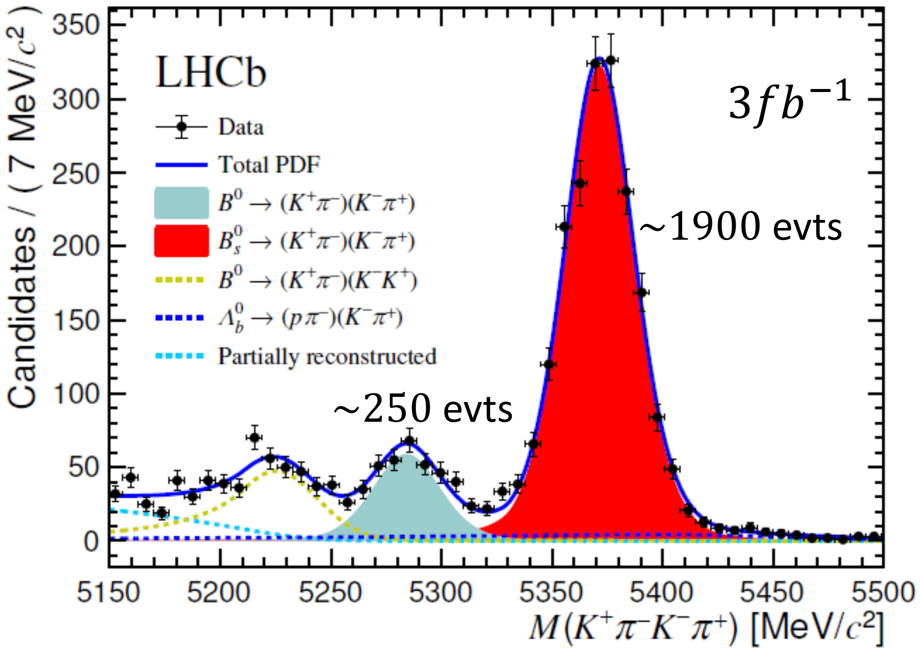
If indeed : $|\lambda_{\phi\phi}| = 1. \pm 0.004$
$\sin\phi_{\phi\phi} = 0.05 \pm 0.009$ rad
is measured @ FCCee

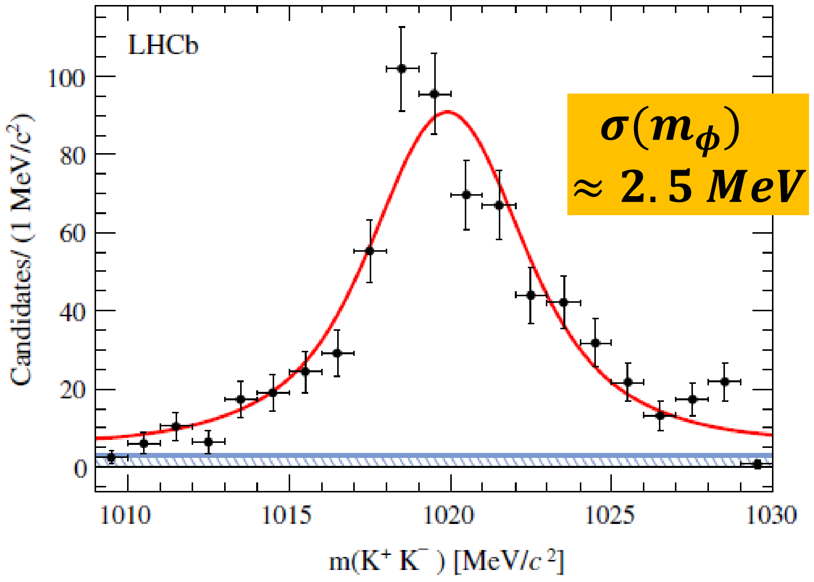
5σ deviation from SM

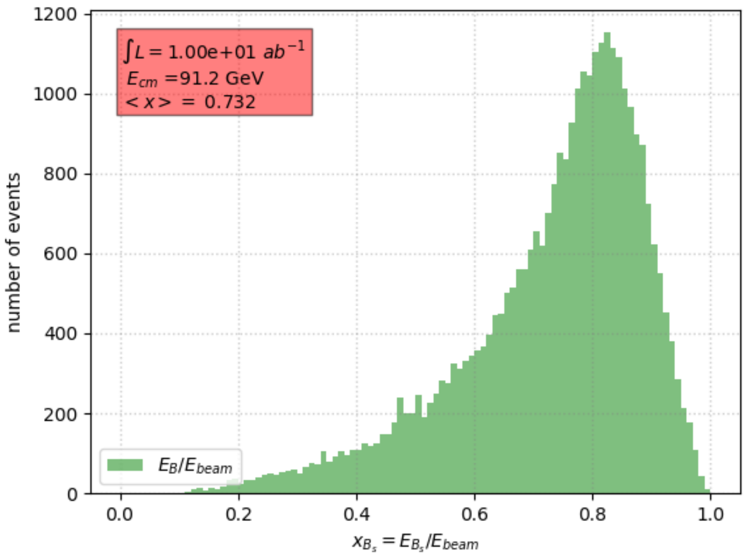
If angular analysis

>~10 σ deviation from SM potentially possible


LHCb
Candidates/ (5.0 MeV/c²)
m(K⁺K⁻K⁺K⁻) [MeV/c²]
σ(mB_s) ≈ 15 MeV


LHCb
3fb⁻¹
Data
Total PDF
B⁰ → (K⁺π⁻)(K⁻π⁺)
B⁰_s → (K⁺π⁻)(K⁻π⁺)
B⁰ → (K⁺π⁻)(K⁻K⁺)
Λ⁰_b → (pπ⁻)(K⁻π⁺)
Partially reconstructed
~1900 evts
~250 evts
Candidates / (7 MeV/c²)
M(K⁺π⁻K⁻π⁺) [MeV/c²]


LHCb
Candidates/ (1 MeV/c²)
m(K⁺ K⁻) [MeV/c²]
σ(m_φ) ≈ 2.5 MeV


∫L = 1.00e+01 ab⁻¹
E_cm =91.2 GeV
< x > = 0.732
E_B/E_beam
number of events
x_Bs = E_Bs/E_beam

Small difference between $\overline{B_d} \to K^{*0}\overline{K^{*0}}$ and $\overline{B_s} \to K^{*0}\overline{K^{*0}}, h$

$$\mathcal{A}\left(\overline{B_d} \to K^{*0}\overline{K^{*0}}, h\right) = \sum_{p=u,c} \lambda_p S^{p,h} A^h\left(\overline{B_d} \to K^{*0}\overline{K^{*0}}\right) + (\lambda_u + \lambda_c) T^{p,h} B^h\left(\overline{B_d} \to K^{*0}\overline{K^{*0}}\right)$$

$$\mathcal{A}\left(\overline{B_s} \to K^{*0}\overline{K^{*0}}, h\right) = \sum_{p=u,c} \lambda'_p S^{p,h} A^h\left(\overline{B_s} \to K^{*0}\overline{K^{*0}}\right) + (\lambda'_u + \lambda'_c) T^{p,h} B^h\left(\overline{B_s} \to K^{*0}\overline{K^{*0}}\right)$$

$$\lambda_p = V_{pb} V^*_{pd}$$
$$\lambda'_p = V_{pb} V^*_{ps}$$

$S^{p,h}$ and $T^{p,h}$ are combinations of Wilson coefficients and are identical in both modes

$$A^0\left(\overline{B_{d,s}} \to K^{*0}\overline{K^{*0}}\right) = \mathrm{i}\,\frac{G_F}{\sqrt{2}} m^2_{B_{d,s}} A_0^{\overline{B_{d,s}} \to \overline{K^{*0}}}(m^2_{K^{*0}}) f_{K^{*0}}$$

$$A^-\left(\overline{B_{d,s}} \to K^{*0}\overline{K^{*0}}\right) = \mathrm{i}\,\frac{G_F}{\sqrt{2}} m_{B_{d,s}} m_{K^{*0}} F_-^{\overline{B_{d,s}} \to \overline{K^{*0}}}(m^2_{K^{*0}}) f_{K^{*0}}$$

Main uncertainty comes from the B_d and B_s form factors obtained from lattice QCD

$$B^0\left(\overline{B_{d,s}} \to K^{*0}\overline{K^{*0}}\right) = B^-\left(\overline{B_{d,s}} \to K^{*0}\overline{K^{*0}}\right) = \mathrm{i}\,\frac{G_F}{\sqrt{2}} f_{B_{d,s}} f^2_{K^{*0}}$$