Determination of one angle of the “squashed” (d,s) unitarity triangle at FCC-ee

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Analysis and write-up advanced, plan to submit soon to arXiv

Unitarity triangles

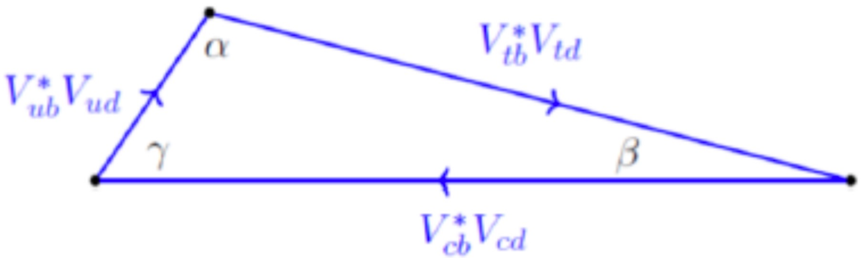
$$V_{CKM} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix}$$

Six triangular relations from unitarity of V_{CKM} .
Among them :

The (usual) "(b, d) triangle" :

$$V^*_{ub} V_{ud} + V^*_{cb} V_{cd} + V^*_{tb} V_{td} = 0$$

$$(\lambda^3, \quad \lambda^3, \quad \lambda^3)$$



All angles are (quite) large.

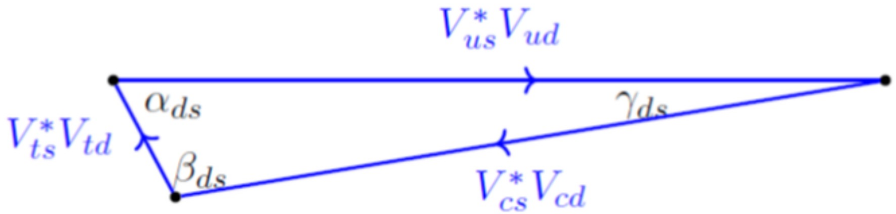
$(\alpha, \beta, \gamma) \sim (85^o, 22^o, 66^o)$

Extensively studied experimentally

The "(d, s) triangle" :

$$V^*_{us} V_{ud} + V^*_{cs} V_{cd} + V^*_{ts} V_{td} = 0$$

$$(\lambda, \quad \lambda, \quad \lambda^2)$$



$(\alpha_{ds}, \beta_{ds}, \gamma_{ds}) \sim (23^o, 157^o, 0.03^o)$

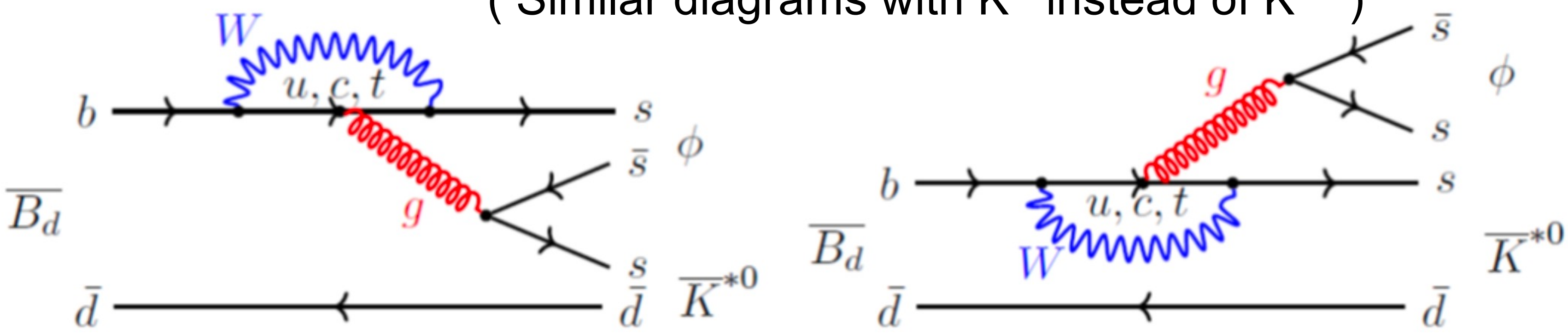
The "(b, s) triangle": 2107.02002, 2107.05311

(SM: Relations between the angles of these triangles)

FCC-ee : direct measurements of the 'non usual' triangles. Important consistency checks of the CKM mechanism of the SM. Here: Study expected precision on α_{ds}

Measurement of α_{ds}

(Similar diagrams with K^0 instead of K^{*0})



When $K^0 \rightarrow K_S$, or $K^{*0} \rightarrow K_S\, \pi^0$ (CP eigenstate) :
interf. between $B \rightarrow \phi\, K_S$ and $B \rightarrow \bar{B} \rightarrow \phi\, K_S$ leads to CP violation.

[Neglecting direct CP violation in the decay to simplify the formula below :]

$$\Gamma\,(\overset{(-)}{B_d}(t) \rightarrow f\,) \sim e^{-\Gamma t}\ [\ 1 \pm (1\text{-}2\omega)\ \sin \Phi_{CKM}\ \sin(\Delta m_d\ t)\ ]$$

ω = mistag rate, (well) measured independently

For the B_d:
$\Phi_{CKM} = \pi - 2\,\alpha_{ds}$

For B_s : $\Phi_{CKM} = \pi + 2\,\alpha_{ds}$

Both B and B_s decays give access to α_{ds} via time-dependent CPV asym.
Must measure both and check that $\Phi_{CKM}(B_s) + \Phi_{CKM}(B_d) = 2\pi$: important consistency check of the SM.

Expected number of signal decays in 150 ab^{-1} at the Z peak

B decay	$\mathrm{Br}(\times 10^{-6})$
$\overline{B}^0 \to \overline{K}^0 \phi$	7.3 ± 0.7
$\overline{B}^0 \to \overline{K}^{*0} \phi$	10.0 ± 0.5
$\overline{B}_s \to \phi K^0$	$1.3 \pm 0.6^*$
$\overline{B}_s \to \phi K^{*0}$	1.14 ± 0.30

B_s signal is small !

(*) $B_s \to \phi\, K^0$ not measured yet. This BR corresponds to $B_s \to K^+ K^- K^0$. Branching used for the numbers below: 1.0 10^{-6}

Expected number of produced B_d and B_s decays:
(to be x'ed by 2 to account for $\overline{B}_d$ and $\overline{B}_s$) :

		B_d	B_s
ϕK^0	$\mathrm{K^+K^-}(\pi^+\pi^-)_{\mathrm{K_s}}$	$\sim 4.9\ 10^5$	$\sim 1.7\ 10^4$
ϕK^{*0}	$\mathrm{K^+K^-}(\pi^+\pi^-)_{\mathrm{K_s}}\pi^0$	$\sim 2.1\ 10^5$	$\sim 6.4\ 10^3$

Modelisation of the detector response

- Stand-alone parametrisation of the detector response :
  - Smearing of the momenta and angles of particles in the decays of interest
    - Parametrisation based on typical performance of a light tracker at a future ee detector
    - Excellent EM calo resolution

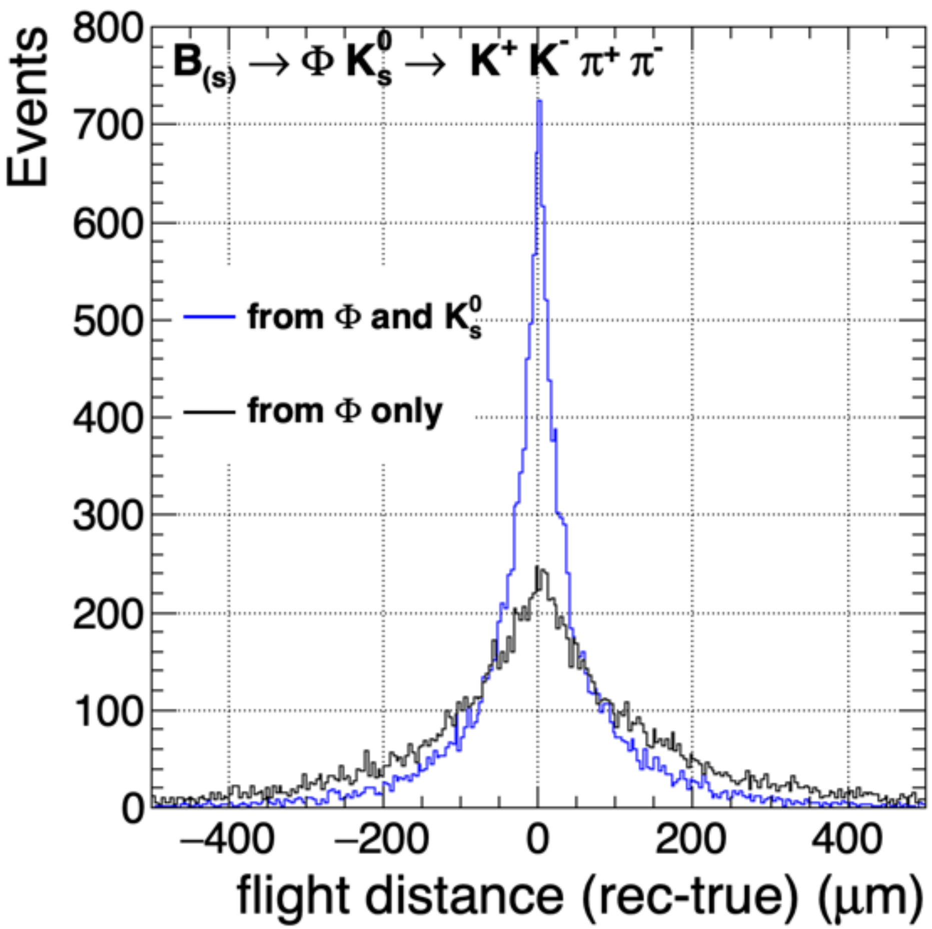
Acceptance :	$\lvert\cos\theta\rvert$	$<$	0.95
Charged particles :			
$\mathrm{p_T}$ resolution :	$\frac{\sigma(p_T)}{p_T^2}$	$=$	$2. \times 10^{-5} \oplus \frac{1.2\times10^{-3}}{p_T \sin\theta}$
ϕ,θ resolution :	$\sigma(\phi,\theta)\ \mu\mathrm{rad}$	$=$	$18 \oplus \frac{1.5\times10^{3}}{p_T \sqrt[3]{\sin\theta}}$
Vertex resolution :	$\sigma(\mathrm{d_{Im}})\ \mu\mathrm{m}$	$=$	$1.8 \oplus \frac{5.4\times10^{1}}{p_T \sqrt{\sin\theta}}$
e,γ particles :			
Energy resolution :	$\frac{\sigma(E)}{E}$	$=$	$\frac{5\times10^{-2}}{\sqrt{E}} \oplus 5 \times 10^{-3}$
EM ϕ,θ resolution :	$\sigma(\phi,\theta)\ \mathrm{mrad}$	$=$	$\frac{7}{\sqrt{E}}$

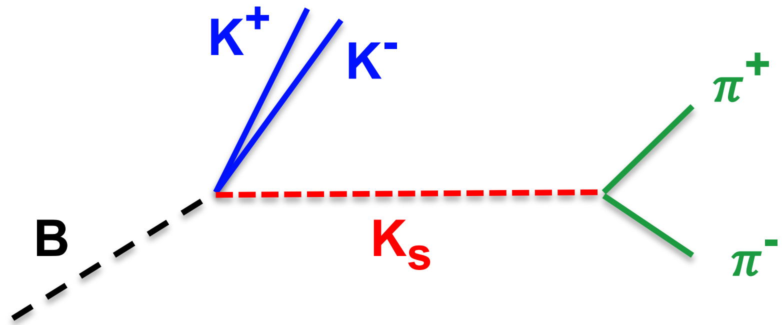
- Common FCCSW : Full MC events + response of the IDEA detector with DELPHES
  - Detailed description of tracks, accounting for multiple scattering
  - Genuine vertex fitting

Vertex reconstruction

- Resolution on K_S, ϕ and B decay vertices : crucial to suppress the backgrounds
- Resolution on B_S decay vertex: crucial for time-dependent measurements !

Vertexing code (F. Bedeschi) extended recently to also handle neutrals. See FB's report at the October Physics Perf. meeting





Using only the tracks from the ϕ: resolution ~ 168 μm only ! (very small angular separation of the two kaon tracks)

Adding the K_S "neutral tracks" : 70 μm

(for comparison: in $B_S \to D_S$ (KKπ) K, resolution was ~ 20 μm)

Very good compared to the average flight distance of the B (~ 3 mm) and no significant dilution of the B_S time-dependent CP asymmetries.

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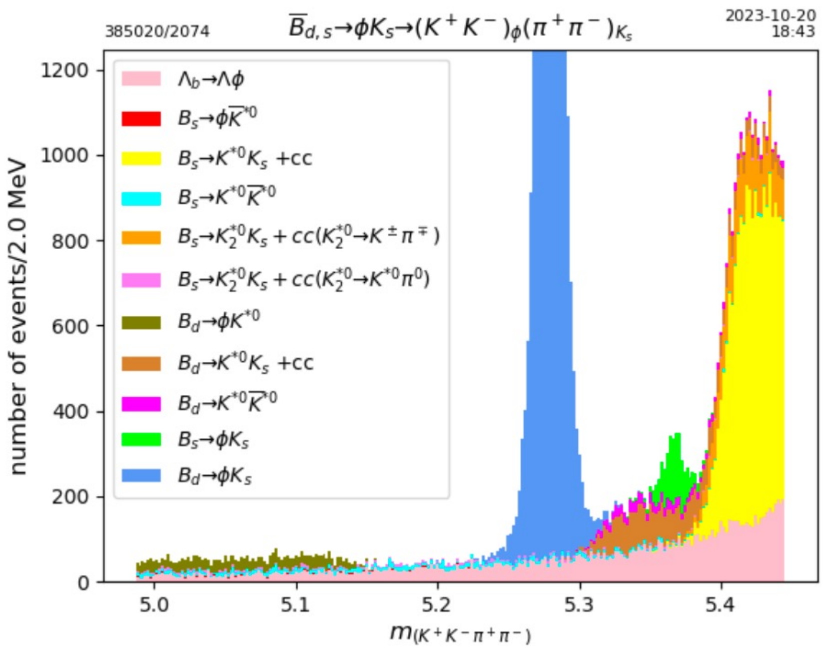
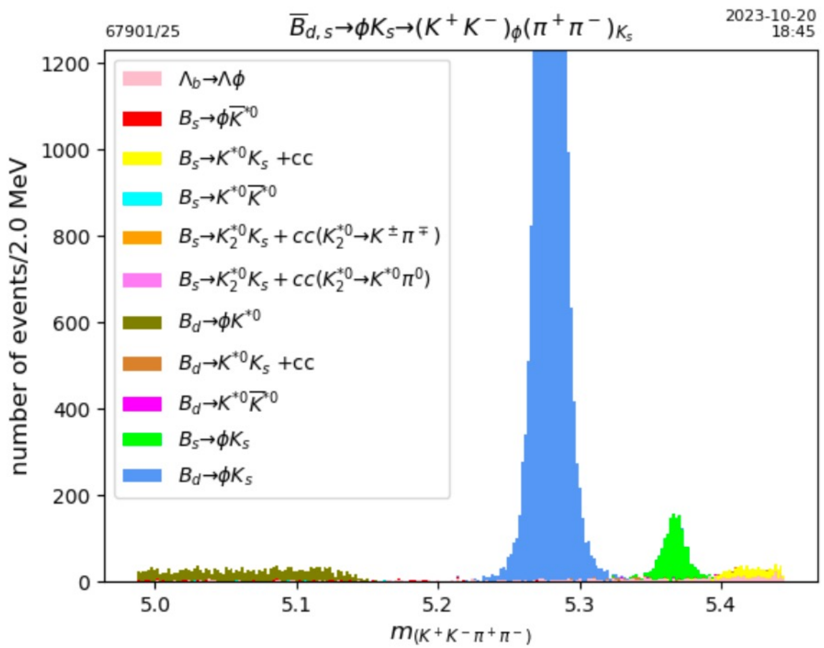
Backgrounds: exclusive final states

Potential background contributions :

- Final states w/o long-lived particles, e.g. ϕ(KK) $\rho(\pi\pi)$ or ϕ(KK) $f_0(\pi\pi)$
  - Demand $M(\pi\pi)$ ~ K_S mass and $\pi\pi$-vertex detached from ϕ
- Final states with K_S (or Λ), e.g. $B \rightarrow K^{*0} K_S$ with $K^{*0} \rightarrow K^{\pm} \pi^{\mp}$
  - They include a π instead of a K, or a p instead of a π
  - Can be reduced even w/o PID thanks to the mass resolution



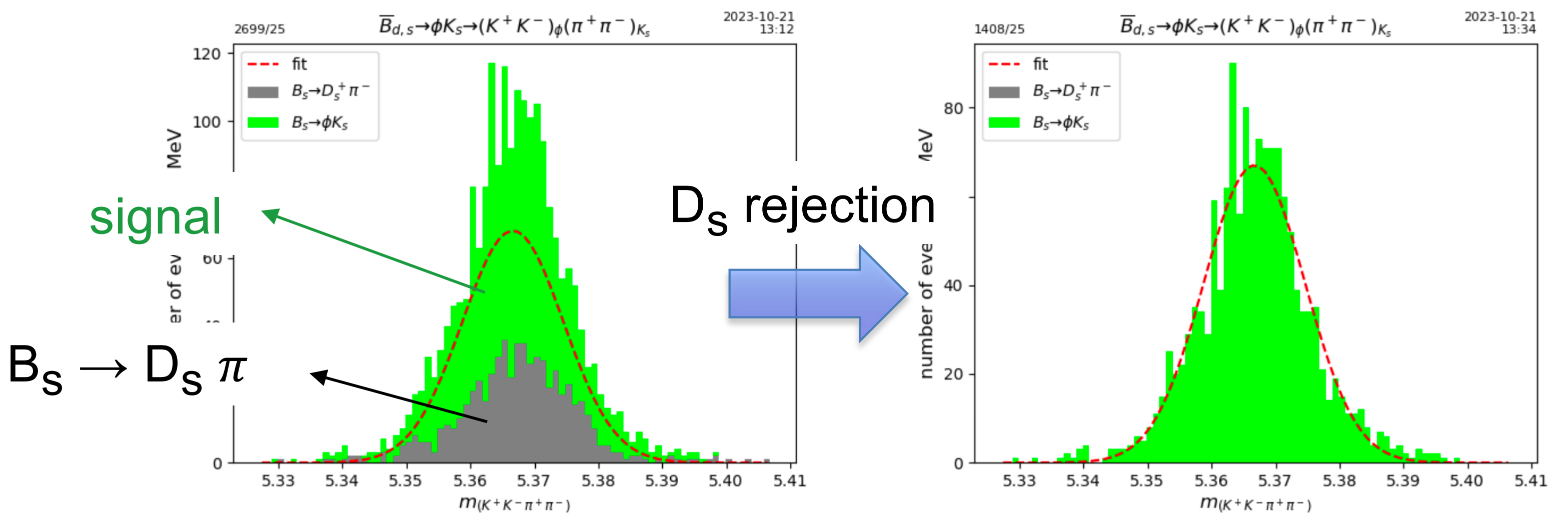
w/o mass cuts



With $m(K^+K^-)$ and $m(\pi^+\pi^-)$ cuts

Backgrounds: (semi-) exclusive final states

- Decays of $B_s \to D_s (\to \phi\, \pi)\, \pi \to K\, K\, \pi\, \pi$
  - Branching is 400x larger than $B_s \to \phi\, K_s \to K\, K\, \pi\, \pi$
  - Can be suppressed by an explicit reconstruction of $D_s \to \phi\, \pi$
    - (take the tracks from the ϕ, fit them with a 3rd track, if the chi2 is good and the vertex mass is consistent with the D_s mass, reject)



- More generally: background candidates come from a random combination of a K_s (e.g. from fragmentation) and a ϕ that comes from a D_s
  - E.g. $D_s \to \phi\, l\, \nu$, or $D_s \to \phi\, \pi + X$
  - Suppressed by a partial reconstruction of D_s decays: if ϕ + track can be fit to a common vertex, with mass < D_s mass + O(2x resolution), reject

Backgrounds: inclusive bb and cc events

Inclusive PYTHIA sample (signal events removed), passed through DELPHES

- 1 billion of bb events, 500 millions of cc events

Reconstruction:

- Identify “primary tracks”, and consequently, “secondary tracks”
- Build ϕ and K_S candidates (opposite-charge tracks, same hemisphere, fit to a common vertex, mass consistent with ϕ or K_S)
  - K_S candidates: restricted to L < 1.5 m from the IP
- Build $B_{(s)}$ candidates from pairs of ϕ and K_S (same hemisphere, vertex fit of ϕ tracks + K_S)

In a first step: assume perfect PID – i.e. use MC-truth information to demand:

ϕ legs = Kaons

K_S legs = Pions

Signal efficiency: ~ 58%

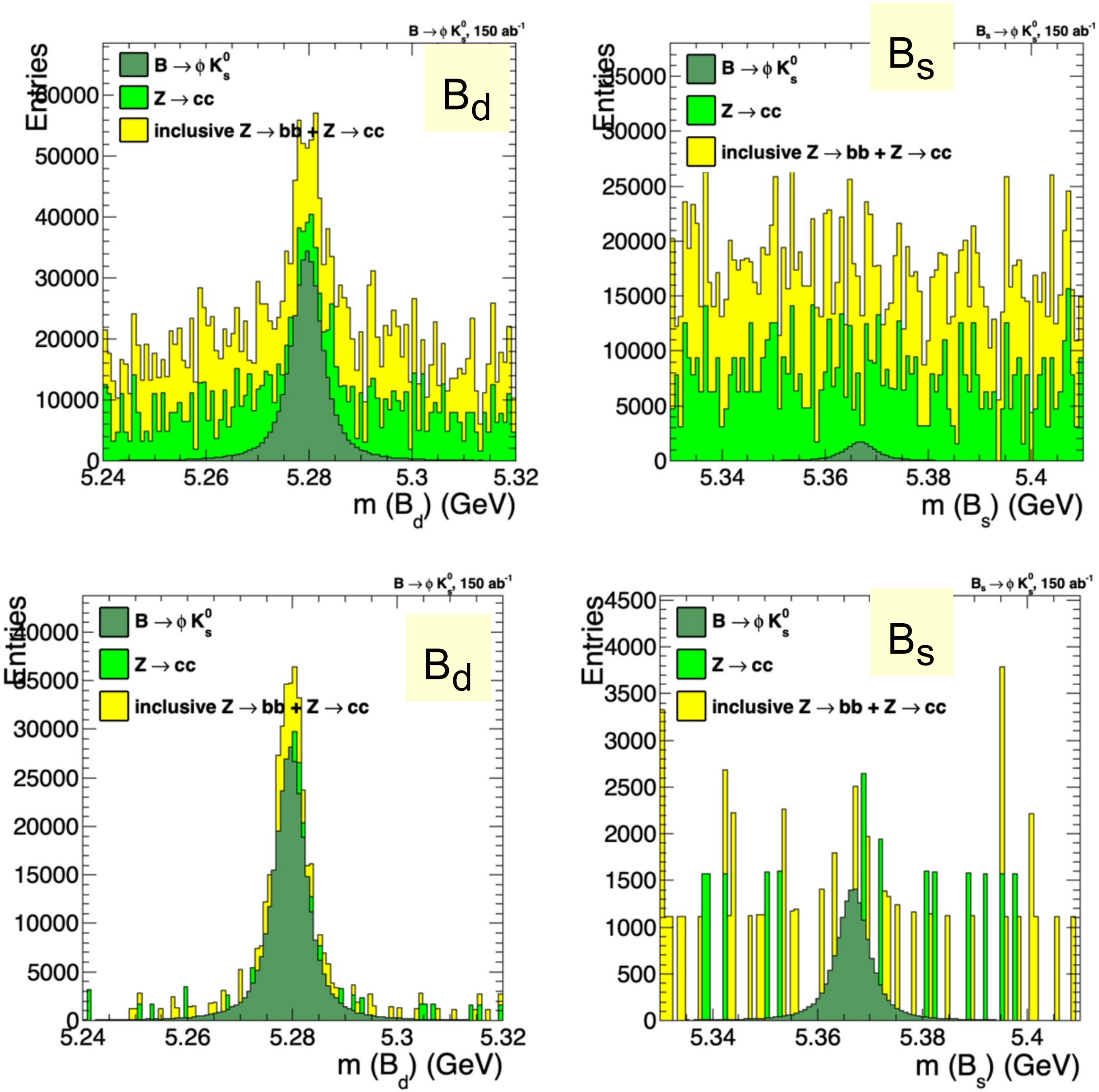
Main loss = acceptance for the K_S

Backgrounds: inclusive bb and cc events

Basic reconstruction :

Cuts against(semi-) exclusive processes:
- L(K_S) > 1 mm
- No reco'ed D_S

Remaining bckgd: mostly combinatorial

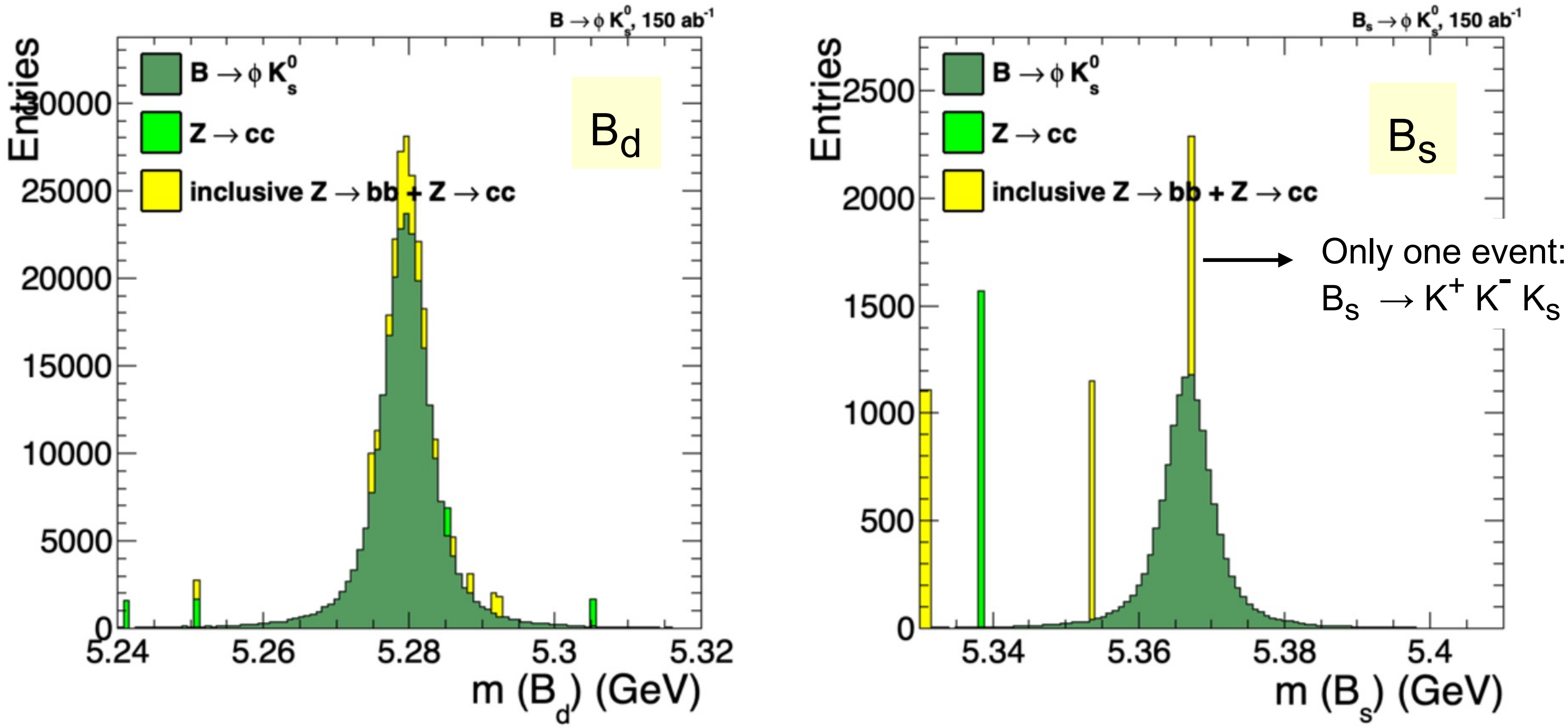


Final selection

Kinematic cuts to suppress combinatorial background:

- loose cuts on p(ϕ) and p(K_S) (> 1 GeV)
- p (B) > 10 GeV
- reco'ed energy in signal hemisphere (w/o B candidate) < 28 GeV

Final signal efficiency: ~ 40%

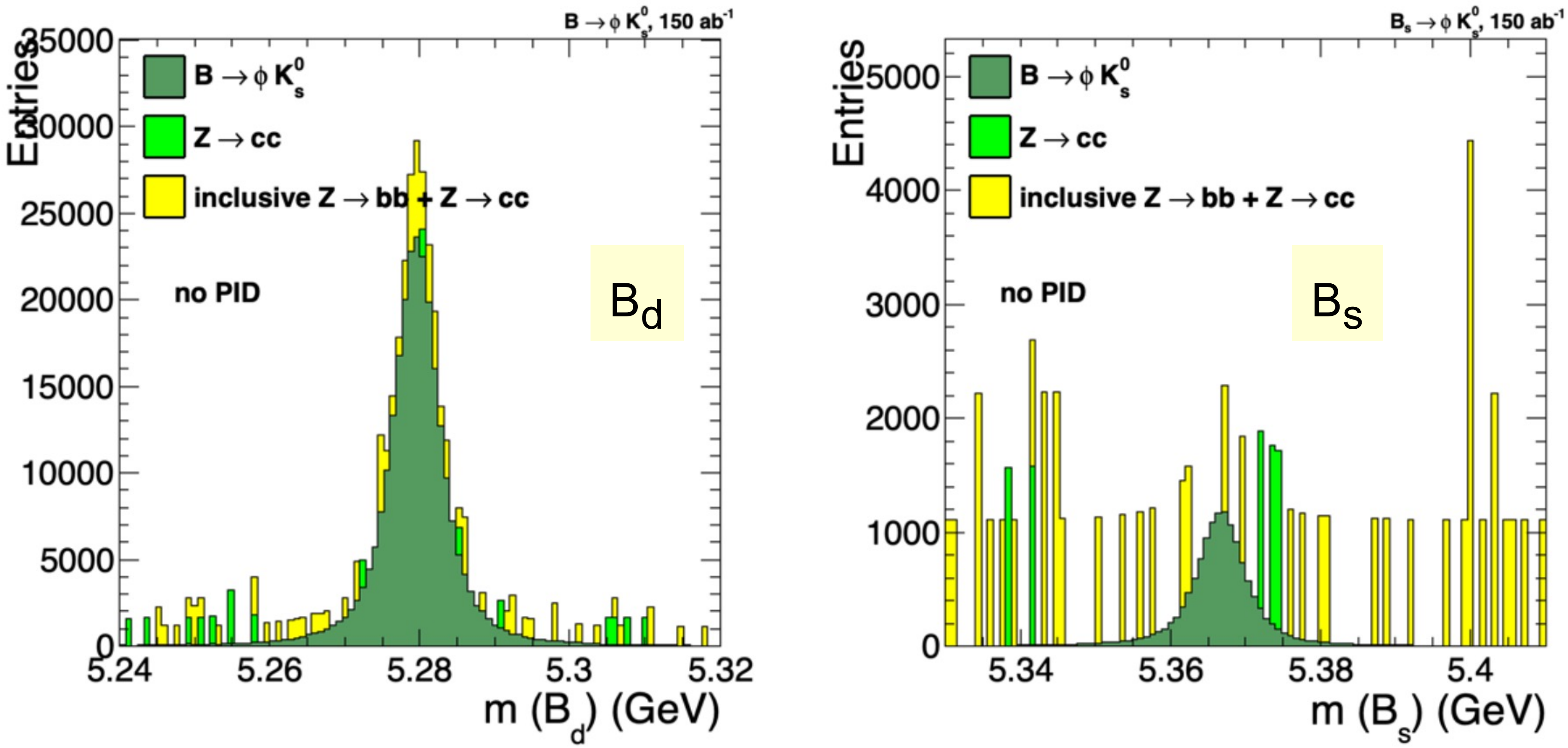


Low MC statistics for B_S ! Still, confidence that the background can be kept small.

Lower limit: S / B > 5 – 6 under the B_S peak.

Final selection (without any PID)

Perfect PID was assumed for the previous plots.
Assuming no PID requirement at all :

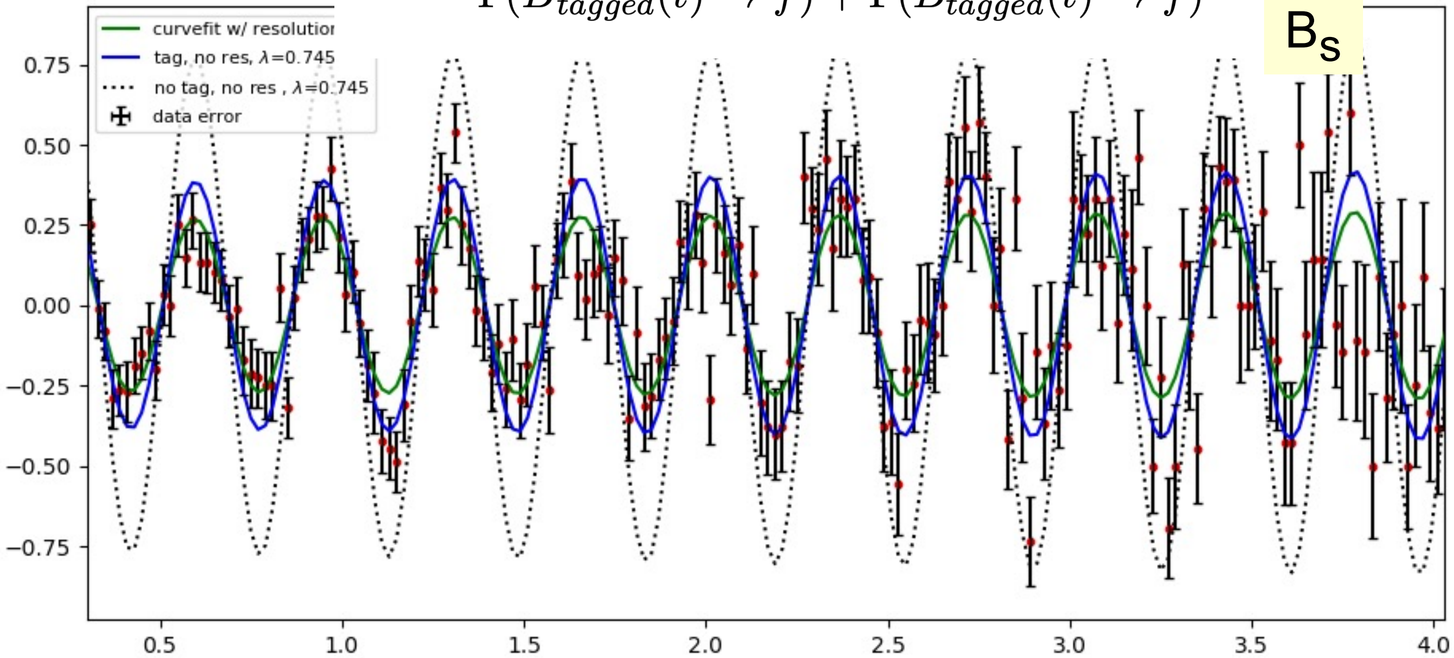


Not much effect for B_d. For B_s, PID is crucial – background would be as large as the signal without any PID.

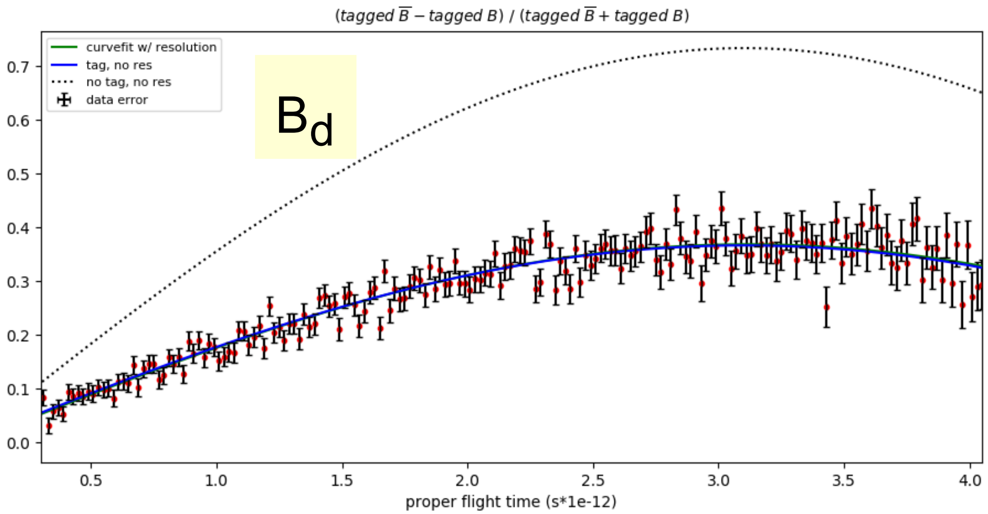
Expected sensitivity to CP parameters from ϕ K_s

$$\mathcal{A}s = \frac{\Gamma(\overline{B}_{tagged}(t) \to f) - \Gamma(B_{tagged}(t) \to f)}{\Gamma(\overline{B}_{tagged}(t) \to f) + \Gamma(B_{tagged}(t) \to f)}$$

- 150 ab^{-1}
- Number of signal decays: BRs given earlier + efficiency O(40%)
- Mistag rate ω = 0.25
- Neglect bckgd



Proper time (ps)



---- ω = 0, perfect vertex

ω = 0.25, perfect vertex

ω = 0.25, vertex resolution

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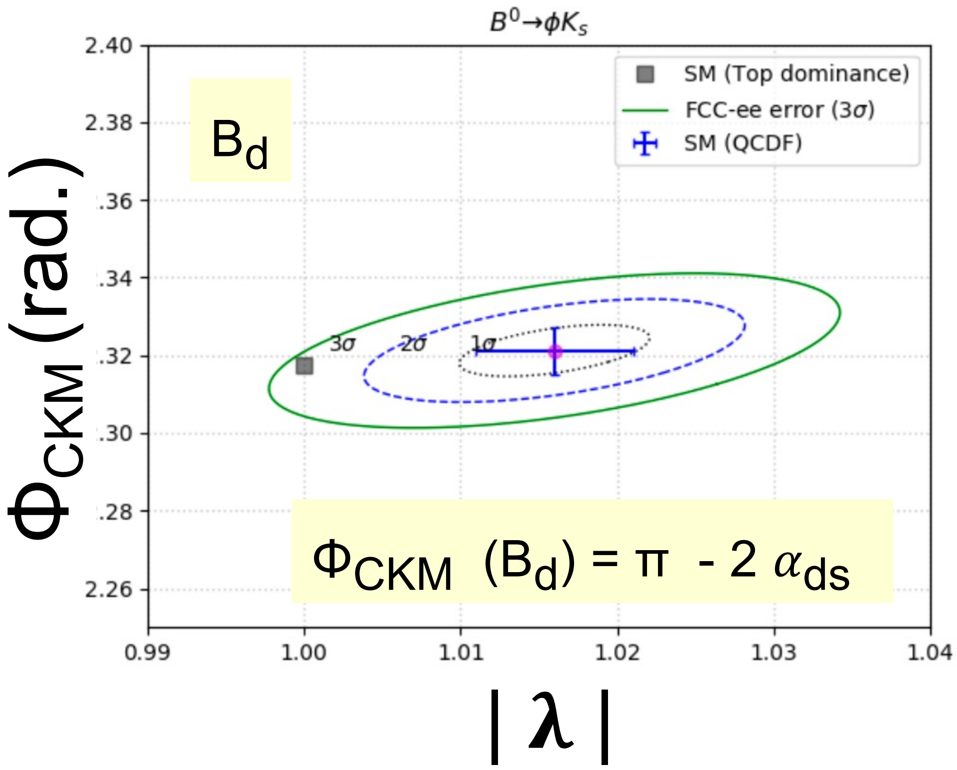
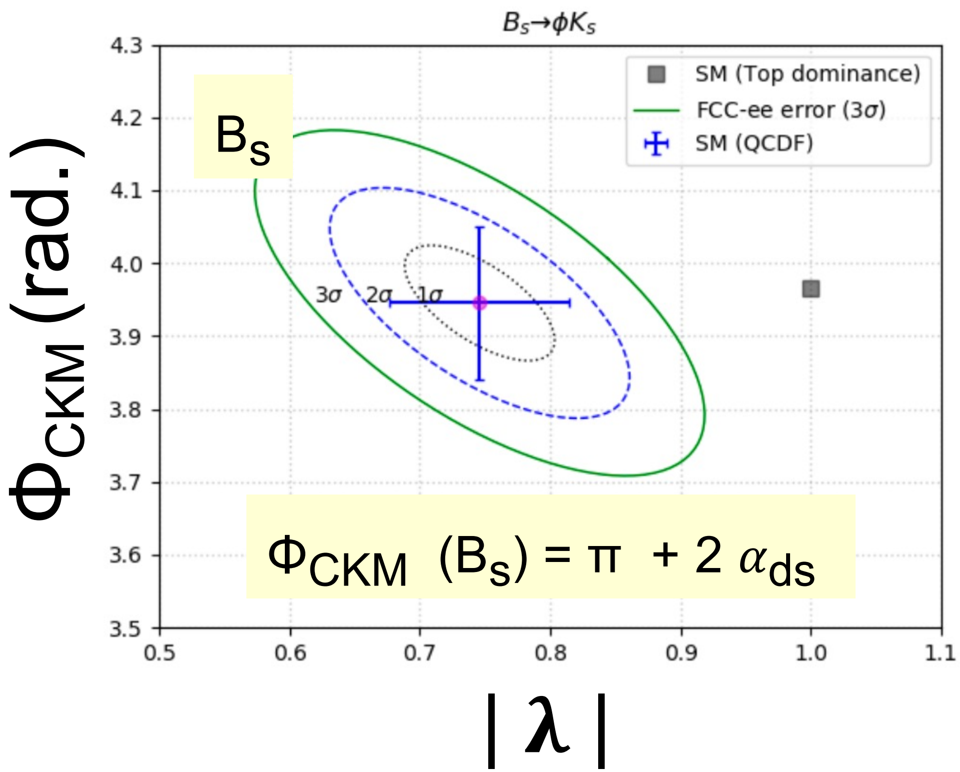
Expected sensitivity to CP parameters from ϕ K_s

Combined fit of Φ_{CKM} and $|\lambda|$ ($|\lambda| \neq 1$ quantifies direct CPV) and Φ_{CKM}





- 4 mrad on α_{ds} from B_d
- 10x better sensitivity with B_d than with B_s

Addition of ϕ K* (K* $\rightarrow$ K_S π^0) decays

Efficiency for ϕ K* : assumes x2 lower than ϕ K_S to account for π^0

B $\rightarrow$ VV decay : CP asymmetries are diluted if one does not separate the different polarisations of the vector mesons

ϕ K_S

Decay	$\sigma(\|\lambda_L\|)$	$\sigma(\alpha_{ds})$
$\overline{B}_d \rightarrow \phi \overline{K}^0$	0.005	0.004
$\overline{B}_s \rightarrow \phi K^0$	0.039	0.045

ϕ K* (no amplitude analysis)

Decay	$\sigma(\lambda_L)$	$\sigma(\alpha_{ds})$
$\overline{B}_d \rightarrow \phi \overline{K}^{*0}$	0.012	0.022
$\overline{B}_s \rightarrow \phi K^{*0}$	0.07	0.14

Amplitude analysis can improve the sensitivity by O(2)

NB: An excellent ECAL resolution is mandatory (e.g. 3% / $\sqrt{E}$) for B_S to ϕ K*, otherwise the B_S signal is polluted by the B_d

Conclusions

- The angle α_{ds} of the "flattest" unitarity angle can be measured at FCC-ee via $B_{(s)}$ to ϕ K_S and $B_{(s)}$ to ϕ K*
- Very interesting sensitivities expected !
  - α_{ds} to 4 mrad
- Importance of :
  - A good reconstruction of K_S decays up to large flight distance
    - Hence a large tracking volume
  - Excellent mass and vertex resolutions
    - Light tracker and highly performant vertex detector
  - PID crucial for the B_S
  - Mode with K* demands in addition a powerful π^0 reconstruction and, for the B_S, an excellent ECAL resolution
- Precise determination of the background for the B_S would require 10 – 100x more Monte-Carlo statistics !
- Write-up is well advanced

Backup

Oscillation formulae including direct CPV

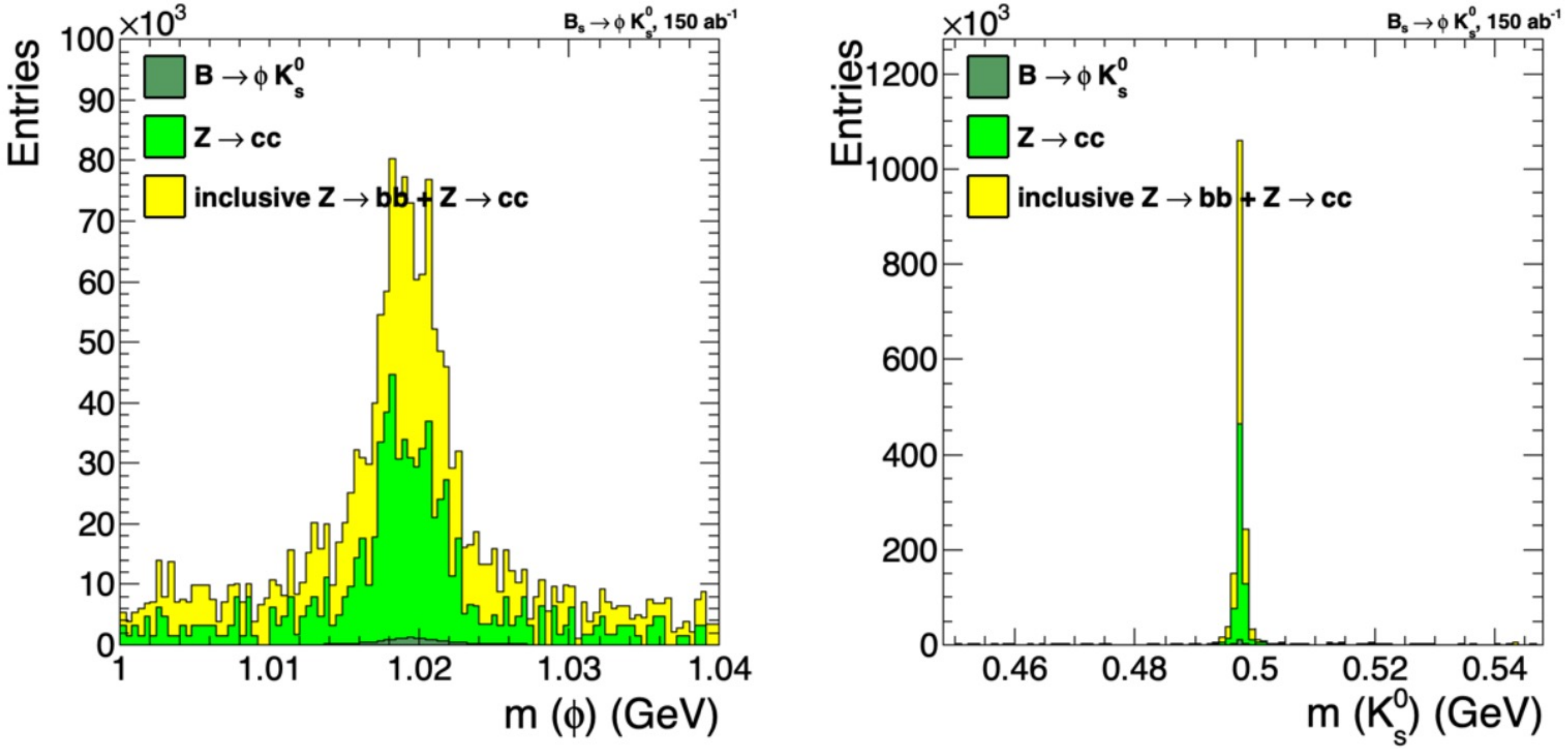
$$\Gamma(\overline{B}_q(t) \to f) = N_{q,f}|A_{q,f}|^2 \left[\frac{1+\rho_q^2}{2}\right] e^{-\Gamma_q t} \times$$
$$\left[\cosh\frac{\Delta\Gamma_q t}{2} - A_{CP}^{dir}\cos(\Delta m_q t) + A_{\Delta\Gamma_q}\sinh\frac{\Delta\Gamma_q t}{2} - A_{CP}^{mix}\sin(\Delta m_q t)\right] \quad (11)$$
$$\Gamma(B_q(t) \to f) = N_{q,f}|A_{q,f}|^2 \left[\frac{1+\rho_q^2}{2}\right] e^{-\Gamma_q t} \times$$
$$\left[\cosh\frac{\Delta\Gamma_q t}{2} + A_{CP}^{dir}\cos(\Delta m_q t) + A_{\Delta\Gamma_q}\sinh\frac{\Delta\Gamma_q t}{2} + A_{CP}^{mix}\sin(\Delta m_q t)\right]$$

with

$$A_{CP}^{dir} = \frac{1-\rho_q^2}{1+\rho_q^2} \quad , \quad A_{\Delta\Gamma_q} = -\frac{2Re\lambda_{q,f}}{1+\rho_q^2} \quad , \quad A_{CP}^{mix} = -\frac{2Im\lambda_{q,f}}{1+\rho_q^2} \quad (12)$$

$$\Gamma(\overline{B}_{tagged}(t) \to f) = (1-\omega)\Gamma(\overline{B}_q(t) \to f) + \omega\Gamma(B_q(t) \to f)$$
$$\Gamma(B_{tagged}(t) \to f) = (1-\omega)\Gamma(B_q(t) \to f) + \omega\Gamma(\overline{B}_q(t) \to f)$$

Mass of Phi and Ks candidates, basic reconstruction



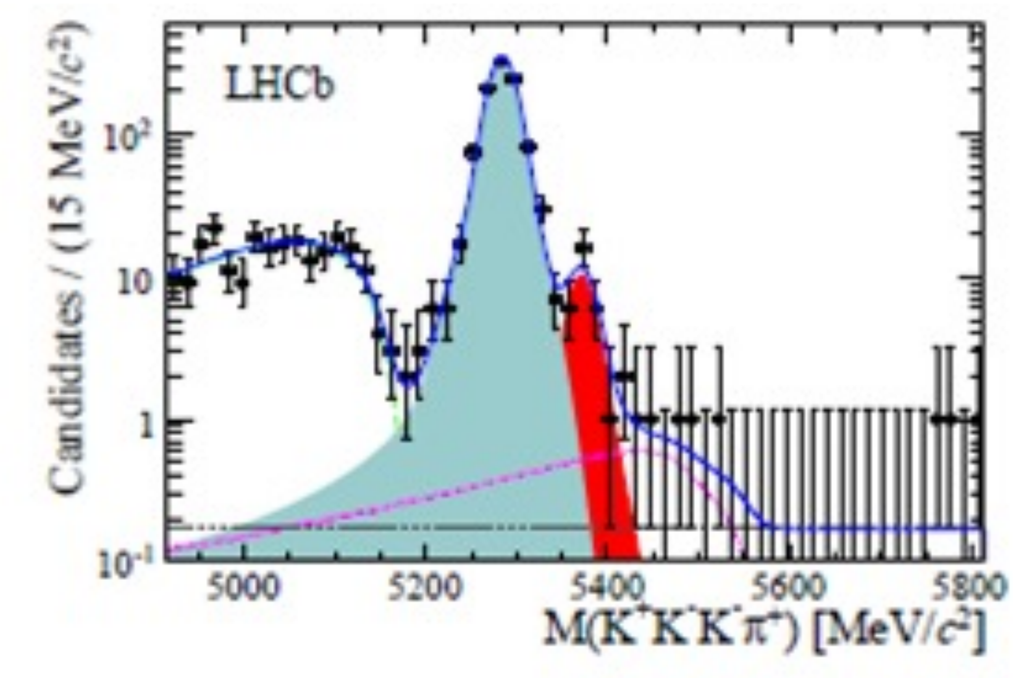
Full list of selection cuts

K_s leg:	$448 < m < 548$ MeV Vertex chi2 < 10 flight distance > 1 mm and < 1.5 m $p > 1.5$ GeV
ϕ leg:	$1.01 < m < 1.03$ GeV Vertex chi2 < 10 $p > 1$ GeV
perfect charged hadron PID for the K_s and ϕ tracks	
$B_{d,s}$ candidate:	the four tracks belong to the same hemishpere vertex $\chi^2 < 7.5$ $5.24 < m < 5.32$ GeV for B_d $5.33 < m < 5.41$ GeV for B_s $p > 10$ GeV
Energy in signal hemisphere: (without the B candidate)	below 28 GeV
no reconstructed $D_s^{\pm} \to \phi + \text{track} + X$ in signal hemisphere.	

Prospects before FCC ?

BELLE: with 50ab-1, 14x less B/Bbar than FCC with 150 ab-1.
With same efficiencies, uncertainty = 3.7 x larger than FCC

LHCb: hard to tell, have not reco'ed phi Ks
(have reco'ed phi K* with K* -> K+ pi-)



Yield of 1000 B0 and 30 Bs for 1 fb^-1.

Also, flavour tagging more difficult…