Study of $B \to \eta' K_L$ at Belle II

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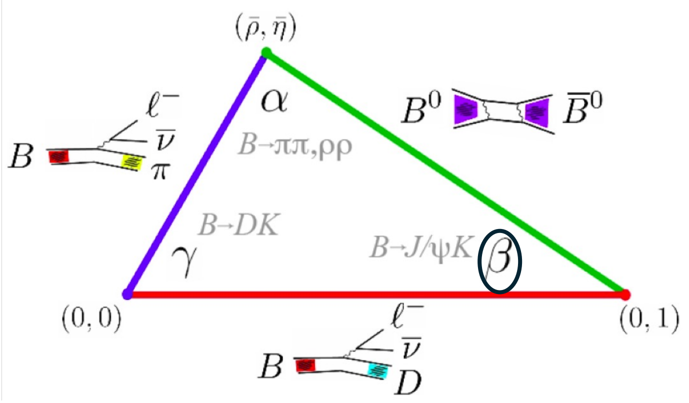
Outline

- Datasets used for the analysis, selection strategy.
- ΔE fit to extract signal yields.
- ΔT fit for TDCPV parameters calculation.

Datasets for the analysis and selection strategy

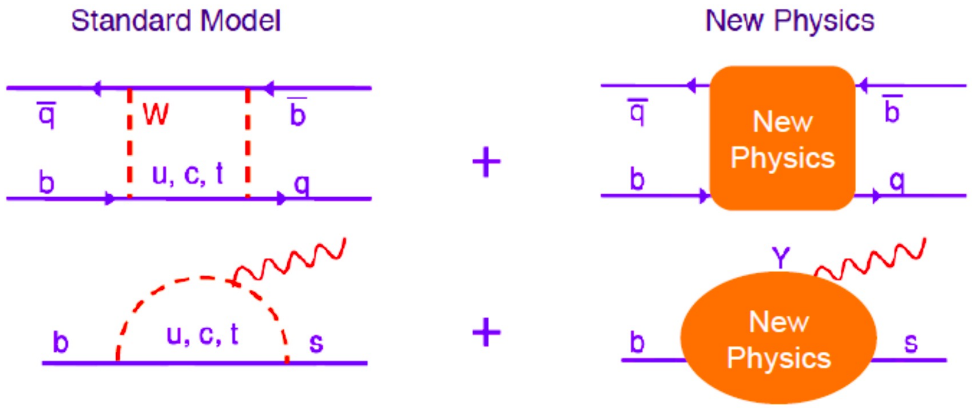
Theoretical aspects



- This decay channel can be useful for the evaluation of the Unitary Triangle angle β (sensitive to mixing).

- It is linked to the study of the Time-Dependent *CP* Violation of B mesons. Inconsistencies with predictions can be justified New Physics Effects.

$$\mathcal{A}_{CP}(\Delta t) = \frac{\Gamma(\bar{B}^0 \to \eta' K_L) - \Gamma(B^0 \to \eta' K_L)}{\Gamma(\bar{B}^0 \to \eta' K_L) + \Gamma(B^0 \to \eta' K_L)} = S_{\eta' K_L} \sin \Delta m_d \Delta t - C_{\eta' K_L} \cos \Delta m_d \Delta t$$



Datasets of the analysis method with MC

To tune the analysis we have used about 2 million events of MC16rd signal samples.

For signal we have reconstructed three separate decay chains:

- $B \rightarrow \eta' K_L$ with $\eta' \rightarrow \eta\, \pi^+\pi^-$ and $\eta \rightarrow \gamma\gamma$ $(BR = 5.6 * 10^{-6})$. ;
- $B \rightarrow \eta' K_L$ with $\eta' \rightarrow \eta\, \pi^+\pi^-$ and $\eta \rightarrow \pi^+\pi^-\pi^0$ $(BR = 3.2 * 10^{-6})$;
- $B \rightarrow \eta' K_L$ with $\eta' \rightarrow \rho^0\gamma$ $(BR = 9.7 * 10^{-6})$.

Analysis is then performed on generic $b\bar{b}$ and continuum $udsc\tau$ in MC simulation, with a full on peak luminosity of $492\ x\ 4\ fb^{-1}$.

η' first reconstruction cuts

For $B \rightarrow \eta' K_L$ with $\eta' \rightarrow \eta \pi^+ \pi^-$ and $\eta \rightarrow \gamma\gamma$:

- 2 pions with binaryPID(π/K)≥ 0.05;
- 2 photons with 60 MeV < E_γ < 6 GeV, >1 ECLhit, E9E21> 0.9 , |clusterTiming| < 600 ns, |clusterTiming/clusterErrorTiming|<2.0;
- 0.50 GeV < $M_{\gamma\gamma}$ < 0.6 GeV ; fit $\eta \pi^+ \pi^-$ vertex with M_η constraint and require 0.94 < $M_{\eta'}$ < 0.98 GeV.

- For $B \rightarrow \eta' K_L$ with $\eta' \rightarrow \eta \pi^+ \pi^-$ and $\eta \rightarrow \pi^+ \pi^- \pi^0$:
  - 4 pions with binaryPID(π/K)≥ 0.05;
  - π^0 from eff40_May2020 list, with 0.12 GeV < M_π < 0.145 GeV, 2 photons with [clusterNHits>1.5] and thetaInCDCAcceptance and [[clusterReg==1 and E>0.080] or [clusterReg==2 and E>0.030] or [clusterReg==3 and E>0.060]];
  - 0.52 GeV < $M_{\gamma\gamma}$ < 0.57 GeV ; fit $\eta \pi^+ \pi^-$ vertex with M_η constraint and require 0.39 < massDifference($\eta' - \eta$) < 0.43 and 0.95 < $M_{\eta'}$ < 0.965 GeV.

- For $B \rightarrow \eta' K_L$ with $\eta' \rightarrow \rho^0 \gamma$
  - 2 pions with binaryPID(π/K)≥ 0.05;
  - A photon with 150 MeV < E_γ < 6 GeV, > 1 ECLhit, E9E21 > 0.9 , |clusterTiming| < 600 ns, |clusterTiming/clusterErrorTiming|<2.0;
  - 0.47 GeV < M_{ρ^0} < 1.07 GeV ; 0.9 < $M_{\eta'}$ < 1.0 GeV, after vertex fit (no mass requirements).

K_L selection

Neutral clusters in each event are associated to an η' candidate to create a B meson if it survives these selctions:

- one cluster in **ECL** with **E > 0.15 GeV (E > 0.25 GeV and PulseShapeDiscriminationMVA <= 0.15 for $\eta_{\pi\pi\pi}$ and $\rho\gamma$**, applied at skim level**);**

- one **KLM** cluster with **1 ≤ Nlayers ≤ 10 and 1 <= InnermostLayer ≤ 10 (KLID >= 0.1 for $\eta_{\pi\pi\pi}$ and $\rho\gamma$**, applied at skim level**);**

- In some events, there are K_L candidates that leave clusters in **BOTH** calorimeters, we create this new category of candidates if clusters are separated by less than 0.35 rad.

Analysis selections strategy for decay channels

- We have used a Bayesian optimization on selections for background suppression, kinematic cuts are treated simultaneously, while the detector specific variables and each subdecay channel are treated independently.

- For Continuum suppression from $udsc\tau$ sample, a BDT based on XGBoost has been developed: for Signal we use MC Signal, while for background we use MC off-resonance. Each subdecay and category of KL is trained and tested independently.

Final selections on datasets

- csbdt > 0.96, 0.95 < etap_M_bf < 0.97, 0.51< eta_M_bf < 0.57, min_gamma_E > 0.07,

  eclbdt_ECL > 0.4, K_L0_clusterPulseShapeDiscriminationMVA_ECL < 0.7,

  K_L0_klmClusterKlId_KLM > 0.1, K_L0_klmClusterLayers_KLM >= 2,

  K_L0_clusterE_BOTH < 2.0, K_L0_clusterPulseShapeDiscriminationMVA_BOTH < 0.9;

- csbdt > 0.94, 0.953 < etap_M_bf < 0.962, 0.525 < eta_M_bf < 0.565, pi0_p > 0.15,

  eclbdt_ECL > 0.6,

  K_L0_klmClusterLayers_KLM >= 2,

  K_L0_clusterE_BOTH < 2.2;

- csbdt > 0.98, 0.945 < etap_M_bf < 0.965, 0.63 < rho0_M_bf < 0.89, gamma_E > 0.36, gamma_clusterPulseShapeDiscriminationMVA > 0.1,

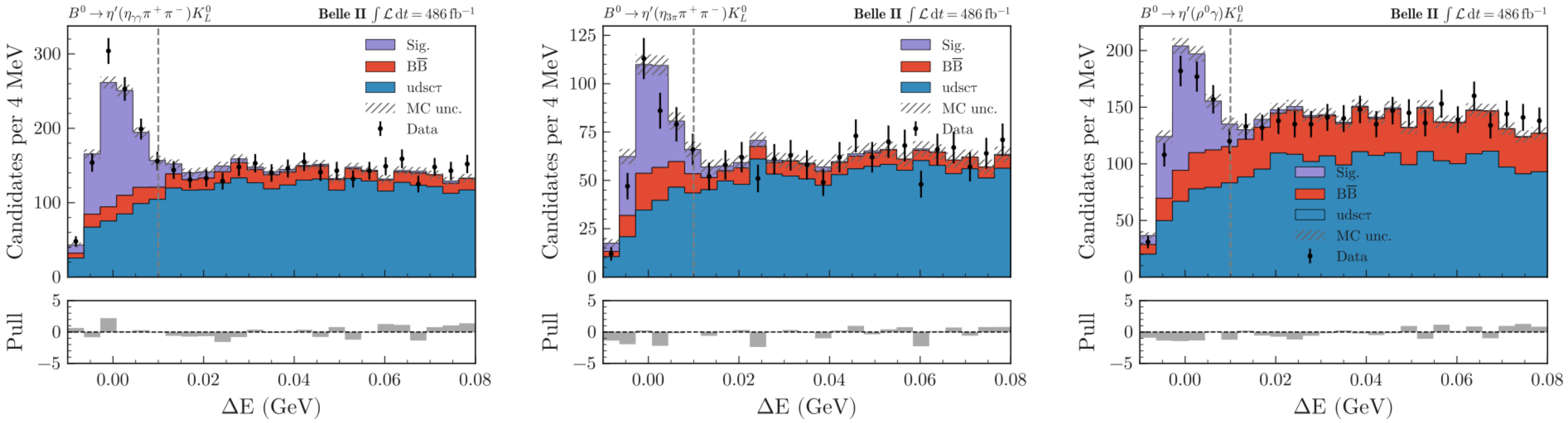
  eclbdt_ECL > 0.8,

  K_L0_klmClusterLayers_KLM >= 2,

  K_L0_clusterE_BOTH > 0.3, K_L0_clusterE_BOTH < 2.5;

Final ΔE distributions

- Yield after "cut and count" in MonteCarlo simulation. The reference yields are calculated in the signal region $\Delta E \in [-0.01, 0.01] GeV$, using the cuts $|\Delta T| < 10$ ps and $0.001 < |\Delta T_{err}| < 2.5$ ps.



channel	$\eta_{\gamma\gamma}$	$\eta_{\pi\pi\pi}$	$\rho\gamma$
# events	488	169	309

ΔE fit

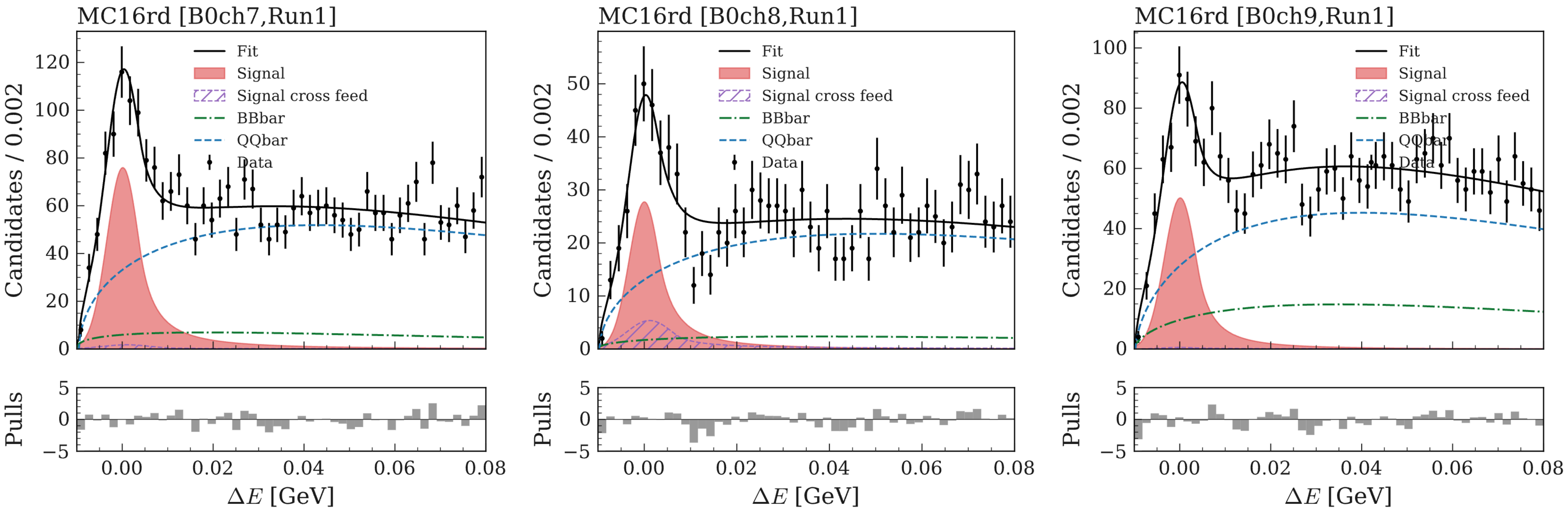
ΔE fit strategy

- Fitting all components independently, MC Signal, SxF, background from generic $b\bar{b}$ and $udsc\tau$, for all 3 deacy modes: the fit for the Signal component is done on a dataset ~10 times larger than the events in the generic MC, while for the SxF we use all the available dataset, and for the two other backgrounds we use all the available datasets (x4 the data luminosity);

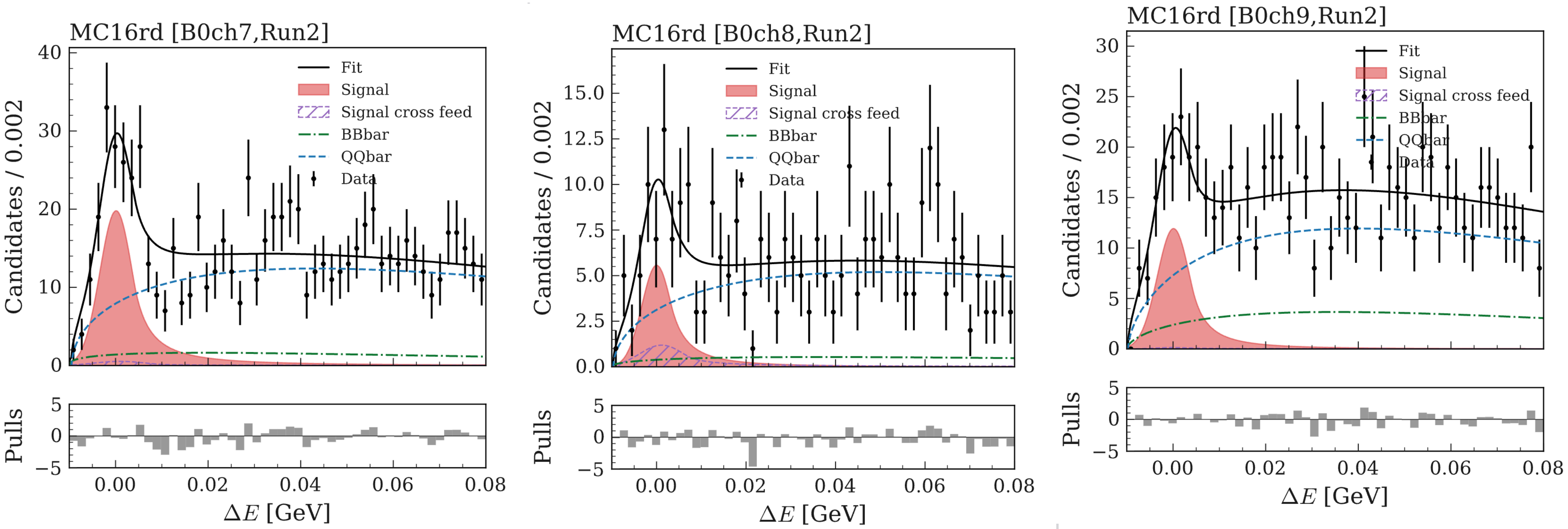
- Fixing all the pdfs shapes, Crystal Ball for Signal and SxF and Inverse argus for backgrounds, and leaving yields floating (SxF and $b\bar{b}$ are fixed from simulation), we extract the signal yields from a fit which includes all components.

- We also treat PXD on and PXD off running periods independently.

ΔE fit (PXD/on)


MC16rd [B0ch7,Run1]
MC16rd [B0ch8,Run1]
MC16rd [B0ch9,Run1]
Fit
Signal
Signal cross feed
BBbar
QQbar
Data
Candidates / 0.002
Pulls
ΔE [GeV]
0.00
0.02
0.04
0.06
0.08

ΔE fit (PXD/off)



Yields in Signal Region

PXD/on	B0ch7	B0ch8	B0ch9
Yield	392$\pm$28	138$\pm$15	256$\pm$25
Significance	13.8	7.7	10.1

PXD/off	B0ch7	B0ch8	B0ch9
Yield	103$\pm$14	28$\pm$7	61$\pm$13
Significance	7.2	3.3	4.8

ΔT fit

ΔT fit strategy

- The ΔT fit is performed on the candidates in the signal region, in 7 bins of the flavour tagging variable |qr|, qrs = [0,0.1,0.25,0.45,0.6,0.725,0.875,1]. The fit will be preliminarily done shape by shape and channel by channel, to be then unified into a combined fit.

- The Signal and SxF are modelled on a convolution between a resolution pdf (based on the lifetime fit of the B meson) and a mistagging probability: all parameters describing these two pdfs are fixed on control samples (respectively $J/\Psi K^*$ and $D^*\pi$). For $b\bar{b}$ we use the sole resolution function to fit the lifetime, while for $udsc\tau$ background we use only the resolution function (no lifetime fit).

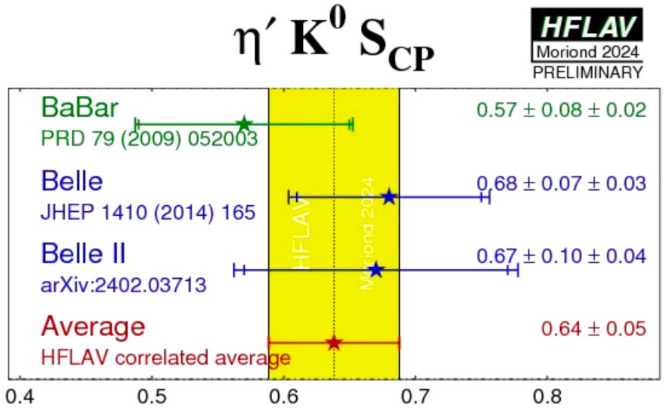
- The aim of the fit is to calculate the TDCPV parameters of this decay, which theoretically amount to S=0.7 and C=0

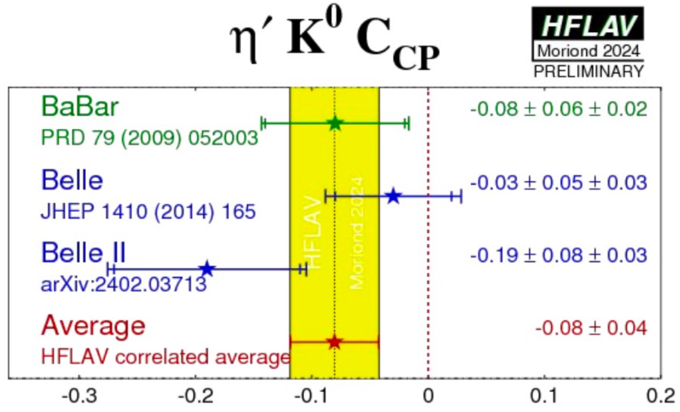
ΔT fit Status

- We are still trying to estimate any possible bias on Signal, SxF and $b\bar{b}$ components by doing an untagged lifetime fit to these components.

- After all of this is done, we will fix the shapes of all of the components and extract the fitted values of S and C in a simultaneous fit across all channels, including channels with a different CP eigenvalue.

Current Status for $\eta' K^0$ TDCPV Parameters





- BelleII 387M $B\bar{B}$

$$C_{\eta' K_S^0} = -0.19 \pm 0.08 \pm 0.03,$$
$$S_{\eta' K_S^0} = +0.67 \pm 0.10 \pm 0.03,$$

- ● Belle 772M $B\bar{B}$

$$\sin 2\phi_1^{\rm eff} = +0.68 \pm 0.07 \pm 0.03,$$
$$-C_{\eta' K} \equiv \mathcal{A}_{\eta' K^0} = +0.03 \pm 0.05 \pm 0.04,$$

- ● BaBar 467M BB

$$S_{\eta' K^0} = 0.57 \pm 0.08 \pm 0.02$$
$$C_{\eta' K^0} = -0.08 \pm 0.06 \pm 0.02$$

$\eta' K_L$ needs to be included

Current analysis and foreseen results

- Discussed in the TDCPV WG. The TDCPV group decided to operate with all collected statistics (run1 + run2) and including new subchannels ($\eta' K_L, \eta'_{\pi\pi\pi} K_S(\pi^+\pi^-), \eta' K_S(\pi^0\pi^0)$).

Scenario:	Total Yield	σ(S)	σ(C)
Current Run1 analysis	884	0.10	0.08
Repeat run1 analysis w/ better eff and new FT (386 $NB\bar{B}$)	1178	0.08	0.06
Add also all additional subchannels as Belle/BaBar (386 $NB\bar{B}$)	1908	0.06	0.05
Include also 2024a/b ($426+53_{noPXD}$ $NB\bar{B}$)	2360	0.054	0.044
Include projected lumi for 2024c w/o PXD ($426+216_{noPXD}$ $NB\bar{B}$)	2904	0.051	0.041
→ Belle lumi with only 2024b/c w/o PXD ($556+216_{noPXD}$ $NB\bar{B}$)	3800	0.044	0.035
HFLAV		**0.05**	**0.04**
Belle (772 $NB\bar{B}$)		**0.07**	**0.05**
BaBar (467M $B\bar{B}$)		**0.08**	**0.06**