$B^0 \to \eta' K_L$ Update

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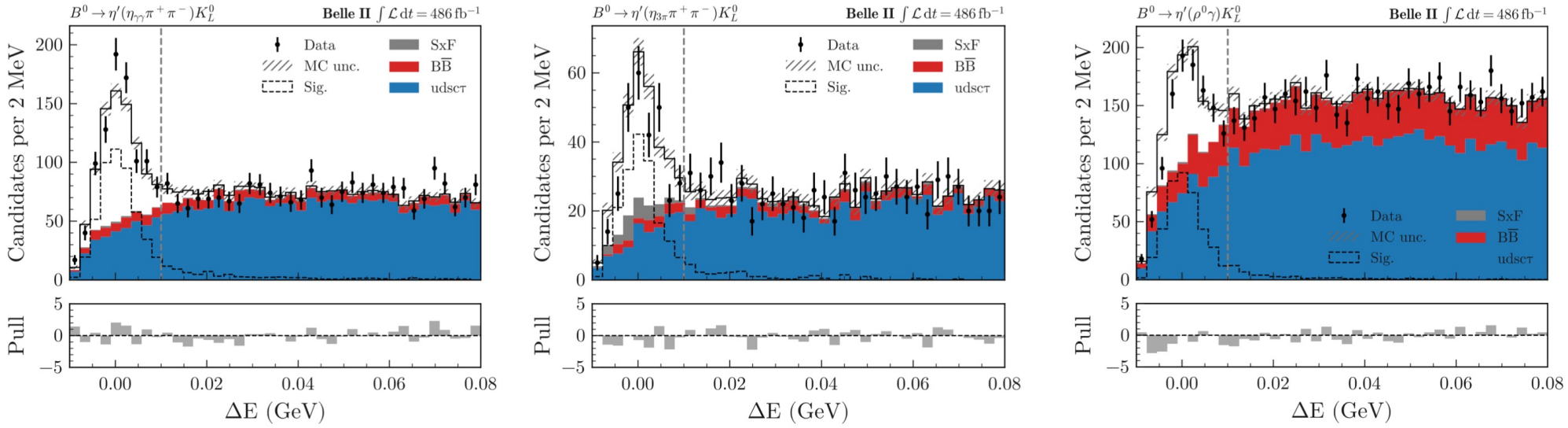
Motivation

- Penguin-dominated $b \to q\bar{q}s$ charmless decay
- Compare CP asymmetries with $B^0 \to \psi K^0$ to probe non-SM physics
  - $S_{\eta' K^0} - \sin 2\phi_1$ expected to be 0.01 ± 0.01 [Phys. Lett. B 620, 143 (2005)]
- Neutrals in the final state, including K_L^0: well-suited for Belle II
- Run 1 Belle II result published in Dec. 2024 [PRD 110 112002 (2024)]
- Improvements:
  - Add $\eta' \to \eta_{3\pi}\pi^+\pi^-$, $K_S^0 \to \pi^0\pi^0$, and K_L^0 modes
  - GNN flavor tagger
  - Prompt Run 2 data ~ 130/fb
  - Expect 3.5 times more signal candidates than in Run 1

Mode	Experiment	$\sin(2\beta^{eff}) \equiv \sin(2\phi_1^{eff})$	C_{CP}
$\eta' K^0$	BaBar N(BB)=467M	$0.57 \pm 0.08 \pm 0.02$	$-0.08 \pm 0.06 \pm 0.02$
	Belle N(BB)=772M	$0.68 \pm 0.07 \pm 0.03$	$-0.03 \pm 0.05 \pm 0.03$
	Belle II N(BB)=387M	$0.67 \pm 0.10 \pm 0.03$	$-0.19 \pm 0.08 \pm 0.03$
	Average	0.64 ± 0.05	-0.08 ± 0.04

Selections

- Standard cuts to final state charged pions and photons (loose).
- K_L: tdcpv skims, cuts on KLID variables and cluster shape both in ECL and KLM.
- Bayesian optimisation to select cuts on all variables (intermediate resonances masses, Continuum Suppression BDT, etc.) in order to maximise significance in signal region |ΔE| <= 0.01.

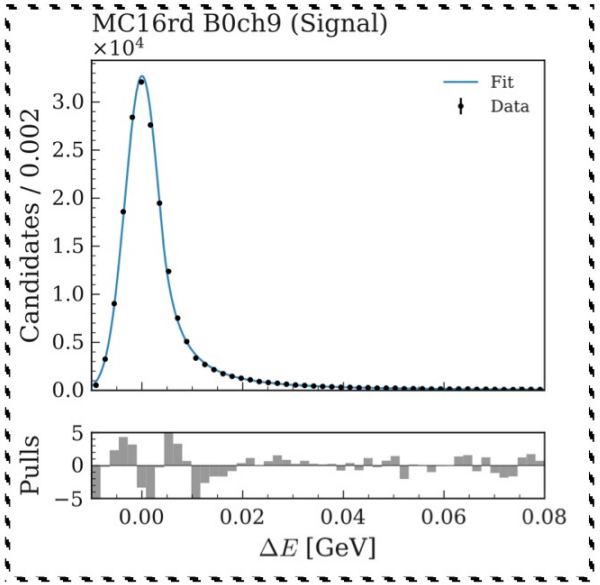


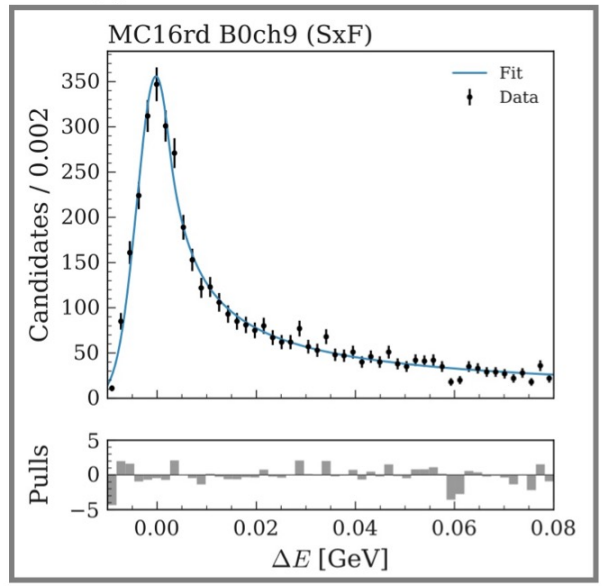
	$B^0 \to \eta'(\to \eta_{\gamma\gamma}\pi^+\pi^-)K_L^0$	$B^0 \to \eta'(\to \eta_{3\pi}\pi^+\pi^-)K_L^0$	$B^0 \to \eta'(\to \rho^0\gamma)K_L^0$
Signal	569 (490)	199 (174)	452 (399)
SxF	14 (7)	41 (29)	12 (7)
$B\overline{B}$	277 (61)	96 (19)	1372 (215)
$q\overline{q}$	2317 (328)	761 (108)	4220 (597)
$S/\sqrt{S+B}$	16.45	9.57	11.44

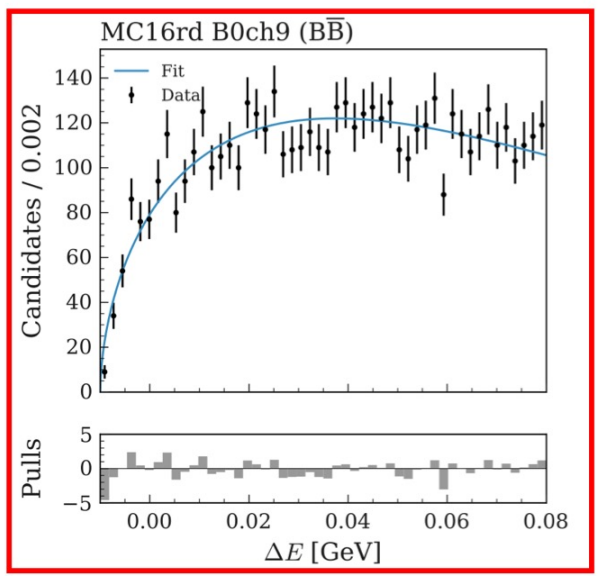
ΔE shapes for K_L^0 modes

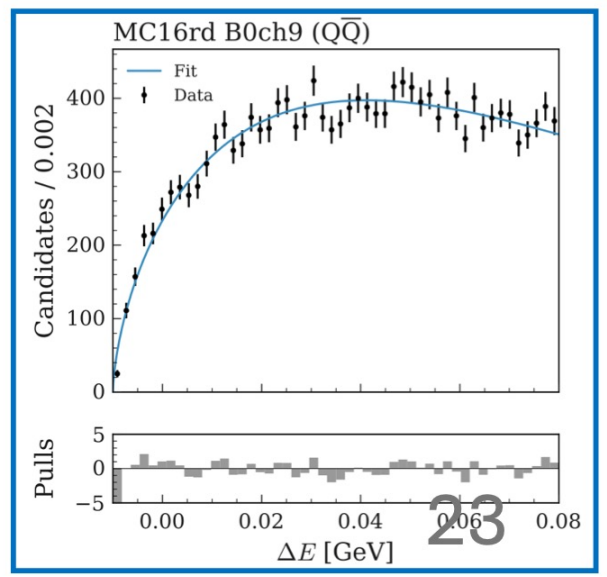
- **Signal**: double-sided Crystal Ball
  - Floating mean and width shared across channels
  - Independent tail parameters for all channels fixed from MC
- **SxF**: double-sided Crystal Ball
  - Independent parameters for all channels fixed from MC
- **$B\bar{B}$ background**: inverse Argus
  - Independent parameters for all channels fixed from MC
- **$q\bar{q}$ background**: inverse Argus
  - Independent parameters for all channels
  - Fix endpoint and power parameters
  - Float shape parameters

B0ch9: $B^0 \to \eta'_{\rho\gamma} K_L^0$









ΔT shapes for KL

SxF correction

$B^0 \to \eta'_{\eta(\gamma\gamma)\pi^+\pi^-} K_L^0$

$B^0 \to \eta'_{\eta(3\pi)\pi^+\pi^-} K_L^0$

$B^0 \to \eta'_{\rho\gamma} K_L^0$

Channel	Run	C_{CP} shift	S_{CP} shift
B0ch7	1	-0.009 ± 0.027	0.115 ± 0.040
B0ch7	2	-0.017 ± 0.057	0.088 ± 0.092
B0ch8	1	0.023 ± 0.013	0.032 ± 0.018
B0ch8	2	-0.005 ± 0.027	0.110 ± 0.042
B0ch9	1	-0.010 ± 0.047	-0.107 ± 0.064
B0ch9	2	-0.087 ± 0.094	-0.078 ± 0.155

- Resolution function parameters are taken from the $B^0 \to J/\Psi K^*$ sample, while flavour tagging is taken form $B^0 \to D^{*-}\pi^+$.
- Signal is modelled with convolution of resolution+tagging, same for SxF, but we apply a correction due to mismodelling.
- Bbbar is modelled with an effective lifetime+effective CP parameters due to CPV decays that fall under the signal window.
- Qqbar is modelled with triple gaussian with ΔTerr conditioning.

Bbbar contamination

Channel	S_{CP}	C_{CP}	$f_{\eta' K_S}$	$f_{\eta' X}$	f_{rest}
$B^0 \to \eta'(\to \eta_{\gamma\gamma}\pi^+\pi^-)K_L^0$	0.163 ± 0.024	-0.038 ± 0.029	0.254	0.446	0.300
$B^0 \to \eta'(\to \eta_{3\pi}\pi^+\pi^-)K_L^0$	0.129 ± 0.034	-0.047 ± 0.037	0.184	0.345	0.471
$B^0 \to \eta'(\to \rho^0\gamma)K_L^0$	0.024 ± 0.005	-0.008 ± 0.007	0.036	0.100	0.865

$B^0 \to \eta' K^0$ framework

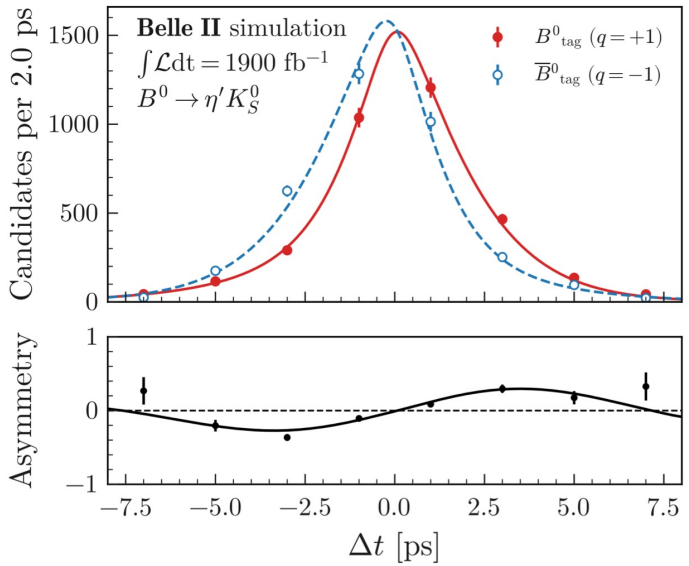
- Synergy with $\eta' K_S$ decays in order to merge the analyses and get a more precise result.

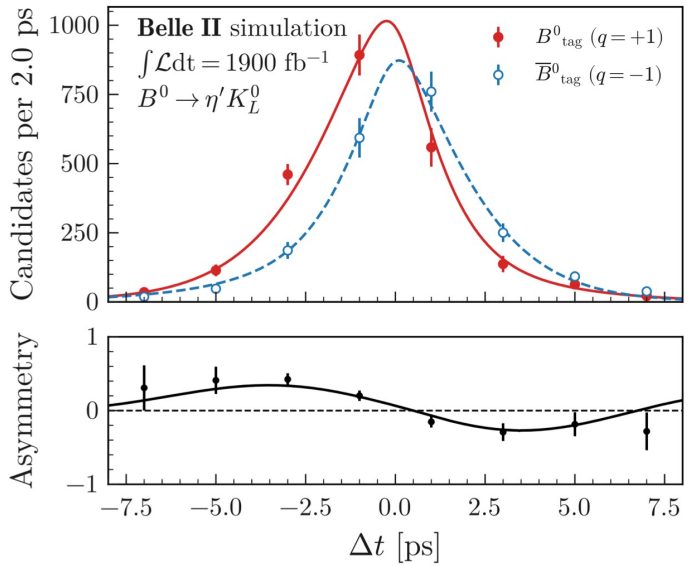
4 streams of generic MC

Channel	C_{CP}	S_{CP}
$B^0 \to \eta'(\to \eta_{\gamma\gamma}\pi^+\pi^-)K_S^0(\to \pi^+\pi^-)$	0.083 ± 0.050	0.584 ± 0.068
$B^0 \to \eta'(\to \eta_{3\pi}\pi^+\pi^-)K_S^0(\to \pi^+\pi^-)$	0.071 ± 0.075	0.661 ± 0.101
$B^0 \to \eta'(\to \rho^0\gamma)K_S^0(\to \pi^+\pi^-)$	0.018 ± 0.046	0.747 ± 0.058
$B^0 \to \eta' K_S^0(\to \pi^+\pi^-)$ combined	0.051 ± 0.031	0.675 ± 0.040

Channel	C_{CP}	S_{CP}
$B^0 \to \eta'(\to \eta_{\gamma\gamma}\pi^+\pi^-)K_S^0(\to \pi^0\pi^0)$	0.148 ± 0.112	0.486 ± 0.154
$B^0 \to \eta'(\to \rho^0\gamma)K_S^0(\to \pi^0\pi^0)$	-0.009 ± 0.121	0.631 ± 0.157
$B^0 \to \eta' K_S^0(\to \pi^0\pi^0)$ combined	0.076 ± 0.082	0.553 ± 0.110

Channel	C_{CP}	S_{CP}
$B^0 \to \eta'(\to \eta_{\gamma\gamma}\pi^+\pi^-)K_L^0$	0.010 ± 0.055	0.735 ± 0.081
$B^0 \to \eta'(\to \eta_{3\pi}\pi^+\pi^-)K_L^0$	-0.052 ± 0.080	0.582 ± 0.123
$B^0 \to \eta'(\to \rho^0\gamma)K_L^0$	-0.049 ± 0.055	0.787 ± 0.097
$B^0 \to \eta' K_L^0$ combined	-0.029 ± 0.035	0.718 ± 0.055





Summary of systematics

- Size of calibration and signal samples
- Parameters fixed from MC
- Analysis biases
- External inputs
- Shared parameters across K_S^0 and K_L^0 are correlated
  - Flavor tagging and resolution function parameters, etc.
- TSI (anti) correlated for S_{CP} (C_{CP})

Syst	Par	$K_S^0 \to \pi^+\pi^-$	$K_S^0 \to \pi^0\pi^0$	K_L^0	$B^0 \to \eta' K^0$
Flavor tagging	C_{CP}	0.007	0.007	0.007	0.007
	S_{CP}	0.003	0.003	0.003	0.003
Δt resolution	C_{CP}	0.005	0.005	0.004	0.004
	S_{CP}	0.008	0.008	0.026	0.010
Signal extraction fit	C_{CP}	0.003	0.030	0.007	0.004
	S_{CP}	0.006	0.045	0.009	0.006
$q\bar{q}$ bkg Δt shapes	C_{CP}	0.001	0.001	0.002	0.001
	S_{CP}	0.002	0.001	0.005	0.002
qr-bin fractions	C_{CP}	0.002	0.011	0.002	0.002
	S_{CP}	0.002	0.007	0.002	0.002
$B\overline{B}$ bkg yields	C_{CP}	0.001	0.001	0.001	0.001
	S_{CP}	0.012	0.011	0.008	0.007
Δt reso. fixed par.	C_{CP}	0.001	0.001	0.020	0.007
	S_{CP}	0.003	0.003	0.034	0.011
SE fixed parameters	C_{CP}	0.002	0.006	0.014	0.005
	S_{CP}	0.010	0.010	0.029	0.011
$B\overline{B}$ bkg Δt shapes	C_{CP}	0.004	0.005	0.002	0.002
	S_{CP}	0.003	0.007	0.004	0.002
SxF fraction and CP asymm.	C_{CP}	< 0.001	< 0.001	< 0.001	< 0.001
	S_{CP}	< 0.001	< 0.001	< 0.001	< 0.001
Fit bias	C_{CP}	0.003	0.008	0.002	0.005
	S_{CP}	0.009	0.012	0.018	0.013
Tag-side interference	C_{CP}	0.040	0.040	0.040	0.008
	S_{CP}	0.010	0.010	0.010	0.010
Physics parameters	C_{CP}	< 0.001	< 0.001	< 0.001	< 0.001
	S_{CP}	< 0.001	< 0.001	< 0.001	< 0.001
Total systematic	C_{CP}	0.041	0.053	0.048	0.015
	S_{CP}	0.024	0.052	0.057	0.027
Statistical	C_{CP}	0.062	0.147	0.080	0.046
	S_{CP}	0.080	0.206	0.106	0.061

TABLE 34. Systematic uncertainties on the separate channel categories and combined fit to all modes.

Conclusion

- The $\eta' K^0$ study entered WGR on 08/04/2026, we are starting to answer some of the questions of the reviewers.

- Currently working on control samples to cross check the analysis procedure and reducing some of the systematics by simplifying the analysis.

- Targeting ICHEP 2026 (hopefully CWR1 can start in a month).