LHCb Workshop on Radiative Decays Valencia

Measuring time-dependent *CP* asymmetry of $B^0 \to K_S^0 \pi^+ \pi^- \gamma$ decays at Belle and Belle II

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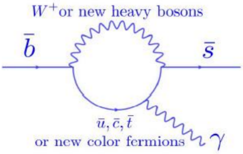
on behalf of the Belle/Belle II collaborations.

April 26, 2023

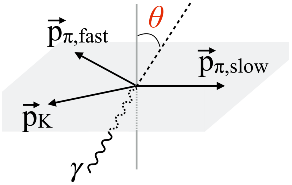
Introduction



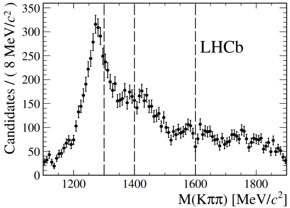
- The photon polarization of the quark-level process $b \to s\gamma$ is an excellent probe of new physics
- The polarization is predominantly left-handed in the Standard Model (SM), the right-handed being suppressed by a factor (m_s/m_b)
- However new physics contributions may modify this.
  - Atwood et al., PRL. 79, (1997) 185 [hep-ph/9704272]
  - E. Kou et al., JHEP 12 (2013) 102 [1305.3173]
  - N. Haba et al., JHEP 03 (2015) 160 [1501.00668]

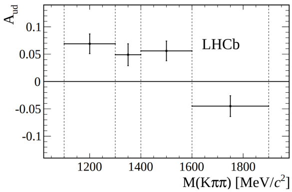
$$\mathcal{H}_{eff} \simeq -\frac{4G_F}{\sqrt{2}} V_{ts}^* V_{tb} \left[C_{7\gamma} \langle \mathcal{O}_{7\gamma} \rangle + C_{7\gamma}^{\prime(NP?)} \langle \mathcal{O}'_{7\gamma} \rangle \right]$$

Via an angular distribution of the photon ($B^{\pm} \to K^{\pm}\pi^{\pm}\pi^{\mp}\gamma$)



$$\mathcal{A}_{ud} \equiv \frac{\int_0^1 d\cos\theta \frac{d\Gamma}{d\cos\theta} - \int_{-1}^0 d\cos\theta \frac{d\Gamma}{d\cos\theta}}{\int_{-1}^1 d\cos\theta \frac{d\Gamma}{d\cos\theta}} \propto \lambda_\gamma$$





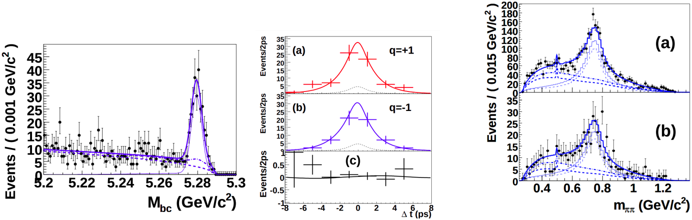
- LHCb reported a parity-violating photon polarization different from zero at 5.2σ significance for the mode $B^{\pm} \to K^{\pm}\pi^{\pm}\pi^{\mp}\gamma$ PRL 112, 161801 (2014) [1402.6852]

Via a time-dependent CP violation (TDCPV) measurement $(B \to K_S^0 \rho^0 \gamma)$

$$\mathcal{A}_{CP}(\Delta t) = \frac{\Gamma(B_{tag=B^0}(\Delta t)\to f_{CP}) - \Gamma(B_{tag=\bar{B}^0}(\Delta t)\to f_{CP})}{\Gamma(B_{tag=B^0}(\Delta t)\to f_{CP}) + \Gamma(B_{tag=\bar{B}^0}(\Delta t)\to f_{CP})} = S \sin(\Delta m \Delta t) + A \cos(\Delta m \Delta t)$$

- $A \simeq 0$ for the B^0 system, and
  $$S_{K_S^0\rho^0\gamma} = \frac{2\mathrm{Im}(\frac{q}{p} C_7 C_7')}{|C_7|^2 + |C_7'|^2}$$
- Measure $S_{B\to K_{res}\gamma \to K_S^0 \pi^+\pi^-\gamma}$ and obtain $S_{B\to K_{res}\gamma\to K_S^0\rho^0\gamma\to K_S^0\pi^+\pi^-\gamma}$ by separately estimating a dilution factor
  $$\mathcal{D} = \frac{S_{K_S^0\pi^+\pi^-\gamma}}{S_{K_S^0\rho^0\gamma}}$$

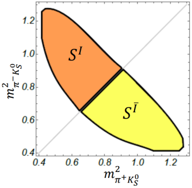
- **Previous measurements of S for this mode:**



- Belle PRL101 (2008): [0806.1980] $S_{K_S^0\rho^0\gamma} = 0.11 \pm 0.33^{+0.06}_{-0.05}$ (657×10^6 $B\bar{B}$)
- Babar PRD93 (2015): 1 [512.03579] $S_{K_S^0\rho^0\gamma} = -0.18 \pm 0.32^{+0.05}_{-0.09}$ (using full dataset : 471×10^6 $B\bar{B}$)

Proposed new observables

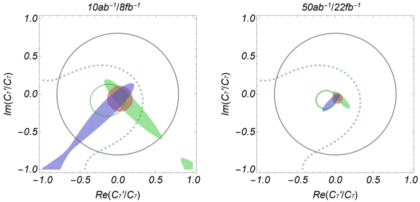
- Recent theoretical work proposes new observables by dividing the dataset in the Dalitz-plane. S. Akar et al., JHEP 09 (2019) 034 [1802.09433]



- New observables :

$$S^+_{K^0_S \pi^+\pi^-\gamma} = S^I + S^{\bar{I}},$$
$$S^-_{K^0_S \pi^+\pi^-\gamma} = S^I - S^{\bar{I}}$$

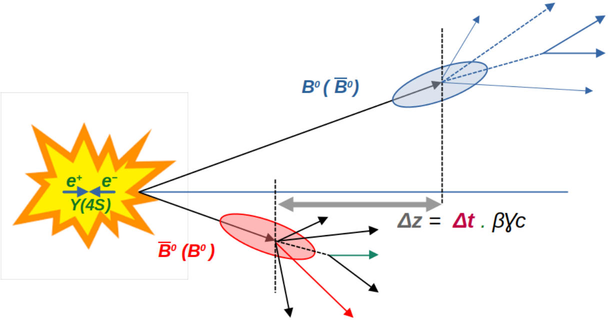
- S^+ and S^-, together with hadronic parameters, a^I and b^I, will constrain C_7'/C_7 in the complex plane.



$[S^+, S^-, a^I, b^I] =$ [0.17, 0.13, -0.5, -0.15] (blue), [0.13, 0.04, -0.3, -0.3] (red) and [0.13, -0.03, -0.15, -0.5] (green).

- We plan to do a measurement of S^+ and S^- with a combination of Belle and currently-available Belle II data.

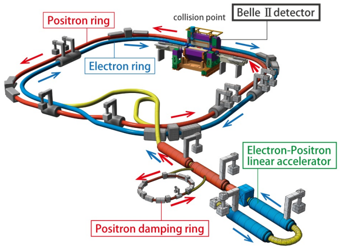
TDCPV via $e^+e^- \to \Upsilon(4S)$ at Belle/ Belle II

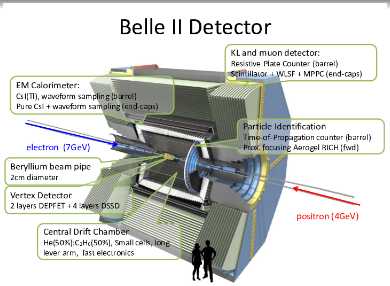


$$\mathcal{A}_{CP}(\Delta t) = S \sin(\Delta m \Delta t) + A \cos(\Delta m \Delta t)$$

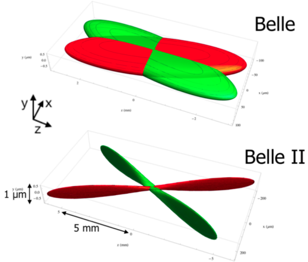
- The $\Upsilon(4S)$ meson ($b\bar{b}$-bound state) decays ~49% of the time to a $B^0 \bar{B}^0$ meson-pair.
- The $B^0 \bar{B}^0$ pair are produced in an quantum-entangled state, and remain so until one of them decays.
- $\Delta t \simeq \Delta z / \beta\gamma c$. For Belle II: $\beta\gamma = 0.29$, $\Delta z \sim 130\ \mu\text{m}$ (For Belle, it was $\beta\gamma = 0.43$, $\Delta z \sim 200\ \mu\text{m}$)

Belle II experiment, super-KEKB accelerator in Tsukuba, Japan

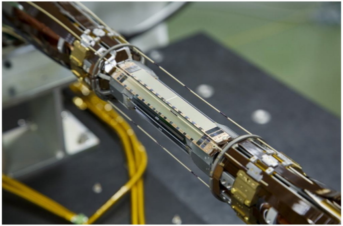


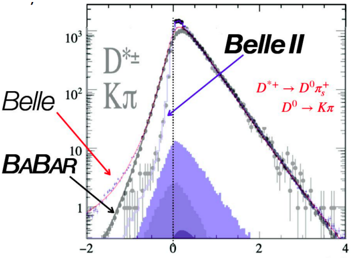


- Novel nano-beam collision scheme, new luminosity world record, $4.7 \times 10^{34} \mathrm{cm}^{-2}\mathrm{s}^{-1}$
- Asymmetric energy collider, allows for measurement of proper decay time difference between B-meson pair.
- Good geometric acceptance for final state particles(FSPs)
- Knowledge of collision energy-momentum very useful for analyses with invisible FSPs
- Ambitious plan to acquire 40 - $50 \mathrm{ab}^{-1}$ over the course of the experiment.



Belle II vertexing





[BELLE2-TALK-CONF-2020-046]

- New 6-layer vertex detector (2-inner layers pixel detectors (PXD) and 4 outer layers of silicon strip detectors(SVD). Belle had a 4-layer vertex detector.)
- Inner PXD layer at 1.4 cm from the interaction-point. Better Δt resolution
- Slew of charm-hadron lifetime measurements

  PRL 127, 211801 - Published 19 November 2021

  $\tau_{D^0} = 410.5 \pm 1.1(\text{stat}) \pm 0.8(\text{syst})$ fs (most precise)

  $\tau_{D^+} = 1030.4 \pm 4.7(\text{stat}) \pm 3.1(\text{syst})$ fs (most precise)

  PRL 130, 071802 - Published 16 February 2023

  $\tau_{\lambda_c^+} = 203.20 \pm 0.89(\text{stat}) \pm 0.77(\text{syst})$ fs (most precise)

  PRD 107, L031103 - Published 21 February 2023

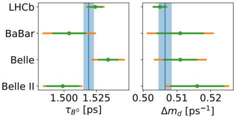
  $\tau_{\Omega_c^0} = 243 \pm 48(\text{stat}) \pm 11(\text{syst})$ fs

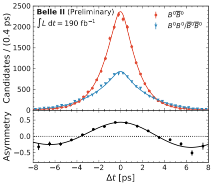
B-meson results

Oscillation frequency measurement: result

$$\tau_{B^0} = 1.499 \pm 0.013\,(\text{stat.}) \pm 0.008\,(\text{syst.})\ \text{ps}$$
$$\Delta m_d = 0.516 \pm 0.008\,(\text{stat.}) \pm 0.005\,(\text{syst.})\ \text{ps}^{-1}$$

Comparison with world average:





arxiv : [2302.12791]

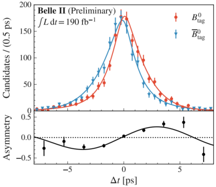
Measurement of the CKM angle β: result

First Belle II measurement of β:

$$\sin 2\beta = S_{CP} = 0.720 \pm 0.062(\text{stat}) \pm 0.016(\text{syst})$$
$$A_{CP} = 0.094 \pm 0.044(\text{stat})\,^{+0.042}_{-0.017}(\text{syst})$$

Corresponds to $\beta = (23.0 \pm 2.6(\text{stat}) \pm 0.7(\text{syst}))^\circ$

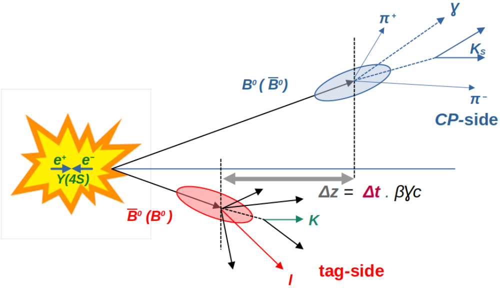
World average (PDG): $(21.9 \pm 0.7)^\circ$



arxiv : [2302.12898]

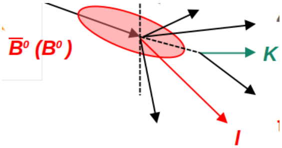
The analysis at hand : Event reconstruction

- Full 711fb^{-1} of Belle I $\Upsilon(4S)$ data and currently 360fb^{-1} of Belle II $\Upsilon(4S)$ data available for our study.
- Since we are still developing the Belle II part of the analysis, the following slides will only describe the Belle analysis.

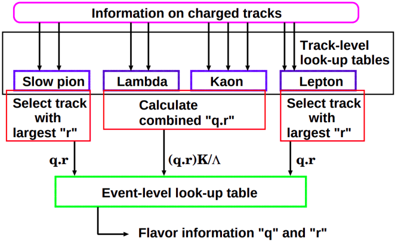


- After the CP-side B candidate is reconstructed and vertexed, the tracks from the rest of the event are vertexed for the tag-vertex.
- Both the CP and tag-side vertices are constrained so as to be consistent with the 2D interaction point profile in the transverse plane ('IP-tube' constraint).
- The flavour tagging algorithm is run on the rest of the event.

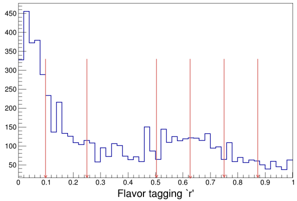
Flavour Tagging at Belle



The flavour tagger outputs a tag-flavour and a dilution-factor 'r'.
H. Kakuno, et. al.,
NIM A: Vol 533, Issue 3, 2004
[0403022]



$$\mathcal{P}(\Delta t, q = \pm 1) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}}\{1 - q\Delta w + q(1-2w)[S\sin(\Delta m\Delta t) + A\cos(\Delta m\Delta t)]\} \quad (1)$$



- Multi dimensional likelihood algorithm based on different flavor categories.
- **Effective tagging efficiency (Belle)** $Q = \varepsilon_{\mathrm{tag}}(1-2w)^2 = (30.1 \pm 0.4)\%$
- Wrong-tag fraction w goes from 0.5 (no power of prediction) to ~ 0.0 in the best case with full flavor prediction power.

Δt resolution function

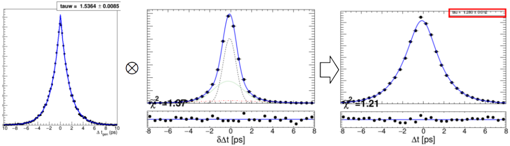
- In Δt, the signal p.d.f. can be written as

$$\mathcal{P}(\Delta t, q = \pm 1) = \frac{e^{-|\Delta t|/\tau_{B0}}}{4\tau_{B0}} \{1 - q\Delta w + q(1 - 2w)[S \sin(\Delta m \Delta t) + A \cos(\Delta m \Delta t)]\} \otimes R(\Delta t) \quad (2)$$

- Has 4 sub-components

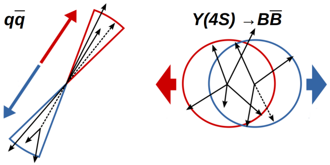
$$R(\Delta t) = R_{det}^{sig}(\Delta t) \otimes R_{det}^{tag}(\Delta t) \otimes R_{np}(\Delta t) \otimes R_k(\Delta t) \quad (3)$$

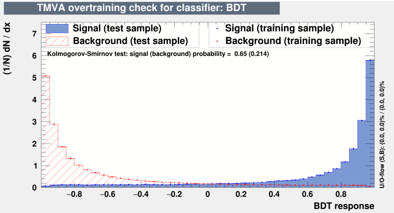
- Modeled as a per-event smearing-function of many conditional variables.
$R(\Delta t; cos\theta_B, E_{CMS}, N_{tracks}^{CP}, \sigma_Z^{CP}, \chi^{2,CP}, N.D.F.^{CP}, N_{tracks}^{tag}, \sigma_Z^{tag}, \chi^{2,tag}, N.D.F.^{tag})$



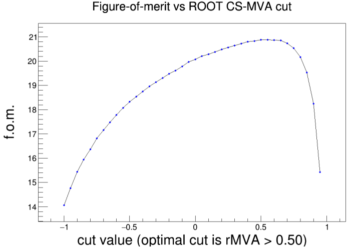
- This has already been calibrated for Belle in the 'tatami' Δt fit-framework.
H. Tajima, et. al., NIM A: Vol533, Issue 3, 2004 [0301026]
- For most analyses, the tag-side vertex resolution is dominant.

Continuum suppression





- **The dominant background comes from the non-resonant $e^+e^- \to q\bar{q}$ $q \in \{u, d, s, c\}$. Has a jet-like event topology as opposed to a more spherically symmetric topology of $\Upsilon(4S) \to B\bar{B}$ events**



- **We build a BDT-classifier based on event-shape variables that discriminate between continuum and resonant events using**
  - **Cosine of the thrust axes of the event,**
  - **Cosine of the B-momentum polar angle**
  - **Fox-Wolfram moments.**
    G. C. Fox and S. Wolfram, Phys. Rev. Lett. 41, 1581 (1978).

$$H_l = \sum_{i,j} \frac{|p_i||p_j|}{E^2_{event}} P_l(\cos\theta_{i,j}) \quad (4)$$

$\Longleftarrow$ **Optimize** $\dfrac{N_S}{\sqrt{N_S + N_B}}$

Event selection

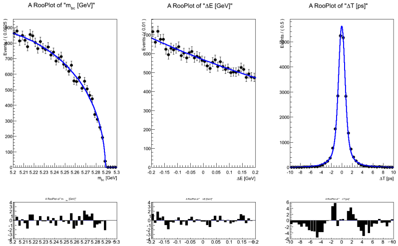
Summary of selection criteria

Selection	Remark
K_S^0-candidate	
Multivariate standard Belle K_S^0 selection	
Photon-candidate	
π^0-veto < 0.2, η-veto < 0.25'	To suppress photon pollution from $\pi^0 \to \gamma\gamma$ and $\eta \to \gamma\gamma$ decays
e9/e25(γ) > 0.95	Avoid merged π^0 ECL clusters
$\cos(\theta)_\gamma$ [-0.65 - 0.86]	To avoid pollution from low-energy
E_γ [1.5 - 3.5 GeV]	photons from beam background
$\pi^\pm$-candidate	
kaon-ID$(\pi+, \pi^-) < 0.25$	To avoid kaon pollution
electron-ID$(\pi+, \pi^-) < 0.25$	To avoid electron pollution
General	
Continuum MVA-classifier > 0.5	To suppress continuum events (optimized)
$M_{\pi+\pi-}$ [0.6 - 0.9 GeV]	To select ρ^0 resonance
$M_{K_S\pi\pi} < 1.8$ GeV	To choose appropriate K_{res} resonances
Vertex fits converged	For both, *CP* and
$\chi^2/N.D.F < 50$	tag-vertices

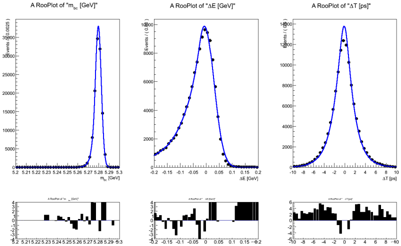
Single candidate selection: If there are multiple B_{CP} candidates, the one with the best *CP*-side vertex C.L. is chosen.

Fit strategy

- We do a 3-D fit of
  $M_{bc} = \sqrt{E_{beam}^{*2} - p_B^{*2}}$,
  $\Delta E = E_B^* - E_{beam}^*$
  and Δt ,
  in 7 flavour tagging r-bins .
- 5 fit components : signal, cross-feed, continuum-background, rare-MC background and $B\bar{B}$ background.
- 3D p.d.f.'s are modelled as the product of 1-D p.d.f.'s.
- The shape parameters in M_{bc} and ΔE are fixed for all the five fit components

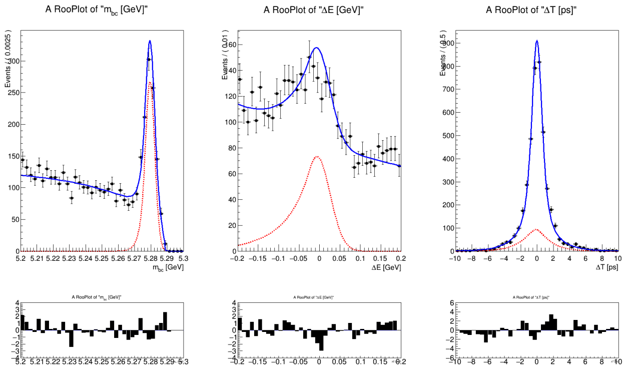


Continuum background:
M_{bc} : Argus
ΔE : Exponential



Signal :
M_{bc} : Crystal-ball
ΔE : Crystal-ball

Full-fit : Stat. uncertainty in MC

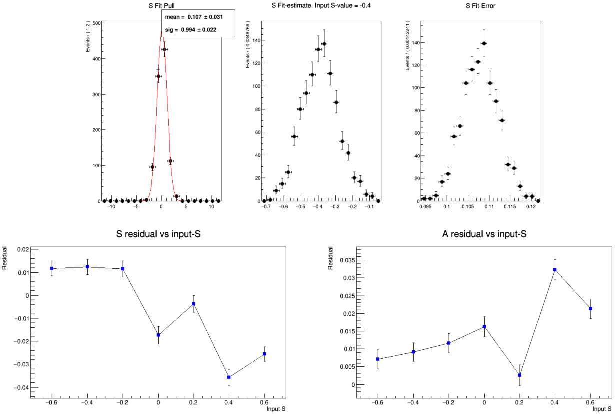


Full fit on an MC cocktail (1 equivalent Belle dataset) after selections and single-candidate selection.

- The relative yield-fraction of signal and cross-feed is fixed from MC. The same is done with the 3 background components using two relative fractions.
- Overall yields $N_{signal+C.F.}$ and $N_{3-component\ background}$ are floated along with S, A and one mean and one width fudge-factors for signal, each in M_{bc} and ΔE
- S and A are estimated with uncertainties, $\sigma_S \simeq 0.11$, $\sigma_A \simeq 0.08$

Linearity study with ensemble-fits

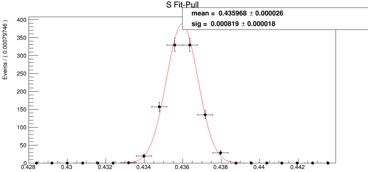
- We generate 1 million events with $A = 0$ and $S =$ [-0.6, -0.4, -0.2, 0.0, 0.2, 0.4, 0.6] using a minimal EvtGen *CP* model.
- We make 1000 bootstrapped datasets for each input value of S with signal and all background components in the correct proportions.
- Perform ensemble fits to study the relationship between input and estimated values of A and S



Where we stand

- Developed simultaneous fit in two Dalitz-plane halves ✓
- Currently estimating systematic uncertainties from various sources.

Source	σ_S^{syst}
1) Fixed parameters of ΔE, M_{bc} & background Δt	✓
2) Fixed parameters of Δt resolution function	
3) Physics parameters Δm and τ_B	
4) Flavor tagging parameters	
5) Fit bias	✓
6) IP-profile smearing and tag-vertex selections	
7) Vertex detector misalignment	
8) Tag-side interference	
CP-asymmetry in the $B\bar{B}$ background	



- Take one bootstrapped dataset corresponding to $S = 0.4$
- The fixed shape parameters are randomly varied about their uncertainties, (covariance matrices when fixing shapes from MC are preserved).
- Ensemble of 1000 fits to estimate systematic uncertainty.

Discussion item (?)

- Is LHCb more suited to measure the a^I and b^I or is this expected to be estimated by Belle?

$$\mathcal{S}^+ \equiv \mathcal{S}^I_{\pi^+\pi^-K^0_S\gamma} + \mathcal{S}^{\overline{I}}_{\pi^+\pi^-K^0_S\gamma} = \frac{8}{1+|\xi|^2}(\mathrm{Im}\xi\cos 2\beta - \mathrm{Re}\xi \sin 2\beta)\,\mathrm{a}^I,$$

$$\mathcal{S}^- \equiv \mathcal{S}^I_{\pi^+\pi^-K^0_S\gamma} - \mathcal{S}^{\overline{I}}_{\pi^+\pi^-K^0_S\gamma} = \frac{8}{1+|\xi|^2}(\mathrm{Re}\xi\cos 2\beta + \mathrm{Im}\xi \sin 2\beta)\,\mathrm{b}^I.$$

$$\frac{\xi}{1+|\xi|^2} = \frac{cc'}{|c|^2+|c'|^2},$$

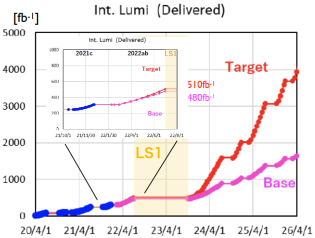
Similarly to Sec. 5.1, the hadronic parameters, a^I and b^I, need to be obtained from an amplitude analysis of $B^+ \to K^+_{\mathrm{res}}\gamma \to K^+\pi^-\pi^+\gamma$ decays. The partition scheme of the Dalitz plane must be optimised as a function of the amplitude content in the different regions and the available data sample. From the anti-symmetric relation shown in Eq. (27),

We emphasise that the measurement of the dilution factor $\mathcal{D}$, which does not require the study of *CP* asymmetries but only that of the intermediate resonance amplitudes, can be obtained independently, for instance from the LHCb experiment, benefiting from a larger data sample of $B^+ \to K^+\pi^-\pi^+\gamma$ decays comparing to the B factories.

Screenshots from : S. Akar et al., JHEP 09 (2019) 034 [1802.09433]

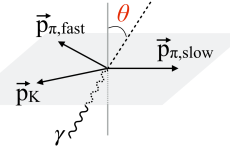
Thank you

Luminosity projections



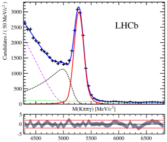
Beam-energy vs int. Luminosity recorded

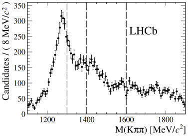
4S	364.436 +/- 0.020
4S_offres	42.329 +/- 0.007
4S_scan	0.078 +/- 0.000
5S_scan	19.662 +/- 0.004
All beam energies:	426.506 +/- 0.021

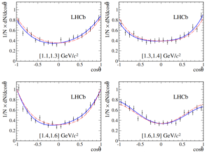


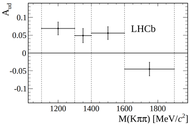
$$\frac{d\Gamma}{ds\,ds_{13}\,ds_{23}\,d\cos\theta} \propto \sum_{i=0,2,4} a(s, s_{13}, s_{23}) \cos^i\theta + \lambda_\gamma \sum_{j=1,3} a(s, s_{13}, s_{23}) \cos^j\theta \quad (5)$$

$$\mathcal{A}_{ud} \equiv \frac{\int_0^1 d\cos\theta \frac{d\Gamma}{d\cos\theta} - \int_{-1}^0 d\cos\theta \frac{d\Gamma}{d\cos\theta}}{\int_{-1}^1 d\cos\theta \frac{d\Gamma}{d\cos\theta}} \propto \lambda_\gamma \quad (6)$$



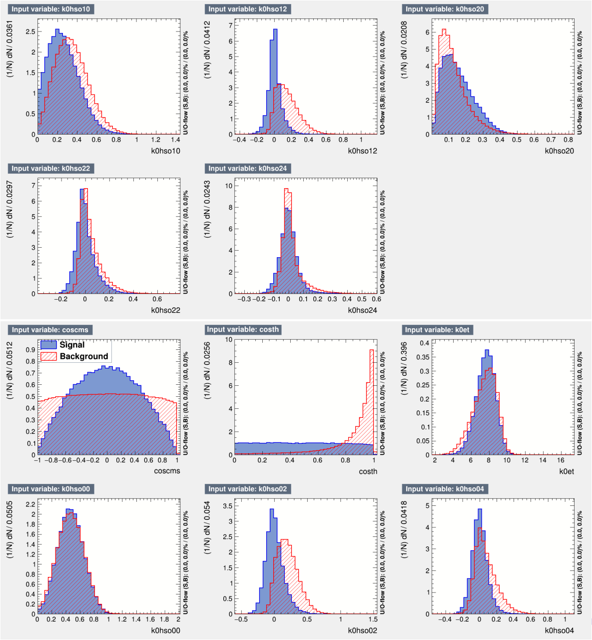




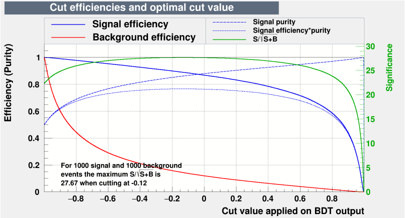


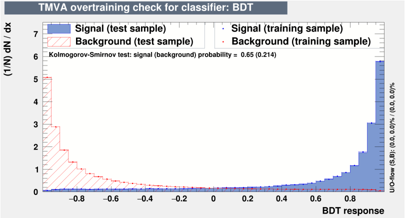
- LHCb reported a parity-violating photon polarization different from zero at 5.2σ significance for the mode $B^\pm \to K^\pm\pi^\pm\pi^\mp\gamma$ PRL 112, 161801 (2014) [1402.6852]

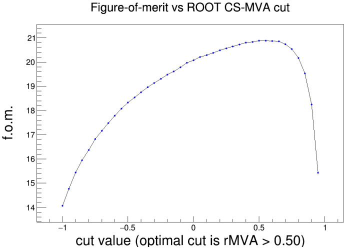
Backup : continuum suppression variables

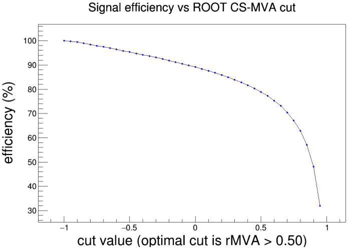


Backup : continuum suppression optimization









Each veto pairs candidate photon (high-energy) with other low-energy photons in the event and calculates the maximum likelihood of it having come from an η or π^0

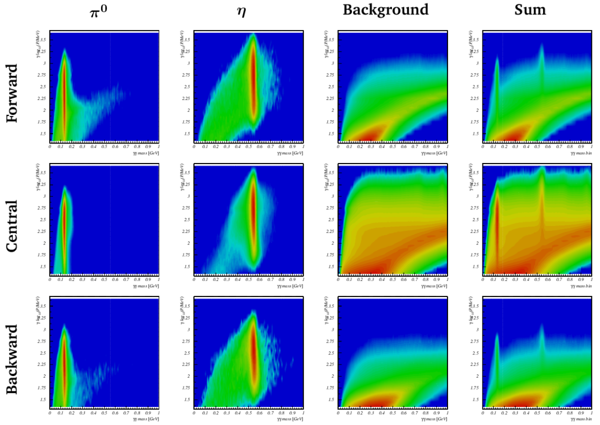
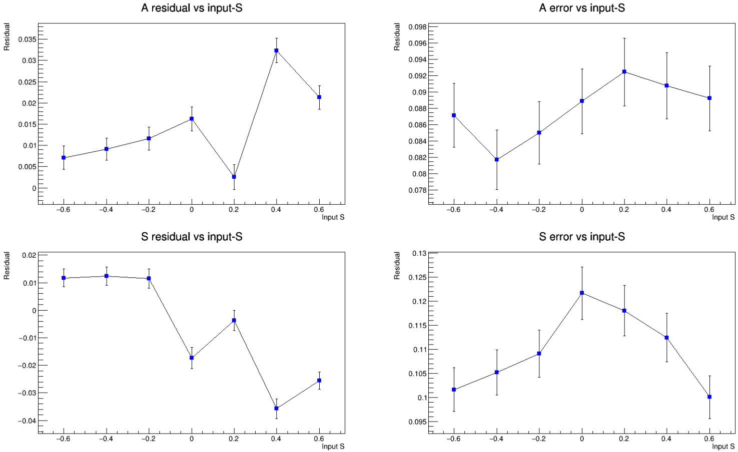
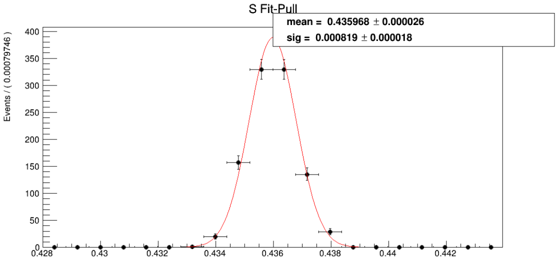


Figure 2: *From left to right, MC probability densities in the* $\log_{10}(E_{\gamma_2}/\mathrm{MeV})$ *versus* $m_{\gamma_1\gamma_2}$ *plane for true* π^0, η, *random combinations and the sum, for three calorimeter zones.*

Backup : Behaviour of A and S residuals

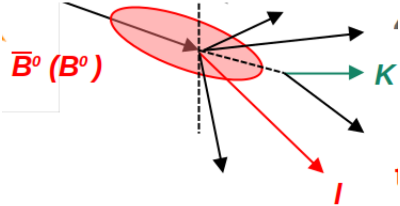


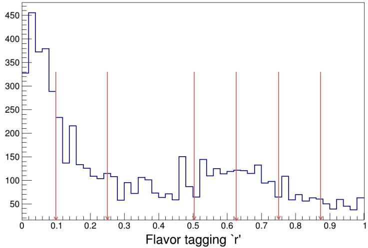
- Some bias observed in the mean of S pull distribution means. S seems to be overestimated on average by a factor $\sim 14\%$
- The source of this bias is not yet known. Could live with it, by assigning an appropriate correction and associated systematic error(?).



- The fixed shape parameters are randomly varied about their uncertainties, (covariance matrices when fixing shapes from MC are preserved).
- Ensemble of 1000 fits to estimate systematic uncertainty.

Backup : Flavour Tagging

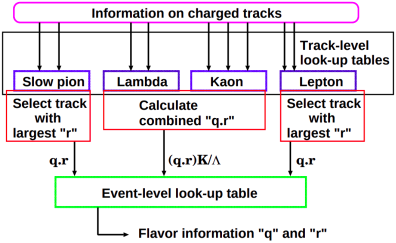




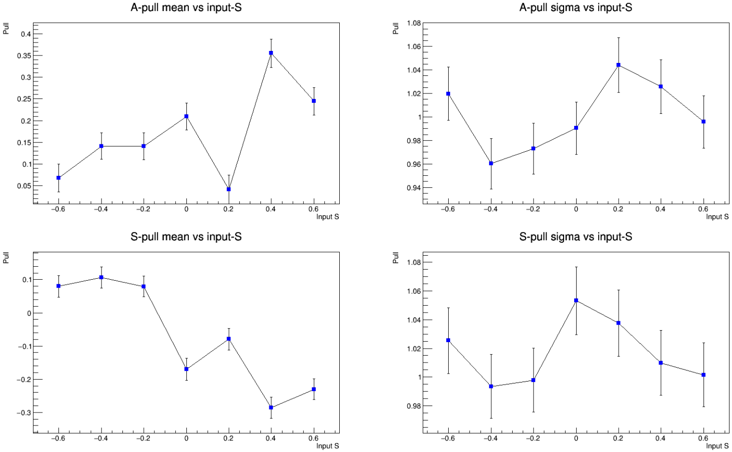
The flavour tagger outputs a tag-flavour and a dilution-factor ‘r’.

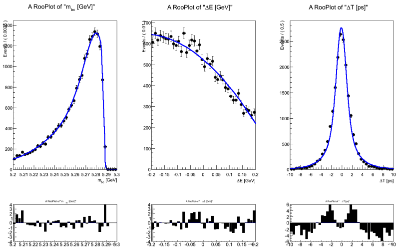
H. Kakuno, et. al., Neutral B flavor tagging for the measurement of mixing-induced CP violation at Belle, NIM A: Vol 533, Issue 3, 2004

(1) high-momentum leptons from $B^0 \to X\ell^+\nu$ decays,
(2) kaons, since the majority of them originate from $B^0 \to K^+$ through the cascade transition $\bar{b} \to \bar{c} \to \bar{s}$,
(3) intermediate momentum leptons from $\bar{b} \to \bar{c} \to \bar{s}\ell^-\bar{\nu}$ decays,
(4) high momentum pions coming from $B^0 \to D^{(*)}\pi^+X$ decays,
(5) slow pions from $B^0 \to D^{*-}X, D^{*-} \to \overline{D}^0\pi^-$ decays, and
(6) $\overline{\Lambda}$ baryons from the cascade decay $\bar{b} \to \bar{c} \to \bar{s}$.

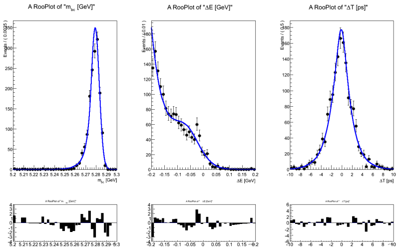


Backup : Linearity study with ensemble-fits

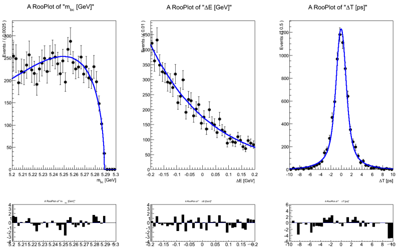




Self cross feed:



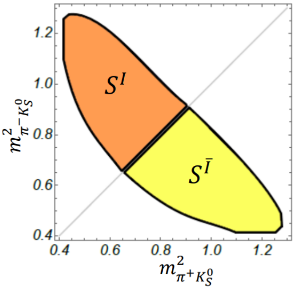
$B\bar{B}$-bkg (missing FSP) :



$B\bar{B}$-bkg (random combination) :

Backup : Simultaneous fit in Dalitz-plane halves

- Developed simultaneous fit in two Dalitz-plane halves ✓



Parameter	Fitted value
Simple-fit	
A	0.10 ± 0.10
N_{bkg}	3397 ± 63
$N_{sig+scf}$	898 ± 38
S	0.43 ± 0.12
Dalitz-fit	
A	0.11 ± 0.10
N^{I}_{bkg}	1768 ± 45
$N^{\bar{I}}_{bkg}$	1630 ± 43
$N^{I}_{sig+scf}$	450 ± 27
$N^{\bar{I}}_{sigscf}$	448 ± 27
S^{I}	0.53 ± 0.17
$S^{\bar{I}}$	0.32 ± 0.18