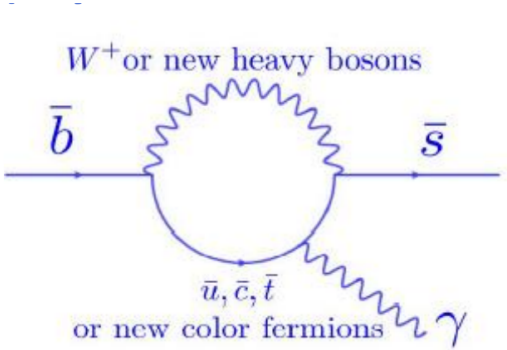
GDR-InF Meeting, Lyon

Measuring time-dependent CP asymmetry of $B^0 \to K^0_S \pi^+ \pi^- \gamma$ at Belle/Belle II.

Varghese Babu,
on behalf of the IPHC group.

November 2, 2022

Introduction



- Time-dependent CP-asymmetry of $B^0 \to K_{res}\gamma \to K_S^0\pi^+\pi^-\gamma$ is sensitive to photon polarization of quark-level process $b \to s\gamma$
- The polarization is predominantly left-handed in the Standard Model (SM), but new physics contributions may modify this.
  - Atwood et al., Phys. Rev. Lett. 79, 185
  - E. Kou et al., JHEP 12 (2013) 102 [1305.3173]
  - N. Haba et al., JHEP 03 (2015) 160 [1501.00668]

$$\mathcal{M} \simeq -\frac{4G_F}{\sqrt{2}} V_{ts}^* V_{tb} \left[(C_{7\gamma}^{SM} + C_{7\gamma}^{NP}) \langle \mathcal{O}_{7\gamma} \rangle + C_{7\gamma}^{\prime NP} \langle \mathcal{O}_{7\gamma}^{\prime} \rangle \right] \quad (1)$$

Introduction

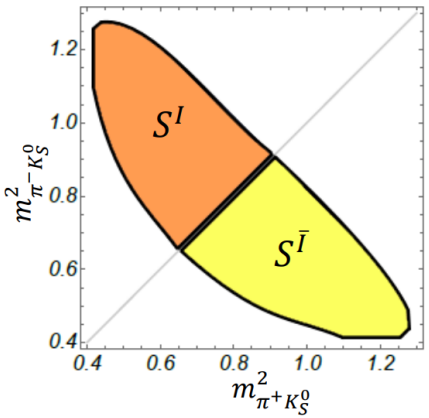
$$\mathcal{A}_{CP}(\Delta t) = \frac{\Gamma(B_{tag=B^0}(\Delta t) \to f_{CP}) - \Gamma(B_{tag=\bar{B}^0}(\Delta t) \to f_{CP})}{\Gamma(B_{tag=B^0}(\Delta t) \to f_{CP}) + \Gamma(B_{tag=\bar{B}^0}(\Delta t)} = S \sin(\Delta m \Delta t) + A \cos(\Delta m \Delta t) \quad (2)$$

- $A \simeq 0$ for the B_d system
- **Previous measurements of S for this mode:**
  - **BaBar PRD93 (2015)**: $S_{K^0_S\pi^+\pi^-\gamma} = 0.14 \pm 0.25 \pm 0.03$ (full stat : 471×10^6 $B\bar{B}$)
  - **Belle PRL101 (2008)**: $S_{K^0_S\pi^+\pi^-\gamma} = 0.11 \pm 0.33 \pm 0.07$ (657×10^6 $B\bar{B}$)
- We plan to do a combined measurement with Belle and current Belle II data.
- We are interested in the S_{CP} measurement of the CP-eigenstate $B^0 \to K_{res}\gamma \to \rho^0 K^0_S \gamma \to K^0_S \pi^+ \pi^- \gamma$
- Therefore non-CP-eigenstates should be appropriately dealt with by considering a dilution factor

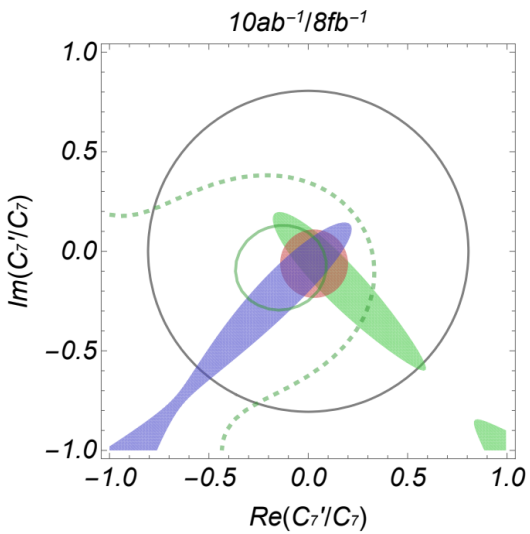
$$\mathcal{D} = \frac{S_{K^0_S\pi^+\pi^-\gamma}}{S_{K^0_S\rho^0\gamma}} \quad (3)$$

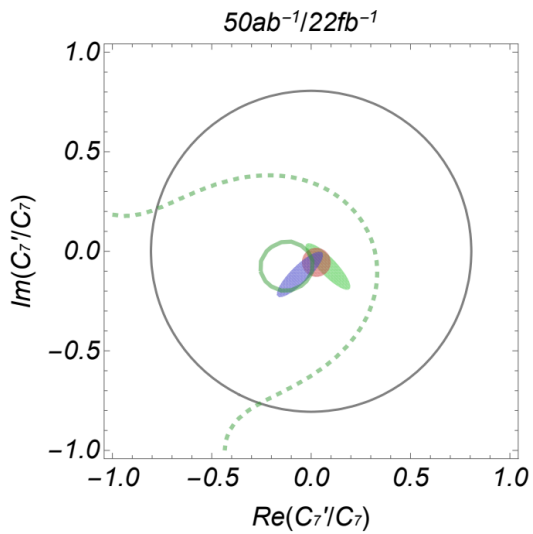
Introduction

- Recent work by *S. Akar, et.al.*, proposes new observables by dividing the dataset in the dalitz-plane. The two new observbles will provide orthogonal constraints to the real and imaginary parts of C_7'/C_7 in the complex plane.
  S. Akar et al., JHEP 09 (2019) 034

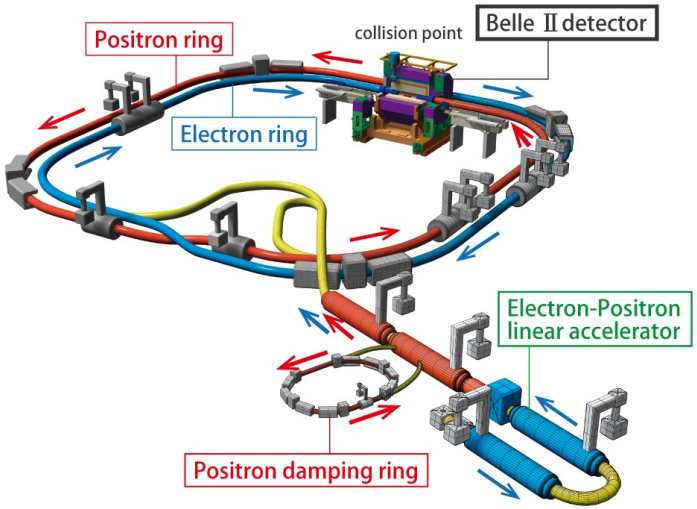


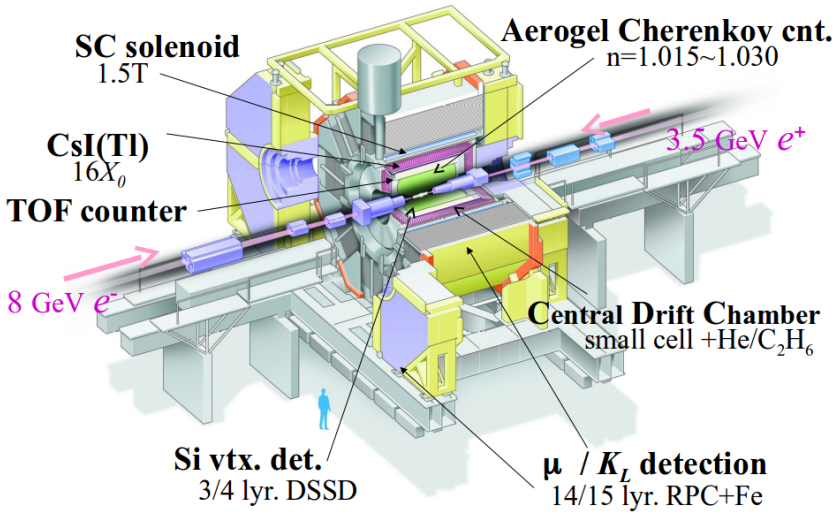
- New observables :
  $S^+_{K^0_S\rho^0\gamma} = S^I + S^{\bar{I}}$,
  $S^-_{K^0_S\rho^0\gamma} = S^I - S^{\bar{I}}$





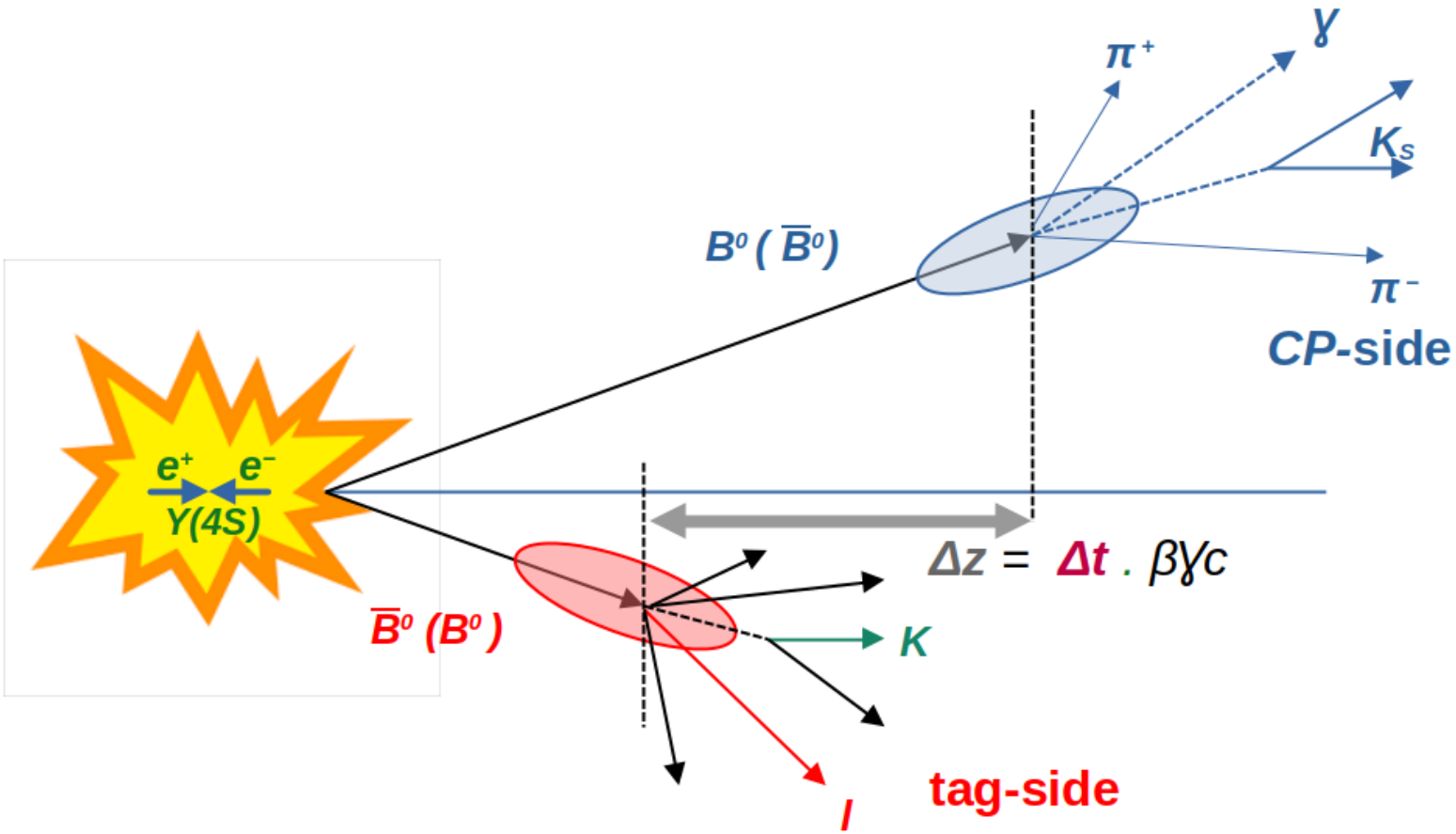
Belle experient





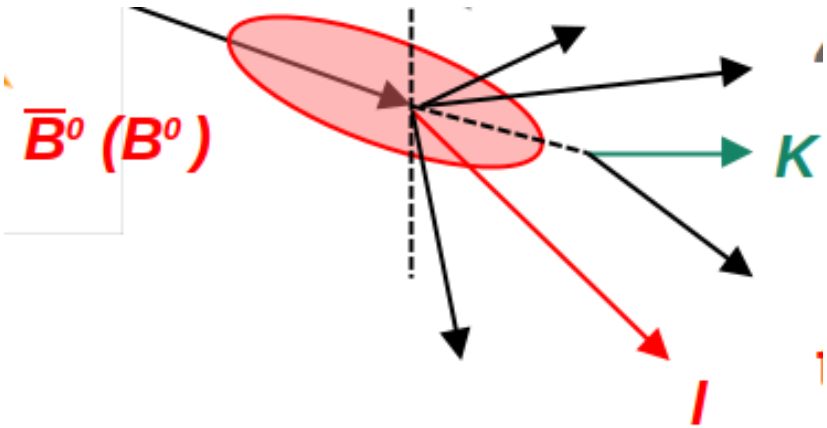
- Experiment with highest instantaneous luminosity in it's own time : $2.11 \times 10^{34} cm^{-2} s^{-1}$
- 711 fb^{-1} of integrated luminosity at the $\Upsilon(4S)$ resonance
- Asymmetric e^+ (3.5 GeV) - e^- (8 GeV) collider, allowing for measurement of proper decay time difference between B-meson pair
- Relatively clean background environment with excellent particle identification capability

Event reconstruction



- After the *CP*-side B candidate is reconstructed and vertexed, the tracks from the rest of the event are vertexed for the tag-vertex.
- The flavour tagging algorithm is run on the rest of the event.

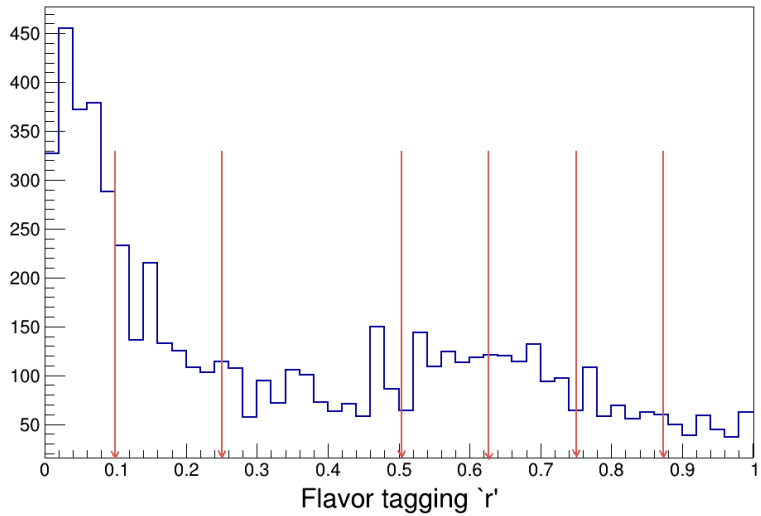
Flavour Tagging



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

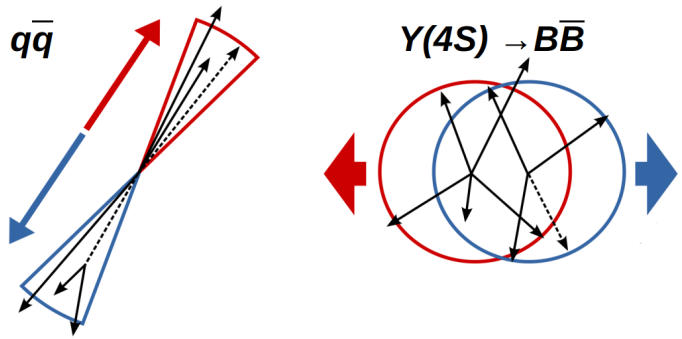
H. Kakuno, et. al., Neutral B flavor tagging for the measurement of mixing-induced CP violation at Belle, NIM A: Vol 533, Issue 3, 2004

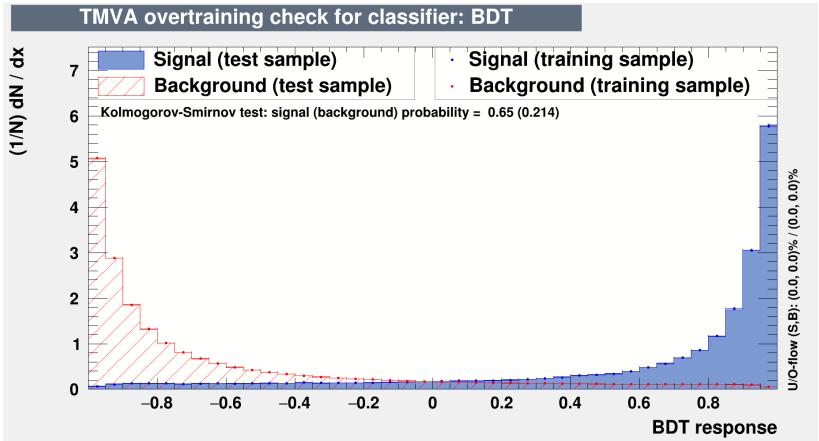
(1) high-momentum leptons from $B^0 \to X\ell^+\nu$ decays,
(2) kaons, since the majority of them originate from $B^0 \to K^+X$ decays through the cascade transition $\bar{b} \to \bar{c} \to \bar{s}$,
(3) intermediate momentum leptons from $\bar{b} \to \bar{c} \to \bar{s}\ell^-\overline{\nu}$ decays,
(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 $\bar{b} \to \bar{c} \to \bar{s}$.



r-bin	w	Δw
0	0.5	0.0
1	0.418826	-0.00877001
2	0.319303	0.0103515
3	0.222948	-0.0109253
4	0.163191	-0.0186365
5	0.104085	0.00168037
6	0.0251454	-0.0036441

Event selection - continuum suppression

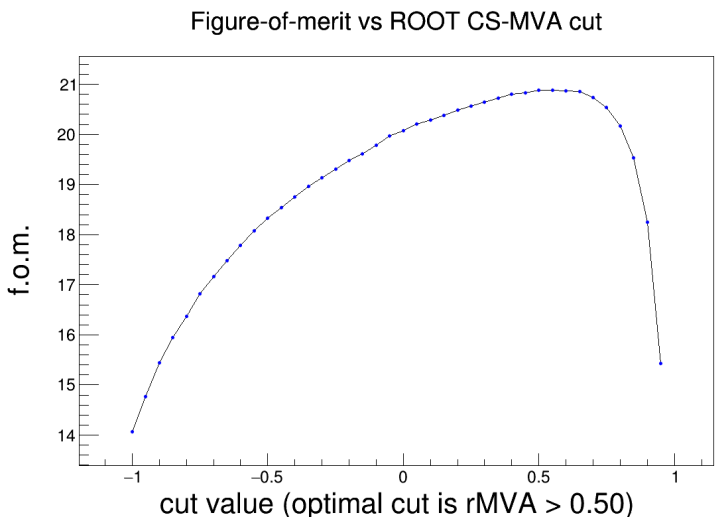




- We build a BDT-classifier based on event-shape variables that discriminate between continuum and resonant events using
  - Cosine of the thrust axes of the event,
  - Cosine of the B-momentum polar angle and
  - Fox-Wolfram moments. G. C. Fox and S. Wolfram, Phys. Rev. Lett. 41, 1581 (1978).

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

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



Event selection

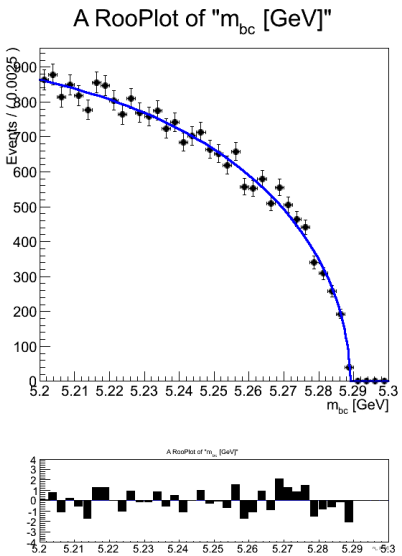
Selection criteria

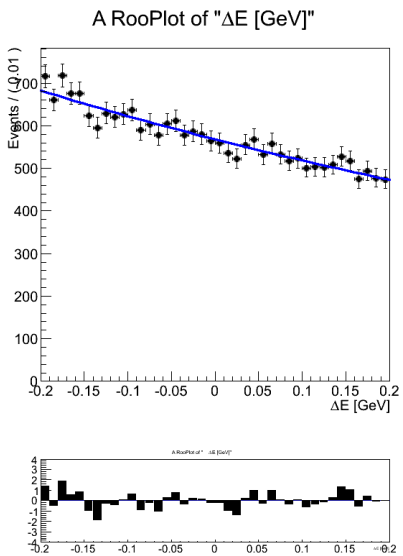
Selection	Remark
MVA-classifier > 0.5	To suppress continuum events (optimized)
π^0-veto < 0.2, η-veto < 0.25'	To suppress photon pollution from $\pi^0 \to \gamma\gamma$ and $\eta \to \gamma\gamma$ decays
Multivariate standard Belle K^0_S selection	
e9/e25(γ) > 0.95	Avoid merged π^0 ECL clusters
cos(θ)$_\gamma$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

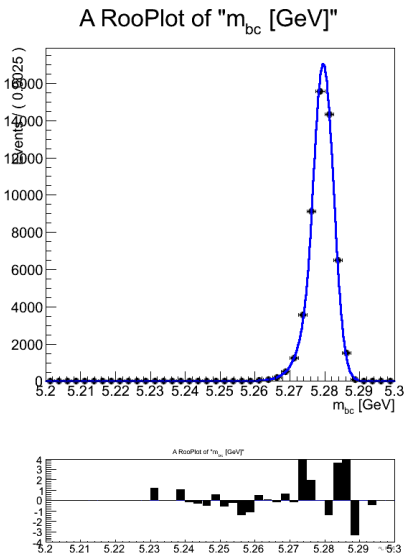
Single candidate selection: If there are multiple B_{CP} candidates, the one with the best *CP*-side vertex C.L. is chosen.

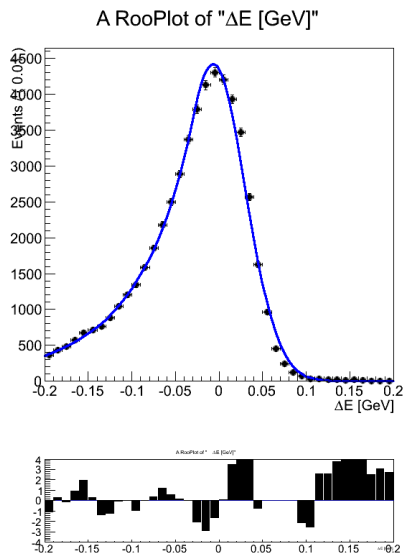
Measurement strategy

- We do a 3-D fit of M_{bc}, ΔE and Δt simultaneously 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

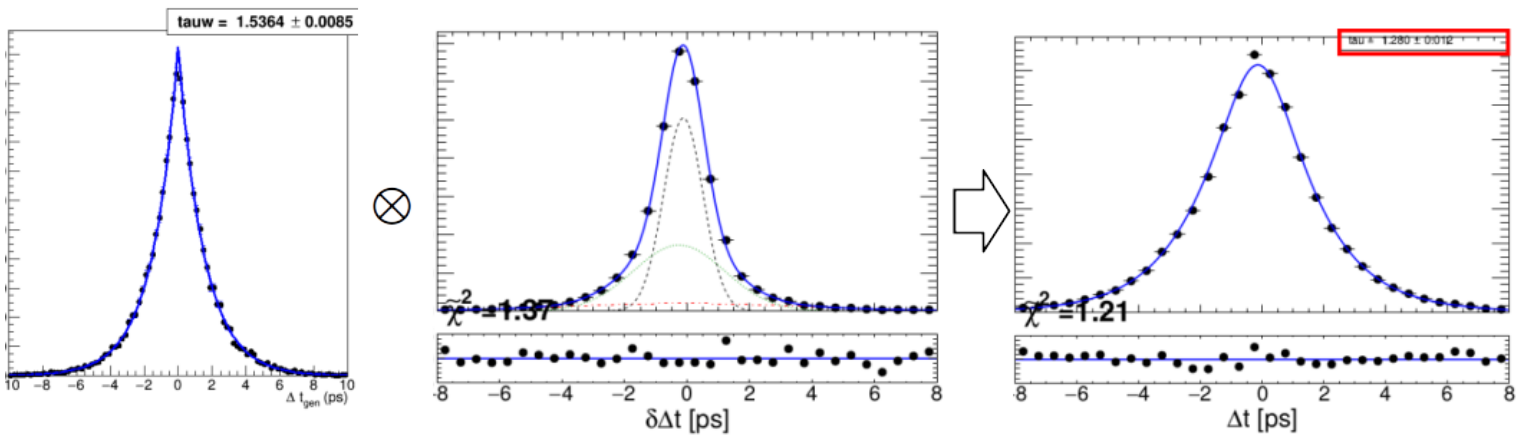
Δt resolution function

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

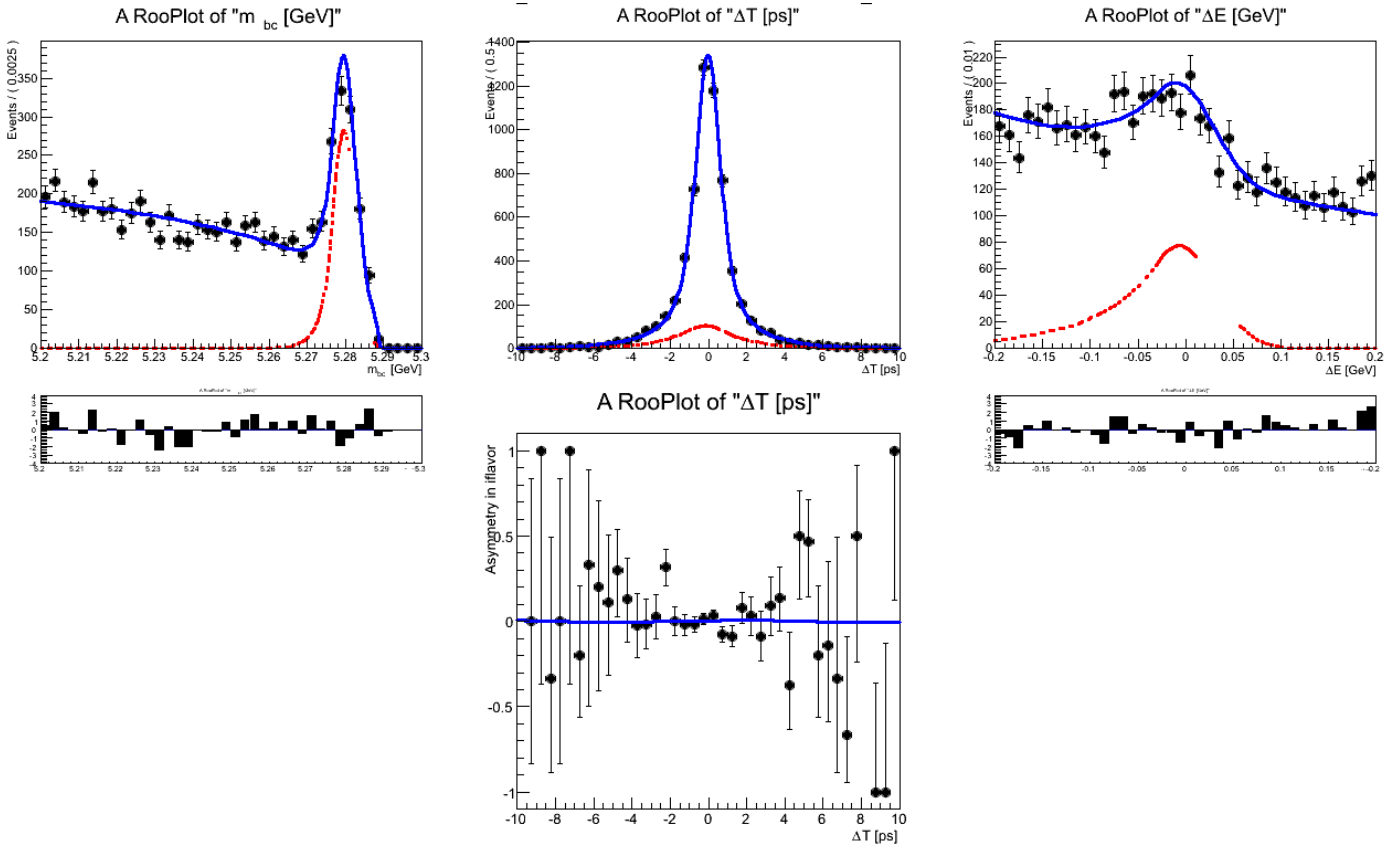
$$\mathcal{P}(\Delta t, q = \pm 1) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}}\{1 - q\Delta w + q(1-2w)[S\sin(\Delta m \Delta t) + A\cos(\Delta m \Delta t)]\} \otimes R_{det} \tag{5}$$

- $R_{det}(cos\theta_B, E_{CMS}, N^{CP}_{tracks}, \sigma^{CP}_Z, \chi^{2,CP}, N.D.F.^{CP}, N^{tag}_{tracks}, \sigma^{tag}_Z, \chi^{2,tag}, N.D.F.^{tag})$ is the Δt resolution function that arises from the finite resolution of the CP and tag-side vertices, together with the kinematic approximation that $\Delta z \simeq \Delta t.\beta\gamma c$.
- This has already been calibrated for Belle in the 'tatami' Δt fit-framework.

  H. Tajima, et. al., Proper-time resolution function for measurement of time evolution of B mesons at the KEK B-Factory, NIM A: Vol533, Issue 3, 2004



Full-fit



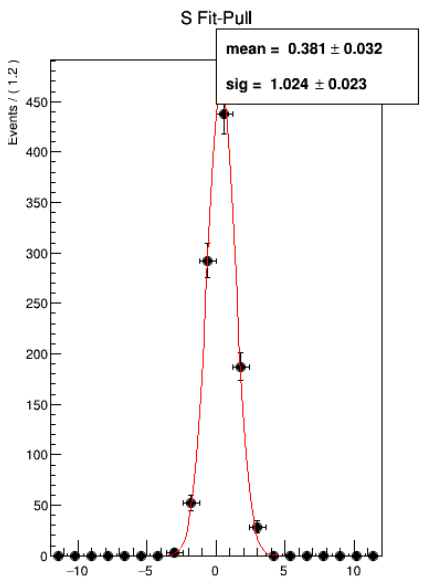
- Full fit on an MC cocktail after selections and single-candidate selection. The cocktail reflects nominal signal and background yields in 1 equivalent Belle dataset.
- Overall $N_{signal+C.F.}$ and $N_{3-component\ background}$ are floated along with S and A

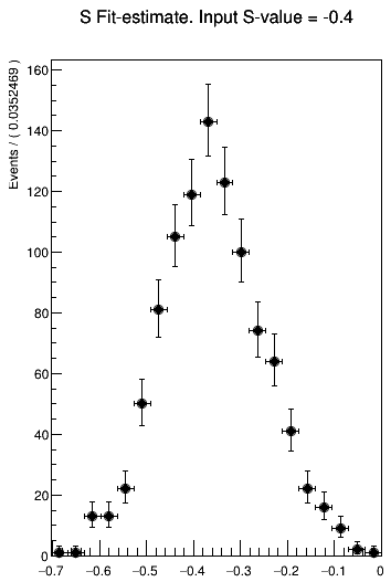
$$S = 0.04 \pm 0.11 \quad (6)$$

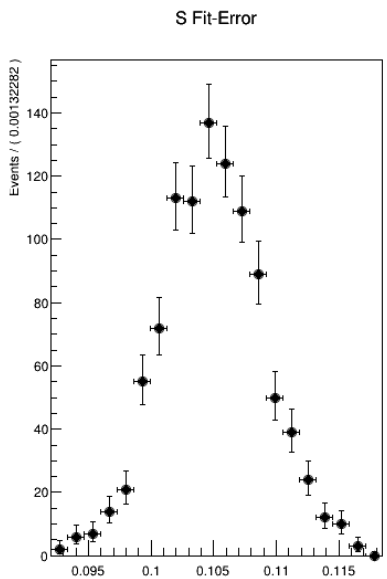
$$A = 0.04 \pm 0.08 \quad (7)$$

Linearity study with ensemble-fits

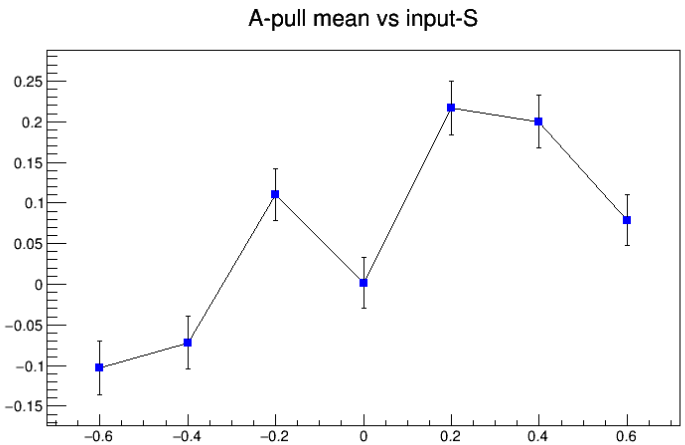
- We generate 1 million events with $A = 0$ and S = [-0.6, -0.4, -0.2, 0.0, 0.2, 0.4, 0.6] using the minimal *CP* model $\mathrm{PHSP\_CP}$ (implemented in Belle software).
- We make 1000 bootstrapped datasets for each input value of S with signal and all background components in the correct proportions.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

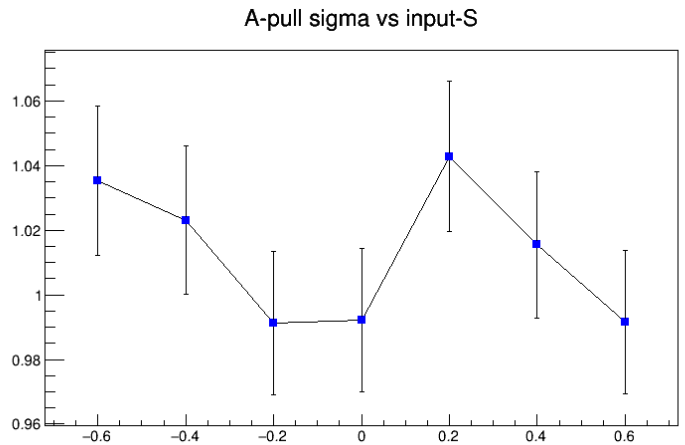


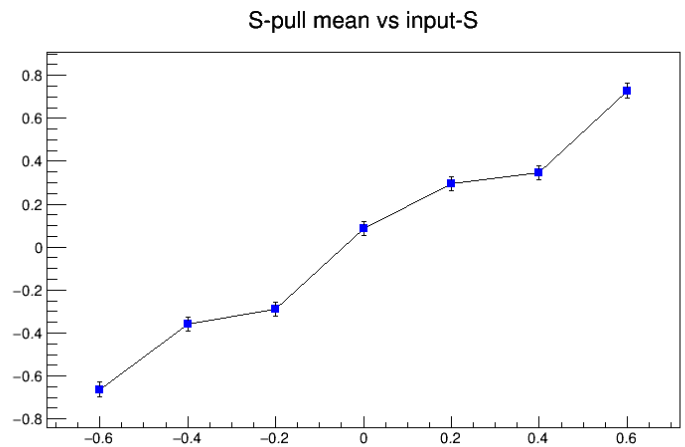


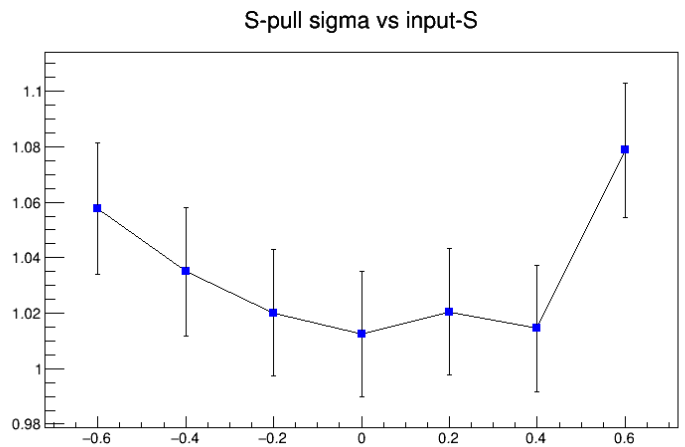


Behaviour of A and S pull-distribution mean and width









- 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(?).

Summary

Status and plans

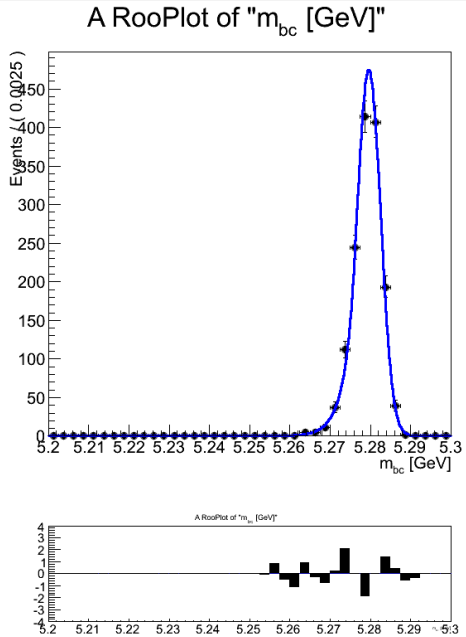
- Plan to start estimating systematic errors from various sources.
- We intend to combine the measurement for Belle and Belle II. Petros has newly joined the group as a Ph.D. student and will start developing the fit strategy for Belle II data.
- Work has already begun on calibrating the Δt resolution function, and the flavour tagging mistag metrics.

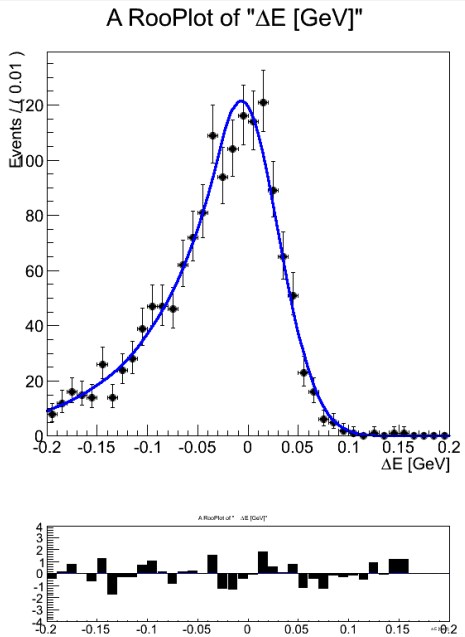
Connected talk (next)

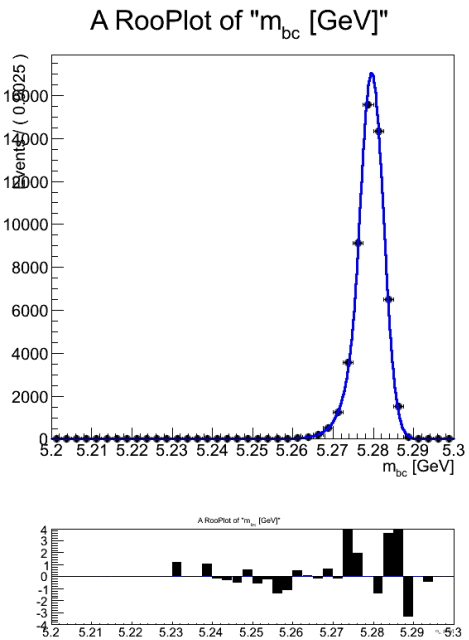
- This physics channel is a good mode to benchmark the performance of the proposed vertex detector upgrade of Belle II. Petros will present his work on this topic.

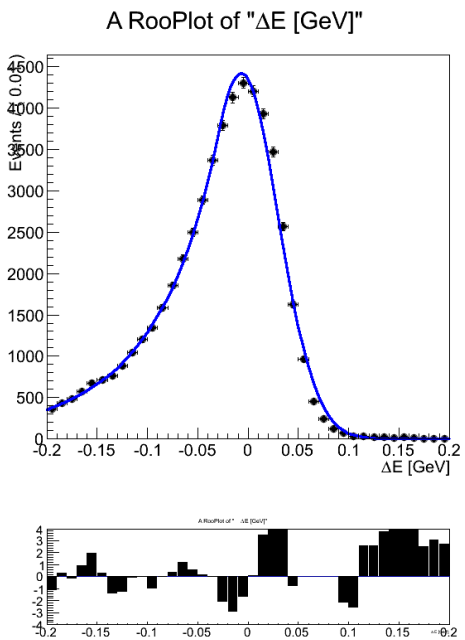
Thank you

Backup : Signal shape

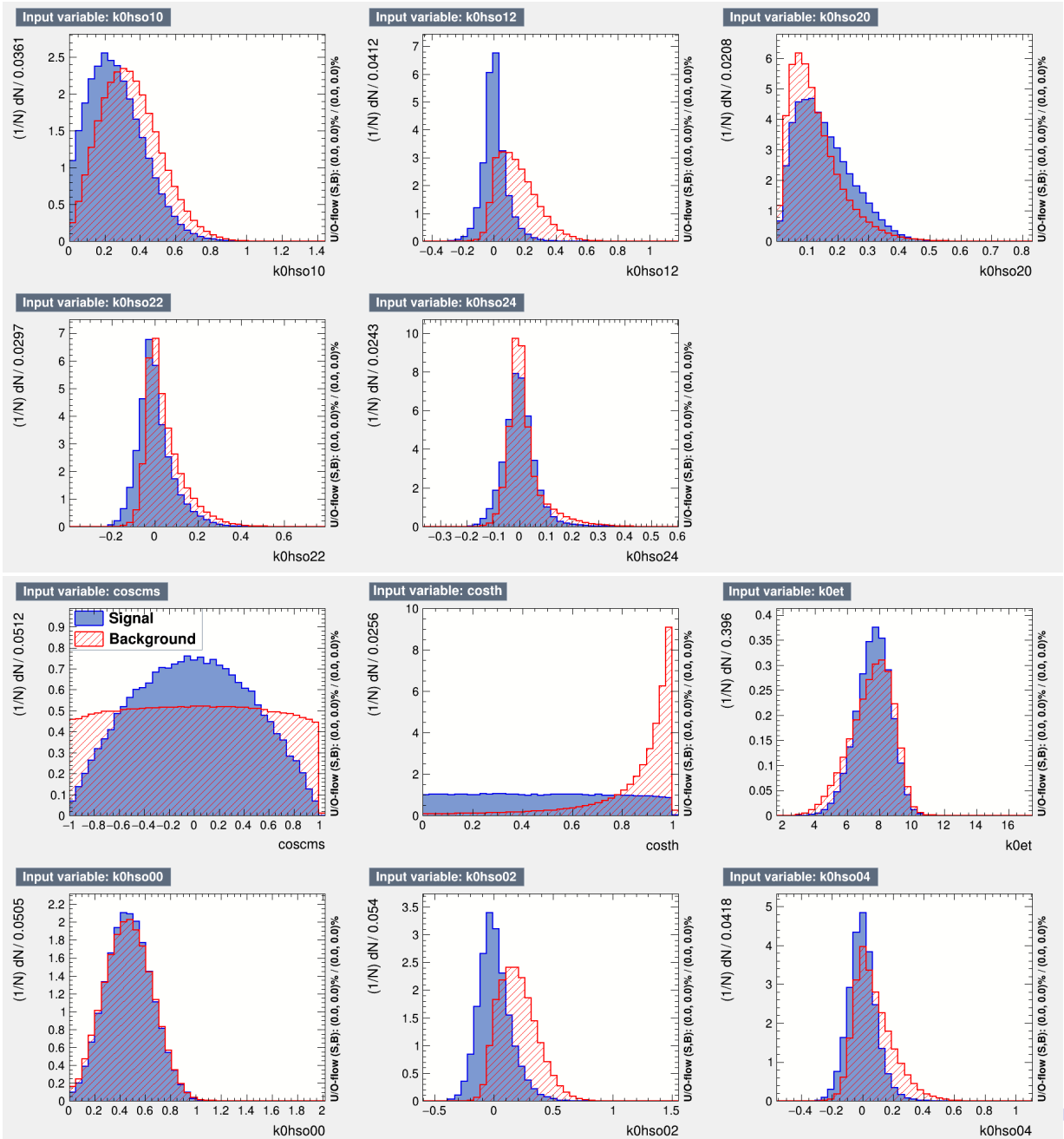




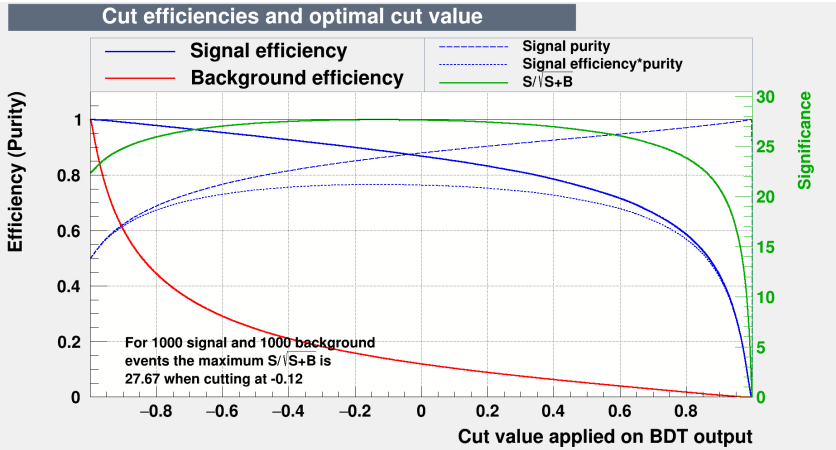




Backup : continuum suppression variables



Backup : continuum suppression optimization



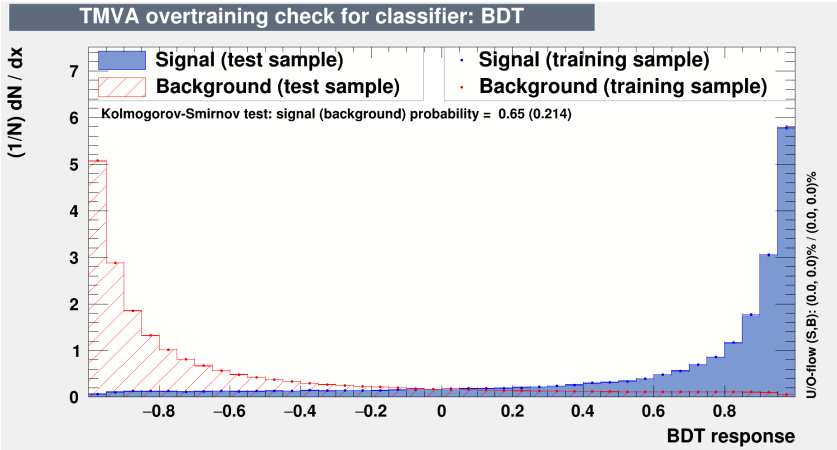
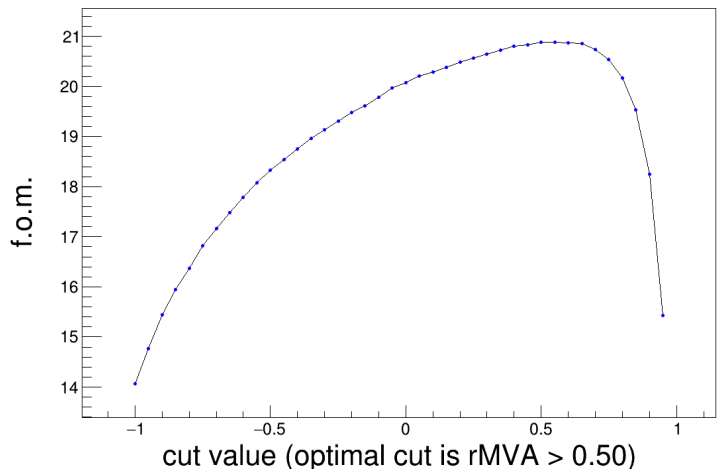
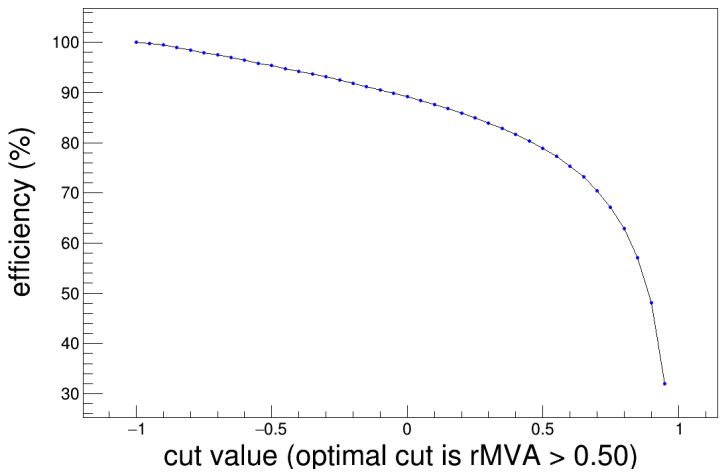


Figure-of-merit vs ROOT CS-MVA cut



Signal efficiency vs ROOT CS-MVA cut



Backup : π^0, η vetoes

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

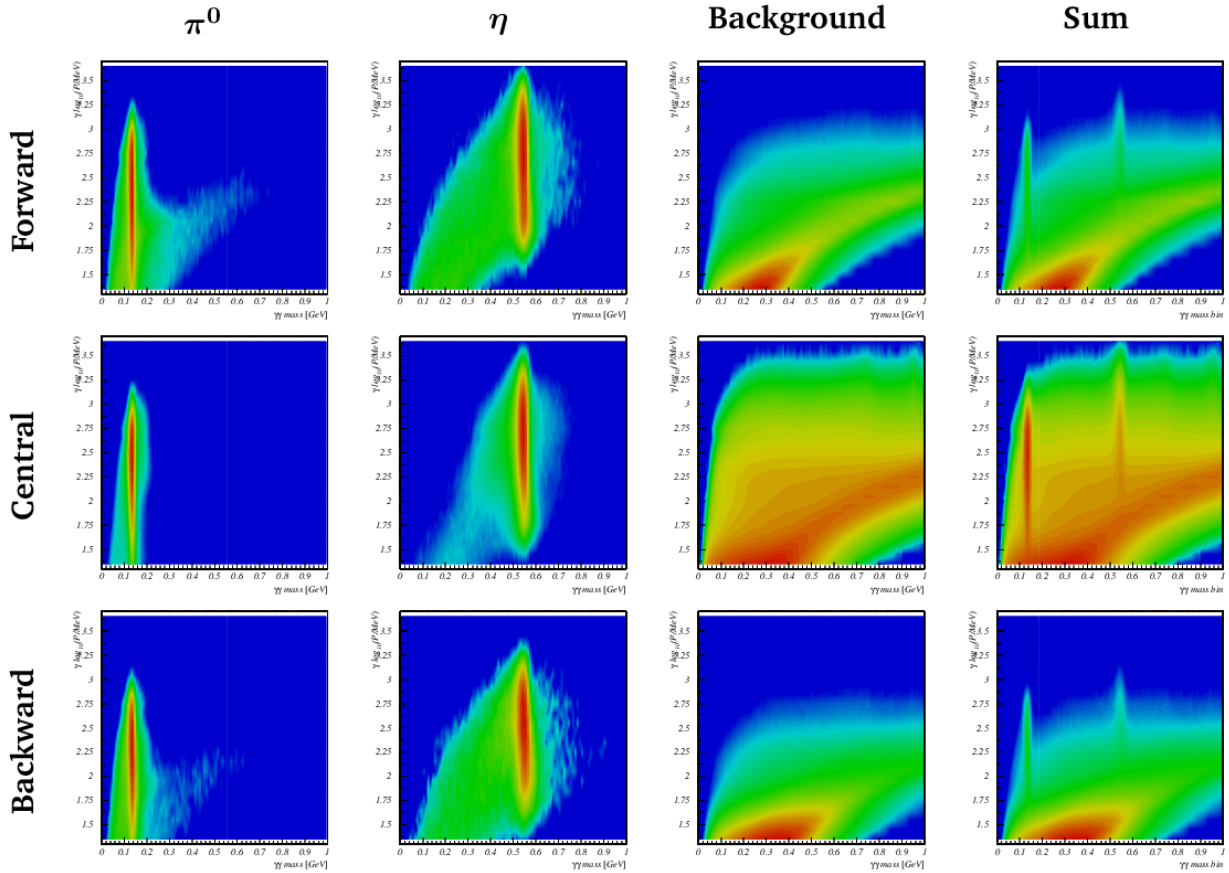
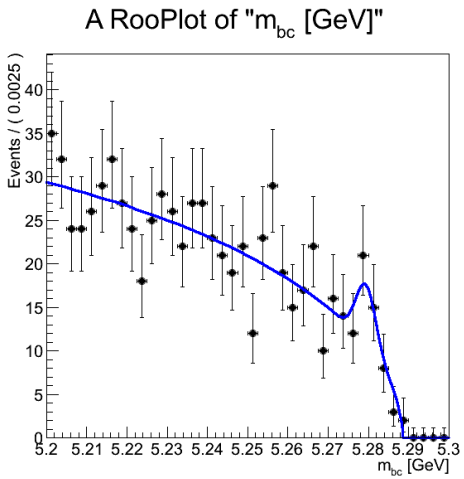
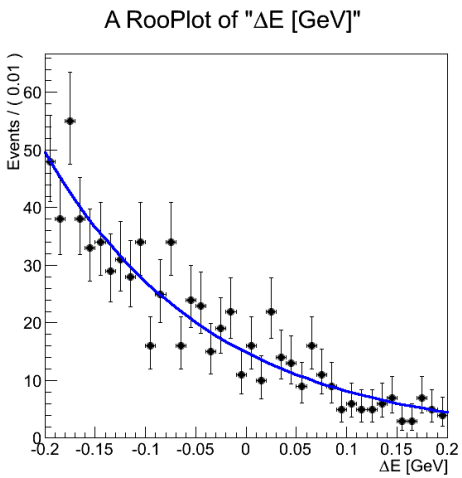
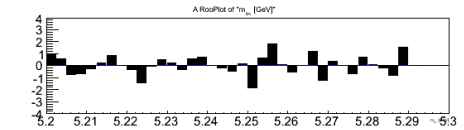


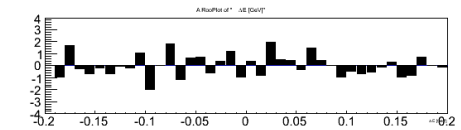
Figure 2: *From left to right, MC probability densities in the* $\log_{10}(E_{\gamma_2}/\mathrm{MeV})$ *versus* $m_{\gamma_1\gamma_2}$ *plane for true* π^0, η, *random combinations and the sum, for three calorimeter zones.*

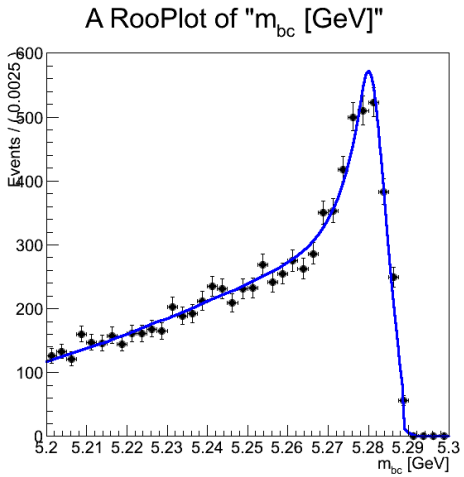
Backup :Background component shapes

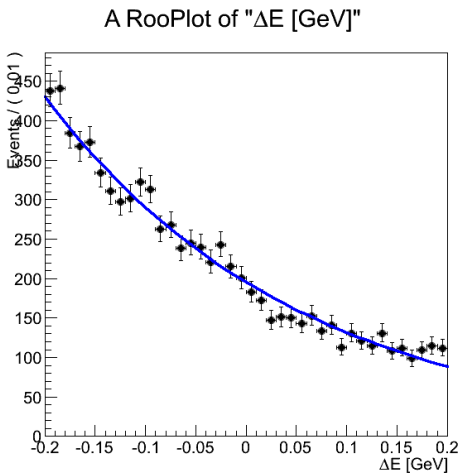


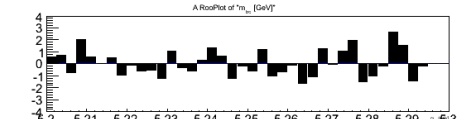


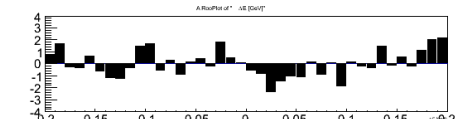








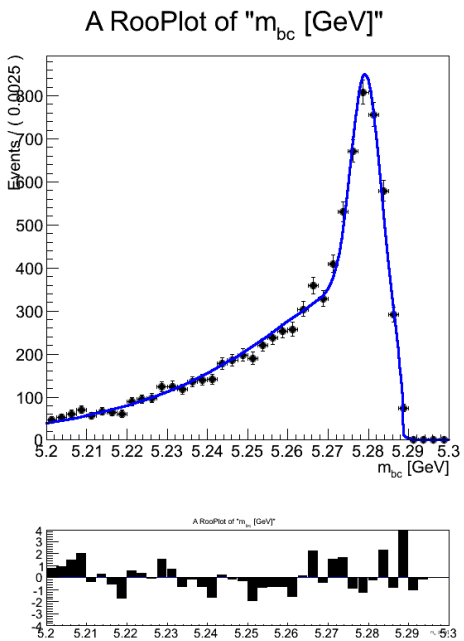


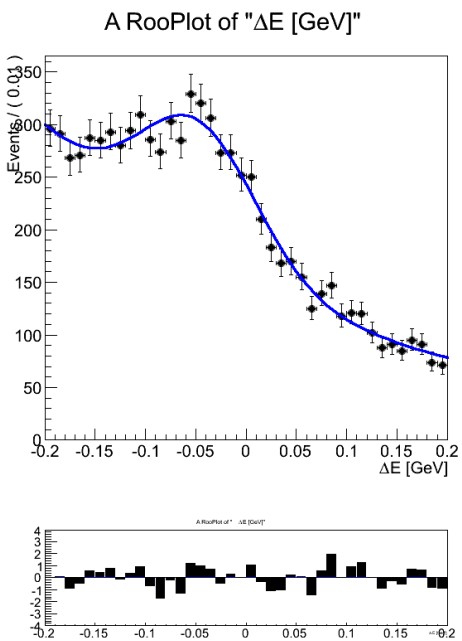


$B\bar{B}$ **background:**
M_{bc} : Gaussian + Argus
ΔE : Exponential

Rare MC background :
M_{bc} : Crystal-ball + Argus
ΔE : Exponential

Backup :cross-feed shape





Cross-feed :
M_{bc} : Crystal-ball + Argus
ΔE : Exponential