Search for ALP through $B \to K a'$ $(a' \to \gamma\gamma)$ Decay

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Jan 17th, 2023

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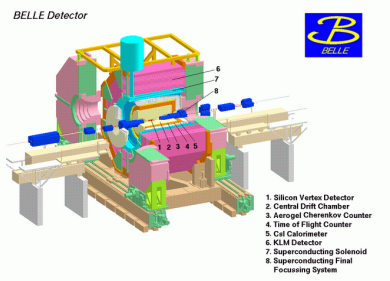
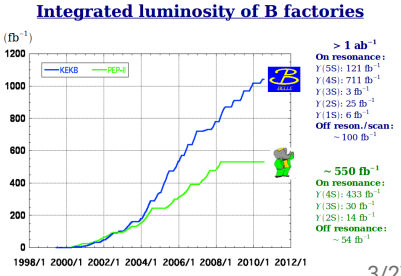
KEKB and Belle Experiment

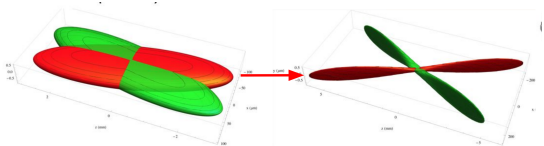
- 8 GeV HER, 3.5 GeV LER head-on colliding ($\beta\gamma = 0.42$)
- Energy set to generate $\Upsilon(4S)$ ($10.58\,\mathrm{GeV/c^2}$)
- $\Upsilon(4S)$ decays into $B\bar{B}$ pair ($5.28\,\mathrm{GeV/c^2}$)
- from 1999 to 2010, $711\,fb^{-1}$ integrated luminocity collected, corresponding to 772 million $B\bar{B}$ pairs
- Highest instantaneous luminocity of $2.1 \cdot 10^{34}\mathrm{cm^{-2}s^{-1}}$ archived
- Have several layers of detectors
- SVD, CDC, TOF, ACC, CsI, KLM



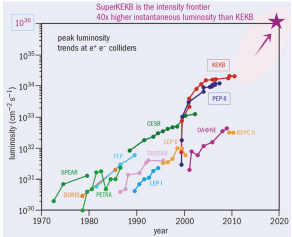


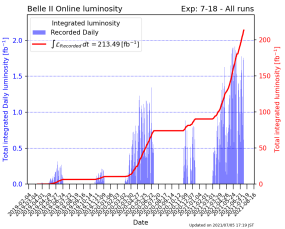
SuperKEKB and Belle II Experiment

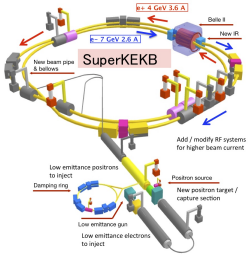
- 7 GeV HER, 4 GeV LER ($\beta\gamma = 0.28$)
- Challenges instantaneous luminocity to $6.5 \cdot 10^{35}\mathrm{cm}^{-2}\mathrm{s}^{-1}$
- More detector layers added, while modifying old detector system.
- PXD, SVD, CDC, ARICH, TOP, ECL, KLM
- Goal : $50ab^{-1}$ integrated

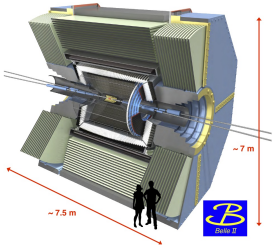


$\sigma_y^* : 940 \rightarrow \sim 50nm$

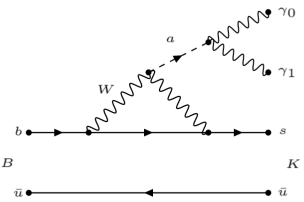








Introduction



- Axion is hypothetical elementary particle , postulated by Peccei-Quinn Theory to resolve the “Strong-CP” problem in QCD
- ALPs are similar to axions, but they are not required to solve the strong CP problem.
- Instead, they are motivated by their potential to explain certain observations in astrophysics and cosmology that cannot be accounted for by the Standard Model.

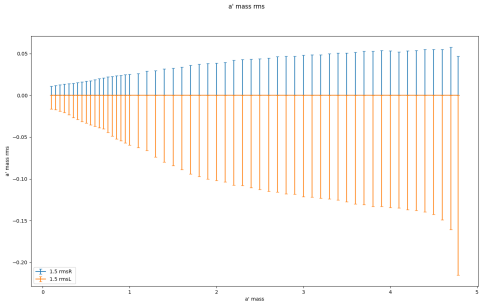
- Searching for Axion-Like-Particle (ALP , a’)
- Belle I MC Dataset is used for analysis
- B2BII is applied to adopt BASF2
- $B \to K^{(*)} a' \, (a' \to \gamma\gamma)$
- a' : Spin-less pseudoscarlar particle
- a' : Decay into $\gamma\gamma$ 100%
- Mass Scanning : $0.2 \sim 4.78$ GeV (K^+, K^0)
- π^0, η, η' mass region is excluded

- Background data skimed include all K mode
- B2BII applied : allow using Belle I data in Belle 2 Analysis Framework (BASF2)
- B2BII conditions : BELLE2_RELEASE = release-05-01-06

Partilce List	Selection Criteria
Charged track	$\|d0\| < 3.0$ cm
	$\|z0\| < 4.0$ cm
	eIDBelle < 0.9
	muIDBelle < 0.9 or muIDBelleQuality = 0
K^+	$\mathscr{L}(K\pi) > 0.6$
	$\mathscr{L}(Kp) > 0.4$
π^+	$\mathscr{L}(\pi K) > 0.4$
	$\mathscr{L}(\pi p) > 0.7$
γ	$E_\gamma > 50$ MeV
	$0.5 < goodBelleGamma < 1.5$
π^0	pi0:mdst
K_S^0	goodBelleKShort
	vertex kFit
	ksnbStandard = 1 (nisKs)

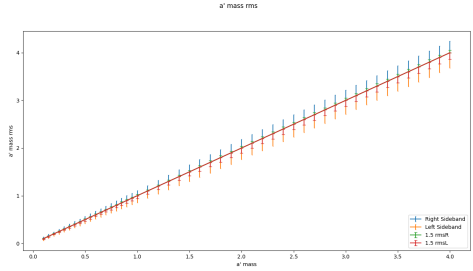
Partilce List	Selection Criteria
K^*	$0.7 < m_{K^*} < 1.1$ GeV
	$K^0 \to K^0 pi^0$
	$K^0 \to K^+ pi^-$
	$K^+ \to K^0 pi^+$
	$K^+ \to K^+ pi^0$
ALP	$0.102 > M_{a'} \| M_{a'} > 0.166$ GeV (M_{π^0})
	$0.480 > M_{a'} \| M_{a'} > 0.584$ GeV (M_η)
	$0.866 > M_{a'} \| M_{a'} > 0.997$ GeV $(M_{\eta'})$
B	$M_{bc} > 5,26$GeV
	$-0.6 < \Delta E < 0.3$ GeV
	$B^0 \to K^0 a'$
	$B^+ \to K^+ a'$
	$B^0 \to K^0 a'$
	$B^+ \to K^+ a'$

Analysis Region



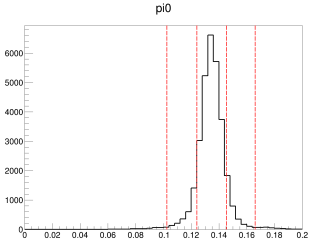
- calculate σ for each a' mass sig MC
- $rms = \sqrt{\frac{\sum(M_{a'} - ref\_Mass)^2}{Nevt}}$
- Main Band : 2.5 rms^L to 2.5 rms^R
- Side Band : main band width

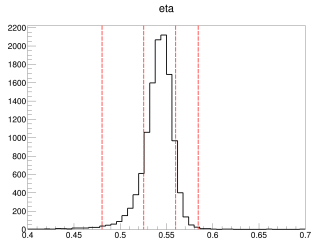
precut	Condition
a' mcPDG	matched
Mbc	5.27~ (GeV)
ΔE	-0.2 ~ 0.1 (GeV)
$M_{a'}$	0.5 ~ 1.2



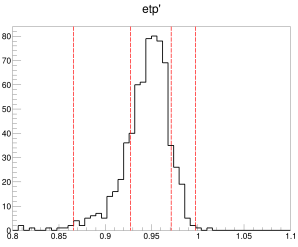
Peaking background veto

- π^0, η, η' are 3 major gamma pair generating SM background.
- $rms_{\pi^0} = \sqrt{\frac{\sum(M_{a'} - M_{\pi^0})^2}{N_{evt}}}$
- 1.5 RMS of each mass region of peaking background is removed form analysis
- $c\bar{c}$ peaking background is substracted from signal yield.





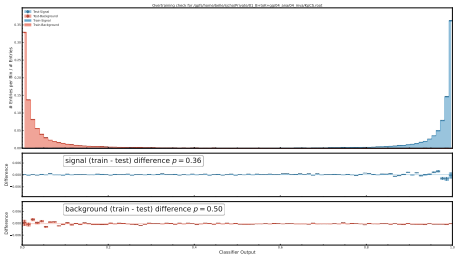
type	veto region (GeV)
π^0	0.102 ~ 0.166
η	0.480 ~ 0.584
η'	0.866 ~ 0.997

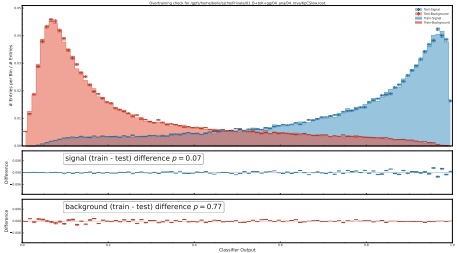


Continuum Suppression

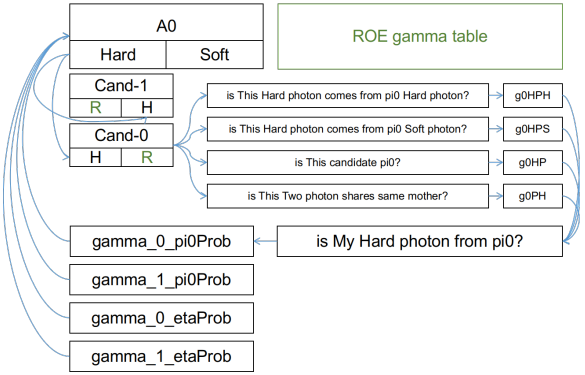
- 2 FBDT MVA for Continuum Suppression
- Generate mass-independence SigMC (0.01~4.78 GeV, 10MeV interval).
- BkgMC data from CHM/UDS str05
- CS2 MVA trained with data pass CS1 loose cut (0.5)
- CS2 trained for low/high mass
- CS1 and CS2 are 2D Optimized for Low/High mass region by Punzi FoM

CS1 Variables	CS2 Variables
R2	R2
cosTBTO	cosTBTO
thrustOm	aplanarity
cosTBz	thrust
et	CleoCone Thrust
mm2	Hemisphere Momentum
$Dasy$	FoxWolfram moment and ratio
KSFW (14)	harmonic Moment Thrust
CleoCone (9)	sphericity
	thrustBm
	roeM
	cosHelicityAngle Beam momentum (K)
	cosHelicityAngle (gamma)
	number on ALP candidates





PEV2



- Since previous π^0, η veto is not applicable anymore
- We generate another π^0 veto FBDT MVA
- train 1st MVA : **[**$(\gamma_{sig} + \gamma_{ROE})$ **vs Bkg]** with various E_{th}
- + **[MC Matched** π^0 **vs Else]** (both from Bkg MC samples)
- Among them, choose MVA which have (most) effective result and combined them as 1 MVA output

- 1st MVA input vars

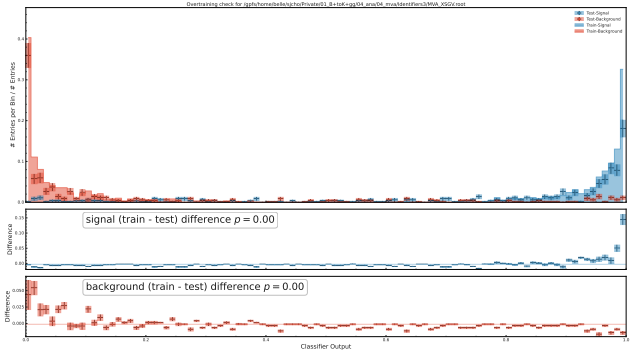
cluster vars	Kinematic Vars
ConnectedRegionID	$p^{(*)}$
E9E25	$p_x^{(*)}$
EoP	$p_y^{(*)}$
ErrorE	$p_z^{(*)}$
ErrorPhi	$p_t^{(*)}$
ErrorTheta	$E^{(*)}$
HighestE	Theta
LAT	***—for a' only—***
NHits	deltaPhi
Phi	deltaAngle
R	E_{asy}^{*}
Theta	

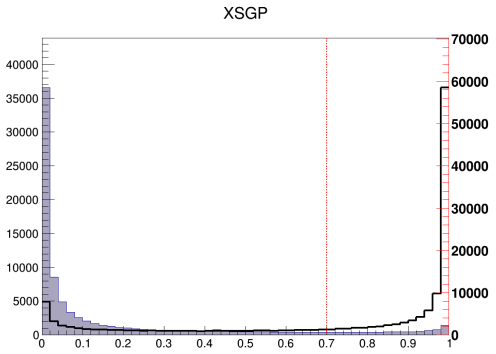
- 2nd MVA input vars

g0PP	g1PP
g0HP	g1PH
g0PH	g1HP
g0HPH	g1PS
g0HPS	g1SP
	g1HPH
	g1SPH
	g1HPS
	g1SPS

- For Training, mass-indep $B \to Ka'$ MC samples are used
- For Training, 00th stream Generic BkgMC are used
- For Optimizing, mass-indep $B^+ \to K^+ a'$ MC samples are used (different from training)
- For Optimizing, All stream BkgMC EXCEPT 00 generic are used
- FoM ($\frac{S}{\sqrt{S+B}}$) are adopted for optimizing

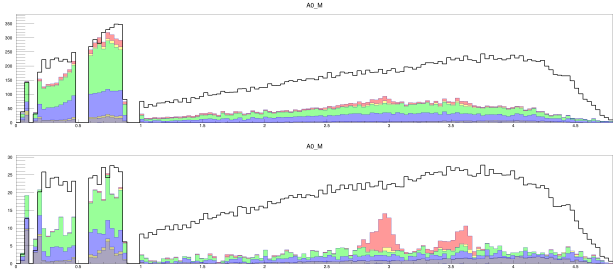
XSGV ($B \to X_s\gamma$ Veto)



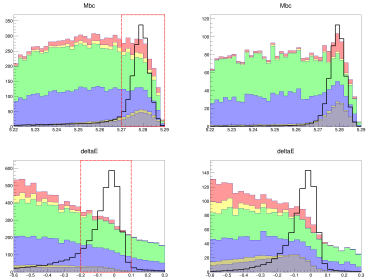


- same variables, same conditions as PEV
- training dataset : **[mass-indep $B \to Ka'$ vs $B \to X_s\gamma$]**
- PFM Optimized point is 0.01 but instead, 0.7 Cut will be applied.
- Low mass region : Additionally $E_{\gamma 1}^{CMS} > 0.4GeV$ Cut applied

Remaining BkgMC



[$M_{a'}$ Bkg distribution w/o MB cut (upper) and inside of the MB (bottom), Signal distribution (Black) is just for ϵ_{sig} comparison, Not scaled]



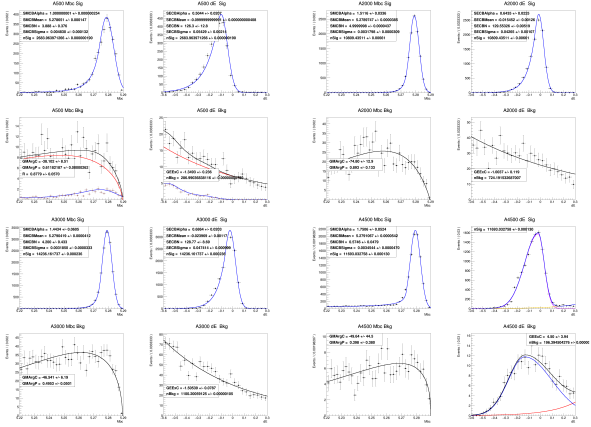
Bkg M_{bc}&ΔE distribution with $0 < M_{a'} < 4.0$ region
left : w/o M_{bc} or ΔE cut
right : Mainband(Red Box) Enhenced distribution

PDF Construction

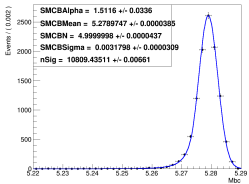
Mass Region	Low (<1 GeV)	Mid	High (>4 GeV)
Sig Mbc	CB	CB	CB
Sig dE	CB	CB	BiGauss + Exp
qq Mbc	ArgusBG	ArgusBG	ArgusBG
qq dE	Exp	Exp	Exp + BiGauss
BB Mbc	KDE		
BB dE	KDE		

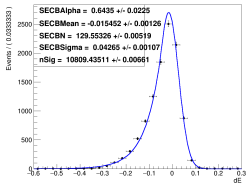
$M_{\mathrm{bc}} : \sqrt{(E_{\mathrm{beam}}/2)^2 - \vec{\mathrm{p}}_B^{\,2}}$, : Beam constraint mass for signal side B ΔE : $(E_{\mathrm{beam}}/2) - E_B$

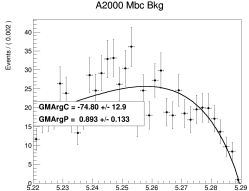
- Default is Mid range PDF set
- Add BB PDF at low mass region
- Delta E distribution sitorted at high mass region

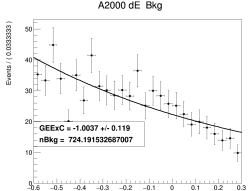


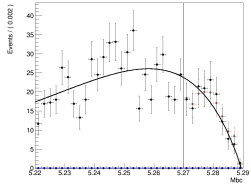
Signal Extraction

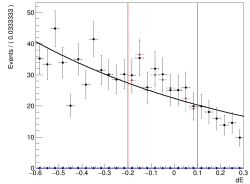










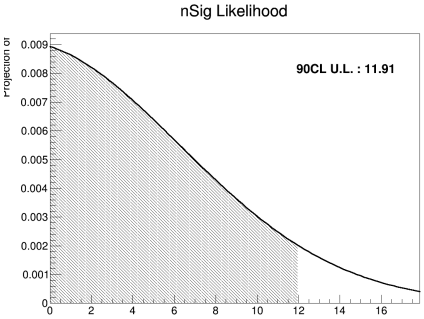


[PDF is normalized in Sideband region]

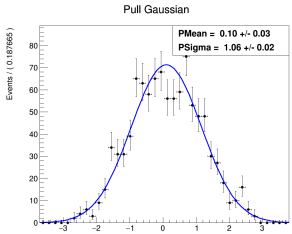
[Projected 1D Sideband histogram scaled to expected value from PDF integration.]

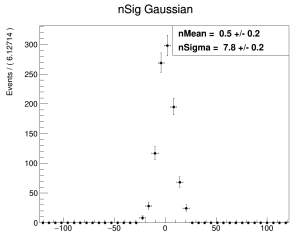
- Extended 2D Unbinned ML Sideband fitting by RooFit
- Signal Yield (nSY)= $N_{Evt}^{MB} - N_{Evt}^{SB} \times \frac{\int_{MB} Bpdf}{\int_{SB} Bpdf} - N_{pkb}^{MB}$
- ϵ_{Sig} = $nSig \times \frac{\int_{MB} Spdf}{\int_{tot} Spdf} / N_{gen}^{Sig}$
- $\sigma_1 = \sigma_{bkg}^{SB} \times \sqrt{\frac{\int_{MB} Bpdf}{\int_{SB} Bpdf}}$
- $\sigma_2 = \sqrt{nSY \times \frac{\int_{tot} Spdf}{\int_{MB} Spdf}}$
- $\sigma(nSY) = \sqrt{(\sigma_1^2 + \sigma_2^2)}$

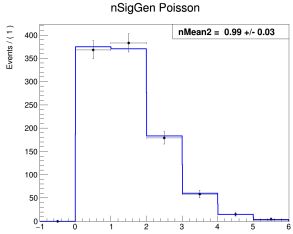
ToyMC

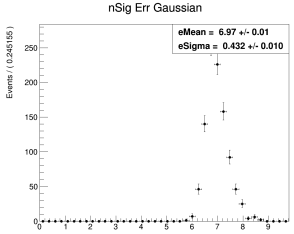


- expected U.L. is estimated with
- mean as nSY earned by sideband pdf substraction
- Sigma of Gaussian fitted to ToyMC output nSig distribution
- (hatched area : 90CL ; 0.90 of total positive integration)
- ToyMC input = $nSY \times \frac{\int_{tot} Spdf}{\int_{MB} Spdf}$
- $\frac{\int_{MB} Spdf}{\int_{tot} Spdf} \approx 0.92$



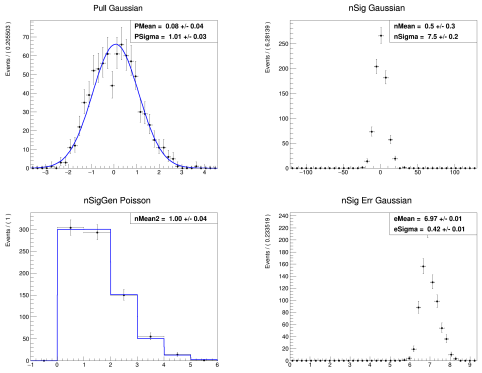




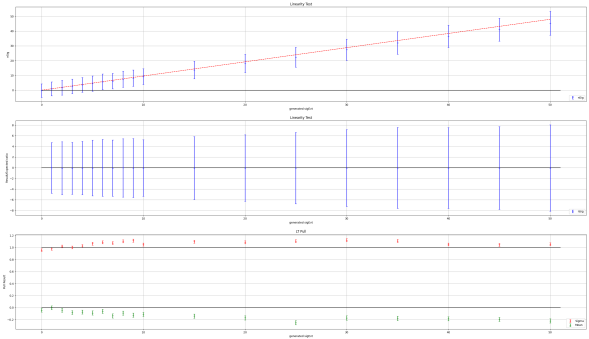


- Result of ToyMC study of $B^+ \to K^+ \eta_c (\to \gamma\gamma)$

Linearity Test

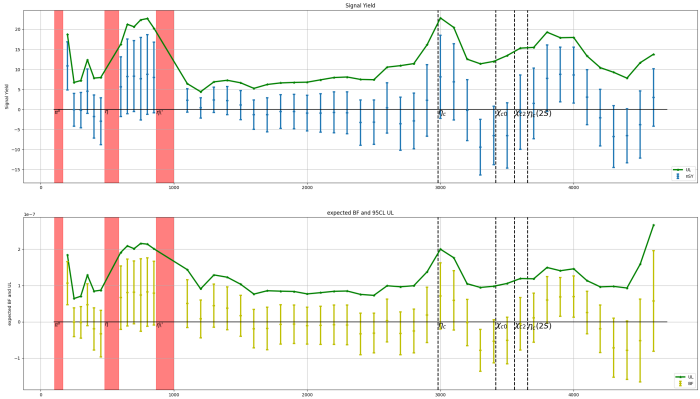


[sample output of LT of $B^+ \to K^+ a'(2000)(\to \gamma\gamma)$ (0 Input)]



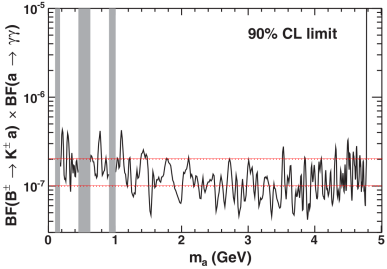
[Linearity Test Result. N_{sig}^{in} vs N_{sig}^{out}, red dashed line is expected value(Upper). Difference between extracted N_{sig} and expected value(middle). Pull Mean and Sigma (bottom)]

Mass Scanning Result

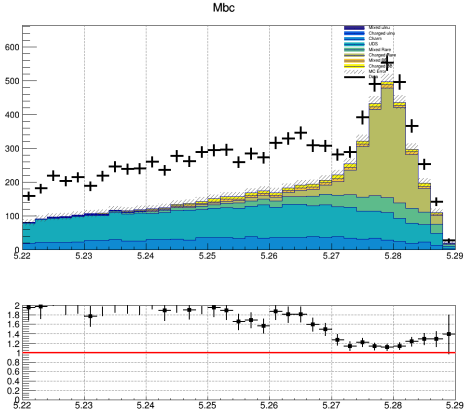


- DECAY.DEC-based substraction result
- Systematic Error not applied

[BaBar]



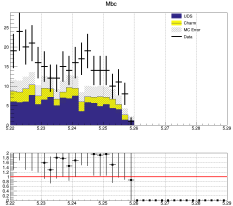
qq Calibration



- M_{bc} of $B^+ \to K^+ a'(\to \gamma\gamma)$ at π^0 mass window
- π^0 veto is applied in inverted way

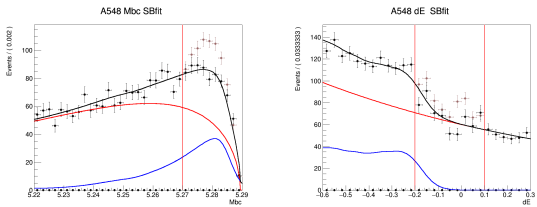
- $q\bar{q}$ seems have large Data/MC discrepancy
- continuum correction with Off-resonance data
- Off-resonance data from Exp 31 to Exp 65

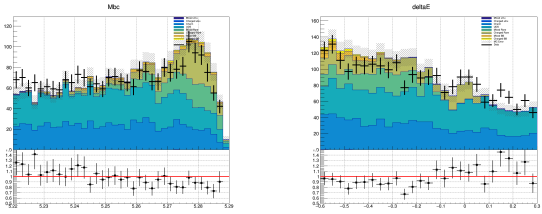
Window	Data/MC Ratio
π^0	1.98
η	2.83
η'	1.49



- Apply correction factor to each mass window dataset :

Control Sample : $B^+ \to K^+\eta(\to \gamma\gamma)$

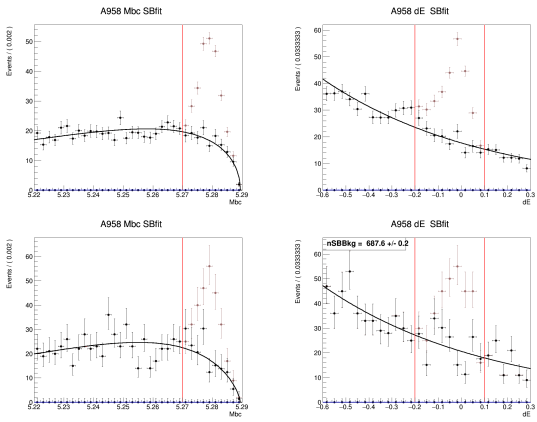




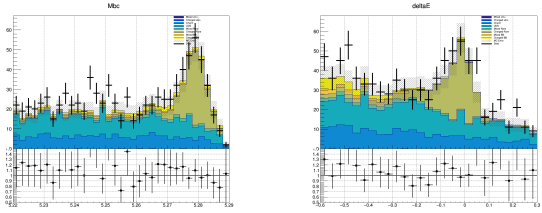
- PDF is normalized in Sideband region
- Projected 1D Sideband histogram scaled to expected value from PDF integration.

$\Gamma(B^+ \to K^+\eta) \times \Gamma(\eta \to \gamma\gamma)(10^{-6})$	
DECAY.DEC	1.06
MC Result	1.36 ± 0.20
MC/DEC ratio	1.28 ± 0.19
PDG	0.94 ± 0.16
Data Result	0.90 ± 0.19
Data/PDG ratio	0.96 ± 0.26
Data/MC ratio	0.75 ± 0.23

Control Sample : $B^+ \to K^+\eta'(\to \gamma\gamma)$

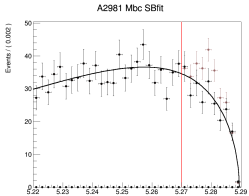


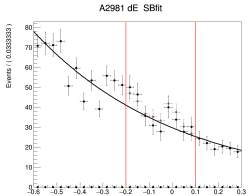
- PDF is normalized in Sideband region
- Projected 1D Sideband histogram scaled to expected value from PDF integration.

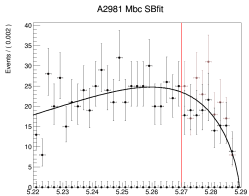


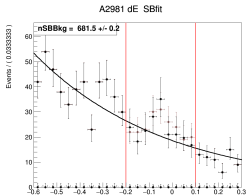
	$\Gamma(B^+ \to K^+\eta') \times \Gamma(\eta' \to \gamma\gamma)(10^{-6})$
DECAY.DEC	1.50
MC Result	1.62 ± 0.15
MC/DEC ratio	1.08 ± 0.10
PDG	1.60 ± 0.01
Data Result	1.62 ± 0.15
Data/PDG ratio	1.01 ± 0.09
Data/MC ratio	0.94 ± 0.12

Control Sample : $B^+ \to K^+ \eta_c (\to \gamma\gamma)$

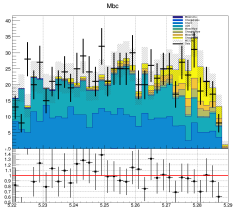


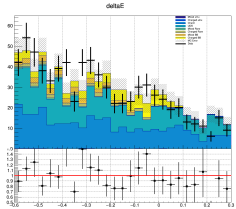






- PDF is normalized in Sideband region
- Projected 1D Sideband histogram scaled to expected value from PDF integration.





$\Gamma(B^+ \to K^+ \eta_c) \times \Gamma(\eta_c \to \gamma\gamma)(10^{-7})$	
DECAY.DEC	3.09
MC Result	2.51 ± 1.04
MC/DEC ratio	0.81 ± 0.34
PDG	1.75 ± 0.18
Data Result	2.24 ± 0.89
Data/PDG ratio	1.28 ± 0.53
Data/MC ratio	1.58 ± 0.93

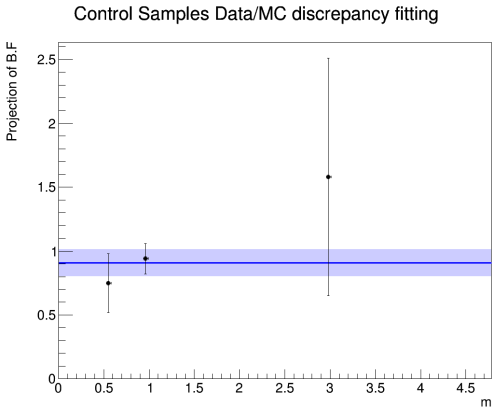
Control Mode Summary

Summary :

- Data and PDG value agreed precisely for η, η' and $\eta_c$control samples.
- Data/MC Discrepancy : 0.908 ± 0.106 for whole mass region

Issues :

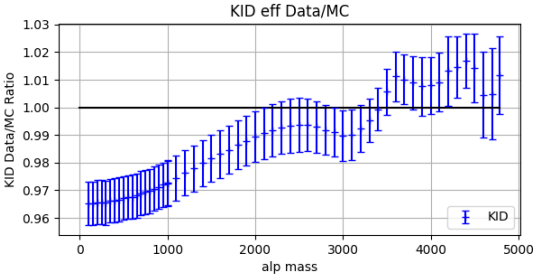
- π^0 Control sample testing was not successful due to ΔE peaking structure –> Use for Calibration Only



[Average descripancy : 0th poly chi2 fitted]

Systematics

Mode	final state	
$K^+ a'$	$K^\pm + 2\gamma$	1 track 2 gammas
$K^0 a'$	$\pi^\pm + \pi^\mp + 2\gamma$	2 tracks 2 gammas
$K^{*0} a'$	$K^\pm + \pi^\mp + 2\gamma$	2 tracks 2 gammas
$K^{*+} a'$	$(\pi^\pm + \pi^\mp) + \pi^\pm + 2\gamma$	3 tracks 2 gammas



Source	error (%)
nBB	1.38
$\Upsilon(4S) \to B^+B^-$	1.17
$\Upsilon(4S) \to B^0\bar{B}^0$	1.23
Photon Detection	2×2
Tracking efficiency	$0.35 \times nTrack$
KID Data/MC	~ 3.6
KID Error	$0.78 \sim 1.64$
K_S^0 recon (nisKsFinder)	1.57
Data/MC discrepancy	10.6
MVA Cut Efficiency	TBD

Total Systematics Error : 11.4 - 11.8%

Status & Plan

Status :

- Background Supression Finalized
- Signal Extraction Method Established
- Signal Extraction Method Validated
- qq Bkg Calibration with Off-resonance Dataset
- Control Mode Validation finished
- Systematics Table ‘almost’ filled up

Plan :

- BN Organizing
- Call for Refree Committee
- Expand to all mass mode

Backup

Selection Criteria

- data skimming for all K mode
- skimming conditions like right
- B2BII conditions :
  - BELLE2_RELEASE = release-05-00-00
  - BELLE_POSTGRES_SERVER = bdb02
  - PGUSER = g0db
  - [INFO] Belle DB server is set to: bdb02

List	Condition
K_S^0	goodBelleKShort
	vertex KFit
	ksnbStandard = 1 (nisKs)
Track	$d0 < 6.0$ and $z0 < 8.0$
K^+	$\mathscr{L}(k\pi) > 0.6$
	$\mathscr{L}(kp) > 0.4$
γ	$E > 0.05$
K^*	$0.7 < M < 1.1$
a'	π^0, η, η' mass region veto
B	$M_{bc} > 5.2$
	$-0.6 < \Delta E < 0.3$

Systematic Study : reference

Source	reference
nBB	nBB
$\Upsilon(4S) \to B^+ B^-$	pdg
$\Upsilon(4S) \to B^0 \bar{B}^0$	pdg
Photon Detection	BN499
Tracking efficiency	BN1165
KID	BN779
PID	BN779
K^0_S recon	BN1472