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

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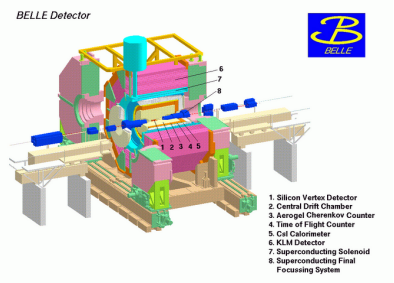
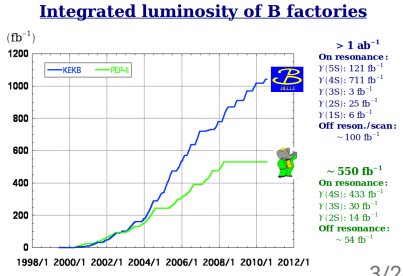
KEKB and Belle Experiment

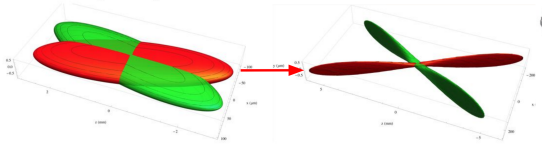
- $8\,\mathrm{GeV}$ HER, $3.5\,\mathrm{GeV}$ LER head-on colliding ($\beta\gamma = 0.42$)
- Energy set to generate $\Upsilon(4S)$ ($10.58\,\mathrm{GeV/c^2}$)
- $\Upsilon(4S)$ decays into $B\bar{B}$ pair ($5.28\,\mathrm{GeV/c^2}$)
- from 1999 to 2010, $711\,fb^{-1}$ integrated luminocity collected, corresponding 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



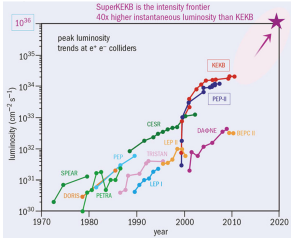


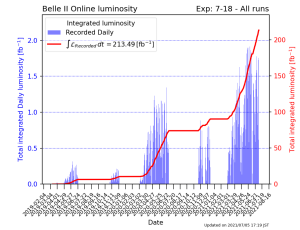
SuperKEKB and Belle II Experiment

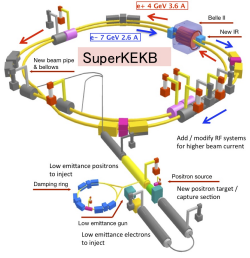
- 7 GeV HER, 4 GeV LER ($\beta\gamma = 0.28$)
- Challenges instantaneous luminocity to $6.5 \cdot 10^{35}\mathrm{cm}^{-2}\mathrm{s}^{-1}$
- More detector layers added, while modifying old detector system.
- PXD, SVD, CDC, ARICH, TOP, ECL, KLM
- Goal : $50ab^{-1}$ integrated

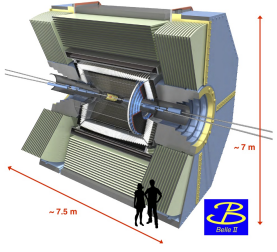


$\sigma_y^* : 940 \rightarrow \sim 50nm$



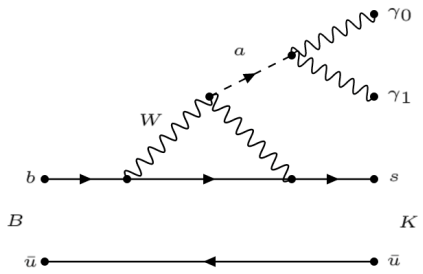






Event generation

- a' stands for **Axion-Like-Particle (ALP)**
- $B^0 \to K^0 a'\ (a' \to \gamma\gamma)$
- $B^+ \to K^+ a'\ (a' \to \gamma\gamma)$ (What we show in this talk)
- $B^0 \to K^{*0} a'\ (a' \to \gamma\gamma)$
- $B^+ \to K^{*+} a'\ (a' \to \gamma\gamma)$
- a' : Spin-less pseudoscarlar particle
- a' : Decay into $\gamma\gamma$ 100%
- $m_{a'}$: $0.1 \sim 1.0$ GeV (0.05 GeV interval)
- $m_{a'}$: $1.0 \sim 3.0$ GeV (0.1 GeV interval)
- Each signal MC sample contains 100K events



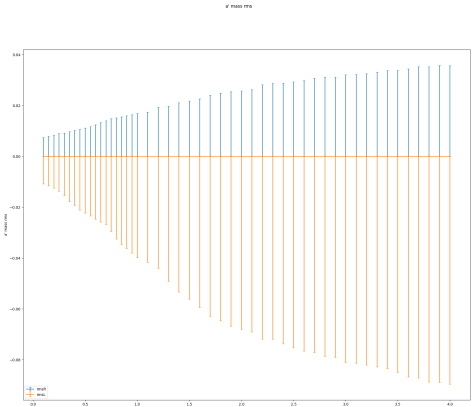
Skim

- 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)

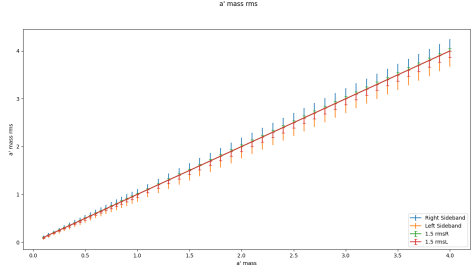
Partilce List	Selection Criteria
K^*	$0.7 < m_{K^*} < 1.1$ GeV
	$K^{*0} \to K^0\pi^0$
	$K^{*0} \to K^+\pi^-$
	$K^{*+} \to K^0\pi^+$
	$K^{*+} \to K^+\pi^0$
ALP	π^0, η, η' region excluded
B	$M_{bc} > 5,26$GeV
	$-0.6 < \Delta E < 0.3$ GeV
	$B^0 \to K^0 a'$
	$B^+ \to K^+ a'$
	$B^0 \to K^{*0} a'$
	$B^+ \to K^{*+} a'$

Analysis Region



- For each a' mass mode, anaysis region should be decided.
- calculate σ for each a' mass sig MC
- $rms = \sqrt{\frac{\Sigma(M_{a'} - m_{a'})^2}{N_{evt}}}$
- Main Band : 2.5 rms^L to 2.5 rms^R
- Side Band : main band width

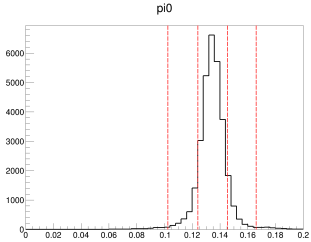
precut	Condition
a' mcPDG	matched
Mbc	5.27~ (GeV)
ΔE	-0.2 ~ 0.1 (GeV)
$M_{a'}$	0.5 ~ 1.2 $\times (m_{a'})$

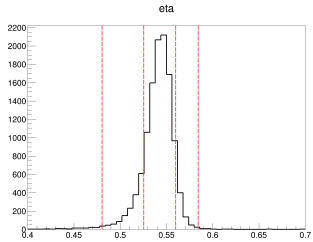


Peaking background veto

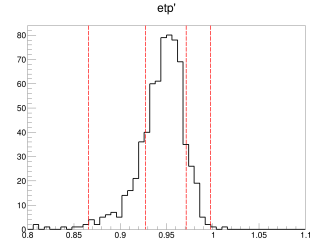
$$\pi^0, \eta, \eta'$$

- major γ pair generating SM background.
- $rms_{\pi^0} = \sqrt{\frac{\sum(M_{\pi^0} - m_{\pi^0})^2}{N_{evt}}}$
- 1.5 RMS of each mass region of peaking background is removed form analysis

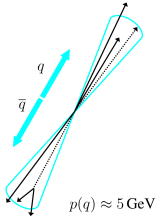


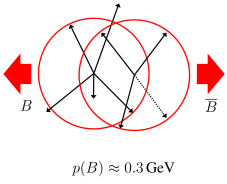


type	veto region (GeV)
π^0	0.102 ~ 0.166
η	0.480 ~ 0.584
η'	0.866 ~ 0.997



Continuum Suppression

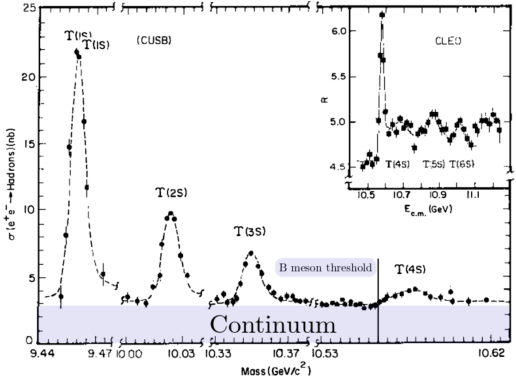




Continuum $(q\bar{q})$ events have to be suppressed to analyse B physics various **Event Shape Variables** are used for continuum suppression

- Thrust and thrust axis
- CLEO Cones
- Fox-Wolfram memoent
- KSFW

But in most of the cases, single variable is not enough to reject continuum events efficiently.



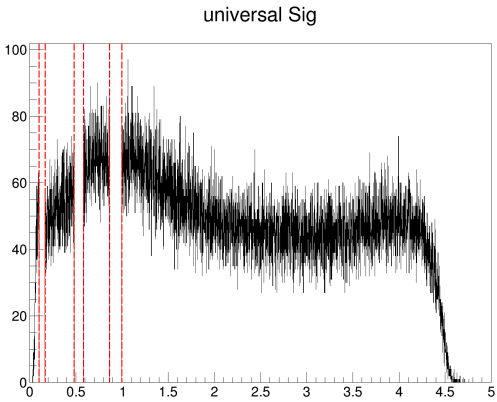
Cross section for hadron production in electron–position collisions with respect to the center-of-mass energy. The energy axis is discontinuous. $B\bar{B}$ pair production occurs above the marked threshold.

Continuum Suppression

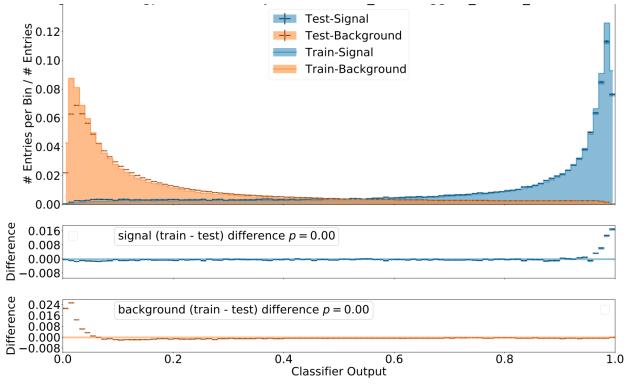
- **MVA**(FBDT) is appied to reject continuum background
- Gernerate mass model independence SigMC
- (0.01~4.5 GeV, 10MeV interval) .
- 100k evts from uniSig MC sample
- 50k evts from CHM/UDS stream01
- Pre-MVA Cuts :

Precut	Conditions
M_{bc}	5.2~
ΔE	-0.6~0.3
E_{asy}	~0.9

- $E_{asy} = \frac{|E_{\gamma 0} - E_{\gamma 1}|}{E_{\gamma 0} + E_{\gamma 1}}$

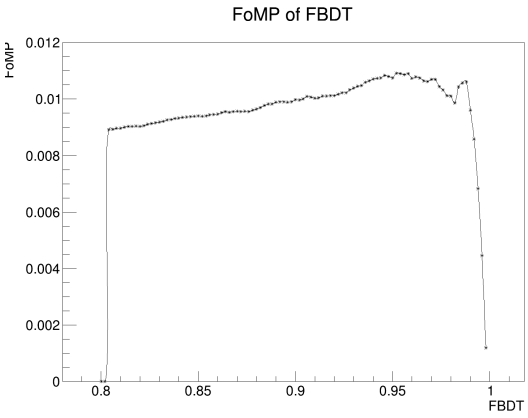


Continuum Suppression



Input variables
$thrustOm$
$cosTBTO$
$cosTBz$
et
$mm2$
$R2$
$KSFW$ (14)
$CleoCone$ (9)
E_{asy}

Optimizing Punzi FoM



Use Punzi FOM for Optimizing CS

- Punzi FoM maximized around 0.95
- unify Punzi FoM cut 0.95 for all mass region
- Fom calc :

Precut	Conditions
Mbc	> 5.27 (GeV)
ΔE	-0.2 ~ 0.1 (GeV)
kopp Prob	< 0.8
Easy	< 0.9

Punzi FoM = $\frac{\epsilon_{sig}}{\sigma/2+\sqrt{N_{bkg}}}(\sigma : 3)$

$M_{a'}$ 1600 MeV representive.

π^0, η veto

MVA for π^0, η Veto

- Koppenburg PEV do not work as expected (B2BII problem?)
- B2 PEV require belle2 variables like 'ZernikeMVA' as mva input
- Need to another method for pi0/eta daughter gamma veto
- Belle I MC dataset + basf2 mva (FBDT)

Precuts	Training DataSet	From	Cuts
$E_\gamma > 0.05$ GeV $E_\gamma^{hard} > E_\gamma^{soft}$	Signal	$B^+ \to K^+ a'$ MC	
goodBellegamma target photon MC matched	Background	GEN+SPE MC	$0.080 < m_{\pi^0} < 0.200\ (\mathrm{GeV/c^2})$ $0.450 < m_\eta < 0.650\ (\mathrm{GeV/c^2})$

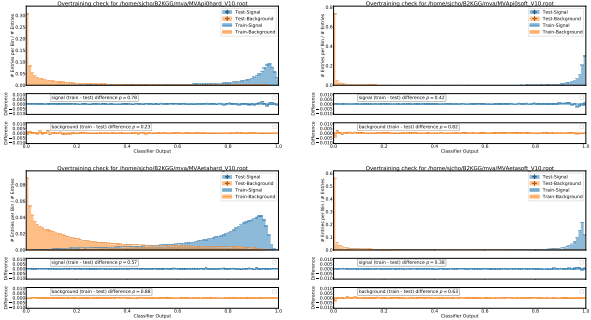
- This MVA expert is not general
- only usable on $B \to K a'$ $(a' \to \gamma\gamma)$ analysis.

π^0, η veto

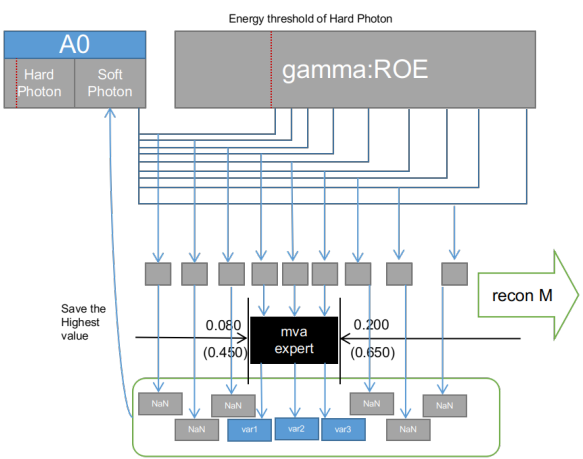
Cluster variables	Kinematic variables
Connected RegionID	p_x
E9E21	p_y
E9E25	p_z
EoP	p
ErrorE	p_t
ErrorPhi	E
ErrorTheta	p_x (CMS)
HighestE	p_y (CMS)
NHits	p_z (CMS)
Phi	p (CMS)
R	p_t (CMS)
Theta	E (CMS)
	E_{asy}

Training PEV

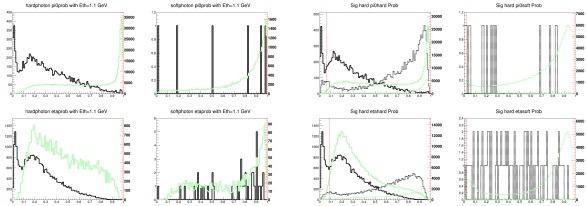
- Target photon (hard/soft) is MC matched before training.
- recon mass is excluded
- recon mass is too powerful that cause the unexpected result



PEV flowchart



If No recon particle pass the mass window
the saved prob value will be “NaN”
and will not show on prob histogram.



- crossprob (hard photon’s π^0/η soft prob. & vice versa) seems useless except SPH (Soft photon’s π^0 Hard photon probabilty)

mode	HPH	SPS	HEH	SES	SPH
$E_{threshold}$	1.1	0.0	1.1	0.0	0.0
sigeff(%)	81	98	24	98	70
bkgrem(%)	27	67	3	86	24

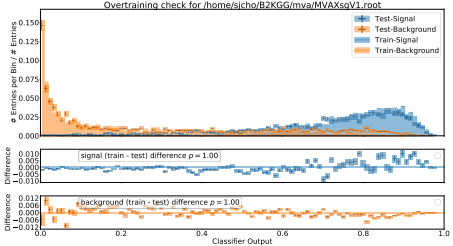
Xsg Veto

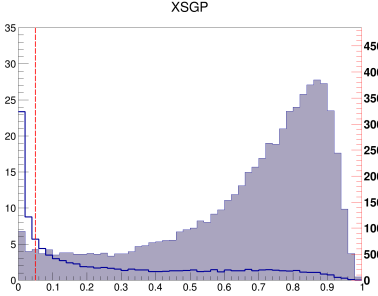
$$X_s\gamma \to K\pi^0\gamma \to K\gamma(\gamma)\gamma$$

can fake the signal event when missing gamma energy is small enough

- not a single variable is enough for veto Xs gamma
- apply another MVA
- Training/Test sample required to pass Continuum Suppression and π^0, η veto

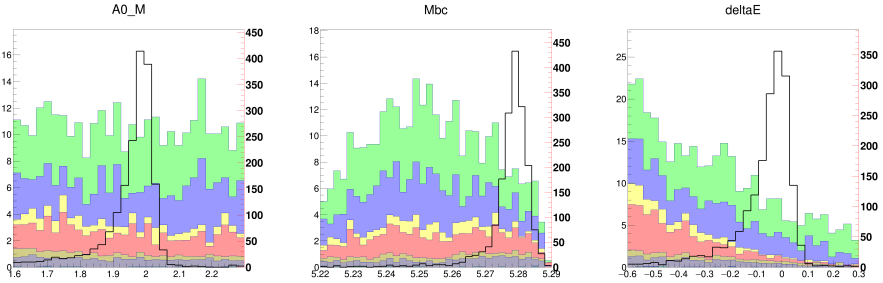
Cluster variables	Kinematic variables
Connected RegionID	$p_x^{(*)}$
E9E21	$p_y^{(*)}$
E9E25	$p_z^{(*)}$
EoP	$p^{(*)}$
ErrorE	$p_t^{(*)}$
ErrorPhi	$E^{(*)}$
ErrorTheta	$E_{asy}^{(*)}$
HighestE	$\Delta\phi$
NHits	Δ Angle
Phi	
R	
Theta	





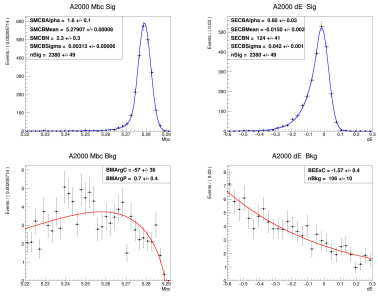
Xsg Veto

remaining evts	#
CHG	53.4
MIX	20.7
CHM	206.8
UDS	281
CR	24.4
MR	9.82
CU	0.4
MU	0.2
BKG	596.75
Eff sig	2.594 %

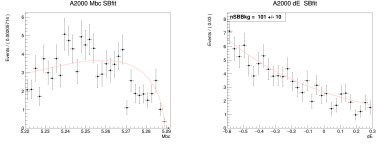


- Cut optimized @ 0.05 (Punzi FoM)
- But instead, use 0.5 cut (already apply too much Punzi FoM)
- **Result shows no peaking background distribution in any histogram**
- histogram and table : representive by $B^+ \to K^+ \eta_C (\to \gamma\gamma)$ Control Sample MC and it's mass region

Signal Extraction



fitting Sig/Bkg pdf on sig/bkg mc



fitting Bkg pdf on bkg mc Sideband

Signal Extraction

obtain # of signal by substracting # of Bkg from # of events in signal region

- Apply $M_{a'}$ cut
- PDF fitted to SB dataset
- fitting : 2D Unbinned Maximum Likelihood Fitting ($M_{bc}, \Delta E$)

$$N_{Bkg}^{MB} = N_{Bkg}^{SB} \times \frac{\int_{MB} pdf}{\int_{SB} pdf}$$

$$N_{Sig} = N_{Tot}^{MB} - N_{Bkg}^{MB}$$

- N_{Bkg}^{SB} : Number of Bkg evts obtained by pdf fitting
- Sig PDF : Cristall Ball X Cristall Ball
- Bkg PDF : ArgusBG X Exponential
- MB : $M_{bc} > 5.27$ && $-0.2 < \Delta E < 0.1$
- SB : $M_{bc} < 5.27$ || $-0.2 > \Delta E$ || $\Delta E > 0.1$

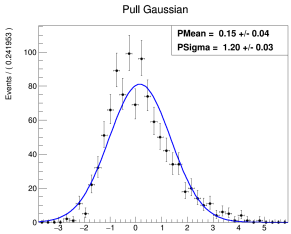
Signal Extraction

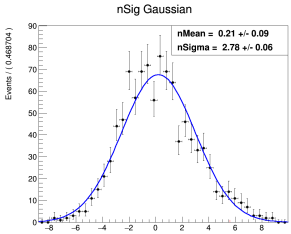
ToyMC Study

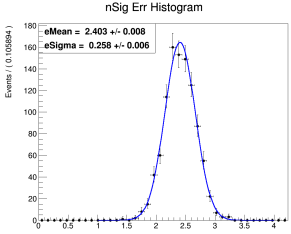
- By generating ToyMC samples with Data PDF (from previous slide)
- We can test our fitter's robustness
- and also can get signal yield distribution
- with it's Error / Pull distribution

Data	Value
nSig Mean	0.212
nSig 95CL UL	5.5965
Expected B.F.	1.15e-08
Expected 95CL UL	3.05e-07

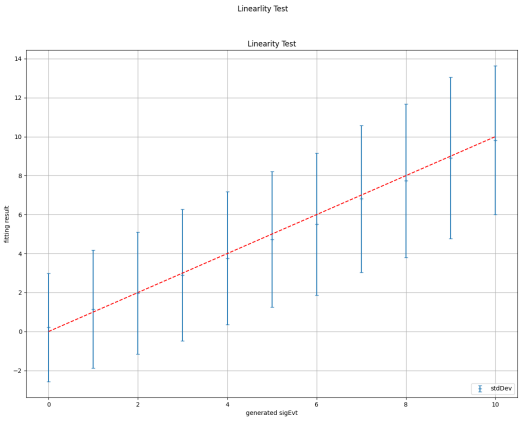
- N_{sig}^{95CL} : x with $\frac{\int_0^x nSigGauss}{\int_+ nSigGauss}$ = 0.95
- B.F. : $\frac{N_{sig}}{N_{BB} \times \epsilon_{sig}}$, $N_{BB} = 772M$







Linearity Test



Linearity Test

- By generating ToyMC samples with Data PDF
- DataPdf = *nTest* * SigPdf + BkgPdf
- We can test our fitter's sensitivity
- result show fitter result mean is sensitive to nSig in 0.5 evt
- But we have a large sigma comes frome Bkg level
- need to reduce Bkg level to reduce nSig Error

conclusion and plan

- conclusion
  - MC data generated and skimmed
  - FBDT MVA trained for CS
  - FBDT MVA trained for pi0 eta veto
  - FBDT MVA trained for Xsg veto
  - Sideband substraction Seems work for now
- plan
  - Get Expected U.L of B.F for each mass region
  - Apply to K0. K* signal mode
  - Systematic study

Back UP

Variables

Selection Criteria	Description
$\|d0\|$	Signed distance to the point of closest approach (POCA) in the $r-\phi$ plane
$\|z0\|$	z coordinate of the POCA
eIDBelle	Belle electron likelihood
muIDBelle	Belle muon likelihood
$muIDBelleQuality$	muIDBelle quaility flag
$\mathscr{L}(ij)$	Belle atcPID $\mathscr{L}_i/(\mathscr{L}_i+\mathscr{L}_j)$
$goodBelleGamma$	dependent energy selection for Belle data and MC (50/100/150 MeV)
goodBelleKShort	$0.468 < M < 0.528$ GeV,Vertex fit not failed
$M_{d'}$ cut	$3 \times RMS$ of π^0, η, η' mass distribution
M_{bc}	$\sqrt{(E_{\mathrm{beam}}/2)^2 - \vec{\mathrm{p}}_B^{\,2}}$, Beam constraint mass for signal side B
ΔE	$(E_{\mathrm{beam}}/2) - E_B$

Continuum Suppersion Variables

Variable	Description
thrustOm	Magnitude of the ROE thrust axis
cosTBTO	Cosine of angle between thrust axis of the signal B and thrust axis of ROE
cosTBz	Cosine of angle between thrust axis of the signal B and z-axis
et	Transverse energy
mm2	Missing mass squeared
R2	Reduced Fox-Wolfram moment R2
KSFW (14)	Kakuno-Super-Fox-Wolfram
CleoCone (9)	variables based on the sum of the absolute values of the momenta of all particles within thrust axis 9 concentric cones