BELLE II
Italian collaboration

Measurement of the Branching Fraction ($B^0/\overline{B}^0 \to pp\overline{pp}$) @ BaBar and prospects @ Belle II

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Master Thesis Project

Outline

- Motivation
- Status of analysis
- Prospects @ Belle II
- Outlook

Motivation

1) B → *baryons* puzzle

- *Inclusive*: total fraction of B decays to baryons was measured in 1992 by ARGUS, **(6.8±0.6)%** (avg. B^0 , B^+)
- *Exclusive*: many channels have been studied, sum only **(0.53±0.06)%** B^0, **(0.85±0.15)%** B^+

Puzzle unsolved!

Motivation

2) Strong Interaction

- Large B mass → large **spectrum** of baryons, different flavors

  ($b \to cX$ dominant weak decay , final states with charmed baryons and mesons are enhanced);

- Better understanding of **hadronisation** into baryons

  ($q\bar{q}$ pairs produced out of vacuum, similar to jet **fragmentation**)

  – theoretical models (pole model, QCD sum rule) are only qualitatively understood.

- **Features**

  (1) Branching Fractions increase with multiplicity of final states;

  (2) Baryon-antibaryon mass threshold enhancement (especially in three-body decays, it explains the enhanced rate and the dibaryon mass distribution → see Backup Slides)

Previous Results @ BaBar

- (Gruenberg et al., 2014) http//dx.doi.org/10.1103/PhysRevD.89.071102

  Measured upper limit for $\mathfrak{B}(\bar{B}^0 \to \Lambda_c^+ p \bar{p} \bar{p})$: 2.8×10^{-6} @0.90 CL

- Useful for rough estimate of $\mathfrak{B}(B^0 \to p p \bar{p} \bar{p})$, only considering Cabibbo suppression:

  $\mathfrak{B}(B^0 \to p p \bar{p} \bar{p}) \sim |V_{ub} / V_{cb}|^2 \cdot \mathfrak{B}(\bar{B}^0 \to \Lambda_c^+ p \bar{p} \bar{p}) \sim 0.01 \cdot \mathfrak{B}(\bar{B}^0 \to \Lambda_c^+ p \bar{p} \bar{p}) \sim 10^{-8}$

- It might be enhanced by Phase Space contribution (→ See table in slide 6)

Why $B^0 \to p p \bar{p} \bar{p}$?

- *4 Baryon Final State*

  Apart from Gruenberg study, it is the only baryonic channel with such baryon mulitplicity to be analysed
- There is still no Upper Limit on PDG…

Status of analysis: Expected BF

MODE	$\bar{B}^0 \to \Lambda_c^+ \; p \bar{p} \bar{p}$	$B^0 \to p p \bar{p} \bar{p}$	Scaling factor $BF(B^0 \to p p \bar{p} \bar{p})/BF(\bar{B}^0 \to \Lambda_c^+ p \bar{p} p)$
Weak Interaction	$b \to c$ $V_{cb} = (40.6 \pm 1.3)x10^{-3}$	$b \to u$ $V_{ub} = (3.89 \pm 0.44)x10^{-3}$	$\|0.1\|^2 = 0.01$
Phase Space	• Heavier mass for Λ_c^+ $(M_B - 3m_p - m_\Lambda \sim 0.186$ GeV)	• Lower mass for proton, $(M_B - 4m_p \sim 1.52$ GeV)	1.52/0.186 ~8.2 (assuming phase space element goes linearly with energy, further investigation needed)
Reconstruction efficiency	• Only $\Lambda_c^+ \to p K \pi$ has been reconstructed • BF ~ 5% of all Λ_c^+ • $\varepsilon = (3.5 \pm 0.1)$ %	• Good tracking of protons with momenta > 100 MeV • ε ~ 35 %	~10

→ Working hypothesis: assumed BF($B^0 \to p p \bar{p} \bar{p}$) $\sim 10^{-7}$

Status of analysis: Event Reconstruction

$B^0 \to p\,p\,\bar{p}\,\bar{p}$

MC & Data Samples:

- Signal MC : official request for SP-11894 mode complete, 687 000 events produced (decay model: Phase Space);
- Background MC: $B^0/\bar{B}^0$ generic, B^+/B^- generic, *uds*, $c\bar{c}$
- BABAR data: AllEventsSkim-Run[1-6]-OnPeak-R24c-v07 ($N_{B\bar{B}} = 471 \times 10^6$)

Sample	Generated events
Signal $B^0 \to pp\bar{p}\bar{p}$	687k
$B^0/\bar{B}^0$	92.2M
B^+/B^-	101.2M
uds	101.7M
$c\bar{c}$	105M

Not whole statistics available used yet!

Initial preselection in the reconstruction code:

- Proton List: 4 protons *pCombinedVeryLoose* *
- Successful kinematic fit to form a common vertex
- Large preliminary cuts on m_{ES}, ΔE

Observed variable	Signal efficiency= #truth-matched / #generated
m_{ES}	(38.50 ± 0.06) %

*particle list generated from a combination of PID selectors (likelihood, boosted decision tree based) of Very Loose tightness level.

Status of analysis: Selection

$B^0 \to p\,p\,\bar{p}\,\bar{p}$

Previous results from cuts based selection:

- Varied variables: ΔE, B vertex probability, PID tightness
- Cuts motivated from Signal MC shaping
- Event shape variables cuts tested
- Best significance: 0.887422

Selection Upgrade

- Different methods of Multivariate Analysis (MVA) tested, Boosted Decision Tree based method (**BDT**) is the best performing.
- BDT method trained on the reconstructed candidates in the *signal region* to optimize Background rejection.
- Input variables (→ distribution plots in the backup slides):
  - ΔE
  - B vertex probability
  - Vertex z coordinate
  - Vertex radius
  - $Cos\theta_B^{CM}$
  - Event shape variables (FoxWolfram, $|cos\theta_{THRUST}|$)

Signal region , **s.r. = [5.27, 5.29 GeV/c^2]**

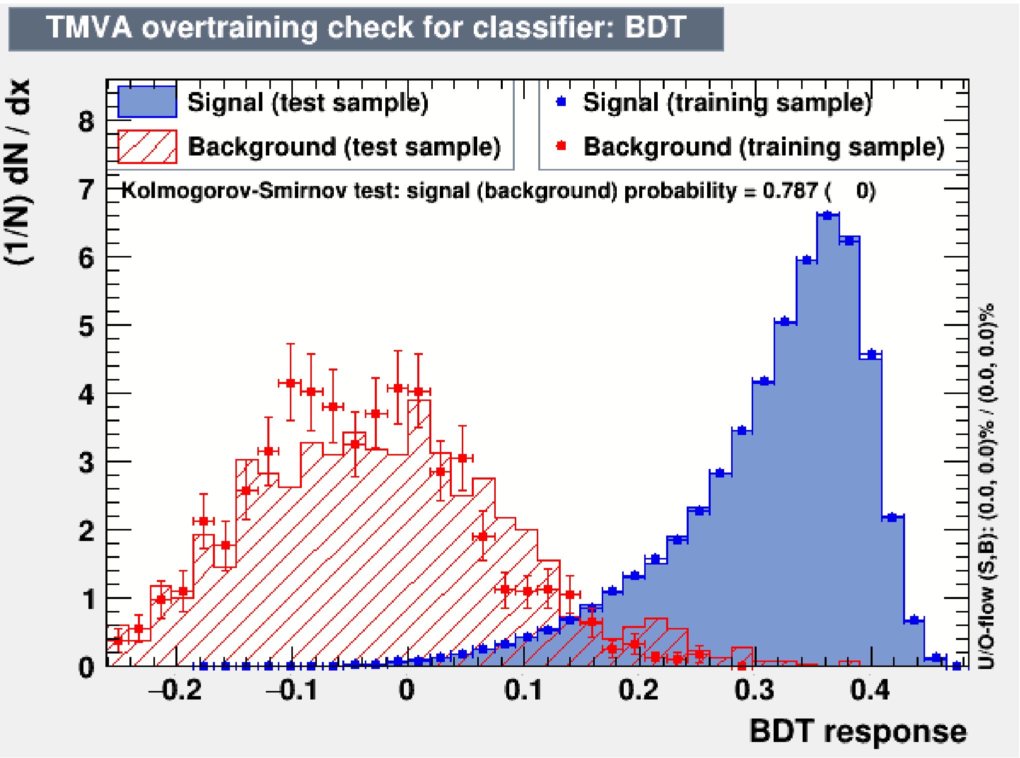
Training performance evaluated on #signal = S and #background = B events expected in **s.r.** , at data integrated luminosity (~ 426 fb^{-1})!

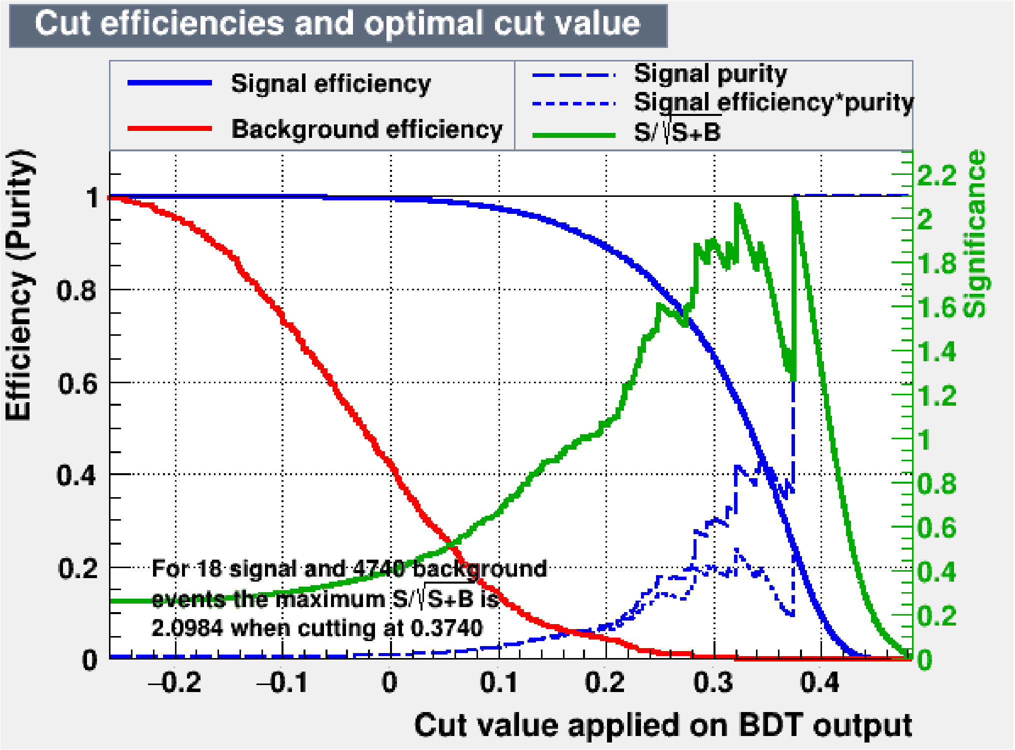
→ S = 18, B = 4580

Status of analysis: BDT training $B^0 \to p\,p\,\bar{p}\,\bar{p}$

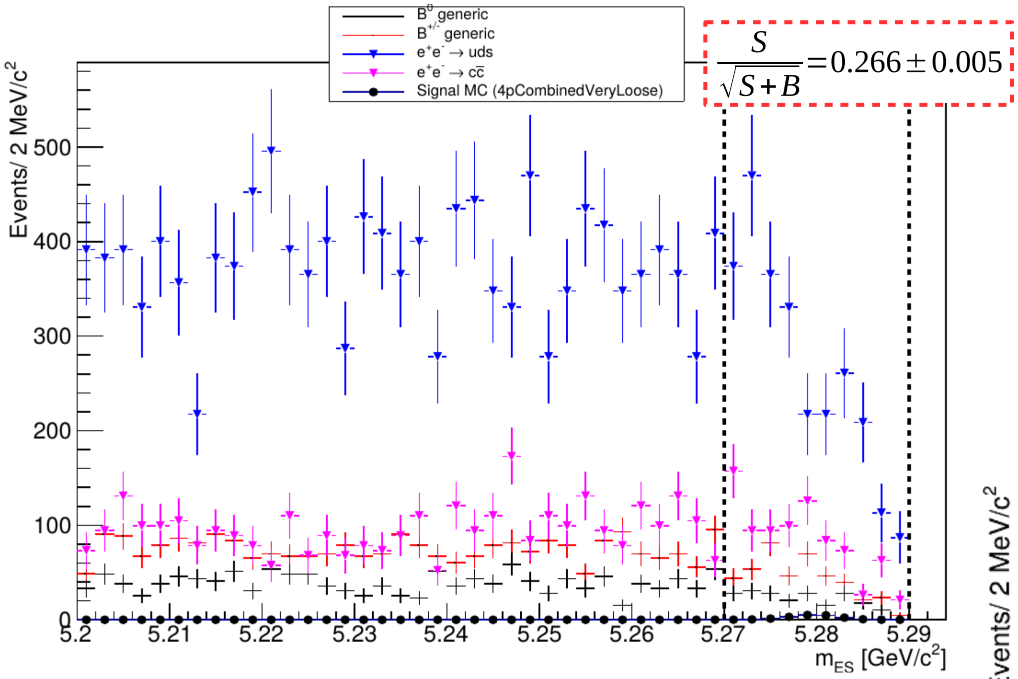
- BDT response from MVA Training for a number of signal and background events S = 18, B = 4580:

MVA Method	Optimal cut	$\frac{S}{\sqrt{S+B}}$	ε_{sign}	ε_{bkg}	N_{sign}	N_{bkg}
BDT	0.3740	2.09841	0.2446	0	4.403339	0





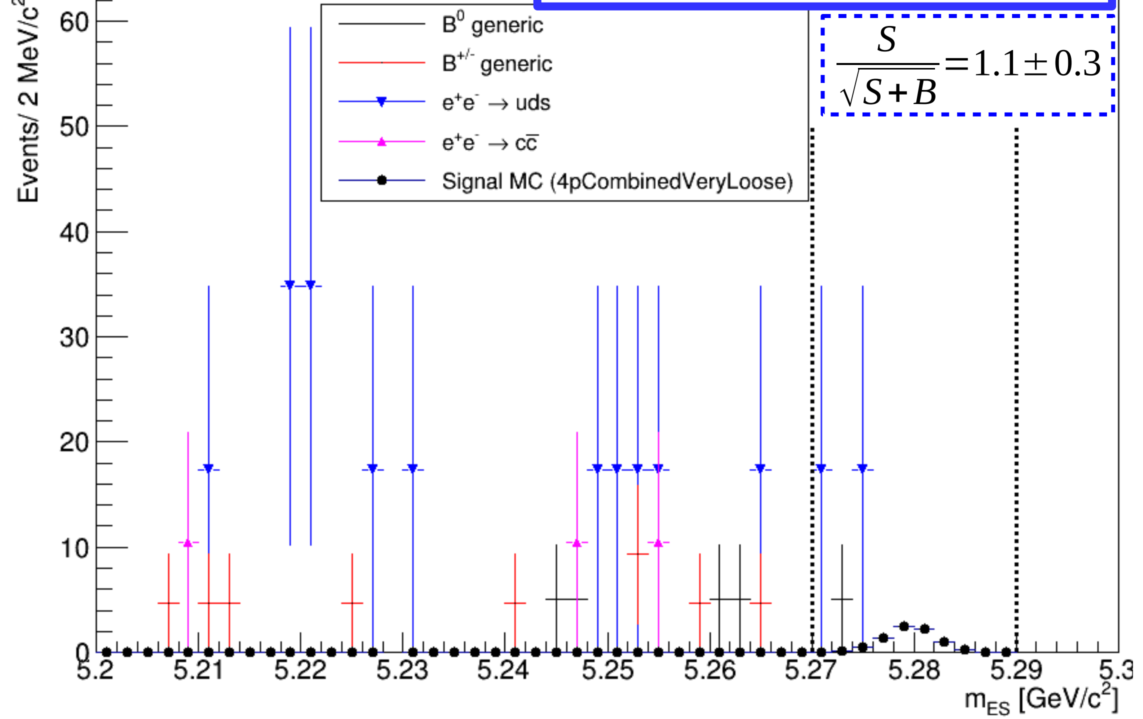
Status of analysis: Selection applied on m_{ES}



Sample	Events in [s.r.] (scaled to data lumi)	
	Before BDT	After BDT
$B^0 \to pp\bar{p}p$	18.03 ± 0.04	7.82 ± 0.03
$B^0/\bar{B}^0$	253 ± 25	5 ± 5
B^+/B^-	512 ± 34	0 ± 0
uds	2966 ± 161	35 ± 25
$c\bar{c}$	849 ± 67	0 ± 0
Bkg *tot*	4580 ± 180	40 ± 25

- m_{ES} distributions for Signal and Background: only **initial preselection** and tag *GoodTracksVeryLoose** on all tracks applied (top left), after BDT selection (bottom right).
- All histograms scaled to BaBar integrated luminosity [Run 1-6] ~ 426 fb^{-1} (471 M $B\bar{B}$).

BDT selection



* Charged Tracks with Max DOCA in XY plane: |1.5 cm|, Max DOCA on Z axis: |2.5 cm|

Prospects @ Belle II

$$BF=\frac{N_{SIGN}}{\epsilon\cdot N_{B\bar{B}}}$$

$$B^0\rightarrow p\,p\,\bar{p}\,\bar{p}$$

THE OPTIMISTIC CASE:

- BDT performance $_{BaBar}$ = BDT performance $_{Belle\ II}$;
- Optimal background rejection (assuming BDT training response);
- $N_{sign} = N_{obs} - N_{bkg}$
- $\sigma_{sign}^2 = N_{obs} + N_{bkg} = (xsection_{sign} + xsection_{bkg})\cdot Luminosity$

$$\rightarrow \left(\frac{\sigma_{BF}}{BF}\right)^2=\left(\frac{\sigma_{sign}}{N_{sign}}\right)^2=\frac{k}{Lumi} \qquad k=\frac{xsection_{bkg}+xsection_{sign}}{(xsection_{sign}-xsection_{bkg})^2}\sim\frac{1}{\epsilon_{sign}}\cdot\left(a+b\cdot\frac{\epsilon_{bkg}}{\epsilon_{sign}}\right)\sim\frac{1}{\epsilon_{sign}}$$

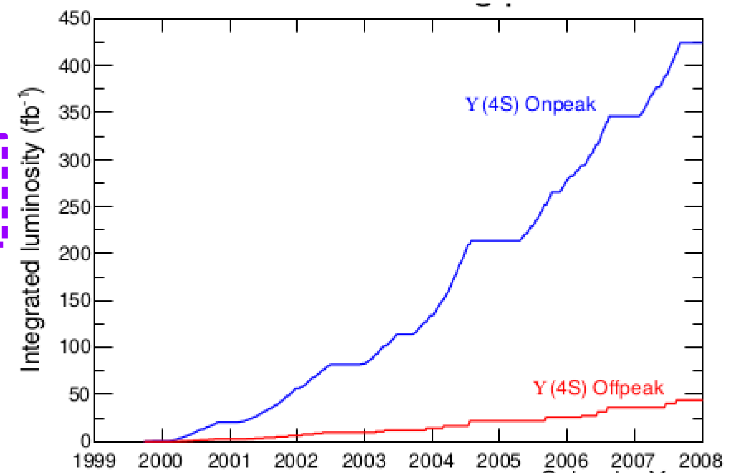
- ➢ Statistical uncertainty of BF will scale as $\frac{1}{\sqrt{Lumi}}\cdot\sqrt{k}$
- ➢ Efficiency is assumed to be constant and to have no uncertainty
- ➢ Rough estimate of improvement factor for $\left(\frac{\sigma_{BF}}{BF}\right)_{stat}$ from BABAR → Belle II:

$$\frac{\sqrt{Lumi_{BaBar}}}{\sqrt{Lumi_{BelleII}}}=\sqrt{\frac{0.423\,ab^{-1}}{50\,ab^{-1}}}\sim\frac{1}{10}$$

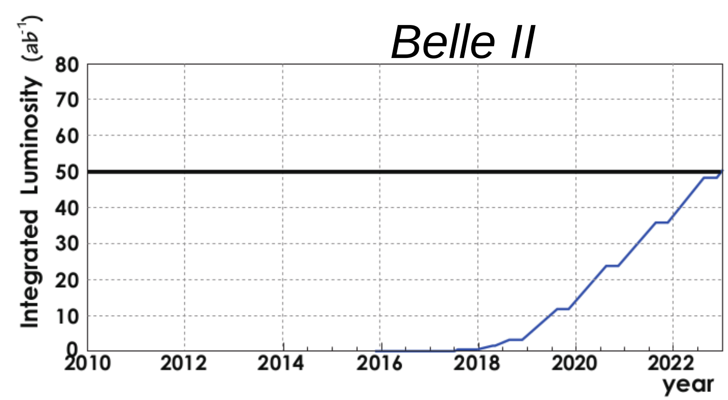
$$\left(\frac{\sigma_{BF}}{BF}\right)_{stat}^{BaBar}\sim\frac{1}{\sqrt{7.82}}=0.358$$

$$\left(\frac{\sigma_{BF}}{BF}\right)_{stat}^{BelleII}\sim\left(\frac{\sigma_{BF}}{BF}\right)_{stat}^{BaBar}\cdot\frac{1}{10}=0.0358$$

BaBar



Belle II



Prospects @ Belle II

$B^0 \to p\, p\, \bar{p}\, \bar{p}$

Belle II

THE (more) REALISTIC CASE:

- BDT performance $_{\text{BaBar}}$ ≠ BDT performance $_{\text{Belle II}}$

$$\left(\frac{\sigma_{BF}}{BF}\right)^2_{Belle\ II} = \left(\frac{\sigma_{sign}}{N_{sign}}\right)^2 = \frac{k'}{Lumi} \;\rightarrow\; \left(\frac{\sigma_{BF}}{BF}\right)_{Belle\ II} = \left(\frac{\sigma_{BF}}{BF}\right)_{BaBar} \cdot \sqrt{\frac{k'}{k} \cdot \frac{1}{10}} \;\rightarrow\; \frac{k'}{k} \sim \frac{\epsilon_{sign}^{BaBar}}{\epsilon_{sign}^{Belle\ II}}$$

k'/k ~ 1 ?

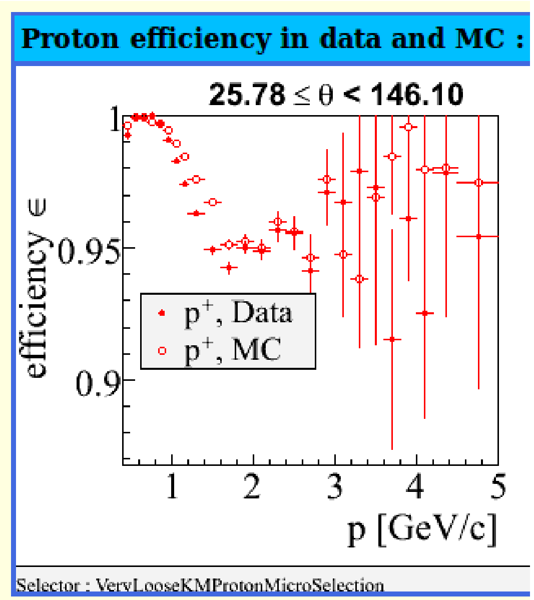
- Efficiency is not a constant:
  - Energy dependence (**different boosts**: shift in momentum distributions for B decays particles → not so relevant for p @ 1 GeV/c);
  - Detector acceptance (BaBar acceptance ~ **conservative** estimate!);
  - PID efficiency for protons @ ~ 1 GeV (→ momentum distributions in backup slides)

BaBar	Provided Info	Belle II
SVT	dE/dx, p	Pixel + SVD
DCH	dE/dx	CDC
DIRC	$\cos\theta_c$	TOP + ARICH

- BaBar:
  → best analysis sensitivity with *pKM* selector (BDT based algorithm)
  → $\epsilon_{p/\bar{p}}$ (1 GeV/c) > 0.99
  → $misID_{p/\pi} < 0.001$, $misID_{p/K} < 0.005$
- Belle II (**not final numbers!**) :
  → ϵ (1 GeV/c) p/π ~ 0.96/0.02
  → ϵ (1 GeV/c) p/K ~ 0.94/0.02

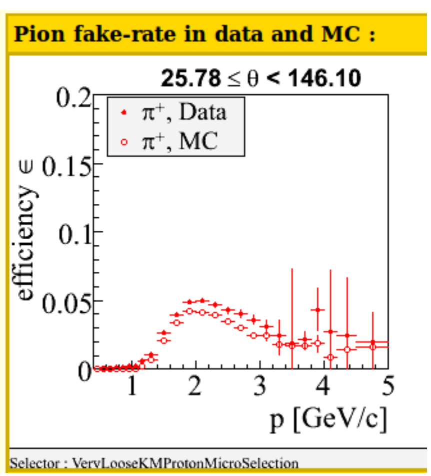
Prospects @ Belle II

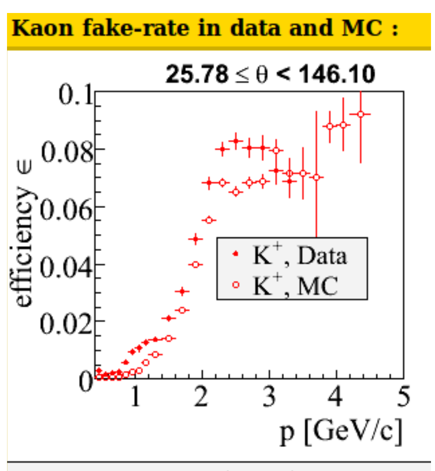
$B^0 \rightarrow p\, p\, \bar{p}\, \bar{p}$

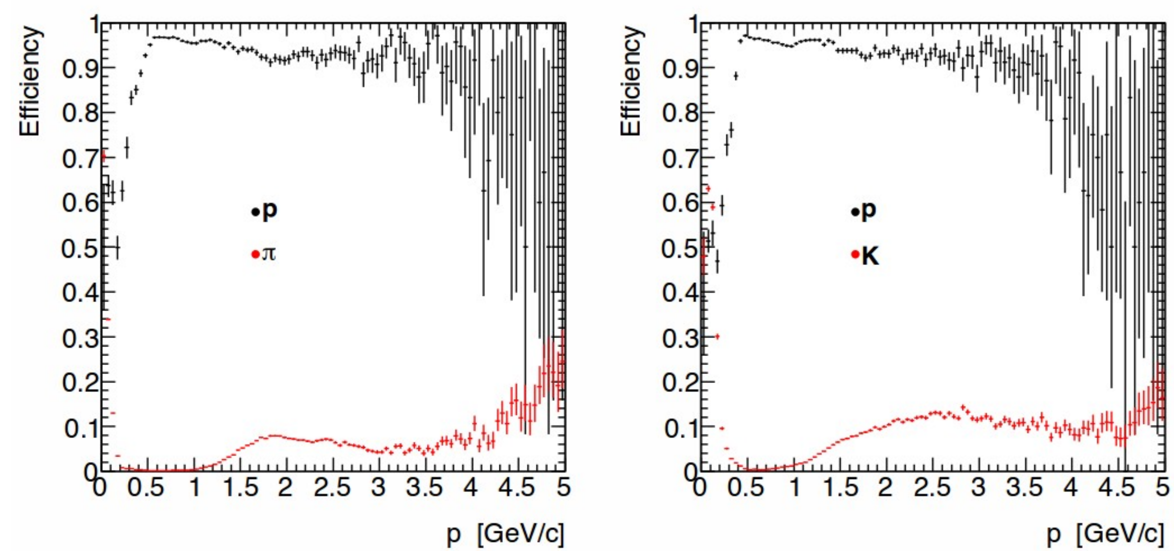


BaBar Wiki Page, Plots for R24 processed data (analysis-51)

- BaBar efficiency and misID probability Vs momentum for *pKMVeryLoose* selector are shown in blue and yellow boxes on the left.
- Belle II PID combined efficiency Vs momentum, calculated for the nominal background regime (BGx1).
  (Left plot p/π and right plot p/K separation)
- Beams background impact on Belle II PID performance not yet clear from MC studies.



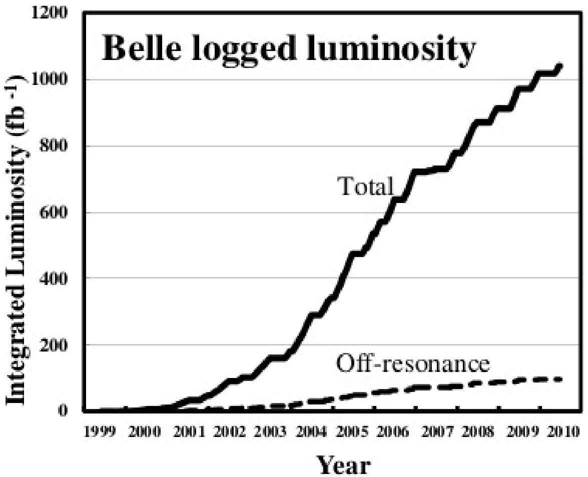




Plots shown in J.Bennet's "Combined Performance" talk, B2GM February 2016

Analysis performance @ Belle

$B^0 \rightarrow p\,p\,\bar{p}\,\bar{p}$



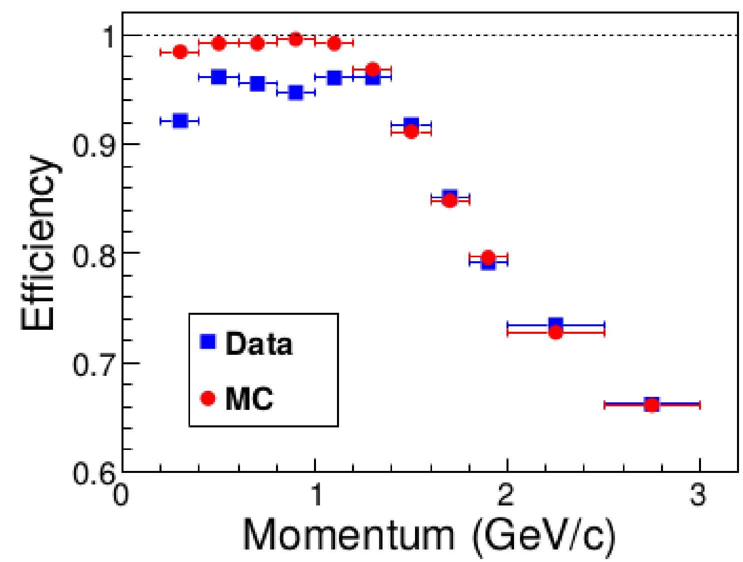
… What with Belle lumi (1 ab^{-1})?

$$\frac{\sqrt{Lumi_{BaBar}}}{\sqrt{Lumi_{Belle}}} = \sqrt{\frac{0.423\,ab^{-1}}{1\,ab^{-1}}} \sim 0.65$$

$$\left(\frac{\sigma_{BF}}{BF}\right)^{Belle}_{stat} \sim \left(\frac{\sigma_{BF}}{BF}\right)^{BaBar}_{stat} \cdot 0.65 = 0.23$$

BaBar	Provided Info	Belle
SVT	dE/dx, p	SVD
DCH	dE/dx	CDC
DIRC	$\cos\theta_c$ / #photons	TOF, ACC

- BaBar:
  → best analysis sensitivity with *pKM* selector (BDT based algorithm)
  → $\epsilon_{p/\bar{p}}$ (1 GeV/c) > 0.99
  → $misID_{p/\pi}$ < 0.001, $misID_{p/K}$ < 0.005
- Belle:
  → PID based on likelihood ratios L(α:β) referred to combined info from CDC, TOF, ACC
  → ϵ (1 GeV/c) > 0.98



(c) Proton identification.

Summary & Outlook

AS concerns BaBar analysis:

- ✓ Selection almost finalized on BaBar analysis (to add whole statistics for sample MC);
- ➔ Further studies to validate MVA results on MC with results on data from side band region / offpeak (BaBar data sample);
- ➔ Analysis Strategy: one-dimensional unbinned likelihood fit to m_{ES} ;
- ➔ Study of Systematic Uncertainties.

Work in progress!

Further invastigation on prospects @ Belle II:

- ➢ Study of the original background composition (before PID) @ BaBar → estimate Belle II expected background using Belle II misID probabilities for protons (have to clarify numbers!);
- ➢ B vertex probability → improved SVD resolution impact?
- ➢ Analysis performance @ Belle?

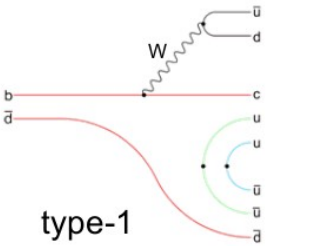
Thank you for your attention.

Backup Slides

Theoretical Models

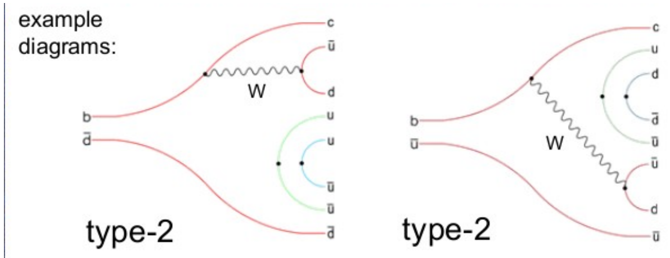
- Two-body baryon-antibaryon decay

Mechanism	Type	Suppression
W- emission	Nonfactorizable, Internal	No Color suppressed (totally antisymmetric wave function)
W- penguin transition	b → s(d)	Cabibbo
W- exchange	Neutral B mesons	Helicity suppressed
W- annhilation	Charged B	Helicity Suppressed



- Three-body decay (baryon-antibaryon+meson)

Mechanism	Type	Suppression
W- emission	1 , External (2 diagrams) 2 , Internal (8 diagrams)	Color suppression can occur
W- penguin transition	b → s(d)	Cabibbo



Status of analysis: Cuts-based Selection

$B^0 \rightarrow p\,p\,\bar{p}\,\bar{p}$

Selection type is defined by the type of cut applied → "**cutXYZ**"

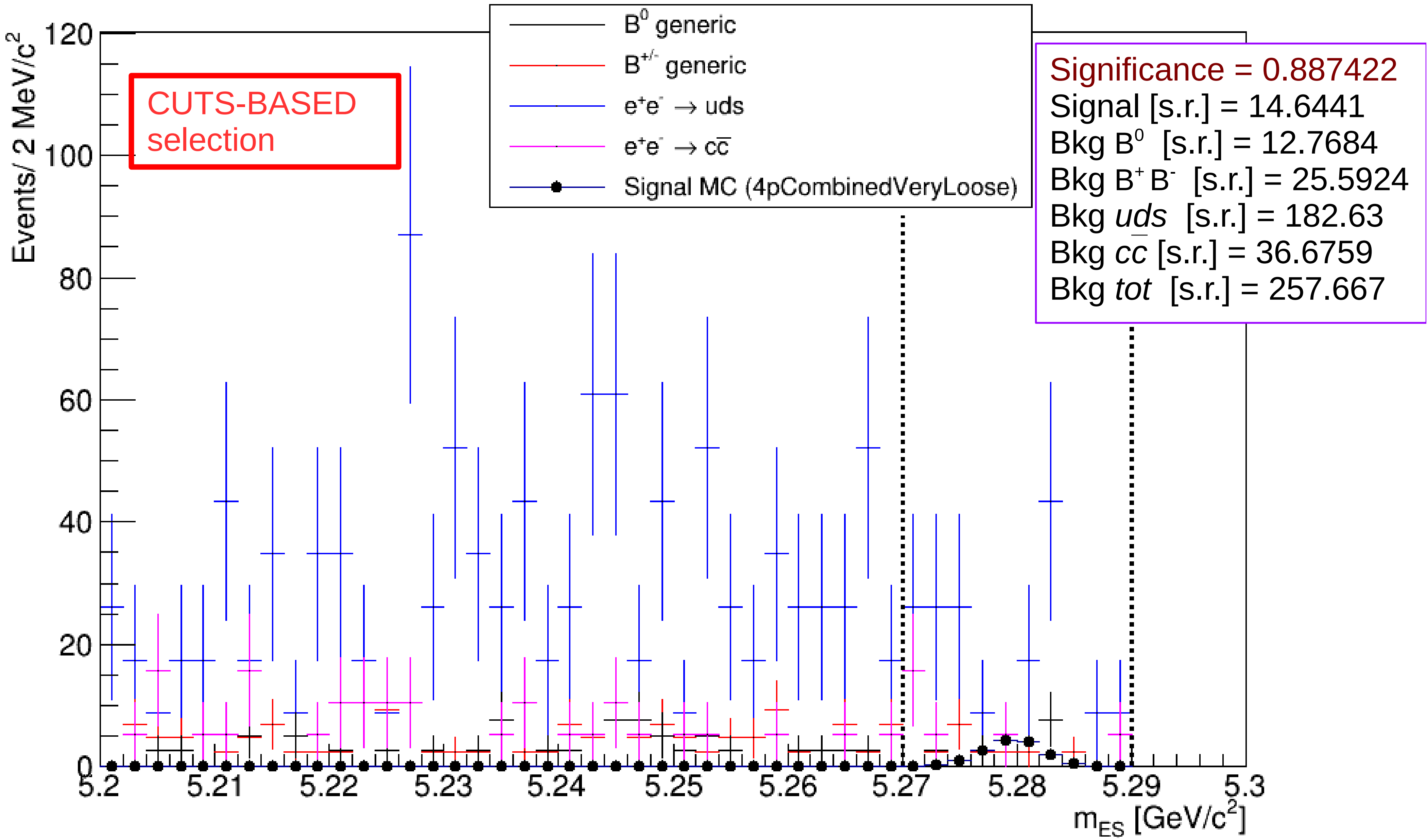
- X, Y, Z are integers representing the tightness of cut applied for each varied variable;
- Cuts on kinematic variables are motivated from Signal MC shaping;
- Significance increases with reduced ΔE window, but decreases with tighter cut on B vertex probability and PID
- Best selection (event shape discrimination added):

Cuts combination	Significance
Cut321	0.793052
Cut321 + FoxWolf < 0.5	0.887422

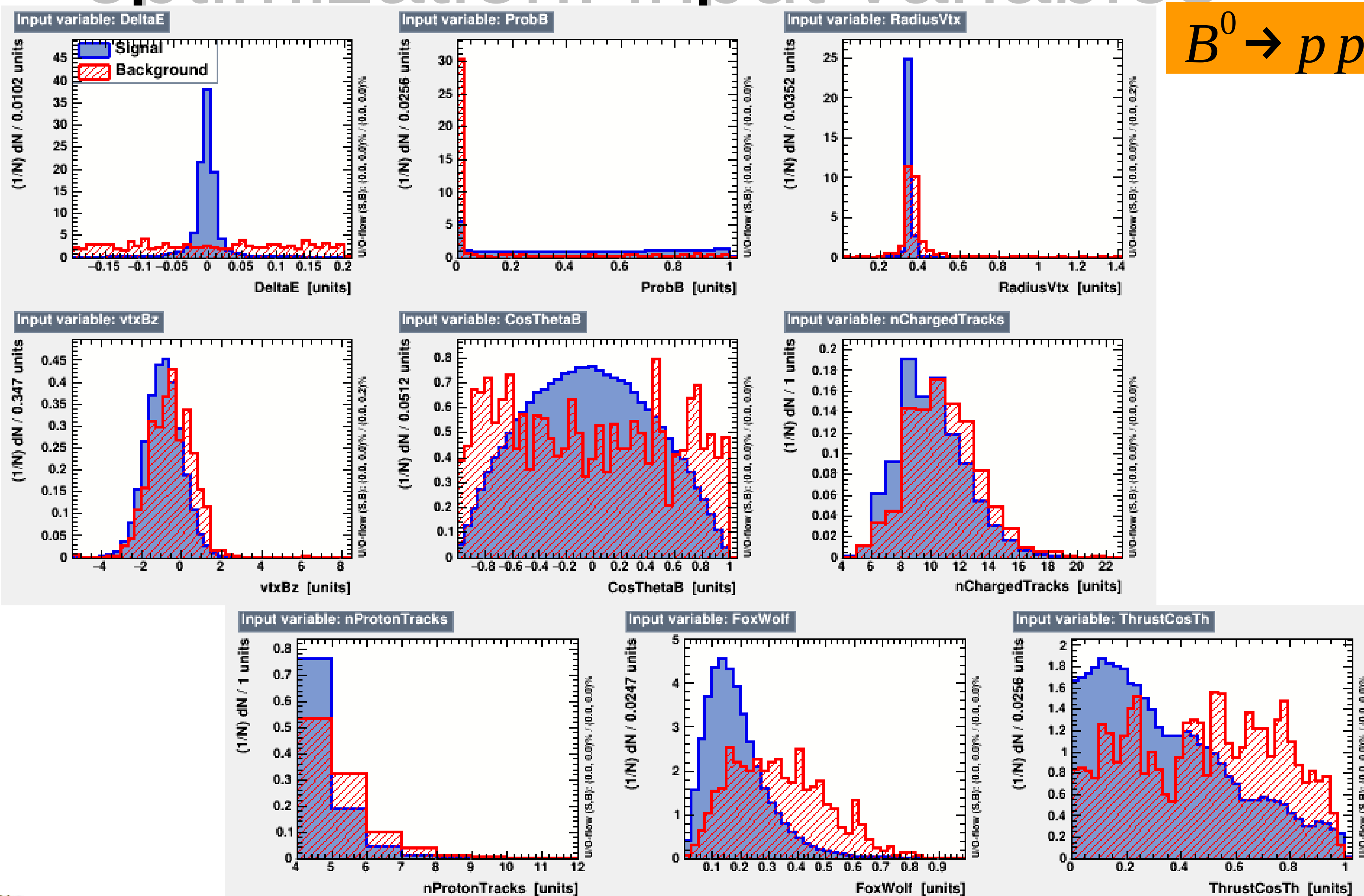
Varied variable	0	1	2	3
X = ΔE	N/A	|ΔE| <0.1	|ΔE| <0.05	|ΔE| <0.03
Y = B vertex prob	N/A	ProbB > 0.00001	ProbB > 0.001	ProbB > 0.01
Z = PID	Default (pCombinedVL)	4 protons KMSuperLoose	4 protons KMVeryLoose	N/A

	Events in signal region [scaled to data lumi]]						Significance
Selection Type	Signal = S	$B^0/\bar{B}^0$	B^+/B^-	*uds*	$c\bar{c}$	Bkg_{tot} = B	$\frac{S}{\sqrt{S+B}}$
cut110	16	77	128	1096	194	1494	0.425804
cut120	16	69	114	1044	173	1399	0.430523
cut130	15.7	61	102	1018	157	1338	0.427714
cut210	16	38	72	470	121	701	0.602771
cut220	15.8	33	65	461	110	669	0.60374
cut230	15.4	26	58	461	105	649	0.595788
cut320	15.2	18	35	296	63	411	0.73673
cut221	15.4	26	49	357	89	520	0.664252
cut222	14.6	26	49	330	89	494	0.649249
cut321	14.8	13	26	244	52	334	0.793052
cut322	14	13	26	244	52	334	0.757609

Status of analysis: Selections applied on m_{ES}



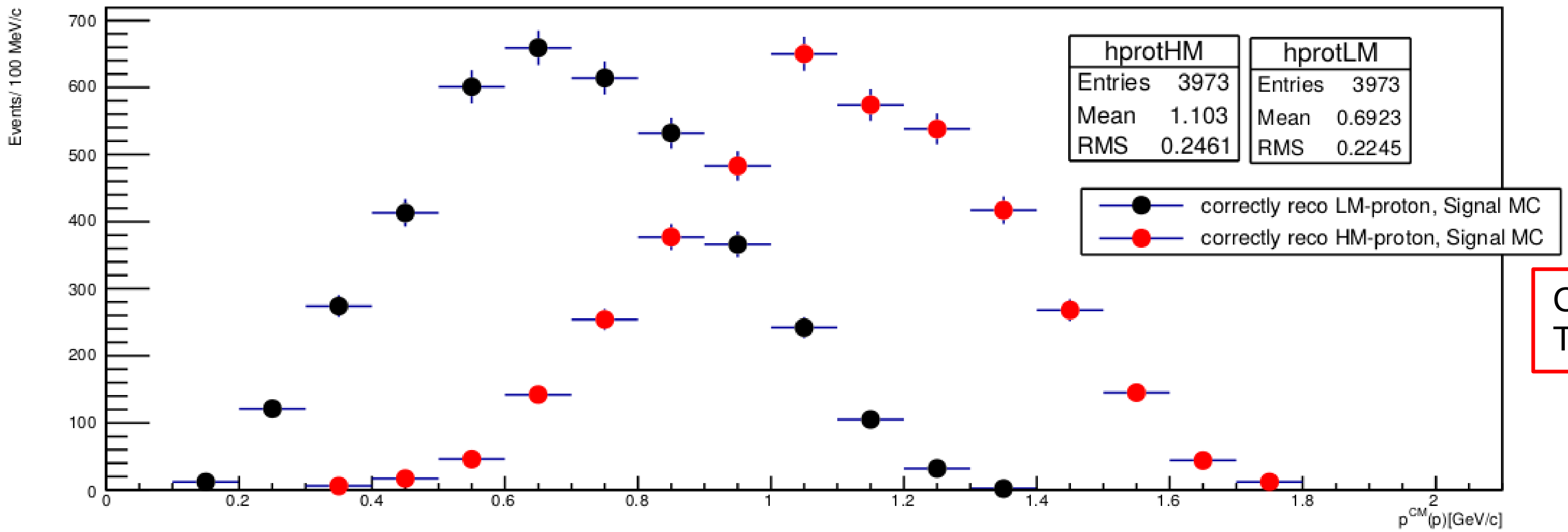
MVA background rejection optimization: input variables



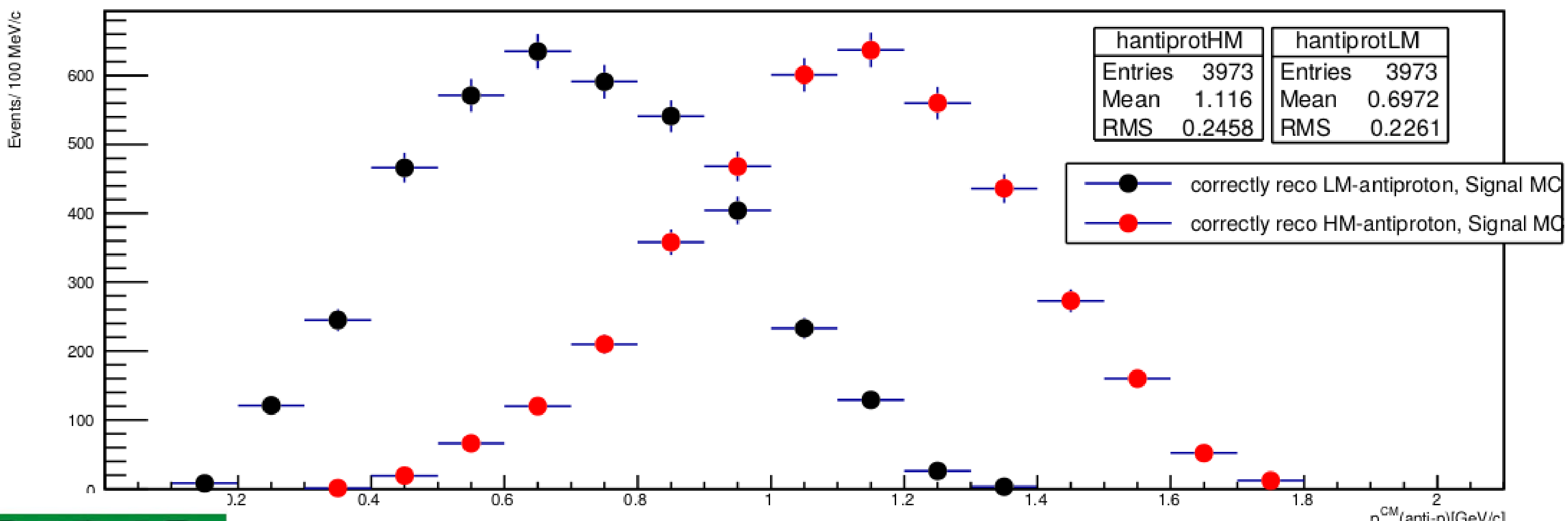
$B^0 \rightarrow p\, p\, \bar{p}\, \bar{p}$

Momentum distributions

$B^0 \to pp\bar{p}\bar{p}$



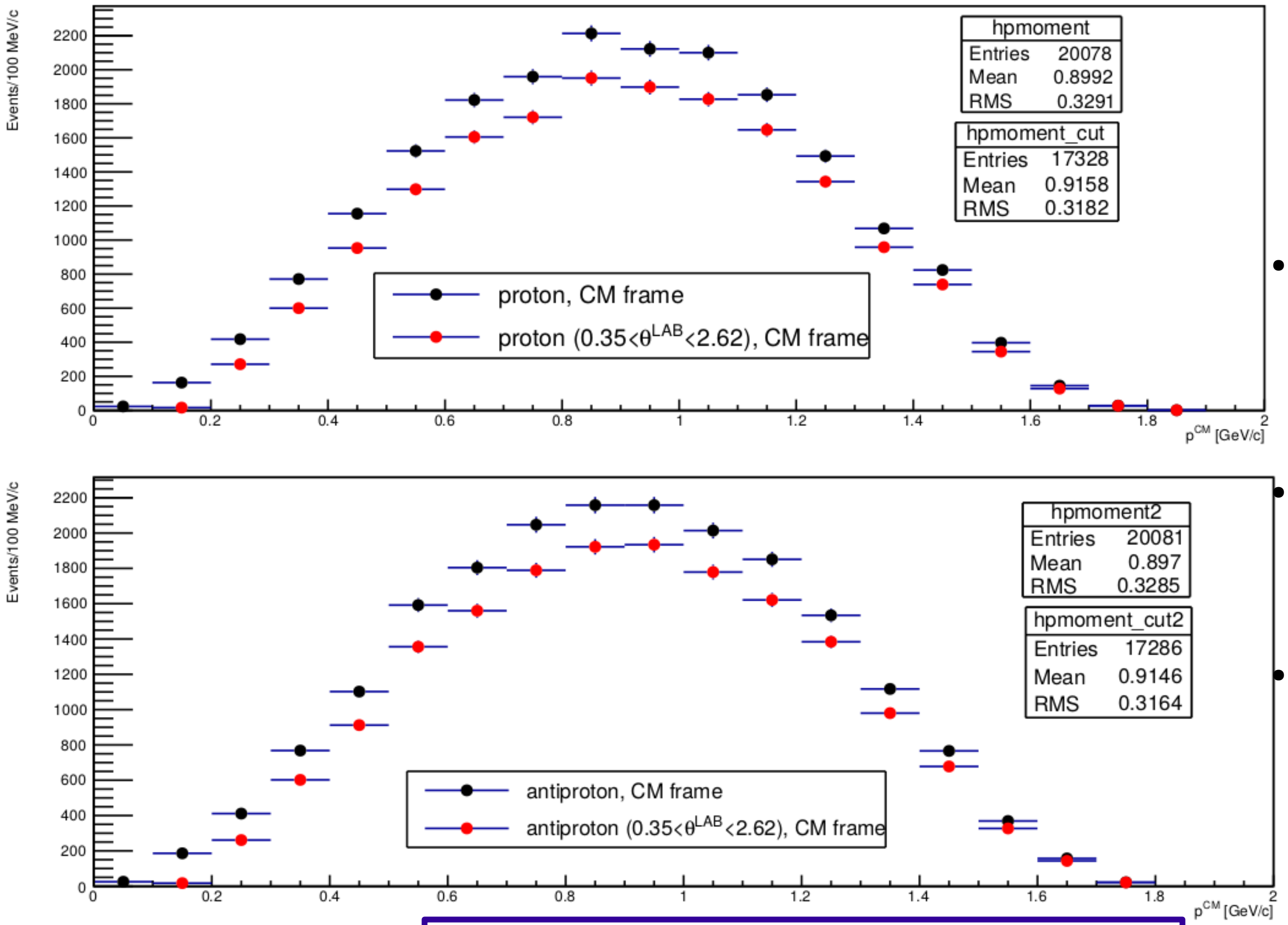
CorrectlyReco= Truthmatched



BABAR

MC studies: Geometrical Acceptance

$B^0 \to p\, p\, \bar{p}\, \bar{p}$



$$\epsilon_p = 0.863 \pm 0.002, \epsilon_{anti\,p} = 0.861 \pm 0.002$$

FIDUCIAL REGION:

- Geometrical acceptance (loss in polar angle coverage due to detector dead region):

  $0.35 < \theta^{LAB} < 2.62$ rad

- ChargedTracksAcc cut (from reconstructed tracks list):

  $0.41 < \theta^{LAB} < 2.54$ rad

- p_T threshold (GoodTracksLoose list):

  $p_T > 50$ MeV

MC studies: Acceptance $B^0 \rightarrow p\,p\,\bar{p}\,\bar{p}$

- Rough estimate of acceptance for 4 tracks: $Accept_{tot} = \epsilon_p^2 \cdot \epsilon_{anti\ p}^2 = 0.552 \pm 0.003$

- The calculated acceptance is the theoretical maximum of efficiency, only detector geometry constraints have been imposed;

- Investigate tracking contribution from Online Prompt Reconstruction lists:

  - *ChargedTracks* reconstruction efficiency+Acceptance:

    $\epsilon_p = 0.860 \pm 0.002, \epsilon_{anti\ p} = 0.816 \pm 0.003$ $\quad \epsilon_{ChTrk} = \epsilon_p^2 \cdot \epsilon_{anti\ p}^2 = 0.493 \pm 0.003$

  - *pCombinedVL* reconstruction efficiency + Acceptance:

    $\epsilon_p = 0.841 \pm 0.003, \epsilon_{anti\ p} = 0.789 \pm 0.003$ $\quad \epsilon_{pVL} = \epsilon_p^2 \cdot \epsilon_{anti\ p}^2 = 0.441 \pm 0.003$

Additional channel

Maximum efficiency achievable (from MC acceptance studies) = 55%

→ *RELAXING PID requirements is not such a big improvement BUT good to extend analysis target:*

- $p\bar{p}$ from *pCombinedVeryLoose* list + 2 *ChargedTracks* with opposite charges and study both: $B^0 \rightarrow pp\bar{p}\bar{p}$, $B^0 \rightarrow p\bar{p}\pi^+\pi^-$

Why $B^0 \rightarrow p\,\bar{p}\,\pi^+\pi^-$?

- Only UL on PDG [CLEO, PhysRevLett.62.8, Issue 1, January 1989]: $BF < 10^{-4}$
- Why has it never been measured before by BaBar?
- Previosly @Babar: Hartmann et al.(2013), [BaBar-PUB-12/028, SLAC-PUB-1536 *Study of the decay $\bar{B}^0 \rightarrow \Lambda^+_c \bar{p}\pi^+\pi^-$ and its intermediate states*]: measured BF ($\bar{B}^0 \rightarrow \Lambda^+_c \bar{p}\pi^+\pi^-_{\text{non-res}}$) = $(79 \pm 4 \pm 4 \pm 20) \times 10^{-5}$