Search for the B-meson decay to four baryons

$B^0 \to p\,p\,\bar{p}\,\bar{p}$ *at* BABAR

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on behalf of the BABAR *Collaboration*

Outline

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

- *BABAR* experiment
- Motivation
- Analysis Method
- Result
- Conclusion

Submitted to PRD!
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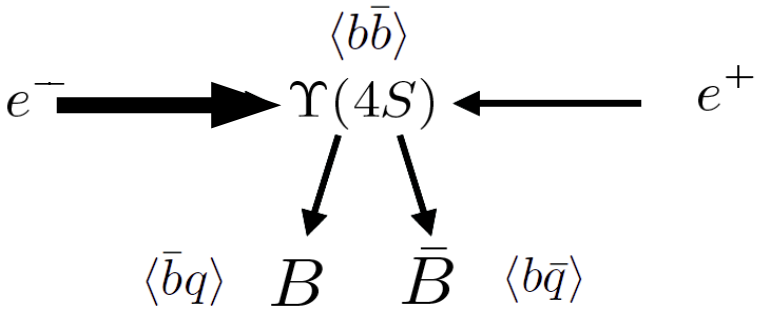
Experiments at the B-factories

B-factories: dedicated experiments at *e^+e^- asymmetric-energy colliders* for the production of quantum coherent $B\bar{B}$ pairs → **CPV studies** and **NP indirect** searches.

$$e^+e^- \to \Upsilon(4S) \to B\bar{B}$$



$\tau_B \approx 1.5 \times 10^{-12}\,\mathrm{s}$

First generation of B-factories

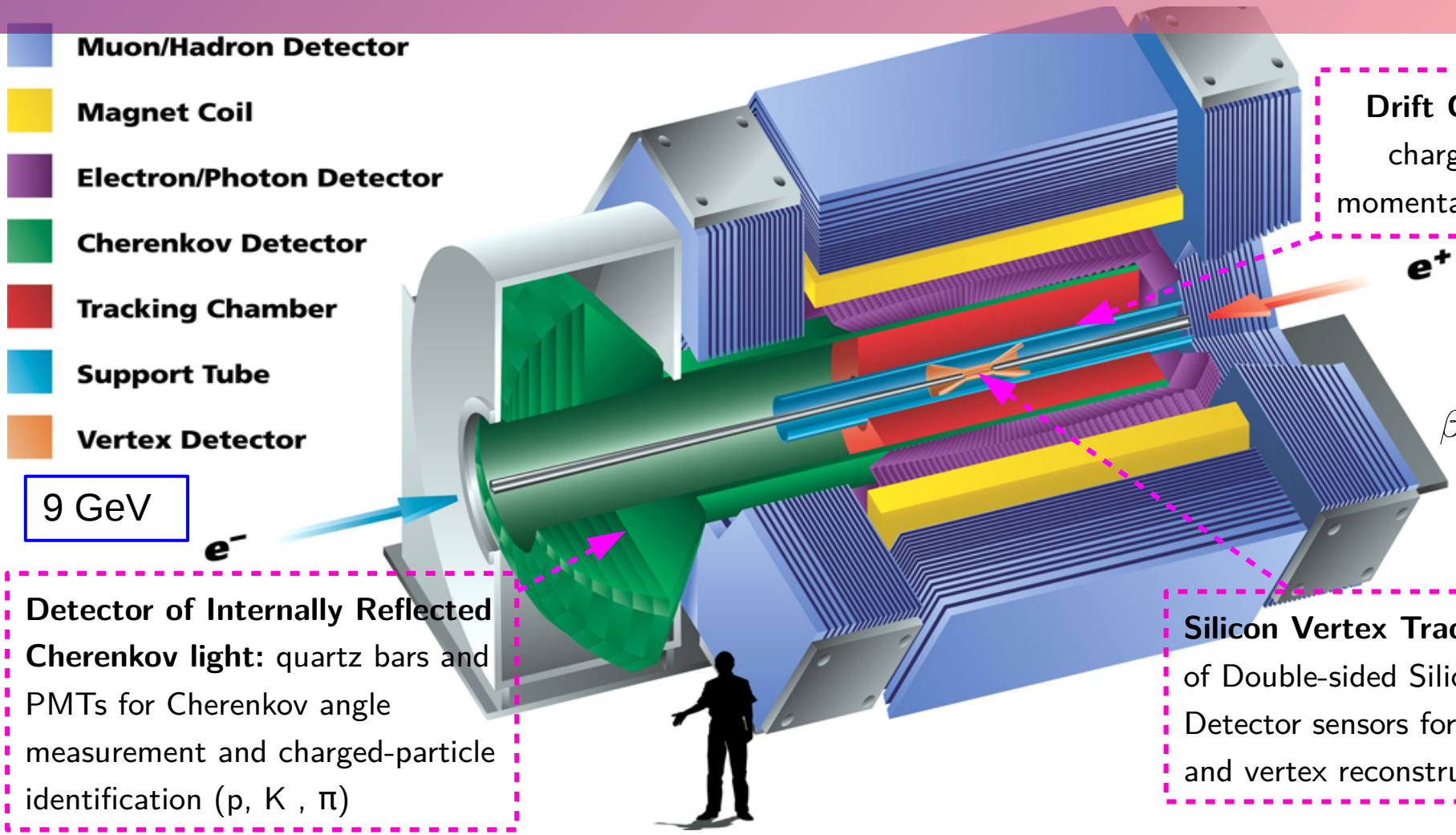
at the KEKB collider, (KEK, Japan)

at the PEP II collider (SLAC, California)

In its 9-year operation (1999-2008), the BaBar experiment collected:

- 424 fb^{-1} ***on-peak*** at $\Upsilon(4S)$ mass, $\sqrt{s}$=10.58 GeV → 471 million $B\bar{B}$ pairs.
- 44 fb^{-1} ***off-peak***, *below $B\bar{B}$ threshold*, $\sqrt{s}$ = 10.54 GeV

The *BaBar* Detector



Drift Chamber for charged-particle momenta measurement

$\beta\gamma \sim 0.56$

Detector of Internally Reflected Cherenkov light: quartz bars and PMTs for Cherenkov angle measurement and charged-particle identification (p, K , π)

Silicon Vertex Tracker: 5 layer of Double-sided Silicon Strip Detector sensors for tracking and vertex reconstruction.

Clean environment allows **outstanding tracking** and **vertex** reconstruction; dE/dx, $\cos\theta_C$ measurements provide **excellent Particle IDentification** performance → *high efficiency* with pion *mis-identification rate* below 1% at any momentum.

Motivation

- B-mesons have large mass and they are able to decay to final states with *baryons*

  $\rightarrow$ optimal laboratory for better understanding the mechanism of ***hadronization into baryons*** (theoretical models poorly understood) [**]

- ***Baryon puzzle***: inclusive branching fraction (~7%) ≠ Σ exclusive branching fraction of baryonic channels (~1%)

- Experimental features: ***threshold enhancement*** and ***branching fraction (BF) hierarchy***

[**] V.L. Chernyak and I.R. Zhitnitsky, Nuclear Physics B, Vol. 345, 1 pp. 137-172 (1990); He Xiao-Gang, Li Tong, Li Xue-Qian and Wang Yu-Ming, Phys. Rev. D, 75, id. 034011 (2007).

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

Previous measurement at *BABAR*:

- Upper limit on BF($\bar{B}^0 \to \Lambda_c^+\ p\,\bar{p}\,\bar{p}$) $< 2.8\times10^{-6}$ at 90% CL

BABAR, Phys. Rev. D 89, 071102 (2014)

Estimate of the BF($B^0 \to p\,p\,\bar{p}\,\bar{p}$):

- Cabibbo suppression, b $\to$ u decay
- Phase space contribution, using the Q-values of the 2 reactions

- Clean signature $\to$ 4 charged tracks from the same vertex
- Potential benefit from threshold enhancement

Working hypothesis for selection optimization:

$$\mathcal{B}(B^0 \to pp\bar{p}\bar{p}) \approx \mathcal{B}^{UL}(\bar{B}^0 \to \Lambda_c^+ \bar{p}p\bar{p}) \cdot \frac{|V_{ub}|^2}{|V_{cb}|^2} \cdot \frac{Q_{pp\bar{p}\bar{p}}}{Q_{\Lambda_c^+ p\bar{p}\bar{p}}} \sim 10^{-7}$$

No PDG limit yet!

Analysis Strategy and Dataset

1) **Event reconstruction**: 4 protons fitted to a common vertex

2) **Selection**: kinematic variables related to B decays, angular distribution and event shape

3) **Fitting procedure**: modeling signal shape in m_{ES}

4) **Signal yield extraction** and branching fraction calculation

MONTE CARLO (MC):

(At least 3 x data luminosity)

- Generic B decays from $\Upsilon(4S)$ *[EvtGen]*
- continuum events $e^+e^- \to q\bar{q}$ *[JetSet]*
- Signal sample: $e^+e^- \to B^0\bar{B}^0$, with one B decaying to $pp\bar{p}p$

$\to$ efficiency estimate and modeling of the signal shape

DATA:

- Full dataset (*on-peak data, 471M* $B\bar{B}$)
- Performed as *blind analysis*, without looking at the **signal region** in data

  ($5.27 < m_{ES} < 5.29$ GeV/c^2)
- **Side band region data**

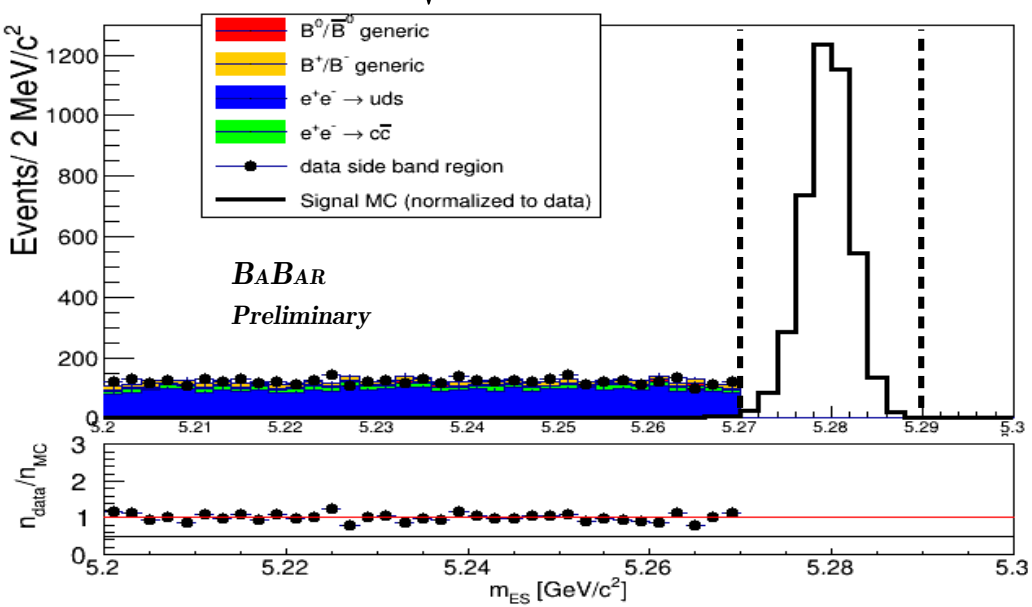
  ($m_{ES} < 5.27$ GeV/c^2) used to validate background MC samples

The Event Reconstruction

- Four oppositely charged tracks, coming from a common vertex, identified as two **protons** and two **anti-protons**
- Kinematic fit to the common vertex with χ^2 probability larger than 0.1 %
- Loose selection on **kinematic variables**

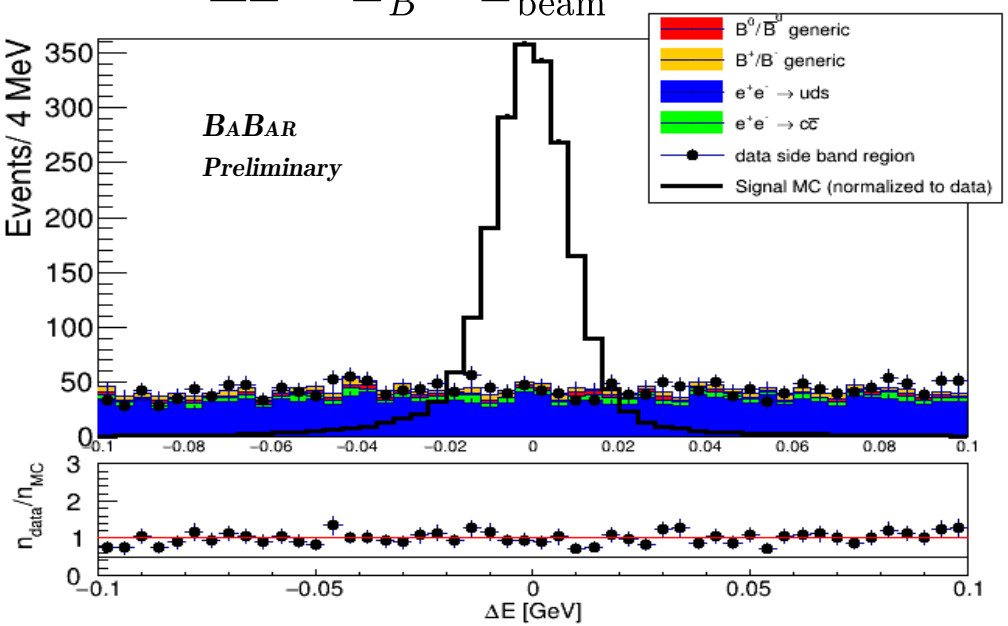
Beam energy substituted mass

$$m_{ES} = \sqrt{(E^*_{\text{beam}})^2 - |\vec{p_B}^*|^2}$$



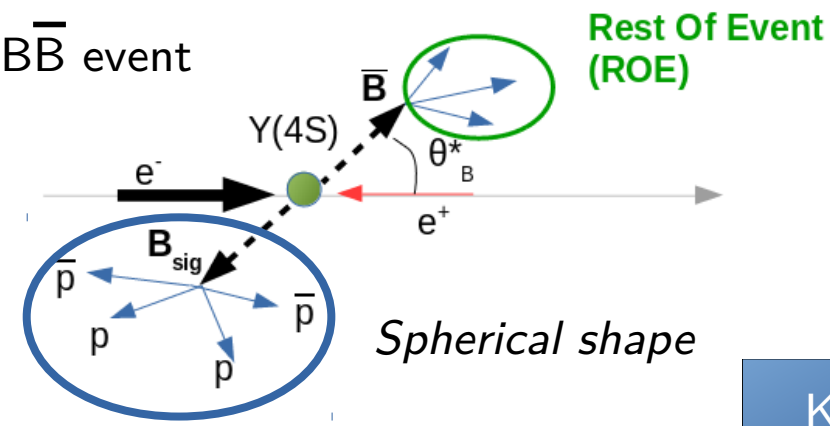
Energy difference

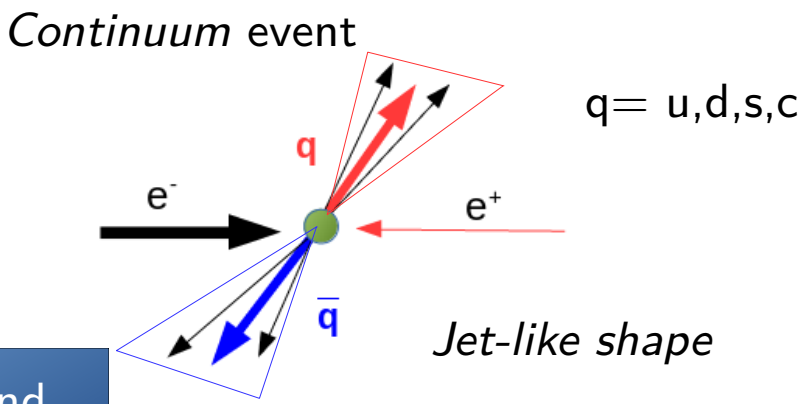
$$\Delta E = E^*_B - E^*_{\text{beam}}$$



The Event Variables

- Mainly **combinatorial background** due to real protons from *continuum events* $e^+e^- \to q\bar{q}$

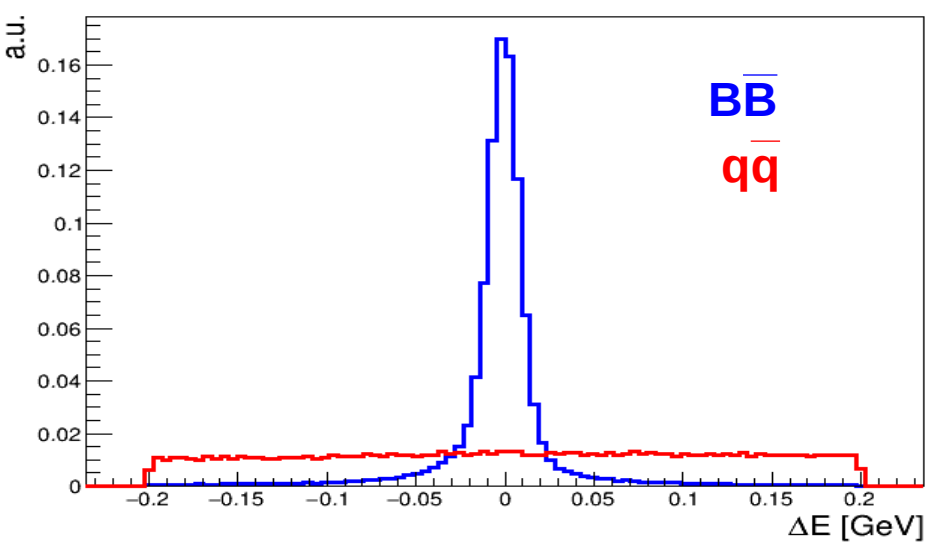




Kinematic and angular variables

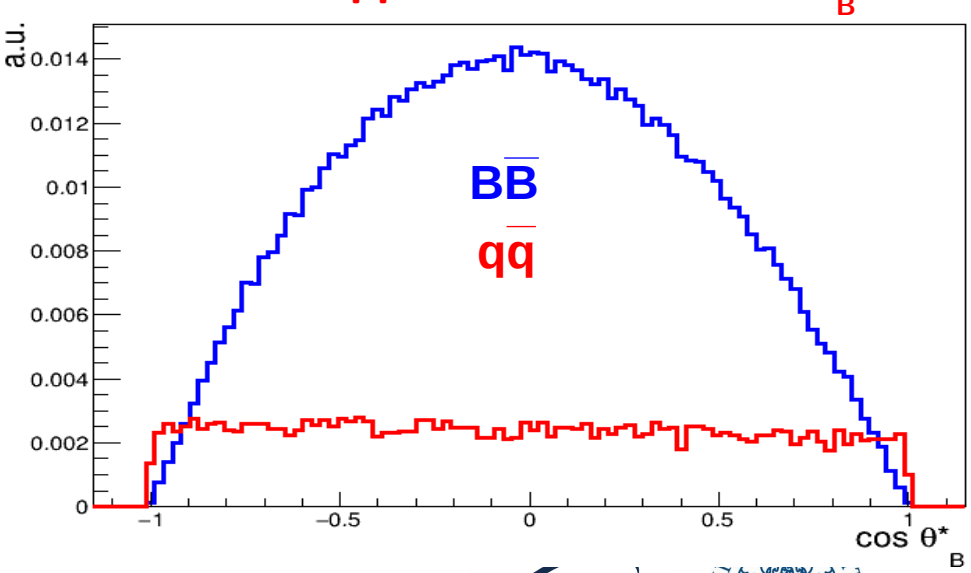
$B\bar{B}$ event: peaking at 0

$e^+e^- \to q\bar{q}$ event: flat in ΔE



$B\bar{B}$ event: $\sin^2\theta^*_B$

$e^+e^- \to q\bar{q}$ event: flat in $\cos\theta^*_B$



The Event Variables (II)

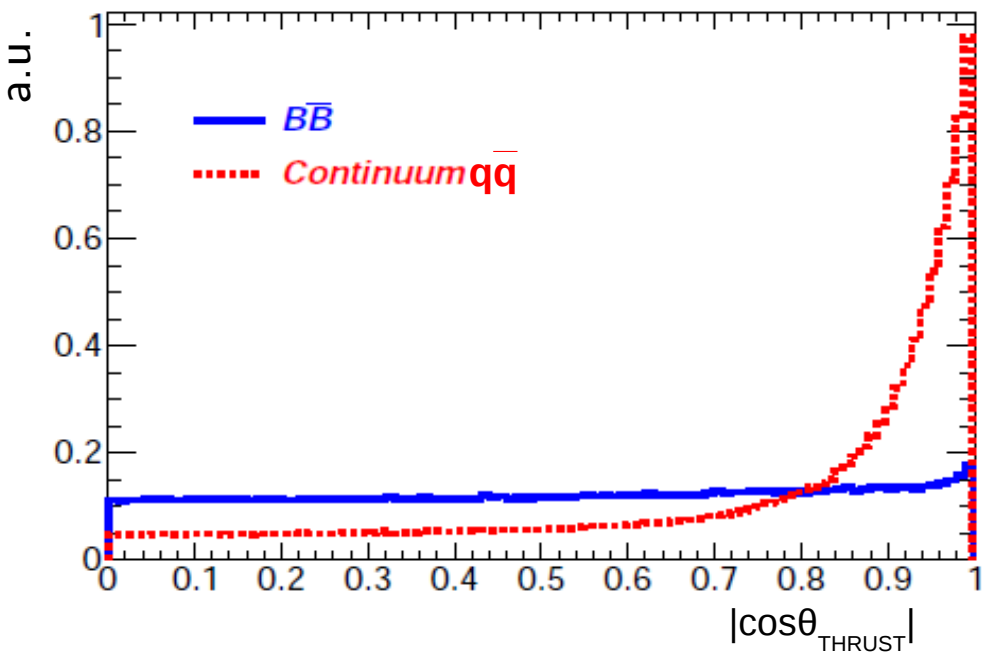
θ_{THRUST} , angle between the *thrust axis* of the B_{sig} and that of the ROE.

R_2 provides information about particle direction correlations.

Event-shape variables

θ_{THRUST}

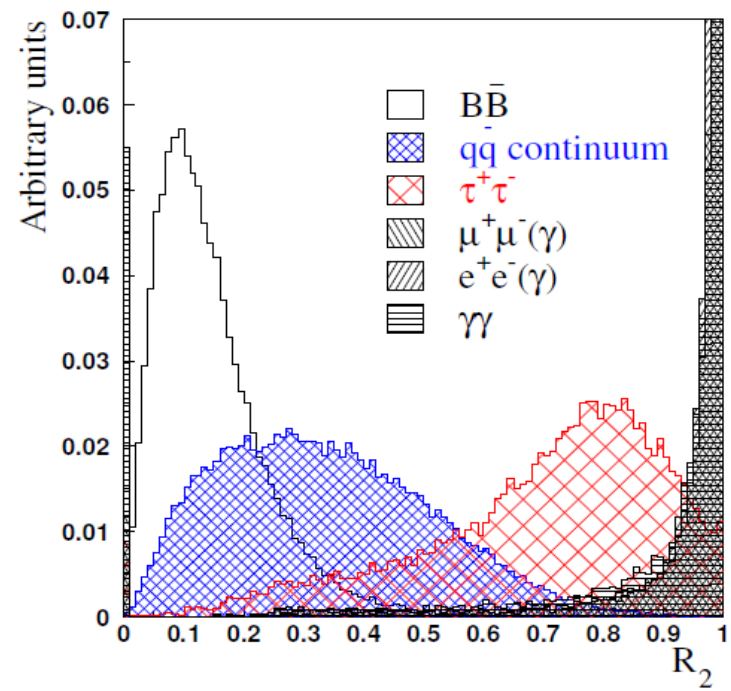
$$T = \frac{\sum_{i=1}^{N} |\vec{T} \cdot \vec{p_i}|}{\sum_{i=1}^{N} |\vec{p_i}|}$$



$R_2 = H_2/H_0$

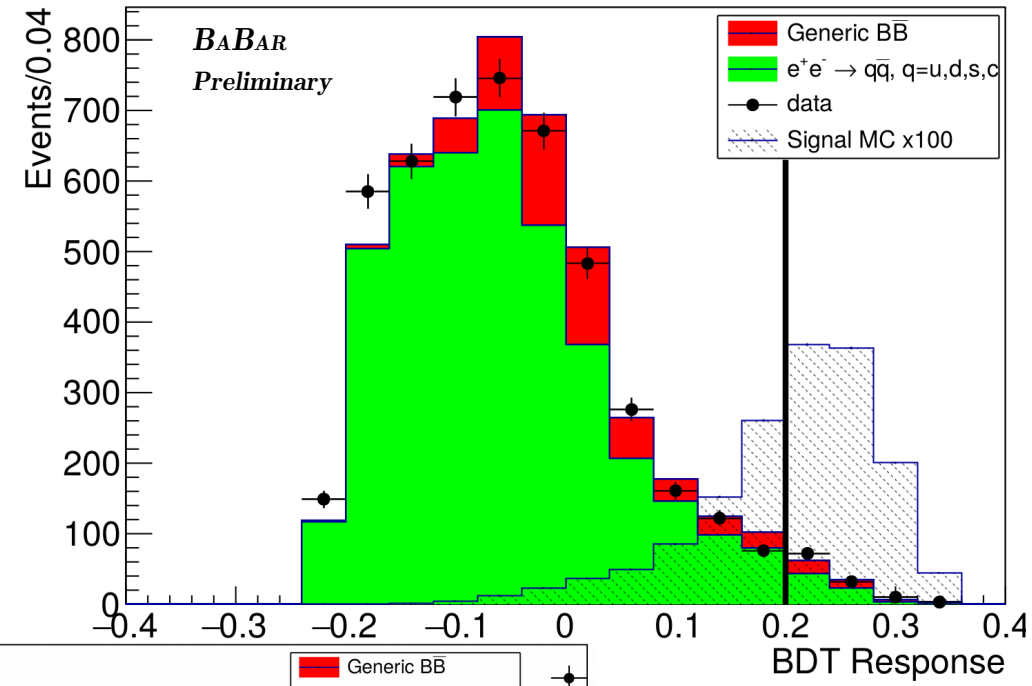
$$H_k = \sum_{i,j} \frac{|\vec{p_i}||\vec{p_j}| P_k(cos\theta_{ij})}{E_i E_j}$$

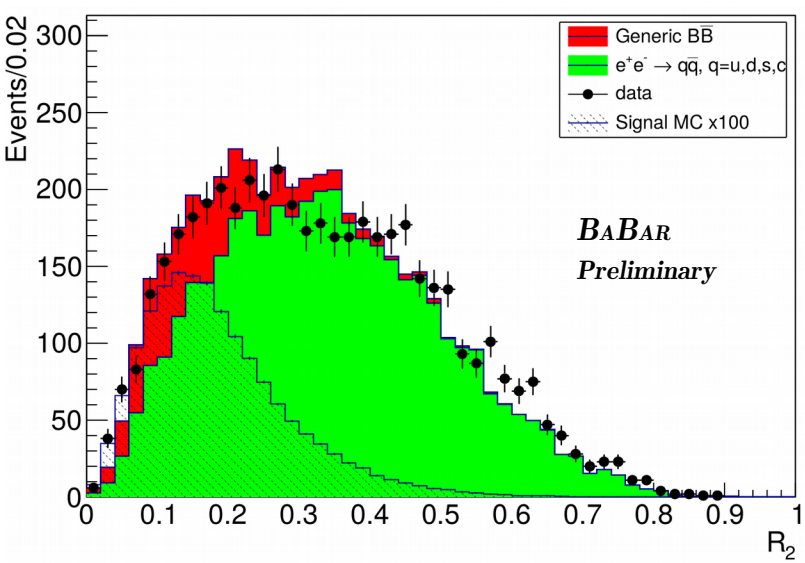
H_k, k-order moment of the *FoxWolfram discriminant*

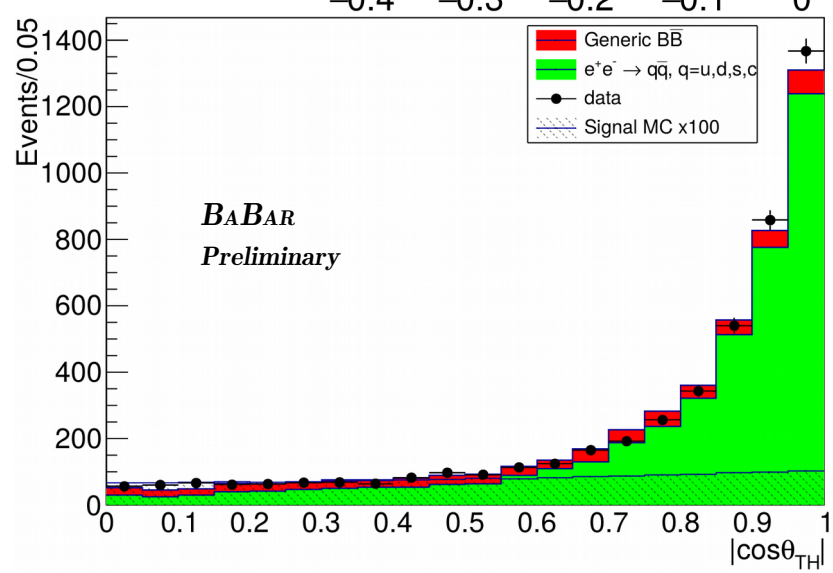


The Event Selection

- Further background rejection achieved by selecting on the **output** of a Boosted Decision Tree (BDT) algorithm.
- The training is performed on ***event shape* variables** (R_2, $|\cos\theta_{THRUST}|$), on kinematic and angular variables (ΔE, $\cos\theta^*_B$).







Background reduction: $1 - \varepsilon_{BDT} > 98\%$

Total Signal efficiency: $\varepsilon = 21\%$

The Fitting Procedure

- The signal yield is extracted from an ***unbinned*** **extended maximum likelihood fit** to the *on-peak data* m_{ES} distribution, in the range $5.2 < m_{ES} < 5.3$ GeV/c^2, after the BDT selection.

$$\log L(N_{\rm sig}, N_{\rm bkg}; x) = -(N_{\rm sig} + N_{\rm bkg}) + \sum_{i=1}^{n} \log(N_{\rm sig} \cdot f_{\rm sig}(x_i) + N_{\rm bkg} \cdot f_{\rm bkg}(x_i))$$

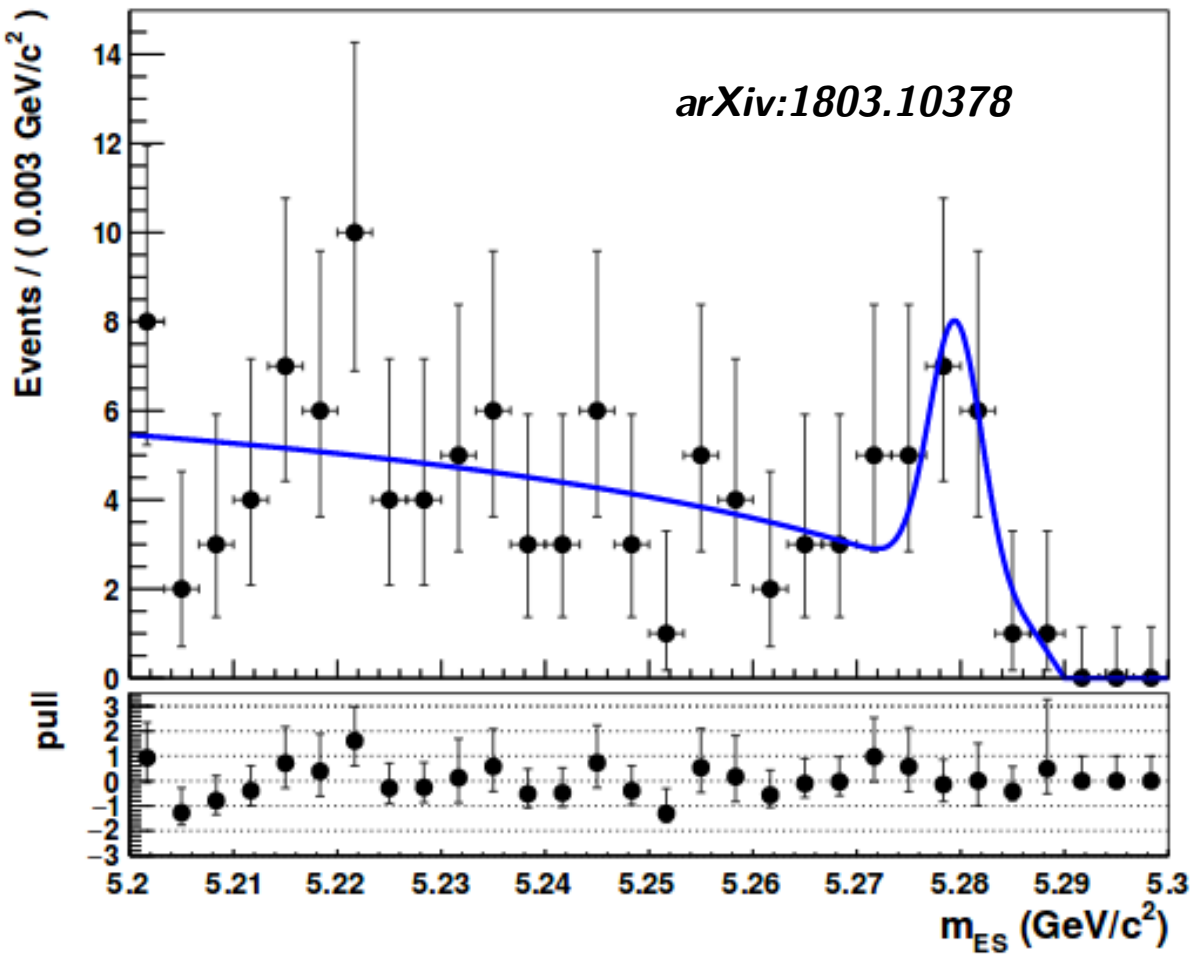
Total Probability Density Function (PDF) **: signal PDF + background PDF**

- Signal PDF (f_{sig}) $\rightarrow$ Gaussian function
- Background PDF (f_{bkg}) $\rightarrow$ empirical ARGUS function, depending on 2 parameters: the *cutoff* (fixed to the endpoint 5.289 GeV/c^2 of the m_{ES} distribution) and the *shape parameter.*
- The *shape parameter, the background and signal yields* (N_{bkg}, N_{sig}) are extracted from the fit to the data.

The signal yield extraction and the BF estimate

The fit to the m_{ES} distribution gives $N_{sig} = (11.1 \pm 4.6)$, with a 2.9σ significance

$$\rightarrow \; BF = N_{sig} / \varepsilon \; N_{B\bar{B}} = (1.14 \pm 0.47 \pm 0.17) \times 10^{-7}$$



→ The statistical uncertainty on N_{sig} is the main source of uncertainty on the branching fraction.

→ The statistical uncertainty already includes the impact of the ARGUS shape parameter, determined in the fit to the data.

→ Systematic uncertainties contribute as a further 15% relative uncertainty in the BF.

Summary&Conclusion

The analysis for the search of the $B^0 \rightarrow p\,p\,\bar{p}\,\bar{p}$ decay has been performed on 471 million $B\bar{B}$ pairs at *BABAR:*

- 11 signal events have been found from the fit to the data m_{ES} distribution, with a significance of 2.9 standard deviations.
- The branching fraction has been computed and the upper limit at 90% CL, including systematic variation, is obtained:

$$BF^{UL} = 2 \times 10^{-7} \text{ at } 90\% \text{ CL}$$

$\rightarrow$ *The first upper limit on this channel!*

SUBMITTED TO PRD, arXiv:1803.10378

Thanks for your attention.

Backup

The Systematic Uncertainties

- Systematic uncertainties contribute as a further 15% relative uncertainty in the BF.

$N_{B\bar{B}}$

- Measured with the *B counting technique*, the main uncertainty is due to the hadronic event selection efficiency.

N_{sig}

- Signal pdf choice, found to be negligible
- ARGUS cutoff fixed in the fit to the data

ε

- **MC-data differences** are the major source of systematic uncertainty on the signal selection efficiency, coming from: **Tracking, PID, BDT** efficiencies, the **decay model** implemented in the Signal MC generation.

Variable	Source	Relative systematic uncertainty (%)
$N_{B\bar{B}}$	B counting	0.6
$N_{\rm sig}$	ARGUS cutoff	0.9
ϵ	MC statistics	0.2
ϵ	PID efficiency	0.9
ϵ	Track finding efficiency	0.9
ϵ	BDT selection	2.2
ϵ	Decay model	14
Total		15

BDT uncertainty study

Weighting technique

- for each input variable distribution, BEFORE THE BDT, define bin by bin weights comparing the background MC samples to the side band region data:

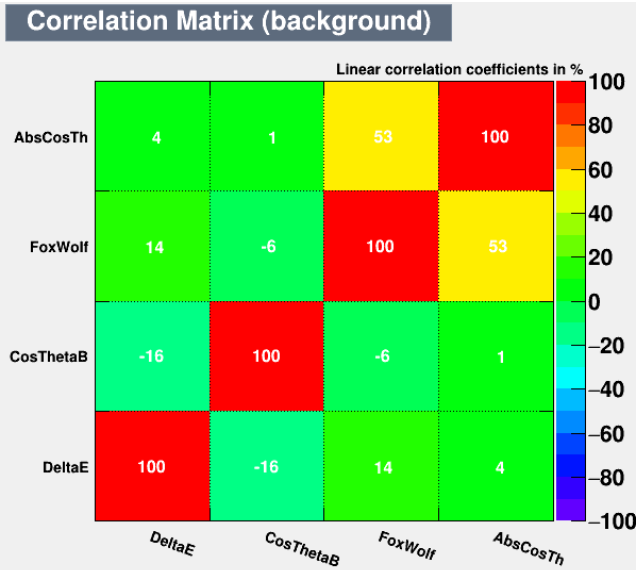
simultaneously preserve tl
ırpose is to adjust only the
ut changing the counting.

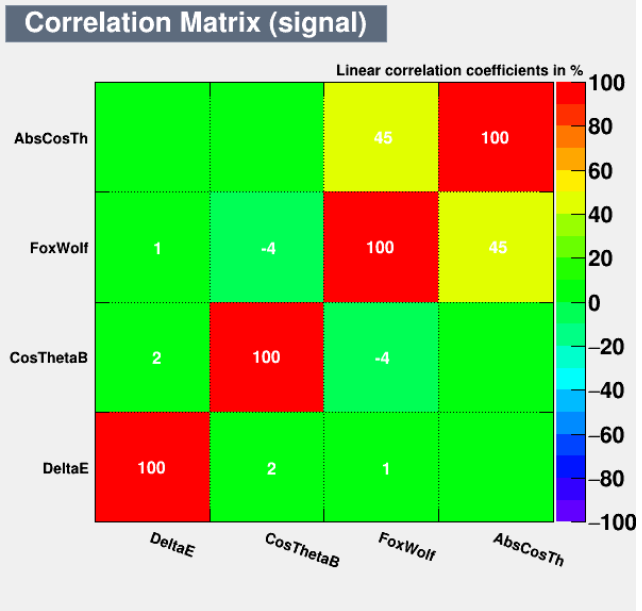
$$C = \frac{N^{\mathrm{sigMC}}}{\sum n_i^{\mathrm{sigMC}} \cdot \frac{n_i^{data}}{n_i^{\mathrm{bkgMC}}}}$$

- Apply the weights to the Signal MC distribution for the given variable AFTER THE BDT cut $\rightarrow$ recalculate efficiency $\rightarrow$ take as uncertainty the difference between *un-weighted and weighted efficiencies.*

- Uncertainty contributions from all the 4 input variables are summed in quadrature, taking into account the correlation coefficients.

$\rightarrow$ BDT relative uncertainty on $\varepsilon = 2.2\%$





Decay model uncertainty study

- There are *no specific four-body baryonic decay models* currently known
- *DEFAULT implemented in simulated signal MC:* ***Phase space* model**, meaning proton momentum probability is flat in the phase space.
- NO PROTON RELATED VARIABLES (momentum, energy, angular distributions) directly exploited in the analysis may relax the dependence of the selection efficiency on the decay model.
- However, systematic studies conservately estimate the contribution from the decay model to the relative systematic uncertainty on BF to be **14%.**

Implemented with the **re-weighting technique:** based on the comparison between the resulting proton momentum spectra from *2 different decay models:*

- *Default (phase space)*
- Assuming a different decay model (e.g., intermediate resonances: $B \to XX(\to p\bar{p}))$

Weights: bin by bin, normalized ratio of the new spectrum to the default one.

Weights are applied to the signal MC sample after the BDT cut $\to$ the difference in the efficiencies with/without weigths is assumed as systematic uncertainty.