Recent QCD-related studies with the BaBar detector

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on behalf of the BaBar Collaboration

BABAR

Outline

- The BaBar experiment
- Measurement of the $D^{*+}(2010) - D^{+}$ mass difference

  BABAR, PRL 119.202003 (2017), arXiv: 1707.09328

- Measurement of the spectral function for the $\tau \to K^{-} K_S \nu_\tau$

  Under internal review

- Search for the B-meson decay to four baryons $B \to p\, p\, \bar{p}\, \bar{p}$

  Submitted to PRD! arXiv:1803.10378

The BaBar Experiment

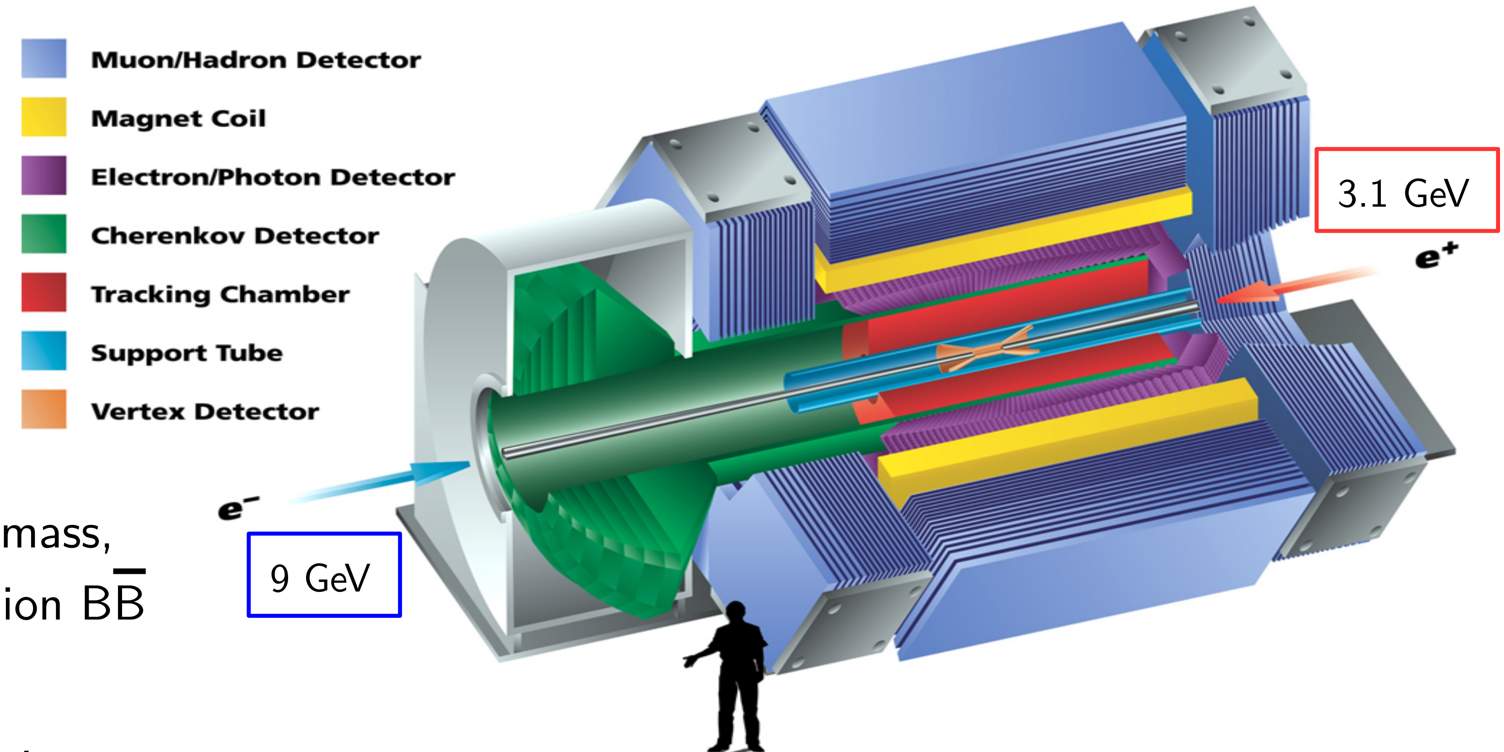
B-factories: dedicated experiments at *e^+e^- asymmetric-energy colliders* for the production of quantum coherent $B\overline{B}$ pairs → **CP-Violation (CPV) studies** and **New Phisics (NP) indirect** searches.

$$e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\overline{B}$$

- $\beta\gamma = 0.56$

In its 9-year operation (1999-2008):

- 424 fb^{-1} *on-peak* at $\Upsilon(4S)$ mass, $\sqrt{s}$=10.58 GeV → 471 million $B\overline{B}$ pairs.
- 44 fb^{-1} *off-peak, in the continuum hadronization region*, $\sqrt{s}$ = 10.54 GeV



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

Measurement of the $(D^{*+}(2010) - D^{+})$ mass difference

Motivation for measuring $\Delta m_+ \equiv m(D^{*+}(2010)) - m(D^+)$

- Extract $\Delta m_D \equiv m(D^+) - m(D^0) = \Delta m_0 - \Delta m_+$, by combining with the measurement of $\Delta m_0 \equiv m(D^{*+}(2010)) - m(D^0)$
- Constrain the symmetry breaking due to *u-d* quark mass difference in chiral perturbation theory & lattice QCD

Previously:

- Most accurate Δm_D measurement from LHCb, $\Delta m_D = (4.76 \pm 0.12 \pm 0.07)$ MeV *JHEP 06, 065 (2013)*
- CLEO reported the measurement $\Delta m_+ = (140.64 \pm 0.08 \pm 0.06)$ MeV based on the decay chain $D^{*+} \to D^+ \pi^0$ with $D^+ \to K^- \pi^+ \pi^+$ *PRL 69, 2046 (1992)*
- BaBar measurement of Δm_0 using the decay chain $D^{*+} \to D^0 \pi^+$ with $D^0 \to K^- \pi^+$ and also $D^0 \to K^- \pi^+ \pi^- \pi^+$ *PRL 111, 111801 (2013)*

Analysis Strategy

- Reconstruct the decay chain:

$$D^{*+} \rightarrow D^{+}\pi^{0}, D^{+} \rightarrow K^{-}\pi^{+}\pi^{+}$$

- Extract $\mathbf{\Delta m_+}$ by fitting the distribution of the mass difference between the reconstructed D^{*+} and D^{+}
- Define the PDF: *MC resolution function* (signal)+ *threshold function* (background contamination)
- Combine with the BaBar measurement of $\mathbf{\Delta m_0}$
- Obtain $\mathbf{\Delta m_D}$

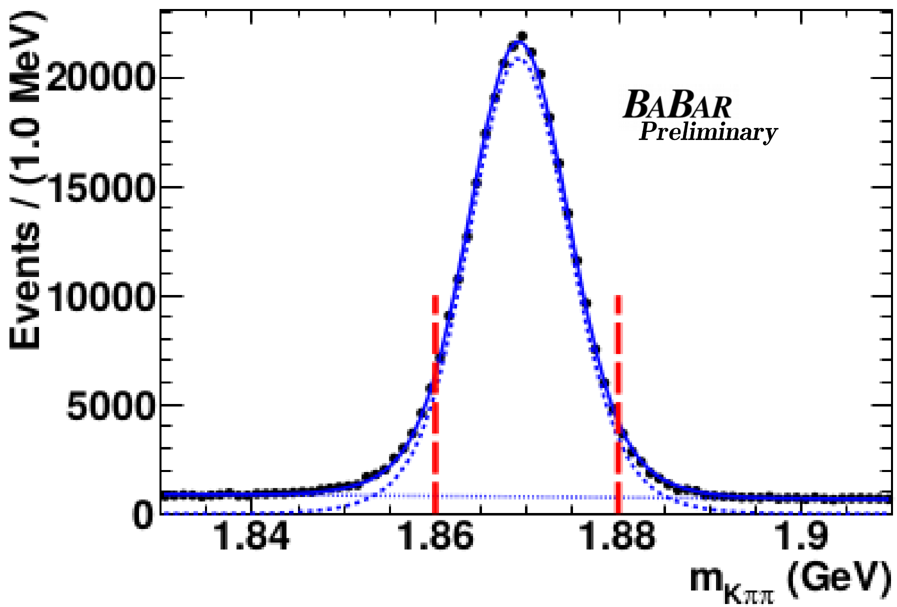
Event Reconstruction and Selection

$D^{*+} \to D^{+}\pi^{0}, D^{+} \to K^{-}\pi^{+}\pi^{+}$

- **"Slow" π^0** (p_π <300 MeV):
  - resolution on pion momentum improved (~3%) by the kinematic fit to the photon pair invariant mass → constrained to the nominal invariant mass of π^0.
  - MC-Data correction for the energy loss in the EMC is also applied

- **D^{*+}** (p^{CM} >3 GeV)
  - reject background contamination from $D^{*+} \to D^0 \pi^+$: $m(K^- \pi^+ \pi^+ \pi^0) - m(K^- \pi^+ \pi^0) < 160$ MeV
  - geometric and kinematic constraint on the D^{*+} production vertex and on D^+ decay vertex (Prob(χ^2)>0.1%)

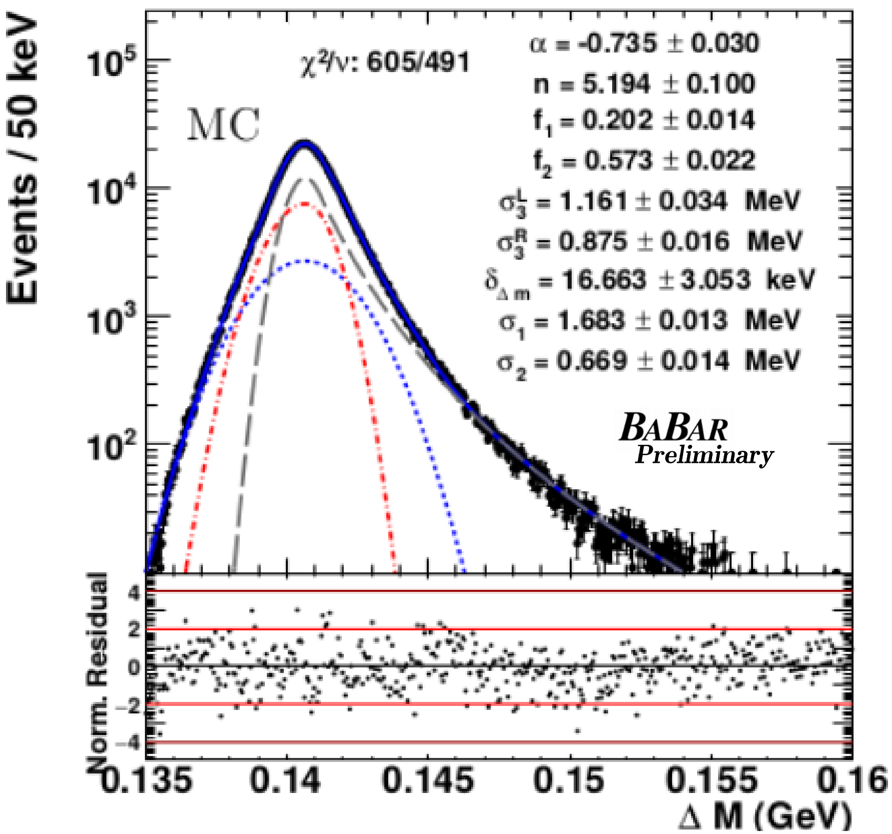
- **D^+** (momentum resolution ~0.5%):
  - pion/kaon particle identification and a selection on the distribution of polar angle of the reconstructed tracks + invariant mass selection
  - selection based on a likelihood variable (Decay vertex, Dalitz-plot position)

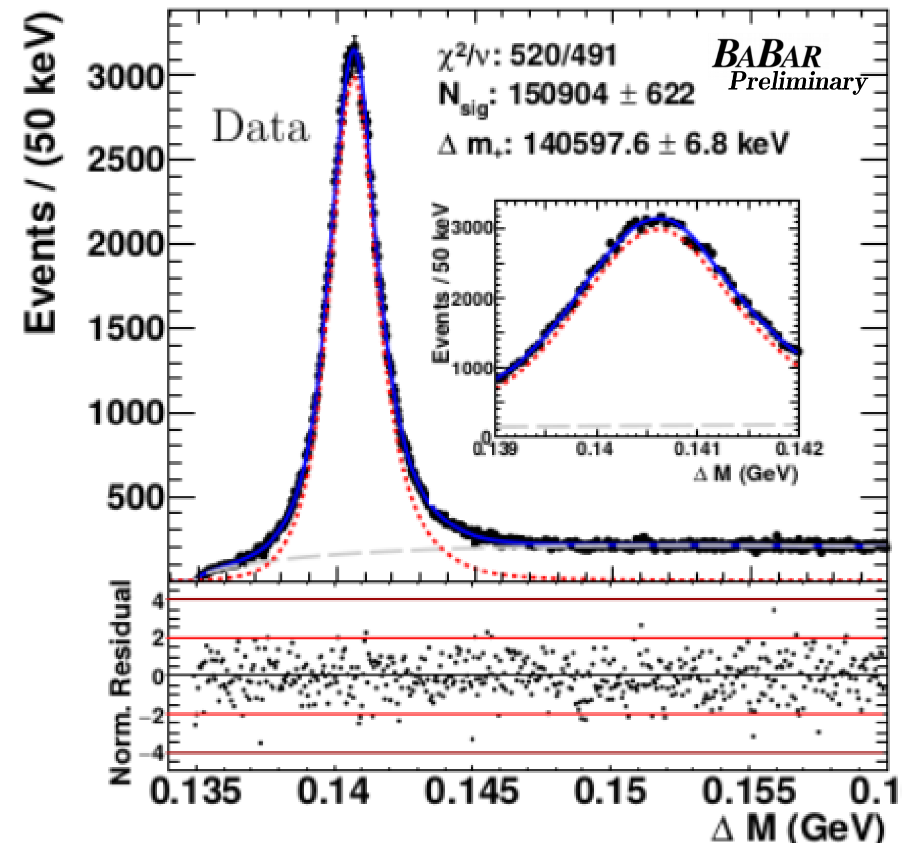


Fitting Procedure

1. Model the signal component in the $\mathbf{\Delta m_+}$ distribution on simulation and extract the shape parameters (***resolution function*** based on Gaussian-like PDFs).

2. Apply an *unbinned maximum likelihood* fit to the data using as PDF *resolution function (signal)* + *threshold function (combinatorial background)* and extract Δm.





Results & Summary (I)

- From the fitted signal events (150 904 $\pm$ 622), we measure **$\Delta m_+ = (140\ 597.6 \pm 6.8_{stat})$ keV**
- The extracted mass difference is corrected for the ***bias* of 3.4 keV** produced by peaking background not considered in the fit (*pseudoexperiments*)
- The main sources of systematic uncertainty are:
  - detector effects not accounted for in the simulation;
  - MC-data differences in the EMC calibration (photon energies).

  Total systematic uncertainty = 12.9 keV
- Summarizing, after adding the fit bias

$$\Delta m_+ = (140\ 601.0 \pm 6.8[\text{stat}] \pm 12.9[\text{syst}])\ \text{keV}$$

- Combine with the measurement of $\Delta m_0 = (145\ 425.9 \pm 0.5[\text{stat}] \pm 1.8[\text{syst}])$ keV based on the same data set and obtain:

$$\Delta m_D = (4\ 824.9 \pm 6.8[\text{stat}] \pm 12.9[\text{syst}])\ \text{keV}$$

$\rightarrow$ **5 times more accurate than world average**

Measurement of the spectral function for the $\tau^- \to K^- K_S \nu_\tau$

- **Motivation**
  - τ decays are an optimal laboratory for NP searches (Lepton Flavor Violation, Hadron Vacuum Polarization contribution to g-2, Standard Model test of CPV)
  - the measurement of the *invariant mass spectrum of the $K^- K_S$ system* allows to measure the spectral function

$$V(q) = \frac{m_\tau^8}{12\pi C(q)|V_{\rm ud}|^2} \frac{\mathcal{B}(\tau^- \to K^- K_S \nu_\tau)}{\mathcal{B}(\tau^- \to e^- \bar{\nu}_e \nu_\tau)} \frac{1}{N}\frac{dN}{dq}$$

  and provide information on isovector part (Isospin=1) of the $e^+ e^- \to K\bar{K}$ cross section:

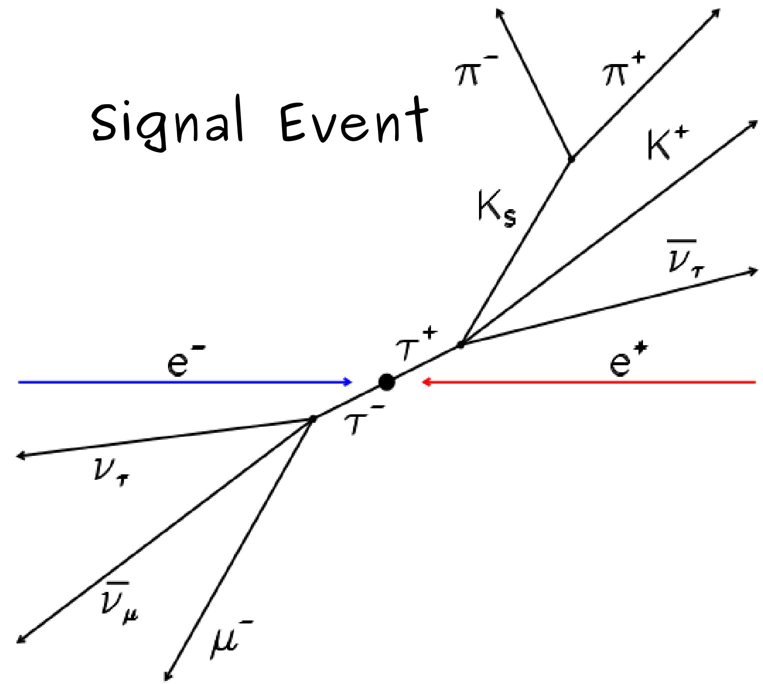
$$\sigma^{I=1}_{e^+e^-\to K\bar{K}}(q) = \frac{4\pi^2\alpha^2}{q^2} V(q)$$

- **Previously**
  - BaBar: measurement of the $e^+ e^- \to K\bar{K}$ *PRD 88, 3, 032013 (2013).*
  - CLEO: $K^- K_S$ mass spectrum measurement on 2.7×10^6 τ pairs *PRD 53, 6037 (1996)*

  $\to$ significantly improving on this measurement by using the full BaBar data sample of **10^9 τ pairs**

Analysis Strategy

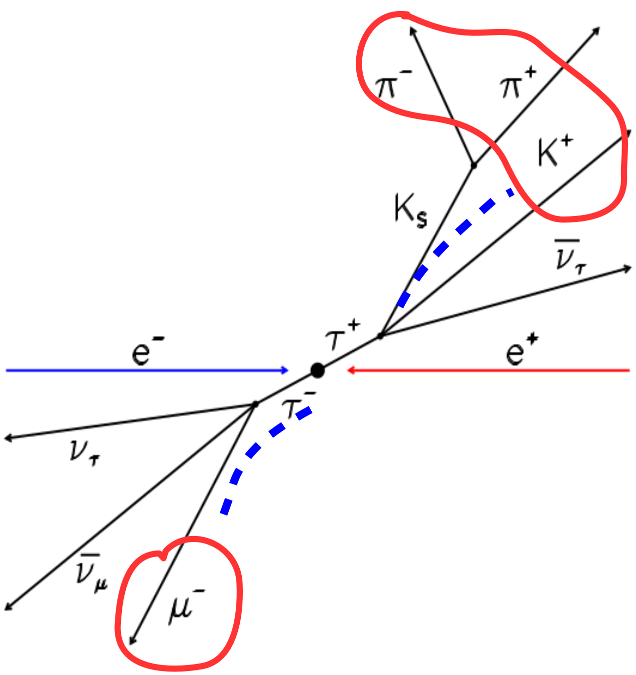
- Exploit the event topology to reconstruct the signal signature
- Apply a *signal-like* selection for rejecting the background
- Subtract the remaining background contaminating the $K^- K_S$ invariant mass spectrum
- Correct for detection efficiency and extract:
  - The mass spectrum of the $K^- K_S$ system
  - The branching fraction $BF(\tau \to K^- K_S \nu_\tau)$

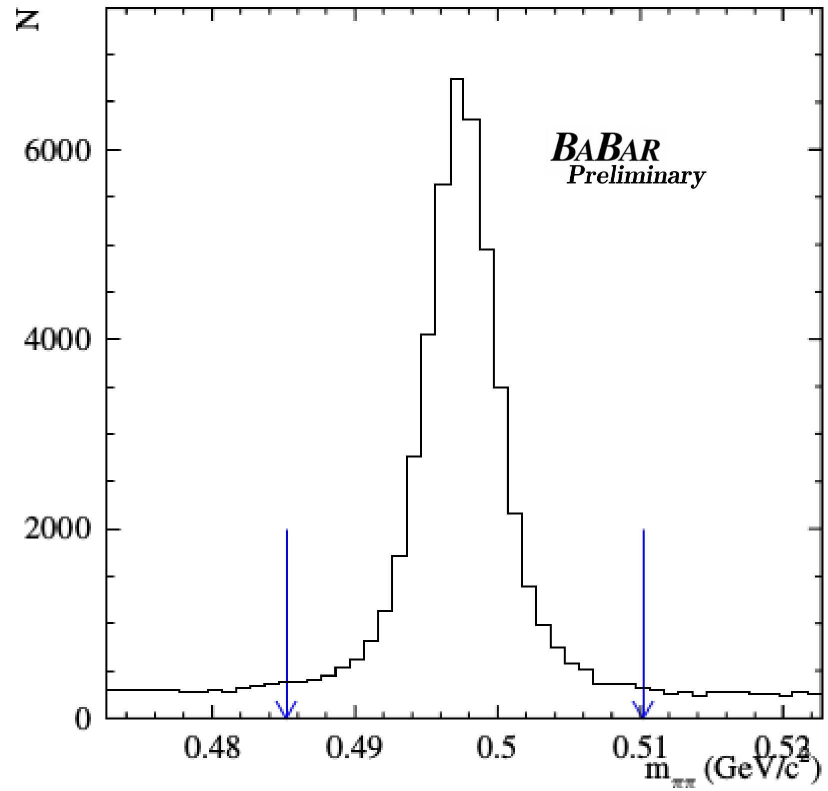


→ Compute the spectral function V(q) from the measured mass spectrum

Event Reconstruction and Selection

- Exploit the signal topology for the reconstruction





- 4 charged tracks with total charge = 0

- 2 oppositely charged tracks coming from the interaction point (PID applied, one lepton + one kaon)

- Selection on angular distribution and measured momenta of the reconstructed tracks

- Constrain the reconstructed invariant mass of two charged pions to lie within 25 MeV/c^2 of nominal K_s mass.

Event Selection (II)

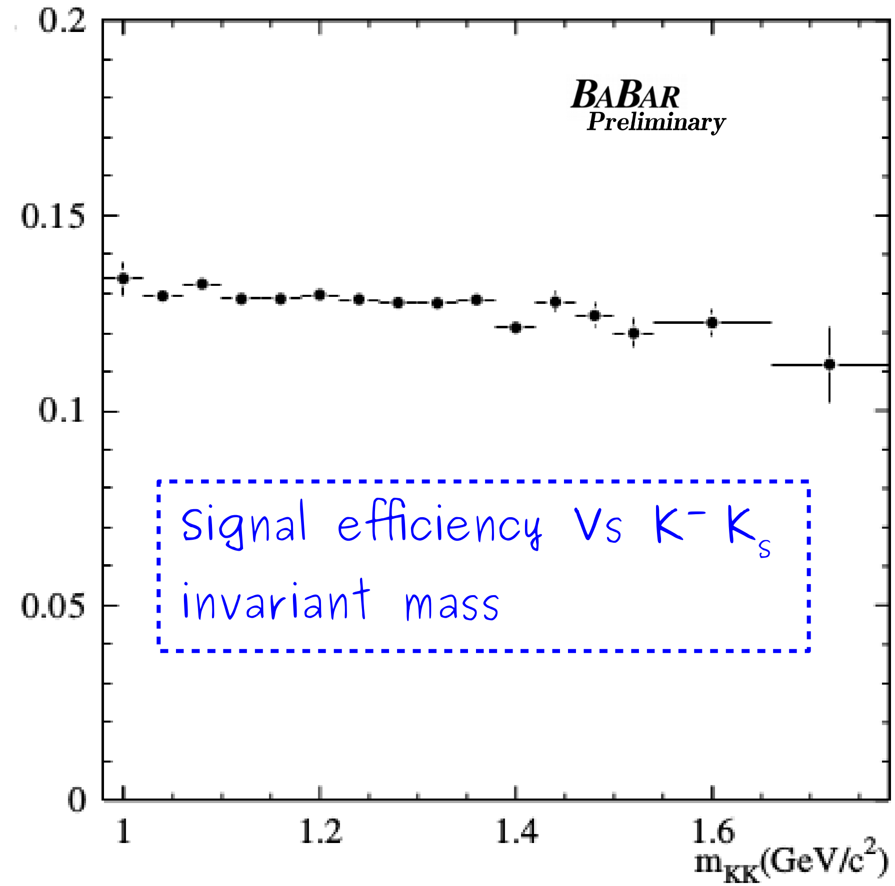
- The applied event selection corresponds to an average signal efficiency (computed on MC simulation) of **13%**.
- The background mainly come from two sources:

$\rightarrow$ **τ background,** $\tau^+\tau^-$ events

Reduced by a factor of 3.5

$\rightarrow$ **$q\bar{q}$ background,** $e^+e^- \rightarrow q\bar{q}$ events

Reduced by a factor of 5.5



$\rightarrow$ The remaining background is subtracted, using both the data (sideband) or computing the expected amount of background events by exploiting previous measurements and MC simulations.

Background Subtraction

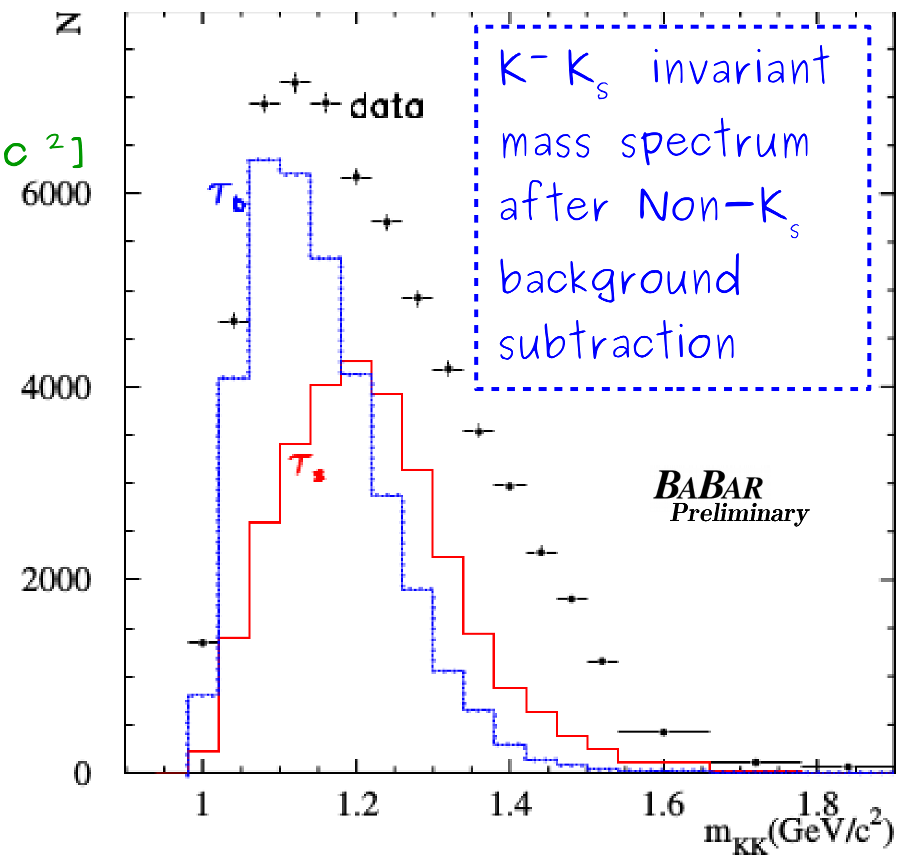
1) Non-K_s background (*combinatorial background*) is subtracted using ***data*** and the ***MC simulation***.

- $N(N_{sb})$ = total number of events measured in data (in the sideband region only)
- N_{KS} (N_b) = number of true (fake) K_s candidates of which a fraction β (α) is estimated to be in the sideband region

$$N = N_{K_S} + N_b, \quad N_{sb} = \alpha N_b + \beta N_{K_S}$$

Signal region: [nominal K_s mass ± 0.0125 GeV/c ^{2}]

Sideband region: otherwise



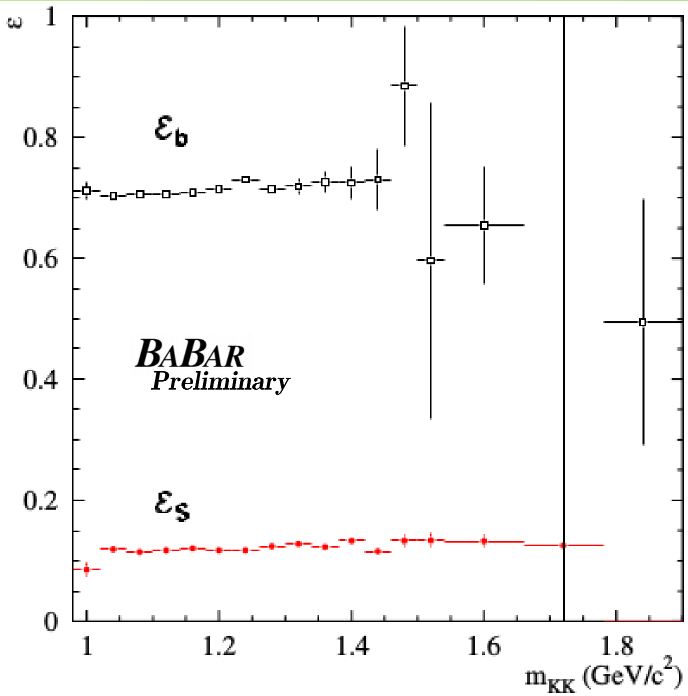
2) τ -background can be:

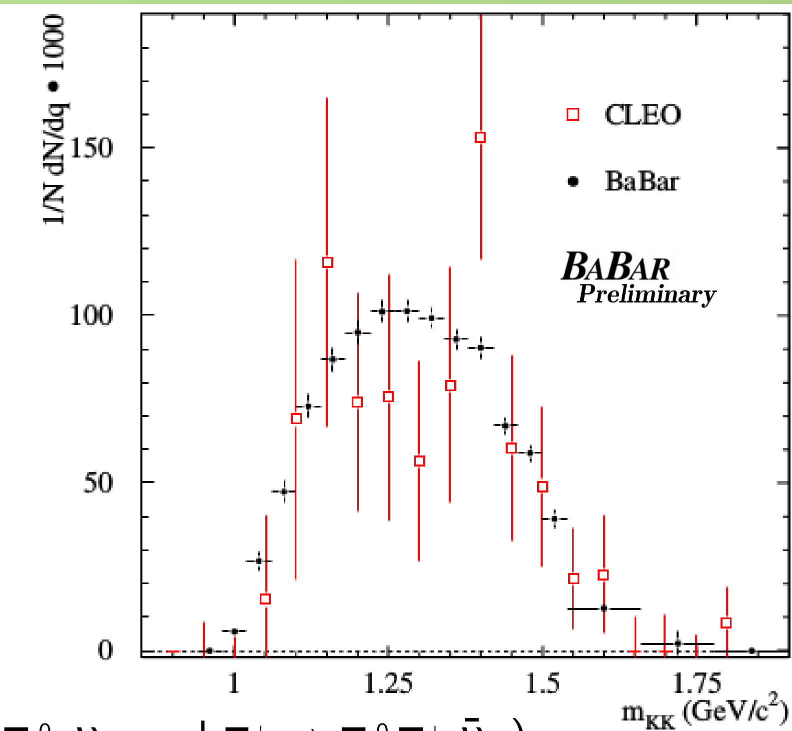
- without a π^0

  ($\tau^- \to \pi^- K_S \nu_\tau$ and $\tau^+ \to \pi^+ \bar{\nu}_\tau$):

  - their branching fractions are measured with precision better than 2% → contamination computed from MC simulation and subtracted

τ-background Subtraction (II)





$K^- K_s$ invariant mass spectrum after τ background subtraction

- With a π^0 ($\tau^- \rightarrow K^- K_S \pi^0 \nu_\tau$, $\tau^- \rightarrow \pi^- K_S \pi^0 \nu_\tau$ and $\tau^+ \rightarrow \pi^0 \pi^+ \bar{\nu}_\tau$):
  - generally measured with lower accuracy (~5%) → subtracted using ***data***
  - A π^0- candidate is defined as a pair of photon whose invariant mass belongs to the range [100-160 MeV/c^2]
  - N_s (N_b) , ϵ_s (ϵ_b) = number of signal (background) events with at least one π^0- candidate detected, and the corresponding detection efficiency evaluated on MC simualtion.

$$N_{0\pi^0} = (1 - \epsilon_s) N_s + (1 - \epsilon_b) N_b$$
$$N_{1\pi^0} = \epsilon_s N_s + \epsilon_b N_b,$$

Results & Summary (II)

- Systematic uncertainties in the BF($\tau \to K^- K_S \nu_\tau$) are estimated by:
  - varying the selection requirements
  - comparing MC-Data distributions (background subtraction contribution)

Total systematic uncertainty 2.8 %

- The preliminary BF for the decay $\tau \to K^- K_S \nu_\tau$ is in good agreement with the world average and of comparable accuracy.

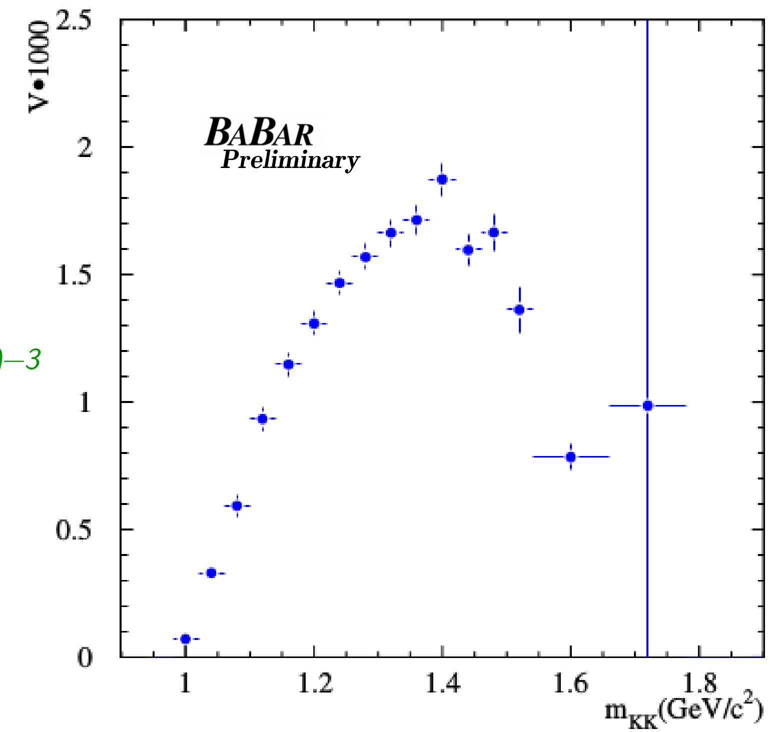
0.70 0.9 nb

$$BF = N_{sig}/(\varepsilon\ L\ BF_{lep}\ \sigma_{\tau\tau}) = (0.740 \pm 0.011 \pm 0.021) \times 10^{-3}$$

- The ***spectral function***

$$V(q) = \frac{m_\tau^8}{12\pi C(q)|V_{\mathrm{ud}}|^2} \frac{\mathcal{B}(\tau^- \to K^- K_S \nu_\tau)}{\mathcal{B}(\tau^- \to e^- \bar{\nu}_e \nu_\tau)} \frac{1}{N} \frac{dN}{dq}$$

is computed from the measured $K^- K_S$ invariant mass spectrum.



Search for the B-meson decay to four baryons

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

    $\rightarrow$ optimal tool for better understanding the mechanism of ***hadronization into baryons*** (theoretical models poorly understood) [**]
  - ***Baryon puzzle***: inclusive BF (~7%) ≠ Σ exclusive baryonic channels (~1%)
  - Experimental features: ***threshold enhancement*** and ***branching fraction hierarchy***

Previous measurement at BaBar:

- Upper limit on BF($\bar{B}^0 \rightarrow \Lambda_c^+ \, p \, \bar{p} \, \bar{p}$) < 2.8×10^{-6} at 0.90 CL (BABAR, Phys. Rev. D 89, 071102 (2014))

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

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

Working hypothesis:

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

First decay mode into four-baryon final state, no PDG limit yet!

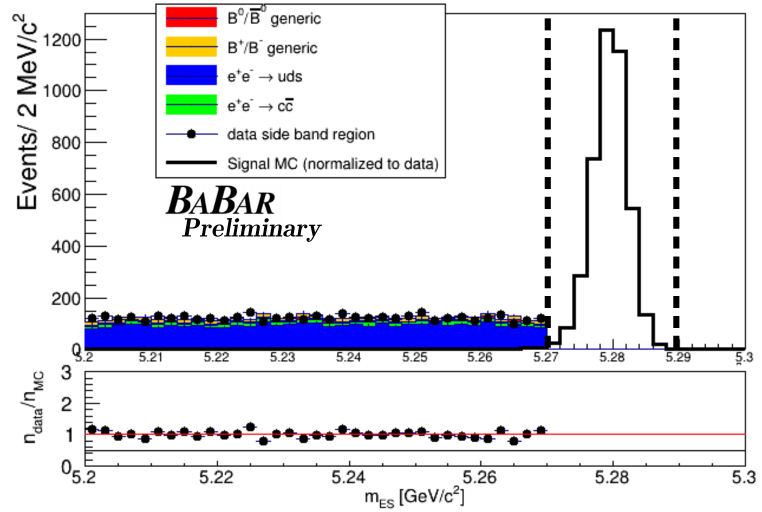
[**] V.L. Chernyak and I.R. Zhitnitsky, Nuclear Physics B, Vol. 345, 1 pp. 137-172 (1990); He Xiao-Gang, Li Tong, Li Xue-Qian and Wang Yu-Ming, Phys. Rev. D, 75, id. 034011 (2007).

Event Reconstruction

- Performed as *blind analysis* → without looking at the **signal region** in data (5.27 < m_{ES} < 5.29 GeV/c^2)
- **Sideband region data** (m_{ES} < 5.27 GeV/c^2) used to validate studies on background Monte Carlo samples

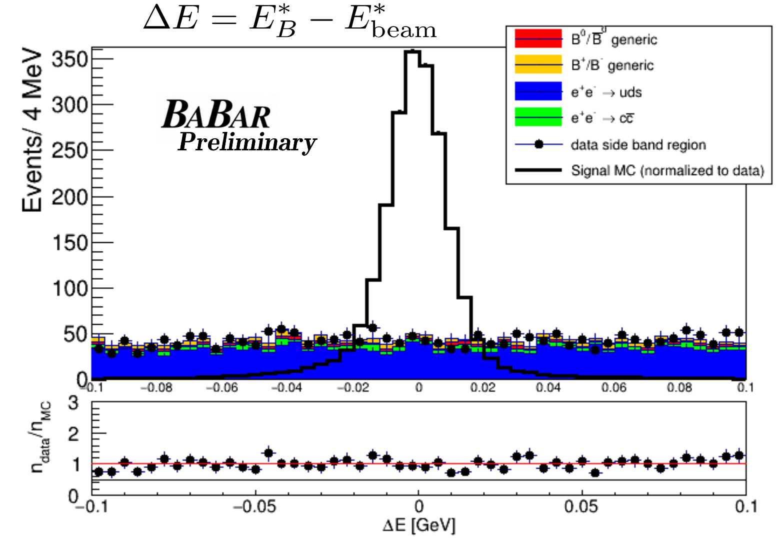
  (*EvtGen* for generic B decays from ϒ(4S) , *JetSet* for continuum events)
- Four oppositely charged tracks, coming from the Interaction Point, identified as two **protons** and two **antiprotons**
- Kinematic fit to the common vertex with a Prob(χ^2)>0.1%
- Loose cuts on **kinematic variables**

- **Beam energy substituted mass** $m_{ES} = \sqrt{(E^*_{\rm beam})^2 - |\vec{p_B}^*|^2}$



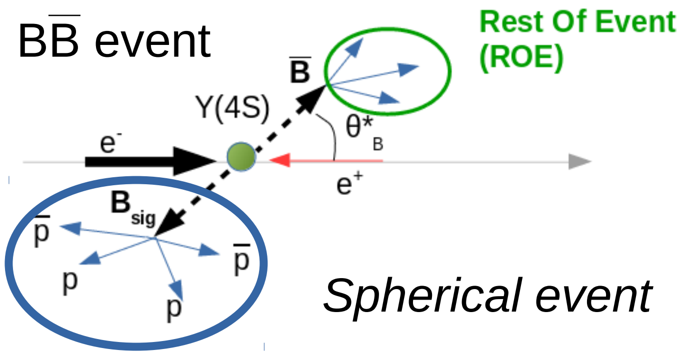
- **Energy difference**

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



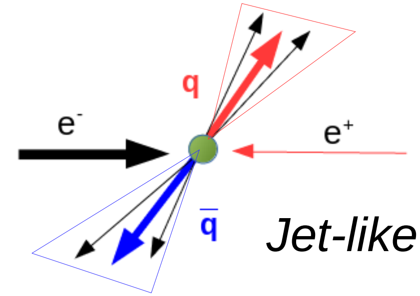
Event Selection

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



Spherical event

  - *Continuum* event

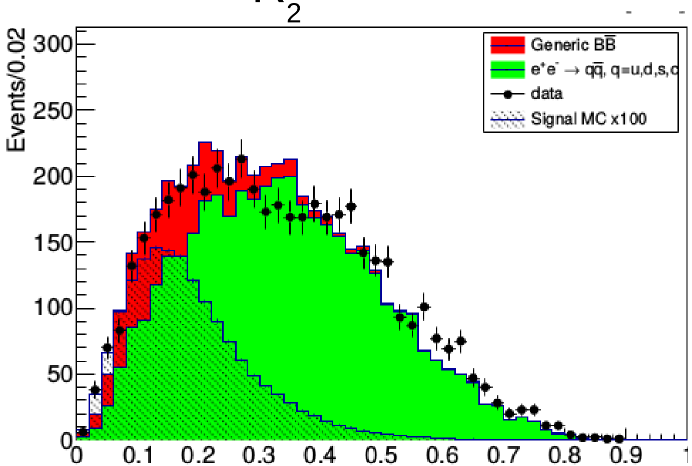


q= u,d,s,c

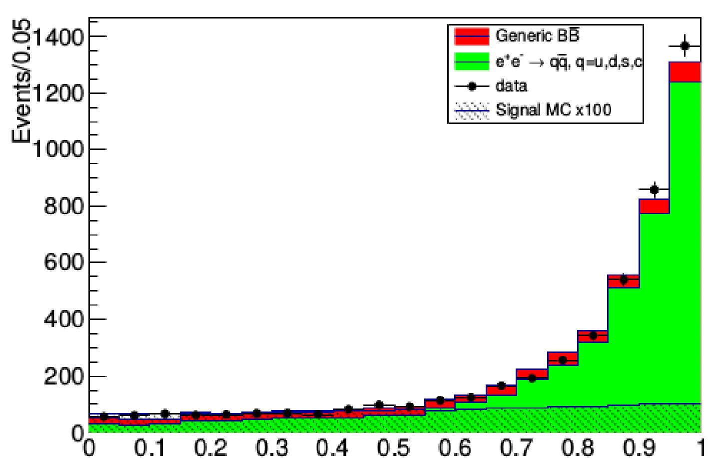
Jet-like event

- Further rejection achieved by applying a signal-like selection on the output of a multivariate Boosted Decision Tree (BDT) algorithm, trained on ***event shape* variables** (R_2, $|\cos\theta_{THRUST}|$), on angular and kinematic variables (ΔE, $\cos\theta^*_B$).

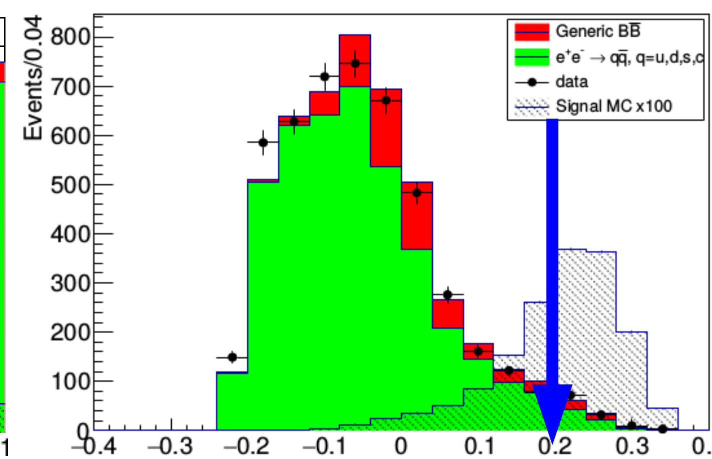
R_2



$|\cos\theta_{THRUST}|$



BDT response



Signal efficiency $\varepsilon = 21\%$

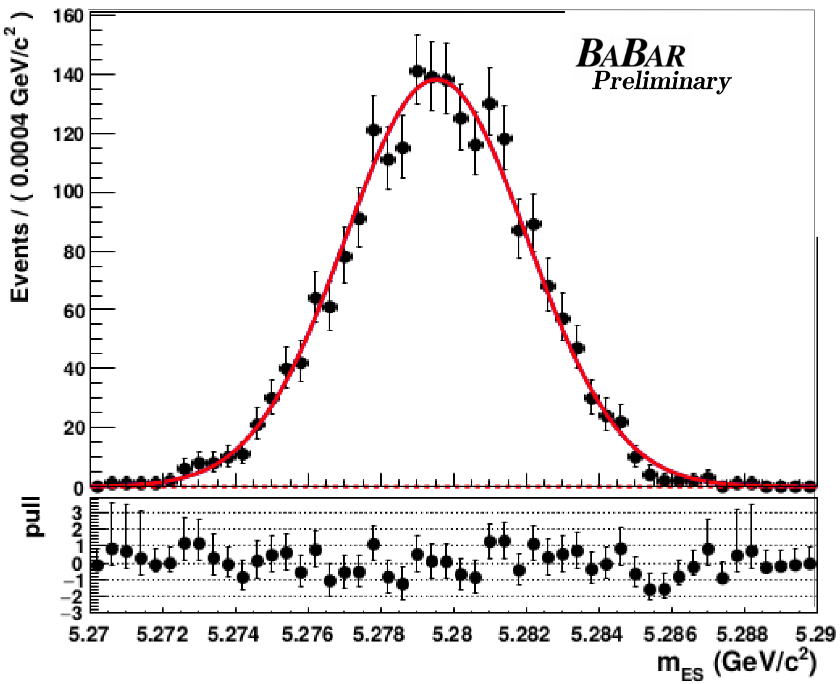
Fitting Procedure

- The signal yield is extracted from an ***unbinned*** **extended maximum likelihood fit** to the data m_{ES} distribution, in the range $5.2 < m_{ES} < 5.3$ GeV/c², after the BDT selection is applied.

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

- Signal PDF (f_{sig}) → Gaussian function
- Background PDF (f_{bkg}) → empirical ARGUS function, depending on 2 parameters: the *cutoff* (fixed to the endpoint 5.28 GeV/c² 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.

Gaussian function fit to Signal MC

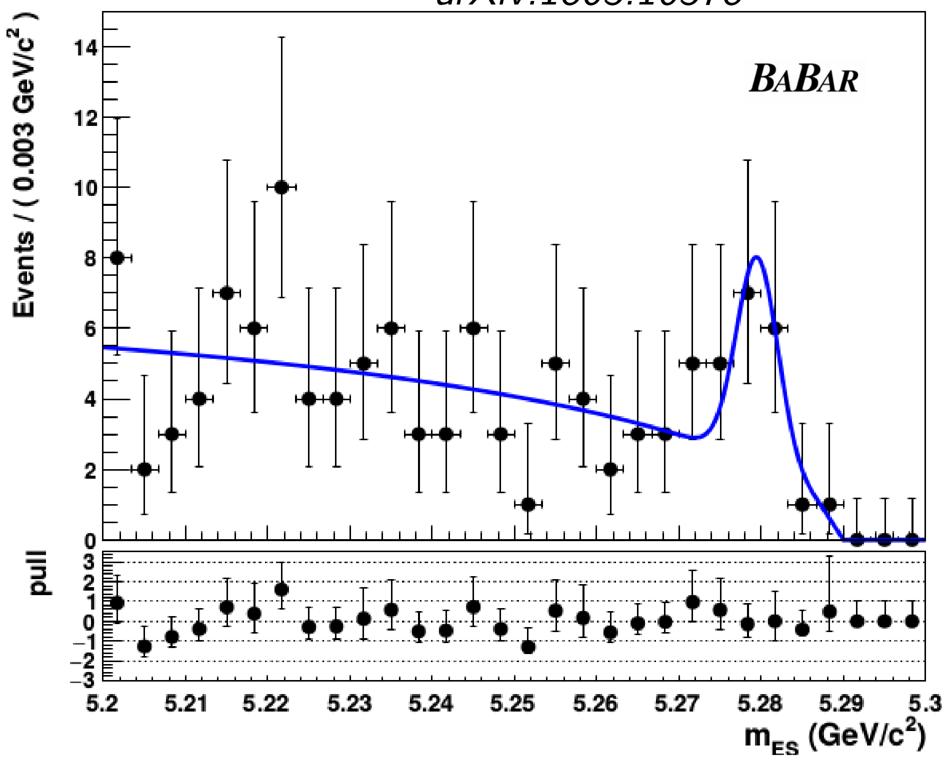


Signal Yield Extraction and BF Estimate

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

→ $BF = (1.14 \pm 0.47 \pm 0.17) \times 10^{-7}$

arXiv:1803.10378



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

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

Variable	Source	Relative systematic uncertainty (%)
$N_{B\bar{B}}$	B counting	0.6
N_{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

Bayesian upper limit at 90% CL: **2 x 10^{-7}**

Summary (III)

SUBMITTED to PRD

arXiv:1803.10378

- The analysis for the search of the BF($B^0 \rightarrow p\, p\, \bar{p}\, \bar{p}$) has been performed on 471 million $B\bar{B}$ pairs at BaBar

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

- 11 decay events with a significance of 2.9 standard deviations
- $BF^{UL} = 2 \times 10^{-7}$ at 90% CL

Thanks for your attention.

Backup: Measurement of the ($D^{*+}(2010)$ – D^{+}) mass difference

Fitting Procedure Details

The total PDF corresponds to the sum of the signal and background PDFs :

$$\mathcal{S}(\Delta m) = f_1 \mathrm{G}(\Delta m; \Delta m_+ + \delta_{\Delta m_+}, \sigma_1) + (1 - f_1)\left[f_2 \mathrm{CB}(\Delta m; \Delta m_+ + \delta_{\Delta m_+}, \sigma_2, \alpha, n) + (1 - f_2)\mathrm{BfG}(\Delta m; \Delta m_+ + \delta_{\Delta m_+}, \sigma_3^L, \sigma_3^R)\right] ,$$

$$T(\Delta m; \kappa) = \Delta m \sqrt{u} \exp(\kappa \cdot u)$$

→ The fixed parameters in the fit to the data are the fraction f_1, f_2 , the CB tails parameters and the bias $\delta_{\Delta m}$

Results

- Sources of systematic uncertainty:

Detector effects not accounted for in the simulation

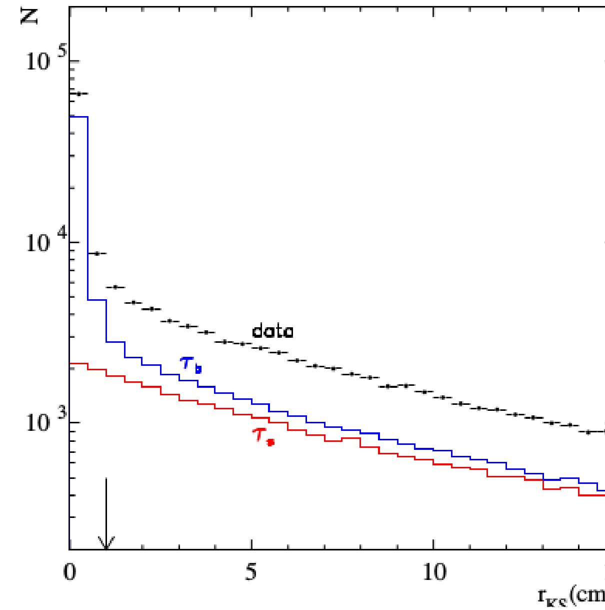
Rescaling technique for evaluating MC–Data differences

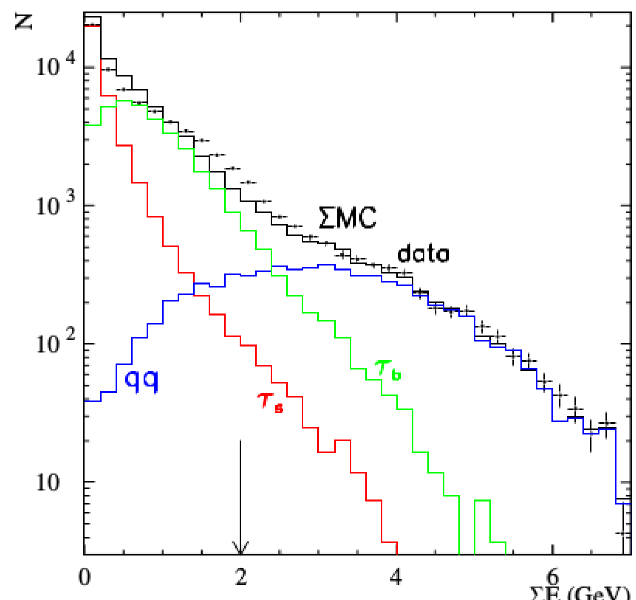
Source	Δm_+ systematic [keV]
Fit bias	1.7
D^{*+} p_{lab} dependence	5.0
D^{*+} $\cos\theta$ dependence	6.9
D^{*+} ϕ dependence	0.0
$m(D^+_{\text{reco}})$ dependence	0.0
Diphoton opening angle dependence	6.1
Run period dependence	0.0
Signal model parametrization	2.1
EMC calibration	7.0
MC π^0 momentum rescaling	0.5
Total	12.9

Backup: Measurement of the spectral function for the $\tau \rightarrow K_S K^- \nu_\tau$

The Event Selection

- Lepton candidate momentum (lab frame) > 1.2 GeV/c, (c.m. frame) < 4.5 GeV/c.
- $\cos\theta_l < 0.9$, where θ_l is the lepton polar angle is measured in the lab frame.
- Charged kaon candidate momentum $0.4 < p_K < 5$ GeV/c.
- $-0.7374 < \cos\theta_K < 0.9005$, with θ_K the polar angle.
- K_S flight length r_{KS} , measured as a distance between the $\pi^+\pi^-$ vertex and the $K^- K_S$ vertex, must be larger than 1 cm.
- $\Sigma E_\gamma < 2$ GeV, where ΣE_γ is the total energy of all photons with $E_\gamma > 10$ MeV found in the event.
- The thrust value is required to be $T > 0.875$.
- $\theta_{lh} > 110°$, where θ_{lh} is the angle between the lepton and the $K^- K_S$ system.





Results

- Systematic uncertainties in the BF($\tau \to K^- K_S \nu_\tau$):

Sources	uncertainty (%)
Luminosity	1.0
Requirement on the K_S decay length	0.4
Requirement on the charged kaon momentum	0.9
Requirement on the lepton momentum	0.5
Requirement on the lepton $\cos\theta$	0.6
Requirement on ΣE_γ energy	1.0
Tracking efficiency	1.0
PID	0.5
non-K_S background subtraction	0.4
$\tau^+\tau^-$ background without π^0	0.2
$\tau^+\tau^-$ background with π^0	1.6
$q\bar{q}$ background	0.5
total	2.8

Estimated by varying the selection criteria

Dependent on the $K^- K_s$ invariant mass

Evaluated as the observed difference in the mass spectra between data and MC

- Systematic uncertainties in the $K^- K_S$ invariant mass spectrum:

m_{K-K_S}(GeV)	$N_s/N_{tot} \times 10^3$	$V \times 10^3$
0.98 - 1.02	5.6 ± 1.4	0.071 ± 0.018 ± 0.007
1.02 - 1.06	26.0 ± 2.7	0.331 ± 0.034 ± 0.030
1.06 - 1.10	46.0 ± 3.2	0.593 ± 0.042 ± 0.052
1.10 - 1.14	70.8 ± 3.5	0.934 ± 0.046 ± 0.065
1.14 - 1.18	84.4 ± 3.4	1.148 ± 0.047 ± 0.069
1.18 - 1.22	92.3 ± 3.3	1.309 ± 0.046 ± 0.065
1.22 - 1.26	98.2 ± 3.2	1.468 ± 0.048 ± 0.059
1.26 - 1.30	98.4 ± 3.2	1.569 ± 0.050 ± 0.063
1.30 - 1.34	96.3 ± 3.0	1.663 ± 0.052 ± 0.050
1.34 - 1.38	90.2 ± 2.9	1.715 ± 0.052 ± 0.052
1.38 - 1.42	87.8 ± 3.1	1.873 ± 0.066 ± 0.056
1.42 - 1.46	65.1 ± 2.6	1.597 ± 0.064 ± 0.043
1.46 - 1.50	57.3 ± 2.5	1.6665 ± 0.073 ± 0.042
1.50 - 1.54	38.1 ± 2.5	1.361 ± 0.090 ± 0.032
1.54 - 1.66	3×(12.3 ± 0.8)	0.785 ± 0.049 ± 0.016
1.66 - 1.78	3×(2.2 ± 3.4)	0.986 ± 1.52 ± 0.020

Backup: Search for the B-meson decay to four baryons

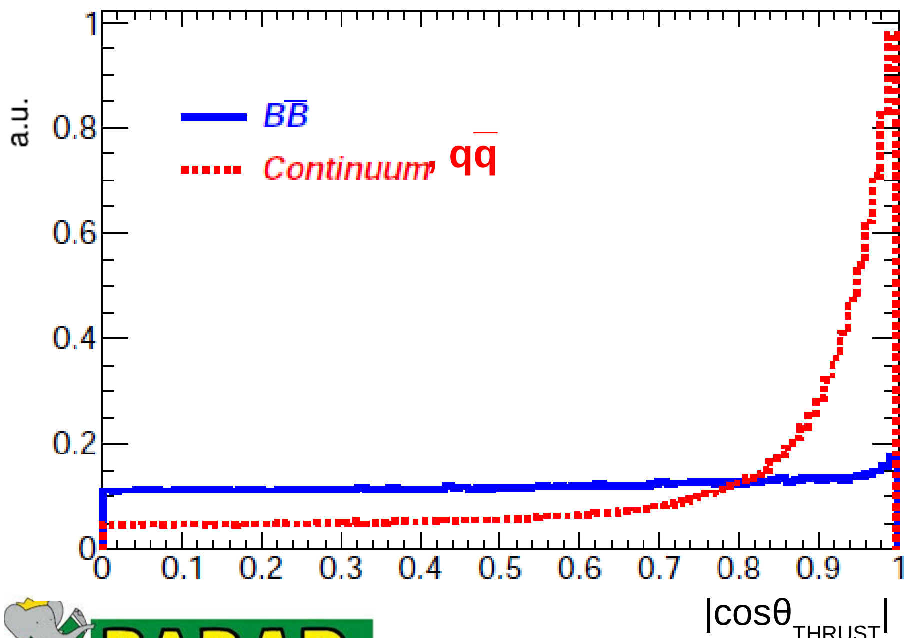
Event shape variables

Shape variables: θ_{THRUST} , R_2

- θ_{THRUST} , angle between the *thrust axis* of the B_{sig} and that of ROE.
- R_2 provides information about particle direction correlations.

θ_{THRUST}

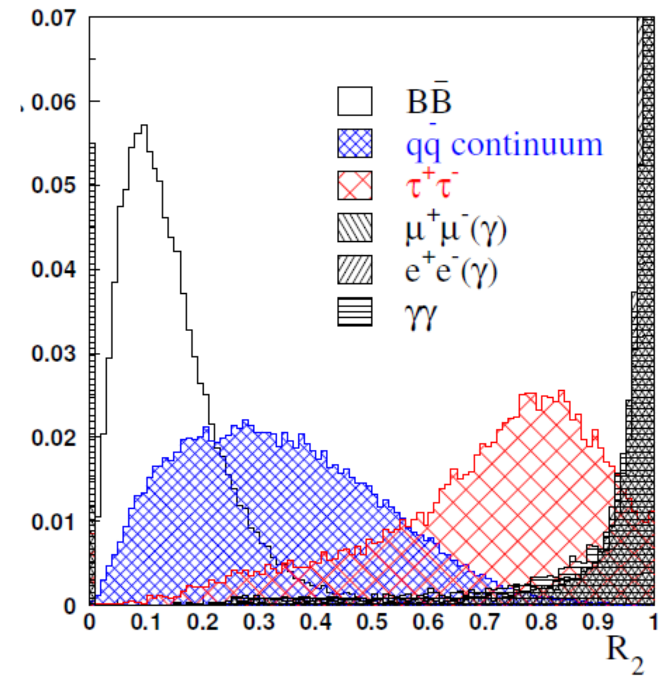
$$T = \frac{\sum_{i=1}^{N} |\vec{T} \cdot \vec{p_i}|}{\sum_{i=1}^{N} |\vec{p_i}|}$$



$R_2 = H_2/H_0$

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

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



Systematic uncertainties

$N_{B\bar{B}}$ →

- $B\bar{B}$ pairs: calculated from the *B counting method*
- Systematic uncertainty ~ 1%(mainly due to the hadronic event selection efficiency)

N_{sig}^{obs} →

- *Signal pdf* choice
- Shape parameter estimates

→ Evaluated by letting them vary in their uncertainty ranges.

ε →

- The **MC-data differences** are the major source of systematic uncertainty on signal selection efficiency, coming from:

1) Tracking (**1%**)

2) PID (**0.86%**)

3) BDT (**2.2%**)

4) Decay model implemented in the Signal MC generation (**14%**)

Weighting technique (3, 4)

BDT uncertainty study

Weighting technique

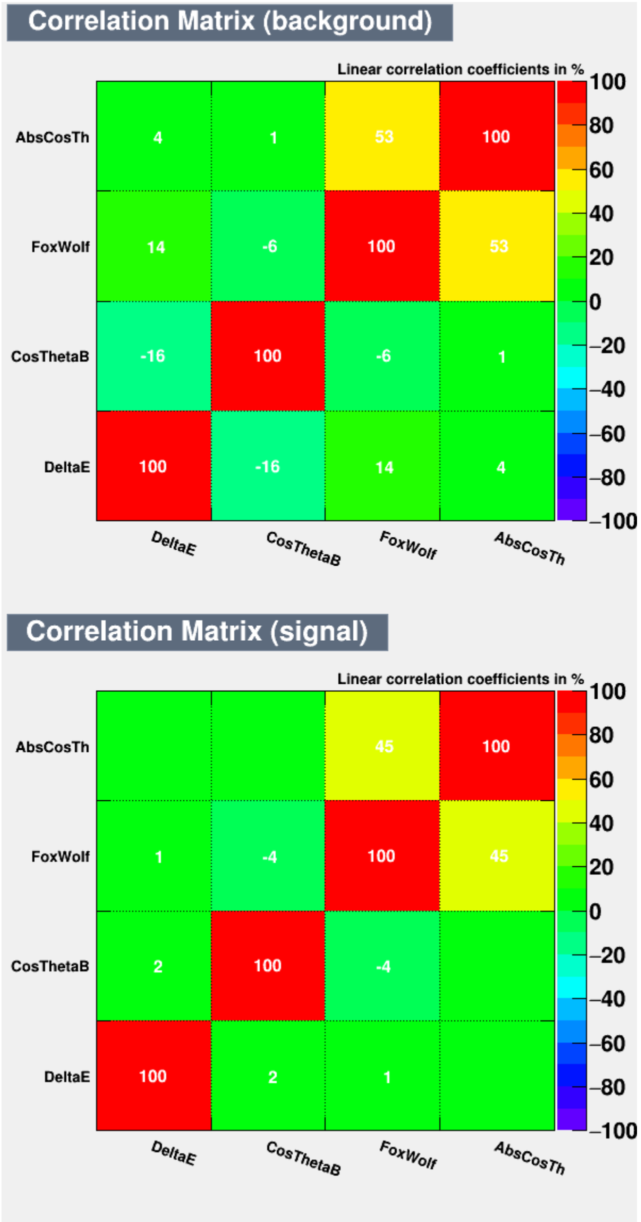
- for each input variable distribution, BEFORE THE BDT, define bin by bin weights comparing background MC-data samples:

$$w_i = \frac{n_i^{data}}{n_i^{\mathrm{bkgMC}}} \cdot C$$

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

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

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 might relax the selection efficinecy dependence on the decay model
- However, systematic studies show the expected contribution from the decay model to the relative uncertainty on BF is **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.

Signal MC: proton momentum distributions