Recent QCD Results from the BaBar Experiment

5 – 12 July 2017, Lido di Venezia

Laura Zani
INFN and University of Pisa

on behalf of the Babar Collaboration

Outline

- The BaBar experiment
- The Dalitz-plot analyses for 3-body charmonium decays

$$J/\Psi \to \pi^+\pi^-\pi^0$$
$$J/\Psi \to K^+K^-\pi^0$$
$$J/\Psi \to K_s K^\pm \pi^\mp$$

BABAR, PRD 95, 072007 (2017), arXiv:1702.01551

- Search for the B-meson decay to four baryons

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

To be submitted soon!

The BaBar Experiment

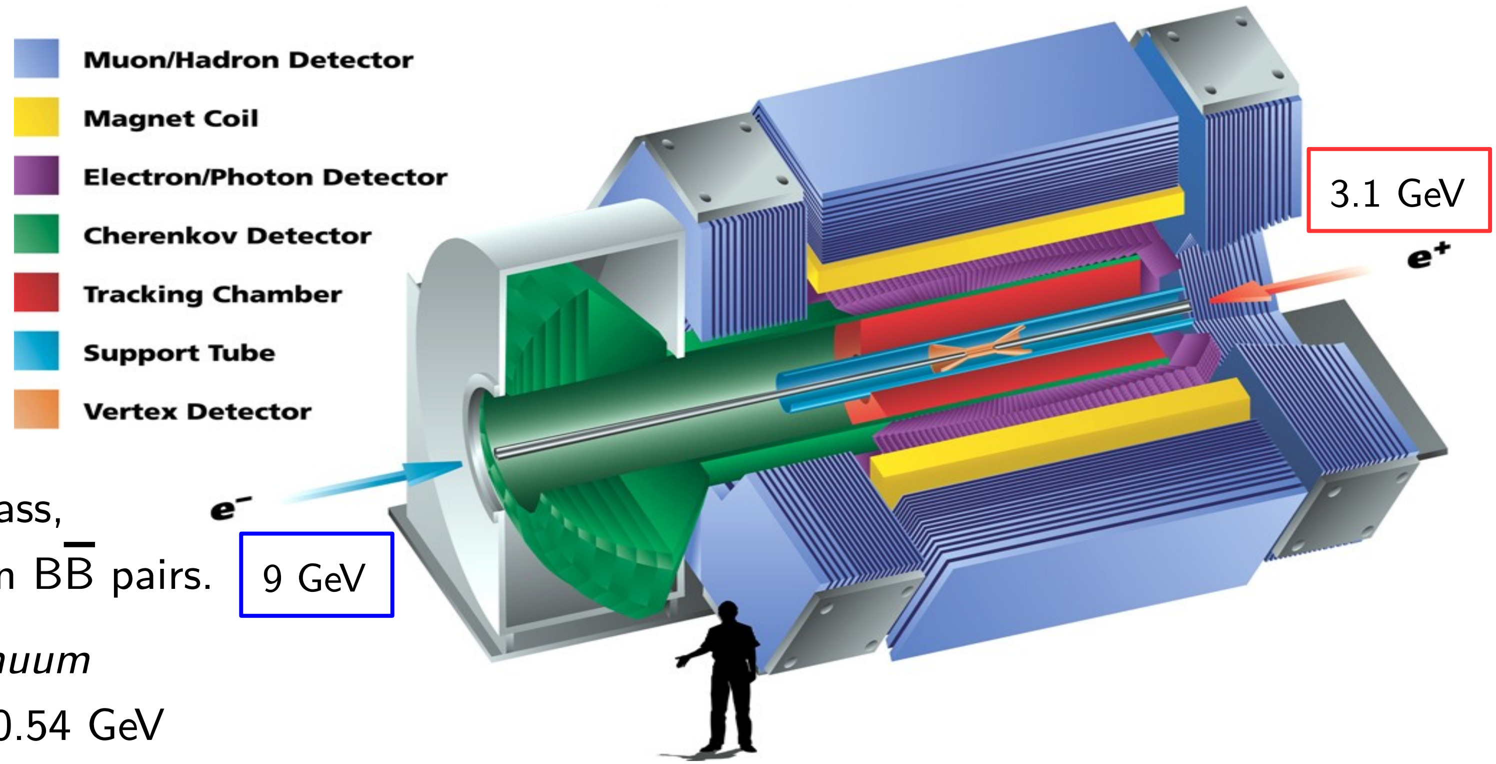
B-factories: dedicated experiments at *e^+e^- asymmetric-energy colliders* for the production of quantum coherent $B\bar{B}$ pairs → **CPV studies** and **NP indirect** searches.

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

- $\beta\gamma = 0.56$

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

- 424 fb^{-1} *on-peak* at $\Upsilon(4S)$ mass, $\sqrt{s}$=10.58 GeV → 471 million $B\bar{B}$ pairs.
- 44 fb^{-1} *off-peak, in the continuum hadronization region*, $\sqrt{s} = 10.54$ GeV
- Lower resonance samples: $\Upsilon(2S)$, $\Upsilon(3S)$



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.

The Dalitz-plot analysis of 3-body charmonium decays

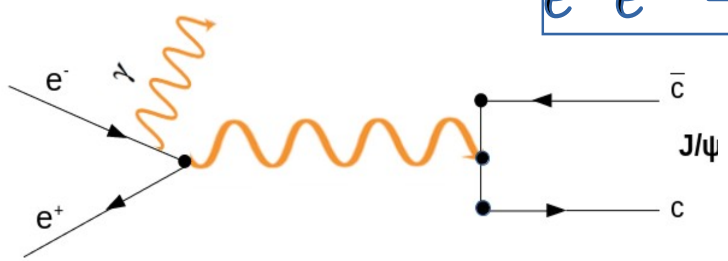
Motivation

- QCD predicts multiquark states in the low mass region of the hadron spectrum
- Initial State Radiation (ISR) processes are used to obtain clean J/ψ samples, selecting events with undetected fast forward γ_{ISR}

  → only J^{PC}=1⁻⁻ resonances can be produced.

- The data set corresponds to 519 fb^{-1} collected with the Babar detector at Υ(nS) resonances, n=2, 3, 4.

$$e^+e^- \to \gamma_{ISR} J/\Psi$$



(I) $J/\Psi \to \pi^+\pi^-\pi^0$

(II) $J/\Psi \to K^+K^-\pi^0$

(III) $J/\Psi \to K_s K^\pm \pi^\mp$

Previously:

- Only preliminary results for Dalitz-plot analysis (**I**, SLAC-PUB-5674 (1991)) or even never done (**III**)
- Branching fractions poorly measured (**II**, MarkII with 25 events)
- Angular analysis results presented for (**II**) by BESIII, detected broad J^{PC}=1⁻⁻ state interpreted as a multiquark state. (Phys. Lett. B 710, 594, 2012)

The Event Reconstruction and Selection

$$e^+e^- \rightarrow \gamma_{ISR} h_1 h_2 h_3, \;\; h = K^\pm/K_s/\pi$$

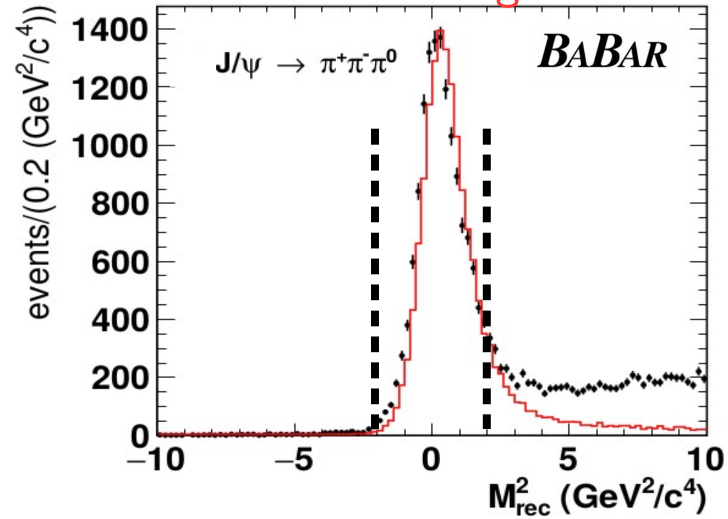
- γ_{ISR} as missing particle, $M^2_{rec} = (p_{e+} + p_{e-} - p_{h1} - p_{h2} - p_{h3})^2$ peaks at zero for ISR events
- The invariant mass of h_1, h_2, h_3 peaks at J/ψ mass for signal events → fit to the mass spectrum with the MC resolution function: Crystal Ball + Gaussian functions.
- From the fitted event yields, the *branching fraction ratios* have been measured:

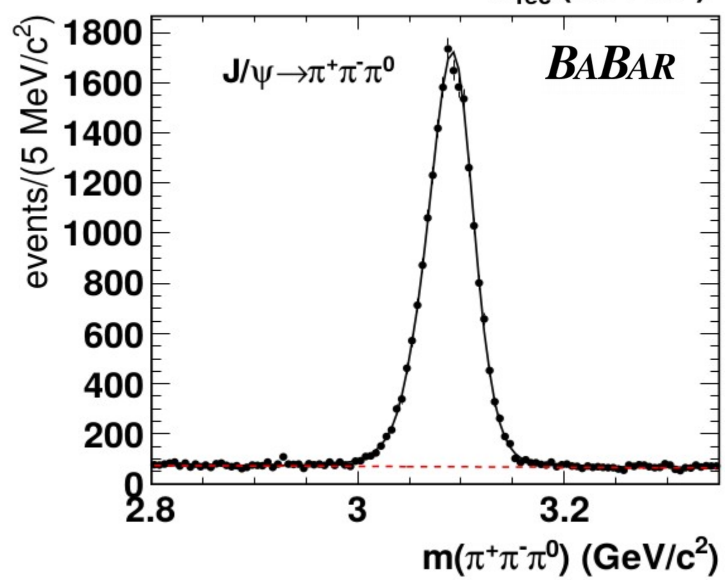
$$\mathcal{R}_1 = \frac{\mathcal{B}(J/\psi \rightarrow K^+K^-\pi^0)}{\mathcal{B}(J/\psi \rightarrow \pi^+\pi^-\pi^0)} = 0.120 \pm 0.003(\text{stat}) \pm 0.009(\text{sys})$$

$$\mathcal{R}_2 = \frac{\mathcal{B}(J/\psi \rightarrow K^0_S K^\pm \pi^\mp)}{\mathcal{B}(J/\psi \rightarrow \pi^+\pi^-\pi^0)} = 0.265 \pm 0.005(\text{stat}) \pm 0.021(\text{sys})$$

Using the PDG value for $B(J/\psi \rightarrow K_s K^\pm \pi^\pm) = (26 \pm 7) \times 10^{-4}$ (Mark I, 126 events) → $R_2^{PDG} = 0.123 \pm 0.033$ ~ 3.6σ deviations

Red line = Signal MC



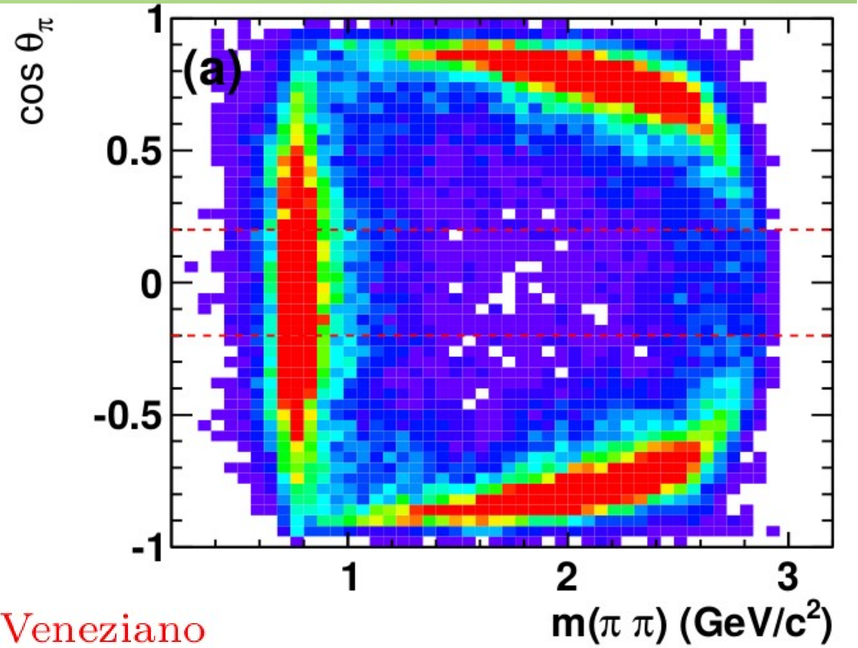


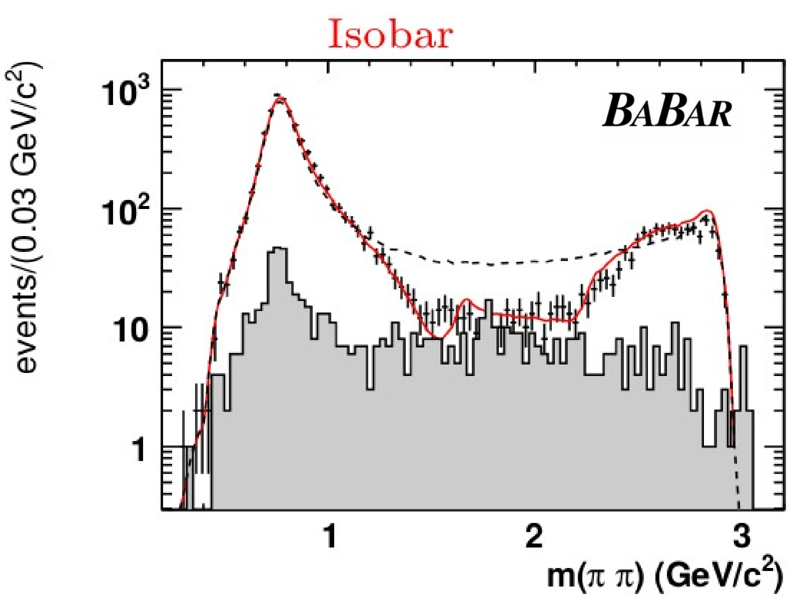
The Dalitz-plot analysis

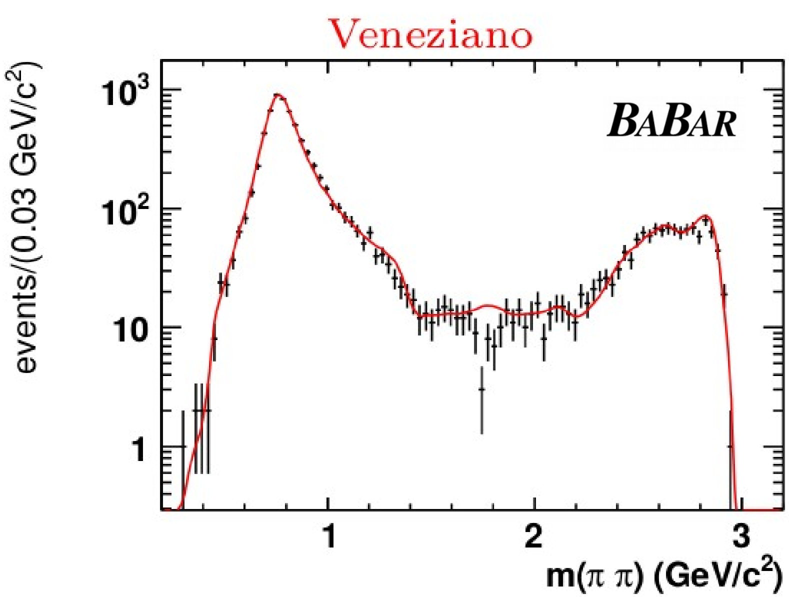
$J/\Psi \rightarrow \pi^+\pi^-\pi^0$

Fitted event yield = 20417, Purity = 91.3 ± 0.2 %

- Two models for implementing the likelihood function in the fit:
  - **Isobar model** *(→ further references in backup slides)*
  - **Veneziano model** *(resonance-Regge poles duality)*
- $m(\pi\pi)$ mass projections for events with $|\cos\theta_\pi| < 0.2$
- Dashed line is the fit without ρ'







The Dalitz-plot analysis

$J/\Psi \to \pi^+\pi^-\pi^0$

- *Fitted fractions*: the main contribution comes from ρ(770)π resonance.

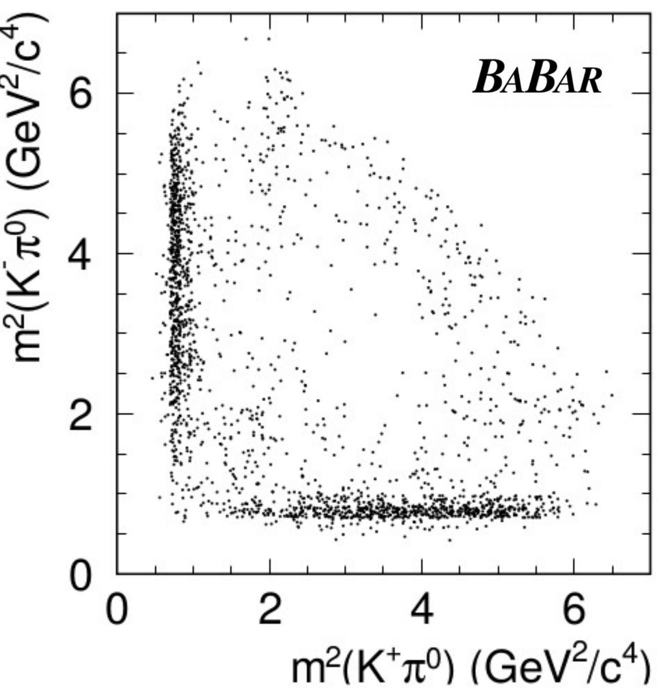
Final state	Amplitude	Isobar fraction (%)	Phase (radians)	Veneziano fraction (%)
$\rho(770)\pi$	1.	$114.2 \pm 1.1 \pm 2.6$	0.	133.1 ± 3.3
$\rho(1450)\pi$	0.513 ± 0.039	$10.9 \pm 1.7 \pm 2.7$	$-2.63 \pm 0.04 \pm 0.06$	0.80 ± 0.27
$\rho(1700)\pi$	0.067 ± 0.007	$0.8 \pm 0.2 \pm 0.5$	$-0.46 \pm 0.17 \pm 0.21$	2.20 ± 0.60
$\rho(2150)\pi$	0.042 ± 0.008	$0.04 \pm 0.01 \pm 0.20$	$1.70 \pm 0.21 \pm 0.12$	6.00 ± 2.50
$\omega(783)\pi^0$	0.013 ± 0.002	$0.08 \pm 0.03 \pm 0.02$	$2.78 \pm 0.20 \pm 0.31$	
$\rho_3(1690)\pi$				0.40 ± 0.08
Sum		$127.8 \pm 2.0 \pm 4.3$		142.5 ± 2.8
χ^2/ν		$687/519 = 1.32$		$596/508 = 1.17$

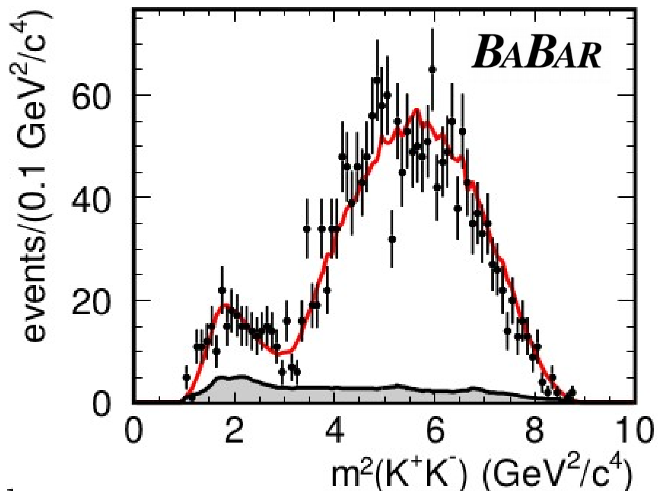
- The two models provide a similar representation of data.
- Better data-fit agreement with Veneziano model may indicate the presence of further resonances.

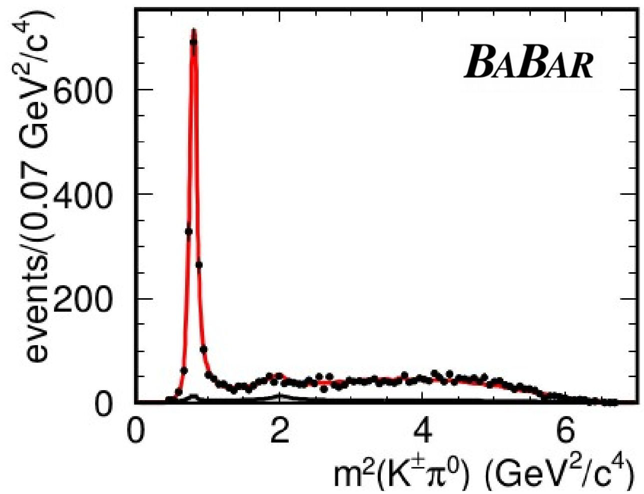
The Dalitz-plot analysis

$J/\Psi \rightarrow K^+K^-\pi^0$

Fitted event yield = 2102, Purity = 88.8 ± 0.7 %







- $K^*(892)^\pm$ resonances observed
- Broad structure in $K\bar{K}$ low mass region found to be compatible with $\rho(1450)^0$

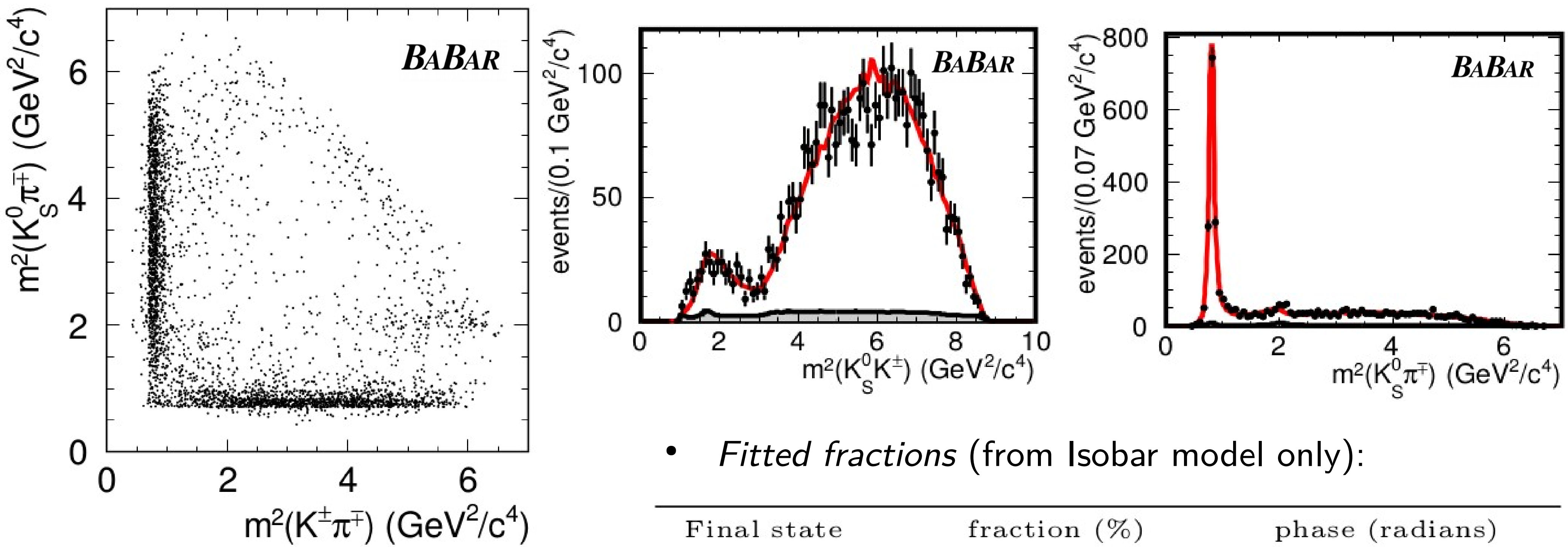
- *Fitted fractions* (only with **Isobar model** because of the low statistics):

Final state	fraction (%)	phase (radians)
$K^*(892)^\pm K^\mp$	$92.4 \pm 1.5 \pm 3.4$	0.
$\rho(1450)^0\pi^0$	$9.3 \pm 2.0 \pm 0.6$	$3.78 \pm 0.28 \pm 0.08$
$K^*(1410)^\pm K^\mp$	$2.3 \pm 1.1 \pm 0.7$	$3.29 \pm 0.26 \pm 0.39$
$K_2^*(1430)^\pm K^\mp$	$3.5 \pm 1.3 \pm 0.9$	$-2.32 \pm 0.22 \pm 0.05$
Total	107.4 ± 2.8	
χ^2/ν	$132/137 = 0.96$	

The Dalitz-plot analysis

$J/\Psi \to K_s K^{\pm}\pi^{\mp}$

Fitted event yield = 3907, Purity =93.1 ± 0.4 %



- $K^*(892)\overline{K}$ and $K^*_2(1430)\overline{K}$ observed
- Broad structure in $K_sK^{\pm}$ low mass region consistent with $\rho(1450)^{\pm}$

- *Fitted fractions* (from Isobar model only):

Final state	fraction (%)	phase (radians)
$K^*(892)\bar{K}$	$90.5 \pm 0.9 \pm 3.8$	0.
$\rho(1450)^{\pm}\pi^{\mp}$	$6.3 \pm 0.8 \pm 0.6$	$-3.25 \pm 0.13 \pm 0.21$
$K^*_1(1410)\bar{K}$	$1.5 \pm 0.5 \pm 0.9$	$1.42 \pm 0.31 \pm 0.35$
$K^*_2(1430)\bar{K}$	$7.1 \pm 1.3 \pm 1.2$	$-2.54 \pm 0.12 \pm 0.12$
Total	105.3 ± 3.1	
χ^2/ν	$274/217 = 1.26$	

Summary (I)

BABAR, PRD 95, 072007 (2017), arXiv:1702.01551

- The Dalitz-plot analyses for $J/\psi \to \pi^+\pi^-\pi^0$, $J/\psi \to K^+K^-\pi^0$, $J/\psi \to K_sK^\pm\pi^\pm$ have been performed
- Broad structures in the low KK mass region were found to be consistent with $\rho(1450)^0$, $\rho(1450)^\pm$ resonances
- The ratio $\frac{\mathcal{B}(\rho(1450)^0 \to K^+K^-)}{\mathcal{B}(\rho(1450)^0 \to \pi^+\pi^-)} = 0.307 \pm 0.084 \pm 0.082$ has been measured.

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($\bar{B}^0 \rightarrow \Lambda_c^+ \, p \, \bar{p} \, \bar{p}$) < 2.8x10^{-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:

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

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

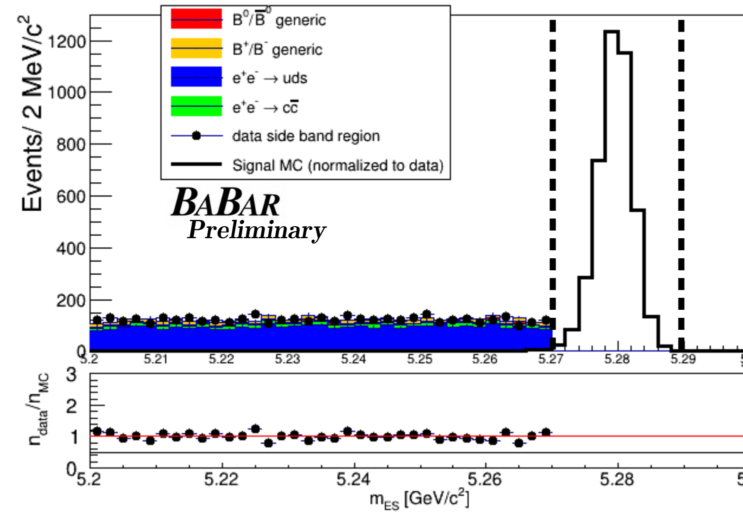
[**] V.L. Chernyak and I.R. Zhitnitsky, Nuclear Physics B, Vol. 345, 1 pp. 137-172 (1990); He Xiao-Gang, Li Tong, Li Xue-Qian and Wang Yu-Ming, Phys. Rev. D, 75, id. 034011 (2007).

The Event Reconstruction

- Performed as *blind analysis* $\rightarrow$ 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 studies on background Monte Carlo samples

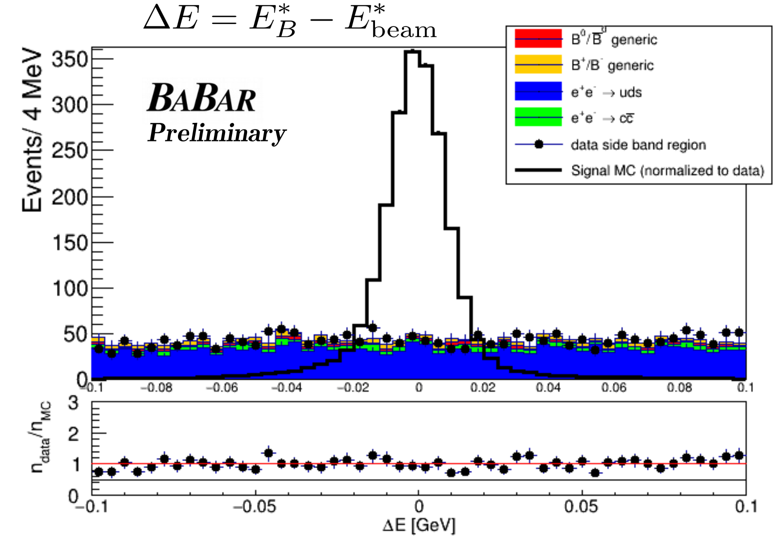
  (*EvtGen* for generic B decays from $\Upsilon(4S)$, *JetSet* for continuum events)
- Four oppositely charged tracks, coming from the Interaction Point, identified as two **protons** and two **antiprotons**
- Kinematic fit to the common vertex with a fit probability larger than 0.1 %
- Loose cuts on **kinematic variables**

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



- **Energy difference**

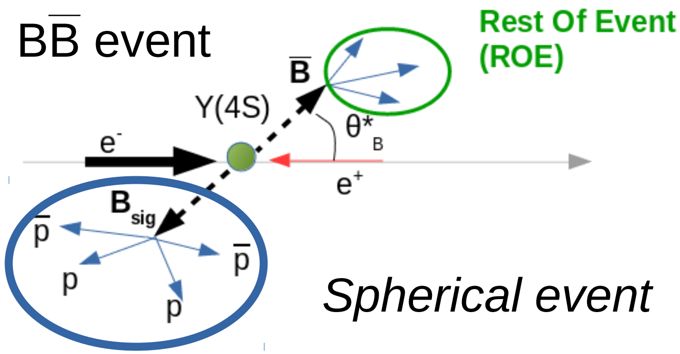
$\Delta E = E^*_B - E^*_{\rm beam}$



The Event Selection

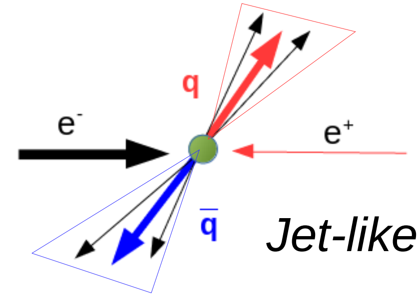
- Mainly **combinatorial background** due to real protons from *continuum events* $e^+e^- \to q\bar{q}$

  - $B\bar{B}$ event



Spherical event

  - *Continuum* event

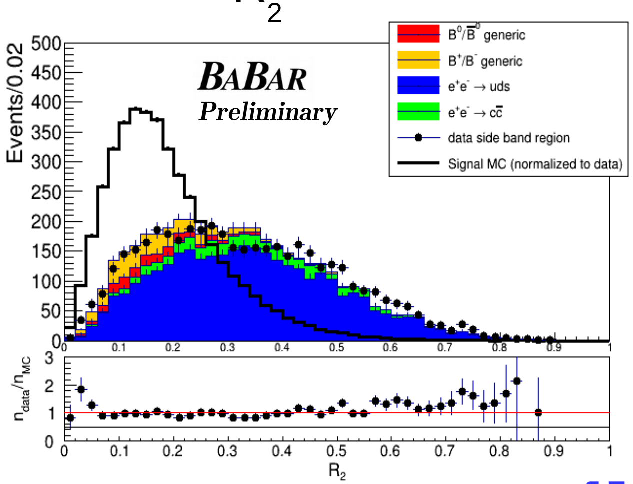


q= u,d,s,c

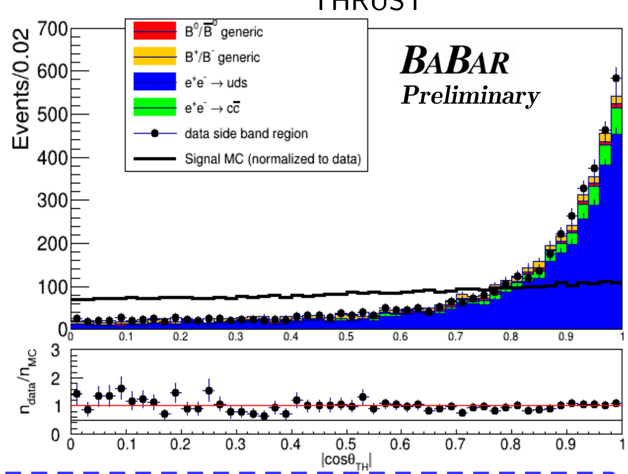
Jet-like event

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

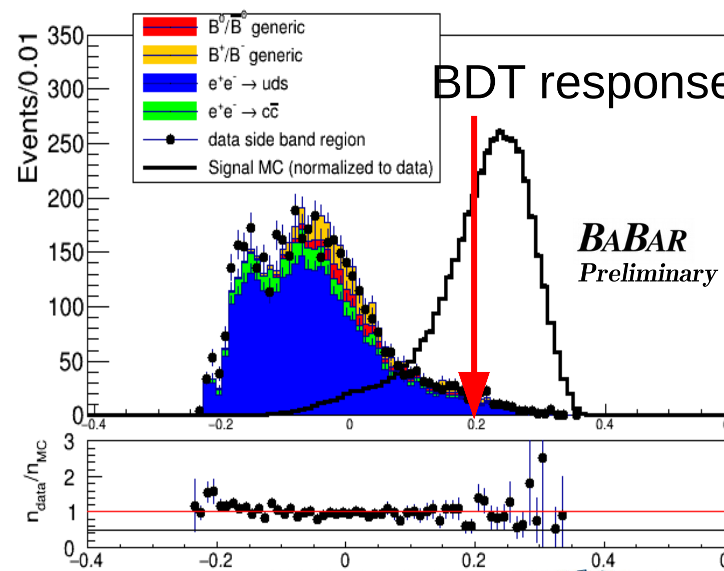
R_2



$|\cos\theta_{THRUST}|$



BDT response



Signal efficiency $\varepsilon = 21\%$

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 cut.

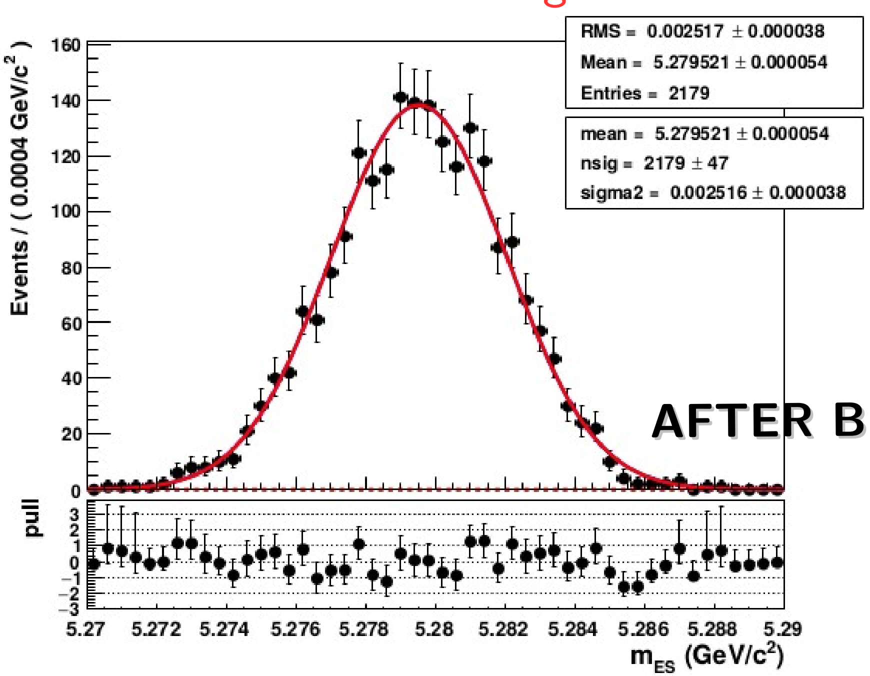
- The **probability density function** is defined:

$$f(x;\vec{p},N_{sig},N_{bkg}) = \frac{1}{N_{sig}+N_{bkg}} \cdot (N_{sig} \cdot f_{sig}(x;\vec{p}_{sig}) + N_{bkg} \cdot f_{bkg}(x;\vec{p}_{bkg}))$$

***Total Pdf* : signal + background**

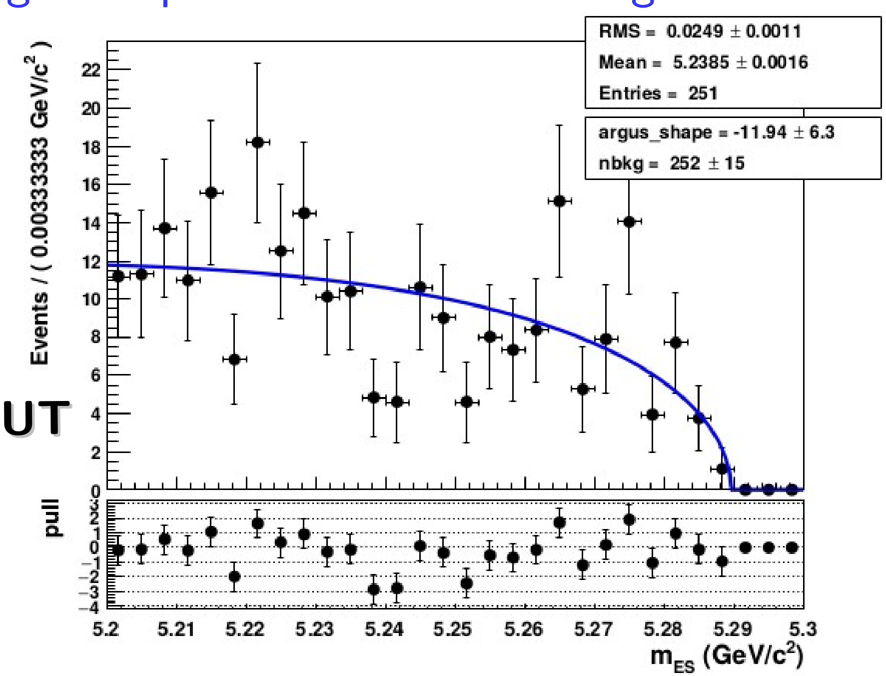
- $f_{sig} \rightarrow$ modeled on signal MC
- $f_{bkg} \rightarrow$ modeled on both MC samples and data
- All shape parameters ($\boldsymbol{p}_{sig}$, $\boldsymbol{p}_{bkg}$) fixed in the *total pdf*
- N_{sig}, N_{bkg} floating parameters in the signal yield extraction fit

Gaussian function fit to Signal MC



AFTER BDT CUT

Argus shape function fit to Background MC



The signal yield extraction and the BF estimate

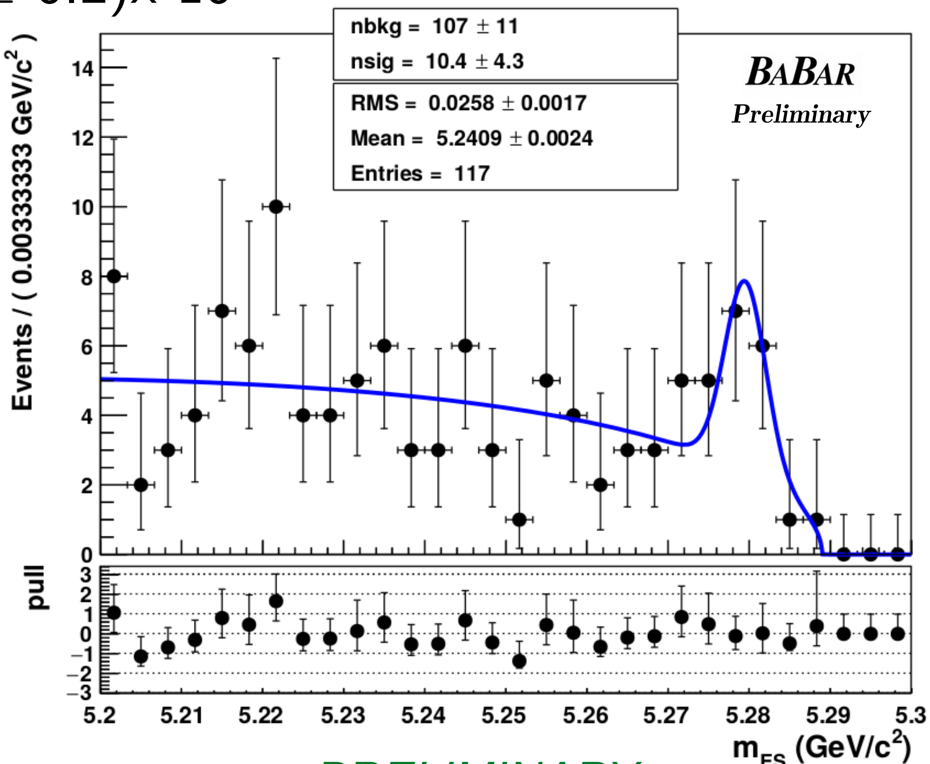
The fit to the m_{ES} distribution gives $N_{sig} = (10.4 \pm 4.3)$, with a 3.2σ significance

$\rightarrow$ BF=$(1.1 \pm 0.5 \pm 0.2) \times 10^{-7}$

$\rightarrow$ The statistical uncertainty on N_{sig} is the main source of uncertainty on the BF.

$\rightarrow$ Systematic uncertainties contribute as a further 20% relative uncertainty on the BF. The main sources are listed in the table:

Variable	Source	Relative systematic uncertainty
$N_{B\bar{B}}$	B counting	1%
N_{sig}	Argus shape a estimate	14%
N_{sig}	Argus cutoff b	3%
ϵ	PID efficiency	0.86%
ϵ	Track finding efficiency	1%
ϵ	BDT selection	2.2%
ϵ	decay model	14%
Total		20%



PRELIMINARY

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

Summary (II)

TO BE SUBMITTED

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

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

Preliminary results:

- Evidence at 3.2σ of 10 decay events!
- $BF^{UL} = 2 \times 10^{-7}$ at 90% CL

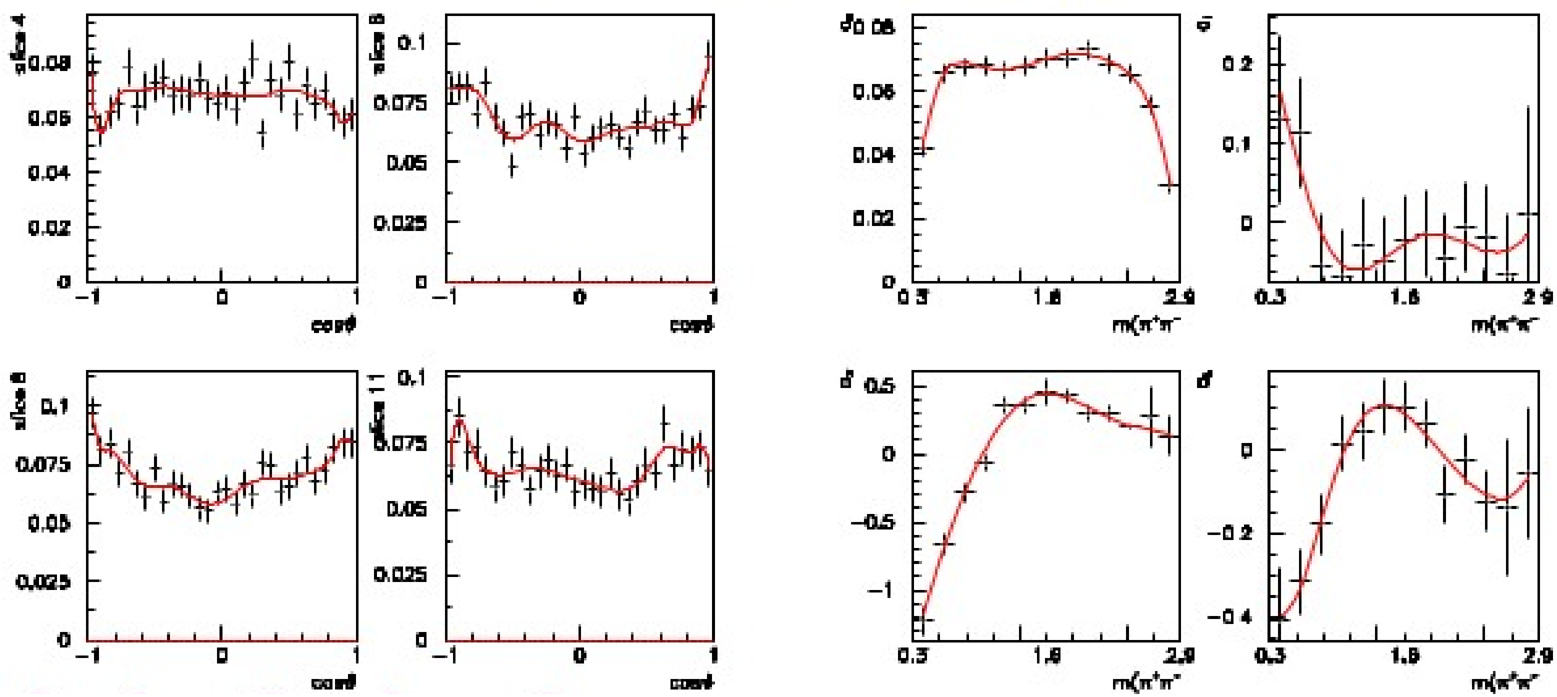
Thanks for your attention.

Backup: The Dalitz-plot analysis for 3-body charmonium decays

The Efficiency

- The efficiency is parameterized as a function of $m(\pi^+\pi^-)$ and $\cos\theta_h$: the mass spectrum is sliced in 13 bins of $\cos\theta_h$ and fitted with Legendre Polynomials up to L=13.

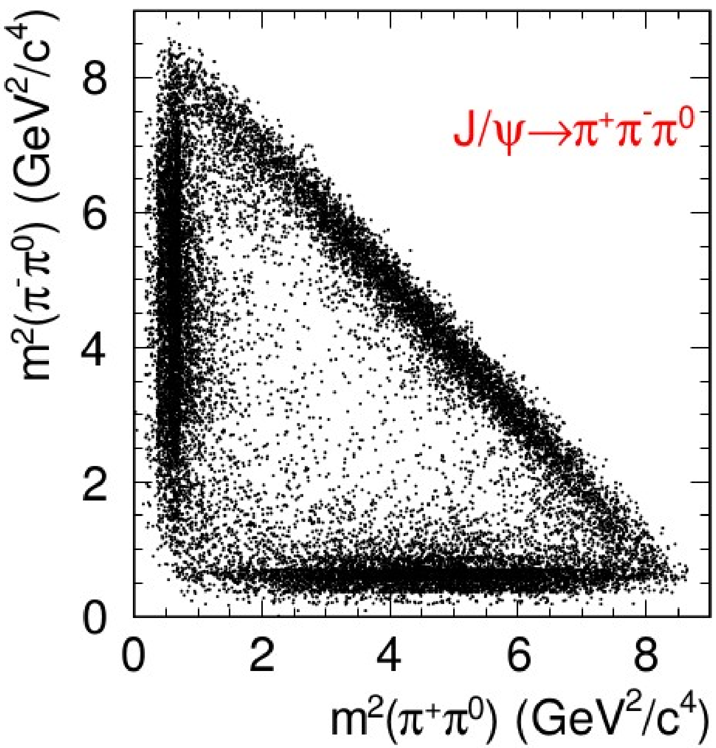
$$\epsilon(cos\theta) = \sum_{L=0}^{13} Y_L^0(cos\theta)$$

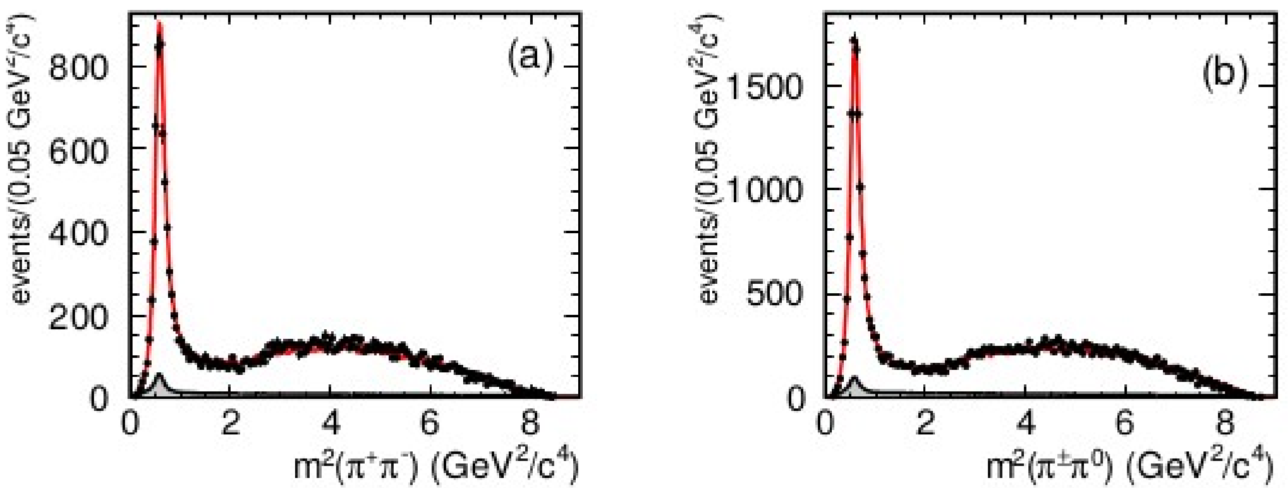


The Dalitz-plot analysis

$J/\Psi \rightarrow \pi^+\pi^-\pi^0$

- In the Dalitz-plot m_{23} Vs. m_{13} is shown and m(ππ) projections are also plotted.





Dalitz-plot analysis with the Isobar model

- Standard Dalitz-plot analysis is done with unbinned maximum likelihood fit
- The amplitudes are usually described by Breit-Wigner functions. Interferences might be taken into account.
- For a resonance decaying as R $\rightarrow$ j +k, t_i is defined aside (p_i is the particle-i momentum)
- The spin-amplitude is described by Zemach tensors.

C. Zemach, Phys Rev. 133, B1201 (1964), C. Dionisi et. al., Nucl. Phys. B169, 1 (1980)

$$\mathcal{L} = \prod_{n=1}^{N} \left[f_{\text{sig}}(m_n) \cdot \epsilon(x'_n, y'_n) \frac{\sum_{i,j} c_i c_j^* A_i(x_n, y_n) A_j^*(x_n, y_n)}{\sum_{i,j} c_i c_j^* I_{A_i A_j^*}} + (1 - f_{\text{sig}}(m_n)) \frac{\sum_i k_i B_i(x_n, y_n)}{\sum_i k_i I_{B_i}} \right] \tag{15}$$

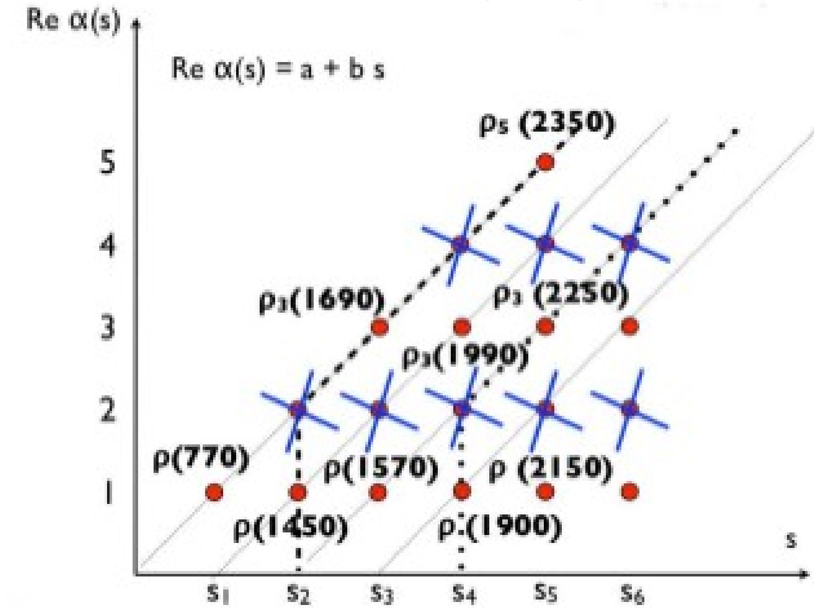
$$t_i^\mu = p_j^\mu - p_k^\mu - (p_j^\mu + p_k^\mu) \frac{m_j^2 - m_k^2}{m_{jk}^2}$$

J/ψ decay mode	Decay	Amplitude
$\pi^+\pi^-\pi^0$	$\rho\pi$	$BW_\rho(m_{13})(\mathbf{t_2} \times \mathbf{p_2}) + BW_\rho(m_{23})(\mathbf{t_1} \times \mathbf{p_1}) + BW_\rho(m_{12})(\mathbf{t_3} \times \mathbf{p_3})$
	NR	$(\mathbf{t_1} \times \mathbf{p_1}) + (\mathbf{t_2} \times \mathbf{p_2}) + (\mathbf{t_3} \times \mathbf{p_3})$
$K\bar{K}\pi$	$K^*\bar{K}$	$BW_{K^*}(m_{13})(\mathbf{t_2} \times \mathbf{p_2}) + BW_{K^*}(m_{23})(\mathbf{t_1} \times \mathbf{p_1})$
	$K_2^*(1430)\bar{K}$	$BW_{K_2^*}(m_{13})(\mathbf{k_2}) + BW_{K_2^*}(m_{23})(\mathbf{k_1})$
	$\rho\pi$	$BW_\rho(m_{12})(\mathbf{t_3} \times \mathbf{p_3})$

The Veneziano model for Dalitz-plot analysis

A. P. Szczepaniak, M.R. Pennington, Phys. Lett. B737, 283 (2014)

- Assumptions:
  - low-mass region is resonance-dominated
  - Resonance-Regge duality :
    - all the resonances are located on Regge trajectories and Regge poles are the only singularities
    - Regge amplitudes are described in terms of Γ functions $$A_{n,m} = \frac{\Gamma(n-\alpha(s))\Gamma(n-\alpha(t))}{\Gamma(n+m-\alpha(s)-\alpha(t))}$$



- The trajectories describe the linear correlation between resonance masses and spins, in the angular momentum complex plane: $\alpha(m_R^2) = J_R$
- The main difficulty is related to the considered number of trajectories, n: for this fit n fixed to 7, 19 free parameters.

$$A_{X\to abc} = \sum_{n,m} c_{X\ \to\ abc}(n,m) A_{n,m}$$

Systematic uncertainties

- The contributions to the systematic uncertainties on the fitted fractions and phases have been evaluated as follows:
  - Purity scaled up and down of one statistical uncertainty
  - Mass resonance parameters varied within one standard deviations of their uncertainties as listed in the PDG
  - Vary the radius of Blatt-Weisskopf factor (fixed in the model to 1.5 GeV/c), enter the relativistic Breit-Wigner function
  - Raw efficiency is used instead of the fitted one
  - Toy MC experiments, simulating a data distribution according to the fit results and re-fitting them $\rightarrow$ evaluate possible biases on the Dalitz-plot results, the whole difference is taken as uncertainty.

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

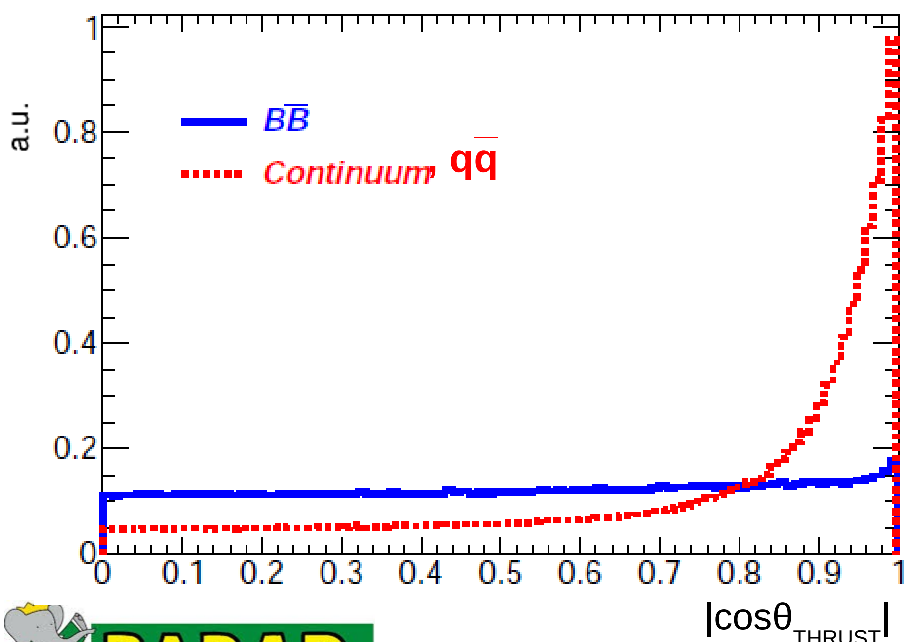
Event shape variables

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}

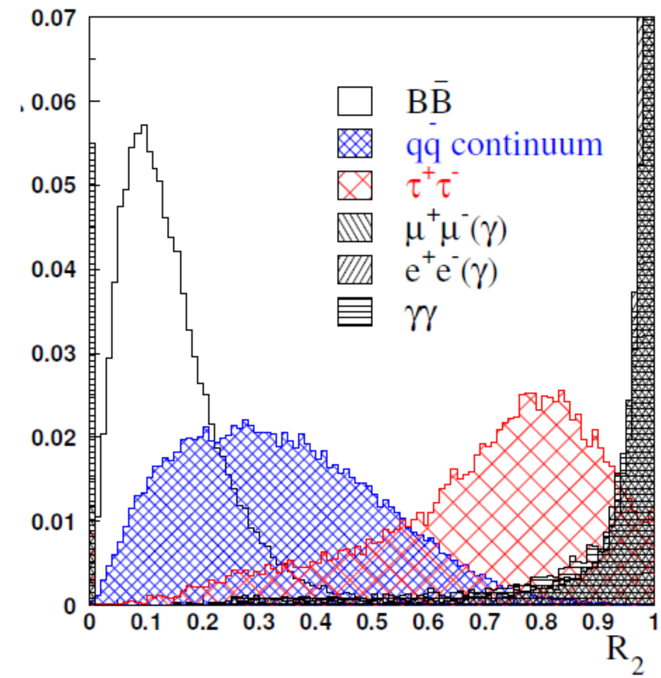
$$T = \frac{\sum_{i=1}^{N} |\vec{T} \cdot \vec{p}_i|}{\sum_{i=1}^{N} |\vec{p}_i|}$$



$R_2 = H_2/H_0$

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

- 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^{obs}_{sig} →

- *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%**)

Weighting technique {

3) BDT (**2.2%**)

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

BDT uncertainty study

Weighting technique

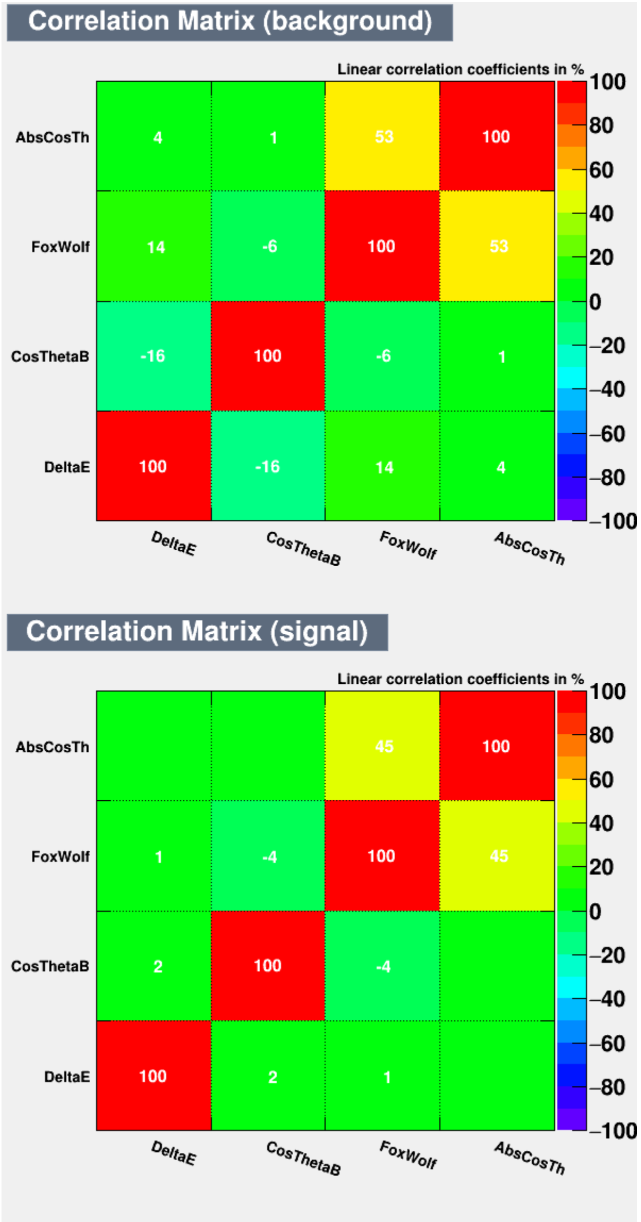
- for each input variable distribution, BEFORE THE BDT, define bin by bin weights comparing background MC-data samples:

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

- 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