Dalitz Plot Analysis of $B \rightarrow DDK$ decays

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for the BaBar collaboration

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Introduction

- Results recently published by BaBar (March 2015)
- Analysis chiefly done by Vincent Poireau (LAPP, Annecy)

PHYSICAL REVIEW D 91, 052002 (2015)

Dalitz plot analyses of $B^0 \to D^- D^0 K^+$ and $B^+ \to \bar{D}^0 D^0 K^+$ decays


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Dalitz plot analyses of $B^0 \to D^- D^0 K^+$ and $B^+ \to \bar{D}^0 D^0 K^+$ decays

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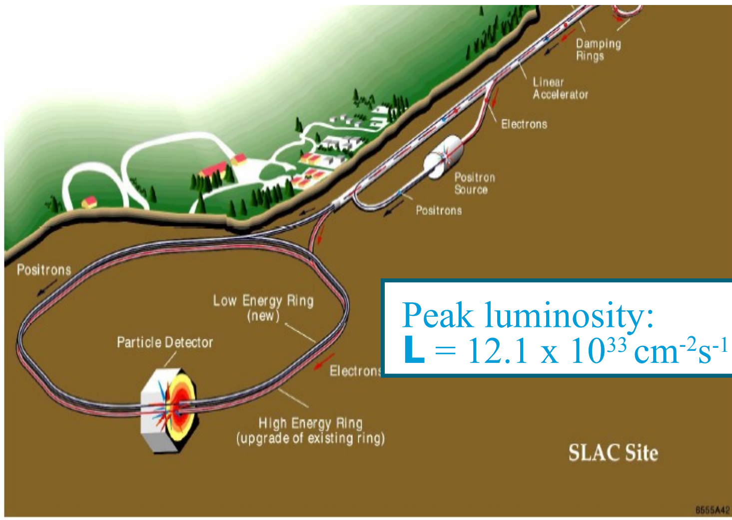
Introduction, continued

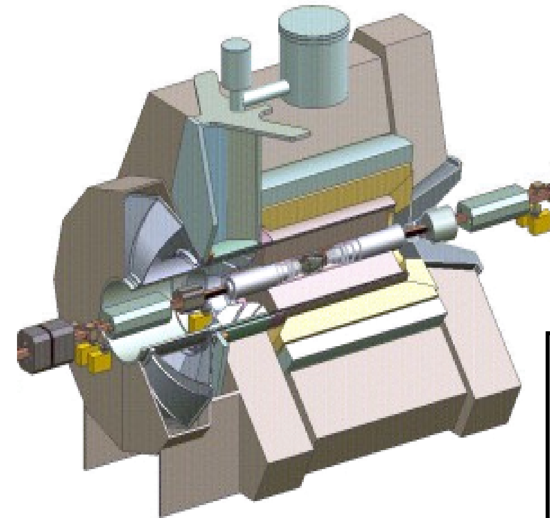
Center of mass: 10.58 GeV
$e^+ e^- \to \Upsilon(4S)\ (b\bar{b}) \to B\bar{B}$



Peak luminosity:
$\mathbf{L} = 12.1 \times 10^{33}\ cm^{-2}s^{-1}$

9 GeV e^-

3.1 GeV e^+



Recorded 531 fb^{-1} in total

- $\Upsilon(4S)$: 433 fb^{-1}
- $\Upsilon(3S)$: 30 fb^{-1}
- $\Upsilon(2S)$: 14 fb^{-1}
- Off-peak: 54 fb^{-1}

- The *BABAR* experiment switched off in 2008, but still produces many interesting results!
  - **549** papers in total
  - **26** in **2013**
  - **15** in **2014**
  - ~**15** expected in **2015**

Introduction, continued

- Studying $B \to D^{(*)}D^{(*)}K$ decays
  - **22 modes**
  - These modes have been the topics of **three previous BaBar papers**
    - Time-dependent ***CP* asymmetry** in $B \to D^{*-}D^{*+}K^0_S$ — **Phys. Rev. D74, 091101, 2006**
    - Study of the **resonances** $\psi(3770)$, $D_{s1}(2536)$, and X(3872) — **Phys. Rev. D77, 011102, 2008**
    - Measurement of 22 **branching fractions** — **Phys. Rev. D83, 032004, 2011**

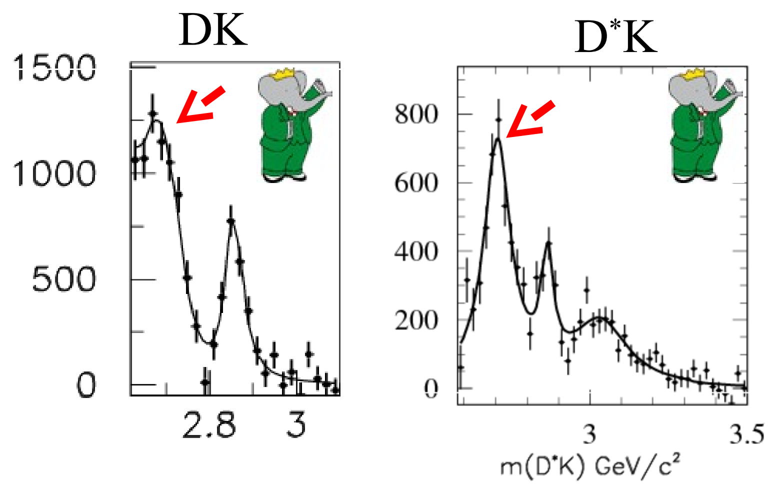
- These decays contain **resonances** in $D^{(*)}D^{(*)}K$ ($c\bar{s}$) or $D^{(*)}D^{(*)}K$ ($c\bar{c}$)

- Here we report on properties of the $D_{s1}(2700)$

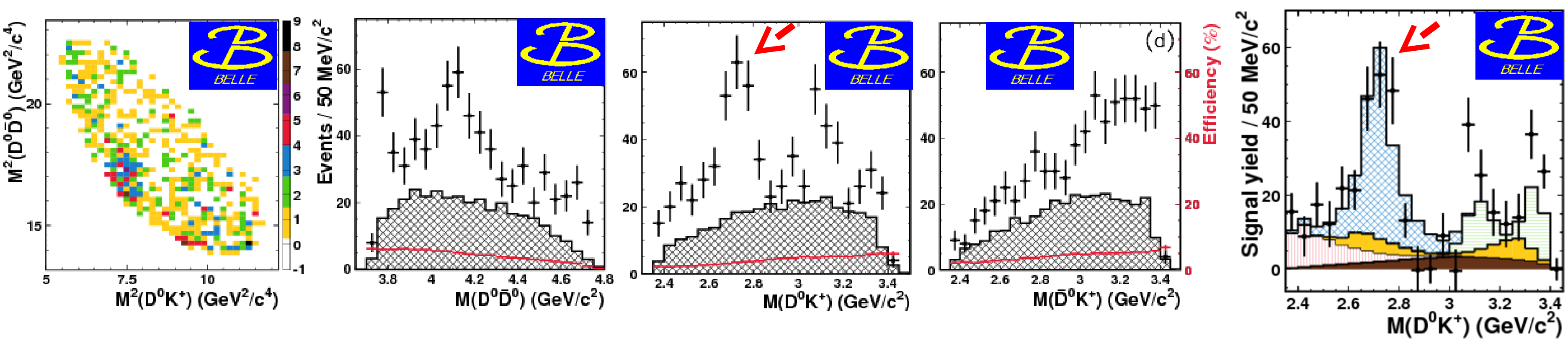
Neutral B mode	Charged B mode
$B^0 \to D^- D^0 K^+$	$B^+ \to \bar{D}^0 D^+ K^0$
$B^0 \to D^- D^{*0} K^+$	$B^+ \to \bar{D}^0 D^{*+} K^0$
$B^0 \to D^{*-} D^0 K^+$	$B^+ \to \bar{D}^{*0} D^+ K^0$
$B^0 \to D^{*-} D^{*0} K^+$	$B^+ \to \bar{D}^{*0} D^{*+} K^0$
$B^0 \to D^- D^+ K^0$	$B^+ \to \bar{D}^0 D^0 K^+$
$B^0 \to D^- D^{*+} K^0 + D^{*-} D^+ K^0$	$B^+ \to \bar{D}^0 D^{*0} K^+$
	$B^+ \to \bar{D}^{*0} D^0 K^+$
$B^0 \to D^{*-} D^{*+} K^0$	$B^+ \to \bar{D}^{*0} D^{*0} K^+$
$B^0 \to \bar{D}^0 D^0 K^0$	$B^+ \to D^- D^+ K^+$
$B^0 \to \bar{D}^0 D^{*0} K^0 + \bar{D}^{*0} D^0 K^0$	$B^+ \to D^- D^{*+} K^+$
	$B^+ \to D^{*-} D^+ K^+$
$B^0 \to \bar{D}^{*0} D^{*0} K^0$	$B^+ \to D^{*-} D^{*+} K^+$

The $D_{s1}(2700)$

- The $D_{s1}(2700)$ was discovered by BaBar in inclusive e^+e^- interactions
  - Decaying to DK
  - Observed later also in D*K
  - Discovered as well $D_{sJ}(2860)$ and $D_{sJ}(3040)$

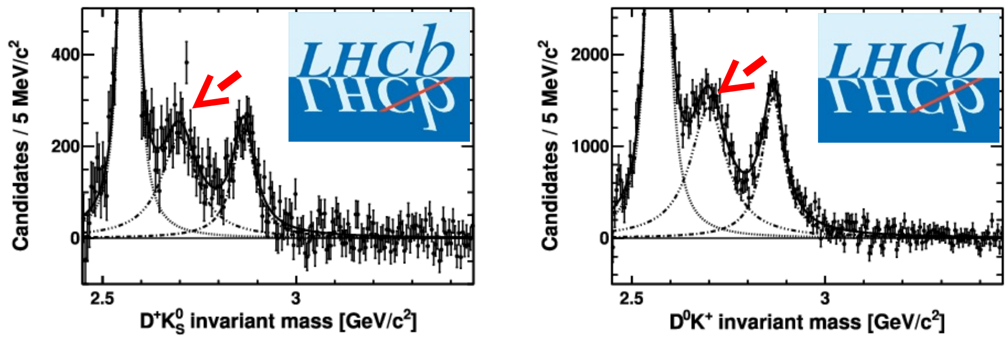


This discovery was
confirmed by Belle in $B^+ \to \bar{D}^0(D^0K^+)$



The $D_{s1}(2700)$, continued

- LHCb also studied this state with 1.0 fb^{-1} R. Aaij *et al*., JHEP 1210 (2012) 151



- Found properties:

Name	J^P	Mass (MeV/c^2)	Width (MeV)
$D^*_{s1}(2700)$ (PDG)	1^-	2709 ± 4	117 ± 13

- Our goal here is to study the $D_{s1}(2700)$ *using a full Dalitz analysis*

- We use both $B^0 \to D^- D^0 K^+$ and $B^+ \to \overline{D}^0 D^0 K^+$ channels
  - We do not attempt to study channels containing **D* mesons (vector)**

The Data Sample

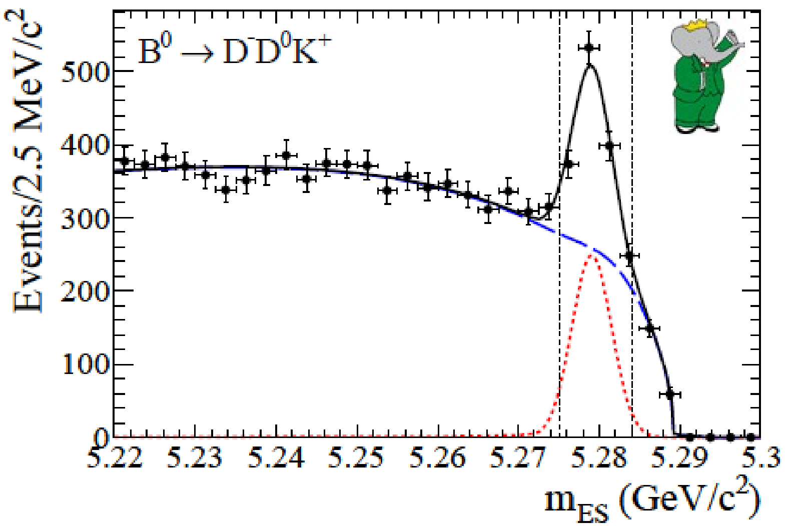
- Run1-Run6, 429 fb^{-1}: $N_{B\bar{B}} = (470.9 \pm 0.1 \pm 2.8) \times 10^6$

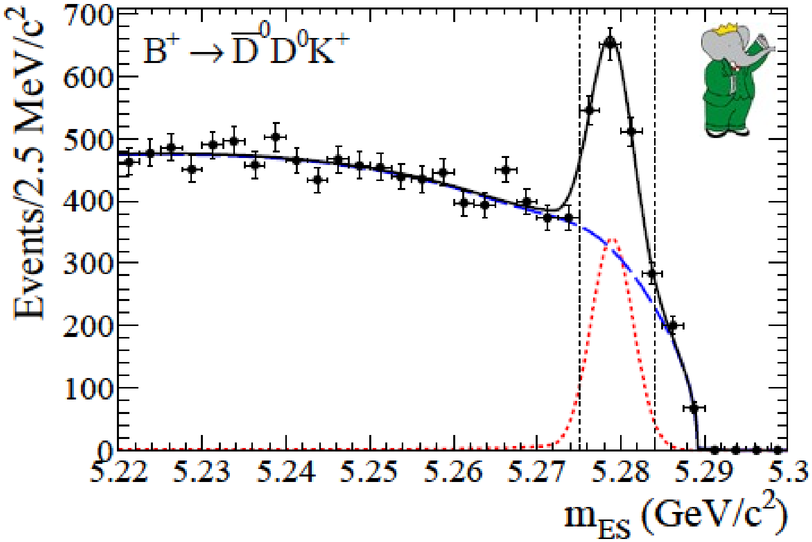
- Exclusive reconstruction
  - $D^0 \to K^- \pi^+$, $D^0 \to K^- \pi^+\pi^0$, $D^0 \to K^- \pi^+\pi^-\pi^+$
  - $D^+ \to K^- \pi^+\pi^+$
  - For $\bar{D}^0 D^0 K^+$, at least one of the D^0's is required to decay to $K^- \pi^+$

- Use the exact same selection as the analysis on the measurement of 22 branching fractions
  - Based on track quality, Particle ID
  - Invariant D mass
  - Topological variables
  - ΔE cut

The Data Sample, continued

- m_{ES} distribution after the complete selection





- To obtain the Dalitz plot, a cut on m_{ES} is also imposed
- **$B^0 \to D^- D^0 K^+$:** 1470 events with a purity of $(38.6 \pm 2.8 \pm 2.1)\%$
- **$B^+ \to \overline{D}^0 D^0 K^+$:** 1894 events with a purity of $(41.6 \pm 2.5 \pm 3.1)\%$

Dalitz Plot Analysis

- Isobar formalism $\mathcal{M} = \sum_i c_i A_i$
  - c_i: complex coefficients representing the **modulus** and **phase**
  - A_i: complex amplitudes representing the **dynamical function** describing **the intermediate resonance**

- Likelihood

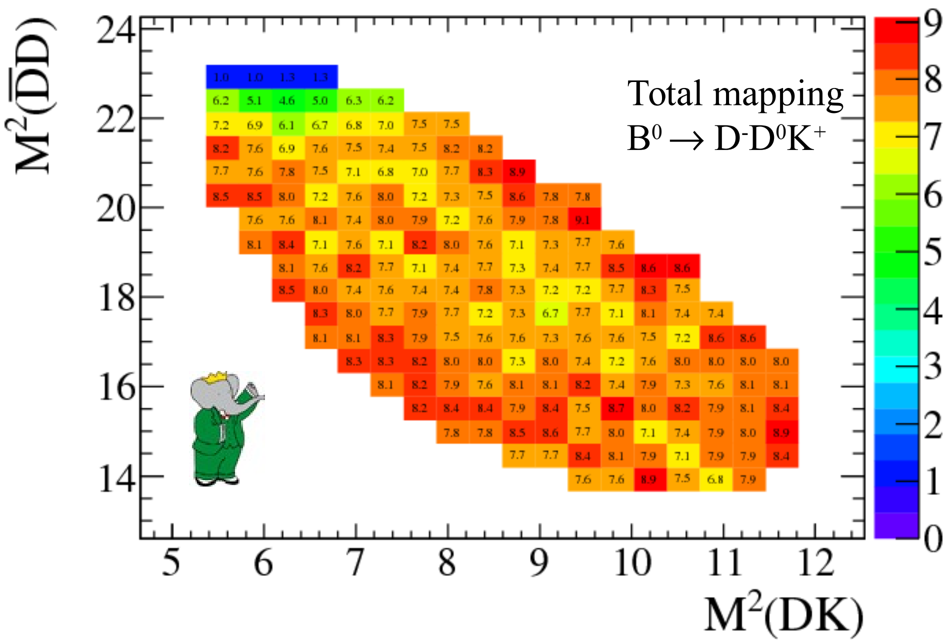
$$\mathcal{L} = p \times \varepsilon(m_1^2, m_2^2) \times \frac{|\mathcal{M}|^2}{\int |\mathcal{M}|^2 \varepsilon(m_1^2, m_2^2) dm_1^2 dm_2^2} + (1-p) \times \frac{B(m_1^2, m_2^2)}{\int B(m_1^2, m_2^2) dm_1^2 dm_2^2}$$

  - p: **purity** from m_{ES} fits
  - ε is the **efficiency** and B the **background** in the Dalitz plane

- Minimizing $\mathcal{F} = \sum_i -2 \times \log(\mathcal{L}_i)$
  - To compare fits we use $\Delta\mathcal{F} = \mathcal{F} - \mathcal{F}_{\text{nominal}}$

Efficiency across the Plot

- Efficiency determined from flat-distribution simulated Dalitz in each D submode
  - 22×22 bins
- Overall efficiency obtained by weighting all D submodes by their Branching Fractions (Bfs)



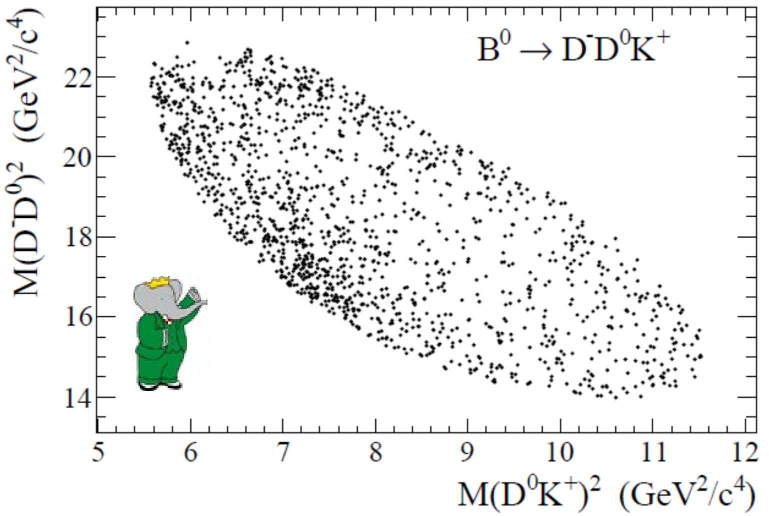
- Bins are combined if <10 events in the bin
- 2D-Interpolation of the binned efficiencies gives efficiency at any point
- At edge of plot do not use interpolation

Background Term in the Fits

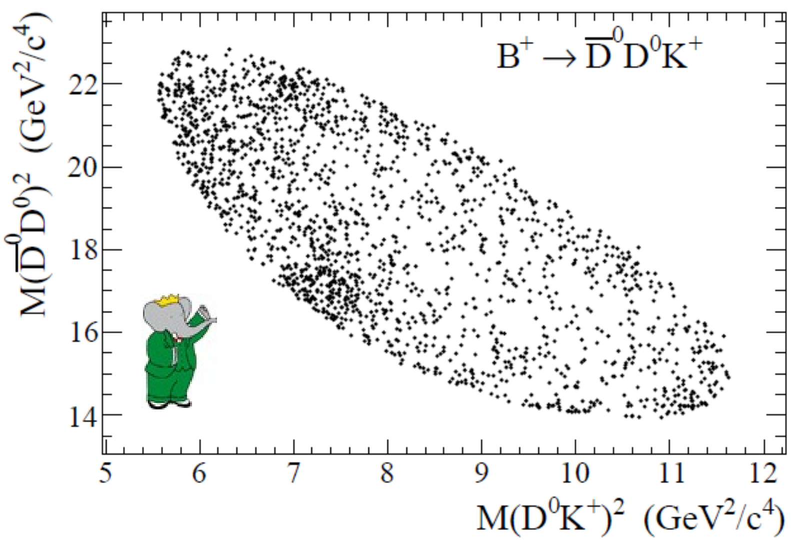
- From generic MC with the same selections as the data
  - We checked using the m_{ES} sideband that the MC correctly reproduces the data
- Histogram the background Dalitz plot (30x30 bins)
  - Non-uniform distribution: no fit done (not expected to fit well)
- Use a 2D-interpolation of the distribution, just as for efficiency

Dalitz Plots

- Expected contributions
  - Nonresonant events
  - $D_{s1}(2700) \to D^0K^+$
  - $D^*_{s2}(2573) \to D^0K^+$
    - Has never been observed in DDK
  - $D^*_{sJ}(2860) \to D^0K^+$
    - Not included in the nominal fit



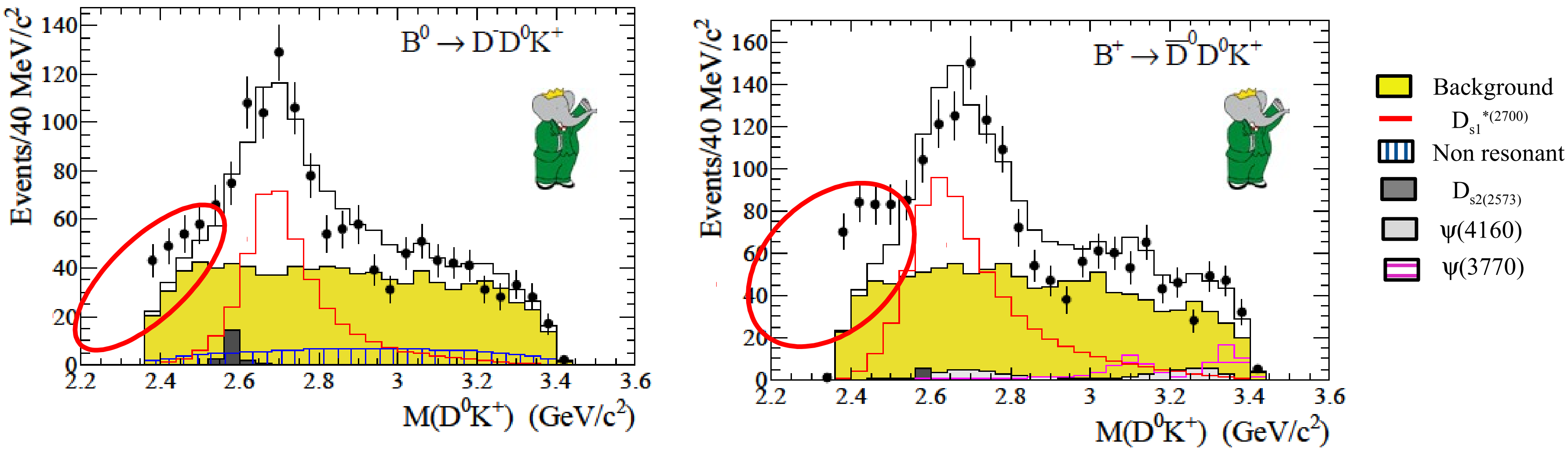
- Additional contributions for $\overline{D}^0D^0K^+$
  - $\psi(3700) \to \overline{D}^0D^0$
  - $\psi(4160) \to \overline{D}^0D^0$
  - $\chi_{c2}(2P)$, $\psi(4040)$, $\psi(4415)$ also possible, not included in the nominal fit



- All resonance parameters fixed to PDG, except $D_{s1}(2700)$ parameters
  - $D_{s1}(2700)$ is the reference amplitude in the Dalitz fit

Fits with known amplitudes

- Fits with known amplitudes



- Fits are not satisfactory
  - **$B^0 \to D^- D^0 K^{+}$:** χ^2/ndof= 82/48, ΔF = 36
  - **$B^+ \to \overline{D}^0 D^0 K^+$:** χ^2/ndof = 265/51, ΔF = 223
- Regions at low D^0K^+ mass not well described

The Low Mass Effect

- Belle also observes this effect in $B^+ \to \overline{D}^0 D^0 K^+$

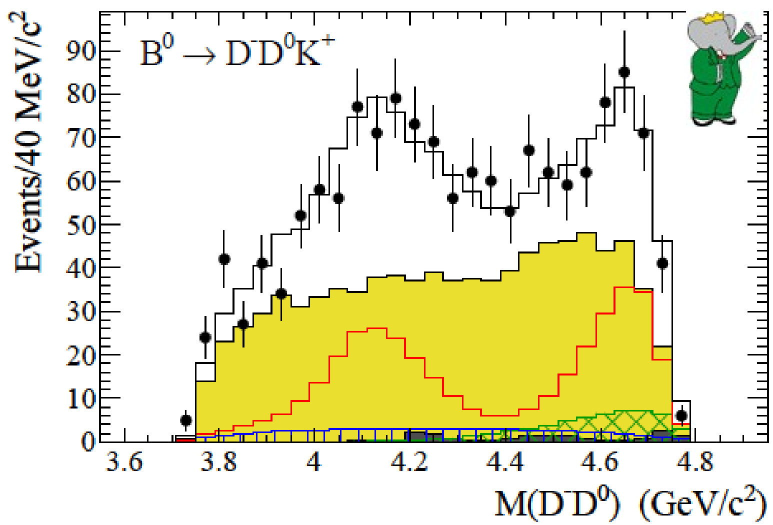
- We checked that this contribution is from $B \to DDK$ signal events and is not background
  - m_{ES} **binwise** fits: fit m_{ES} in bins of $m(D^0K^+)$
  - **sPlot**

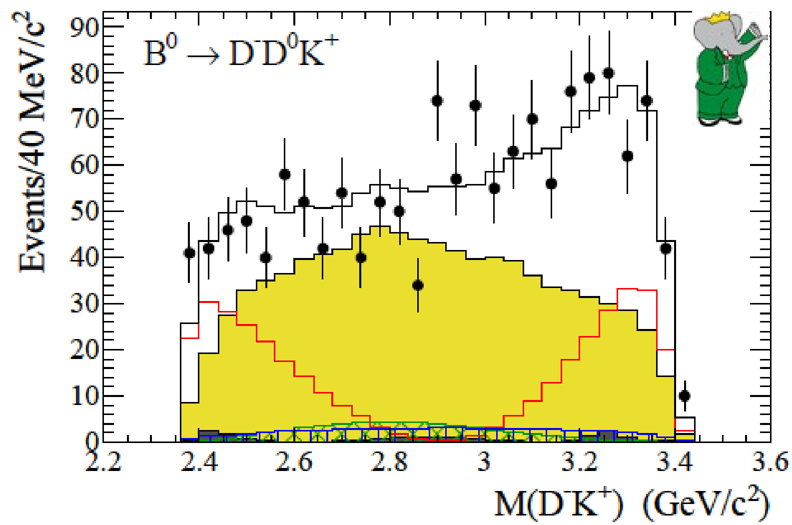
- We checked that this is not the reflection of a known resonance in another cross-feed mode
  - No contribution from $\mathbf{D_{s1}(2536)} \to D^*K$
  - No contribution from $\mathbf{D_{s1}(2700)} \to D(^*)K$

- Fits performed adding a scalar amplitude at low mass
  - Quality of fits improves
  - $\mathbf{B^0 \to D^- D^0 K^+}$: $M_{scalar} = 2412 \pm 16$ MeV, $\Gamma_{scalar} = 163 \pm 64$ MeV
  - $\mathbf{B^+ \to \overline{D}^0 D^0 K^+}$: $M_{scalar} = 2453 \pm 20$ MeV, $\Gamma_{scalar} = 283 \pm 45$ MeV
  - We **reject** this solution
    - Only ~**1.5σ** different
    - Such a **wide resonance** at this mass would be **speculative**

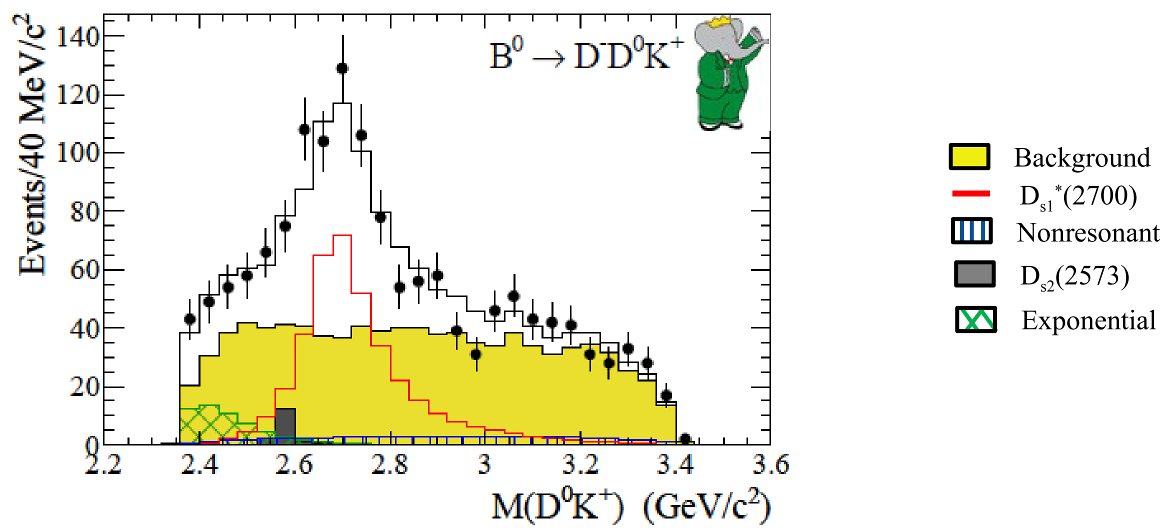
- It is not possible to conclude that a resonance contributes here
  - We use an **arbitrary function** to describe it
  - **Exponential** function $A_{\text{Expo}} = e^{-\alpha(m_2^2 - m_{2\,\text{thr}}^2)}$
    - (Some authors integrate this term into the nonresonant one)

The Nominal Fit: B^0

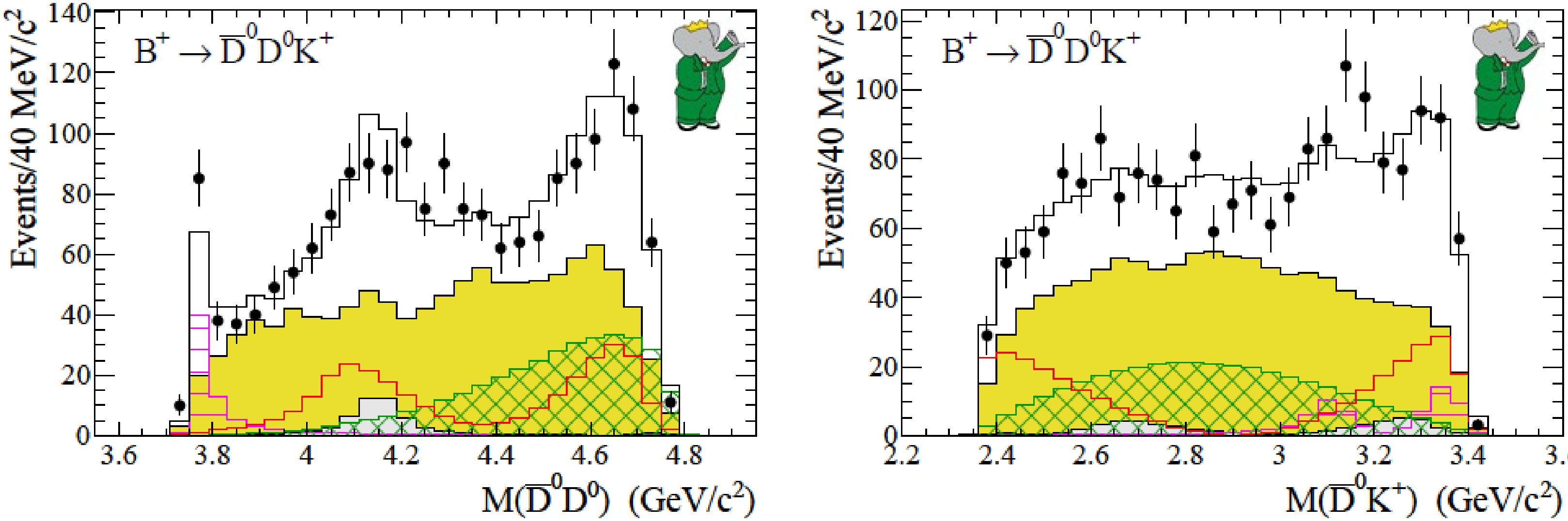




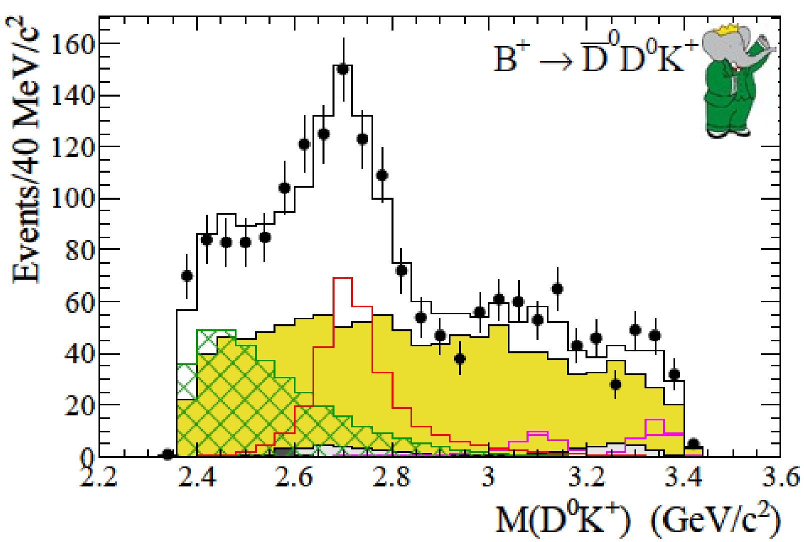
$\chi^2/\text{ndof} = 56/45$



The Nominal Fit: B^+



$\chi^2/\mathrm{ndof} = 86/48$



Nominal Fits, continued

- Each fit result is in fact the best fit among 250; these use randomized initial parameters [within their bounds].
  - Choose the **smallest negative log likelihood**
  - Avoids **local minima** (as opposed to the global minimum)

- We reject nonconverging fits + fits with fit fraction sum > 250%
  - Due to the **unusually large interference** between the exponential and the non-resonant components for $B^0 \to D^- D^0 K^+$

- We include in the systematics the small differences in the resonance parameters for the fits close to the minimum

- The presence of several close minima is confirmed by toy MC

Systematic Effects

- Fit bias
  - Generate **toy MC samples** using the fit parameters and fit these toys to extract the fit bias
- Efficiency
  - **Raw efficiency** instead of interpolation
  - **Statistical fluctuation** taken into account by randomizing (within stat. uncertainty) the efficiency in each bin
- Background description
  - **Signal purity** varied according to its total uncertainty
- Fit model
  - **Blatt-Weisskopf** factor varied from 0 to 5 GeV^{-1} (nominal 1.5 GeV^{-1})
  - **Low-mass effect**: use a scalar fit or an alternative arbitrary function
  - **ψ(3770):** using KEDR exp. results instead of PDG values
  - **D_{s2}(2573)**: fit repeated without this (small) contribution
- Local minima
  - Use the **other** minima (close enough to the global one)

Estimates of Systematic errors

Units are MeV/c² (for M), MeV (for Γ)

- Breakdown of systematic errors on the $D_{s1}(2700)$ parameters

$$B^0 \to D^- D^0 K^+$$

Parameter	Value	Bias	Eff.	Eff. II	Bkg	BW	Low mass	D^*_{s2}	Min.	Total
$M(D^*_{s1}(2700)^+)$	2694	± 2	0	± 1	0	$^{+13}_{-2}$	$^{+0}_{-1}$	0	$^{+3}_{0}$	$^{+13}_{-3}$
$\Gamma(D^*_{s1}(2700)^+)$	145	± 8	± 1	± 3	$^{+4}_{-3}$	$^{+17}_{-9}$	$^{+5}_{-0}$	-6	$^{+11}_{-4}$	$^{+22}_{-14}$

$$B^+ \to \overline{D}^0 D^0 K^+$$

Parameter	Value	Bias	Eff.	Eff. II	Bkg	BW	Low mass	D^*_{s2}	ψ	Min.	Total
$M(D^*_{s1}(2700)^+)$	2707	± 4	0	± 1	± 3	$^{+7}_{-4}$	$^{+0}_{-4}$	$+1$	0	$^{+0}_{-5}$	± 8
$\Gamma(D^*_{s1}(2700)^+)$	113	± 5	± 1	± 3	$^{+9}_{-7}$	$^{+17}_{-0}$	$^{+0}_{-9}$	-5	$+2$	$^{+0}_{-7}$	$^{+20}_{-16}$

Results

- $D_{s1}(2700)$ observed for the first time in $B^0 \rightarrow D^- D^0 K^+$ decays
- Low-mass effect has an important contribution
- $D_{s2}(2573)$ observed with a 3.4σ significance (including systematics) in $B^0 \rightarrow D^- D^0 K^+$
- ψ(4160) observed with a 3.3σ significance (including systematics) in $B^+ \rightarrow D^0 D^0 K^+$
- No need for $D^*_{sJ}(2860)$, $D_{sJ}(3040)$, $\chi_{c2}(2P)$, ψ(4040), ψ(4415)

$B^0 \rightarrow D^- D^0 K^+$

Contribution	Modulus	Phase (∘)	Fraction (%)
$D^*_{s1}(2700)^+$	1.00	0	$66.7 \pm 7.8^{+3.5}_{-3.8}$
$D^*_{s2}(2573)^+$	$0.031 \pm 0.008 \pm 0.002$	$277 \pm 17^{+6}_{-9}$	$3.2 \pm 1.6^{+0.3}_{-0.4}$
Nonresonant	$1.33 \pm 0.63^{+0.46}_{-0.35}$	$287 \pm 21^{+10}_{-15}$	$10.9 \pm 6.6^{+7.0}_{-4.3}$
Exponential	$6.94 \pm 1.83^{+0.82}_{-0.43}$	$269 \pm 33^{+17}_{-15}$	$9.9 \pm 2.9^{+3.0}_{-3.3}$
Sum			$90.6 \pm 10.7^{+8.4}_{-6.7}$

$B^+ \rightarrow \overline{D}^0 D^0 K^+$

Contribution	Modulus	Phase (∘)	Fraction (%)
$D^*_{s1}(2700)^+$	1.00	0	$38.3 \pm 5.0^{+0.8}_{-6.2}$
$D^*_{s2}(2573)^+$	$0.021 \pm 0.010^{+0.009}_{-0.003}$	$267 \pm 30^{+17}_{-13}$	$0.6 \pm 1.1^{+0.4}_{-0.2}$
$\psi(3770)$	$1.40 \pm 0.21^{+0.20}_{-0.24}$	$284 \pm 22^{+26}_{-30}$	$9.0 \pm 3.1^{+0.4}_{-0.8}$
$\psi(4160)$	$0.78 \pm 0.20^{+0.18}_{-0.14}$	$188 \pm 13^{+14}_{-17}$	$6.4 \pm 3.1^{+1.9}_{-2.4}$
Exponential	$16.15 \pm 2.26^{+1.09}_{-1.74}$	$308 \pm 8^{+6}_{-5}$	$44.5 \pm 6.2^{+1.3}_{-2.1}$
Sum			$98.9 \pm 9.2^{+2.5}_{-7.0}$

Branching Fractions

- We measure the partial branching fractions of the resonances
- We use f_{res}, the fit fraction of the resonance and B_{tot}, the total branching fraction of the mode measured in our previous publication

$$\mathcal{B}_{\rm res} = f_{\rm res} \times \mathcal{B}_{\rm tot}$$

Mode	$\mathcal{B}$ (10^{-4})
$B^0 \to D^- D^*_{s1}(2700)^+[D^0 K^+]$	$7.14 \pm 0.96 \pm 0.69$
$B^+ \to \bar{D}^0 D^*_{s1}(2700)^+[D^0 K^+]$	$5.02 \pm 0.71 \pm 0.93$
$B^0 \to D^- D^*_{s2}(2573)^+[D^0 K^+]$	$0.34 \pm 0.17 \pm 0.05$
$B^+ \to \bar{D}^0 D^*_{s2}(2573)^+[D^0 K^+]$	$0.08 \pm 0.14 \pm 0.05$
$B^+ \to \psi(3770) K^+[\bar{D}^0 D^0]$	$1.18 \pm 0.41 \pm 0.15$
$B^+ \to \psi(4160) K^+[\bar{D}^0 D^0]$	$0.84 \pm 0.41 \pm 0.33$

$D_{s1}(2700)$ results

- Mass and width of the $D_{s1}(2700)$ for the two modes

Mode	Mass (MeV/c^2)	Width (MeV)
$B^0 \to D^- D^0 K^+$	$2694 \pm 8^{+13}_{-3}$	$145 \pm 24^{+22}_{-14}$
$B^+ \to \bar{D}^0 D^0 K^+$	$2707 \pm 8 \pm 8$	$113 \pm 21^{+20}_{-16}$

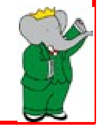
  - The two modes are **in agreement** within their uncertainties

- The two measurements are combined by computing a weighted mean taking into account the asymmetric uncertainties; this works well for all uncorrelated uncertainties. The Blatt-Weisskopf factor uncertainties are *correlated,* so these are removed from the combination, and taken accounted for later in a conservative fashion.

$D_{s1}(2700)$ results, continued

- Mass and width after combining modes (with total uncertainties)

$$M(D^*_{s1}(2700)^+) = 2699^{+14}_{-7}\ \mathrm{MeV}/c^2,$$
$$\Gamma(D^*_{s1}(2700)^+) = 127^{+24}_{-19}\ \mathrm{MeV},$$



  - **Compatible** with the world average

$$M(D^*_{s1}(2700)^+) = 2709 \pm 4\,\mathrm{MeV}/c^2$$
$$\Gamma(D^*_{s1}(2700)^+) = 117 \pm 13\,\mathrm{MeV}$$

- Spin of $D_{s1}(2700)$
  - Analysis performed with J = 1
  - Fits repeated with **J = 0 and J = 2**

	$J=0$		$J=1$	$J=2$	
Mode	$\Delta\mathcal{F}$	χ^2/n_{dof}	χ^2/n_{dof}	$\Delta\mathcal{F}$	χ^2/n_{dof}
$B^0 \to D^- D^0 K^+$	131	131/45	**56/45**	108	125/45
$B^+ \to \bar{D}^0 D^0 K^+$	63	137/48	**86/48**	99	145/48

  - Assuming parity conservation, we deduce **$D_{s1}(2700)$ is a 1^- state**

Conclusions

- We performed a Dalitz analysis of the modes $B^0 \to D^- D^0 K^+$ and $B^+ \to \bar{D}^0 D^0 K^+$
  - We extract moduli and phases for all contributions

- We observe the $D_{s1}(2700)$ meson in both final states
  - We measure precisely its **mass and width**

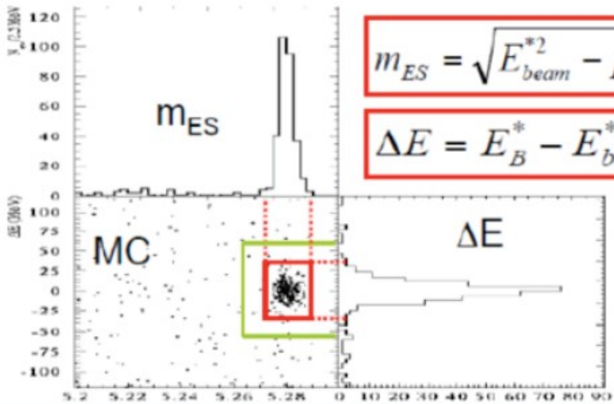
- We observe an enhancement between 2350 and 2500 MeV in the D^0K^+ invariant mass
  - We are **not able** to interpret this effect
  - It is described in the fit by an **ad-hoc function**
  - Could be a **new D_s** excited state?
  - A specific form of a **nonresonant amplitude**?
  - More information will be brought by **LHCb** and **Belle II**

- We do not observe the $D_{sJ}(2860)$ and $D_{sJ}(3040)$ in these final states

ADDITIONAL SLIDES

Common analysis techniques

Kinematics of fully reconstructed B

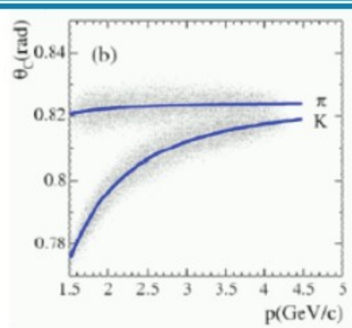


$$m_{ES} = \sqrt{E^{*2}_{beam} - p^{*2}_B}$$

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

K/π separation

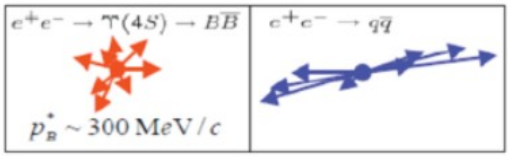
Very good **particle ID** between 1.5 and 4 GeV/c



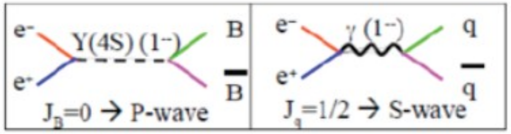
Background discrimination

Suppression by **multi-variable classifiers** based on **event-shape variables**: Fisher discriminant, Boosted Decision Trees (BTD)...

Topology:



Angular distribution:



- Strongly discriminate continuum events ($e^+e^- \to q\bar{q}$ (q = u,d,s,c)
- Background from B decays

Variables are often combined to a **likelihood function**, used in a **maximum likelihood fit** for signal/background separation and to measure parameters of interest

EVENT SELECTION

Selection for the primary charged K	**Selection for the primary neutral K**
1 - `GoodTrackLoose` + `KLHNotAPion` 2 - `KLHTight`	1 - $\lvert M(K_S^0) - M(K_S^0)_{PDG}\rvert < 9.5\,\mathrm{MeV}/c^2$ + $p(\chi^2) > 0.1\%$ + Length of flight > 2 mm
Selection for $D^0 \to K^-\pi^+$	**Selection for $D^0 \to K^-\pi^+\pi^0$**
1 -$\lvert M(D^0) - M(D^0)_{Meas.}\rvert < 2.5\sigma$ + K `KLHNotAPion` + $p(\chi^2) > 0.1\%$ 2 - K `KLHTight`	1 - $\lvert M(D^0) - M(D^0)_{Meas.}\rvert < 2.5\sigma$ + K `KLHNotAPion` + $p(\chi^2) > 0.1\%$ 2 - K `KLHTight` 3 - Dalitz weight > 10
Selection for $D^0 \to K^-\pi^+\pi^-\pi^+$	**Selection for $D^+ \to K^-\pi^+\pi^+$**
1 - $\lvert M(D^0) - M(D^0)_{Meas.}\rvert < 2.5\sigma$ + K `KLHNotAPion` + $p(\chi^2) > 0.1\%$ 2 - K `KLHTight`	1 - $\lvert M(D^+) - M(D^+)_{Meas.}\rvert < 2.5\sigma$ + K `KLHNotAPion` + $p(\chi^2) > 0.1\%$ 2 - K `KLHTight`
Selection for $D^{*+} \to D^0\pi^+, D^+\pi^0$	**Selection for $D^{*0} \to D^0\pi^0, D^0\gamma$**
1 - $\lvert\Delta M - \Delta M_{PDG}\rvert < 3\,\mathrm{MeV}/c^2$ where $\Delta M = M(D^{*+}) - M(D^0/D^+)$ + $p^*(\pi) < 450\,\mathrm{MeV}/c$ + D^0/D^+ selection steps described above	1 - $\Delta M \in [138, 146](D^0\pi^0), [130, 150](D^0\gamma)\,\mathrm{MeV}/c^2$ where $\Delta M = M(D^{*0}) - M(D^0)$ + $p^*(\pi^0) < 450\,\mathrm{MeV}/c$ + $E(\gamma) > 100\,\mathrm{MeV}$ + D^0 selection steps described above
Selection for B	**Final step**
1 - $D^{(*)}$ and K at least satisfying the level of selection 1 described above + $R_2 < 0.3$ + $\lvert\cos(\theta_B)\rvert < 0.9$	1 - Best ΔE candidate + ΔE cut (see Table 5 of BAD 2141) + m_{ES} cut (see text)