Absolute branching fractions of exclusive two-body decays $B^+ \to K^+$ + Charmonium

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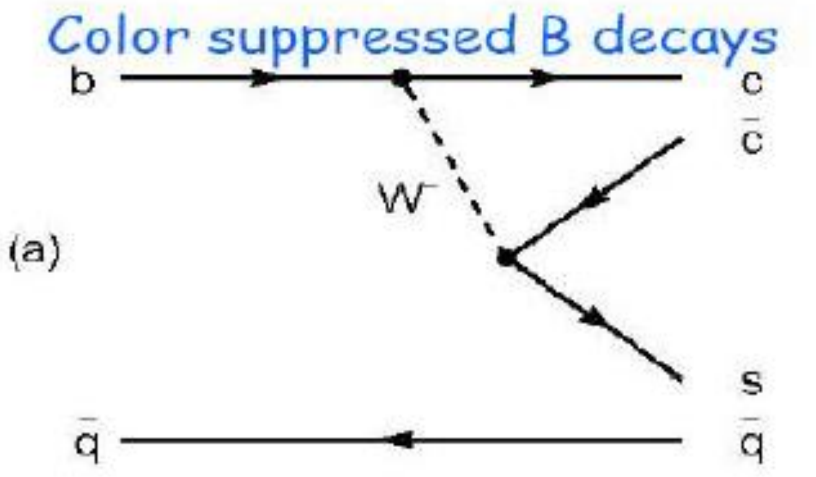
On behalf of BABAR collaboration

Main physics motivations (I)



- Test of QCD: « democratic » prediction for BR(B➔K Charmonium) except:
  - factorization suppression for the χ_0 state, M. Diehl, G. Hiller, JHEP 0106:067,2001, hep-ph/0105194
  - No J=2 weak current leads to χ_2 suppression
- Informations upon classical charmonium
  - Determination of the absolute BR provides access to absolute BR for all X decays, as in the η_c case
  - Mass and widths of not-so-well-measured particles such $\eta_c(2S)$

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Main physics motivation

- **Information upon new charmonium states, especially X(3872)**
  - Both the production rate $BR(B^{\pm} \rightarrow K^{\pm} X(3872))$ and the absolute decay rate $BR(X(3872) \rightarrow J/\psi\pi^{+}\pi^{-})$ will give key information on the complex nature of this particle
- Access to other X,Y,Z particles is difficult with this method is difficult because of their large width
- A search can however be made for a charged companion of the X(3872) in rate $BR(B^{0} \rightarrow K^{\pm} X^{\mp})$

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The $K^{\pm}$ momentum spectrum method

- B-factories can take advantage to the Y(4S) decay to B^+B^-
- Full exclusive reconstruction of one B provides the precise knowledge of the boost to the center-of-mass of the other B
- In this frame, each exclusive two-body $B^{\pm} \rightarrow K^{\pm} X$ corresponds to a monochromatic peak in the Kaon momentum spectrum
- Since the recoiling system is most often composed of a $c\bar{c}$ pair, it provides an unbiased « hydrogen atom-like » spectroscopy of the charmonium system
- This method was pionneered by BABAR in 2006 with 210 fb^{-1}

  Phys. Rev. Letters 96 052002 (2006)
- Belle published their results in 2018, based on the same method.

  Phys. Rev. D 97, 012005 (2018)

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The analysis workflow-I : B-reco and event selection

- 1 – Fully reconstruct as many B as possible
  - Typical efficiency of a few per mill when adding many many modes of the form $Dn\pi(\pi^\circ)$, DD_s, $J/\psi Kn\pi(\pi^\circ)$, where many modes are used for D reco.
  - In Babar, several thousand modes are considered, ranked by their signal-to-noise, the so-called « purity »
  - Illustrations
- 2- B candidate selection when there is more than 1 candidate per event (happens quite often when trying to use all these modes)
- Event selection –Rejection against udsc events (small contribution from B° as well)

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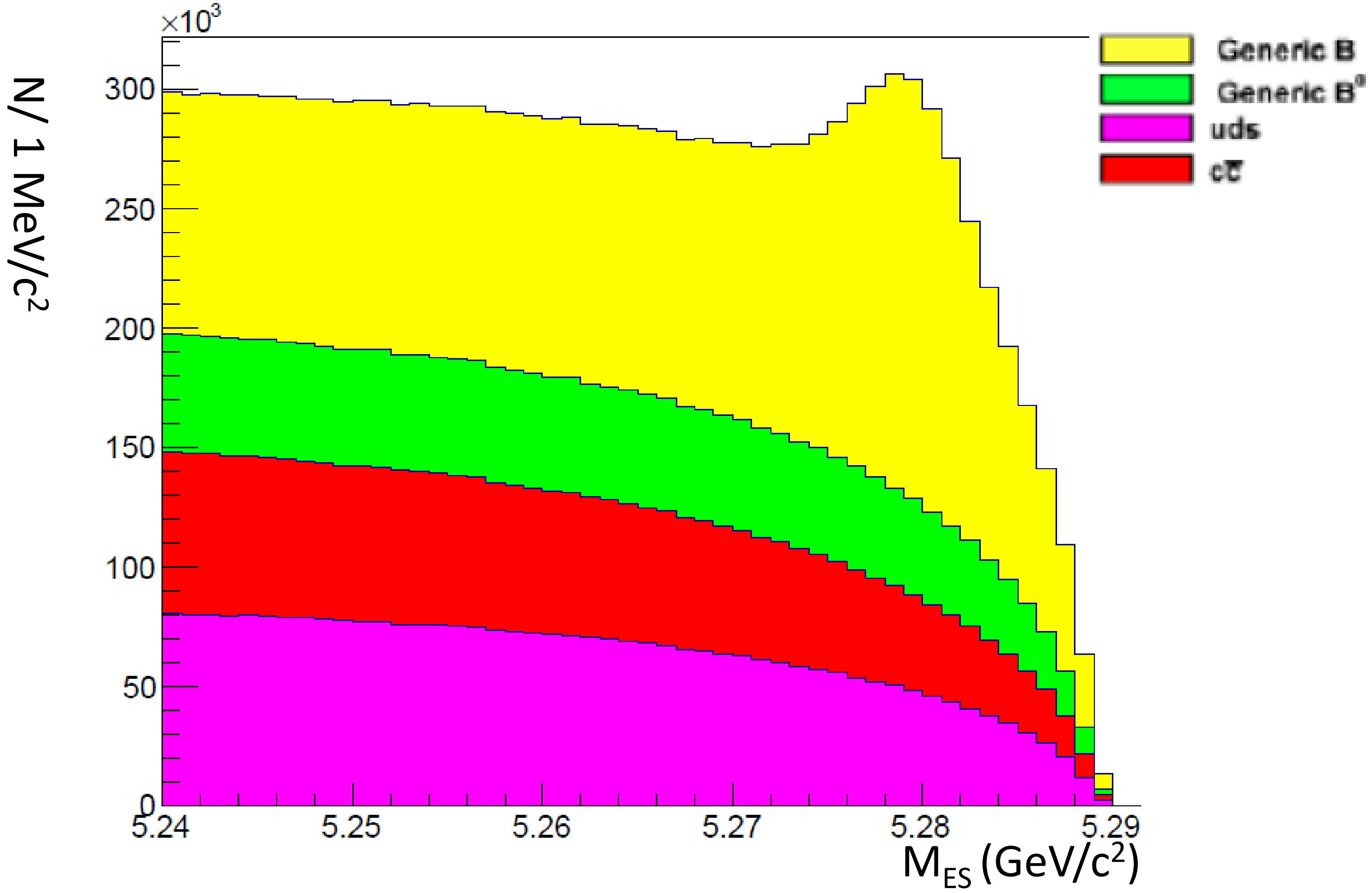
The M_{ES} spectrum with the various components from simulation

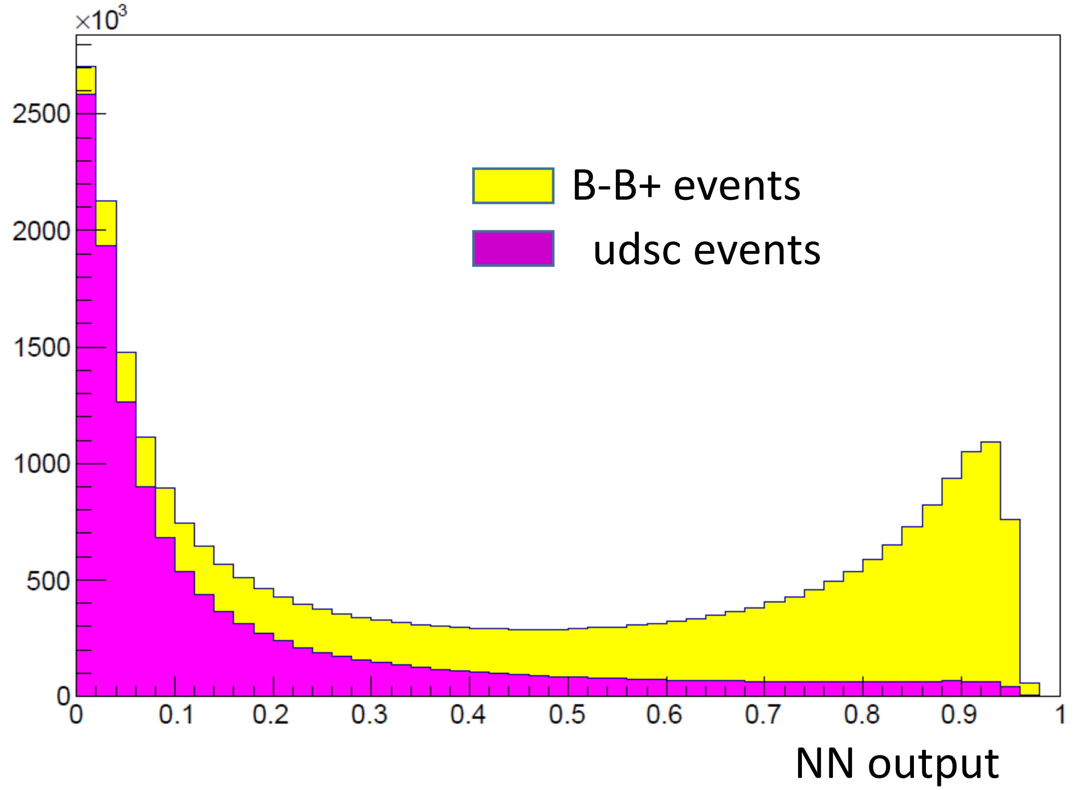
Total sample available :

1.67 M B^+ events for 424 fb $^{-1}$



Separation from udsc

A neural net NN is used with the usual variables linked to the sphericity of BB events compared to the jet-like shape of udsc events



The analysis workflow -II

- Find a Kaon candidate in the tracks not used to reconstructed the B candidate
  - Stringent PID cuts
  - K charge opposite to the reco-B charge
- Discriminate between two-body primary Kaons and the secondary kaons from B decays : This is the largest background (true kaons from true B decays
- Plot the Kaon momentum in the B-reco center of mass (or the missing mass)

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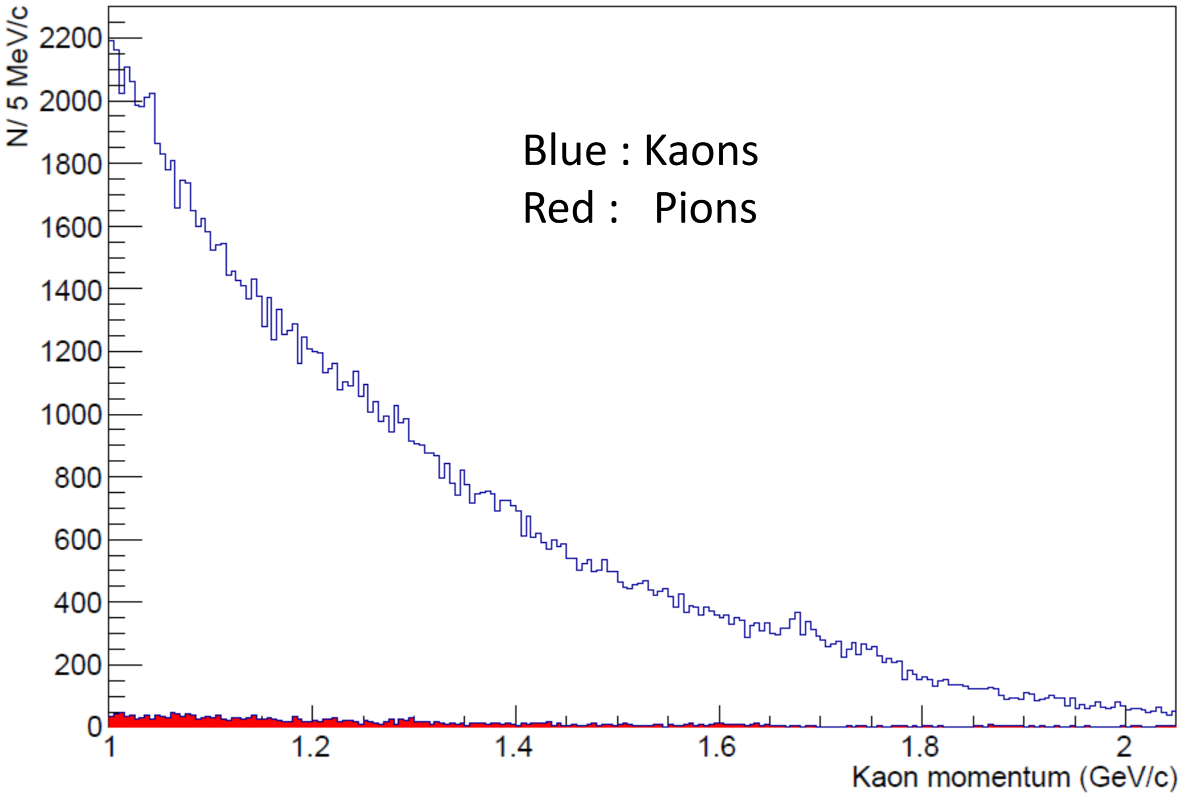
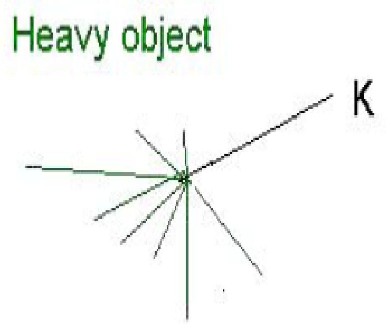
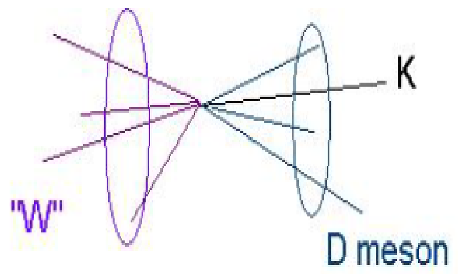
The Kaon purity

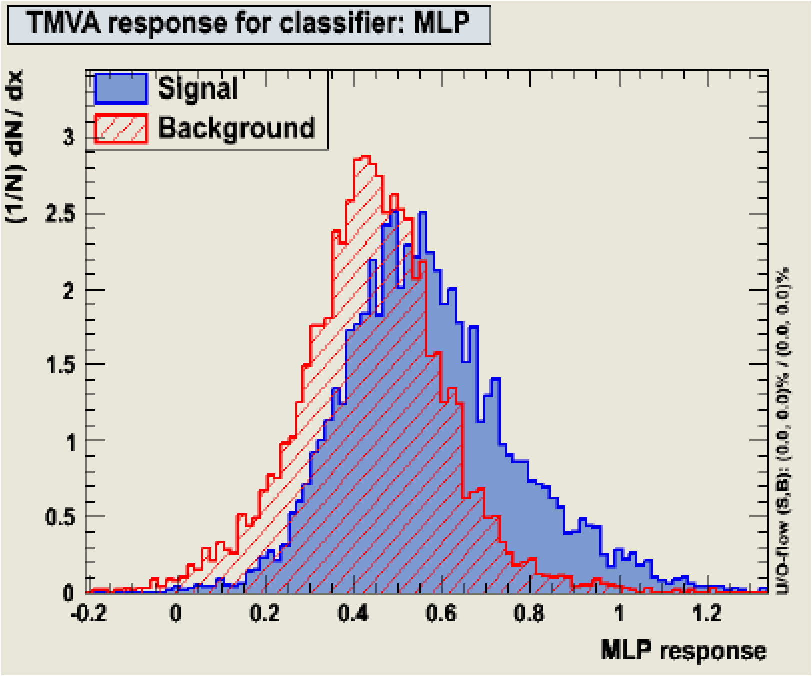
The Kaon purity is extremely good in these momenta range thanks to the DIRC (1.5 GeV in the B rest frame corresponds to about 2.5 GeV in the lab c.m)



Primary-secondary Kaon Separation







The event shape can give a (modest but useful) discrimination between primary and secondary kaons

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The issues with past workflow

- The best B candidate is selected before looking for Kaons : it can happen that the signal side B is the best candidate ->the event is lost

  Spurious interplay between tag and signal sides

- The best B candidate could be the wrong one : The kaon momentum is computed with the wrong boost, the signal is severely degraded

- One common solution : take all combinations: increased efficiency!!
  - For the X(3872) the efficiency gain is up to a factor 3.

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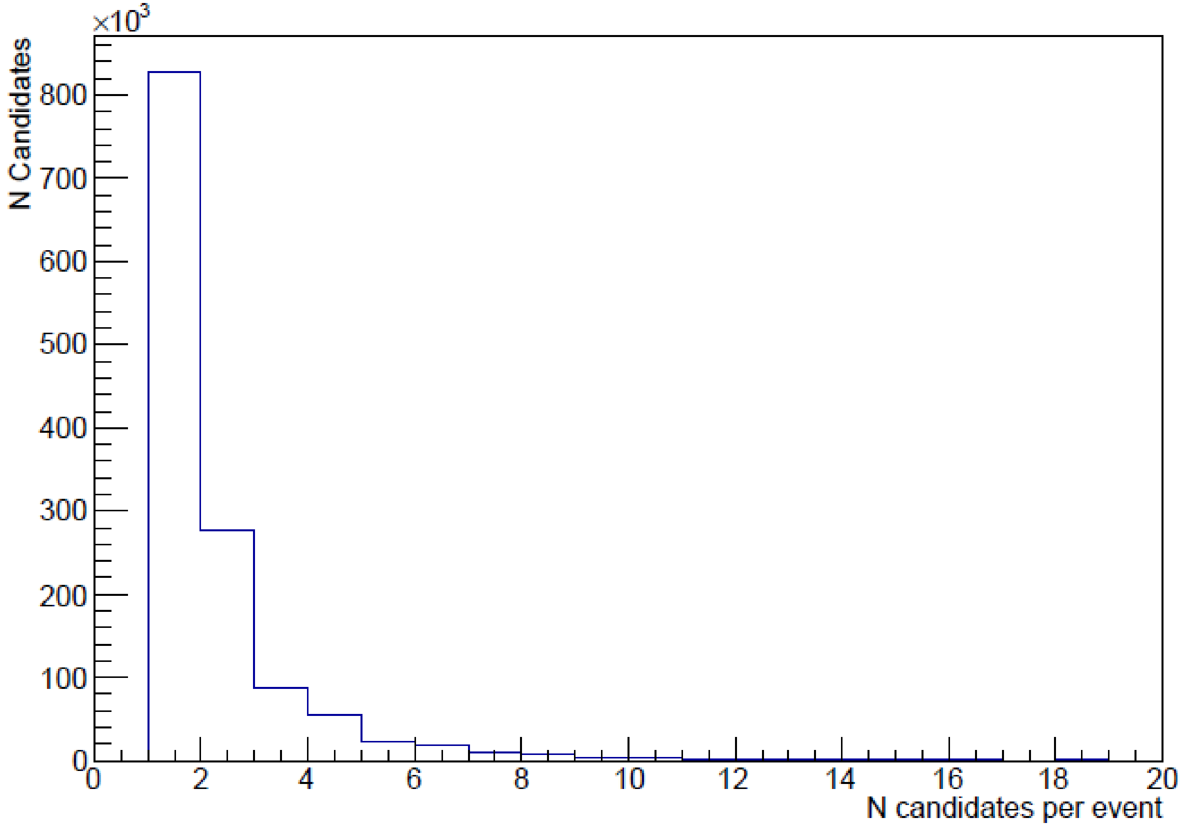
Number of candidates per event



Mean value of candidates per event is still reasonable : 1.35

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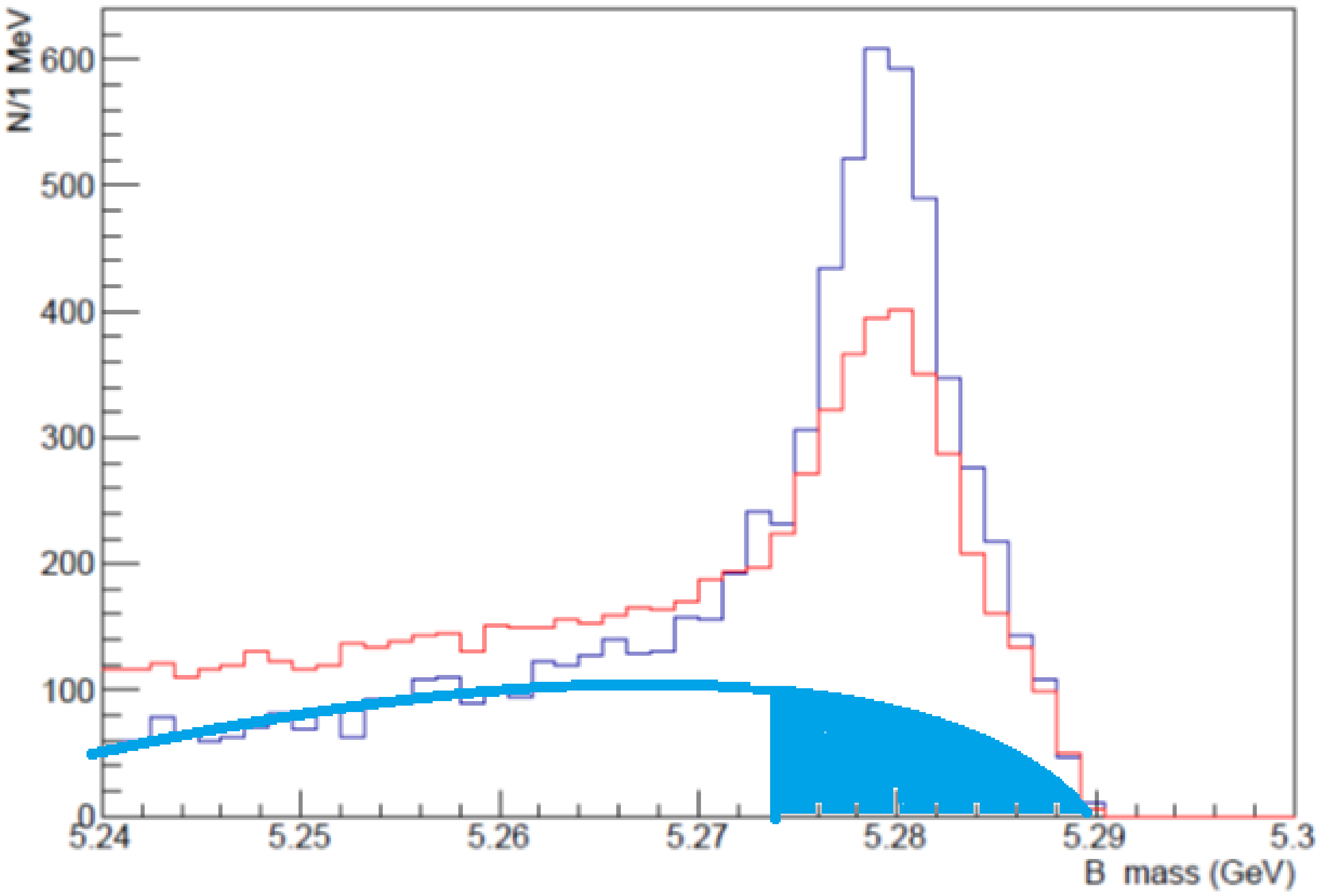
The expected signal shape

- For each (charmonium) resonance, the signal shape is the sum of the components:
  - A narrow gaussian due to a good signal kaon associated with a perfect B-reco tag (ie correct boost)
  - A wide component due to a good signal kaon associated with an imperfect B-reco tag although they have a correct B mass (ie events under the mass signal peak)
- The narrow gaussian width is dominated by the Kaon momentum resolution in the lab, ie decreases when the resonance mass increases
- The wide component width and fraction has (unfortunately) a small dependance upon the resonance decay channels

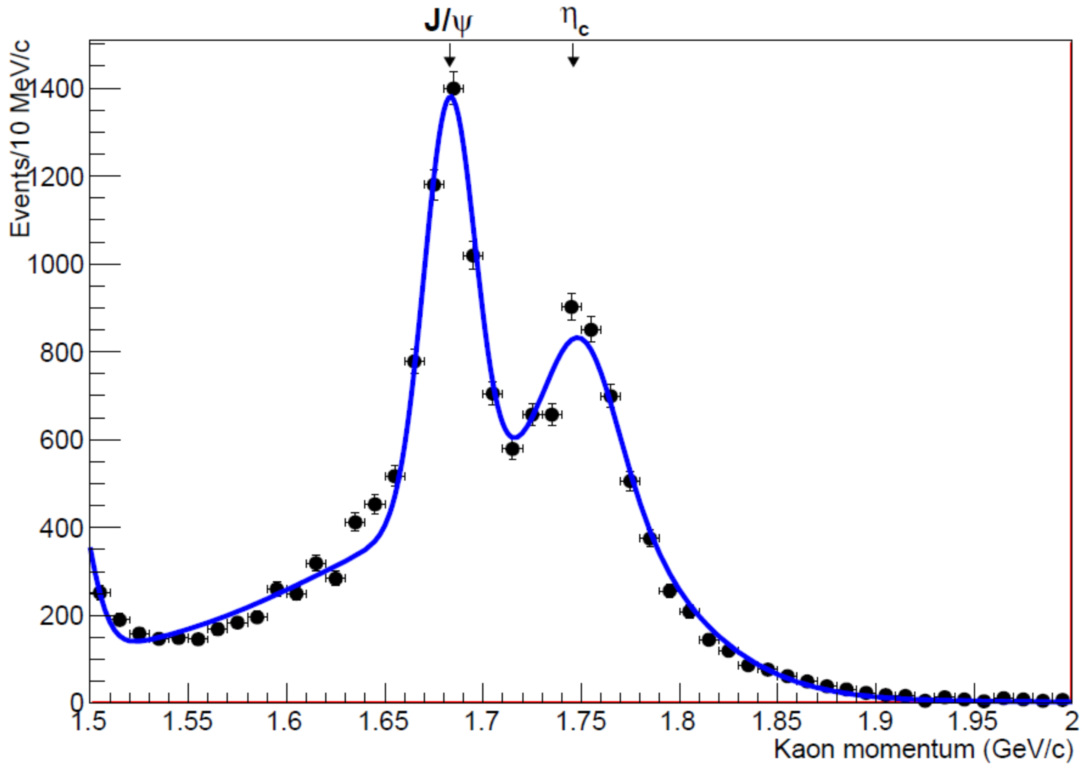
The B shape depends of the recoiling particle

Blue: J/ψ region
Red: X(3872)

The blue area leads to candidates described with the wide gaussian.



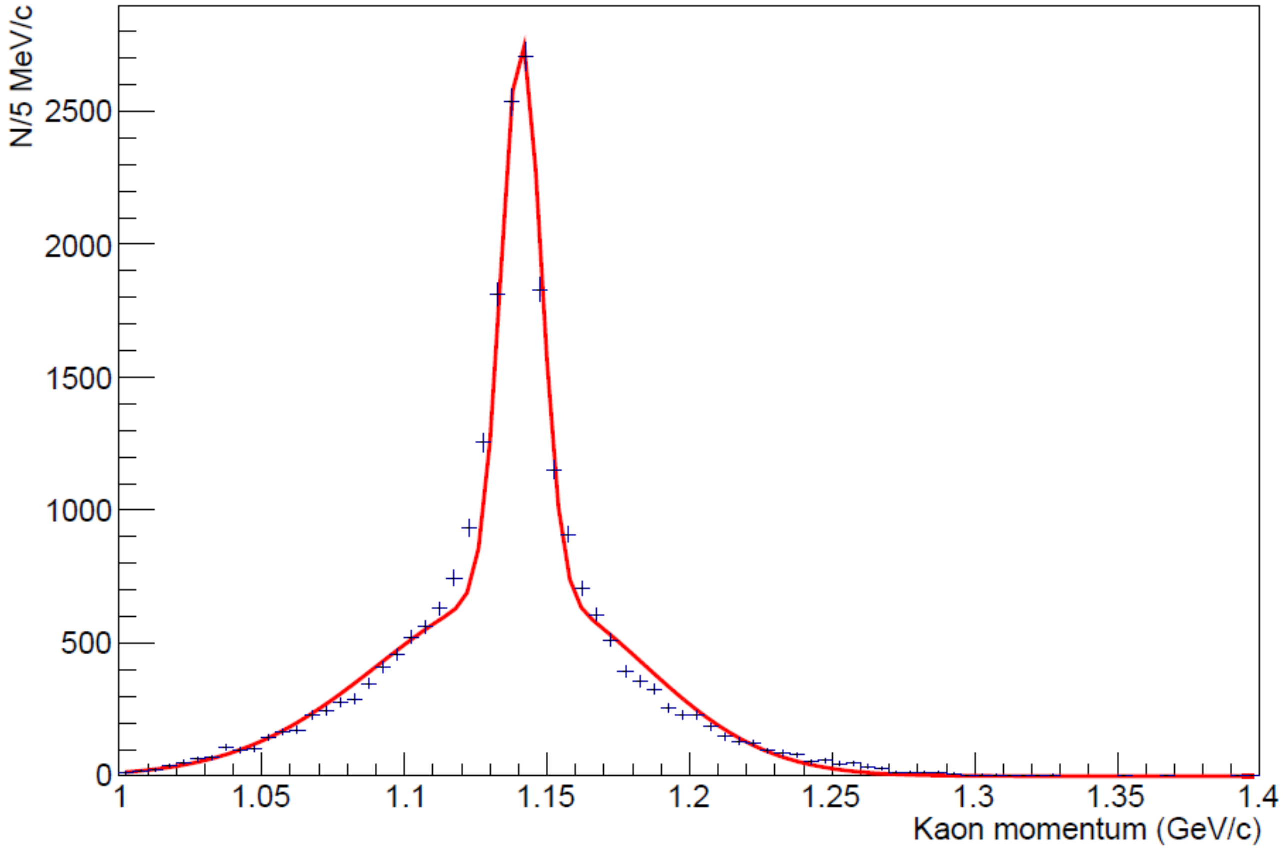
Description of the signal shape in the J/ψ-η_c region (MC)



MC simulation :
Primary Kaons from two-body decays

The X(3872) signal shape

Narrow gaussian width: 7 MeV
Wide gaussian : 45 MeV



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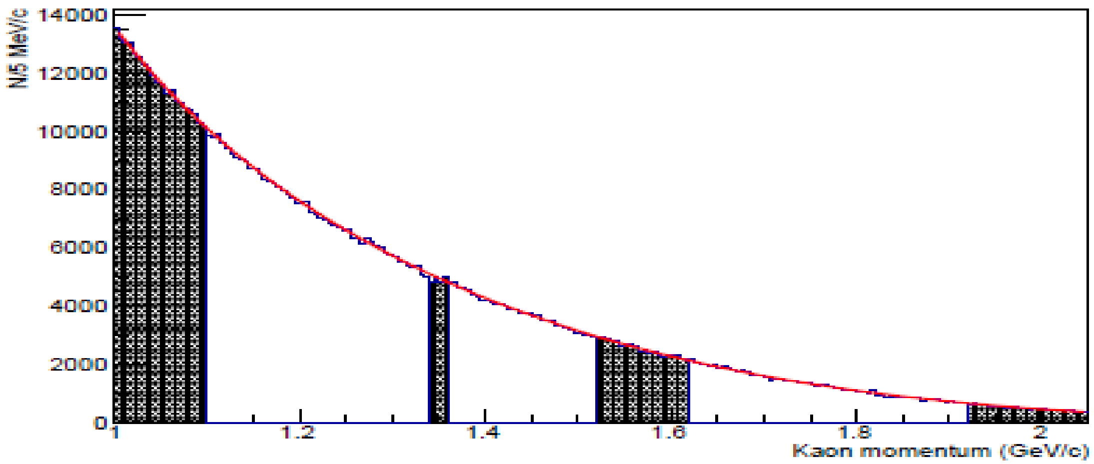
The background shape

- As discussed previously, the main background comes from secondary kaons from B decays. It depends upon a large number of channels involving high-multiplicity B and D decays. It is therefore not expected that the MonteCarlo will describe perfectly
- We have chosen a data driven approach using Kaon momentum domains where no signal is present.
  - Two good regions : Masses above the X(3872) and below the η_c
  - Two intermediate regions needed, where some signl tails are present
    - MonteCarlo is used to take into account small signal leaks in these regions

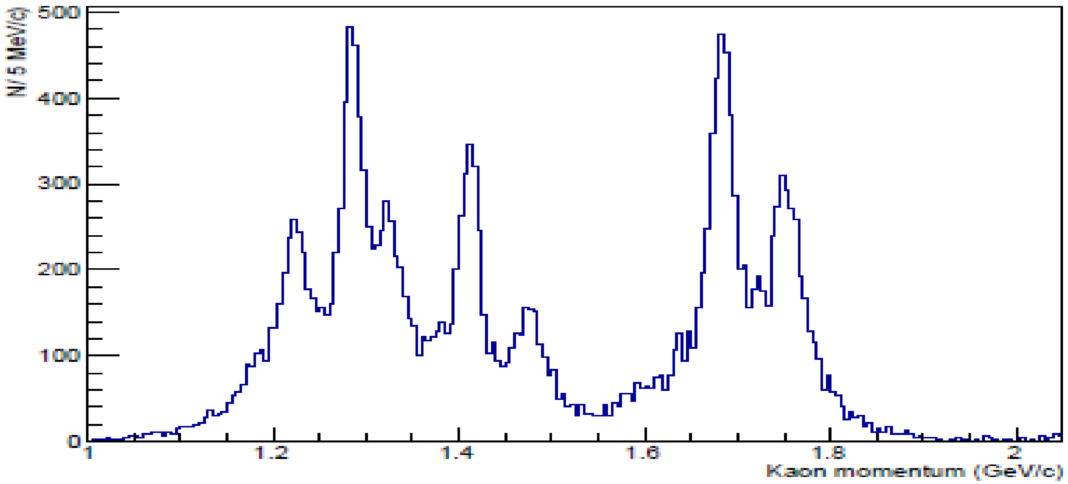
Determination of the background from signal free regions

MC without signal kaons



(a)

Signal-only distributions used to estimate the signal contributions in the « signal-free » regions



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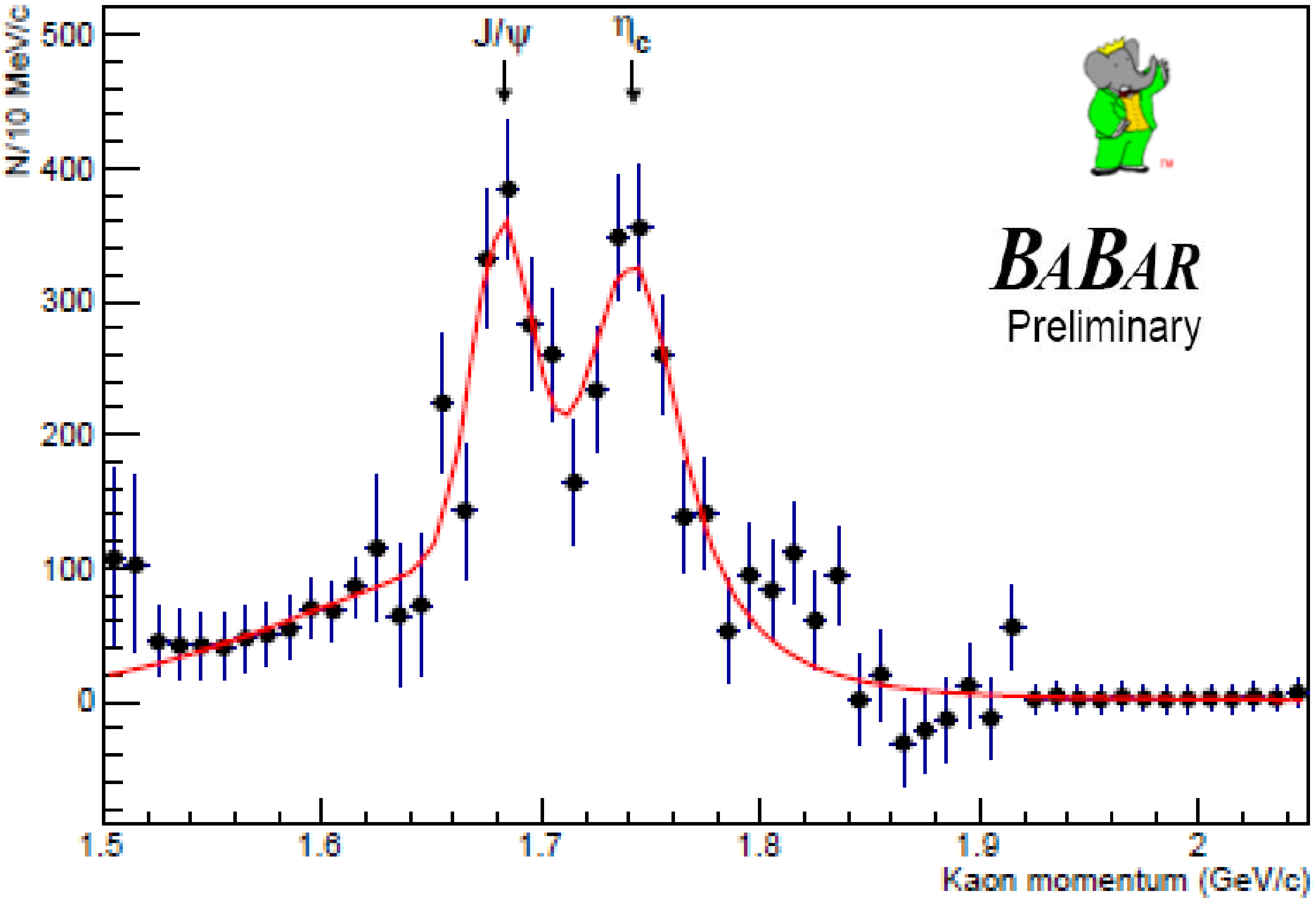
$K^{\pm}$ momentum recoil in the B center-of-mass

NN tuned for low mass region

Full BABAR luminosity
424 fb^{-1}

N J/ψ = 1463 ± 133
N η_c = 1334 ± 129



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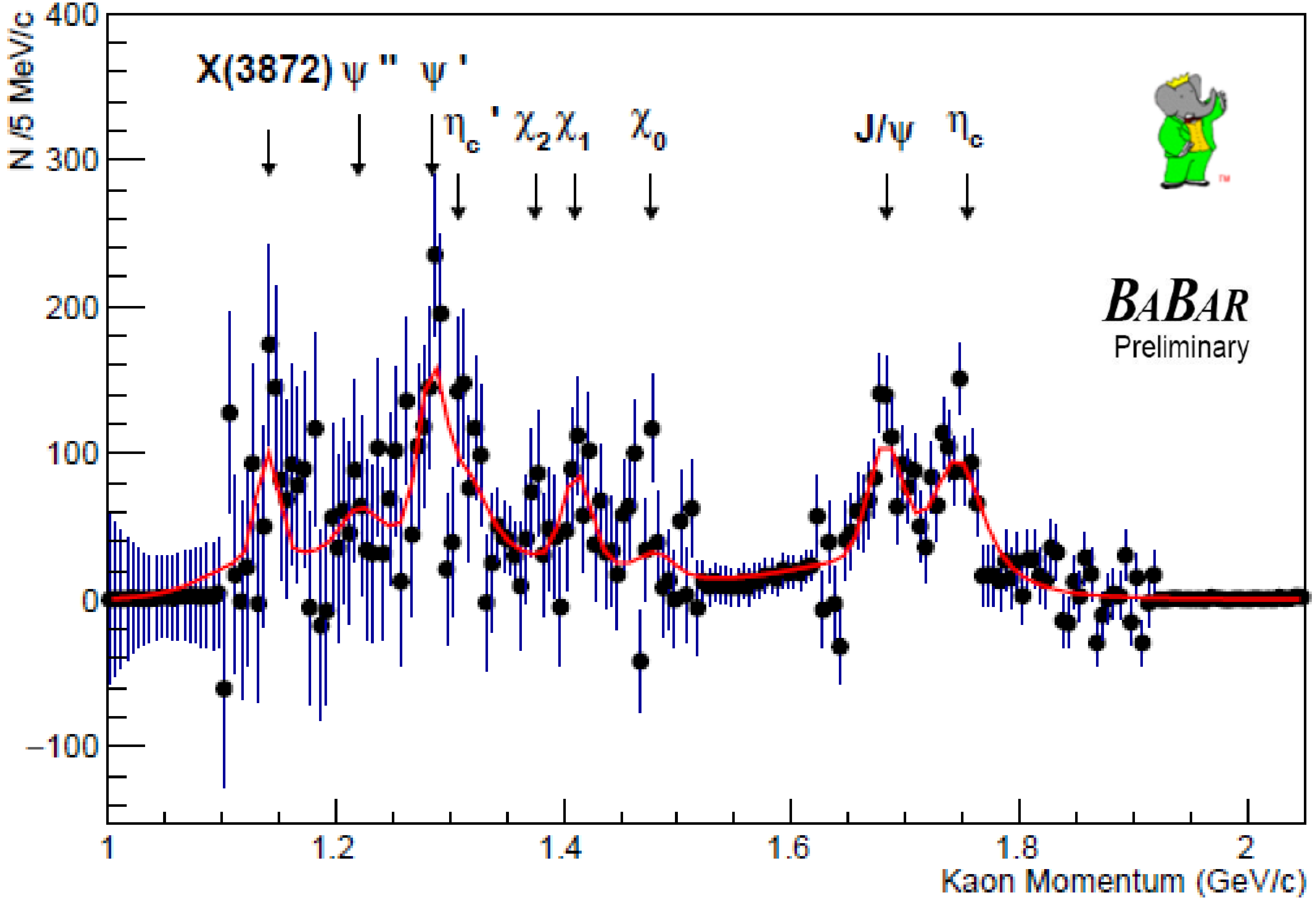
First evidence of the $B^+ \rightarrow X(3872)\ K^+$ transition

NN tuned for large mass region

N χ_1 = 1035 ± 193
N ψ'= 1278 ± 285
N X(3872)= 992 ± 285



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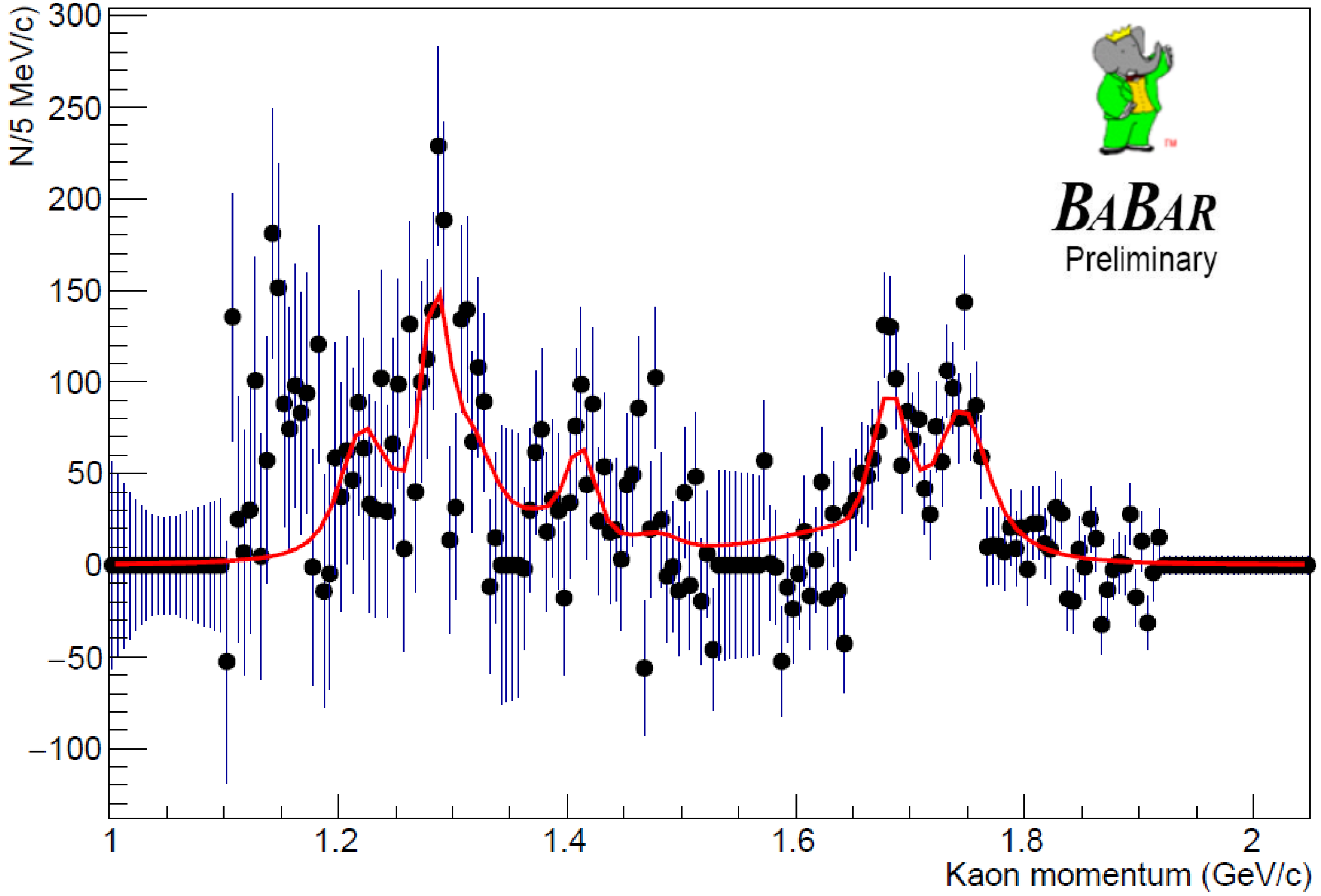
Fit without X3872



Delta χ^2=9
3σ significance

Systematics studies

Resonance	η_c (%)	$X(3872)$ (%)
K identification	1	5
Decay modes	-	
Efficiency	0	5
p_K spectrum: peak posiition	2	2
p_K spectrum: signal narrow width	1	1
p_K spectrum: signal wide width	5	5
p_K spectrum: narrow width fraction	2	2
p_K spectrum: background shape	-	13
Decay width	1	-
Signal residuals	-	4
Total	6	15.5

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Branching Fractions determination

- In this analysis, an absolute BR measurement can be done either by B counting, or by reference to a well known BR. Both can be combined
- In the first method , one does not have to pay the price of the uncertainty in the reference BR nor the statistical uncertainty associated to its measurement. However, the B counting systematic uncertainty is not negligible (~5%) and there is no cancellation of systematics in the selection process.
- Given the **good precision of the BR($B^+ \rightarrow J/\psi\, K^+$) in the PDG (3%)** **and** **our good statistical precison on this channel (8%),** we chose to use the second method.
- The BR extraction therefore only relies **on the ratio of the selection efficiencies of the X(3872) and J/ψ, given by the MC.**

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Branching fraction results

Particle	Yield	BF(10^{-4})
J/ψ	1463±133	10.1±0.29 (Ref from [12])
η_c	1334±129	9.6±1.2(stat)±0.4(sys)±0.3(ref)
χ_{c0}	287±181	2.0±1.3(sat)±0.3 (sys)
χ_{c1}	1035±193	4.0±0.8(stat)±0.6(sys)
χ_{c2}	200±164	<2.0
$\eta_c(2S)$	527±271	3.4±1.7(stat)±0.5(sys)
ψ'	1278±285	4.6±1(stat)±0.7(sys)
$\psi(3770)$	497±308	3.2±2.0(stat)±0.5(syst)
$X(3872)$	992±285	2.1±0.6(stat)±0.3(syst)

Recent BELLE-1 measurements
Phys.Rev.D97(2018)012005
8.9±0.6±0.5
12.0±0.8±0.7

2.0±0.9±0.1
5.8±0.9±0.5

4.8±1.1±0.3
6.4±1.0±0.4
<2.3
1.2±1.1±0.1 <2.6

Consistent with PDG 2016 (ie our previous results!)

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Interpretation of the X(3872) results

- Production
  - Not many predictions exist of the **BR($B^+ \to K^+$ X(3872)) but this BR must depend as well of the nature of the X(3872) particle.**
  - Liu, X. & Wang, YM. Eur. Phys. J. C (2007) 49: 643 predicted a BR too large when assigning X(3872) to a normal charmonium state
- Decay
  - Using 1 MeV as the X(3872) total width (the present upper limit), the measured width of the transition **Γ(X(3872)$\to$J/$\psi\pi\pi$) is of order 40 KeV.**
  - This is much smaller than ~1 MeV expected for a normal charmonium particle or a tetraquark tightly bound state
  - A prediction for a molecule is $\Gamma[X \to J/\psi\, \pi^+\pi^-] = |G_{X\psi\rho}|^2\,(223\,\mathrm{keV})$.

    from E. Braaten and M. Kusunoki, **Phys.Rev. D72 (2005) 054022**
  - **Predictions for Γ(X(3872)$\to$J/$\psi\gamma$) can be found around 100 keV (Aceti et al.,** Phys.Rev. D86 (2012) 113007) while this result gives a range around 10 KeV

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Conclusion

- **Three significant updates** to the original 2006 BABAR analysis:
  - statistics (x2 luminosity, and x4 number of B reco)
  - analysis workflow (usage of all B candidates)
  - background shape from signal -free regions
- This led to the **first evidence of the decay $B^+ \rightarrow K^+ X(3872)$ at 3σ level**

$$\mathbf{BR(B^+ \rightarrow K^+ X(3872)) = (2.1 \pm 0.6 \pm 0.3 \pm 0.1)10^{-4}}$$

- From this, it follows:

$$\mathbf{BR(X(3872) \rightarrow J/\psi\pi\pi) = (4.1 \pm 1.3)\%}$$

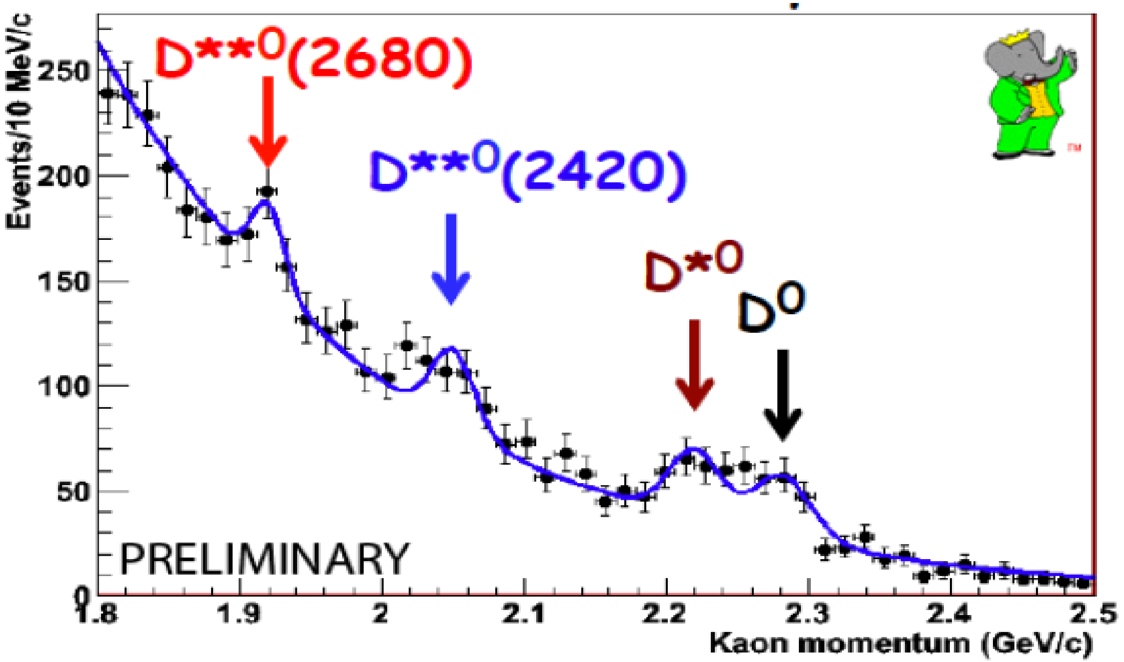
. These results will certainly bring very useful information to better understand the complex nature of the X(3872) particule. They support a molecular interpretation

- The other charmonia $BR(B^+ \rightarrow K^+ X_{cc})$ are in agreement with BELLE recent results and of similar precision

Backup

$B^{\pm} \rightarrow K^{\pm}X^0$; Lower charmonium mass region, Search for Neutral D^*

D**(2680) significance less than 3 σ when taking into account the LookElsewhereEffect (Courtesy of ATLAS BUMPHUNTER)



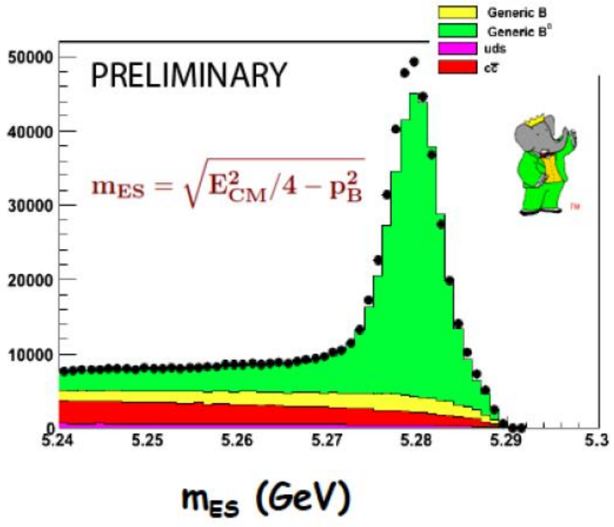
Very high K momentum region (blinded)

Statistical significance of the $D^{**}(2680) \sim 3.3\sigma$

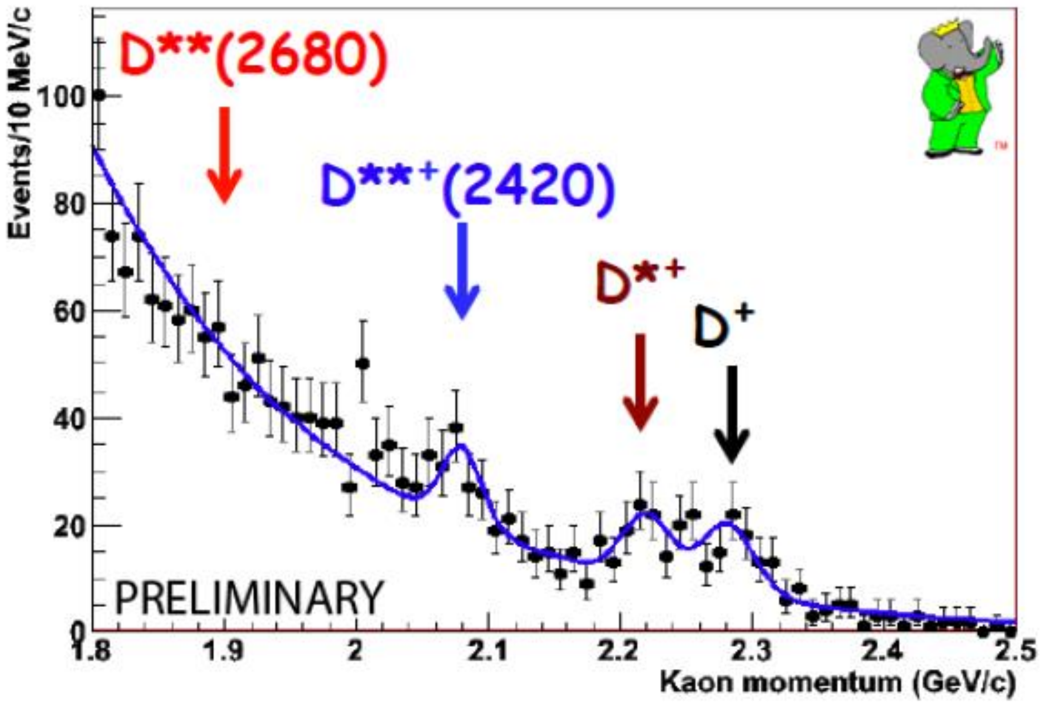
Particle	Yield	Peak Position	$BF(10^{-4})$	PDG 2014
D^0	126 ± 20		$3.5 \pm 0.5 \pm 0.3$	3.7 ± 0.17
D^{*0}	126 ± 21		$3.5 \pm 0.5 \pm 0.3$	4.2 ± 0.34
$D_1(2420)^0$	97 ± 25		$2.1 \pm 0.5 \pm 0.3$	-
$D^{**0}(2680)$	95 ± 29	2.68 ± 0.003	$2.1 \pm 0.6 \pm 0.3$	-

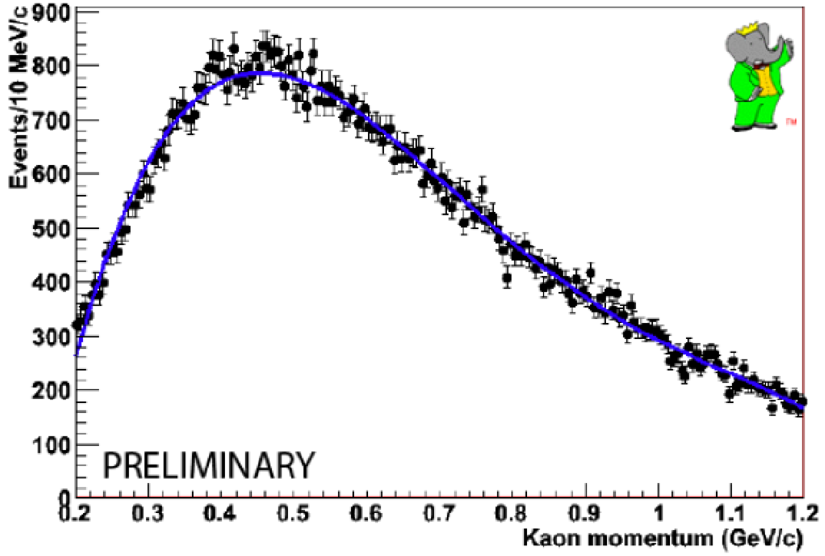
The branching fractions are consistent with PDG 2014 values.

Two-body decays $B^0 \rightarrow K^- X^+$



Very high Kaon momentum region





No observation of narrow charged« charmonium » states in the mass range 3.7 -4.7 GeV

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Summary results

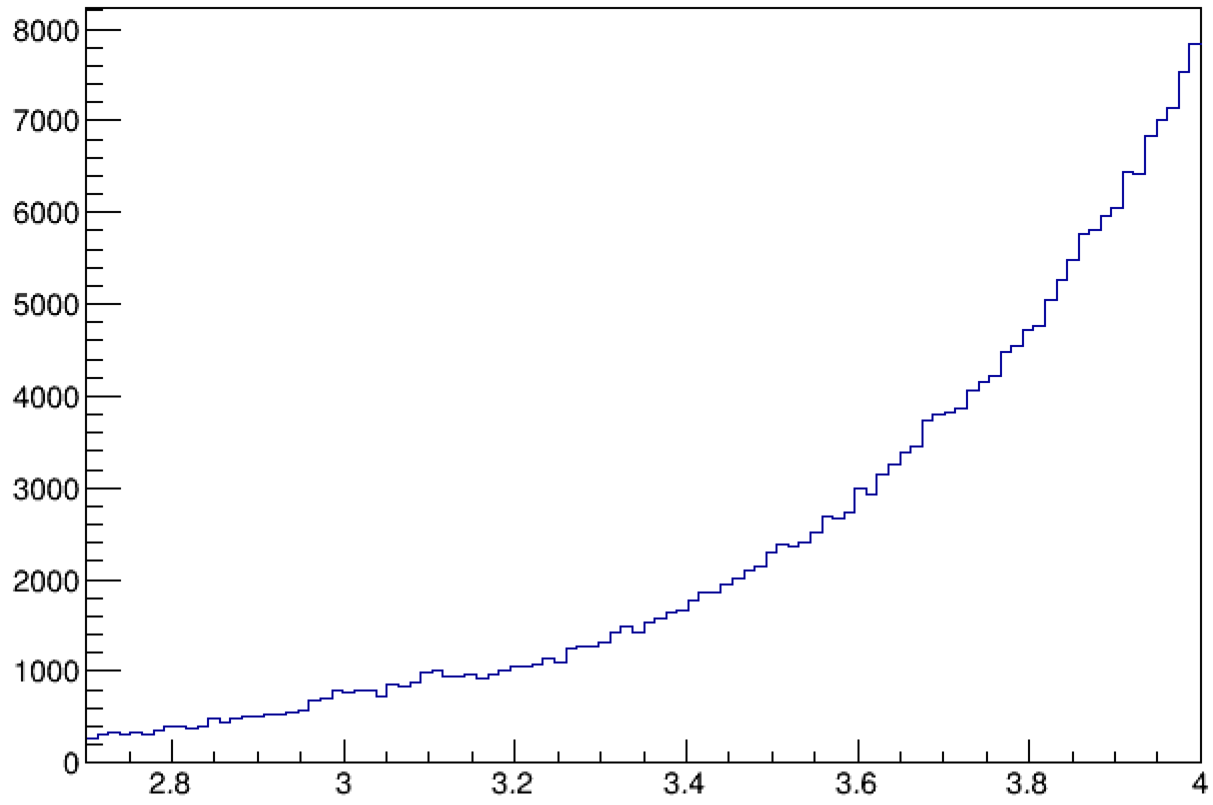
- Analysis extendend to D mass region

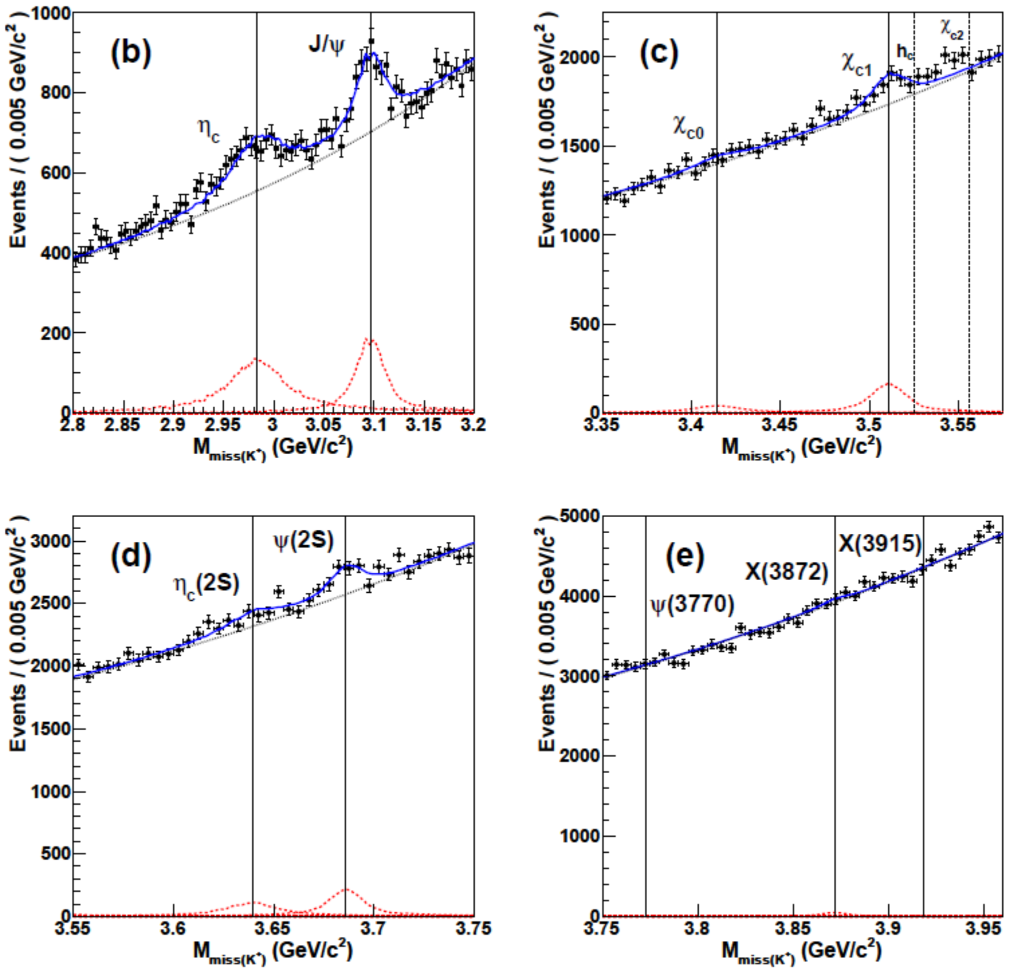
NEW

Particle	Yield	Peak Position	BF(10^{-4})	PDG 2014	PDG 2017
D^0	126±20		3.5±0.5(sta)±0.3(sys)	3.7±0.17	3.74±0.16
D^{*0}	126±21		3.5±0.5(stat)±0.3(sys)	4.2±0.34	
$D_1(2420)^0$	97±25		2.1±0.5(stat))±0.3(sys)	-	
$D^{**0}(2680)$	95±29	2.68±0.003	2.1±0.6(stat)±0.3(sys)	-	
$D^{\pm}$	44±10		3.3±0.8(sta)±0.3(sys)	2.0±0.21	1.86±0.20
$D^{*\pm}$	40±10		3.0±0.8(stat)±0.3(sys)	2.1±0.16	2.12±0.15
D*$(2420)^{\pm}$	52±13		3.9±1.0(stat))±0.3(sys)	-	

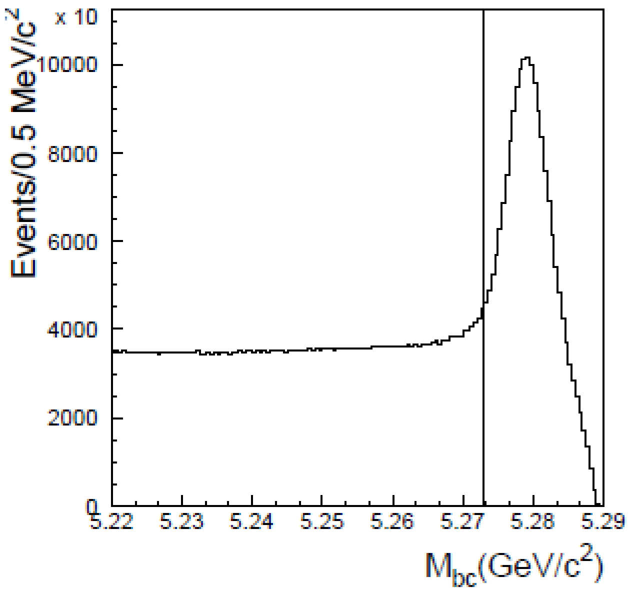
Results from the fits of the K momentum spectra in the D region mass, performed for $B^{\pm}$ and B^0 samples of 1.67 M and 0.8 M reconstructed B events, respectively.

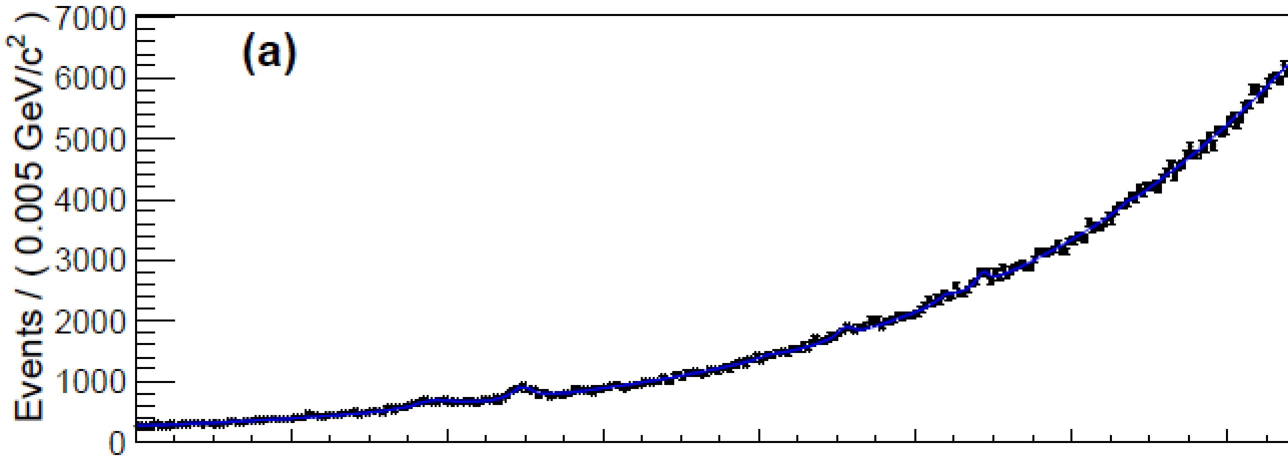
Mass distribution




(b)
J/ψ
η_c
(c)
χ_c0
χ_c1
h_c
χ_c2
(d)
ψ(2S)
η_c(2S)
(e)
ψ(3770)
X(3872)
X(3915)
Events / (0.005 GeV/c²)
M_miss(K*) (GeV/c²)

Belle analysis

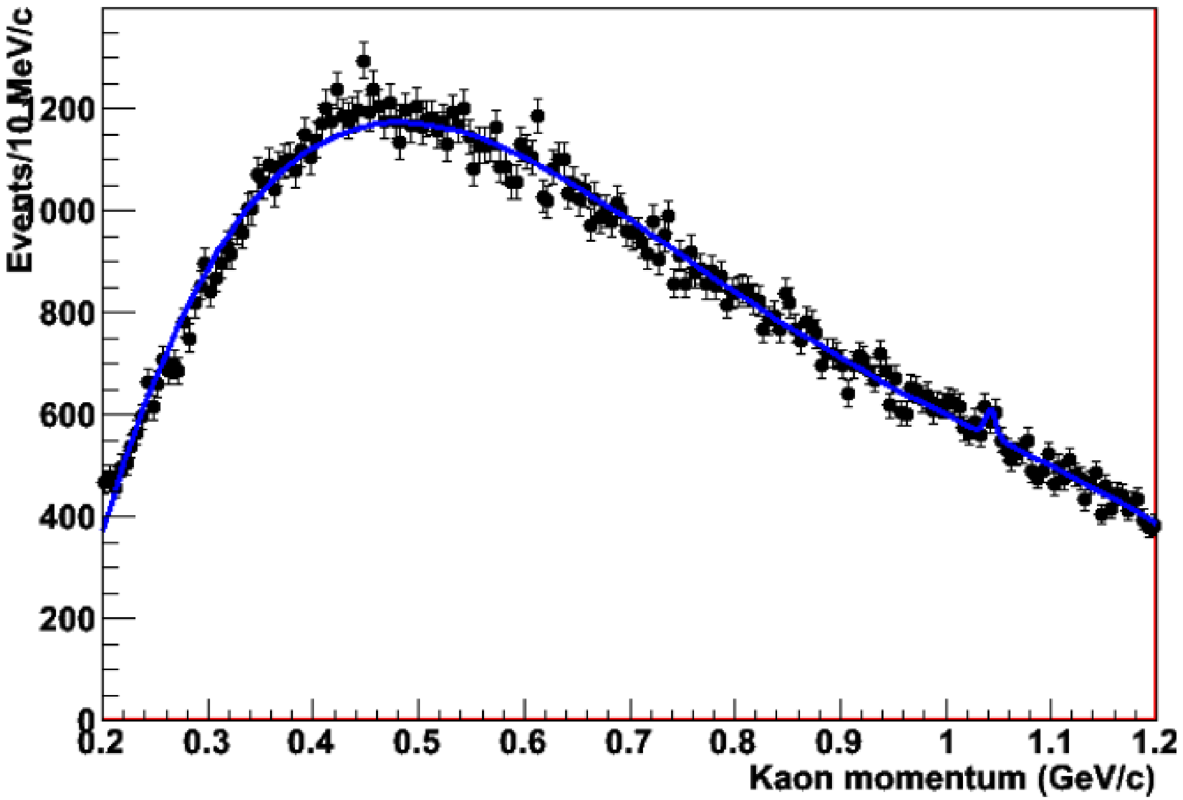




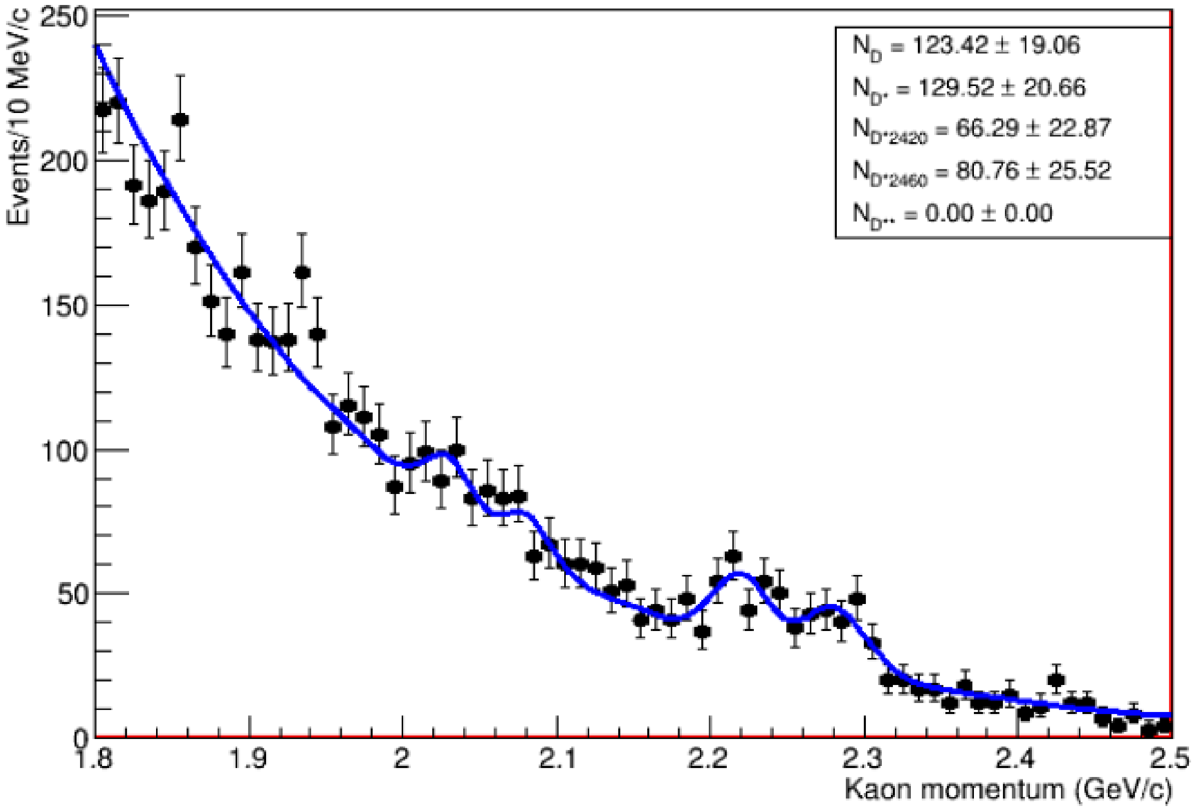
Belle results

Mode	Yield	Significance (σ)	$\epsilon(10^{-3})$	$\mathcal{B}$ (10^{-4})	World average for $\mathcal{B}$ (10^{-4}) [10]
η_c	2590 ± 180	14.2	2.73 ± 0.02	$12.0 \pm 0.8 \pm 0.7$	9.6 ± 1.1
J/ψ	1860 ± 140	13.7	2.65 ± 0.02	$8.9 \pm 0.6 \pm 0.5$	10.26 ± 0.031
χ_{c0}	430 ± 190	2.2	2.67 ± 0.02	$2.0 \pm 0.9 \pm 0.1$ (< 3.3)	$1.50^{+0.15}_{-0.14}$
χ_{c1}	1230 ± 180	6.8	2.68 ± 0.02	$5.8 \pm 0.9 \pm 0.5$	4.79 ± 0.23
$\eta_c(2S)$	1050 ± 240	4.1	2.77 ± 0.02	$4.8 \pm 1.1 \pm 0.3$	3.4 ± 1.8
$\psi(2S)$	1410 ± 210	6.6	2.79 ± 0.02	$6.4 \pm 1.0 \pm 0.4$	6.26 ± 0.24
$\psi(3770)$	-40 ± 310	-	2.76 ± 0.02	$-0.2 \pm 1.4 \pm 0.0$ (< 2.3)	4.9 ± 1.3
$X(3872)$	260 ± 230	1.1	2.79 ± 0.01	$1.2 \pm 1.1 \pm 0.1$ (< 2.6)	(< 3.2)
$X(3915)$	80 ± 350	0.3	2.79 ± 0.01	$0.4 \pm 1.6 \pm 0.0$ (< 2.8)	-

The higher mass region



The D region



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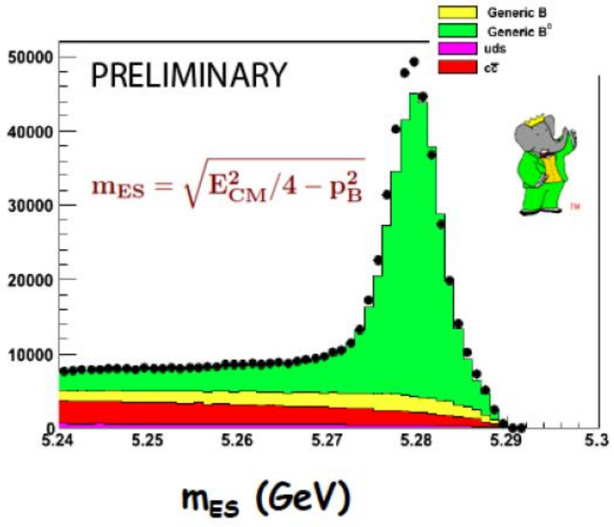
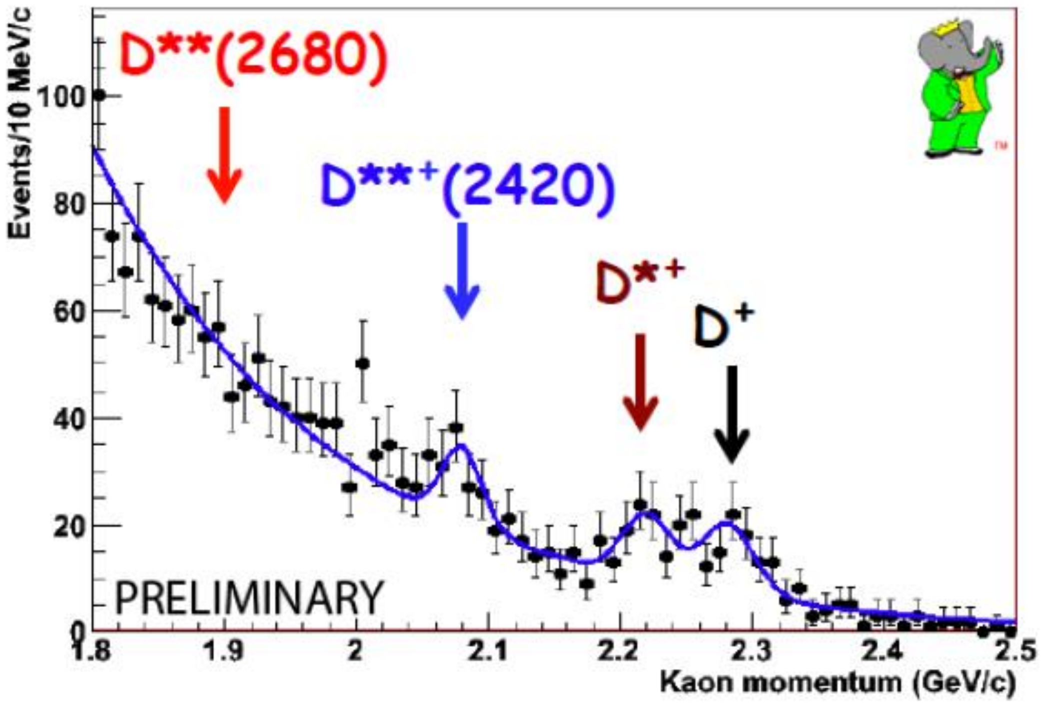
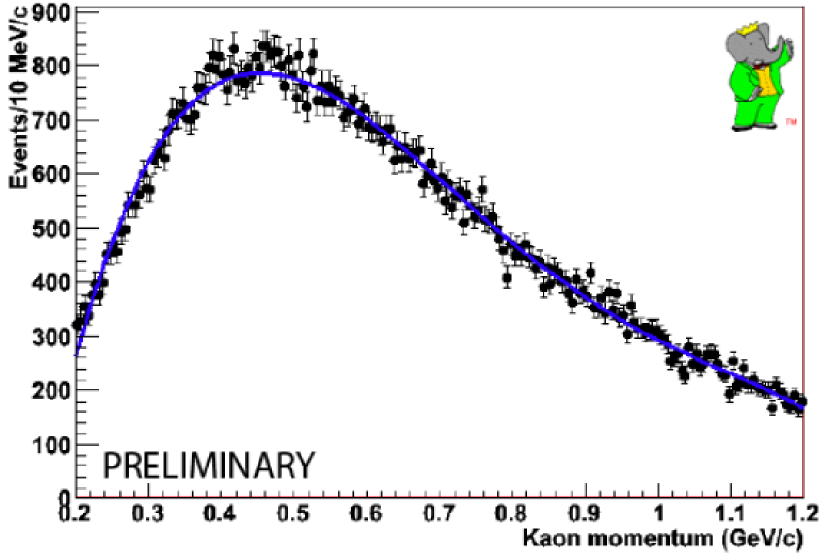
Particle	Yield	Peak Position	BF(10^{-4})
D^0	126±20	-	3.5±0.5(sta)±0.3(sys)
D^{*0}	126±21	-	3.5±0.5(stat)±0.3(sys)
$D_1(2420)^0$	97±25	-	2.1±0.5(stat))±0.3(sys)
$D^{**0}(2680)$	95±29	2.68±0.003	2.1±0.6(stat)±0.3(sys)
$D^{\pm}$	44±10	-	3.3±0.8(sta)±0.3(sys)
$D^{*\pm}$	40±10	-	3.0±0.8(stat)±0.3(sys)
D*[2420]$^{\pm}$	52±13	-	3.9±1.0(stat))±0.3(sys)

Two-body decays $B^0 \rightarrow K^- X^+$



Very high Kaon momentum region





No observation of narrow charged« charmonium » states in the mass range 3.7 -4.7 GeV

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