XYZ spectroscopy at LHCb

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Physics at LHCb, Bad Honnef, Germany, 28/04/2011

Outline

- Introduction: review on exotic states
- $X(3872)$:
  - LHCb first mass measurement
  - Future measurements: mass, quantum numbers, di-pion mass spectrum and width
- Other exotic states and LHCb propsects:
  - $Z^{\pm}(4430)$
  - Search for resonnances in $J/\psi\phi$, $J/\psi\pi\pi$ and $J/\psi J/\psi$ mass spectra
  - Search for exotic bottomonium
- Conclusion

Exotic mesons

In recent years, new exotic mesons have been observed by different experiments:

- $X(3872)$, $X(4140)$, $Z^{\pm}(4430)$...
- First assigned to $c\bar{c}$ charmonium states but they don't fit diquark model.
- Many models exists, all with limited success.
  - **Tetraquark:** Tightly bound four quark.
  - **Molecular state:** Loosely bound mesons with a quark/color exchange (short distance) or pion exchange (large distance).
  - **Charmonium hybrids:** States with a excited gluonic degrees of freedom.
  - **Threshold effects:** Virtual states at thresholds.

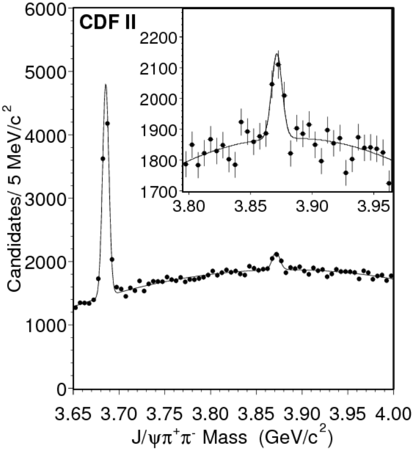
Exotic mesons

State	m (MeV)	Γ (MeV)	J^{PC}	Process (mode)	Experiment ($\#\sigma$)	Year	Status
$X(3872)$	3871.52 ± 0.20	1.3 ± 0.6	$1^{++}/2^{-+}$	$B \to K(\pi^+\pi^- J/\psi)$	Belle , BABAR	2003	OK
		(<2.2)		$p\bar{p} \to (\pi^+\pi^- J/\psi) + ...$	CDF, DØ		
				$B \to K(\omega J/\psi)$	Belle BABAR		
				$B \to K(D^{*0}\bar{D}^0)$	Belle, BABAR		
				$B \to K(\gamma J/\psi)$	Belle, BABAR		
				$B \to K(\gamma\psi(2S))$	BABAR, Belle		
$X(3915)$	3915.6 ± 3.1	28 ± 10	$0/2^{?+}$	$B \to K(\omega J/\psi)$	Belle, BABAR	2004	OK
				$e^+e^- \to e^+e^-(\omega J/\psi)$	Belle		
$X(3940)$	3942^{+9}_{-8}	37^{+27}_{-17}	$?^{?+}$	$e^+e^- \to J/\psi(D\bar{D}^*)$	Belle	2007	NC!
				$e^+e^- \to J/\psi\ (...)$	Belle		
$G(3900)$	3943 ± 21	52 ± 11	1^{--}	$e^+e^- \to \gamma(D\bar{D})$	BABAR, Belle	2007	OK
$Y(4008)$	4008^{+121}_{-49}	226 ± 97	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^- J/\psi)$	Belle	2007	NC!
$Z_1(4050)^+$	4051^{+24}_{-43}	82^{+51}_{-55}	?	$B \to K(\pi^+\chi_{c1}(1P))$	Belle	2008	NC!
$Y(4140)$	4143.4 ± 3.0	15^{+11}_{-7}	$?^{?+}$	$B \to K(\phi J/\psi)$	CDF	2009	NC!
$X(4160)$	4156^{+29}_{-25}	139^{+113}_{-65}	$?^{?+}$	$e^+e^- \to J/\psi(D\bar{D}^*)$	Belle	2007	NC!
$Z_2(4250)^+$	4248^{+185}_{-45}	177^{+321}_{-72}	?	$B \to K(\pi^+\chi_{c1}(1P))$	Belle	2008	NC!
$Y(4260)$	4263 ± 5	108 ± 14	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^- J/\psi)$	BABAR	2005	OK
					CLEO		
					Belle		
				$e^+e^- \to (\pi^+\pi^- J/\psi)$	CLEO		
				$e^+e^- \to (\pi^0\pi^0 J/\psi)$	CLEO		
$Y(4274)$	$4274.4^{+8.4}_{-6.7}$	32^{+22}_{-15}	$?^{?+}$	$B \to K(\phi J/\psi)$	CDF	2010	NC!
$X(4350)$	$4350.6^{+4.6}_{-5.1}$	$13.3^{+18.4}_{-10.0}$	$0,2^{++}$	$e^+e^- \to e^+e^-(\phi J/\psi)$	Belle	2009	NC!
$Y(4360)$	4353 ± 11	96 ± 42	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^-\psi(2S))$	BABAR, Belle	2007	OK
$Z(4430)^+$	4443^{+24}_{-18}	107^{+113}_{-71}	?	$B \to K(\pi^+\psi(2S))$	Belle	2007	NC!
$X(4630)$	4634^{+9}_{-11}	92^{+41}_{-32}	1^{--}	$e^+e^- \to \gamma(\Lambda_c^+\Lambda_c^-)$	Belle	2007	NC!
$Y(4660)$	4664 ± 12	48 ± 15	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^-\psi(2S))$	Belle	2007	NC!
$Y_b(10888)$	10888.4 ± 3.0	$30.7^{+8.9}_{-7.7}$	1^{--}	$e^+e^- \to (\pi^+\pi^-\Upsilon(nS))$	Belle	2010	NC!

Taken from "Heavy quarkonium: progress, puzzles, and opportunities", arXiv:1010.5827

$X(3872)$: discovery and properties

- First exotic meson observed.
  - Discovered in $B^{\pm} \to K^{\pm}X(3872)(\to J/\psi\pi^+\pi^-)$ by Belle in 2003
  - Confirmed by CDF in 2004
  - Confirmed by Babar in 2008
- Most abundant exotic state:
  - Already well studied:
    - Dipion mass spectrum studied by CDF
    - Quantum numbers constrainted to be $J^{PC} = 1^{++}$ or 2^{-+}
  - Nature still incertain: most popular model: molecular state with $J^{PC} = 1^{++}$



PRL 93:072001, 2004

$X(3872)$ at LHCb: first measurement

- First measurement at LHCb: mass of the $X(3872)$ meson
  - Using the inclusive production (both prompt and from b mesons decay components)
  - In the $X(3872) \to J/\psi\pi^+\pi^-$ channel, using $\psi(2S) \to J/\psi\pi^+\pi^-$ as a control
  - May gives some hint on the nature of the particle: in the molecular state hypothesis, the mass should be below the $D^{*0}\bar{D}^0$ threshold (3871.79 ± 0.29 MeV/c^2)
  - World average is: $m_{X(3872)} = 3871.56 \pm 0.22$ MeV/c^2 (below $D^{*0}\bar{D}^0$ threshold)
  - Difference between the $X(3872)$ mass and the $D^{*0}\bar{D}^0$ threshold does not exclude the possibility that the mass could be above the threshold.

$X(3872)$ at LHCb: selection

Offline requirements used to select $\psi(2S) \to J/\psi\pi^+\pi^-$ and $X(3872) \to J/\psi\pi^+\pi^-$ candidates:

Candidate	Variable	Requirement
$\mu^\pm$	track fit χ^2/ndof	< 4
	clone removal: $\Delta_{\mathrm{KL}}^{\mathrm{min}}$	> 5000
	p_T	> 1 GeV$/c$
	p	> 10 GeV$/c$
	particle identification	identified as muon
$J/\psi \to \mu^+\mu^-$	vertex χ^2/ndof	< 20
	p_T	> 3.5 GeV$/c$
	$M_{\mu\mu}$	$\in [3040; 3140]$ MeV$/c^2$
$\pi^\pm$	track fit χ^2/ndof	< 5
	clone removal: $\Delta_{\mathrm{KL}}^{\mathrm{min}}$	> 5000
	p_T	> 0.5 GeV$/c$
	particle identification: $\Delta \ln L_{K\pi}$	< 0
$J/\psi\pi^+\pi^-$	vertex χ^2/ndof	< 5
	$Q = M_{\mu\mu\pi\pi} - M_{\mu\mu} - M_{\pi\pi}$	< 300 MeV$/c^2$
	$M_{J/\psi\pi\pi}$ (after J/ψ mass constraint)	$\in [3600; 3950]$ MeV$/c^2$

$X(3872)$ at LHCb: fit function

- Background:

$$F_{bg}(M; m_r, c_0, c_1, c_2) = \frac{1}{a}(M - m_r)^{c_0} e^{-Mc_1 - M^2 c_2}$$

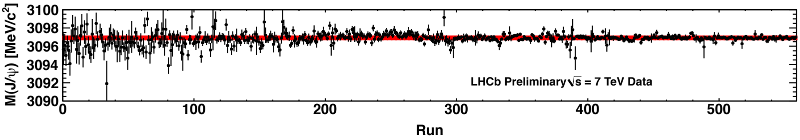
  - a is a normalization factor
  - $m_r = m_{J/\psi} + 2m_\pi = 3376.05\text{MeV}/c^2$ is the threshold
  - c_0, c_1 and c_2 describe the shape of the background
  - c_2 is fixed fitting the same-sign candidates mass distribution
- Signal Voigt function:

$$V(M; \mu, \sigma, \Gamma) = \int_{-\infty}^{\infty} G(M - M'; \sigma) L(M'; \mu, \Gamma)\, dM'$$

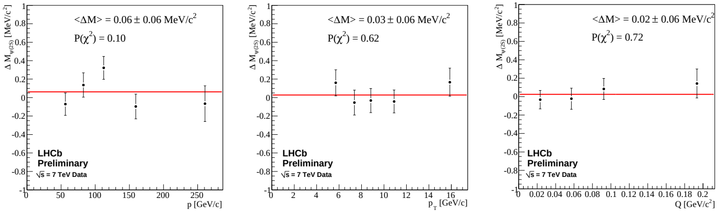
  - $G(M; \mu, \sigma)$: Gaussian function centred at zero with a resolution σ
  - $L(M; \mu, \Gamma)$: Breit-Wigner function centred at μ with a full width Γ at half-maximum
  - The intrinsic width of the $\psi(2S)$ is fixed to the PDG value, $\Gamma_{\psi(2S)} = 0.317\ \text{MeV}/c^2$
  - The intrinsic width of the $X(3872)$ is fixed to $\Gamma_{X(3872)} = 1.3\ \text{MeV}/c^2$

$X(3872)$ at LHCb: calibration and systematics

- Detector calibration:
  - J/ψ mass is constant over the whole data-taking period:



- Systematics are under control:
  - $M_{\psi(2S)} = 3686.12 \pm 0.06$ (stat) MeV$/c^2$, consistent with world average (3686.09 ± 0.04 MeV$/c^2$),
  - The $\psi(2S)$ mass does not depend on any kinematic variable:

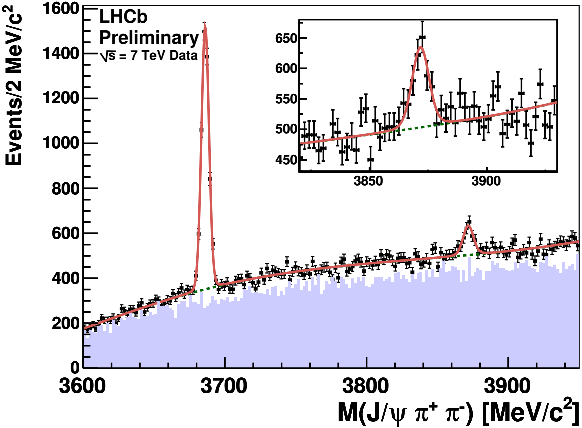


$X(3872)$ at LHCb: calibration and systematics

- Systematics:

Source of uncertainty	Value [MeV/c^2]
Mass fitting:	
Signal model (natural width)	0.02
Background model	0.02
Momentum calibration:	
Average momentum scale	0.05
η dependence of momentum scale	0.03
Detector description:	
Energy loss correction	0.05
Detector alignment:	
Tracking stations (TT information)	0.05
Vertex detector (track slopes)	0.01
Quadratic sum	0.10

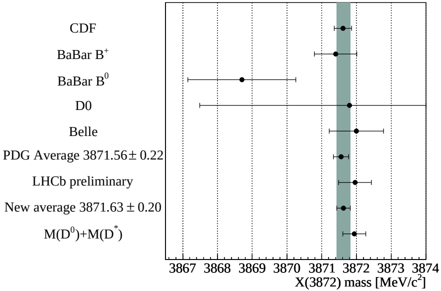
$X(3872)$ at LHCb: $J/\psi\pi^+\pi^-$ mass spectrum



- Results:
  - $N_{X(3872)} = 585 \pm 74$
  - $M_{X(3872)} = 3871.96 \pm 0.46$ (stat) ± 0.10 (syst) MeV$/c^2$
  - $\sigma = 2.75 \pm 0.54$ MeV$/c^2$

$X(3872)$ at LHCb: comparison with other experiments

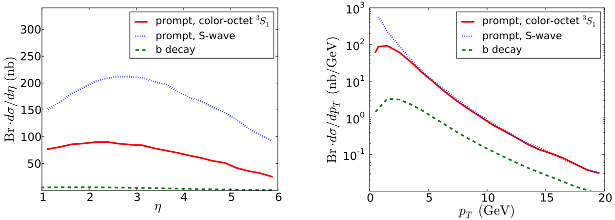
- $X(3872)$ mass compatible with measurement from other experiment
- New average: 3871.63 ± 0.20 MeV$/c^2$ is indistinguishable from the $D^{*0}\bar{D}^0$ threshold (3871.79 ± 0.29 MeV$/c^2$)
- A new measurement will be done with 500 pb^{-1}, a statistical error of $\sim$0.12 MeV$/c^2$ is expected
- A measurement of the $X(3872)$ mass respect to the $D^{*0}\bar{D}^0$ threshold to reduce systematics will be done too



$X(3872)$ at LHCb: future

LHCb can make great contributions on the understanding of the $X(3872)$:

- Production cross section measurement, for both for the prompt and b meson component

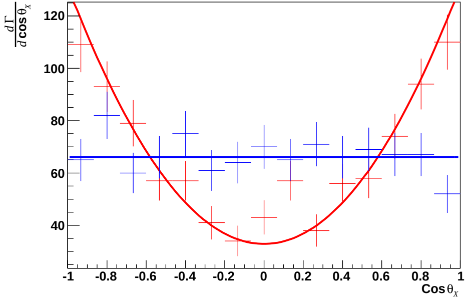


P. Artoisenet and E. Braaten; arXiv:0911.2016v1.

- Theoretical predictions: for $p_T > 0.5 GeV$ and $1.6 < \eta < 5.3$
  - Prompt cross section: 270 nb and 688 nb (for color-octet or S-wave dominance)
  - b-decay cross section: 14 nb
- Studies are underway with 2010 data

$X(3872)$ at LHCb: future

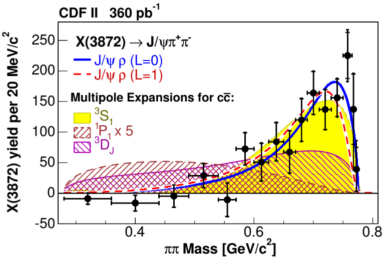
- Determination of the quantum numbers using $B^+ \to X(3872)(\to J/\psi\pi^+\pi^-)K^+$
  - $\sim$1000 reconstructed $X(3872)$ events are expected with 2 fb^{-1}
  - Enough to disentangle between the $J^{PC} = 1^{++}$ and 2^{-+} states! (CERN-LHCb-PUB-2010-003)



Decay rate as a function of $\cos\theta_X$ for the 1^{++} (blue) and 2^{-+} (red) hypothesis for 1000 simulated decays.

$X(3872)$ at LHCb: future

- Study of the $M_{\pi\pi}$
  - usefull to understand the $X(3872)$ decay mechanism and constrain models
  - will be done in 2011



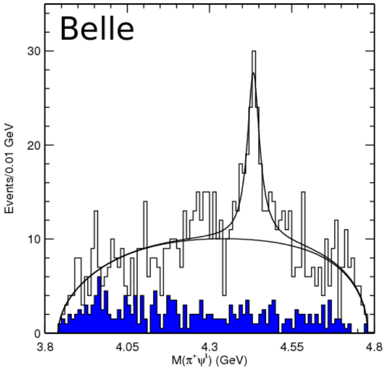
PRL. 96, 102002 (2006)

- $X(3872)$ width:
  - Now (PDG): $\Gamma < 2.3$ MeV$/c^2$, CL $= 90\%$
  - Nothing can be done with 2010 data, studies will be done in 2011 with more statistics
  - Challenging because we need very good signal/background modeling and a good understanding of our resolution

$Z^{\pm}(4430)$: discovery?

$Z^{\pm}(4430)$: first charged charmonium-like state.

- Discovered by Belle in the $\psi(2S)\pi$ system:
  - $m = 4433 \pm 4 \pm 2$ MeV/c^2
  - $BR(B \to KZ) \times BR(Z \to \psi(2S)\pi) = (4.1 \pm 1.0 \pm 1.3) \times 10^{-5}$
  - most likely to be a tetraquark state with $c\bar{c}d\bar{u}$ quark content.

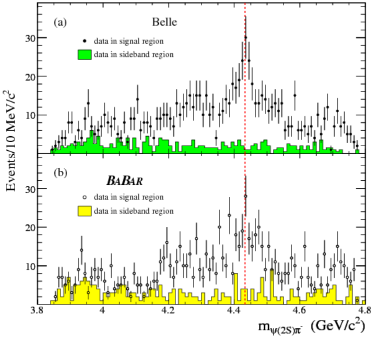


6.5σ confidence level
PRL 100:142001, 2008

$Z^{\pm}(4430)$: confirmation?

$Z^{\pm}(4430)$: first charged charmonium-like state.

- Babar analysis found no evidence for $Z^{\pm}(4430)$ existence:
  - $BR(B^0 \to Z^-(4430)K^+) \times BR(Z^- \to \psi(2S)\pi^-) < 3.1 \times 10^{-5}$ at 95% CL
  - Too small data sample.
- Need another experiment to confirm (or discard) Belle's dicovery



1.9σ confidence level

PRD 79:112001, 2009

$Z^{\pm}(4430)$ at LHCb

- $Z^{\pm}(4430)$ signal from b mesons yield at LHCb with an integrated luminosity $L_{int} = 1\ \text{fb}^{-1}$ (CERN-THESIS-2009-129):

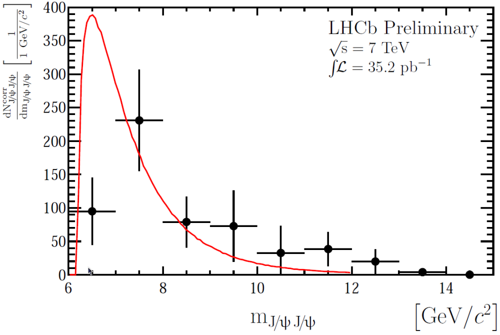
$$N_{phys} = L_{int} \times 2 \times \sigma_{b\bar{b}} \times f_{B^0} \times BR^{sig}_{vis} \times \epsilon^{sig}_{tot} \approx 860 \text{ events}$$

  - $\sigma_{b\bar{b}} = 288\ \mu$b the $b\bar{b}$ production cross section in pp collisions at $\sqrt{s} = 7$TeV (from arXiv:1103.0423).
  - $f_{B^0} = 39.9$ % the fraction of b quarks that hadronize to a B^0 meson.
  - $BR^{sig}_{vis} = BR(B^{\pm} \rightarrow (Z^{\pm}(4430) \rightarrow (\psi(2S) \rightarrow \mu\mu)\pi)K) = 2.99 \times 10^{-7}$ is the decay visible branching fraction.
  - $\epsilon^{sig}_{tot} = 1.25$ % the total reconstruction efficiency (estimate from Monte Carlo study).

LHCb has an important role to play in the confirmation of $Z^{\pm}(4430)$ existence.

Other searches

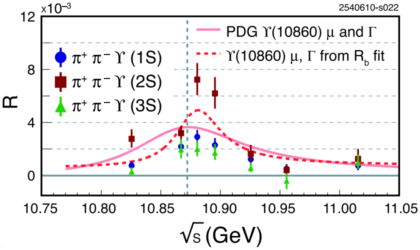
- LHCb will also do some "bump-hunting" in mass spectra
  - $J/\psi\phi$ and $J/\psi\pi\pi$: confirmation of the $X(4140)$, $X(3940)$ or discovery of some new states...
  - Exotic resonnances can also be seen in the $J/\psi J/\psi$ channel (see Vanya Belyaev's talk at 15:45)



- The 35 pb^{-1} data sample is too small, the hunt will start seriously this year with more data

Exotic bottomonium

- Belle observed an anomalously large $\Upsilon(nS)\pi\pi$ cross section near the $\Upsilon(5S)$
- Data correspond to a resonance of $m = 10888.4 \pm 3.0$ MeV/c^2 and $\sigma = 30.7 \pm 8.0$ MeV/c^2
- The enhancement could be a 1^{--} exotic Y_b state distinct from the $\Upsilon(5S)$
  - Equivalent of the XYZ states may exists for the b family
  - LHCb will study the $\Upsilon(nS)\pi^+\pi^-$ spectrum and look for resonances
  - No studies yet, we will start with 2011 data



Phys. Rev. D 82:091106 (2010)

Conclusion

- *XYZ* spectroscopy is a new and exciting field.
  - A lot has been done already
  - But a lot of work is needed to understand all these states
- Great results are expected from LHCb in the next two years:
  - study of the "not so" well known states $X(3872)$: mass, quantum numbers, width...
  - confirmation of discoveries: $Z^{\pm}(4430)$, $X(4140)$...
  - new exotic states in the $J/\psi\pi\pi$, $J/\psi\phi$, $J/\psi J/\psi$ spectra, or bottomonium states?

Backup: $X(3872)$ yields

- $X(3872)$ signal from b mesons decay yield after 18 month of running:

$$N_{phys} = L_{int} \times 2 \times \sigma_{b\bar{b}} \times f_{B^\pm} \times BR^{sig}_{vis} \times \epsilon^{sig}_{tot} \approx 1000 \text{ events}$$

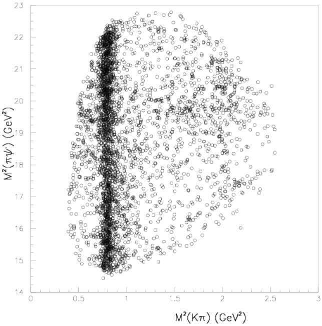
  - $L_{int} = 2\ \text{fb}^{-1}$ the integrated luminosity
  - $\sigma_{b\bar{b}} = 288\ \mu\text{b}$ the $b\bar{b}$ production cross section in pp collisions at $\sqrt{s} = 7\text{TeV}$ (from arXiv:1103.0423).
  - $f_{B^\pm} = 39.9\ \%$ is the fraction of b quarks that hadronize to a $B^\pm$ meson.
  - $BR^{sig}_{vis} = BR(B^\pm \to (X(3872) \to (J/\psi \to \mu\mu)\pi\pi)K^\pm) = 6.76 \times 10^{-7}$ is the visible decay branching fraction.
  - $\epsilon^{sig}_{tot} = 0.45\ \%$ is the total reconstruction efficiency. From MC study.

Backup: $Z^{\pm}(4430)$ at LHCb

We will do $B^0 \to J/\psi\pi K$ and $B^0 \to \psi(2S)\pi K$ Dalitz analyses

- Since $\frac{BR(B\to J/\psi K^*)}{BR(B\to\psi(2S)K^*)} \times \frac{BR(J/\psi\to\mu\mu)}{BR(\psi(2S)\to\mu\mu)} \simeq 15$, the first analysis will be $B^0 \to J/\psi\pi K$. it might also show evidence of a $Z^{\pm}(4430)$.
- $B^0 \to \psi(2S)\pi K$ will be done after and will follow the same procedure.

- Difficult analysis: pay attention to resonnances ($K^*(892)$, $K_2^*(1430)$) and $K\pi$ reflections into the $J/\psi\pi$ masses (S, P and D-waves).



PRD 79:112001

Backup: $J/\psi\pi\pi$ fit results

Quantity	$\psi(2S)$	$X(3872)$
N_S	3998 ± 84	585 ± 74
S/B	1.5	0.15
M [MeV/c^2]	3686.12 ± 0.06	3871.96 ± 0.46
σ [MeV/c^2]	2.54 ± 0.06	2.75 ± 0.54
N_B	73064 ± 286	
c_0	8.00 ± 0.13	
c_1 [$\mathrm{MeV}^{-1}c^2$]	0.140 ± 0.003	