Simulation of *Zc(3900)*-production and decays in $\bar{p}$-*d* collisions at PANDA

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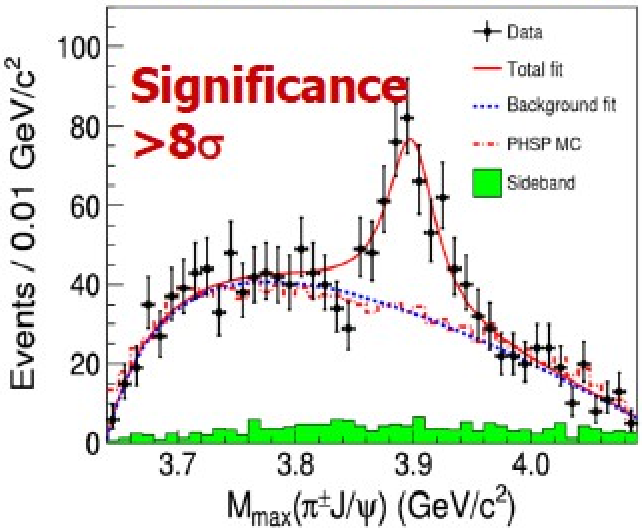
1. Status of *Z*-states,
2. *Zc*-coupling with nucleon-antinucleon channel,
3. *Zc*-production in $\bar{p}$-*d* collisions,
4. *R*econstruction of $Z_c(3900) \longrightarrow \pi^- J/\psi \longrightarrow l^+l^-$,
5. Conclusions.

Observation of Zc(3900) at BESIII

PRL110, 252001 (2013)

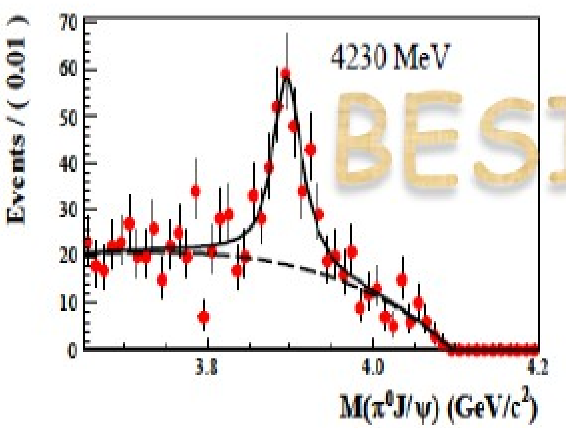


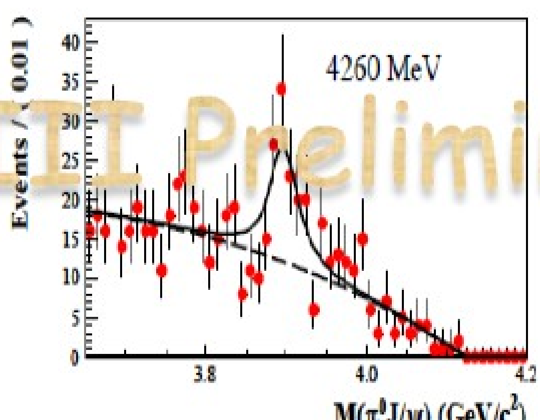
$e^+e^- \to \pi Z_c(4020) \to \pi^+\pi^- J/\psi$

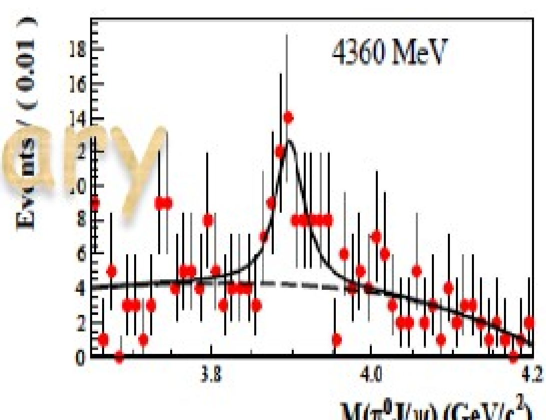
- $M = 3899.0 \pm 3.6 \pm 4.9$ MeV/c²
- $\Gamma = 46 \pm 10 \pm 20$ MeV

$e^+e^- \to \pi Z_c(4020) \to \pi^0\pi^0 J/\psi$

- $M = 3894.8 \pm 2.3$ MeV/c²
- $\Gamma = 29.6 \pm 8.2$ MeV

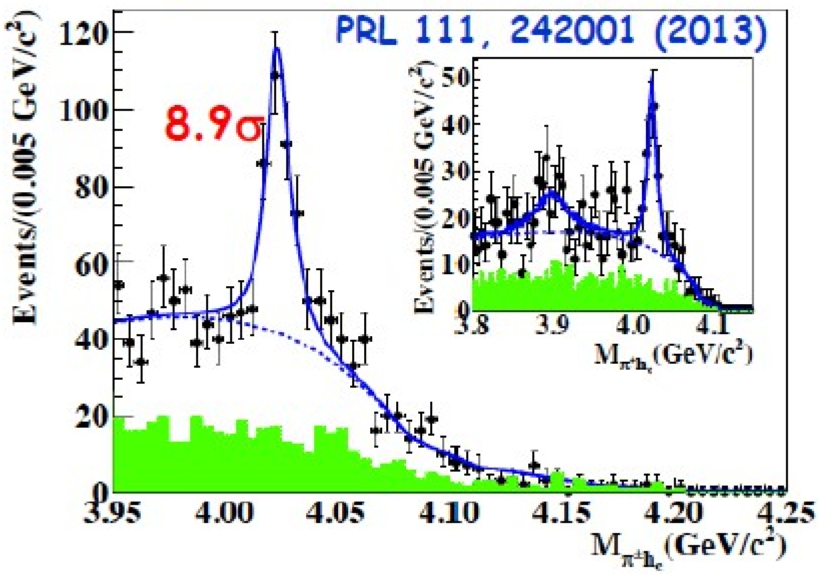




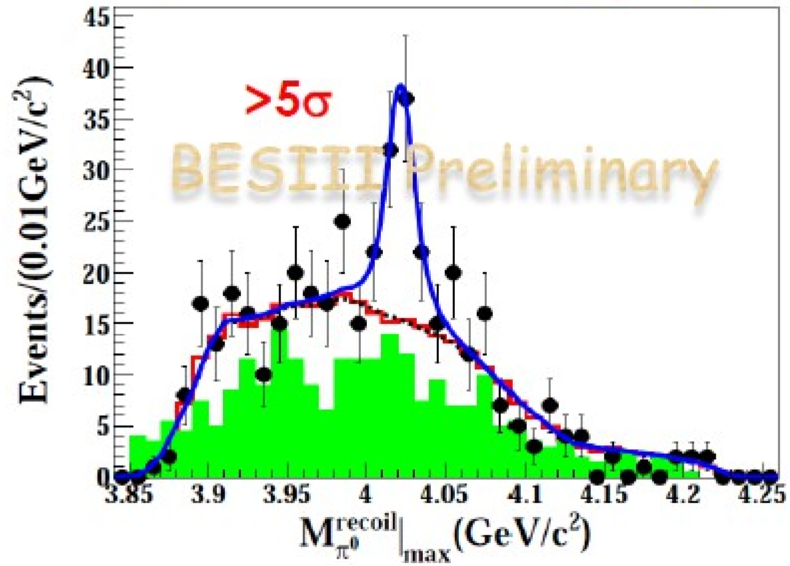


Observation of Zc(4020) in $e^+e^-\to\pi\pi h_c$

$e^+e^-\to\pi^+\pi^-h_c$



$e^+e^-\to\pi^0\pi^0h_c$



No significant: $Z_c(3900)$ (2.1σ)

M = 4022.9±0.8±2.7 MeV/c²

Γ = 7.9±2.7±2.6 MeV

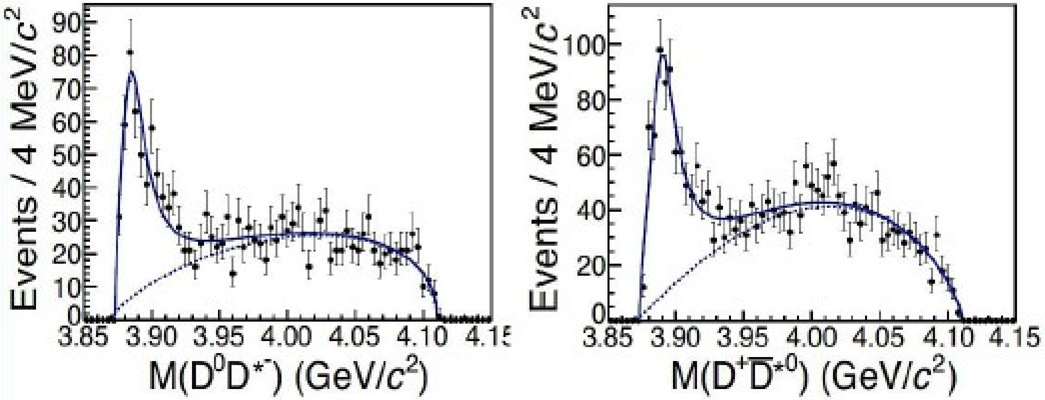
$$\frac{\sigma(e^+e^-\to\pi^0 Z_c(4020)^0\to\pi^0\pi^0 h_c)}{\sigma(e^+e^-\to\pi^\pm Z_c(4020)^\mp\to\pi^\pm\pi^\mp h_c)}$$

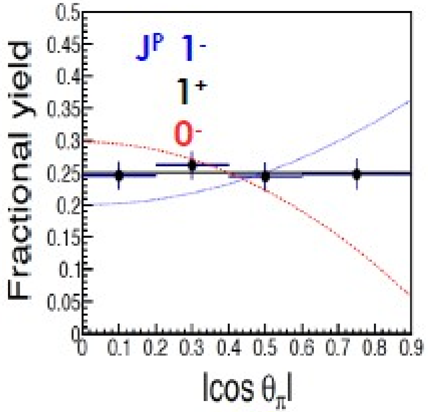
M = 4023.6±2.3±3.9 MeV/c²

$\sqrt{s}$ (GeV)	$R_{\pi Z_c(4020)}$
4.230	$0.79 \pm 0.30 \pm 0.26$
4.260	$1.18 \pm 0.46 \pm 0.37$
4.360	$0.99 \pm 0.47 \pm 0.32$

Observation of Zc(3885) and $Z_c(4025)$

$e^+e^- \to \pi^- (D^* \bar{D})^+$





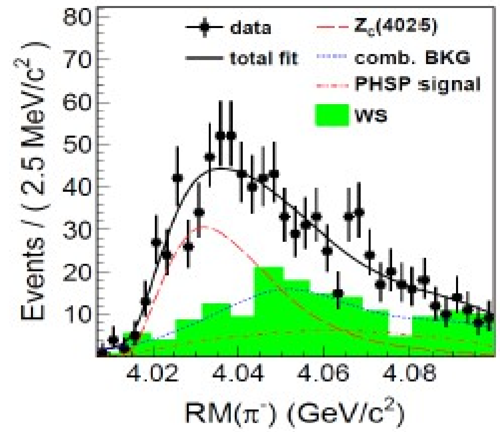
$M = 3883.9 \pm 1.5 \pm 4.2$ MeV/c^2

$\Gamma = 24.8 \pm 3.3 \pm 11.0$ MeV

- fits favor 1^+ distribution assumption

PRL 112, 022001 (2014)

$e^+e^- \to \pi^- (D^* \bar{D}^*)^+$



$M = 4026.3 \pm 2.6 \pm 3.7$ MeV/c^2

$\Gamma = 24.8 \pm 5.6 \pm 7.7$ MeV

PRL 112, 132001 (2014)

the Zc states at BESIII

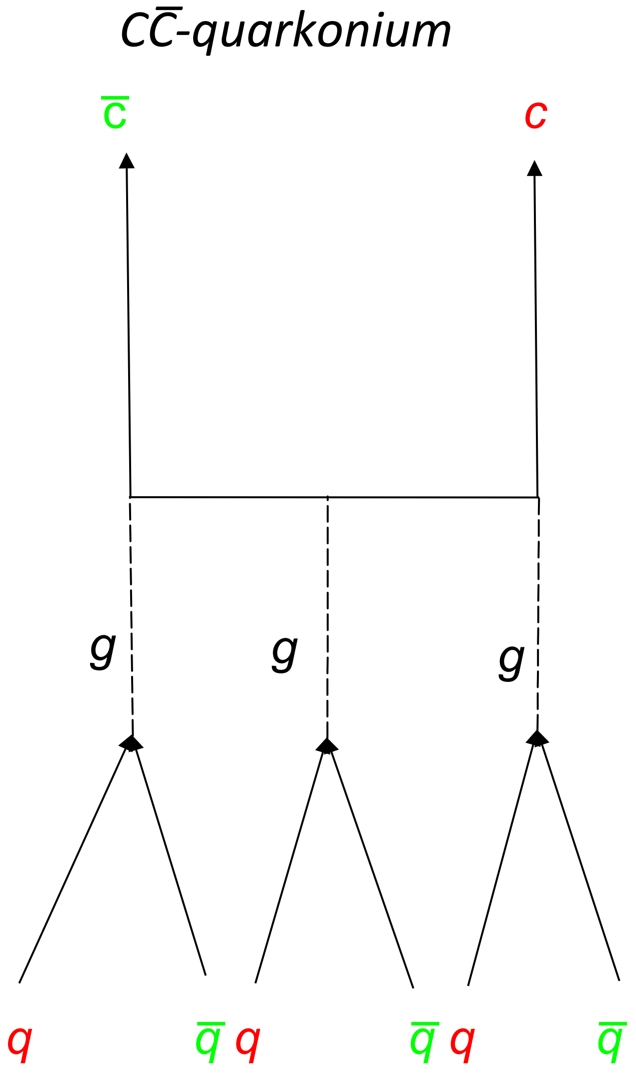
Channel	Mass (MeV/c^2)	Width (MeV)
$\pi J/\psi$	$3899.0 \pm 3.6 \pm 4.9$ 3894.8 ± 2.3(Prel.)	$46 \pm 10 \pm 20$ 29.6 ± 8.2 (Prel.)
$(D\bar{D}^*)^\pm$	$3883.9 \pm 1.5 \pm 4.2$	$24.8 \pm 3.3 \pm 11.0$
	2σ difference	1σ difference
πh_c	$4022.9 \pm 0.8 \pm 2.7$ $4022.9 \pm 0.8 \pm 2.7$(Prel.)	$7.9 \pm 2.7 \pm 2.6$
$(D^*\bar{D}^*)^\pm$	$4026.3 \pm 2.6 \pm 3.7$	$24.8 \pm 5.6 \pm 7.7$
	1σ difference	2σ difference

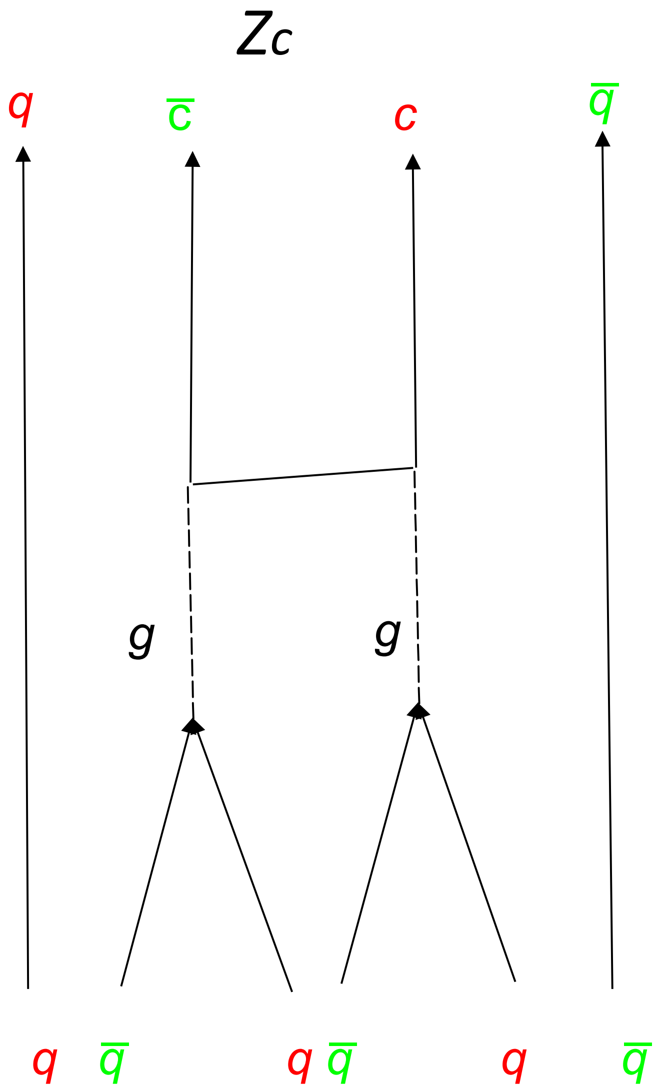
Close to $D\bar{D}^*$ threshold (3875 MeV)

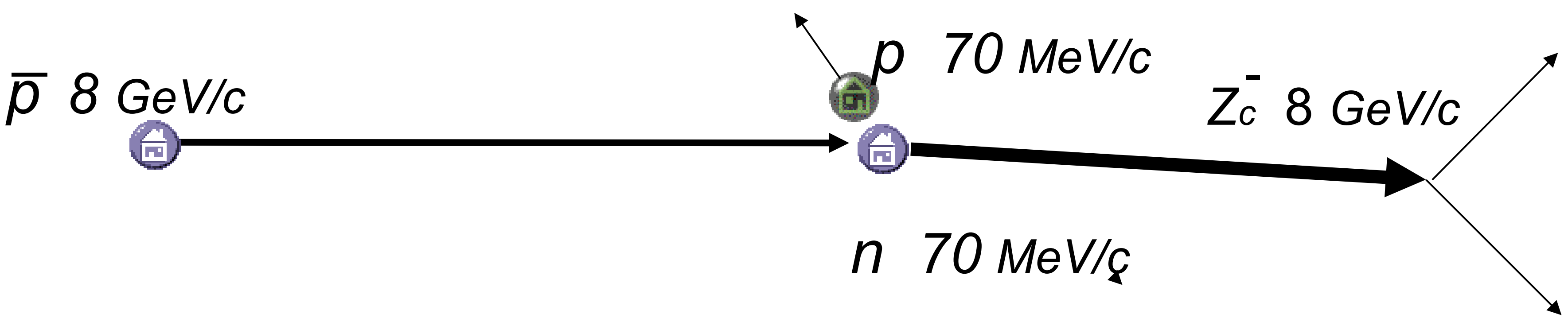
Close to $D^*\bar{D}^*$ threshold (4017 MeV)

- At least 4-quarks; Near threshold;
- Isospin: I=1, hint of a new spectroscopy ?
- Whether they are two states need further understanding (couple channel analysis? quantum number determination? interference?)

Couplings with nucleon-antinucleon channel: $c\bar{c}$ *v.s.* Z_c

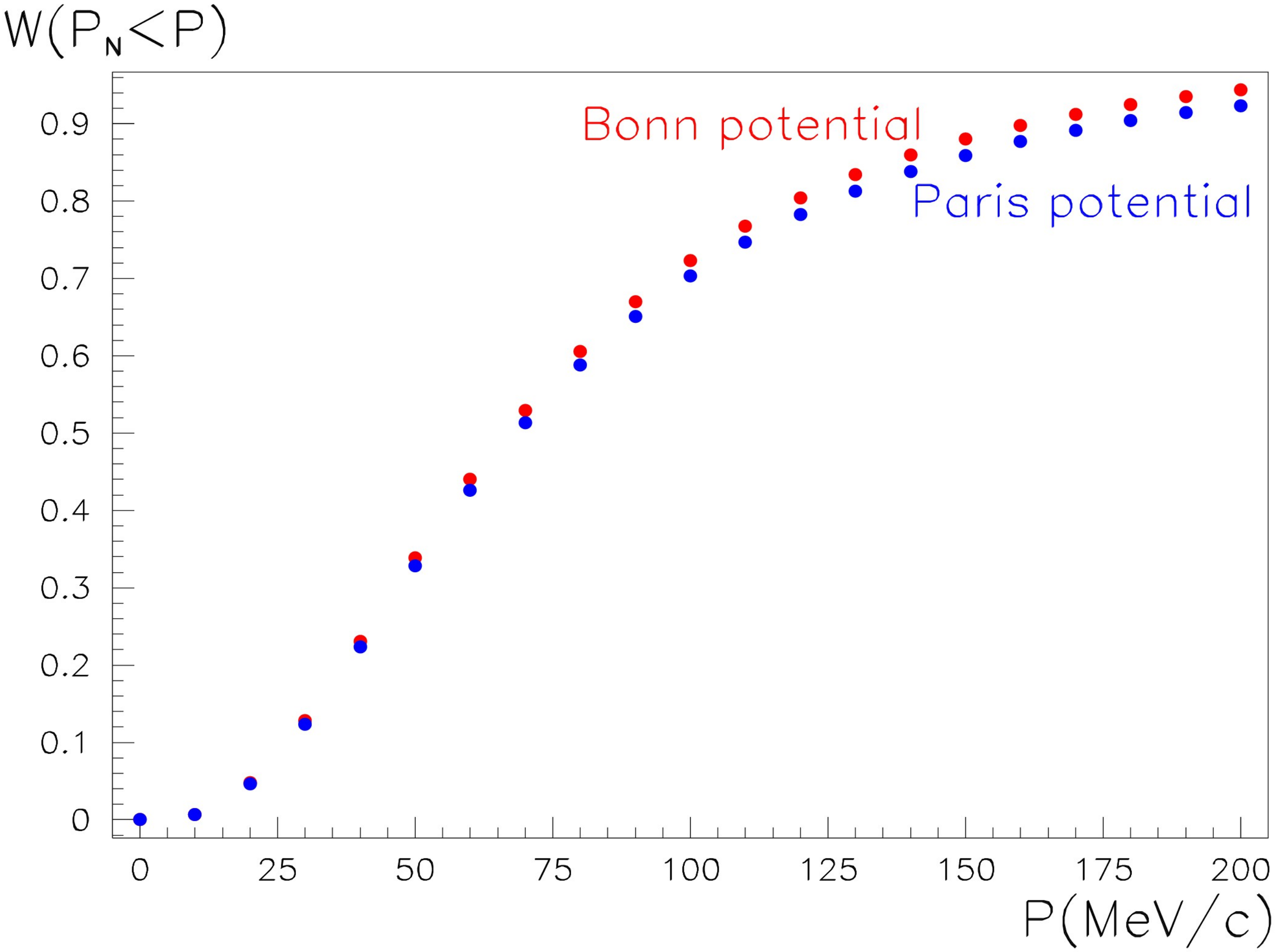




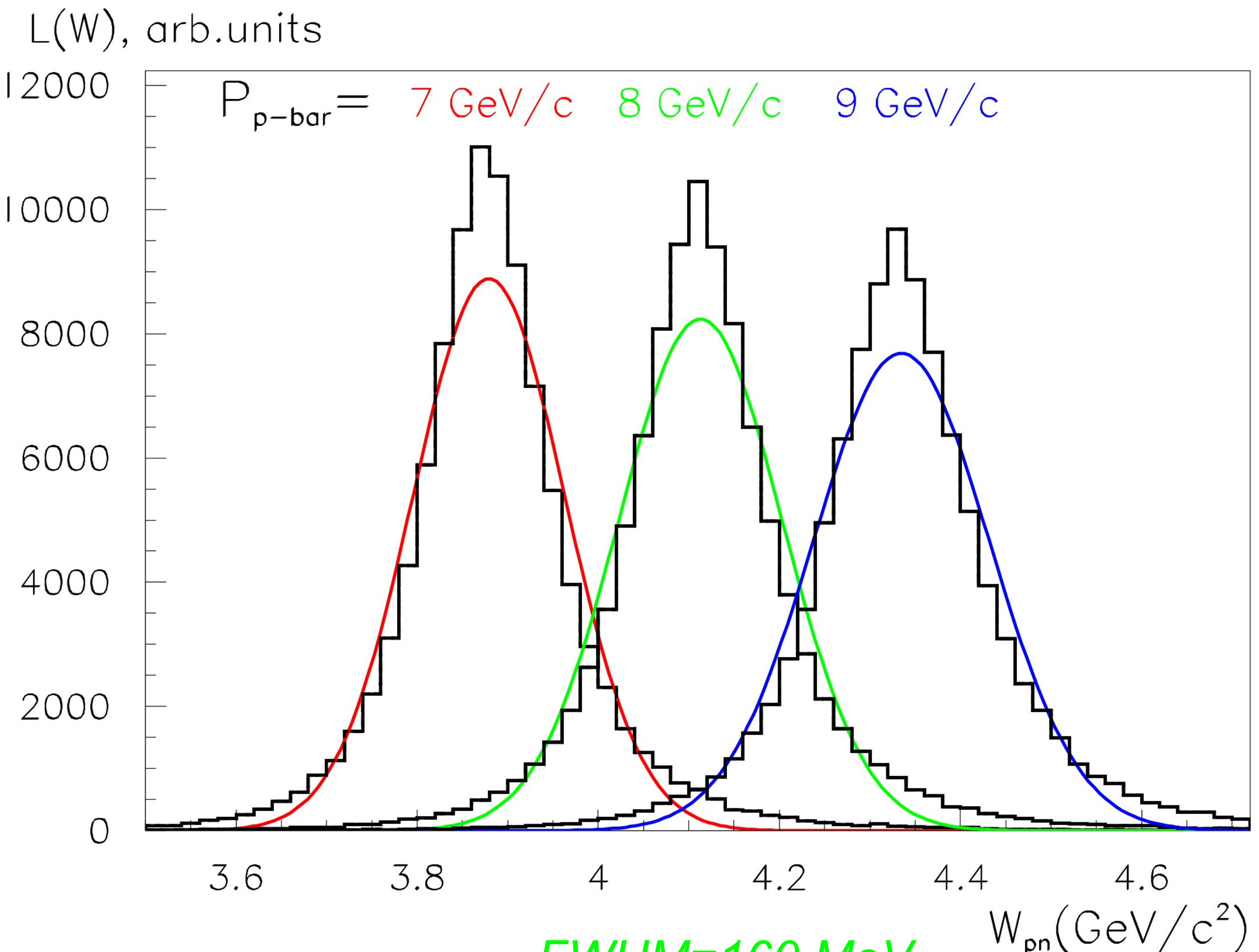


$\bar{p}$ 8 GeV/c
p 70 MeV/c
Z_c^- 8 GeV/c
n 70 MeV/c

Cumulative probability distribution of P_N in deuteron



W distribution of $\bar{p}$-n collisions



FWHM=160 MeV

Simulation of $\bar{p}$-d collisions in PANDAroot (A.Gillitzer)

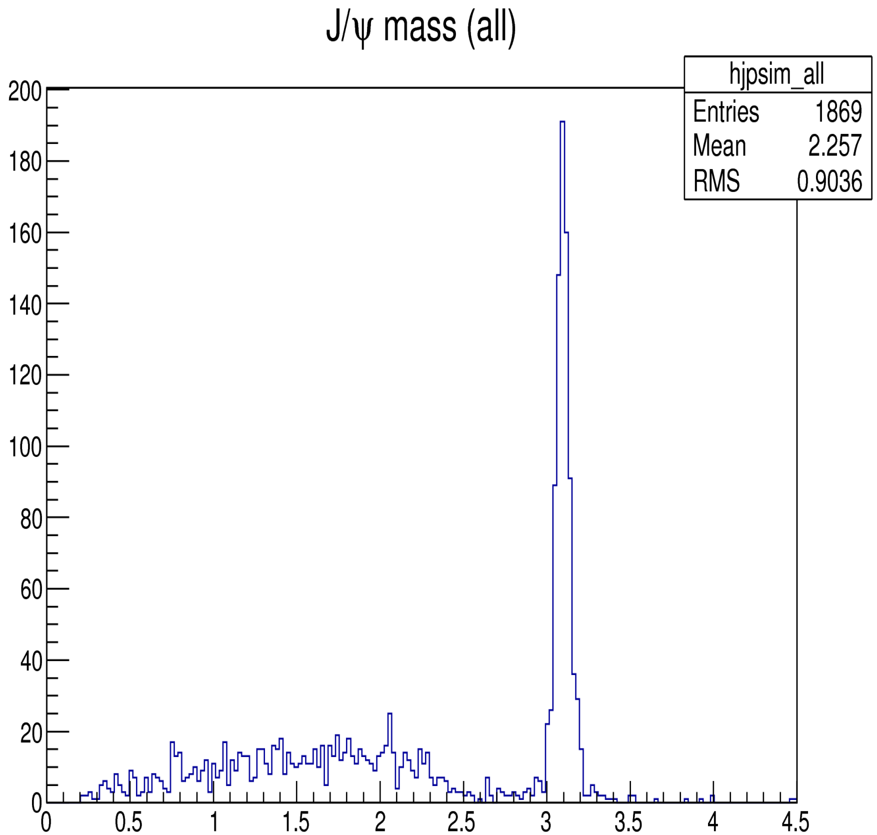
```
Decay pbardSystem
  1.0   p+  pbarnSystem        DeuteronSpectator 1.0  3.25;
Enddecay
#
Decay pbarnSystem
  1.0   J/psi pi-       PHSP;
Enddecay
#
Decay J/psi
  1.0   mu+ mu-         VLL;
Enddecay
#
End
```

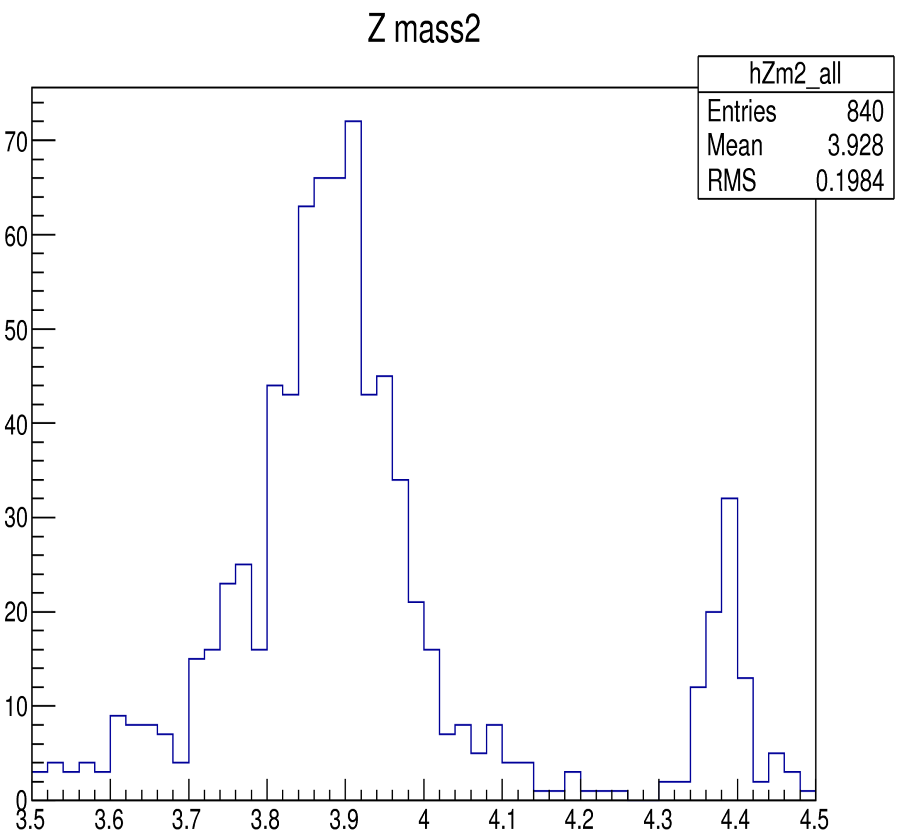
```
Decay pbardSystem
  1.0   p+  pbarnSystem        DeuteronSpectator 1.0  3.25;
Enddecay
#
Decay pbarnSystem
  1.0   pi+ pi- pi-     PHSP;
Enddecay
#
End
```

Simulation of non-resonant p d⟶π- J/ψ⟶μ+μ-

Ppbar = 7.05 GeV/c, 1000 events

Mass distributions of track pairs and track + J/ψ candidates





π J/ψ

J/ψ with track splitting

Simulation of p d $\longrightarrow Z_c(3900) \longrightarrow \pi\ J/\psi \longrightarrow \mu^+\mu^-$

Inputs & assumptions:

$M(Z_c) = 3890\ MeV\quad (P_{pbar} = 7.05\ GeV/c)$

$\Gamma(Z_c) = 35\ MeV$

$Br(Z_c \rightarrow J/\psi + \pi) = 100\%,\quad Br(J/\psi \longrightarrow \mu^+\mu^-) = 5.93\%$

Coupling $(Z_c$ *-PbarN) = Coupling* $(\psi(3770)$*-PbarP)* $\Rightarrow$

$\sigma(Pbar\ N \longrightarrow Z_c) = \sigma(Pbar\ P \longrightarrow \psi(3770)) \times \Gamma(\psi(3770))/\Gamma(Z_c) = 7.5 nb$

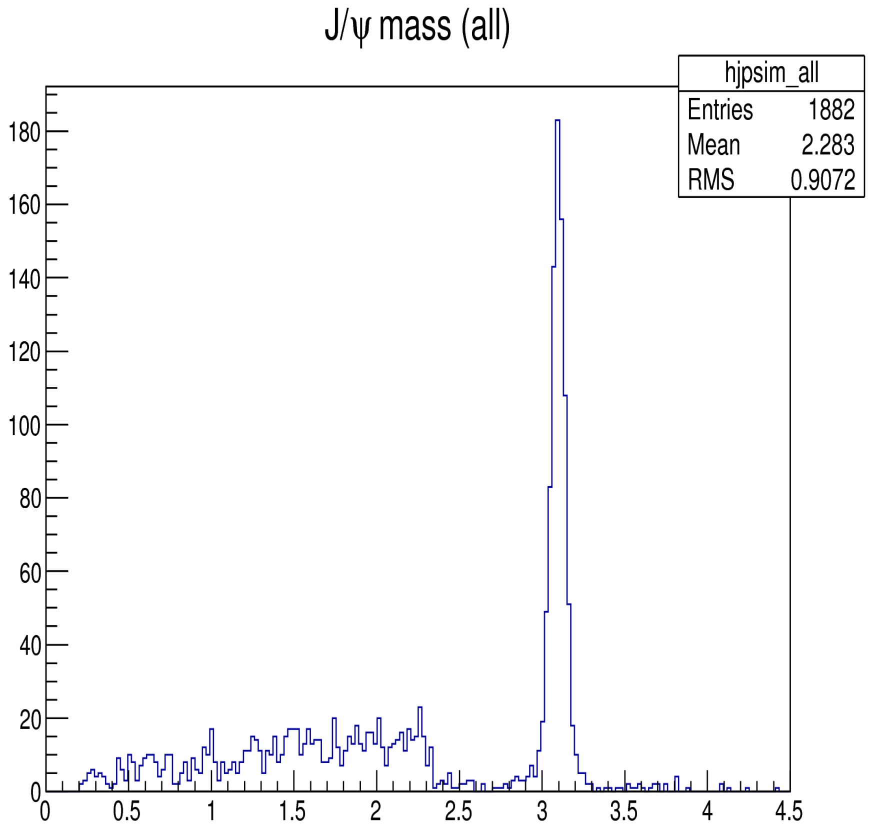
$\langle \sigma(Pbar\ N \longrightarrow Z_c) \rangle = 0.23\ \sigma_{peak}(Pbar\ N \longrightarrow Z_c) = 1.7\ nb$

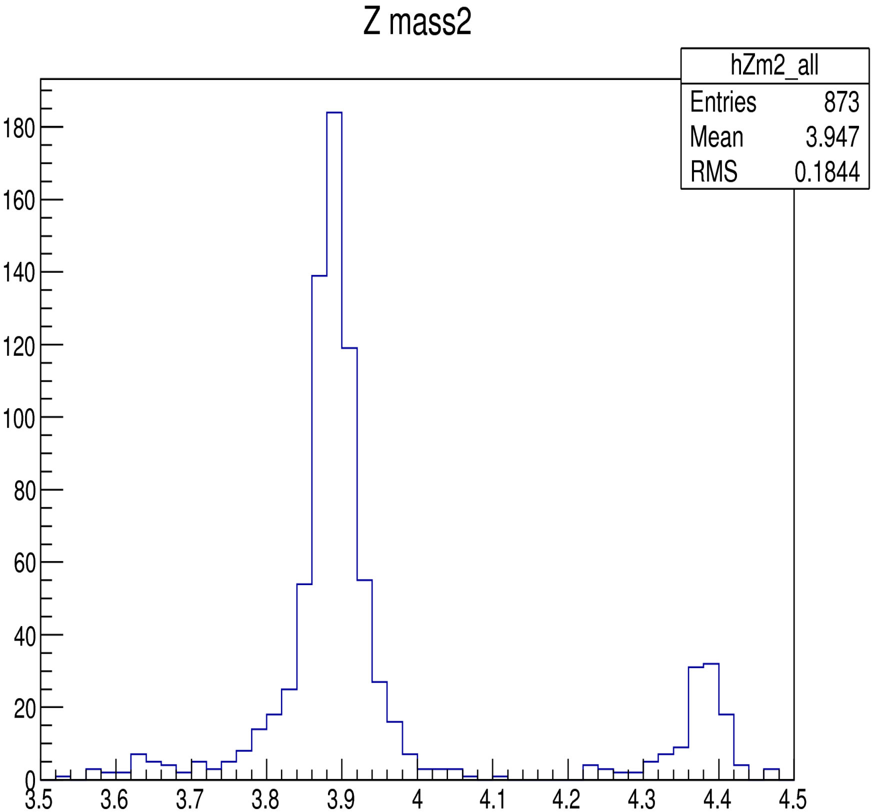
$\sigma(Pbar\ N \longrightarrow Z_c \longrightarrow \pi\ J/\psi \longrightarrow l^+l^-) = 0.44\ \langle 0.1 \rangle\ nb$ => *it takes 10 pb-1 (12 days of data taking) to get 1000* $Z_c \longrightarrow \pi\ J/\psi \longrightarrow \mu^+\mu^-$ *events*

Simulation of p d⟶$Z_c(3900)$⟶π- J/ψ⟶μ+μ-

Ppbar = 7.05 GeV/c,   1000 events

Mass distributions of track pairs   and   track + J/ψ candidates



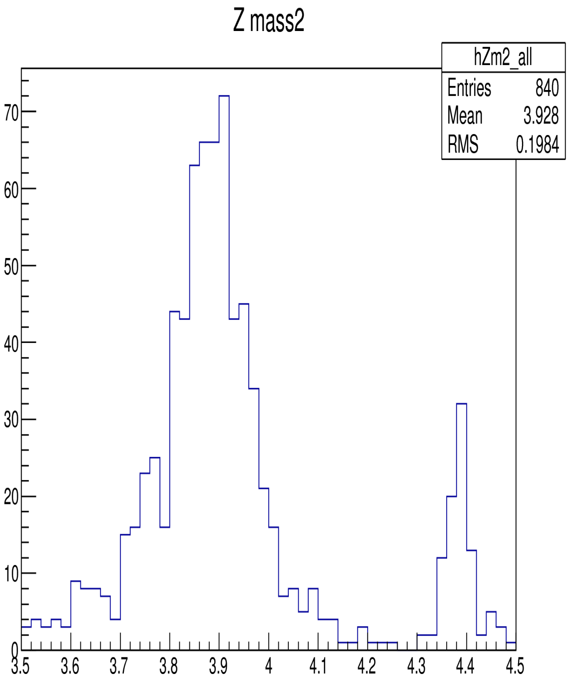


$Z_c(3900)$

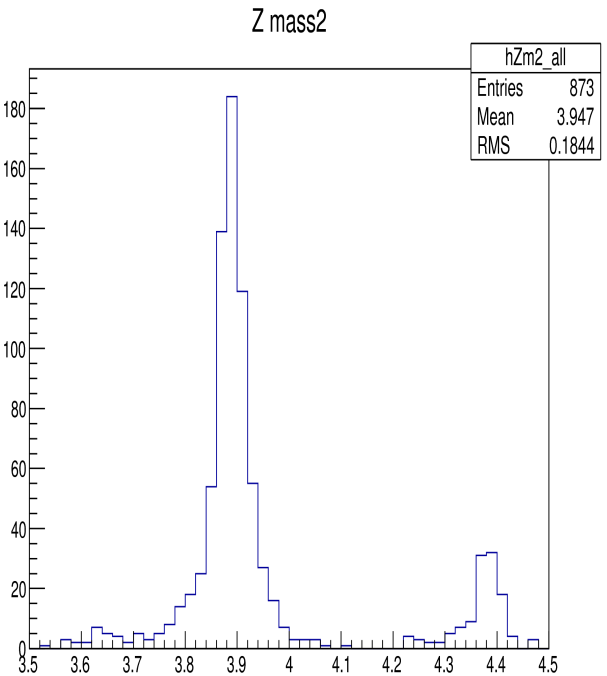
J/ψ with track splitting

Non-resonant v.s. resonant p d⟶π- J/ψ⟶μ+μ-

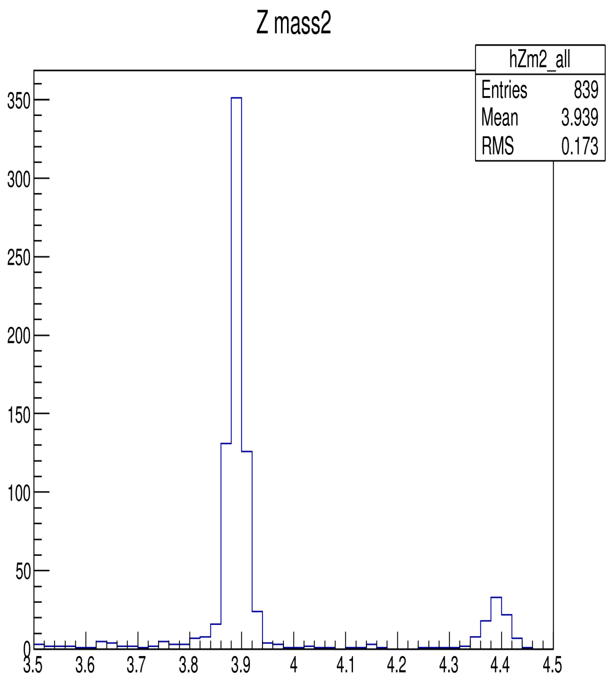
Non-resonant



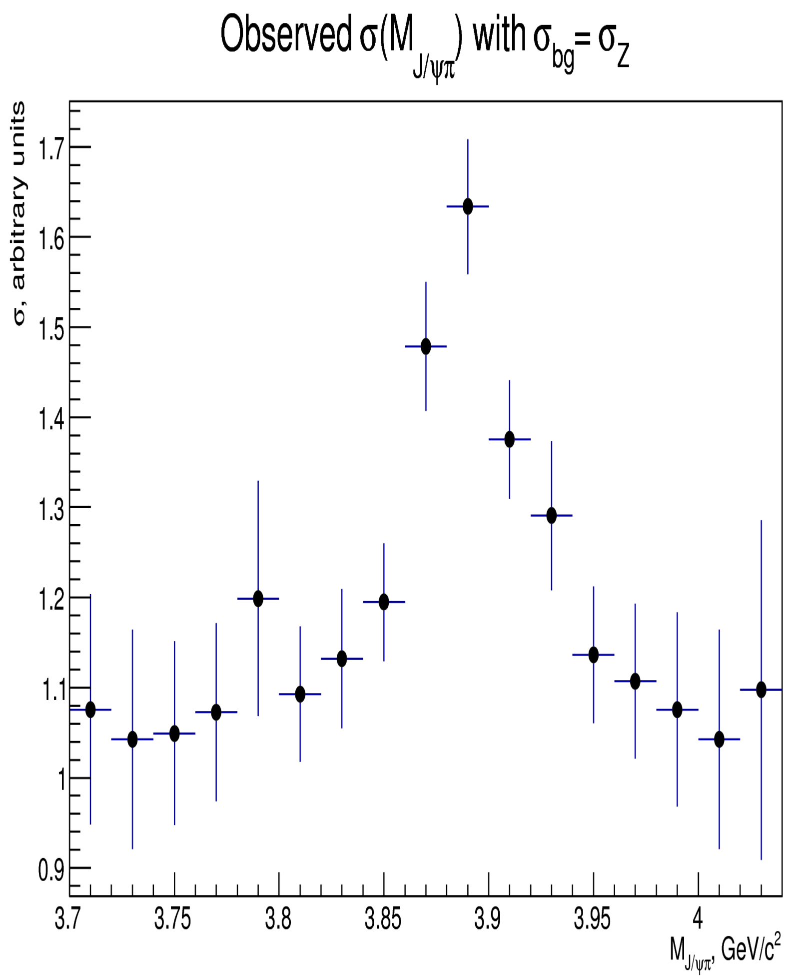
Γ(Zc) = 35 MeV

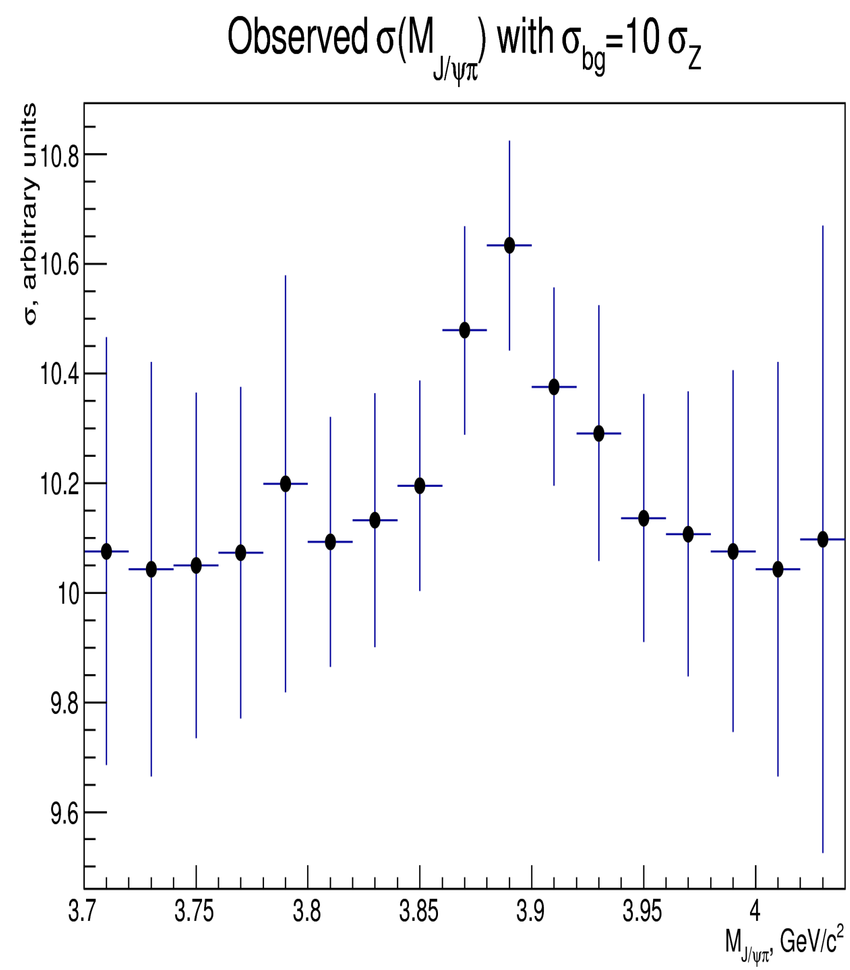


Γ(Zc) = 1 MeV



Simulation of Z-search with σ_{bg} / σ_{Z} = 1 and 10

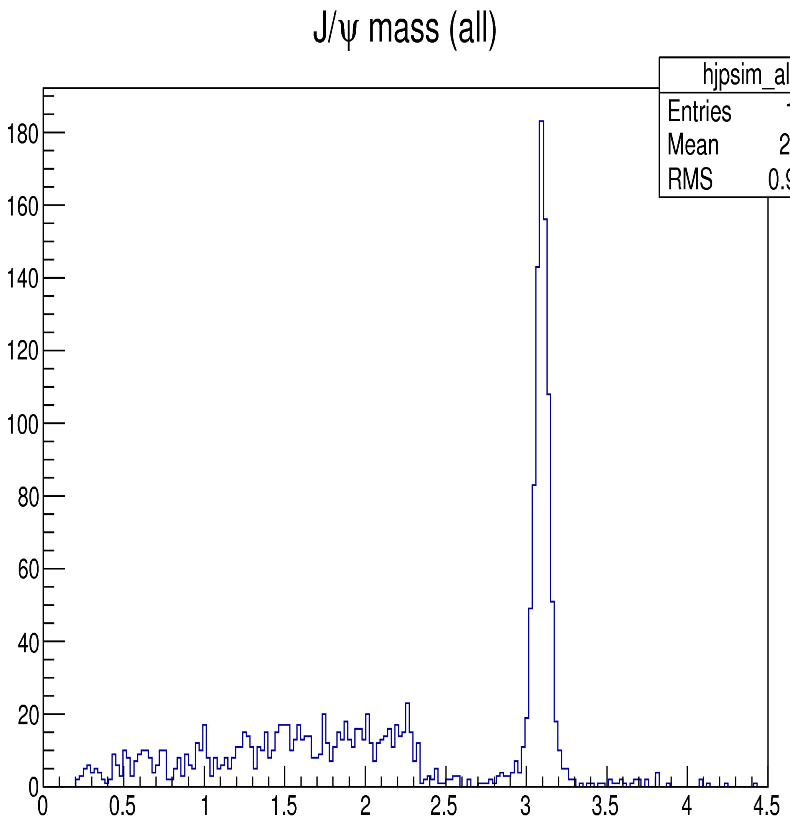


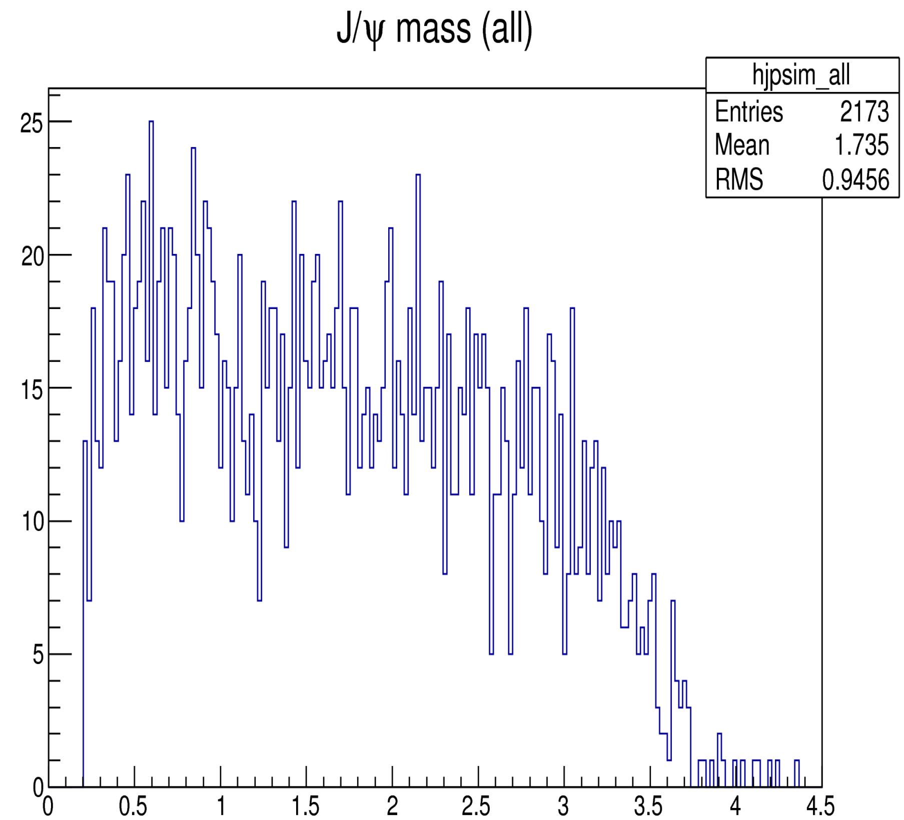


However, σ(Pbar N⟶Zc⟶π- J/ψ⟶l+l-) = 0.44 nb and

σ(Pbar N⟶π-π+π-) = 20 000 nb (FTF model)

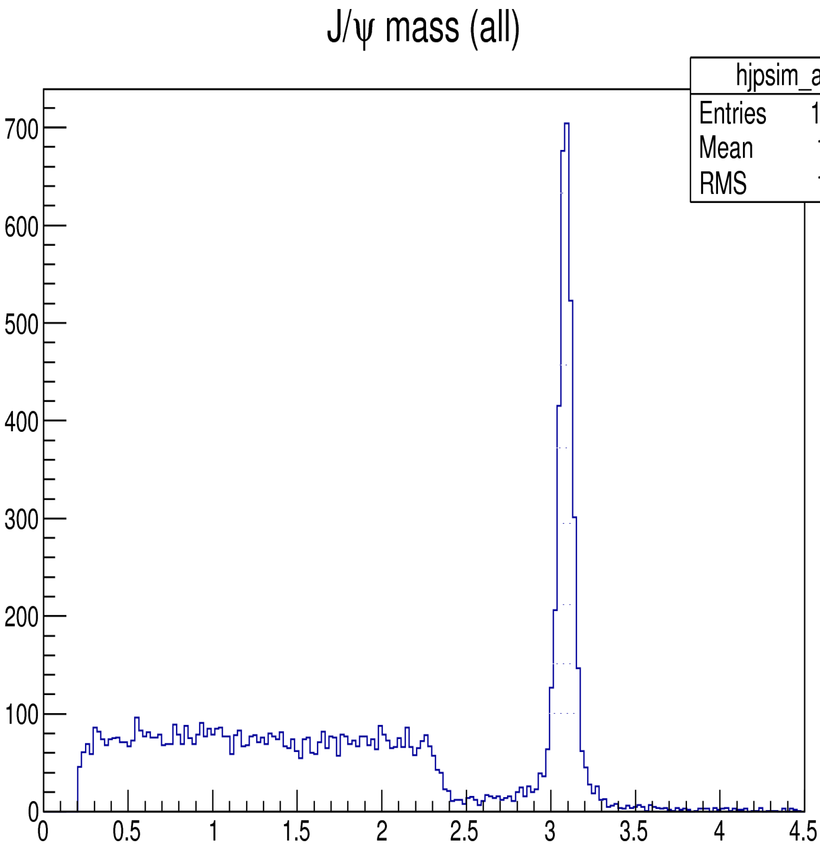
Pbar N⟶π- J/ψ⟶l+l-   v.s.   Pbar N⟶π-π+π-



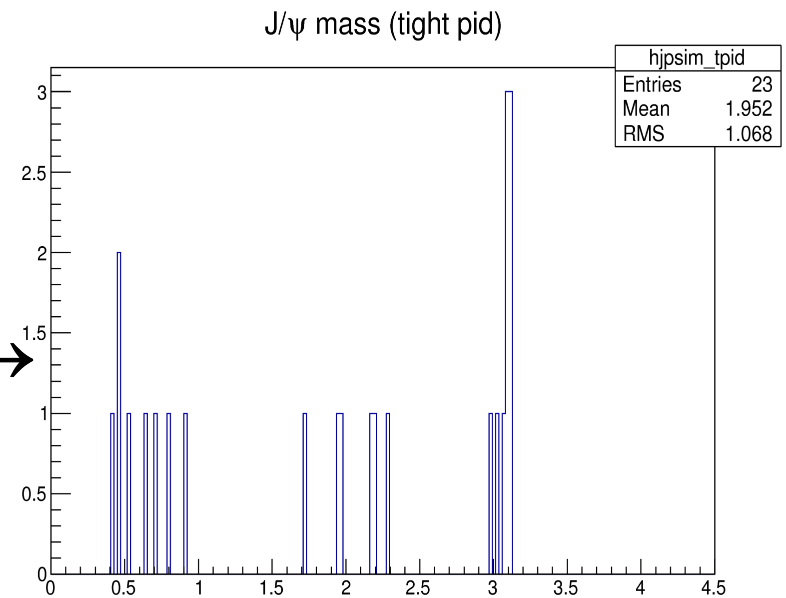


Pbar N⟶π- J/ψ⟶l+l- v.s. Pbar N⟶π-π+π-

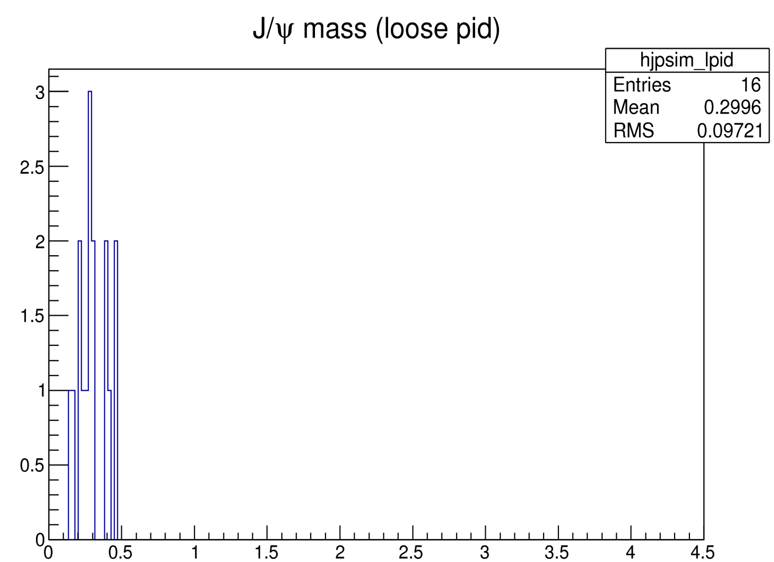
5000 π- J/ψ⟶π+π-



μpid ⟶



epid ⟶



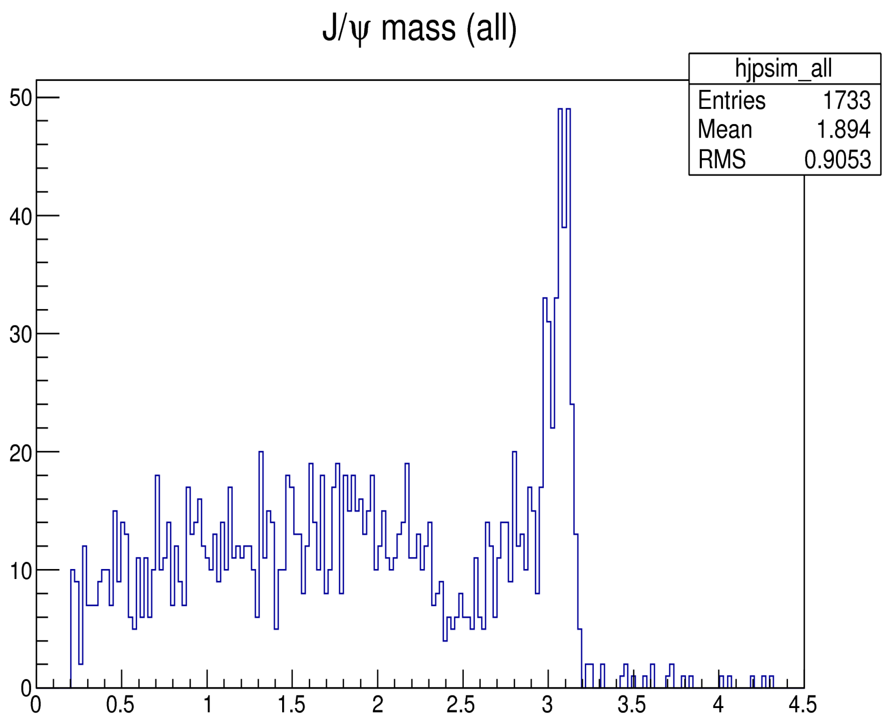
Conclusion

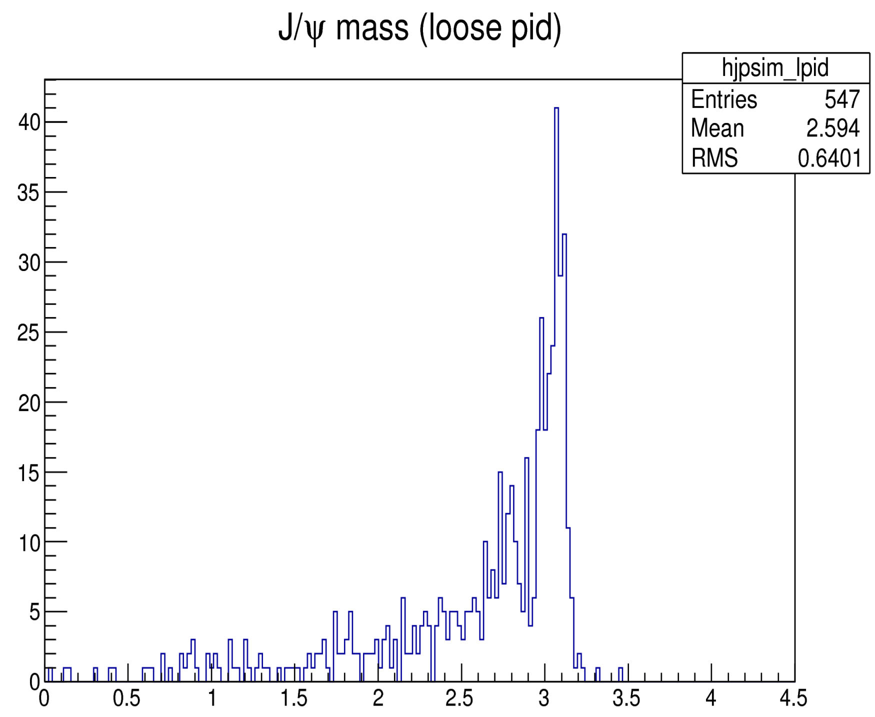
A search for p d⟶Z_c(3900)⟶π^- J/ψ⟶l^+l^- looks promising in $\mu^+\mu^-$ and even more promising in e^+e^- mode.

Simulation of p d⟶Z_c(3900)⟶π- J/ψ⟶e+e-

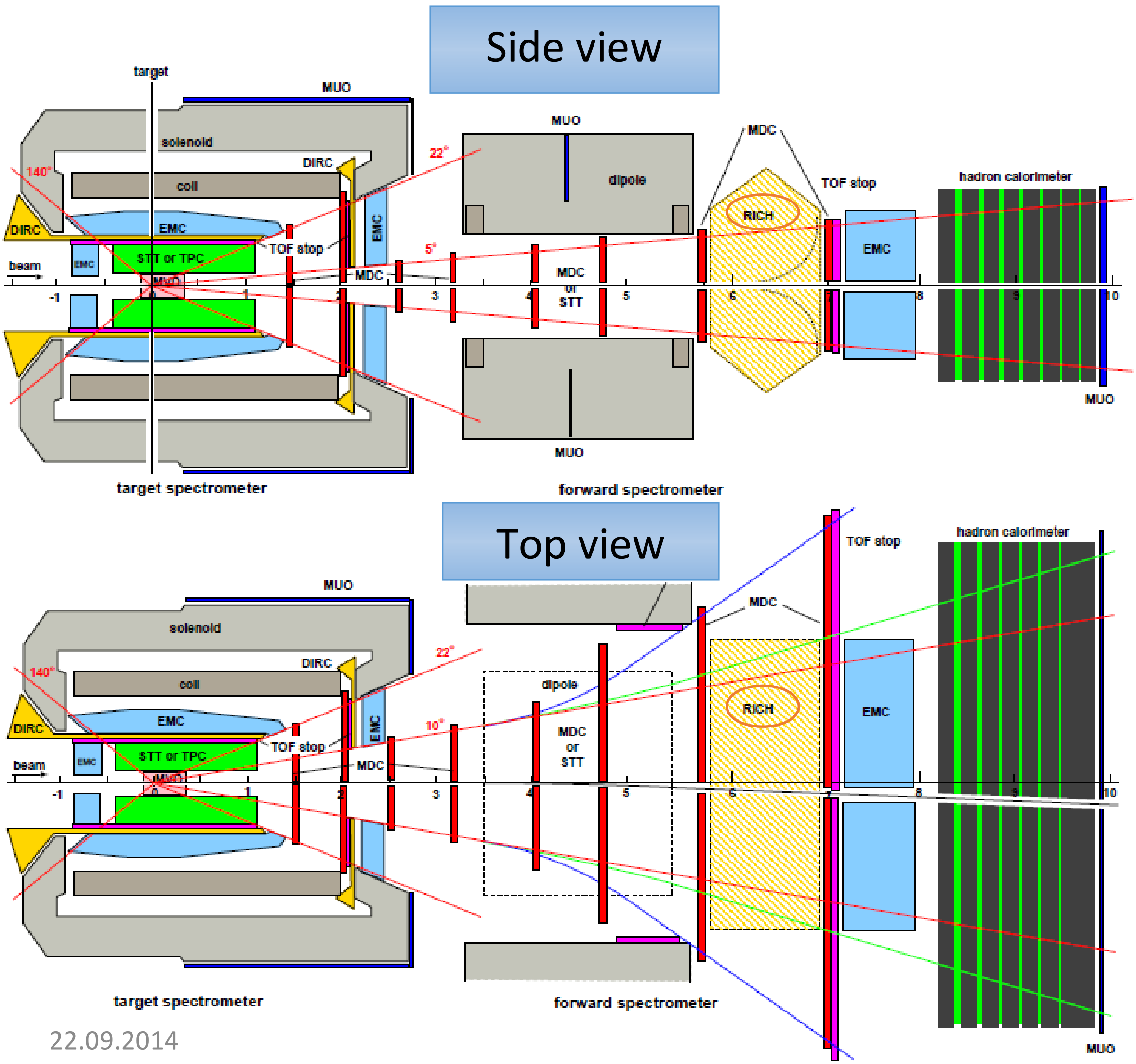
Ppbar = 7.05 GeV/c,   1000 events

Mass distributions of all track pairs and with e pid





Forward RICH for PANDA



Old pictures dated 2005 just to represent position of FRICH

Forward RICH
$|\theta x| < 10°$, $|\theta y| < 5°$
PID π/K for P>3 GeV/c

Observation of Zb(10610) and Zb(10650) by BELLE

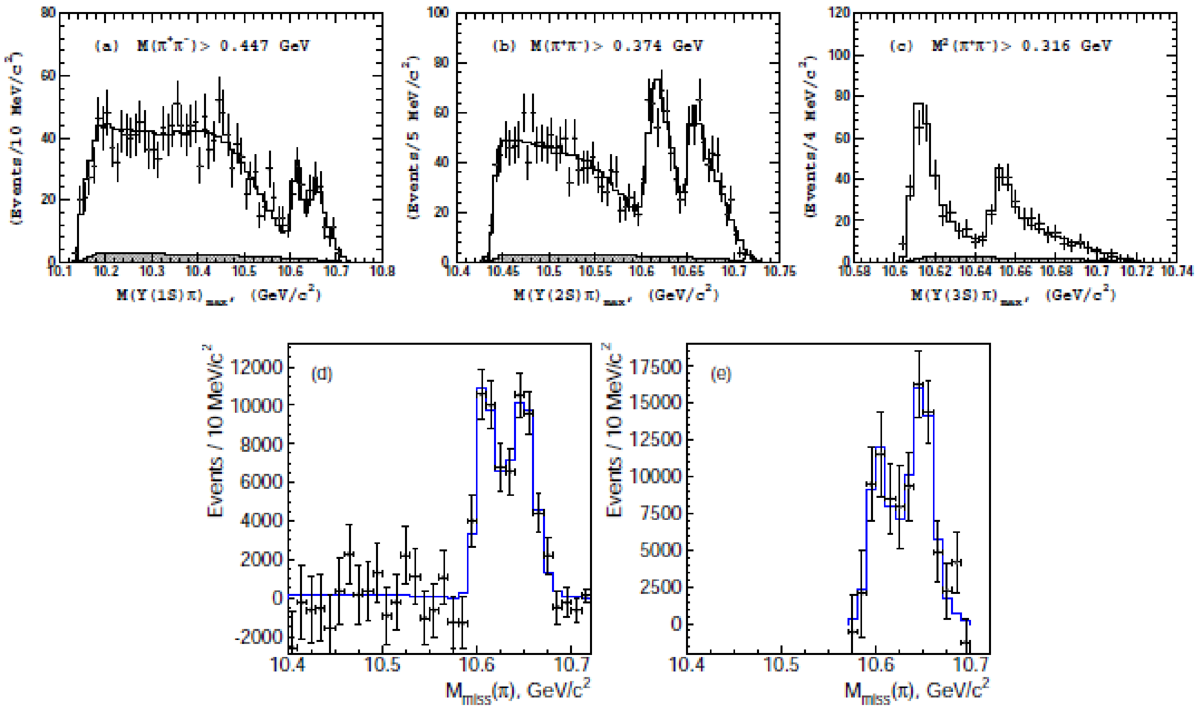


Figure 1: Invariant mass spectra of the (a) $\Upsilon(1S)\pi^{\pm}$, (b) $\Upsilon(2S)\pi^{\pm}$, (c) $\Upsilon(3S)\pi^{\pm}$, (d) $h_b(1P)\pi^{\pm}$ and (e) $h_b(2P)\pi^{\pm}$ combinations.

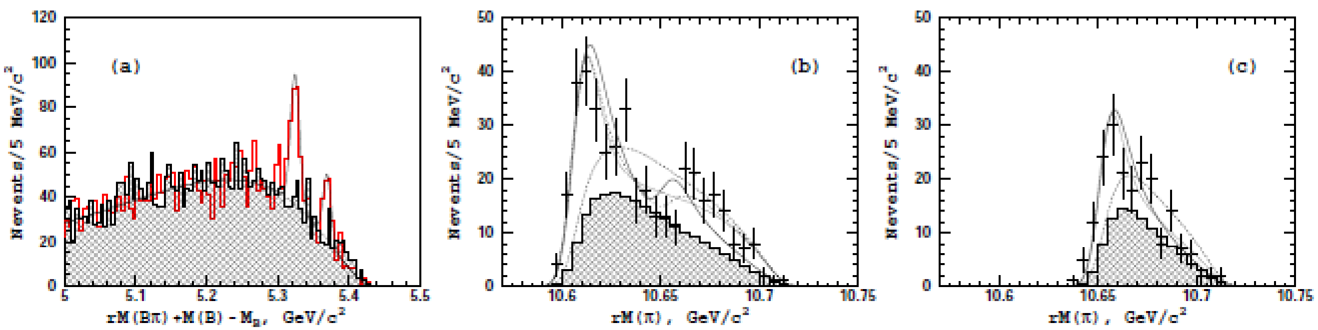


Figure 3: Missing mass of the pairs formed from the reconstructed B candidate and charged pion (a) and missing mass of the charged pions for the $B\pi$ combinations for (b) $\Upsilon(5S) \to B\bar{B}^{*}\pi$ and (c) $\Upsilon(5S) \to B^{*}\bar{B}^{*}\pi$ candidate events.

Parameters of Z_b(10610) and Z_b(10650) states

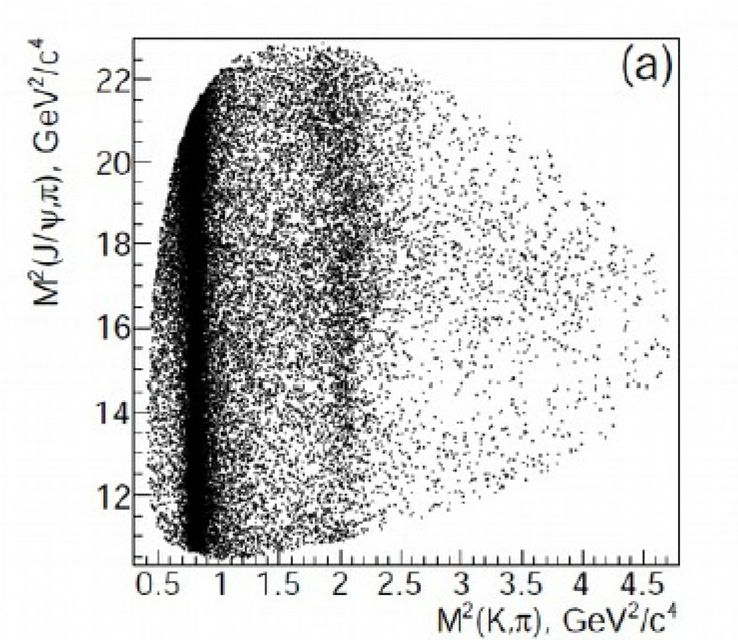
$$M_1 = (10607.4 \pm 2.0)\,\mathrm{MeV}/c^2, \qquad M_2 = (10652.2 \pm 1.5)\,\mathrm{MeV}/c^2,$$

$$\Gamma_1 = (18.4 \pm 2.4)\,\mathrm{MeV}, \qquad \Gamma_2 = (11.5 \pm 2.2)\,\mathrm{MeV}.$$

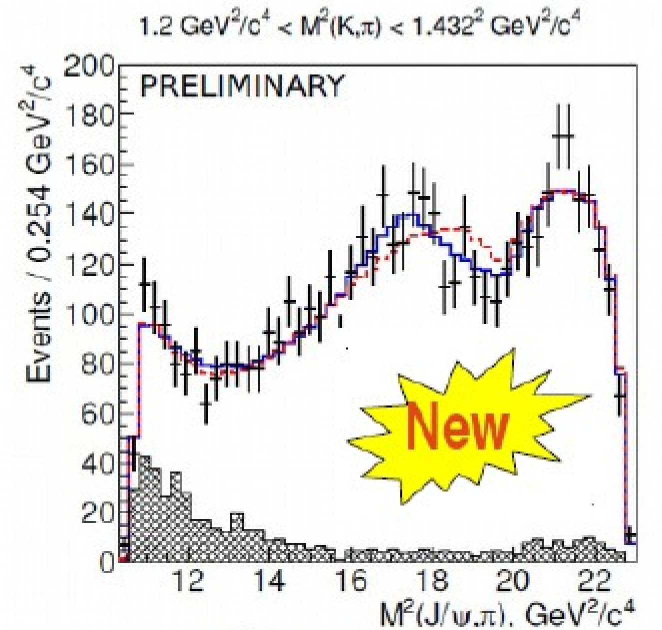
Table 1: Branching fractions ($\mathscr{B}$) of $Z_b(10610)$ and $Z_b(10650)$ assuming that the observed so far channels saturate their decays.

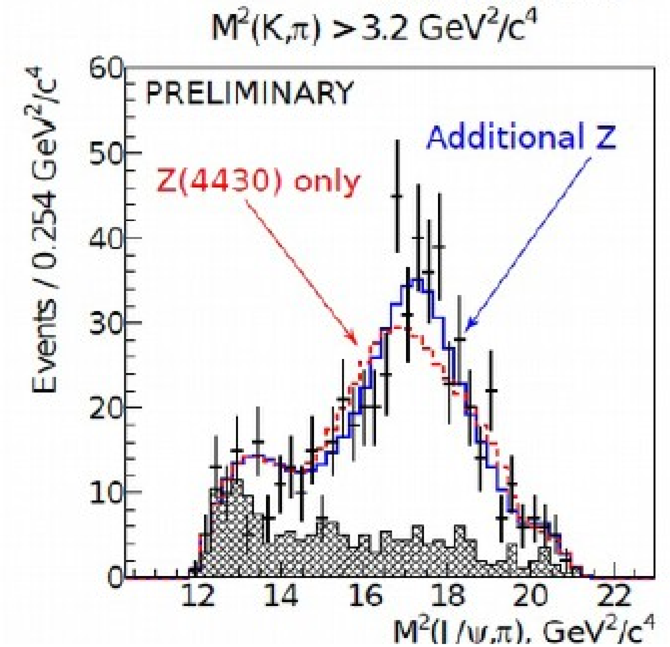
Channel	$\mathscr{B}$ of $Z_b(10610)$, %	$\mathscr{B}$ of $Z_b(10650)$, %
$\Upsilon(1S)\pi^+$	0.32 ± 0.09	0.24 ± 0.07
$\Upsilon(2S)\pi^+$	4.38 ± 1.21	2.40 ± 0.63
$\Upsilon(3S)\pi^+$	2.15 ± 0.56	1.64 ± 0.40
$h_b(1P)\pi^+$	2.81 ± 1.10	7.43 ± 2.70
$h_b(2P)\pi^+$	2.15 ± 0.56	14.8 ± 6.22
$B^+\bar{B}^{*0} + \bar{B}^0 B^{*+}$	86.0 ± 3.6	–
$B^{*+}\bar{B}^{*0}$	–	73.4 ± 7.0

$B^0 \to J/\psi\, K^- \pi^+$



- 4D amplitude analysis
- 10 K* resonances, $Z^+(4430)$, Z^+(new)
- 6.6σ significance
- $M = 4196\ ^{+31}_{-29}\ ^{+17}_{-13}$ MeV/c^2
- $G = 370 \pm 70\ ^{+70}_{-132}$ MeV
- $J^P = 1^+$



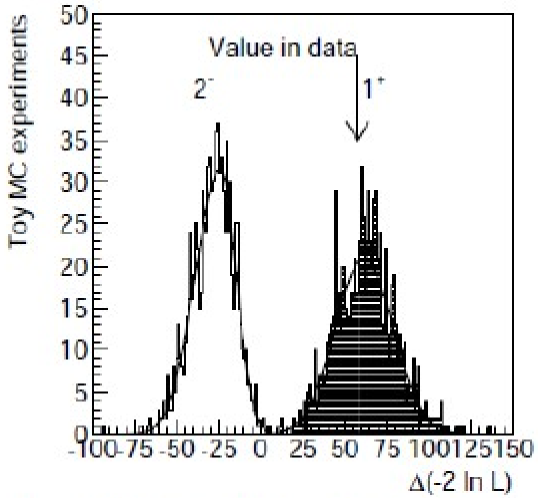


$Z^+(4200)$

Preliminary results

New

$J^P=1^+$, other J^P are excluded



Exclusion levels of other spin-parity hypothesis

Model	0^-	1^-	2^-	2^+
Without $K^*(1680)$	8.5σ	8.5σ	8.0σ	9.0σ
Without $K_0^*(1950)$	8.4σ	8.8σ	7.3σ	8.9σ
LASS	6.1σ	7.4σ	4.4σ	7.0σ
Free masses and widths	7.6σ	7.9σ	5.9σ	7.8σ
Free r	7.4σ	8.7σ	7.5σ	9.2σ
Nonresonant ampl. (S)	7.6σ	8.1σ	7.2σ	8.5σ
Nonresonant ampl. (S,P)	7.4σ	8.1σ	7.2σ	8.4σ
Nonresonant ampl. (S,P,D)	7.2σ	8.1σ	7.1σ	8.4σ

TABLE III. The fit fractions and significances of all resonances in the default model ($J^P = 1^+$).

Resonance	Fit fraction	Significance (local)
$K_0^*(800)$	$(7.1^{+0.7}_{-0.5})\%$	22.5σ
$K^*(892)$	$(69.0^{+0.6}_{-0.5})\%$	166.4σ
$K^*(1410)$	$(0.3^{+0.2}_{-0.1})\%$	4.1σ
$K_0^*(1430)$	$(5.9^{+0.6}_{-0.4})\%$	22.0σ
$K_2^*(1430)$	$(6.3^{+0.3}_{-0.4})\%$	23.5σ
$K^*(1680)$	$(0.3^{+0.2}_{-0.1})\%$	2.7σ
$K_3^*(1780)$	$(0.2^{+0.1}_{-0.1})\%$	3.8σ
$K_0^*(1950)$	$(0.1^{+0.1}_{-0.1})\%$	1.2σ
$K_2^*(1980)$	$(0.4^{+0.1}_{-0.1})\%$	5.3σ
$K_4^*(2045)$	$(0.2^{+0.1}_{-0.1})\%$	3.8σ
$Z_c(4430)^+$	$(0.5^{+0.4}_{-0.1})\%$	5.1σ
$Z_c(4200)^+$	$(1.9^{+0.7}_{-0.5})\%$	8.2σ