Последние результаты по поиску и изучению экзотических состояний в эксперименте DØ

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Overview

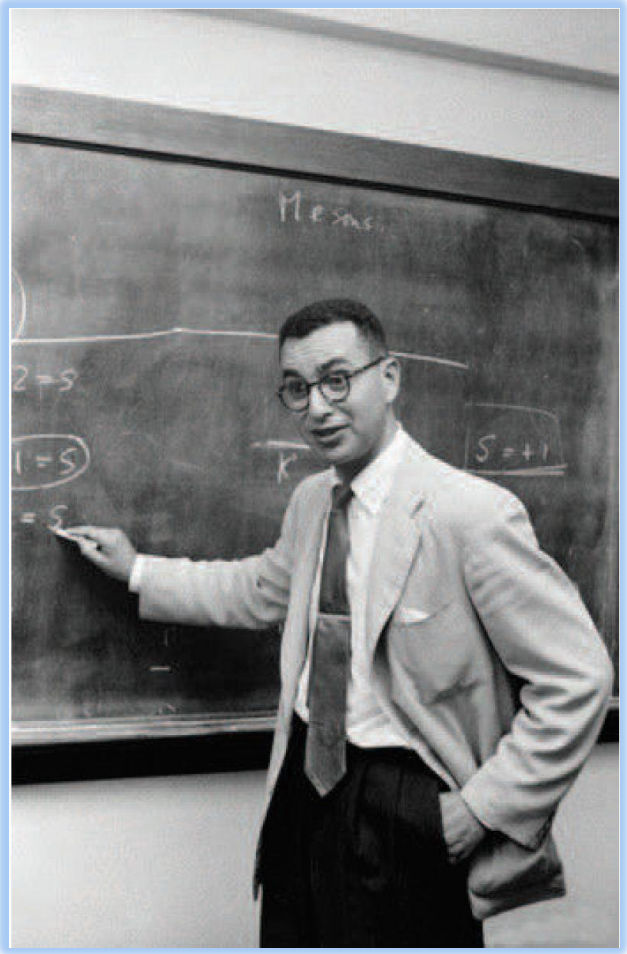
- Introduction to non-$q\bar{q}$ states.
- Studies of $Z_c(3900)$ at DØ experiment.
- Inclusive production of the P_c resonances at DØ.
- Summary.

Introduction

Multi-quark hadrons are allowed by the quark model. Gell-Mann explicitly mentioned them in the original paper introducing quarks.

"… Baryons can now be constructed from quarks by using the combinations (qqq), $(qqqq\bar{q})$, etc, while mesons are made out of $(q\bar{q})$, $(qq\bar{q}\bar{q})$, etc …"

M. Gell-Mann, "A schematic model of baryons and mesons", PL 8 (1964) 214

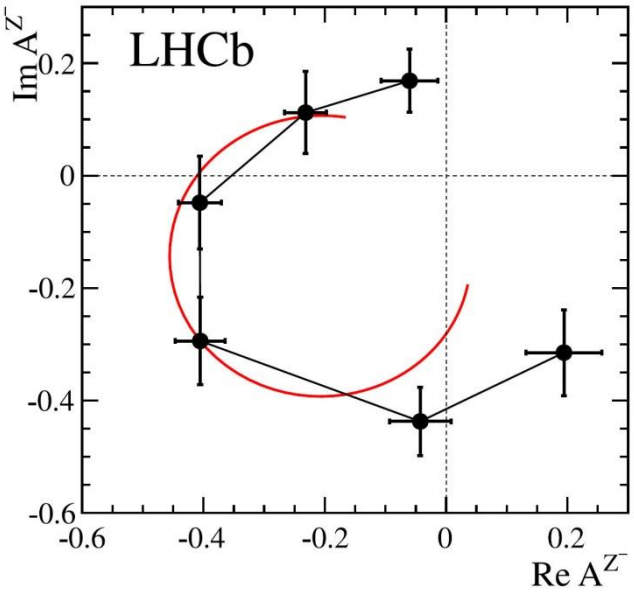


Introduction

The 2003 discovery of $X(3872) \to J/\psi\,\pi^+\pi^-$ by Belle marked the new era. The flavor contents are not obviously exotic, but a conventional $c\bar{c}$ interpretation of a state with $J^{PC} = 1^{++}$ (measured by LHCb) at this mass is disfavored.

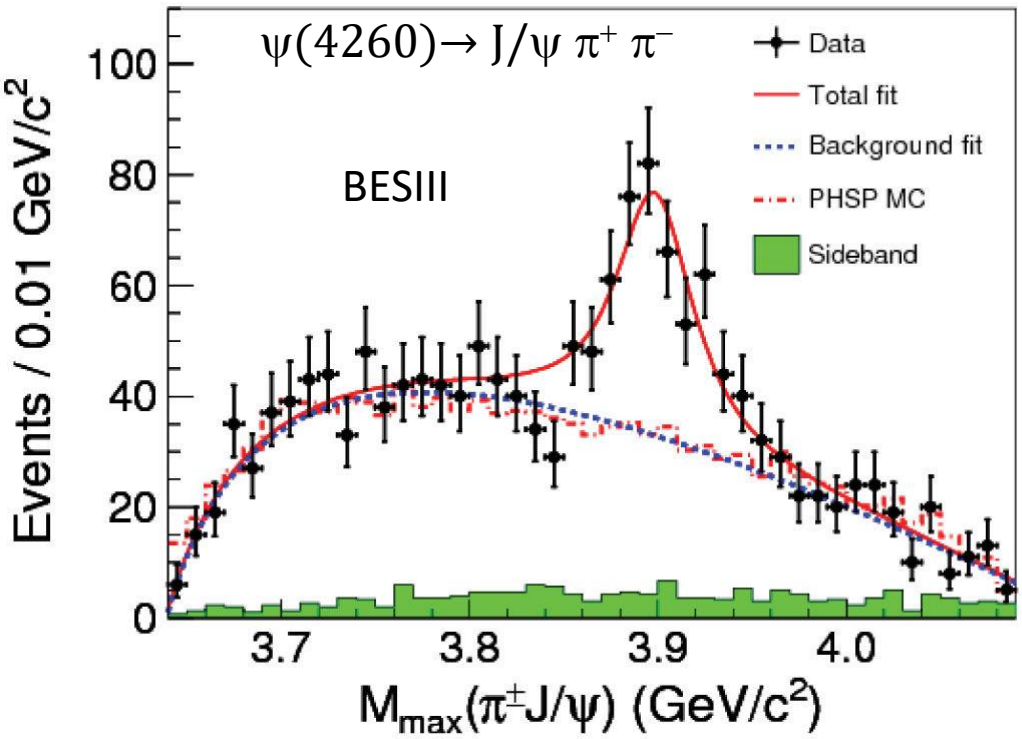
Since then more than 20 charmonium-like and bottomonium-like states that do not fit the $q\bar{q}$ or qqq picture have been discovered in B-factories, at the Tevatron and at the LHC.

Most importantly $Z_c(4430) \to \psi(2S)\,\pi^\pm$ discovered by Belle – was confirmed by LHCb to be a proper Breit-Wigner resonance by the phase motion. Evidence for quarkonium-like states made of four or five valence quarks is established.



$Z_c(3900)$

Initially was found by BESIII and Belle in $\pi^{\pm}J/\psi$ mass spectrum from $\psi(4260)\rightarrow J/\psi\ \pi^+\ \pi^-$ decays.



Ablikim, M., *et al.* (BESIII Collaboration), Phys. Rev. Lett. 110, 252001 (2013).

Liu, Z. Q., *et al.* (Belle Collaboration), Phys. Rev. Lett. 110, 252002 (2013).

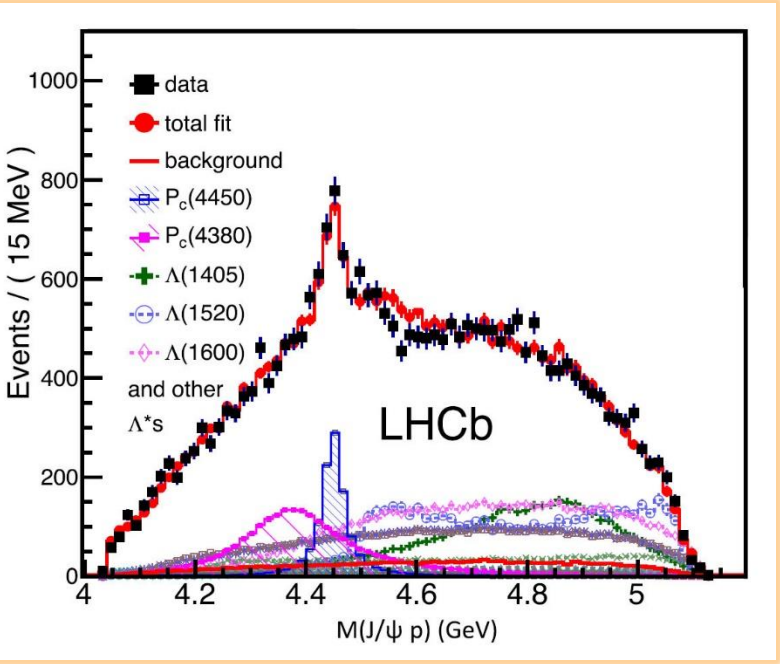
$Z_c(3885)$ seen by BESIII in D^0D^{*-} mass spectrum most probably is the same state as seen in $\pi^{\pm}J/\psi$.

Mass and width (BESIII, $\pi^{\pm}J/\psi$ mode)

$$M = 3899.0 \pm 6.1\ \text{MeV},$$

$$\Gamma = 46 \pm 22\ \text{MeV}$$

Pentaquarks



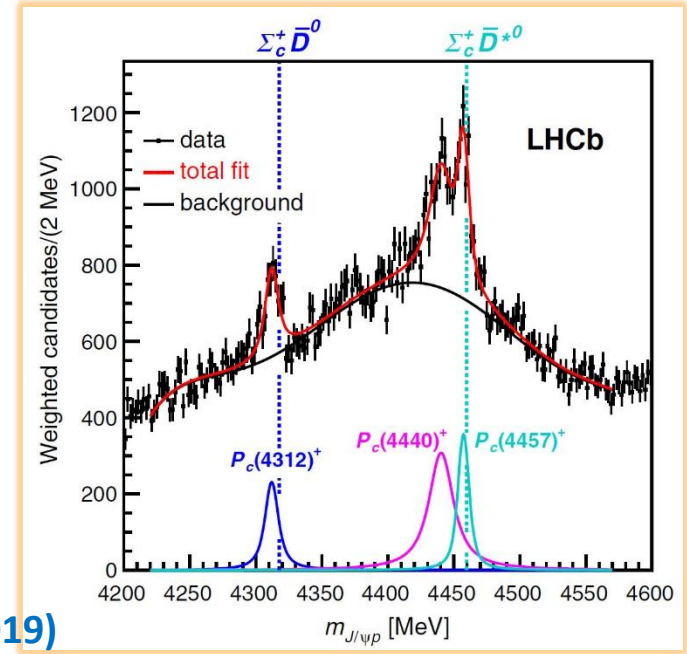
In 2015, the LHCb collaboration reported two structures $P_c(4450)$ and $P_c(4380)$ in the decay $\Lambda_b \to P_c^+ K^-$, $P_c^+ \to J/\psi\, p$. The minimal quark content is $uud\bar{c}c$, manifestly an exotic pentaquark.

Aaij, R., *et al.* (LHCb Collaboration), Phys. Rev. Lett. 115, 072001 (2015).

Recently, the new results from LHCb supersede the result above: new states $P_c(4312)$, $P_c(4440)$, $P_c(4457)$ were reported with mass and width values:

$$M = 4311.9 \pm 0.7^{+6.8}_{-0.6},\ \Gamma = 9.8 \pm 2.7^{+3.7}_{-4.5}\ \text{MeV};$$
$$M = 4440.3 \pm 1.3^{+4.1}_{-4.7},\ \Gamma = 20.6 \pm 4.9^{+8.7}_{-10.1}\ \text{MeV};$$
$$M = 4457.3 \pm 0.6^{+4.1}_{-1.7},\ \Gamma = 6.4 \pm 2.0^{+5.7}_{-1.9}\ \text{MeV}.$$

Aaij, R., *et al.* (LHCb Collaboration), Phys. Rev. Lett. 122, 222001 (2019)



DØ Detector in Tevatron Run II

Tevatron

$p\bar{p}$ collider, $\sqrt{S} = 1.96$ TeV.

In operation from 2001 to 2011 (Run II).

Total integrated luminosity delivered ~12 fb^{-1} (~10 fb^{-1} for physics analysis per experiment).

DØ detector

Scintillator counters and drift tubes.
Thick calorimeter and iron toroids.

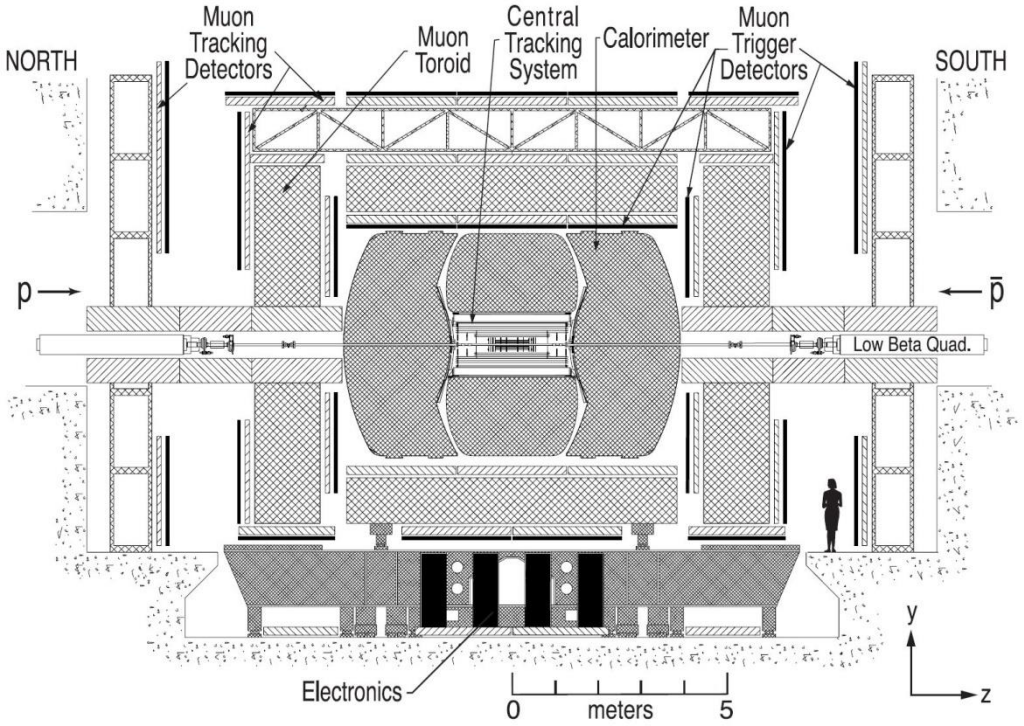
Excellent muon triggering and ID.

Silicone Microstrip Tracker.

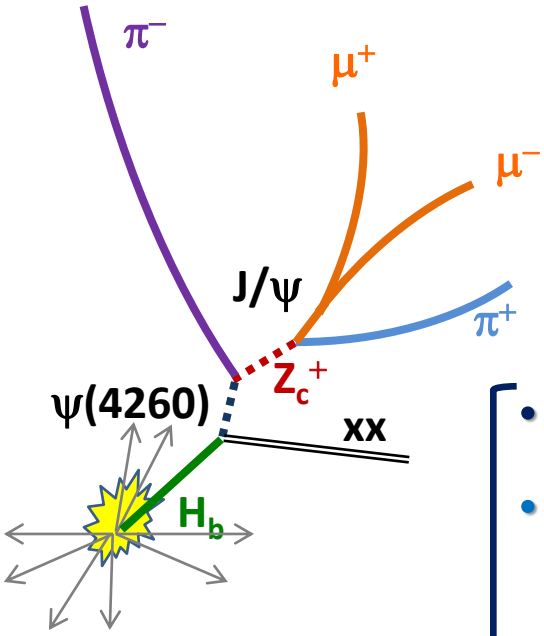
Excellent vertex reconstruction.

Central Fiber Tracker.

Good mass resolution.



Excellent for B-physics with muons!



Evidence for $Z_c(3900)$ in semi-inclusive decays of b-flavored hadrons

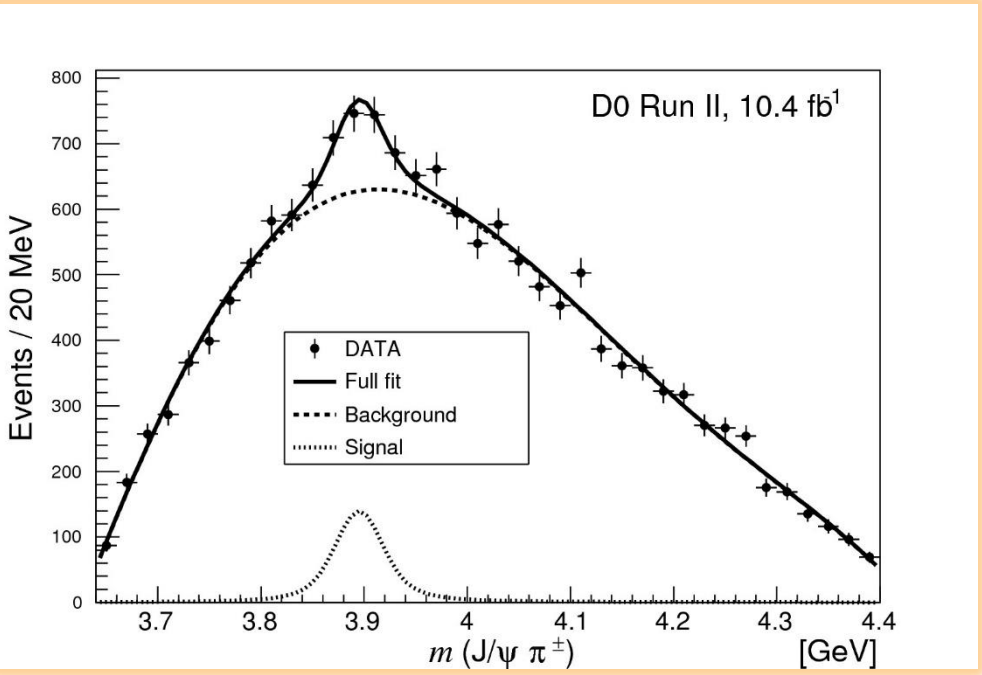
$$H_b \to \psi(4260) + \text{anything}, \psi(4260) \to Z_c^{\pm}(3900)\,\pi^{\mp}, Z_c^{\pm}(3900) \to J/\psi\,\pi^{\pm}$$

Cuts

- $10.4\ fb^{-1}$ of $p\bar{p}$ data at 1.96 TeV.
- J/ψ+2tracks, $p_T^1 > 1\ GeV$, $p_T^2 > 0.8\ GeV$, opposite charge.
- Veto $K^* \to K\pi(\pi K)$, $\phi \to KK$, γ conversion.
- Displaced vertex:
  $L_{xy}(J/\psi\,\pi^{\pm})/\sigma(L_{xy})>5$, $IP_{xy}(\pi^{\pm})/\sigma(IP)>2$
- Vertex fits: $J/\psi\,\pi^{\pm}$ $\chi^2<10$, adding extra pion $\delta\chi^2<6$.
- Select events with displaced $J/\psi\,\pi^+\pi^-$ vertices, L_{xy} distribution has a slope consistent with B hadron decays lifetime.
- $4.1 < M(J/\psi\,\pi^+\pi^-) < 5.0\ GeV$.

Published in
Phys. Rev. D98, 052010 (2018)

Studies of $Z_c(3900)$ at DØ experiment



Fit to data

Background parametrization:
Chebyshev polynomials.
Signal parametrization:
S-wave Breit-Wigner smeared with resolution (17 ± 2 MeV).
Γ fixed to PDG value (28.2 MeV).
$4.2 < M(J/\psi\,\pi^+\pi^-) < 4.7$ GeV.

Systematic uncertainties:

Mass calibration, mass resolution, background shape (different degrees of Chebyshev polynomials), bin size, signal model (different Breit-Wigner forms), natural width variations.

Results

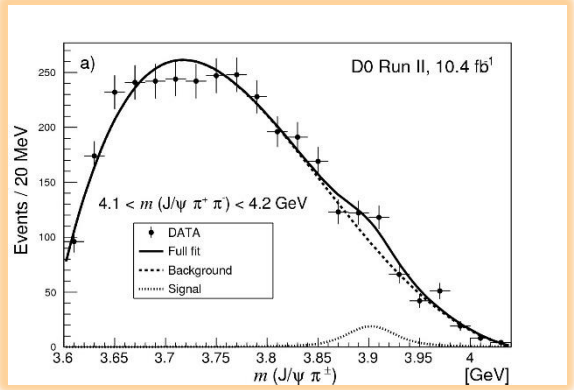
$$M_x = 3895.0 \pm 5.2(stat)^{+4.0}_{-2.7}(syst)\ \text{MeV},$$

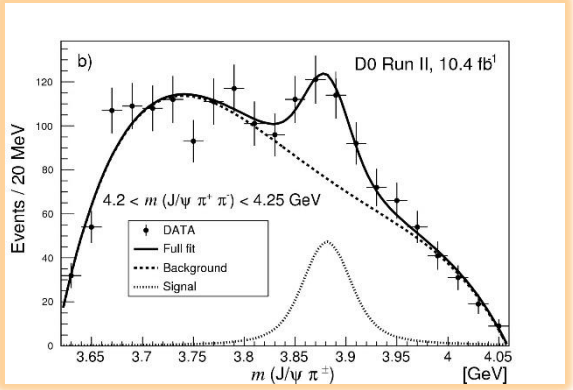
$$N_{ev} = 505 \pm 92(stat) \pm 64(syst).$$

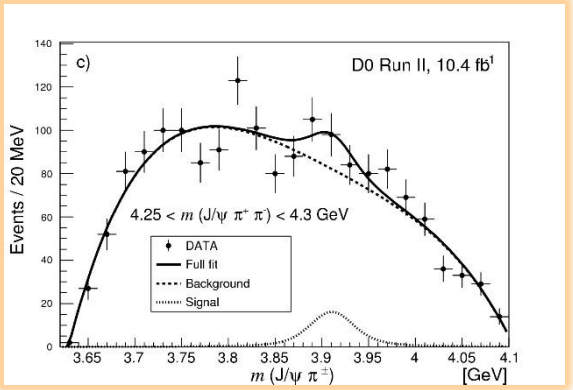
Local significance ($S = \sqrt{-2 \cdot \ln \frac{\mathcal{L}_0}{\mathcal{L}_{max}}}$): 5.6σ

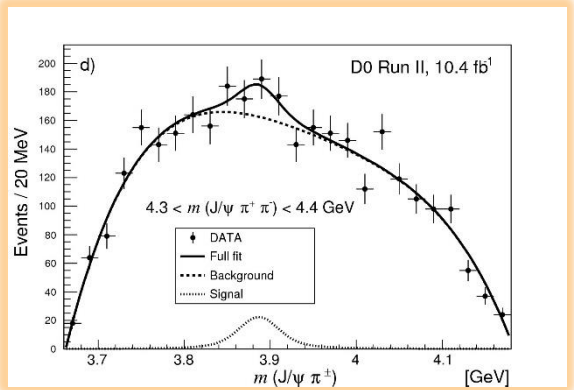
Significance with systematics: 4.6σ

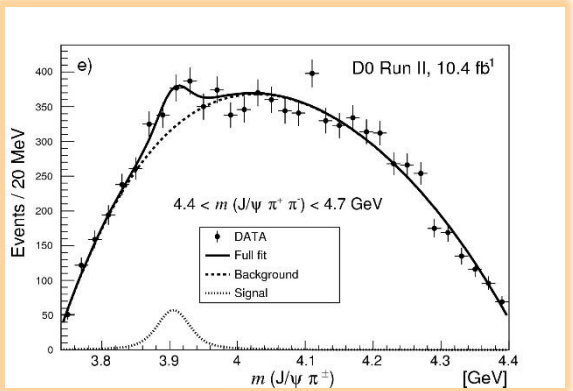
Studies of $Z_c(3900)$ at DØ experiment

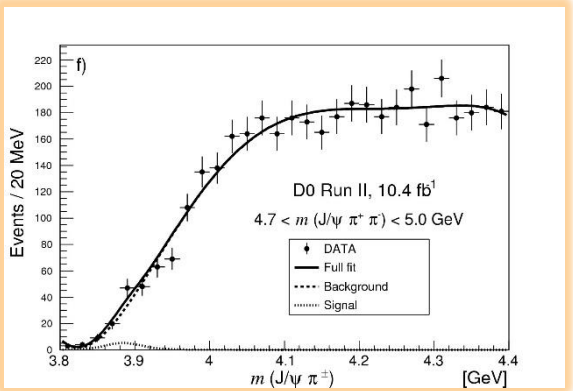


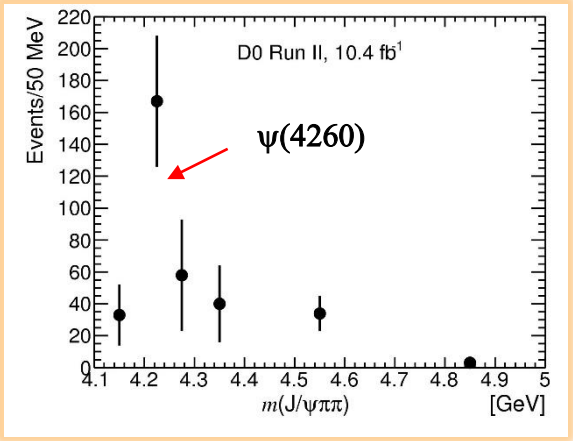


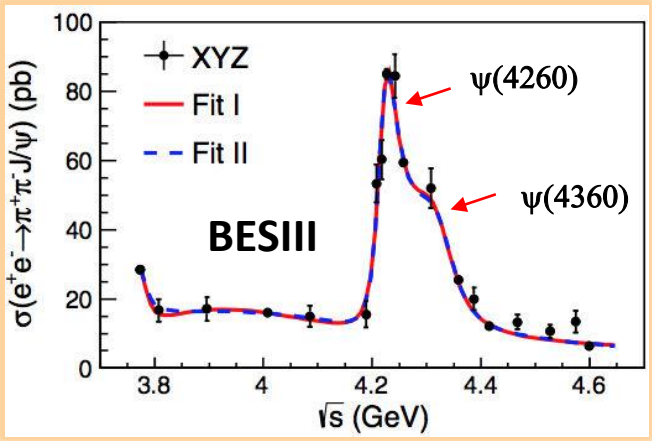




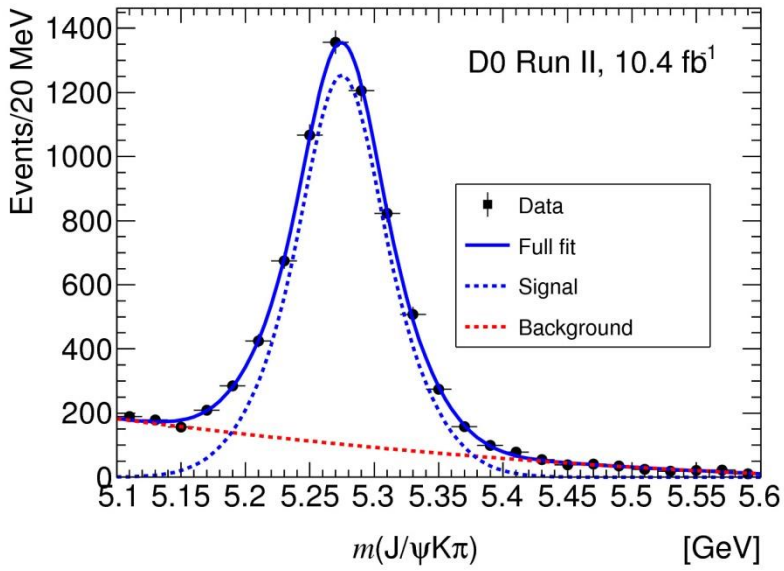








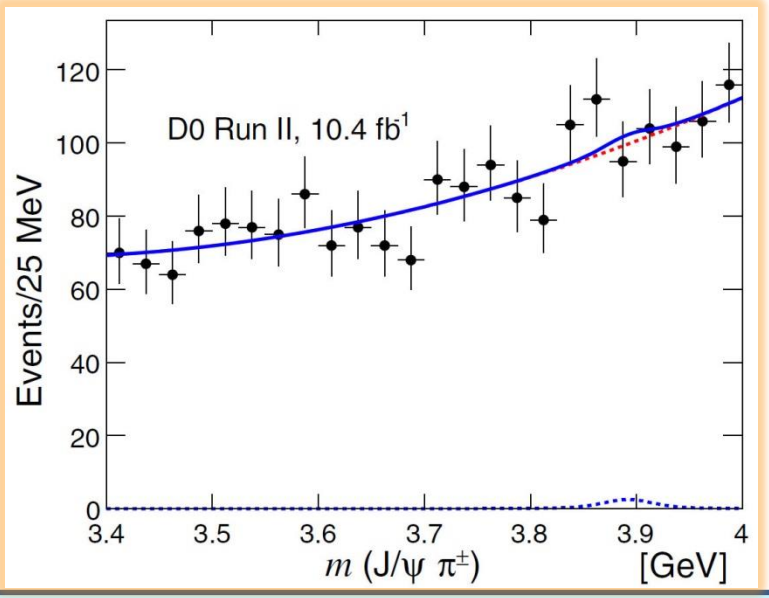
Studies of $Z_c(3900)$ at DØ experiment



Since $Z_c(3900) \to J/\psi\,\pi$ and $B_d^0 \to J/\psi\,K^*$ have the similar topology and efficiencies, they are cancel out in the ratio

$$\frac{N(Z_c(3900) \to J/\psi\,\pi)}{N(B_d^0 \to J/\psi\,K^*)} = 0.085 \pm 0.019$$

Belle Collaboration did not see a significant signal from $Z_c(3900)$ in $\bar{B}_d^0 \to J/\psi\ \pi^+K^-$. In our case the mass spectrum for $J/\psi\,\pi^+$ also show no indication of the $Z_c(3900)$ $(5.15 < M(J/\psi\ \pi^+K^-) < 5.4\ \text{GeV}, \text{no } K^*)$ Upper limit on the ratio to the $B_d^0 \to J/\psi\,K^*$ process of 0.015 (at 90% CL) is obtained.



New DØ results for $Z_c(3900)$ including a search for prompt production

V. M. Abazov et al., Phys. Rev. D100, 012005 (2019)

- Same sequential decay studied: $\psi(4260) \to Z_c^{\pm}(3900)\,\pi^{\mp}$, $Z_c^{\pm}(3900) \to J/\psi\,\pi^{\pm}$.
- The data sample was 50% larger due to the use of an extended track finding algorithm optimized for reconstructing low-p_T tracks.
- As a result: $p_T^{1,2} > 0.7$ GeV for the $\pi^{\pm}$ tracks.
- Prompt production of $Z_c(3900)$ in sequential process, mentioned above, was also studied.
- Two nonoverlapping samples: "displaced vertex" events (with the same selections as in previous analysis) and a complementary "primary vertex" events.
- $4.1 < M(J/\psi\,\pi^+\pi^-) < 4.7$ GeV.

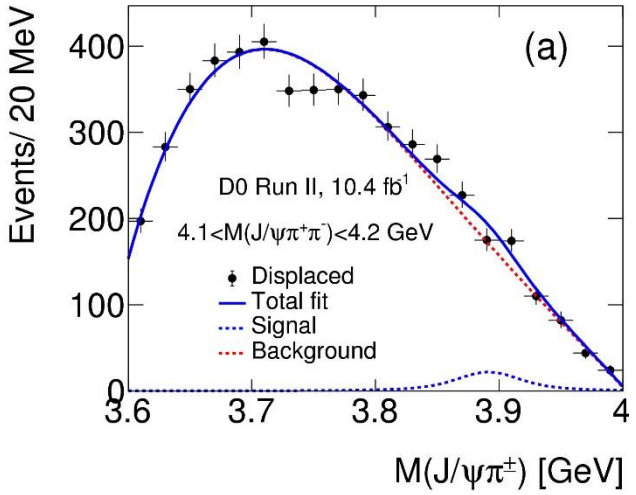
Studies of $Z_c(3900)$ at DØ experiment

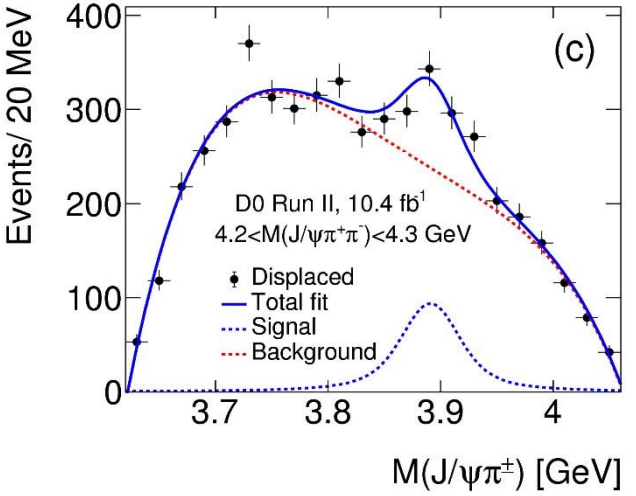
Mass fits

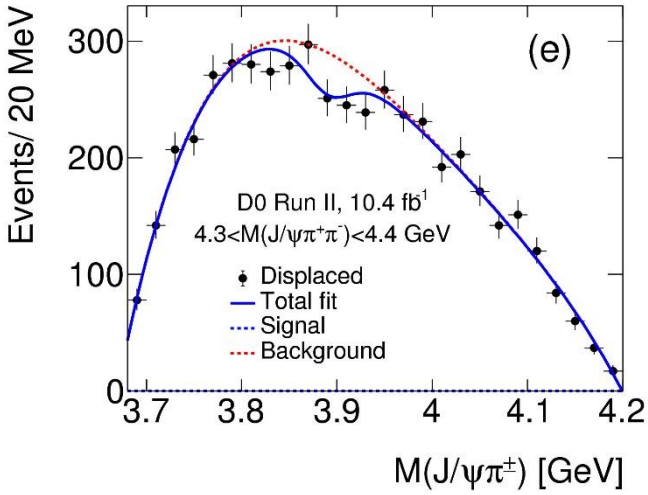
- Six intervals on $M(J/\psi\,\pi^+\pi^-)$: $4.1\text{-}4.2,\ 4.2\text{-}4.3,\ 4.3\text{-}4.4,\ 4.4\text{-}4.5,\ 4.5\text{-}4.6,\ 4.6\text{-}4.7\ \mathrm{GeV}$.
- Signal parametrization: S-wave relativistic BW convolved with a Gaussian mass resolution ($17 \pm 2\ \mathrm{MeV}$).
- Mass and width of $Z_c(3900)$ are fixed on PDG average for $J/\psi\pi$ channel: $M = 3893.3 \pm 2.7\ \mathrm{MeV};\ \Gamma = 36.8 \pm 6.5\ \mathrm{MeV}$.
- Background parametrization: Chebyshev polynomials of the first kind; "displaced vertex" – fourth order, "primary vertex" – fifth order (based on *Akaike information test (AIC)*).
- Negative values of the signal yields from the fit are allowed.
- Local statistical significance: $S = \sqrt{-2 \cdot \ln \frac{\mathcal{L}_0}{\mathcal{L}_{\max}}}$, in case of a negative signal yield S corresponds to the statistical significance of the depletion.

Studies of $Z_c(3900)$ at DØ experiment

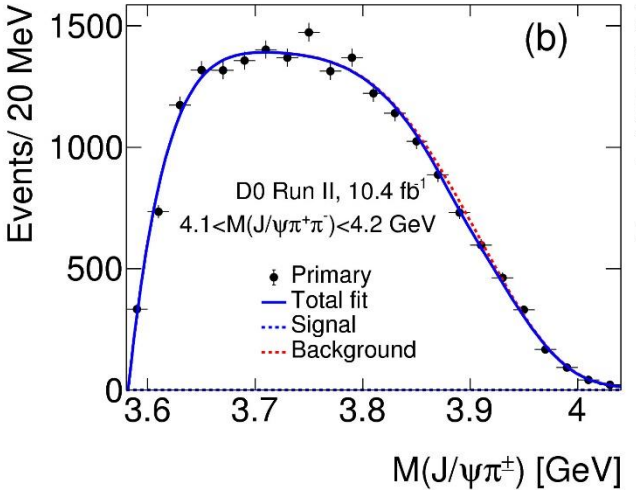
"Displaced vertex" ($M(J/\psi\,\pi^+\pi^-)$: 4.1 – 4.4 GeV)

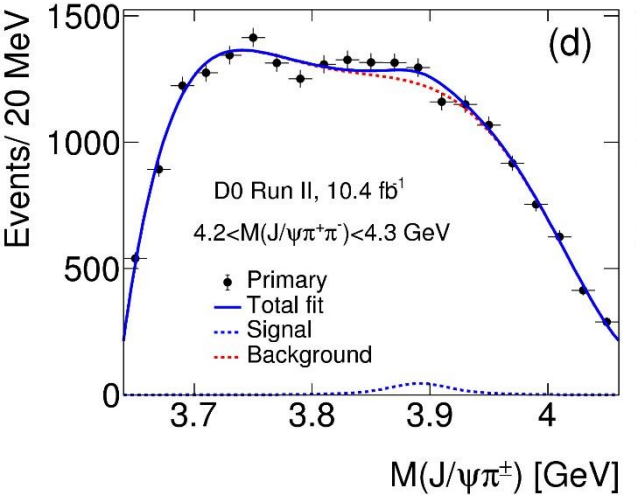


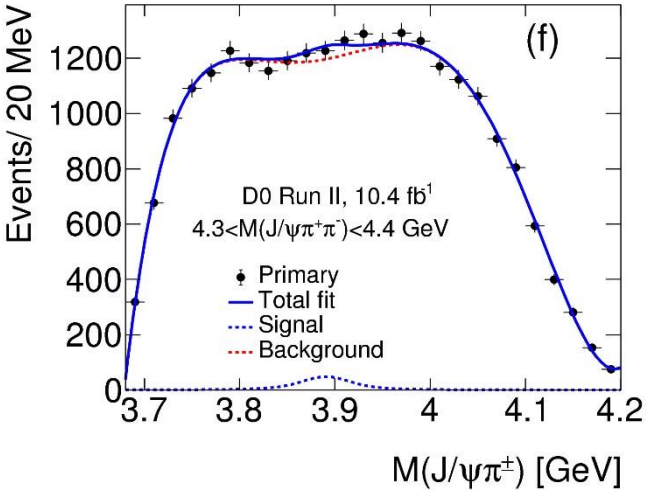




"Primary vertex" ($M(J/\psi\,\pi^+\pi^-)$: 4.1 – 4.4 GeV)

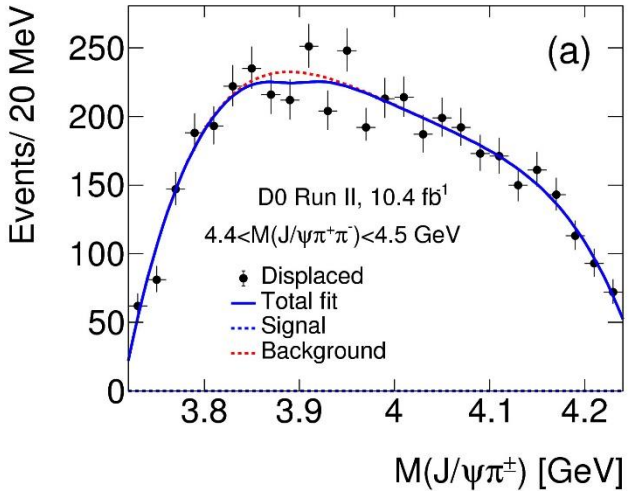


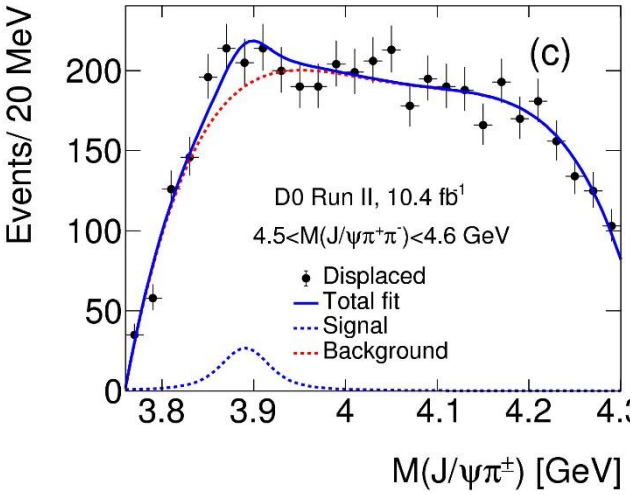


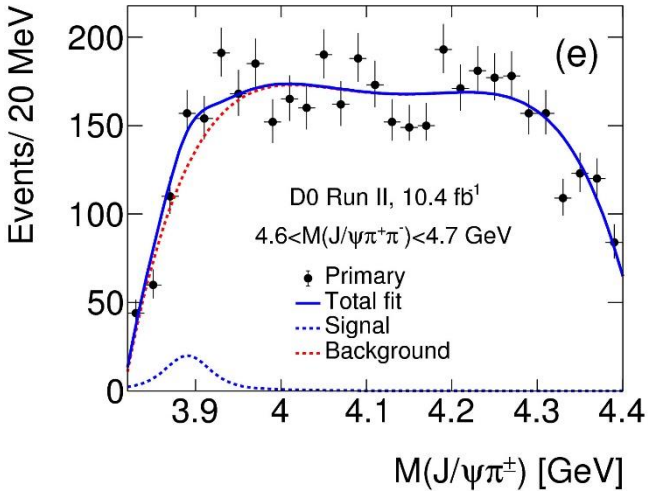


Studies of $Z_c(3900)$ at DØ experiment

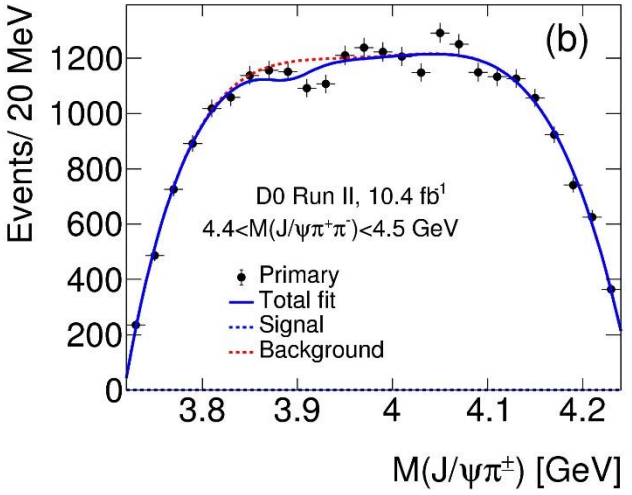
"Displaced vertex" ($M(J/\psi\,\pi^+\pi^-)$: 4.4 – 4.7 GeV)

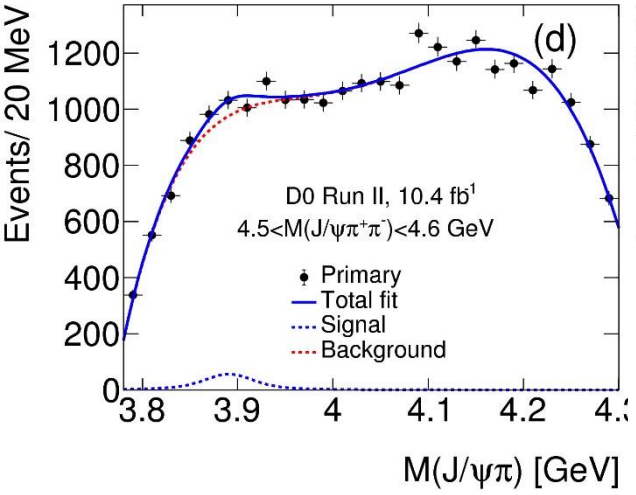


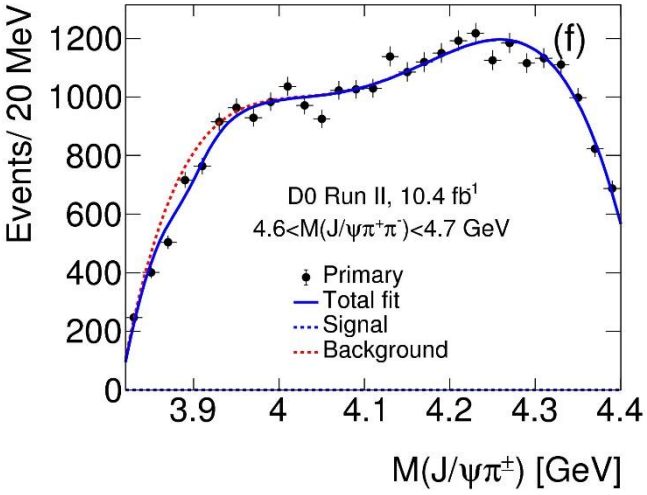




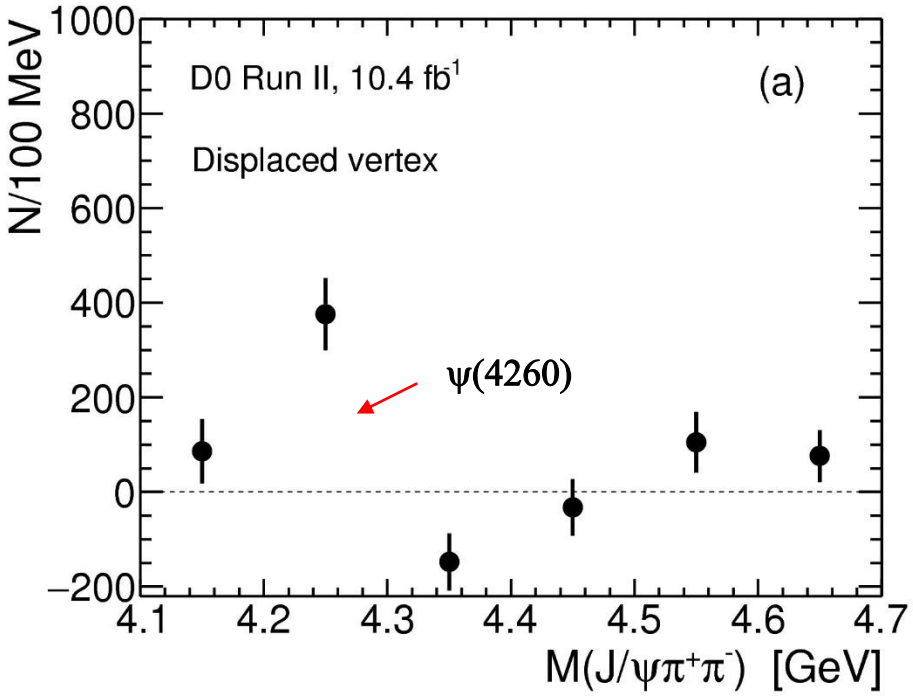
"Primary vertex" ($M(J/\psi\,\pi^+\pi^-)$: 4.4 – 4.7 GeV)

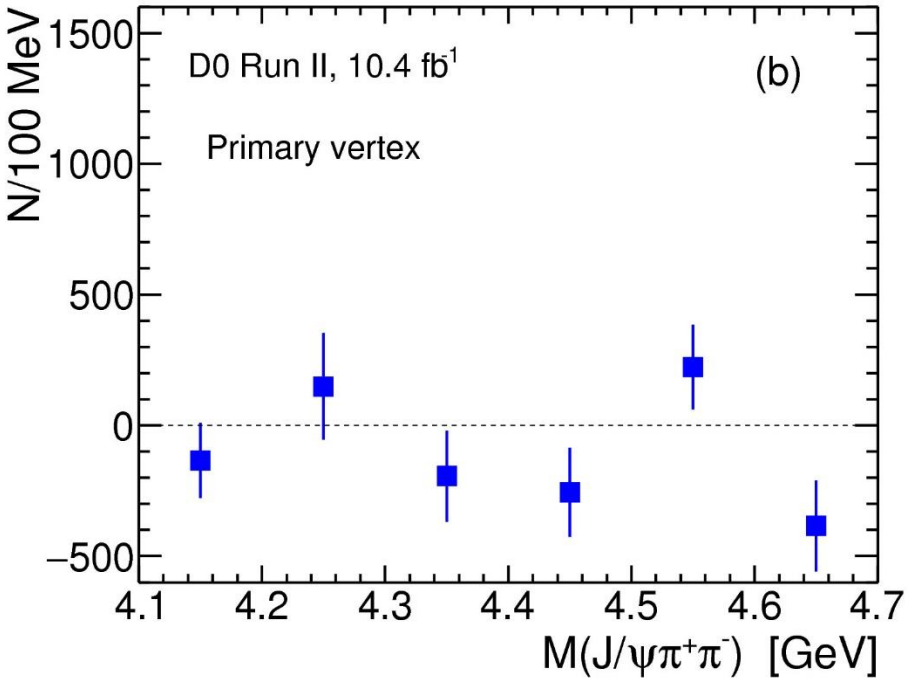






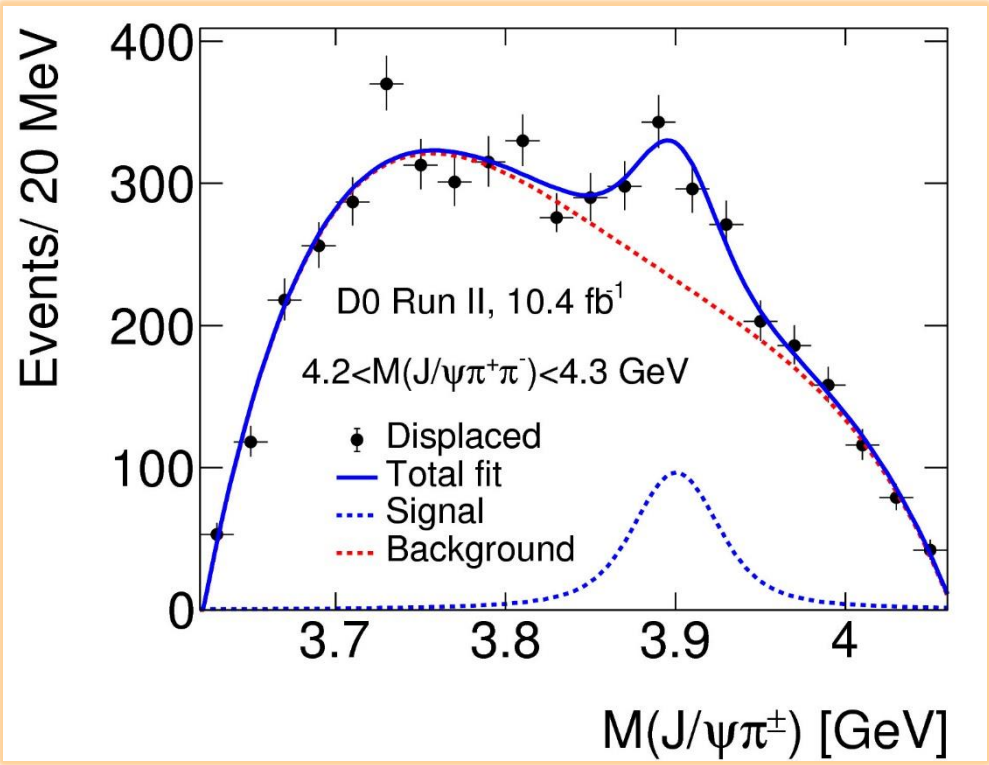
Studies of $Z_c(3900)$ at DØ experiment





	Displaced vertex			Primary vertex		
$M(J/\psi\pi^+\pi^-)$ GeV	Event yield	χ^2/ndf	S (σ)	Event yield	χ^2/ndf	S (σ)
4.1–4.2	86 ± 68	18.7/14	1.3	-134 ± 144	52.7/15	0.9
4.2–4.3	376 ± 76	28.1/16	5.2	149 ± 203	21.9/14	0.5
4.3–4.4	-148 ± 64	17.4/15	2.3	194 ± 174	16.7/19	1.1
4.4–4.5	-33 ± 60	26.6/15	0.5	-256 ± 170	30.9/18	1.5
4.5–4.6	105 ± 64	23.7/25	1.7	223 ± 162	42.3/23	1.4
4.6–4.7	76 ± 55	57.4/25	1.4	-384 ± 174	46.3/23	2.2

Studies of $Z_c(3900)$ at DØ experiment



Fit with the mass and width allowed to vary

$$4.2 < M(J/\psi\,\pi^+\pi^-) < 4.3\ \text{GeV}$$

"Displaced vertex" sample

$$\chi^2 / \text{ndf} = 24.1/14$$

Results

$$M = 3902.6^{+5.2}_{-5.0}\ \text{MeV},\quad \Gamma = 32^{+28}_{-21}\ \text{MeV},$$

$$N_{ev} = 364 \pm 156.$$

Local significance: 5.4σ

Studies of $Z_c(3900)$ at DØ experiment

Systematic uncertainties

Source	Mass, MeV	Width, MeV
Mass calibration	$^{+3}_{-0}$	0
Mass resolution	± 0.1	± 7
Background shape	± 1.4	$^{+25}_{-0}$
Total (sum in quadrature)	$^{+3.3}_{-1.4}$	$^{+26}_{-7}$

Mass/width and signal yields uncertainties

Source	Displaced vertex	Primary vertex
Mass resolution	± 18	± 18
Trigger bias	± 19	...
Acceptance	± 7	...
Signal mass	± 11	± 55
Signal width	± 40	± 30
Background shape	± 2	$^{+0}_{-149}$
Total (sum in quadrature)	± 49	$^{+65}_{-163}$

Limits on prompt production rates

Acceptance of the "displaced vertex" selection calculated with a help of $B_d^0 \to J/\psi\ \pi^{\pm}K^{\mp}$ decay: 0.66 ± 0.02.

Calculations below were performed for the interval $4.2 < M(J/\psi\ \pi^+\pi^-) < 4.3$ GeV.

$N_{nonprompt} = 570 \pm 137(stat+syst)$, $N_{prompt} = -45 \pm 237(stat+syst)$,

$R = N_{prompt}/N_{nonprompt} = -0.08^{+0.38}_{-0.46}$

Assuming gaussian uncertainties and setting the Bayesian prior for negative values of R to zero we obtain an upper limit of 0.7 at the 95% CL.

Inclusive production of the P_c resonances at DØ

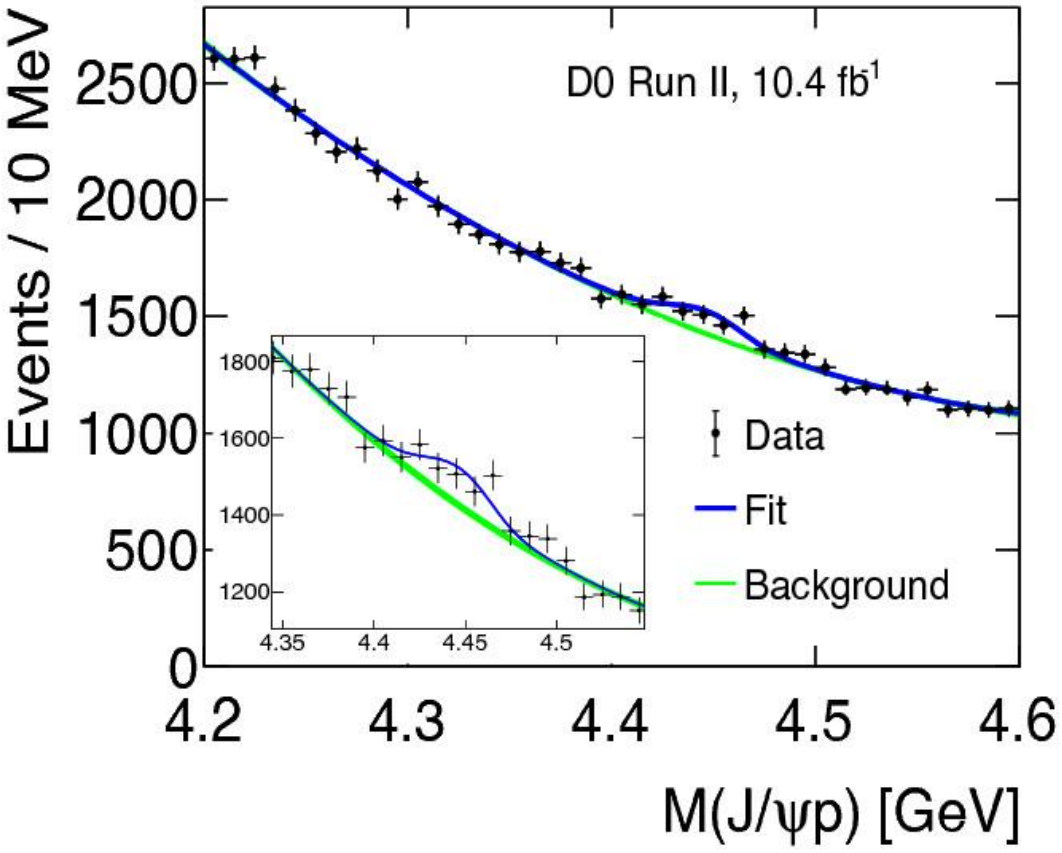
- Search for prompt and non-prompt ($B_c \to P_c X$) inclusive production of the P_c.
- Data sample corresponds to $10.4\ fb^{-1}$ of $p\bar{p}$ data at $1.96\ TeV$.
- Due to limited mass resolution and high background this study is confined to a search for a signal, consisting of an incoherent sum of $P_c(4440)$ and $P_c(4457)$ with a mass and width parameters taken from the latest LHCb results.
- Inclusive $J/\psi\ p$ sample was used. Although the amount of background in data decreases by about a factor of 20 going from the inclusive to exclusive selection, the P_c signal also would decrease by a factor of more than $\sqrt{20}$, leading to a higher significance for the inclusive selection.
- Events were collected with single muon and di-muon triggers.
- Muon $p_T > 1.5$ GeV.

Inclusive production of the P_c resonances at DØ

Cuts

- A pair of oppositely charged μ ($2.92 < M(\mu^+\mu^-) < 3.25$ GeV) accompanied by a third charged particle with $p_T > 2$ GeV.
- Constrained fit to the world average J/ψ mass (for $M(\mu^+\mu^-)$) and to the common vertex.
- Difference between L_{xy} for J/ψ and proton candidates < 30 μm, same difference in 3D space < 500 μm.
- "Displaced vertex" selection: $L_{xy} > 250$ μm, $L_{xy}/\sigma(L_{xy}) > 3$.
- Isolation ($\mathcal{I}$) cut ($\mathcal{I} = p(P_c) / (p(P_c) + p(\text{other}))$. "Other" is any reconstructed charged particle in a cone $\Delta R > 1.0$: $\mathcal{I} > 0.5$.
- $p_T(J/\psi\ p) < 12$ GeV.
- $4.2 < M(J/\psi\ p) < 4.6$ GeV
- Resulting "displaced vertex" sample contains 68007 events.

Inclusive production of the P_c resonances at DØ



$N_{sig} = 523 \pm 145;$

$\chi^2/ndf = 31.2/36;$

$S = 3.6\,\sigma.$

M(J/ψ p) fit

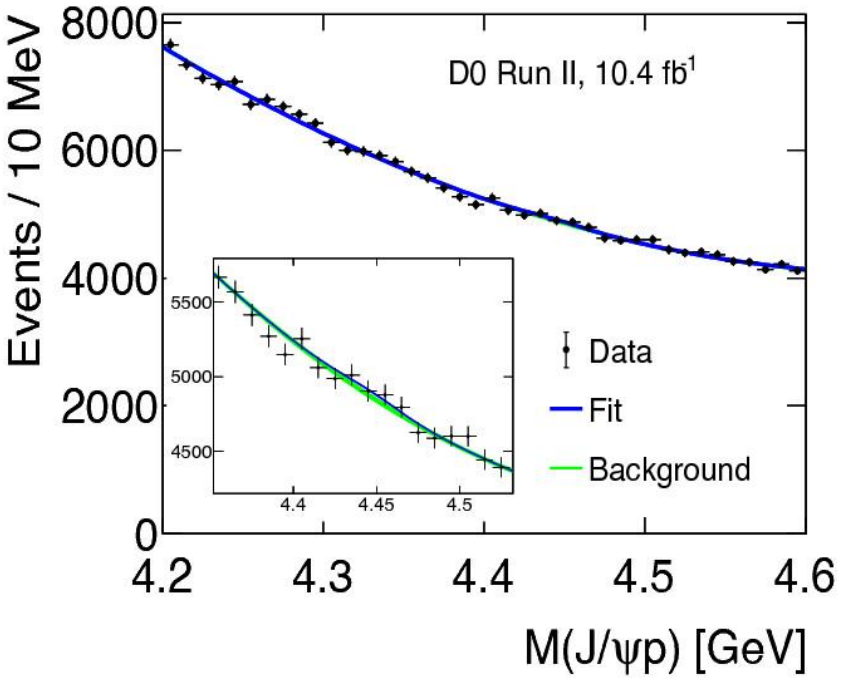
"Displaced vertex" sample.

Signal: incoherent sum of $P_c(4440)$ and $P_c(4457)$ convolved with a Gaussian resolution (12 ± 2 MeV).

Mass and width parameters are fixed on LHCb values, $f = N(4440)/(N(4440)+N(4457)) = 0.68 \pm 0.08 \pm 0.05$ taken from LHCb and fixed.

Background: second order polynomial.

Inclusive production of the P_c resonances at DØ



M(J/ψ p) fit

Complementary "Primary vertex" sample.

$$N_{sig} = 188 \pm 263;$$
$$\chi^2/ndf = 34.3/36;$$
$$S = 0.7\,\sigma.$$

Systematic uncertainties

Source	Displaced vertex	Primary vertex
Mass resolution	±37	±12
Background shape	±56	±18
LHCb resonance parameters	±64	–
Total (sum in quadrature)	±93	±22

Significance for "displaced vertex" sample fit with systematics:

$$S = 3.0\,\sigma$$

Inclusive production of the P_c resonances at DØ

Using the decay $B^+ \to J/\psi\, K^+$ assuming the distribution of the L_{xy} and its uncertainty for the B^+ decay is a good representation for the average b-hadron, the acceptance for the "displaced vertex" selection was estimated: $A = 0.77 \pm 0.05$.

The ratio $(H_b \to P_c + X)/(B^+ \to J/\psi\, K^+) = 0.03 \pm 0.01$.

Acceptance corrected yields of prompt and nonprompt production and their ratio:

$N_{nonprompt} = 677 \pm 207(stat+syst)$, $N_{prompt} = 34 \pm 267(stat+syst)$,
$R = N_{prompt}/N_{nonprompt} = 0.05 \pm 0.39$.

Assuming gaussian uncertainties and setting the Bayesian prior for negative values of R to zero we obtain an upper limit of 0.8 at the 95% CL.

arXiv:1910.11767v3 [hep-ex] 2 Mar 2020

Summary

- DØ observed $Z_c^{\pm}(3900)$ exotic state decaying to $J/\psi\,\pi^{\pm}$ in a sequential process $H_b \to \psi(4260) + \text{anything}, \psi(4260) \to Z_c^{\pm}(3900)\,\pi^{\mp}$ with 4.6σ significance.
- No evidence for prompt production $\psi(4260) \to Z_c^{\pm}(3900)\,\pi^{\mp}$, upper limit is 0.7 at 95% CL.
- For the subsample of events consistent with coming from decays of b-hadrons, DØ finds an enhancement in the $J/\psi\,p$ invariant mass consistent with a sum of resonances $P_c(4440)$ and $P_c(4457)$. The statistical significance of the pentaquark signal with the parameters set to the LHCb values is 3.0σ.
- There is no evidence of prompt production of the P_c states, the upper limit for this production was estimated as 0.8 at 95% CL.
- We find no evidence for the state $P_c(4312)$.
- This is the first confirmatory evidence for the P_c states firstly observed by LHCb.