Study of $Z_c(3900)$ Production in $p\bar{p}$ Collisions

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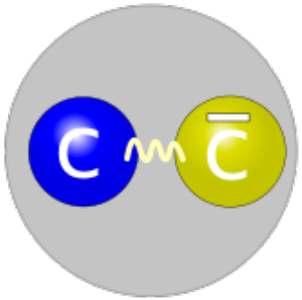
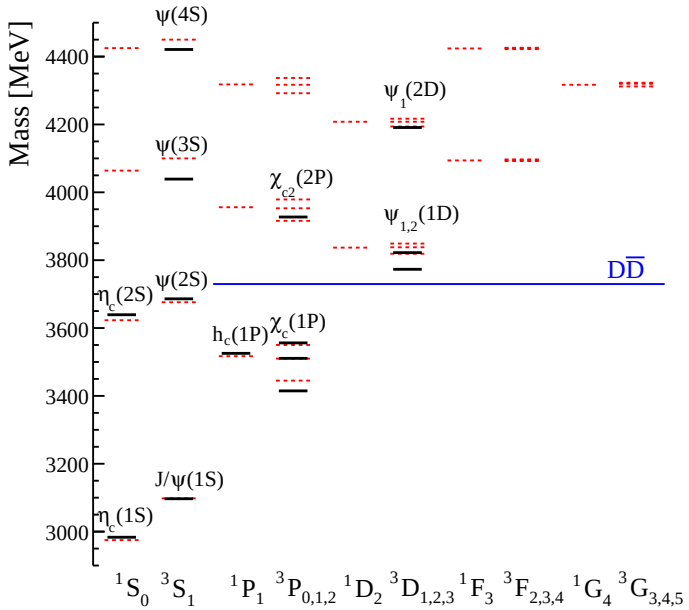
- Charmonium $c\bar{c}$ states with radial & angular excitation.

Charmonium



Spectrum



- Number of states discovered that don't fit the charmonium model ($c\bar{c}$).
  - For example (*state discussed in this presentation*):
    - $Z_c(3900)$ ***discovered by BELLE and BESII***

$$e^+e^- \rightarrow Y(4260)$$
$$Y(4260) \rightarrow Z_c^{\pm}(3900)\pi^{\mp}$$
$$Z_c^{\pm}(3900) \rightarrow J/\psi\pi^{\mp}$$

Belle: Phys. Rev. Lett. 110, 252001 (2013)
BESII: Phys. Rev. Lett. 110, 252002 (2013)

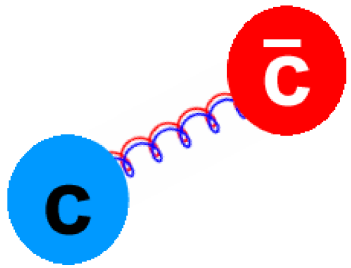
- Decay is similar to a charmonium excited state
  for example: $\psi(2S) \rightarrow J/\psi\pi^+\pi^-$
- $Z_c(3900)$ cannot be charmonium since it is charged and decays via the strong interaction to charmonium.
- Minimum quark content $c\bar{c}u\bar{d}$.

Models

Strongly bound:

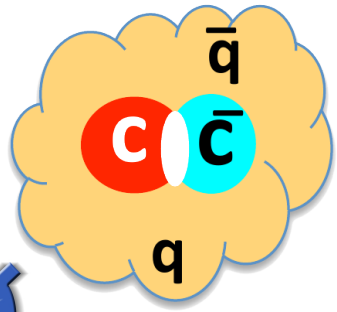
Tetraquarks

$c\bar{c}$ - gluon hybrid

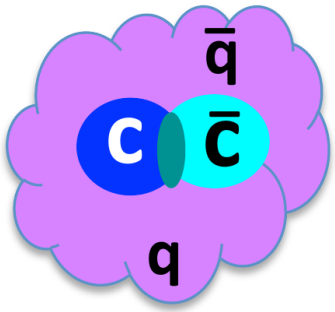


Weakly bound:

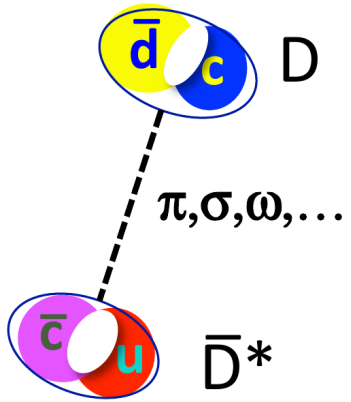
Hadroncharmonium
Color Singlet $c\bar{c}$



Hadroncharmonium
Color Octet $c\bar{c}$

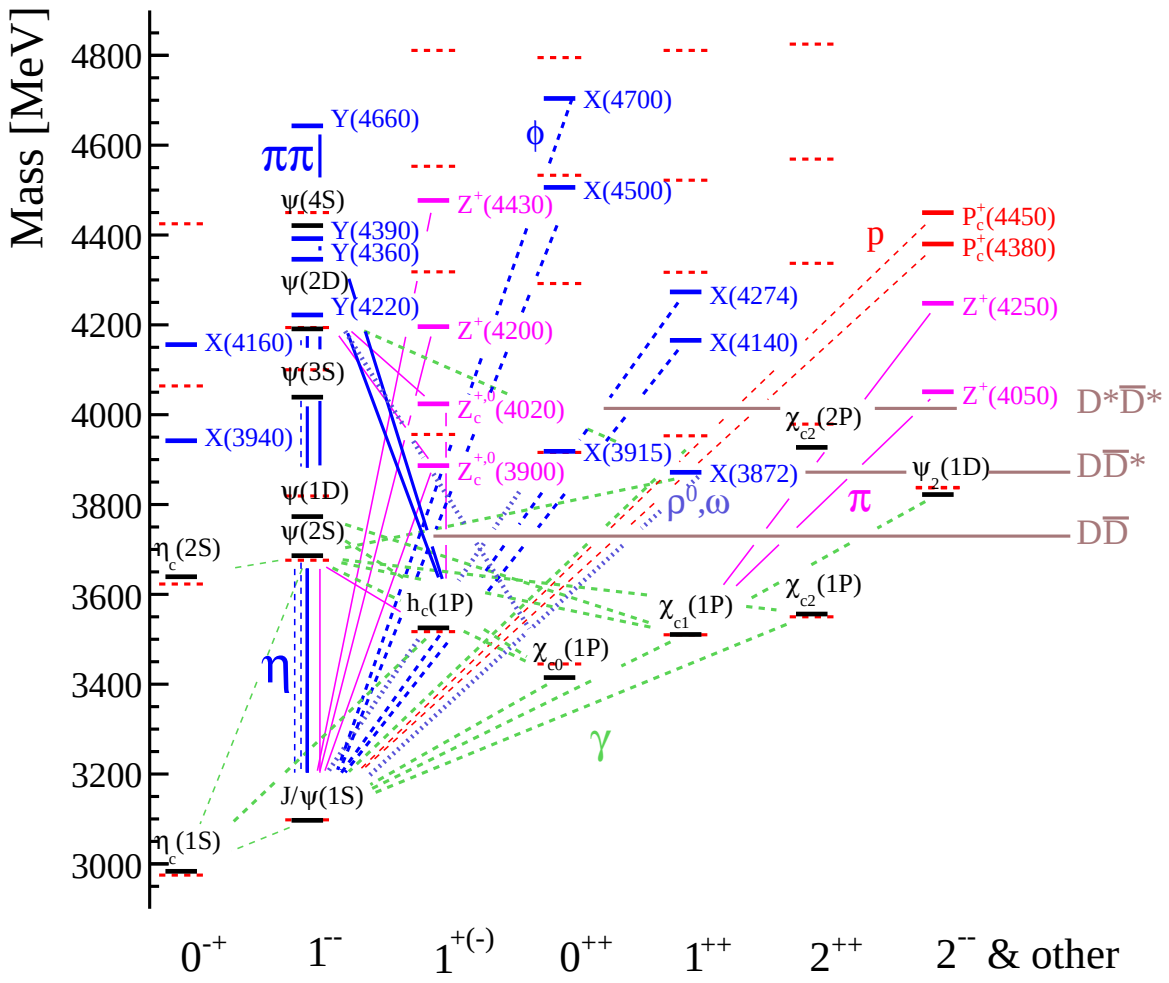


Mesonic Molecule



Charmonuim & Charmonuim-Like States

Rev. Mod. Phys **90** (2018)



- DØ has performed a search for $Z_c(3900)$ from b hadrons (H_b) decays at $\sqrt{s} = 1.96$ TeV using $\int \mathcal{L}\, dt = 10.4$ fb^{-1}

  Phys. Rev. D **98**, 052010 (2018)

- Previous searches using exclusive hadronic decays proved inconclusive:
  - Belle – Not observed $\bar{B}^0 \to (J/\psi\pi^+)K^-$

    Phys. Rev. D **90**, 112009 (2014)
  - LHCb – Not observed $B^0 \to (J/\psi\pi^+)\pi^-$

    Phys. Rev. D **90**, 012003 (2014)
  - BaBar – Maybe observed $\bar{B}^0 \to J/\psi\pi\pi K$

    Phys. Rev. D **73**, 011101 (2006)

- Since the process may be spread over many channels DØ used a semi-inclusive search $H_b \to Y(4260) + X$.

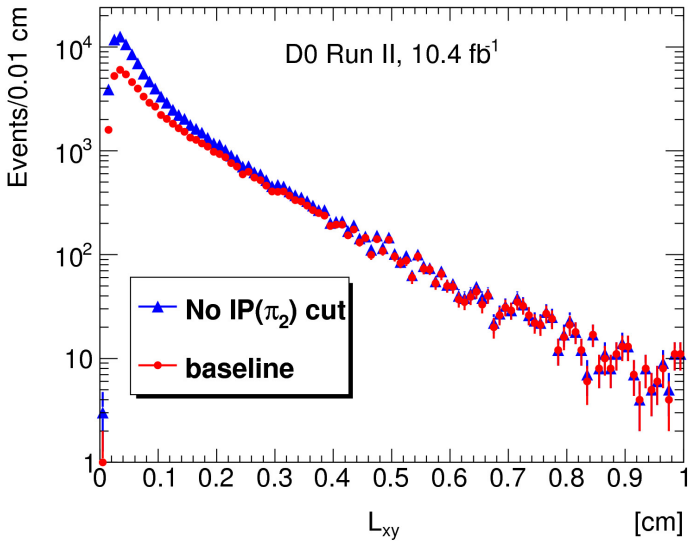
Evidence for $H_b \to Z_c^{\pm}(3900)\pi^{\mp} + X$

Search Strategy

Phys. Rev. D **98**, 052010 (2018)

- Search topology $Y(4260) \to Z_c^{\pm}(3900)\pi^{\mp} \to \left(J/\psi\pi^{\pm}\right)\pi^{\mp}$
  - Hence a secondary vertex comprised of $J/\psi \to \mu^+\mu^-$ plus 2 opposite sign charged particle tracks.
- Vertex requirements: secondary vertex pointing at primary vertex; impact parameter in added tracks.
- Invariant mass requirement $4.1 < M_{J/\psi\pi^{\pm}\pi^{\mp}} < 5.0$ GeV
  - Less than lowest B meson mass
  - Includes $Y(4260)$

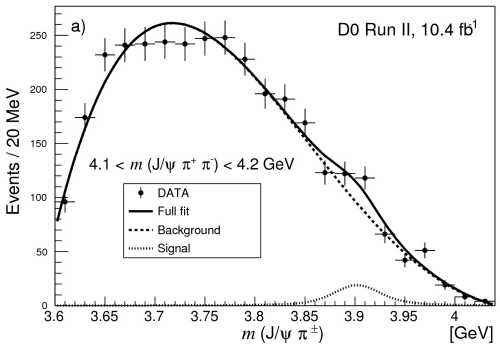
Transverse Decay Length



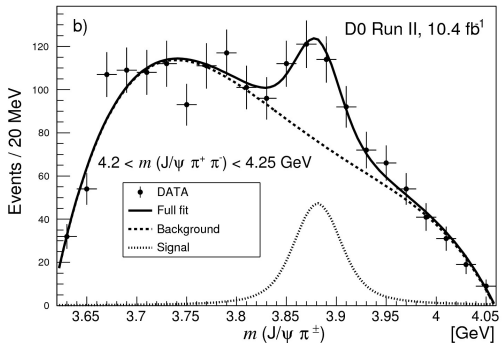
Evidence for $H_b \to Z_c^{\pm}(3900)\pi^{\mp} + X$

$J/\psi\pi^+\pi^-$ Invariant Mass

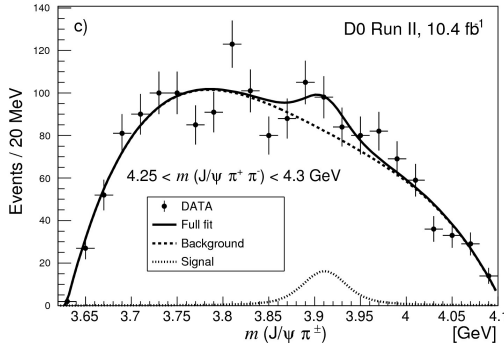
$4.1 < M(J/\psi\pi^{\pm}\pi^{\mp}) < 4.2$ GeV



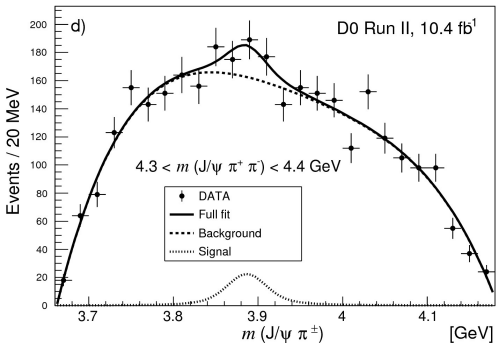
$4.2 < M(J/\psi\pi^{\pm}\pi^{\mp}) < 4.25$ GeV



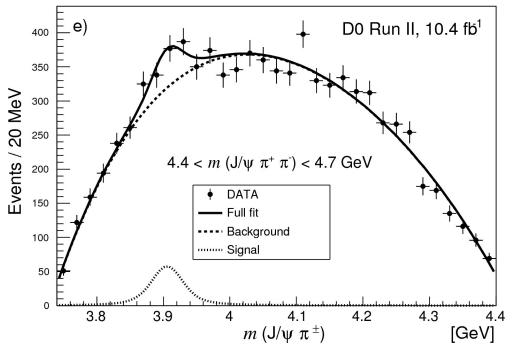
$4.25 < M(J/\psi\pi^{\pm}\pi^{\mp}) < 4.3$ GeV



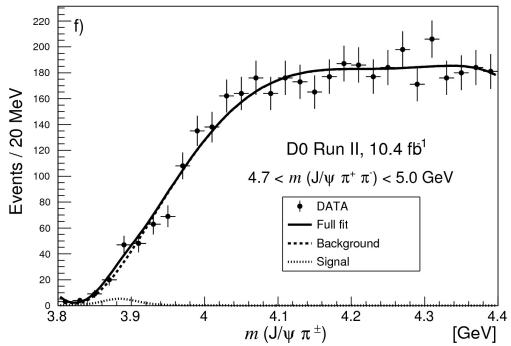
$4.3 < M(J/\psi\pi^{\pm}\pi^{\mp}) < 4.4$ GeV



$4.4 < M(J/\psi\pi^{\pm}\pi^{\mp}) < 4.7$ GeV



$4.7 < M(J/\psi\pi^{\pm}\pi^{\mp}) < 5.0$ GeV

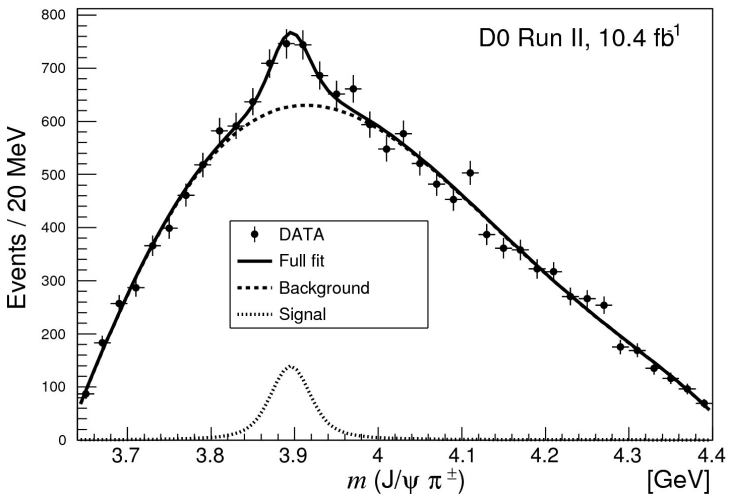


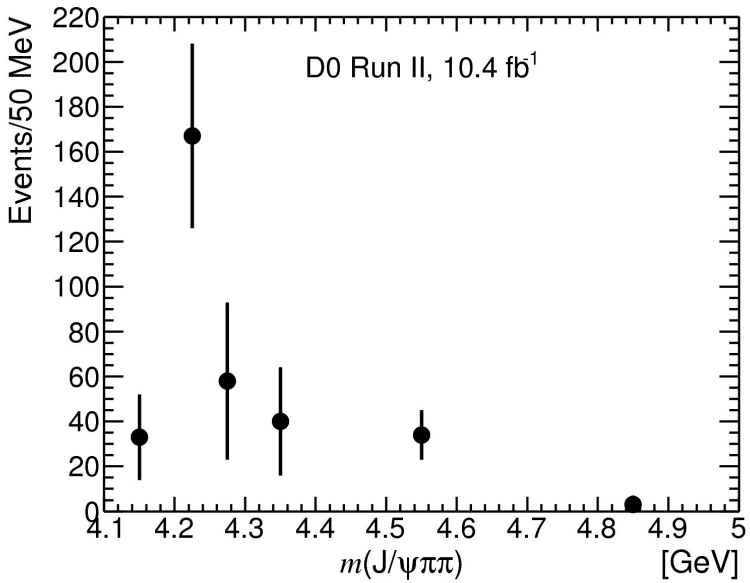
Evidence for $H_b \to Z_c^{\pm}(3900)\pi^{\mp} + X$

$Z_c(3900)$ Signal

- Signal at $M\left(J/\psi\pi^{\pm}\right) = 3895.0 \pm 5.2\ (\text{stat})^{+4.0}_{-2.7}\ (\text{syst})$ MeV
- Significance of 4.6σ (with syst.)

$4.2 < M(J/\psi\pi^{\pm}\pi^{\mp}) < 4.7$ GeV



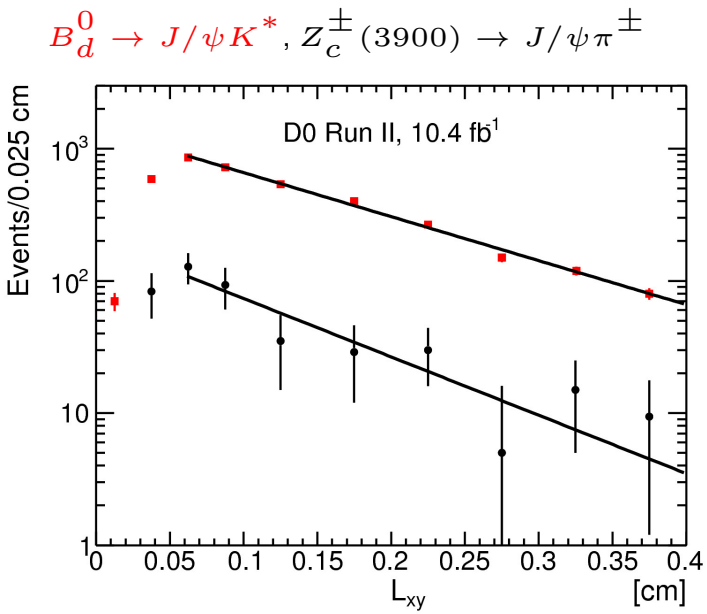


Evidence for $H_b \to Z_c^{\pm}(3900)\pi^{\mp} + X$

DØ Results

- Rate relative to $B_{\mathrm{d}}^0 \to J/\psi K^*$

$$\frac{N\left[H_b \to \left(Z_c^{\pm}(3900) \to J/\psi\pi^{\pm}\right)\pi^{\mp} + X\right]}{N\left[B_d^0 \to J/\psi K^*\right]} = 0.085 \pm 0.019$$

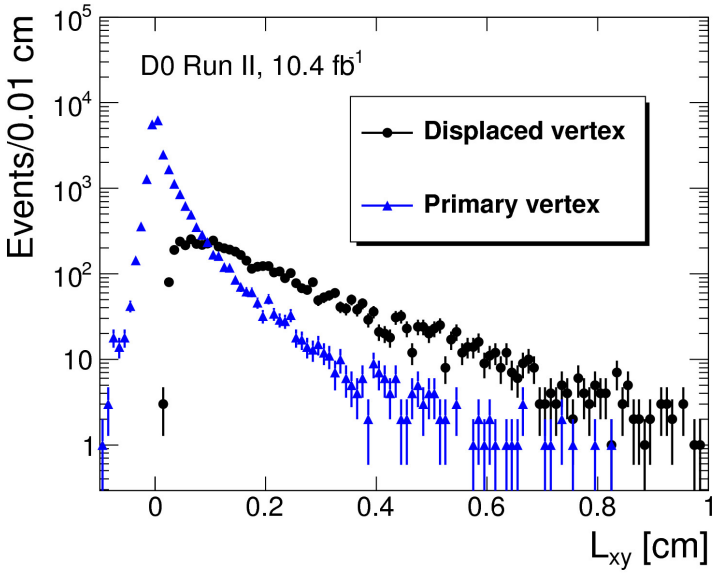


$$\frac{N\left[H_b \to \left(Z_c^{\pm}(3900) \to J/\psi\pi^{\pm}\right)K^{\mp}\right]}{N\left[B_d^0 \to J/\psi K^*\right]}$$

< 0.015 at 90% C.L.

Phy. Rev. D **100** 012005

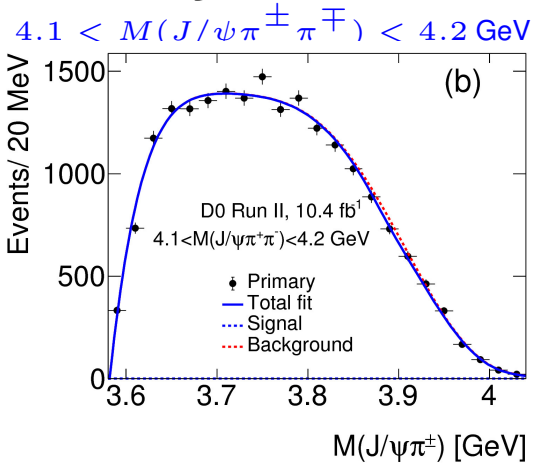
- Same channel $Y(4260) \to \left(J/\psi\pi^{\pm}\right)\pi^{\mp}$.
- Data is reprocessed to optimize low p_T track reconstruction (50%) increase in sample.
- Split data into 2 non-overlapping subsets:
  - Consistent with primary vertex.
  - Displaced vertex.

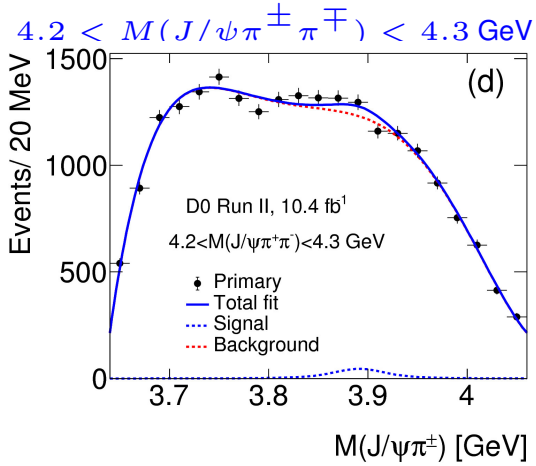


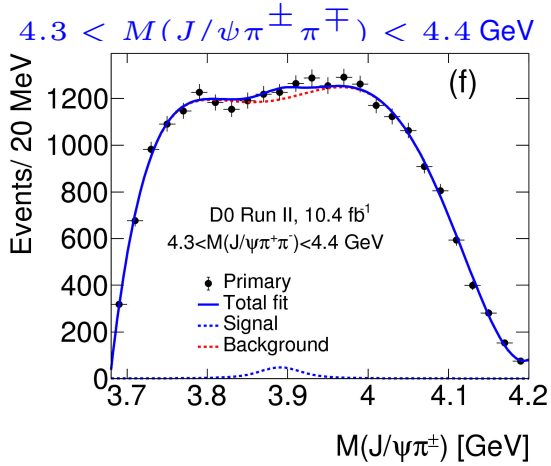
Prompt Production $Y(4260) \to Z_c^{\pm}(3900)\pi^{\mp}$

Invariant Mass

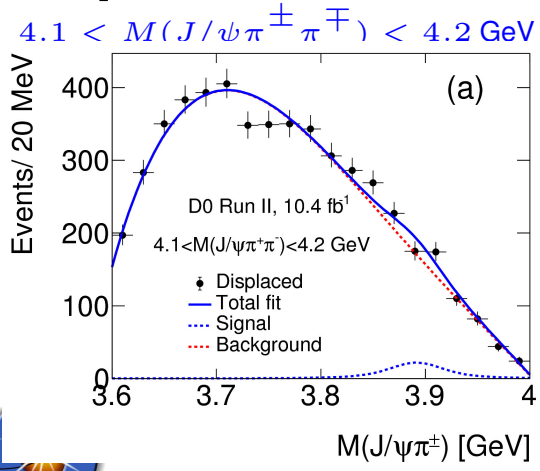
Primary vertex

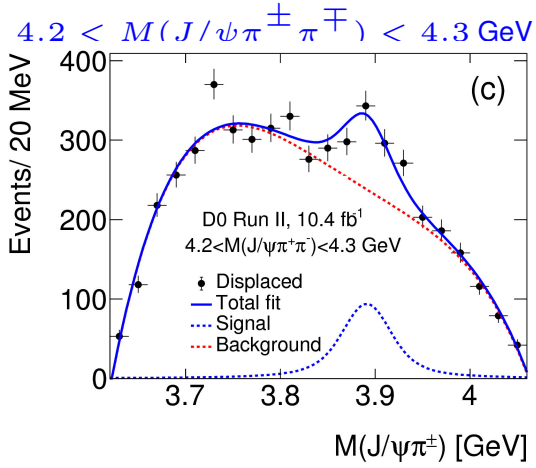


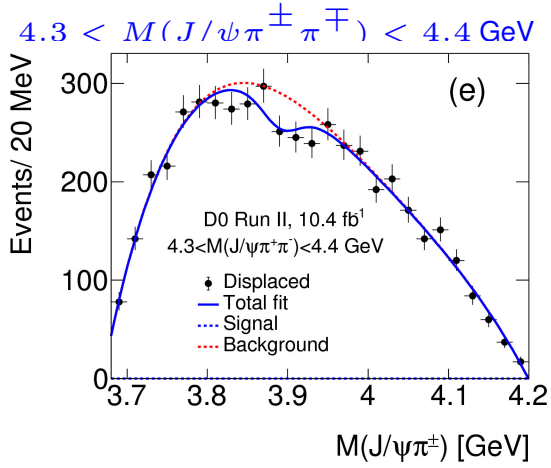




Displaced Vertex



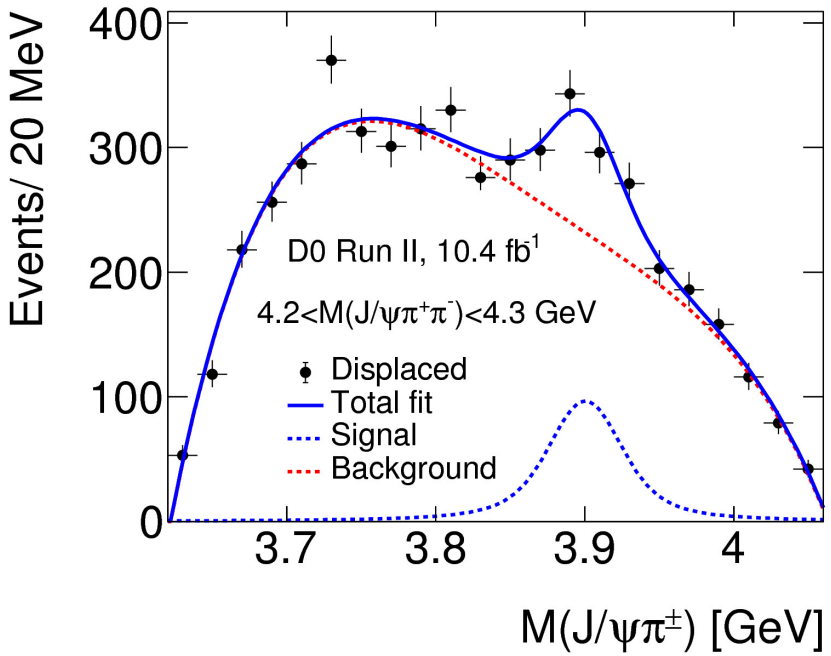




Prompt Production $Y(4260) \to Z_c^{\pm}(3900)\pi^{\mp}$

Results $Z_c(3900)$ properties

- For the $Y(4260)$ displaced vertex mass range $4.2 < M(J/\psi\pi^{\pm}\pi^{\mp}) < 4.3$ GeV
  - Signal significance 5.4σ
  - $M = 3902.6 \pm 5.2$ (stat)$^{+3.4}_{-1.4}$ (syst) MeV
  - $\Gamma = 32^{+28}_{-21}$ (stat)$^{+26}_{-7}$ (syst) MeV

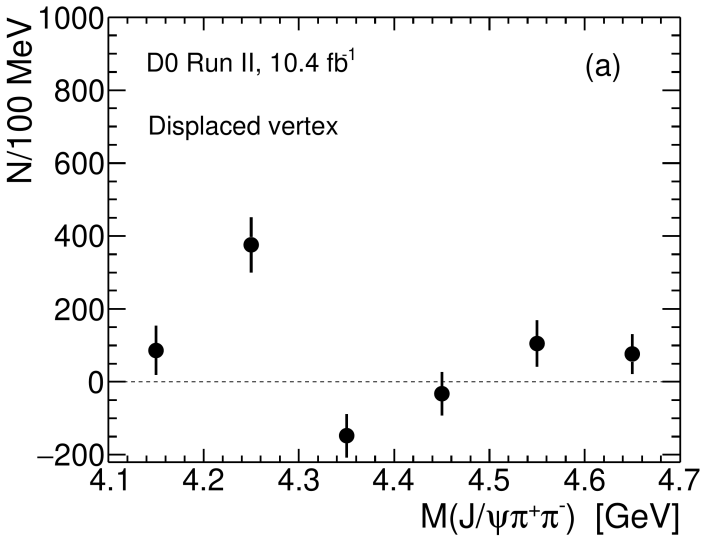


Prompt Production $Y(4260) \to Z_c^{\pm}(3900)\pi^{\mp}$

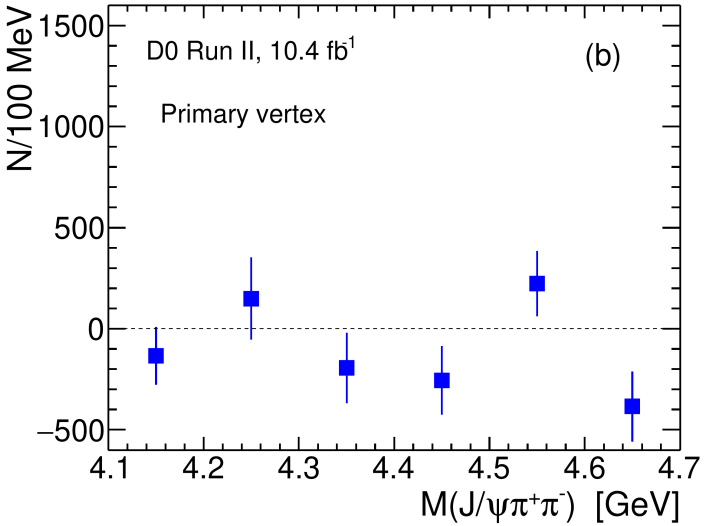
Results prompt production

State	$N_{\text{prompt}}/N_{\text{non-prompt}}$
$Y(4260) \to Z_c^{\pm}(3900)\pi^{\mp}$	< 0.7 at 95% C.L.
$X(3872) \to J/\psi\pi^{\pm}\pi^{\mp}$	≈ 2.5 CMS & ATLAS
$X(4140) \to J/\psi\phi$	≈ 1.5 DØ

Displaced Vertex



Primary Vertex



Summary

- Measured the properties of the $Z_c(3900)$
- Observed $Y(4260) \to Z_c^{\pm}(3900)\pi^{\mp}$ in semi-inclusive H_b decays.
  - But not in $B_d^0 \to J/\psi\pi^+K^-$
- Prompt production of the $Y(4260) \to Z_c^{\pm}(3900)\pi^{\mp}$ is not observed.
  - Significantly less than $X(3872)$ abd $X(4140)$.

Dø nabs $Z_c^{\pm}(3900)$

Following first observations of the charmonium-like state $Z_c^{\pm}(3900)$ at e^+e^- colliders in 2013, the Dø collaboration has published 5.4σ evidence for its presence in the decay chain of b-quarks in $p\bar{p}$ collisions

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