Recent Heavy Flavor Results from the Tevatron

Non-Standard (Exotic) Hadrons

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31st Rencontres de Blois
Particle Physics and Cosmology
2 – 7 June 2019

Non-Standard Hadrons

Explore at:

- e^+e^- 2 – ~10 GeV
- $p\bar{p} \quad \sim q - \bar{q}$ 1.96 GeV
- $pp \quad \sim g - g$ 7 – 13 TeV

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CDF and DØ at Tevatron

Production of $Y(4260)$ and $Z_c^+(3900)$

Prompt or in decays

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Production of $Y(4260)$ and $Z_c^+(3900)$

Prompt or in decays

Outline

- Non-standard hadron models (quarkonium-like)
  e.g., Rev.Mod.Phys. **90** (2018) 1, 015003; arXiv:1708.04012 [hep-ph]
- Evidence for $Z_c^+(3900)$ in semi-inclusive *b* decays
  Phys.Rev. D **98** (2018), 052010; arXiv:1807.00183 [hep-ex]
- Search for prompt production of $Y(4260)$, $Z_c^+(3900)$
  arXiv:1906.13704 [hep-ex], submitted to Phys. Rev. D

Non-Standard (Exotic) Hadrons (quarkonium-like)

Strongly Bound

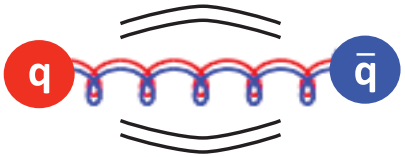
- Tetraquark

$Z_c^+(3900)$?

$X(3872)$?

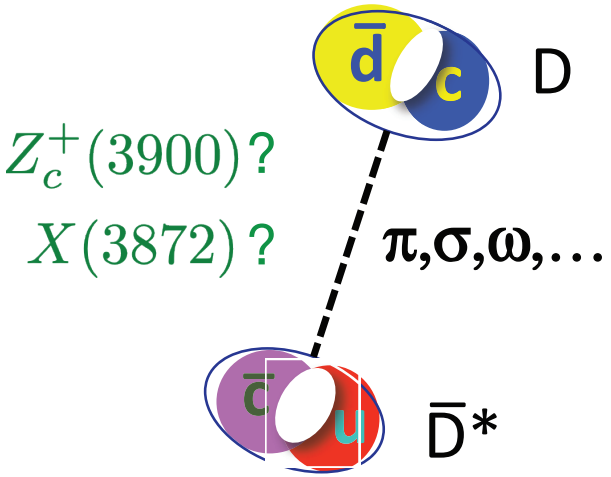
- Hybrid quarkonium, excited gluons

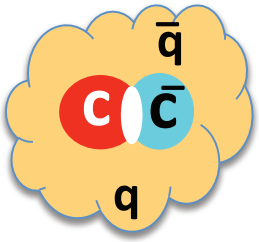
$Y(4260)$?

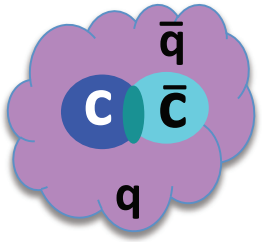


Weakly Bound

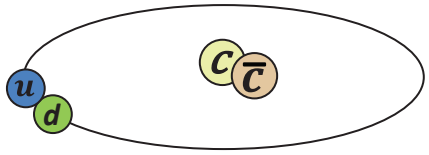
- Mesonic Molecule
- Hadroncharmonium







Adjoint



Born-Oppenheimer

* figures adapted from arXiv:1708.04012 [hep-ph]

Evidence for $Z_c^+(3900)$ in *b* decays

- Discovered at Belle and BESII in

Phys. Rev. Lett. **110**, 252001 (2013)
Phys. Rev. Lett. **110**, 252002 (2013)

$$e^+e^- \to Y(4260)$$
$$Y(4260) \to Z_c^+(3900)\pi^-$$
$$Z_c^+(3900) \to J/\psi\pi^+$$

- $Z_c^+(3900)$ cannot be a conventional quark-antiquark meson since it is charged and decays via strong interaction to charmonium
- Minimum quark content $c\bar{c}u\bar{d}$; $Y(4260)$ may also be an exotic

Evidence for $Z_c^+(3900)$ in *b* decays

Presence of $Z_c^+(3900)$ in decays of *b* hadron decays unclear

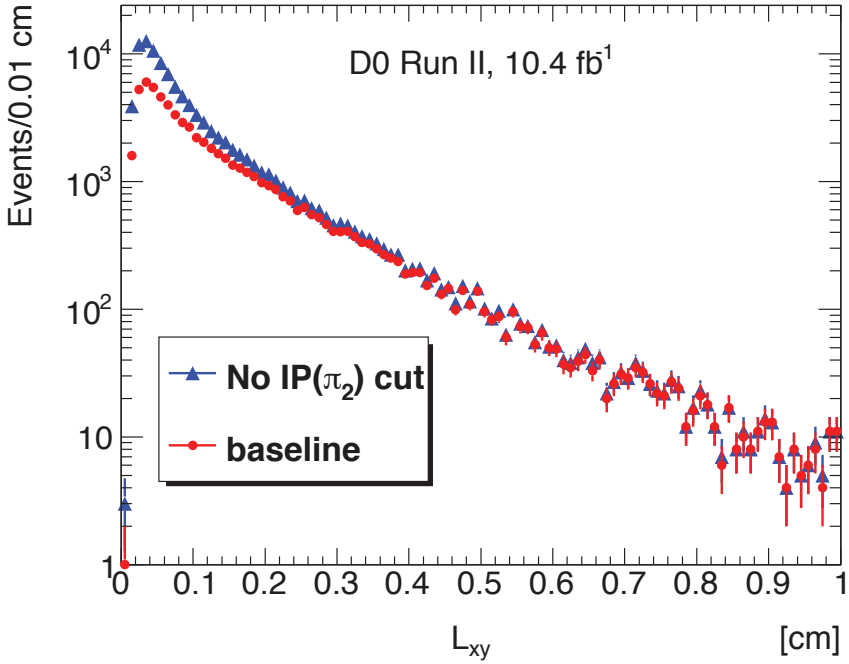
- Not seen by Belle in $\bar{B}^0 \to (J/\psi\pi^+)K^-$ Phys. Rev. D **90**, 112009 (2014)
- Not seen by LHCb in $B^0 \to (J/\psi\pi^+)\pi^-$ Phys. Rev. D **90**, 012003 (2014)
- May have been seen by BABAR in $B^0 \to J/\psi\pi\pi K$ Phys. Rev. D **73**, 011101 (2006)

- Process may be spread over many channels and escape observation in a particular channel; look for it semi-inclusive decays (containing muons from J/ψ decay) of all *b* hadrons (H_b)

$$H_b \to Y(4260) + \text{anything}$$
$$Y(4260) \to Z_c^+(3900)\pi^-$$
$$Z_c^+(3900) \to J/\psi\pi^+$$

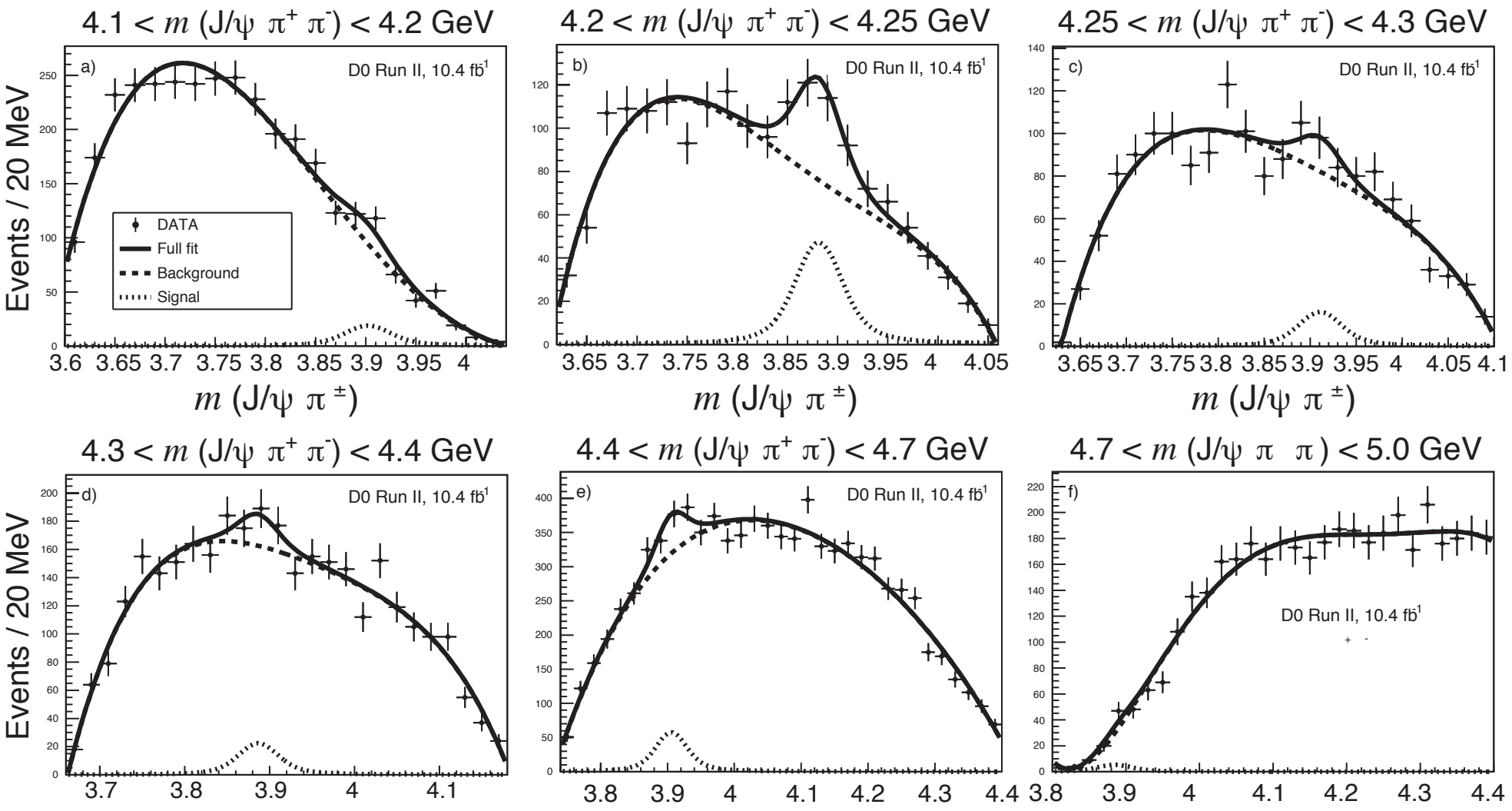
Evidence for $Z_c^+(3900)$ in *b* decays

- Topology: J/ψ + 2 tracks at a detached vertex; $H_b \to J/\psi h^+ h^-$
- Single and dimuon triggers
- Vertexing requirements, requirements on vertex detached from primary vertex, pointing, impact parameter requirements on added tracks
- $4.1 < m(J/\psi\pi^+\pi^-) < 5.0$ GeV
  - includes $Y(4260)$ states
  - high enough for $Z_c^+(3900)$
  - low enough to exclude fully reconstructed decays of *b* hadrons $H_b \to J/\psi h^+ h^-$



Evidence for $Z_c^+(3900)$ in *b* decays

- $H_b \to Y(4260) + X,\ Y(4260) \to Z_c^+(3900)^+\pi^- \to (J/\psi\pi^+)\pi^-$



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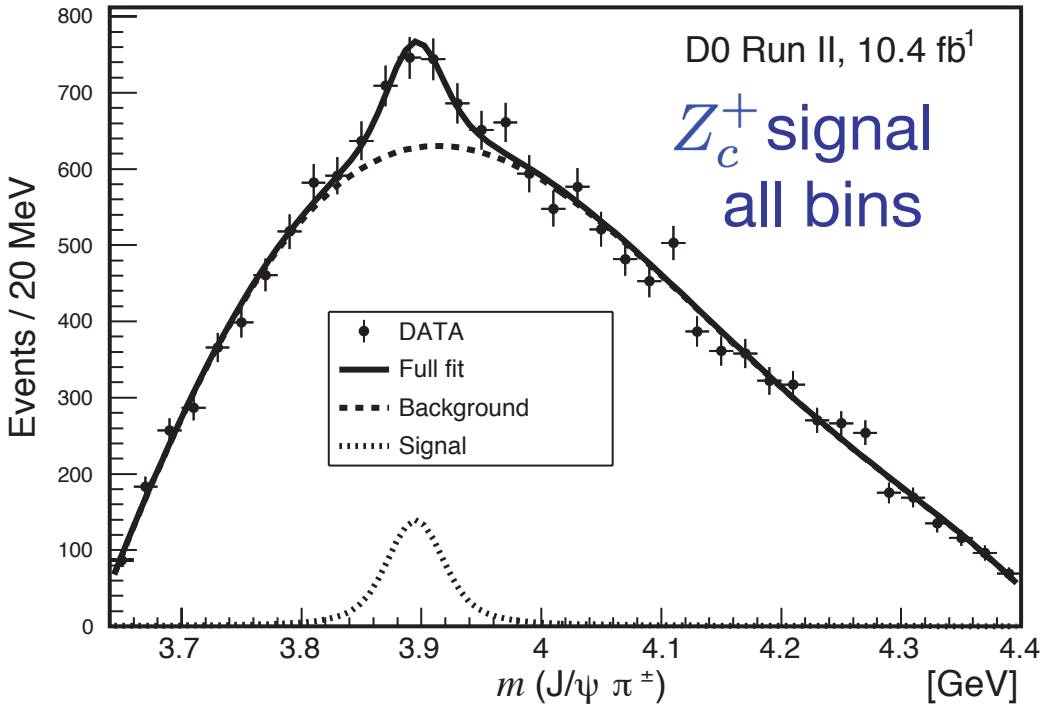
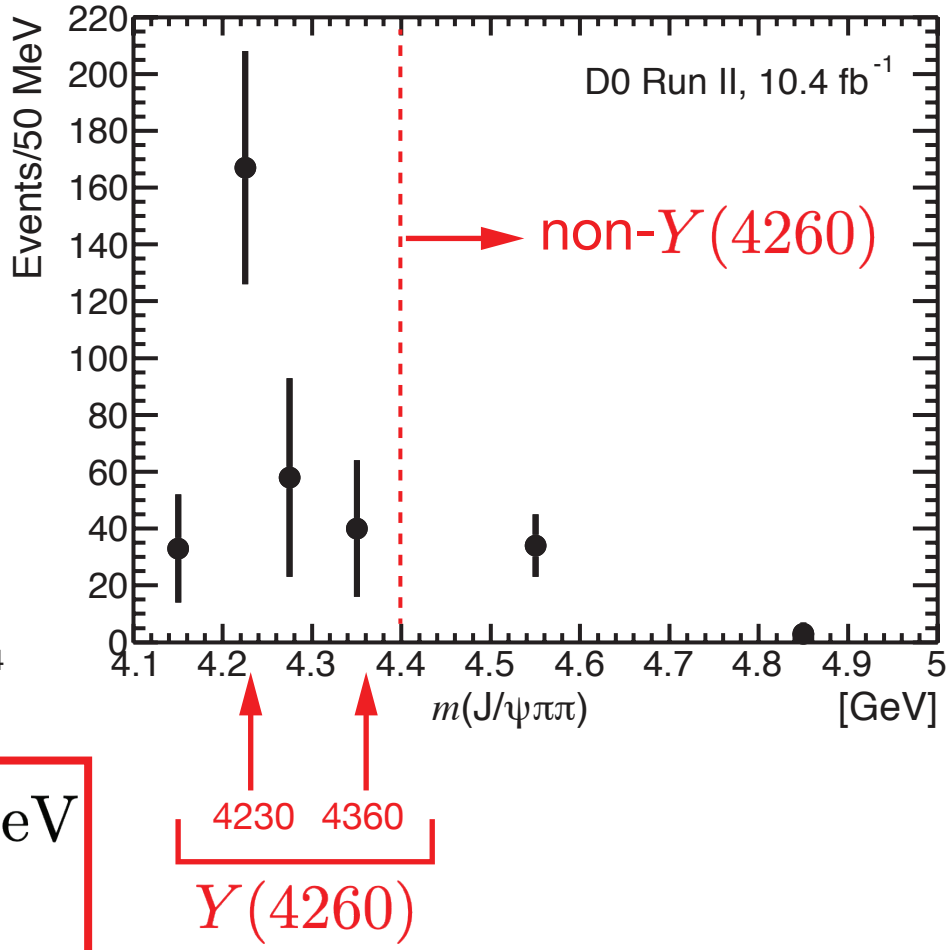


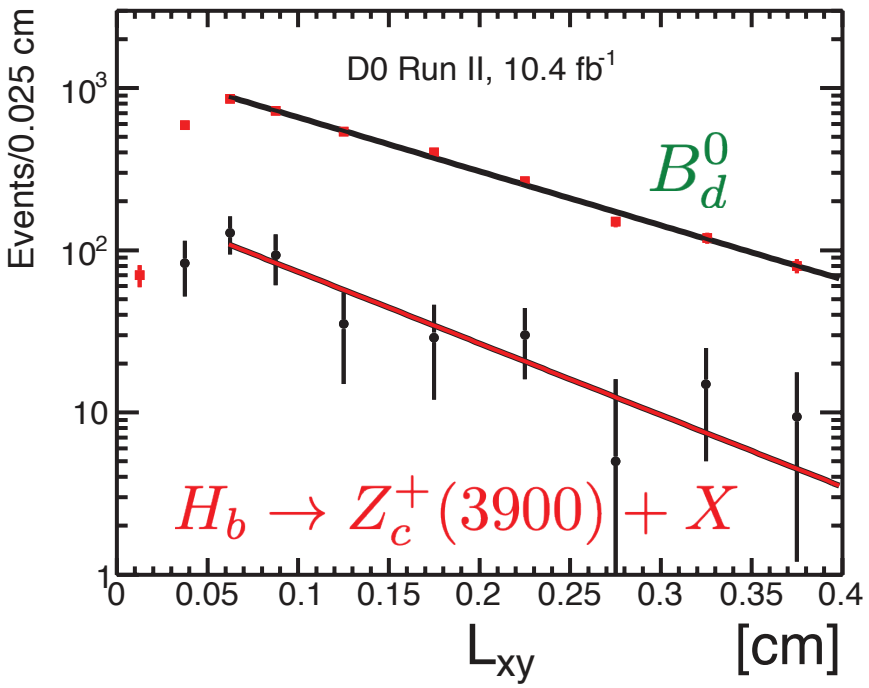


$$m = 3895.0 \pm 5.2\,(\text{stat})^{+4.0}_{-2.7}\,(\text{syst})\ \text{MeV}$$

(consistent with PDG)

Significance: 4.6σ (with syst.)

Evidence for $Z_c^+(3900)$ in *b* decays



- Rate: normalize to B_d^0

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

- Belle: did not see significant $Z_c^+(3900)$ signal in $\bar{B}_d^0 \to J/\psi\pi^+K^-$

Check: also no significant production:

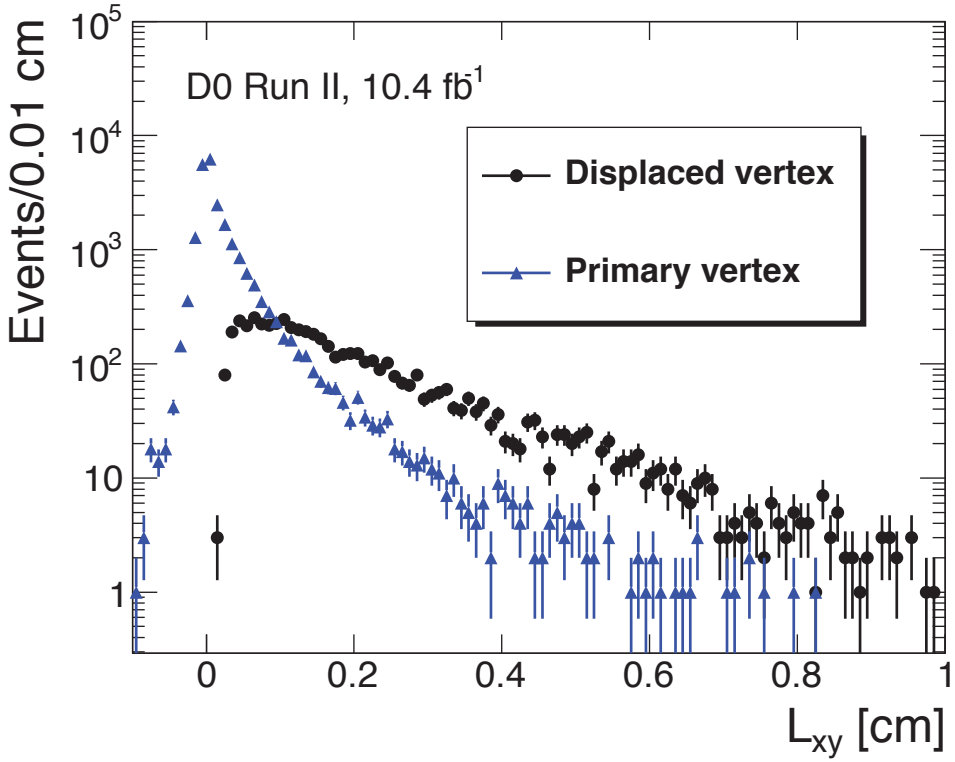
$$\frac{N(H_b \to (Z_c^+(3900) \to J/\psi\pi^+)K^-)}{N(B_d^0 \to J/\psi K^*)} < 0.015 \text{ at } 90\% \text{ C.L.}$$

Prompt production of $\mathbf{Y(4260)}$, $\mathbf{Z_c^+(3900)}$?

- Data re-processed with extended track-finding algorithm optimized for reconstructing low-p_T tracks → ~50% larger
- Same channel: $Y(4260) + \text{anything}$

$$Y(4260) \to Z_c^+(3900)\pi^-$$

$$Z_c^+(3900) \to J/\psi\pi^+$$



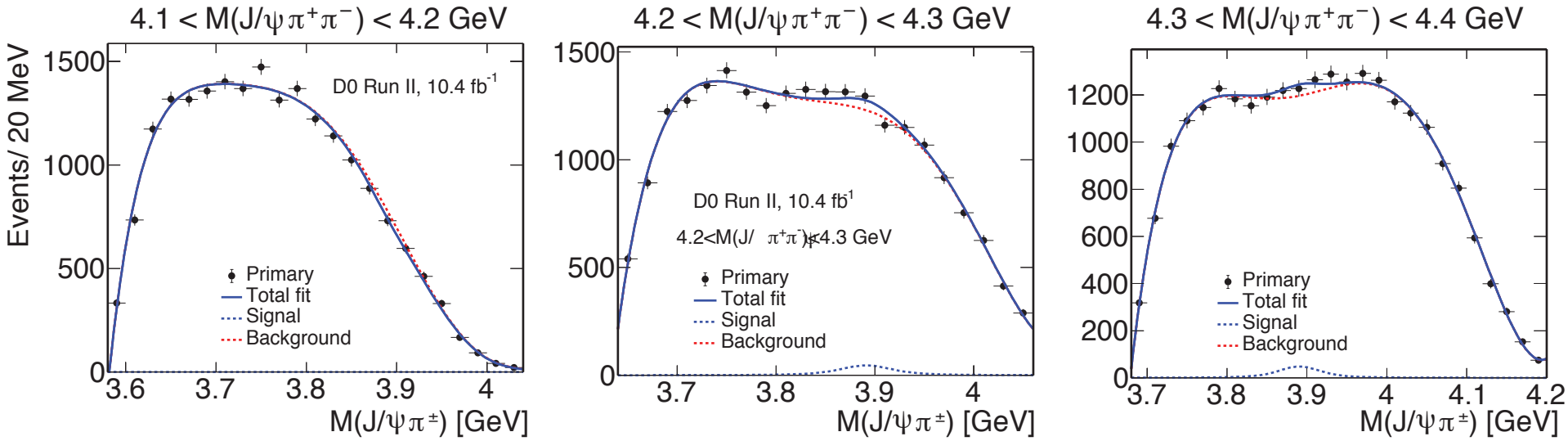
$(J/\psi\pi^+)\pi^- + X$ vertex

Split into two exclusive samples:

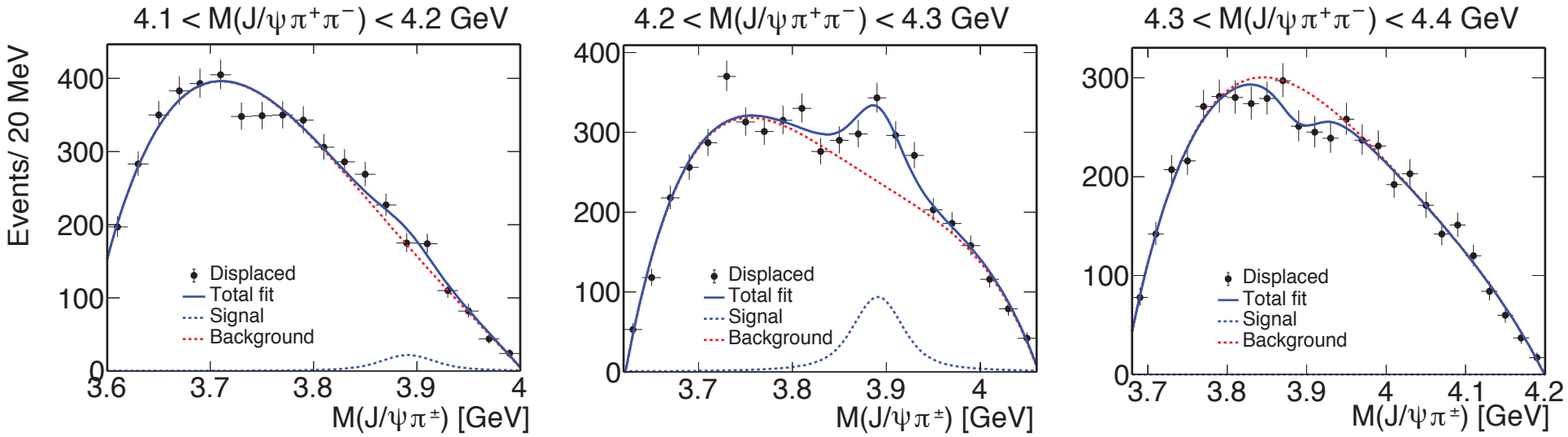
- consistent with primary vertex
- displaced vertex

Prompt production of $Y(4260)$, $Z_c^+(3900)$?

Primary vertex →



Displaced vertex →



$\sim m(Y(4260))$

...more mass bins

Prompt production of $\mathbf{Y(4260)}$, $\mathbf{Z_c^+(3900)}$?

- For $4.2 < M(J/\psi\pi^+\pi^-) < 4.3$ GeV $\sim m(Y(4260))$

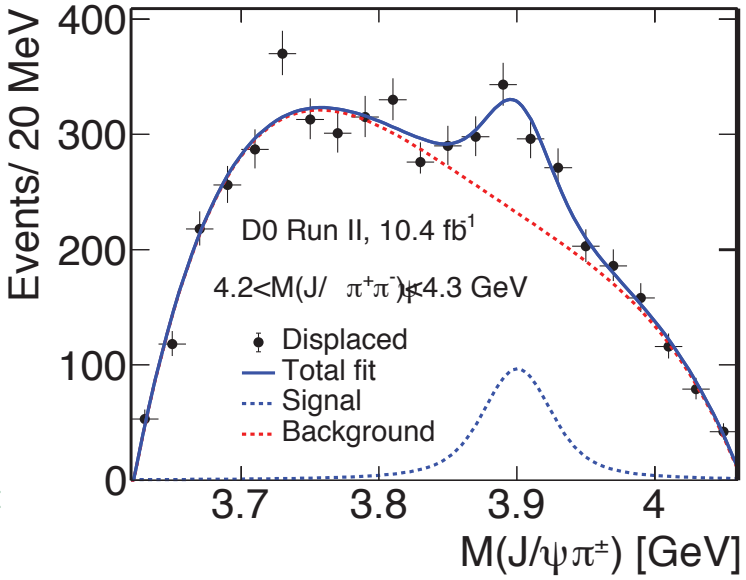
  Displaced vertex $H_b \to (J/\psi\pi^+)\pi^- X$

  $Z_c^+(3900)$ signal at 5.4σ

  $$m = 3902.6 \pm 5.2\,(\text{stat})^{+3.3}_{-1.4}\,(\text{syst})\ \text{MeV}$$

  $$\Gamma = 32^{+28}_{-21}\,(\text{stat})^{+26}_{-7}\,(\text{syst})\ \text{MeV}$$

  (consistent with PDG)



- Acceptance of displaced-vertex selection found using $B_d^0 \to J/\psi K^\pm \pi^\mp$

- No significant signal in primary vertex sample

Prompt production of $\mathbf{Y(4260)}$, $\mathbf{Z_c^+(3900)}$?

State	$N_{\mathrm{prompt}}/N_{\mathrm{non-prompt}}$	
$Y(4260) \to Z_c^+(3900)\pi^-$	$-0.08^{+0.36}_{-0.45}$	< 0.66 at 95% C.L.
	Small compared to:	
$X(3872)$ [1]	~ 2.5	Large prompt production rate often used as argument against it as weakly bound charm-meson molecule e.g., arXiv:1811.08876 [hep-ph]
$X(4140)$ [2]	~ 1.5	

[1] CMS, JHEP **04**, 154 (2013)

[2] ATLAS, JHEP **01**, 117 (2017)

Summary/Conclusion

- Tevatron continues modest contribution in studies of non-standard (exotic) hadrons
- Properties of states including production in $p\bar{p}$ $(\sim q\bar{q})$ at 1.96 TeV and in *b* hadron decays
- $Y(4260)$, $Z_c^+(3900)$ observed in semi-inclusive *b* hadron decays (although not in $\bar{B}_d^0 \to J/\psi\pi^+K^-$)
- $Y(4260)$, $Z_c^+(3900)$ observed in prompt production but at relatively smaller rate than other non-standard states – more likely meson molecular states?