Aleksei Popov (NRC "Kurchatov Institute" - IHEP, Protvino)
on behalf of the DØ Collaboration

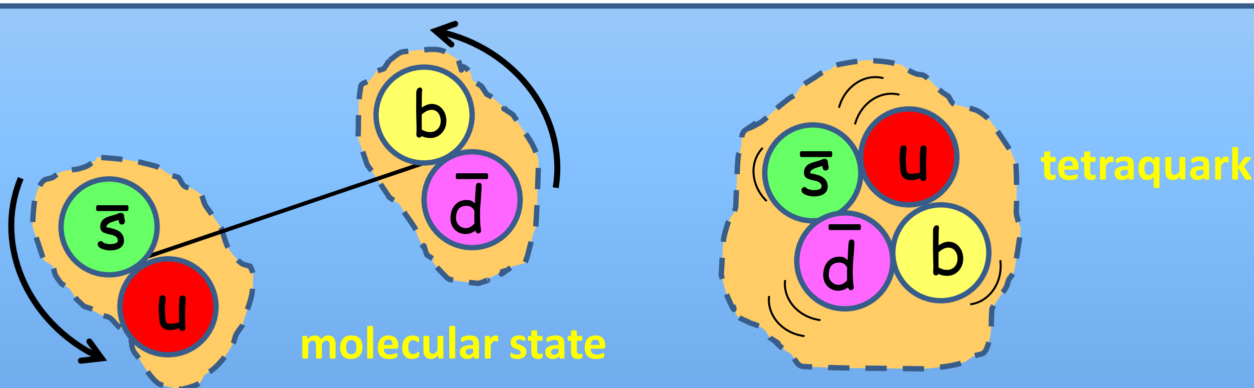
The New Results from Multi-quark Exotic States Searches at DØ Experiment

IV International Conference on Particle Physics and Astrophysics October 26, 2018

Multi-quark States

~20 multi-quark states were observed since 2003 with high significance. Important examples of four-quark states:
$X(3782) \to J/\psi\ \pi\ \pi$, $Z_c(4430) \to \psi(2S)\pi$, $X(4140) \to J/\psi\ \phi$;
pentaquarks: $P_c(4380) \to J/\psi\ p$, $P_c(4450) \to J/\psi\ p$.

Recent review: ***Olsen, Skwarnicki, Zieminska, Rev. Mod. Phys. 90, 015003 (2018)***

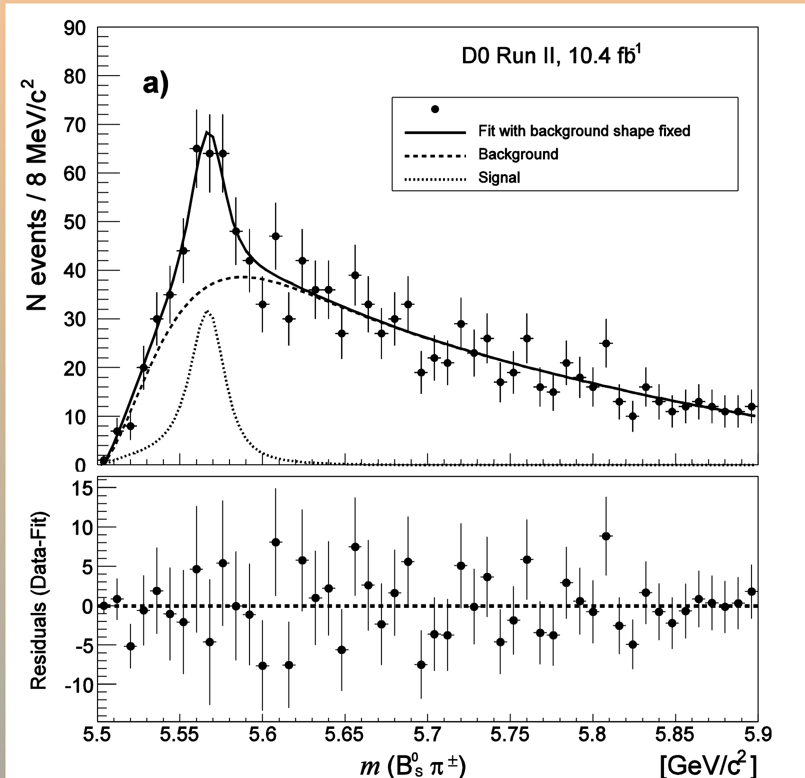


Four-quark states

Meson-meson molecule – two white states loosely bound by a pion exchange.
Compact tetraquark – diquark-antidiquark pair connected by color forces.

Evidence for $B_s\pi$ state, $B_s \to J/\psi\ \phi(1020)$

V.M. Abazov et al (D0 Collaboration), Phys. Rev. Lett. 117, 022003 (2016)



X(5568)

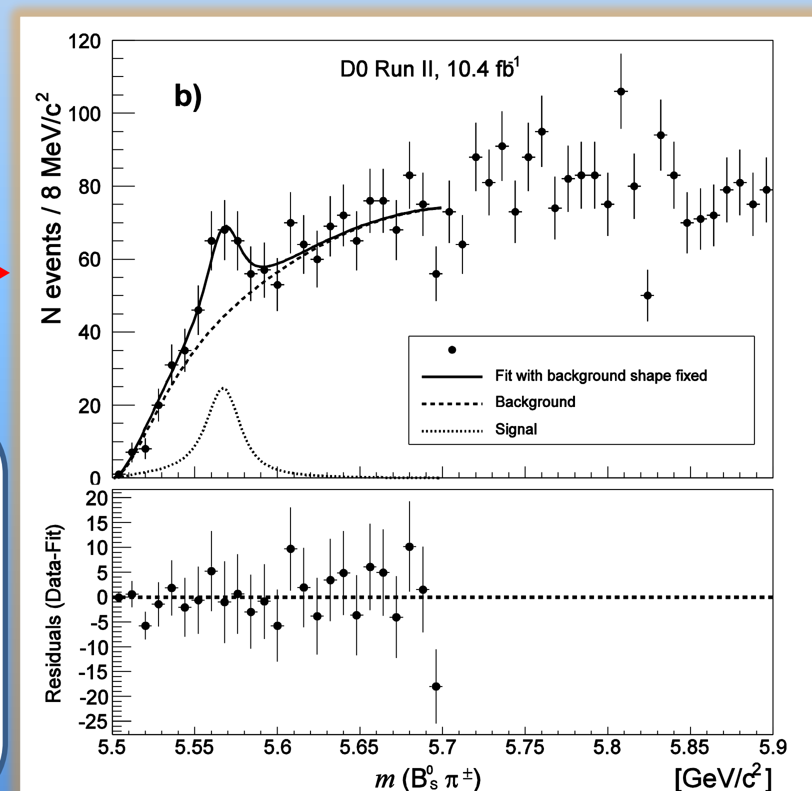
$$M = 5567.8 \pm 2.9(\mathrm{stat})^{+0.9}_{-1.9}(\mathrm{syst})\,\mathrm{MeV/c^2}$$

$$\Gamma = 21.9 \pm 6.4(\mathrm{stat})^{+5.0}_{-2.5}(\mathrm{syst})\,\mathrm{MeV/c^2}$$

$$\rho(X(5568)/B_s) = 8.6 \pm 1.9(\mathrm{stat}) \pm 1.4(\mathrm{syst})\%$$

← ΔR cut

No ΔR cut →



Statistical significance (with systematics and LEE)

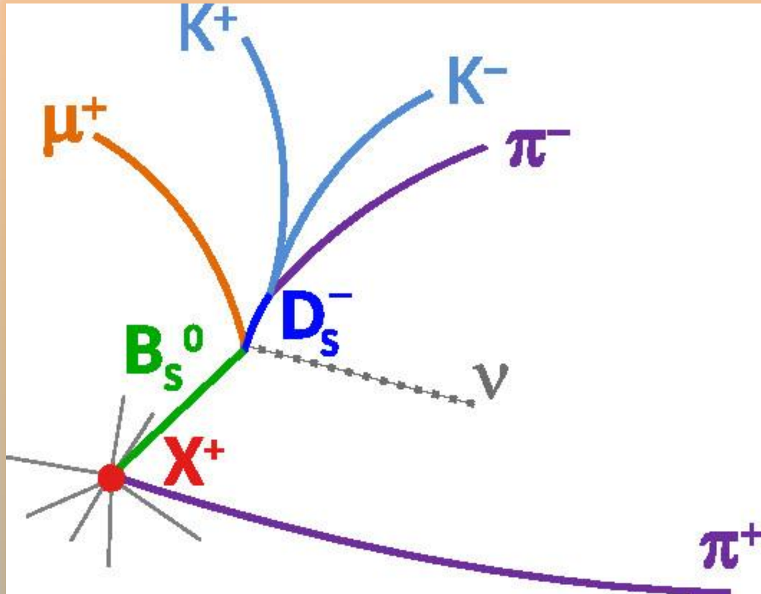
With $\Delta R = \sqrt{\Delta\eta(B_s,\pi) + \Delta\phi(B_s,\pi)} < 0.3$ **cut:**

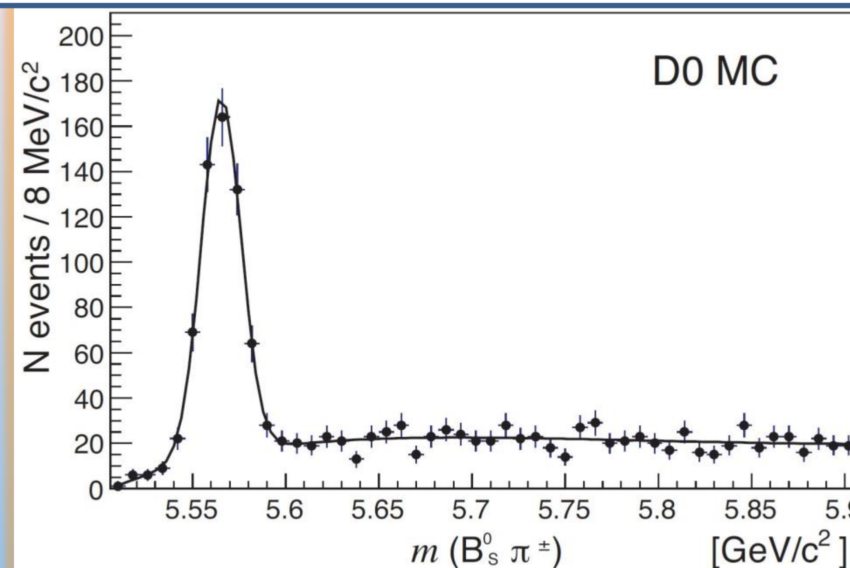
5.1σ

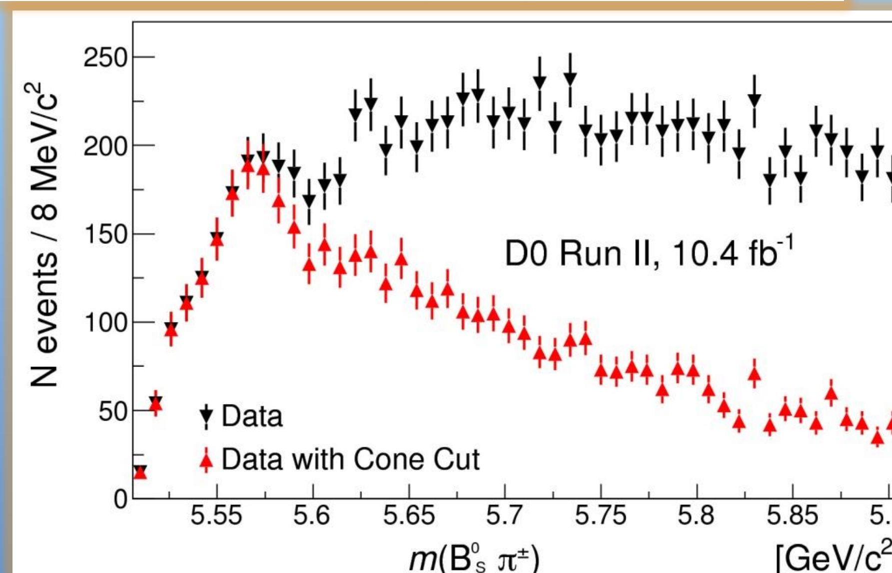
Without ΔR cut: 3.9σ

X(5568)→$B_s\pi$ with semileptonic decays of the B_s mesons

$X(5568) \to B_s \pi,\ B_s \to D_s \mu X_{any},\ D_s \to \phi(1020)\,\pi$







Event reconstruction and selection

D0 Run II integrated luminosity 10.4 fb^{-1}

$3 < p_T(\mu) < 25$ GeV/c; $p_T(K) > 1$ GeV/c;
$1.012 < M(KK) < 1.03$ GeV/c^2
$4.5 < M(D_s\mu) < M(B_s)$; $p_T(D_s\mu) > 10$ GeV/c

$M(B_s\pi) = M(D_s\mu\pi) - M(D_s\mu) + M(B_s)$,
where $M(B_s) = 5.3667$ GeV/c^2

$5.506 < M(B_s\pi) < 5.906$ GeV/c^2

$X(5568)\to B_s\pi$ with semileptonic decays of the B_s mesons

Background parametrization

$F_{bgr}(m)=(C_1\cdot m+C_2\cdot m^2+C_3\cdot m^3+C_4\cdot m^4)\times \exp(C_5\cdot m+C_6\cdot m^2)$, where $m=M-M_{thr}$

Fit to data

$F_{fit}(m,M_x,\Gamma_X)=f_{bgr}\cdot F_{bgr}(m)+f_{sig}\cdot F_{sig}(m,M_x,\Gamma_X)$

where $F_{sig}(m,M_x,\Gamma_X)$ - S-wave BW function convoluted with resolution (including missing neutrino effect), f_{bgr}, f_{sig} - normalization coefficients.

Fit results without ΔR cut

$M_x = 5566.7^{+3.6}_{-3.4}$ MeV/c²

$\Gamma_x = 6.0^{+9.5}_{-6.0}$ MeV/c², $N_{ev} = 139^{+51}_{-63}$

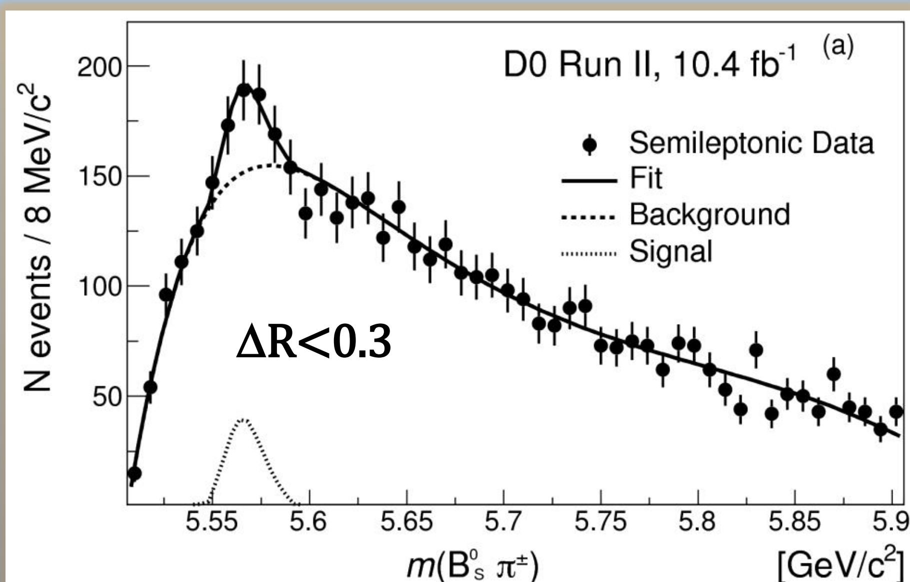
Local significance: 4.5σ

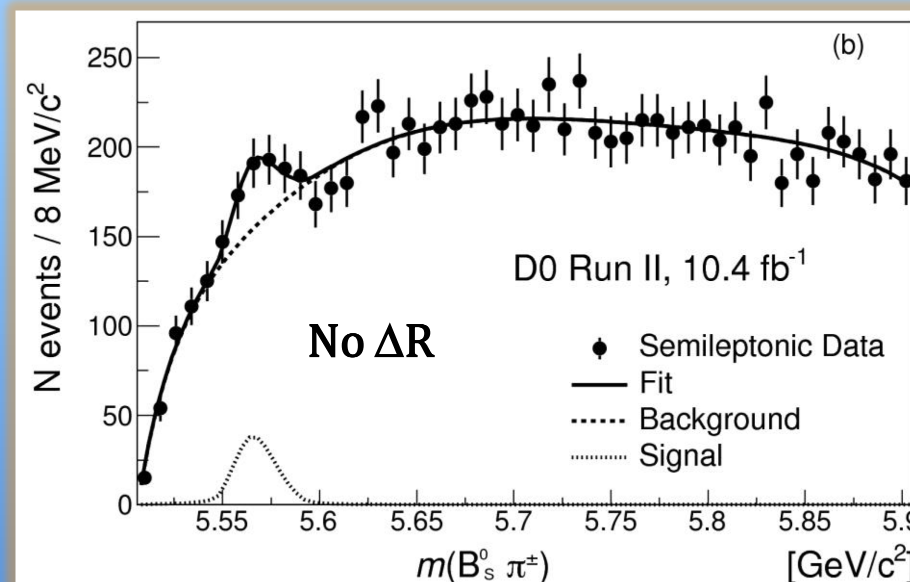
Fit results with ΔR cut

$M_x = 5566.4^{+3.4}_{-2.8}$ MeV/c²

$\Gamma_x = 2.0^{+9.5}_{-2.0}$ MeV/c², $N_{ev} = 121^{+51}_{-34}$

Local significance: 4.3σ





$X(5568) \to B_s\pi$ with semileptonic decays of the B_s mesons

Systematic uncertainties

Background shape description, background reweighting, B_s mass scale (MC and data), detector resolution and missing neutrino effect, P-wave Breit-Wigner.

Significance with systematics

without ΔR cut: 3.4σ
with ΔR cut 3.2σ

Production ratio of $X(5568)$ to B_s

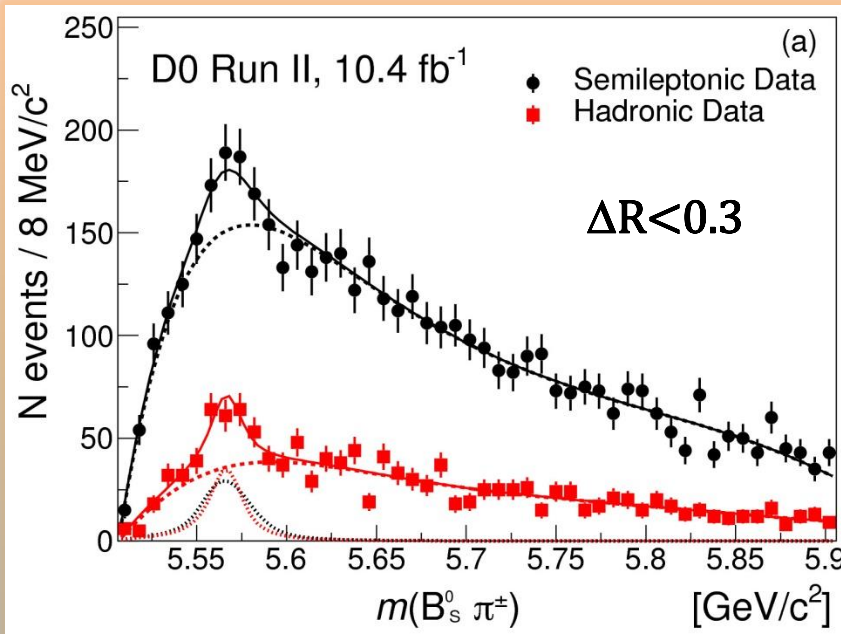
$$\rho(X(5568)/B_s) = 7.3^{+2.8}_{-2.4}(\text{stat})^{+0.6}_{-1.7}(\text{syst})\%$$

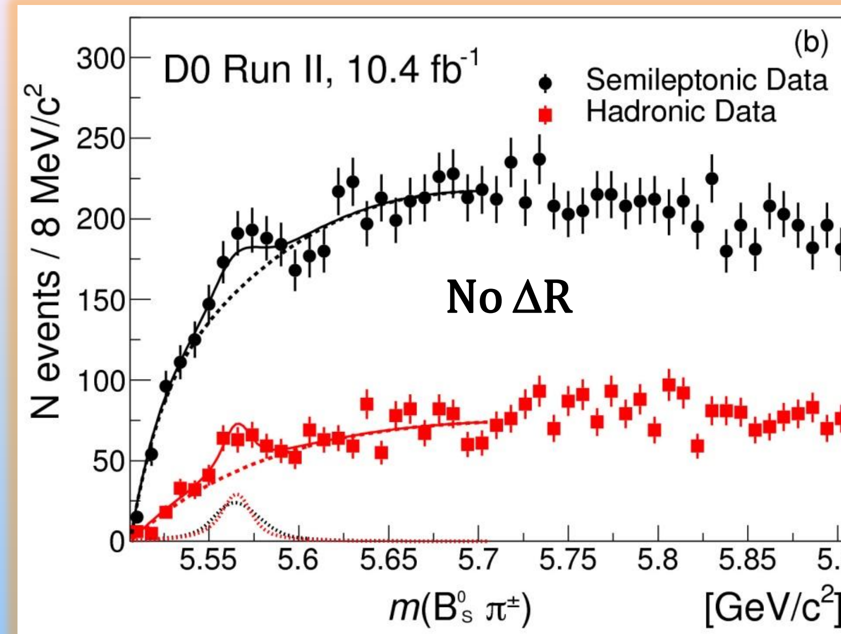
Comparison with hadronic channel

	Semileptonic		Hadronic (from Ref. [15])	
	Cone cut	No cone cut	Cone cut	No cone cut
Fitted mass, MeV/c^2	$5566.4^{+3.4}_{-2.8}{}^{+1.5}_{-0.6}$	$5566.7^{+3.6}_{-3.4}{}^{+1.0}_{-1.0}$	$5567.8 \pm 2.9^{+0.9}_{-1.9}$	5567.8
Fitted width, MeV/c^2	$2.0^{+9.5}_{-2.0}{}^{+2.8}_{-2.0}$	$6.0^{+9.5}_{-6.0}{}^{+1.9}_{-4.6}$	$21.9 \pm 6.4^{+5.0}_{-2.5}$	21.9
Fitted number of signal events	$121^{+51}_{-34}{}^{+9}_{-28}$	$139^{+51}_{-63}{}^{+11}_{-32}$	$133 \pm 31 \pm 15$	106 ± 23(stat)
Local significance	4.3σ	4.5σ	6.6σ	4.8σ
Significance with systematics	3.2σ	3.4σ	5.6σ	...
Significance with LEE + systematics	...	...	5.1σ	3.9σ

Results in semileptonic channel are compatible with those in hadronic channel within uncertainties.

Simultaneous fit to hadronic and semileptonic channels





	Cone cut	No cone cut
Fitted mass, MeV/c^2	$5566.9^{+3.2}_{-3.1}(\text{stat})^{+0.6}_{-1.2}(\text{syst})$	$5565.8^{+4.2}_{-4.0}(\text{stat})^{+1.3}_{-2.0}(\text{syst})$
Fitted width, MeV/c^2	$18.6^{+7.9}_{-6.1}(\text{stat})^{+3.5}_{-3.8}(\text{syst})$	$16.3^{+9.8}_{-7.6}(\text{stat})^{+4.2}_{-6.5}(\text{syst})$
Fitted number of hadronic signal events	$131^{+37}_{-33}(\text{stat})^{+15}_{-14}(\text{syst})$	$99^{+40}_{-34}(\text{stat})^{+18}_{-33}(\text{syst})$
Fitted number of semileptonic signal events	$147^{+42}_{-37}(\text{stat})^{+17}_{-16}(\text{syst})$	$111.7^{+46}_{-39}(\text{stat})^{+20}_{-38}(\text{syst})$
χ^2/ndf	$94.7/(100-6)$	$54.2/(50-6)$
p-value	2.2×10^{-14}	1.9×10^{-8}
Local significance	7.6σ	5.6σ
Significance with LEE	6.9σ	5.0σ
Significance with LEE + systematics	6.7σ	4.7σ

Significance increases with addition of semileptonic sample

$X(5568) \to B_s \pi$ with semileptonic decays of the B_s mesons

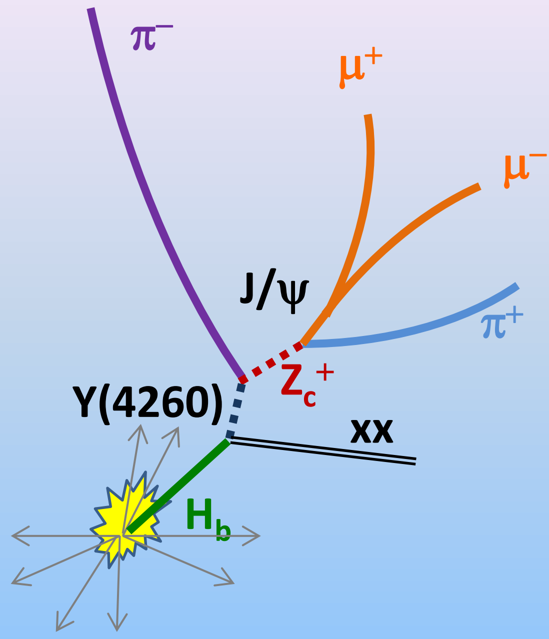
Published: *V.M. Abazov et al (D0 Collaboration), Phys. Rev. D 97, 092004 (2018)*

World comparison

Analysis	Production ratio (B_s / X(5568))	Reference
D0 ($J/\psi\ \phi$)	8.6 ± 1.9 ± 1.4%	PRL 117,022003(2016)
D0 ($\mu\ D_s$)	$7.3^{+2.8}_{-2.4}{}^{+0.6}_{-1.7}\%$	PRD 97, 092004 (2018)
LHCb	< 2.4% ($p_T(B_s^0)$ > 10 GeV)	PRL 117,152003 (2016)
CMS	< 1.1% ($p_T(B_s^0)$ > 10 GeV)	PRL 120, 202005 (2018)
ATLAS	< 1.5% ($p_T(B_s^0)$ > 10 GeV)	PRL 120, 202007 (2018)
CDF	< 6.7% (2.3 ± 1.9 ± 0.9%)	PRL 120, 202006 (2018)

LHC experiments do not observe X(5568), but CM energy is rather different. CDF results is in $\sim 2\sigma$ tension with DØ, kinematic selections vary substantially. Without theoretical model for X(5568) production and decays it is hard to compare various experiments quantitatively.

A search for $Z_c(3900)$ at DØ experiment



$Z_c^{\pm}(3900)$ was discovered in 2013 by Belle and BESIII in the process:

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

Y(4260): two interfering resonances ψ(4260) and ψ(4360) (BESIII).

- Which component decays to $Z_c^{\pm}(3900)$?
- Are there decays $H_b \to Y(4260)\left(\to Z_c^{\pm}(3900)\,\pi^{\mp}\right) + \text{anything}$

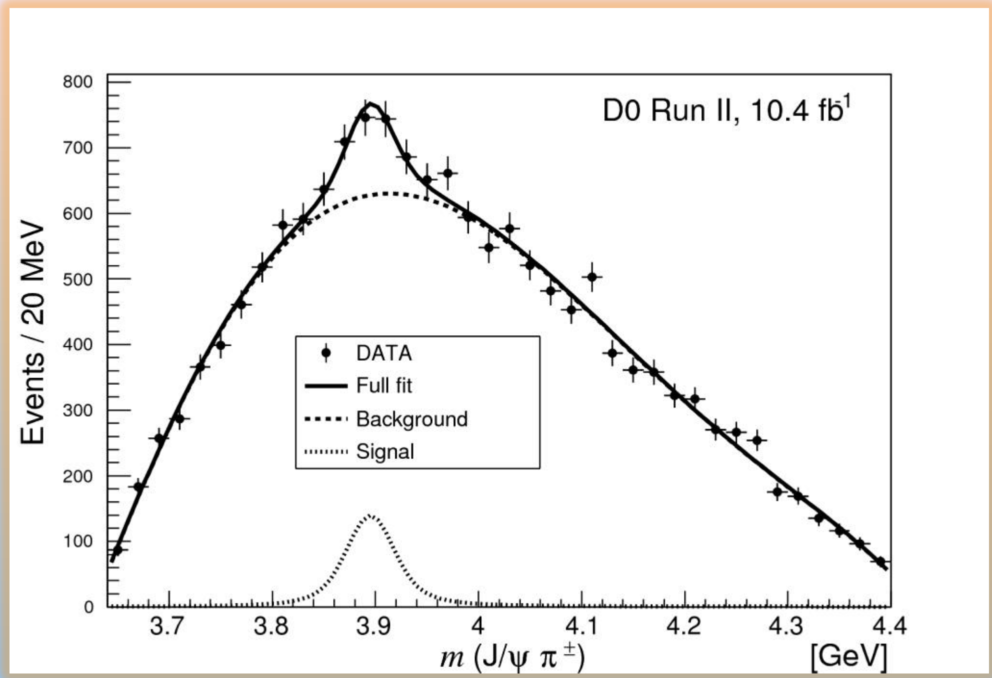
$$H_b \to Y(4260) + \text{anything},\ Y(4260) \to Z_c^{\pm}(3900)\,\pi^{\mp},\ Z_c^{\pm}(3900) \to J/\psi\,\pi^{\pm}$$

- 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.

A search for $Z_c(3900)$ at DØ experiment



Fit to data

Background parametrization:
Chebyshev polynomials.
Signal parametrization:
S-wave Breit-Wigner smeared with resolution (17 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

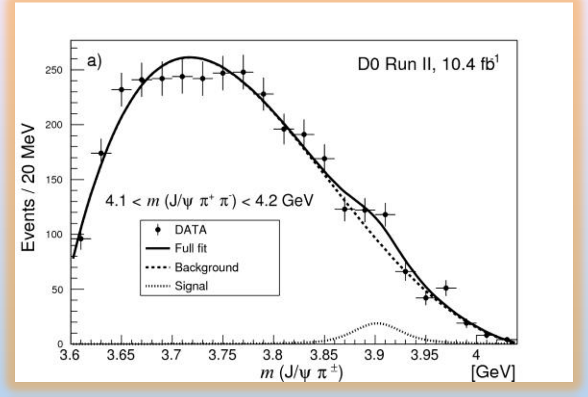
$$M_x = 3895.0 \pm 5.2(stat)^{+4.0}_{-2.7}(syst)$$ MeV,

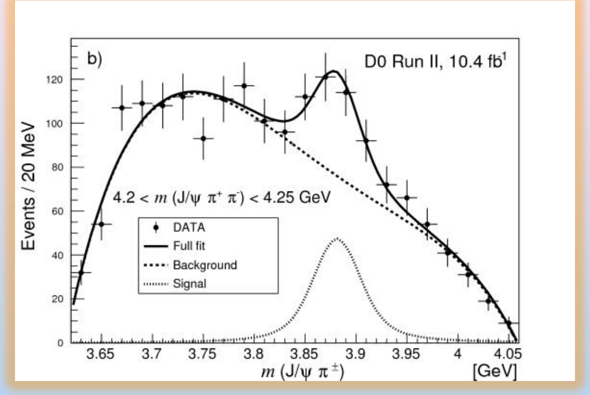
$$N_{ev} = 505 \pm 92(stat) \pm 64(syst).$$

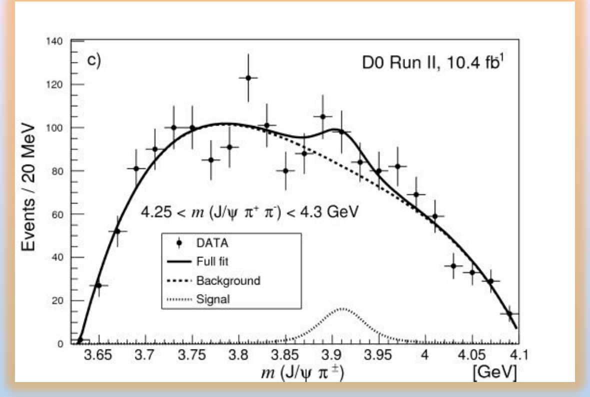
Local significance: 5.6σ

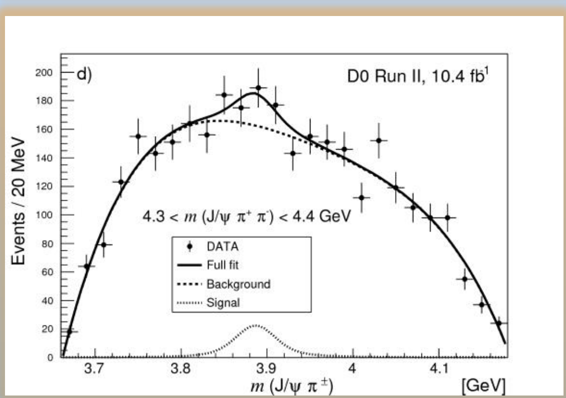
Significance with systematics: 4.6σ

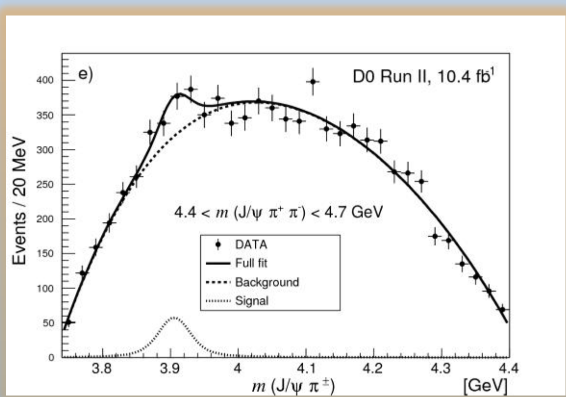
A search for $Z_c(3900)$ at DØ experiment

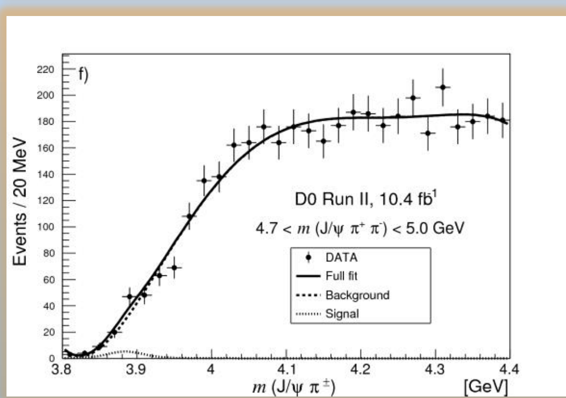


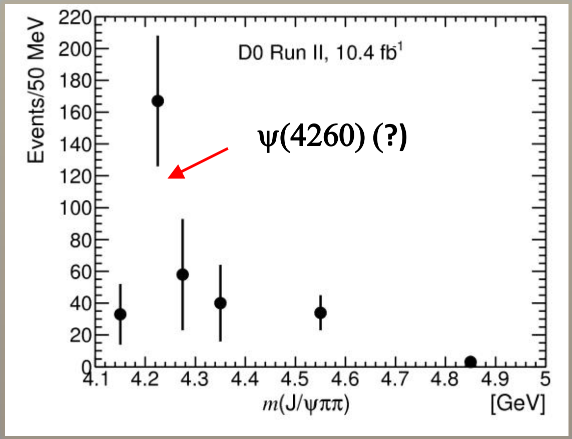


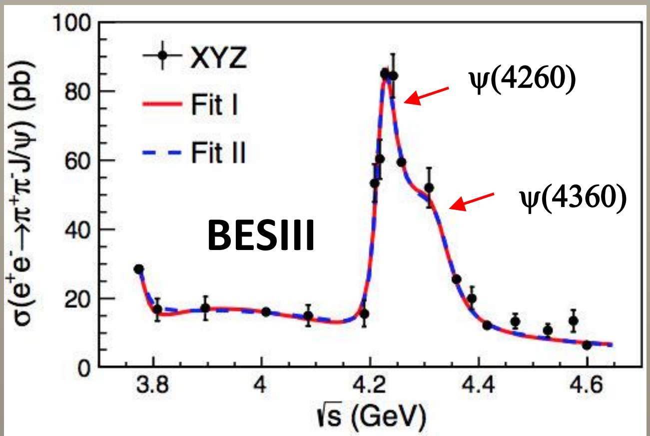




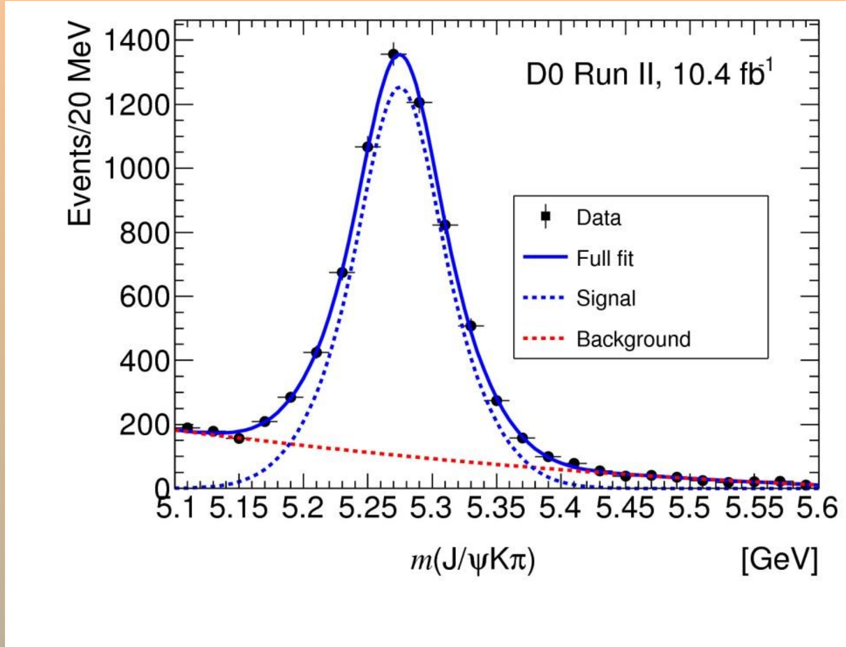








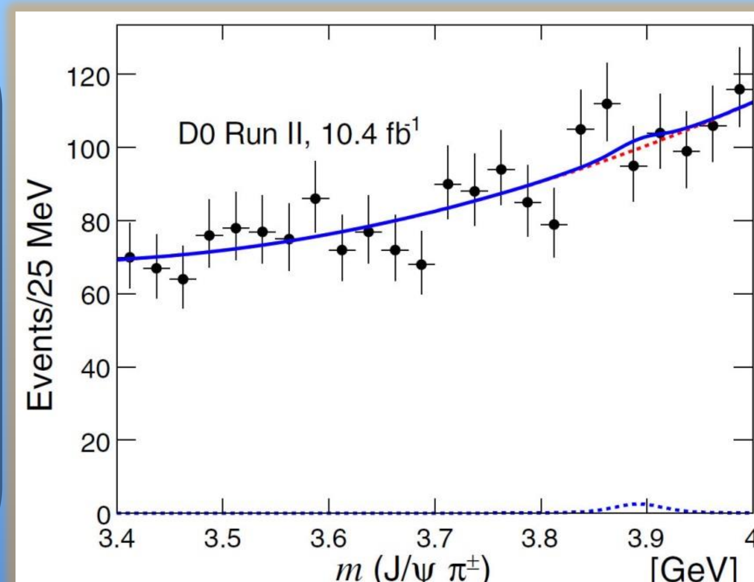
A search for $Z_c(3900)$ at DØ experiment



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 $Z_c(3900)$ ($5.15 < M(J/\psi\ \pi^+ K^-) < 5.4$ GeV, 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.



Conclusion

- We confirm production of $X(5568)$ state in proton-antiproton collisions at 1.96 TeV with an independent data set with semileptonic decay of B_s^0 meson.
- $X(5568)$ properties in hadronic and semileptonic channels are consistent.
- Combined significance of $X(5568)$ state observation in these two channels is 6.7σ.
- DØ observed $Z_c^{\pm}(3900)$ exotic state decaying to $J/\psi\ \pi^{\pm}$ in proton-antiproton collisions at 1.96 TeV with 4.6σ significance.
- Measured mass of $Z_c^{\pm}(3900)$ is $M_X = 3895.0 \pm 5.2(stat)^{+4.0}_{-2.7}(syst)$ MeV consistent with Belle and BESIII measurements.
- Ratio $\frac{N(Z_c(3900)\to J/\psi\ \pi)}{N(B_d^0\to J/\psi\ K^*)} = 8.5 \pm 1.9\ \%$.
- Published in *Phys. Rev. D98, 052010 (2018)*.

Backup slides

$X(5568) \to B_s\pi$ with semileptonic decays of the B_s mesons

Background parametrization

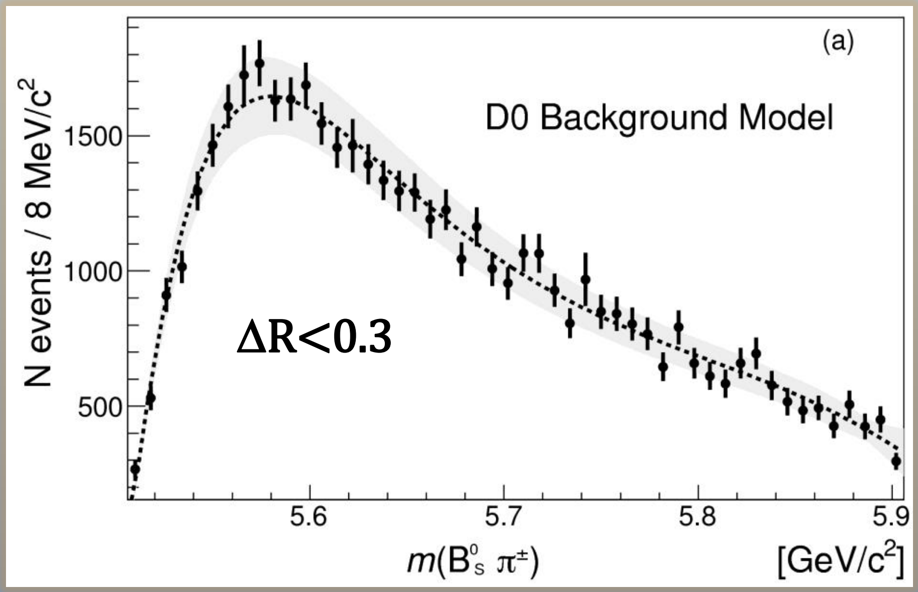
Background distribution is obtained from MC and reweighted to data.

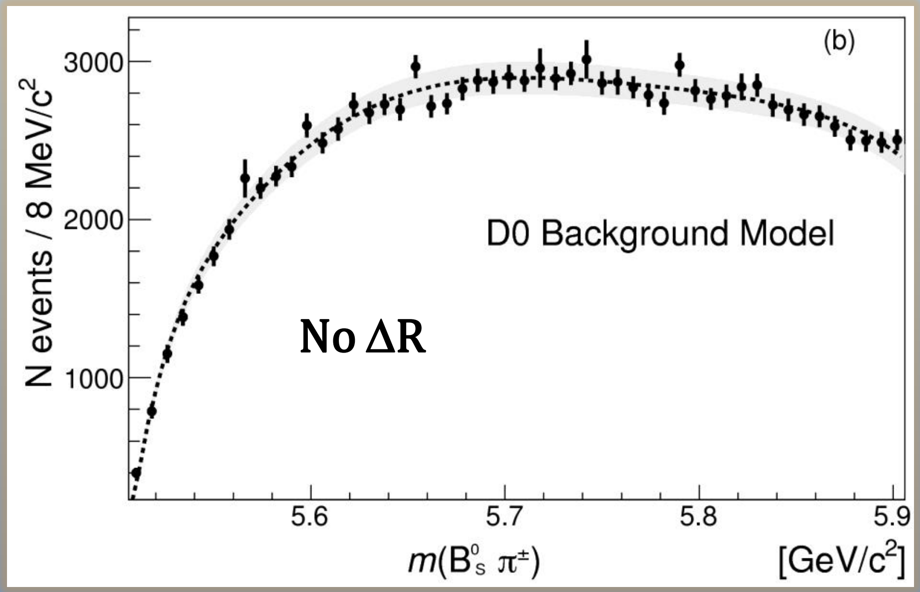
$F_{bgr}(m)=(C_1 \cdot m+C_2 \cdot m^2+C_3 \cdot m^3+C_4 \cdot m^4)\times \exp(C_5 \cdot m+C_6 \cdot m^2)$, where $m=M-M_{thr}$

Several alternative parametrizations of the background were used to model the background for background shape systematics estimation.

Alternative parametrizations

1. $F_{bgr}(M)=(C_1+C_2 \cdot m^2+C_3 \cdot m^3+C_4 \cdot m^4)\times \exp(C_5 \cdot m+C_6 \cdot m^2)$, where $m=M-\Delta$, $\Delta=5.5$ GeV/c^2.
2. $F_{bgr}(M) = M \cdot \left(\frac{M^2}{M_{thr}^2} - 1\right)^{C_1} \times \exp(C_2 \cdot M)$, where M_{thr} is a $B_s\pi$ threshold.
3. Histogram smoothing (one iteration of 353QH algorythm).





X(5568)→$B_s\pi$ with semileptonic decays of the B_s mesons

Systematic uncertainties

Source	Mass, MeV/c^2	Width, MeV/c^2	Event yield, events
Cone cut			
(i) Background shape description	+0.7; −0.3	+0.0; −1.0	+0.0; −26.6
(ii) Background reweighting	+0.1; −0.1	+0.4; −0.4	+3.9; −4.2
(iii) B_s^0 mass scale, MC simulation and data	+0.1; −0.3	+0.8; −1.0	+5.1; −7.8
(iv) Detector resolution	+0.9; −0.0	+2.7; −1.0	+6.5; −0.0
(v) P-wave Breit-Wigner	+0.0; −0.4	+0.0; −1.0	+0.0; −3.7
(vi) Missing neutrino effect	+1.0; −0.0	...	...
Total	+1.5; −0.6	+2.8; −2.0	+9.1; −28.3
No cone cut			
(i) Background shape description	+0.0; −0.7	+0.7; −2.5	+4.8; −28.0
(ii) Background reweighting	+0.1; −0.1	+0.7; −0.7	+5.0; −5.0
(iii) B_s^0 mass scale, MC simulation and data	+0.3; −0.5	+1.0; −1.4	+7.5; −9.6
(iv) Detector resolution	+0.0; −0.5	+1.3; −2.6	+3.7; −6.4
(v) P-wave Breit-Wigner	+0.0; −0.2	+0.0; −2.4	+0.0; −7.0
(vi) Missing neutrino effect	+1.0; −0.0	...	...
Total	+1.0; −1.0	+1.9; −4.6	+10.9; −31.5

A search for $Z_c(3900)$ at DØ experiment

Systematic uncertainties

Systematic uncertainty	Mass (MeV)	Yield
Mass calibration	$^{+3}_{-0}$	< 1
Mass resolution	< 0.1	± 27
Background shape	± 0.4	± 53
Bin size	± 1.1	± 9
Signal model	± 2.4	± 3
Natural width variation	< 0.1	± 23
Total (sum in quadrature)	$-2.7, +4.0$	± 64

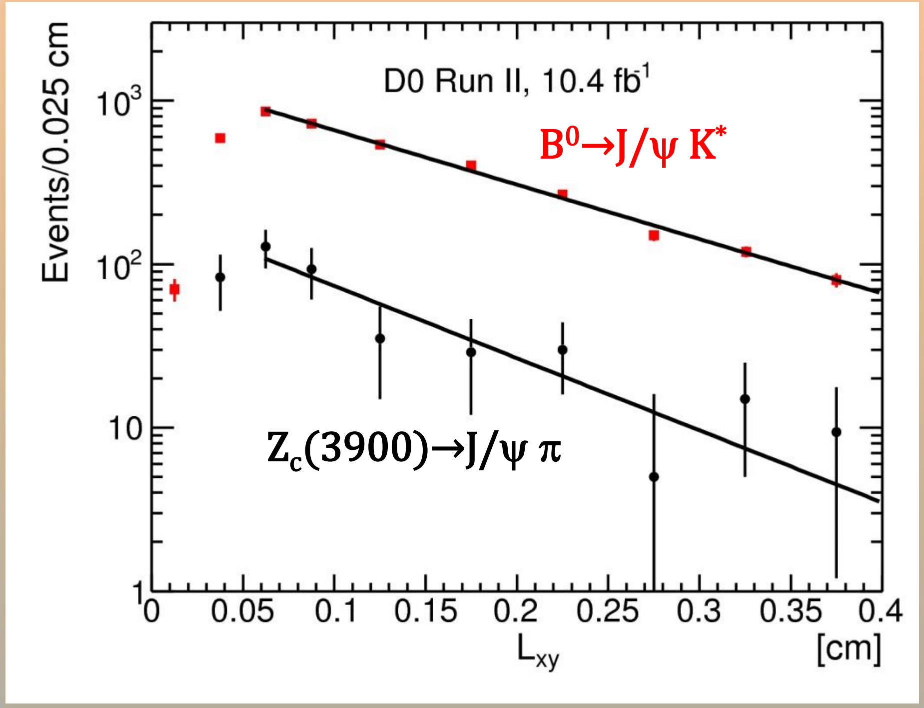
A search for $Z_c(3900)$ at DØ experiment

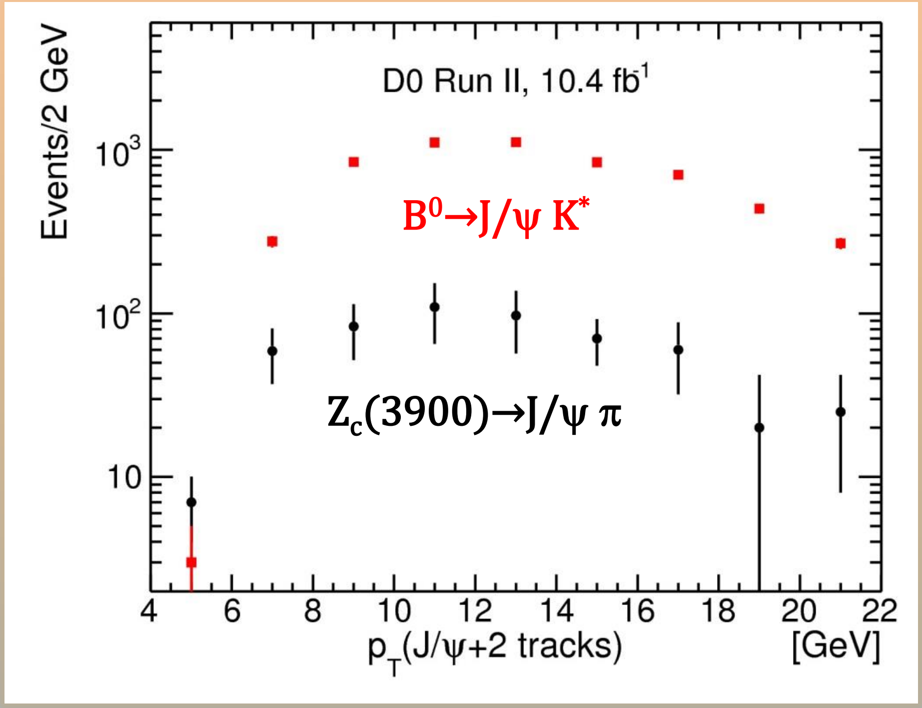
Cross-checks

- Two ranges of $p_T(\pi)$ from $J/\psi\ \pi$ system (>1.5 or < 1.5 GeV).
- Three pseudorapidity ranges ($|\eta|<0.9$, $0.9 < |\eta|<1.3$, $1.3 < |\eta|<2.0$).
- Z_c^+ and Z_c^-.
- Events in the high χ^2 tail.
- Various Run II periods.
- J/ψ mass window and sidebands.
- $M(\pi^+\pi^-)$ from $J/\psi\ \pi^+\pi^-$ system (>1.0 or < 1.0 GeV).
- Reversed IP cut on second track (to show predominant non-prompt production).
- Same sign pion pairs from $J/\psi\ \pi\ \pi$ system.

All cross-checks provided expected results.

A search for $Z_c(3900)$ at DØ experiment





The L_{xy} distribution was fitted with $\sim e^{-L_{xy}/\Lambda}$

$Z_c(3900) \to J/\psi\ \pi$: $\Lambda = 0.098 \pm 0.030$;
$B^0 \to J/\psi\ K^*$: $\Lambda = 0.130 \pm 0.004$. Consistent with each other.

The two p_T distributions are also similar.