Search for Multi-quark Exotic states with Heavy Flavor at DØ Experiment

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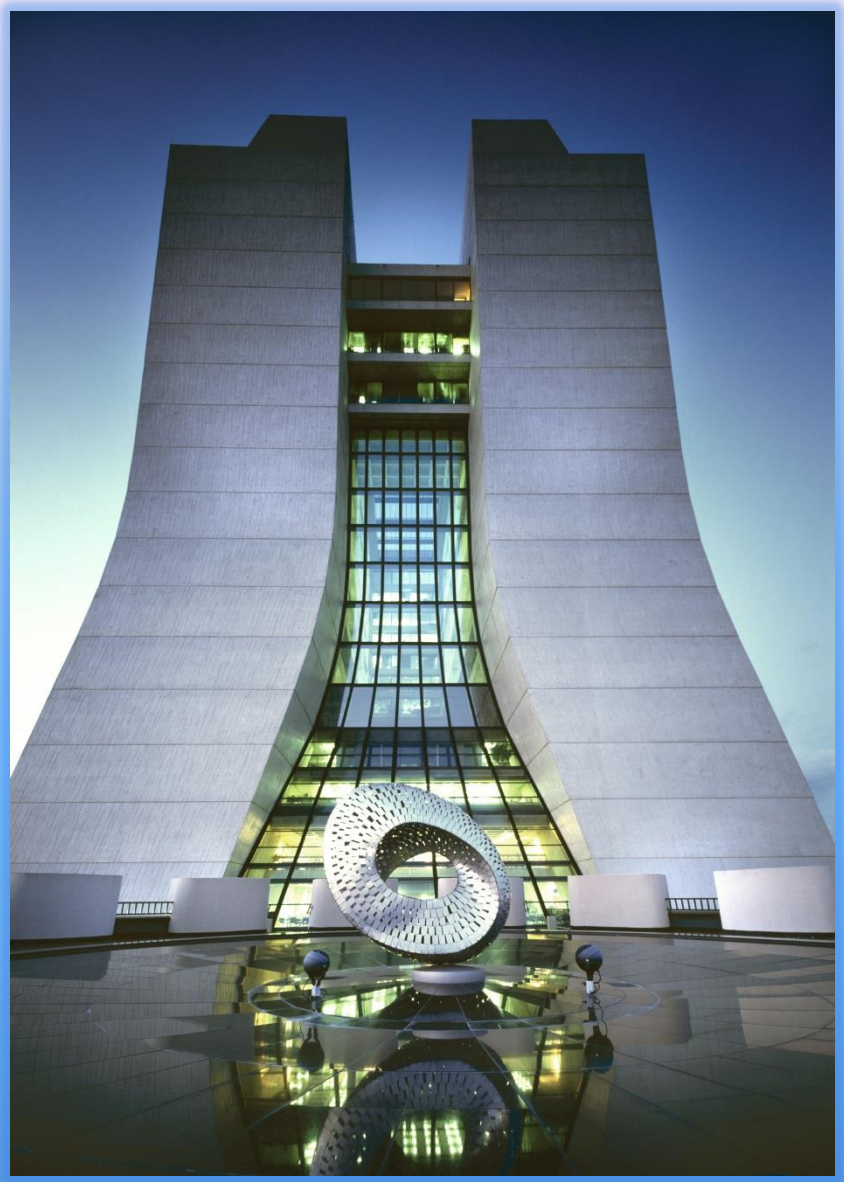
on behalf of the DØ Collaboration

October 4, 2017

Outline

- Evidence for a $X(5568) \rightarrow B_s\pi$
- Confirmation of the $X(5568)$ with semileptonic decays of B_s meson
- Search for exotic baryons decaying to $J/\psi\ \Lambda$ pairs
- Conclusion



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

$$X(5568) \to B_s^0\,\pi^{\pm},$$
$$B_s^0 \to J/\psi\phi\,,\ J/\psi \to \mu^+\mu^-,\ \phi \to K^+K^-.$$

Event reconstruction and selection

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

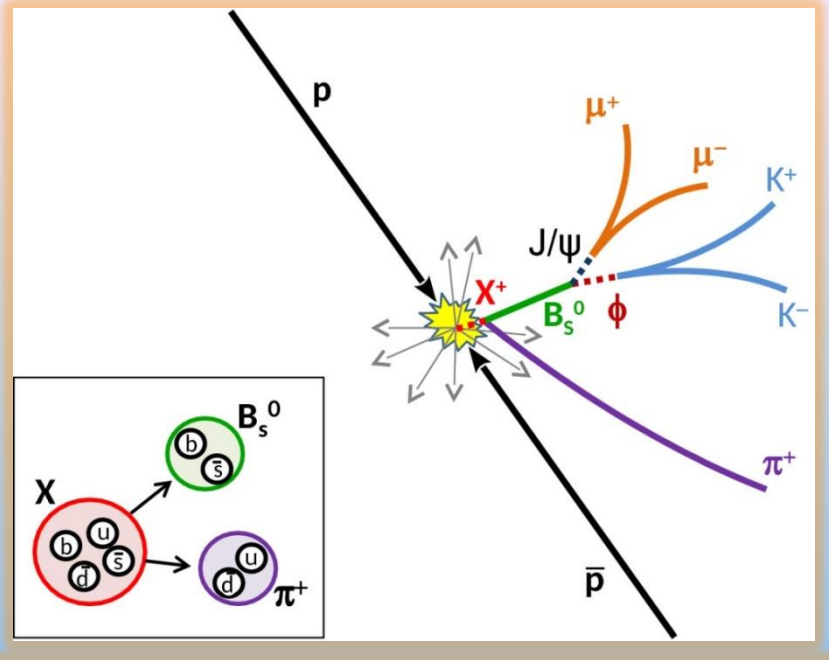
$p_T(\mu) < 1.5$ GeV/c;
$2.92 < M(\mu\mu) < 3.25$ GeV/c^2;
$p_T(K) > 0.7$ GeV/c;
$1.012 < M(K^+K^-) < 1.03$ GeV/c^2
$5.303 < M(J/\psi\ K^+K^-) < 5.423$ GeV/c^2;

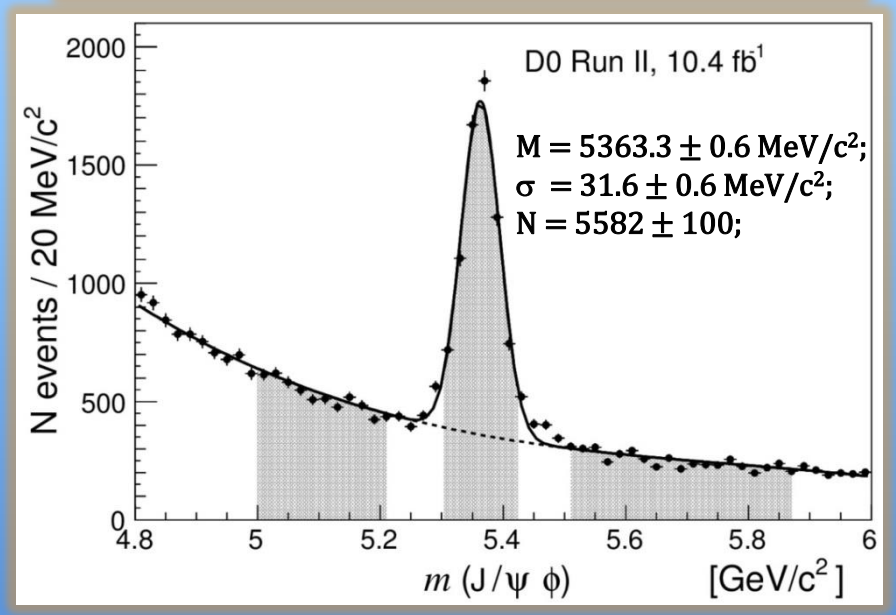
$p_T(\pi) > 0.5$ GeV/c;
$p_T(B_s^0\pi) > 10$ GeV/c;

$\Delta R = \sqrt{\Delta\varphi^2 + \Delta\eta^2} < 0.3$, the "cone" cut between B_s and π.

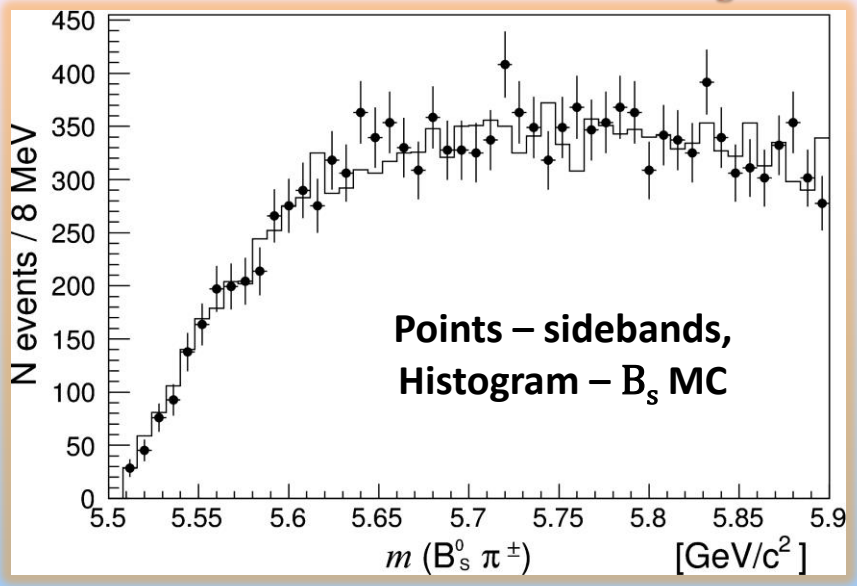
$M(B_s\pi) = M(J/\psi\phi\pi) - M(J/\psi\phi) + M(B_s)$,
where $M(B_s) = 5.3667$ GeV/c^2

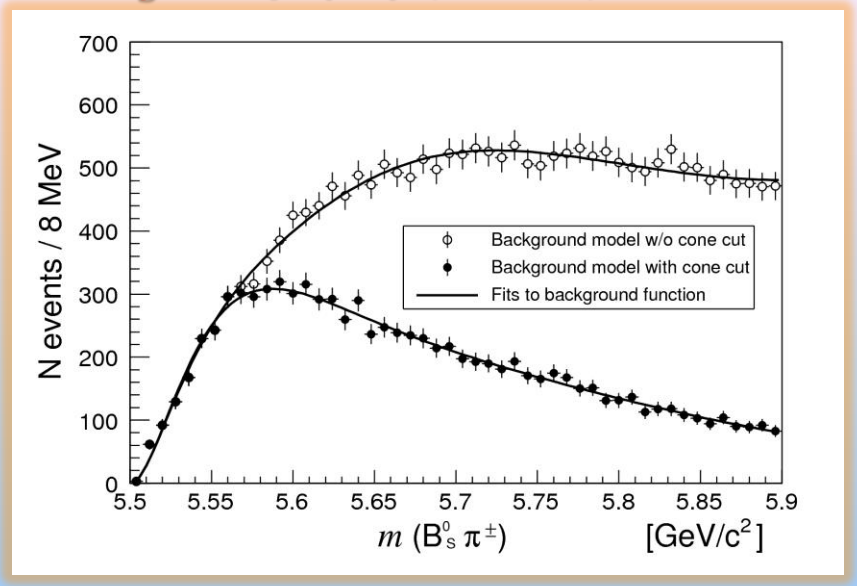
$5.5 < M(B_s\pi) < 5.9$ GeV/c^2





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





Background:

a.) Real B_s – modeled by MC; b.) non-B_s (combinatorial) – taken from B_s sidebands (data). Both have a similar shape and were combined in right proportion.

Background parametrization:

$(c_1+c_2\cdot m^2+c_3\cdot m^3+c_4\cdot m^4)\times \mathrm{Exp}(c_5+c_6\cdot m+c_7\cdot m^2)$ **, where** $m = M - 5.5\ \mathrm{GeV}/c^2$.

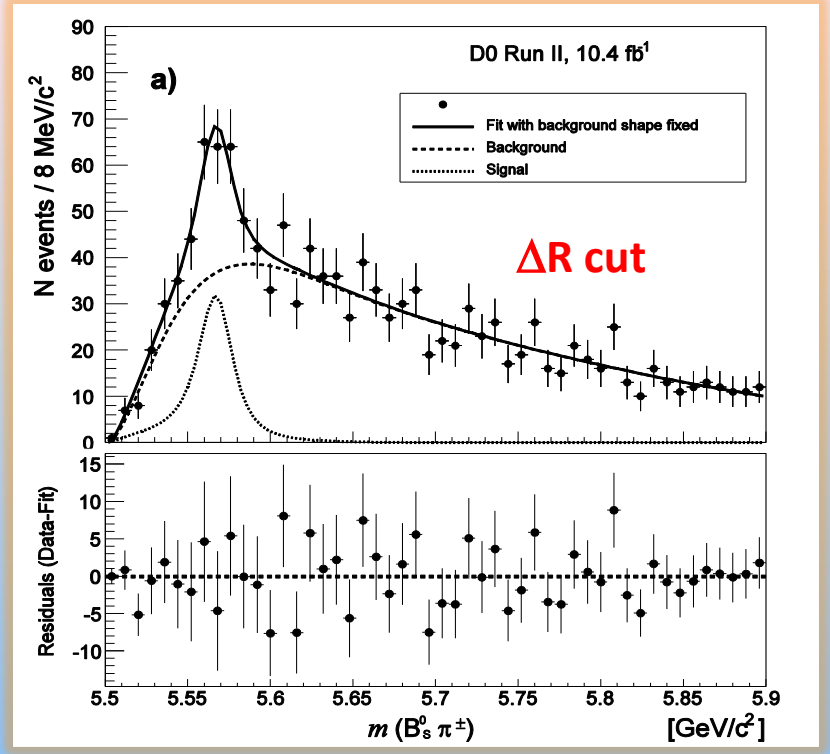
Signal: Relativistic S-wave Breit-Wigner convoluted with Gaussian resolution $\sigma = 3.8\ \mathrm{MeV}/c^2$.

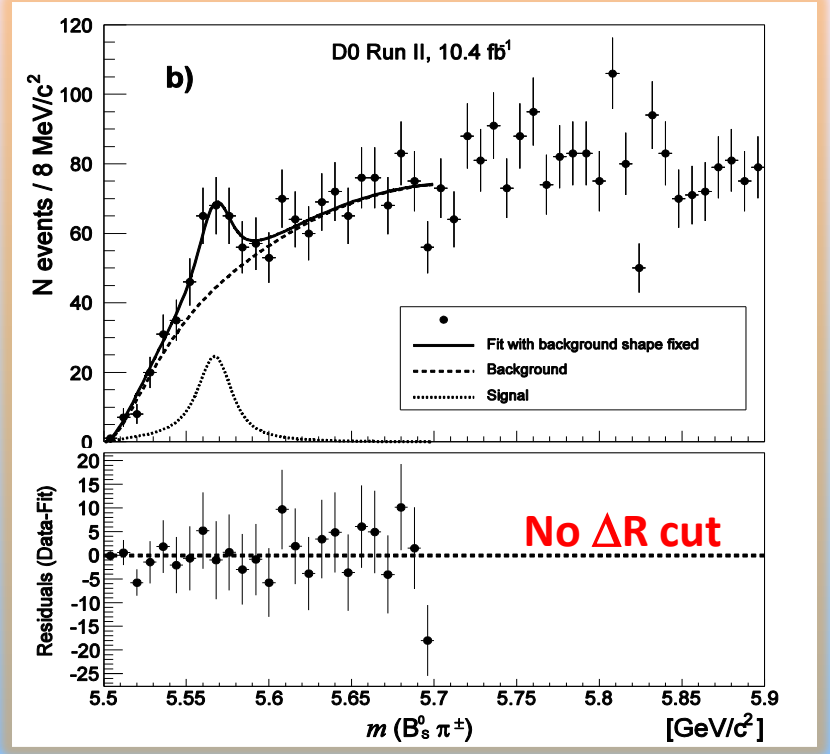
Fitting function:

$N_X \cdot F_{sig}(m,M_X,\Gamma_X) + f_{bkg} \cdot F_{bkg}(m)$,

with free N_X, M_X, Γ_X, f_{bkg}.

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





X(5568)

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

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

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

Statistical significance (with systematics and LEE)

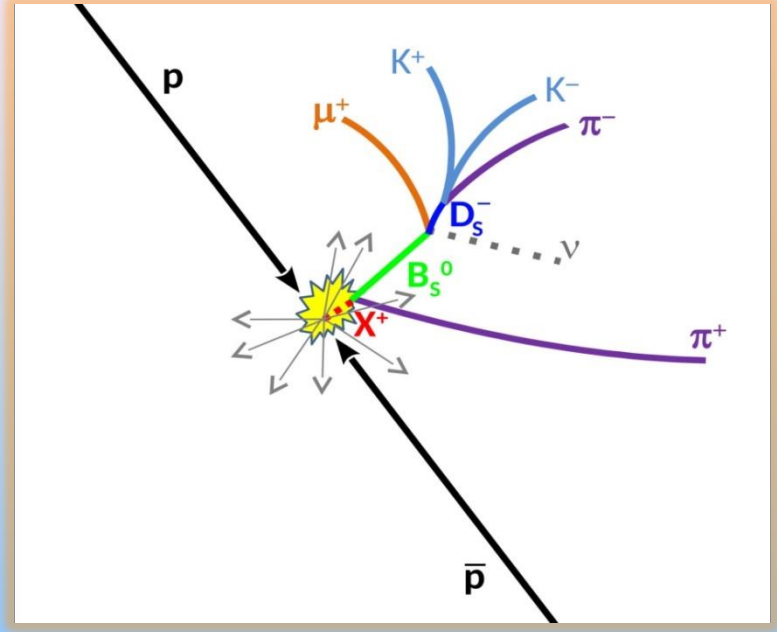
With $\Delta R = \sqrt{\Delta\eta + \Delta\phi} < 0.3$ cut: 5.1σ

Without ΔR cut: 3.9σ

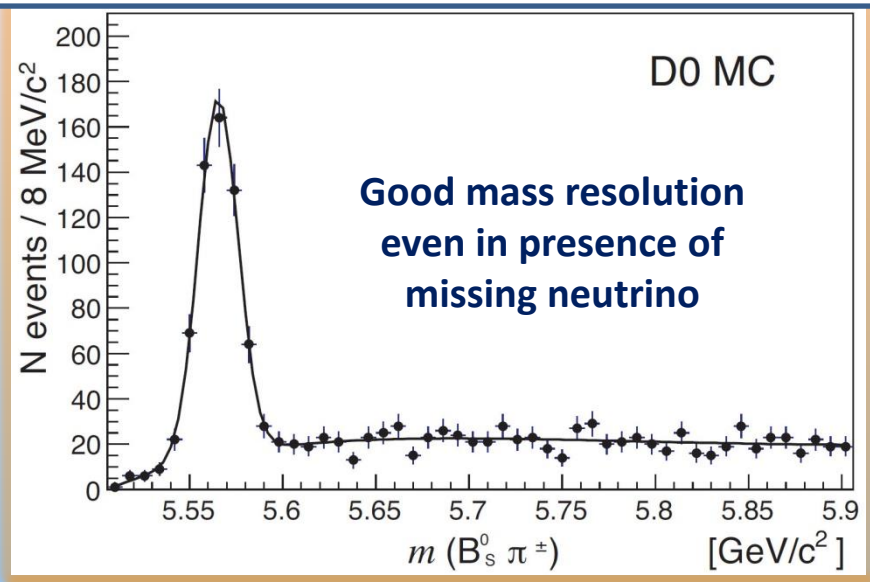
Not seen by LHCb and CMS in pp collisions at 7 and 8 TeV/c^2.

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

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



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



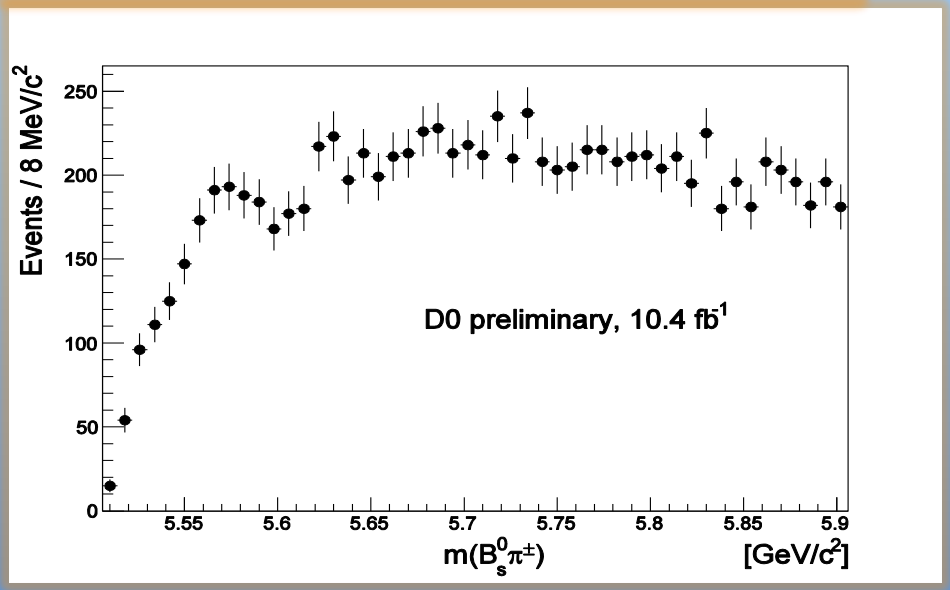
Event reconstruction and selection

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

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.

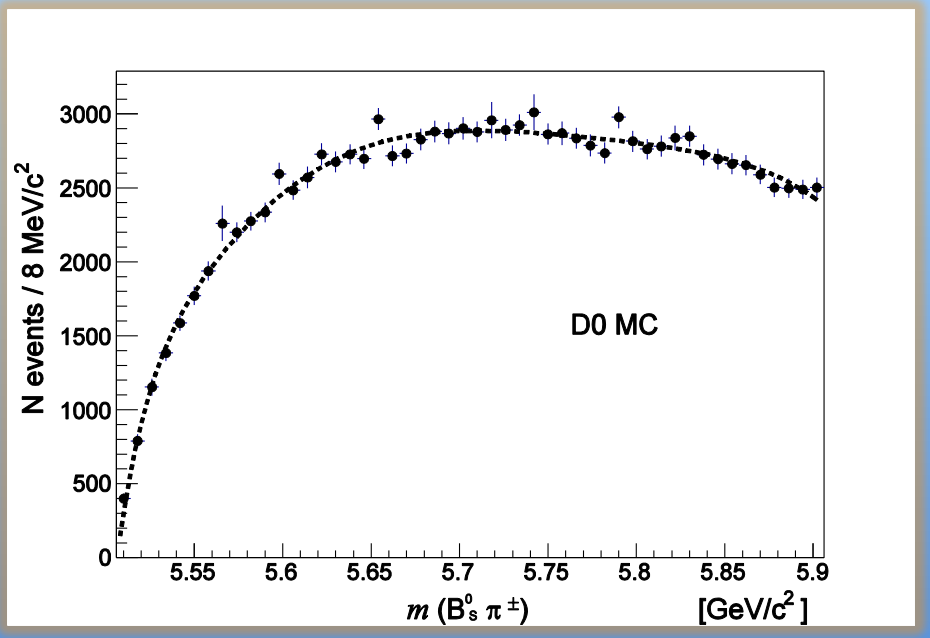
Fit to data

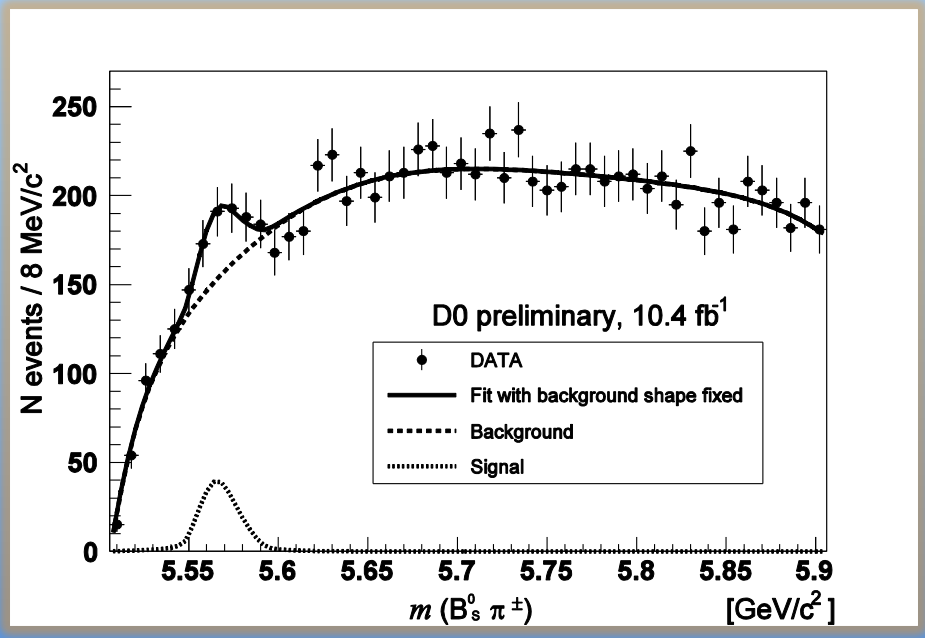
$F_{fit}(m,M_x,\Gamma_X)=f_{bgr} \cdot F_{bgr}(m)+f_{sig} \cdot F_{sig}(m,M_x,\Gamma_X)$

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.

$$M_x = 5566.7^{+3.6}_{-3.4}\ \text{MeV/c}^2$$

$$\Gamma_x = 6.0^{+9.5}_{-6.0}\ \text{MeV/c}^2,\ N_{ev} = 139^{+51}_{-63}$$





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

Local statistical significance

$$\sqrt{-2 \cdot \ln \frac{\mathcal{L}_0}{\mathcal{L}_{\max}}}$$

4.5σ from the fit, 3.2σ with the systematic uncertainties.

Systematic uncertainties

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

Comparison with hadronic channel

	Semileptonic	Hadronic, ΔR cut	Hadronic, no ΔR cut
Fitted mass, MeV/c^2	$5566.7^{+3.6\ +1.0}_{-3.4\ -1.0}$	$5567.8 \pm 2.9^{+0.9}_{-1.9}$	5567.8
Fitted width, MeV/c^2	$6.0^{+9.5\ +1.9}_{-6.0\ -4.6}$	$21.9 \pm 6.4^{+5.0}_{-2.5}$	21.9
Fitted number of signal events	$139^{+51\ +11}_{-63\ -32}$	$133 \pm 31 \pm 15$	106 ± 23

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

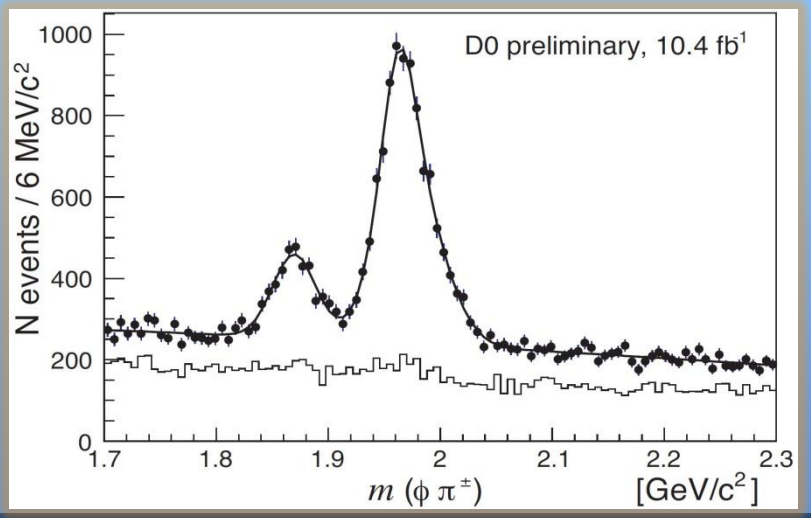
X(5568)→$B_s\pi$ with semileptonic decays of the B_s mesons

	Semileptonic	Hadronic, ΔR cut	Hadronic, no ΔR cut
Local significance	4.5σ	6.6σ	4.8σ
Significance with systematics	3.2σ	5.6σ	-
Significance LEE+systematics	-	5.1σ	3.9σ

Combined significance

$$p_{comb} = p_{sl} \cdot p_{had} \cdot [1 - \ln(p_{sl} \cdot p_{had})],$$

$p_{comb} = 5.6 \cdot 10^{-9}$ ($1.1 \cdot 10^{-6}$ without ΔR cut) which corresponds to combined significance 5.7σ (4.7σ without ΔR cut)



Production ratio of X(5568) to B_s

Calculated by fitting $M(\phi\pi)$ distributions in the opposite sign and same sign $D_s\,\mu$ samples.

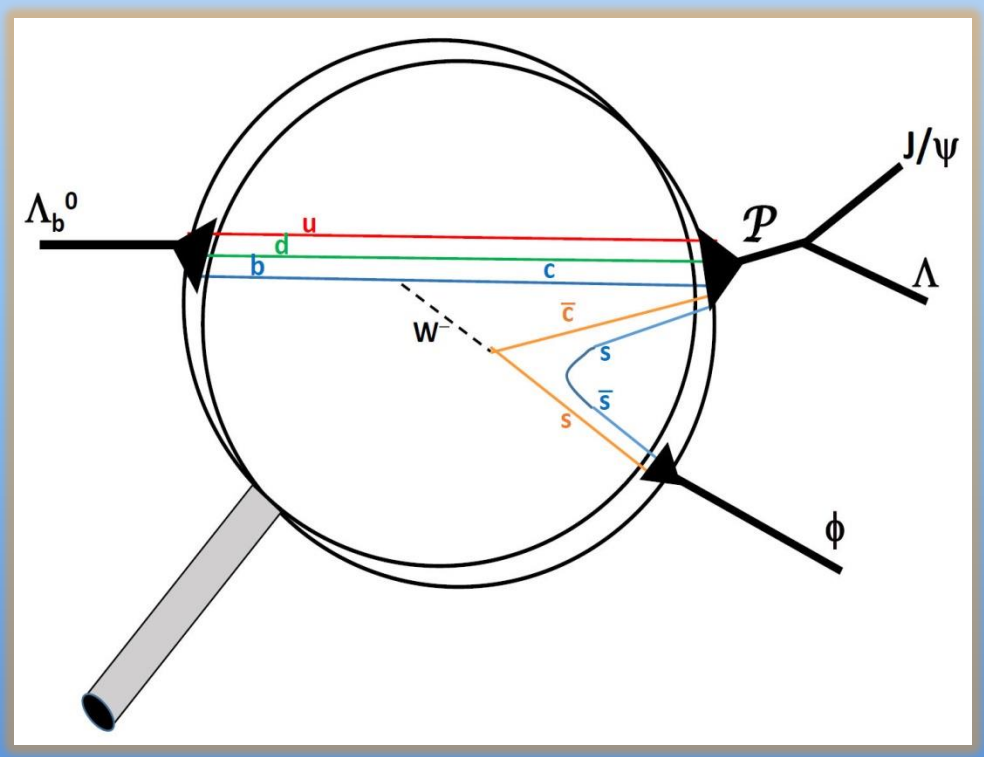
$$\rho(X(5568)/B_s) = 7.3^{+2.8}_{-2.4}(stat)^{+0.6}_{-1.7}(syst)\%$$

which is in agreement with the ratio measured in the hadronic channel.

Search for exotic baryons decaying to $J/\psi\ \Lambda$

- Observation of two J/ψ p states named P_c around 4380 MeV/c² and 4450 MeV/c² in $\Lambda_b \to J/\psi$ p K^- decays reported by LHCb.
- Numerous states with the quark contents including $c\bar{c}$ pair and three light quarks are expected to exist within 500 MeV of the J/ψ p threshold.

Search in the M($J/\psi\ \Lambda$), where $J/\psi \to \mu\mu$, $\Lambda \to p\pi^-$.



Event reconstruction

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

$p_T(\mu) > 1$ GeV/c; $p_T(\mu\mu) > 4$ GeV/c

$2.92 < M(\mu\mu) < 3.25$ GeV/c²

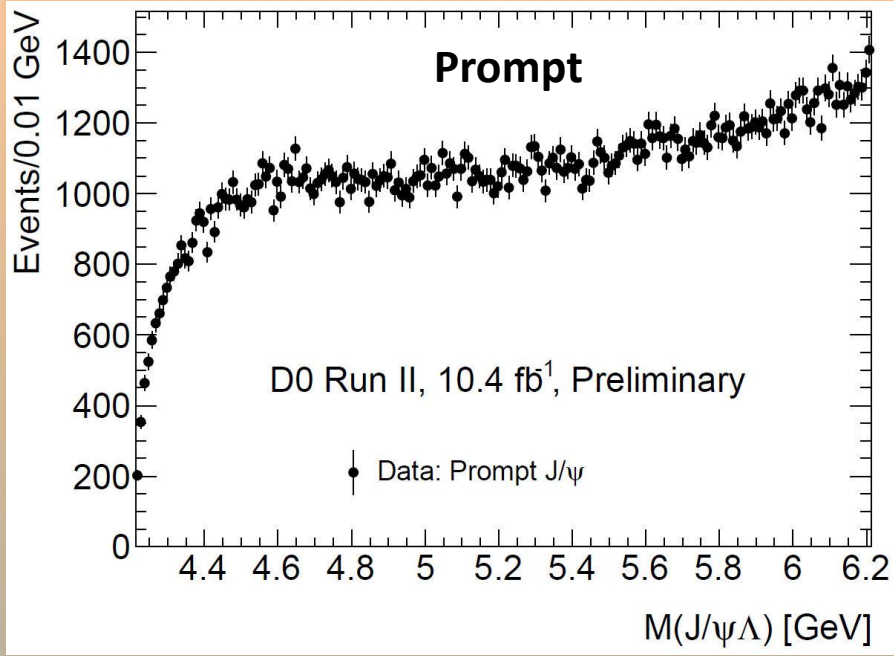
$p_T(\Lambda) > 0.7$ GeV/c

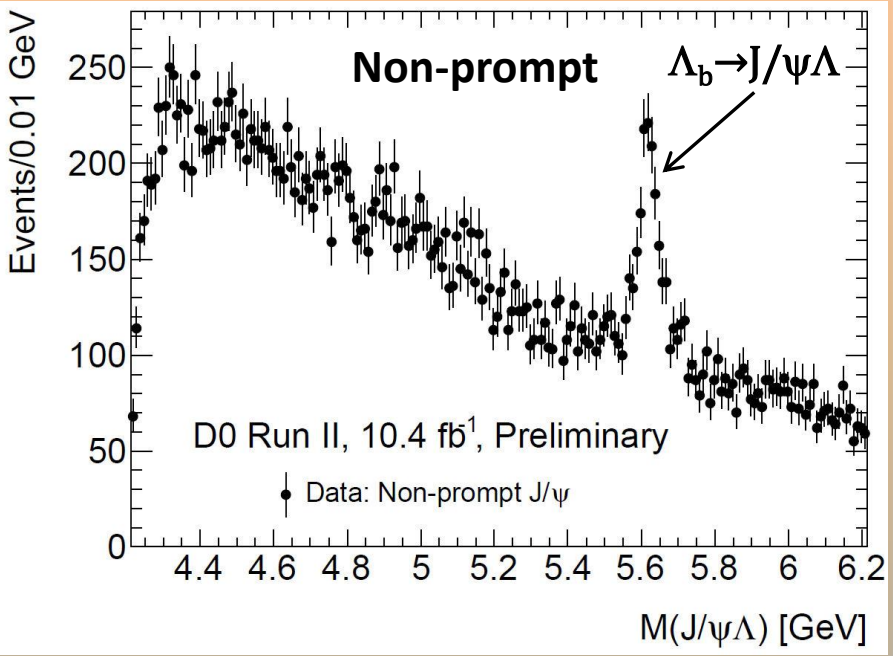
$1.110 < M(\Lambda) < 1.122$ GeV/c²

$p_T(\pi) > 0.15$ GeV/c

Non-prompt: J/ψ decay length significance in the transverse plane is greater than 3 and Λ decay vertex is closer to J/ψ decay vertex than to the primary vertex.

Search for exotic baryons decaying to J/ψ Λ





Search procedure

Binned maximum likelihood fits to the distribution of the J/ψ Λ invariant mass in the range from the J/ψ Λ threshold to 4.7 GeV/c².

$$F_{fit}(M,M_x,\Gamma_x)=f_{bgr}\cdot F_{bgr}(M)+f_{sig}\cdot F_{sig}(M,M_x,\sigma_x),$$

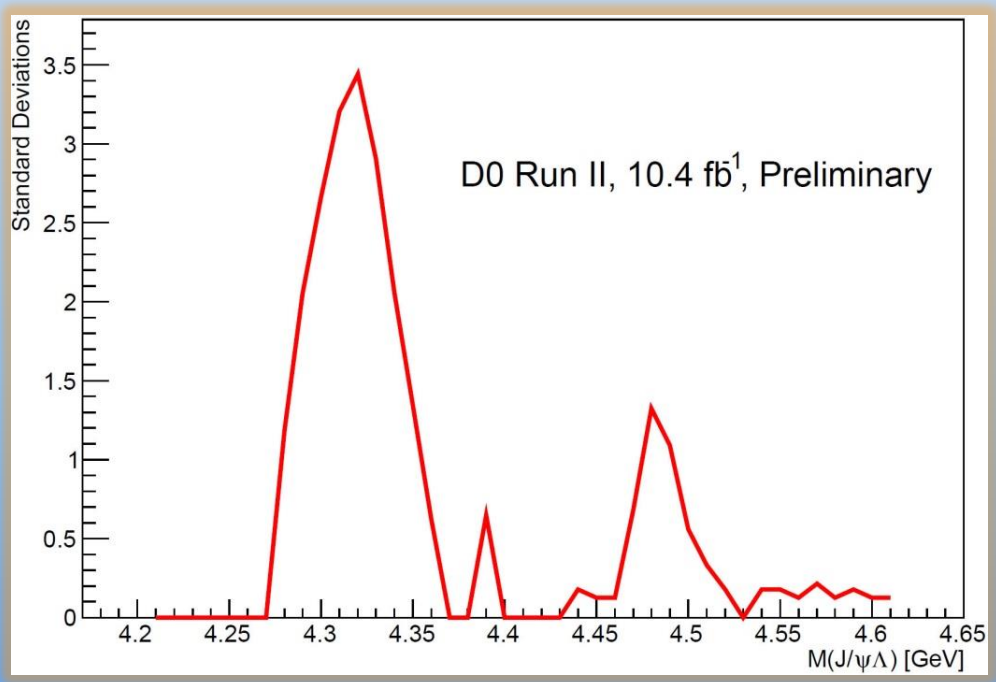
where $F_{sig}(M,M_x,\sigma_x)$ - Gaussian function with M_x, σ_x; f_{bgr}, f_{sig} - normalization coefficients.

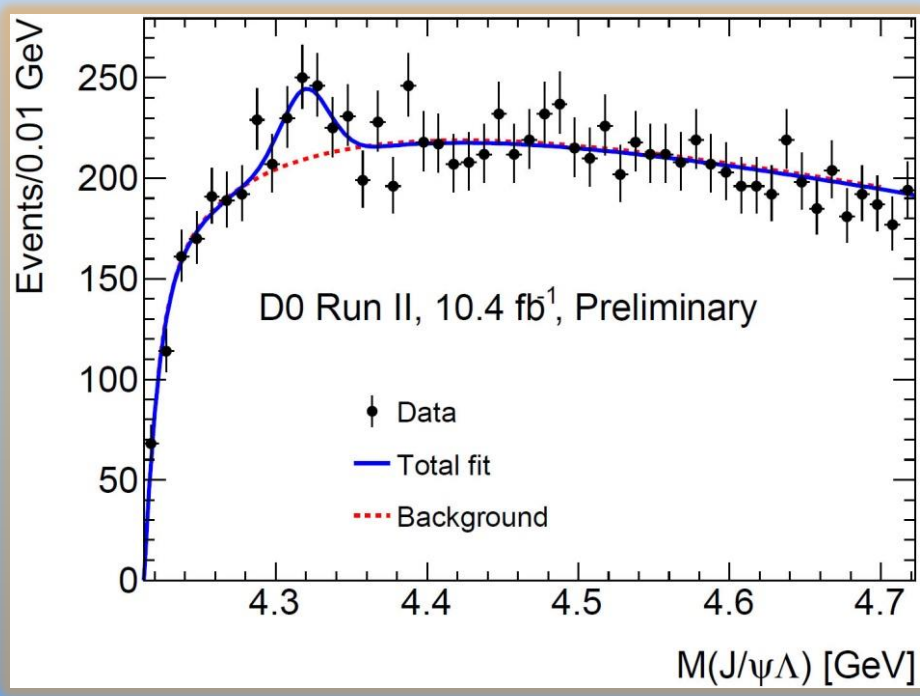
$$F_{bgr}(M) \propto M\cdot(M^2/M_{thr}^2-1)^{c_1}\cdot e^{-c_2 M}\cdot(1-e^{-(M-M_{thr})/b}),$$

where M_{thr} is the J/ψ Λ threshold

Search for exotic baryons decaying to $J/\psi\ \Lambda$

Mass fits of the sum of signal + background or background only to the data were performed with the signal mass set at fixed values in 10 MeV steps. Local statistical significance is defined as $\sqrt{-2 \cdot \ln(\mathcal{L}_0/\mathcal{L}_{max})}$. The highest local significance of 3.45σ occurs at $M = 4.32\ GeV/c^2$. If LEE (computed in the same 500 MeV interval) is taken into account it leads to the global significance of 2.8σ.





No evidence for new baryons decaying to $J/\psi\ \Lambda$

Conclusion

- $X(5568) \rightarrow B_s\pi$, $B_s \rightarrow J/\psi\phi(1020)$. We report evidence for a narrow structure, $X(5568)$. This is evidence for the first instance of a hadronic state with valence quarks of four different flavors (u,d,b,s). The statistical significance of this evidence is 5.1σ with $\Delta R<0.3$ cut and 3.9σ without it.

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

- $X(5568) \rightarrow B_s\pi$, $B_s \rightarrow D_s\mu X$. There is an excess of events in the data consistent with the decay $X(5568) \rightarrow B_s\pi$, $B_s \rightarrow J/\psi\,\phi$. The mass, natural width and production rates in the semileptonic and hadronic channels are consistent. Combined significance for semileptonic and hadronic channels is 5.7σ.

  https://www-d0.fnal.gov/Run2Physics/WWW/results/prelim/B/B68/

- Search for exotic baryons $\rightarrow J/\psi\,\Lambda$. In the mass range between threshold and 4.7 GeV/c^2 no evidence for new baryons decaying to $J/\psi\,\Lambda$ have been found, the most significant deviation from background-only hypothesis is seen at $M(J/\psi\,\Lambda) = 4.32$ GeV/c^2 with a global significance (including LEE) 2.8σ.

  https://www-d0.fnal.gov/Run2Physics/WWW/results/prelim/B/B69/

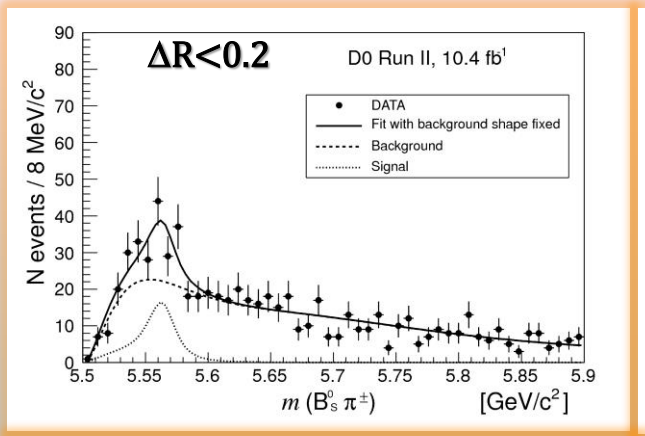
Backup slides

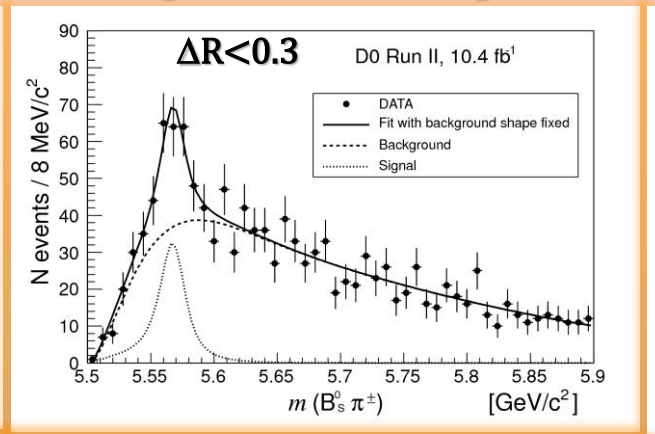
Evidence for $B_s\pi$ state, $B_s \to J/\psi\,\phi(1020)$

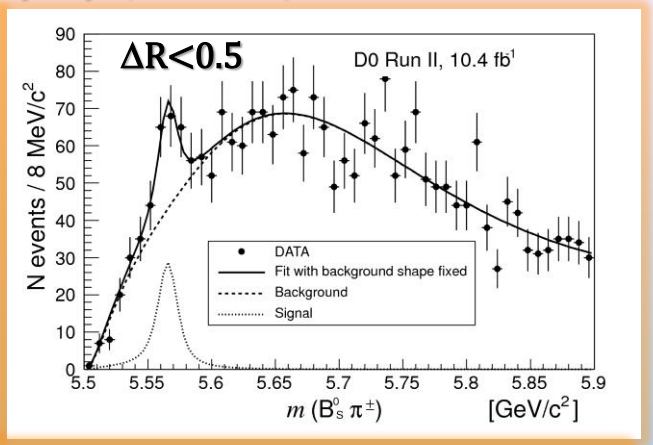
TABLE I: Systematic uncertainties for the observed $X^+(5568)$ state mass, natural width, and event number.

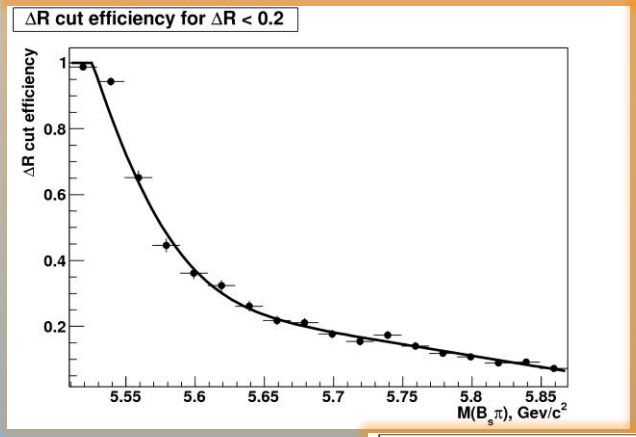
Systematic uncertainty	mass, MeV/c^2	width, MeV/c^2	Events, %
Background shape			
a) MC sample soft or hard	+0.2 ; -0.6	+2.6 ; -0.	+8.2 ; -0.
b) Sideband mass ranges	+0.2 ; -0.1	+0.7 ; -1.7	+1.6 ; -9.3
c) Sideband mass calculation method	+0.1 ; -0.	+0. ; -0.4	+0 ; -1.3
d) MC to sideband events ratio	+0.1 ; -0.1	+0.5 ; -0.6	+2.8 ; -3.1
e) Background function used	+0.5 ; -0.5	+0.1 ; -0.	+0.2 ; -1.1
f) B_s^0 mass scale, MC and data	+0.1 ; -0.1	+0.7 ; -0.6	+3.4 ; -3.6
Signal shape			
a) Detector resolution	+0.1 ; -0.1	+1.5 ; -1.5	+2.1 ; -1.7
c) Non-relativistic BW	+0. ; -1.1	+0.3 ; -0.	+3.1 ; -0.
d) P-wave BW	+0. ; -0.6	+3.1 ; -0.	+3.8 ; 0.
Others			
a) Binning	+0.6 ; -1.1	+2.3 ; -0.	+3.5 ; -3.3
Total	+0.9 ; -1.9	+5.0 ; -2.5	+11.4 ; -11.2

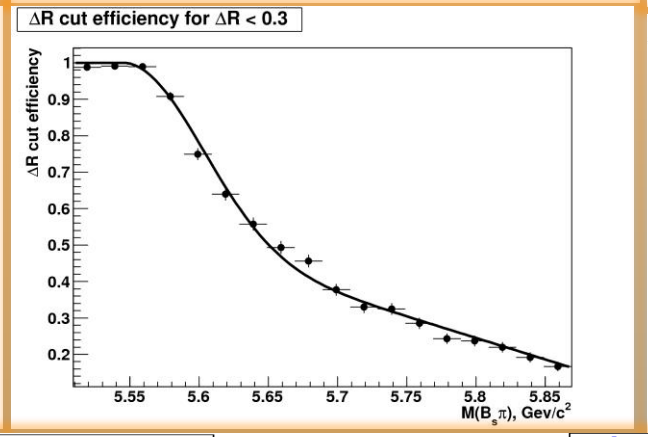
Evidence for $B_s\pi$ state, $B_s \to J/\psi\,\phi(1020)$

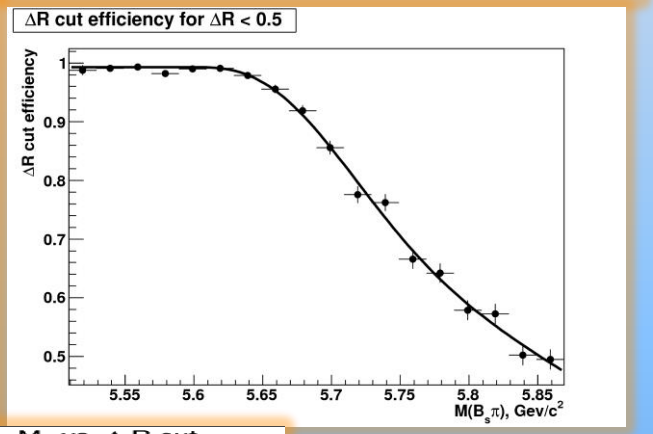


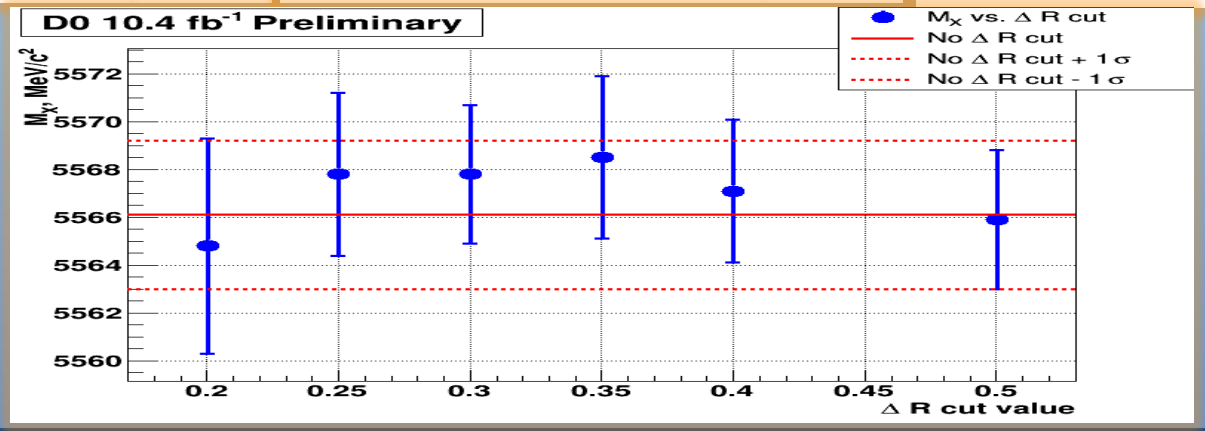










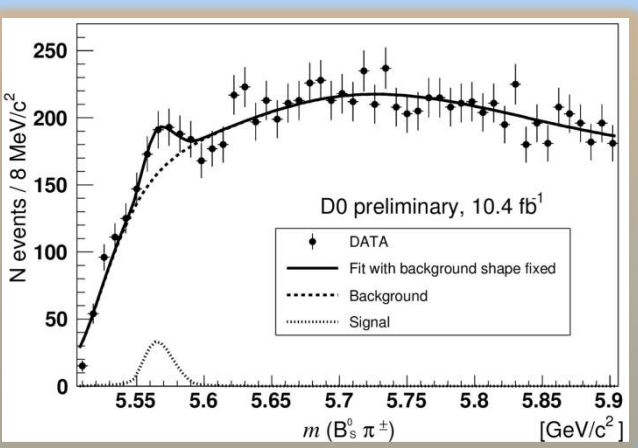


$X(5568) \to B_s\pi$ with semileptonic decays of the B_s mesons

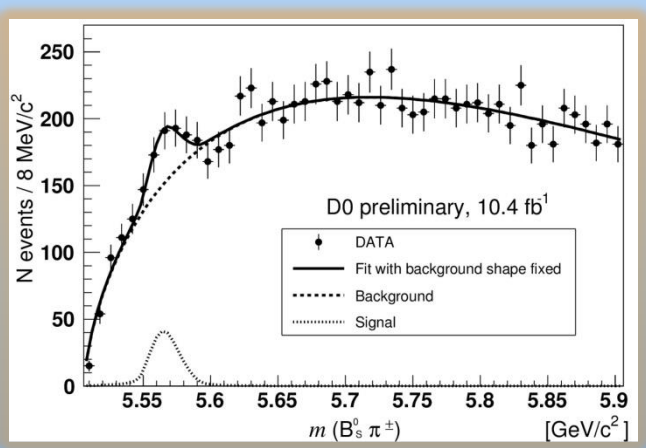
Alternative background parametrizations

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).

(1)



(2)



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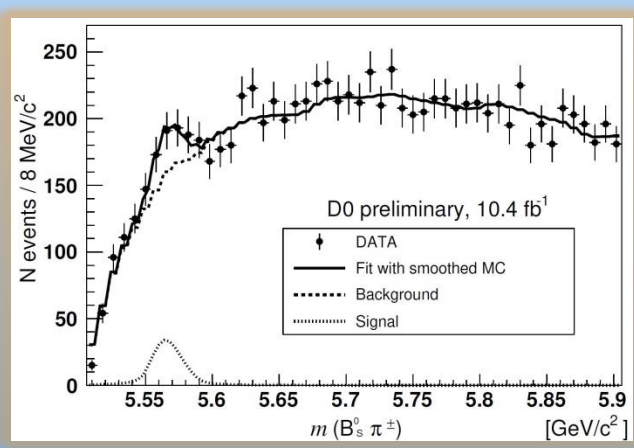

	Parametrization (1)	Parametrization (2)	Parametrization (3)
Fitted mass, MeV/c^2	$5566.2^{+4.2}_{-4.1}$	$5566.0^{+3.6}_{-3.4}$	5564^{+5}_{-5}
Fitted width, MeV/c^2	$6.0^{+12.0}_{-6.0}$	$6.5^{+8.9}_{-6.5}$	10^{+17}_{-10}
Fitted number of signal events	$115.9^{+51.8}_{-47.7}$	$145.7^{+50.7}_{-54.3}$	136^{+59}_{-48}
Local significance	3.7σ	4.7σ	3.9σ

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
Background shape description	$+0.0$; -0.7	$+0.7$; -2.5	$+4.8$; -28.0
Background reweighting	$+0.1$; -0.1	$+0.7$; -0.7	$+5.0$; -5.0
B_s^0 mass scale, MC and data	$+0.3$; -0.5	$+1.0$; -1.4	$+7.5$; -9.6
Detector resolution	$+0.0$; -0.5	$+1.3$; -2.6	$+3.7$; -6.4
P-wave Breit-Wigner	$+0.0$; -0.2	$+0.0$; -2.4	$+0.0$; -7.0
Missing neutrino effect	$+1.0$; -0.0	-	-
Total	$+1.0$; -1.0	$+1.9$; -4.6	$+10.9$; -31.5