Exotic states at D0

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(On behalf of D0 Collaboration)

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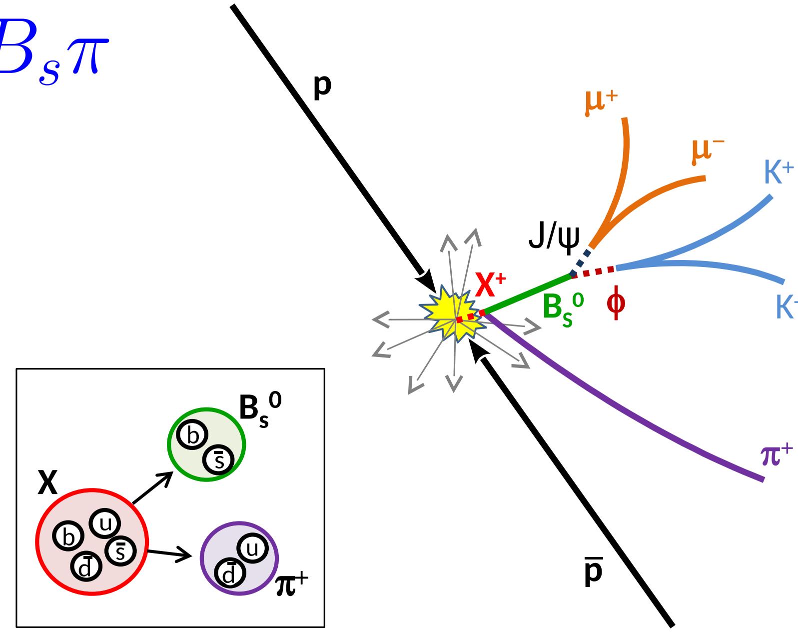
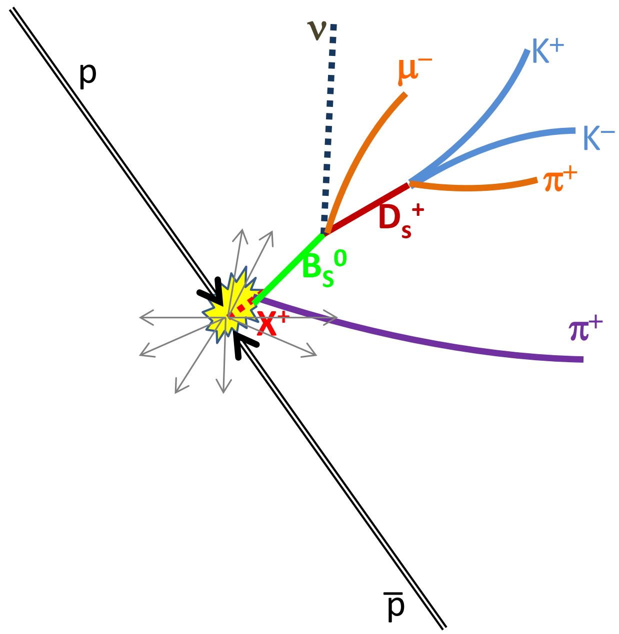
$X(5568) \rightarrow B_s\pi$



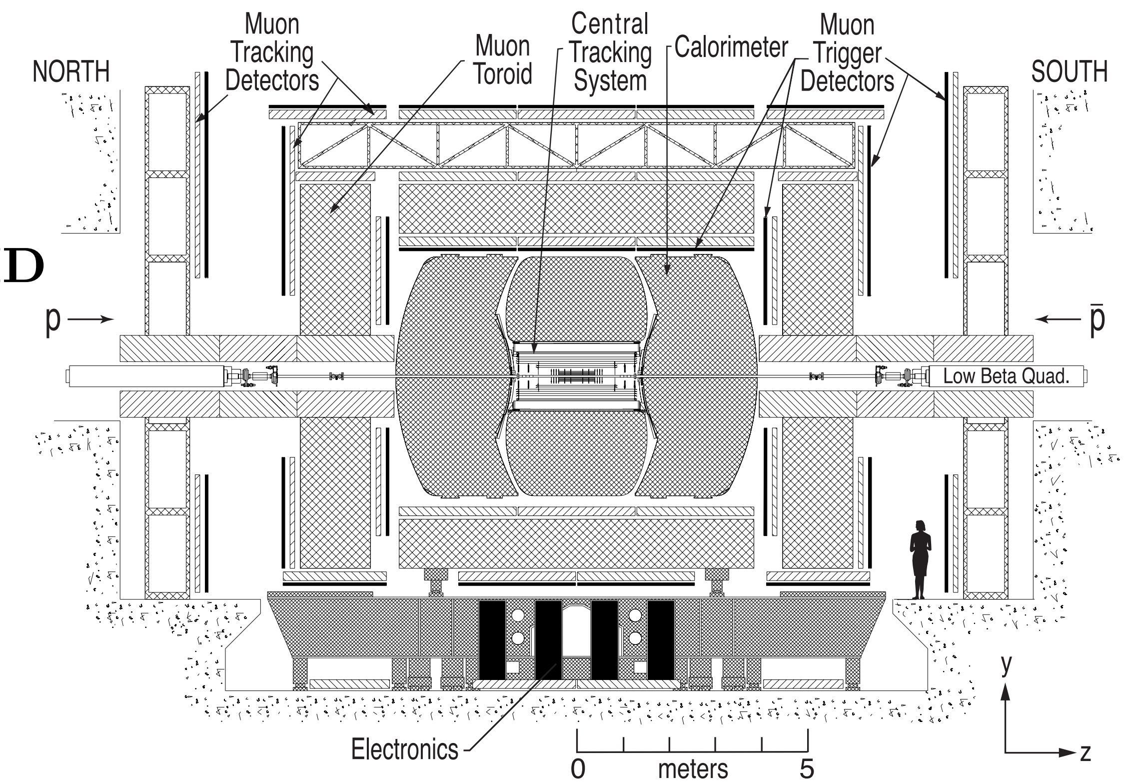
$B_s\pi^{\pm}$ state with $B_s^0 \rightarrow J/\psi\phi$
(PRL 117, 022003 (2016))



New: $B_s^0 \rightarrow D_s\mu\nu$ channel

D0 detector in Tevatron Run II

Scintillator counters and drift tubes
Thick calorimeter and iron toroids
Excellent muon triggering and ID



Silicon Microstrip Tracker
Excellent vertex resolution

Central Fiber Tracker
Good mass resolution

Excellent for B physics with muons

Data

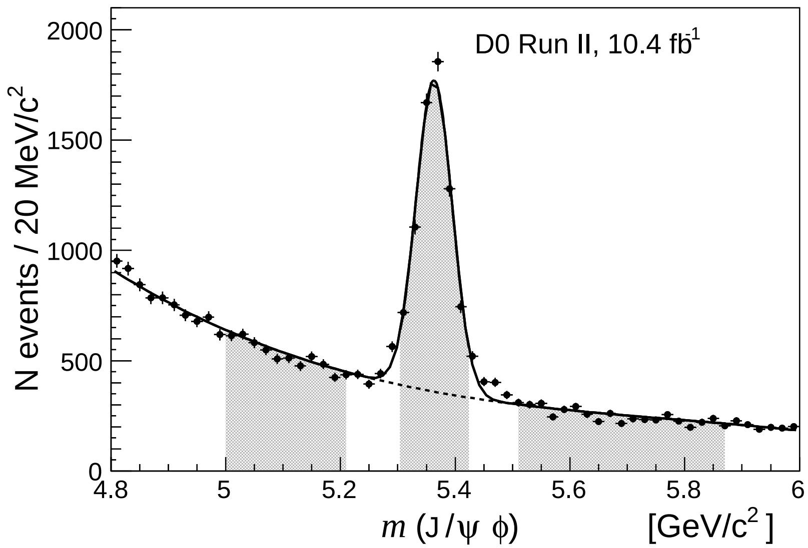
Looking for a state decaying strongly to $B_s\pi^\pm$ using the full Run II dataset of 10.4 fb^{-1} collected at Tevatron between 2001 and 2011.

Require a single muon or dimuon trigger.
Reconstruct $B_s^0 \to J/\psi\phi$, $J/\psi \to \mu^+\mu^-$, $\phi \to K^+K^-$
Require a displaced decay vertex $L_{xy}/\sigma(L_{xy}) > 3$

Add a track assumed to be a pion, consistent with coming from $p\bar{p}$ interaction vertex

- $p_T(\pi) > 0.5$ GeV, $IP_{xy} < 200\ \mu$m, $IP_{3D} < 1200\ \mu$m (charm decay not ruled out)
- $p_T(B_s\pi) > 10$ GeV, $|y(B_s\pi)| < 2$
- We perform the analysis with and without a limit on the angular separation between the B_S^0 and the pion:
  $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2} < 0.3$ (the "cone" cut)

Two background components



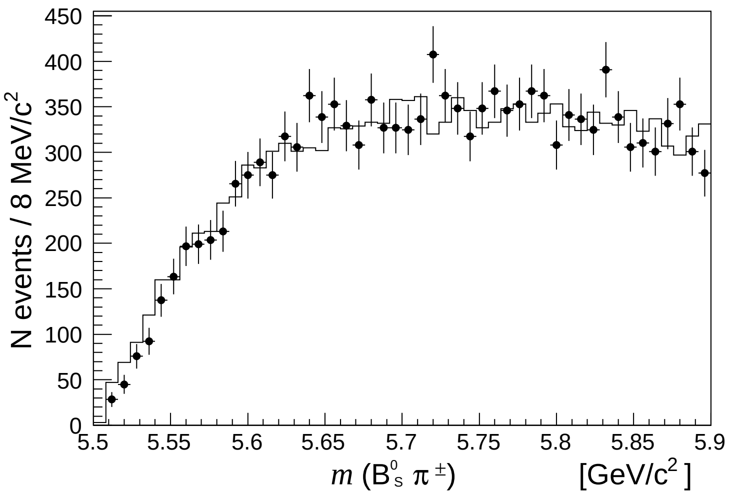
The B_s^0 signal:
$M = 5363.3 \pm 0.6$ MeV
$\sigma = 31.6 \pm 0.6$ MeV
$N = 5582 \pm 100$
B_s^0 signal region $(\pm 2\sigma)$
$5303 < m(J/\psi\phi) < 5423$ MeV
B_s^0/non-B_s^0 = 71%/29%

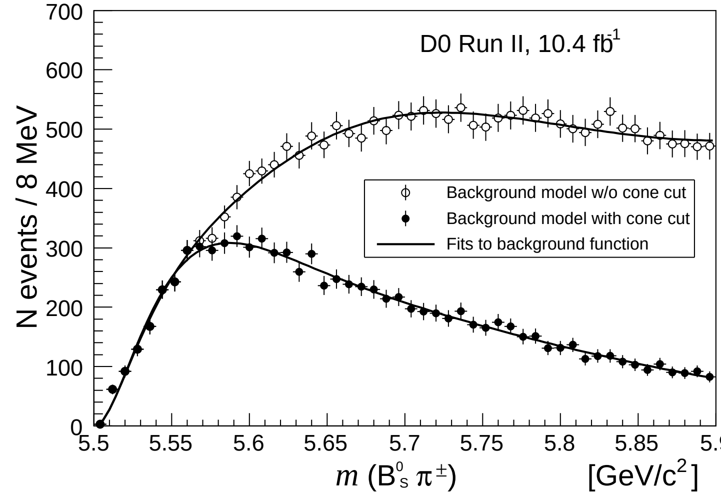
We pair a B_s^0 candidate in the signal region with a charged track assumed to be a pion to form a $B_s^0\pi^{\pm}$ candidate.

In the B_s^0 signal region, there is (1) B_s^0 signal and (2) Non-B_s^0 background. (1) is simulated with Pythia, (2) is taken from sidebands selected such that their "center-of-gravity" is at $M(B_s)$. (1) + (2) are combined in the right proportion.

We define the $B_s^0\pi$ mass as: $m(B_s^0\pi^{\pm}) = m(J/\psi\phi\,\pi^{\pm}) - m(J/\psi\phi) + 5366.7\ \mathrm{MeV}/c^2$

Background model





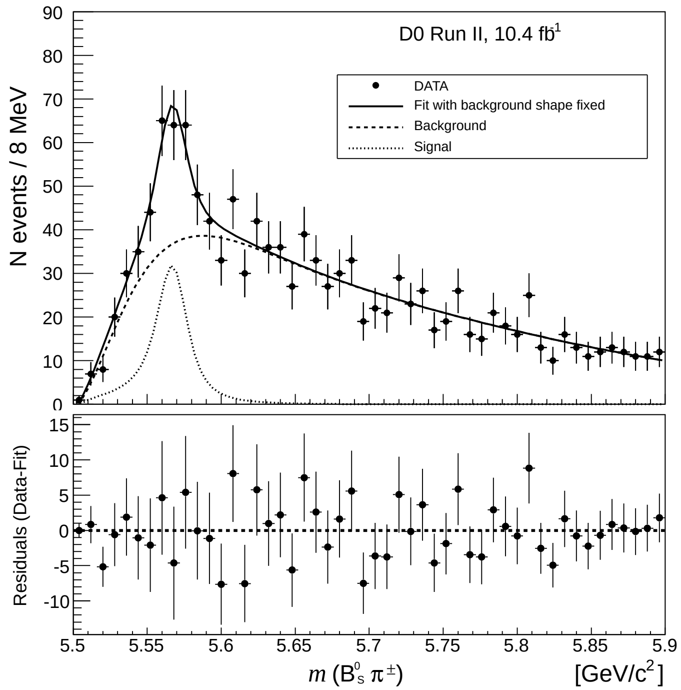
Points: non-B_s^0, histogram: B_s^0 MC

Background shape w/without ΔR cut

The two background components have a very similar shape. It is parametrized as $(c_0 + c_2 \cdot x^2 + c_3 \cdot x^3 + c_4 \cdot x^4) \times \exp(c_5 + c_6 \cdot x + c_7 \cdot x^2)$, $x \equiv m(B_s^0\pi^\pm) - 5.5$.

The same parametrization (with different values) works for background with and without the $\Delta R < 0.3$ cut. The cut efficiency is 100% up to $m = 5.57$ GeV, then it drops. It is taken into account in the signal model.

Results for the case with ΔR cut



$$M_X = 5567.8 \pm 2.9 \text{ MeV}$$
$$\Gamma_X = 21.9 \pm 6.4 \text{ MeV}$$
$$N = 133 \pm 31$$

Signif. (with syst and LEE) $S = 5.1\sigma$ ("Local" $S = 6.6\sigma$).

(PRL 117, 022003 (2016))

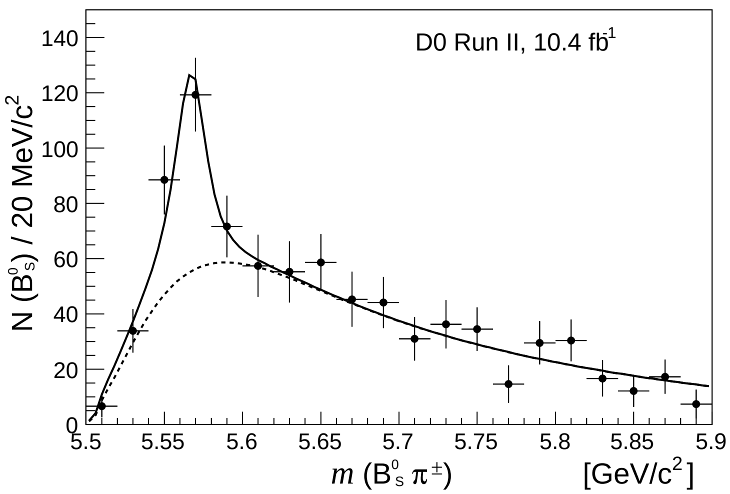
Signal is modeled by a relativistic Breit-Wigner function convolved with a Gaussian resolution of $\sigma = 3.8$ MeV (MC) and multiplied by mass-dependent efficiency.

With background shape parameters obtained from a mixture of MC and side-bands, the only free parameters are the signal and background normalizations and the signal mass and natural width.

Alternative signal extraction

Reverse the search: Look for the B_s^0 signal as a function of $m(J/\psi\phi\pi)$

For each of 20 bins in the $m(J/\psi\phi\pi)$ distribution, fit for the number of B_s^0. Plot the B_s^0 yield as a function of $m(J/\psi\phi\pi)$ as shown in the figure. Fit this distribution to obtain the yield of X(5568). This method only has the background from real B_s^0 and a random pion.



$\Delta R < 0.3$

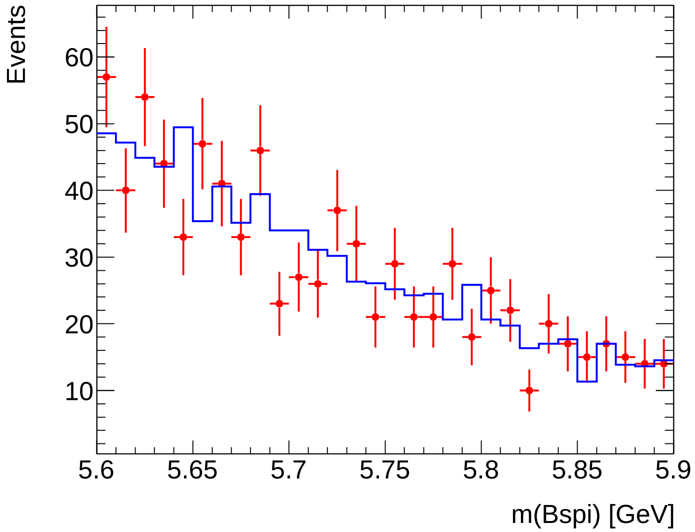
$M_X \equiv 5567.8$ MeV

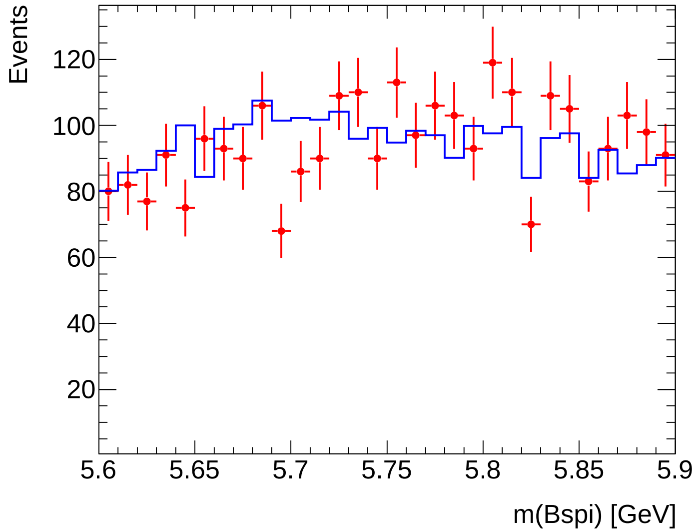
$\Gamma_X \equiv 21.9$ MeV

$N = 118 \pm 22$

No ΔR cut analysis

Data (red points) vs background model (blue lines) at $m(B_s^0\pi^\pm) > 5.6$ GeV





$\Delta R < 0.3$ KS probability=0.999

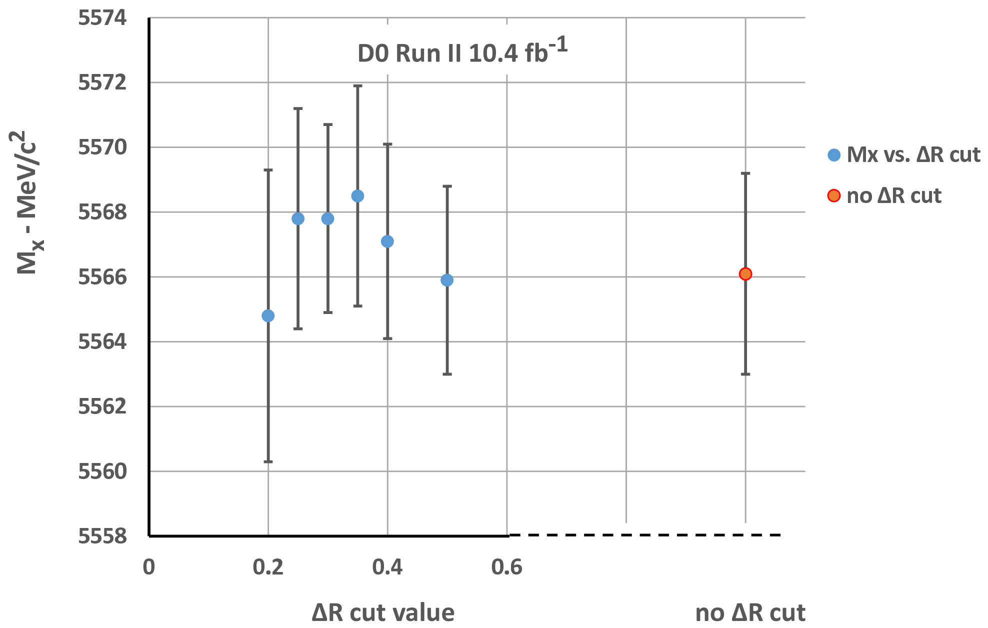
No cone cut KS probability=0.003

In the case of no ΔR cut, the model is above data at lower masses and below data at higher masses. This may be due to sources of B_s^0 not included in the simulations, e.g. $B_c \to B_s^0\pi^+\pi^0$.

Without the ΔR cut, $N = 106 \pm 33$.

Significance (with syst and LEE) = 3.9σ.

Does the ΔR cut sculpt the $X(5568)$ signal?



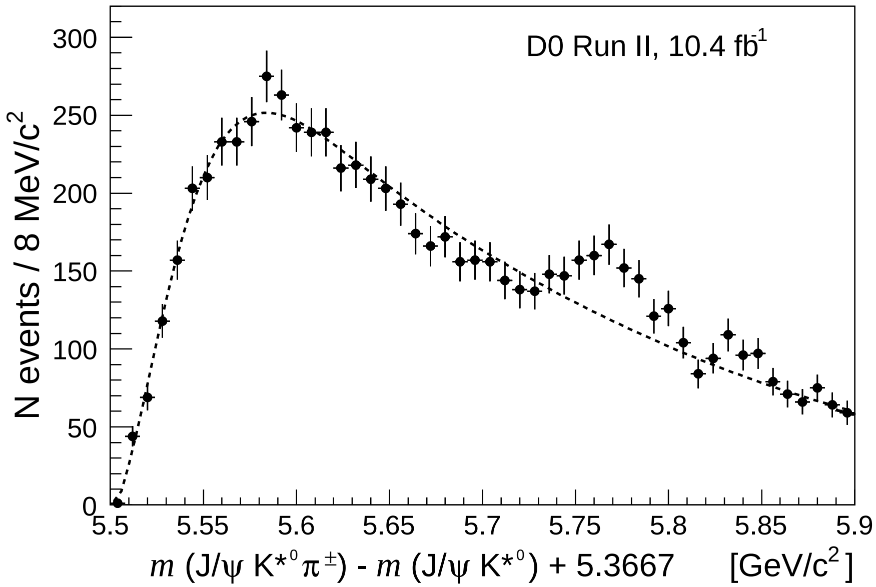
We repeated the fits varying the ΔR cut below and above 0.3. (The non-ΔR point is marked in red.) The signal mass is stable.

Cross-checks performed

- Use left (right) sideband for the non-B_s^0 background
- Use two versions of Pythia for the B_s^0 background
- Compare sidebands with "undersignal"
- Allow background shape parameters to be free
- Use different B_s^0 mass ranges; modify the B_s^0 vertex cuts
- Compare π^+ and π^- subsamples
- Examine different detector regions (ϕ, η)
- Examine different data taking periods (over 10 years)
- Test $B_s^0 K$ and $B_s^0 p$ hypotheses
- Study $m(B_d^0 \pi^{\pm})$ on the full Run II data sample *
- Look for decay $B_s^{**} \rightarrow B_s^0 \pi^+ \pi^-$

Cross-check with $B_d^0 \pi^\pm$

The decay chain $B_d^0 \to J/\psi K^*$, $K^* \to K^\pm \pi^\mp$ has a topology similar to $B_s^0 \to J/\psi \phi$, $\phi \to K^+ K^-$. We reconstructed the quantity
$m(J/\psi\, K^*\, \pi^\pm) - m(J/\psi\, K^*) + 5.3667$ GeV$/c^2$
using the same selection criteria, including the ΔR cut.
The distribution is in agreement with the background model derived for the published analysis. The observed enhancements correspond to three known excited B meson states reported by D0 in PRL 99, 172001 (2007).



Systematic uncertainties

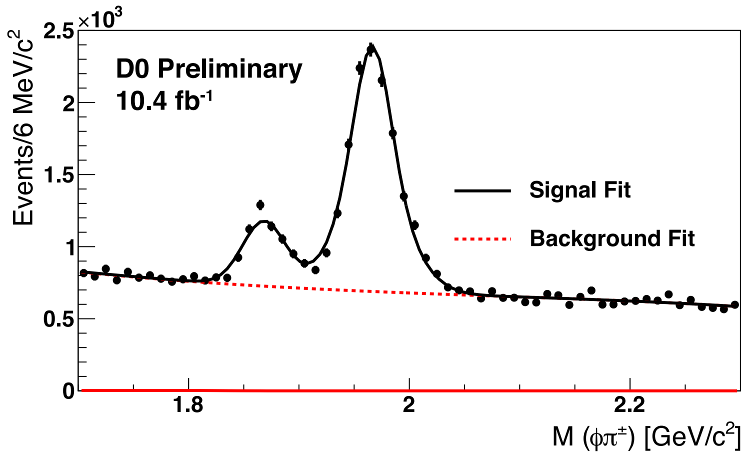
Source	mass, MeV/c^2	width, MeV/c^2	rate, %
Background shape			
MC sample soft or hard	+0.2 ; -0.6	+2.6 ; -0.	+8.2 ; -0.
Sideband mass ranges	+0.2 ; -0.1	+0.7 ; -1.7	+1.6 ; -9.3
Sideband mass calculation method	+0.1 ; -0.	+0. ; -0.4	+0 ; -1.3
MC to sideband events ratio	+0.1 ; -0.1	+0.5 ; -0.6	+2.8 ; -3.1
Background function used	+0.5 ; -0.5	+0.1 ; -0.	+0.2 ; -1.1
B_s^0 mass scale, MC and data	+0.1 ; -0.1	+0.7 ; -0.6	+3.4 ; -3.6
Signal shape			
Detector resolution	+0.1 ; -0.1	+1.5 ; -1.5	+2.1 ; -1.7
Non-relativistic BW	+0. ; -1.1	+0.3 ; -0.	+3.1 ; -0.
P-wave BW	+0. ; -0.6	+3.1 ; -0.	+3.8 ; -0.
Other			
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

Systematic errors smaller than statistical error.

The yield of the $X(5568)$ signal reconstructed through $B_s^0\pi^\pm$, $B_s^0 \rightarrow J/\psi\phi$ is $N = 133 \pm 31 \pm 15$.

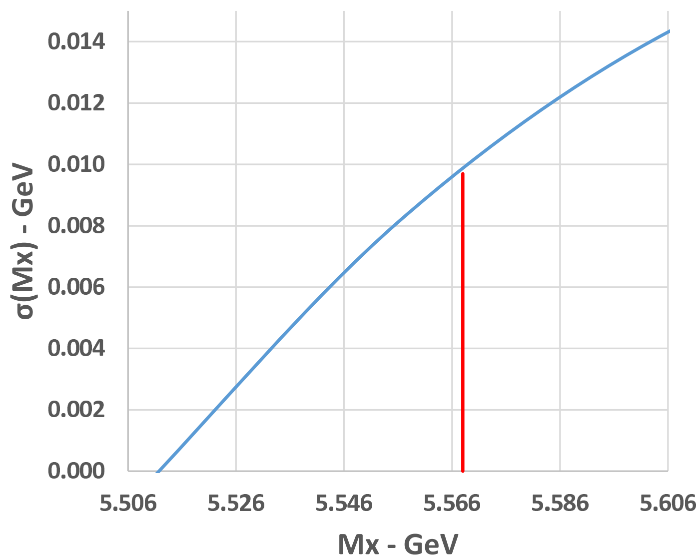
New channel: $B_s^0 \to D_s \mu \nu$ reconstruction

Reconstruct $D_s \to \phi\pi$, $\phi \to K^+K^-$
require $1.92 < m(\phi\pi) < 2.02$ GeV



The lower peak is due to $D^{\pm}$ decays.

Add a μ coming from the same vertex
require $4.5 < m(\mu D_s) > 5.4$ GeV
to minimize the effect of the undetected ν
MC: $\sigma = 10$ MeV at $M = 5.57$ GeV.



New channel: $B_s^0\pi^\pm$, $B_s^0 \to D_s\mu\nu$

Estimate the number of expected events

$\boldsymbol{B_s^0 \to D_s\mu\nu}$

The number of reconstructed D_s decays in D_s window is ≈8900

MC: more than 90% of them come from from B_s.

So, we have ≈8000 B_s events compared to ≈5500 in the $J/\psi\phi$ channel.

$\boldsymbol{X(5568) \to B_s^0\pi^\pm}$ **candidates:**

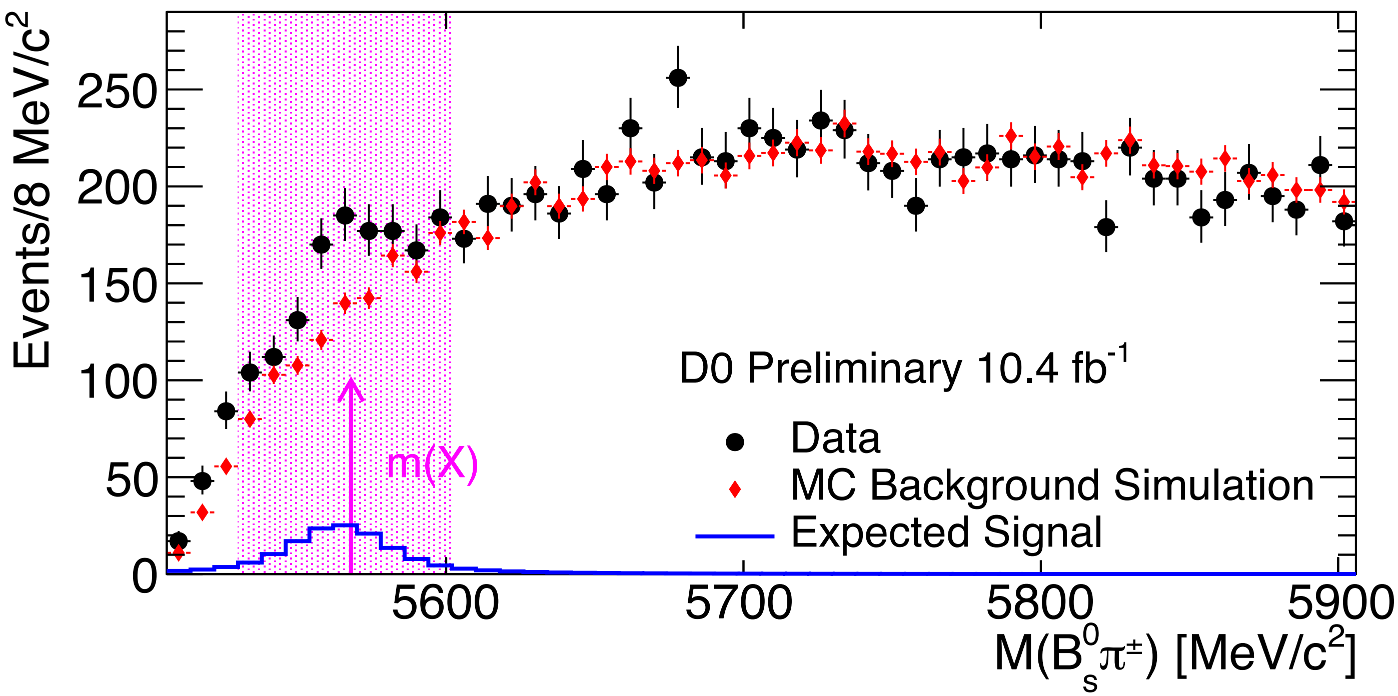
Add a charged pion as in the published analysis.

Focus on the case of no ΔR cut where the significance was lower.

Based on the ≈100 event yield in the $J/\psi\phi$ channel, we expect ≈150 $X(5568)$ events in the $B_s^0 \to D_s\mu\nu$ channel.

Comparison of data and simulated background

We simulate the component of the background due to random combinations of $B_s^0 \to D_s \mu\nu$ with a track assumed to be a pion and compare it to data.



We see an enhancement whose mass, width and yield are consistent with those in the $X(5568) \to B_s^0\pi^{\pm}$, $B_s^0 \to J/\psi\phi$ publication.

Summary

D0 reported seeing a state decaying to $B_s^0\pi^\pm$ with $B_s^0 \to J/\psi\phi$

PRL 117, 022003 (2016)

It is produced in $p\bar{p}$ collisions promptly or via charm decay

It undergoes a strong decay to $B_s\pi$ or to $B_s^*\pi$ followed by $B_s^* \to B_s\gamma$ with unseen γ

$X \to B_s^0\pi^\pm$ $(J^P = 0^+)$ $m = 5567.8 \pm 2.9\,(\text{stat})^{+0.9}_{-1.9}\,(\text{syst})$ MeV

$X \to B_s^*\pi^\pm$ $(J^P = 1^+)$ $m = 5616$ MeV

The mass is 60 MeV (if 0^+) and 110 MeV (if 1^+) above the $B_s\pi$ threshold and ≈200 MeV below the BK threshold.

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

$\rho = \sigma(X(5568)^\pm)BF(X \to B_s^0\pi^\pm)/\sigma(B_s^0) = (8.6 \pm 1.9 \pm 1.4)\%$

New: We see an enhancement in $m(B_s^0\pi^\pm)$ with $B_s^0 \to D_s\mu\nu$ at the same mass and at the expected width and rate.