Observation of a new $B_s\pi^\pm$ state

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for D0 Collaboration

FNAL Seminar February 25, 2016

Overview

- Introduction to non-$q\bar{q}$ states

- Observation of X(5568)
  a strange charged beauty

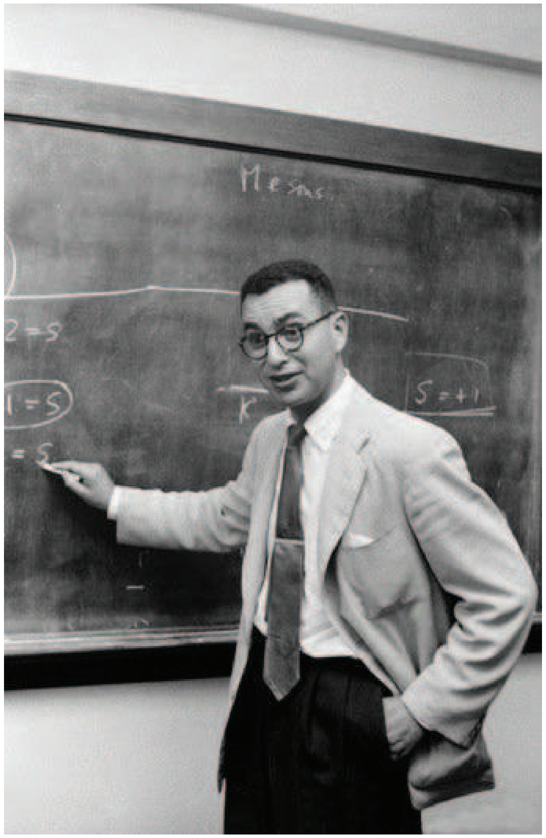
- Summary and outlook

1. Introduction

Multi-quark hadrons are allowed by the quark model. Gell-Mann explicitly mentioned them in the original paper introducing quarks.
(And so did Zweig with Aces.)

"...Baryons can now be constructed from quarks by using the combinations (qqq), $(qqqq\bar{q})$, etc, while mesons are made out of $(q\bar{q})$, $(qq\bar{q}\bar{q}$, etc...."

M. Gell-Mann "A schematic model of baryons and mesons", PL 8 (1964) 214

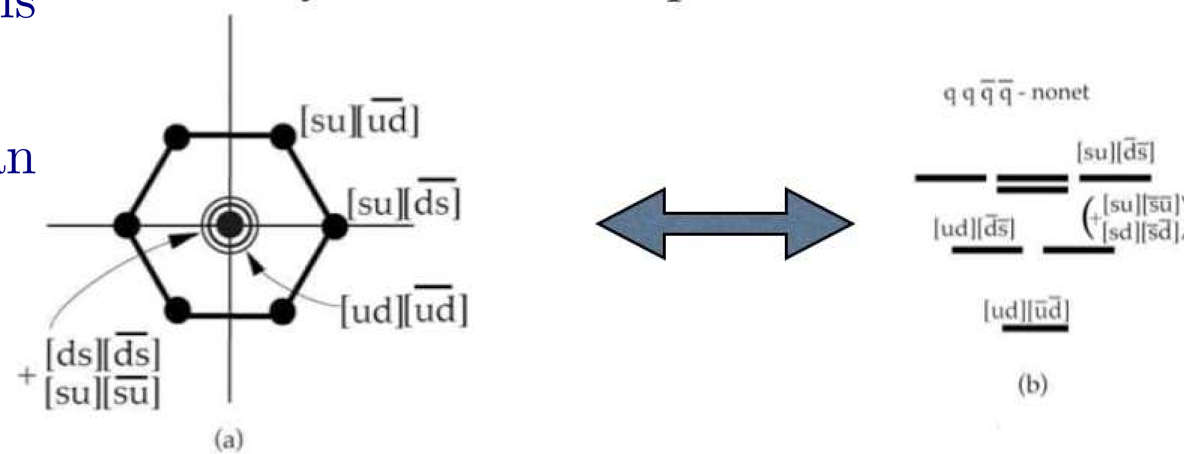


The nonet of light scalars

The success of hadron spectroscopy since the 1960s led to the paradigm of $q\bar{q}$ mesons and qqq baryons.

But the nonet of scalar mesons does not fit the picture: $a_0(980) = (u\bar{d})$ is heavier than $\kappa(800) = (u\bar{s})$.

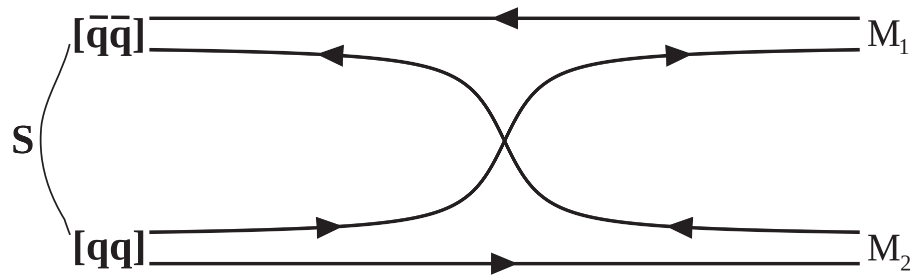
Antisymmetric tetraquarks work better



The tetraquark model with fully asymmetric color antitriplet [qq] states fits better: $a_0(980) = [su][\bar{d}\bar{s}]$, $\quad \kappa(800) = [su][\bar{u}\bar{d}]$.

L. Maiani, F. Piccinini, A. D. Polosa, and V. Riquer, "New Look at Scalar Mesons", PRL **93**, 212002 (2004)

Light scalars as tetraquarks and implications for heavy mesons



A graphical representation of the OZI-allowed strong decay of a scalar tetraquark to a pair of ordinary mesons through switching a q-$\bar{q}$ pair between the diquarks. The lightest decay channel is a pair of pseudoscalar mesons.

"A firm prediction of the present scheme is the existence of analogous states where one or more quarks are replaced by charm or beauty".

L. Maiani, F. Piccinini, A. D. Polosa, and V. Riquer, "New Look at Scalar Mesons", PRL **93**, 212002 (2004)

The XYZ states

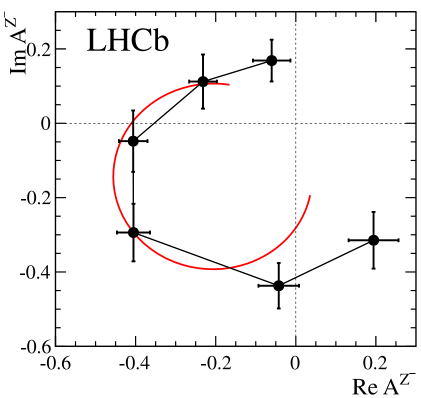
The 2003 discovery of $\boldsymbol{X(3872) \to J/\psi\pi^+\pi^-}$ by Belle marked a new era. The flavor contents are not obviously exotic, but a conventional $\boldsymbol{c\bar{c}}$ interpretation of a state with $\boldsymbol{J^{PC}=1^{++}}$ (measured by LHCb) at this mass is disfavored.

Since then more than 20 charmonium-like and bottomonium-like states that do not fit the $q\bar{q}$ picture have been discovered in B factories, at the Tevatron, and at the LHC.

All found (first) as peaks in 2-body mass in 3-body decays of higher states.

Most happen to be near a two-meson threshould. Some have exotic flavor.

Most importantly, the $\boldsymbol{Z_c(4430) \to \psi(2S)\pi^{\pm}}$ - discovered by Belle - was confirmed by LHCb to be a proper Breit-Wigner resonance by the phase motion. **Evidence for quarkonium-like states made of four valence quarks is established.**



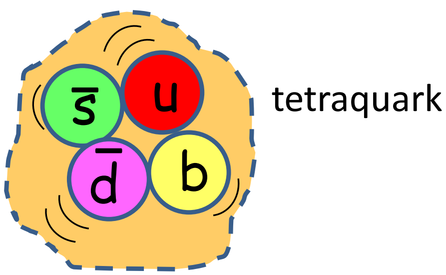
The XYZ states

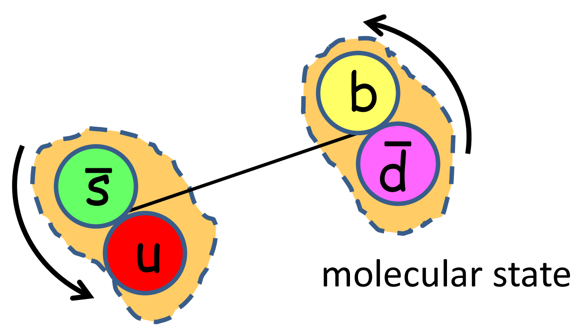
PDG names all non-$q\bar{q}$ candidates $X(mass)$. Authors and theorists use Z for charged states, Y for 1^{--} states, and X for the rest. There are various competing phenomenological models proposed to explain their nature.

Two popular interpretations:

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

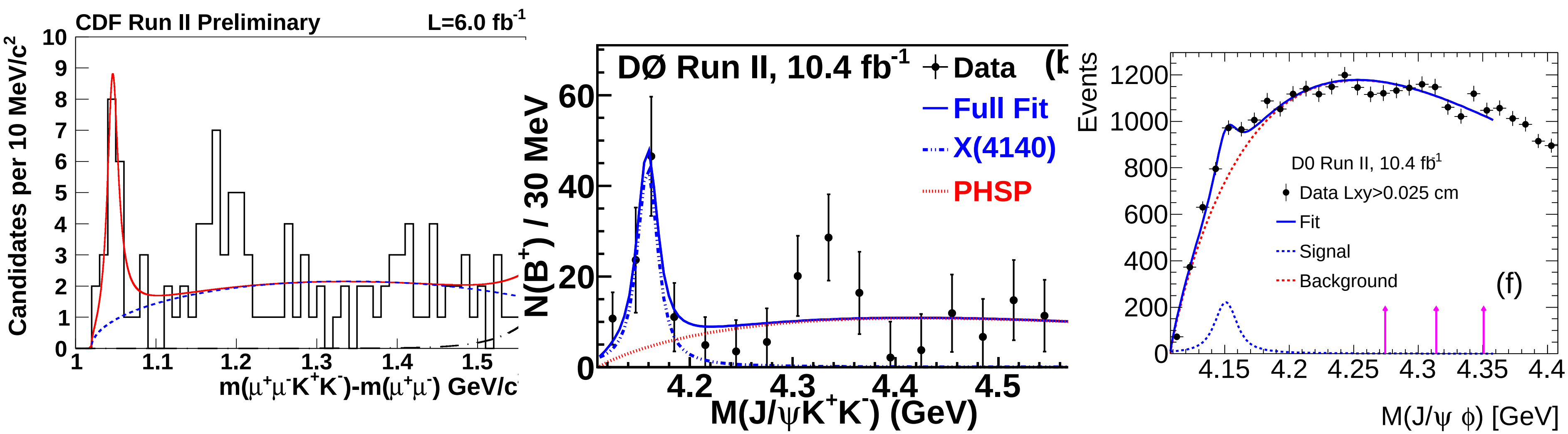
The latter attempts to provide a unified picture. A new paradigm with predictions for a tetraquark spectroscopy.





$X(4140)$

Among the >20 "XYZ" states is $X(4140)$ (a.k.a $Y(4140)$) decaying to $J/\psi\phi$ (a tetraquark $[cs][\bar{c}\bar{s}]$??) first seen by CDF in 2009 and more recently confirmed by CMS and D0.



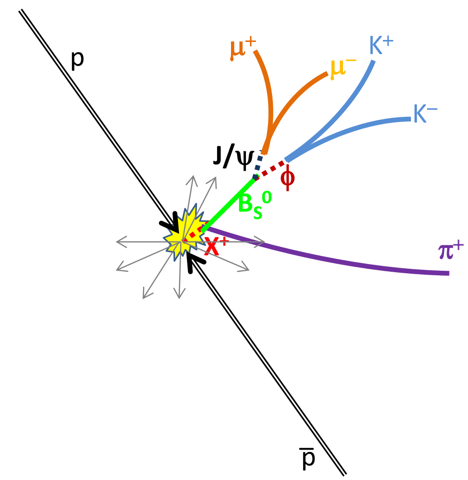
D0 reports evidence for the inclusive production, both prompt and non-prompt, in addition to a bump in a 2-body mass in a 3-body weak decay $B^+ \to J/\psi\phi K^+$.

2. $X(5568)$ analysis

We study the decay chain

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

(It includes $B_s^0\pi^+$, $B_s^0\pi^-$, $\overline{B}_s^0\pi^+$, $\overline{B}_s^0\pi^-$)



X → Bs π

We adopt a two-way strategy:

1. Search for a peak in $m(B_s^0\pi^{\pm})$ after selecting events in the B_s^0 signal window

2. Search for a peak in the B_s^0 signal yield as function of $m(J/\psi\phi\pi)$

D0 detector in Tevatron Run II

Scintillator counters and drift tubes

Thick calorimeter and iron toroids

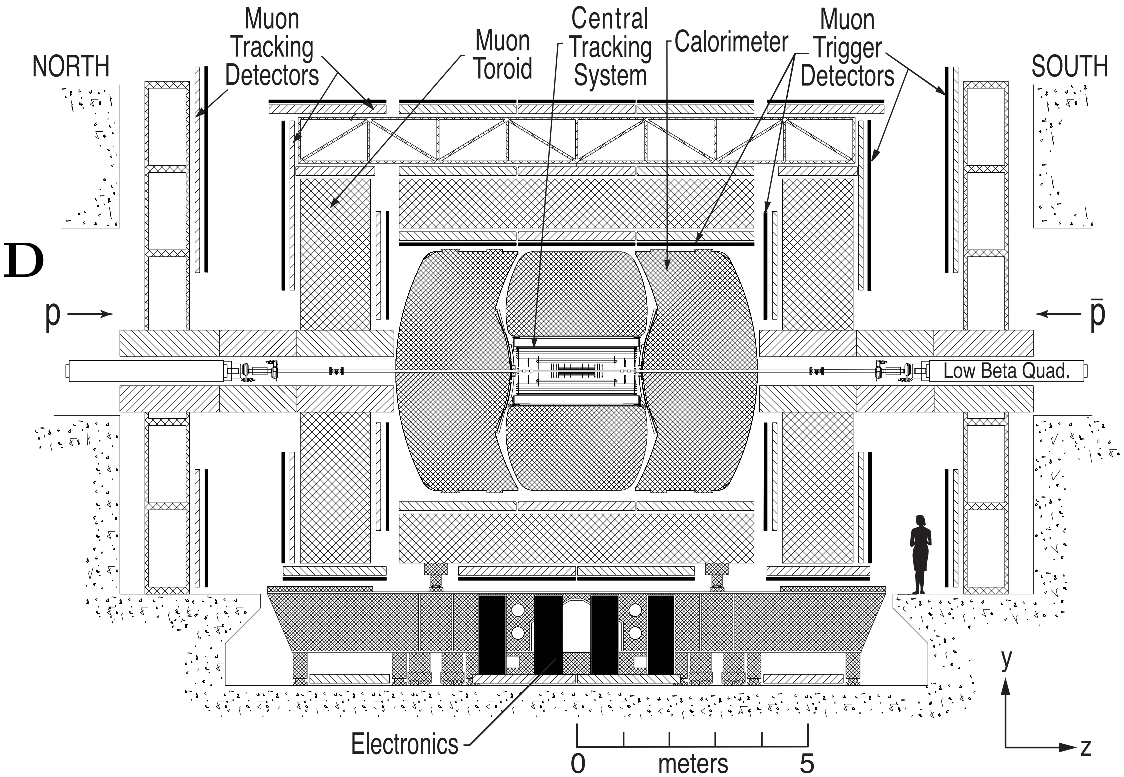
Excellent muon triggering and ID

Silicon Microstrip Tracker

Excellent vertex resolution

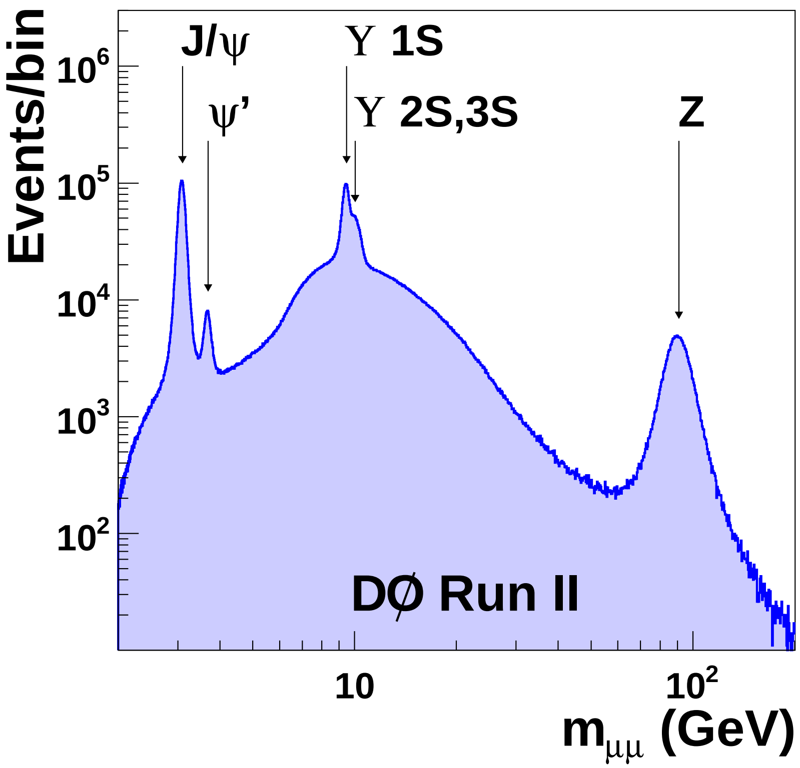
Central Fiber Tracker

Good mass resolution

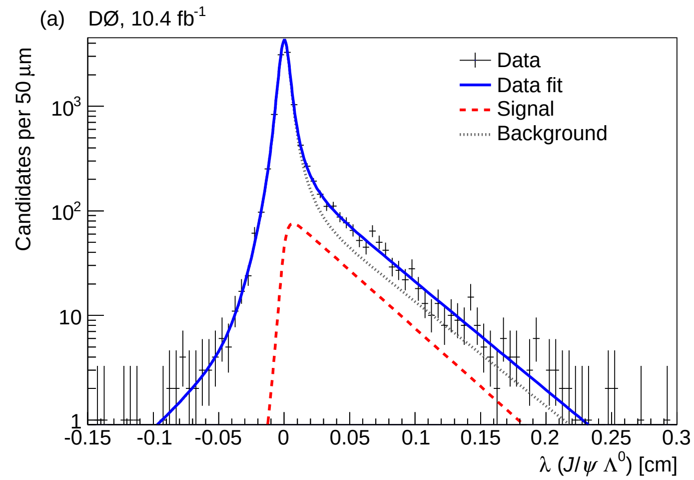


Excellent for B physics with muons

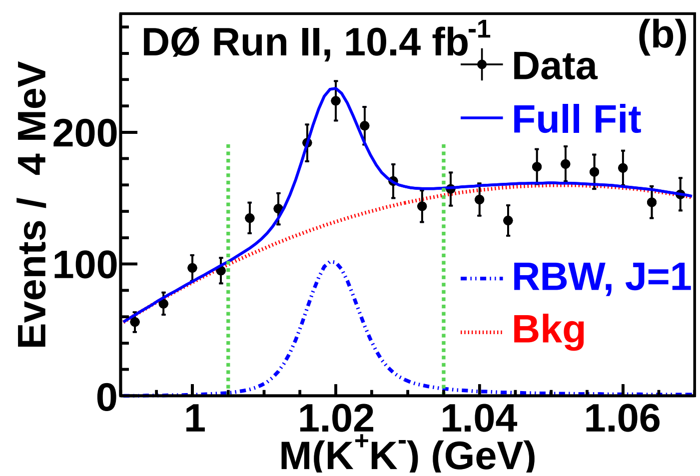
Examples of D0 Run II data



A subsample of $m(\mu^+\mu^-)$



Λ_b lifetime



$\phi \to K^+K^-$

Data

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

Thank you Fermilab!

Require a single muon or dimuon trigger.

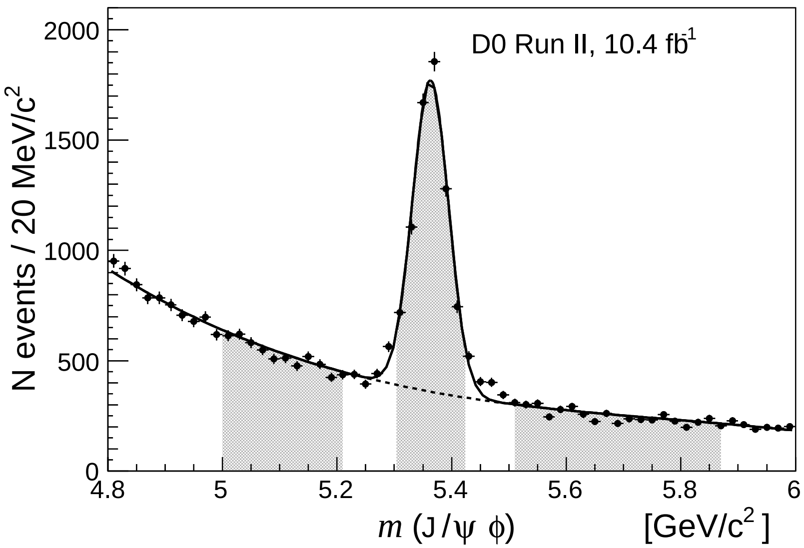
Select $B_s^0 \to J/\psi\phi$ candidates:

- $2.92 < M(\mu\mu) < 3.25$ GeV
- $p_T(K) > 0.7$ GeV; $1.012 < M(KK) < 1.03$ GeV
- $5.304 < M(J/\psi K^+K^-) < 5.424$ GeV; $L_{xy}/\sigma(L_{xy}) > 3$

Add a track assumed to be a pion, consistent with coming from PV:

- $p_T(\pi) > 0.5$ GeV, $IP_{xy} < 0.02$ cm, $IP_{3D} < 0.12$ cm
- $p_T(B_s\pi) > 10$ GeV
- $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2} < 0.3$ (the "cone" cut)

Two background components

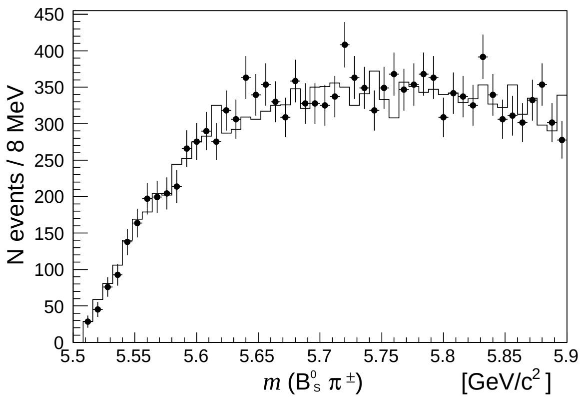


The B_s^0 signal:
$M = 5363.3 \pm 0.6$ MeV
$\sigma = 31.6 \pm 0.6$ MeV
$N = 5582 \pm 100$
B_s^0 signal region $(\pm 2\sigma)$
$5303 < m(J/\psi\phi) < 5423$ MeV

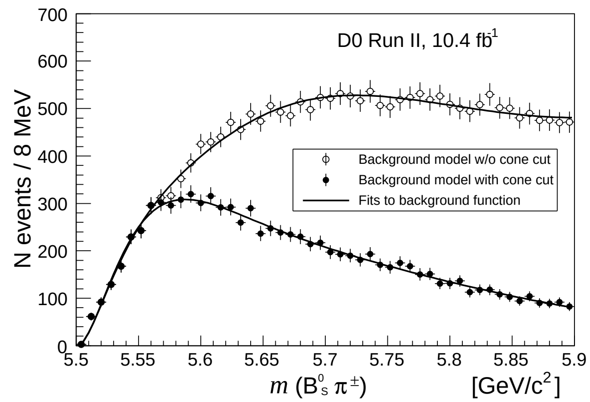
We pair a B_s candidate in the signal region with a charged track assumed to be a pion to form a $B_s^0\pi^{\pm}$ candidate.

In the B_s signal region, there is (1) B_s 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 (0.709:0.291).
We define the $B_s^0\pi$ mass as: $m(B_s^0\pi^{\pm}) = m(J/\psi\phi\,\pi^{\pm}) - m(J/\psi\phi) + 5366.7$ MeV$/c^2$

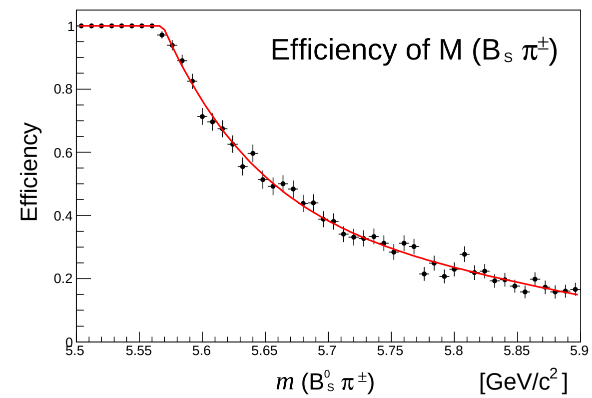
Background model



No ΔR cut



Effect of $\Delta R < 0.3$



$\epsilon(m)$

Points: sidebands, histogram: B_s^0 MC

The two background components have a very similar shape. It is parametrized as $(c_0 + c_2 \cdot m^2 + c_3 \cdot m^3 + c_4 \cdot m^4) \times \exp(c_5 + c_6 \cdot m + c_7 \cdot m^2)$.

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

Signal model

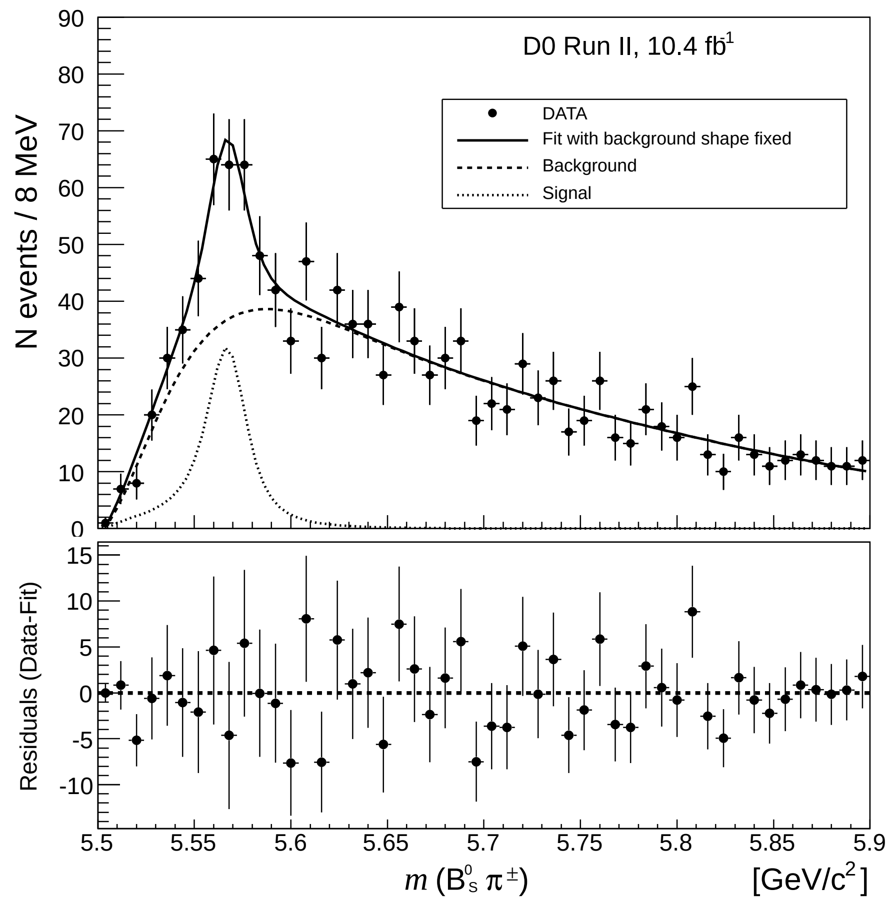
Relativistic Breit-Wigner function with mass M_X and natural width Γ_X.
BW for a near-threshold S-wave two-body decay has mass-dependent width (with Blatt-Weisskopf factor) :

$$BW(m_{B_s\pi}) \propto \frac{M_X \Gamma(m_{B_s\pi})}{(M_X^2 - m_{B_s\pi}^2)^2 + M_X^2 \Gamma^2(m_{B_s\pi})}, \qquad (1)$$

$\Gamma(m_{B_s\pi})$=$\Gamma_X \cdot (q_1/q_0)$ is proportional to the natural width Γ_X, where q_1 and q_0 are the decay momenta at the invariant mass $m_{B\pi}$ and M_X, respectively.

It is corrected for mass-dependent efficiency and smeared with the resolution of $\sigma = 3.8$ MeV$/c^2$

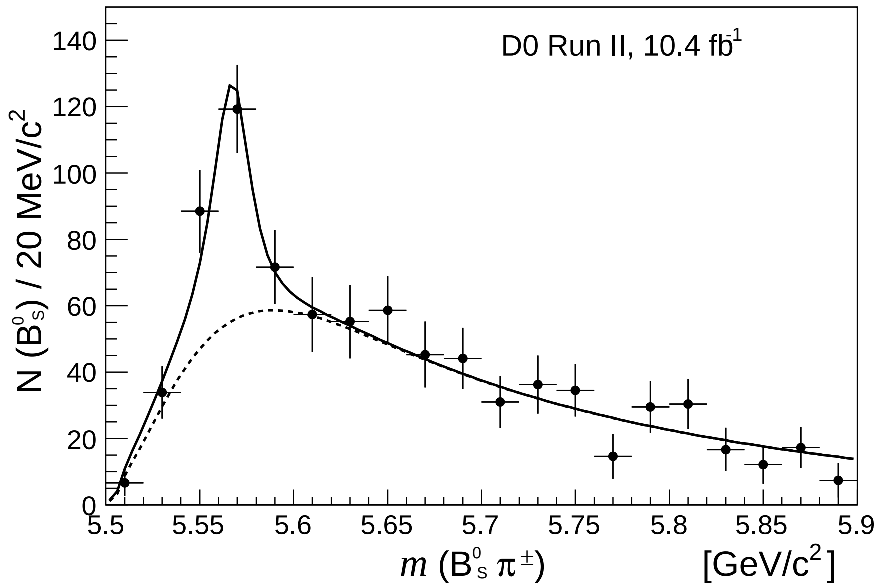
Fit results



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

With background shape parameters fixed, the free parameters are the signal and background normalizations and signal mass and natural width.

Alternative signal extraction



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

Extract the B^0_s signal individually in fits to $m(J/\psi\phi)$ in 20 intervals of $m(J/\psi\phi\pi)$ and plot the resulting B^0_s yields. The result is the $B^0_s\pi$ mass distribution with pure B^0_s, there is no non-B^0_s background.

$M_X \equiv 5567.8$ MeV; $\Gamma_X \equiv 21.9$ MeV, $N = 118 \pm 22$

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

Signal significance from simulations

Generate mass spectra using background model

Fit with and without signal

Define $t_0 = -2\ln(\mathcal{L}_0/\mathcal{L}_{\max})$

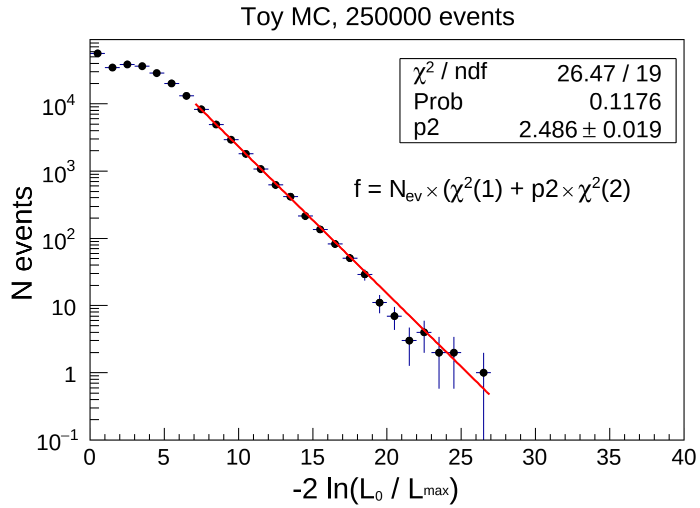
(the most significant fluctuation)

$P(t_0) = P(\chi^2(t_0, 1))$.

Convolve $P(t_0)$ with a Gaussian

corresponding to the syst. uncertainty.

S(local)=6.6σ $\Rightarrow$ S(local+syst)=5.6σ.



Look-elsewhere effect (LEE)

a la Gross and Vitells Eur. Phys. J., **C70**, 525 (2010).

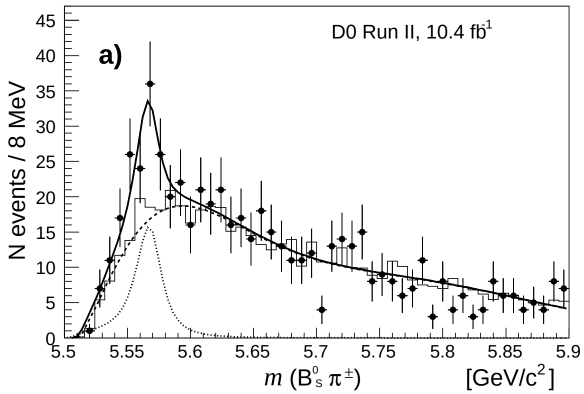
N independent search regions; within each search window, we maximize the likelihood by fitting the mass in the neighborhood of the fluctuation.

Fit the (t_0) distribution to

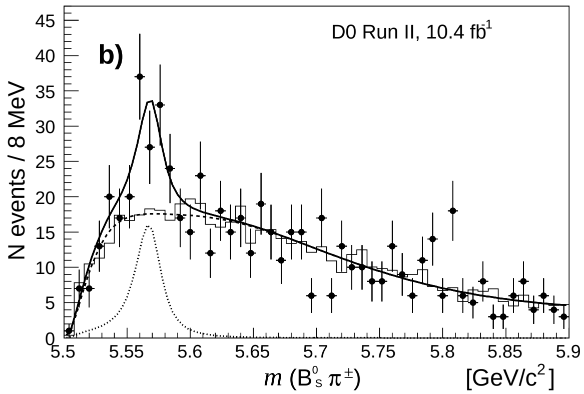
$f = \chi^2(1) + N\chi^2(2)$

Tail beyond 5.6^2 $\Rightarrow$ S(LEE+syst)= 5.1σ.

The ratio ρ of $X(5568)$ to B_s^0



$10 < p_T(B_s^0) < 15$ GeV



$15 < p_T(B_s^0) < 30$ GeV

Parameter	$10 < p_T(B_s^0) < 15$ GeV/c^2	$15 < p_T(B_s^0) < 30$ GeV/c^2
N $(X(5568))$	58.6 ± 16.7	67.5 ± 21.8
M $(X(5568))$	5566.3 ± 3.3	5568.9 ± 4.4
Γ $(B_s^+(5568))$	18.4 ± 7.0	21.7 ± 8.4
N (B_s^0)	2463 ± 63	1961 ± 56
$\epsilon(\pi^\pm)$	$(26.1 \pm 3.2)\%$	$(42.1 \pm 6.5)\%$
$\rho(X(5568)/B_s^0)$	$(9.1 \pm 2.6 \pm 1.6)\%$	$(8.2 \pm 2.7 \pm 1.6)\%$

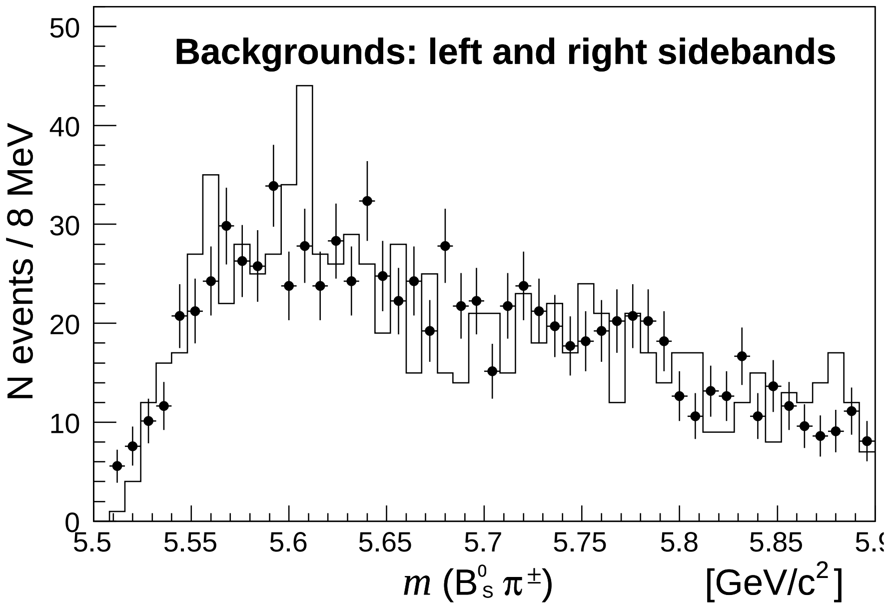
Averaging over $10 < p_T(B_s^0) < 30$ GeV $\quad \rho = (8.6 \pm 1.9 \pm 1.4)\%.$

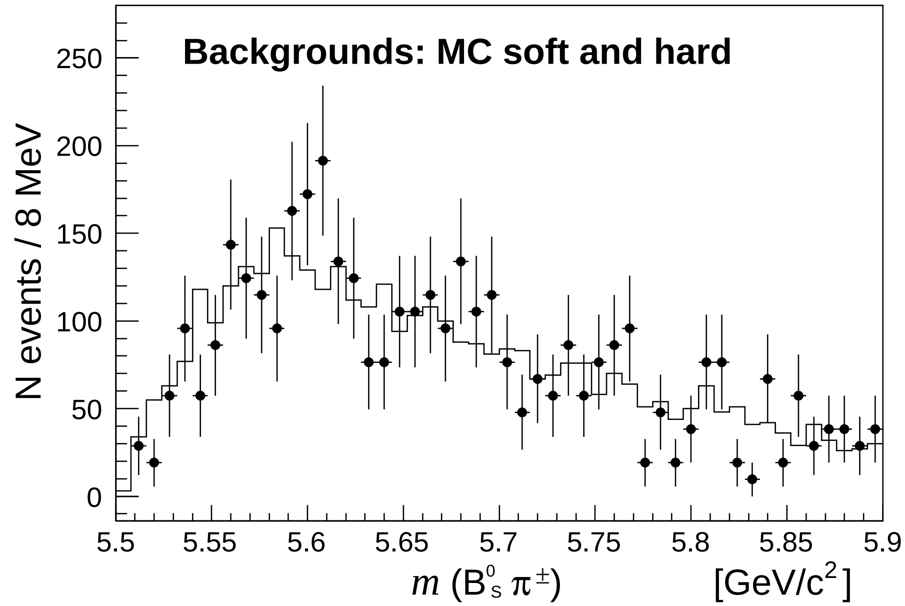
This study also makes a good cross-check.

More cross-checks performed

1. Use left (right) sideband for the non-B_s^0 background
2. Use two versions of Pythia for the B_s^0 background
3. Compare sidebands with "undersignal"
4. Allow background shape parameters to be free
5. Extract the signal yield without the cone cut
6. Use different B_s^0 mass ranges; modify the B_s^0 vertex cuts
7. Compare π^+ and π^- subsamples
8. Examine different detector regions (ϕ, η)
9. Test $B_s^0 K$ and $B_s^0 p$ hypotheses
10. Study $m(B_d^0\pi^\pm)$ on the full Run II data sample
11. Look for decay $B_s^{**} \to B_s^0\pi^+\pi^-$

Cross-checks

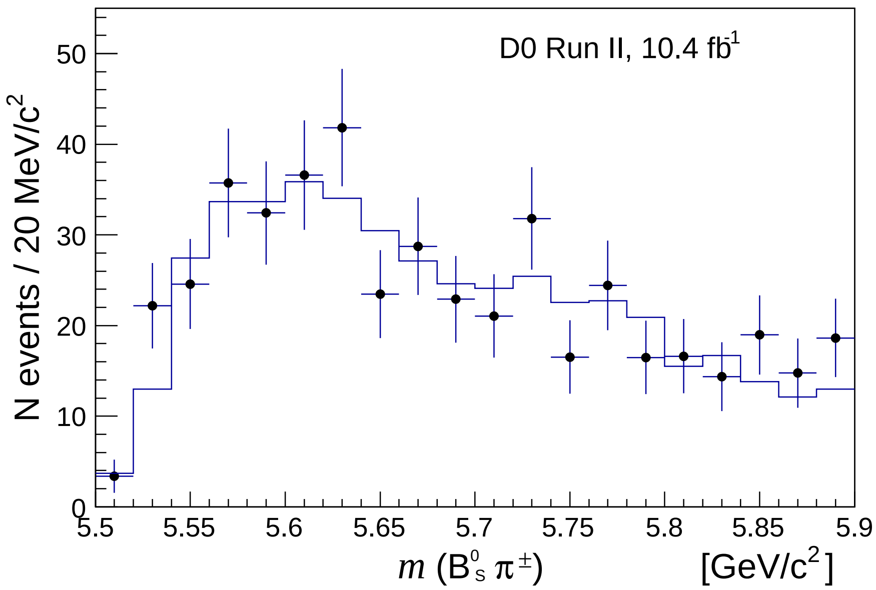




Left and right B_s^0 sideband (data)

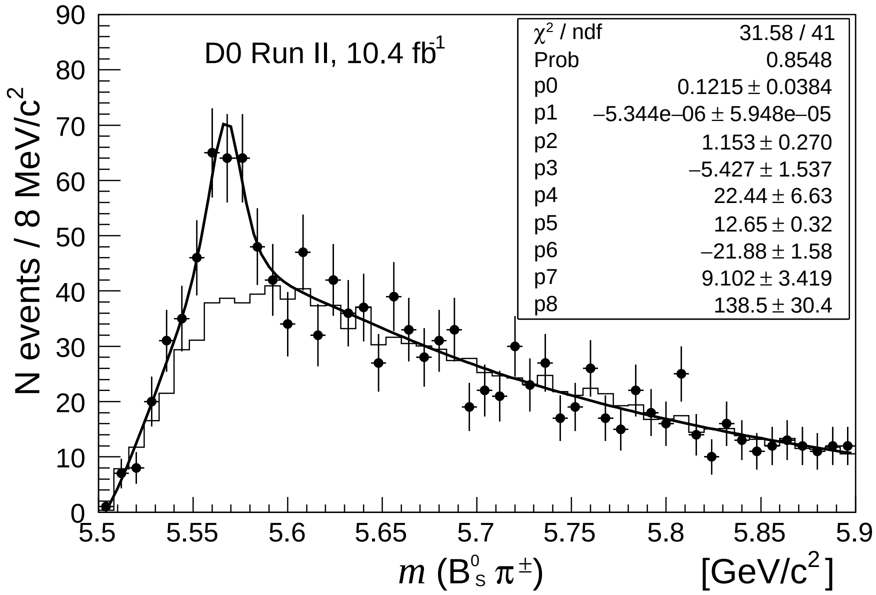
Pythia versions 6.323 and 6.409 used in the simulation of B_s^0 + anything

Cross-check



The B_s fits in $m(B_s\pi)$ bins provide a useful byproduct: the fitted non-B_s background vs $m(B_s\pi)$. Here is a comparison of the fit results with the sidebands. The agreement confirms that the sidebands are a good representation of the non-B_s background under the signal, i.e. "sidebands=undersignal".

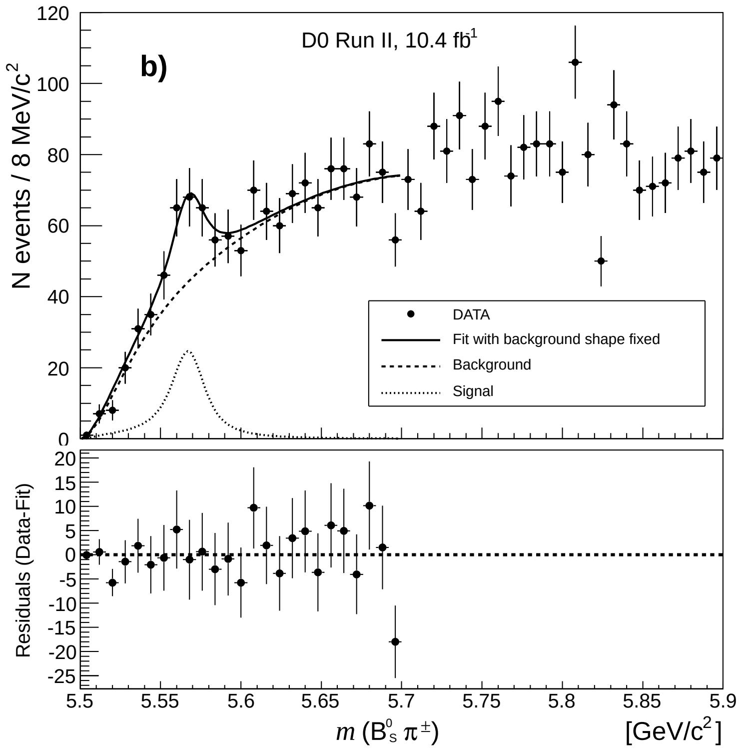
Cross-check

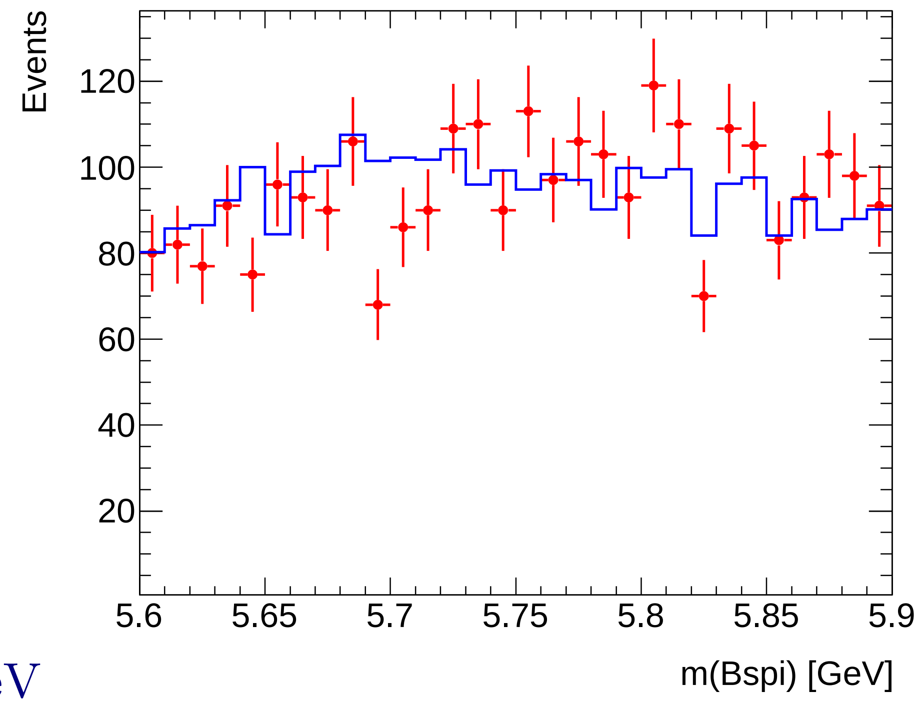


Allow background shape parameters to vary

$M_X \equiv 5567.8$ MeV; $\Gamma_X \equiv 21.9$ MeV, $N = 140 \pm 28$

Cross-check: fit with "no cone cut"



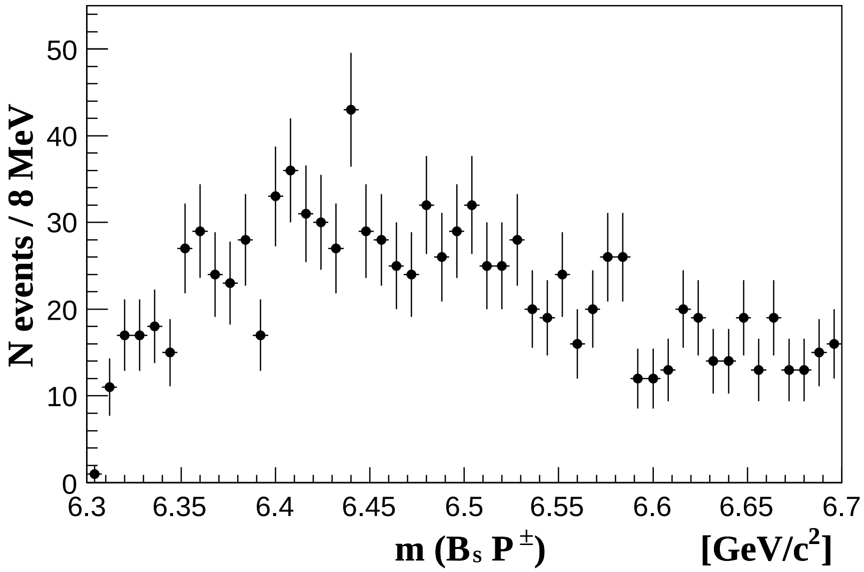


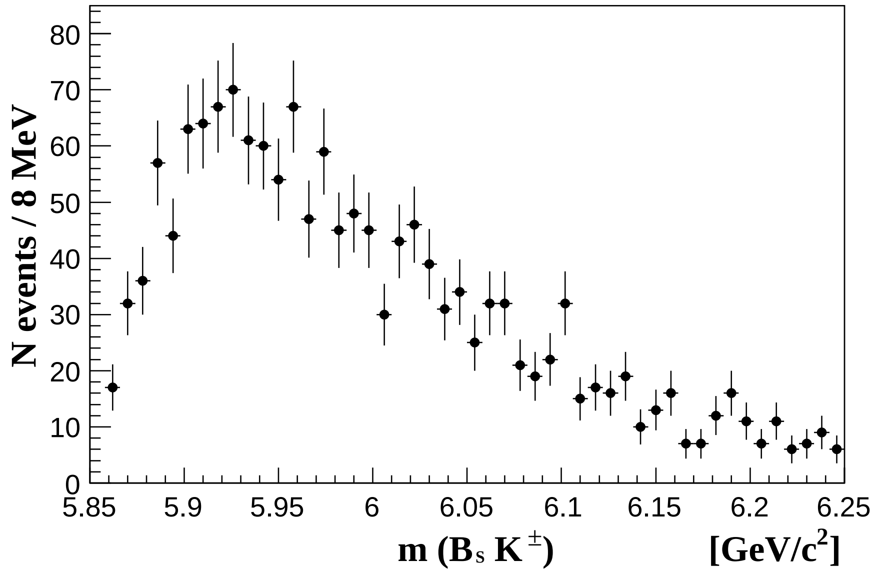
$M_X \equiv 5567.8$ MeV, $\Gamma_X \equiv 21.9$ MeV

$N = 106 \pm 33$

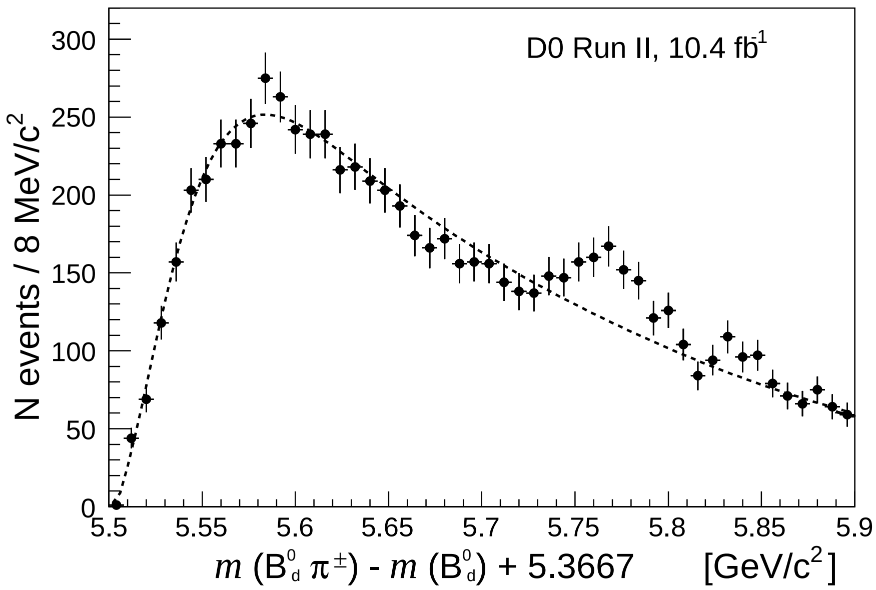
At $\Delta R > 0.3$ there is an excess in high-mass background that may be due to sources of B_s^0 not included in the simulations. Examples of "physics beyond Pythia" are $B_c \to B_s^0\pi^+\pi^0$, including $B_c \to B_s^0\rho^+$. Or higher tetraquark states ?? (discussed later). There is a large systematic uncertainty on the resulting signal yield.

Cross-check: No peaks in $m(B_s^0 p)$ or $m(B_s^0 K^{\pm})$





Cross-check $m(B_d^0\pi^{\pm})$



$B_d^0 \rightarrow J/\psi K^{*0}$, $K^{*0} \rightarrow K^{\pm}\pi^{\mp}$ candidates paired with a charged track assumed to be a pion for the charge combinations consistent with a B_1 decay. The B_1 signal is seen. There is no peak in the $X(5568)$ mass region.

The mass has been defined as $m(B_d^0\pi) - m(B_d^0) + 5.3667$ GeV to have the same mass range as in the main analysis.

3. Summary of what we know about $X(5568)$

It is produced in $p\bar{p}$ collisions

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

($m = 5567 + 48$ MeV if it is $X \to B_s^* \pi^\pm$)

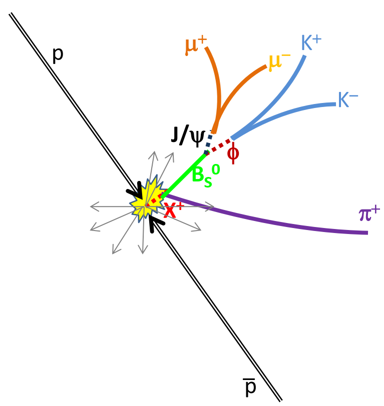
$\Gamma = 21.9 \pm 6.4\,(\text{stat})^{+5.0}_{-2.5}\,(\text{syst})$ MeV

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

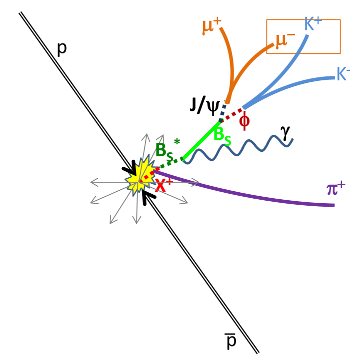
The significance is 5.1σ including systematic uncertainties and the "look-elsewhere effect"

It undergoes a strong decay to

$X \to B_s^0 \pi^\pm \quad J^P = 0^+$ or $X \to B_s^* \pi^\pm \quad J^P = 1^+$



X → B_s π



X → B_s^* π → B_s γ π

3. Summary and outlook

After six decades, the $q\bar{q}$ and qqq paradigm of hadron structure is challenged by the discoveries of 4-quark and 5-quark states with a hidden charm or hidden beauty.

We have presented an observation of a new structure, in $m(B_s^0\pi^{\pm})$:
a strange charged beauty produced in $p\bar{p}$ collisions promptly or through a decay of a charmed particle.

$J^P = 0^+$ if $X \to B_s^0\pi^{\pm}$ (analog of $a_0(980)$ with a substitution $s\bar{s} \Rightarrow b\bar{s}$)
$J^P = 1^+$ if $X \to B_s^*\pi^{\pm}$ (analog of the Z_b states with a substitution $b\bar{b} \Rightarrow b\bar{s}$)

This would be the first 4-quark state that has a pair $b\bar{s}$.
Letter submitted to PRL on February 24 2016.

Outlook

The diquark-antidiquark tetraquark model (refined wrt 2004)

L. Maiani, F. Piccinini, A. D. Polosa and V. Riquer,

"The Z(4430) and a New Paradigm for Spin Interactions in Tetraquarks , Phys. Rev. D **89**, 114010 (2014).

has predictions for a rich spectrum of states.

With the basis $|s, \bar{s}>_J$ of states with diquark (antidiquark) spin s ($\bar{s}$) coupling to spin 0 or 1, and the diquark pairs' spins coupling to the total spin spin J, the following 6 combinations for the relative S wave are expected within a few hundred MeV:

$J^P = 0^+, \quad I = 0 \quad |0,0>_0, \; |1,1>_0$

$J^P = 1^+, \quad I = 0 \quad |1,0>_1 + |0,1>_1$

$J^P = 1^+, \quad I = 1 \quad |0,0>_1 - |1,1>_1, \; |1,1>_1$ Physical states = lin. combs.

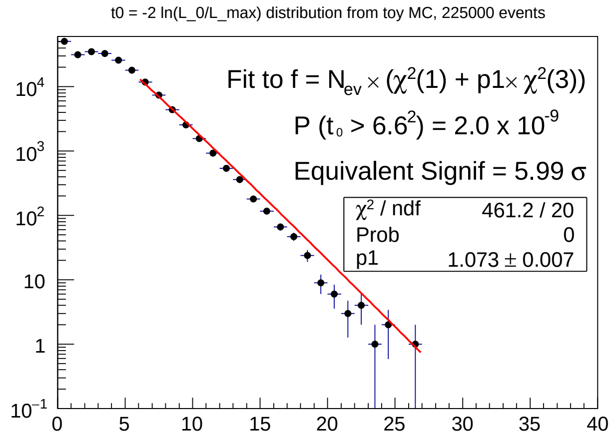
$J^P = 2^+, \quad I = 0 \quad |1,1>_2$

Observing these states and measuring their decay modes could bring crucial information on QCD interactions.

BACKUP

More on S(LEE)

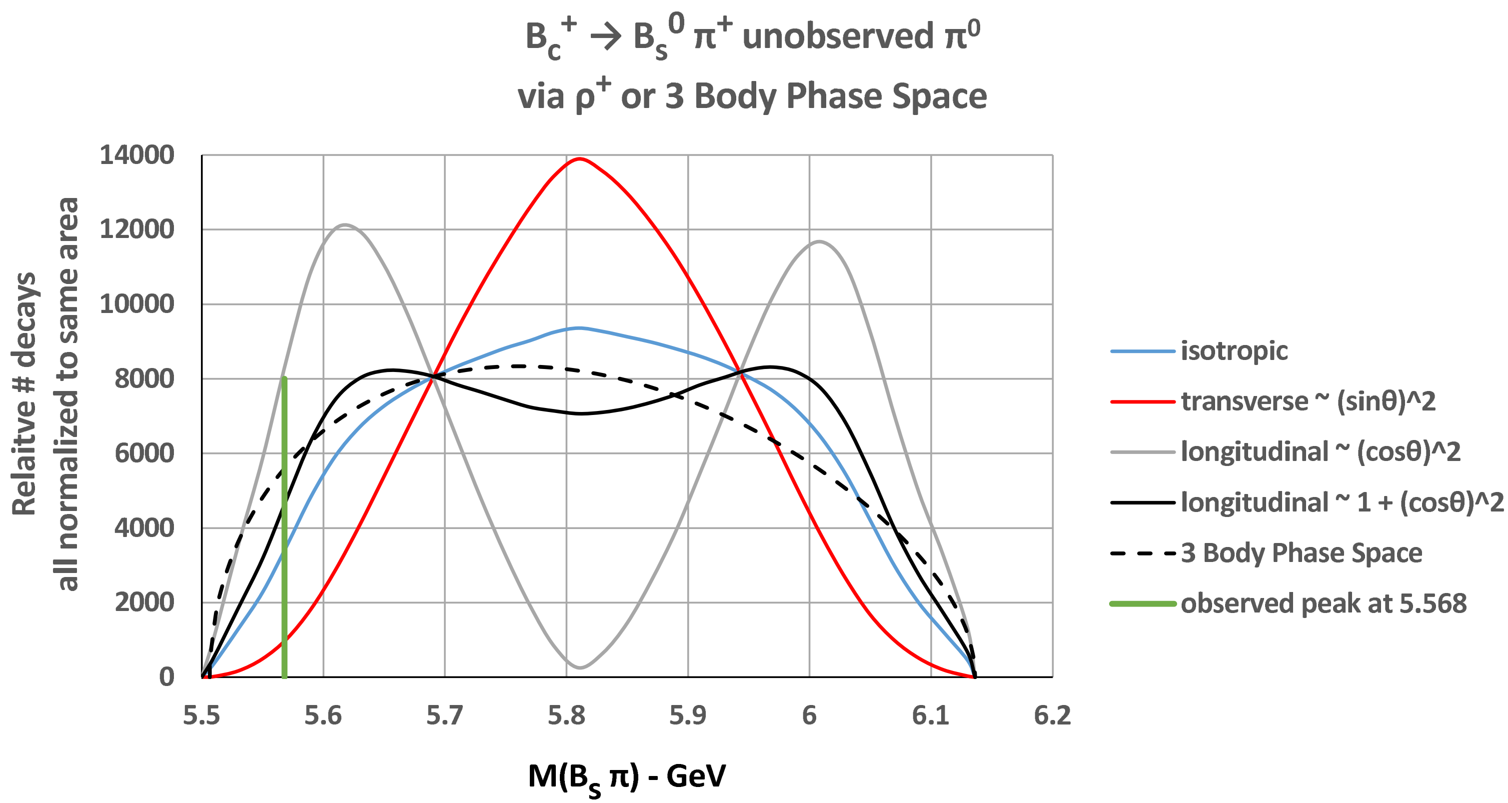
Generate mass spectra using the background model.
Plot $t_0 = -2\ln(\mathcal{L}_0/\mathcal{L}_{max})$
(the same simulation as before.)



In principle, since we allow for a free natural width Γ in addition to the free yield and mass, $\chi^2(2)$ should be replaced by $\chi^2(3)$. However, the fit to this function is found to be worse. We interpret it as being due to a correlation of the width and yield parameters, meaning that the number of independent parameters is de facto less than three, and the fact that Γ is small compared to the mass range. The difference in the resulting significance is small:

S(LEE)=6.0σ instead of S(LEE)=6.1σ.

$B_c \to B_s^0\pi^+\pi^0$ simulation



References

M. Gell-Mann "A schematic model of baryons and mesons", PL 8 (1964) 214

L. Maiani, F. Piccinini, A. D. Polosa, and V. Riquer,"New Look at Scalar Mesons", PRL **93**, 212002 (2004)

L. Maiani, F. Piccinini, A. D. Polosa and V. Riquer, "The Z(4430) and a New Paradigm for Spin Interactions in Tetraquarks", Phys. Rev. D **89**, 114010 (2014).