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

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for D0 Collaboration

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Overview

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

- Observation of X(5568)
  a strange charged beauty

- Summary

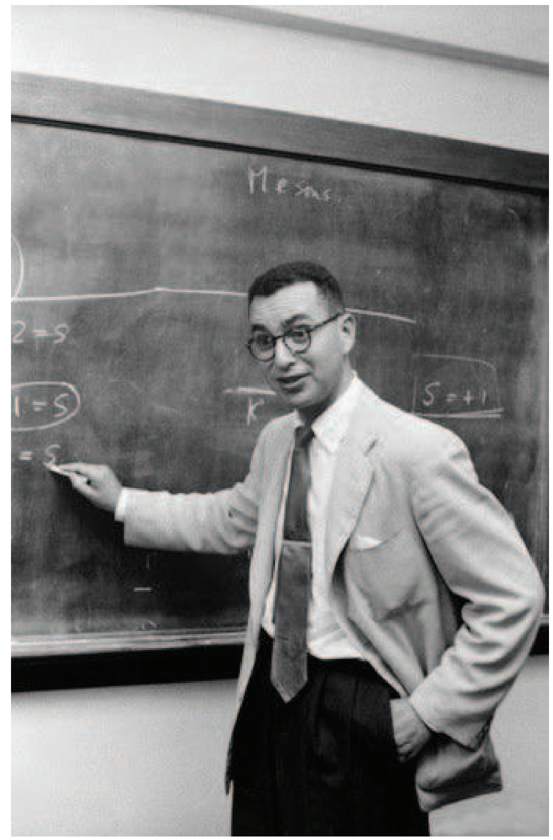
- Interpreting $X(5568)$

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



$q\bar{q}$ and qqq orthodoxy

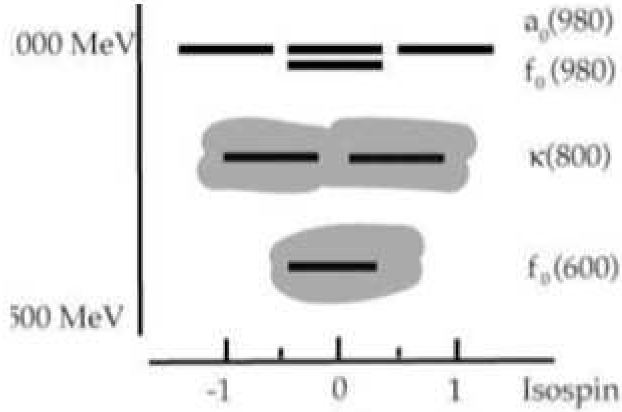
Decades of research in hadron spectroscopy since the 1960s led to the paradigm of $q\bar{q}$ mesons and qqq baryons.
Based on the absence of $I = 2$ $\pi\pi$ resonances and $S > 0$ baryons.

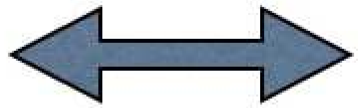
But the nonet of scalar mesons does not fit the picture:
$a_0(980) = (u\bar{d})$ is heavier than $\kappa(800) = (u\bar{s})$.

The tetraquark model fits better:
$a_0(980) = [su][\bar{d}\bar{s}], \quad \kappa(800) = [su][\bar{u}\bar{d}]$.

Maiani, Piccinini, Polosa, and Riquer,"New Look at Scalar Mesons", PRL **93**, 212002 (2004)

The nonet of light scalars (L. Maiani)





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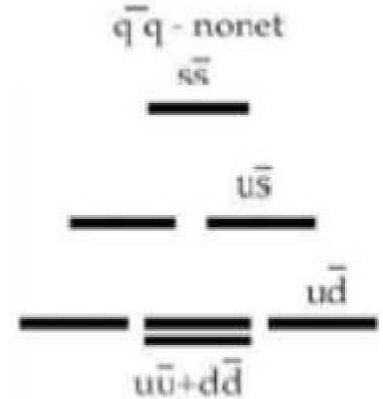
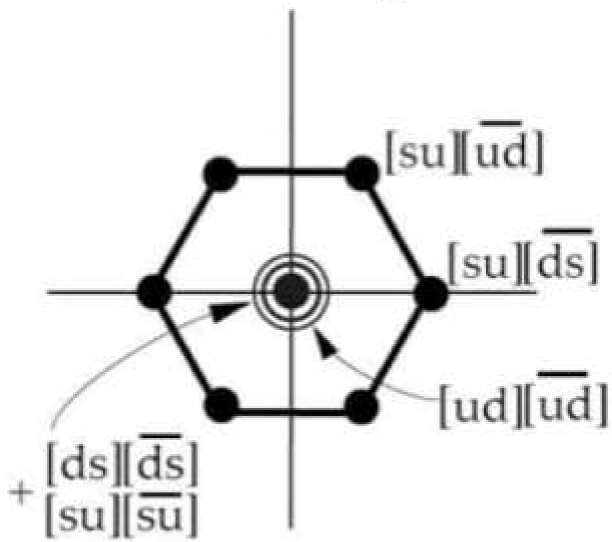
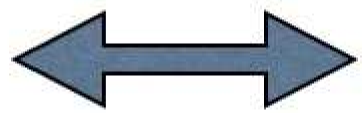
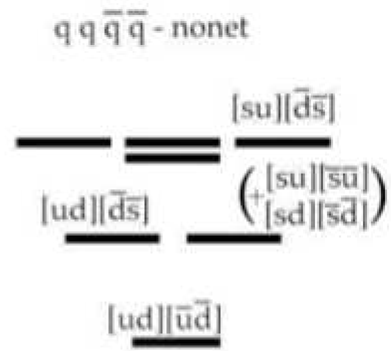


Antisymmetric tetraquarks work better



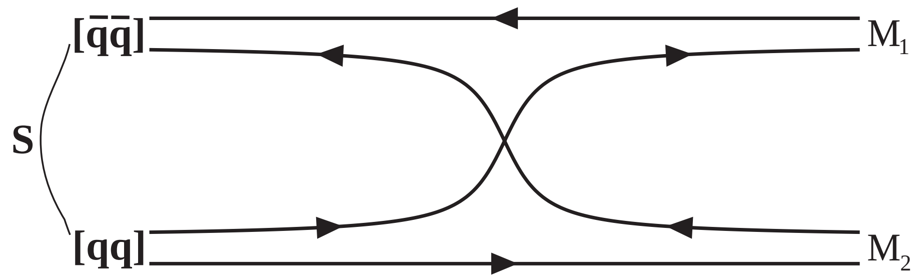
(a)





(b)

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".

Maiani, Piccinini, Polosa, and Riquer, "New Look at Scalar Mesons", PRL **93**, 212002 (2004)

The XYZ states

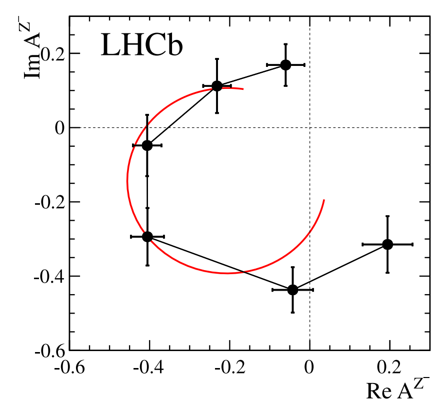
The 2003 discovery of $\boldsymbol{X(3872)\to J/\psi\pi^+\pi^-}$ by Belle marked a new era. The flavor contents are not obviously exotic, but a conventional $\boldsymbol{c\bar{c}}$ interpretation of a state with $\boldsymbol{J^{PC}=1^{++}}$ (measured by LHCb) at this mass is disfavored.

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

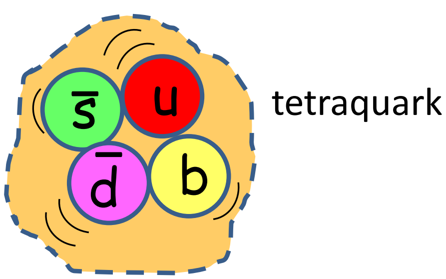
PDG names all non-$q\bar{q}$ candidates $X(mass)$. Authors and theorists use Z for charged states, Y for 1^{--} states, and X for the rest.

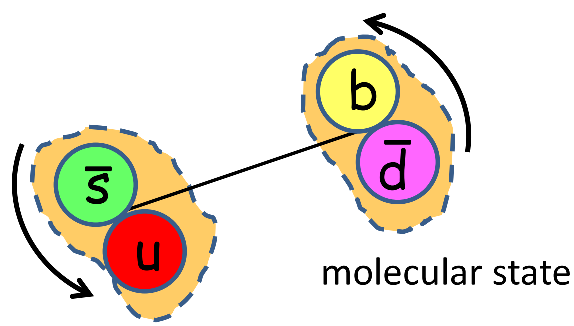
There are various competing phenomenological models proposed to explain their nature.

Two popular interpretations are:

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

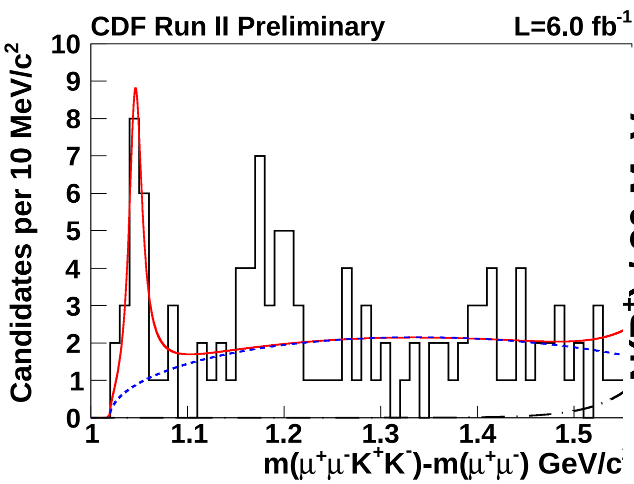
The latter predicts a rich spectroscopy.

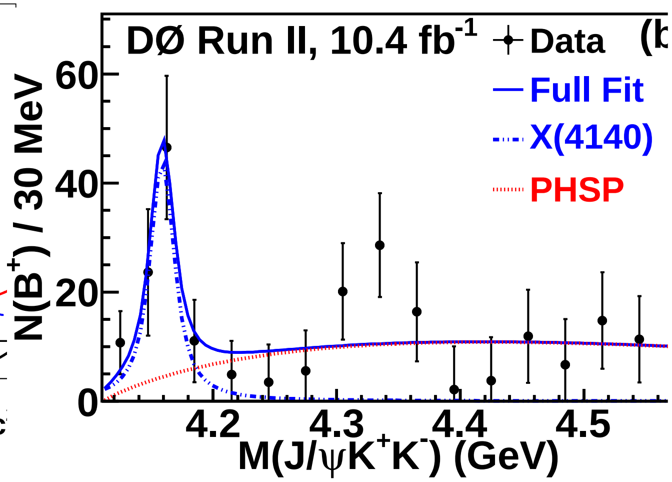


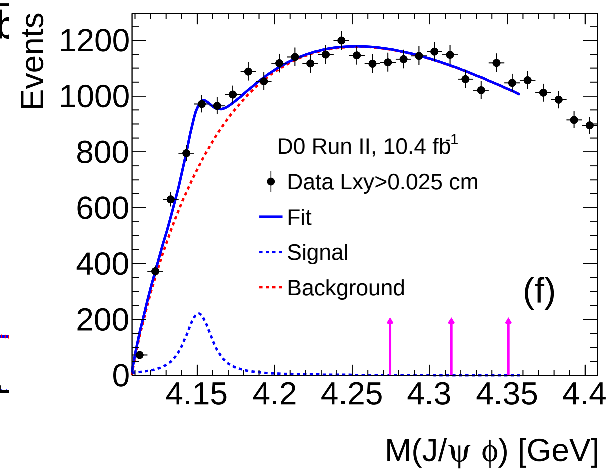


$X(4140)$

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. (LHCb found no evidence, in 2.4σ disagreement with the CDF result.)







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 $B^+ \to J/\psi\phi K^+$.

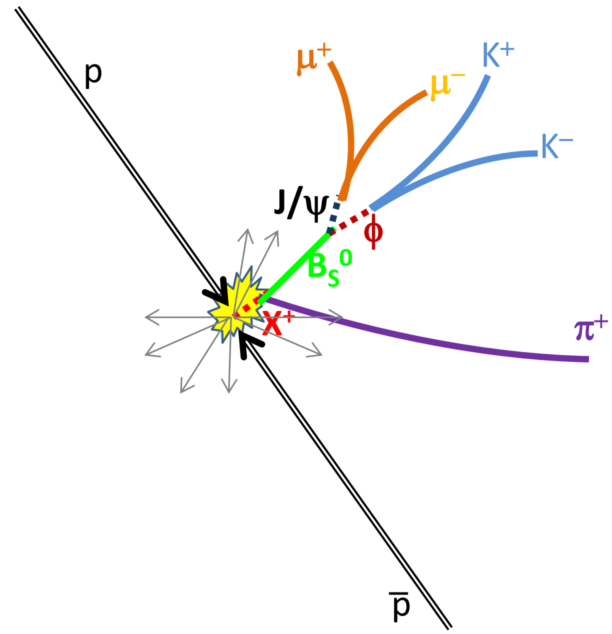
2. $X(5568)$ analysis

We study the decay chain

$X(5568) \to B_s^0\pi^\pm$, $B_s^0 \to J/\psi\phi$

$J/\psi \to \mu^+\mu^-$, $\phi \to K^+K^-$

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



X → B$_s$ 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

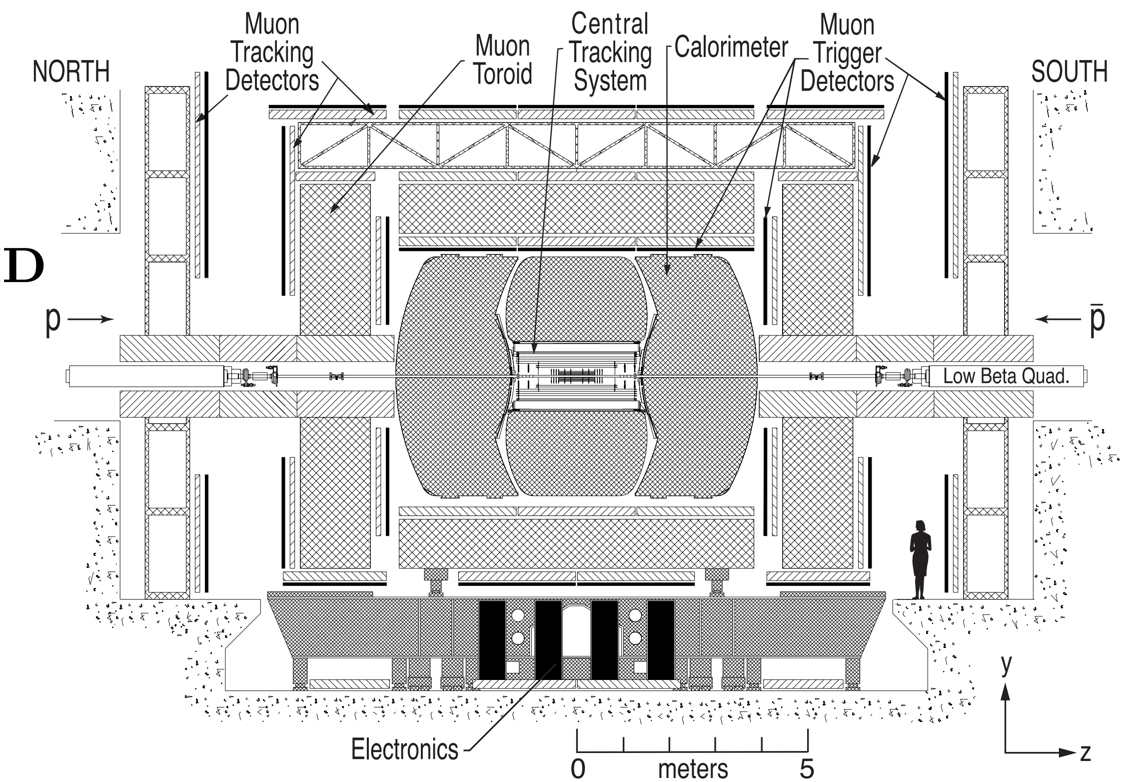
Excellent muon triggering and ID

Silicon Microstrip Tracker

Excellent vertex resolution

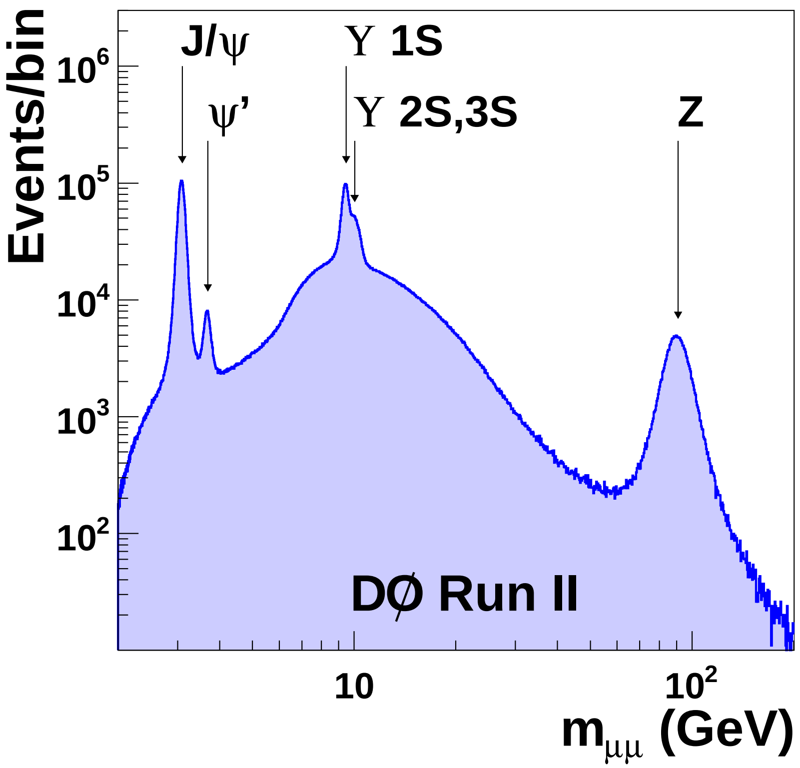
Central Fiber Tracker

Good mass resolution

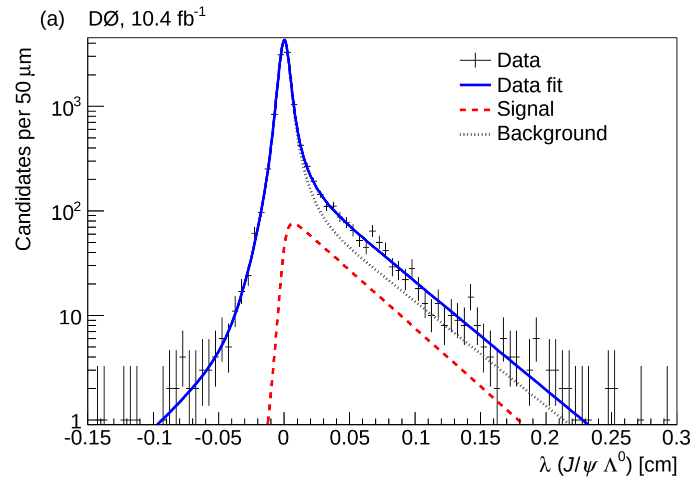


Excellent for B physics with muons

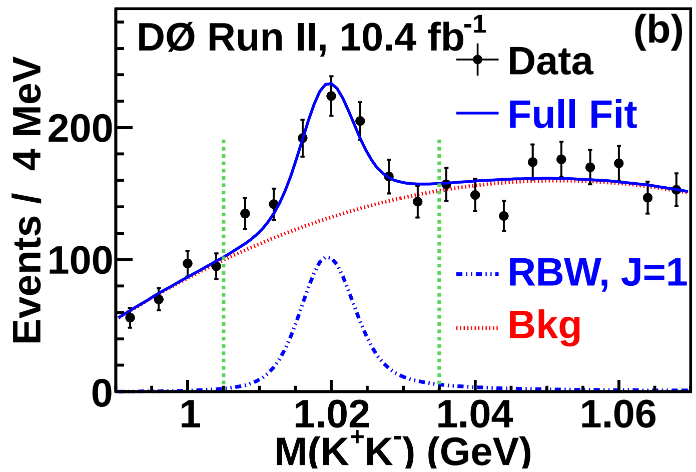
Examples of D0 Run II data



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.

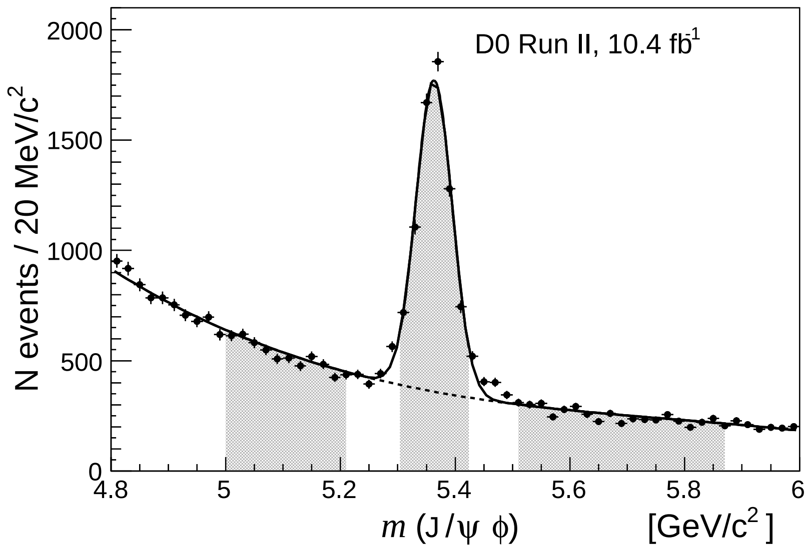
Select $B_s^0 \to J/\psi\phi$ candidates:

- $2.92 < M(\mu\mu) < 3.25$ 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, $IP_{xy} < 200\ \mu$m, $IP_{3D} < 1200\ \mu$m (charm decay not ruled out)
- $p_T(B_s\pi) > 10$ GeV, $|y(B_s\pi)| < 2$
- $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2} < 0.3$ (the "cone" cut)

Two background components

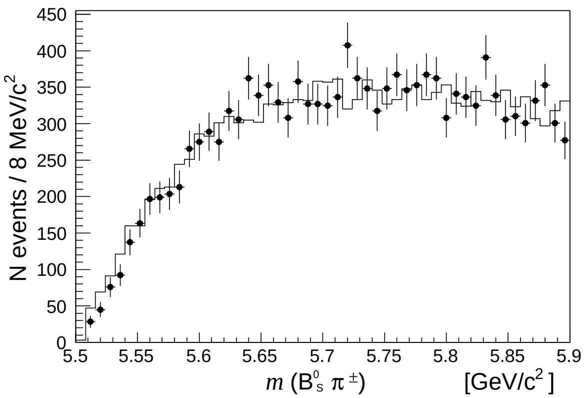


The B_s^0 signal:
$M = 5363.3 \pm 0.6$ MeV
$\sigma = 31.6 \pm 0.6$ MeV
$N = 5582 \pm 100$
B_s^0 signal region ($\pm 2\sigma$)
$5303 < m(J/\psi\phi) < 5423$ MeV

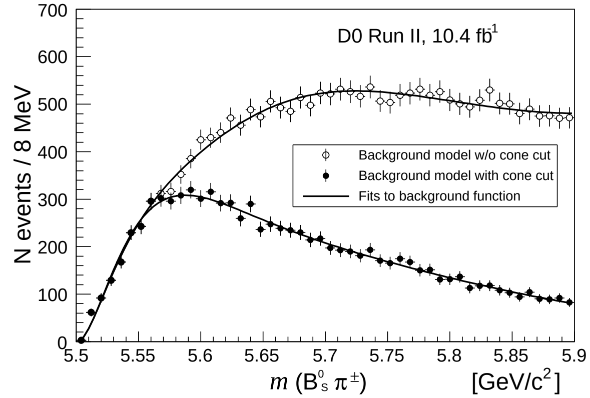
We pair a B_s candidate in the signal region with a charged track assumed to be a pion to form a $B_s^0\pi^{\pm}$ candidate.

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$/c^2$

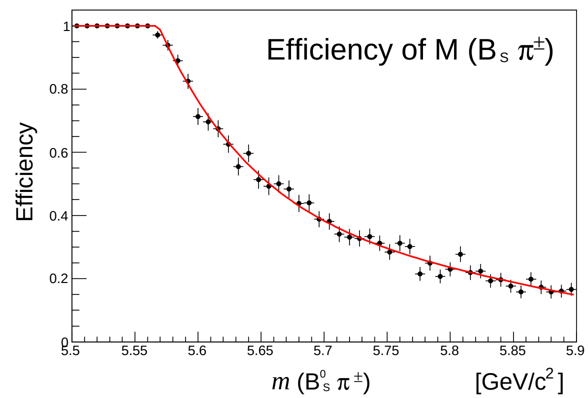
Background model



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

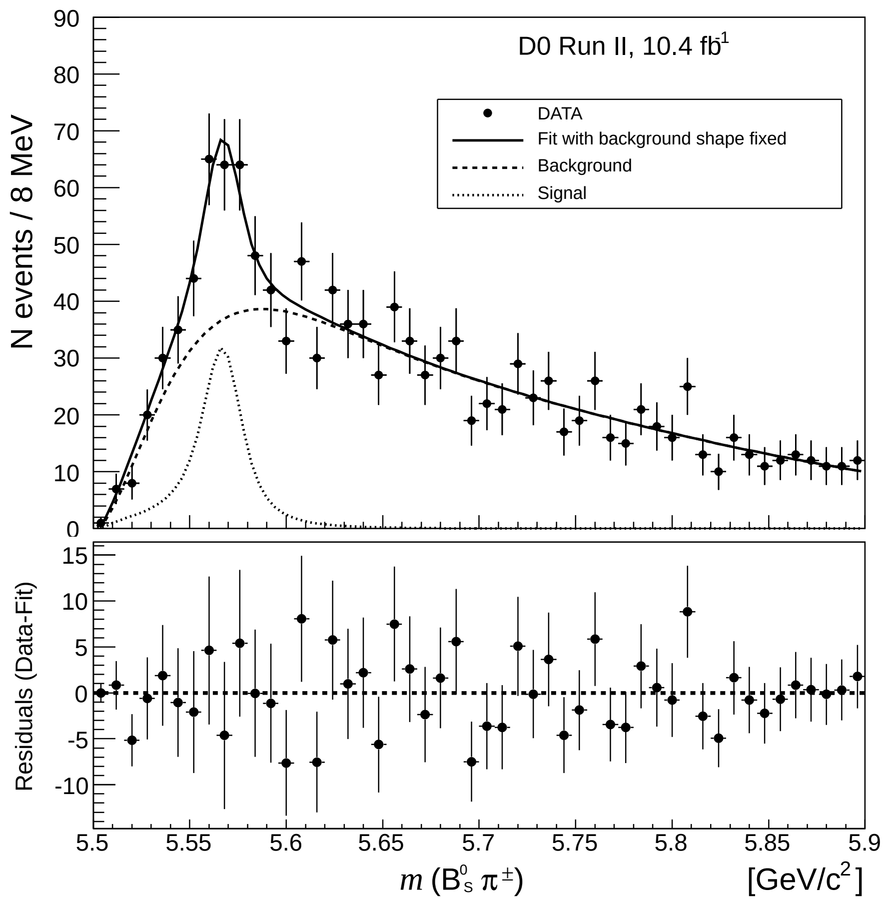
Relativistic Breit-Wigner function with mass M_X and width Γ_X:

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

BW for a near-threshold S-wave two-body decay has mass-dependent width (with Blatt-Weisskopf factor) $\Gamma(m_{B_s\pi})$=$\Gamma_X \cdot (q_1/q_0)$ 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.

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

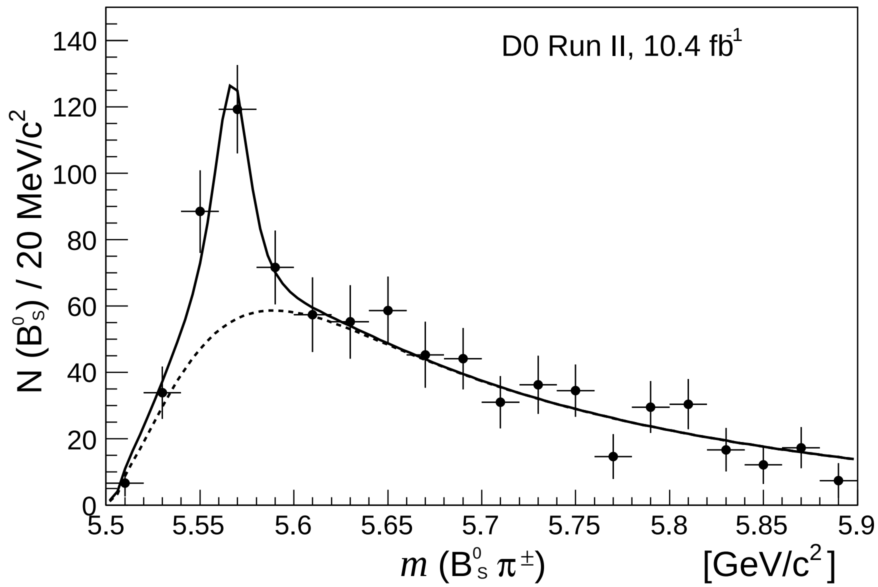
Fit results



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

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

Alternative signal extraction



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

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

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

Systematic uncertainties

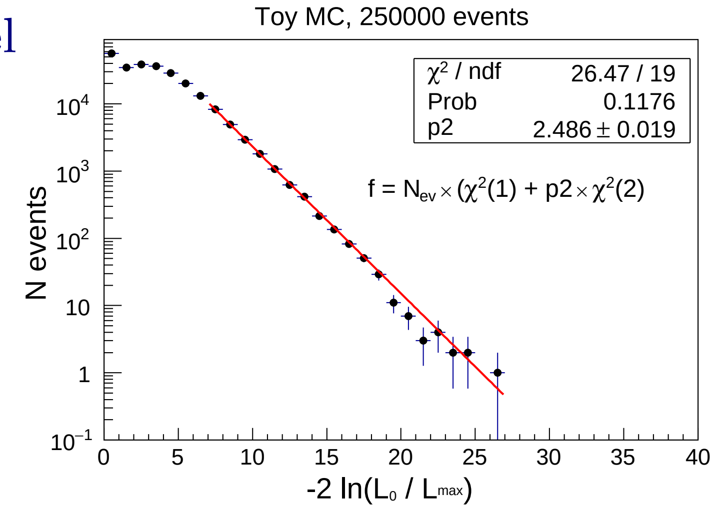
Source	**mass, MeV/c^2**	**width, MeV/c^2**	**rate, %**
Background shape			
MC sample soft or hard	+0.2 ; -0.6	+2.6 ; -0.	+8.2 ; -0.
Sideband mass ranges	+0.2 ; -0.1	+0.7 ; -1.7	+1.6 ; -9.3
Sideband mass calculation method	+0.1 ; -0.	+0. ; -0.4	+0 ; -1.3
MC to sideband events ratio	+0.1 ; -0.1	+0.5 ; -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

Systematic errors smaller than statistical error.

The yield is $N = 133 \pm 31 \pm 15$.

Signal significance from simulations

Generate mass spectra using background model
Fit with and without signal
Define $t_0 = -2\ln(\mathcal{L}_0/\mathcal{L}_{\max})$
for 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.

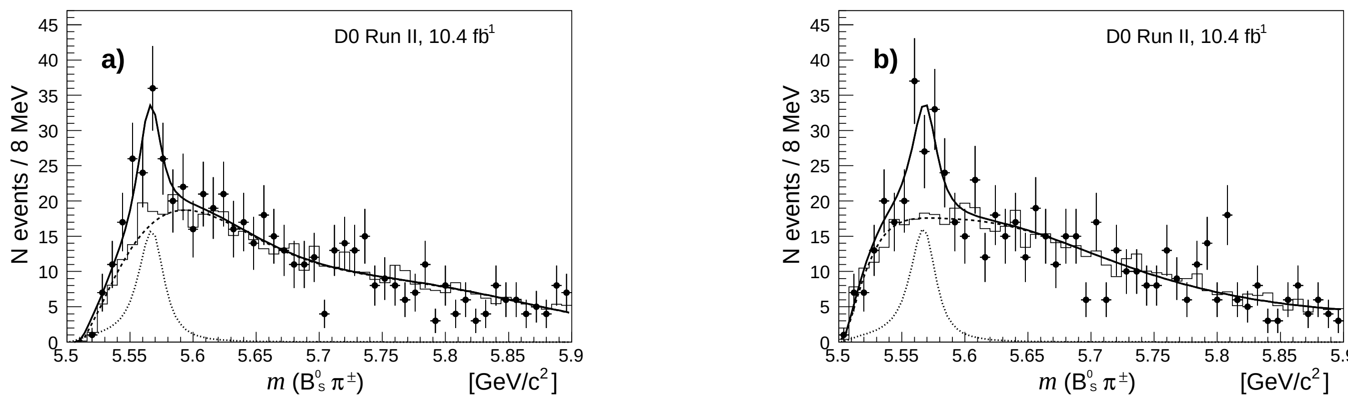


Look-elsewhere effect (LEE)
a la Gross and Vitells Eur. Phys. J., **C70**, 525 (2010).

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 ($X(5568)$)	18.4 ± 7.0	21.7 ± 8.4
N ($X(5568)$)	2463 ± 63	1961 ± 56
$\epsilon(\pi^\pm)$	(26.1 ± 3.2)%	(42.1 ± 6.5)%
$\rho(X(5568)/B_s^0)$	(9.1 ± 2.6 ± 1.6)%	(8.2 ± 2.7 ± 1.6)%

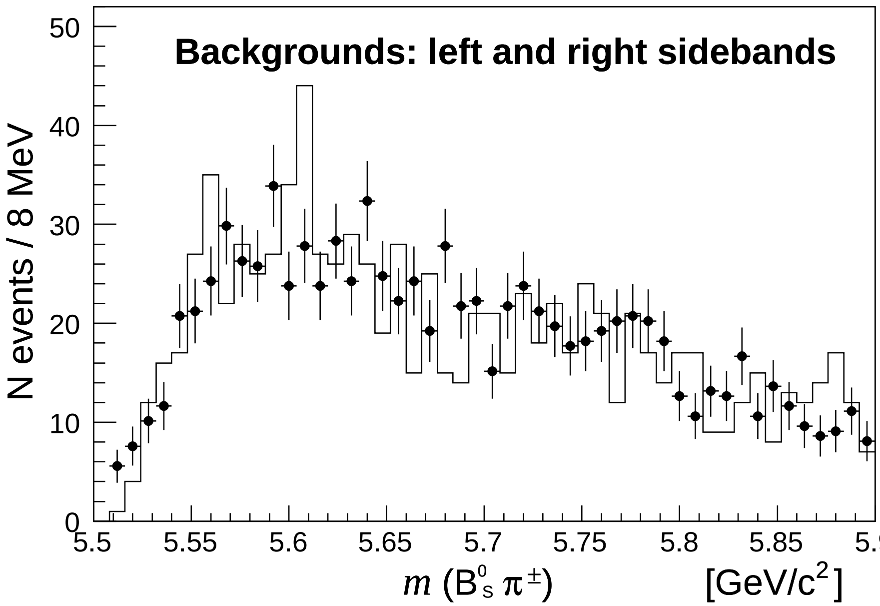
Averaging over $10 < p_T(B_s^0) < 30$ GeV $\rho = (8.6 \pm 1.9 \pm 1.4)\%.$

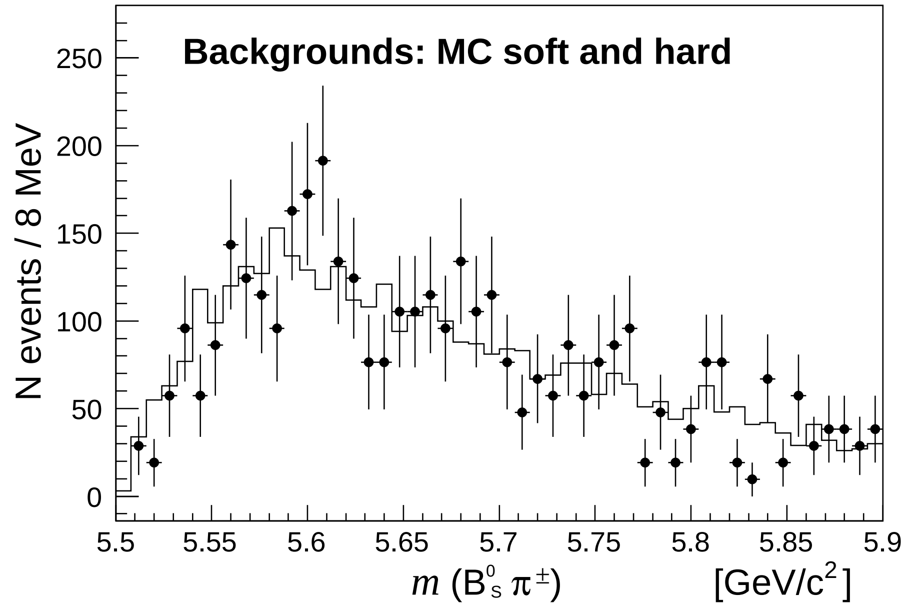
This study also makes a good cross-check. The results for M, Γ in the two subsets are consistent while the background peak shifts as $p_T(B_s)$ increases.

More 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
- Extract the signal yield without the cone cut
- 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^0K and B_s^0p hypotheses
- Study $m(B_d^0\pi^{\pm})$ on the full Run II data sample
- Look for decay $B_s^{**} \to B_s^0\pi^+\pi^-$

Cross-checks

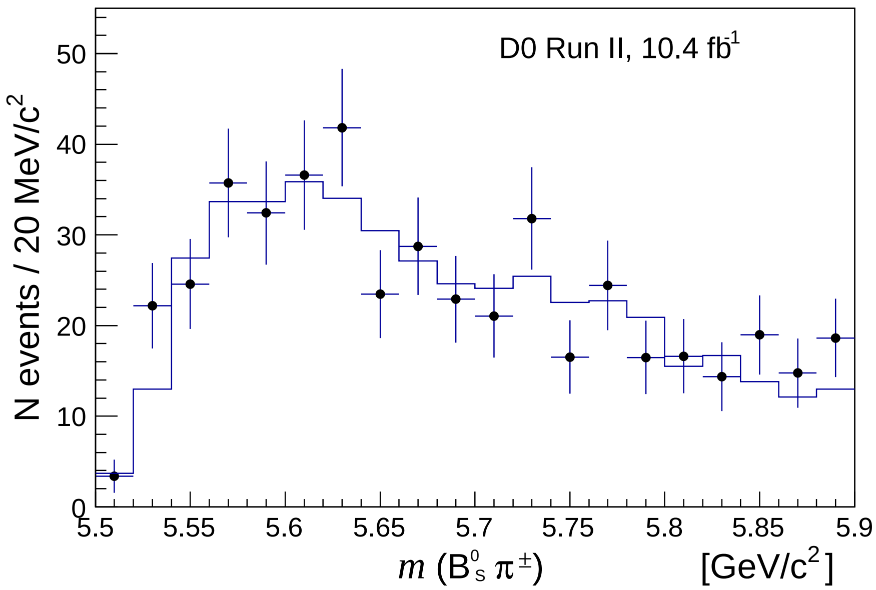




Left and right B_s^0 sideband (data)

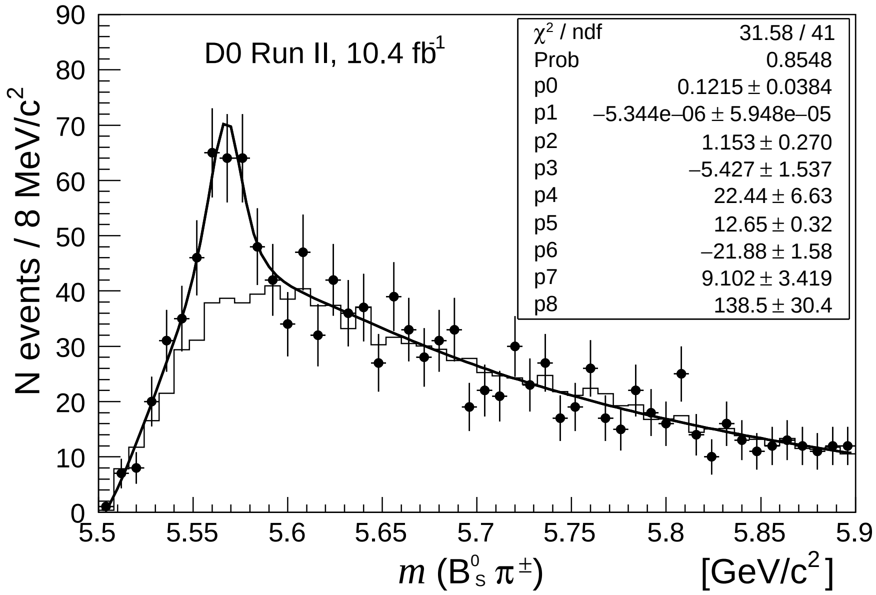
Pythia versions 6.323 and 6.409 used in the simulation of B_s^0 + anything

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".

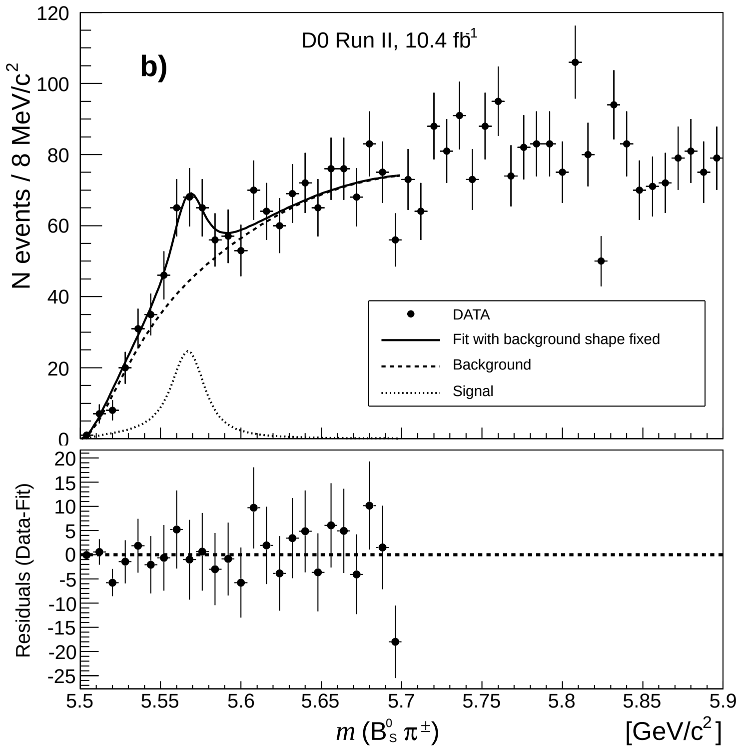
Cross-check

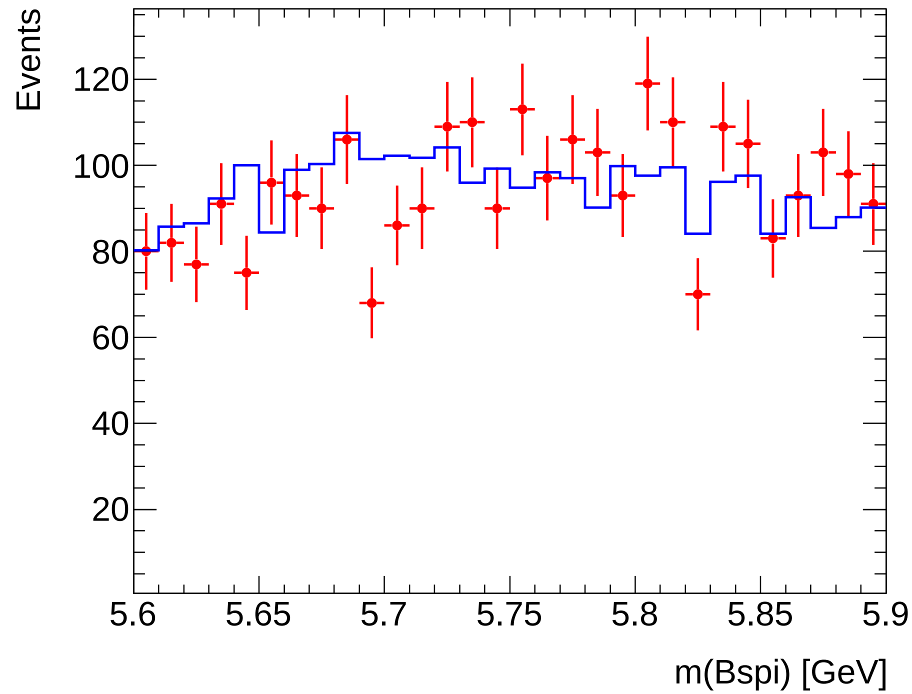


Allow background shape parameters to vary

$$M_X \equiv 5567.8 \text{ MeV}; \qquad \Gamma_X \equiv 21.9 \text{ MeV}, \qquad N = 140 \pm 28$$

Cross-check: fit with “no cone cut”



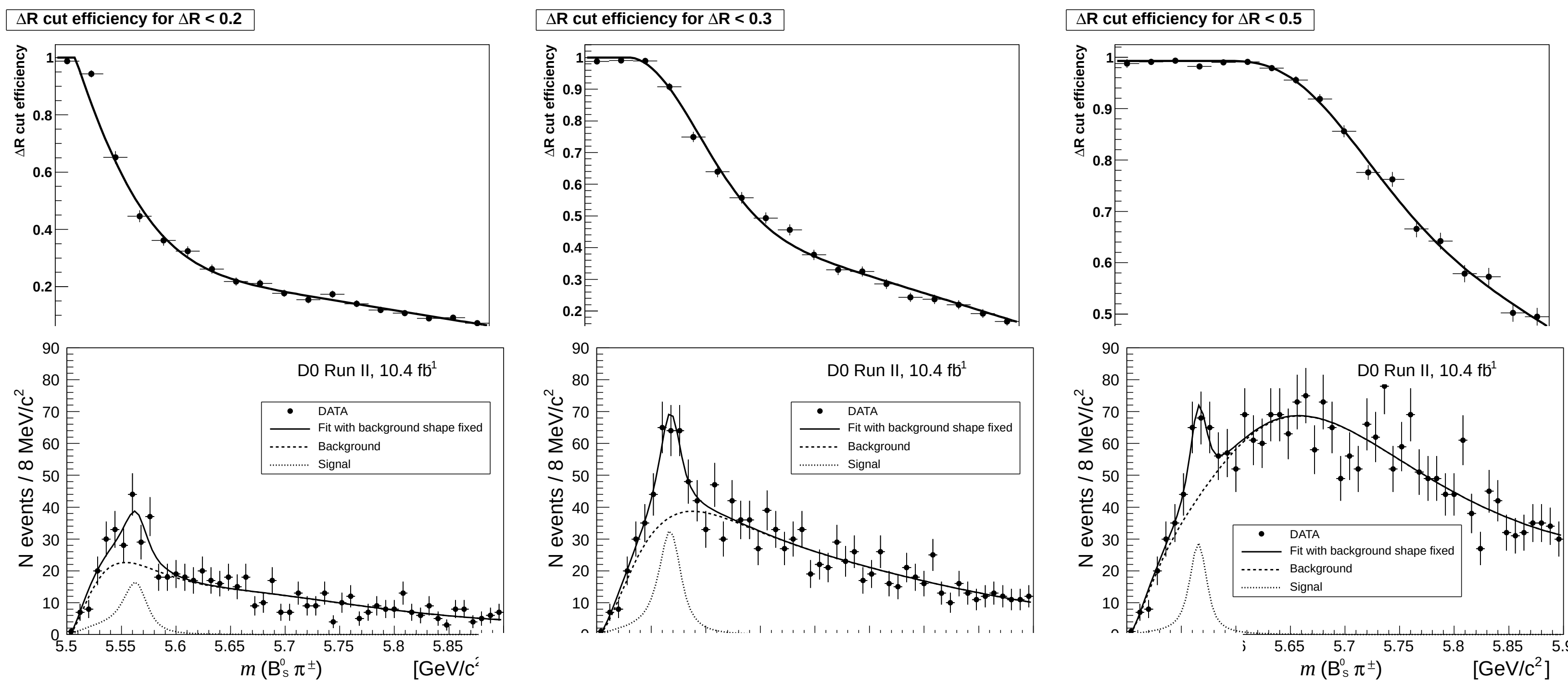


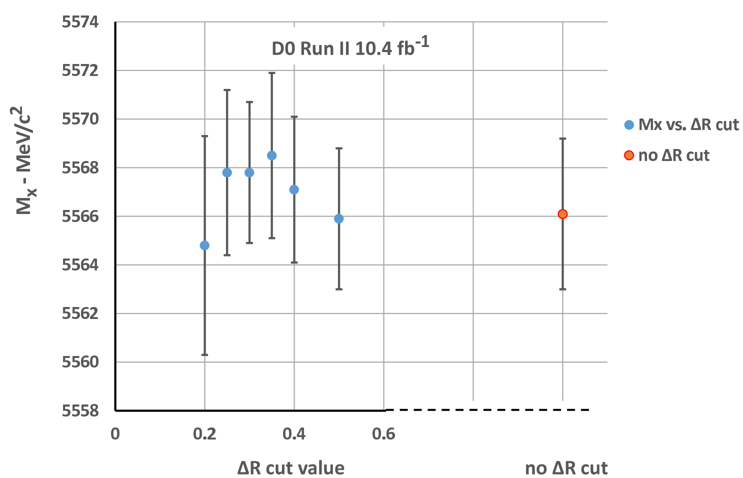
$$M_X \equiv 5567.8 \text{ MeV}, \;\; \Gamma_X \equiv 21.9 \text{ MeV}$$

$$N = 106 \pm 33$$

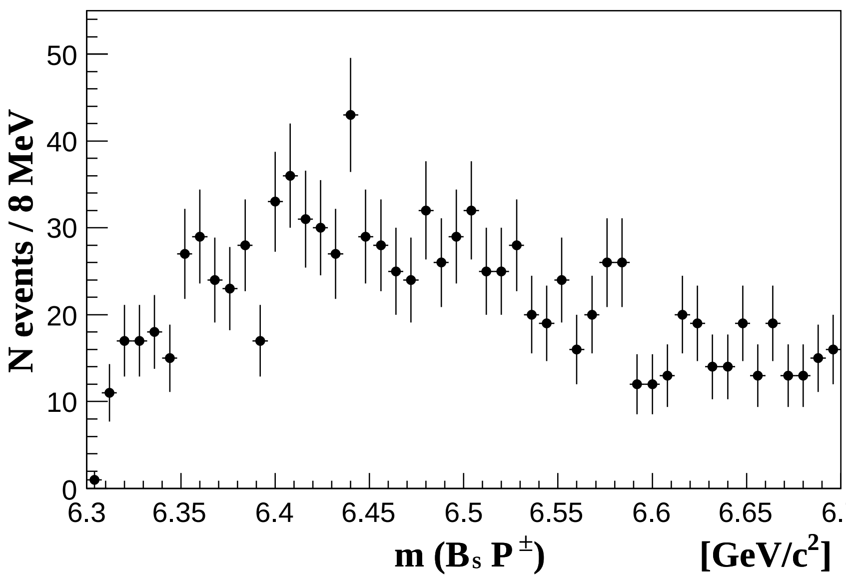
At $\Delta R > 0.3$ there is an excess in high-mass background that may be due to sources of B_s^0 not included in the simulations. Examples of “physics beyond Pythia” are decays $B_c \to B_s^0\pi^+\pi^0$, including $B_c \to B_s^0\rho^+$. There is a large systematic uncertainty on the resulting signal yield.

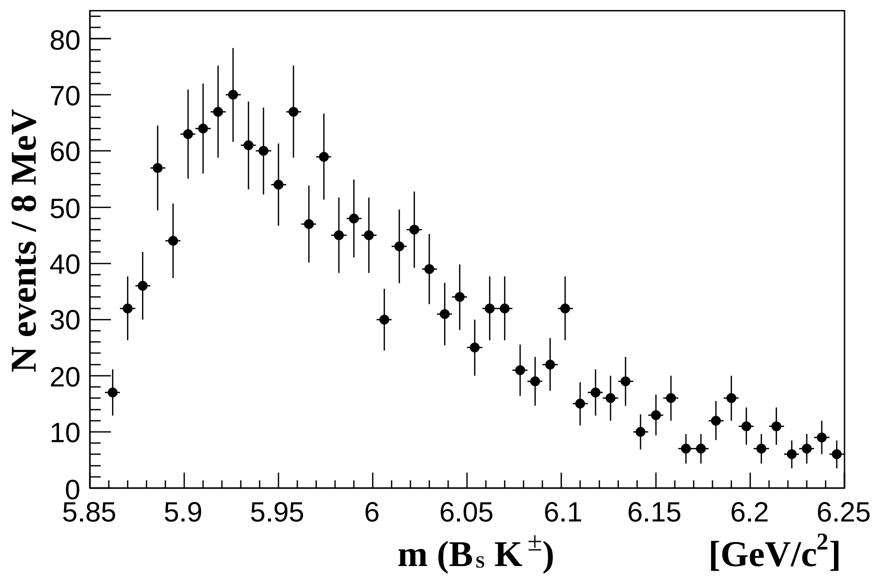
Cross-check: $M(5568)$ stability with ΔR cut



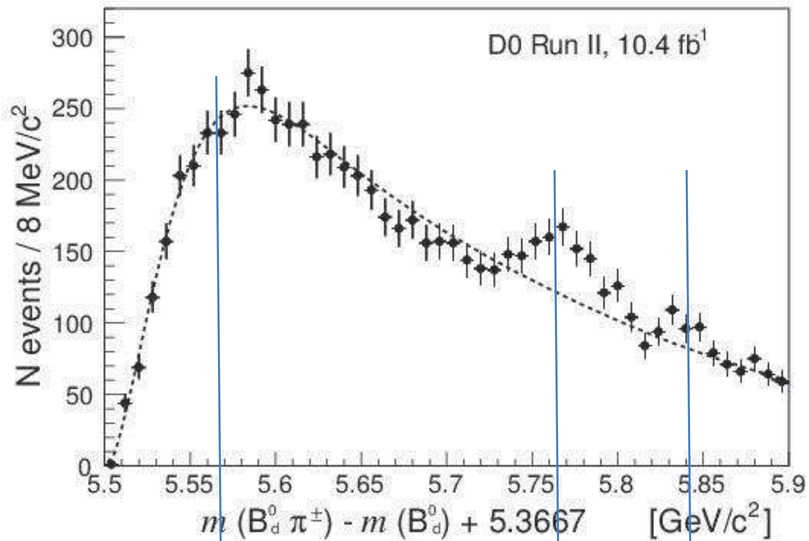


Cross-check: No peaks in $m(B_s^0 p)$ or $m(B_s^0 K^{\pm})$





Test with $B_d^0\,\pi^+$ combination

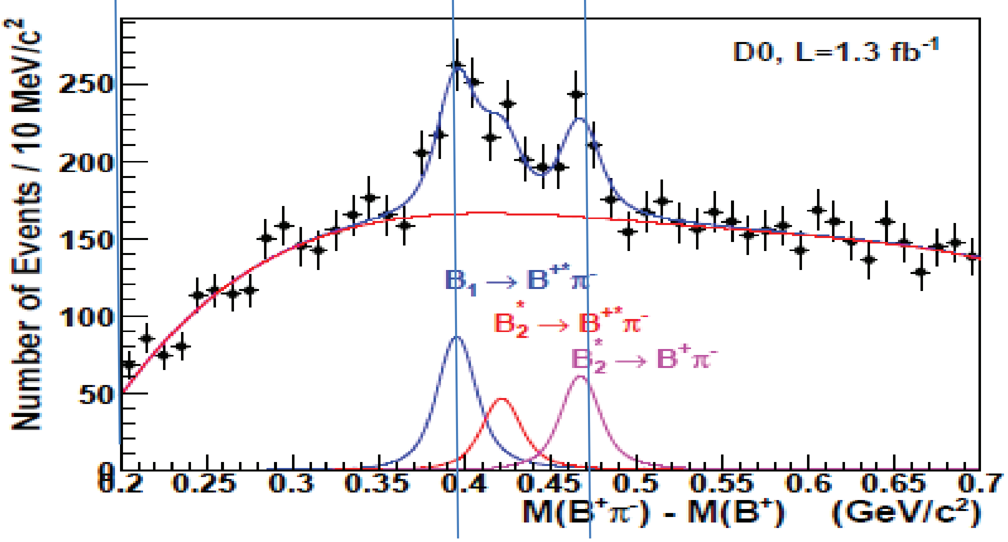


$B_d^0\,\pi^+$; $B_d^0 \to J/\psi\, K^{*0}$;

$J/\psi \to \mu^+\mu^-$; $K^{*0} \to K^+\pi^-$

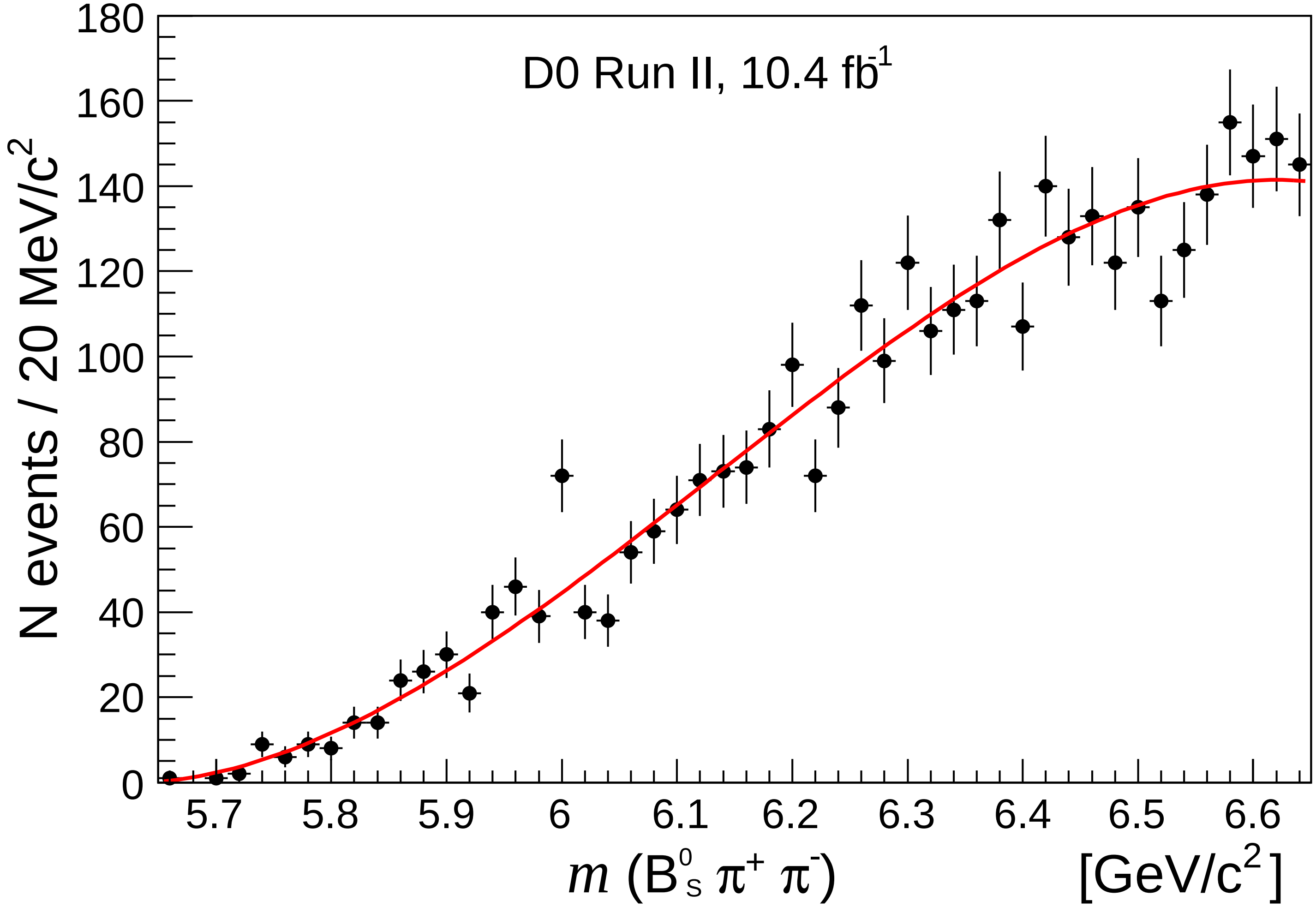
Cuts are very similar to $B_s^0\,\pi^+$ analysis

Cone cut does not produce peaks



D0 published paper:
Phys.Rev.Lett.99:172001,2007

Cross-check $m(B_s^0\pi^\pm\pi^\mp)$



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

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

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

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

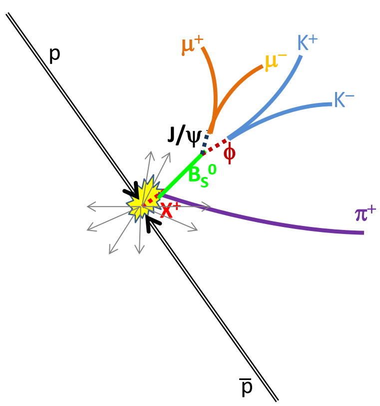
$\Gamma = 21.9 \pm 6.4\,(\text{stat})^{+5.0}_{-2.5}\,(\text{syst})$ MeV

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

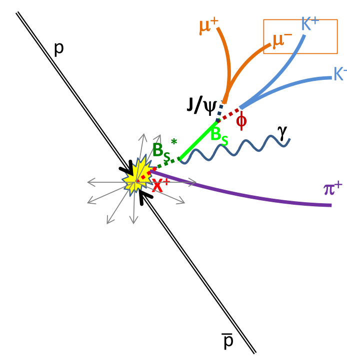
The significance is 5.1σ including systematic uncertainties and the "look-elsewhere effect"

It undergoes a strong decay to

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



$X \to B_s\,\pi$



$X \to B_s^*\,\pi \to B_s\,\gamma\,\pi$

5. Summary

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 $m(B_s^0\pi^{\pm})$: 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 $\boldsymbol{b\bar{s}}$.
Letter submitted to PRL on February 24 2016.
We wait for studies by CDF and LHC groups

Diquark-antidiquark tetraquark model

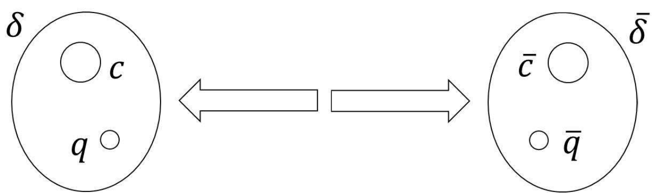
Ali, Maiani, Polosa, Riquer, arXiv:1604.01731

From a Hamiltonian with dominant spin-spin interactions between quarks (antiquarks) in the same tightly bound diquark (antidiquark) the mass formula is:

$$M(X_{bS}) = m_{[bq]} + 2\kappa_{bq}\,\mathbf{S}_{\bar{b}} \cdot \mathbf{S}_{\bar{q}} + m_{[sq]} + 2\kappa_{sq}\,\mathbf{S}_s \cdot \mathbf{S}_{q'}$$

Using as input the masses of tetraquark candidates $a_0(980)$, Z_b, and Z_b', the authors estimate the masses of resonant $J^P = 0^+$ $B_s\pi$ states to be ≈ 5770 MeV, about 200 MeV higher than the $X(5568)$.

3. Dynamical diquarks Brodsky, Hwang, Lebed, archiv:1406.7281



The XYZ states are not conventional nonrelativistic bound states in the sense of solutions of a Schrödinger equation for a static potential, but are instead collective modes of a $\delta\bar{\delta}$ pair produced at a high relative momentum. Their large relative kinetic energy is gradually converted into potential energy of the color flux tube connecting them. Eventually they are brought relatively to rest after achieving a substantial separation.

Because the extended $\delta\bar{\delta}$ system contains a great deal of color energy, it hadronizes (albeit with a small width) almost as soon as a threshold for creating hadrons with the same quantum numbers is passed, and final states with the smallest number of particles should dominate.