Поиск экзотических состояний с b- и c-кварками в эксперименте D0

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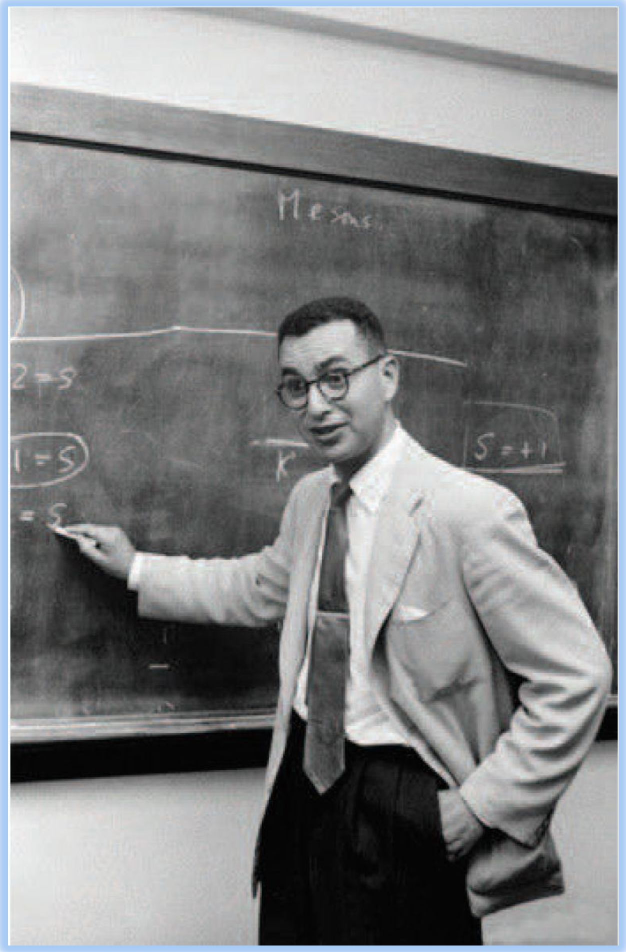
Overview

- Introduction to non-$q\bar{q}$ states.
- Evidence for a $X(5568) \to B_s\pi$ with hadronic decays of B_s meson.
- Confirmation of the $X(5568) \to B_s\pi$ with semileptonic decays of B_s meson.
- Search for exotic baryons decaying to $J/\psi\ \Lambda$ pairs.
- Summary.

Introduction

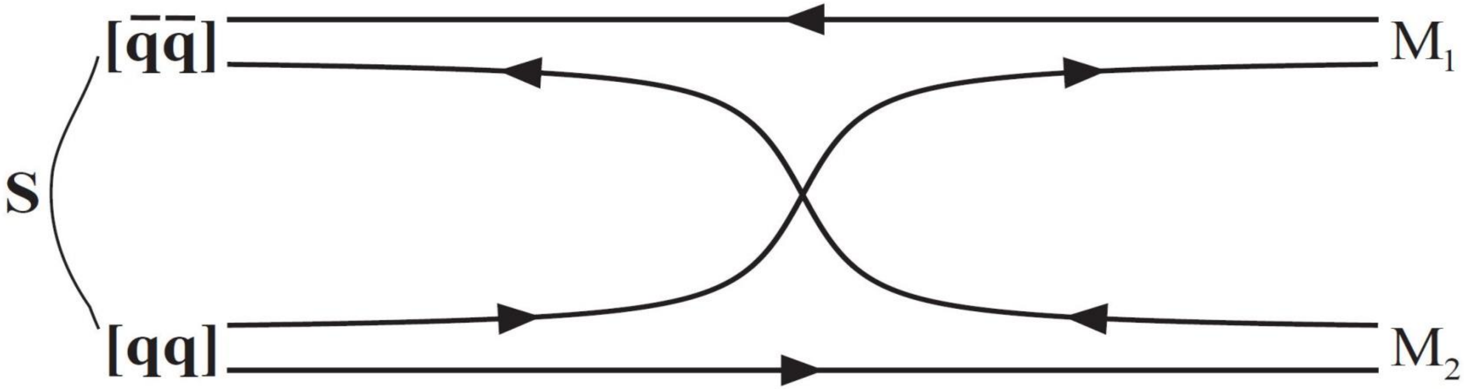
Multi-quark hadrons are allowed by the quark model. Gell-Mann explicitly mentioned them in the original paper introducing quarks.

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



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

Light scalars as tetraquarks



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 di-quarks.

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

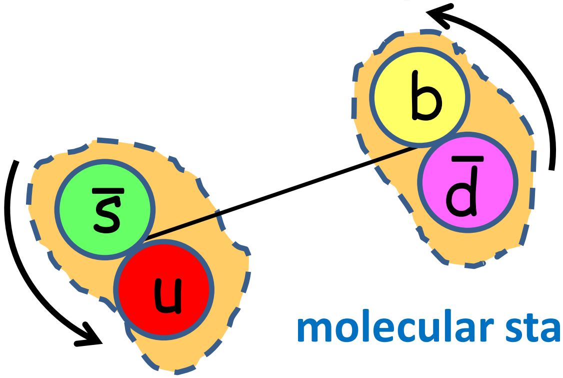
L. Maiani, F. Piccinini, A.D. Polosa, and V. Riquer, “New Look at Scalar Mesons”, PRL 93, 212002 (2004)

The XYZ states

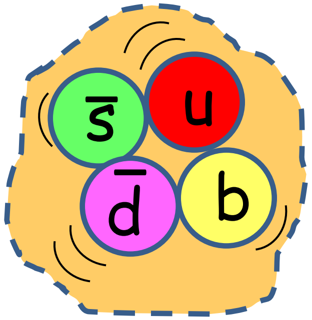
PDG names all non-$q\bar{q}$ candidates as $X(\mathrm{mass})$. Authors and theorists use Z for charged states, Y for 1^{--} states and X for the rest. There are various competing phenomenological models proposed to explain their nature.

Popular interpretations:

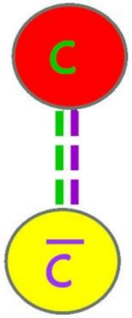
- **Meson-meson molecule** – two white states loosely bound by a pion exchange.
- **Compact tetraquark** – diquark-antidiquark pair connected by color forces.
- **A Hybrid** state of quark, antiquark and gluon in an overall color singlet … or a **Glueball** with no quarks in it.



molecular state



tetraquark



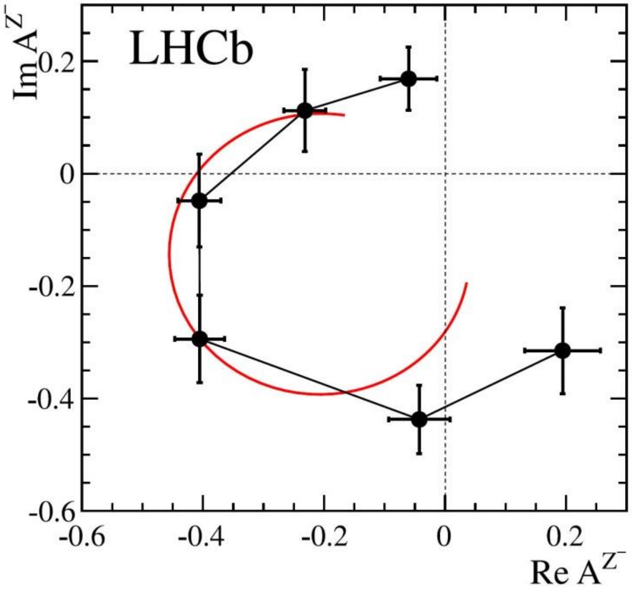
hybrid

The XYZ states

The 2003 discovery of $X(3872) \rightarrow J/\psi\ \pi^+\pi^-$ by Belle marked the new era. The flavor contents are not obviously exotic, but a conventional $c\bar{c}$ interpretation of a state with $J^{PC} = 1^{++}$ (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.

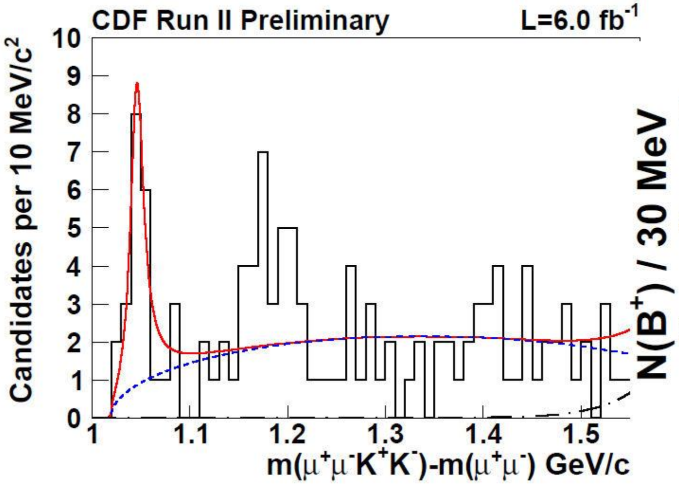
Most importantly $Z_c(4430) \rightarrow \psi(2S)\ \pi^{\pm}$ discovered by Belle – was confirmed by LHCb to be a proper Breit-Wigner resonance by the phase motion.

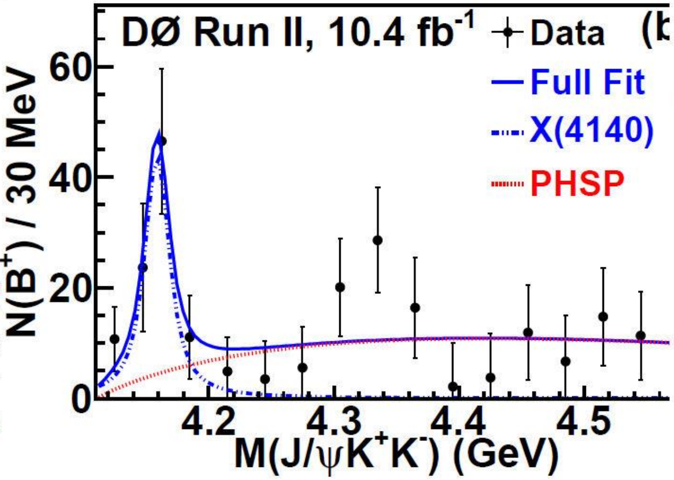


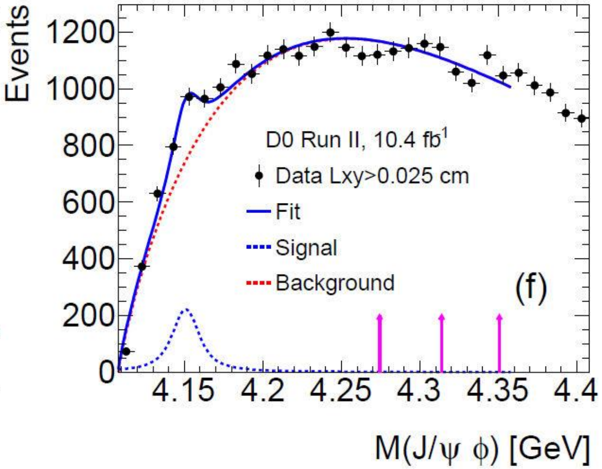
Evidence for quarkonium-like states made of four or five valence quarks is established.

Y(4140)

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



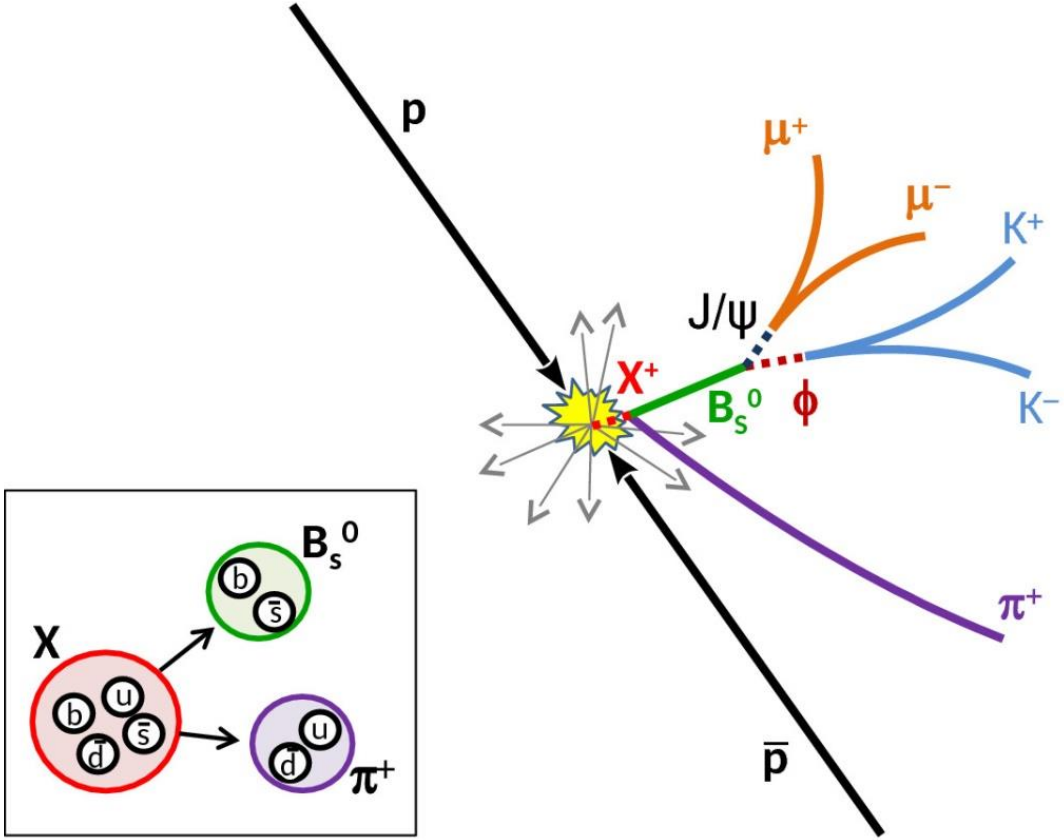




DØ reports evidence for the inclusive production, both prompt and non-prompt, in addition to a bump in a 2-body mass in a 3-body weak decay $B^+ \to J/\psi\ \phi\ K^+$.

X(5568) analysis (hadronic decays of B_s meson)

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



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 $B_s^0\pi^+, B_s^0\pi^-, \overline{B}_s^0\pi^+, \overline{B}_s^0\pi^-$.

DØ Detector in Tevatron Run II

Tevatron

$\mathbf{p\bar{p}}$ collider, $\sqrt{S} = 1.96\ \mathrm{TeV}$.

In operation from 2001 to 2011 (Run II).

Total integrated luminosity delivered ~12 fb^{-1} (~10 fb^{-1} for physics analysis per experiment).

DØ detector

Scintillator counters and drift tubes.
Thick calorimeter and iron toroids.

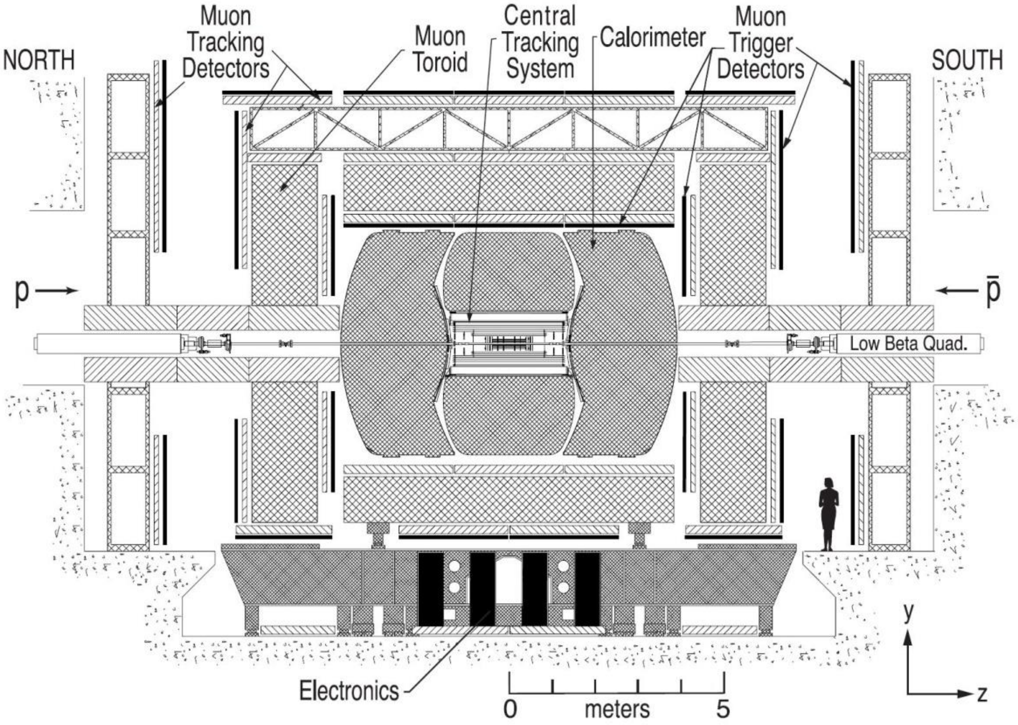
Excellent muon triggering and ID.

Silicone Microstrip Tracker.

Excellent vertex reconstruction.

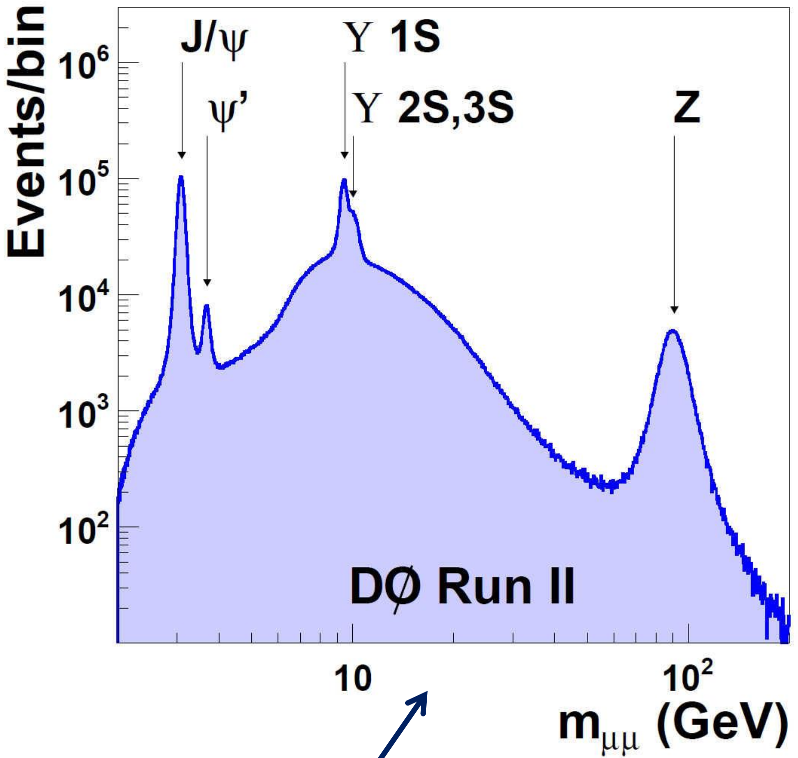
Central Fiber Tracker.

Good mass resolution.



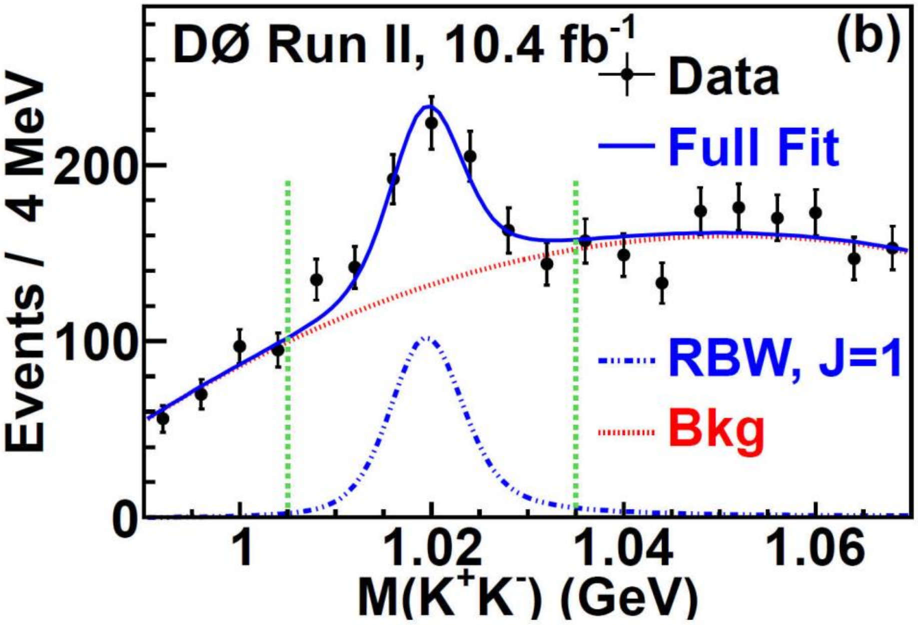
Excellent for B-physics with muons!

Examples of DØ Run II data



A subsample of $M(\mu^+\mu^-)$:
from J/ψ to Z

$M(K^+K^-)$ distribution:
clear signal from $\phi(1020) \to K^+K^-$



Data selection

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

Require a single muon or dimuon trigger.

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

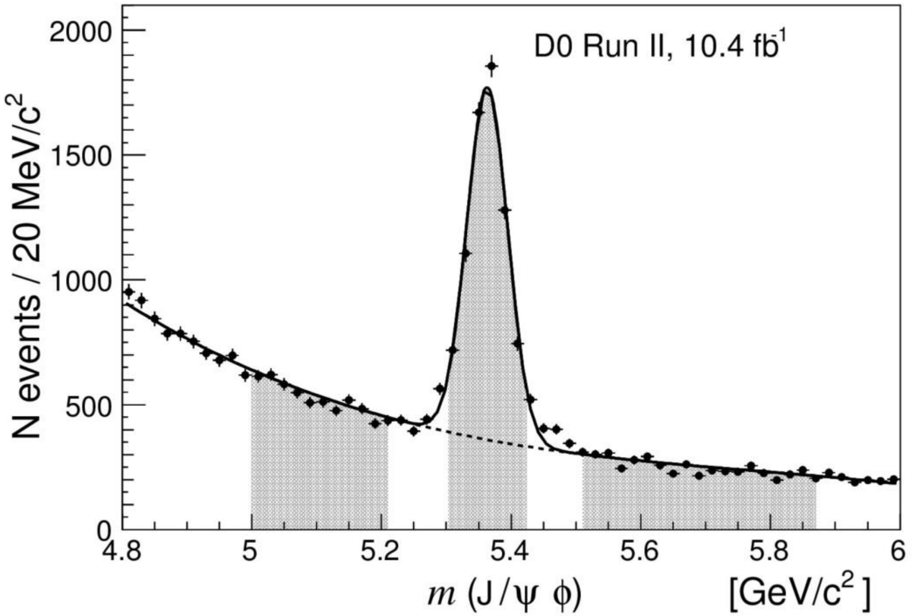
- $2.92 < M(\mu\mu) < 3.25\ \mathrm{GeV/c^2}$;
- $p_T(K) > 0.7\ \mathrm{GeV/c}$; $1.012 < M(KK) < 1.03\ \mathrm{GeV/c^2}$;
- $5.304 < M(J/\psi K^+K^-) < 5.423\ \mathrm{GeV/c^2}$; $\frac{L_{xy}}{\sigma(L_{xy})} > 3.$

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

- $p_T(\pi) > 0.5\ \mathrm{GeV/c}$; $IP_{xy} < 0.02\ \mathrm{cm}$; $IP_{3D} < 0.12\ \mathrm{cm}$;
- $p_T(B_s^0\pi) > 10\ \mathrm{GeV/c}$; $\Delta R = \sqrt{\Delta\varphi^2 + \Delta\eta^2} < 0.3$, the “cone” cut.

$$M(B_s\pi) = M(J/\psi\ \phi\ \pi) - M(J/\psi\ \phi) + M(B_s)\ (\mathrm{PDG}).$$

Background



The B_s^0 signal:

$M = 5363.3 \pm 0.6$ MeV/c^2;

$\sigma = 31.6 \pm 0.6$ MeV/c^2;

$N = 5582 \pm 100$;

B_s^0 signal region (±2σ):

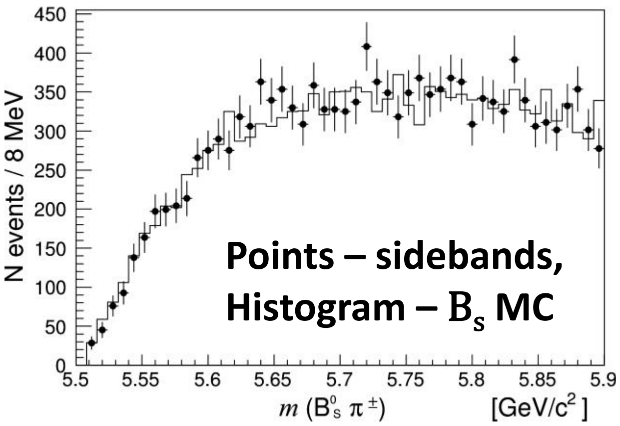
$5303 < M(J/\psi\ \phi) < 5423$ MeV/c^2.

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.

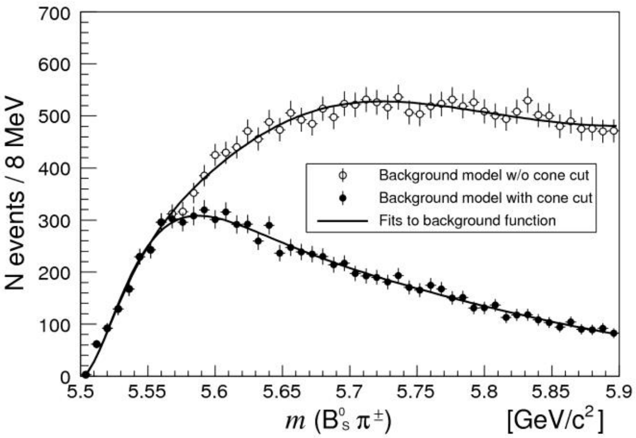
In the B_s signal region there are (1) B_s signal and (2) non-B_s background. (1) is simulated with Pythia; (2) is taken from sidebands selected such that their "center of gravity" is at $M(B_s)$.

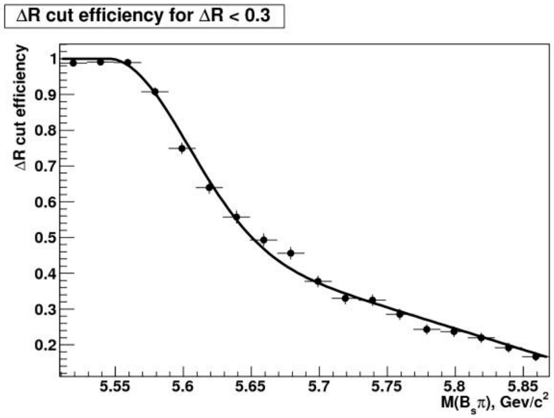
(1)+(2) are combined in the right proportion (71% + 29%).

Background and signal model



Points – sidebands,
Histogram – B_s MC



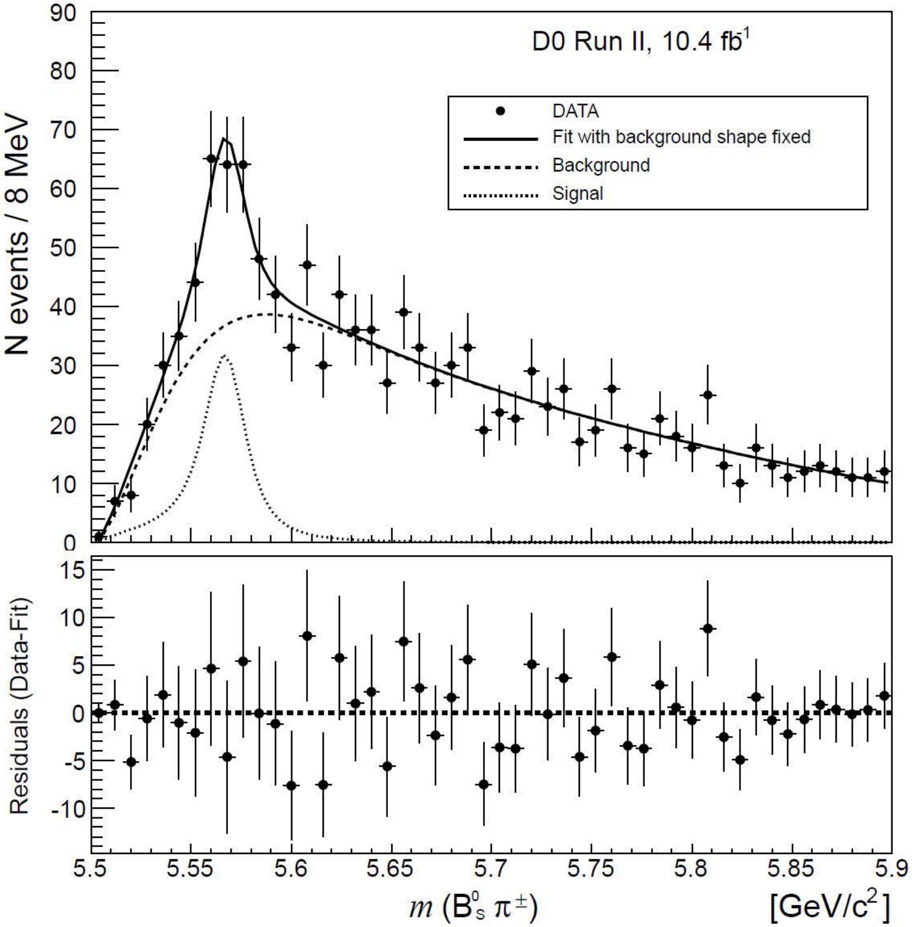


The two background components have a very similar shape. It is parametrized as $(c_1+c_2\cdot m^2+c_3\cdot m^3+c_4\cdot m^4)\times \mathrm{Exp}(c_5+c_6\cdot m+c_7\cdot m^2)$.
The same parametrization (with different values for parameters) works for background with and without ΔR cut.

The signal X is assumed to be a relativistic S-wave Breit-Wigner with a mass-dependent width $\Gamma(M) = \Gamma_X \cdot q_M/q_0$, where q_M is a rest-frame momentum of B_s at $M(B_s\pi)=M$ and q_0 is the momentum at the central M_X value. The BW is convoluted with the Gaussian resolution $\sigma = 3.8$ MeV.

Fit data to $N_X \cdot BW(M_X,\Gamma_X) + f_{bkg} \cdot F_{bkg}$ with free parameters $N_X, M_X, \Gamma_X, f_{bkg}$.

Fit results



$\Delta R<0.3$

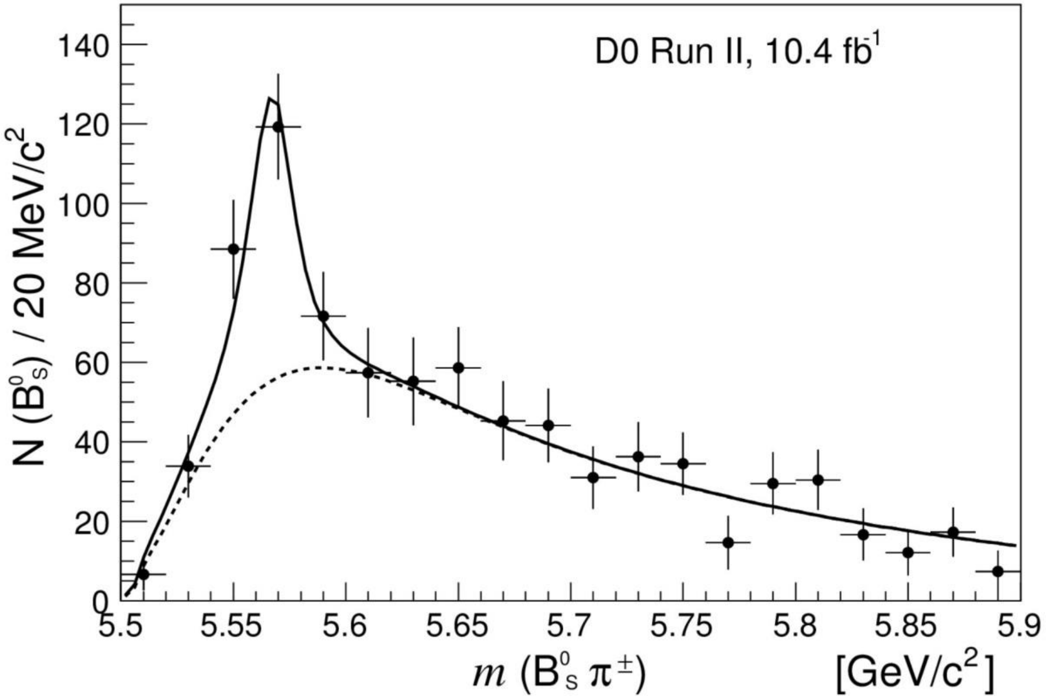
$M_X = 5567.8 \pm 2.9$ MeV/c^2

$\Gamma_X = 21.9 \pm 6.4$ MeV/c^2

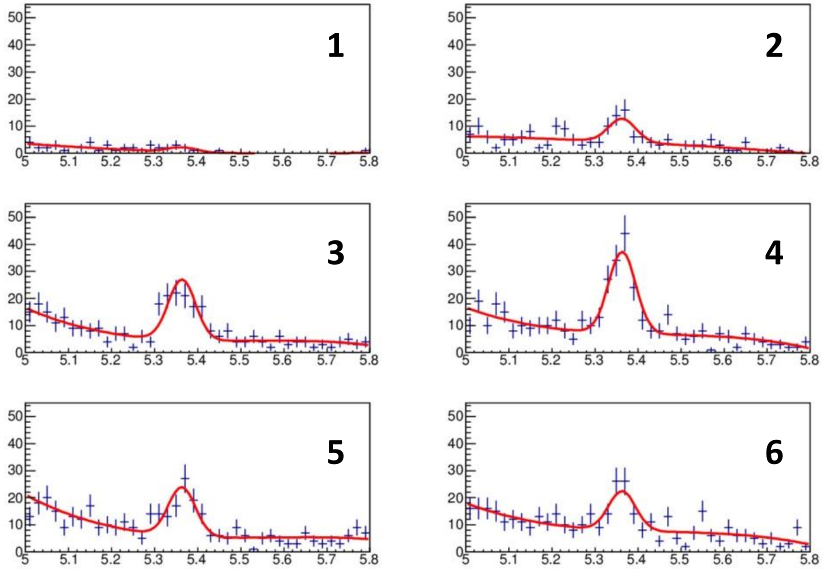
$N = 133 \pm 31$ events

Probability for null (background only) hypothesis to reproduce the yield gives the local statistical significance 6.6σ. Taking into account Looks Elsewhere Effect (LEE) get 6.1σ global statistical significance.

Alternative signal extraction



First 6 $M(B_s\pi)$ bins from the left plot



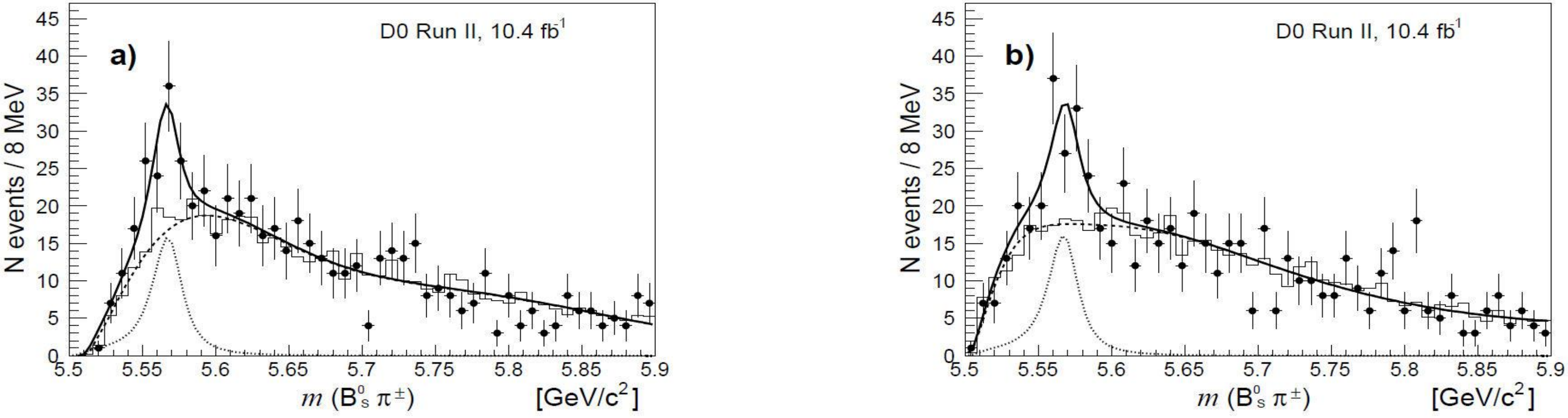
$M(J/\psi\phi)$, GeV/c^2

Reverse the search: look for B_s signal yield as a function of $M(J/\psi\ \phi\ \pi)$

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

$M_X \equiv 5567.8$ MeV/c^2 $\Gamma_X \equiv 21.9$ MeV/c^2 $N = 118 \pm 22$ events

Fits in two $p_T(B_s)$ intervals and production ratio ρ



$10 < p_T(B^0_s) < 15$ GeV

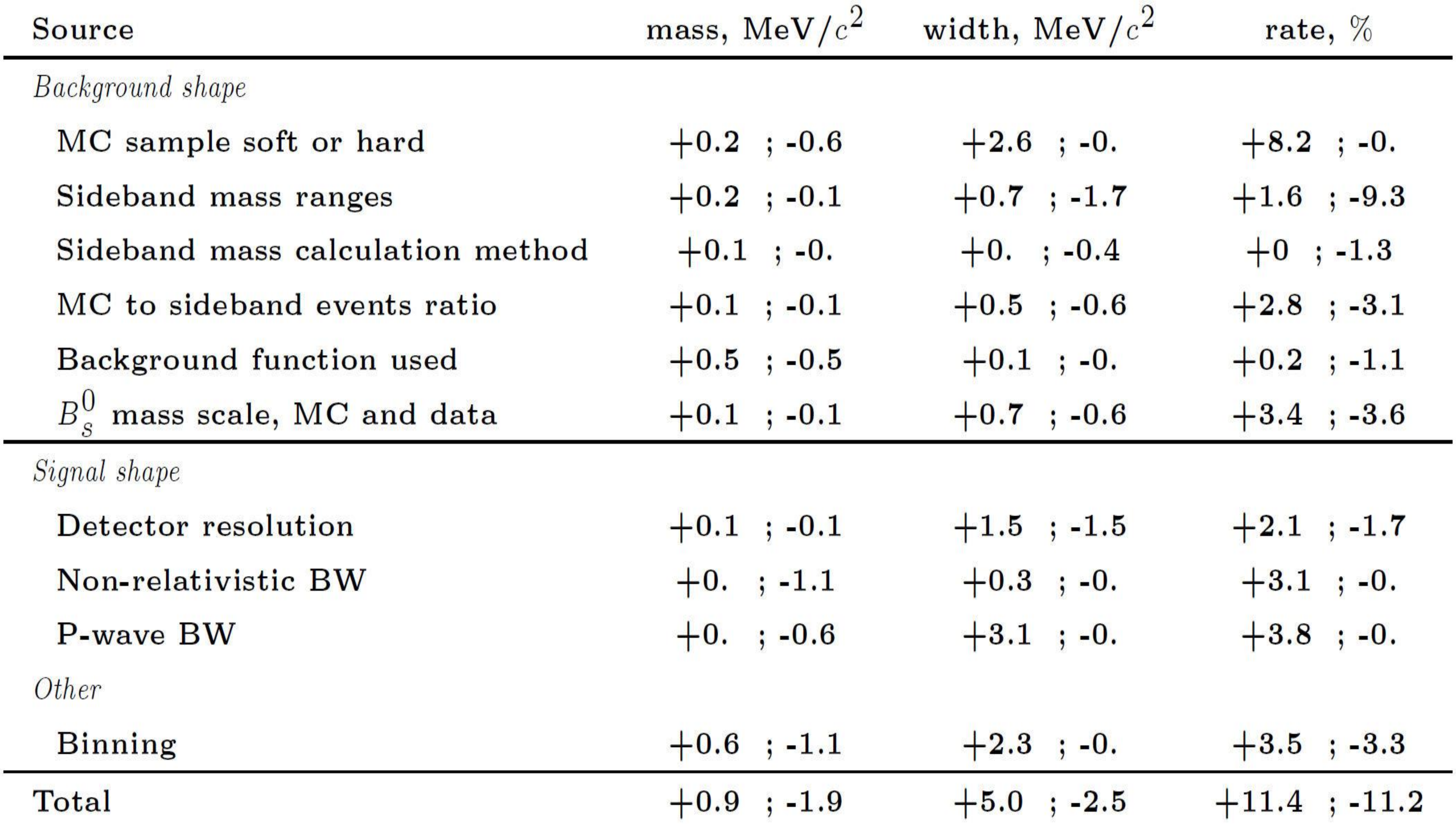
$15 < p_T(B^0_s) < 30$ GeV

Parameter	$10 < p_T(B^0_s) < 15$ GeV/c^2	$15 < p_T(B^0_s) < 30$ 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
$\Gamma\,(B_s^+(5568))$	18.4 ± 7.0	21.7 ± 8.4
N (B^0_s)	2463 ± 63	1961 ± 56
$\epsilon(\pi^\pm)$	$(26.1 \pm 3.2)\%$	$(42.1 \pm 6.5)\%$
$\rho(X(5568)/B^0_s)$	$(9.1 \pm 2.6 \pm 1.6)\%$	$(8.2 \pm 2.7 \pm 1.6)\%$

Averaging over $10 < p_T(B_s) < 30$ GeV/c:

$$\rho = \sigma(X(5568)^\pm) \times \mathrm{Br}(X(5568)^\pm \to B^0_s\pi^\pm)/\sigma(B^0_s) = (8.6 \pm 1.9 \pm 1.4)\%$$

Systematic uncertainties



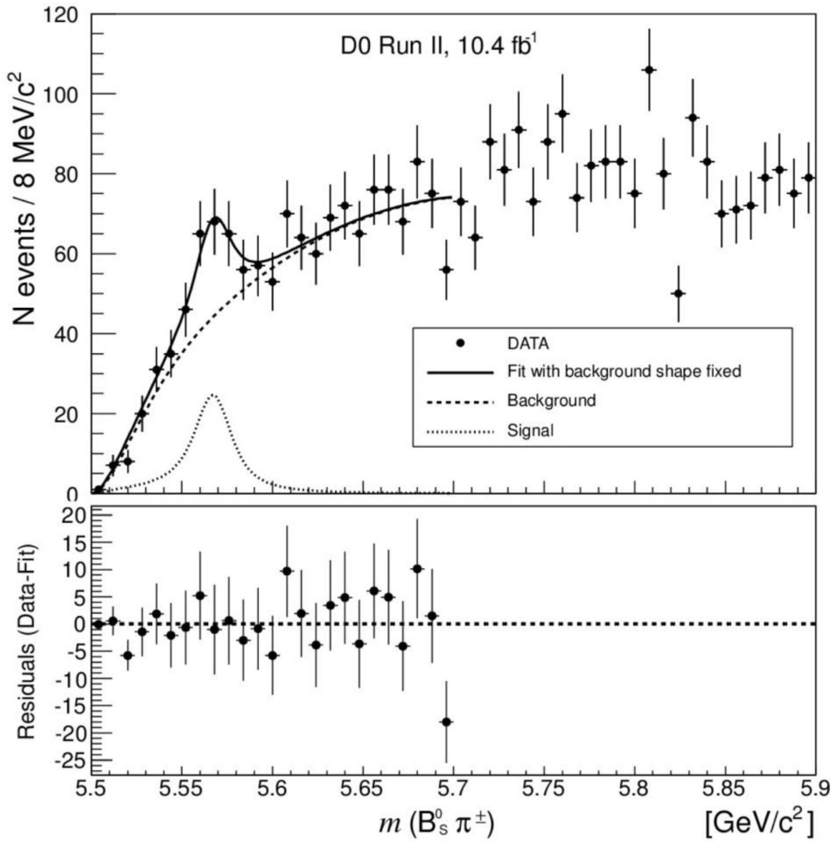
Source	mass, MeV/c^2	width, MeV/c^2	rate, %
Background shape			
MC sample soft or hard	+0.2 ; -0.6	+2.6 ; -0.	+8.2 ; -0.
Sideband mass ranges	+0.2 ; -0.1	+0.7 ; -1.7	+1.6 ; -9.3
Sideband mass calculation method	+0.1 ; -0.	+0. ; -0.4	+0 ; -1.3
MC to sideband events ratio	+0.1 ; -0.1	+0.5 ; -0.6	+2.8 ; -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

Significance with systematic uncertainties and LEE is 5.1 σ.

Cross-checks

- ➢ Use left (right) sideband for the non-B_s background.
- ➢ Use two versions of Pythia for the B_s background.
- ➢ Test $B_sK^{\pm}$ and B_sp hypotheses.
- ➢ Compare sidebands with “undersignal” background.
- ➢ Allow background shape parameters to be free.
- ➢ Extract the signal yield without the “cone” cut.
- ➢ Use different B_s mass ranges; modify the B_s vertex cut.
- ➢ Compare π^+ and π^- subsamples.
- ➢ Examine different detector regions (φ,η).
- ➢ Study $M(B_d^0\pi^{\pm})$ on the full Run II data sample.
- ➢ Look for decay $B_s^{**} \to B_s^0\pi^+\pi^-$.

Fit with no “cone” cut



$M_X \equiv 5567.8$ MeV/c^2

$\Gamma_X \equiv 21.9$ MeV/c^2

$N = 106 \pm 33$ events

The corresponding local statistical significance for this fit is 4.8 σ. If LEE and systematics are taken into account it leads to the global statistical significance 3.9 σ.

The lower yield without the cone cut led PRL to insist on “Evidence” rather than “Observation” despite on 5.1 σ global significance with the cone cut

There is an excess of events in high mass ($5.7 < M(B_s\pi) < 5.9$ GeV) background that may be due to sources of B_s not included in the simulations. Examples of “physics beyond Pythia” are $B_c \to B_s\pi^+\pi^0$, including $B_c \to B_s\rho^+$. Or may be a higher mass tetraquark states? The inclusion of added high-mass backgrounds would cause the yield of the no-cone-cut case to increase.

X(5568)→ $B_s\pi$, with hadronic decays of B_s: Summary

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

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

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

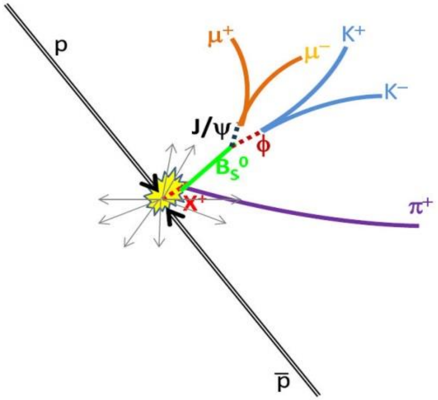
$$\rho = \sigma(X(5568)^{\pm}) \times Br(X(5568)^{\pm} \to B_s^0\pi^{\pm})/\sigma(B_s^0) = (8.6 \pm 1.9 \pm 1.4)\%$$

The significance (including systematic uncertainties and LEE): 5.1σ

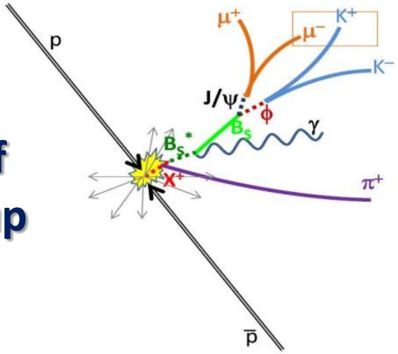
It undergoes a strong decay to:

$X \to B_s^0\pi^{\pm}\quad J^P = 0^+$

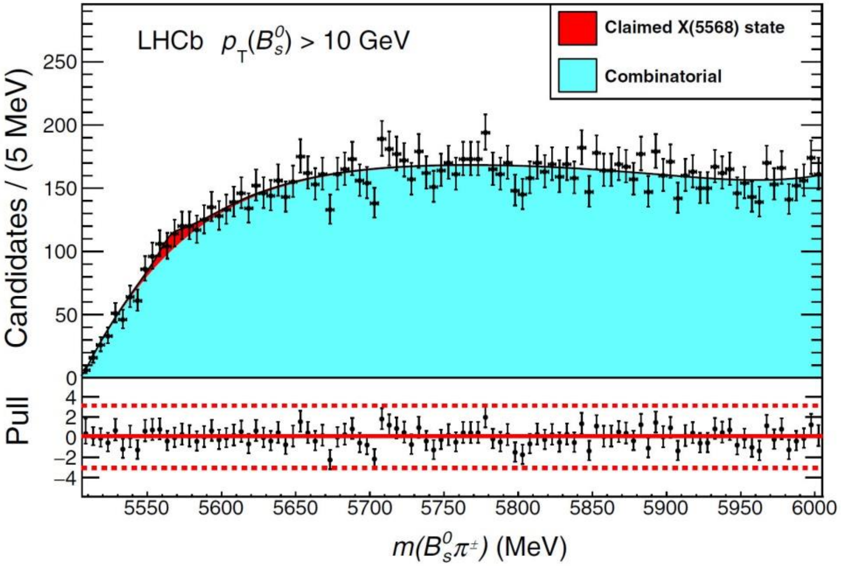
$X \to B_s^*\pi^{\pm}, B_s^* \to B_s^0\gamma\quad J^P = 1^+$



In the second case the mass of the X(5568) should be shifted up by 48 MeV/c².



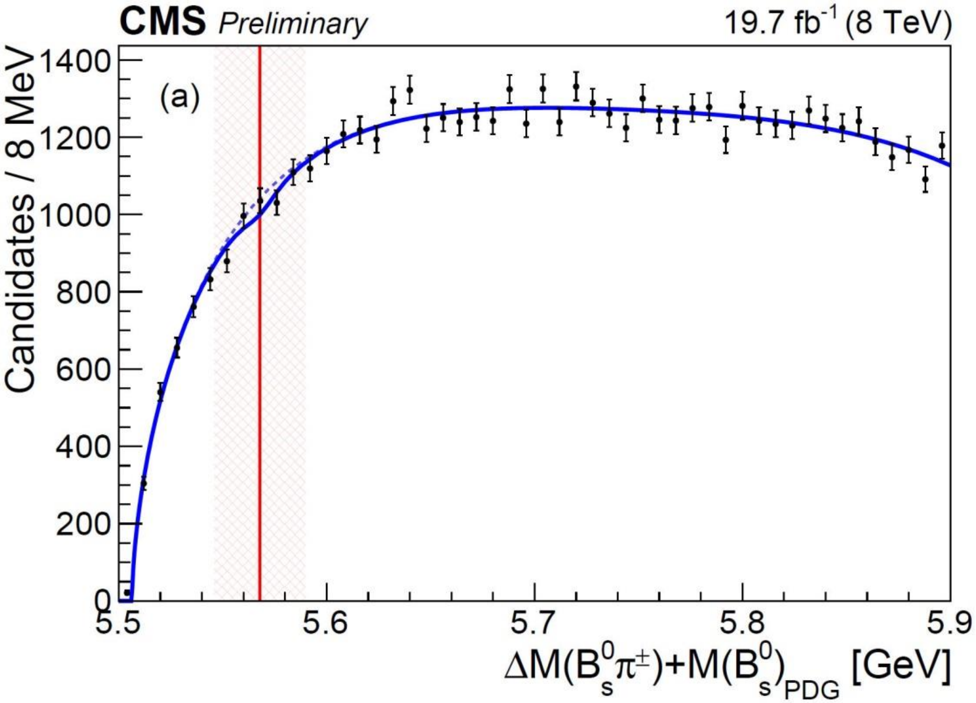
X(5568)→ $B_s\pi$ hadronic: Other experiments



LHCb (pp collisions, 7 & 8 TeV) sees no evidence for X(5568). Fraction of B_s that comes from X(5568) is less than 2.4% (95 CL) in compare with 8.6% from DØ.

R. Aaij et al., PRL 117, 152003 (2016)

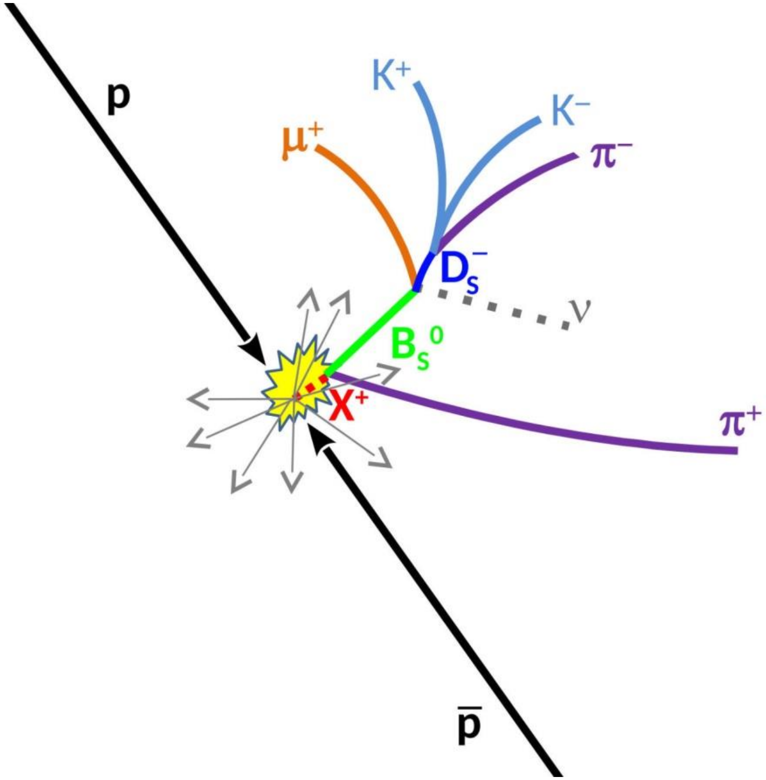
CMS (pp collisions at 8 TeV) set limit at fraction of B_s from X(5568) less than 3.9% (95% CL). ***CMS PAS BPH-16-002***



So, is the X(5568) dead? Or are there differences due to production or energy differences between Tevatron and LHC?

Additional studies would be very important!

X(5568) analysis (semileptonic decays of B_s meson)



In preliminary analysis for Moriond QCD 2017, DØ undertook to search for X(5568) in a complementary decay channel for B_s (semileptonic):

$$X(5568) \rightarrow B_s \pi,$$
$$B_s \rightarrow D_s \mu \nu + X_{any},$$
$$D_s \rightarrow \phi(1020) \pi,$$
$$\phi(1020) \rightarrow K^+K^-$$

(and charge conjugates)

- The backgrounds in semileptonic channel are different from those in hadronic channel.
- The presence of neutrino – different mass resolution.
- The character of possible reflections of other resonance structures is different in the semileptonic and hadronic channels.

Thus, the study of semileptonic channel can provide an independent confirmation of X(5568) existence.

Semileptonic X(5568): Data selection

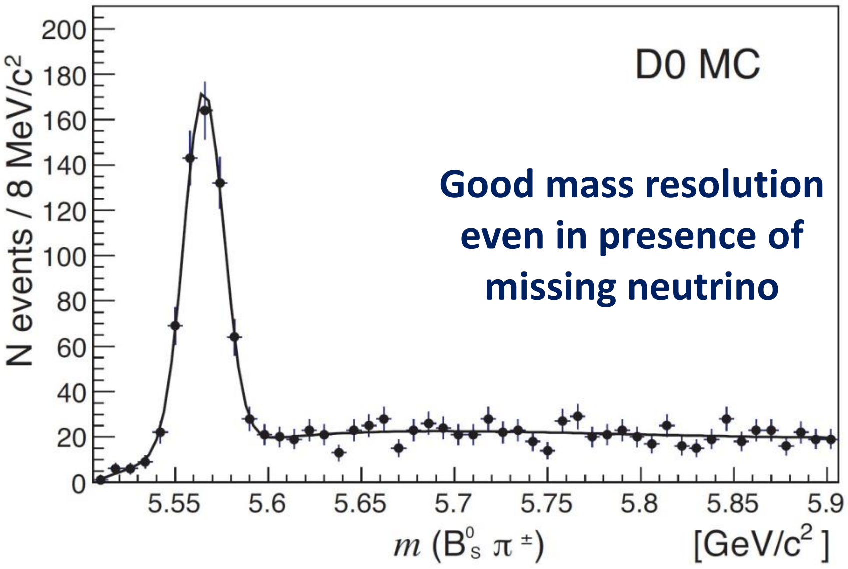
Event reconstruction and selection

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

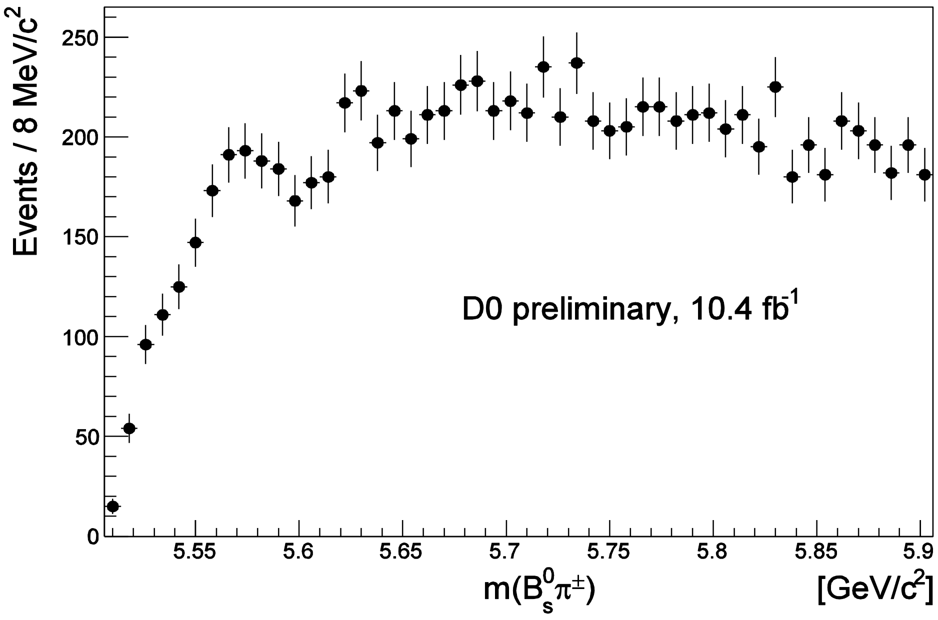
$3 < p_T(\mu) < 25$ GeV/c;
$p_T(K) > 1$ GeV/c;
$1.012 < M(KK) < 1.03$ GeV/c²
B_s and D_s vertices well separated from primary vertex;
$4.5 \text{ GeV} < M(D_s\mu) < M(B_s)$;
$p_T(D_s\mu) > 10$ GeV/c;
$p_T(\pi) > 0.5$ GeV/c;

$M(B_s\pi) = M(D_s\mu\pi) - M(D_s\mu) + M(B_s)$,
where $M(B_s) = 5.3667$ GeV/c² (PDG)

Looking at the same mass range:
$5.506 < M(B_s\pi) < 5.906$ GeV/c²



Good mass resolution even in presence of missing neutrino



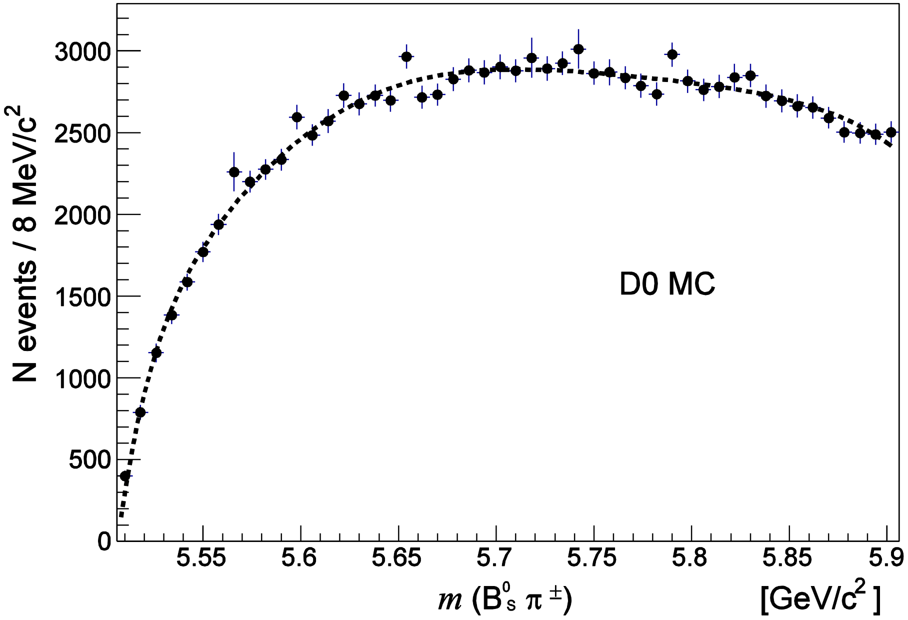
Semileptonic X(5568): Background

Background parametrization

Background distribution is obtained from MC and reweighted to data.

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

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



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 (same as for hadronic channel).
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 algorithm).

Semileptonic X(5568): Signal parametrization and fit results

The signal is modeled with the same relativistic Breit-Wigner S-wave shape, convoluted with mass resolution, which also includes the missing neutrino effect.

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 $F_{sig}(M,M_x,\Gamma_X)$ – signal function, f_{bgr}, f_{sig} - normalization coefficients.

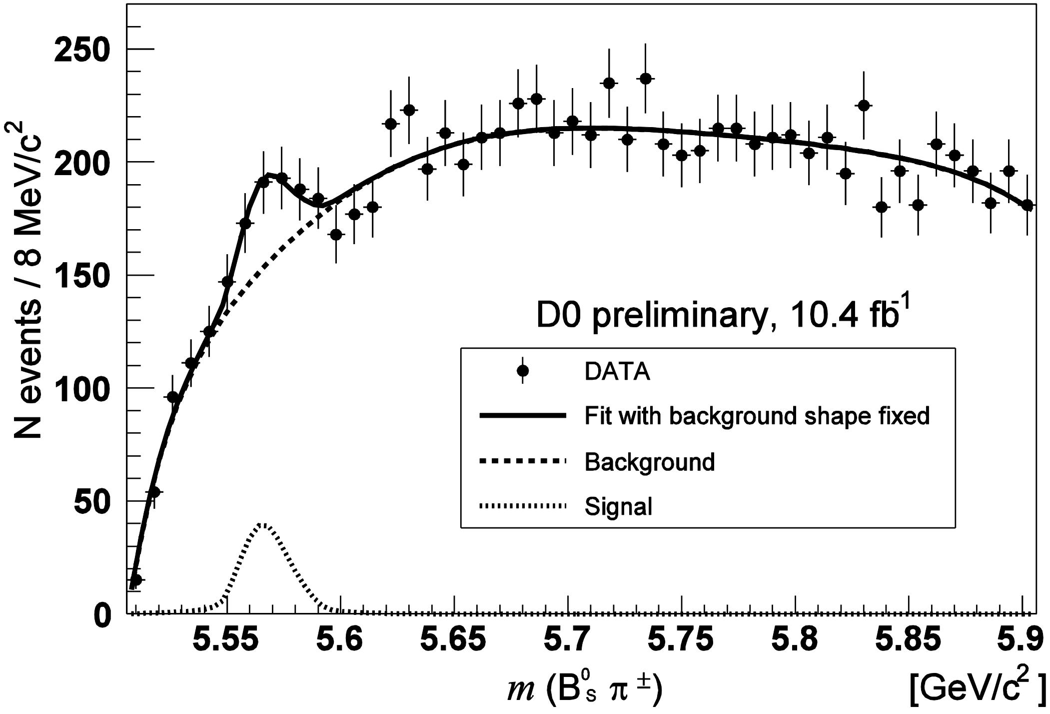
$$M_x = 5566.7^{+3.6}_{-3.4}\ \mathrm{MeV/c^2},$$

$$\Gamma_x = 6.0^{+9.5}_{-6.0}\ \mathrm{MeV/c^2},$$

$$N_X = 139^{+51}_{-63}.$$

Significance

4.5σ local (statistical) significance,
3.2σ with systematics.

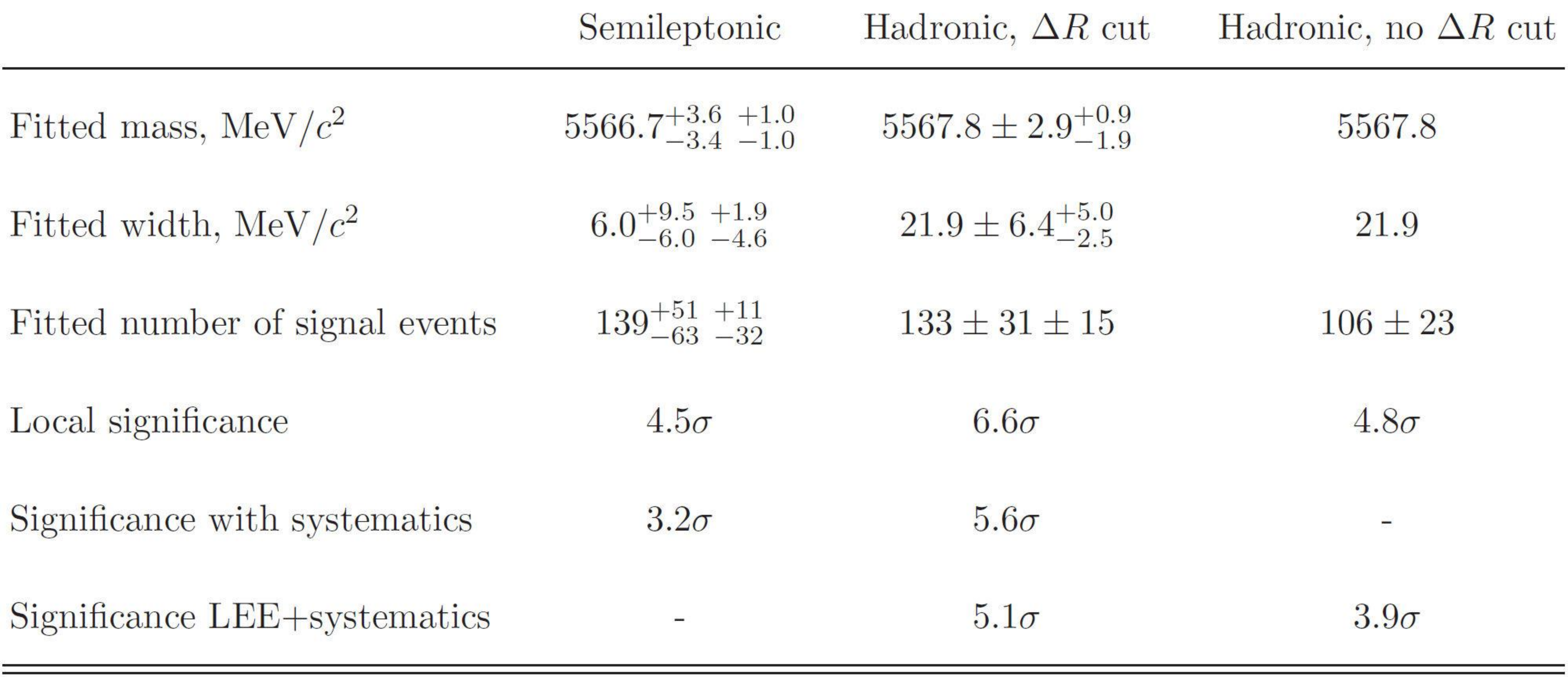


Semileptonic X(5568): Systematic uncertainties

Vary MC energy scale and mass resolution, fit signal to P-wave BW, vary the resolution smearing due to the missing neutrino.
Dominant uncertainty is due to background shape description.

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	$+1.0\ ;\ -1.0$	$+1.9\ ;\ -4.6$	$+10.9\ ;\ -31.5$

Semileptonic X(5568): Comparison with hadronic channel



	Semileptonic	Hadronic, ΔR cut	Hadronic, no ΔR cut
Fitted mass, MeV/c^2	$5566.7^{+3.6}_{-3.4}\,^{+1.0}_{-1.0}$	$5567.8 \pm 2.9^{+0.9}_{-1.9}$	5567.8
Fitted width, MeV/c^2	$6.0^{+9.5}_{-6.0}\,^{+1.9}_{-4.6}$	$21.9 \pm 6.4^{+5.0}_{-2.5}$	21.9
Fitted number of signal events	$139^{+51}_{-63}\,^{+11}_{-32}$	$133 \pm 31 \pm 15$	106 ± 23
Local significance	4.5σ	6.6σ	4.8σ
Significance with systematics	3.2σ	5.6σ	-
Significance LEE+systematics	-	5.1σ	3.9σ

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

Fraction of B_s from X(5568) ($p_T(D_s\mu) > 10$ GeV):

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

is also in agreement with the ratio measured in hadronic channel (8.6±2.4%).

Semileptonic X(5568): combined significance

The backgrounds and other sources of systematic uncertainties for hadronic and semileptonic channels are nearly independent.

Combined significance

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

$p_{had} = 3.8 \cdot 10^{-7}$ (with ΔR cut), $p_{sl} = 6.4 \cdot 10^{-4}$

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

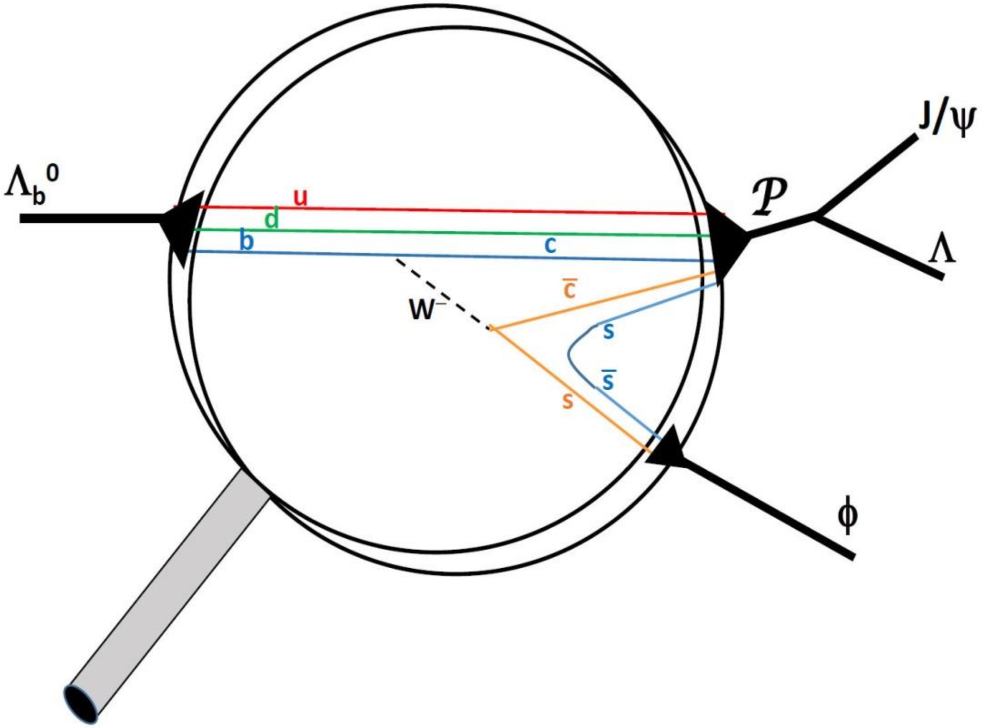
DØ sees a strongly decaying (Γ>0) state X(5568) in two quite different channels with different backgrounds etc. The combined significance for two channels is 5.7σ (4.7σ without ΔR cut).
The X(5568) would be the first meson that includes four different flavors.

No other experiment is observed X(5568) so far; awaiting results from ATLAS and CDF (especially CDF since LHC and Tevatron production might differ).

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

DØ Pentaquark search

Just as exotic mesons can be constructed from $q\bar{q}q\bar{q}$, exotic baryons can be constructed from $qqqq\bar{q}$ (so called pentaquarks).
In 2015, the LHCb collaboration reported two structures $P_c(4450)^+$ and $P_c(4380)^+$ in the decay $\Lambda_b \rightarrow P_c^+ K^-$, $P_c^+ \rightarrow J/\psi\, p$. These P_c states are within 400 MeV from $J/\psi\, p$ threshold. The minimal quark content is $uud\bar{c}c$, manifestly an exotic pentaquark.
Numerous states with the quark contents including $c\bar{c}$ pair and three light quarks are expected to exist within 500 MeV of the threshold.



Motivated by the LHCb result, DØ searched for strange analogs of LHCb states: e.g. $\Lambda_b \rightarrow P_c\ \phi$, $P_c \rightarrow J/\psi\, \Lambda$, $J/\psi \rightarrow \mu\mu$, $\Lambda \rightarrow p\, \pi^-$.

Such states ($P_c \rightarrow J/\psi\, \Lambda$) can be produced directly in $p\bar{p}$ collisions (prompt production) or from weak decays of b-baryons such as Λ_b, depictured here (non-prompt production).

Search for $P_c \rightarrow J/\psi\ \Lambda$: Event selection

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

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

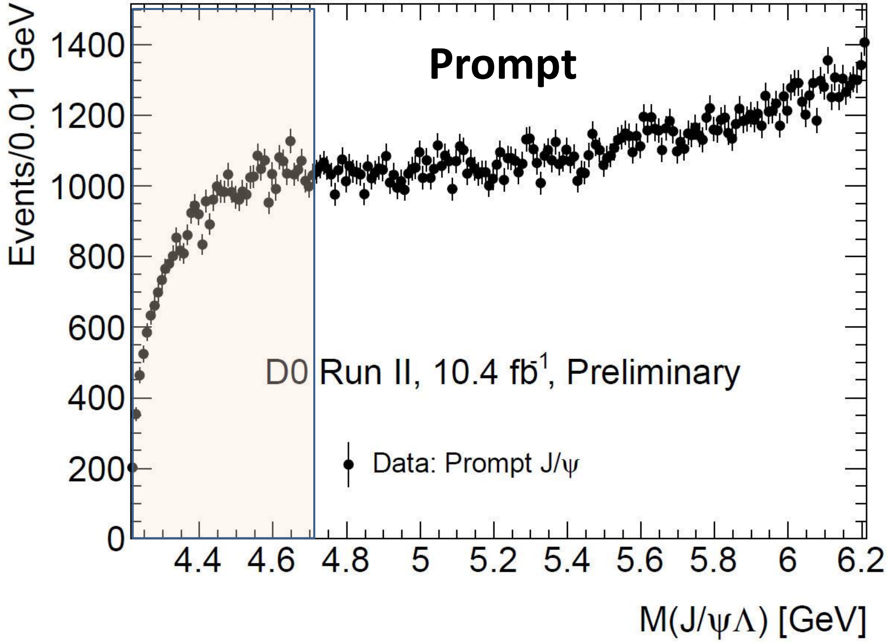
$2.92 < M(\mu\mu) < 3.25$ GeV/c^2

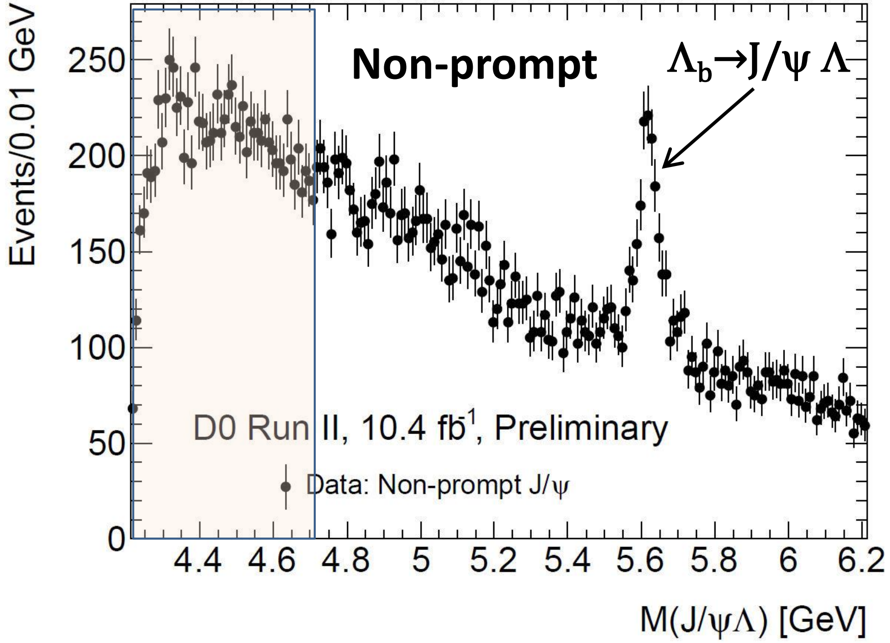
$p_T(\Lambda) > 0.7$ GeV/c

$1.110 < M(\Lambda) < 1.122$ GeV/c^2

$p_T(\pi) > 0.15$ 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 $P_c \rightarrow J/\psi\ \Lambda$: Search procedure

Binned maximum likelihood fits to the distribution of the $J/\psi\ \Lambda$ invariant mass in the range from the $J/\psi\ \Lambda$ 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 free** M_x, σ_x;

f_{bgr}, f_{sig} **- normalization coefficients.**

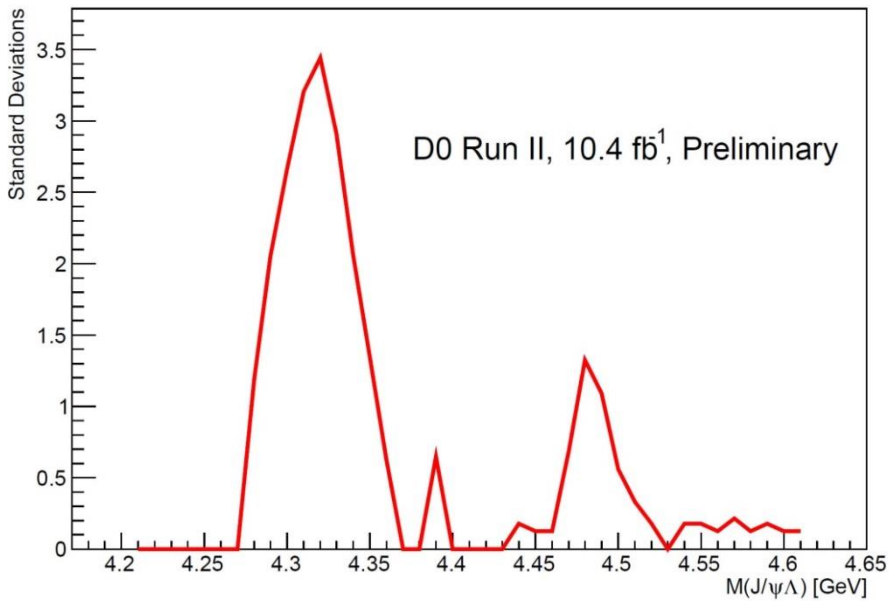
$$F_{bgr}(M) \propto M \cdot (M^2/M_{thr}^2 - 1)^{c_1} \cdot e^{-c_2 M} \cdot (1 - e^{-(M-M_{thr})/b}),$$

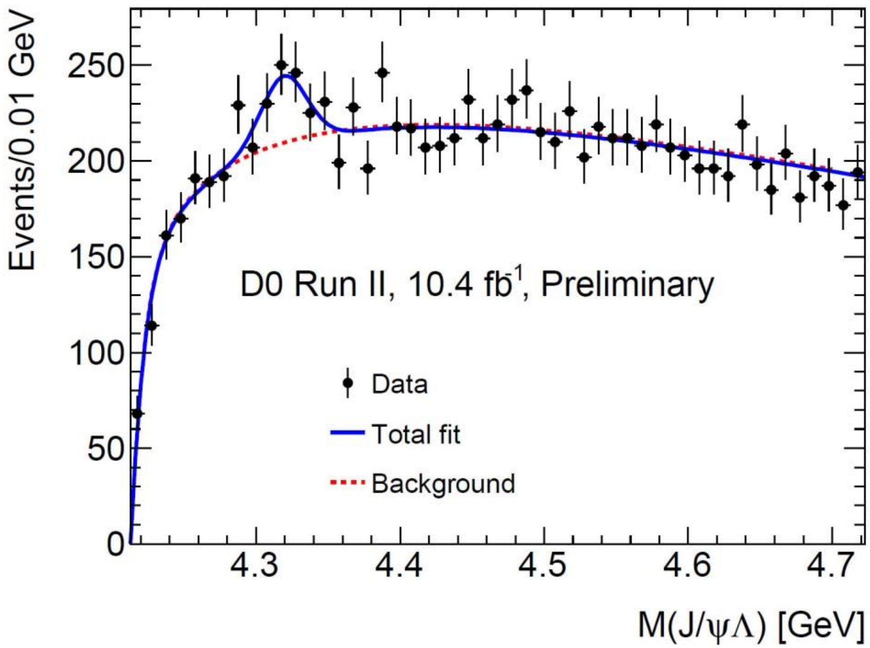
where M_{thr} is the $J/\psi\ \Lambda$ threshold.

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 scan in the mass range of interest.

Local statistical significance is defined as $\sqrt{-2 \cdot \ln(\mathcal{L}_0/\mathcal{L}_{max})}$.

Search for $P_c \rightarrow J/\psi\ \Lambda$: Results





The highest local significance of 3.45σ occurs at $M = 4.32\ \mathrm{GeV}/c^2$.

Looks Elsewhere Effect (LEE) was estimated in the same interval (from the $J/\psi\ \Lambda$ threshold to $4.7\ \mathrm{GeV}/c^2$) with 6400 pseudoexperiments to determine a probability of a 3.45σ or higher fluctuation anywhere in the search range. The global significance with LEE is 2.8σ

Thus no evidence for strange analog of LHCb pentaquarks in $J/\psi\ \Lambda$, but at least a pointer on where one might look.

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

Summary

- During the last year DØ presented several results for exotic states searches.

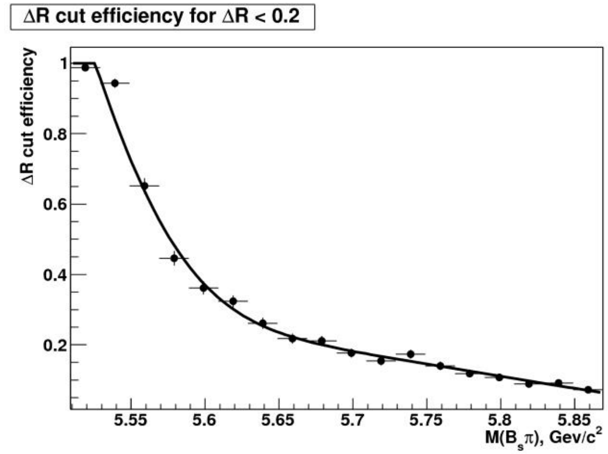
- $X(5568) \rightarrow B_s\pi$, $B_s \rightarrow J/\psi\ \phi$. Evidence for the first instance of a hadronic state with valence quarks of four different flavors. The statistical significance for this state (including systematics and LEE) is 5.1σ. LHC experiments (LHCb and CMS) do not observe it.

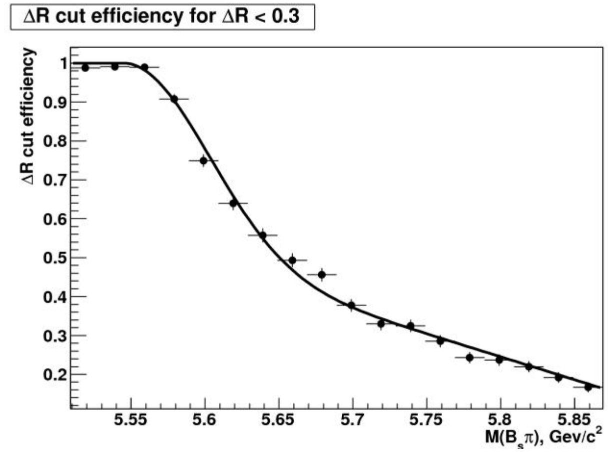
- $X(5568) \rightarrow B_s\pi$, $B_s \rightarrow D_s \mu\ \nu + X$. There is an excess of events in the data consistent with the decay $X(5568) \rightarrow B_s\pi$, $B_s \rightarrow J/\psi\ \phi$. The mass, natural width and production rates in the semileptonic and hadronic channels are consistent. Combined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

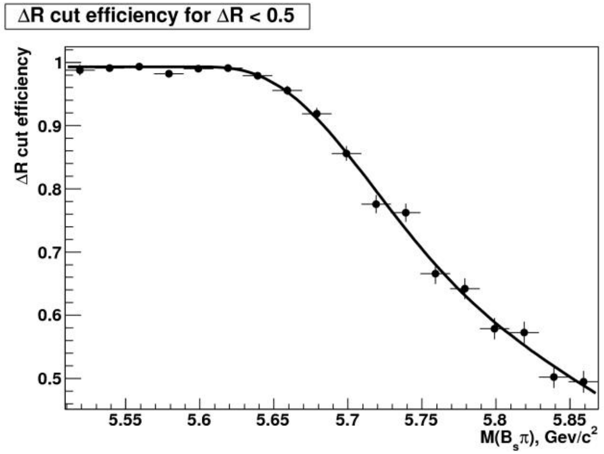
- Search for exotic baryons $\rightarrow J/\psi\ \Lambda$. In the mass range between threshold and $4.7\ \mathrm{GeV}/c^2$ no evidence for new baryons decaying to $J/\psi\ \Lambda$ have been found, the most significant deviation from background-only hypothesis is seen at $M(J/\psi\ \Lambda) = 4.32\ \mathrm{GeV}/c^2$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

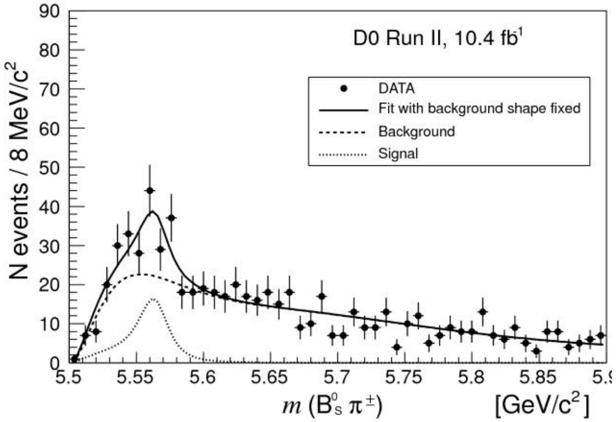
Backup slides

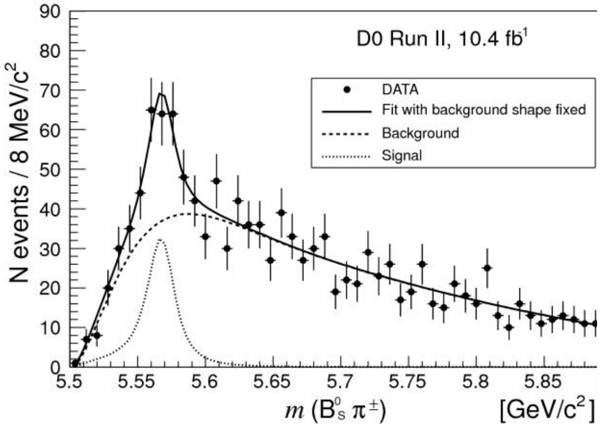
ΔR cut: does it “sculpted” the X(5568) peak?

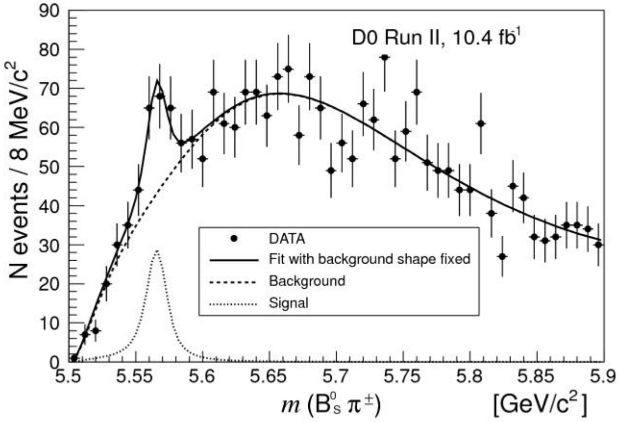


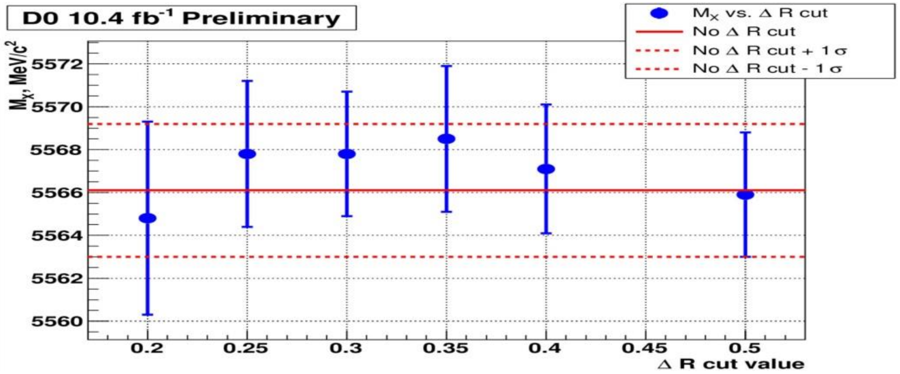






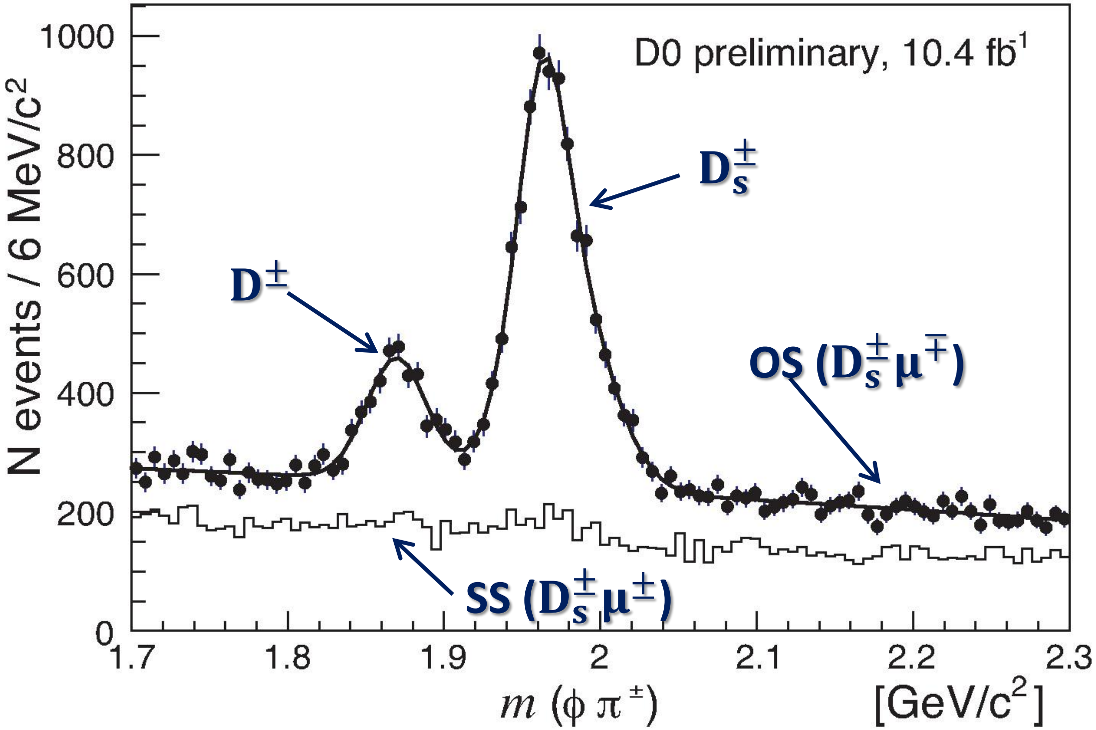






Fitted mass is stable with various value of the cone cut

Semileptonic X(5568): production ratio ρ



Production ratio of X(5568) to B_s

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

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

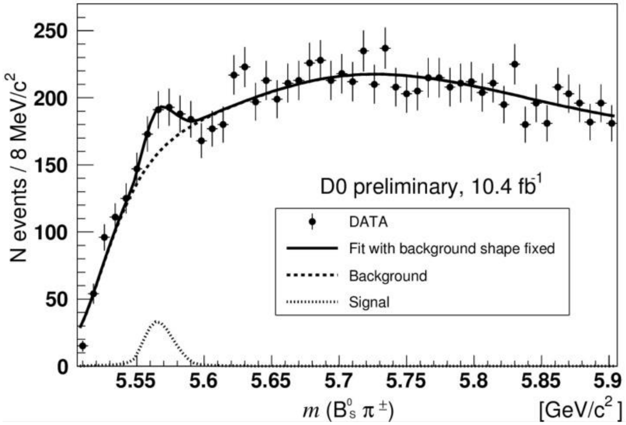
$$(p_T(D_s\mu) > 10\ \mathrm{GeV/c})$$

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

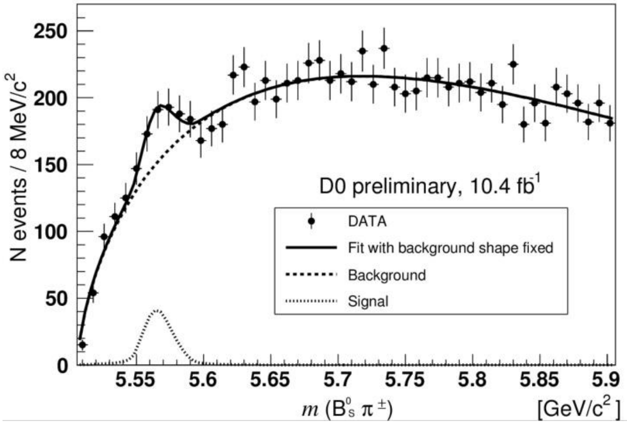
Semileptonic X(5568): fits with alternative background parametrizations

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).

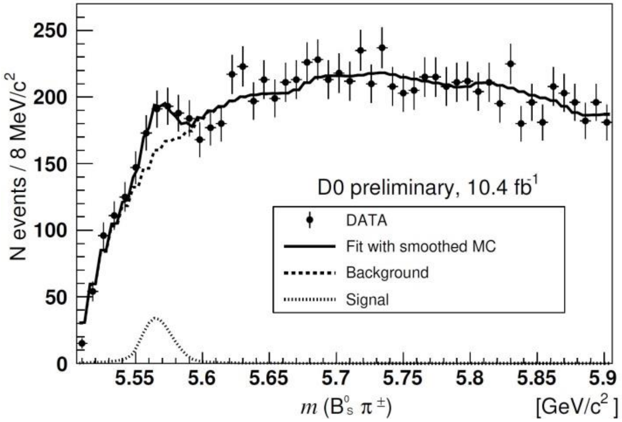
(1)



(2)



(3)



	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