A. Drutskoy

LPI, Moscow

P.N. Lebedev Physical Institute of the Russian Academy of Sciences
Физический институт имени П.Н.Лебедева

Recent Heavy Flavor results from Tevatron

29th Rencontres de Blois

Particle Physics and Cosmology

May 28- June 2, 2017, Blois, France

Outline

- Introduction
- **DØ**: Confirmation of $\mathbf{X(5568) \to B_s^0 \pi^{\pm}}$ in semileptonic $B_s^0 \to D_s^- \mu^+ \nu$ mode
- **DØ**: Search for exotic baryons decaying to $J/\psi \Lambda$ combination
- **CDF**: Measurement of low P_t D^+ meson production cross section
- Conclusion

Detectors

Tevatron $p\bar{p}$ at $\sqrt{s}$ = 1.96 TeV

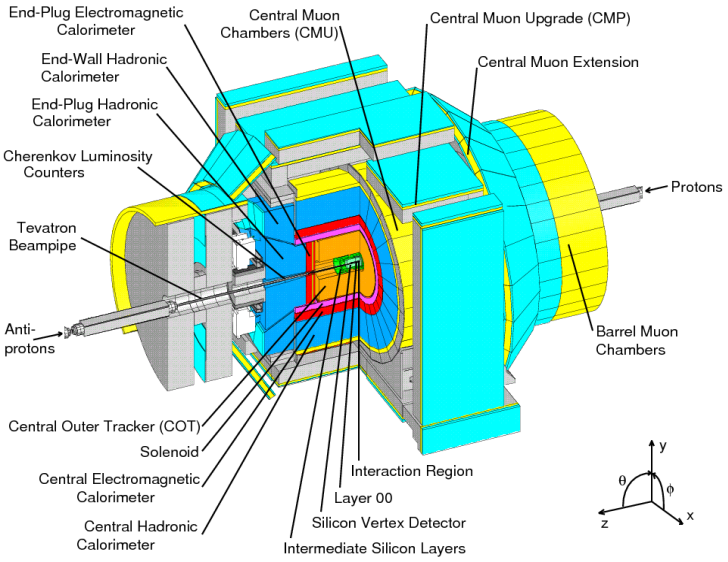
Run II operation from 2001 to 2011

Run II : CDF and D0 (b-physics)

$\int \mathcal{L}\, dt$ ~ 10 fb^{-1}

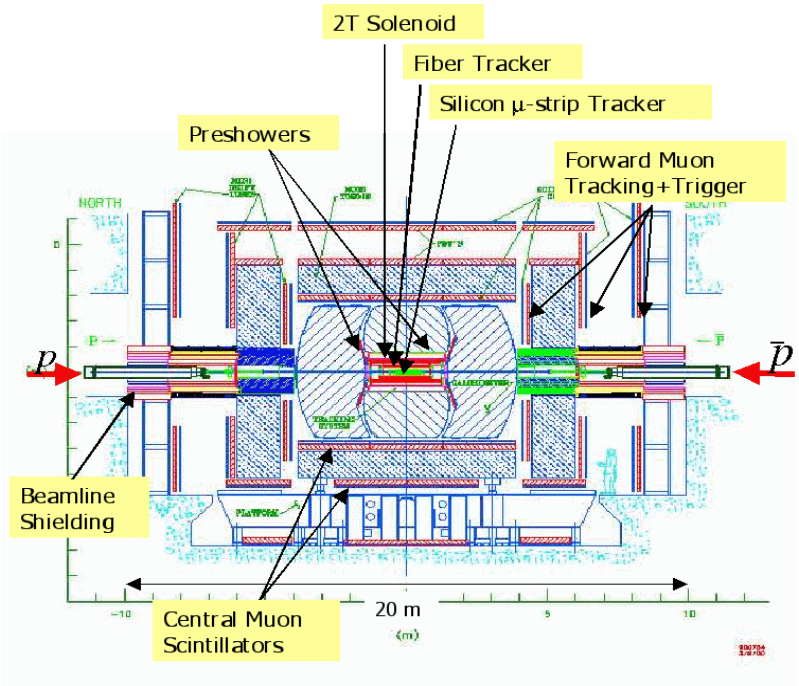
Both are multipurpose, high acceptance detectors with good tracking and vertex systems

CDF: displaced vertex triggers, PID by *dE/dx* and TOF



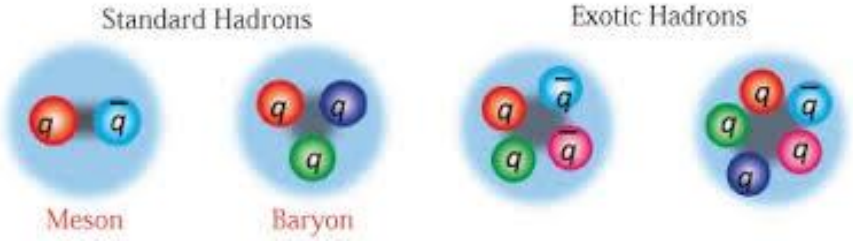
Detector CDF

D0: excellent μ-ID, magnet polarity flips



Detector D0

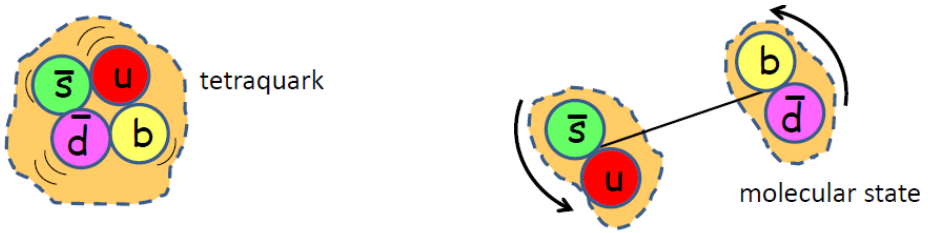
Multi-quark states



~20 multi-quark states were recently observed with high stat. significance.

Vivid examples of four-quark states: $Z(4430)^+ \to \Psi' \pi^+$, $X(4140) \to J/\psi\, \phi$, $Z_b(10610)^+ \to \Upsilon\pi^+$, $Z_b(10650)^+ \to \Upsilon\pi^+$; pentaquarks: $P_c(4450)^+ \to J/\psi\, p$, $P_c(4380)^+ \to J/\psi\, p$. *Also many others.*

Many observed multi-quark states lie close to two-hadron mass thresholds and, therefore, they can be interpreted as molecular states.



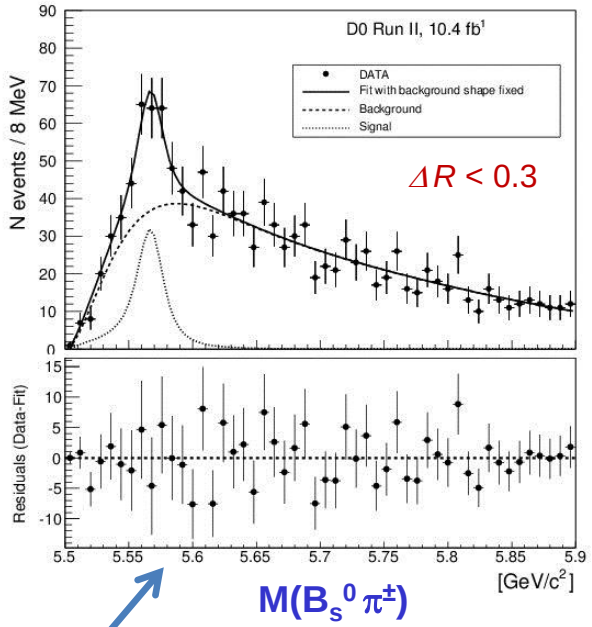
Good candidate for tetraquark was found by D0: X(5568), far below BK threshold

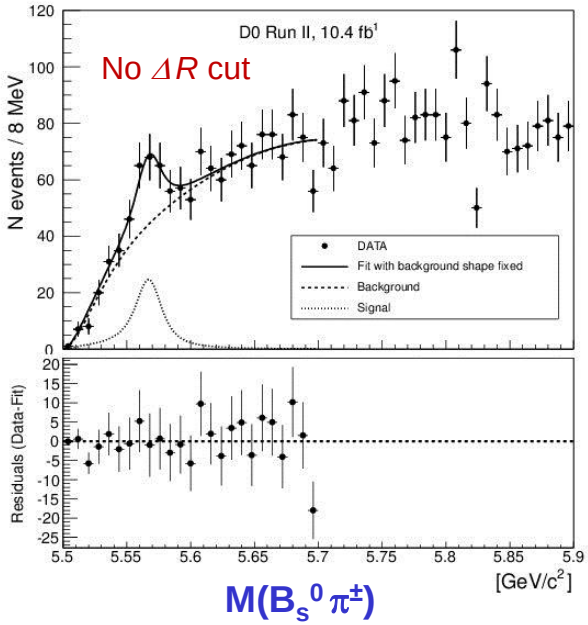
$X^+(5568) \to B_s^0 \pi^+$; $B_s^0 \to J/\psi\, \phi$; $J/\psi \to \mu^+ \mu^-$; $\phi \to K^+ K^-$

X(5568) is not seen at LHCb & CMS (E=7-8 TeV, pp). Unclear theoretical interpretation due to low mass. It's possible for scalar-scalar diquark-antidiquark 0^+ (arXiv:1705.03741).

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

D0 collaboration, Phys. Rev. Lett. 117, 022003 (2016)





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

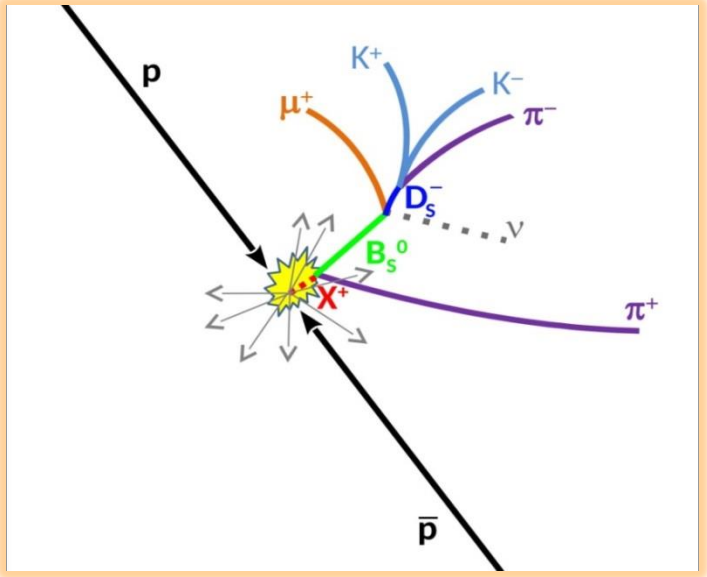
$$\Gamma = 21.9 \pm 6.4(\text{stat})^{+5.0}_{-2.5}(\text{syst})\ \text{MeV}/c^2$$

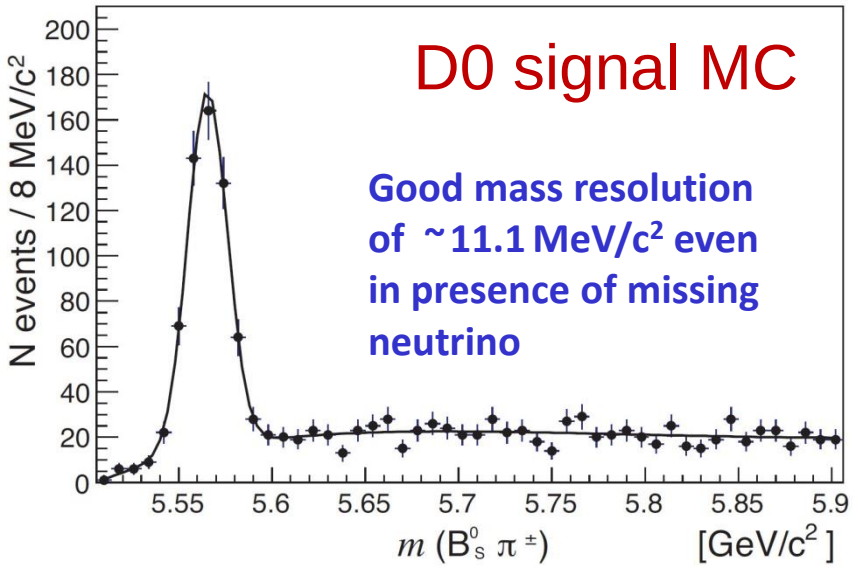
$$\rho(X(5568)/B_s) = 8.6 \pm 1.9(\text{stat}) \pm 1.4(\text{syst})\%$$

$$\Delta R = \sqrt{\Delta\eta^2 + \Delta\varphi^2} \qquad (B_s \angle \pi^+)$$

Significance = 5.1σ with *ΔR* cut including look-elsewhere effect (LEE) and systematics
(3.9 σ without *ΔR* cut)

$X(5568) \to B_s^0 \pi^\pm$ with semileptonic B_s^0 decay





$X^+(5568) \to B_s \pi^+$; $B_s \to D_s^- \mu^+ X_{any}$; $D_s^- \to \phi(1020) \pi^-$

Selections:

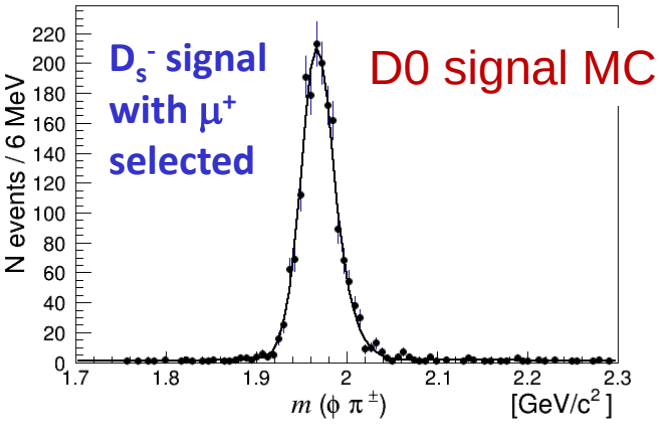
no ΔR cut; $4.5 < M(D_s \mu) < M(B_s)$;

$3 < p_T(\mu) < 25$ GeV/c; $p_T(K) > 1$ GeV/c;

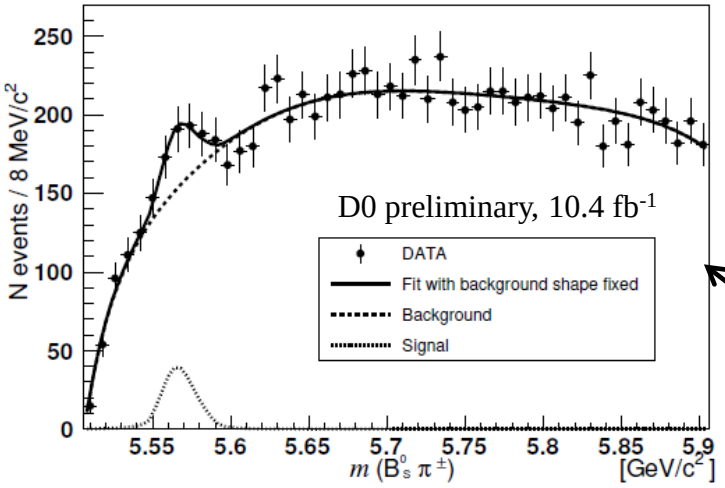
$1.012 < M(KK) < 1.03$ GeV/c²; $p_T(D_s\mu) > 10$ GeV/c

$M(B_s\pi) = M(D_s\mu\pi) - M(D_s\mu) + M(B_s)$,

where $M(B_s) = 5.3667$ GeV/c²



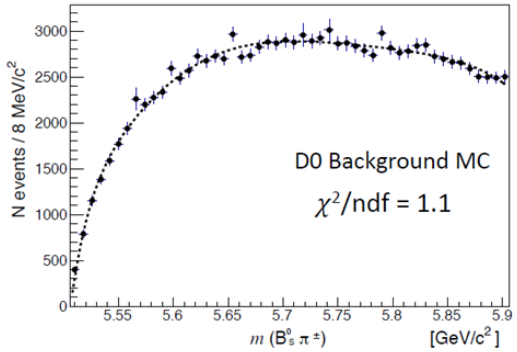
$X(5568) \to B_s^0 \pi^\pm$ with semileptonic B_s^0 decay



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

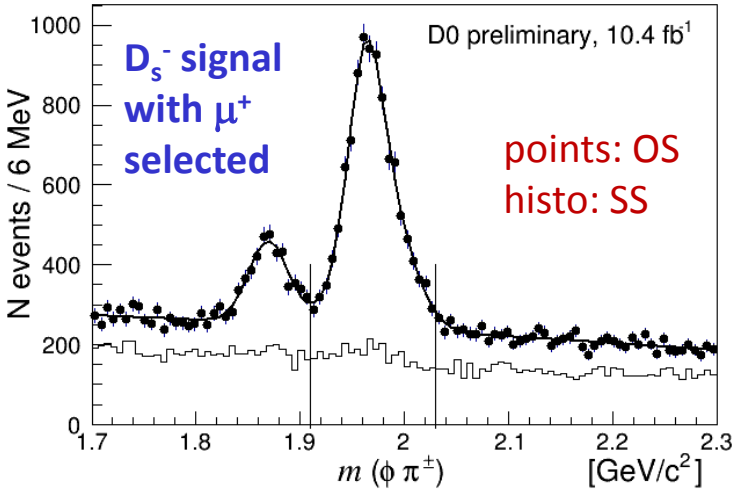
where $F_{sig}(M,M_x,\Gamma_X)$ - S-wave relativistic BW function convoluted with resolution, f_{bgr}, f_{sig} - normalization coefficients.

$$M_x = 5566.7^{+3.6}_{-3.4}\ \text{MeV}/c^2$$
$$\Gamma_x = 6.0^{+9.5}_{-6.0}\ \text{MeV}/c^2$$
$$N_{ev} = 139^{+51}_{-63}$$



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 $m=M-M_{thr}$



Comparison of X(5568) production in two channels

	Semileptonic, no ΔR cut	Hadronic, ΔR<0.3	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 natural 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	$139^{+51\ +10.9}_{-63\ -31.5}$	$133 \pm 31 \pm 15$	106 ± 23
Local significance	4.5σ	6.6σ	4.8σ
Significance with systematics	3.2σ	5.6σ	-
Significance with LEE+systematics	-	5.1σ	3.9σ

Combined significance: $p_{comb} = p_{sl} \cdot p_{had} \cdot [1 - \ln(p_{sl} \cdot p_{had})] =$ **5.7σ (4.7σ without ΔR cut)**

Production ratio of X(5568) to B_s :

$\rho(X(5568)/B_s) = 7.3^{+2.8}_{-2.4}(stat)^{+0.6}_{-1.7}(syst)\%$ - **semileptonic channel, no cone cut**

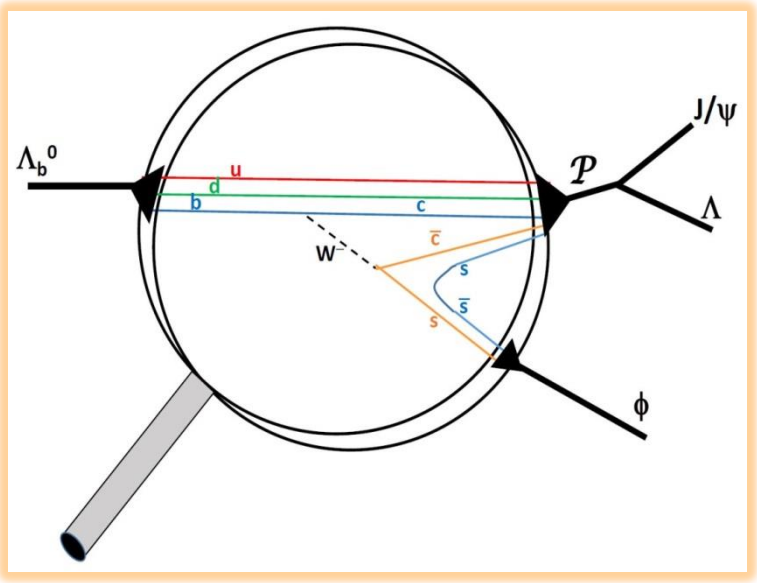
$\rho(X(5568)/B_s) = 8.6 \pm 1.9(stat) \pm 1.4(syst)\%$ - **hadronic channel, cone cut**

⇨ **Good agreement between results obtained in hadronic and semileptonic channels**

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

Two resonant structures were observed by LHCb in $J/\psi\,p$ combination around 4380 MeV/c^2 and 4450 MeV/c^2 in $\Lambda_b \rightarrow J/\psi\, p\, K^-$ decays, which are pentaquarks P_c.

Idea of this analysis: search for similar states in $M(J/\psi\,\Lambda)$, where $J/\psi \rightarrow \mu^+\mu^-$, $\Lambda \rightarrow p\pi^-$.



Selections:

$p_T(\mu) > 1$ 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

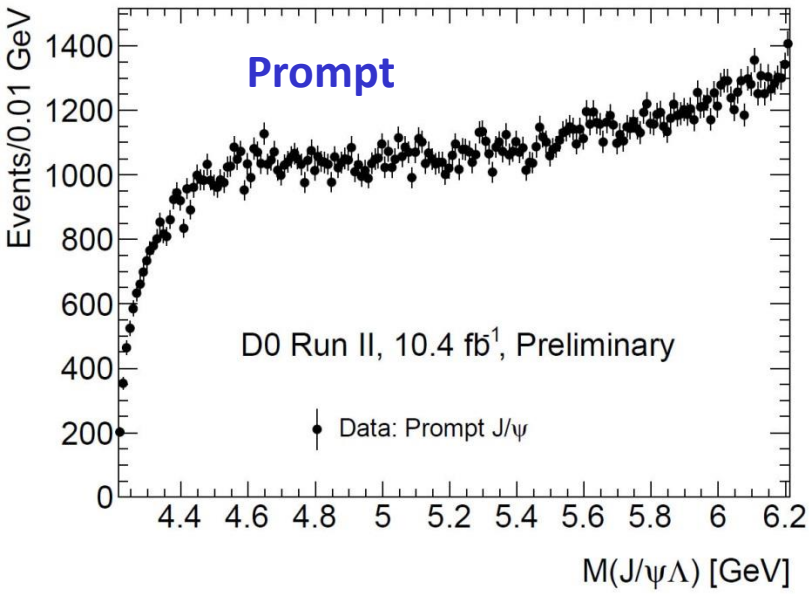
$1.110 < M(\Lambda) < 1.122$ GeV/c^2

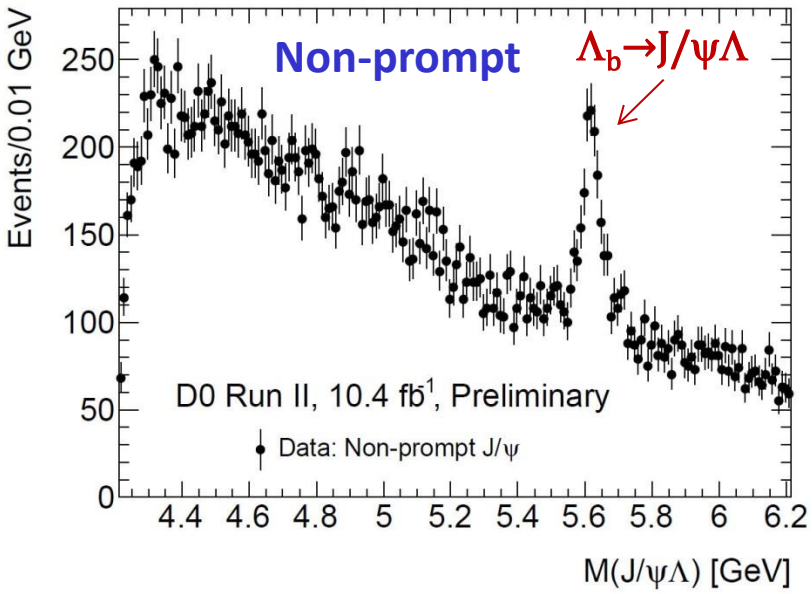
$p_T(\pi) > 0.15$ GeV/c

Prompt production: from primary vertex.
Non-prompt production: from b-hadrons.

Non-prompt selection : J/ψ decay length significance in the transverse plane is greater than 3 and Λ is pointing to J/ψ decay vertex rather than to $p\bar{p}$ interaction vertex.

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





No bumps are found in prompt data sample.

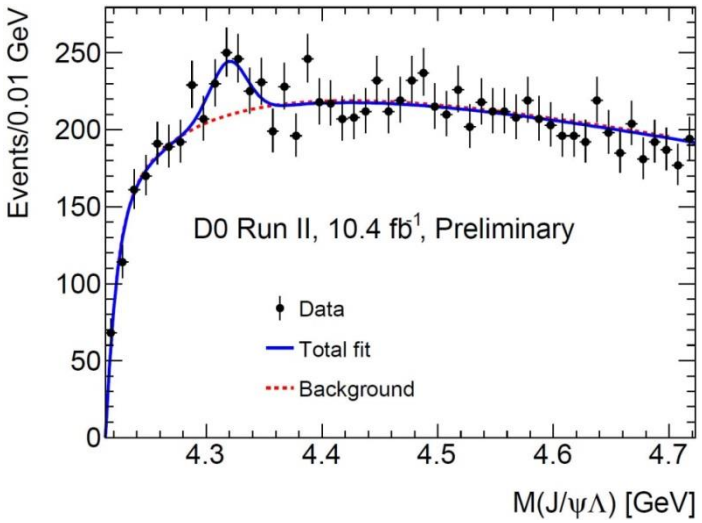
Non-prompt sample is studied in detail in the following analysis in mass range 4.2-4.7 GeV/c^2. Pentaquarks are predicted to populate region within ~ 500 MeV/c^2 from threshold (A. Ali, I. Ahmed, M. J. Aslam, and A. Rehman, *Phys. Rev.*, D94, no. 5, 054001, 2016).

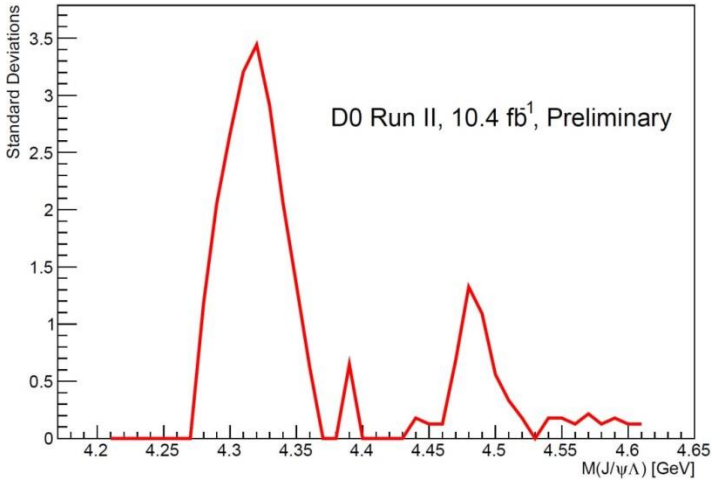
Search for exotic baryons decaying to $J/\psi\,\Lambda$

Binned maximum likelihood fits to $M(J/\psi\,\Lambda)$ with sum of signal + background or background only were performed with signal mass set at fixed values in 10 MeV steps.

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

$$F_{bgr}(M) \propto M\cdot\left(M^2/M_{thr}^2-1\right)^{c_1}\cdot e^{-c_2 M}\cdot\left(1-e^{-(M-M_{thr})/b}\right),$$ M_{thr} is $J/\psi\,\Lambda$ threshold





Largest local significance of 3.45σ occurs at $M = 4.32$ GeV/c^2. If LEE (for 500 MeV interval) is taken into account the global significance is 2.8σ.

⇨ **No evidence is found for new baryons decaying to $J/\psi\,\Lambda$**

Measurement of low p_T D^+ meson production cross section

Goal: to test QCD models at small momentum transfer (non-perturbative regime)

Previous CDF measurement in $p\bar{p}$ collisions was restricted to $p_T > 6$ GeV/c region.

CDF Note:
https://www-cdf.fnal.gov/physics/new/bottom/160519.blessedLowPtDPlus/cdfpubnote.pdf

Decay mode: $D^+ \rightarrow K^- \pi^+ \pi^+$

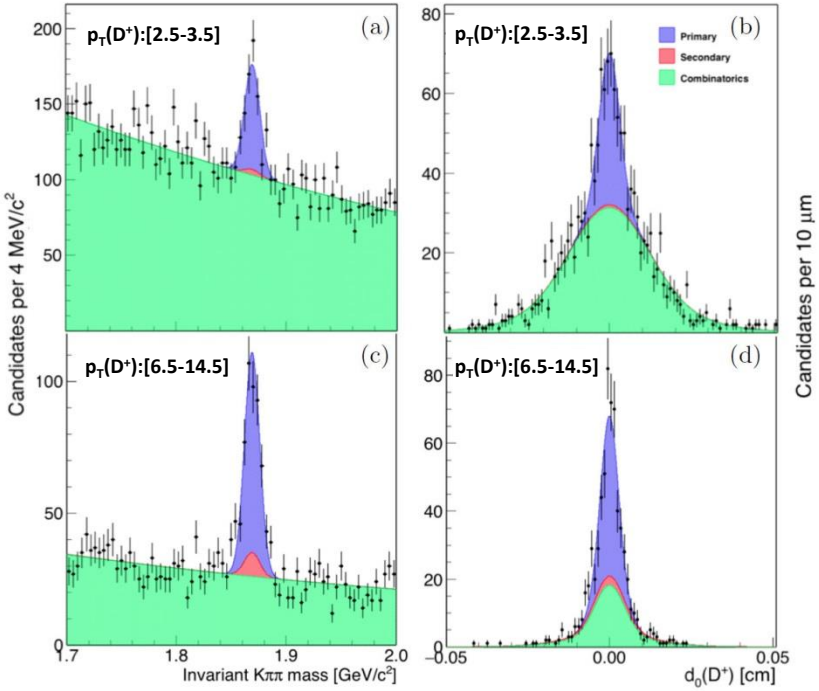
Selections:

$p_T(D^+) > 1.5$ GeV/c

Zero and minimum bias triggers

5 p_T bins: 1.5-2.5, 2.5-3.5, 3.5-4.5, 4.5-6.5, 6.5-14.5 GeV/c

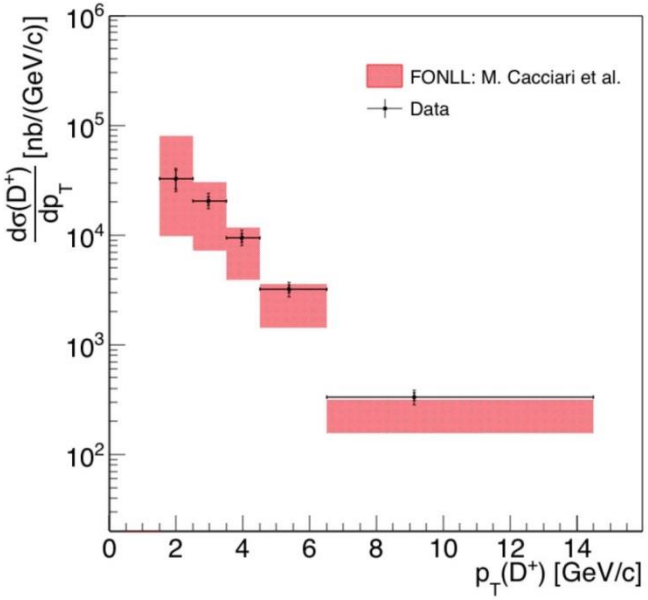
Rapidity interval: $|y| < 1$



Simultaneous ML fit to unbinned distributions of $M(K^- \pi^+ \pi^+)$ and D^+ impact parameter (to separate prompt from non-prompt production).

Measurement of low p_T D^+ meson production cross section

p_T range (GeV/c)	Eff. p_T (GeV/c)	$d\sigma(D^+, \|y\| < 1)/dp_T$ (μb/GeV/c)	$\sigma_i(D^+, \|y\| < 1)$ (μb)
$1.5 - 2.5$	1.99	$32.7 \pm 6.5 \pm 4.2$	$32.7 \pm 6.5 \pm 4.2$
$2.5 - 3.5$	2.97	$20.6 \pm 1.8 \pm 2.7$	$20.6 \pm 1.8 \pm 2.7$
$3.5 - 4.5$	3.97	$9.50 \pm 0.84 \pm 1.2$	$9.50 \pm 0.84 \pm 1.2$
$4.5 - 6.5$	5.37	$3.23 \pm 0.26 \pm 0.42$	$6.46 \pm 0.52 \pm 0.84$
$6.5 - 14.5$	9.14	$0.34 \pm 0.04 \pm 0.04$	$2.69 \pm 0.22 \pm 0.35$



$$\sigma_i = \frac{N_i/2}{\int \mathcal{L}dt \cdot \epsilon_i \cdot \mathcal{B}}$$

Efficiency ϵ_i which includes detection, reconstruction and selection efficiencies, varies from 0.27 to 7.5% depending on p_T bin.

The total fiducial cross section, obtained by summing over all p_T bins, is:

71.9 ± 6.8 (stat) ± 9.3 (syst) μb

$1.5 < p_T(D^+) < 14.5$ GeV/c, $|y| < 1$

⇨ **Although exp points lie within theoretical bands, there is a tendency for theory to underestimate data**

Conclusions

- **X(5568)** $\rightarrow \mathbf{B_s^0 \pi^\pm}$ state observed in hadronic B_s^0 decay is seen with semileptonic B_s^0 decays. Signal parameters obtained in these two channels are in good agreement.

- Search is performed by D0 for exotic baryons in $\mathbf{J/\psi\ \Lambda}$ final state. No significant signals are observed. Largest signal at mass 4.32 GeV/c^2 has global significance (including LEE) 2.8 σ.

- $\mathbf{D^+}$ meson production cross section is measured by CDF in low p_T region. Data lie within theoretical bands, however there is tendency for theory to underestimate data. It should help to improve theoretical calculations in perturbative regime.

Retrospective to four-quark states

Four-quark states are not forbidden *theoretically*.
These states can be separated using information about masses, widths, charges, quantum numbers, production and decay modes (and their rates).

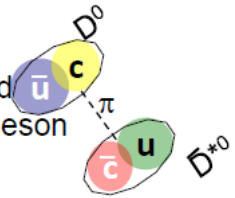
Exotic four-quark states can be theoretically described as tightly bounded (tetraquark) or loosely bounded (molecule, hadroquarkonium):

Tetraquark mesons

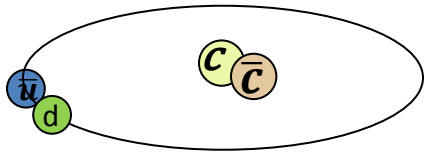
tightly bound
diquark-diantiquark

molecule

loosely bound
meson-antimeson
"molecule"



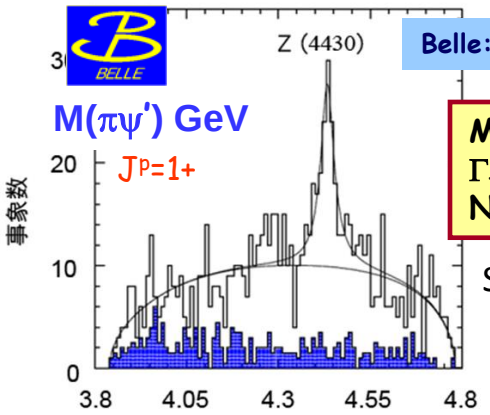
Hadrocharmonium (like earth & moon)



Observed with high stat significance four-quark states: **$Z(4430)^+ \to \Psi' \pi^+$, $X(4140) \to J/\psi\, \phi$, $Z_b(10610)^+ \to \Upsilon\pi^+$, $Z_b(10650)^+ \to \Upsilon\pi^+$** , not well established **$Z(4050)^+ \to \chi_{c1}\, \pi^+$, $Z(4250)^+ \to \chi_{c1}\, \pi^+$.**
Probably **X(3872)** is mixture of four- and two-quark states. Molecular interpretation works well for the states. Other exotic states: pentaquarks **$P_c(4450)^+ \to J/\psi\, p$, $P_c(4380)^+ \to J/\psi\, p$**

More information about exotic multiquark states is required to build explicit theory.

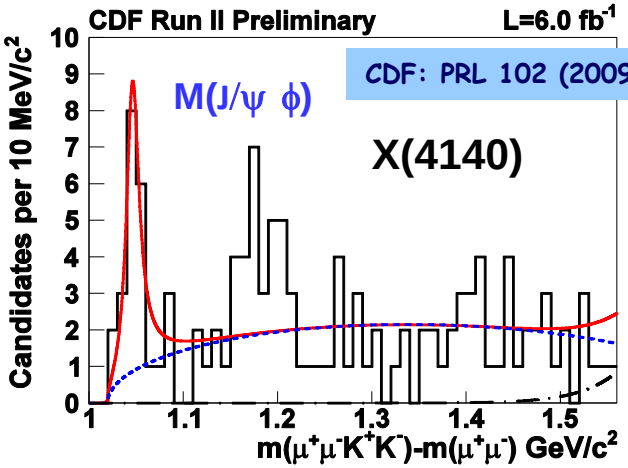
Non-standard states observed with high significance



Belle: PRL 100 (2008) 142001

$M = 4433 \pm 4 \pm 2$ MeV
$\Gamma_{tot} = 45\ ^{+18}_{-13}\ ^{+30}_{-13}$ MeV
Nsig = 121 ± 30 evts

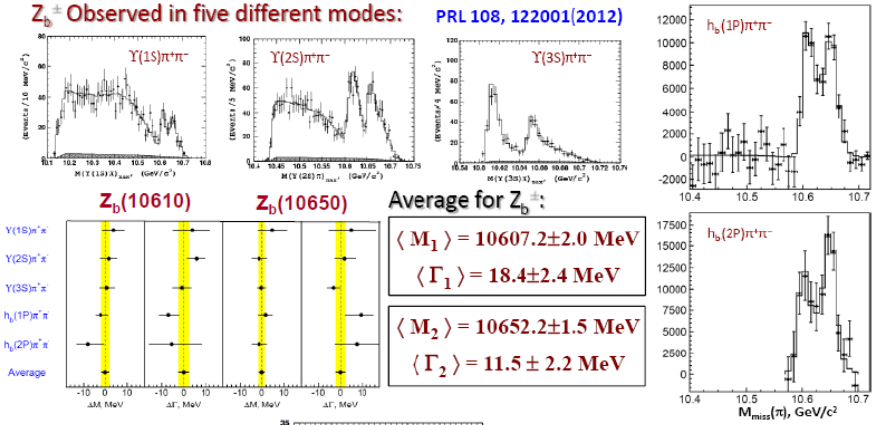
Sign = 6.1s (no syst)



CDF: PRL 102 (2009) 242002

Properties of $Z_b(10610)$ & $Z_b(10650)$

$Z_b^{\pm}$ Observed in five different modes: PRL 108, 122001(2012)



Average for $Z_b^{\pm}$:

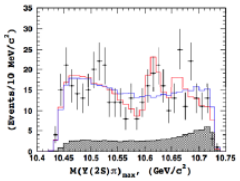
$\langle M_1 \rangle = 10607.2 \pm 2.0$ MeV
$\langle \Gamma_1 \rangle = 18.4 \pm 2.4$ MeV

$\langle M_2 \rangle = 10652.2 \pm 1.5$ MeV
$\langle \Gamma_2 \rangle = 11.5 \pm 2.2$ MeV

Z_b^0 Results:

$\langle M_1 \rangle = 10609 \pm 7 \pm 6$ MeV

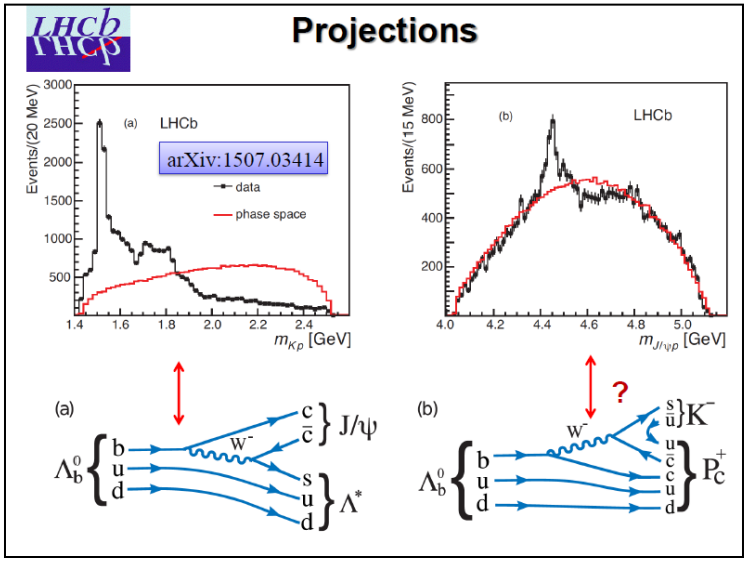
Consistent with $Z_b^{\pm}$



M_1-M_B-M_{B^*} = 2.36 ± 2.1 MeV
M_2-M_{B^*}-M_{B^*} = 1.8 ± 1.75 MeV

Jᴾ=1++ and 2++

Projections

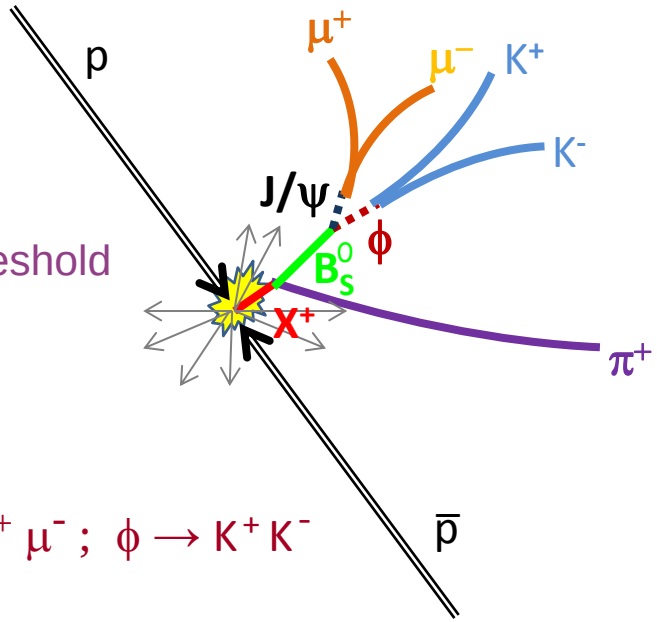


Observation of new $B_s^0\pi^\pm$ state

$B_s^0\pi^\pm$ includes $B_s^0\pi^+$, $B_s^0\pi^-$, $\bar{B}_s^0\pi^+$ and $\bar{B}_s^0\pi^-$.

$B_s\pi^+$ system: 4 different quark flavors $\bar{b}s\bar{d}u$

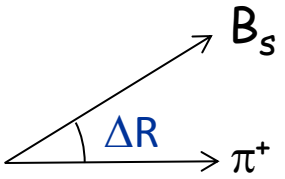
Invariant mass of $B_s^0\pi^\pm$ was studies up to BK mass threshold



Decay chain: $X^+ \to B_s^0\,\pi^+$; $B_s^0 \to J/\psi\,\phi$; $J/\psi \to \mu^+\mu^-$; $\phi \to K^+K^-$

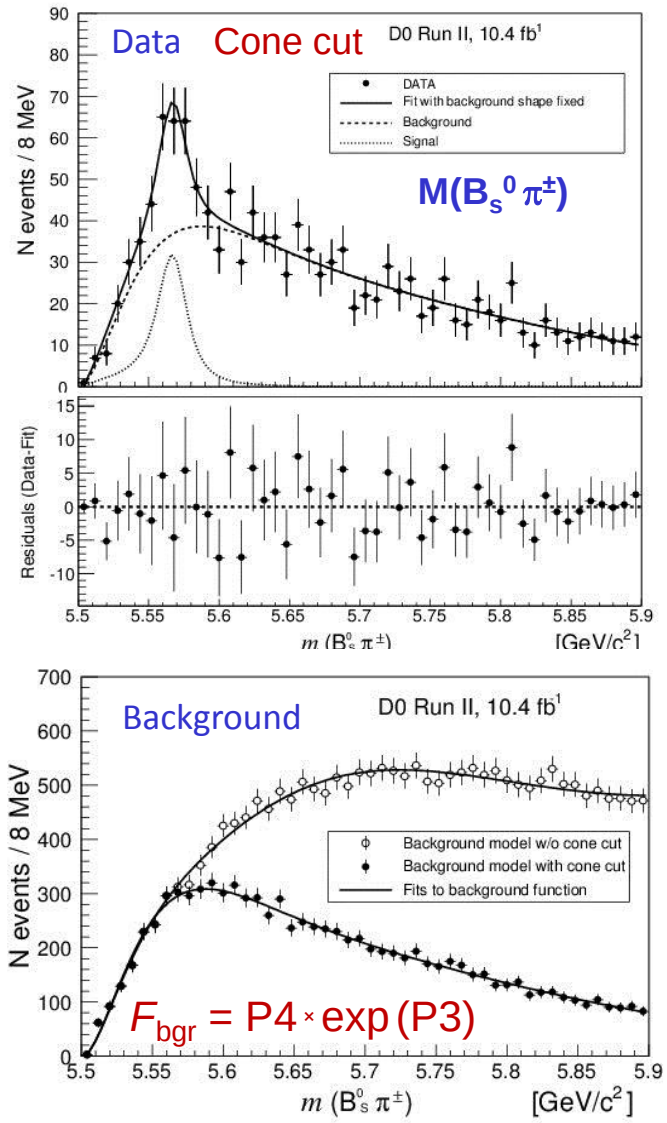
<u>Selections:</u> basic B_s^0 requirements + π^+ from $p\bar{p}$ interaction vertex

$\Delta R = \sqrt{[\phi(B_s) - \phi(\pi)]^2 + [\eta(B_s) - \eta(\pi)]^2} < 0.3$ - cone cut



To improve resolution: $m(B_s\pi^+) = m(J/\psi\,\phi\,\pi^+) - m(J/\psi\,\phi) + 5.3667$

Observation of new $B_s^0\pi^\pm$ state



D0: arXiv:1602.07588 [hep-ex], submitted to PRL.

$$F = f_{\rm sig} \times F_{\rm sig}(m_{B\pi}, M_X, \Gamma_X) + f_{\rm bgr} \times F_{\rm bgr}(m_{B\pi})$$

F_{sig} – relativistc S-wave BW convolved with gaussian (3.8 MeV/c^2 detector resolution)

$$BW(m_{B\pi}) \propto \frac{M_X \Gamma(m_{B\pi})}{(M_X^2 - m_{B\pi}^2)^2 + M_X^2 \Gamma^2(m_{B\pi})}.$$

M = 5567.8 $\pm$ 2.9 (stat) MeV/c^2

Γ = 21.9 $\pm$ 6.4 (stat) MeV/c^2

N = 133 $\pm$ 31 (stat)

Significance = 6.6σ (local significance, obtained from Wilk's theorem)

Significance = 5.1σ including look-elsewhere effect (LEE) and systematics

High Energy Physics - Experiment

Observation of a new $B_s^0\pi^\pm$ state

D0 Collaboration

(Submitted on 24 Feb 2016 (v1), last revised 25 Feb 2016 (this version, v2))

We report the observation of a narrow structure, $X(5568)$, in the decay sequence $X(5568) \to B_s^0\pi^\pm$, $B_s^0 \to J/\psi\phi$, $J/\psi \to \mu^+\mu^-$, $\phi \to K^+K^-$. This is the first observation of a hadronic state with valence quarks of four different flavors. The mass and natural width of the new state are measured to be $m = 5567.8 \pm 2.9\,(\mathrm{stat})^{+0.9}_{-1.9}\,(\mathrm{syst})$ MeV/c^2 and $\Gamma = 21.9 \pm 6.4\,(\mathrm{stat})^{+5.0}_{-2.5}\,(\mathrm{syst})$ MeV/c^2, and the significance including look-elsewhere effect and systematic uncertainties is 5.1σ. The observation is based on $10.4\ \mathrm{fb}^{-1}$ of $p\bar{p}$ collision data at $\sqrt{s}$ = 1.96 TeV collected by the D0 experiment at the Fermilab Tevatron collider.

Comments: 8 pages, 4 figures, submitted to Phys. Rev. Lett
Subjects: **High Energy Physics - Experiment (hep-ex)**; High Energy Physics - Phenomenology (hep-ph)
Report number: FERMILAB-PUB-16-038-E
Cite as: arXiv:1602.07588 **[hep-ex]**
(or arXiv:1602.07588v2 **[hep-ex]** for this version)

Submission history

From: Alexey Drutskoy [view email]
[v1] Wed, 24 Feb 2016 16:44:51 GMT (41kb)
[v2] Thu, 25 Feb 2016 16:56:39 GMT (59kb)