P.N. LEBEDEV PHYSICAL INSTITUTE OF THE RUSSIAN ACADEMY OF SCIENCES
Физический институт имени П.Н. Лебедева РАН

A. Drutskoy
LPI, Moscow

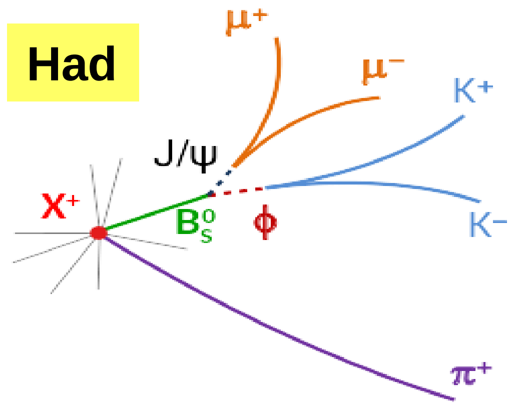
Heavy Flavor results from Tevatron

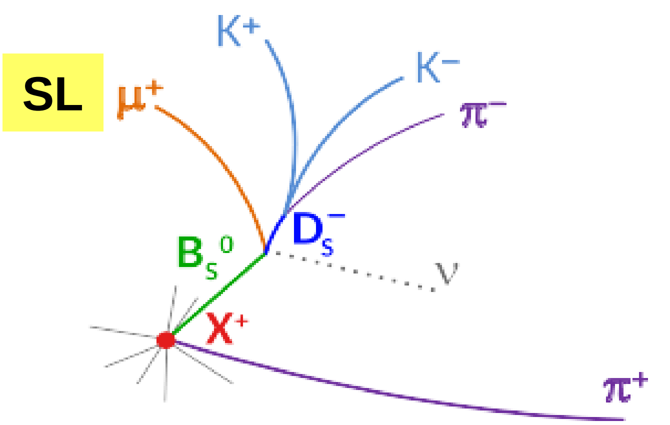
30th Rencontres de Blois
Particle Physics and Cosmology

June 3- 8, 2018, Blois, France

Outline

- Introduction
- Study of $X(5568) \to B_s^0 \pi^\pm$ at D0 and CDF
  - D0: first evidence in hadronic mode $B_s^0 \to J/\psi\ \phi$
  - D0: confirmation with semileptonic mode $B_s^0 \to D_s^- \mu^+ \nu$
  - CDF: upper limit in hadronic mode $B_s^0 \to J/\psi\ \phi$
  - Comparison of analyses details
- Conclusion





Detectors

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

Run II operation from 2001 to 2011

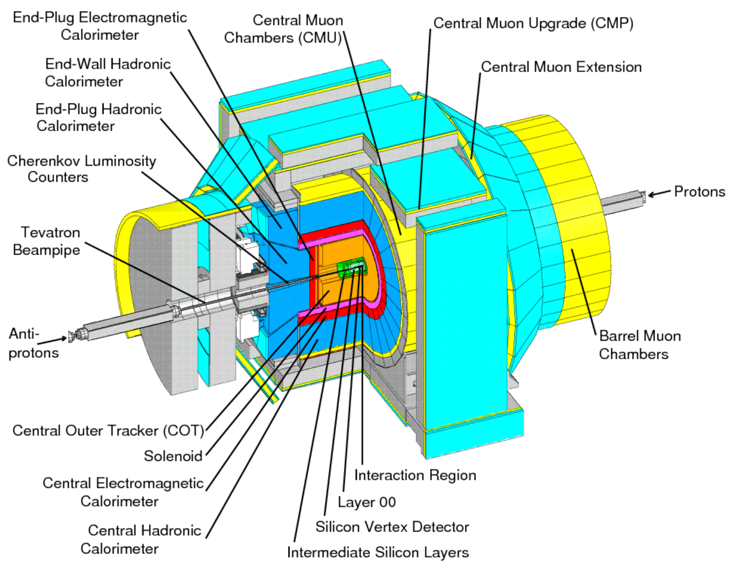
Run II : CDF and D0 (b-physics)

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

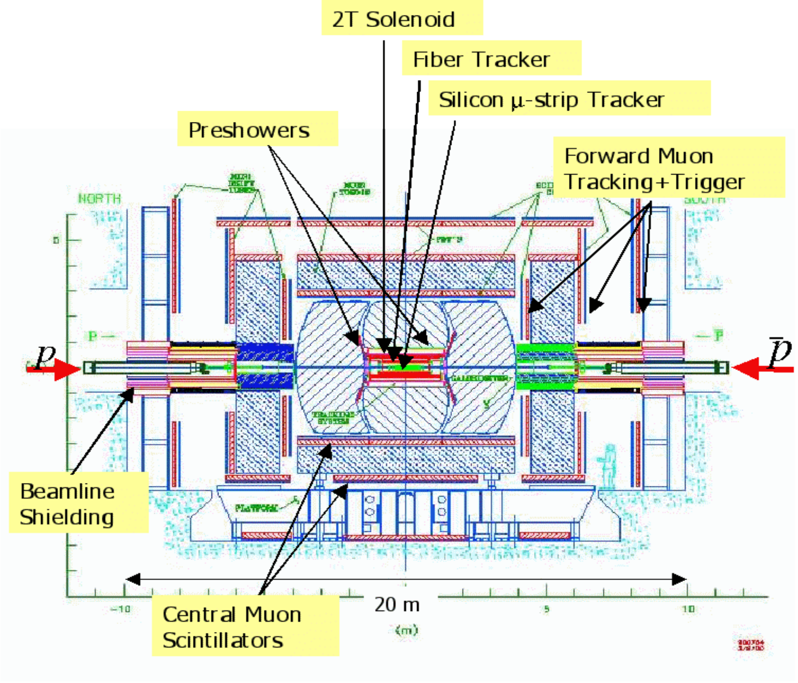
Both are multipurpose, high acceptance detectors with good tracking and vertex systems

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

D0: excellent μ-ID, forward muon system, magnet polarity flips (decreasing systematics)

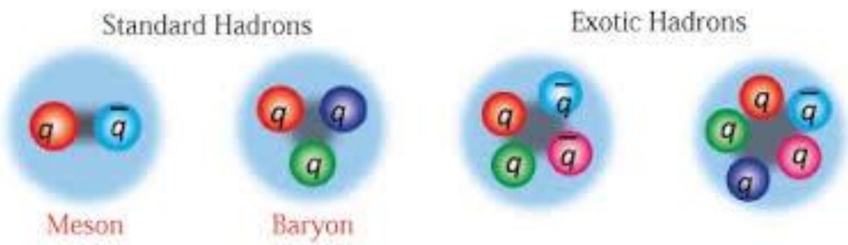


Detector CDF



Detector D0

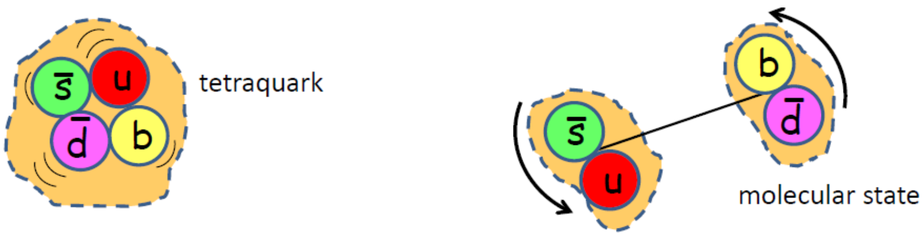
Multi-quark states



~20 multi-quark states were observed since 2003 with high significance.

Vivid examples of four-quark states: **X(3782)**$\to J/\psi\ \pi^+\pi^-$, **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)**$^+\to J/\psi\ p$.

4-quark states interpretations: tetraquarks (large binding energy), molecular states (small binding energy), mixture with conventional states (if possible).

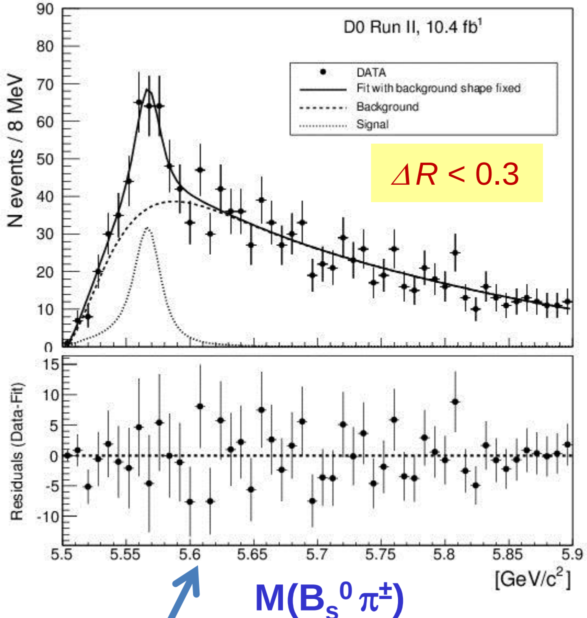


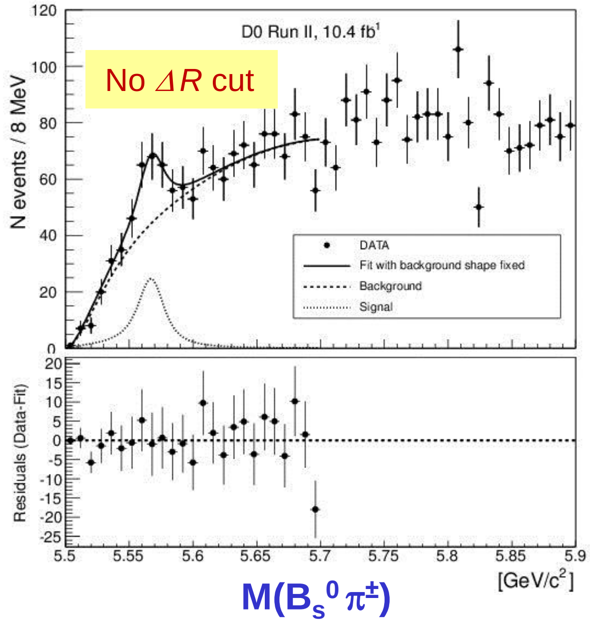
Many observed multi-quark states lie close to two-hadron mass thresholds and, therefore, they can be interpreted as molecular states (but not all).

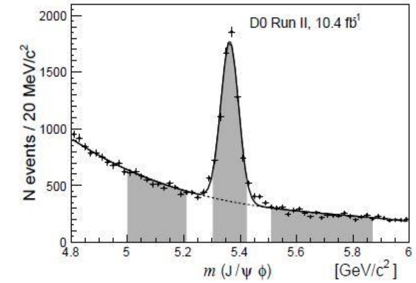
Recent review on multiquark states: Olsen, Skwarnicki, Zieminska, Rev.Mod.Phys. 90, 015003 (2018)

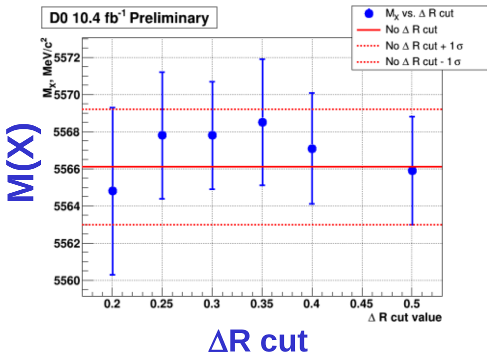
Evidence for X(5568)$\rightarrow B_s^0\pi^\pm$ state with $B_s^0 \rightarrow J/\psi\ \phi$

D0 collaboration, PRL 117, 022003 (2016)









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

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

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

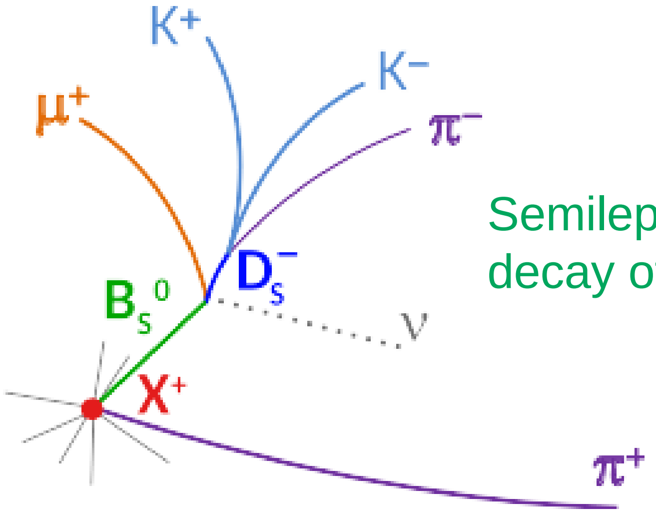
Disfavor molecular interpretation

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

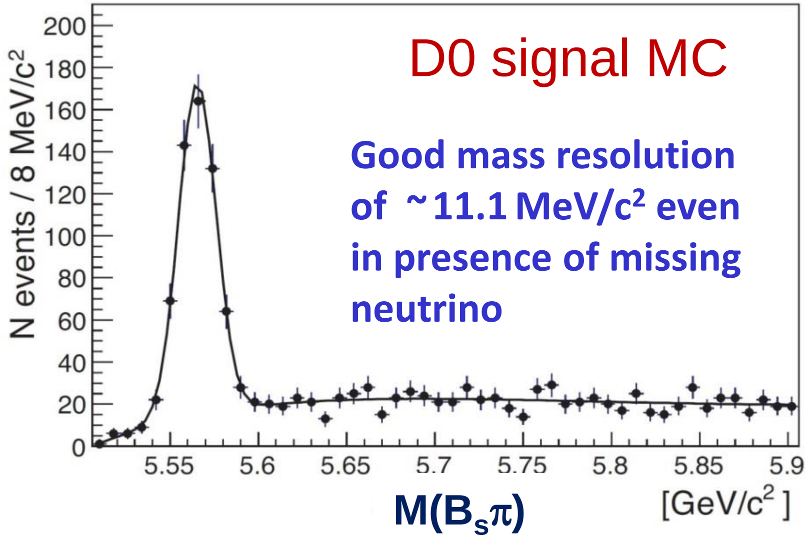
Significance = 5.1σ with *ΔR* cut including look-elsewhere effect (LEE) and systematics (3.9 σ without *ΔR* cut)

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

D0 collaboration, PRD 97, 092004 (2018)



Semileptonic decay of B_s^0



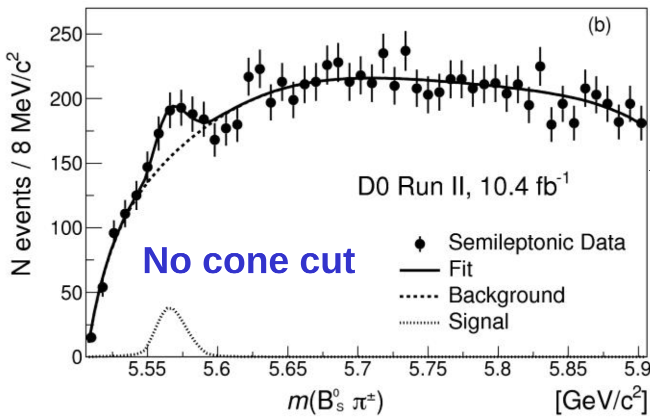
$X^+(5568) \to B_s \pi^+ ; \quad B_s \to D_s^- \mu^+ X_{any} ; \quad D_s^- \to \phi(1020)\, \pi^- ; \; \phi \to K^+K^-$

1. Calculate visible mass $M(D_s^- \mu^+)$
2. Use visible mass as B_s mass
3. Combine B_s and π^+ to form X
4. Estimate $M(X) = M(B_s^0 \pi^{\pm}) = M(D_s \mu \pi) - M(D_s \mu) + M_{PDG}(B_s^0)$

Selections: $4.5 < M(D_s \mu) < M(B_s)$;
$3 < p_T(\mu) < 25$ GeV/c; $p_T(K) > 1$ GeV/c;
$1.012 < M(KK) < 1.03$ GeV/c²; $p_T(D_s\mu) > 10$ GeV/c;
$1.91 < M(KK\pi) < 2.03$ GeV/c²

➔ **Resolution is good enough to check X(5568)**

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



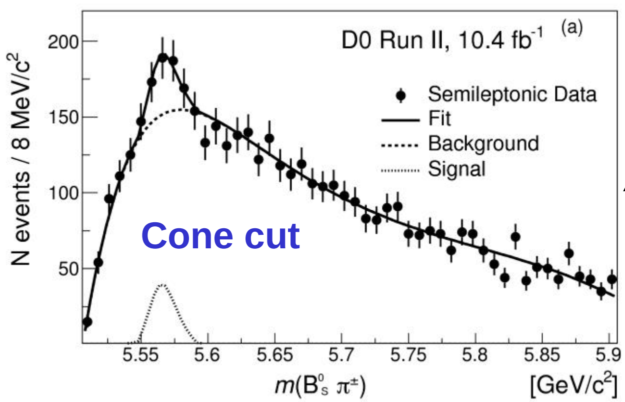
$M_x = 5566.7^{+3.6+1.9}_{-3.4-1.0}$ MeV/c^2

$\Gamma_x = 6.0^{+9.5+1.9}_{-6.0-4.6}$ MeV/c^2

$N_{ev} = 139^{+51+11}_{-63-32}$

Signif(local) = 4.5 σ

Signif(local+syst) = 3.4 σ



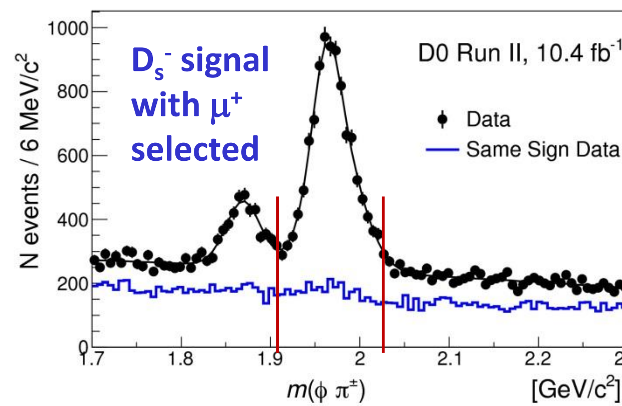
$M_x = 5566.4^{+3.4+1.4}_{-2.8-0.6}$ MeV/c^2

$\Gamma_x = 2.0^{+9.5+2.8}_{-2.0-2.0}$ MeV/c^2

$N_{ev} = 121^{+51+9}_{-34-28}$

Signif(local) = 4.3 σ

Signif(local+syst) = 3.2 σ



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

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

Comparison of X(5568) production in two channels

	Semileptonic		Hadronic (from Ref. [15])	
	Cone cut	No cone cut	Cone cut	No cone cut
Fitted mass, MeV/c^2	$5566.4^{+3.4}_{-2.8}\,^{+1.5}_{-0.6}$	$5566.7^{+3.6}_{-3.4}\,^{+1.0}_{-1.0}$	$5567.8 \pm 2.9^{+0.9}_{-1.9}$	5567.8
Fitted width, MeV/c^2	$2.0^{+9.5}_{-2.0}\,^{+2.8}_{-2.0}$	$6.0^{+9.5}_{-6.0}\,^{+1.9}_{-4.6}$	$21.9 \pm 6.4^{+5.0}_{-2.5}$	21.9
Fitted number of signal events	$121^{+51}_{-34}\,^{+9}_{-28}$	$139^{+51}_{-63}\,^{+11}_{-32}$	$133 \pm 31 \pm 15$	106 ± 23 (stat)
Local significance	$4.3\,\sigma$	$4.5\,\sigma$	$6.6\,\sigma$	$4.8\,\sigma$
Significance with systematics	$3.2\,\sigma$	$3.4\,\sigma$	$5.6\,\sigma$	...
Significance with LEE+systematics	...	...	$5.1\,\sigma$	$3.9\,\sigma$

Production ratio of X(5568) to B_s :

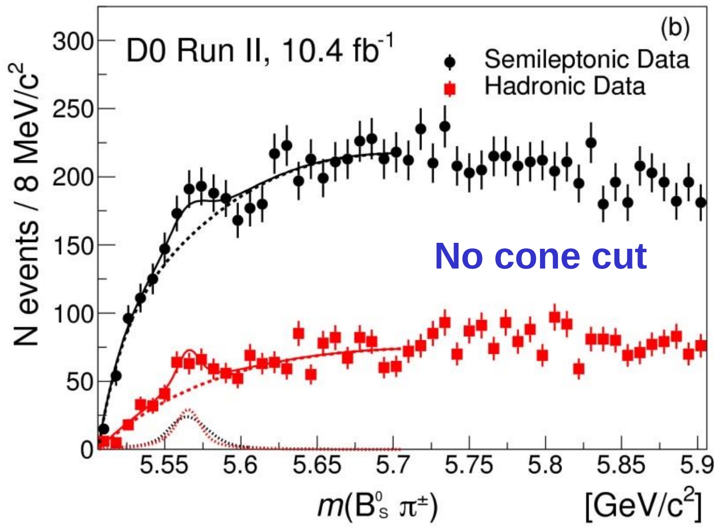
$\rho(X(5568)/B_s) = 7.3^{+2.8}_{-2.4}(\text{stat})^{+0.6}_{-1.7}(\text{syst})\%$ **- semileptonic channel, no cone cut**

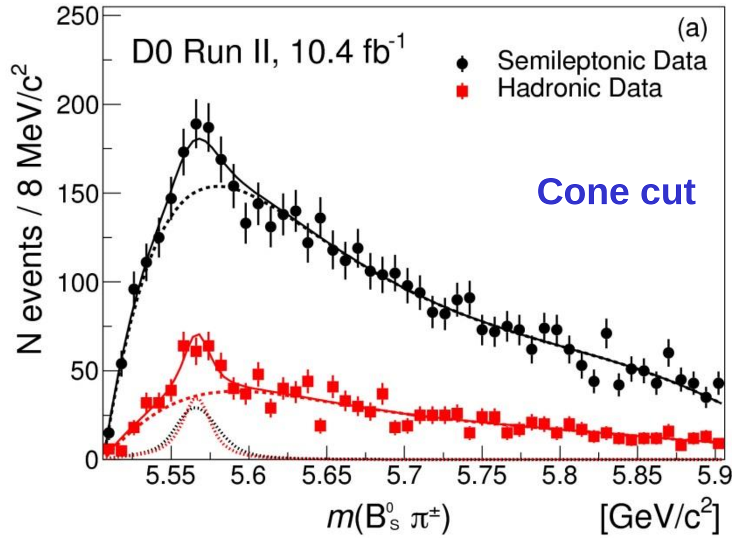
$\rho(X(5568)/B_s) = 8.6 \pm 1.9(\text{stat}) \pm 1.4(\text{syst})\%$ **- hadronic channel, cone cut**

⇨ **D0 measurement in semileptonic channel confirms X(5568) observed in hadronic channel**

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

D0: simultaneous fit to hadronic and semileptonic channels





	Cone cut	No cone cut
Fitted mass, MeV/c^2	$5566.9^{+3.2}_{-3.1}$ (stat) $^{+0.6}_{-1.2}$ (syst)	$5565.8^{+4.2}_{-4.0}$ (stat) $^{+1.3}_{-2.0}$ (syst)
Fitted width, MeV/c^2	$18.6^{+7.9}_{-6.1}$ (stat) $^{+3.5}_{-3.8}$ (syst)	$16.3^{+9.8}_{-7.6}$ (stat) $^{+4.2}_{-6.5}$ (syst)
Fitted number of hadronic signal events	131^{+37}_{-33} (stat) $^{+15}_{-14}$ (syst)	99^{+40}_{-34} (stat) $^{+18}_{-33}$ (syst)
Fitted number of semileptonic signal events	147^{+42}_{-37} (stat) $^{+17}_{-16}$ (syst)	111.7^{+46}_{-39} (stat) $^{+20}_{-38}$ (syst)
χ^2/ndf	$94.7/(100-6)$	$54.2/(50-6)$
p-value	2.2×10^{-14}	1.9×10^{-8}
Local significance	$7.6\,\sigma$	$5.6\,\sigma$
Significance with LEE	$6.9\,\sigma$	$5.0\,\sigma$
Significance with LEE+systematics	$6.7\,\sigma$	$4.7\,\sigma$

⇨ Significance increased with semileptonic channel added

CDF search for X(5568)$\rightarrow B_s^0\pi^\pm$ with $B_s^0 \rightarrow J/\psi\ \phi$

CDF collaboration, PRL 120, 202006 (2018)

Selections:

Only central muons selected:

- $pT(\mu)$ > 1.4 GeV/c for $|\eta| < 0.6$
- $pT(\mu)$ > 2.0 GeV/c for $0.6 < |\eta| < 1.0$

$M(\mu^+\mu^-)$: $M_{PDG}(J/\psi) \pm 80$ MeV/c^2

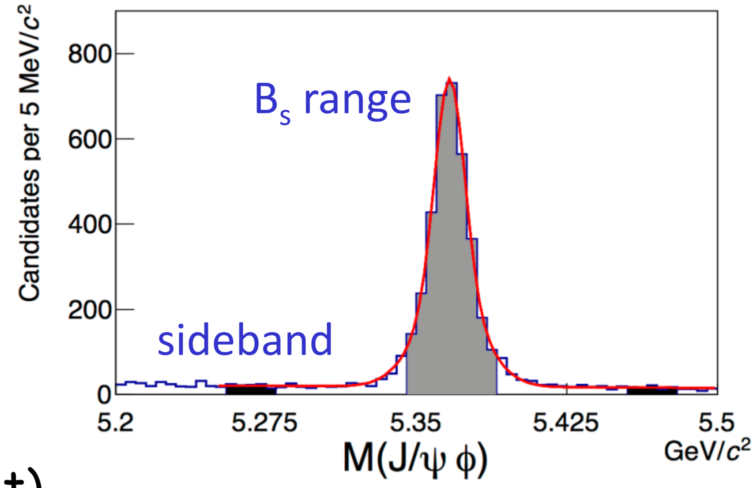
4-track constrained vertex fit (non-prompt)

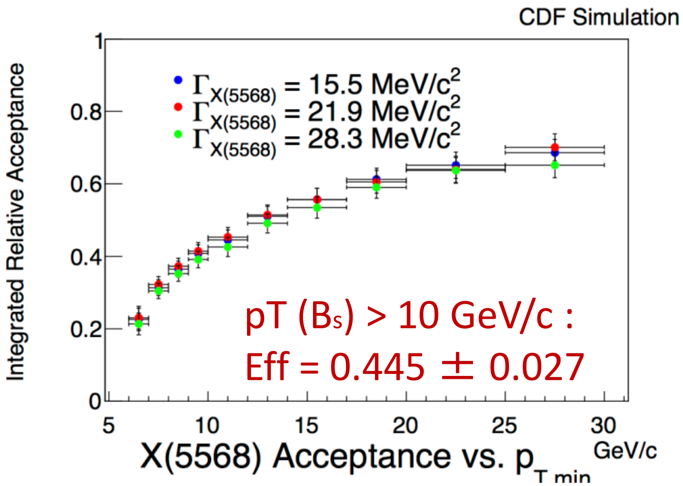
$M(J/\psi\ \phi)$: $M_{PDG}(B_s) \pm 30$ MeV/c^2

pT (B_s) > 10 GeV/c

Combine B_s with pion from primary vertex

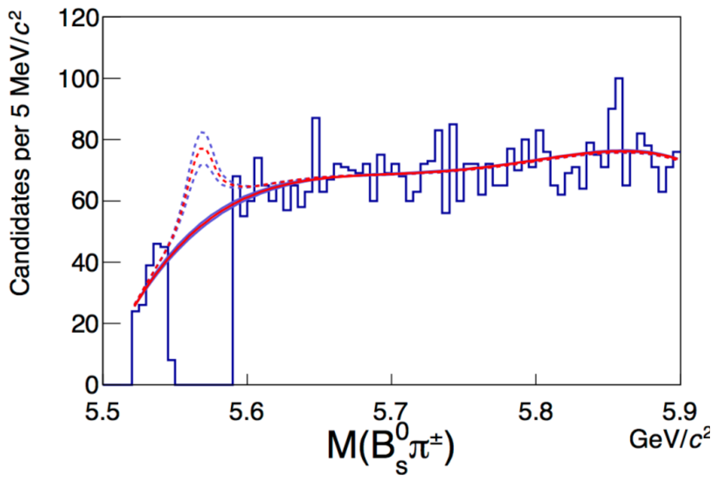
pT (π^+) > 0.4 GeV/c

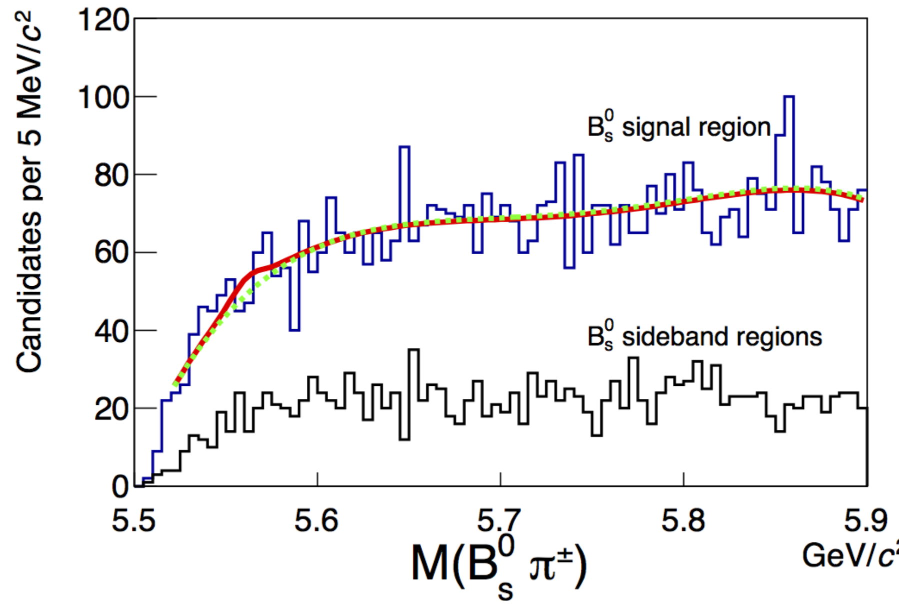




$M(B_s^0\ \pi^\pm) = M(J/\psi\phi\pi^\pm) - M(J/\psi\phi) + M_{PDG}(B_s^0)$ - resolution 1.8 MeV/c^2

CDF search for X(5568)$\rightarrow B_s^0\pi^\pm$ with $B_s^0 \rightarrow J/\psi\ \phi$





Model using sidebands omitting range of $\pm\Gamma_{X(5568)}$ (21.6 MeV) around 5568 MeV
Parametrize bkg with polynomial and combine w/ X(5568) signal shape to fit data.

Fit yields 36 ± 30 events.

It results in $\rho(X(5568)/B_s) = 2.3 \pm 1.9\ (stat) \pm 0.9\ (syst)\ \%$

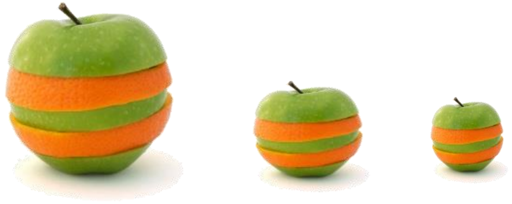
CDF searched for X(5568), as did not see signal, set upper limit:
ρ (X(5568) / Bs) < 6.7% at 95% *CL.*

World Comparison

Analysis	Production ratio (B_s / X(5568))	Reference
D0 ($J/\psi\ \phi$)	$8.6 \pm 1.9 \pm 1.4\%$	PRL 117,022003(2016)
D0 ($\mu\ D_s$)	$7.3^{+2.8}_{-2.4}{}^{+0.6}_{-1.7}\%$	PRD 97, 092004 (2018)
LHCb	< 2.4% ($p_T(B_s^0) > 10$ GeV)	PRL 117,152003 (2016)
CMS	< 1.1% ($p_T(B_s^0) > 10$ GeV)	PRL 120, 202005 (2018)
ATLAS	< 1.5% ($p_T(B_s^0) > 10$ GeV)	PRL 120, 202007 (2018)
CDF	< 6.7% ($2.3 \pm 1.9 \pm 0.9\%$)	PRL 120, 202006 (2018)

LHC experiments do not confirm X(5568), CM energy is rather different.

CDF result has 2 sigma tension with D0 result.



Different kinematic ranges make “apples-to-apples” comparison difficult.

Conclusions

- **X(5568)** $\rightarrow$ **$B_s^0\pi^{\pm}$** state observed by D0 in hadronic B_s^0 decay is seen also in semileptonic B_s^0 channel. Signal parameters obtained by D0 in these two channels are in good agreement.

- CDF searched for **X(5568)**, as did not see signal, set upper limit on production ratio **<6.7% at 95% *CL.*** Corresponding mean value is equal to **2.3$\pm$1.9 (stat)$\pm$0.9(syst)%,** that has about 2σ tension with D0 result.

- LHC experiments do not see **X(5568)** with upper limits about (1-2)%. However kinematic conditions on LHC are rather different from Tevatron.

Bob Hirosky slide, Moriond QCD, 2018

Tevatron Comparison

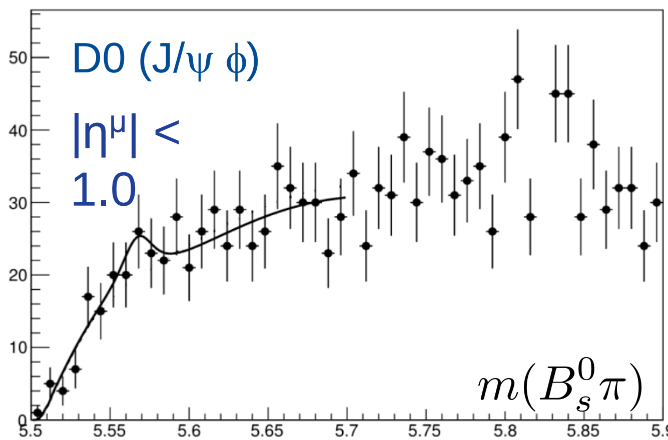
	Analysis	$f_{Bs/X(5568)}$	Ref.
First evidence	D0 ($J/\psi\ \phi$)	$8.6 \pm 1.9 \pm 1.4\%$	PRL 117,022003(2016)
Confirmation	D0 ($\mu\ D_s$)	$7.3^{+2.8}_{-2.4}{}^{+0.6}_{-1.7}\%$	arXiv:1712.10176
Limit set	CDF ($J/\psi\ \phi$)	$< 6.7\%$ ($2.3 \pm 1.9 \pm 0.9\%$)	arXiv:1712.09620

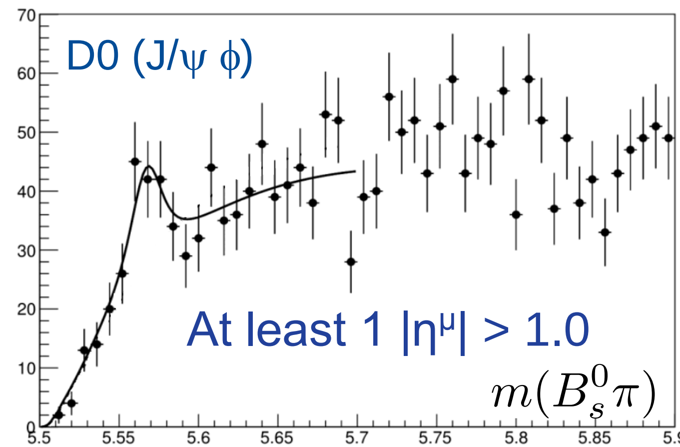
μ acceptance:

CDF $|\eta^{\mu}| < 1.0$

D0 $|\eta^{\mu}| < 2.0$

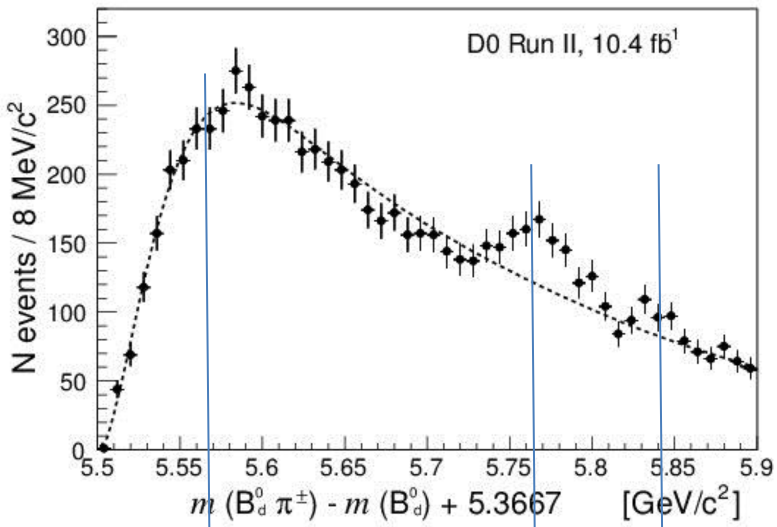
Apply same boost cut as in CDF data $p_T(B_s^0) > 10$ GeV





D0 observes signal enhancement for 1 or both muons having $|\eta^{\mu}| > 1.0$, where CDF analysis has no acceptance.

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

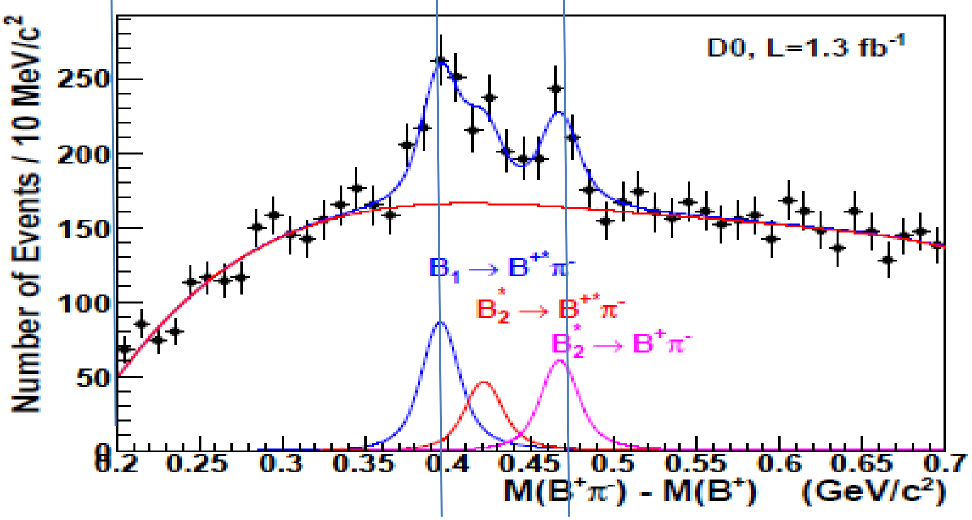


$B_d^0 \pi^+$; $B_d^0 \rightarrow J/\psi K^{*0}$;

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

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

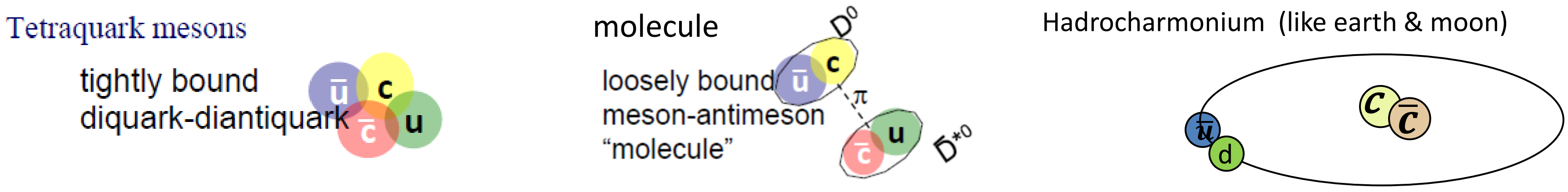
Systematic uncertainties on combined fit of decay modes

Source	Sample	mass, MeV/c^2	width, MeV/c^2	event yields, events	
				hadronic	semileptonic
		No Cone Cut			
(i) Background shape description	Both	$+1.1$; -1.9	$+1.4$; -5.1	$+7.6$; -32.8	$+8.4$; -37.1
(ii) SL background reweighting	Semileptonic	$+0.1$; -0.0	$+0.1$; -0.3	$+1.8$; -1.1	$+2.0$; -1.4
(iii) Hadronic MC samples	Hadronic	$+0.3$; -0.0	$+1.1$; -0.0	$+7.2$; -0.0	$+7.9$; -0.0
(iv) Hadronic Sidebands	Hadronic	$+0.3$; -0.1	$+0.2$; -0.6	$+4.5$; -3.7	$+4.9$; -4.2
(v) SL MC/Data ratio	Not Applicable	— ; —	— ; —	— ; —	— ; —
(v) Hadronic MC/Data ratio	Hadronic	$+0.1$; -0.0	$+0.5$; -0.0	$+7.4$; -0.1	$+8.1$; -0.2
(vii) B_s^0 mass scale, MC and data	Both	$+0.1$; -0.1	$+0.9$; -0.2	$+5.1$; -0.0	$+5.6$; -0.0
(viii) Detector resolution	Both	$+0.1$; -0.2	$+1.6$; -3.9	$+1.5$; -3.5	$+1.6$; -4.0
(ix) Missing neutrino effect	Semileptonic	$+0.2$; -0.1	$+0.1$; -0.1	$+0.4$; -0.0	$+0.1$; -0.3
(x) P-wave Breit-Wigner	Both	$+0.0$; -0.6	$+3.3$; -0.0	$+10.7$; -0.0	$+11.8$; -0.0
(xi) Mass offset	Both	$+0.4$; -0.4	$+0.2$; -0.2	$+0.0$; -0.0	$+0.0$; -0.1
(xii) Production fraction	Both	$+0.0$; -0.0	$+0.1$; -0.1	$+0.8$; -0.8	$+3.5$; -3.6
Total		$+1.3$; -2.0	$+4.2$; -6.5	$+18.2$; -33.2	$+20.3$; -37.8

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):

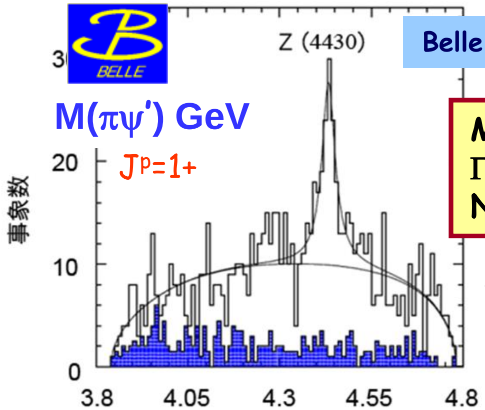


Observed with high stat significance four-quark states: **Z(4430)$^+$→ $\Psi'\pi^+$, X(4140)→ J/ψ ϕ, Z_b(10610)$^+$→ $\Upsilon\pi^+$, Z_b(10650)$^+$→$\Upsilon\pi^+$**, not well established **Z(4050)$^+$→$\chi_{c1}\pi^+$, Z(4250)$^+$→$\chi_{c1}\pi^+$.** Probably **X(3872)** is mixture of four- and two-quark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

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

Non-standard states observed with high significance

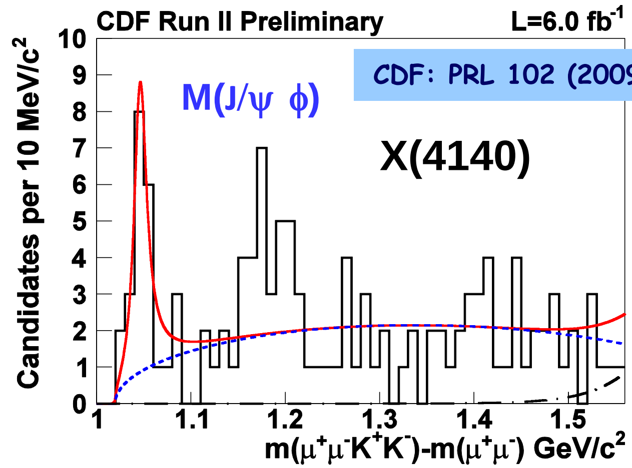
Belle: PRL 100 (2008) 142001

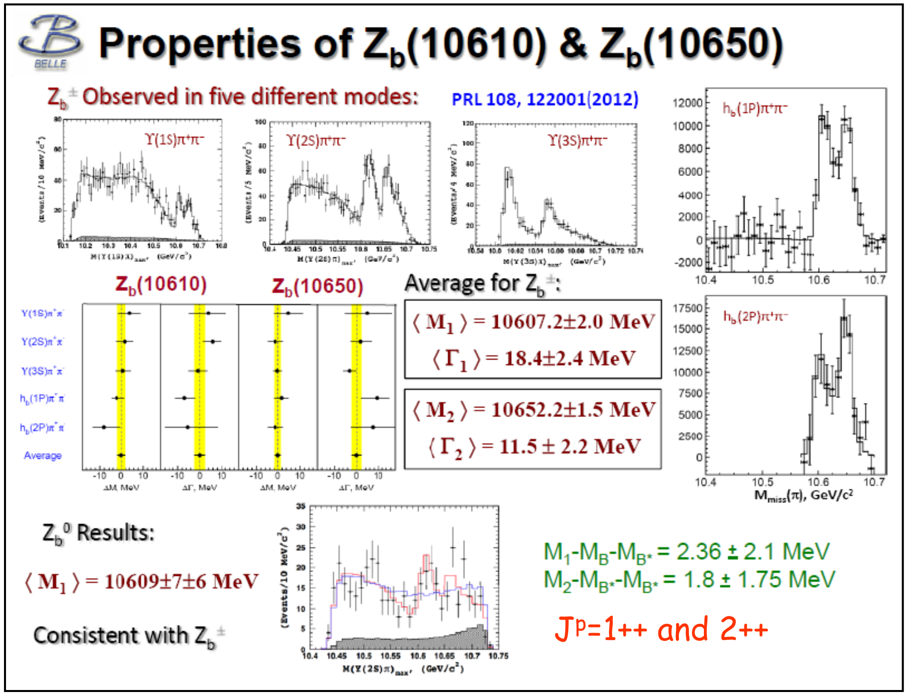


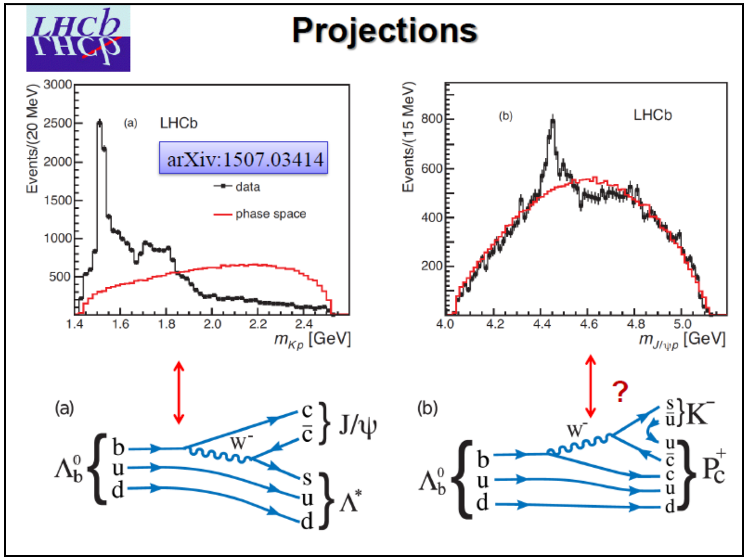
$M = 4433 \pm 4 \pm 2$ MeV
$\Gamma_{tot} = 45\ ^{+18}_{-13}\ ^{+30}_{-13}$ MeV
Nsig =121 ± 30 evts

Sign = 6.1s (no syst)

CDF: PRL 102 (2009) 242002

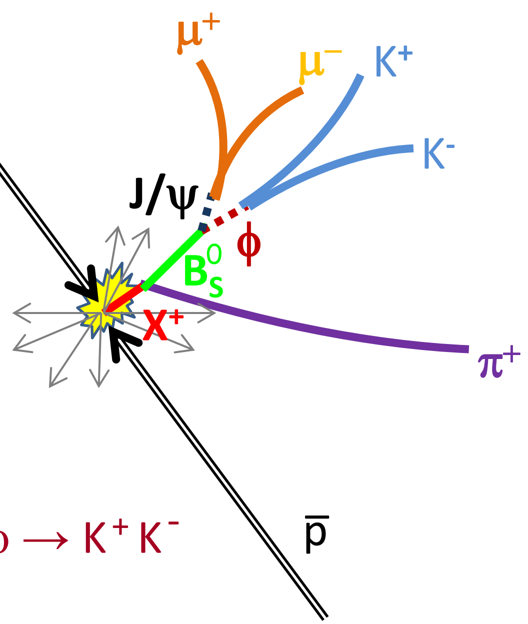






Observation of new $B_s^0\pi^\pm$ state

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



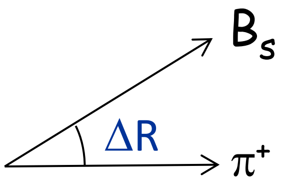
$B_s\pi^+$ system: 4 different quark flavors $\bar{b}s\bar{d}u$

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

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

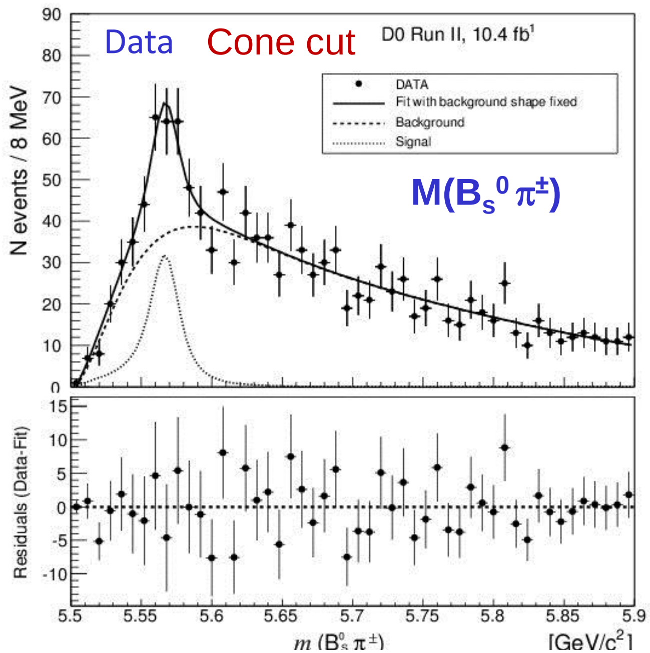
Selections: basic B_s^0 requirements + π^+ from $p\bar{p}$ interaction vertex

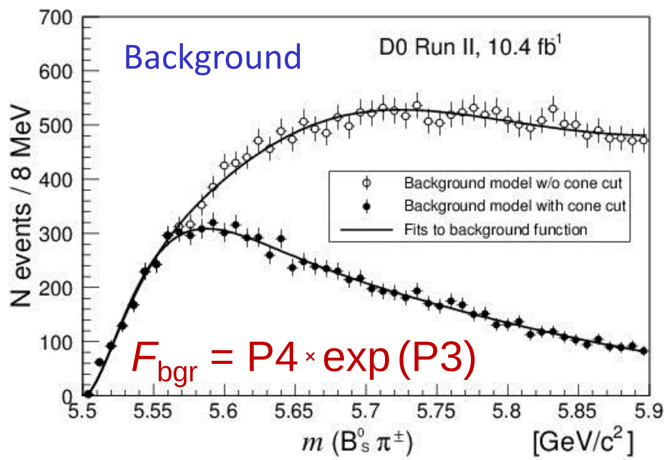
$\Delta R = \sqrt{[\phi(B_s) - \phi(\pi)]^2 + [\eta(B_s) - \eta(\pi)]^2} < 0.3$ - cone cut



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

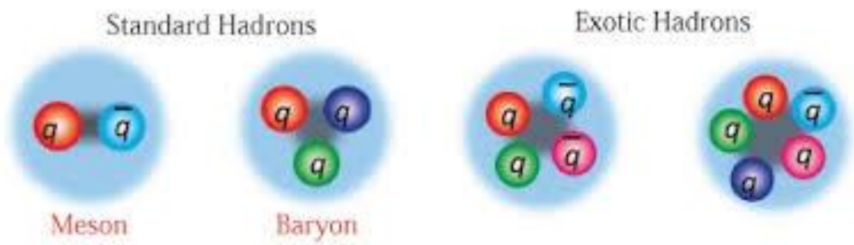
Γ = 21.9 $\pm$ 6.4 (stat) MeV/c^2

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

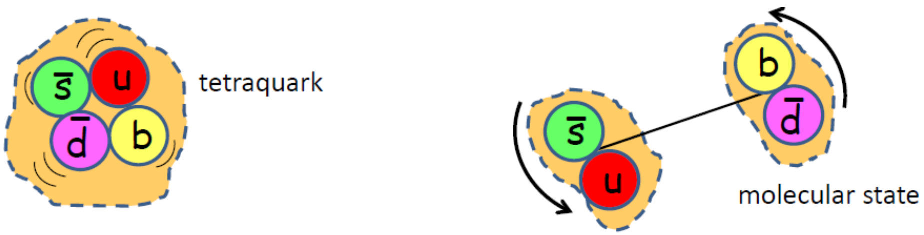
Multi-quark states



~20 multi-quark states were observed since 2003 with high 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).