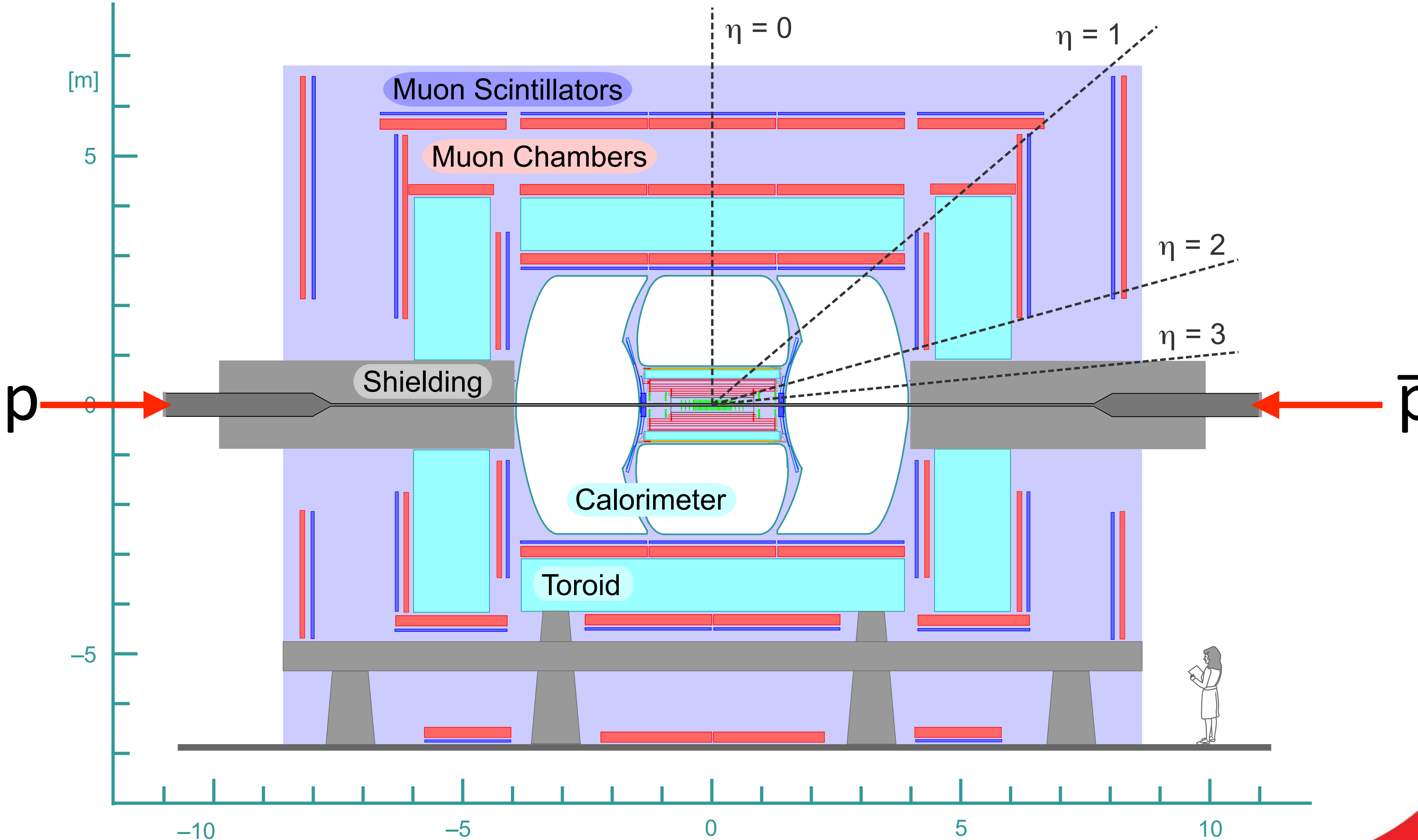
Inclusive Production of X(4140) and Observation of a new $B_s\pi^\pm$ state

Iain Bertram, Lancaster University
for the D0 Collaboration
DIS 2016 - 14 April 2016

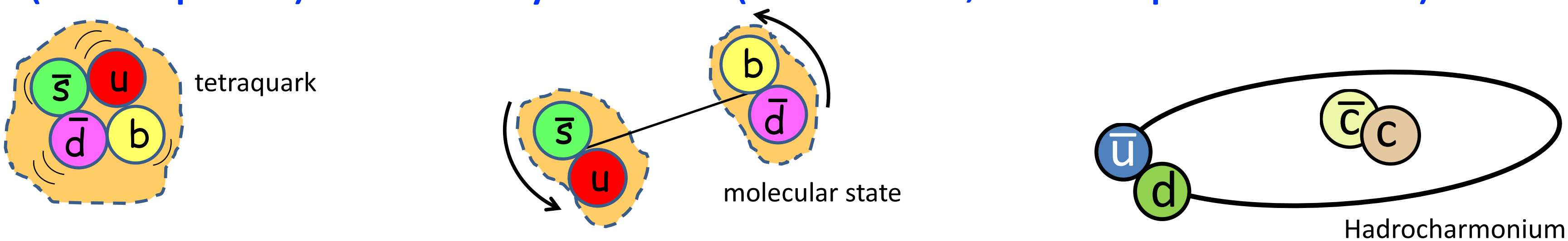
The D0 Detector

- Multi-purpose, high acceptance, well understood detector. Excellent muon id and acceptance. $\int \mathscr{L} dt \sim 10\ \mathrm{fb}^{-1}$



"Four" quark states

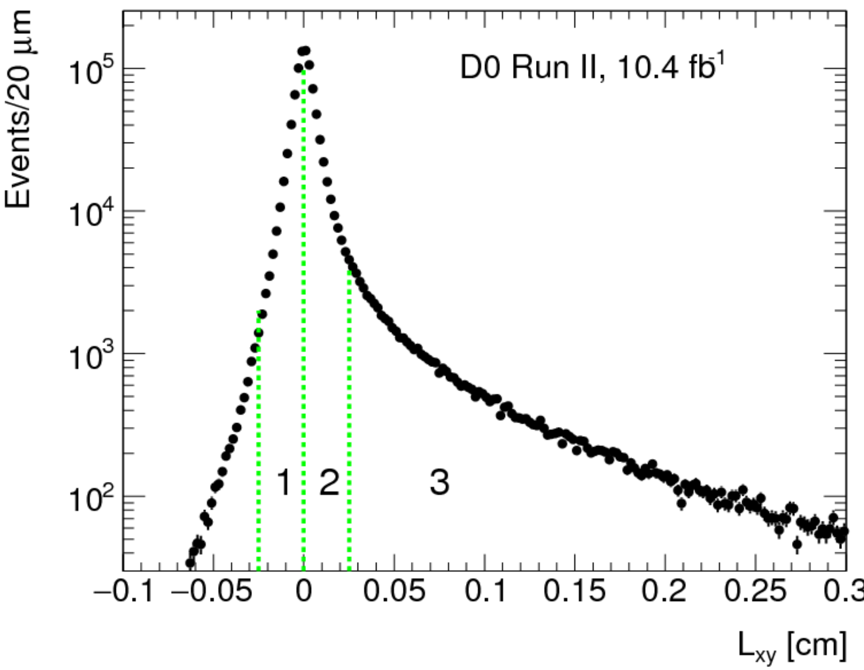
- Four quark states can be distinguished from regular mesons by comparing the mass, width, charge, other quantum numbers, production and decay modes with predictions.
- Exotic four-quark states can be described as tightly bound (tetraquark) or loosely bound (molecule, hadroquarkonium):



- Observed four-quark states (high statistical significance): $Z(4430)^+ \rightarrow \psi'\pi^+$, $X(4140) \rightarrow J/\psi\phi$, $Z_b(10610)^+ \rightarrow \Upsilon\pi^+$, $Z_b(10650)^+ \rightarrow \Upsilon\pi^+$.
- Not well established: $Z(4050)^+ \rightarrow \chi_{c1}\pi^+$, $Z(4250)^+ \rightarrow \chi_{c1}\pi^+$.
- X(3872) is probably a mixture of two- and four-quark states.
- All of these states can be interpreted as molecules (their masses are close to the sum of two regular mesons).
- Also, pentaquarks $P_c(4450)^+ \rightarrow J/\psi p$, $P_c(4380)^+ \rightarrow J/\psi p$

Inclusive Production of X(4140)

- X(4140) was first observed by CDF in 2009 in the decay $B^+ \rightarrow X(4140)K^+ \rightarrow J/\psi\phi K^+$
  - ✓ D0 and CMS confirmed the observation
  - ✗ LHCb was unable to confirm and disagrees at 2.4σ with CDF (Phys. Rev. D 85, 091103(R) (2012))
  - Observed in decays of B^+
- D0: First inclusive X(4140) measurement
  Phys. Rev. Lett. 115, 232001 (2015), & arXiv:1508.07846
- $J/\psi\phi$ is selected in three L_{xy} intervals and in two mass intervals:
  - X(4140): $M(J/\psi\phi) < 4.36$ GeV
  - B_s: $4.8 < M(J/\psi\phi) < 5.7$ GeV
- Number of B_s and X(4140) extracted using mass fits.

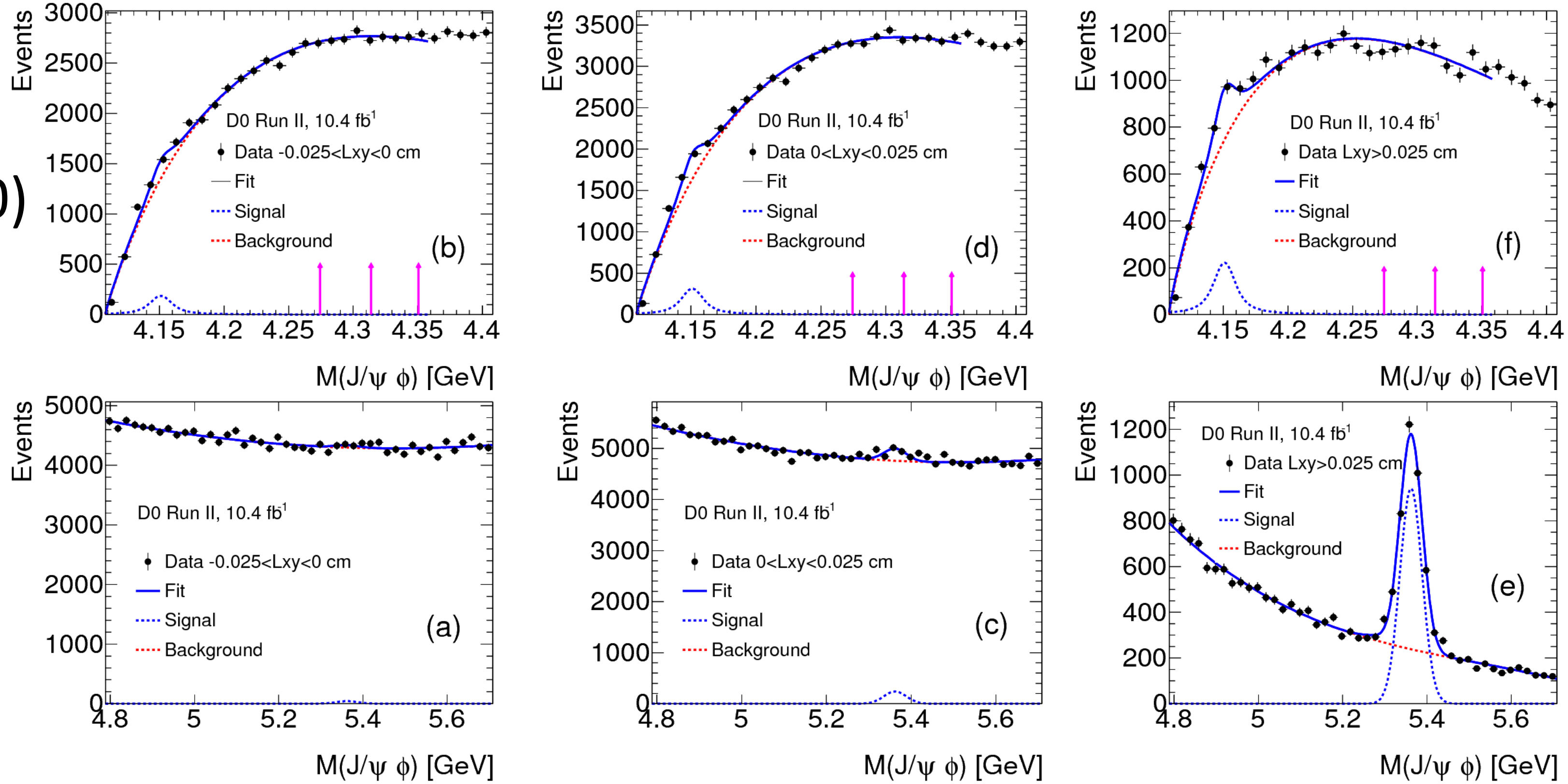


Inclusive Production of X(4140)

-250 < L_{xy} < 0 μm | 0 < L_{xy} < 250 μm | L_{xy} > 250 μm

X(4140)

B_s



Parent	$-0.025 < L_{xy} < 0$ cm	$0 < L_{xy} < 0.025$ cm	$L_{xy} > 0.025$ cm	Sum
B_s^0	191 ± 143	804 ± 169	3166 ± 81	4161 ± 236
$X(4140)$	511 ± 120	837 ± 135	616 ± 170	1964 ± 248
$X(4140)$ non-prompt	37 ± 26	156 ± 54	616 ± 170	809 ± 175
$X(4140)$ prompt	474 ± 123	681 ± 149	$\equiv 0$	1155 ± 193

Inclusive Production of X(4140)

TABLE III: Summary of $X(4140)$ measurements.

Experiment	Process	Mass (MeV)	Width (MeV)
CDF [2]	$B^+ \to J/\psi\phi K^+$	$4143.0 \pm 2.9 \pm 1.2$	$11.7^{+8.3}_{-5.0} \pm 3.7$
CMS [4]	$B^+ \to J/\psi\phi K^+$	$4148.0 \pm 2.4 \pm 6.3$	$28^{+15}_{-11} \pm 19$
D0 [5]	$B^+ \to J/\psi\phi K^+$	$4159.0 \pm 4.3 \pm 6.6$	$19.9 \pm 12.6^{+3.0}_{-8.0}$
D0 (this work)	$\overline{p}p \to J/\psi\phi + \text{anything}$	$4152.5 \pm 1.7^{+6.2}_{-5.4}$	$16.3 \pm 5.6 \pm 11.4$

- The non-prompt production rate of X(4140) relative to B_s^0 is

$$R = 0.19 \pm 0.05\,(\text{stat}) \pm 0.07\,(\text{syst})$$

- The fraction originating from b hadron decays

$$f_b = 0.39 \pm 0.07\,(\text{stat}) \pm 0.10\,(\text{syst})$$

which implies prompt production of the X(4140).

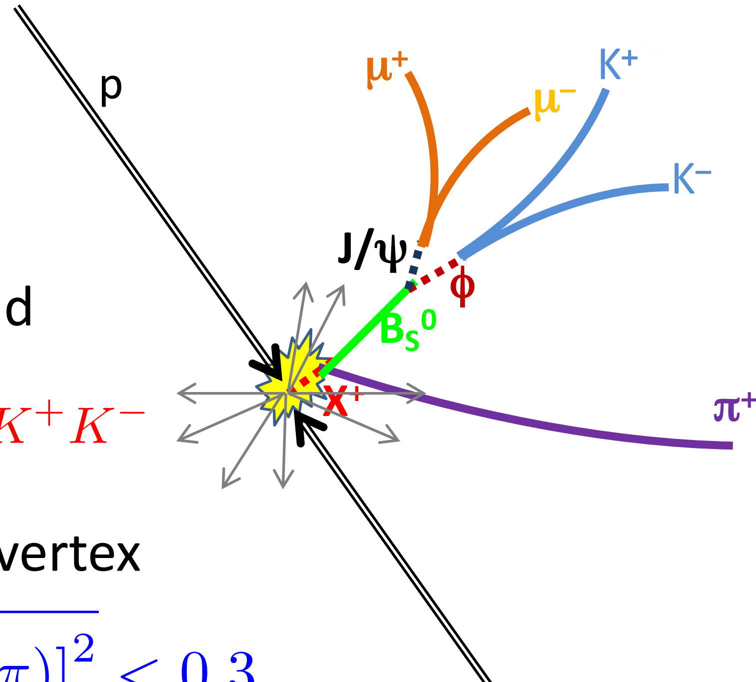
- For $L_{xy} > 250$ µm the estimated number of X(4140) from B^+ decays is 130 ± 60 and we observe a total of 616 ± 170 implying that the b-hadron decays are contributing to X(4140) production

Observation of a new $B_s\pi^{\pm}$ 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 contains 4 quark flavours
  $\bar{b}s\bar{d}u$
- Study invariant mass up to BK mass threshold

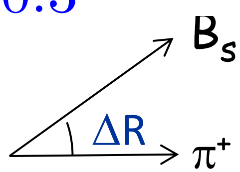
$$X^+ \to B_s^0\pi^+;\, B_s^0 \to J/\psi\phi;\, J/\psi\phi \to \mu^+\mu^-;\, \phi \to K^+K^-$$



- Selections: Standard B_s plus π from primary vertex

$$\Delta R = \sqrt{[\phi(B_s^0) - \phi(\pi)]^2 + [\eta(B_s^0) - \eta(\pi)]^2} < 0.3$$

$$p_T(B_s^0) > 10 \text{ GeV}$$

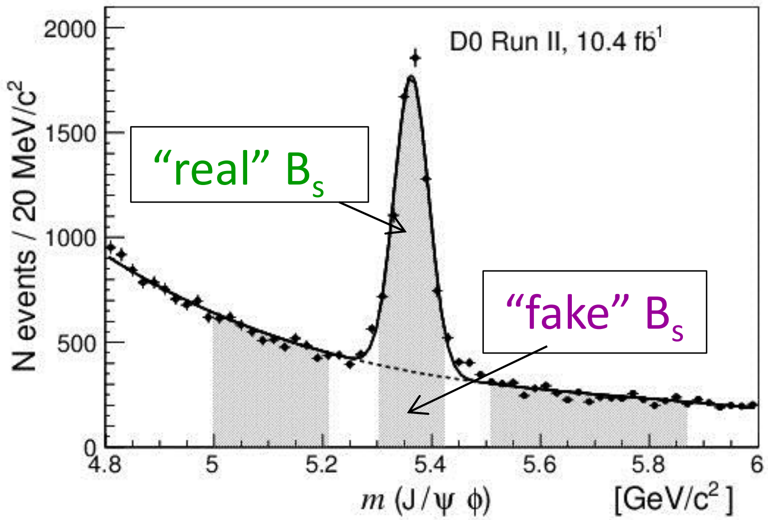


- To improve mass resolution we measure:

$$m(B_s^0\pi^{\pm}) = m(J/\psi\phi\pi^{\pm}) - m(J/\psi\phi\pi) + m(B_s^0)$$

★ We can also have $B_s^*\pi$ which shifts the mass of the resonance by "$m(B_s^*)$ - $m(B_s)$" and does not effect the width

Modelling Background



$M(B_s) = 5363.3 \pm 0.6$ MeV/c^2

$\sigma(B_s) = 31.6 \pm 0.6$ MeV/c^2

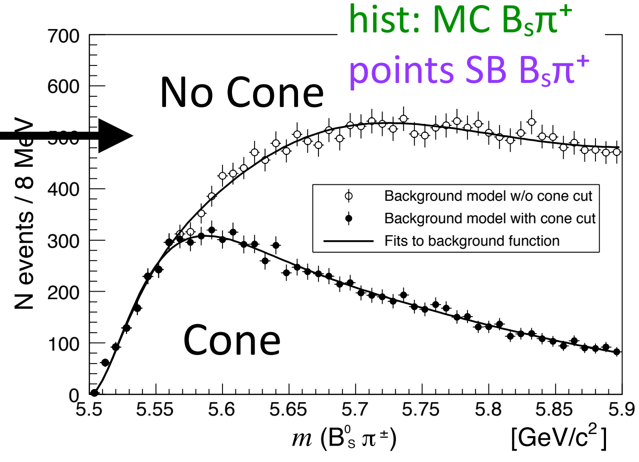
$N(B_s) = 5582 \pm 100$

$M(B_s)$: $[5.303-5.423]$ GeV/c^2 (about ±2σ)

$$\frac{N_{real}}{N_{real}+N_{false}} = (70.9 \pm 0.6)\%$$

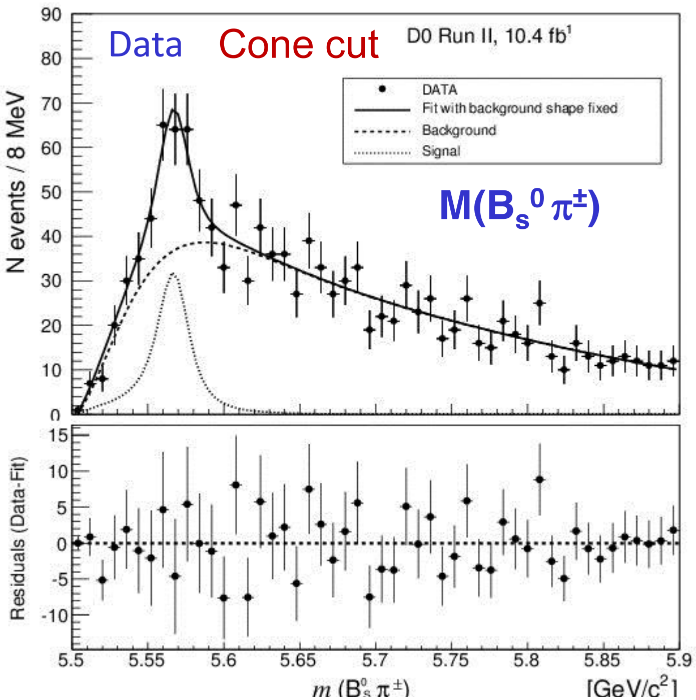
"Real" B_s^0 are modeled using PYTHIA MC of B_s^0 production (random combination of B_s^0 and $\pi^\pm$).
"Fake" B_s^0 are modeled by sidebands: $5.0 < M(B_s) < 5.21$ GeV/c^2 and $5.51 < M(B_s) < 5.87$ GeV/c^2.

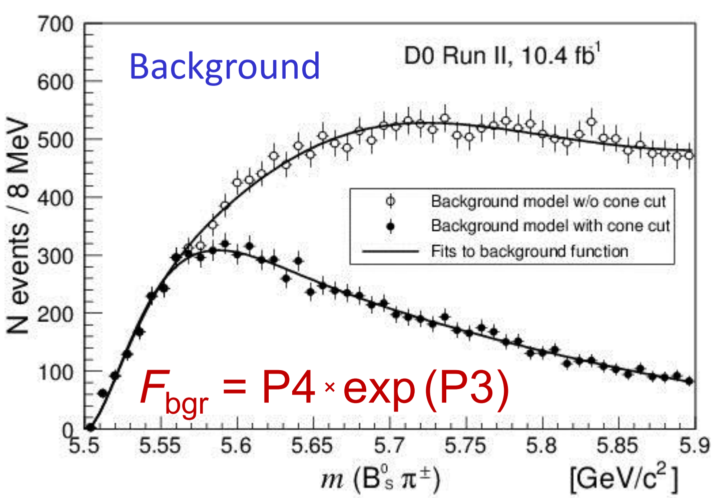
Shapes of $B_s\pi^+$ backgrounds are similar for "real" and "fake" B_s models (MC & Sidebands).



These two background model samples are mixed in measured proportion 70.9% / 29.1% to obtain full background model.

Signal Fit





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

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

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

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)

- Local significance = 6.6σ (obtained using Wilk's theorem)
- **Significance = 5.1σ** including look-elsewhere effect (LEE) and systematics

Production ratio of $X(5568)/B_s$

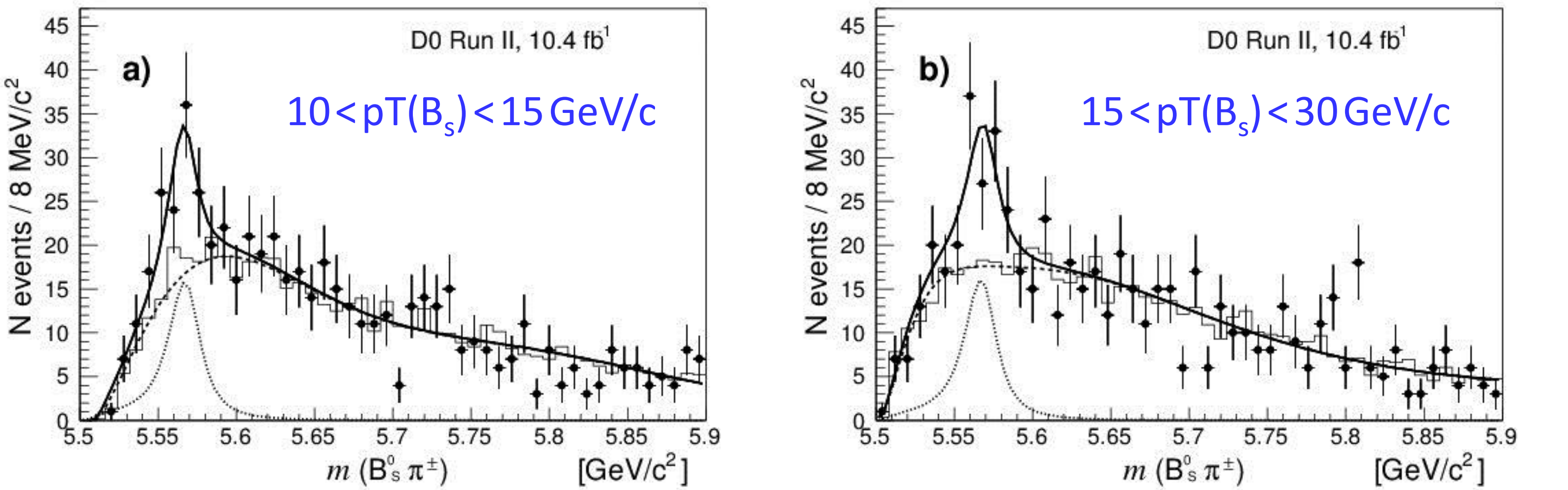


TABLE II: The $X_{bs}(5568)$ number of events, mass, and natural width, the number of reconstructed B^0_s mesons, the reconstruction efficiency of the soft pion $\epsilon(\pi^\pm)$, and the production ratio R ($X_{bs}(5568)/B^0_s$) for two $p_T(B^0_s)$ ranges.

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

Events	58.6 ± 16.7	67.5 ± 21.8

Averaging over $10 < pT(B_s^0) < 30$ GeV/c $R = (8.6 \pm 1.9 \pm 1.4)\%$

Within uncertainties production ratio R ($X(5568)^+ / B_s^0$) does not depend on $pT(B_s^0)$

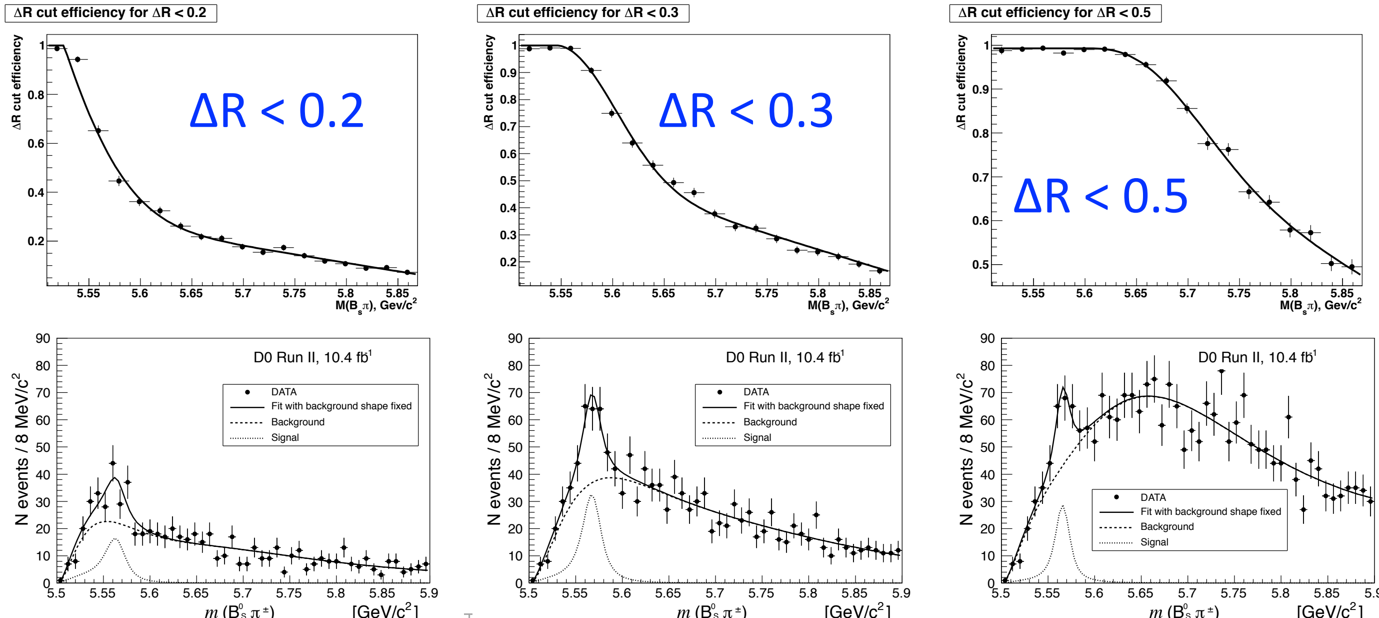
The mass of the X_{bs} remains consistent with change in background shape.

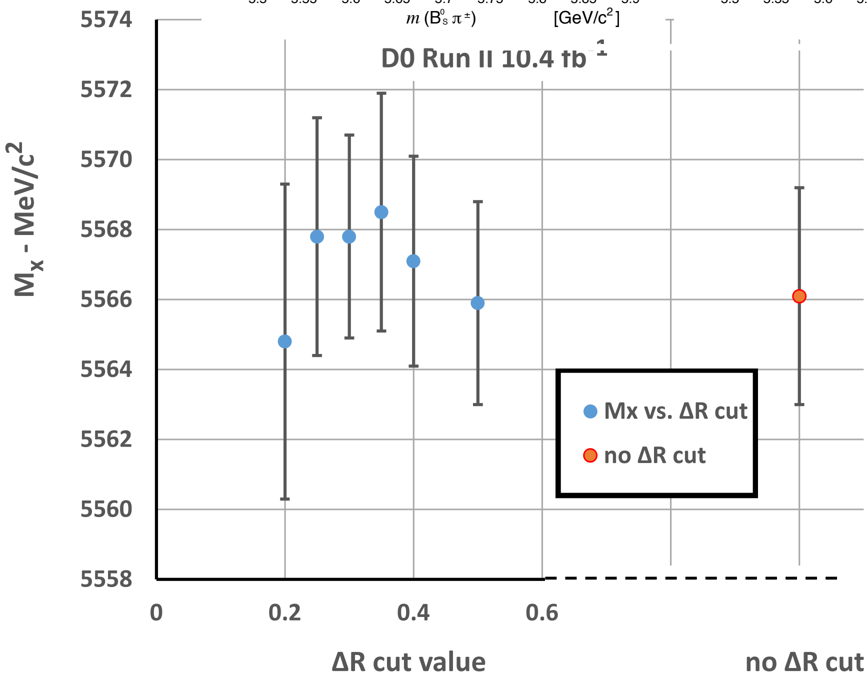
Checks

- subsamples with different pion charge;
- different angular and momentum intervals;
- different B_s vertex distance
- Use B_d instead of B_s
- changing background shape description
- mass distributions of $B_s K^{\pm}$ and $B_s p$
- mass distribution of $B_s\pi^+\pi^-$

All results are consistent within statistical uncertainties.

$B_s\pi$ Peak position vs. ΔR



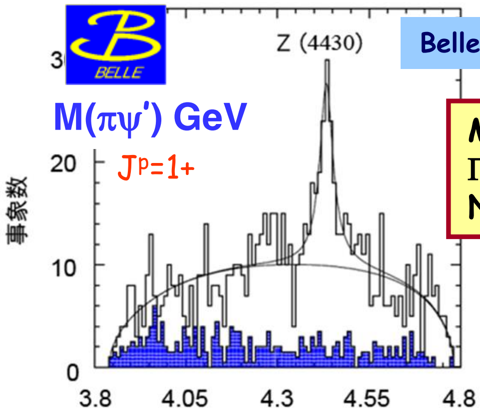


- The position of the peak does not depend on the ΔR cut

Conclusions

- Prompt production of X(4140) has been studied by D0.
  - The Fraction of X(4140) produced in the decays of b-hadrons is **f_b = 0.39 ± 0.07 (stat) ± 0.10 (syst)**.
  - The resulting mass and width (in the J/ψϕ mode) agree with the values measured by CDF&CMS.
- D0 has observed a resonant structure in the $B_s\pi^{\pm}$ system with a significance of 5.1 σ (including LEE effect and systematics).
  - The large difference between the mass of this state and the sum of the B_d and $K^{\pm}$ masses implies that X(5568) is unlikely to be a molecular state composed of loosely bound B_d and $K^{\pm}$ mesons.
  - We wait for the studies from all LHC experiments and from CDF.

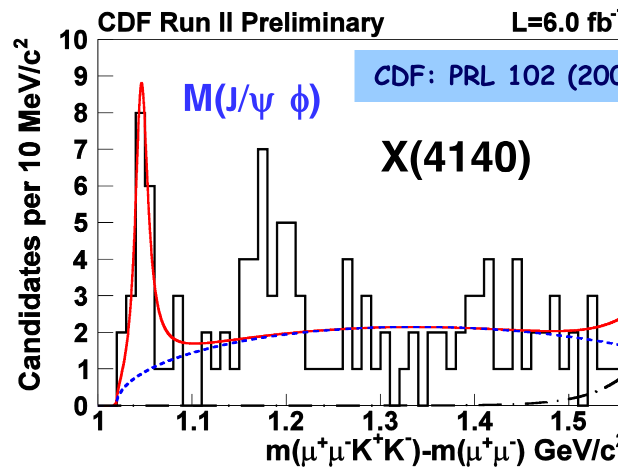
Non-standard states observed with high significance



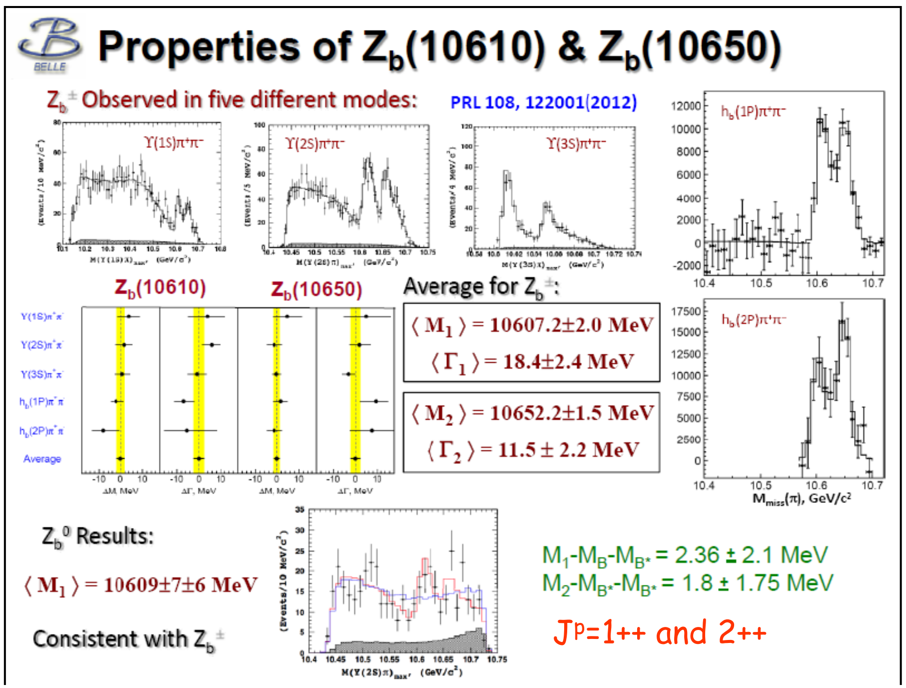
Belle: PRL 100 (2008) 142001

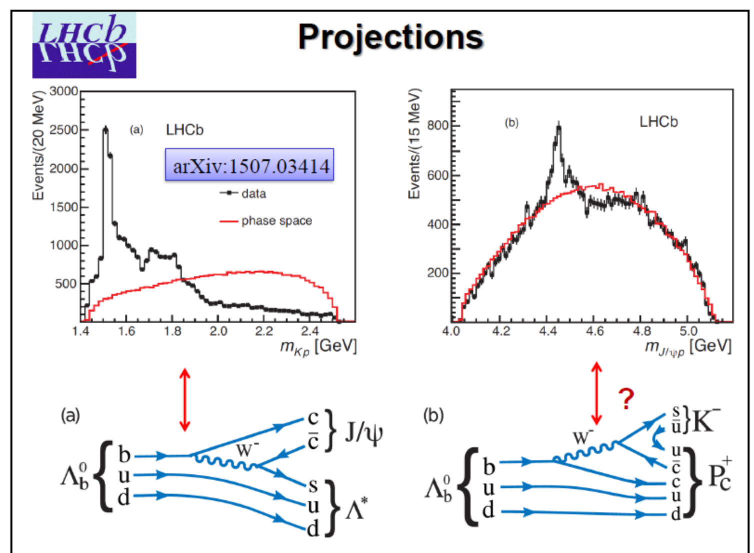
$M = 4433 \pm 4 \pm 2$ MeV
$\Gamma_{tot} = 45^{+18}_{-13}{}^{+30}_{-13}$ MeV
Nsig =121 ± 30 evts

Sign = 6.1s (no syst)



CDF: PRL 102 (2009) 242002





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

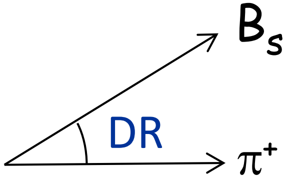
- $pT(\mu) > 1.5$ GeV/c, SMT > 0, at least one μ - matching
- $M(J/\psi)$: [2.92 – 3.25] GeV/c^2

- $pT(K) > 0.7$ GeV/c, SMT > 0 (SMT- Silicon Microstrip Tracker hits)
- $M(\phi)$: [1.012 – 1.03] GeV/c^2

- $M(B_s)$: [5.303 – 5.423] GeV/c^2
  $\chi^2(B_s) < 30$, Length B_s > 3 sigma

- $pT(\pi^+) > 0.5$ GeV/c, SMT > 1, $\chi^2(\pi\text{->}PV) < 16$,
  $|IP_{xy}(p)| < 0.02$ cm , $|IP_{3D}(p)| < 0.12$ cm

- $pT(B_s\pi^+) > 10$ GeV/c



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

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

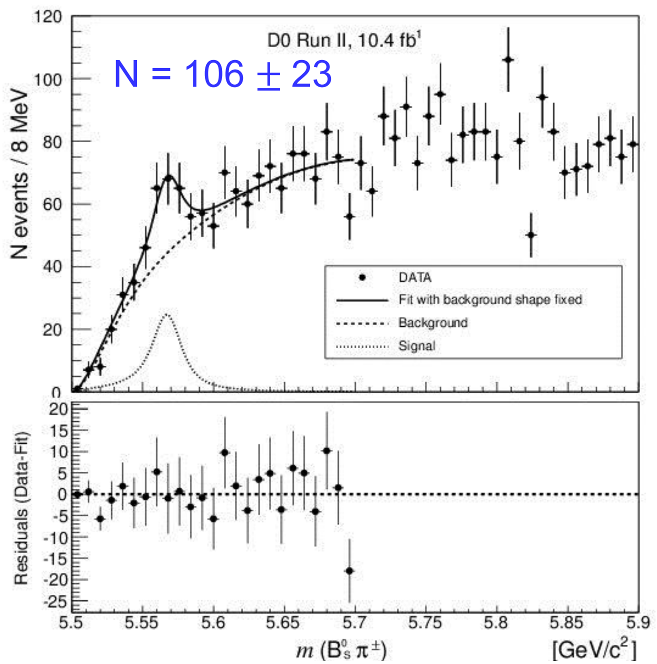
Systematics

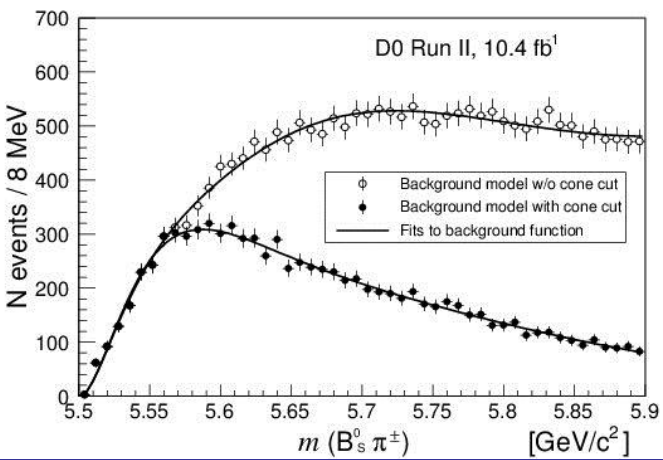
TABLE I: Systematic uncertainties for the observed $X(5568)$ state mass, natural width and event number.

Source	mass, MeV/c^2	width, MeV/c^2	rate, %
Background shape			
MC samples with soft or hard B_s^0	+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.
Others			
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 are slightly smaller than statistical errors.

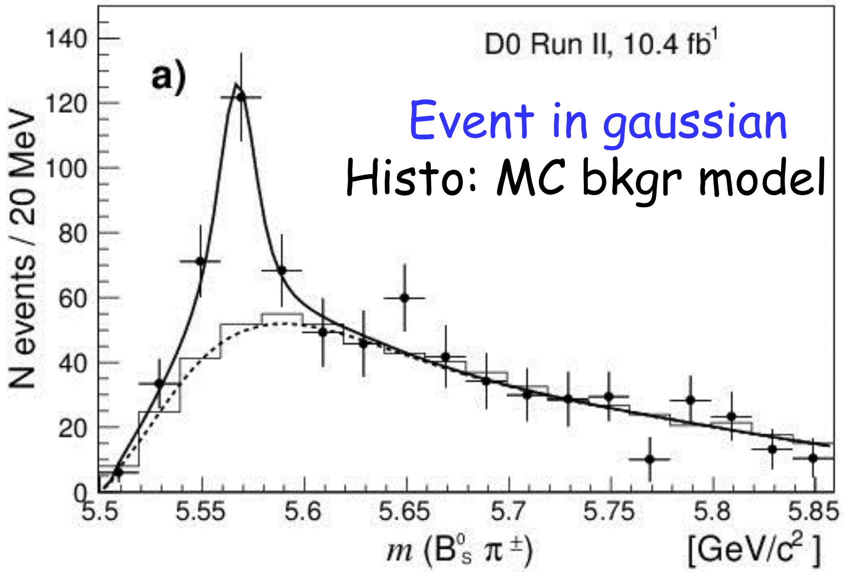
No cone cut: $B_s^0\pi^{\pm}$ state



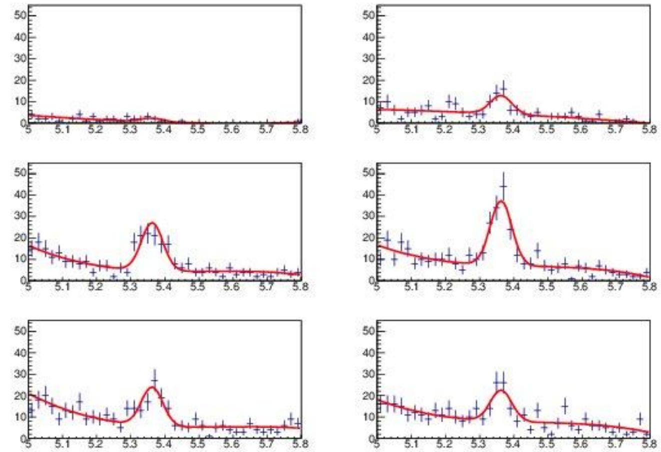


Mass and width are fixed to the values, obtained with cone cut.

Alternative signal extraction method



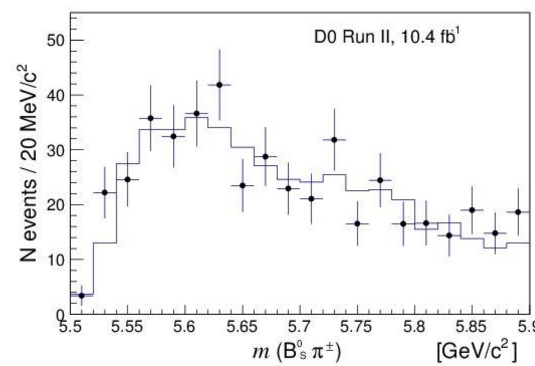
Fits in first six bins



We fit $M(B_s)$ in each $M(B_s\,p+)$ bin, using second order polinomial to model background and gaussian with fixed mass and width to model signal.

With this method (cone cut) we get 118 ± 22 events, comparing with 133 ± 31 using standard method.

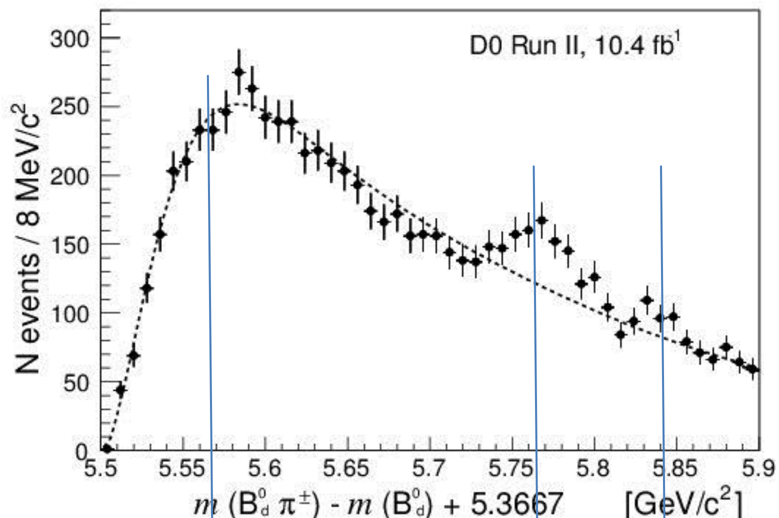
No signal for undergaussain events ("false" B_s), agreement with bkgr shape modeled from SB.



Events under gaussian

Histo: SB bkgr model

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

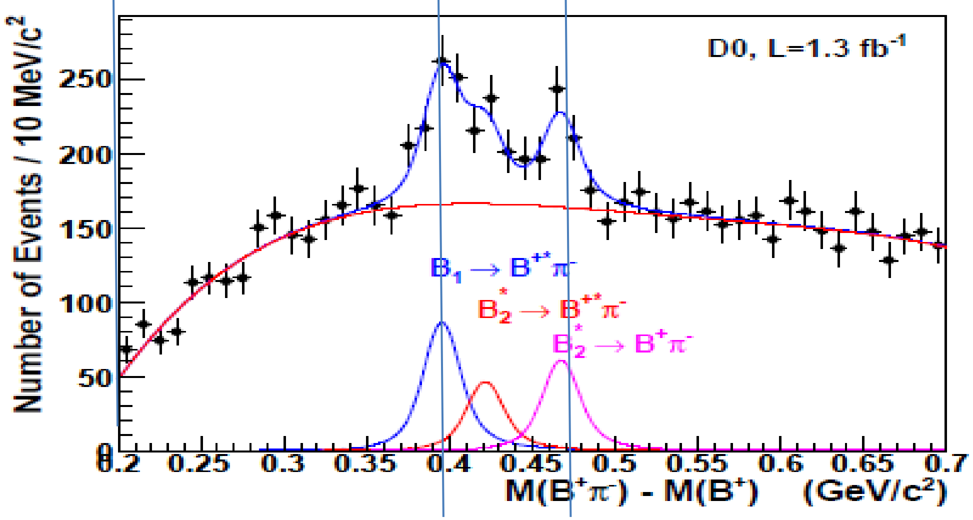


$B_d^0\ \pi^+$; $B_d^0 \rightarrow J/\psi\ K^{*0}$;

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

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

Background vs. ΔR

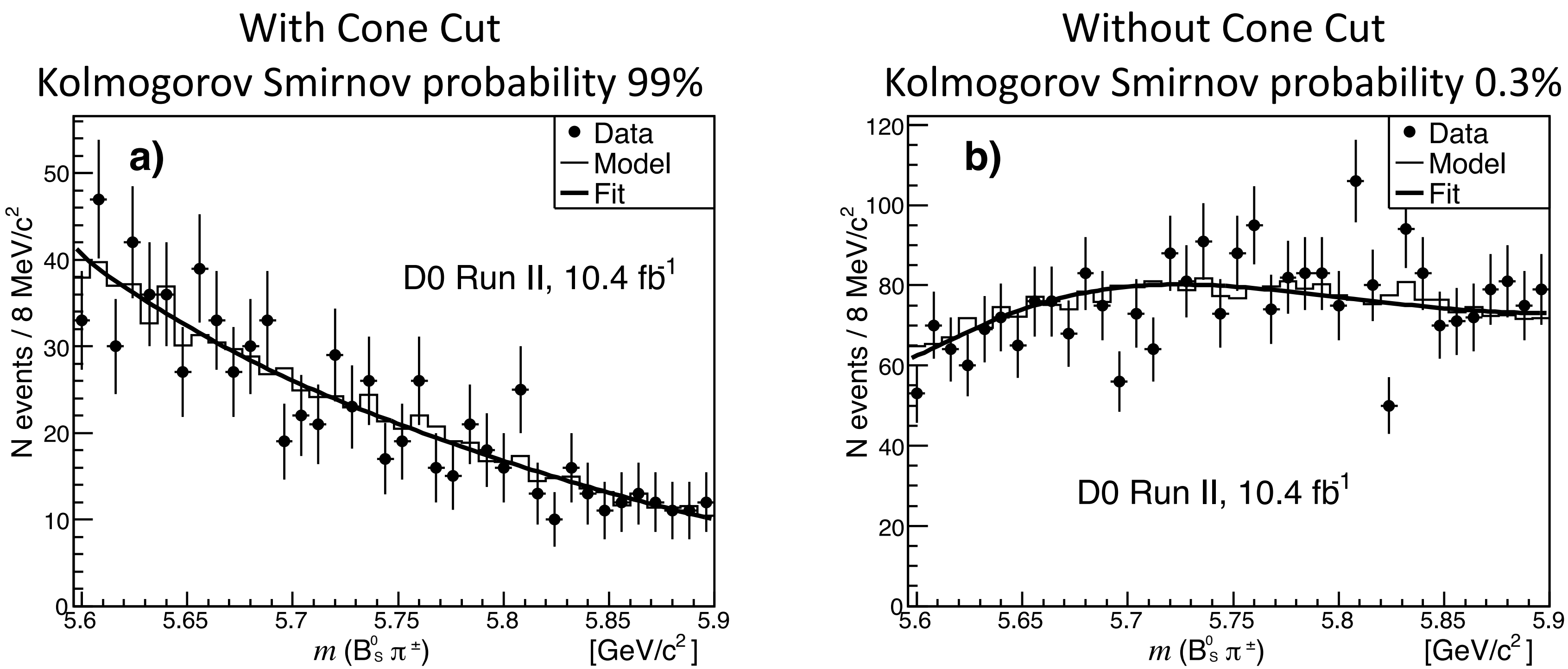


FIG. 4: Comparison of the shapes of the $m(B_s^0\pi^\pm)$ distributions of data and the background model in the range 5.6 – 5.9 GeV/c^2 above the $X(5568)$ (a) after applying the cone cut and (b) without the cone cut.