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Searches for exotic hadronic states at D0

Search for exotic baryons decaying to J/ψΛ pairs

Confirmation of X(5568) with semileptonic decays of the B_s

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for the D0 Collaboration
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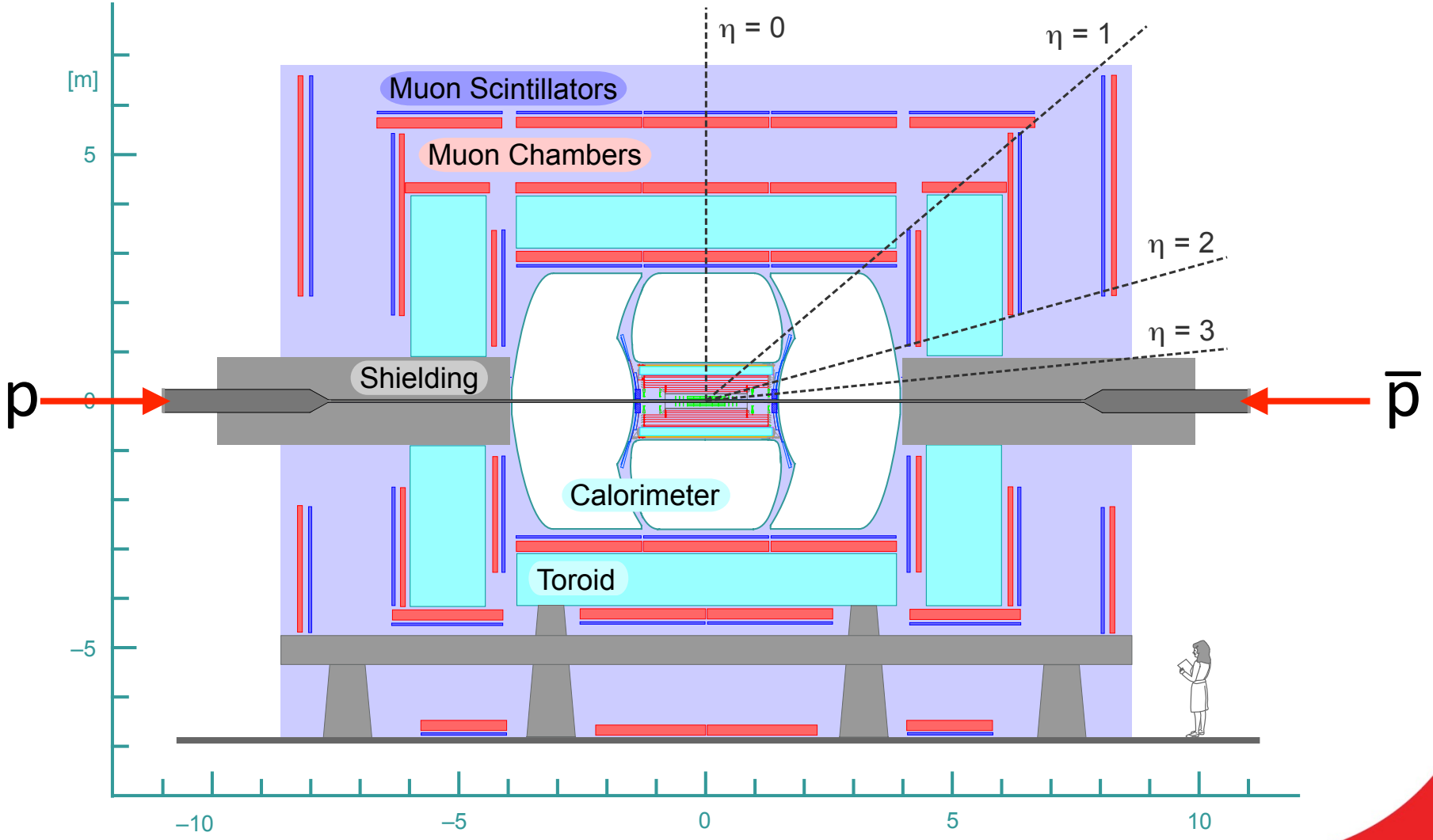
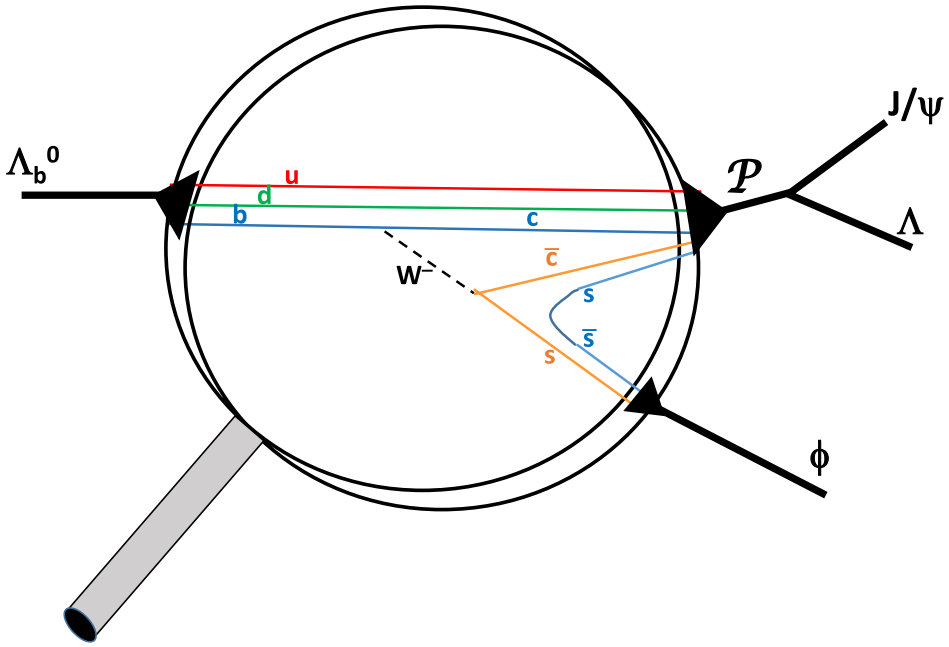
The D0 Detector

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



Search for exotic baryons decaying to J/ψΛ

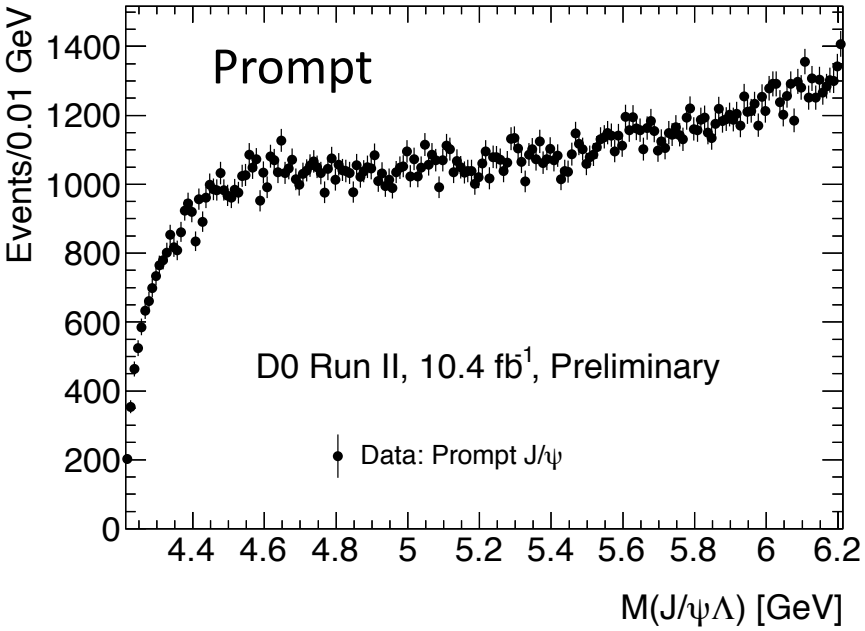
- LHCb observed two exotic baryon states (P^c) in in $\Lambda_b \rightarrow J/\psi p K^-$ at 4380 MeV/c^2 and 4450 MeV/c^2.
- Numerous states with the quark contents including a $\bar{c}c$ pair and three light quarks are expected to exist within 500 MeV of the threshold.
- Search in the M(J/ψ Λ), where $J/\psi \rightarrow \mu^+\mu^-$, $\Lambda \rightarrow p\pi^-$.

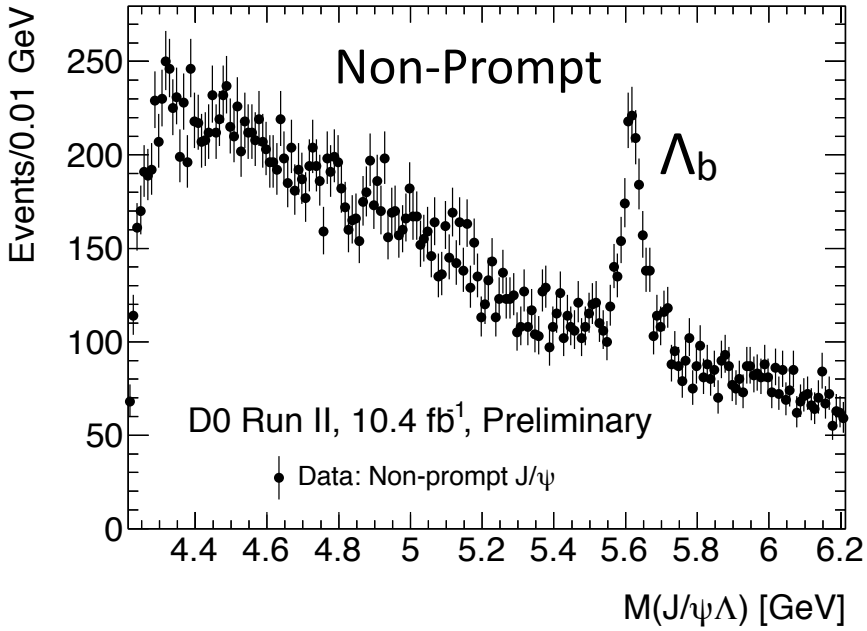


Event Reconstruction

- 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
- $p_T(p) > 0.15$ 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 exotic baryons decaying to J/ψΛ





- Search: concentrate on Non-prompt sample
  - no indication of signal in prompt sample.

Search for exotic baryons decaying to J/ψΛ

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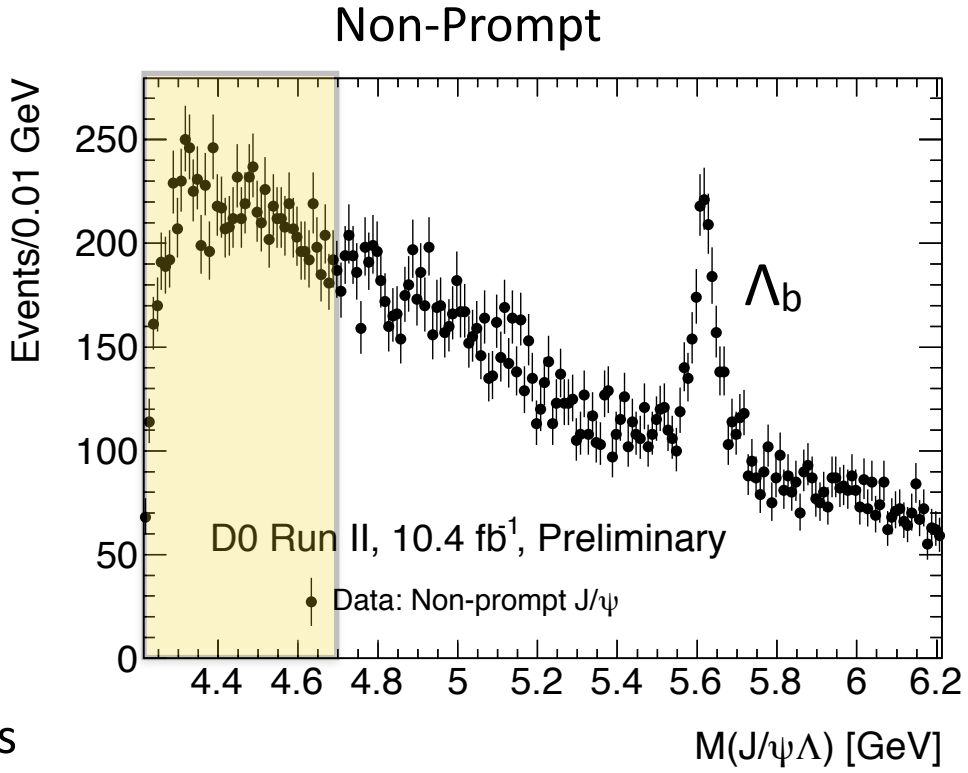
- **Search procedure**
- Binned maximum likelihood fits to the distribution of the J/ψ Λ invariant mass in the range from the J/ψ Λ threshold to 4.7 GeV/c^2.

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

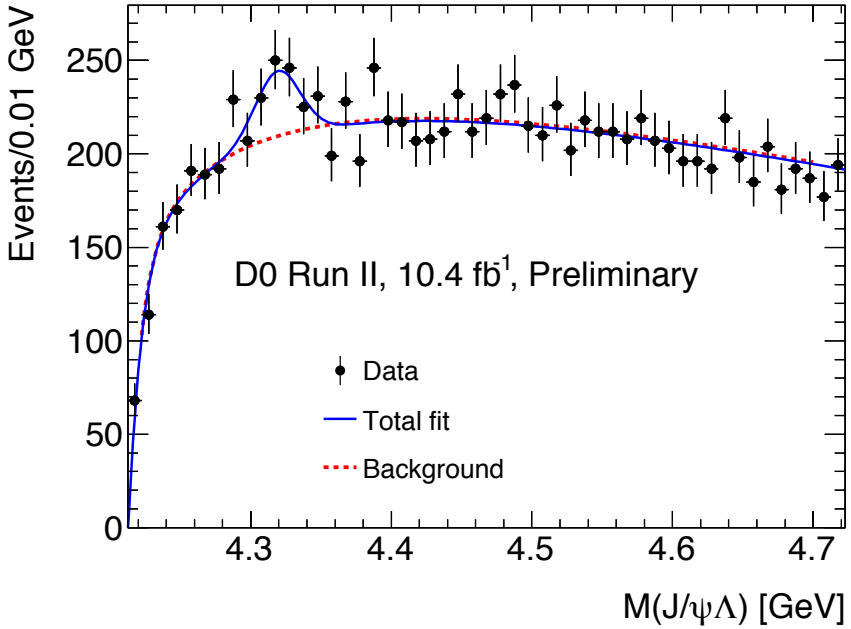


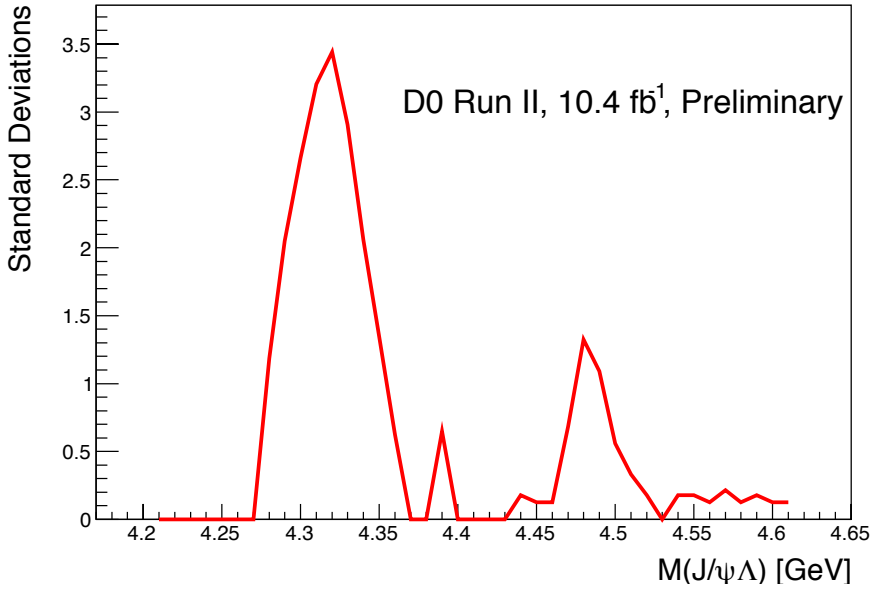
- $F_{sig}(M, M_X, \sigma_X)$ is a Gaussian with free mass and width.
- f_{bg} and f_{sig} are normalisation constants
- The background is a threshold function where M_{th} is the J/ψ Λ invariant mass threshold.

$$F_{\text{bg}} \propto M \left(\frac{M^2}{M_{\text{th}}^2}\right)^{c_1} \exp(c_2 M) \left[1 - \exp\left(\frac{M - M\text{th}}{c_3}\right)\right]$$

Search for exotic baryons decaying to J/ψΛ

- 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 is defined as $\sqrt{-2\ln\left(\mathcal{L}_0/\mathcal{L}_{\max}\right)}$.
- The highest local significance of 3.45σ occurs at M = 4.32 GeV/c2.
- If LEE is taken into account it leads to the global significance of 2.8σ.



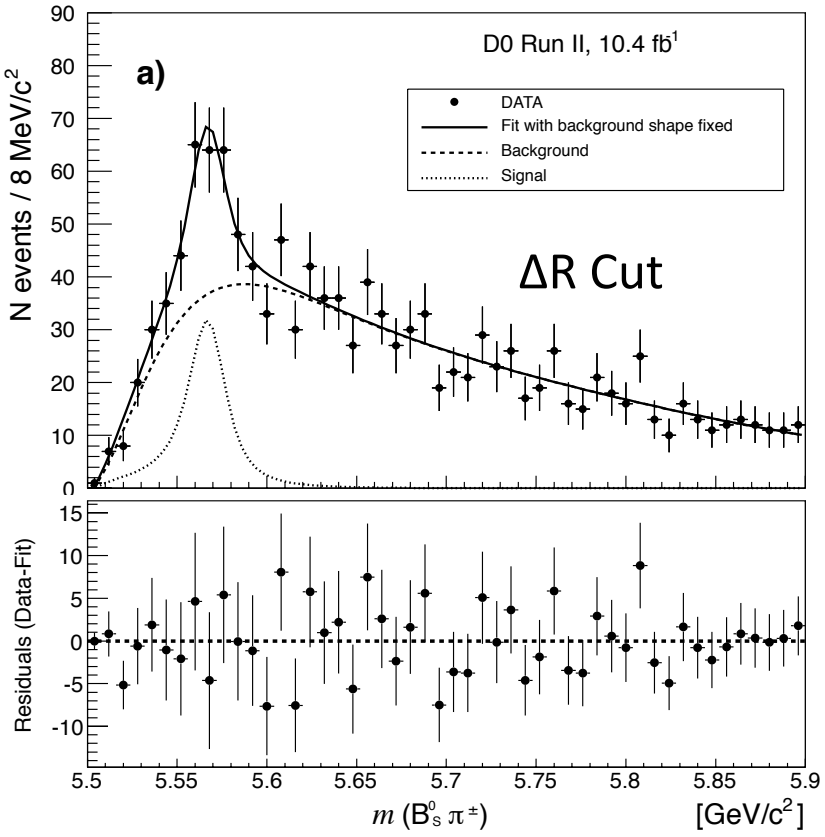


No evidence for new particles decaying to J/ψΛ

… but could point the way for other searches.

Previous Result: Evidence for X(5568), $B_s \rightarrow J/\psi\phi$

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

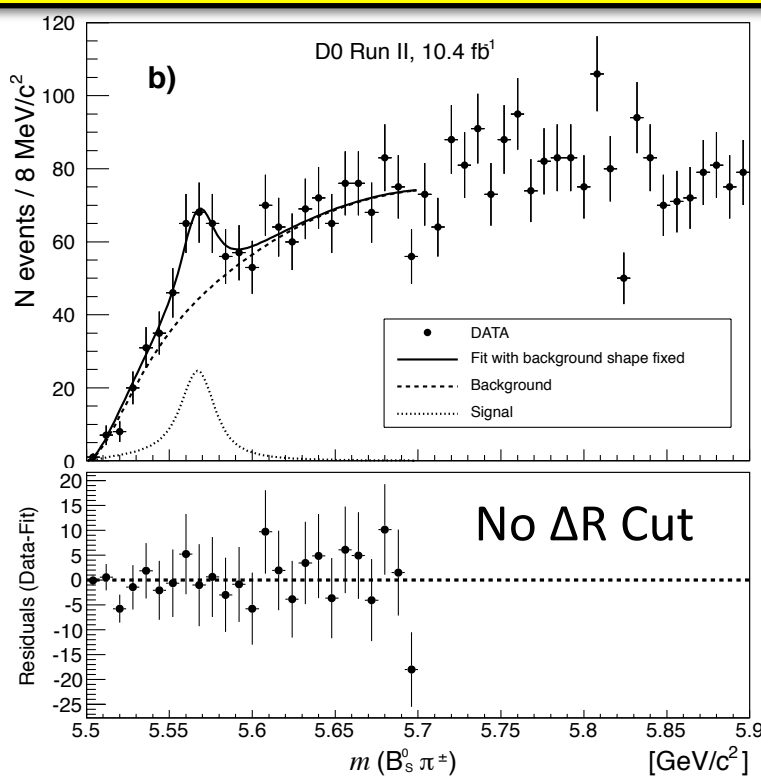


$$X(5568)$$

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

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

$$\rho = [8.6 \pm 1.9\,(\text{stat}) \pm 1.4\,(\text{syst})]\ \%$$



Statistical significance of signal (including systematics and LEE)

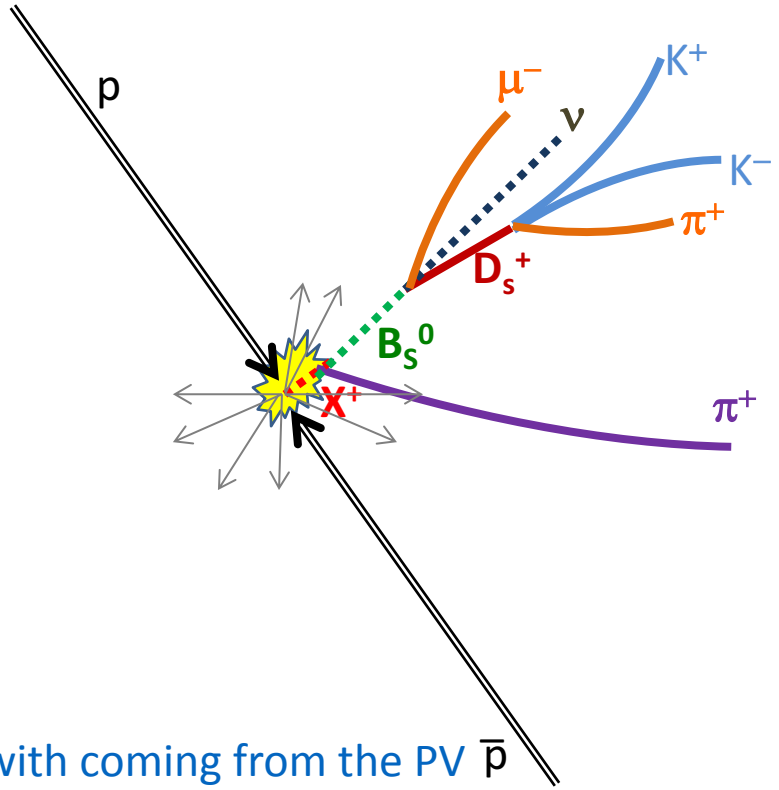
$$\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2} < 0.3$$

With ΔR Cut: 5.1 σ, Without ΔR Cut: 3.9 σ

Not seen at LHCb and CMS

Confirmation of X(5568) with semileptonic decays of the B_s

- Look to confirm X(5568) using additional channel
  - Optimise cuts to minimise effect of missing neutrino and reduce size of background.



$B_s \rightarrow D_s\mu\nu$ reconstruction:

Reconstruct $D_s \rightarrow \phi\pi$, $\phi \rightarrow K^+K^-$.

Require $1.92 < m(\phi\pi) < 2.02$ GeV.

Add a muon that forms a vertex with the D_s.

Require $4.5 < m(\mu D_s) < 5.4$ GeV

to minimise the effect of the missing neutrino.

X(5568) → $B_s\pi$ candidates:

Add a charged pion with $p_T > 0.5$ GeV/c consistent with coming from the PV

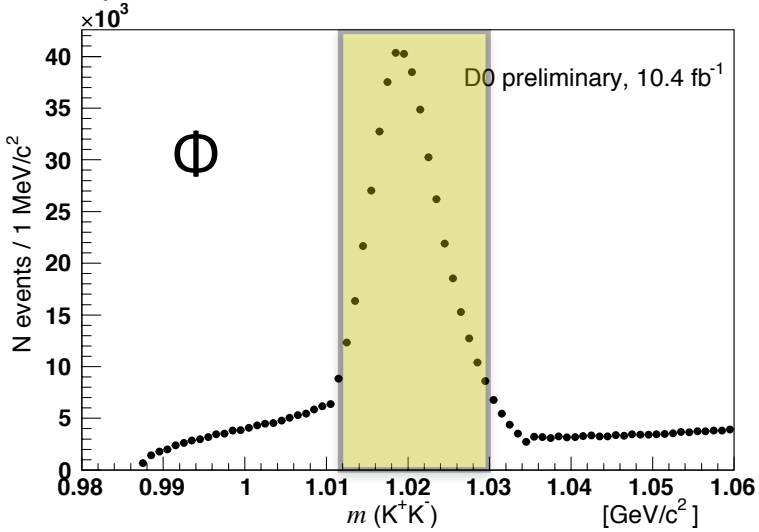
Additional pion chosen with identical cuts as used in $B_s^0 \rightarrow J/\psi\phi$ analysis.

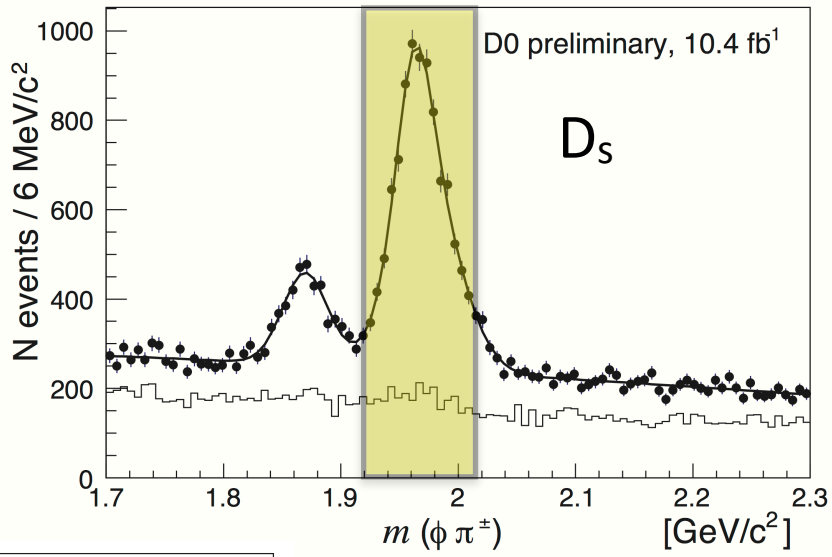
- To improve mass resolution we define the invariant mass as

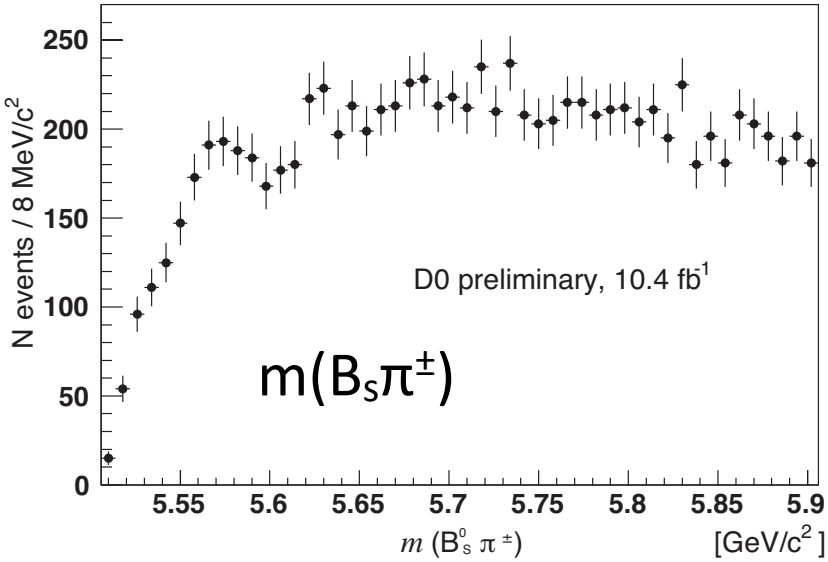
$$M(B_s^0\pi^{\pm}) = m(\mu D_s\pi) - m(\mu D_s) + m(B_s^0)$$

Data

- Look to confirm X(5568) using additional channel
  - Optimise cuts to minimise effect of missing neutrino and reduce size of background.

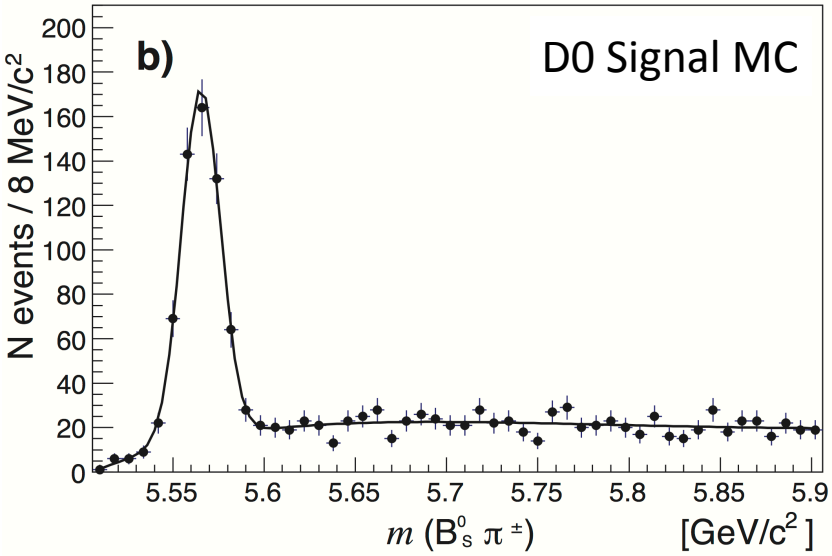




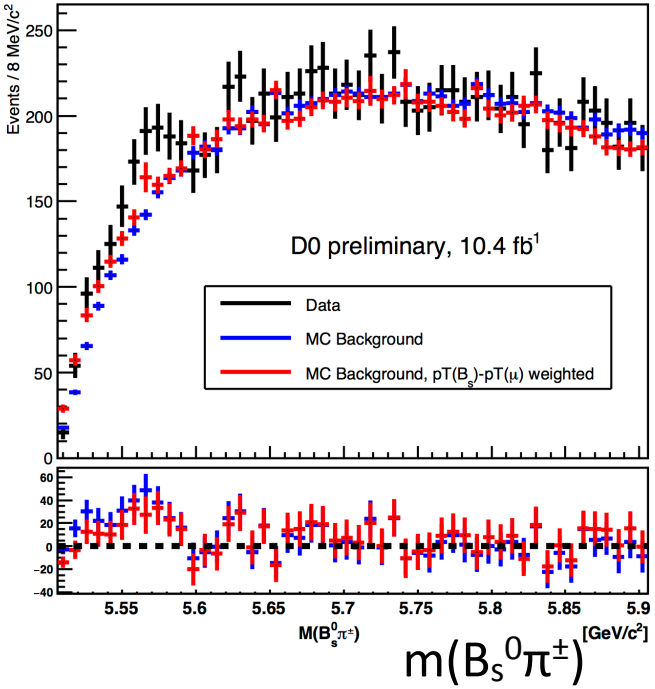


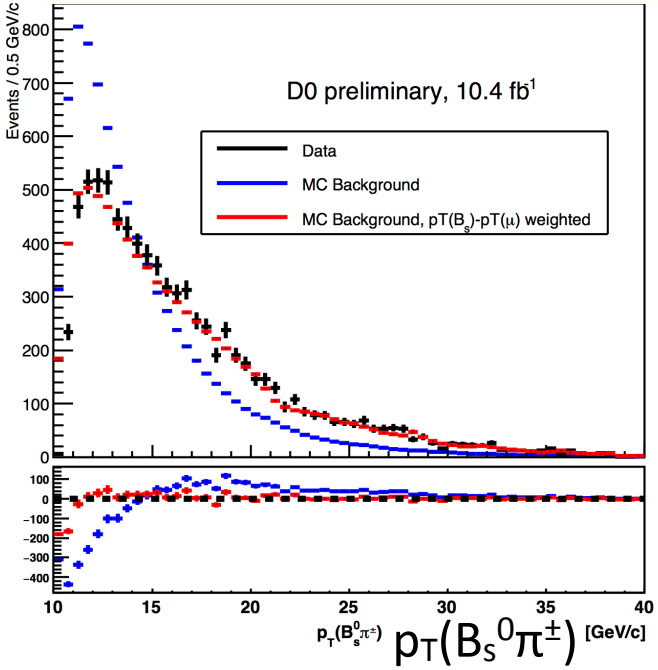
Simulation

- Model signal with modified spin-0 meson in Pythia.
- Background $\mu^- D_s^+$ events generated inclusively and selected based on kinematics.
- MC is weighted as a function of $p_T(\mu)$ and $p_T(\mu D_s)$ to account for trigger and reconstruction efficiencies



Data and Background MC





Signal Extraction

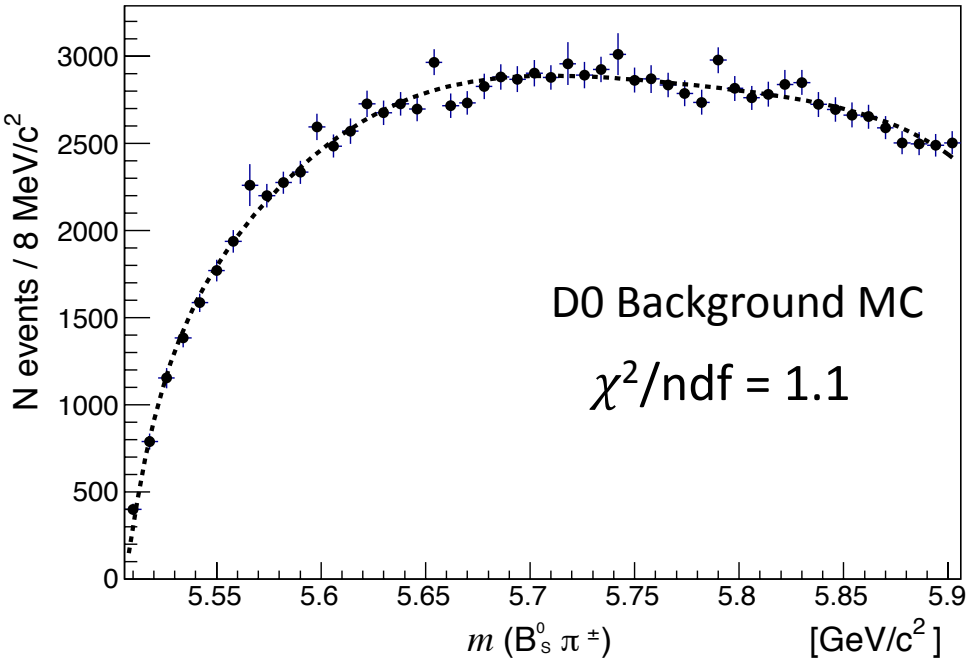
- Fix shape of background by fitting MC background simulation.
- Fit data to background model plus signal
  - signal represented by relativistic Breit-Wigner convoluted wth detector resolution and smearing due to the missing neutrino.

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

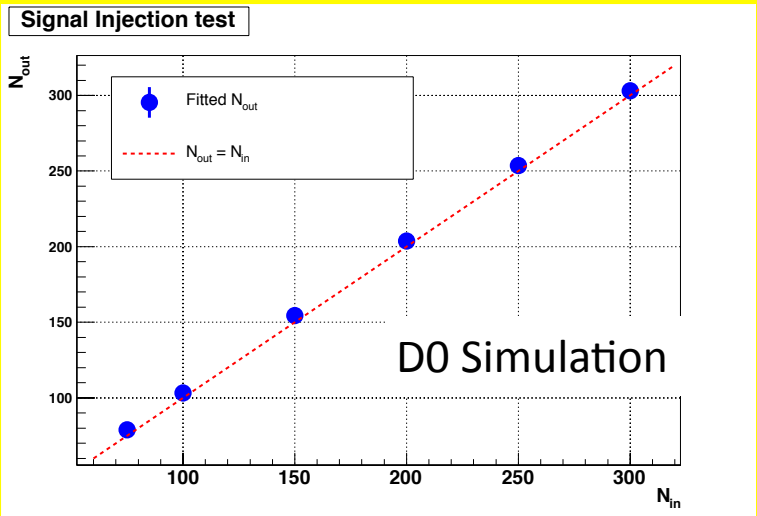
Background function:

$$F_{\mathrm{bgr}}(m) = \left(C_1 m_0 + C_2 m_0^2 + C_3 m_0^3 + C_4 m_0^4\right) \exp\left(C_5 m_0 + C_7 m_0^2\right),$$

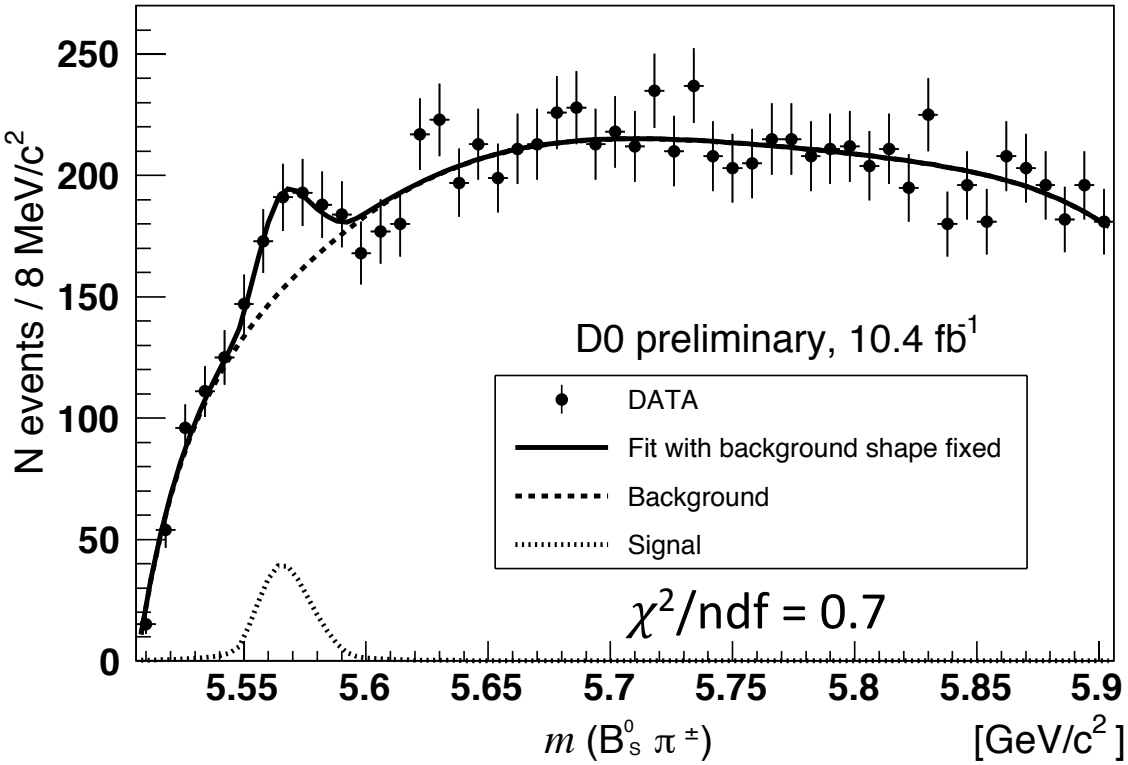
where $m = m(B_s^0 \pi^{\pm})$, $m_0 = m - m_{\mathrm{th}}$ and $m_{\mathrm{th}} = 5.5063\,\mathrm{GeV}c^2$ is the threshold value.



Results of signal injection closure test



Fit results



$$X(5568)$$

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

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

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

Local Signficance

$$\sqrt{-2\ln\frac{\mathcal{L}_0}{\mathcal{L}_{\max}}}$$

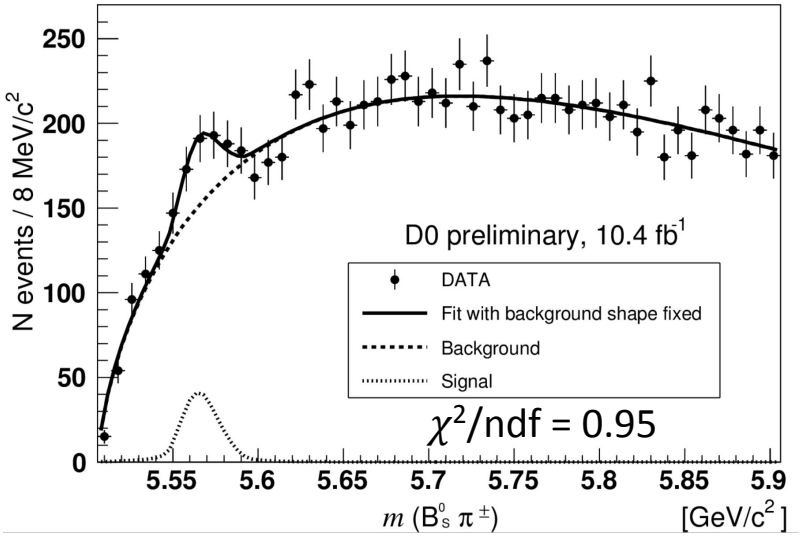
Statistical Significance $4.5\,\sigma$.
Including Systematics $3.2\,\sigma$.

Systematics

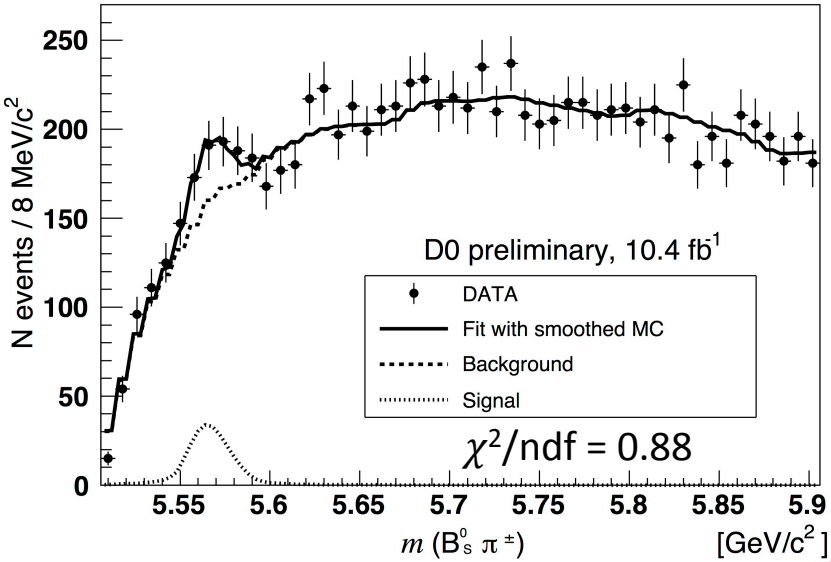
Source	mass, MeV/c^2	width, MeV/c^2	event yield, events
Background shape description	$+0.0$; -0.7	$+0.7$; -2.5	$+4.8$; -28.0
Background reweighting	$+0.1$; -0.1	$+0.7$; -0.7	$+5.0$; -5.0
B_s^0 mass scale, MC and data	$+0.3$; -0.5	$+1.0$; -1.4	$+7.5$; -9.6
Detector resolution	$+0.0$; -0.5	$+1.3$; -2.6	$+3.7$; -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

Alternate Background Shape

Argus Type background



Smoothed MC



Combination with Hadronic Channel

	Semileptonic	Hadronic, cone cut	Hadronic, no cone 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

- Assume measurements are independent
  - presence of neutrino in semileptonic supports this assumption

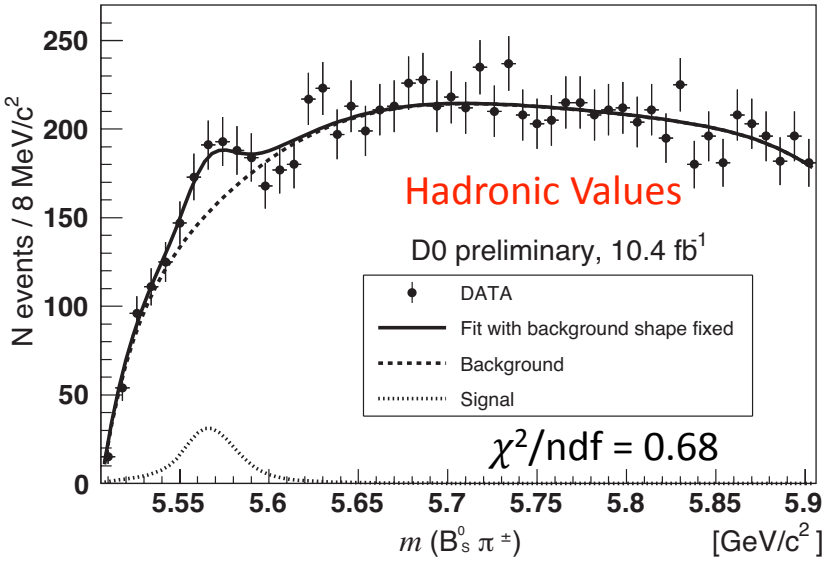
$$p_{\mathrm{comb}} = p_{\mathrm{had}} p_{\mathrm{sl}} \left[1 - \ln(p_{\mathrm{had}} \times p_{\mathrm{sl}})\right],$$

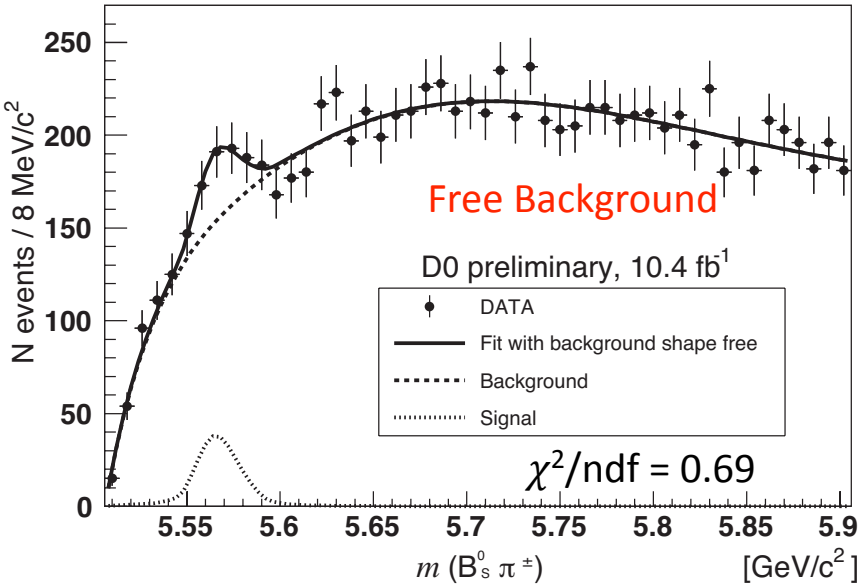
- Combine with J/ψϕ with ΔR Cut
  p-value = 5.6×10^{-9} corresponding to **5.7 σ.**

If combined with J/ψϕ without ΔR Cut significance is 4.7 σ.

Cross Checks

- Alternative Fits
  - Fix $M_X = 5567.8$ MeV/c^2 and $\Gamma_X = 21.9$ MeV/c^2 from Hadronic analysis
  - Free all background parameters.

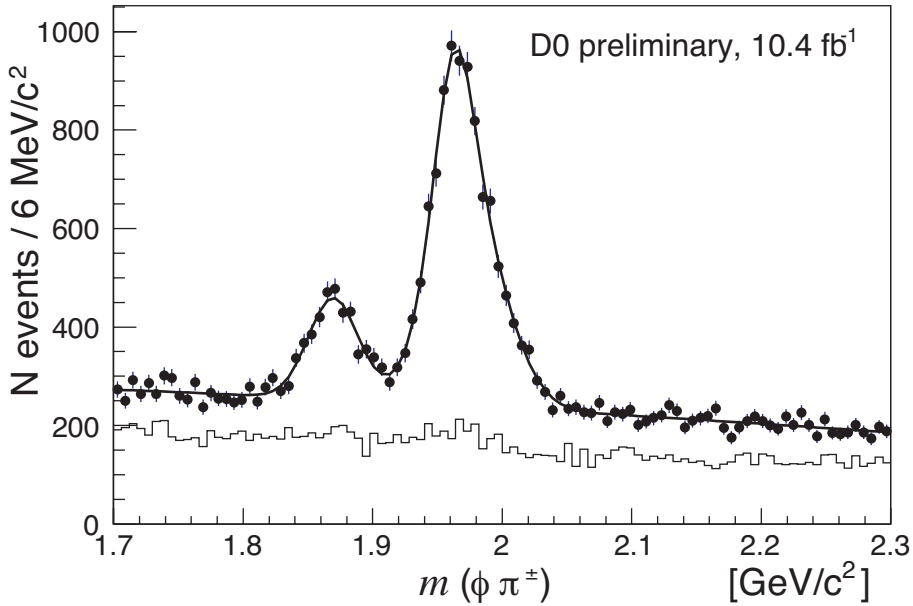




	Nominal Fit	All Parameters free	Mass and Width Fixed to $J/\psi\phi$
Fitted mass, MeV/c^2	$5566.7^{+3.6}_{-3.4}$	5566.6 ± 3.5	5567.8
Fitted width, MeV/c^2	$6.0^{+9.5}_{-6.0}$	8.4 ± 14.5	21.9
Fitted number of signal events	$138.6^{+50.8}_{-63.3}$	143.7 ± 101.1	168 ± 42
χ^2/ndf	$30.4/(50-4)$	$27.4/(50-10)$	$32.8/(50-2)$
Local significance	$4.5\,\sigma$	$4.4\,\sigma$	$4.2\,\sigma$

Fraction of B_s from X(5568) decays

- Determine number of B_s mesons by fitting the m($\phi\pi^{\pm}$) distribution.
- Remove prompt/non B_s mesons using same sign μD_s samples.
- Semileptonic sample satisfies $p_T(\mu D_s) > 10$ GeV/c



$$\text{For } p_T(\mu^+ D_s^-) > 10\,\text{GeV/c and } 4.5\,\text{GeV}/c^2 < m(\mu^+ D_s^-) < m(B_s^0)$$
$$\rho(\text{sl}) = \left[7.3^{+2.8}_{-2.4}\,(\text{stat})^{+0.6}_{-1.7}\,(\text{syst})\right]\,\%$$

$$\text{For } p_T(J/\psi\phi) > 10\,\text{GeV/c}$$
$$\rho(\text{had}) = [8.6 \pm 1.9\,(\text{stat}) \pm 1.4\,(\text{syst})]\,\%$$

Conclusion

X(5568)

- We have presented the results of a search for the X(5568) → $B_s^0\pi^\pm$ with semileptonic decays of the B_s^0 meson. There is an excess of events in the data consistent with the decay X(5568) → $B_s^0\pi^\pm$ with B_s^0 → J/ψϕ.
- The mass, natural width and production rates in the semileptonic and hadronic channels are consistent.
- The signal p-value for the semileptonic channel is 6.4×10^{-4} and the significance is 3.2σ when including systematic uncertainties.
- The combined p-value for the hadronic and semileptonic channels is 5.6×10^{-9} with a corresponding significance is 5.7σ.

Search for exotic baryons → J/ψΛ

- In the mass range between threshold and 4.7 GeV/c^2 no evidence for new baryons decaying to J/ψΛ have been found.
- The most significant deviation from background-only hypothesis is seen at M(J/ψΛ)= 4.32 GeV/c^2 with a global significance (including LEE) 2.8σ.

Bibliography

X(5568)

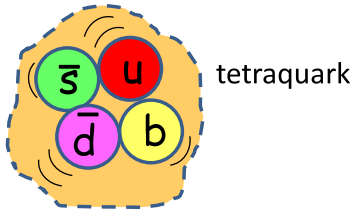
- D0 Conference Note 6496:
  https://www-d0.fnal.gov/Run2Physics/WWW/results/prelim/B/B68/

Search for exotic baryons → J/ψΛ

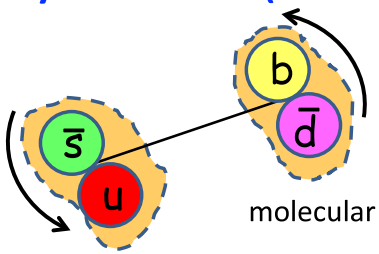
- D0 Conference Note 6494:
  https://www-d0.fnal.gov/Run2Physics/WWW/results/prelim/B/B69/

“Four” quark states

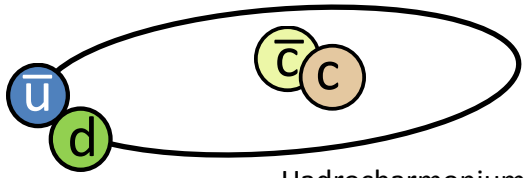
- Four quark states can be distinguished from regular mesons by comparing the mass, width, charge, other quantum numbers, production and decay modes with predictions.
- Exotic four-quark states can be described as tightly bound (tetraquark) or loosely bound (molecule, hadroquarkonium):



tetraquark



molecular state

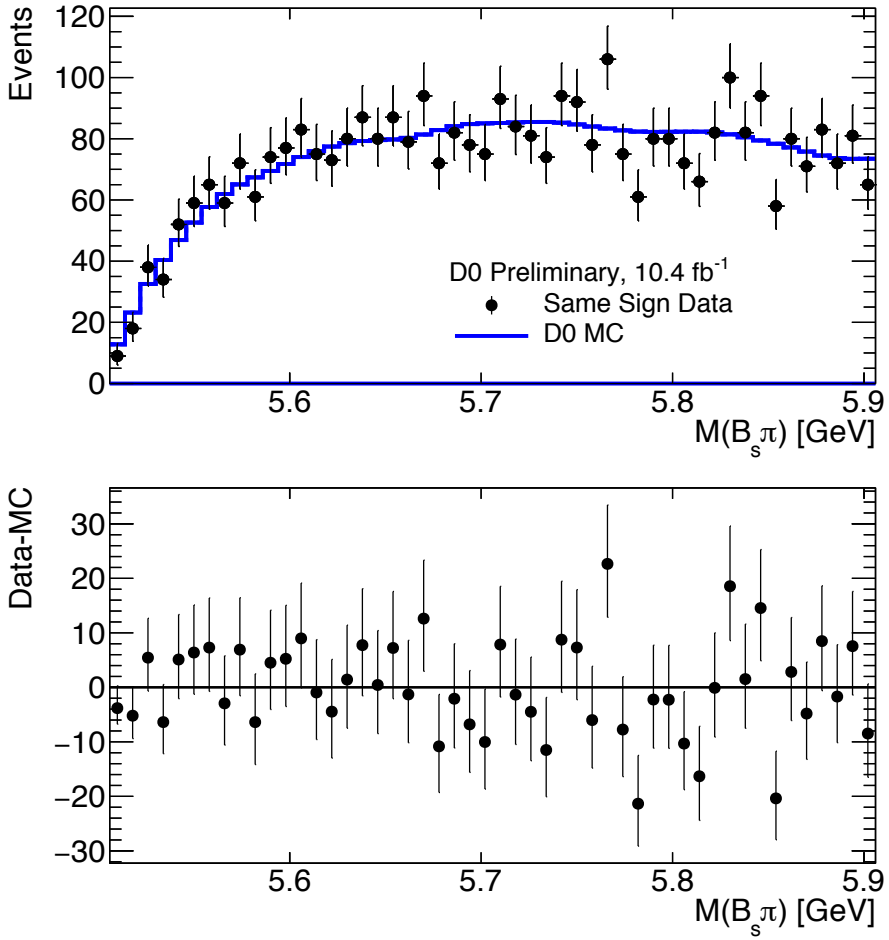


Hadrocharmonium

- Observed four-quark states (high statistical significance): $Z(4430)^+ \to \psi'\pi^+$, $X(4140) \to J/\psi\phi$, $Z_b(10610)^+ \to \Upsilon\pi^+$, $Z_b(10650)^+ \to \Upsilon\pi^+$.
- Not well established: $Z(4050)^+ \to \chi_{c1}\pi^+$, $Z(4250)^+ \to \chi_{c1}\pi^+$.
- 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 $P_c(4450)^+ \to J/\psi p$, $P_c(4380)^+ \to J/\psi p$

MC Cross Checks

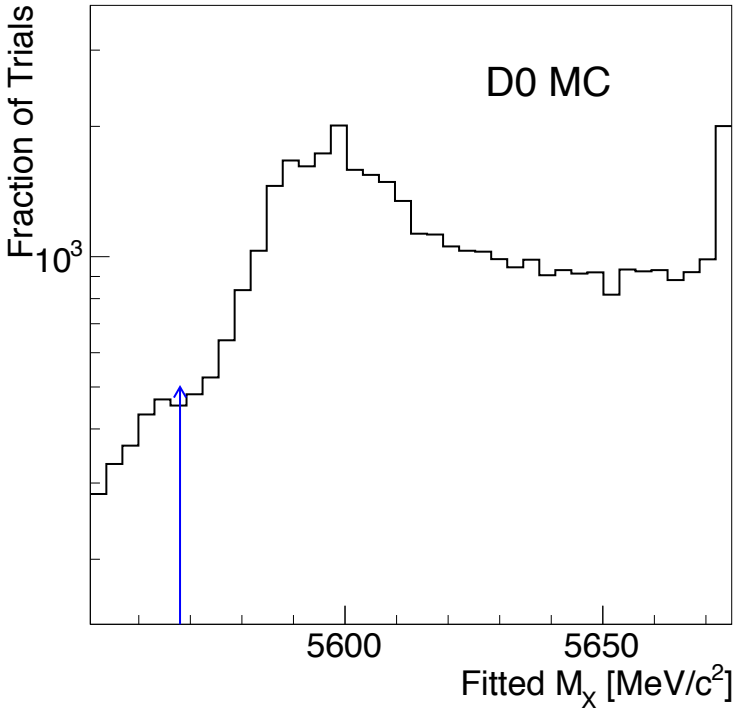
- Comparison between same sign ($\mu^+ D_s^+$) data and MC background

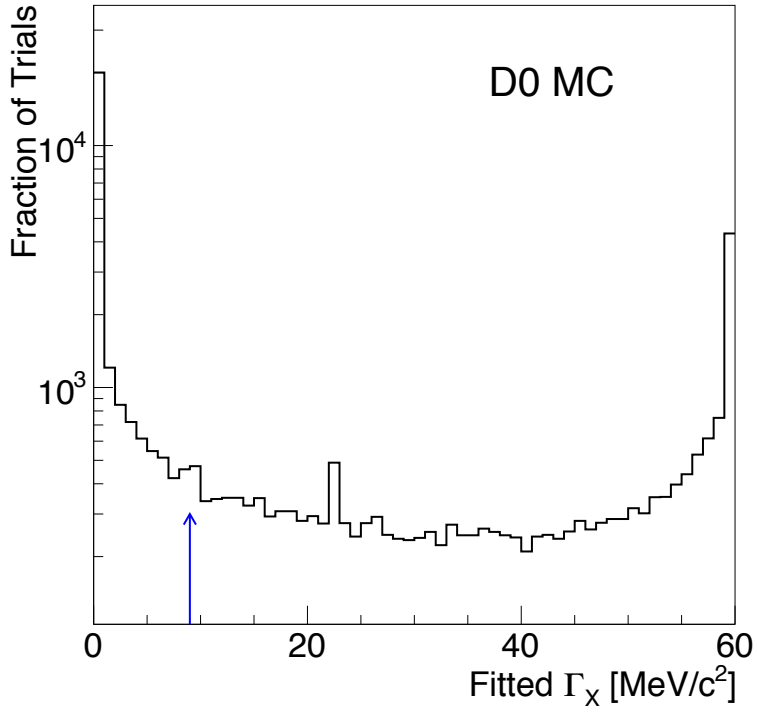


χ^2/ndf = 1.0

Tests of Procedure

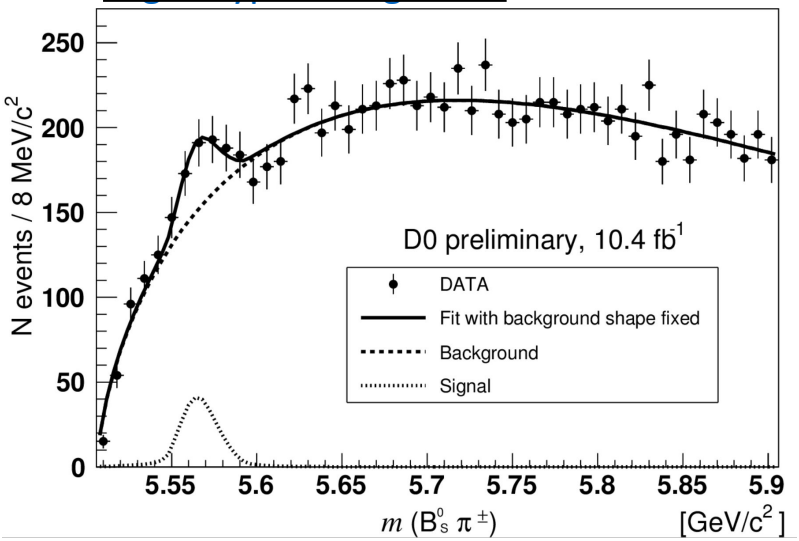
- Use weighted MC background to generate 45k invariant mass distributions with same sample size of the data.
  - Apply the fit procedure to each trial with initial mass of 5600 MeV.
  - Blue arrows represent $M_X = 5568$ MeV and $\Gamma_X = 8$ MeV
  - Confirm that there is no bias in the method that would produce the peak and the significance calculation.



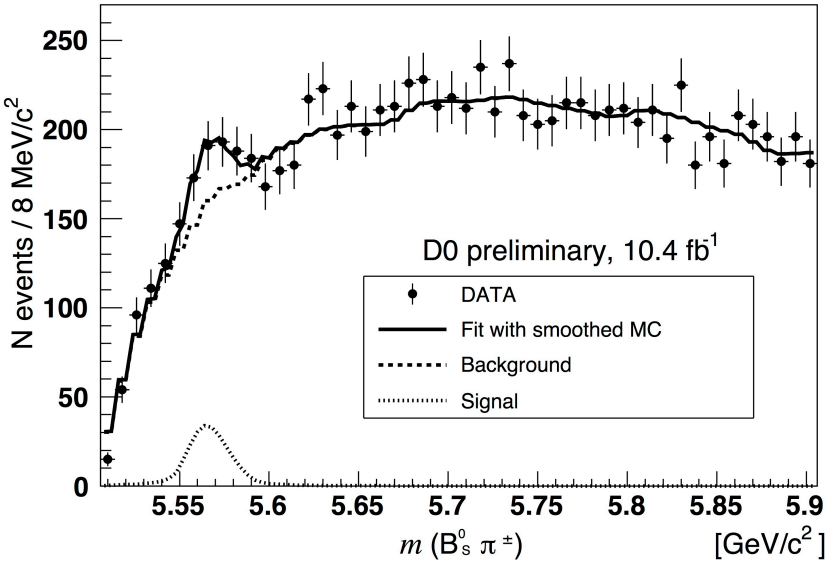


Alternate Background Shapes

Argus Type background



Smoothed MC



	Nominal Fit	Argus Type Background	Smoothed MC
Fitted mass, MeV/c^2	$5566.7^{+3.6}_{-3.4}$	$5566.0^{+3.6}_{-3.4}$	5564^{+5}_{-5}
Fitted width, MeV/c^2	$6.0^{+9.5}_{-6.0}$	$6.5^{+8.9}_{-6.5}$	10^{+17}_{-10}
Fitted number of signal events	$138.6^{+50.8}_{-63.3}$	$145.7^{+50.7}_{-54.3}$	136^{+59}_{-48}
χ^2/ndf	$30.4/(50-4)$	$43.8/(50-4)$	$40.6/(50-4)$
Local significance	$4.5\,\sigma$	$4.7\,\sigma$	$3.9\,\sigma$