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Search for $X(5568) \to B_s^0 \pi^\pm$ in CDF data

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Joint Experimental - Theoretical Seminar

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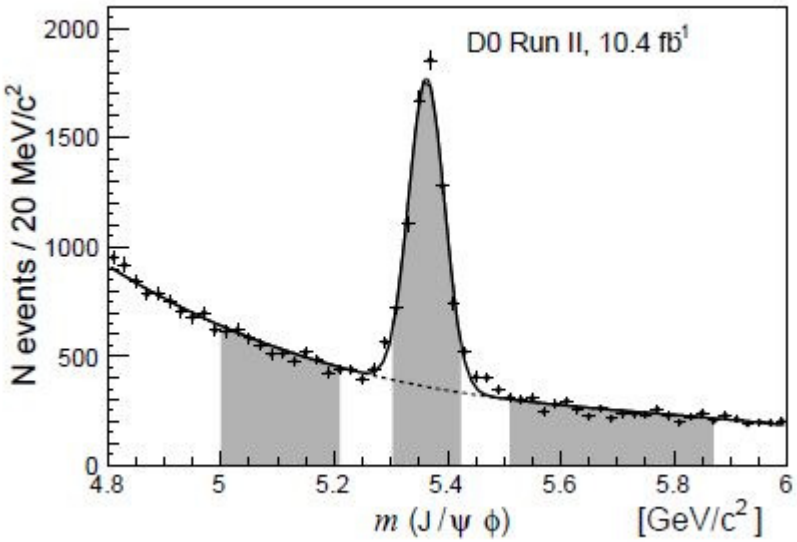
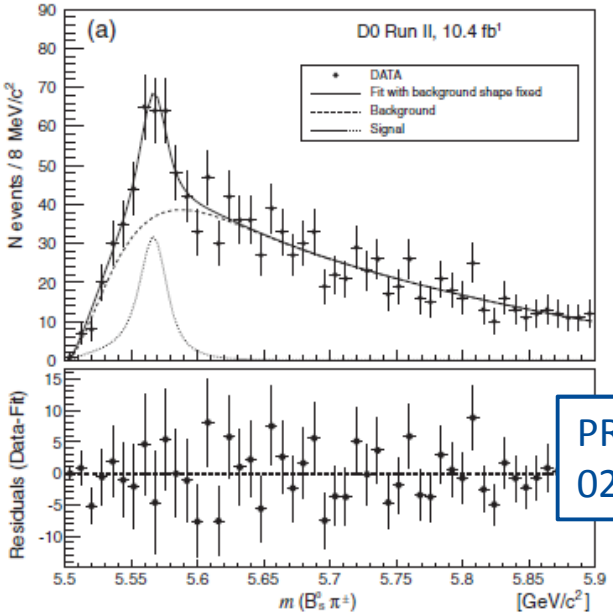
Exotic hadrons

- A large body of evidence exists to support exotic hadrons
  - Mesons that aren't $q\bar{q}$, baryons that aren't qqq.
- Most observations are to final states containing $c\bar{c}$ or $b\bar{b}$
  - X(3872)→J/ψ $\pi^+\pi^-$, X(3915) →J/ψ ω, Y(4260)→J/ψ $\pi^+\pi^-$
  - Z^+ (4430) →ψ(2S) π^+
  - P_c^+(4380)→J/ψ p^+
- Large data sets at Belle, BES, LHCb are yielding these
- Understanding is lacking
- Nice recent review in Rev. Mod. Physics 90 (2018)

D0 – Observation of structure in $B_s\pi$ final state

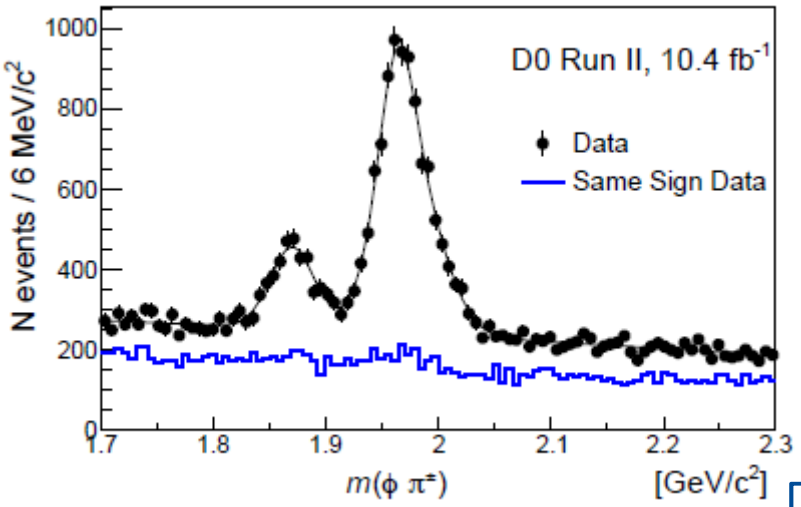


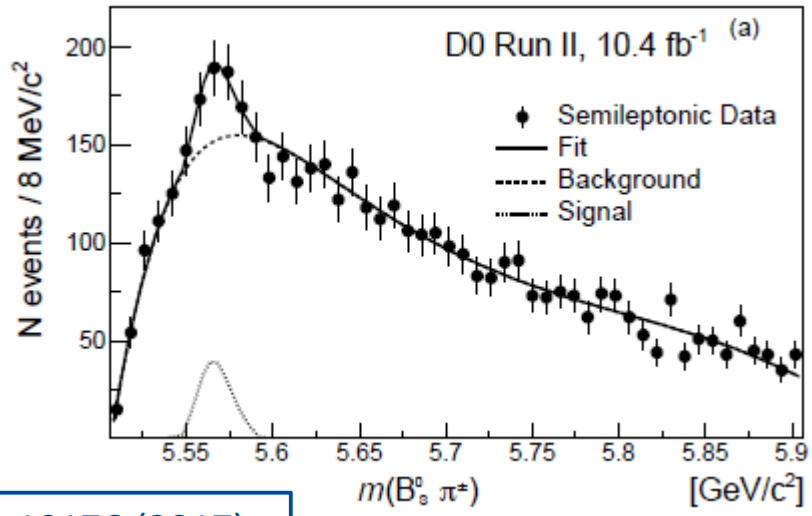


PRL 117 (2016), 022003

- D0 observes X(5568) → $B_s^0\pi^\pm$, B_s^0 → J/ψφ
  - Final state with four flavors (*b,s,u,d*)
  - Signal with a mass of $5567.8 \pm 2.9^{+0.9}_{-1.9}$ MeV/c^2
  - $\Gamma = 21.9 \pm 6.4^{+5.0}_{-2.5}$ MeV/c^2
- Suggests a tetraquark object

D0 – Confirmation of structure in semileptonic final state





arXiv:1712.10176 (2017)

- Recent confirmation of the X(5568) by D0 in $B_s^0 \to \mu^\pm D_s^\mp X$
  - $D_s^\pm \to \phi\,\pi^\pm$, $M(B_s^0\,\pi^\pm) = M(\mu^\pm D_s^\mp\,\pi^\pm) - M(\mu^\pm D_s^\mp) + M(B_s^0)$
- Updated mass and width values

CDF search for the X(5568)

- This work is a report on the CDF search for the X(5568)
  - Posted in arXiv:1712.09620
- Our job is to measure the fraction of B_s^0 produced through X(5568) decay

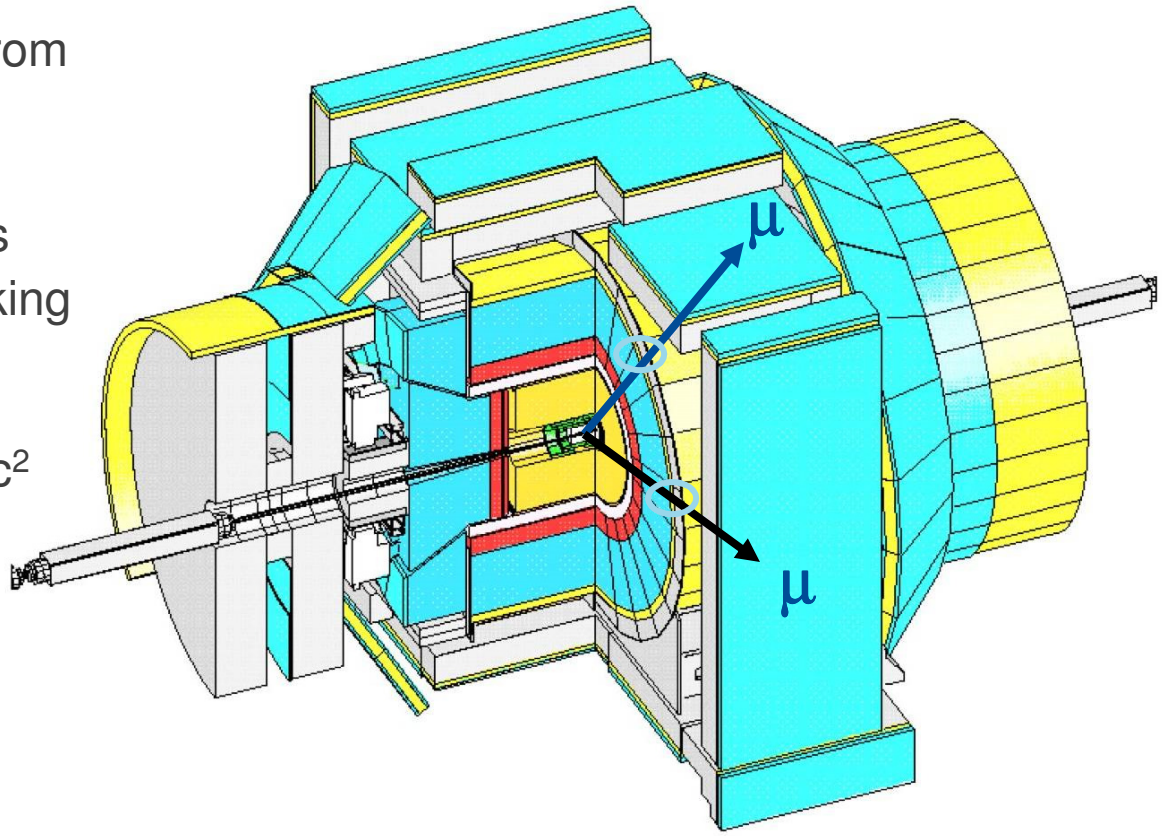
$$f_{B_s^0 / X(5568)} = \frac{\sigma(p\bar{p} \to X(5568) + x) * B(X(5568) \to B_s^0 \pi^{\pm})}{\sigma(p\bar{p} \to B_s^0 + x)} = \frac{N_{X(5568)}}{\alpha_{X(5568), B_s^0}} * \frac{1}{N_{B_s^0}}$$

  - $N_{X,B}$ number of X(5568), B_s^0
  - α is the X(5568) acceptance and reconstruction efficiency, having reconstructed the B_s^0

- This work uses $B_s^0 \to J/\psi\phi$
- Data exists to also study $B_s^0 \to D_s^{\pm}\pi^{\mp}$
  - Effort will probably prevent this

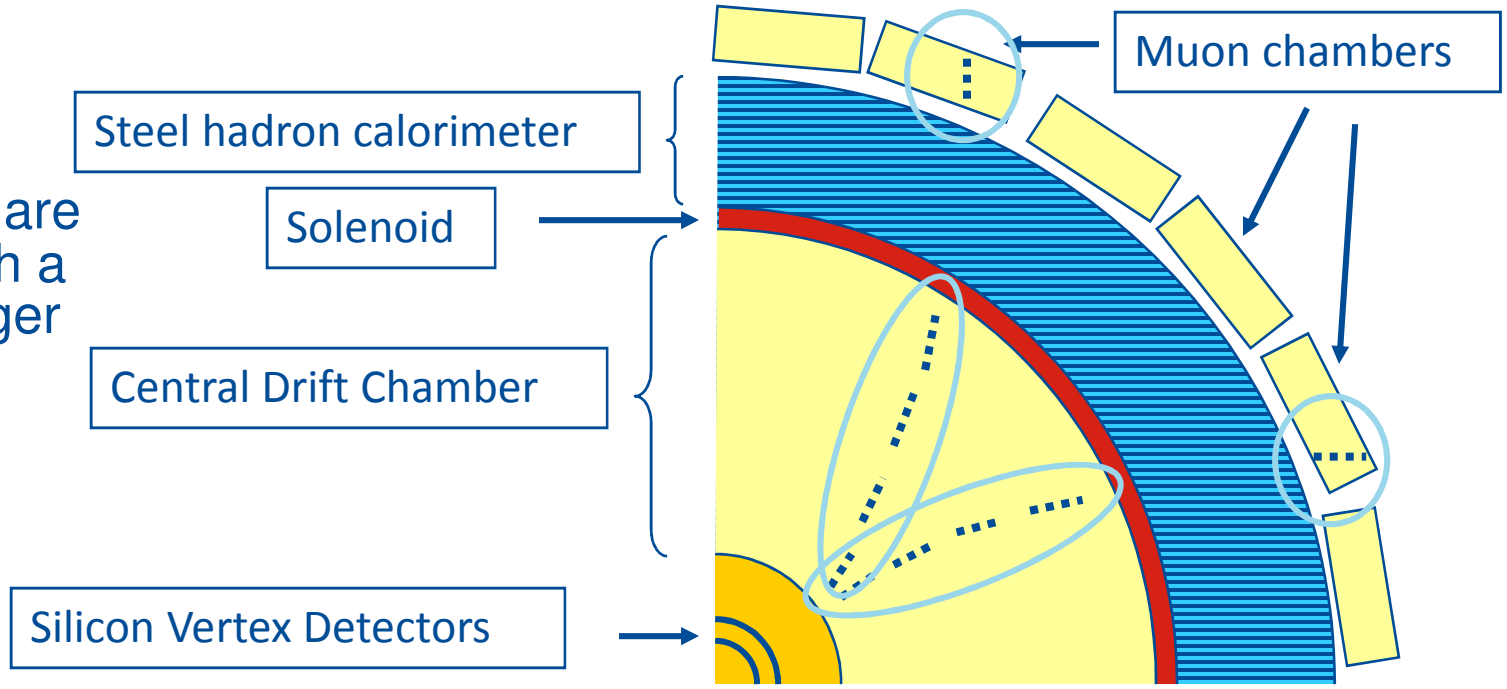
The CDF II Detector

- The data used in this analysis was collected with the CDF II Detector.
  - This analysis uses data from 9.6 fb^{-1}. Full data set.
- The trigger requires
  - Tracks in muon chambers
  - Tracks in the central tracking chamber (COT)
    - $p_T > 1.5$ GeV
  - $2.7 < M(\mu^+\mu^-) < 4.0$ GeV/c^2
- Unbiased with respect to decay time for *b*-hadrons



Collecting *b* Hadrons with a J/ψ Final State

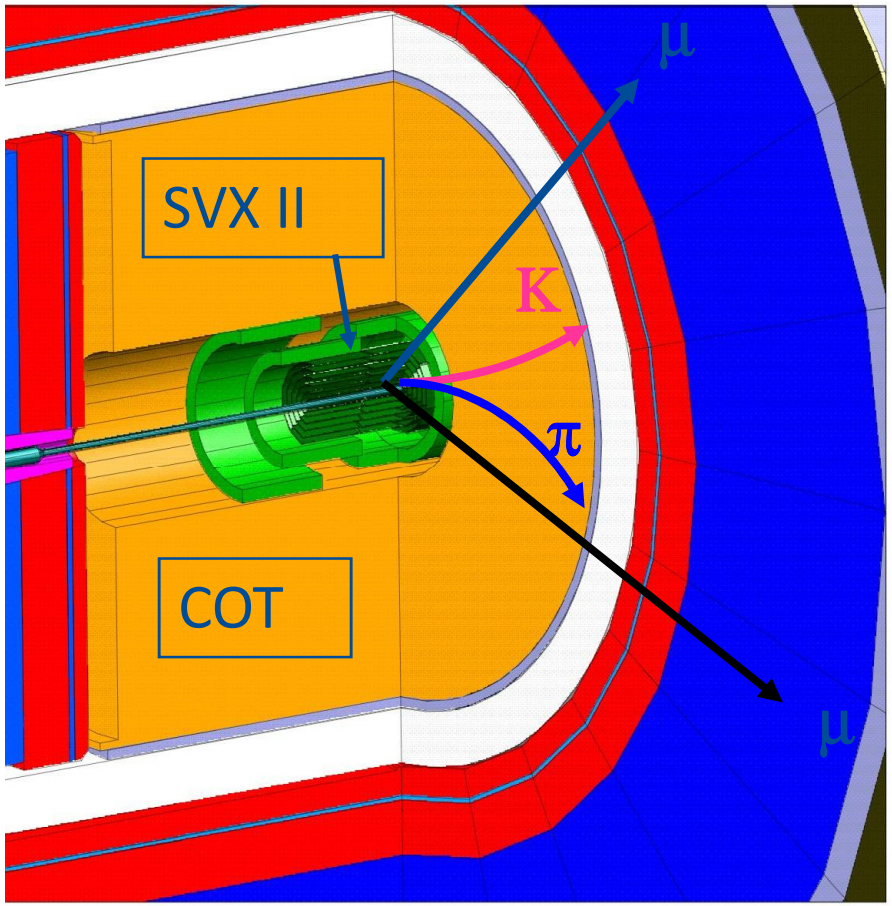
- $J/\psi \rightarrow \mu^+\mu^-$ are collected with a 2–muon trigger



- This trigger matches central tracker and muon chamber tracks.
- A successful match will trigger acceptance of the event.

The CDF II Detector

- Events that satisfy the trigger are fully analyzed.
- Track reconstruction identifies all tracks with p_T>0.4 GeV/c
- Three SVX II measurements are required for all tracks in this analysis.

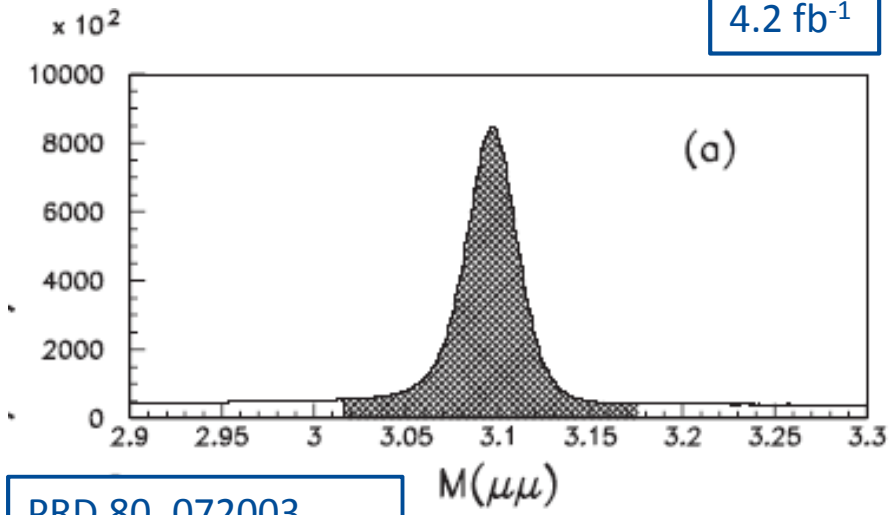


Reconstruction strategy

- Approach taken is deliberately conservative
- CDF has several successful particle searches in its history
  - B Baryons, B_c^+
- The strategy is to stick with the approach used previously
  - No new selection techniques
- The recipe:
  - Obtain a J/ψ sample
  - Combine with ϕ candidates to form a B_s^0 sample
    - Form a constrained fit and require decay time inconsistent with prompt production
  - Combine with a π candidate

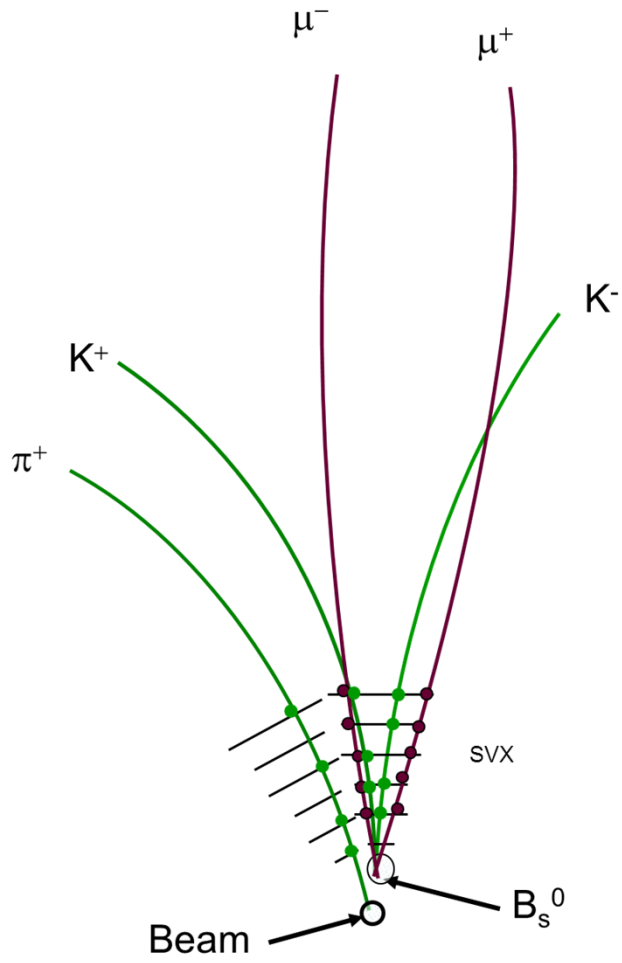
J/ψ selection

- The analysis is based data collected from 9.6 fb^{-1} of collisions.
  - Full data set from 2001-11
- J/ψ sample requires
  - Muon chamber/COT track match
  - $p_T(\mu^{\pm}) > 2.0$ GeV/c
  - 3 or more silicon hits/track
  - Dimuon mass within 80 MeV/c^2 of PDG



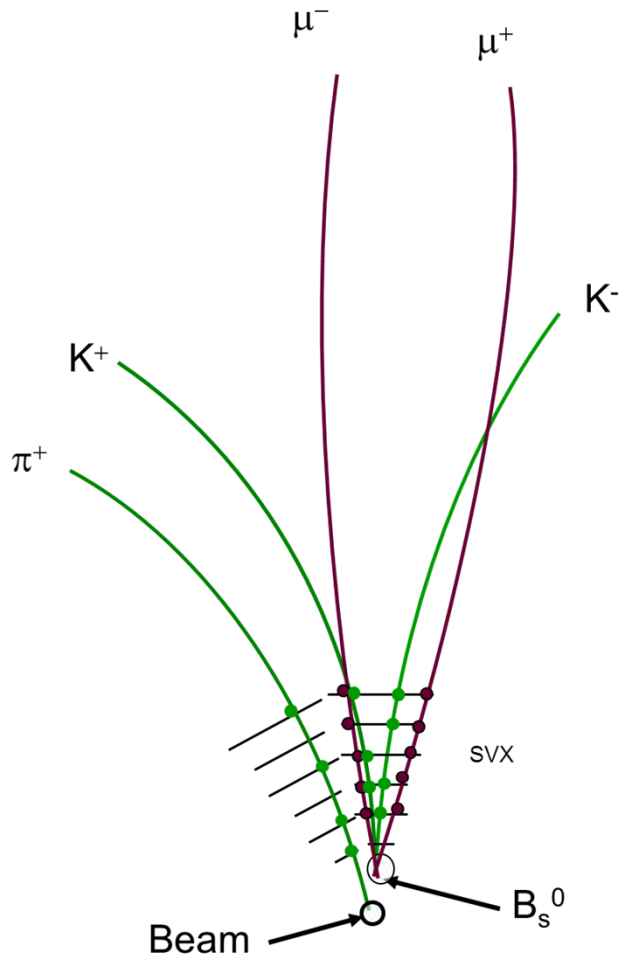
B_s^0 and X(5568) reconstruction

- $\phi \rightarrow K^+K^-$ candidates:
  - Opposite charge pairs
  - 3 or more silicon hits/track
  - Mass within 2.5 Γ of the ϕ
    - (10 MeV/c^2)
  - p_T > 2.0 GeV/c
- π candidates:
  - 3 or more silicon hits
  - p_T > 400 MeV/c
  - |impact| < 100 μm
    - Respect to the beamline

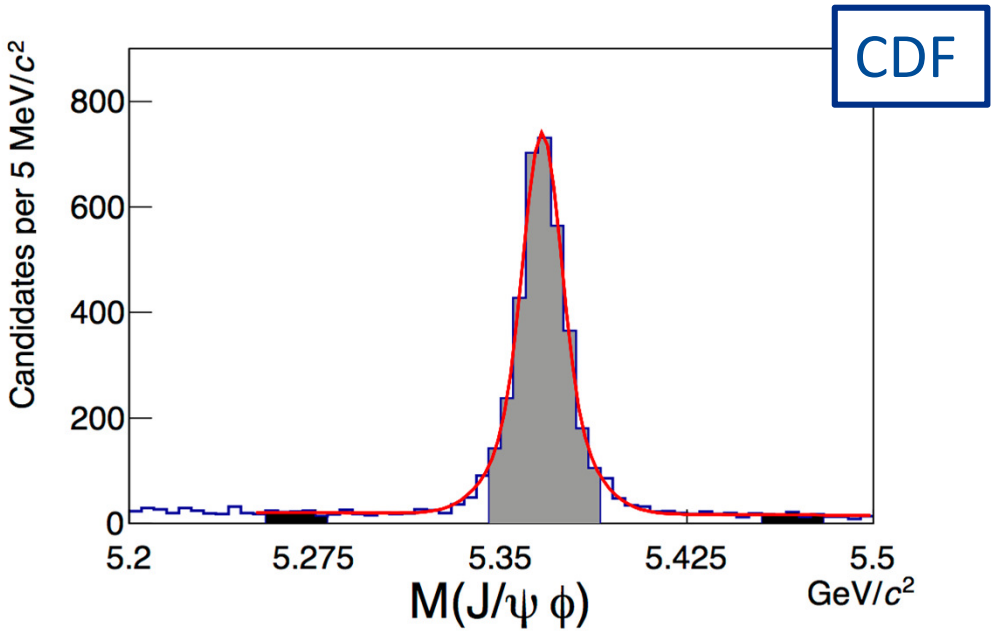


B_s^0 and X(5568) reconstruction

- $B_s^0 \rightarrow J/\psi\,\phi$ candidates:
  - Require 4-track constrained fit
  - Muons constrained to J/ψ mass
  - $J/\psi\,\phi$ mass within 20 MeV/c^2 of the B_s^0
  - $p_T > 10.0$ GeV/c
  - Decay time – $ct < 100\ \mu m$
- X(5568) candidates:
  - Require 5-track, 2-vertex constrained fit
  - To remove B_s^0 resolution, plot $M(B_s^0\,\pi^{\pm}) = M(J/\psi\phi\pi^{\pm}) - M(J/\psi\phi) + M(B_s^0)$



B_s^0 reconstruction

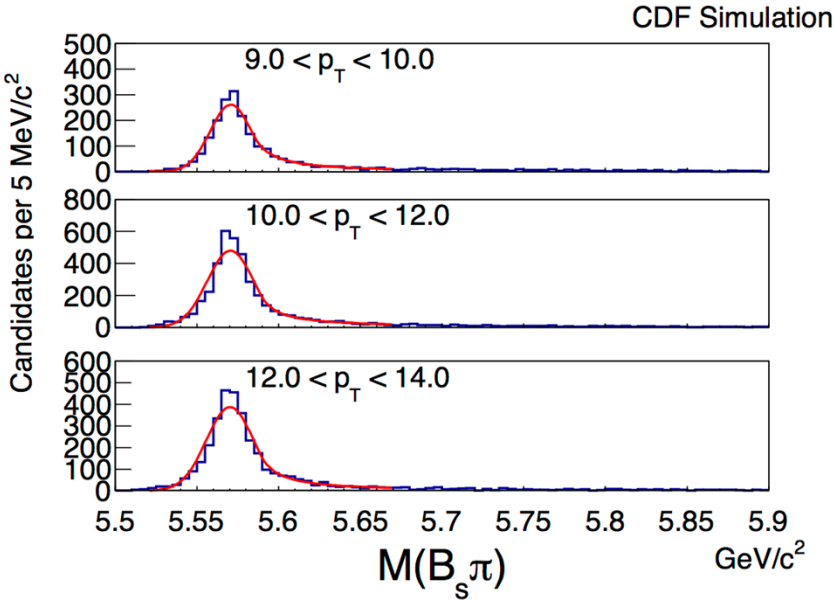


- J/ψ φ candidates considered B_s^0 highlighted in gray
  - 3552 ± 65 candidates
  - Sidebands for demonstration, ±100 MeV/c^2 from B_s^0
- Acceptance limits sample to $|\eta| < 1.0$.

Fermilab

X(5568) signal at CDF

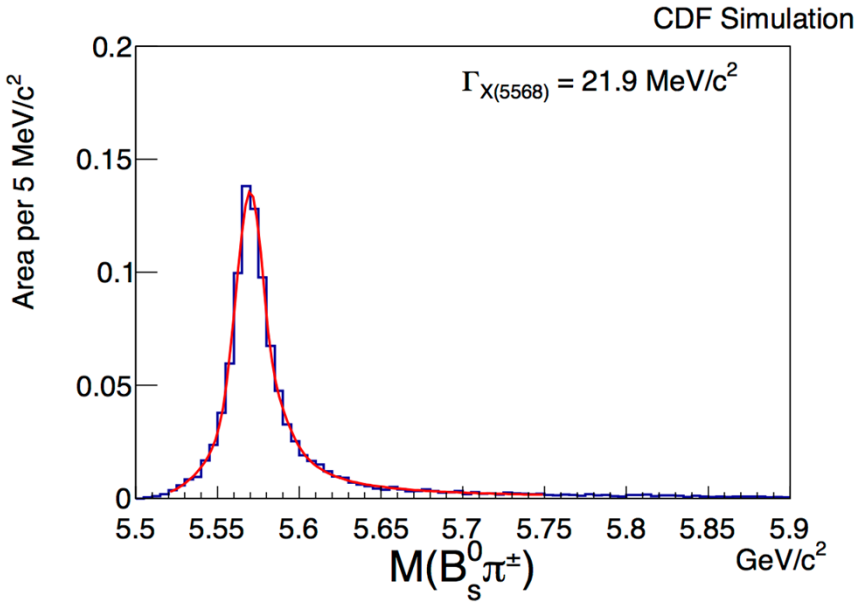
- The X(5568) has been simulated through CDF
  - Full analysis applied to the simulated events
- Reconstructed signal is asymmetric around the central value
  - Low momentum cutoff of tracking cuts into acceptance
  - Signal shape will have some dependence on $p_T(B_s^0)$



- Reconstructed simulated X(5568), three ranges of $p_T(B_s^0)$

X(5568) signal at CDF

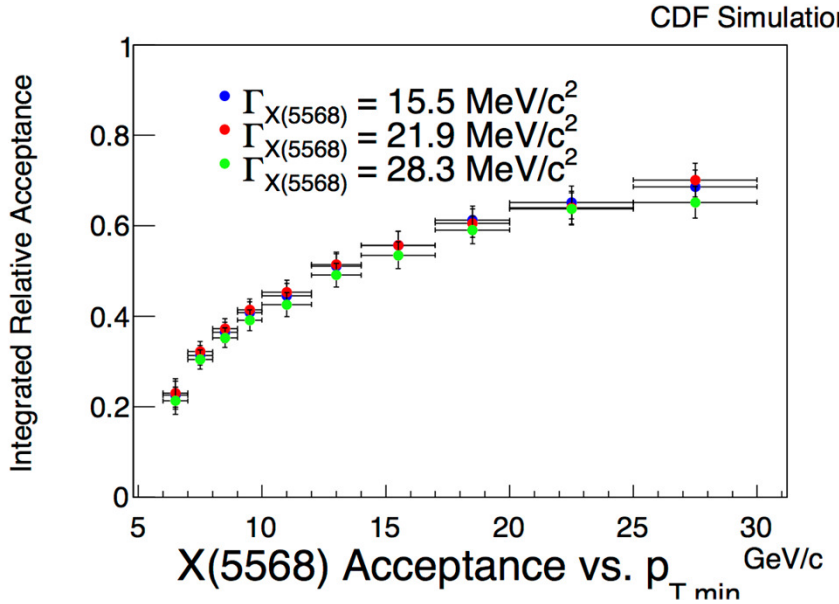
- The X(5568) signal shape integrated in $p_T(B_s^0)$ is obtained by a weighted average of the simulation
  - Weight by the observed $p_T(B_s^0)$
- Expected signal then modeled with a Crystal Ball function



- Normalized signal shape expected for $p_T(B_s^0) > 10$ GeV/c

X(5568) acceptance and efficiency

- The X(5568) acceptance and reconstruction efficiency integrated in $p_T(B_s^0)$ is obtained with the simulation
  - Weight by the acceptance corrected $p_T(B_s^0)$
- Obtain the relative acceptance
  - Acceptance for X(5568) given that the is B_s^0 reconstructed
- Calculation repeated for the reported $\pm\sigma$ on $\Gamma_{X(5568)}$.

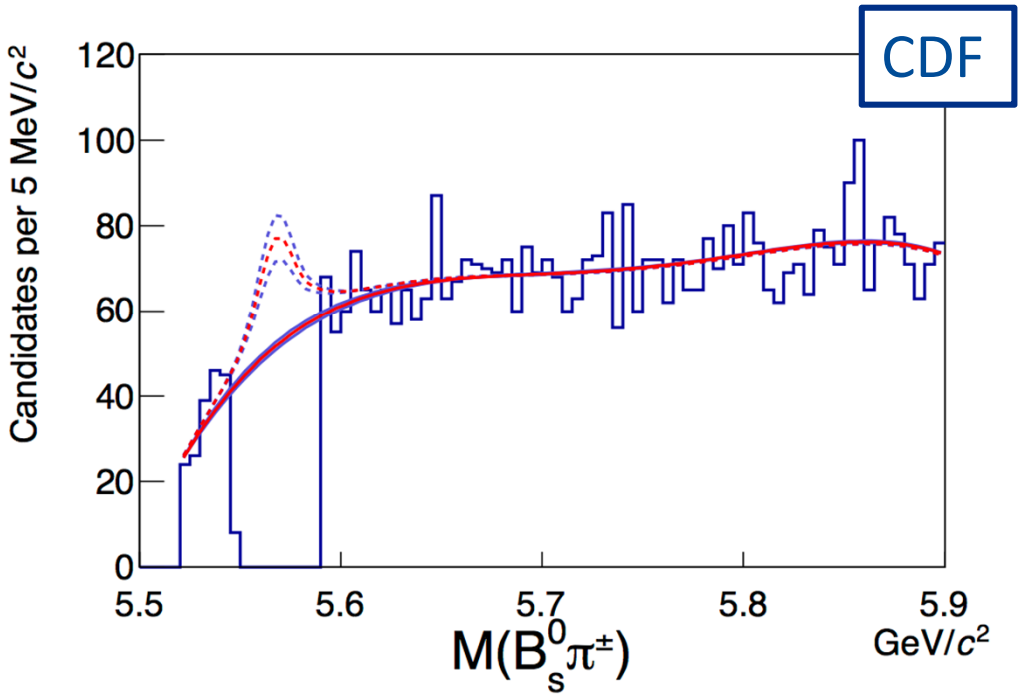


- The relative X(5568) acceptance and reconstruction efficiency is $0.445 \pm 0.027 \pm 0.018$ for $p_T(B_s^0) > 10$ GeV/c

Modeling the background to X(5568) → $B_s^0\pi^\pm$

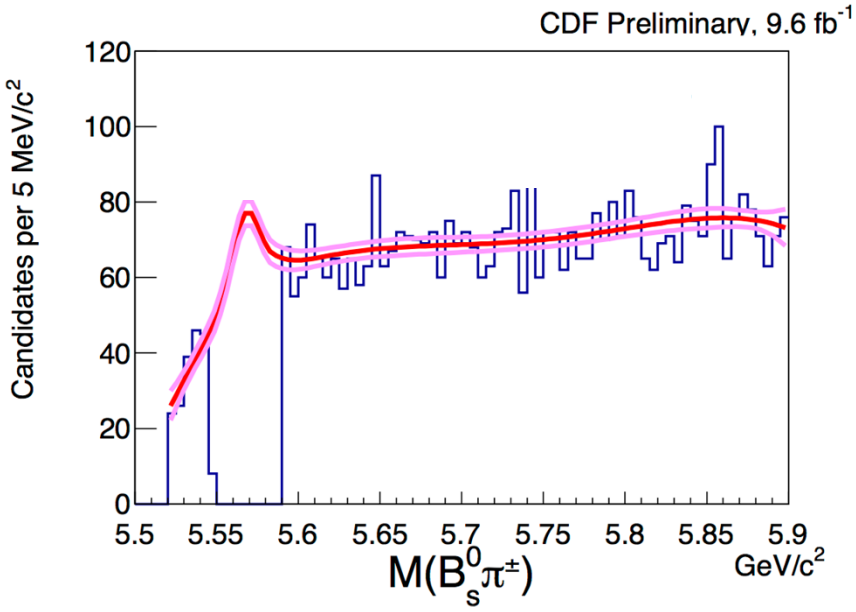
- Sources of background
  - Prompt particles produced in association with the B_s^0
  - Fake B_s^0
  - Tracks from other B hadron – small effect for such low mass
- We model this with the data
- Examine M($B_s^0\,\pi^\pm$) distribution away from the X(5568)
  - Omit range of $\pm\Gamma_{X(5568)}$ around 5568 MeV/c^2.
  - Assume D0 measurement of X(5568)
    - B_s^0 fraction from X(5568) = 8.6 ±2.4%
  - Model the distribution with a polynomial and X(5568) signal

Background model



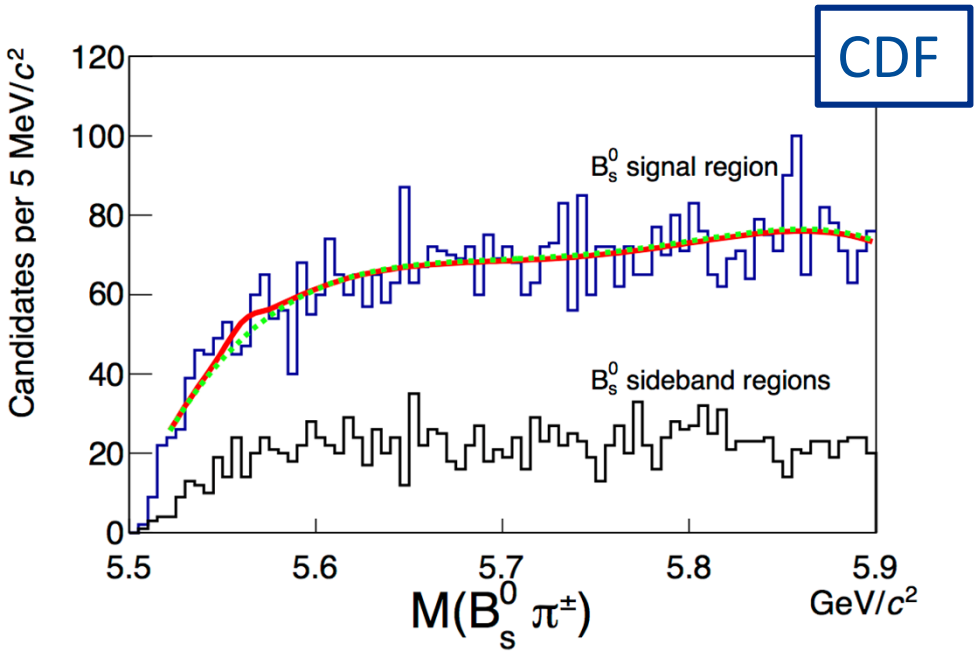
- $M(B_s^0\,\pi^\pm)$ with omitted entries around the X(5568)
- Dashed contours are full fit to the data
- Solid contours are background-only components

Background model



- M($B_s^0\,\pi^\pm$) with omitted entries around the X(5568)
  - Nominal signal component
- Pink contours indicate statistical uncertainty on the model

Fit to full M($B_s^0 \pi^{\pm}$) distribution



- Fit with floating signal amplitude (red), null (green dashed)
  - B_s^0 fraction from X(5568) = 2.3 ±1.9%
- Distribution from sidebands shown for comparison

Systematic uncertainties on production fraction

Issue	Relative change in yield
Width of X(5568)	17%
Amplitude	31%
Mass	17%
B_s^0 yield	1.8%
Acceptance and Efficiency	6.1%
Total	39%

- Affect of assumptions on value of the production fraction
- Total is the quadrature sum
- Final result for fraction of B_s^0 fraction from X(5568) decay $2.3 \pm 1.9(\text{stat.}) \pm 0.9(\text{syst.})\%$

Simulating background fluctuation

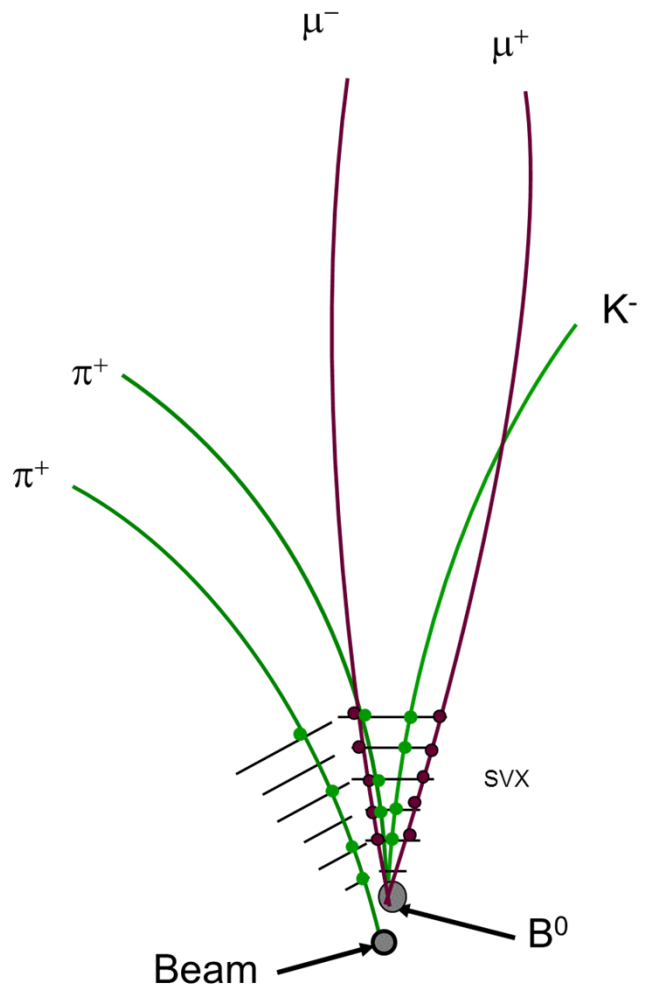
- The result for the production fraction is consistent with 0.
- An upper limit at 95% confidence is estimated with a frequentist Neyman construction
  - $2\delta\log\mathcal{L}$ as the test statistic
- Simulations of our background model provide an estimate for frequency of fluctuation to an observable signal
- We find that the production fraction is less than 5.5% in 95% of occurrences.

Systematic uncertainties on the upper limit

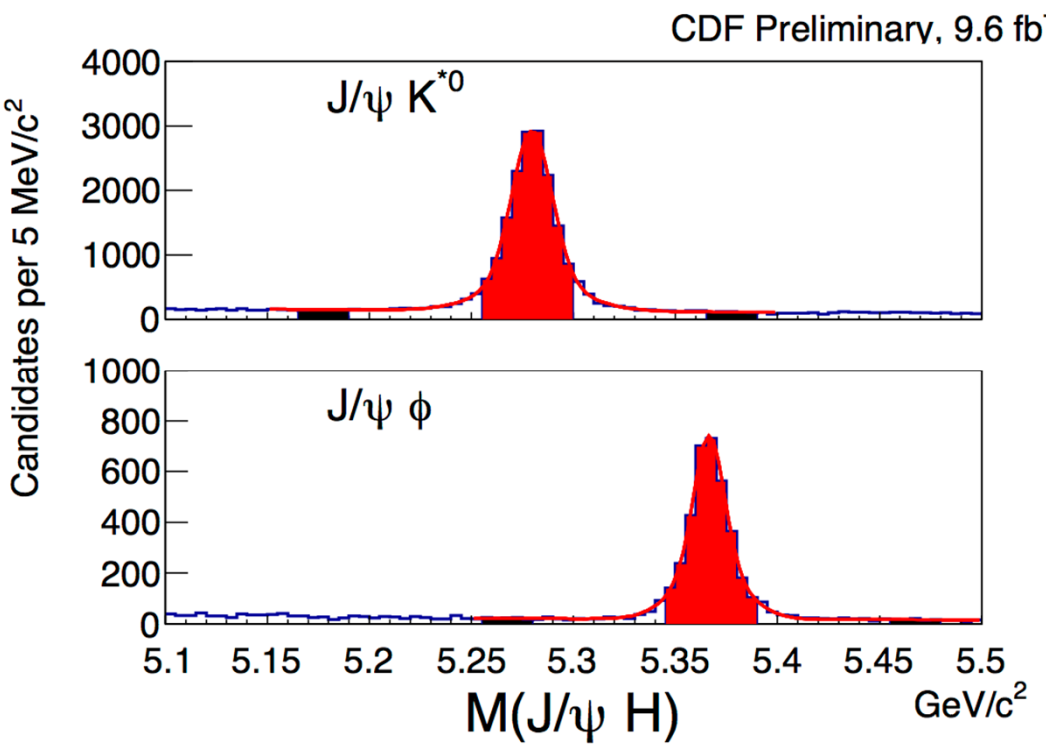
- For the limit – 11%:
  - Calculation of production fraction – 6.6%
    - Acceptance and efficiency – 6.1 %
    - B_s^0 yield – 1.8%
    - B_s^0 $\pi^{\pm}$ sample size – 1.4%
  - D0 signal amplitude impact on background model – 9%
    - Found by repeating the simulation after modifying the background model by 1 σ in the D0 rate.
- Choose to interpret this as a σ, and increase the upper limit by 2σ, for 95% limit
  - 5.5% → 6.7%

The shadow analysis

- What if we look elsewhere?
- Exact same track fits where we substitute one $K^{\pm}$ for a $\pi^{\pm}$.
  - Select $K^{*0} \rightarrow K^{+}\pi^{-}$
  - Then $B^{0} \rightarrow J/\psi\, K^{*0}$
- Now look for $B^{0}\,\pi^{\pm}$ final states
  - Define $M(B_s^{0}\,\pi^{\pm})$ as before

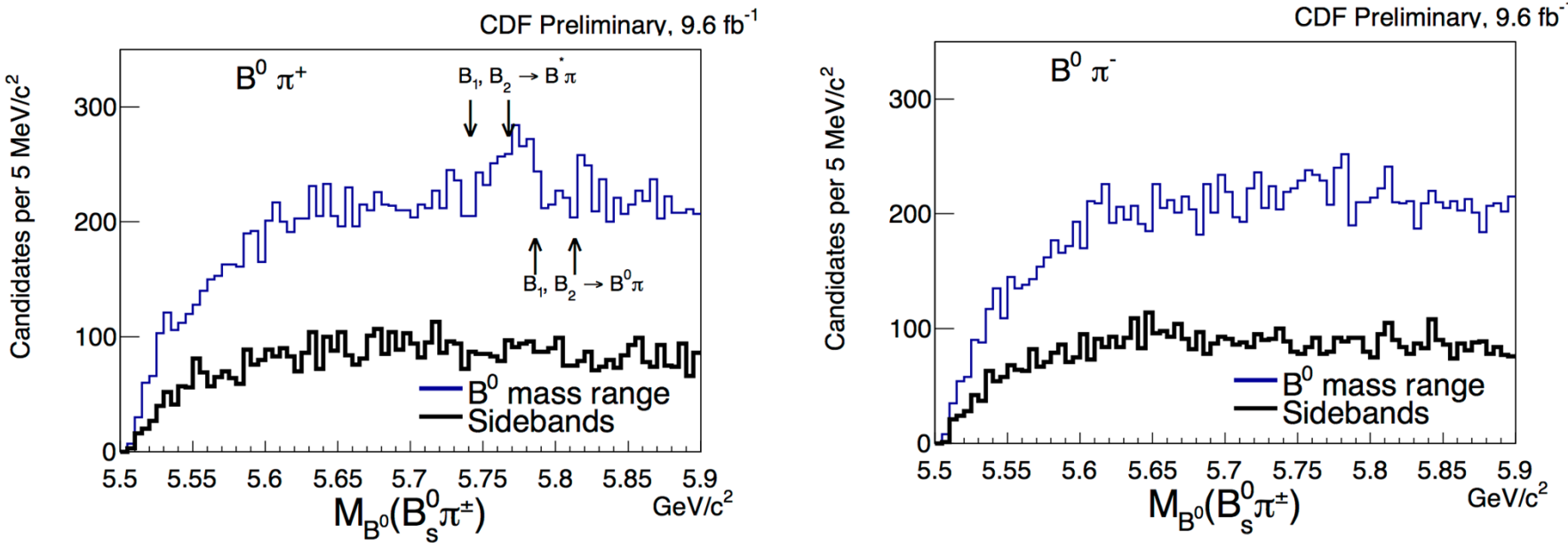


Parallel approach



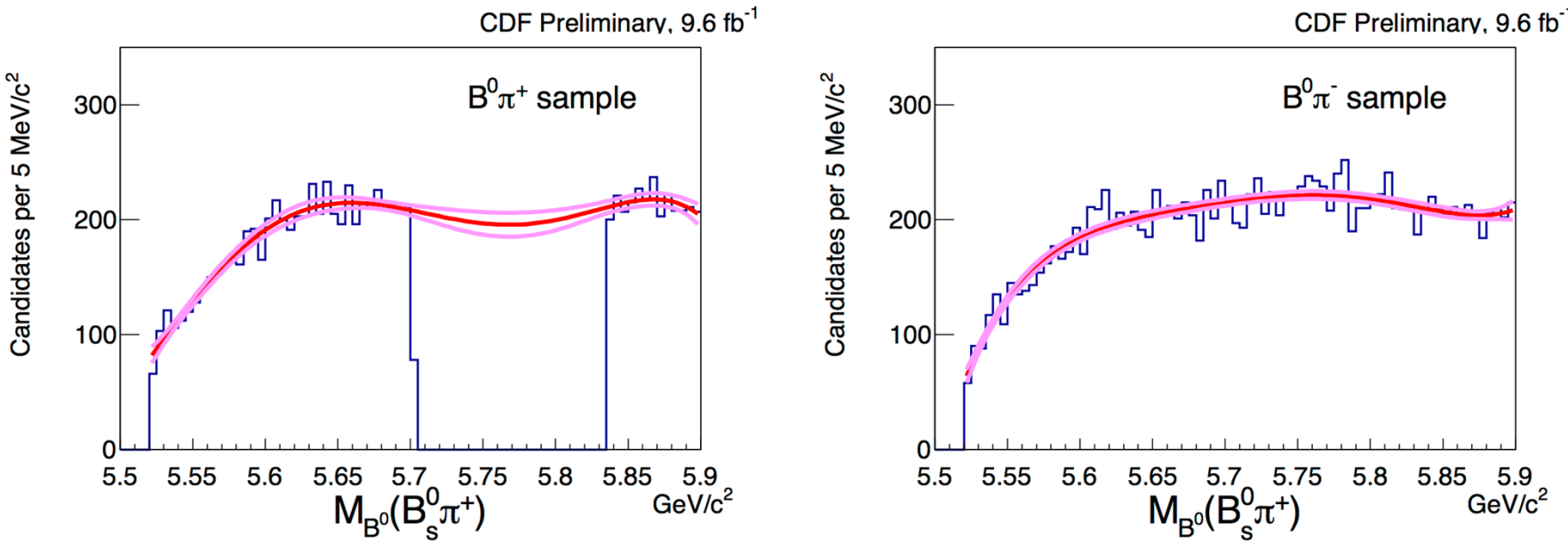
- Only the K^{0*} mass window differs from the B_s^0 selection.
  - Find 16560 ± 165 B^0 candidates

$B^0 \pi^\pm$ as a proxy for $B_s^0 \pi^\pm$



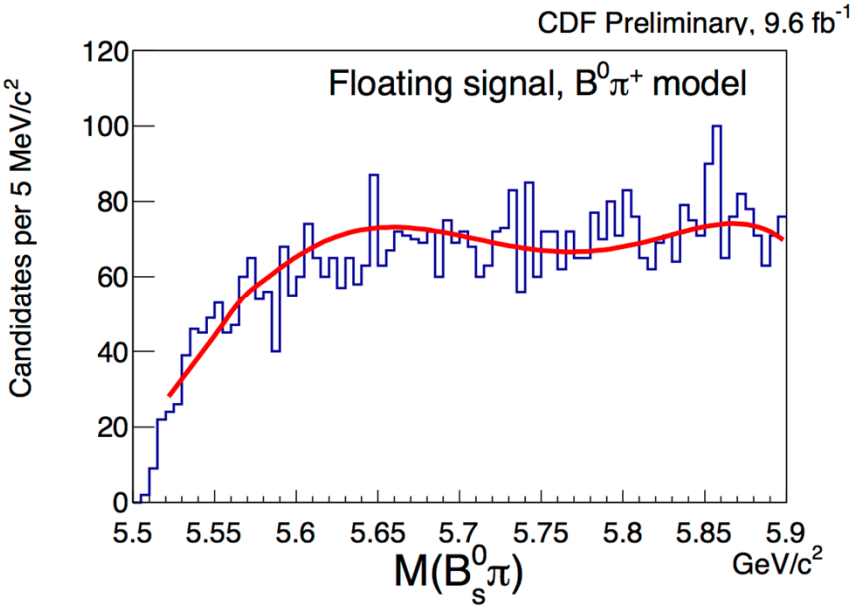
- Combine B^0 with $\pi^\pm$ to form a model for the $B_s^0 \pi^\pm$ distribution
  - Define $M_{B0}(B_s^0 \pi^\pm) = M(J/\psi K^{*0} \pi^\pm) - M(J/\psi K^{*0}) + M(B_s^0)$
- Evidence for excited B states, expected
- No features where none are expected

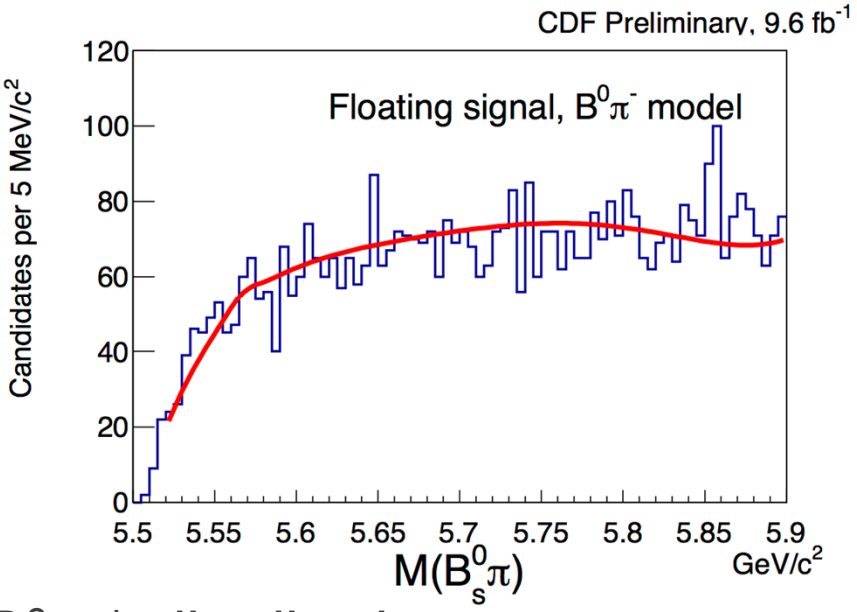
$B^0\pi^\pm$ as a proxy for $B_s^0\pi^\pm$



- Background models from the $B^0\pi^\pm$ distributions
- Omit range of excited B states
- Pink indicates statistical uncertainty

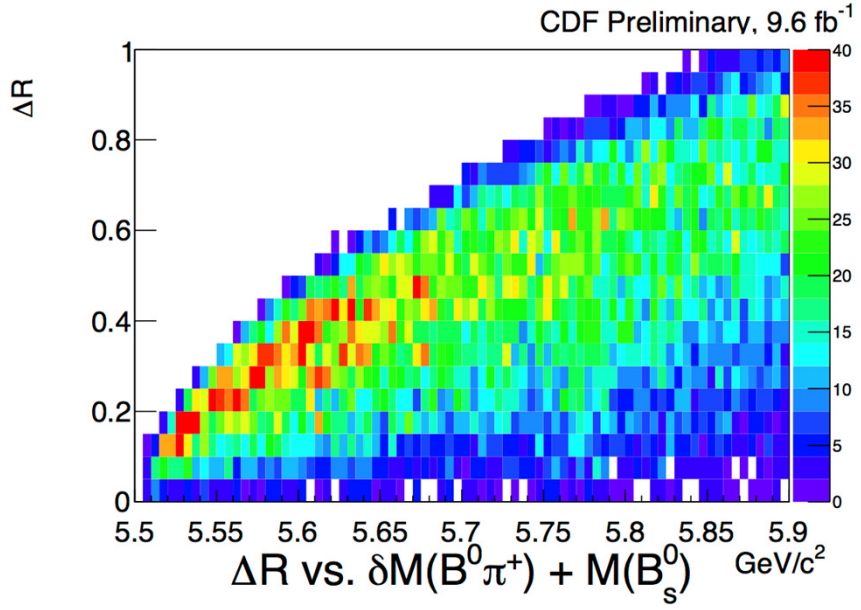
$B^0\pi^\pm$ backgrounds applied to the $B_s{}^0\pi^\pm$





- Background models from the $B^0\pi^\pm$ distributions
- Signal fit for $B_s{}^0$ production fraction from X(5568) finds
  - $0.9 \pm 1.9\%$ for $B^0\pi^+$ model
  - $1.7 \pm 1.9\%$ for $B^0\pi^-$ model
- 95% upper limits with each model are comparable to one based on $B_s{}^0\pi^\pm$

Selecting on ΔR, $B^0\pi^+$ control sample

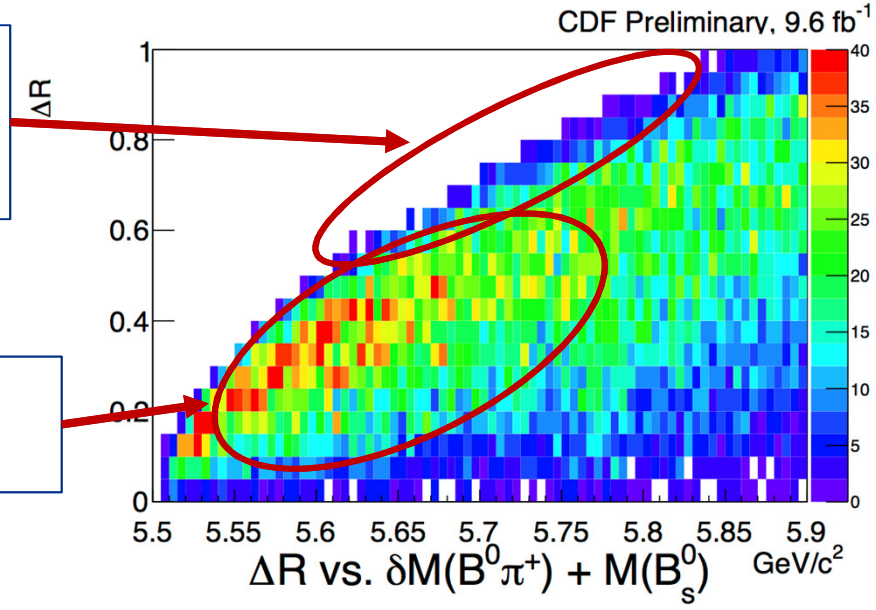


- A selection tool used by D0 is to limit $\Delta R = (\Delta\phi^2 + \Delta\eta^2)^{1/2}$
  - $\Delta\phi$ and $\Delta\eta$ are between B_s^0 and $\pi^\pm$
  - ΔR is the opening between B_s^0 and $\pi^\pm$
- Not used at CDF, highly correlated with mass

Selecting on ΔR, $B^0\pi^+$ control sample

Sharp cut off due to $p_T(\pi) > 400$ MeV/c requirement

Strong correlation between ΔR and mass



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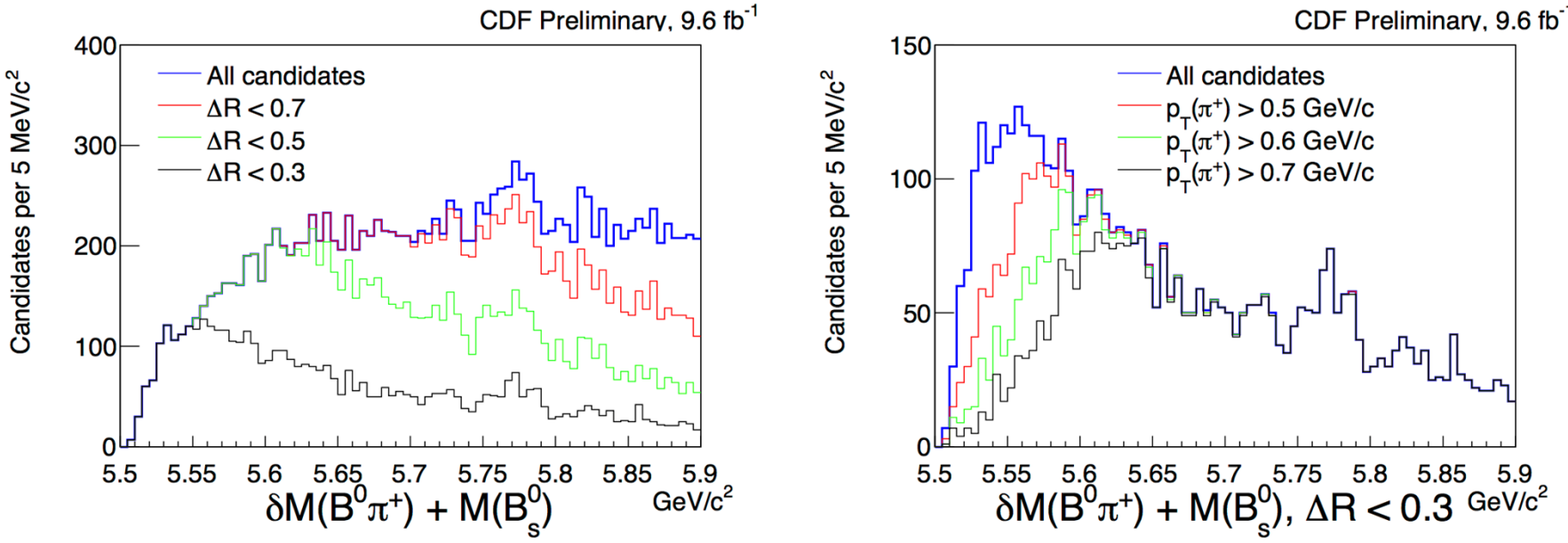
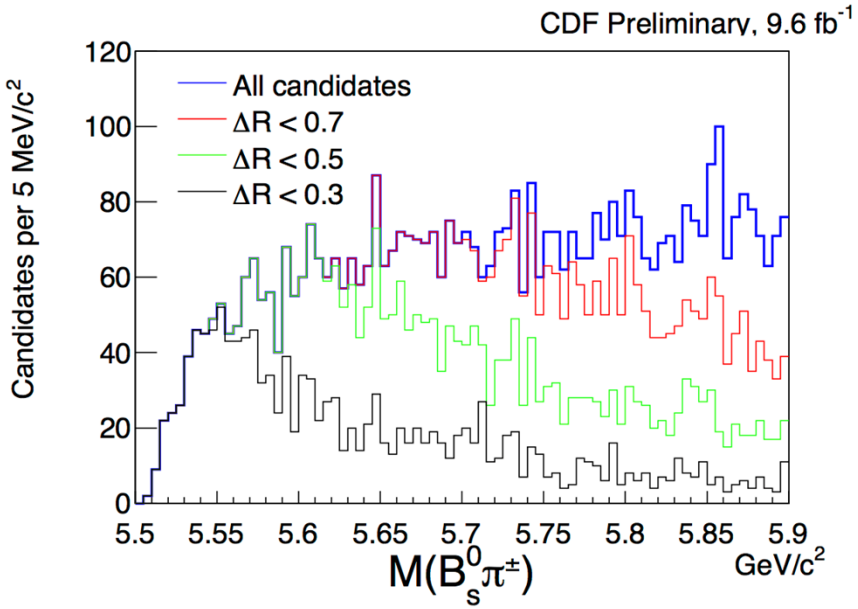
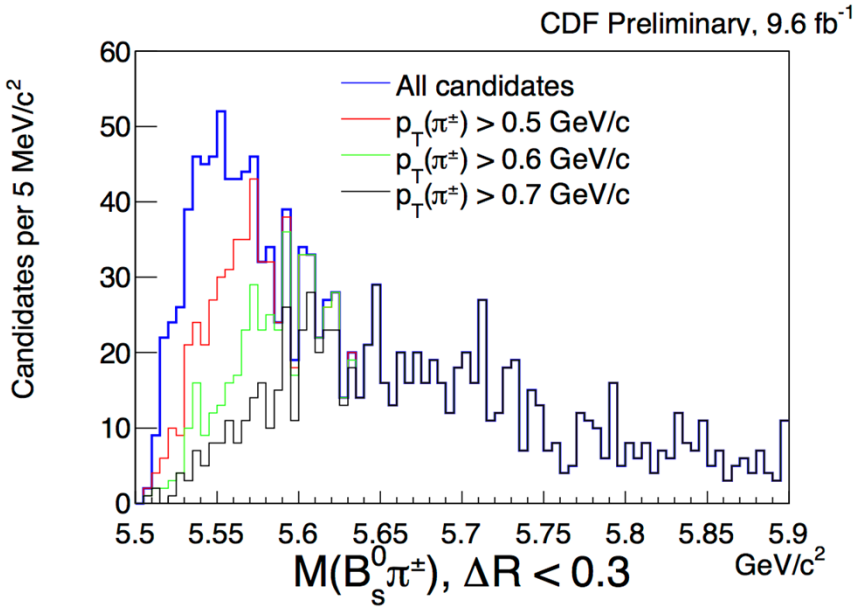
Selecting on ΔR, $B^0\pi^+$ system



- A ΔR requirement sculpts the mass distribution, removing higher mass candidates
  - In $B^0\pi^+$ system, background under excited B states is reduced
- The interplay between the ΔR and $p_T(\pi^\pm)$ requirements defines the background maximum.
  - Simple kinematics plus underlying momentum distribution

Selecting on ΔR, $B_s^0\pi^\pm$ system





- Same kinematics at work in the $B_s^0\pi^\pm$ system
  - ΔR requirement sculpts the high side
  - $p_T(\pi^\pm)$ requirement sculpts low side.
- Too much correlation, too much impact on the background shape at $M(B_s^0\pi^\pm) = 5568$ MeV/c²
- Not used in this analysis

Current Status

Analysis	$f_{Bs/X(5568)}$	Ref.
D0 ($J/\psi\,\phi$)	$8.6 \pm 1.9 \pm 1.4\%$	PRL 117,022003(2016)
D0 ($\mu\, D_s$)	$7.3^{+2.8}_{-2.4}{}^{+0.6}_{-1.7}\%$	arXiv:1712.10176
LHCb	$< 2.4\%$ ($p_T(B_s^0) > 10$ GeV)	PRL 117,152003 (2016)
CMS	$< 1.1\%$ ($p_T(B_s^0) > 10$ GeV)	arXiv:1712.07588
ATLAS	$< 1.5\%$ ($p_T(B_s^0) > 10$ GeV)	arXiv:1802.01840
CDF	**$< 6.7\%$ ($2.3 \pm 1.9 \pm 0.9\%$)**	**arXiv:1712.09620**

- Status of the X(5568) searches
  - D0 first observation
  - Confirming observation in a second final state
- No confirmations from other experiments, limits set
- Our central value is about 2σ in tension with D0

Summary

- CDF has looked for the reported process $X(5568) \rightarrow B_s^0 \pi^{\pm}$
  - $B_s^0 \rightarrow J/\psi\phi$, $J/\psi \rightarrow \mu^+ \mu^-$, $\phi \rightarrow K^+ K^-$
- Approach chosen is simple, select on track p_T, impact, decay time, mass of combinations
  - No opening angles or other new techniques
- The background under the target was modeled with the data
  - Smooth extrapolation through the search area
  - Model assumes the reported X(5568), varied by its uncertainties
- The yield of the X(5568) found is not significant from 0
  - About 2σ tension with D0 report
  - Upper limit of 6.7% estimated (95% C.L.)