Studies of X(5568) and Evidence for $Z_c^{\pm}(3900)$ in b-flavored Hadron Decays

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For the D0 Collaboration

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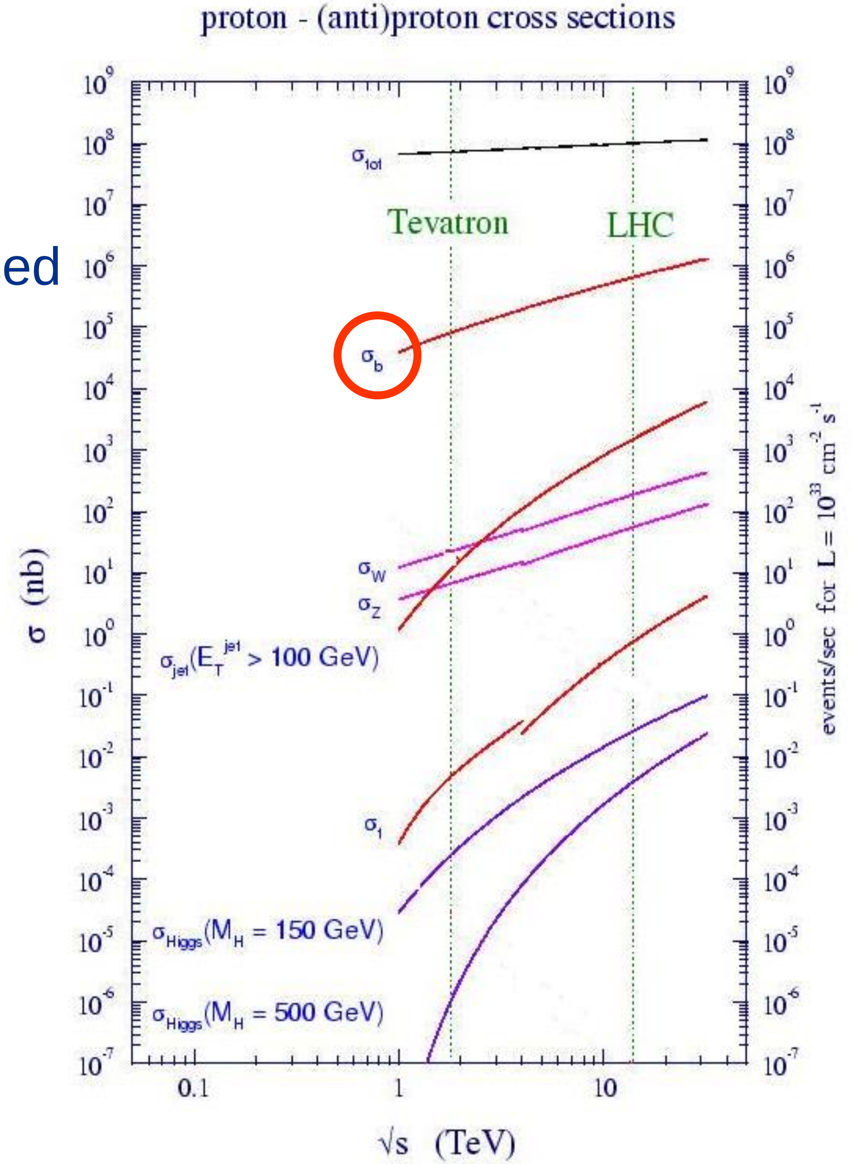
Heavy Flavor Studies at Hadron Colliders

High b quark cross section: $\sim 10^{-3}\ \sigma_{tot}$

$\sim 10^4$ b's per second produced!

All species containing b quark are produced

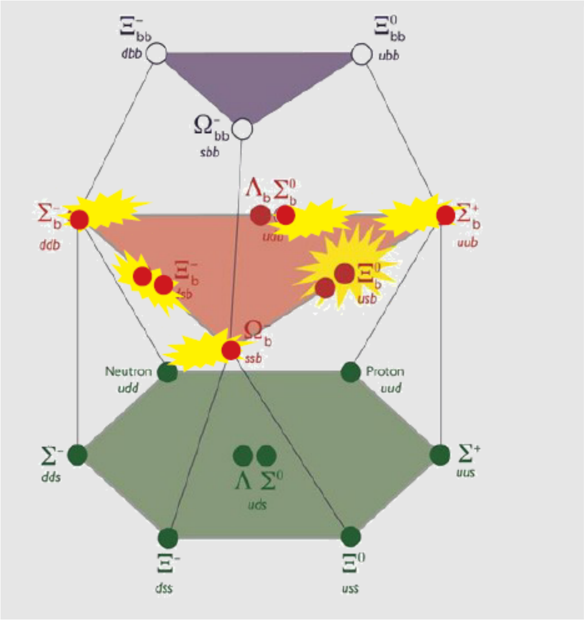
$B^{\pm}$, B^0, B_s, B_c, Λ_b…

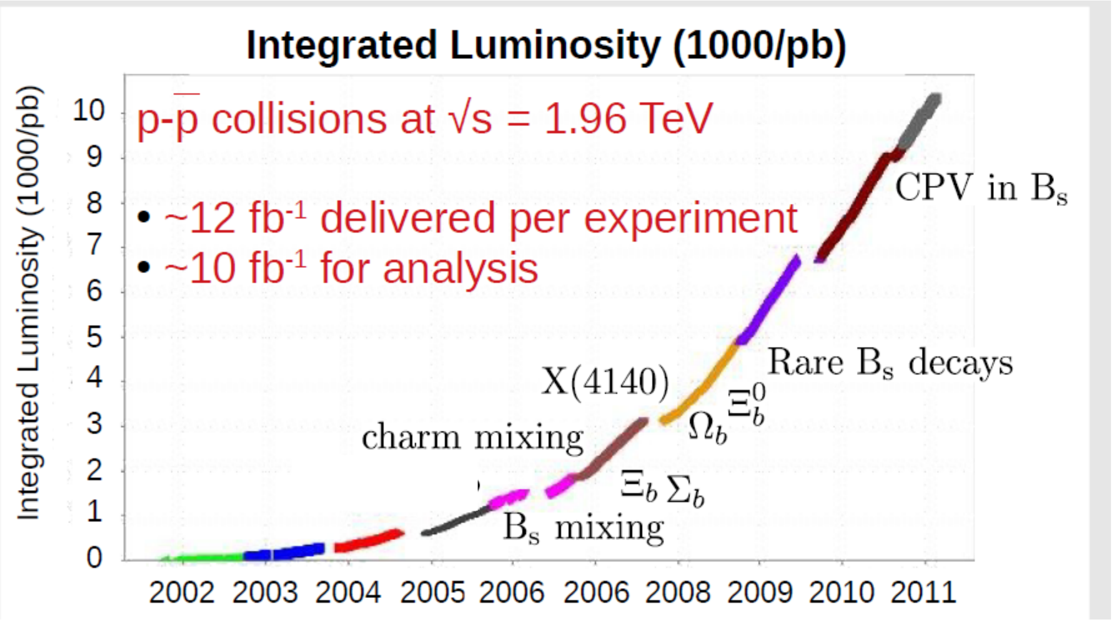


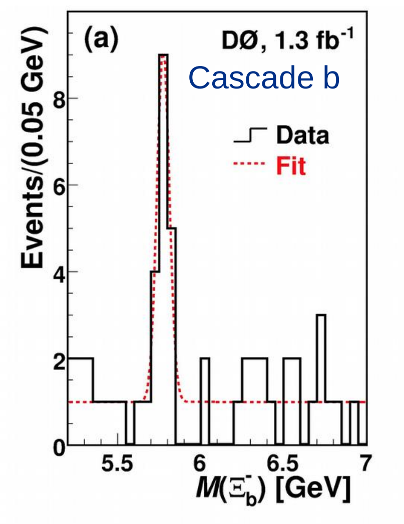
Large b quark data samples provide

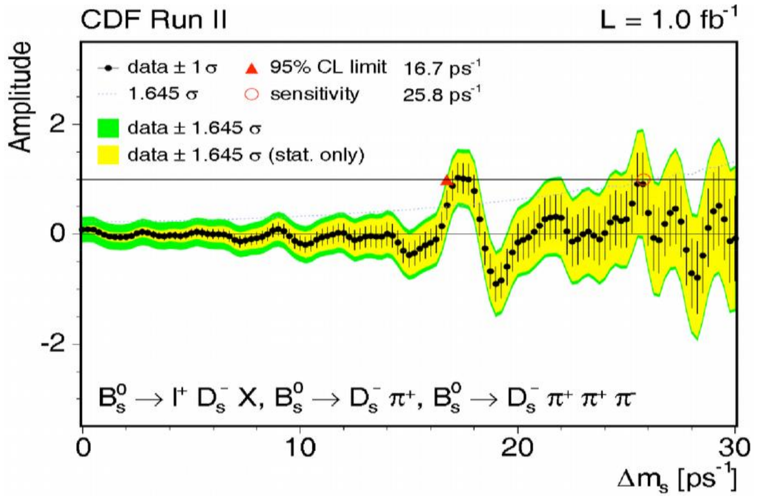
- B mesons lifetime studies
- Mass spectroscopy (B_c, etc.)
- Studies of B_s oscillations
- CP violation studies
- Search for new b hadrons
- Search for rare decays

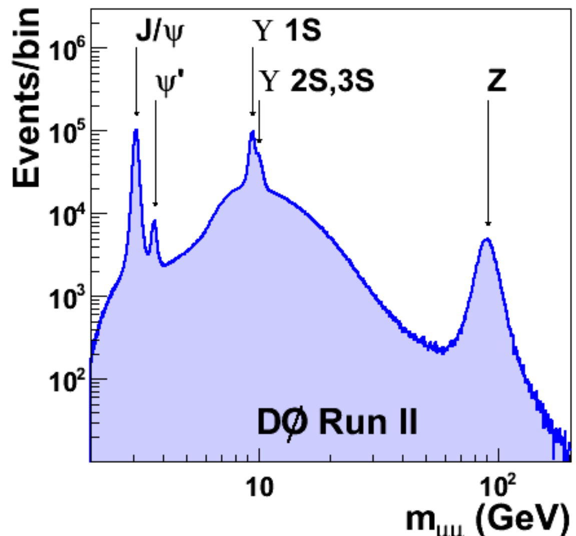
Many Legacy Heavy Flavor Results from the Tevatron



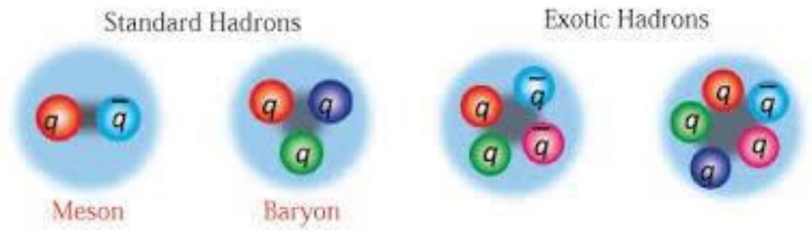




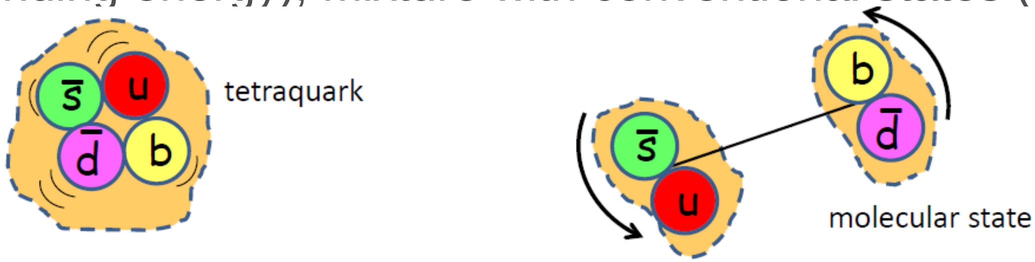




Multi-quark States



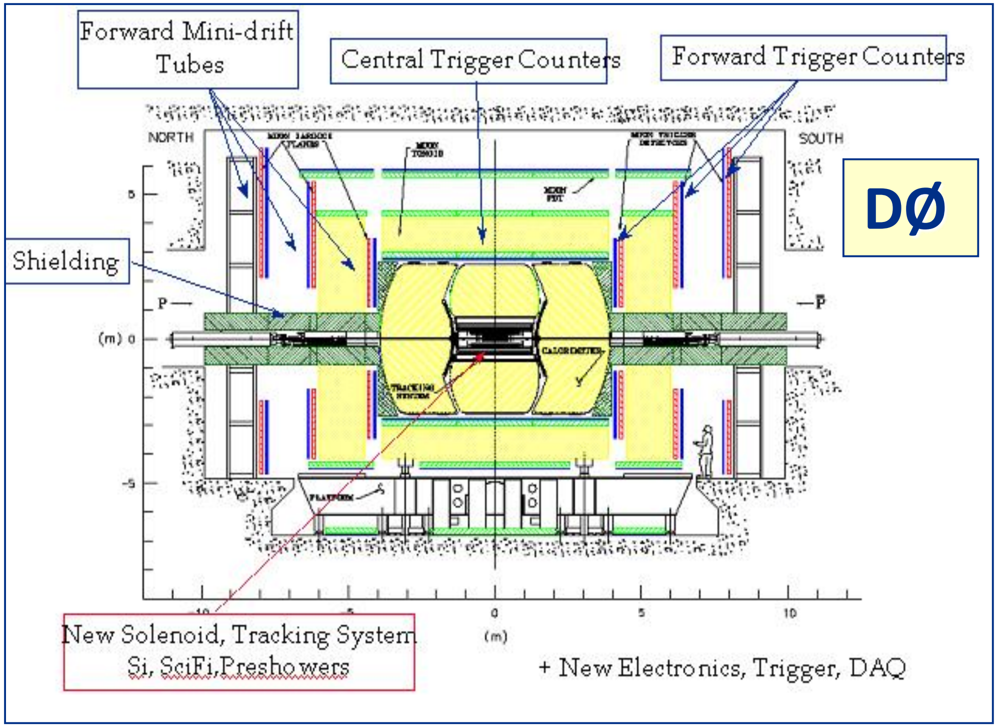
- ~20 multi-quark states are observed since 2003 with high significance
  - BES, Belle, Babar, CDF, D0, LHCb, Atlas, CMS
- Some examples of multi-quark states
  - Tetraquarks candidates **X(3782)**$\rightarrow J/\psi\pi^+\pi^-$, **$Z^+$(4430)**$\rightarrow \Psi'\pi^+$, **X(4140)**$\rightarrow J/\psi\phi$, **$Z_b^+$(10610)**$\rightarrow \Upsilon\pi^+$, **$Z_b^+$(10650)** $\rightarrow \Upsilon\pi^+$
  - Pentaquarks candidates **P_c^+(4450)** $\rightarrow J/\psi p$, **P_c^+(4380)** $\rightarrow J/\psi p$
- Four-quark states interpretations: tetraquarks (large binding energy), molecular states (small binding energy), mixture with conventional states (if possible)

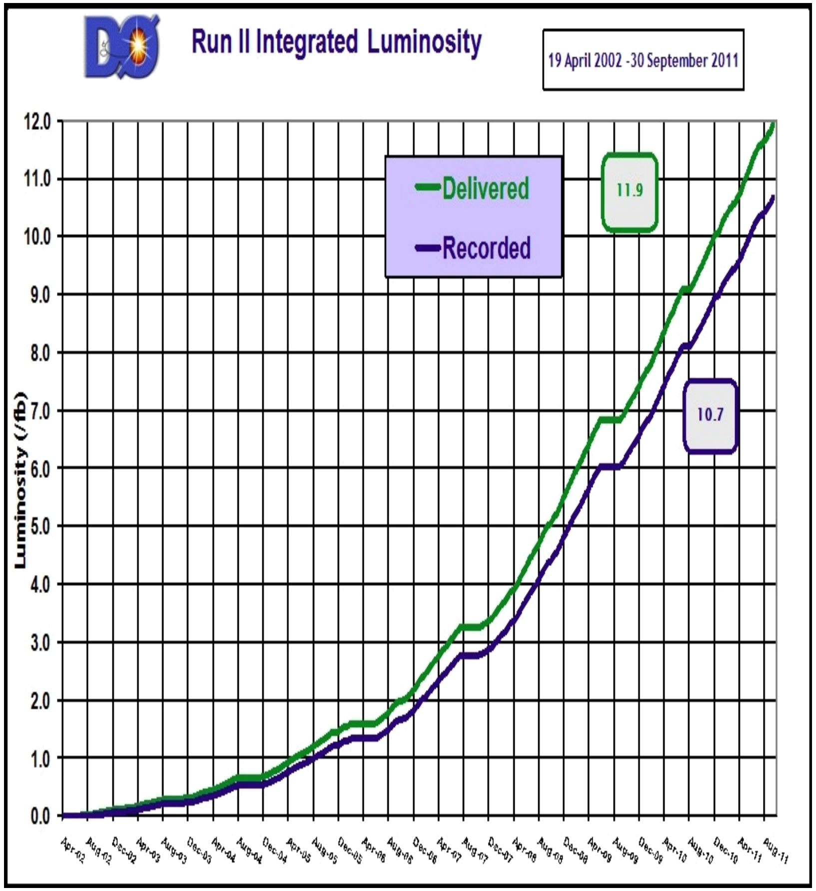


- Many observed multi-quark states lie close to two-hadron mass thresholds and, therefore, they can be interpreted as molecular states

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

DØ Detector and Data Collection



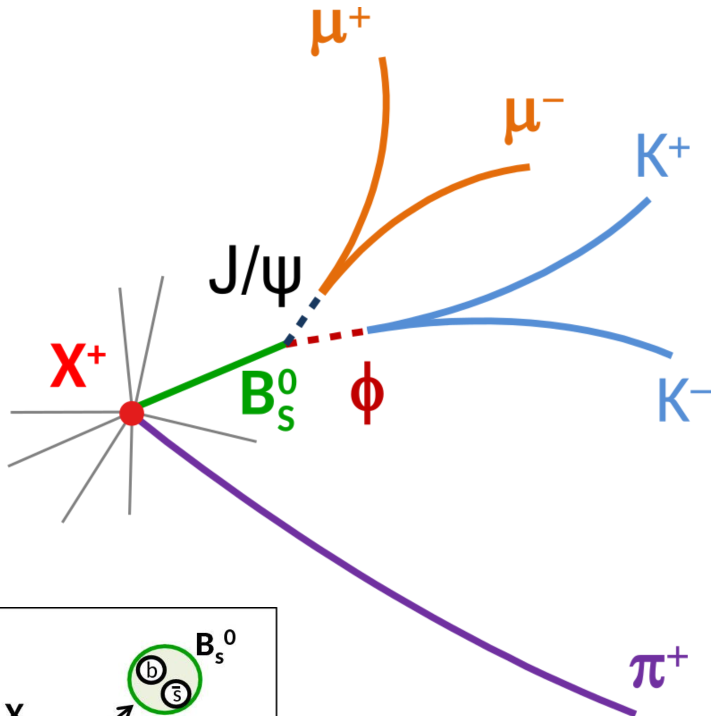


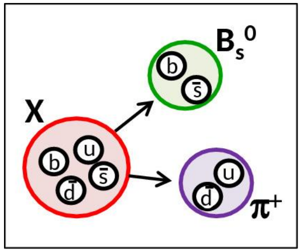
2001 2011

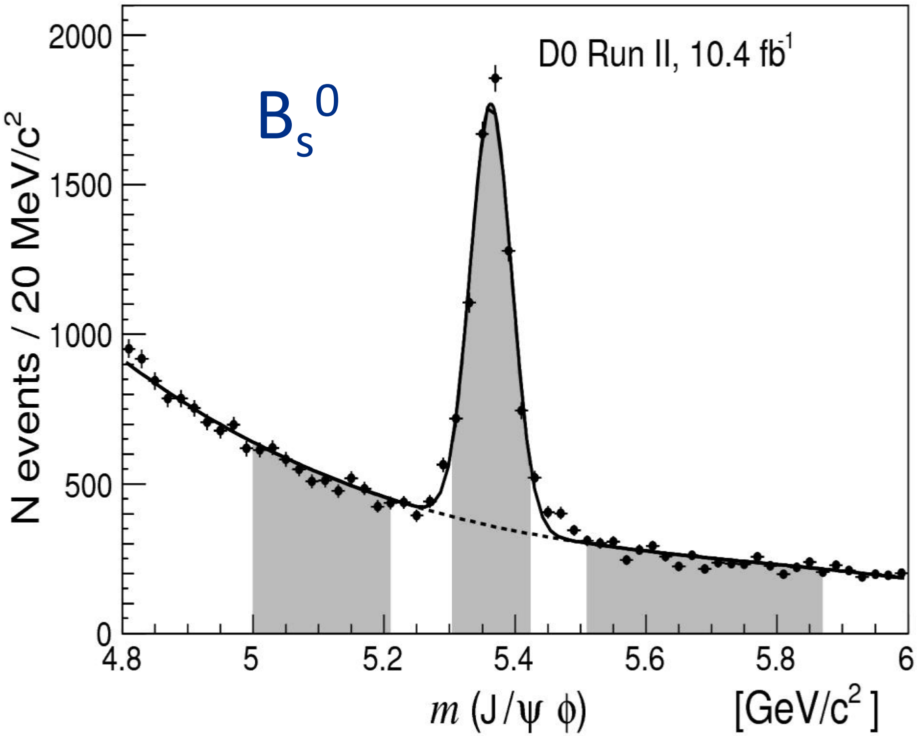
Silicon Detector
2 T solenoid and central fiber tracker
Large eta coverage muon system
Fast electronics

- ~10 fb^{-1} of data for analysis
  - Billions of events recorded with single and di-muon triggers

Search for Four Quarks State X(5568)→$B_s^0\pi^\pm$, B_s^0→J/ψφ

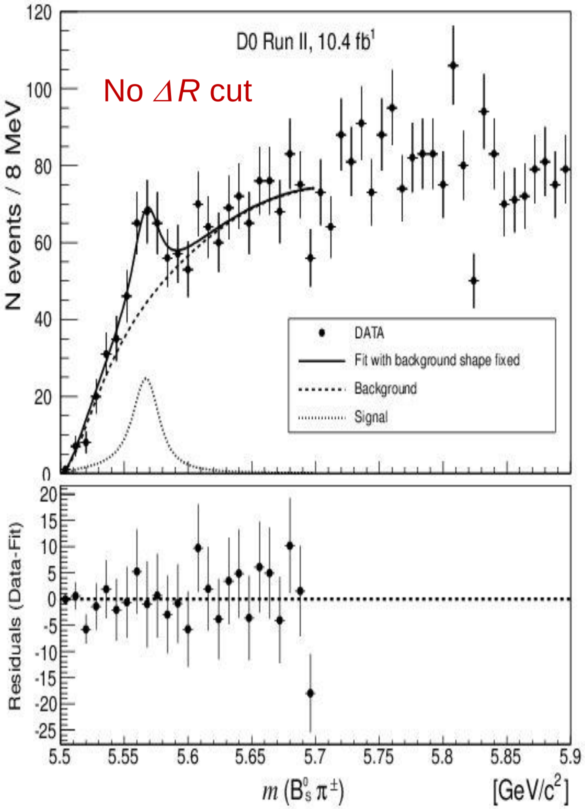




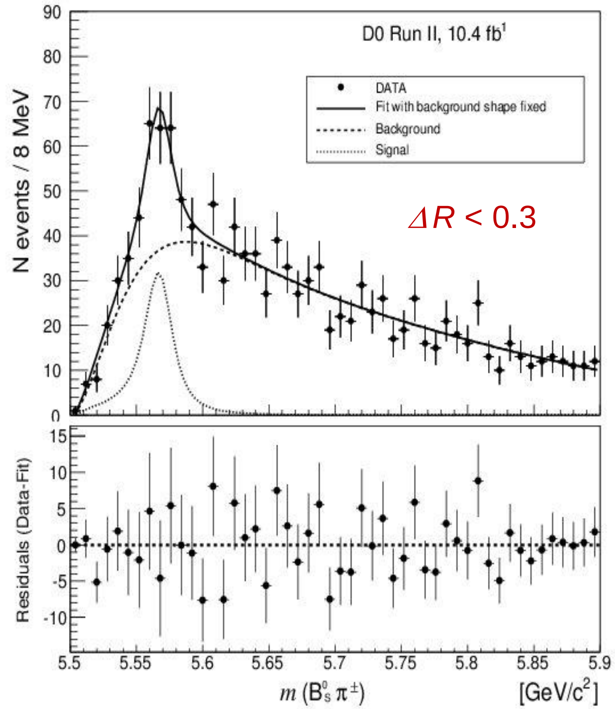


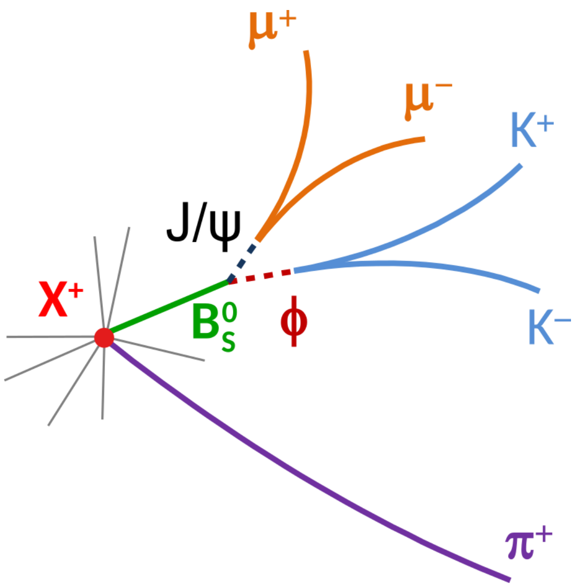
- Looking for possible strong decays of four-quarks object containing four different quarks: u, d, s and b
- Require that the pion comes from the proton-antiproton interaction vertex

Observation of X(5568)$\rightarrow B_s^0\pi^\pm$, $B_s^0\rightarrow J/\psi\varphi$



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





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

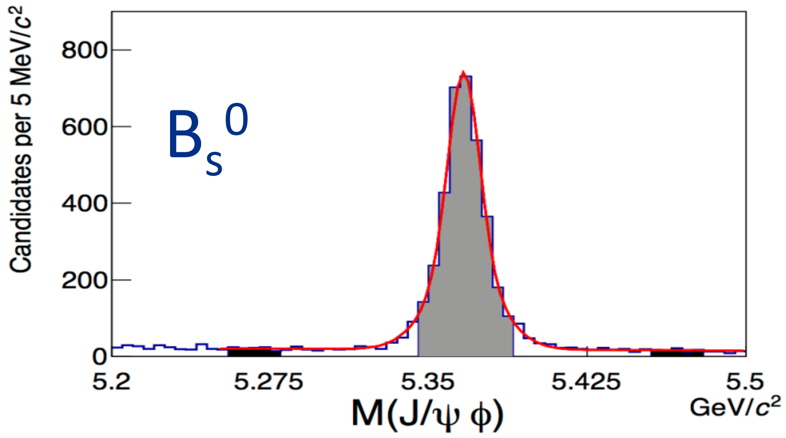
$$\Gamma = 21.9 \pm 6.4(\text{stat})^{+5.0}_{-2.5}(\text{syst})\ \text{MeV/c}^2$$

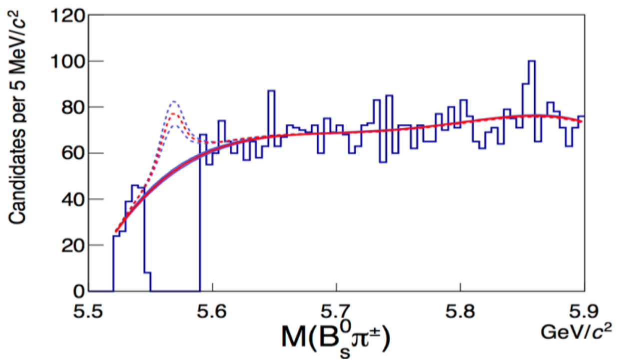
$$R\ (X(5568)/B_s) = 8.6 \pm 1.9\ (\text{stat}) \pm 1.4\ (\text{syst})\%$$

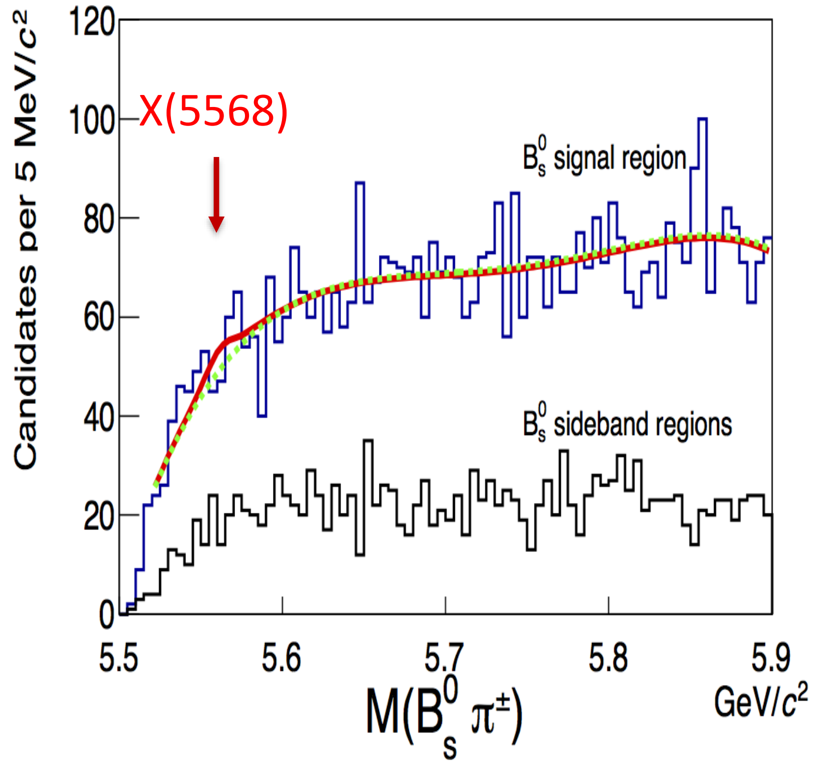
Significance = 5.1 σ with ΔR cut including look-elsewhere effect and systematics

3.9 σ without ΔR cut

CDF Search for X(5568) → $B_s^0\pi^{\pm}$, $B_s^0 \to J/\psi\varphi$



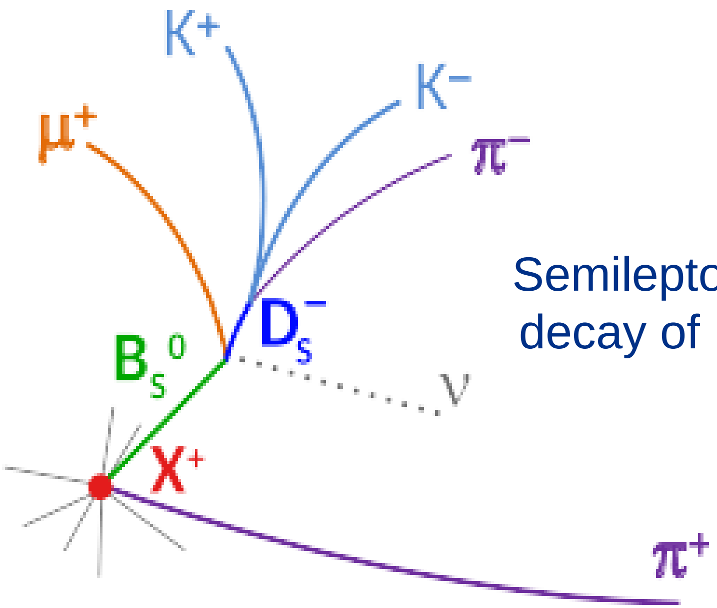




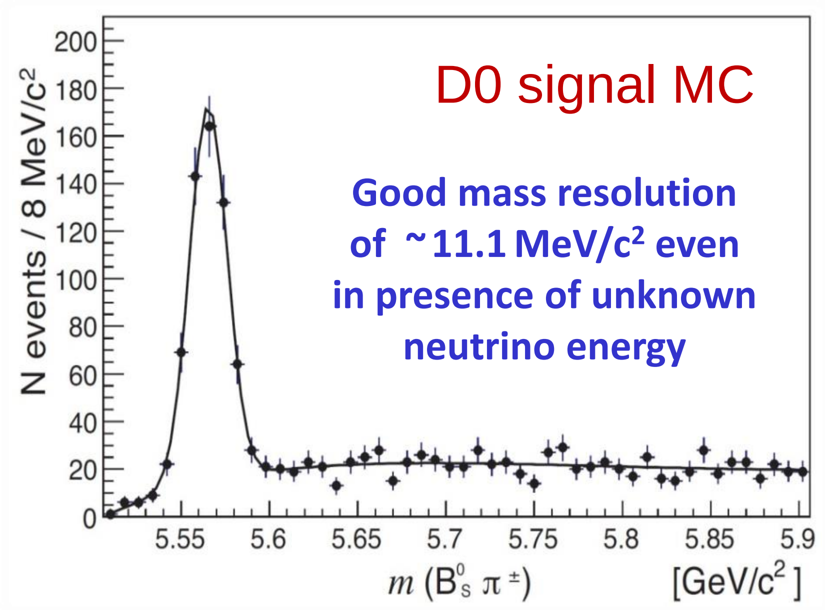
- CDF repeated the measurement with somewhat different selections, and substantially smaller muon rapidity coverage /eta/<1 vs /eta/<2
- No significant signal observed and upper limit set at 6.7% at 95% CL
- If DØ restricts eta coverage to CDF value, most of the X(5568) signal is gone
  - Critical to understand physics of the production and decay of multi-quark objects

X(5568) → $B_s^0\pi^\pm$, with Semileptonic B_s^0 decay

D0 collaboration, PRD 97, 092004 (2018)



Semileptonic decay of B_s^0

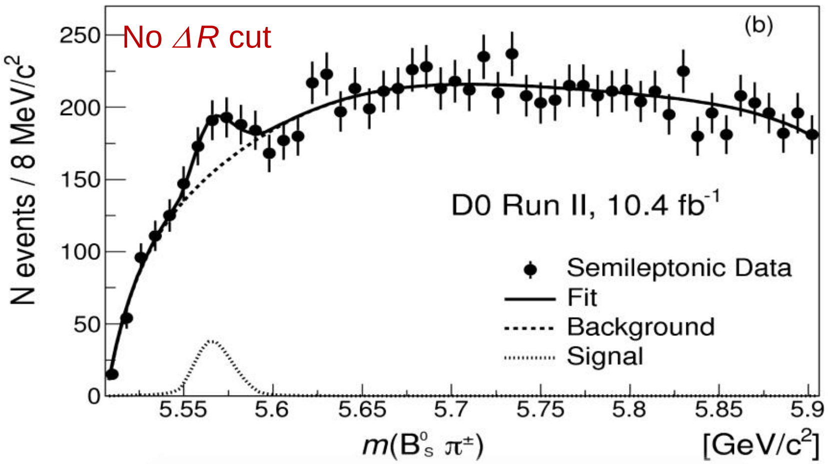


$X^+(5568) \rightarrow B_s\pi^+$, $B_s \rightarrow D_s^-\mu^+ X_{any}$, $D_s^- \rightarrow \phi(1020)\pi^-$, $\phi \rightarrow K^+K^-$

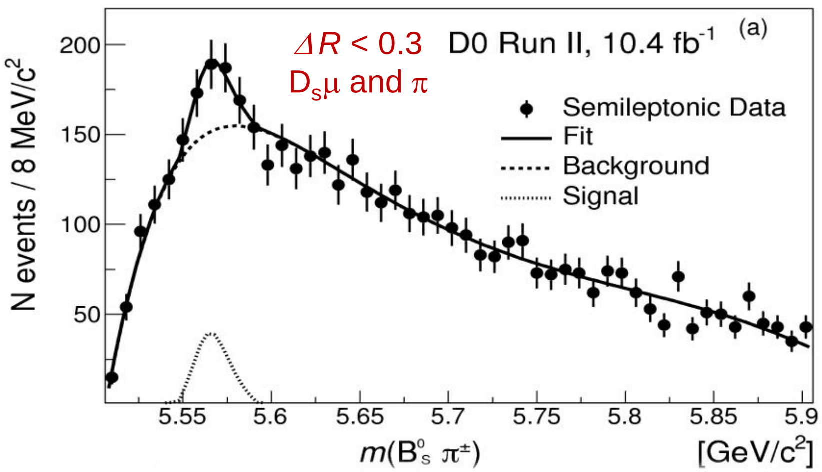
1. Calculate visible mass $M(D_s^-\mu^+)$
2. Use visible mass as B_s mass
3. Combine B_s and π^+ to form X
4. Estimate $M(X) = M(B_s^0\pi^\pm) =$ $M(D_s\mu\pi) - M(D_s\mu) + M_{PDG}(B_s^0)$

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

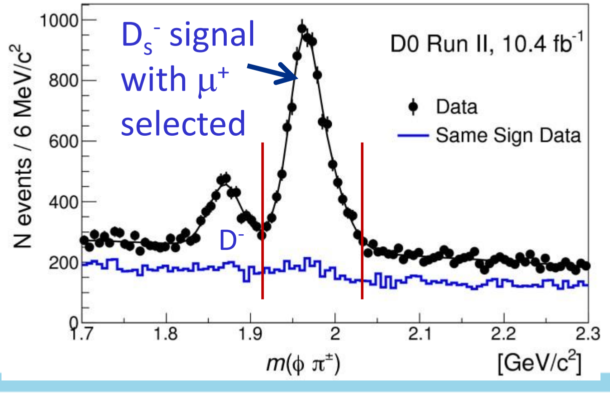
X(5568) → $B_s^0\pi^\pm$, with Semileptonic B_s^0 decay



$M_X = 5566.7^{+3.6+1.9}_{-3.4-1.0}$ MeV/c²
$\Gamma_X = 6.0^{+9.5+1.9}_{-6.0-4.6}$ MeV/c²
$N_{ev} = 139^{+51+11}_{-63-32}$
Significance(local) = 4.5 σ
Significance(local+syst) = 3.4 σ



$M_X = 5566.4^{+3.4+1.4}_{-2.8-0.6}$ MeV/c²
$\Gamma_X = 2.0^{+9.5+2.8}_{-2.0-2.0}$ MeV/c²
$N_{ev} = 121^{+51+9}_{-34-28}$
Significance(local) = 4.3 σ
Significance(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

Background shape estimated using data and MC

Comparison of X(5568) Production in two B_s^0 Decay 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	4.3σ	4.5σ	6.6σ	4.8σ
Significance with systematics	3.2σ	3.4σ	5.6σ	...
Significance with LEE+systematics	...	...	5.1σ	3.9σ

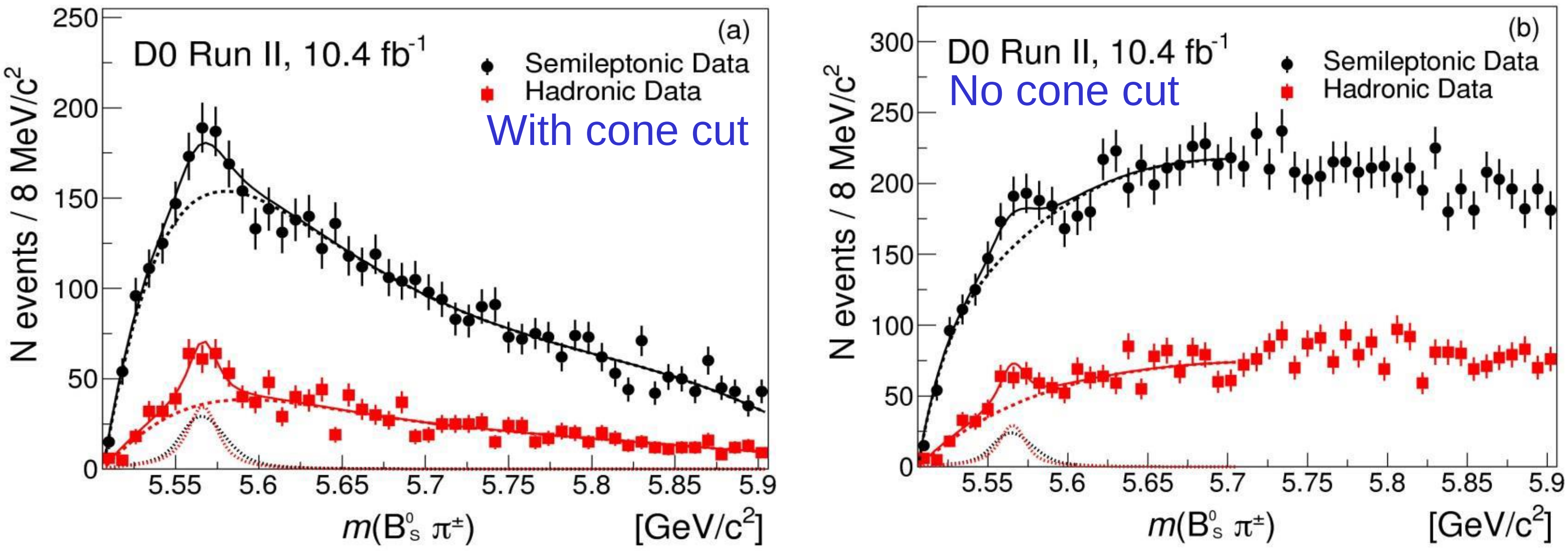
Production ratio of X(5568) to B_s

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

$X(5568)/B_s = 8.6 \pm 1.9(\mathrm{stat}) \pm 1.4(\mathrm{syst})\%$ **Hadronic channel, cone cut**

- Study in semileptonic channel confirms X(5568) observed in hadronic channel
- Good agreement between results obtained in hadronic and semileptonic channels

Simultaneous X (5568) 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	$6.7\,\sigma$	$4.7\,\sigma$

Substantial increase in significance combining two independent data samples

Results from Five Collider Experiments on X(5568)

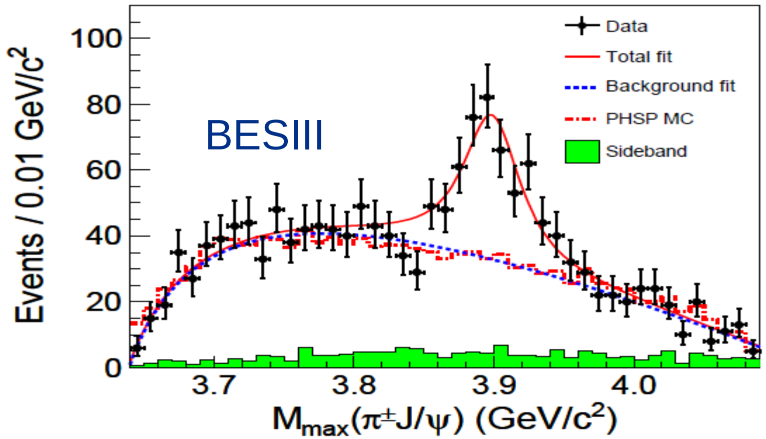
Analysis	Production ratio (B_s / X(5568))	Reference
D0 ($J/\psi\ \phi$)	8.6 ± 1.9 ± 1.4%	PRL 117,022003(2016)
D0 ($\mu\ D_s$)	$7.3^{+2.8}_{-2.4}{}^{+0.6}_{-1.7}$%	PRD 97, 092004 (2018)
LHCb	< 2.4% ($p_T(B_s^0)$ > 10 GeV)	PRL 117,152003 (2016)
CMS	< 1.1% ($p_T(B_s^0)$ > 10 GeV)	PRL 120, 202005 (2018)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

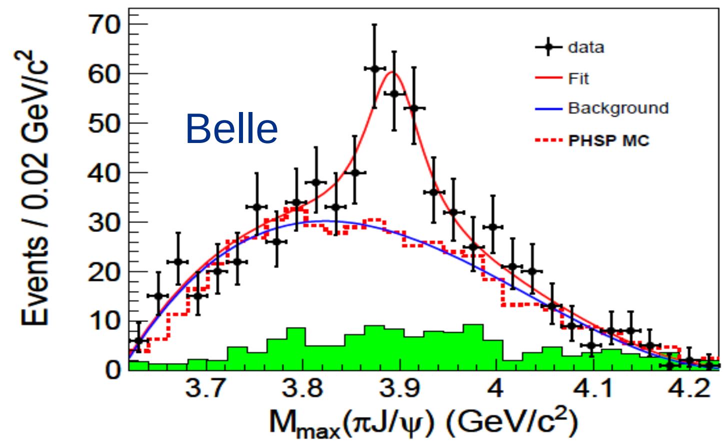
- LHC experiments do not observe X(5568) at higher collisions energy
- CDF result is in ~2σ tension with DØ studies in hadronic decay channel
  - Kinematic selections vary substantially
  - Ratio to B_s^0 production might not be the best metric
- Without theoretical model of X(5568) production and decays it is hard to compare various experiments quantitively

$Z_c^+(3900)$ Search in Hadron Collisions

- $Z^+(3900)$ was discovered in 2013 by Belle and BESIII in the process

$$e^+e^- \to Y(4260) \to Z_c^+(3900)\pi^-,\ Z_c^+ \to J/\psi\pi^+ \ (+c.c.)$$

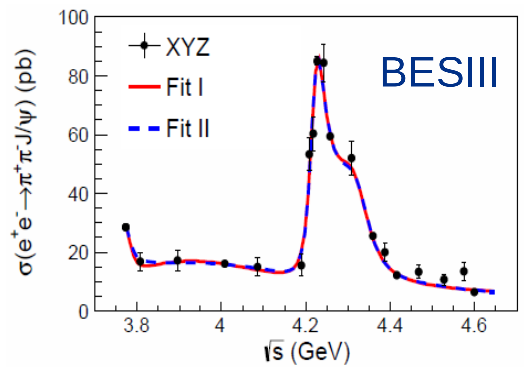




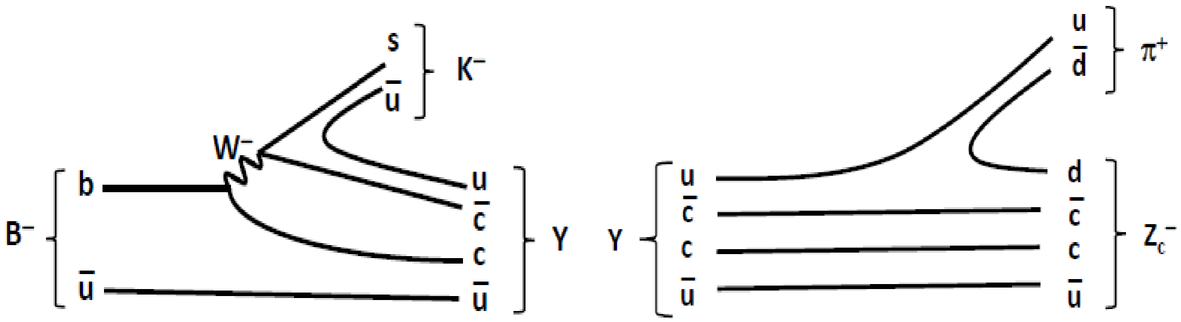
- Minimum $Z_c^+(3900)$ quark content cc(bar)ud(bar)

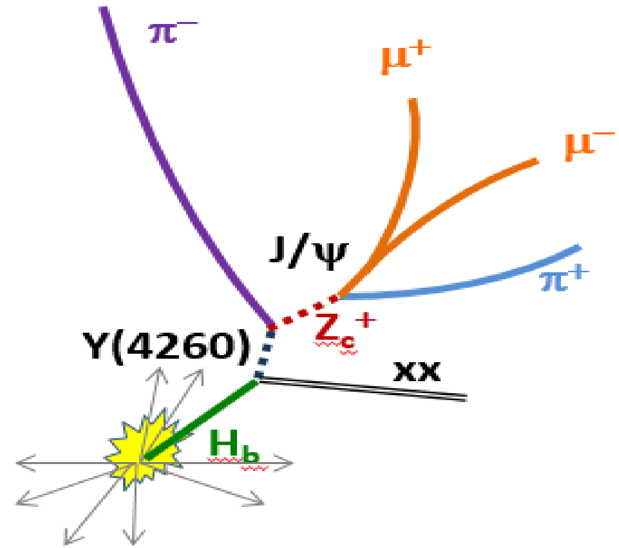
$M = 3886.6 \pm 2.4$ MeV $\quad \Gamma = 28.1 \pm 2.6$ MeV

- Latest from BESIII
  - "Y (4260)" consists of two interfering resonances
  - PDG 2018 names them ψ(4260) and ψ(4360)
- Questions
  - Which component of the "Y (4260)" decays to the $Z_c(3900)$?
  - Are there decays $H_b \to Y (\to Z_c^+(3900)\pi^-)$ + anything?



Production of $Z_c^{\pm}(3900)$ in b-hadron Decays





- We search for the $Z_c^{+}(3900)$ production in H_b decays via the following decays

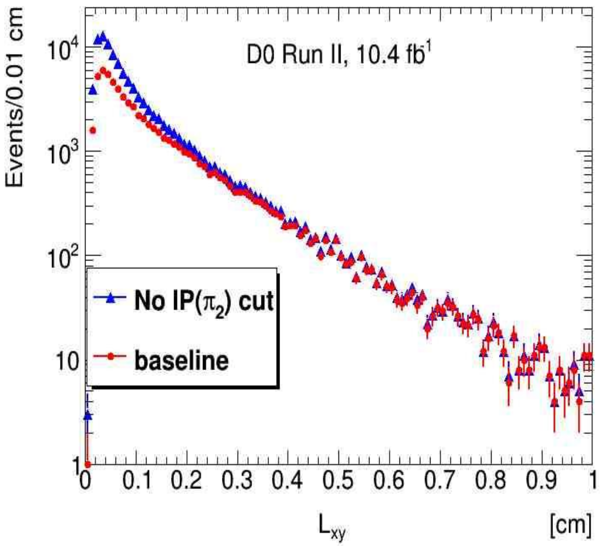
$$H_b \rightarrow Y(4260) + \text{anything}\ ,\ Y(4260) \rightarrow Z_c^{\pm}(3900)\pi^{\mp}\ ,\ Z_c^{\pm}(3900) \rightarrow J/\psi\pi^{\pm}$$

where H_b is any b-flavored hadron

arXiv:1807.00183

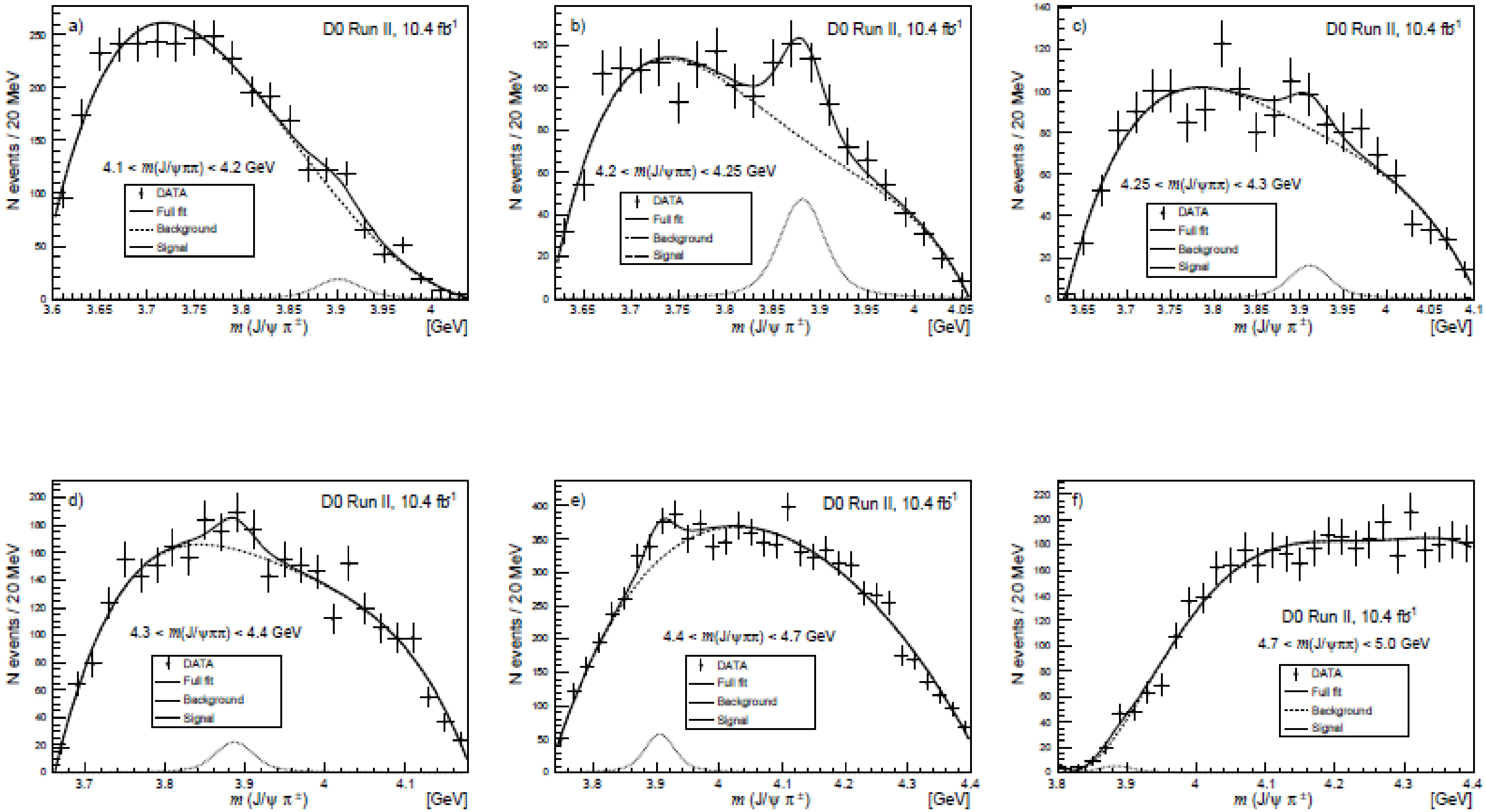
Data Sample

- 10.4 fb^{-1} of proton antiproton collisions at 1.96 TeV
- Collected with single and di-muon triggers
- Select events with $J/\psi \to \mu^+\mu^-$ in the final state plus two tracks
  - p_T ($track_1$) > 1.0 GeV, p_T ($track_2$) > 0.8 GeV
- Treat both tracks as pions
  - Charge($track_1$) ∗ Charge($track_2$) < 0
- Veto $K^* \to \pi K(K\pi)$, $\varphi \to KK$, and γ conversions
- Displaced vertex selection
  - $L_{xy}(J/\psi\pi^+)/\sigma(L_{xy}) > 5$, $IP_{xy}(track_{1(2)})/\sigma(IP) > 2(1)$
- Vertex fits
  - $J/\psi\pi^+$ $\chi 2 < 10$, adding extra pion $J/\psi\pi^+\pi^-$ $\delta\chi 2 < 6$
- After above cuts we selected events with displaced $J/\psi\pi^+\pi^-$ vertices
  - L_{xy} distribution has slope consistent with B hadron decays lifetime



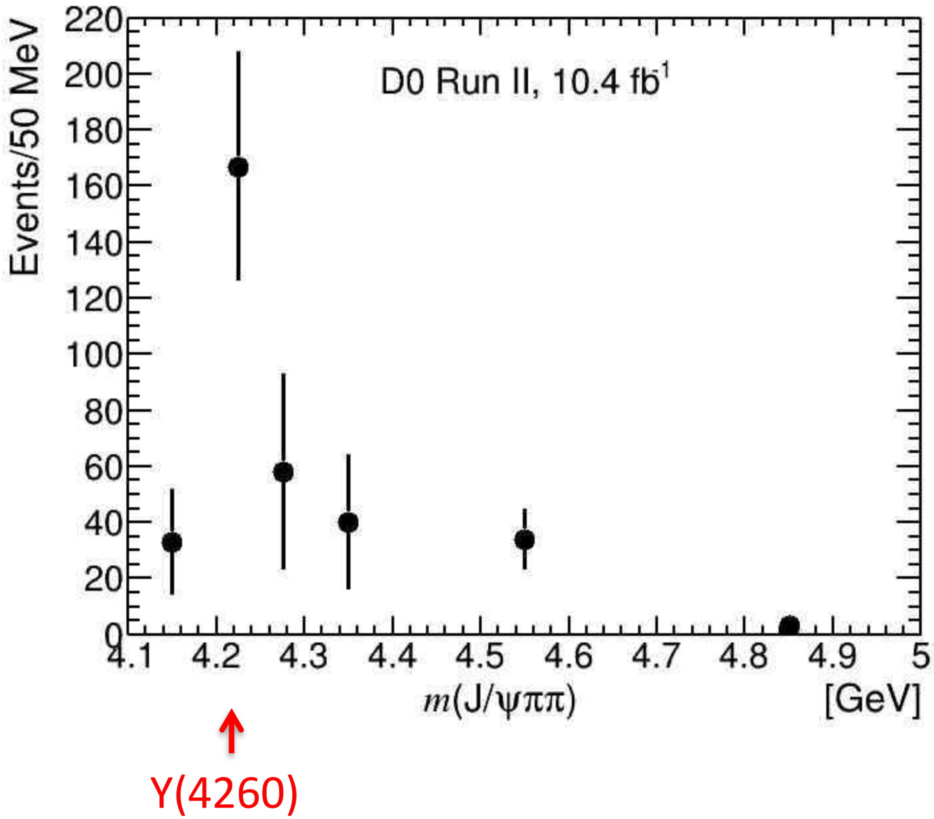
We study $m(J/\psi\pi)$ in the events that have $4.1 < m(J/\psi\pi^+\pi^-) < 5.0$ GeV

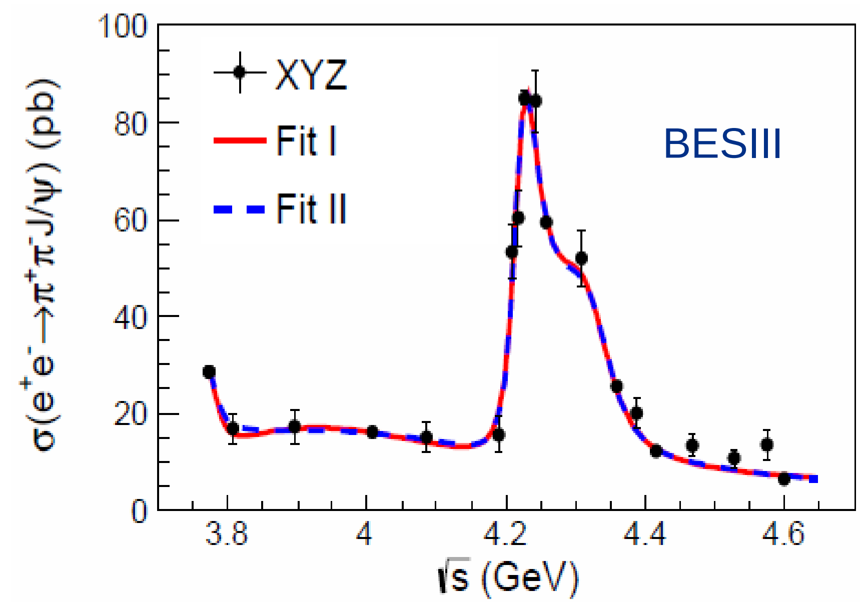
$m(J/\psi\pi^+)$ Mass Distributions in Slices of $m(J/\psi\pi^+\pi^-)$



We fit $m(J/\psi\pi^+)$ in six slices of $m(J/\psi\pi^+\pi^-)$ using the S-wave relativistic Breit-Wigner function with Γ fixed to PDG value for the $Z_c^+(3900)$ signal and background parametrized with Chebyshev polynomials

Number of $Z_c^+(3900)$ Events vs $m(J/\psi\pi^+\pi^-)$

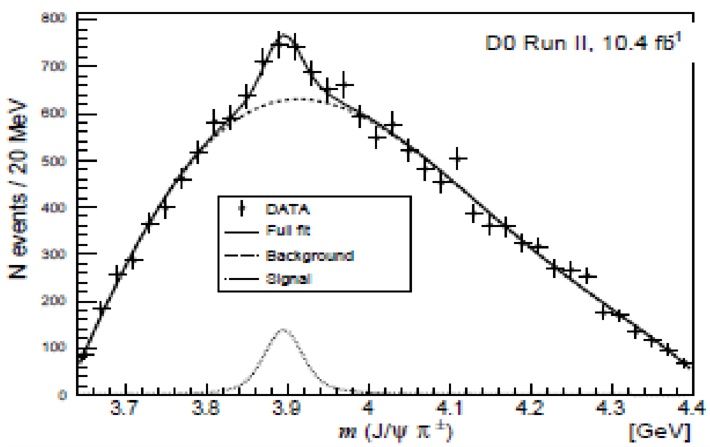




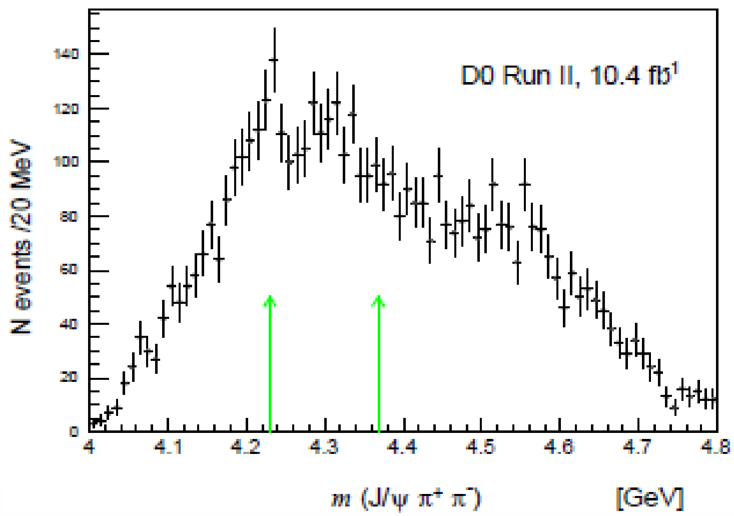
- Majority of $Z_c^+(3900)$ events, as expected, are coming from ψ states with masses in the 4.2 to 4.3 GeV region
  - But there is an indication that some Z_c events come from J/psiππ masses above the ψ(4260) and ψ(4360)

$Z_c^+(3900)$ Signal

- Select events with $4.2 < m(J/\psi\pi^+\pi^-) < 5.0$ GeV
  - Fit parameters of $Z_c^+(3900)$ signal (width is fixed at PDG value)



Z_c signal
$N(Z_c) = 502 \pm 92$
Statistical significance 5.6σ
$M = 3895.0 \pm 5.2$ MeV



$M(J/\psi\pi\pi)$ for events around Z_c peak

If we select events with $J/\psi\pi^+$ mass in the vicinity of $Z_c^+(3900)$ we can see clear enhancement in $\psi(4260)$ mass region even though signal/background ratio is low

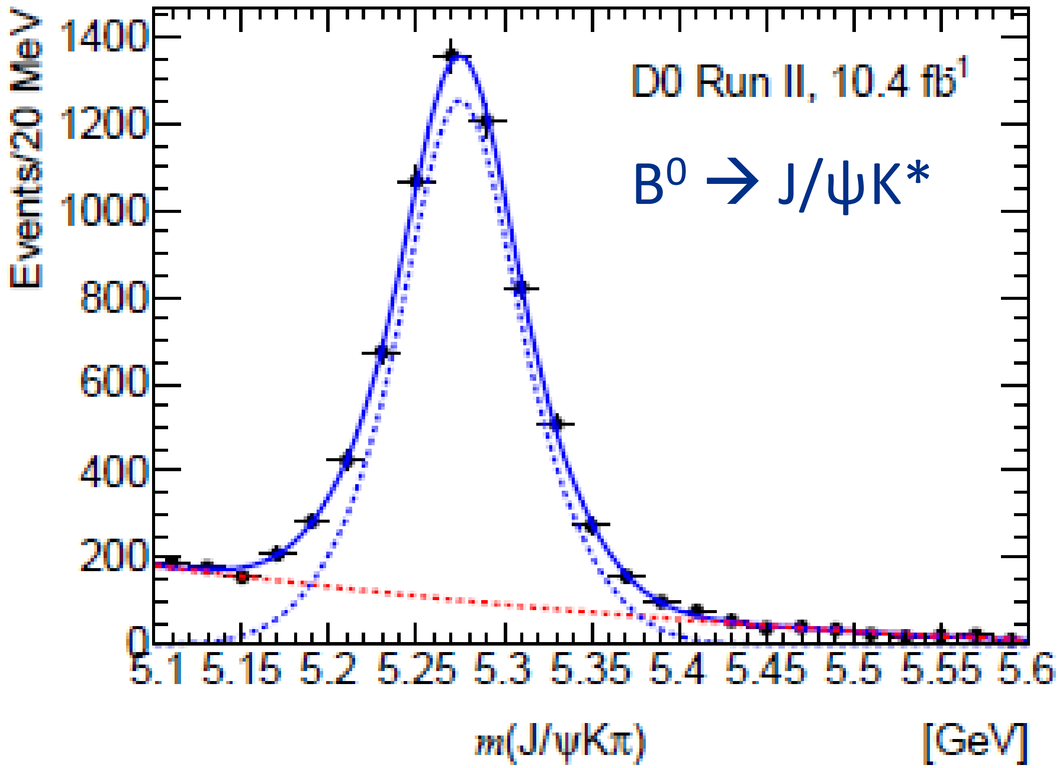
Systematic Uncertainties

Table 1: Systematic uncertainties for the $Z_c^+(3900)$ mass and yield

Systematic uncertainty	Mass (MeV)	Yield
Mass calibration	$^{+3}_{-0}$	0
Mass resolution	< 0.1	± 27
Background shape	± 0.4	± 53
Bin size	± 1.1	± 9
Signal model	± 2.4	± 3
Natural width variation	0	± 23
Total (sum in quadrature)	$-2.7, +4.0$	± 64

- Measured $Z_c^+(3900)$ mass is $M = 3895.0 \pm 5.2$ (stat)$^{+4.0}_{-2.7}$ (syst) MeV
  - In good agreement with BESIII and Belle
- Systematic uncertainties reduce significance of $Z_c^+(3900)$ peak to 4.6 σ

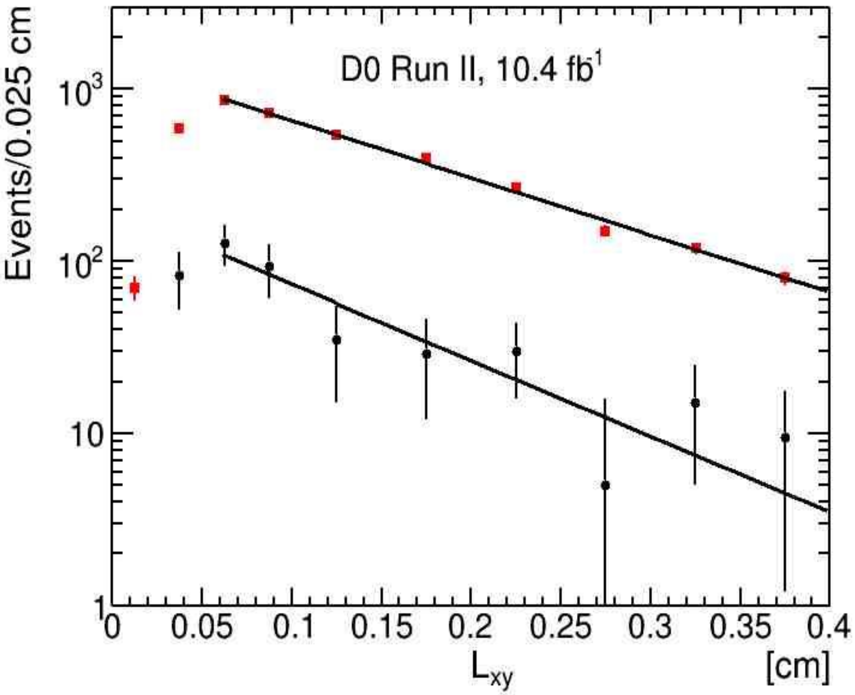
Normalizing $Z_c^+(3900)$ Signal Yield



- Decay $B_d^0 \rightarrow J/\psi K^*$ has similar efficiencies to
  - $H_b \rightarrow Y(4260)$, $Y(4260) \rightarrow Z_c^{\pm}(3900)\pi^{\mp}$, $Z_c^{\pm}(3900) \rightarrow J/\psi\pi^{\pm}$
- The ratio is
  - $N(H_b \rightarrow Z_c^+(3900)\text{+anything})/N(B^0 \rightarrow J/\psi K^*) = 8.5 \pm 1.9\%$

Cross Checks

- $p_T(\pi)$ > 1.5 GeV and <1.5 GeV
- Three $Z_c^+(3900)$ rapidity ranges
- $m(\pi^+\pi^-)$ > 1 GeV and <1 GeV
- π^+ and π^-
- Various run periods
- Reversed IP cut on $track_2$
- Same sign pion pairs
- Events in the high chi2 tail
- J/ψ sidebands
- And many others



L_{xy} distribution for $Z_c^+(3900)$ obtained in slices of L_{xy} (black) compared to the similar distribution for $B^0 \rightarrow J/\psi K^*$ (red)

All cross checks provide expected results

Conclusions

- DØ observed $Z_c^{\pm}(3900)$ exotic state decaying to $J/\psi\pi^{\pm}$ in proton-antiproton collisions at 1.96 TeV with 4.6σ significance
  - Measured mass of $Z_c^{+}(3900)$ is $M = 3895.0 \pm 5.2\ (stat)^{+4.0}_{-2.7}\ (syst)$ MeV
  - Consistent with Belle and BESIII measurements

- Production of $Z_c(3900)$ is consistent with coming from heavy flavor hadron decays
  - $H_b \rightarrow Y(4260)$, $Y(4260) \rightarrow Z_c^{\pm}(3900)\pi^{\mp}$, $Z_c^{\pm}(3900) \rightarrow J/\psi\pi^{\pm}$

- Yield of $Z_c^{\pm}(3900)$ in proton-antiproton collisions
  - $N(H_b \rightarrow Z_c^{+}(3900)+anything)/N(B^0 \rightarrow J/\psi K^*) = 8.5+-1.9\%$

- We confirm production of X(5568) state in proton-antiproton collisions at 1.96 TeV
  - In an independent data set with semileptonic decay of B_s^0 meson
  - X(5568) properties in B_s^0 meson hadronic and semileptonic decays are consistent
  - Combined significance of X(5568) state observation in these two channels is 6.7σ

- Studies of exotic mesons, including their properties, production and decay mechanisms should help to develop models of multi-quark configurations
  - Such models are critical to guide experimental studies
  - Important for our understanding of strong interactions