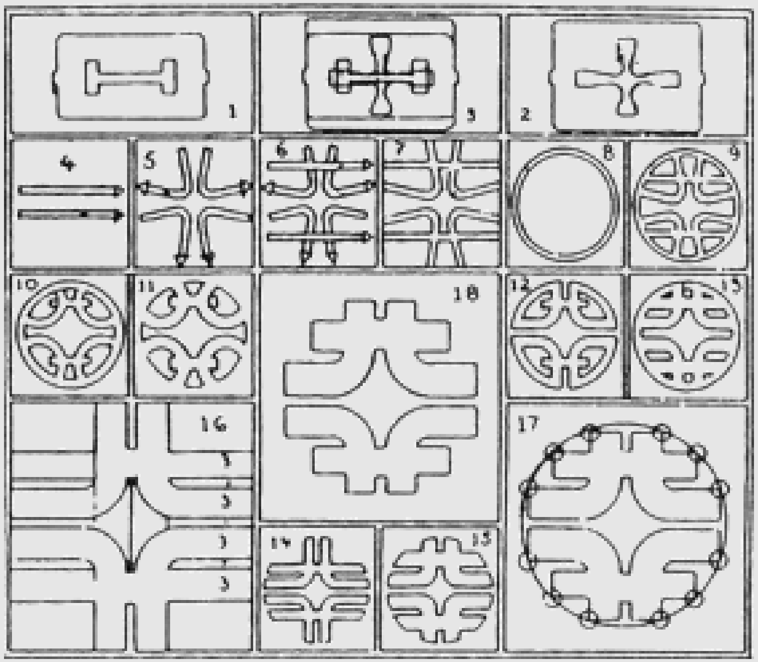
New heavy flavor resonances at D0

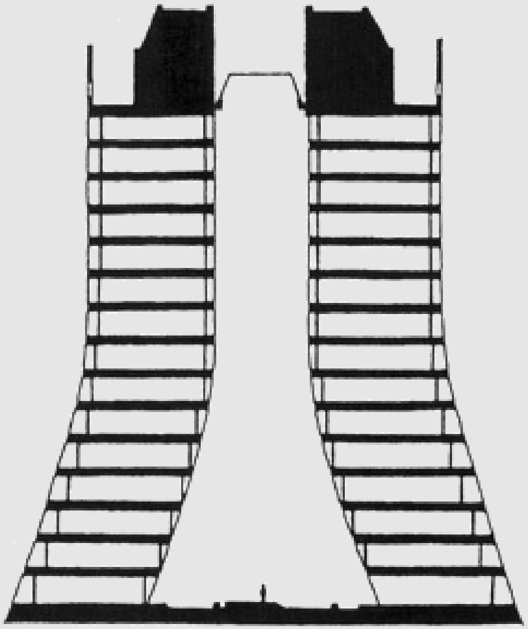
~~and Zb states~~
(tbd)



The Evolution of a Logo

HQL 2016

Virginia Tech

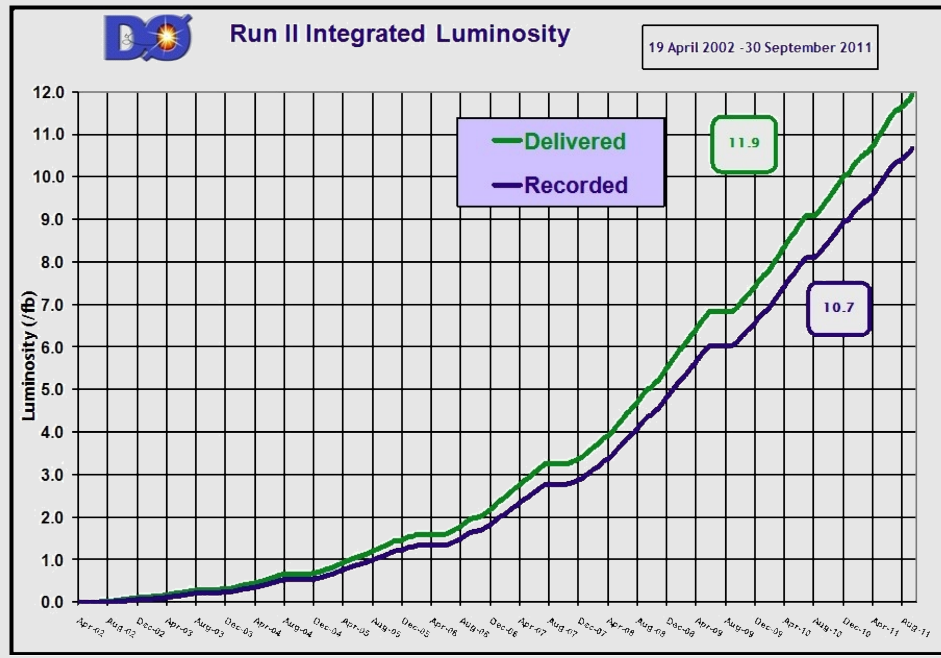


Bob Hirosky
for the D0 Collaboration

TEVATRON DATA

D0 continues a rich physics program analyzing ~10fb^{-1} of recorded data from ~2001-2011

- World's highest energy p-$\bar{p}$ data set (2 TeV C.O.M.)
- Unique physics studies
- Many complementary/competitive results in LHC era



The D0 Detector

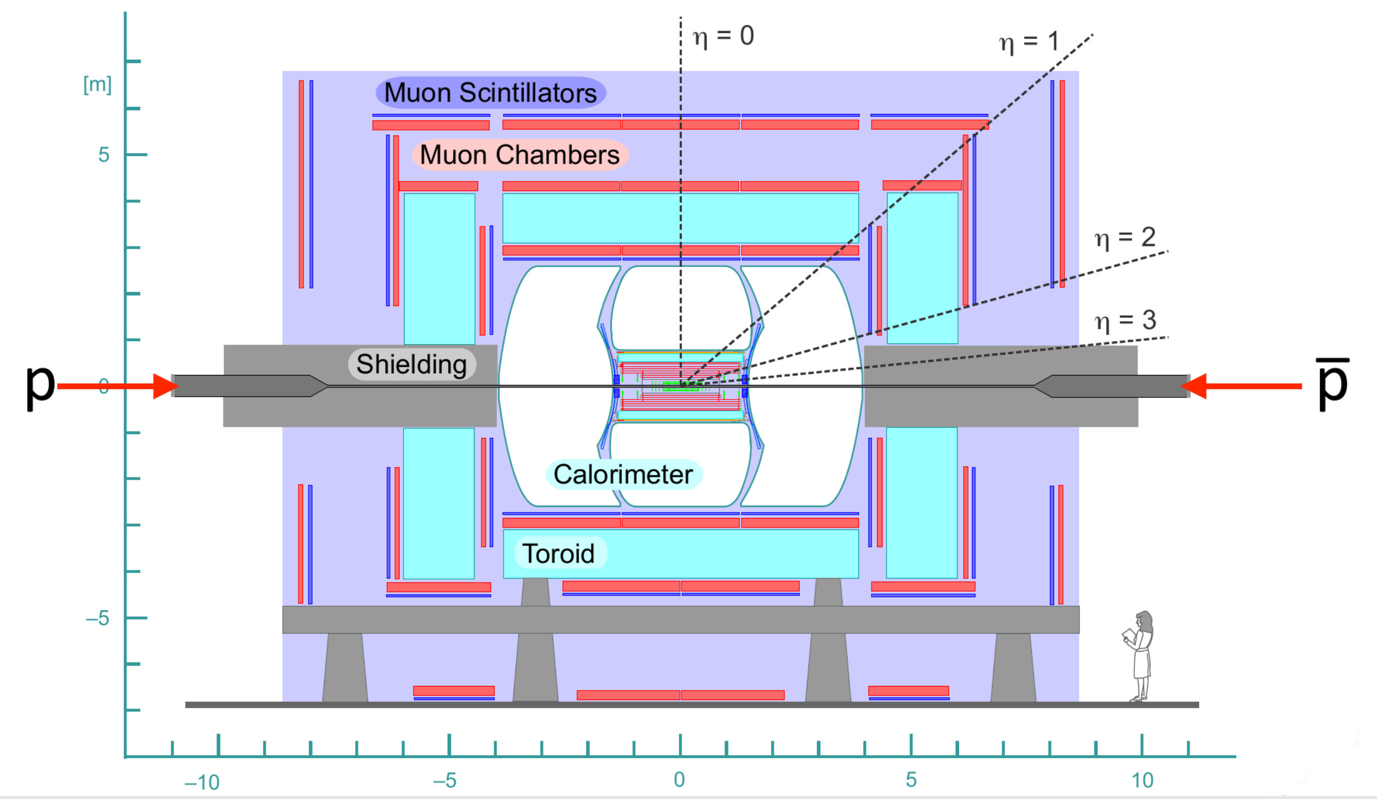
Multipurpose, large acceptance, well understood detector.

Tracking & Muon System

• Scintillator counters and drift tubes
• Thick calorimeter and iron toroids
Excellent muon triggering and ID

• Silicon Microstrip Tracker
Excellent vertex resolution

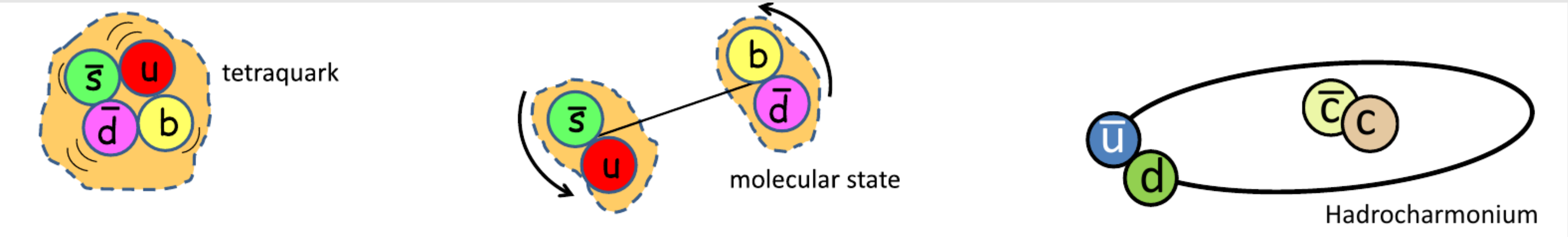
• Central Fiber Tracker
Good mass resolution



Excellent for B physics with muons

“Four quark” States

- Four quark distinguished from regular mesons by comparing mass, width, charge, other quantum #s, production and decay modes with predictions
- Exotic 4-quark states are described as tightly bound (tetraquark) or loosely bound (molecule, hadroquarkonium):



Observed four-quark states

- High stat. significance: $Z(4430)+ \to \psi'\pi^+$, $X(4140) \to J/\psi\varphi$, $Z_b^+(10610/50) \to \Upsilon\pi^+$
- 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 (masses are close to sum of two regular mesons).

Also pentaquarks $P_c^+(4450) \to J/\psi p$, $P_c^+(4380) \to J/\psi p$

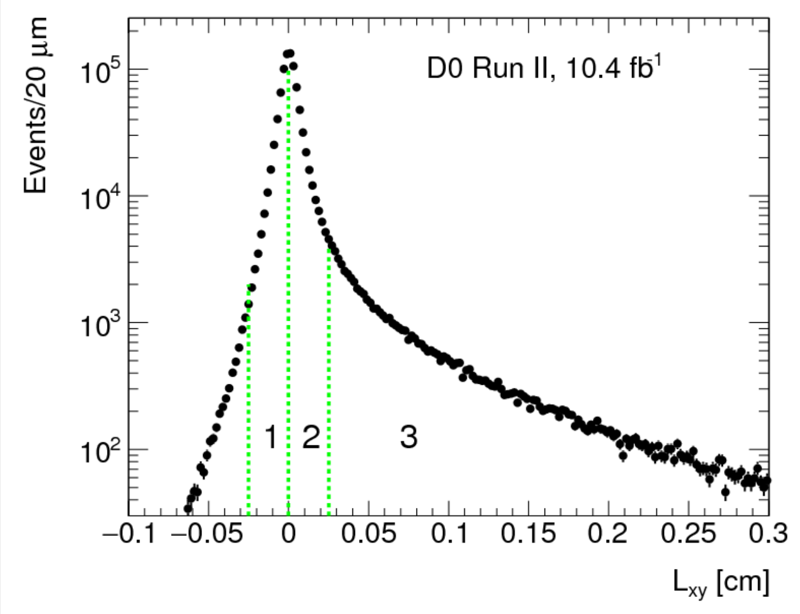
Inclusive Production of X(4140)

X(4140) first observed by CDF in 2009 in decay $B+ \rightarrow X(4140)\ K^+ \rightarrow J/\psi\varphi\ K^+$

- Observed in decays of B^+
  - ✓ 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))

D0:First inclusive X(4140) measurement

Phys. Rev. Let. 115, 232001 (2015), arXiv:1508.07846



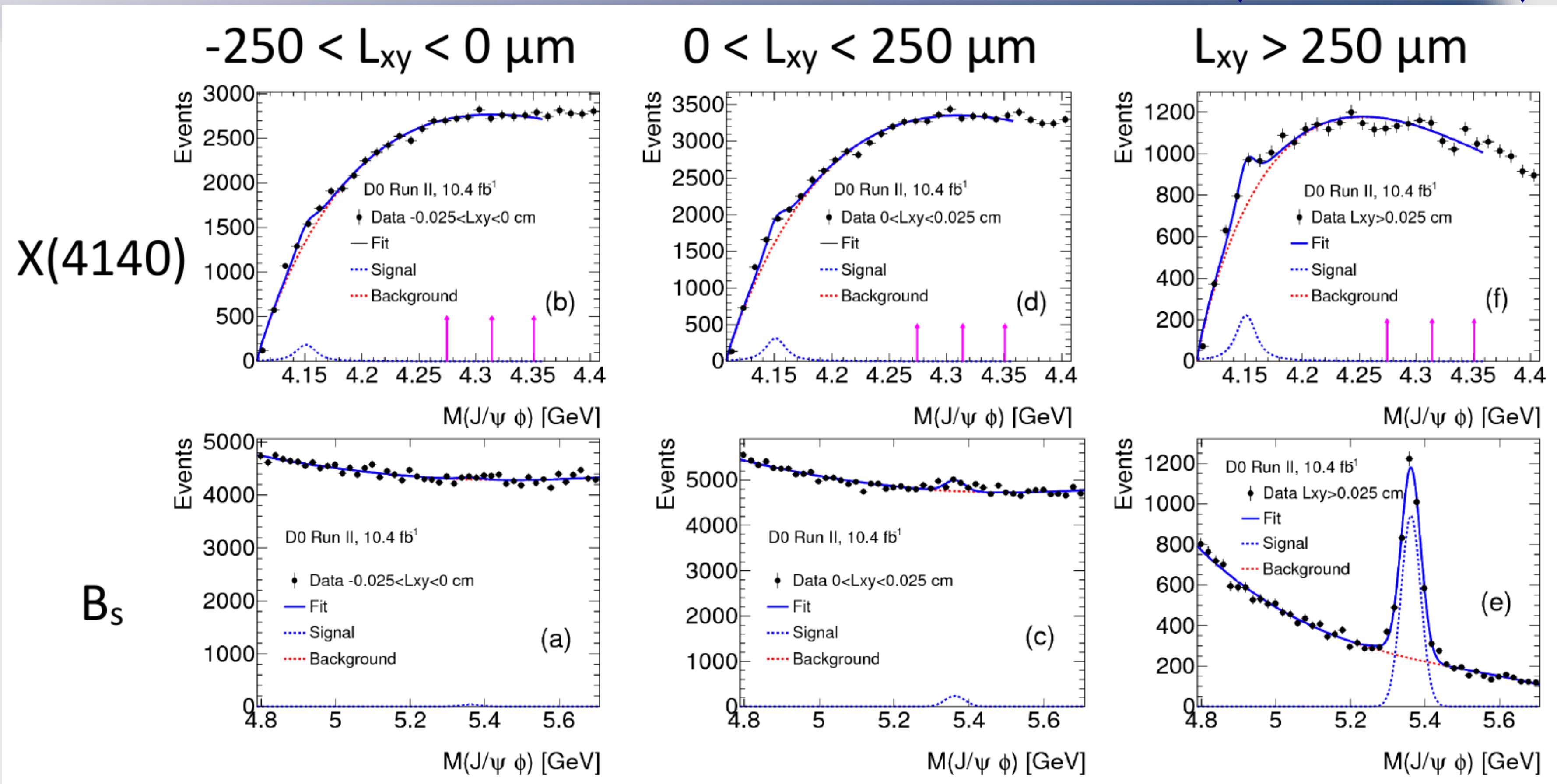
J/ψφ is selected in three transverse decay length (Lxy) intervals and in two mass intervals:

- X(4140): $M(J/\psi\varphi) < 4.36$ GeV
- B_s: $4.8 < M(J/\psi\varphi) < 5.7$ GeV

Number of B_s and X(4140) extracted using mass fits.

$M(J/\Psi\phi)$

Inclusive Production of X(4140)



X(4140) Background

Low Lxy: J/ψ mesons with random particles from the ULE

Higher Lxy: J/ψ mesons with random products of b hadron decays

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 of X(4140) originating from b hadron decays

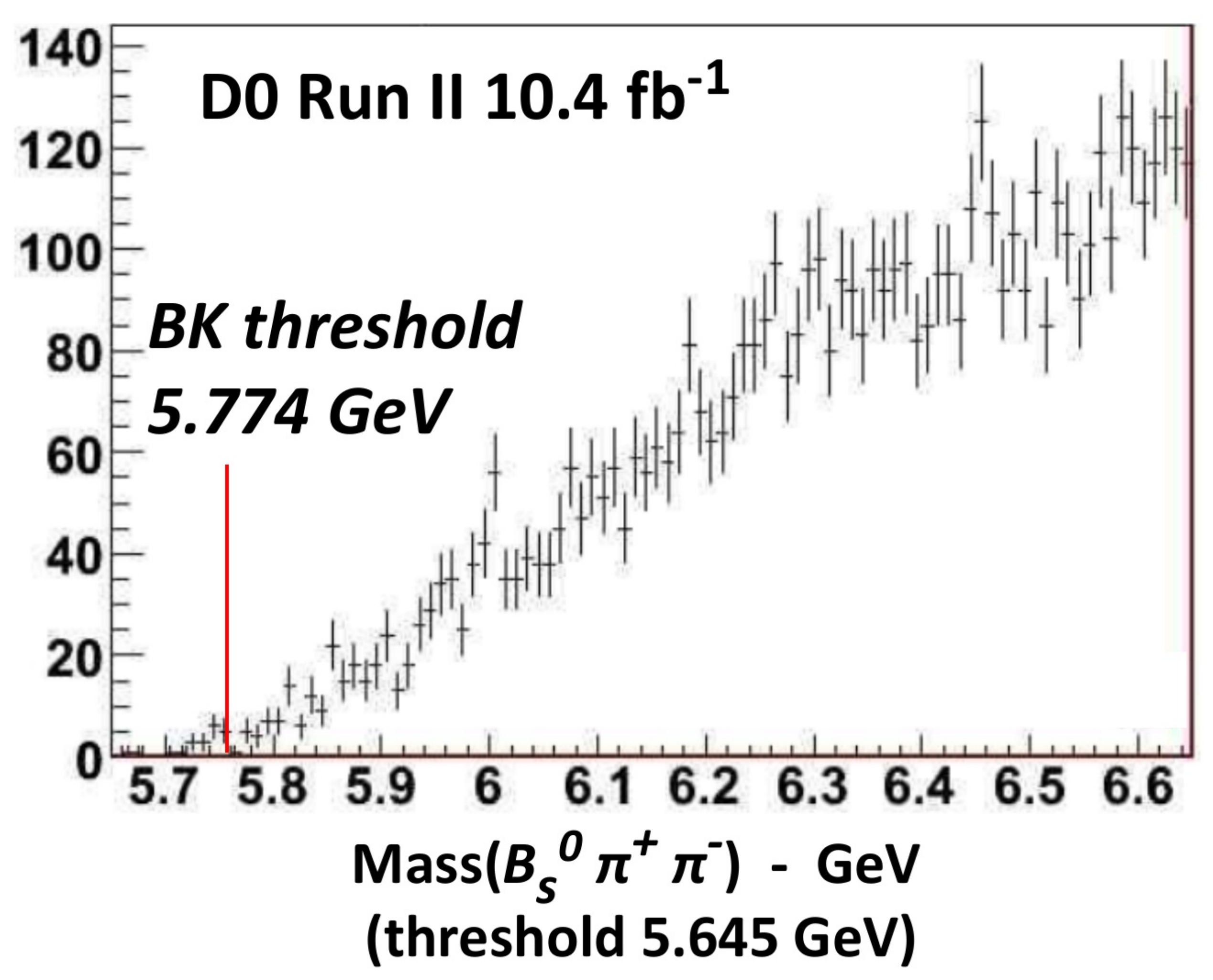
$$f_b = 0.39 \pm 0.07\,(\text{stat}) \pm 0.10\,(\text{syst})$$

=> also prompt production of the X(4140)

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

$B_s^0\pi^\pm$ State

Initially searching for strong decays of excited $B_s^{**} \rightarrow B_s^0\pi^+\pi^-$



No resonances found

Look at $B_s^0\ \pi^\pm$

→ exotic = b, s, u, d

But, quite a few exotic candidates recently reported, e.g. tetra-quarks or penta-quarks

so worth a look!

$B_s^0\pi^\pm$ State

$X \rightarrow B_s^0\ \pi^\pm$

$B_s^0 \rightarrow J/\psi\ \varphi$

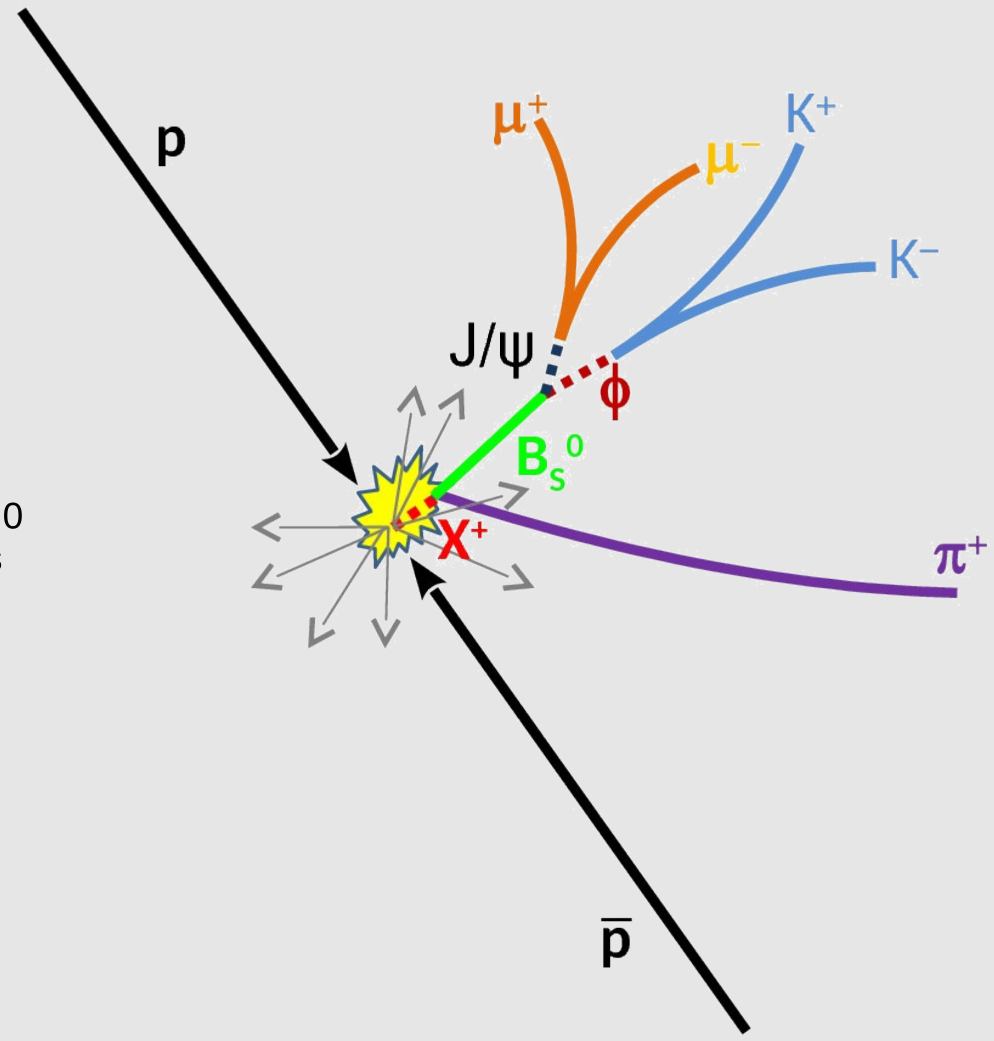
$J/\psi \rightarrow \mu+\ \mu-$

$\varphi \rightarrow K+\ K-$

Can not differentiate B_s^0 from $\overline{B}_s^0$

also could have $X \rightarrow B^*{}_s^0\ \pi^\pm$

with $B^*{}_s^0 \rightarrow B_s^0$ + missing γ



$B_s^0\pi^\pm$ STATE

Used full Run II data set 2001-2011 of 10.4 fb^{-1}

Require a single muon or dimuon trigger.

Select $B_s^0 \to J/\psi\phi$ candidates:

- $2.92 < M(\mu\mu) < 3.25$ GeV
- $p_T(K) > 0.7$ GeV; $1.012 < M(KK) < 1.03$ GeV
- $5.304 < M(J/\psi K^+K^-) < 5.424$ GeV; $L_{xy}/\sigma(L_{xy}) > 3$

Add a track assumed to be a pion, consistent with coming from PV:

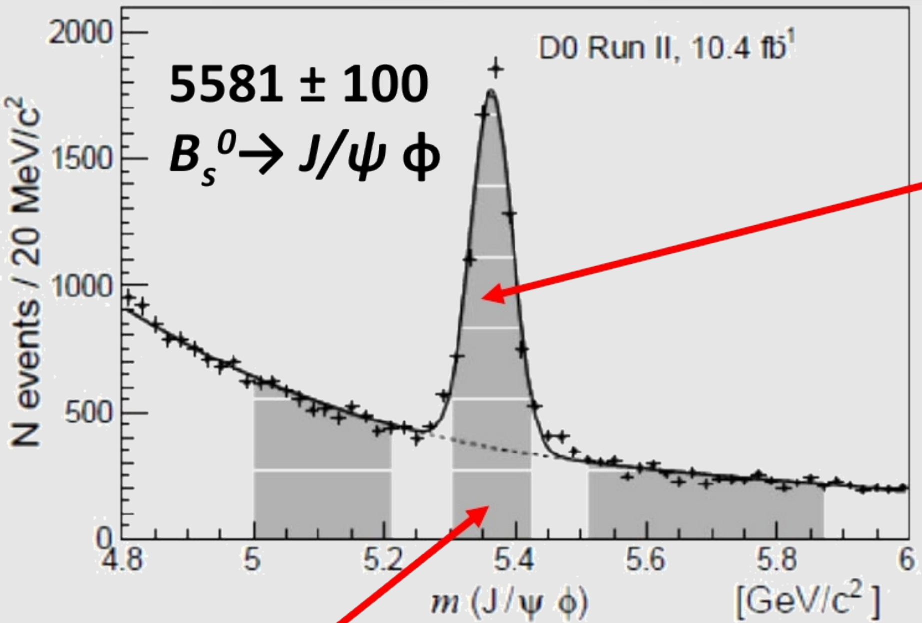
- $p_T(\pi) > 0.5$ GeV, $IP_{xy} < 0.02$ cm, $IP_{3D} < 0.12$ cm
- $p_T(B_s\pi) > 10$ GeV
- $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2} < 0.3$ (the "cone" cut)

  = angle between B_s^0 and $\pi^\pm$

$B_s^0\pi^\pm$ State

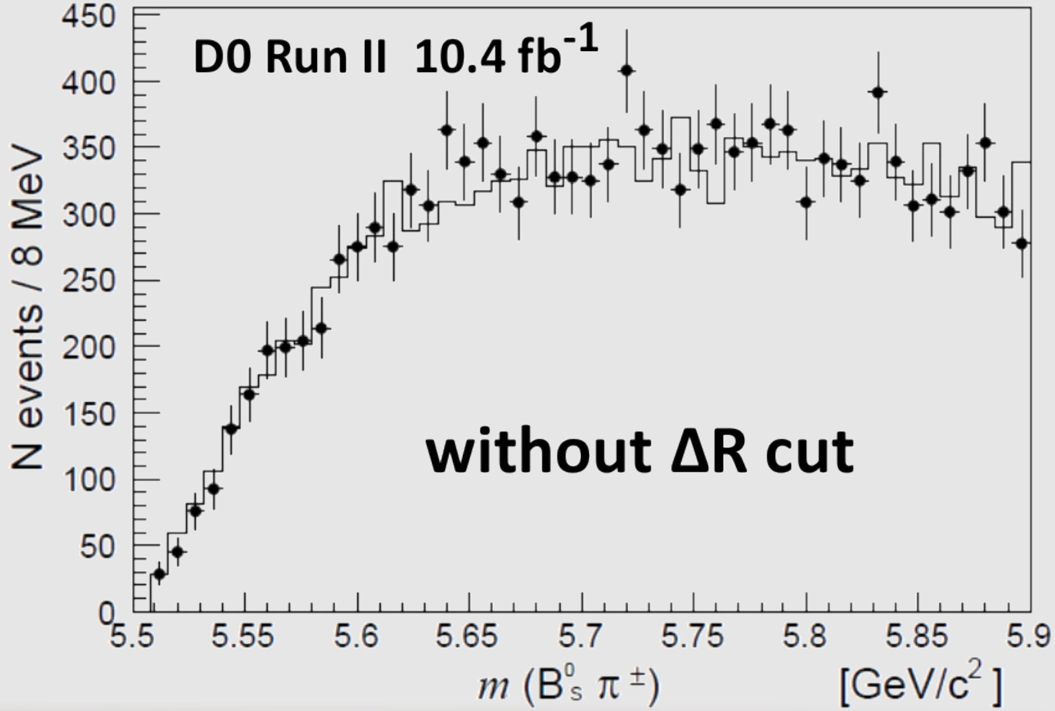
2 component background model:

"Genuine Background" is the B_s^0 peak: use Monte Carlo B_s^0 peak + random π
71% of total background (*histogram*) ↓



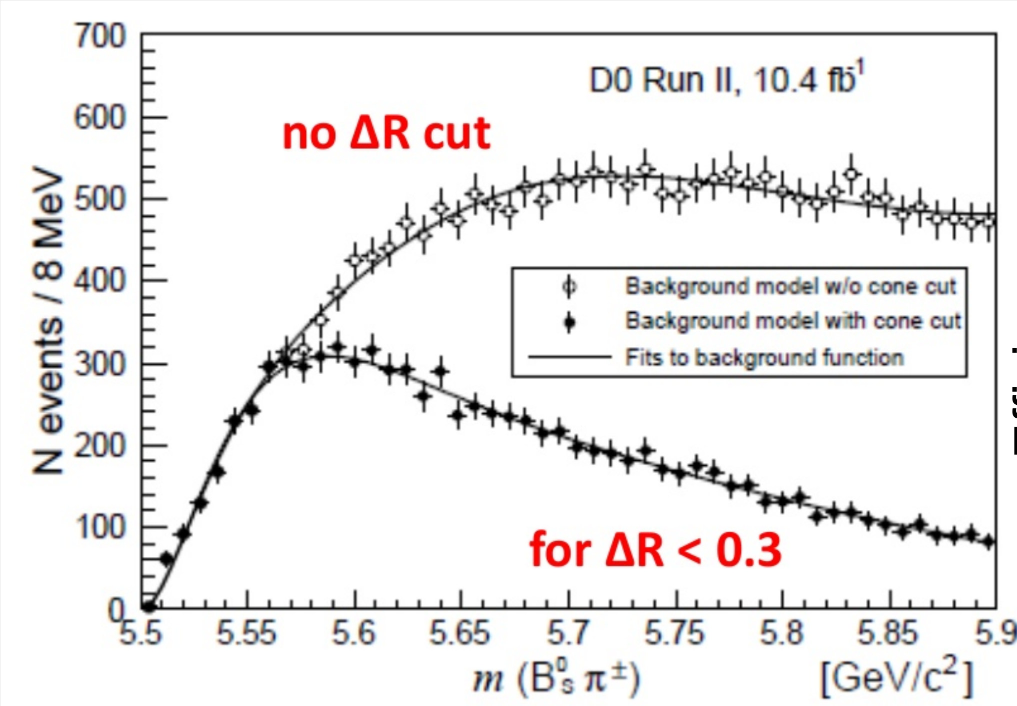
± 2 σ selection band

"Combinatorial Background" under the B_s^0 peak:
use data: sidebands + random π
29% of total background (*points*) →

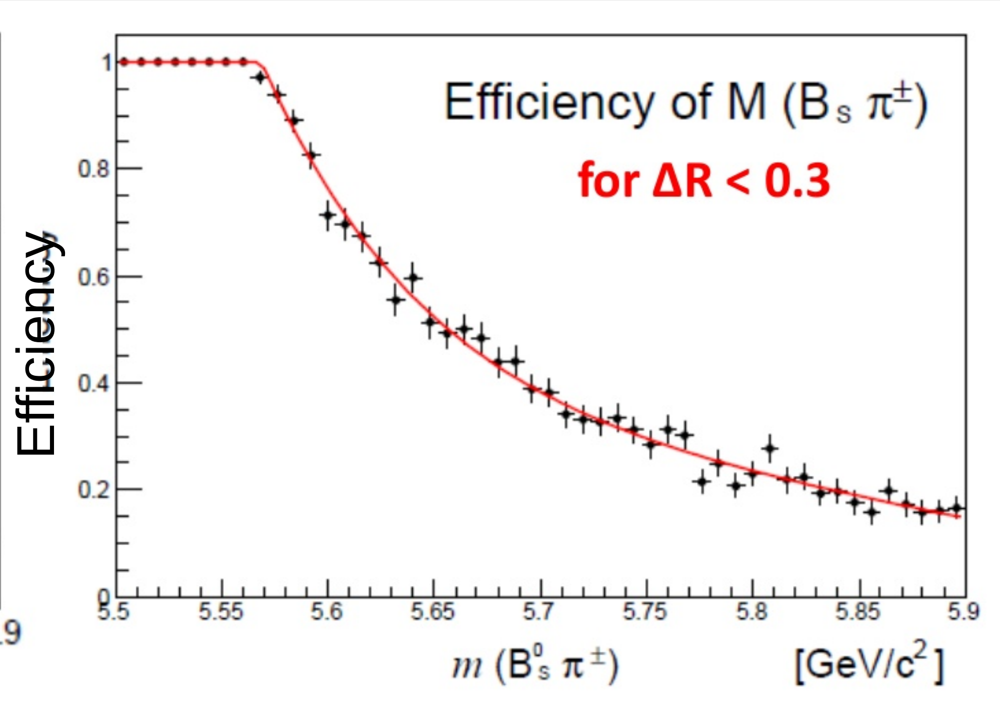


$B_s^0\pi^\pm$ State

background model



efficiency vs m of topological cut



$$F_{bgr}(m_{B\pi}) = \left(C_1 + C_2 \cdot m_0^2 + C_3 \cdot m_0^3 + C_4 \cdot m_0^4\right) \times exp\left(C_5 + C_6 \cdot m_0 + C_7 \cdot m_0^2\right)$$

$B_s^0\pi^\pm$ State

Optimal mass resolution using:

$M(B_s\,\pi) = M(\mu\mu\,KK\,\pi) - M(\mu\mu\,KK) + M(B_s)$
$\quad = M(\mu\mu\,KK\,\pi) - M(\mu\mu\,KK) + 5.3667\ GeV/c^2$

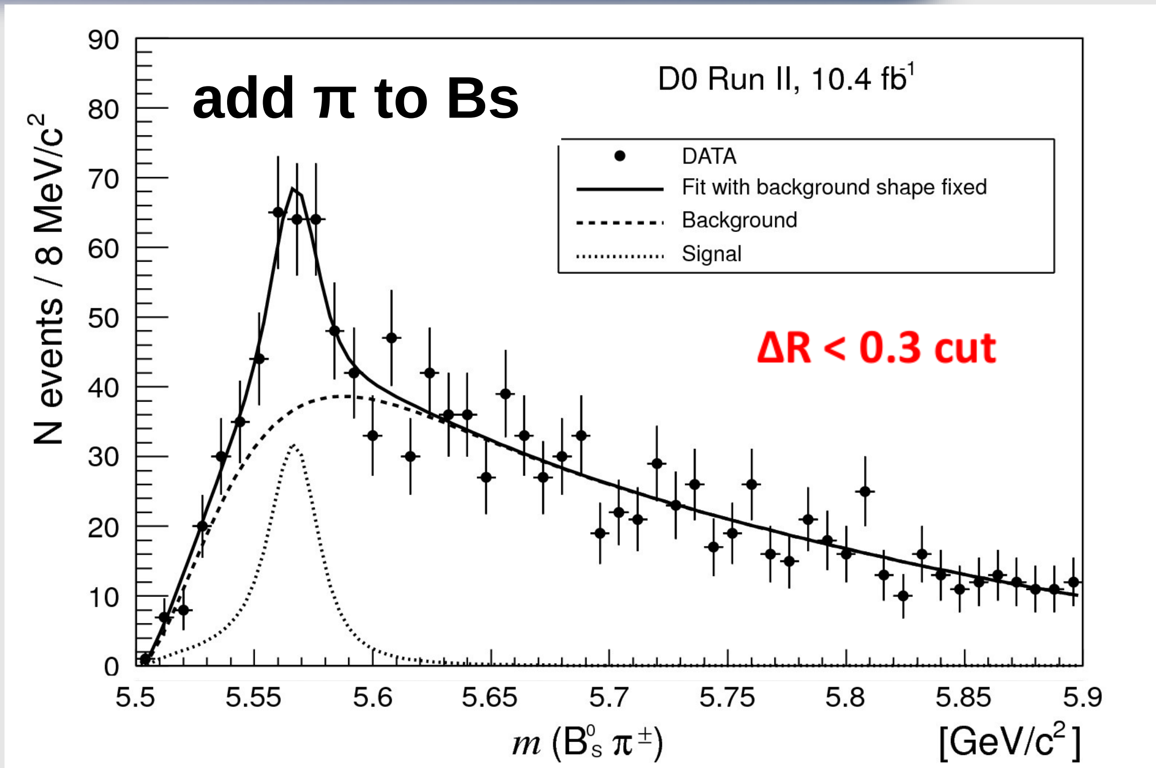
Model peak as:
S-wave relativistic Breit Wigner

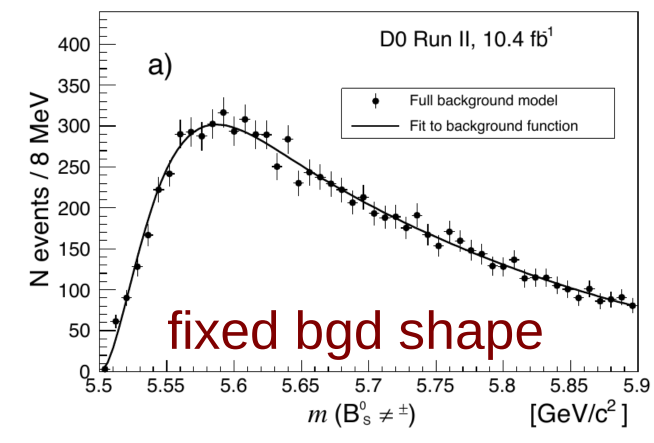
$$BW(m_{B\pi}) \propto \frac{M_X^2\Gamma(m_{B\pi})}{(M_X^2 - m_{B\pi}^2)^2 + M_X^2\Gamma^2(m_{B\pi})}$$

Convolute BW with MC mass resolution σ = 3.9 MeV
and multiply by
Eff(MB_s π, ΔR cut = from prior slide)

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

fitting function vary: f_{sig} , M_X , Γ_x , f_{bkg}

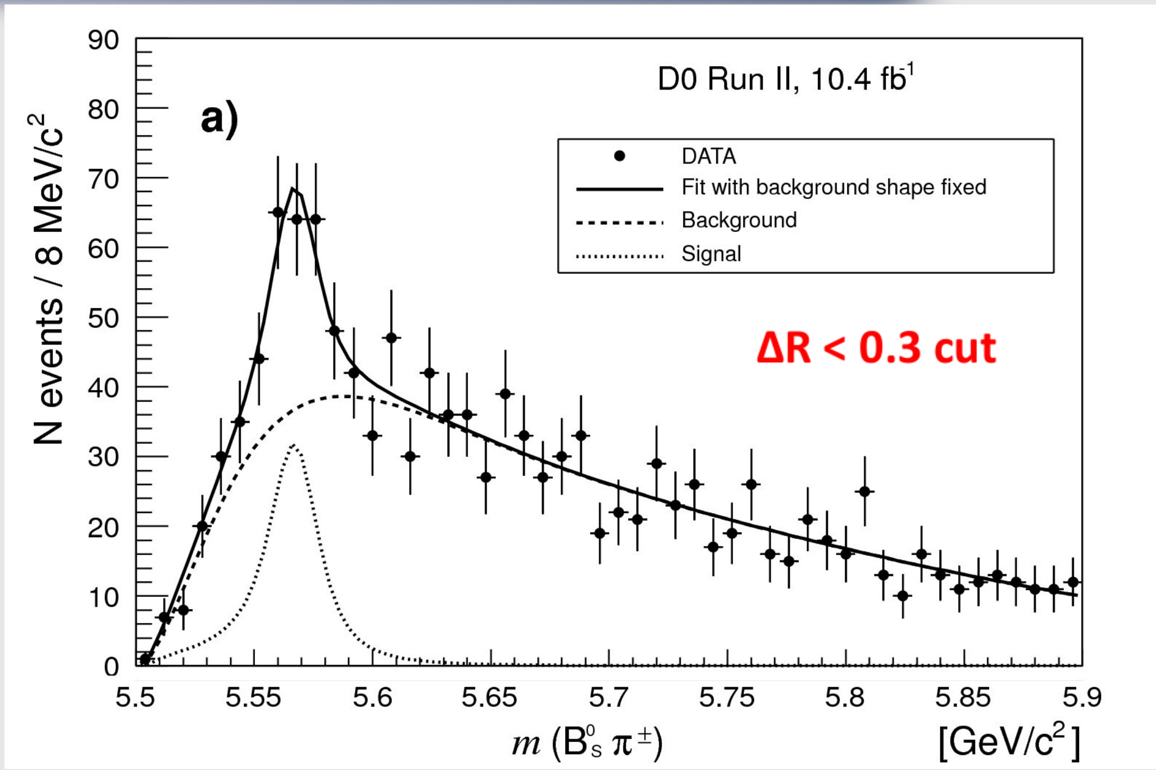




$B_s^0\pi^\pm$ State

Fit for ΔR < 0.3 cut:

- M_X = 5567.8 ± 2.9 (stat) MeV
- Γ_X = 21.9 ± 6.4 MeV
  - strong decay! Mass resolution is ± 3.9 MeV r.m.s.
- N_X = 133 ± 31 events
- χ2 = 32.4 for 46 D.O.F



Local significance = sqrt(-2 ln (L0/L max)) = sqrt(43.56) = 6.6 σ

Global significance using Gross & Vitells LEE => 6.1 σ

Statistical uncertainties only

$B_s^0\pi^\pm$ State

Systematic Uncertainties

Systematic uncertainty	mass, MeV/c^2	width, MeV/c^2	Events, %
Background shape			
a) MC sample soft or hard	+0.2 ; -0.6	+2.6 ; -0.	+8.2 ; -0.
b) Sideband mass ranges	+0.2 ; -0.1	+0.7 ; -1.7	+1.6 ; -9.3
c) Sideband mass calculation method	+0.1 ; -0.	+0. ; -0.4	+0 ; -1.3
d) MC to sideband events ratio	+0.1 ; -0.1	+0.5 ; -0.6	+2.8 ; -3.1
e) Background function used	+0.5 ; -0.5	+0.1 ; -0.	+0.2 ; -1.1
f) B_s^0 mass scale, MC and data	+0.1 ; -0.1	+0.7 ; -0.6	+3.4 ; -3.6
Signal shape			
a) Detector resolution	+0.1 ; -0.1	+1.5 ; -1.5	+2.1 ; -1.7
c) Non-relativistic BW	+0. ; -1.1	+0.3 ; -0.	+3.1 ; -0.
d) P-wave BW	+0. ; -0.6	+3.1 ; -0.	+3.8 ; 0.
Others			
a) 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

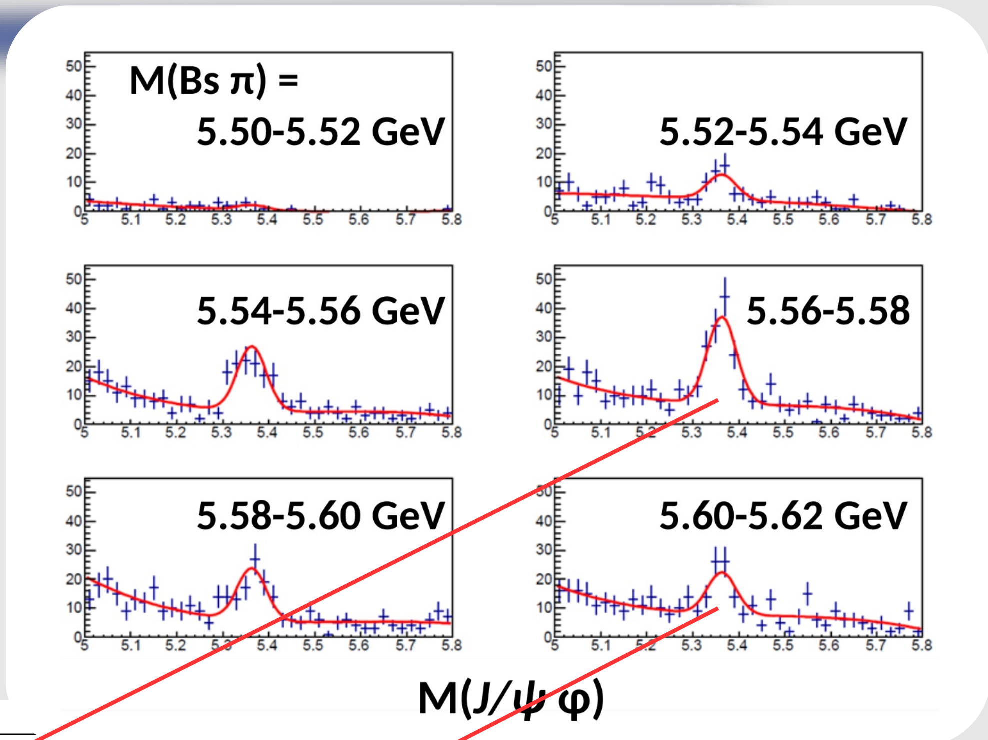
applying ± 11.3% systematic uncertainty to yield of X(5568) reduces significance to 5.1 σ (incl. LEE & syst.)

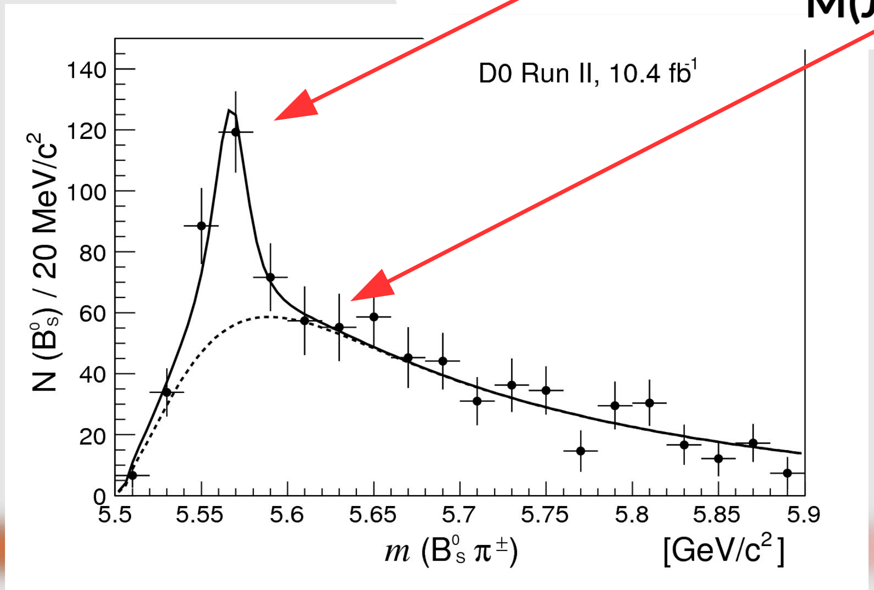
$B_s^0\pi^\pm$ State

Alternate method:

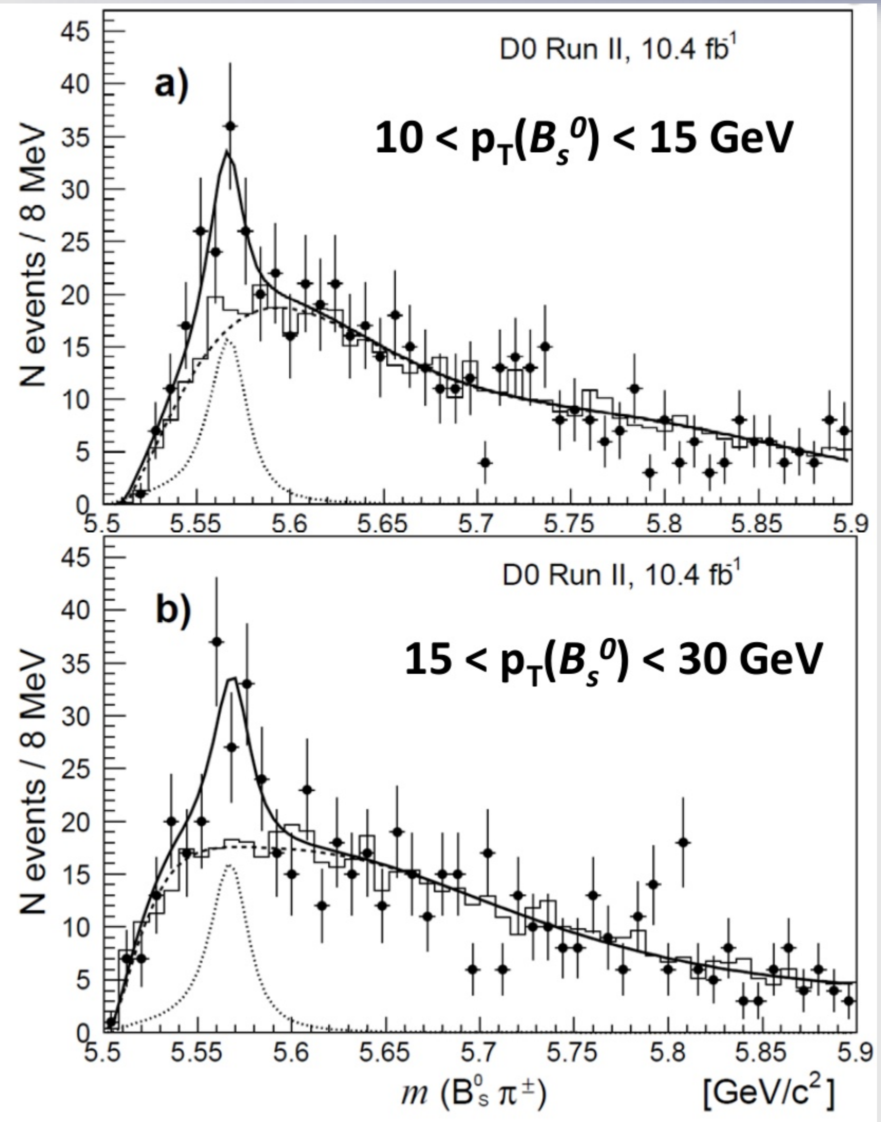
Use all J/ψ φ with
4.8 < M(J/ψ φ) < 6 GeV
and later fit for B_s^0
rather than mass selection cut

This removes the "combinatorial" background component
fix M_X and Γ_X
fit N_X = 118 ± 22 events





$B_s^0\pi^\pm$ State



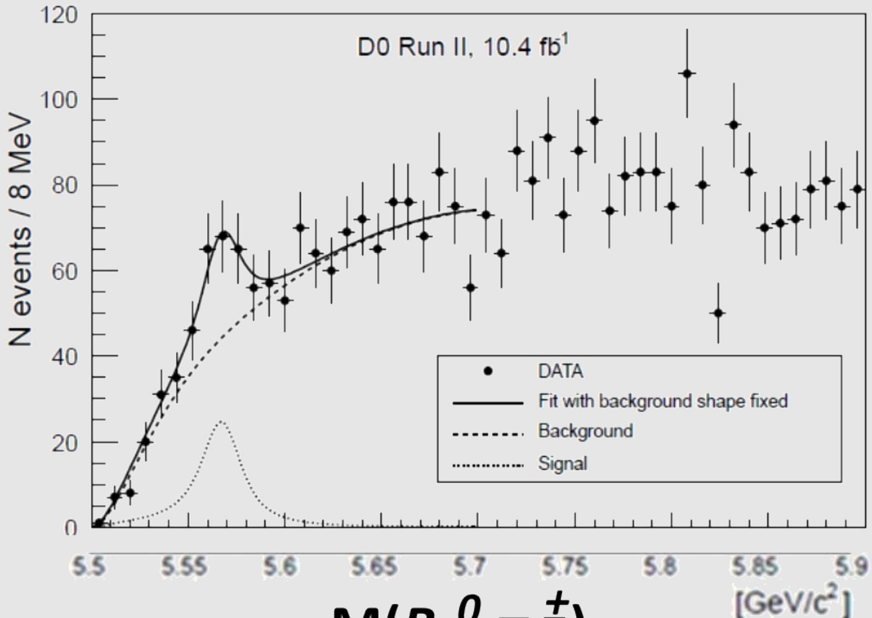
a cross-check

$p_T(B_s^0)$	10-15	15-30	GeV
N_X	58.6	67.5	
	± 16.7	± 21.8	events
M_X	5566.3	5568.9	MeV
	± 3.3	± 4.4	MeV
Γ_X	18.4	21.7	MeV
	± 7.0	± 8.4	MeV

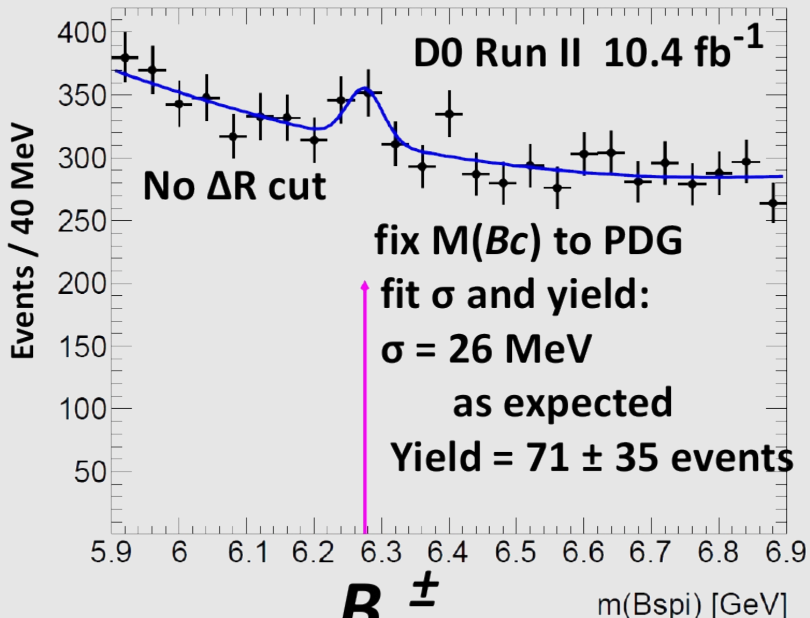
background shape varies, but M_X and Γ_X do not!

$B_s^0\pi^\pm$ State

without ΔR cut **do we see $B_c^\pm \rightarrow B_s^0\,\pi^\pm$?**



$M(B_s^0\,\pi^\pm)$



$B_c^\pm$

$M(B_s^0\,\pi^\pm)$

for no ΔR cut, 5.506 < $M(B_s^0\,\pi^\pm)$ < 5.700 GeV

fix: M_X = 5567.8 MeV as for ΔR < 0.3

fix: Γ_X = 21.9 MeV as for ΔR < 0.3

fit: N_X = 106 ± 25 events $\chi2$ = 18.4 for 23 DF

$B_s^0\pi^\pm$ State

Variety of cross-checks performed

Use left (right) sideband for the non-B_s^0 background

Use two versions of Pythia for the B_s^0 background

Compare sidebands with "undersignal"

Allow background shape parameters to be free

Extract the signal yield without the cone cut

Use different B_s^0 mass ranges; modify the B_s^0 vertex cuts

Compare π^+ and π^- subsamples

Examine different detector regions (ϕ, η)

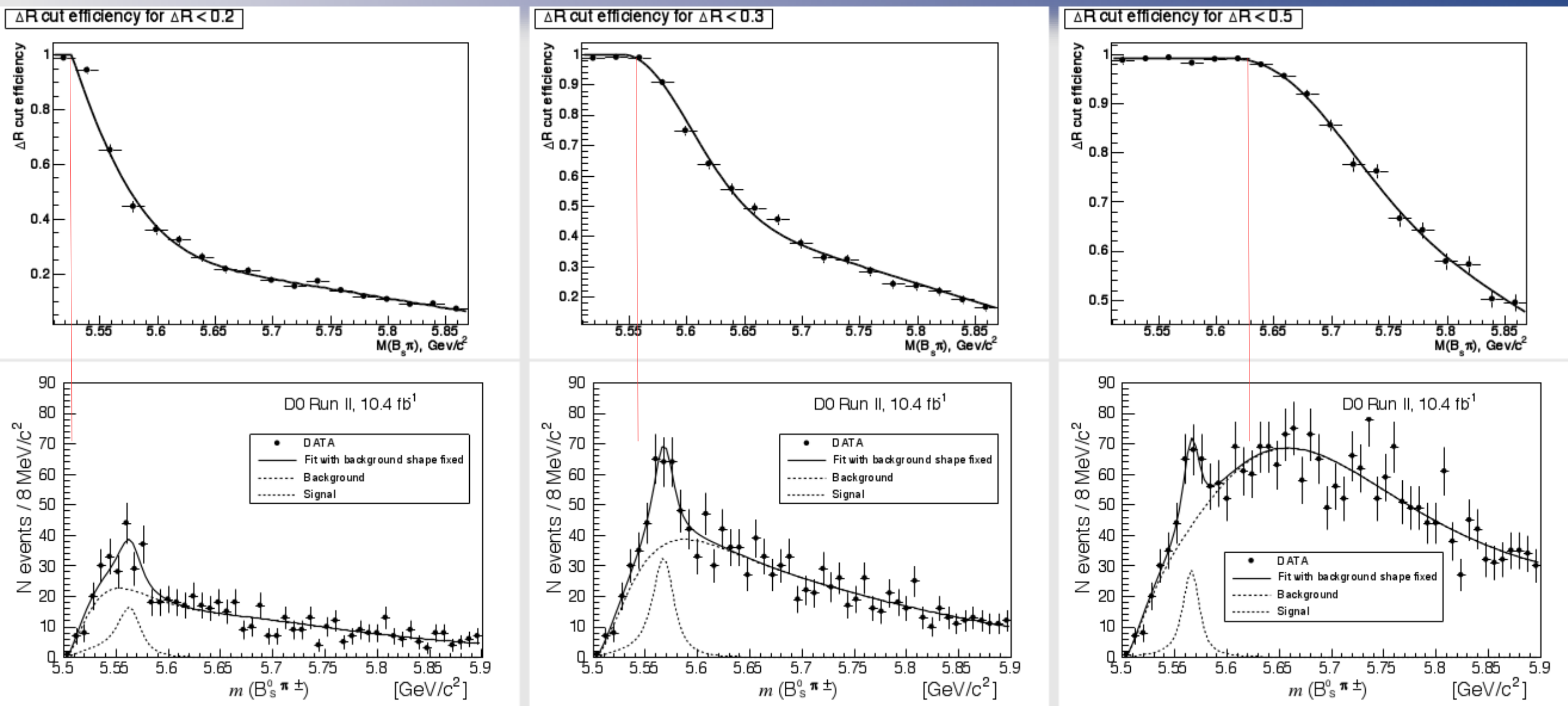
Test $B_s^0 K$ and $B_s^0 p$ hypotheses

Study $m(B_d^0\pi^\pm)$ on the full Run II data sample

Look for decay $B_s^{**} \to B_s^0\pi^+\pi^-$

Cross-check: mass V. ΔR

$B_s^0\pi^\pm$ State

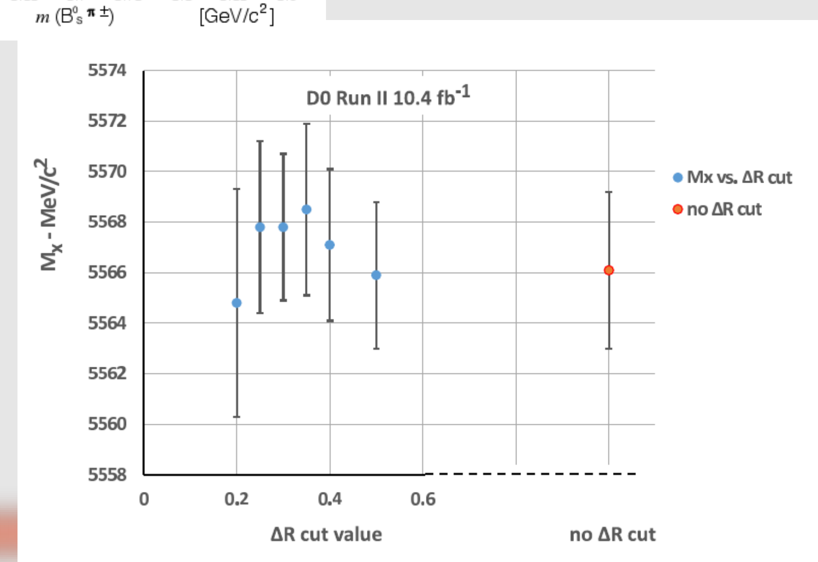


Selection efficiency vs ΔR cut

Mass measurement vs ΔR cut

Fitted M_X is independent of the ΔR cut - cone cut doesn't generate peak

even though relative positions of signal peak & maximum of background vary



Normalize to B_s production

$B_s^0\pi^\pm$ State

How many $X(5568)$ particles are produced?

Ratio = $\sigma(X)^*\mathcal{B}(X \to B_s\,\pi)/\sigma(Bs)$

Since we have same B_s decay mode,

$$\sigma(X)^*\mathcal{B}(X \to B_s\,\pi)/\sigma(B_s) = \frac{N(X \to B_s\,\pi)}{N(B_s)} \; \frac{1}{\mathrm{eff}(\pi) \sim 34\,\%}$$

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

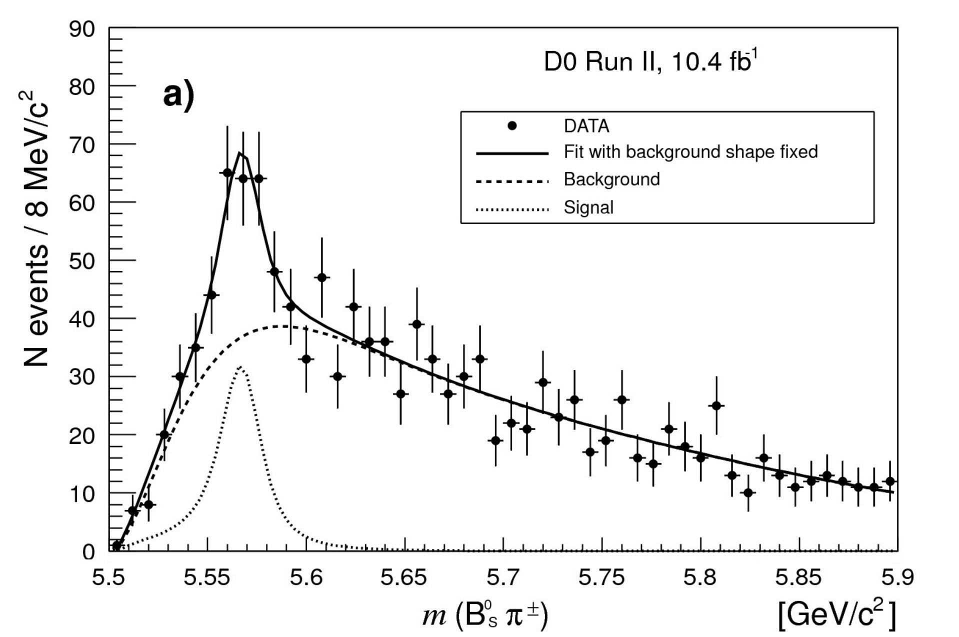
average Ratio($10 < p_T(B_s) < 30$ GeV) =

$\sigma(X)^*\mathcal{B}(X \to B_s\,\pi)/\sigma(B_s) = (8.6 \pm 1.9 \pm 1.4)\%$

$B_s^0\pi^\pm$ State

Interpretations:

4 different flavors = b, s, u, d
X(5568)$^\pm$ → B_s^0 π ± with JP=0$^+$
also possible
X(5615)± → B^{*0}_s $\pi^\pm$ with JP = 1+



M_X = 5567.8 ± 2.9(stat) $^{+0.9}_{-1.9}$ (syst) MeV

Γ_X = 21.9 ± 6.4 MeV

significance of 5.1 σ incl. LEE & systematics

$\sigma(X)*B\,(X \rightarrow B_s^0\pi)/\sigma(B_s^0) = (8.6 \pm 1.9 \pm 1.4)\%$
→ 8-9% of B_s^0 are from X(5568)±

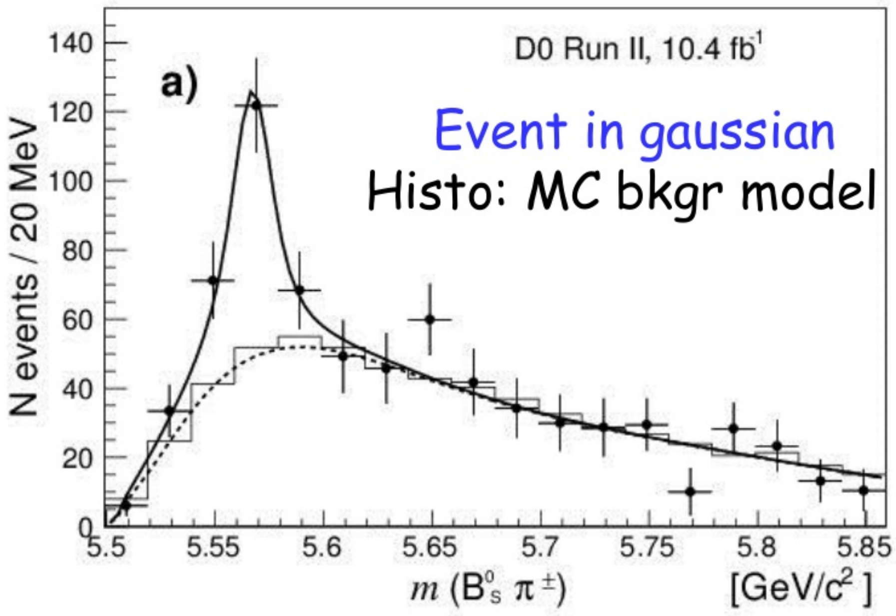
Conclusions

- **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)
  - Find both prompt (4.7σ) and non-prompt production (5.6σ)
  - The resulting mass and width agree with the values measured by CDF & CMS

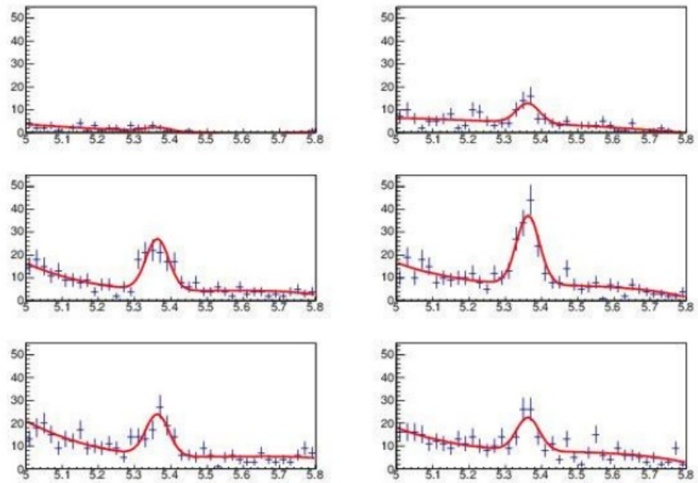
- **D0 sees a resonant structure in the $B_s\pi^{\pm}$ system with a significance of 5.1σ (including LEE effect and systematics)**
  - We wait for information on additional studies(channels), including all LHC experiments and from CDF

Additional Slides

Alternative signal extraction method



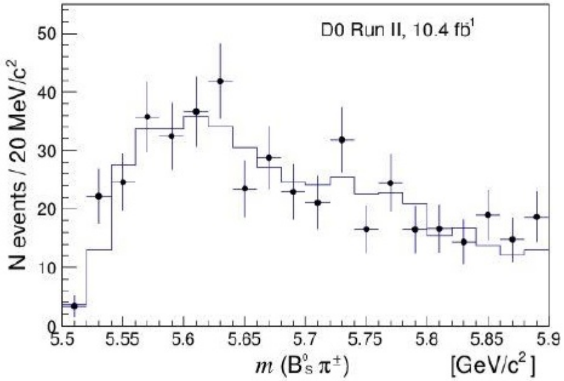
Fits in first six bins



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.

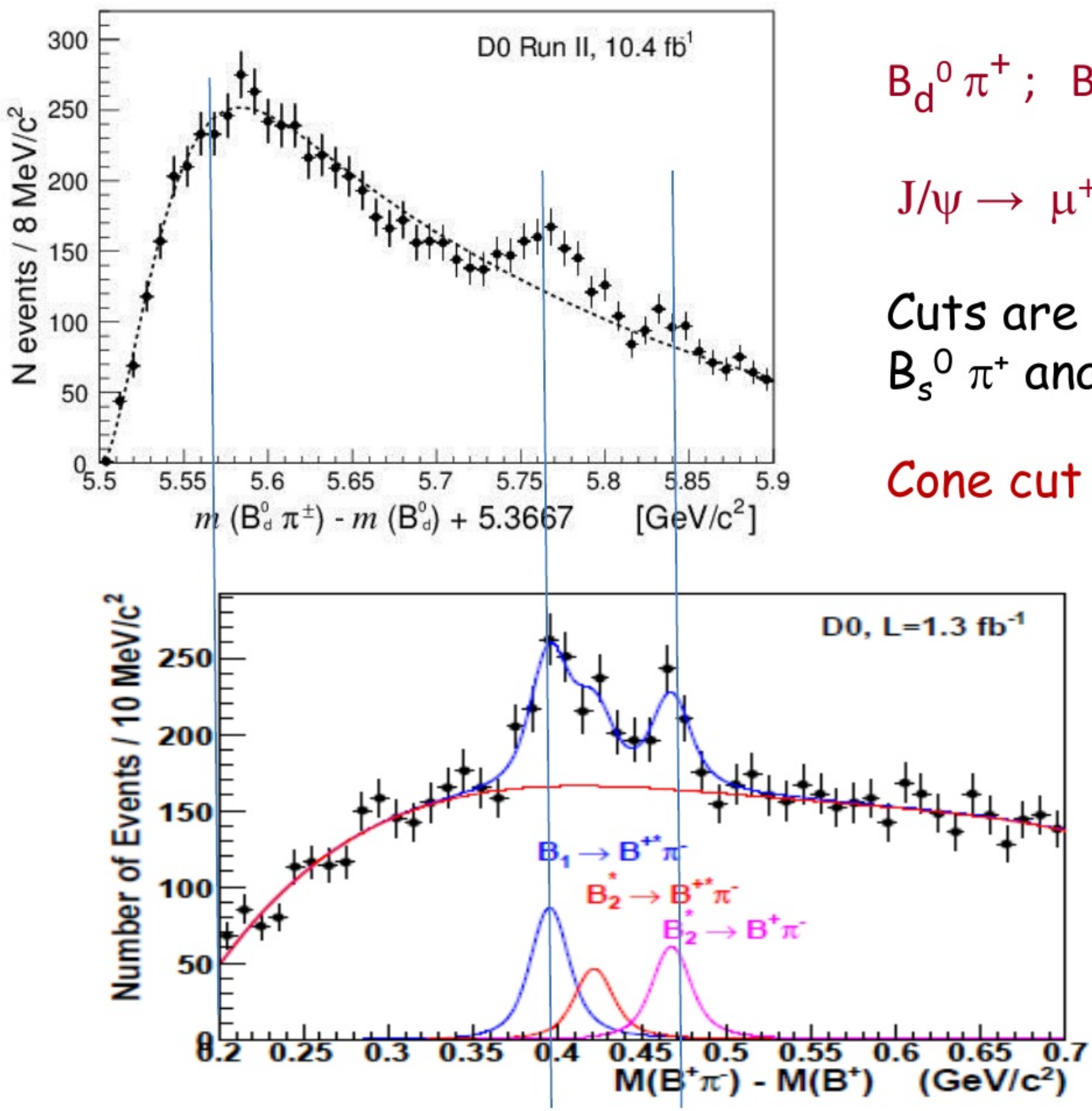
With this method (cone cut) we get 118 ± 22 events, comparing with 133 ± 31 using standard method.

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



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

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

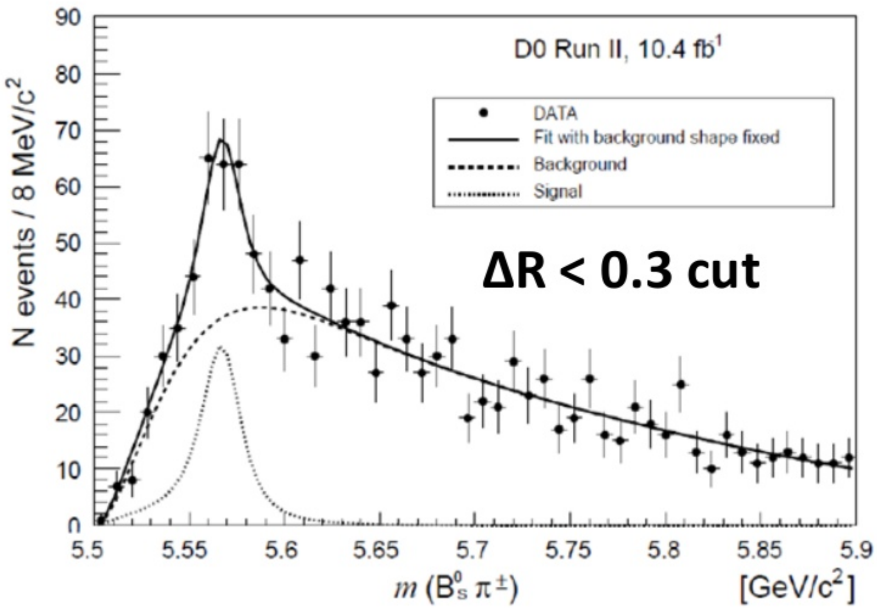
Cuts are very similar to $B_s^0\ \pi^+$ analysis

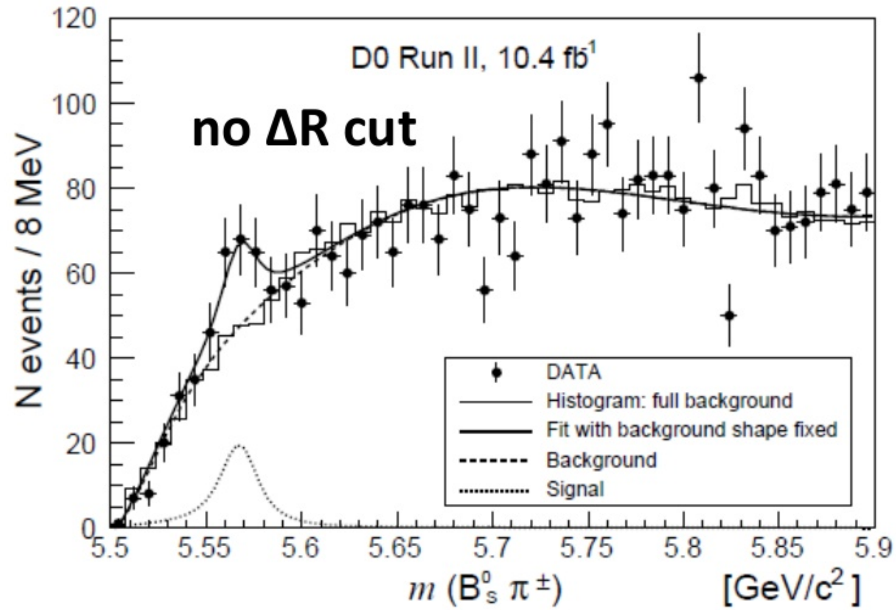
Cone cut does not produce peaks

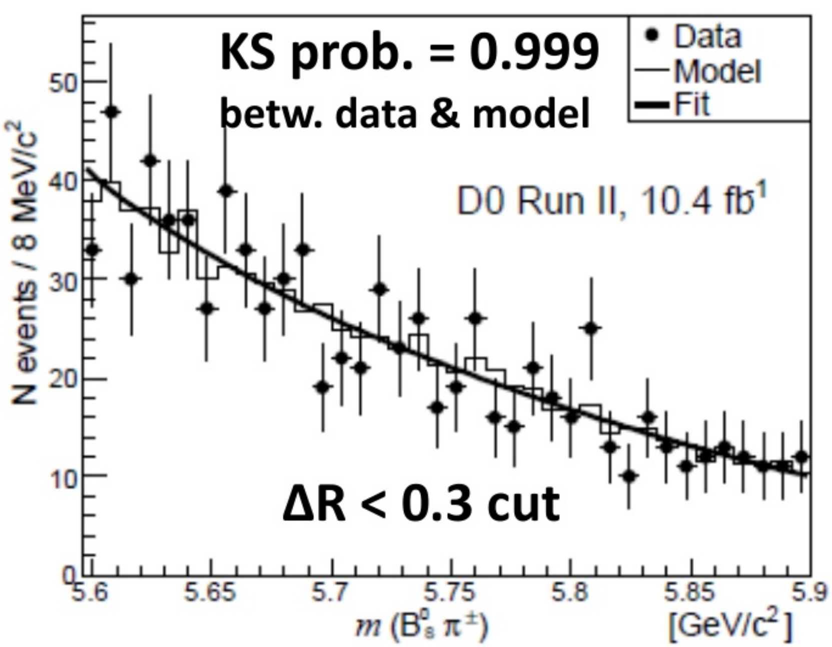
D0 published paper:
Phys.Rev.Lett.99:172001,2007

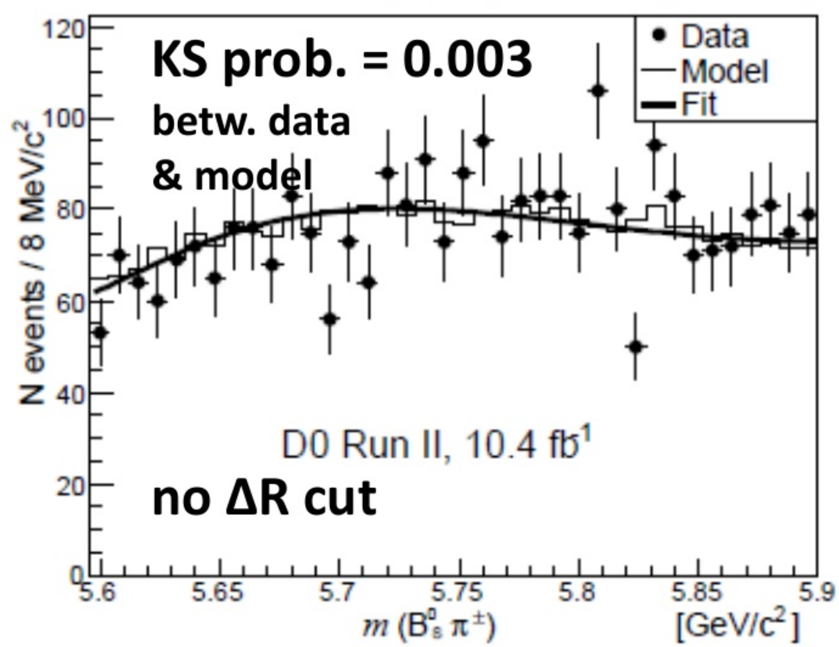
Background vs. ΔR

How well does background model fit the data, above the X(5568) peak for M > 5.6 GeV?

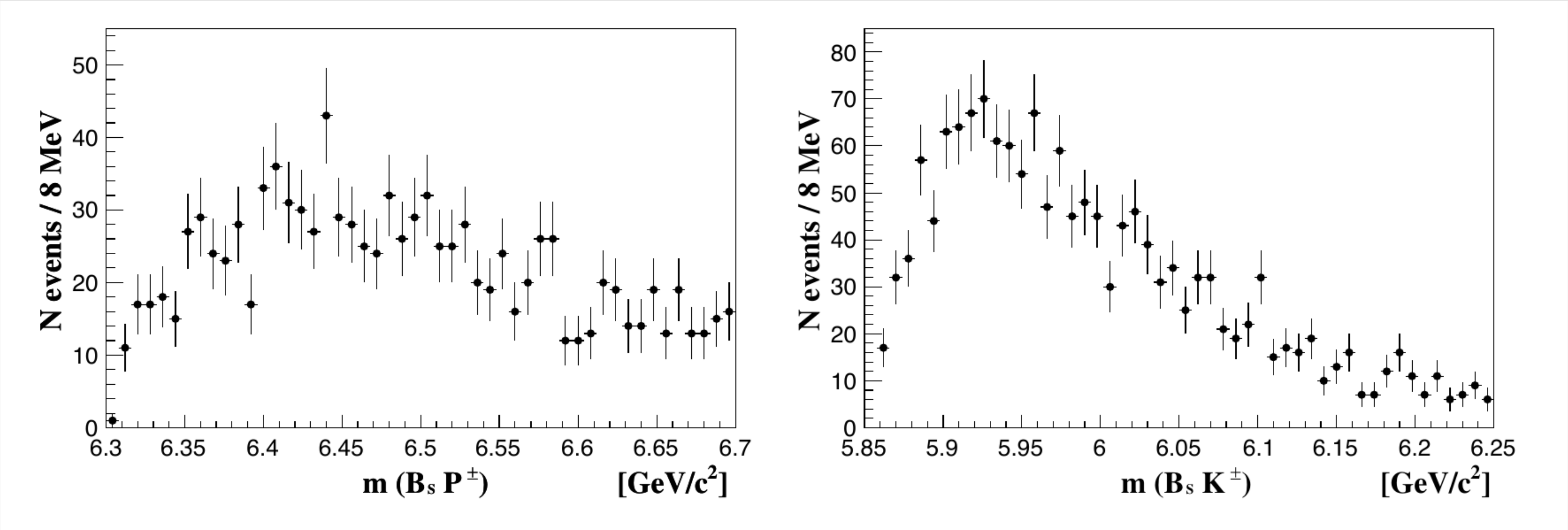




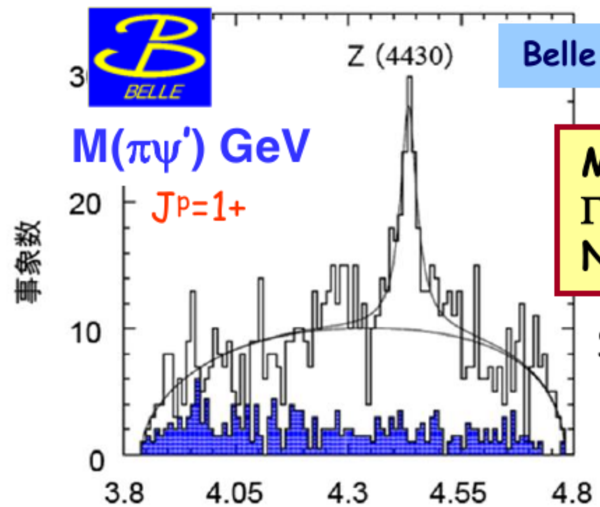




Cross-check: No peaks in m(B_s^0P) or m($B_s^0K^\pm$)



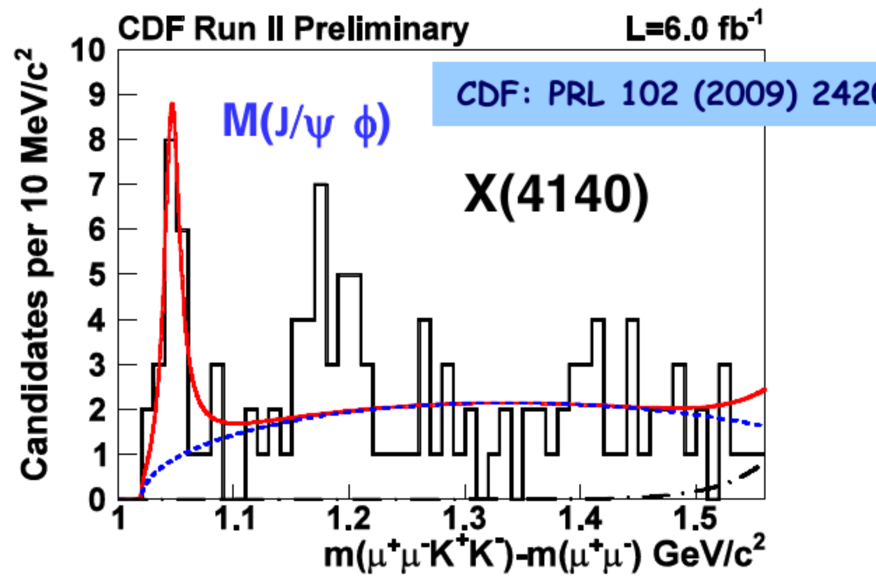
Non-standard states observed with high significance

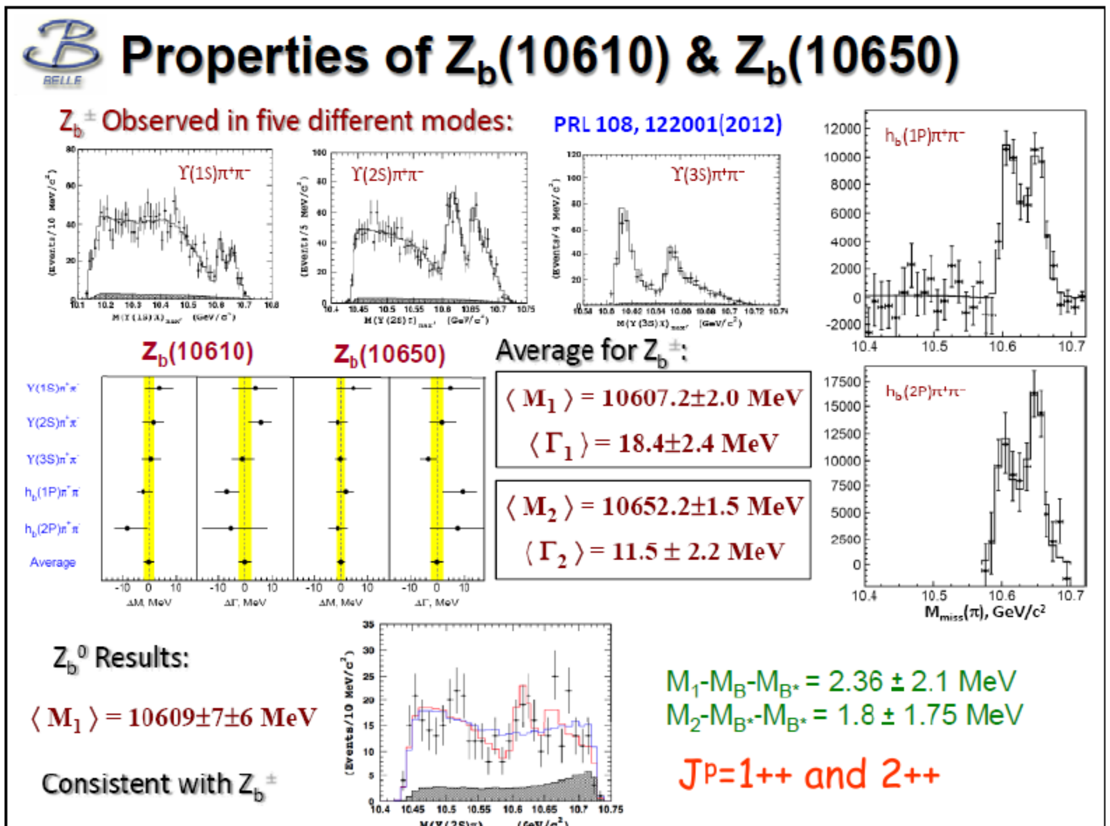


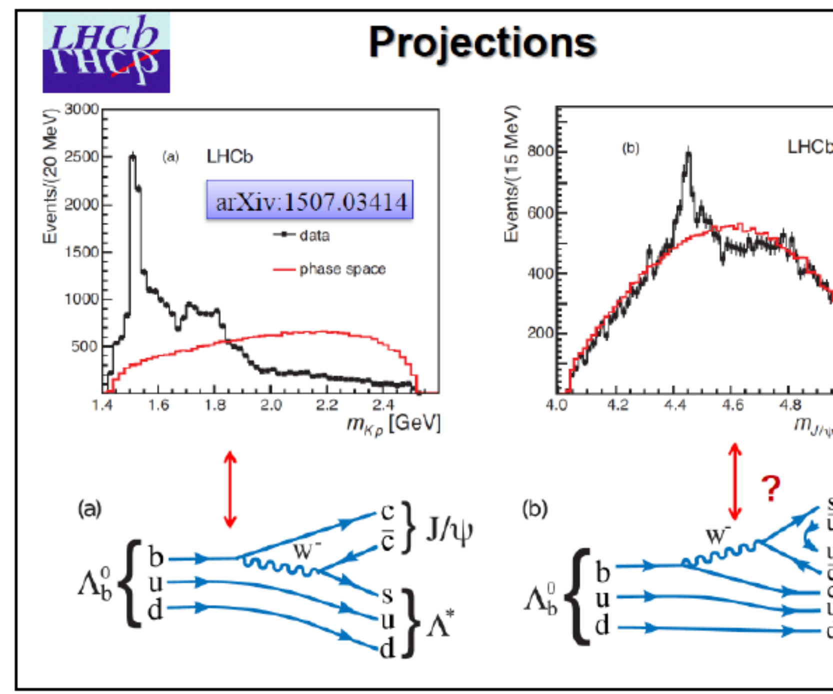
Belle: PRL 100 (2008) 142001

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

Sign = 6.1s (no syst)







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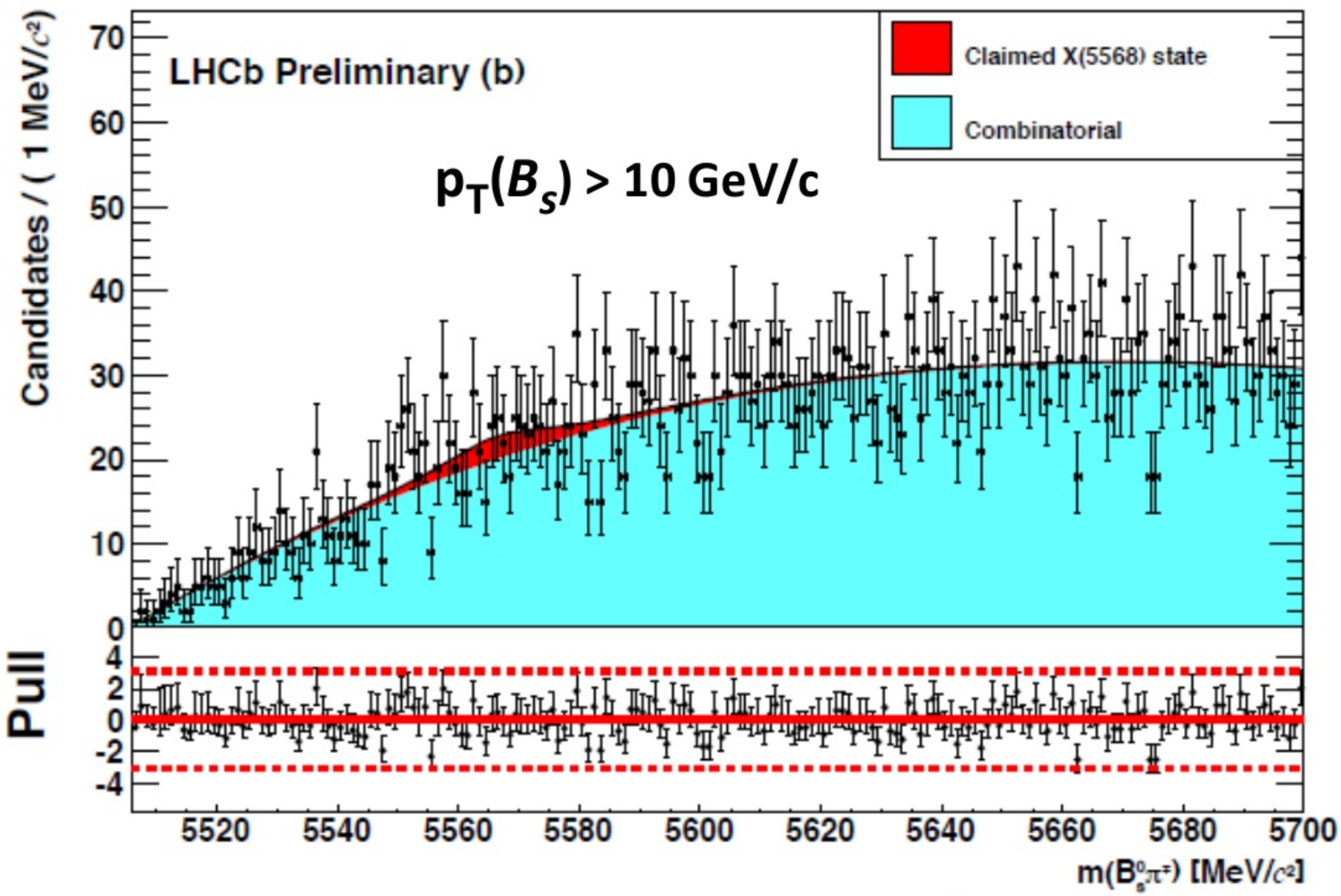
3 fb^{-1} at 7 & 8 TeV, $2 < \eta < 5$, $p_T(B_s) > 10$ GeV/c

$m(B_s^0 \pi^\pm)$ for $B_s^0 \to J/\Psi\, \phi$ and $B_s^0 \to D_s^- \pi^+$

~ 20 X the sample of B_s^0 decays by D0



note: *X(4140)* → *J/Ψ* ϕ was *not* seen by LHCb although observed by CDF, CMS, and D0 (two modes)

only X(3872) → J/Ψ $\pi^+\pi^-$ *was seen by all*

$$\mathcal{R} = \sigma(X)*\mathcal{B}(X \to B_s \pi)/\sigma(B_s) < 1.6\ \%\ @\ 90\%\ \text{CL}$$

reminder D0: $\mathcal{R} = (8.6 \pm 1.9 \pm 1.4)\%$