Stony Brook University

Recent Heavy Flavor Results from Tevatron

LHCP'17

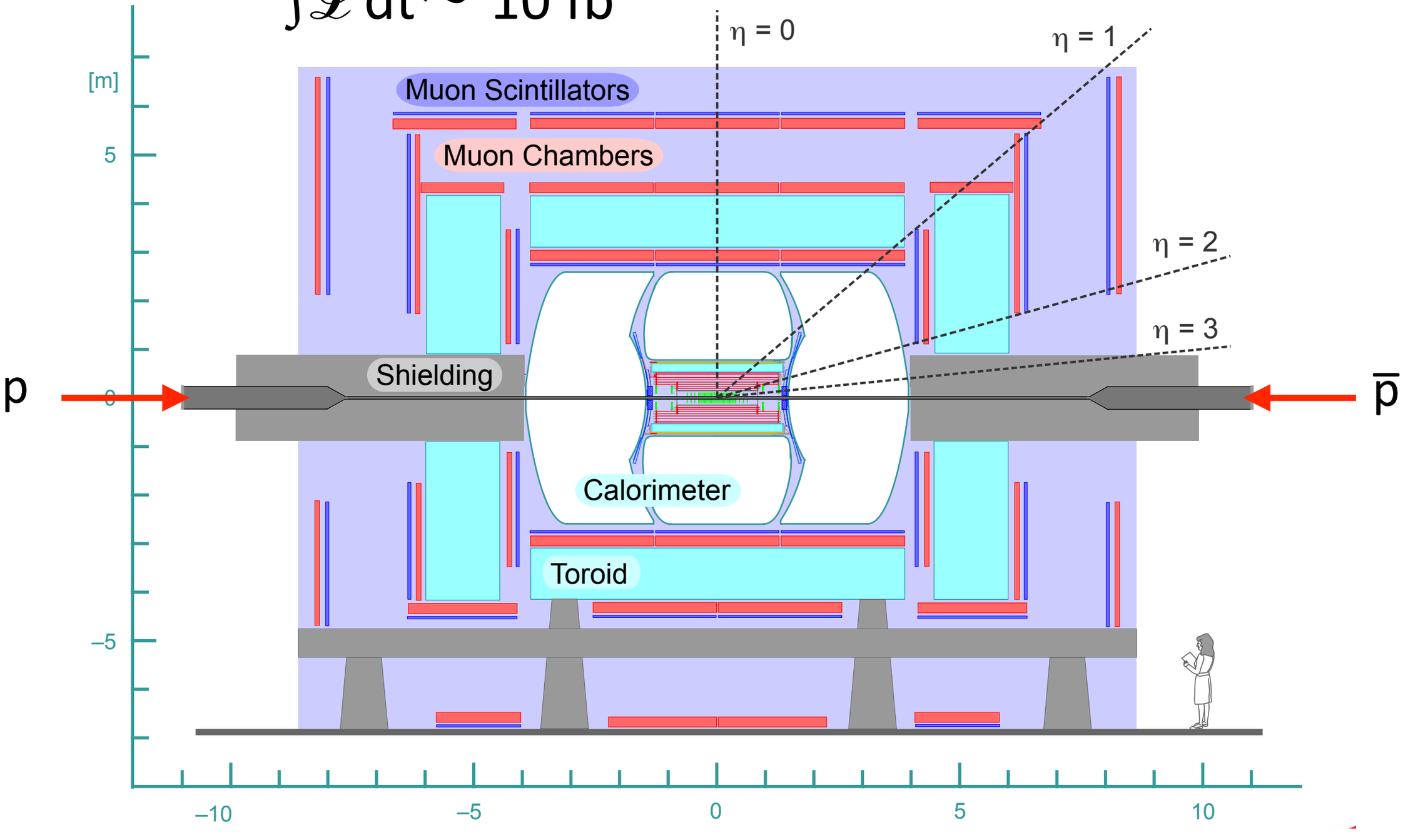
Shanghai, China

Dmitri Tsybychev on behalf of D0
Stony Brook University, USA

The D0 Detector

Multi-purpose, high acceptance, well understood detector
High muon acceptance, excellent triggering and ID

$\int \mathscr{L} dt \sim 10\ fb^{-1}$

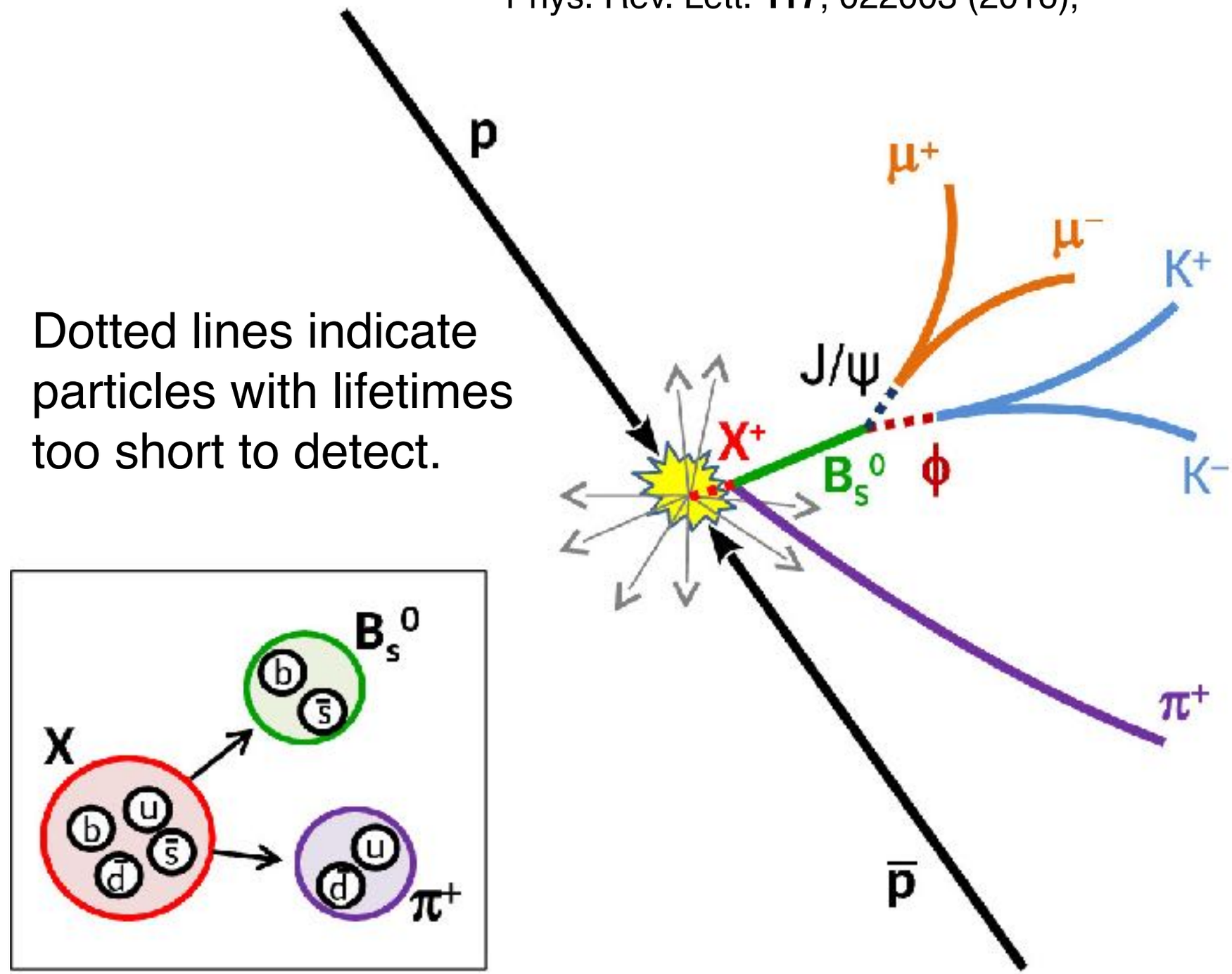


D0 $B_s \pi^{\pm}$ hadronic channel

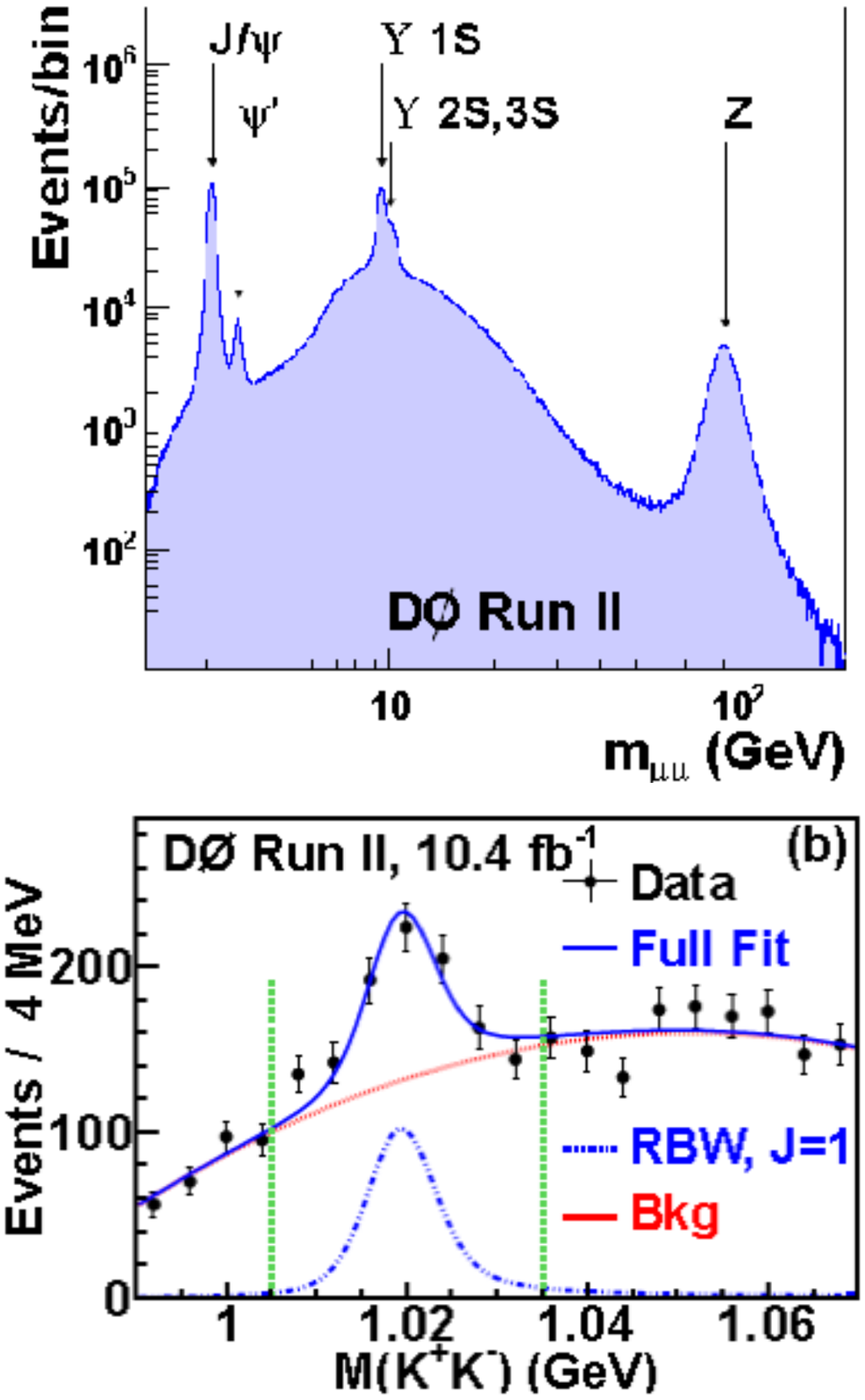
Phys. Rev. Lett. **117**, 022003 (2016),

'hadronic' refers to the decay $B_s \rightarrow J/\psi\ \phi$ as opposed to the semileptonic decay $B_s \rightarrow D_s^+ \mu^- X$ to be discussed later.

Dotted lines indicate particles with lifetimes too short to detect.



$B_s\,\pi^{\pm}$ hadronic: Selections



- **J/ψ:** $p_T^{\mu} > 1.5$ GeV; $M(\mu\mu) = (2.92, 3.25)$ GeV; selected dimuons are constrained to the PDG J/ψ mass.
- **ϕ:** $p_T^{K} > 0.7$ GeV: $M_{KK} = (1.012, 1.030)$ GeV
- **B_s candidate:** $M(\mu^+\mu^-\,K^+K^-) = (5.304, 5.425)$ GeV; $L_{xy}/\sigma(L_{xy}) > 3$
- **Additional** $\pi^{\pm}$: add a track assumed to be a π with $p_T^{\pi}>0.5$ GeV; $IP_{xy}<0.02$ cm, $IP_{3D}<0.12$ cm

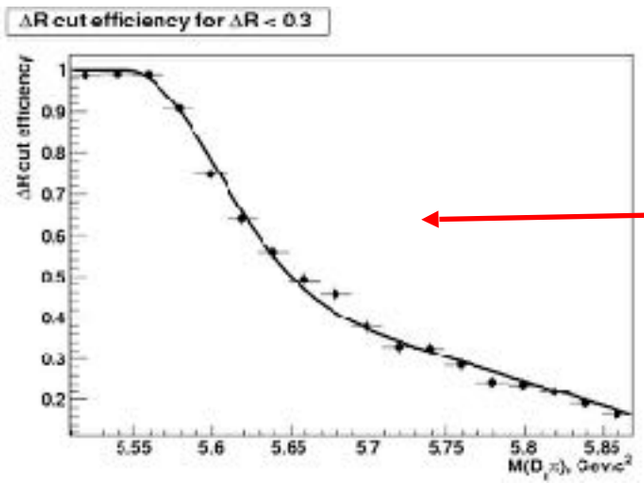
- **$p_T(B_s\pi) > 10$ GeV**
- Optional cut on the angular separation of B_s and $\pi^{\pm}$ $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2} < 0.3$ **(the "cone cut")**
- Improve $B_s\,\pi$ mass resolution by using $M(B_s\,\pi) = M_{obs}(\mu^+\mu^-\,K^+K^-\,\pi) - M_{obs}(\mu^+\mu^-\,K^+K^-) + M_{PDG}(B_s)$
- $B_s\,\pi$ candidates are restricted to 5506(threshold) < M < 5900 GeV

$B_s \pi^{\pm}$ hadronic: Background and signal model

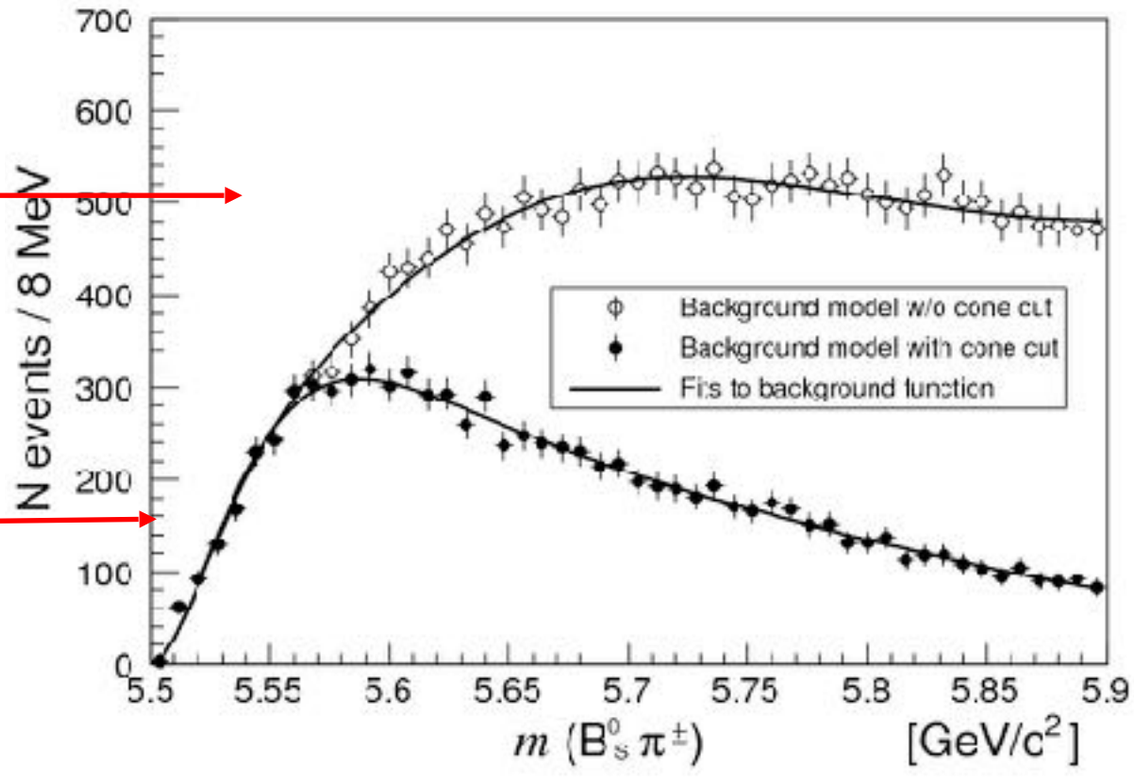
Fit the **background** to a product of polynomial and exponential:

$$F_{BKD} = (C_1 + C_2 m^2 + C_3 m^3 + C_4 m^4) * \exp(C_5 + C_6 m + C_7 m^2)$$

Fit is good both with and without the cone cut.



The $\Delta R < 0.3$ cone cut suppresses the events at high mass:



The **signal X** is assumed to be a relativistic s-wave Breit-Wigner with a mass-dependent width $\Gamma(m) = \Gamma_X (q_m/q_0)$ where q_m is the rest frame momentum of B_s at $M(B_s \pi)=m$ and q_0 is the momentum at the central M_X value. The BW is convoluted with the Gaussian resolution, σ=3.8 MeV

Fit data (or MC pseudo-expts) to $N_X \cdot BW(M_X,\Gamma_X) + (N_{tot}-N_X) \cdot F_{BKD}$

$B_s \pi^{\pm}$ hadronic: Results

$$\underline{X(5568)}$$

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

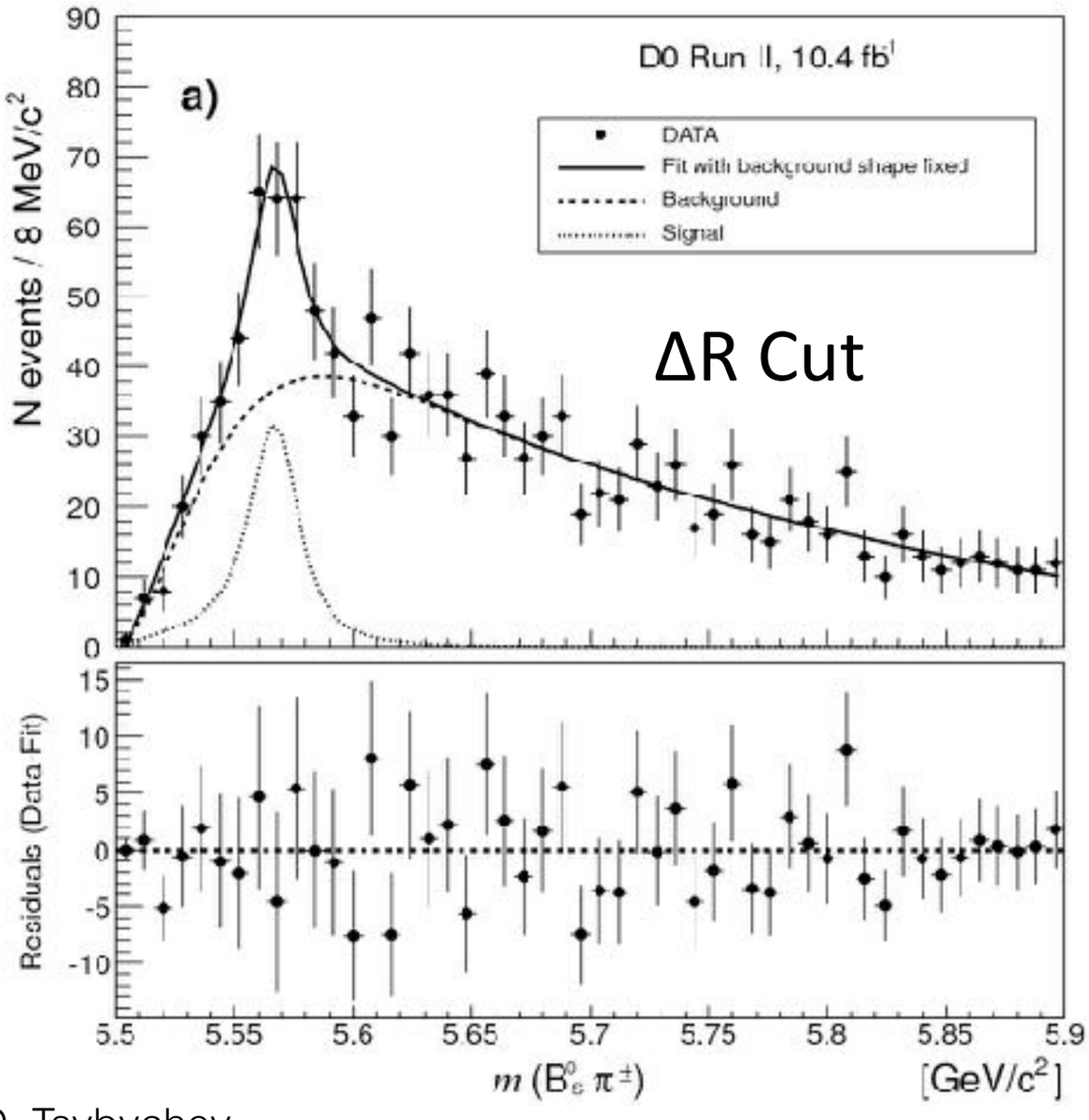
$$\Gamma_X = 21.9 \pm 6.4\,(\mathrm{stat})^{+5.0}_{-2.5}\,(\mathrm{syst})\ \mathrm{MeV/c^2}$$

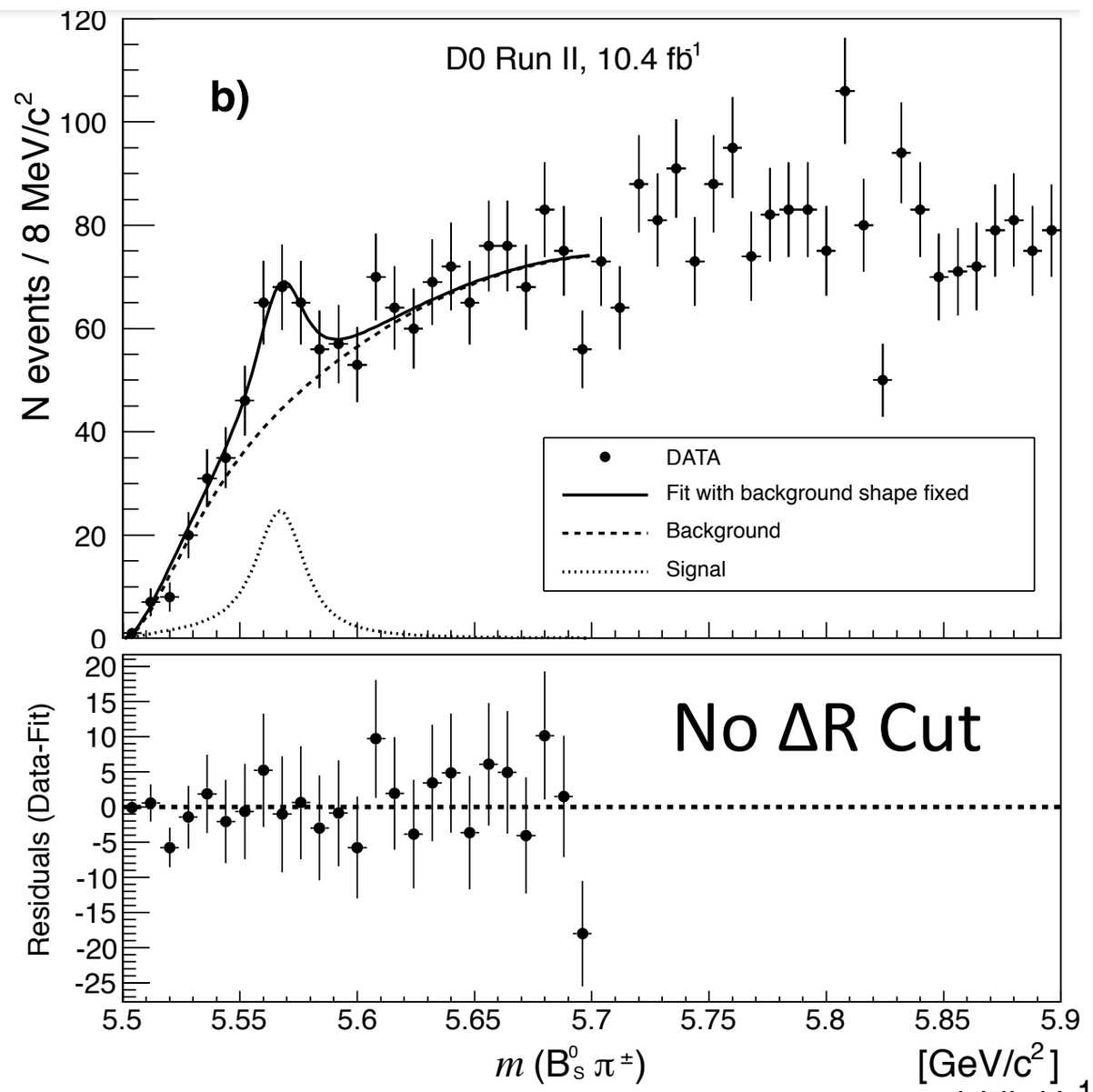
$$\rho = [8.6 \pm 1.9\,(\mathrm{stat}) \pm 1.4\,(\mathrm{syst})]\,\%$$

Statistical significance of signal (including systematics and LEE)

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

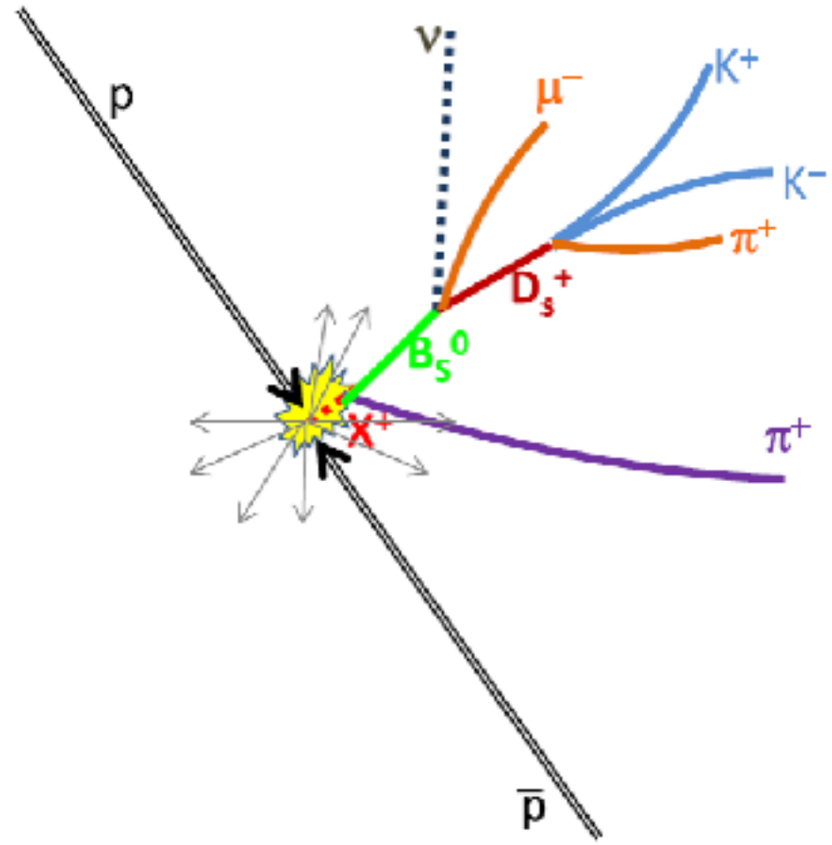
With ΔR Cut: 5.1 σ, Without ΔR Cut: 3.9 σ





$B_s \pi^\pm$ semileptonic channel

In preliminary analysis for Moriond QCD2017, D0 searched for X(5568) in a complementary decay channel:



$X(5568) \rightarrow B_s \pi^\pm$

with $B_s \rightarrow D_s^- \mu^+ \nu$ (+X)

$D_s^- \rightarrow \phi \pi^- \rightarrow K^+ K^- \pi^-$

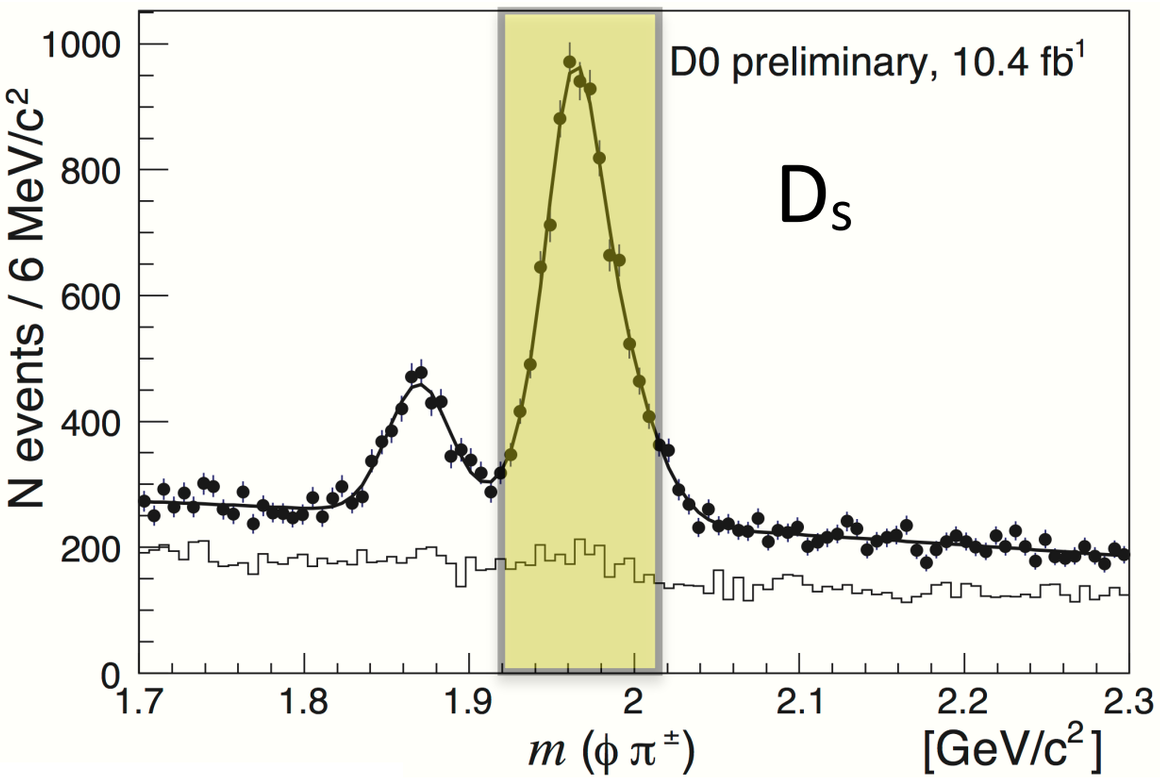
X = possible other particles from B_s

(& charge conjugates)

Selections:

- K's: p_T>1.0 GeV, opposite charge, M_{KK} = (1.012, 1.030) GeV
- μ: p_T = (3, 25) GeV; opposite charge to π from D_s; good vertex with D_s
- D_s and B_s decay vertices well separated from primary vertex
- π in $B_s \pi$ decay: p_T=(0.5, 25) GeV (same selection as in hadronic channel)
- $p_T(\mu D_s) > 10$ GeV
- 4.5 GeV<$M(\mu D_s)$<$M(B_s)$ to minimize effect of final state ν
- **No cone cut is imposed**

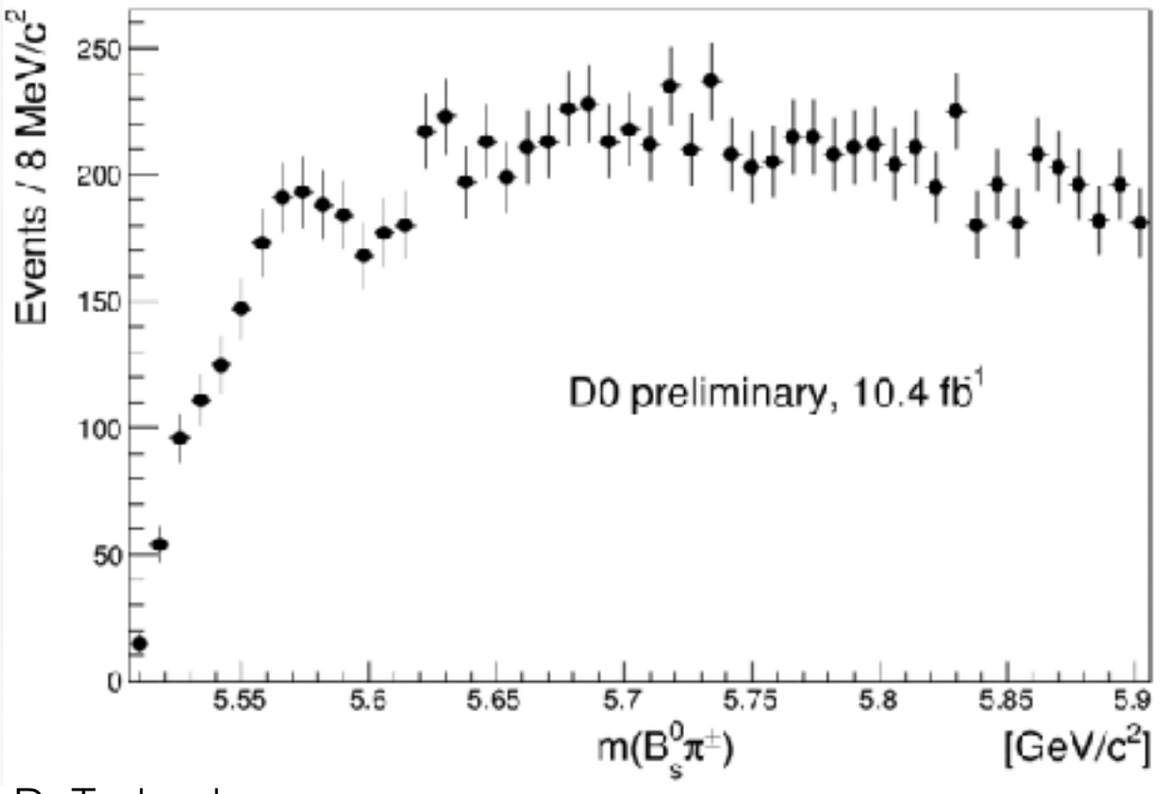
$B_s \pi^{\pm}$ semileptonic data

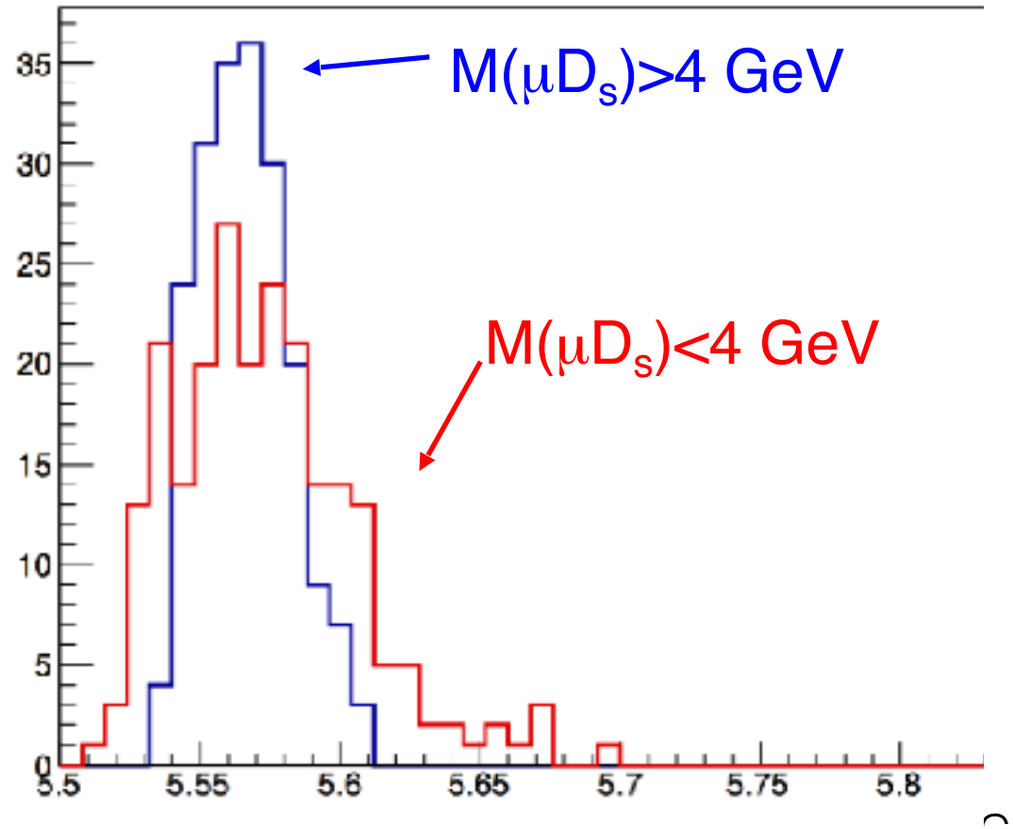


Restricting $M(\mu D_s)$ to be large (E_ν low) improves mass resolution for $B_s \pi$

To further improve mass resolution, define:
$M(B_s\pi)=m(\mu D_s\pi)-m(\mu D_s)+m_{PDG}(B_s)$

After correcting for efficiency/ acceptances, expect ~20% more semileptonic X(5568) than hadronic





D0 MC

$B_s\,\pi^{\pm}$ semileptonic: background modeling

Fit reweighted MC background with baseline function:

$F_{bkg} = (C_1\Delta+C_2\Delta^2+C_3\Delta^3+C_4\Delta^4)*\exp(C_5\Delta+C_6\Delta^2)$ where $\Delta = m(B_s\,\pi) - m_{threshold}$

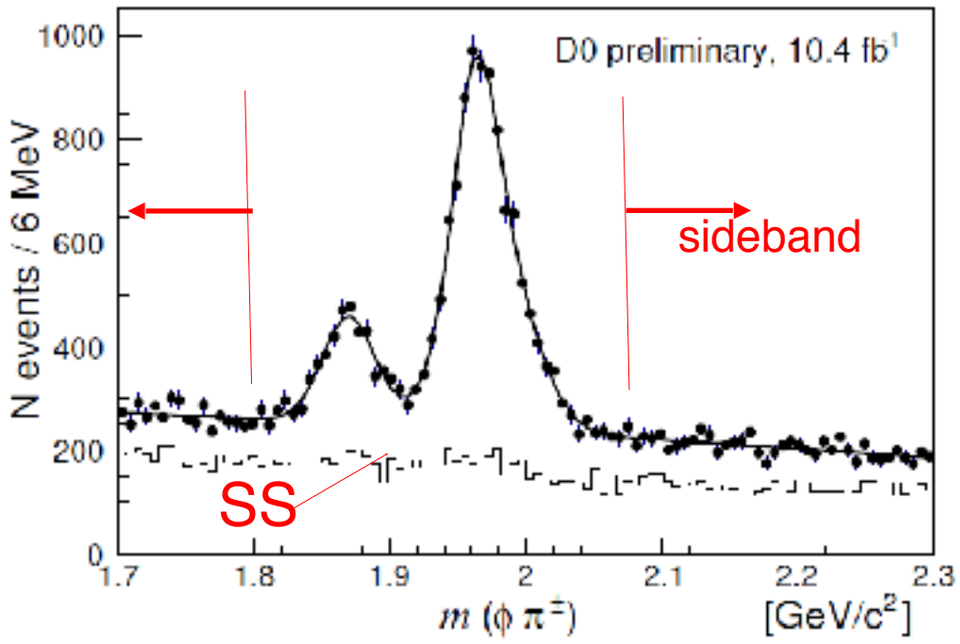
Three alternate fits of MC background:

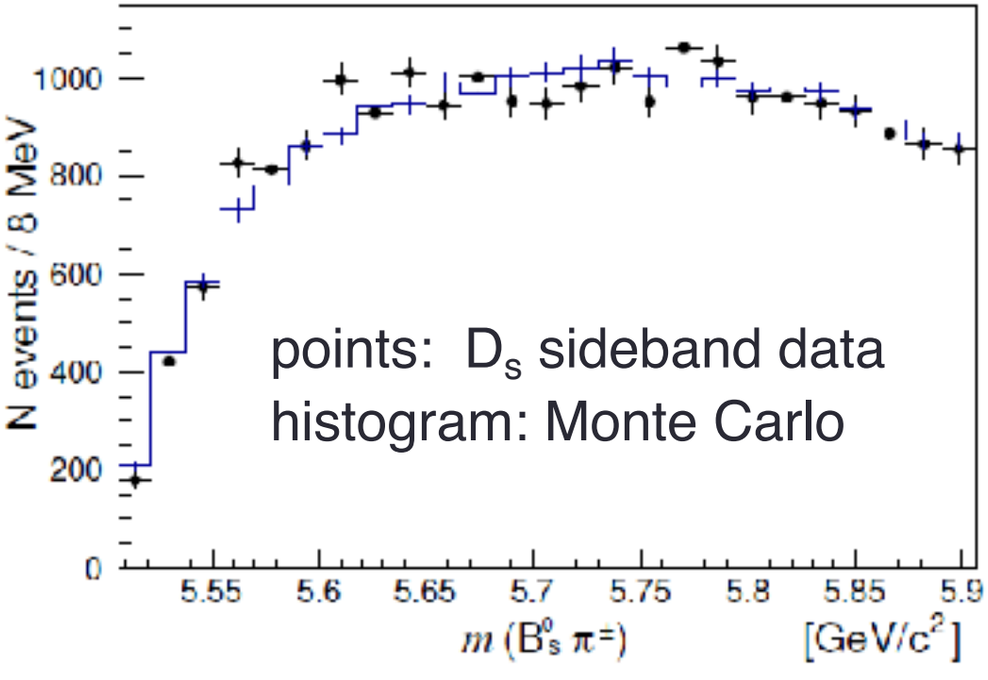
1) $F_{bkg} = (C_1+C_2\Delta^2+C_3\Delta^3+C_4\Delta^4)\exp(C_5+C_6\Delta+C_7\Delta^2)$
   from the hadronic channel analysis
2) $F_{bkg} = m[\,(m/m_{threshold})^2-1\,]^{C1}\exp(C_2 m)$
   the 'ARGUS' function for resonances near threshold
3) The MC histogram itself, smoothed by ROOT.

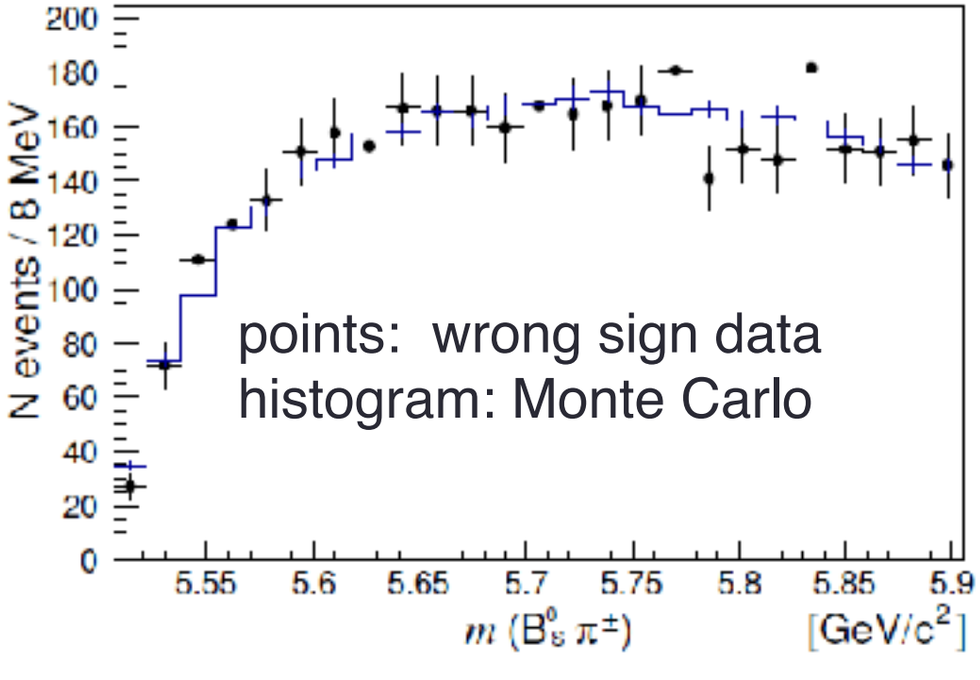
Also consider two alternate background shape choices to the MC:

(a) Data sidebands in $m(\phi\pi^{\pm})$ distribution

(b) Data same (wrong) sign $D_s^{\pm}\,\mu^{\pm}$ events

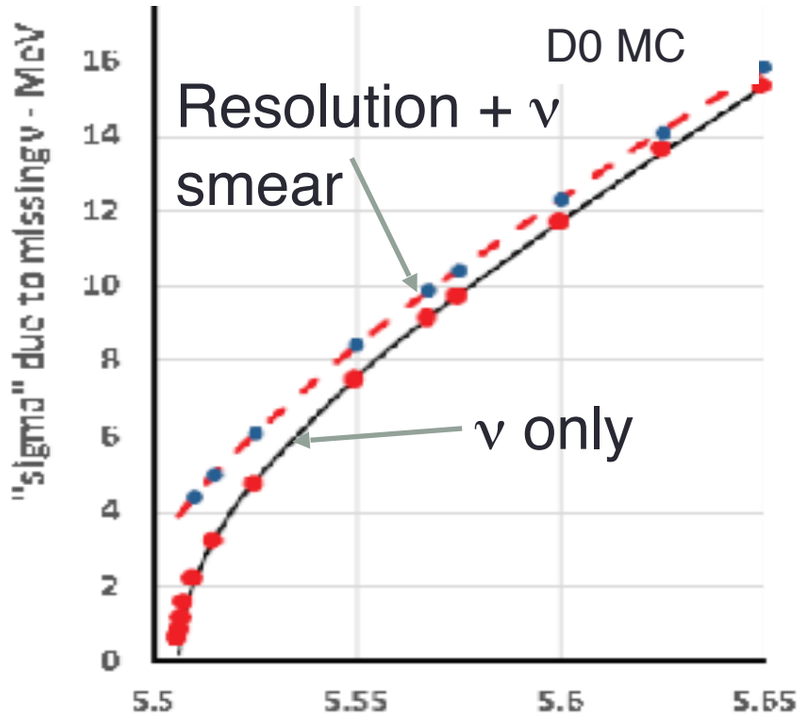






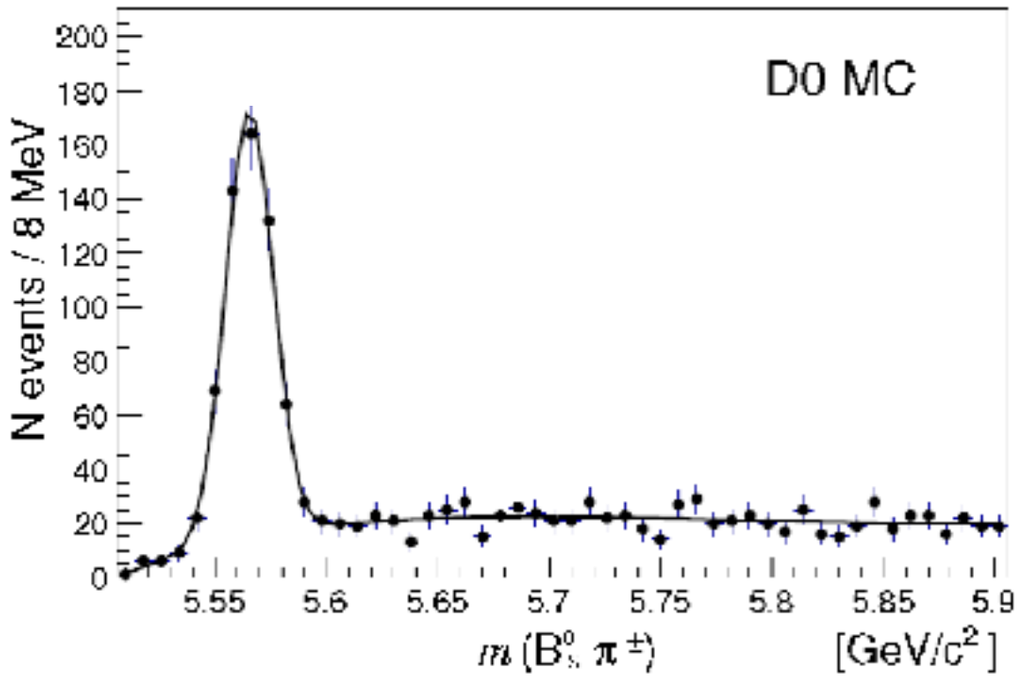
B_s $\pi^{\pm}$ semileptonic: signal modeling

The signal is modeled with the same relativistic Breit Wigner s-wave shape as used for the hadronic channel, convoluted with a Gaussian mass resolution whose (mass-dependent) width is taken from MC. This resolution is dominated by the missing ν.



3.8 MeV mass resolution due to track curvature resolution is convoluted with the smearing due to missing ν.

MC of X(5568) signal including resolution effects and the effects of the unseen neutrino shows a narrow peak with a broad flat tail due to an association of a B_s with an incorrect $\pi^{\pm}$



$B_s \pi^{\pm}$ semileptonic: Systematics

Vary energy scale and resolution by 1σ
Fit signal to p-wave BW
Vary resolution smearing due to ν
Dominant uncertainty due to background shape, estimated by comparing baseline and alternate background models

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

Source	mass, MeV/c^2	width, MeV/c^2	events 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

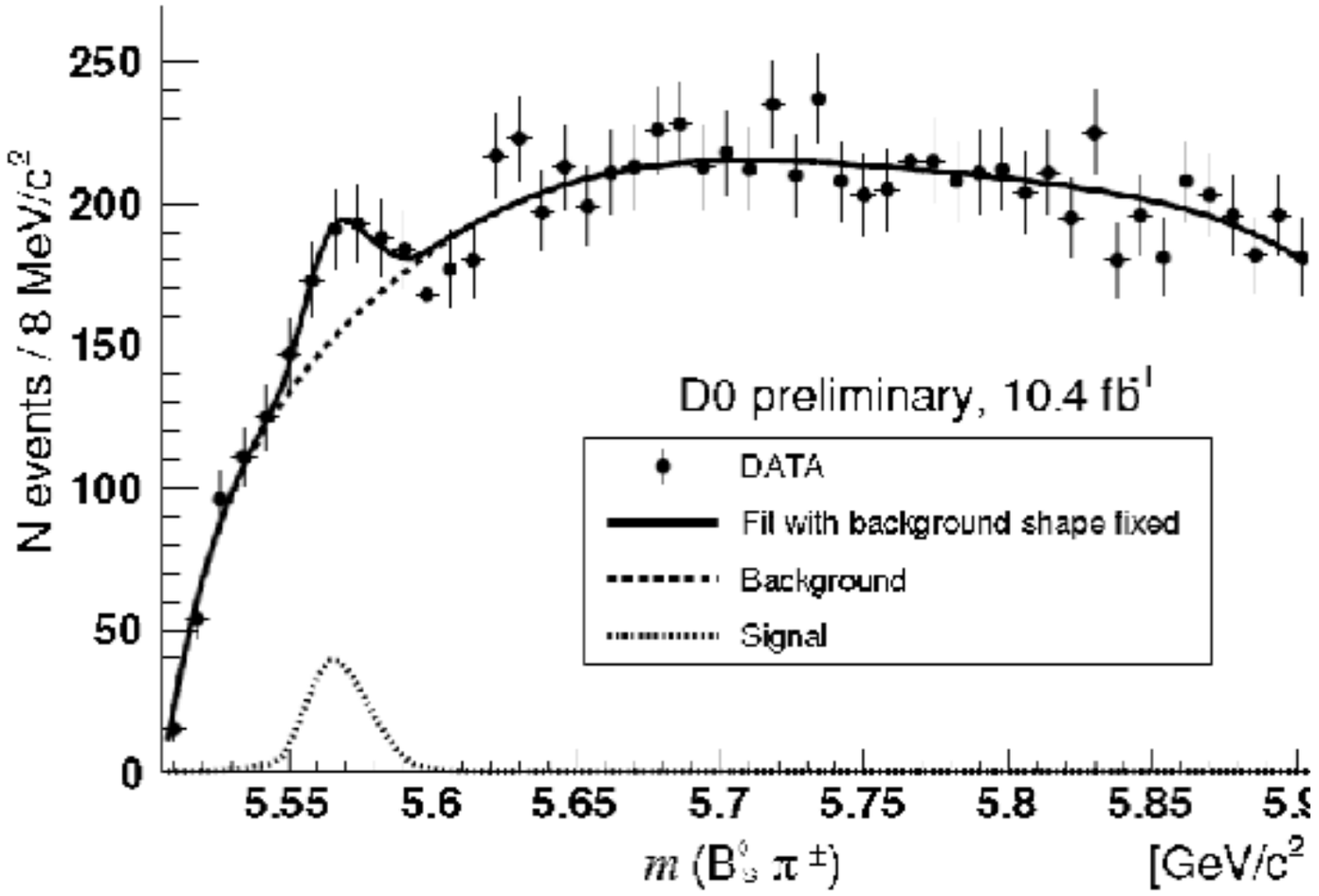
$B_s \pi^{\pm}$ semileptonic: Results

<u>Fit results</u>:

$M_X = 5566.7\ ^{+3.6}_{-3.4}\ ^{+1.0}_{-1.0}$ MeV

$\Gamma_X = 6.0\ ^{+9.5}_{-6.0}\ ^{+1.9}_{-4.6}$ MeV

$N_X = 139\ ^{+51}_{-63}\ ^{+10.9}_{-31.5}$

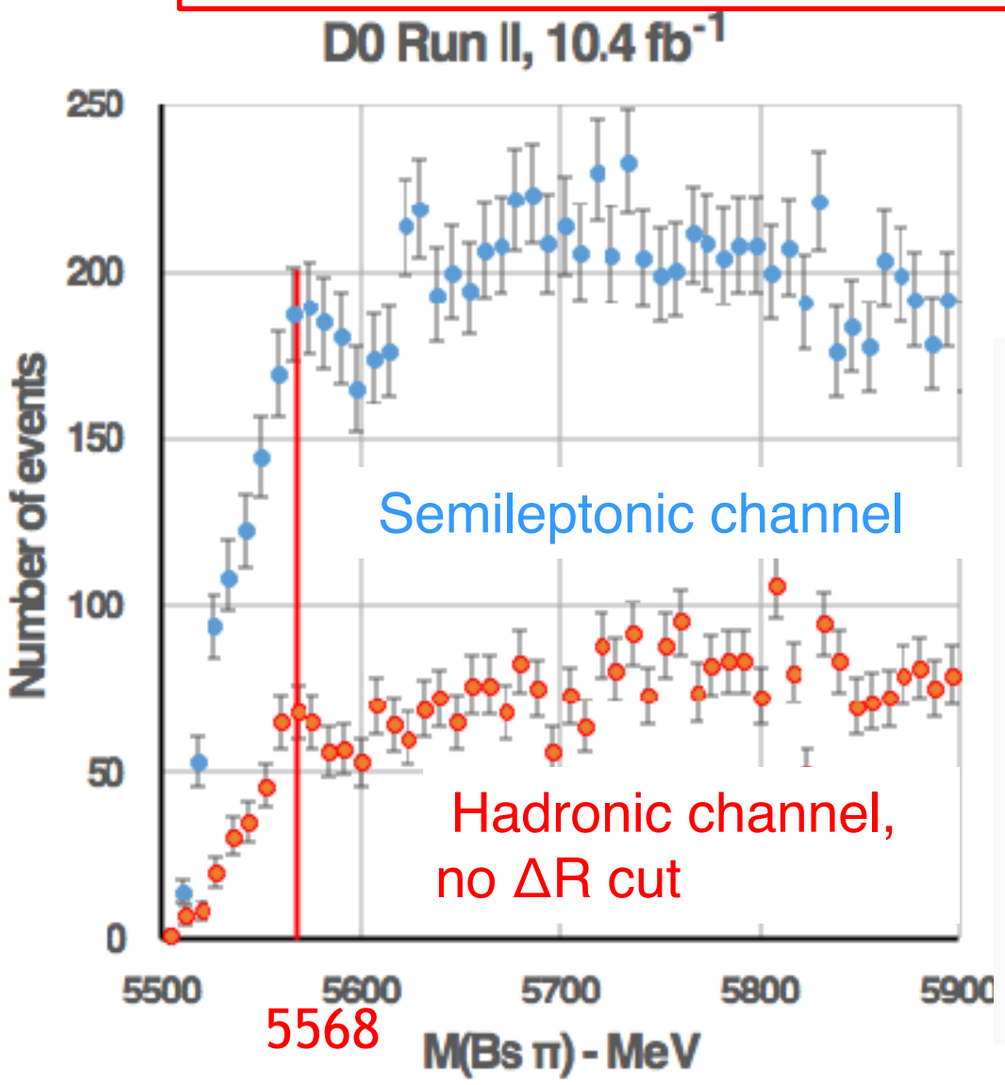


Statistical significance 4.5σ; significance with syst: 3.2σ

⇨ We have evidence for X(5568) in the semileptonic channel, with consistent M_X and Γ_X as hadronic channel,

Fraction of B_s from X(5568) ($p_T(\mu D_s)$>10 GeV) is 7.6±2.9% in SL channel.
Compare this with the hadronic fraction of 8.6±2.4% for $p_T(J/\psi\ \phi)$>10 GeV.

Comparison of $B_s \pi^{\pm}$ hadronic and semileptonic channels



The hadronic and semileptonic channels agree on mass and width of X(5568), produce a combination of the two.

Inputs to combination	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

and

or

For $p_{had} = 3.8 \times 10^{-7}$ (with cone cut) and $p_{SL} = 6.4 \times 10^{-4}$, we obtain

$p_{comb} = 5.6 \times 10^{-9}$ corresponding to 5.7σ significance

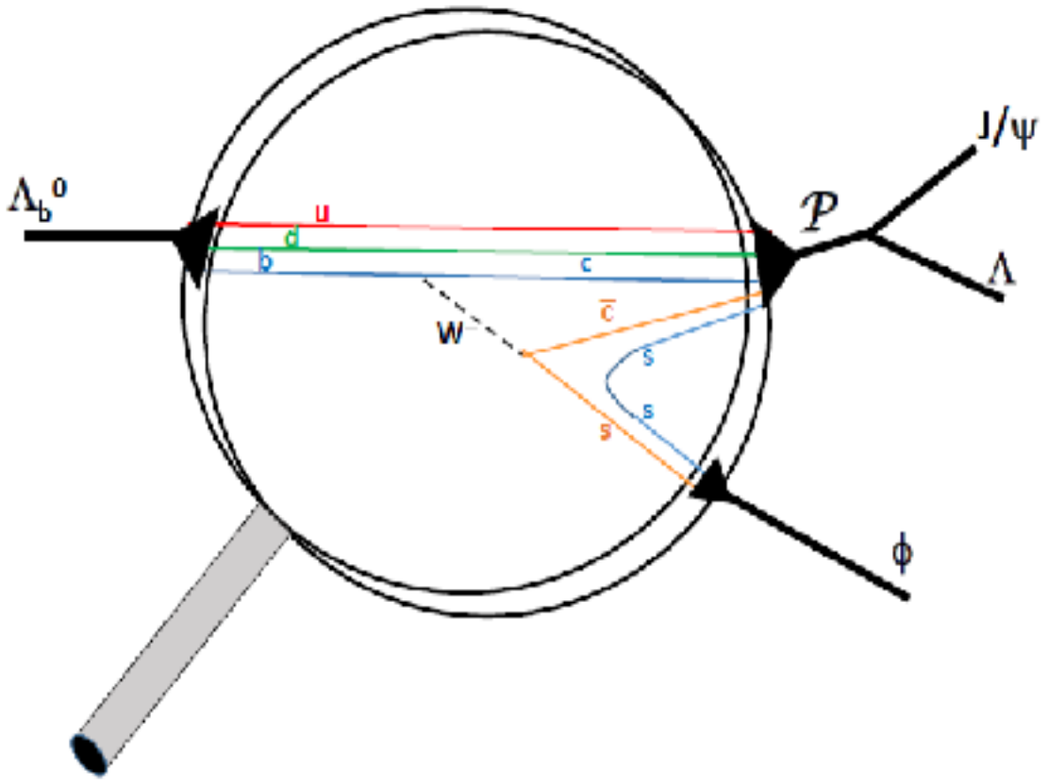
Combining the hadronic result without cone cut and the semileptonic result, we get a significance of 4.7σ.

D0 Pentaquark search

Motivated by the LHCb result, D0 searched for strange analogs of the LHCb states: e.g. $\Lambda_b \rightarrow P_c^+ \phi$ with $P_c^+ \rightarrow J/\psi\, \Lambda$, and $J/\psi \rightarrow \mu^+\mu^-$, $\Lambda \rightarrow p\pi^-$ (and charge conjugates).

https://www-d0.fnal.gov/Run2Physics/WWW/results/prelim/B/B69/

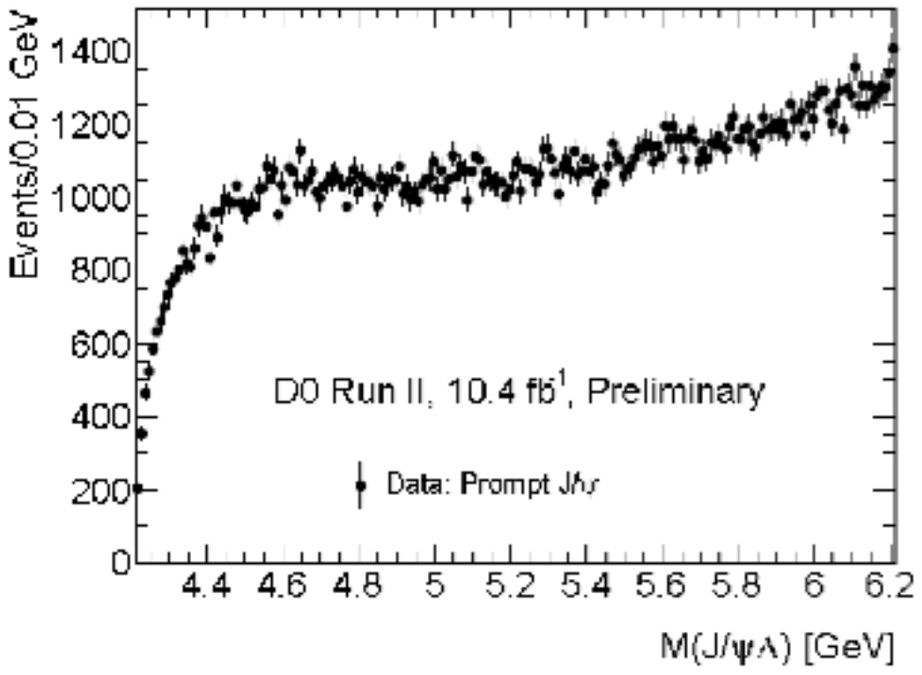
Such P_c states could come from decays of Λ_b^0, Ξ_b^-, etc. Take search window up to 500 MeV above $J/\psi\, \Lambda$ threshold, based on the LHCb states and theoretical models.

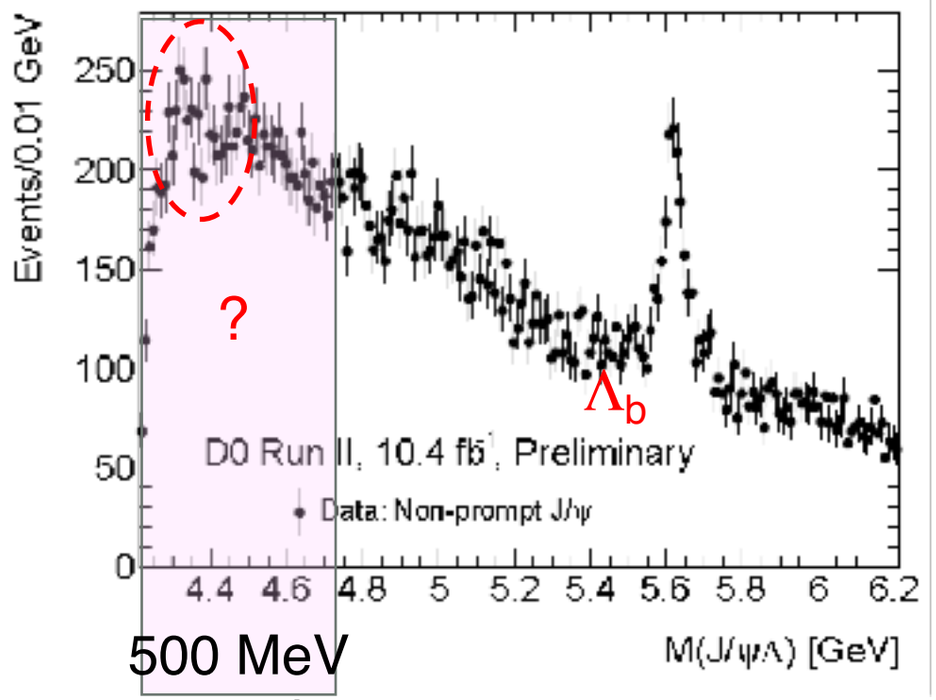


Event selection is based on that for the D0 Λ_b lifetime measurement; extended tracking version to increase acceptance for low momentum π from Λ decay.

D0 Pentaquark search

Divide J/ψ Λ sample into 'prompt' and 'non-prompt' subsets based on J/ψ decay length significance. See clear Λ_b signal in non-prompt sample, so focus on this subset.





Perform a series of fits of the form

$$F = f_{\rm sig} \times F_{\rm sig}(M(J/\psi\Lambda), M_X, \sigma_X) + f_{\rm bgr} \times F_{\rm bgr}(M(J/\psi\Lambda)),$$

where F_{sig} is a Gaussian of width σ_X and M_X is incremented in 10 MeV steps from threshold to 4.7 GeV, and F_{bgr} is the background function

$$F_{\rm bgr} \propto m \cdot (m^2/m_{\rm thr}^2 - 1)^{c_1} \cdot e^{-m \cdot c_2} \cdot (1 - e^{-(m-m_{\rm thr})/b}),$$

D0 Pentaquark search

Fit result at the step with maximum significance.

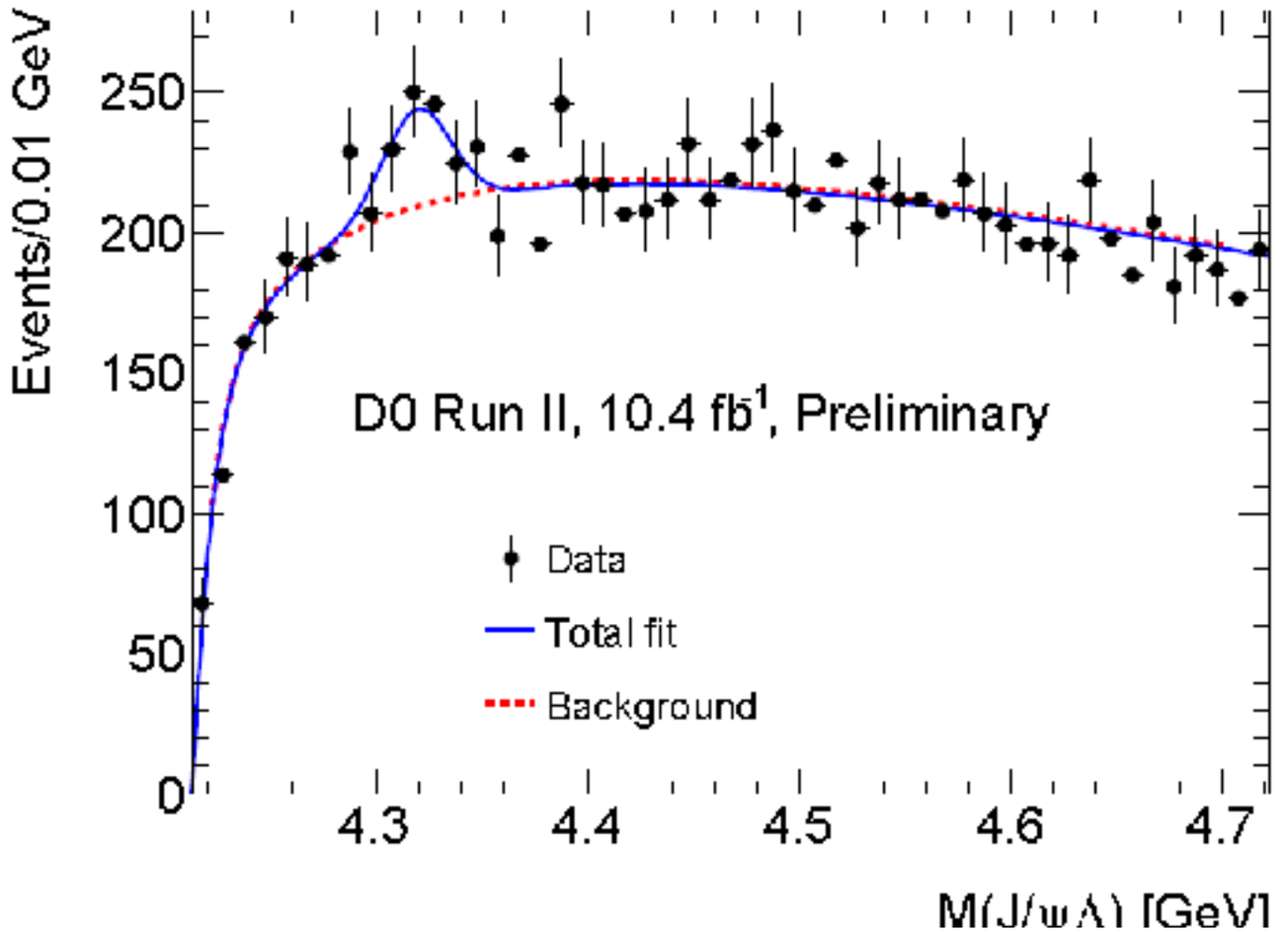
M_X = 4319.3± 6.6 MeV

σ_X = 15.6 ± 7.7 MeV

N_X = 142 ± 66

(mass resolution here is 5 MeV)

Local significance = 3.45σ



Perform 6400 pseudoexperiments to determine the probability of a 3.45σ or higher fluctuation anywhere in the search range.

Global significance = 2.8σ.

Use of alternate signal model, alternate background function, or J/ψ or Λ sidebands increase the observed yield, so systematic uncertainties do not diminish the significance.

Thus no evidence for strange analog of LHCb pentaquark in J/ψ Λ, but at least a pointer on where one might look.

Summary

Exotic mesons and baryons are now definitively observed but their construction is still not well understood

D0 sees a strongly decaying (Γ>0) meson in two quite different channels with different backgrounds
The combined significance is 5.7σ (4.7σ when using the hadronic channel without cone cut.)

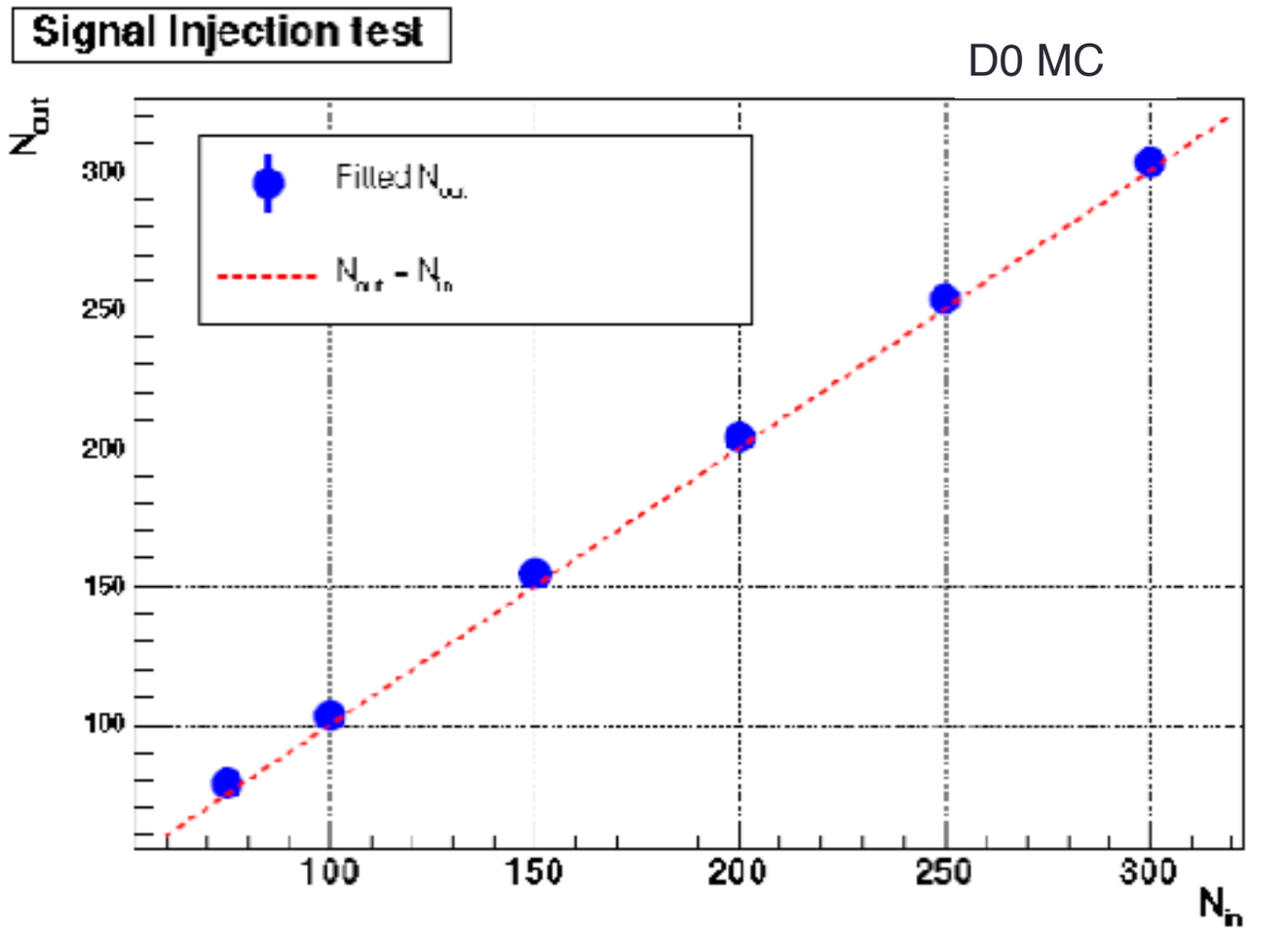
The X(5568) would be the first meson that includes four quark flavors.

LHC experiments do not observe it.

The recent pentaquark baryons P_c seen by LHCb should have close family relations.
The D0 search was negative, but suggests a place to focus attention.

BACKUP

B_s $\pi^{\pm}$ semileptonic – fit

We test the closure of the fit and background model by injecting signals of various sizes in MC ensembles with M=5568, Γ=21.9 MeV and fitting for M_X, Γ_X and N_X.

Output N_X and M_X agree with inputs; Fits tend to have small Γ_X for small N_{input}.