Latest Results on Orbitally Excited Bottom Mesons with CDF II Detector

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1 – Outline

- Introduction.
- b-Physics at Tevatron with CDF II detector.
- CDF II Triggers and Datasets involved.
- Strange Orbital B_{sJ} Mesons with CDF II Detector.
  - $\surd$ Modes.
  - $\surd$ Predictions and Status.
  - $\surd$ Preparation of Candidates.
  - $\surd$ Selection of Candidates.
  - $\surd$ Results.
- Summary.

2 – Introduction

⇒ **H.Q.E.T. models:** $m_Q \to \infty$, $m_Q \gg \Lambda_{QCD}$

⇒ In **HQET** Bottom B-mesons $\bar{\mathbf{q}}\mathbf{Q}$ can be treated as a quark "hydrogen atom":

- heavy bottom quark spin $s_Q = \frac{1}{2}^+$ **decouples** from light quark degrees of freedoms.
- the light anti-quark spin-parity $s_{\bar{q}} = \frac{1}{2}^-$ couples with its orbital momentum L .
- $\vec{j_q} = \vec{s_{\bar{q}}} + \vec{L}$ is a good quantum number.
- $\vec{J} = \vec{j_q} + \vec{s_Q}$ is a total momentum.

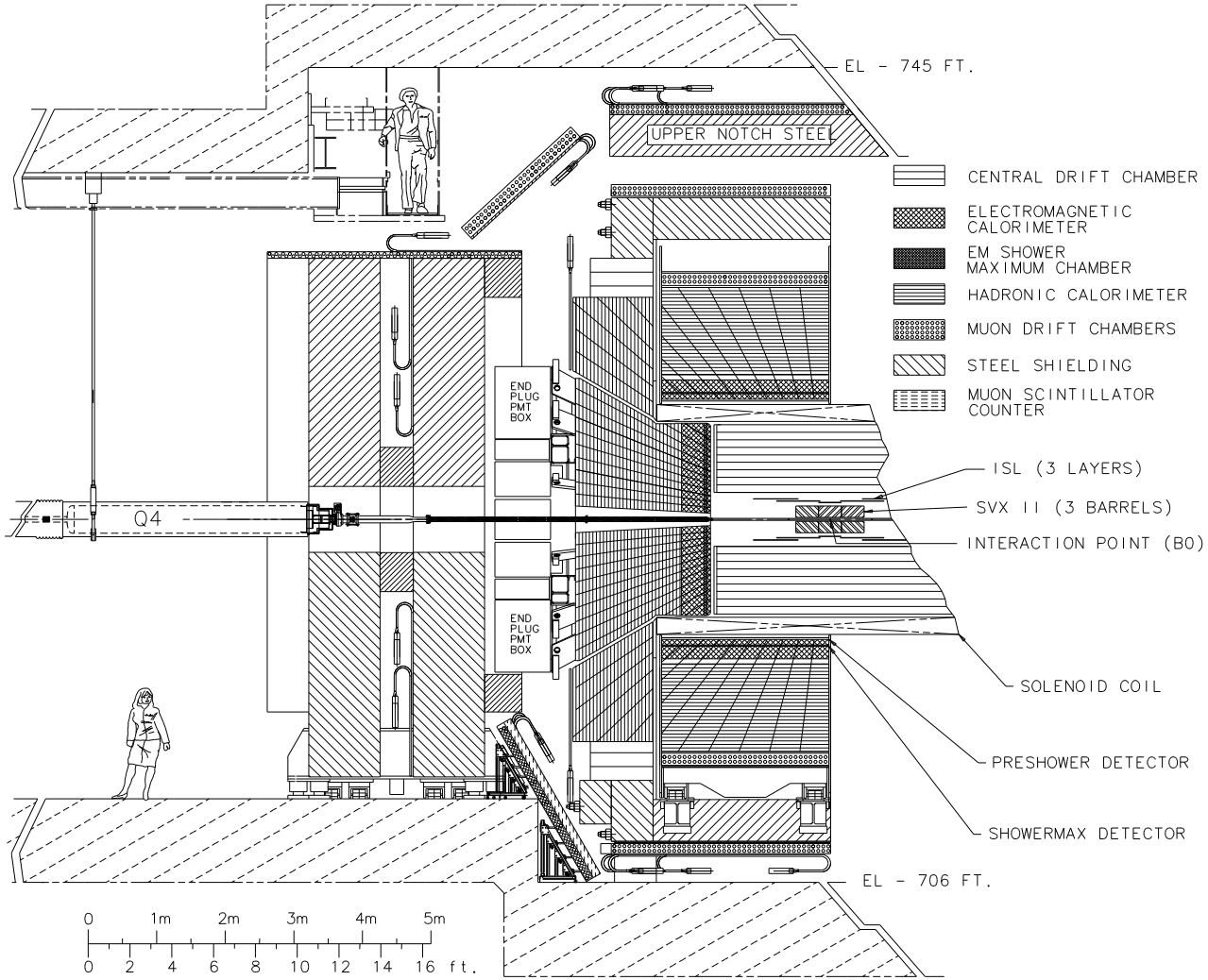
⇒ **Consider L=1, B-mesons:**

- $J = \frac{1}{2}^+ \oplus \frac{1}{2}^+$ or
  - $\mathbf{B'_1}$ **meson,** $\mathbf{1^+}$ $(\mathbf{^1P_1})$ **and** $\mathbf{B_0^*}$ **meson,** $\mathbf{0^+}$ $(\mathbf{^1P_0})$.
- $J = \frac{3}{2}^+ \oplus \frac{1}{2}^+$ or
  - $\mathbf{B_1}$ **meson,** $\mathbf{1^+}$ $(\mathbf{^1P_1})$ **and** $\mathbf{B_2^*}$ **meson,** $\mathbf{2^+}$ $(\mathbf{^1P_2})$.
- As m_Q is large, **but not infinite**, $\vec{j_q} - \vec{s_Q}$ interaction splits the mass states within these doublets.

3 – b- Physics at Tevatron@$\mathbf{1.96\ TeV}$

- Compare $\sigma(\mathbf{b\overline{b}})$
  - $\mathbf{\Upsilon(4S)} \approx \mathbf{1}$ nb (only B^0, B^+)
  - $\mathbf{Z^0} \approx \mathbf{7}$ nb
  - $\mathbf{p\overline{p}} \approx \mathbf{20}\ \mu\mathrm{b}\ (|\eta| < \mathbf{1.0})$, @$\mathbf{1.96\ TeV}$
- A reach variety of heavy quark and excited states are available at Tevatron
  - ... among them $\mathbf{B_s}$, $\mathbf{B_c}$, $\mathbf{B_J}$, $\mathbf{\Lambda_b^0}$ etc.
- enormous inelastic total cross-section of $\sim \mathbf{60}$ mb
- b- Hadron Triggers required
  - based on leptons
  - based on displaced tracks
- high occupancy
  - precise tracking with good resolution are required

4 – CDF II Detector at Tevatron

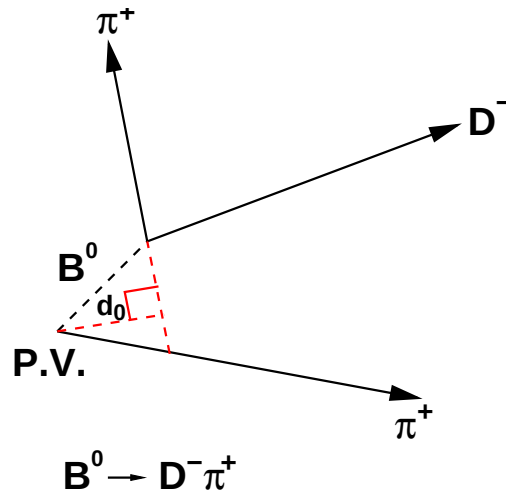


$\Rightarrow$ Critical for present results: COT (central tracker), SVX II (Si), μ-chambers

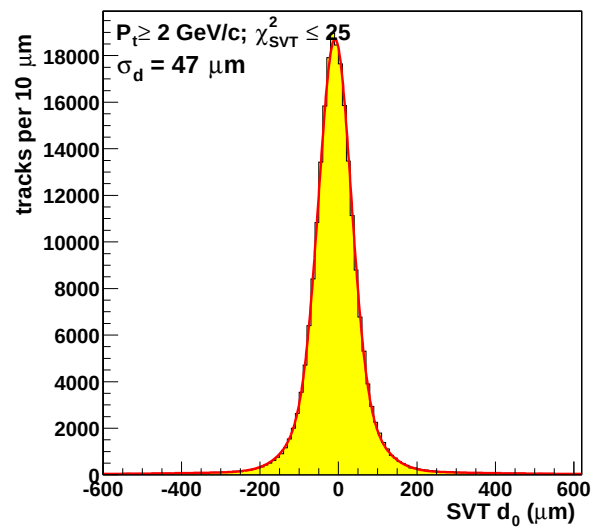
5 – b- Physics Triggers in CDF II

⇒ **Trigger on Hadron Modes**

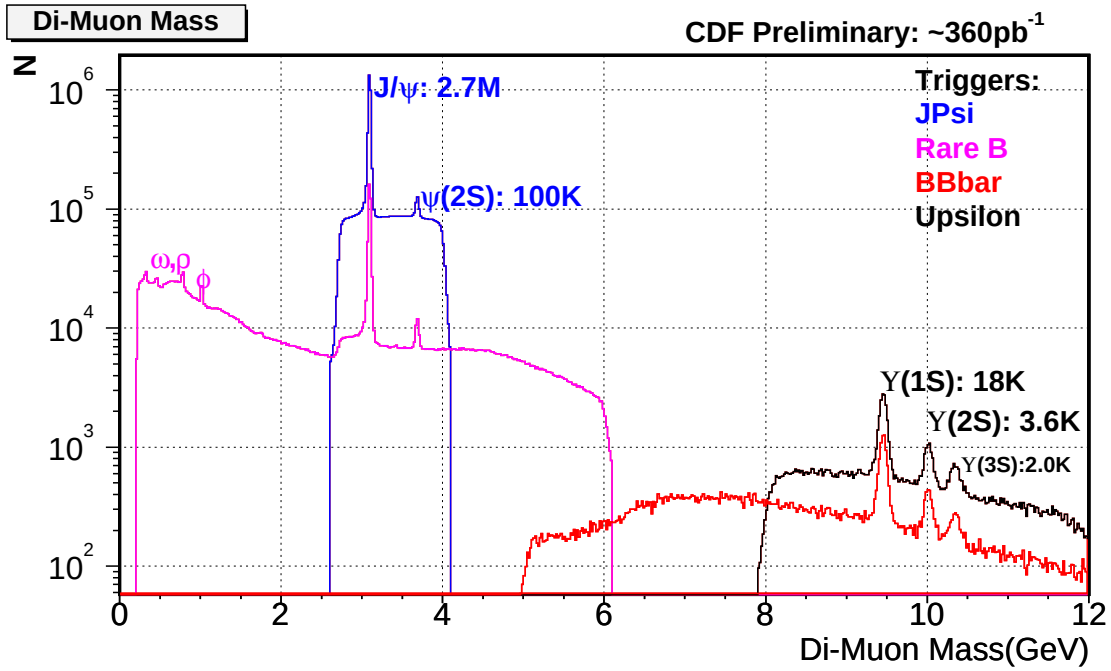
⇒ **of Heavy B-, D- Mesons, Baryons**



- Level 1 eXtremely Fast Tracker (XFT) Trigger: high p_T
- Level 2 Silicon Vertex Trigger (SVT): large track d_0
- impact parameter resolution by SVX II $\sigma(\mathrm{d}_0) = \sigma_{\mathrm{beam}} \oplus \sigma_{\mathrm{SVX}} = 47\mu\mathrm{m}$
- At a Level 3: a full event reconstruction.
- Improves Run I sensitivity by 4-5 orders of magnitude.
- **Present orbital B-mesons analysis use as a base mode:** $\mathbf{B}^+ \to \overline{\mathbf{D}}^0\pi^+, \overline{\mathbf{D}}^0 \to \mathbf{K}^+\pi^-$



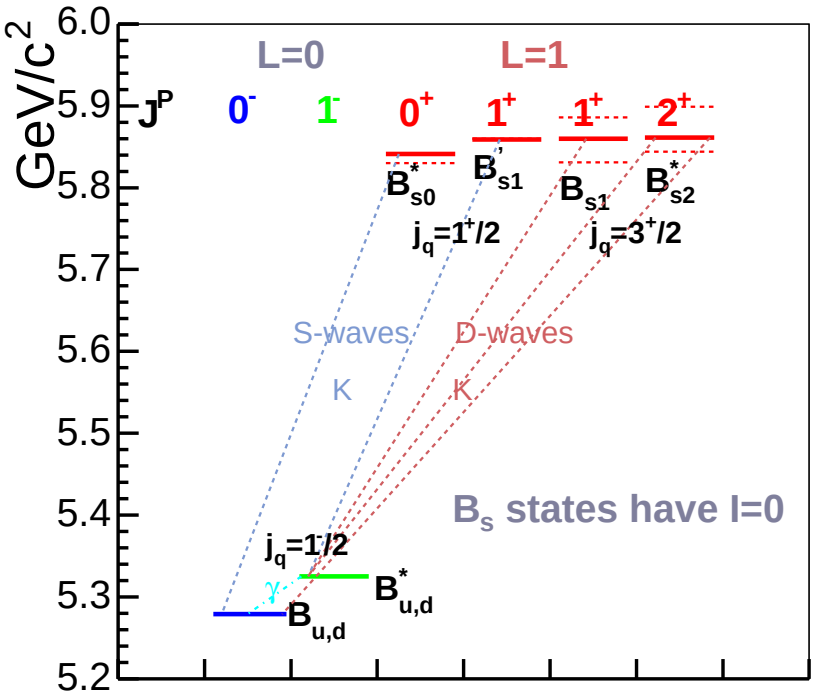
$\Rightarrow J/\psi$ Trigger



- Reach of $\mathbf{B}^+ \to \mathbf{J}/\psi\,\mathbf{K}^+$, $\mathbf{J}/\psi \to \mu^+\mu^-$ mode
- Level 1 eXtremely Fast Tracker (XFT) Trigger: tracks are reconstructed in the COT and matched to hits in the Muon Chambers.
- Level 2: transparent
- Level 3: full reconstruction with cut $M(\mu^+\mu^-) \in [2.7, 4.0]\,\mathrm{GeV}/c^2$

6 – Orbitally Excited $\mathbf{B_{sJ}}$ Mesons: Predictions

$\Rightarrow$ $S-$ and $P-$wave multiplets of strange B_s-mesons, similar to $B_{u,d}$



$\Rightarrow$ **... and their possible decay modes:**

- $\mathbf{B_{sJ}}$ **states are isotop-singlets, I=0,**
  NO $\mathbf{B_s\pi}$ modes allowed.
  - $\mathbf{P}-$parity and $\mathbf{I}-$, $\mathbf{S}-$ are conserved.
- $\frac{1}{2}^+ \to \frac{1}{2}^- + 0^-$, K in $S-$wave
  - broad states
  - $\mathbf{B'_{s1}} \to \mathbf{B^+K^-}$, $1^+ \to 1^- + 0^-$
  - $\mathbf{B^*_{s0}} \to \mathbf{B^{*+}K^-}$, $0^+ \to 0^- + 0^-$
- $\frac{3}{2}^+ \to \frac{1}{2}^- + 0^-$, K in $D-$wave
  - narrow states
  - $\mathbf{B_{s1}} \to \mathbf{B^{*+}K^-}$, $1^+ \to 1^- + 0^-$
  - $\mathbf{B^*_{s2}} \to \mathbf{B^+K^-}$, $2^+ \to 0^- + 0^-$
  - $\mathbf{B^*_{s2}} \to \mathbf{B^{*+}K^-}$, $2^+ \to 1^- + 0^-$
    with $\mathbf{B^*} \to \mathbf{B}\gamma$, and γ is undetected.

⇒ Mass and Width predictions $\mathbf{B_{sJ}}$ states from several authors ...

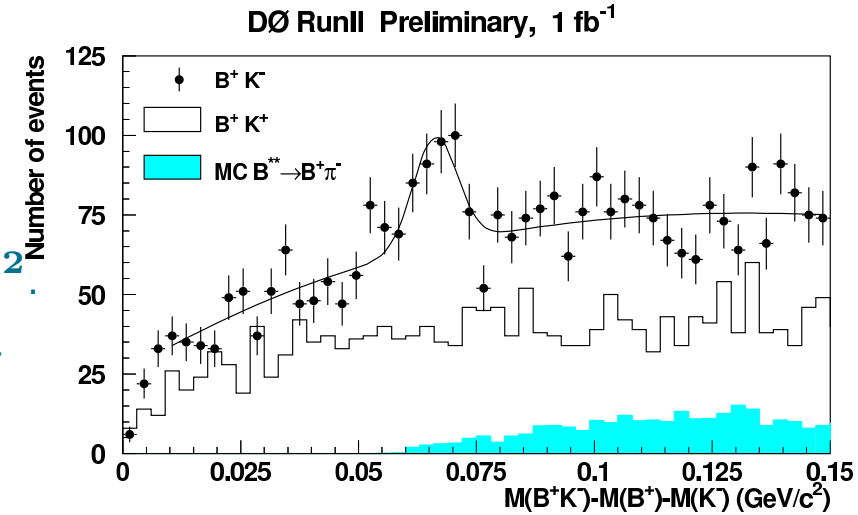
State/ref.	Ebert *et al.*		Godfrey *et al.*		Eichten *et al.*		Falk *et al.*	
$[\mathrm{MeV}/c^2]$	M	Γ	M	Γ	M	Γ	M	Γ
B^*_{s0}	5841.0	-	5830.0	170	-	-	-	-
B'_{s1}	5859.0	-	5860.0	-	-	-	-	-
$\mathbf{B_{s1}}$	5831.0	-	5860.0	-	5834.0	$<$1.0	5886.0	2.8$\pm$1.2
$\mathbf{B^*_{s2}}$	5844.0	-	5888.0	2.6	5846.0	1.0	5899.0	7$\pm$3

- From HQET $\mathcal{B}(B^*_{s2} \to B^+K^-)/\mathcal{B}(B^*_{s2} \to B^{*+}K^-) \sim 12.0$
- $B^{*+} \to B^+\gamma$ with γ going undetected causes a shift of possible B^*_{s2}, B_{s1} peak positions by $\Delta M(B^{*+} - B^+) = 45.78\,\mathrm{MeV}/c^2$ (see PDG)
- $B^*_{s2} \to B^+K^-$ is expected to appear at $\mathbf{Q} \sim (70...130)\,\mathrm{MeV}/c^2$
- If B^*_{s2} is above $B^{*+}K^-$ threshold, a weaker signal by 45.78 MeV/c^2 less.
- $B_{s1} \to B^{*+}K^-$, a narrow peak at $\mathbf{Q} \sim (10...70)\,\mathrm{MeV}/c^2$, shifted due to γ.
- **Search for narrow signals in $\mathbf{Q = M(B^+K^-) - M(B^+) - M(K^-)}$**

7 – Orbitally Excited $\mathbf{B_{sJ}}$ Mesons: Experimental Status

- OPAL (LEP): 1-st observation.
  $\mathbf{149 \pm 30}$evts in $M(B^+K^-)$.
  $\mathbf{M(B^+K^-) = 5853 \pm 15}\,\mathrm{MeV/c^2}$.
  B^+K^- vs $B^{*+}K^-$, coarse resolution.

- DELPHI (LEP): a signal in
  $\mathbf{Q = M(B^+K^-) - M(B^+) - M(K^-)}$.
  $\mathbf{134 \pm 32}(\mathrm{stat}) \pm \mathbf{12}(\mathrm{syst})$ evts
  at $\mathbf{Q = 79.0 \pm 4.0}(\mathrm{stat})$
  $\pm\mathbf{2.0}(\mathrm{syst})\,\mathrm{MeV/c^2}$.
  Claimed $B^*_{s2} \to B^+K^-$ observation.



$\mathbf{D\emptyset}$ Collab. reported (Note 5027-Conf)
$135 \pm 31(\mathrm{stat})$ evts
at $\mathbf{Q = 66.4 \pm 1.4}(\mathrm{stat})$
$\pm\mathbf{2.0}(\mathrm{syst})\,\mathrm{MeV/c^2}$,
$\sigma(\mathbf{Q}) = \mathbf{4.7 \pm 1.2}(\mathrm{stat})\,\mathrm{MeV/c^2}$
interpreted as a $B^*_{s2} \to B^+K^-$
with $\mathbf{M = 5839.1 \pm 1.4}(\mathrm{stat})\,\mathrm{MeV}$

8 – Orbitally Excited $\mathrm{B_{sJ}}$ Mesons: Candidate Preparation

⇒ **Reconstruction of Candidates:**

$\mathbf{B^0_{sJ} \to B^+K^-,\ B^+ \to J/\psi\, K^+}$

$\mathbf{J/\psi} \to \mu^+\mu^-$ + chrg.conj.combs.

- $\mathcal{L} = \mathbf{1066 \pm 64}$ pb^{-1} with J/ψ trigger
- $''J/\psi''(\mu^+\mu^-) \in (2.9, 3.3)\,\mathrm{GeV}$
- 3-d Vertex Fit for $''J/\psi''$
- $''J/\psi''K^+ \in (4.6, 6.8)\,\mathrm{GeV}/c^2$
- 3-d Vertex Fit for $''J/\psi''K^+$
- $''B^+''K^-$, B^0_{sJ} candidate prepared.

⇒ **Reconstruction of Candidates:**

$\mathbf{B^0_{sJ} \to B^+K^-,\ B^+ \to \overline{D}^0\pi^+}$

$\mathbf{\overline{D}^0} \to \mathbf{K^+\pi^-}$ + chrg.conj.combs.

- $\mathcal{L} = \mathbf{976 \pm 59}$ pb^{-1} with 2-trk trigger
- $''\overline{D}^0''(K^+\pi^-) \in (1.77, 1.97)\,\mathrm{GeV}$
- 3-d Vertex Fit for $''\overline{D}^0''$
- $''\overline{D}^0''\pi^+ \in (4.4, 6.6)\,\mathrm{GeV}/c^2$
- 3-d Vertex Fit for $''B^+''$
- 4-track $B^0_{sJ} \to ''B^+''K^-$ candidate prepared.

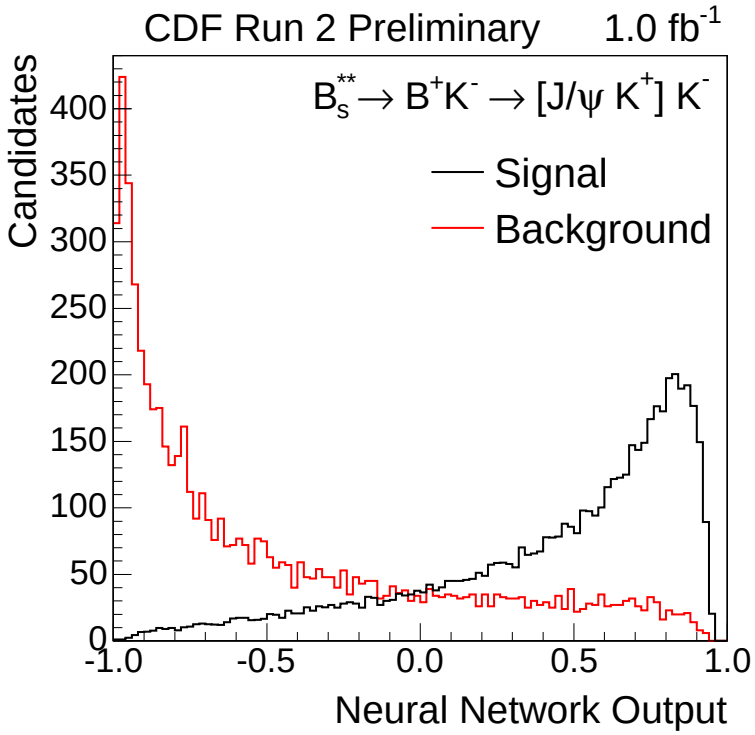
9 – Orbitally Excited $\mathrm{B_{sJ}}$ Mesons: Candidate Selection

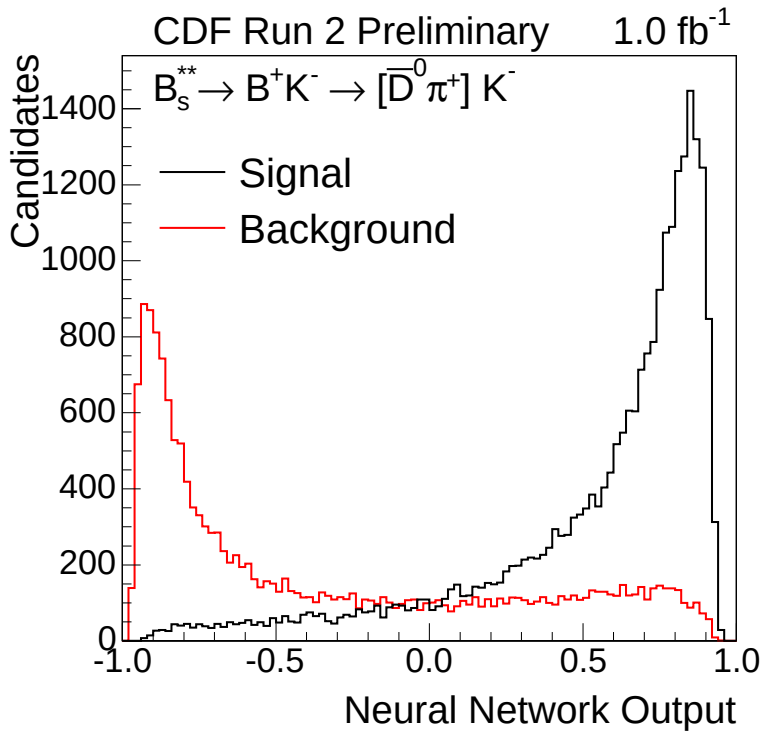
$\Rightarrow \mathbf{B^0_{sJ} \to B^+K^-,\ B^+ \to J/\psi K^+}$

$\Rightarrow \mathbf{B^0_{sJ} \to B^+K^-,\ B^+ \to \bar{D}^0\pi^+}$

- For further selection of reconstructed candidates apply $\mathcal{N}$eural $\mathcal{N}$etwork software $NeuroBayes^{©}$, developed by Karlsruhe Univ. (Germany) team of CDF Collab.
  - Feed the topological quantities: $L_{xy},\ d_0,\ \mathrm{Prob}(\mathrm{B}^+)$ etc.
  - Feed the kinematic variables: $p_T,\ \cos(\theta^*)(K^-)$ etc.
  - Use $\mathbf{PID}(K^-)$ based on ToF or/and dE/dx
  - $\mathcal{NN}$ output from selected B^+ candidate for B_{sJ} selection.
- **$\mathcal{NN}$ training:**
  - **for background patterns:** exp. data from side bands of parent candidates
  - **for signal patterns:** MC Generator + CDF full simulation with $\mathbf{Q}$ shape generated as a background one.

⇒ **The $\mathcal{N}$eural $\mathcal{N}$etwork produces the output distributed as:**





⇒ **The optimization of $\mathcal{N}\mathcal{N}$ cut for every mode:**

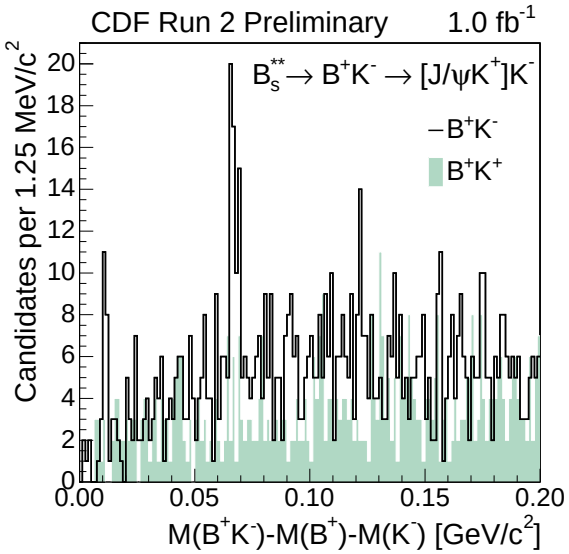
$$\mathbf{F.o.M.} = \mathbf{N^{MC}_{cands}}(\mathcal{NN}) / \sqrt{\mathbf{N^{Data}_{cands}}(\mathcal{NN})}$$

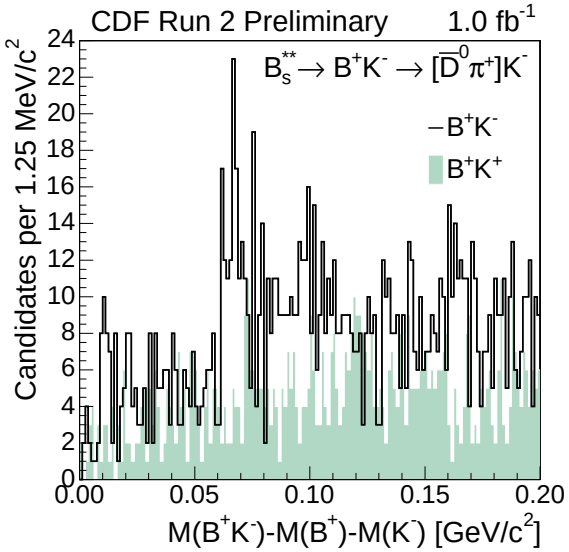
10 – $\mathbf{B_{sJ}}$ Mesons: Results

⇒ **Make final cuts:**

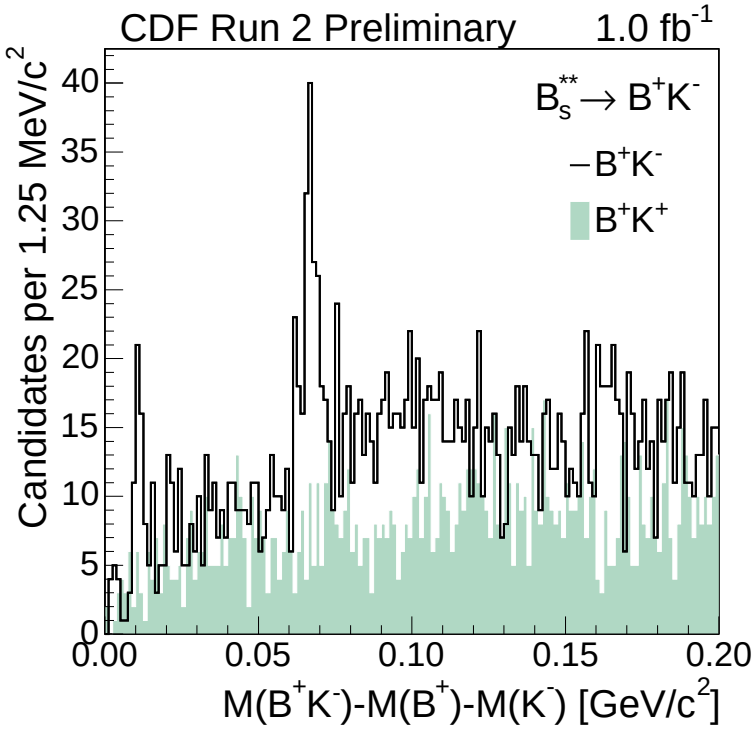
- the output of the $\mathcal{NN}$
  - $\mathcal{NN} > \mathbf{0.5}$ for $\mathbf{B^+ \to J/\psi K^+}$
  - $\mathcal{NN} > \mathbf{0.3}$ for $\mathbf{B^+ \to \overline{D}^0 \pi^+}$
- **a number of candidates** $''\mathbf{B_{sJ}}'' \to \mathbf{B^+K^-}$ **per event**
  - $\mathbf{n_{cands}(''B_{sJ}'') < 4}$
  - ... to further suppress a background.
- **control background with wrong charge candidates** $''\mathbf{B_{sJ}}'' \to \mathbf{B^+K^+}$
- $\mathbf{Q = M(''B^+K^-'') - M(''B^+'') - M(K^-)}$

⇒ **Experimental data: $\mathbf{Q}$ Spectra, two basic modes $\mathbf{B^+ \to J/\psi K^+,\ \bar{D}^0 \pi^+}$**





⇒ **Both modes are added.**



⇒ **Two narrow peaks at**

⇒ $\mathbf{Q} \sim 10,\ \sim 70\,\mathrm{MeV}/c^2$ **are visible.**

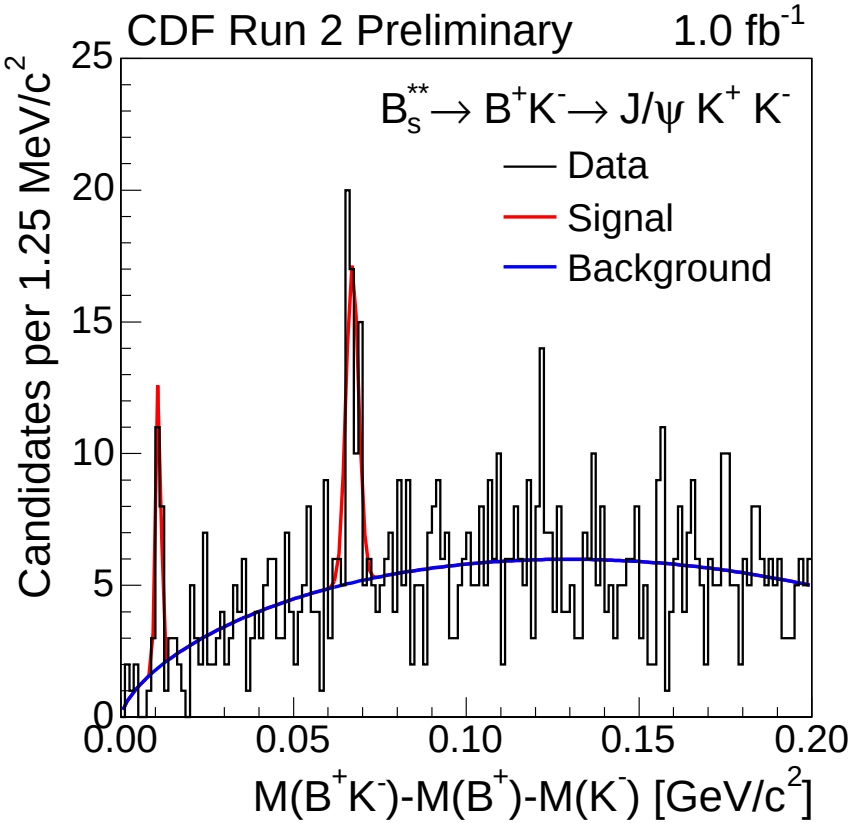
⇒ **Wrong charge $\mathbf{B^+K^+}$ are shown.**

$\Rightarrow$ **Fit Results.**

State	$B_{s1} \to B^{*+}K^-$
B^+ Mode	$B^+ \to J/\psi K^+$
$Q[\mathrm{MeV}]$	10.87 ± 0.19
$\sigma[\mathrm{MeV}]$	0.64 ± 0.25
N_{evts}	16.98 ± 5.14

State	$B^*_{s2} \to B^+K^-$
B^+ Mode	$B^+ \to J/\psi K^+$
$Q[\mathrm{MeV}]$	67.03 ± 0.44
$\sigma[\mathrm{MeV}]$	1.79 ± 0.42
N_{evts}	44.15 ± 13.36

$\Rightarrow \mathbf{B_{sJ}} \to \mathbf{B^+K^-}, (\mathbf{B^+} \to \mathbf{J/\psi K^+})$



$\Rightarrow$ **unbinned N.L.L. fit**

$\Rightarrow$ **Assign narrow peaks**

$\Rightarrow$ @ $\mathbf{Q} \sim \mathbf{10.9}\,\mathrm{MeV} \mapsto \mathbf{B_{s1}}$

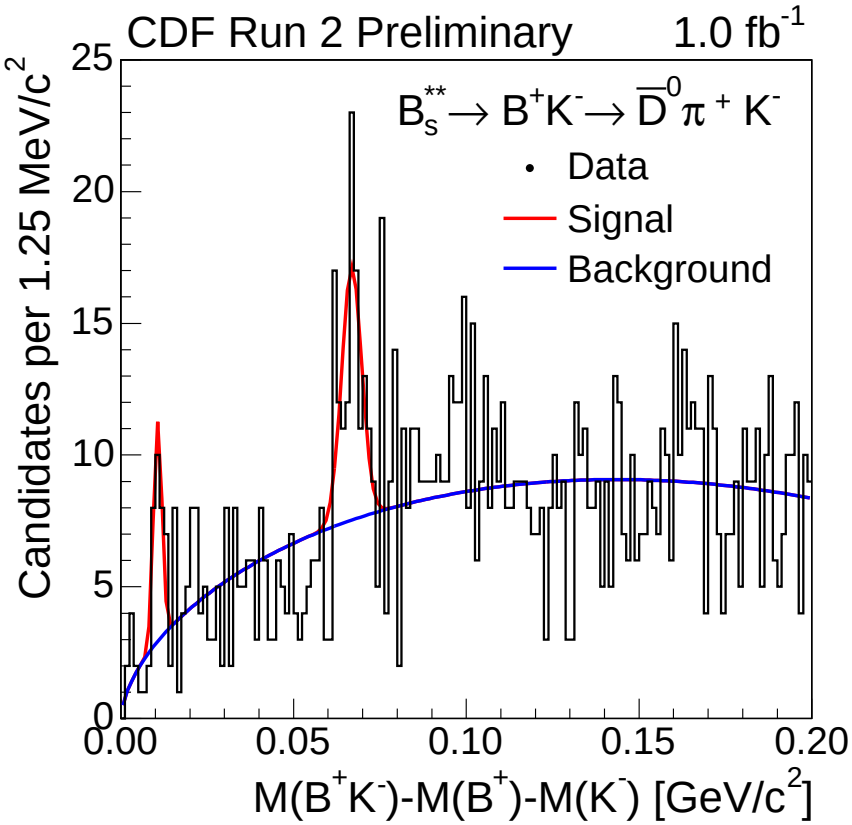
$\Rightarrow$ @ $\mathbf{Q} \sim \mathbf{67.0}\,\mathrm{MeV} \mapsto \mathbf{B^*_{s2}}$

$\Rightarrow$ **Fit Results.**

State	$B_{s1} \to B^{*+}K^-$
B^+ Mode	$B^+ \to \overline{D}^0\pi^+$
$Q[\mathrm{MeV}]$	10.68 ± 0.46
$\sigma[\mathrm{MeV}]$	1.18 ± 0.56
N_{evts}	20.66 ± 7.12

State	$B^*_{s2} \to B^+K^-$
B^+ Mode	$B^+ \to \overline{D}^0\pi^+$
$Q[\mathrm{MeV}]$	66.85 ± 0.76
$\sigma[\mathrm{MeV}]$	2.88 ± 0.75
N_{evts}	55.74 ± 19.20

$\Rightarrow \mathbf{B_{sJ}} \to \mathbf{B^+K^-}, (\mathbf{B^+} \to \overline{\mathbf{D}}^{\mathbf{0}}\pi^+)$



$\Rightarrow$ **unbinned N.L.L. fit**

$\Rightarrow$ **Assign narrow peaks**

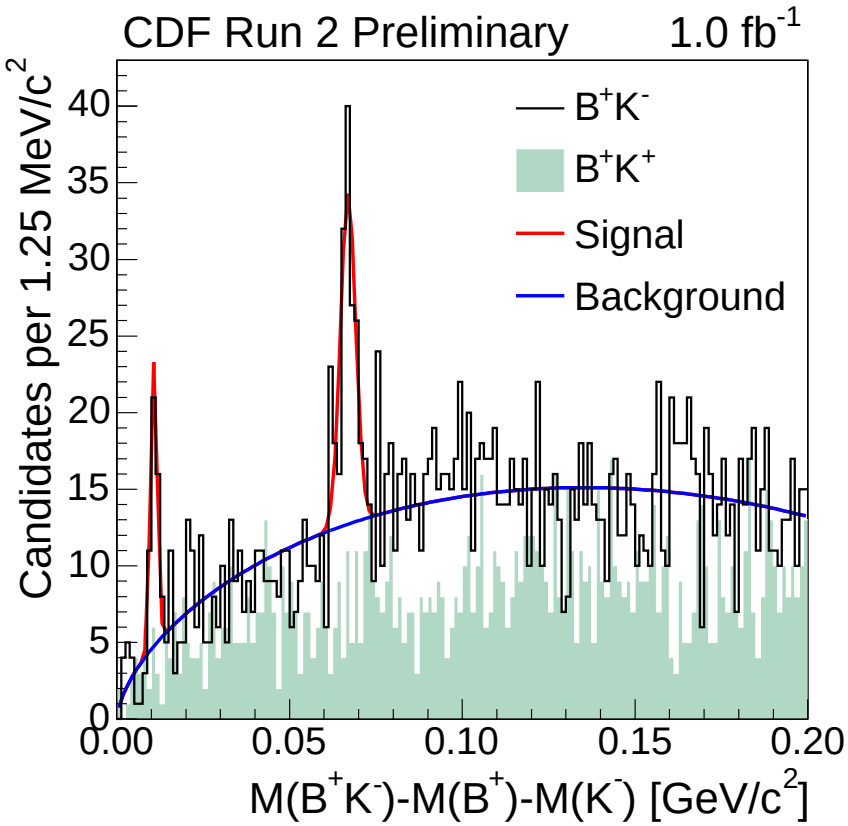
$\Rightarrow$ @ $\mathbf{Q} \sim \mathbf{10.9}\,\mathrm{MeV} \mapsto \mathbf{B_{s1}}$

$\Rightarrow$ @ $\mathbf{Q} \sim \mathbf{67.0}\,\mathrm{MeV} \mapsto \mathbf{B^*_{s2}}$

$\Rightarrow$ **Fit Results for combined statistics:**

- $\mathbf{Q(B_{s1}) = 10.73 \pm 0.21}(\mathrm{stat})\,\mathrm{MeV}$
  $\mathbf{N_{evts} = 36.4 \pm 9.0}(\mathrm{stat})$
- $\mathbf{Q(B^*_{s2}) = 66.96 \pm 0.39}(\mathrm{stat})\,\mathrm{MeV}$
  $\mathbf{N_{evts} = 94.8 \pm 23.4}(\mathrm{stat})$
- From unbinned N.L.L. fits, assuming
  $-2\ln\mathcal{L}/\mathcal{L}_0 \sim \chi^2$
  - $\mathbf{B_{s1}}$ significance is $\mathbf{6.3}\sigma$
  - $\mathbf{B^*_{s2}}$ significance is $\mathbf{7.7}\sigma$

$\Rightarrow \mathbf{B_{sJ} \to B^+K^-}$
$\Rightarrow (\mathbf{B^+ \to J/\psi K^+, \bar{D}^0\pi^+})$

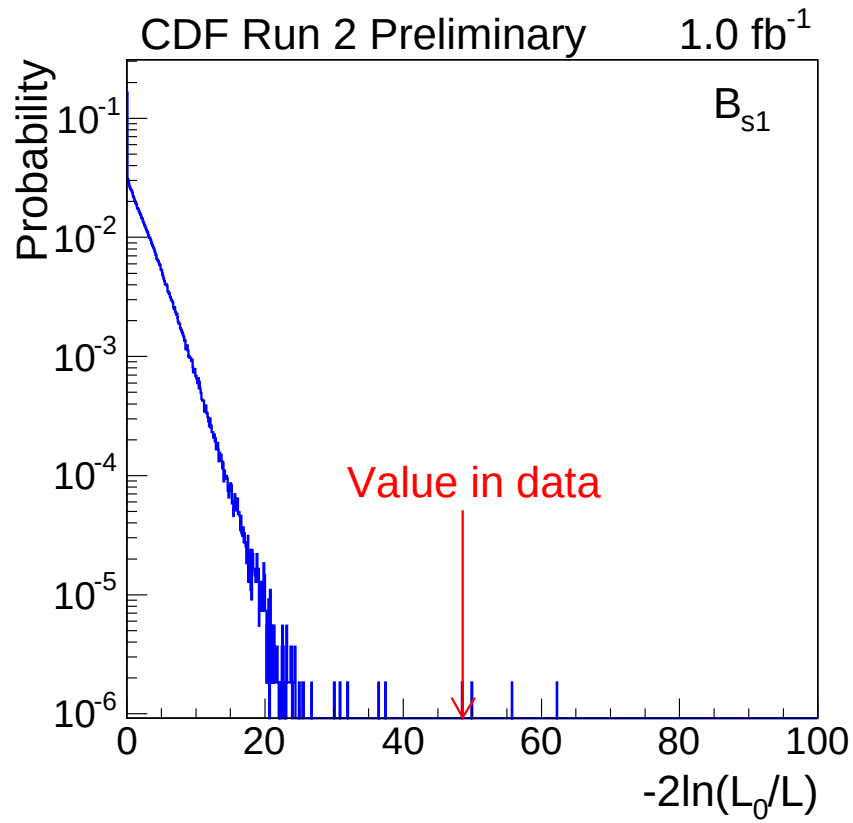


$\Rightarrow$ **unbinned N.L.L. fit**

⇒ **Significance of $\mathbf{B_{s1}}$ with toy MC**

- $\mathbf{B^*_{s2}}$ **has already been seen**
- $\mathbf{B_{s1}}$ is a **first observation**
- Search window $\mathbf{Q} \in (\mathbf{0.0}, \mathbf{50})\,\mathrm{MeV}$
- Generate only background and $\mathbf{B^*_{s2}}$ and fit it
- Figure of Merit: $-2\ln\mathcal{L}/\mathcal{L}_0$
- **p-value for $\mathbf{B_{s1}}$ is $\mathbf{7.32 \cdot 10^{-6}}$**

⇒ **p-value**



⇒ $-2\ln\mathcal{L}/\mathcal{L}_0$ **from unbinned N.L.L. fit**

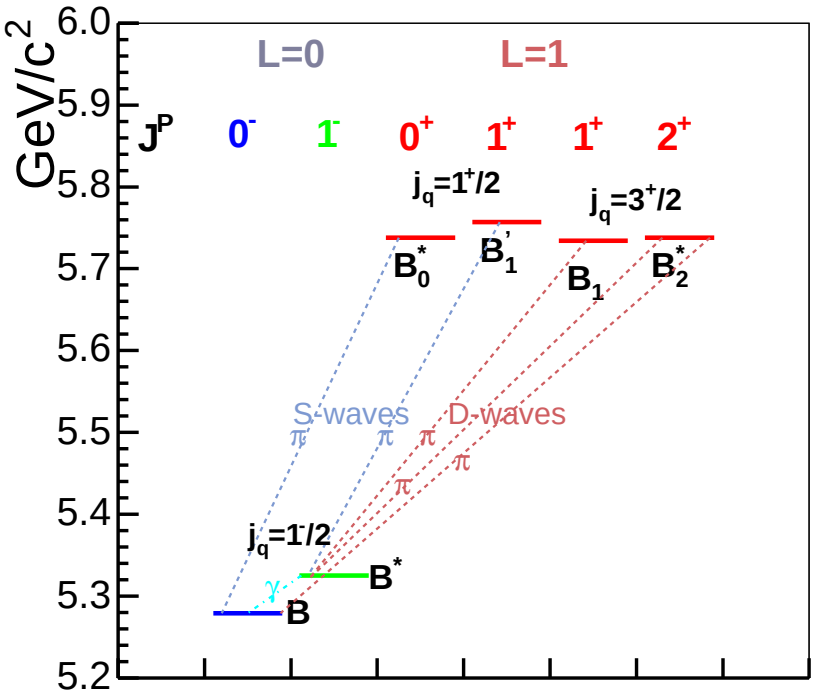
11 – Summary

- $\mathbf{Q(B_{s1}) = 10.73 \pm 0.21}(\mathrm{stat}) \pm \mathbf{0.14}(\mathrm{syst})\,\mathrm{MeV}$
  $N_{evts} = 36.4 \pm 9.0(\mathrm{stat})$, $\mathbf{6.3}\sigma$
  p-value for $\mathbf{B_{s1}}$ is $\mathbf{7.32 \cdot 10^{-6}}$, $Q \in (0, 50)\,\mathrm{MeV}$
  The presented results are a first observation of a narrow $\mathbf{B_{s1}}$ state.
- $\mathbf{Q(B^*_{s2}) = 66.96 \pm 0.39}(\mathrm{stat}) \pm \mathbf{0.14}(\mathrm{syst})\,\mathrm{MeV}$
  $N_{evts} = 94.8 \pm 23.4(\mathrm{stat})$, $\mathbf{7.7}\sigma$
- $\mathbf{M(B_{s1}) = 5829.41 \pm 0.21}(\mathrm{stat}) \pm \mathbf{0.14}(\mathrm{syst}) \pm \mathbf{0.6(PDG)}\,\mathrm{MeV}$
- $\mathbf{M(B^*_{s2}) = 5839.64 \pm 0.39}(\mathrm{stat}) \pm \mathbf{0.14}(\mathrm{syst}) \pm \mathbf{0.5(PDG)}\,\mathrm{MeV}$
- $\mathbf{\Delta M = 10.20 \pm 0.44}(\mathrm{stat}) \pm \mathbf{0.35(PDG)}\,\mathrm{MeV}$
- **The widths of measured $\mathbf{B_{sJ}}$ states are found to be at the level of a detector resolution.**
- **CDF II measurements on $\mathbf{B^*_{s2}}$ are in agreement with other experiments.**

THE END OF THE TALK.

12 – Backup Slides

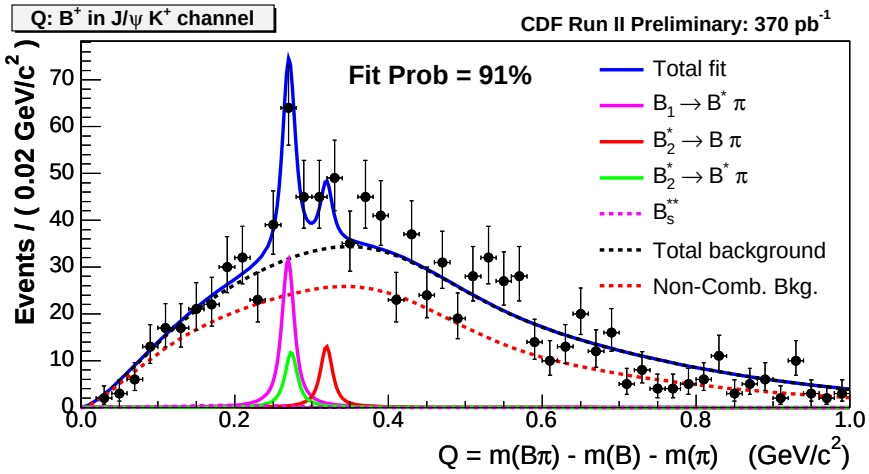
$\Rightarrow$ $S-$ and $P-$wave multiplets of non-strange $\mathbf{B_{u,d}}$ -mesons:

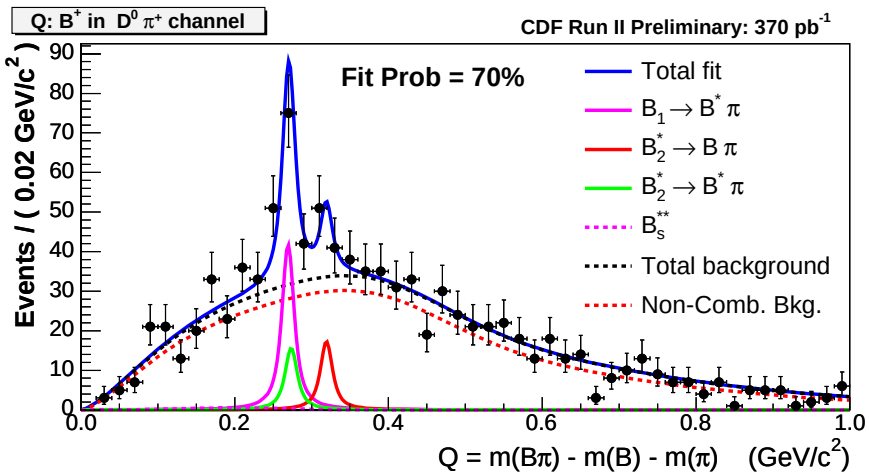


$\Rightarrow$ ... and their possible decay modes:

- **strong decays** with emission of π, 0^-
  - $\mathbf{P}-$parity and $\mathbf{I}-$ are conserved.
- $\frac{1}{2}^+ \to \frac{1}{2}^- + 0^-$,
  π emitted in $S-$wave, $L = 0$.
  - $\Gamma_{theor.} \sim 100\,\mathrm{MeV}/c^2$, broad.
  - $\mathbf{B'_1} \to \mathbf{B^*}\pi$, $1^+ \to 1^- + 0^-$
  - $\mathbf{B^*_0} \to \mathbf{B}\pi$, $0^+ \to 0^- + 0^-$
- $\frac{3}{2}^+ \to \frac{1}{2}^- + 0^-$,
  π emitted in $D-$wave, $L = 2$.
  - $\Gamma_{theor.} \sim 10 - 20\,\mathrm{MeV}/c^2$, narrow.
  - $\mathbf{B_1} \to \mathbf{B^*}\pi$, $1^+ \to 1^- + 0^-$
  - $\mathbf{B^*_2} \to \mathbf{B}\pi$, $2^+ \to 0^- + 0^-$
  - $\mathbf{B^*_2} \to \mathbf{B^*}\pi$, $2^+ \to 1^- + 0^-$
    with $\mathbf{B^*} \to \mathbf{B}\gamma$, and γ is undetected.

⇒ **Earlier (Fall 2005) CDF presented results on orbitally excited $\mathbf{B_1}$ and $\mathbf{B_2^*}$ mesons.**





⇒ **using two main CDF B-Physics Trigger streams.**

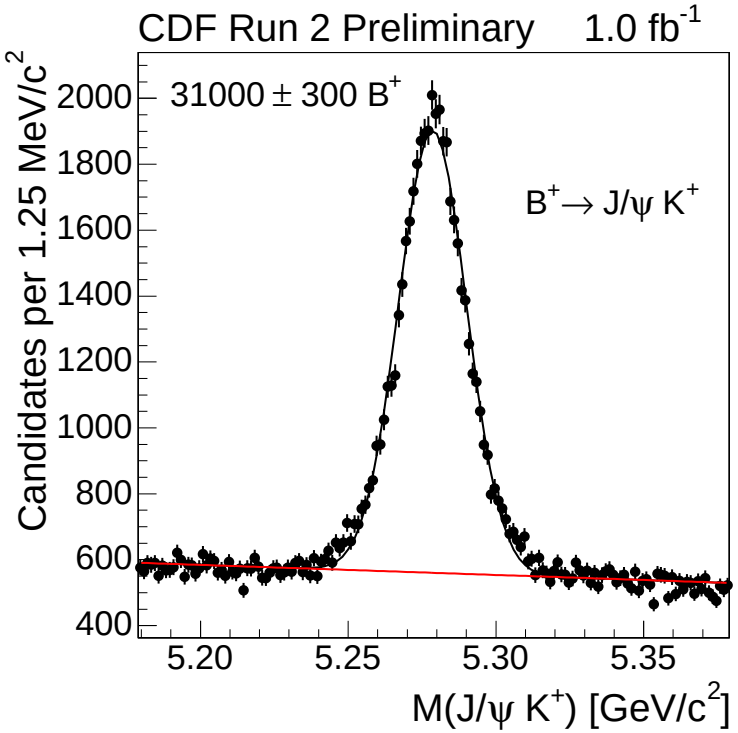
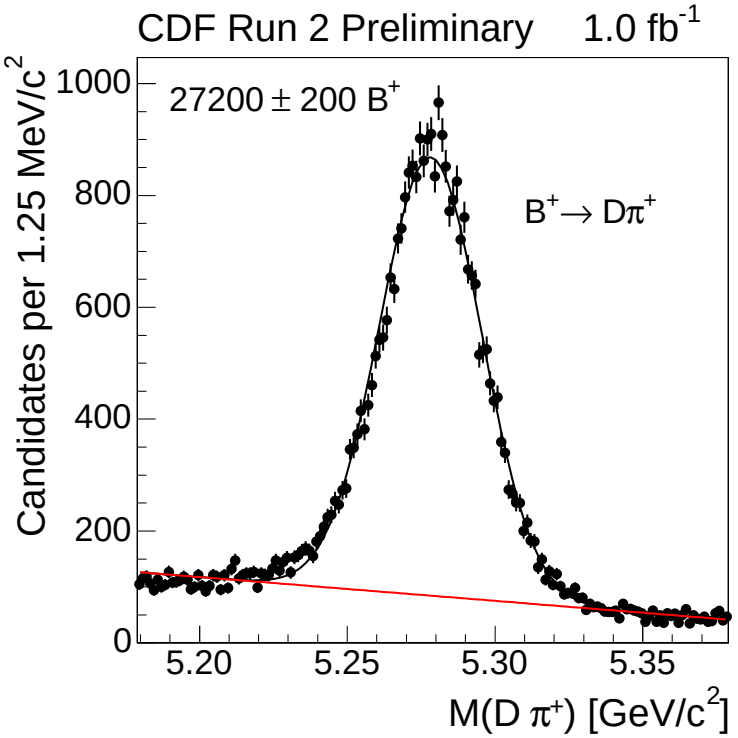
- $\mathbf{B^+ \to J/\psi K^+}$, J/ψ Trigger.
- $\mathbf{B^+ \to \overline{D}^0 \pi^+}$, "2-trk Trigger".
- $\mathbf{Q = M(B^+\pi^-) - M(B^+) - M(\pi^-)}$
- $\mathbf{M(B_1) = 5734 \pm 3(\mathrm{stat}) \pm 2(\mathrm{syst})\ \mathrm{MeV/c^2}}$
- $\mathbf{M(B_2^*) = 5738 \pm 5(\mathrm{stat}) \pm 1(\mathrm{syst})\ \mathrm{MeV/c^2}}$
- DØ has presented recently (DØ Note 5026-CONF) the measurements using a total available statistics of 1 fb^{-1}

⇒ Quantities used to feed NN

$\mathbf{B^0_{sJ} \to B^+K^-}$, $\mathbf{B^+ \to J/\psi K^+}$

- $\mathbf{B^+ \to J/\psi K^+}$
  - $L_{xy}(J/\psi)$ w.r.t. PVX
  - $p_T(K^+)$
  - $d_0(K^+)$ and $d_0(K^+)/\sigma$
  - $d_0(B^+)$
  - $\mathrm{Prob(B^+)}$
- $\mathbf{B_{sJ} \to B^+K^-}$
  - $d_0(B_{sJ})/\sigma$
  - $\mathcal{NN}$ output from B^+ candidate
  - $\mathbf{PID}(K^-)$ based on ToF
  - $\cos(\theta^*)(K^-)$ in B_{sJ} rest frame
  - $\eta(K^-)$, pseudorapidity
- **$\mathcal{NN}$ training: bgr., exp. data (s.b.)...**

$\mathbf{B^0_{sJ} \to B^+K^-}$, $\mathbf{B^+ \to \bar{D}^0\pi^+}$

- $\mathbf{B^+ \to \bar{D}^0\pi^+}$
  - $L_{xy}(B^+)/\sigma$ w.r.t. PVX
  - $p_T(\pi^+)$
  - $d_0(B^+)$
  - $\mathrm{Prob(B^+)}$
- $\mathbf{B_{sJ} \to B^+K^-}$
  - $d_0(B_{sJ})$
  - $p_T(B_{sJ})$
  - $\mathcal{NN}$ output from B^+ candidate
  - $\mathbf{PID}(K^-)$ based on ToF or dE/dx
  - $\mathbf{M}(B^+)$, inv. mass
- **... and signal, BGEN + CDF sim.**

$\Rightarrow \mathbf{B^+ \to J/\psi K^+, \overline{D}^0 \pi^+}$ after optimized NN Selection...