Hot Topics at CDF

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on behalf of the CDF Collaboration

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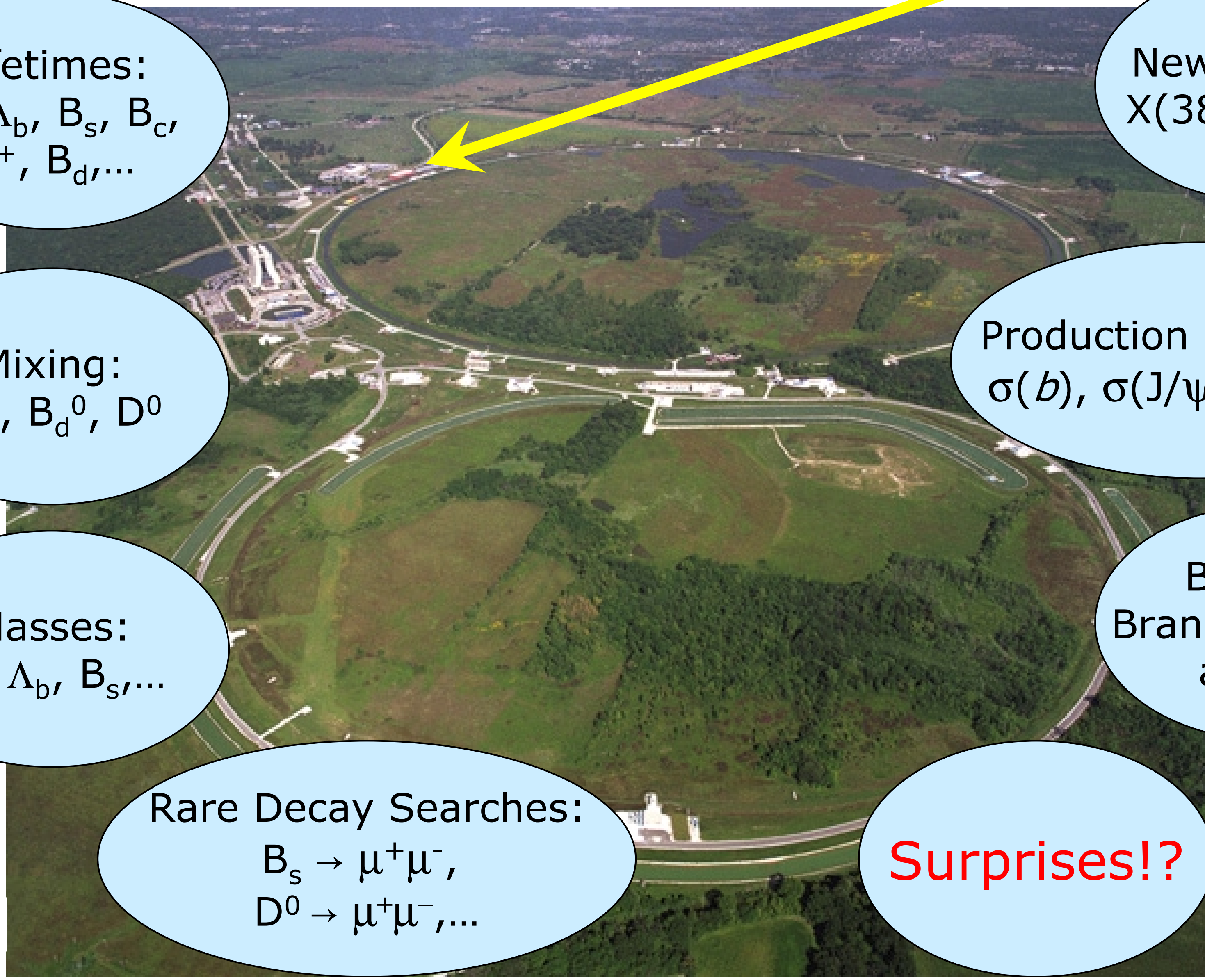
Heavy Flavor Physics at CDF…



Lifetimes:
$\Delta\Gamma$, Λ_b, B_s, B_c, B^+, B_d,…

New Particles:
X(3872), Σ_b^*,…

Mixing:
B_s^0, B_d^0, D^0

Production Properties:
$\sigma(b)$, $\sigma(J/\psi)$, $\sigma(D^0)$,…

Masses:
B_c, Λ_b, B_s,…

B and D:
Branching ratios and A_{CP}

Rare Decay Searches:
$B_s \to \mu^+\mu^-$,
$D^0 \to \mu^+\mu^-$,…

Surprises!?

Outline

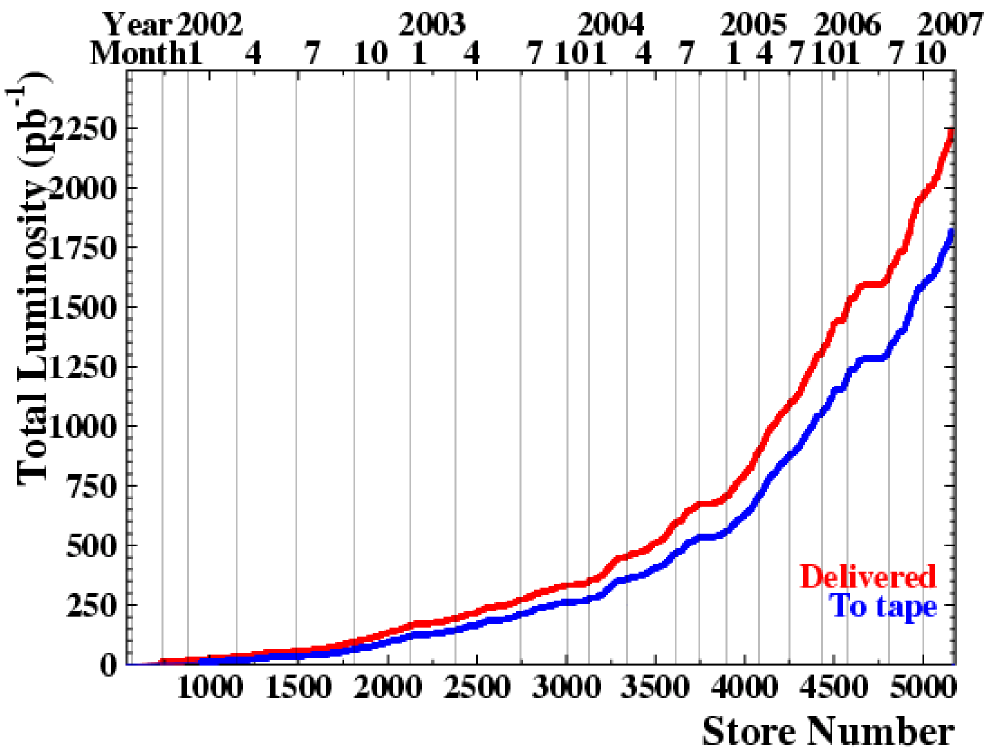
- Tevatron performance
- CDF detector and heavy flavor triggers
- Focus on new results:
  - First observation of $\Sigma_b^{(*)\pm}$ baryons
  - $B \rightarrow h^+h'^-$ results
    - Three new charmless decays
    - Measurement of branching ratios and A_{cp}

Not covered in this talk:

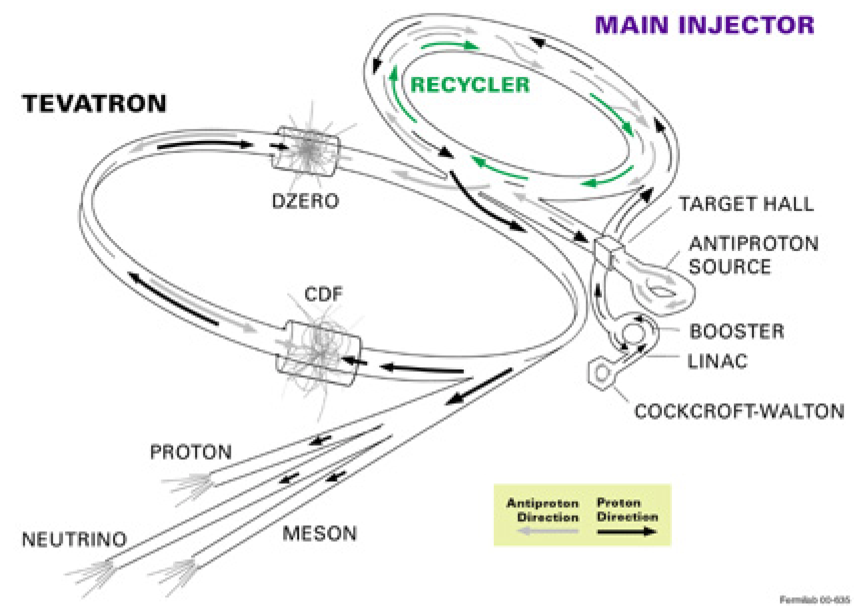
- Many recent results!
  - Not enough time to mention all
  - See A. Rahaman's talk for B_s^0 mixing

Tevatron Performance

- Collide $p\bar{p}$ at $\sqrt{s}$ = 1.96 TeV
- Record peak luminosity 2.52×10^{32} sec^{-1} cm^{-2}
- CDF II collected ~ 1.8 fb^{-1} out of > 2 fb^{-1} delivered

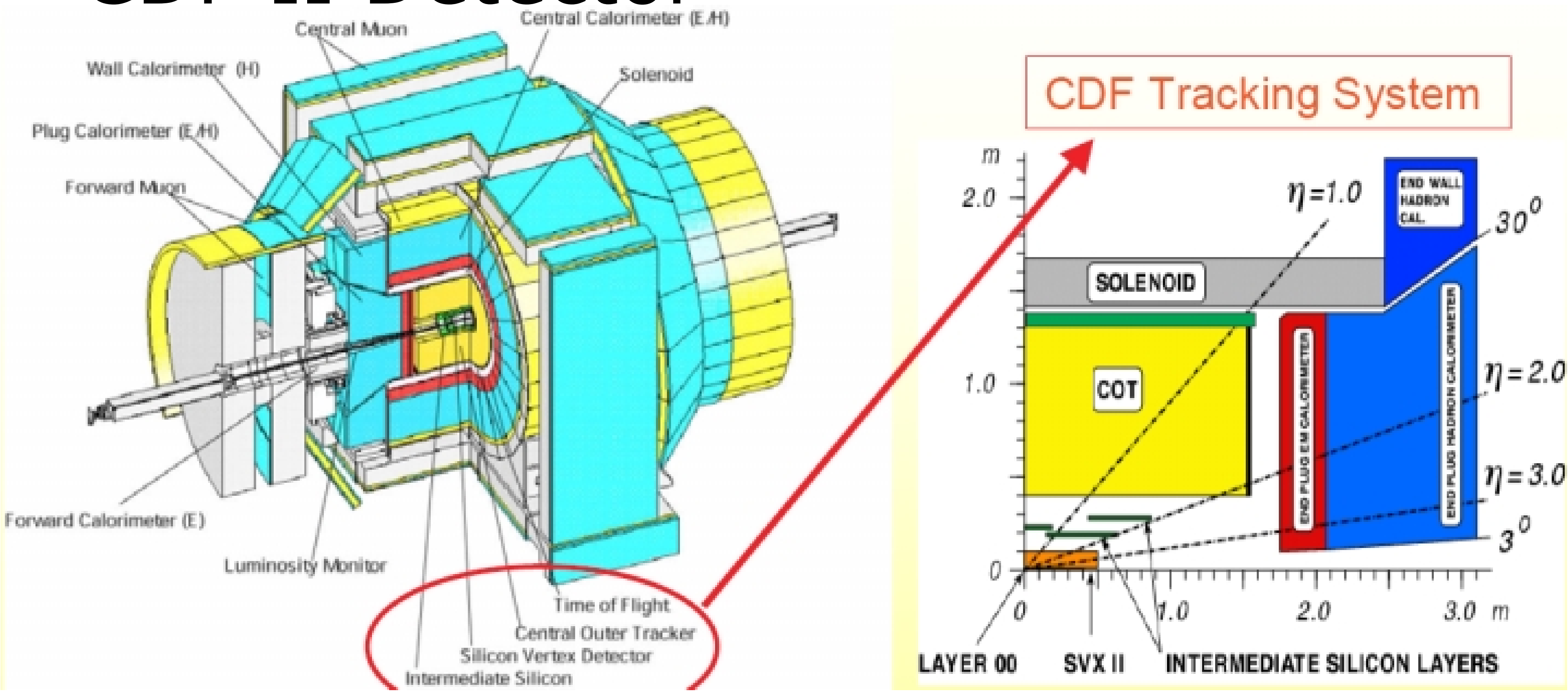


FERMILAB'S ACCELERATOR CHAIN



- Current analyses use about 1 fb^{-1} of data
- Analyses with more data in the works
- Expect ~8 fb^{-1} by 2009

CDF II Detector



- SVX II – 5 layers of double-sided silicon
  - Trigger on displaced tracks
- Particle ID
  - dE/dx in COT and Time of Flight detector

Heavy Flavor Physics at a $p\bar{p}$ collider

Advantages:

- Huge *b* cross-section (~100 mb total)
- Produce all *b* species
  - B^+, B^0, B_s, B_c, B^{**}, B_s^{**}, Λ_b, Σ_b,...

Disadvantages:

- "messy" environment
  - Multiple interactions, $p\bar{p}$ debris
- Only 1 $b\bar{b}$ per ~1000 soft QCD collisions
- Low acceptance for opposite side *b*-hadron

→ Live and die by the trigger!

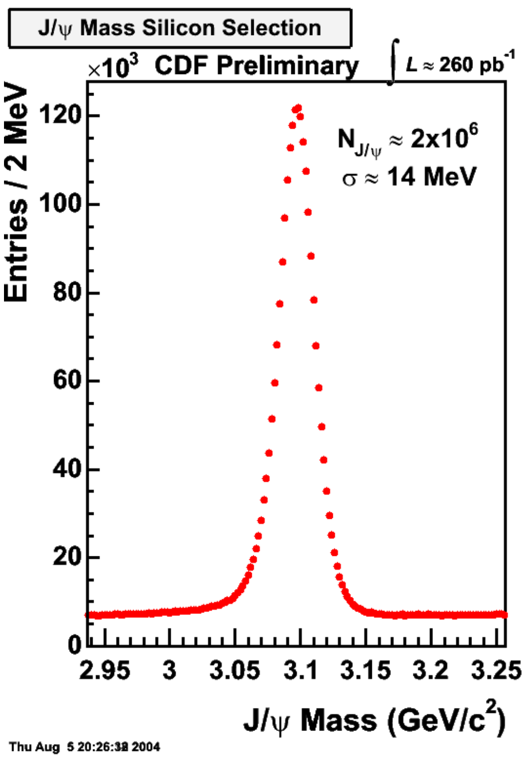
B Physics Triggers

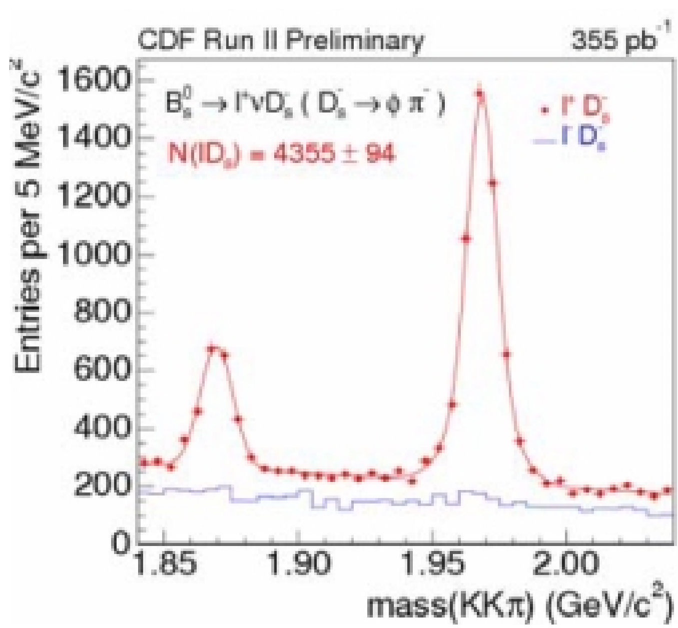
Used in Σ_b and $B \to hh$ analyses!

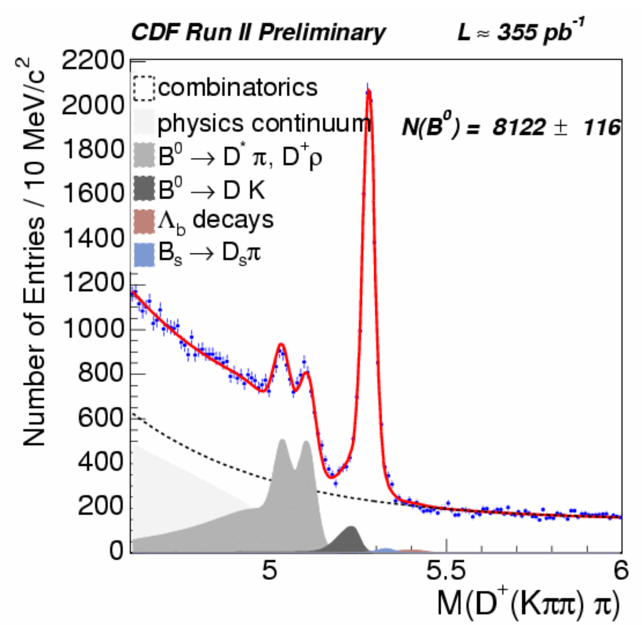
Di-muon
$J/\psi \to \mu\mu$
$B \to \mu\mu$
Two muons with:
$p_T(\mu) > 1.5$ GeV/c

One displaced track + lepton (e, μ)
$B \to \ell\nu X$
Lepton:
$p_T(\ell) > 4.0$ GeV/c
Track:
$p_T > 2.0$ GeV/c,
$d_0 > 120\ \mu m$

Two displaced tracks
$B \to hh$
Two tracks with:
$p_T > 2.0$ GeV/c
$\Sigma p_T > 5.5$ GeV/c
$d_0 > 100\ \mu m$

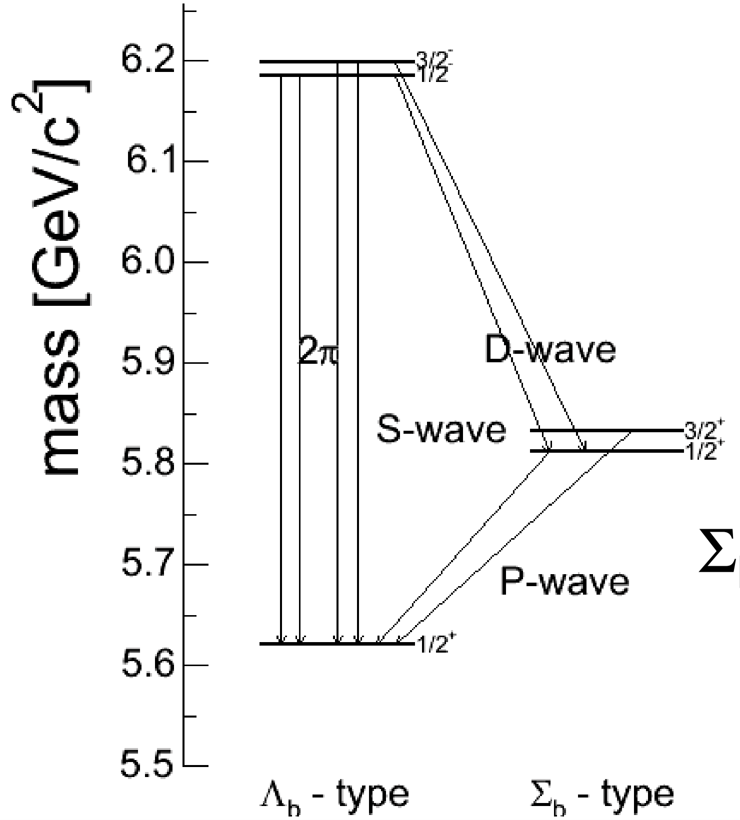






Observation of $\Sigma_b^{(*)}$ Baryons

Σ_b Motivation



- Λ_b only established *b* baryon
- Enough statistics at Tevatron to probe other heavy baryons
- Next accessible baryons:

$= 3/2^+(\Sigma_b^*)$

Σ_b: *b*{*qq*}, *q* = *u,d*; $J^P = S_Q + s_{qq}$

$= 1/2^+ (\Sigma_b)$

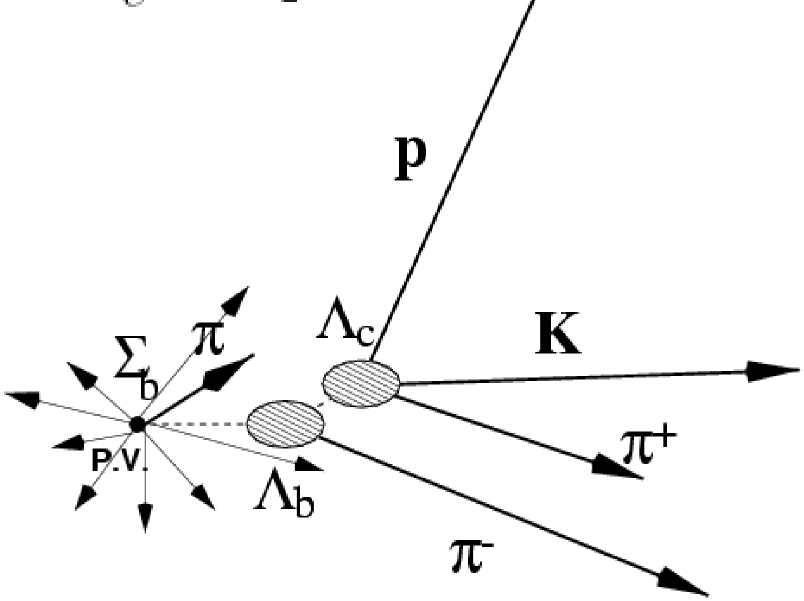
Σ_b property	Expected values (MeV/c^2)
m(Σ_b) - m(Λ_b^0)	180 – 210
m(Σ_b^*) - m(Σ_b)	10 – 40
m(Σ_b^-) - m(Σ_b^+)	5 – 7
$\Gamma(\Sigma_b), \Gamma(\Sigma_b^*)$	~8, ~15

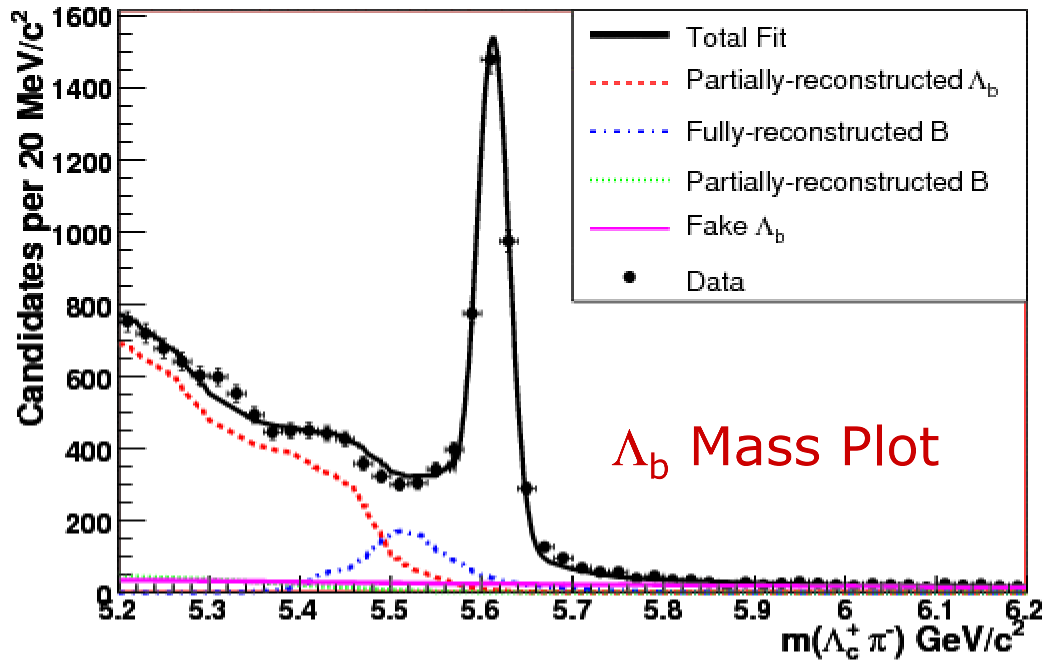
- HQET extensively tested for *Qq* systems; interesting to check predictions for *Qqq* systems
- Baryon spectroscopy also tests Lattice QCD and potential quark models

Reconstructing Σ_b

- With 1.1 fb^{-1}, world's largest sample of Λ_b: ~3000
- Use two displaced tracks trigger to reconstruct:

$$\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-$$
$$\Lambda_c^+ \rightarrow \mathrm{p} K^- \pi^+$$





- Σ_b decays at primary vertex
- Combine Λ_b with a prompt track to make a Σ_b candidate

Σ_b Search Methodology

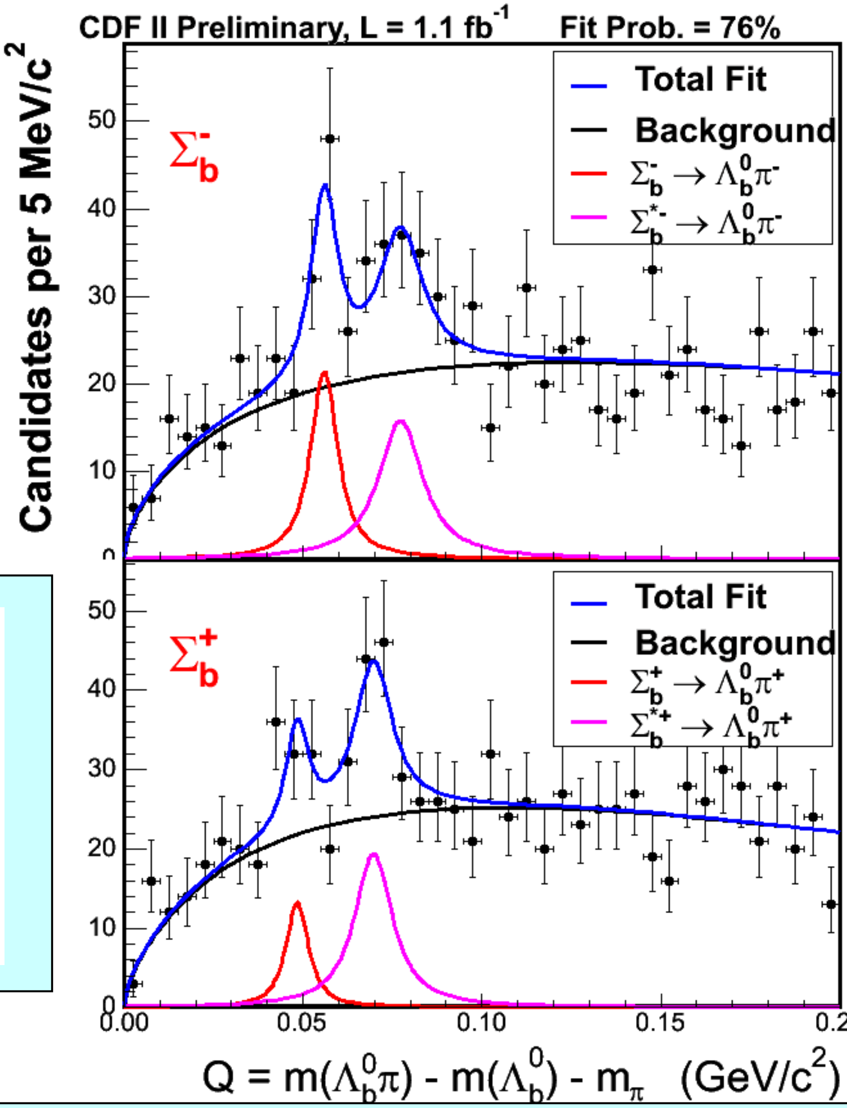
- Separate Σ_b^- and Σ_b^+:
  - $\Sigma_b^{(*)-} \rightarrow \Lambda_b^0 \pi^- \rightarrow \Lambda_c^+ \pi^- \pi^-$ (+ c.c.)
  - $\Sigma_b^{(*)+} \rightarrow \Lambda_b^0 \pi^+ \rightarrow \Lambda_c^+ \pi^- \pi^+$ (+ c.c.)
- Search for resonances in mass difference:
  $Q = m(\Lambda_b\pi) - m(\Lambda_b) - m_\pi$
  - Use reconstructed Λ_b mass → remove Λ_b mass systematic error
- Unbiased optimization
  - Optimize Σ_b cuts with Σ_b signal region blinded: $30 < Q < 100$ MeV/c^2
- Σ_b backgrounds:
  - Λ_b Hadronization + Underlying Event – Dominant!
  - B Meson Hadronization
  - Combinatorial Bkg
- Fix background contributions from data or PYTHIA Monte Carlo

Λ_b^0 Signal Region Composition $\Lambda_b^0 \in [5.565, 5.670]$ GeV/c^2	
$N(\Lambda_b^0)$	86%
$N(B)$	9%
Comb. Bkg.	5%

Σ_b Observation

- Signals consistent with lowest lying charged Σ_b states at > 5σ significance level
- With unbinned likelihood fit, measure events

$$N(\Sigma_b^-) = 60^{+14.8}_{-13.8}\ (\text{stat})\ ^{+8.4}_{-4.0}\ (\text{syst})$$
$$N(\Sigma_b^+) = 29^{+12.4}_{-11.6}\ (\text{stat})\ ^{+5.0}_{-3.4}\ (\text{syst})$$
$$N(\Sigma_b^{*-}) = 74^{+18.2}_{-17.4}\ (\text{stat})\ ^{+15.6}_{-5.0}\ (\text{syst})$$
$$N(\Sigma_b^{*+}) = 74^{+17.2}_{-16.3}\ (\text{stat})\ ^{+10.3}_{-5.7}\ (\text{syst})$$



- And mass difference values:

$$m(\Sigma_b^-) - m(\Lambda_b^0) - m_\pi = 55.9^{+1.0}_{-1.0}\ (\text{stat}) \pm 0.1\ (\text{syst})\ \text{MeV}/c^2$$
$$m(\Sigma_b^+) - m(\Lambda_b^0) - m_\pi = 48.4^{+2.0}_{-2.3}\ (\text{stat}) \pm 0.1\ (\text{syst})\ \text{MeV}/c^2$$
$$m(\Sigma_b^*) - m(\Sigma_b) = 21.3^{+2.0}_{-1.9}\ (\text{stat})\ ^{+0.4}_{-0.2}\ (\text{syst})\ \text{MeV}/c^2$$

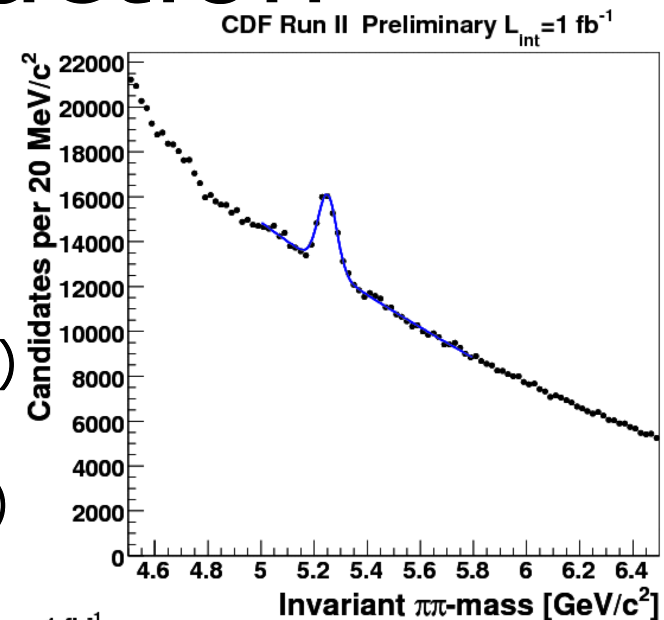
$B \to h^+h'^-$ Measurement

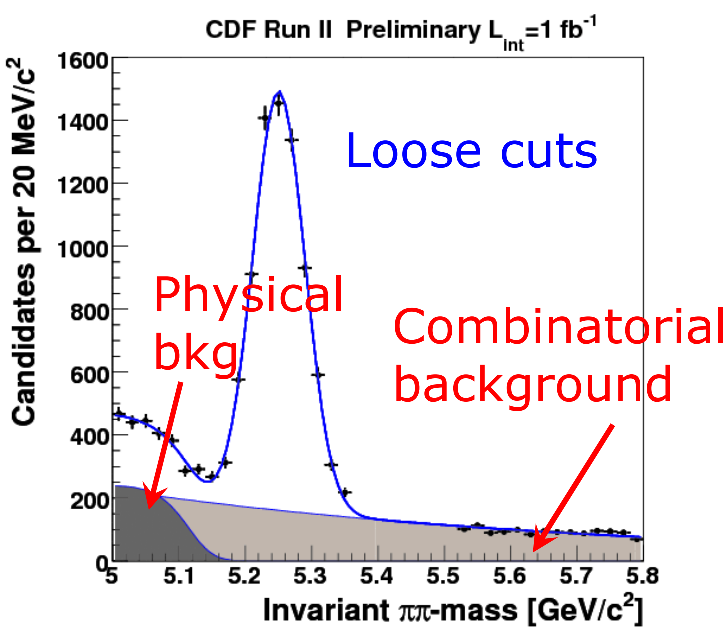
$B \rightarrow h^+h'^-$ Motivation

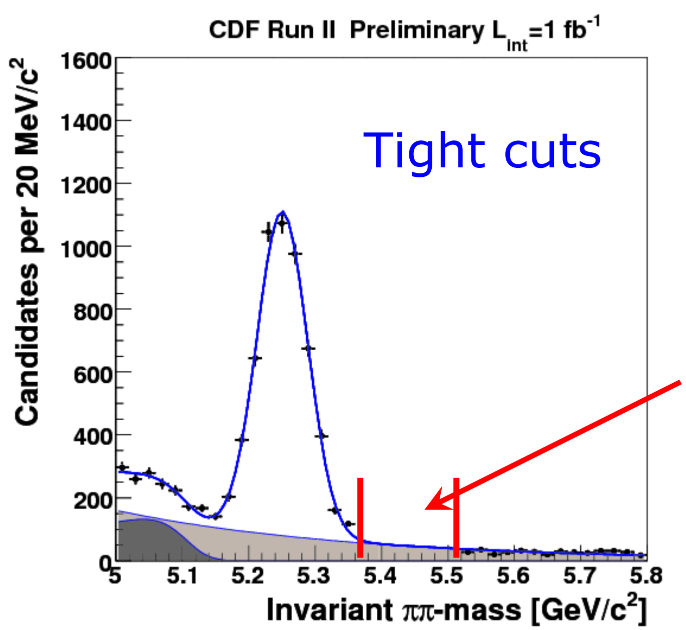
- Why study charmless B decays?
  - Study direct CP violation (DCPV) in the B^0 system
    - Large effect (~10%) established; why is it not compatible with the B^+ system? [Gronau and Rosner, Phys.Rev. D71 (2005) 074019]
  - Sensitive to new physics
    - Comparing rates and asymmetries of $B^0 \rightarrow K^+\pi^-$ and $B_s^0 \rightarrow K^-\pi^+$ uses only SM assumptions [Lipkin, Phys.Lett. B621 (2005) 126]
  - $BR(B^0 \rightarrow \pi^-\pi^+)$ and $BR(B_s^0 \rightarrow K^-K^+)$ may provide info on CKM angle γ by comparing to theoretically allowed regions [Fleischer, Matias, PRD66 (2002) 054009]
  - Comparing rates of $B_s^0 \rightarrow K^-K^+$ and $B^0 \rightarrow K^+\pi^-$ may shed light on the size of SU(3) symm breaking [Descotes-Genon et al, PRL97 (2006) 061801][Khodjamirian et al, PRD68 (2003) 114007]
- Primary analysis goals:
  - Measure $A_{CP}(B^0 \rightarrow K^+\pi^-)$
  - Measure $BR(B_s^0 \rightarrow K^-\pi^+)$

B → h⁺h′⁻ Reconstruction

- Offline trigger confirmation → visible B peak of ~14500 events, S/B ~ 0.2
- Optimize cuts by minimizing statistical error on observable to be measured
- Loose selection to measure $A_{CP}(B^0 \to K^+\pi^-)$ and other large yield modes
- Tight selection to measure $BR(B_s^0 \to K^-\pi^+)$ and other rare modes







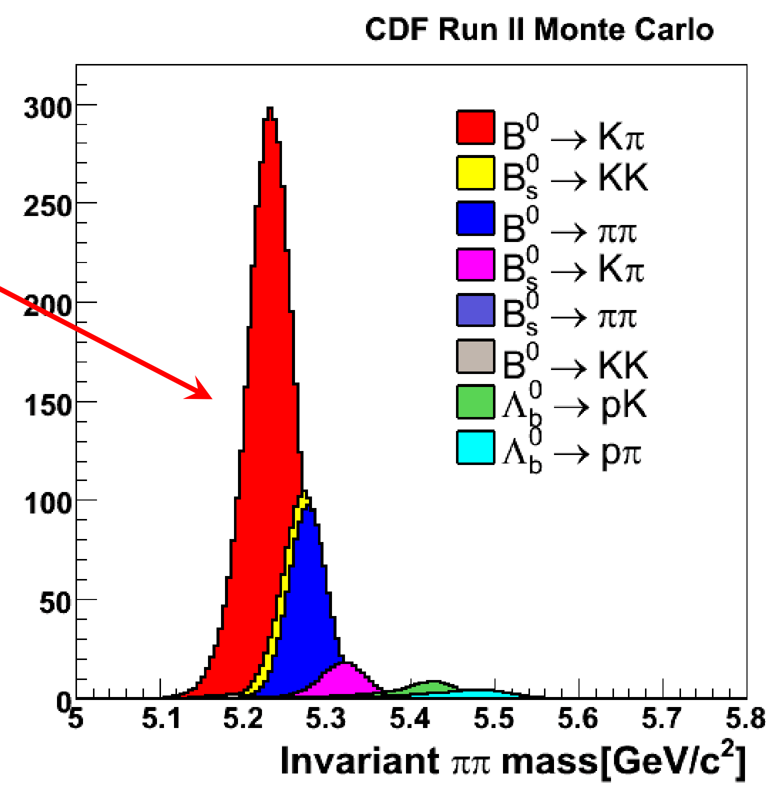
Simple 1-dim binned mass fit, excludes region of rare modes

Signal Extraction

- Modes will overlap
  - Despite excellent mass resolution (~22 MeV/c^2)
- Particle ID (PID) insufficient for event-by-event separation

→ Fit of composition:

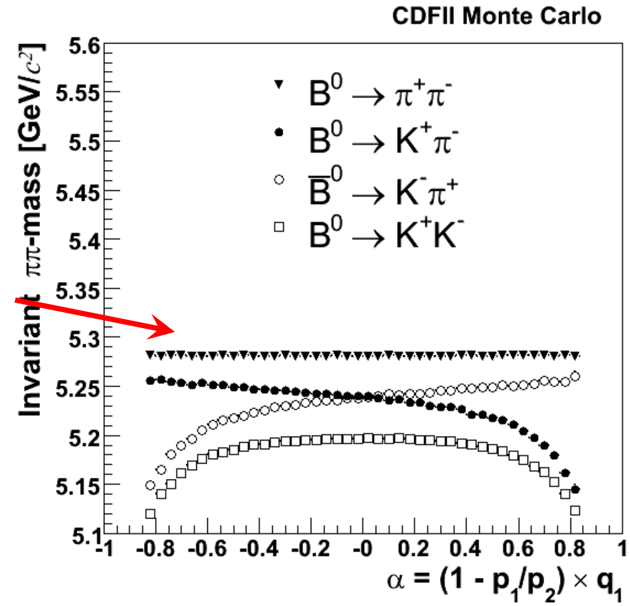
- Likelihood which combines information from
  - Kinematics (mass and momenta)
  - PID (dE/dx)

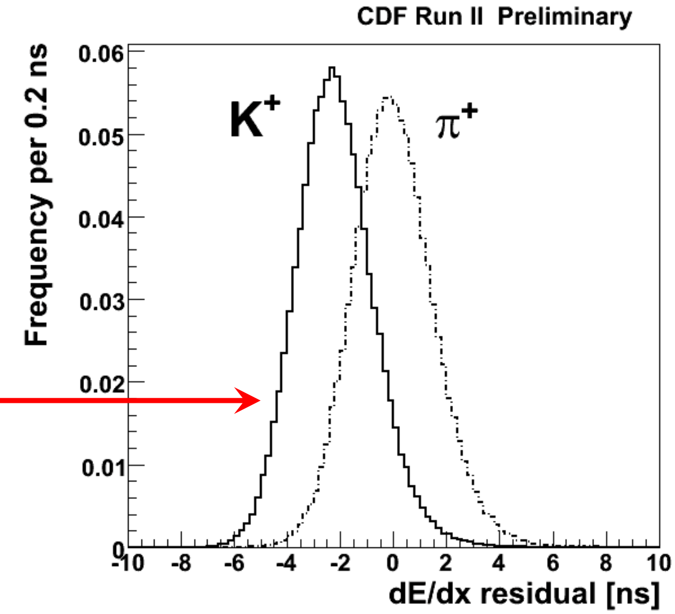


Monte Carlo simulation of reconstructed $\pi\pi$ invariant mass

Peak Composition Handles

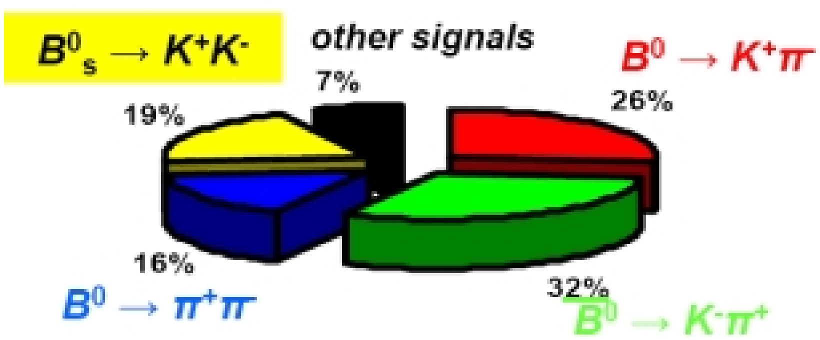
- Kinematics
  - Exploit the small kinematic differences between the modes
  - $\alpha = (1 - p_1/p_2) \cdot q_1$ is the signed kinematic imbalance
    - $p_{1,2}$ are the 3D track momenta ($p_1 < p_2$)
    - q_1 is the sign of the charge of track with 3D momentum p_1
  - Two other kinematic variables are $M_{\pi\pi}$ (invariant $\pi\pi$ mass) and $p_{tot} = p_1 + p_2$
  - These 3 variables carry all kinematic information about the 2-body decay
- dE/dx
  - 1.4σ K/π separation at p > 2.0 GeV/c after calibration on D*

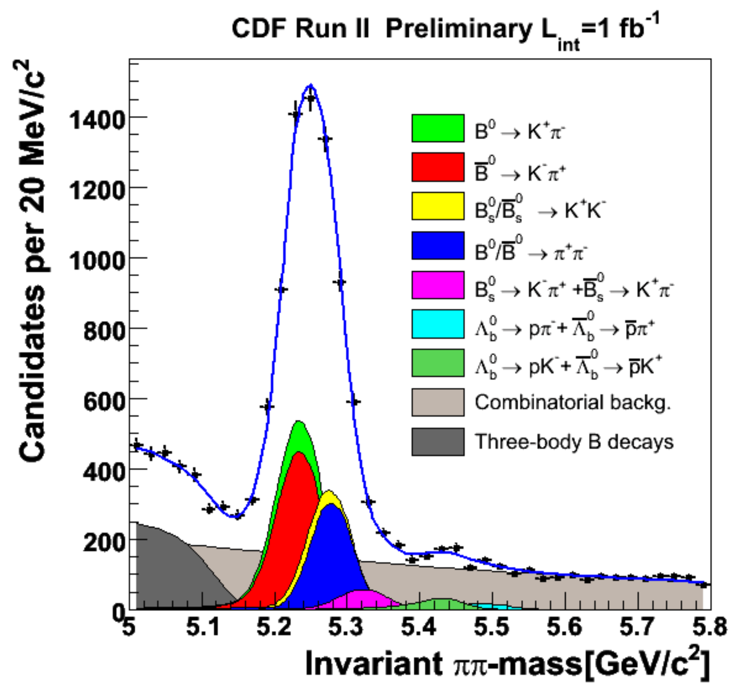




"Raw" measurement of $A_{CP}(B^0 \rightarrow K^+\pi)$

Uncorrected fractions





parameter	fraction	yield
$B^0 \rightarrow \pi^+\pi^-$ + c.c.	(0.160 ± 0.009)	1121 ± 63
$B^0 \rightarrow K^+\pi^-$ + c.c.	(0.577 ± 0.010)	4045 ± 84
$B_s^0 \rightarrow K^+K^-$ + c.c.	(0.186 ± 0.009)	1307 ± 64

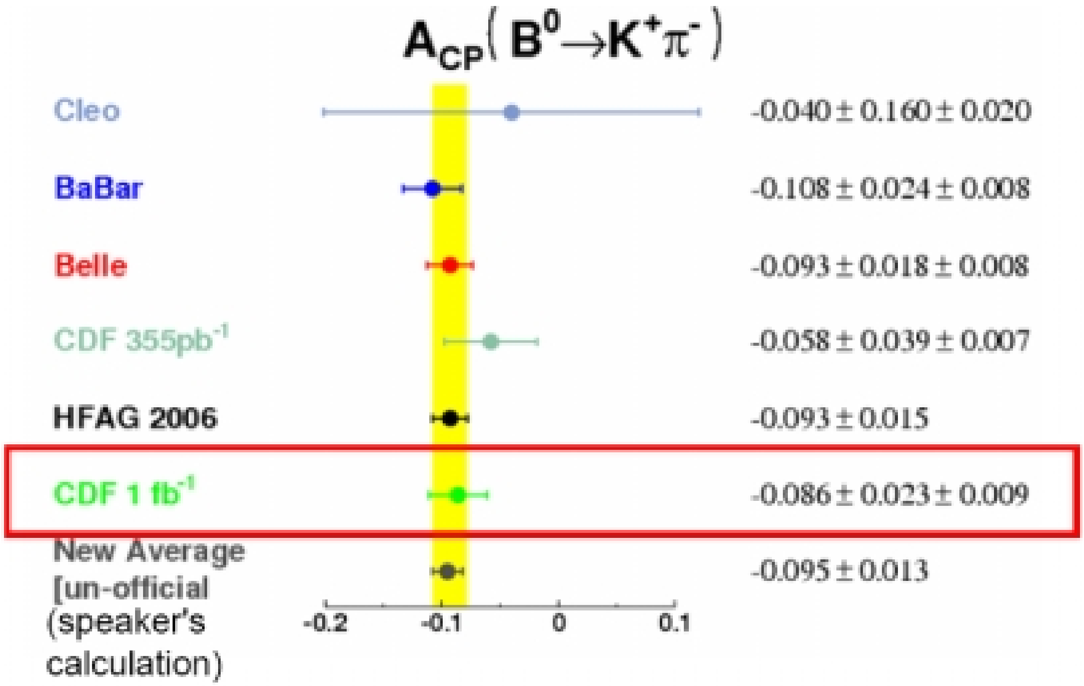
$B^0 \rightarrow h^+h'^-$ yield like B factories, and unique large sample of $B_s{}^0 \rightarrow h^+h'^-$

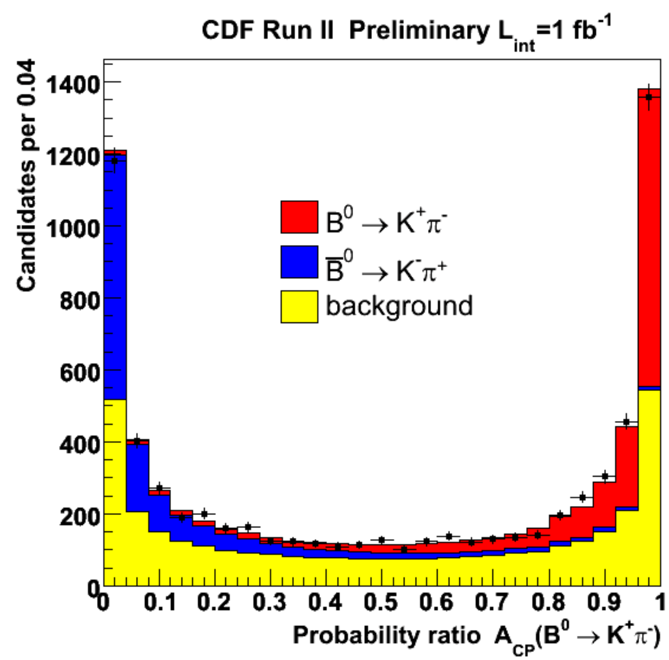
$$A_{\mathrm{CP}}\Big|_{\mathrm{raw}} = \frac{N_{\mathrm{raw}}(\overline{B}^0 \rightarrow K^-\pi^+) - N_{\mathrm{raw}}(B^0 \rightarrow K^+\pi^-)}{N_{\mathrm{raw}}(\overline{B}^0 \rightarrow K^-\pi^+) + N_{\mathrm{raw}}(B^0 \rightarrow K^+\pi^-)} = -0.092 \pm 0.023$$

Direct CP asymmetry of $B^0 \to K^+\pi^-$

After correcting for K^+/K^- interaction rate asymmetry and evaluating systematic effects, find:

$$A_{CP} = \frac{N(\overline{B}^0 \to K^-\pi^+) - N(B^0 \to K^+\pi^-)}{N(\overline{B}^0 \to K^-\pi^+) + N(B^0 \to K^+\pi^-)} = -0.086 \pm 0.023\ (stat.) \pm 0.009\ (syst.)$$



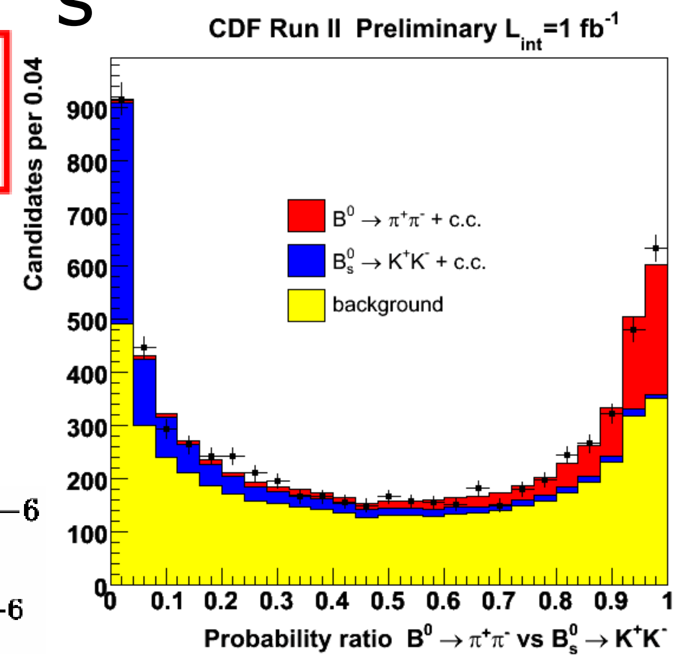


Second best single measurement of $A_{CP}(B^0 \to K^+\pi^-)$

BRs: $B^0 \to \pi^+\pi^-$ and $B_s^0 \to K^+K^-$

$$\frac{f_s \cdot BR(B_s^0 \to K^+K^-)}{f_d \cdot BR(B^0 \to K^+\pi^-)} = 0.324 \pm 0.019\ (stat.) \pm 0.041\ (syst.)$$

$$\frac{BR(B^0 \to \pi^+\pi^-)}{BR(B^0 \to K^+\pi^-)} = 0.259 \pm 0.017\ (stat.) \pm 0.016\ (syst.)$$



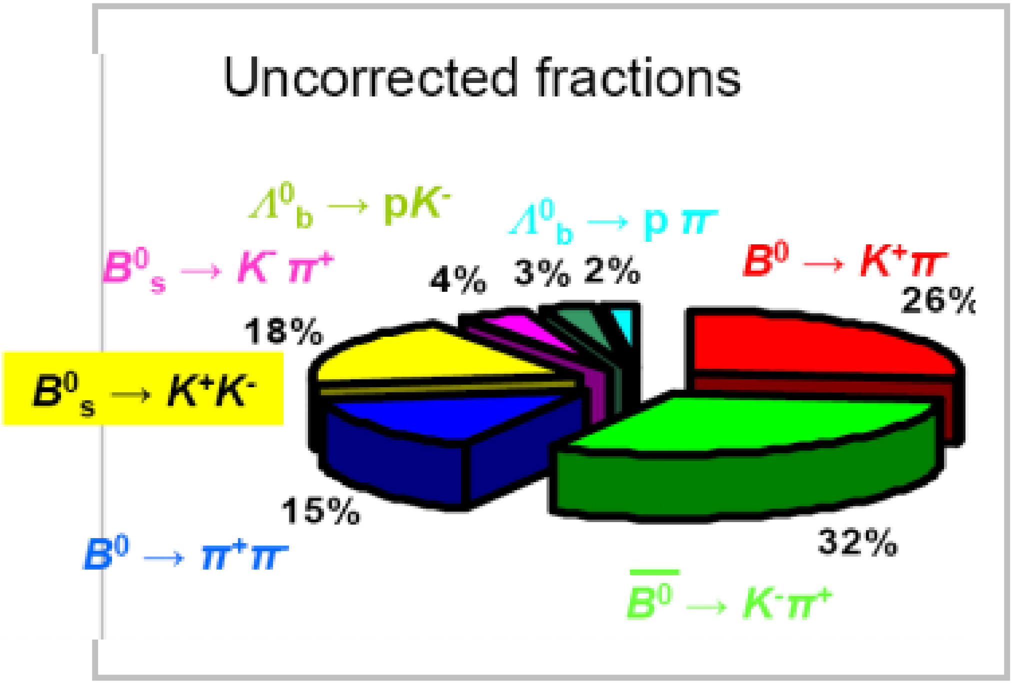
Using HFAG:

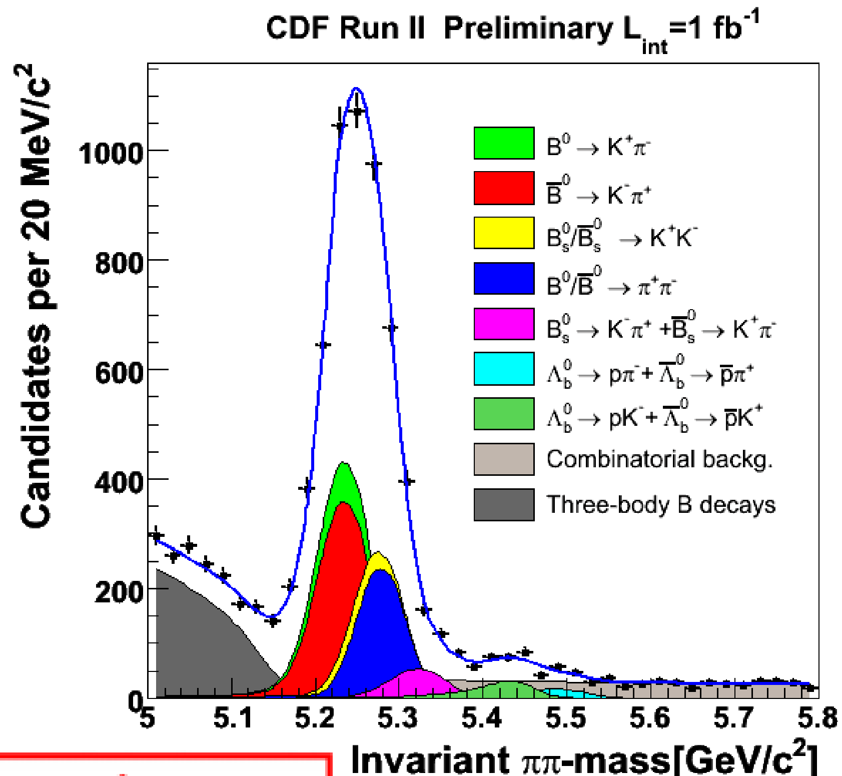
$$BR(B_s^0 \to K^+K^-) = (24.4 \pm 1.4\ (stat.) \pm 4.6\ (syst.)) \times 10^{-6}$$

$$BR(B^0 \to \pi^+\pi^-) = (5.10 \pm 0.33\ (stat.) \pm 0.36\ (syst.)) \times 10^{-6}$$

- $BR(B^0 \to \pi^+\pi^-)$, $BR(B_s^0 \to K^+K^-)$ becoming precision measurements
  - Conservative systematics for B_s^0, but soon syst. ≈ stat. error
- Not completely in agreement with theoretical predictions:
  - [Descotes-Genon et al] $BR(B_s^0 \to K^+K^-)/BR(B^0 \to K^+\pi^-) \approx 1$
  - [Khodjamirian et al] predict large SU(3) breaking (≈2)
  - CDF measurement disfavors predictions of large breaking

Rare modes search (tight cuts)





New rare modes observed

$$N_{\rm raw}(B_s^0 \to K^-\pi^+) = 230 \pm 34\ (stat.) \pm 16\ (syst.) \quad (8\sigma)$$

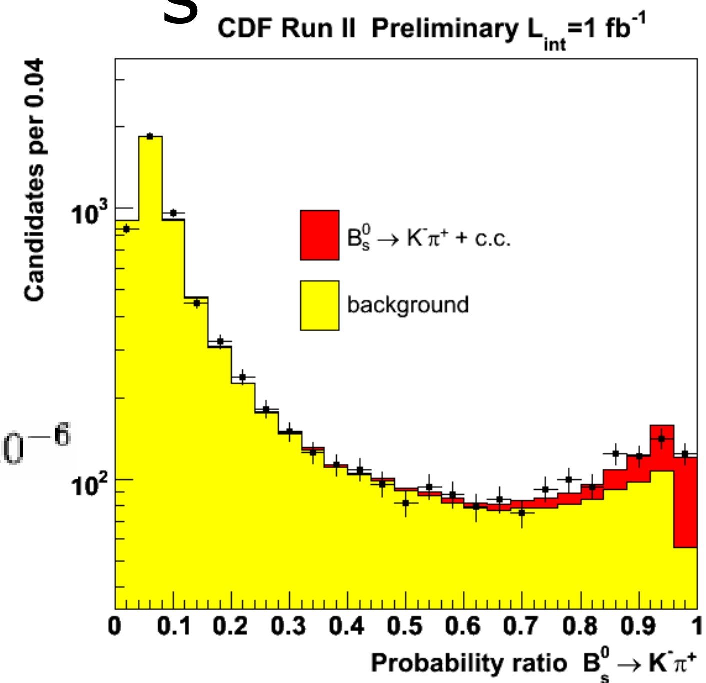
$$N_{\rm raw}(\Lambda_b^0 \to p\pi^-) = 110 \pm 18\ (stat.) \pm 16\ (syst.) \quad (6\sigma)$$

$$N_{\rm raw}(\Lambda_b^0 \to pK^-) = 156 \pm 20\ (stat.) \pm 11\ (syst.) \quad (11\sigma)$$

First observation of $B_s^0 \to K^-\pi^+$

$$N_{\text{raw}}(B_s^0 \to K^-\pi^+) \;=\; 230 \pm 34\ (stat.) \pm 16\ (syst.)$$

$$\frac{f_s \cdot BR(B_s^0 \to K^-\pi^+)}{f_d \cdot BR(B^0 \to K^+\pi^-)} \;=\; 0.066 \pm 0.010\ (stat.) \pm 0.010\ (syst.)$$



Using HFAG:

$$BR(B_s^0 \to K^-\pi^+) \;=\; (5.0 \pm 0.75\ (stat.) \pm 1.0\ (syst.)) \times 10^{-6}$$

Good agreement with recent theo. predictions.
From SM, expect large $A_{CP} \approx 0.37$ (calculated using above BR). Measure:

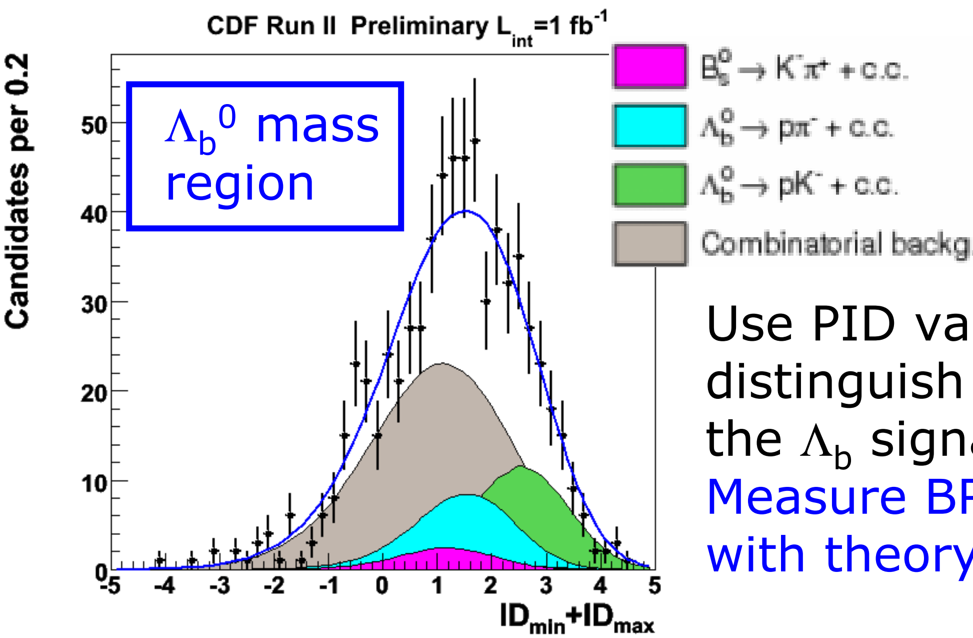
$$A_{CP} = \frac{N(\overline{B}_s^0 \to K^+\pi^-) - N(B_s^0 \to K^-\pi^+)}{N(\overline{B}_s^0 \to K^+\pi^-) + N(B_s^0 \to K^-\pi^+)} \;=\; 0.39 \pm 0.15\ (stat.) \pm 0.08\ (syst.)$$

Asymmetry 2.5 σ

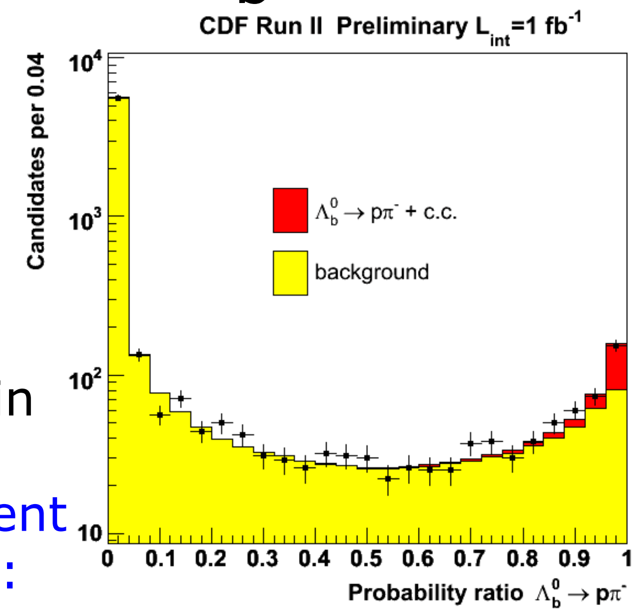
Compare rates and asymmetries of $B^0 \to K^+\pi^-$ and $B_s^0 \to K^-\pi^+$ to probe NP with only SM assumptions [Lipkin, Phys.Lett. B621 (2005) 126]:

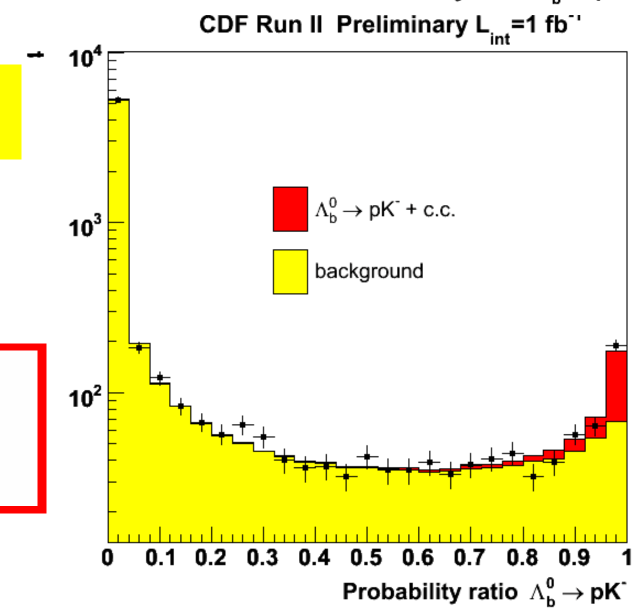
$$\frac{\Gamma(\overline{B}^0 \to K^-\pi^+) - \Gamma(B^0 \to K^+\pi^-)}{\Gamma(B_S^0 \to K^-\pi^+) - \Gamma(\overline{B}_S^0 \to K^+\pi^-)} = 0.84 \pm 0.42 \pm 0.15$$ (= 1 SM)

First observation: $\Lambda_b^0 \to p\pi^-$, $\Lambda_b^0 \to pK^-$



Use PID variable to distinguish the modes in the Λ_b signal region.
Measure BR in agreement with theory predictions:





$$N_{\rm raw}(\Lambda_b^0 \to pK^-) = 156 \pm 20\ (stat.) \pm 11\ (syst.)$$ **11 σ**

$$N_{\rm raw}(\Lambda_b^0 \to p\pi^-) = 110 \pm 18\ (stat.) \pm 16\ (syst.)$$ **6 σ**

$$\frac{BR(\Lambda_b^0 \to p\pi^-)}{BR(\Lambda_b^0 \to pK^-)} = 0.66 \pm 0.14\ (stat.) \pm 0.08\ (syst.)$$

Upper limits: $B^0 \to K^+K^-$, $B_s^0 \to \pi^+\pi^-$

- Both modes are annihilation-dominated decays
  - Hard to predict BR
  - Not yet observed anywhere

$$\frac{f_s \cdot BR(B_s^0 \to \pi^+\pi^-)}{f_d \cdot BR(B^0 \to K^+\pi^-)} = 0.007 \pm 0.004\ (stat.) \pm 0.005\ (syst.)$$ **1.5 σ**

$$\frac{BR(B^0 \to K^+K^-)}{BR(B^0 \to K^+\pi^-)} = 0.020 \pm 0.008\ (stat.) \pm 0.006\ (syst.)$$ **1.5 σ**

$$BR(B^0 \to K^+K^-) = (0.39 \pm 0.16\ (stat.) \pm 0.12\ (syst.)) \times 10^{-6}$$ ($< 0.7 \cdot 10^{-6}$ @ 90% C.L.)

Expected [0.01 - 0.2] $\cdot 10^{-6}$ [Beneke&Neubert NP B675, 333(2003)]

$$BR(B_s^0 \to \pi^+\pi^-) = (0.53 \pm 0.31\ (stat.) \pm 0.40\ (syst.)) \times 10^{-6}$$ ($<1.36 \cdot 10^{-6}$ @ 90% C.L.)

Expected: [0.007 - 0.08] $\cdot 10^{-6}$ [Beneke&Neuber t NP B675, 333(2003)]
Expected: 0.42 ± 0.06 [Ying Li et al. hep-ph/0404028]

World's best upper limit on $B_s^0 \to \pi^+\pi^-$
Same resolution as B-factories for $B^0 \to K^+K^-$

Summary

- First observation of lowest lying charged Σ_b states!
  - With $m(\Lambda_b) = 5619.7 \pm 1.2$ (stat) ± 1.2 (syst) MeV/c^2,

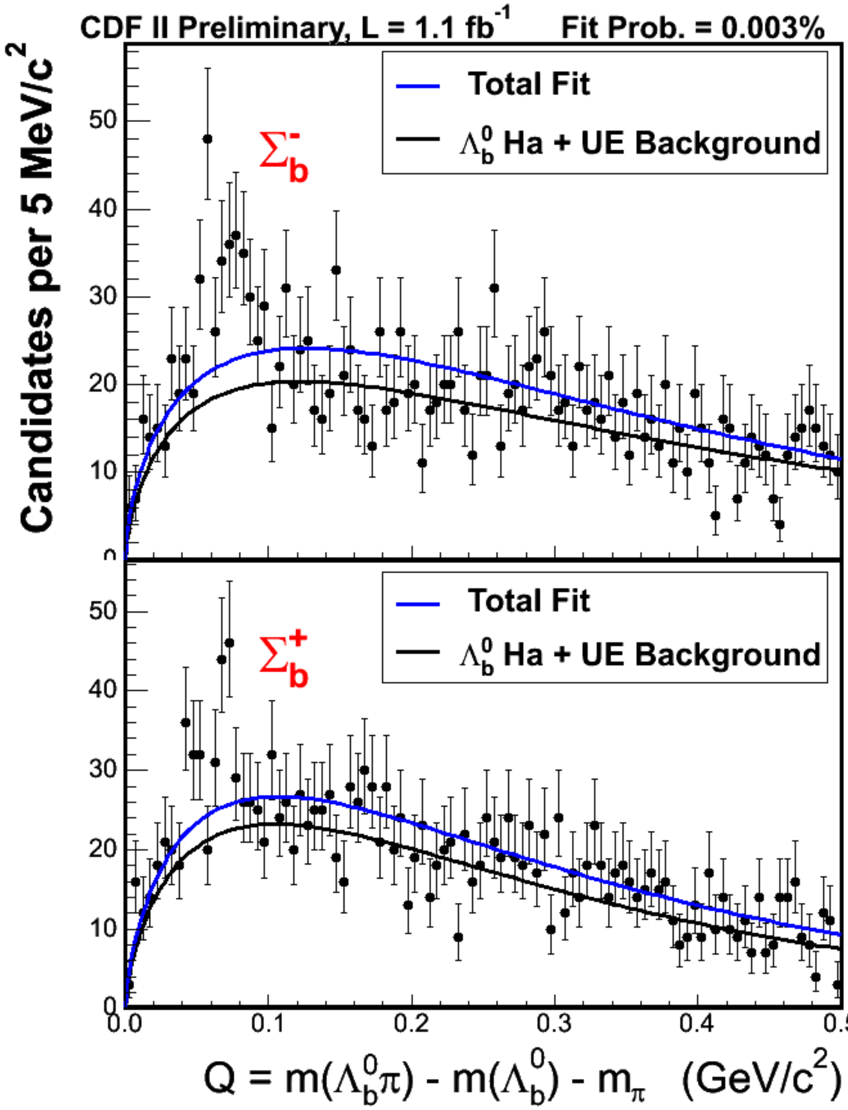
$$m(\Sigma_b^-) = 5816^{+1.0}_{-1.0}\ (\text{stat})\ \pm 1.7\ (\text{syst})\ \text{MeV}/c^2$$
$$m(\Sigma_b^+) = 5808^{+2.0}_{-2.3}\ (\text{stat})\ \pm 1.7\ (\text{syst})\ \text{MeV}/c^2$$
$$m(\Sigma_b^{*-}) = 5837^{+2.1}_{-1.9}\ (\text{stat})\ \pm 1.7\ (\text{syst})\ \text{MeV}/c^2$$
$$m(\Sigma_b^{*+}) = 5829^{+1.6}_{-1.8}\ (\text{stat})\ \pm 1.7\ (\text{syst})\ \text{MeV}/c^2$$

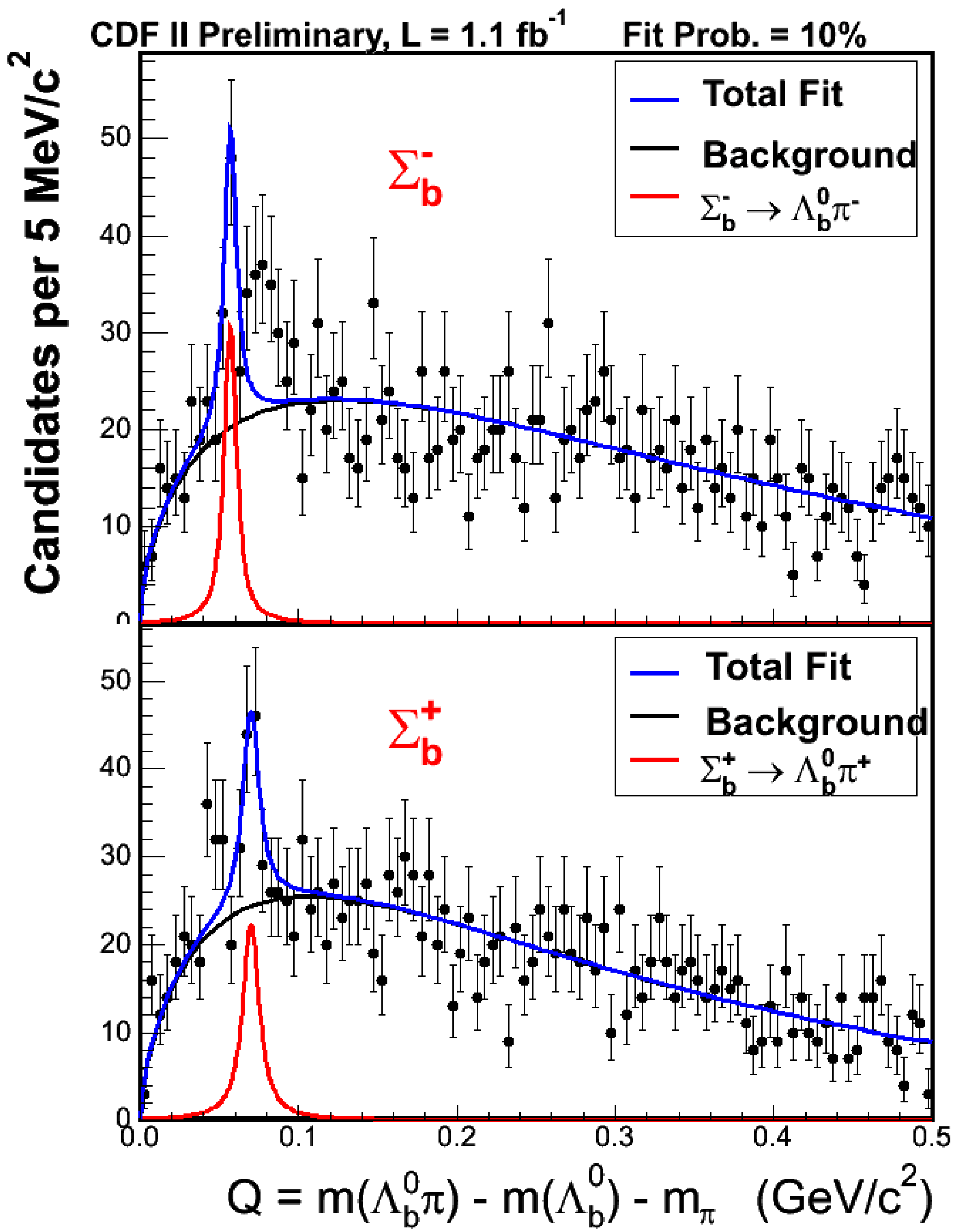
- New $B \rightarrow h^+ h'^-$ results
  - First observation of $B_s^0 \rightarrow K^-\pi^+$, $\Lambda_b^0 \rightarrow p\pi^-$, $\Lambda_b^0 \rightarrow pK^-$
  - First measurement of A_{CP} and $BR(B_s^0 \rightarrow K^-\pi^+)$
  - Precision $A_{CP}(B^0 \rightarrow K^+\pi^-)$ measurement
  - Updated $BR(B_s^0 \rightarrow K^+K^-)$ and $BR(B^0 \rightarrow \pi^+\pi^-)$ measurements
- With more data on the way, more precision measurements and new discovery potential!

Backup Slides

Σ_b Fit Likelihood Ratios

Hypothesis	$\Delta(\ln £)$	LR
"NULL" vs. "4 Peak"	**44.7**	**2.6e19**
"2 Peak" vs. "4 Peak"	**14.3**	**1.6e6**
No Σ_b^- Peak	**10.4**	**3.3e4**
No Σ_b^+ Peak	**1.1**	**3**
No Σ_b^{*-} Peak	**10.1**	**2.4e4**
No Σ_b^{*+} Peak	**9.8**	**1.8e4**

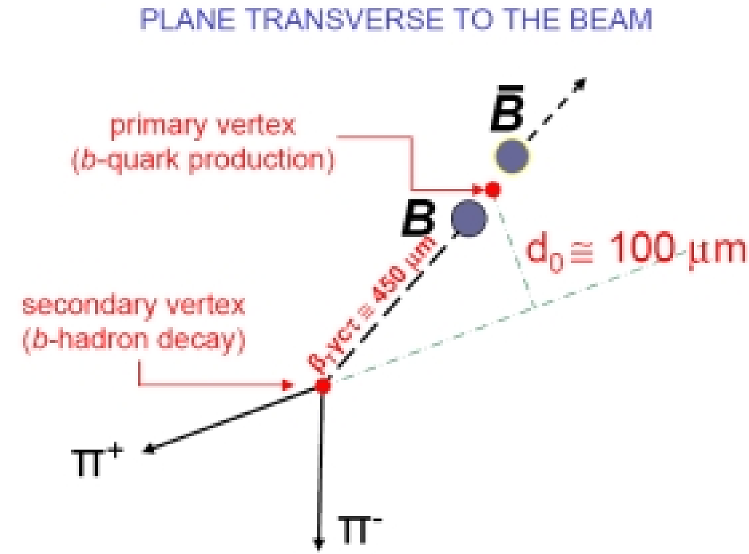


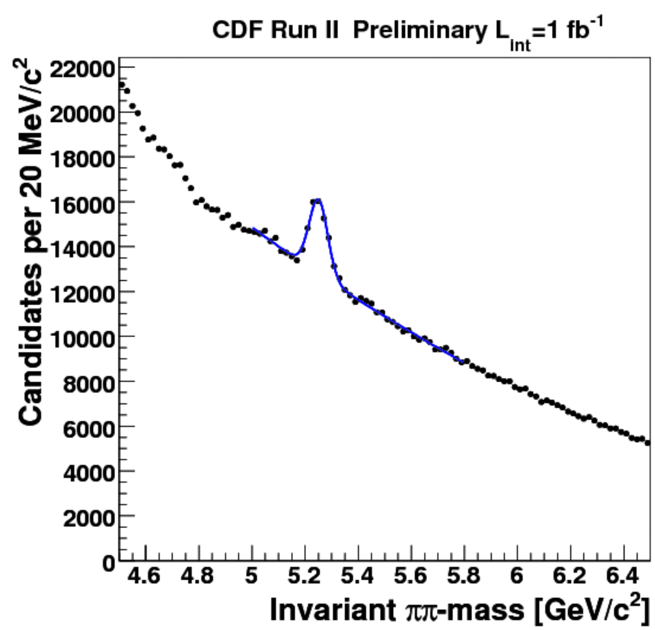


Σ_b Two Peak Fit

B → h+h'- Reconstruction

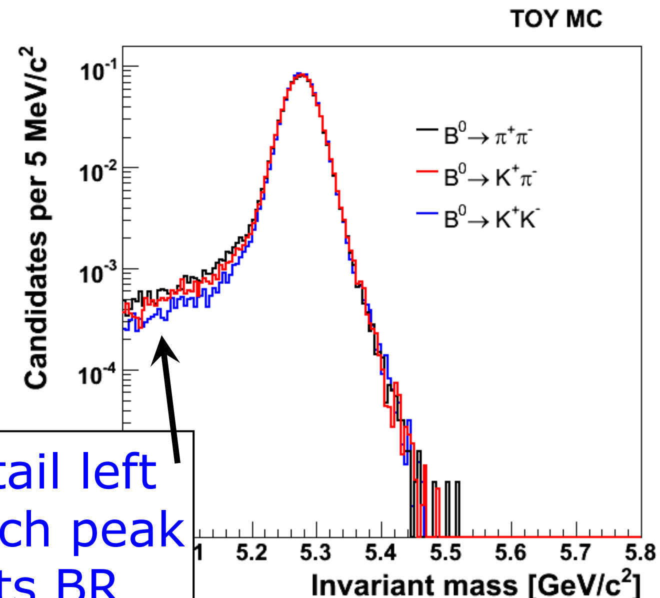
- Offline trigger confirmation
  - Two opposite charge tracks (i.e. B candidate) from long-lived decay:
    - Track impact parameter > 100 μm
    - B transverse decay length > 200 μm
  - B candidate points back to the primary vertex
    - B impact parameter < 140 μm
  - Reject light quark background from jets:
    - Transverse opening angle [20°, 135°]
    - p_{T1} and p_{T2} > 2.0 GeV/c
    - $p_{T1} + p_{T2}$ > 5.5 GeV/c
- Visible B peak of ~14500 events with S/B ~ 0.2



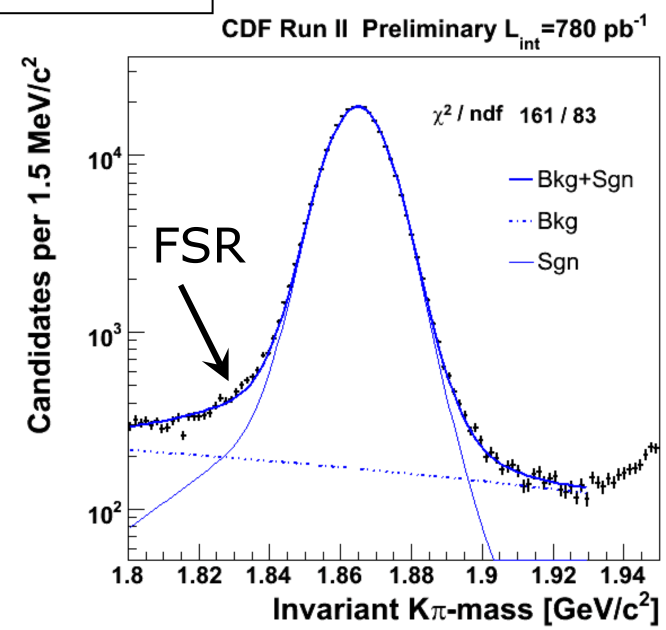


Peak Composition Handle 1: Mass

- BR measurements sensitive to detailed shape of mass resolution function
  - e.g. radiative tails, non-Gaussian tails
  - Need careful parameterization of all resolution effects!
  - Used QED calculation from [Baracchini and Isidori, Phys.Lett. B633 (2006) 309] for B(D) → $\pi\pi$, $K\pi$, KK mass resolution templates
- Use huge $D^0 \rightarrow K\pi$ sample for an accurate test of resolution model
  - 1 dim binned fit, signal mass line shape fixed from model
  - Check model fits data!

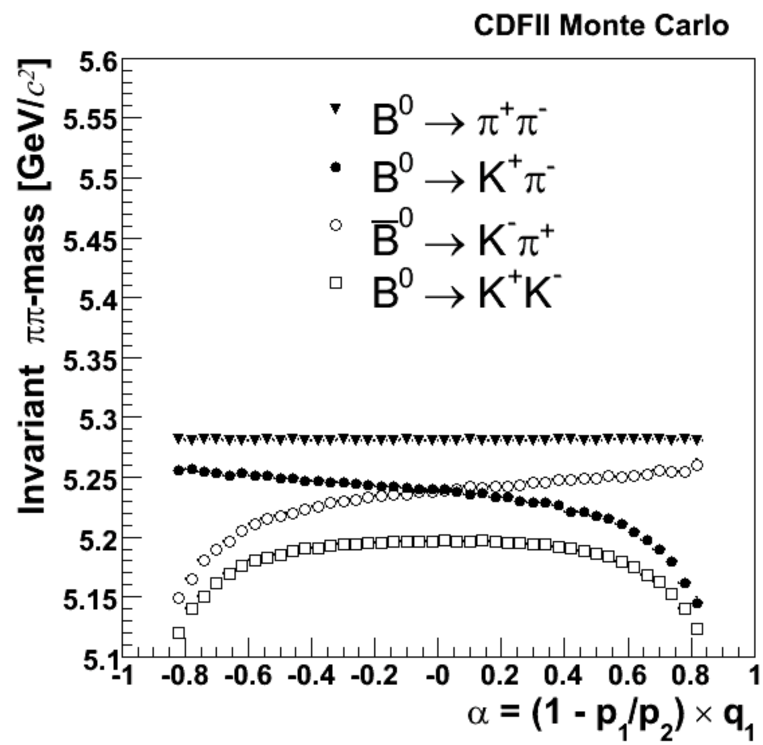


FSR tail left of each peak affects BR

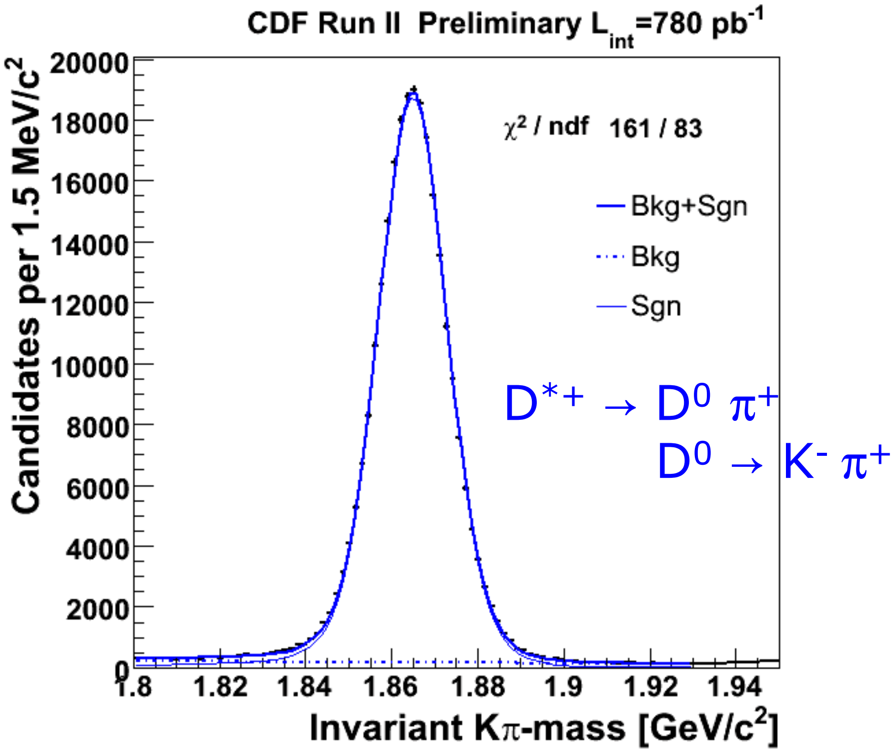


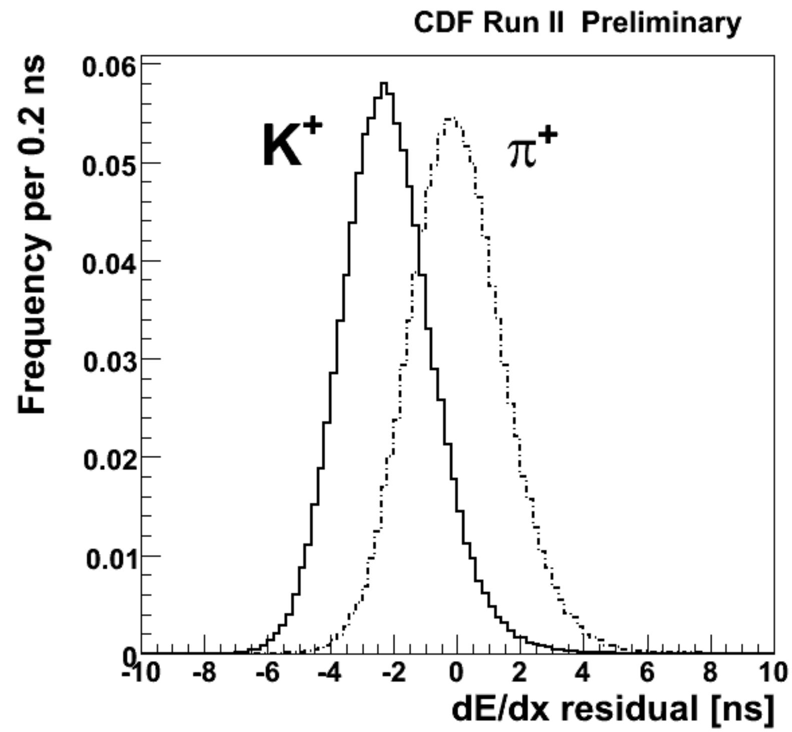
Peak Composition Handle 2: Momenta

- Exploit the (small) kinematic difference between the modes:
  - $\alpha = (1 - p_{min}/p_{max}) \cdot q_{min}$ is the signed kinematic imbalance
  - p_{min} (p_{max}) are 3D track momenta, with $p_{min} < p_{max}$
  - q_{min} is the sign of the charge of track with p_{min}
- Two other kinematic variables of interest:
  - $M_{\pi\pi}$, the invariant $\pi\pi$ mass
  - $p_{tot} = p_{min} + p_{max}$, the scalar sum of the 3D track momenta



Peak Composition Handle 3: dE/dx





- Strong D^{*+} decay tags D^0 flavor
  - ~95% pure K and π samples from ~1.5 million D^{*+} decays
- dE/dx accurately calibrated over tracking volume and time
- 1.4σ K/π separation at p > 2.0 GeV/c
- Statistical uncertainty only 60% worse than achievable with PERFECT separation