Measurement of the Ratio of Branching Fractions

$\frac{\mathrm{Br}(\mathrm{B_s^0 \to D_s^- \pi})}{\mathrm{Br}(\mathrm{B^0 \to D^- \pi})}$ at CDFII

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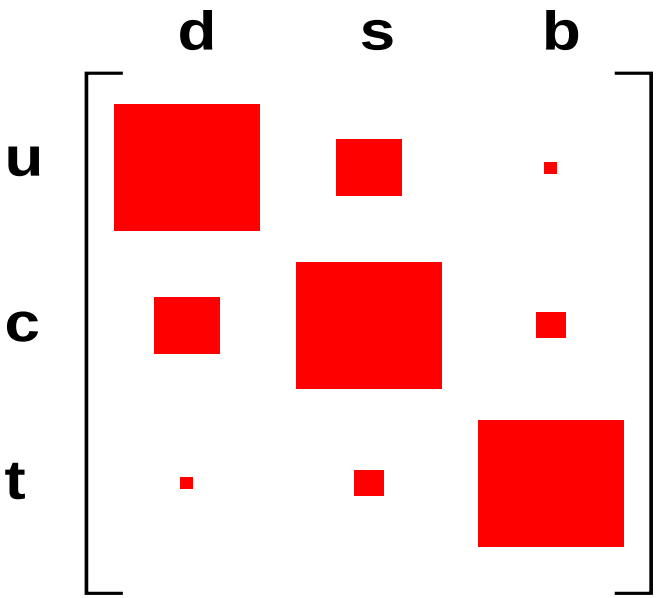
Talk Overview

- Introduction and Theoretical Prediction
- Experimental Apparatus
- Analysis:
  - Trigger
  - B Meson Reconstruction
  - Counting B Mesons
  - Monte Carlo Correction Factors
  - Systematic Uncertainties
- Outlook

Introduction to the B_s^0 Meson

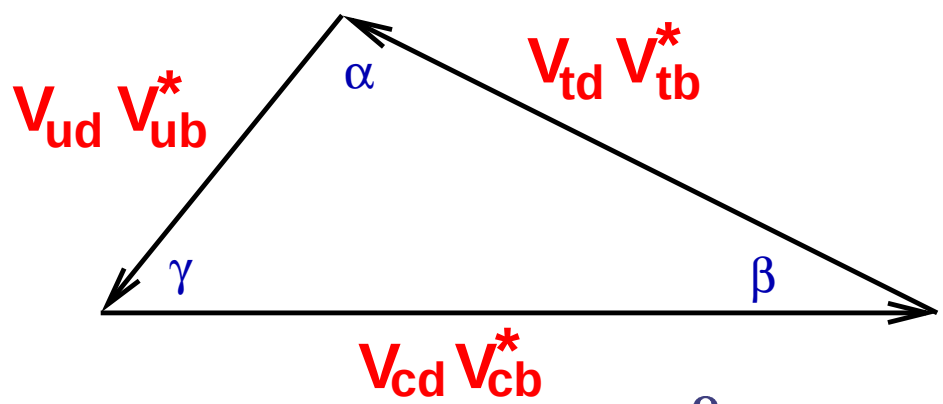
- not much is known about the B_s^0 meson
- mass measured with few events (CDF-I: 32)
- lifetimes mostly from semi-leptonic decays
- branching ratios at best known to 30%
- expected to be similar to the B^0 meson
- mixing frequency $\sim 40\times$ faster than B^0
- $B_s^0 \to D_s^- \pi^+$ "golden mode" for B_s^0 mixing
  - fully hadronic, flavor specific
  - seen at LEP, branching fraction? (PDG: $< 13\%, 95\%$ CL)
  - few tracks $\to$ "easy" to trigger, reconstruct
- this thesis investigates the properties of $B_s^0 \to D_s^- \pi^+$ decays in $p\overline{p}$ collisions

Weak Interactions in the SM



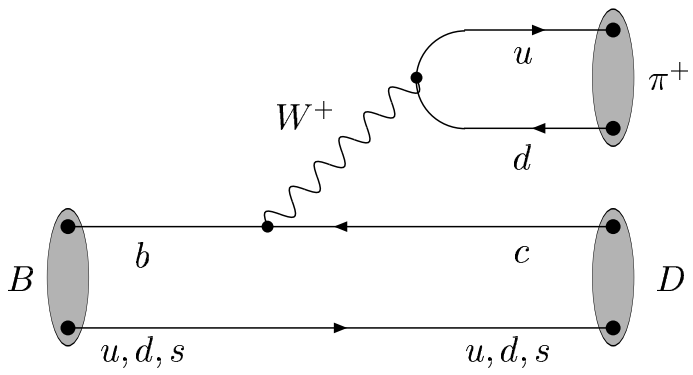
- CKM matrix: $W^{\pm}$ boson couplings to quarks
- area $\sim |V_{ij}|$
- interaction strength $\sim |V_{ij}|^2$
- unitary matrix: $VV^{\dagger} = 1$

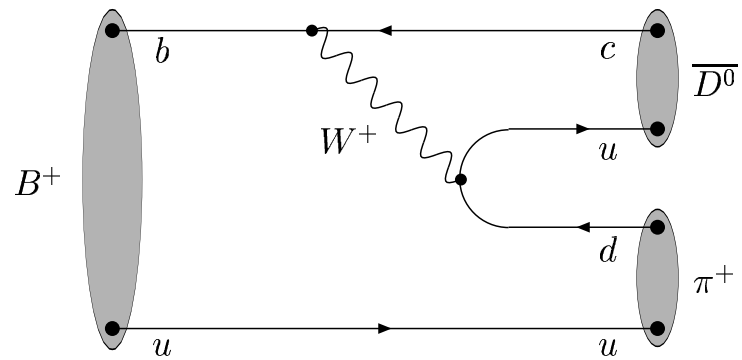
- unitary triangle
- 1 observable phase
  ($\sim$ area, $\sim$ CP violation)



- what does it predict about hadronic B_s^0 decays? (and how they relate to hadronic B^0 decays?)

Prediction From Theory



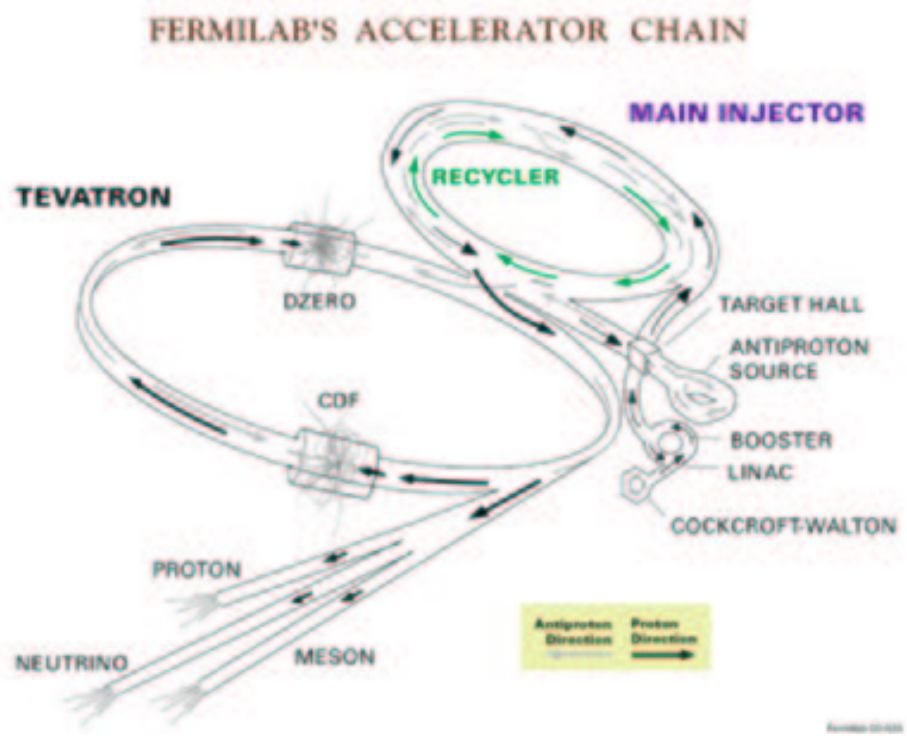


- spectator diagrams are the same for B_s^0 and B^0
- $m(B_s^0) - m(D_s^-) \sim m(B^0) - m(D^-)$
- kinematics are very similar
- according to light flavor symmetry, expect same decay amplitude
- $\tau(B_s^0) \sim \tau(B^0)$
- expect $Br(B_s^0 \to D_s^- \pi) \simeq Br(B^0 \to D^- \pi)$

Apparatus: Tevatron

Main Injector

- New injection stage for Tevatron
- Ability to accelerate and deliver higher intensity of protons
- More efficient $\overline{\mathrm{p}}$ transfer
- $\overline{\mathrm{p}}$ recycler (in progress)

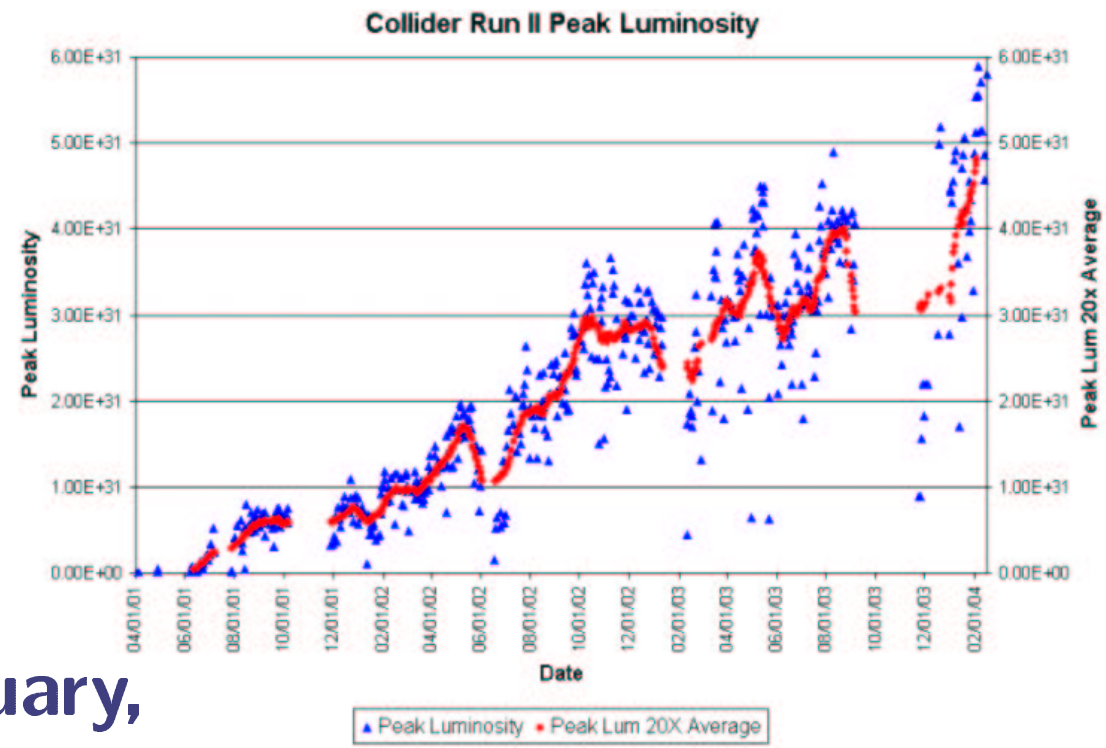


- Higher Collision rate: 396ns (36x36 bunches)
  $\Rightarrow$ **5-10 Higher Luminosity than Run I**
- Higher C.M. Energy:
  Run I: $1.8\ \mathrm{TeV} \rightarrow$ Run II $1.96\ \mathrm{TeV}$

Tevatron Performance

Luminosity:

- typical luminosity: $4.5 \cdot 10^{31} \mathrm{cm}^{-2} \mathrm{s}^{-1}$
- record luminosity: $6.1 \cdot 10^{31} \mathrm{cm}^{-2} \mathrm{s}^{-1}$

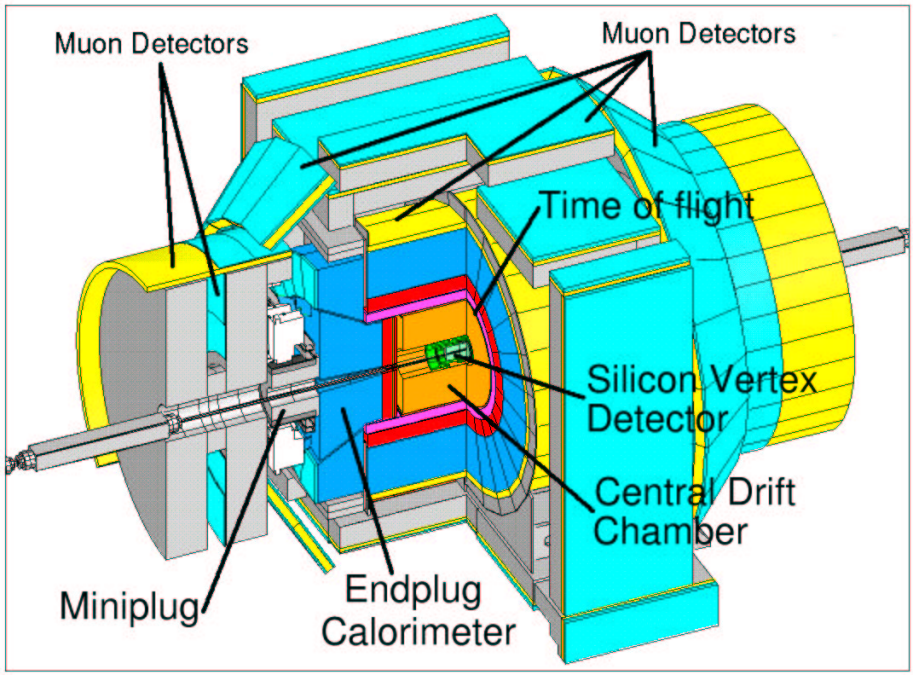


- at the end of January, $370\ \mathrm{pb}^{-1}$ delivered, $290\ \mathrm{pb}^{-1}$ recorded
- efficiency in the high 80%'s, dead time $< 5\%$
- this analysis uses $115\ \mathrm{pb}^{-1}$ of data, maximum available when it was done

Apparatus: The CDF II Detector

Inherited from Run I:

- Central Calor. ($|\eta| < 1$)
- Solenoid (1.4 T)



Partially new:

- Muon System (extended to $|\eta| < 2$)

Completely new:

- 3D Silicon Tracker ($|\eta| < 2$)
- Faster Drift Chamber
- Plug and Forward Calorimeters, Time Of Flight
- Trigger System (trigger on displaced vertices)

B Hadron Production

Accelerator	PEPII/KEK(e^+e^-)	Tevatron ($p\overline{p}$)
$\sigma(b\overline{b})$	1 nb	100 μb
$\sigma(b\overline{b}) : \sigma(had)$	0.26	0.001
Production	$\Upsilon(4S) \to B\overline{B}$ coherent	$b\overline{b}X$ incoherent
Hadrons	B^0, B^+	$B^0, B^+, B_s^0, \Lambda_b, B_c^+ ...$
Environment	clean	messy
Boost	0.5	2-4
Event pile-up	no	yes
Trigger	inclusive	selective
Energy constraint	yes	no
ct resolution	~ 1.1ps	$\sim 70 fs$

Rate of B_s vs B^0

- want to understand rate of $B_s \to D_s^- \pi^+$
- compare to similar decay $B^0 \to D^- \pi^+$
- what is different?

- rate of B_s production (f_s) different from B^0 (f_d)

- final state $D_s \to \phi\pi$ vs $D^- \to K^+\pi^-\pi^-$
- account for by using PDG ratio of BR's

- kinematics slightly different $\to$ efficiency?
- $\epsilon = \epsilon(acc) \cdot \epsilon(det) \cdot \epsilon(trig) \cdot \epsilon(rec)$
- will need to consult Monte Carlo simulation for this

$Br(B_s^0 \to D_s^- \pi^+)$ Measurement

We measure the ratio of branching fractions:

$$\frac{f_s}{f_d} \cdot \frac{Br(B_s^0 \to D_s \pi)}{Br(B^0 \to D^- \pi)} = \frac{N(B_s^0)}{N(B^0)} \cdot \frac{\epsilon(B^0)}{\epsilon(B_s^0)} \cdot \frac{Br(D^+ \to K\pi\pi)}{Br(D_s \to \phi\pi, ..)}$$

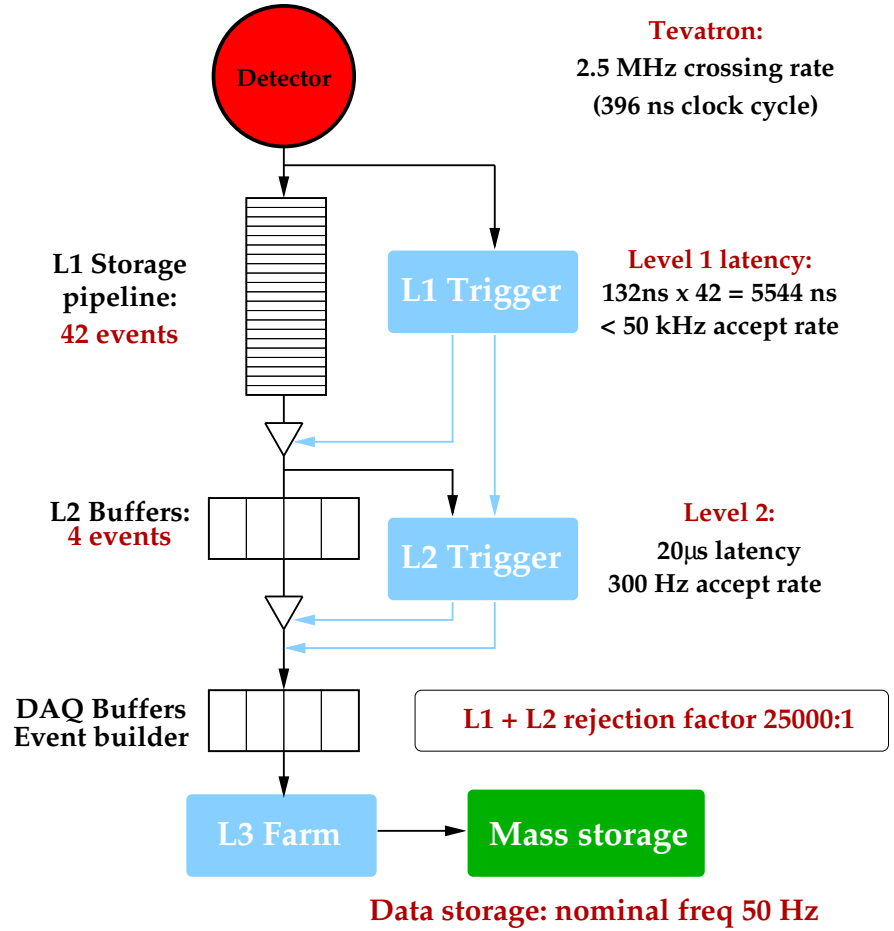
- control sample: $B^+ \to \overline{D^0}\pi^+$ and corresponding BR relative to $B^0 \to D^- \pi^+$
- N(B_s^0), N(B^+), N(B^0) obtained from fits to data
- $\epsilon(B^0)$ / $\epsilon(B_s^0)$, $\epsilon(B^0)/\epsilon(B^+)$ from realistic MC
- $BR(D^-/D_s^-/D^0)$ are taken from PDG

Key issues:

- reconstruction of B mesons with good S/B
- robust and correct extraction of $N(B)$
- realistic trigger and analysis simulation

Triggering in $p\bar{p}$

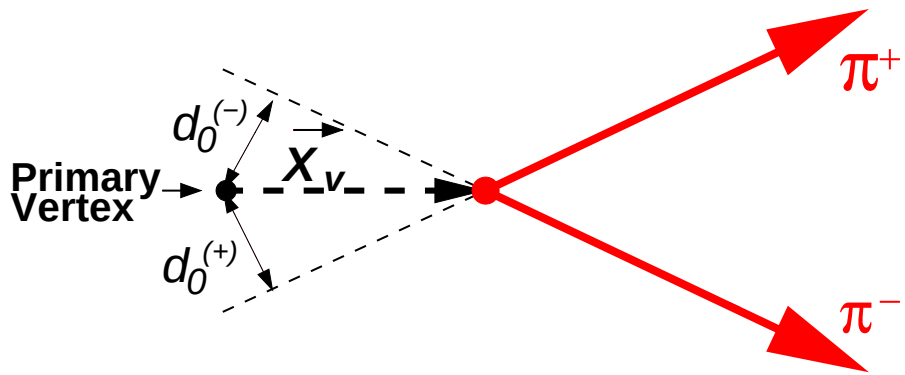
- event size ~ 250 kb
- can't save all collisions (2.5 MHz $\rightarrow$ 0.6 Tb/s)
- feasible to record and analyze ~ 50 Hz
- drastic reduction, in 3 steps (L1, L2, L3)
- each step has more time, can reach better decision

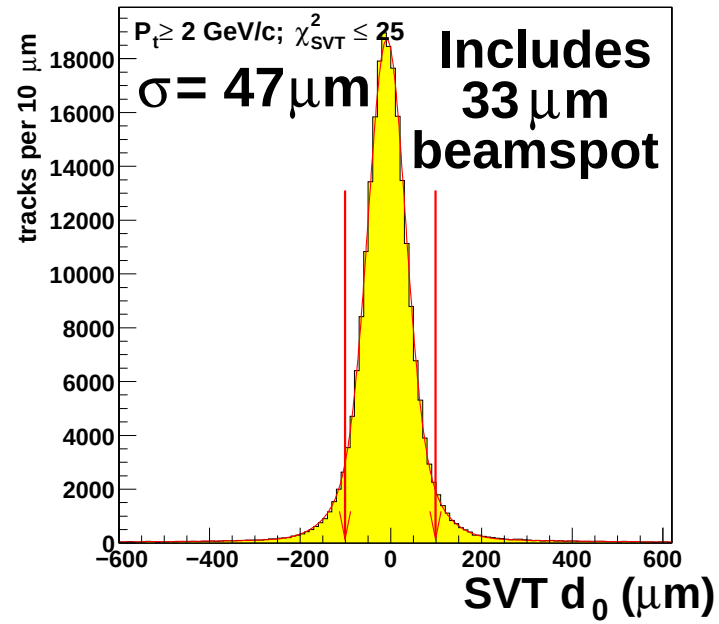


- highly selective triggers, events marked with bits
- trigger paths protect against volunteers

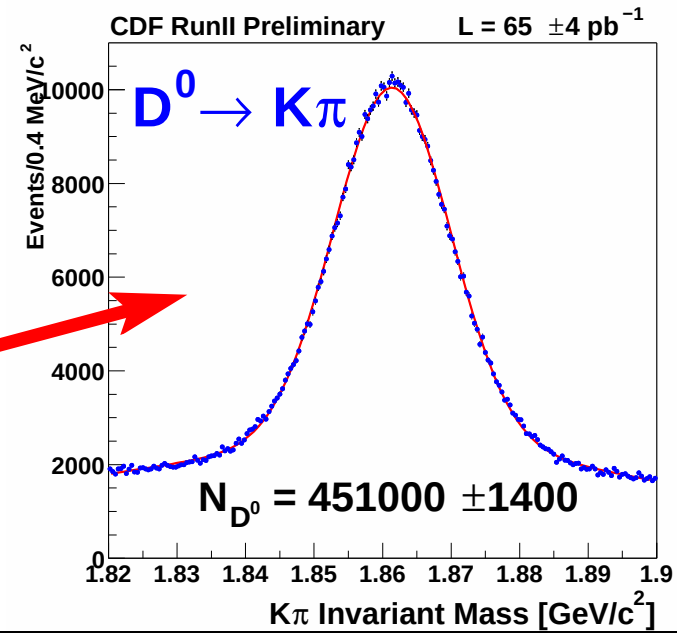
Triggering on displaced tracks

- trigger $\mathrm{B} \to \pi\pi, \mathrm{B_s} \to \mathrm{D_s}\pi$
- challenge: read out SVX and track at 10's of kHz $\to$ SVT



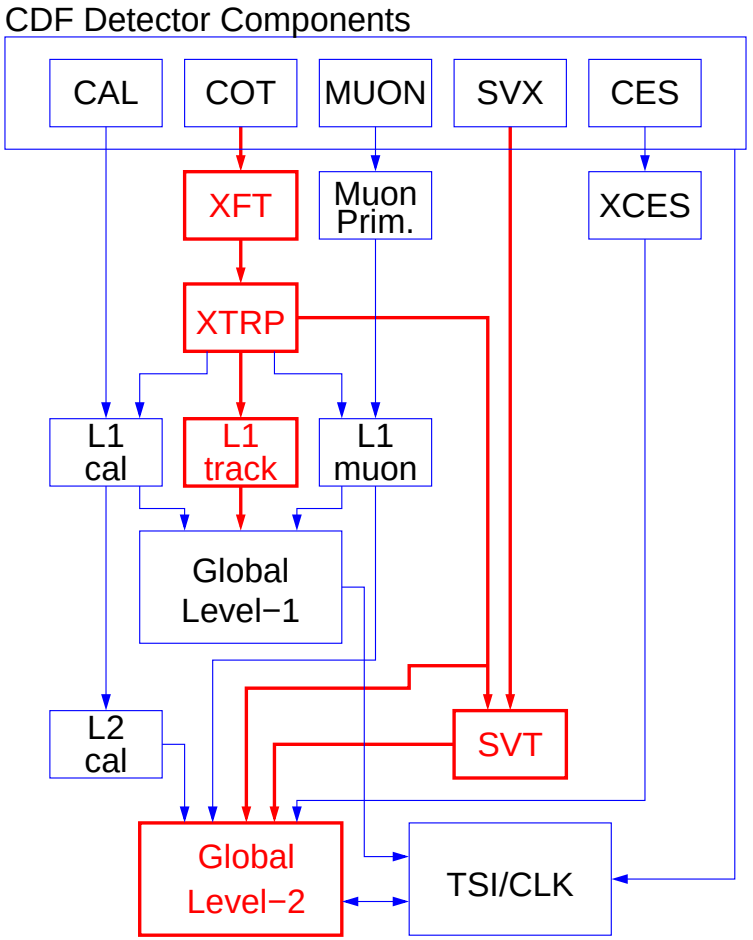


- trigger on 2 displaced tracks
  $(\mathrm{p_T} > 2\ \mathrm{GeV}/c, 120\ \mu\mathrm{m} < |d_0| < 1\ \mathrm{mm})$
- huge charm samples gathered
- with small int. luminosity, competitive charm analyses



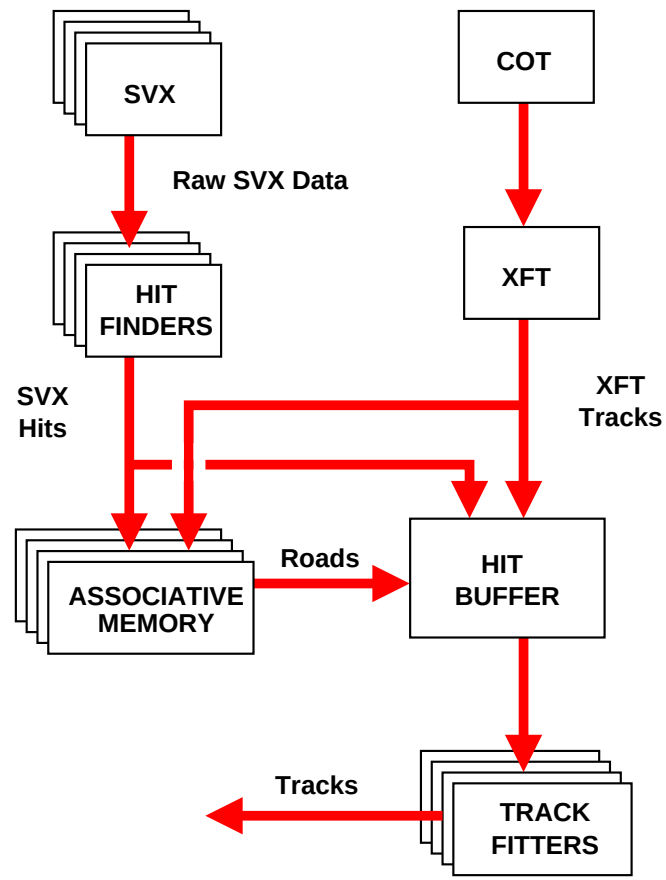
The Two Track Trigger Path

- **Level 1:**
- r-φ fast COT tracking based on preloaded patterns
- COT segmented into 15° bins
- max two tracks reported /bin
- require opposite charge, p_T, $\sum p_T$, opening angle
- **Level 2 (SVT):**
- COT-seeded SVX r-φ tracking
- confirm L1 requirements, add $|d_0|$ requirement
- **Level 3:** repeat Level 2 with better tracks (COT offline track + SVT d_0 measurement)



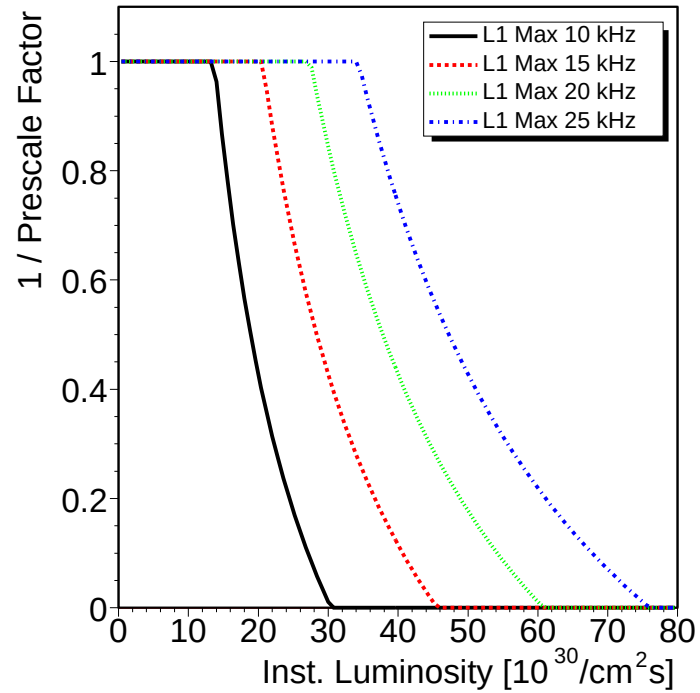
How Does the SVT Work?

- **Hit Finders** read raw SVX data
- pedestal subt, noisy strips, clustering $\rightarrow$ hit coordinates
- **Associative Memory**: coarse pattern recognition in $250\ \mu\mathrm{m}$ roads around XFT seeds
- candidate tracks, XFT tracks and SVX hits stored in **Hit Buffer**
- **Track fitters** perform linearized r-φ fit, return track parameters
- **Parallelized:** done per SVX wedge (12 wedges)



Dynamic Prescaling

- event bandwidth pre-defined at each trigger level
- trigger accept rate can exceed bandwidth
- avoid deadtime: **prescale ($\times n$)** trigger decision (accept n'th)



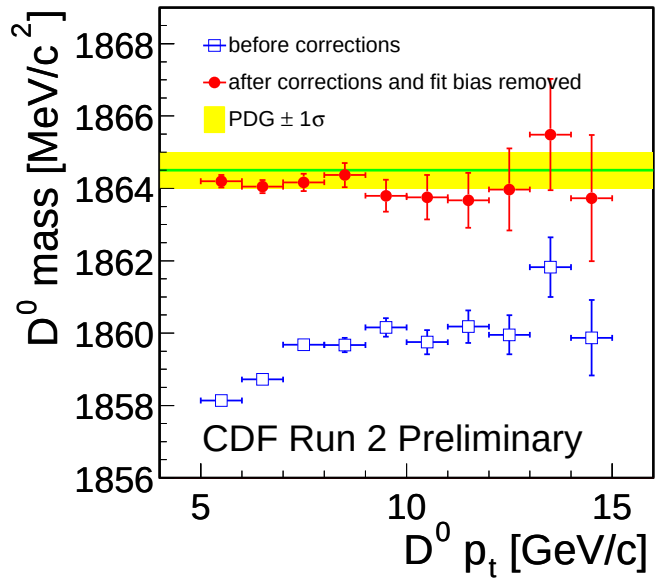
- **dynamic:** factor adjusts to populate bandwidth
- Level 1 records $N(prescale)$ and $N(unprescale)$
- luminosity is corrected for this effect
  $\rightarrow$ multiply by ratio prescale/unprescale

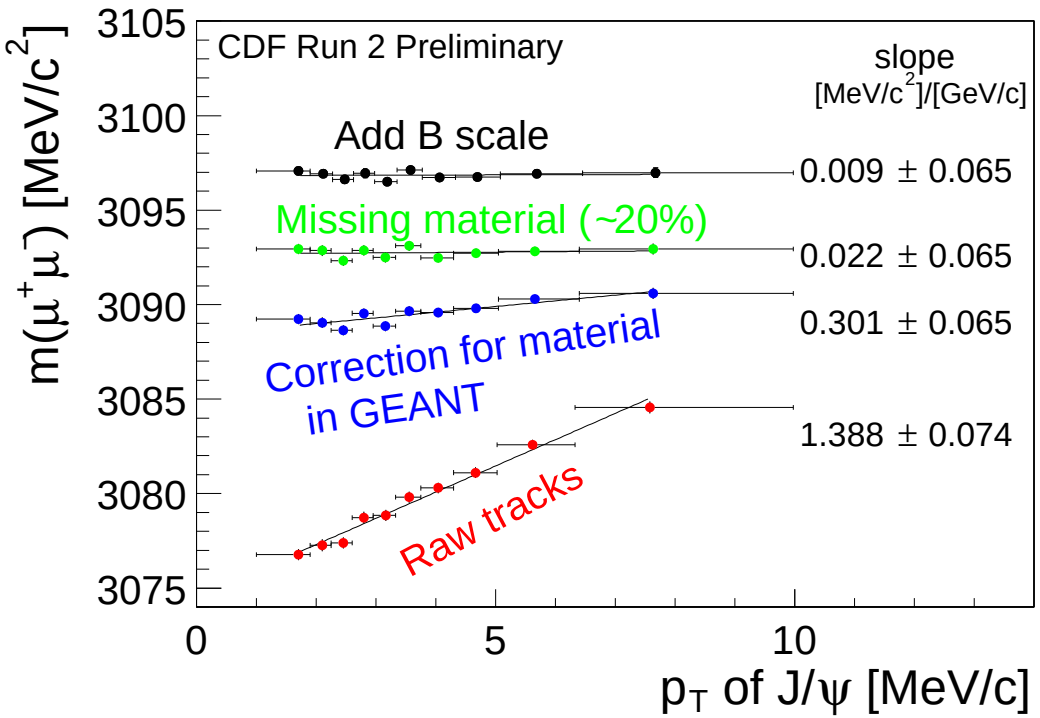
Track Preparation

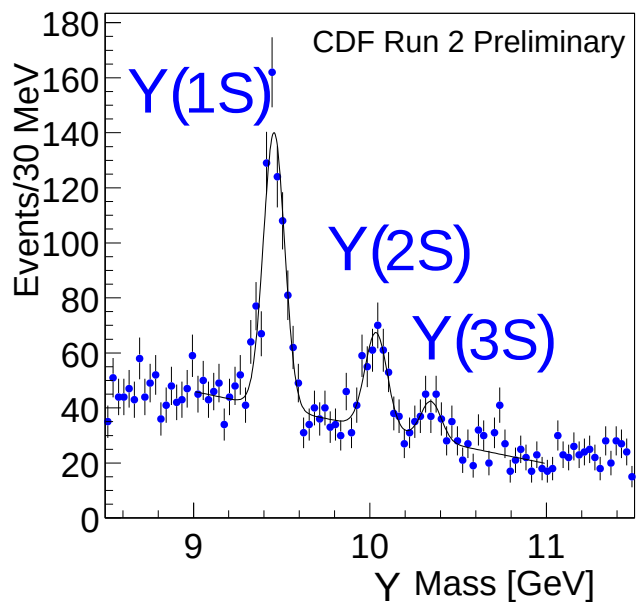
- offline tracks need to be prepared before they are used in analysis
- COT tracking does not account for multiple scattering
- scale COT error matrix to compensate
- scale factors come from Monte Carlo studies
- default Silicon tracking does not account for energy loss
- refit the COT+SVX track to account for energy loss
- rely partially on GEANT detector description for material distribution
- additional corrections from momentum scale calibration

Momentum Scale Calibration

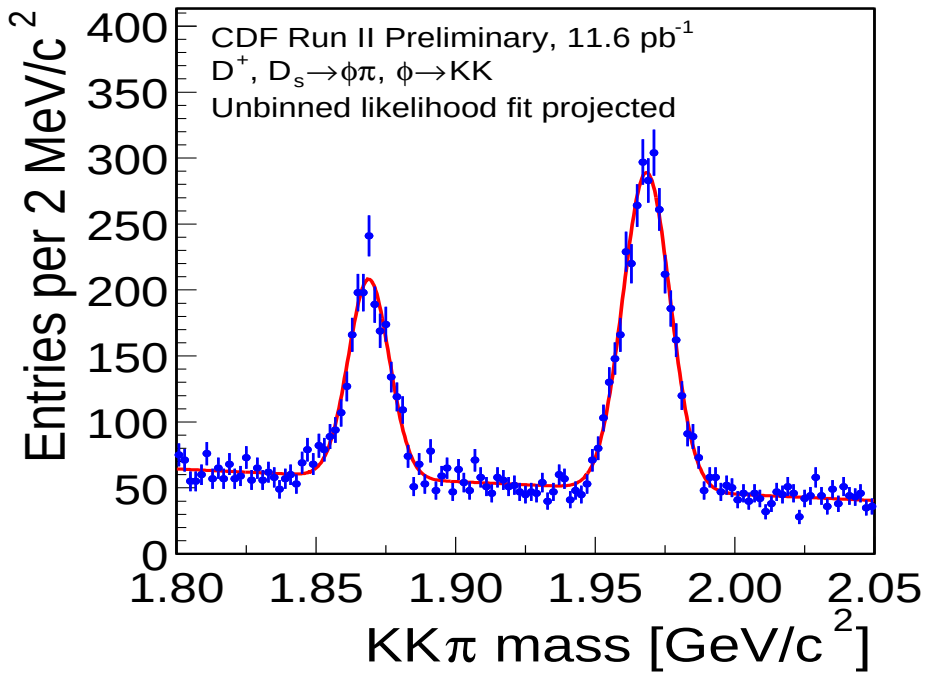
- study J/ψ's to calibrate:
  - energy loss in detector
  - magnetic field value
- crosscheck with other decays







D Meson Mass Difference



$$m(D_s^+) - m(D^+) = 99.41 \pm 0.38(stat) \pm 0.21(syst)\ \mathrm{MeV}/c^2$$

PRD 68 (2003) 072004 - First Tevatron Run II publication

- **PDG '02:** $99.2 \pm 0.5\ \mathrm{MeV}/c^2$
- **CLEO2 (1998):** $99.5 \pm 0.6 \pm 0.3\ \mathrm{MeV}/c^2$
- **BaBar (2002):** $98.4 \pm 0.1 \pm 0.3\ \mathrm{MeV}/c^2$

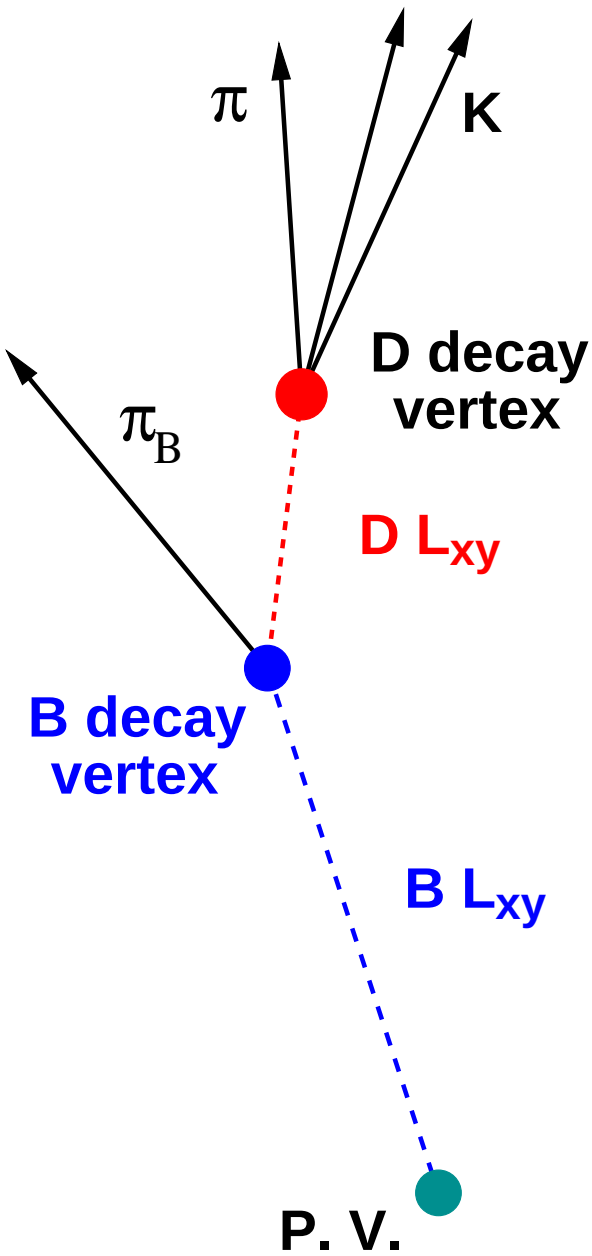
Reconstructing B Mesons

- measure the relative rate of reconstructed decays
- want to keep selection requirements similar
- want good $S/\sqrt{S+B}$
- optimize on data (background) + Monte Carlo (signal)
- exclude volunteer candidates
- confirm trigger bits for `B_CHARM` path
- trigger confirmation on candidate tracks
- eliminates volunteer events and candidates

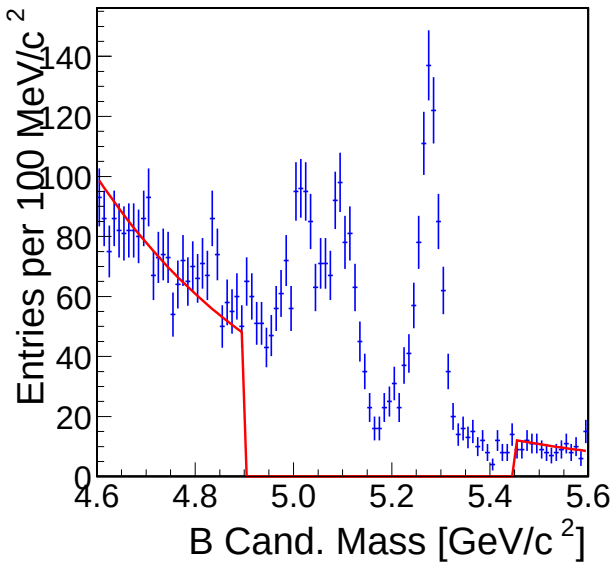
Typical B meson selection cuts:

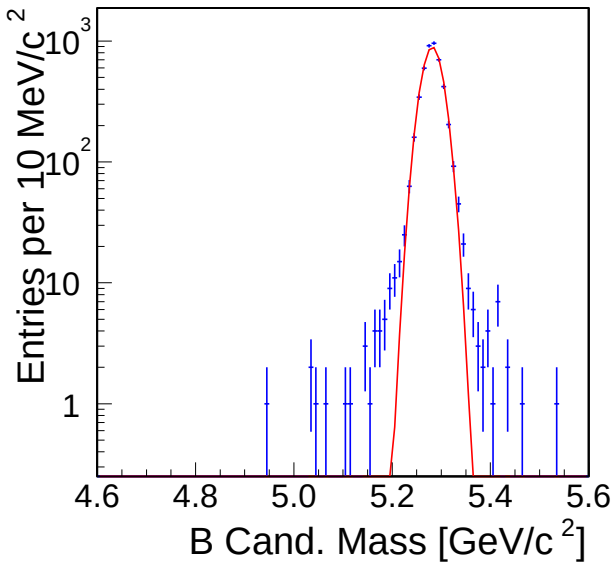
- $\chi^2_{r,\varphi}(D) < 14$
- $\chi^2_{r,\varphi}(B) < 15$
- $p_T(D) > 3.5\ \mathrm{GeV}/c$
- $p_T(B) > 5.5\ \mathrm{GeV}/c$
- $L_{xy}(B) > 400\mu\mathrm{m}$
- $L_{xy}(B \to D) > -150\mu\mathrm{m}$
- $\Delta R(D, \pi_B) < 1.5$
- $p_T(\pi_B) > 1.6\ \mathrm{GeV}/c$
- $|d_0(B)| < 80\mu\mathrm{m}$
- ϕ^0 mass cut for B^0_s

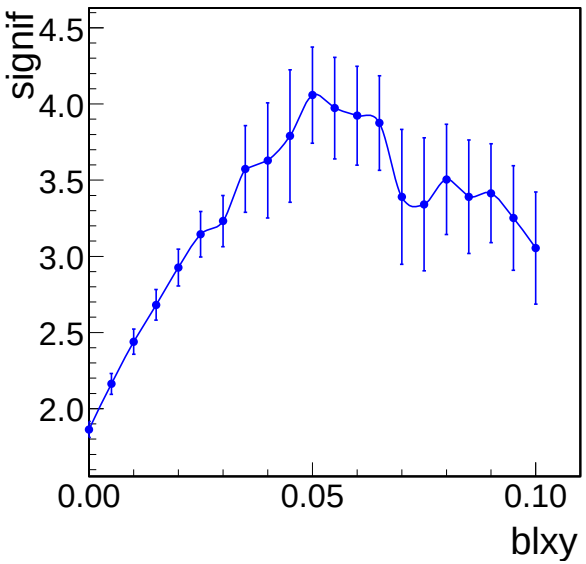
  ($1013\ \mathrm{MeV}/c^2 < m(\phi^0) < 1028\ \mathrm{MeV}/c^2$)



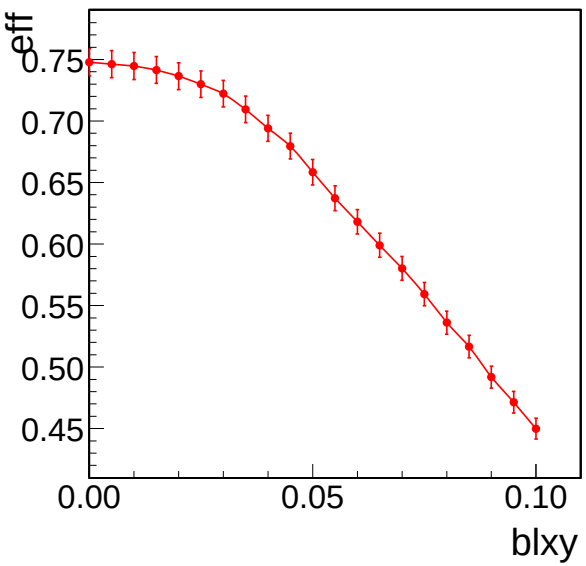
B Meson Selection Optimization





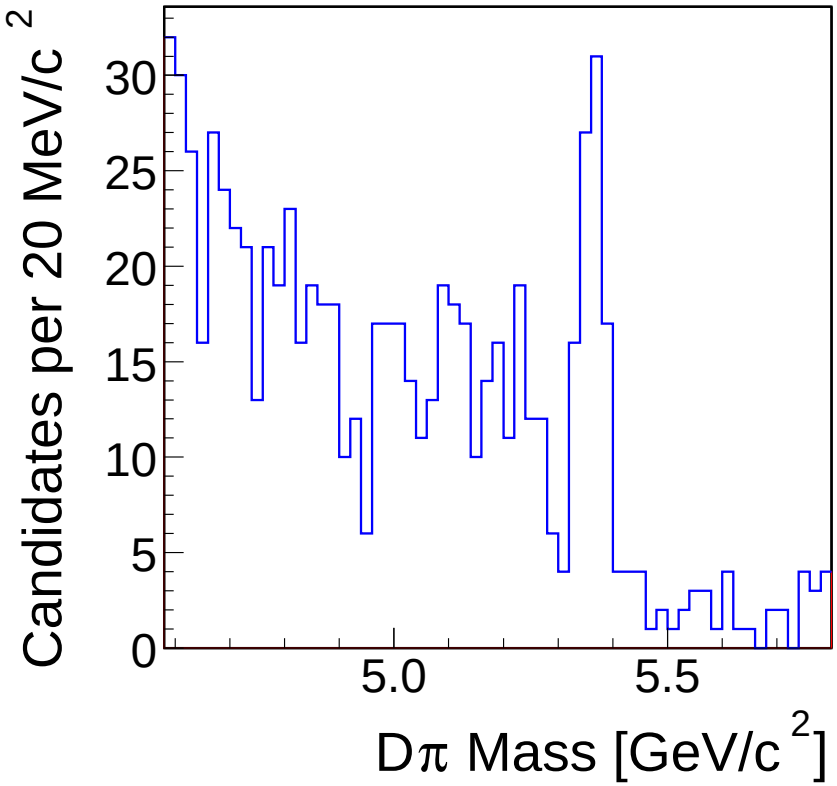


- optimize $S/\sqrt{S+B}$
- keep efficiency high
- background estimate from data
- signal estimate from scaled MC

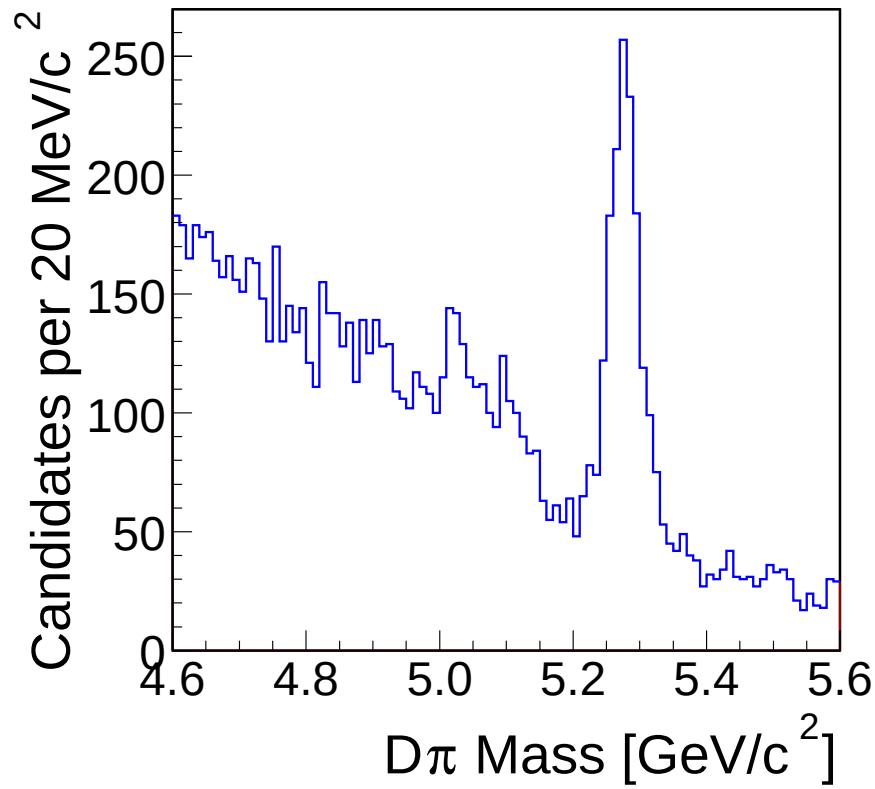


B Meson Mass Spectra

$B_s^0 \to D_s^- \pi^+$



$B^0 \to D^- \pi^+$

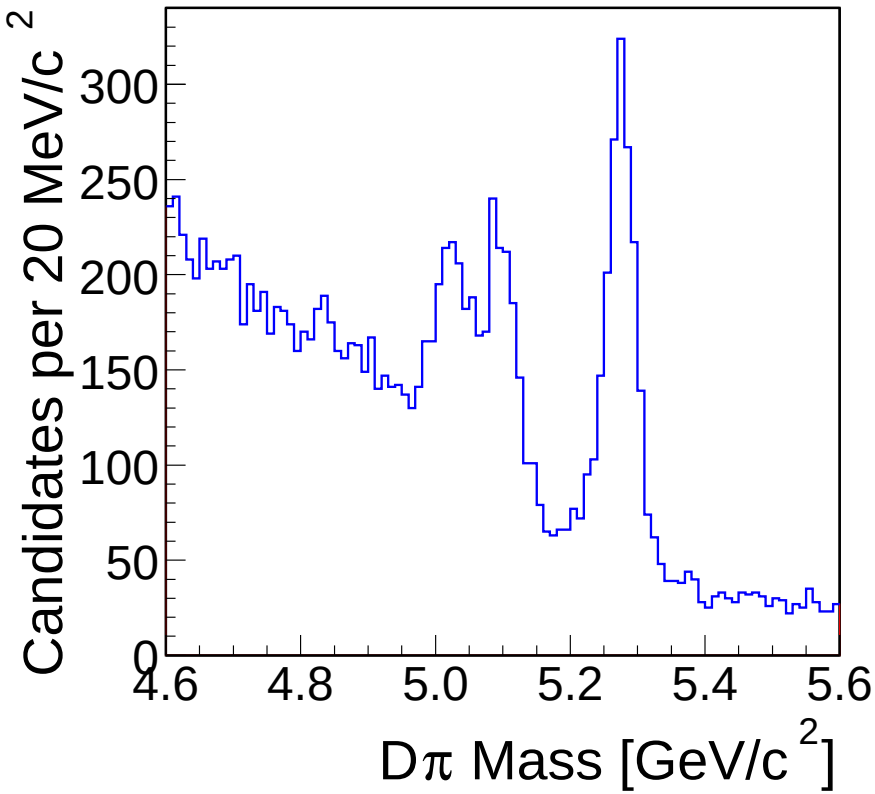


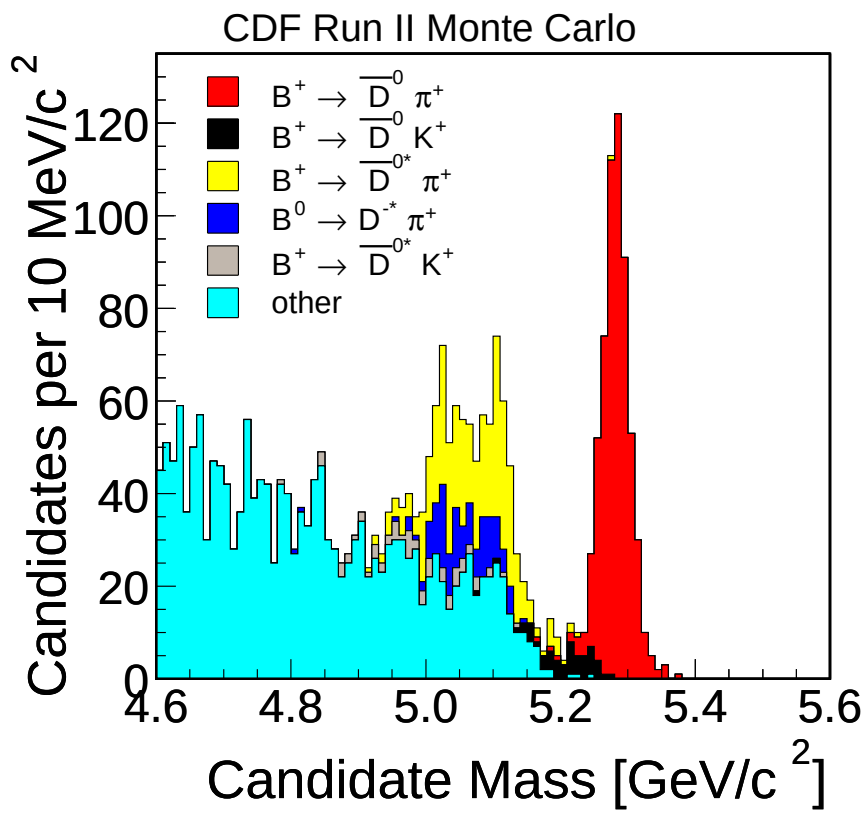
- B mass peaks are quite clean $(S/N > 2:1)$
- spectra have interesting structures
- use Monte Carlo to study background shapes

Counting $B_s^0 \to D_s^- \pi^+$ Decays

- mass spectra have interesting features
- to measure the relative rates, need $N(B)$
- need to account for:
  - combinatorial background
  - reflections of other decays under signal peak
- simulate generic B decays to study reflections
- exponential model for combinatorial background
- estimate systematic uncertainty

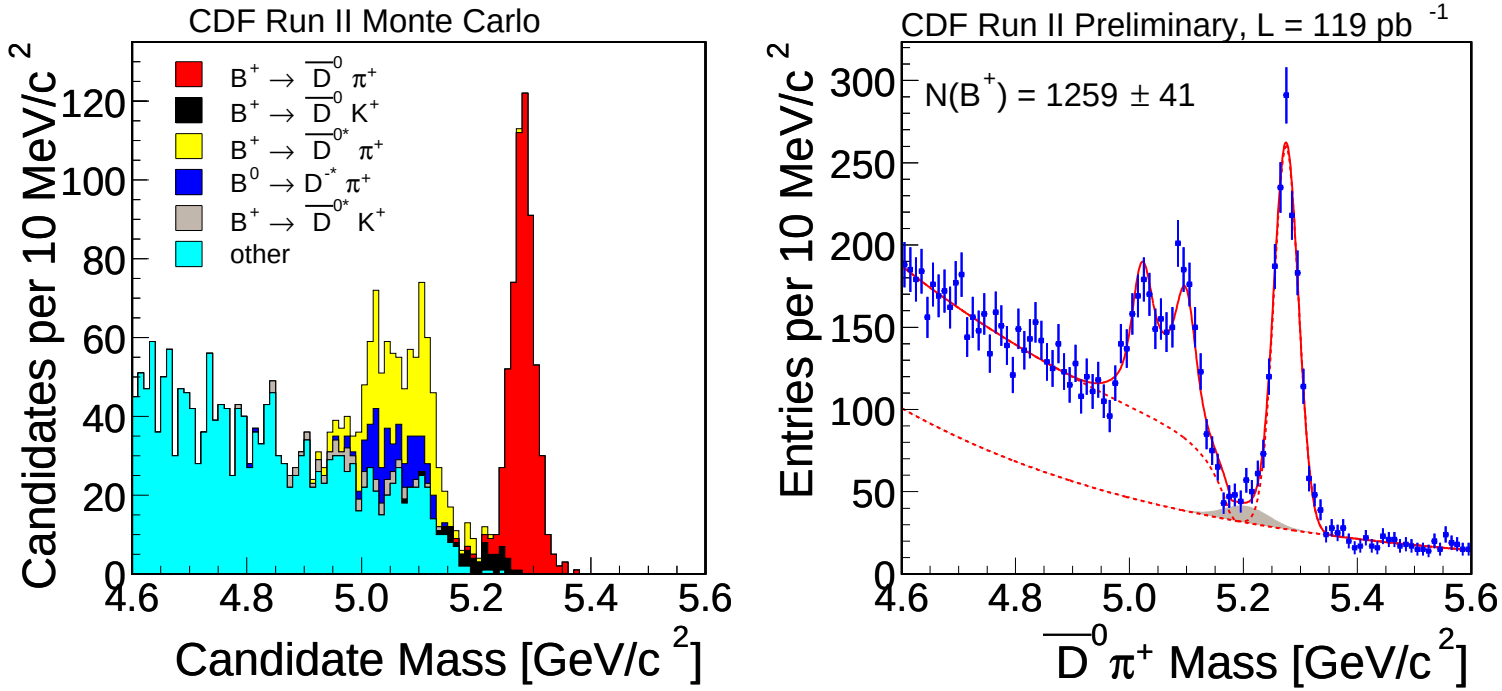
Background Shapes ($B^+ \to \overline{D^0}\pi^+$)





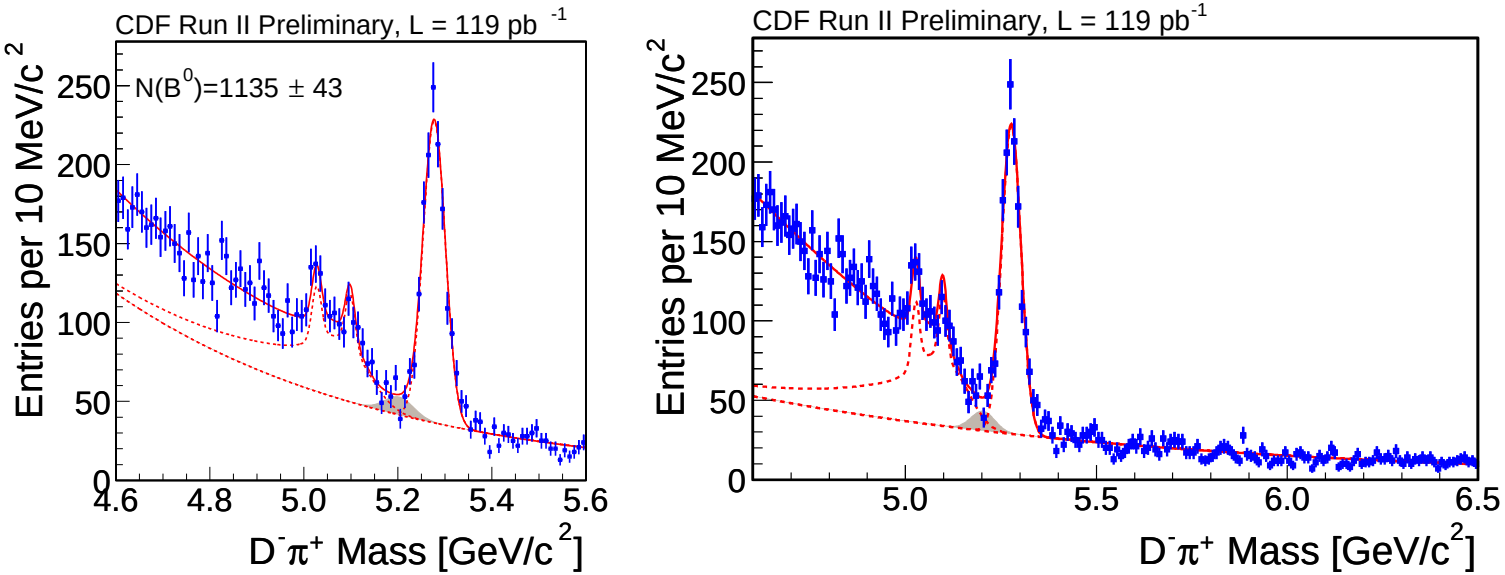
- **Monte Carlo:** $B \to \overline{D^0}X, \overline{D^0} \to K^+\pi^-$
- **GEANT simulation of detector and trigger**
- **spiky structures are signatures of D^* polarization**

Fitting With Templates



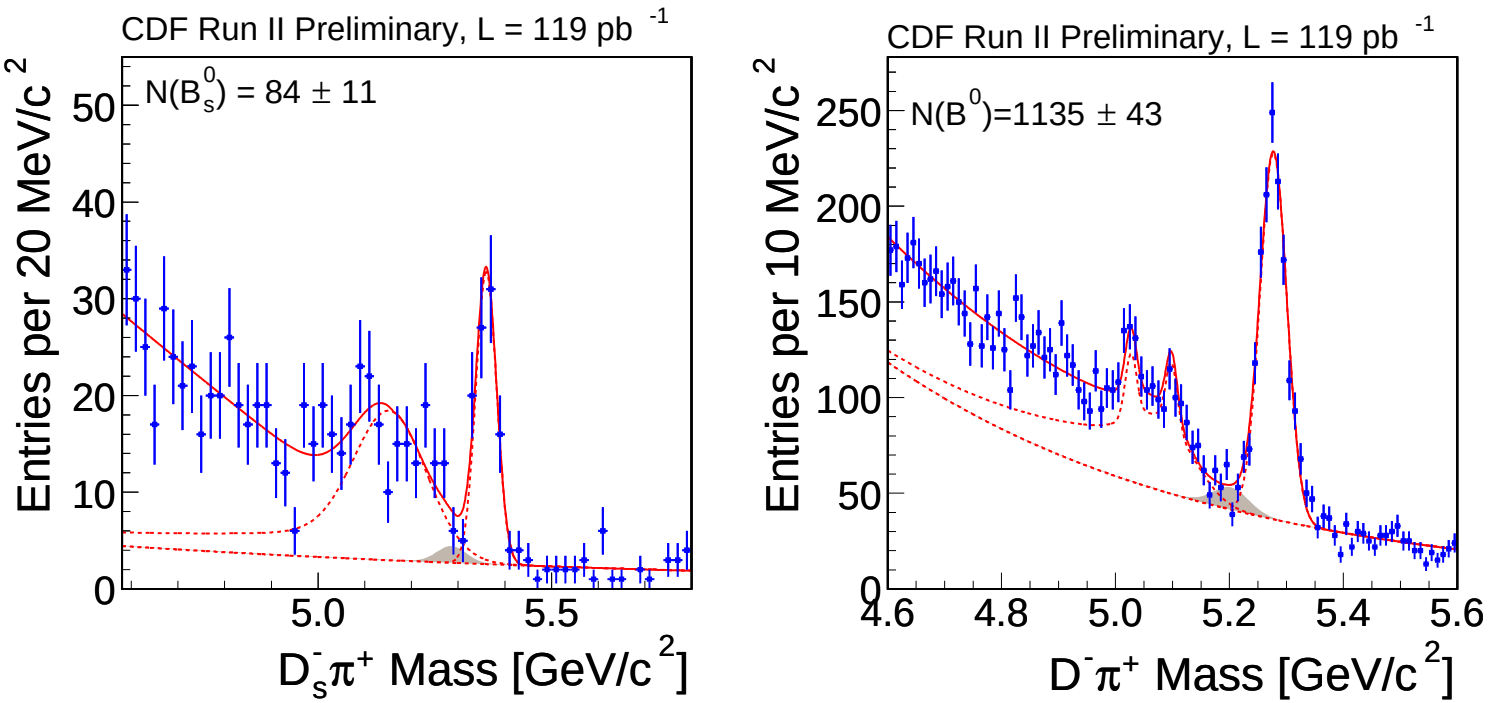
- decompose background into groups with similar features (spiky, Cabibbo suppressed, ..)
- based on Monte Carlo, create analytical templates
- extract shape parameters from MC
- keep shape parameters fixed in fit to data
- combinatorial background $\to$ single exponential

Fit Result N(B) Stability



- how reliable is our counting method? (assign counting systematic error)
- vary shape parameters for templated background
- extend fit range, fix continuum parametrization
- fits result change up to $\sim 7\%$
- can improve background parametrization

Fit Results for B_s^0 and B^0

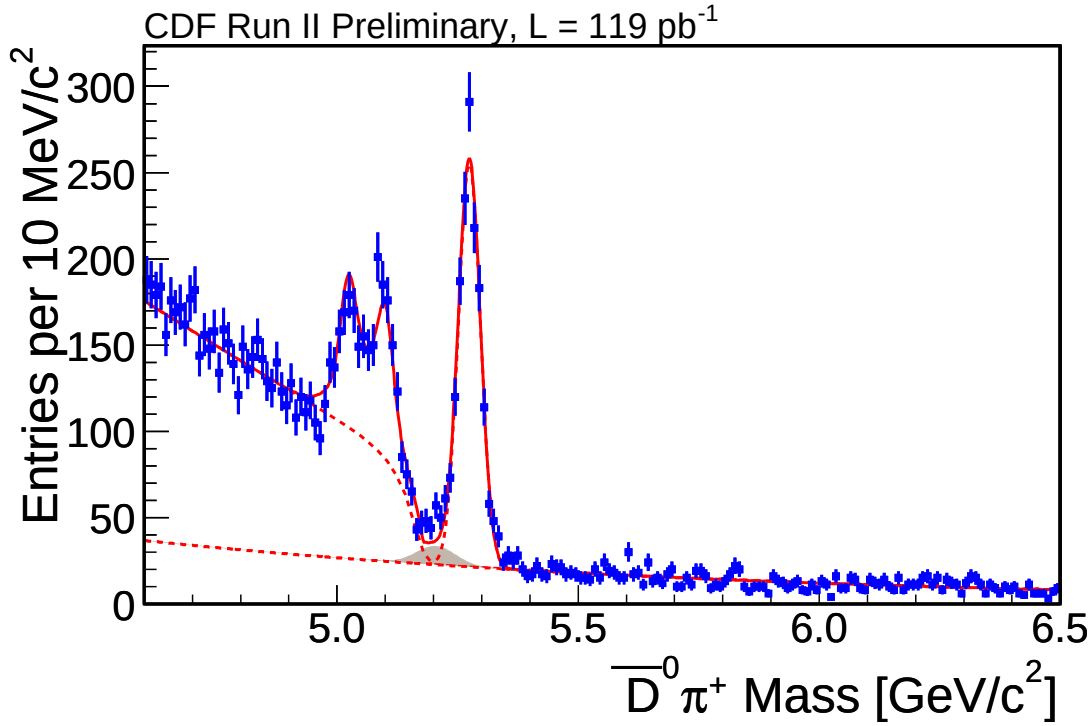


- counting systematic error $\sim 7\%$
- $84 \pm 11(stat) \pm 4(syst)$ B_s candidates
- $1135 \pm 43(stat) \pm 80(syst)$ B^0 candidates
- this determines the ratio $N(B_s)/N(B_d)$
- remaining work: correct for detector effects (different efficiencies for B_s, B^0) $\Rightarrow$ from MC

Corrections from Monte Carlo

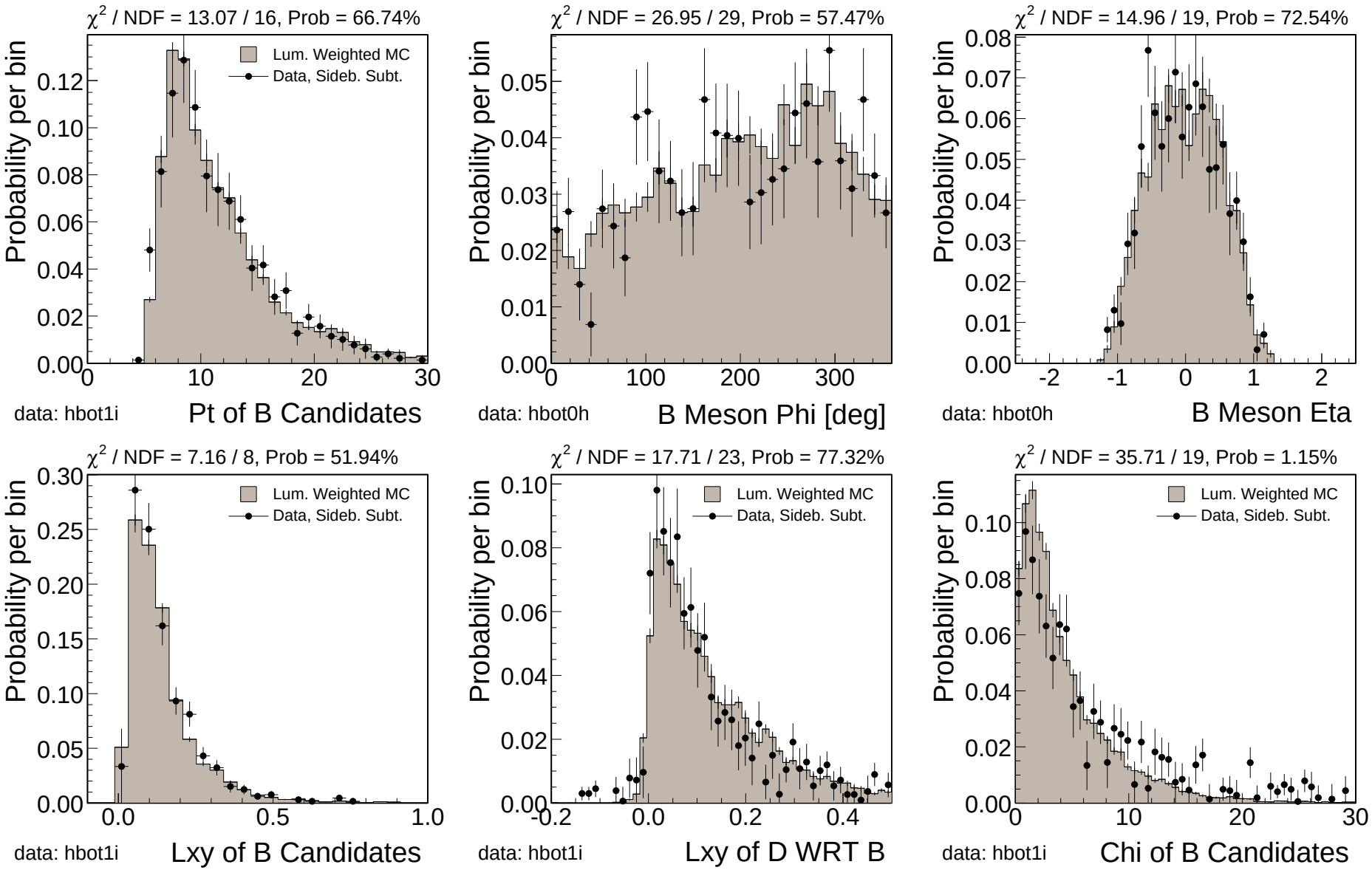
- $N(B_s^0), N(B^0)$ extracted from data
- need to correct for different detector, trigger, reconstruction efficiencies
- differences caused by slightly different kinematics
- utilize realistic detector simulation
- folds in SVX dead regions, SVT pattern recognition
- need relative corrections, not absolute efficiencies
- need to check that MC reproduces data
- use sideband subtraction (tricky)

Monte Carlo Validation Method



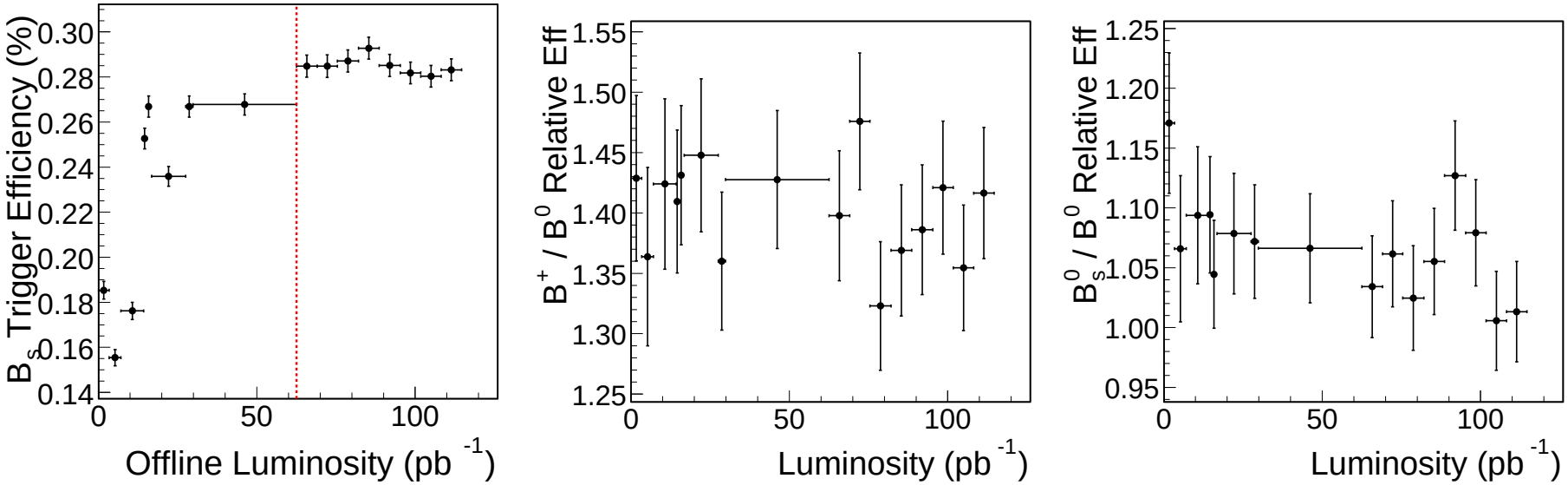
- high and low-mass sideband: different composition
- subtract only high-mass sideband
- but scale up number of events
  (using the exponential fit for the comb. background)
- check relevant distributions for both B^0 and B^+
- in addition, check N-1 cut efficiencies

Monte Carlo Validation



- **check many variables, good agreement for most**

Stability of Efficiency Ratios:



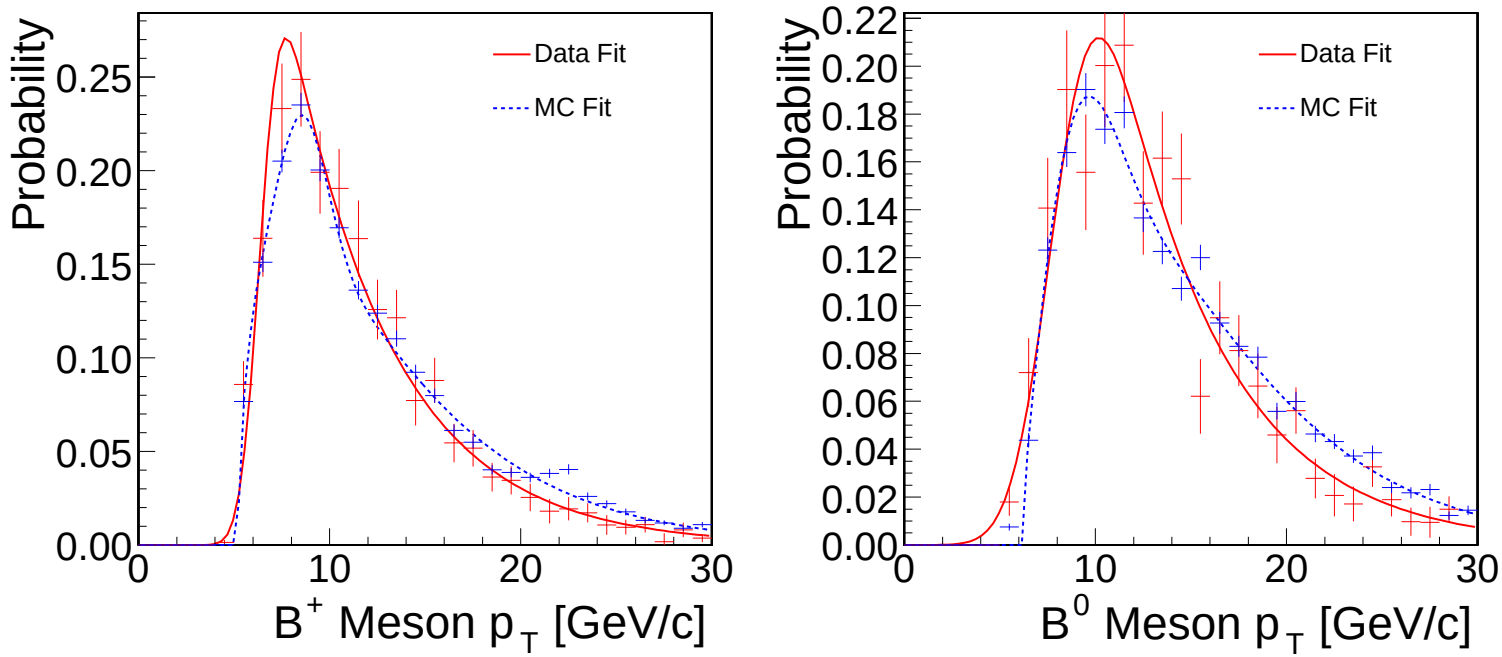
- trigger was constantly being upgraded
- concern: may affect the efficiencies
- the ratio of total efficiencies is stable regardless of trigger efficiency change
- measurement robust to trigger conditions
- expect small systematic uncertainties

Systematic Uncertainties

- already estimated $N(B)$ systematic uncertainty

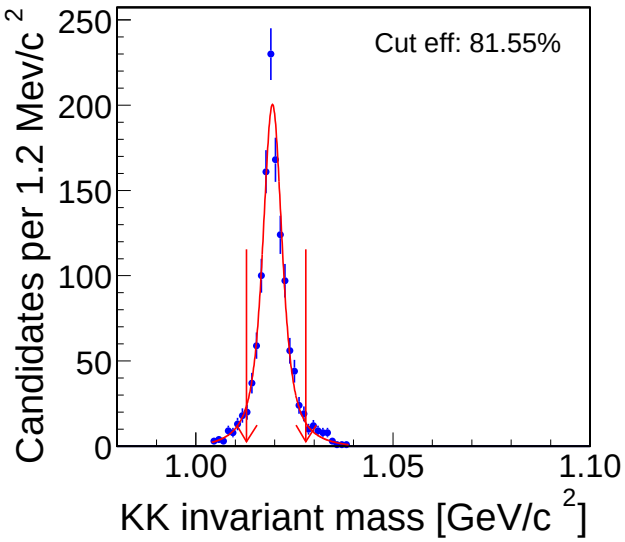
- MC B meson input p_T spectra
- details of XFT simulation:
  XFT efficiencies for K and π tracks are slightly different (6% per track difference)
- selection requirement efficiencies
- B and D meson lifetimes

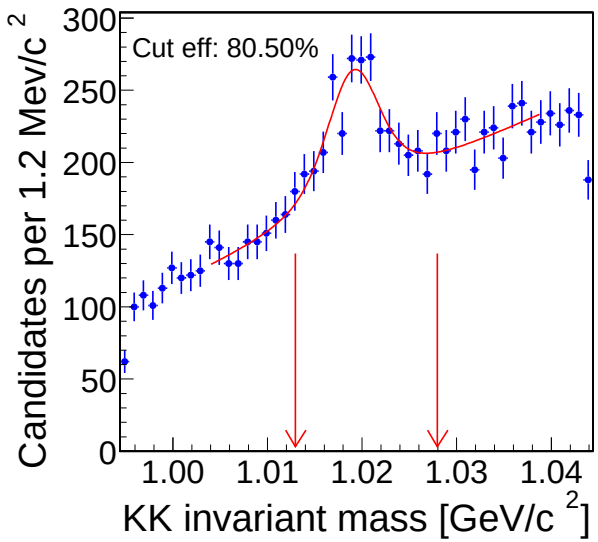
p_T Spectrum Systematic

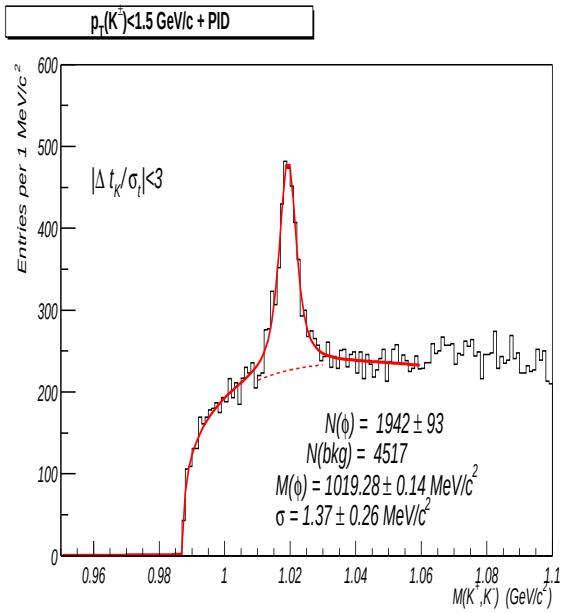


- p_T spectra disagree slightly between data and MC
- affects kinematics and acceptance
- reweight Monte Carlo to match data
- compare efficiencies before and after reweighting
- assign $\pm 1.5\%$ systematic uncertainty

ϕ Mass Cut Systematic







- concern: ϕ mass cut only applied to B_s^0 decays
- fit mass with Gaus $\otimes$ Breit-Wigner + background
- extract cut efficiency from fit integral
- compare MC to J/ψ and ToF data
- assign $\pm 1.0\%$ syst. uncertainty

Summary of Systematic Uncertainties:

Effect	Syst. Unc.
B p_T spectrum	± 1.5 %
XFT simulation	± 1.0 %
ϕ^0 mass cut	± 1.0 %
cut efficiencies	± 5.0 %
B_s^0 lifetime	± 1.4 %
D_s^+ lifetime	± 0.3 %
B^0 lifetime	± 0.4 %
D^+ lifetime	± 0.04%
B_s^0 fitting	± 5.0 %
B^0 fitting	± 7.0 %
Total	± 10.4 %

Measurement Results

$$\frac{f_s}{f_d} \cdot \frac{Br(B_s^0 \to D_s^- \pi^+)}{Br(B^0 \to D^- \pi^+)} = 0.35 \pm 0.05(stat) \pm 0.04(syst) \pm 0.09(BR)$$

Using world average for $\frac{f_s}{f_d}$ $\left(\frac{f_s}{f_d} = 0.26 \pm 0.03\right)$

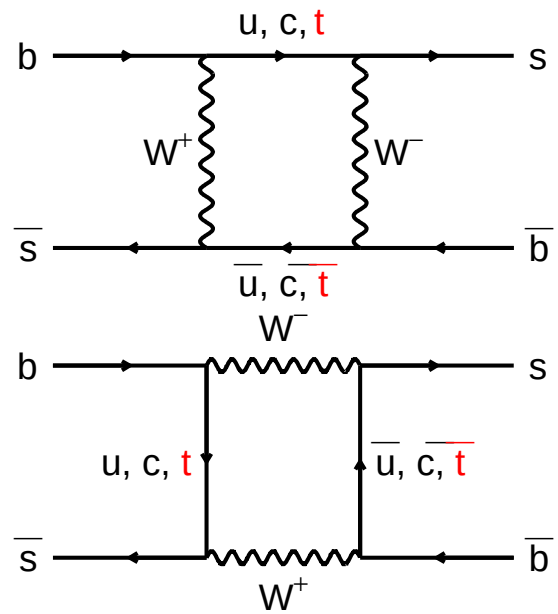
$$\frac{Br(B_s^0 \to D_s^- \pi^+)}{Br(B^0 \to D^- \pi^+)} = 1.4 \pm 0.2(stat) \pm 0.2(syst) \pm 0.4(BR) \pm 0.2(PR)$$

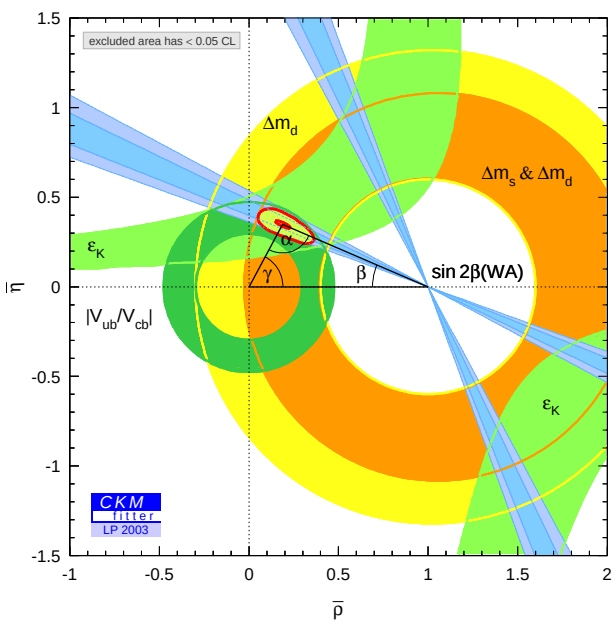
Measurement assumes same fragmentation model for B_s^0 and B^0.

... now we can estimate our B_s mixing reach

B Mixing and the Unitarity Triangle

- both B_d and B_s mesons mix
- ratio of mixing frequencies: **measures one side of the unitarity triangle ($|V_{td}/V_{ts}|$)**
- indir. meas: $\Delta m_s \leq 24\ \mathrm{ps}^{-1}$
- overconstrain $\rightarrow$ **test SM**





Input for unitarity triangle fits:

- CP violation in K, B system
- $B \rightarrow \pi l \nu X$ vs $B \rightarrow D l \nu X$
- B_d, B_s meson mixing
- direct measurements of α, γ

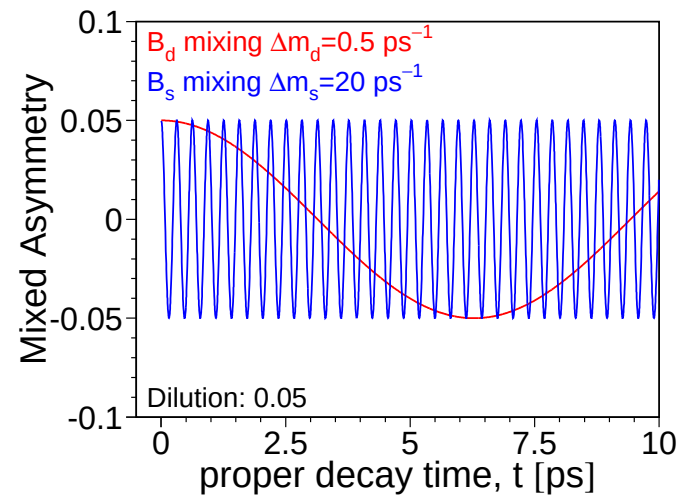
$B_{(s)}$ Mixing Measurement Ingredients

Per B meson decay,

- **determine decay flavor [use flavor specific states]**
- **identify B meson production flavor [flavor tagging]**
- **measure B proper decay time [ct resolution]**

Time-dependant asymmetry:

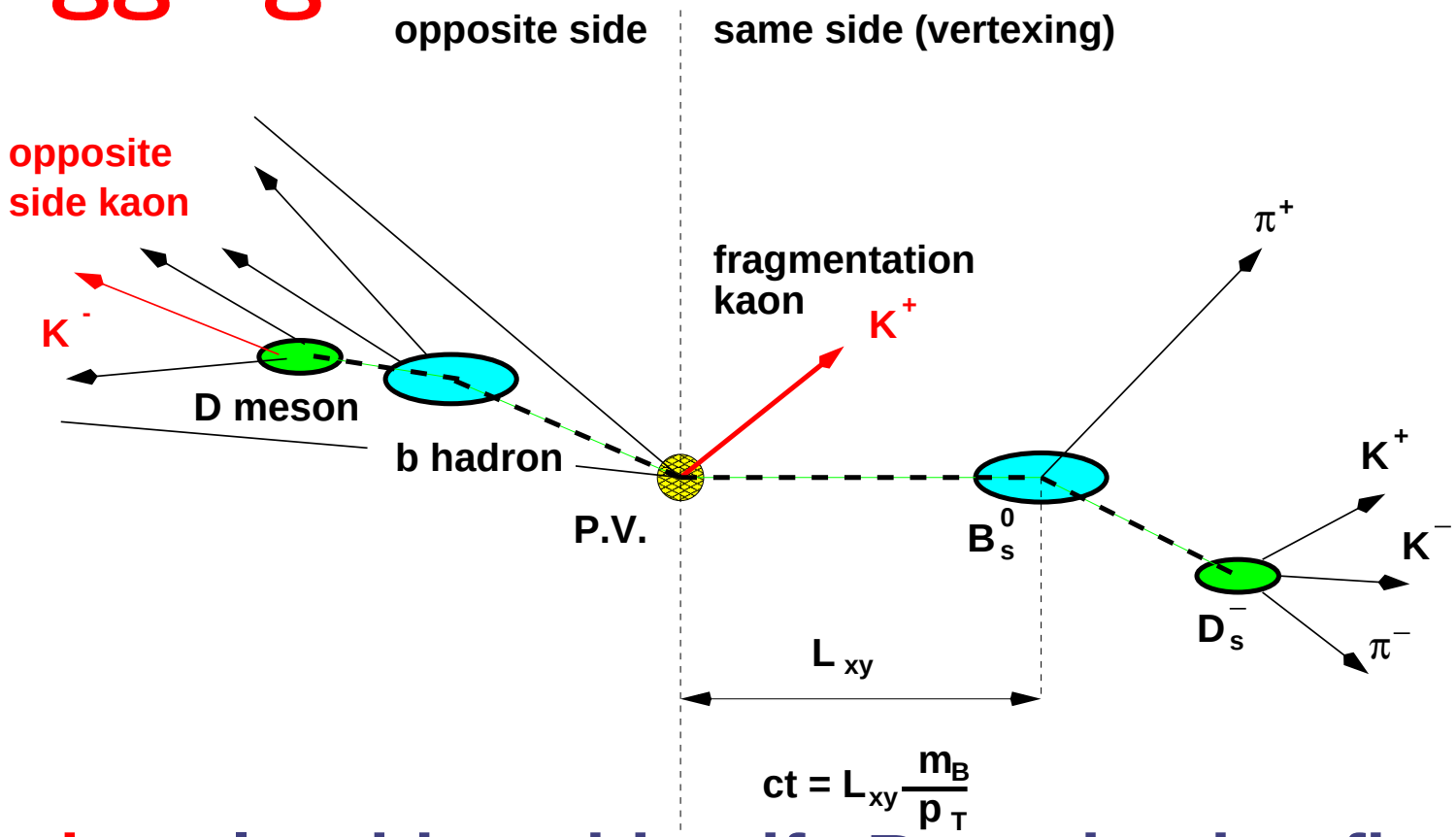
$$A_{mix}(t) = \frac{N^{obs}_{unmix}(t) - N^{obs}_{mix}(t)}{N^{obs}_{unmix}(t) + N^{obs}_{mix}(t)} = (2p-1)\cdot\cos(\Delta m \cdot t)$$



Oscillation amplitude: $2p - 1 = D$ [dilution]

$$\text{Significance} = \sqrt{\frac{S\epsilon D^2}{2}} e^{\frac{-(\Delta m)\sigma(c\tau)}{2}} \sqrt{\frac{S}{S+B}}$$

Tagging The Production Flavor



- **Tagging** algorithms identify B production flavor
- **Opposite Side Tagging**: B's produced in pairs, identify flavor of opposite B meson
- **Same Side Tagging**: hadronization π/K charge is correlated to B_d/B_s production flavor

B_s^0 Mixing Reach Estimates

- **Current performance:**
- $S = 1600/\mathrm{fb}^{-1}$, $\mathrm{S/B} = 2:1$
- $\epsilon D^2 = 4\%$, $\sigma(ct) = 67$ fs

2σ sensitivity
$\Delta m_s = 15\ \mathrm{ps}^{-1}$
with 500 pb^{-1}

- **With "modest" improvements:**
- $S = 2000/\mathrm{fb}^{-1}$, $\mathrm{S/B} = 2:1$
  (improve trigger, more modes)
- $\epsilon D^2 = 4\%$, $\sigma(ct) = 50$ fs
  (event by event prim vertex, Si on beampipe)
- **3σ for $\Delta m_s = 18\ \mathrm{ps}^{-1}$ with 1.3 fb^{-1}**
- **5σ for $\Delta m_s = 18\ \mathrm{ps}^{-1}$ with 1.7 fb^{-1}**
- **5σ for $\Delta m_s = 24\ \mathrm{ps}^{-1}$ with 3.2 fb^{-1}**
- **this is a difficult measurement**

Conclusions

- collected world's largest sample of $B_s^0 \to D_s^- \pi$
- first measurement of the branching fraction

$$\frac{Br(B_s^0 \to D_s^- \pi^+)}{Br(B^0 \to D^- \pi^+)} = 1.4 \pm 0.2(stat) \pm 0.2(syst) \pm 0.4(BR) \pm 0.2(PR)$$

- within errors, in agreement with theory expectation
- measurement is limited by (in descending order):
  - $D_s^- \to \phi\pi$ branching fraction uncertainty
  - f_s/f_d uncertainty
  - statistics
  - signal and background modeling

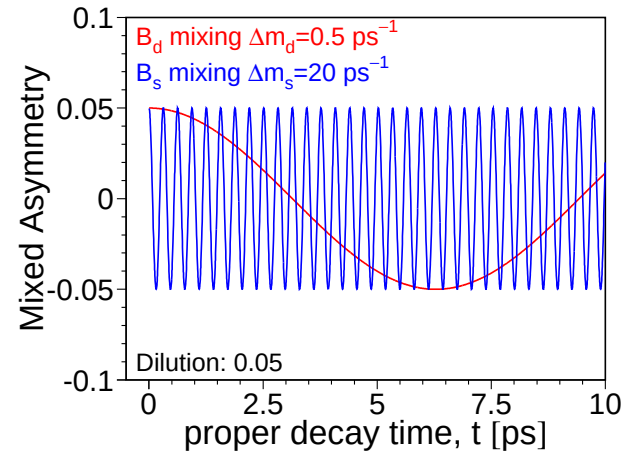
Implications for B_s^0 Mixing

- established reconstruction of B_s^0 decays with good S/B
- established B_s^0 counting method
- B_s^0 rate estimate for mixing sensitivity
- assuming $\epsilon D^2 = 5\%$ and the ct resolution is correctly predicted by Monte Carlo studies,
  - surpass world best limit with 500 pb^{-1}
  - cover SM predicted range with 3.2 fb^{-1}

Backup Slides

Precise ct Measurements

- rapid oscillations:
  $\Delta m_s \geq 13.1\ \mathrm{ps}^{-1}$ (90%CL, PDG)
  (indir. meas: $\leq 24\ \mathrm{ps}^{-1}$)
- very good ct resolution needed:

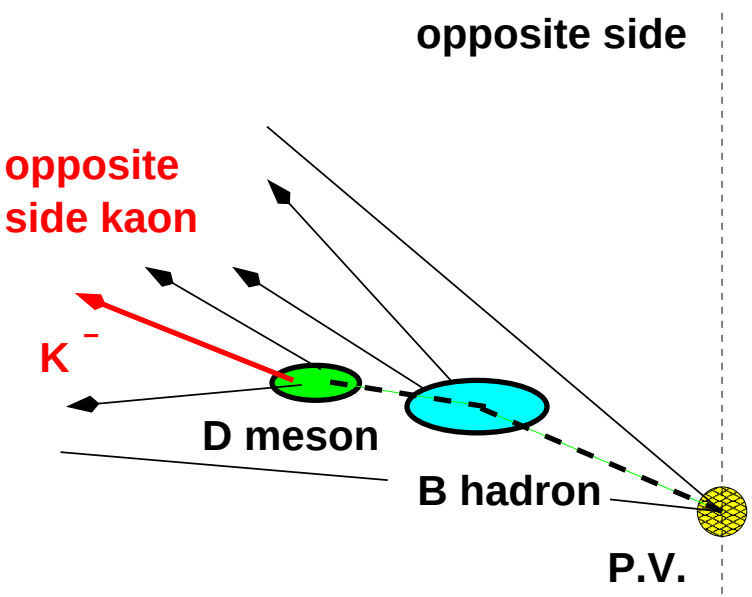


$$\sigma_{ct} = \left(\frac{\sigma_L}{\gamma\beta}\right) \oplus \left(\frac{\sigma_{\gamma\beta}}{\gamma\beta}\right) \cdot ct$$

- semileptonic decays: B momentum error $\sim 15\%$
- hadronic decay ($B_s \to D_s\pi$) negligible ($\sim 0.1\%$)
- using base RunII silicon : 60 fs $\Delta m_s \sim 17\ \mathrm{ps}^{-1}$
- layer of Si on beampipe: 45 fs $\Delta m_s \sim\ 22\ \mathrm{ps}^{-1}$
- Problem: how do we trigger on these decays?

Tagging: Opposite Side Tagging

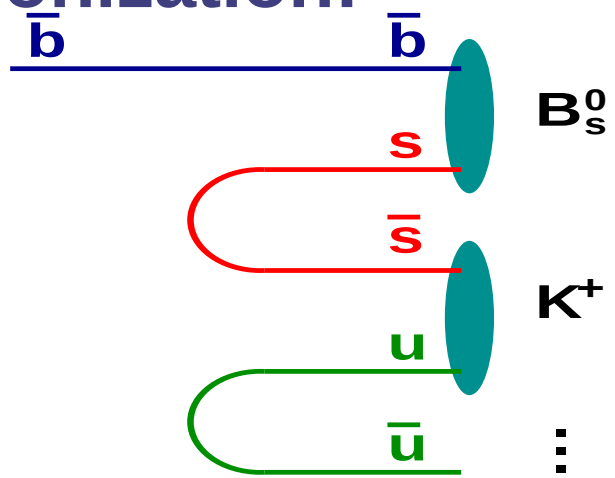
- **Lepton Tagging**: find lepton from $B \to Dl\nu X$
- **Jet Charge Tagging**: momentum-weighted sum of track charge in B jet (+ displacement)
- **Kaon Tagging**: assume $b \to c \to s$ decay, find kaon in B jet

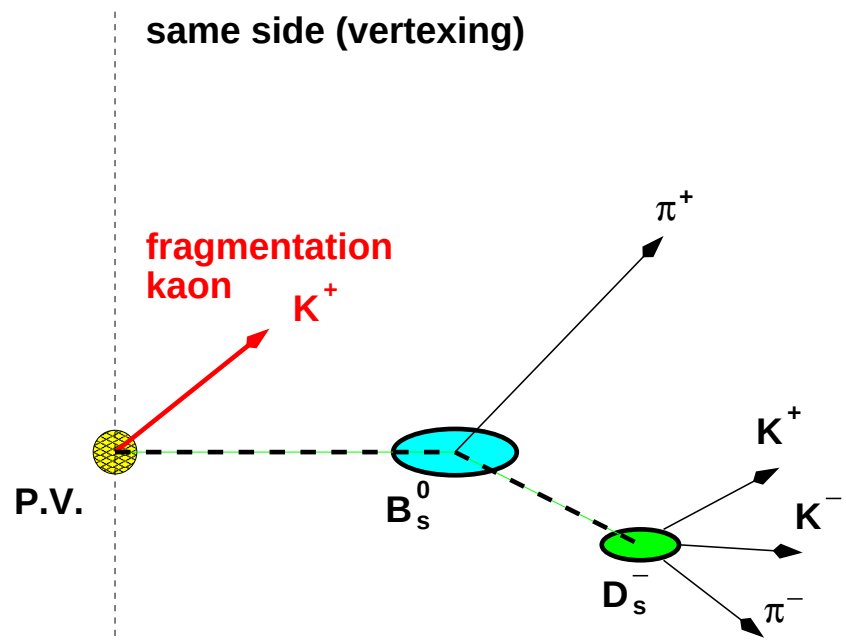


- Difficulties with OST:
- 20-40% opposite side B's inside detector acceptance
- B^0, B_s^0 mix $\to$ production flavor information lost

Tagging: Same Side Tagging

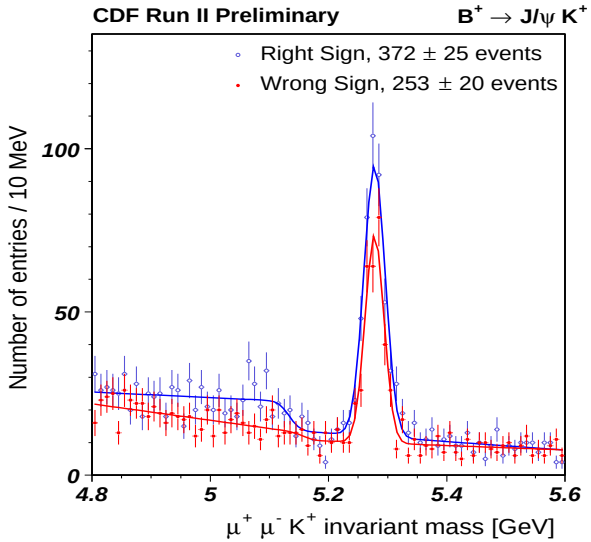
Exploit signature of B_s hadronization:

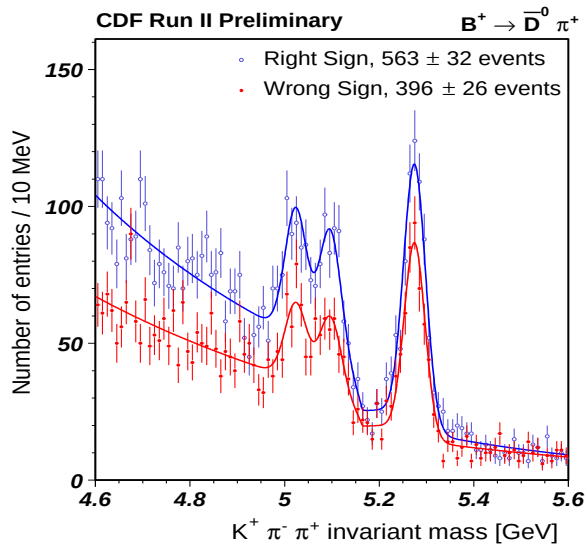


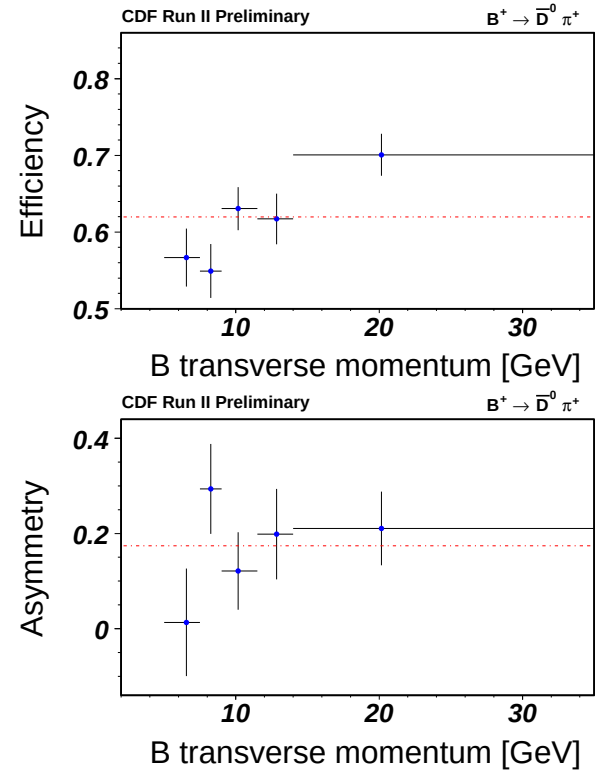


- 80% of tracks in event are pions [kaons $\sim 10\%$]
- fragmentation tracks are soft $\rightarrow$ TOF particle ID
- Run I B^0 mixing using track SST
- expect improvement using TOF particle ID
- combined (OST + SST) tagging power: $\epsilon D^2 \sim 5\%$

Tagging Efforts in Run II

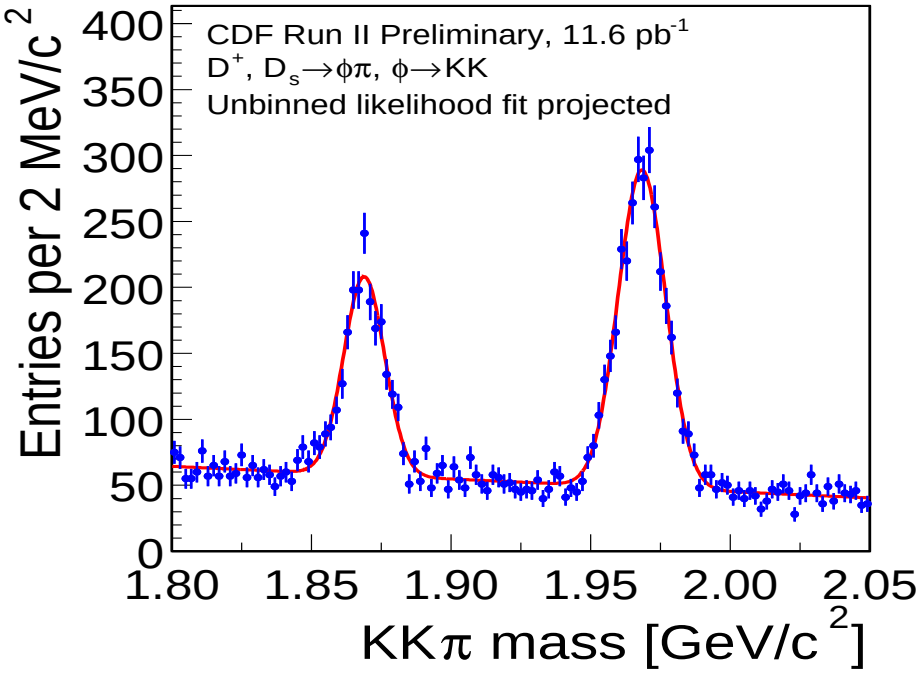


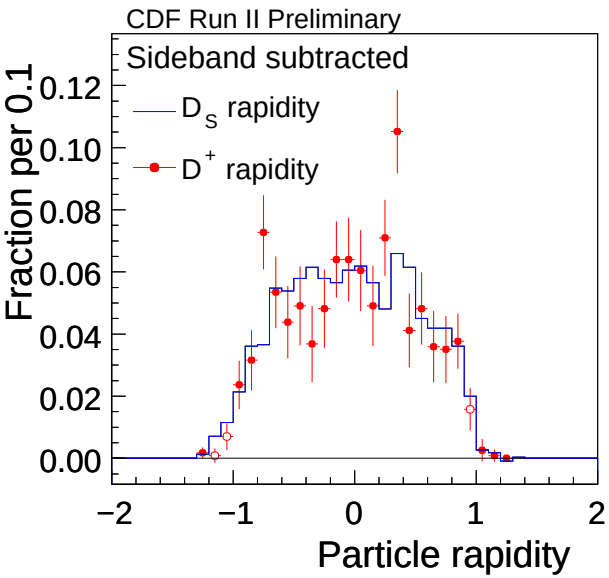




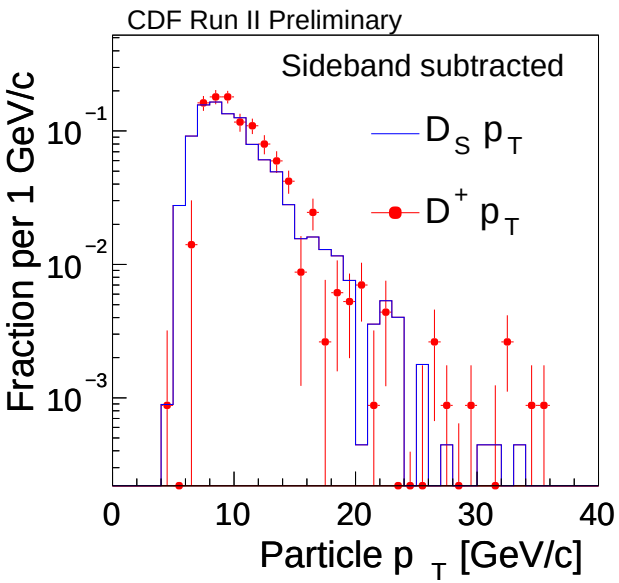
- fully reconstructed B^+ decays
- measure efficiency and dilution
- example: same side pion tag
- $B^+ \to J/\psi K^+$: $\epsilon D^2 = 2.4 \pm 1.2(stat)\%$
- $B^+ \to \overline{D^0}\pi$: $\epsilon D^2 = 1.9 \pm 0.9(stat)\%$
- Run I $J/\psi K^*$: $\epsilon D^2 = 1.8 \pm 0.4(stat)\%$

D Meson Mass Difference





- $1.4\text{k } D^+, 2.4\text{k } D_S^+ \to \phi\pi^+$
- mass resolution $\sim 8\,\mathrm{MeV}/c^2$
- similar kinematics
- expect small syst. errors



Mass Difference Result

$$m(D_s^+) - m(D^+) = 99.41 \pm 0.38(stat) \pm 0.21(syst)\ \mathrm{MeV}/c^2$$

PRD 68 (2003) 072004 - First Tevatron Run II publication

systematics small, dominated by bkg model:

Effect	Syst.$[\mathrm{MeV}/c^2]$
fitting	0.14
event selection	0.11
momentum scale	0.10
tracker effects	0.06
calibration procedure	0.03
Total	0.21

- **PDG '02:** $99.2 \pm 0.5\ \mathrm{MeV}/c^2$
- **CLEO2 (1998):** $99.5 \pm 0.6 \pm 0.3\ \mathrm{MeV}/c^2$
- **BaBar (2002):** $98.4 \pm 0.1 \pm 0.3\ \mathrm{MeV}/c^2$