Results on CP Violation from CDF

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HEP2003-EPS, Aachen Jul 17-23, 2003

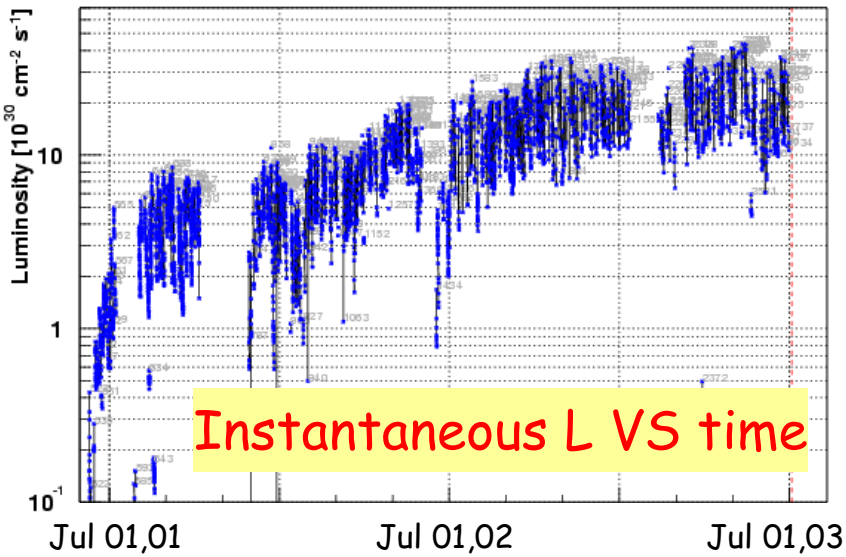
Outline

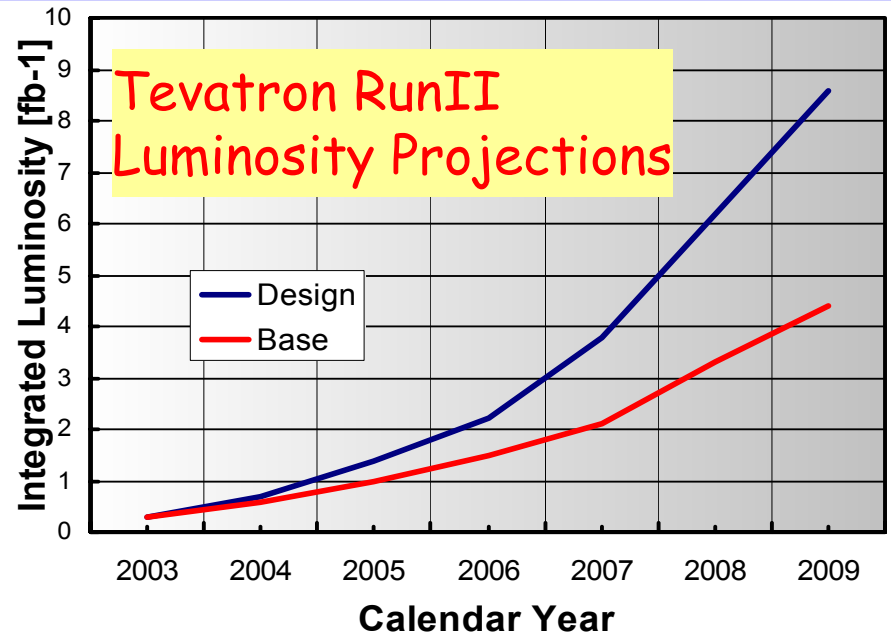
- Introduction
  - Tevatron operations and luminosity projections
  - Status of the CDF-II detector
- CP violation in CDF: First Results and Perspectives
  - Introduction
  - Two-body Charmless B decays
  - CP-violating decay rate asymmetries in D^0 decays
- Conclusion

Related Presentations at EPS2003

- S.D'Auria: *B Hadron Masses and Branching Ratios at CDF (PS #10)*
- S.Farrington: *J/psi, B Lifetime and flavor tagging at CDF (PS #10)*
- J.Thom: *Rare Charm Decays from CDF (PS #3)*
- T.Shears: *Bottom and Charm Quark Production in CDF (PS #4)*

Tevatron Performances and Luminosity Projections





- L(max): ~4.6x10^{31} cm^{-2}sec^{-1}
- Int. L/week (max): 9 pb^{-1}/week
- Written to tape by CDF: ~200 pb^{-1}
- ~160 pb^{-1} with all systems on

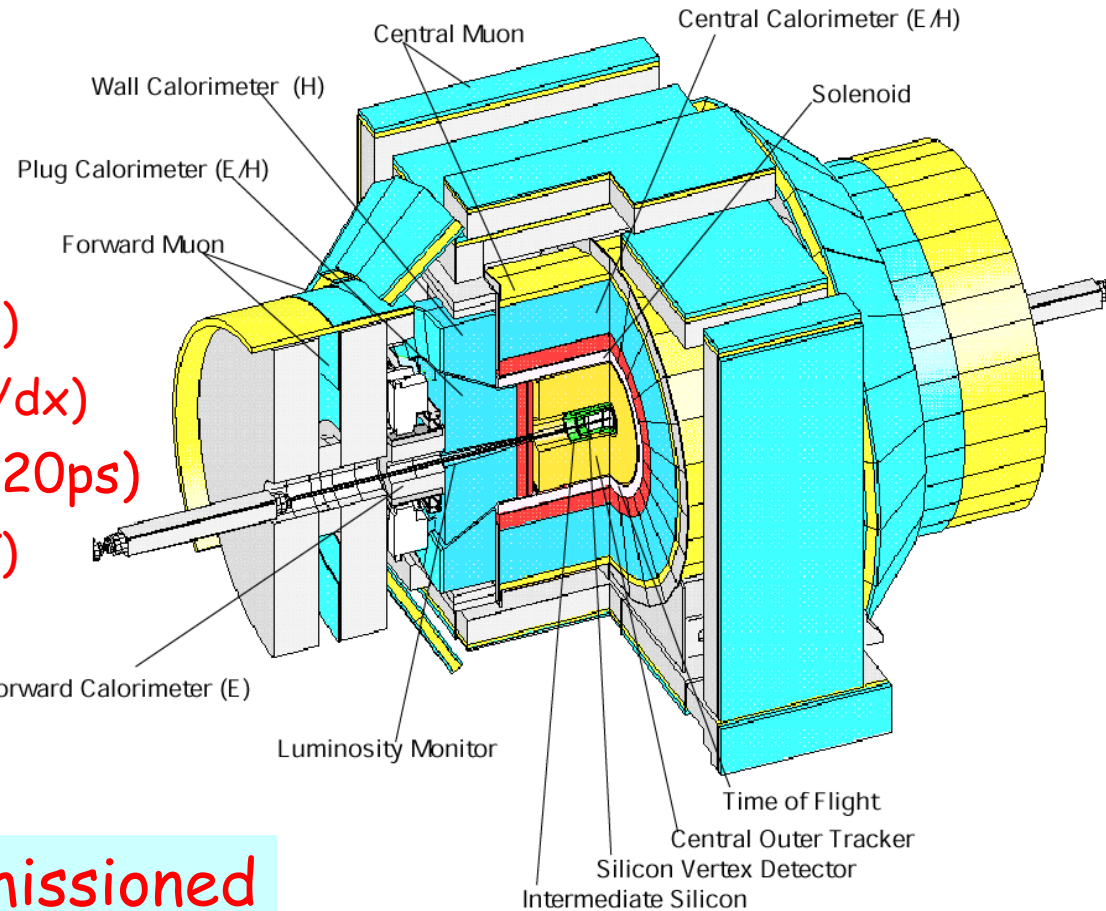
- Report presented June 15 DOE
- "Design": require electron cooling
- "Base": conservative assumptions
- 4-5 fb-1 before LHC turn on …

First CPV analysis results based on the first 65 pb^{-1} …

CDF Detector

New

- Front-End electronic
- DAQ system
- 3D Silicon Tracker (up to $|\eta|$~2)
- Central drift chamber (also dE/dx)
- Time-of-Flight detector (σ_t =120ps)
- Hadronic B Triggers (XFT/SVT)



Detector fully commissioned and working well!

HF Physics Trigger Evolution in CDF: From RunI to RunII

RunI: HF triggers based on leptons only:

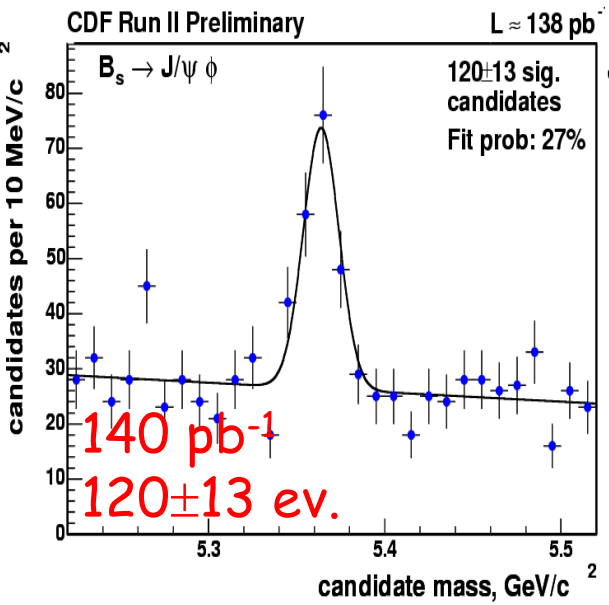
J/ψ: $\mu\mu$ in the final state

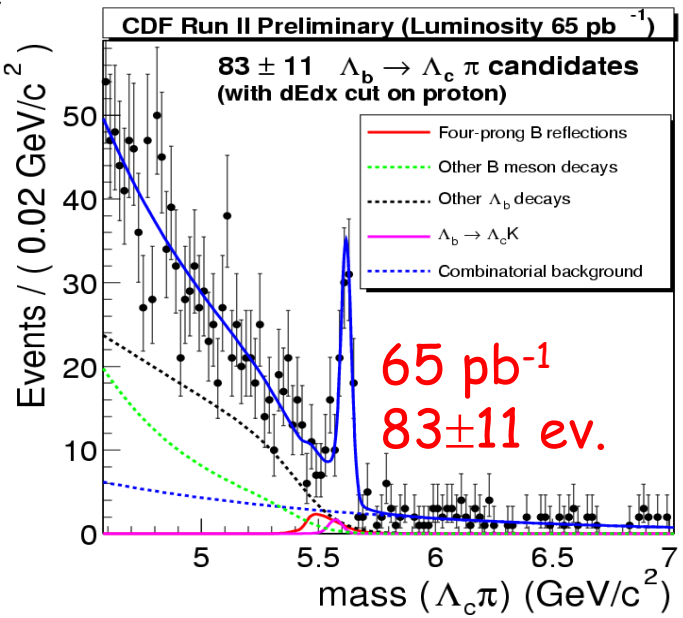
Semi-leptonic decays: high Pt(lept) threshold

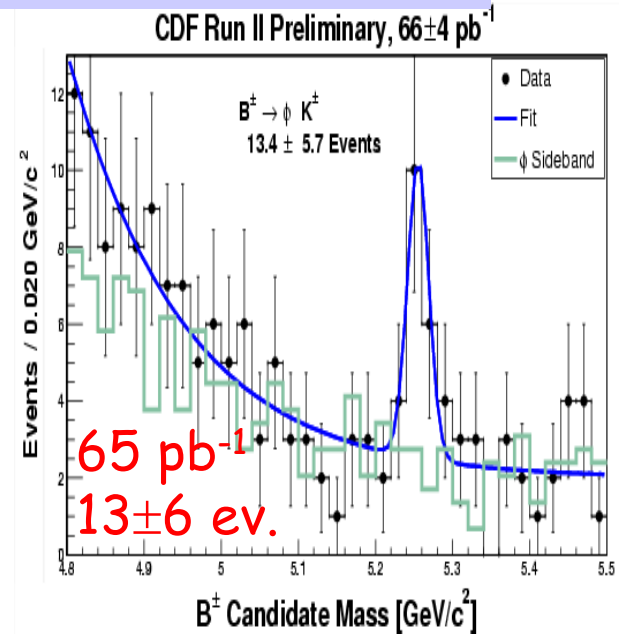
RunII: a new era for B-physics@colliders:

- XFT: charged tracks trigger available @Level1 Trigger
- SVT: displaced tracks trigger available @Level2 Trigger
- Access to high statistic sample of fully reconstructable hadronic decays
- Lepton + track with high impact parameter (displaced):
  - Semi-leptonic B-decays with lower momentum and better S/B

Event Yields …







$B_s \to J/\psi\phi$ $\Lambda_b \to \Lambda_c\pi$ $B^\pm \to \phi K^\pm$

- ✓ Bs→J/ψφ: already ×2 RunI sample
- ✓ Clean Fully Hadronic B/Bs/Λ_b signals:
  - ✓ Yields ×2 respect one year ago
  - ✓ S/B > 1
- ✓ Semileptonic B sample: ×5 RunI (see S.Farrington talk)
- ✓ High statistic charm sample: ~2M $D^0 \to K\pi$ decays

CDF Plans for $\not{C}\not{P}$ in RunII

B_s and Λ_b Physics:

- Unique to Tevatron until LHC turn-on
- Ultimate Goal: Precision CKM measurements and search for non SM sources of CPV

Bs mixing: $|V_{td}/V_{ts}| = f(x_s/x_d)$

CKM angle γ: B→hh (also: Bs→DsK and B/Bs→VV)

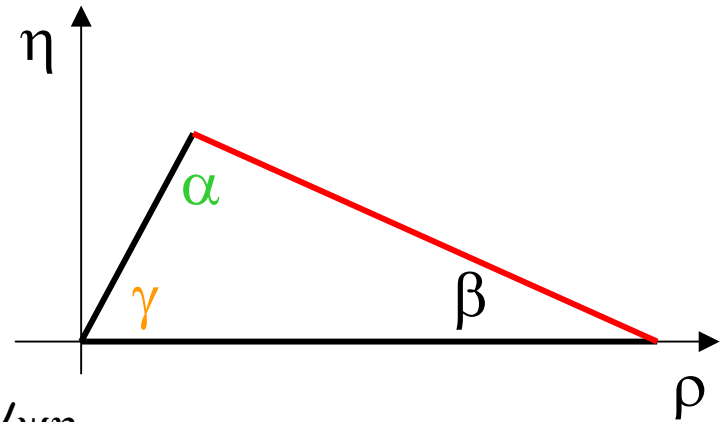
CKM angle α: B/Bs→VV

Direct CPV searches

CPV in Baryion decays: $\Lambda_b \to pK, p\pi$

Test new CP violating physics: βs from Bs→J/$\psi\phi$, J/$\psi\eta$

Measure $\Delta\Gamma s$: Bs→νlDsX, Dsπ, J/$\psi\phi$, Ds^+Ds^- and B→hh



The world's largest B_s/Λ_b sample…

CDF Plans for $\not{C}\not{P}$ in RunII (2)

$B_{u,d}$ Physics:

- Comparable sensitivity to B-factories for self-tagging modes or direct CP measurements
- Indipendent sin(2β) measurement (σ(sin(2β)) ~ 0.06 with 2 fb^{-1})

CPV in the Charm sector:

- Expect $O(10^7)$ $D^0 \rightarrow K\pi$ decays reconstructed in RunIIa (2fb^{-1})
- CDF can address DCPV, D Mixing and rare decay before CLEO-c

Mode	CDF Yield (*)	B-factory Yield	CDF/B-fact
$B^0 \rightarrow K\pi$	2.3 ev./pb^{-1}	7.7 ev./fb^{-1} (Belle03)	1.2
$D^* \rightarrow D^0\pi$, $D^0 \rightarrow K\pi$	3K ev./pb^{-1}	3K ev./fb^{-1} (BaBar03)	2

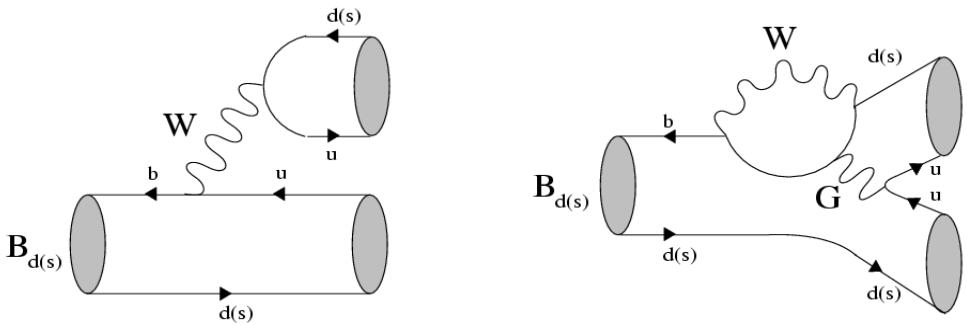
Assume:
300 pb^{-1}/Year CDF
150 fb^{-1}/Year B-factory

(*) CDF yields today

Current goals: Observation of decay modes, improve trigger strategy, first measurements on high statistic channels …

$\not{C}\not{P}$ in Charmless 2-body B Decays

- B→hh' observed in CDF:
  - ~400 candidates in 65 pb^{-1}
  - Mix of: $B^0, Bs \rightarrow \pi\pi, K\pi, KK$



- Only at Tevatron:
  - Bs channels: alternative ways to extract physical parameters
  - γ from time dependent asymmetries in $B^0 \rightarrow \pi^+\pi^-/B_s \rightarrow K^+K^-$ (R.Fleischer PLB 459 (1999) 306):
    - $B^0 \rightarrow \pi^+\pi^-$ measure $\sin 2(\beta+\gamma)$ up to ~30% penguins pollution
    - Measure of the P/T ratio by simultaneous fit to the time depending asymmetries on $B_s \rightarrow K^+K^-$

- Experimental challenges:
  - Signal extraction (trigger)
  - Disentangling of the different contributions

Today

...Future

$$A_{CP}(K\pi) = A_{CP}(dir) = (N_+ - N_-) / (N_+ + N_-)$$

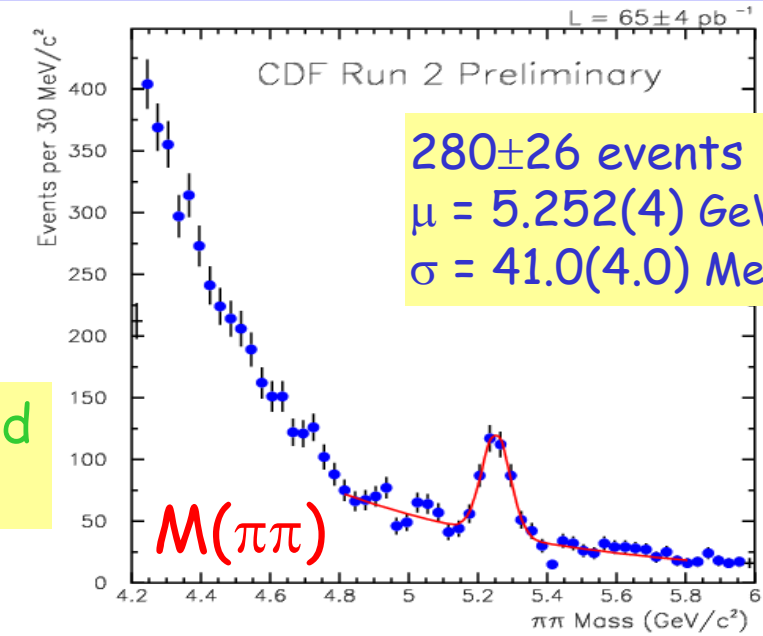
$$A_{CP}(\pi\pi, KK) = A_{CP}(dir)\cos(\Delta m \times t) + A_{CP}(mix)\sin(\Delta m \times t)$$

B→hh': Signal extraction

- Trigger:
  - Two opposite charged tracks: $P_t > 2$ GeV/c, $\sum P_t > 5.5$ GeV/c
  - Displaced: $100\mu m \leq |d_0| \leq 1mm$
  - $20^0 \leq \Delta\varphi \leq 135^0$

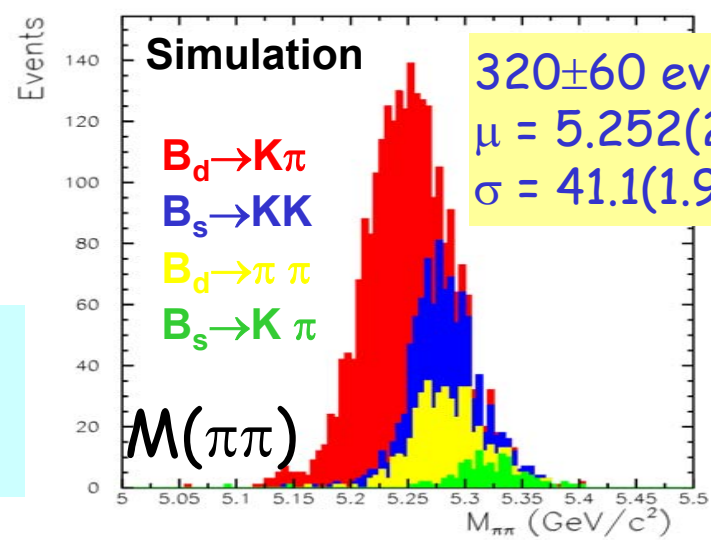
Cut single jet and di-jet BG

Select long-lived decays



280±26 events
μ = 5.252(4) GeV/c²
σ = 41.0(4.0) MeVc²

- Offline:
  - B pointing to the PV: $|dB| \leq 80\ \mu m$
  - B displaced: $L_{xy} \geq 300\ \mu m$
  - B isolated



320±60 events
μ = 5.252(2) GeV/c²
σ = 41.1(1.9) MeV/c²

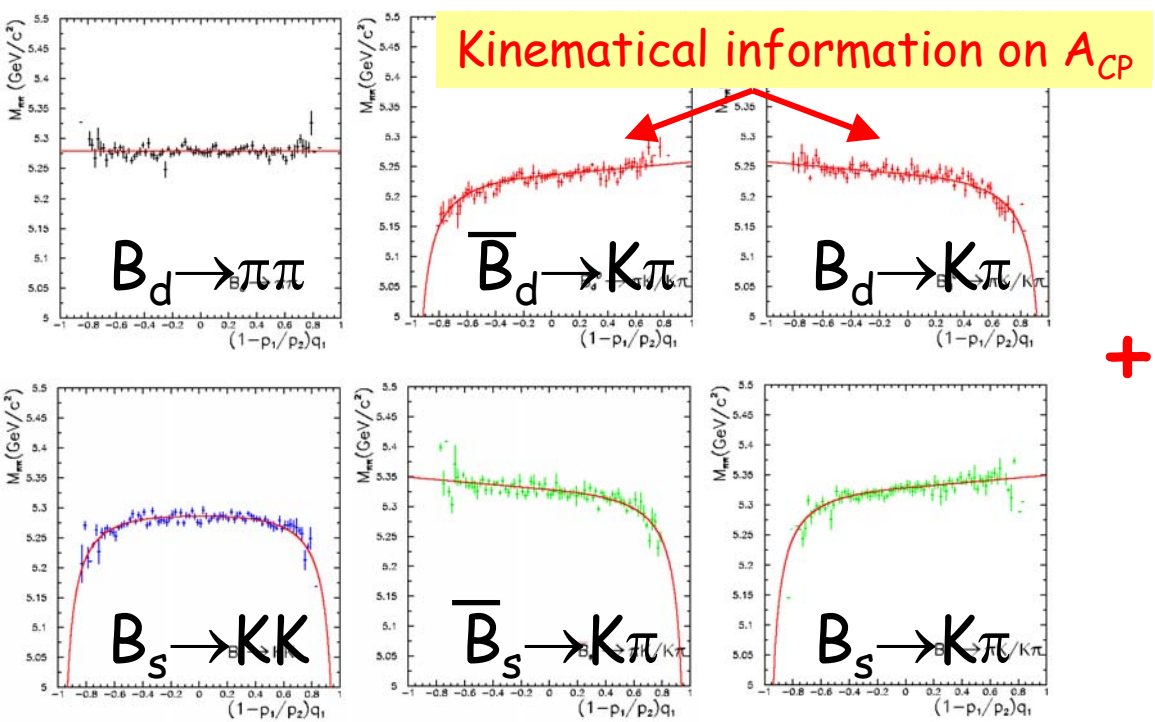
After optimization ($S/\sqrt{(S+B)}$):
- ~300 candidate events/65 pb^{-1}
- S/B ~ 2 (better than expectations)

B→hh': Disentagling contributions

Disentangle 4 contributions: Bd→ππ/Kπ and Bs→KK/Kπ → Relative BR
Separation B÷$\bar{B}$ → A_{CP}(dir)

Statistical separation via un-binned likelihood fit:

- 2 kinematical variables: M(ππ), $\alpha = (1-p_1/p_2)q_1$ (with $p_1 < p_2$)
- PID (dE/dx in the central drift chamber): 1.3σ K/π separation



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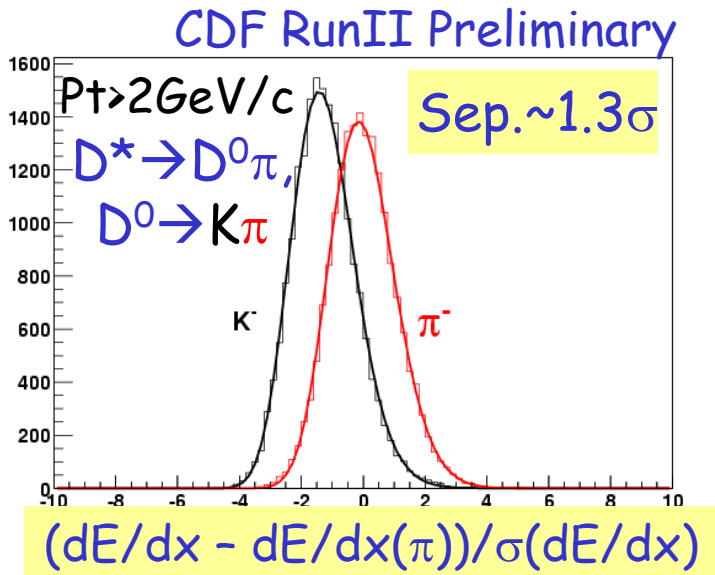


$B \to hh'$: $A_{CP}(B^0 \to K\pi)$ and relative BR

65 pb^{-1}

	Fraction	Yield
$B^0 \to K\pi$	0.53 ± 0.06	$148 \pm 17(stat.) \pm 17(syst)$
$B^0 \to \pi\pi$	0.14 ± 0.05	$39 \pm 14(stat.) \pm 17(syst)$
$B_s \to KK$	0.32 ± 0.06	$90 \pm 17(stat.) \pm 17(syst)$
$B_s \to K\pi$	0.01 ± 0.04	$3 \pm 11(stat.) \pm 17(syst)$
$A_{CP}(B^0 \to K\pi)$	$0.02 \pm 0.15(stat) \pm 0.02(syst)$	
$BR(B^0 \to \pi\pi)/ BR(B^0 \to K\pi)$ (*)	$0.26 \pm 0.11(stat) \pm 0.06(syst)$	

Consistent with zero

(*) includes acceptance corrections ($\varepsilon_{K\pi}/\varepsilon_{\pi\pi} = 0.966 \pm 0.009$)

Systematic (ACP/BR ratio):

- dE/dx ($\pm 0.01/\pm 0.05$)
- Background model ($\pm 0.01/ \pm 0.02$)
- Acceptance corrections
- Mass scale
- Mass resolution (B_d/B_s)

- Substantial $Bs \to KK$ yield
- Comparable B^0 yields with B-factory
- Systematic on A_{CP} already at level of B-factory

$B \to hh'$: Prospects

Two-body B_d/B_s charmless decay will provide a large number of interesting measurements in the near future:

With $2fb^{-1}$ integrated luminosity:

Untagged Sample:

- High precision Bs relative BR
- Direct CP on $B \to K\pi$:
  - $\sigma A_{CP} \sim O(1\% \div 10\%)$
- $\Delta\Gamma$s from simultaneous fits to lifetimes

Tagged Sample:

- require flavor tagging
  - assumed $\varepsilon D^2 = 9\%(B_d)\ 11\%(B_s))$
- time dependent asymmetries for $B_d \to \pi\pi$/Bs→KK:

σA_{CP} (dir, mix) ~ 0.2 ($B_d \to \pi\pi$)
σA_{CP} (dir, mix) ~ 0.1 ($B_s \to KK$)

- CKM γ angle:
  $\sigma\gamma \sim \pm 10°(stat)\ \pm 3°(th.)$

20% SU(3) U-spin breaking included

Can be tested comparing relative BR:

$BR(B_d \to \pi\pi)/BR(B_s \to K\pi)$ VS $BR(B_d \to K\pi)/BR(B_s \to KK)$

Direct CP-Violation in Cabibbo suppressed D decays

✓ Charm CPV in the SM very small $O(10^{-3} \div 10^{-4})$ → alternative way to detect non SM sources of CPV

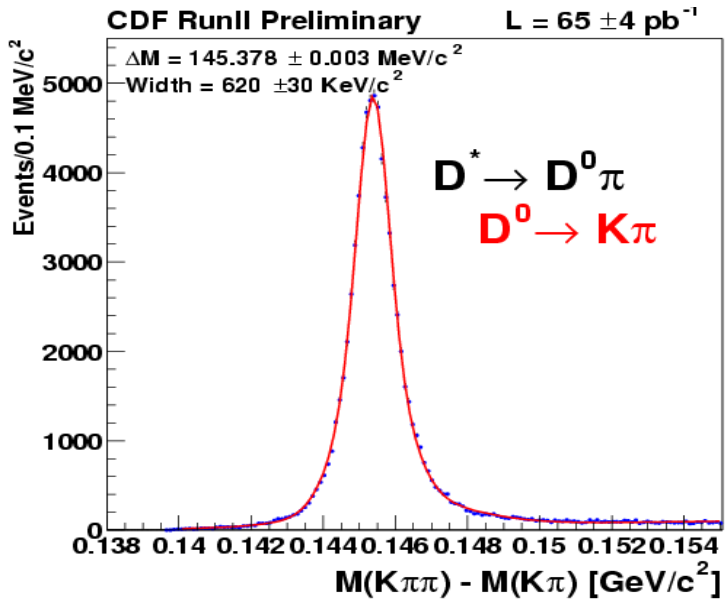
✓ Can be observed as an asymmetry A_{CP} between D→f e CP conjugated

$$A_{CP} = \frac{\Gamma(f) - \Gamma(\bar{f})}{\Gamma(f) + \Gamma(\bar{f})} = \frac{2 Im A_1 A_2^* \sin(\delta_1 - \delta_2)}{|A_1|^2 + |A_2|^2 + 2 Re A_1 A_2^* \cos(\delta_1 - \delta_2)}$$

Many interesting processes in CDF: $D^0 \to KK, \pi\pi, \phi Ks$; $D^{\pm} \to KK\pi, \pi\pi\pi$

Huge statistical samples:
Excellent S/B

Dominant systematic:
- detector asymmetries
- background subtraction



D^*/D^0 Selection

- Trigger:

Two opposite charged tracks:

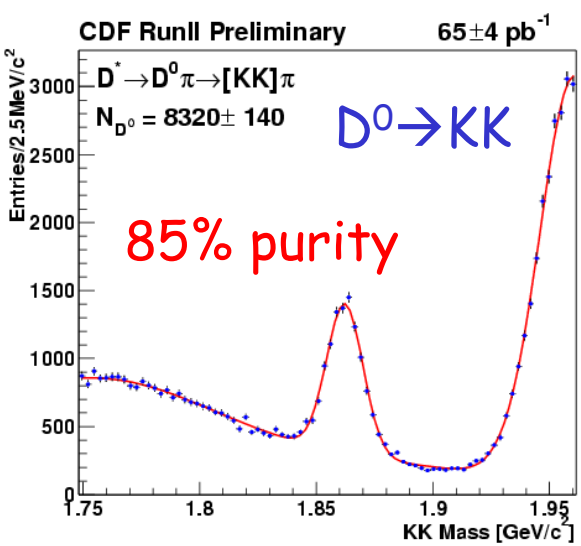
- $P_t > 2$ GeV/c, $\sum P_t > 5.5$ GeV/c

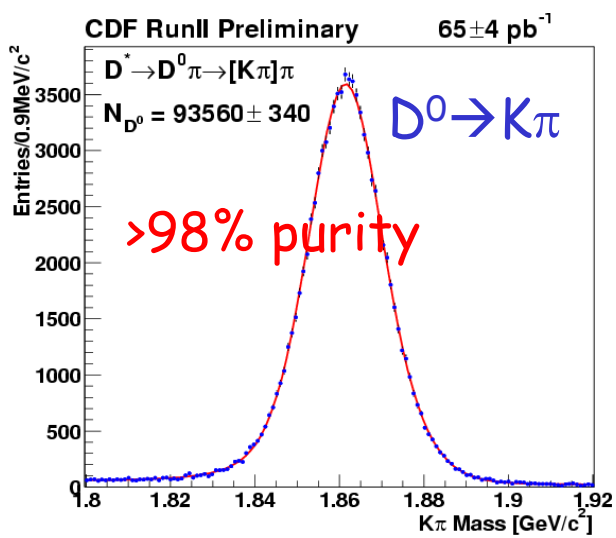
Displaced:

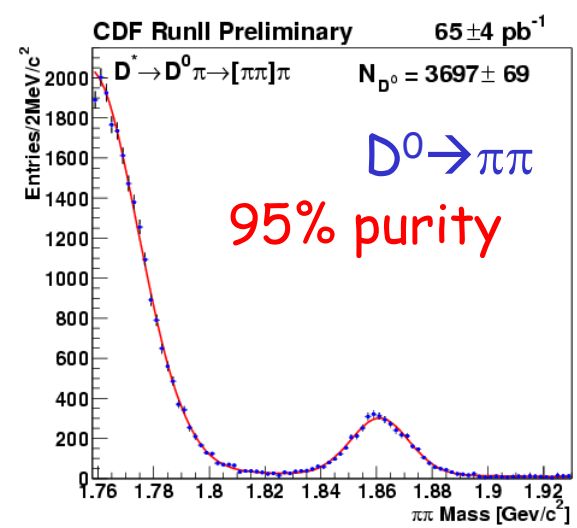
- $120\mu m \leq |d_0| \leq 1mm$

Selection Cut	
Pt(D0)	> 5.5 GeV/c
Lxy(D0)	> 350 μm
$\Delta M(D^*,D^0)$	$\pm 3\sigma_{\Delta M}$ window
IP(D0)	< 100 μm
$d_0(K)*d_0(\pi)$	≤ 0

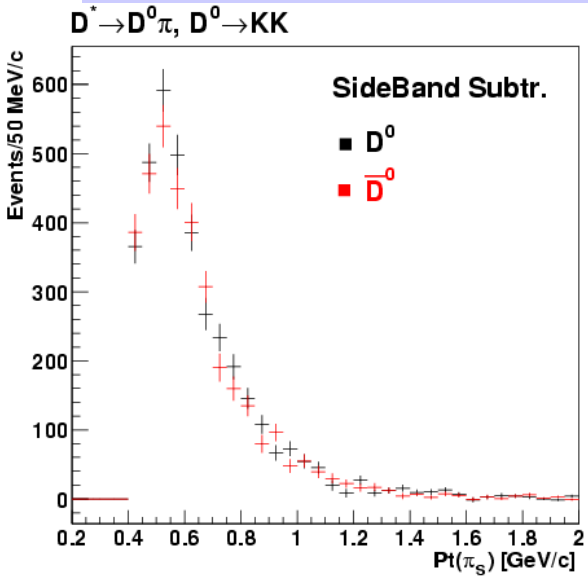
Minimize non prompt contamination (<10%)







Detector Asymmetry



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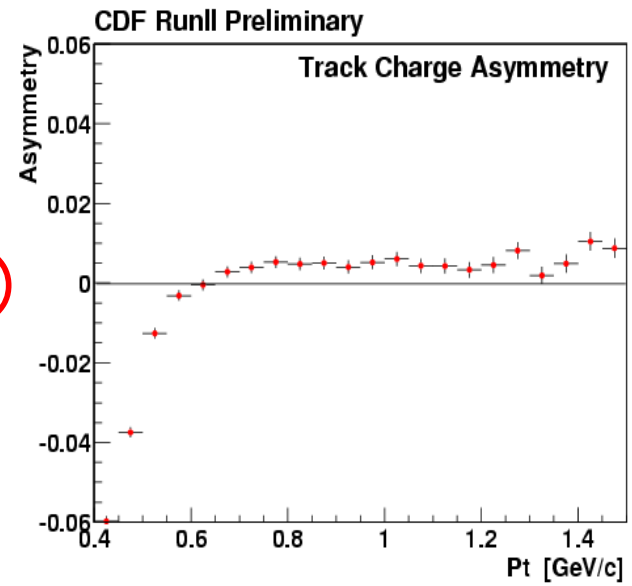


➡ Detector induced Asymmetry ~-1%

- D^0 Flavor tagged using π_S charge:
  - $Q(\pi_S) > 0 \rightarrow D^0$ / $Q(\pi_S) < 0 \rightarrow \overline{D}^0$
- Systematic effect: charge asymmetry for low-Pt tracks: $\varepsilon(\pi_S^-) \neq \varepsilon(\pi_S^+)$
- Measure track charge asymmetry and correct the observed asymmetries

- Residual effects studied on decays where A_{CP} effects are not expected:
  - $D^{*\pm} \rightarrow D^0\pi^\pm \rightarrow [K\pi]\pi^\pm$
  - $K^{*\pm} \rightarrow Ks\pi^\pm$
  - $D^\pm \rightarrow K\pi\pi^\pm$ ← Not yet included
  - $Ks \rightarrow \pi^+\pi^-$

A(residual) = 0.35 ± 0.57 % ← scale with L

$D^0 \to hh$: Relative BR and A_{CP}

$\Gamma(D^0 \to KK)/\Gamma(D^0 \to K\pi) = 9.38 \pm 0.18(stat) \pm 0.10(syst)$ %

$\Gamma(D^0 \to \pi\pi)/\Gamma(D^0 \to K\pi) = 3.686 \pm 0.076(stat) \pm 0.036(syst)$ %

Main Systematic:

Background model (0.6%)

Relative acceptances (0.3%)

CP lifetimes (0.5%)

Competitive with FOCUS2003

$A_{CP}(D^0 \to KK) = 2.0 \pm 1.7\ (stat) \pm 0.6\ (syst)$ %

$A_{CP}(D^0 \to \pi\pi) = 3.0 \pm 1.9\ (stat) \pm 0.6\ (syst)$ %

Main Systematic:

Background model ($\pm$0.2%)

Detector Asymmetries ($\pm$0.5%)

Competitive with CLEO2002

Future: A_{CP} on $D^{\pm}$, D^0 mixing

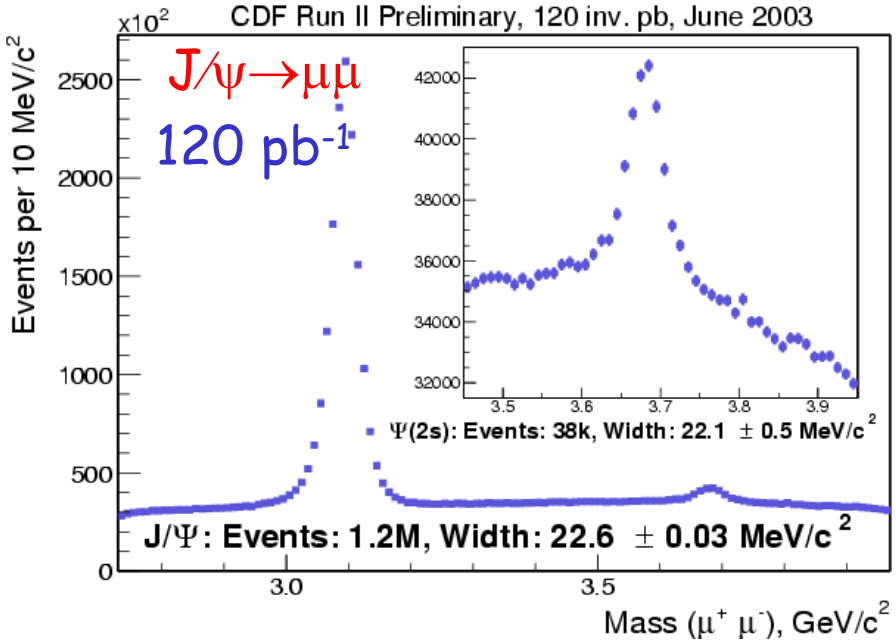
With 2 fb^{-1} → $\sigma A_{CP} \sim O(10^{-3})$

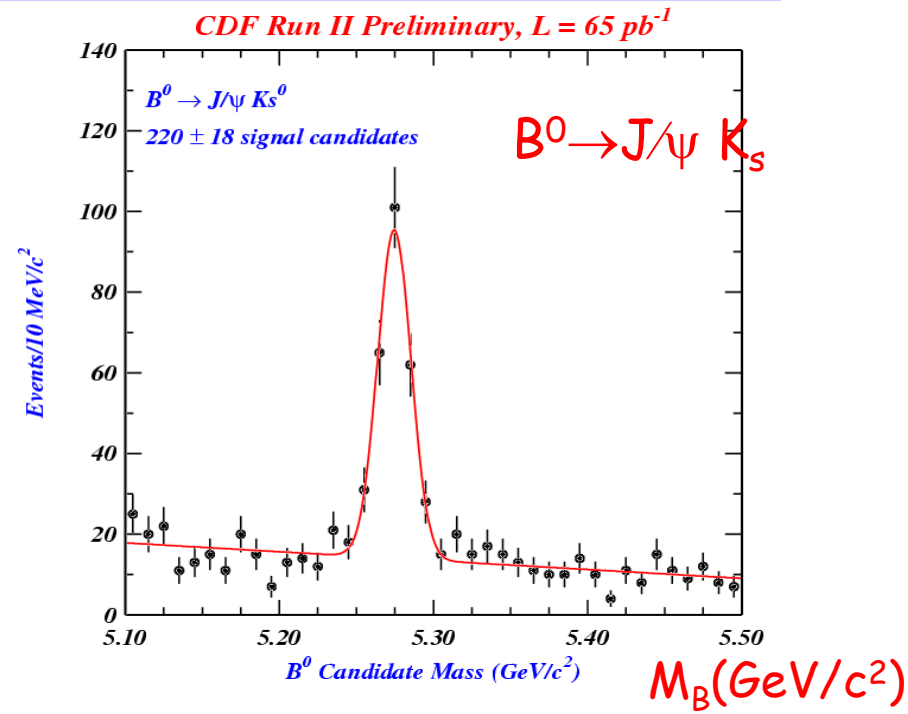
Summary and Conclusion

- Tevatron is slowly but steadily improving (a large effort in FNAL beam division)
- CDF is working well:
  - Data taking efficiency now stably $\geq$ 90%
  - $\times$2 in the B/D yields respect one year ago (further improvements are expected)
- CPV First Measurements & Prospects:
  - Competitive charm measurements with only 65 pb^{-1} integrated luminosity
  - Comparable sensitivity with B-factories for Two-body Charmles B_d decays on direct-CP
  - Promising perspectives for an exciting programme of unique measurements on B_s and Λ_b …

BKUP Slides

More J/ψ Trigger Signals

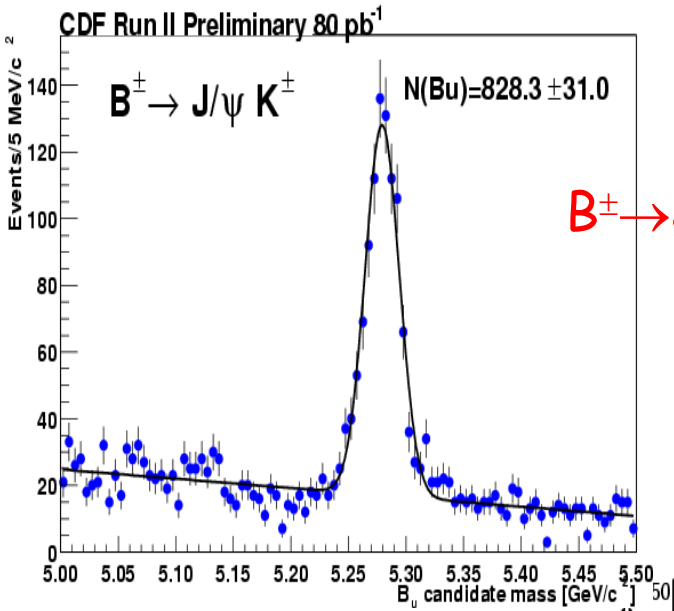




Trigger: 2 muons: Pt > 1.5 GeV/c (RunI 2 GeV/c)
J/ψ yield, resolutions and S/B consistent with expectations (~2.5×RunI)
J/ψφ sample (2×RunI)

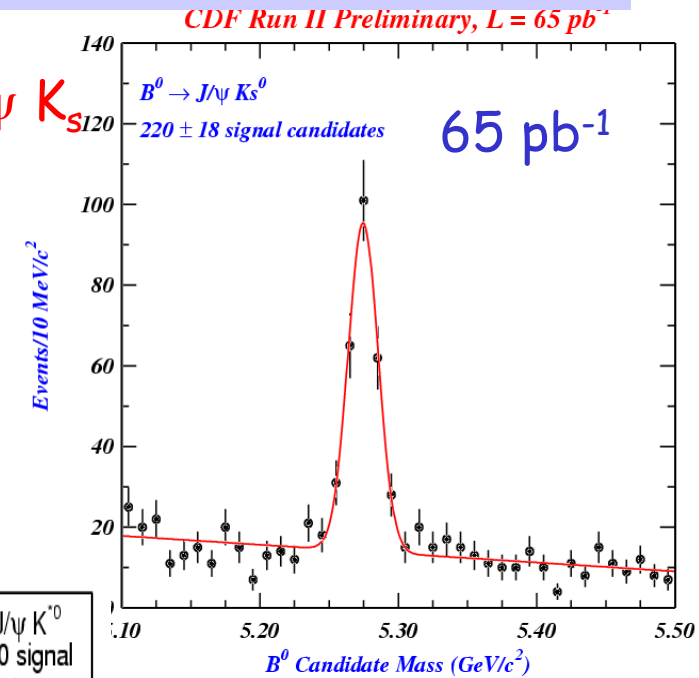
~O(10K) $B^0 \to J/\psi K_s$ ($J/\psi \to \mu\mu$) per 1 fb^{-1}
~O(1K) $Bs \to J/\psi\phi / \Lambda_b \to J/\psi\Lambda$ per 1 fb^{-1}

More B→J/ψX Signals



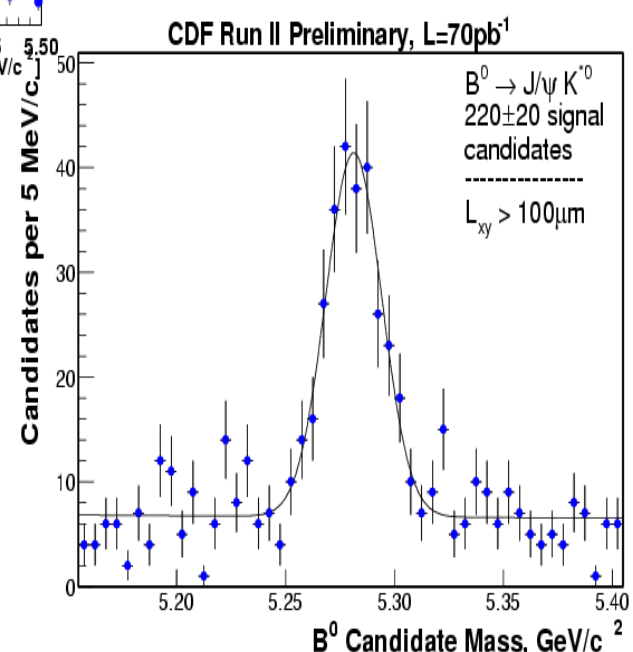
$B^{\pm} \rightarrow J/\psi\ K^{\pm}$

$B^{0} \rightarrow J/\psi\ K_{S}$



$M_B(GeV/c^2)$

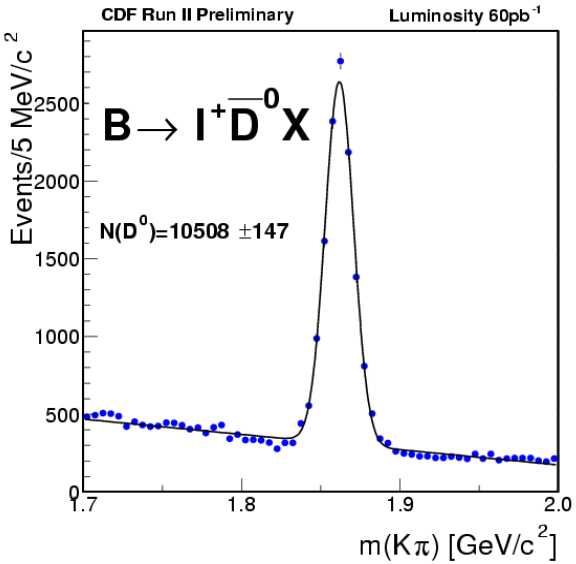
$B^{0} \rightarrow J/\psi\ K^{*}$



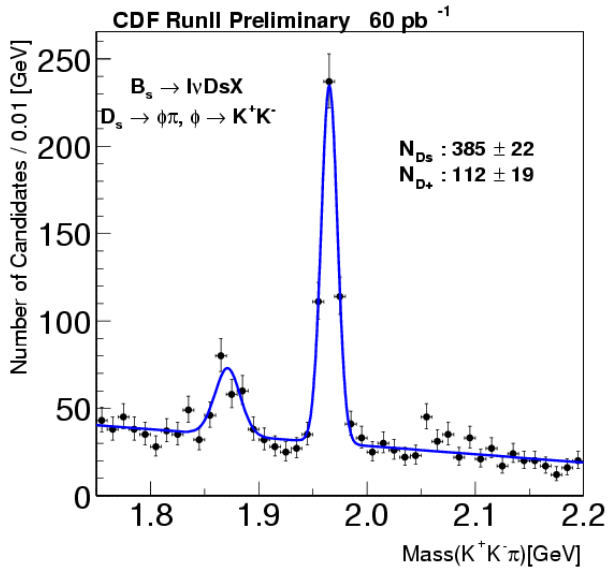
Trigger: 2 muons:
Pt > 1.5 GeV/c (RunI 2 GeV/c)

Lepton+SVT signals

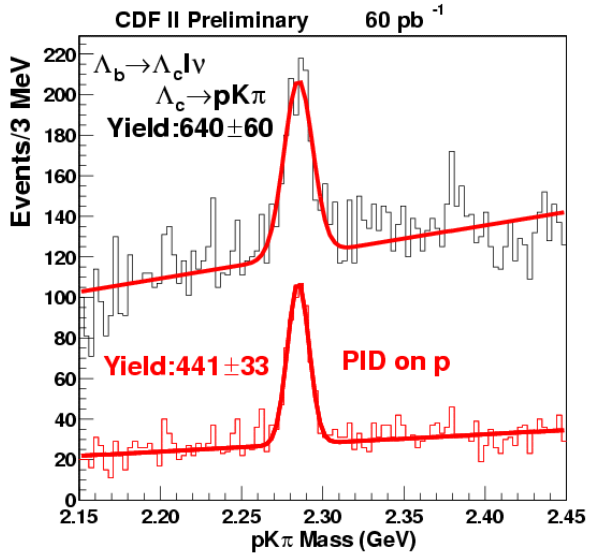
$B \to D^0 l$



$B_s \to D_s l$



$\Lambda_b \to \Lambda_c l$



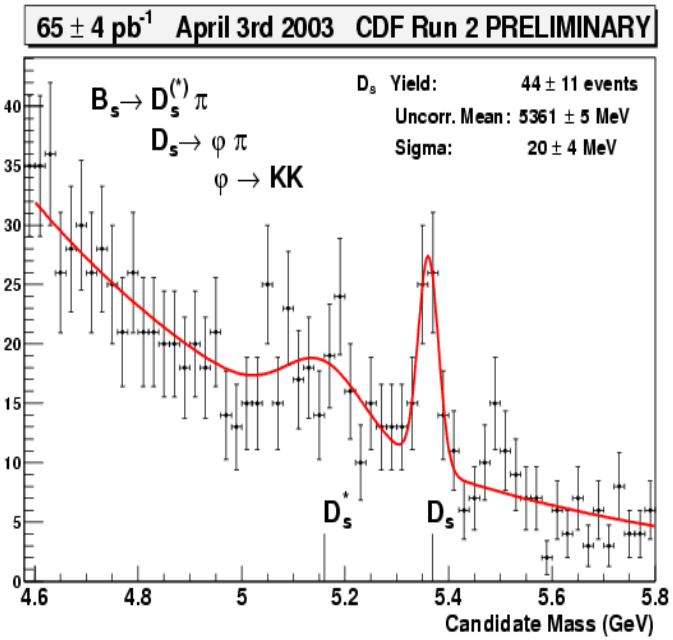
Trigger: lepton + displaced track (SVT)

- reduced Pt threshold for lepton (RunI 8 GeV → RunII 4 GeV)
- Compare to RunI: yields×5 and better S/B

~O(10K) Λ_b, B_s per 1 fb^{-1}

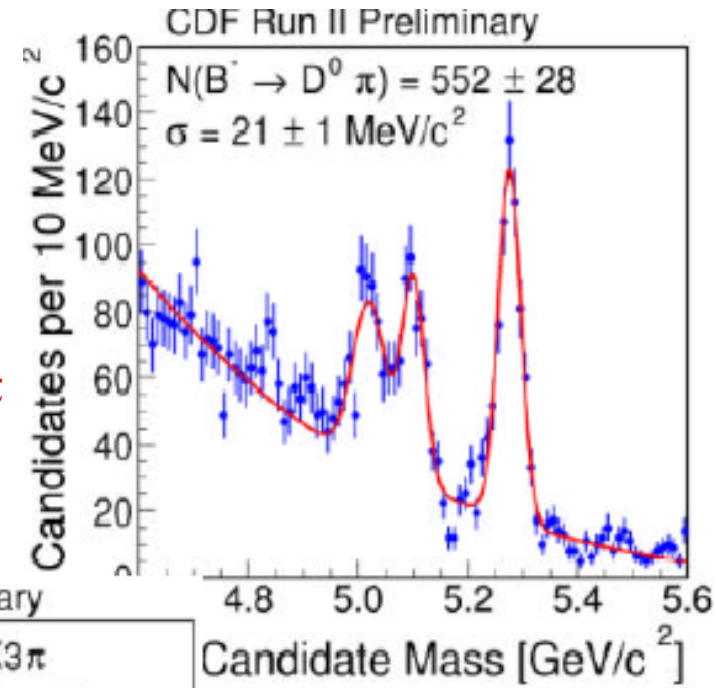
Tune flavor tagging, precision lifetimes, Bs mixing,…

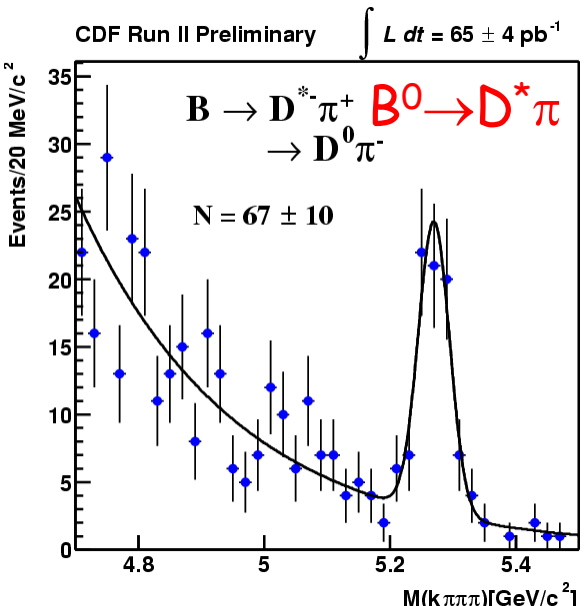
More Hadronic Signals …



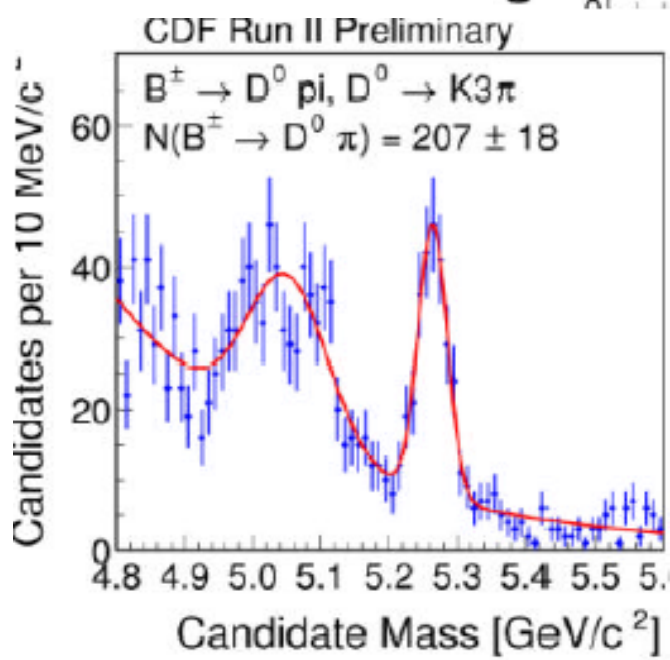
$B_s \to D_s \pi$

$B^{\pm} \to D^0 \pi \to [K\pi]\pi$



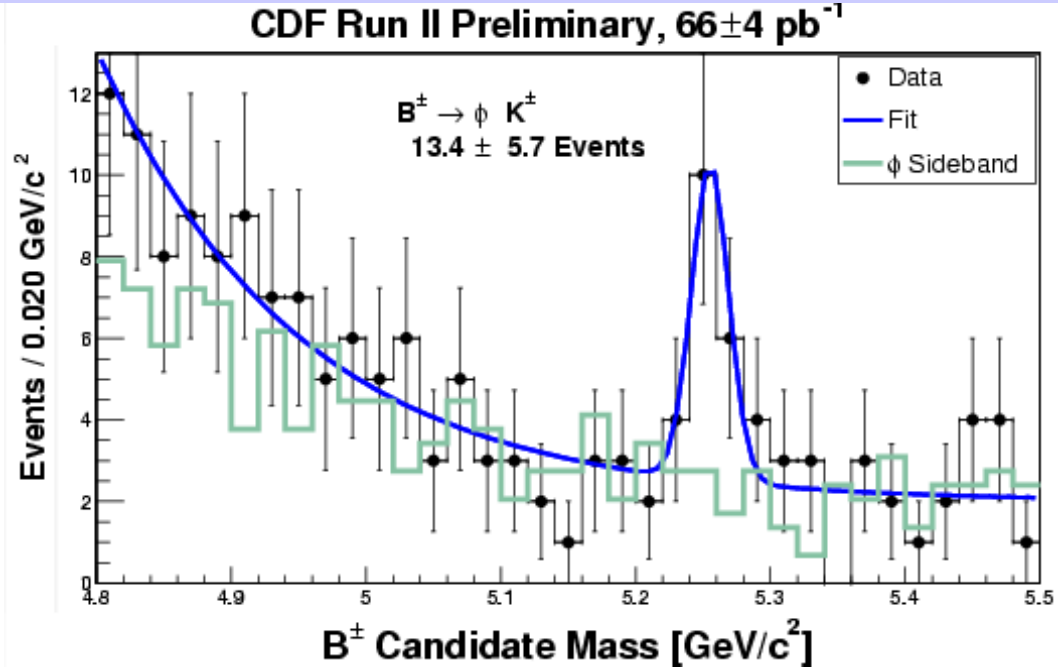


$B^0 \to D^* \pi$



$B^{\pm} \to D^0 \pi \to [K3\pi]\pi$

Multy-body Charmless B decay



$B^{\pm} \to \phi K^{\pm}$

Other accessible decays:

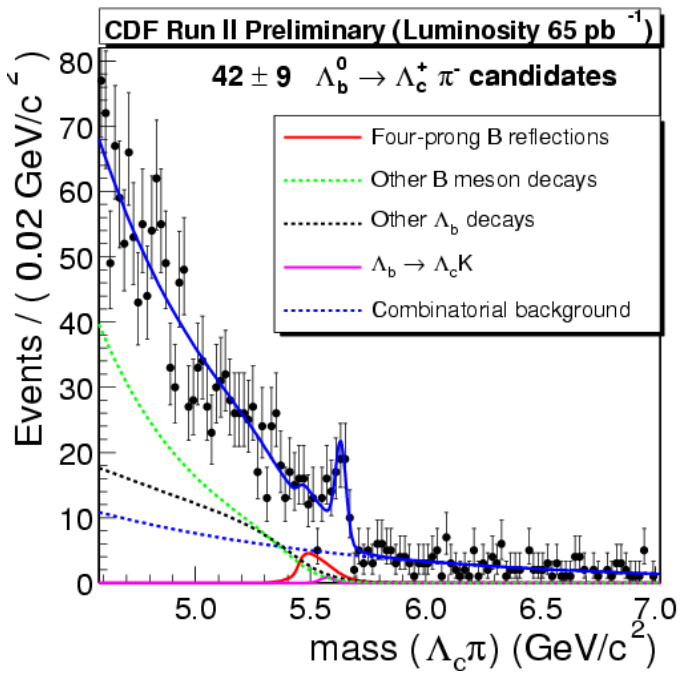
- $B^0 \to \phi K_s$ $(\varepsilon(\phi Ks)/\varepsilon(\phi K^{\pm}) \sim 0.5)$
- $B_{u,d,s} \to VV$:
  - $B^{\pm} \to K^{*\pm} \rho^0, \phi K^{*\pm}$
  - $B^0 \to \rho^0\rho^0, \phi K^{*0}$
  - $B_s \to \phi\phi, K^{*0}K^{*0}, K^{*0}\rho^0$
- α, γ via direct CP asymmetries

[D.Atwood, A.Soni Phys.Rev. D65(2002)073018]

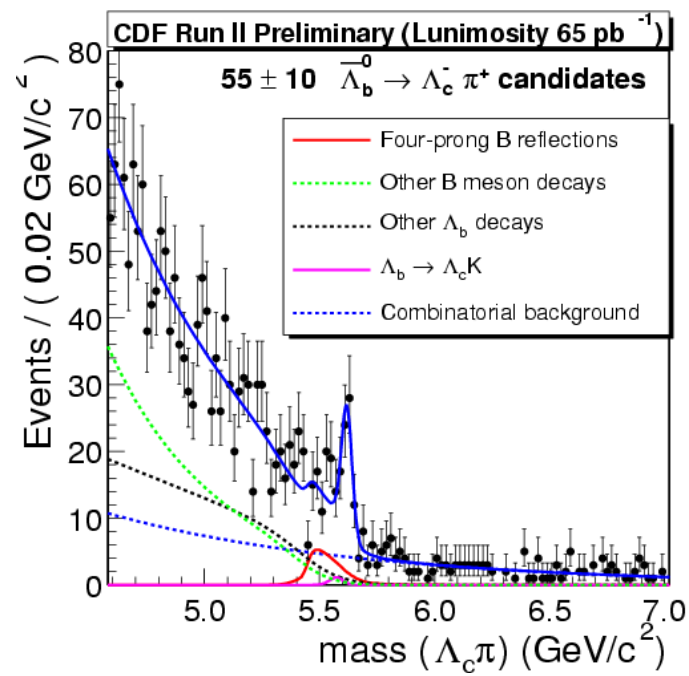
Fully hadronic Λ_b decay

Raw asymmetry

$\Lambda_b \rightarrow \Lambda_c \pi^-$



$\overline{\Lambda}_b \rightarrow \Lambda_c \pi^+$



With more statistic:

- Direct CPV on $\Lambda_b \rightarrow p\pi$, $\Lambda_b \rightarrow pK$
- BR unknown, not signal observed yet …
- SM predict $A_{CP} \sim O(10 \div 30\%)$

CP-Asymmeties in $B_s \rightarrow J/\psi\phi$ e $J/\psi\eta^{(\prime)}$

Measure the week phase of V_{ts}: $\sin(2\beta_s)$ ~ small in the SM

Sensitive to New Physics effects

Only accessible at Tevatron (and LHC ...)

Experimental issues are complementary in the two decays:

$B_s \rightarrow J/\psi\phi$:

needs to separate the two CP-eigenstates

→ angular analysis (complicate)

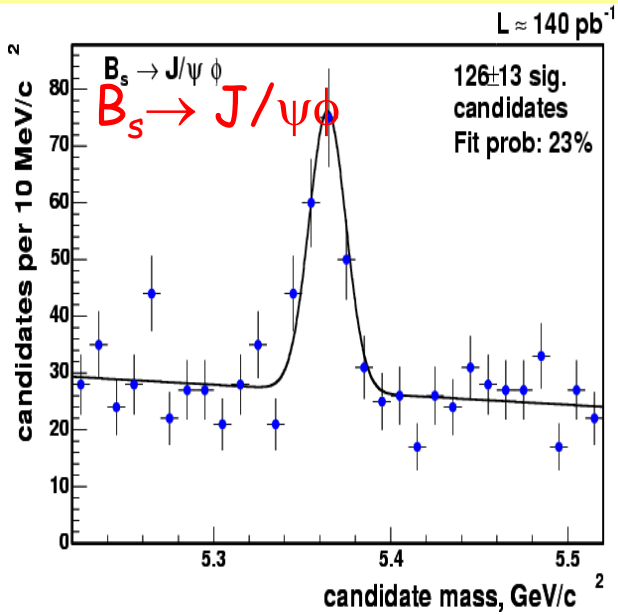
→ allows also the measurement of $\Delta\Gamma_s$

$B_s \rightarrow J/\psi\eta^{(\prime)}$:

Is a CP-eigenstate

neutrals in the final state → degradation

~×2 in the invariant mass resolution

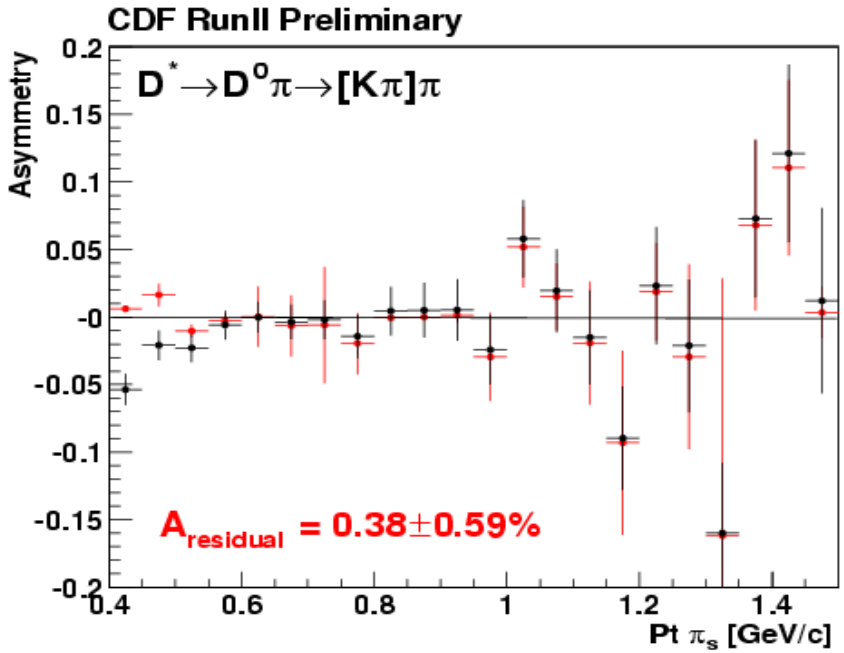


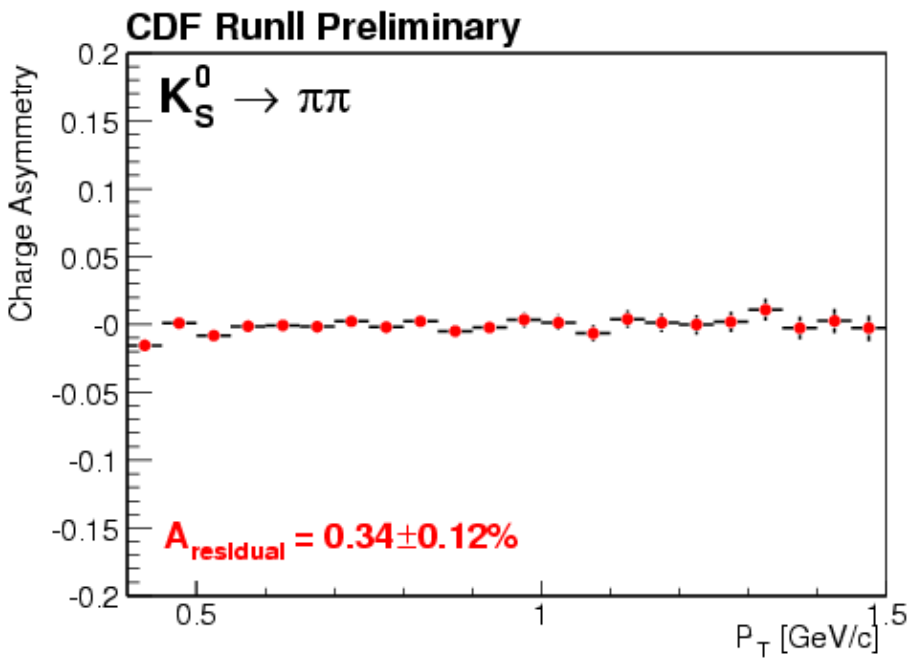
Expected ~2000 events RunIIa:

σ_A ~ 0.1 (x_s = 25, εD^2 = 11.3%, σ_t=45 fs, f=0.5)

$B_s \rightarrow J/\psi\eta$: expected O(2000) events at the end of RunIIb

Detector Asymmetry





Residual effects studies on decays where A_{CP} effects are not expected

B→hh: Fit procedure - Likelihood

(for one event)

$$\mathcal{L} = \left[(1-b)\sum_i f_i \cdot \mathcal{F}_i(\alpha, M_{\pi\pi}, id1, id2, \Delta) + b \cdot \mathcal{F}_{BG}(\alpha, M_{\pi\pi}, id1, id2, \Delta)\right]$$

Index i run on channels:

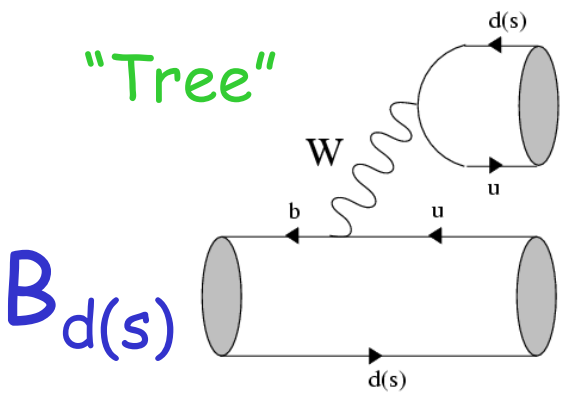
- $B_d \to \pi\pi$
- $B_d \to K\pi$
- $\overline{B}_d \to K\pi$
- $B_s \to K\pi$
- $\overline{B}_s \to K\pi$
- $B_s \to KK$

- F_i = distrib. function signal
- F_{BG}= distrib. func. background
- f_i = fraction(signal) $\Rightarrow \sum_i f_i = 1$
- b = background fraction
- id1/id2: PID info distributions

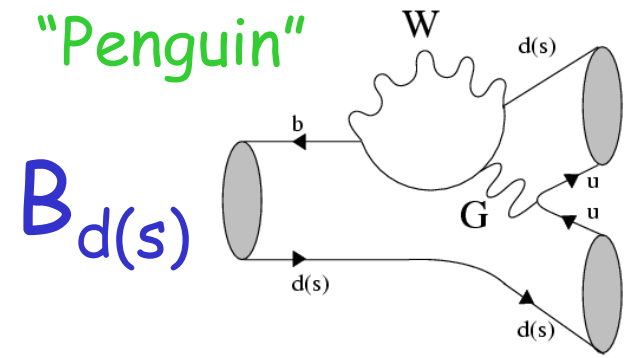
γ via $B_d \to \pi^+\pi^-$ / $B_s \to K^+K^-$

$B_d \to \pi^+\pi^-$ and $B_s \to K^+K^-$ have two decay amplitudes:

"Tree"



"Penguin"



direct $\not{CP}$ $\qquad$ $\not{CP}$ from mixing alone

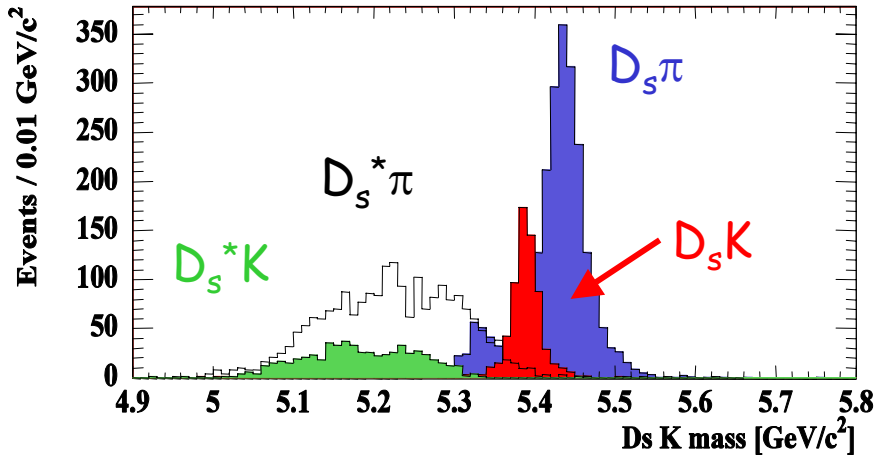
$$A_{CP}(t) = A_{CP}^{dir} \cos(\Delta m_{d(s)}\, t) + A_{CP}^{mix} \sin(\Delta m_{d(s)}\, t)$$

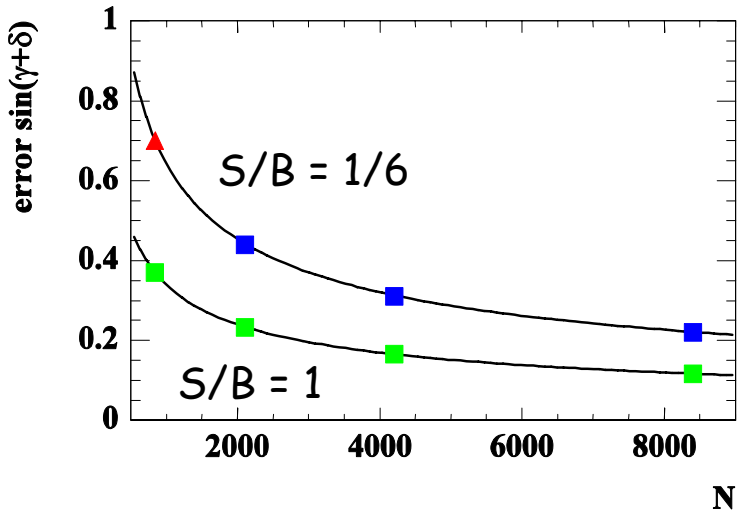
A_{CP}^{dir}, A_{CP}^{mix} functions of γ, β, d, θ $\quad$ ($d e^{i\theta} \approx$ P/T decay amplitude)

<u>R. Fleischer</u> *(PLB 459 (1999) 306):*
Assume U-spin symmetry ($d \leftrightarrow s$)
The 4 asymmetries can be expressed as function of γ, β and P/T amplitude ratio
Parameters can be extracted from fit of meas. of $A_{CP}(t)$ for $B_d \to \pi\pi$ and $B_s \to KK$

An alternative method to measure γ: $B_s \to D_s K^{\pm}$

- CP violation by interference between direct decay and mixed decay of $B_s \to D_s^{\mp} K^{\pm}$
- Measure of γ w/o theoretical uncertainties
- Challenging from an experimental point of view:
  - Physics BG from $B_s \to D_s \pi$ ($\times 15$)
  - Combinatorial BG
  - Time dependent asymmetries





~ O(1K) events expected in RunIIa

Heavy Flavor Physics @Tevatron collider

- ✓ Huge x-sections:
  - o TeV $\approx 4\mu b$, $c\bar{c}$:$\approx 10\mu b$
  - o $\Upsilon(4S) \approx 1$ nb
  - o $Z^0 \approx 7$ nb
- ✓ All hadron species produced:
  - o $B^{\pm}$, B^0, B_s, B_c, Λ_b, Ξ_b, etc.
  - o $\Upsilon(4S)$ B^0, $B^{\pm}$ only
- ✓ B hadrons produced with high boost:
- ✓ Total x-section: ~ $10^3 \times \sigma(b\bar{b})$
- ✓ Average charged track multiplicity ~$\times 4$ $\Upsilon(4S)$
- ✓ Multiple interactions (increase with L)

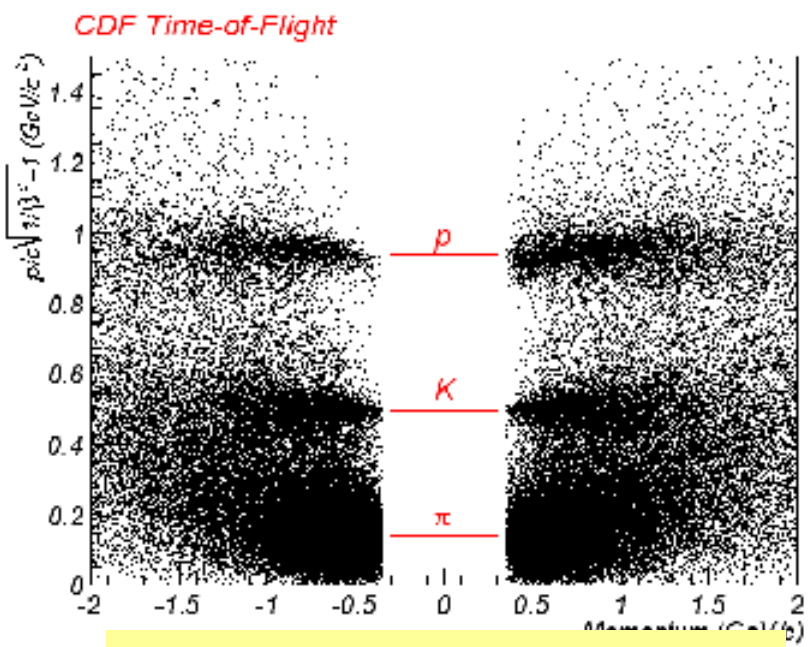
Challenge: selecting the interesting 1 B decay from 10^4 QCD events

CDF Solution:

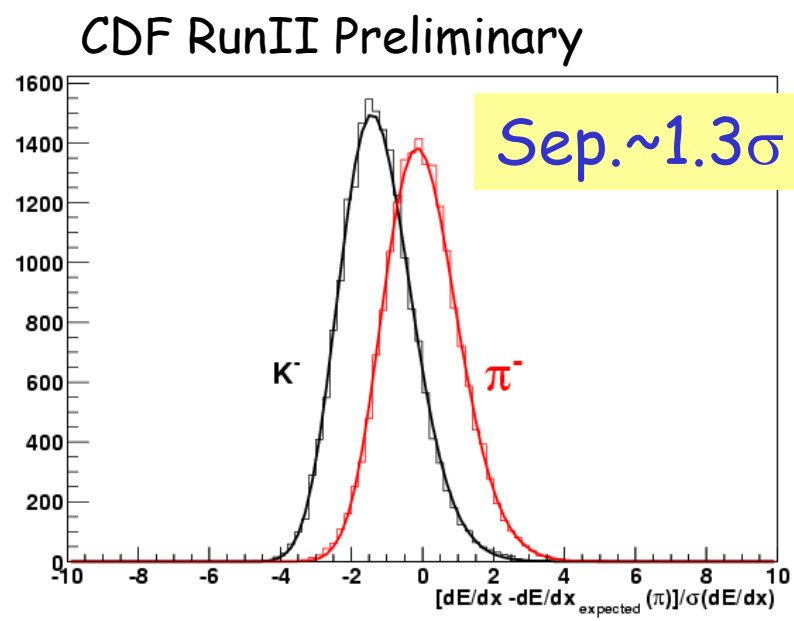
High-precision Vertex detector (σ(IP) ~ 15 μm)
Specialized triggers (XFT, SVT)
Excellent resolution on invariant mass measurement ($\sigma(Pt)/Pt^2$ ~ 0.3%)
PID

TOF&dE/dx: performances today …

- RunI: only specific ionization in the central drift chamber (dE/dx)
- RunII: dE/dx + TOF (complementary)
- TOF design resolution: 100 ps (measured so far 120 ps)
- dE/dx already at at design specifications



TOF: Mass VS Momentum

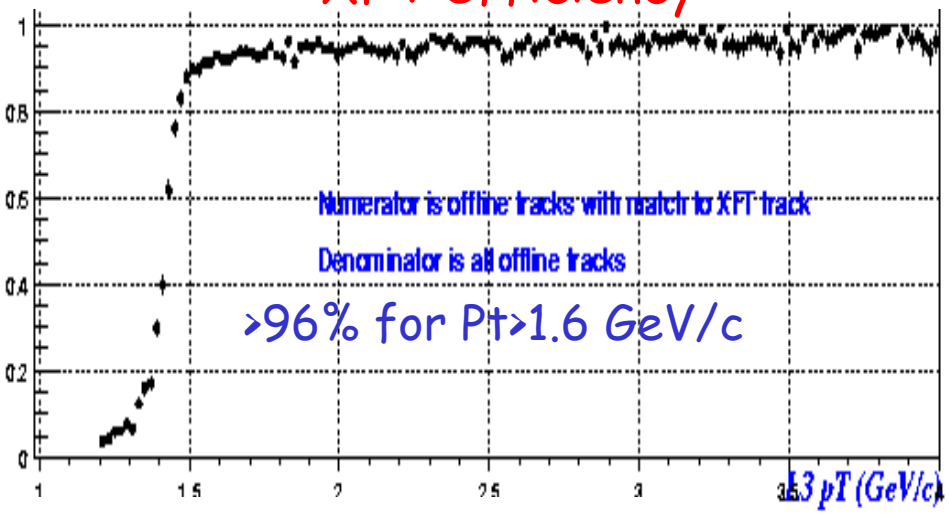


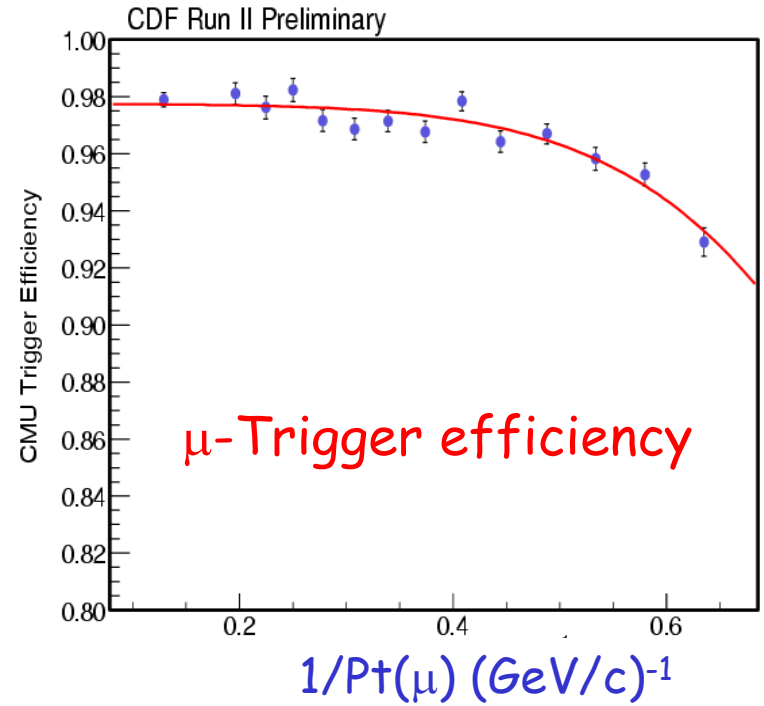
(dE/dx – dE/dx(π))/σ(dE/dx)

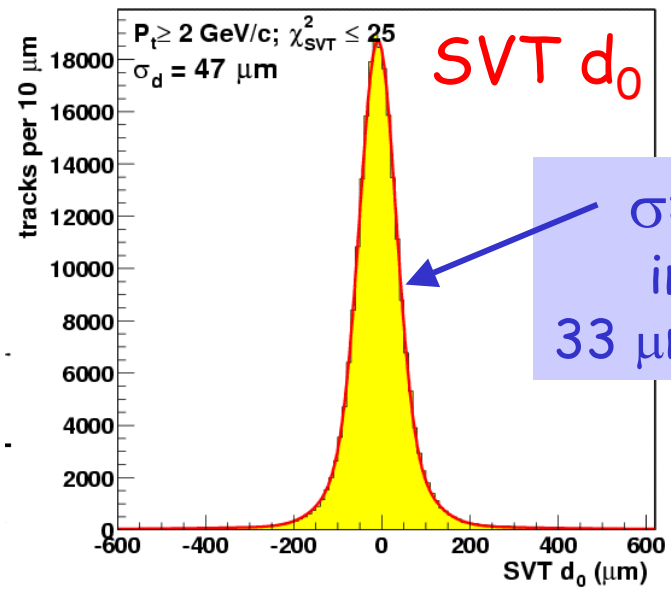
Already useable for PID

HF Triggers: performances today

XFT efficiency







σ=47 μm
includes
33 μm beamspot

Recent/on going improvements:
SVT with 4/5: +50% on B/D yields
DPS B-Triggers: +~30÷50%
XFT upgrade (in progress)