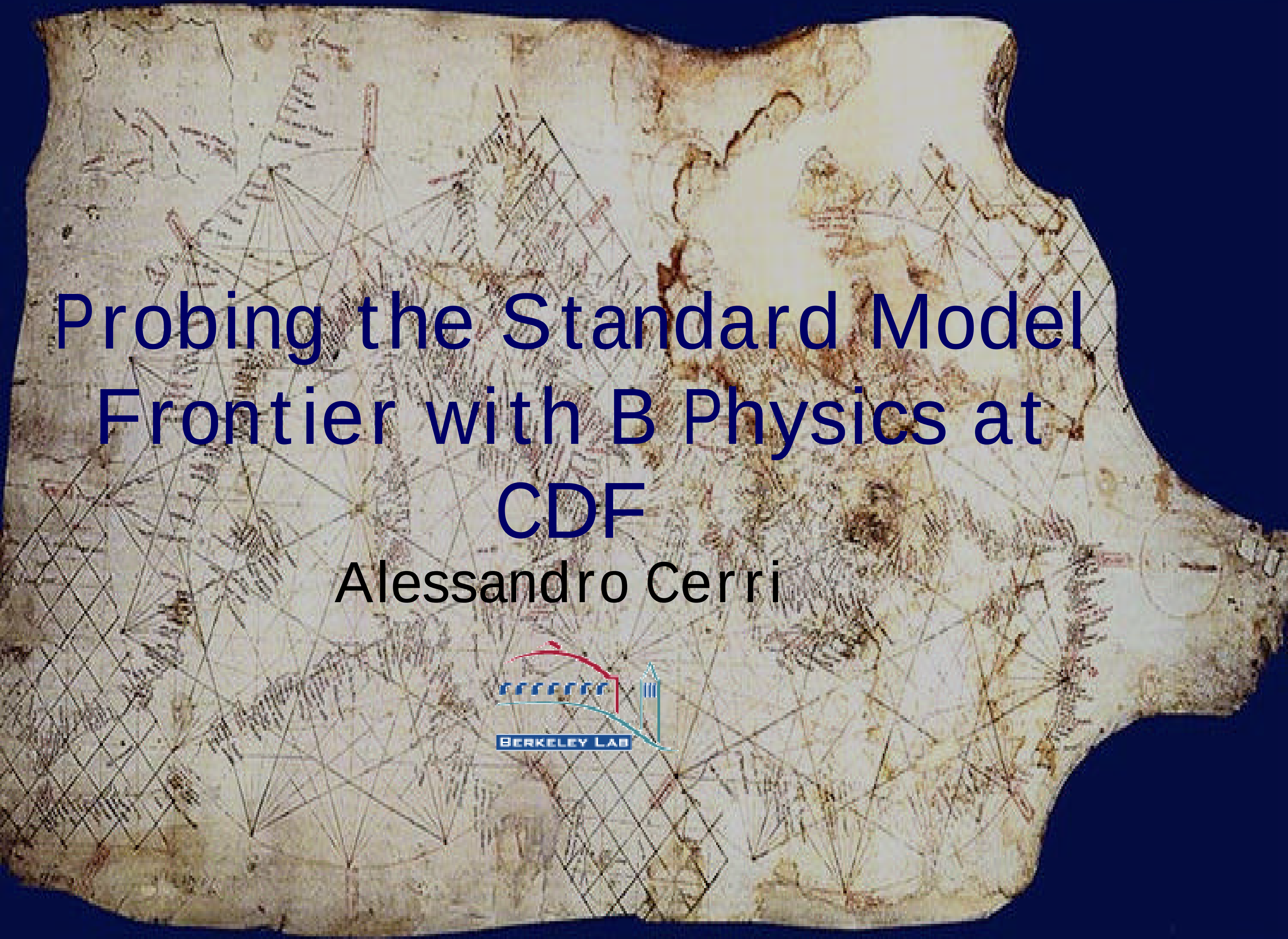
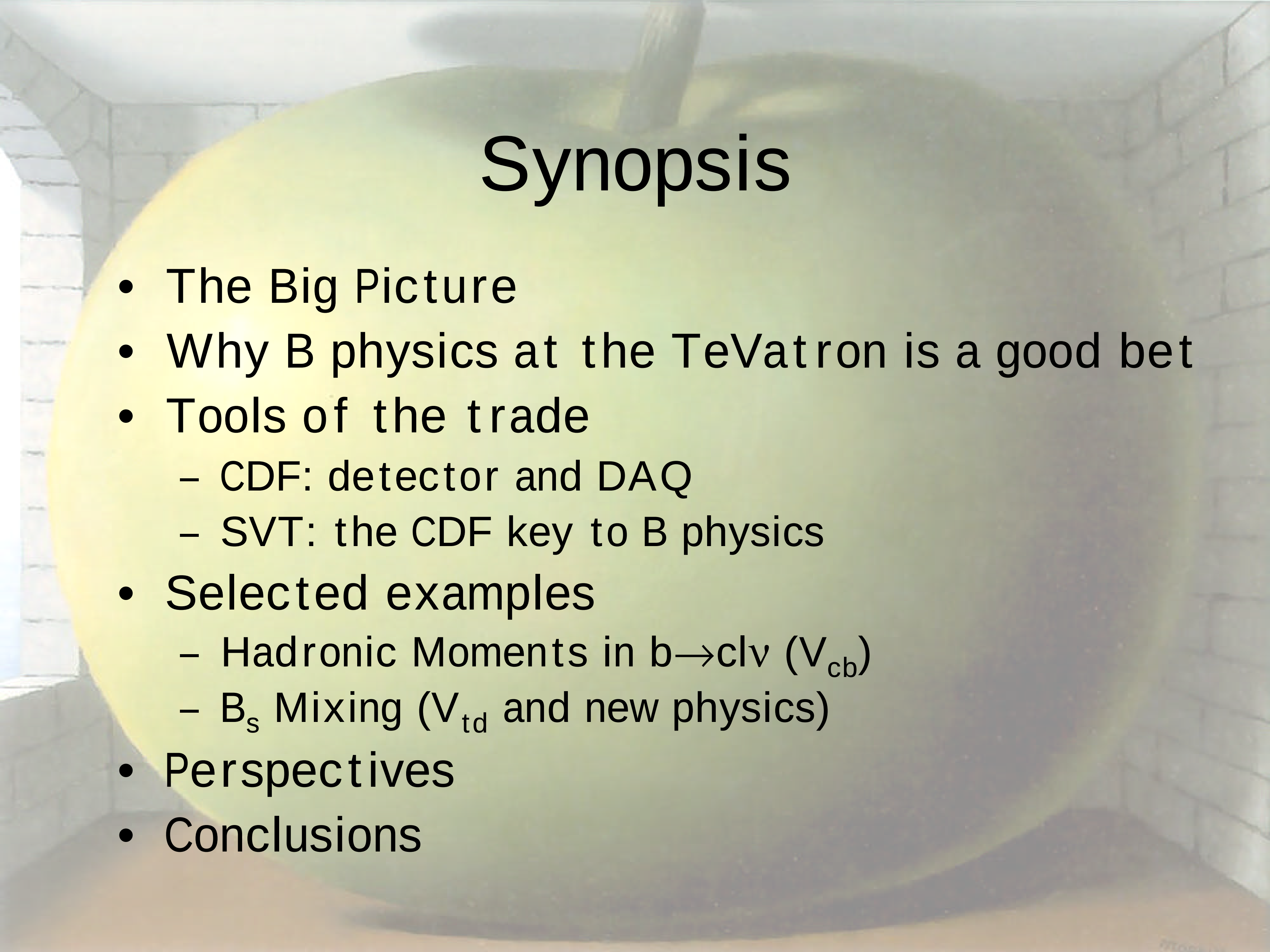


# Probing the Standard Model Frontier with B Physics at CDF

Alessandro Cerri

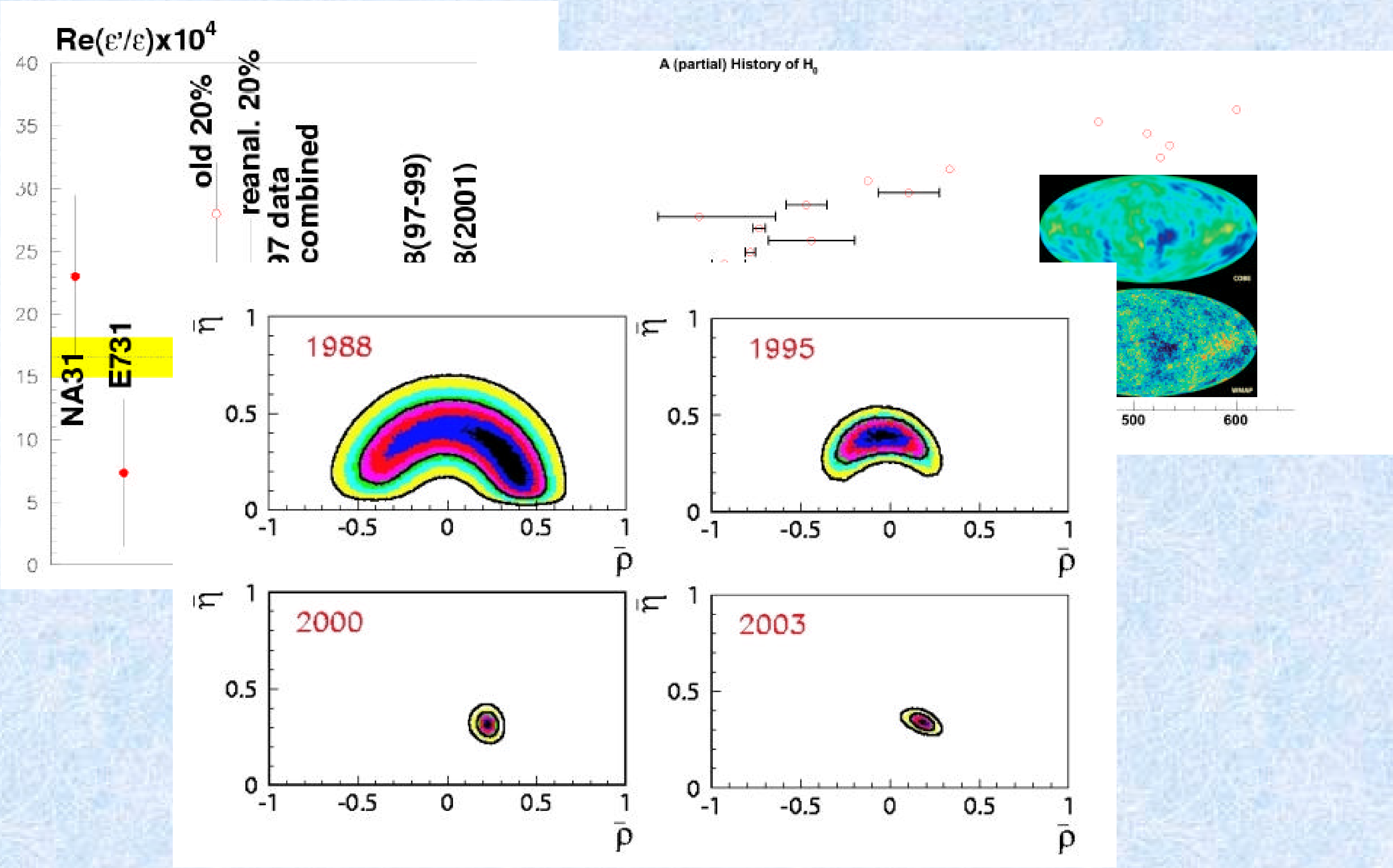
BERKELEY LAB



# Synopsis

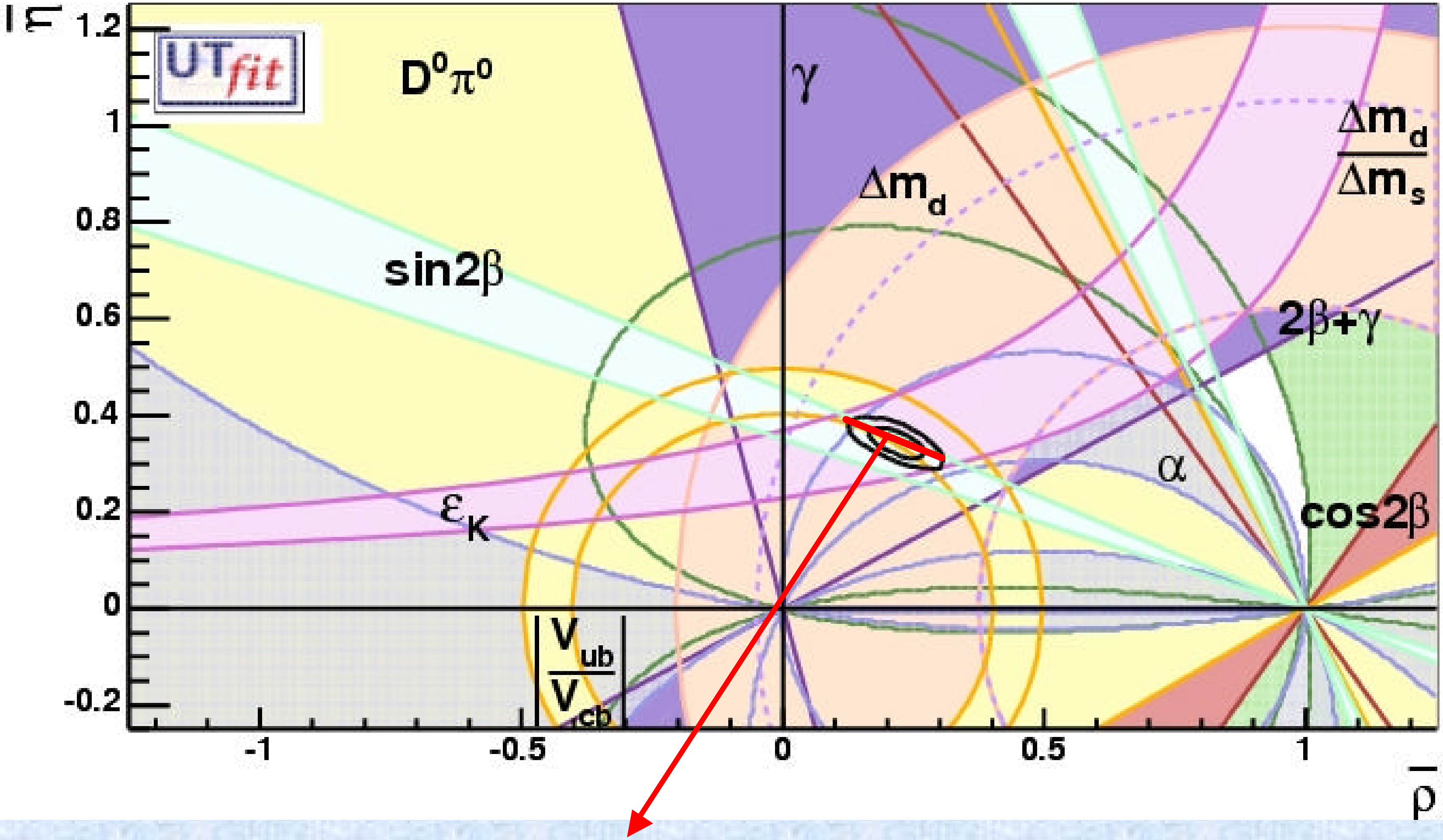
- The Big Picture
- Why B physics at the TeVatron is a good bet
- Tools of the trade
  - CDF: detector and DAQ
  - SVT: the CDF key to B physics
- Selected examples
  - Hadronic Moments in $b \to c l \nu$ ($V_{cb}$)
  - $B_s$ Mixing ($V_{td}$ and new physics)
- Perspectives
- Conclusions

# Qualitative to Quantitative



Like other areas, CKM physics can now precisely probe the Standard Model

# B physics: precision probe of SM and beyond!



TeVatron contribution is critical!

# The Tevatron as a b factory

- B factories program extensive and very successful BUT limited to $B_u$,$B_d$
- Tevatron experiments can produce all b species: $B_u$,$B_d$,$B_s$,$B_c$, B**, $\Lambda_b$, $\Xi_b$

$$\boxed{s_{B^\circ} = 3.51 \pm 0.42 \pm 0.53\, mb\ @\ |y| < 1\quad p_t > 6}$$

Compare to:

•$\Upsilon(4S) \approx 1$ nb (only $B^0$, $B^+$)

•$Z^0 \approx 7$ nb

Unfortunately

•$p\bar{p} \approx 100$ mb

•b production in pp collisions is so large (~300 Hz @ $10^{32}$ cm$^{-2}$ Hz) that we could not even cope with writing it to tape!

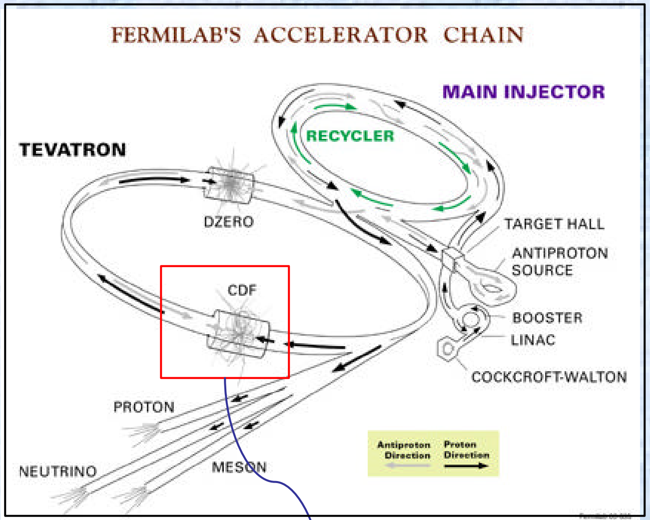
# Path to New Physics

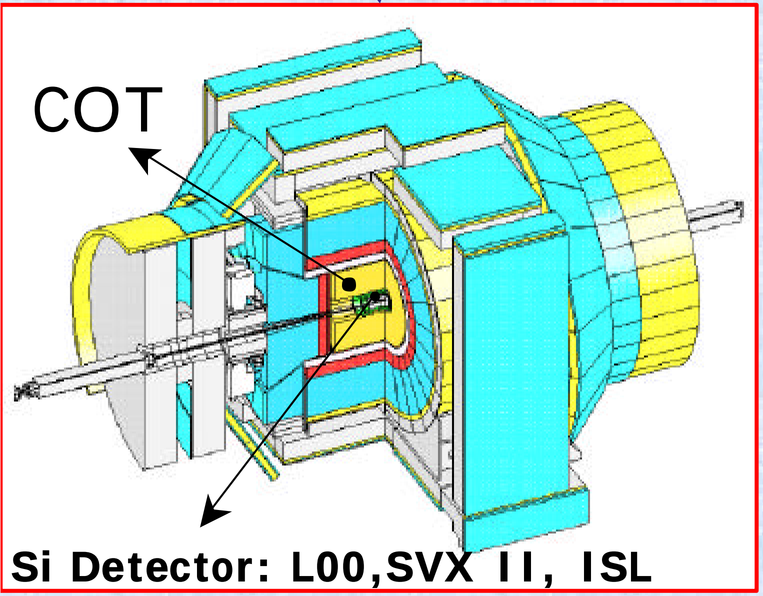
CKM measurements could hint to new physics through discrepancies with SM predictions. How do we get there?

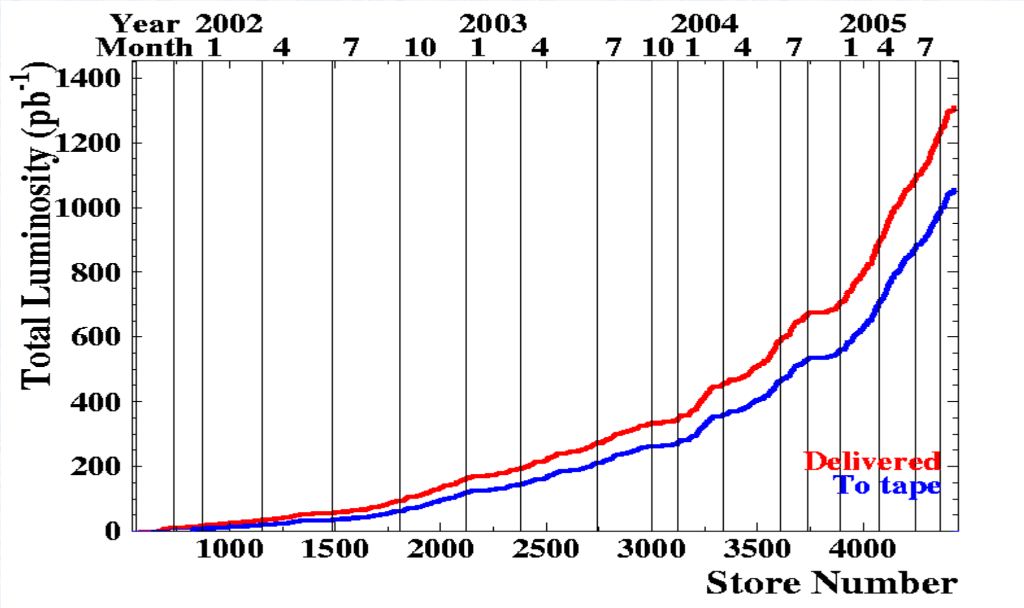
- Design/improve the "tools of the trade"
  - Experimental (detector & techniques)
  - Theoretical (phenomenological devices)
- Measure uncharted properties at the boundaries of our knowledge
  - Masses
  - Lifetimes
  - Branching ratios
- Press further ahead and investigate beyond the boundaries:
  - Mixing
  - CP asymmetries

# CDF and the TeVatron

- Renewed detector & Accelerator chain:
  - ॐHigher Luminosity → higher event rate
  - →Detector changes/improvements:
    - →DAQ redesign
    - →Improved performance:
    - ➢Detector Coverage
    - ➢Tracking Quality
      - ➢New Trigger strategies for heavy flavors: displaced vertex trigger





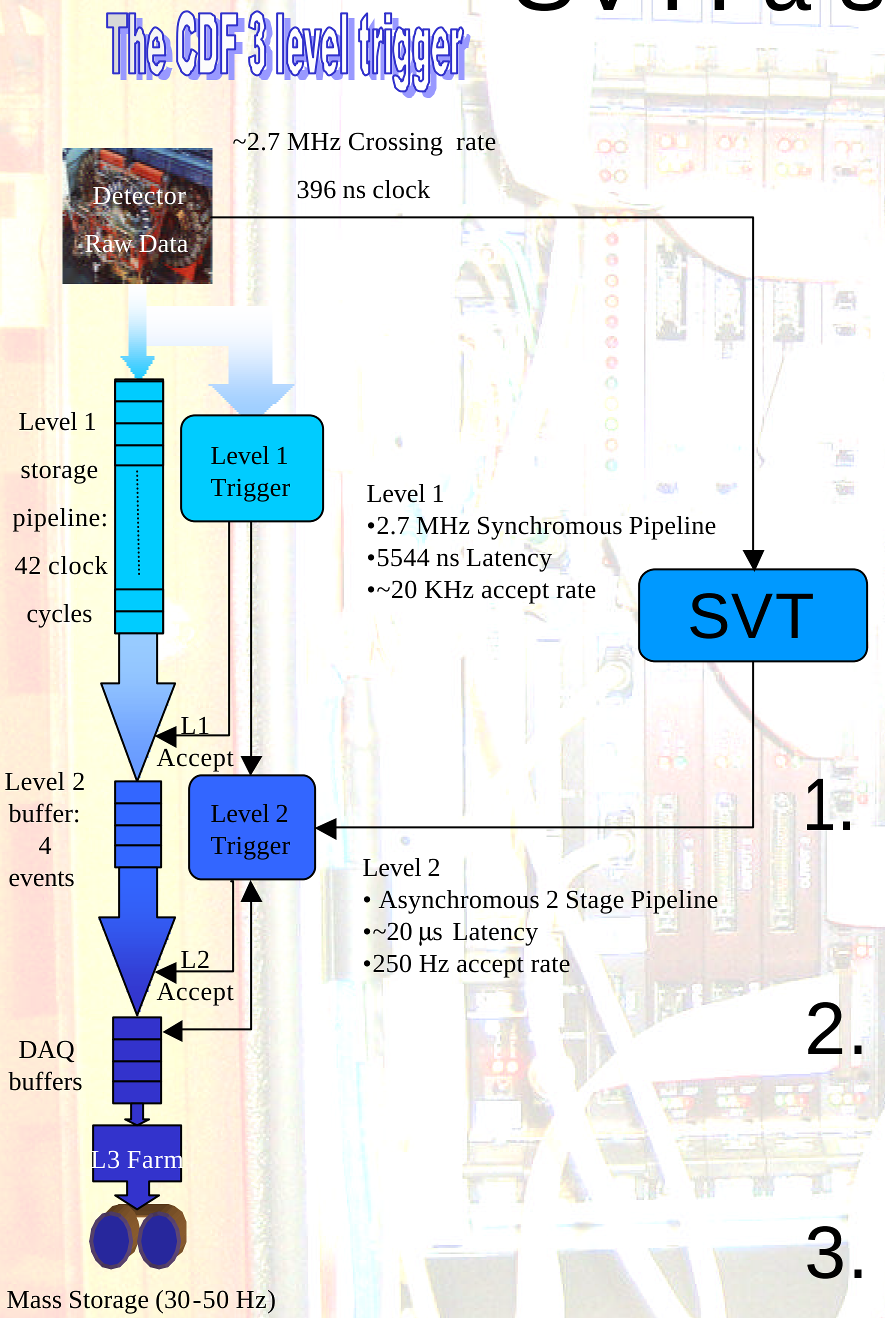


# SVT: a specialized B physics trigger

requirements

- Good IP resolution
- ASAP (≈10 μsec)
- No Dead Time

1. @ earliest L2 where silicon data starts flowing
2. Drop stereo info: 2D tracking
3. Extensive custom design



**The CDF 3 level trigger**

~2.7 MHz Crossing rate

396 ns clock

Detector

Raw Data

Level 1 storage pipeline: 42 clock cycles

Level 1 Trigger

SVT

L1 Accept

Level 2 buffer: 4 events

Level 2 Trigger

L2 Accept

DAQ buffers

L3 Farm

Mass Storage (30-50 Hz)

Level 1
- 2.7 MHz Synchromous Pipeline
- 5544 ns Latency
- ~20 KHz accept rate

Level 2
- Asynchromous 2 Stage Pipeline
- ~20 μs Latency
- 250 Hz accept rate

# …and a successful endeavor!

- SVT is capable of digesting >20000 evts/second to identifying tracks in the silicon

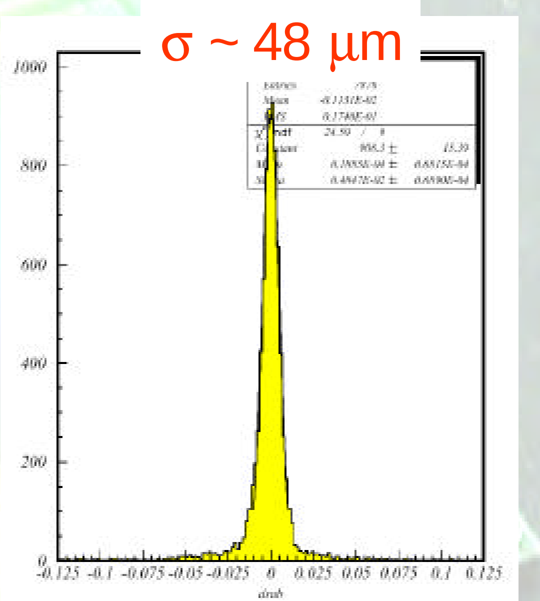
- CDFII has been running it since day -1

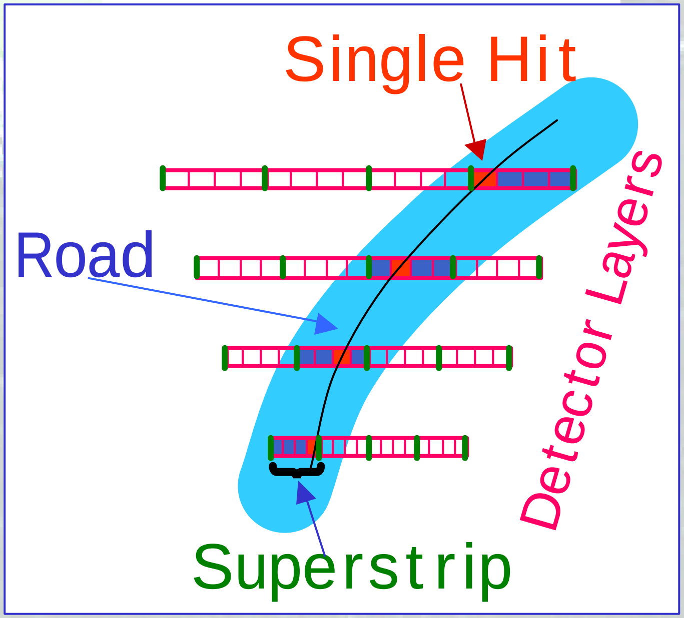
- The recipe uses specialized hardware:
  - 1)Clustering

    Find clusters (hits) from detector 'strips' at full detector resolution
  - 2)Template matching

    Identify roads: pre-defined track templates with coarser detector bins (superstrips)
  - 3)Linearized track fitting

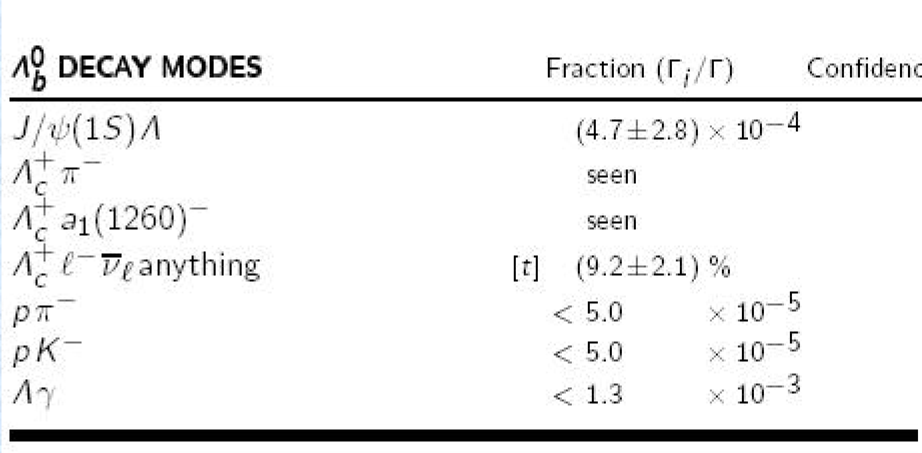
    Fit tracks, with combinatorial limited to clusters within roads



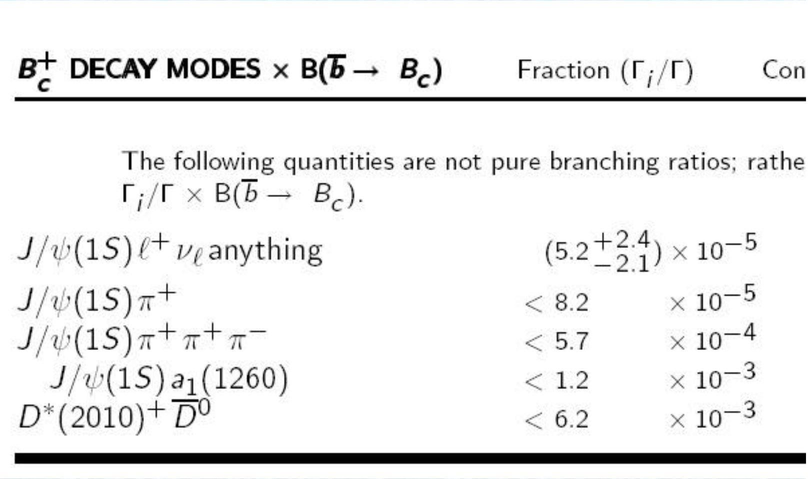


# Benchmarks

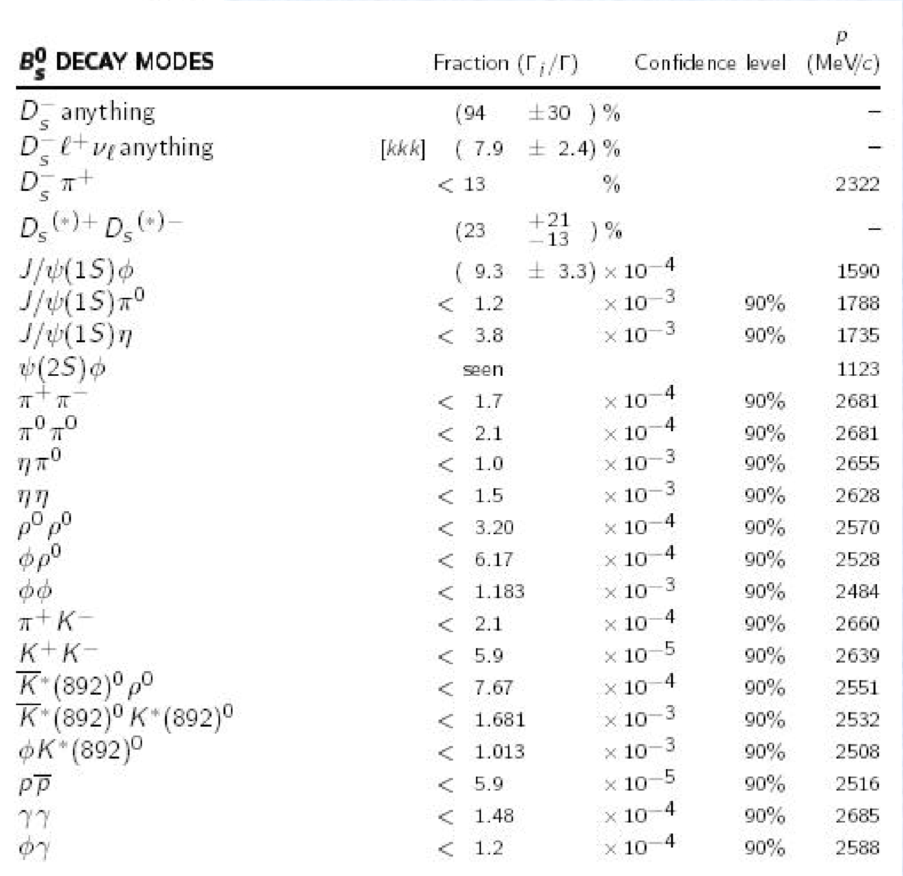
# What was known about non-$\Upsilon$-produced b (PDG'04)



| $\Lambda_b^0$ DECAY MODES | | Fraction ($\Gamma_i/\Gamma$) | Confidence level | $p$ (MeV/$c$) |
|---|---|---|---|---|
| $J/\psi(1S)\Lambda$ | | $(4.7\pm2.8)\times10^{-4}$ | | 1744 |
| $\Lambda_c^+\pi^-$ | | seen | | 2345 |
| $\Lambda_c^+ a_1(1260)^-$ | | seen | | |
| $\Lambda_c^+\ell^-\overline{\nu}_\ell$ anything | [$t$] | $(9.2\pm2.1)$ % | | |
| $p\pi^-$ | | $< 5.0 \times10^{-5}$ | | |
| $pK^-$ | | $< 5.0 \times10^{-5}$ | | |
| $\Lambda\gamma$ | | $< 1.3 \times10^{-3}$ | | |

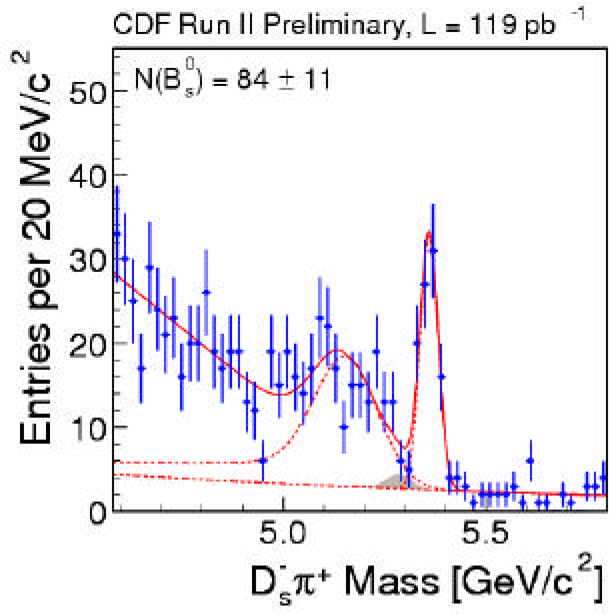


| $B_c^+$ DECAY MODES × B($\overline{b}\to B_c$) | Fraction ($\Gamma_i/\Gamma$) | Con |
|---|---|---|
| The following quantities are not pure branching ratios; rathe<br>$\Gamma_i/\Gamma\times$ B($\overline{b}\to B_c$). | | |
| $J/\psi(1S)\ell^+\nu_\ell$ anything | $(5.2^{+2.4}_{-2.1})\times10^{-5}$ | |
| $J/\psi(1S)\pi^+$ | $< 8.2 \times10^{-5}$ | |
| $J/\psi(1S)\pi^+\pi^+\pi^-$ | $< 5.7 \times10^{-4}$ | |
| $J/\psi(1S)a_1(1260)$ | $< 1.2 \times10^{-3}$ | |
| $D^*(2010)^+\overline{D}^0$ | $< 6.2 \times10^{-3}$ | |



| $B_s^0$ DECAY MODES | | Fraction ($\Gamma_i/\Gamma$) | Confidence level | $p$ (MeV/$c$) |
|---|---|---|---|---|
| $D_s^-$ anything | | $(94 \pm30)$ % | | – |
| $D_s^-\ell^+\nu_\ell$ anything | [$kkk$] | $(7.9 \pm 2.4)$ % | | – |
| $D_s^-\pi^+$ | | $< 13$ % | | 2322 |
| $D_s^{(*)+}D_s^{(*)-}$ | | $(23 {}^{+21}_{-13})$ % | | – |
| $J/\psi(1S)\phi$ | | $(9.3 \pm 3.3)\times10^{-4}$ | | 1590 |
| $J/\psi(1S)\pi^0$ | | $< 1.2 \times10^{-3}$ | 90% | 1788 |
| $J/\psi(1S)\eta$ | | $< 3.8 \times10^{-3}$ | 90% | 1735 |
| $\psi(2S)\phi$ | | seen | | 1123 |
| $\pi^+\pi^-$ | | $< 1.7 \times10^{-4}$ | 90% | 2681 |
| $\pi^0\pi^0$ | | $< 2.1 \times10^{-4}$ | 90% | 2681 |
| $\eta\pi^0$ | | $< 1.0 \times10^{-3}$ | 90% | 2655 |
| $\eta\eta$ | | $< 1.5 \times10^{-3}$ | 90% | 2628 |
| $\rho^0\rho^0$ | | $< 3.20 \times10^{-4}$ | 90% | 2570 |
| $\phi\rho^0$ | | $< 6.17 \times10^{-4}$ | 90% | 2528 |
| $\phi\phi$ | | $< 1.183 \times10^{-3}$ | 90% | 2484 |
| $\pi^+K^-$ | | $< 2.1 \times10^{-4}$ | 90% | 2660 |
| $K^+K^-$ | | $< 5.9 \times10^{-5}$ | 90% | 2639 |
| $\overline{K}^*(892)^0\rho^0$ | | $< 7.67 \times10^{-4}$ | 90% | 2551 |
| $\overline{K}^*(892)^0K^*(892)^0$ | | $< 1.681 \times10^{-3}$ | 90% | 2532 |
| $\phi K^*(892)^0$ | | $< 1.013 \times10^{-3}$ | 90% | 2508 |
| $p\overline{p}$ | | $< 5.9 \times10^{-5}$ | 90% | 2516 |
| $\gamma\gamma$ | | $< 1.48 \times10^{-4}$ | 90% | 2685 |
| $\phi\gamma$ | | $< 1.2 \times10^{-4}$ | 90% | 2588 |

# Measure: Branching Ratios



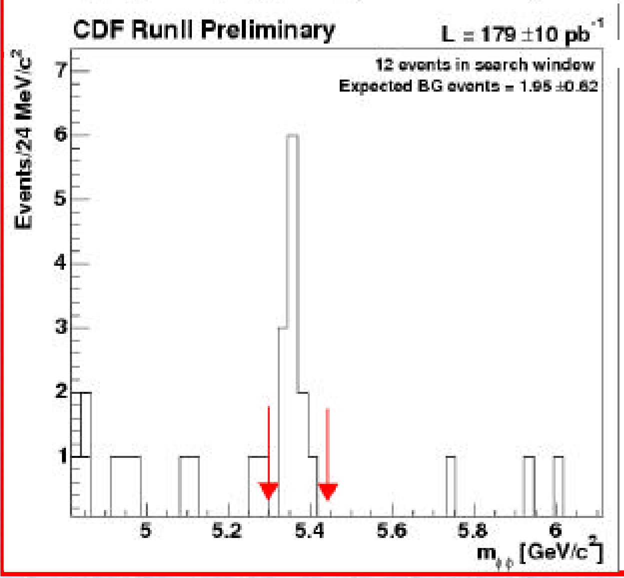
## First-time measurement of many $B_s$ and $\Lambda_b$ Branching Fractions

$$\frac{f_s}{f_d}\cdot\frac{Br(B_s\to D_s^-\pi^+)}{Br(B^0\to D^-\pi^+)} = 0.35\pm0.05(stat)\pm0.04(syst)\pm0.09(BR)$$

http://www-cdf.fnal.gov/physics/new/bottom/031002.blessed-bs-br/

$$BR(B_s\to\phi\phi) = (1.4\pm0.6(stat.)\pm0.2(syst.)\pm0.5(BR's))\cdot10^{-5}$$

Hep-ex/0502044



$$\frac{\mathrm{Br}(B_s\to\psi(2S)\phi)}{\mathrm{Br}(B_s\to J/\psi\phi)} = 0.52\pm0.13[\mathrm{stat}]\pm0.06[BR]\pm0.04[\mathrm{sys}]$$

http://www-cdf.fnal.gov/physics/new/bottom/050310.blessed-dsd/

$$\frac{Br(B^0\to\ D_s^+D^-)}{Br(B^0\to\ D^-3\pi)} = 2.00\pm0.16(NC)\pm0.12(syst)\pm0.50(BR)$$

http://www-cdf.fnal.gov/physics/new/bottom/050310.blessed-dsd/

$$\frac{BR(\Lambda_b\to\Lambda_c^+\pi^-)}{BR(\bar{B}^0\to D^+\pi^-)} = 3.3\pm0.3\ (\mathrm{stat})\pm0.4\ (\mathrm{syst})\pm1.1\ (\mathrm{BR+FR})$$

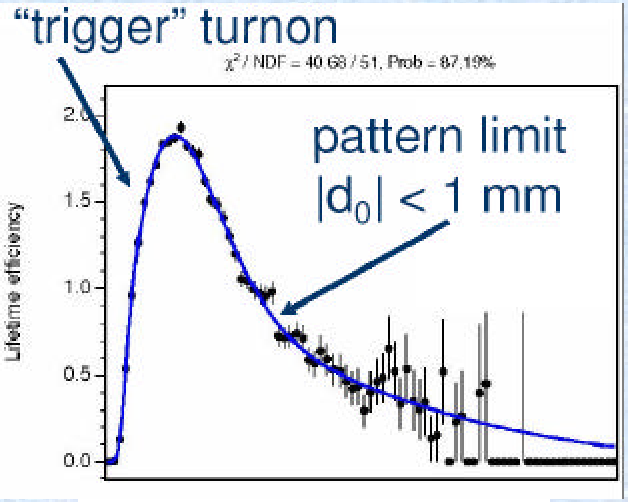
http://www-cdf.fnal.gov/physics/new/bottom/030702.blessed-lblcpi-ratio_new/

$$\frac{\mathcal{B}(\Lambda_b\to\Lambda_c^+\mu^-\overline{\nu}_\mu)}{\mathcal{B}(\Lambda_b\to\Lambda_c^+\pi^-)} = 20.0\ \pm3.0\ (stat)\pm1.2\ (syst)\begin{matrix}+0.7\\-2.1\end{matrix}\ (BR)\pm0.5\ (UBR)$$

http://www-cdf.fnal.gov/physics/new/bottom/050407.blessed-lbbr/

# Lifetimes: fully reconstructed hadronic modes

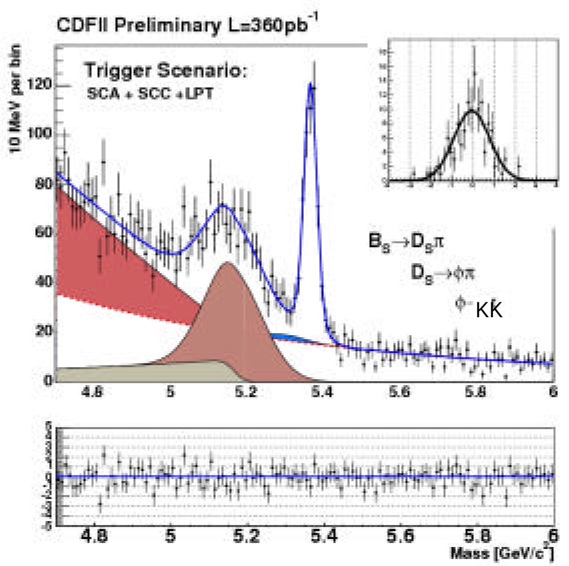
- Testbed for our ability to understand trigger biases
- Large, clean samples with understood backgrounds
- Excellent mass and vertex resolution
- Prerequisite for mixing fits!

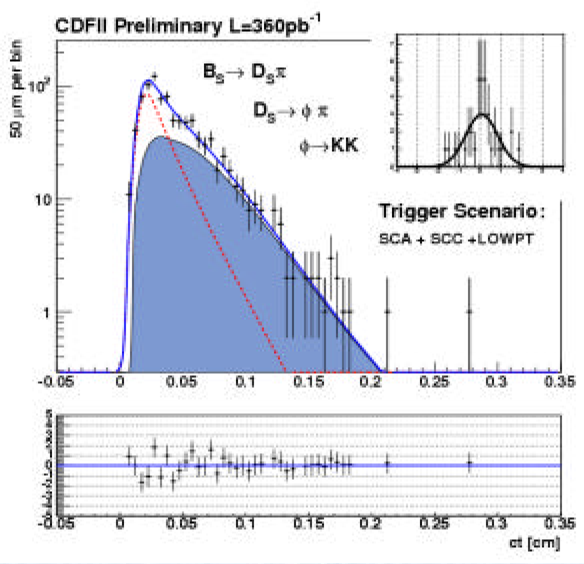

“trigger” turnon

pattern limit $|d_0| < 1$ mm

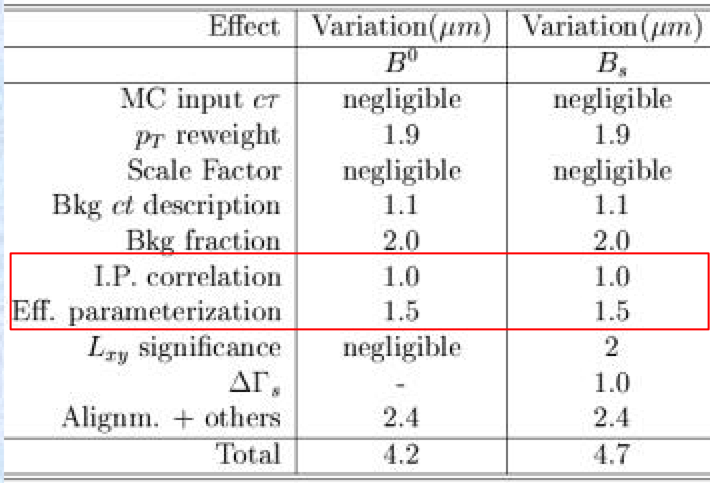
$\tau(B^+)$ = **1.661±0.027±0.013 ps**
$\tau(B^0)$ = **1.511±0.023±0.013 ps**

$\tau(B_s)$ = **1.598±0.097±0.017 ps**





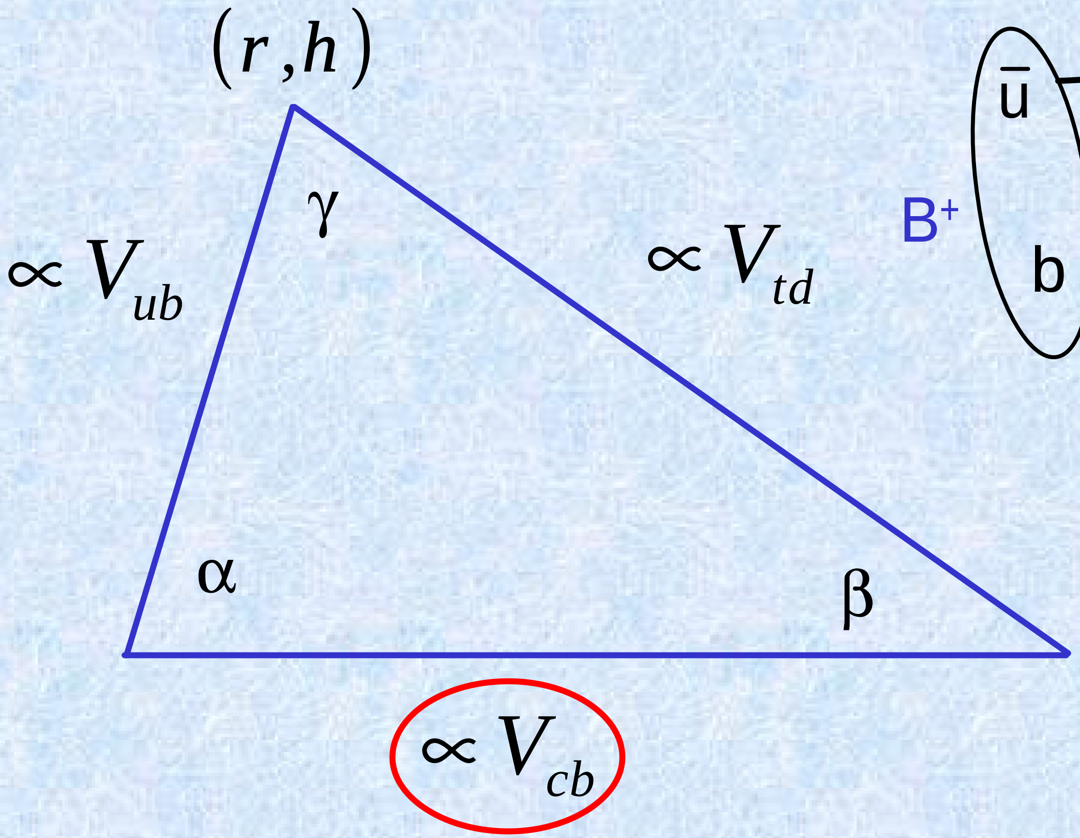
## Systematics (μm)

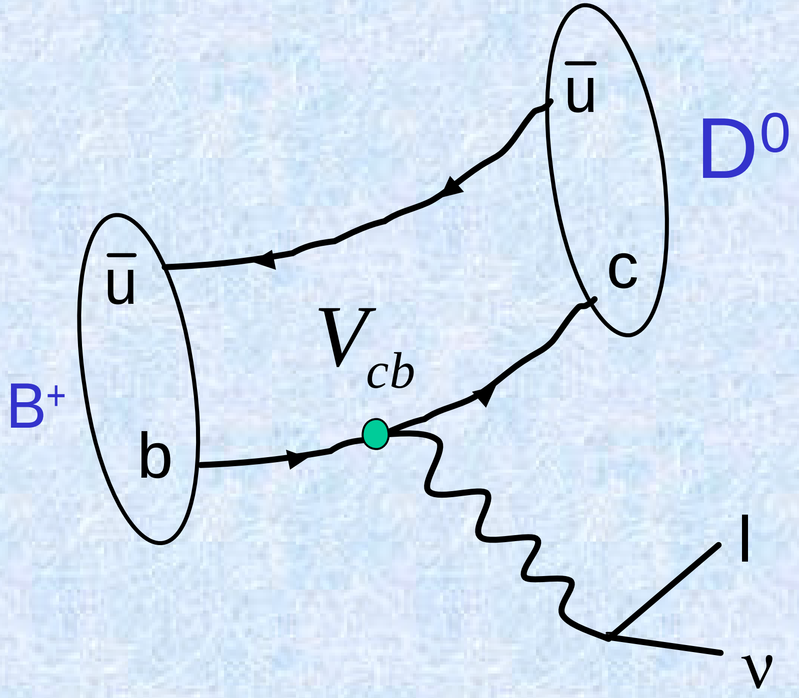


| Effect | Variation($\mu m$) | Variation($\mu m$) |
|---|---|---|
| | $B^0$ | $B_s$ |
| MC input $c\tau$ | negligible | negligible |
| $p_T$ reweight | 1.9 | 1.9 |
| Scale Factor | negligible | negligible |
| Bkg $ct$ description | 1.1 | 1.1 |
| Bkg fraction | 2.0 | 2.0 |
| I.P. correlation | 1.0 | 1.0 |
| Eff. parameterization | 1.5 | 1.5 |
| $L_{xy}$ significance | negligible | 2 |
| $\Delta\Gamma_s$ | - | 1.0 |
| Alignm. + others | 2.4 | 2.4 |
| Total | 4.2 | 4.7 |

# Improving SM Tools

# Closing up on CKM





- QCD corrections ↔ uncertainty on the b wave function inside the meson
- This is something that can be constrained experimentally!

# Improving phenomenological tools: Hadronic Moments

No room for everything… I will focus on one example:

- HQET/OPE is a fundamental tool for CKM physics with B mesons. For instance it relates:
  - $B \to X_u l\nu$ to $[b \to u l\nu] \Rightarrow V_{ub}$
  - $B \to X_c l\nu$ to $[b \to c l\nu] \Rightarrow V_{cb}$
- OPE is “semi-empirical”: parameterizes any prediction in a series expansion of effective operators
- Expectation value of these operators is a “universal” property of the theory which can be assessed with concurrent measurements
- Example: $V_{cb}$ $(\pm 1\%_{exp} \pm 2.5\%_{theo})$ ⇔ Hadronic Moments

# Moments-ology

Many inclusive observables can be written using the same expansion (same non-perturbative parameters). The spectral moments:

- **Photonic moments:** Photon energy in b → s $\gamma$ (CLEO)
- **Leptonic moments:** $B \to X_c l\nu$, lepton E in B rest frame (CLEO, DELPHI, BABAR)
- **Hadronic moments:** $B \to X_c l\nu$, recoil mass $M(X_c)$ (CLEO, DELPHI, BABAR, CDFII)

$$M_1 = \int_{s_H^{min}}^{s_H^{max}} ds_H \left(s_H - \overline{m}_D^2\right) \frac{1}{\Gamma_{sl}} \frac{d\Gamma_{sl}}{ds_H} = \langle s_H \rangle - \overline{m}_D^2 \,, \qquad s_H \equiv M_{X_c}^2$$

$$M_2 = \int_{s_H^{min}}^{s_H^{max}} ds_H \left(s_H - \langle s_H \rangle\right)^2 \frac{1}{\Gamma_{sl}} \frac{d\Gamma_{sl}}{ds_H} = \left\langle \left(s_H - \overline{m}_D^2\right)^2 \right\rangle - M_1^2$$

**Aim:** Constrain the unknown non-pert. parameters and reduce $|V_{cb}|$ uncertainty.

With enough measurements: test of underlying assumptions (duality...).

# What is $X_c$?

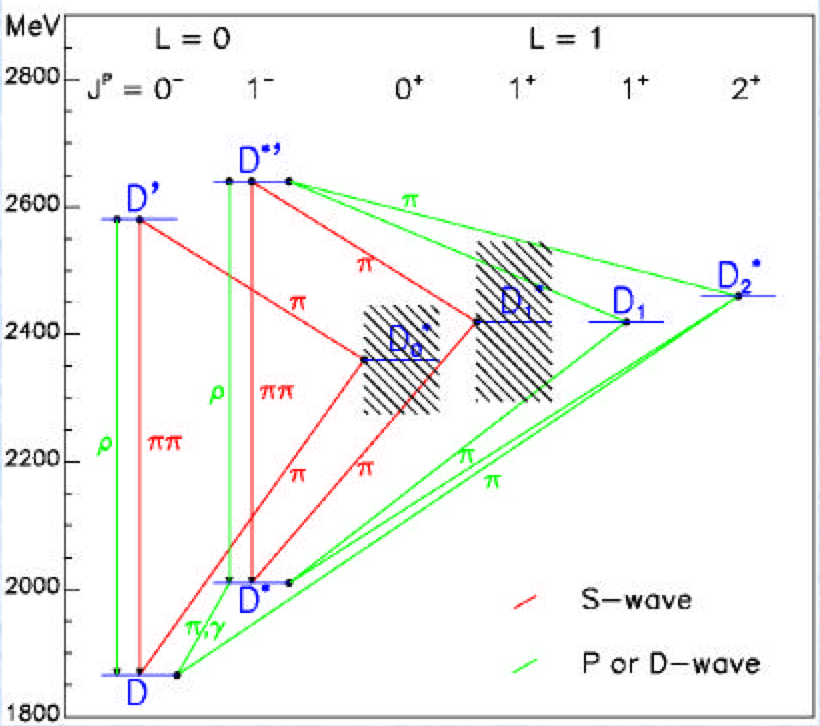
Semi-leptonic widths (PDG 04):

| | Br (%) |
|---|---|
| $B^+ \rightarrow X_c$ l n | 10.99 ± 0.31 |
| $B^+ \rightarrow D^*$ l n | 6.04 ± 0.23 |
| $B^+ \rightarrow D$ l n | 2.23 ± 0.15 |

(PDG b/$B^+$/$B^0$ combination, b→u subtracted)

→~25% of semi-leptonic width is poorly known

Higher mass states: D**



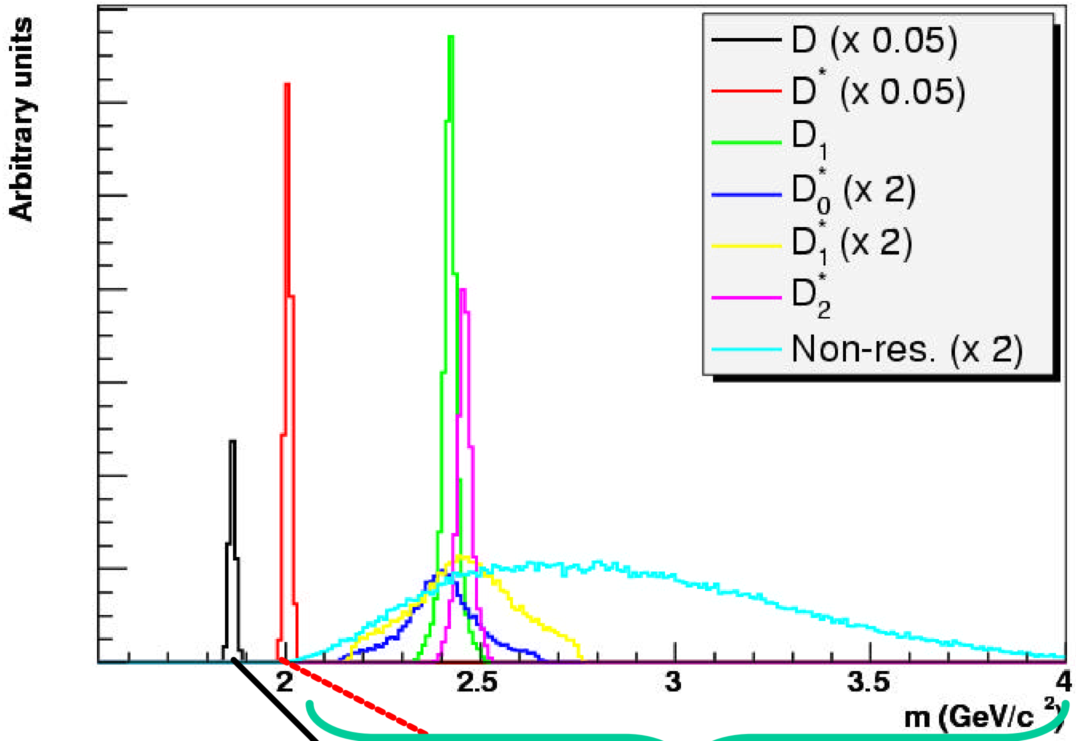
Possible D'→$D^{(*)}\pi\pi$ contributions neglected:

- No B→lD' experimental evidence so far
- DELPHI limit: $\begin{cases} BR(b \rightarrow D^+ p^+ p^- \ell^- n) < 0.18\% \text{ @ } 90\% \ CL \\ BR(b \rightarrow D^{*+} p^+ p^- \ell^- n) < 0.17\% \text{ @ } 90\% \ CL \end{cases}$

We assume no D' contribution in our sample

# Analysis Strategy

Typical mass spectrum $M(X^0_c)$ (Monte Carlo):



$$s_H \equiv M^2_{X_c}$$

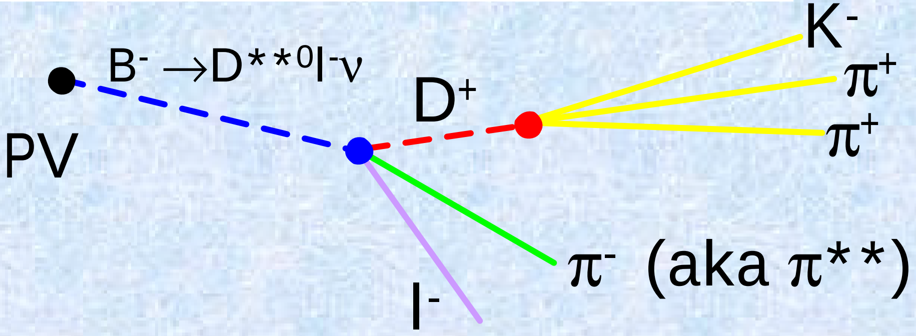
$D^0$ and $D^{*0}$ well-known
➔ measure only f**
➔ only shape needed

1) Measure $f^{**}(s_H)$
2) Correct for background, acceptances, bias
➔ moments of D**
3) Add D and D* ➔ $M_1, M_2$
4) Extract OPE parameters $(L, l_1)$

$$\frac{1}{\Gamma_{sl}}\frac{d\Gamma_{sl}}{ds_H} = \frac{\Gamma_0}{\Gamma_{sl}}\cdot\delta(s_H - m^2_{D^0}) + \frac{\Gamma_*}{\Gamma_{sl}}\cdot\delta(s_H - m^2_{D^{*0}}) + \left(1 - \frac{\Gamma_0}{\Gamma_{sl}} - \frac{\Gamma_*}{\Gamma_{sl}}\right)\cdot f^{**}(s_H)$$

# $D^+/D^{*+}$ Reconstruction

Exclusive reconstruction of $D^{**}$:



$D^{**0} \Rightarrow D^{*+}\, \pi^{**-}$

"$D^{*+}$"

$\hookrightarrow D^0\, \pi^{*+}$ (Br=67.7%)

$\hookrightarrow K^-\, \pi^+$ (Br=3.8%)

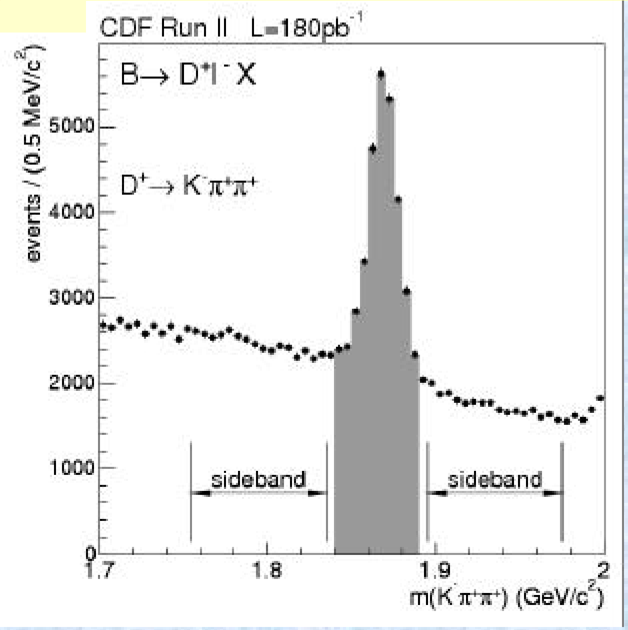
$\hookrightarrow K^-\, \pi^+\, \pi^-\, \pi^+$ (Br=7.5%)

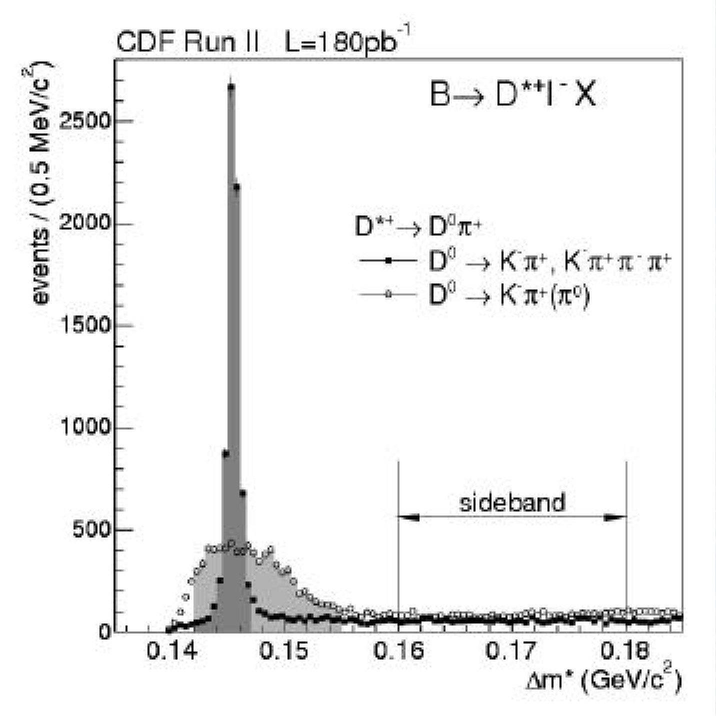
$\hookrightarrow K^-\, \pi^+\, \pi^0$ (Br=13.0%)

$D^{**0} \Rightarrow D^+\, \pi^{**-}$

"$D^+$"

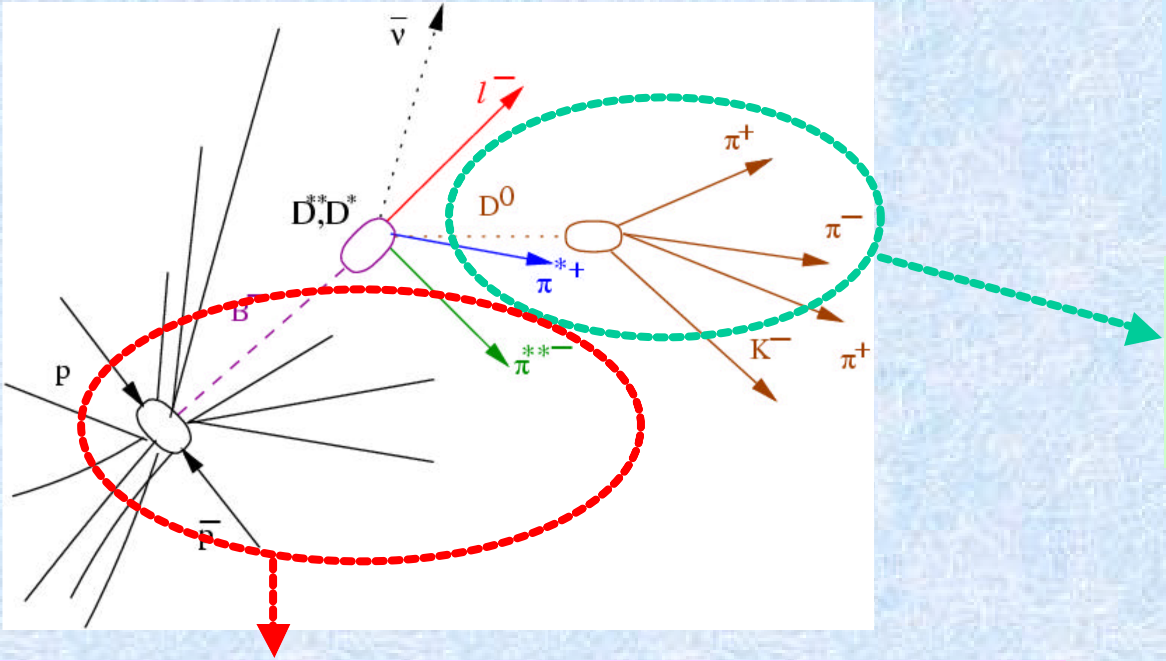
$\hookrightarrow K^-\, \pi^+\, \pi^+$ (Br=9.2%)





~28K e/$\mu$D Candidates in total!

# Backgrounds



Physics background:
$B \rightarrow D^{(*)+}D_s^-$, $D_{(s)} \rightarrow Xl\nu$
➔ MC, subtracted

Combinatorial background under the $D^{(*)}$ peaks:
➔ sideband subtraction

Prompt pions faking $\pi^{**}$:

- **fragmentation**
- **underlying event**

**➔separate B and primary vertices**
(kills also prompt charm)
➔ use impact parameters to discriminate
➔ model: wrong-sign $\pi^{**+}\ell^-$ combinations

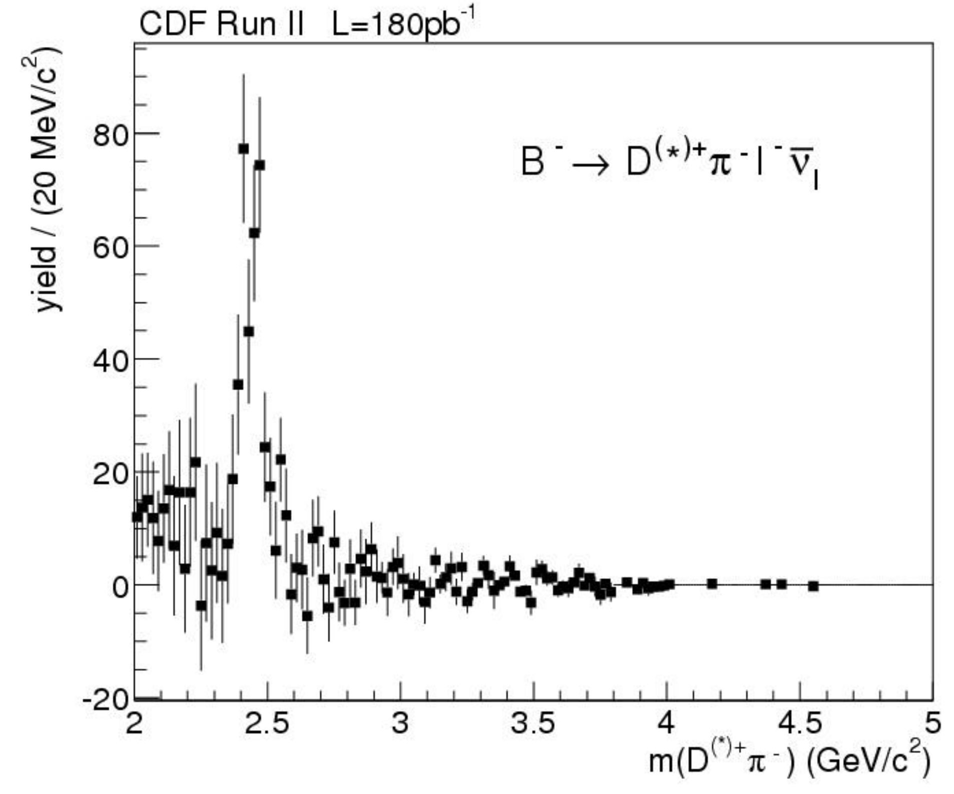
Feed-down in signal:
$D^{**0} \rightarrow D^{*+}(\rightarrow D^+\pi^0)\pi^-$
irreducible background to $D^{**0} \rightarrow D^+\pi^-$.
➔subtracted using data:
➔shape from $D^0\pi^-$ in
$D^{**0} \rightarrow D^{*+}(\rightarrow D^0\pi^+)\pi^-$
➔rate:
½ (isospin) x eff. x BR

# Corrected Mass and D** moments

## Procedure:

- Unbinned procedure using weighted events.
- Assign negative weights to background samples.
- Propagate efficiency corrections to weights.
- Take care of the $D^+$ / $D^{*+}$ relative normalization.
- Compute mean and sigma of distribution.

## Results (in paper):



$$m_1 = \left\langle m_{D^{**}}^2 \right\rangle = \left(5.83 \pm 0.16_{stat}\right) GeV^2$$

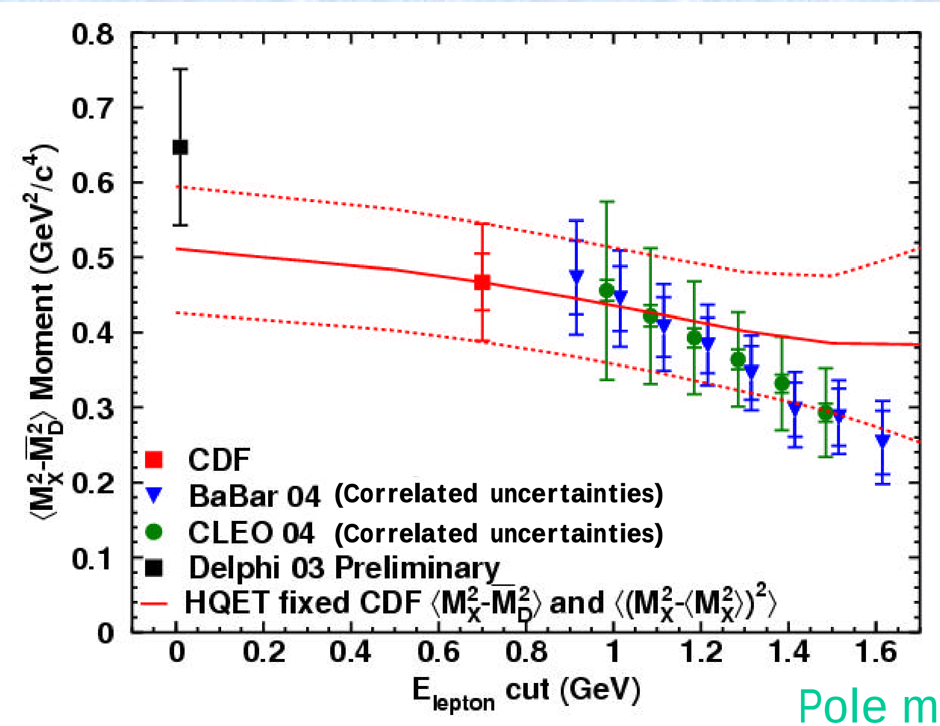
$$m_2 = \left\langle \left(m_{D^{**}}^2 - m_1\right)^2 \right\rangle = \left(1.30 \pm 0.69_{stat}\right) GeV^4$$

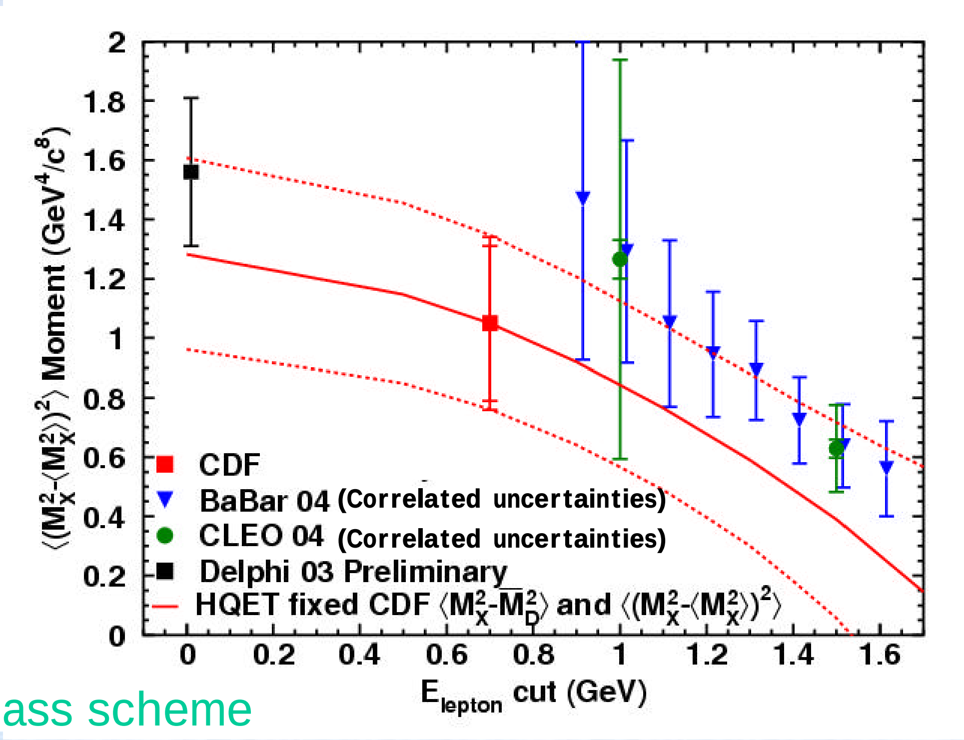
No Fit !!!

# Systematic Errors

| | $\Delta m_1$ ($GeV^2$) | $\Delta m_2$ ($GeV^4$) | $\Delta M_1$ ($GeV^2$) | $\Delta M_2$ ($GeV^4$) | $\Delta\Lambda$ (GeV) | $\Delta\lambda_1$ ($GeV^2$) |
|---|---|---|---|---|---|---|
| Stat. | 0.16 | 0.69 | 0.038 | 0.26 | 0.078 | 0.057 |
| Syst. | 0.08 | 0.22 | 0.068 | 0.13 | 0.091 | 0.082 |
| Mass resolution | 0.02 | 0.13 | 0.005 | 0.04 | 0.012 | 0.009 |
| Eff. Corr. (data) | 0.03 | 0.13 | 0.006 | 0.05 | 0.014 | 0.011 |
| Eff. Corr. (MC) | 0.06 | 0.05 | 0.016 | 0.03 | 0.017 | 0.006 |
| Bkgd. (scale) | 0.01 | 0.03 | 0.002 | 0.01 | 0.003 | 0.002 |
| Bkgd. (opt. Bias) | 0.02 | 0.10 | 0.004 | 0.03 | 0.006 | 0.006 |
| Physics bkgd. | 0.01 | 0.02 | 0.002 | 0.01 | 0.004 | 0.002 |
| $D^+$ / $D^{*+}$ BR | 0.01 | 0.02 | 0.002 | 0.01 | 0.004 | 0.002 |
| $D^+$ / $D^{*+}$ Eff. | 0.02 | 0.03 | 0.004 | 0.01 | 0.005 | 0.002 |
| Semileptonic BRs | | | 0.065 | 0.10 | 0.064 | 0.022 |
| $\rho_1$ | | | | | 0.041 | 0.069 |
| $T_i$ | | | | | 0.032 | 0.031 |
| $\alpha_s$ | | | | | 0.018 | 0.007 |
| $m_b$, $m_c$ | | | | | 0.001 | 0.008 |
| Choice of $p_l^*$ cut | | | | | 0.019 | 0.009 |

# Results & Comparison with other experiments

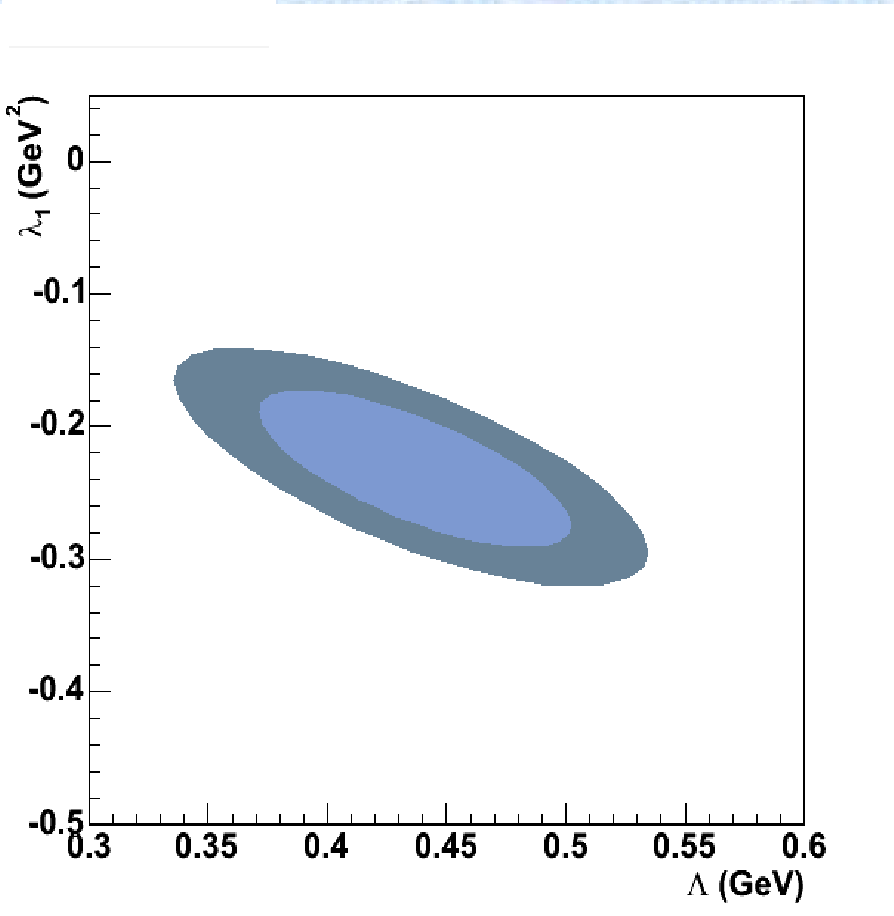




Pole mass scheme

- Good agreement with HQET ⊕ previous determinations.
- First measurement at hadron machines: different environment and experimental techniques.
- Competitive with other experiments.
- Little model dependency. No assumptions on shape or rate of D** components.
- Through integration with other experiments and other “moments” we can seriously probe HQET/QHD

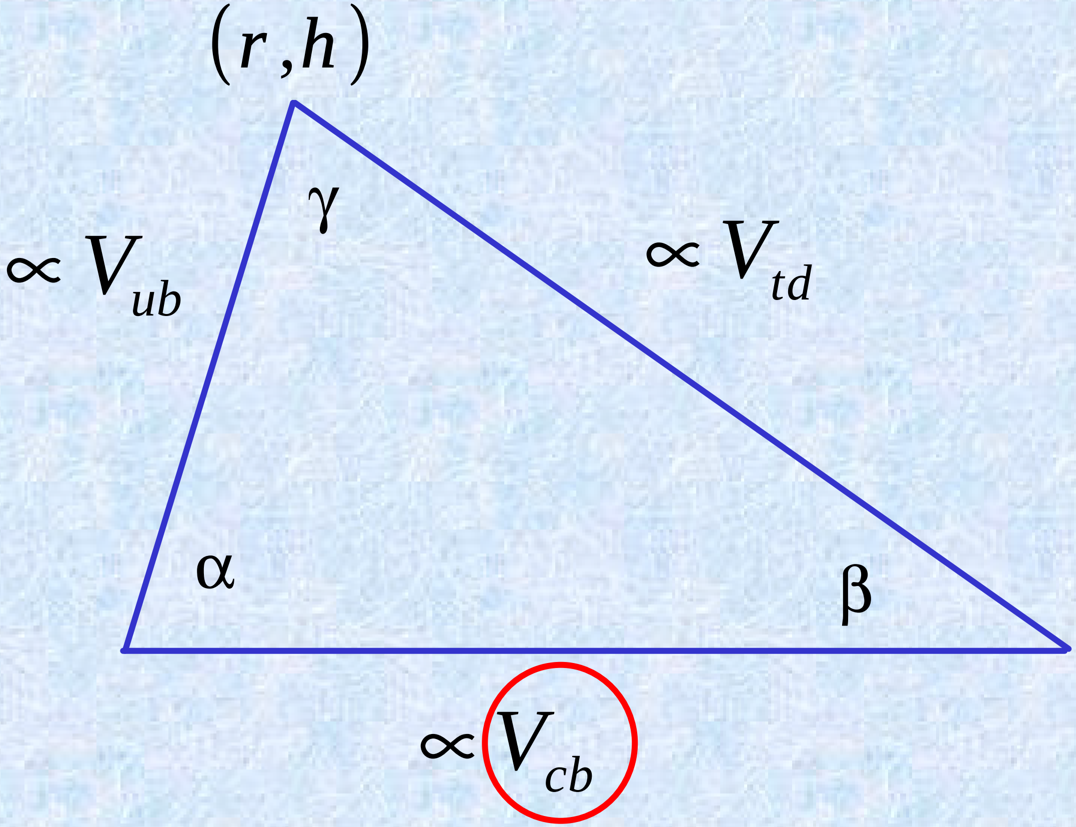
# Extraction of the HQE Parameters

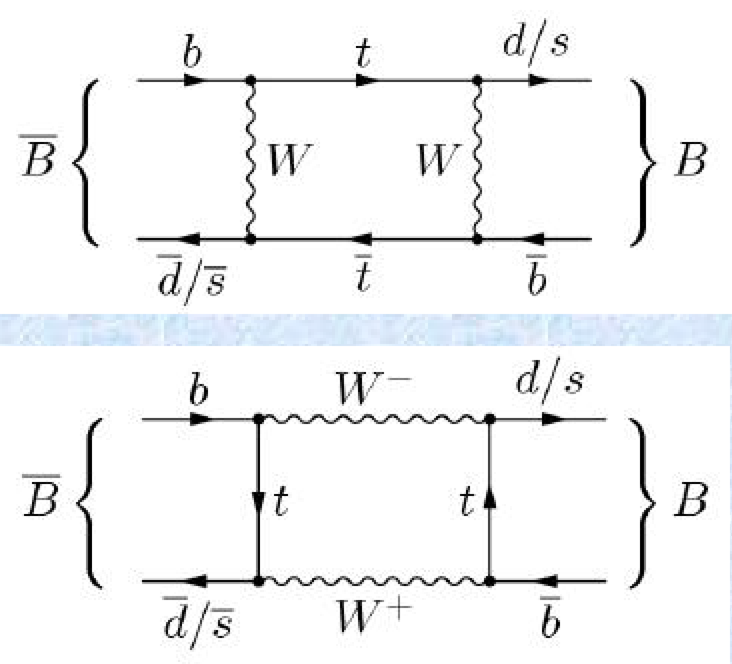


- Combination of all the experimental measurements of the hadronic moments
- Effective determination of the two OPE operators relevant at order $1/m_B$ ($\Lambda$) $1/m_B^2$ ($\lambda_1$)
- CDF contributes as much as the B factories in this determination!

# $B_s$ Mixing

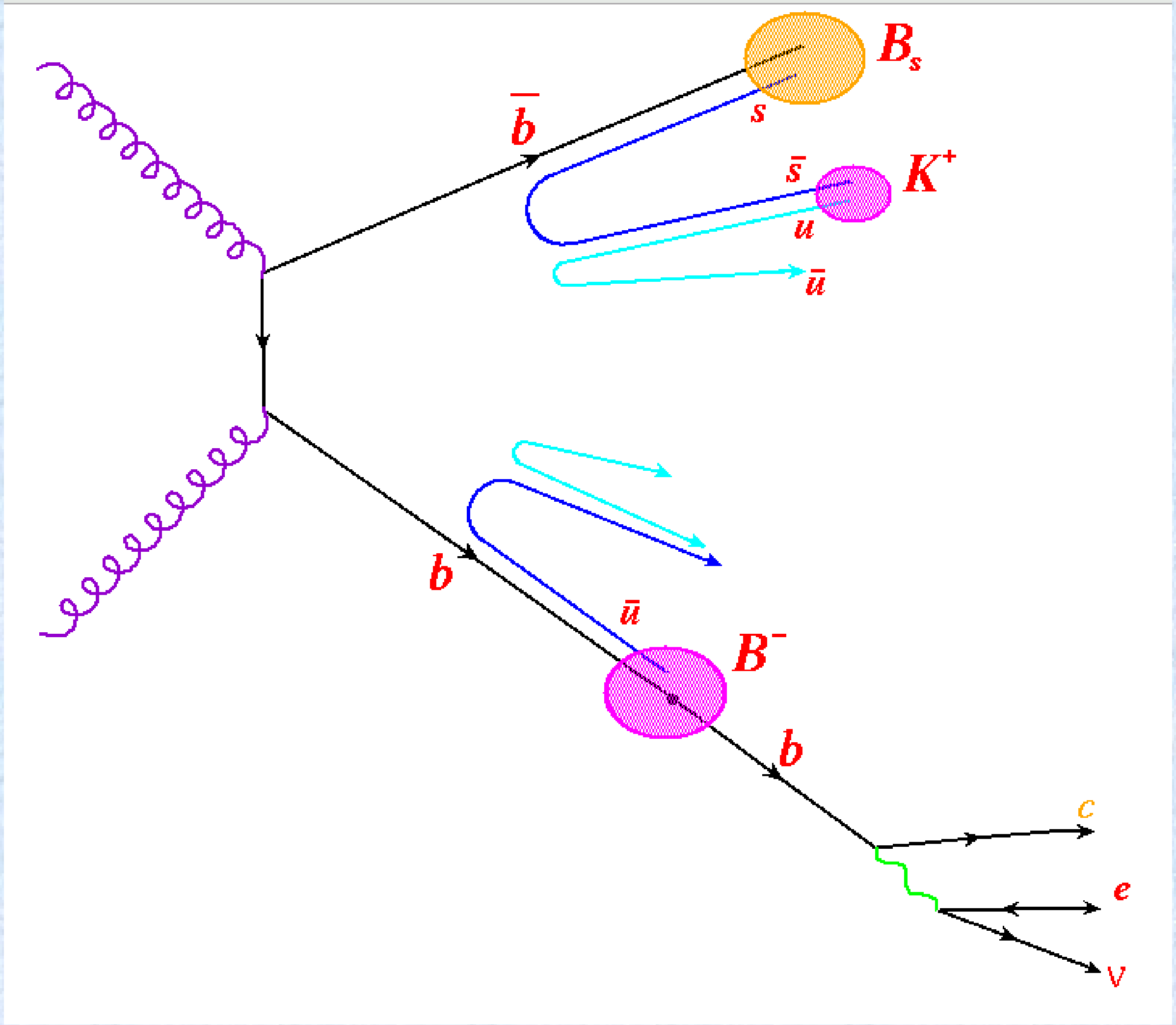
# Working our way on CKM sides





- $V_{td}$ is derived from mixing effects
- QCD uncertainty is factored out in this case resorting to the relative Bs/Bd mixing rate ($V_{td}/V_{ts}$)
- Beyond the SM physics could enter in loops!

# B production at the TeVatron



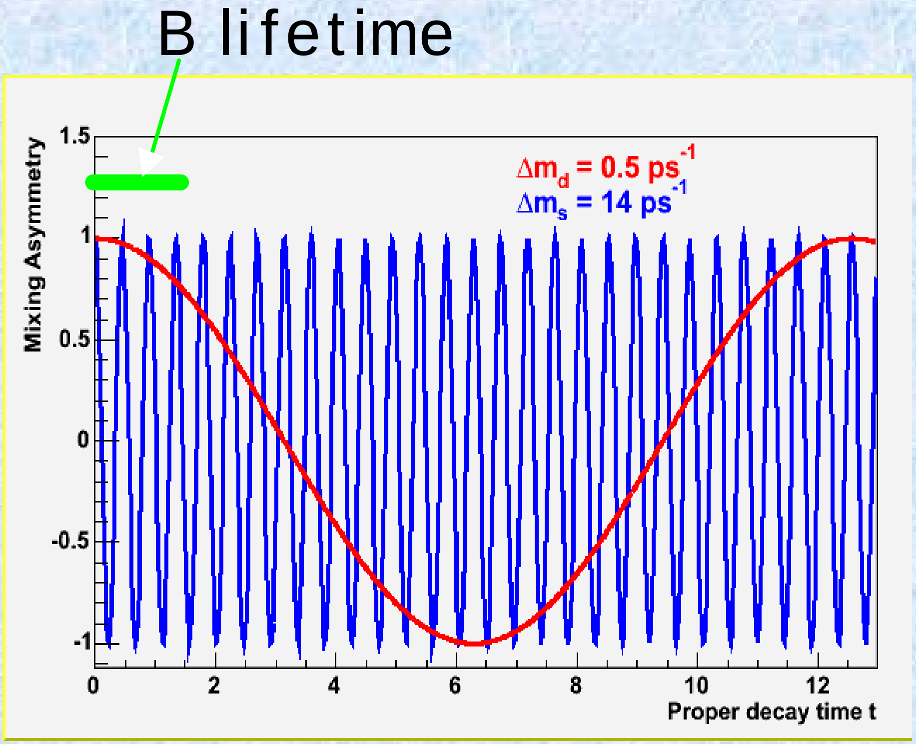
- Production: gg→bb
- NO QM coherence, unlike B factories
- Opposite flavor at production→one of the b quarks can be determined to assess the flavor of the other at production
- Fragmentation products have some memory of b flavor as well

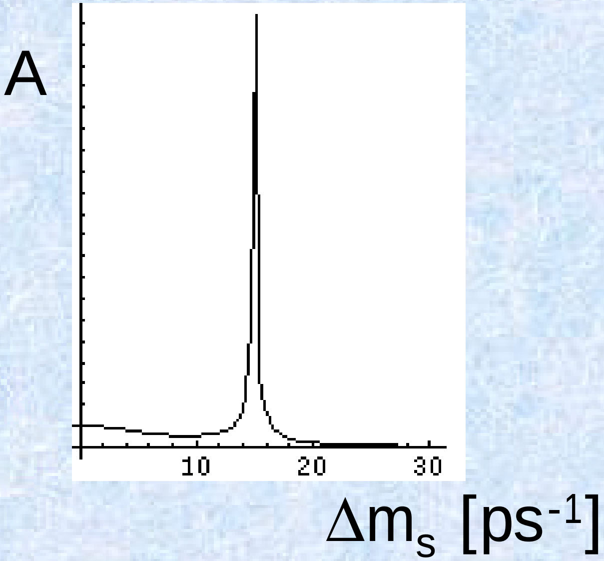
# $B_s$ Mixing 101

$$A=\frac{N_{unmix}-N_{mix}}{N_{unmix}+N_{mix}}$$

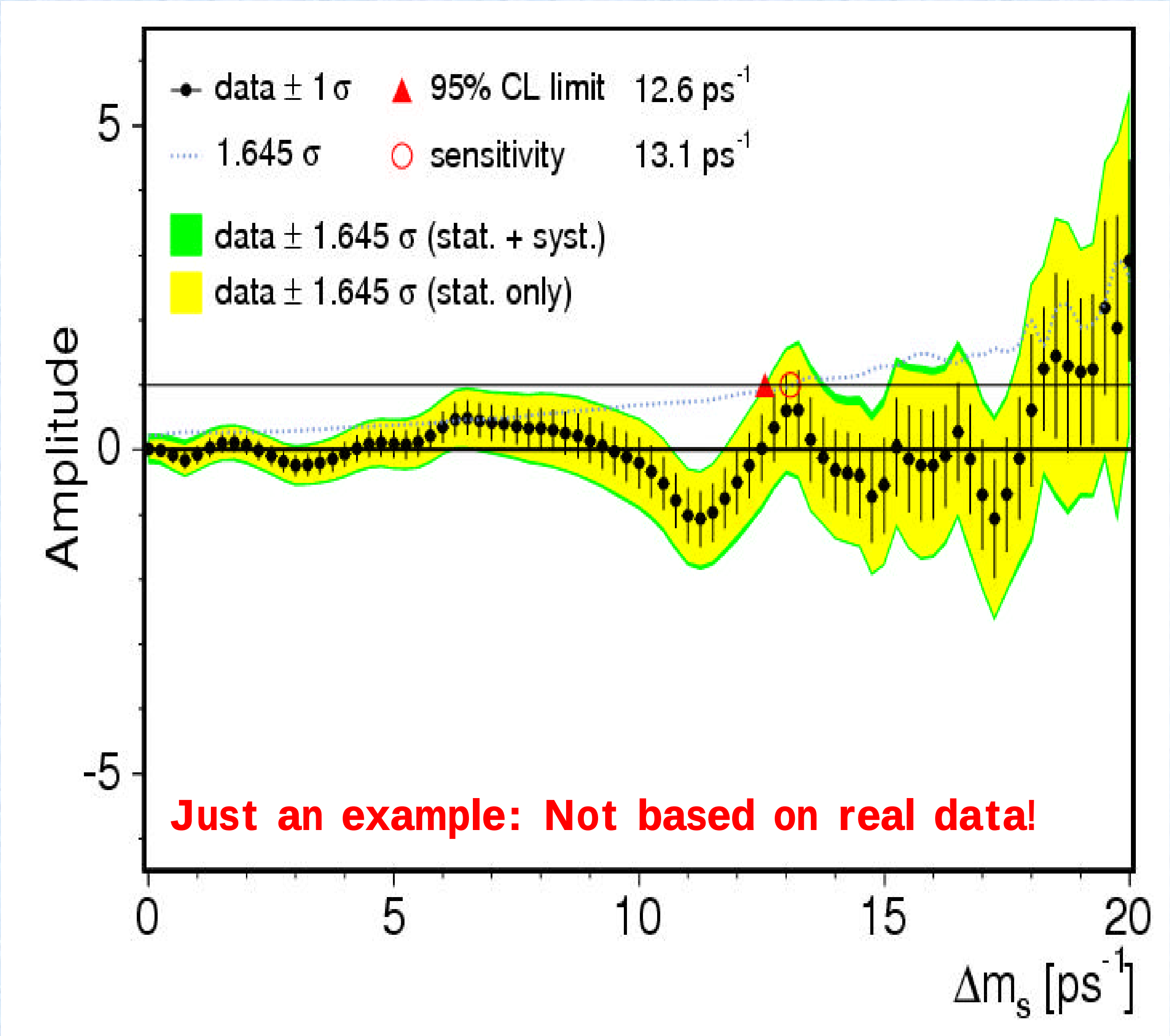
- $\Delta m_s \gg \Delta m_d$
- Different oscillation regime → Amplitude Scan

Perform a ‘fourier transform’ rather than fit for frequency



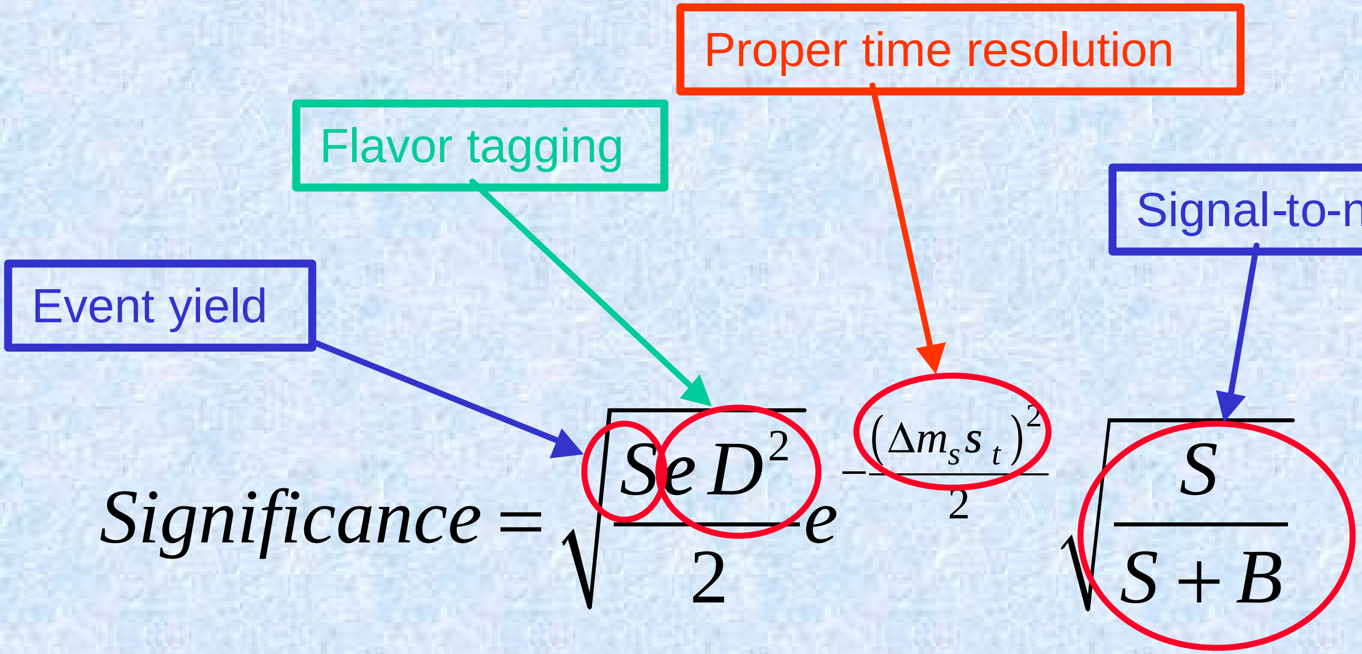


# Amplitude Scan



- Mixing amplitude fitted for each (fixed) value of Δm
- On average every Δm value (except the true Δm) will be 0
- "sensitivity" defined for the average experiment [mean 0]
- The actual experiment will have statistical fluctuations
- Actual limit for the actual experiment defined by the systematic band centered at the measured asymmetry

# $B_s$ Mixing Ingredients



Proper time resolution

Flavor tagging

Signal-to-noise

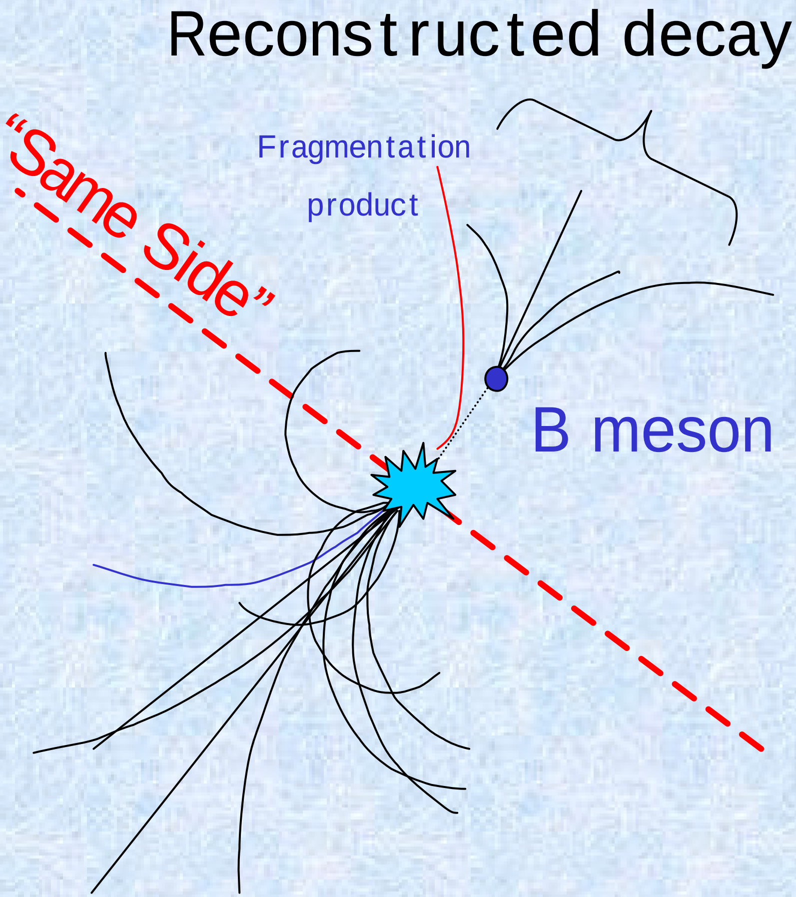
Event yield

$$Significance = \sqrt{\frac{S\epsilon D^2}{2}}\, e^{-\frac{(\Delta m_s \sigma_t)^2}{2}} \sqrt{\frac{S}{S+B}}$$

# Flavor Tagging

$$Significance = \sqrt{\frac{S\boxed{e D^2}}{2}}\, e^{-\frac{(\Delta m_s s_t)^2}{2}} \sqrt{\frac{S}{S+B}}$$

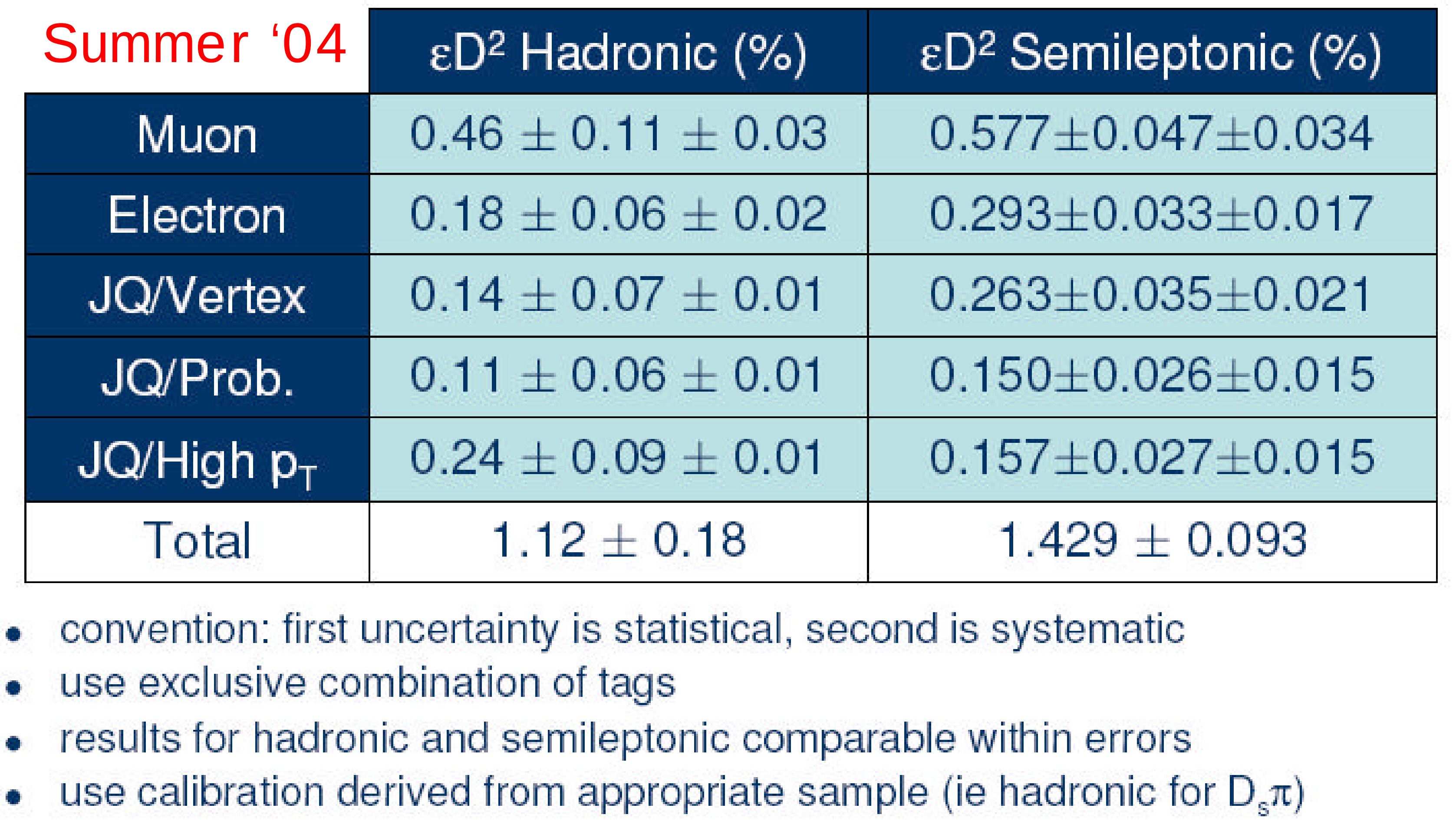
$$A = \frac{N_{unmix} - N_{mix}}{N_{unmix} + N_{mix}}$$



Several methods, none is perfect !!!

# $B_s$ Mixing: tagging performance

Measured from $B_d$ data!



| Summer '04 | $\varepsilon D^2$ Hadronic (%) | $\varepsilon D^2$ Semileptonic (%) |
|---|---|---|
| Muon | $0.46 \pm 0.11 \pm 0.03$ | $0.577 \pm 0.047 \pm 0.034$ |
| Electron | $0.18 \pm 0.06 \pm 0.02$ | $0.293 \pm 0.033 \pm 0.017$ |
| JQ/Vertex | $0.14 \pm 0.07 \pm 0.01$ | $0.263 \pm 0.035 \pm 0.021$ |
| JQ/Prob. | $0.11 \pm 0.06 \pm 0.01$ | $0.150 \pm 0.026 \pm 0.015$ |
| JQ/High $p_T$ | $0.24 \pm 0.09 \pm 0.01$ | $0.157 \pm 0.027 \pm 0.015$ |
| Total | $1.12 \pm 0.18$ | $1.429 \pm 0.093$ |

- convention: first uncertainty is statistical, second is systematic
- use exclusive combination of tags
- results for hadronic and semileptonic comparable within errors
- use calibration derived from appropriate sample (ie hadronic for $D_s\pi$)

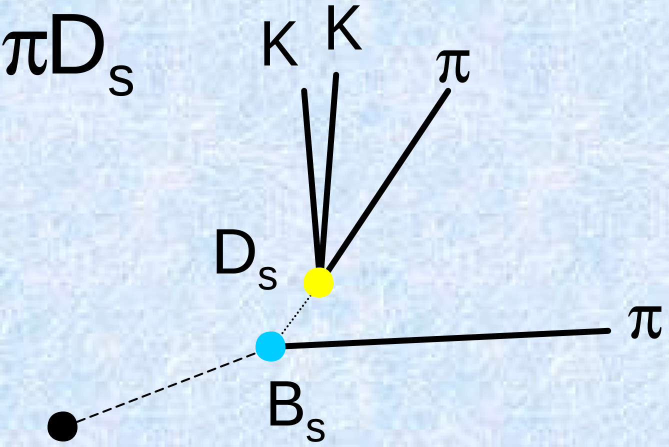
Fall '05 (mostly re-optimize existing taggers):

- $1.12 \pm 0.18 \rightarrow 1.55 \pm 0.16$
- $1.43 \pm 0.093 \rightarrow 1.55 \pm 0.085$

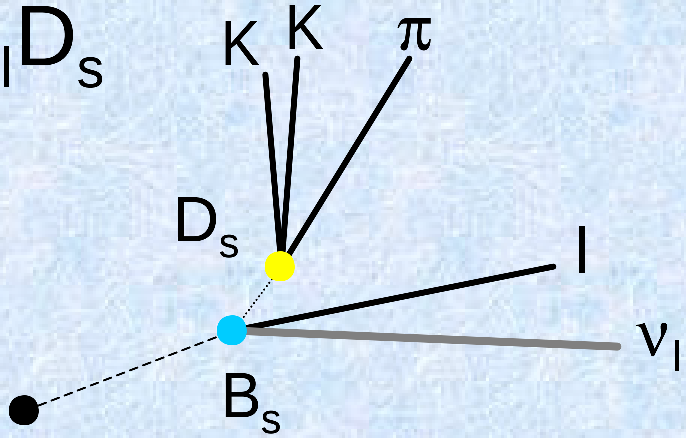
# Proper time resolution

$$Significance = \sqrt{\frac{S e D^2}{2}}\, e^{-\frac{(\Delta m_s \boxed{s_t})^2}{2}} \sqrt{\frac{S}{S+B}}$$

$B_s \rightarrow \pi D_s$



$B_s \rightarrow l \nu_l D_s$



$$ct = \frac{L_{xy}}{(bg)} = \frac{L_{xy} m_B}{p_T}$$

$$s_{ct} = \frac{m_B}{p_T} s_{L_{xy}} \oplus ct\left(\frac{s_{p_T}}{p_T}\right)$$

~0.5%

~15%

$$ct = \frac{m_B L_{xy}}{P_t(lD_s)} \cdot \left\langle \frac{P_t(lD_s)}{P_t(B_s)} \right\rangle_{mc}$$

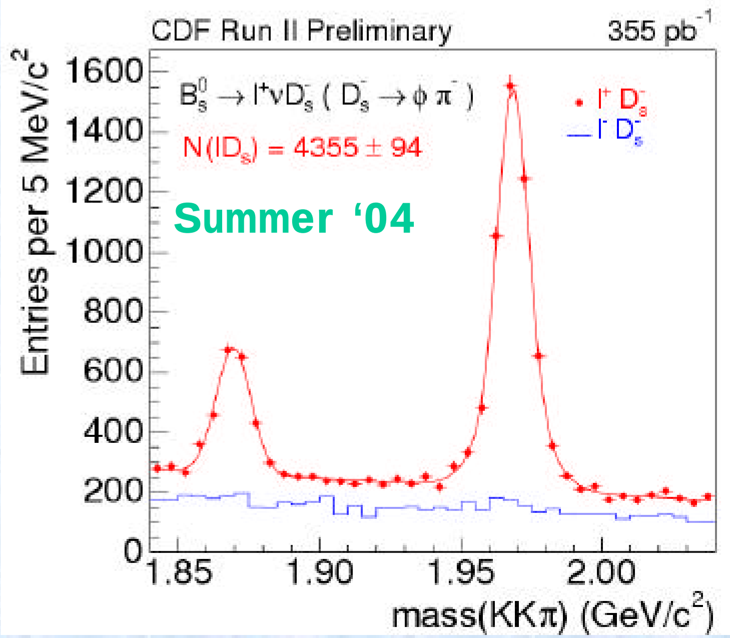
$$s_{ct} = \frac{m_B}{P_t} s_{L_{xy}} \oplus ct\overbrace{\left(\frac{s_{P_t}}{P_t}\right) \otimes s_K}$$

Semileptonic modes: momentum uncertainty

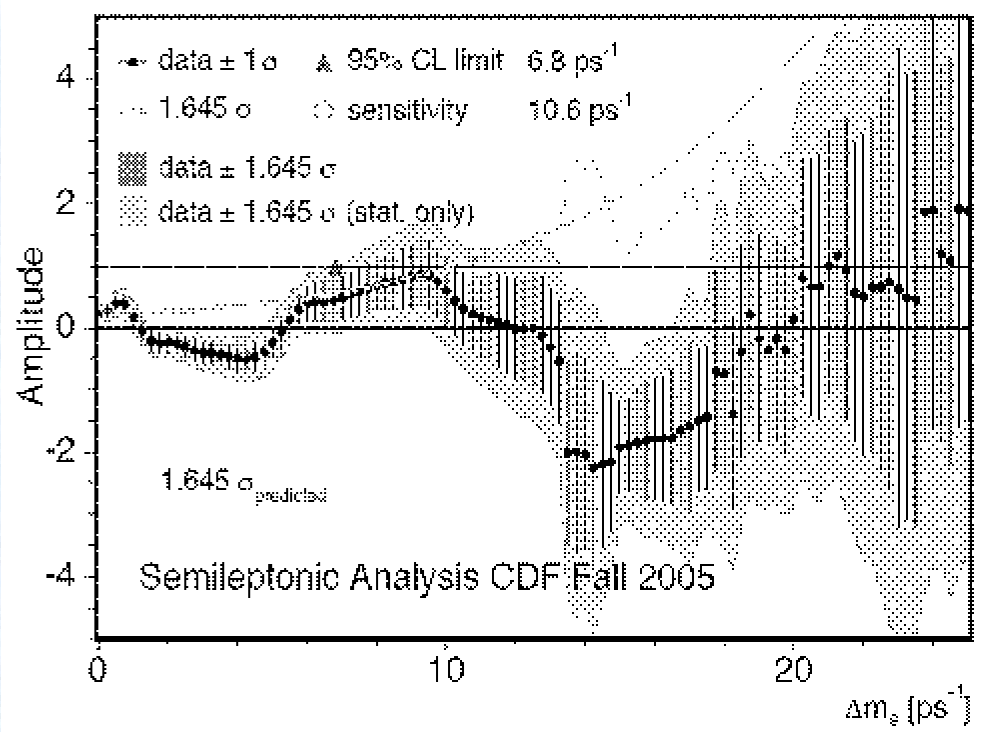
Fully reconstructed: Lxy uncertainty → improve reconstruction

# $B_s$ Mixing: semileptonic

- $B_s \rightarrow D_s l\nu$ Yield s/b
  - $D_s \rightarrow \phi\pi$ (4350±100 3.1 )
  - $D_s \rightarrow K^*K$ (1750±80 0.42 )
  - $D_s \rightarrow \pi\pi\pi$ (1570±90 0.32)



Summer '04



$\Delta m_s > 6.8\ \mathrm{ps}^{-1}$ @ 95% CL

Sensitivity: 10.6 ps$^{-1}$

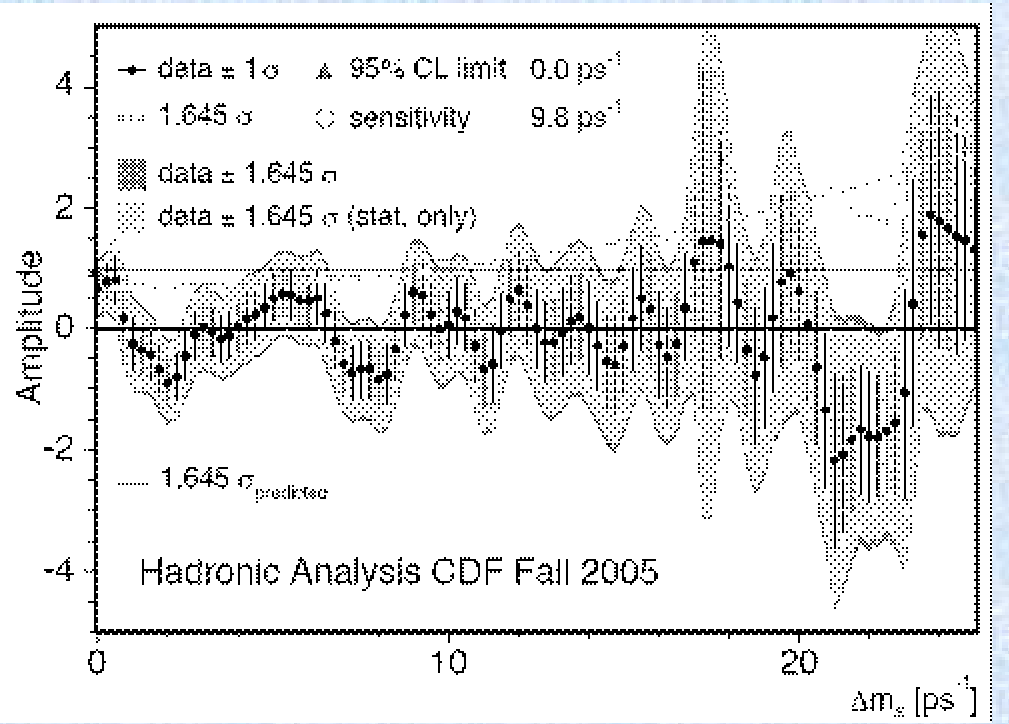
Reach at large $\Delta m_s$ limited by incomplete reconstruction ($\sigma_{ct}$)!

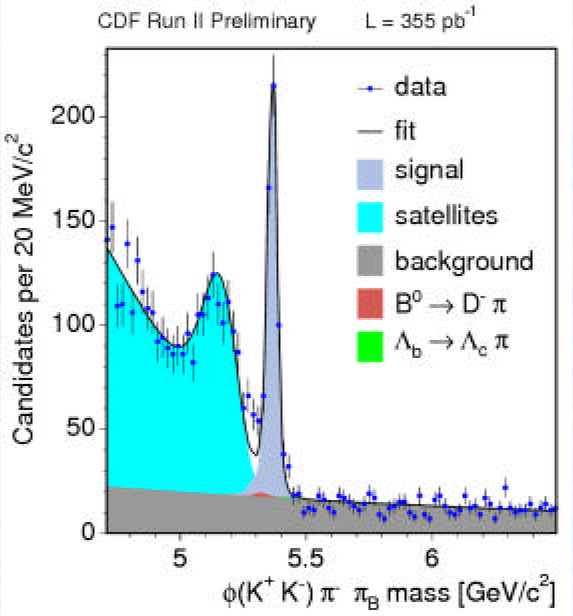
# $B_s$ Mixing: hadronic

- $B_s \to D_s \pi$

Yield s/b

  - $D_s \to \phi\pi$ (550±40 ~1.8)
  - $D_s \to K^*K$ (240±40 ~1.7)
  - $D_s \to \pi\pi\pi$ (110±25 ~1.0)
- Using also $B_s \to D_s \pi\pi\pi$ [about 1/3 more statistics]



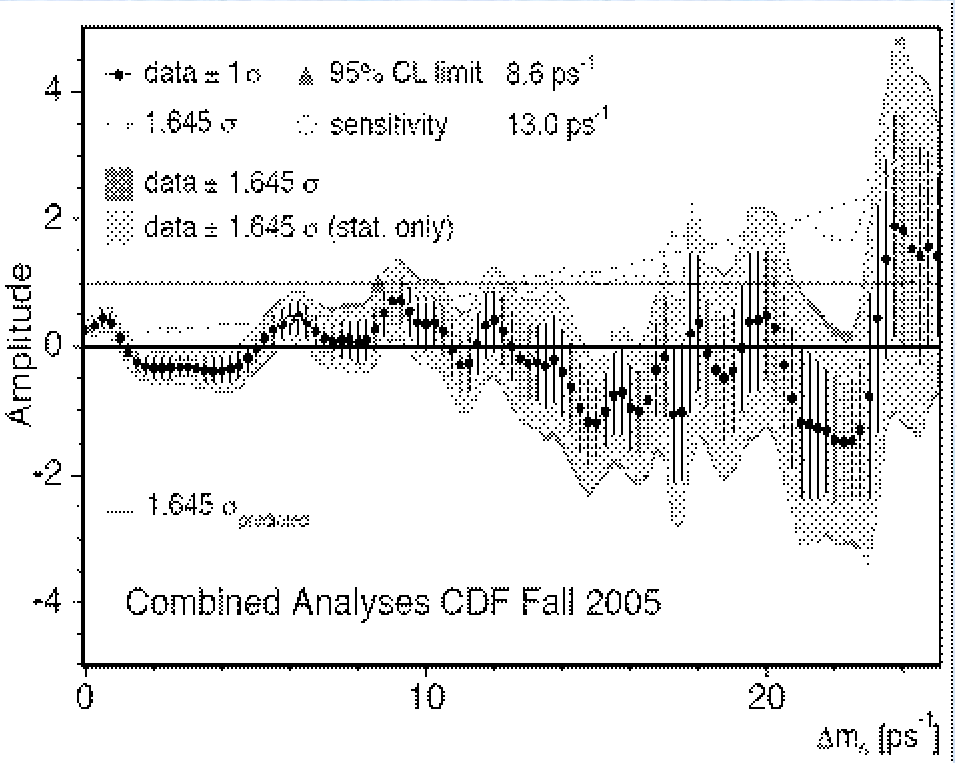


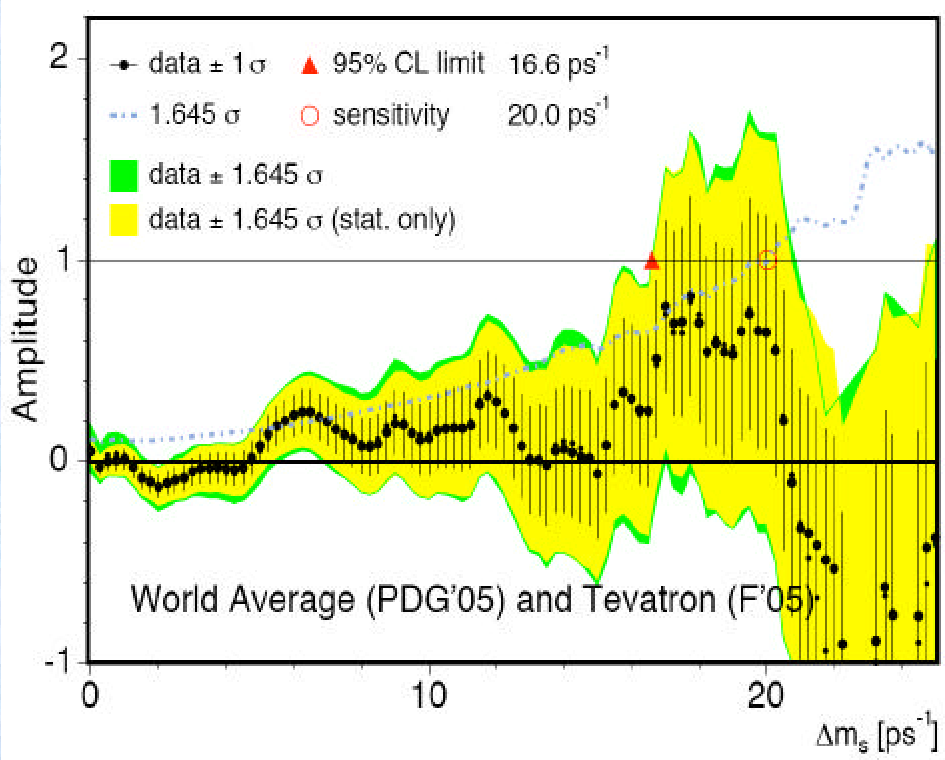
$\Delta m_s > 0.0\ \mathrm{ps}^{-1}$ @ 95% CL

Sensitivity: $9.8\ \mathrm{ps}^{-1}$

Low statistics, but promising!

# Combined Bs mixing limit





$\Delta m_s > 8.6$ ps$^{-1}$ @ 95% CL

Sensitivity: 13.0 ps$^{-1}$

$\Delta m_s > 16.6$ ps$^{-1}$ @ 95% CL

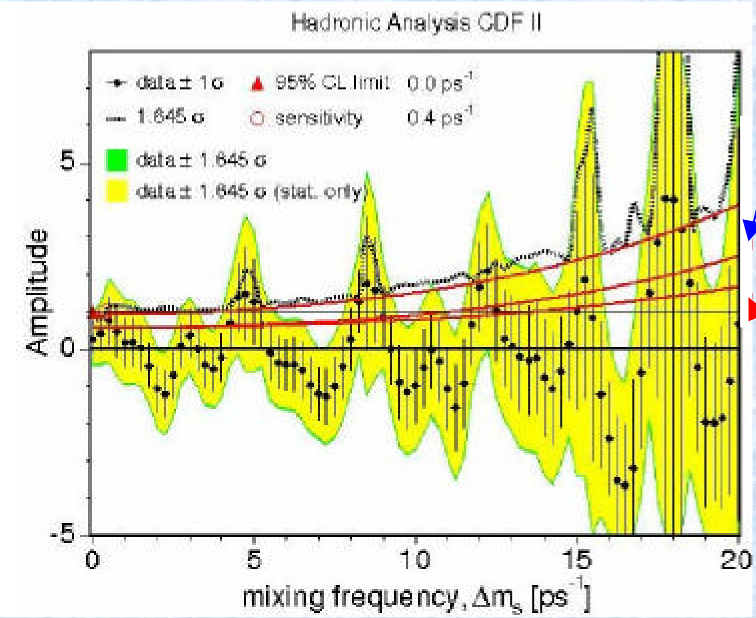
Sensitivity: 20.0 ps$^{-1}$

**Competitive in precision with best experiment at large $\mathrm{Dm}_s$**

More statistics and improvements to come...

# $B_s$ Mixing Perspectives

Analysis is pretty much defined! We know where we can improve:



- Statistics
    - Data (lumin.: $350pb^{-1} \rightarrow 600pb^{-1} \rightarrow$??)
    - New Modes (e.g. $Bs \rightarrow Ds^* \pi$ >2x?)
    - $\varepsilon D^2$ :
        - Additional taggers (SSK, OSK...)
        - Improve existing algorithms
- Proper time resolution
    - Refine event-by-event reconstruction
    - Optimal usage of kinematics for non-closed modes

With the March 2006 data sensitivity~SM value

# What happens for large $x_s$?

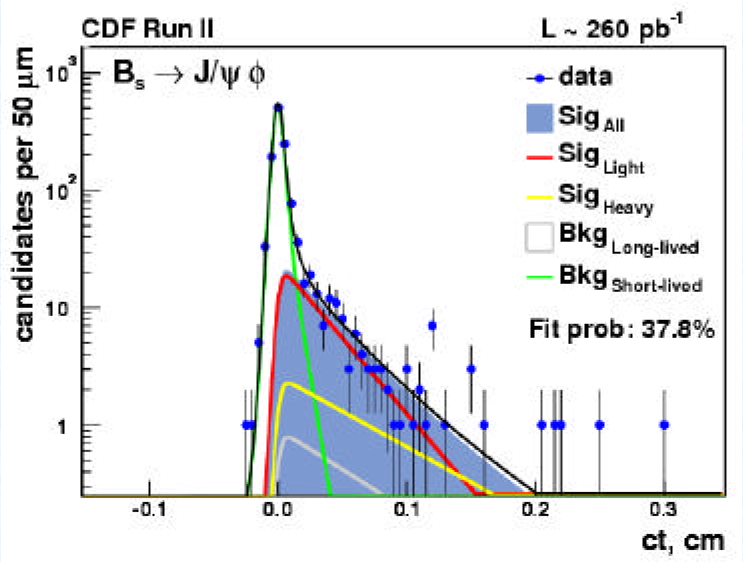
Indirect Measurement of $\Delta m_s$:

$$\left.\frac{\Delta\Gamma_s}{\Delta m_s}\right|_{SM} = \frac{2}{3p}\,\frac{m_t^2}{m_b^2}\,\frac{h\left(\frac{m_t^2}{M_W^2}\right)}{\left(1-\frac{8}{3}\frac{m_c^2}{m_b^2}\right)} = \left(3.7^{+0.8}_{-1.5}\right)\times 10^{-3}$$

–SM $\Delta\Gamma_s/\Gamma_s=0.12\pm0.06$ (Dunietz, Fleischer & Nierste)

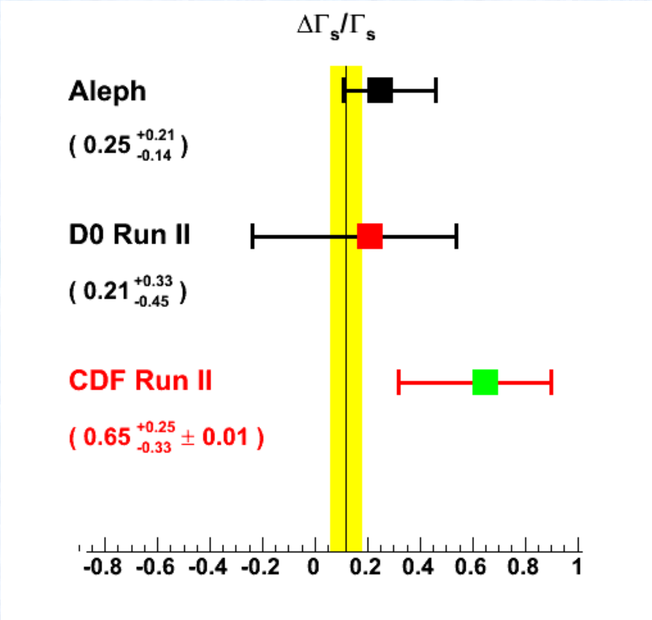
# Probing at large $\Delta m_s$: $\Delta\Gamma/\Gamma$

- $B_s \to J/\psi\phi$
  - *B* →VV, mixture of CP even/odd separate by angular analysis
  - Combine two-lifetime fit + angular → $\Delta\Gamma_s = \Gamma_H - \Gamma_L$



$$\frac{\Delta\Gamma_s}{\Gamma_s} = 0.65^{+0.25}_{-0.33} \pm 0.01$$

few ps$^{-1}$ in $\Delta m_s$ !



PRL 94, 101803 2005

# Beyond the SM

Analyses like this have laid down the path and the tools and techniques for the exploration of the SM boundaries:

- Non SM effects:
  - $b \to d$ ?
  - $b \to s$
    - Rare decays ($b \to s\gamma$)
      - $B_s \to \mu\mu, \mu\mu\phi$ etc.
    - $B \to \phi K$
    - $B_s \to \phi\phi$
    - $x_s$

# Rare decays

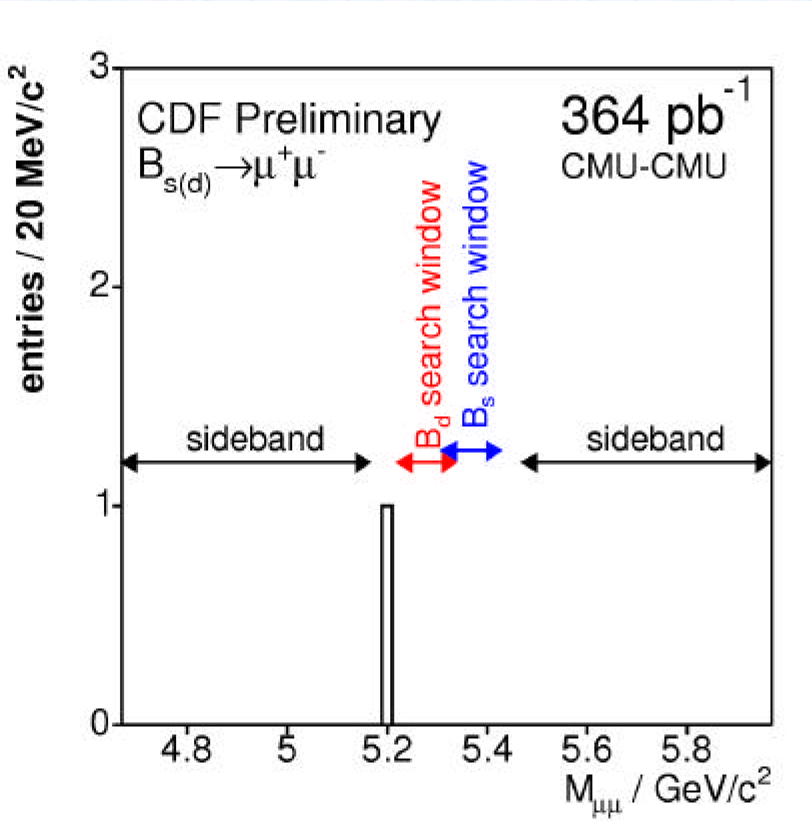
- Exploit the large B production rate
- Measure relative BR (e.g. $\mu\mu$ to $J/\psi K$) to factor out absolute $\varepsilon$ and luminosity measurements
- SM: BR($B_s \to \mu\mu$) <3.8E-9
- Sensitive to new physics!

**Result: World's best limits**

$BR(B_s \to \mu\mu) < 2.0\text{x}10^{-7}$ @95% CL

$BR(B_d \to \mu\mu) < 4.9\text{x}10^{-8}$ @95% CL

Publ: PRL 93, 032001 2004 Update: Hep-ex/0502044



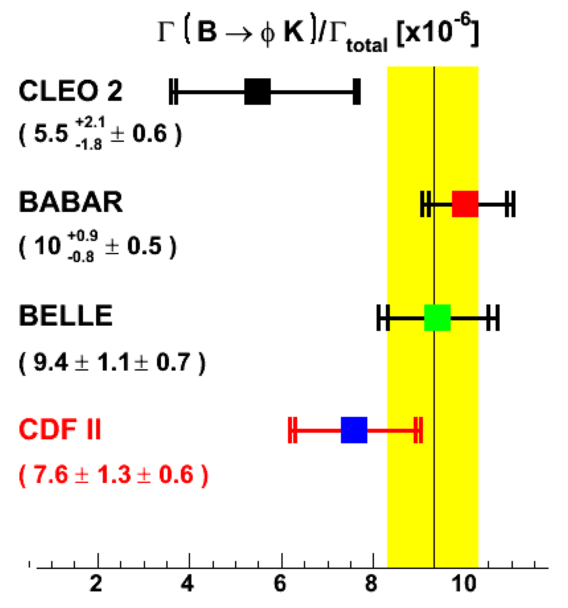
$$BR(D^0 \to mm) \leq 2.4 \times 10^{-6} \; at \; 90\% CL$$

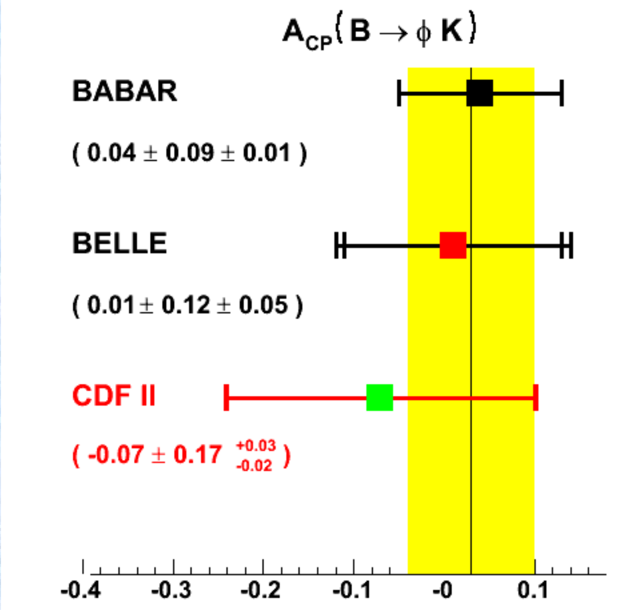
PRD 68, 091101 2003

# CP: $s\bar{s}s$

hep-ex/0502044

- b→sss transitions are ‘misbehaving’ at B factories
- …CDF II can look at them too. We started from φK:

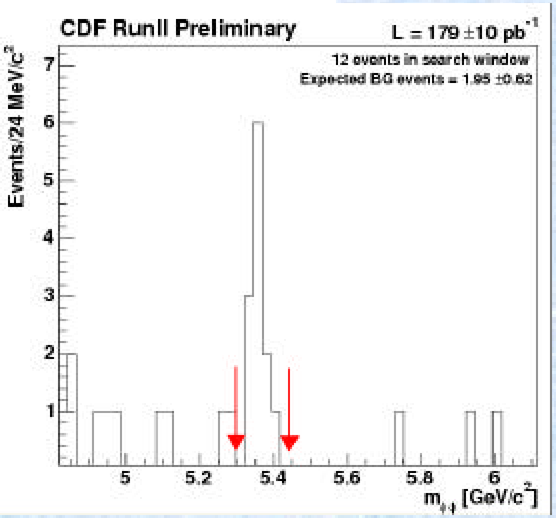




$$\frac{BR(B^\pm \to \phi K^\pm)}{BR(B^\pm \to J/\psi K^\pm)} = 0.0076 \pm 0.0013\,(stat.) \pm 0.0006\,(syst.)$$

$$A_{CP}(B^\pm \to \phi K^\pm) = -0.07 \pm 0.17\,(stat.)\,{}^{+0.03}_{-0.02}\,(syst.)$$

- …With the advantage of being able to look at Bs too:



$$BR(B_s \to \phi\phi) = (1.4 \pm 0.6(stat.) \pm 0.2(syst.) \pm 0.5(BR's)) \cdot 10^{-5}$$

# Perspectives

Exciting times ahead:

- Most analyses sensitive to BSM physics are statistically limited
- Significant improvements can be made including new modes and techniques
- $B_s$ results will be an important complementary addition to the CKM mapping!

# Conclusions

- We are living an exciting transition era of more and more quantitative results in the CKM sector
- BSM physics could be around the corner, but hard to discern models without direct evidences
- With LHC we will soon jump in the completely uncharted territory!
- Living this constant exploration of new discoveries puts us at the forefront of human knowledge, but this is not news!

“Modern science did not spring perfect and complete, as Athena from the head of Zeus, from the mind of Galileo and Descartes”

# Purgatory

# A guiding theme

- Exploring the boundaries of knowledge is a recurrent theme in history
- Geographical explorations exemplify the paradigm:

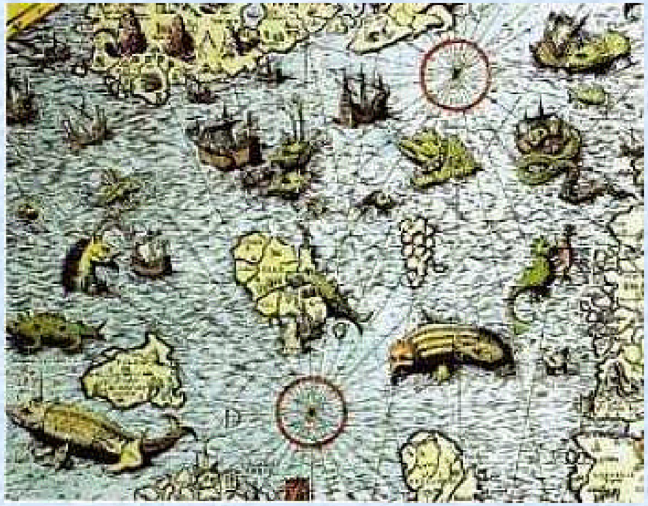
**Question**
(Why? Where? What? When? Who?)

**Development of tools**
(ships, telescope, microscope…)

**Explore the boundaries of knowledge**
(ships, telescope, microscope)

**Jump in! (the unknown)**
(America, planets, atoms…)

G. Galilei



# Hadronic Moments, HQET and Vcb

Most precise determination of $V_{cb}$ comes from $\Gamma_{sl}$ ("inclusive" determination):

$$\Gamma_{sl}(b \to c\ell^-\bar{\nu}) = \frac{BR(b \to c\ell^-\bar{\nu}_\ell)}{\tau_b} = |V_{cb}|^2 \times F_{theory}$$

$\Upsilon$(4S), LEP/SLD, CDF measurements. Experimental $\Delta|V_{cb}|$~1%

Theory with pert. and non-pert. corrections. $\Delta|V_{cb}|$~2.5%

$F_{theory}$ evaluated using OPE in HQET: expansion in $\alpha_s$ and $1/m_B$ powers:

O($1/m_B$) → 1 parameter: $\Lambda$

(Bauer et al., PRD 67 (2003) 071301)

O($1/m_B^2$) → 2 more parameters: $\lambda_1, \lambda_2$

O($1/m_B^3$) → 6 more parameters: $\rho_1, \rho_2, T_{1\text{-}4}$

Constrained from pseudo-scalar/vector B and D mass differences

$$\Gamma_{sl} = \frac{G_F^2|V_{cb}|^2}{192\pi^3} m_B^5 c_1 \left\{1 - c_2\frac{\alpha_s}{\pi} + \frac{c_3}{m_B}\Lambda\left(1 - c_4\frac{\alpha_s}{\pi}\right) + \frac{c_5}{m_B^2}(\Lambda^2 + c_6\lambda_1 + c_7\lambda_2) + O\left(\frac{1}{m_B^3}\right) + O\left(\frac{\alpha_s^2}{\pi}\right)\cdots\right\}$$

# How can CDF look at it?

Must reconstruct all channels to get all the $D^{**}$ states.
➔ However CDF has limited capability for neutrals

- $B^0 \rightarrow D^{**-} l^+ \nu$ always leads to neutral particles ➔ ignore it

- $B^- \rightarrow D^{**0} l^- \nu$ better, use isospin for missing channels:
  - $D^{**0} \rightarrow D^+ \pi^-$ OK
  - $D^{**0} \rightarrow D^0 \pi^0$ Not reconstructed. Half the rate of $D^+ \pi^-$
  - $D^{**0} \rightarrow D^{*+} \pi^-$
    - $D^{*+} \rightarrow D^0 \pi^+$ OK
    - $D^{*+} \rightarrow D^+ \pi^0$ Not reconstructed. Feed-down to $D^+ \pi^-$
  - $D^{**0} \rightarrow D^{*0} \pi^0$ Not reconstructed. Half the rate of $D^{*+} \pi^-$

# How to solve the problem in practice

## Reconstruct $D^*/D^+$ → Add another $\pi^{**} \to D^{**}$ → Correct for $\varepsilon(m_{**})$, $\varepsilon(D^+)/\varepsilon(D^*)$ → Measure $\langle m_{**}^2\rangle$, $\langle m_{**}^4\rangle$

### Reconstruct $D^*/D^+$

- Collect as many modes as possible:
  - $(K\pi)\pi^*$
  - $(K\pi\pi\pi)\pi^*$
  - $(K\pi\pi\pi^0)\pi^*$
  - $K\pi\pi$
- Check yields
- Validate MC

### Add another $\pi^{**} \to D^{**}$

- Selection:
  - Optimize on MC+WS combinations
  - Cross check on $\pi^*$
- $\pi^{**}$ Background
  - Combinatorial
  - D'
  - $B \to DD$
  - $c\bar{c}$
  - …

### Correct for $\varepsilon(m_{**})$, $\varepsilon(D^+)/\varepsilon(D^*)$

- Measure selection bias on $m_{**}$ from:
  - MC
  - $D^*$ candidates
- Rely on MC (& PDG) for:
  - $\varepsilon(D^+)/\varepsilon(D^*)$
  - Unseen modes (Isospin)
  - Lepton spectrum acceptance

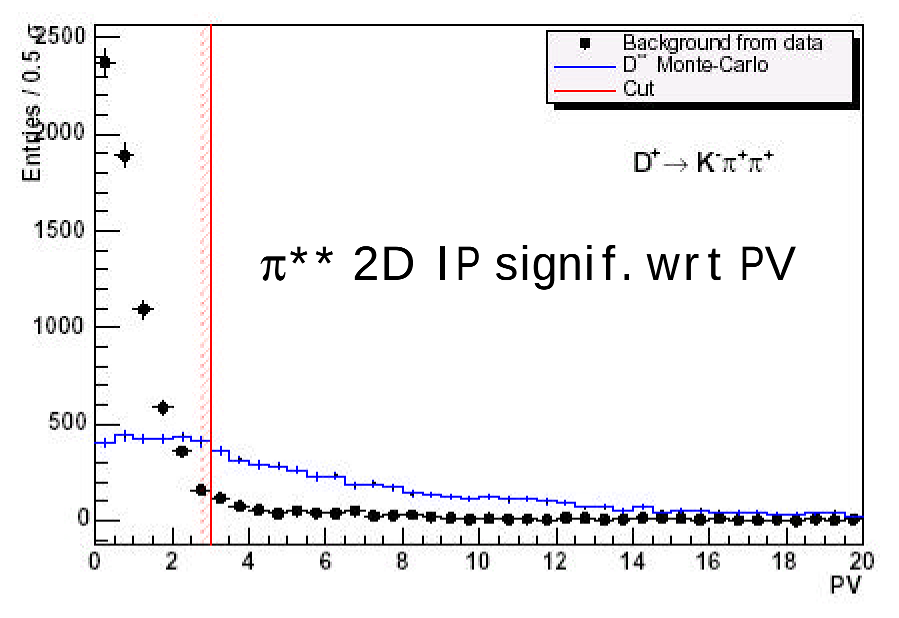
### Measure $\langle m_{**}^2\rangle$, $\langle m_{**}^4\rangle$

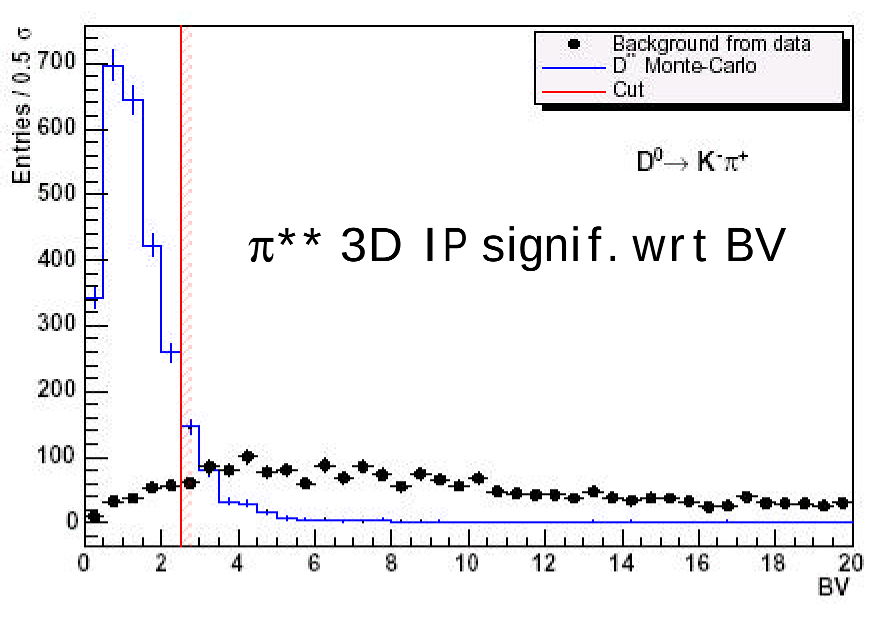
- Subtract backgrounds
- Use PDG to go $\Delta m_{**} \to m_{**}$
- Compute $\langle m_{**}^2\rangle$ & $\langle m_{**}^4\rangle$
- Include $D^{(*)0}$
- Extract $\Lambda$, $\lambda_1$
- Systematics

# $\pi^{**}$ Selection

Based on topology:

- impact parameter significances w.r.t. primary, B and D vertices





Cuts are optimized using MC and background (WS) data:

Additional cuts only for $D^+$:

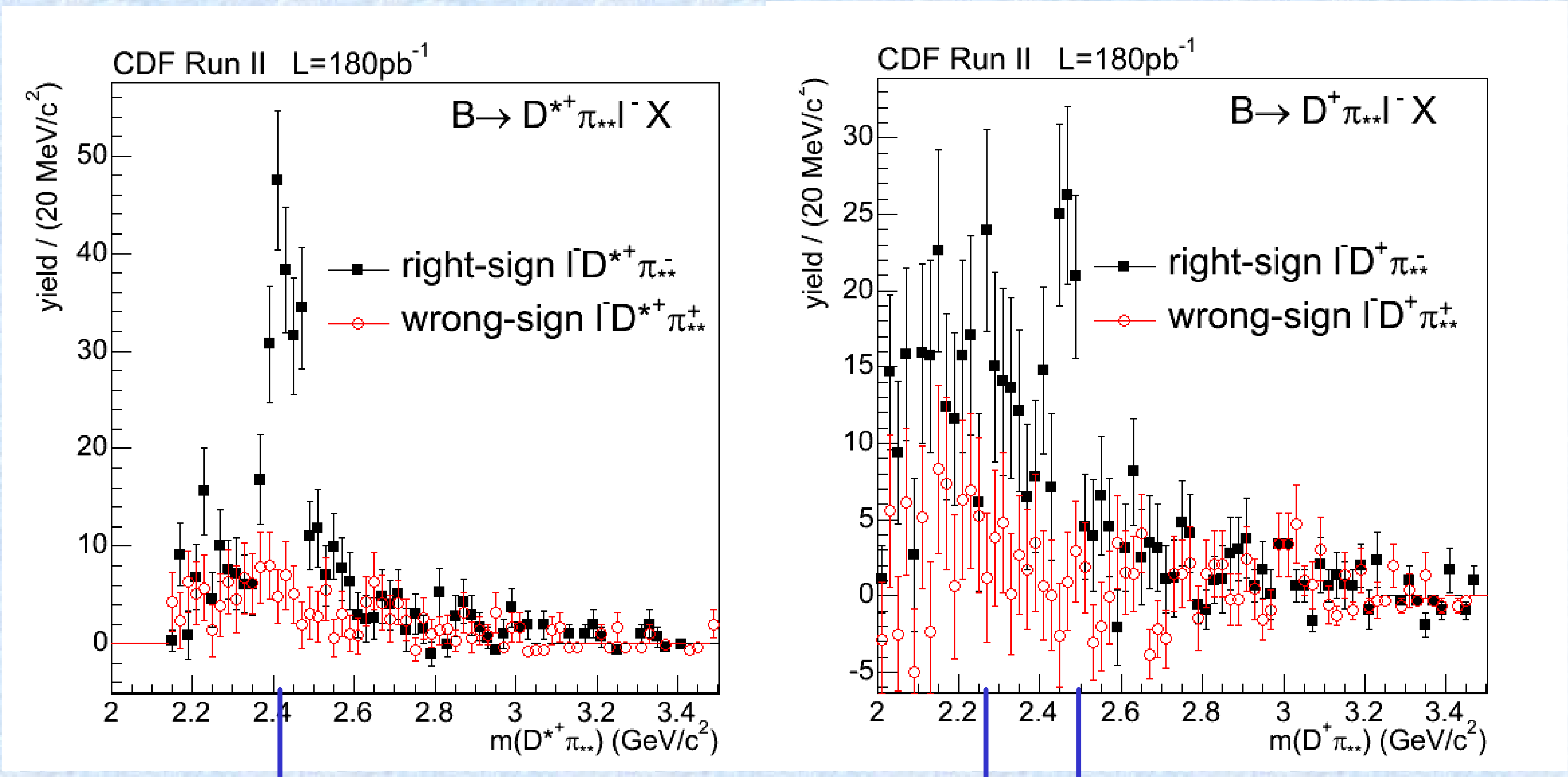
- $p_T > 0.4$ GeV
- $\Delta R < 1.0$
- $|d_0^{PV}/\sigma| > 3.0$
- $|d_0^{BV}/\sigma| < 2.5$

$|d_0^{DV}/\sigma| > 0.8$

$L_{xy}^{B\rightarrow D} > 500\mu m$

# Raw m** distributions

Measured in $\Delta m^{**}$, shifted by $M(D^{(*)+})$, side-band subtracted.



**$D_1, D_1^*, D_2^*$**

**Feed-down**

**$D_2^*, D_0^*$**

# Efficiency Corrections

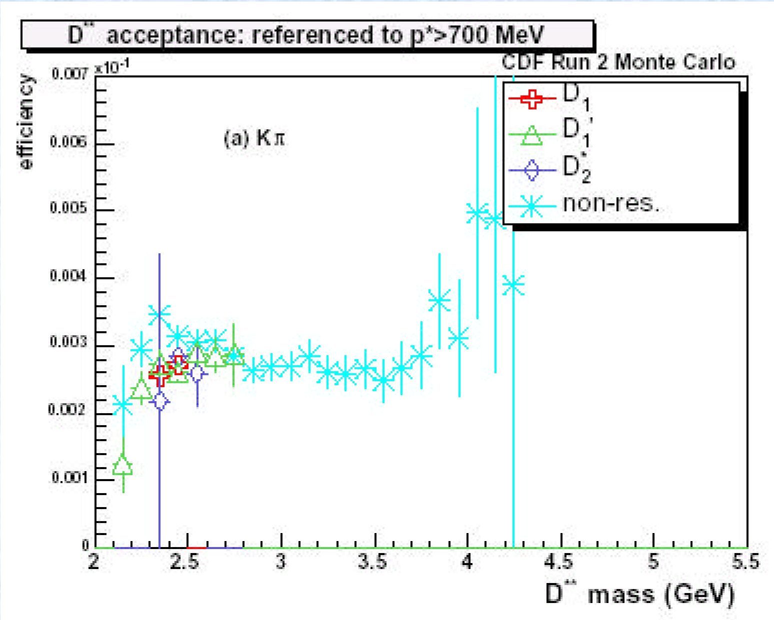
1) Correct the raw mass for any dependence of $\varepsilon_{reco}$ on M(D**):

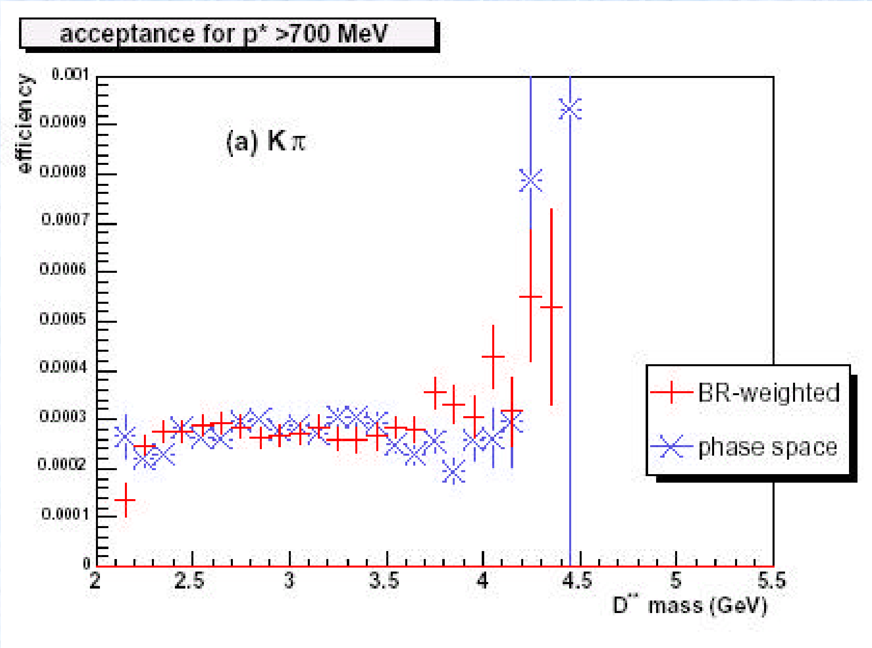
- Possible dependence on the D** species (spin).
- Monte-Carlo for all D** (Goity-Roberts for non-resonant), cross-checked with pure phase space decays.
- Detector simulation shortcomings cause residual data/MC discrepancy: derive corrections from control samples (D* and D daughters)

2) Cut on lepton energy in B rest frame:

- Theoretical predictions need well-defined $p_l^*$ cut.
- We can't measure $p_l^*$, but we can correct our measurement to a given cut:

  ➔ $p_l^* > 700$ MeV/c.





# Final Result

$$m_1 \equiv \left\langle m^2_{D^{**}} \right\rangle = (5.83 \pm 0.16_{\rm stat} \pm 0.08_{\rm syst})\ \mathrm{GeV}^2$$

$$m_2 \equiv \left\langle \left( m^2_{D^{**}} - \left\langle m^2_{D^{**}} \right\rangle \right)^2 \right\rangle = (1.30 \pm 0.69_{\rm stat} \pm 0.22_{\rm syst})\ \mathrm{GeV}^4$$

$\rho(m_1,m_2)=0.61$

$$M_1 \equiv \langle s_H \rangle - m^2_{\bar{D}} = (0.467 \pm 0.038_{\rm stat} \pm 0.019_{\rm exp} \pm 0.065_{\rm BR})\ \mathrm{GeV}^2$$

$$M_2 \equiv \left\langle (s_H - \langle s_H \rangle)^2 \right\rangle = (1.05 \pm 0.26_{\rm stat} \pm 0.08_{\rm exp} \pm 0.10_{\rm BR})\ \mathrm{GeV}^4\ ,$$

$\rho(M_1,M_2)=0.69$

Pole mass scheme

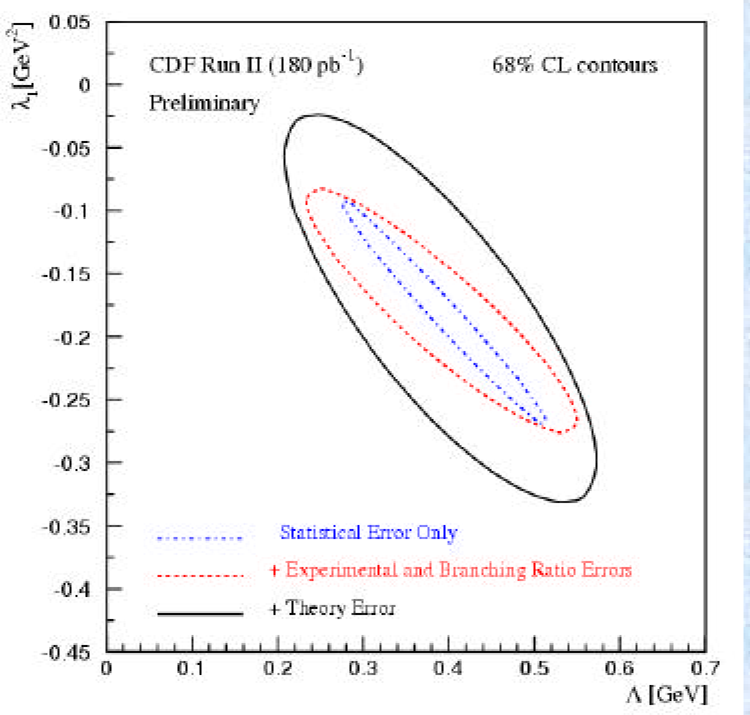
$$\Lambda = (0.397 \pm 0.078_{\rm stat} \pm 0.027_{\rm exp} \pm 0.064_{\rm BR} \pm 0.058_{\rm theo})\ \mathrm{GeV}$$

$$\lambda_1 = (-0.184 \pm 0.057_{\rm stat} \pm 0.017_{\rm exp} \pm 0.022_{\rm BR} \pm 0.077_{\rm theo})\ \mathrm{GeV}^2$$

1S mass scheme

$$m_b^{1S} = (4.654 \pm 0.078_{\rm stat} \pm 0.027_{\rm exp} \pm 0.064_{\rm BR} \pm 0.089_{\rm theo})\ \mathrm{GeV}$$

$$\lambda_1^{1S} = (-0.277 \pm 0.049_{\rm stat} \pm 0.017_{\rm exp} \pm 0.022_{\rm BR} \pm 0.094_{\rm theo})\ \mathrm{GeV}^2$$



# Systematics

- Input parameters
  - $D^{(*)+}$ Masses, in combining $D^{(*)}$ with $D^{**}$ $m \to M$ [PDG errors]
  - BR ($B \to D^{+}/D^{*+}$ $m \to M$) [PDG errors]
- Experimental
  - Detector resolution [re-smear satellite sample by full resolution: ±60MeV]
  - Data/MC Efficiency discrepancies [measure $P_t$ and m dependency on control sample, probe different fit models]
  - Decay models in MC [full kinematic description vs pure phase space]
  - $P_l^*$ cut correction [repeat measurement at various $P_l^*$ thresholds]
- Backgrounds
  - Scale [charge correlation WS/RS from fully reconstructed B: ±4%]
  - Optimization Bias [repeat optimization procedure on bootstrap copies of the sample]
  - Physics background [vary ±100%]
  - $B \to X_c \tau \nu$ [estimate $\tau/\mu$ yield and kinematic differences using MC]
  - Fake leptons [no evidence in WS $D^{+}l^{+}$, charge-correlated negligible]

# CP: hh modes

- Good agreement with B factories
- First measurement ever of $B_s \to KK$

$$\frac{BR(B_d \to \pi^\pm\pi^\mp)}{BR(B_d \to K^\pm\pi^\mp)} = 0.24 \pm 0.06\ (stat.) \pm 0.05\ (syst.)$$

$$A_{\rm CP} = \frac{N(\overline{B}^0_d \to K^-\pi^+) - N(B^0_d \to K^+\pi^-)}{N(\overline{B}^0_d \to K^-\pi^+) + N(B^0_d \to K^+\pi^-)} = -0.04 \pm 0.08\ (stat.) \pm 0.01\ (syst.)$$

$$\frac{f_d \cdot BR(B_d \to \pi^\pm\pi^\mp)}{f_s \cdot BR(B_s \to K^\pm K^\mp)} = 0.48 \pm 0.12\ (stat.) \pm 0.07\ (syst.)$$

$$\frac{f_s \cdot BR(B_s \to K^\pm K^\mp)}{f_d \cdot BR(B_d \to K^\pm\pi^\mp)} = 0.50 \pm 0.08\ (stat.) \pm 0.07\ (syst.)$$

$$\frac{BR(B_s \to \pi^\pm\pi^\mp)}{BR(B_s \to K^\pm K^\mp)} < 0.10\ @\ 90\%\ C.L.$$

$$\frac{BR(B_d \to K^\pm K^\mp)}{BR(B_d \to K^\pm\pi^\mp)} < 0.17\ @\ 90\%\ C.L.$$

$$\frac{f_s \cdot BR(B_s \to K^\pm\pi^\mp)}{f_d \cdot BR(B_d \to K^\pm\pi^\mp)} < 0.11\ @\ 90\%\ C.L.$$

http://www-cdf.fnal.gov/physics/new/bottom/040722.blessed-bhh/

$$BR(\Lambda_b \to hh) < 22 \cdot 10^{-6}\quad (90\% C.L.)$$

http://www-cdf.fnal.gov/physics/new/bottom/040624.blessed_Lb_hh_limit/