Probing the Boundaries of the Standard Model with B Physics at CDF II

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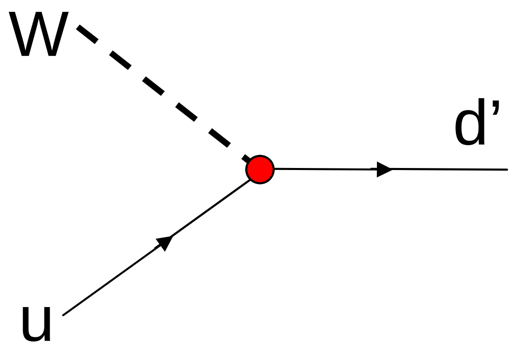
Synopsis

- 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 $b \rightarrow c l \nu$ (V_{cb})
  - B_s Mixing (V_{td} and new physics)
- Perspectives
- Conclusions

The Flavor Sector: CKM Matrix



$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} & & \\ & V_{CKM} & \\ & & \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

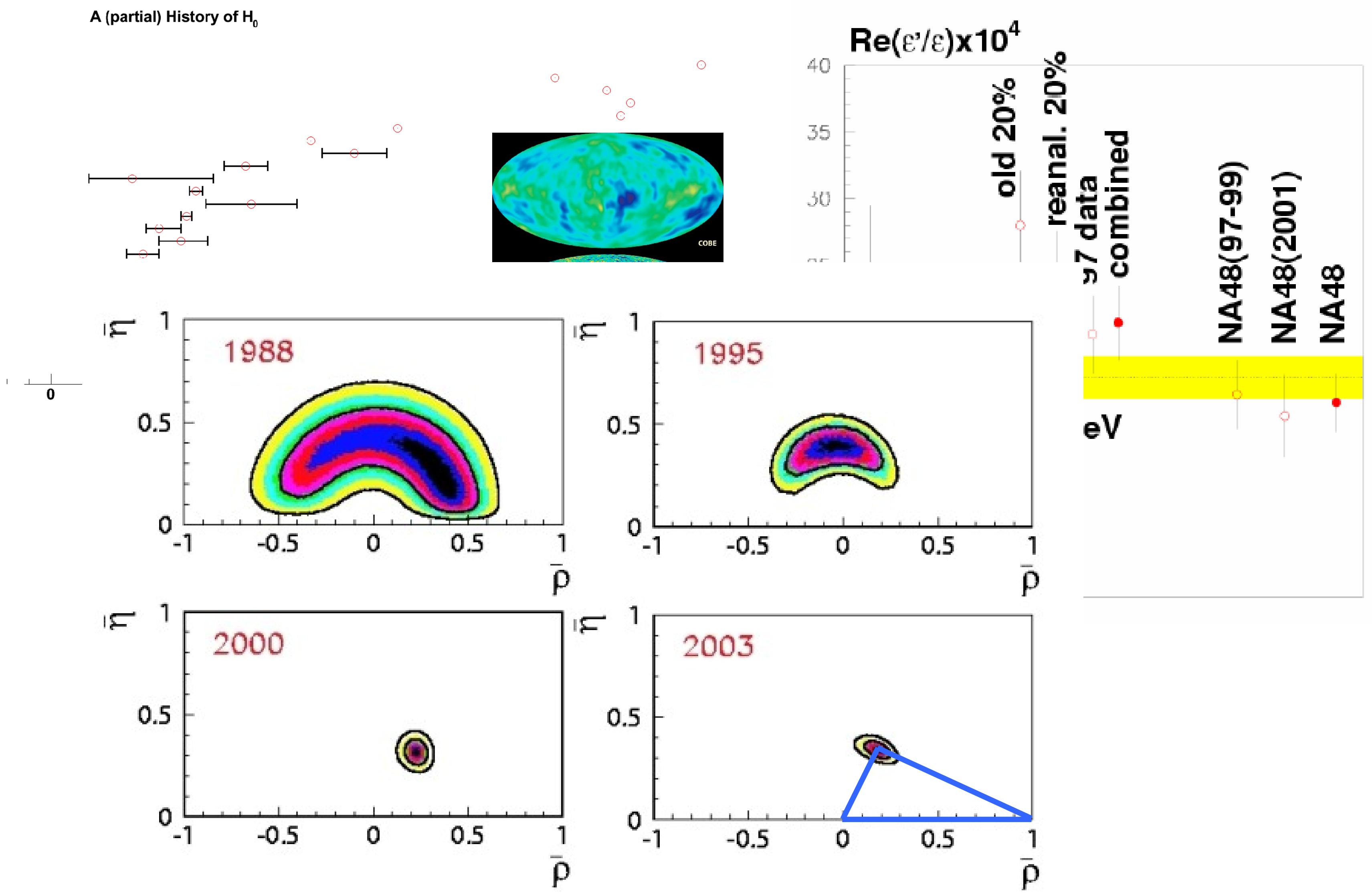
Quarks couple to W through V_{CKM}: rotation in flavor space!

$$V_{\mathrm{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

V_{CKM} is Unitary

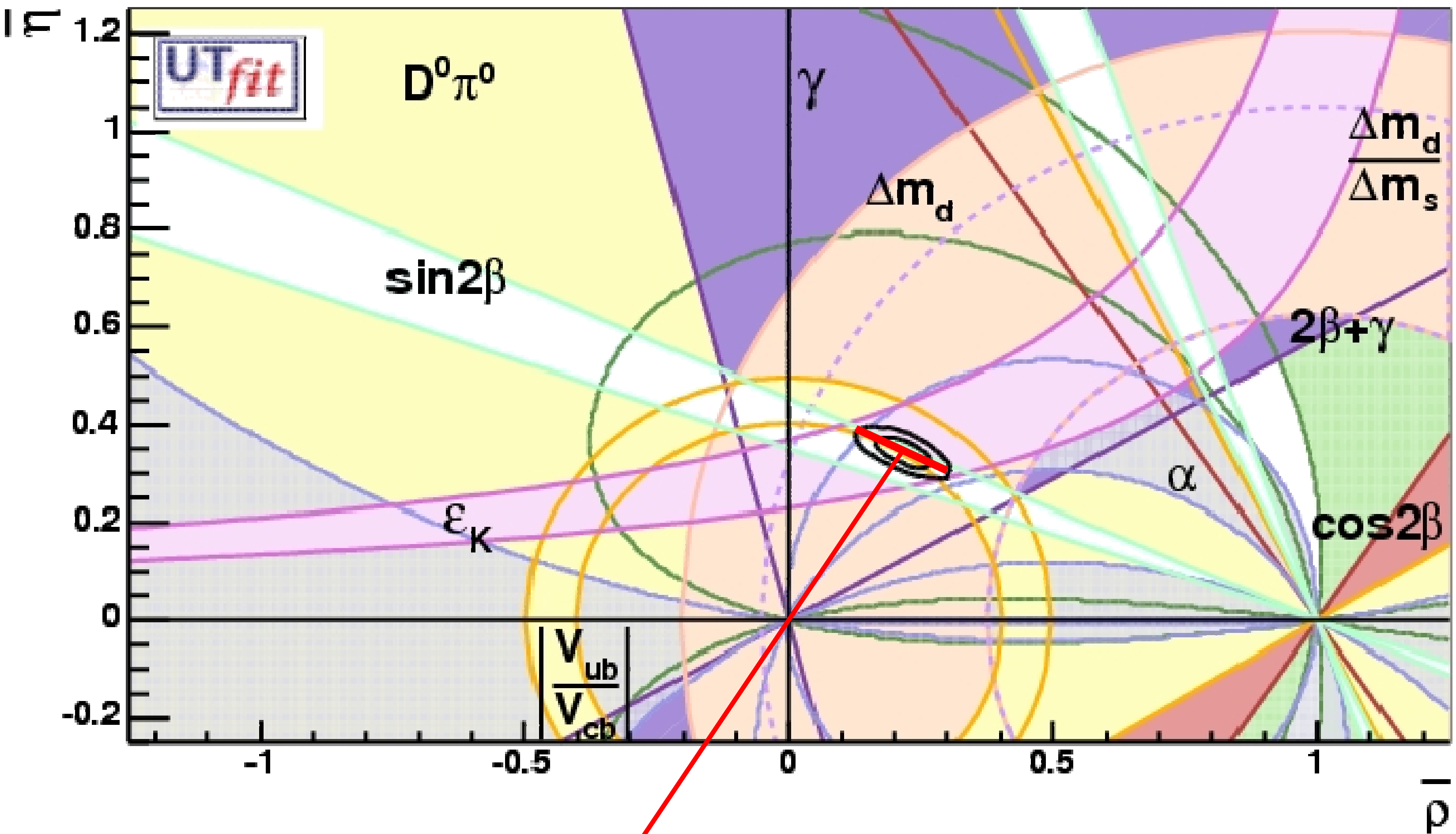
$$\boxed{V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0}$$

Qualitative to Quantitative



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

B physics probes the SM



TeVatron contribution is critical!

The Tevatron as a b factory

- $\Upsilon(4s)$ 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^{**}, Λ_b, Ξ_b

See PRD 71, 032001 2005

$$\boxed{\sigma_{B^\circ} = 3.51 \pm 0.42 \pm 0.53\ \mu b\ @\ |y| < 1 \quad p_t > 6}$$

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 $p\bar{p}$ collisions is so large (~300 Hz @ 10^{32} cm^{-2} Hz) that we could not even cope with writing it to tape!

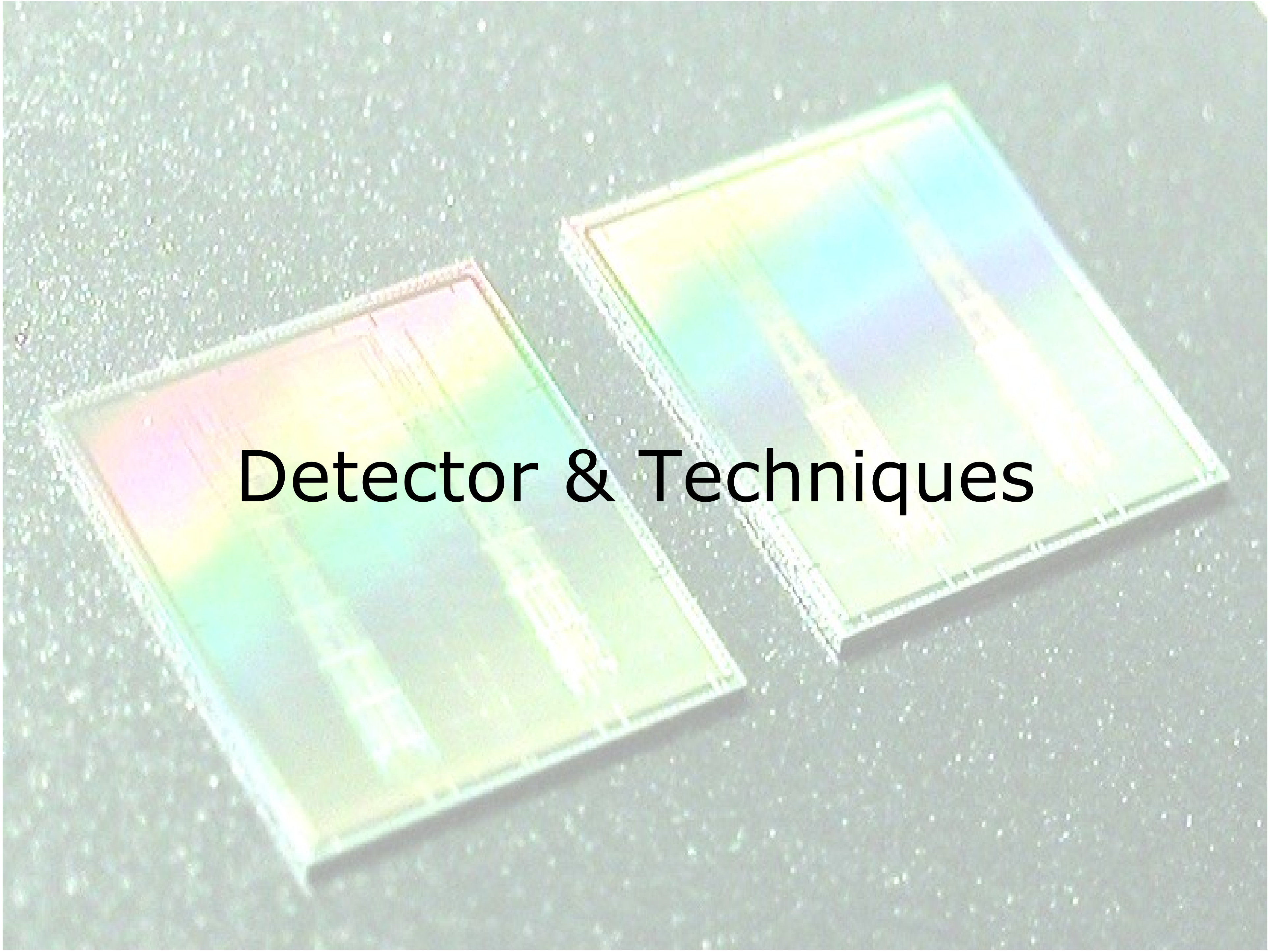
Path to New Physics

CKM meas. $\rightarrow$ discrepancies $\rightarrow$ new physics hints

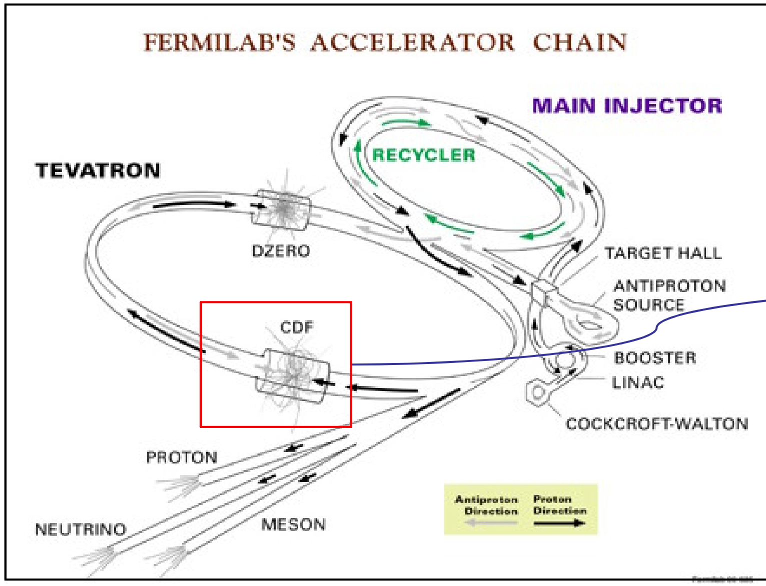
How do we achieve this ability?

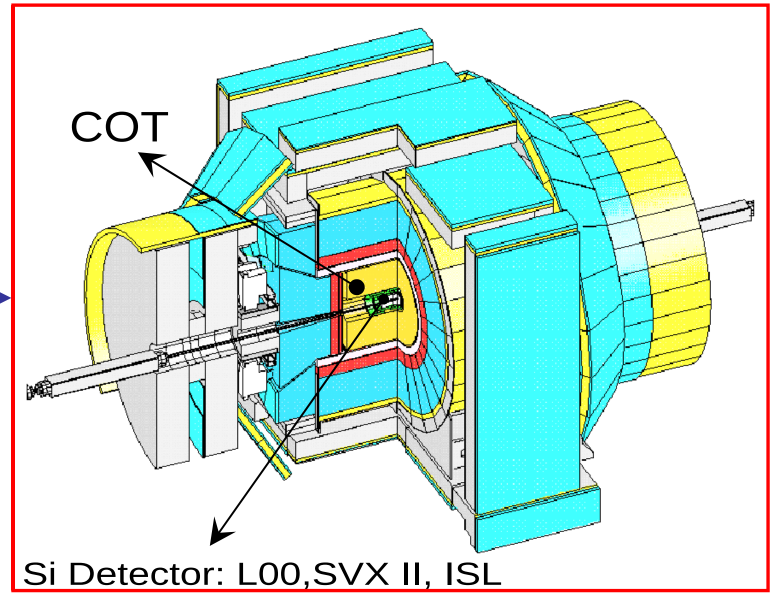
- Design/ improve the “tools of the trade”
  - Experimental (detector & techniques)
  - Theoretical (phenomenological devices)
- Measure uncharted properties at the boundaries of our knowledge
  - Masses
  - Lifetimes
  - Branching ratios
- Press further ahead and investigate the boundaries:
  - Mixing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

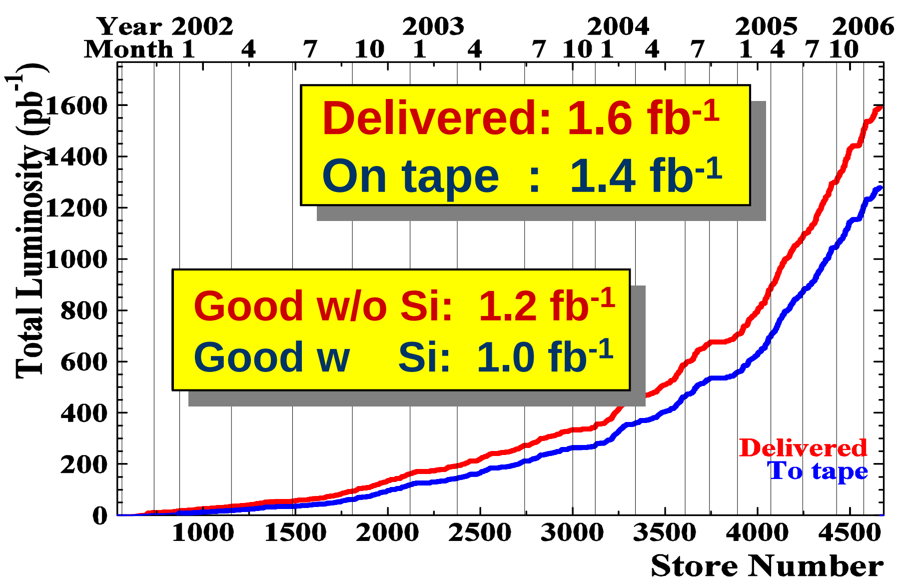
Detector & Techniques



CDF and the TeVatron







Renewed detector & Accelerator chain:

- Higher Luminosity ➡ higher event rate

→Detector changes/improvements:

→DAQ redesign

→Improved performance:

➢Detector Coverage

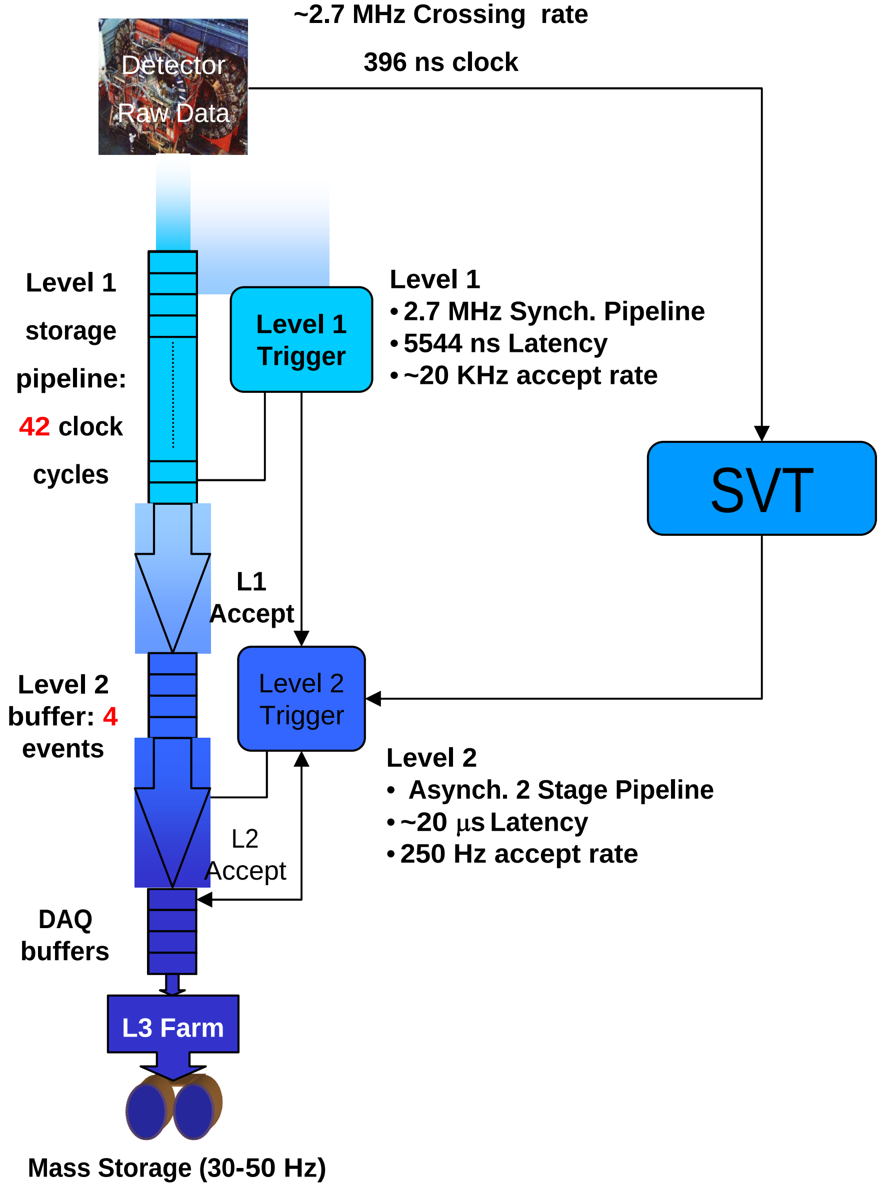
➢Tracking Quality

➢New Trigger strategies for heavy flavors:

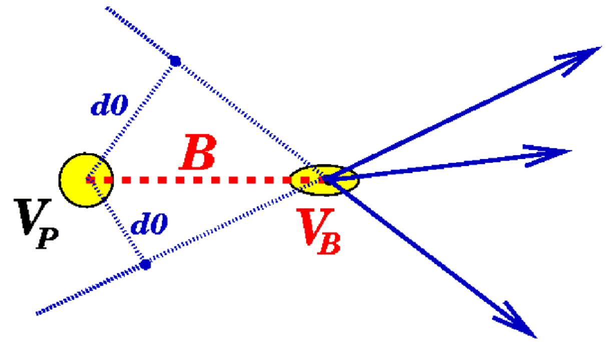
displaced vertex trigger

SVT: a specialized B physics trigger

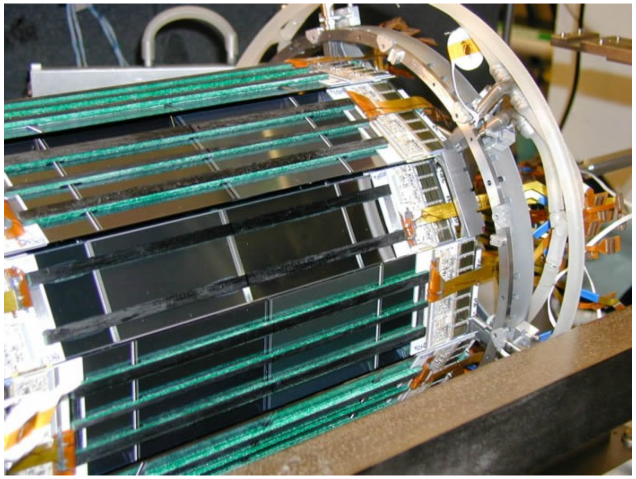
The CDF Trigger



requirements



- Good IP resolution



- As fast as possible

→Customized Hardware

...and a successful endeavor!

- The recipe: specialized hardware

1)Clustering

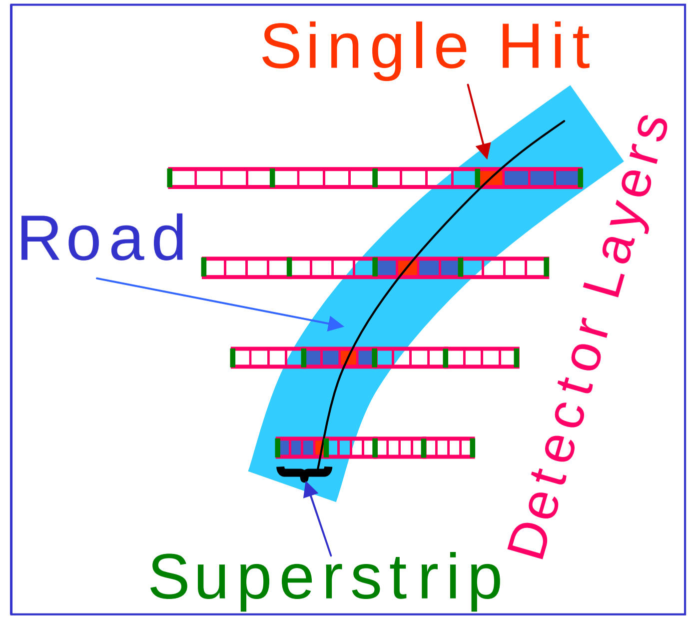
Find clusters (hits) from detector ‘strips’ at full detector resolution

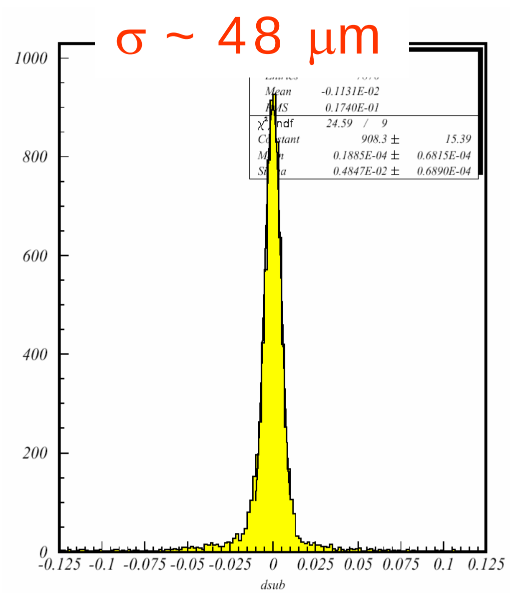
2)Template matching

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

3)Linearized track fitting

Fit tracks, with combinatorial limited to clusters within roads



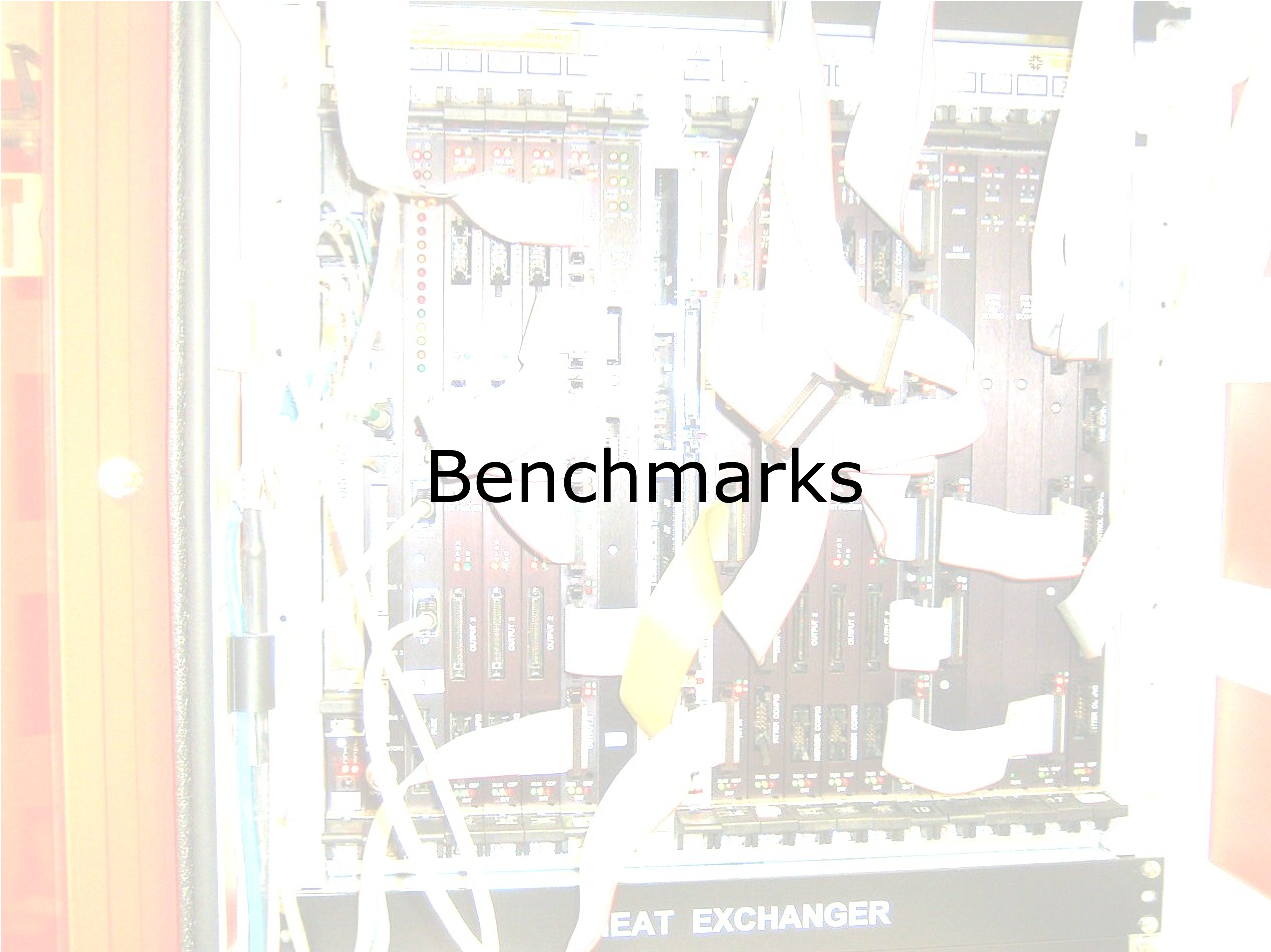


- SVT is capable of digesting >20000 evts/second, identifying tracks in the silicon

- CDFII has been running it since day -1

SVT is the reason of the success and variety of B physics in CDF run II

Benchmarks



Knowledge of non-Υ(4s)-produced b (PDG'04)

Λ_b^0 DECAY MODES	Fraction (Γ_i/Γ)	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 ± 2.1) %		
$p\pi^-$	$<5.0\times10^{-5}$		
pK^-	$<5.0\times10^{-5}$		
$\Lambda\gamma$	$<1.3\times10^{-3}$		

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

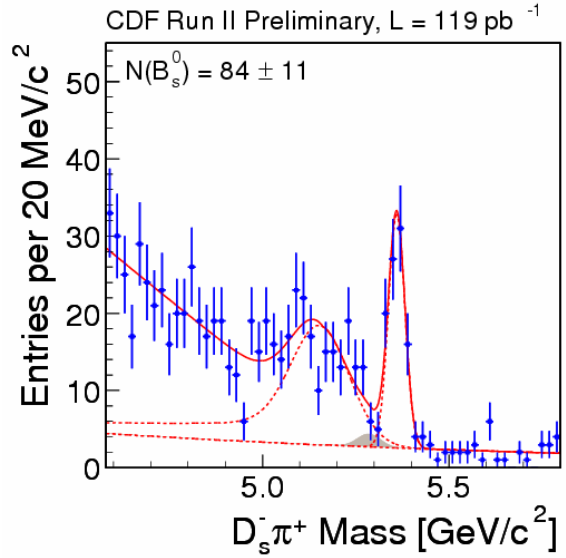
B_s^0 DECAY MODES	Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
D_s^- anything	(94 ± 30) %		–
$D_s^-\ell^+\nu_\ell$ anything	[kkk] (7.9 ± 2.4) %		–
$D_s^-\pi^+$	<13 %		2322
$D_s^{(*)+}D_s^{(*)-}$	(23^{+21}_{-13}) %		–
$J/\psi(1S)\phi$	$(9.3\pm3.3)\times10^{-4}$		1590
$J/\psi(1S)\pi^0$	$<1.2\times10^{-3}$	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
π^+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 Λ_b Branching Fractions

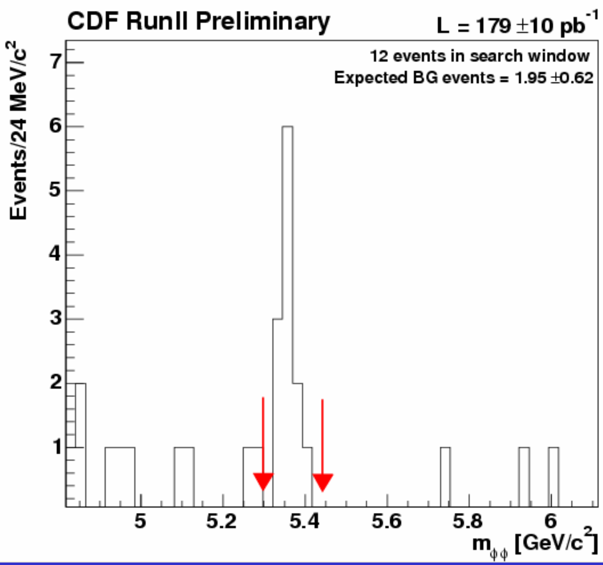
$$\frac{f_s}{f_d}\cdot\frac{Br(B_s\to D_s^-\pi^+)}{Br(B^0\to D^-\pi^+)} = 0.35\pm0.05(stat)\pm\boxed{0.04(syst)}\pm0.09(BR)$$

Hep-ex/0508014



$$BR(B_s\to\phi\phi) = (1.4\pm0.6(stat.)\pm\boxed{0.2(syst.)}\pm0.5(BR's))\cdot10^{-5}$$

Hep-ex/0502044



$$\frac{\mathrm{Br}(B_s\to\psi(2S)\phi)}{\mathrm{Br}(B_s\to J/\psi\phi)} = 0.52\pm0.13[\mathrm{stat}]\pm0.06[BR]\pm\boxed{0.04[\mathrm{sys}]}$$

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

$$\frac{Br(B^0\to D_s^+D^-)}{Br(B^0\to D^-3\pi)} = 2.00\pm0.16(NC)\pm\boxed{0.12(syst)}\pm0.50(BR)$$

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

$$\frac{BR(\Lambda_b\to\Lambda_c^+\pi^-)}{BR(\bar{B}^0\to D^+\pi^-)} = 3.3\pm0.3\ (\mathrm{stat})\pm\boxed{0.4\ (\mathrm{syst})}\pm1.1\ (\mathrm{BR{+}FR})$$

Hep-ex/0601003

$$\frac{\mathcal{B}(\Lambda_b\to\Lambda_c^+\mu^-\bar{\nu}_\mu)}{\mathcal{B}(\Lambda_b\to\Lambda_c^+\pi^-)} = 20.0\ \pm3.0\ (stat)\pm\boxed{1.2\ (syst)}{}^{+0.7}_{-2.1}\ (BR)\pm0.5\ (UBR)$$

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

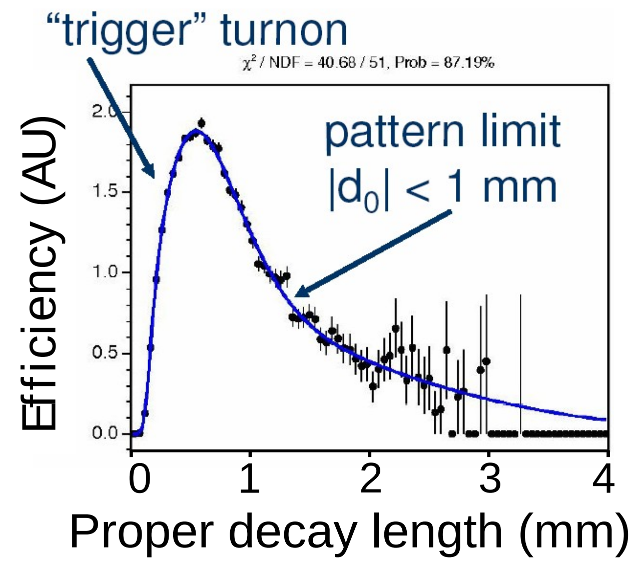
Lifetimes: fully reconstructed hadronic modes

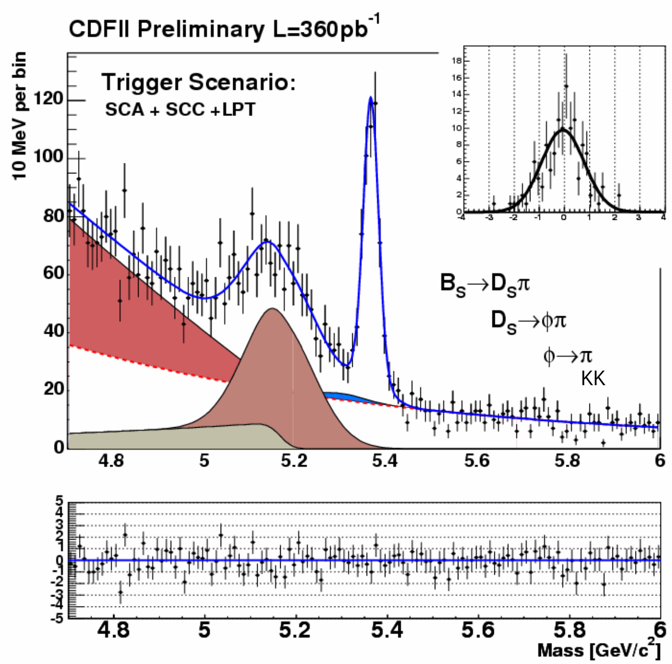
- Testbed for our ability to understand trigger biases
- Large, clean samples with understood backgrounds
- Excellent mass and vertex resolution
- Prerequisite for mixing fits!

$\tau(B^+)$ = **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**





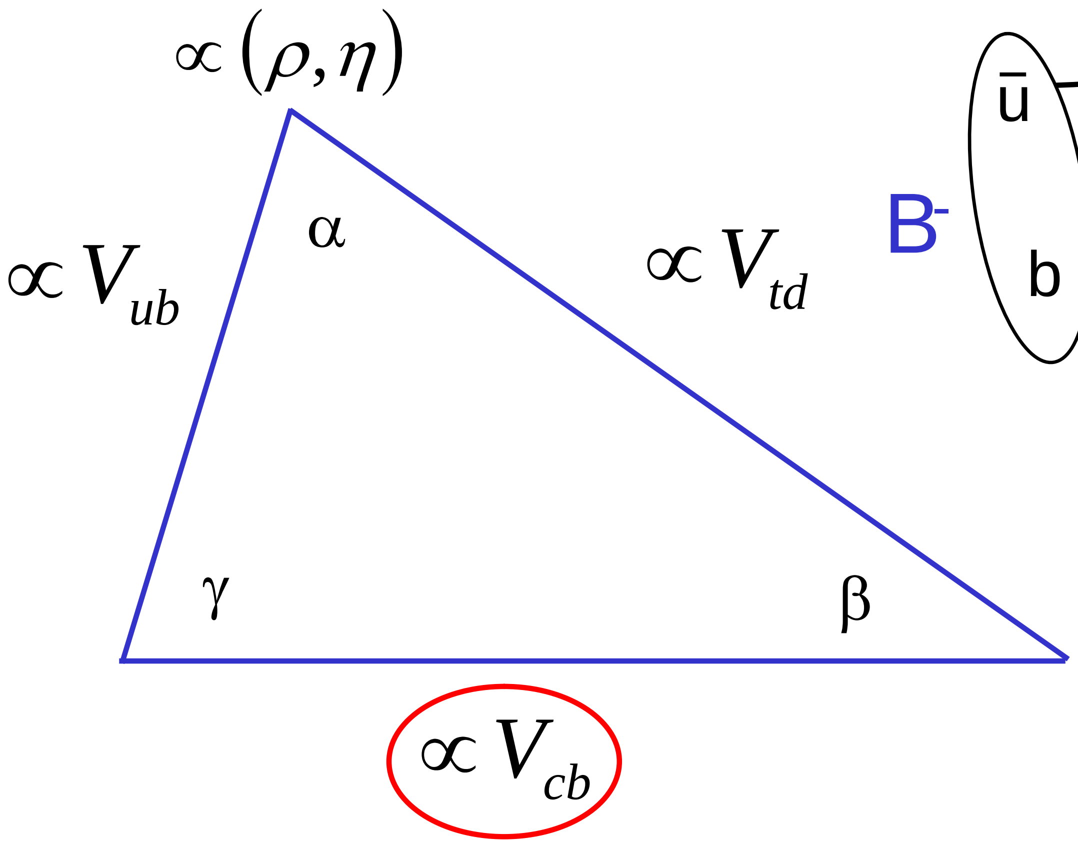
Systematics (μm)

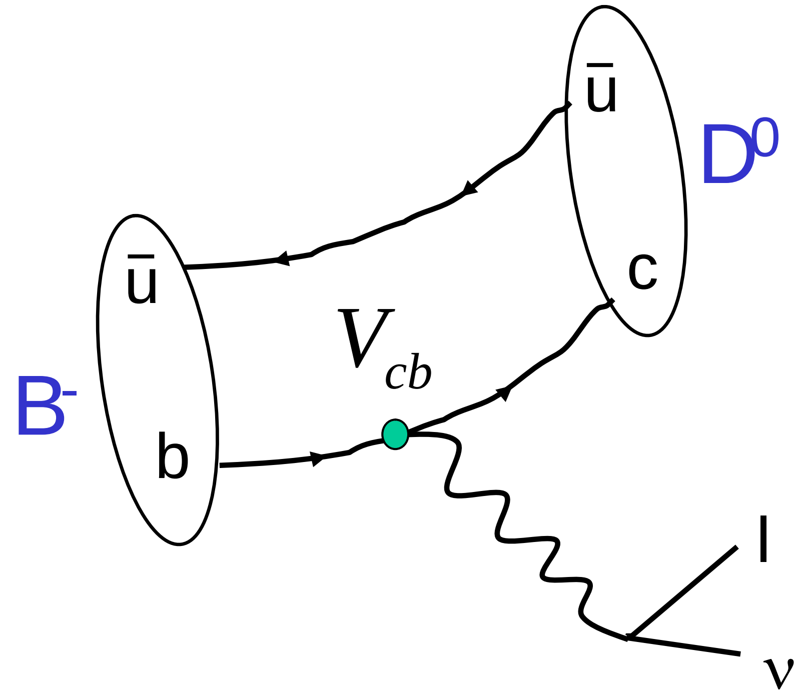
Effect	Variation(μm)	Variation(μm)
	B^0	B_s
MC input $c\tau$	negligible	negligible
p_T reweight	1.9	1.9
Scale Factor	negligible	negligible
Bkg ct description	1.1	1.1
Bkg fraction	2.0	2.0
I.P. correlation	1.0	1.0
Eff. parameterization	1.5	1.5
L_{xy} significance	negligible	2
$\Delta\Gamma_s$	-	1.0
Alignm.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

http://www-cdf.fnal.gov/physics/new/bottom/050303.blessed-bhadlife/

Improving SM Tools

Closing in on CKM





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

Phenomen. Tools Improvement

Hadronic Moments

- HQET/OPE is a fundamental tool for CKM physics with B mesons. For instance it relates:
  - $B \to X_u l\nu$ to $[b \to ul\nu] \Rightarrow V_{ub}$
  - $B \to X_c l\nu$ to $[b \to cl\nu] \Rightarrow V_{cb}$
- "semi-empirical" approach: parameterizes any prediction in a series expansion of effective operators
- Expectation value of these operators is a "universal" property $\Rightarrow$can be assessed with concurrent measurements
- Example:

$$V_{cb}\ (\pm 1\%_{exp} \pm 2.5\%_{theo}) \Leftrightarrow \text{Hadronic Moments: } (\mu, \sigma) \text{ of } M(X_c)^2$$

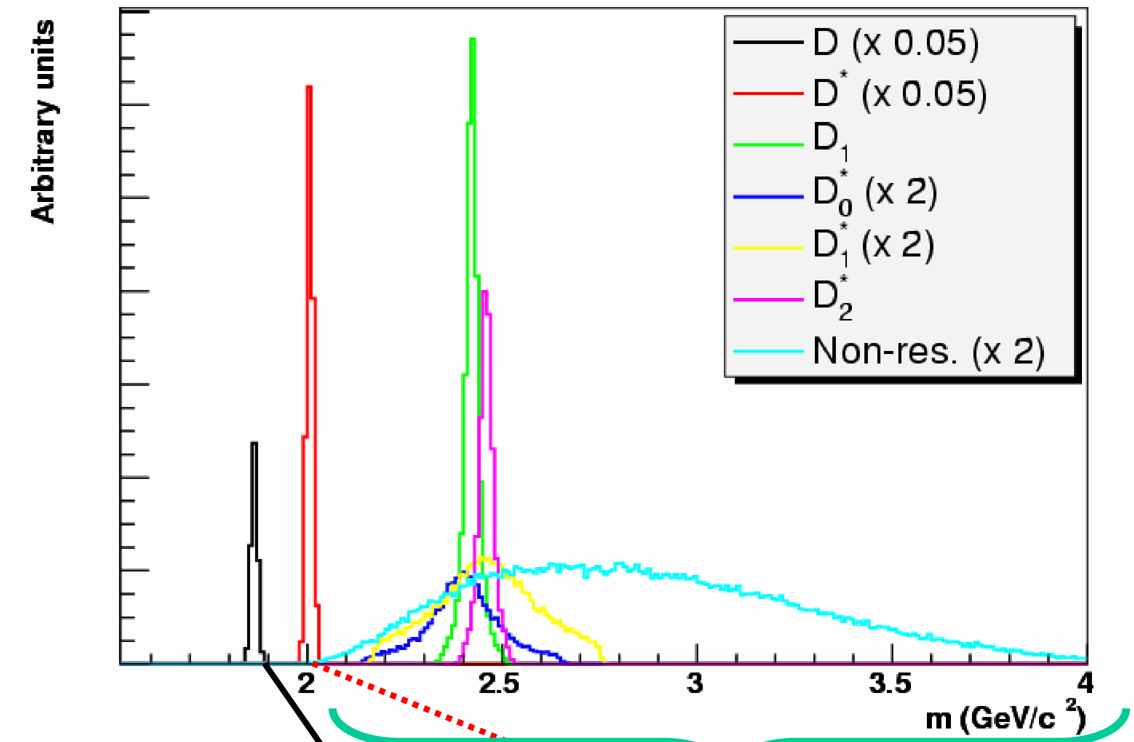
Aim: Constrain the unknown parameters and reduce $|V_{cb}|$ uncertainty.

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

Analysis Strategy

PRDRC 71, 051103 2005

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



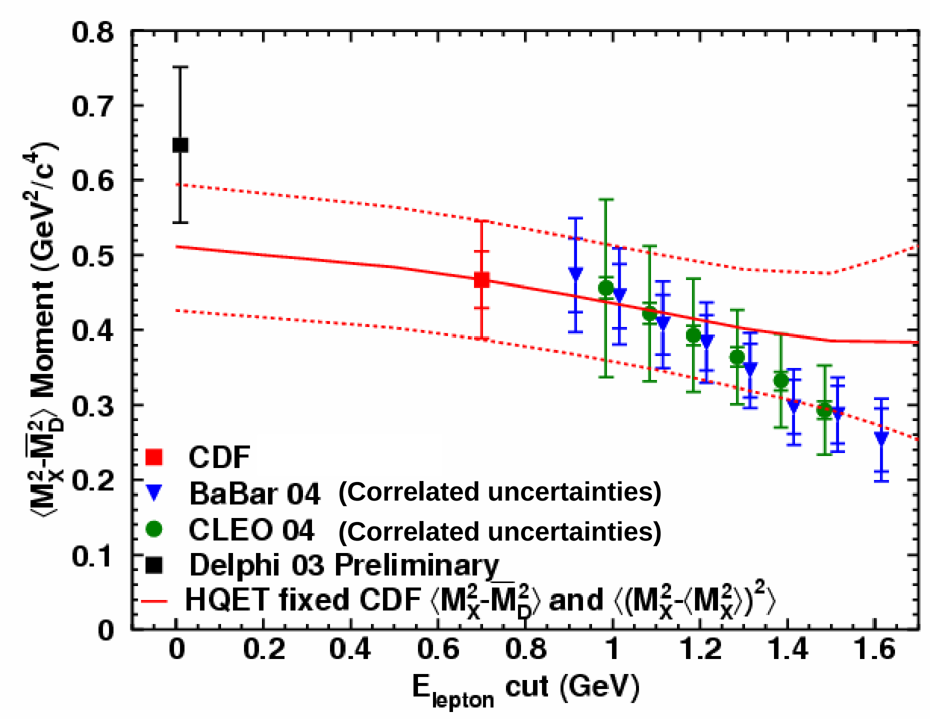
D^0 and D^{*0} well-known
➔ measure only f**
➔ only shape needed

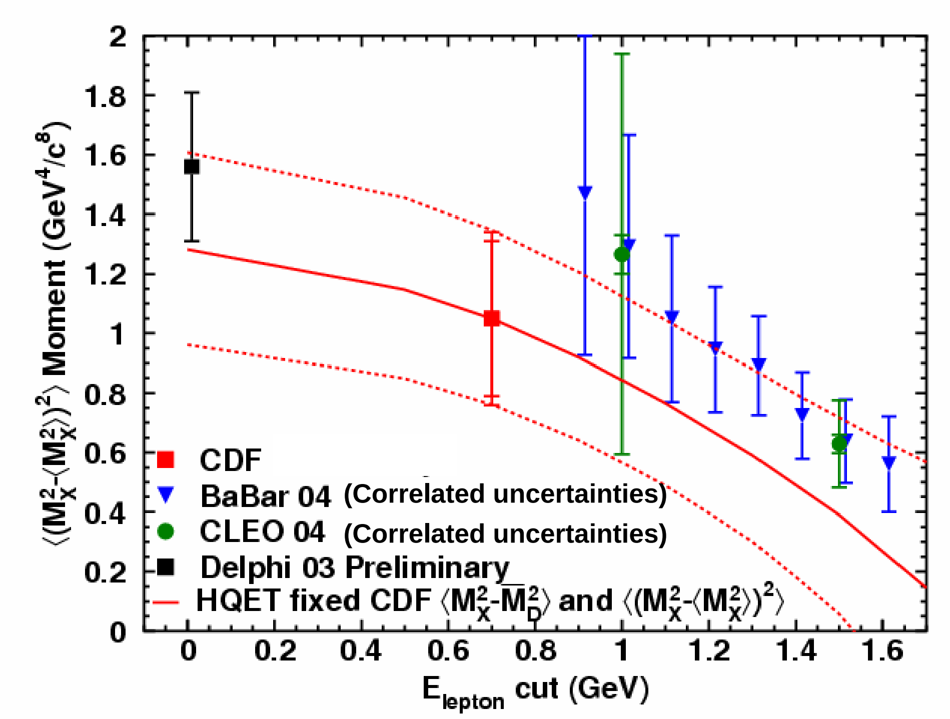
1) Measure $f^{**}(s_H)$
2) Correct for background, acceptances, bias
➔ (μ,σ) of $M(D^{**})^2$
3) Add D and D* ➔ M_1, M_2
4) Extract OPE parameters (Λ, λ_1)

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

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

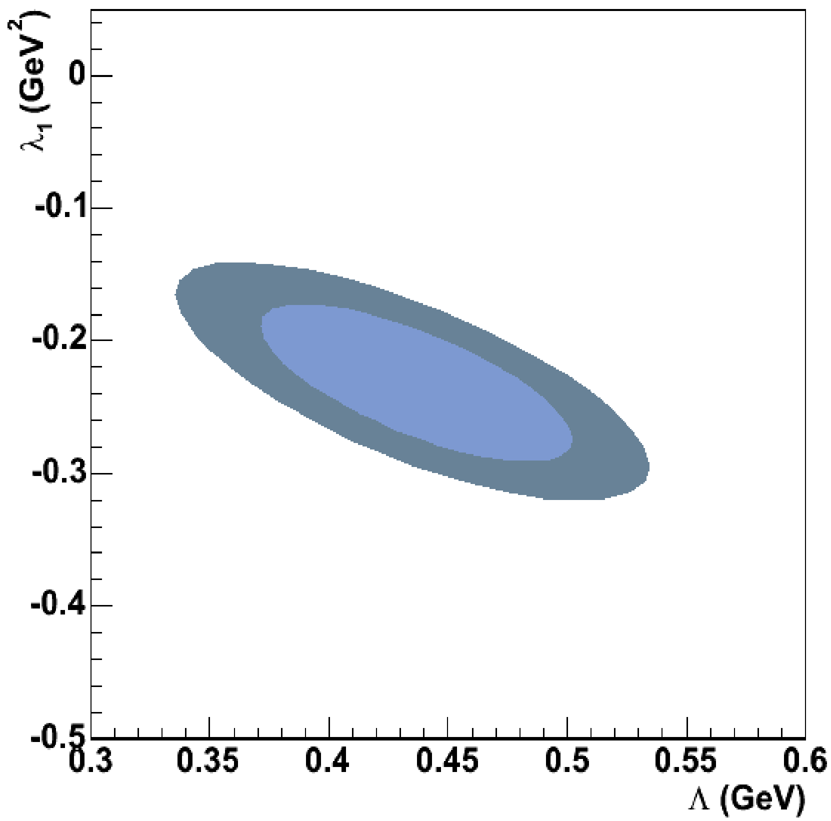
Results & Comparison with other experiments





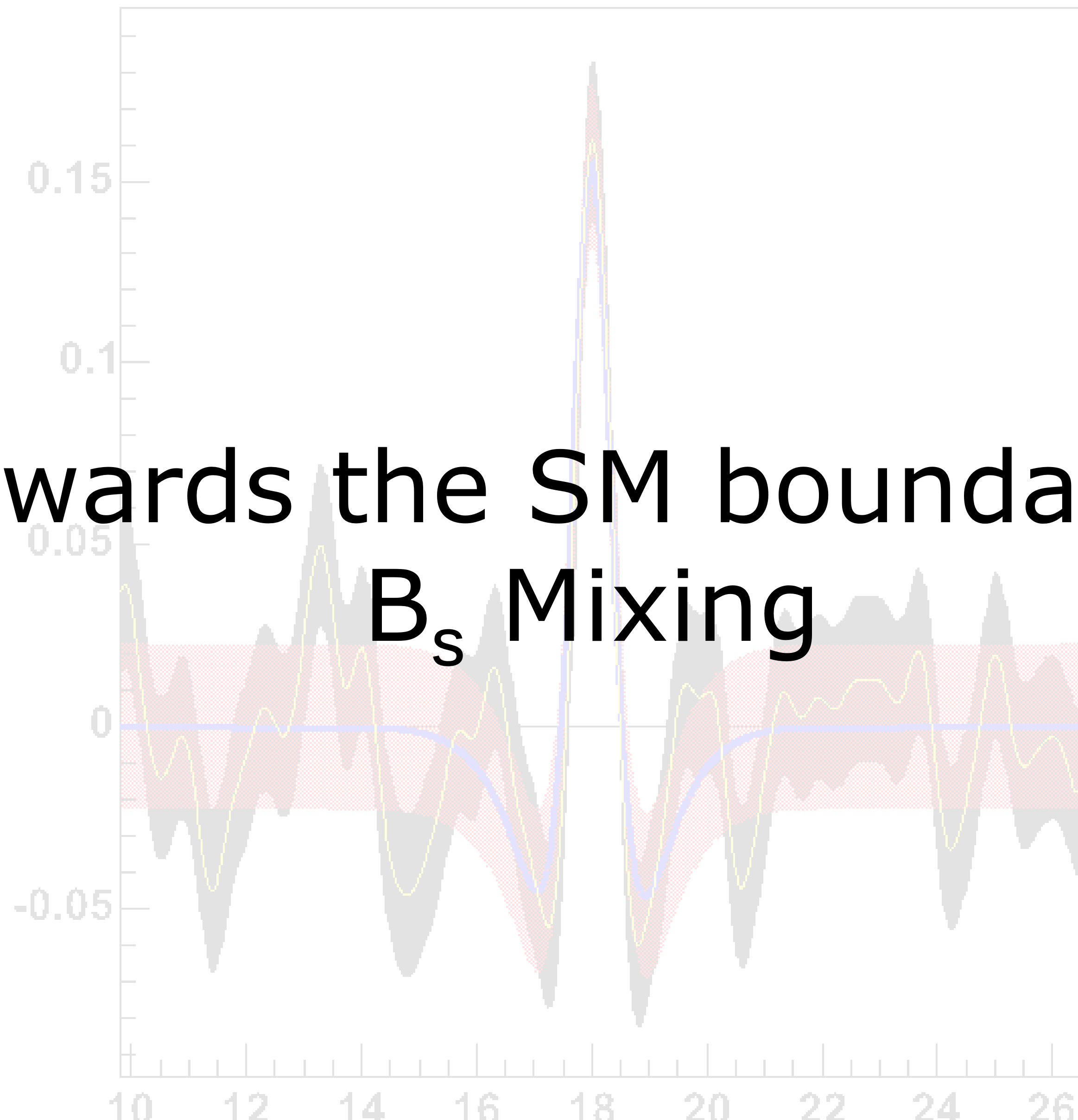
- Good agreement with HQET ⊕ previous determinations.
- First measurement at hadron machines: different environment and experimental techniques.
- Competitive with other experiments.
- Little model dependency. No assumptions on shape or rate of D** components.
- Through integration with other experiments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

Extraction of the HQE Parameters

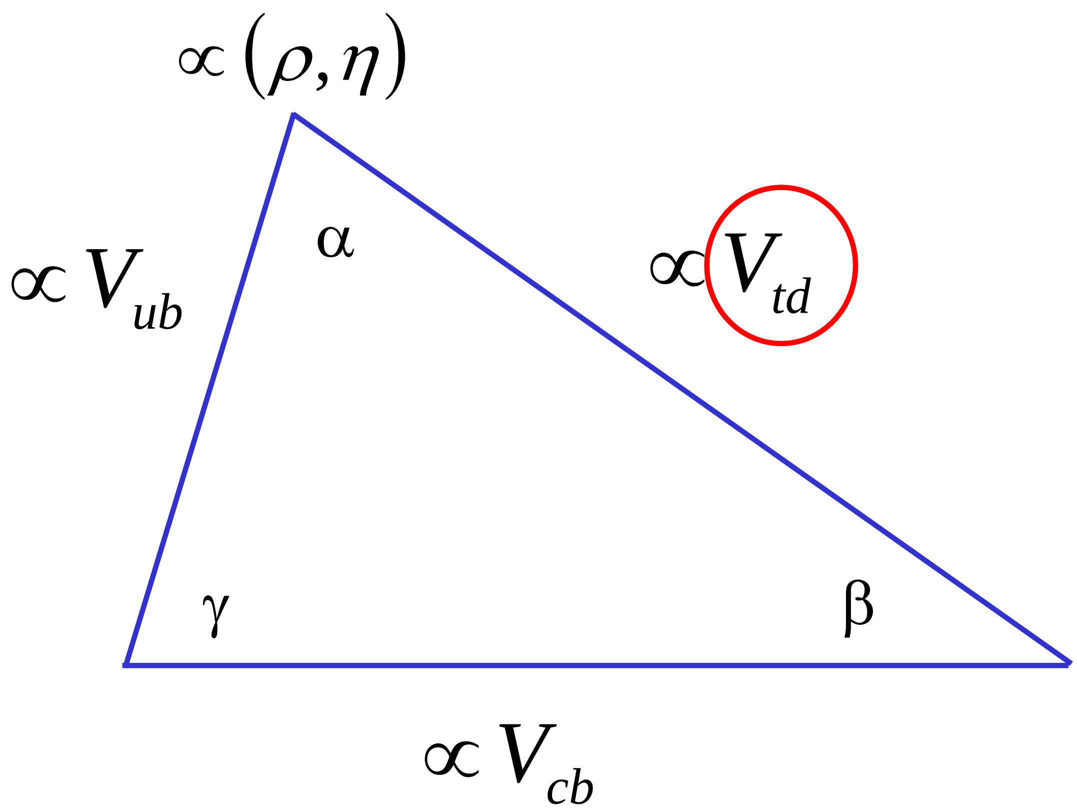


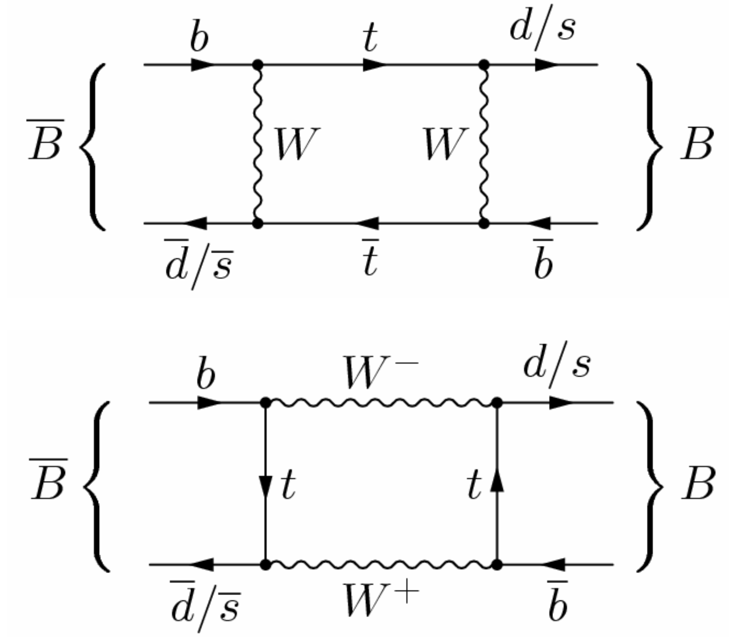
- Combination of all the experimental measurements of the hadronic moments
- Effective determination of the two OPE operators relevant at order $1/m_B$ (Λ) $1/m_B^2$ (λ_1)
- CDF contributes as much as the B factories in this determination!

Towards the SM boundaries: B_s Mixing



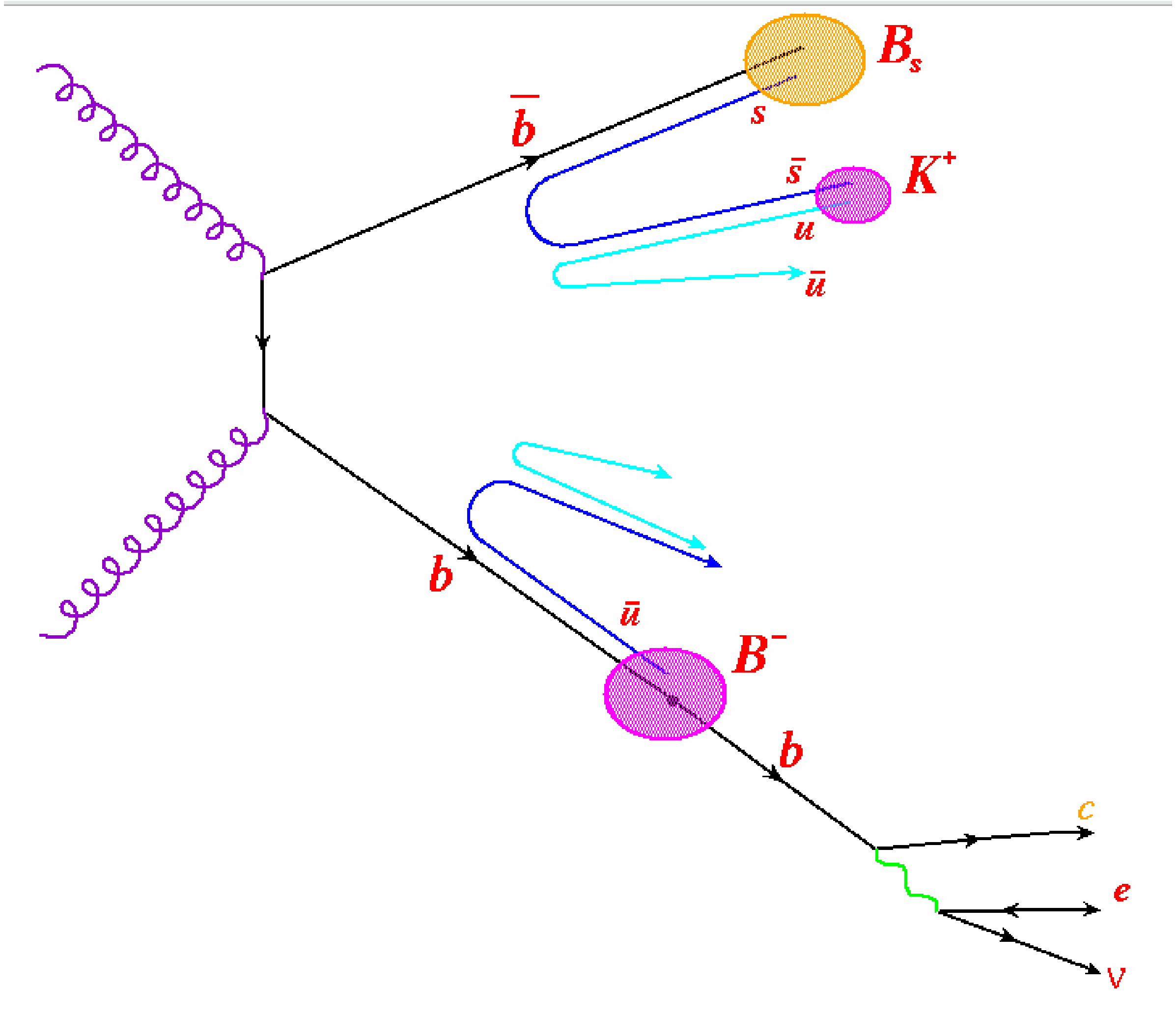
Working our way through CKM sides





- 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



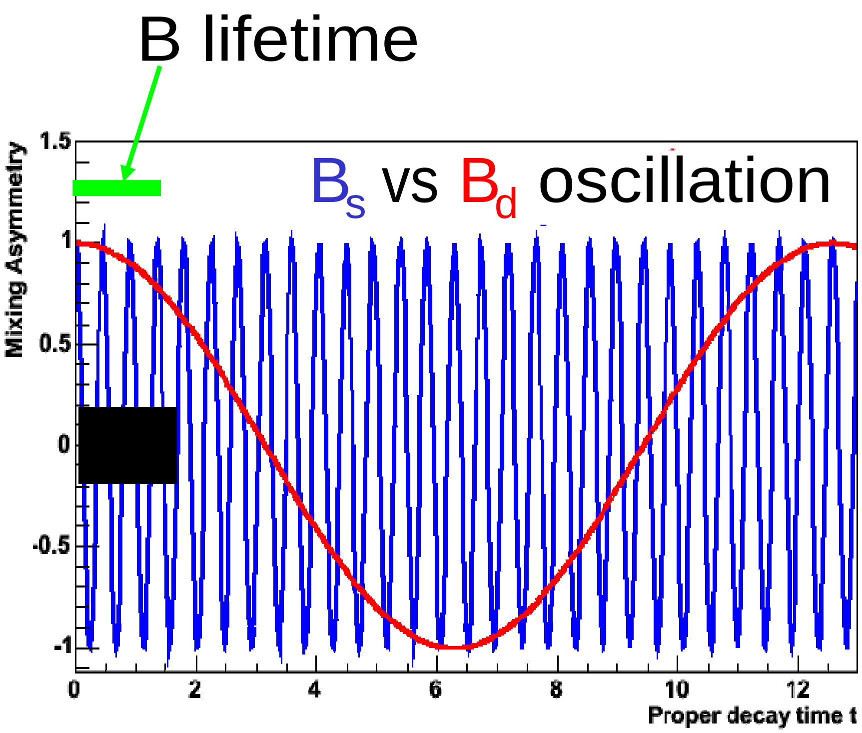
- Production: gg→bb
- NO QM coherence, unlike B factories
- Opposite flavor at production→one of the b quarks can be used to tell the flavor of the other at production
- Fragmentation products have some memory of b flavor as well

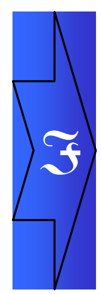
B_s Mixing 101

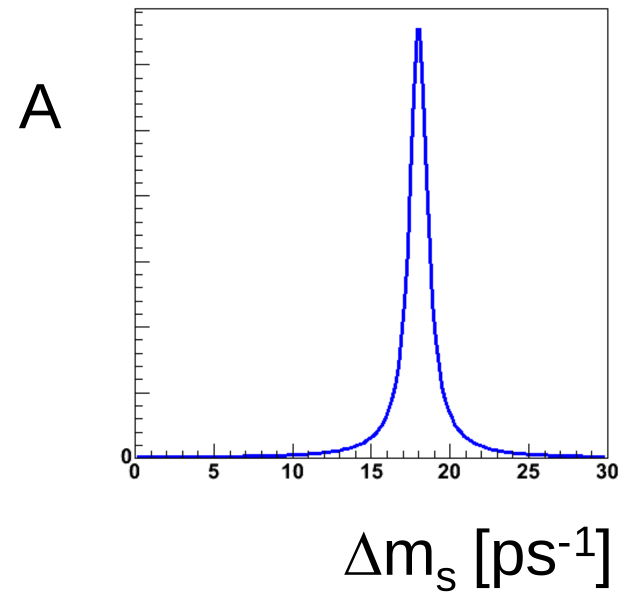
$$A = \frac{N_{unmix} - N_{mix}}{N_{unmix} + N_{mix}}$$

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

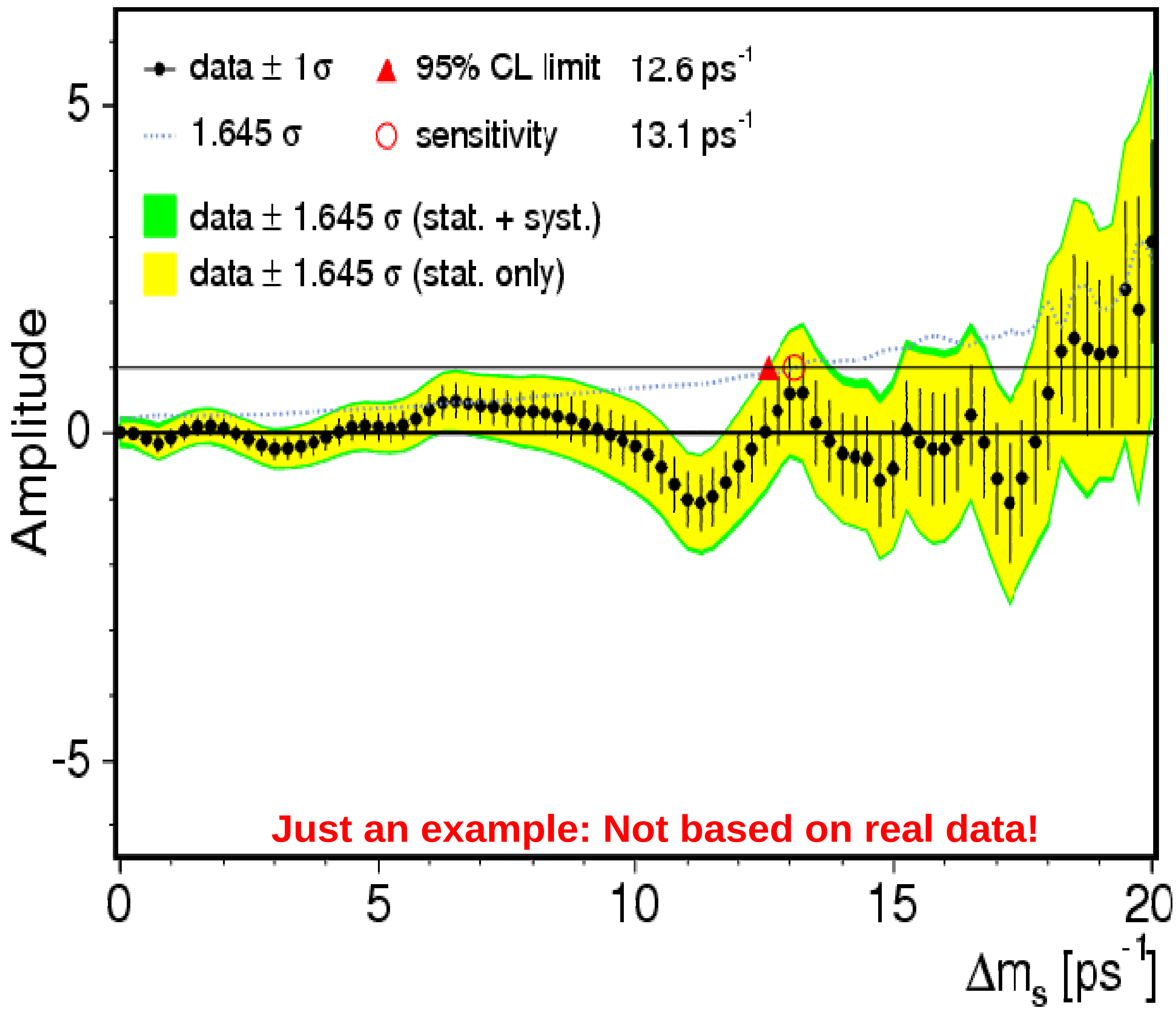
Perform a 'fourier transform' rather than fit for frequency





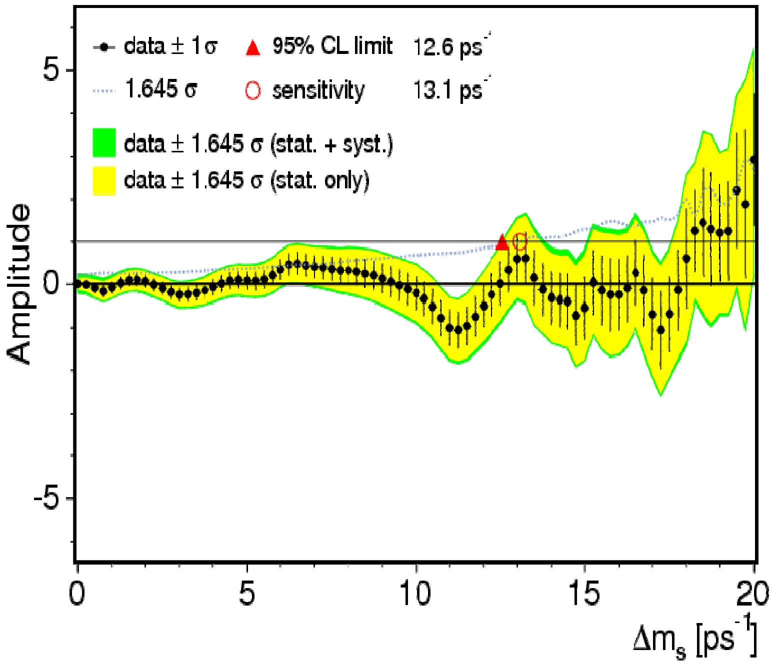


Amplitude Scan



- 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

Amplitude Scan do and don't



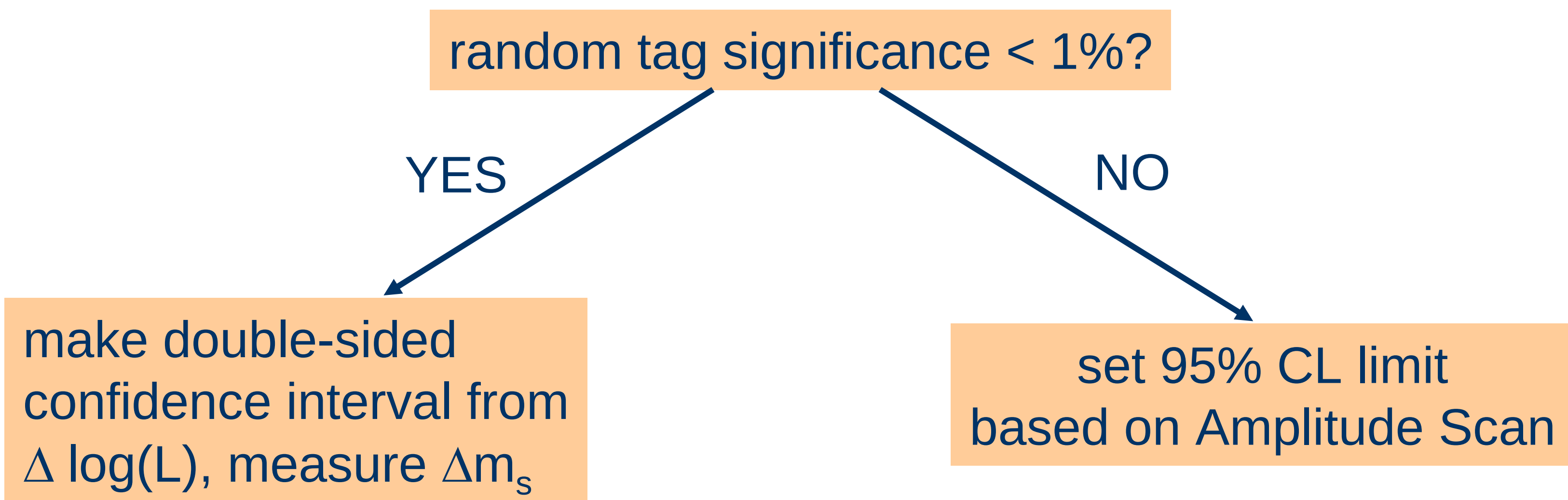
- Amplitude scan is helpful to:
  - Set a Δm limit
  - Combine experimental results
- It is not easy to measure mixing from it
- How does an evidence of a signal look like?
- What procedure should one follow if aiming at a measurement?
- These questions must be asked before performing the analysis!
- Otherwise lack of coverage is the punishment!

Remember:

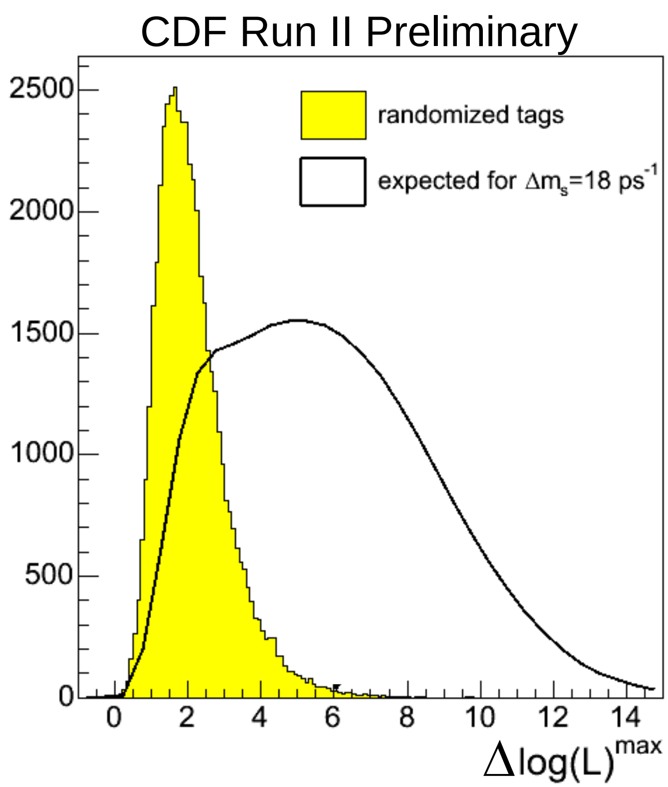
- Not to confuse the individual significance of each A measurement with the overall significance of the 'feature'
- 'Discovery threshold' is an arbitrary cut on the probability for non-signal to produce the same features: nothing to do in general with how significant the value of a given parameter you measure is!

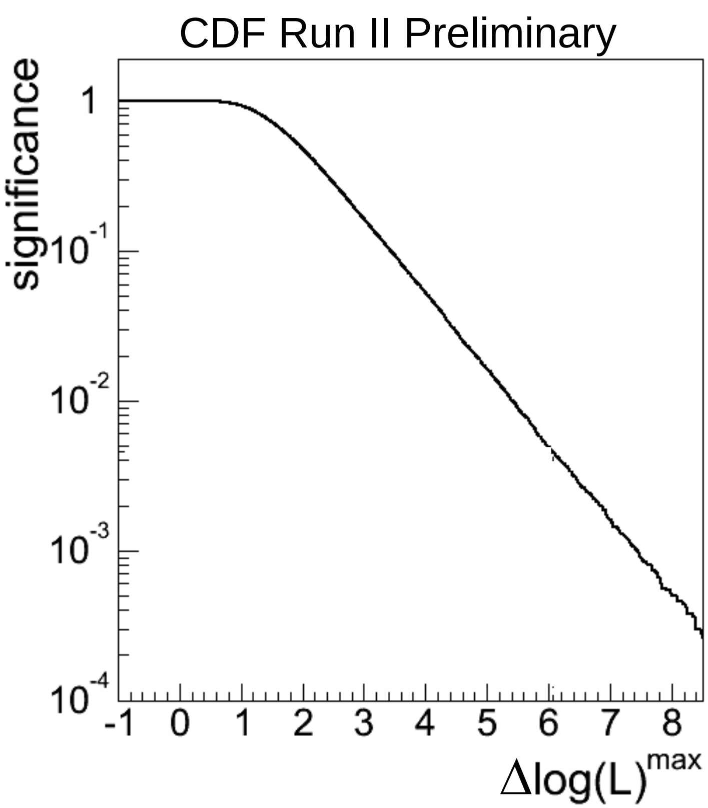
CDFs Choice of Procedure

- decided upon before un-blinding the data
- “random tag” significance to be estimated using Δ(ln L) method
- no search window to be used



Significance





- Δlog(L) = log[L(A=1) / L(A=0)] → likelihood "dip" at signal
- more powerful discriminant than A/σ(A)
- probability of random tag fluctuations evaluated on data (with randomized tags) → checked that toy Monte Carlo gives same answer

B_s Mixing Ingredients

Proper time resolution

Flavor tagging

Signal-to-noise

Event yield

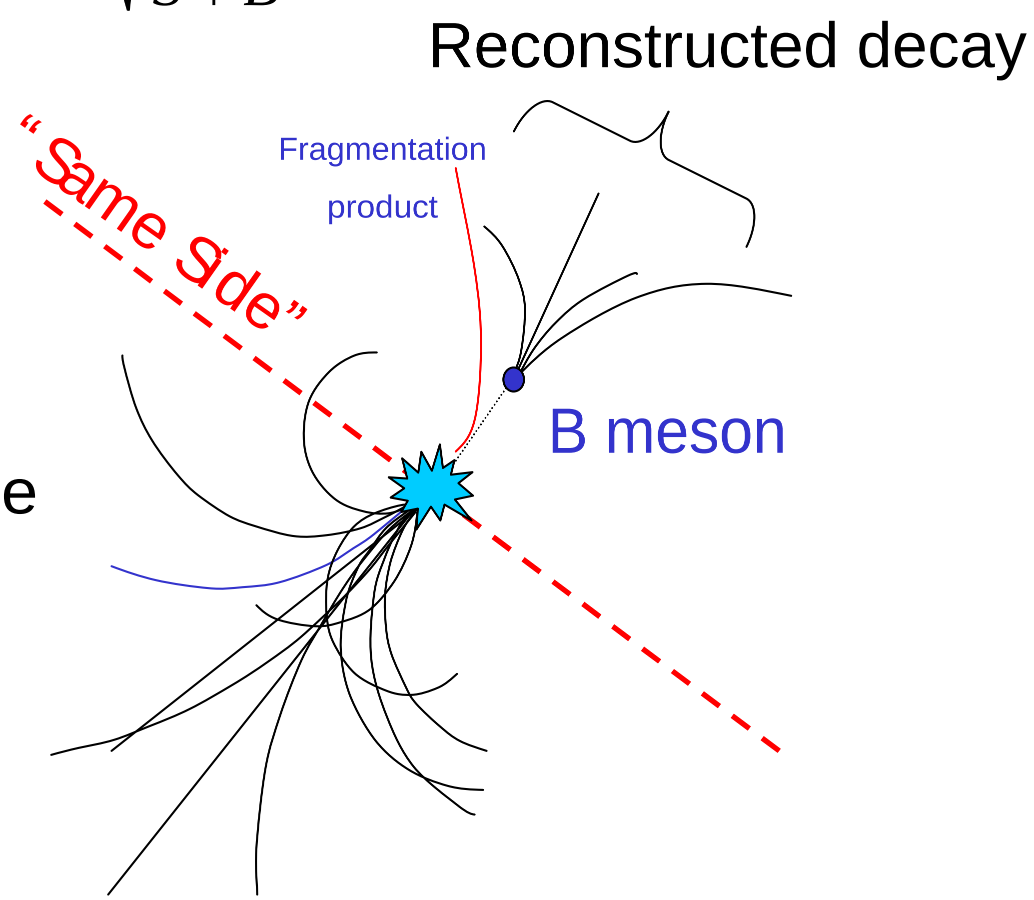
$$Significance = \sqrt{\frac{S\varepsilon D^2}{2}} e^{-\frac{(\Delta m_s \sigma_t)^2}{2}} \sqrt{\frac{S}{S+B}}$$

Flavor Tagging

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

$$D = \frac{N_{right} - N_{wrong}}{N_{right} + N_{wrong}}$$

Amplitude $\rightarrow$ D$\times$Amplitude



Several methods, none is perfect !!!

B_s Mixing: tagging performance

- use exclusive combination of tags on opposite side
- same side – opposite side combination assumes independent tagging information

Measured from B_d data!

	εD^2 Hadronic (%)	εD^2 Semileptonic (%)
Muon	0.48 ± 0.06 (stat)	0.62 ± 0.03 (stat)
Electron	0.09 ± 0.03 (stat)	0.10 ± 0.01 (stat)
JQ/Vertex	0.30 ± 0.04 (stat)	0.27 ± 0.02 (stat)
JQ/Prob.	0.46 ± 0.05 (stat)	0.34 ± 0.02 (stat)
JQ/High p_T	0.14 ± 0.03 (stat)	0.11 ± 0.01 (stat)
Total OST	1.47 ± 0.10 (stat)	1.44 ± 0.04 (stat)
SSKT	3.42 ± 0.06 (stat)	4.00 ± 0.04 (stat)

~5% of the Events are effectively used!

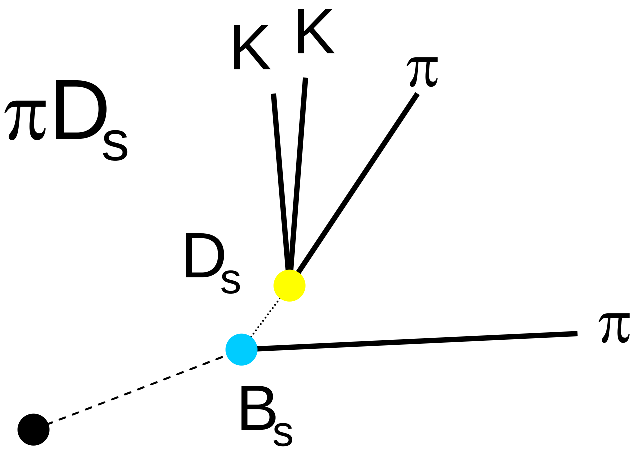
B_s Mixing Ingredients: σ_{ct}

Proper time resolution

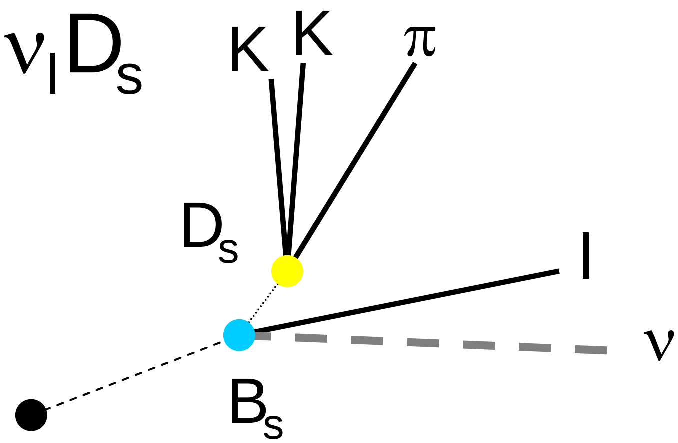
$$Significance = \sqrt{\frac{S\varepsilon D^2}{2}e^{-\frac{(\Delta m_s \sigma_t)^2}{2}}}\sqrt{\frac{S}{S+B}}$$

Proper time resolution

$B_s \to \pi D_s$



$B_s \to l \nu_l D_s$



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

~0.5%

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

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

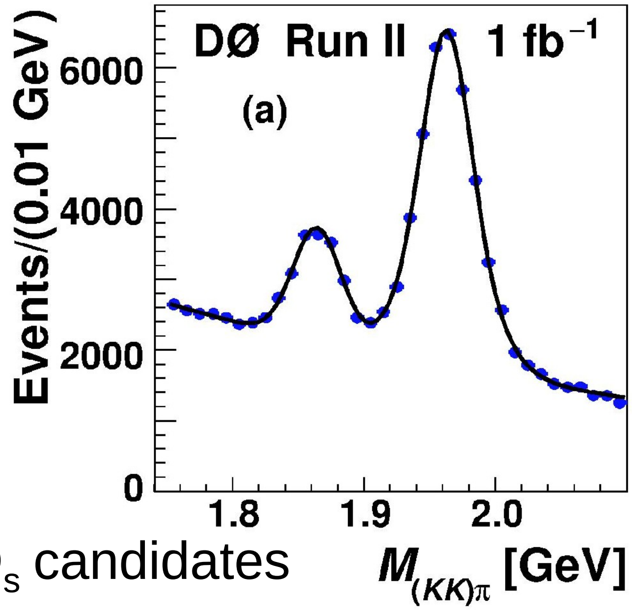
$$\sigma_{ct} = \frac{m_B}{P_t}\sigma_{L_{xy}} \oplus \overbrace{ct\left(\frac{\sigma_{P_t}}{P_t}\right) \otimes \sigma_K}^{\sim 15\%}$$

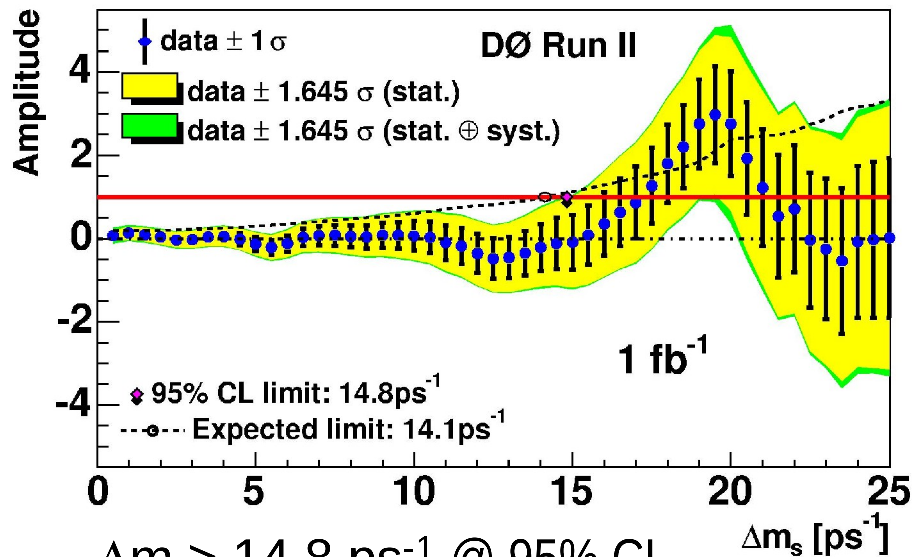
Semileptonic modes: momentum uncertainty

Fully reconstructed: Lxy uncertainty → improve reconstruction

B_s Mixing: D0 Result

Hep-ex/0603029



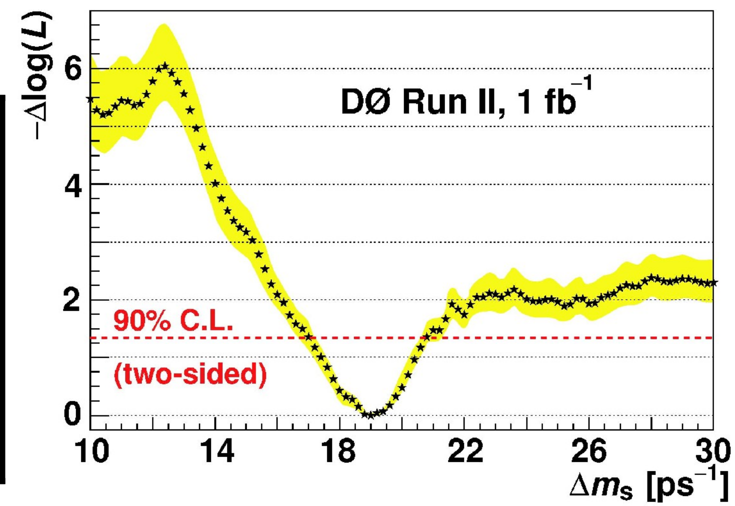


- 26700 lD_s candidates
- εD^2~2.5%
- Very exciting: is this a mixing signal???

Δm_s> 14.8 ps^{-1} @ 95% CL

Sensitivity: 14.1 ps^{-1}

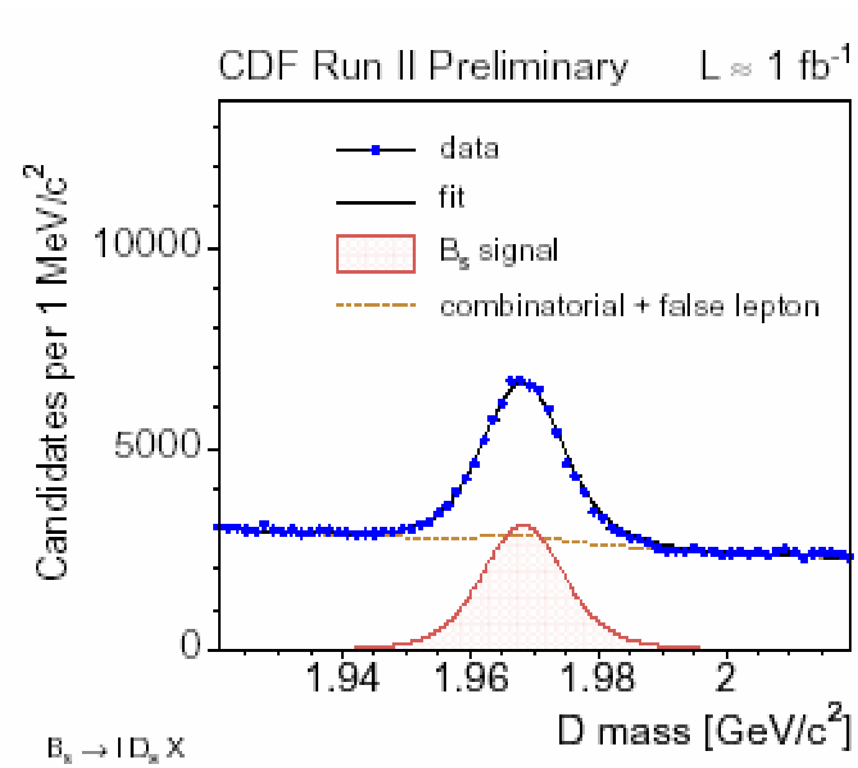
Pros	Cons
$\Delta m \approx 19$	$\Delta m \approx 19$
$A/\sigma_A \approx 2.5$	$(A-1)/\sigma_A \approx 1.6$
L has a nice dip	..but shallow

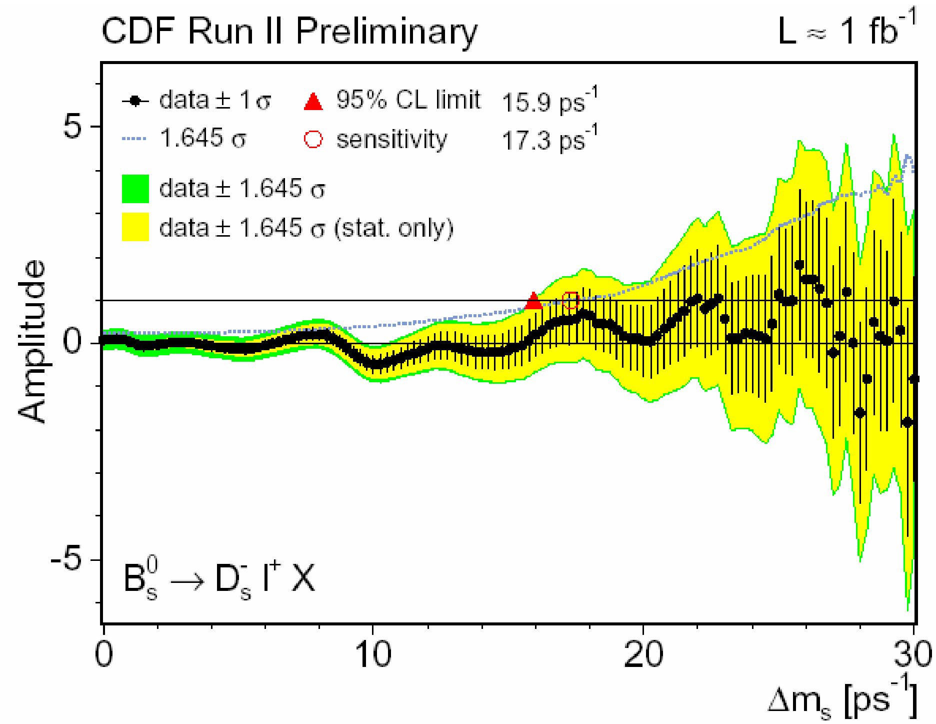


B_s Mixing: CDF semileptonic

http://www-cdf.fnal.gov/physics/new/bottom/051020.semi_Bsmix/

$B_s \to D_s l \nu$	Yield	s/b
$D_s \to \phi\pi$	32300	?
$D_s \to K^*K$	10900	?
$D_s \to \pi\pi\pi$	10100	?





$\Delta m_s > 15.9\ ps^{-1}$ @ 95% CL

Sensitivity: $17.3\ ps^{-1}$

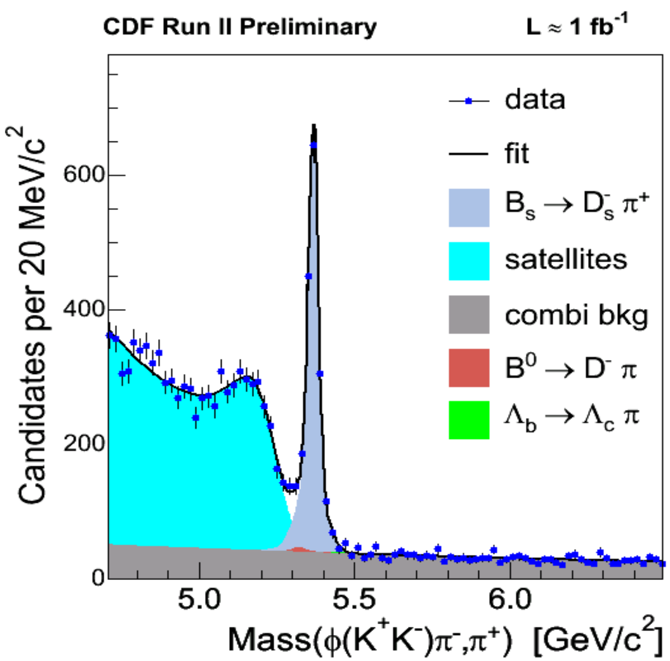
Reach at large Δm_s limited by incomplete reconstruction (σ_{ct})!

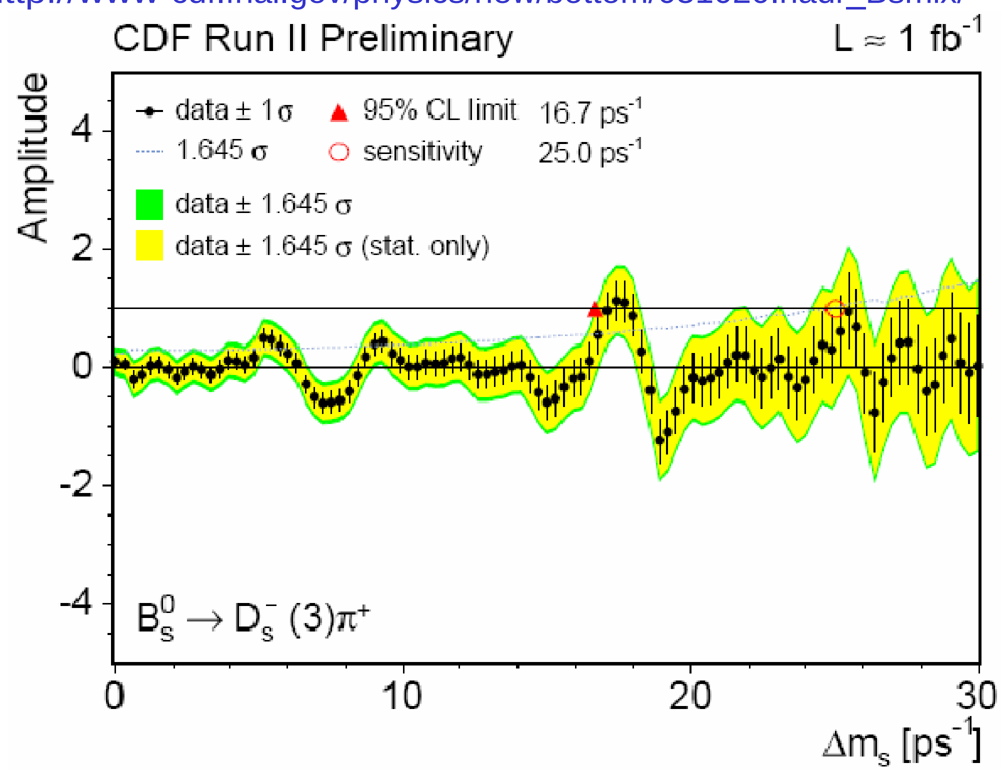
B_s Mixing: CDF hadronic

http://www-cdf.fnal.gov/physics/new/bottom/051020.hadr_Bsmix/

$B_s \to D_s\pi$	Yield	s/b
$D_s \to \phi\pi$	1600	?
$D_s \to K^*K$	800	?
$D_s \to \pi\pi\pi$	600	?

Using also **$B_s \to D_s\pi\pi\pi$ [~1/4 more statistics]**





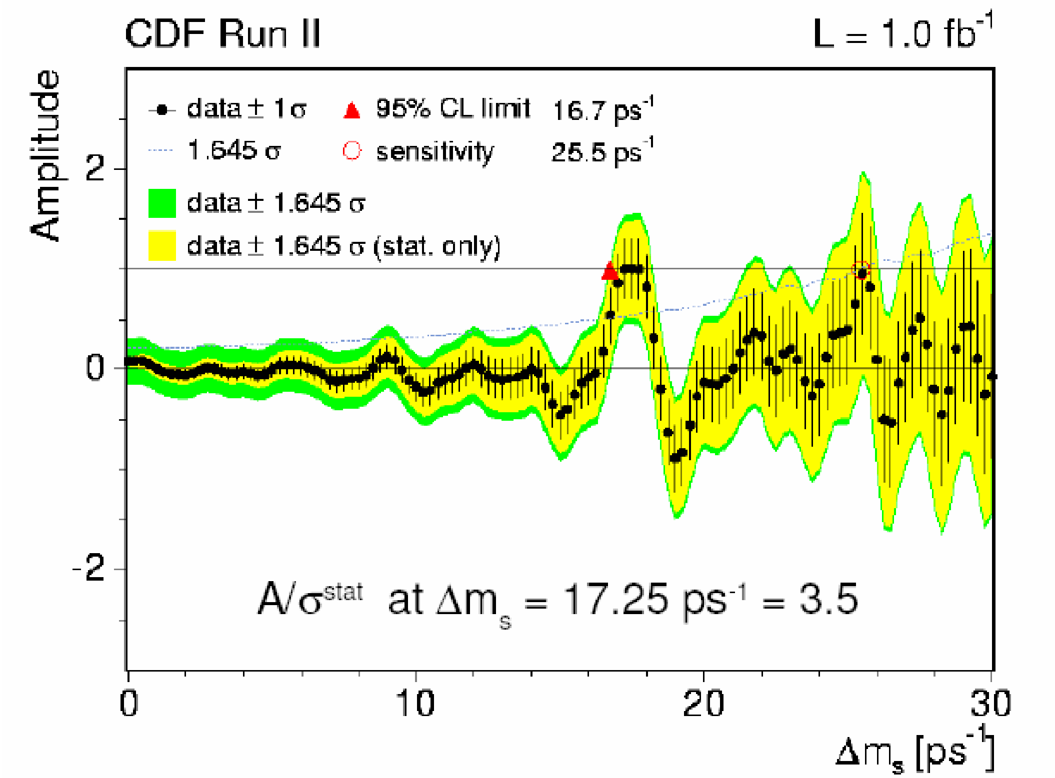
$\Delta m_s > 16.7\ ps^{-1}$ @ 95% CL

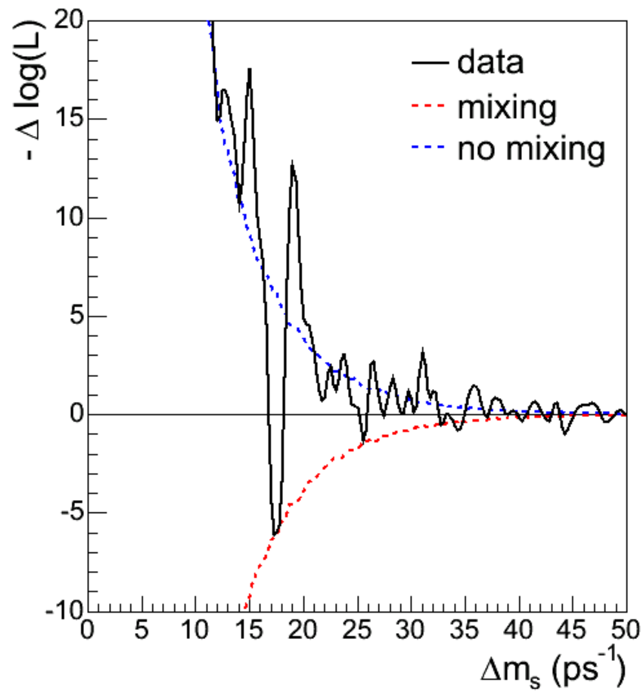
Sensitivity: $25.0\ ps^{-1}$

Is there something?

B_s Mixing: combined CDF result

http://





$\log[\mathcal{L}(A=1)/\mathcal{L}(A=0)]^{max} = 6.06$

$\Delta m_s > 16.7$ ps^{-1} @ 95% CL

Sensitivity: 25.5 ps^{-1}

Background has ~0.5% probability to mimic this!

$$\Delta m_s = 17.33^{+0.42}_{-0.21} \pm 0.07(\mathrm{syst})\,\mathrm{ps}^{-1}$$

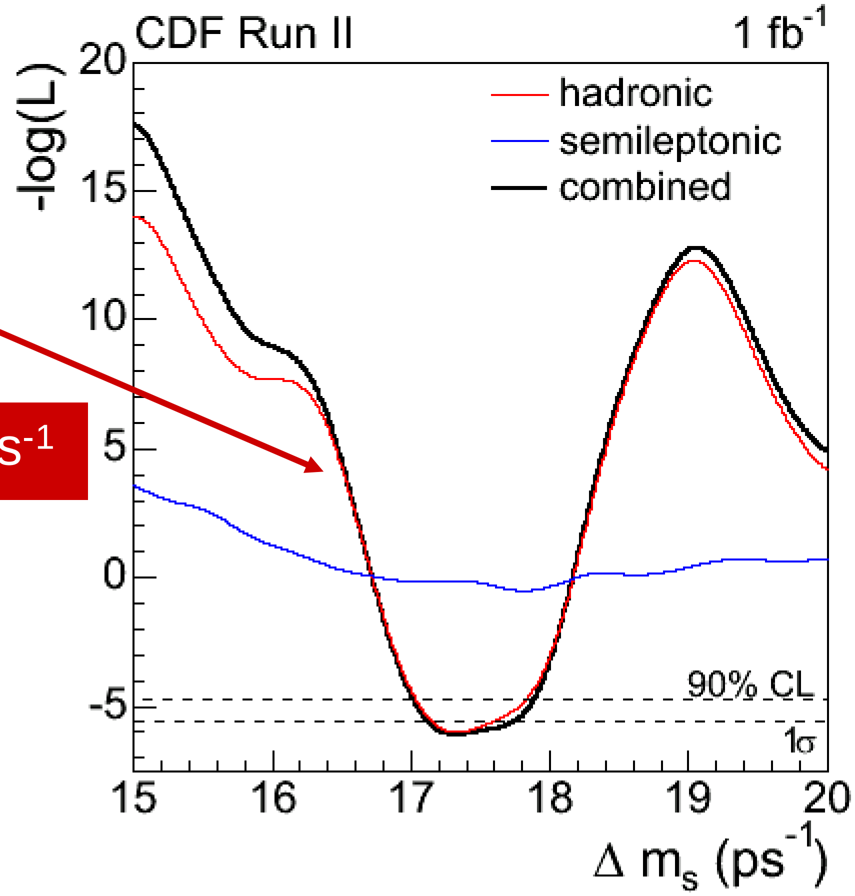
$\Delta m_s \in [17.00, 17.91]$ at 90 % CL

$\Delta m_s \in [16.94, 17.97]$ at 95 % CL

Likelihood Ratio

combined likelihoods from hadronic and semileptonic channels

$\Delta m_s = 17.33\,^{+0.42}_{-0.21}$ (stat) $\pm$ 0.07 (syst) ps^{-1}



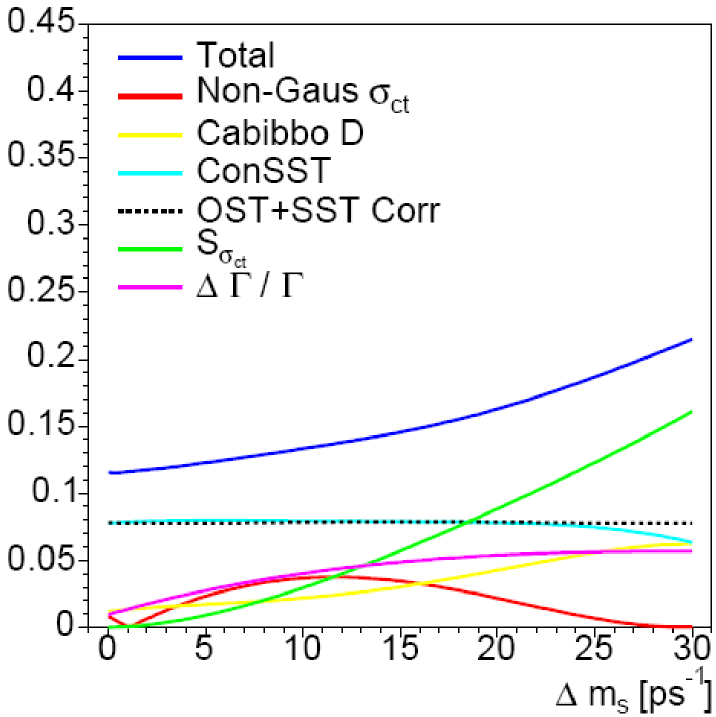
the measurement is already very precise! (at 2.5% level)

Δm_s in [17.00, 17.91] ps^{-1} at 90% CL

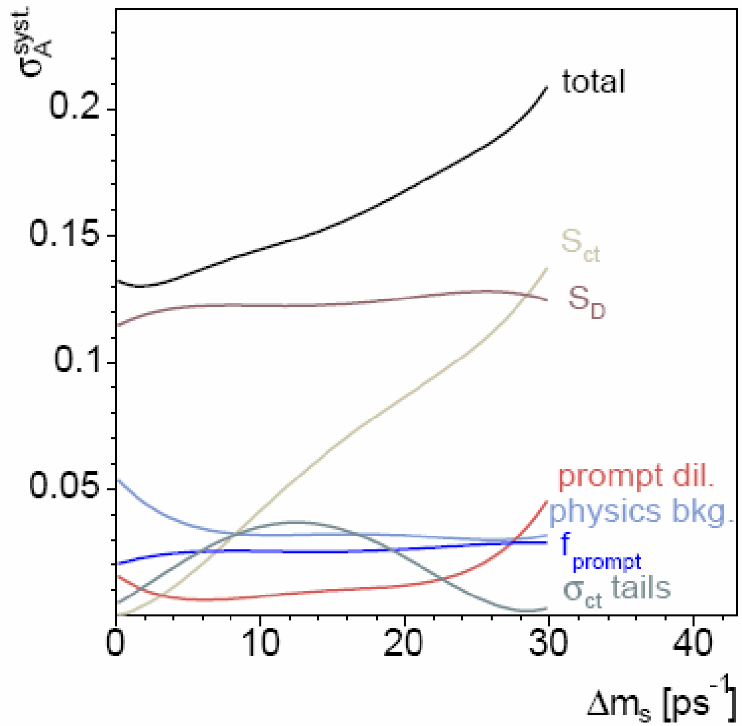
Δm_s in [16.94, 17.97] ps^{-1} at 95% CL

Systematic Uncertainties I

Hadronic



Semileptonic



- related to absolute value of amplitude, relevant only when setting limits
  - cancel in A/σA, folded in in confidence calculation for observation
  - systematic uncertainties are very small compared to statistical

Systematic Uncertainties II

- systematic uncertainties from fit model evaluated on toy Monte Carlo
- have negligible impact
- relevant systematic unc. from lifetime scale

	Syst. Unc
Fitting Model	< 0.01ps^{-1}
SVX Alignment	0.04 ps^{-1}
Track Fit Bias	0.05 ps^{-1}
PV bias from tagging	0.02 ps^{-1}
Total	0.07 ps^{-1}

All relevant systematic uncertainties are common between hadronic and semileptonic samples

Δm_s and V_{td}

$$\frac{\Delta m_s}{\Delta m_d} = \frac{m_{Bs}}{m_{Bd}} \xi^2 \frac{|V_{ts}|^2}{|V_{td}|^2}$$

- inputs:
  - → $m(B^0)/m(B_s) = 0.9830$ (PDG 2006)
  - → $\xi = 1.21^{+0.47}_{-0.35}$ (M. Okamoto, hep-lat/0510113)
  - → $\Delta m_d = 0.507 \pm 0.005$ (PDG 2006)

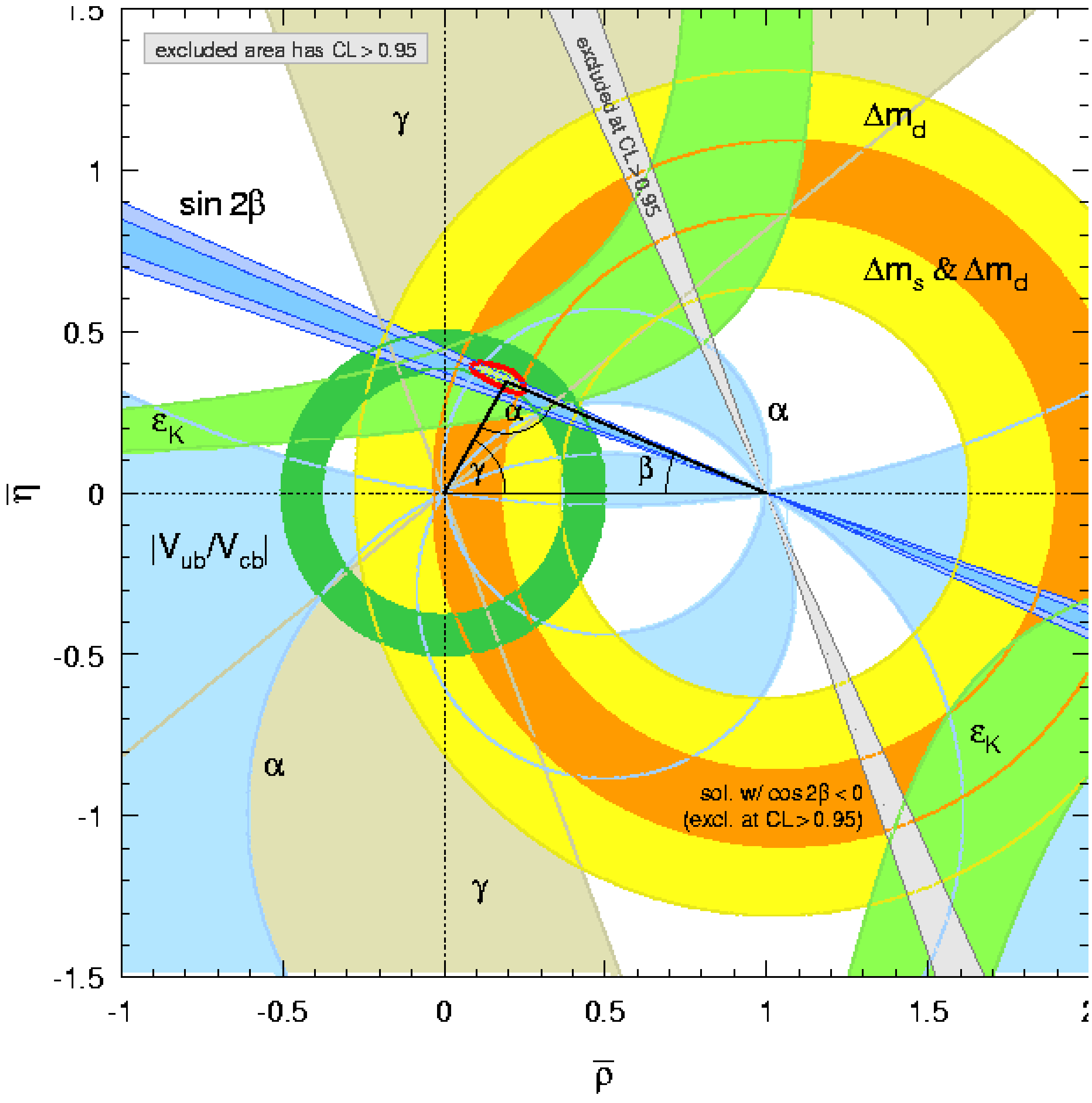
$|V_{td}| / |V_{ts}| = 0.208^{+0.008}_{-0.007}$ (stat + syst)

- compare to Belle $b \rightarrow s\gamma$ (hep-ex/050679):

$|V_{td}| / |V_{ts}| = 0.199^{+0.026}_{-0.025}$ (stat) $^{+0.018}_{-0.015}$ (syst)

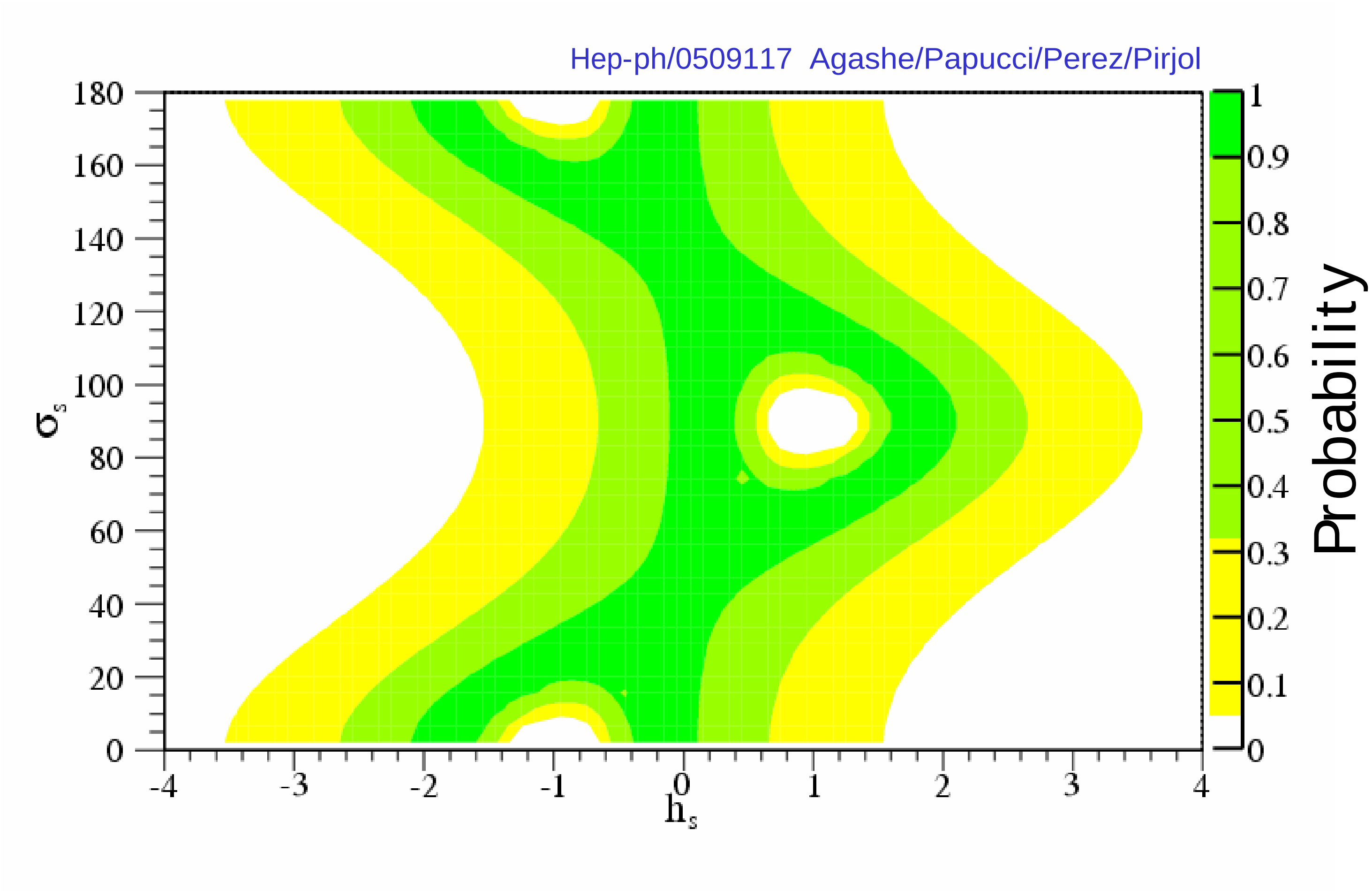
Δm_s & CKM

Thanks to
M. Papucci



Δms from Tevatron & BSM Limits

$$A_{SM} \rightarrow A_{SM}\left(1 + h_s e^{i\sigma_S}\right)$$



B Physics BSM: Perspectives

Exciting times ahead:

- Most analyses sensitive to BSM physics are statistically limited
- B_s results has become an important complementary addition to the CKM mapping!
- ...but remember: TeVatron is not alone anymore in the game!

Conclusions

- **We are living an exciting transition era of increasingly quantitative results in the CKM sector**
- **Beyond SM physics could be around the corner, but hard to discern models without direct evidences**
- **LHC will investigate the completely uncharted territory!**
- **Living this constant exploration of new discoveries puts us at the forefront of human knowledge, a recurring theme in the history of science:**

"Modern science did not spring perfect and complete, as Athena from the head of Zeus, from the mind of Galileo and Descartes**"** A. Koyre`, "Galileo and the Scientific Revolution of the Seventeenth Century"

LHC

The next frontier of knowledge!

Jan Cossiers, “ Prometheus Carrying Fire”

Backup Slides

What happens for large x_s?

Indirect Measurement of Δm_s:

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

– SM $\Delta\Gamma_s / \Gamma_s = 0.12 \pm 0.06$ (Dunietz, Fleischer & Nierste)

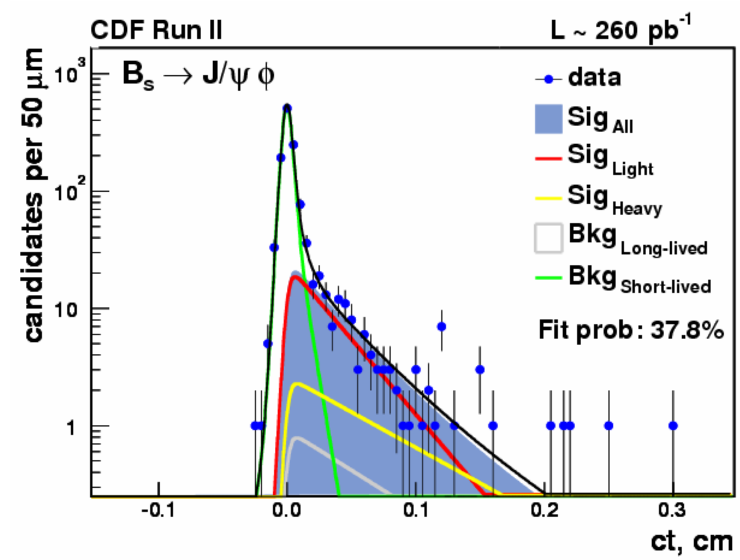
Probing large Δm_s: $\Delta\Gamma/\Gamma$

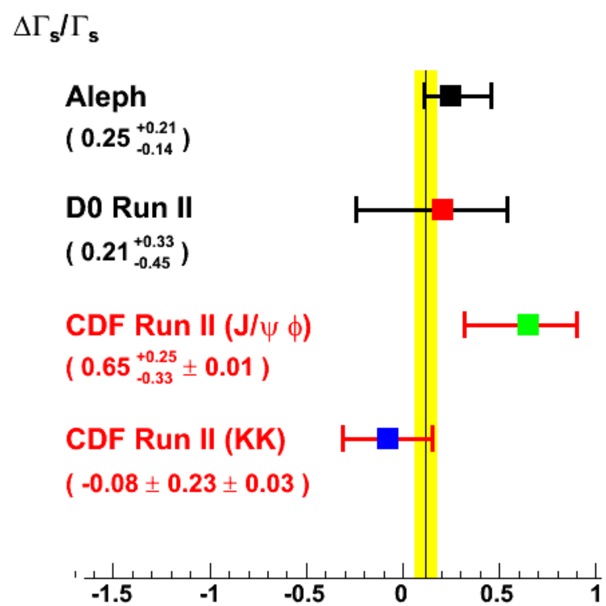
- $B_s \to J/\psi\phi$
  - $B \to VV$, mixture of CP even/odd separate by angular analysis
  - Combine two-lifetime fit + angular $\to \Delta\Gamma_s = \Gamma_H - \Gamma_L$

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

PRL 94, 101803 2005

few ps^{-1} in Δm_s !





- $B_s \to KK$ (360 pb^{-1})

$$\left.\begin{array}{ll} CDFII & c\tau(B_s \to KK) = 1.53 \pm 0.18 \pm 0.02\ ps \\ HFAG & c\tau(B_s \to FS) = 1.454 \pm 0.04\ ps \end{array}\right\}$$

$$\frac{\Delta\Gamma_s}{\Gamma_s} = -0.08 \pm 0.23 \pm 0.03$$

Beyond the SM

Analyses like these 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 ε and luminosity measurements
- SM: BR($B_s \to \mu\mu$) <3.8E-9
- Sensitive to new physics!

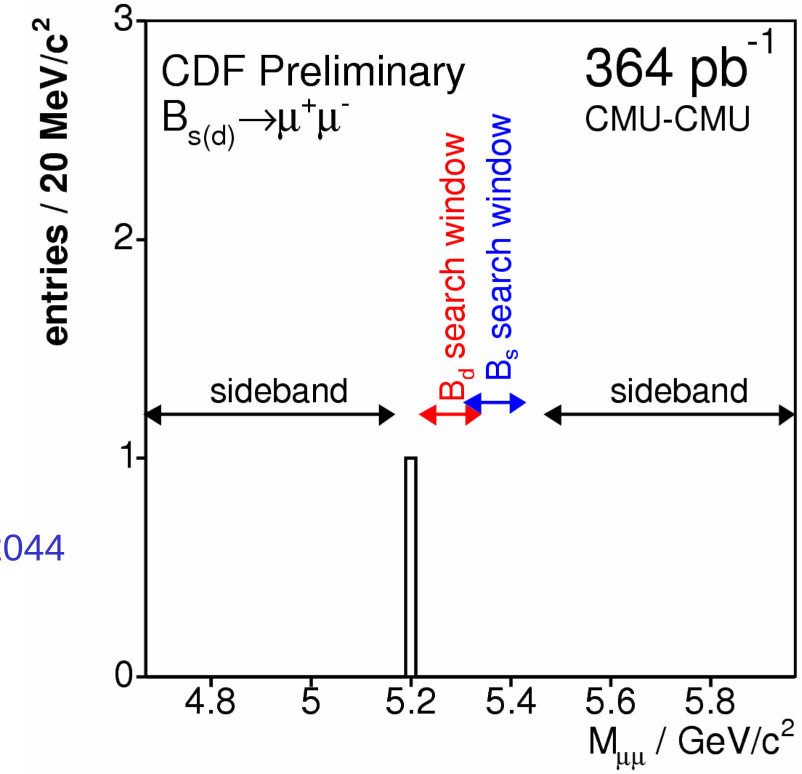
Result: World's best limits

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

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

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

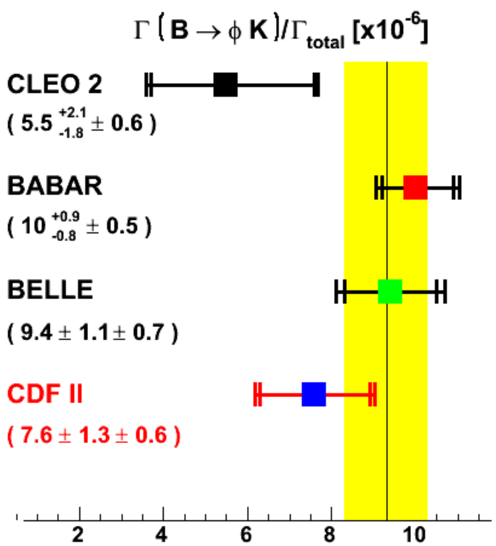
$$BR(D^0 \to \mu\mu) \leq 2.4\times10^{-6}\ at\ 90\%\ CL$$

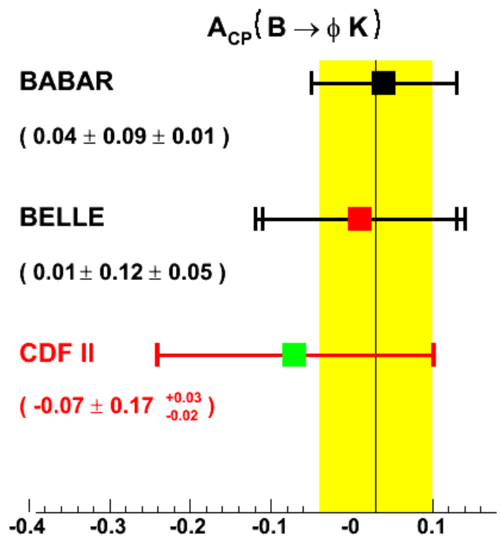


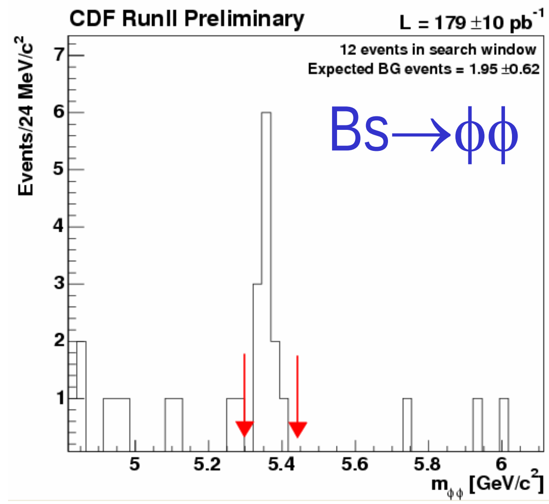
CP: $s\bar{s}s$

hep-ex/0502044

- $b \to sss$ transitions are 'misbehaving' at B factories
- CDF II can look at them too. We started from ϕK:







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

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

Phenomen. Tools Improvement

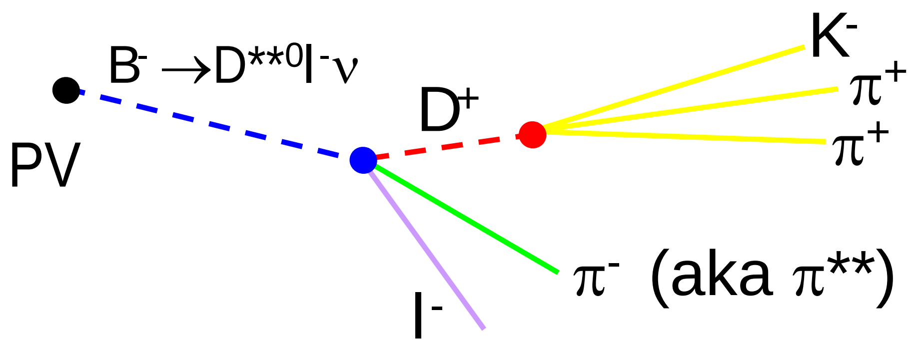
Hadronic Moments

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 $[b \to ul\nu] \Rightarrow V_{ub}$
  - $B \to X_c l\nu$ to $[b \to cl\nu] \Rightarrow V_{cb}$
- "semi-empirical" approach: parameterizes any prediction in a series expansion of effective operators
- Expectation value of these operators is a "universal" property $\Rightarrow$can be assessed with concurrent measurements
- Example: V_{cb} ($\pm 1\%_{exp} \pm 2.5\%_{theo}$) $\Leftrightarrow$ Hadronic Moments

D^+/D^{*+} Reconstruction

Exclusive reconstruction of D^{**}:



$D^{**0} \rightarrow D^{*+} \pi^{**-}$

↳ $D^0 \pi^{*+}$ (Br=67.7%)

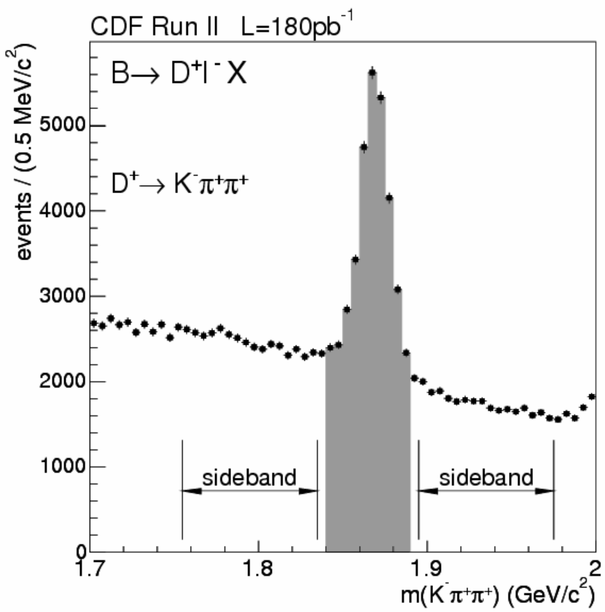
↳ $K^- \pi^+$ (Br=3.8%)

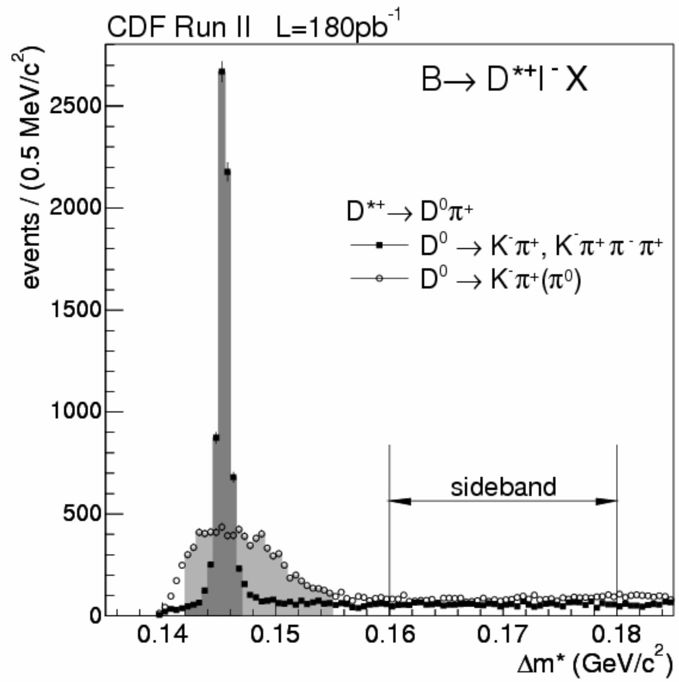
↳ $K^- \pi^+ \pi^- \pi^+$ (Br=7.5%)

↳ $K^- \pi^+ \pi^0$ (Br=13.0%)

$D^{**0} \rightarrow D^+ \pi^{**-}$

↳ $K^- \pi^+ \pi^+$ (Br=9.2%)



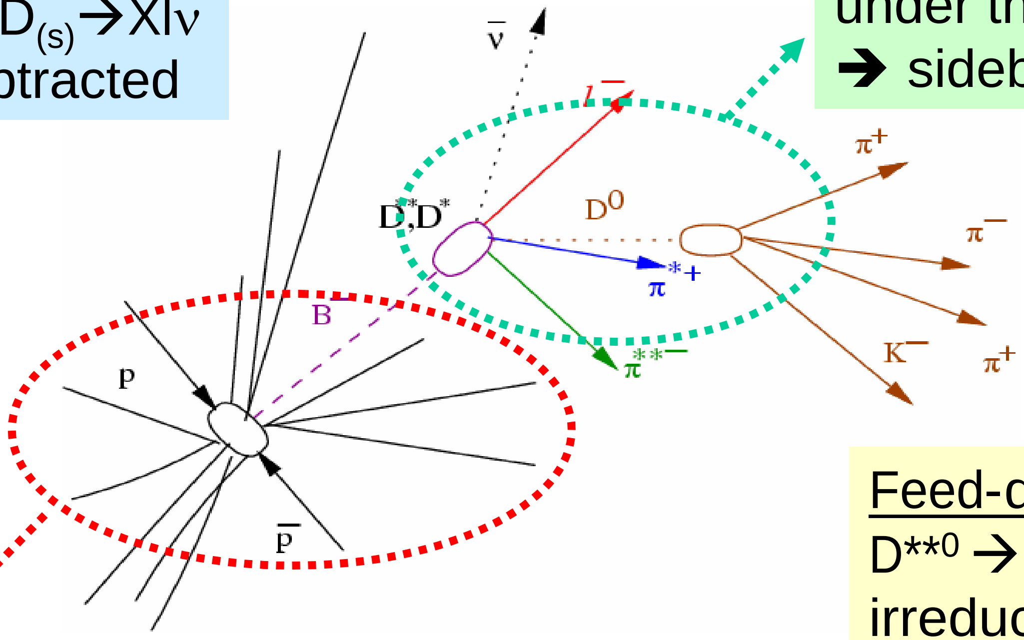


~28K e/μD Candidates in total!

Backgrounds

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

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



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

Prompt pions faking π^{**}:
- **fragmentation**
- **underlying event**

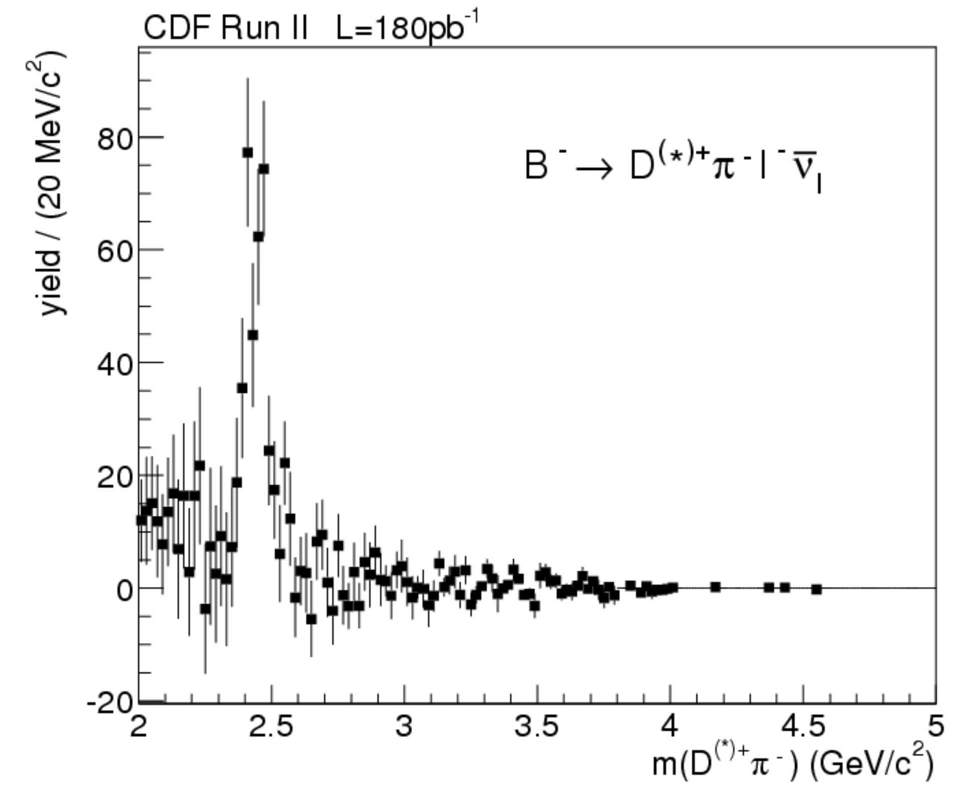
➔**separate B and primary vertices**
(kills also prompt charm)
➔ use impact parameters to discriminate
➔ model: wrong-sign $\pi^{**+}\ell^-$ combinations

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.

Result:



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

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

No Fit !!!

Systematic Errors

	Δm_1 (GeV^2)	Δm_2 (GeV^4)	ΔM_1 (GeV^2)	ΔM_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
ρ_1					0.041	0.069
T_i					0.032	0.031
α_s					0.018	0.007
m_b, m_c					0.001	0.008
Choice of p_l^* cut					0.019	0.009

Moments-ology

HQET $\rightarrow$ Distributions (e.g. E_γ) $\rightarrow$ Mean, RMS (n^{th} moment…)

Measurement

- Photonic moments: Photon energy in $b \rightarrow s\,\gamma$

(CLEO)

- Leptonic moments: $B \rightarrow X_c l \nu$, lepton E in B rest frame

(CLEO, DELPHI, BABAR)

- Hadronic moments: $B \rightarrow X_c l \nu$, recoil mass^2: $M(X_c)^2$

(CDFII, CLEO, DELPHI, BABAR)

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

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

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

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

Hadronic Moments, HQET and Vcb

Most precise determination of V_{cb} comes from Γ_{sl} (“inclusive” determination):

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

Υ(4S), LEP/SLD, CDF measurements. Experimental $\Delta|V_{cb}|\sim1\%$

Theory with pert. and non-pert. corrections. $\Delta|V_{cb}|\sim2.5\%$

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

$O(1/m_B) \to$ 1 parameter: Λ (Bauer et al., PRD 67 (2003) 071301)

$O(1/m_B^2) \to$ 2 more parameters: λ_1, λ_2

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

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

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

What is X_c?

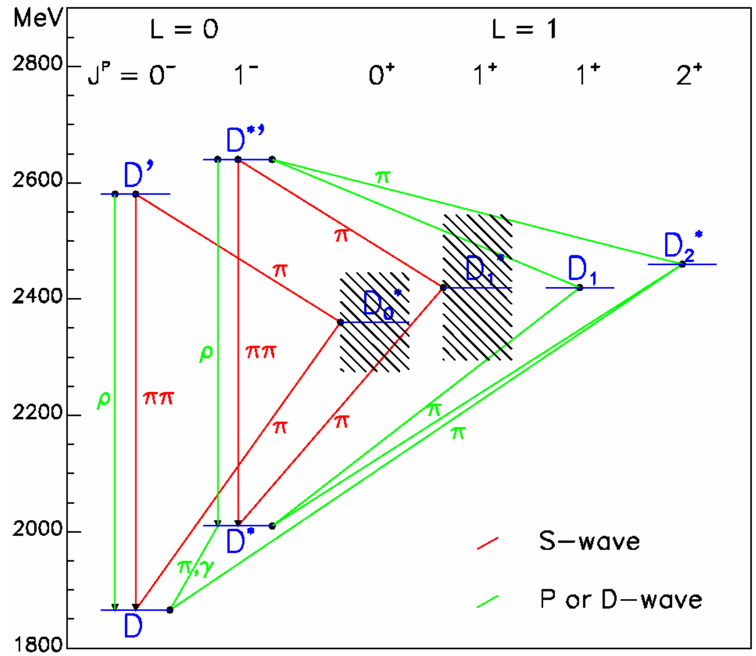
Semi-leptonic widths (PDG 04):

	Br (%)
$B^+ \to X_c\, l\, \nu$	10.99 ± 0.31
$B^+ \to D^*\, l\, \nu$	6.04 ± 0.23
$B^+ \to D\, l\, \nu$	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**



No B→lD' experimental evidence so far. DELPHI limit:

$$\begin{cases} BR\left(b \to D^+\pi^+\pi^-\ell^-\nu\right) < 0.18\% \text{ @ } 90\%\ CL \\ BR\left(b \to D^{*+}\pi^+\pi^-\ell^-\nu\right) < 0.17\% \text{ @ } 90\%\ CL \end{cases}$$

We assume no D'→$D^{(*)}\pi\pi$ contribution in our sample

How can CDF look at X_c?

Must reconstruct all channels to get all the D^{**} states.

➔ However CDF has limited capability for neutrals

- $B^0 \to D^{**-} l^+ \nu$ always leads to neutral particles ➔ ignore it
- $B^- \to D^{**0} l^- \nu$ better, use isospin for missing channels:
  - $D^{**0} \to D^+ \pi^-$ OK
  - $D^{**0} \to D^0 \pi^0$ Not reconstructed. Half the rate of $D^+ \pi^-$
  - $D^{**0} \to D^{*+} \pi^-$
    - $D^{*+} \to D^0 \pi^+$ OK
    - $D^{*+} \to D^+ \pi^0$ Not reconstructed. Feed-down to $D^+ \pi^-$
  - $D^{**0} \to D^{*0} \pi^0$ 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 π^*
- π^{**} Background
  - Combinatorial
  - D'
  - $B \to DD$
  - $c\bar{c}$
  - ...

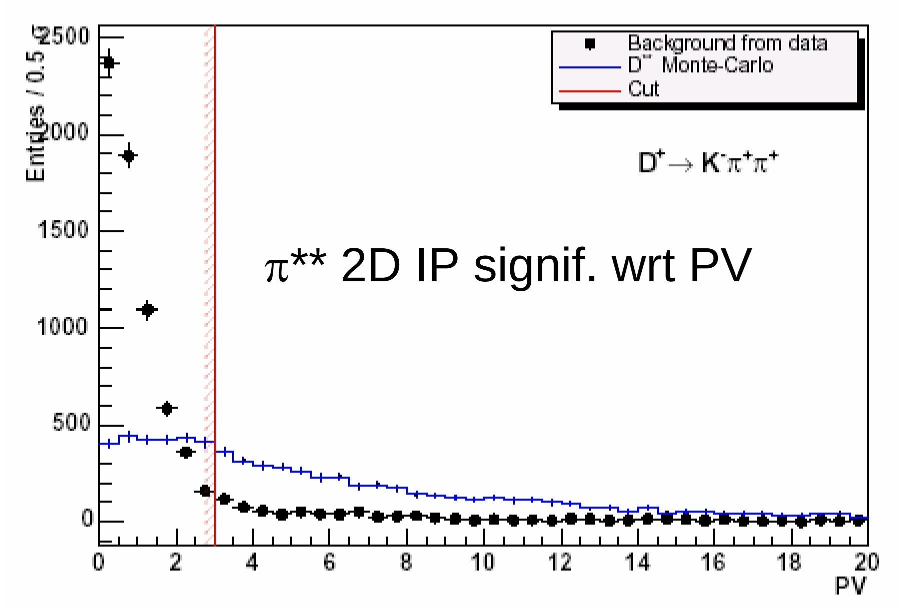
Correct for $\varepsilon(m_{**})$, $\varepsilon(D+)/\varepsilon(D^*)$
- Measure selection bias on m_{**} from:
  - MC
  - D* candidates
- Rely on MC (& PDG) for:
  - $\varepsilon(D+)/\varepsilon(D^*)$
  - Unseen modes (Isospin)
  - Lepton spectrum acceptance

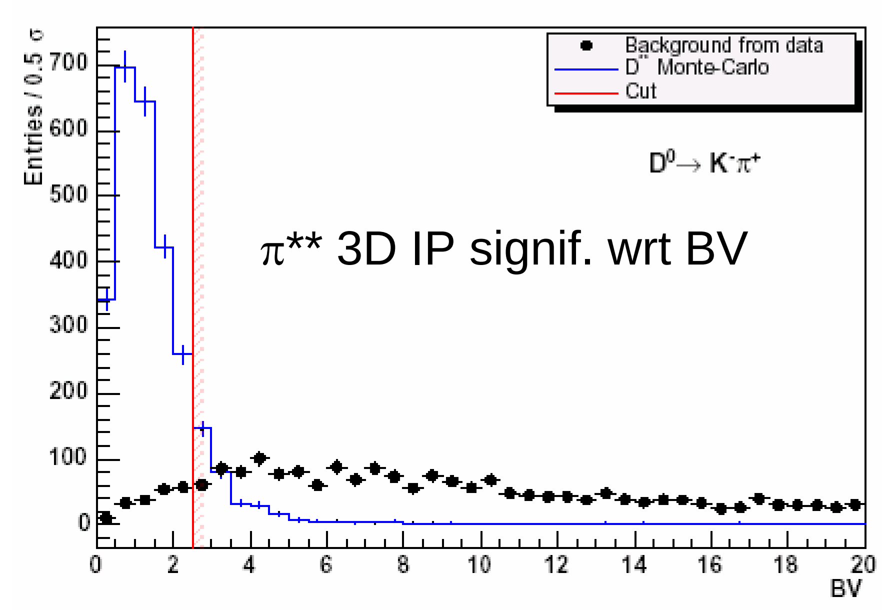
Measure $\langle m_{**}^2 \rangle$, $\langle m_{**}^4 \rangle$
- Subtract backgrounds
- Use PDG to go $\Delta m_{**} \to m_{**}$
- Compute $\langle m_{**}^2 \rangle$ & $\langle m_{**}^4 \rangle$
- Include $D^{(*)0}$
- Extract Λ, λ_1
- Systematics

π** 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^+:

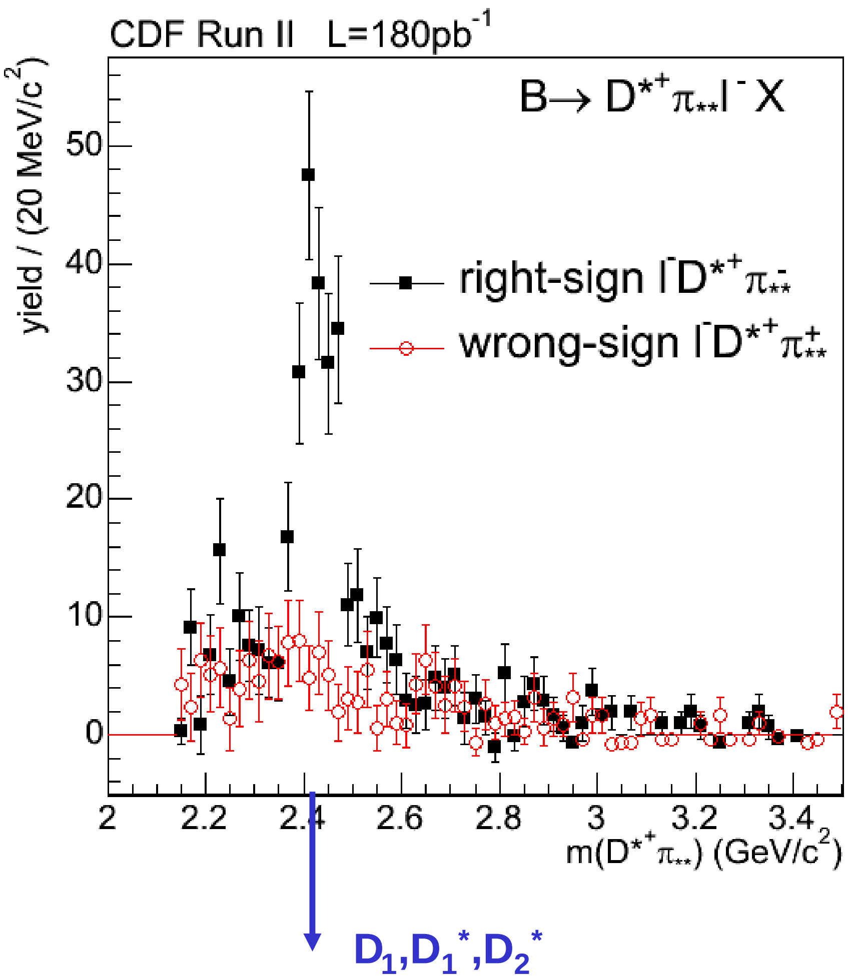
- $p_T > 0.4$ GeV
- $\Delta R < 1.0$
- $|d_0^{PV}/\sigma| > 3.0$
- $|d_0^{BV}/\sigma| < 2.5$

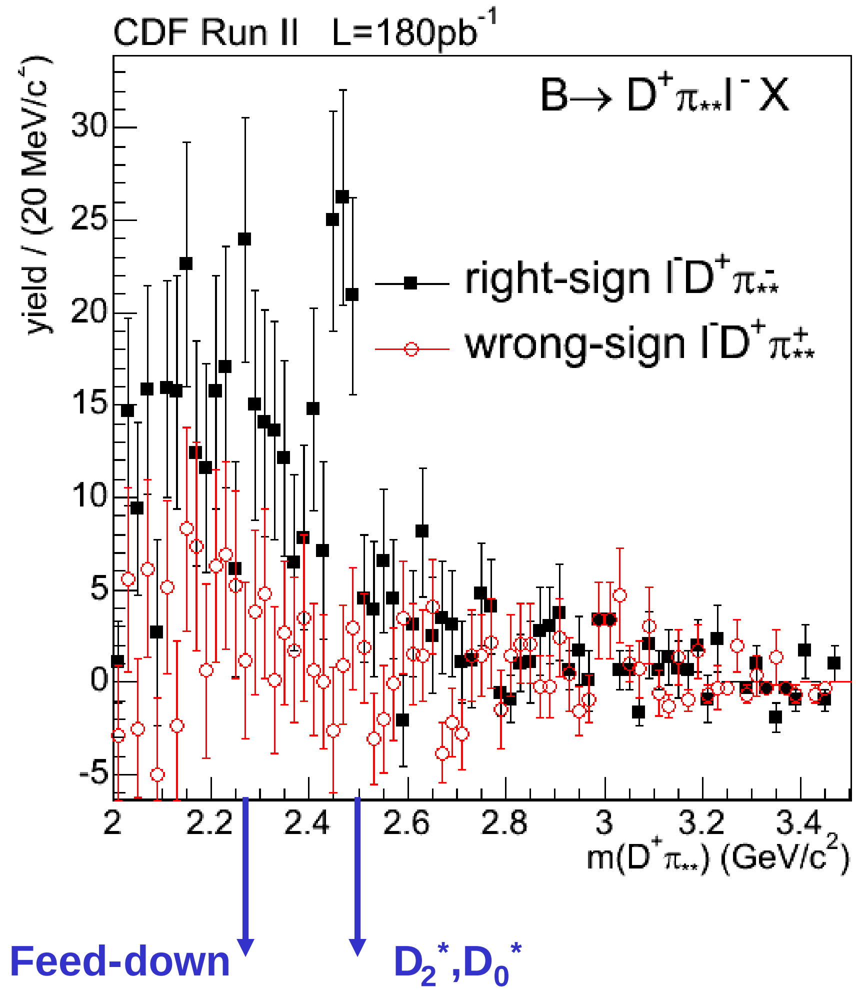
$|d_0^{DV}/\sigma| > 0.8$

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

Raw m** distributions

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





Efficiency Corrections

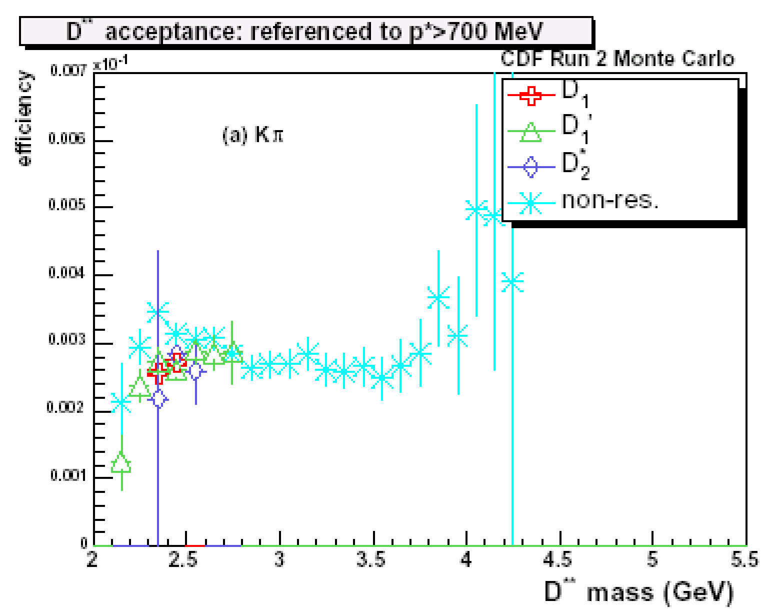
1) Correct the raw mass for any dependence of ε_{reco} on M(D**):

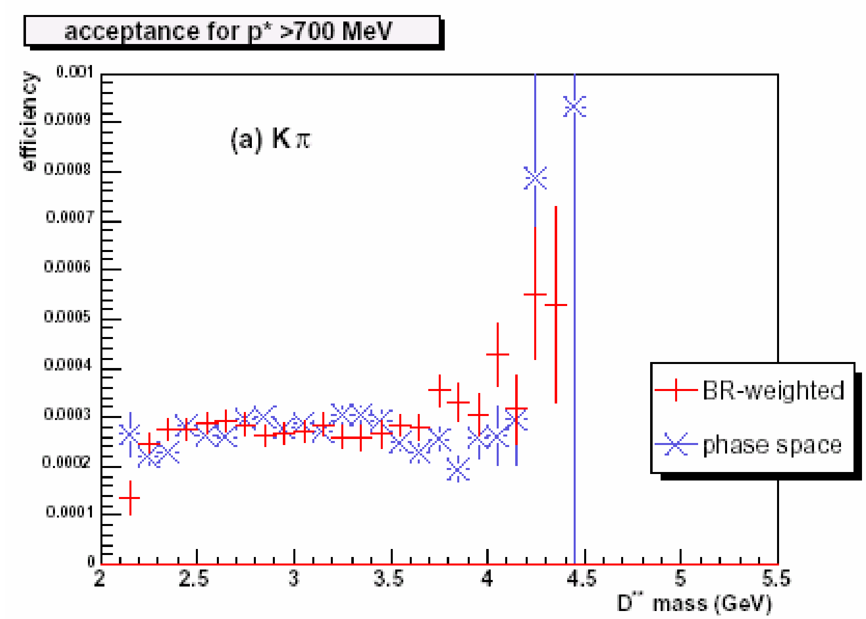
- Possible dependence on the D** species (spin).
- Monte-Carlo for all D** (Goity-Roberts for non-resonant), cross-checked with pure phase space decays.
- Detector simulation shortcomings cause residual data/MC discrepancy: derive corrections from control samples (D* and D daughters)

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.



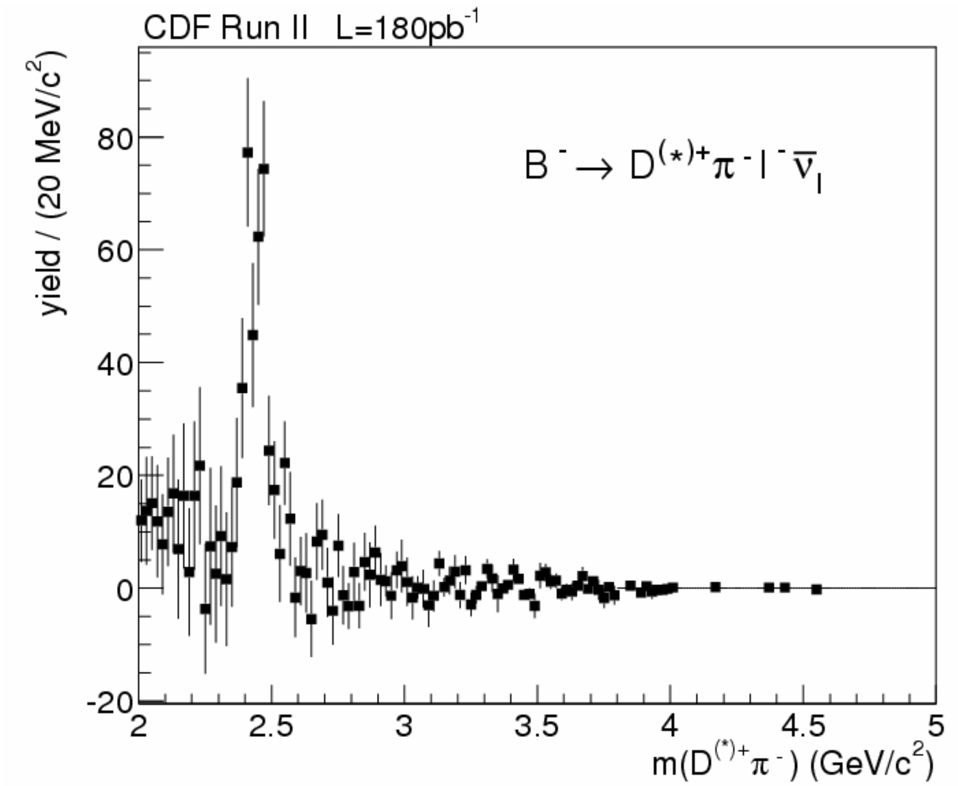


Corrected Mass and D** moments

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.

Result:



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

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

No Fit !!!

Final Result

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

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

$\rho(m_1,m_2)=0.61$

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

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

$\rho(M_1,M_2)=0.69$

Pole mass scheme

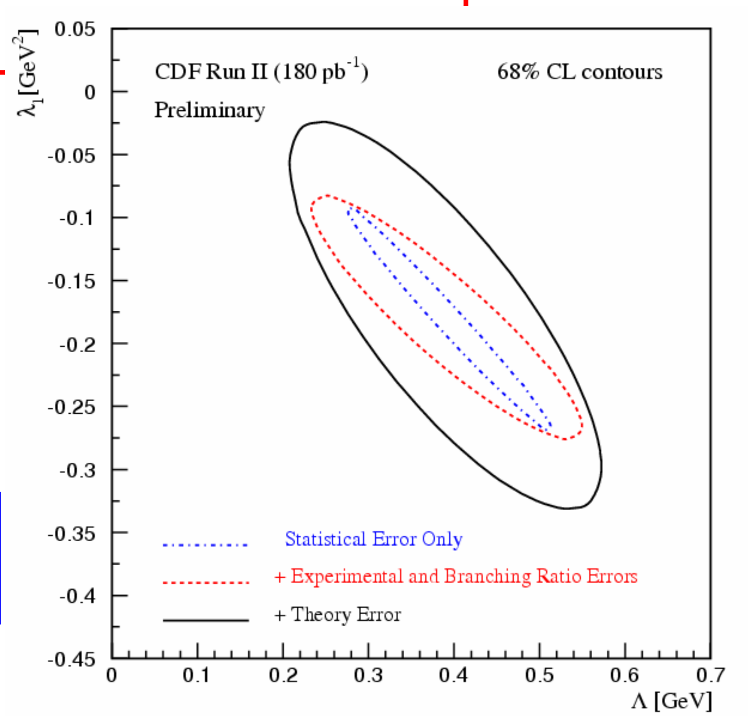
$$\Lambda = (0.397 \pm 0.078_{\rm stat} \pm 0.027_{\rm exp} \pm 0.064_{\rm BR} \pm 0.058_{\rm theo})\ \ {\rm GeV}$$

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

1S mass scheme

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

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



Systematics

- Input parameters
  - $D^{(*)+}$ Masses, in combining $D^{(*)}$ with D** $m \rightarrow M$ [PDG errors]
  - BR ($B \rightarrow D^{+}/D^{*+}$ $m \rightarrow M$) [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%]
  - $B \rightarrow X_c \tau \nu$ [estimate τ/ μ 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 $B_s \to KK$

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

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

$$\boxed{\begin{array}{l} \dfrac{f_d \cdot BR(B_d \to \pi^\pm \pi^\mp)}{f_s \cdot BR(B_s \to K^\pm K^\mp)} = 0.48 \pm 0.12\ (stat.) \pm 0.07\ (syst.) \\ \dfrac{f_s \cdot BR(B_s \to K^\pm K^\mp)}{f_d \cdot BR(B_d \to K^\pm \pi^\mp)} = 0.50 \pm 0.08\ (stat.) \pm 0.07\ (syst.) \end{array}}$$

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

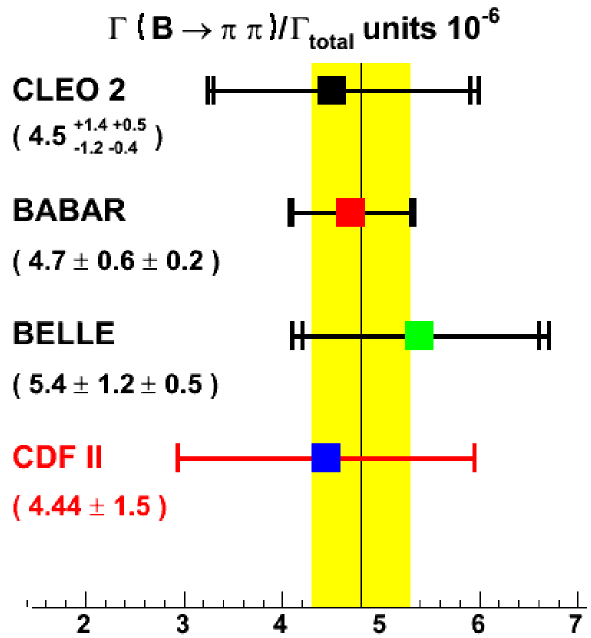
$$\frac{BR(B_d \to K^\pm K^\mp)}{BR(B_d \to K^\pm \pi^\mp)} < 0.17\ @\ 90\%\ C.L.$$

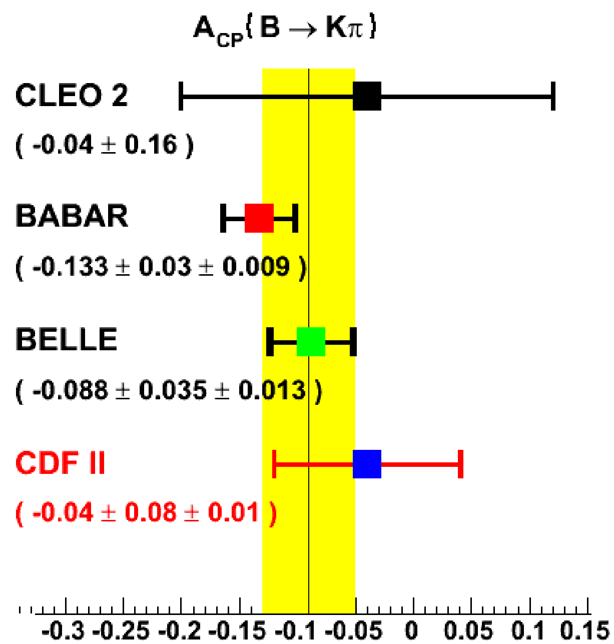
$$\frac{f_s \cdot BR(B_s \to K^\pm \pi^\mp)}{f_d \cdot BR(B_d \to K^\pm \pi^\mp)} < 0.11\ @\ 90\%\ C.L.$$

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

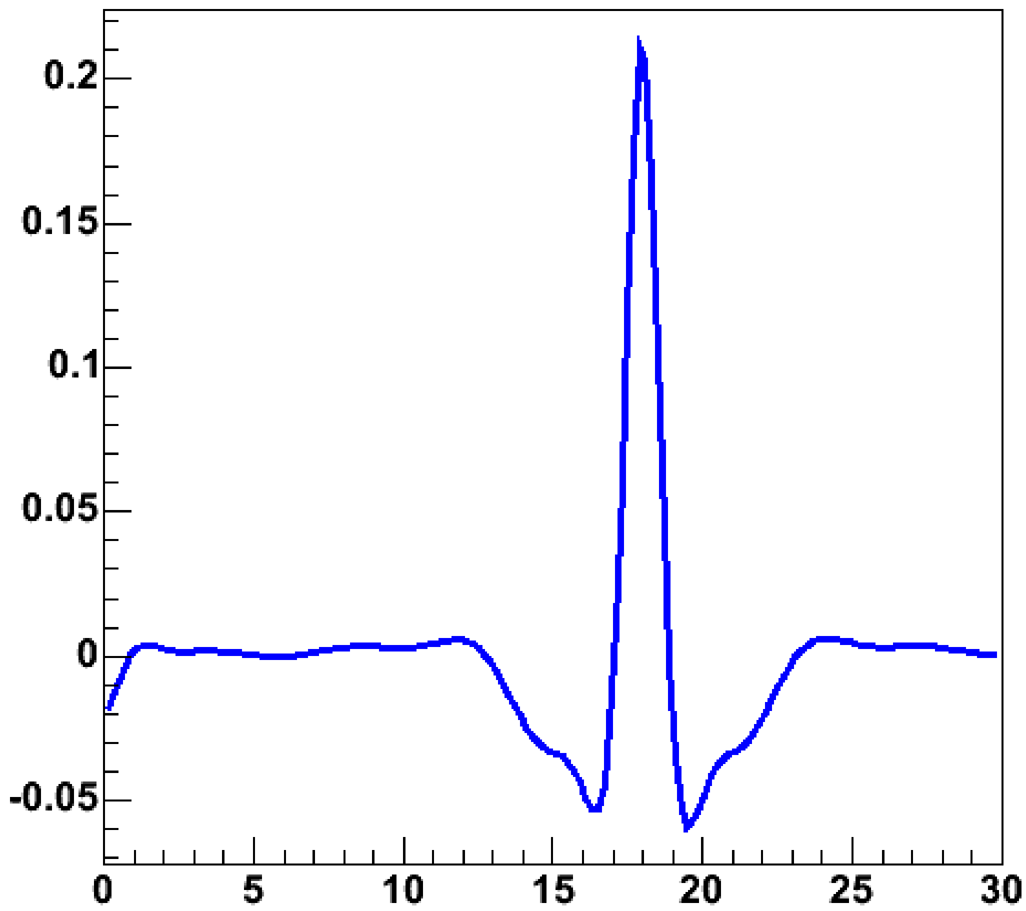
$$BR(\Lambda_b \to hh) < 22 \cdot 10^{-6}\quad (90\% C.L.)$$

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



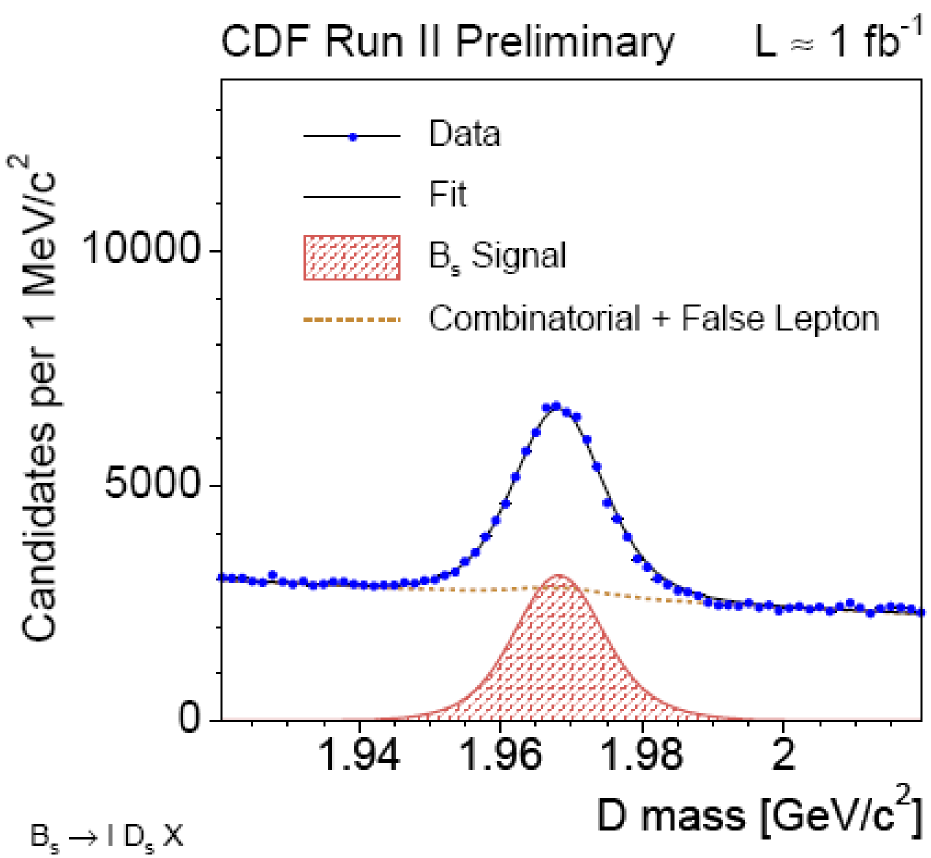


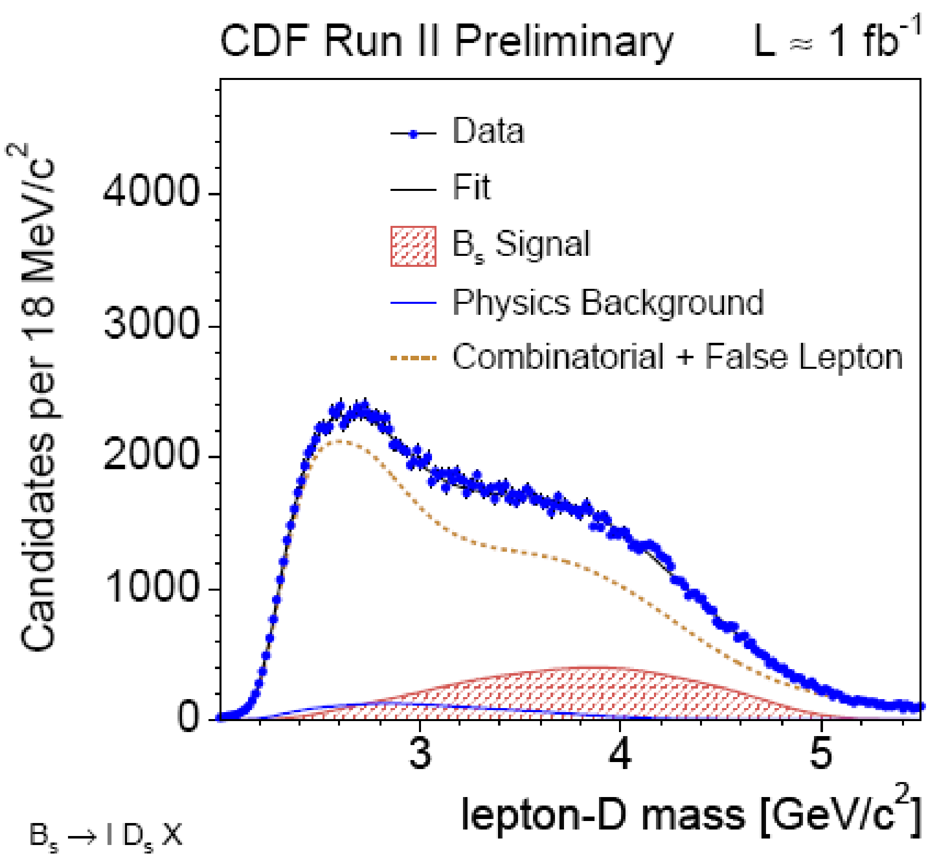
Mixing & Fourier Transforms



Samples of B_s Decays

Semileptonic Samples: $D_s^- l^+ X$





~53 K events

$m(lD_s^-)$ distribution

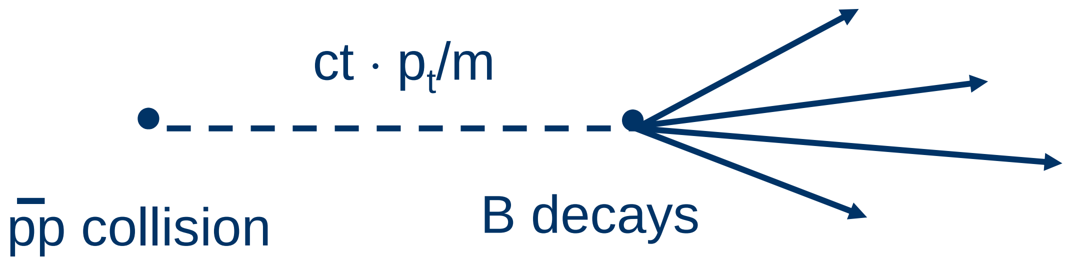
Signal Yield Summary: Semileptonic

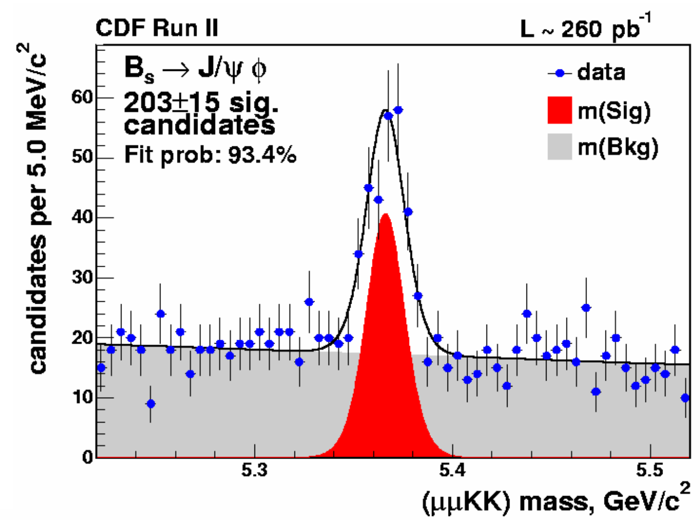
	muon	electron
lD_s: $D_s \to \phi\pi$	~ 24 K	~ 8 K
lD_s: $D_s \to K^*K$	~ 8 K	~ 3 K
lD_s: $D_s \to \pi\pi\pi$	~ 7.5 K	~ 2.5 K

lD^0: $D^0 \to K\pi$	~ 400 K	~ 140 K
lD^{*-}: $D^0 \to K\pi$	~ 54 K	~ 21 K
lD^-: $D^- \to K\pi\pi$	~ 220 K	~ 80 K

B Lifetime Measurements

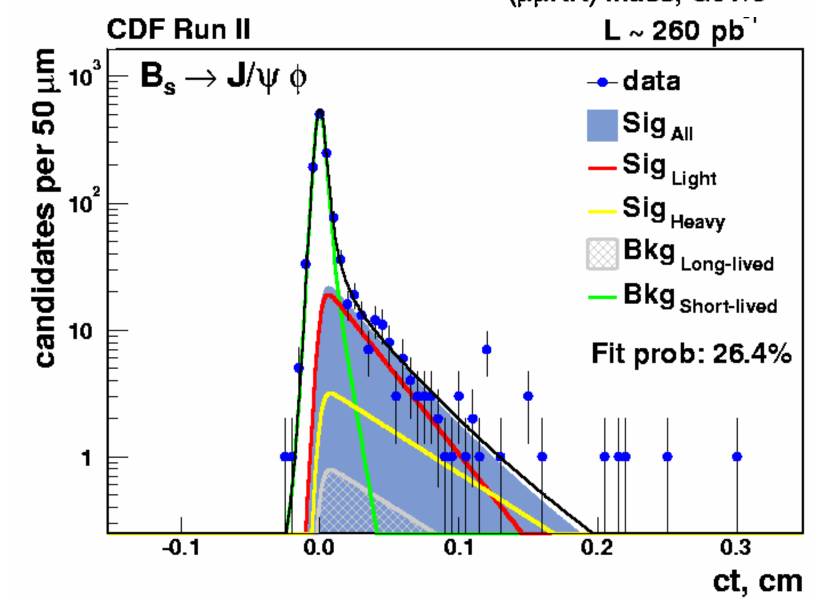
"Classic" B Lifetime Measurement





- reconstruct B meson mass, p_T, L_{xy}
- calculate proper decay time (ct)
- extract $c\tau$ from combined mass+lifetime **fit**
- signal probability:

  $p_{signal}(\mathbf{t}) = e^{-t'/\tau} \otimes R(t', \mathbf{t})$

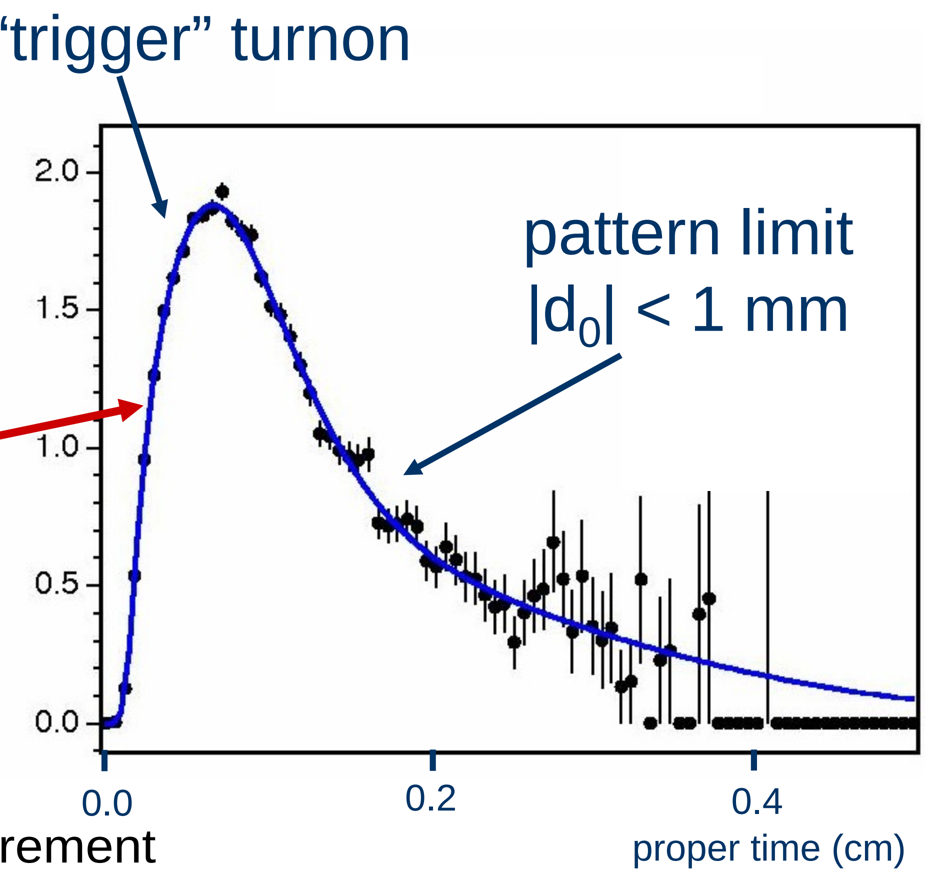


- background p_{bkgd}(t) modeled from sidebands

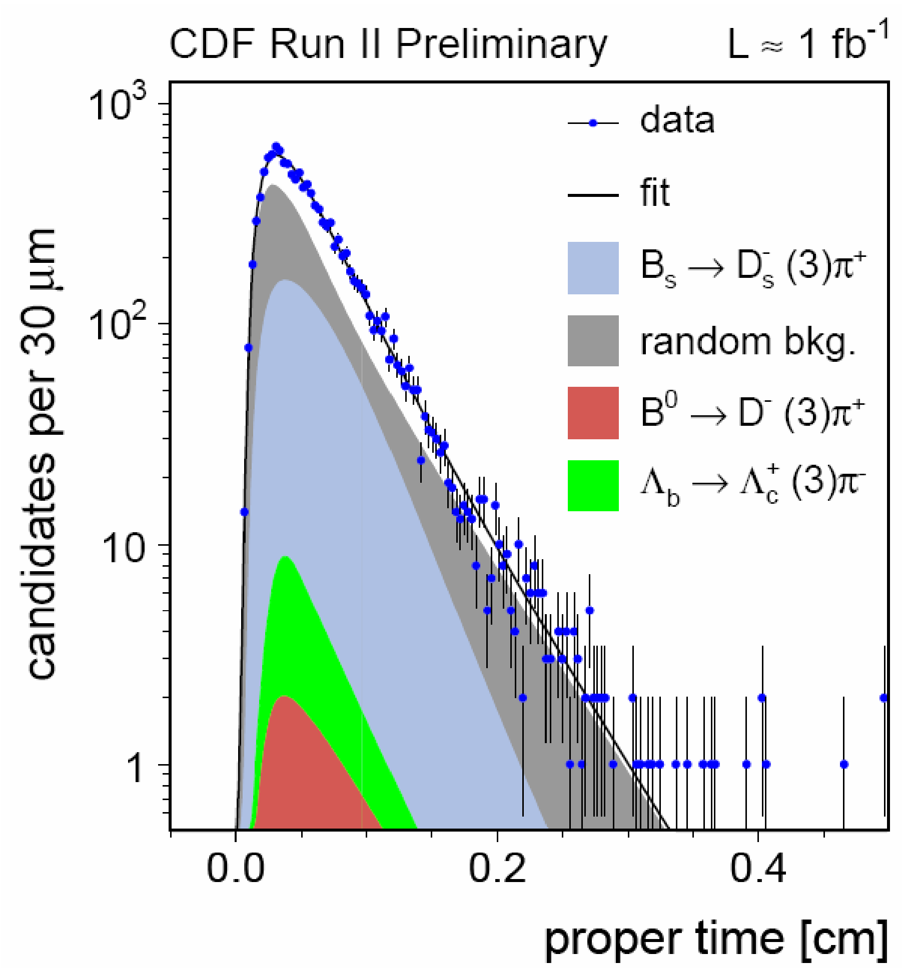
Hadronic Lifetime Measurement

- SVT trigger, event selection sculpts lifetime distribution
- correct for on average using efficiency function:

  $p = e^{-t'/\tau} - R(t',t) \otimes \varepsilon(t)$
- efficiency function shape contributions:
  - event selection, trigger
- details of efficiency curve
  - important for lifetime measurement
  - inconsequential for mixing measurement



Hadronic Lifetime Results



Mode	Lifetime [ps] (stat. only)
$B^0 \to D^- \pi^+$	1.508 ± 0.017
$B^- \to D^0 \pi^-$	1.638 ± 0.017
$B_s \to D_s \pi(\pi\pi)$	1.538 ± 0.040

- World Average:

B^0 1.534 ± 0.013 ps^{-1}

B^+ 1.653 ± 0.014 ps^{-1}

B_s 1.469 ± 0.059 ps^{-1}

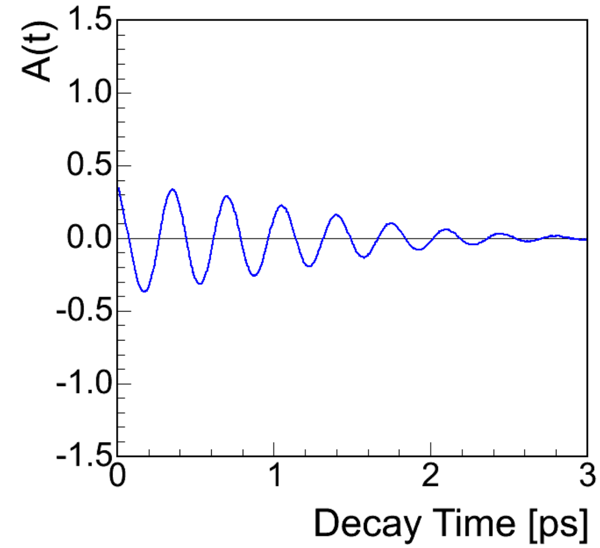
Excellent agreement!

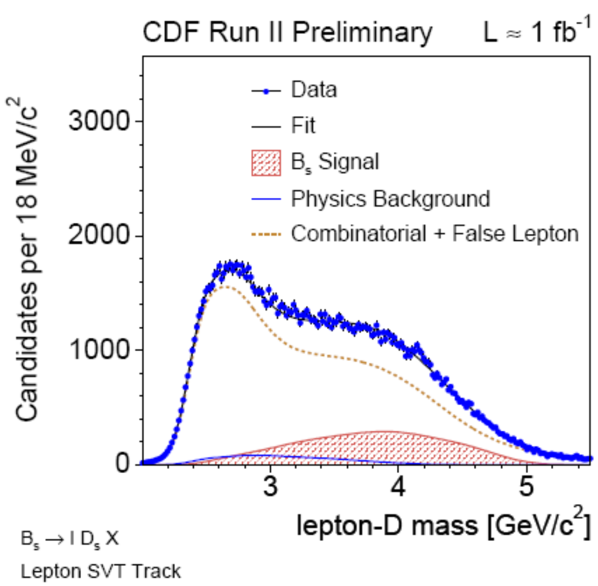
Semileptonic Lifetime Measurement

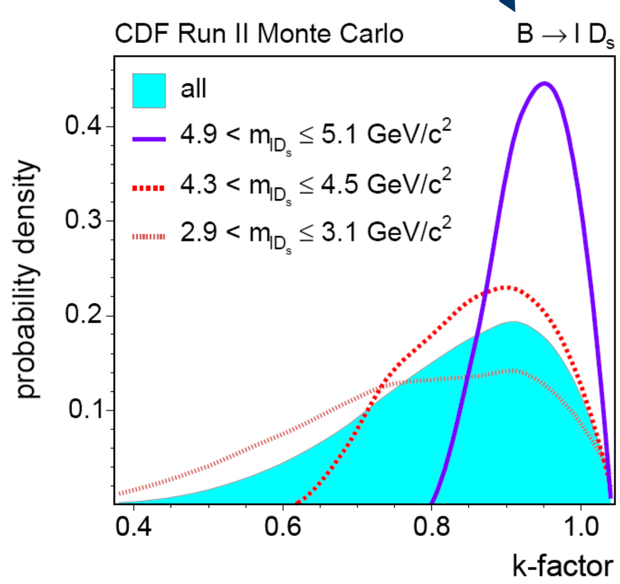
- neutrino momentum not reconstructed

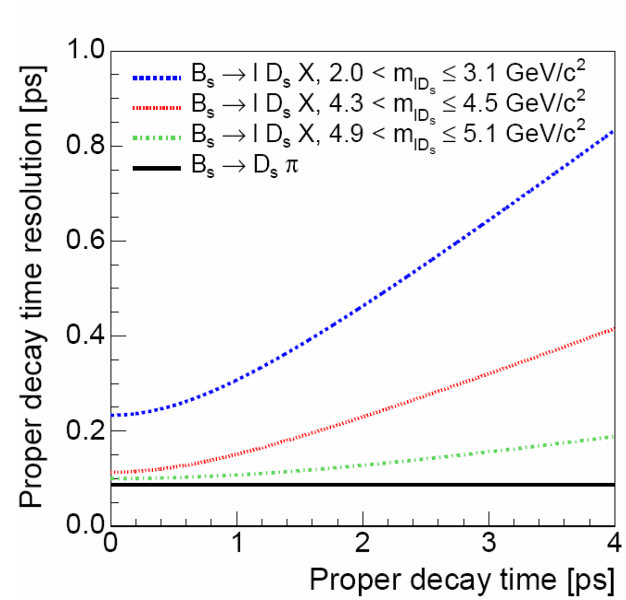
$$K = \frac{p_T(lD)}{p_T(B)} \cdot \frac{L(B)}{L(lD)}$$

- correct for neutrino on average



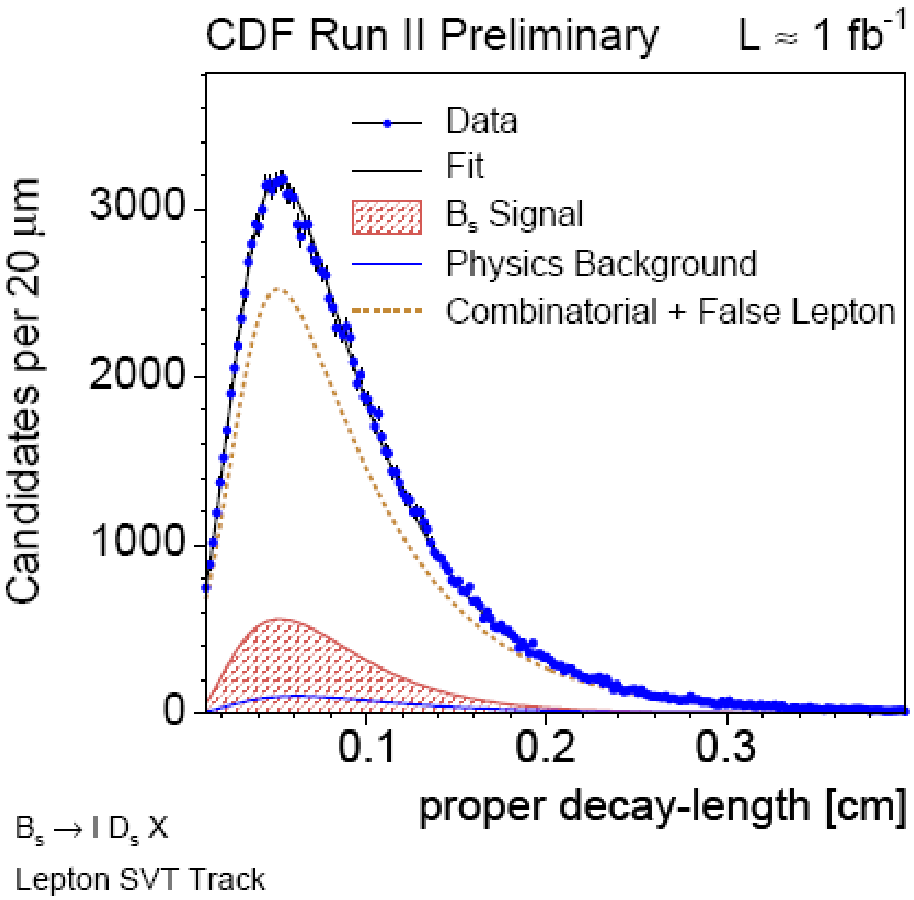




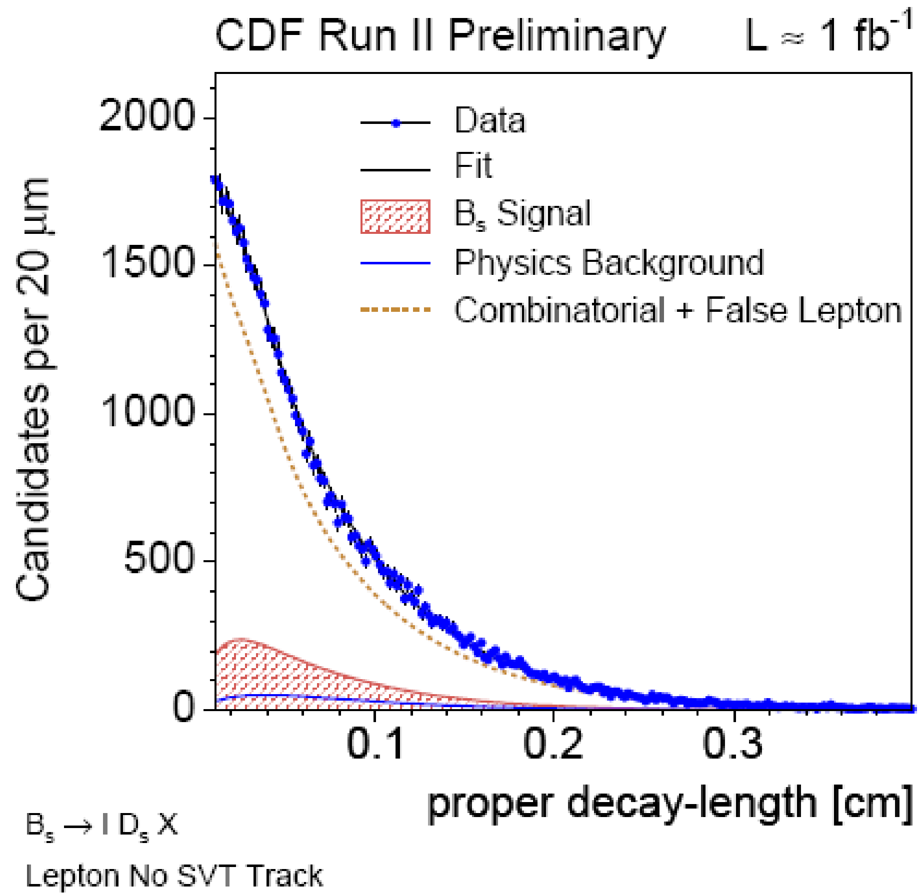


lD_s ct* Projections

Lepton fires displ. trigger



Lepton does not fire trigger



Semileptonic Lifetime Results

	Lifetime (ps)
Bs: Ds $\rightarrow \phi\pi$	1.51 ± 0.04 stat. only
Bs: Ds $\rightarrow$ K*K	1.38 ± 0.07 stat. only
Bs: Ds $\rightarrow \pi\pi\pi$	1.40 ± 0.09 stat. only
Bs combined	1.48 ± 0.03 stat. only

- lifetimes measured on first 355 pb^{-1}
- compare to World Average: B_s: (1.469 ± 0.059) ps

Proper Time Resolution

Proper Time Resolution

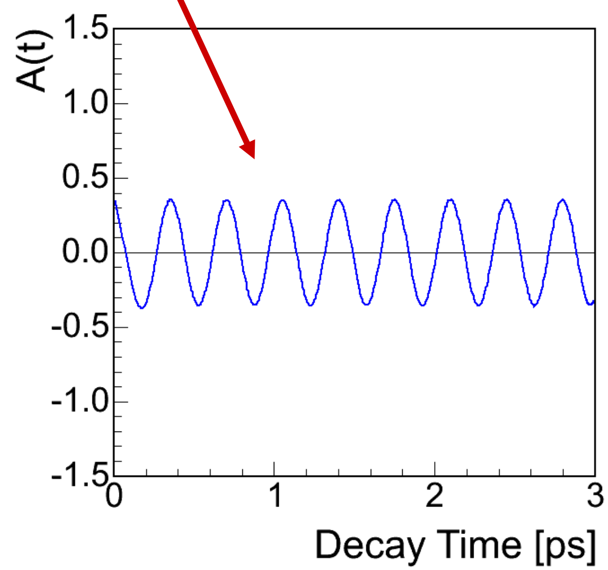
- Reminder,
  measurement
  significance: $\mathrm{Signif} = \sqrt{\frac{N\epsilon D^2}{2}e^{-\frac{(\Delta m_s \sigma_t)^2}{2}}}\sqrt{\frac{S}{S+B}}$

- significant effect

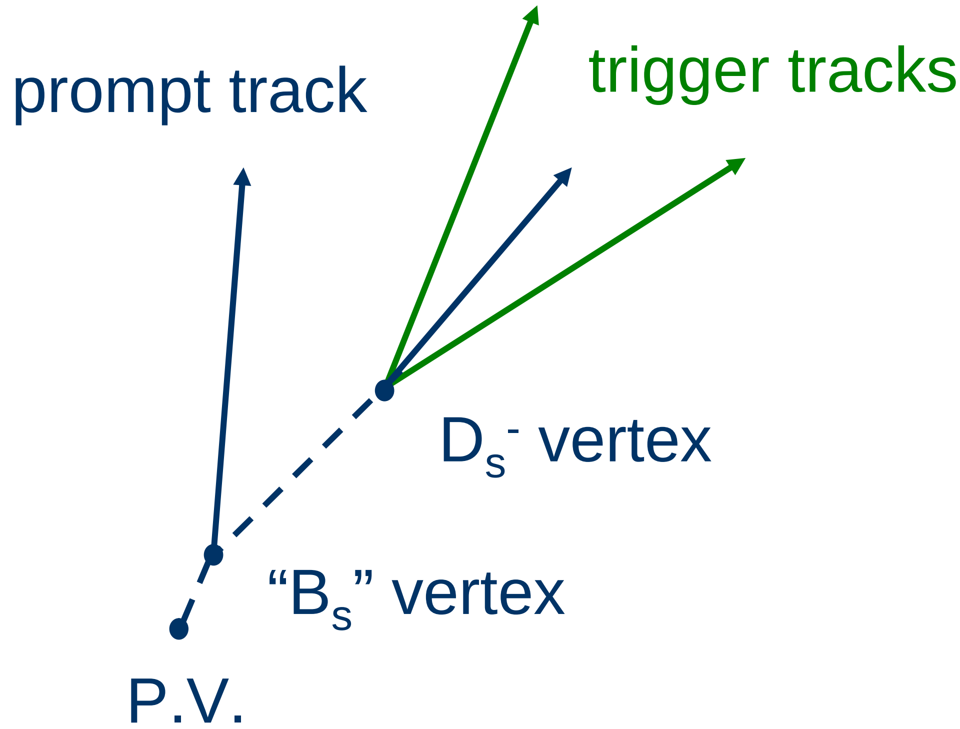
- fitter has to correctly account for it

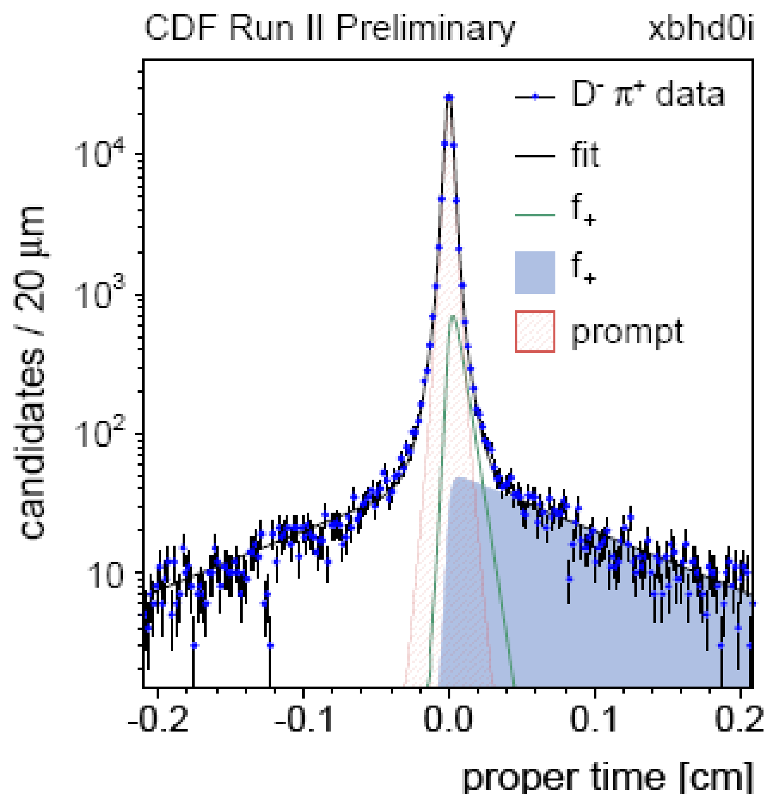
- lifetime measurements not very sensitive to resolution

- a dedicated calibration is needed!



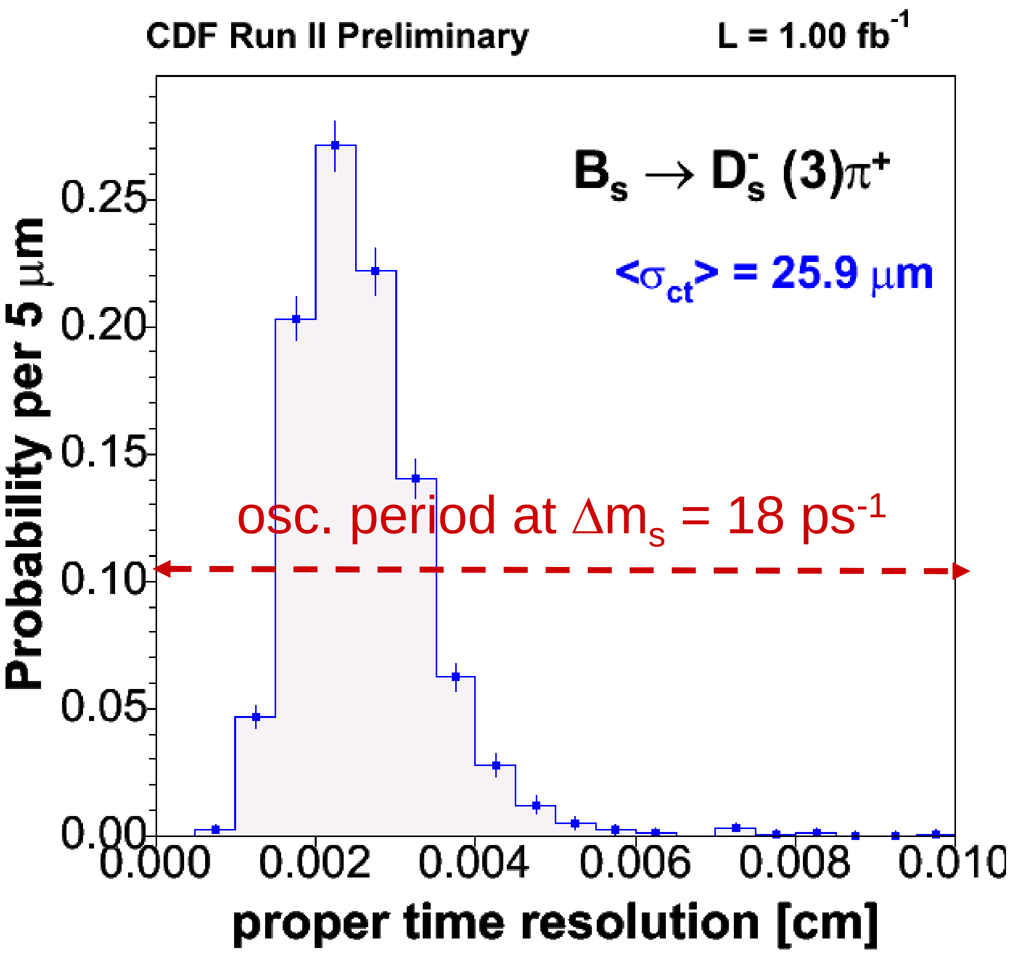
Calibrating the Proper Time Resolution





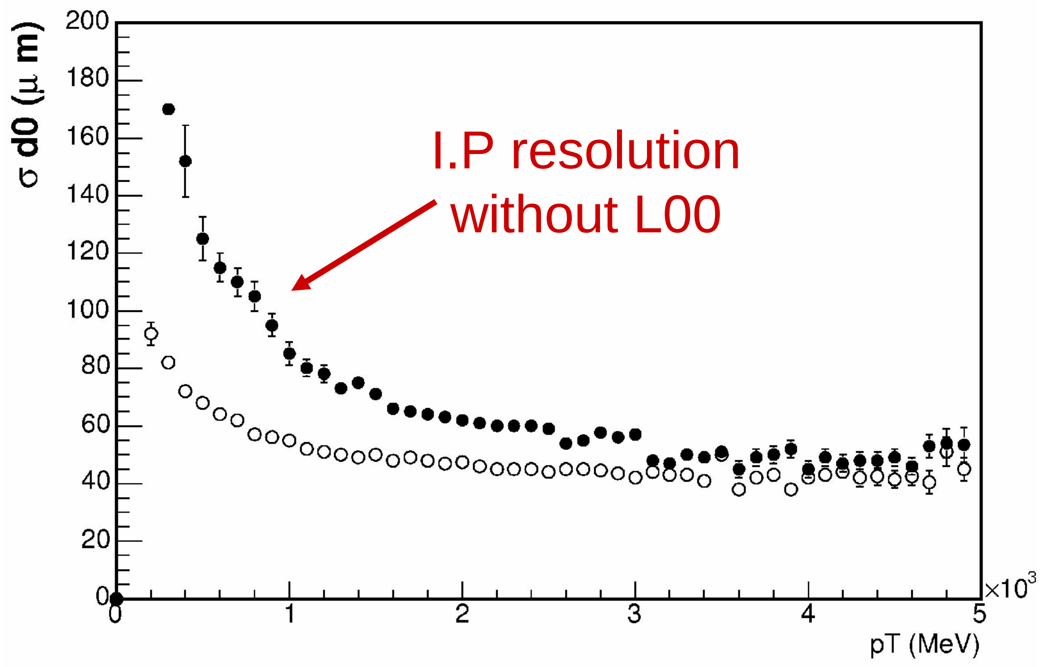
- utilize large prompt charm cross section
- construct "Bs-like" topologies of prompt D_s^- + prompt track
- calibrate ct resolution by fitting for "lifetime" of "Bs-like" objects

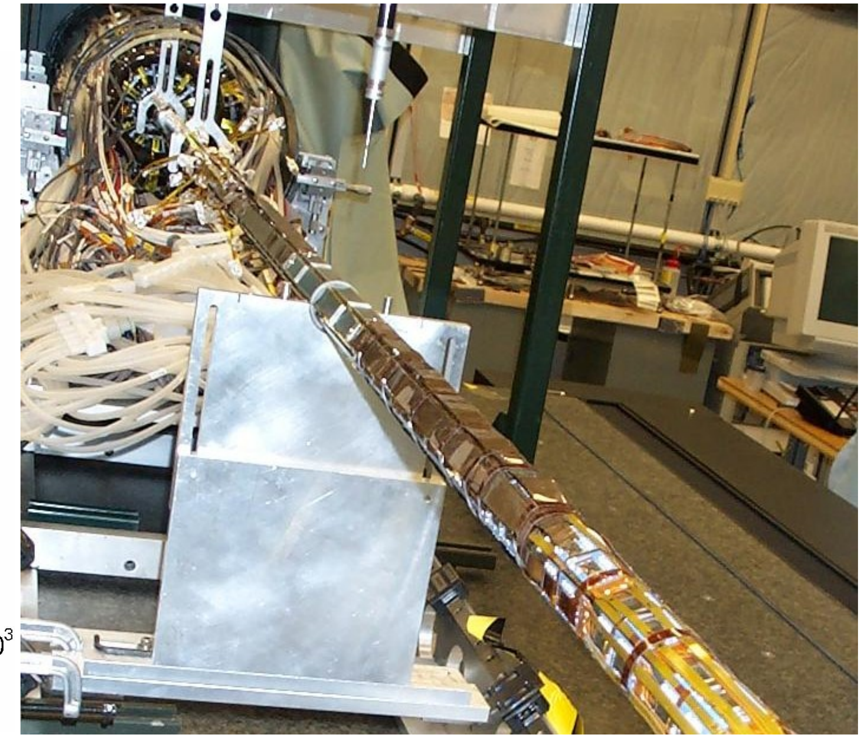
B_s Proper Time Resolution



- event by event determination of primary vertex position used
- average uncertainty ~ 26 μm
- this information is used per candidate in the likelihood fit

Layer “00”

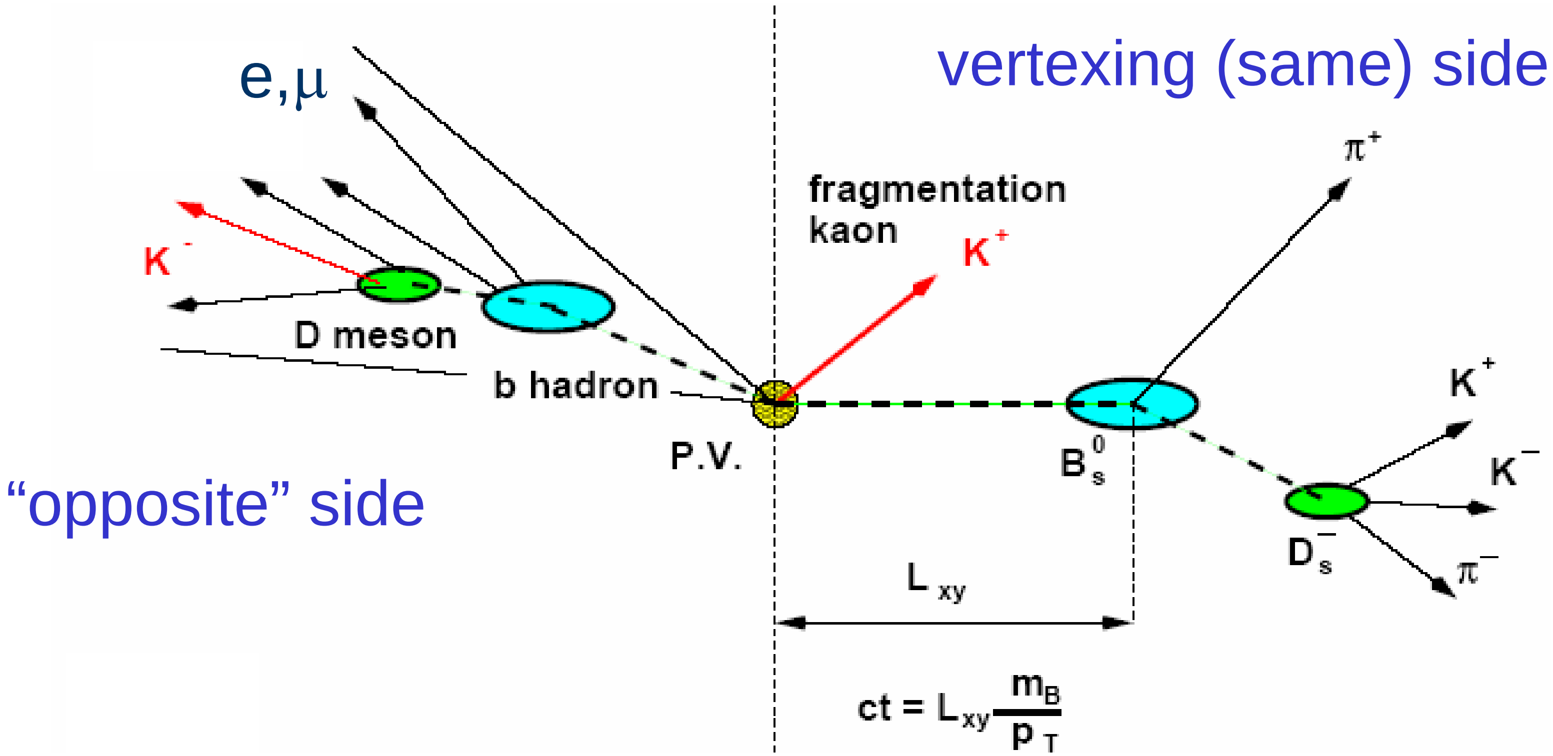




- layer of silicon placed directly on beryllium beam pipe
- radial displacement from beam ~1.5 cm
- additional impact parameter resolution, radiation hardness

Flavor Tagging

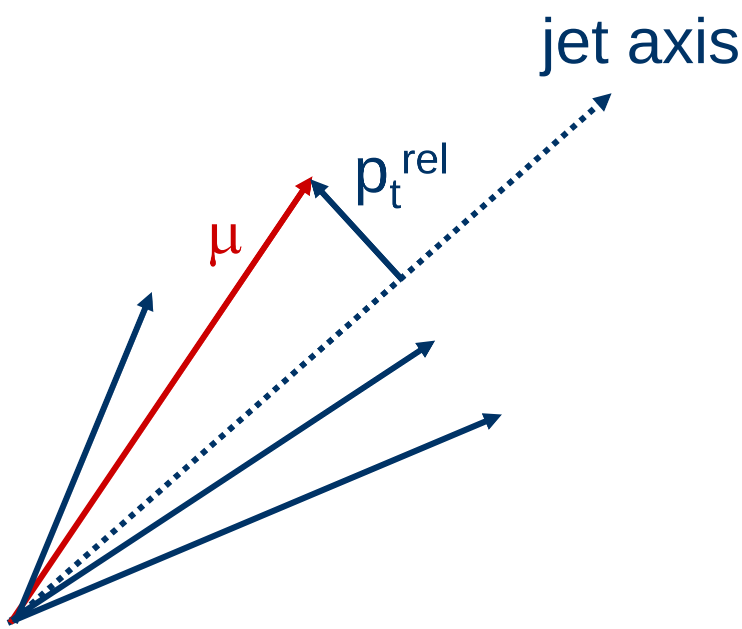
Tagging the B Production Flavor

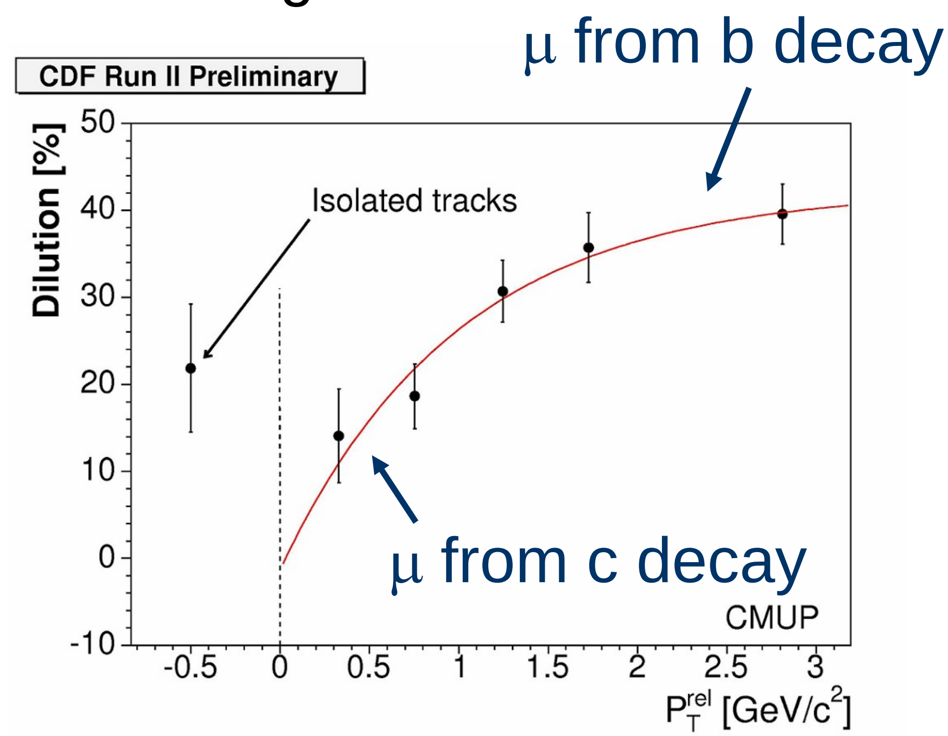


- use a combined same side and opposite side tag!
- use muon, electron tagging, jet charge on opposite side
- jet selection algorithms: vertex, jet probability and highest p_T
- particle ID based kaon tag on same side

Parametrizing Tagger Decisions

- use characteristics of tags themselves to increase their tagging power, example: muon tags



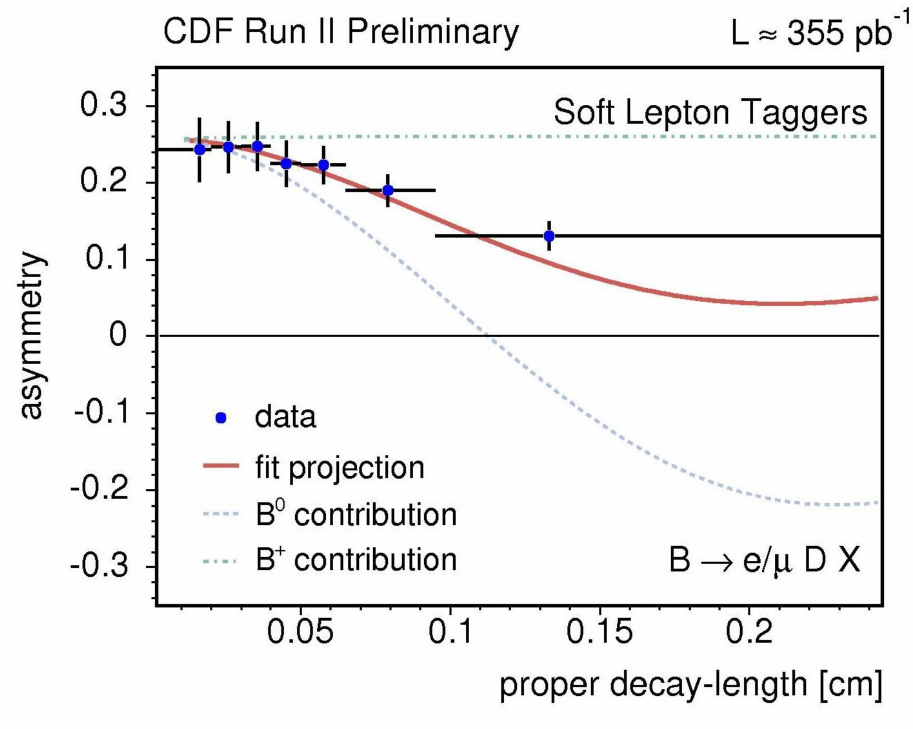


- tune taggers and parametrize event specific dilution
- technique in data works with opposite side tags

Unbinned Likelihood Δm_d Fits

- fit separately in hadronic and semileptonic sample
- per sample, simultaneously measure
  - tagger performance
  - Δm_d
- projection incorporates several classes of tags

semileptonic, lD^-, muon tag



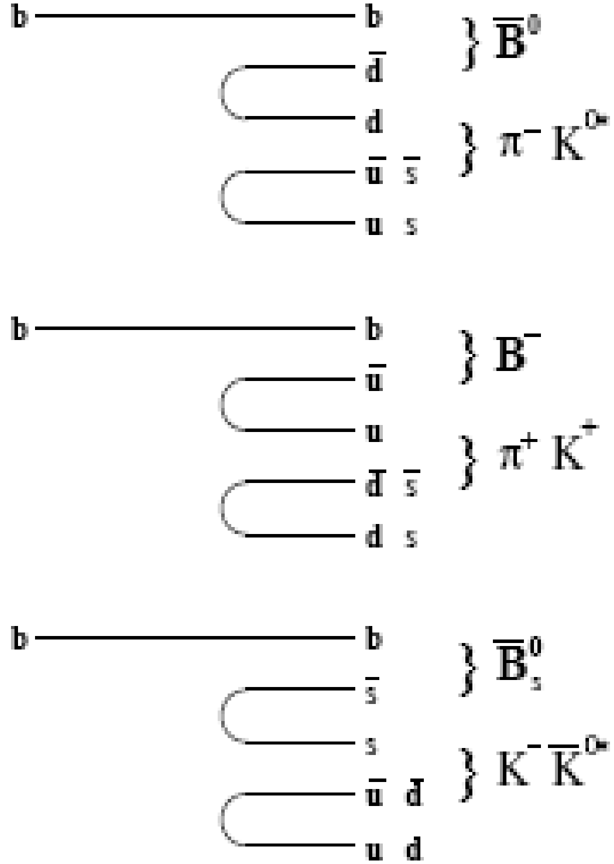
hadronic: $\Delta m_d = 0.536 \pm 0.028$ (stat) ± 0.006 (syst) ps^{-1}

semileptonic: $\Delta m_d = 0.509 \pm 0.010$ (stat) ± 0.016 (syst) ps^{-1}

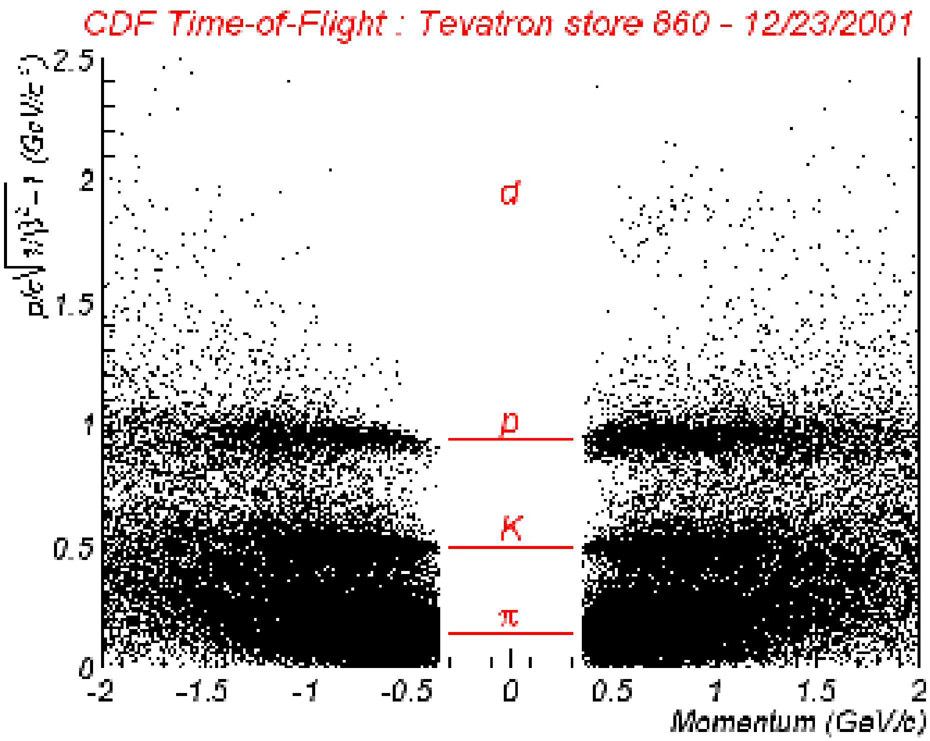
world average: $\Delta m_d = 0.507 \pm 0.004$ ps^{-1}

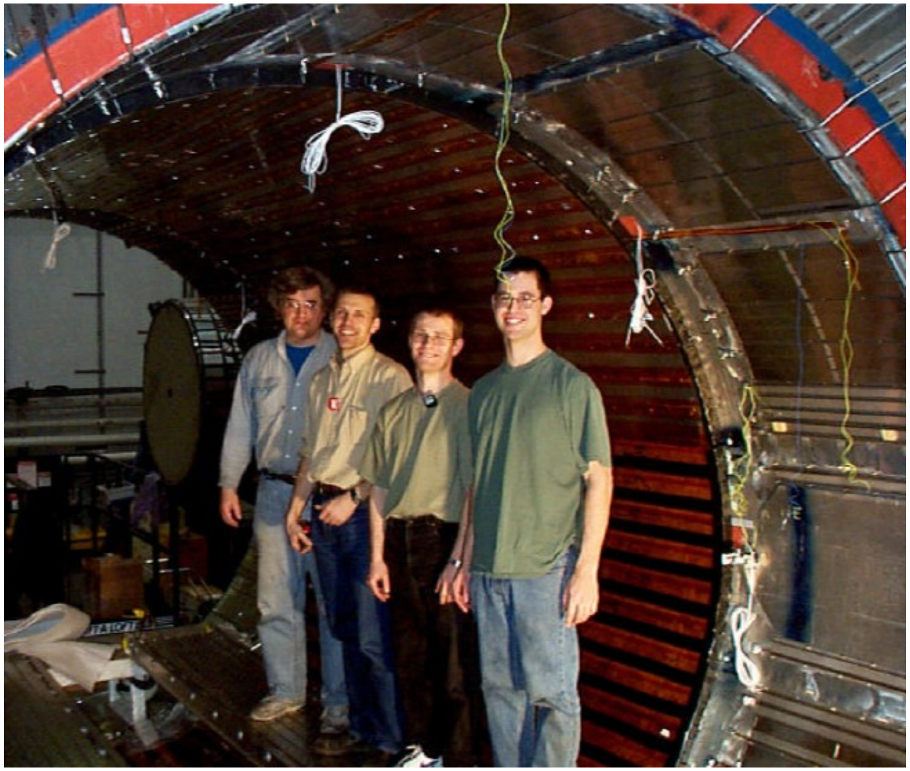
Same Side Kaon Tags

- exploit b quark fragmentation signatures in event
- B^0/B^+ likely to have a π^-/π nearby
- B_s^0 likely to have a K^+
- use TOF and COT dE/dX info. to separate pions from kaons
- problem: calibration using only B^0 mixing will not work
- tune Monte Carlo simulation to reproduce B^0, B^- distributions, then apply directly to B_s^0



Time Of Flight System

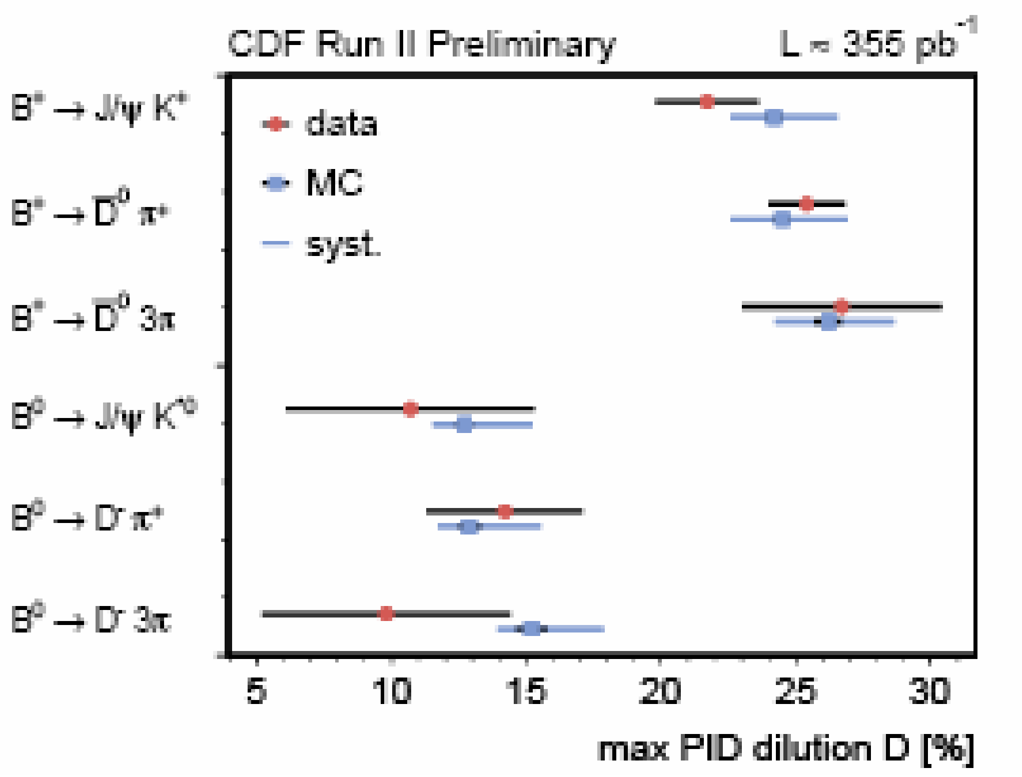




- timing resolution ~100 ps ! resolves kaons from pions up to p ~ 1.5 GeV/ c
- TOF provides most of the Particle ID power for SSKT

Calibrating SSKT

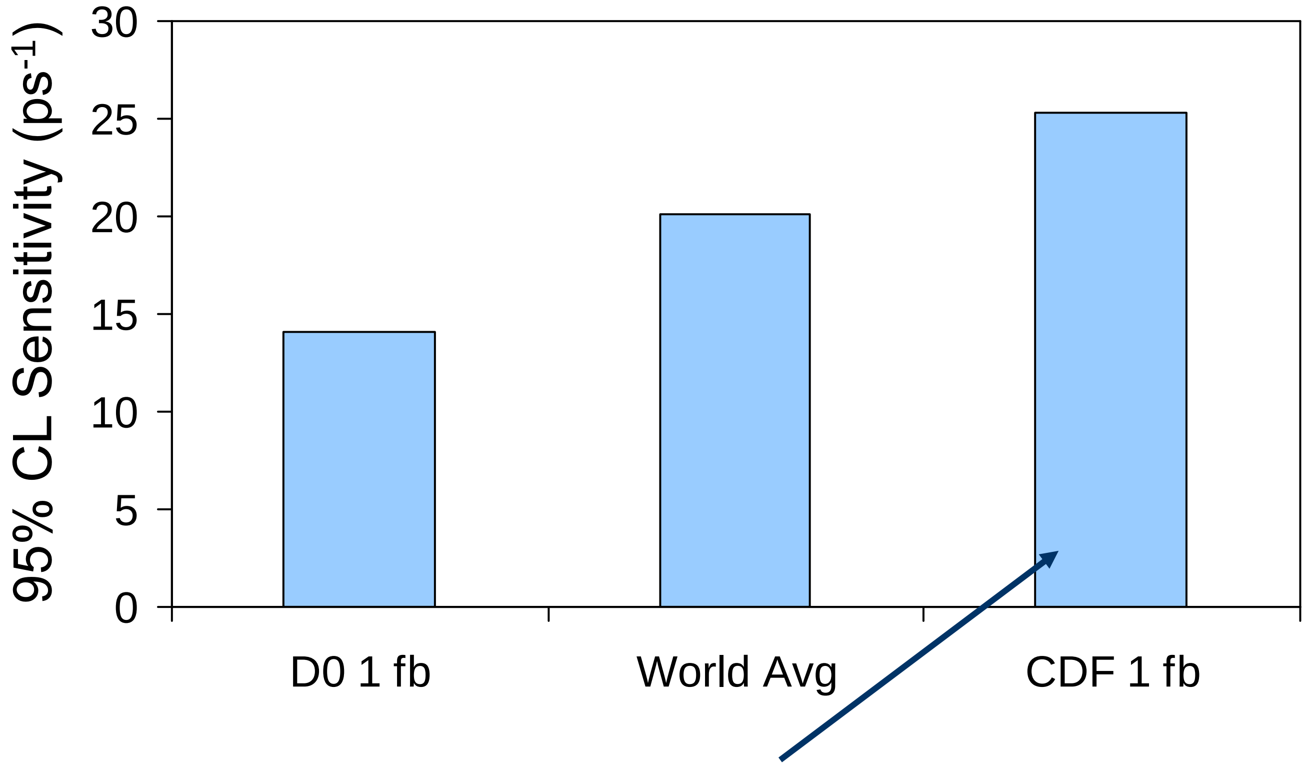
- Analogous to transfer scale factor in Opposite Side Tags
- Check dilution in light B meson decays



Data/MC agreement is the largest systematic uncertainty ! O(8%)

Fitter Preparation

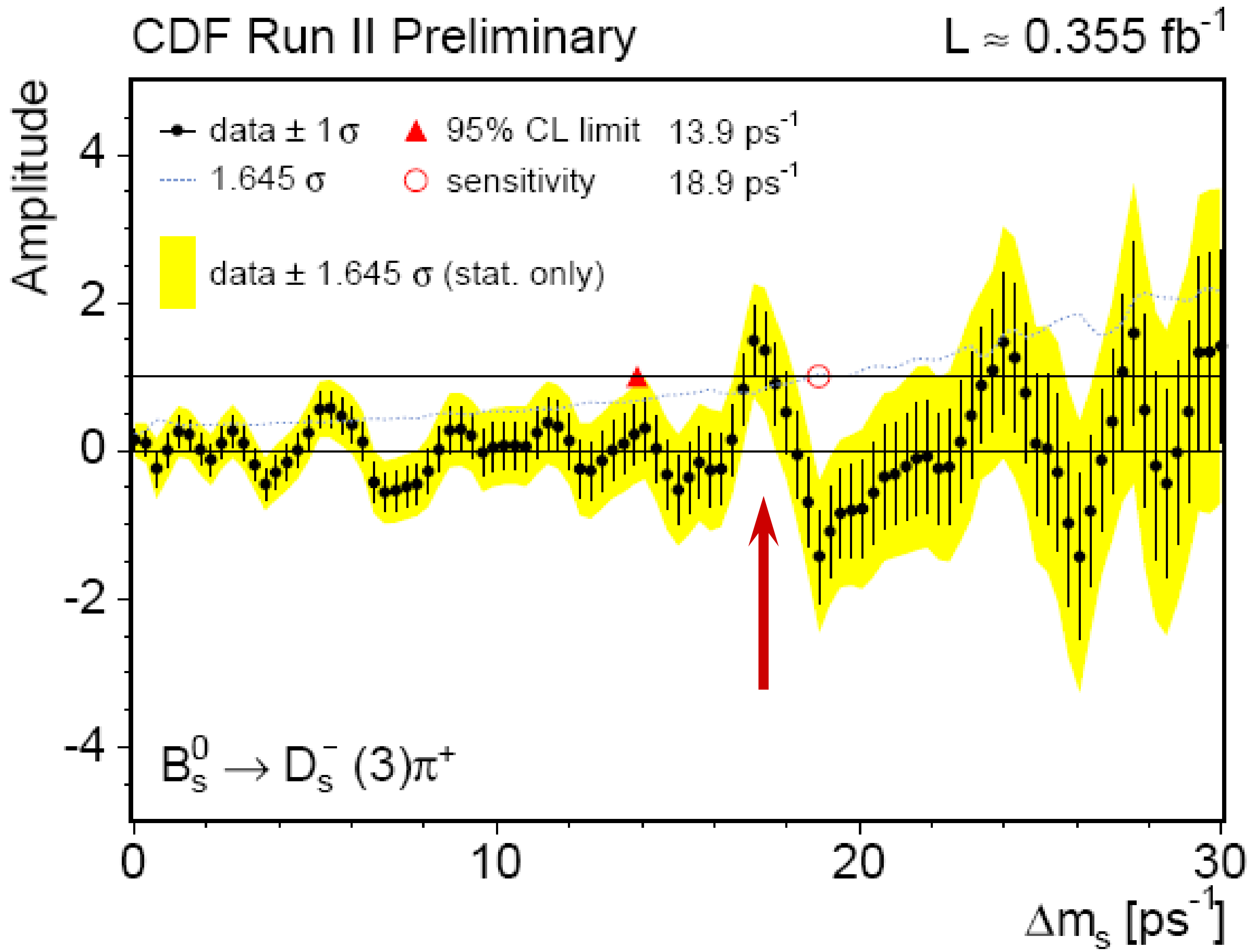
Measurement Sensitivity



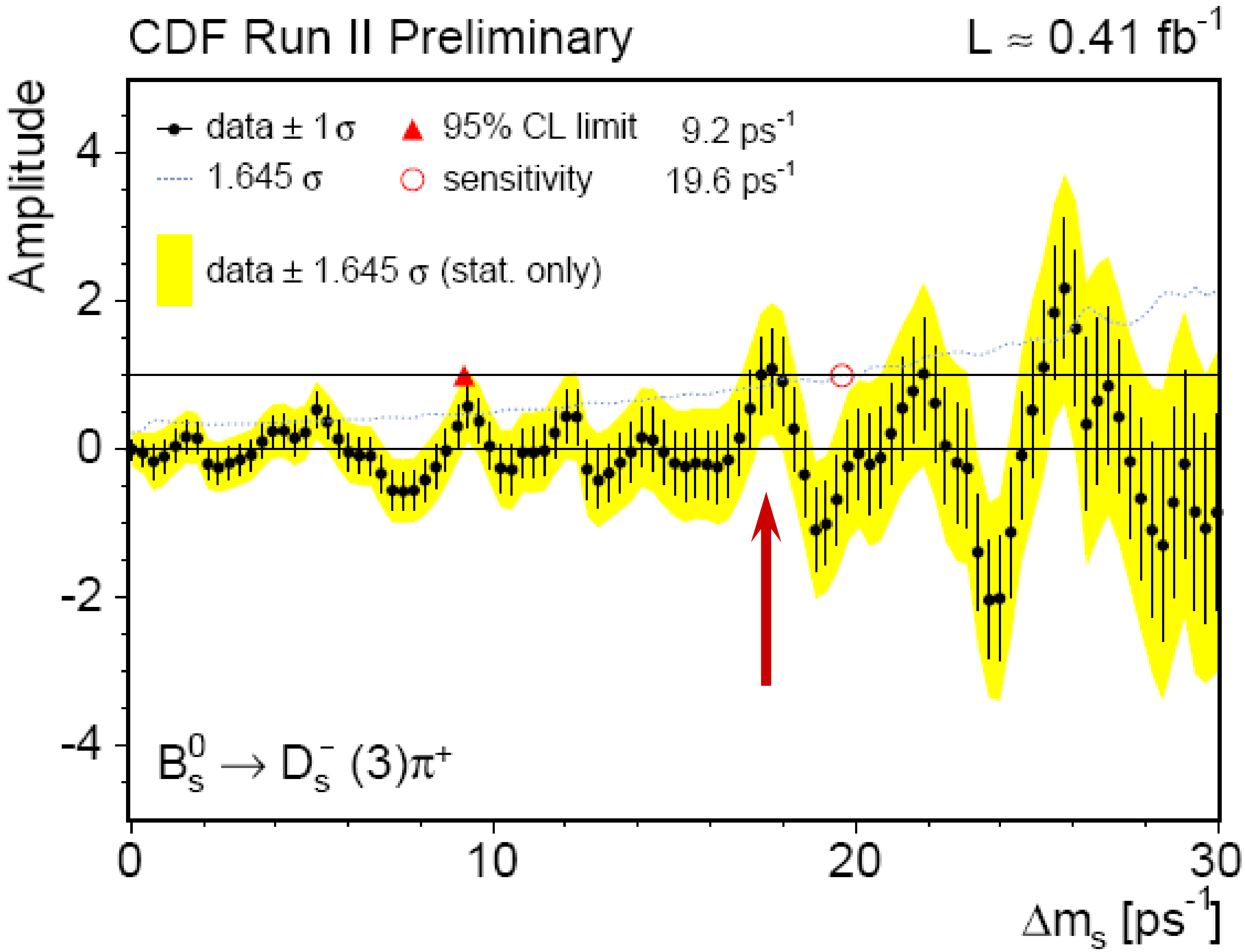
- estimated from scan on "blinded" data (randomized tags)
- unusual situation – one single measurement more sensitive than the world average knowledge!

The Data

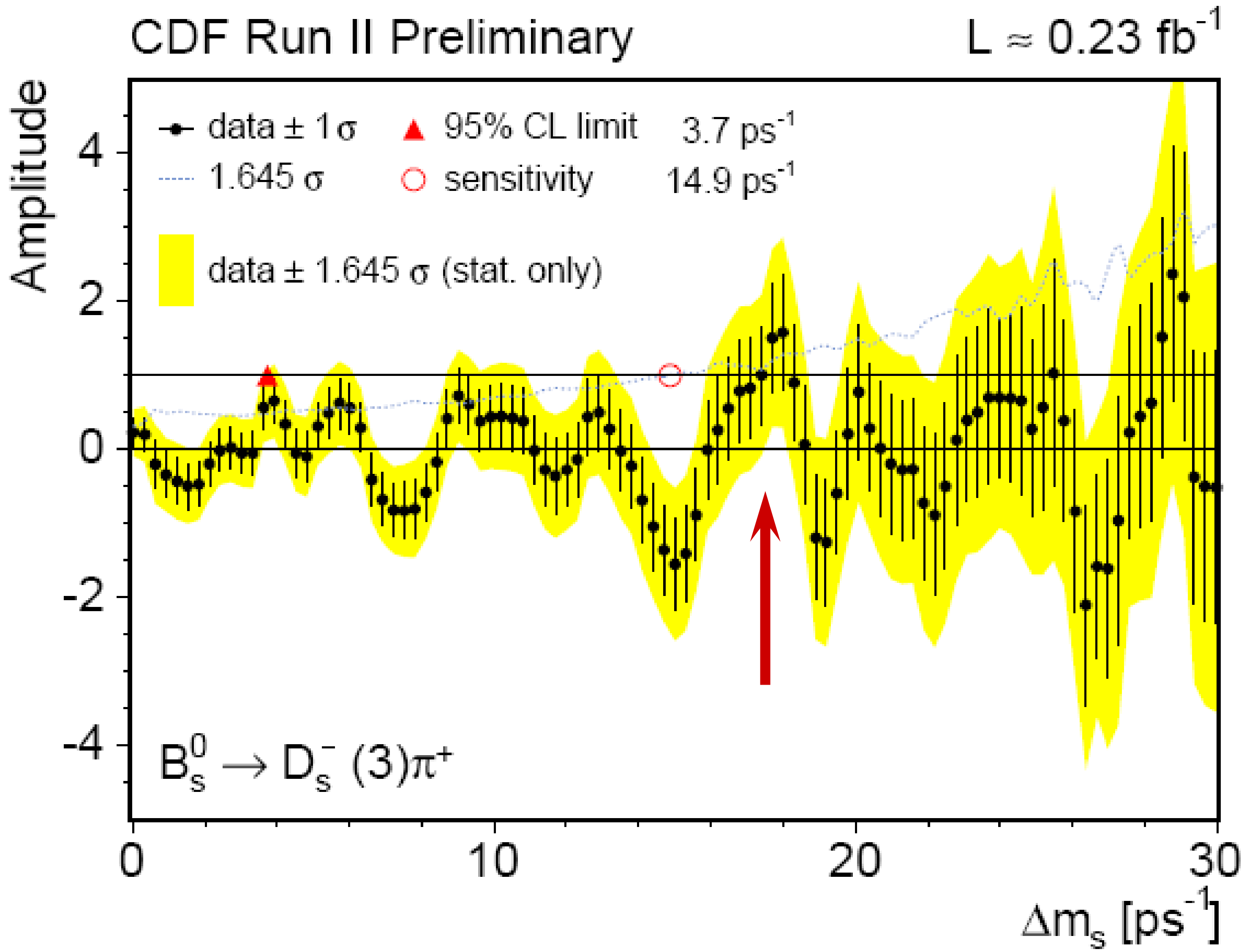
Amplitude Scan: Hadronic Period 1



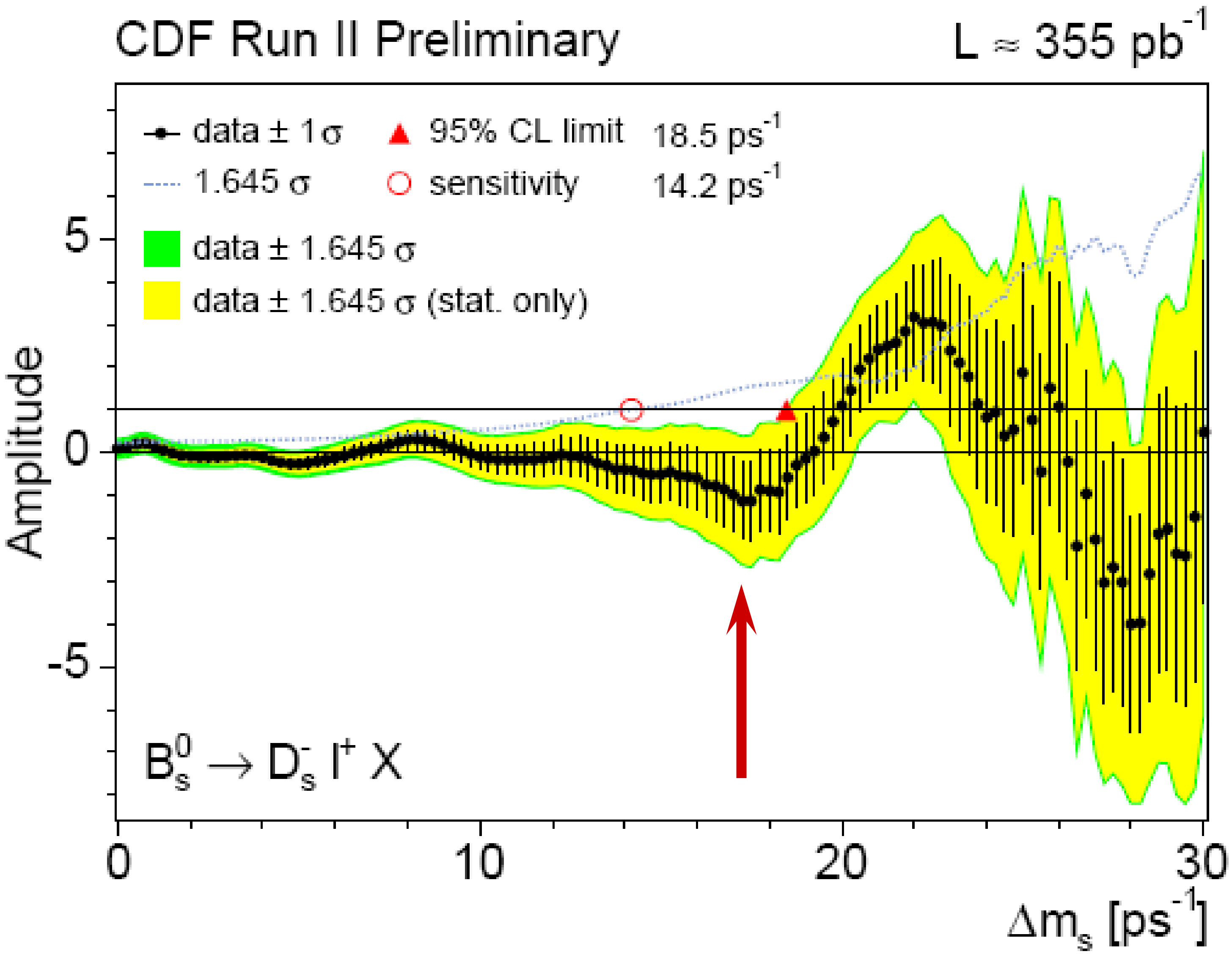
Amplitude Scan: Hadronic Period 2



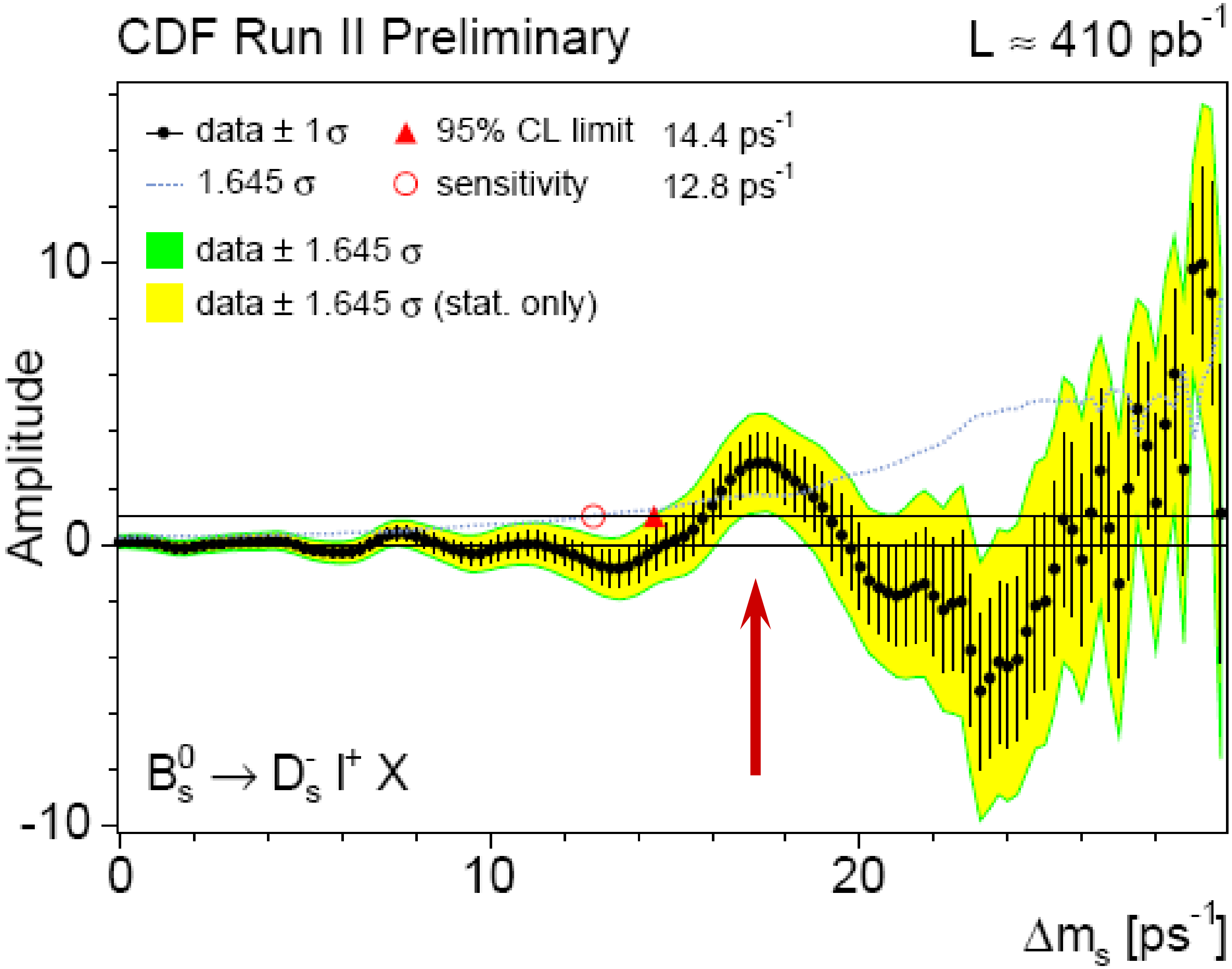
Amplitude Scan: Hadronic Period 3



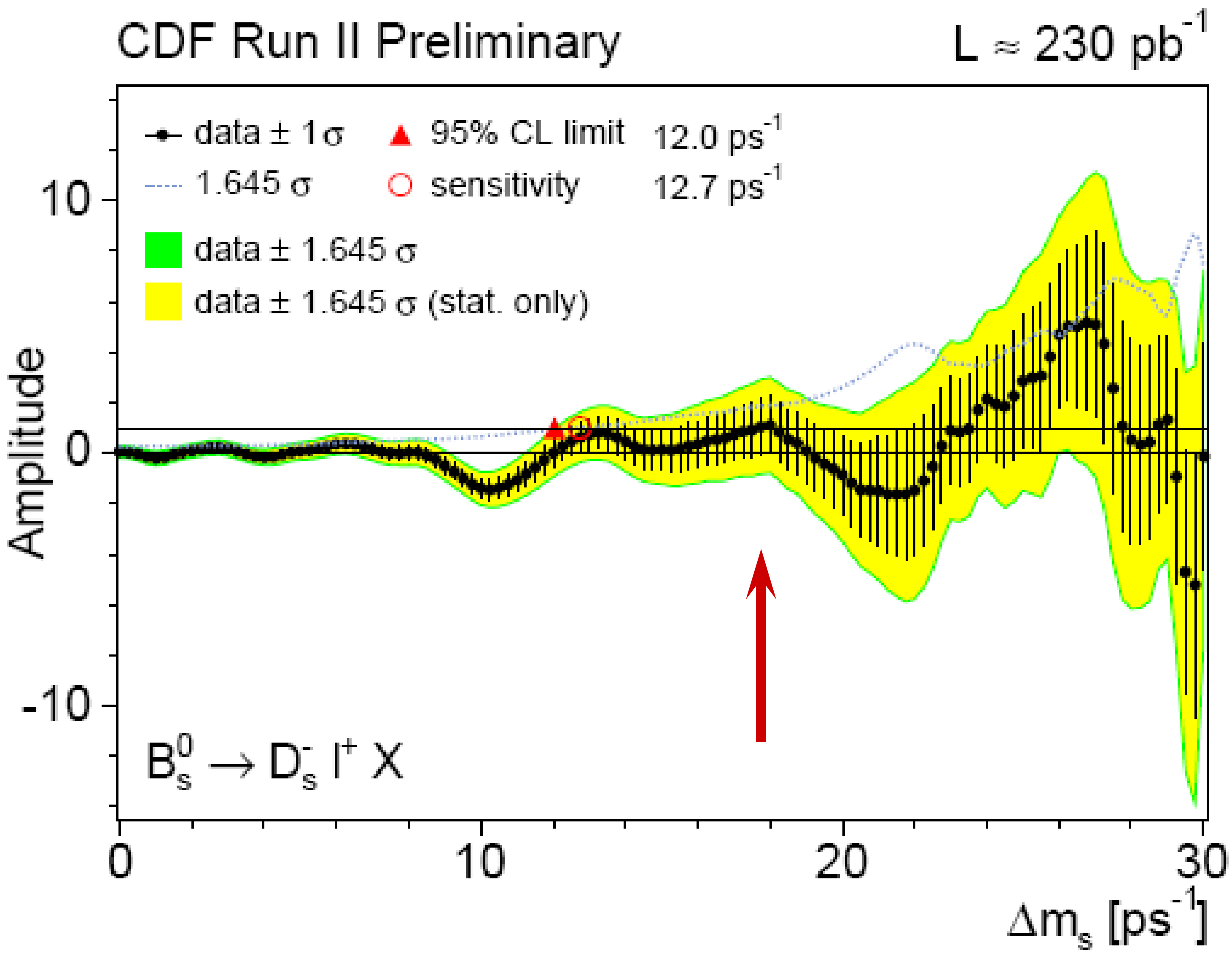
Semileptonic Scan: Period 1



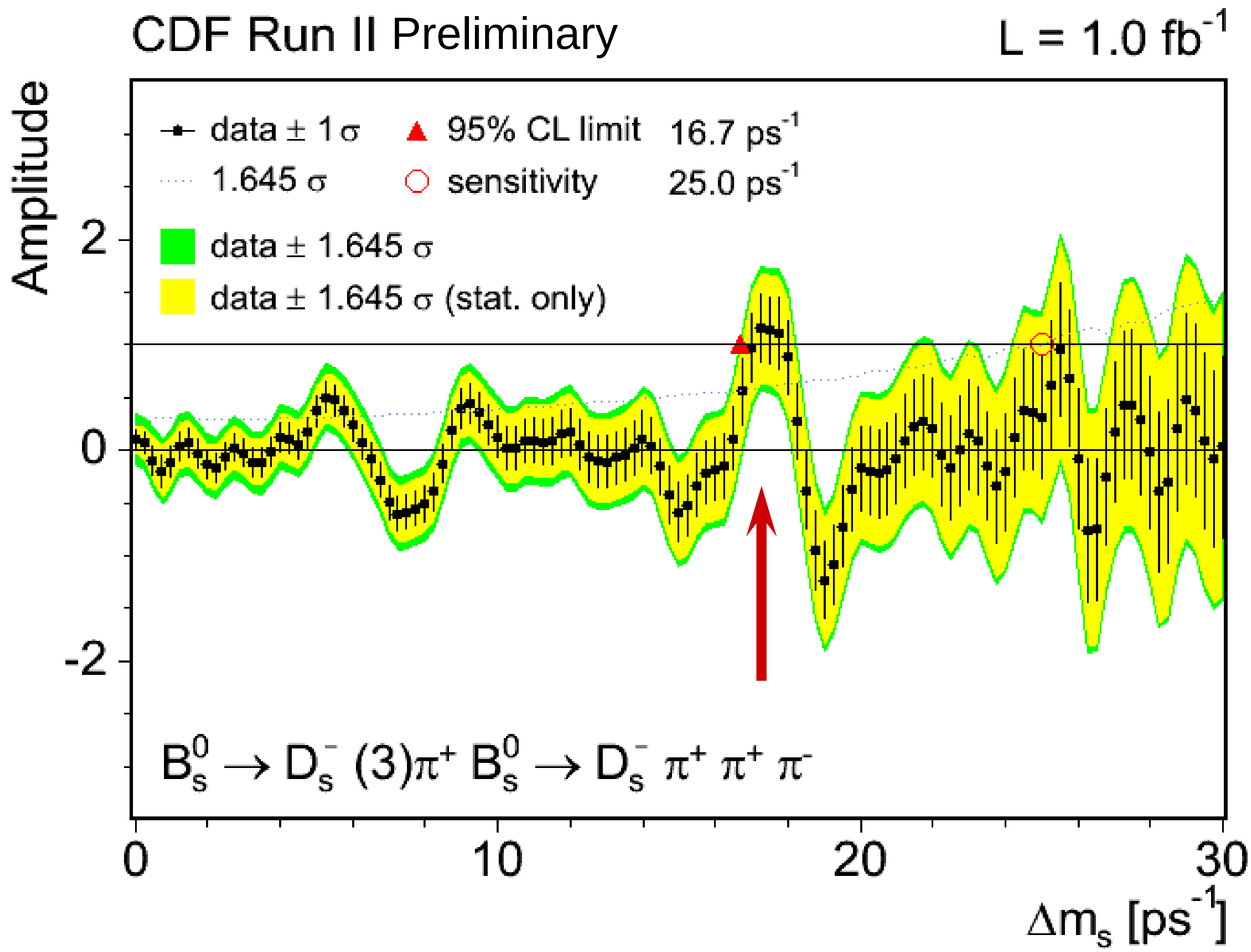
Semileptonic Scan: Period 2



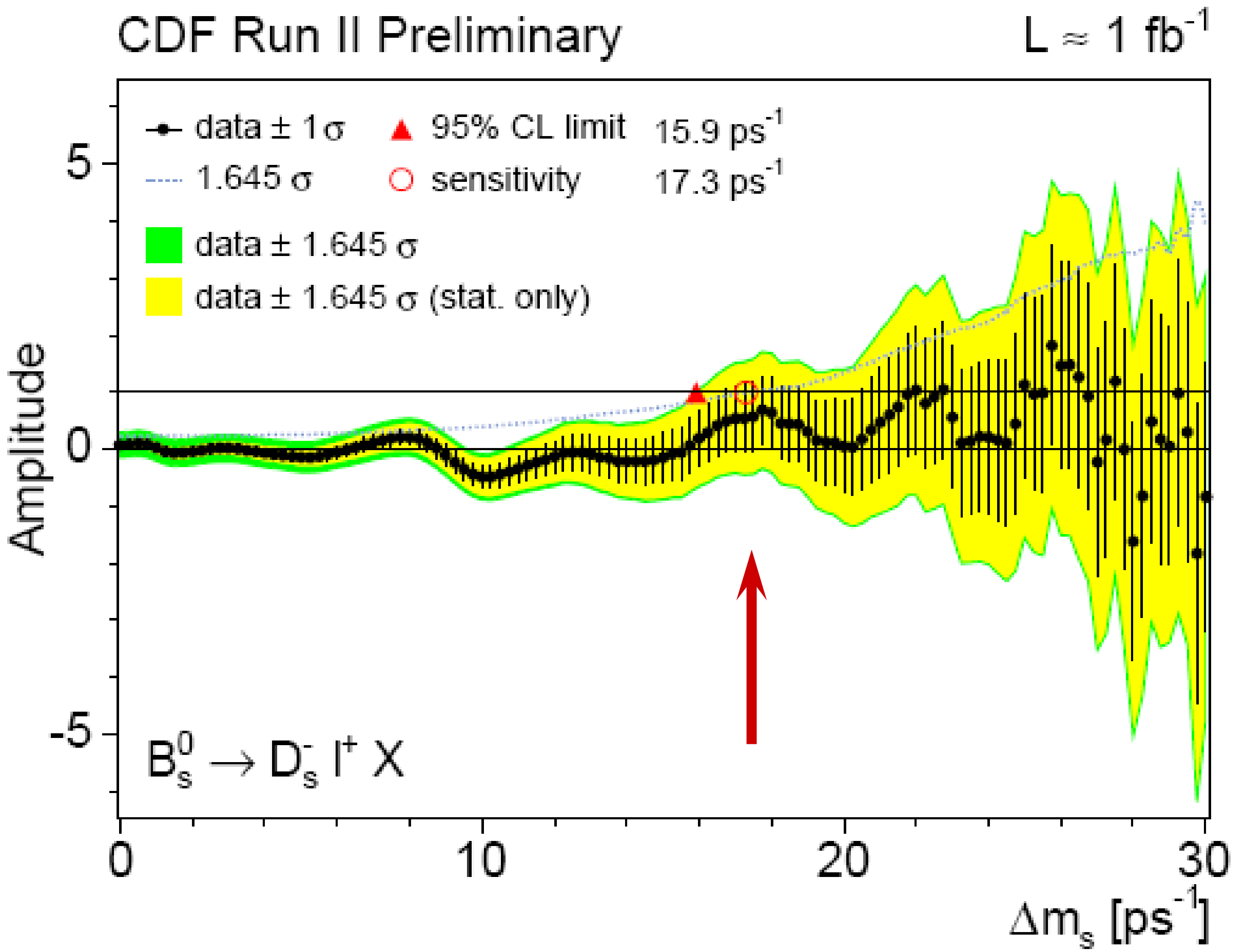
Semileptonic Scan: Period 3



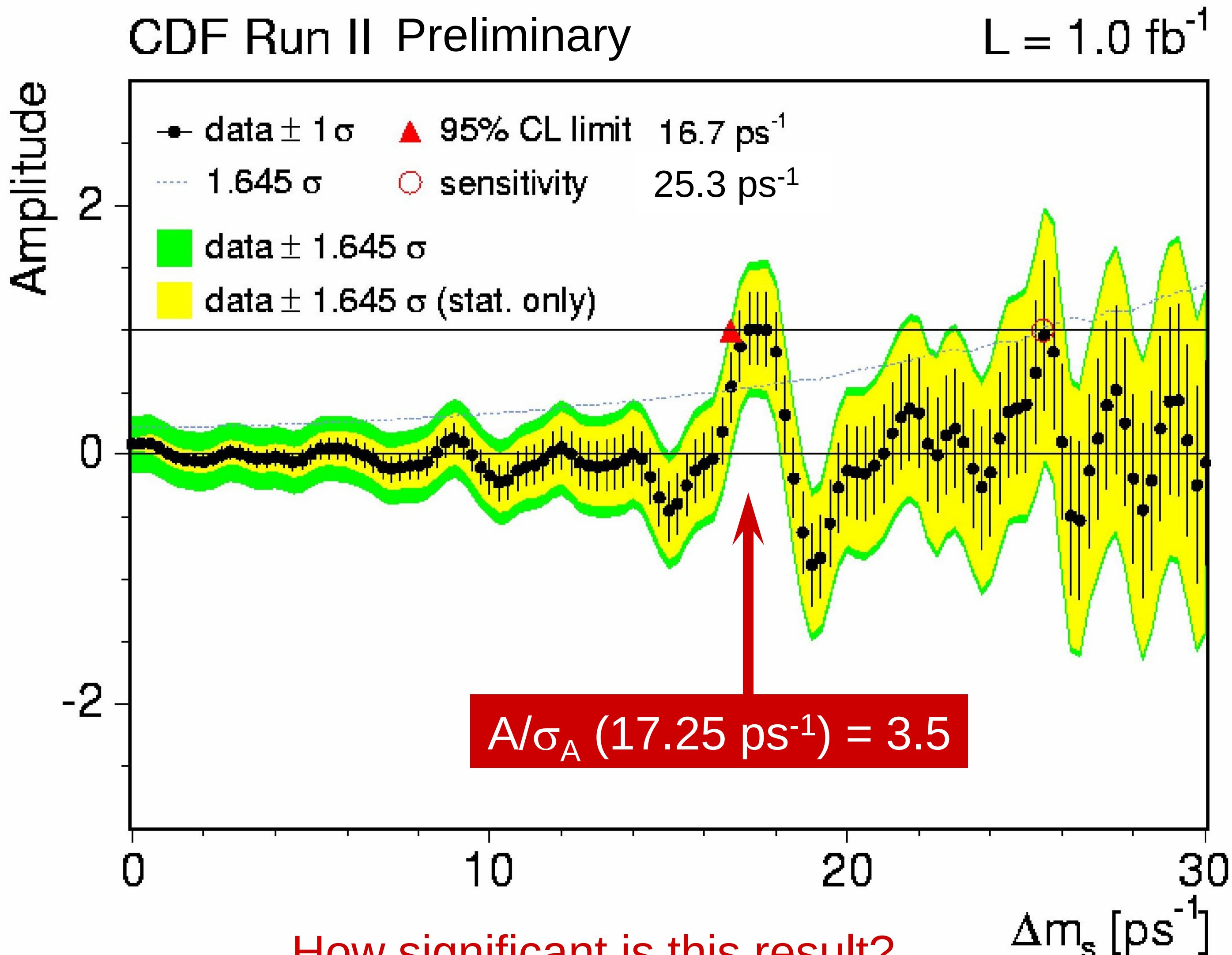
Hadronic Scan: Combined



Semileptonic Scan: Combined

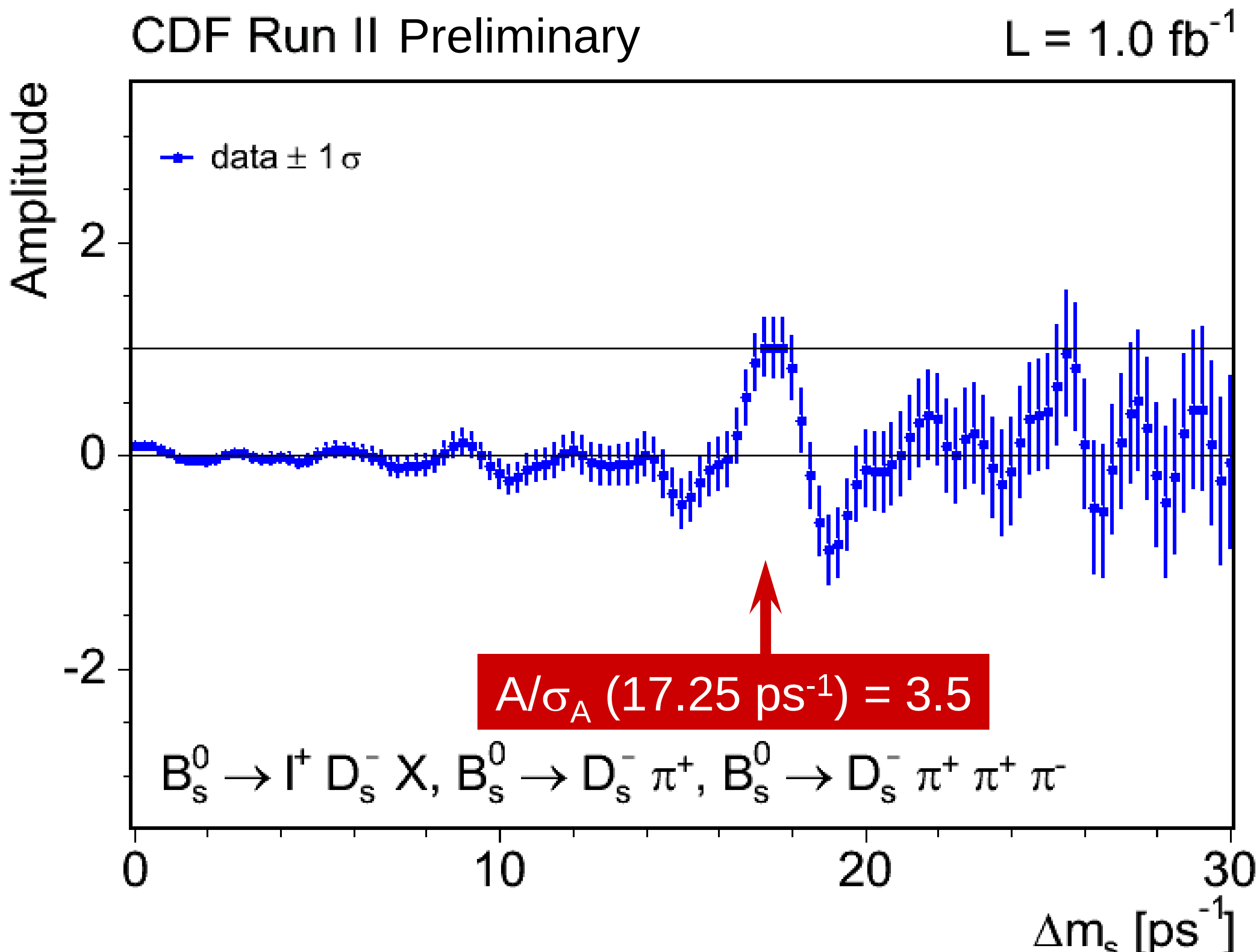


Combined Amplitude Scan



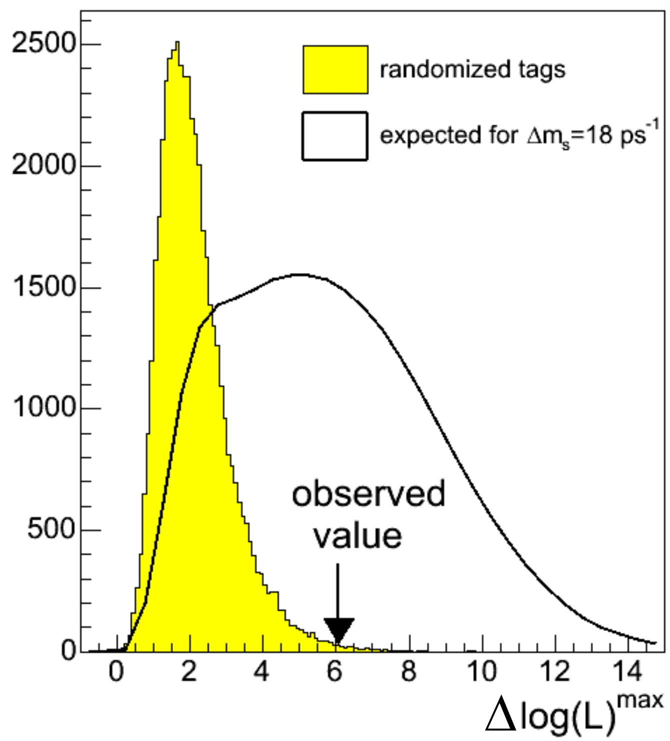
How significant is this result?

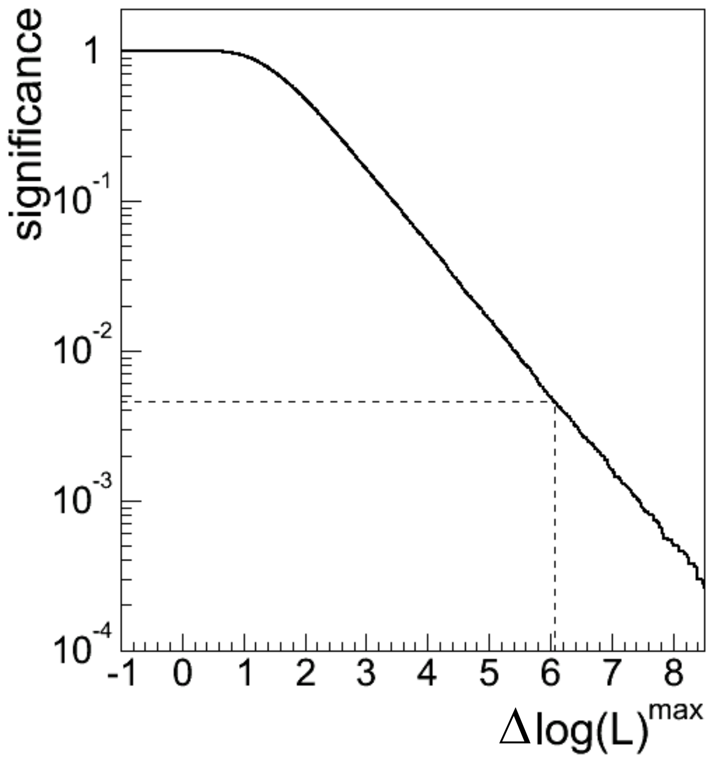
Combined Amplitude Scan



How significant is this result?

Likelihood Significance

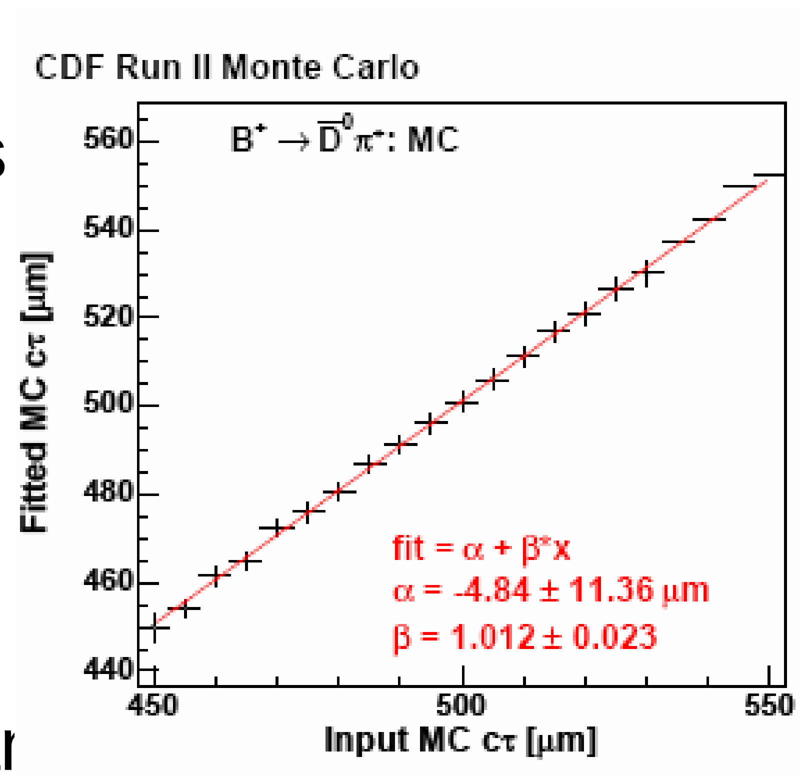




- randomize tags 50 000 times in data, find maximum $\Delta\log(LR)$
- in 228 experiments, $\Delta\log(LR) \geq 6.06$
- probability of fake from random tags = 0.5% $\Rightarrow$ measure Δm_s!

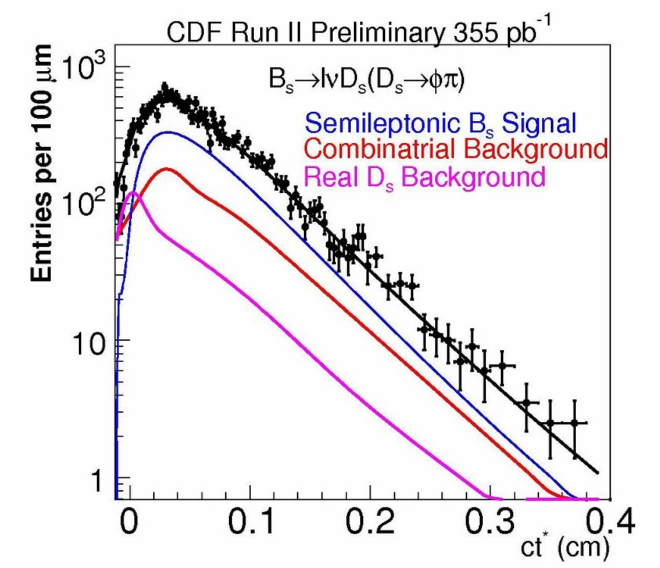
Does the MC bias the answer?

- efficiency function is derived from Monte Carlo
- the Monte Carlo is derived with an input lifetime
- does the input lifetime bias the fit outcome?
- test: fit many Monte Carlos with various input lifetimes
- derive efficiency function using one lifetime (500 µm)
- compare fit result to input lifetime
- observe no bias for ±50 µm
- measurement stat error ~7µ



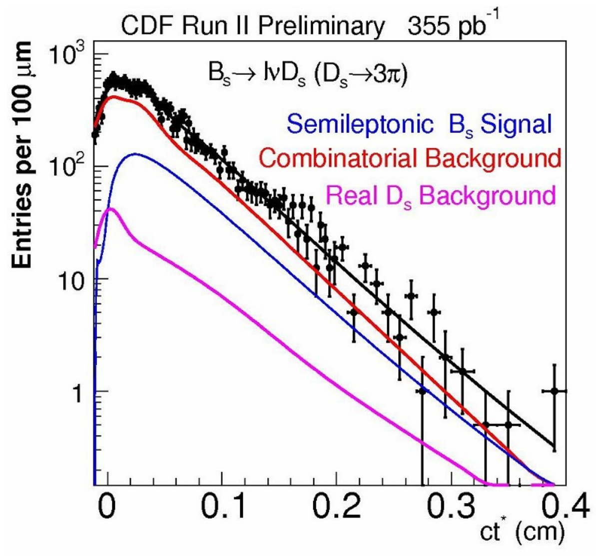
Semileptonic Lifetime Fits (Winter '05)

$D_s^- \rightarrow \phi\pi^-$



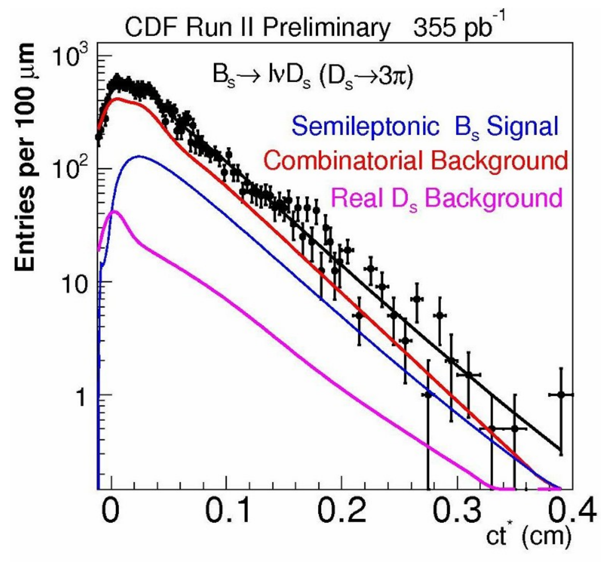
$c\tau$ = 455.9±11.9 μm

$D_s^- \rightarrow K^*K$



$c\tau$ = 413.8 ± 20.1 μm

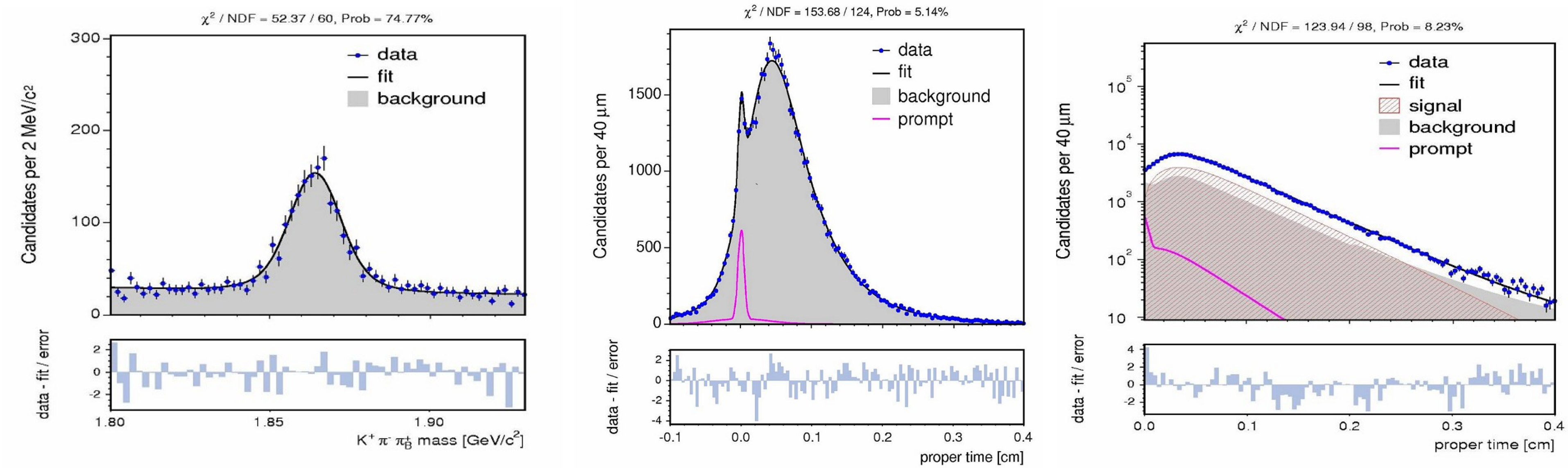
$D_s^- \rightarrow \pi^+\pi^-\pi^-$



$c\tau$ = 422.6 ± 25.7 μm

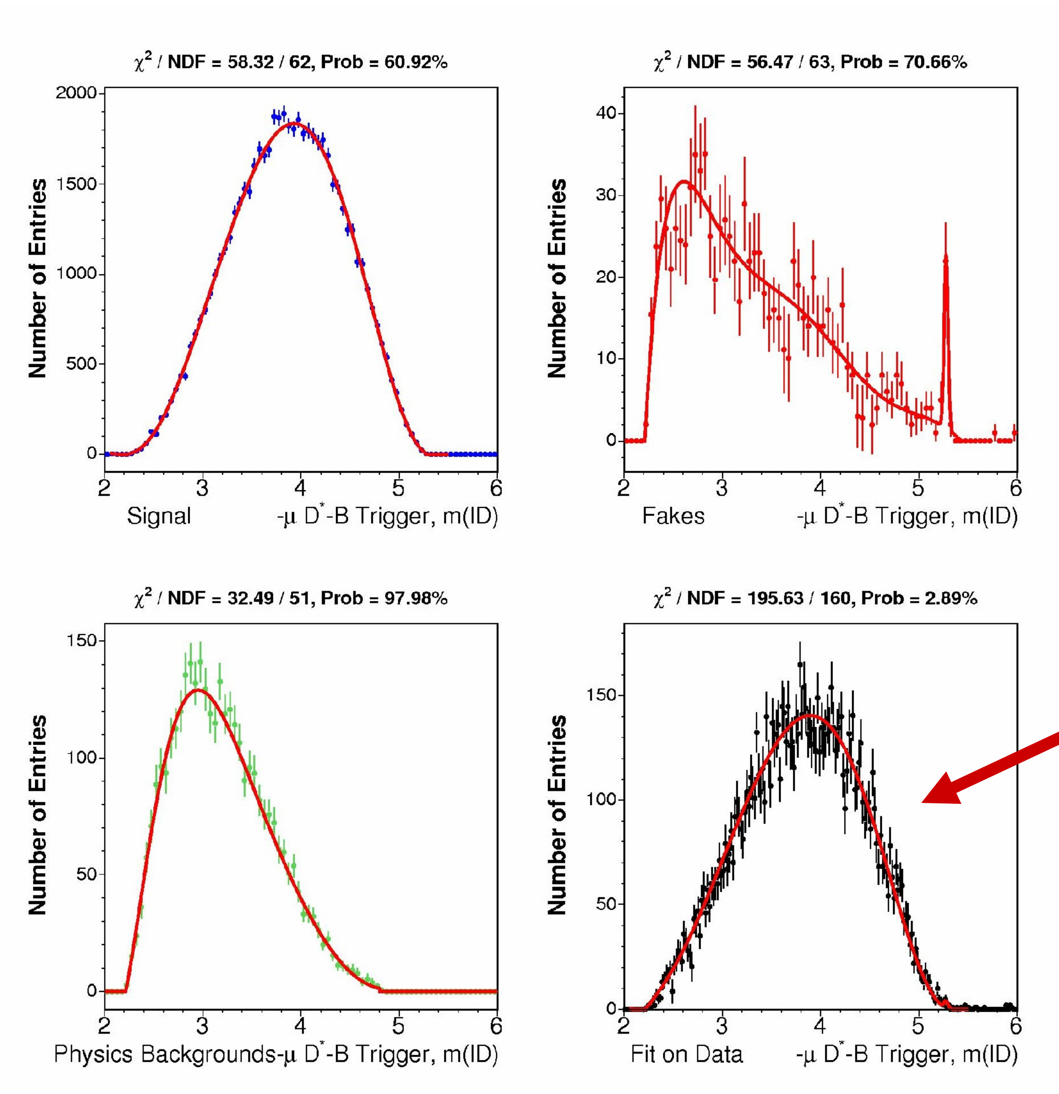
- B^0, B^+ lifetimes within 20 μm of world average values
- combined lD_s^- lifetime fit result: 445 ± 9.5 (stat) μm
- world average value: 438 ± 17 μm

"Prompt" Charm Background



- due to fake leptons, reconstruct some amount of prompt charm (D^-, D^0, D^{*-}) as B signal (in D mass signal region)
- can not disentangle from signal in any variable
- need to account for in lifetime, mixing fits
- extract shape from wrong-sign l^-D^- sample, use in fit

m(lD) fits

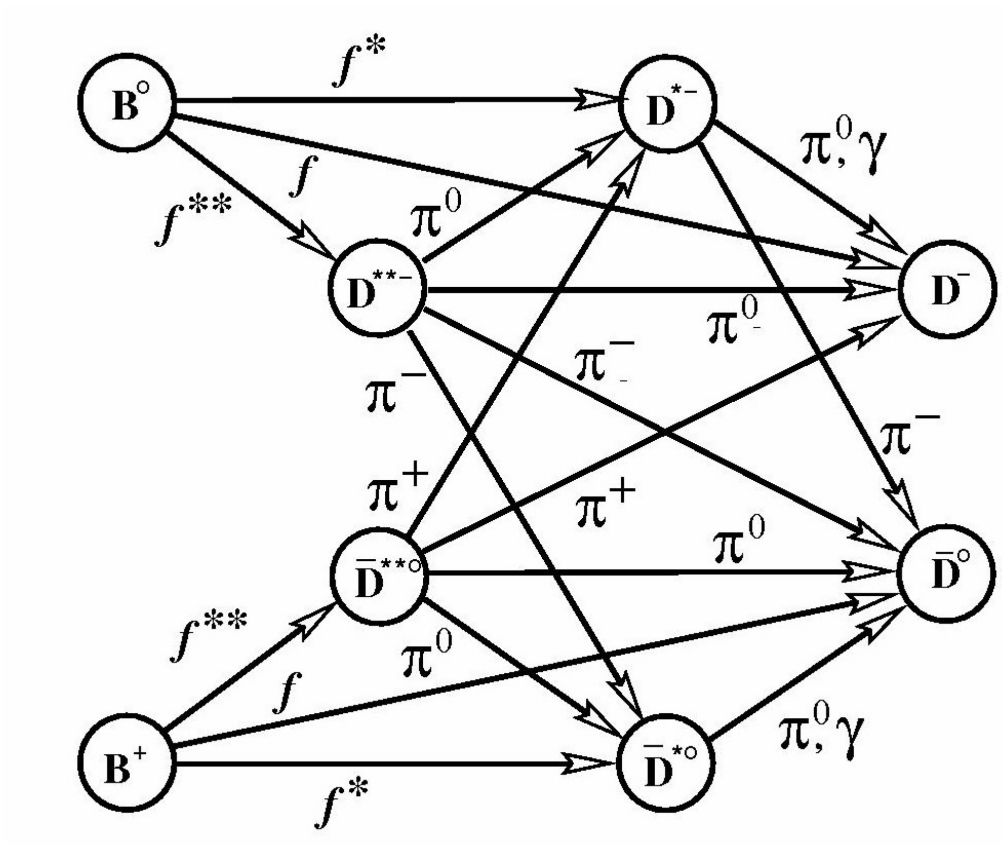


- signal distribution from Monte Carlo
- distribution for "fake" leptons from data
- physics background distribution from MC
- fit linear combination to sideband subtracted data to extract fractions

I.K.F1

Cross-Talk

- problem:
- lD^-, lD^0 are a mixture of B^+, B^0
- when fitting for lifetimes and mixing amplitude, account for this effect in fitter



Slide 112

I.K.F1 goes to backup
Ivan K Furic, 3/14/2005

Tagger Calibration

- taggers are parametrized in l+track sample
- kinematically different from final ($D_s\,\pi$, l+D_s^-)
- final tagger calibration:
- perform B^0 mixing fit in hadronic and semi-leptonic sample
- use per-event dilution, extract tagger scale factor:
- p ~ ½ [1 § S_D D_i cos(Δm_D **t**)]
- use per-event corrected dilutions in $\Delta\, m_s$ **fit**
- for hadronic sample, final calibration in $D^{-/0}\pi$, J/ψ $K^{(*)}$
- for semileptonic sample, final calibration in $D^{-/0}$ l, D^{*-} l

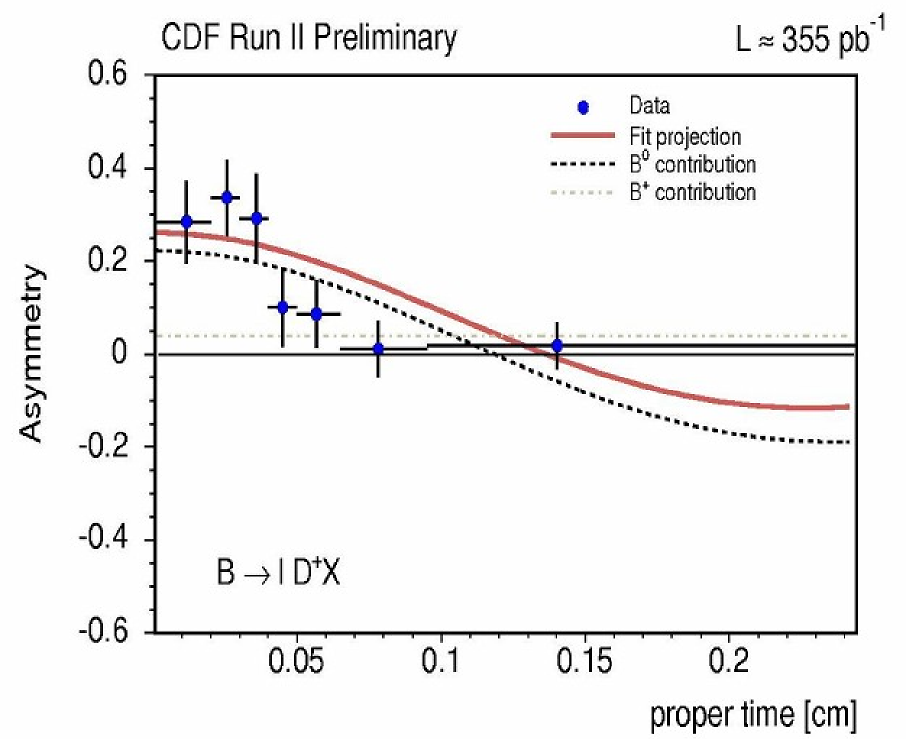
I.K.F2

I.K.F2 move all this to backup
Ivan K Furic, 3/14/2005

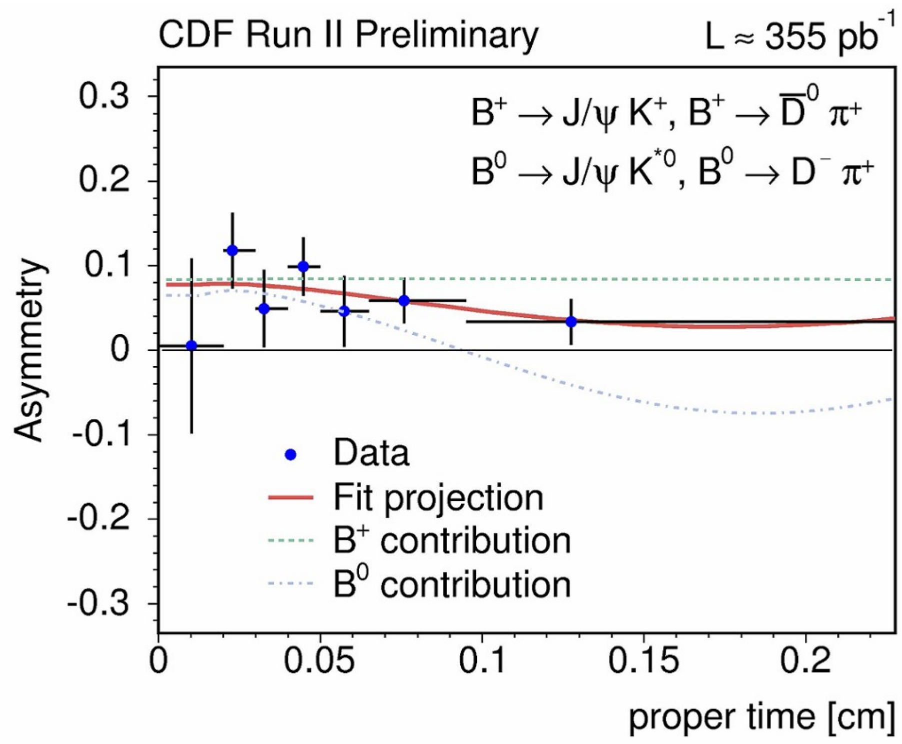
I.K.F3

Δ m_d Fits

semileptonic, lD^-, muon tag



hadronic, all channels, all tags



hadronic: $\Delta m_d = 0.503 \pm 0.063$ (stat) ± 0.015 (syst) ps^{-1}

semileptonic: $\Delta m_d = 0.497 \pm 0.028$ (stat) ± 0.015 (syst) ps^{-1}

I.K.F3 unbinned likelihood fit

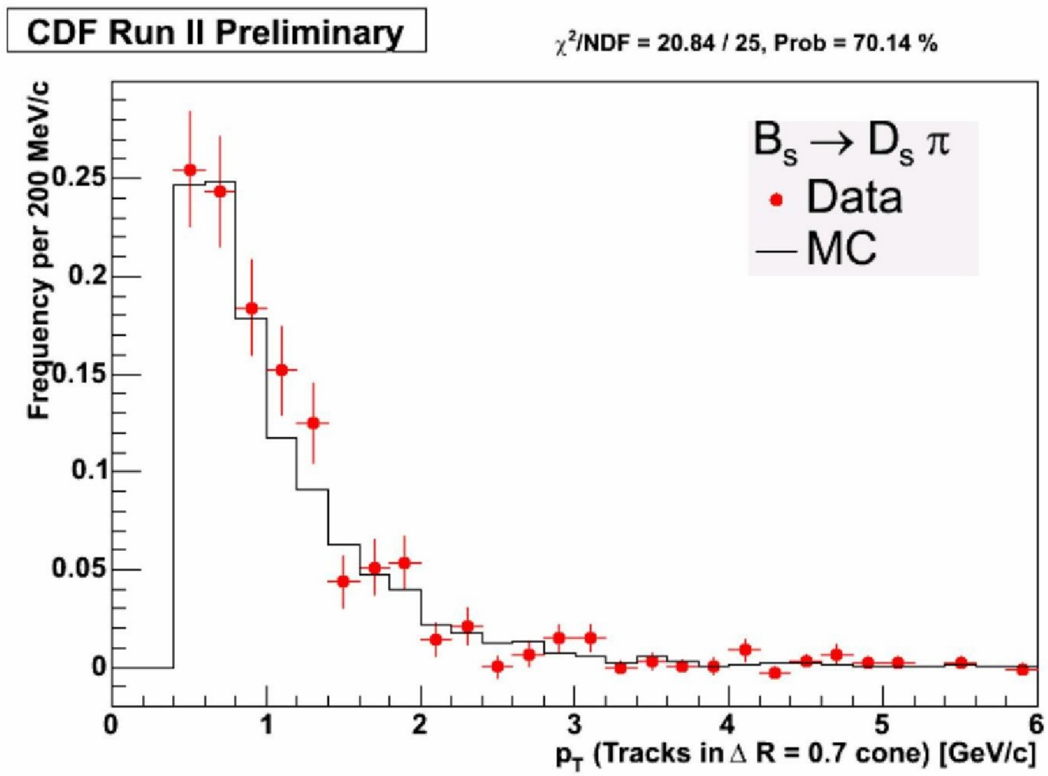
simultaneously measure

- tagger performance
- delta md

Ivan K Furic, 3/14/2005

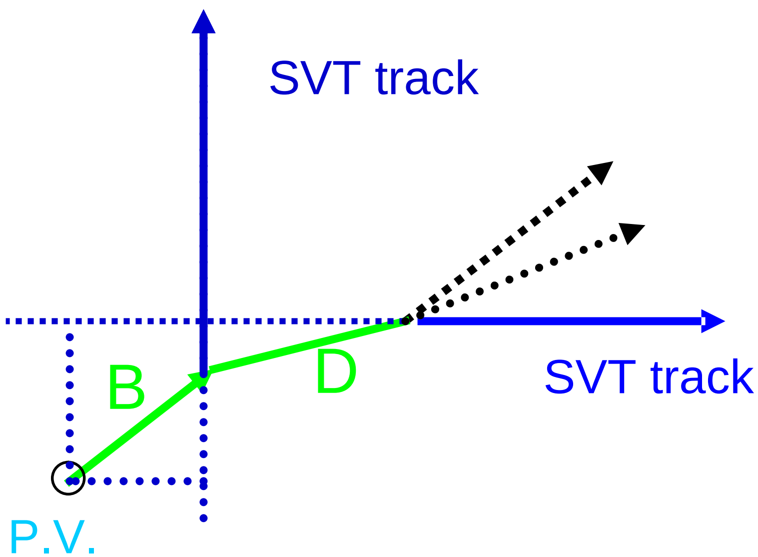
Kaon Tagging

- no straight way to determine tagger dilution from data unless B_s mixing is observed
- but we need to know the dilution to set the limit
- must use MC to measure dilution
- tune MC on B^0, B^+
- predict B_s

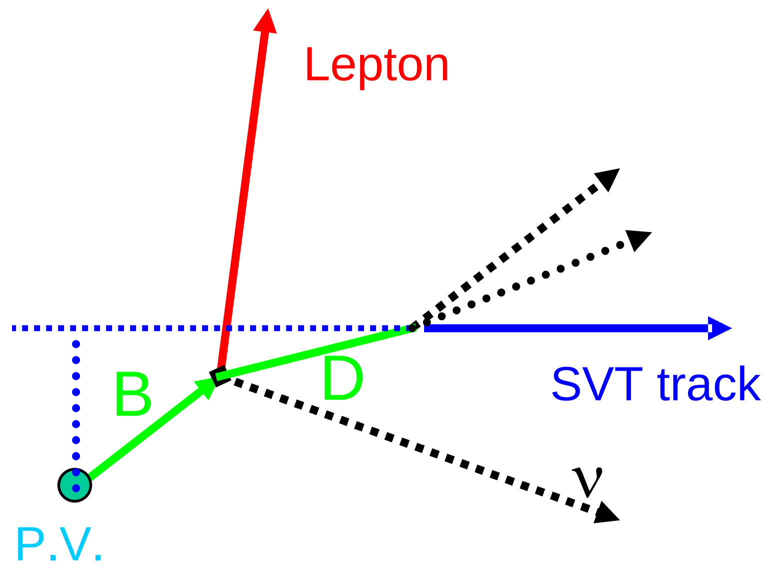


SVT based Triggers

- hadronic channel
- require two SVT tracks
  - p_T>2GeV/c
  - $p_{T1}+p_{T2}$ > 5.5 GeV/c
  - opposite charge
  - 120 μm < SVT IP < 1 mm
  - Lxy > 200 μm

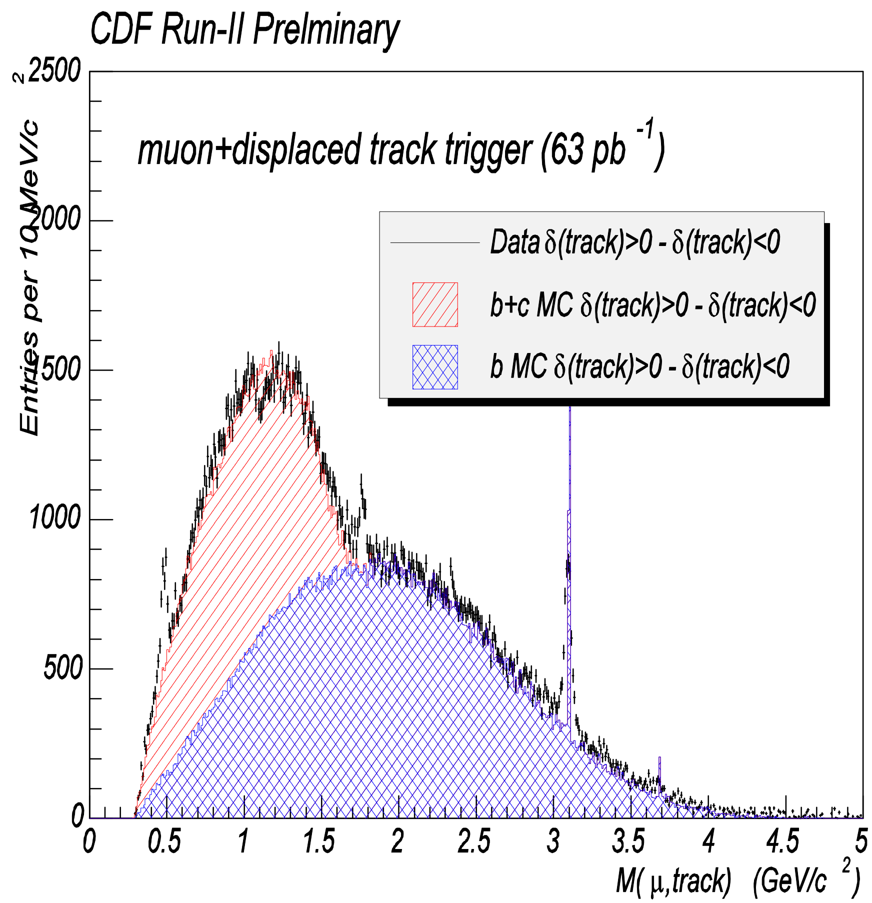


- semileptonic channel
- require 1 Lepton + 1 SVT track
  - 1 muon/electron p_T> 4 GeV
  - 1 additional SVT track with
    - p_T > 2 GeV
    - 120 μm < SVT IP < 1 mm



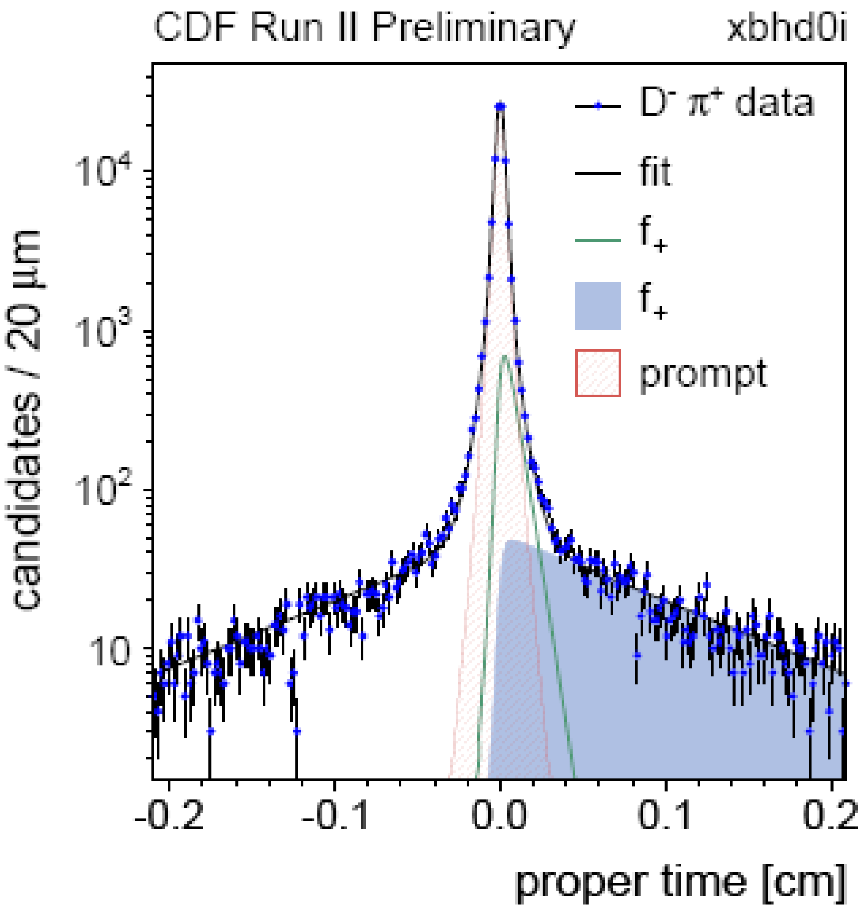
Calibrating Opposite Side Tags

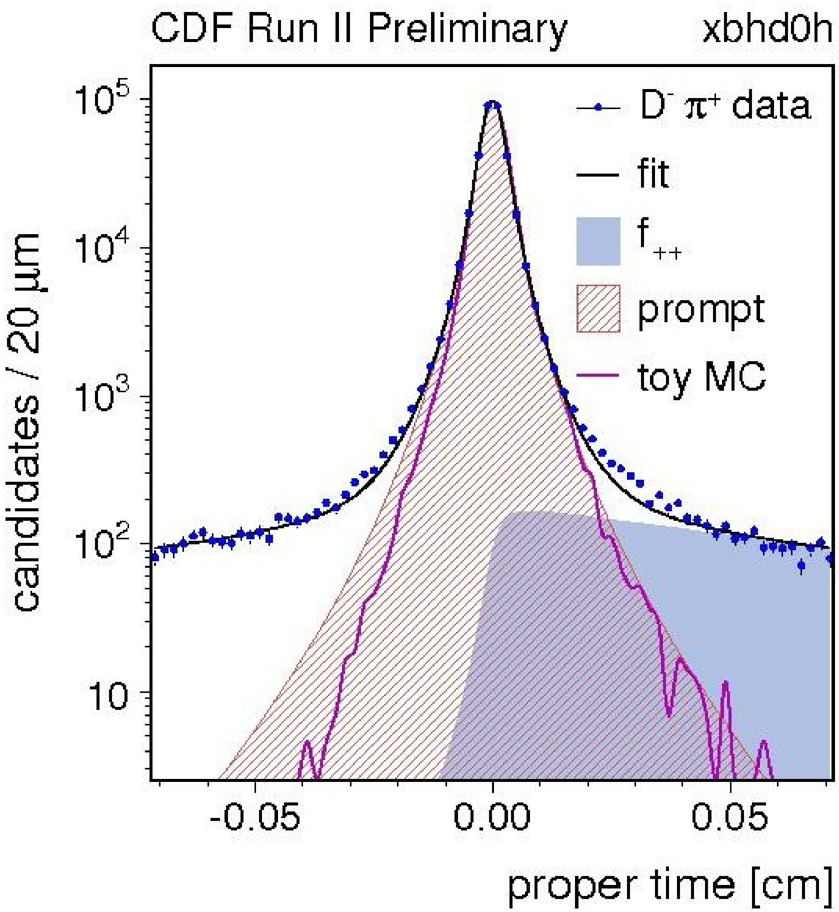
- Statistical Power of the tag: εD^2
  - Tagging efficiency (ε)
  - Tagging dilution ($D = 1\text{-}2w$)
    - w = mistag rate
- "Binned Tagger"
  - Tag1: ε_1=50%, $D_1 = 0.5$
  - Tag2: ε_2=50%, $D_2 = 0.1$
  - $\langle D \rangle = (D_1 + D_2)/2 = 0.3$
  - $\langle D^2 \rangle = 0.36$
- Dividing events into different classes based on tagging power improves εD^2
- Calibration the tagger performance requires high statistics



- inclusive B →track+lepton
- 1.4 M events of flavor specific B

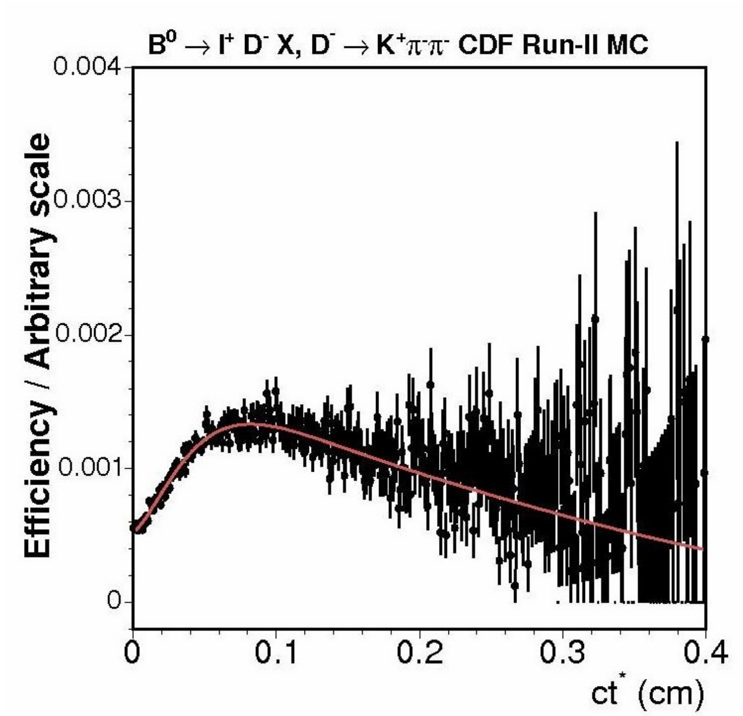
Non-Gaussian Tails

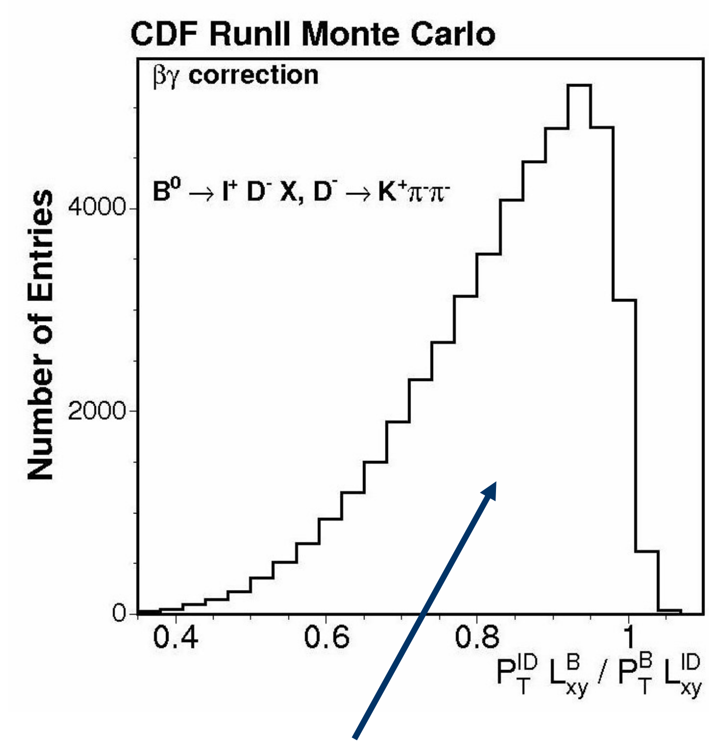




- amplitude corrected for effects of non-Gaussian tails
- correction derived from toy Monte Carlo, tuned to reproduce data

Lifetime Measurement: Semileptonic Subsample

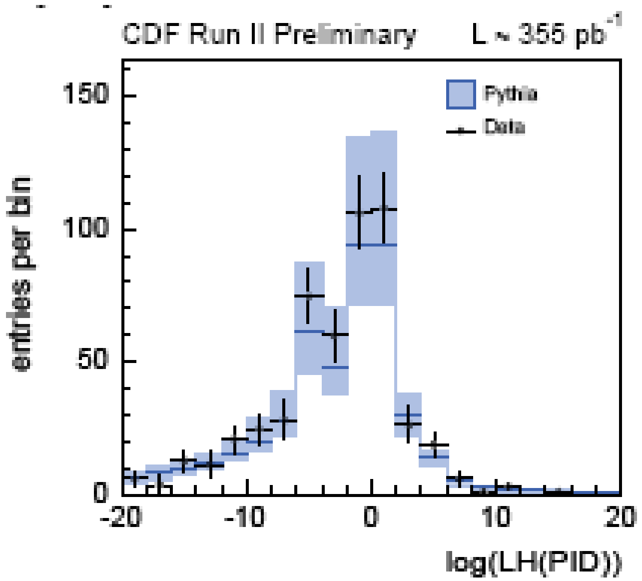




- in addition to SVT bias, correct for missing energy (K-factor)
- bin K-factor in l+D invariant mass to obtain narrow K-factor distributions

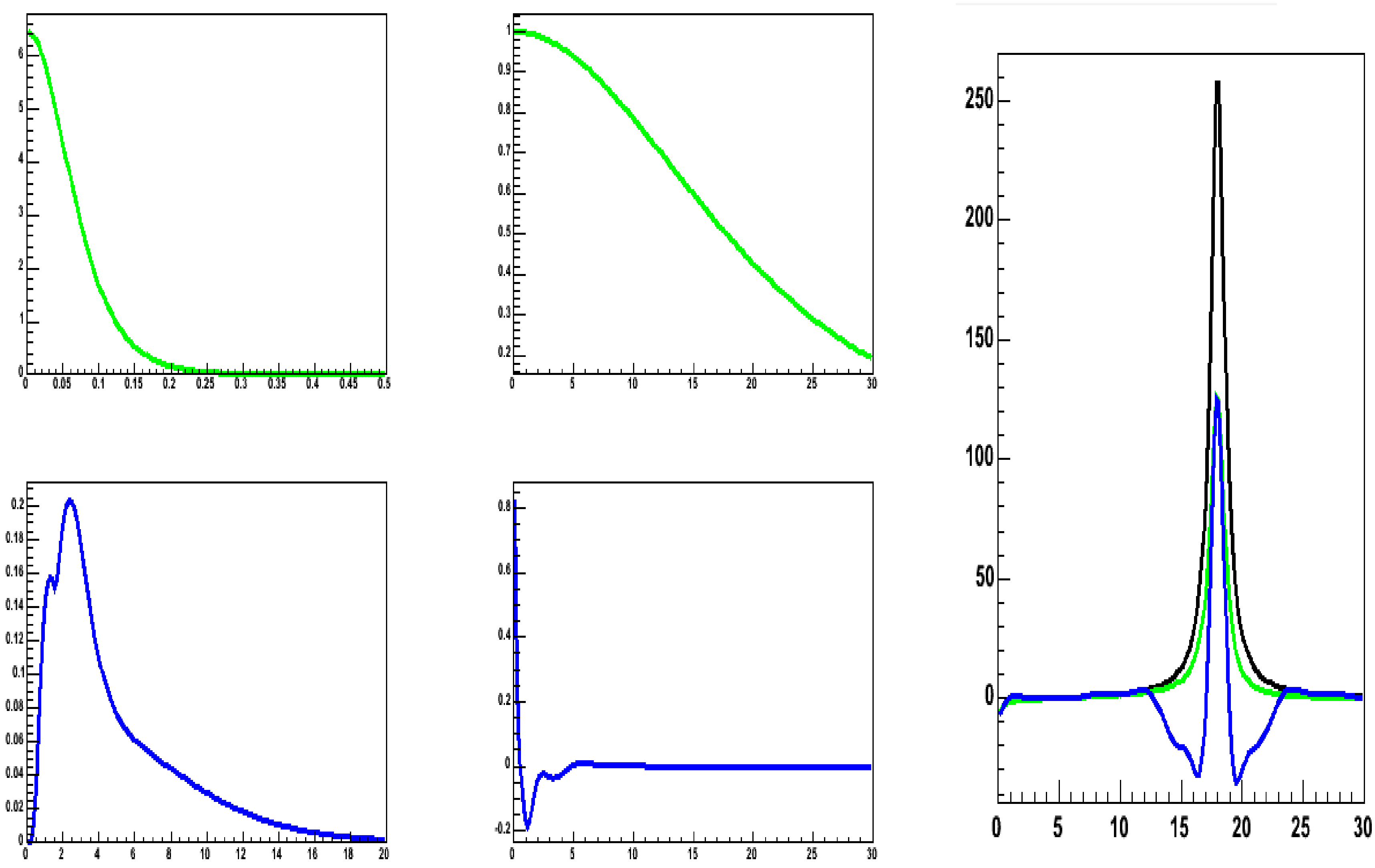
Calibrating SSKT (1)

- use combined PID likelihood, select most "kaon-like" track as tagging track
- parametrize dilution based on maximum PID likelihood value
- verify kinematic distributions (p_T, tagging track p_T, multiplicity, isolation) of light B mesons in Pythia simulation
- verify particle ID simulation
- test for dependences on:
  - fragmentation model
  - bb production mechanisms
  - detector/PID resolution
  - multiple interactions
  - pid content around B meson
  - data/MC agreement



- Final test: cross-check tagging power against high statistics light B decays

Mixing & Fourier Transforms



The Method

- We are looking for a periodic signal: Fourier space is the natural tool
  - Moser and Roussarie already mentioned this!
  - They use it to derive the most useful properties of A-scan
  - Amplitude approach is approximately equivalent to the Fourier transform

Amplitude from scan $\leftrightarrow$ Re[Fourier]

- Aim: move to Fourier transform based analysis
  - Computationally lighter
  - As powerful as A-scan
  - As is, no need *in principle* for measurements of D, ε etc. (however these ingredients add information and tighten the limit)
  - Will provide an alternate path to the A-scan result!

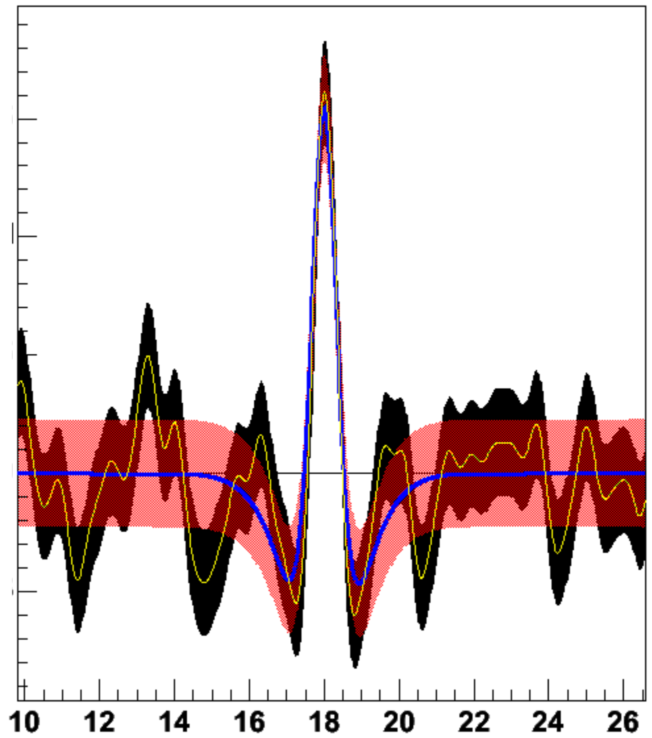
Dilution weighted transform

- Discrete Fourier transform definition
  - Given N measurements $\{t_j\}$ → $g(\omega) = \sum_{k=1}^{N} D_k e^{-i\omega t_k}$
- Properties:
  - A particular application of $g(\omega) = \sum_{k=1}^{N} w_k e^{-i\omega t_k}$ (CDF8054)
  - Average: $\langle g(\omega) \rangle = N \langle D \rangle \tilde{f}(\omega)$

    (f(t) is the parent distribution of $\{t_j\}$)
  - Corresponds to dilution-weighted Likelihood approach
  - Errors computed from data: $\sigma^2(\mathrm{Re}\, g(\omega)) \approx \frac{N}{2}\left(\langle D^2 \rangle + o\left(\frac{1}{N}\right)\right)$
    - NB: Errors can be calculated directly from the data!
    - $\Delta(\omega) \equiv g_{\mathrm{Un}Mix}(\omega) - g_{Mix}(\omega)$ behaves "as you'd expect"
    - While Δ and its uncertainty are fully data-driven, predicted Δ requires exactly the same ingredients as the amplitude scan fit

Properties of Δ…

- Re[Δ]
  a) contains information equivalent to the standard amplitude scan
  b) (Amplitude scan)≈Re[Δ]
- Re[F] and $\sigma_{Re[F]}$ can be computed directly from data!
- b) ⇒ Sensitivity is exactly:



$$\frac{\Delta(\omega = \Delta m_s)}{\sigma_\Delta} = \sqrt{N\varepsilon\langle D\rangle^2}\sqrt{\frac{S}{S+B}}e^{-\Delta m^2\sigma_{ct}^2/2}\sqrt{1+\frac{\sigma_D^2}{\langle D^2\rangle}}$$

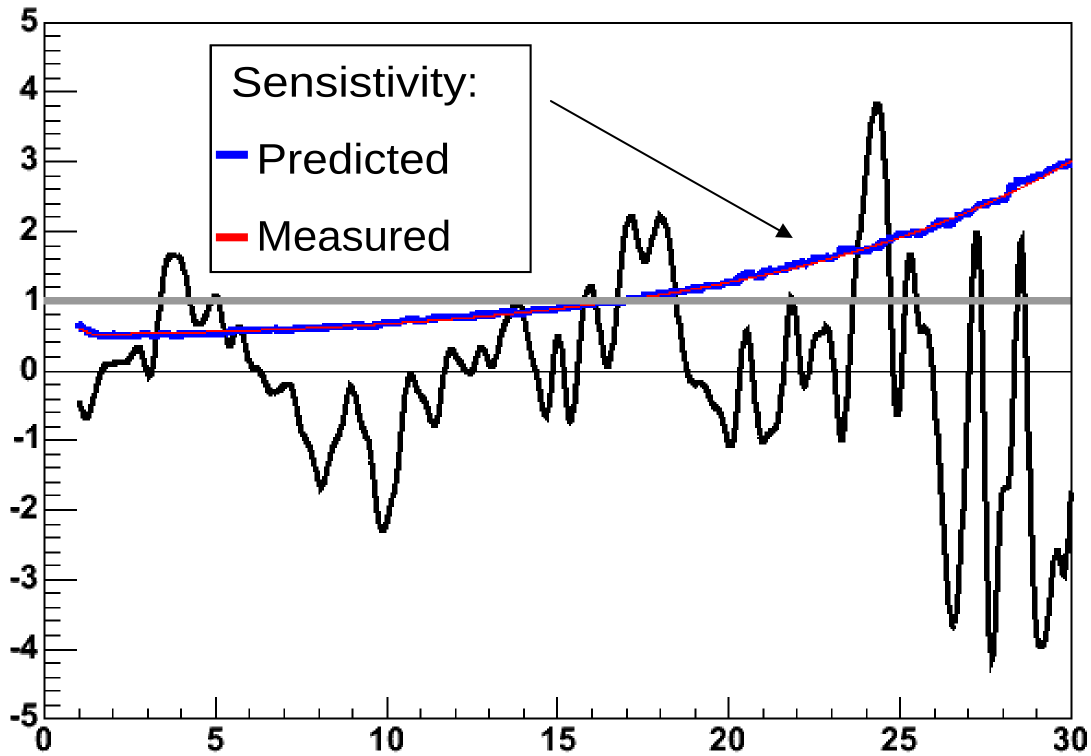
Can we reproduce the A-scan itself?

Toy Example

- 1000 toy events
- Δm_s=18
- S/B=2.
- εD_{signal}^2=1.6%
- εD_{back}^2=0.4%
- Background and signal parameterized according to standard analyses
- Histogrammed σ_{ct}
- Best knowledge on SF parameterization

" A-scan" a` la fourier

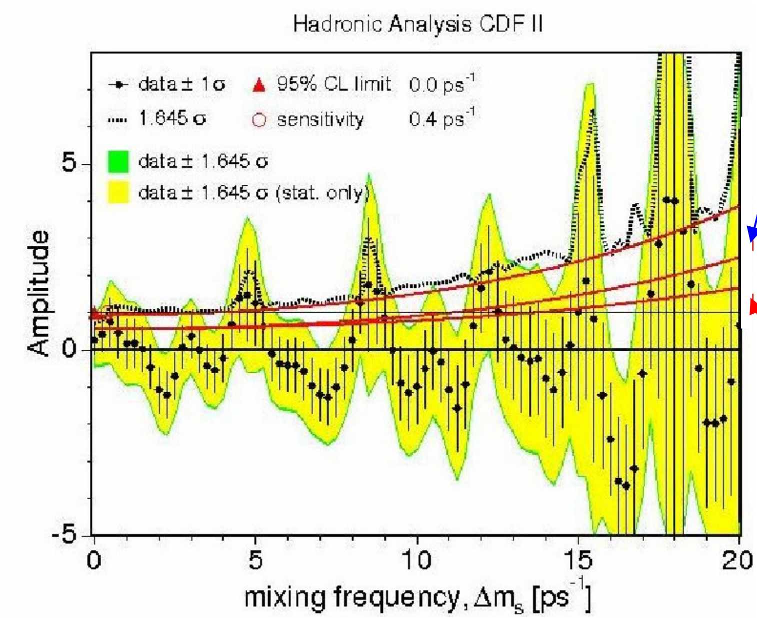
$$\frac{\Delta(\omega)}{pred.\Delta(\omega;\ \Delta m_s = \omega)}$$



No actual fit involved: this method allows to flexibly study systematics!

B_s Mixing Perspectives

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



- **Statistics**
  - Data (lumin.: $350 pb^{-1} \rightarrow 600 pb^{-1} \rightarrow 1\ fb^{-1}$)
  - New Modes (e.g. $Bs \rightarrow Ds^*\pi$ >2x?)
  - εD^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 data collected up to March 2006: sensitivity~SM value