Recent results from the Tevatron on CKM matrix elements from B_s oscillations and single top production, and studies of CP violation in B_s decays

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Introduction

In this talk we deal with completely different analysis strategies but with the same aim : more precise knowledge of CKM matrix elements at the Tevatron.

- |Vtb|

  through single top production

- |Vts|

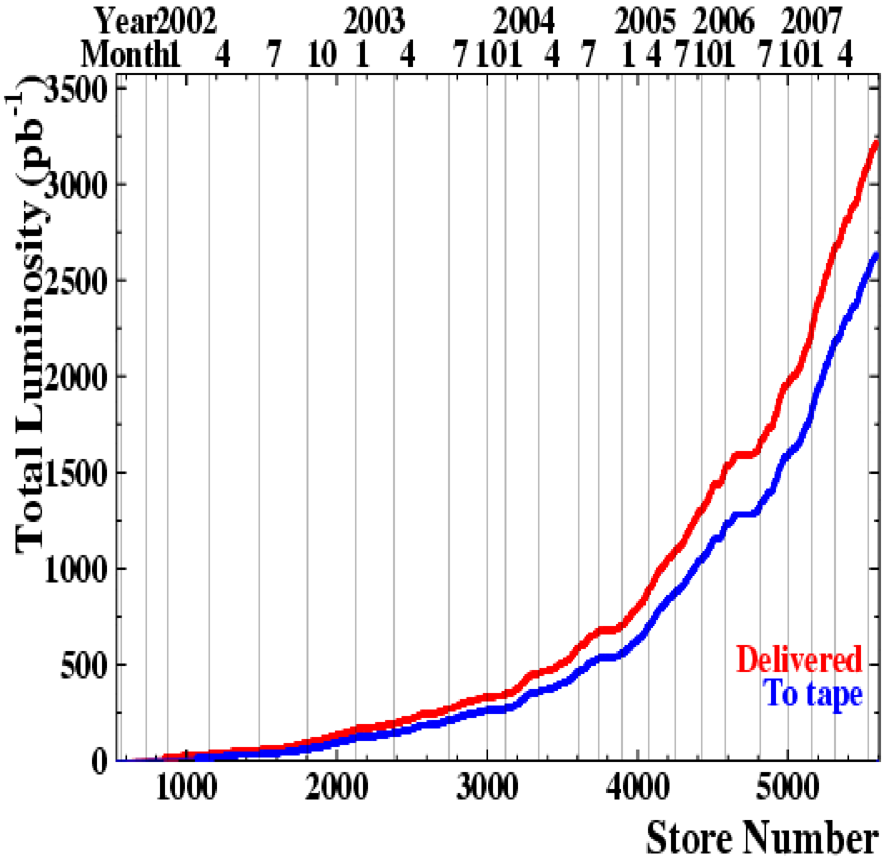
  through Bs mixing

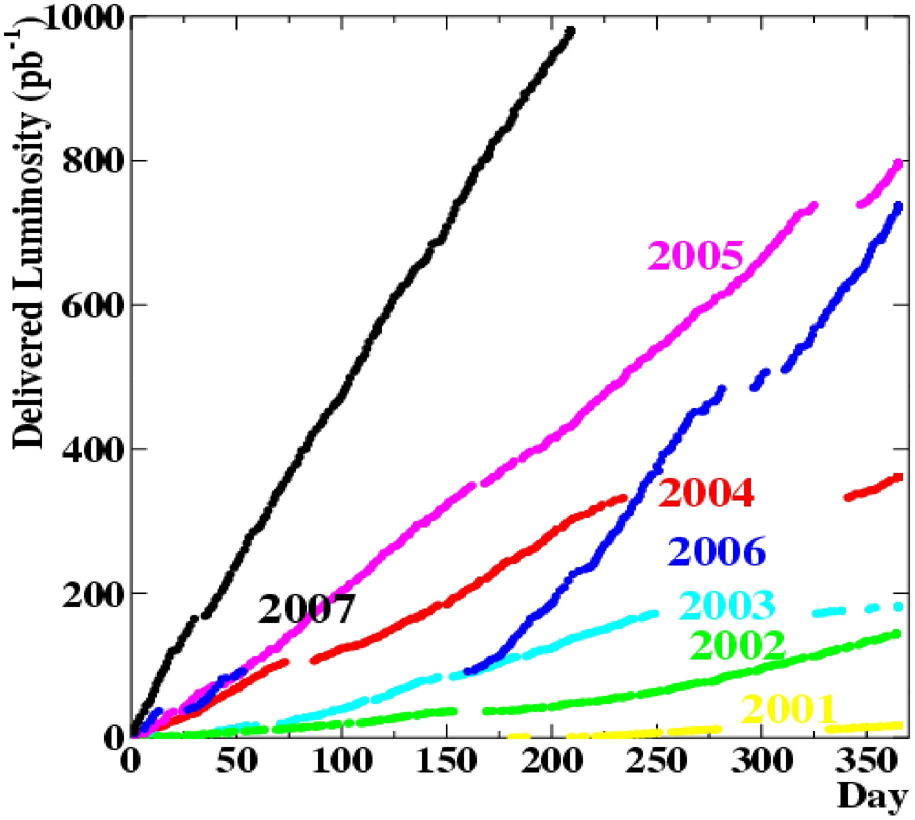
- $\arg(V_{ts} V_{tb}^{*} / V_{cs} V_{cb}^{*})$

  through CP violation

Tevatron

- $p\bar{p}$ colisions at $\sqrt{s} = 1.96$ TeV
- Peak luminosity ~ 3 x 10^{32} cm^2s^{-1}
- 2.7 fb^{-1} per experiment collected already
- Accelerator and experiments performing well
- Aim for 4-9 fb^{-1} int. luminosity in Run II



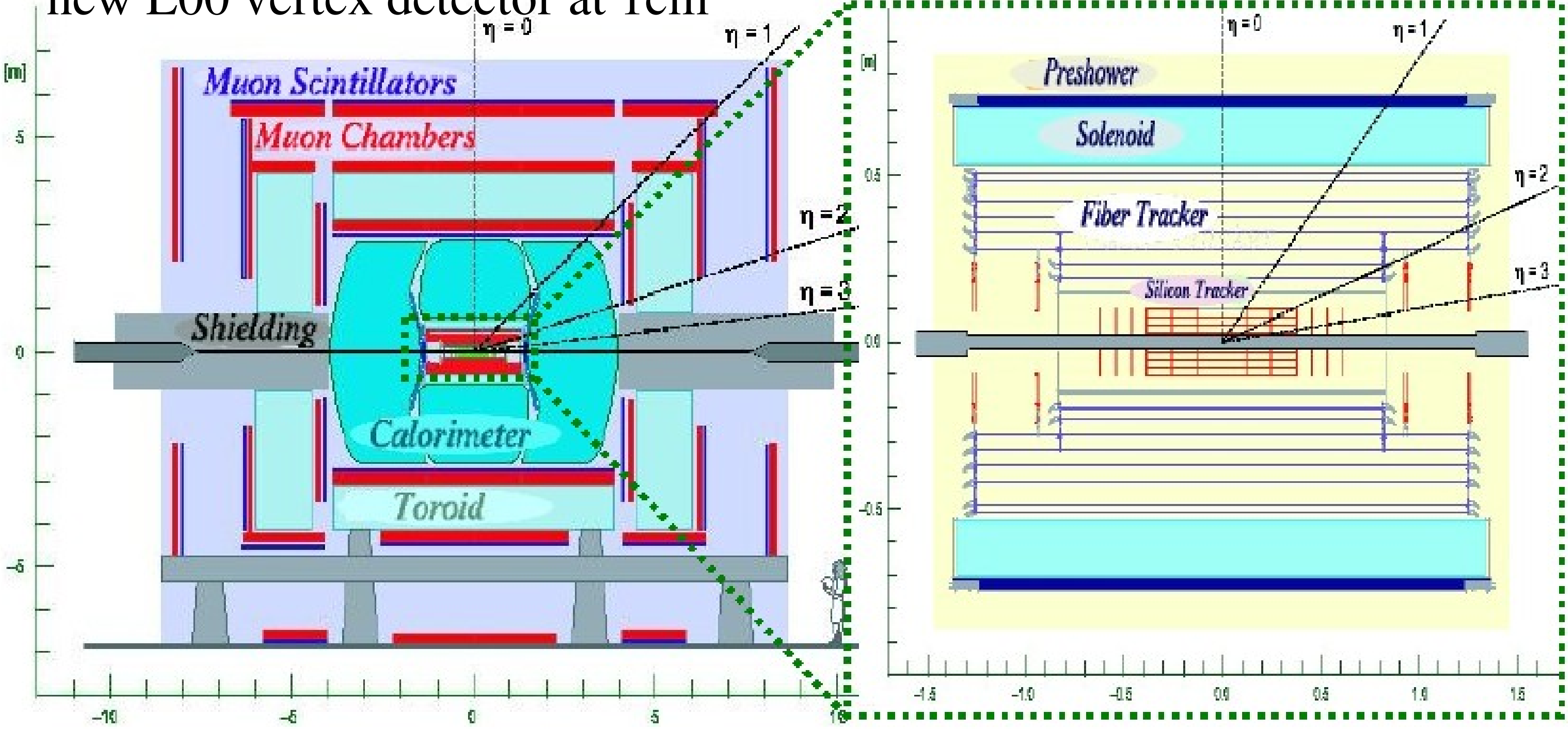


D0 detector

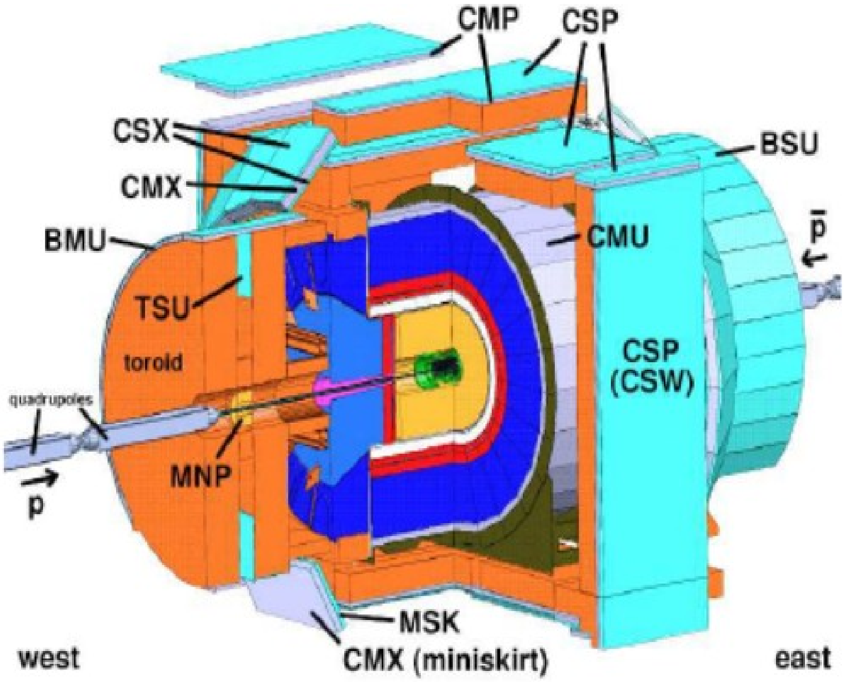
- Good coverage of Tracking and Muon system (|η|<2)
- Good calorimetry and electron identification
- High efficiency muon trigger.
- Silicon vertex Detector

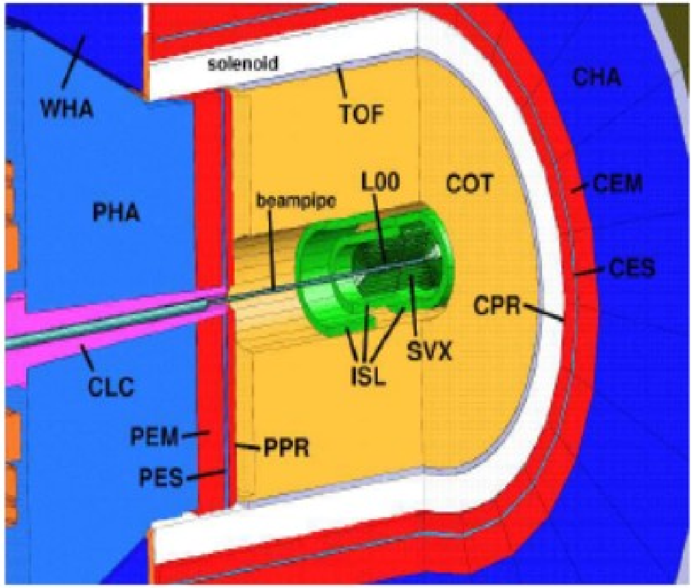
⇒ Good vertex resolution

new L00 vertex detector at 1cm



CDF detector





- Drift chamber (COT)

  ⇒ Good tracking resolution

  $\sigma(p_T)/p_T \sim 0.1\ \%\ \mathrm{GeV}^{-1}$
- Silicon vertex detector

  ⇒ Good vertex resolution

  ⇒ Important for triggering
- TOF detector and dE/dx from COT

  ⇒ Good particle identification
- Muon System up to $|\eta| < 1.5$

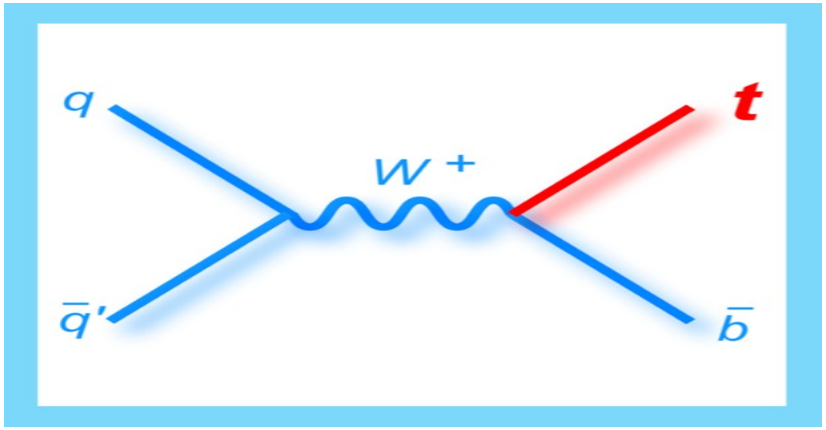
  ⇒ Important for triggering

Single top at the Tevatron

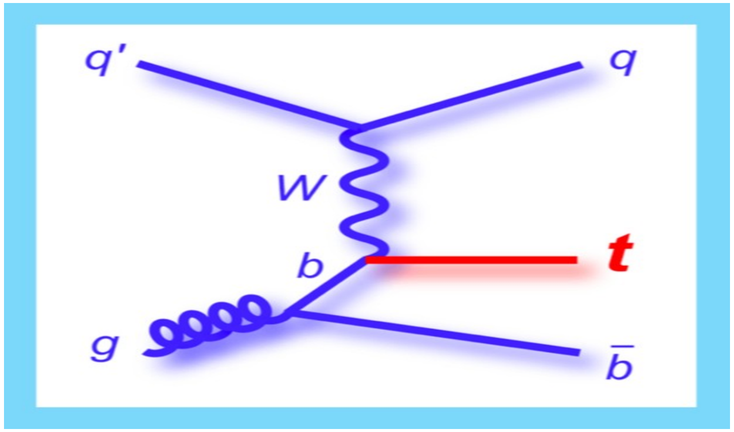
Single top: Introduction

At the Tevatron, top quarks are primarily produced in pairs via the strong interaction. The SM also predicts a single top quark prod. via electroweak interact.

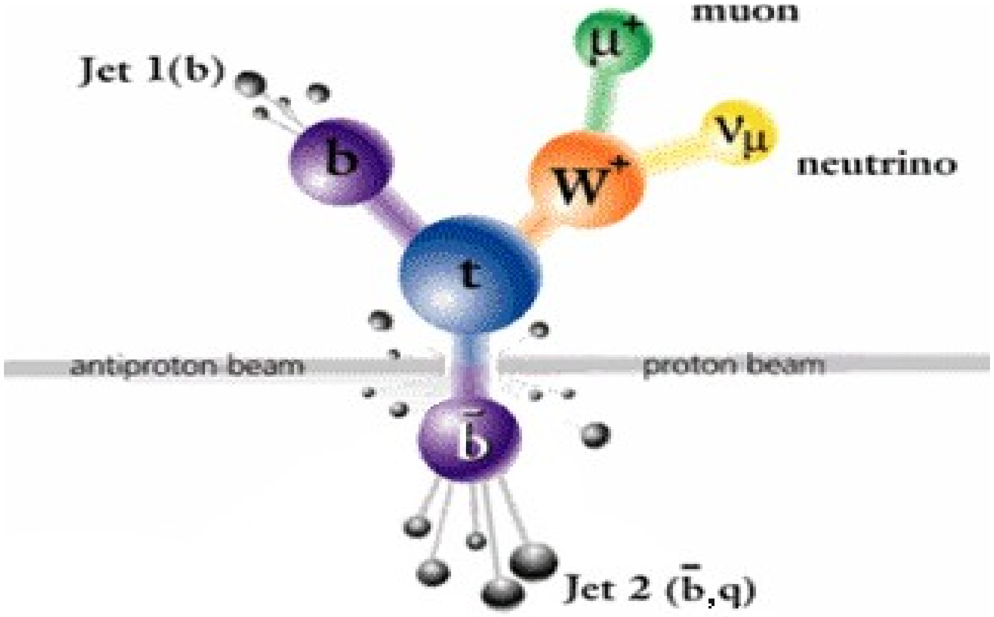
Two dominant single top production channels at the Tevatron :



tb (s-channel) SM σ ~1 pb,



tqb (t-channel) σ ~2 pb.



- $\sigma \sim |V_{tb}|^2$.
- New physics could enhance σ

Experimental signature:

lepton + missing E_t + b-tagging

D0 **Source**	Event Yields in 0.9 fb^{-1} Data Electron+muon, 1tag+2tags combined 2 jets	3 jets	4 jets
tb	16 ± 3	8 ± 2	2 ± 1
tqb	20 ± 4	12 ± 3	4 ± 1
$t\bar{t} \rightarrow ll$ (*)	39 ± 9	32 ± 7	11 ± 3
$t\bar{t} \rightarrow l$+jets	20 ± 5	103 ± 25	143 ± 33
$W+b\bar{b}$ (**)	261 ± 55	120 ± 24	35 ± 7
$W+c\bar{c}$	151 ± 31	85 ± 17	23 ± 5
W+jj	119 ± 25	43 ± 9	12 ± 2
Multijets (***)	95 ± 19	77 ± 15	29 ± 6
Total background	686 ± 41	460 ± 39	253 ± 38
Data	697	455	246

CDF Yields (preliminary) [1.5 fb^{-1}]

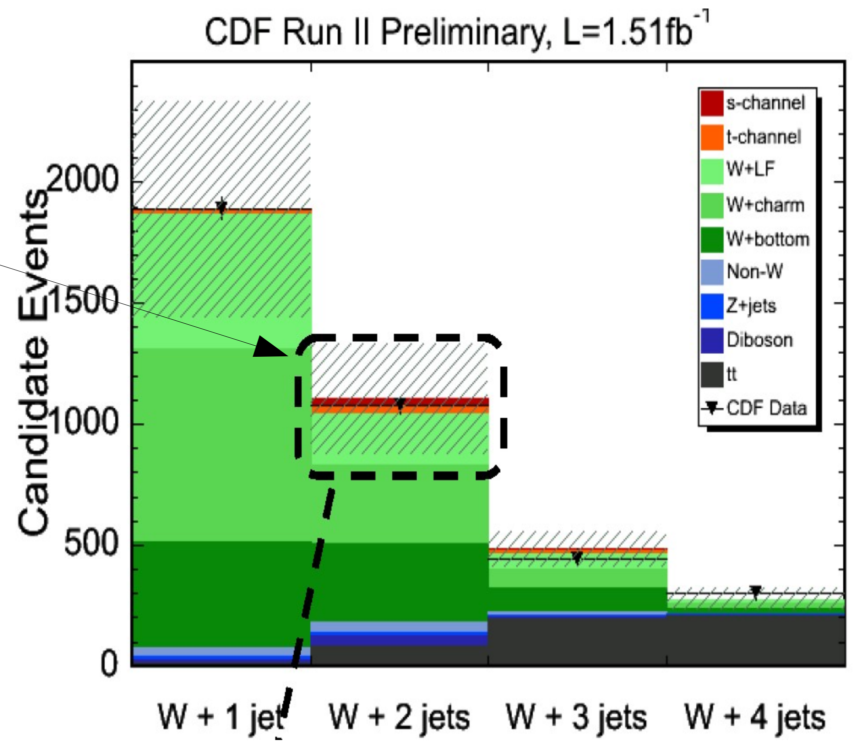
2 jets

s-channel	23.9	±	6.1
t-channel	37.0	±	5.4
Single top	60.9	±	11.5
tt	85.3	±	17.8
Diboson	40.7	±	4.0
Z + jets	13.8	±	2.0
W + bottom	319.6	±	112.3
W + charm	324.2	±	115.8
W + light	214.6	±	32.2
Non-W	44.5	±	17.8
Total background	1042.8	±	218.2
Total prediction	1103.7	±	230.9
Observed	1078		

Using 2,3,4 jets to increase acceptance

Single top hidden behind background uncertainty!

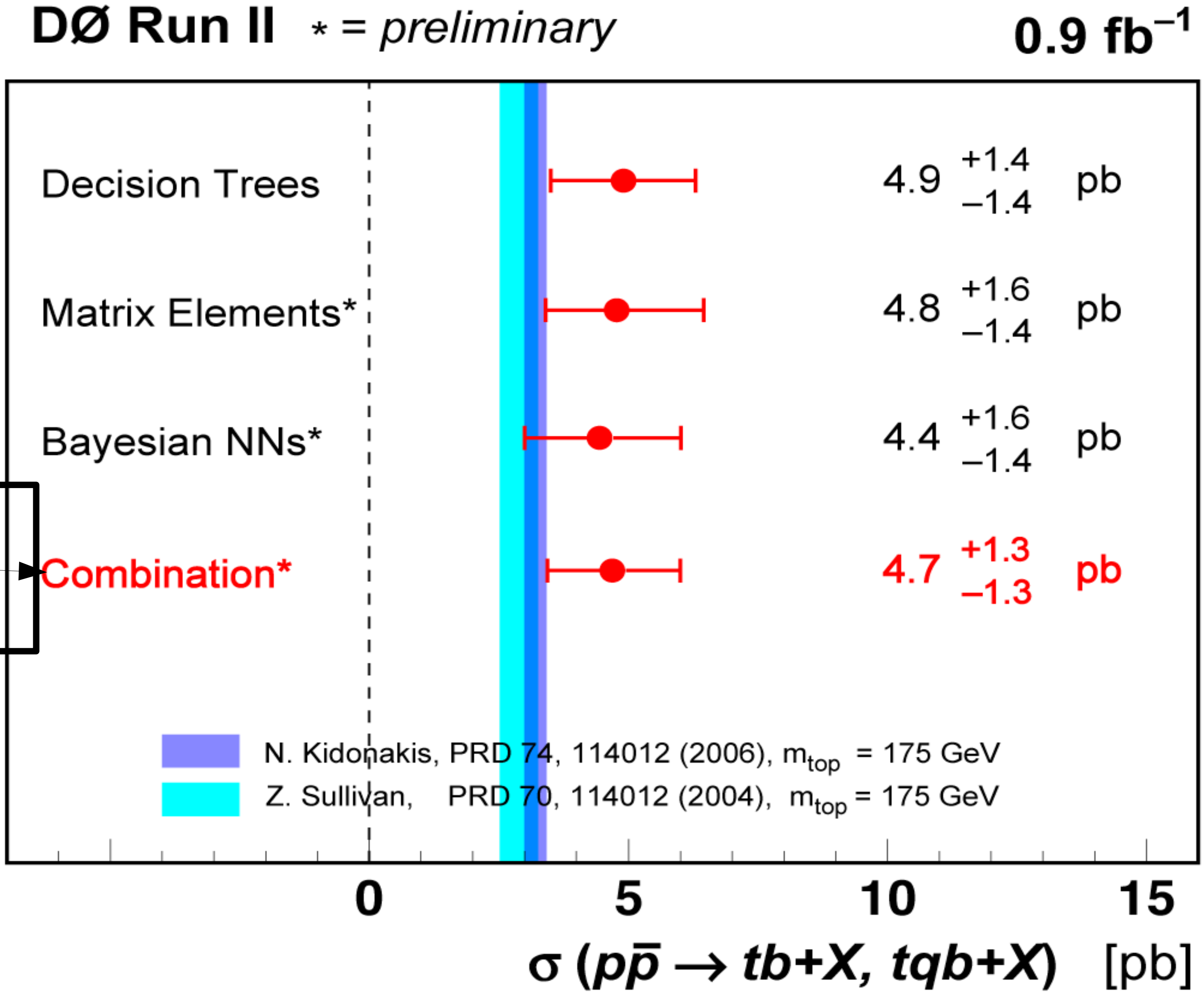
- Makes counting experiment impossible!
- Multivariate Techniques necessary



(*) from Alpgen, normalized to NNLO SM σ = 6.7 pb
(**) shapes from Alpgen, normalized to data before tagging
(***) QCD from data

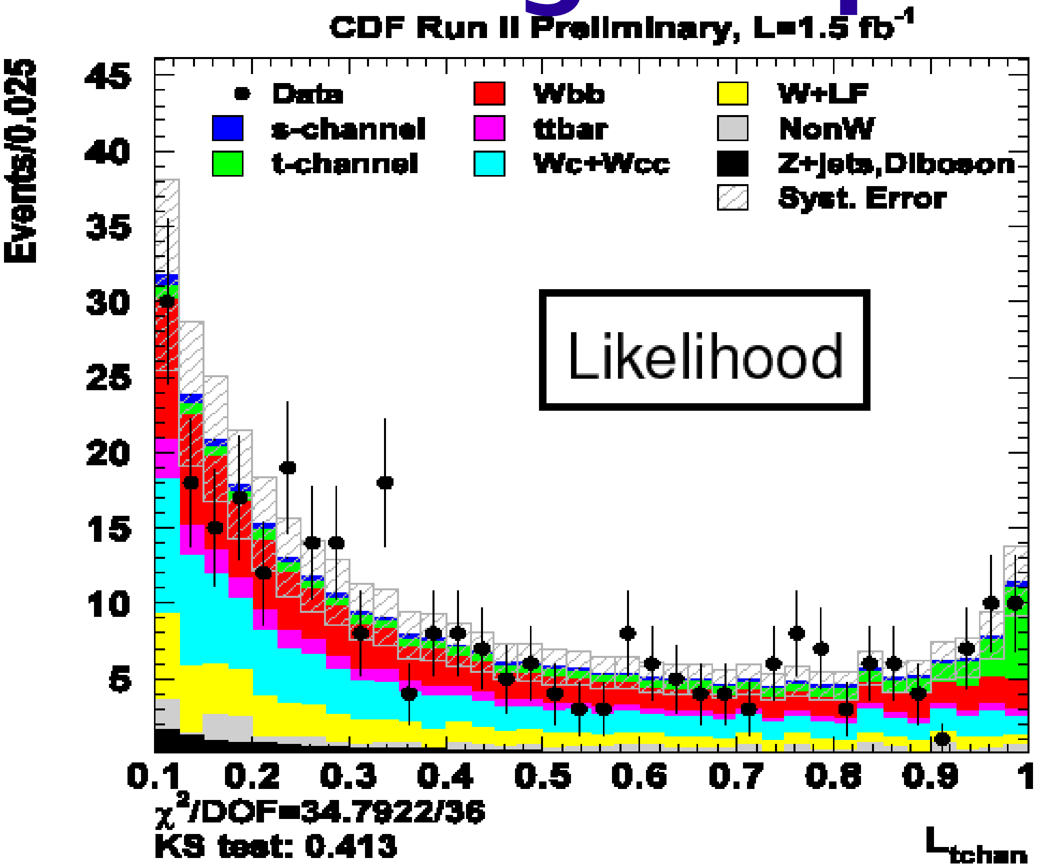
Single top : D0 Results

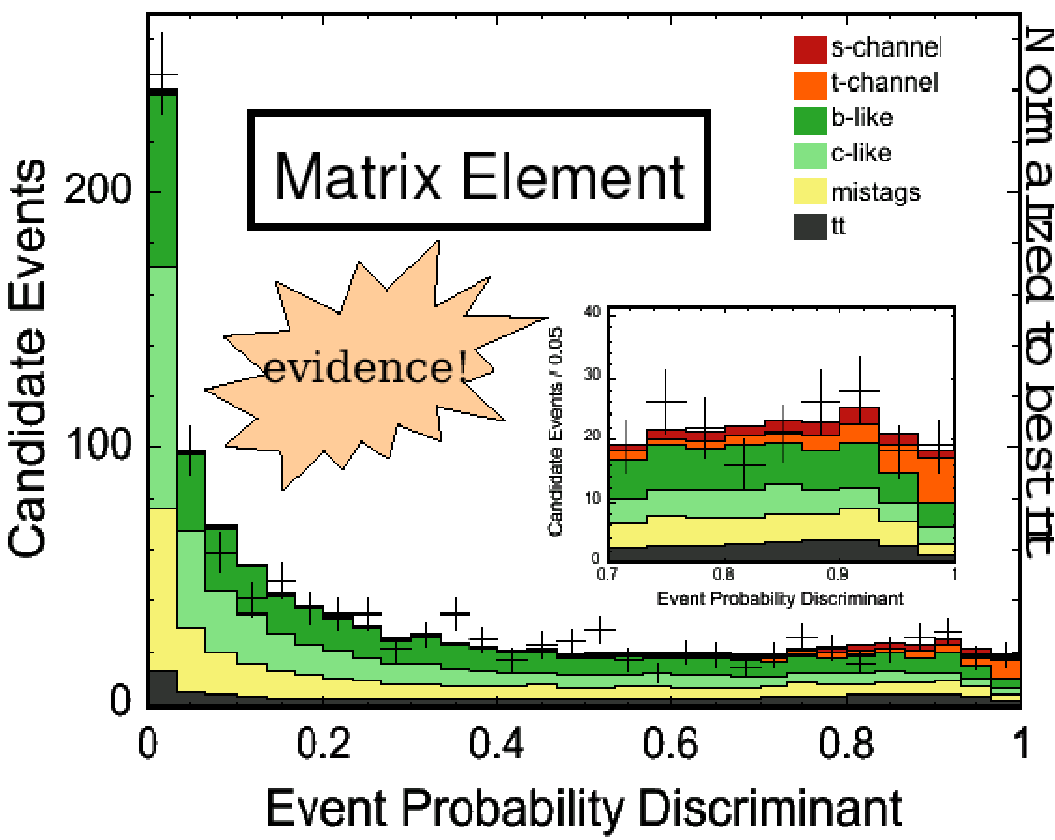
D0 applied three independent multivariate discriminants to the data and their results were combined to obtain a 3.5σ sigma evidence.



3.5 σ evidence →

Single top : CDF Results





Observed p-value = 0.31% / 2.7σ

Expected p-value = 0.20% / 2.9σ

$\sigma_{s+t} = 2.7^{+1.3}_{-1.1}$ pb

$\sigma_{s} = 1.1^{+1.4}_{-1.1}$ pb

$\sigma_{t} = 1.3^{+1.2}_{-1.0}$ pb

Observed p-value = 0.09% / 3.1σ

Expected p-value = 0.13% / 3.0σ

$\sigma_{s+t} = 3.0^{+1.2}_{-1.1}$ pb

$\sigma_{s} = 1.1^{+1.0}_{-0.8}$ pb

$\sigma_{t} = 1.9^{+1.0}_{-0.9}$ pb

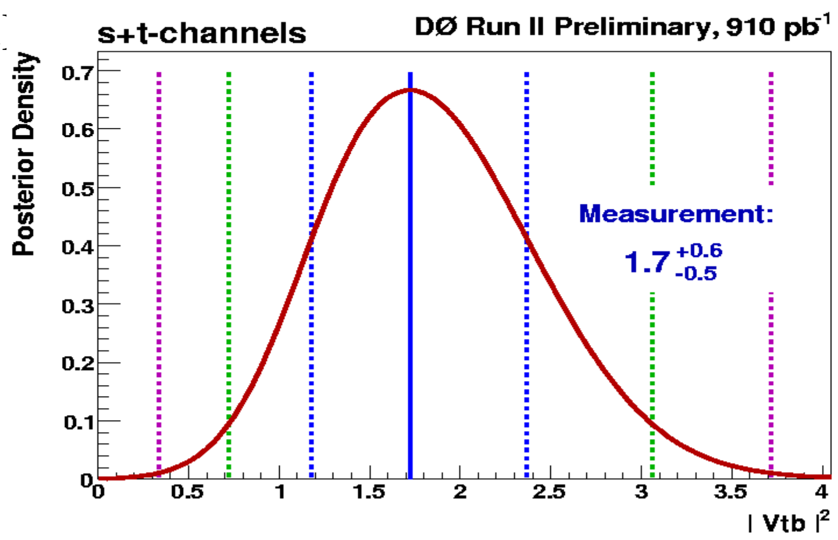
|Vtb| Measurement (from D0,CDF)

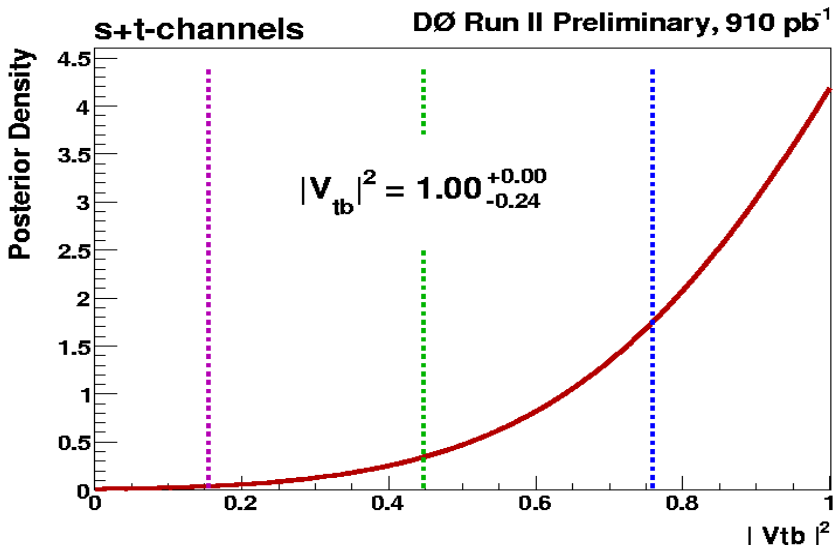
The decision tree measurement of the tb+tqb cross section of D0 is used to derive a first direct measurement of the strength of the V-A coupling $|V_{tb} f^L|$ in the Wtb vertex, where f^L is an arbitrary left-handed form factor. $|V_{tb} f^L| = 1.3 \pm 0.2$. CDF measures 1.02 ± 0.18

These measurement assumes $|V_{td}|^2 + |V_{ts}|^2$ $|V_{tb}|^2$ and a pure V-A and CP-conserving Wtb interaction. Assuming in addition that $f^L=1$(SM) and using a flat prior for $|V_{tb}|^2$ from 0 to 1,

D0 obtains: $0.68 < |V_{tb}| \leq 1$

at 95% C.L. These measurements make no assumptions about the number of quark families or C



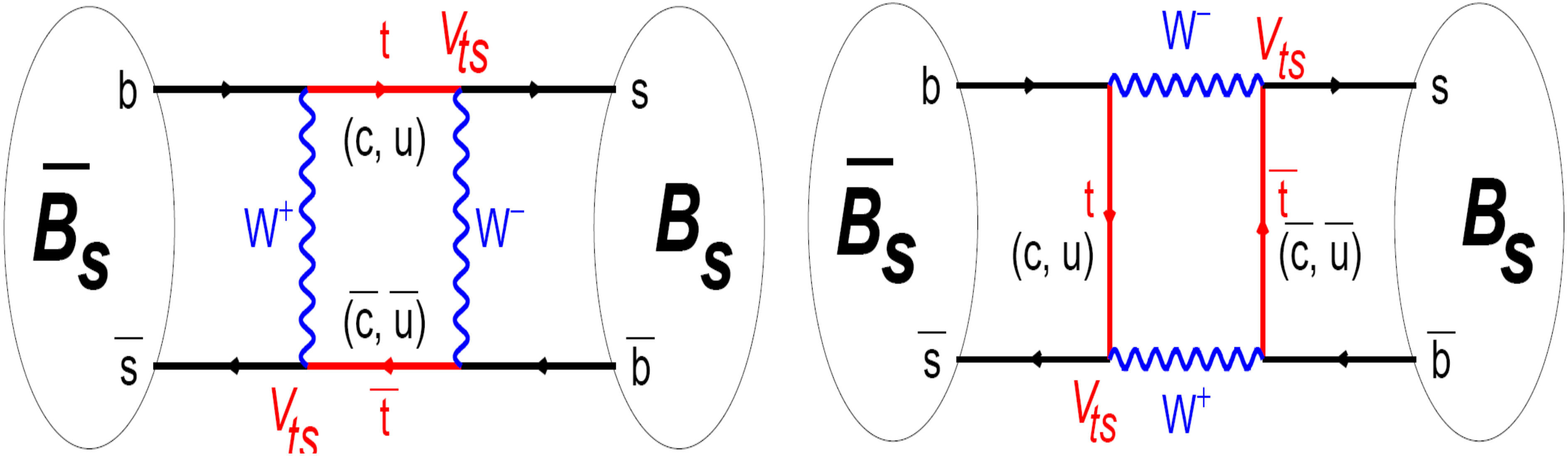


CDF obtains $|V_{tb}| > 0.5$ at 95% C.L.

Bs mixing at the Tevatron

Introduction

Neutral B mesons experience virtual transitions in the corresponding anti-particle



↔ In SM described by "box diagrams"→ **measure $|V_{ts(d)}|$**

↔ **$\Delta m_{s(d)} \sim |V_{ts(d)}|$; Δ m ratio** measures one side of the unitarity triangle (many uncertainties cancel in the ratio):

$$\frac{\Delta m_s}{\Delta m_d} = \frac{m_{B_s}}{m_{B_d}} \xi^2 \left| \frac{V_{ts}}{V_{td}} \right|^2 \qquad \xi = 1.210 ^{+0.047}_{-0.035}$$

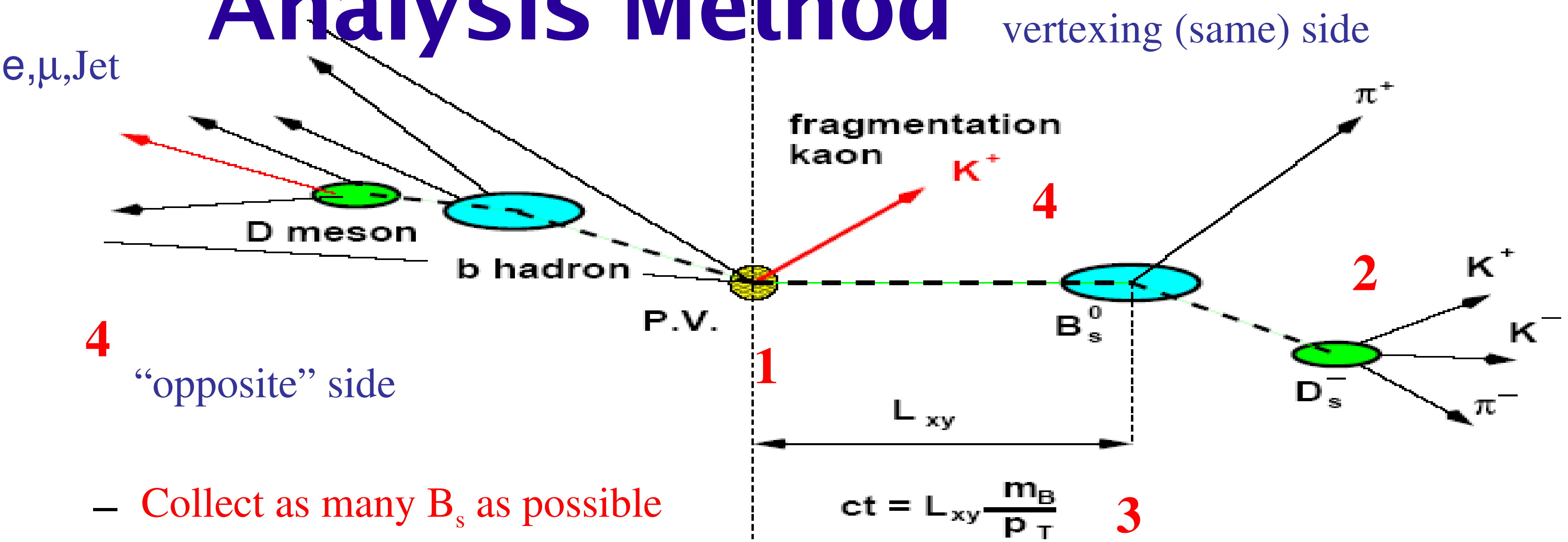
known at ~4 %

(hep-lat/0510113)

- $|V_{ts}|/|V_{td}|$ can be determined at~4%

New physics can influence oscillation frequency → test of the standard model

Analysis Method



- Collect as many B_s as possible
  - Tevatron, Trigger:select tracks from displaced vertices (high purity) and single inclusive muons (semileptonics: high statistics)
- Extract Signal
  - B_s flavor at decay inferred from decay products
- Measure proper decay time of the B_s meson
  - L00, per event primary vertex, candidate specific decay time resolution
- Determine B_s flavor at production (flavor tagging)
  - PID (TOF, dE/dx)
  - Flavor tag quantified by Dilution: D=1-2w, w = mistag probability
- Measure oscillation frequency (asymmetry between unmixed and mixed events) vs t

$$A(t) = \frac{P_{nomix} - P_{mix}}{P_{mix} + P_{nomix}} = D\cos(\quad m\cdot t)$$

- <u>In practice</u>: perform likelihood fit to expected unmixed and mixed distributions

Key Experimental Issues

Uncertainty on Amplitude

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

Signal size S

efficient tracking,
displaced track trigger

Signal to Background $\sqrt{\frac{S+B}{S}}$

excellent mass resolution
Particle ID: TOF, dE/dx

Production flavor Tag performance ϵD^2

lepton id, Kaon id with TOF

Proper time Resolution $e^{(\Delta m_s \sigma_t)^2/2}$

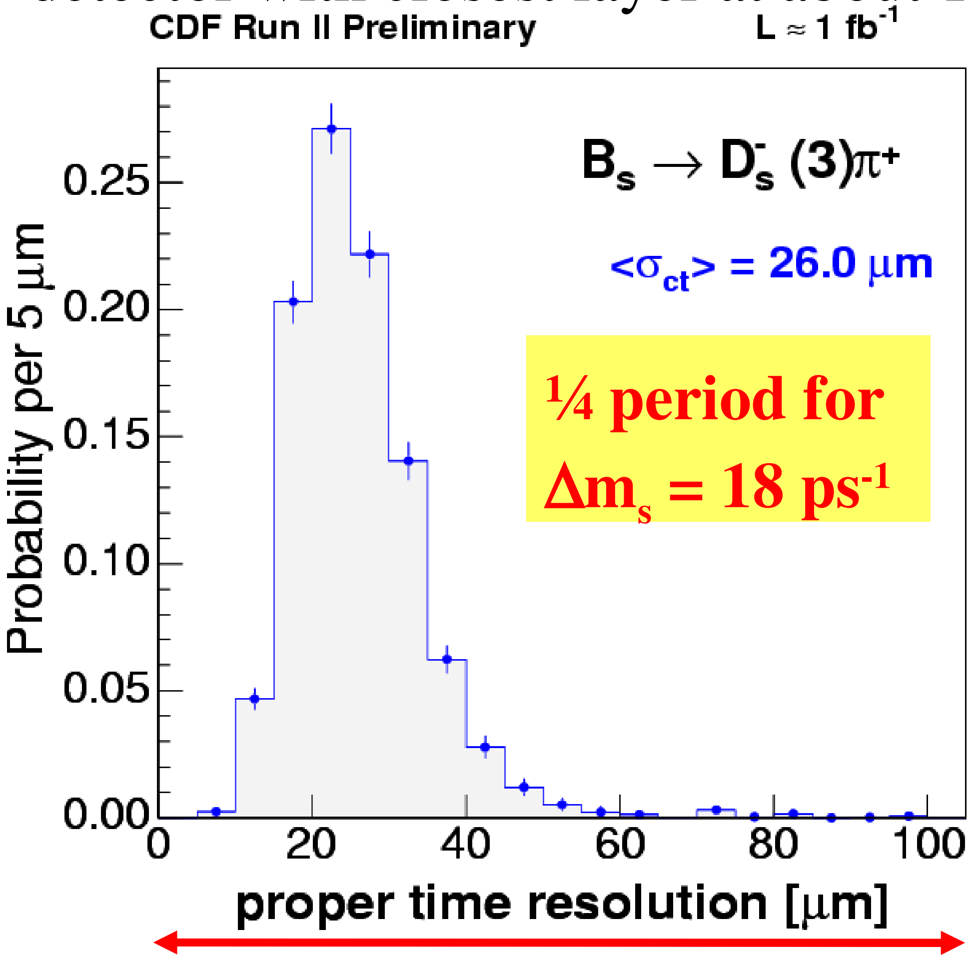
Silicon on beampipe (Layer 00)

$$(\sigma_t)^2 = \left(\frac{m}{p}\delta L\right)^2 \oplus \left(t\frac{\delta p}{p}\right)^2$$

Fully reconstructed signal crucial

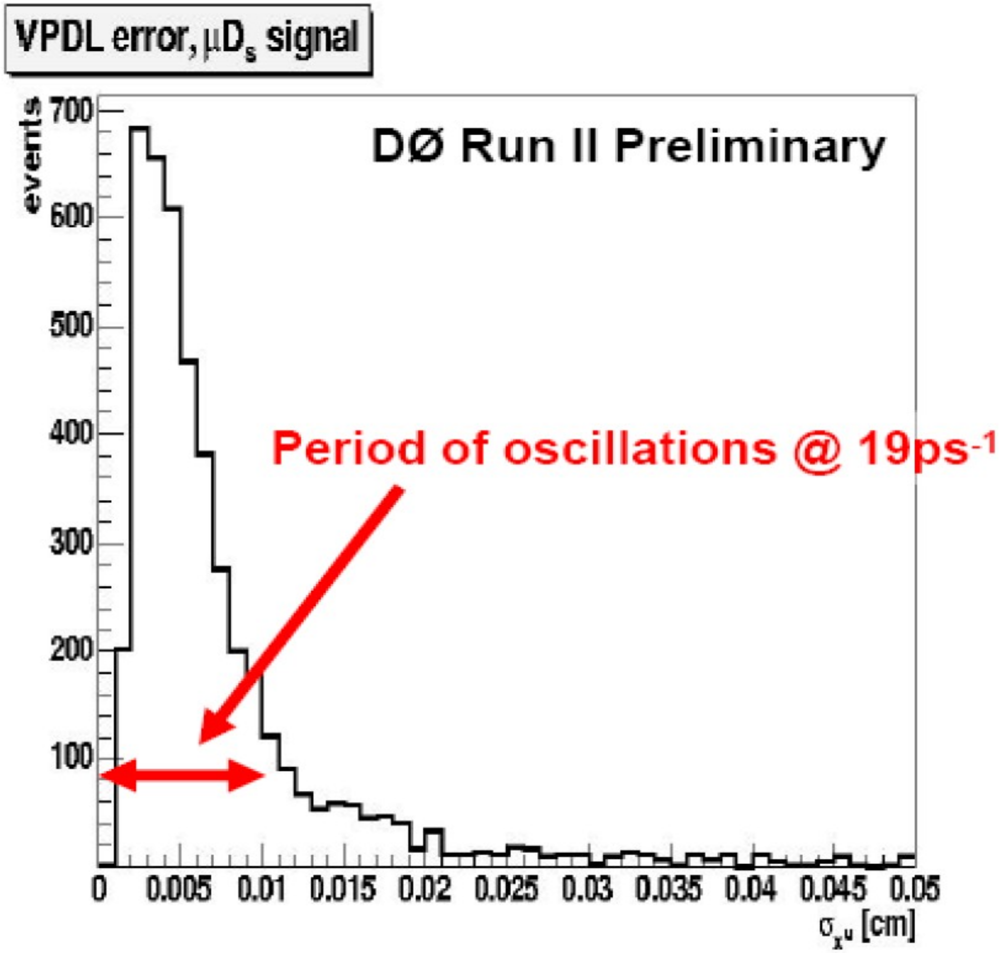
Proper Time Resolution:

Requires good tracking as close as possible to the interaction point. CDF/D0 have good tracking with large drift chamber followed by silicon detector with closest layer at about 1cm for good vertex resolution



¼ period for $\Delta m_s = 18$ ps^{-1}

Oscillation period for $\Delta m_s = 18$ ps^{-1}

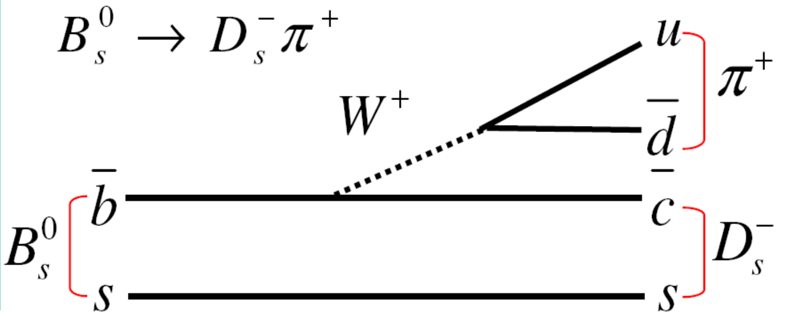


Period of oscillations @ 19ps^{-1}

Good decay time resolution improves sensitivity for Δm_s

In the Δm_s fit each event weighted by its resolution

Data sample. Example: Fully Reconstructed Signal

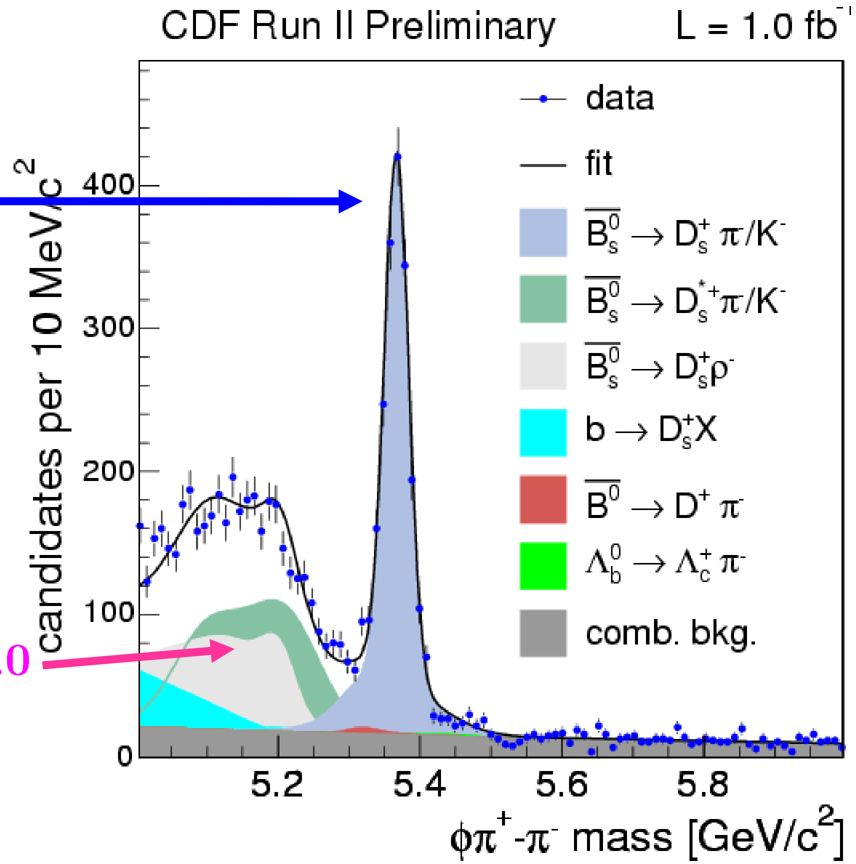


Cleanest decay sequence

$$\bar{B}_s^0 \to D_s^+ \pi^-$$

$$D_s^+ \to \phi \pi^+$$

$$(D_s^+ \to K^{*0} K^+, \pi^+\pi^-\pi^+)$$



Add partially reconstructed decays:

$D_s^{*+}\pi^-$ $D_s^+\rho^-$ missing γ or π^0

Also use 6 body modes:

$$\bar{B}_s^0 \to D_s^+ \pi^-\pi^+\pi^-, \; D_s^+ \to \phi\pi^+, K^{*0}K^+, \pi^+\pi^-\pi^+$$

Flavor specific modes, to get b flavour at decay

Flavor tagging performances

Estimate flavour at production from the rest of the event

Two types of flavor tags used

- OST: produce bb pairs: find 2nd b, determine flavor, infer flavor of 1st b
  - calibrated on large samples of B^0 ad B^+ decays
- SST: use charge correlation between the b flavor and the leading product of b hadronization (the other s quark not in the B_s will create a K)
  - performances (D) evaluated in MC, after extensive comparison data VS MC

Performance	εD^2 (Hadronic) [%]	εD^2 (semil.)
• OST (D0) :	-	4.5 ± 0.9 (stat)
• OST (CDF) :	1.8 ± 0.2 (stat)	1.8 ± 0.2 (stat)
• SST (CDF) :	3.5 ± 1.0 (stat)	4.8 ± 1.0 (stat)
• SST (D0) :	-	1.7 ± 0.6 (stat)

Same-side kaon tag increases effective statistics × ~4

Results(CDF)

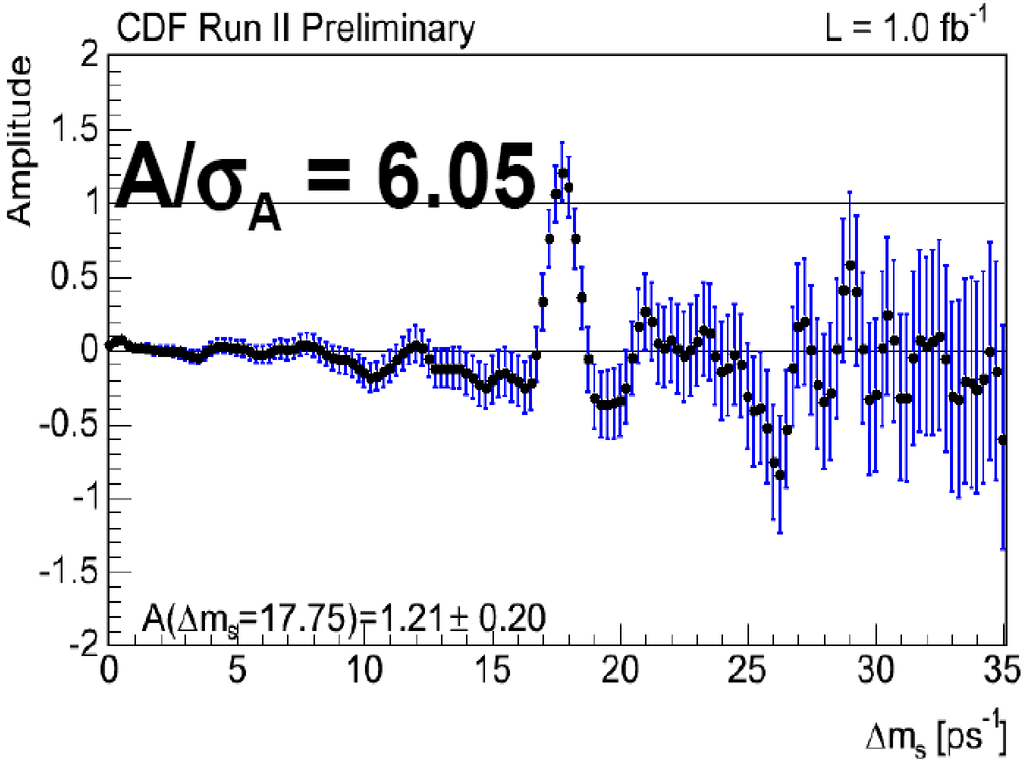
$$P_s(t,\xi,\sigma_t) \propto (1/\tau)(1+\xi A D\cos(\Delta m_s t))/(1+|\xi|)e^{-t/\tau}$$

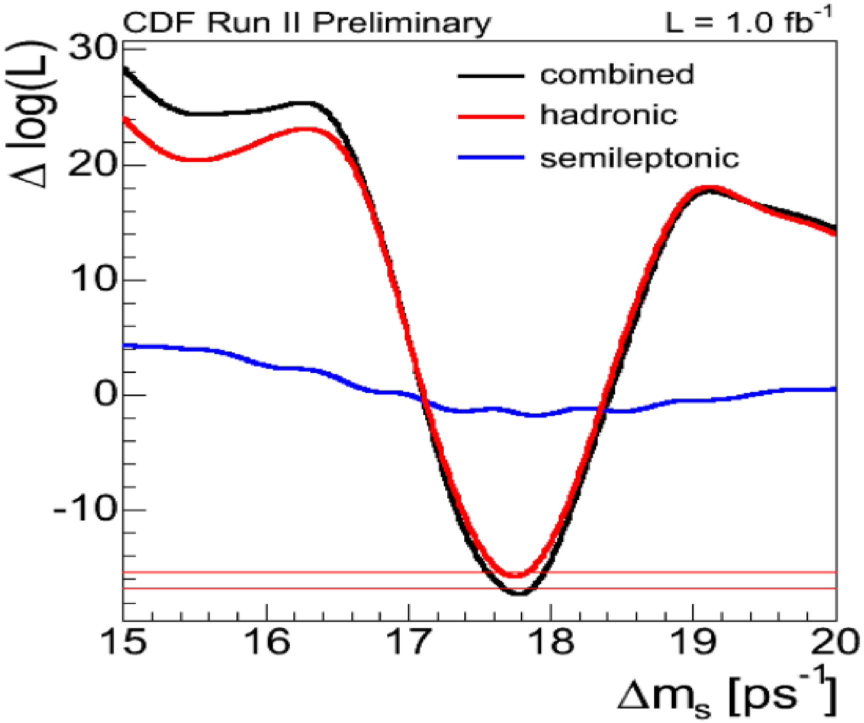
- fit only amplitude(A) and fix frequency (Δm_s)
- scan through frequencies

Fourier Analysis which should have maximum at true oscillation frequency

Unbinned maximum likelihood fit >5σ significance :

$\Delta m_s = 17.77 \pm 0.10 \pm 0.07\ \mathrm{ps}^{-1} \rightarrow |V_{td}/V_{ts}| = 0.2060 \pm 0.007\ (\mathrm{exp})\ ^{+0.008}_{-0.006}(\mathrm{theo.})$

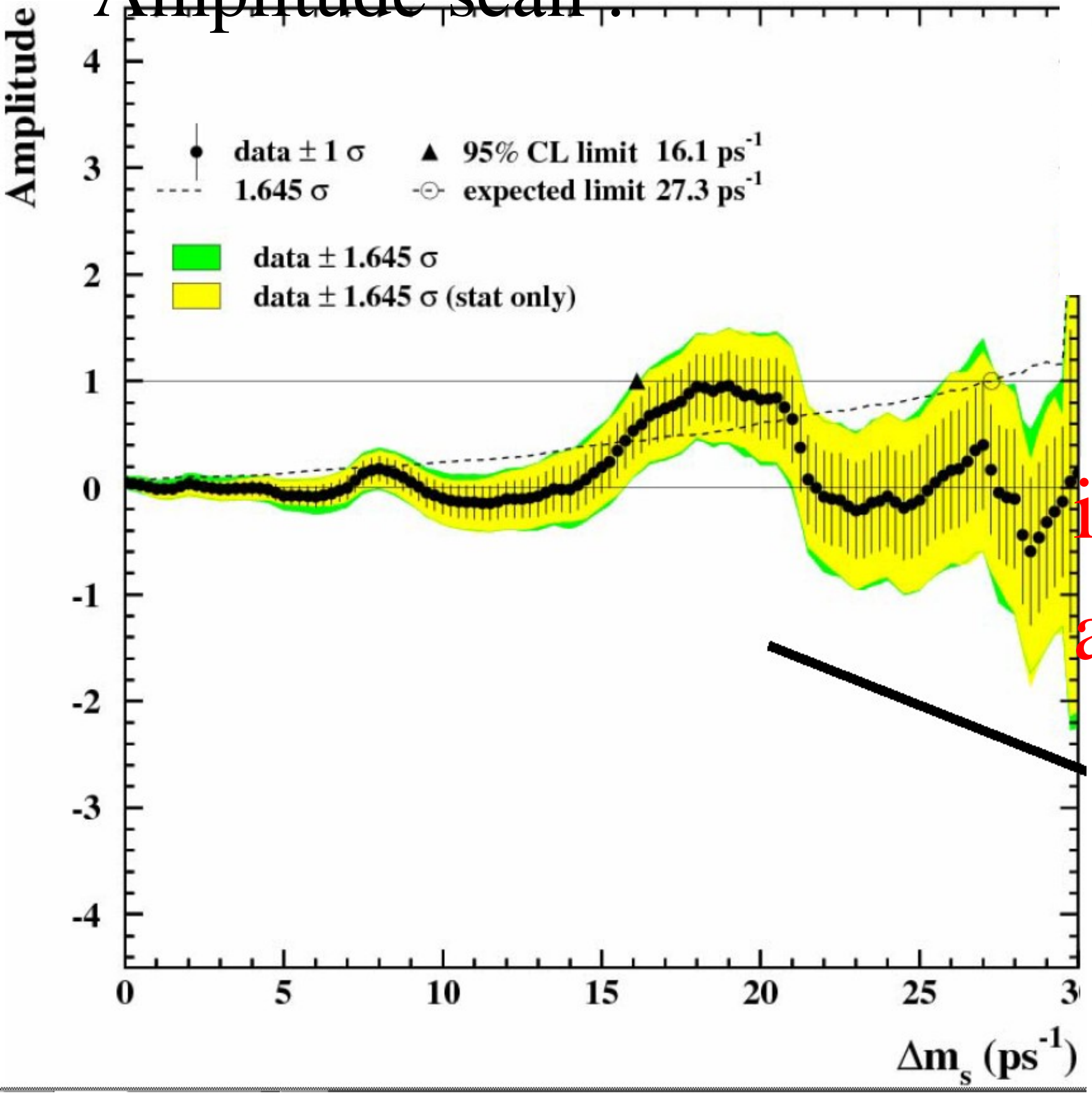


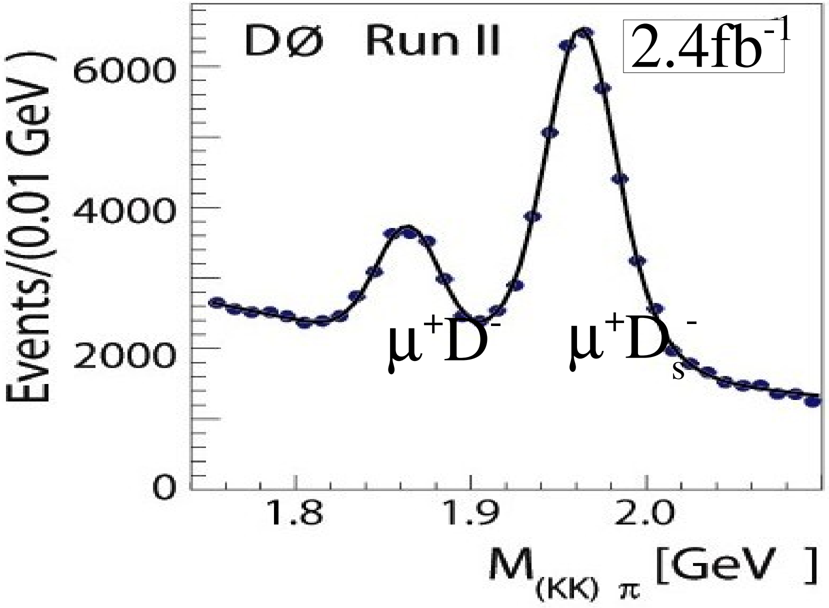


Results (D0)

Semileptonic decay of B^0_s

Amplitude scan :





2.5σ deviation from 0 in the Amplitude scan at $\Delta m_s = 19\ \mathrm{ps}^{-1}$

Δm_s :$18.6 \pm 0.8\ \mathrm{ps}^{-1}$

Studies of CP violation in Bs decays

Introduction

3 types of CP violation : direct, mixing, interference. Each of them needs different physics requirements. In this talk we will cover two types

- Direct CP violation in B^0_s K$^-\pi^+$

  Interesting case of large direct CP violation predicted under the SM. Observation of this decay offers a unique opportunity of checking for the SM origin of direct CP violation when combined with analogous measurement in B K$^-\pi^+$ decay .

- CP violatoin in mixing in B$^0_s \rightarrow J/\psi\ \phi$
  - $\Delta\Gamma_s$ and ϕ_s CP violating phase (untagged analysis).
  - ϕ_s tagged analysis

EW sym. breaking => Weak(B^0_s) ≠ Mass (B$_{H,L}$)≠ CP Eigenstates(B$_{even,odd}$)

$$|B_s\rangle = (\bar{b}s);\ \ |\bar{B}_s\rangle = (b\bar{s})$$

$$i\frac{\partial}{\partial t}\begin{pmatrix}|B_s^0(t)\rangle\\ |\bar{B}_s^0(t)\rangle\end{pmatrix} = \left(M - i\frac{\Gamma}{2}\right)\begin{pmatrix}|B_s^0(t)\rangle\\ |\bar{B}_s^0(t)\rangle\end{pmatrix} \longrightarrow$$

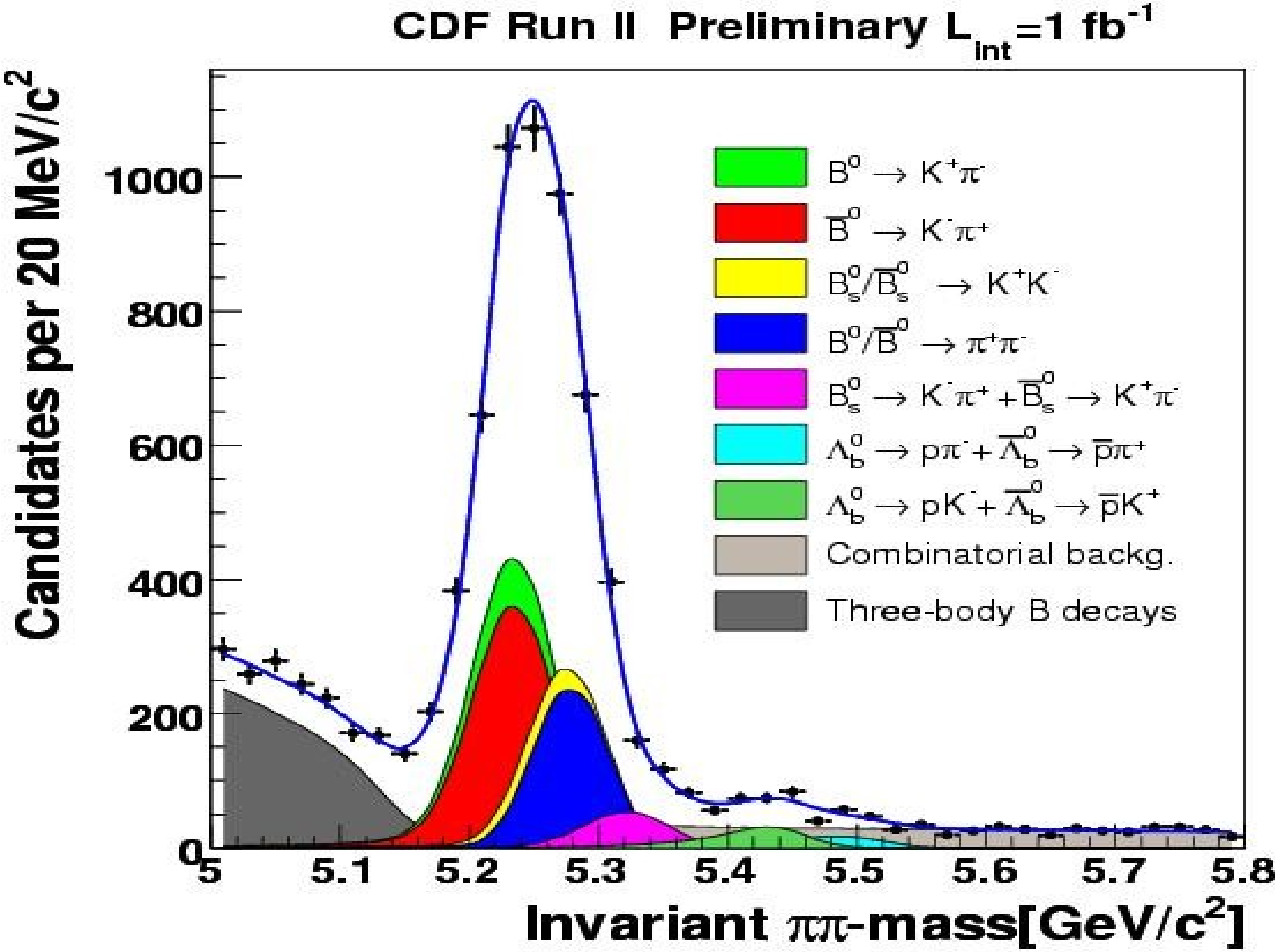
$$|B_H(t)\rangle = p|B_s(t)\rangle + q|\bar{B}_s(t)\rangle = |B_H(t=0)\rangle e^{-iM_H t - \frac{1}{2}\Gamma_H t}$$

$$|B_L(t)\rangle = p|B_s(t)\rangle - q|\bar{B}_s(t)\rangle = |B_L(t=0)\rangle e^{-iM_L t - \frac{1}{2}\Gamma_L t}$$

Observables: $\Delta m_s = M_H - M_L$, $\Delta\Gamma_{CP} = \Gamma_{even} - \Gamma_{odd}$, $\Delta\Gamma_s = \Gamma_H - \Gamma_L = \Delta\Gamma_{CP}\cos\phi_s$

ϕ_s~1% in SM => mass and CP states close, sensitive to new physics

First measurement a of a direct CP asymmetry $A_{CP}(B^0_s$ K^- π^+) in a B^0_s decay



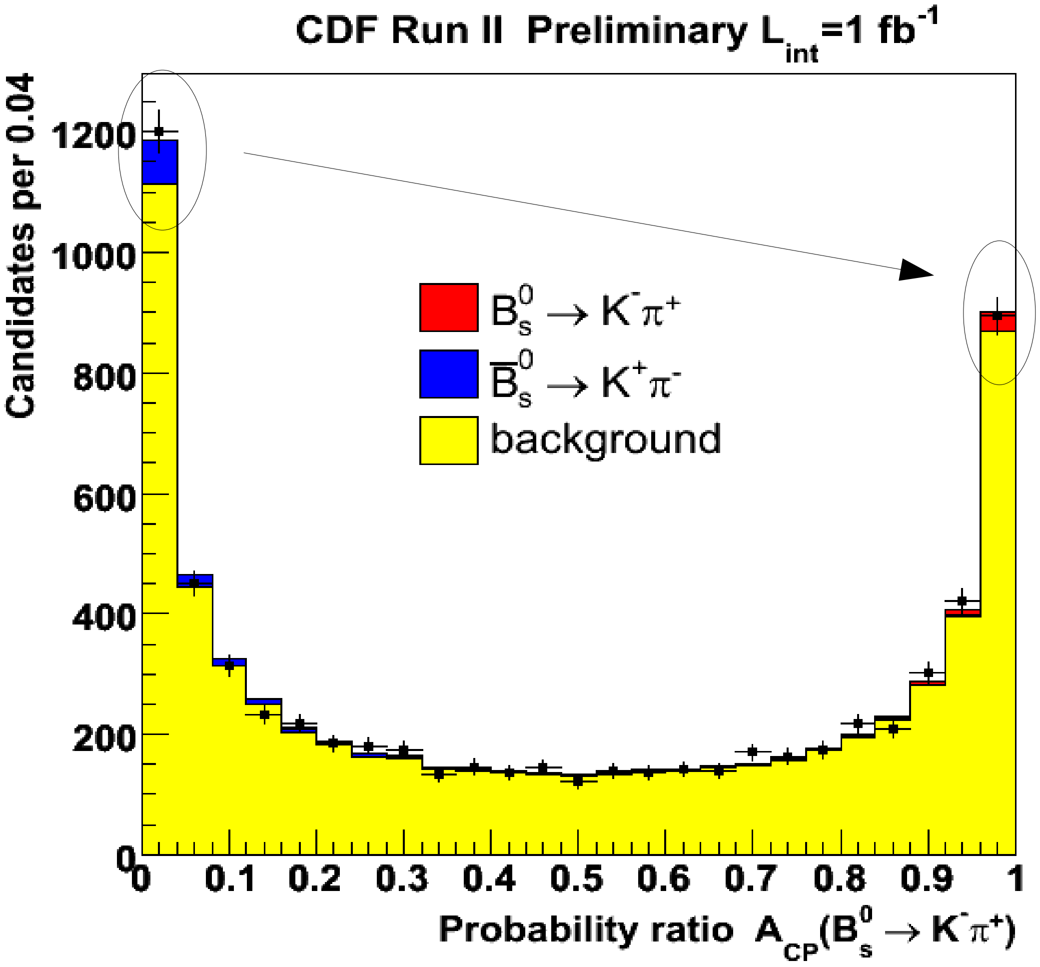
Observed for the first time three new rare charmless modes:

B^0s $K^-\pi^+$, ${}^0_b$ p ${}^-$and ${}^0_b$ pK$^-$

The significance for these rare modes is: 8 , 6   and 11   respectively

First measurement a of a direct CP asymmetry $A_{CP}(B^0_s\ \ K^-\pi^+)$ in a B^0_s decay

This mode is a self tagging mode, thus CDF measured its direct CP asymmetry :



A_{CP}= 0.39 ± 0.15 (stat.) ± 0.08 (syst.)

2.5 σ

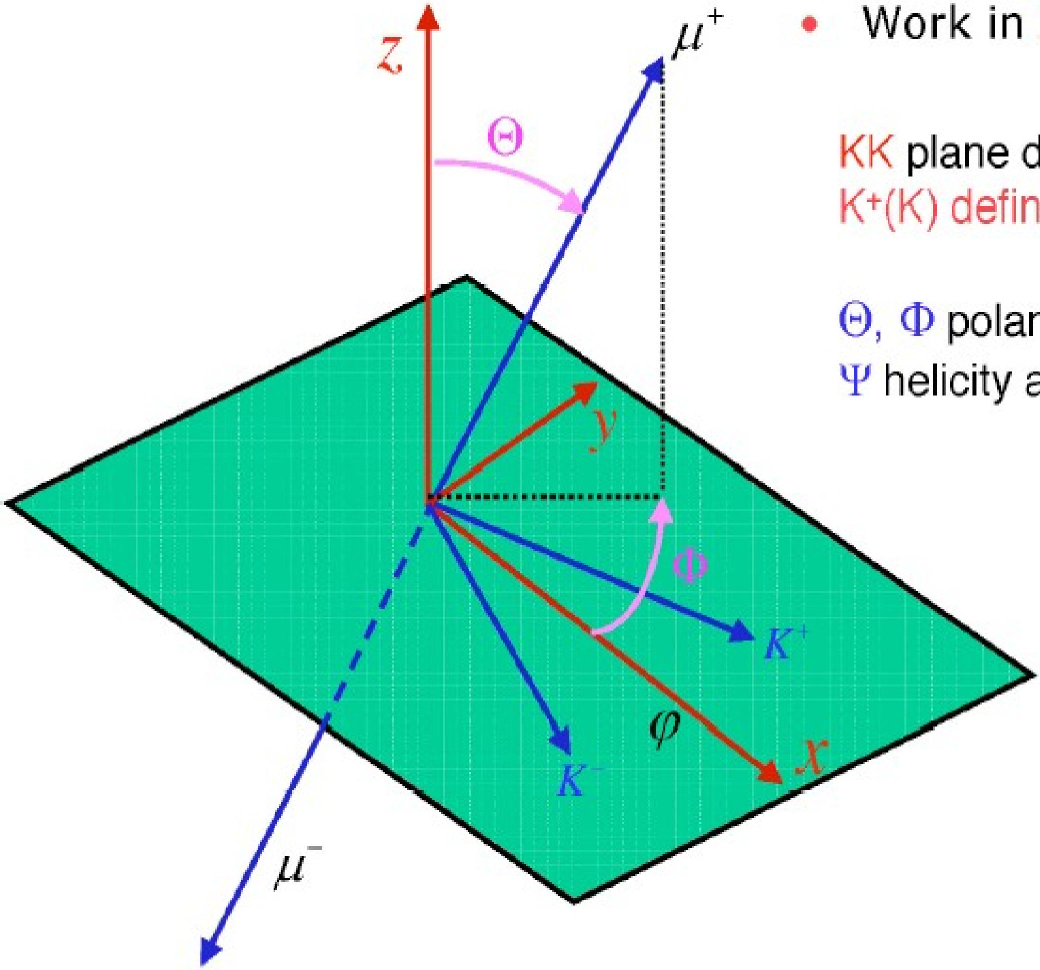
$$\frac{\Gamma(\overline{B}^0 \to K^-\pi^+) - \Gamma(B^0 \to K^+\pi^-)}{\Gamma(B^0_s \to K^-\pi^+) - \Gamma(\overline{B}^0_s \to K^+\pi^-)}$$

$$= 0.84 \pm 0.42\ (\text{stat.}) \pm 0.15\ (\text{syst.})$$

- first measurement of CPV in the Bs mesons system ; 2.5 apart from 0
- The measurement is in agreement with the Standard Model expectation

$\Delta\Gamma_s$ and ϕ_s from $B^0_s \to J/\psi\,\phi$

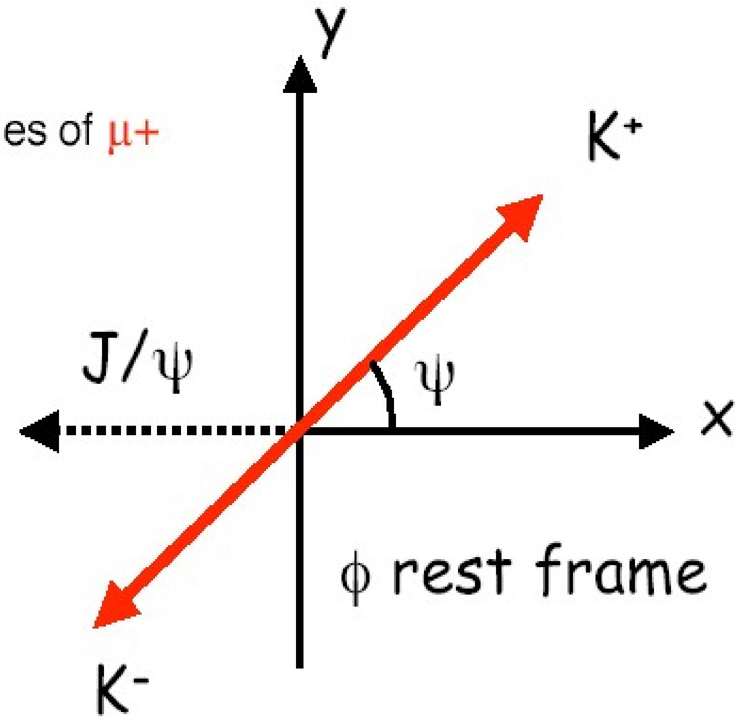
- Directly measure lifetimes in $B^0_s \to J/\psi\,\phi$
- Separate CP states by angular distribution and measure lifetimes
- Simultaneous fit of mass, lifetime, time dependent angular distributions
- Extract $\Delta\Gamma_s$, ϕ_s , CP even, CP odd amplitudes and strong phases



- Work in J/Ψ rest Frame

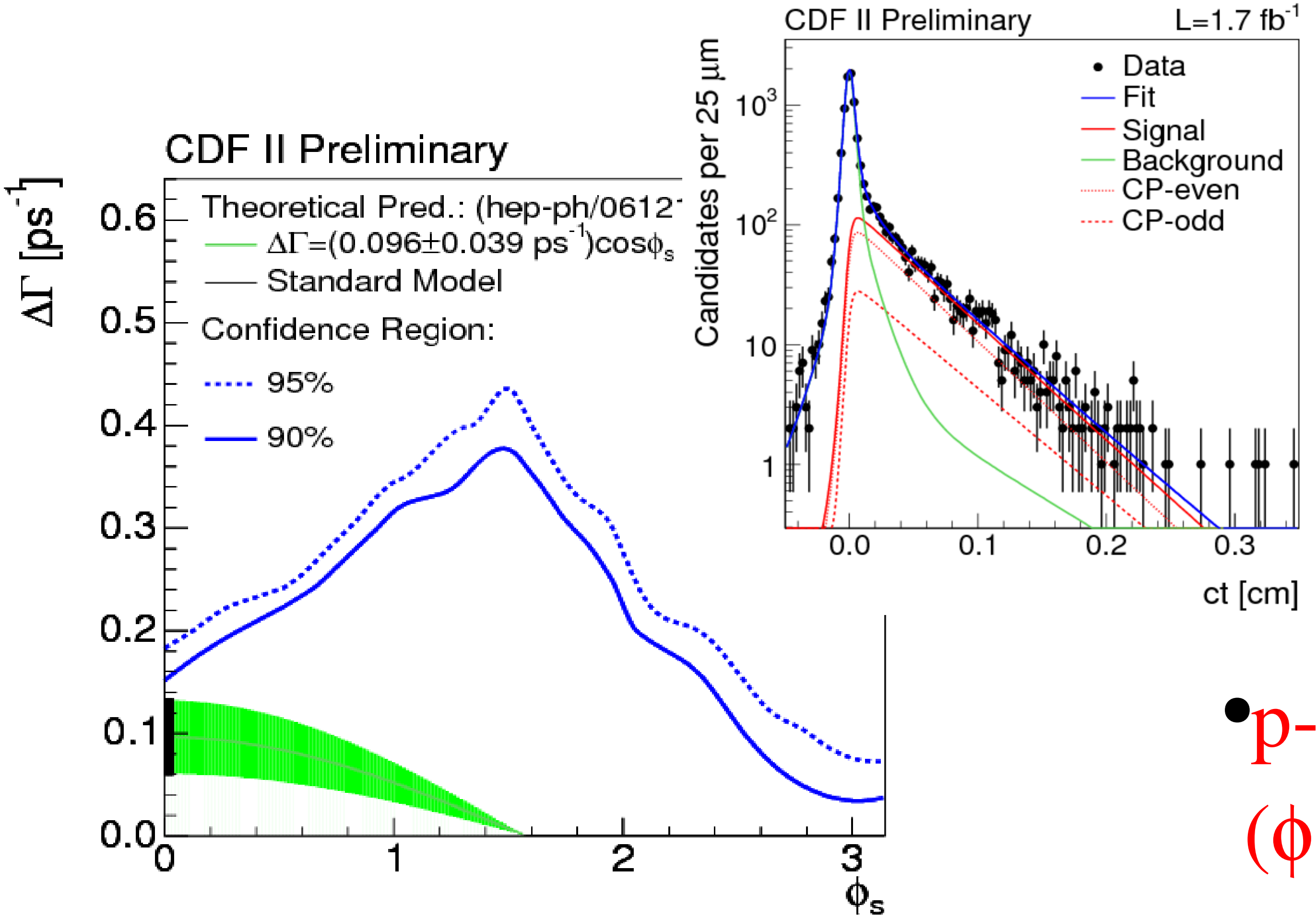
KK plane defines (x,y) plane
K^+(K) defines +y direction

Θ, Φ polar & azimuthal angles of $\mu+$
Ψ helicity angle of ϕ (K*)



Results for $\Delta\Gamma_s$ and ϕ_s

Observable	CDF (1.7 fb^{-1})	D0 (1.1 fb^{-1})	D0 ϕ_s free
$N(B^0_s)$	2506 ± 51	1039 ± 45	
$\Delta\Gamma_s$ (ps^{-1})	$0.076^{+0.059}_{-0.063} \pm 0.006$	$0.12^{+0.08}_{-0.03} \pm 0.02$	0.17 ± 0.09
$< \tau >$ (ps^{-1})	$1.52 \pm 0.04 \pm 0.02$	$1.52 \pm 0.08 ^{+0.01}_{-0.01}$	1.49 ± 0.08
ϕ_s	$\equiv 0$	$\equiv 0$	$-0.79 \pm 0.56^{+0.14}_{-0.10}$



Bias at low $\Delta\gamma_s,\phi_s$ observed in toy MC. Quote p-value and confidence region instead of point estim.

Define p-value as fraction $\#(R_{toy} > R_{data})/\#R_{toy}$

where

$$R(\Delta\Gamma_s,\phi_s)=\log \frac{L(\hat{\Delta\Gamma}_s,\hat{\phi}_s,\hat{\Theta})}{L(\Delta\Gamma_s,\phi_s,\hat{\Theta})}$$

^ → free parameter in fit

- p-value close to SM ($\phi_s = 0$, $\Delta\Gamma_s = 0.1$): 22%

Summary

Performed measurements of the CKM matrix elements at Tevatron:

- **CKM matrix element that describes the Wtb coupling** :

D0: $0.68 < |V_{tb}| \leq 1$ at 95% C.L. within the standard model.

CDF: $|V_{tb}| > 0.5$ at 95% C.L.

- **Observation of B_s Oscillations and precise measurement of Δm_s**

D0 : $\Delta m_s = 18.6 \pm 0.8\ \mathrm{ps}^{-1}\ (3.1\ \sigma)$

CDF: $\Delta m_s = 17.77 \pm 0.10\ (\mathrm{stat.}) \pm 0.07\ (\mathrm{syst.})\ \mathrm{ps}^{-1}$

Most precise measurement of $|V_{td}/V_{ts}|$

$$\left|\frac{V_{td}}{V_{ts}}\right| = 0.2060 \pm 0.0007\ (\mathrm{exp.})^{+0.0081}_{-0.0060}\ (\mathrm{theo.})$$

- First measurement of direct CP violation in the Bs mesons system ;

$A_{CP}(B^0_s\ \ K^-\pi^+)$ 2.5 apart from 0. In agreement with the SM expectation.

- Untagged measured $\Delta\Gamma_s$ and ϕ_s from $B^0_s \to J/\psi\ \phi$
- Tagged measurement of sin $2\beta_s$ (sin ϕ_s) in $B^0_s \to J/\psi\ \phi$ soon

Back up

$\sin 2\beta_s$ analysis

- The 1st step to β_s is to compute the proper decay time (t) and then the particle-antiparticle assymetry , $A_{CP}(t)$, as a function of t

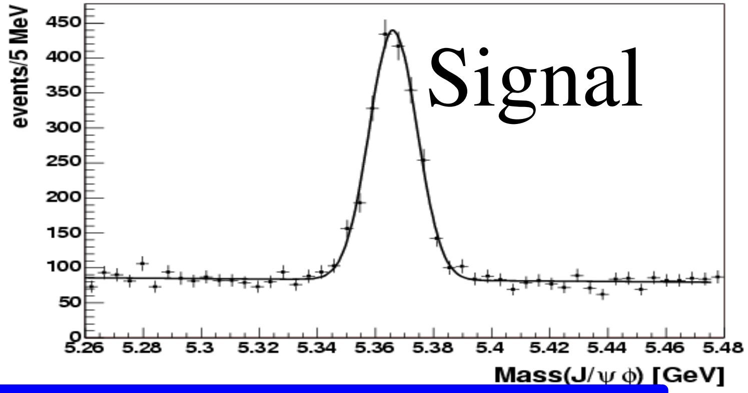
$$A_{CP}(t) = \frac{N_{\bar{B}0_s \to J/\psi\,\phi}(t) - N_{B0_s \to J/\psi\,\phi}(t)}{N_{\bar{B}0_s \to J/\psi\,\phi}(t) + N_{B0_s \to J/\psi\,\phi}(t)} = D \sin(2\beta_s) \sin(\Delta m_s t)$$

In order to determine $N_{B0_s \to J/\psi\,\phi}(t)$ ones needs flavor tagging

- We perform an unbinned multivariate likelihood fit (m, t, σ_t, D, ξ)

Exp. key issues : statistics, selection using NN and tagging using TOF

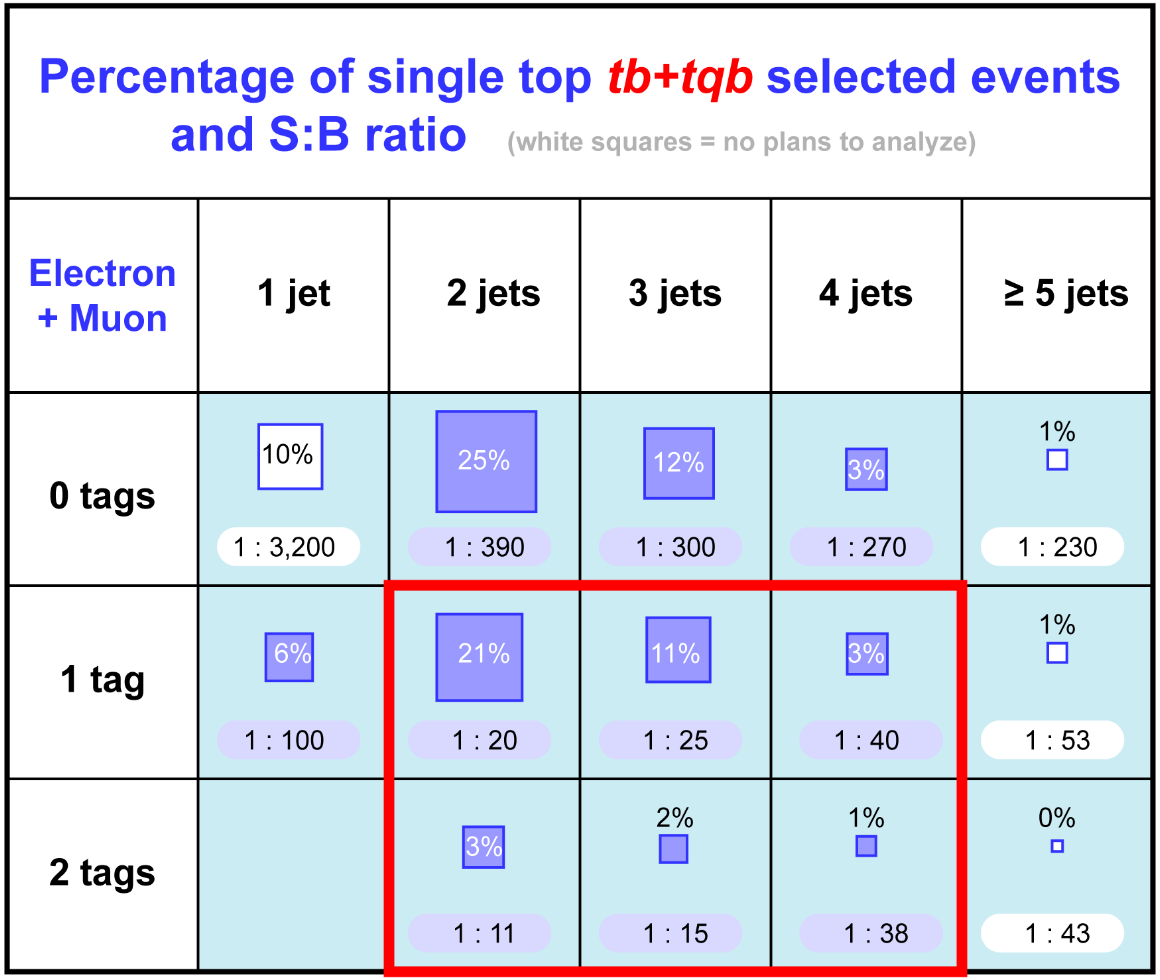
$B^0_s \to J/\psi\,\phi$ ~1700 candidates in $1.3\,\mathrm{fb}^{-1}$



angle	mode	no. events (K)	error on $2\,\mathrm{fb}^{-1}$
β	$B^0 \to J/\psi\, K^0_{s,l}$	10	$0.05 - 0.1$ in $\sin 2\beta$
β_s	$B^0_s \to J/\psi\,\phi$	3	$0.1 - 0.2$ in $\sin 2\beta_s$

Single top: signal fraction and S:B ratios in each subsample

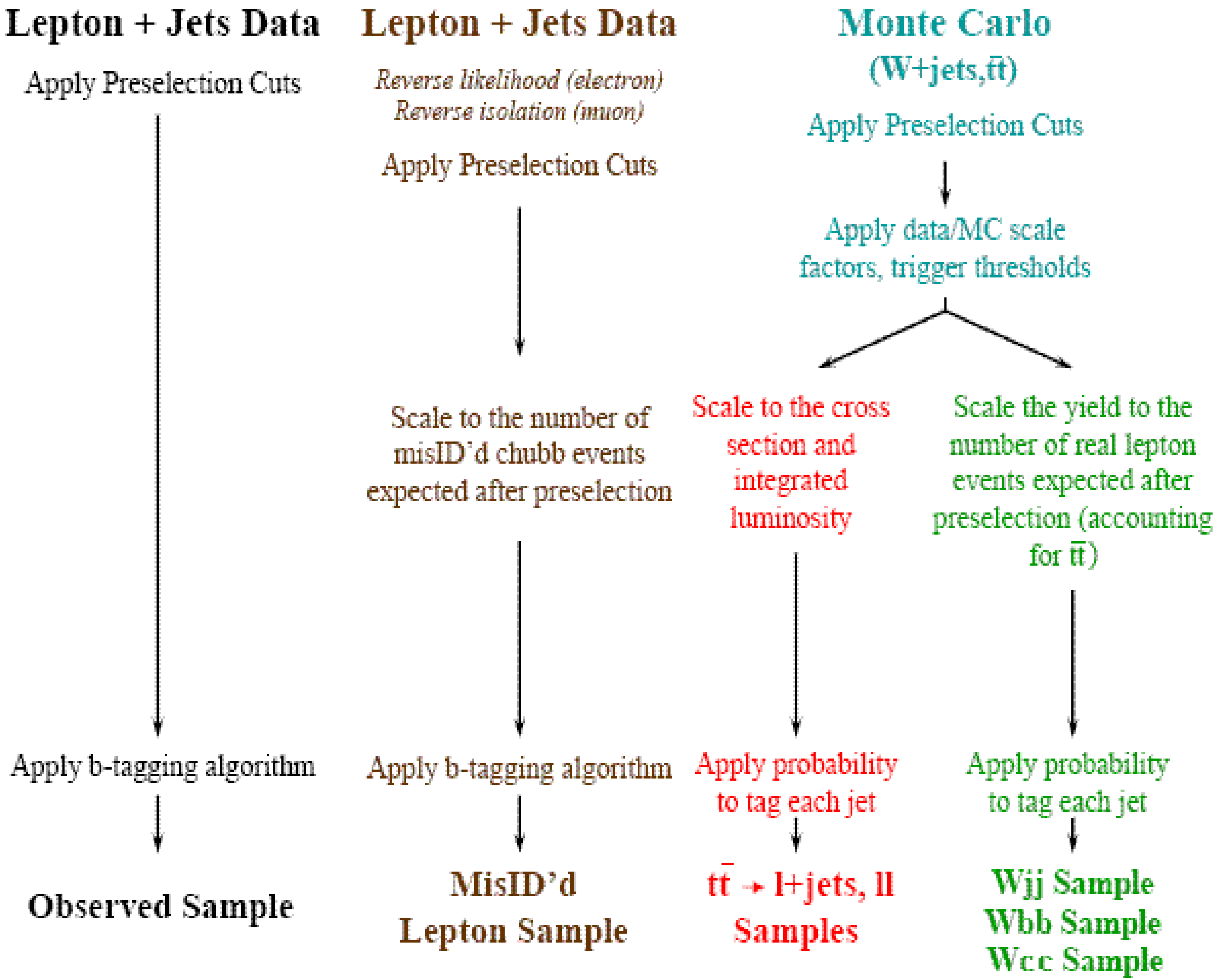
The selected events are divided into 12 nonoverlapping samples depending on the flavor of the lepton (e or mu), the number of jets (2,3,4), and the number of b-tagged jets (1,2). The signal:background ratios and fractions of expected signal in each set differ significantly :



Percentage of single top *tb+tqb* selected events and S:B ratio (white squares = no plans to analyze)

Electron + Muon	**1 jet**	**2 jets**	**3 jets**	**4 jets**	**≥ 5 jets**
0 tags	10% 1 : 3,200	25% 1 : 390	12% 1 : 300	3% 1 : 270	1% 1 : 230
1 tag	6% 1 : 100	21% 1 : 20	11% 1 : 25	3% 1 : 40	1% 1 : 53
2 tags		3% 1 : 11	2% 1 : 15	1% 1 : 38	0% 1 : 43

Single top : Analysis overview



Lepton + Jets Data

Apply Preselection Cuts

Apply b-tagging algorithm

Observed Sample

Lepton + Jets Data

Reverse likelihood (electron)
Reverse isolation (muon)

Apply Preselection Cuts

Scale to the number of misID'd chubb events expected after preselection

Apply b-tagging algorithm

MisID'd Lepton Sample

Monte Carlo
(W+jets,$t\bar{t}$)

Apply Preselection Cuts

Apply data/MC scale factors, trigger thresholds

Scale to the cross section and integrated luminosity

Apply probability to tag each jet

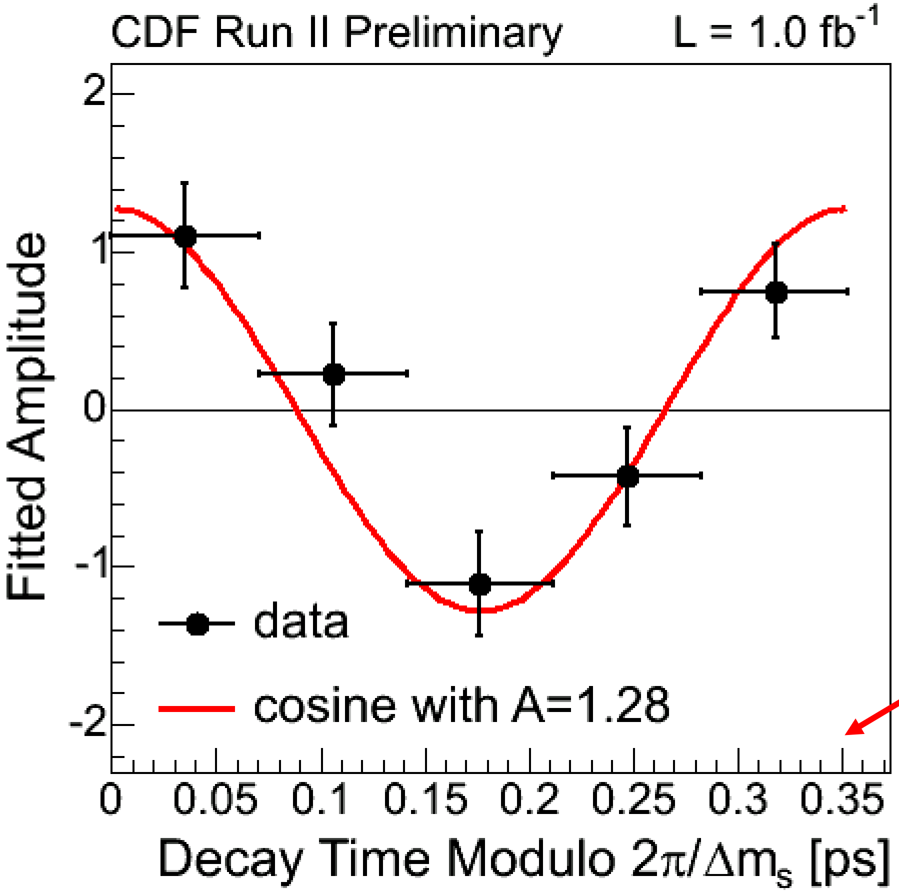
$t\bar{t} \rightarrow$ l+jets, ll Samples

Scale the yield to the number of real lepton events expected after preselection (accounting for $t\bar{t}$)

Apply probability to tag each jet

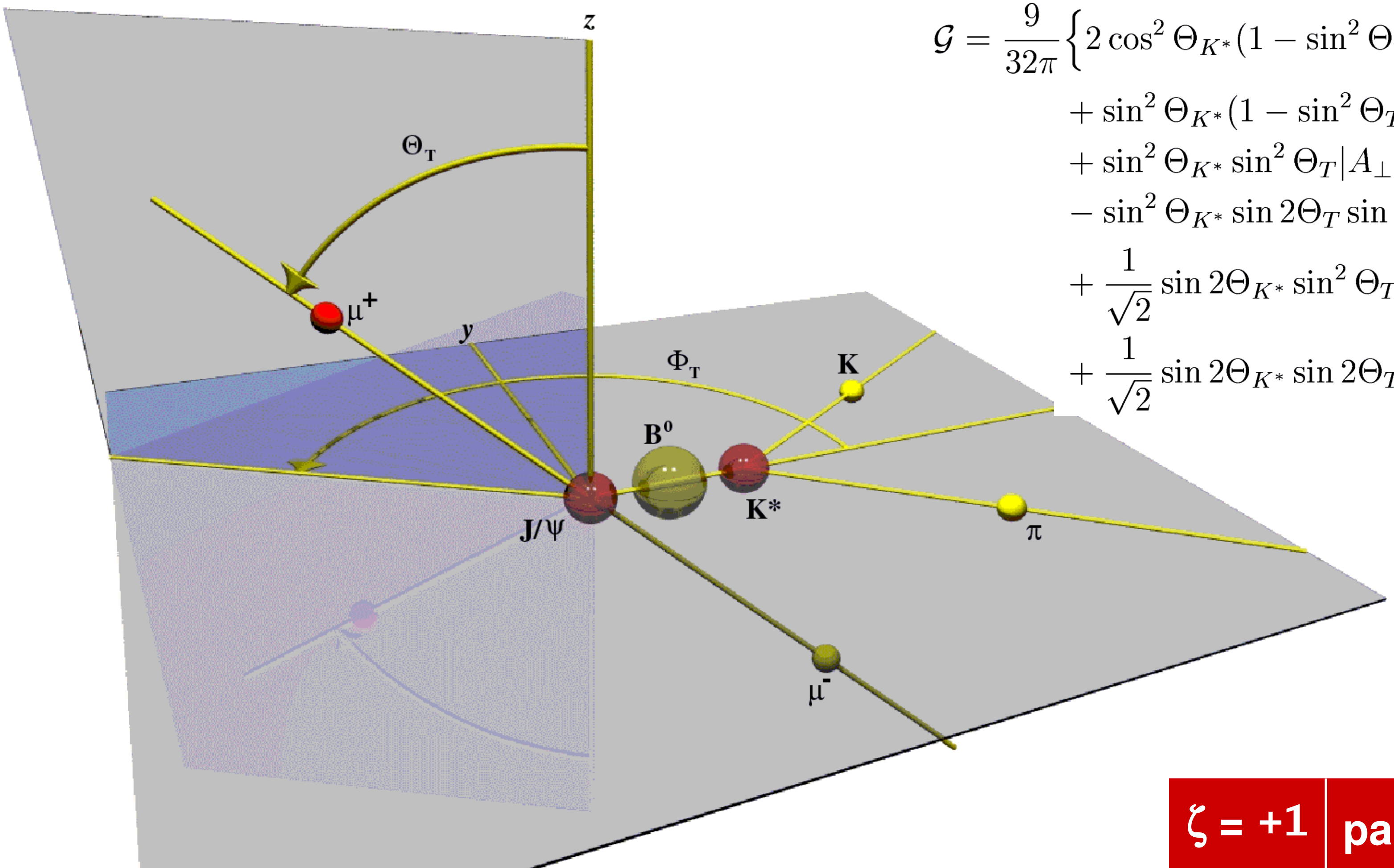
Wjj Sample
Wbb Sample
Wcc Sample

Asymmetry (Oscillations) in Time Domain



Period 0.35 ps

Aside: for B^0 Period = 12.6 ps



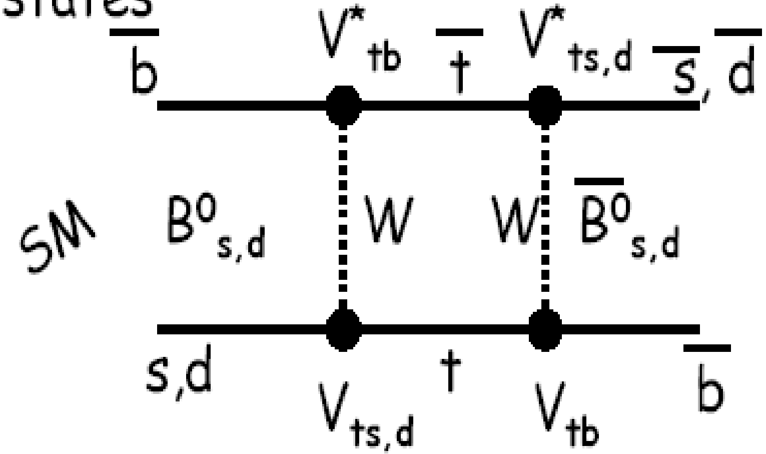
$$\mathcal{G} = \frac{9}{32\pi}\Big\{2\cos^2\Theta_{K^*}(1-\sin^2\Theta_T\cos^2\Phi_T)|A_0|^2$$
$$+\sin^2\Theta_{K^*}(1-\sin^2\Theta_T\sin^2\Phi_T)|A_{||}|^2$$
$$+\sin^2\Theta_{K^*}\sin^2\Theta_T|A_\perp|^2$$
$$-\sin^2\Theta_{K^*}\sin 2\Theta_T\sin\Phi_T Im(A_{||}^*A_\perp)\zeta$$
$$+\frac{1}{\sqrt{2}}\sin 2\Theta_{K^*}\sin^2\Theta_T\sin 2\Phi_T Re(A_0^*A_{||})$$
$$+\frac{1}{\sqrt{2}}\sin 2\Theta_{K^*}\sin 2\Theta_T\cos\Phi_T Im(A_0^*A_\perp)\zeta\Big\}$$

ζ = +1	**particle**
ζ = −1	**antiparticle**
ζ = 0	**untagged**

- Transversity basis ≡ *J/ψ* rest frame
- *ϕ* flight direction ≡ +*x*
- *KK* plane ≡ *xy* plane

B^0_s mixing and CP violation

EW Symmetry Breaking ⇒ Weak ≠ Mass ≠ CP Eigenstates



$|B_H\rangle = p|B^0\rangle + q|B^0\rangle$ $\quad |B_{odd}\rangle = |B^0\rangle + |B^0\rangle$

$|B_L\rangle = p|B^0\rangle - q|B^0\rangle$ $\quad |B_{even}\rangle = |B^0\rangle - |B^0\rangle$

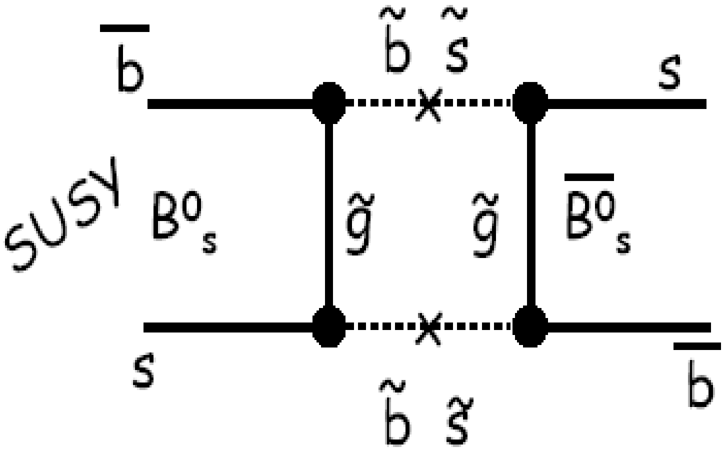
Observables

$\Delta m_s = M_H - M_L \sim 2|M_{12}|$ sens. to NP

$\Delta\Gamma_{CP} = \Gamma_{even} - \Gamma_{odd} \sim 2|\Gamma_{12}|$ not sens. to NP

$\Delta\Gamma_s = \Gamma_L - \Gamma_H = \Delta\Gamma_{CP} \times \cos(\phi_S)$ very sens. to NP

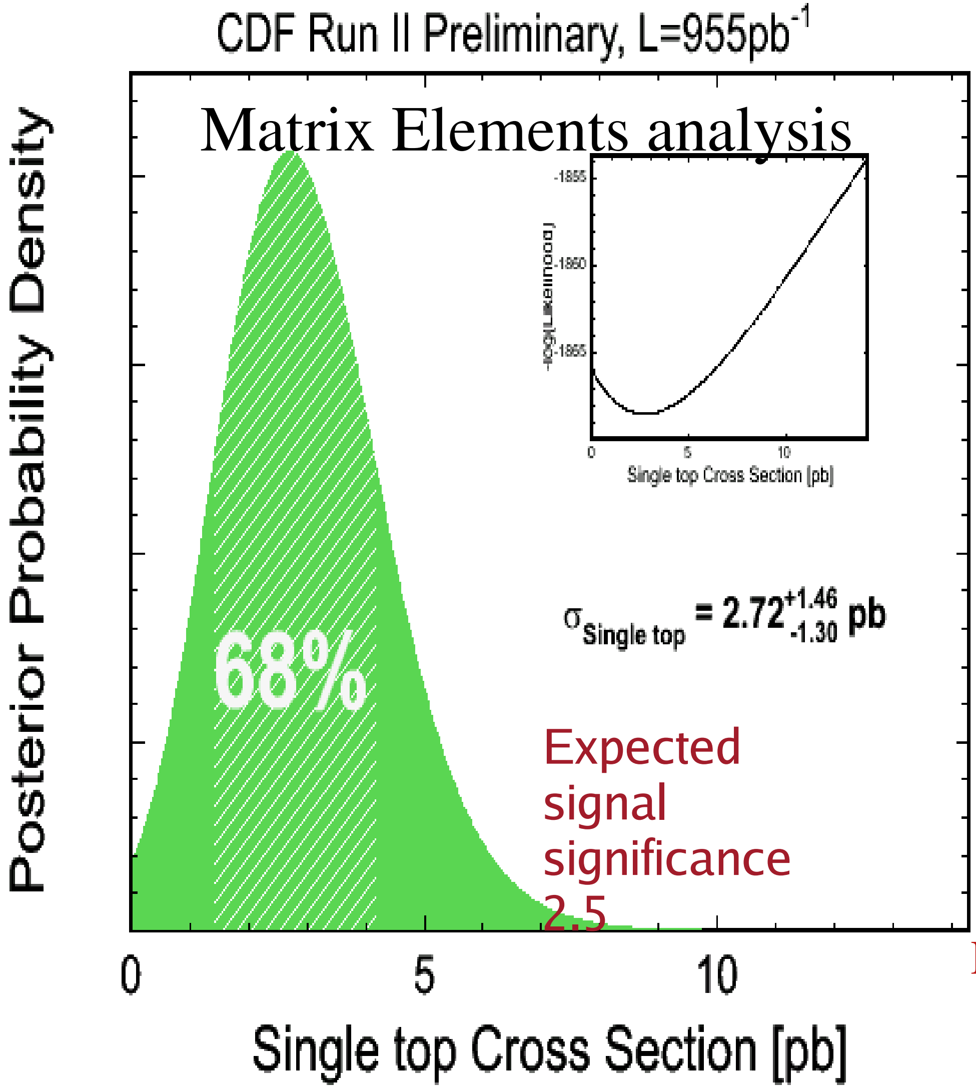
($\phi_S =$ -0.5 - -0.8 in 4-gen models, hep-ph/0610385)



In the Standard Model

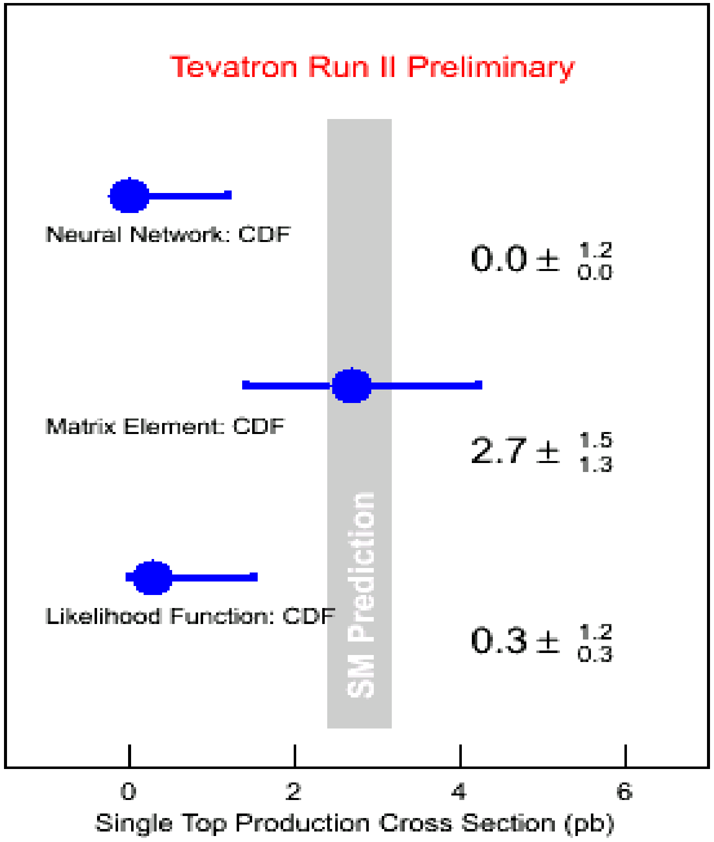
- $\Delta\Gamma_s/\Delta m_s = O(m^2_b/m^2_t)$ (QCD)
- $\phi_s \sim (4.2 \pm 1.4) \times 10^{-2}$ (hep-ph/0612167)

Single top : CDF Results



Matrix Elements analysis

Expected signal significance 2.5



Compatibility of CDF Results

2.6

Performed common pseudo-experiments

- Correlation among analyses: ~60-70%
- 1.2% of these pseudo-experiments fluctuated as unlucky as the observed data

Neural Networks (Likelihood) analysis:

No evidence of signal σ_{s+t}<2.7(2.6) pb at 95% C.L.

Expected signal significance 2.0 (2.6)

•Extensive cross-checks performed

•Next round of analysis will

p-value & confidence region

- Fit on data: fixing the parameters of interest ($\Delta\Gamma$, ϕ_s) to determine all other parameters Θ
- Generating toy distribution with parameters derived before
- Fit twice, once with all parameters free (hat), once with $\Delta\Gamma$ and ϕ_s fixed
- Calculate likelihood ratio:

$$R(\Delta\Gamma, \phi_s) = \log \frac{\mathcal{L}(\widehat{\Delta\Gamma}, \hat{\phi}_s, \hat{\Theta})}{\mathcal{L}(\Delta\Gamma, \phi_s, \hat{\Theta}')}$$

- p-value is fraction with #(R(toy)>R(data))/#R(toy)
- For confidence region: Calculate p-values for different points in $\Delta\Gamma$ and ϕ_s plane