



La Fisica dei Saponi Pesanti

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**Simposio in onore di Romano Bizzarri
Roma, La Sapienza, 10 Febbraio 2004**

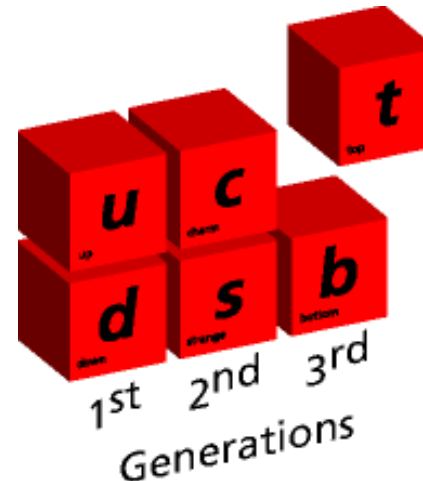
Heavy Flavor and the Standard Model



The Standard Model of particle physics has been very successful at explaining all the data at hand. Includes 3 generations of lepton and quarks iso-doublets

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix} \quad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix} \quad \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}$$

$$\begin{pmatrix} u \\ d' \end{pmatrix} \quad \begin{pmatrix} c \\ s' \end{pmatrix} \quad \begin{pmatrix} t \\ b' \end{pmatrix}$$



With strong, EWK, electromagnetic interactions specified by
 $SU(3)_C \times SU(2)_L \times U(1)_Y$ symmetry

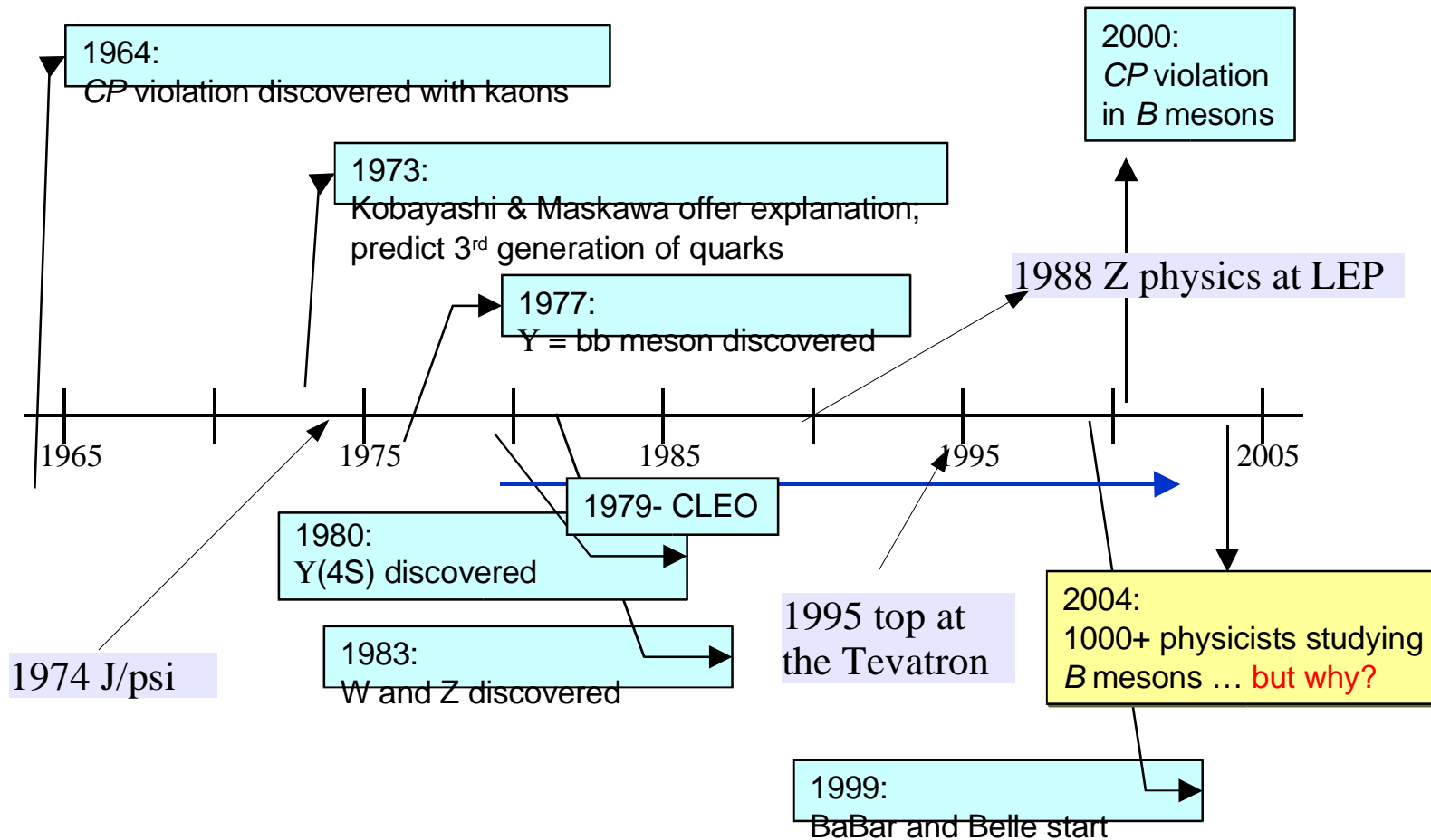
However, many unanswered questions remain:

why 3 generations? What is the physics that sets masses and mixing?
What phenomenon causes Symmetry Breaking? And so on....

NEW PHYSICS must be around that explains all these questions

We will review some aspects of Heavy Flavor Physics to search for NP.

History of progress: charm to top



The CKM matrix



1963: Cabibbo (based on K and pi leptonic decays) finds that the d and s quarks mix

$$d'_L = d_L \cos\theta_C + s_L \sin\theta_C$$

1964: **CP** violation discovered in K decays

1973 : Kobayashi and Maskawa propose a 3x3 quark mixing matrix that can be complex, thus incorporating CP violation in the SM. This required a third generation (charm was not discovered yet!).

The CKM matrix relates the eigenstates of the quark masses to those of the weak current.

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{matrix} \blacksquare \\ \blacksquare \\ \blacksquare \end{matrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

CKM explanation of CP Violation



Wolfenstein parameterization

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} 1 - \frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Where A , λ , ρ and η are determined from experiments.

$$V_{us} = \lambda = \sin\theta_C$$

Is CP violation the result of a single weak phase in the CKM matrix or is it due to new physics, beyond the standard model? Or both?

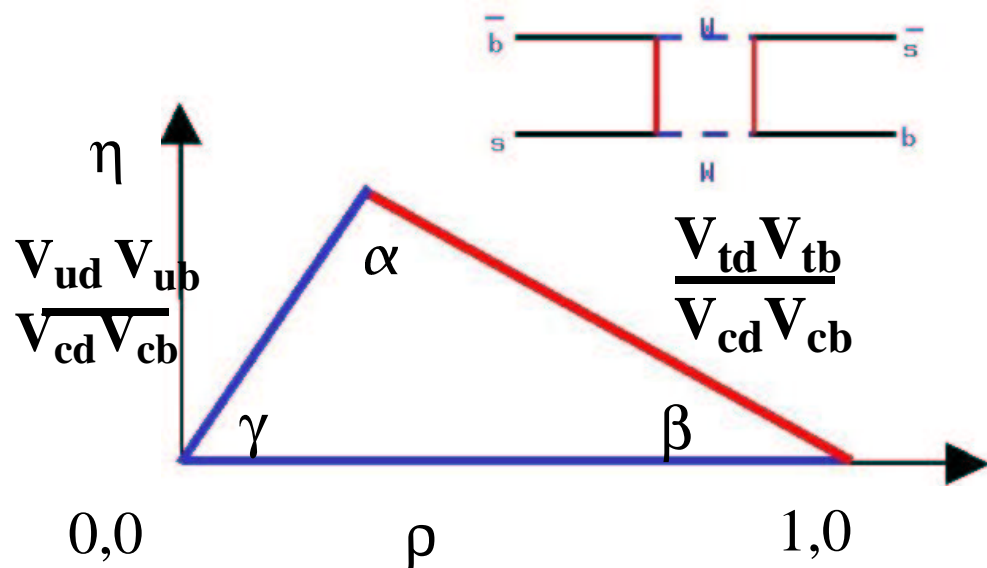
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Experiments will have to test expectations from the CKM hypothesis

The Unitary triangle



From a unitary complex matrix. We expect



$$\alpha = \arg - \frac{V_{td} V_{tb}}{V_{cb} V_{cb}}$$

$$\beta = \arg - \frac{V_{cd} V_{cb}}{V_{td} V_{tb}}$$

$$\gamma = \arg - \frac{V_{ud} V_{ub}}{V_{cd} V_{cb}}$$

CP violation in b system if $\alpha, \beta, \gamma \neq 0$

Standard model with CP violation requires $\alpha + \beta + \gamma = \pi$

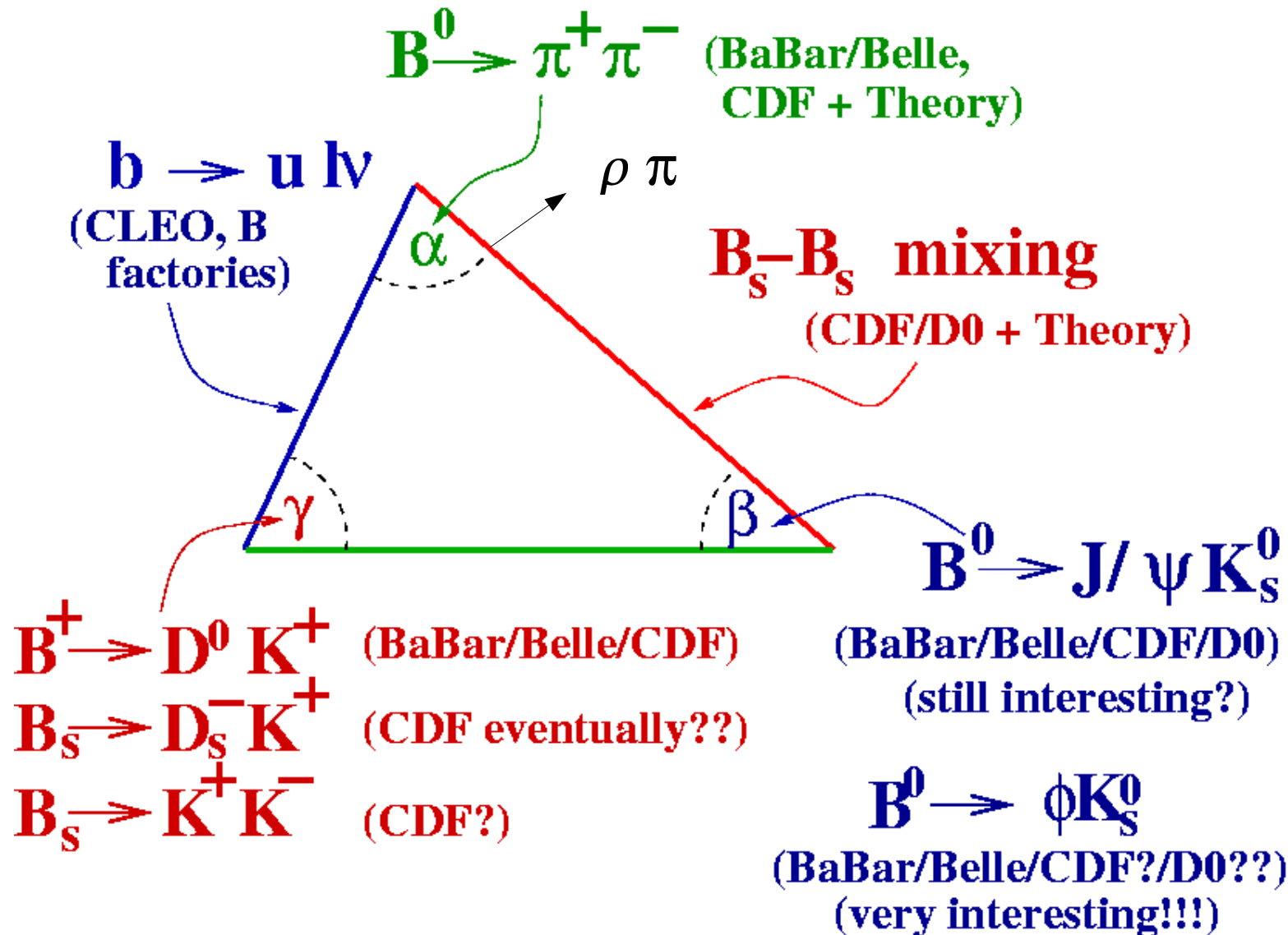
Red side of triangle measured by measuring B-B mixing

Δm_d , obtained from time dependent mixing in $B^0-\bar{B}^0$

Δm_s , obtained from time dependent mixing in $B_s^0-\bar{B}_s^0$

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Overall game plan

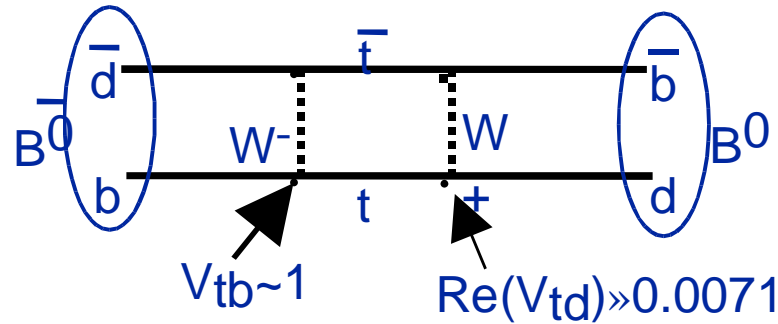


Courtesy of P. Macsimovic (JHU)

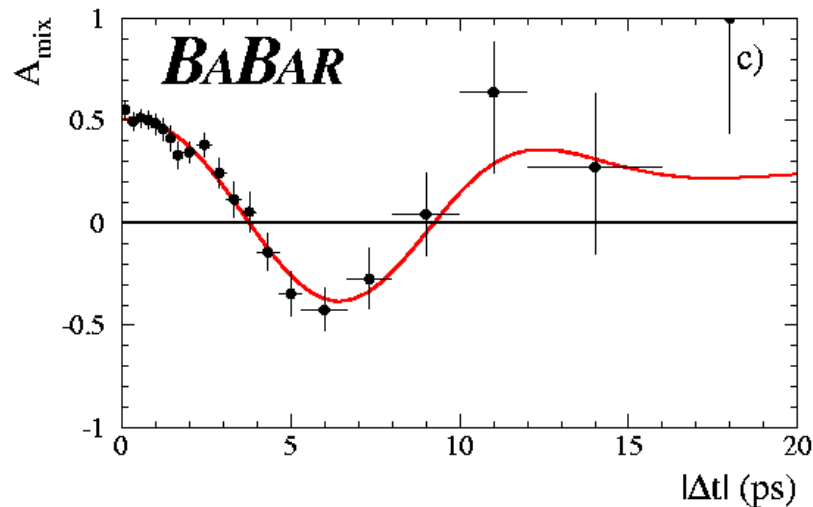
B_d Mixing



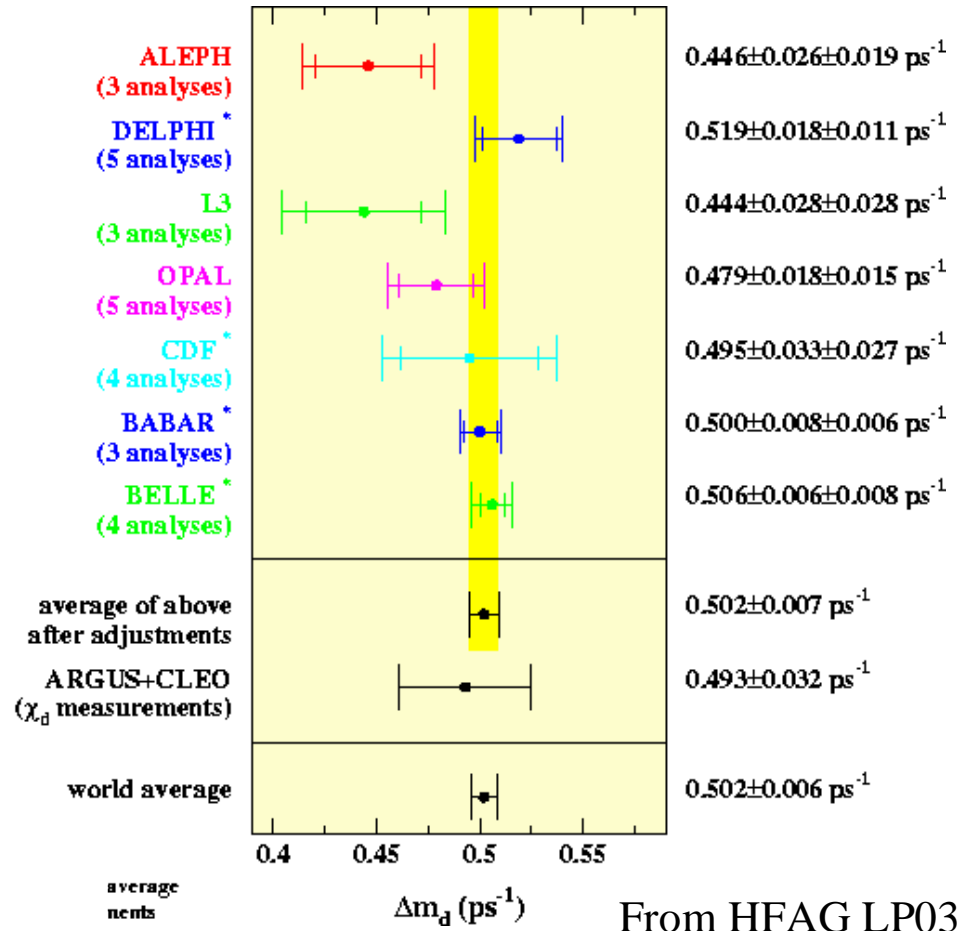
B_d mixing measured with great precision measures of Dm_d



Ba-bar and Belle measure Dm using hadronic B decays

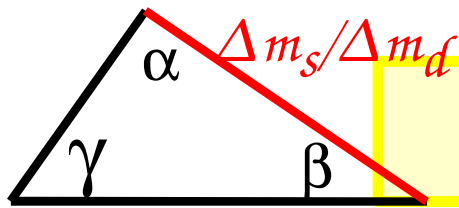


World average now dominated by Babar and Belle



$$\Delta m_d = 0.502 \pm 0.006 \text{ ps}^{-1}$$

B_d fully mixes in about 4.1 lifetimes

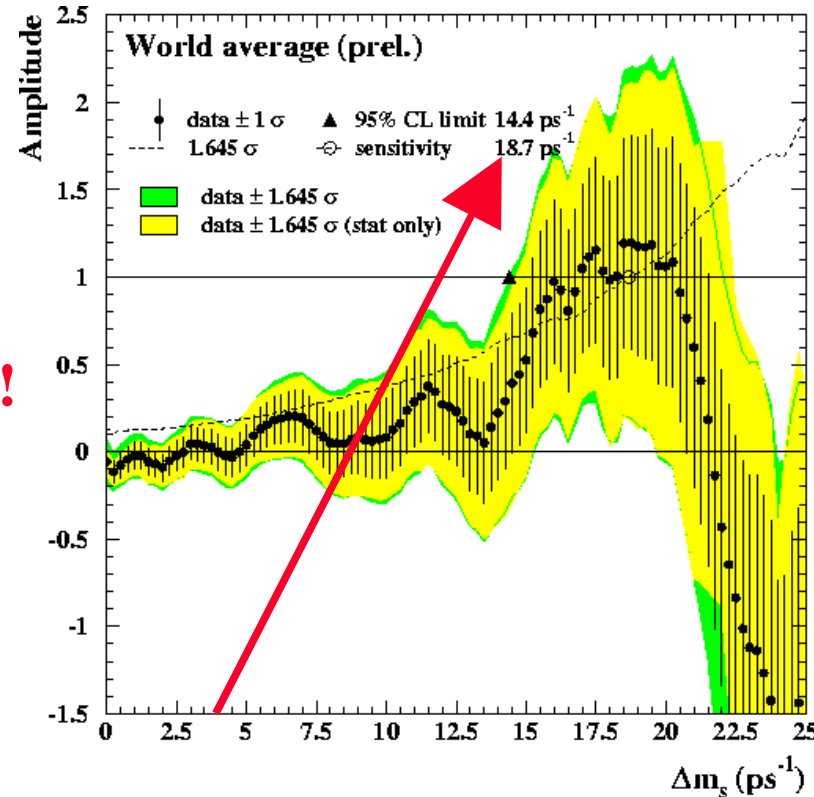
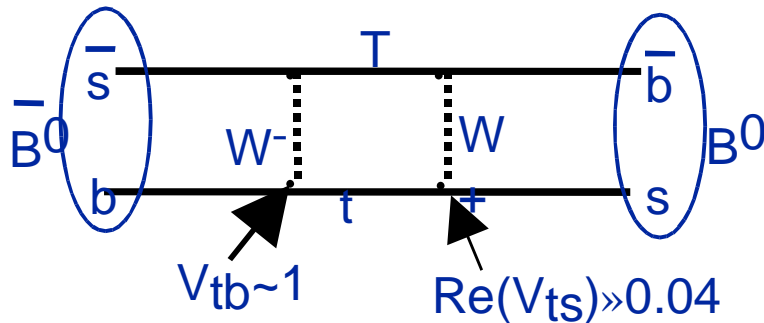


Towards B_S Mixing



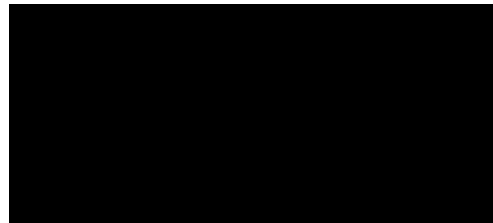
Measurement of Δm_S helps improve our knowledge of CKM triangle.

- Combined world limit on B_S mixing
 - $\Delta m_S > 14.4 \text{ ps}^{-1}$ @95%CL
 - **B_S fully mixes in < 0.15 lifetime!!**
- B_S oscillation: much faster than B_D because of coupling to top quark:
 $\text{Re}(V_{ts}) \gg 0.040 > \text{Re}(V_{td}) \gg 0.007$



Combined limit comes from 13 measur. from LEP, SLD & CDF Run I

Unitary triangle status

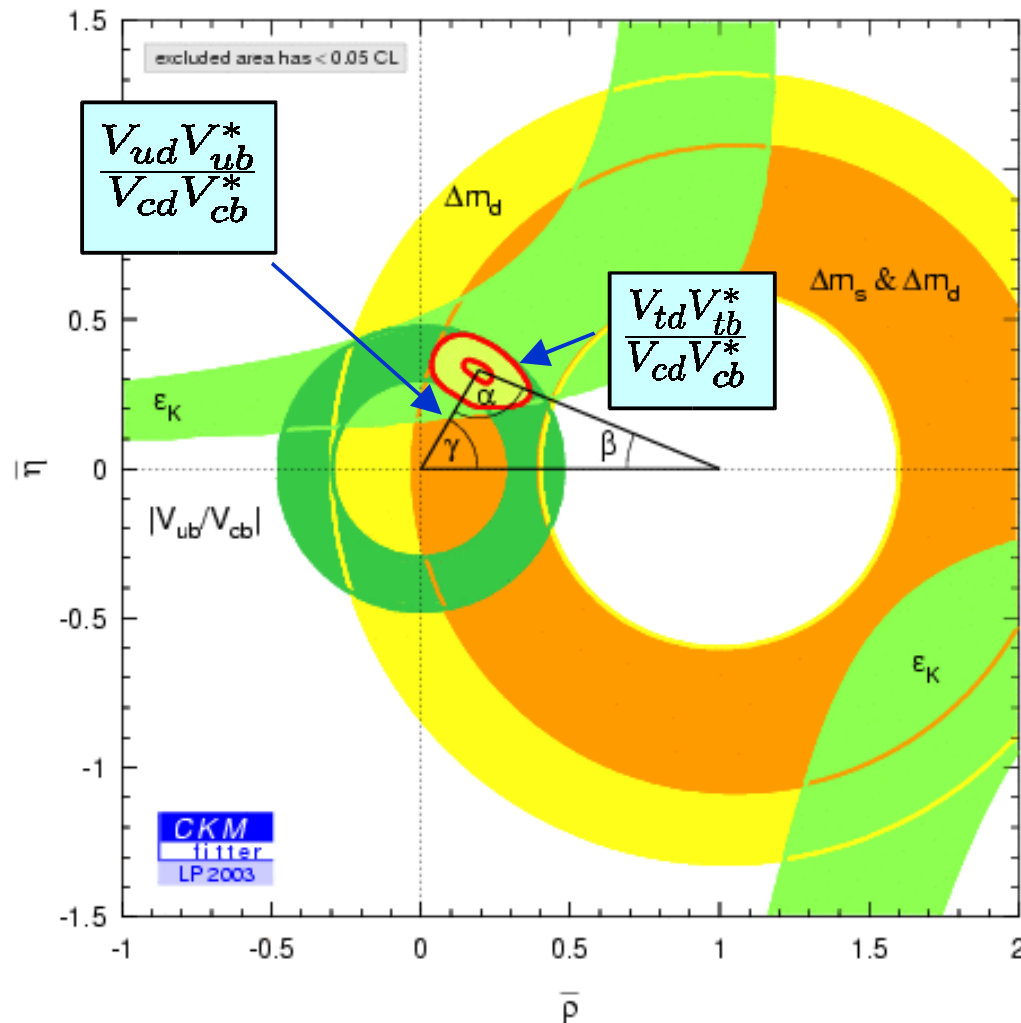


Unitarity:

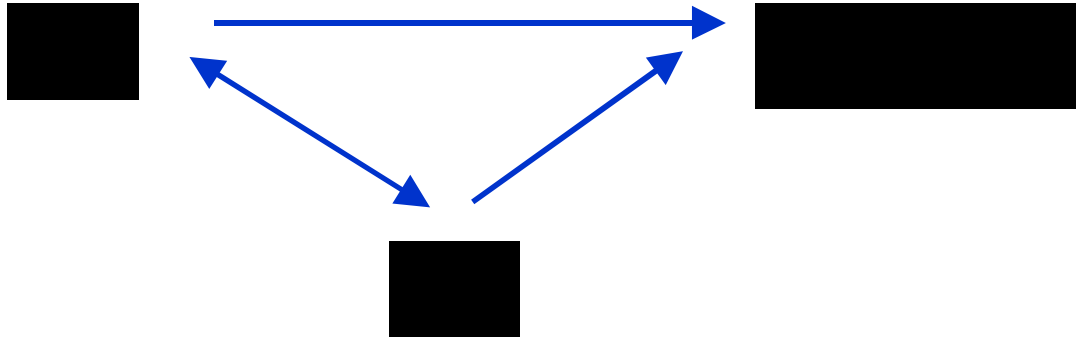


Measure in as many ways as possible:

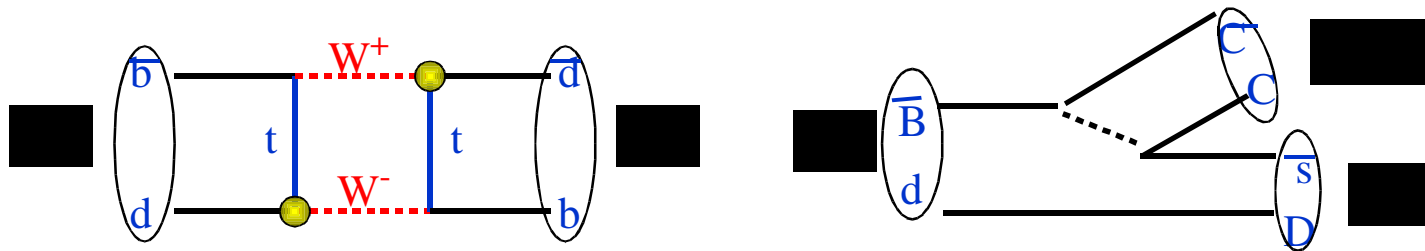
- Is CKM right at all?
- Do new physics phases appear?



CKM angles: $\sin 2\beta$ with $J/\psi K_S$



$J/\psi K_S$ is CP = -
 $J/\psi K_L$ is CP = +



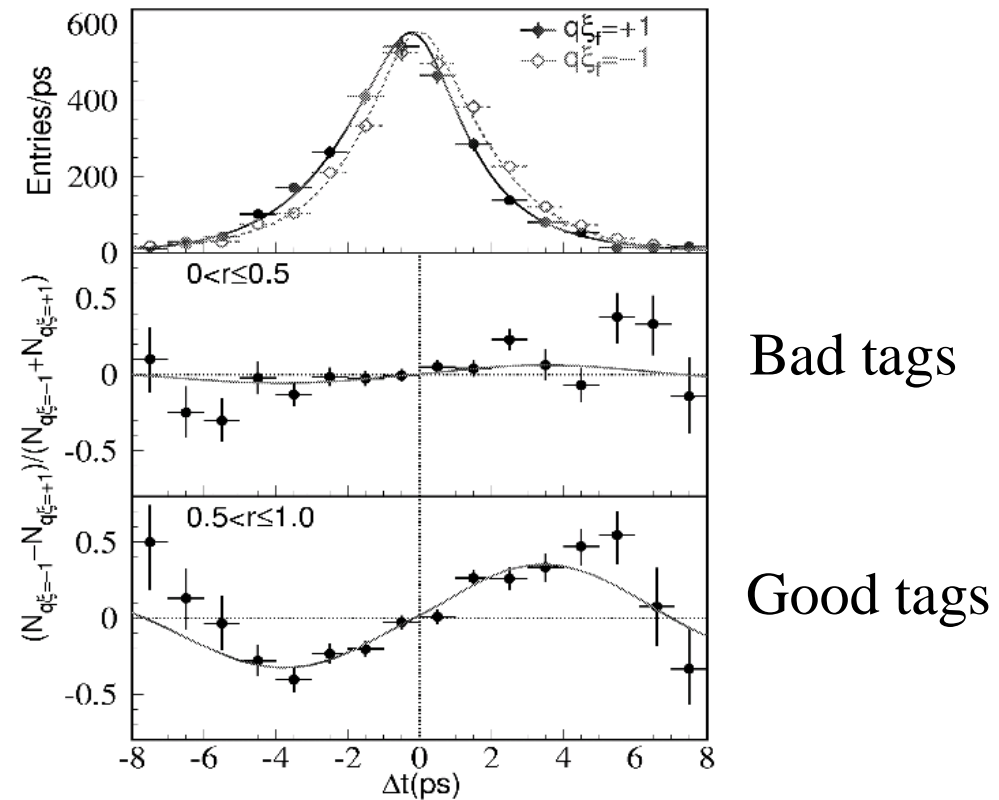
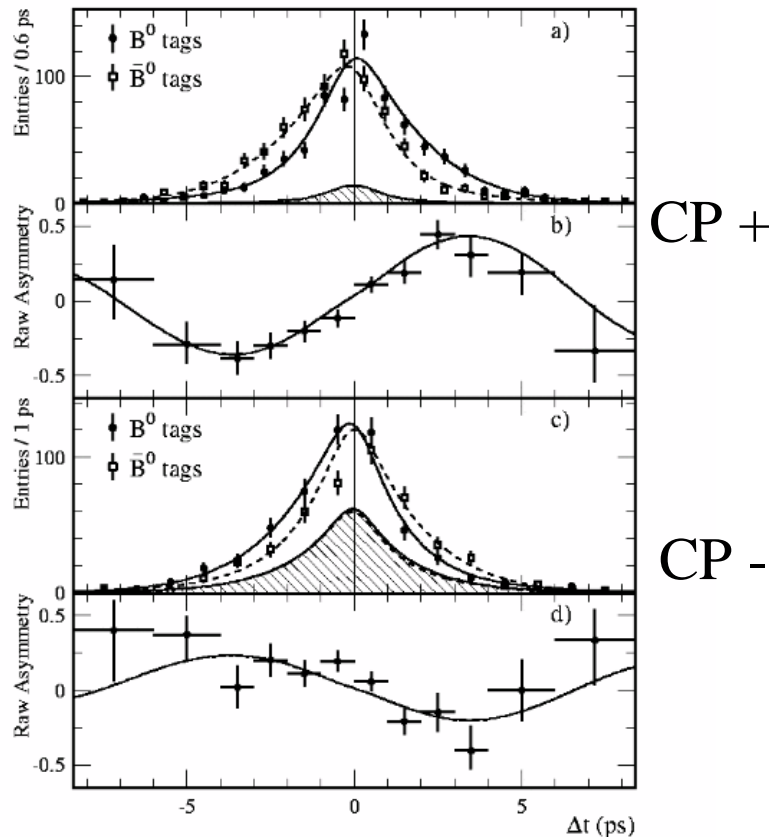
Time dependent BB mixing \rightarrow time dependent interference

- Tag other b decay as B^0 ($q=+$) or \bar{B}^0 ($q=-1$)
- Measure decay time difference Δt ($t_{CP} - t_{tag}$)
- $\xi_f =$ CP eigenvalue
- $A_{CP}(t) \propto \sin 2\beta \sin(\Delta m t)$

Ba-bar and Belle $\sin 2\beta$ from $J/\psi K_S$



$\sin 2\beta$ (New 2003 World Av.) = 0.736 ± 0.049



$\sin 2\beta$ (BaBar 2002, 81 fb^{-1}) =
 $0.741 \pm 0.067 \pm 0.033$

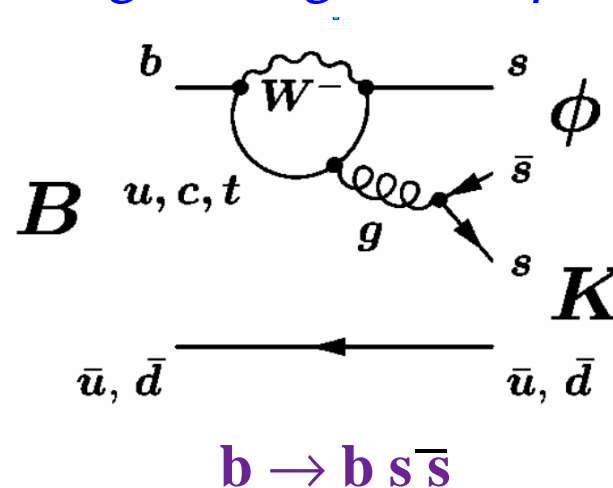
$\sin 2\beta$ (Belle 2003, 140 fb^{-1}) =
 $0.733 \pm 0.057 \pm 0.028$

New Physics?

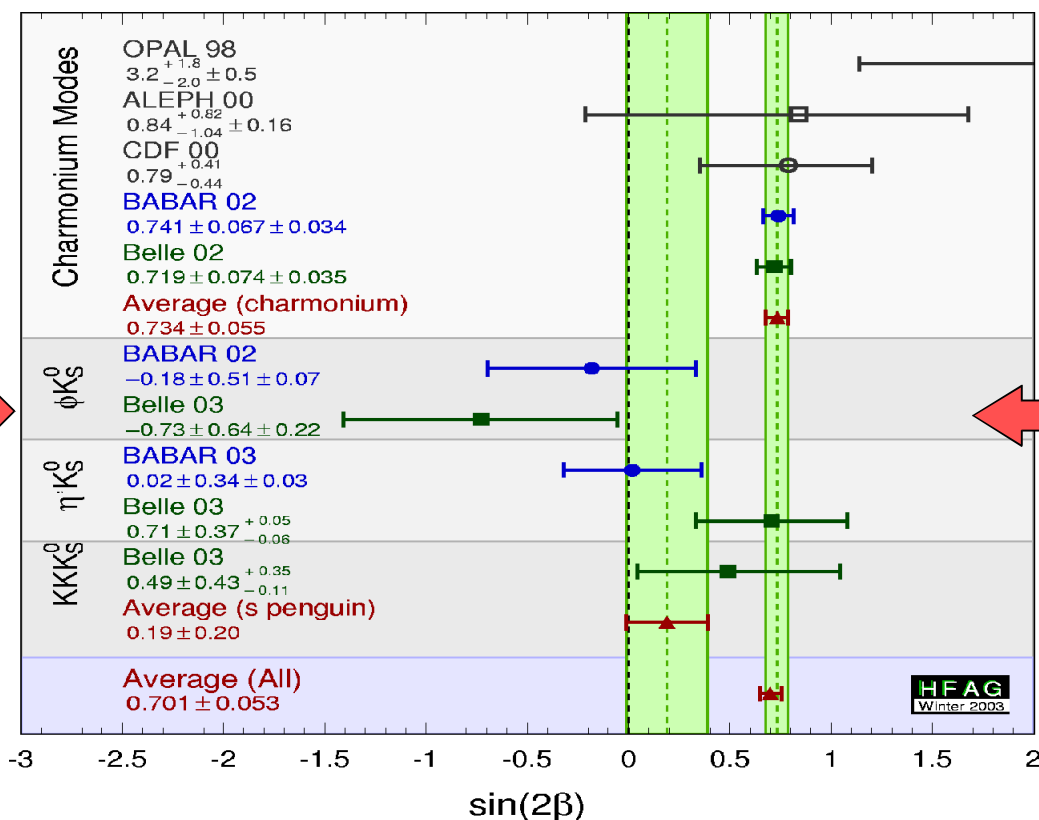


Values of $\sin(2\beta)$ are expected to be the same independently from the decay

Penguin diagram in ϕK_S

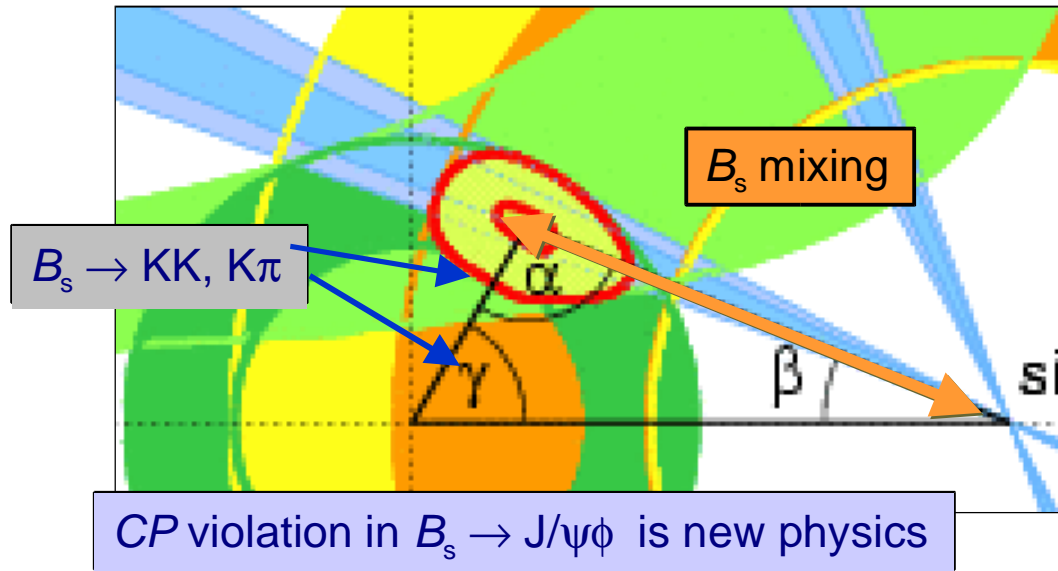


New physics from heavy particles in the loop diagram?



In the SM: $\sin(2\beta)^{\text{eff}} (B \rightarrow \phi K_S) = \sin(2\beta) (B \rightarrow J/\psi K_S)$

New Game in town: B_s mesons

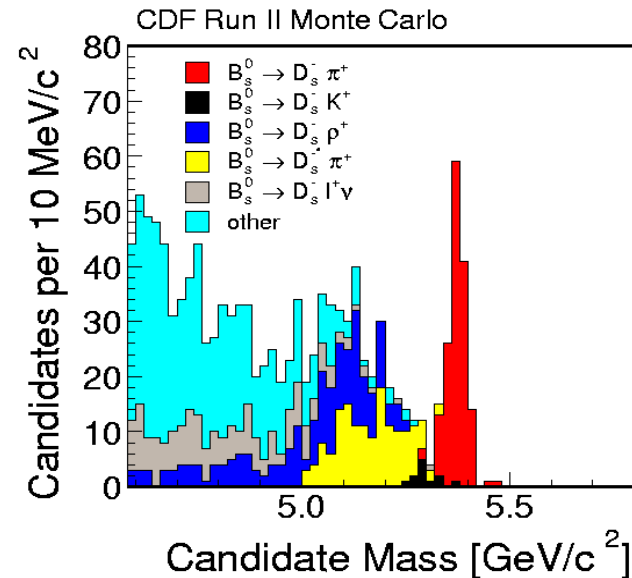
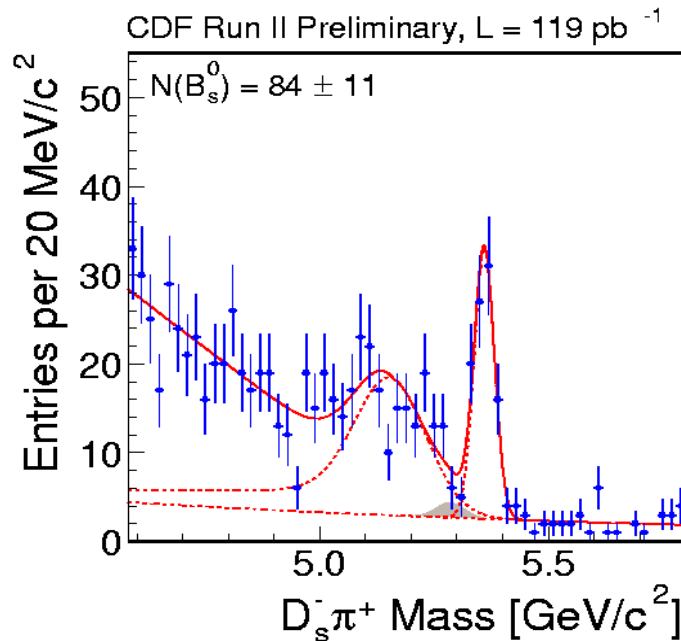


- Not made at B factories (BaBar and Belle)
 - After LEP, we need Tevatron or BTeV, LHC
- Several important B_s measurements: fully reconstructed hadron decays possible at the Tevatron. For B_s^0 - B_s^0 mixing expect:
 - 5σ sensitivity for $\Delta m_s=18\text{ps}^{-1}$ with 1.7fb^{-1} data**
 - 5σ sensitivity for $\Delta m_s=24\text{ps}^{-1}$ with 3.2fb^{-1} data**

B_s Yields: CDF $B_s \rightarrow D_s \pi^+$



First observation of $B_s \rightarrow D_s \pi$



$B_s \rightarrow D_s \pi$ with $D_s \rightarrow \phi \pi^+$ and $\phi \rightarrow K^- K^+$

$$BR(B_s \rightarrow D_s \pi^\pm) = (4.8 \pm 1.2 \pm 1.8 \pm 0.8 \pm 0.6) \cdot 10^{-3}$$

▲ (Stat) ▲ (BR) ▲ (sys) ▲ (f_s/f_d)

New measurement !

Previous limit set by OPAL: $BR(B_s \rightarrow D_s p^\pm) < 13\%$

BR result uses less data than shown in plot.

B to h h at CDF



- Mixture of many channels, use $\pi^+\pi^-$ hypothesis

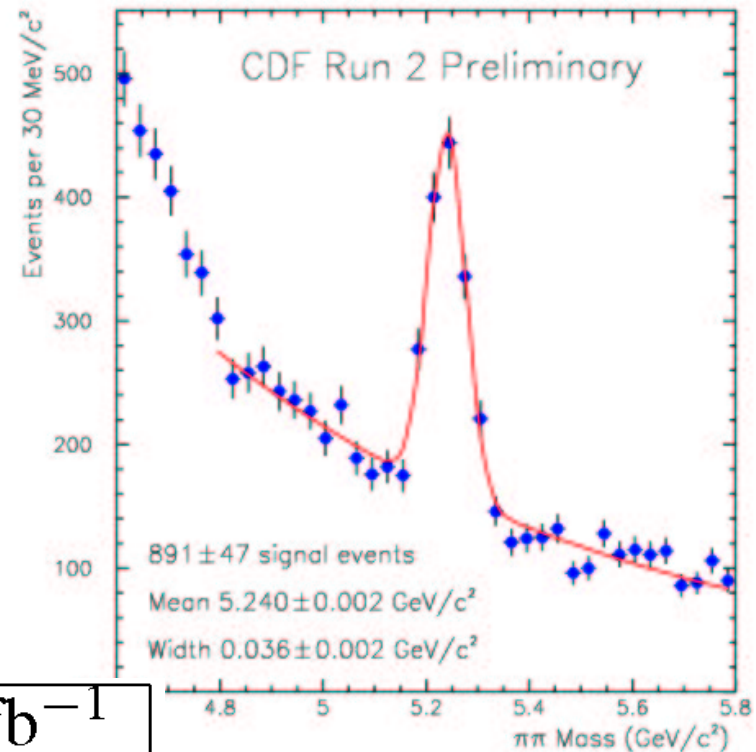
$$B_d \rightarrow K\pi$$

$$B_d \rightarrow \pi\pi$$

$$B_s \rightarrow KK$$

$$B_s \rightarrow K\pi$$

Use dE/dx to separate channels on a statistical basis. Large statistics expected



Mode	Yield 2 fb^{-1}	Yield 3.5 fb^{-1}
$B_d \rightarrow K\pi$	6700	11,725
$B_d \rightarrow \pi\pi$	1770	3097
$B_s \rightarrow KK$	4040	7070
$B_s \rightarrow K\pi$	1070	1870

Measures γ ?

Observation of $B_s \rightarrow KK$



65 pb⁻¹ of data

First observation of $B_s \rightarrow KK$

Includes error on fs/fd

mode	Yield (65 pb ⁻¹)
$B^0 \rightarrow K\pi$	$148 \pm 17(\text{stat.}) \pm 17(\text{syst})$
$B^0 \rightarrow \pi\pi$	$39 \pm 14(\text{stat.}) \pm 17(\text{syst})$
$B_s \rightarrow KK$	$90 \pm 17(\text{stat.}) \pm 17(\text{syst})$
$B_s \rightarrow K\pi$	$3 \pm 11(\text{stat.}) \pm 17(\text{syst})$

$$\frac{BR(B_s \rightarrow K^\pm K^\mp)}{BR(B_d \rightarrow K^\pm \pi^\mp)} = 2.71 \pm 1.15$$

Most of the systematic error comes from DE/dx

(work by the Rome group)

Will improve as statistics improves

B Physics Summary



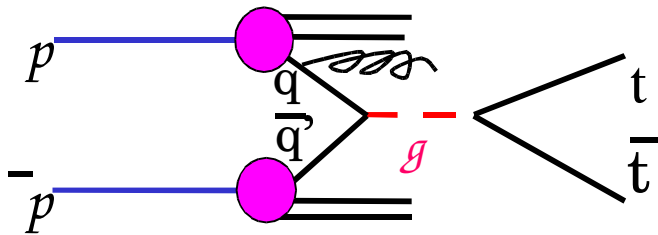
- **CP violation in the B system is centered around measurements of the unitary triangle parameters (B factories, soon the Tevatron)**
- Measurement of $\sin 2\beta$ is now a precision measurement
- **First hint of new physics in $B \rightarrow \phi K_s$ (loop diagram)**
- **Many models for possible new physics have been developed**
- **Measurements of the α and γ angle are being pursued**
- **B_s physics at the Tevatron can help understand the situation**
- **Long term: BTeV, LHCb**

Top Physics at the Tevatron



Evidence for top in 1994 (CDF)
 Observation by CDF and D0 in 1995

$t\bar{t}$ Production at the TeV:



$$t\bar{t} \rightarrow W^+ b W^- b$$

Top quark is heavy: decays very fast!

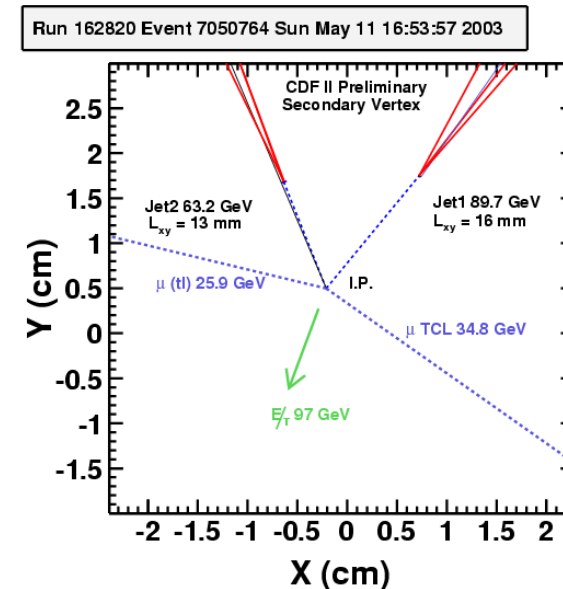
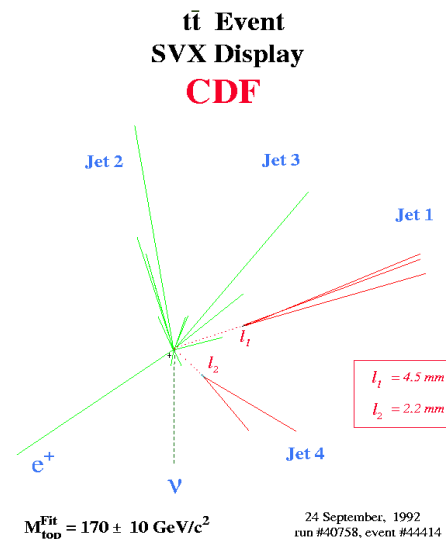
$$\Gamma(t \rightarrow Wb) \approx 1.5 \text{ GeV}, t = 4 \times 10^{-25} \text{ sec}$$

$$\Lambda_{\text{QCD}} = 100 \text{ MeV}, \Lambda^{-1} = 10^{-23} \text{ sec}$$

No hadronization:

No top mesons or baryons

Displaced vertices
 from b decays are good
 signature for top events



The Top quark



Tevatron only source of top quarks for several years

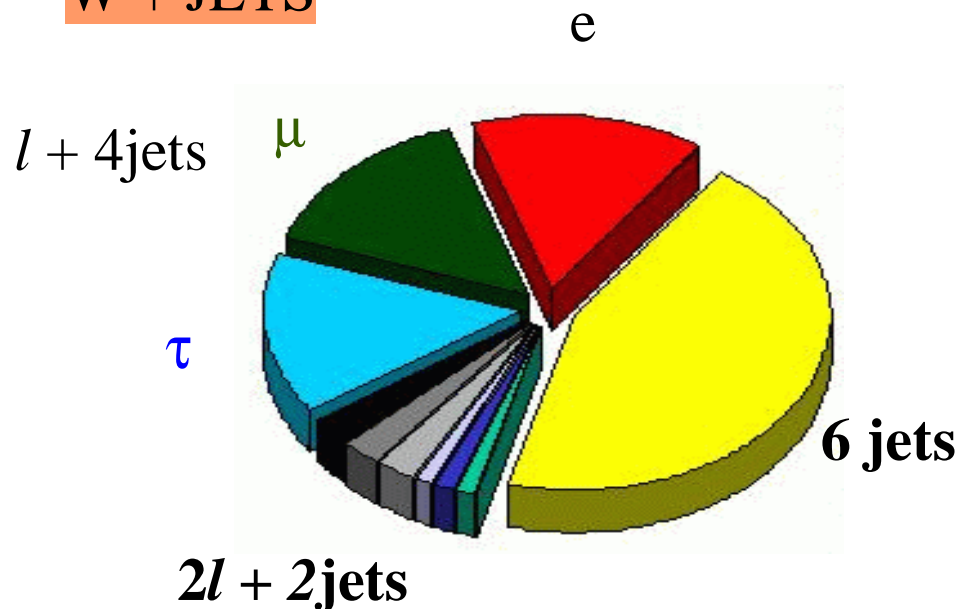
$\sigma = 5.3 \pm 1.2 \text{ pb}$ at 1.80 TeV (100 pb^{-1} of data)

$6.5 \pm 1.5 \text{ pb}$ at 1.96 TeV (200 pb^{-1} of data so far)

expect 3-6 fb^{-1} by summer of 2008

W + JETS

Top decay: $t \rightarrow W+b \sim 100\%$



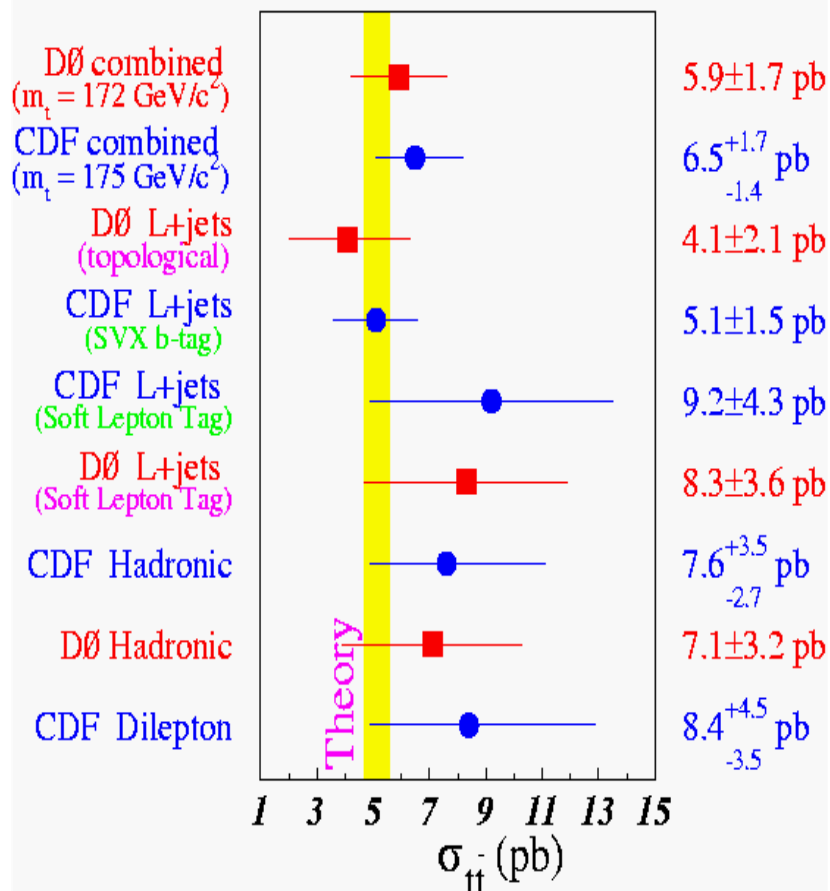
Deviations from this:
NEW PHYSICS

First measurements of:
pair production cross section
decay properties
mass
single top production limit (V_{tb})

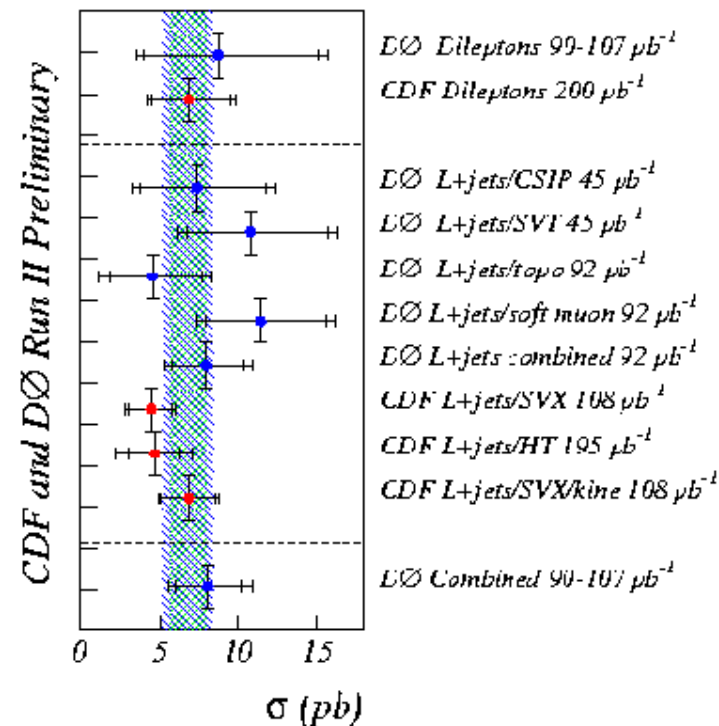
Top Cross section Run I and II (CDF+D0)



Run 1 cross section results $\sim 100 \text{ pb}^{-1}$



Run II preliminary $\sim 200 \text{ pb}^{-1}$



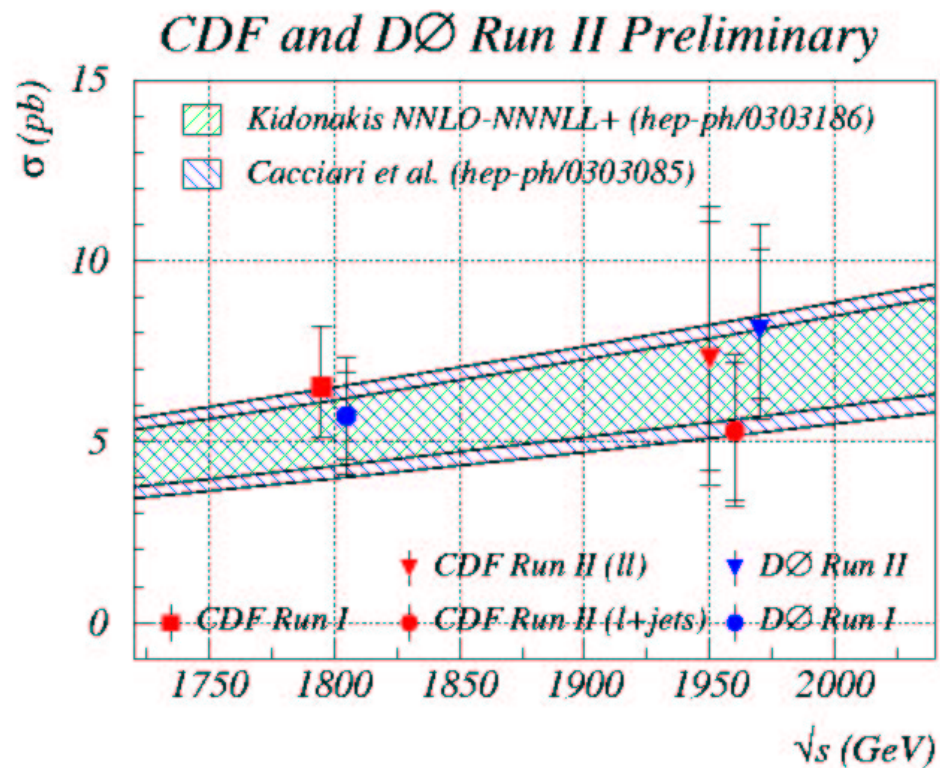
Channels use different luminosity

Within statistics all channels agree with expected cross section

Top cross section

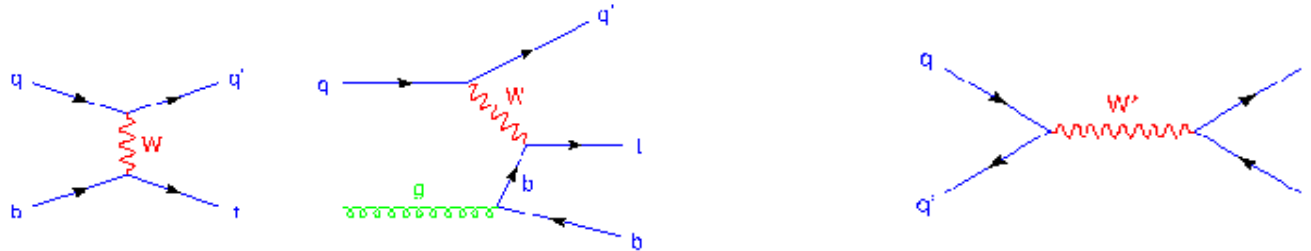


Run I and preliminary Run II cross sections agree with QCD expectation



Larger statistics and more channel measurements already available ¹

Single Top Production



Electroweak top production: can measure V_{tb}

Different sensitivity to new physics:

t channel: anomalous couplings, FCNC

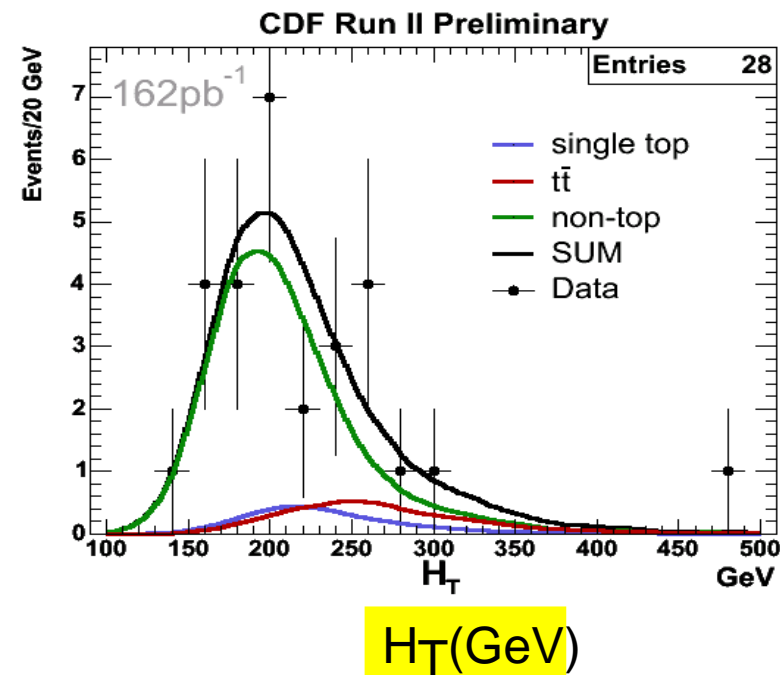
$$\sigma = 1.98 \pm 0.24 \text{ pb}$$

s channel: new charged gauge bosons

$$\sigma = 0.88 \pm 0.11 \text{ pb}$$

Analyse separately the two channels. Use total energy in event, H_T

Find 28 events and 25 resp. , compatible with background.



$$\sigma(\text{combined}) < 13.7 \text{ pb @95\% C.L.}$$

Top Mass Run I (CDF+D0)



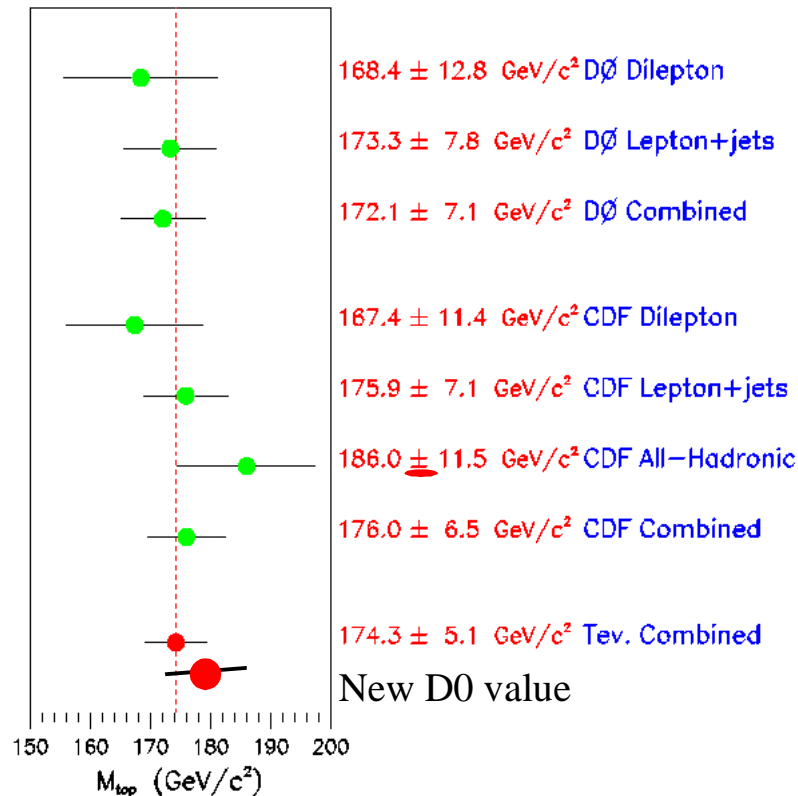
Several reconstruction methods have been used to measure the top mass.

$$M_{\text{top}} = 174.3 \pm 5.1 \text{ GeV}/c^2$$

All channels were used:

- Lepton + 4 jets
- Dileptons+ 2jets
- 6 jets

- Major systematic error:
jet energy measurement



New preliminary D0 measurement:

$$M_{\text{top}} = 180.1 \pm 3.6 \text{ (stat)} \pm 4.0 \text{ (syst)} \text{ GeV}/c^2 = 180.1 \pm 5.3 \text{ GeV}/c^2$$

it was $173.3 \pm 7.5 \text{ GeV}/c^2$

Run II Top mass measurement: lepton+jets



Kinematic fitting of event to
 $t\bar{t} \rightarrow W^+bW^-b$ (12 combinations)

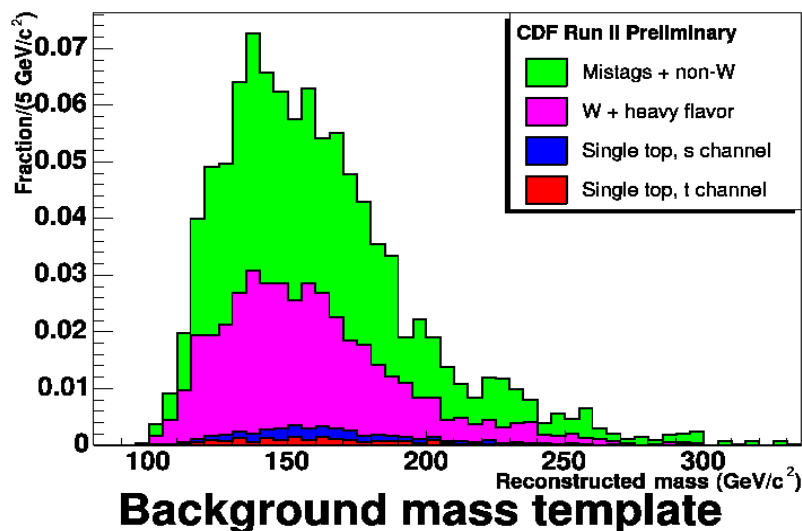
$W \rightarrow e + \nu$

1 high PT lepton, high MET, 1 b-tag

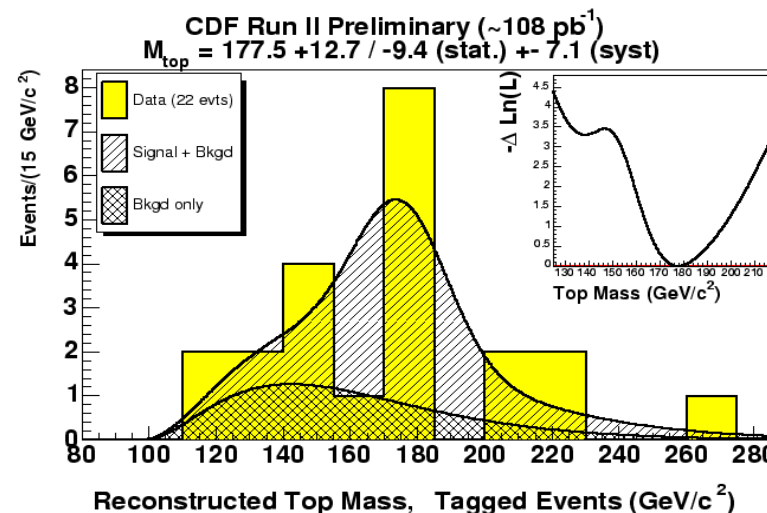
Jets (1-3) $E_T > 15$ GeV, Jet (4) $E_T > 8$ GeV,

- Find 22 candidate events
 - Expect 5.9 ± 2.1 background
 - Likelihood comparison of fit events with templates from MC
- All events use same templates**

$$M = 177.5^{+12.7}_{-9.4}(\text{stat}) \pm 7.1(\text{syst}) \text{ GeV}$$



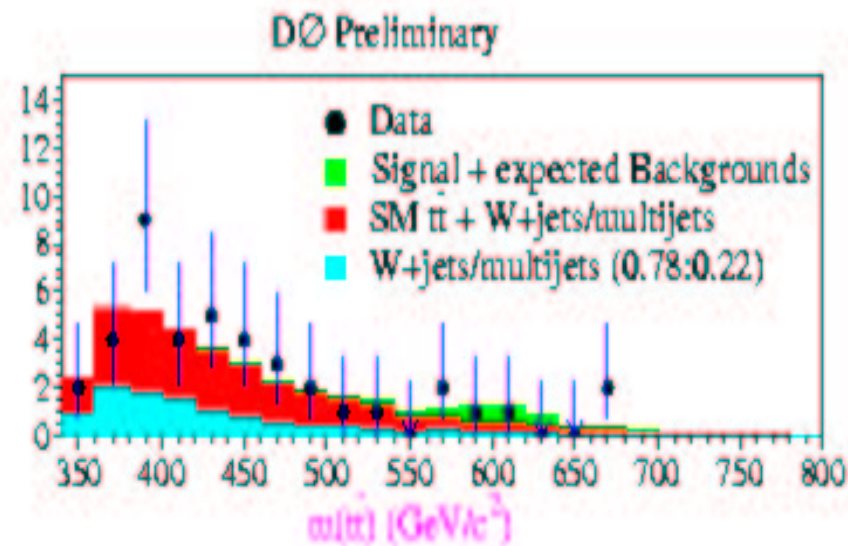
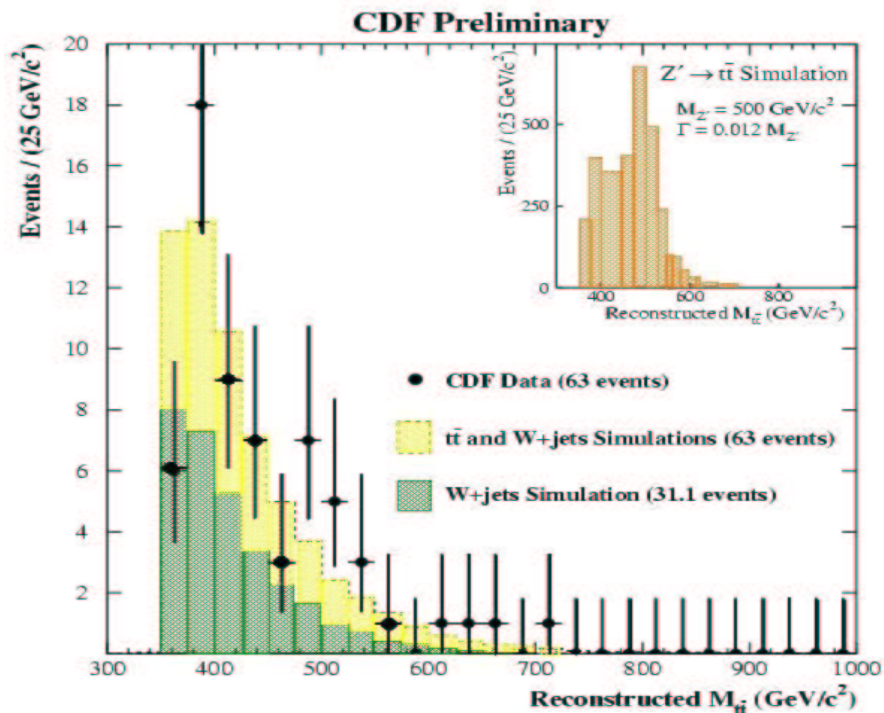
CDF Run II preliminary 108 pb⁻¹



Test for new physics in $t\bar{t}$ production



Model independent search for a narrow resonance $X \rightarrow t\bar{t}$



Exclude a narrow, leptophobic X boson with

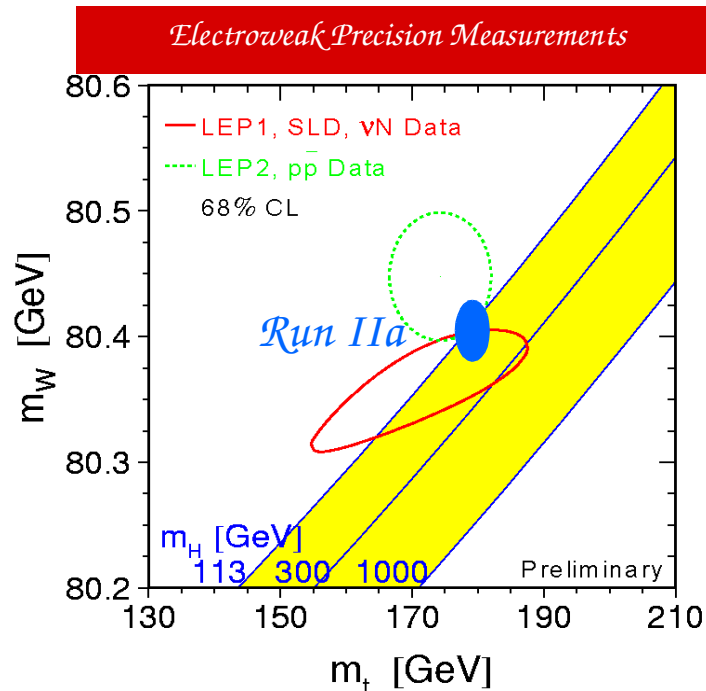
$$m_X < 560 \text{ GeV}/c^2 \text{ (CDF) and } m_X < 585 \text{ GeV}/c^2 \text{ (DØ)}$$

Top Quark Mass in the Standard Model



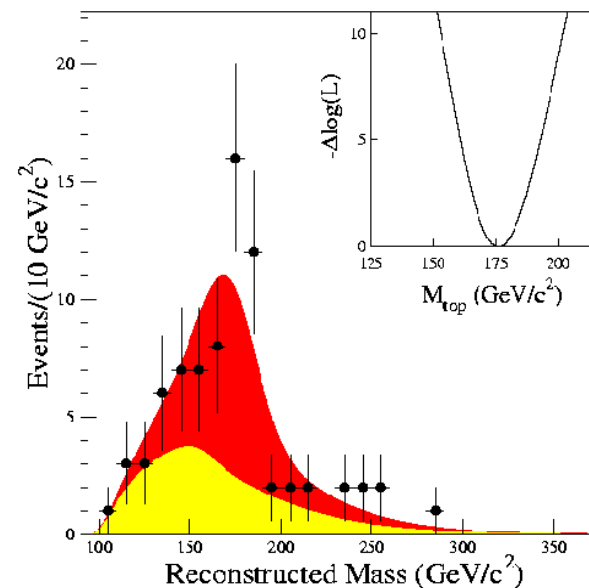
- The Standard Model predicts the Higgs mass once the W and Top mass are measured with high precision.
- In Run II we need to improve the systematic error on the mass, working on this aggressively: jets, methodology, etc.
- Expect $dM_{\text{top}} = 2-3 \text{ GeV}$ $dM_W = 20-30 \text{ MeV}$

$M(\text{top}) = 174.3 \pm 5.1 \text{ GeV}$ CDF+D0 comb.



Run I

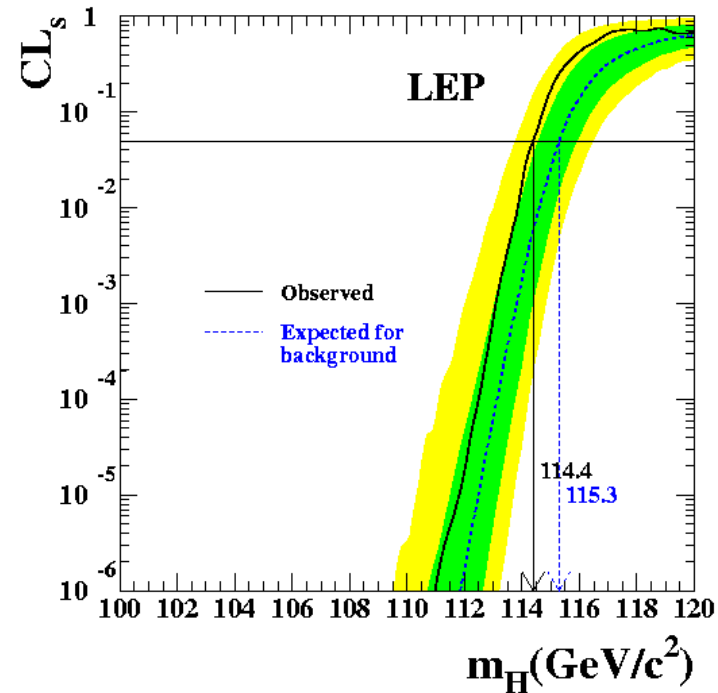
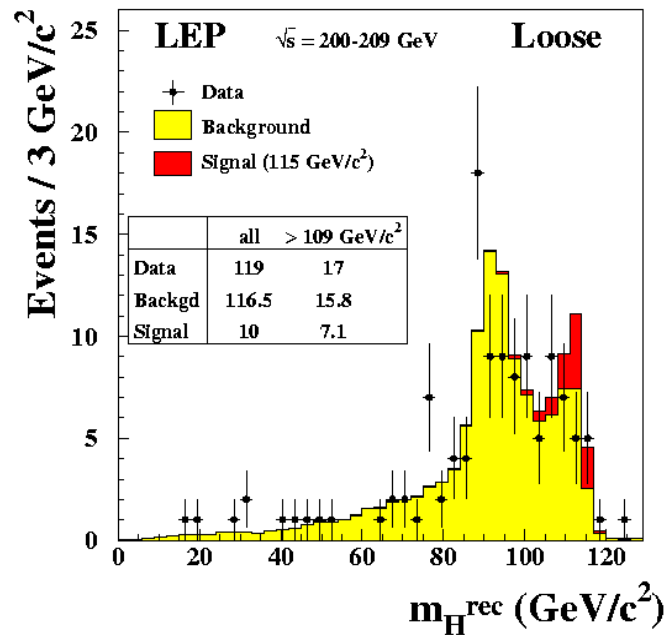
CDF Top mass measurement



Standard Higgs Search



Direct search: average of all LEP experiments:



M(Higgs) > 114.4 GeV at 95% CL

Summer 2003 LEP-SLD EWK WG Fit



Fit includes ALEPH new M_W measurement.

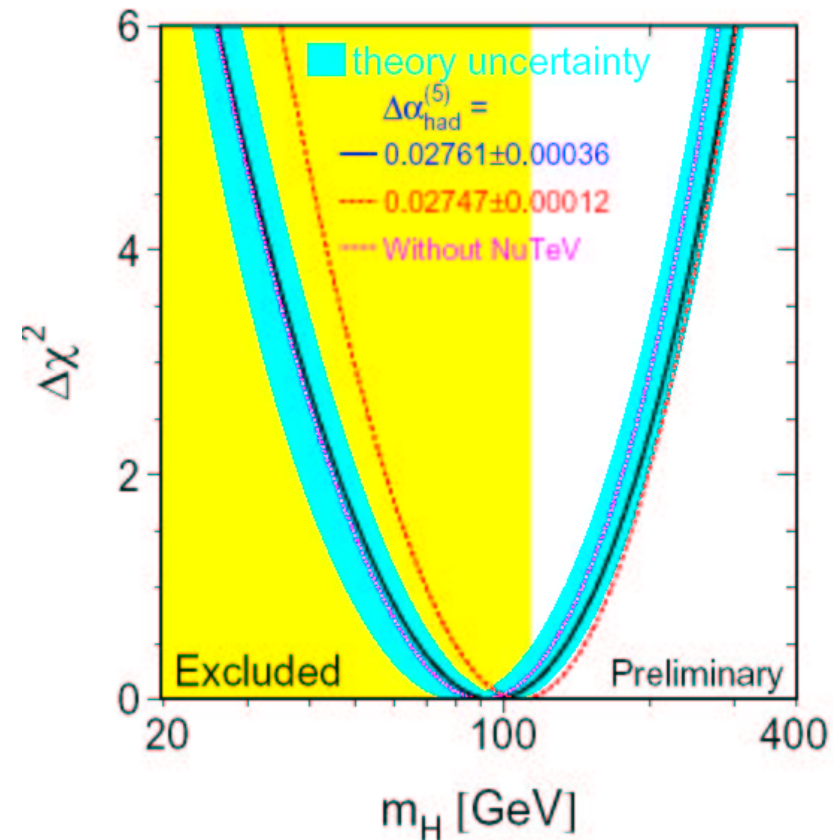
Does not include NuTeV results

$$M_H^{\text{fit}} = 91 \text{ GeV}$$

$$M_H < 202 \text{ GeV at 95\% CL}$$

$$\chi^2/\text{dof} = 16.8/14 \quad \text{probability 26.5\%}$$

Results consistent with direct Higgs mass limit



Consistency of data

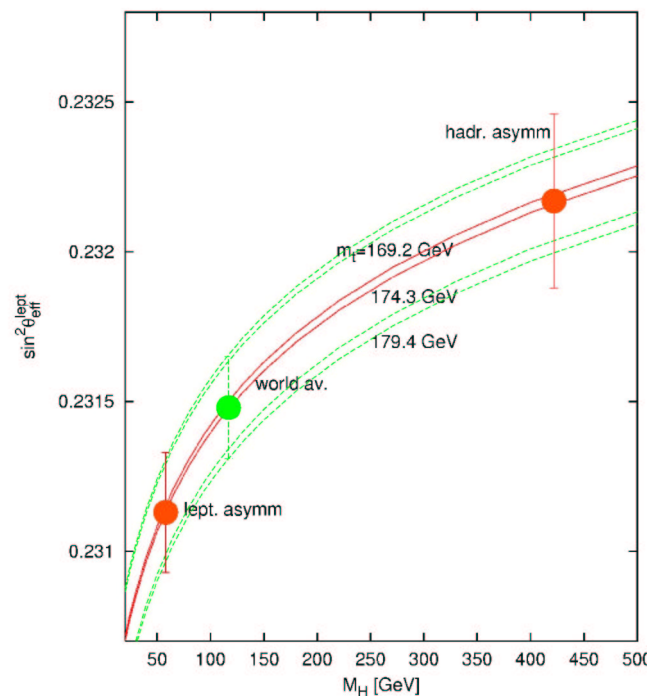


The Chanowitz argument (PRL 87,2001)

Summer 2003



Discrepancy between LR asymmetry from SLD and the LEP FB asymmetry for the bottom channel: different M_H



Taken from P. Gambino LP03 (8/2003)

Consistency of EWK data: new physics?

The Chanowitz argument



without $A_{FB}(b)$, the M_H fit is very good,

$M_H = 42 \text{ GeV}$, $M_H < 120 \text{ GeV}$ at 95%CL

but somewhat in conflict with direct lower bound $M_H > 114.4 \text{ GeV}$

- Is it a statistical fluctuation, or a systematic effect not included?
- Does this indicate new physics?

If true, not difficult to find NP that mimics a light Higgs.

Non-trivially, SUSY can do that with light sleptons, $\tan\beta > 4$

Altarelli, Caravaglios, Giudice, Gambino, Ridolfi

JHEP 2001

Statistically weak : is 5% probability for $M_H > 114 \text{ GeV}$ small enough ?

Very sensitive to M_t

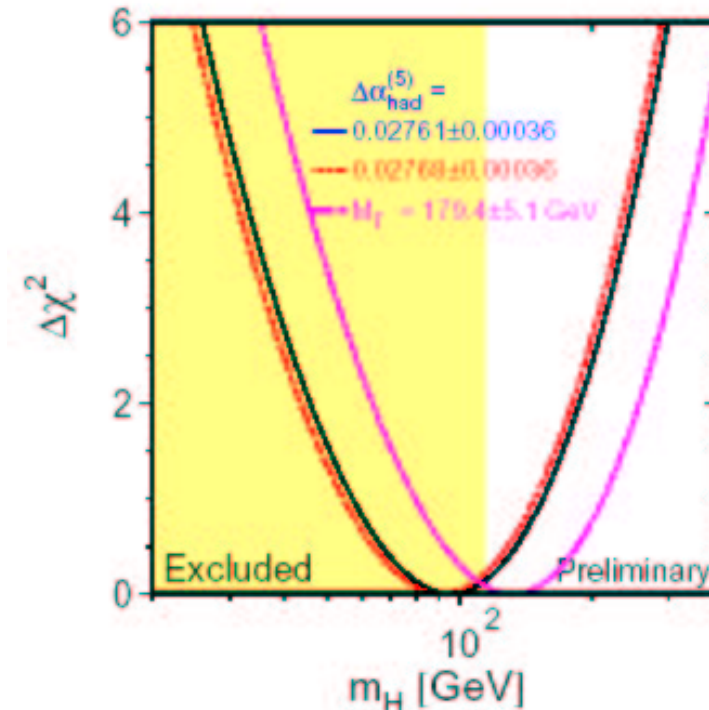
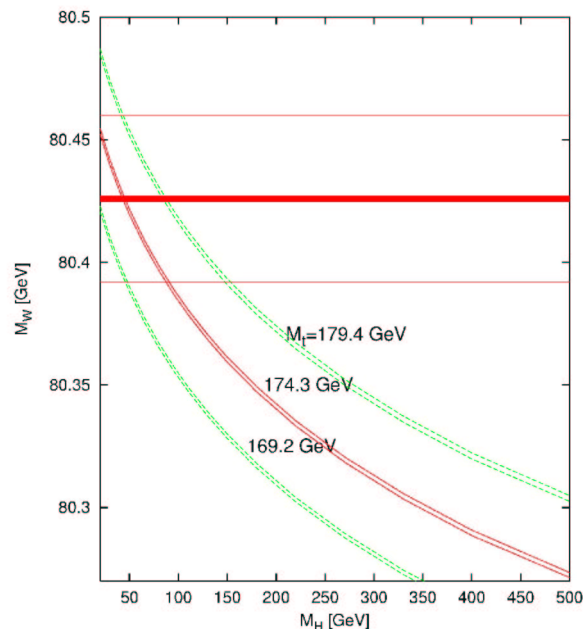
Top mass precision is crucial



A shift of the top mass by 1 s (to 179.4 GeV) to higher masses and the above inconsistency would be alleviated.

Similarly a 5 GeV shift would shift the 202 GeV upper limit for the global fit to 280 GeV.

A factor 2 improvement in δM_t would lower the upper bound on M_H by ~ 35 GeV



Top Quark : what we have learned?



- ★ Production cross sections: agrees with Standard Model
- ★ Top decays: no deviation from the Standard Model
- ★ Very large mass: Yukawa coupling at its maximum (=1)
 $M_{\text{top}} = 1 \cdot v/\sqrt{2} = \text{Higgs vacuum expectation value}$
- ★ Why the top quark couples so strongly to the Higgs?
- ★ The top quark may be a window to the origin of fermion masses.
- ★ Expect at least 50 times more events than in Run I.
Need a factor two smaller error on the top mass. Stay tuned!