Weak Decays, CKM, CP Violation

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Presented at the
International Conference on
Weak **I**nteractions and **N**eutrinos
Delphi, Greece, June 6-11, 2005

Flavor Physics

- The study of flavor physics has proved another success of the standard model.
  - The goal is no longer to test the standard model,
  - but rather to look for effects beyond the standard model.

- I will review some test of the standard model and what I think will be of interest in the future.
- Many results from BaBar, Belle, CLEO, CDF, D0, KTeV...
  - I will only be able to discuss a small number of results from this program

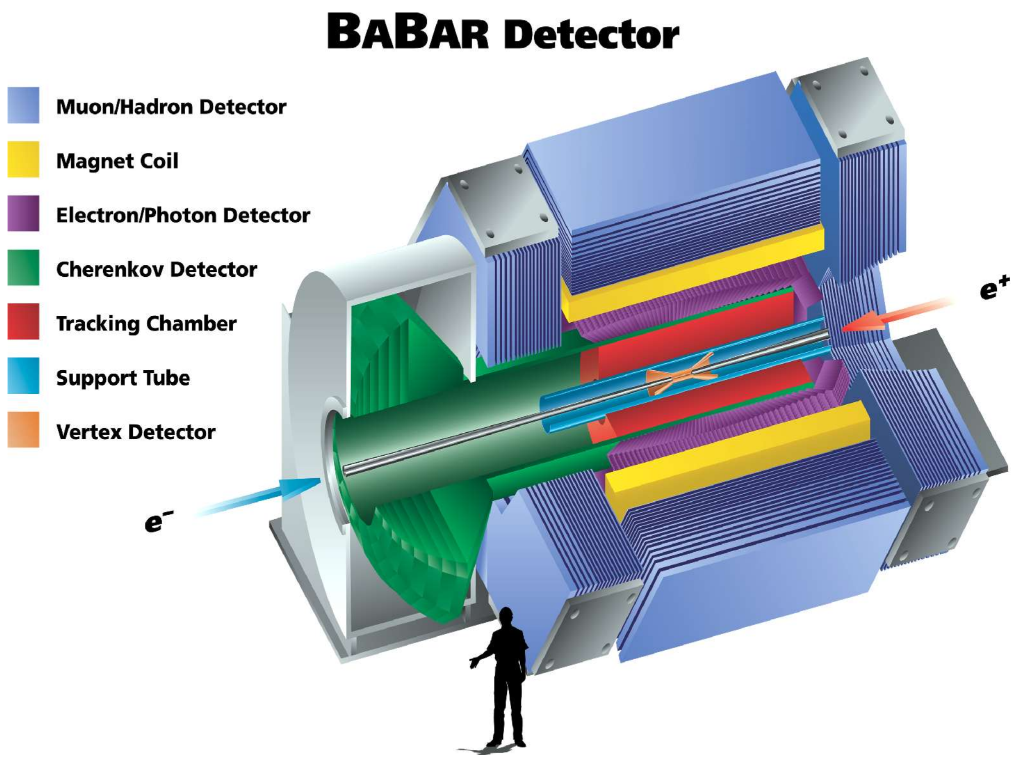
Outline

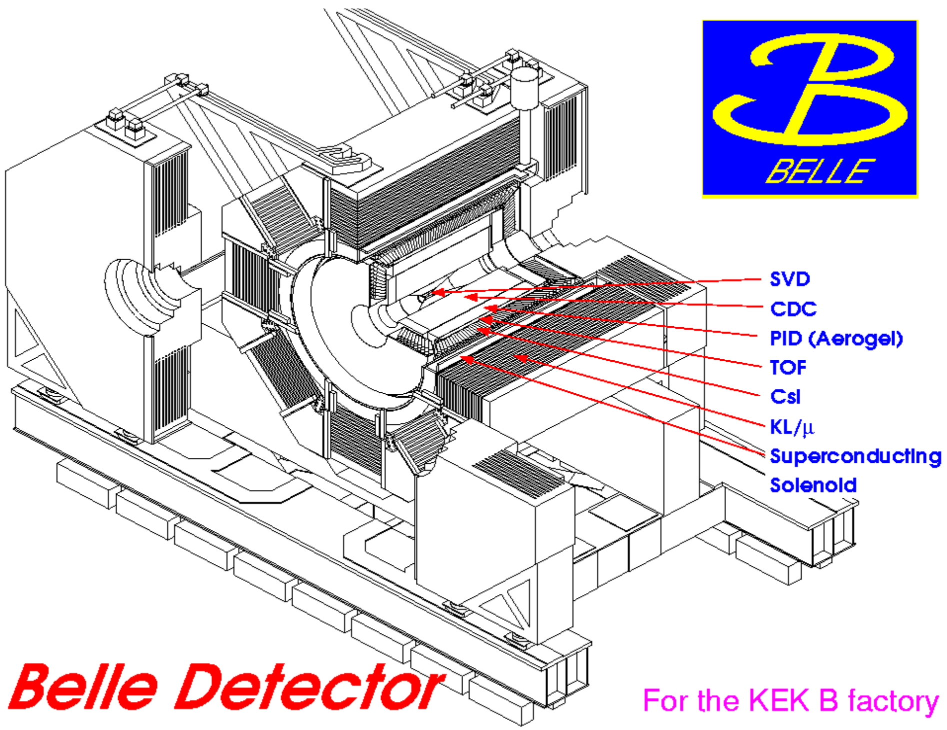
- Overview of experiments
- Recent progress on magnitudes of CKM matrix elements
  - V_{us}, V_{cb}, V_{ub}, V_{td}
- CP violation in B decays
  - Measurements of , , and
- Rare decays
- Future experiments

B-Factory Experiments

Similar capabilities:

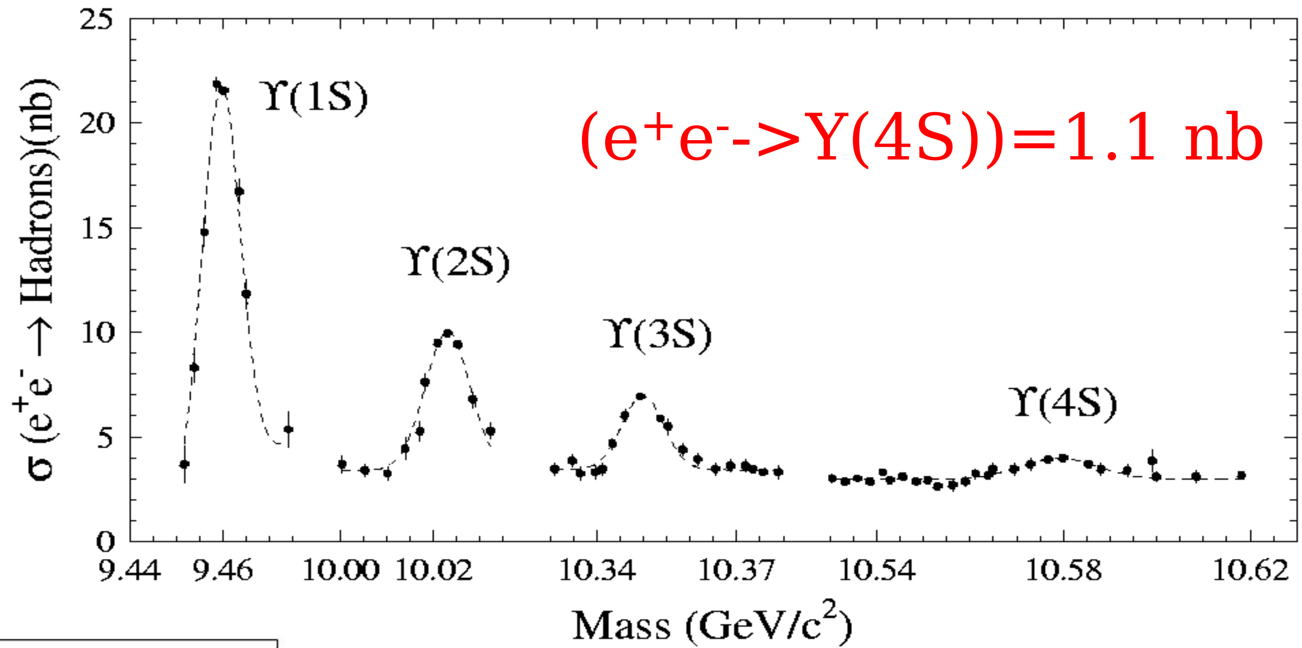
- Si Vertex Detector
- Driftchamber for p meas.
- CsI for EMC
- Cherenkov detector for /K separation
- Muon detection



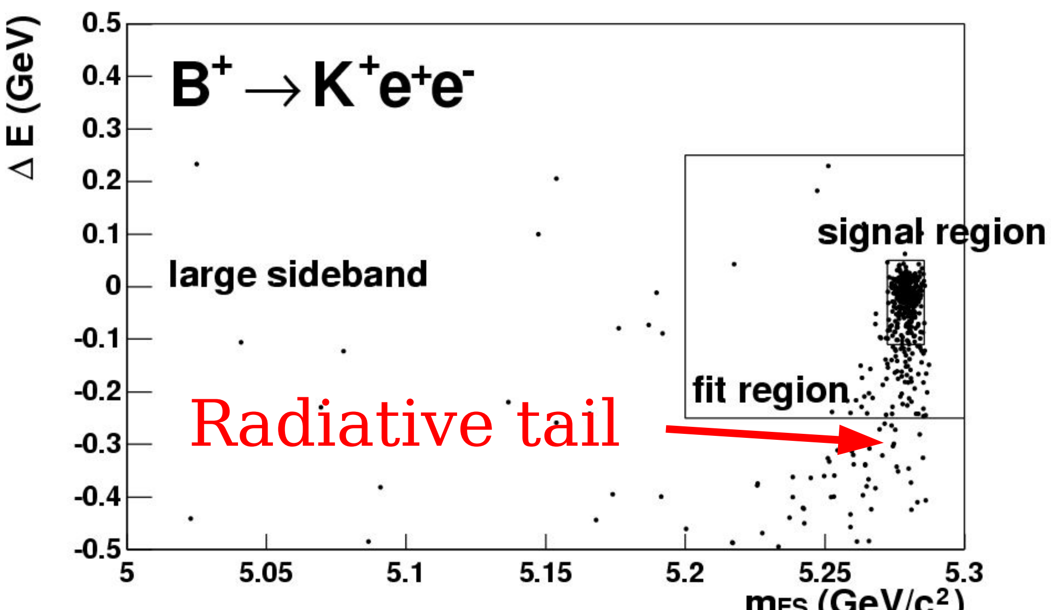


For the KEK B factory

B Reconstruction at Υ(4S)



$$\Delta E = \sum_i \sqrt{p_i^2 + m_i^2} - E_{\text{beam}}$$

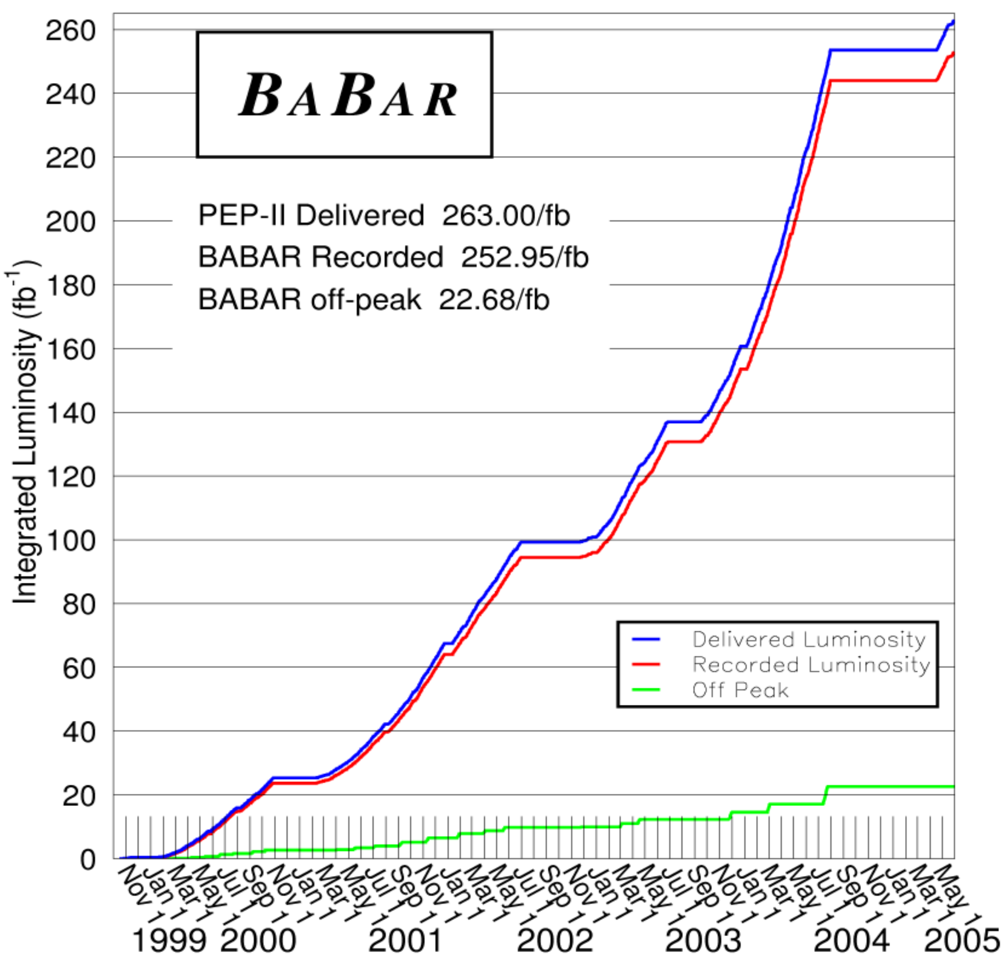


$$m_{\text{ES}} = \sqrt{E_{\text{beam}}^2 - \left(\sum_i p_i\right)^2}$$

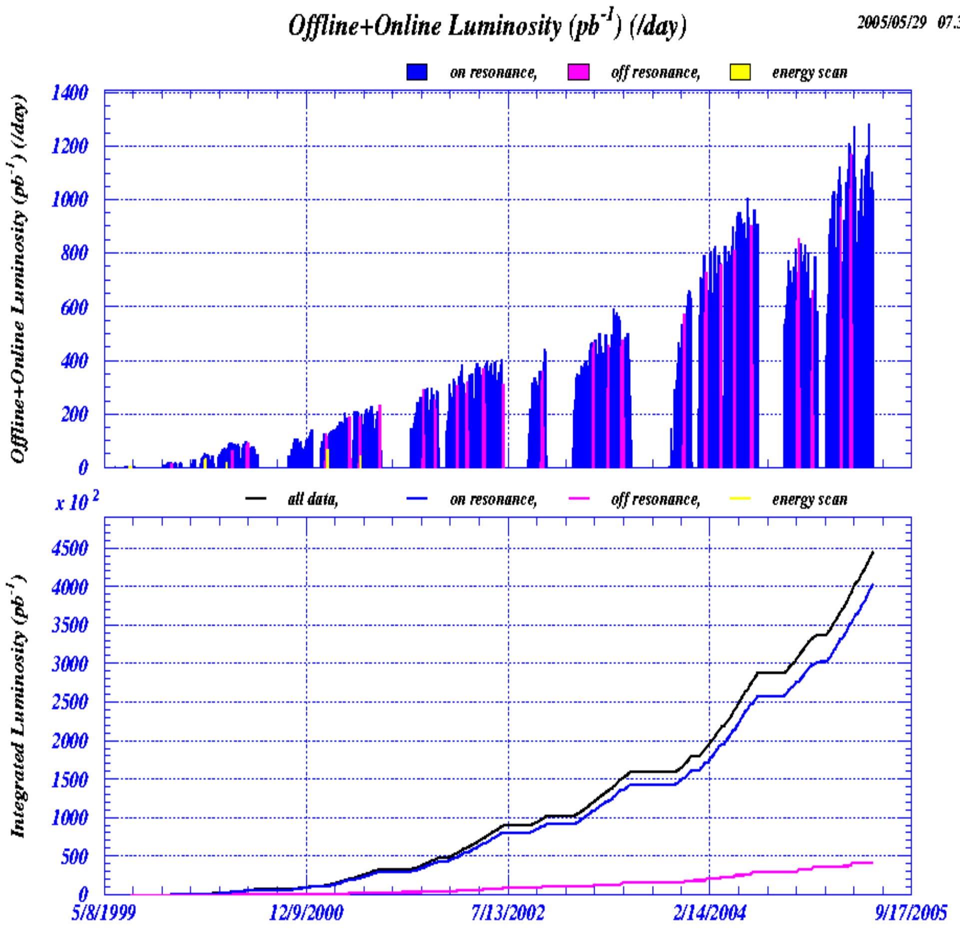
B-Factory Luminosities

Both B-factories have been very successful

PEP-II 250 fb^{-1} 2005/05/31 10.34

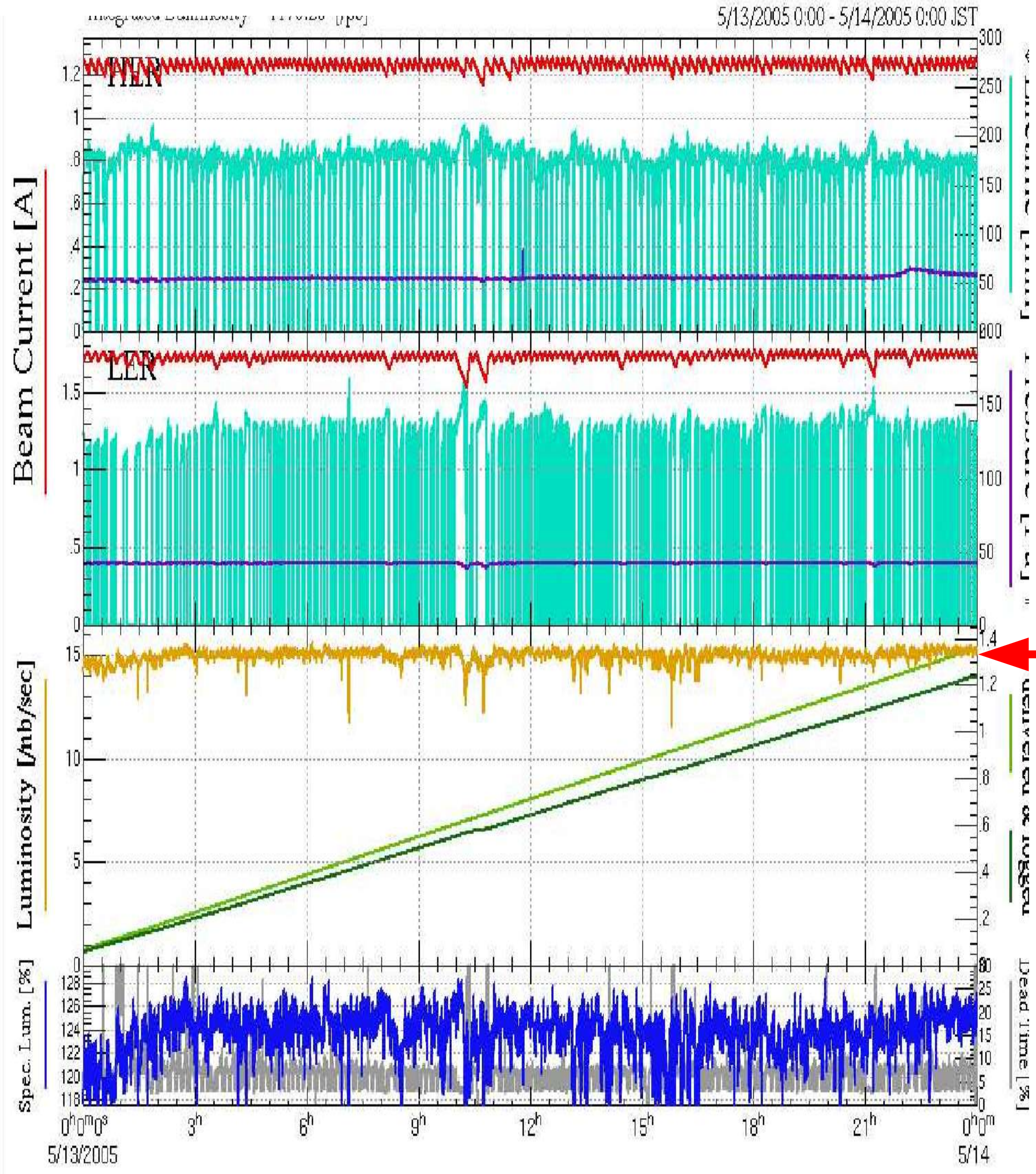


KEK-B 450 fb^{-1}



Continuous Injection

24 hours at KEK-B



- Both PEP-II and KEK-B run with continuous injections.

$1.5\times10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-2}$

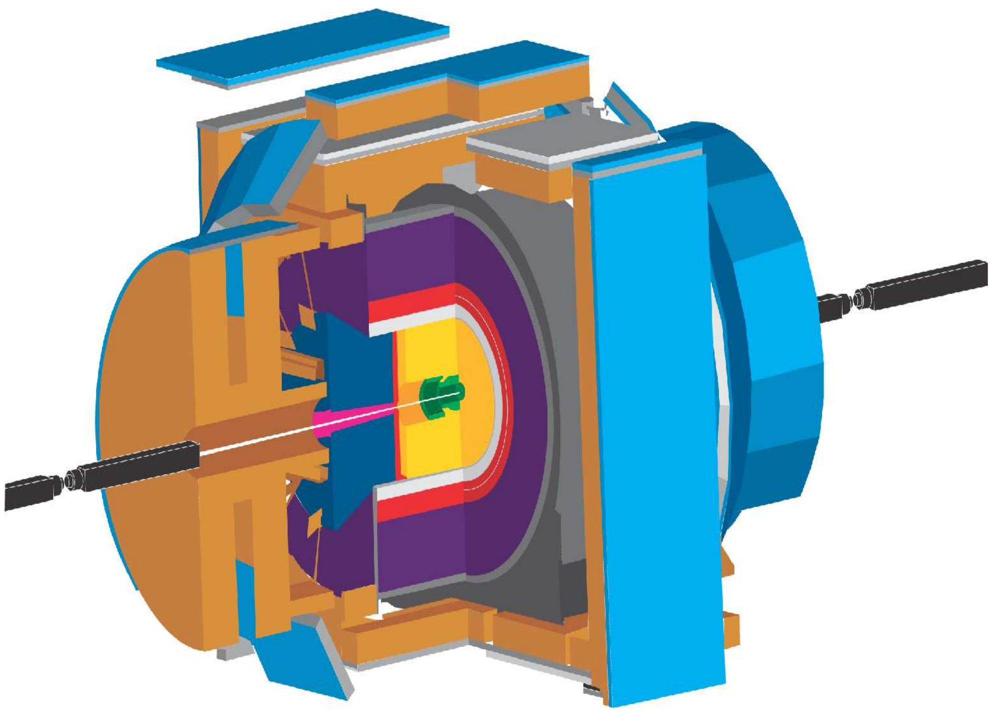
Experiments at Tevatron

- Run II started March 2001
- So far recorded ~600 pb^{-1}
- Large b cross-section ~30 b

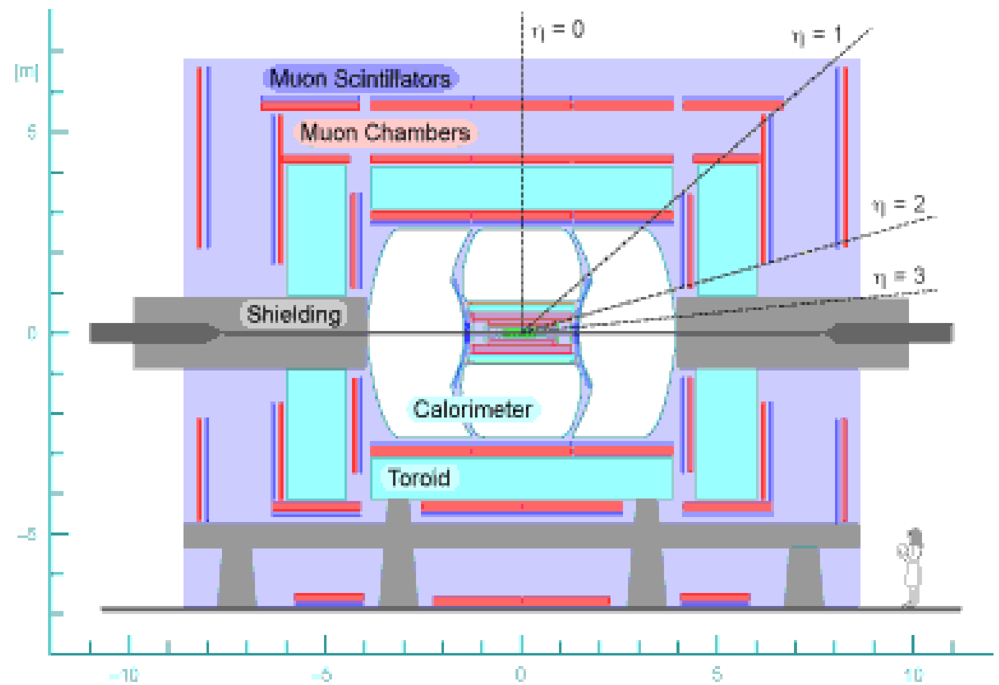
Major upgrades include

- CDF: Vertex information in trigger, and better coverage
- D0: Tracking, with vertexing, in magnetic field

CDF



D0



CKM Matrix

$$V_{CKM} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \approx \begin{bmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{bmatrix} + O(\lambda^4)$$

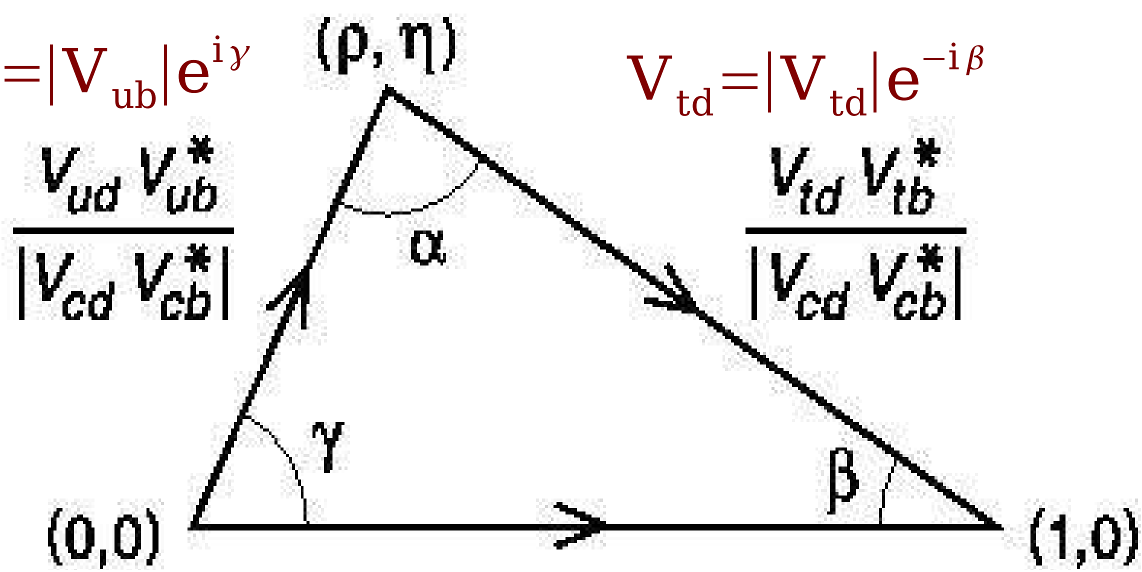
- Unitary: $1 = V^*_{CKM} V_{CKM}$
  - Unitarity in 1st row

    $$1 = |V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2$$

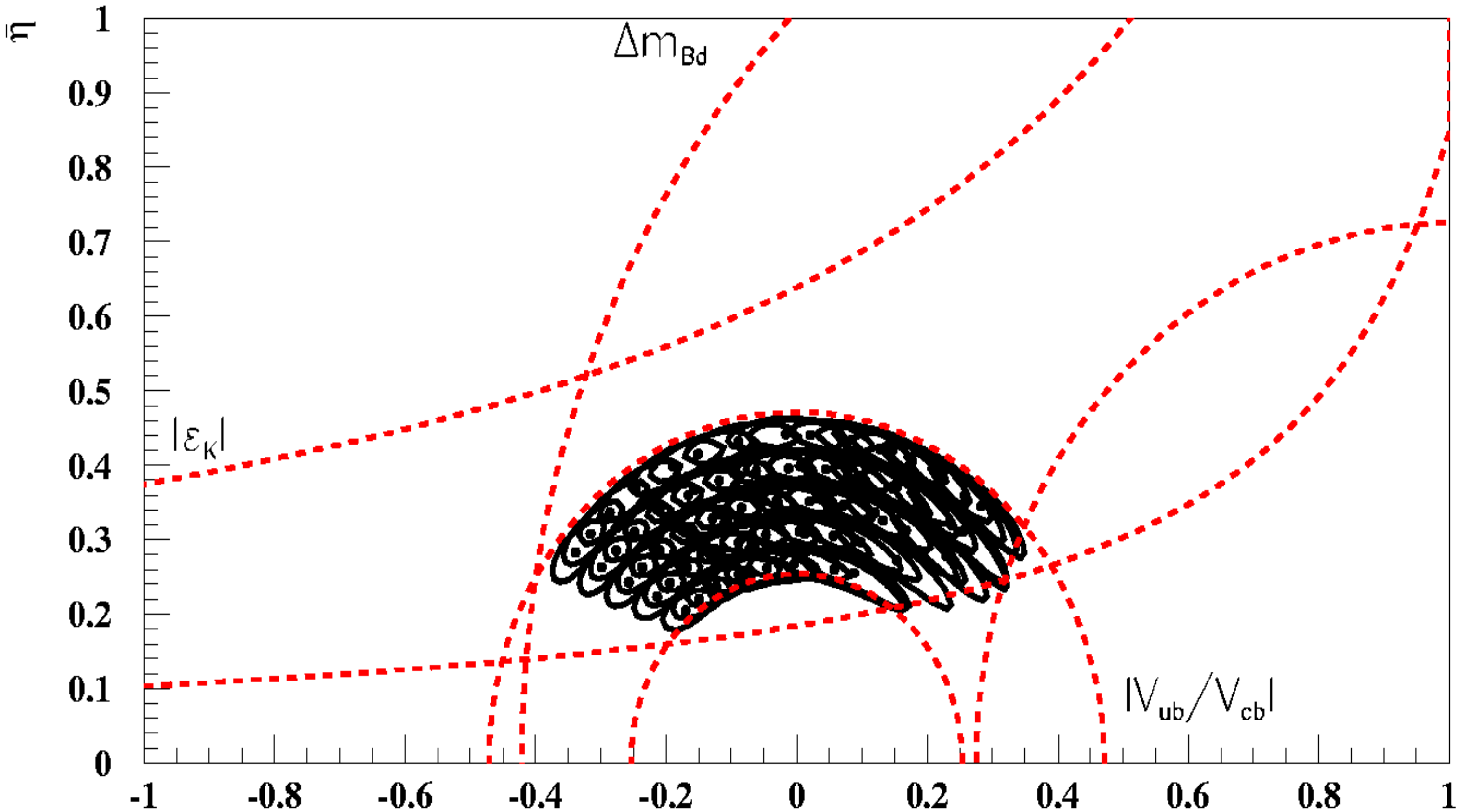
  - Unitarity 1st and 3rd row

    $$0 = V_{ud} V^*_{ub} + V_{cd} V^*_{cb} + V_{td} V^*_{tb}$$

$V^*_{ub} = |V_{ub}| e^{i\gamma}$ $\qquad$ $V_{td} = |V_{td}| e^{-i\beta}$

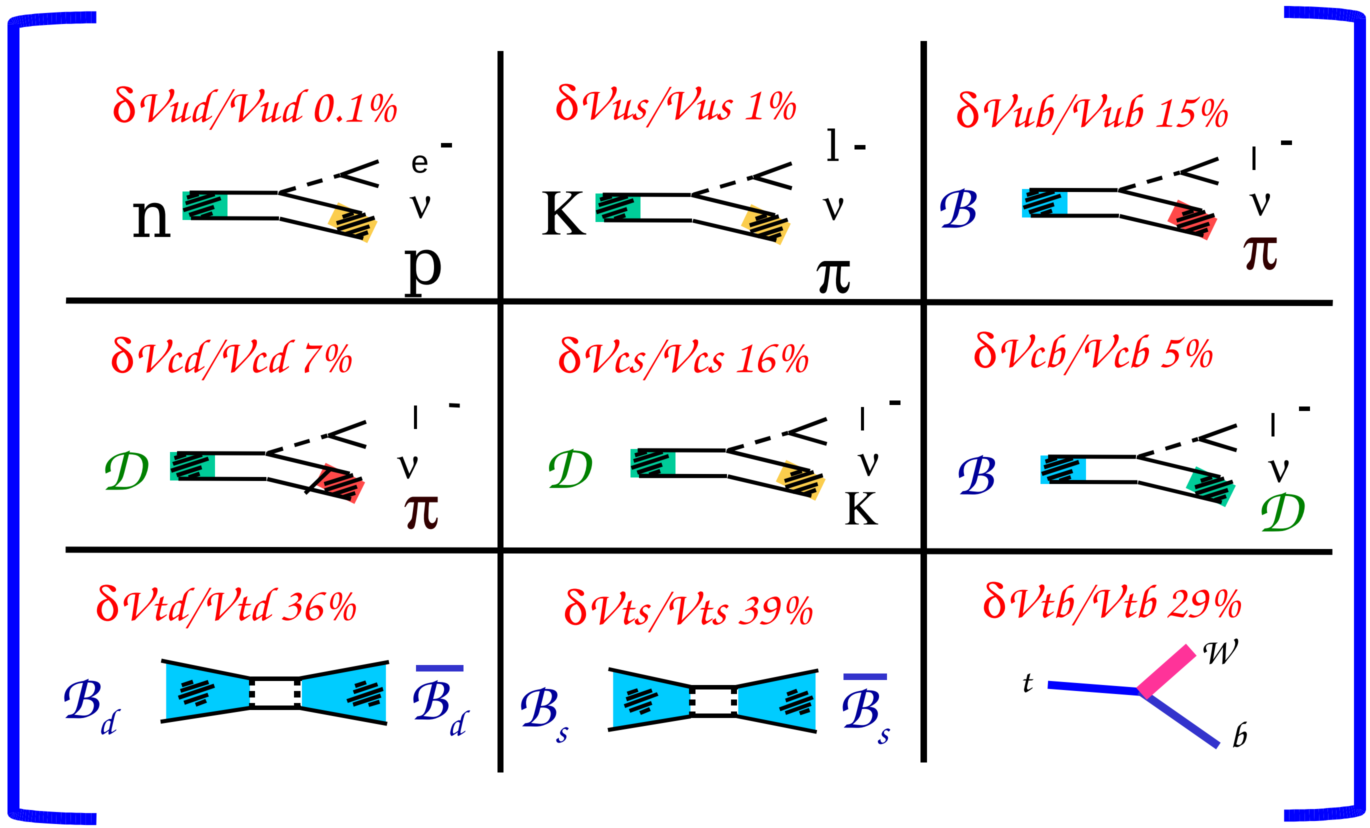


Pre B-factory UT (1998)



- Measurements limited by theory

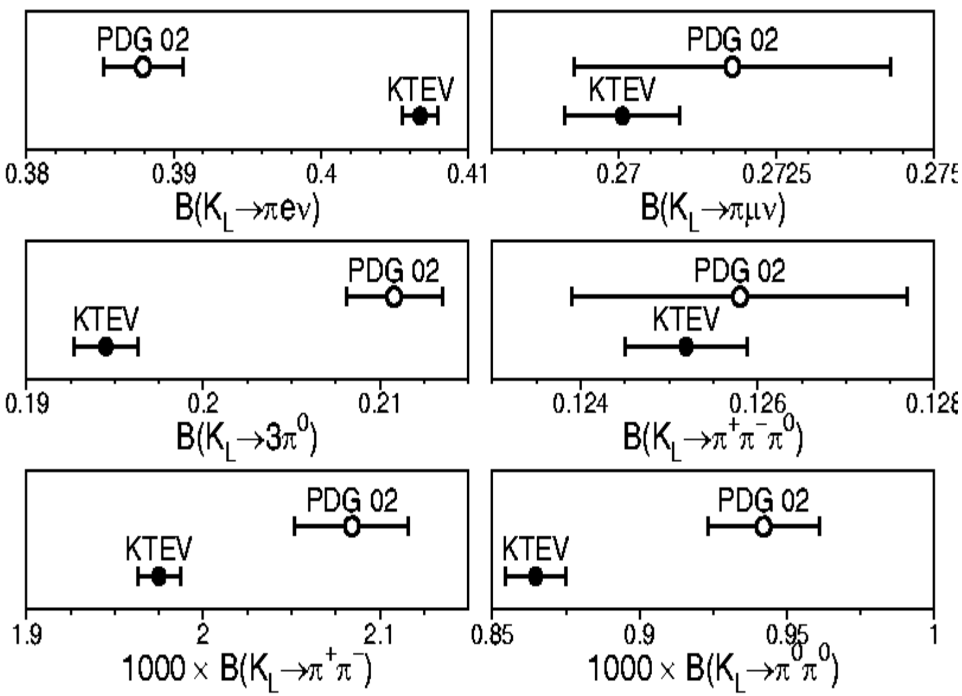
Magnitude of CKM Matrix Elements

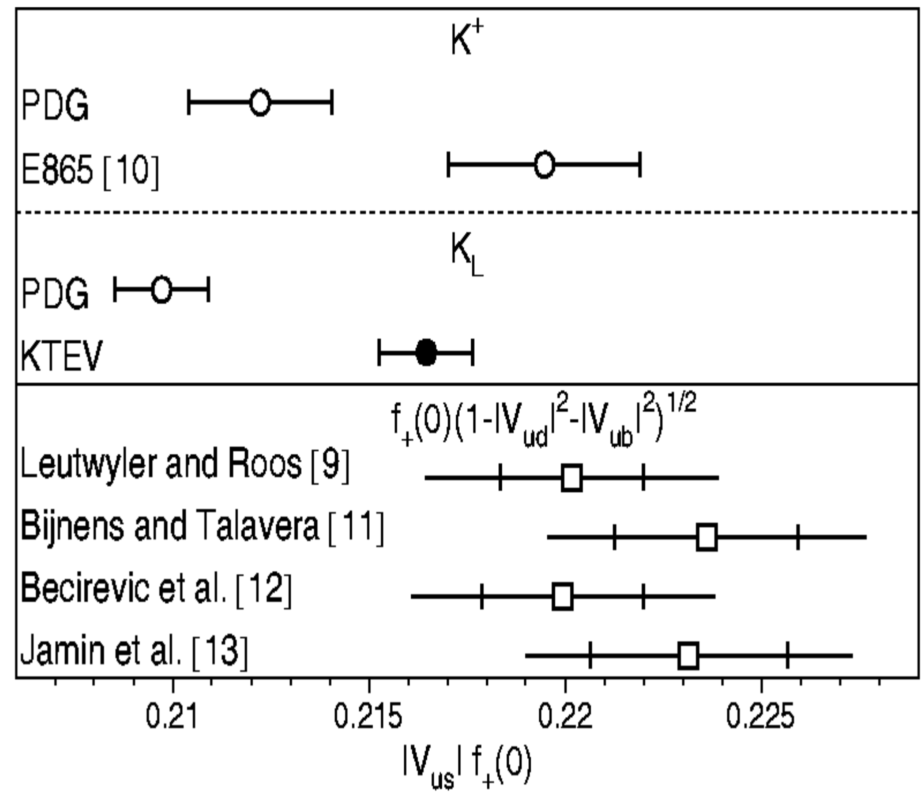


- Current status of magnitudes

Recent V_{us} Changes (KTeV)

- V_{us} determined from K_L decays
- Large changes in K_L branching fractions from KTeV
- Changed V_{us} by 5 – detailed treatment of radiation
  - PDG was average of many (old) measurements

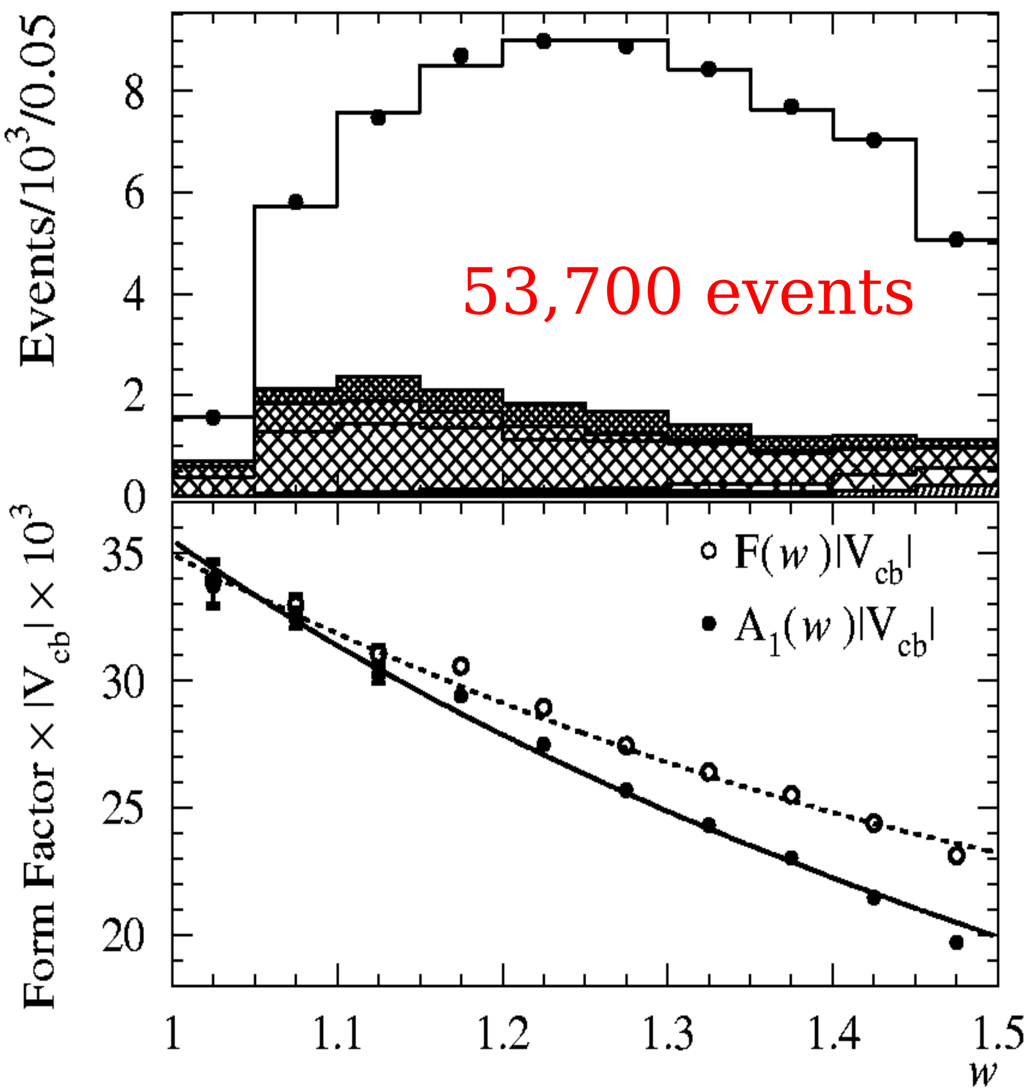




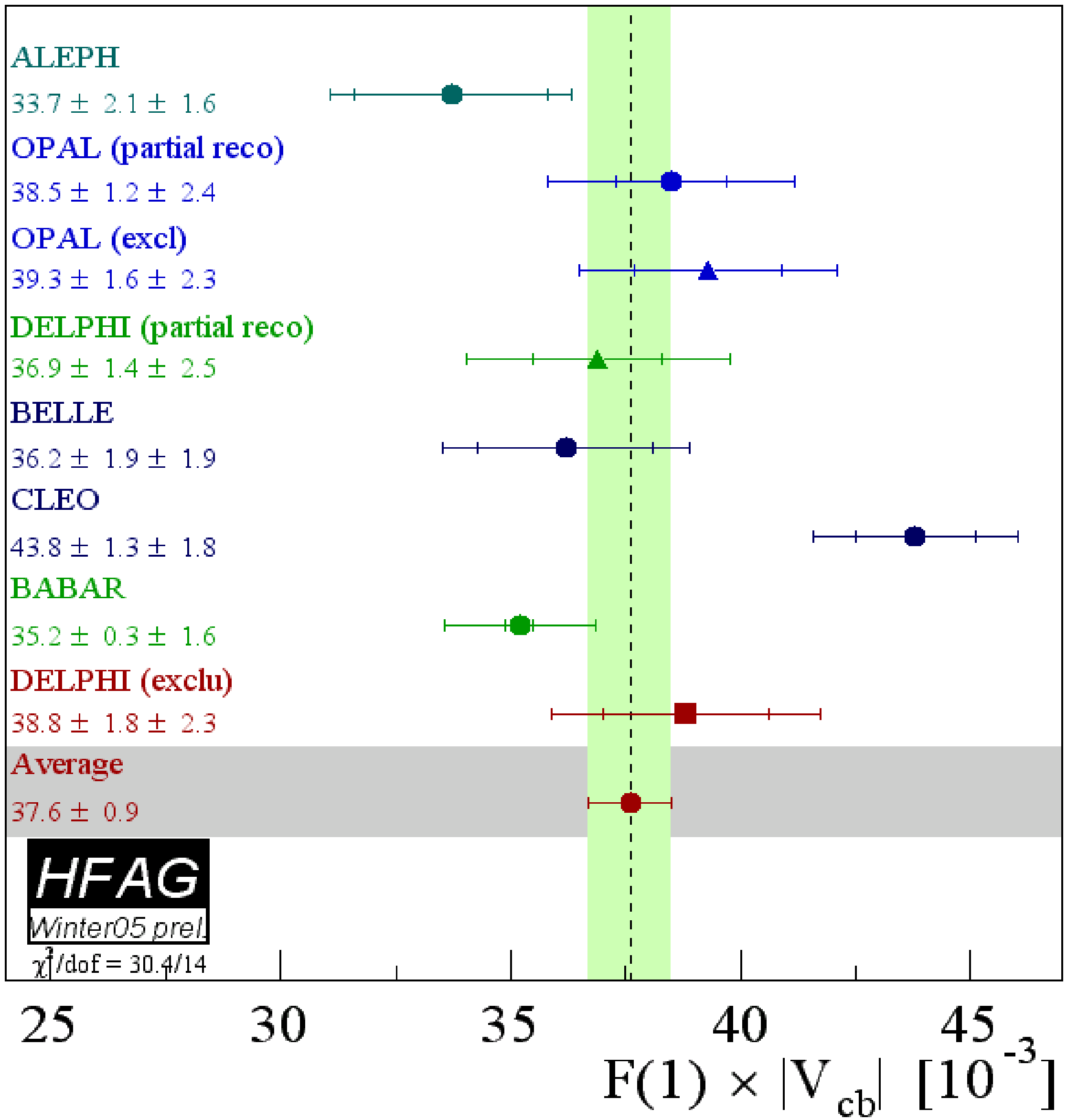
$|V_{cb}|$ from $B \to D^*l$

- HQET allow determination of the form factor in the zero recoil configuration.
- Rate is zero at this point so one has to extrapolate.

BaBar 79 fb^{-1}



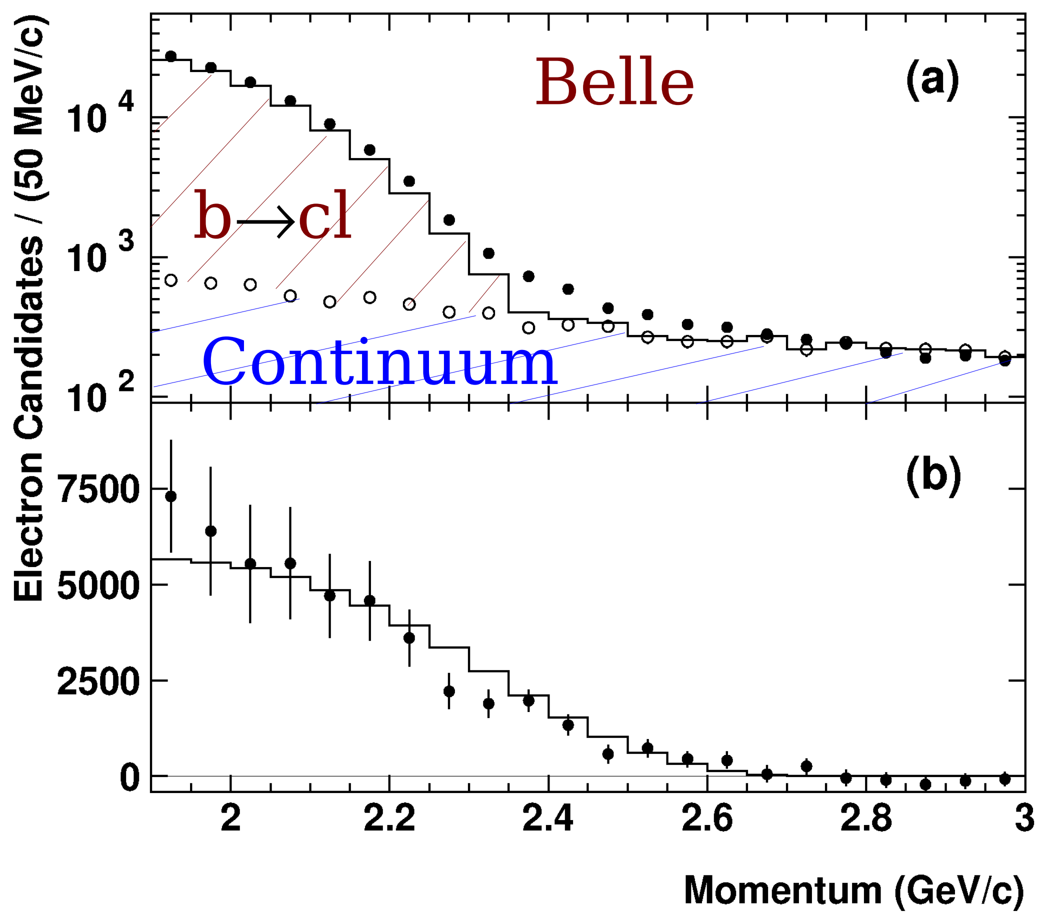
$|V_{cb}|$ from $B \to D^* l$



- With $F(1) = 0.91 + 0.04$
- We have
  $V_{cb} = (41.3 \pm 1.0 \pm 1.8) \times 10^{-3}$
- This is in good agreement with determinations from inclusive $b \to cl$

$|V_{ub}|$ from Lepton Endpoint

- The first evidence for a nonzero $|V_{ub}|$ came from the lepton endpoint – beyond the charm endpoint.
- BaBar and Belle has high statistics measurements.
- Though the inclusive rate for $b \rightarrow ul\nu$ can be calculated, the rate at the endpoint is harder to predict.
- However, use of 'shape' functions from $b \rightarrow s\gamma$ allows rather precise extraction of V_{ub}

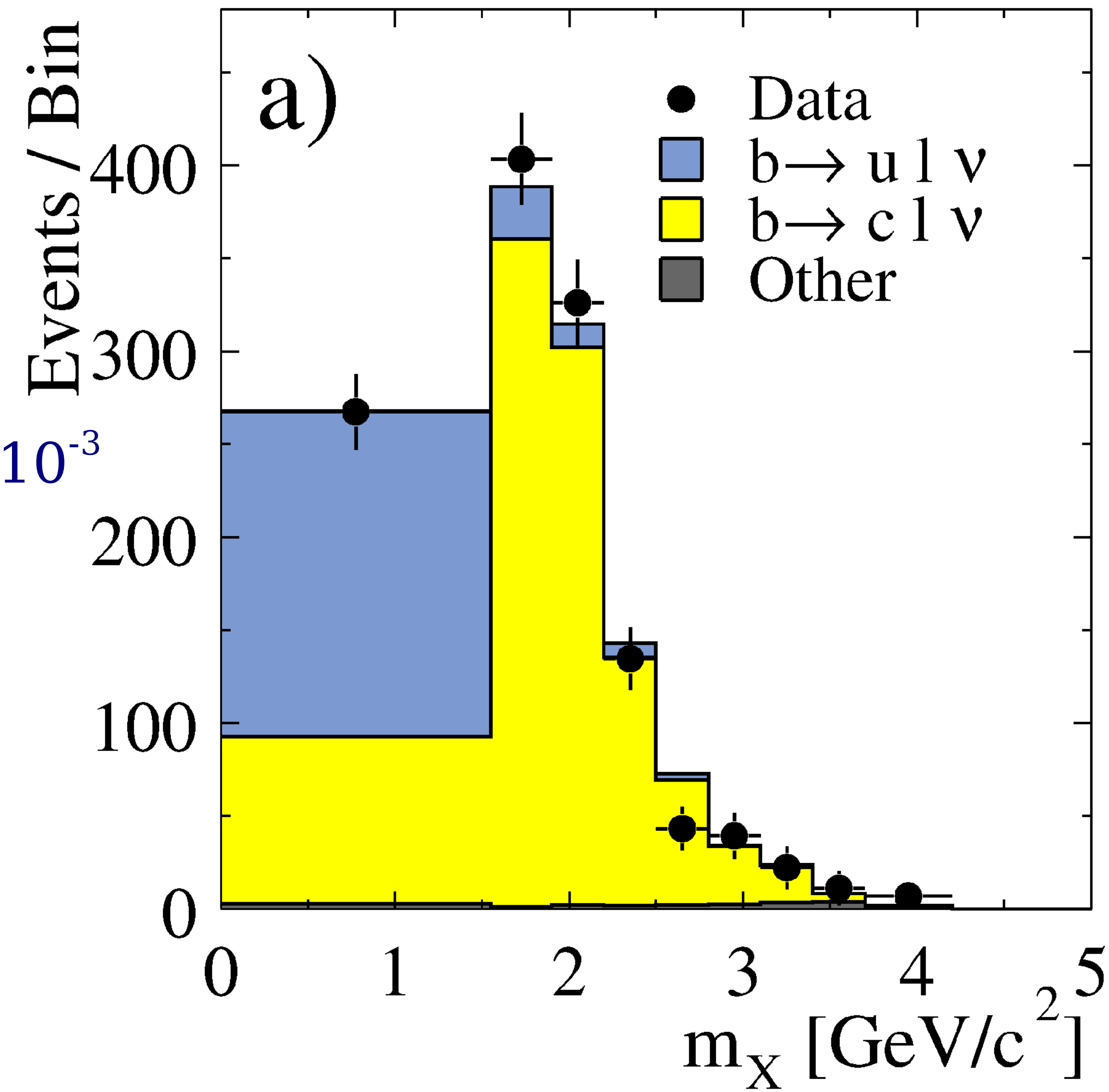


$V_{ub}=(4.46\pm0.23\pm0.61)\times10^{-3}$

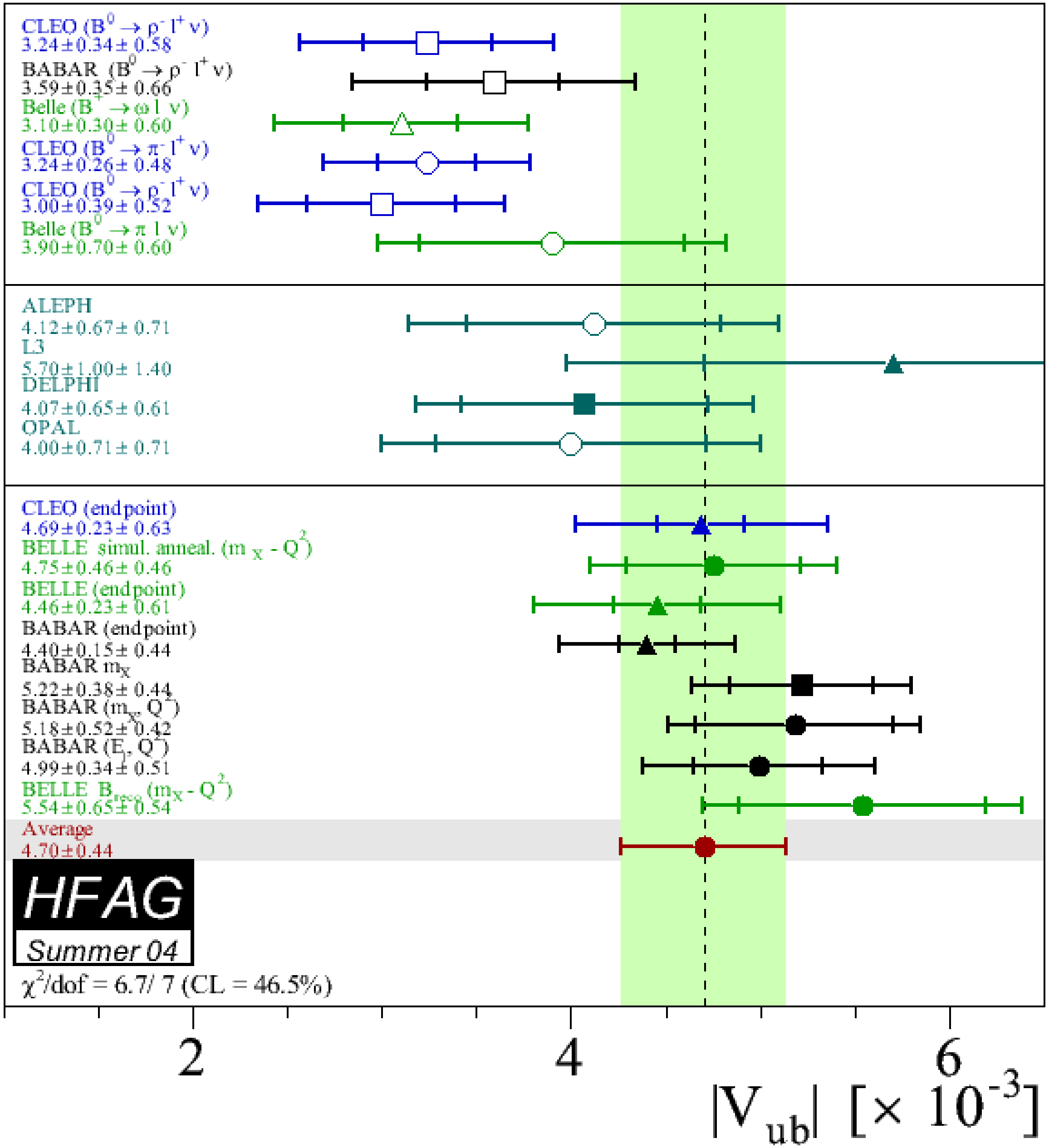
BaBar $|V_{ub}|$ from m_X

- Can also use the hadronic mass to separate signal from the large $b \to cl$ background.

$V_{ub}=(5.22 \pm 0.36 \pm 0.44) \times 10^{-3}$



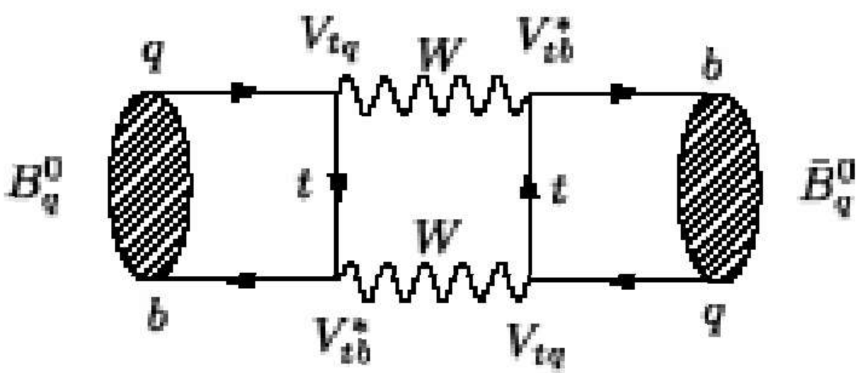
$|V_{ub}|$ Summary



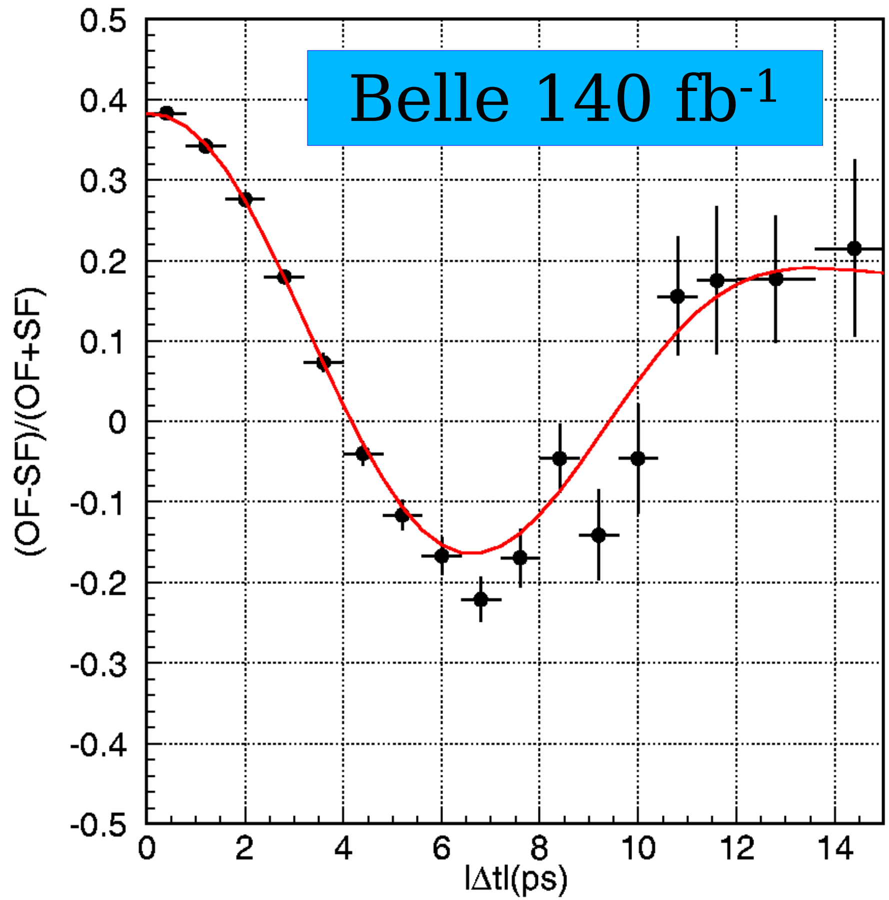
- Exclusive modes prefers smaller V_{ub}
- Uses model calculation or lattice for form factors.
- CLEO-c can measure form factors in D→(,)l .

B_d Mixing

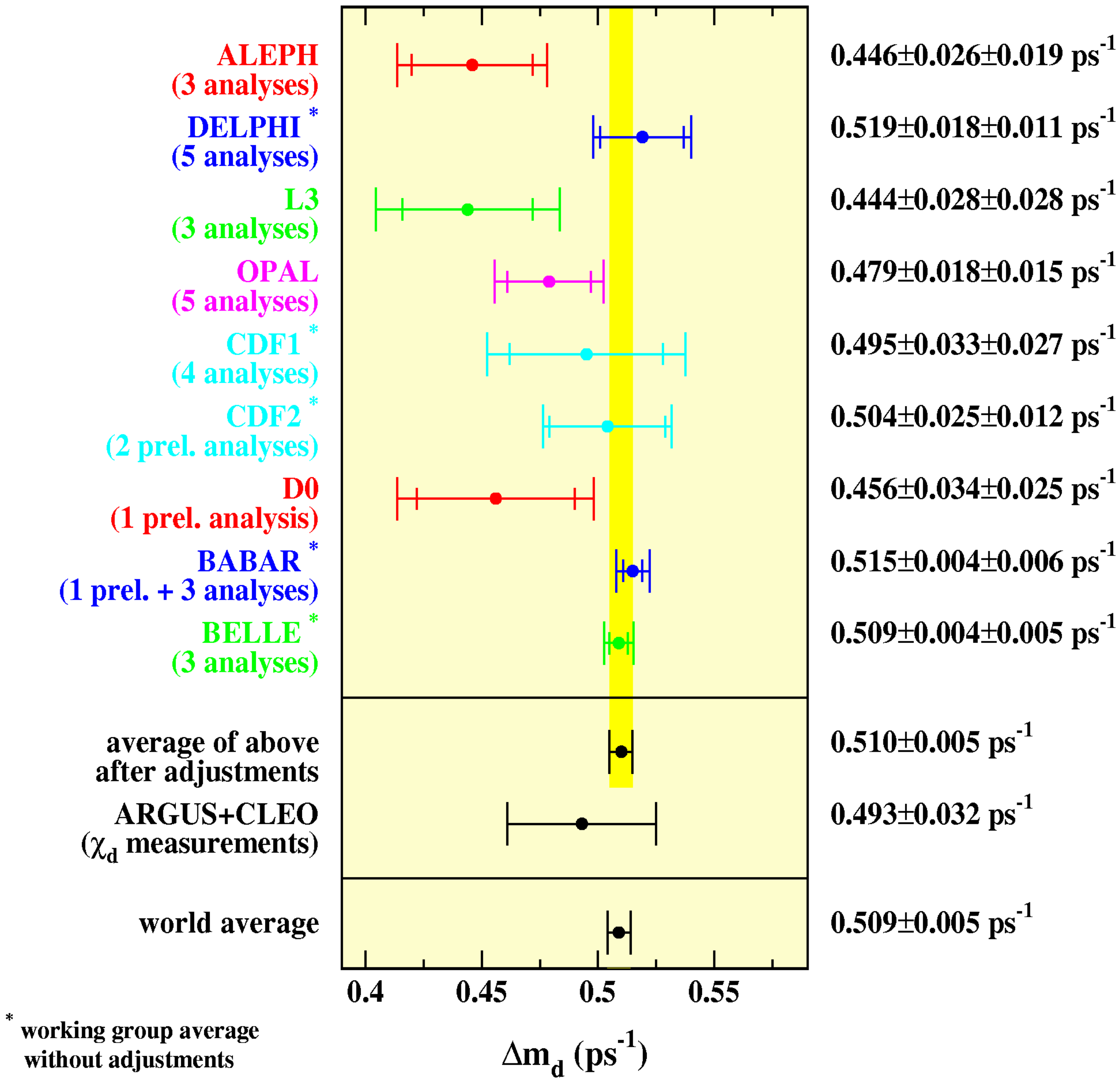
- First observed by ARGUS in 1987
  - Using events with same sign leptons
- Now dominated by Belle and BABAR doing a lifetime analysis.



$$P_{mix}=\frac{e^{-|\Delta t|/\tau_B}}{8\tau_B}(1-\cos(\Delta M \Delta t))$$



B_d Mixing

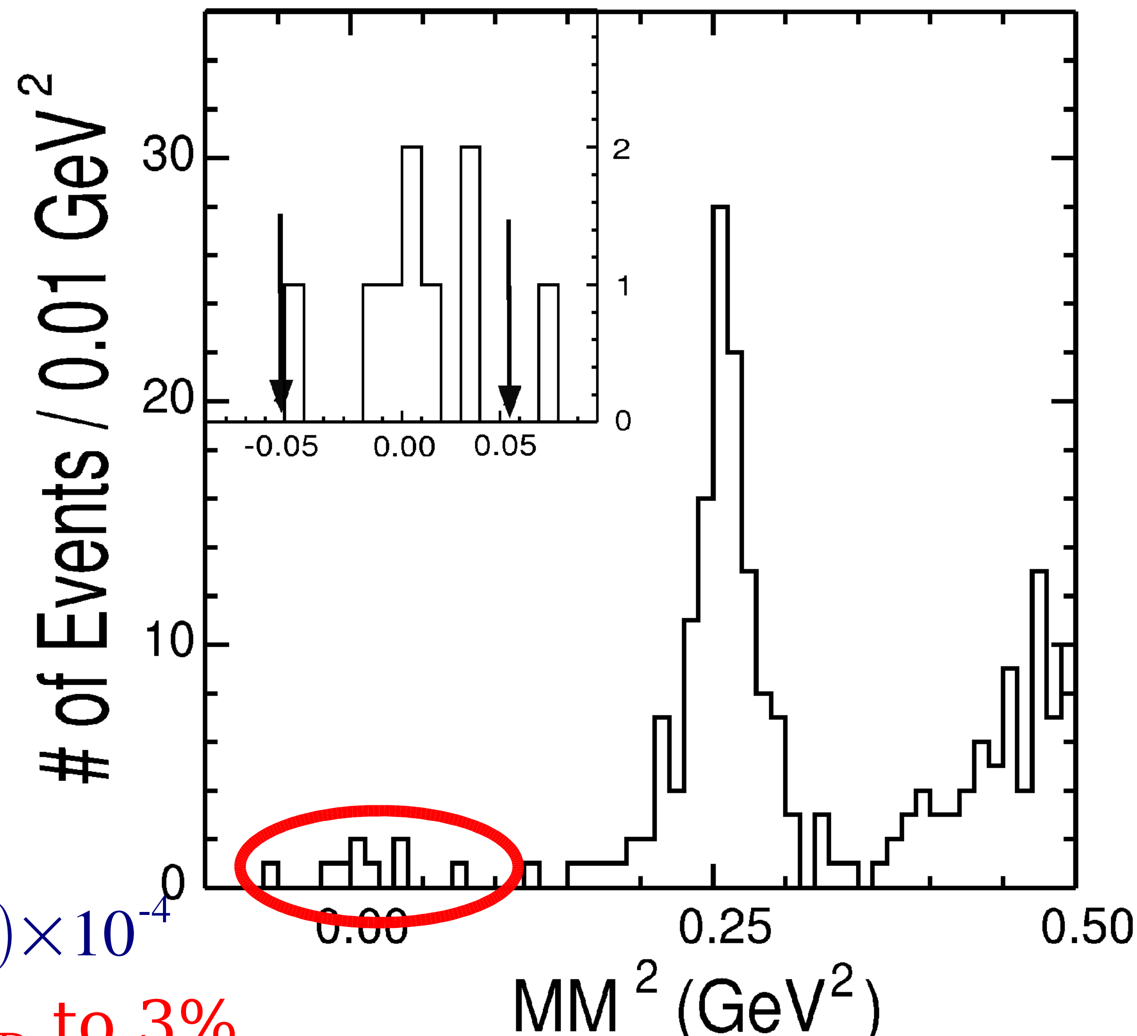

ALEPH
(3 analyses)
0.446±0.026±0.019 ps-1
DELPHI *
(5 analyses)
0.519±0.018±0.011 ps-1
L3
(3 analyses)
0.444±0.028±0.028 ps-1
OPAL
(5 analyses)
0.479±0.018±0.015 ps-1
CDF1 *
(4 analyses)
0.495±0.033±0.027 ps-1
CDF2 *
(2 prel. analyses)
0.504±0.025±0.012 ps-1
D0
(1 prel. analysis)
0.456±0.034±0.025 ps-1
BABAR *
(1 prel. + 3 analyses)
0.515±0.004±0.006 ps-1
BELLE *
(3 analyses)
0.509±0.004±0.005 ps-1
average of above
after adjustments
0.510±0.005 ps-1
ARGUS+CLEO
(χd measurements)
0.493±0.032 ps-1
world average
0.509±0.005 ps-1
0.4
0.45
0.5
0.55
* working group average
without adjustments
Δmd (ps-1)

Extraction of $|V_{td}|$

$$\Delta m_d = \frac{G_F^2}{6} M_B M_W^2 |V_{td} V_{tb}^*|^2 \eta_B S_0(x_t) f_B^2 B_B$$

CLEO-c $D^+ \to \quad ^+$ (57 pb^{-1})

- f_B and and B_B are nonperturbative.
- Dominated by theory error in f_B and B_B
  - Lattice error ~15%
- CLEO-c can measure f_D and f_{Ds} which allow calibration of Lattice calculations



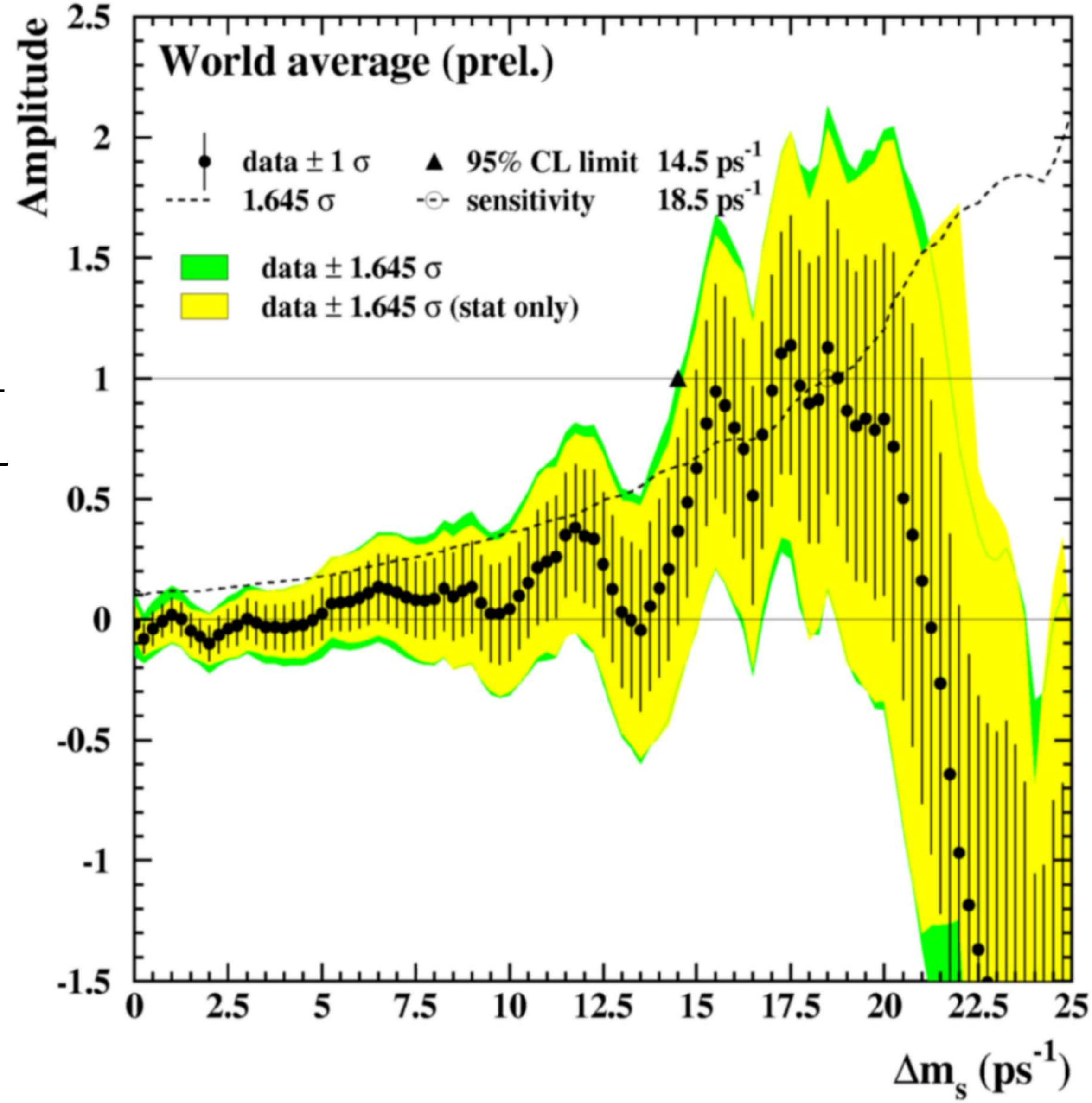
$$f_{D^+} = (202 \pm 41 \pm 17)\,\mathrm{MeV}$$

$$Br(D^+ \to \mu^+ \nu) = (3.5 \pm 1.4 \pm 0.6) \times 10^{-4}$$

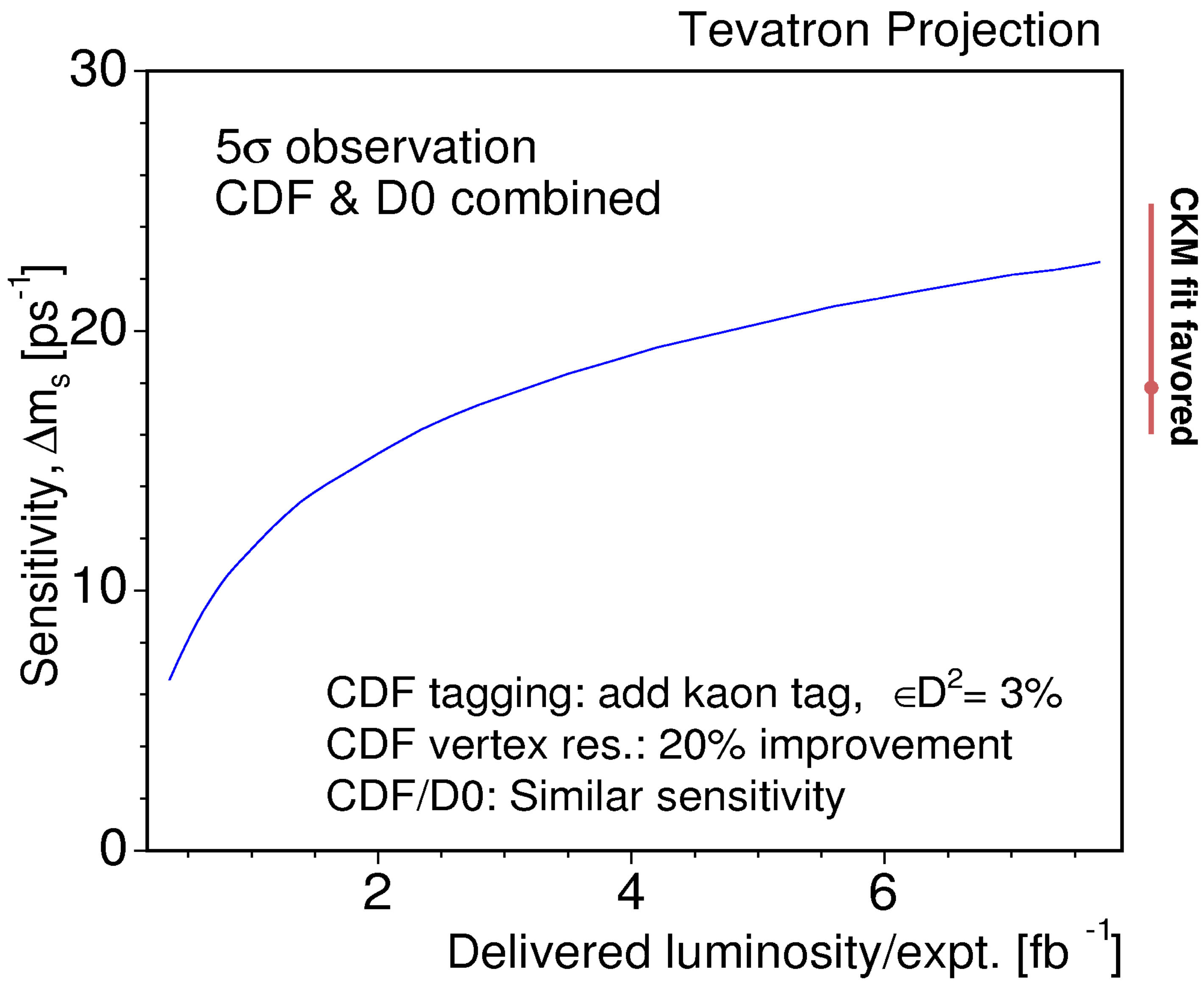
CLEO-c should measure f_D to 3%

B_s Mixing

- Searched for by SLD, LEP exp., CDF/D0
- Amplitude for mixing plotted.
- SM: m_s about 20 ps^{-1}
- Current limit: 14.5 ps^{-}
- CDF run II limit: 7.5 ps^{-1}



CDF/D0 Prospects on B_s Mixing

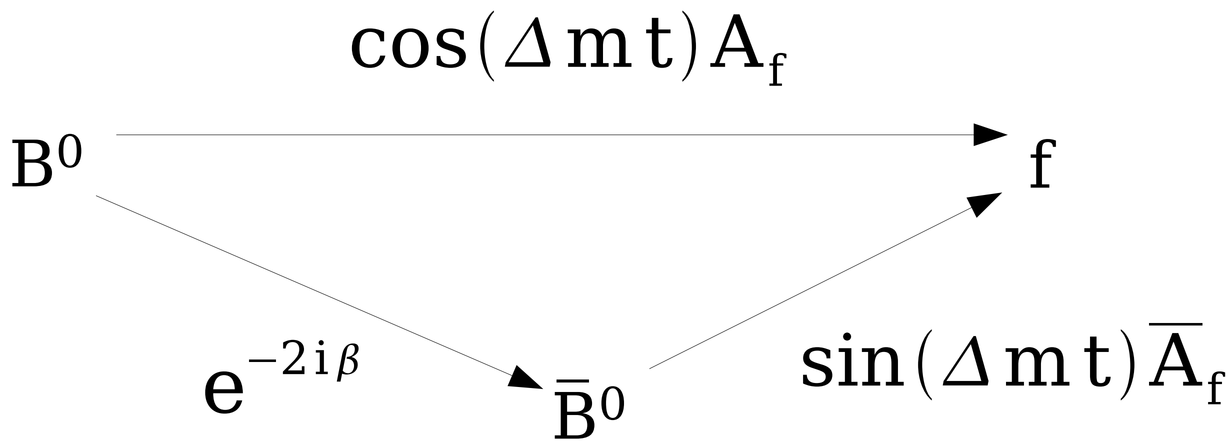


CP Violation

- First observed in 1964 in $K_L \rightarrow \;^{+}\;$ decays
  - CP violation is small, $|\epsilon| = (2.284 \pm 0.014) \times 10^{-3}$
- The B-factories have established CP violation in B mesons
  - CP violation via mixing and,
  - Direct CP violation

CP Violation via Mixing

- Interference between direct decay and mixing

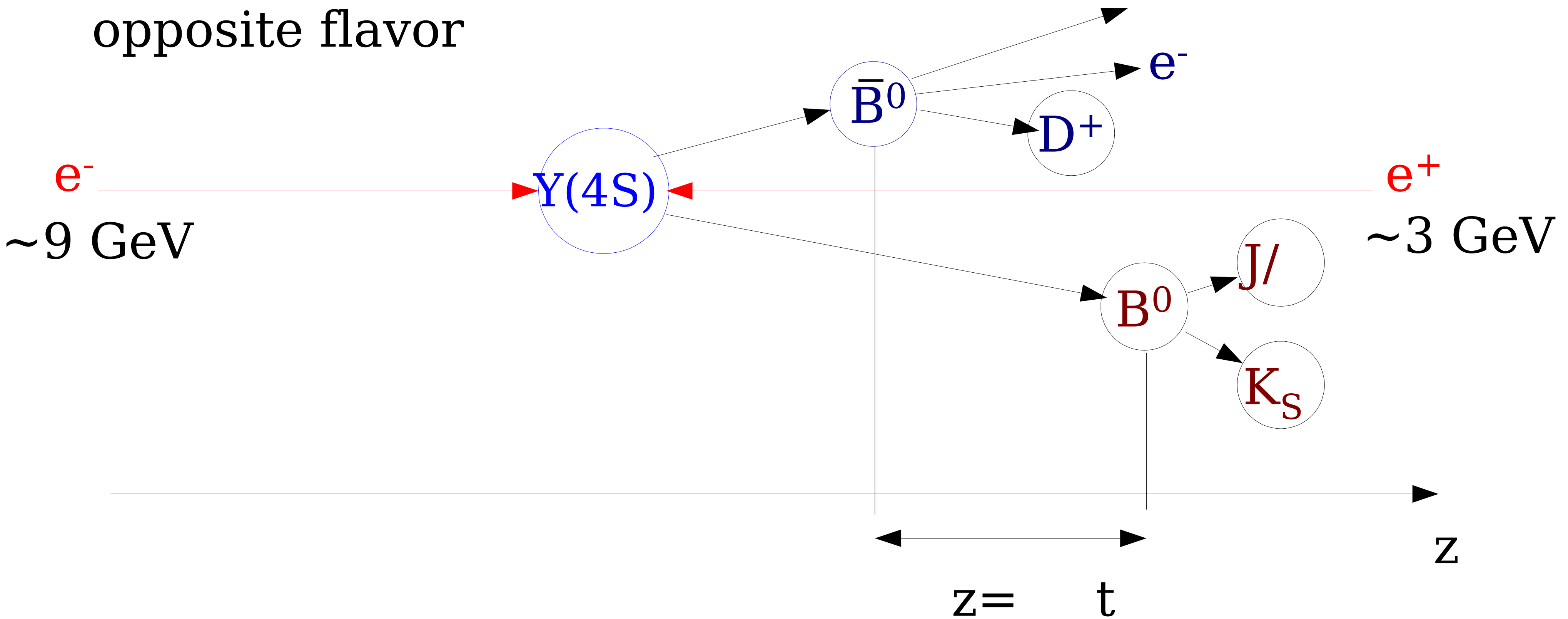


$$A_{CP}(\Delta t) = \frac{\Gamma(B^0 \to f) - \Gamma(\overline{B^0} \to f)}{\Gamma(B^0 \to f) + \Gamma(\overline{B^0} \to f)} = S \sin \Delta m \Delta t + C \cos \Delta m \Delta t$$

For J/ K_S S=sin2   and C=0

Experimental Technique at Υ(4S)

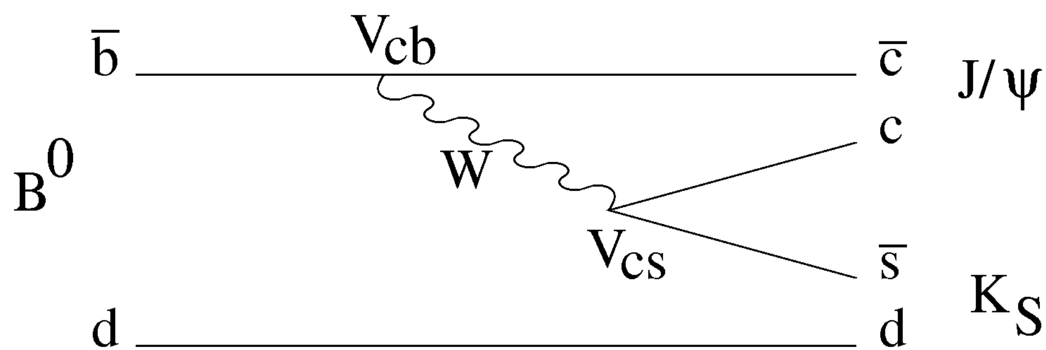
- Υ(4S)→B$\bar{B}$ is a coherent CP=-1 state
  - Tag B decay project other B to opposite flavor



- Determine t, from vertex separation
- Determine flavor from tag D decay products

'Golden' Modes for Measuring

- The modes B→J/ K_S and B→J/ K_L are known as the golden modes for measuring
  - Common final states of the B^0 and $\bar{B}^0$



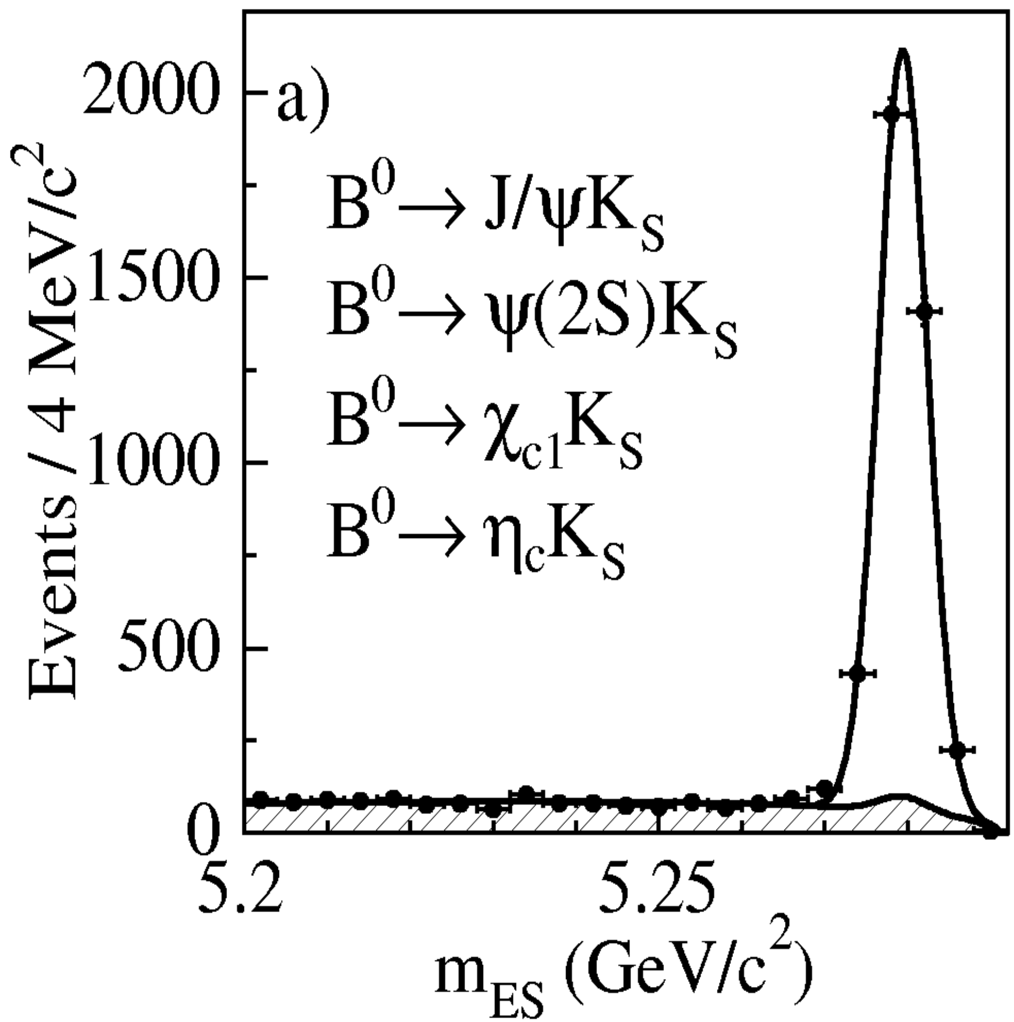
  - Tree level decays – large branching fractions

$$Br(B^0 \rightarrow J/\psi K_S) = (4.3 \pm 0.3) \times 10^{-4}$$

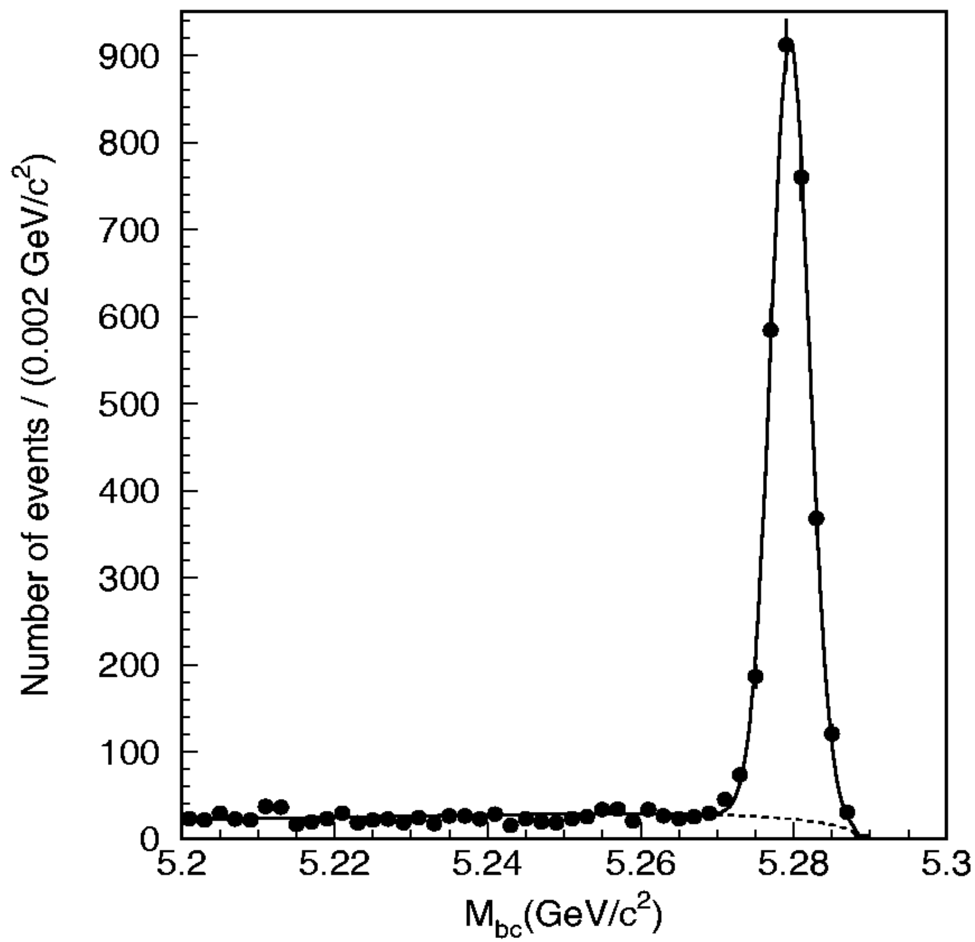
  - Easy to reconstruct, at least for the K_S final state

B→J/ K_S Yields

BaBar 192 fb^{-1}

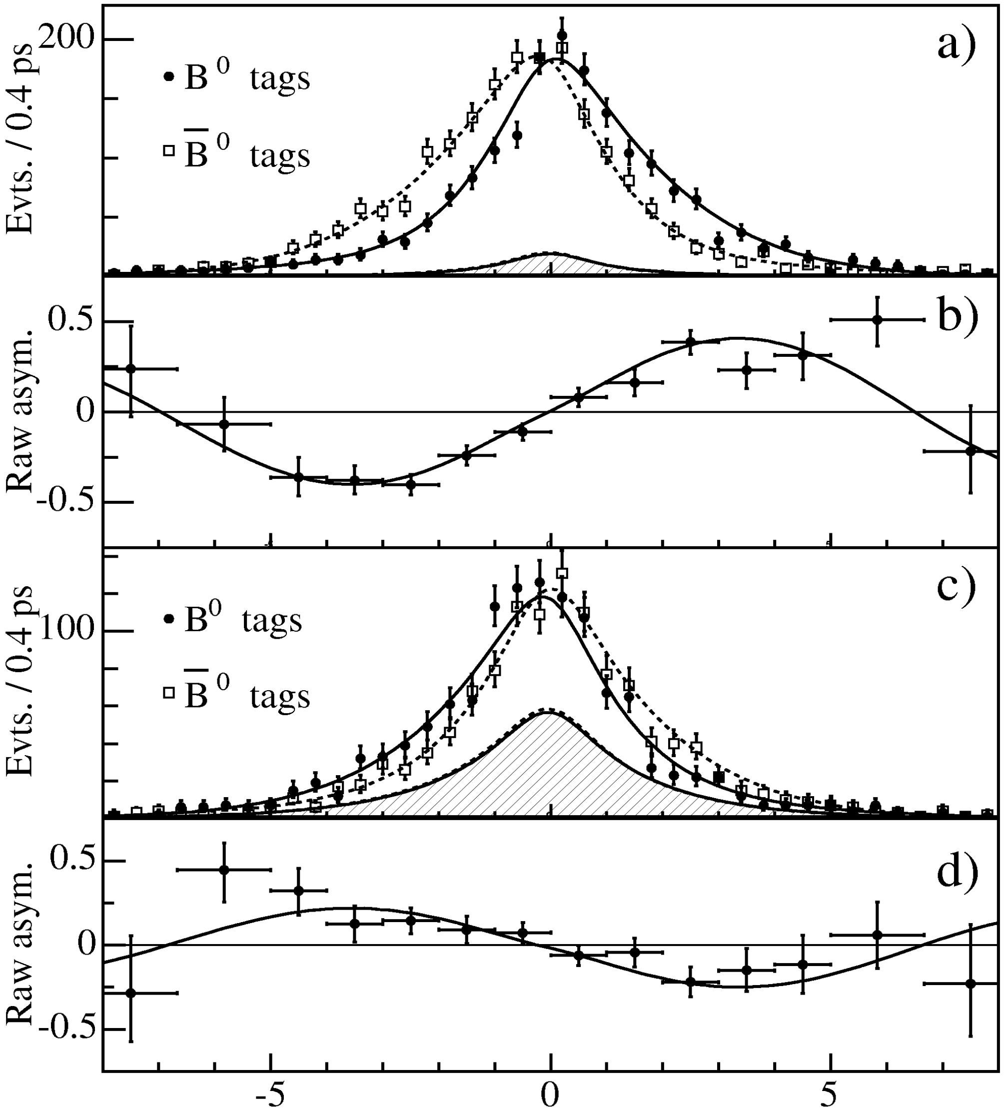


Belle 253 fb^{-1}

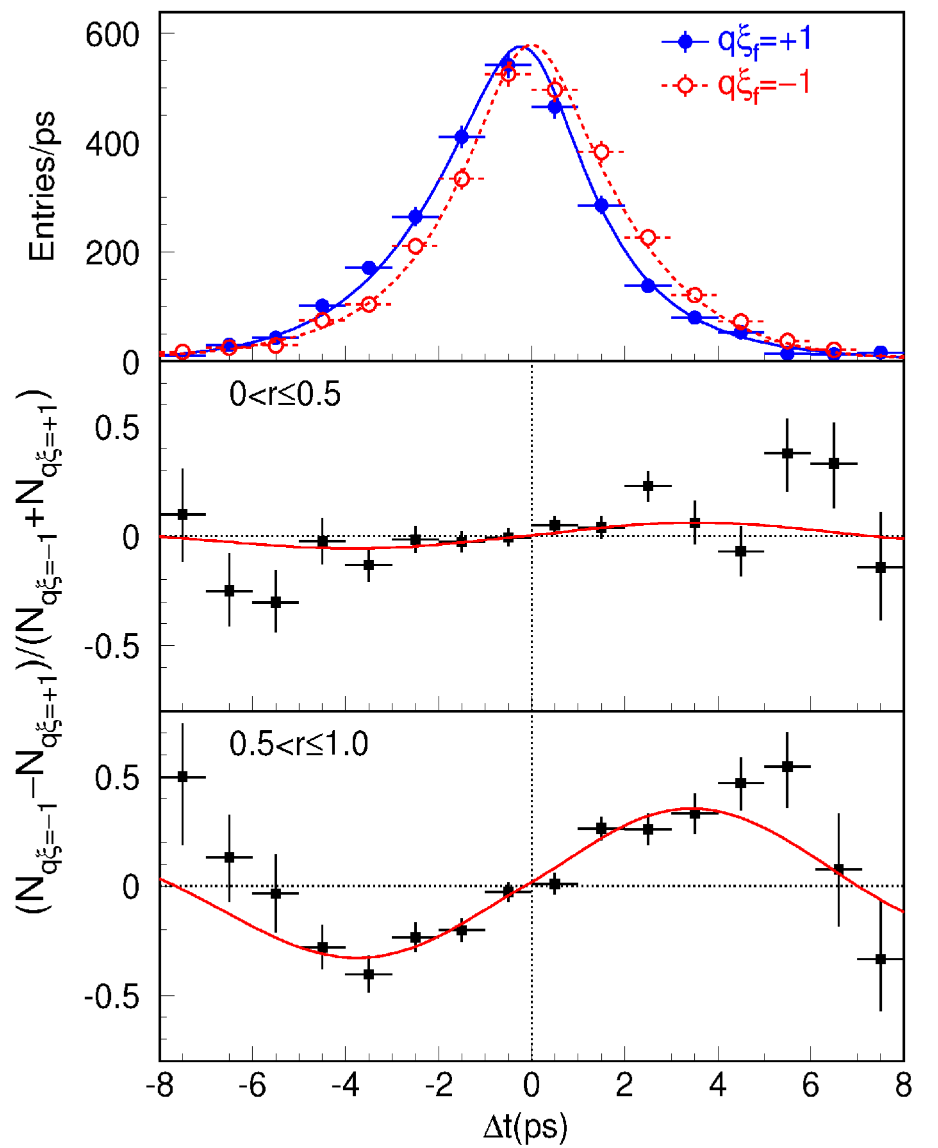


A_{CP} for J/ K_S

BABAR



Belle



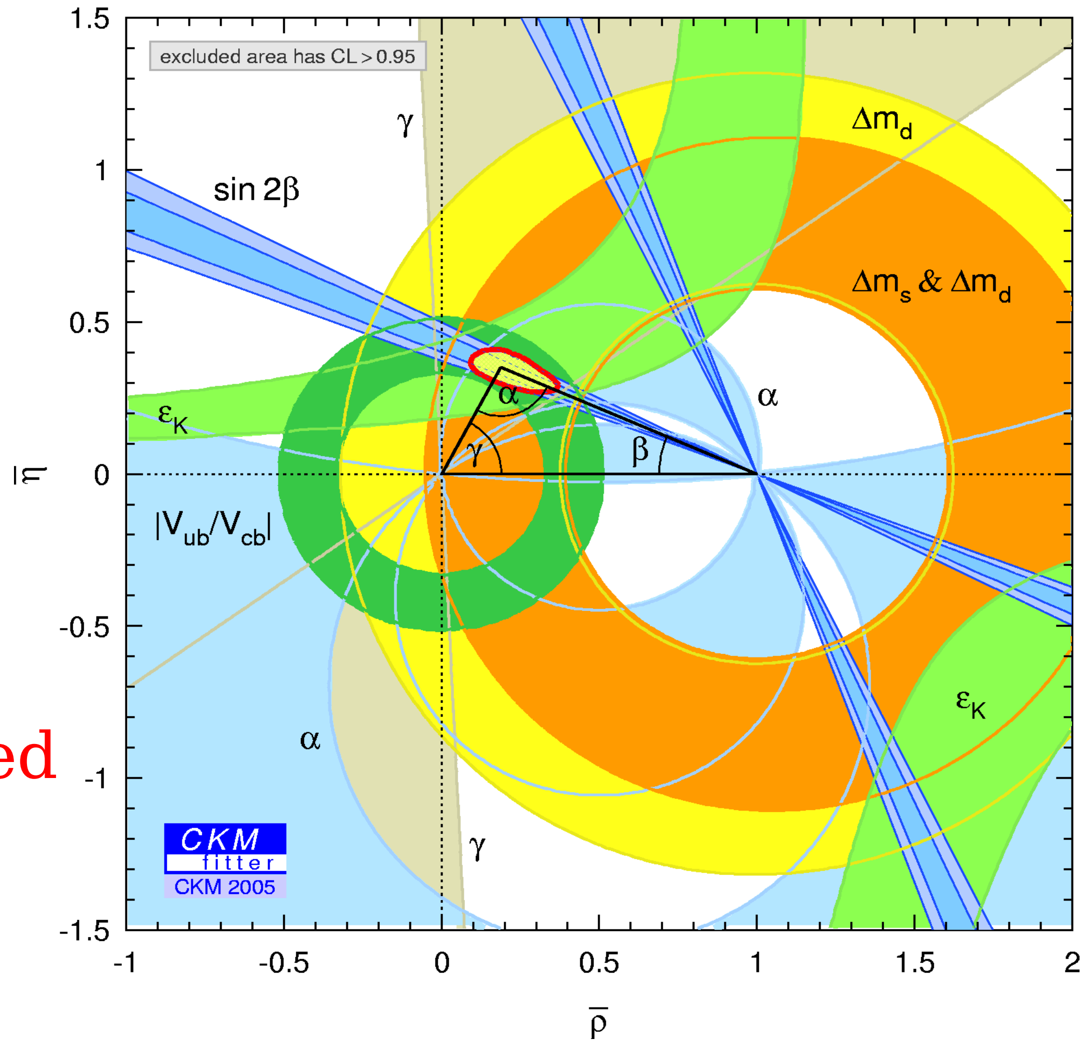
Summary of J/ K_S

- BaBar

  $\sin(2\beta)=0.722\pm0.040\pm0.023$
- Belle

  $\sin(2\beta)=0.728\pm0.056\pm0.023$
- Average:

  $\sin(2\beta)=0.725\pm0.037$

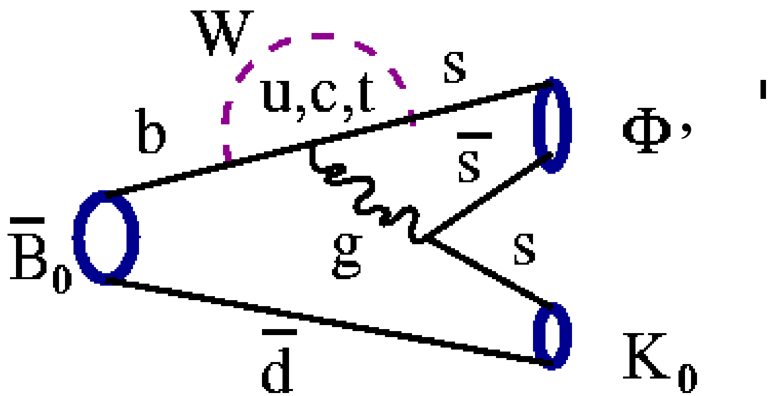


CP violation clearly established

- Consistent with constraints from e.g. V_{ub}

from Gluonic Penguins

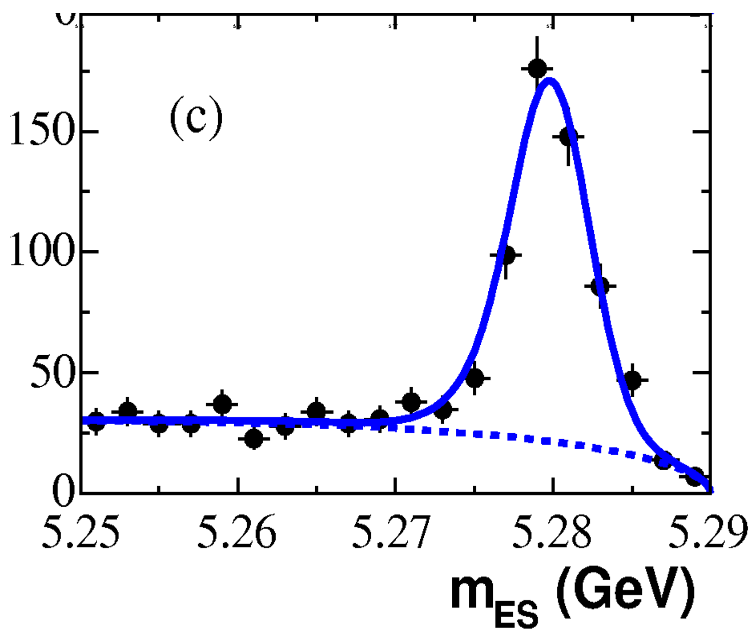
- In the standard model there are other modes that provides a clean measurement of sin2 .
- For example consider the decays $B\to$ K_S, $'K_S$

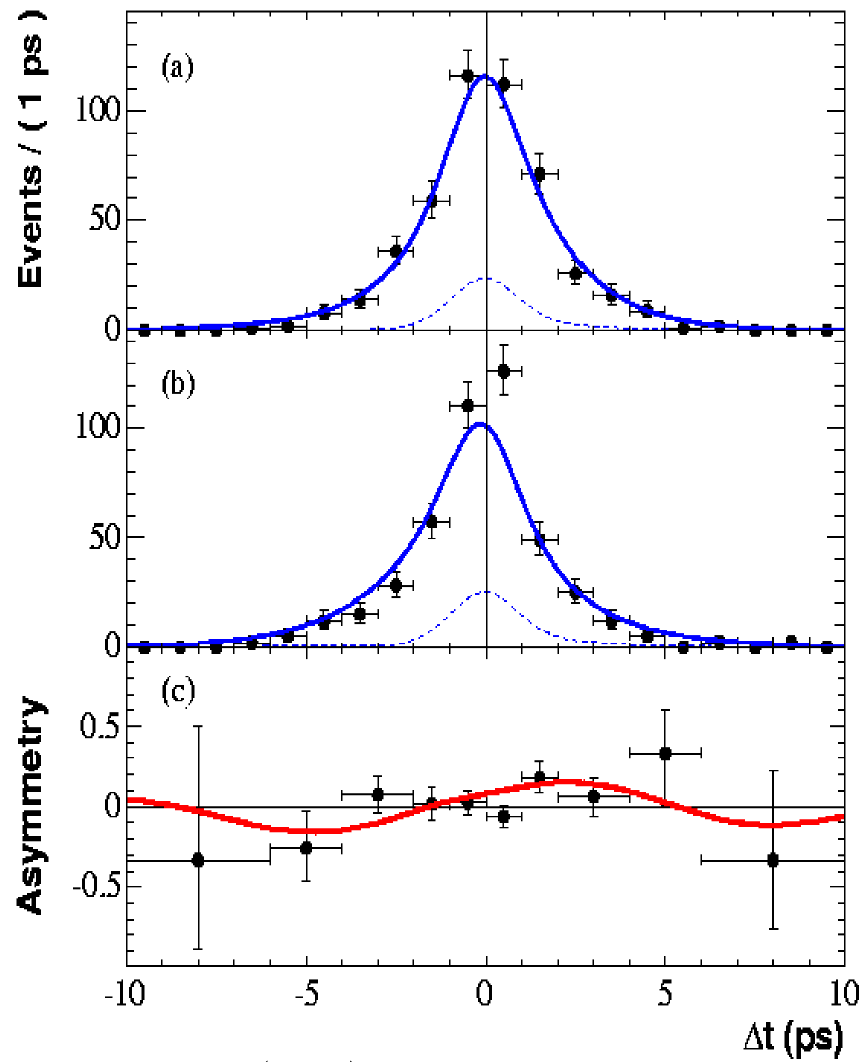


- Strong penguin – no weak phase – should just measure sin2 .
- Could have new physics contributions in loops.

$B\to$ 'K_S

BABAR 211 fb^{-1}



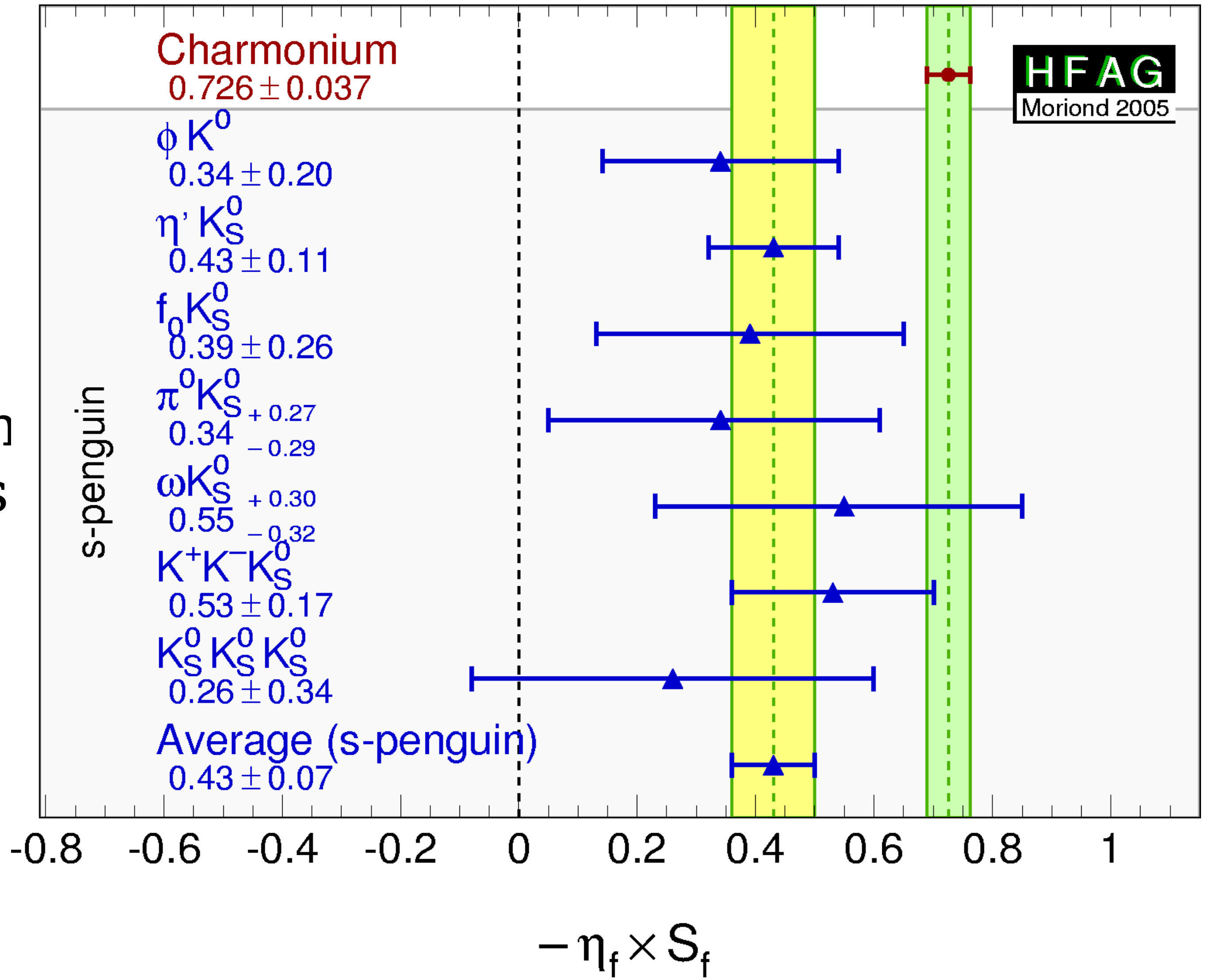


$\sin(2\beta) = 0.30 \pm 0.14$

Experimental Results

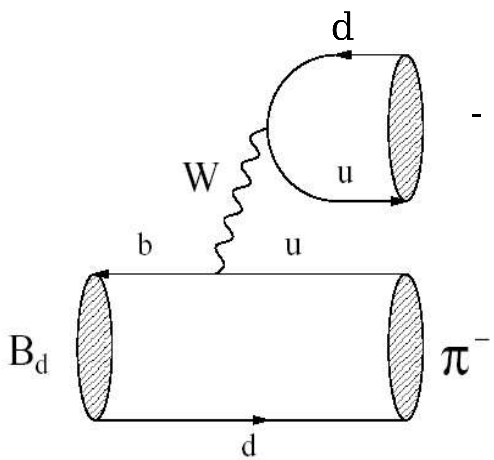
- Many strong penguin modes have been studied

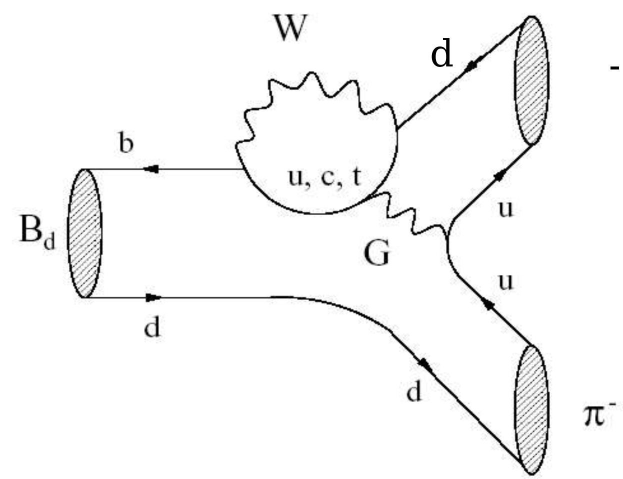
- Average of these modes are below sin2   from the golden modes by 3.7
- Still large errors on individual channels
- More data needed to settle this



Measurements of

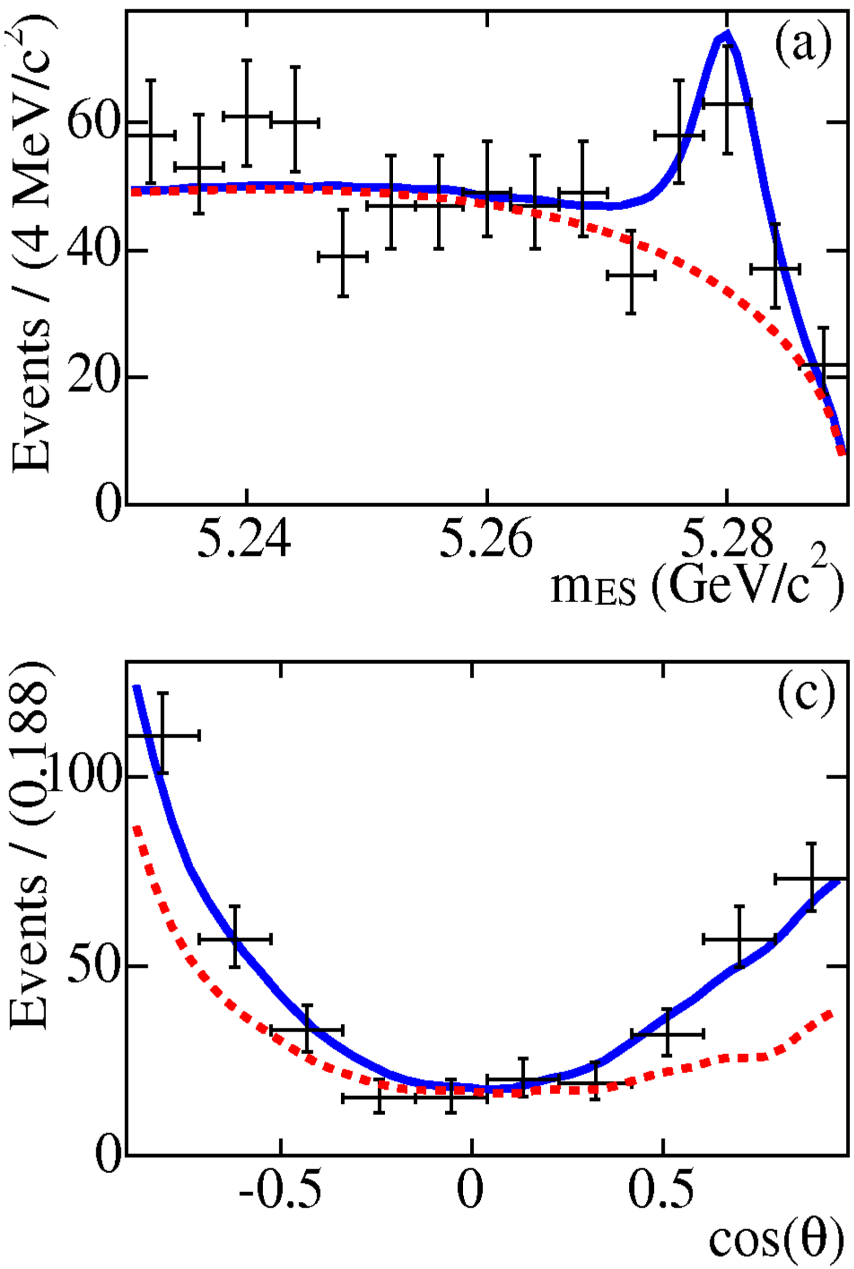
- First, it was thought that sin2   could be measured using   in the same way as sin2   in J/ K_S.
- However, there were large 'penguin' pollution





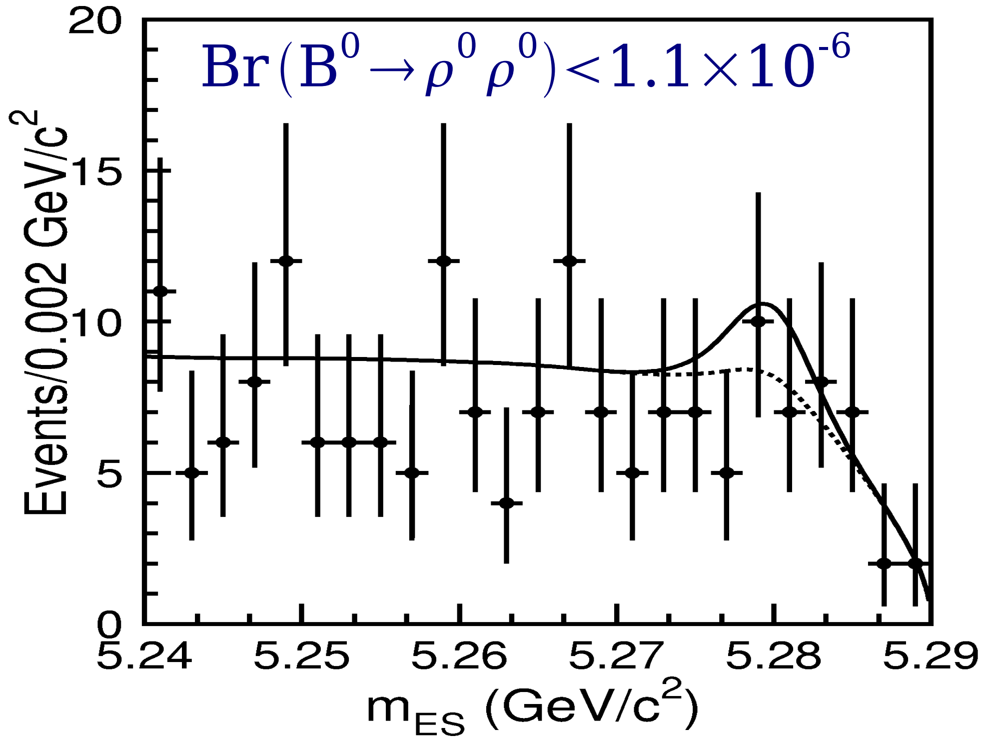
- The Gronau-London construction allows one to disentangle the penguin pollution with an isospin construction if one measures ^{0} ^{0}.
-     also has direct CP violation

$B^0 \rightarrow\ ^+$ (BaBar 205 fb^{-1})

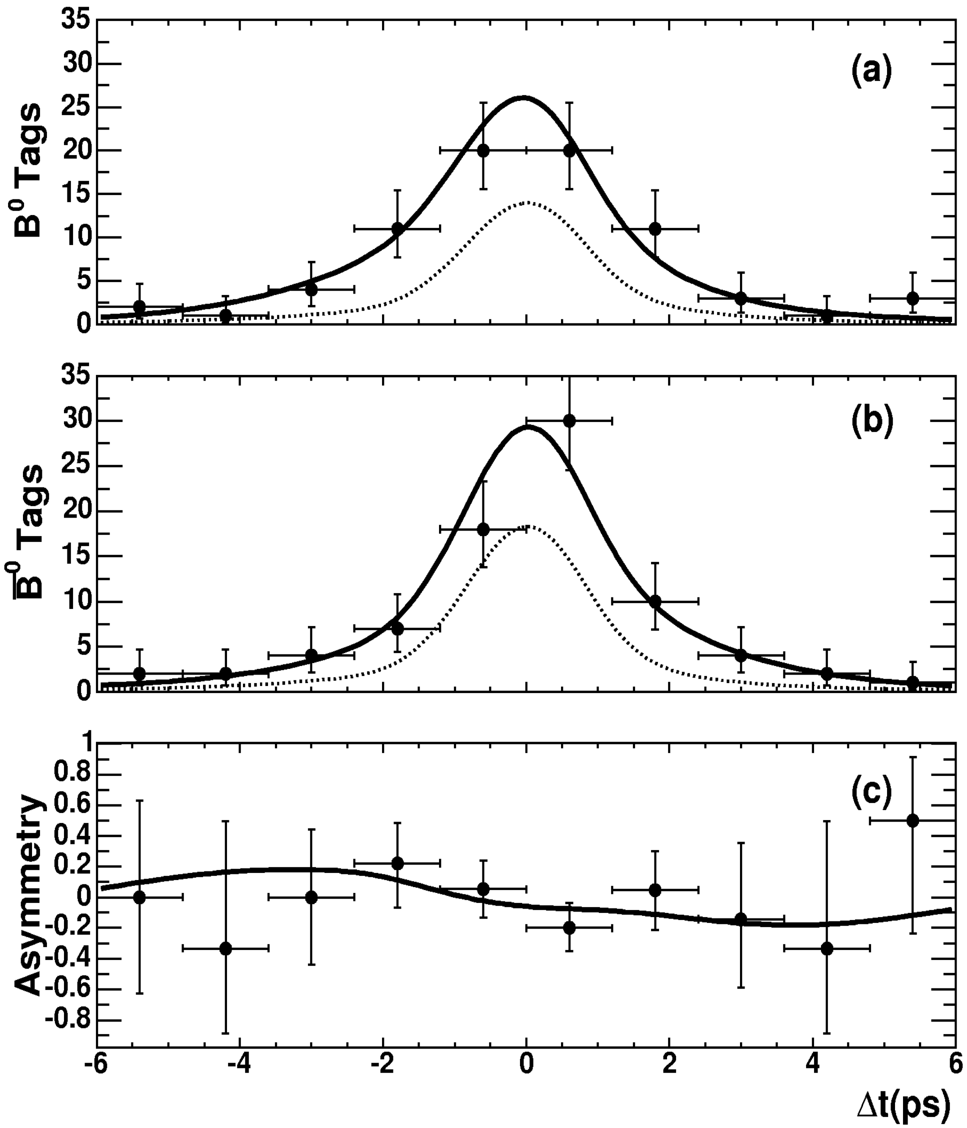


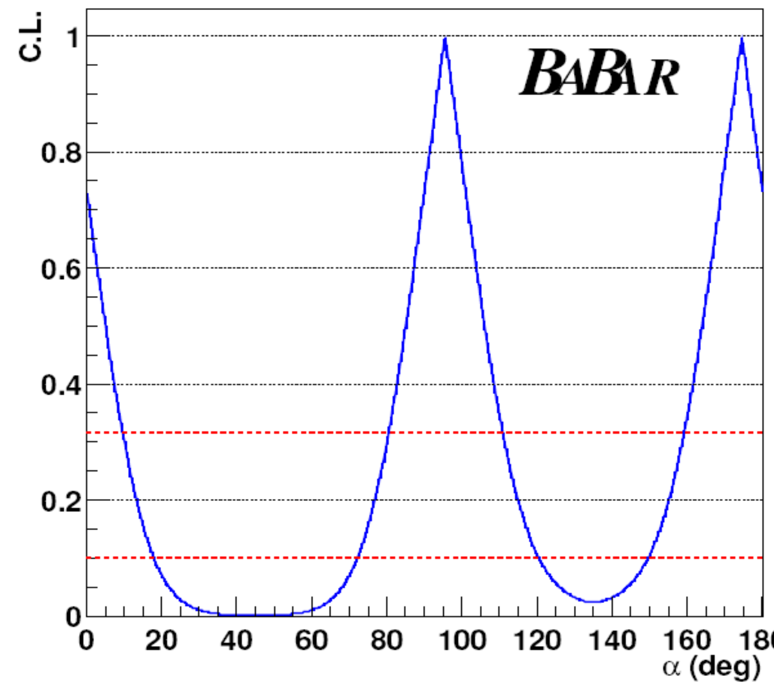
- Can do same analysis as for $^+$
- Only longitudinal polarization
- Smaller penguin pollution

$B^0 >\ ^0\ ^0$



$B^0 \to$ + -





$$\alpha_{\rho\rho} = \left[102^{+16\,+5}_{-12\,-4} \pm 11 \right]^\circ$$

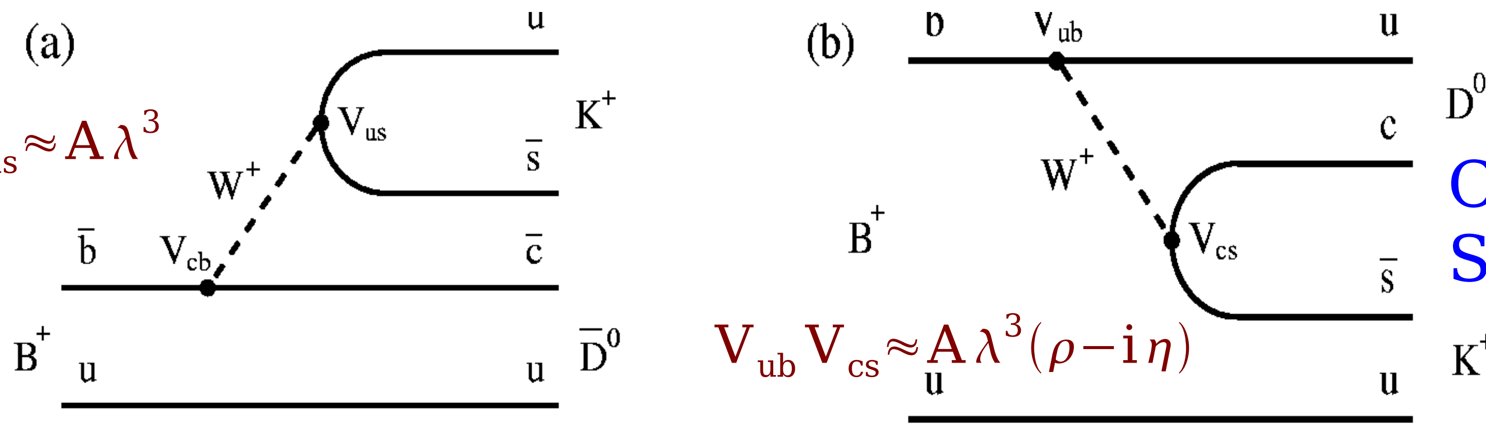
Averaging measurements

CKMfitter UTFit

$$\alpha = \left[97.9^{+5.0}_{-6.4} \right]^\circ \quad \alpha = \left[94.9 \pm 6.6 \right]^\circ$$

from $B^+ \to D^0K^{(*)+}$

- There are two contributions to this rate



$V_{cb}V_{us} \approx A\lambda^3$

Color Suppressed

$V_{ub}V_{cs} \approx A\lambda^3(\rho - i\eta)$

- Need final state that are common of the D^0 and $\bar{D}^0$
  - 'Mixed states' like D^0->K_S $^{+}$ with no definite CP

$$M_+ = f(m_+^2, m_-^2) + r e^{i\gamma + i\delta} f(m_-^2, m_+^2)$$

$$M_- = f(m_-^2, m_+^2) + r e^{-i\gamma + i\delta} f(m_+^2, m_-^2)$$

$$m_+^2 = m_{K_S\pi^+}^2 \quad m_-^2 = m_{K_S\pi^-}^2$$

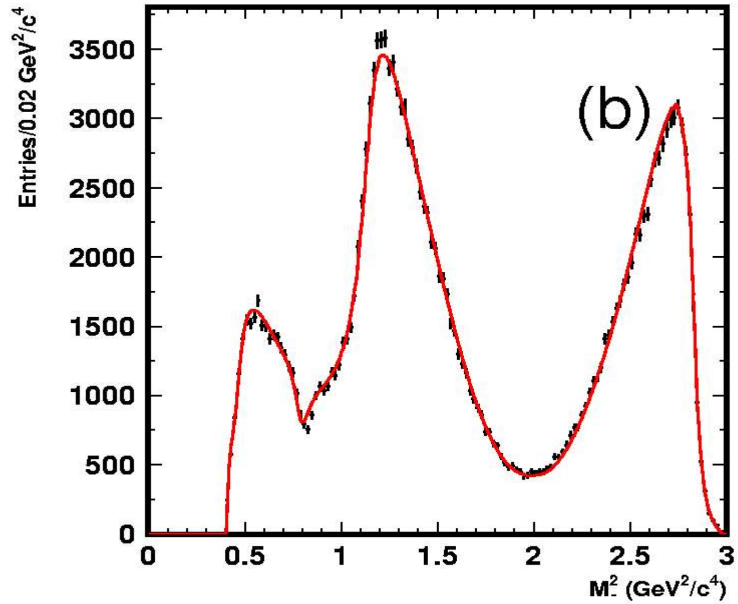
$f(m_+, m_-)$ is the complex Dalitz amplitude

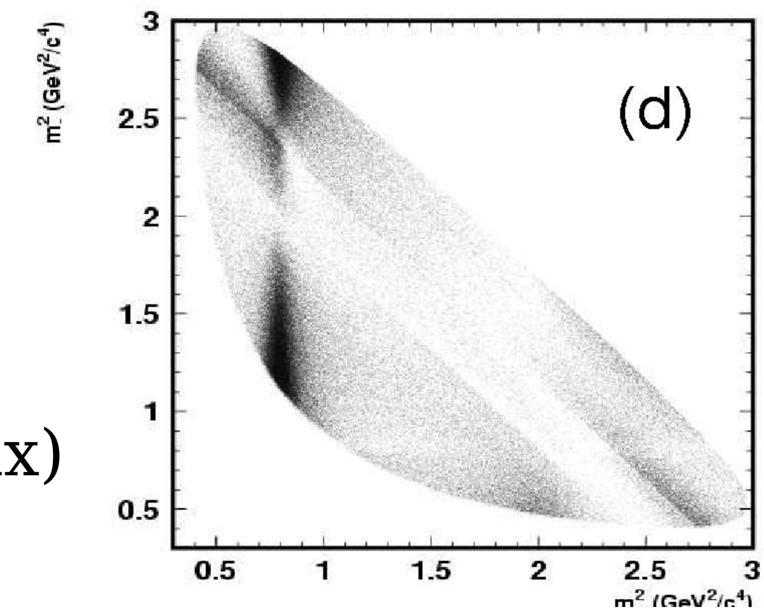
r is ratio of suppressed to favored amplitude

$D^0 \to K_S$ $^+$ Dalitz Plot

- Belle fit 187K $D^{*+} \to D^0(\to K_S\ ^{+}\ )\ ^{+}$

Intermediate state	Amplitude	Phase (°)	Fit fraction
$K_S\sigma_1$	1.57 ± 0.10	214 ± 4	9.8%
$K_S\rho^0$	1.0 (fixed)	0 (fixed)	21.6%
$K_S\omega$	0.0310 ± 0.0010	113.4 ± 1.9	0.4%
$K_S f_0(980)$	0.394 ± 0.006	207 ± 3	4.9%
$K_S\sigma_2$	0.23 ± 0.03	210 ± 13	0.6%
$K_S f_2(1270)$	1.32 ± 0.04	348 ± 2	1.5%
$K_S f_0(1370)$	1.25 ± 0.10	69 ± 8	1.1%
$K_S\rho^0(1450)$	0.89 ± 0.07	1 ± 6	0.4%
$K^*(892)^+\pi^-$	1.621 ± 0.010	131.7 ± 0.5	61.2%
$K^*(892)^-\pi^+$	0.154 ± 0.005	317.7 ± 1.6	0.55%
$K^*(1410)^+\pi^-$	0.22 ± 0.04	120 ± 14	0.05%
$K^*(1410)^-\pi^+$	0.35 ± 0.04	253 ± 6	0.14%
$K_0^*(1430)^+\pi^-$	2.15 ± 0.04	348.7 ± 1.1	7.4%
$K_0^*(1430)^-\pi^+$	0.52 ± 0.04	89 ± 4	0.43%
$K_2^*(1430)^+\pi^-$	1.11 ± 0.03	320.5 ± 1.8	2.2%
$K_2^*(1430)^-\pi^+$	0.23 ± 0.02	263 ± 7	0.09%
$K^*(1680)^+\pi^-$	2.34 ± 0.26	110 ± 5	0.36%
$K^*(1680)^-\pi^+$	1.3 ± 0.2	87 ± 11	0.11%
non-resonant	3.8 ± 0.3	157 ± 4	9.7%



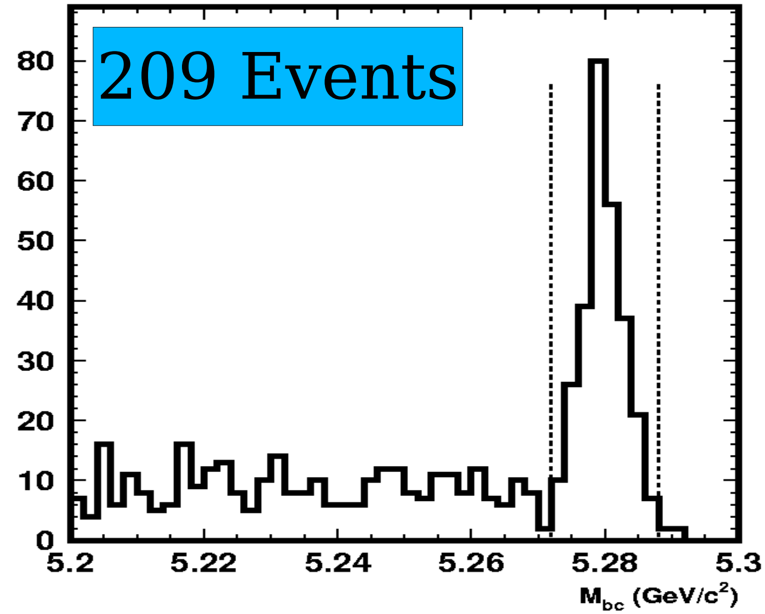


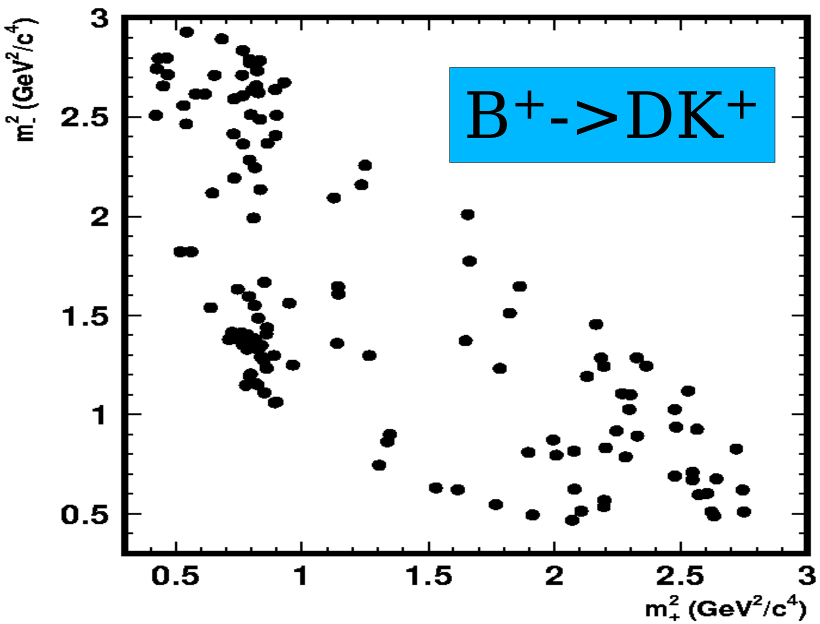
- Model uncertainty can be reduced
  - Better parameterization (K-matrix)
  - CLEO-c can measure phase with CP-tagged D^0 events

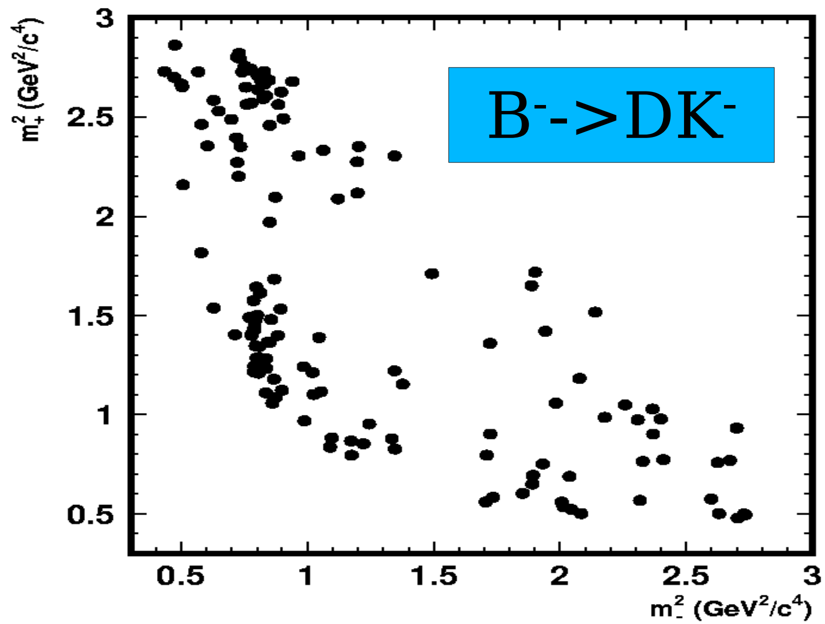
$B^+ \to D(K_S)$ K^+ (Belle 253 fb^{-1})

- Likelihood fit to Dalitz distribution for B^+ and B^- decays.

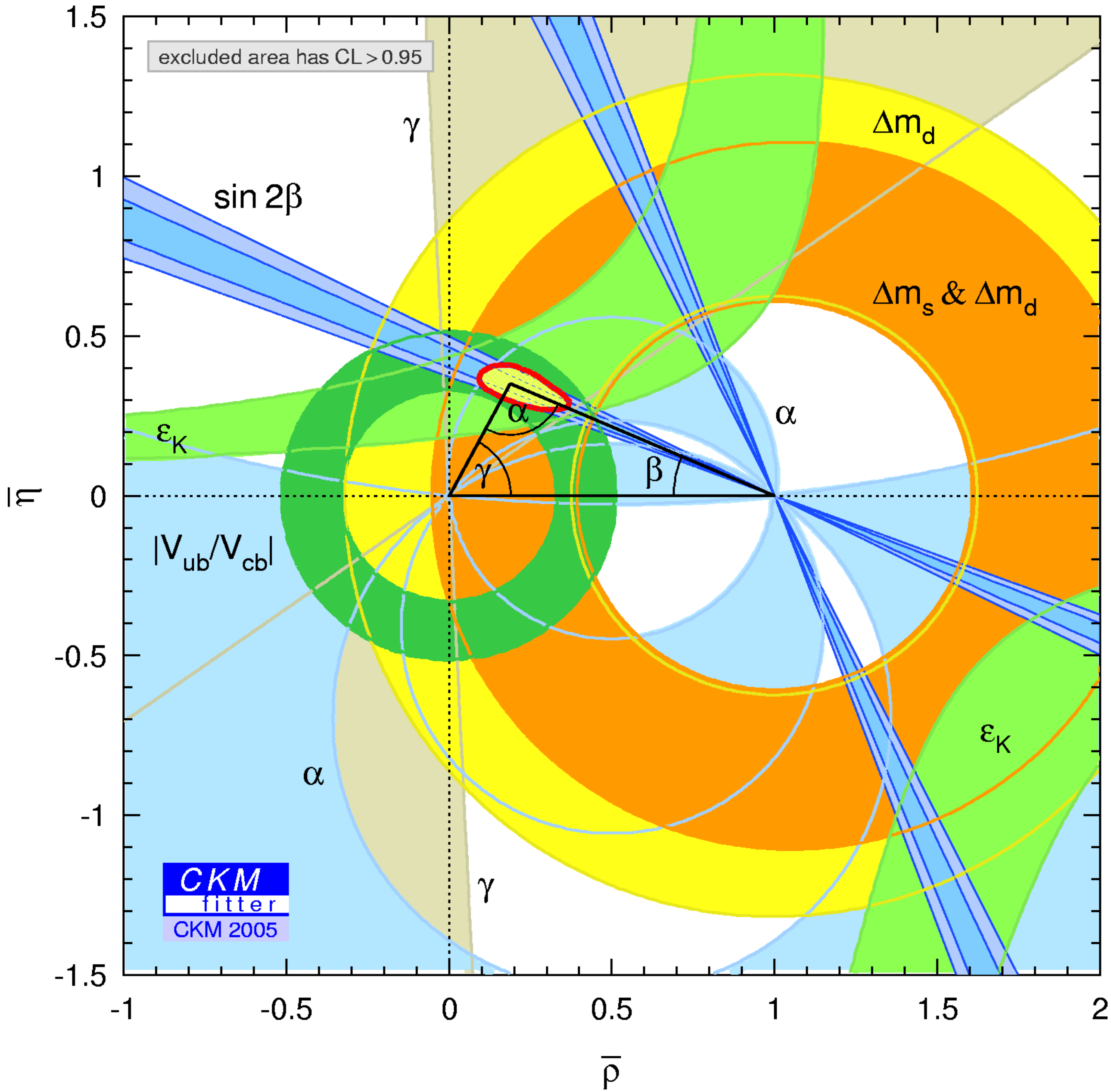
$$\gamma = \left[68^{+14}_{-15} \pm 13 \pm 11 \right]^\circ$$





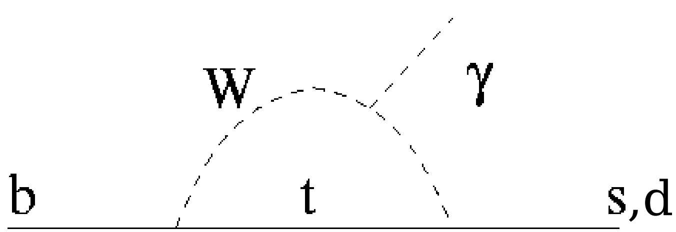


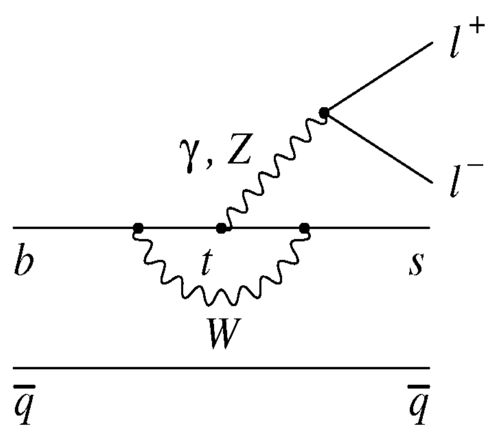
UT Constraints

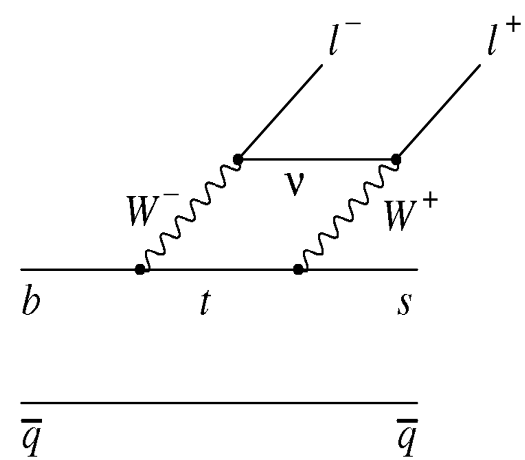


Rare B Decays

- The study of rare B decays provides a window to look for physics beyond the standard model
- Look at decays that are small or forbidden in the SM.
  - Proceeding via loop
- New physics can have amplitudes comparable – or larger – than the standard model contributions.

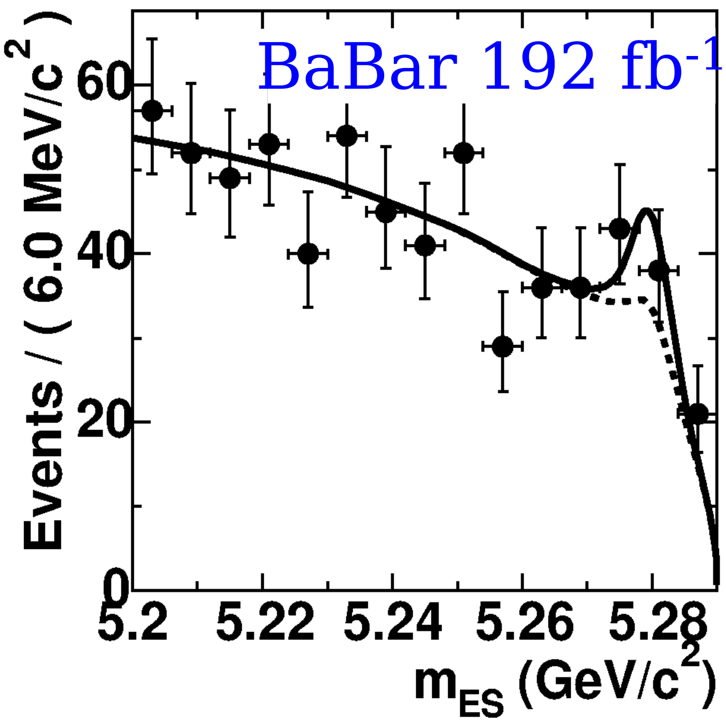


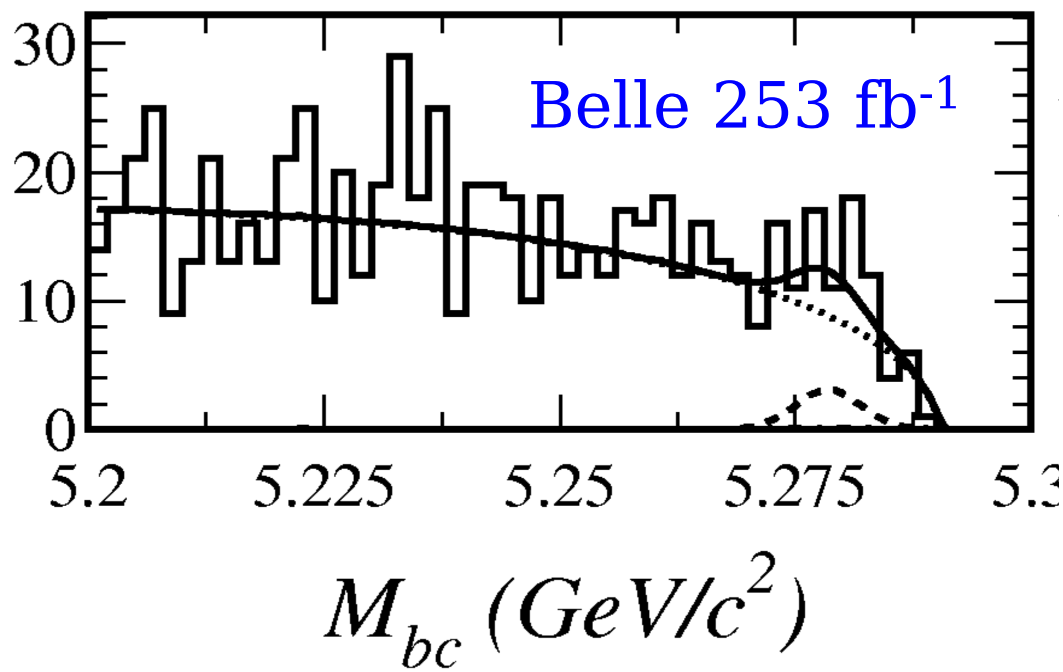




Searches for b→d

- Inclusive searches very hard
  - BaBar and Belle has searched for B→ , and B→
- No evidence yet for signal, though sensitivity to standard model signal is close: $Br_{SM}(B \to \rho \gamma) = (0.9 - 1.8) \times 10^{-6}$





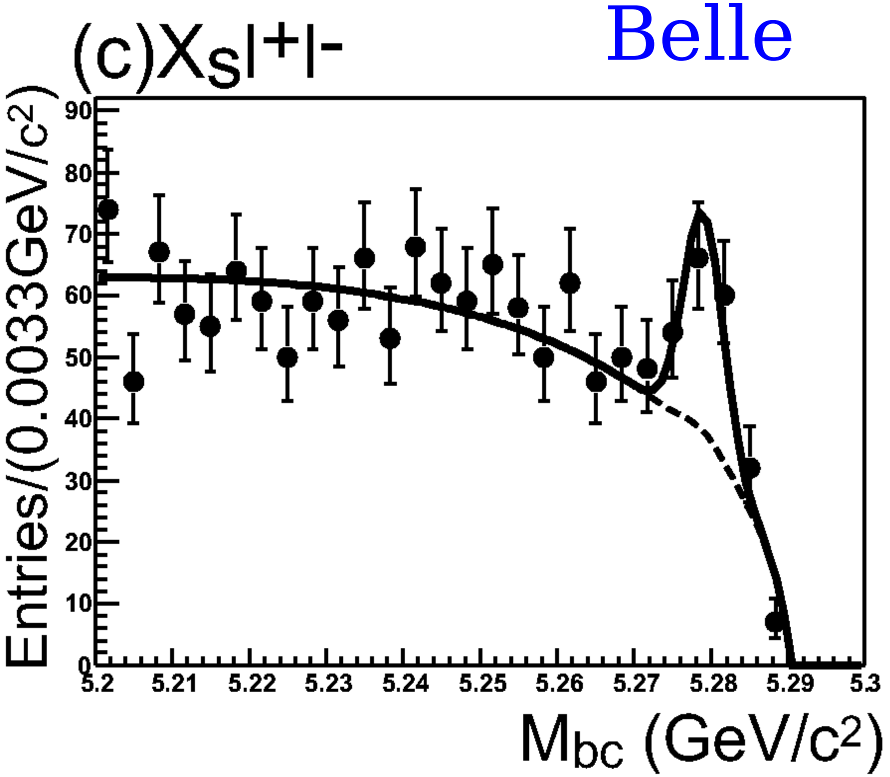
$Br(B \to \rho \gamma) < 1.2 \times 10^{-6}$

$Br(B \to \rho \gamma) < 1.4 \times 10^{-6}$

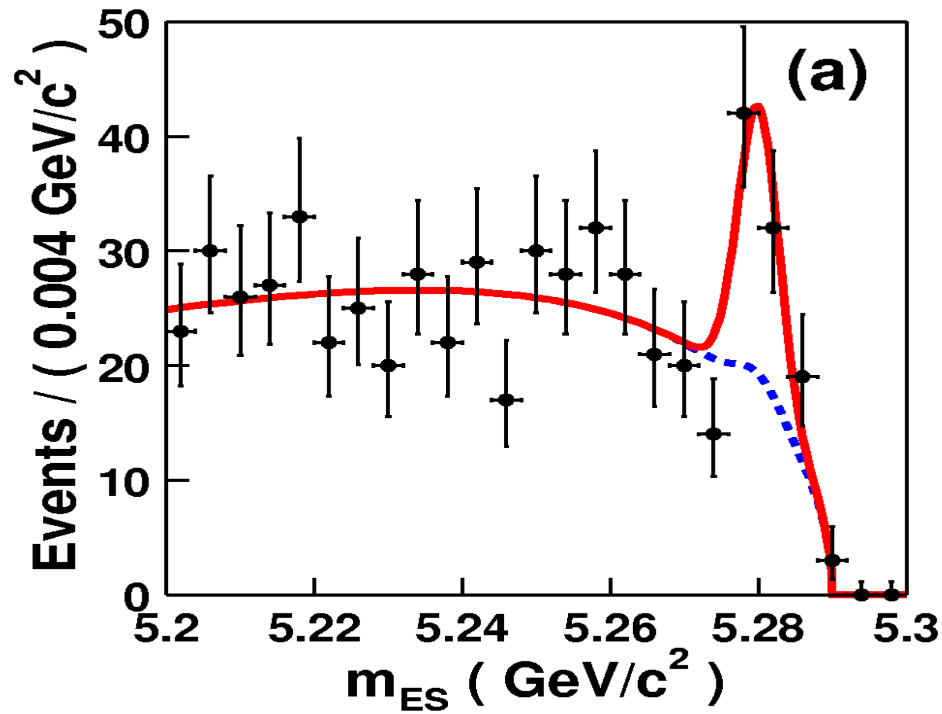
$B \to X_s ll$

- Inclusive and exclusive $b \to sll$ transitions have been observed by both BaBar and Belle
- Use sum of exclusive modes K+n , n<4
- Standard model prediction: $Br(B \to X_s ll) = (4.2 \pm 0.7) \times 10^{-6}$

Belle



BaBar

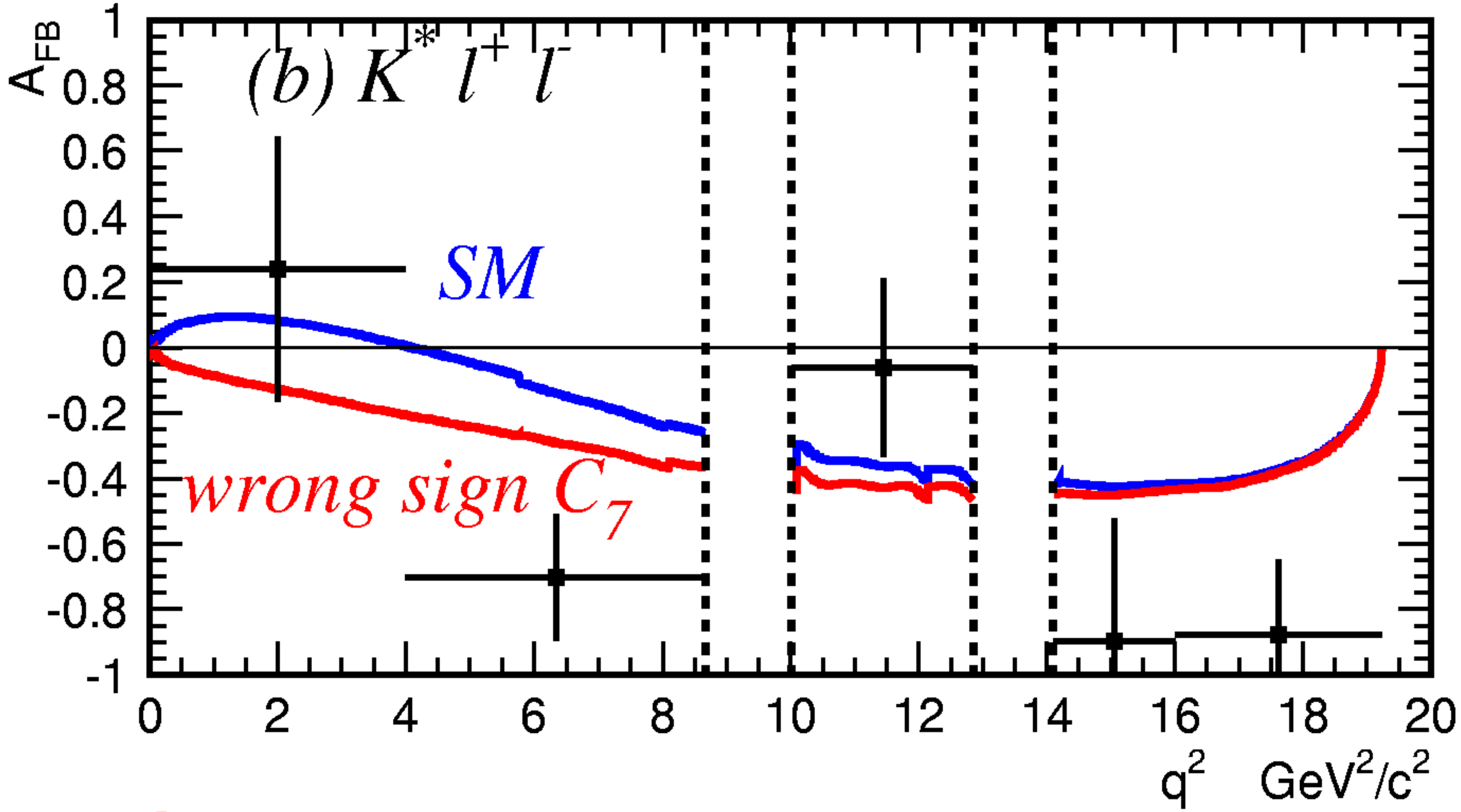


$Br(B \to X_s ll) = (4.11 \pm 0.83 {}^{+0.85}_{-0.85}) \times 10^{-6}$

$Br(B \to X_s ll) = (5.6 \pm 1.5 \pm 0.6 \pm 1.1) \times 10^{-6}$

$B \rightarrow K^*ll$

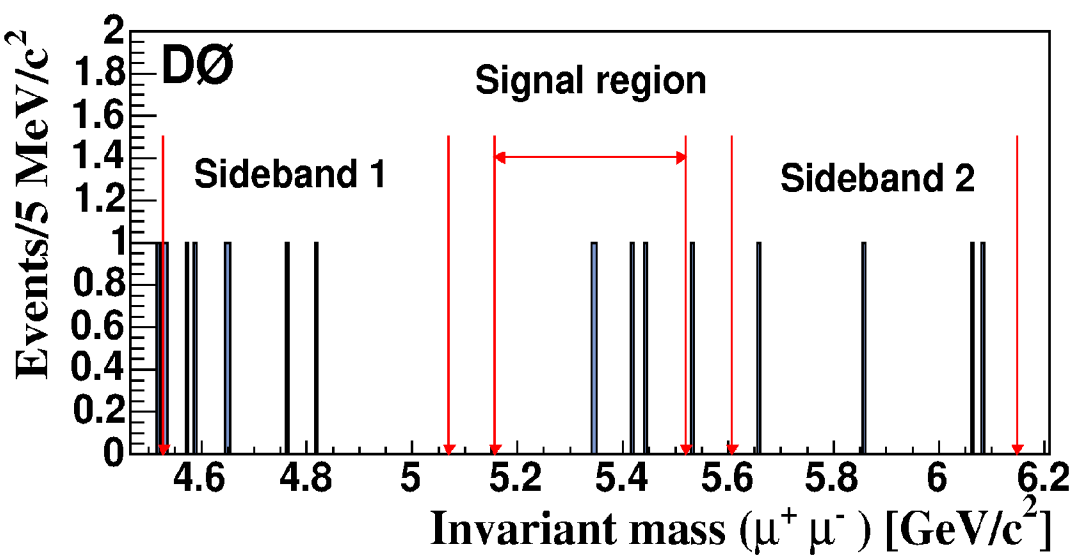
- Belle has also done a first study of the lepton forward-backward asymmetry

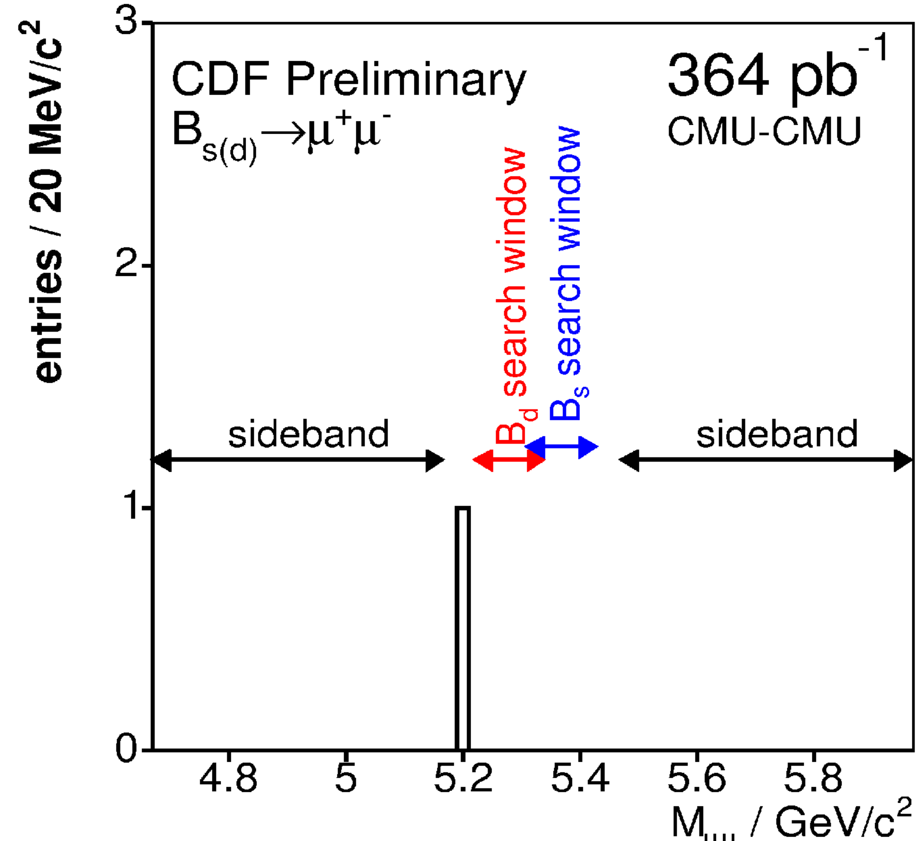


Need more statistics!

$B_{d,s} \to {}^{+}$

Both CDF and D0 has searched for $B_{d,s} \to {}^{+}$



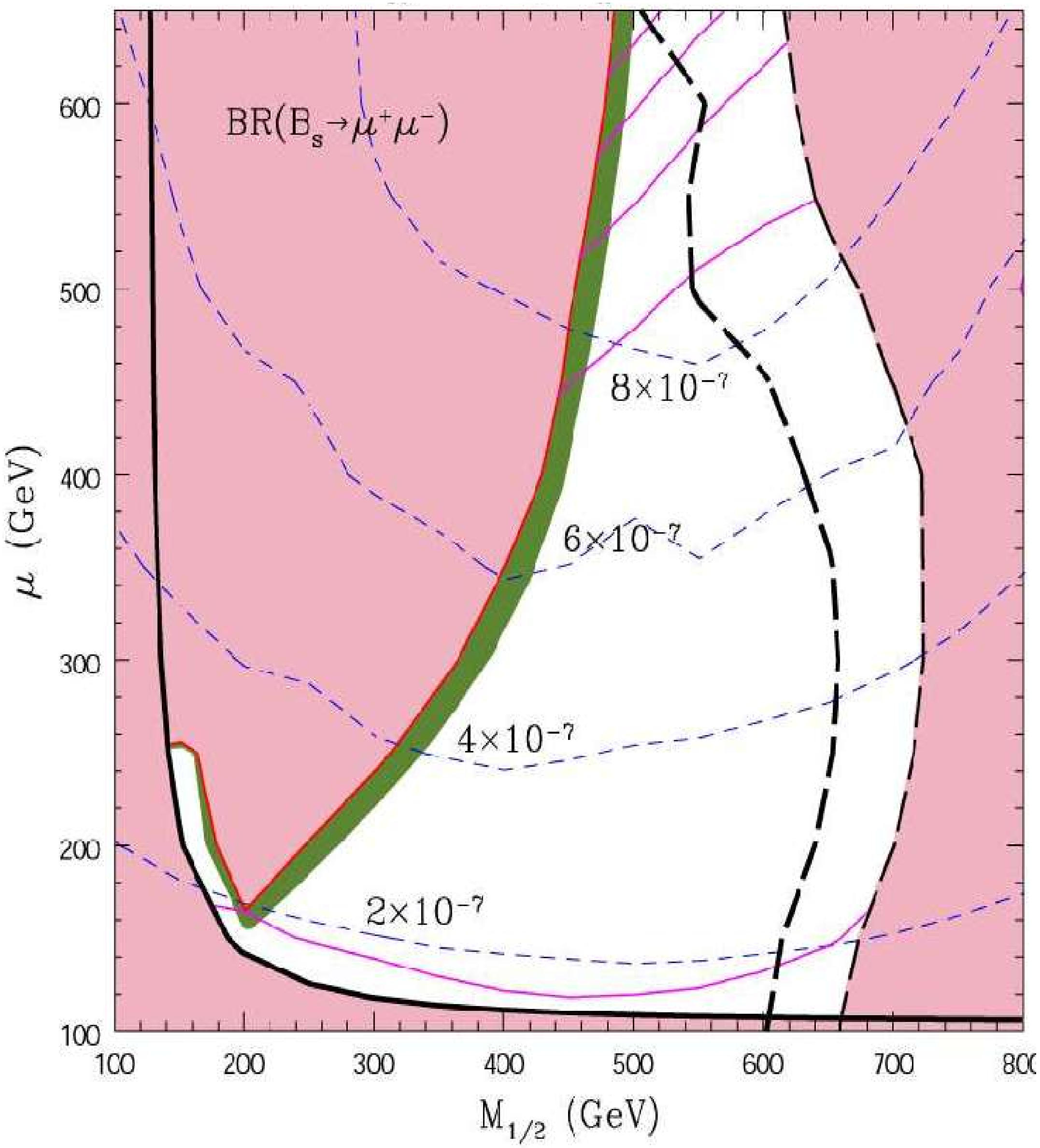


$$\mathrm{Br}(B_s \to \mu^+ \mu^-) < 4.1 \times 10^{-7}$$

$$\mathrm{Br}(B_d \to \mu^+ \mu^-) < 3.8 \times 10^{-8}$$

$$\mathrm{Br}(B_s \to \mu^+ \mu^-) < 1.5 \times 10^{-7}$$

Limits on New Physics



- SO(10) model with soft SUSY breaking.
- tan( )~50
- New limit rules out most allowed parameters space (white).

$$Br(B_s \to \mu^+\mu^-) < 1.5\times10^{-7}$$

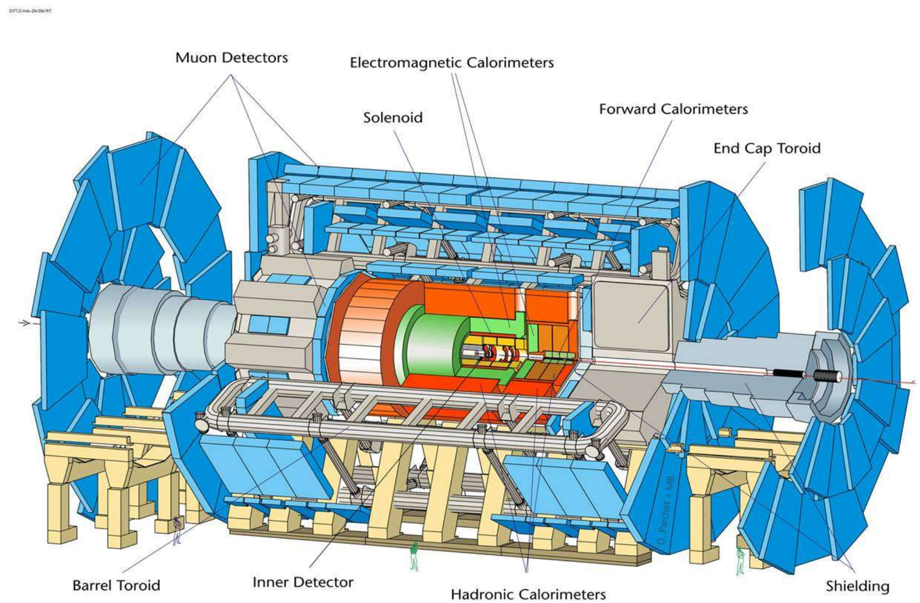
Future Experiments

- BaBar and Belle has so far recorded 250 and 450 fb^{-1} respectively.
- Experiments are expecting to collect about 1 ab^{-1} each.
- CDF/D0 has recorded about 600 pb^{-1}, and expect to collect a few fb^{-1} in the current run.

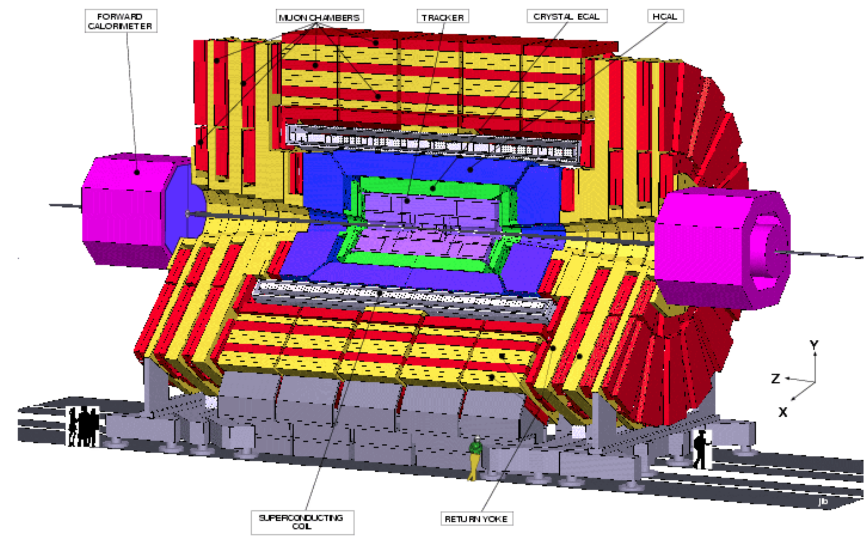
- Many more results expected from this generation of experiments in the next ~3 years.

LHC Experiments

ATLAS



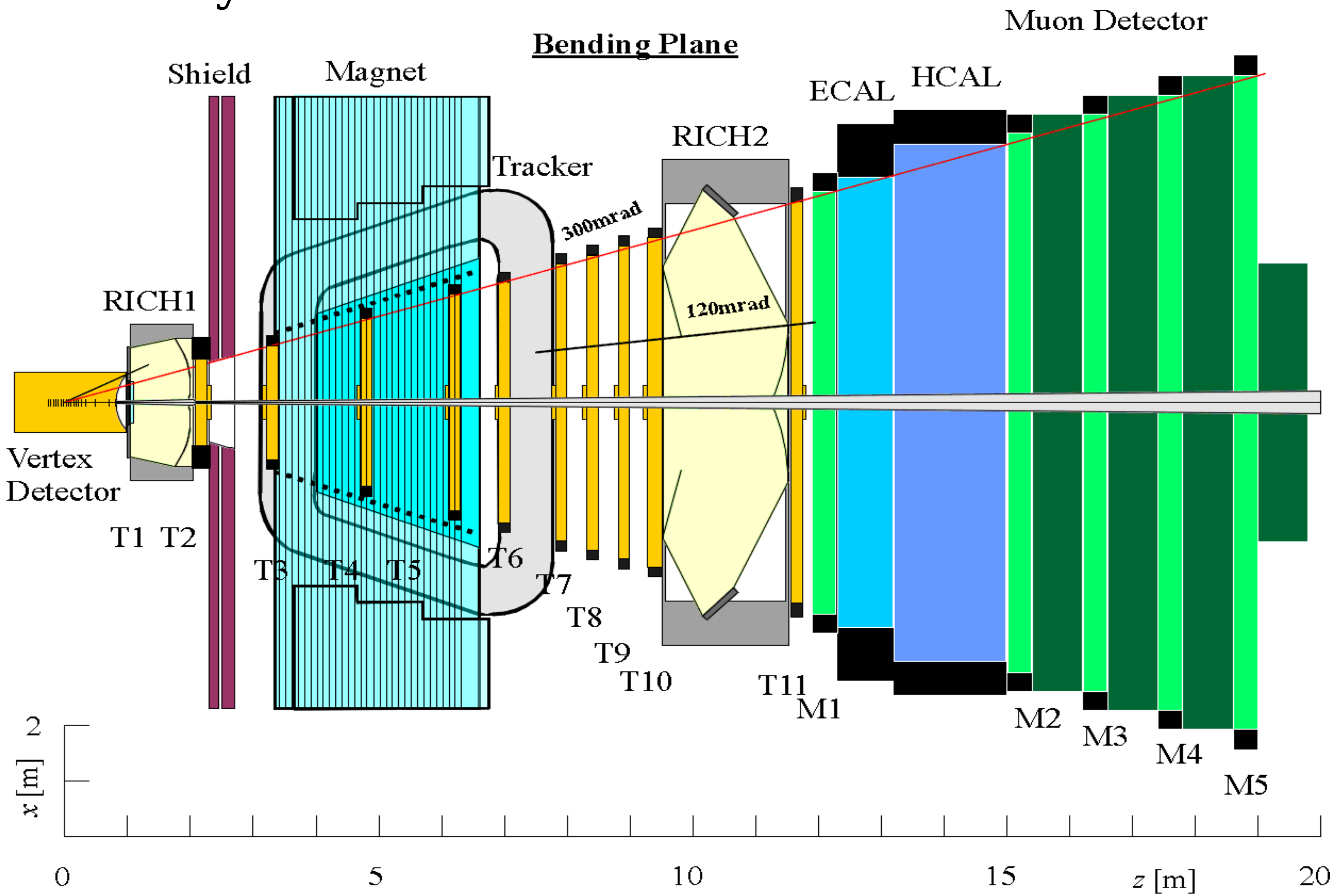
CMS



- ATLAS and CMS are high p_t discovery experiments
- Both have good vertexing and muon capabilities
- Can do B-physics in modes that they trigger on, e.g.$B \to \mu\mu$, $B \to K^{(*)}$.

LHCb

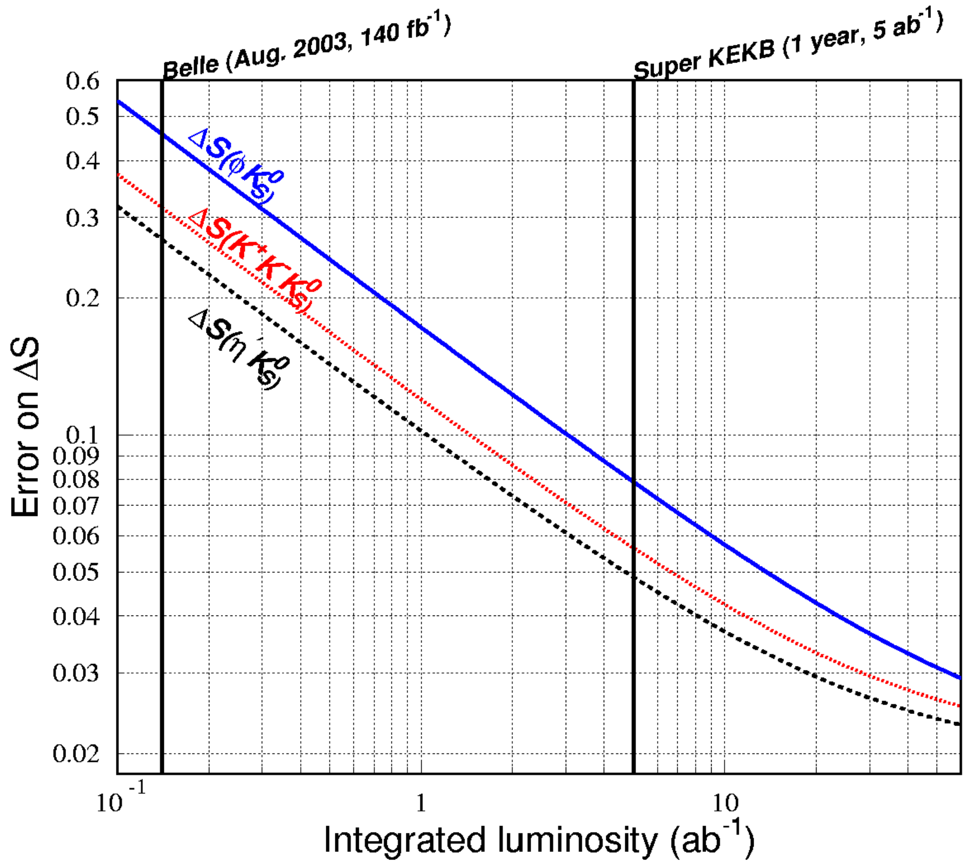
- At the LHC the dedicated B-physics experiment LHCb will study B mesons

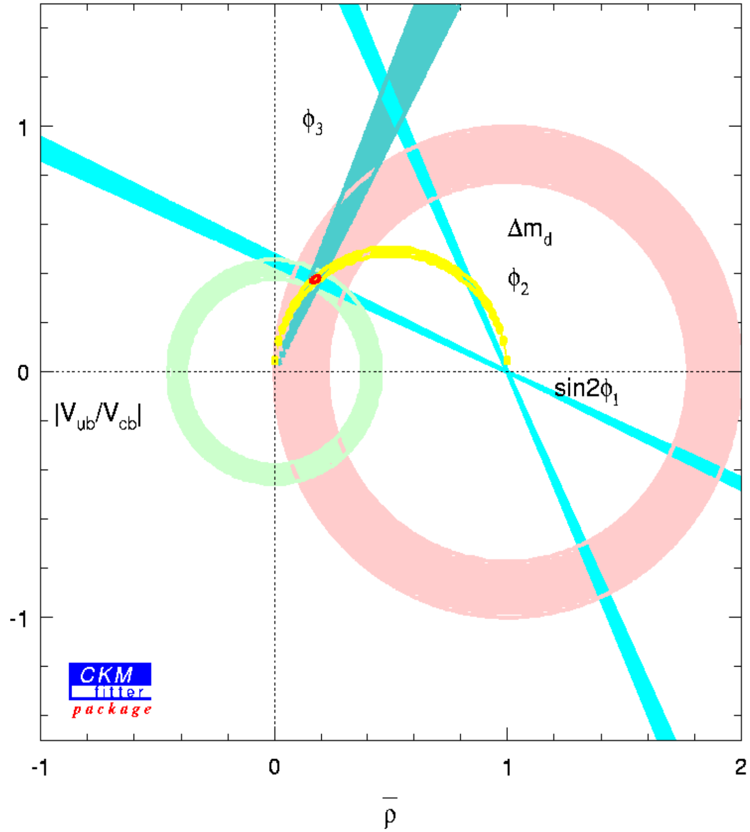


Super B-factory

- Both BaBar and Belle has studied the physics case for a high luminosity B-factory.
- Examples from SuperBelle LoI

50 ab^{-1}



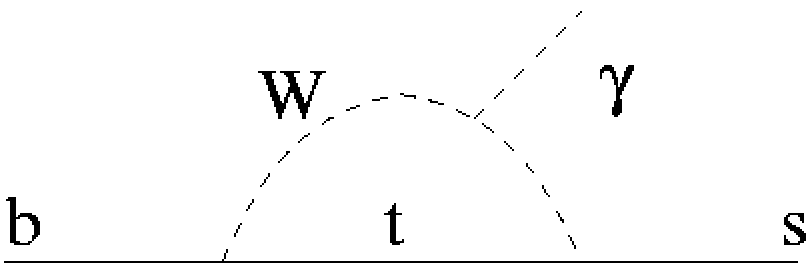


Conclusions

- CKM physics is fairly mature
  - Standard model explanation for CP violation from phase in the CKM matrix confirmed.
- Attention now at physics beyond the standard model
- New physics expected at or below the TeV scale
  - Makes the LHC physics program so exciting
  - Should have some observables in B physics
- Many results from B-factories will come with their increases data samples
- CDF/D0 are now accumulating large data samples more results to come

Backup Slides

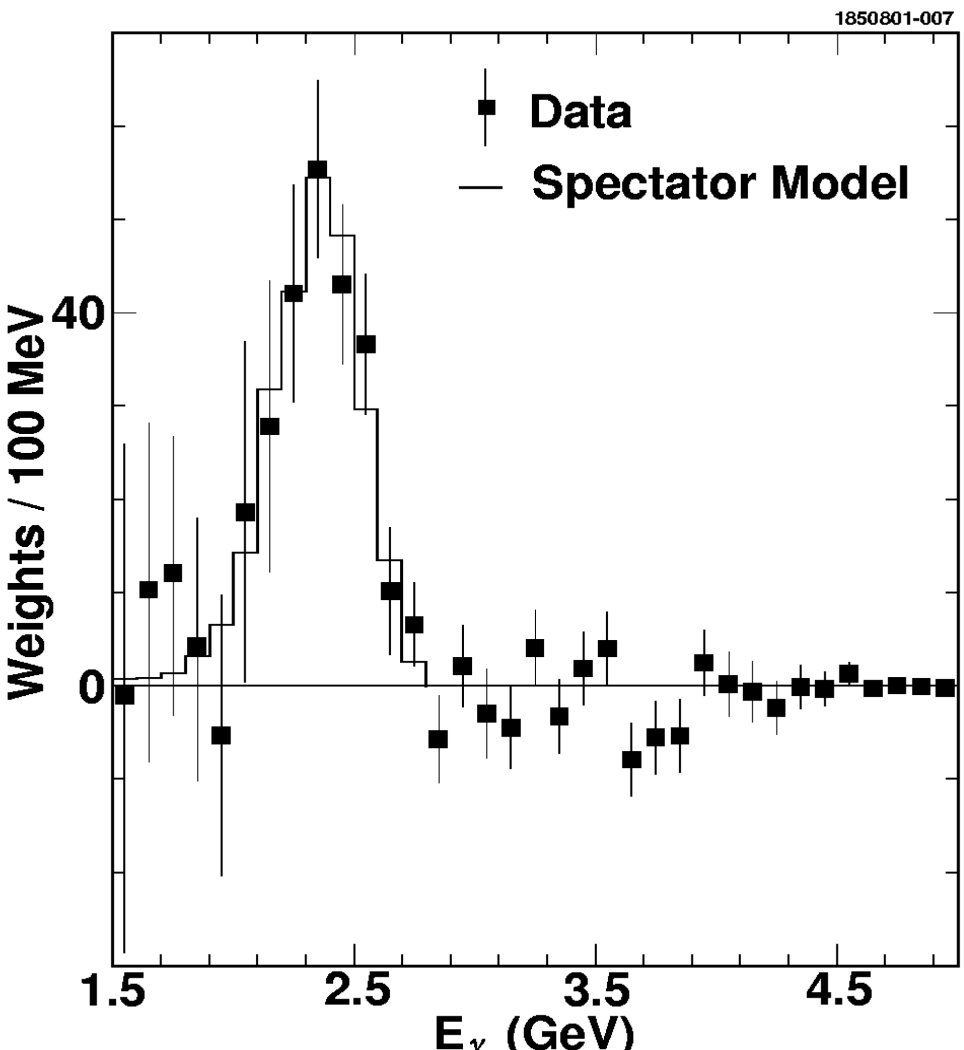
$B \to X_s$



- CLEO II measures

  $Br(B \to X_s \gamma) = (3.21 \pm 0.53) \times 10^{-4}$
- This branching fraction is important in constraining new physics.
- The shape of the photon spectrum is also important to parametrize non-pertubative QCD effects which can be used to extract Vub in semileptonic B decays.

CLEO (PRL 87, 251807)

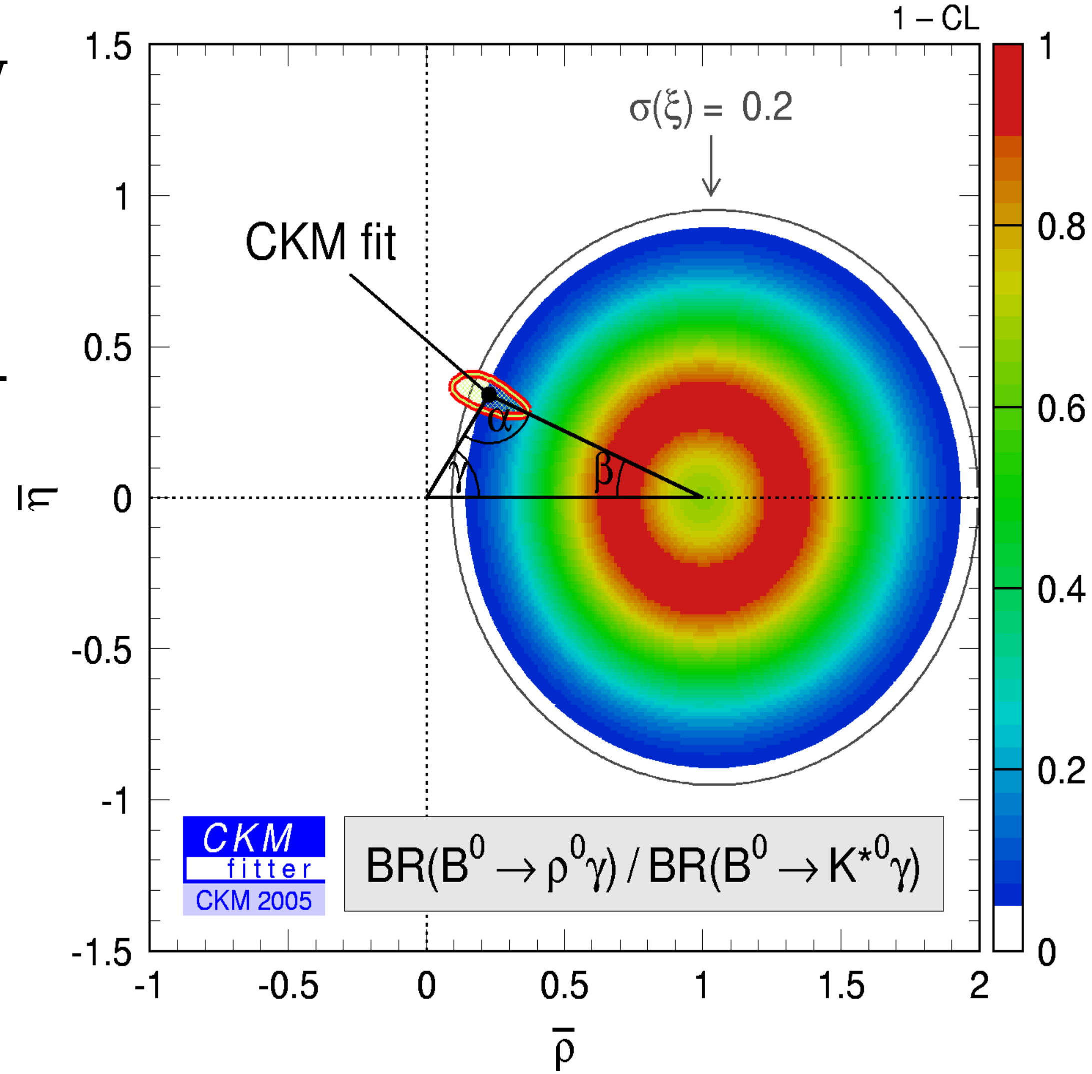


Modern $b \to sg$

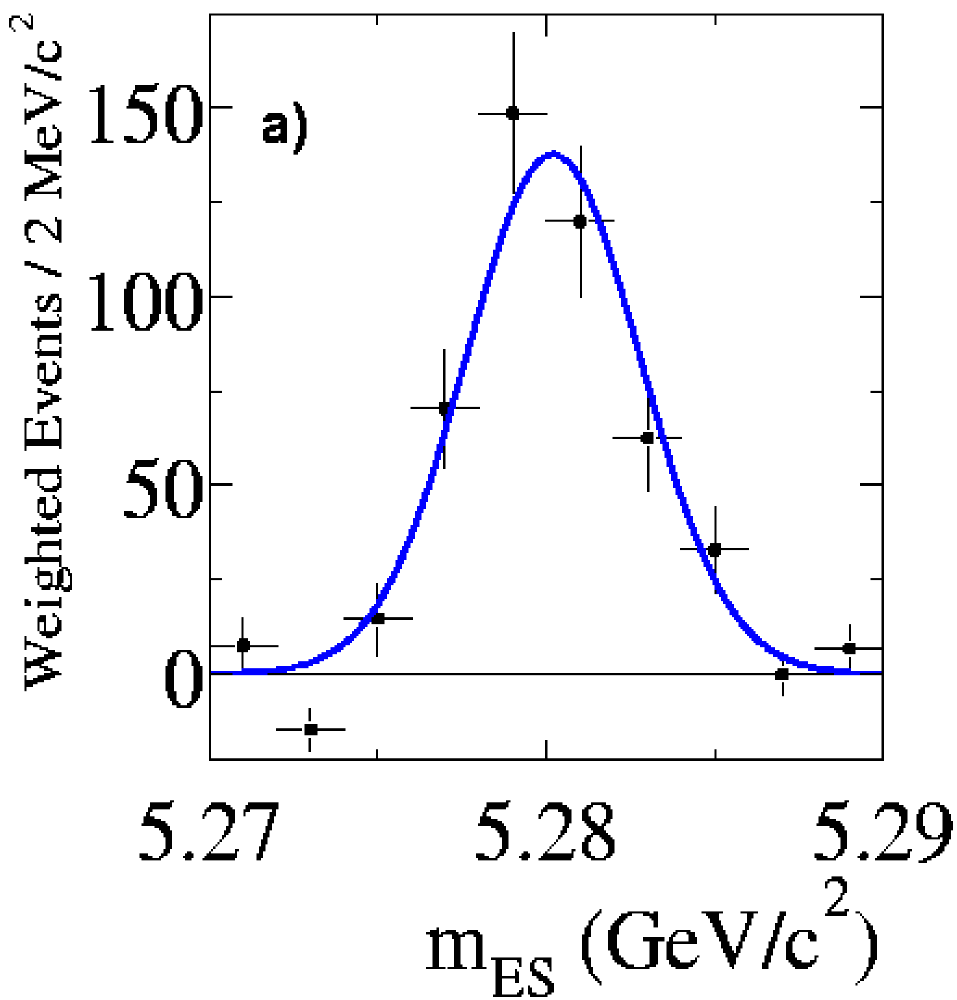
- Today $b \to sg$ transitions are also of interest to probe the state of the B meson
  - The photon energy spectrum, mean and spread, are sensitive to the b quark mass and momentum inside the B meson
  - This provides important information for the shape functions used in the determination of V_{ub} from the lepton endpoint.

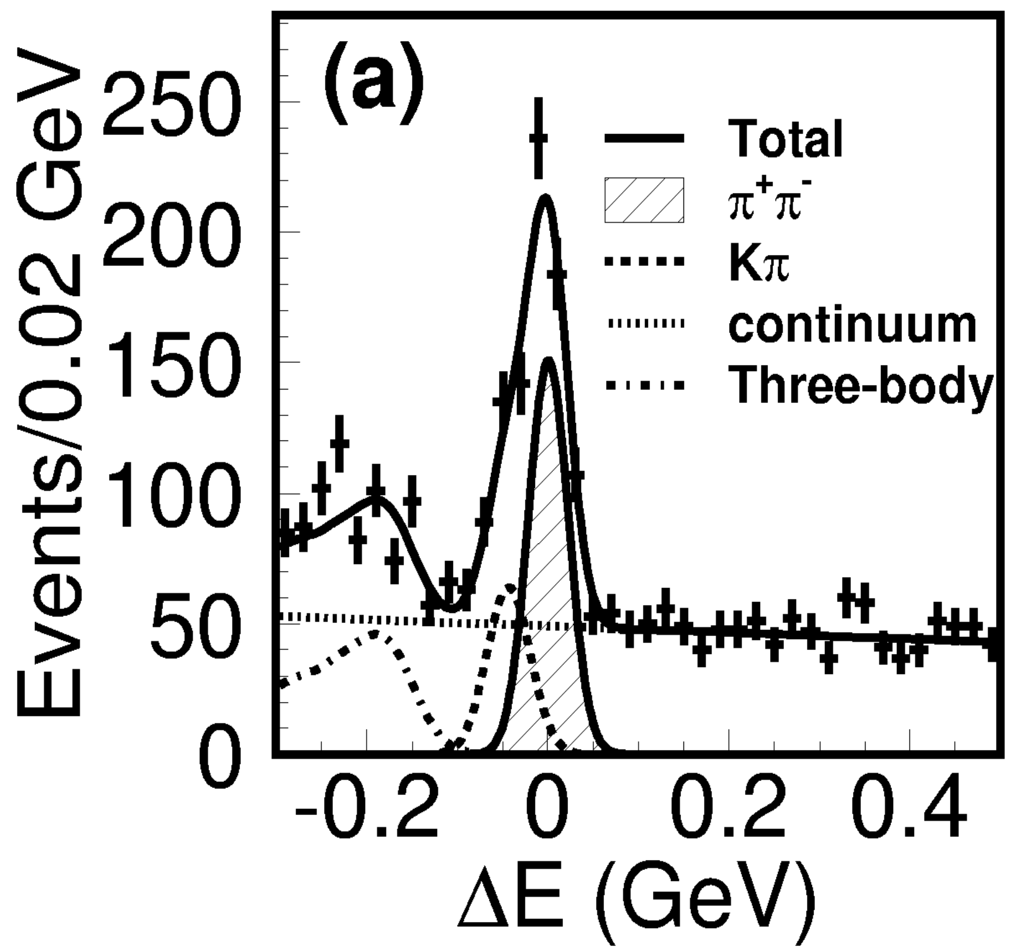
UT Constraint From B→

- Limits on B→ are now close to the standard model expectations – hints of signals.
- Limits on V_{td} are good – though model dependence large



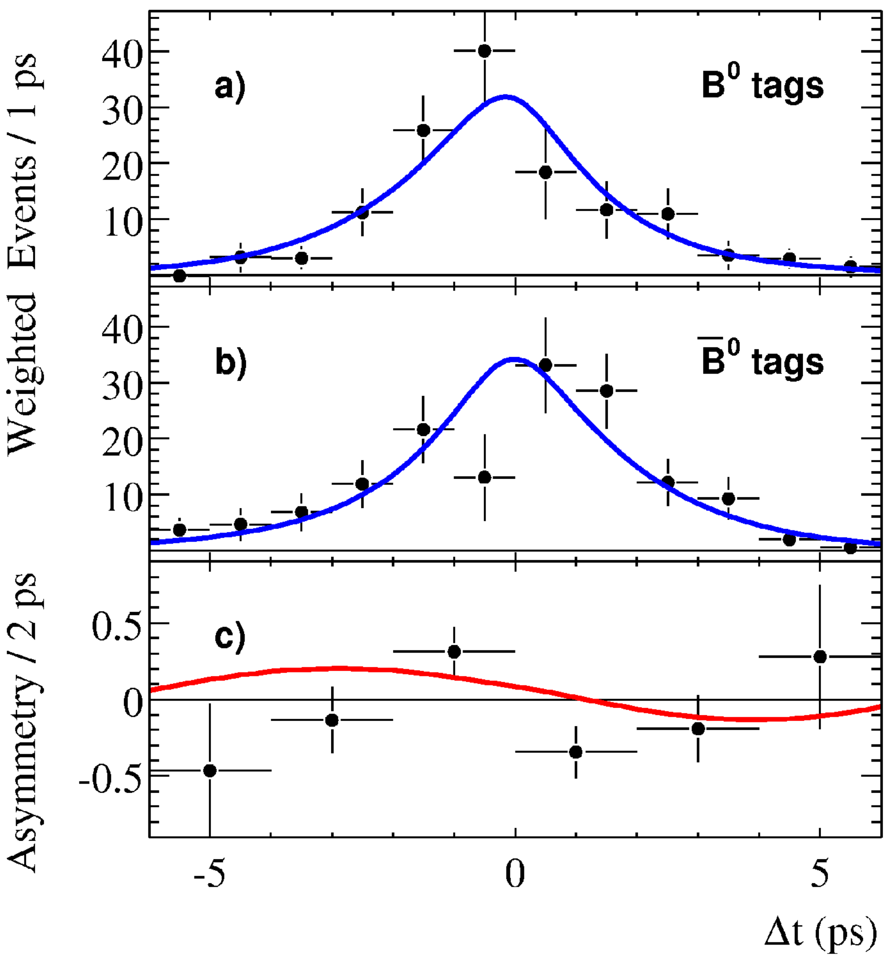
BaBar and Belle B→ +





CP Asymmetry for B→ +

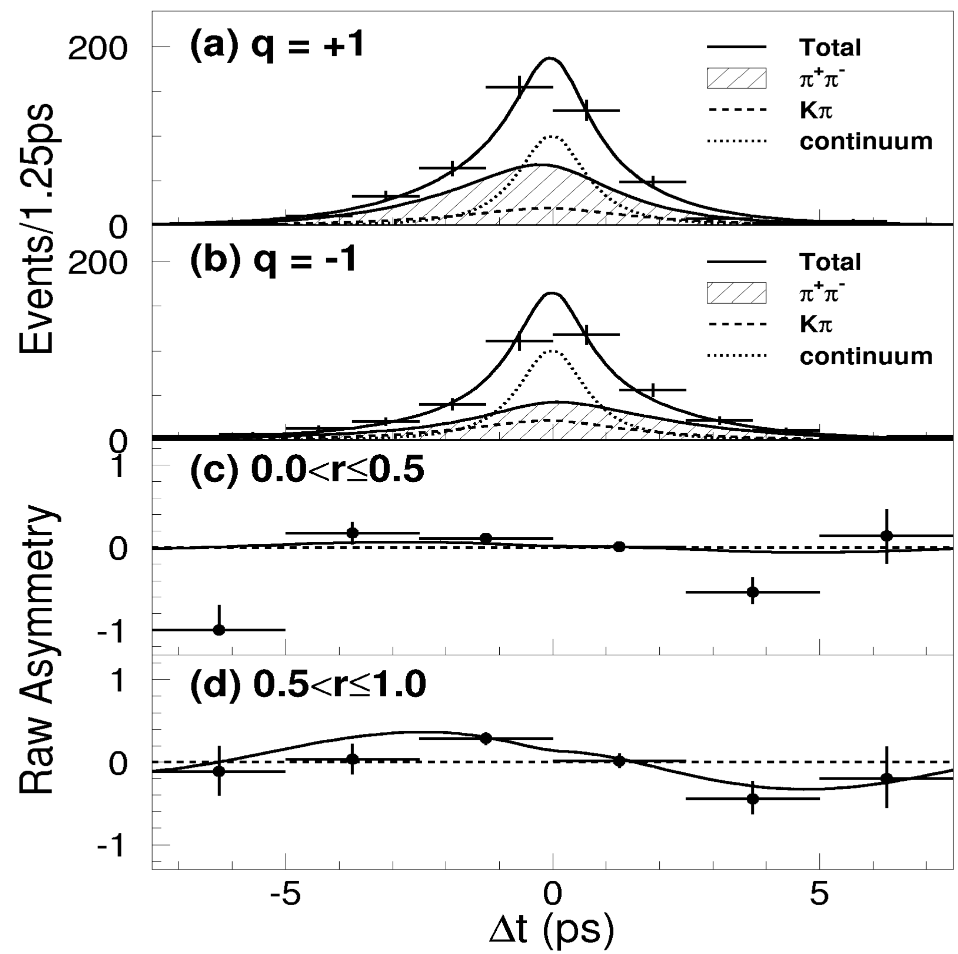
BABAR



$S_{\pi\pi} = -0.30 \pm 0.17 \pm 0.03$

$C_{\pi\pi} = -0.09 \pm 0.15 \pm 0.04$

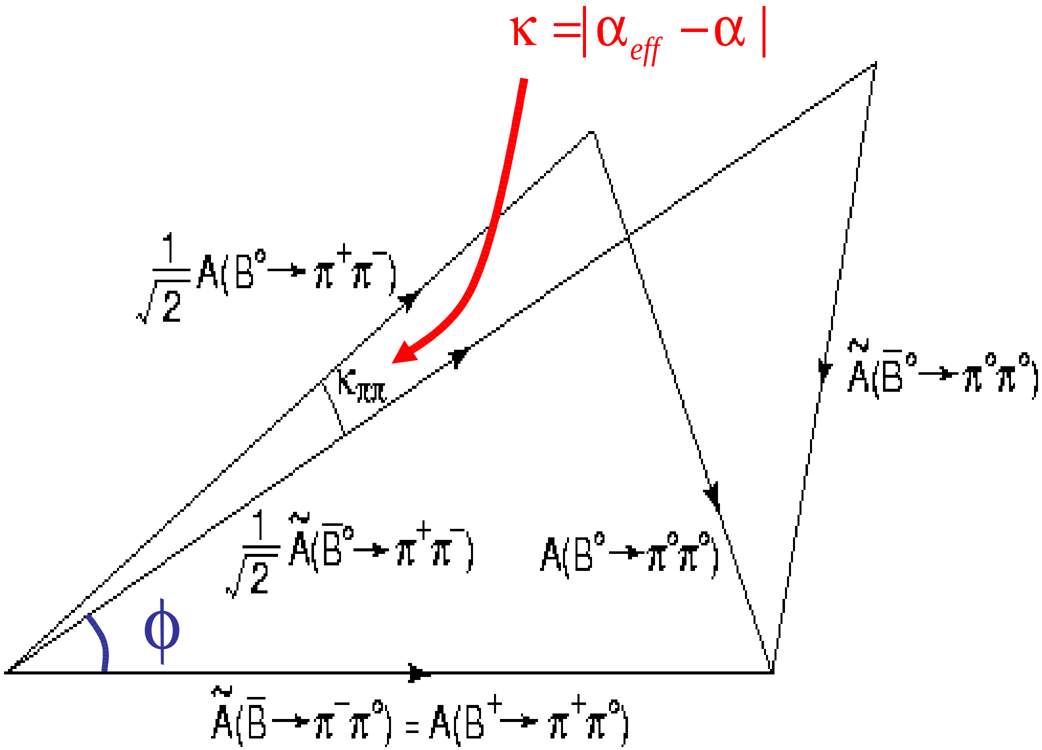
Belle



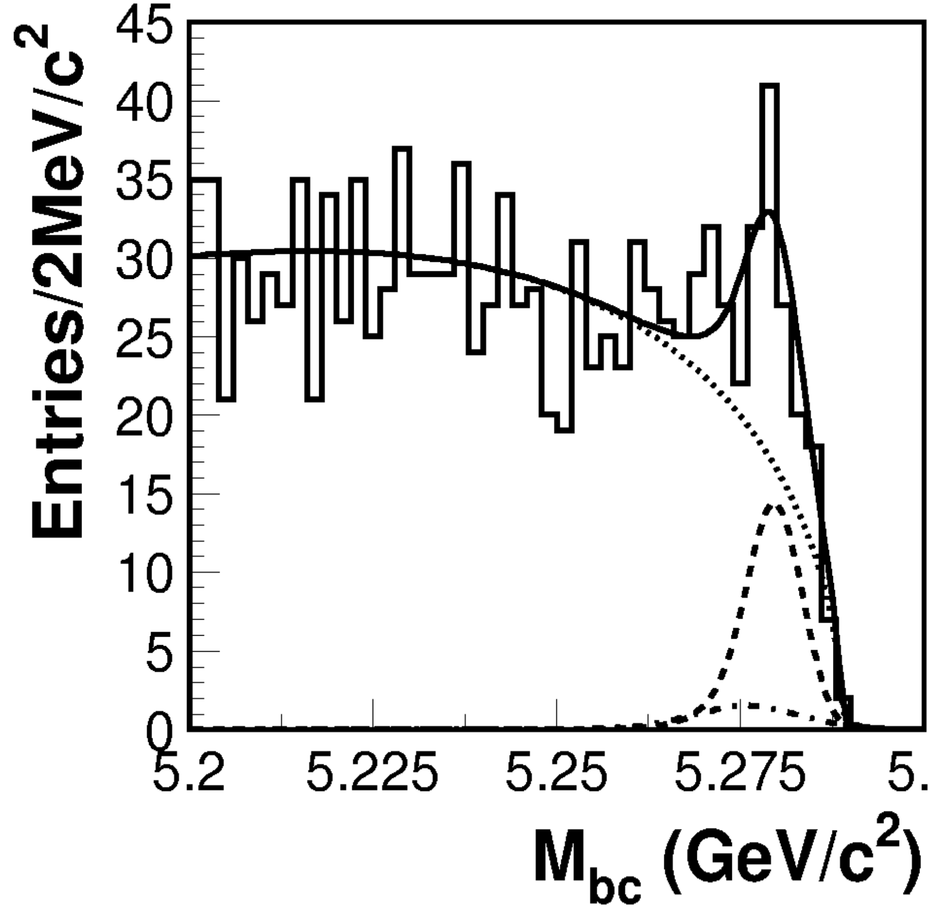
$S_{\pi\pi} = -0.67 \pm 0.16 \pm 0.06$

$C_{\pi\pi} = -0.56 \pm 0.12 \pm 0.06$

sin2 $_{\text{eff}}$



Belle B^0-> ^{0} ^{0}



BaBar limits | $_{\text{eff}}$-a|<35^{o}