Physics 222 UCSD/225b UCSB

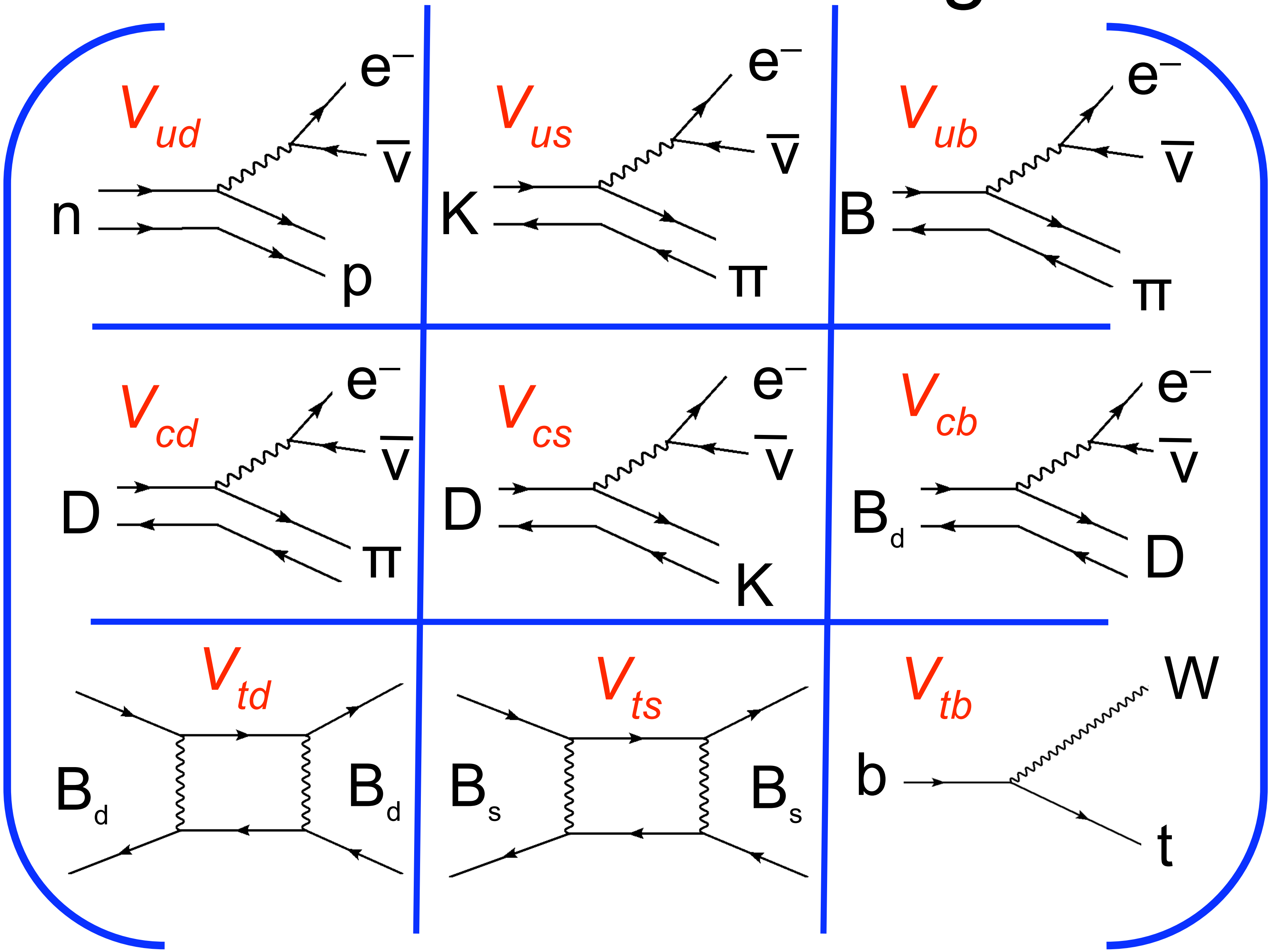
Lecture 7

Mixing & CP violation (3 of 3)

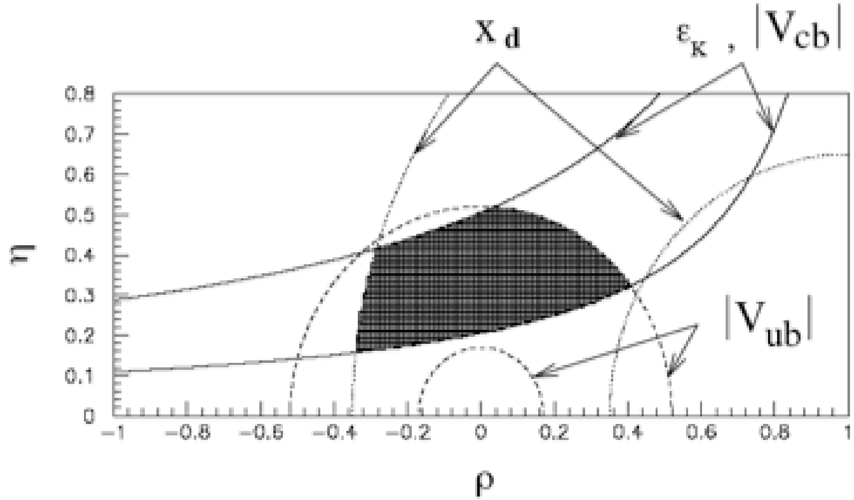
Today, we focus on how to measure things, and what the present knowledge is from the combination of theory and experiment.

Take 2 sources as references:
David MacFarlane at SSI 2002
Soeren Prell at Lepton-Photon 2009

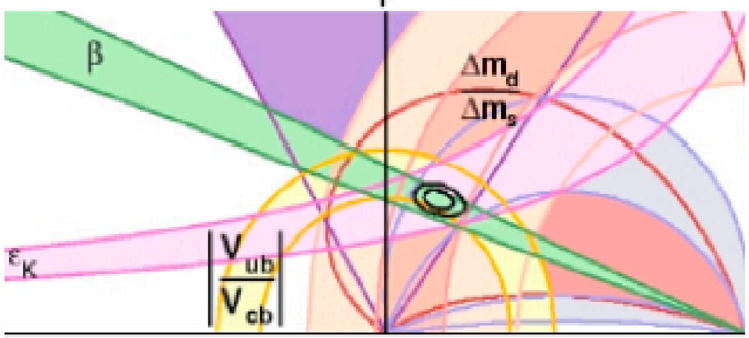
CKM Matrix Element Magnitudes



Experimental Knowledge



~1998



2007

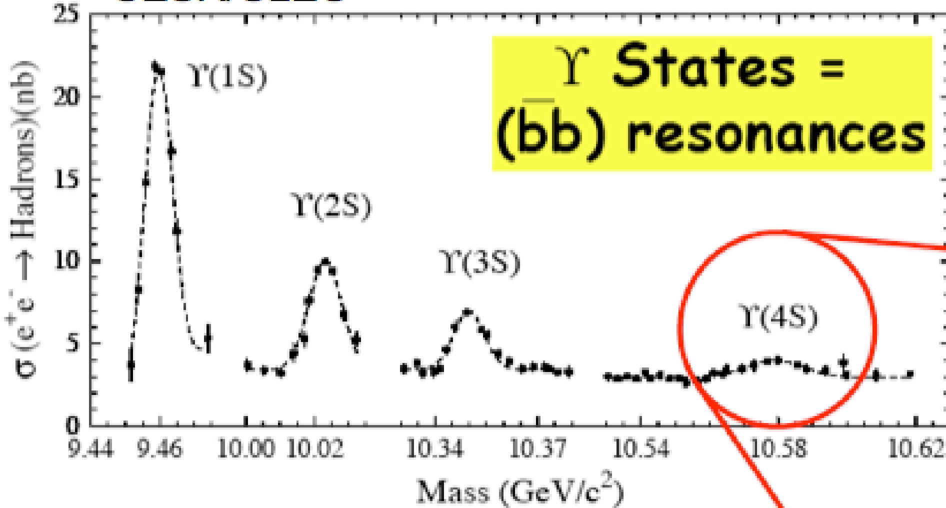
The experimentally allowed region in the ρ-η plane has decreased dramatically due to a VERY large number of precision measurements, mostly from BaBar and Belle.

The Experimental Facilities

- Virtually all information on Bd and Bu mesons today comes from BaBar and Belle, both operating at the Y(4S).
  - e+ e- -> Y(4S) -> B Bbar
- Virtually all information on all other beauty hadrons today comes from CDF, plus some info from D0.
  - p pbar -> b bbar jets -> hadronizing into b-hadrons
- Information on D decays comes from CLEO-C, BaBar, Belle, and a little from CDF.
  - CLEO-C is e+ e- -> charmonium -> D Dbar

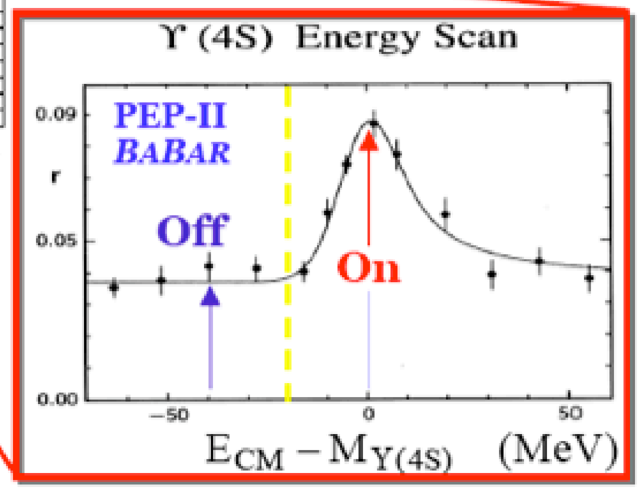
e+ e- -> Υ(4S)

CESR/CLEO



Υ States = ($b\bar{b}$) resonances

B Bbar are produced in coherent quantum state. Just like EPR.



Cross Sections at Υ(4S):

$b\bar{b} \sim 1.1$ nb

$c\bar{c} \sim 1.3$ nb

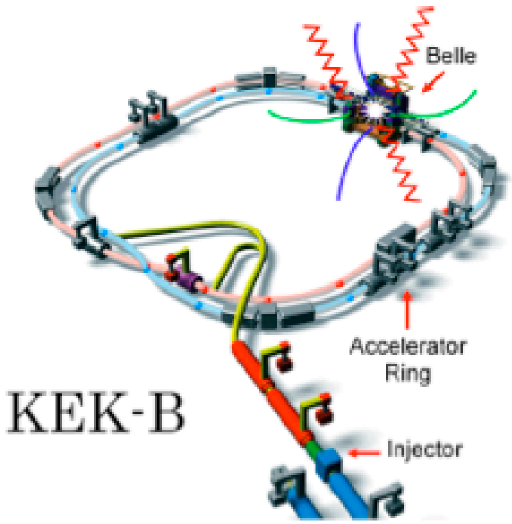
$d\bar{d}, s\bar{s} \sim 0.3$ nb

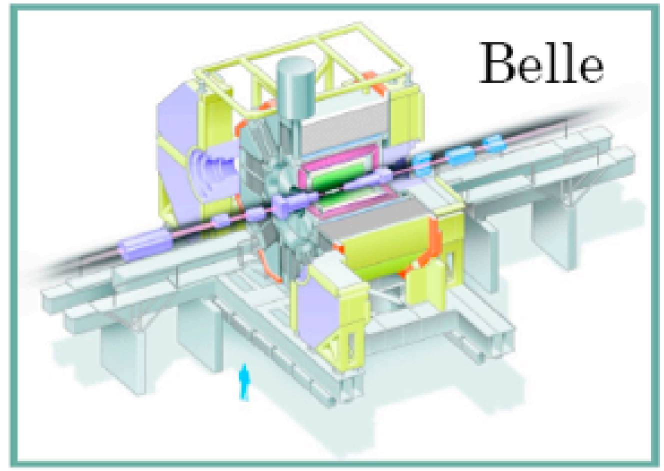
$u\bar{u} \sim 1.4$ nb

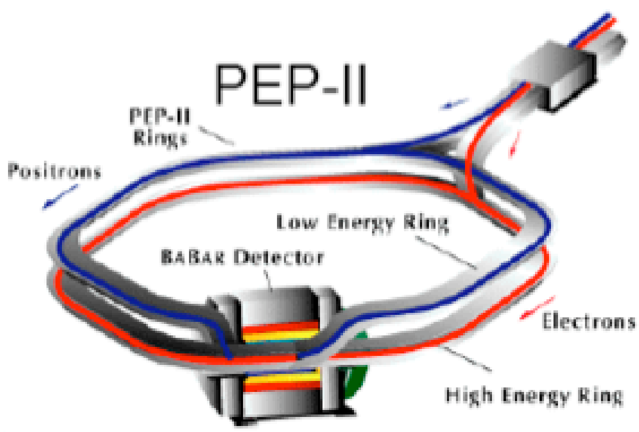
$e^+e^- \to \Upsilon(4S) \to B\bar{B}$

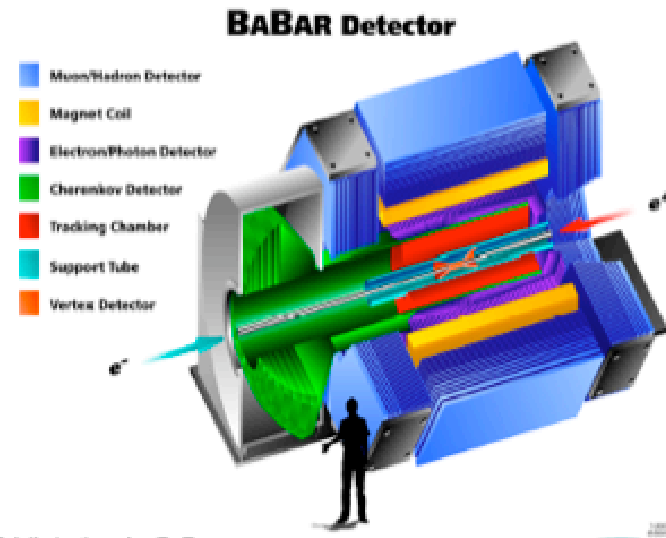
$L = 1$ state

Υ(4S) boosted with βγ~0.5





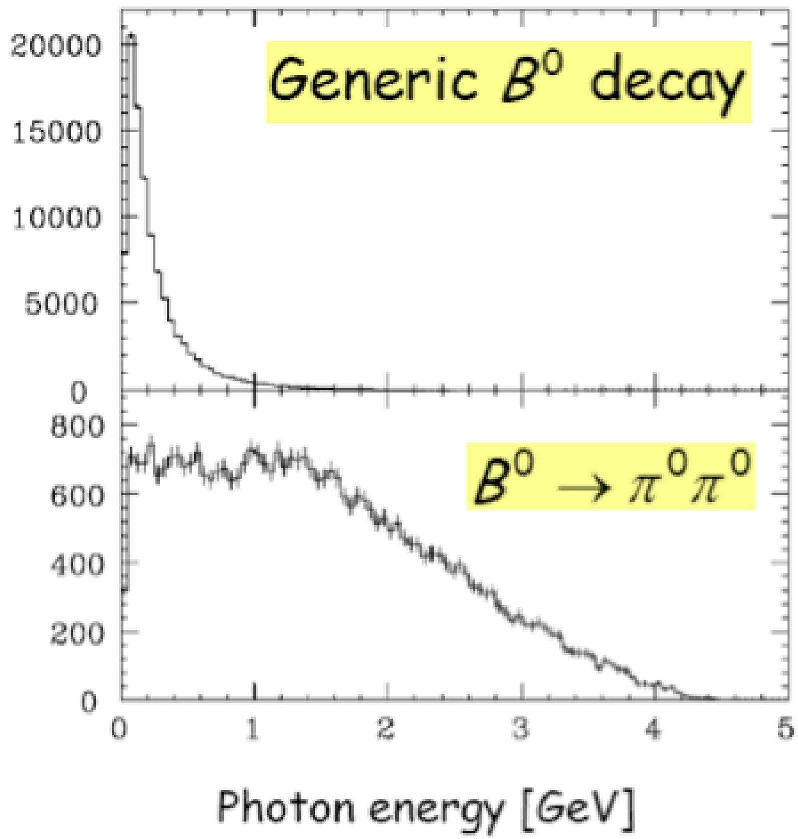




Main Features

- Accelerator with two independent rings, one for electrons, one for positrons.
  - "Asymmetric B factory", i.e. the Y(4S) is boosted.
  - Boost is necessary because Q-value of decay is too small to provide boost for B's to measure their flight distance, and thus decay time.
  - Essential to distinguish + from - delta t's, otherwise mixing and CP asymmetries average out.
- Typical event environment:
    - ~10 tracks & 10 photons per event
    - 50MeV to ~4GeV charged particles and pizero's.
    - Kaon vs Pion particle ID up tp 4GeV.

Typical Photon Energies



Most B decay products have very low momenta.

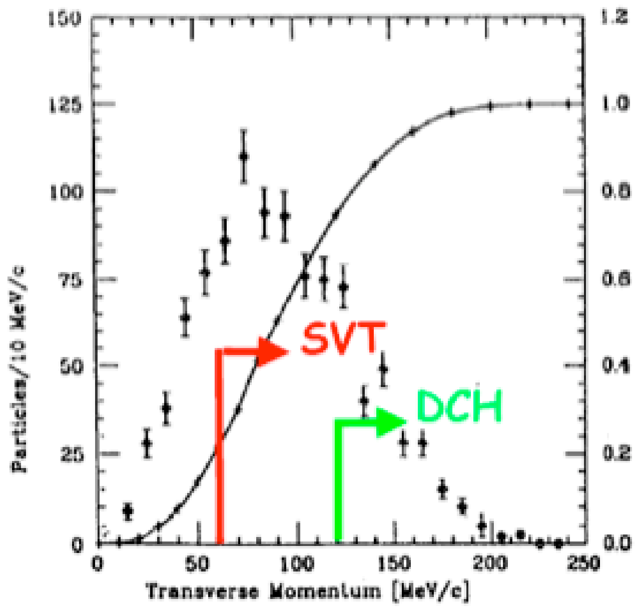
However, some of the most important processes involve 2-body B decays.

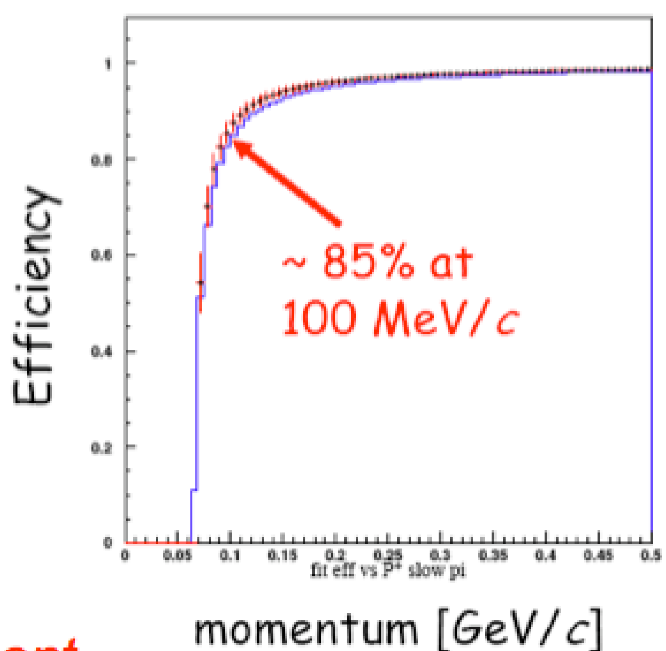
Requirements: Low p_t Tracking

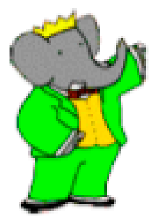
Common to reconstruct $D^{*+} \to D^0\pi^+$ with very soft π^+

Advantage: *Excellent resolution for mass difference*

Disadvantage: *Small bending radius, difficult to track*







Crucial for Vcb measurement

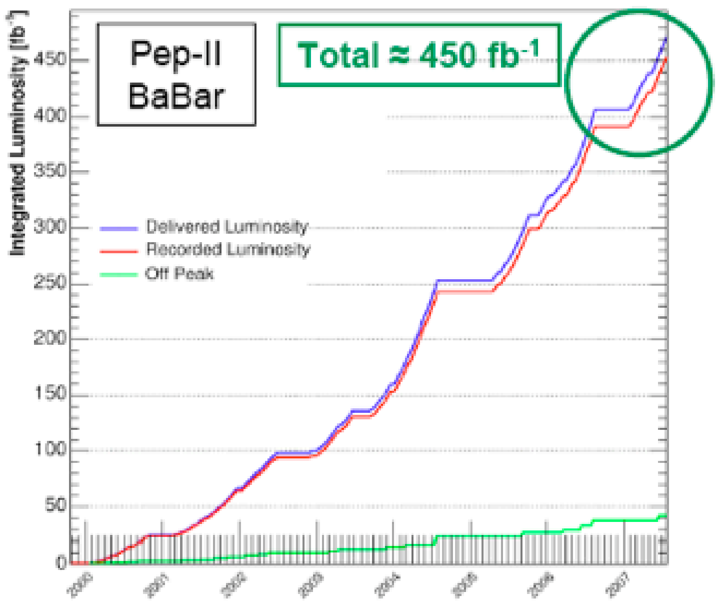
Why does this matter?

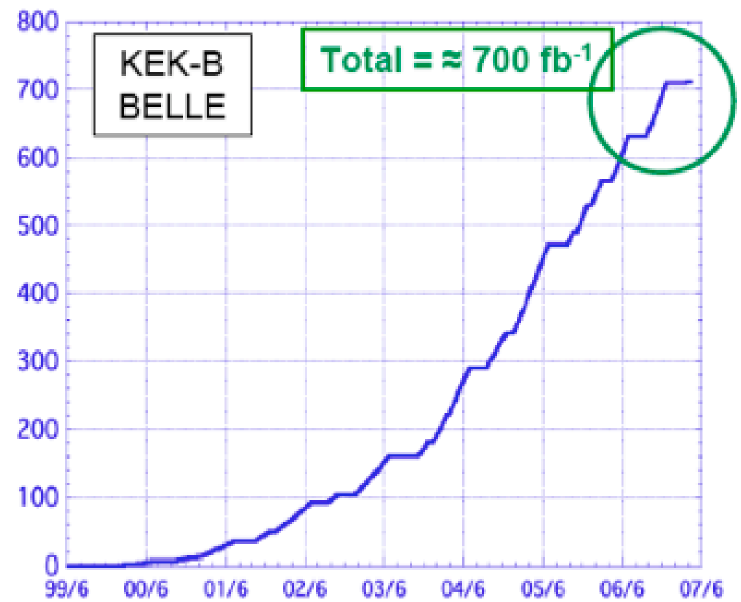
Heavy Quark Symmetry predicts that the B -> D* transition in B -> D* l nu has trivial form factor for the part of phase space when the D* is at rest in the B restframe.

However, this also leads to minimal pT for the slow pion in the D* -> D pi decay.

$|V_{cb}|$ is theoretically most accurately extracted from experimental data where it is experimentally most difficult.

Datasets by 2007

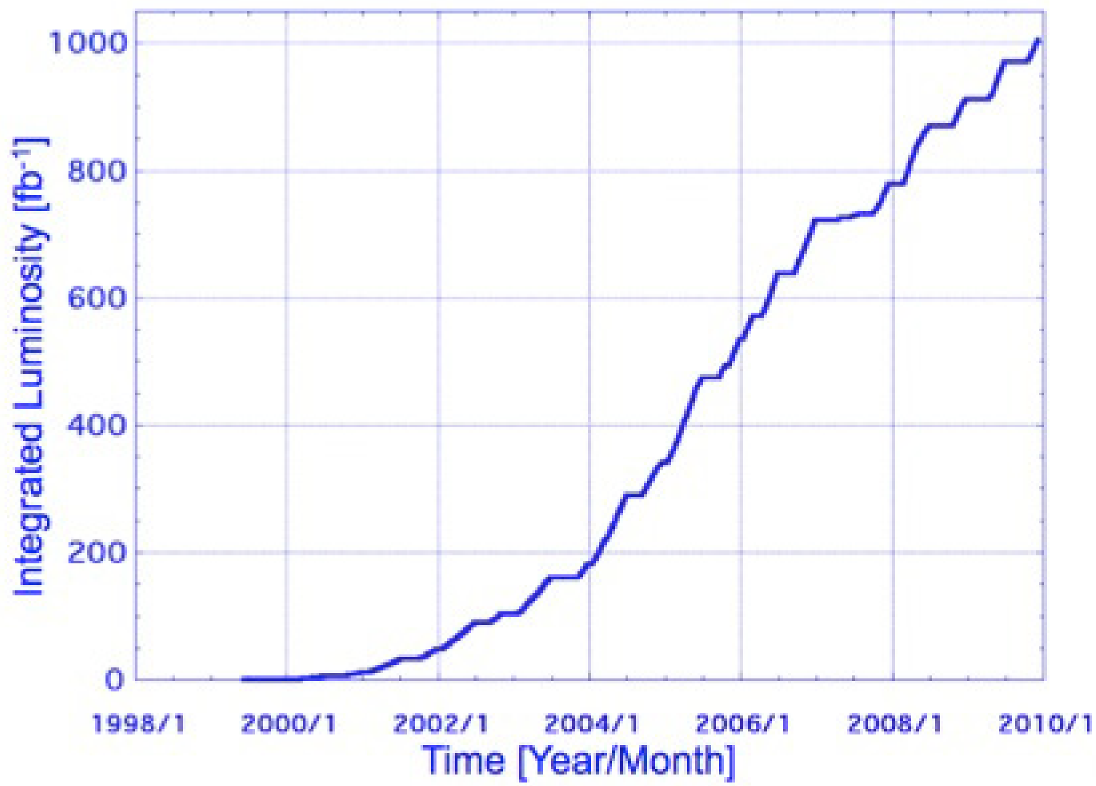




1fb-1 is roughly 1 Million B Bbar pairs.
⇒Together, they have more than 1 Billion B Bbar pairs !!!

In comparison, my thesis (1995) used <10 Million B Bbar's.

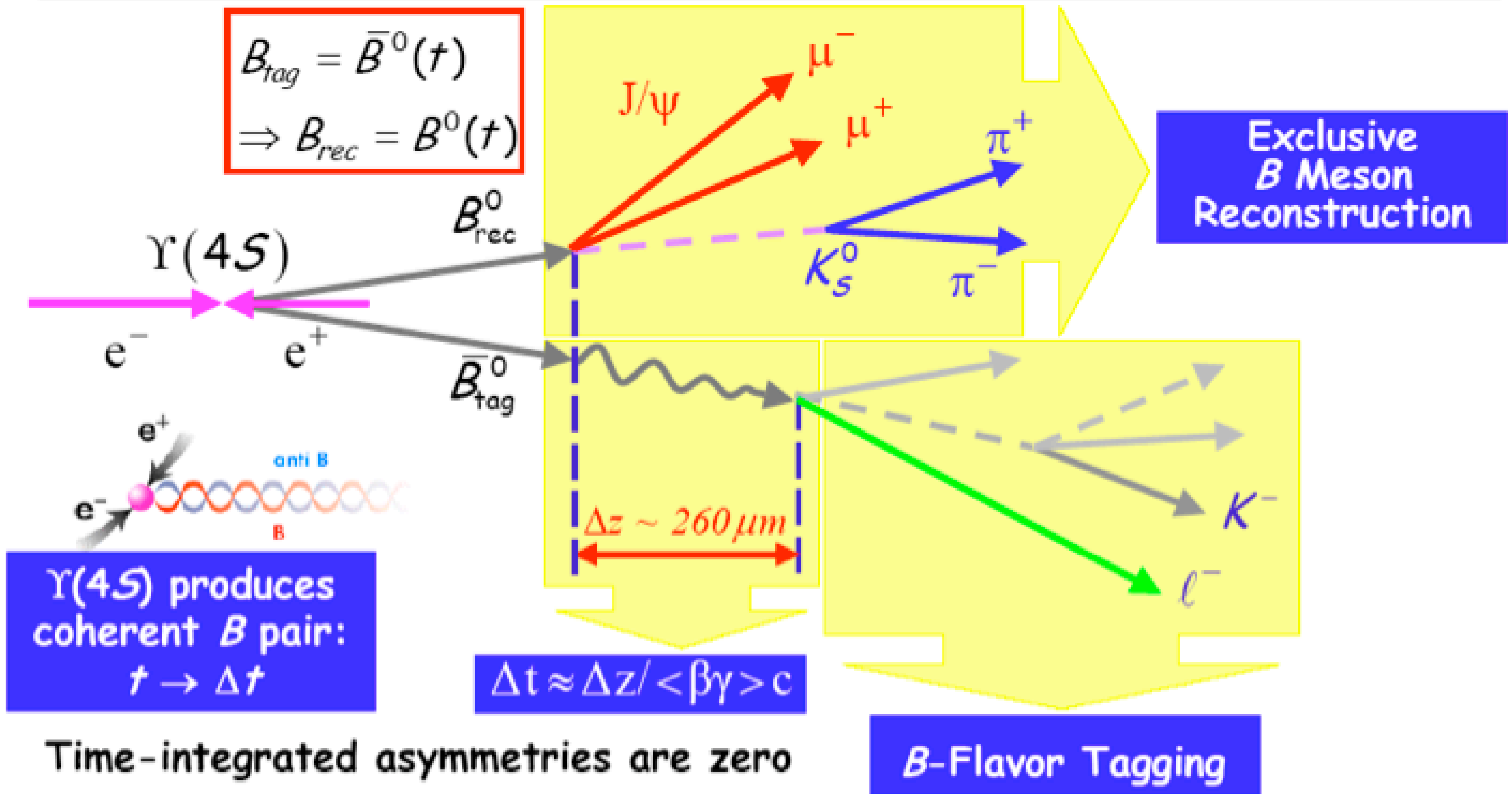
Luminosity accumulated by Belle reached 1000/fb on November 29th 2009.



Outline of lecture

- Walk through one measurement in detail.
  - Time dependent CP violation.
- Mention the conceptual ideas of some of the others that determine the CKM matrix.
- Provide a brief outlook of the key goals for the future.

Experimental Technique for B Factories

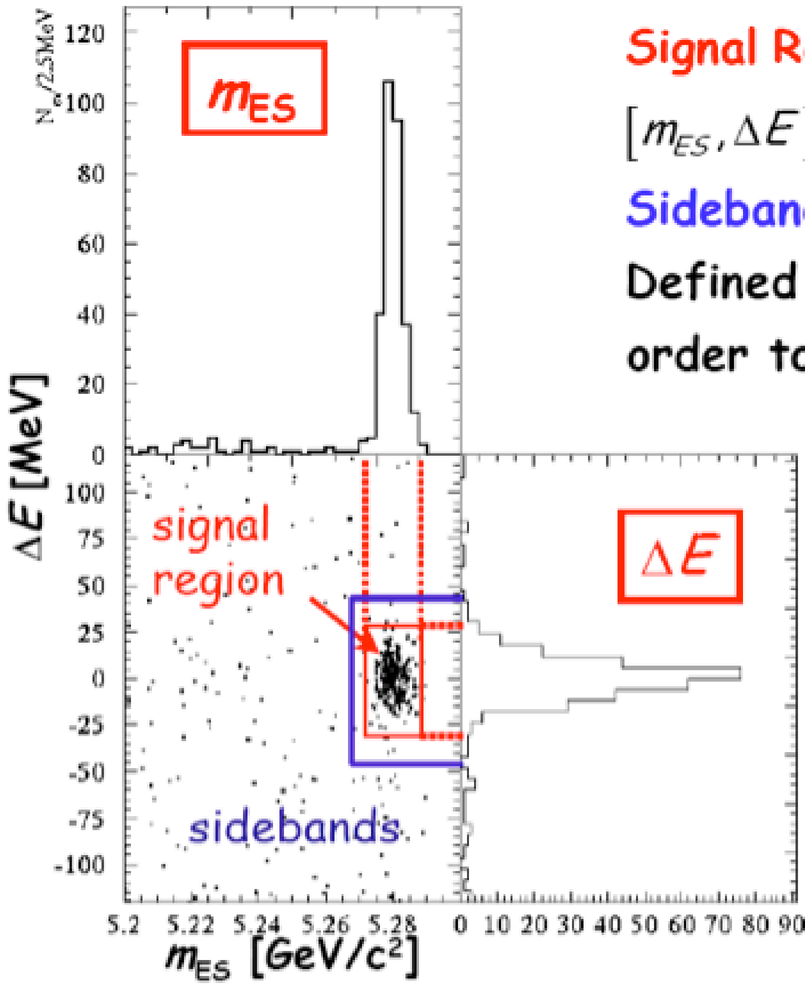


Time-integrated asymmetries are zero

$B^0_{rec} = B^0_{flav}$ (flavor eigenstates) → lifetime, mixing analyses

$B^0_{rec} = B^0_{CP}$ (*CP* eigenstates) → *CP* analysis

Example for Hadronic B Decays



Signal Region :

$$[m_{ES}, \Delta E] = [m_B \pm 3\sigma_{m_{ES}}, 0 \pm 3\sigma_{\Delta E}]$$

Sideband Region :

Defined outside signal region in order to estimate backgrounds

$B^0 \to J/\psi K_S$

Time-Dependent Analysis Strategies

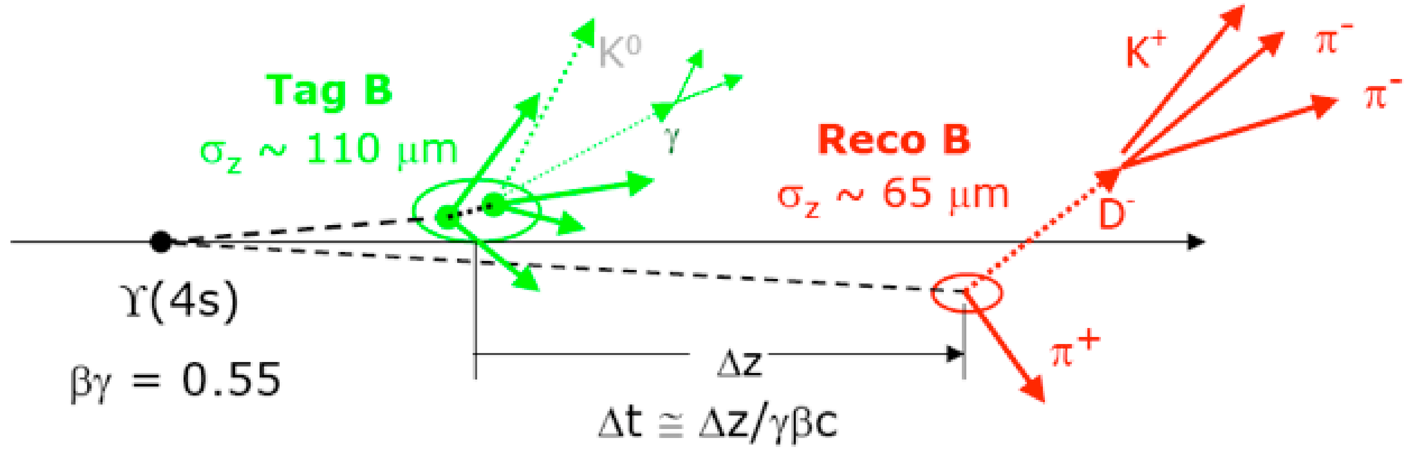
Factorize the analysis into building blocks

Measurements	Analysis Ingredient
B^+ / B^0 Lifetimes	a) Reconstruction of B mesons in flavor eigenstates b) B vertex reconstruction
$B^0\bar{B}^0$ Mixing	c) Flavor Tagging + a + b
CP Asymmetries	d) Reconstruction of neutral B mesons in CP eigenstates + a + b + c

Higher precision (↑)

Increasing complexity (↓)

Measurement of B^0 and B^+ Lifetime

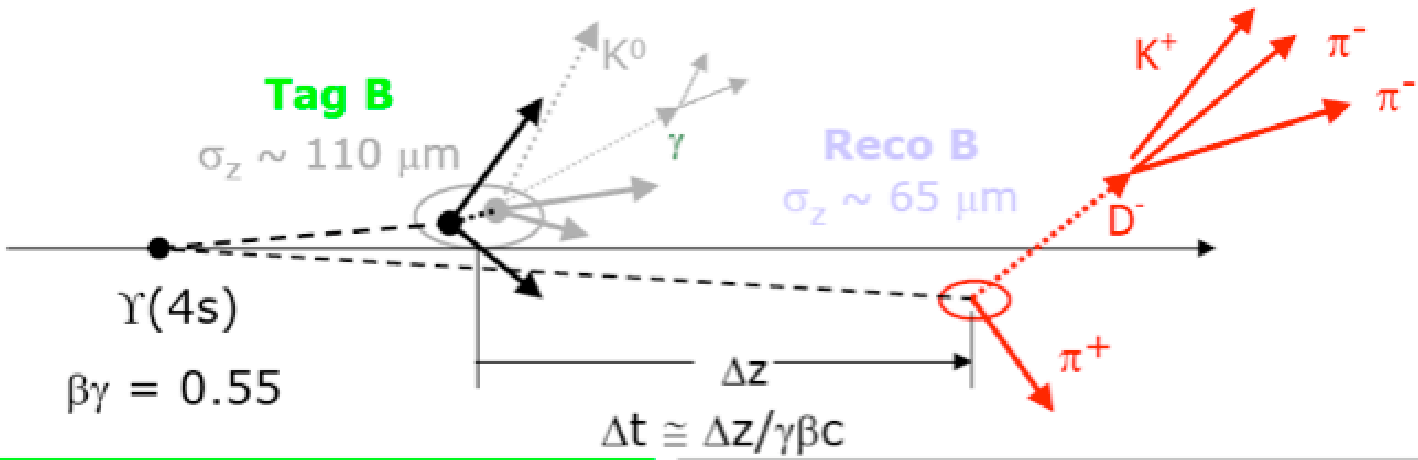


3. Reconstruct inclusively the vertex of the "other" B meson (B_{TAG})

1. Fully reconstruct one B meson in flavor eigenstate (B_{REC})
2. Reconstruct the decay vertex

4. Compute the proper time difference Δt
5. Fit the Δt spectra

Measurement of $B^0\overline{B^0}$ Mixing



3. Reconstruct Inclusively the vertex of the "other" B meson (B_{tag}) ✓
4. Determine the flavor of B_{tag} to separate Mixed and Unmixed events

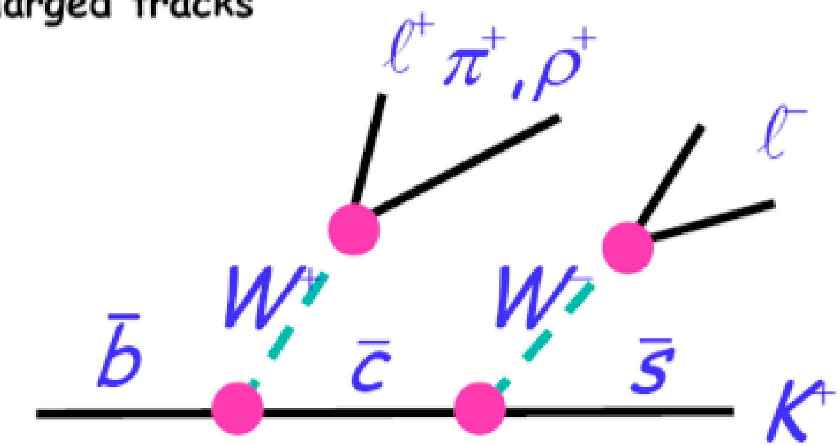
1. Fully reconstruct one B meson in flavor eigenstate (B_{rec}) ✓
2. Reconstruct the decay vertex ✓

5. compute the proper time difference Δt ✓
6. Fit the Δt spectra of mixed and unmixed events

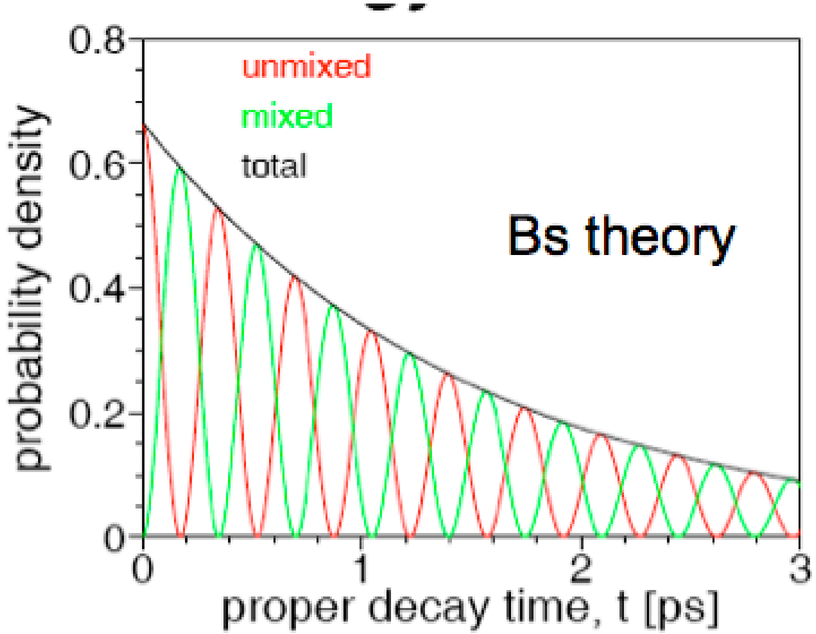
Methods for B Flavor Tagging

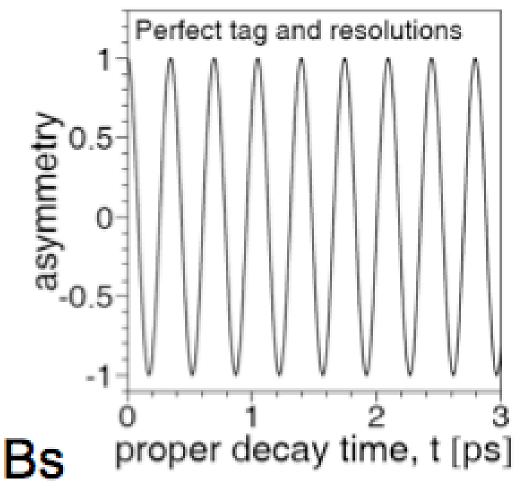
Many different physics processes can be used

Primary lepton	$B^0 \to D^{*-} \ell^+ \nu$
Secondary lepton	$B^0 \to D^- \pi^+, D^- \to K^{*+} \ell^- \bar{\nu}$
Kaon(s)	$B^0 \to \bar{D} X, \bar{D} \to K^+ X$
Soft pions from D^* decays	$B^0 \to D^{*-} X^+, D^{*-} \to \bar{D}^0 \pi_s^-$
Fast charged tracks	

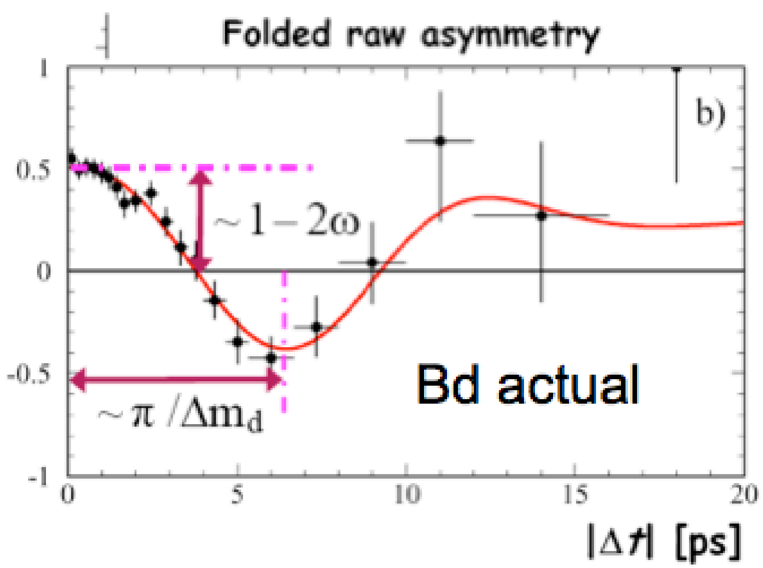


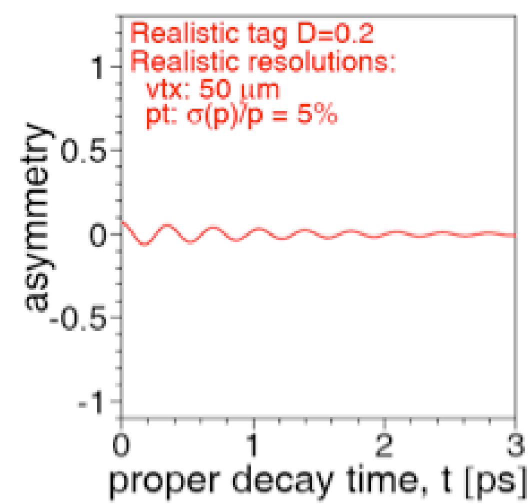
Bd and Bs Mixing



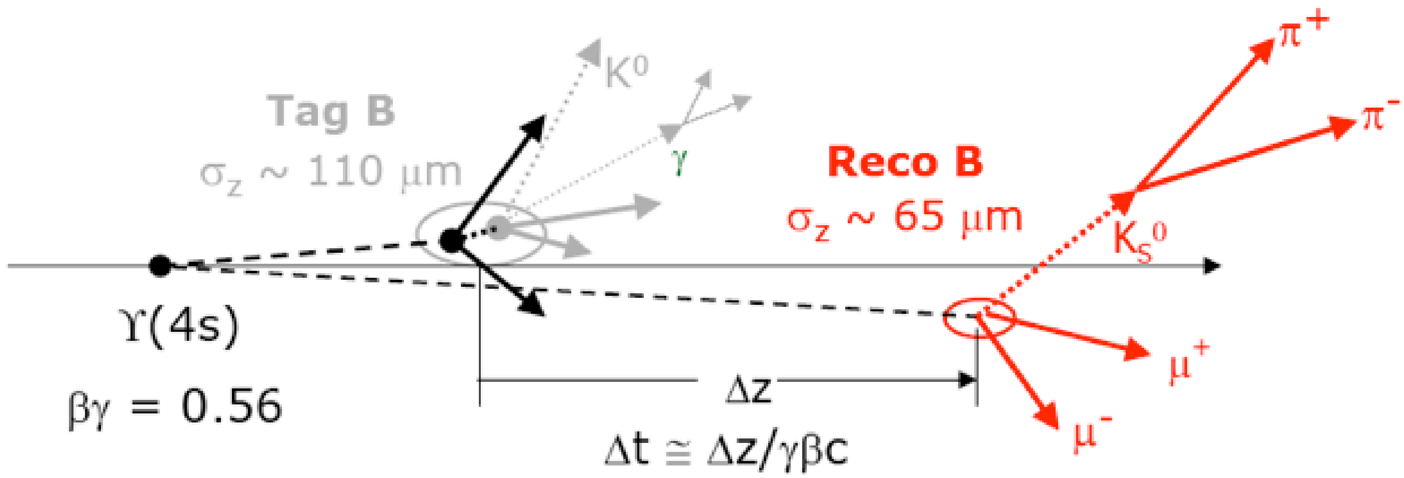


Bs





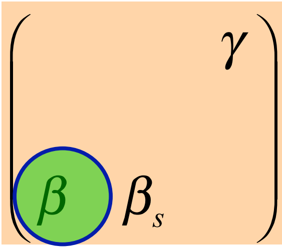
Measurement of sin2β



3. Reconstruct Inclusively the vertex of the "other" B meson (B_{tag}) ✓
4. Determine the flavor of B_{tag} to separate B^0 and $\overline{B}^0$ ✓

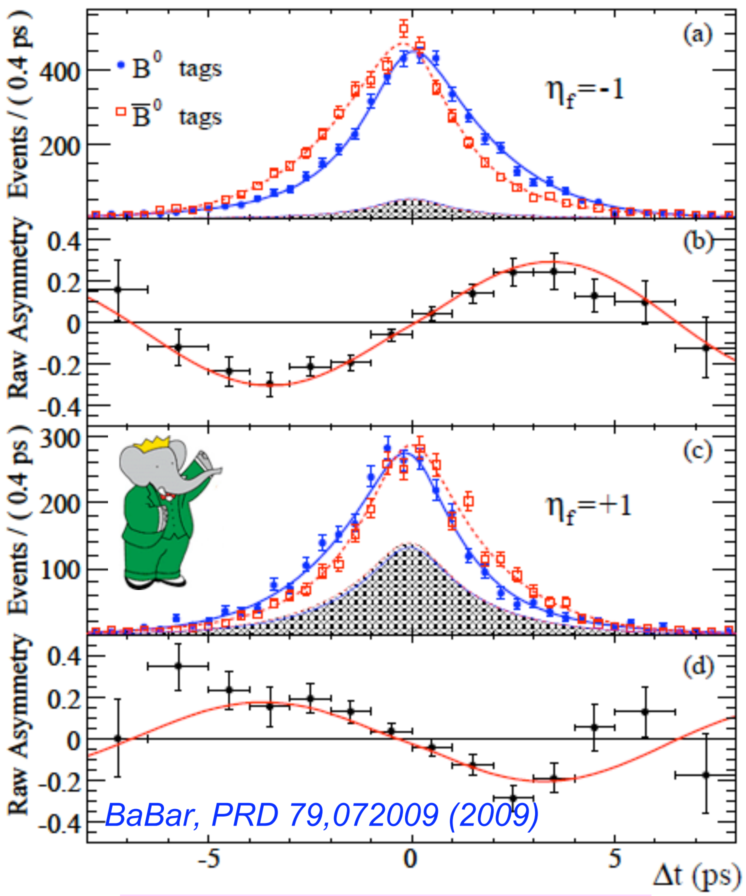
1. Fully reconstruct one B meson in CP eigenstate (B_{rec})
2. Reconstruct the decay vertex ✓

5. compute the proper time difference Δt ✓
6. Fit the Δt spectra of B^0 and $\overline{B}^0$ tagged events

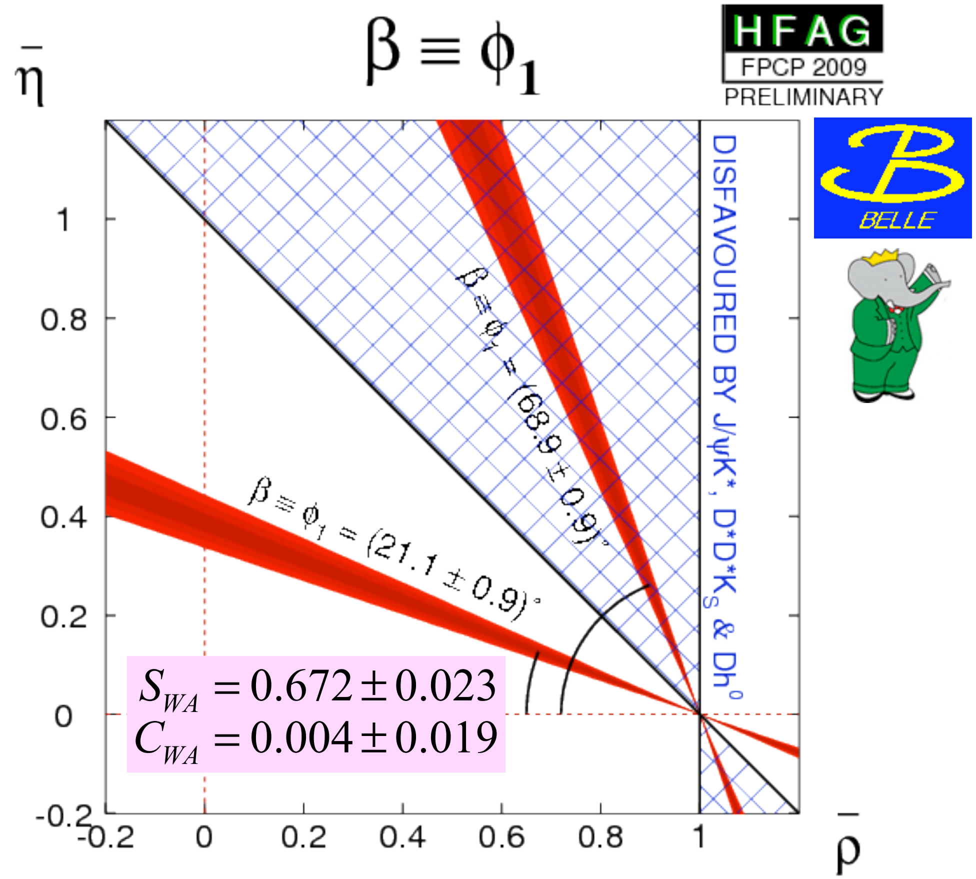


β from b →(*cc*) s decays

Theor. clean measurement of |S| = sin2β with B → J/ψ K^0, J/ψ K*, ψ(2S)K_S, $\eta_c K_S$, & $\chi_{c1} K_S$ by BaBar and Belle



$$S = 0.687 \pm 0.028 \pm 0.012$$
$$C = 0.024 \pm 0.020 \pm 0.016$$



statistically limited

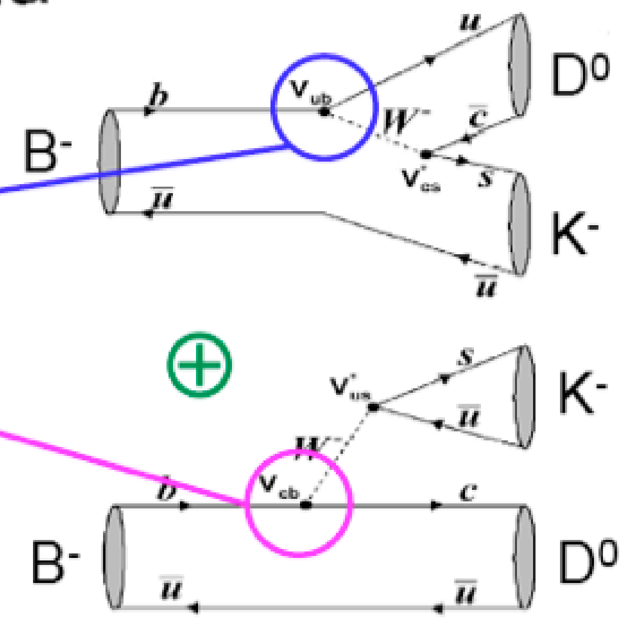
$$\beta = (21.1 \pm 0.9)^\circ$$

Comments

- There's a large number of other final states that have been used to measure the same phase.
  - Systematic verification of the standard model across different processes involving both tree and penguin type decays.
- Measurement of the angle alpha is more involved.
  - Both tree and penguin contribute, and need to be disentangled.
  - Body of experimental and theoretical knowledge too vast to cover in this course.
- Measurement of the angle gamma is overall different strategy.
  - Use tree level interference of b->u with b->c transition.
  - Body of experimental and theoretical knowledge again too vast to cover here.

Gamma

$$\gamma = \phi_3 = \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$



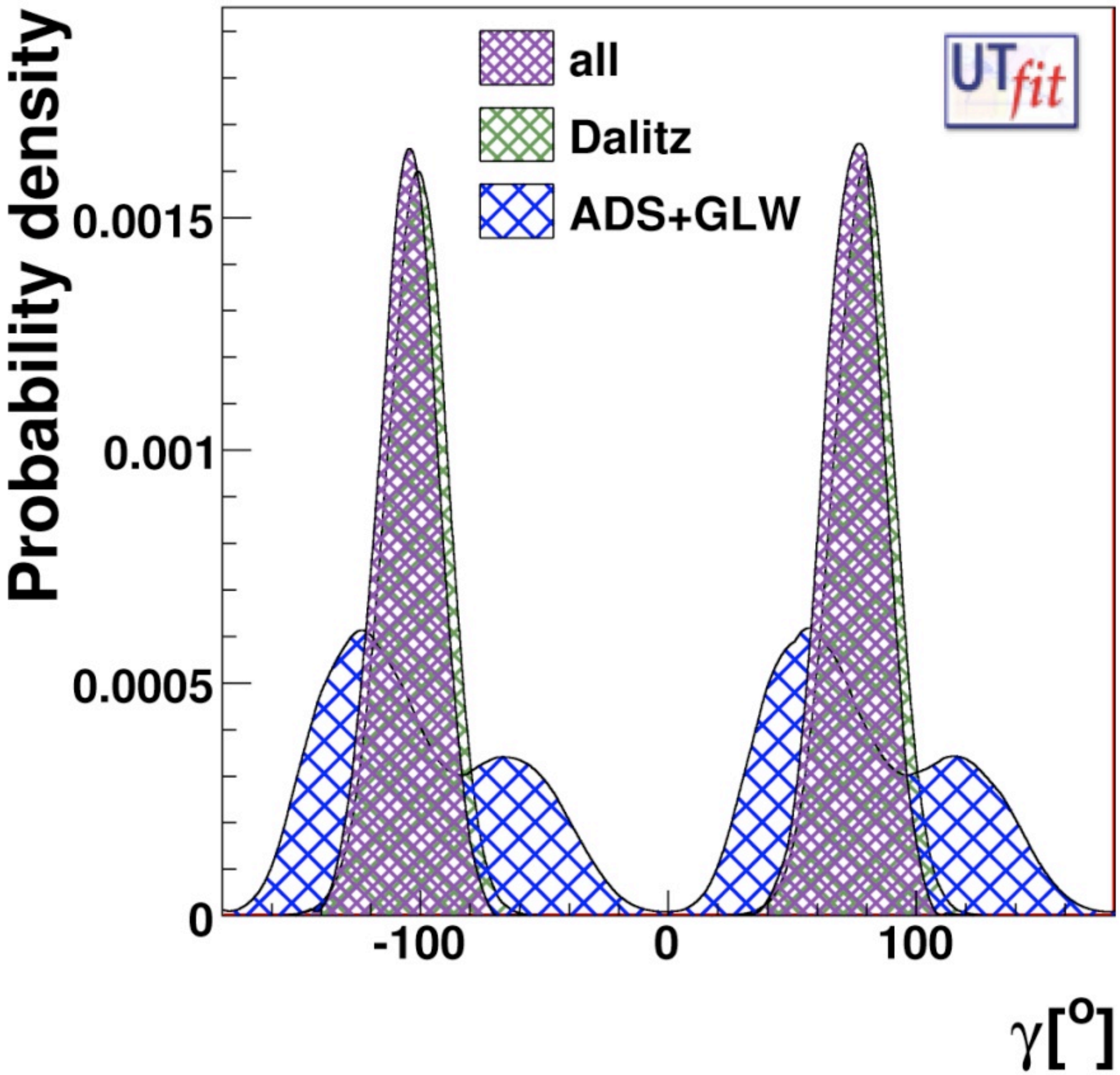
The conceptual idea is simple.
The actual techniques are varied, and generally complex.

For details see:

GLW =Gronau, London (1991),Gronau, Wyler (1990)
ADS = Atwood, Danietz, Soni (1997)
GGSZ =Giri, Grossman, Soffer, Zupan (2003)

Lepton-photon 2009

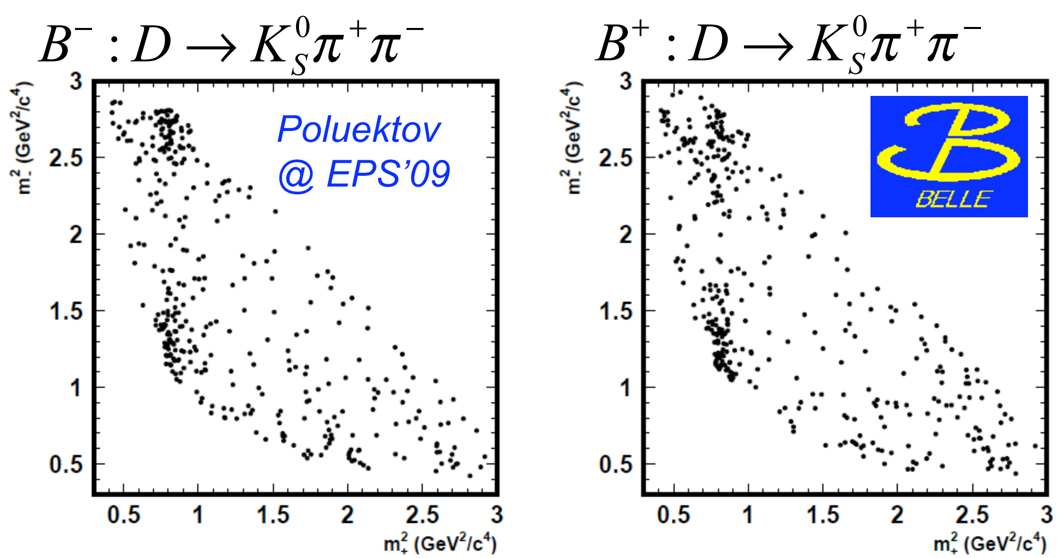
Dalitz analysis now clearly dominates the precision.



$$\gamma_{UTFit} = (75 \pm 12)^{o}$$

Basic idea:
b -> u transition with c-bar quark from virtual W
interferes with b -> c transition,
IFF one chooses a decay of the D meson that is common for
D and anti-D meson.

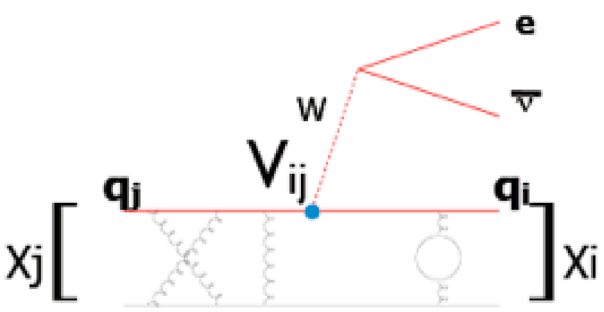
The resonance structure then provides the CP conserving
“phase analyzer” to measure gamma from the interference.



Measuring the sides

- Knowledge comes primarily from semi-leptonic decays:
  - |Vcb| from B -> D decays, both exclusive and inclusive.
  - |Vub| from b -> u decays, both exclusive and inclusive.
  - |Vcd|, |Vcs| from D -> K
  - |Vus| from K -> pi

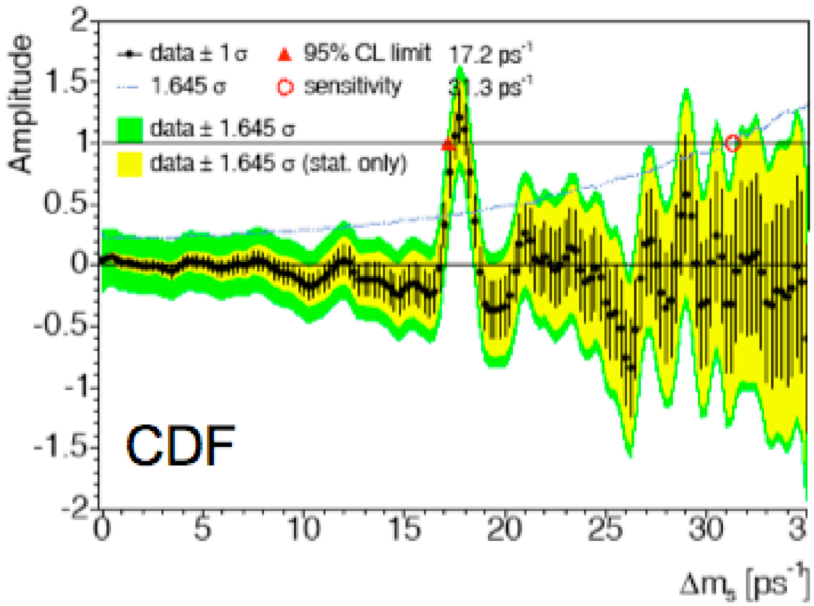
Once again, a vast topic !!!



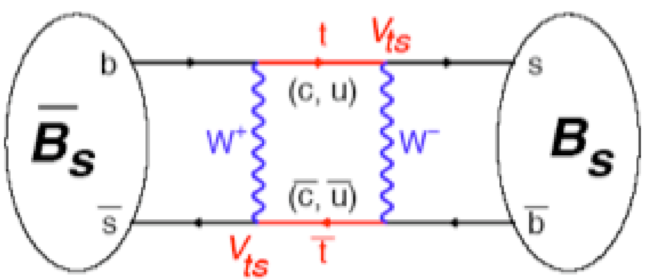
One Exception

- |Vts / Vtd| comes from the ratio of $\Delta m_s / \Delta m_d$

$$\frac{\Delta m_s}{\Delta m_d} = \frac{m_{B_s}}{m_{B_d}} \xi^2 \frac{|V_{ts}|^2}{|V_{td}|^2} \quad \text{with} \quad \xi = 1.21 ^{+0.047}_{-0.035}$$



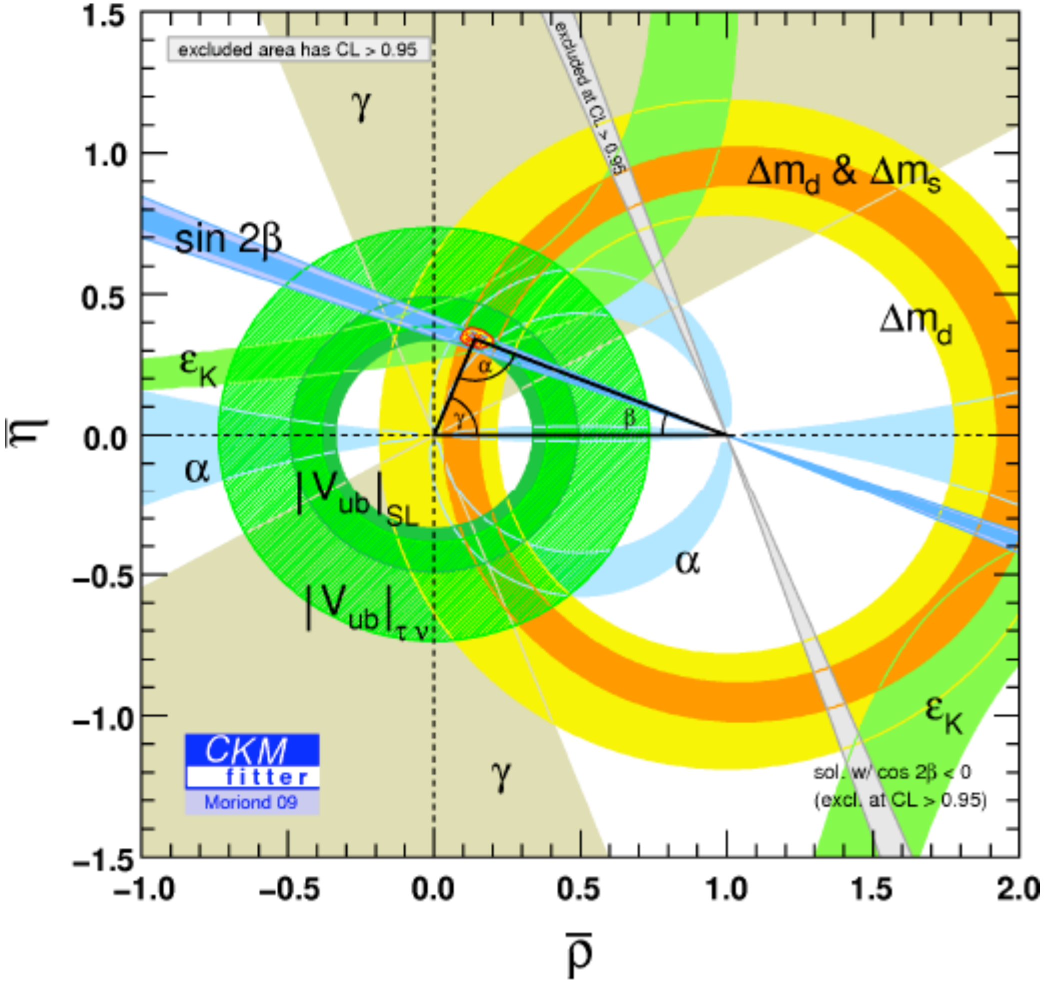
From lattice QCD



$$\Delta m_s = 17.77 \pm 0.10(\text{stat}) \pm 0.07(\text{syst})$$

Global CKM Fit

All constraints



UTFit: $\bar{\rho} = 0.154 \pm 0.022$	CKMFitter: $\bar{\rho} = 0.139^{+0.025}_{-0.027}$
$\bar{\eta} = 0.342 \pm 0.014$	$\bar{\eta} = 0.341^{+0.016}_{-0.015}$

- Consistency of angles

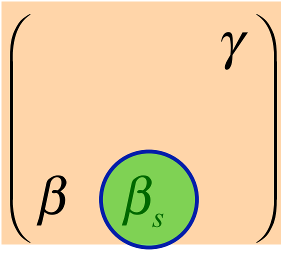
$$\alpha = \left(89.0^{+4.4}_{-4.2}\right)^o$$
$$\beta = \left(21.1 \pm 0.9\right)^o$$
$$\gamma = \left(75 \pm 12\right)^o$$

$$\alpha + \beta + \gamma = \left(185 \pm 13\right)^o$$

- Consistency of angles and sides from global fit
  - Overall good fit (CKMFitter: global p-value 45%)
  - ~2σ tension between sin2β and ε_K / V_{ub}
    - correction to ε_K will make it worse (Buras, Guadagnoli, PRD78, 033005 (2008))

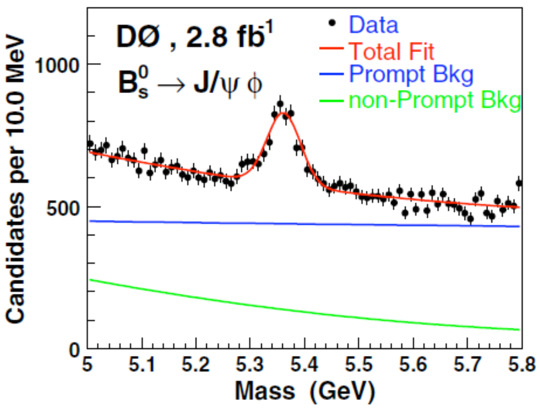
Future directions

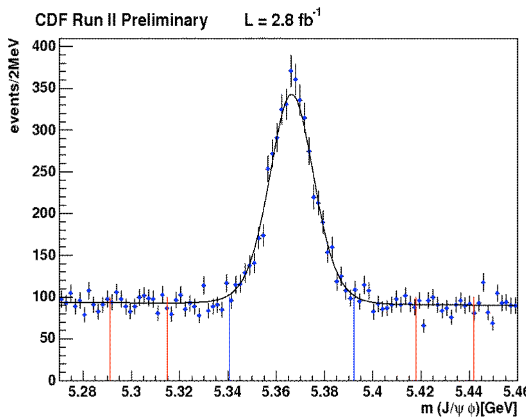
- Ever more precise measurement of:
  - $\sin 2\beta$ from $J/\psi\ K_s$
  - γ from Dalitz analysis
- Measurements of processes that only occur at 2nd order weak interaction in standard model
  - B -> s l+ l-
  - B -> s nu nubar
- Measurements of helicity suppressed decays
  - B to mu+mu-
- CP violation in the B_s system

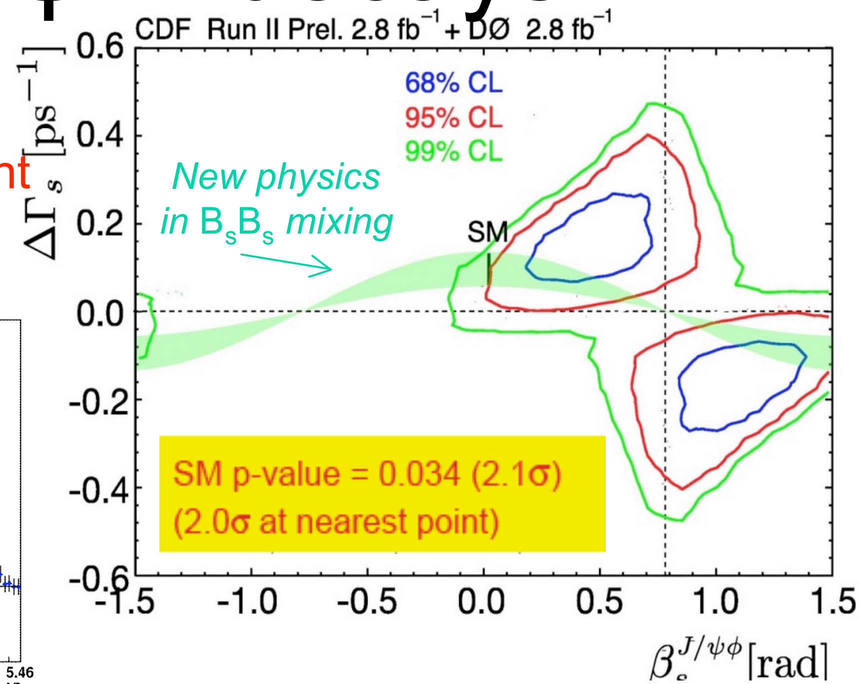


β_s from $B_s \rightarrow J/\psi\ \Phi$ decays

D0 and CDF measure β_s with angular dependent fit to decay time distributions of $B_s \rightarrow J/\psi\ \Phi$

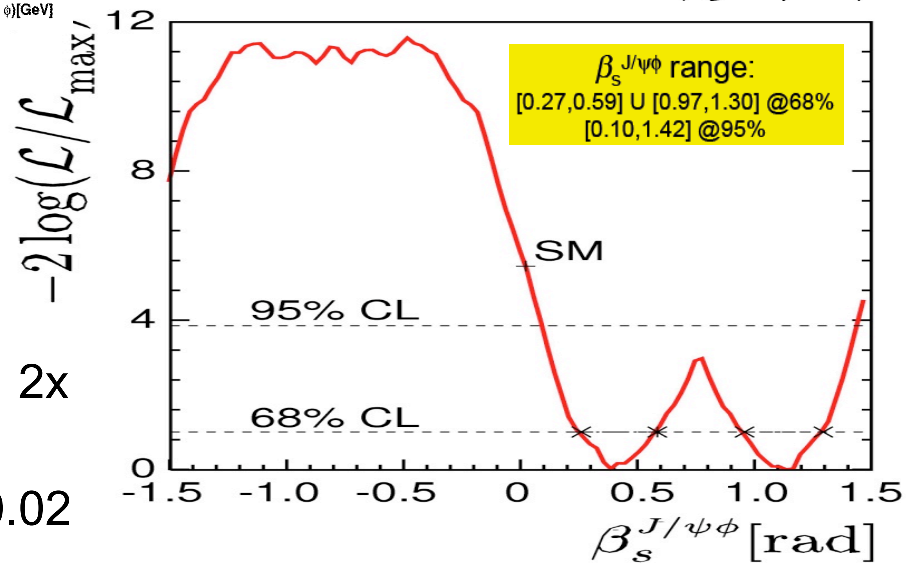






CDF/PHYS/BOTTOM/CDFR/9787, DØ Note 5928-CONF

- Simultaneous fit for $\Delta\Gamma_s$ and β_s
- SM predicts β_s very small (~0.02)
  - sensitive to new physics in B_s mixing
- Prospects
  - D0 and CDF working on updates with 2x samples
  - LHCb sensitivity with 0.5 fb^{-1}: $\sigma(\beta_s) = 0.02$



Final Comments

- There's a HUGE range of topics in heavy flavor topics that I could not cover.
- Most egregiously:
  - Constraints (and history) from Kaon physics
  - Decays like b->s gamma, b->s l+l-, B->l+l-, B->tau nu, b->s nunubar, … that provide some of the most sensitive probes on physics beyond the standard model because they occur only via loops.
  - CP violation in Bs -> J/psi phi
- This field is still very active:
  - LHCb and plans for Super B-factory on Y(4S).