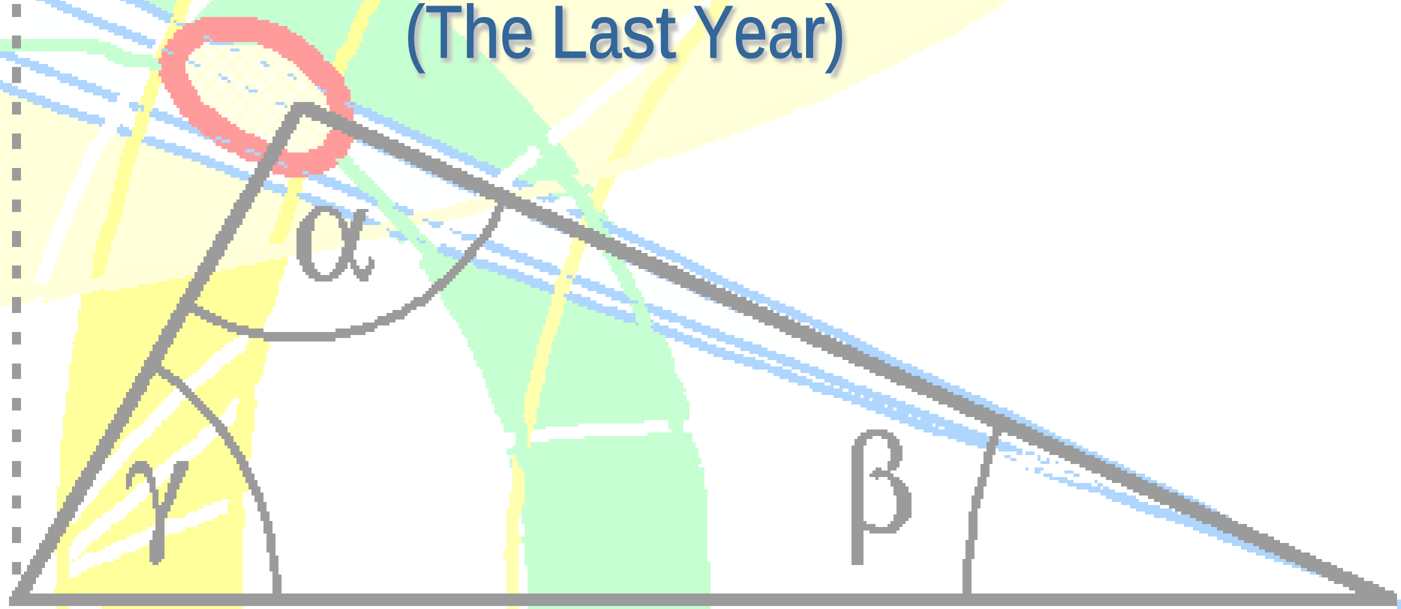
Annual Workshop of the European Flavour Physics Network FLAVIAnet
IPPP, Durham, 22-26 September 2008

Review of B-Physics: Experiment

(The Last Year)



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Outline

- Introduction
- News about angles of the unitarity triangle:
  - sin(2β) from b→s penguins
  - Recent results on γ
- A few other highlights from the last 12 months:
  - New physics in B → Kπ Direct CP asymmetries ?
  - New physics in B_S mixing? (B_S → J/ψ ϕ decays)
  - Results on B → τ ν
  - Observation of the bottomonium ground state η_b
- Summary, conclusion and perspectives

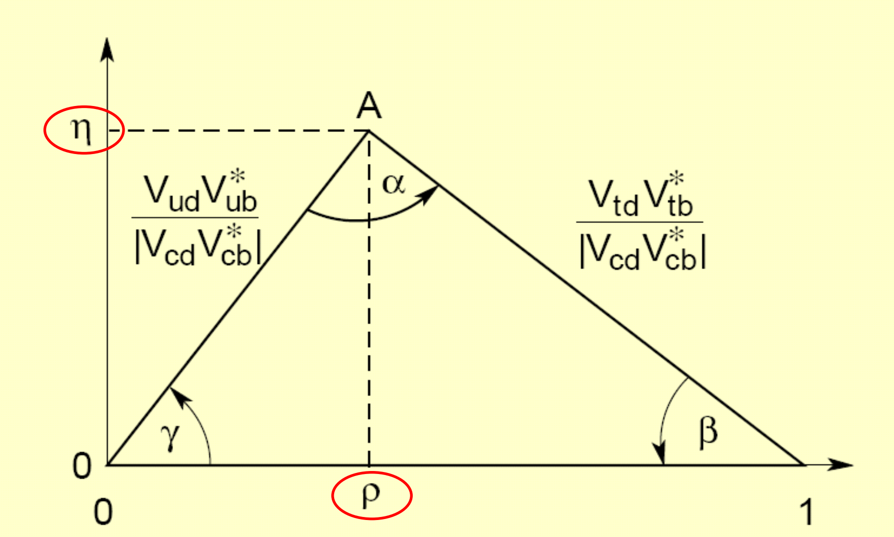
Quick Reminder of Basics

CKM matrix $\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \simeq$ Wolfenstein parameterization: $\begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$

V_{CKM} Unitarity ⇒

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

$\propto\lambda^3$ $\propto\lambda^3$ $\propto\lambda^3$



In other unitarity conditions (triangles) sides are very different.

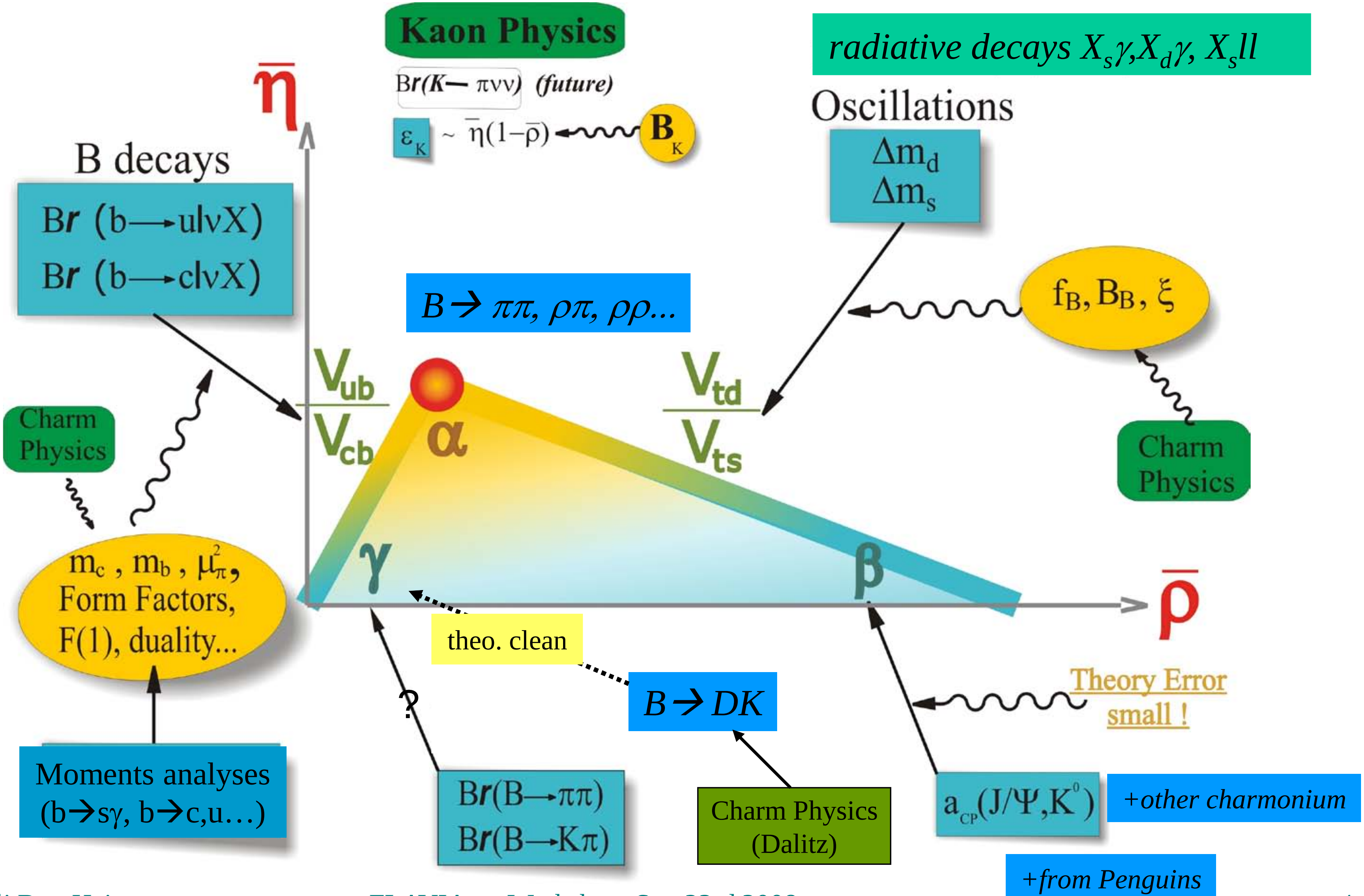
Second and third columns: flat triangle for B_S

CP Violation is possible in the Standard Model only if

V_{CKM} is complex ⇔ $\eta \neq 0$ ⇔ Unitarity Triangle is not flat

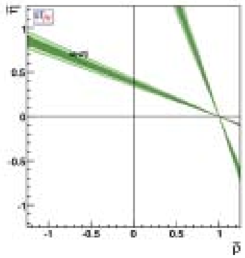
We want to determine ρ and η experimentally

How to Get ρ and η from Experiments?

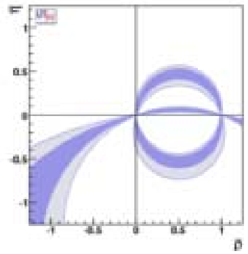


The Actual Individual Constraints

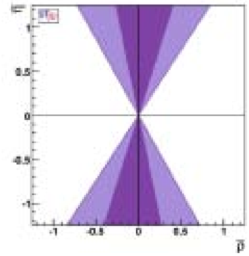
$\sin(2\beta)$



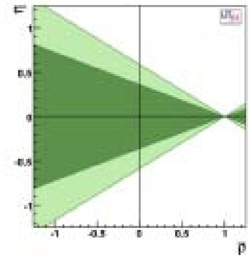
α



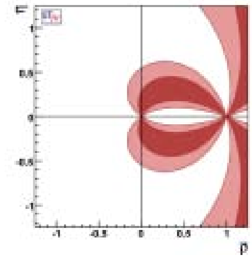
γ



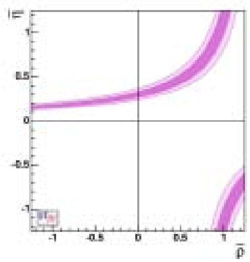
$\cos(2\beta)$



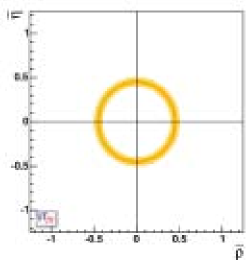
$\sin(2\beta+\gamma)$



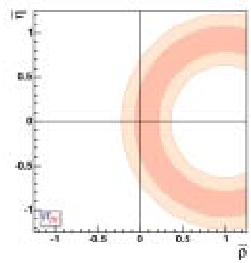
ε_K



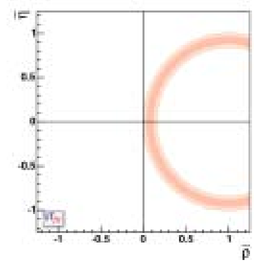
V_{ub}/V_{cb}



Δm_d



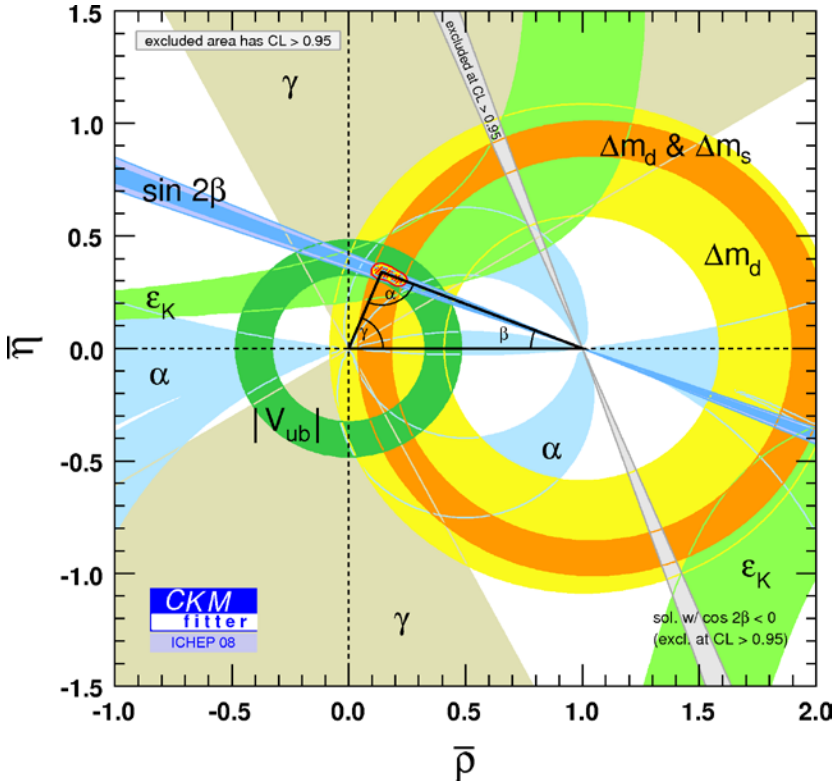
$\Delta m_d / \Delta m_s$



From UTfit Collaboration (M. Bona *et al.*), http://www.utfit.org

Putting it All Together…

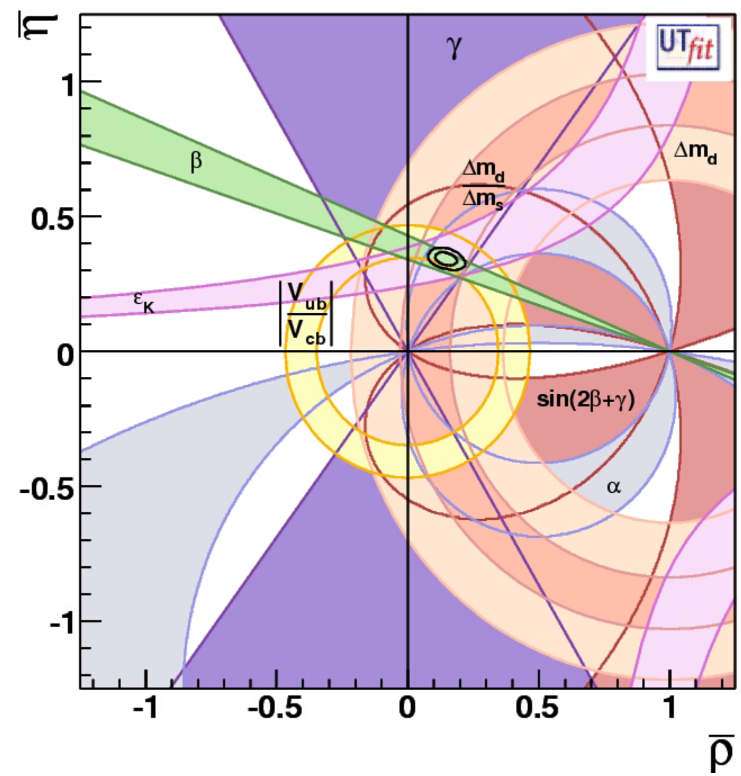
- To get a global fit: consistency check of the CKM picture and state of the art of the actual knowledge.



$$\bar{\rho} = 0.141 \pm ^{0.029}_{0.017}$$

$$\bar{\eta} = 0.343 \pm 0.016$$

From CKMfitter Group (J. Charles et al.) http://ckmfitter.in2p3.fr



$$\bar{\rho} = 0.147 \pm 0.029$$

$$\bar{\eta} = 0.342 \pm 0.016$$

From UTfit Collaboration (M. Bona *et al.*), http://www.utfit.org

Why Study All This?

CP violation is one of the necessary conditions to explain matter-antimatter asymmetry in the universe Sakharov, JETP Lett. 5, 24 (1967)

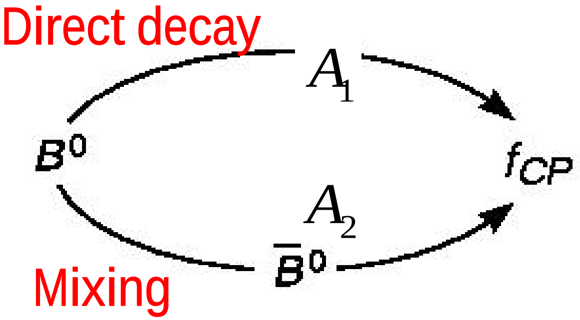
$\rightarrow$ But the CKM source of CP violation is too small to explain that.

- **Quantify CP violation by precision measurements of CKM angles and sides**
- **Constrain the Standard Model (SM) by measuring its free parameters. Flavor sector was one of its less known parts before B-Factories**
- **Test the SM and eventually challenge it by showing discrepancies between several measurements of the same parameters**

  → a window for discovery of New Physics (NP)
- **Constrain NP models**
- **LHC Era: flavor physics would provide clues for interpretation of discoveries at the high energy frontier**

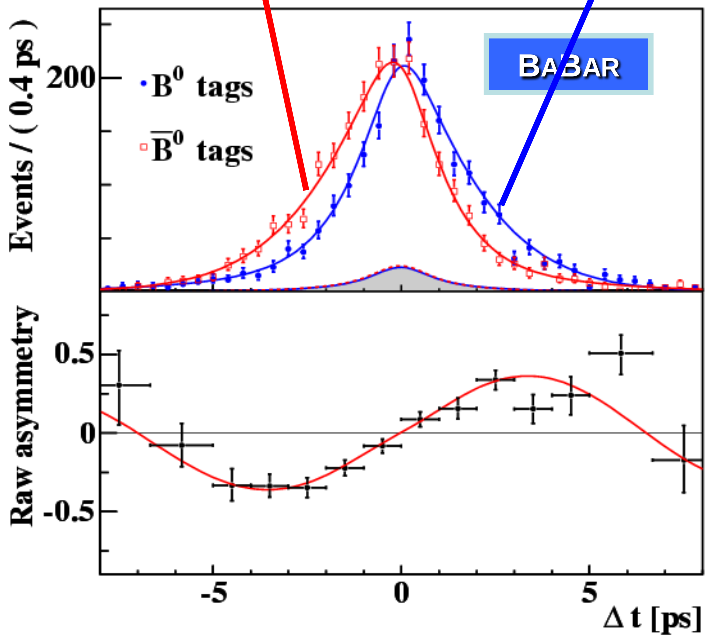
sin(2β) From b→s Penguins (I)

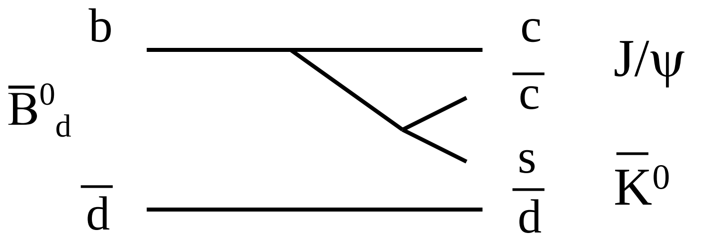
- sin(2β) can be extracted from time dependent CP asymmetry (interference between decay and mixing).



- For example, in the "Golden Mode" ($B^0 \to J/\psi\, K^0_S$):

$$A_{CP}(t) = \frac{\Gamma(\bar{B}^0(t) \to J/\psi K_S) - \Gamma(B^0(t) \to J/\psi K_S)}{\Gamma(\bar{B}^0(t) \to J/\psi K_S) + \Gamma(B^0(t) \to J/\psi K_S)} = S \sin(\Delta m_d t) - C\cos(\Delta m_d t)$$





~only one amplitude

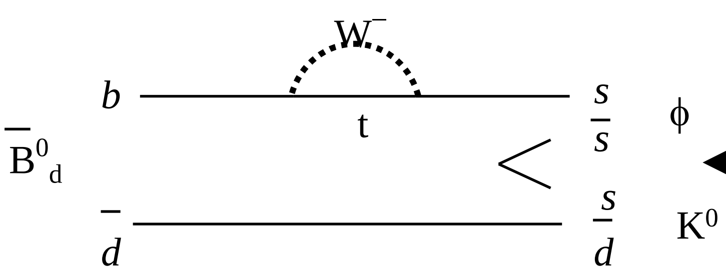
$$C_f = 0$$

$$S_f = -\eta_{CP} \sin 2\beta$$

⇒ Extraction of sin(2β) from A_{cp}

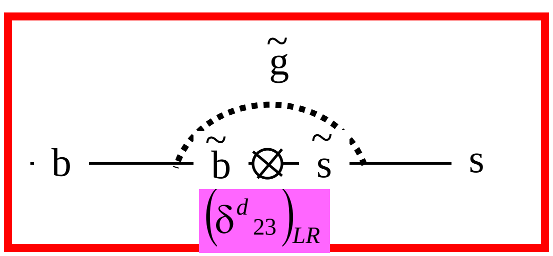
sin(2β) From b→s Penguins (II)

- When penguin contributions are significant, new physics in the loop may cause deviation in the value of S.
- The SM penguin contributes S=sin(2β)



Standard Model contribution

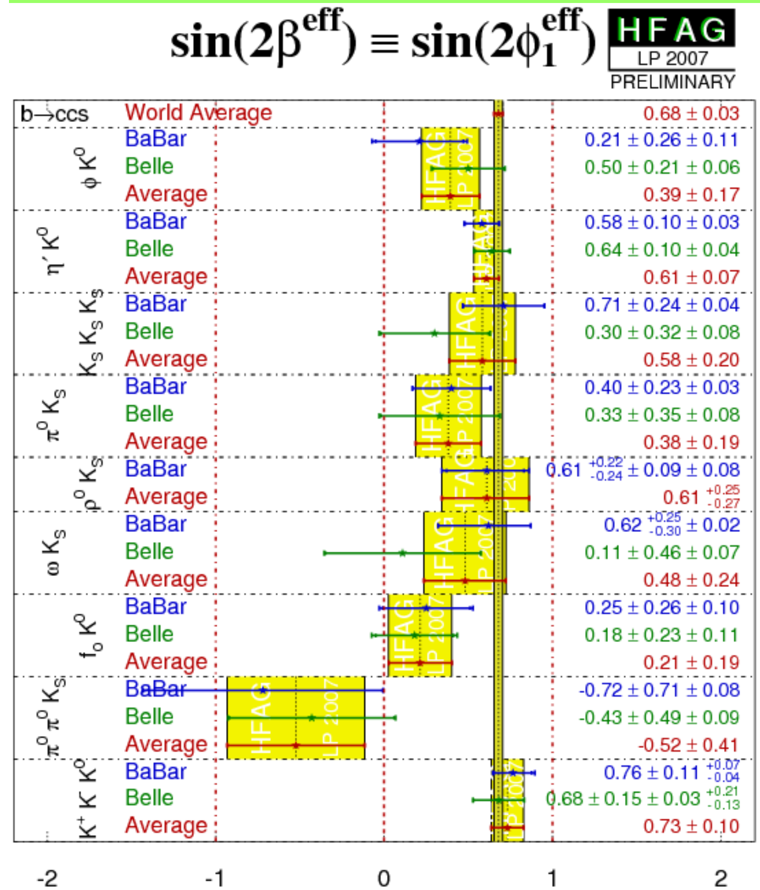
- New physics contribution might shift S



New Physics contribution

$\Delta S = \sin 2\beta(q\bar{q}s) - \sin 2\beta(c\bar{c}s)$

A year ago:



Tensions between sin2β from b→c$\bar{c}$s and b→q$\bar{q}$s

$\sin(2\beta)$ From $b \to s$ Penguins (III)

The situation today is quite different

- **Fresh $\sin(2\beta)$ world averages from HFAG:**

  $b \to c\bar{c}s$: 0.067 ± 0.02

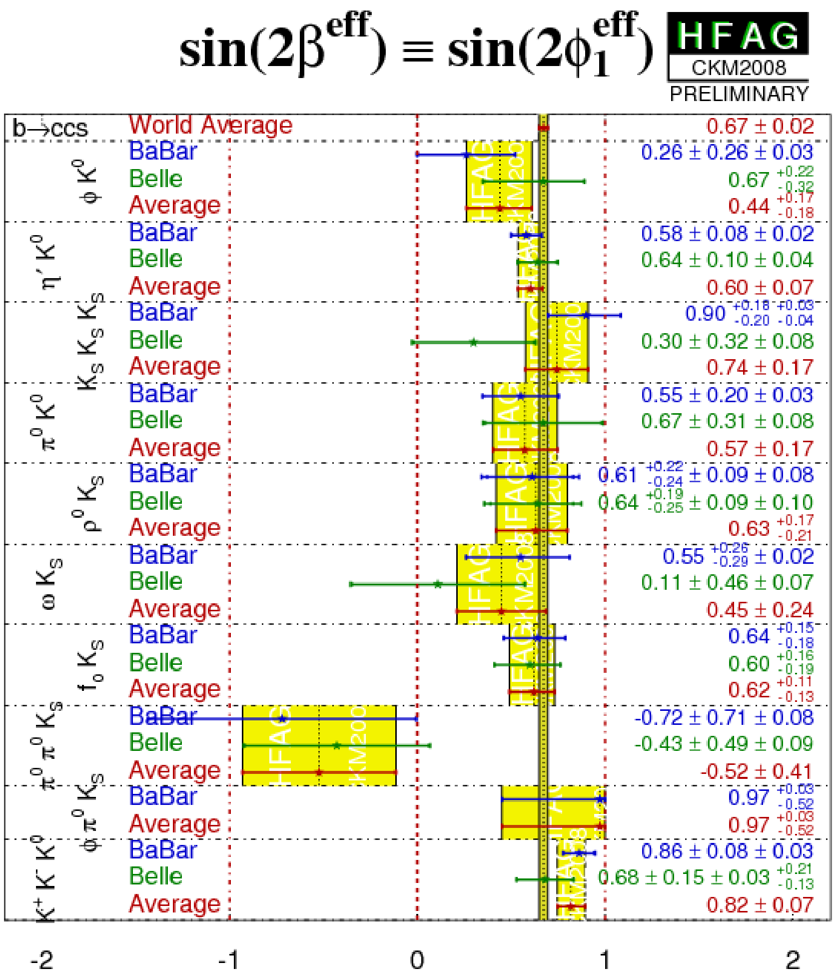
  $b \to q\bar{q}s$: 0.062 ± 0.04 (naïve !)

- Many of the results in the compilation are new (ICHEP, CKM).
- Big effort from B factories to clarify hints of trends/deviations in previous measurements
- Improvement: several results from (Time Dependent) Dalitz Plot analyses

  See talk by Jelena Ilic:
  "Hadronic Charmless Three-body B decays at BaBar"

- **Still… for most of the modes the theoretical SM prediction is $\Delta S > 0$**

$\to$ More data needed…



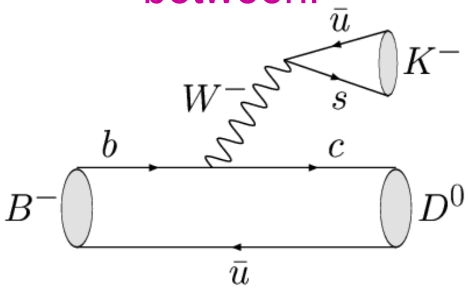
Recent Results On γ (I)

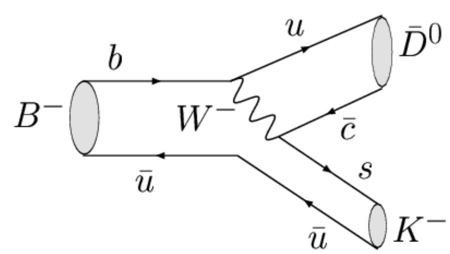
Hardest angle of all to measure: ($\gamma = -\arg(V_{ub})$, *and* V_{ub} *is small*)

Main methods

- Direct CPV in $B \to D^{(*)0} K^{(*)}$ decays
  - 3-body Dalitz Decays (Giri,Grossman,Soffer,Zupan)
    - $D^0 \to K_S \pi^+ \pi^-$
  - CP eigenstates (Gronau,London,Wyler)
    - $D^0 \to \pi\pi, KK, \ldots$
  - Doubly Cabibbo-suppressed (Atwood,Dunietz,Soni)
    - $D^0 \to K^+\pi^-$ vs $D^0 \to K^-\pi^+$
- Several complementary techniques
  - Time-dependent CPV in $B^0 \to D^{(*)}\pi$, $D^{(*)}\rho$
    - Measures $\sin(2\beta+\gamma)$

Exploit interferences between:



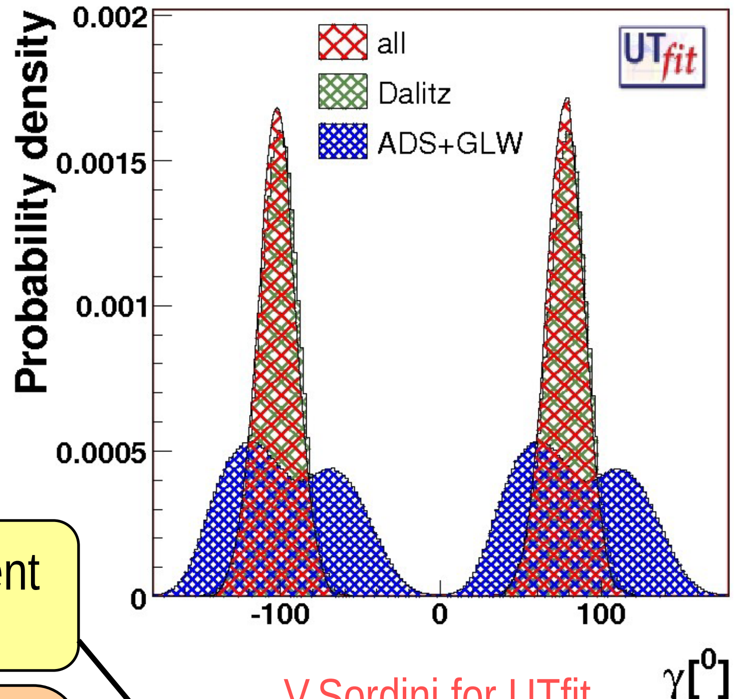


Key parameter: r_B, the ratio of $|A(b \to u)/A(b \to c)|$

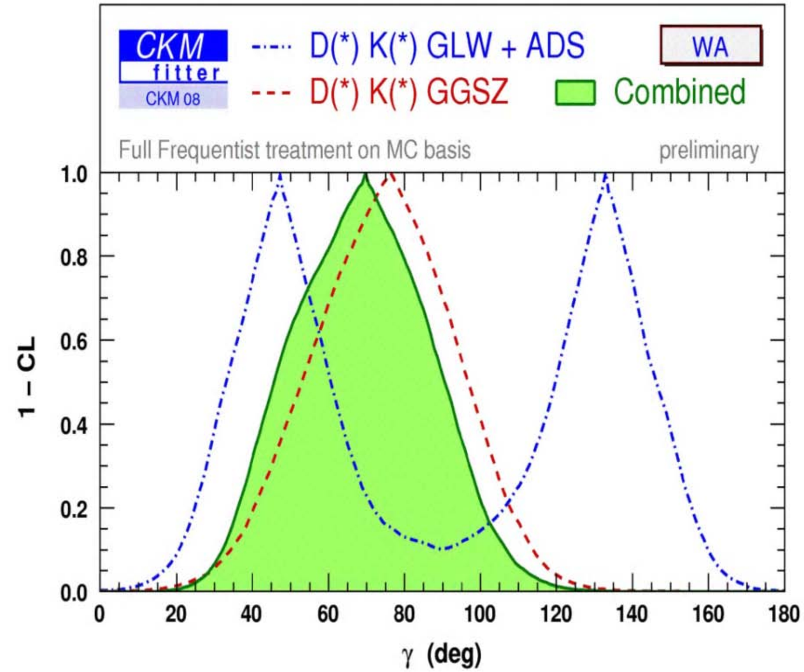
Big progress has been made in the last year

Recent Results On γ (II)

- Combination of constraints (from CKM workshop talks) :



V.Sordini for UTfit



K. Trabelsi for CKMfitter

Measurement of γ

$\gamma = (78 \pm 12)^\circ, [2\sigma] = (54^\circ, 100^\circ)$

$\gamma = (70^{+27}_{-29})^\circ, [2\sigma] = (29^\circ, 113^\circ)$

Comparing to unitarity triangle fit with no γ information

$\gamma = (65.1 \pm 6.5)°$

$\gamma = (67.6 \pm^{2.7}_{4.8})°$

- **Good achievement of B factories, but… limited by statistics (error ~20°)**
- LHCb will improve the situation and possibly a SuperB factory

$B \to K\pi$ Direct CP Asymmetries (I)

sensitive to γ

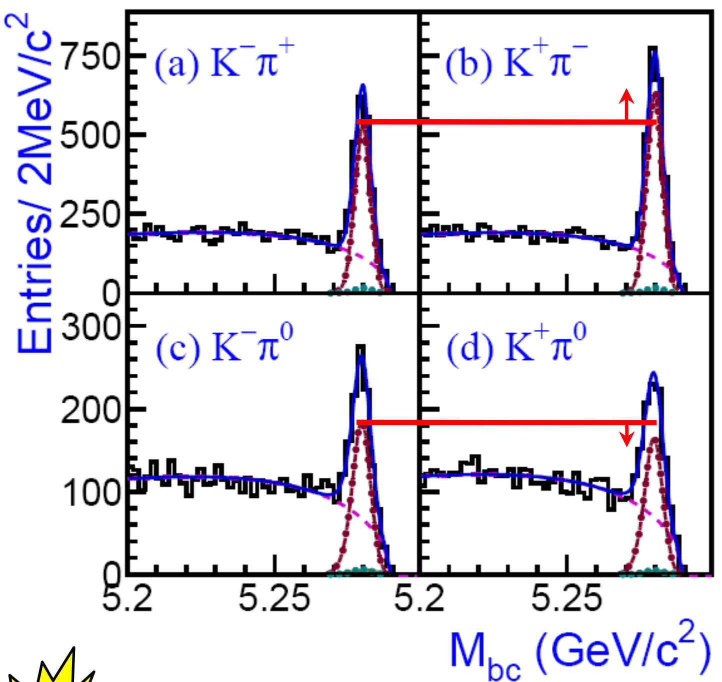
$$\mathcal{A}_{CP}(B \to f) = \frac{|\overline{A}|^2 - |A|^2}{|\overline{A}|^2 + |A|^2} \propto \sum_{i,j} A_i A_j \sin(\delta_i - \delta_j)\sin(\phi_i - \phi_j)$$

$A_{cp}(K^+\pi^-)$ =

$-0.107 \pm 0.016\ ^{+0.006}_{-0.004}$	**BaBar**
$-0.094 \pm 0.018 \pm 0.008$	**Belle**
$-0.086 \pm 0.023 \pm 0.009$	**CDF**
$-0.04 \pm 0.16 \pm 0.02$	**CLEO**
$\Rightarrow -0.098\ ^{+0.012}_{-0.011}$ @ 8.1σ	**AVG**

$A_{cp}(K^+\pi^0)$ =

$+0.030 \pm 0.039 \pm 0.010$	**BaBar**
$+0.07 \pm 0.03 \pm 0.01$	**Belle**
$-0.29 \pm 0.23 \pm 0.02$	**CLEO**
$\Rightarrow +0.050 \pm 0.025$ @2.0σ	**AVG**



Belle, Nature 452, 332 (2008)

$\Delta A_{K\pi} = A_{cp}(K^+\pi^-) - A_{cp}(K^+\pi^0) = -0.147 \pm 0.028$ @ 5.3σ !

From SM & QCD factorization we expect **$\Delta A_{K\pi} \sim 0$**

Indication for NP in EW penguins?

Yoshikawa 2003; Mishima & Yoshikawa 2004; Buras et. al. 2004, 2006; Baek & London 2007; Hou et. al. 2007; Feldmann, Jung & Mannel 2008

Hadronic corrections?

Chiang et. al. 2004; Charng, Li, Mishima & Sanda 2005

Tantalizing but not conclusive

B → Kπ Direct CP Asymmetries (II)

- To further examine this problem: measure $\mathcal{A}_{CP}$ asymmetry in $B^0 \to K^0\pi^0$ and compare with prediction of SU(3) symmetry derived sum rule:

$$\mathcal{A}_{CP}(K^+\pi^-) + \mathcal{A}_{CP}(K^0\pi^+)\frac{\mathcal{B}(K^0\pi^+)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_0}{\tau_+} = \mathcal{A}_{CP}(K^+\pi^0)\frac{2\mathcal{B}(K^+\pi^0)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_0}{\tau_+} + \mathcal{A}_{CP}(K^0\pi^0)\frac{2\mathcal{B}(K^0\pi^0)}{\mathcal{B}(K^+\pi^-)}$$

M. Gronau, PLB 627, 82 (2005); D. Atwood & A. Soni, Phys. Rev. D 58, 036005(1998)

Deviations ⇒ New Physics

Using $\mathbf{B^+ \to K^0 \pi^+}$ world Average: $\mathcal{A}_{cp}(K^0\pi^+) = 0.009 \pm 0.025$

(Theoretical Prediction: $\mathcal{A}_{cp}(K^0\pi^+) \sim 0$)

New results for $\mathbf{B^0 \to K^0 \pi^0}$

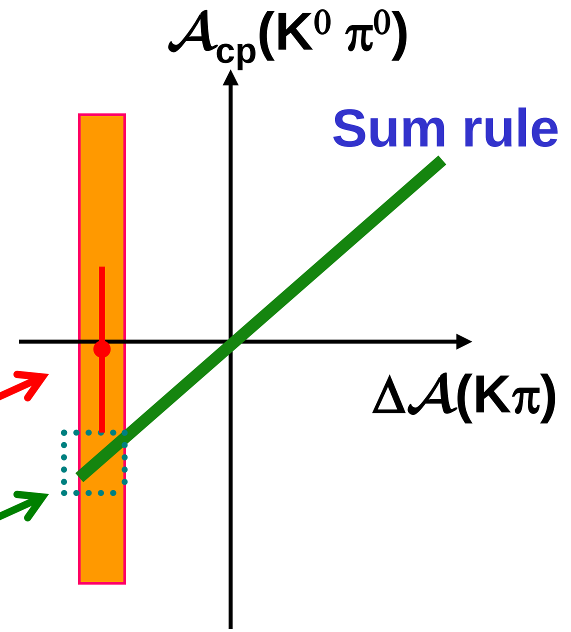
analysis for SuperB…

$\mathcal{A}_{CP} = -0.13 \pm 0.13 \pm 0.03$

$\mathcal{A}_{CP} = +0.14 \pm 0.13 \pm 0.06$

HFAG Average: -0.01 ± 0.10

Sum rule prediction: $A_{cp}(K^0\pi^0) = -0.151 \pm 0.043$



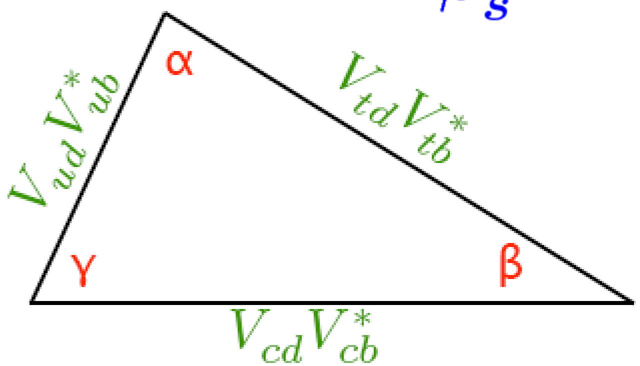
$B_S \rightarrow J/\psi\ \phi$ Decays (I)

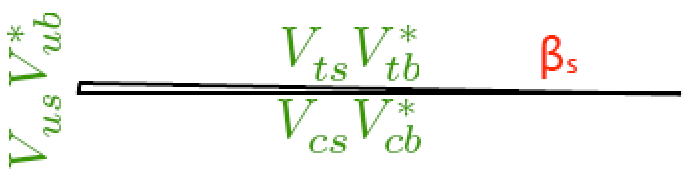
- Analogically to what we saw in for the CKM angle β:
  time dependent CP asymmetry in $B_S \rightarrow J/\psi\ \phi$ ➔ determine β_S.

$$\beta_s^{SM} = \arg\left(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right)$$

- Expect βs *to be small in SM* ($|\beta s^{SM}| \approx 0.02$) - beyond current reach
  => Current interest: Search for enhanced CP violation through **new physics:**

$$2\beta_s^{J/\psi\phi} = 2\beta_s^{SM} - \phi_s^{NP}$$



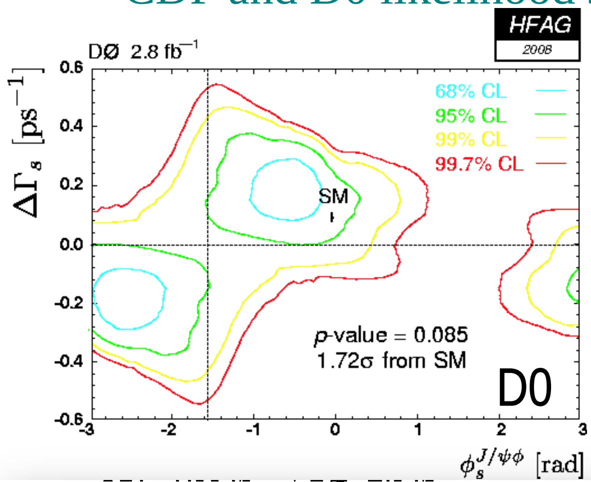


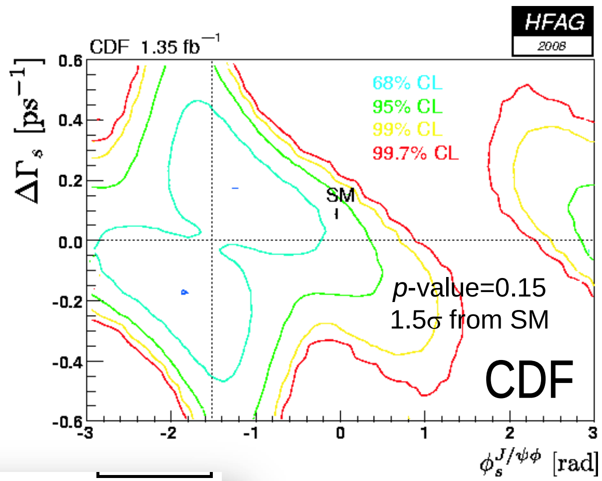
- CDF and D0 perform a time dependent analysis of $B_S \rightarrow J/\psi\ \phi$ to get a correlated measurement of *(β_S ,$\Delta\Gamma_S$)*
  CDF, Phys.Rev.Lett.100:161802 (2008) ; D0, arXiv: 0802.2255, submitted to PRL

$B_s \rightarrow J/\psi\ \phi$ Decays (II)

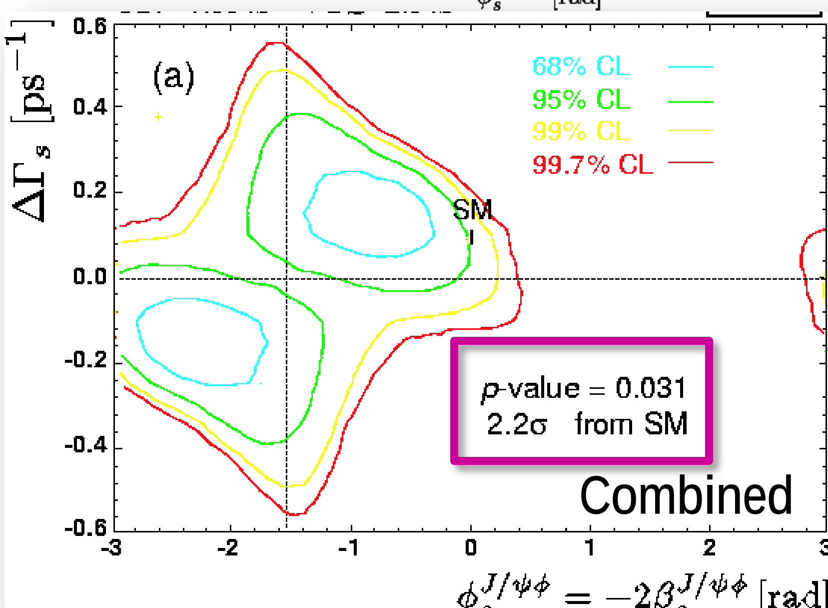
- After a few controversial "start up" problems…

  CDF and D0 likelihood scans are now combinable. State of the art:





CDF has also a preliminary sample of ~2/fb that shows p-value (SM) =0.07 (~1.8 σ) (not yet in the combination)



$$\phi_s = -2.37\ ^{+0.38}_{-0.27}\ \text{rad}, \quad -0.75\ ^{+0.27}_{-0.38}\ \text{rad}$$

$$\Delta\Gamma_s = -0.150\ ^{+0.066}_{-0.059}\ \text{ps}^{-1}, \quad 0.150\ ^{+0.059}_{-0.066}\ \text{ps}^{-1}$$

90% C.L. 1-d regions:

$$\phi_s \in [-2.85, -1.65], \quad [-1.47, -0.29]$$

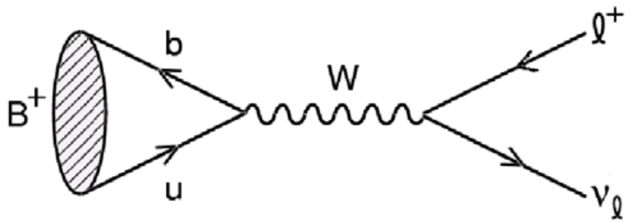
$$\Delta\Gamma_s \in [-0.265, -0.036], \quad [0.036, 0.265]$$

Results on $B \rightarrow \tau \nu$ (I)

the measurement of the leptonic decay $B \rightarrow \tau\nu$ is the first leptonic decay seen on B mesons.
(modes with light leptons are suppressed)

- In the SM:

$$\mathcal{B}(B \to \ell\nu) = \frac{G_F^2 m_B m_\ell^2}{8\pi}\left(1 - \frac{m_\ell^2}{m_B^2}\right)^2 f_B^2 |V_{ub}|^2 \tau_B$$



Using $|V_{ub}| = (44.3 \pm 5.4) \times 10^{-4}$ (HFAG) **and** $f_B = 0.189 \pm 0.027$ GeV (LQCD)
$\Rightarrow$ expected BF: $(1.2 \pm 0.4) \times 10^{-4}$

Previous results:

PDG: $\mathcal{B}(B \to \tau\nu) = (1.8 \pm 0.7) \times 10^{-4}$

Belle hadronic tag

$\mathcal{B}(B \to \tau\nu) = (1.79\ ^{+0.56+0.46}_{-0.49-0.51}) \times 10^{-4}$

447 M $B\bar{B}$ excluding 0 with 3.5σ

BaBar hadronic & semileptonic tags

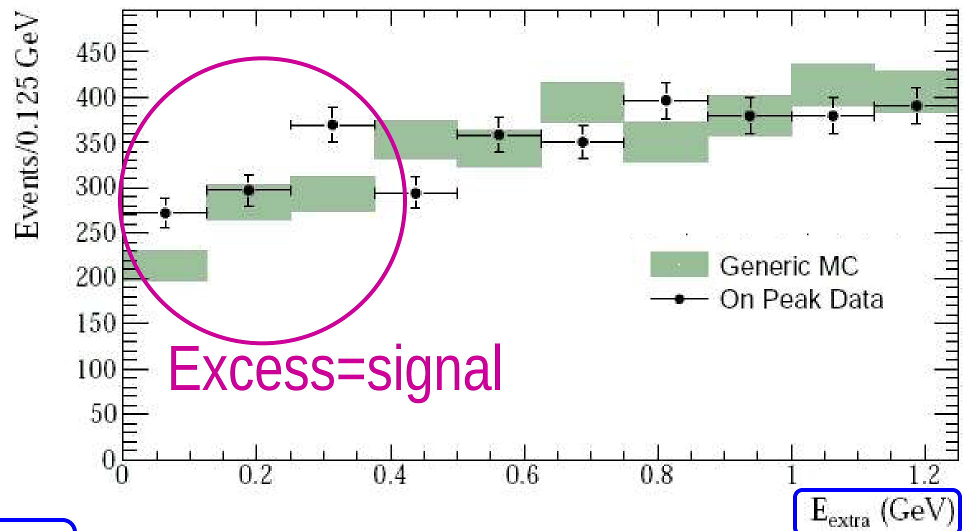
$\mathcal{B}(B \to \tau\nu) = (1.2 \pm 0.4 \pm 0.3 \pm 0.2) \times 10^{-4}$

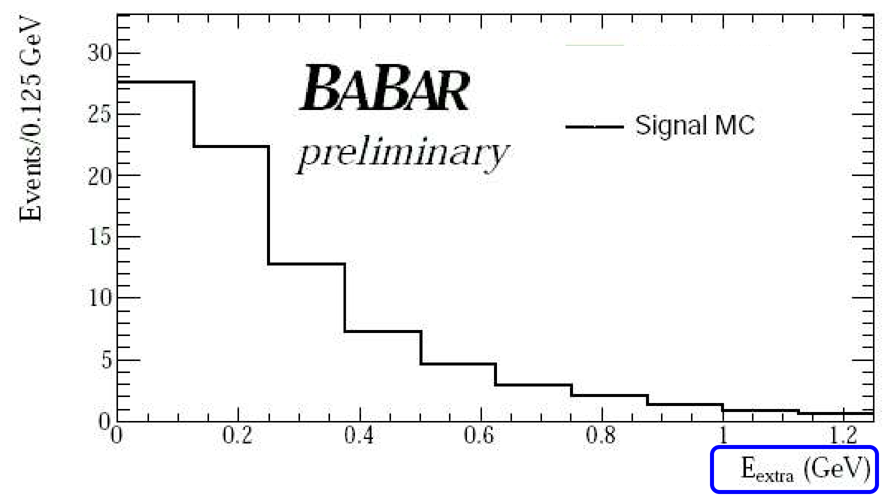
383 M $B\bar{B}$ excluding 0 with 2.6σ

New results are available from BaBar and Belle

Results on B → τ ν (II)

- **New result from BaBar (CKM 2008):**
  - Reconstruct the ***tag B***$^-$ from ***B***$^-$ → $\bar{D}^0$ $l^-\nu X$ events (semileptonic tag)
    l = e or μ; X = nothing, π^0 or γ from excited D
  - Reconstruct the ***signal*** $B^+ \rightarrow \tau^+\nu$ using 4 exclusive ***τ*** decays





E_{extra} = energy not associated to reconstructed B mesons → near zero for a signal event.

BaBar semileptonic tag: $\mathcal{B}(B\rightarrow\tau\nu) = (1.8 \pm 0.8 \pm 0.1)\times10^{-4}$ 459 M $B\bar{B}$ with 2.4σ

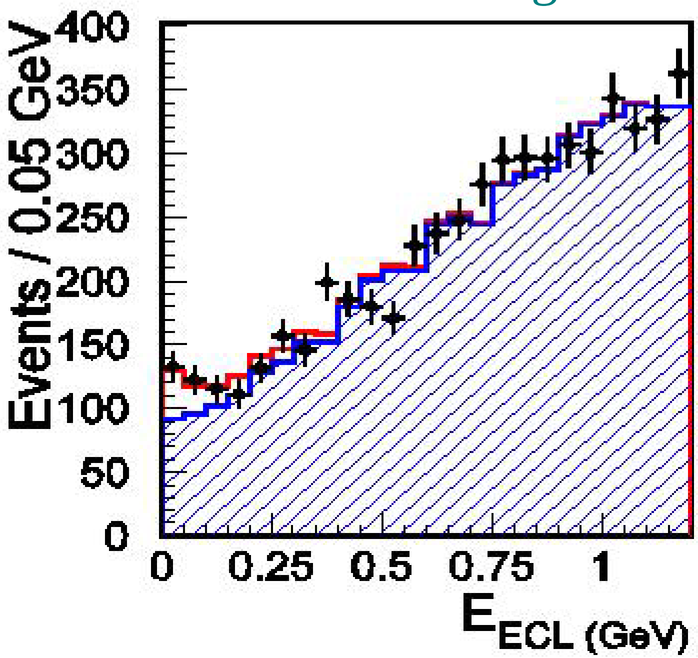
- Combining this result with the latest hadronic tagged measurement:

BaBar both tags: $\mathcal{B}(B\rightarrow\tau\nu) = (1.8 \pm 0.6)\times10^{-4}$ Excluding 0 with 3.3σ

larger than previous result !

Results on B → τ ν (III)

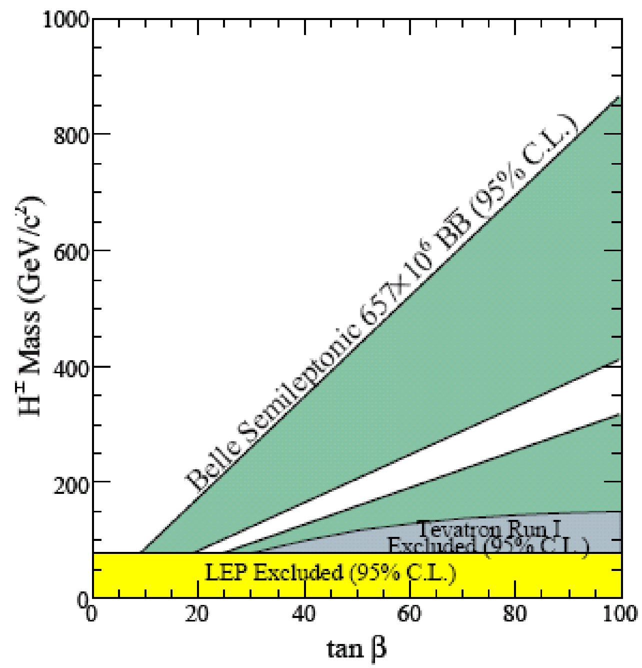
- **New result from Belle (ICHEP 2008):**
  - Tag B on one side (both hadronic tag and $D^{(*)}\, l\, \nu$ tag)
  - Look for τ signature with "extra" energy in the ECAL



Belle both tags: $\mathcal{B}(B\to\tau\nu) = (1.65\,^{+0.38}_{-0.37}\,^{+0.35}_{-0.37})\times 10^{-4}$

657 M $B\bar{B}$ with 3.8σ

Constraint on the two-Higgs doublet model m_H vs. tan(β)



Charged Higgs may contribute to BF:

$$\mathcal{B}(B\to\tau\nu) = \mathcal{B}(B\to\tau\nu)_{SM}\times r_H$$

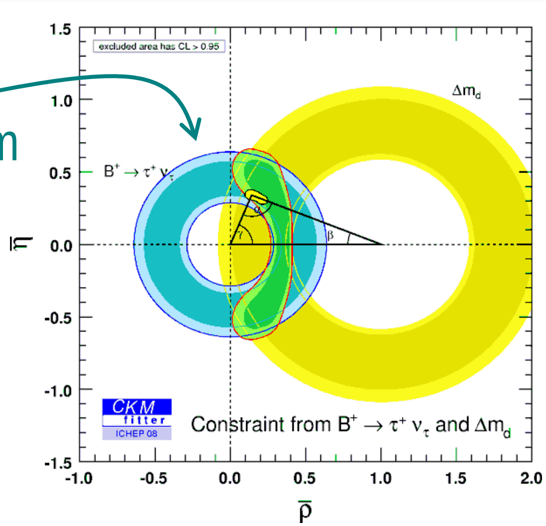
$$r_H = \left(1 - \frac{m_B^2}{m_H^2}\tan^2\beta\right)^2$$

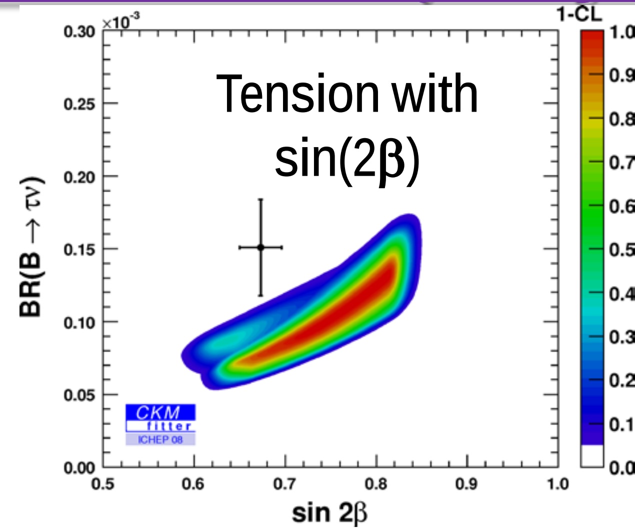
destructive

Results on B → τ ν (IV)

- **Tension of this measurement with the unitarity triangle :**

constraint from B → τ ν

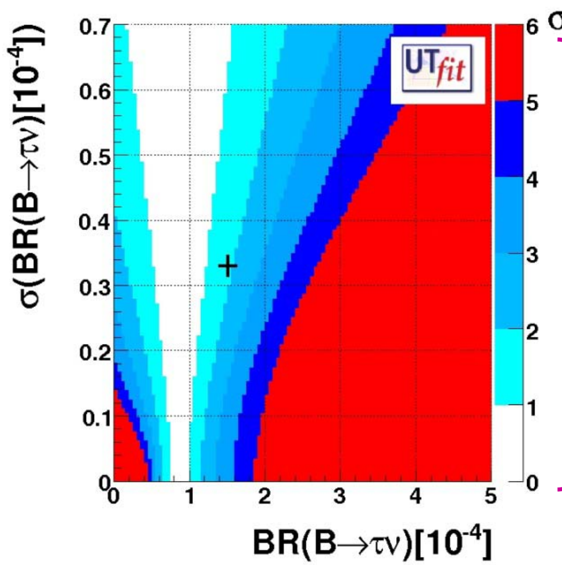




This does not yet take into account the latest result from BaBar.

Tension is higher

To be confirmed with more data…

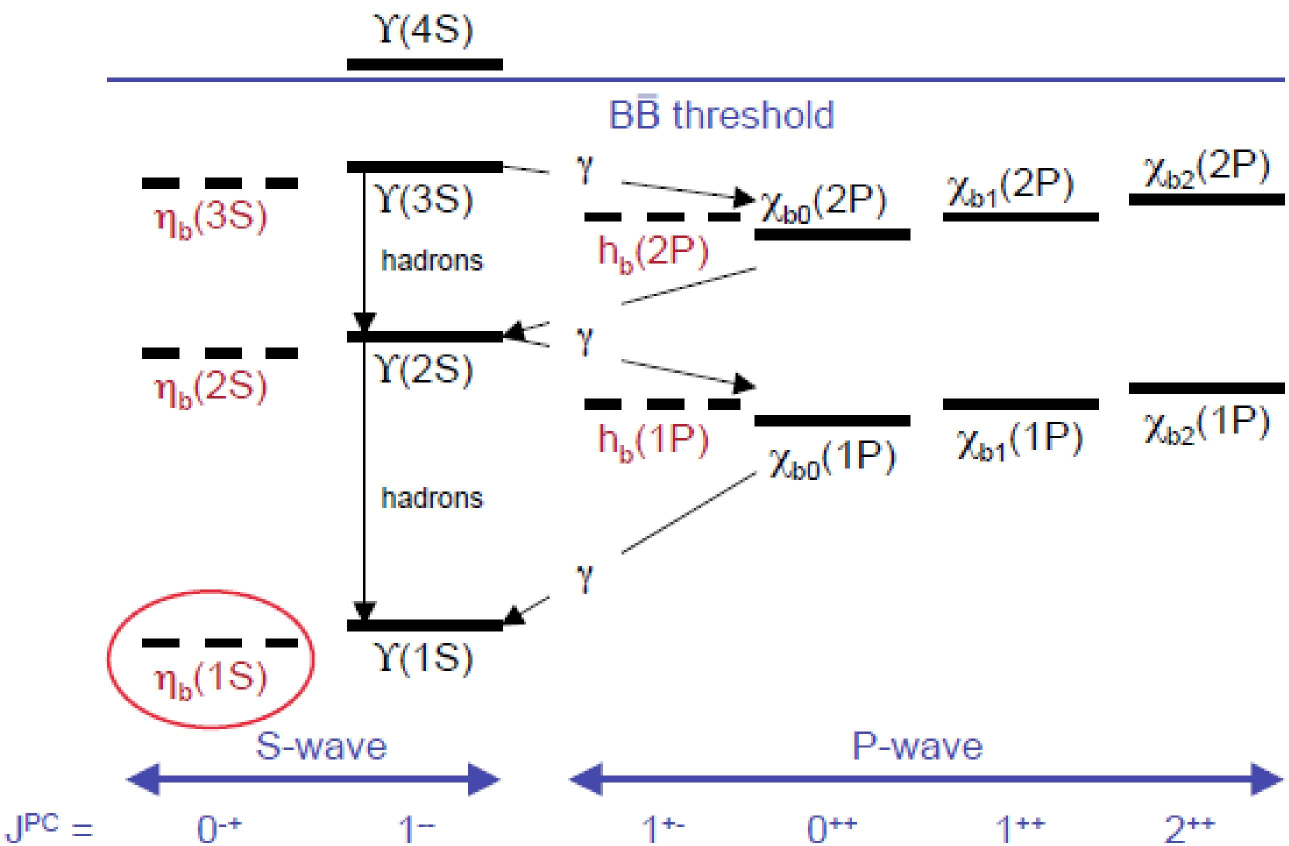


Including latest result from BaBar.

(many thanks to V. Sordini)

Observation of η_b (I)

30 years after the discovery of bottomonium, its ground state is observed by BaBar in a dedicated run at the Υ(3S) resonance pole

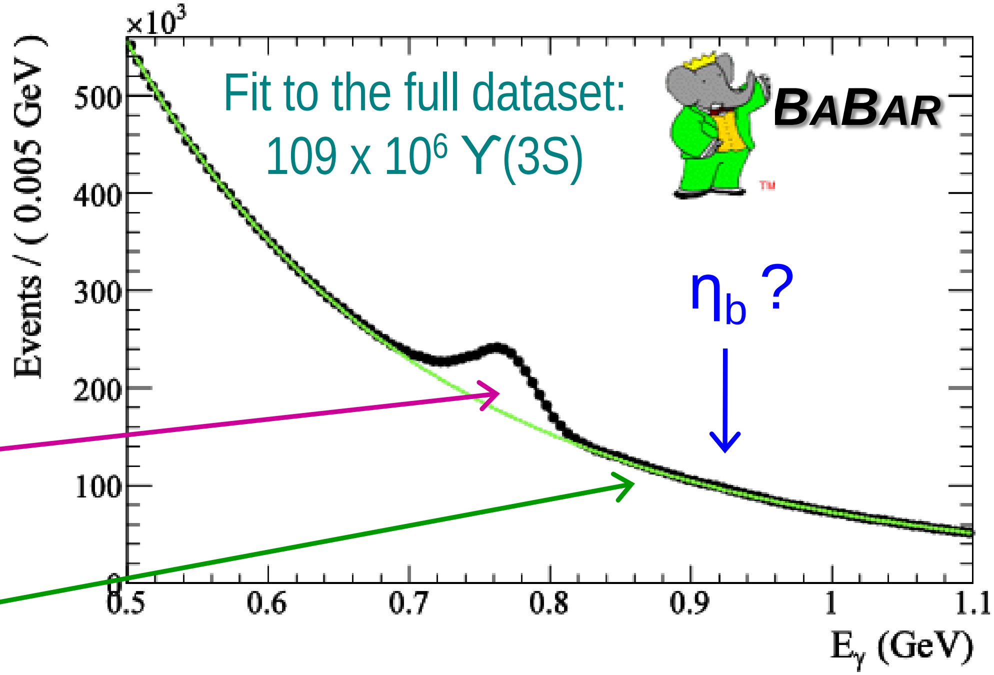


Observation of η_b (II)

Analysis Strategy

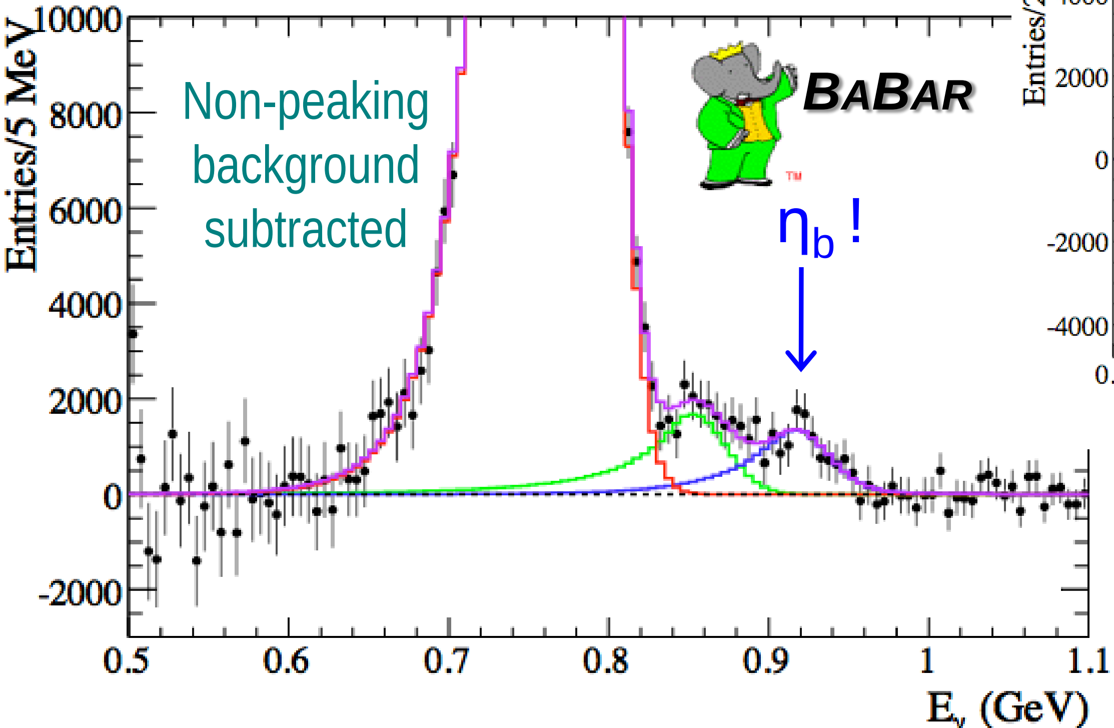
- Inclusive search of $e^+e^- \to \Upsilon(3S) \to \gamma\eta_b$ decays (BF prediction $\approx 10^{-4}$)
- Expecting monochromatic signal photon: $M(\eta_b)$=9.4 GeV $\to E_\gamma$ = 911 MeV
  $\Rightarrow$ look for a "bump" in the E_γ distribution around 900 MeV

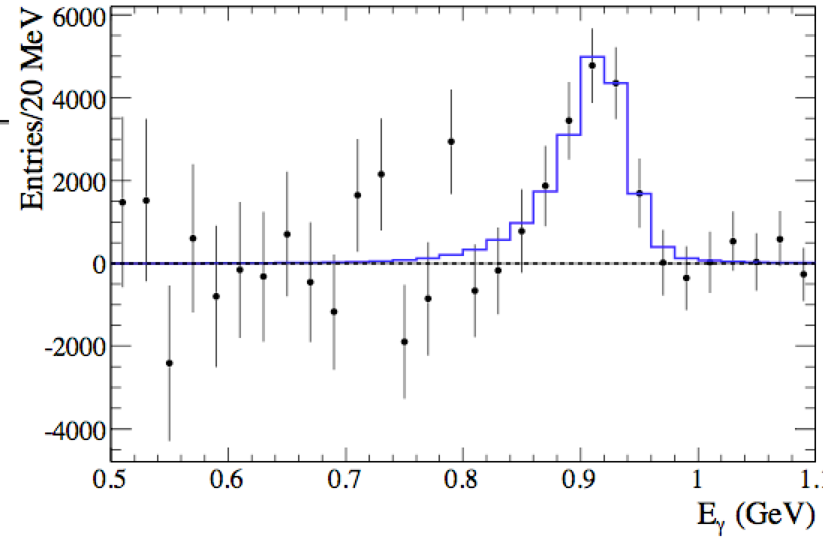
- Performing one dimensional fit to the E_γ distribution , containing:
  1) Non-peaking continuum
  $\to$ fitted to single component
  2) Peaking, next to signal
    - $\Upsilon(3S) \to \gamma\, \chi_{bJ}(2P)$ then $\chi_{bJ}(2P) \to \gamma\, \Upsilon(1S)$: 770 MeV
    - $e^+e^- \to \gamma_{ISR}\, \Upsilon(1S)$: 855 MeV



Observation of η_b (III)

- η_b signal observed with a statistical significance of 10σ





PRL 101, 071801 (2008)

$m(\eta_b) = 9388.9^{+3.1}_{-2.3}(\text{stat}) \pm 2.7(\text{syst})\ \text{MeV}/c^2$

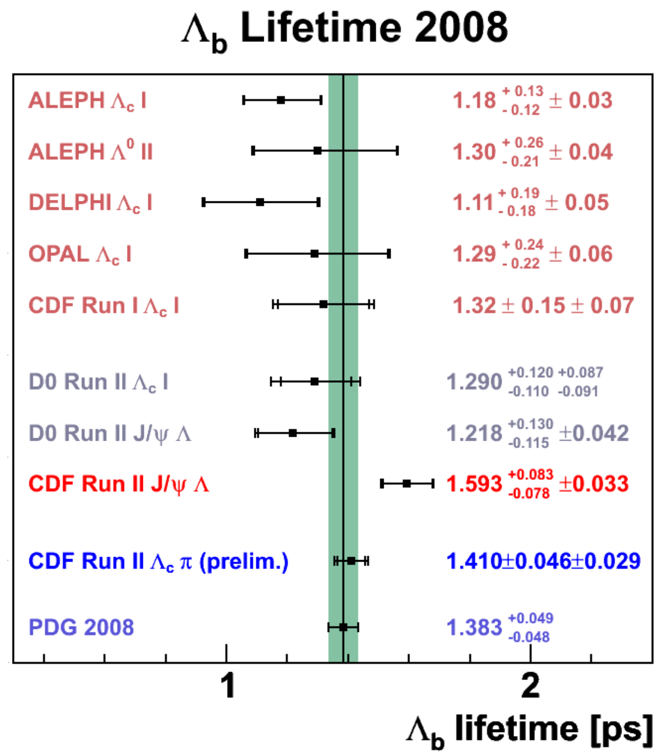
$BF(\Upsilon(3S)\rightarrow\gamma\eta_b) = [4.8 \pm 0.5(\text{stat}) \pm 1.2(\text{syst})] \times 10^{-4}$

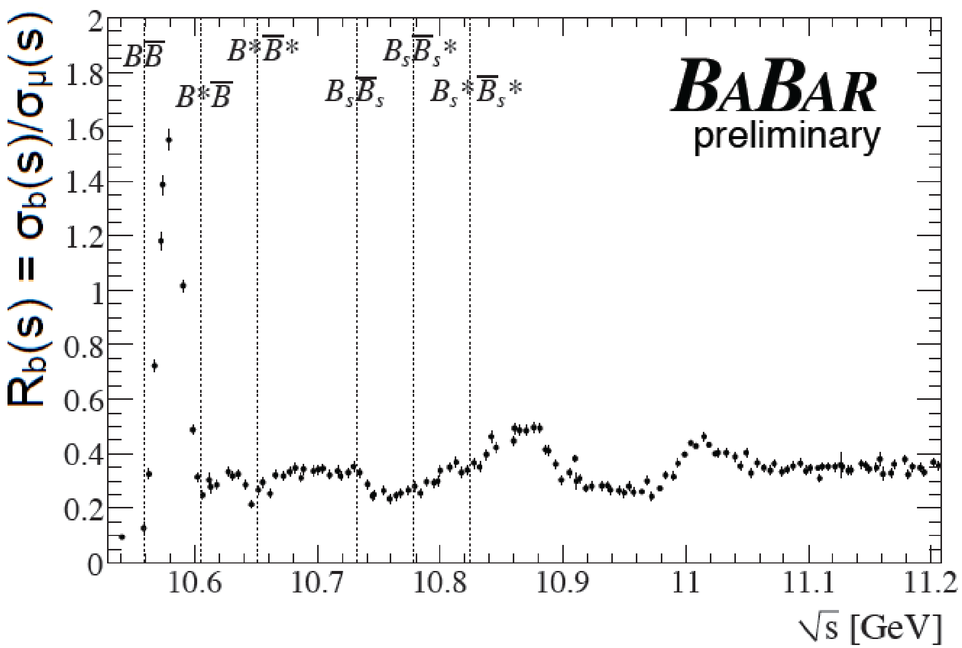
$m(\Upsilon(1S)) - m(\eta_b) = 71.4^{+2.3}_{-3.1}(\text{stat}) \pm 2.7(\text{syst})\ \text{MeV}/c^2$

Among the many things I did not mention…

- Lifetimes of B_S and Λ_B, Observation of Σ_B, Ξ_B from the TeVatron
  ⇒ see talk by Manfred Paulini (ICHEP 2008)
  "Properties of Heavy B Hadrons"

world averege $\tau(B_S{}^0)$ / $\tau(B^0)$ = 0.95 ± 0.02

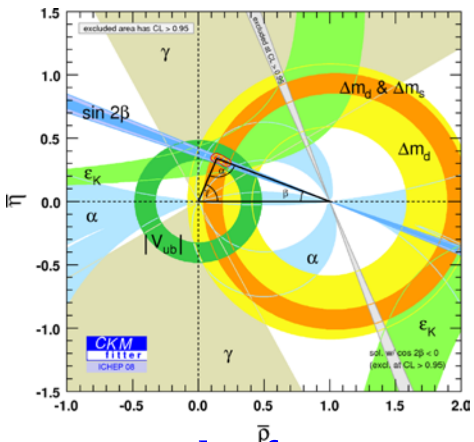


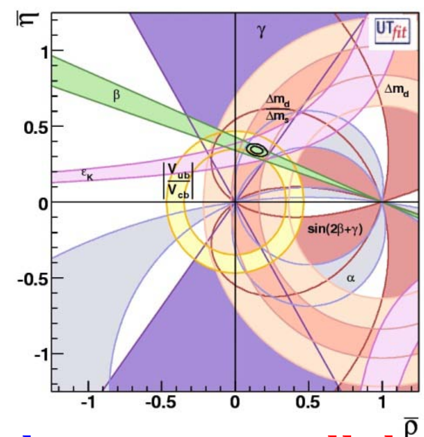


- Scan above the Υ(4S) at BaBar
  ⇒ see talk by Paul Jackson (ICHEP 2008)
  "Bottomonium Spectroscopy: an Experimental Review"

Summary, Conclusions and Perspectives (I)

- A summary of a big part of this talk (and much more…) is given by this:





  - After many results from B-Factories and the TeVatron all the independent constraints superimpose in a small region of the (ρ,η) plane!
  - Great success of the Standard Model and the CKM Picture!
- Some tantalizing “tensions”, still need confirmation: more statistics, improve errors on lattice expectations…
- Measurements provide non-trivial constrains on NP. Many of them are still limited by statistics.

Summary, Conclusions and Perspectives (II)

- What we have today and in the short term:
  - Final dataset from BaBar (~500M B decays)
  - Belle continues operations to O(1000M decays)
  - Expect roughly to double the dataset at the TeVatron

- Measurements in the B system can continue to provide important insights and constraints on the flavor structure of physics within and beyond the Standard Model. High precision is needed…
  - Final, combined B Factory and Tevatron datasets
  - LHCb
  - In the planning stages: Super flavor factory

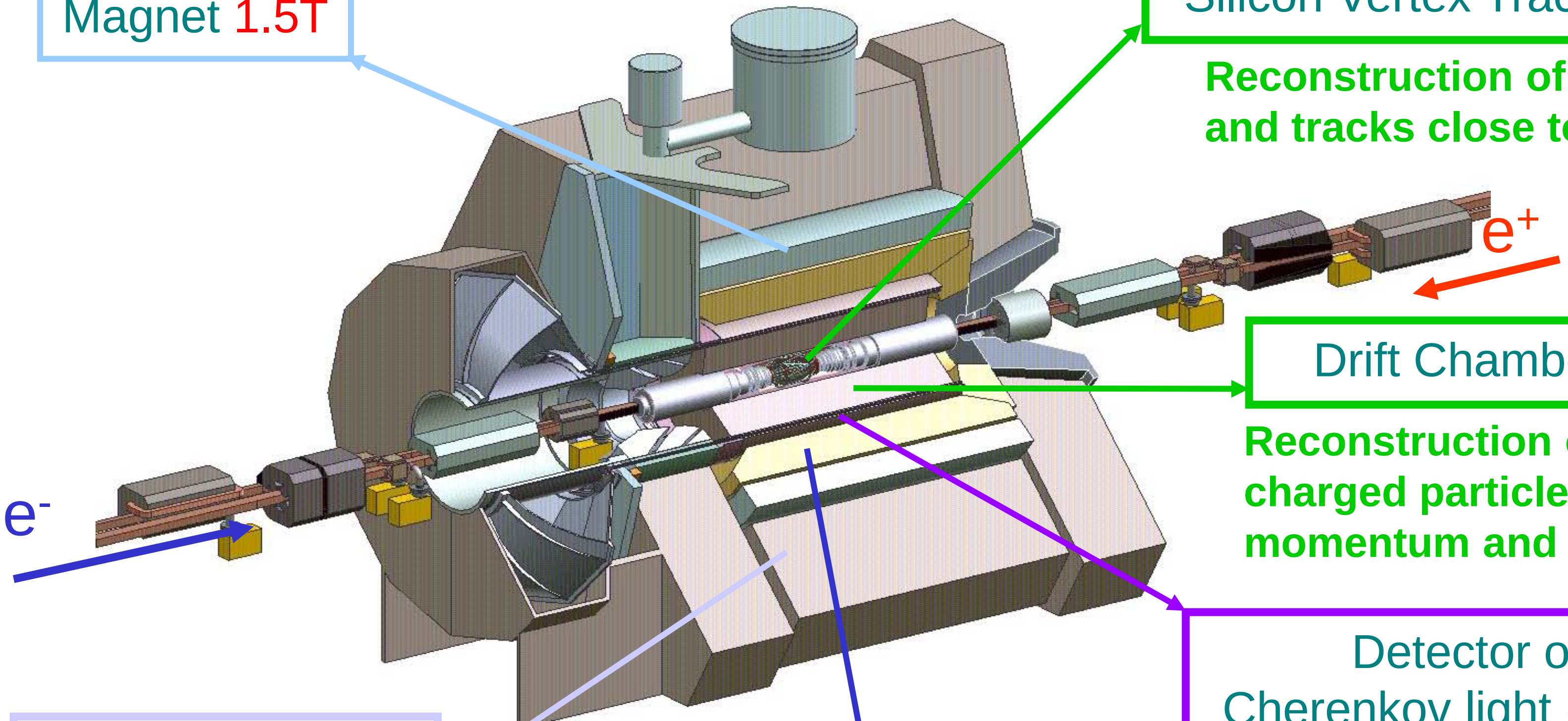
Backup

The BaBar Detector

Magnet 1.5T

Silicon Vertex Tracker (SVT)

Reconstruction of decay vertex and tracks close to the IP



Drift Chamber (DCH)

Reconstruction of deviated charged particles tracks: momentum and angles

Detector of Cherenkov light (DIRC)

Identification of charged particles
Separation $K/\pi > 2.5\sigma$ up to 4 GeV/c

Intrumented flux return (IFR)

Identification of $\mu^{+/-}$

Electromagnetic calorimeter (EMC)

Detection of γ, e^- identification
Reconstruction of $\pi^0 \to \gamma\gamma$, Energy measurement

ΔS Prediction From Theory

Browder,Gershon,Pirjol,AS,Zupan,arXiv:0802.3201(RMP)

TABLE VIII Expectations for ΔS_f in three cleanest modes.

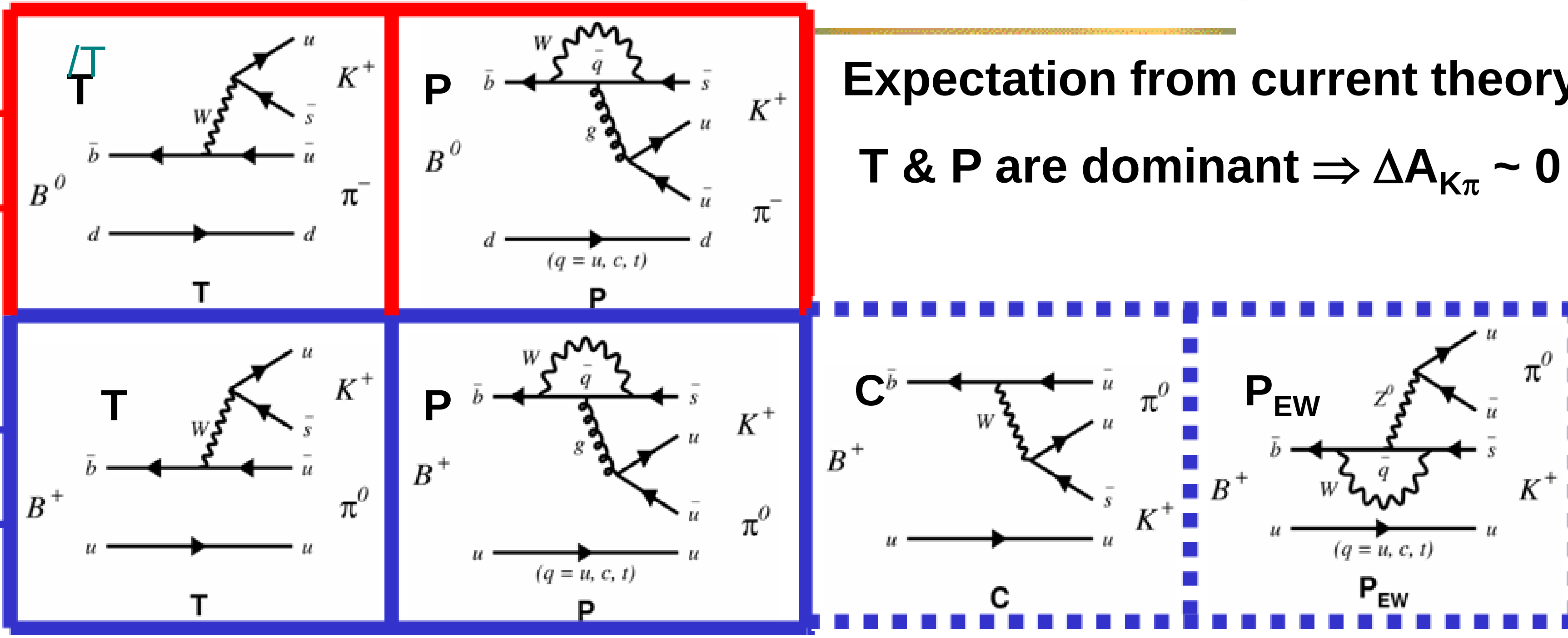
Model	ϕK^0	$\eta' K^0$	$K_S K_S K^0$
QCDF+FSI[a]	$0.03^{+0.01}_{-0.04}$	$0.00^{+0.00}_{-0.04}$	$0.02^{+0.00}_{-0.04}$
QCDF[b]	0.02 ± 0.01	0.01 ± 0.01	
QCDF[c]	0.02 ± 0.01	0.01 ± 0.02	
SCET[d]		-0.019 ± 0.009 -0.010 ± 0.010	
pQCD[e]	0.02 ± 0.01		

[a]Cheng *et al.* (2005a,b) [b]Beneke (2005)
[c]Buchalla *et al.* (2005) [d]Williamson and Zupan (2006)
[e]Li and Mishima (2006)

B → Kπ Direct CP asymmetries: diagrams

$K^+\pi^-$

$K^+\pi^0$

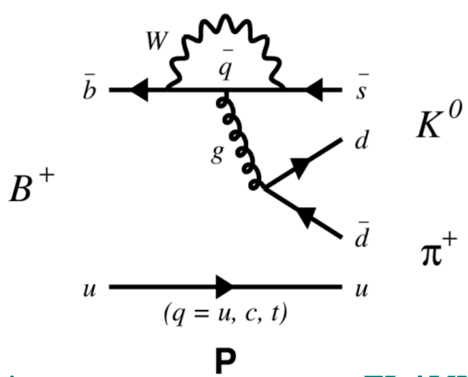


Expectation from current theory

T & P are dominant ⇒ $\Delta A_{K\pi}$ ~ 0

• Enhancement of large C with large strong phase to T ⇒ strong inter. !?

• Enhancement of large P_{EW} ⇒ New physics



$B^+ \rightarrow K^0 \pi^+$

Penguin dominants.

⇒$A_{cp}(K^0\pi^+)$~ 0

$B \to \tau \nu$ and Δm_d

$$\frac{BR(B \to \tau \nu)}{\Delta m_d} = \frac{3\pi}{4} \frac{m_\tau^2}{m_W^2 S(x_t)} \left(1 - \frac{m_\tau^2}{m_B^2}\right)^2 \tau_{B^+} \frac{1}{B_{B_d}} \frac{1}{|V_{ud}|^2} \left(\frac{\sin\beta}{\sin\gamma}\right)^2$$