CP Violation
in B-physics
Status and perspectives

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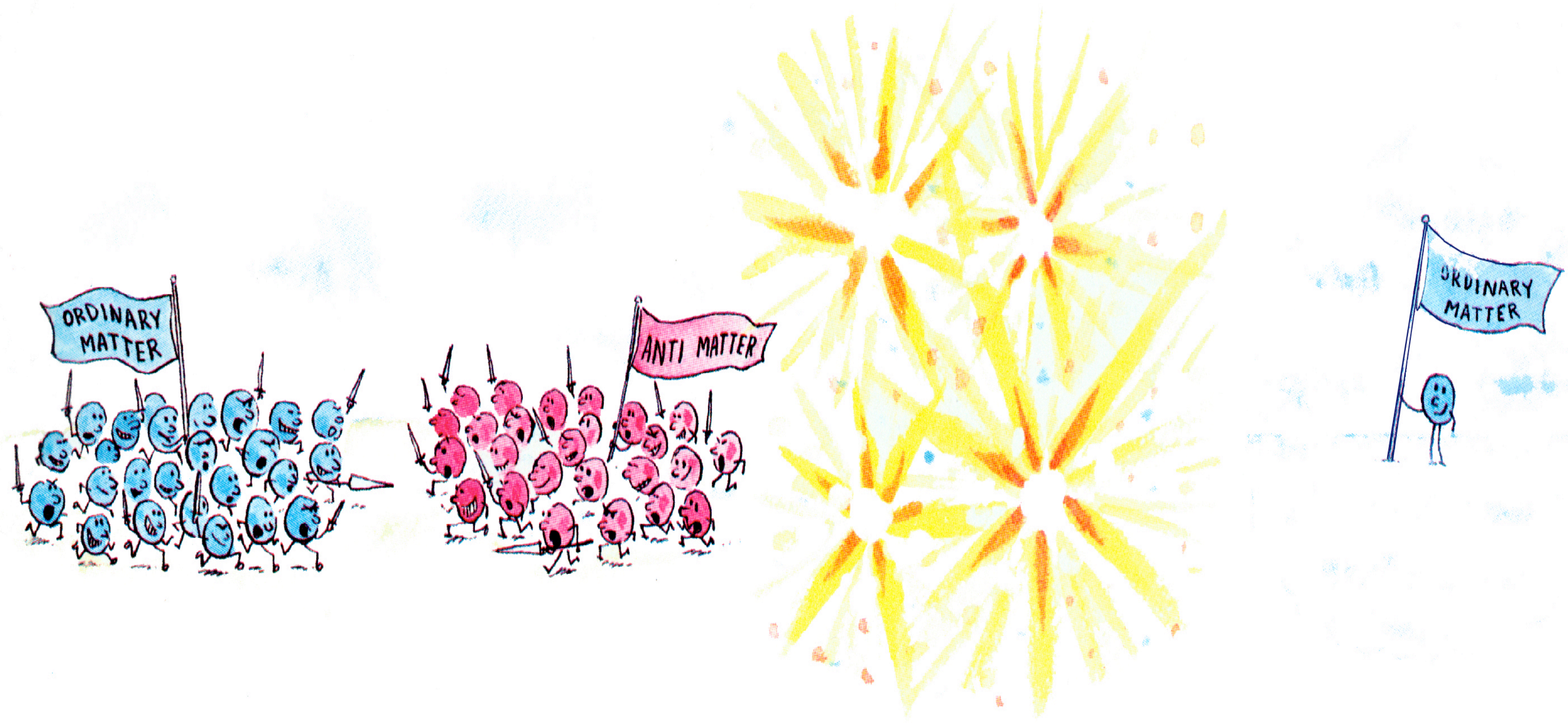
Outline

- What is all about
- B factories
- CP Violation in B decays
- Future
- Conclusions

What is all about



For every billion ordinary particles annihilating with antimatter in the early Universe, one extra was left "standing."

$B^0 \to K^+\pi^-$

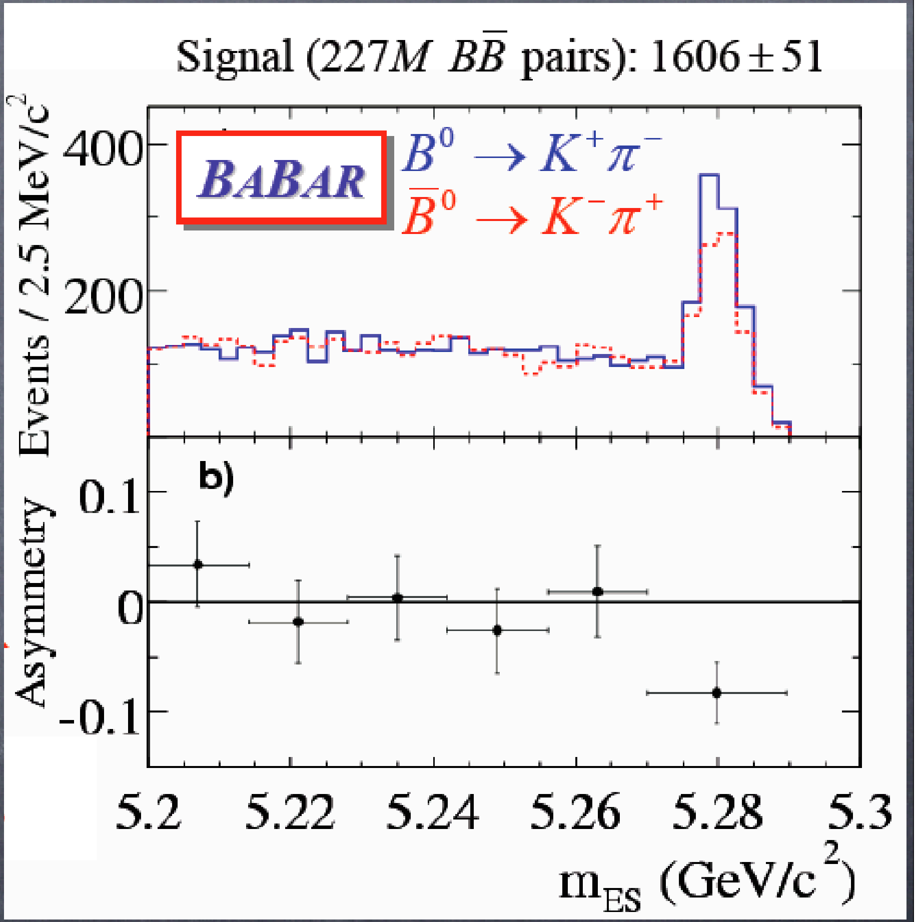
as simple as such (an appetizer)

First observation of Direct CPV in *B* decays

BABAR $A_{CP} = -0.133 \pm 0.030 \pm 0.009$

Belle $A_{CP} = -0.101 \pm 0.025 \pm 0.005$

Average $A_{CP} = -0.114 \pm 0.020$



40 years for the K

4 years for the B

can't deny improvement !

CP violation and Standard Model

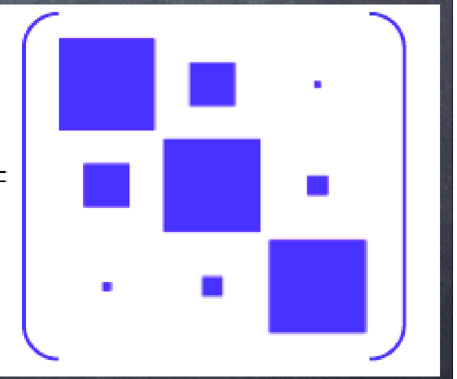
CP violation generated by complex coupling constant in the quark mixing matrix

Cabibbo Kobayashi Maskawa matrix

$\lambda = \sin(\theta_{Cabibbo})$

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

3 quark generations allows for one non-removable phase

$=$ 

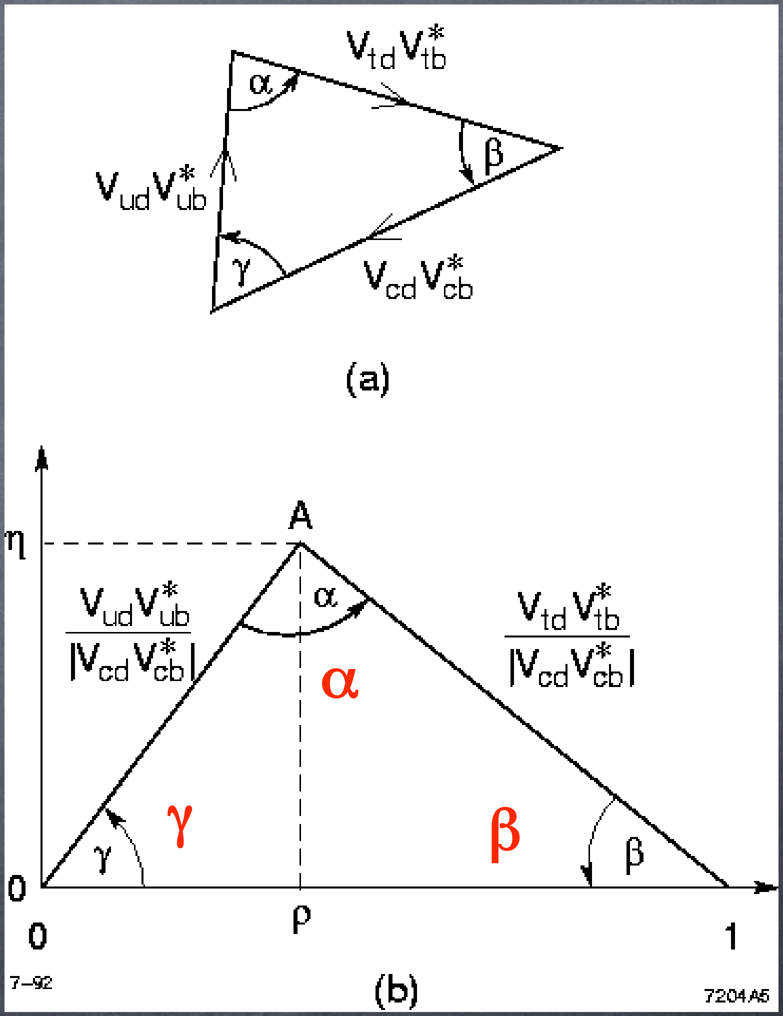
The 'Triangles'

CKM matrix is unitary

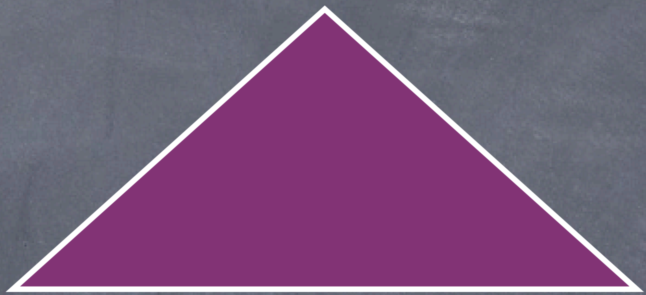
B_d system

phases→angles α, β, *and* γ
a.k.a. $\varphi_1, \varphi_2, \varphi_3$

CP violation proportional to triangle area:
measure sides and angles independently



The B (and K) triangle



B sector:

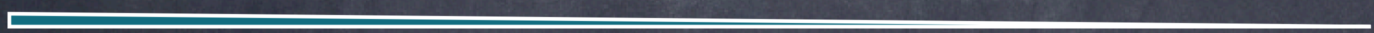
$$V_{ud}V_{ub}^{*} + V_{cd}V_{cb}^{*} + V_{td}V_{tb}^{*} = 0$$

$$\propto A\lambda^{3} \quad \propto -A\lambda^{3} \quad \propto A\lambda^{3}$$

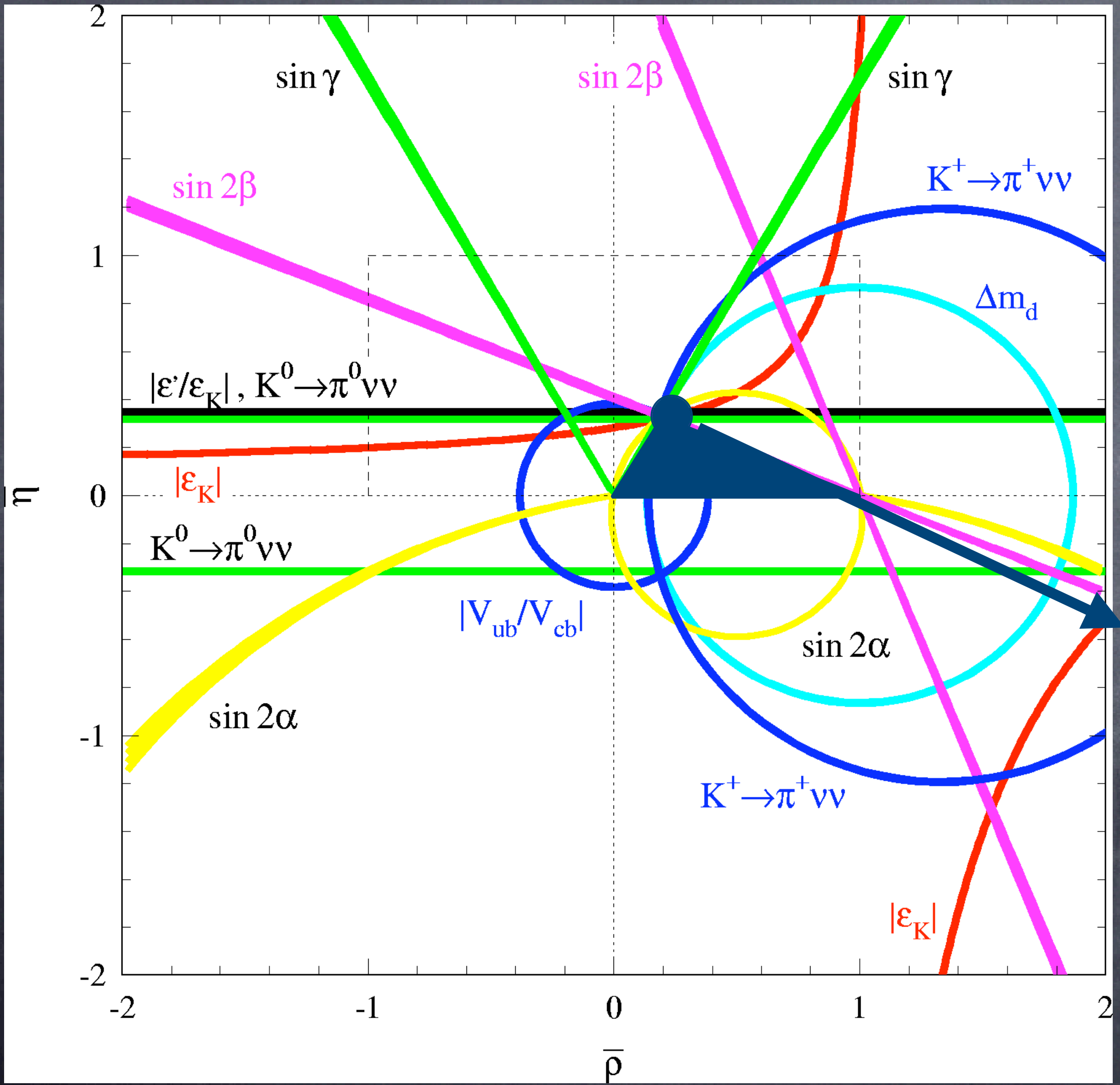
K sector:

$$V_{ud}V_{us}^{*} + V_{cd}V_{cs}^{*} + V_{td}V_{ts}^{*} = 0$$

$$\propto \lambda \quad \propto -\lambda \quad \propto -A^{2}\lambda^{5}$$



The name of the game



λ, A, ρ, η are enough ?

SM or New Physics?

As simple as such, as difficult as can it be

- CP violation is the area of the triangle.

  Roughly (if SM holds): 10^{-6}

- CP violation is roughly $(\Gamma - \overline{\Gamma})$

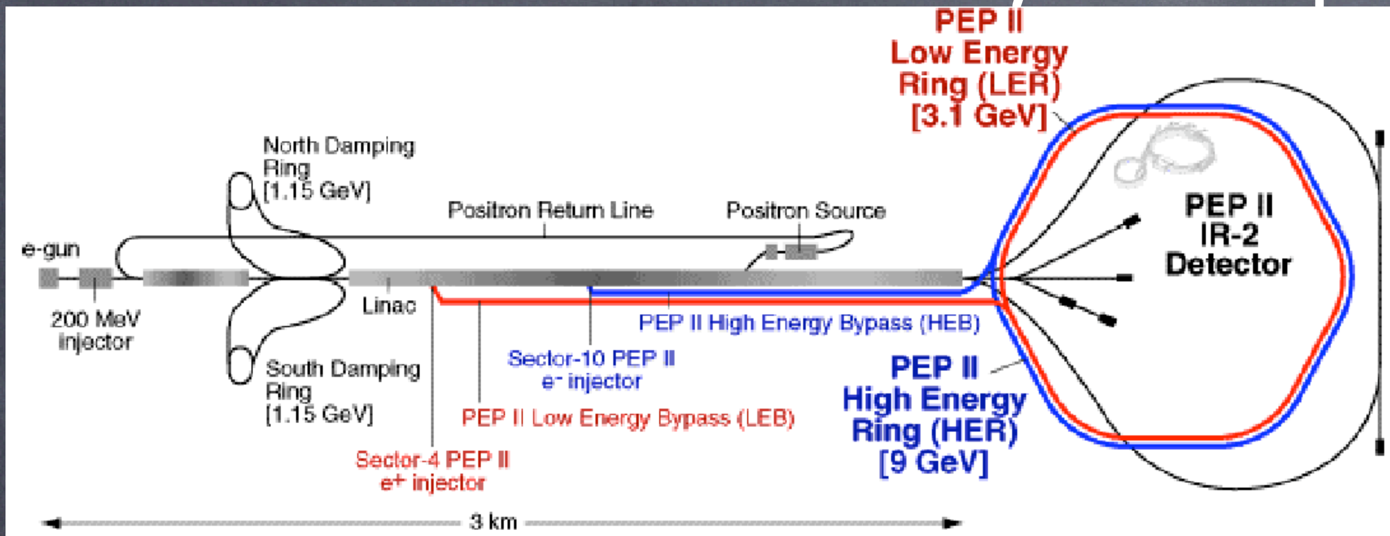
- It is a large effect only if Γ is painfully low

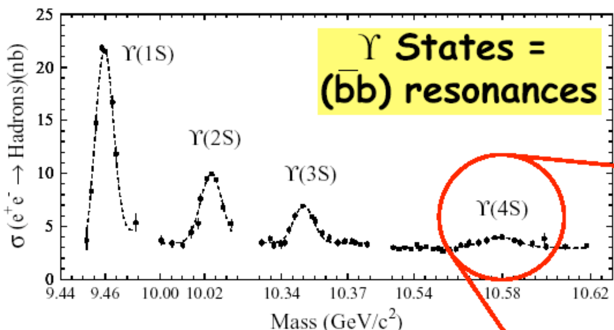
$$A(t) = \frac{\Gamma(t) - \overline{\Gamma}(t)}{\Gamma(t) + \overline{\Gamma}(t)}$$

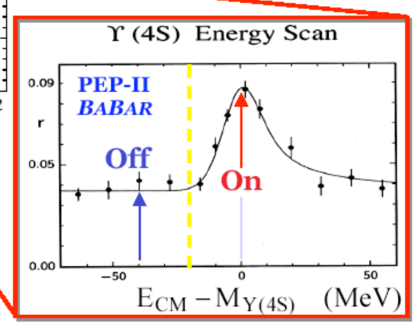
To measure a 10^{-6} effect, take a channel with 10^{-5} BR and measure 10^{3} of them.
So that you end up with a couple of % error. If your global efficiency is very high !

Little annoyance: produce no less than 10^{8} B's

The B-factory concept







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

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

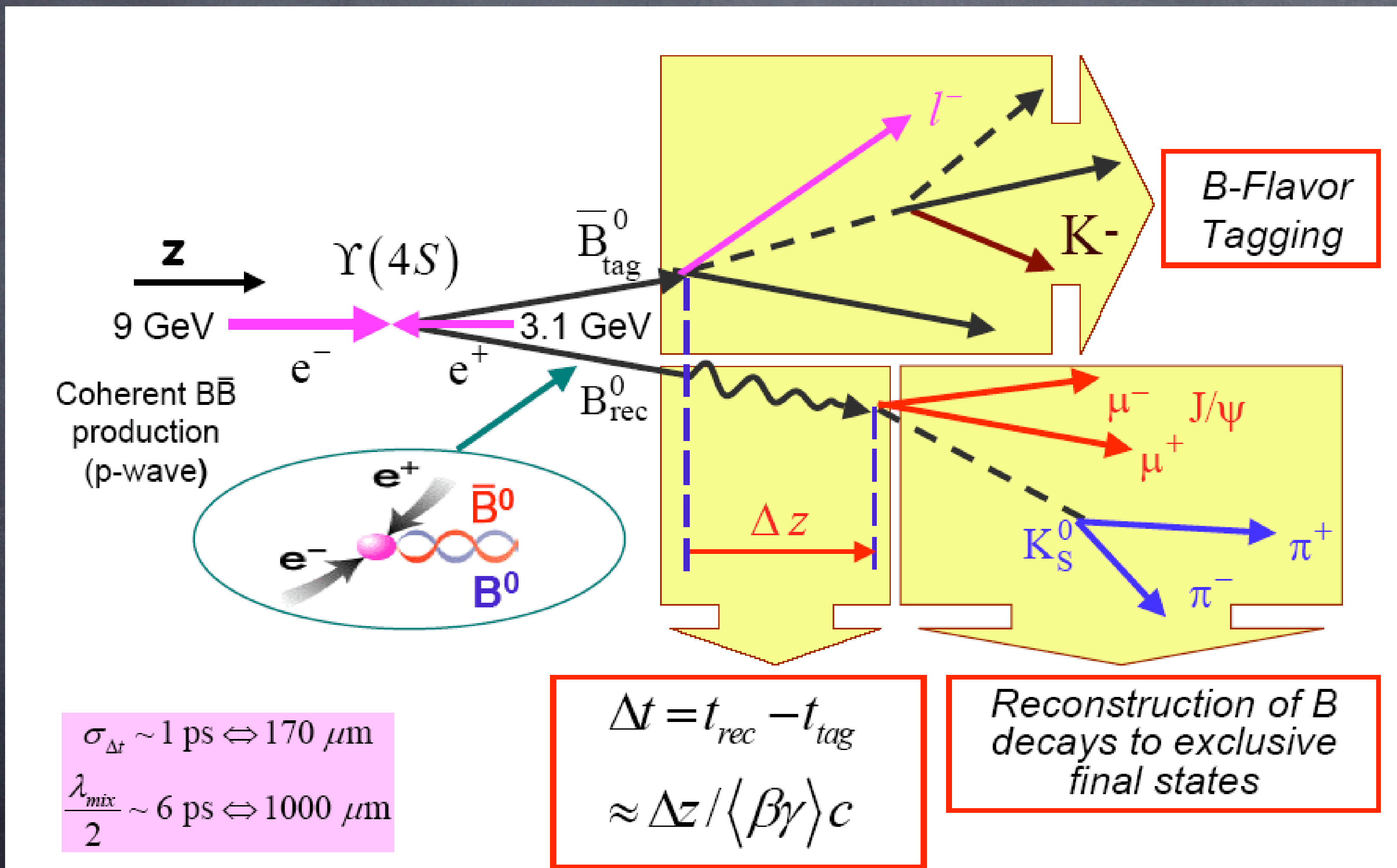
$L = 1$ state

High luminosity asymmetric B factory @ (4S)

9 GeV e^- on 3.1 GeV e^+

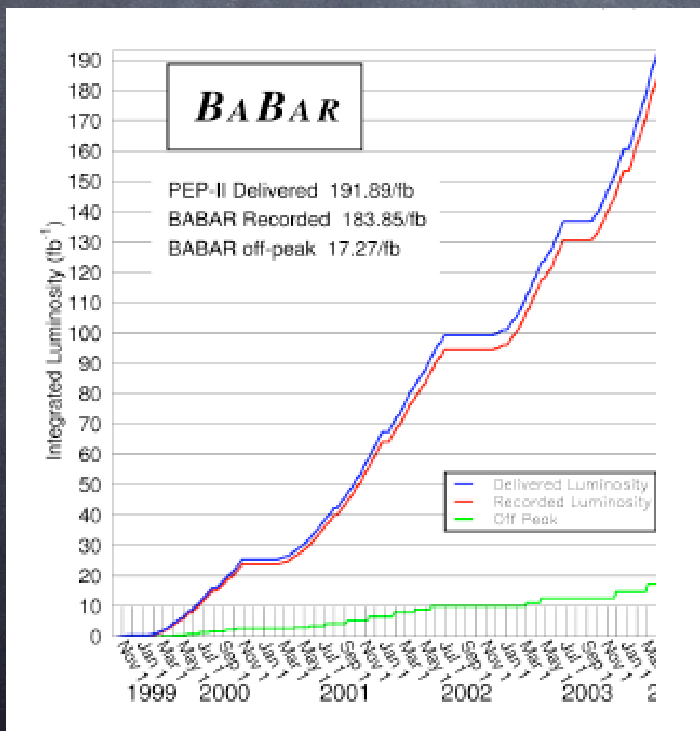
(4S) boost: $\langle\beta\gamma\rangle \sim 0.55$

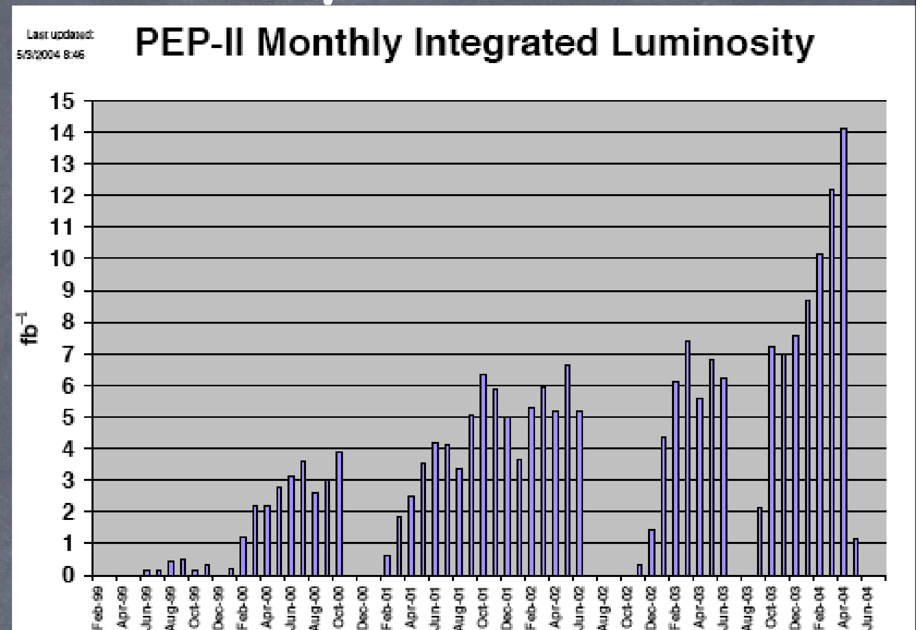
Experimental Technique for B-factories

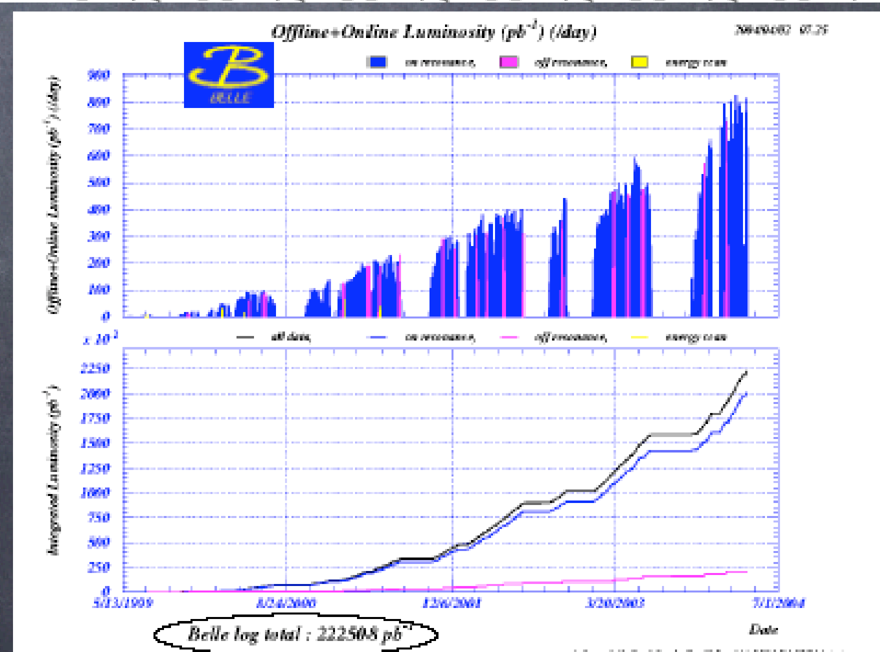


for being Luminous they are !

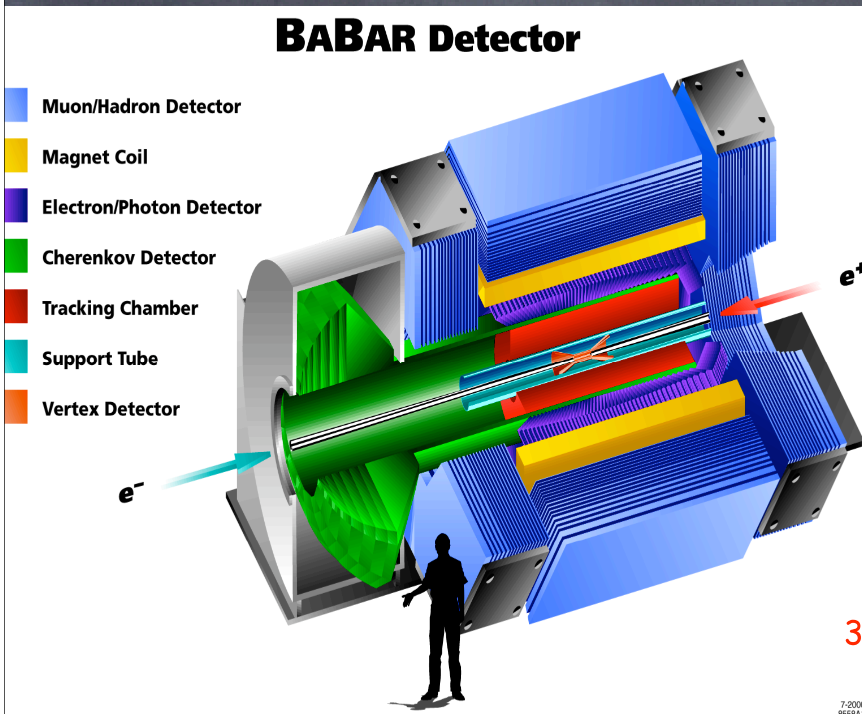
Exp	BaBar	Belle
Lpeak	$9.2\ 10^{33}$	$12.3\ 10^{33}$
Lint	250	350

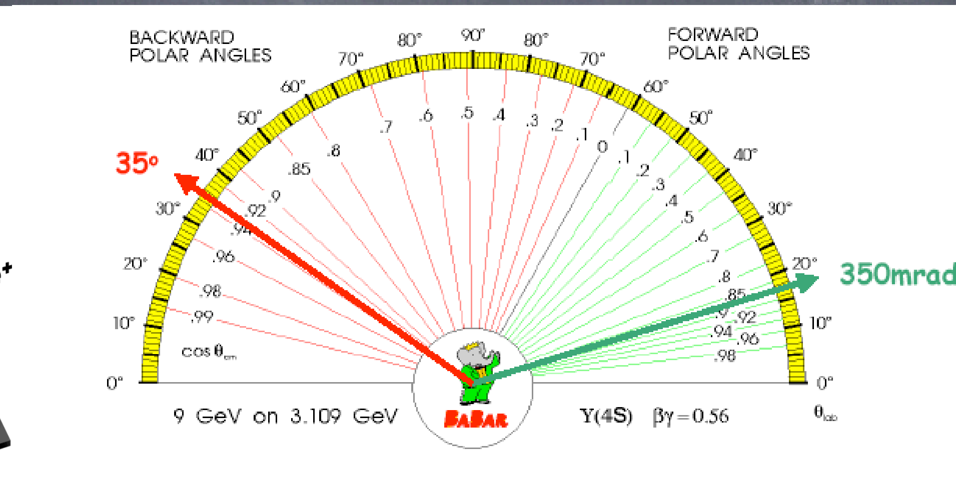


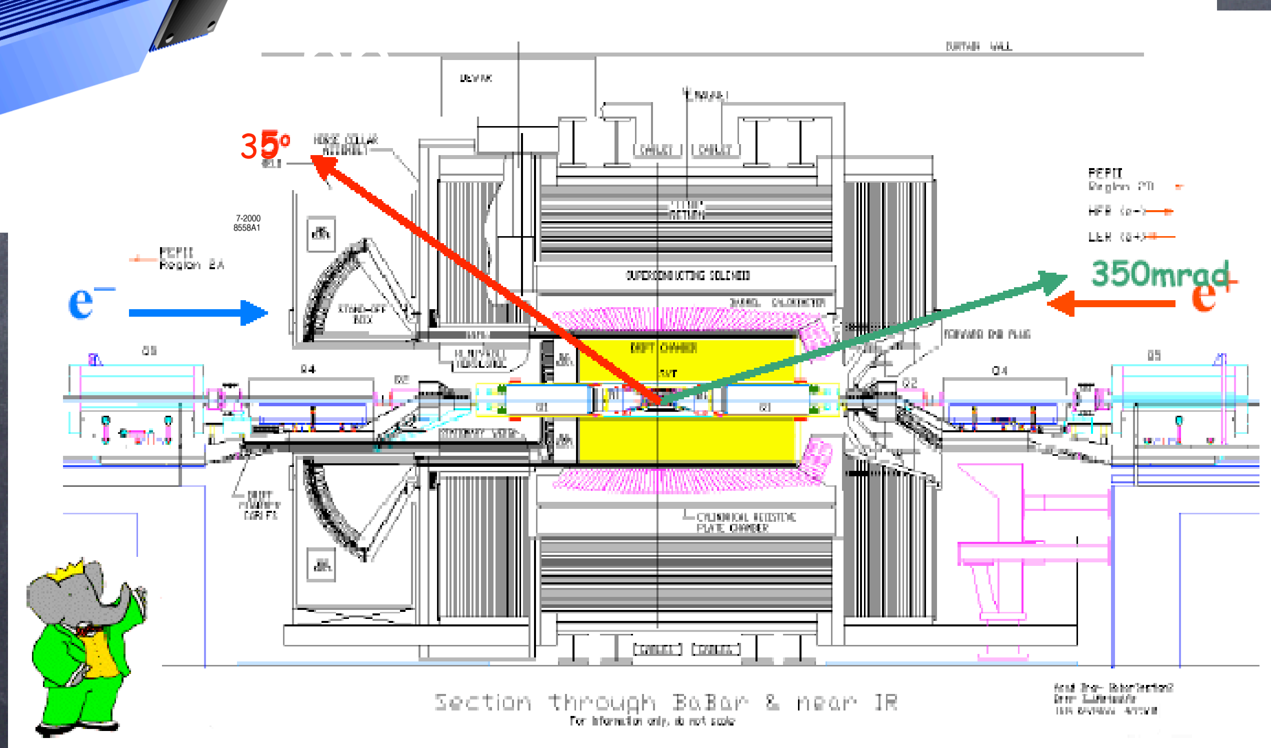




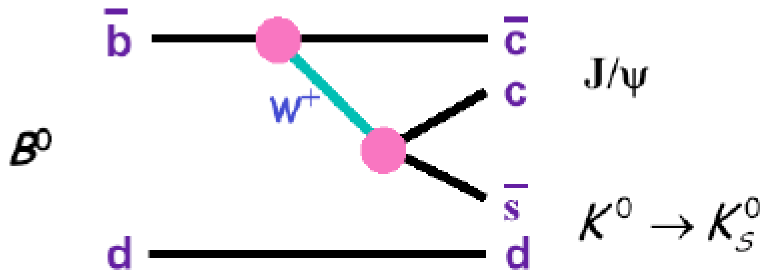
BaBar Detector



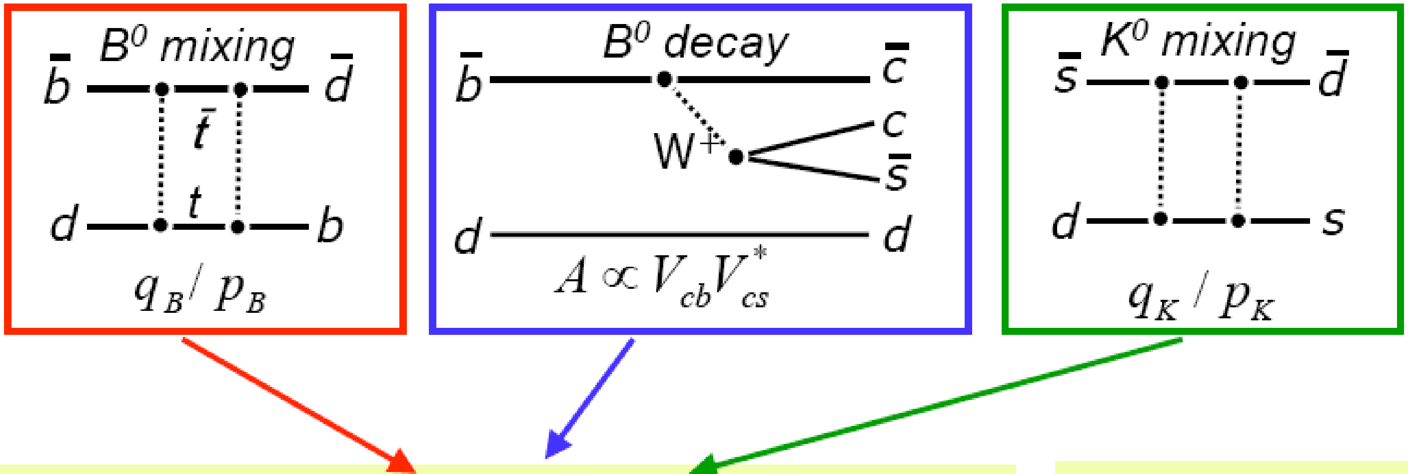




The paradigma



CP Eigenstate:
η_{CP} = -1



$$\lambda_{\psi K_S} = \frac{q_B}{p_B}\frac{\bar{A}_{\psi K_S}}{A_{\psi K_S}} = -\frac{V^*_{tb}V_{td}}{V_{tb}V^*_{td}}\frac{V_{cb}V^*_{cs}}{V^*_{cb}V_{cs}}\frac{V_{cs}V^*_{cd}}{V^*_{cs}V_{cd}} = -\frac{V^*_{tb}V_{td}}{V_{tb}V^*_{td}}\frac{V_{cb}V^*_{cd}}{V^*_{cb}V_{cd}}$$

$$\Rightarrow \mathrm{Im}(\lambda_{\psi K_S}) = \sin(2\beta)$$

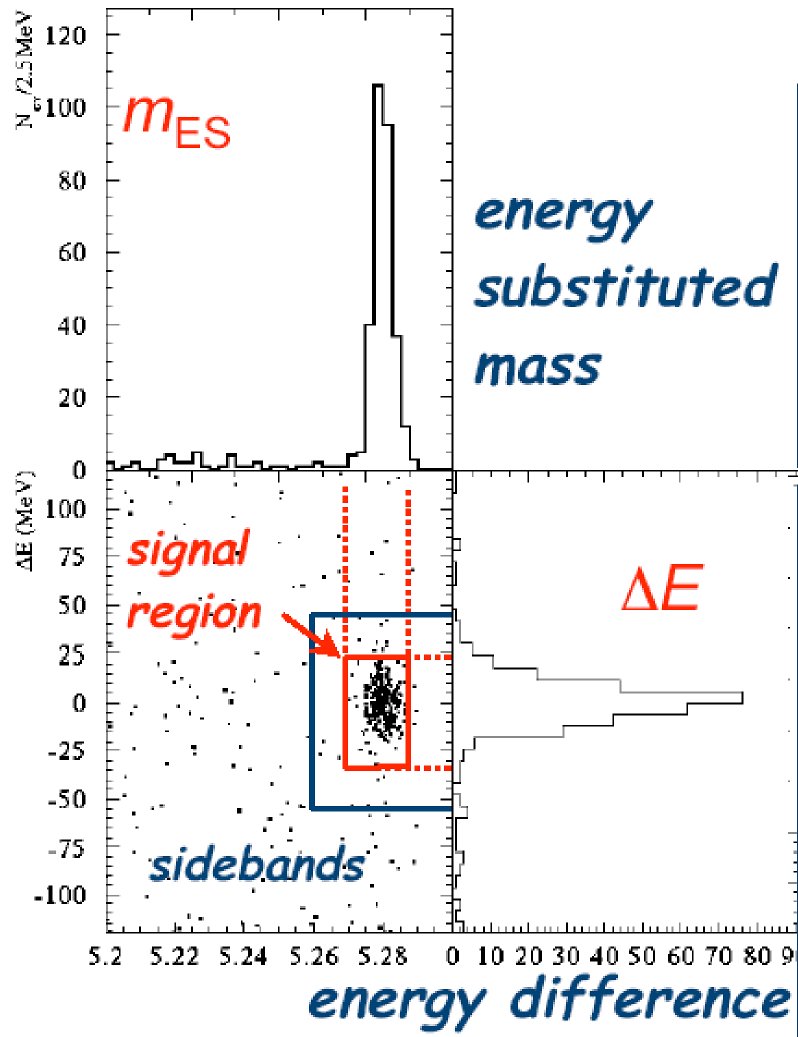
$$\Rightarrow |\lambda_{\psi K_S}| = 1$$

$$\lambda_{\psi K_L} = -\lambda_{\psi K_S}$$

$$A_{CP}(t) = -\ \eta_{CP} \sin 2\beta \sin(\Delta m\ t)$$

η_{CP} = -1 (+1)
for $J/\psi\ K^0_{S(L)}$

Reconstruction of B mesons



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

$$m_{ES} = \sqrt{E^{*2}_{beam} - p^{*2}_{B}}$$

$$\Delta E = E^*_B - E^*_{beam}$$

Resolutions

$$\sigma^2_{\Delta E} = \sigma^2_{beam} + \sigma^2_E \sim \sigma^2_E$$

$$\sigma^2_{m_{ES}} = \sigma^2_{beam} + \left[\frac{p}{m_B}\right]^2 \sigma^2_p \sim \sigma^2_{beam}$$

$$\sigma_{\Delta E} \sim 10 - 40 \text{ MeV}$$

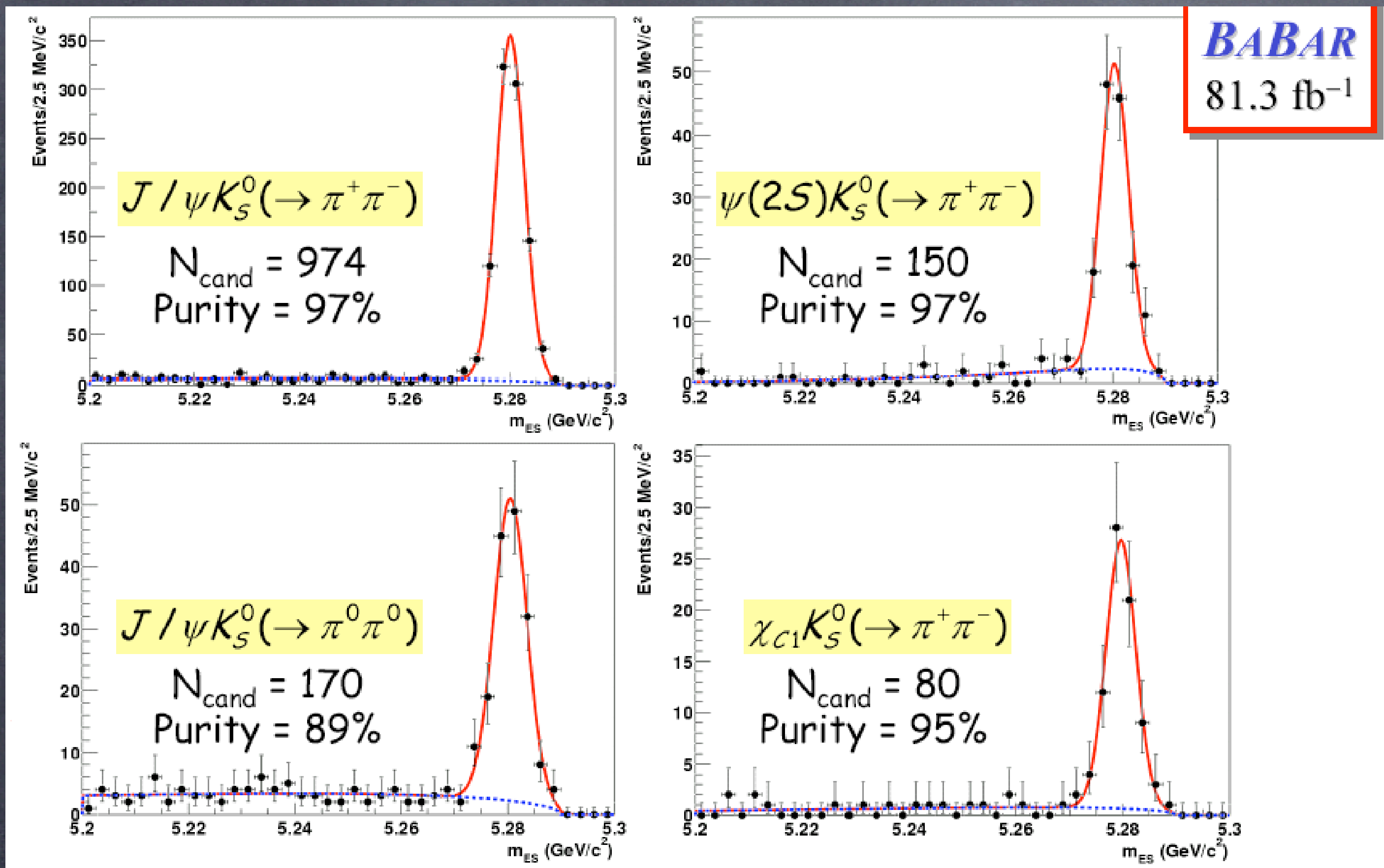
$$\sigma_{m_{ES}} \sim 2.6 \text{ MeV}/c^2$$

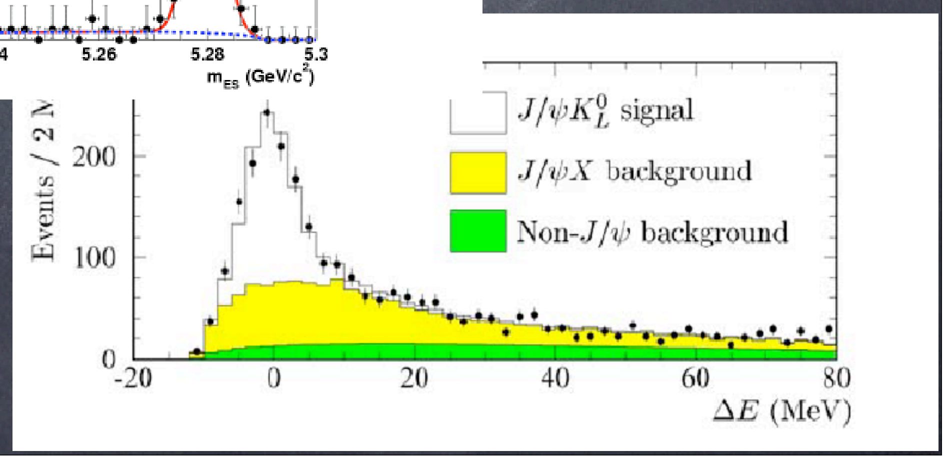
The program

(as understood today)

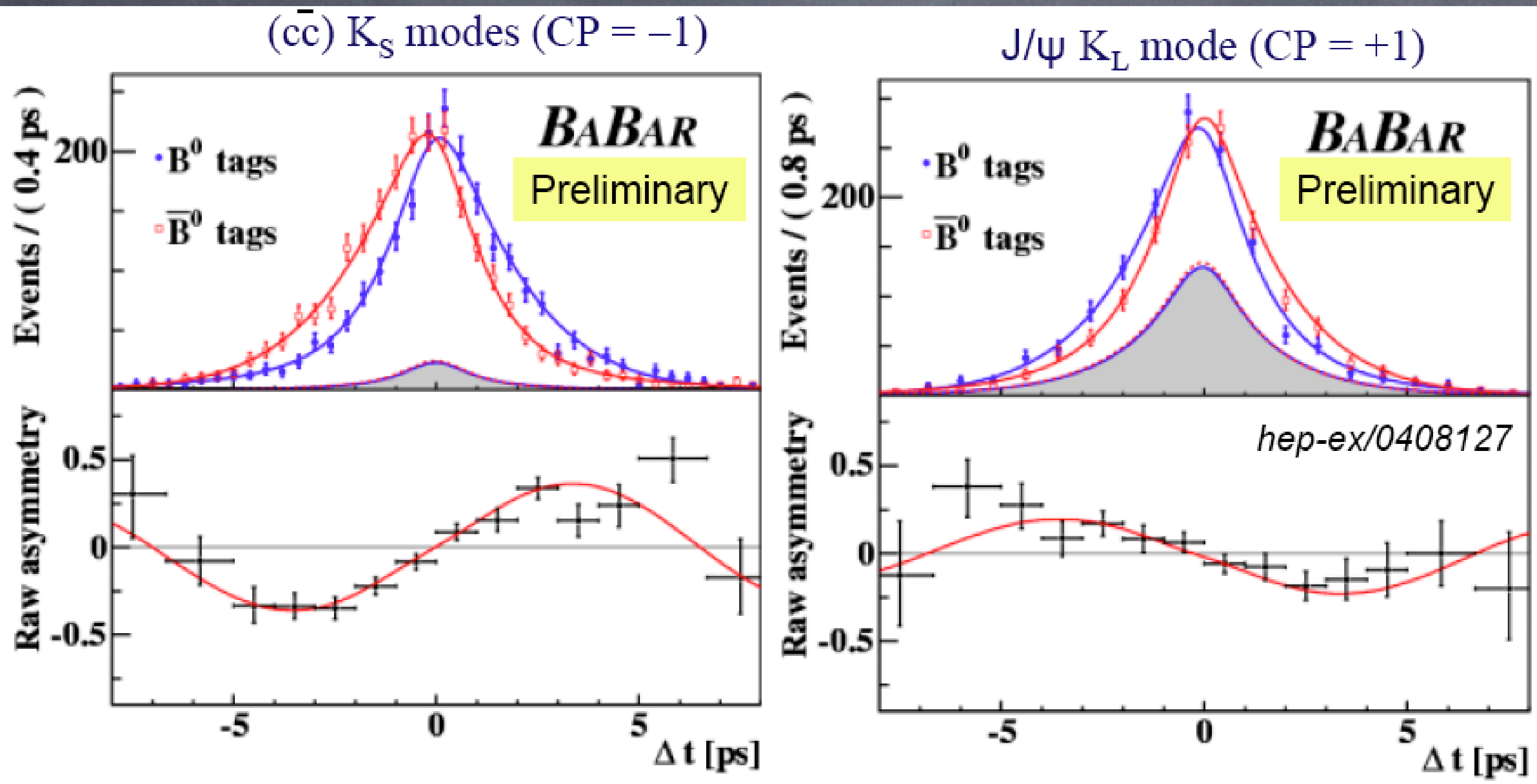
- β as measured by Golden Channel to validate SM
- β as measured in $b \to s s \bar{s}$ to open a window on New Physics
- α and γ for the elegance of closing a triangle
- (the sides are also well measured but this would be another talk)

Golden sample



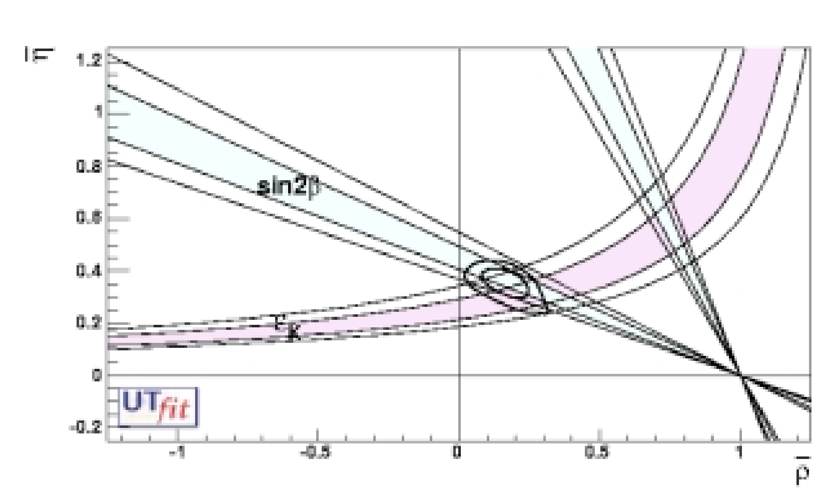


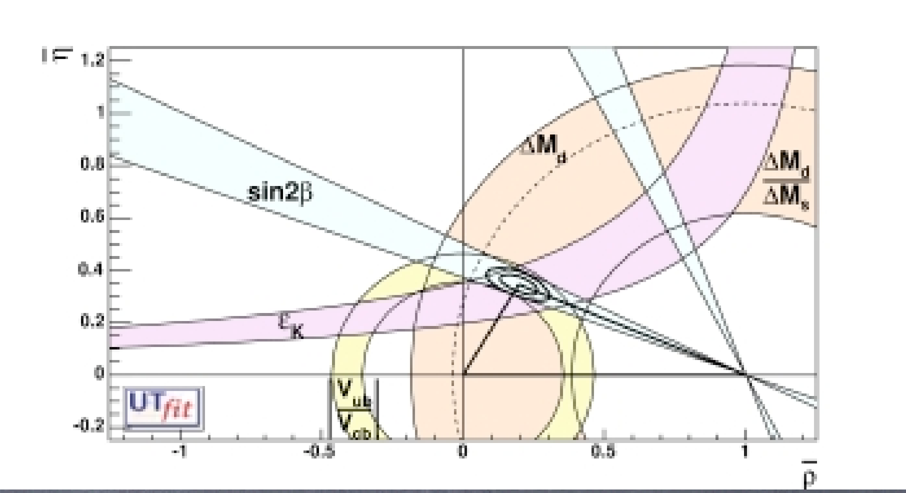
BaBar result on sin2β



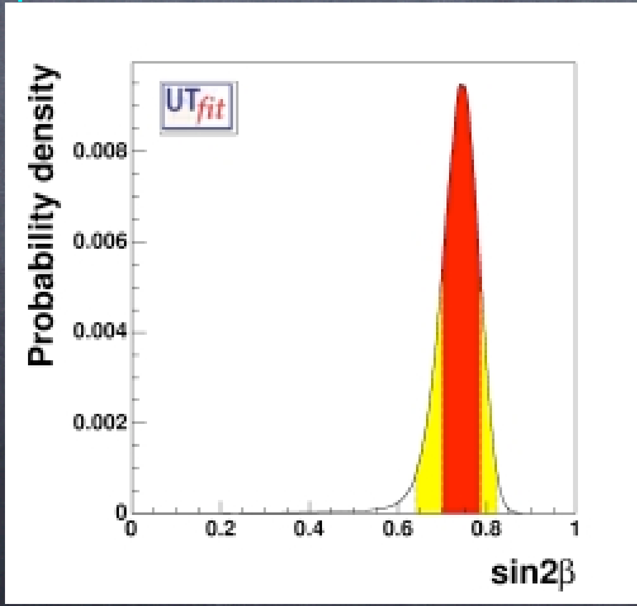
sin2β = 0.722 ± 0.040 (stat) ± 0.023 (syst)

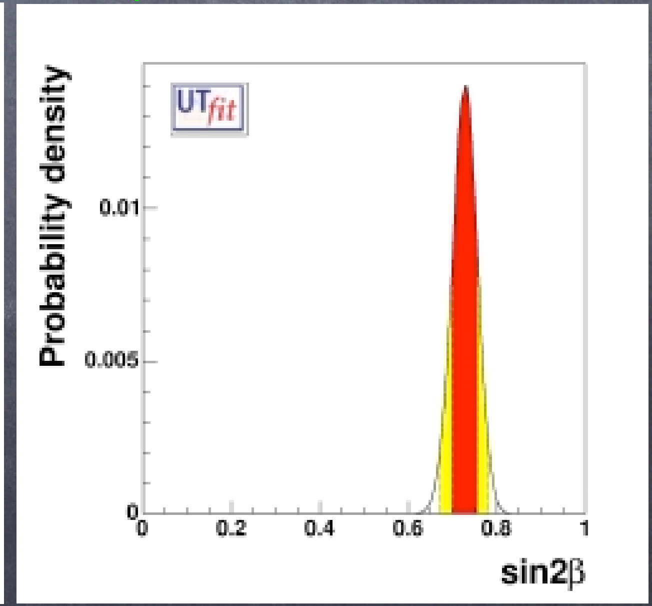
Oh yeah, SM is invincible !





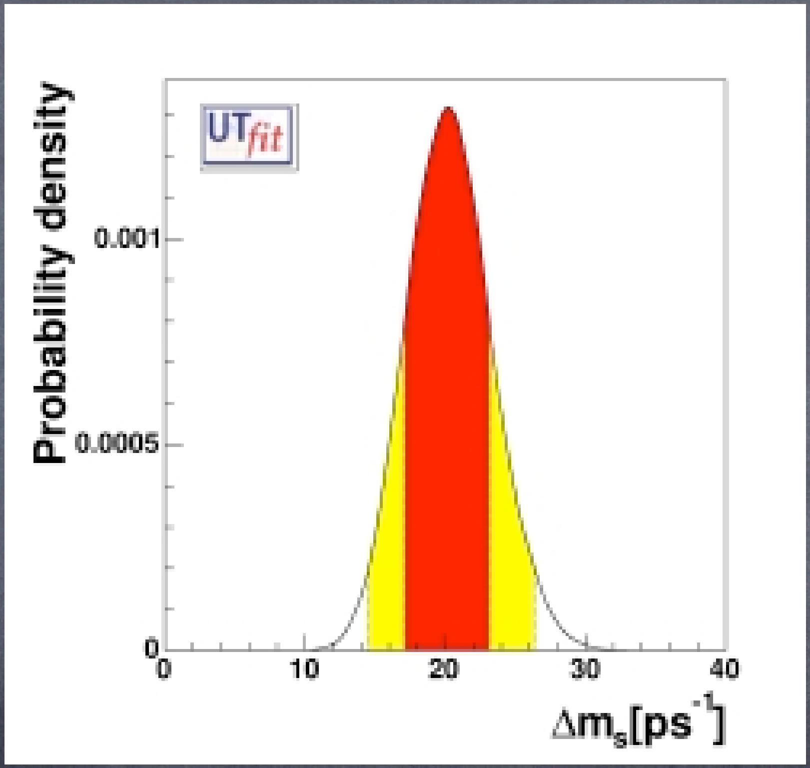
sin 2β = 0.734 ± 0.043 (from UT sides)   sin 2β = 0.726 ± 0.028 (all constraints)





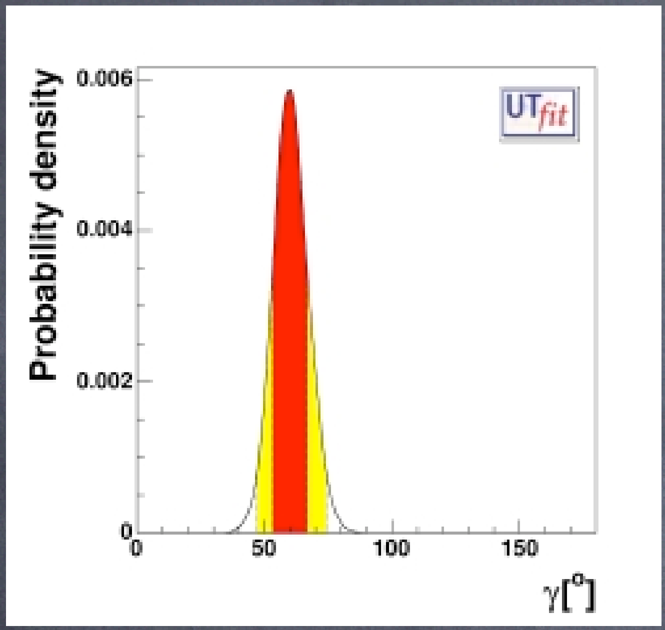
sin 2β = 0.726 ± 0.037 (from $J/\Psi K^0$)

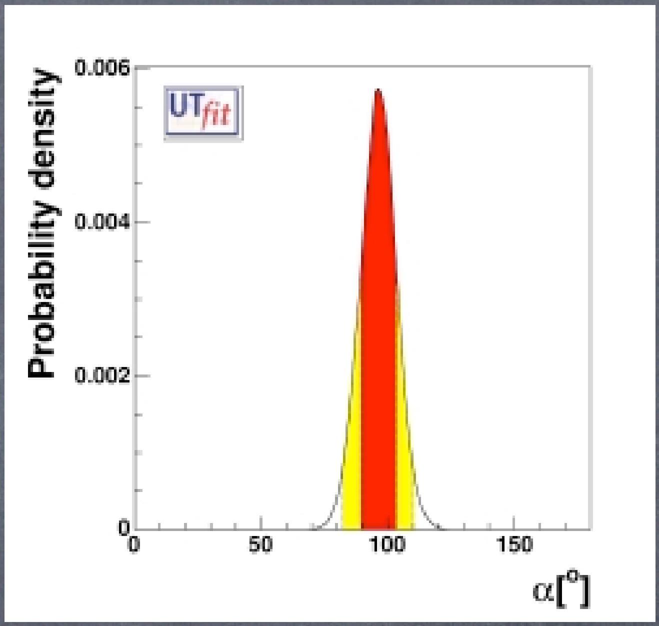
The most important prediction



$$\Delta m_s = 21.2 \pm 3.2$$

and some more



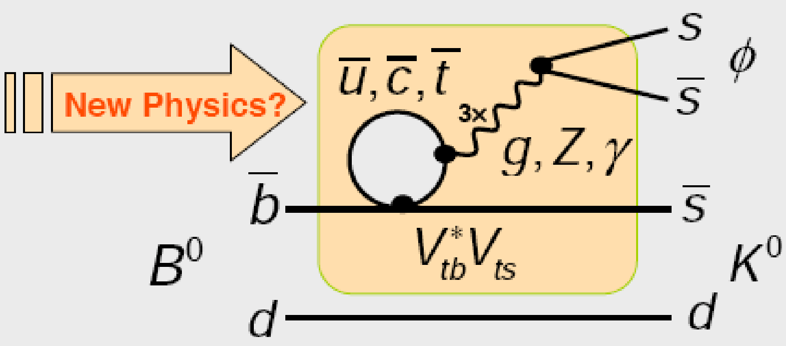


$\gamma = (60.3 \pm 6.8)^\circ$

$\alpha = (96.1 \pm 7.0)^o$

Hic sunt leones

Penguin :



$b \to s\bar{s}s$

$$\lambda_{\phi K_S} = +\left(\frac{q}{p}\right)_B \left(\frac{V_{tb}V_{ts}^{*}}{V_{tb}^{*}V_{ts}}\right)\left(\frac{p}{q}\right)_K \approx -e^{-2i\beta}$$

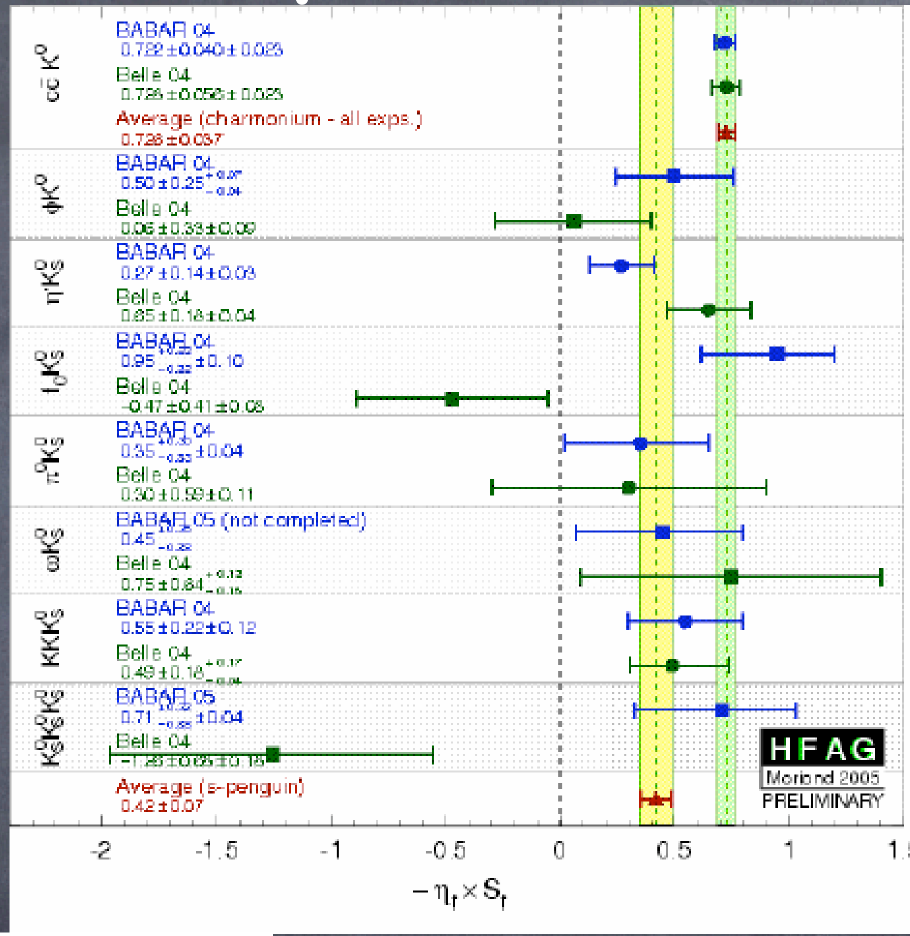
the same phase as: $b \to c\bar{c}s$ $\lambda_{J/\psi K_S} = +\left(\frac{q}{p}\right)_B \left(\frac{V_{cb}V_{cs}^{*}}{V_{cb}^{*}V_{cs}}\right)\left(\frac{p}{q}\right)_K = -e^{-2i\beta}$

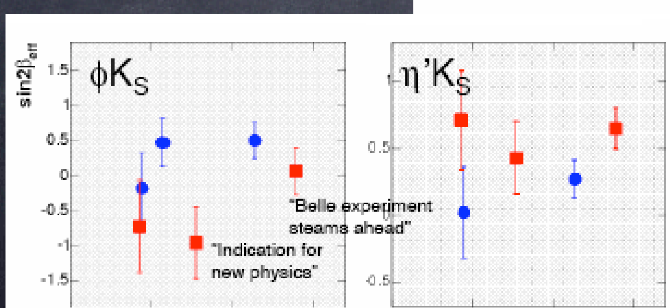
sin2β(charmonium) $\stackrel{?}{=}$ sin2β(penguin)

CP Modes

$\phi K_S (K_L)$
$\eta' K_S$
$f_0 K_S$
$\pi^0 K_S$
ωK_S
$KK K_S$
$K_S K_S K_S$

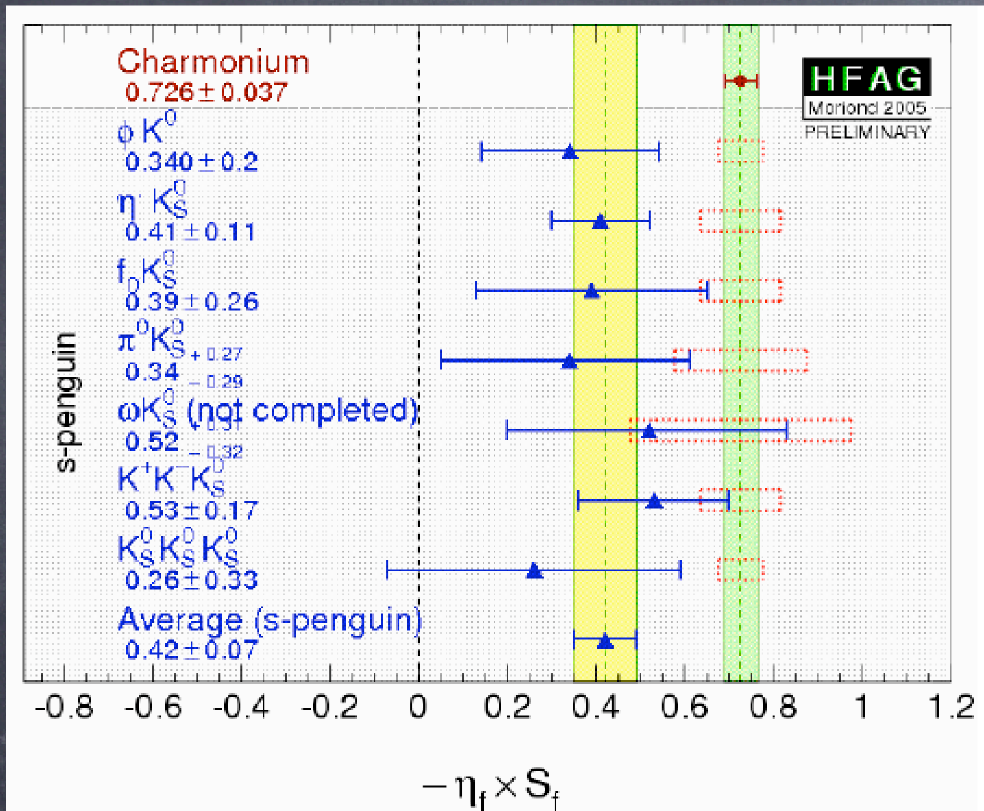
The experimental status





fair agreement BaBar-Belle

and the struggle with theoretical uncertainty



Wait

take (much) more data

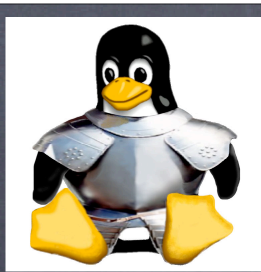
and see

$B^0 \to f$	SU(3)	U-spin	$\Delta\sin2\beta$
ϕK_S	0.65	0.19	~0.3
$\eta' K_S$	0.14	0.07	~0.1
KKK_S	–	0.19	~0.2
$\pi^0 K_S$	0.18	–	~0.2

SCET…

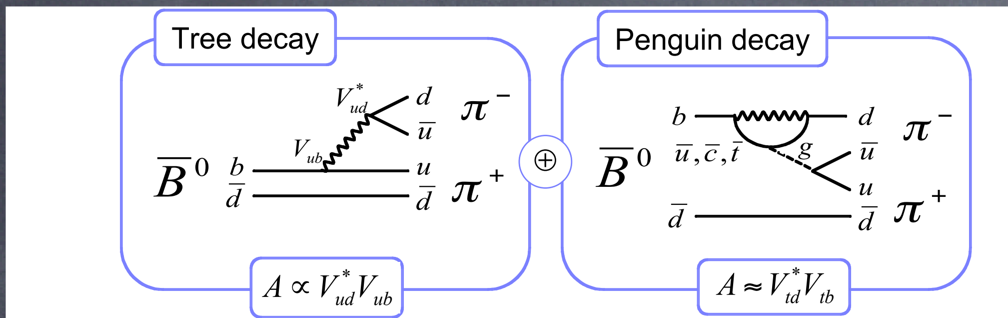
- Some estimates (from QCDF):

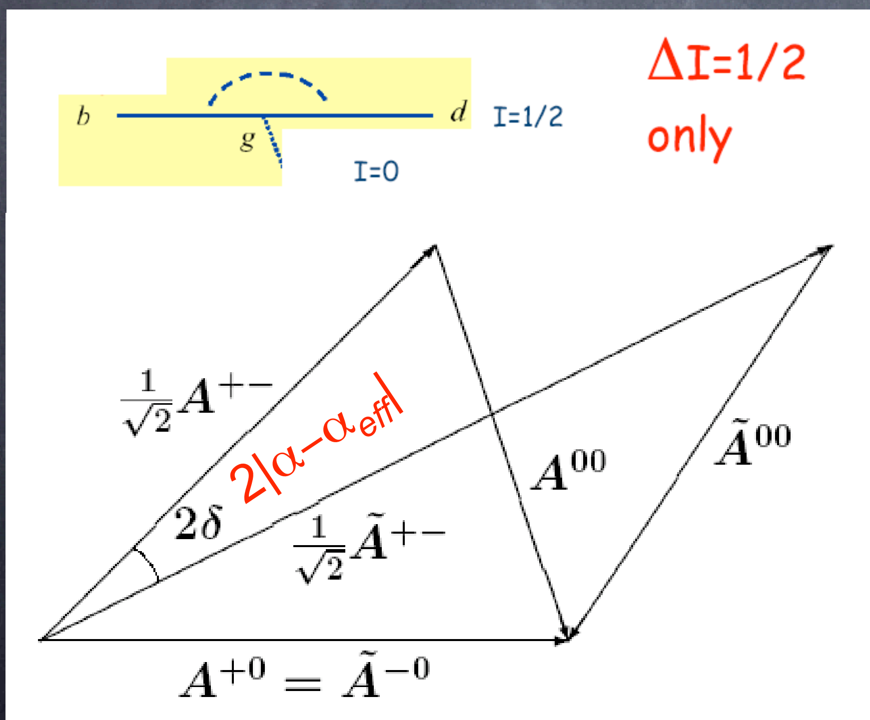
$B^0 \to f$	$\Delta\sin2\beta$	
ϕK_S	0.025±0.012±0.010	[Beneke, Buchalla, Neubert, Sachrajda, NPB591]
$\eta' K_S$	0.011±0.009±0.010	
$\pi^0 K_S$	0.13±0.07	[Buras, Fleischer, Recksiegel, Schwab, NPB697] [Ciuchini at al., hep-ph/0407073]

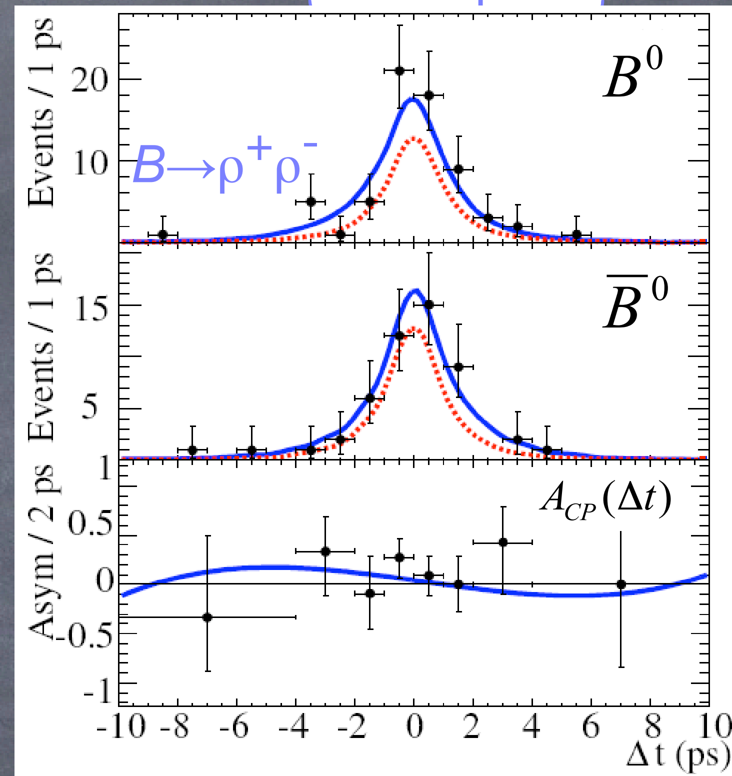


Several routes to α

$B \rightarrow \pi\,\pi$
$B \rightarrow \rho\,\rho$
$B \rightarrow \rho\,\pi$





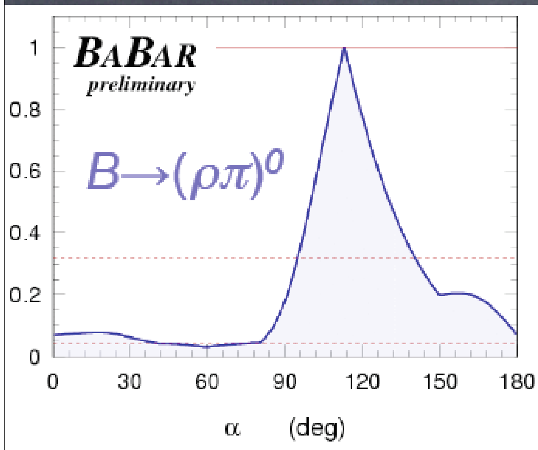


$$B(B^0 \rightarrow \rho^+\rho^-) = (33 \pm 4 \pm 5)\cdot 10^{-6}$$

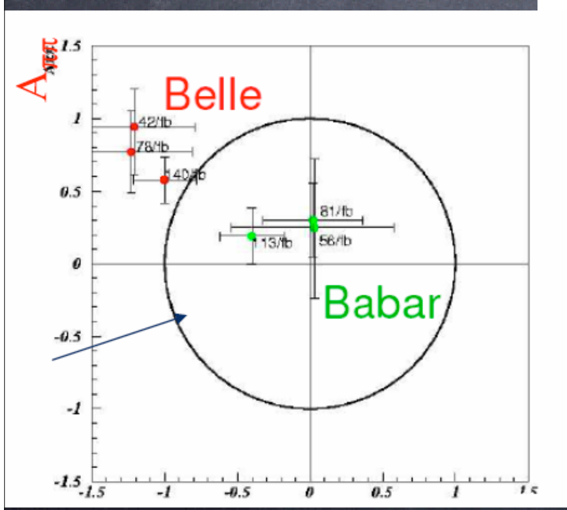
$$B(B^0 \rightarrow \rho^0\rho^0) = (0.54^{+0.36}_{-0.32} \pm 0.19)\cdot 10^{-6}$$

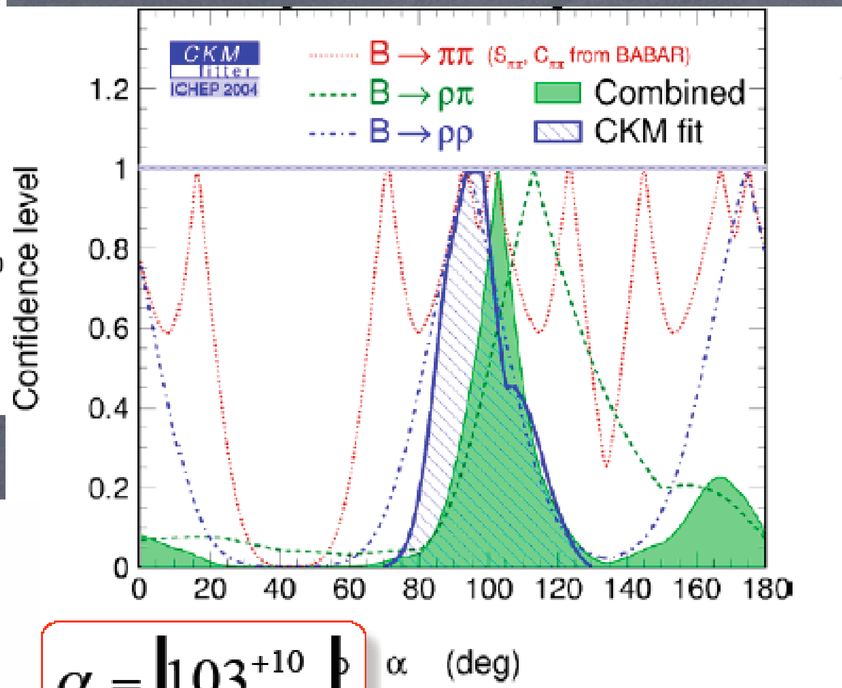
$$< \; 1.1\cdot 10^{-6} \quad 90\%\ \text{C.L.}$$

and the results are:



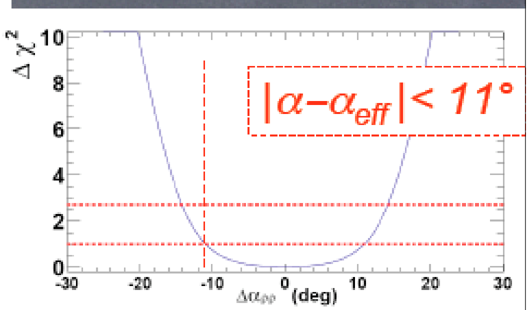
$$\alpha = \left[113^{+27}_{-17}(stat.) \pm 6(syst.)\right]^{\circ}$$

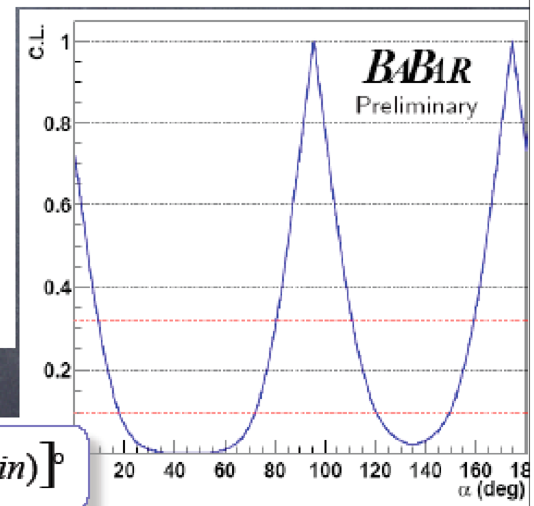




$$\alpha = \left[103^{+10}_{-11}\right]^{\circ}$$

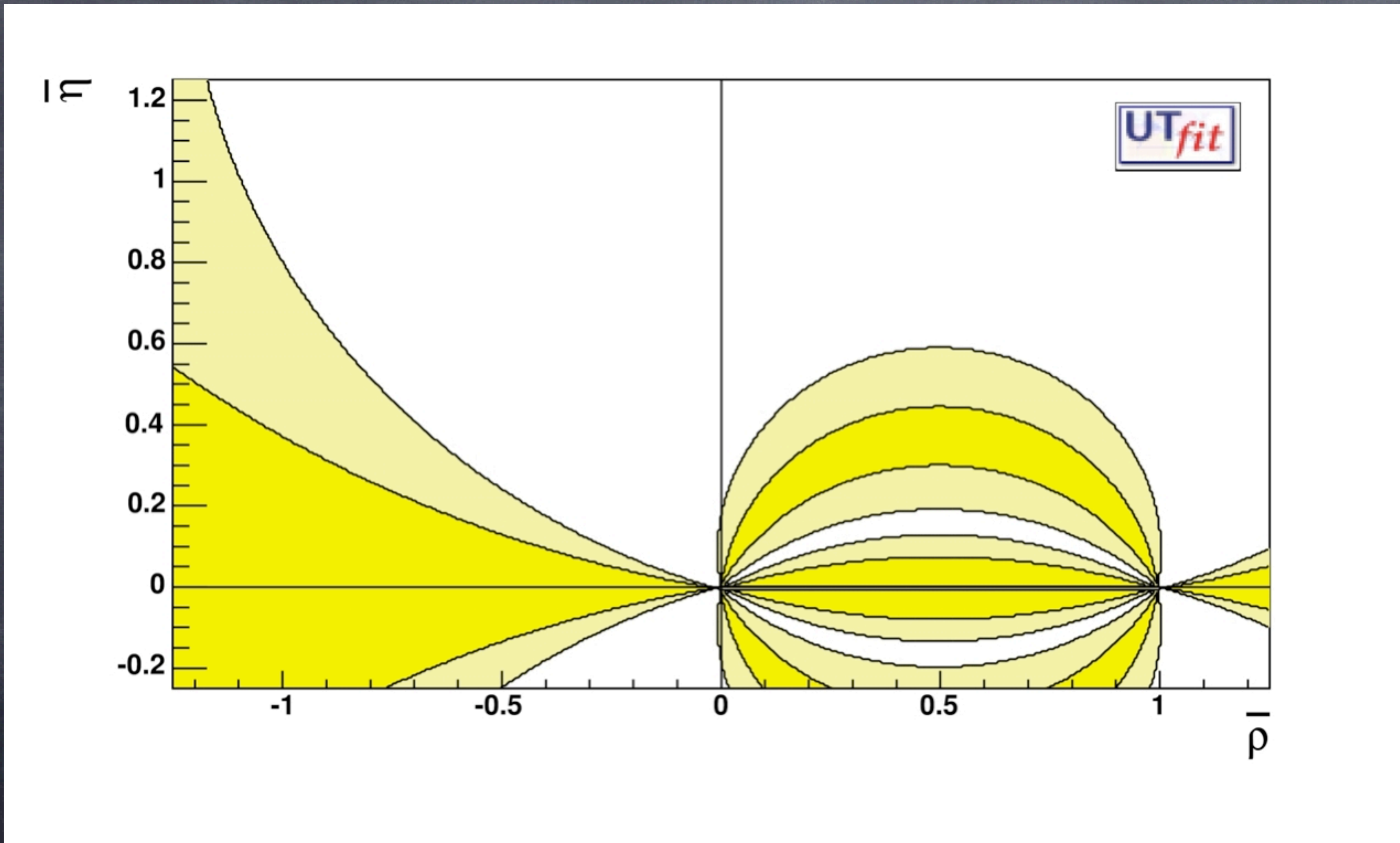
B→ρρ





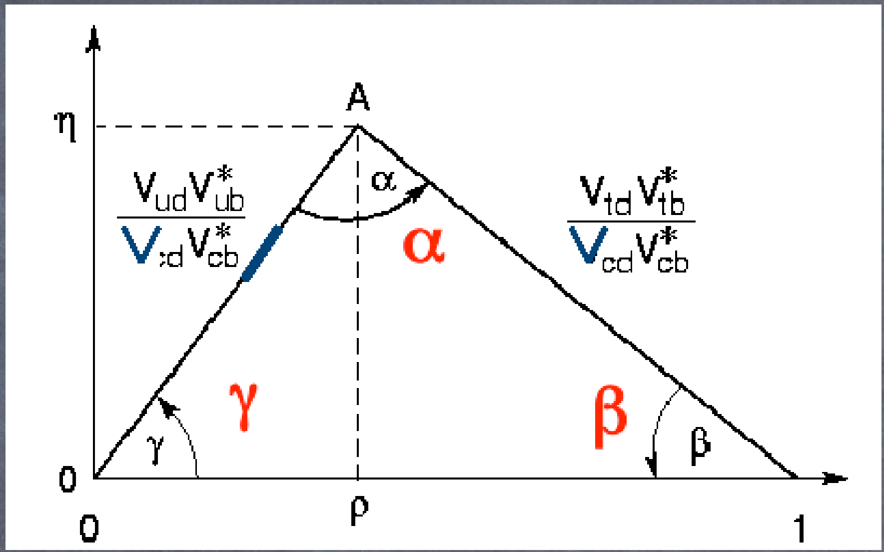
$$\alpha = \left[96 \pm 10(stat.) \pm 4(syst.) \pm 11(penguin)\right]^{\circ}$$

from which



γ at the B-factories

There is no straight (easy) way of measuring it at the B-factories running at the B_d



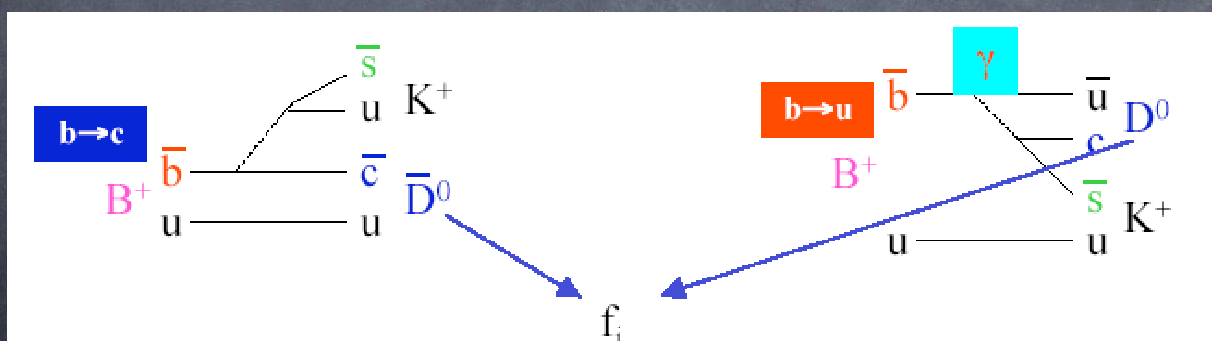
As for β (mixing phase (V_{td}) + real V_{cb} decay) the equivalent for γ is (no mixing phase (V_{ts}) + V_{ub} decay) that unfortunately requires a B_s

but......if we...

- get rid of β → go to charged B's
- find relatively large BR → scan the PDG
- discard most of theorist proposals → after a couple of failures it comes natural
- find diagrams interfering as much as they can → cross the fingers

Determining γ using $B^{\pm} \to DK^{\pm}$ with multibody D decays

Anjan Giri,[1] Yuval Grossman,[1] Abner Soffer,[2] and Jure Zupan[1,3]

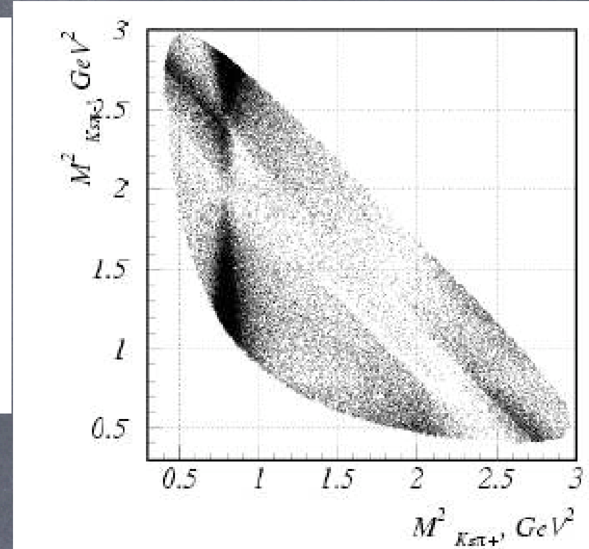


Take the many decays common to D^0 and $\bar{D}^0$; as an illustration $D^0 \to K_S\pi^+\pi^-$

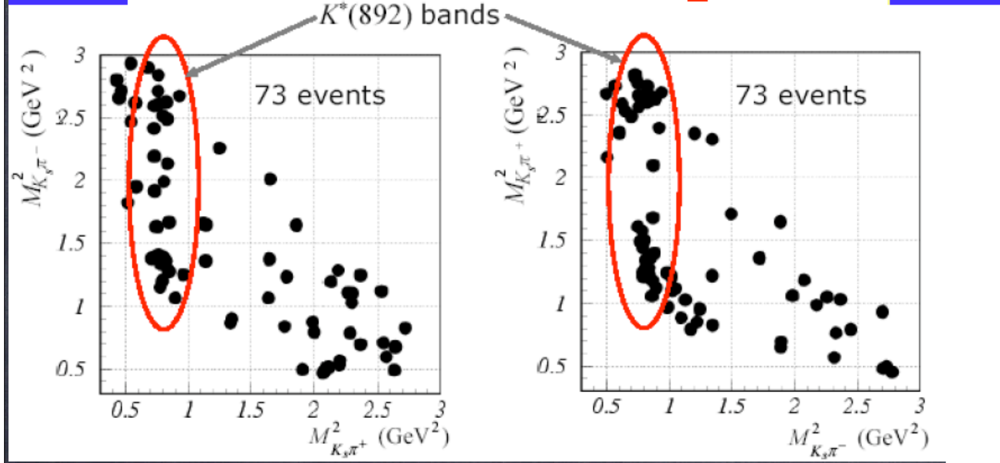
we start to dig into γ-land

$$\underbrace{}_{}\overbrace{A(B^-) = f(M_-^2, M_+^2)}^{B^- \to D} + \overbrace{r_B e^{(-i\gamma+i\delta)} f(M_+^2, M_-^2)}^{B^- \to \bar{D}}$$

$$\underbrace{A(B^+) = f(M_+^2, M_-^2)}_{B^+ \to \bar{D}} + \underbrace{r_B e^{(+i\gamma+i\delta)} f(M_-^2, M_+^2)}_{B^+ \to D}$$

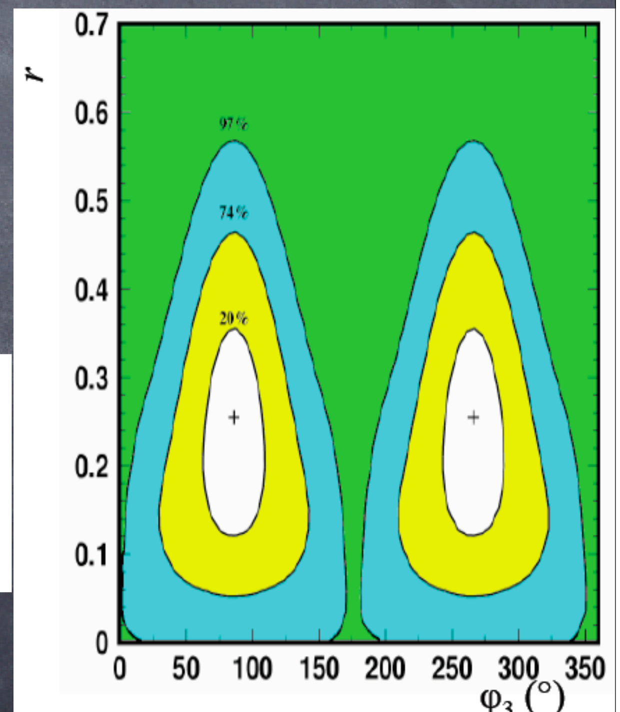


$B \to D/\bar{D}\,K \qquad D/\bar{D} \to K_S\pi^+\pi^-$



$B^+ \to D^0K^+$ and $B^+ \to D^{*0}K^+$:

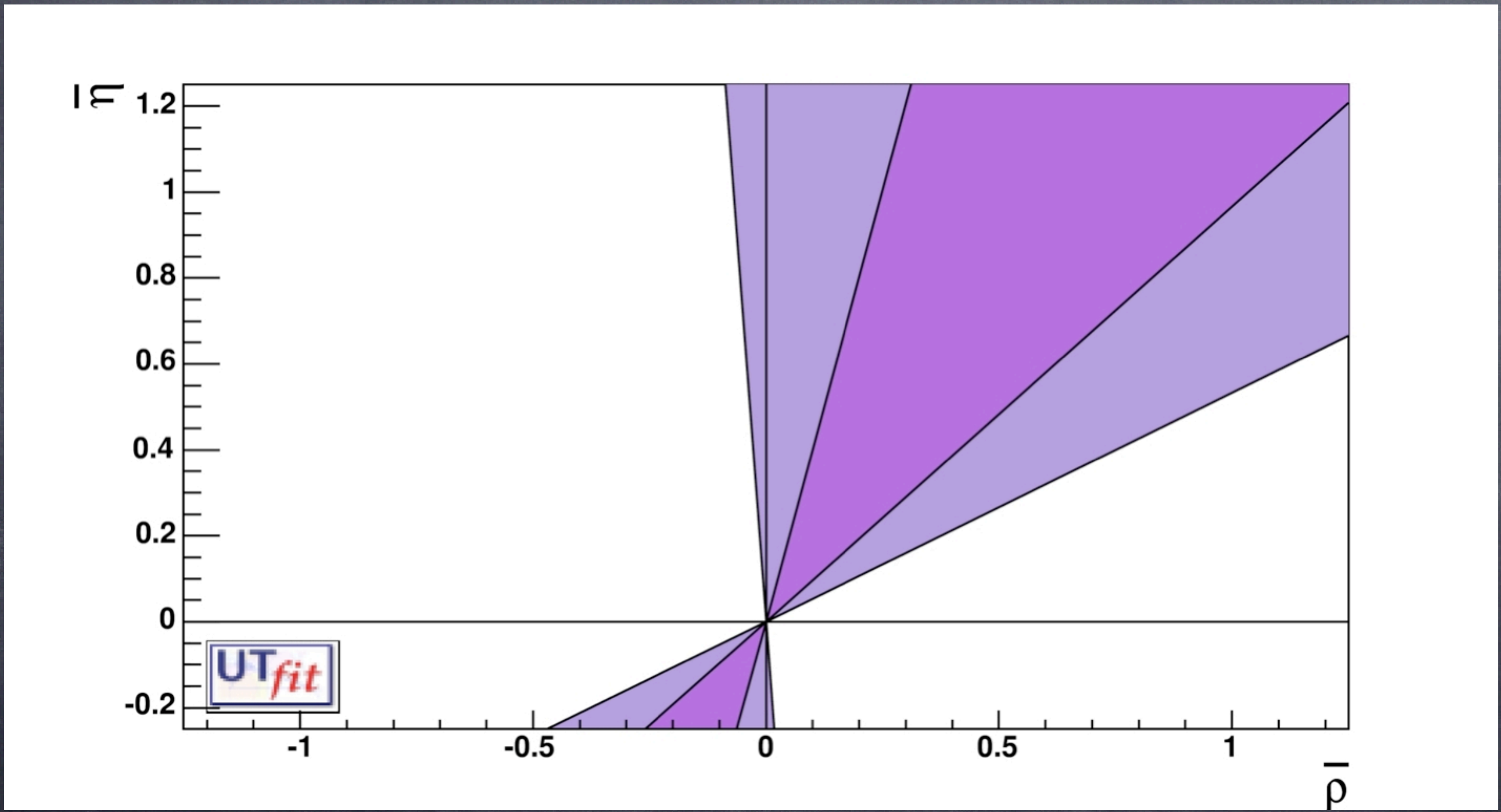
$$r_B = \left| \frac{A(b \to u)}{A(b \to c)} \right|$$



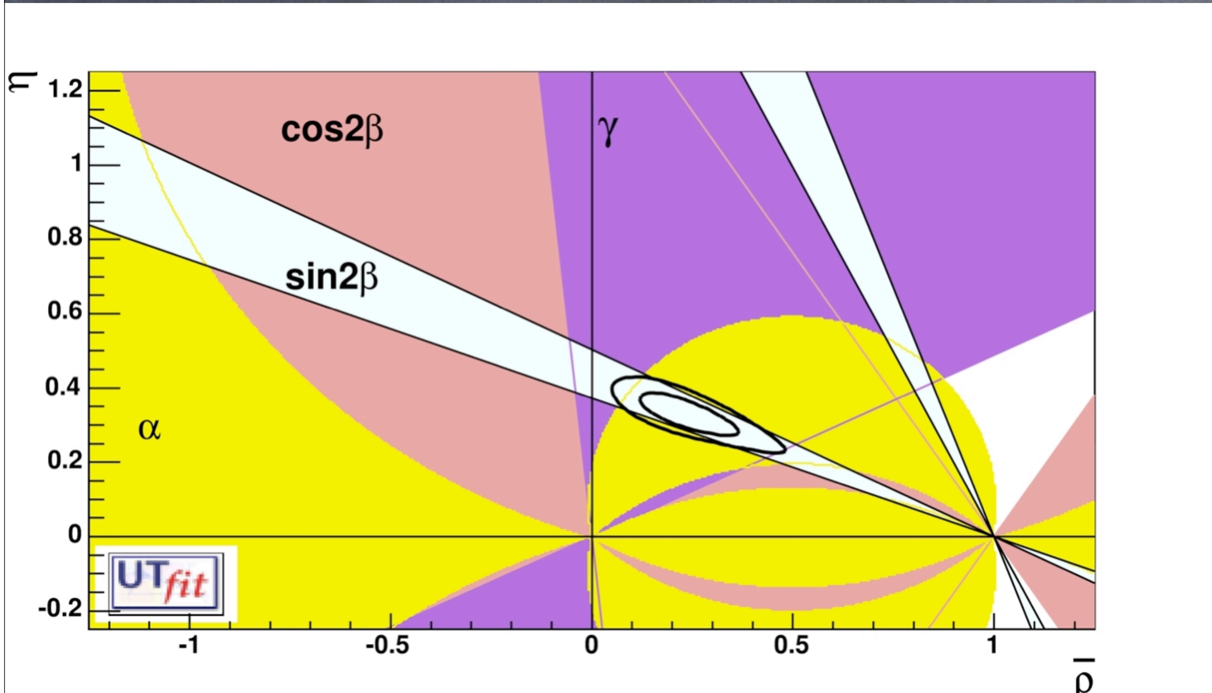
$\varphi_3 = 77^{+17°}_{-19°} \pm 13°\text{(syst)} \pm 11°\text{ (model)}$

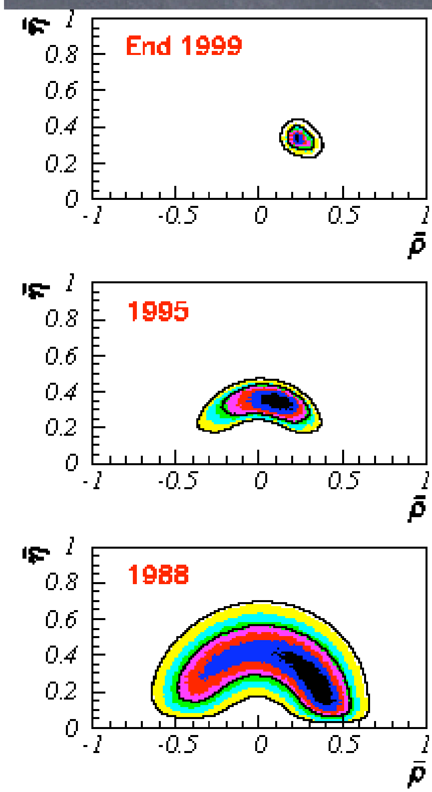
r_B = 0.26± ± 0.03(syst) ± 0.04(model)

γ adds info



CP violating decays in B-physics only

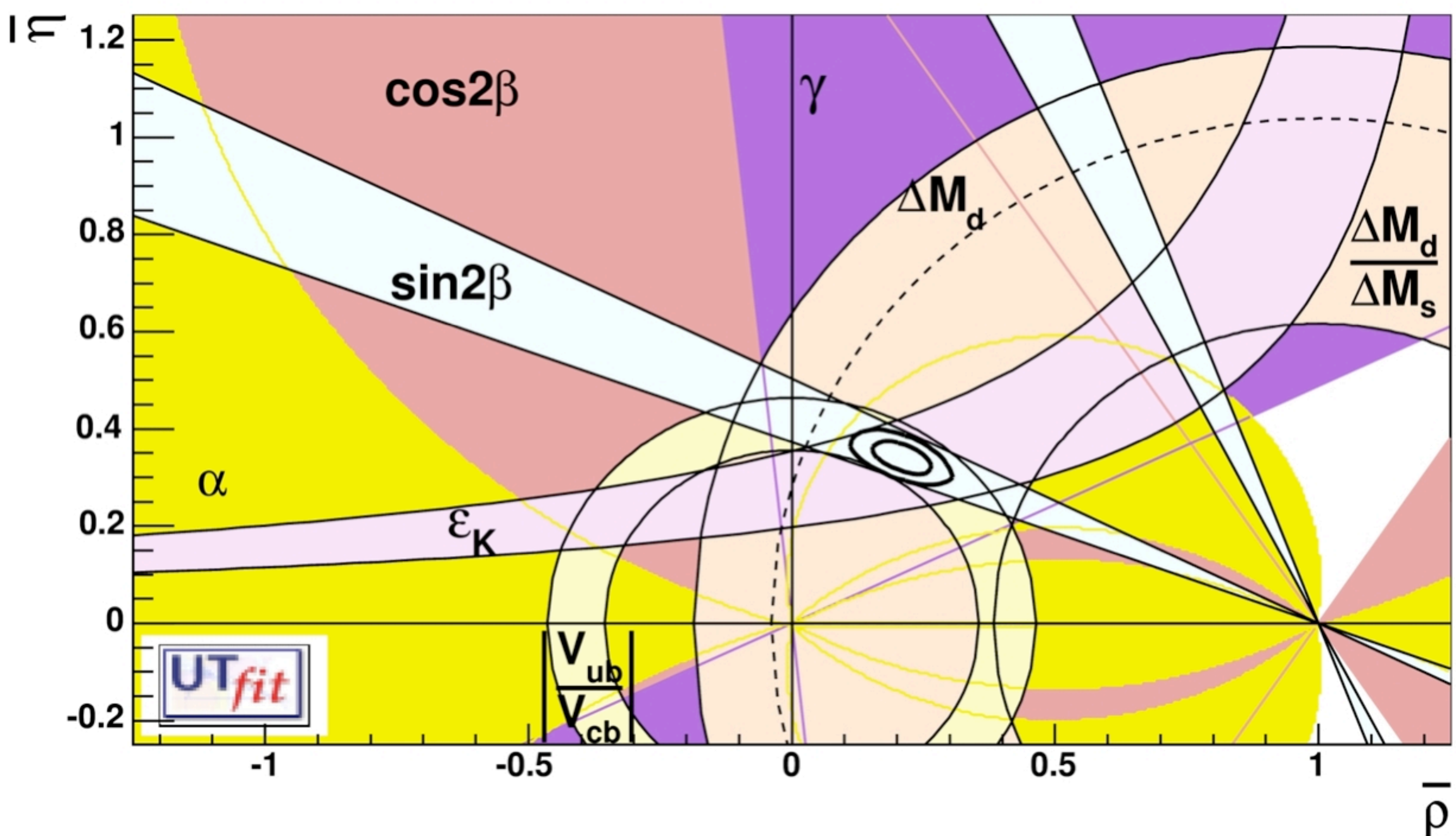




The allowed region for $\bar{\rho}$ and $\bar{\eta}$ from 1988 to the end of 1999

The constraint from the angle alone (CP violating quantities) is as strong as it was the one from the sides at the beginning of the B-factories adventure

all together now



$\rho = 0.207 \pm 0.038$

$\eta = 0.341 \pm 0.023$

Future

- statistics improve as $1/N^{\alpha}$ and $\alpha \geq 1/2$ (add more channels)
- experimental systematics will never be a problem
- theoretical understanding improves as $1/t$ (better models tuned on several decay modes)
- Now BaBar+Belle ~ 500 fb^{-1} ; at the end of the decade ≥ 2 ab^{-1}

Conclusion

- CP violation observed in B physics : mission accomplished
- β has become a precision measurement
- α,γ are laborious but will be done pretty well in the lifespan of the B-factories
- Never give up on New Physics search