New Results from *BABAR*

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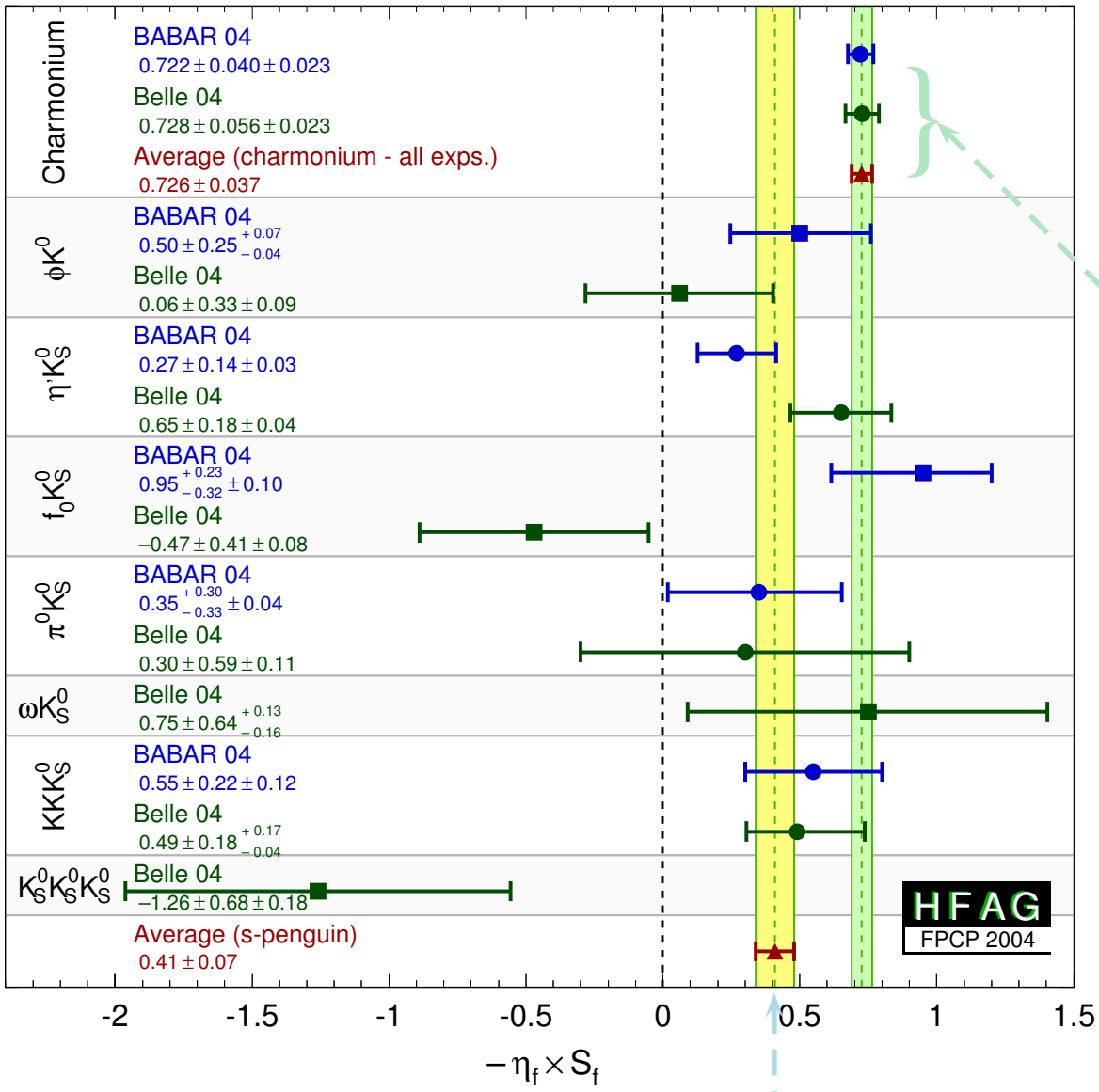
Representing the *BABAR* Collaboration

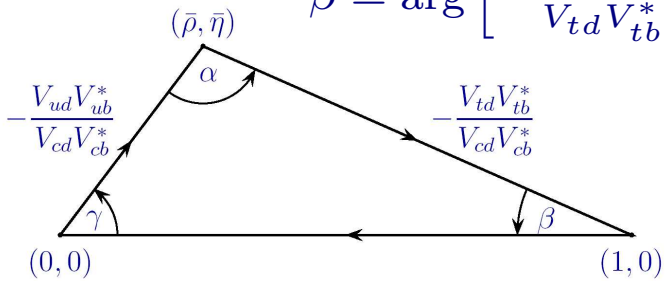
2005 ASPEN WINTER CONFERENCE ON PARTICLE PHYSICS

- Branching fraction and $A_{CP}(t)$ of $B^0 \to K^0_S K^0_S K^0_S$
- Search for lepton flavor violating decay $\tau \to \mu\gamma$
- Measurement of CKM angle α

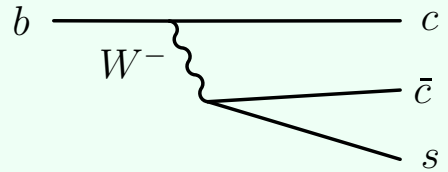
$\sin 2\beta$ from many channels



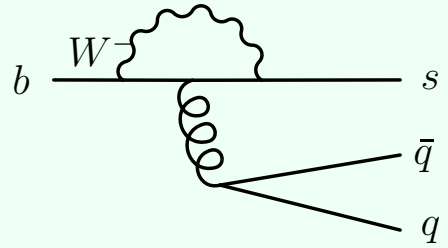
$$\beta = \arg\left[-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right]$$



charmonium: high precision



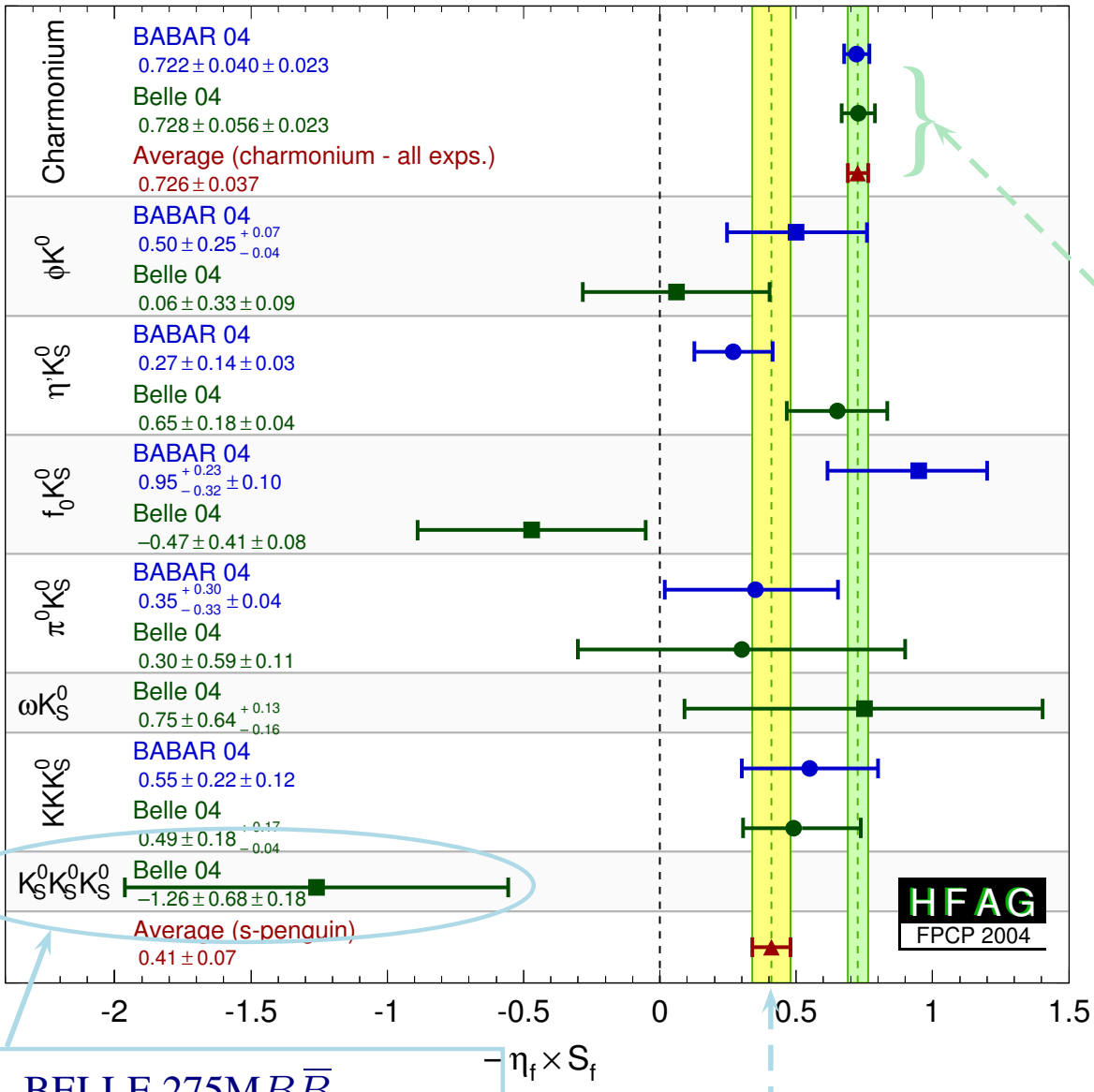
$b \to s$ penguin



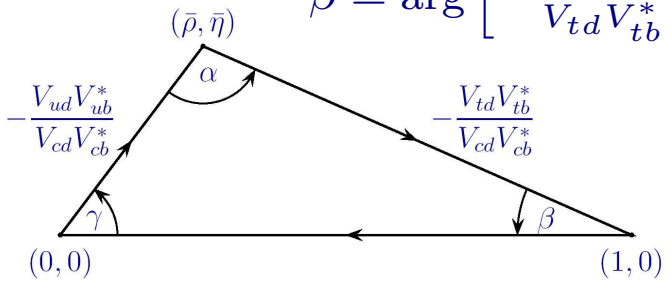
$\sim$ same weak phase as $b \to c\bar{c}s$

Naive average: $\sim 4\sigma$ difference from $b \to c\bar{c}s$

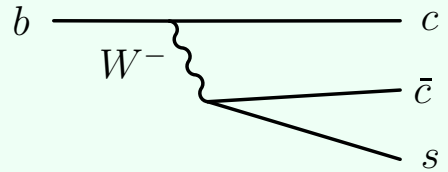
$\sin 2\beta$ from many channels



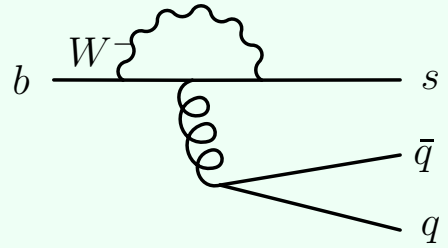
$$\beta = \arg\left[-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right]$$



charmonium: high precision



$b \to s$ penguin



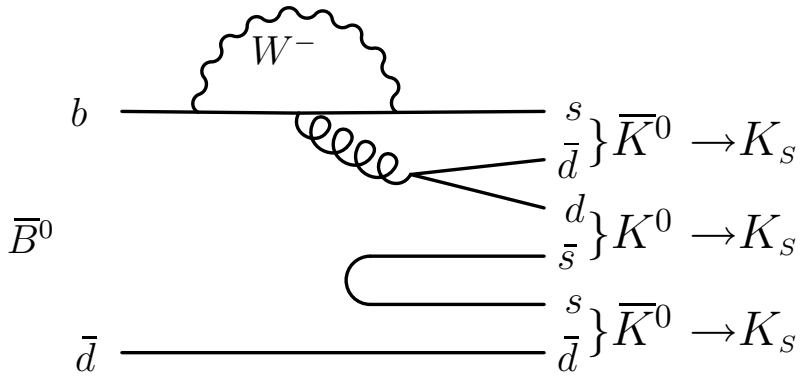
$\sim$ same weak phase as $b \to c\bar{c}s$

BELLE 275M$B\bar{B}$
hep-ex/0411056, FPCP 04

Naive average: $\sim 4\sigma$
difference from $b \to c\bar{c}s$

Overview of $B^0 \to K^0_S K^0_S K^0_S$

- Dominantly $b \to s$ gluonic penguin decay.
- Decay proper time difference between $B \to f_{CP}$ and $B \to f_{\rm tag}$ in $\Upsilon(4S) \to B^0 \overline{B}^0$ system:



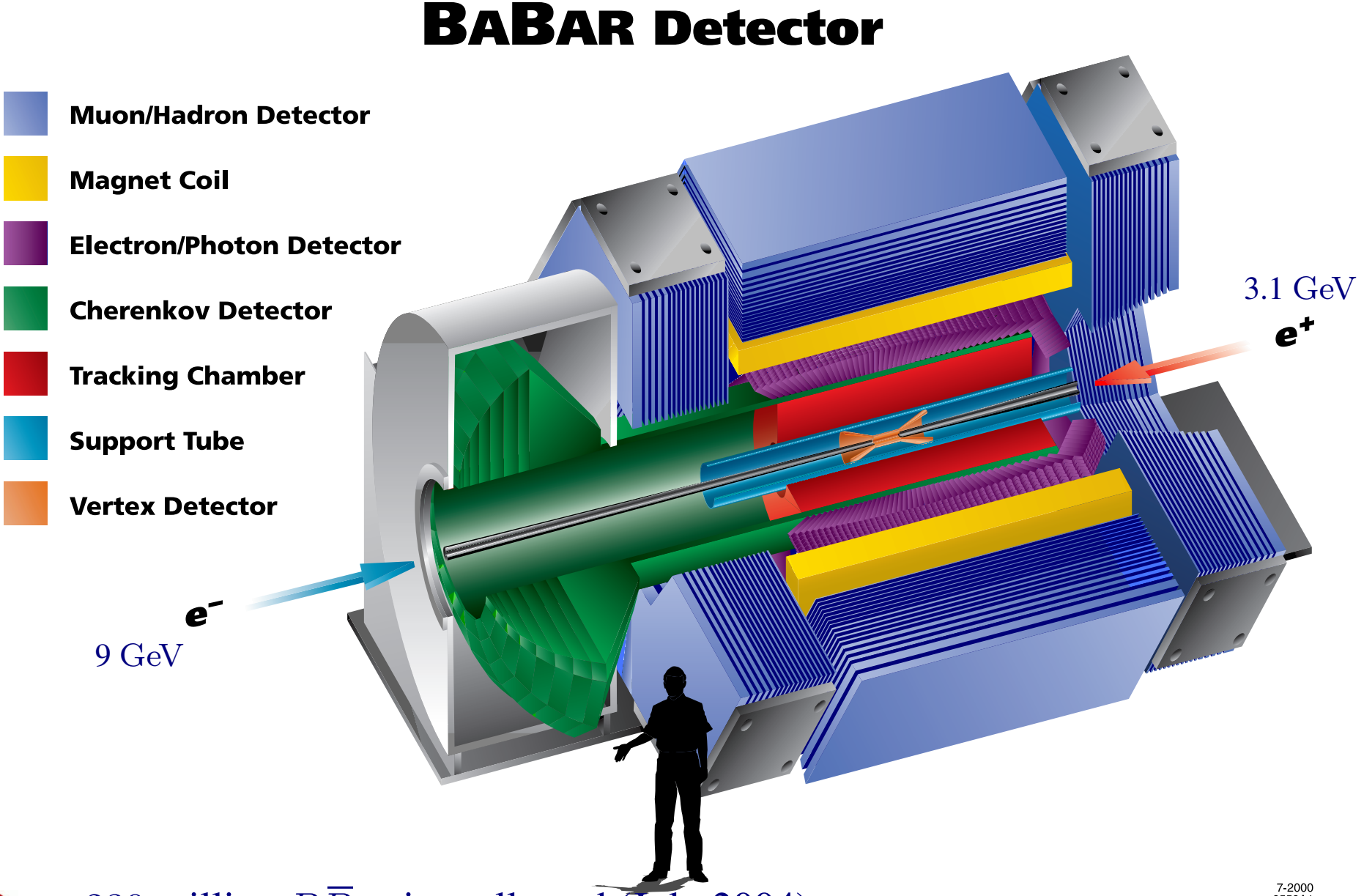
$$f_\pm(\Delta t) = \frac{e^{-|\Delta t|/\tau}}{4\tau} \times [1 \pm S \sin(\Delta m \Delta t) \mp C \cos(\Delta m \Delta t)]$$

$$S = \frac{-2{\rm Im}\lambda}{1+|\lambda^2|} \simeq -\eta \sin 2\beta, \quad C = \frac{1-|\lambda^2|}{1+|\lambda^2|} \simeq 0. \quad \text{Good approx. in SM}$$

$$\lambda = \frac{q}{p}\frac{\overline{A}}{A},$$

- $B^0 \to K^0_S K^0_S K^0_S$ is pure CP even ($\eta = +1$).
- Needs good vertexing technique because no tracks from B^0 vertex.
- Deviation from $\sin 2\beta(J/\psi K^0_S)$ would indicate new physics.

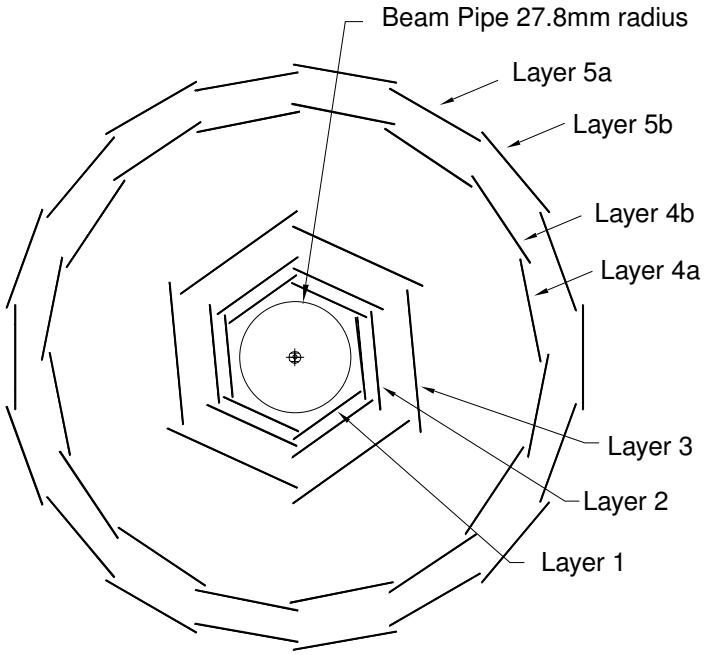
BABAR detector and dataset

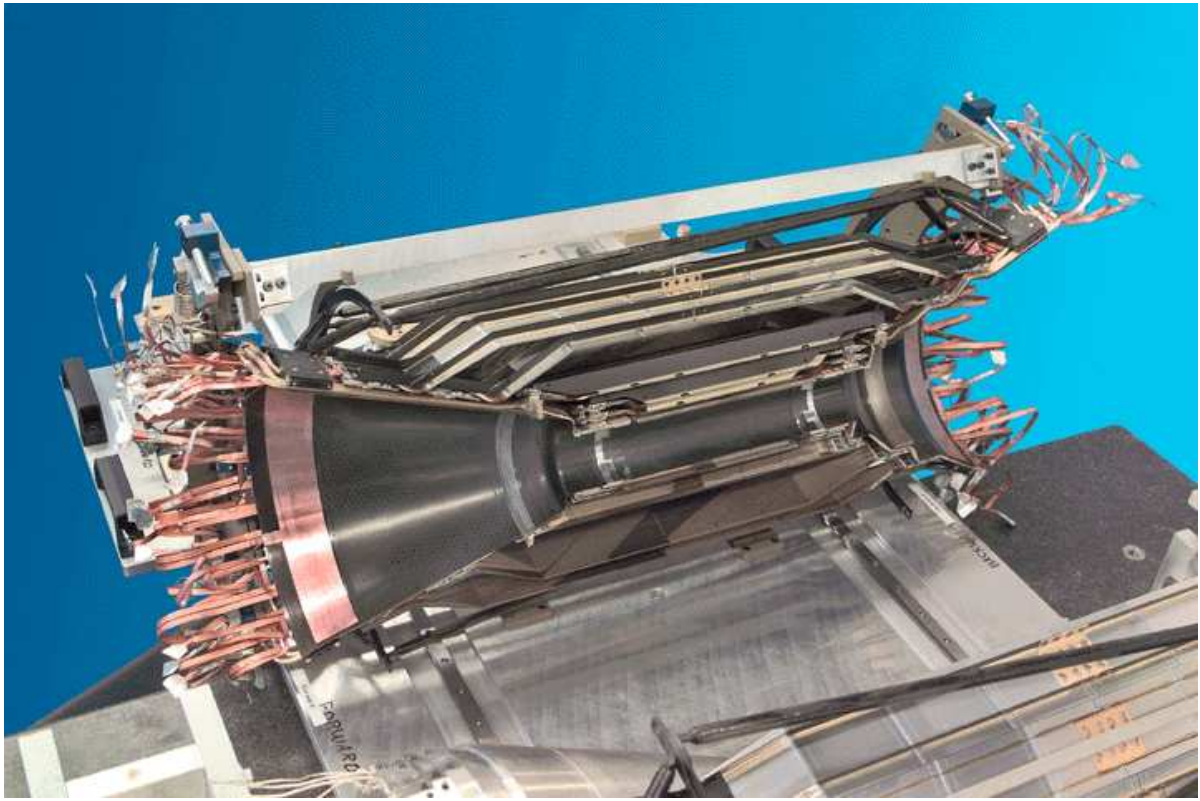


- $\sim$ 230 million $B\overline{B}$ pairs collected (July 2004).

Need excellent vertexing for long-lived K_S^0

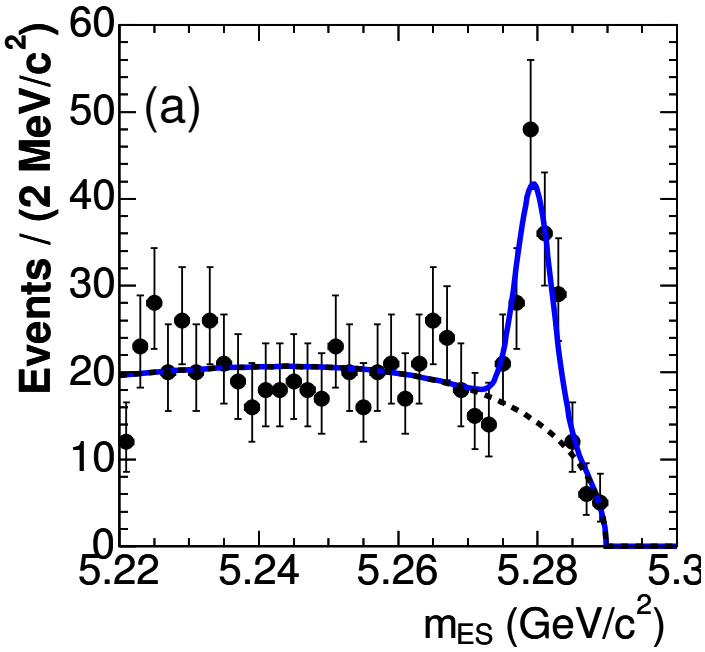
- Silicon Vertex Tracker: Five-layer double-sided Si strips.
- Provides $80\mu m$ or better resolution for fully reconstructed B vertex.
- Radii of inner layers are 32, 40 and 54mm;
  outer layers are more than 90mm.
- $c\tau(K_S^0) \simeq 27\mathrm{mm}$; K_S^0 can decay well outside of inner layers.

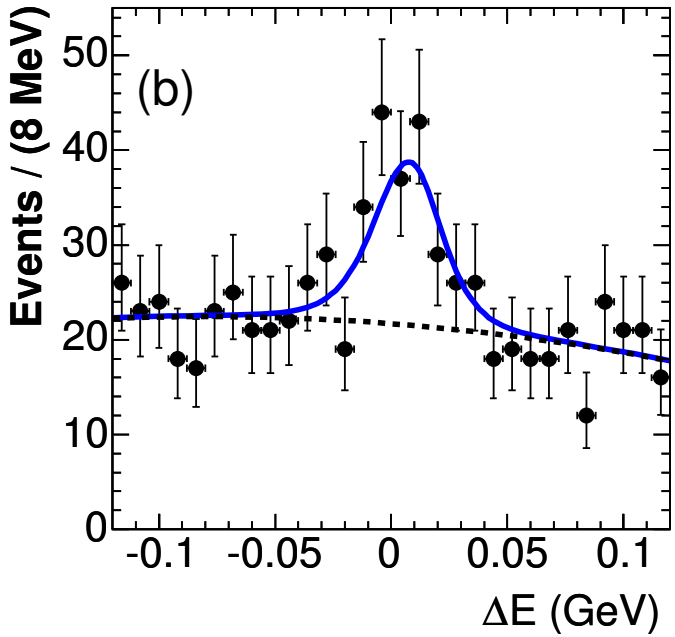




$B^0 \to K^0_S K^0_S K^0_S$ branching fraction

- Discriminating variables:
  $m_{\rm ES} = \sqrt{(s/2 + \vec{p}_i \cdot \vec{p}_B)^2/E_i^2 + p_B^2}$, $\Delta E = E_B^* - \sqrt{s}/2$, and
  Fisher discriminant (using event shape variables to separate signal and $q\bar{q}$).





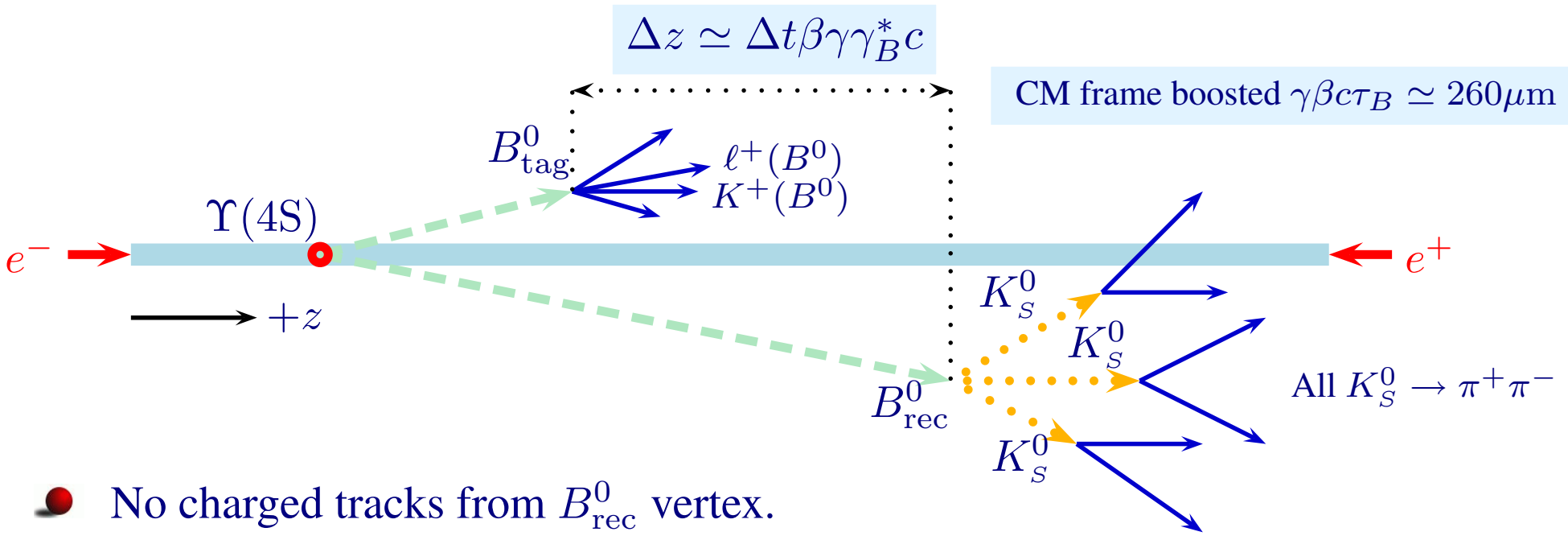
721 events in the fit; fit result:
$N_S = 88 \pm 10$
$N_B = 633 \pm 26$

- $(\varepsilon_{\rm sig} = 5.6\%, \quad N_{B\bar{B}} = 227 \times 10^6)$

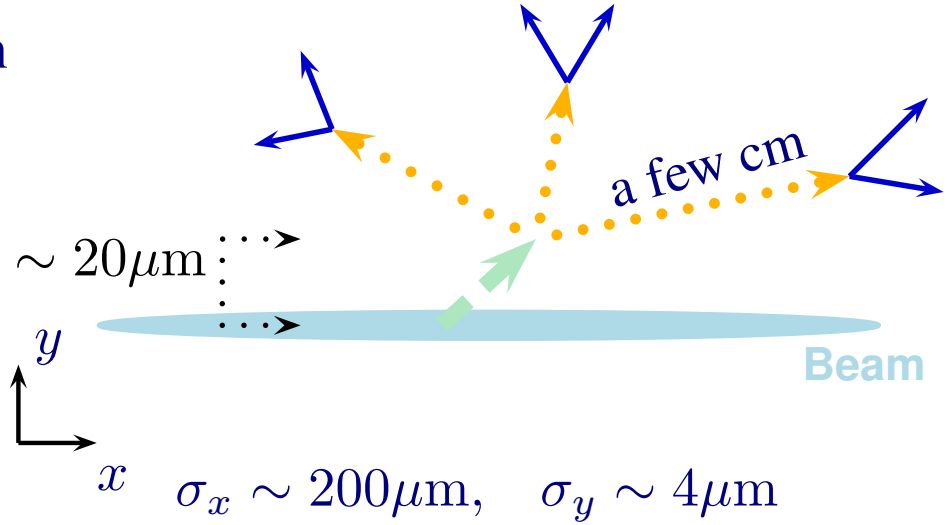
$$\mathcal{B}(B^0 \to K^0_S K^0_S K^0_S) = (6.9^{+0.9}_{-0.8} \pm 0.6) \times 10^{-6}$$

- Main systematic errors:
  - $K^0_S \to \pi^+\pi^-$ reco eff;
  - B candidate selection eff;
  - PDF parametrization.

$B^0 \to K^0_S K^0_S K^0_S$ vertex reconstruction

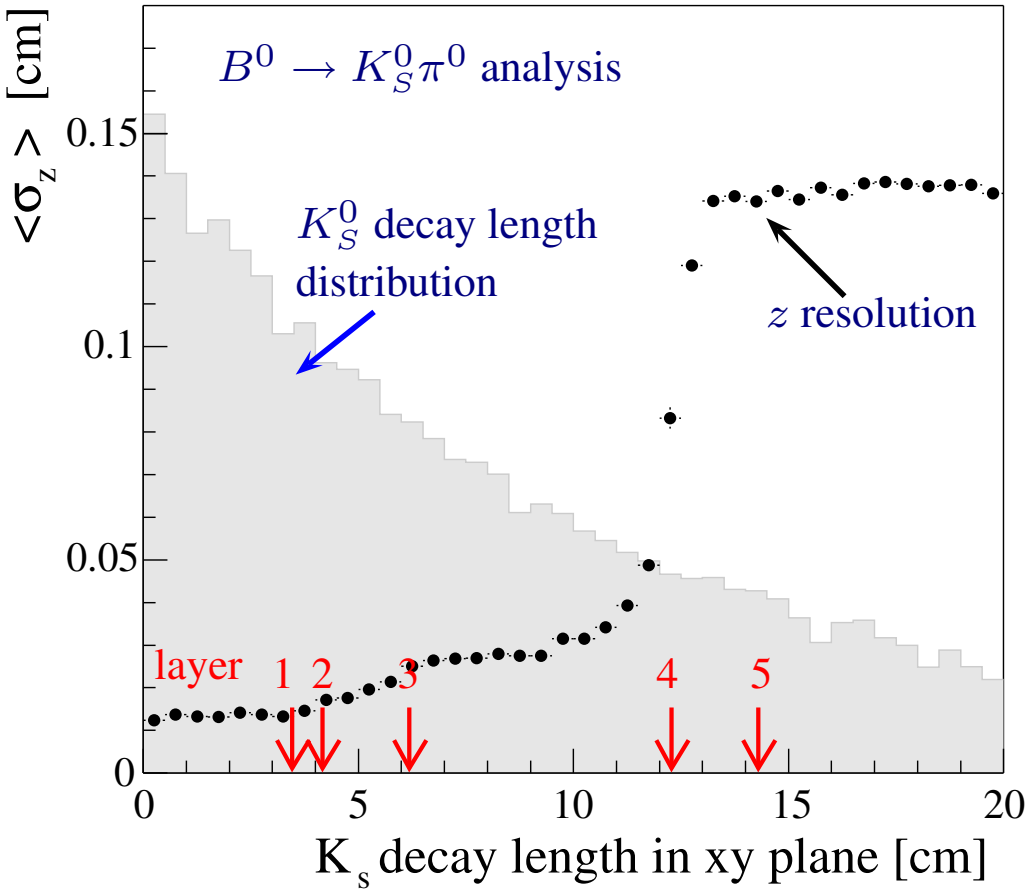


- No charged tracks from $B^0_{\rm rec}$ vertex.
- Take advantage of small beam size:
  B^0 production vertex is constrained in the beam spot on x-y plane to improve resolution.
  - method pioneered by *BABAR* in $B^0 \to K^0_S \pi^0$ analysis.



Vertex resolution

- Resolution with *single* K^0_S and beam spot constraint is very good when K^0_S decays before SVT layer 3.



- In $B^0 \to K^0_S K^0_S K^0_S$, more than 99% of events have at least one K^0_S whose both π have at least 1 ϕ and 1 z hit in any of the first 3 layers.
- Δt resolution is similar to other fully reconstructed B decays such as $B \to D^* \pi/\rho$.
  - dominated by the resolution of tag-side vertexing.

Time-dependent CP asymmetry fit

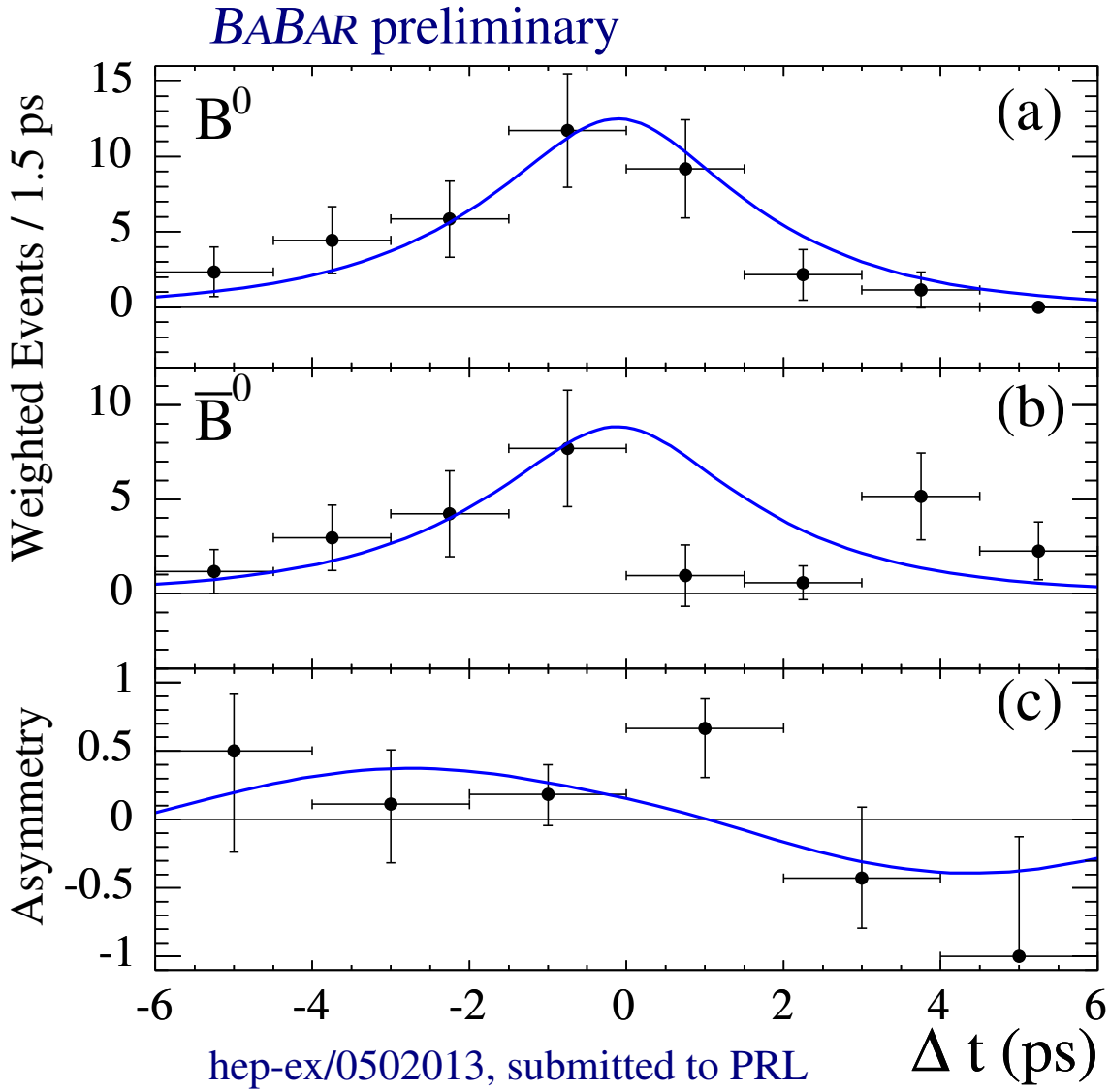
- Result:

$$S = -0.71^{+0.38}_{-0.32} \pm 0.04$$

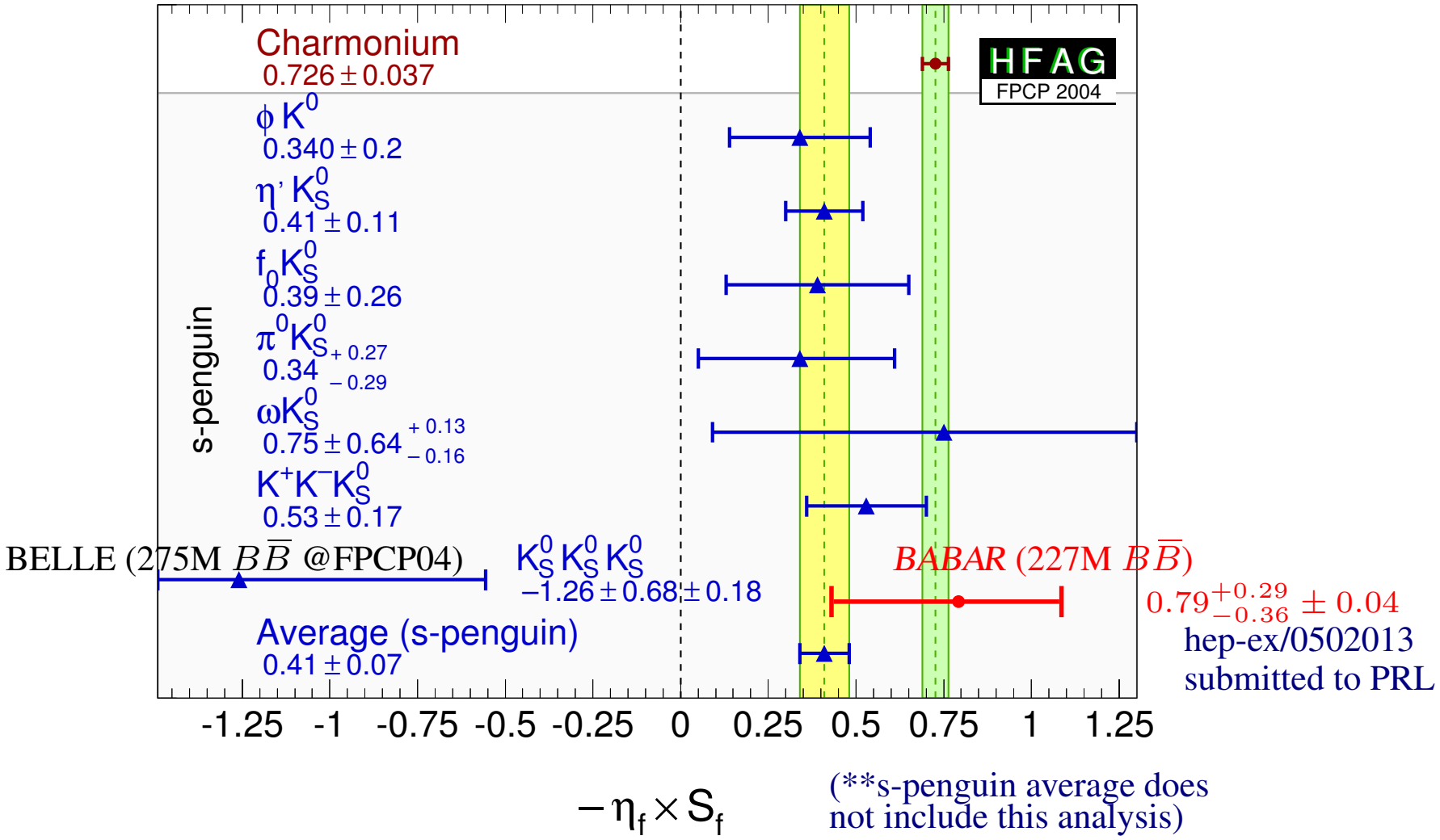
$$C = -0.34^{+0.28}_{-0.25} \pm 0.05$$

Fixing $C = 0$,

$$\sin 2\beta_{\rm eff} = -S$$
$$= 0.79^{+0.29}_{-0.36} \pm 0.04$$



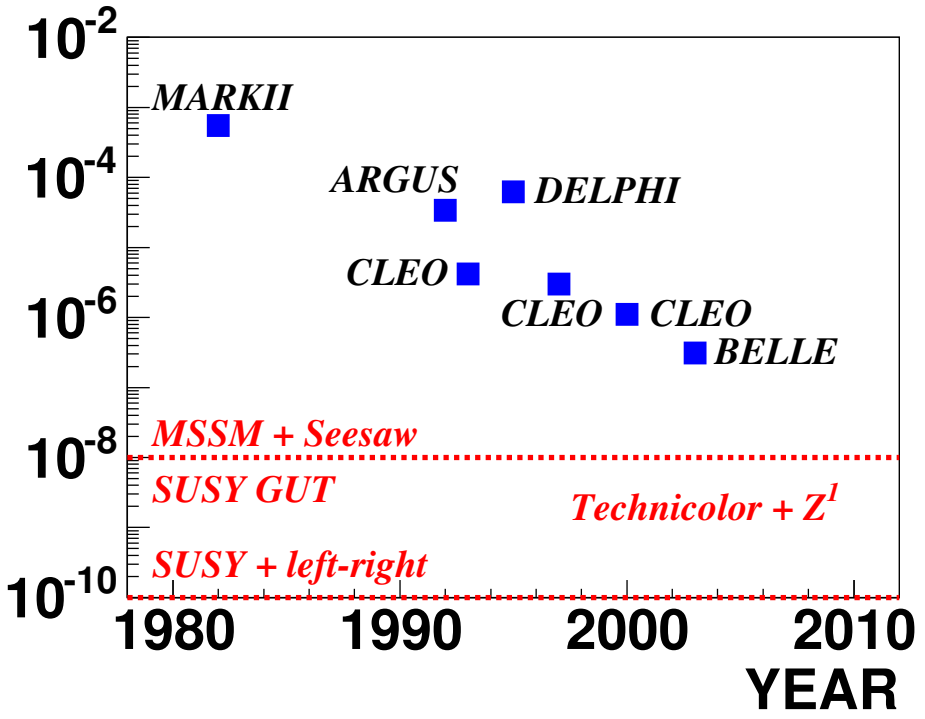
Fit into the picture



- Result consistent with Standard Model
- Precision comparable to other $b \to s$ penguin modes.

Search for lepton flavor violation $\tau \to \mu\gamma$

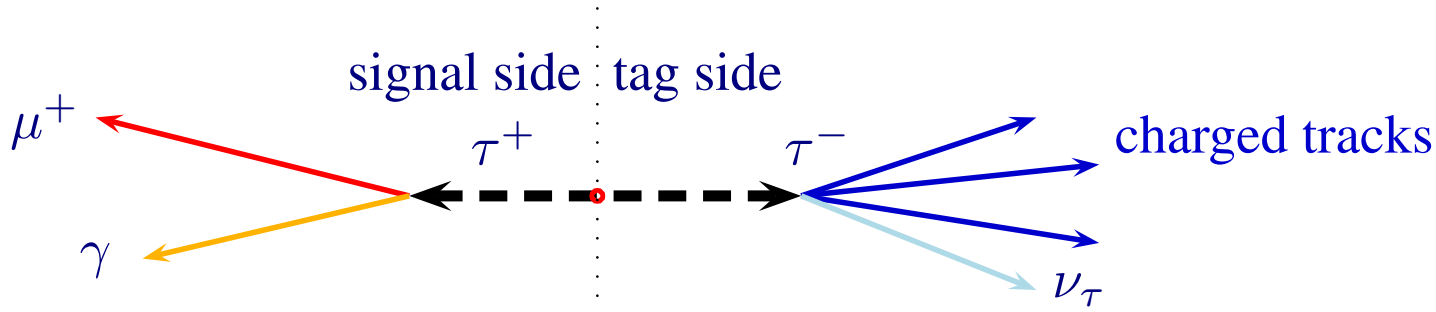
- Modest extension to Standard Model to incorporate finite m_ν
  $\Rightarrow \mathcal{B}(\tau \to \mu\gamma) \sim \mathcal{O}(10^{-54})$
  $\Rightarrow$ clear indication of new physics if observed.
- Various extensions to SM predict $\sim \mathcal{O}(10^{-8} - 10^{-10})$



best current limit

- BELLE(86.3 fb^{-1}, 2004): $\mathcal{B}(\tau \to \mu\gamma) < 3.1 \times 10^{-7}$

Select from τ 1-1 & 1-3 topology

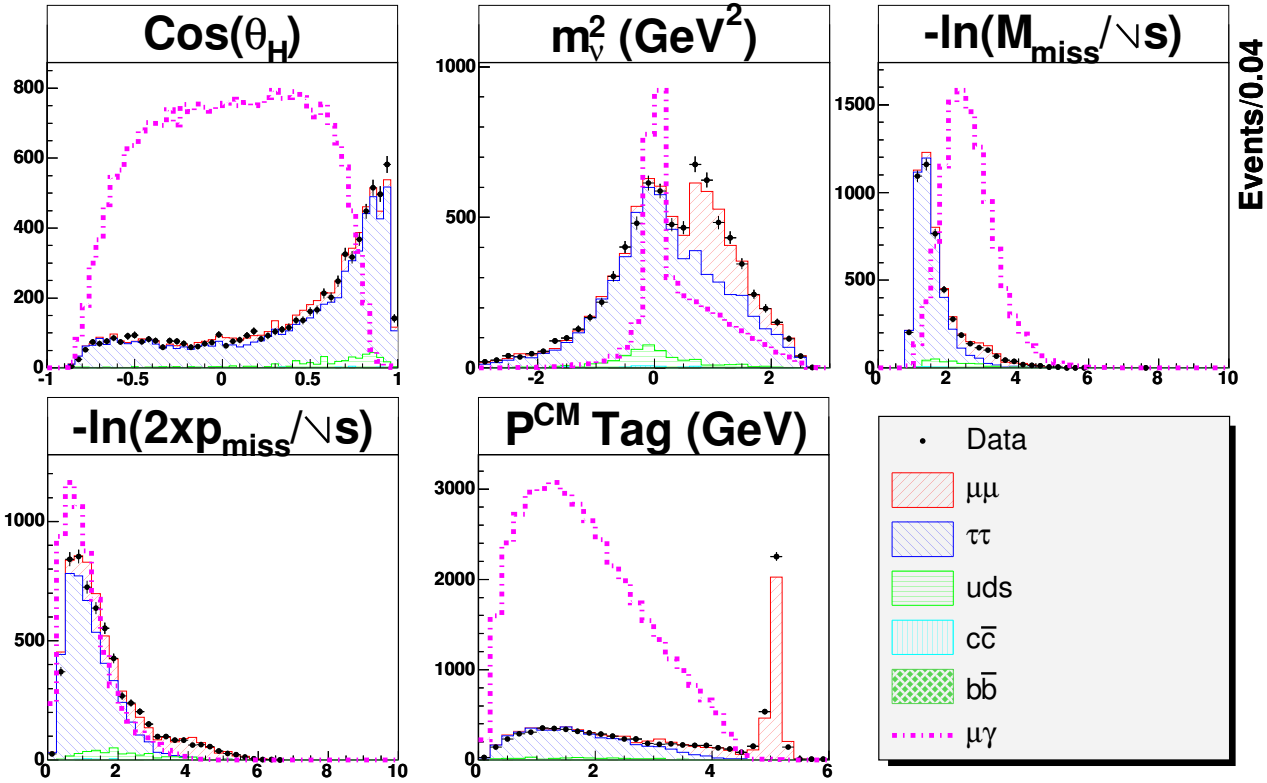


1 lepton (plus 2 neutrinos), or
1 or 3 hadron tracks (plus 1 neutrino),
plus n γ's.

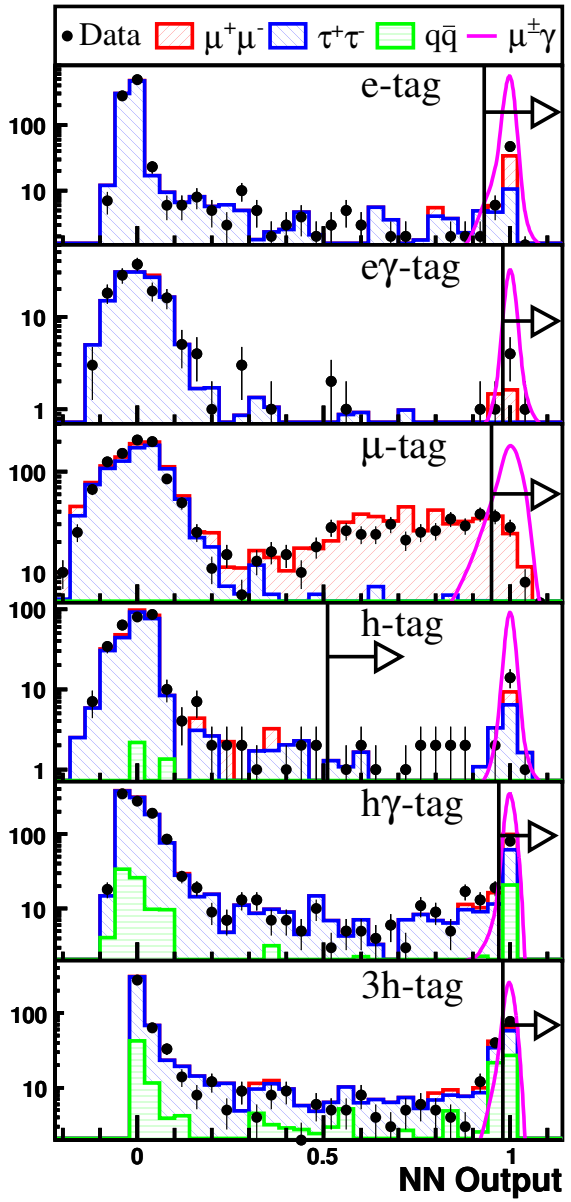
- Events selection highlights
  - Signal side: an identified μ and an energetic photon.
  - Removing high-thrust $\mu^+\mu^-\gamma$ candidates and low-thrust $q\bar{q}$ candidates.
  - Non-zero missing transverse momentum.
  - Neutrino mass ~ 0 when only one ν is expected.

$\tau \to \mu\gamma$ neural net

Discriminating variables for NN inputs

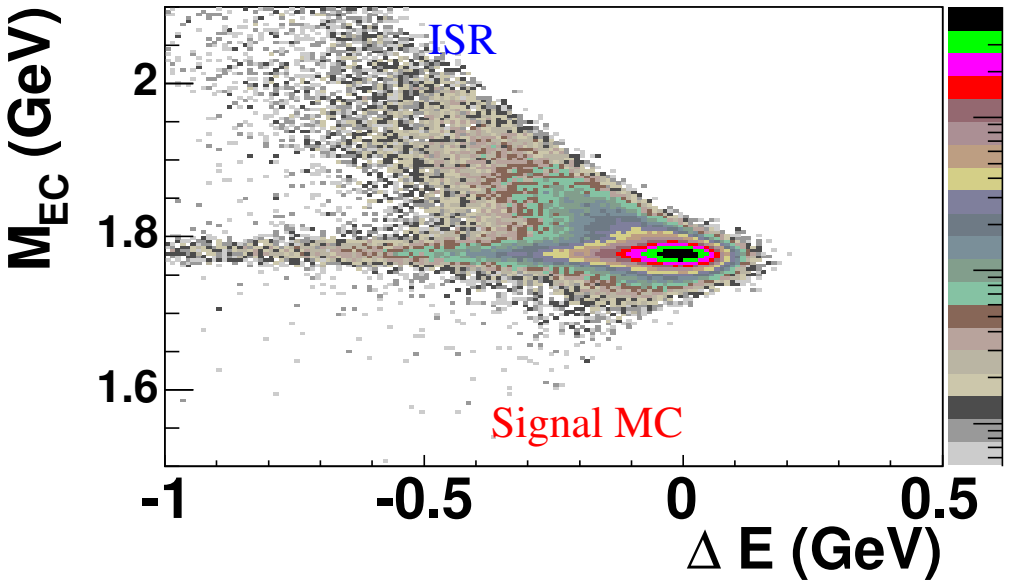


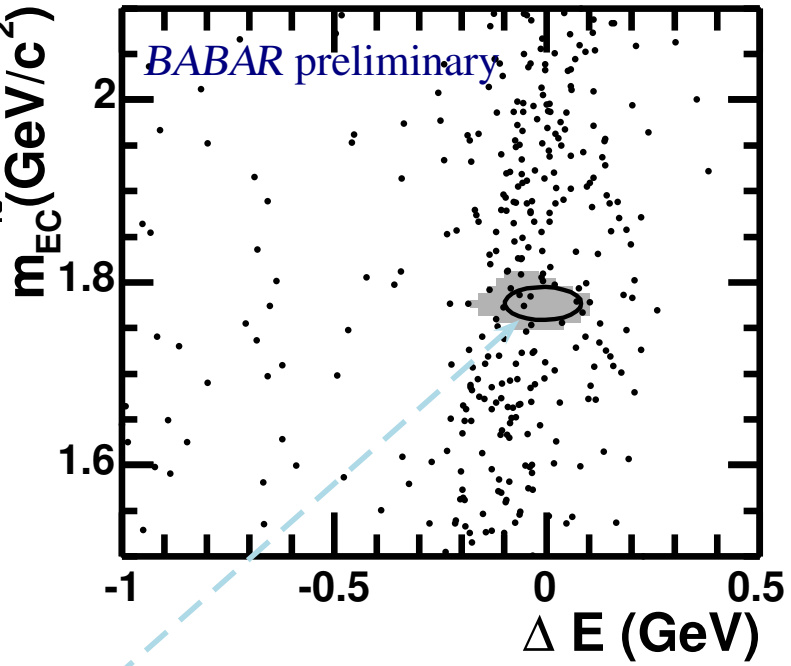
NN outputs



Observables, $m_{\rm EC}$ and ΔE

- $m_{\rm EC}$: $\mu\gamma$ mass with $E_{\mu\gamma}$ constraint at $\sqrt{s}/2$.
  - γ origin is assigned at POCA of μ to beam axis to improve resolution.
- $\Delta E = E^*_{\mu\gamma} - \sqrt{s}/2$.



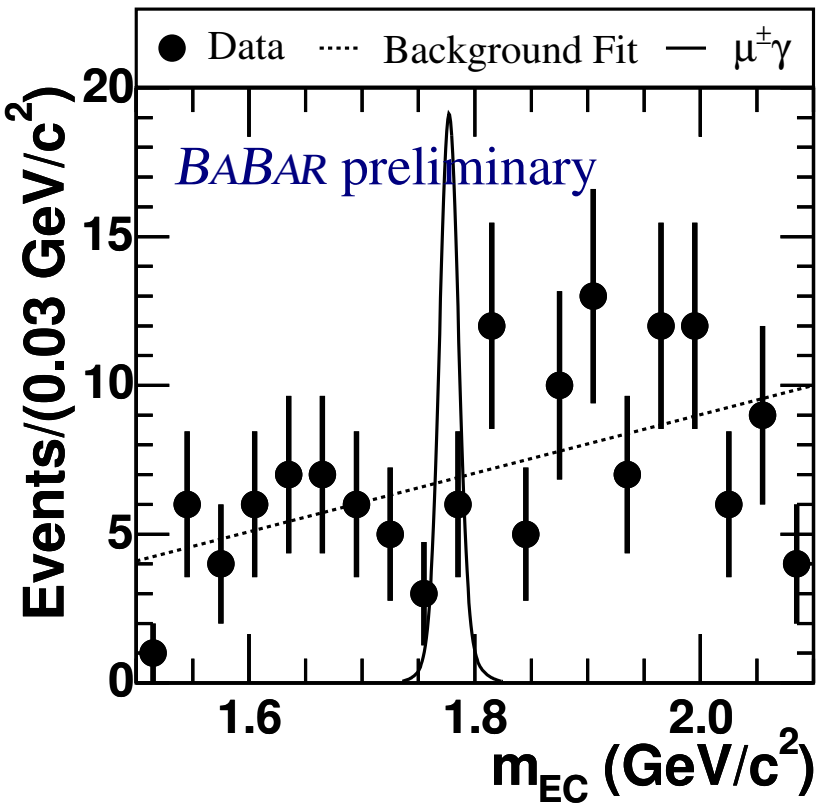


$\langle m_{\rm EC}\rangle = 1777$ MeV, $\sigma(m_{\rm EC}) = 9$ MeV
$\langle \Delta E\rangle = -9$ MeV, $\sigma(\Delta E) = 45$ MeV

Expected: 6.2 ± 0.5,
Observed: 4 events
in 2σ ellipse. (signal $\varepsilon = 7.4\%$)

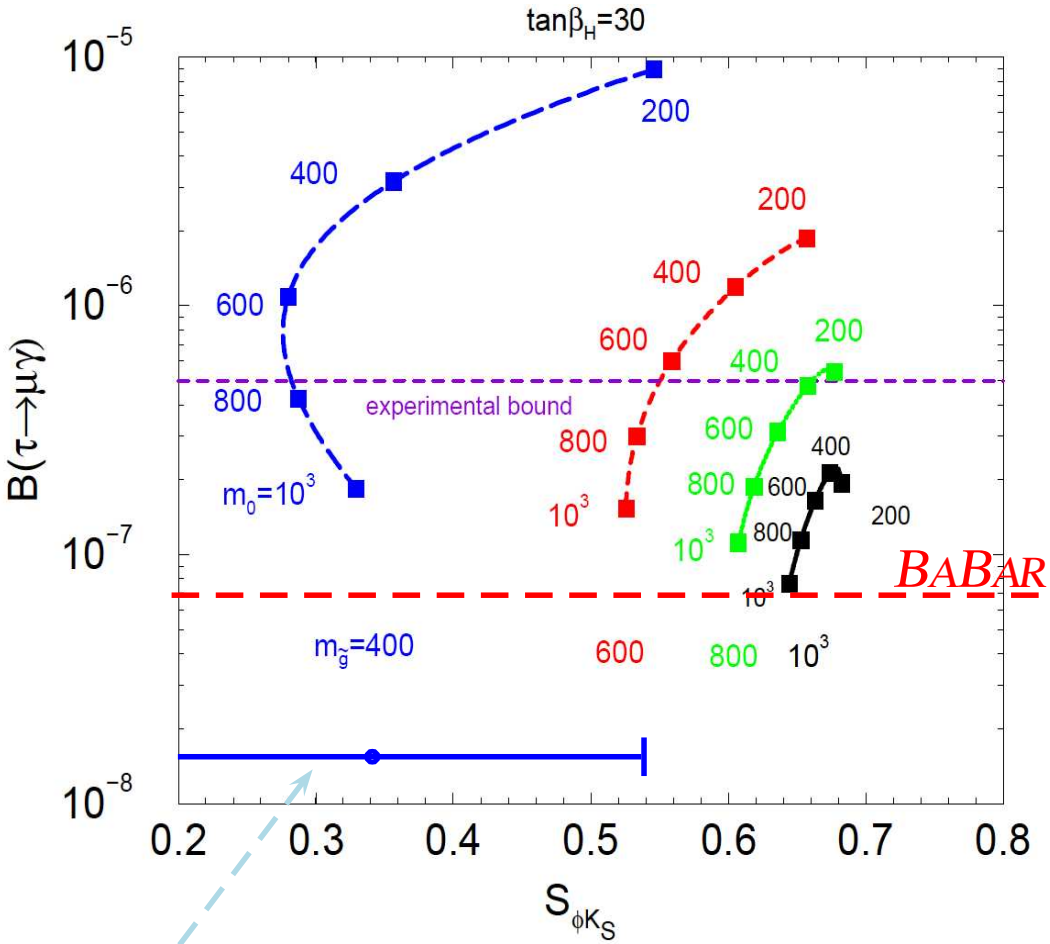
Upper limit

- Unbinned likelihood fit to $m_{\rm EC}$ in $\pm 2\sigma$ of ΔE yields $-2.2^{+3.2}_{-2.4}$ signal events.
- Frequentist limit using toy MC:
  - scaning the expected number signal (s) in the PDF, while fixing the mean of # bkg at the expected # of bkg. For each value of s, generating large number of toy experiments, (allowing Poisson fluctuation).
  - find expected s when 90% of samples yield fitted s larger than the fit to data.
- $\mathcal{B}(\tau \to \mu\gamma) < 6.8 \times 10^{-8}$ at 90% C.L.

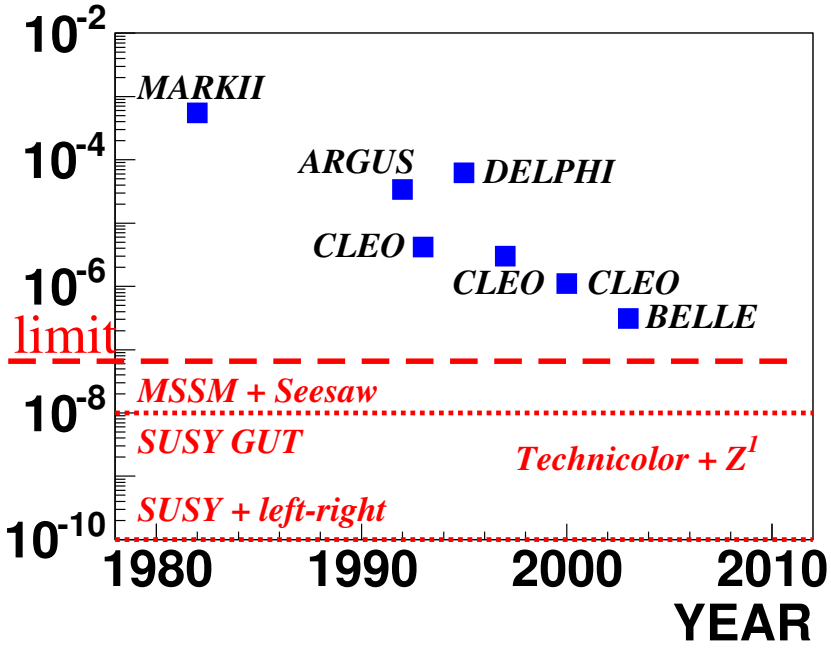


Compare with new physics models

- J. Hisano (Tau04): SUSY GUT (flavor-changing right-handed current) predictions are larger than *BABAR* limit.

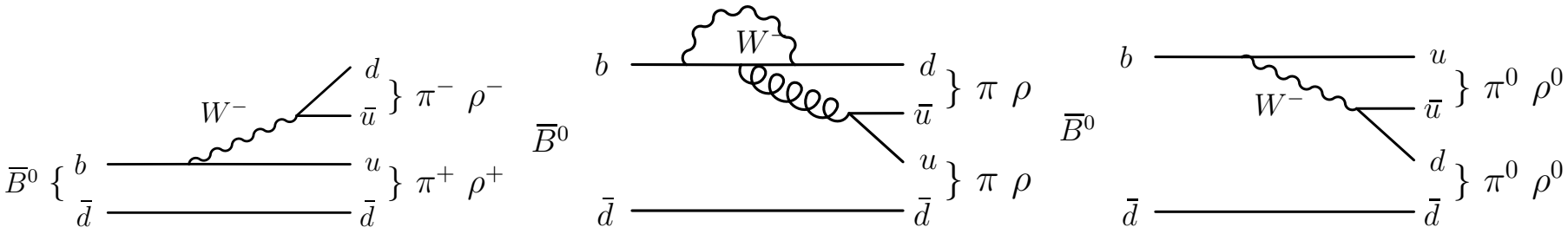


current $B^0 \to \phi K_S^0$ asymmetry from B-factories



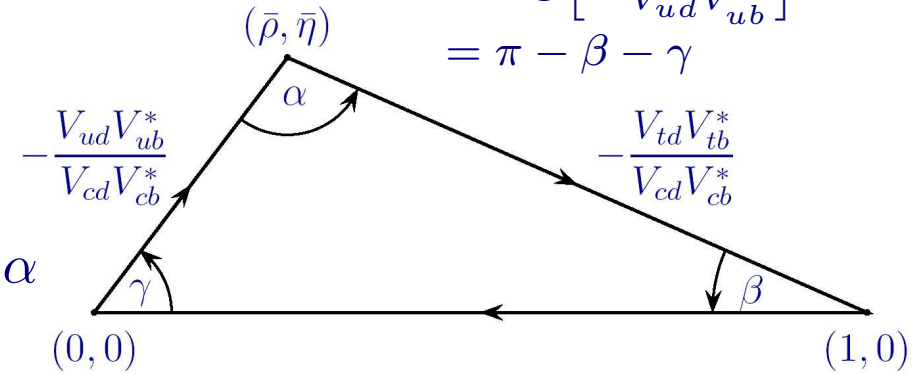
CKM angle α with $\pi\pi$, $\rho\rho$, $\rho\pi$

- $B^0 \to \pi^+\pi^-$, $\rho^+\rho^-$: tree diagram with penguin pollution:
  $B^0 \to \pi^0\pi^0$, $\rho^0\rho^0$: color-suppressed tree plus penguin



- If only tree: $\quad [f_\pm(\Delta t) \propto 1 \pm S\sin(\Delta m\Delta t) \mp C\cos(\Delta m\Delta t)]$
  $\lambda = e^{2i\alpha}$.
  $S = \sin 2\alpha, \;\; C = 0$
- But penguin can be significant:
  $\lambda = e^{2i\alpha}\,\frac{1+|P/T|e^{i\delta}e^{i\gamma}}{1+|P/T|e^{i\delta}e^{-i\gamma}}$
  $S = \sqrt{1-C^2}\sin 2\alpha_{\rm eff}, \;\; \alpha_{\rm eff} = \alpha + \Delta\alpha$
  $C \propto \sin\delta$.

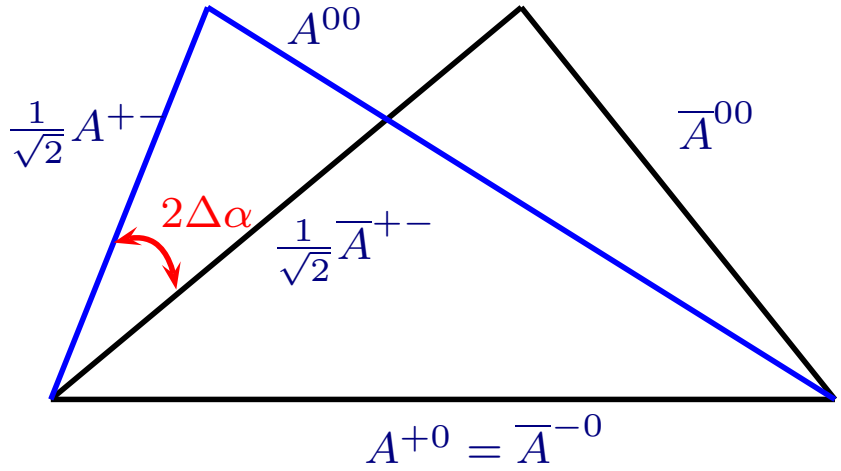
$$\alpha = \arg\left[-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right] = \pi - \beta - \gamma$$



Isospin analysis

- Use isospin relations to disentangle penguin contribution:
  - $A^{+0} = \frac{1}{\sqrt{2}} A^{+-} + A^{00}, \quad A^{-0} = \frac{1}{\sqrt{2}} \overline{A}^{+-} + \overline{A}^{00}.$

- Use as many modes as possible to resolve ambiguities because penguin contributions and strong phases can be different.

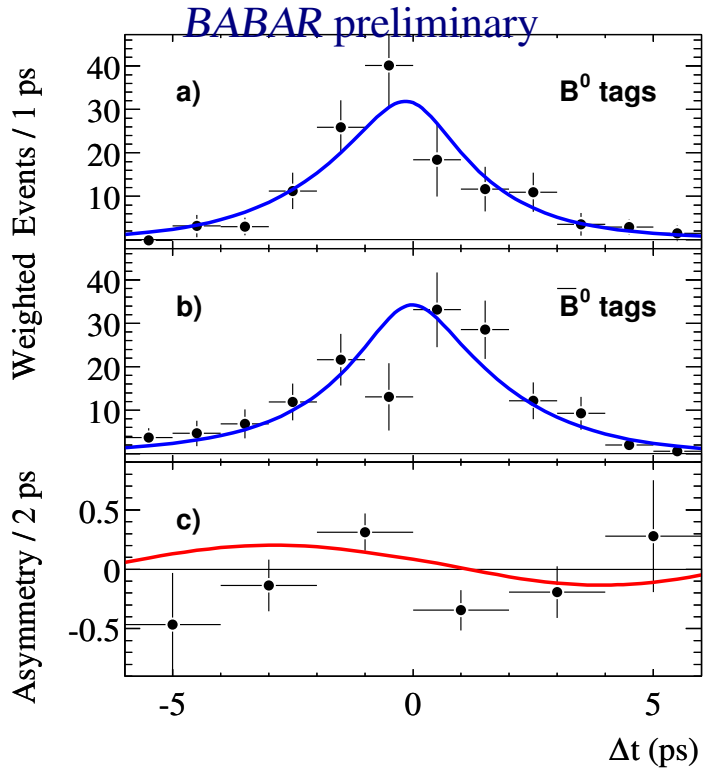


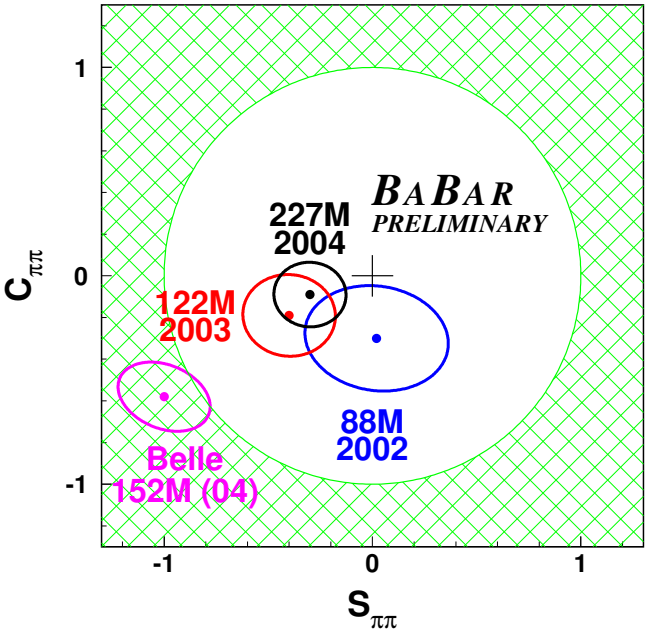
$B^0 \to \pi^+\pi^-$

- Using 227×10^6 $B\overline{B}$ events, we obtain $n_{\pi\pi} = 467 \pm 33$

$$S_{\pi\pi} = -0.30 \pm 0.17 \pm 0.03$$
$$C_{\pi\pi} = -0.09 \pm 0.15 \pm 0.04$$

(hep-ex/0501071, submitted to PRL)





- BELLE saw CPV (5.2σ), and evidence for direct CPV (3.2σ), but...
  - $> 3\sigma$ difference between *BABAR* and BELLE results.

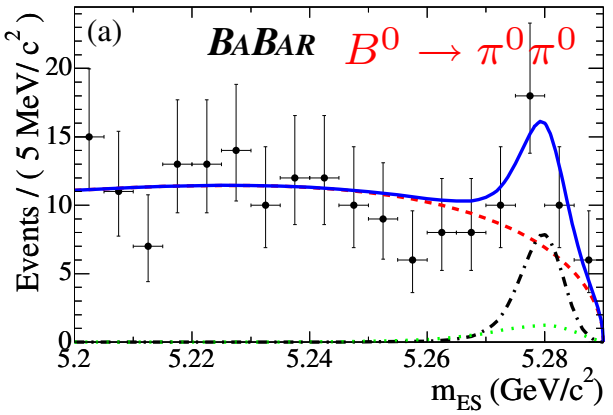
$B^{0,-} \to \pi^{0,-}\pi^0$ and bound on α

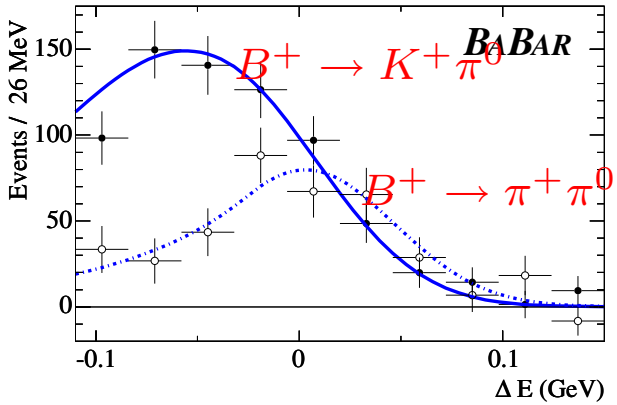
- $B^0 \to \pi^0\pi^0$ events $= 61 \pm 17, \quad (5.2\sigma)$

  $\mathcal{B}(B^0 \to \pi^0\pi^0) = (1.17 \pm 0.32 \pm 0.10) \times 10^{-6}$
  CP asymmetry $= -0.12 \pm 0.56 \pm 0.06$.

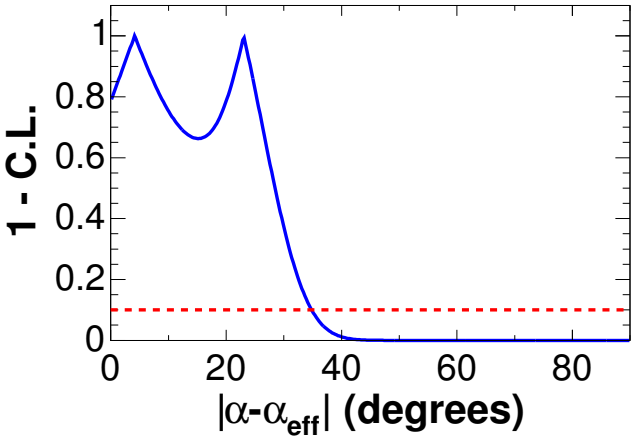
- $B^\pm \to \pi^\pm\pi^0$ events $= 379 \pm 41$
  $\mathcal{B}(B^+ \to \pi^+\pi^0) = (5.8 \pm 0.6 \pm 0.4) \times 10^{-6}$
  CP asymmetry $= -0.01 \pm 0.10 \pm 0.02$.

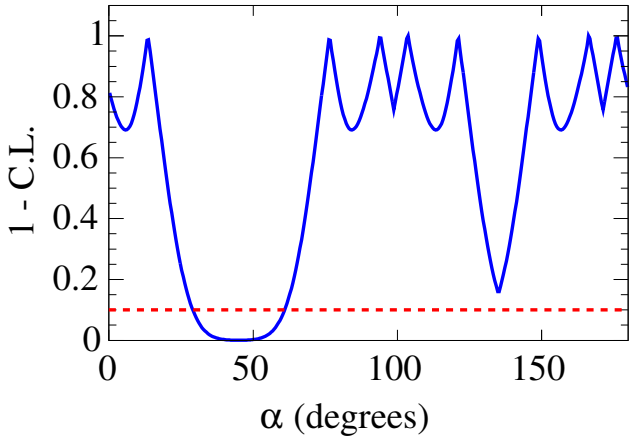
- Upper bound $|\alpha - \alpha_{\rm eff}| < 35°$ at 90% C.L.
  - require a large amount of data to resolve α.





hep-ex/0412037, submitted to PRL

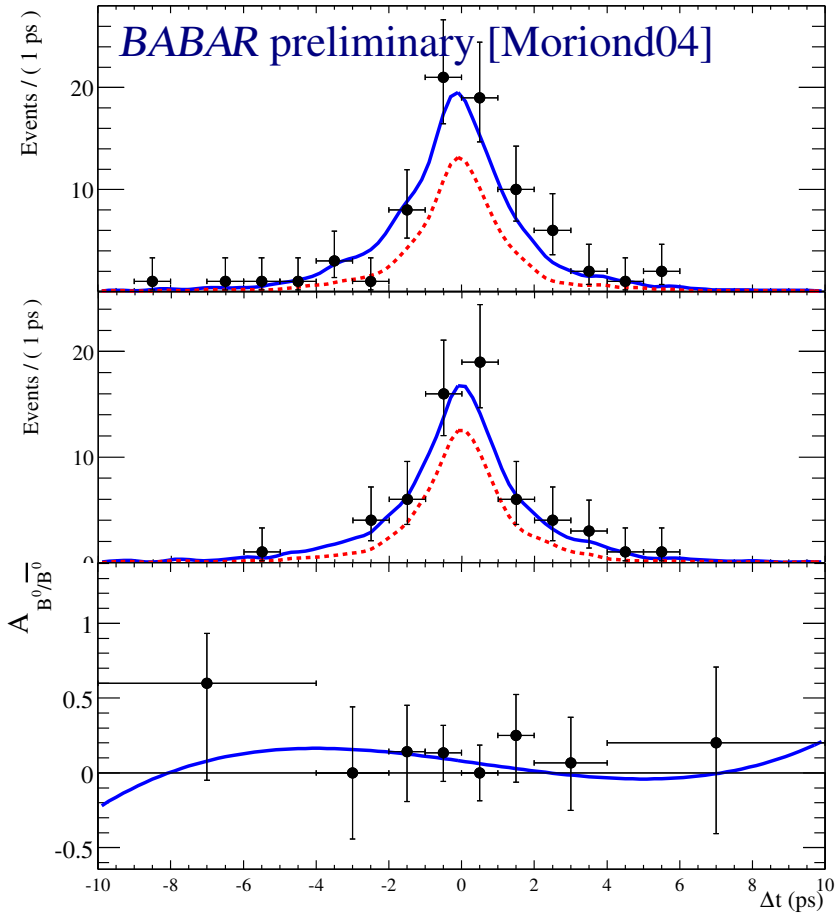




- $[29°, 61°]$ excluded at 90% C.L.

$B^0 \to \rho\rho$

- VV final state : mixture of CP-even and CP-odd. $\Rightarrow$need angular analysis
  - fortunately it's almost 100% longitudinally polarized $\Rightarrow CP$-even.
- $B^0 \to \rho^+\rho^-$ with 121 million $B\overline{B}$
  - $n_{\rm sig} = 314 \pm 34$
    $f_L = 1.00 \pm 0.02$
    $S_{\rm long} = -0.19 \pm 0.33 \pm 0.11$
    $C_{\rm long} = -0.23 \pm 0.24 \pm 0.14$
  - Analysis with 227 million $B\overline{B}$ events is finalizing.



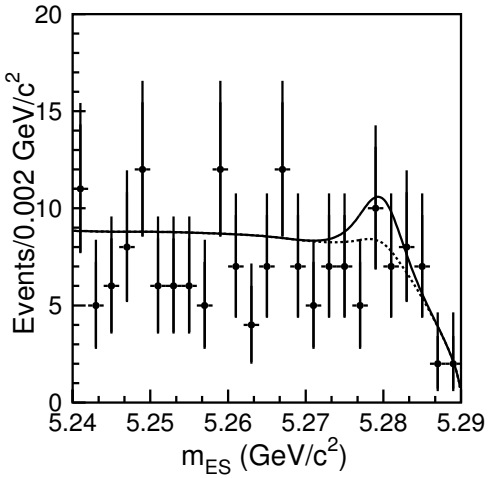
$B^0 \to \rho\rho$ and measurement of α

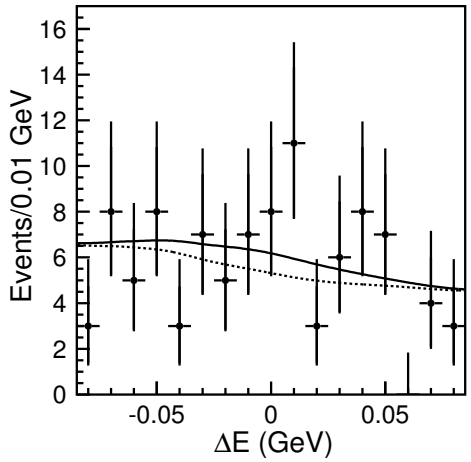
- With 227 million $B\overline{B}$ events:
  $B^0 \to \rho^0\rho^0$: $n_{\rm sig} = 33^{+22}_{-20}$

  $\mathcal{B}(B^0 \to \rho^0\rho^0) < 1.1 \times 10^{-6}$ (90% C.L.)

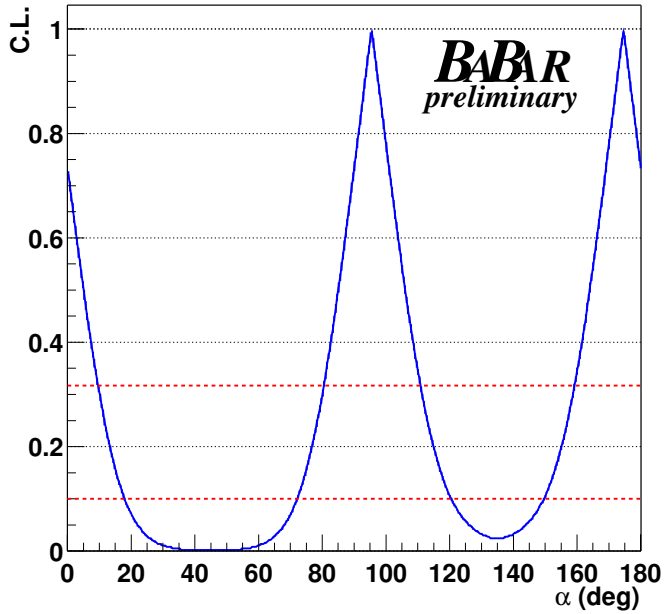
  - penguin contribution is small in $B^0 \to \rho\rho$
  - isospin analysis shows

    $|\alpha - \alpha_{\rm eff}| < 11^\circ$ (68% C.L.)





hep-ex/0412067, submitted to PRL



- $\alpha = (96 \pm 10(\text{stat.}) \pm 4(\text{syst.}) \pm 11(\text{theo.}))^\circ$
  - total error in quadrature: 15°
    (with $B^0 \to \rho^+\rho^-$ result from 112 million $B\overline{B}$)

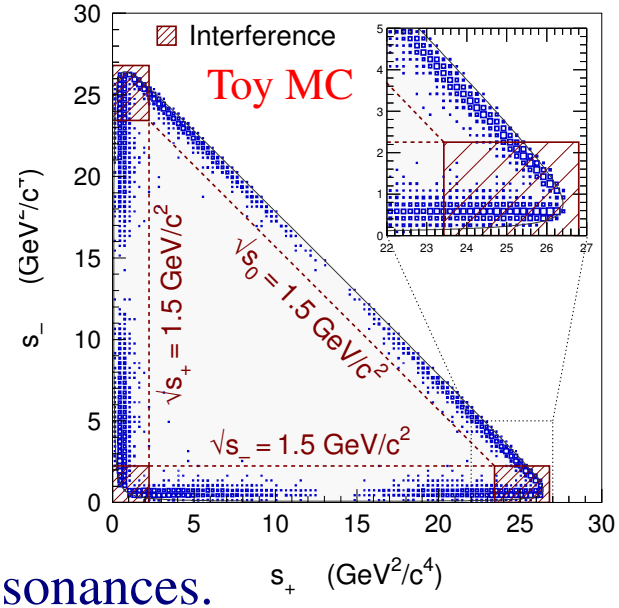
$B^0 \to (\rho\pi)^0 \to \pi^+\pi^-\pi^0$ Dalitz analysis

- $\rho^\pm\pi^\mp$ is not a CP eigenstate. Isospin analysis is more complicated and needs much more statistics.
- Taking advantage of variation of strong phase on the Dalitz plane, one can constrain α without ambiguity [Quinn/Snyder PRD48,2139].
- Combine Dalitz and time-dependent analysis:

$$|\mathcal{A}^{\pm}_{3\pi}(\Delta t)|^2 \propto |\mathcal{A}_{3\pi}|^2 + |\overline{\mathcal{A}}_{3\pi}|^2 \mp (|\mathcal{A}_{3\pi}|^2 - |\overline{\mathcal{A}}_{3\pi}|^2)\cos(\Delta m \Delta t) \pm 2\mathrm{Im}[\overline{\mathcal{A}}_{3\pi}\mathcal{A}^*_{3\pi}]\sin(\Delta m \Delta t)$$

$$\mathcal{A}_{3\pi} = f_+ A^+ + f_- A^- + f_0 A^0$$

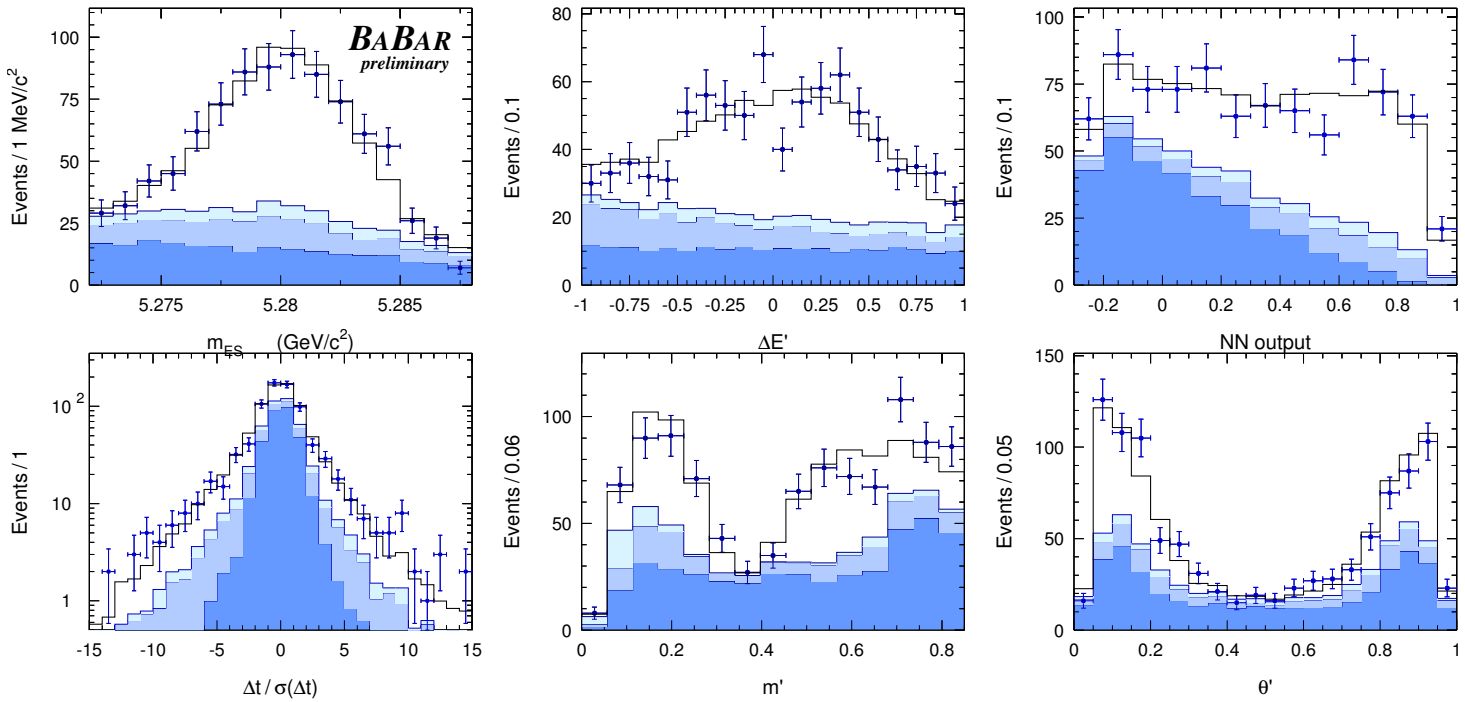
$$\overline{\mathcal{A}}_{3\pi} = f_+ \overline{A}^+ + f_- \overline{A}^- + f_0 \overline{A}^0$$



  - $f_{+,-,0}$: functions of Dalitz variables for $\rho^{+,-,0}$ resonances.
  - $A^{+,-,0}$: decay amplitudes, independent of Dalitz.
- Fit a PDF of Δt, Dalitz and other signal/bkg discriminating variables to extract amplitudes.

$B^0 \to (\rho\pi)^0$ fit

- Projection of discriminating variables:



- $n_{\rm sig} = 1184 \pm 58$: dominated by $B^0 \to \rho^\pm\pi^\mp$; no significant $\rho^0\pi^0$.
- Direct CPV: $A = -0.088 \pm 0.049 \pm 0.013$. Osc. coeff.

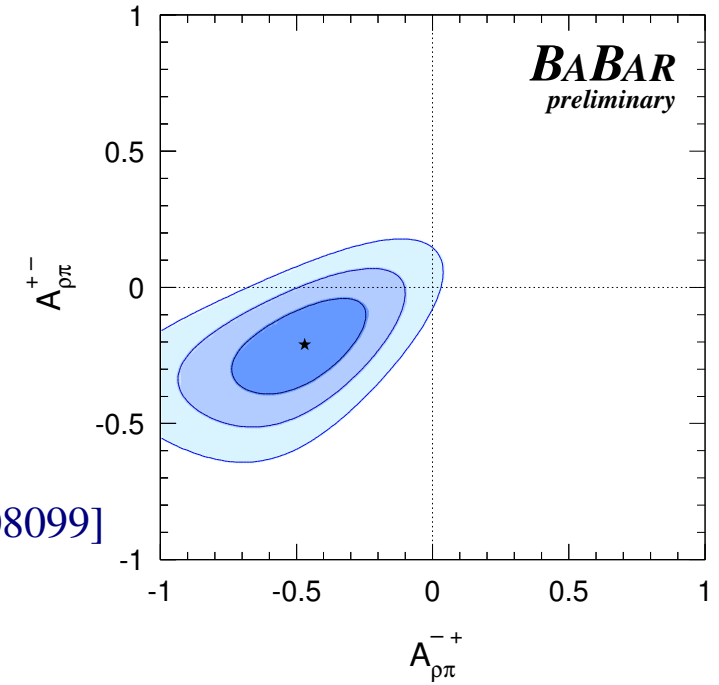
$C = 0.34 \pm 0.11 \pm 0.05, \quad \Delta C = 0.15 \pm 0.11 \pm 0.03 \quad (C_{\rho^\pm\pi^\mp} = C \pm \Delta C)$

$S = -0.10 \pm 0.14 \pm 0.04, \quad \Delta S = 0.22 \pm 0.15 \pm 0.03 \quad (S_{\rho^\pm\pi^\mp} = S \pm \Delta S)$

$B^0 \to (\rho\pi)^0$ CPV and α

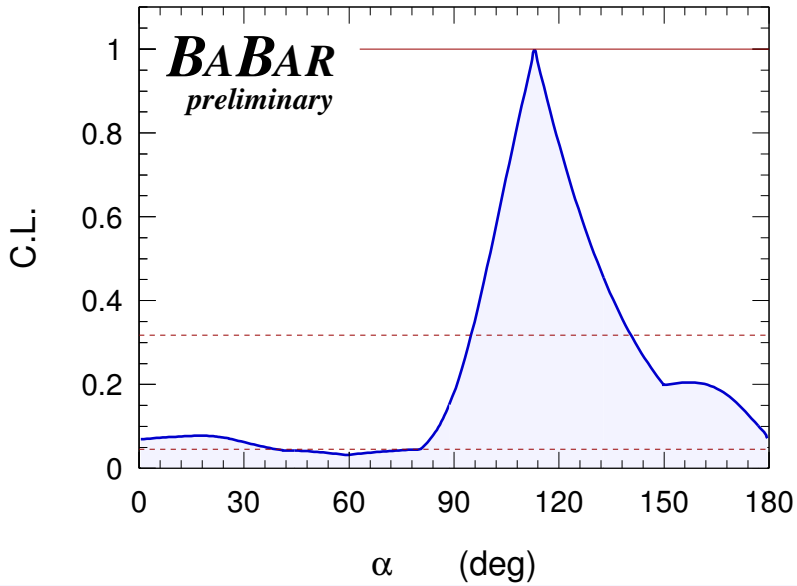
- Combine A and C to form two independent direct CPV
  variables: $\mathcal{A}_{\rho\pi}^{+-} = -0.21 \pm 0.11 \pm 0.04$
  $\mathcal{A}_{\rho\pi}^{-+} = -0.47^{+0.14}_{-0.15} \pm 0.04$
  - $\Rightarrow 2.9\sigma$ effect of direct CPV.

[hep-ex/0408099]



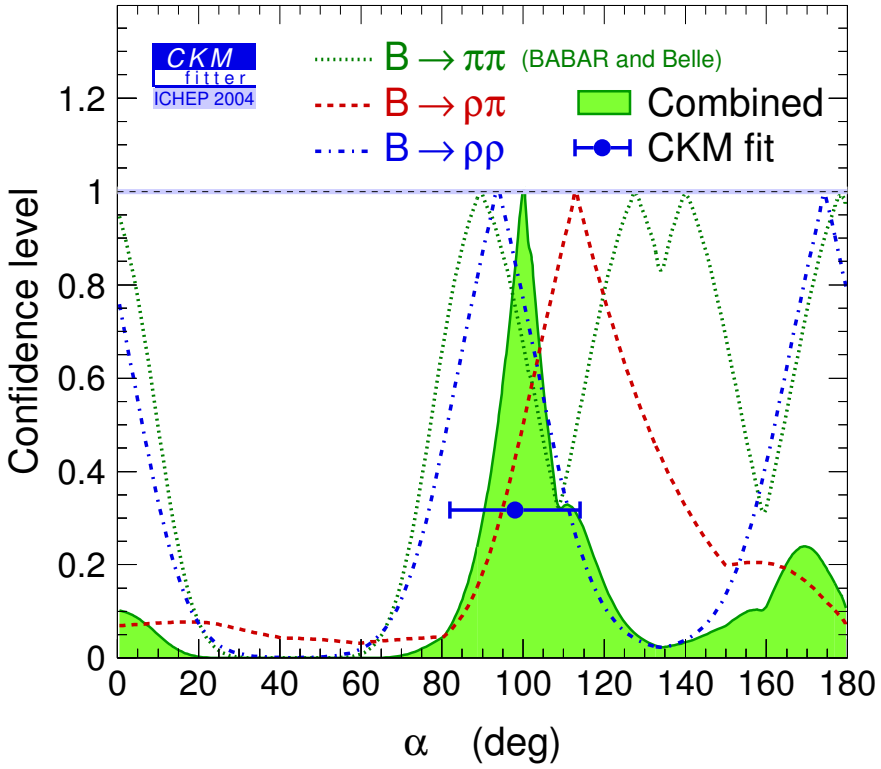
- Rewrite amplitudes in terms of tree and penguin and use isospin symmetry to obtain constraint on α (and relative strong phase btw $B^0 \to \rho^{\pm}\pi^{\mp}$).

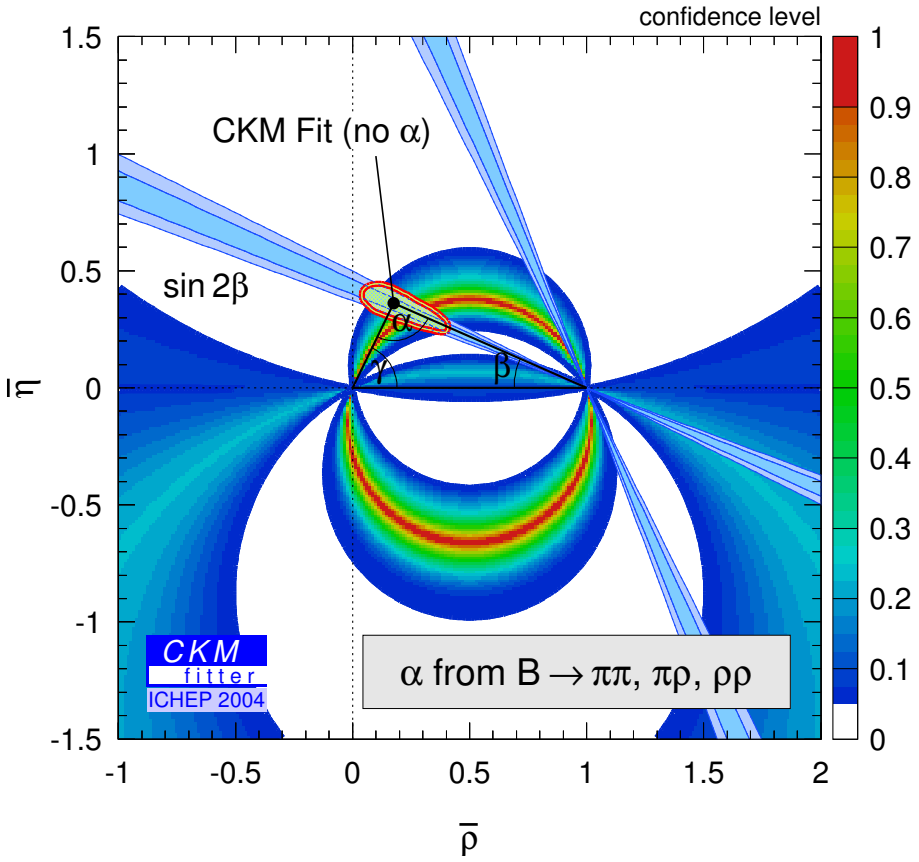
- $\alpha = (113^{+27}_{-17} \pm 6)^\circ$ (68% C.L.)



α and CKM picture

- Combined fit: $\Rightarrow \alpha = (100^{+9}_{-10})^\circ$ ($[80^\circ, 129^\circ]$ at 2 standard deviation.)
- Consistent with CKM fits with other constraints.





[phenomenolgical analysis performed by the CKMfitter group]

Conclusion

- *BABAR* has measured time-dependent CP using $B^0 \to K^0_S K^0_S K^0_S$
  - $\sin 2\beta(K^0_S K^0_S K^0_S) = 0.79^{+0.29}_{-0.36} \pm 0.04$
  - precision comparable to other $b \to s$ penguin modes;
  - result consistent with Standard Model;
  - very interesting to watch for $\sin 2\beta$ discrepancy between $b \to sq\overline{q}$ and $b \to c\overline{c}s$ with more data.
- *BABAR*'s search for lepton flavor violation pushed the upper limit of $\mathcal{B}(\tau^\pm \to \mu^\pm\gamma)$ down by a factor of four.
  - $\mathcal{B}(\tau \to \mu\gamma) < 6.8 \times 10^{-8}$ at 90% C.L.
  - start to be meaningful to compare with New Physics models.
- CKM angle α has been measured at *BABAR*.
  - uncertainty from the combined analysis of $B^0 \to \pi\pi,\ \rho\rho,\ \rho\pi$ is about 10°.
  - CKM picture is still consistent under Standard Model.
- Lots more data to come. Stay tuned.