Observations of CP Violation in B-meson Decays

Experimental Particle Physics Seminar
Southern Methodist University

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… and there was light.

(Genesis 1:3)

A Brief History of the Universe:

Events	*Time*	*Temperature*
Big Bang	0	∞
Quantum gravity threshold	10^{-43} sec	10^{19} GeV
Grand Unification transition	10^{-35} sec	10^{15} GeV
Electroweak symmetry breaking	10^{-11} sec	10^{3} GeV
Hadrons form from quarks	10^{-6} sec	1 GeV
Nucleosynthesis (D, He, Li)	1 sec	1 MeV
Electron-nuclei recombination	400,000 years	1 eV
Today	15×10^{9} years	2.73 K

$$H^2(t) = \left(\frac{1}{R}\frac{dR}{dt}\right)^2 = \frac{8\pi G_N \rho(t)}{3}$$

$$H(\text{now}) = 50 \div 85 \frac{\text{km}}{\text{sec}\cdot\text{Mpc}}$$

$$T_{\text{Universe}}(\text{MeV}) \approx \frac{1}{\sqrt{t(\text{sec})}}$$

$$m_{\text{Planck}} = \sqrt{\frac{\hbar c}{G_N}} = 1.221047(79)\times10^{19}\,\text{GeV}/c^2$$

etc.

But none of this would matter if it were not for the…

Matter-Antimatter Asymmetry the Universe

We are survivors of the post-Big Bang mutual annihilation of matter and antimatter

Baryonic asymmetry of the Universe: $\dfrac{N_{B}-N_{\bar{B}}}{N_{\gamma}} \simeq \dfrac{N_{B}}{N_{\gamma}} \simeq 5\times 10^{-10}$

Sakharov's three conditions

The three conditions necessary to produce the baryonic asymmetry of the Universe:

(photo circa 1943)

А. Д. Сахаров, *Письма в ЖЭТФ*, **5**, № 1, 32-35, 1 января 1967
A. D. Sakharov, *Soviet Journal of Experimental and Theoretical Physics, Letters to the Editor,* **5**, No. 1, 24-27, 1st January 1967

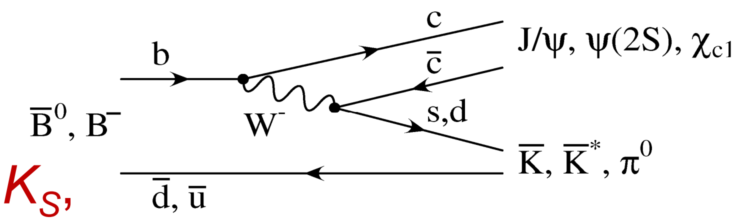
(the original reads quite a bit better than the English translation!)

1. **Baryon number violation**
2. ***C* and *CP* violation**
3. **Departure from thermal equilibrium**

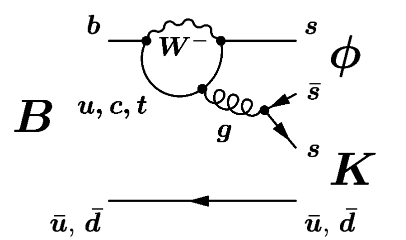
Through the *CPT* Theorem, *CP* violation implies the existence of *T* violation

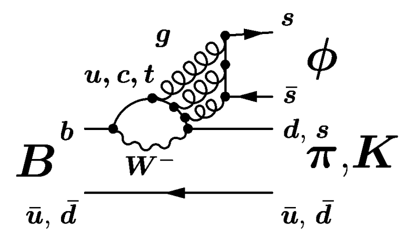
Structure of this talk

- **Theory:** The CKM matrix; *CP* violation in B^0 mesons
- **The facilities:** Overview of PEP-II/*BaBar,* KEKB/Belle; their performance
- **Time-dependent *CP* analysis at a *B* factory:** event selection, background suppression, vertex reconstruction, tagging

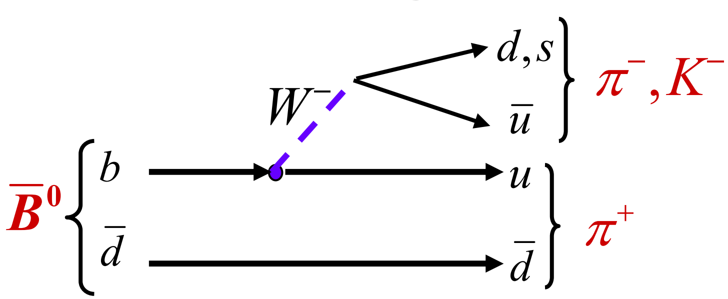


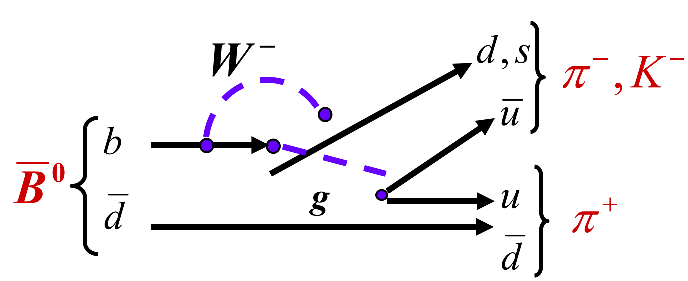
- ***CP* violation in sin(2*β*) modes:**
  - charmonium modes: $J/\psi K_S$, $J/\psi K_L$, $\psi(2S) K_S$, $\chi_{c1} K_S$, $\eta_c K_S$, $J/\psi K^{*0}$ $(K^{*0} \rightarrow K_S \pi^0)$
  - penguin-dominated modes: $\eta' K_S$, φK^0





- ***CP* violation in $\pi^+\pi^-$ and $K^+\pi^-$**
- **Improvements currently in the works in *BaBar***





The Quark Mixing Matrix

The only Standard-Model source of CP violation in the quark sector

The Cabibbo-Kobayashi-Maskawa matrix relates the electroweak (q') and the mass (q) quark eigenstates:

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$$V_{\text{CKM}} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4) + iO(\lambda^6)$$

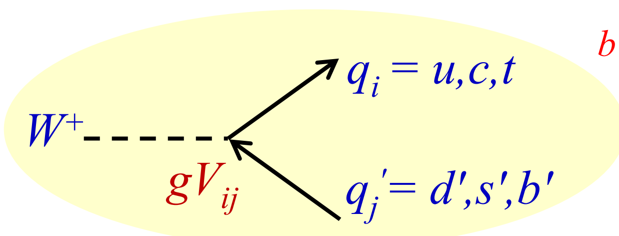
$$V^\dagger V = 1 \Rightarrow \quad V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

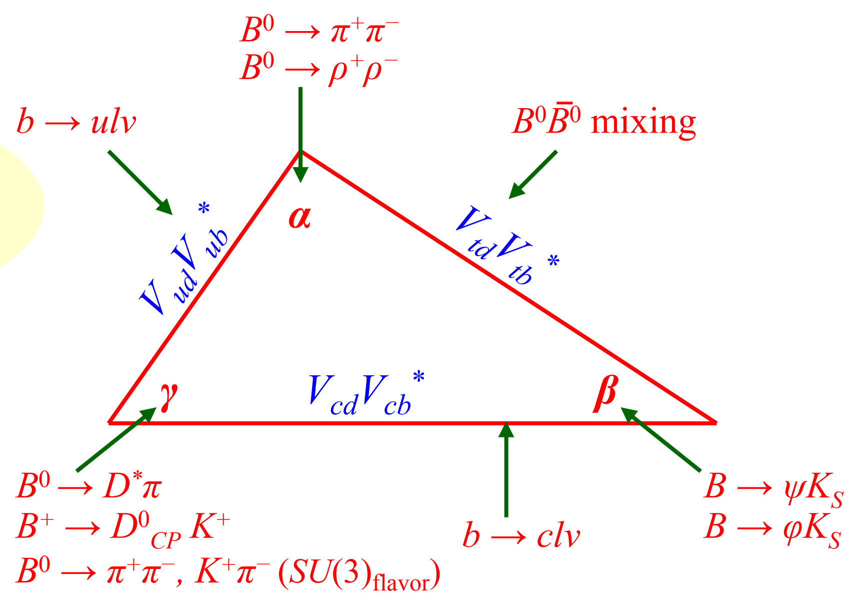
The "unitarity triangle"

$$\alpha \equiv \arg\left[-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right]$$

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

$$\gamma \equiv \arg\left[-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right]$$





*CKM matrix overview: Review of Particle Physics, W.-M. Yao et al. [Particle Data Group], J. Phys. G **33**, 1 (2006)*

Time evolution of the B^0 meson

The time-dependent rate for $\overline{B}^0$ (f_+) or B^0 (f_-) decays to a final state f (neglecting the lifetime difference between the mass eigenstates B_H and B_L):

$$f_\pm(\Delta t) = \frac{e^{-|\Delta t|/\tau_B}}{4\tau_B}[1 \mp C_f \cos(\Delta m \Delta t) \mp S_f \sin(\Delta m \Delta t)]$$

where

S and C is what we measure

$$|B_{L/H}> = p|B^0> \pm q|\overline{B^0}>, \quad \lambda_f = \frac{q}{p}\frac{\overline{A}_f}{A_f}, \quad S_f = \frac{-2\,\mathrm{Im}\,\lambda_f}{1+|\lambda_f|^2}, \quad C_f = \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2}$$

a_f is the time-evolution asymmetry:

$$a_f(\Delta t) = \frac{f_+(\Delta t) - f_-(\Delta t)}{f_+(\Delta t) + f_-(\Delta t)}$$

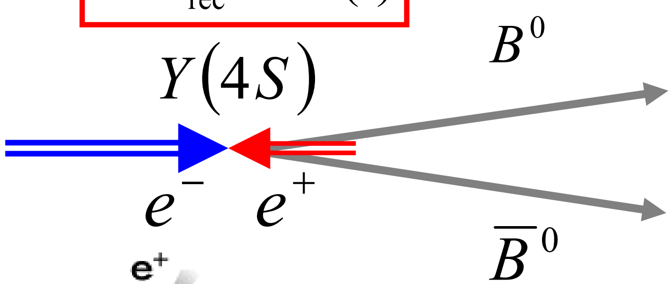
If f is a CP eigenstate, f_{CP}, we have CP violation if $\lambda_f \neq \pm 1$:

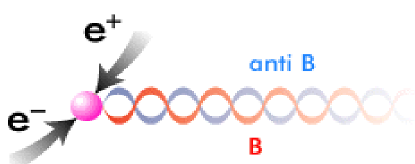
- $|q/p| \neq 1$ (CP violation in mixing, negligible)
- $|\overline{A}_{\overline{f}}/A_f| \neq 1$ (direct CP violation, small in $b \to c\overline{c}s$)
- **$\mathrm{Im}(\lambda_f) \neq 0$ (interference between mixing and decay)**

B. Aubert et al. (BaBar Collaboration) Phys. Rev. Lett. 96, 251802 (2006)

Time-dependent *CP* analysis at a *B*-meson factory

$$B_{\text{tag}} = \overline{B}^0(t)$$
$$\Rightarrow B_{\text{rec}} = B^0(t)$$





Y **(4*S*) produces a <u>coherent</u> pair of neutral *B* mesons**

Time-dependent *CP* analysis at a *B*-meson factory

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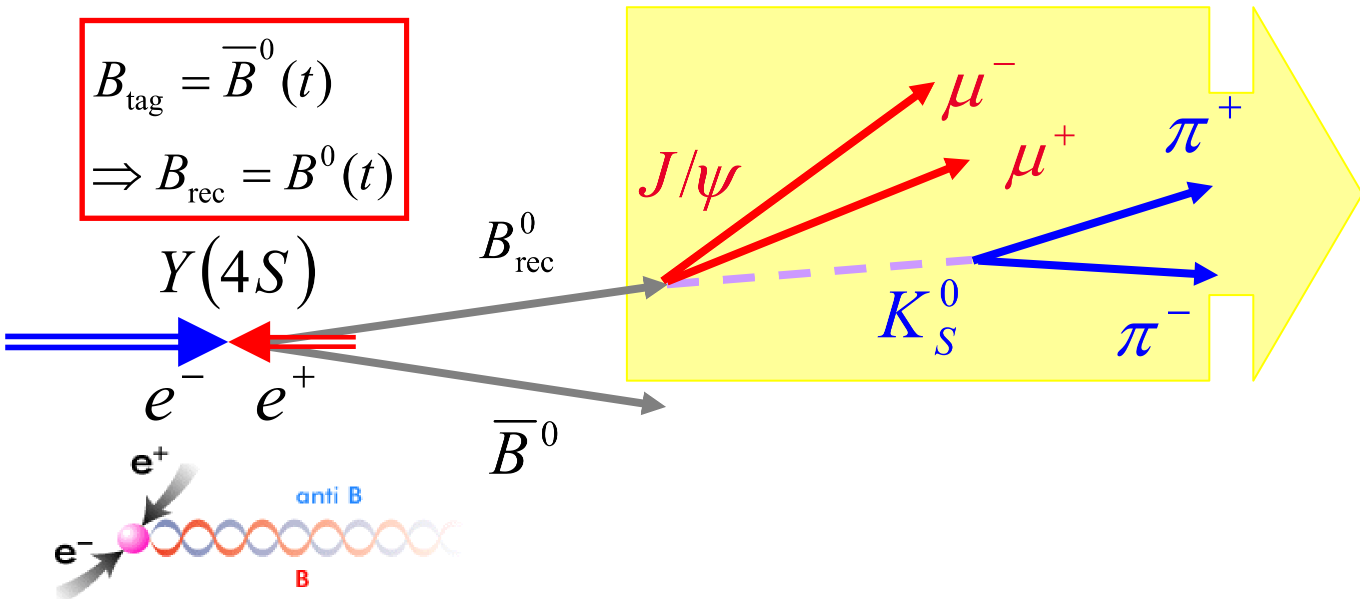
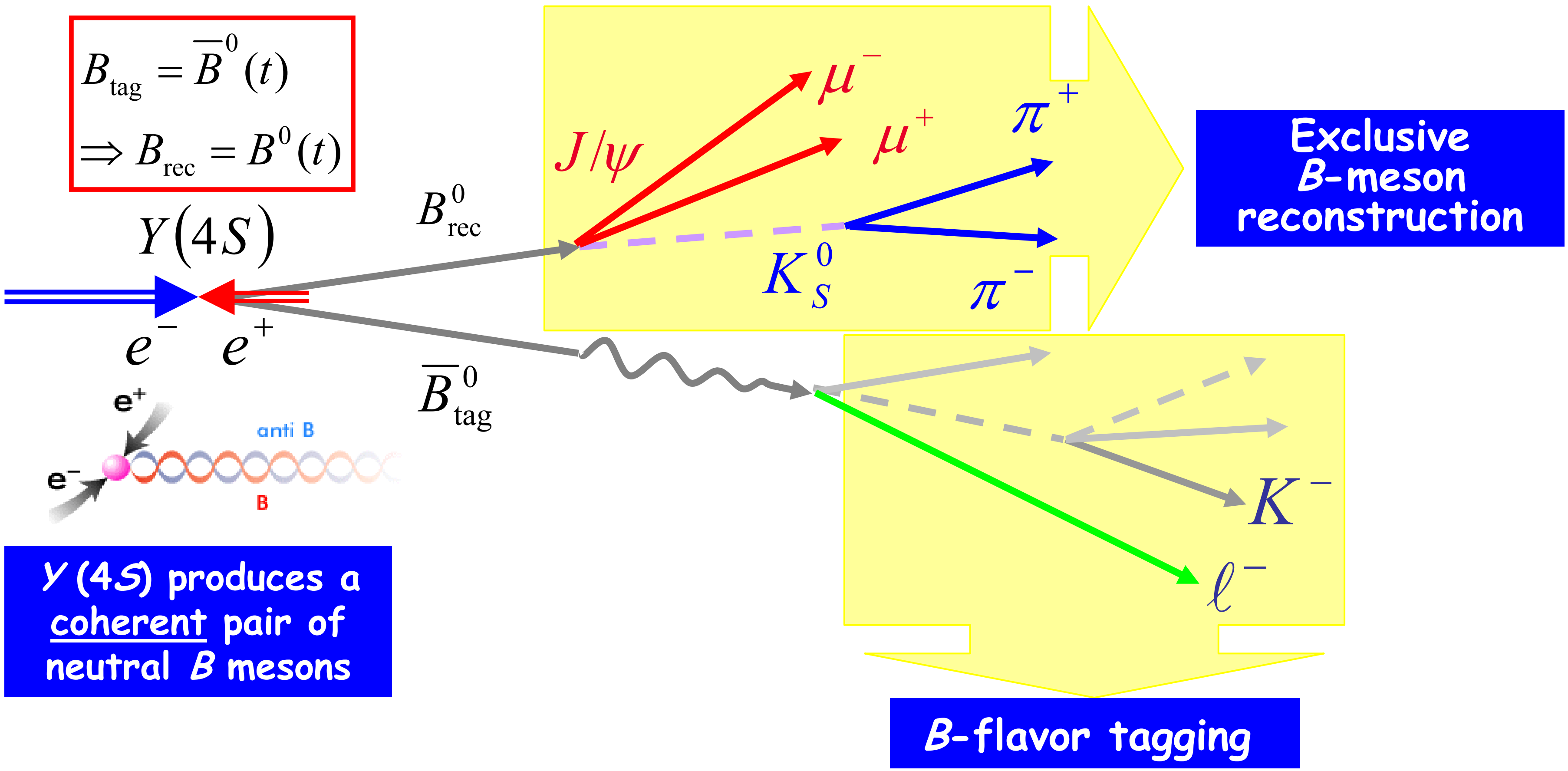


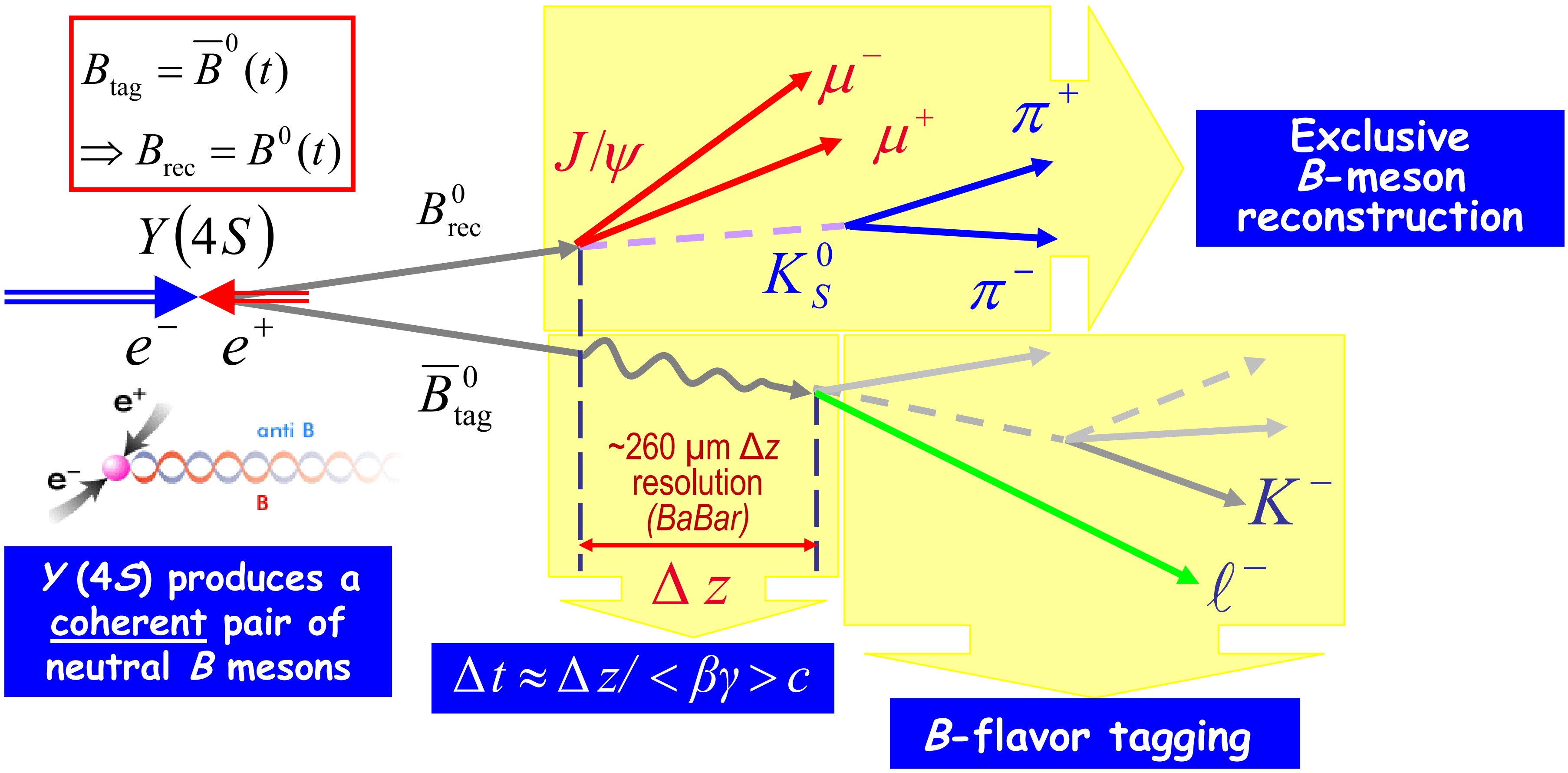
Exclusive *B*-meson reconstruction

$\Upsilon(4S)$ produces a <u>coherent</u> pair of neutral *B* mesons

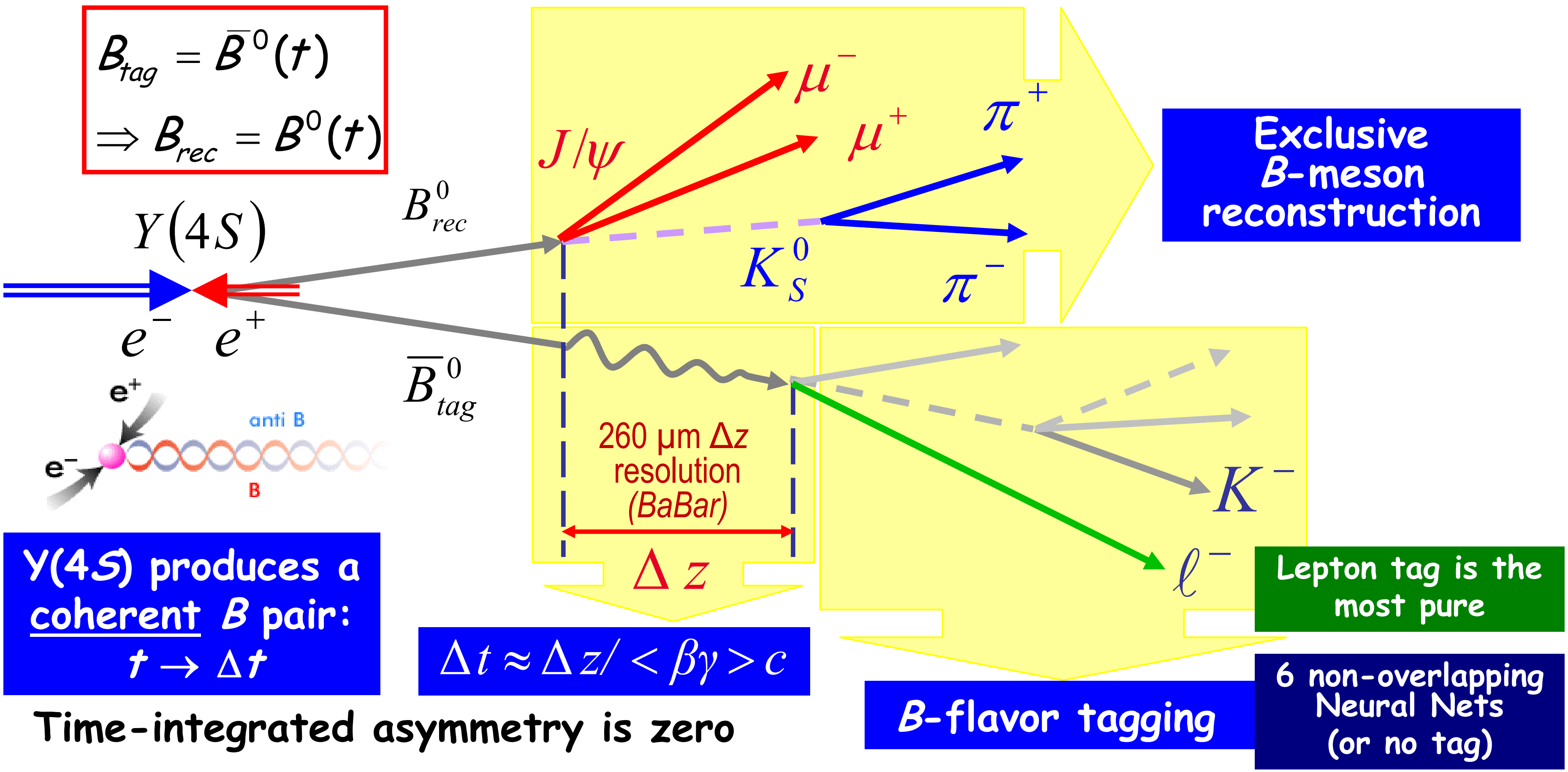
Time-dependent *CP* analysis at a *B*-meson factory



Time-dependent *CP* analysis at a *B*-meson factory



Time-dependent *CP* analysis at a *B*-meson factory



Time-integrated asymmetry is zero

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

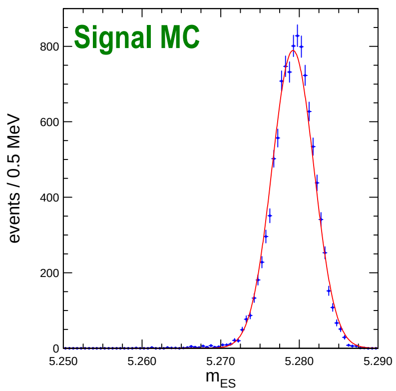
$B^0_{rec} = B^0_{CP}$ (*CP* eigenstates) → *CP* analysis

Discriminating variables: kinematic

A pair of weakly correlated variables that reflect energy and momentum conservation: peaking for fully reconstructed *B* decays, smooth for combinatorial background

$$m_{\mathrm{ES}} \equiv \sqrt{E^2_{\mathrm{CM\,beam}} - p^2_{\mathrm{CM}\,B}} = m_B$$

$$\Delta E \equiv E_{\mathrm{CM}\,B} - E_{\mathrm{CM\,beam}} = 0$$

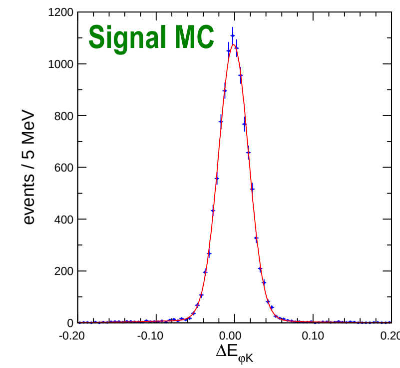


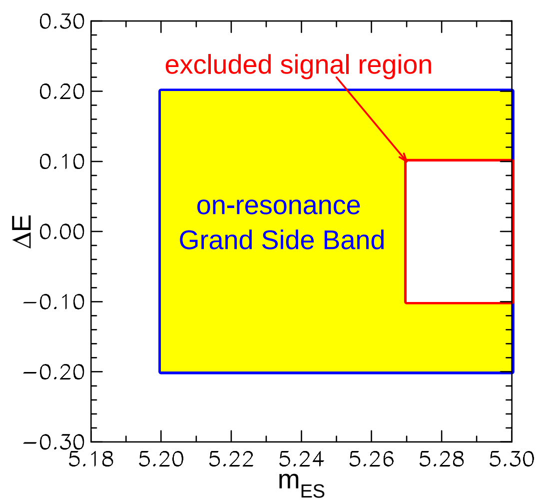
resolution ~2.6 MeV/c^2

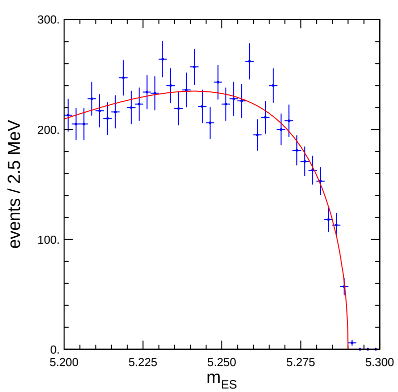
determined by the beam energy spread

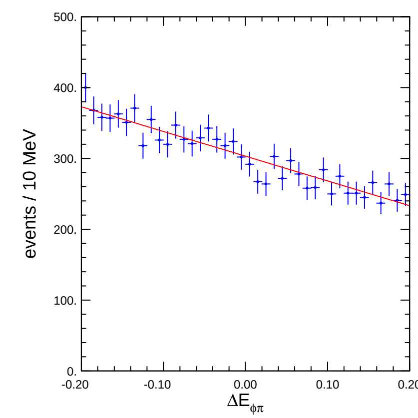
resolution ~15−80 MeV

depending on the number of tracks and presence of neutrals in the final state





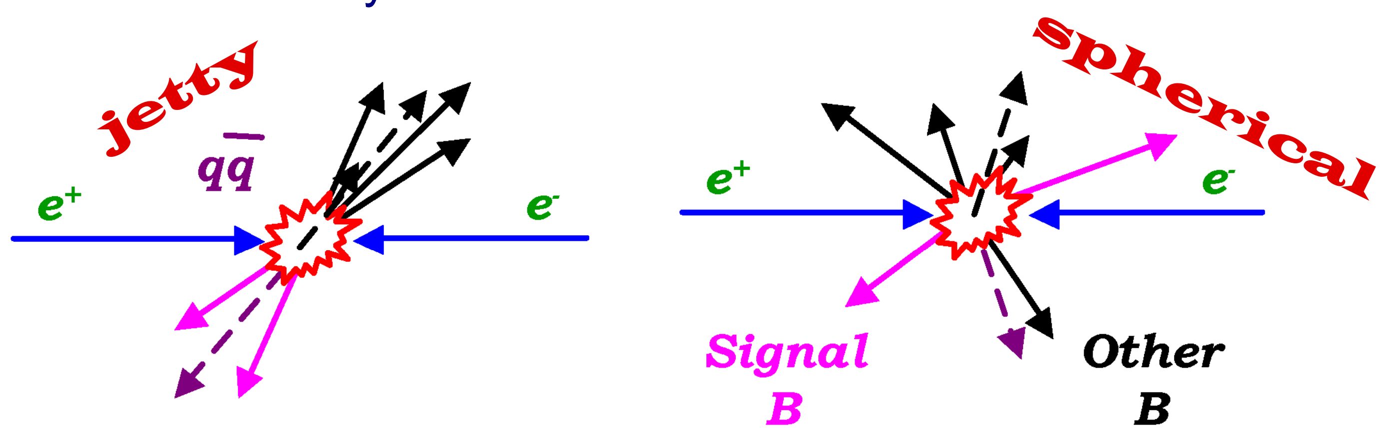




continuum background in the Grand Side Band

Discriminating variables: event shape

- The principal source of background to rare *B* decays: random track/neutral combinations from quark-pair (*udsc*) production in the continuum:
  - total *udsc* cross section ~3.4 nb, compared to ~1.1 nb for $\Upsilon(4S)$
  - *udsc* events have jet-like topology, while *B* decays are nearly spherical in CM
  - several topological variables are employed to suppress this background
- Backgrounds from $\tau^+\tau^-$ production and two-photon physics are usually negligible
- Backgrounds from other *B* decays tend to be small



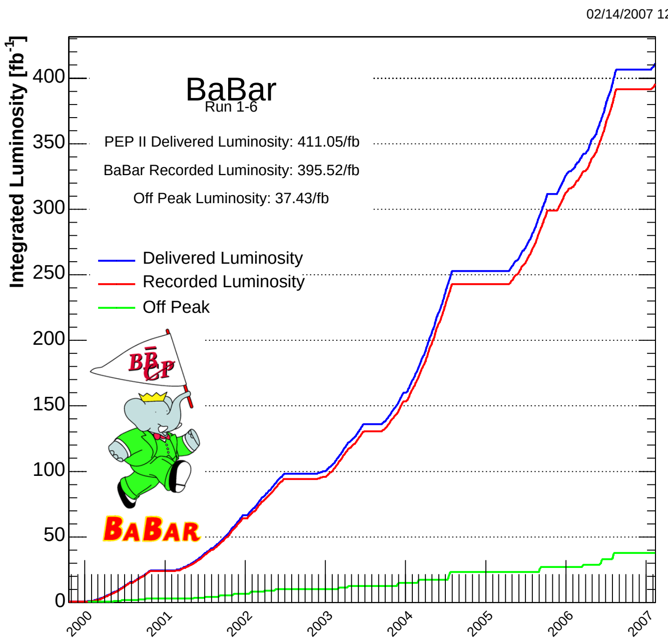
Analyses are <u>blind</u> until the methodology has been finalized and frozen

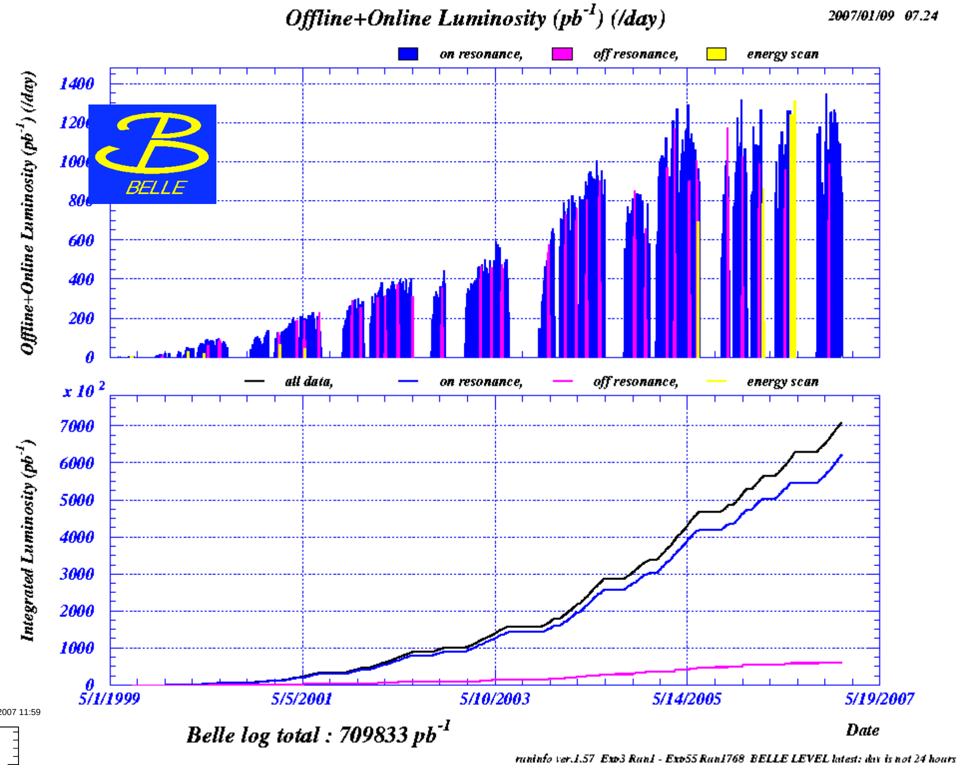
Key parameters of the PEP-II and KEKB asymmetric *B*-meson factories

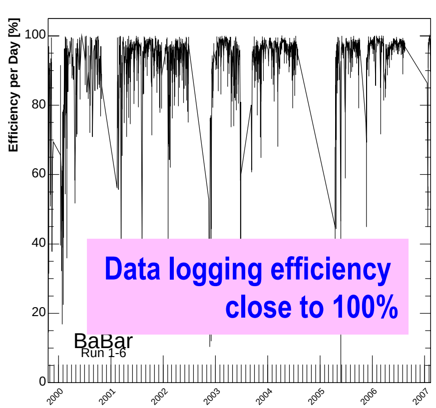
February 14, 2007	KEKB	PEP-II
CM energy, GeV	10.580	
Beam energies, GeV	8.0 e^-, 3.5 e^+	9.0 e^-, 3.1 e^+
Beam currents, A	1.34 e^-, 1.66 e^+ 1.1 e^-, 2.6 e^+ design	1.88 e^-, 2.90 e^+ 0.7 e^-, 2.1 e^+ design
Number of bunches	1389 / 5000 design	1722 / 1658 design
Peak luminosity, 10^{33} $cm^{-1}s^{-2}$	17.1 / 10 design	12.1 / 3 design
Best 24 hours, pb^{-1} (3 consecutive 8-hour shifts)	1232	911 / 135 design
Total recorded luminosity, fb^{-1}	**710**	**396**

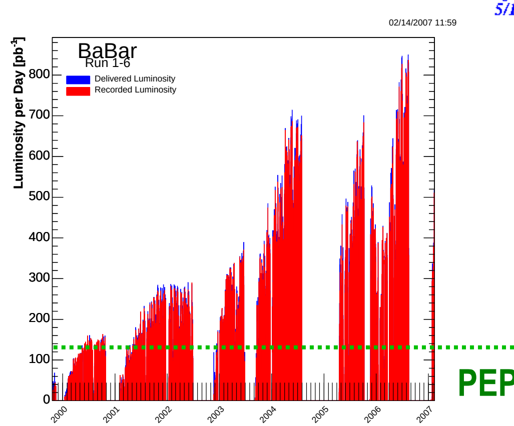
Compare this to the ~40 pb^{-1} delivered in 10 years of VEPP-4 operation at Υ(nS)!

KEKB/Belle and PEP-II/*BaBar* both perform extremely well







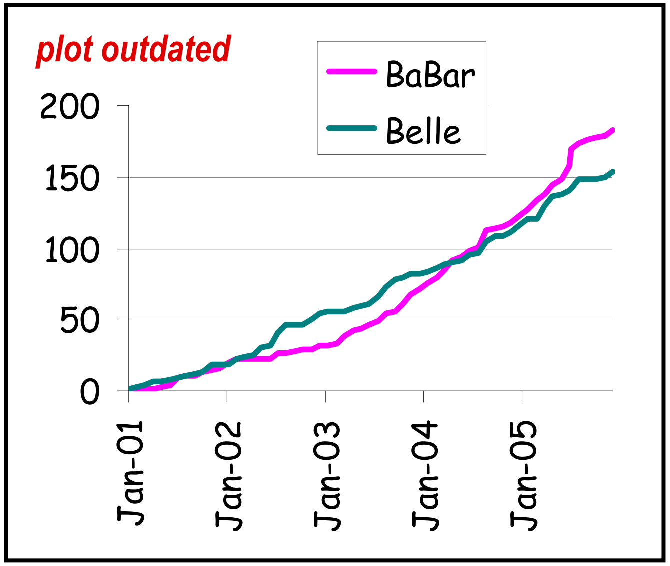


PEP-II/*BaBar* design: 135 pb^{-1} per day

Physics productivity

Journal papers as of today: ***BaBar*: 258 submitted, 244 published**
Belle: 202 submitted, 188 published

***BaBar* 2004-06 average: close to 60 papers/year, by far the greatest addition to PDG-RPP '06**

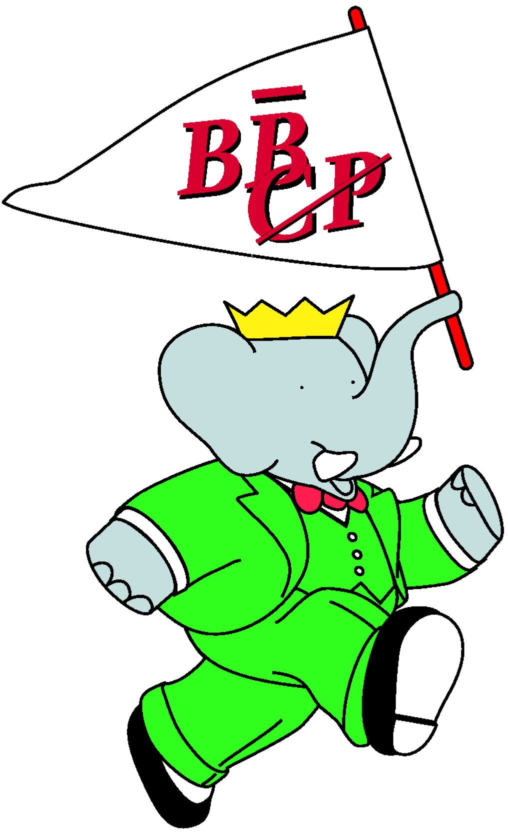


*We are **very** fortunate that two B-meson factories exist!*

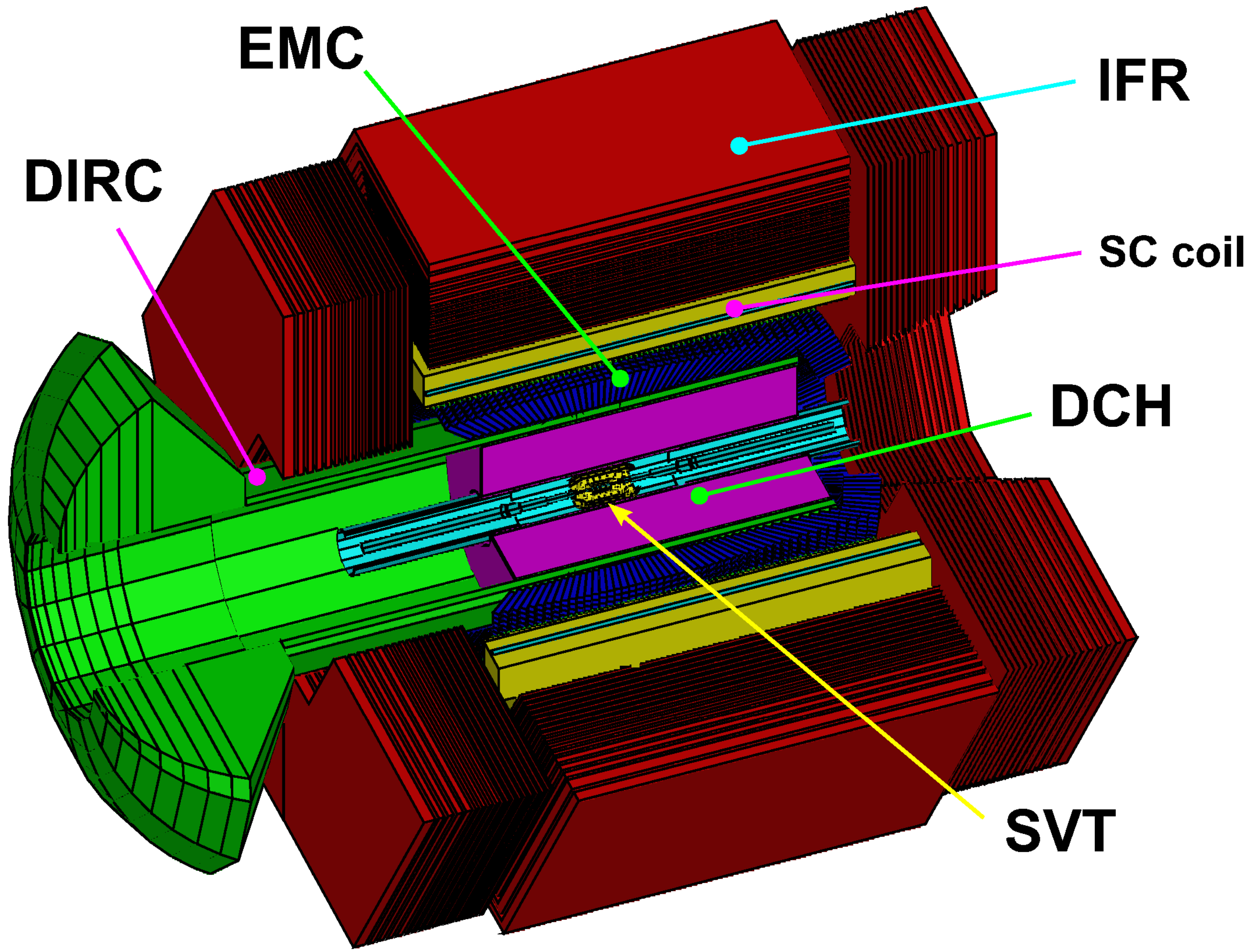
Running currently authorized until
BaBar: September 30, 2008 (close to 1 ab^{-1} expected)
Belle: 1 ab^{-1}
Analysis to continue for several more years

Belle and *BaBar* datasets are unique, may never be superseded

BaBar detector outline



BABAR



BaBar Detector details

SVT: 5 double-sided layers; 97% eff.; 15 μm *z* hit resolution for inner layers; radiation tolerance 10 Mrad expected, exceeded

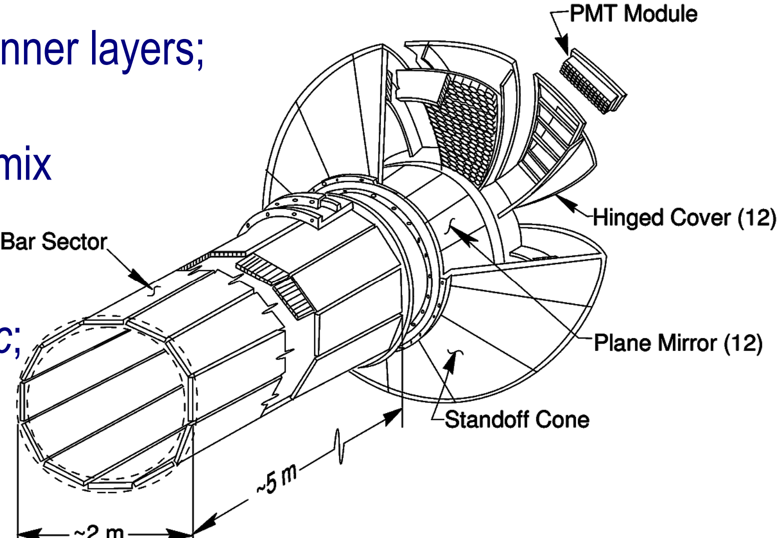
DCH: 40 axial and stereo layers; 80% Argon / 20% i-C_4H_{10} gas mix

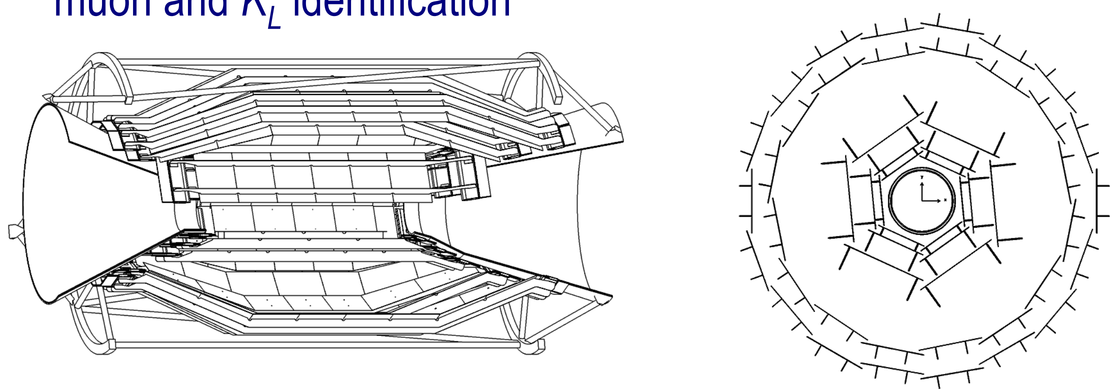
Tracking: 0.92 x 4π coverage; $\sigma(p_t)/p_t$=0.13% x p_t + 0.45%; $\sigma(z_0)$ = 65μm @ 1 GeV/c

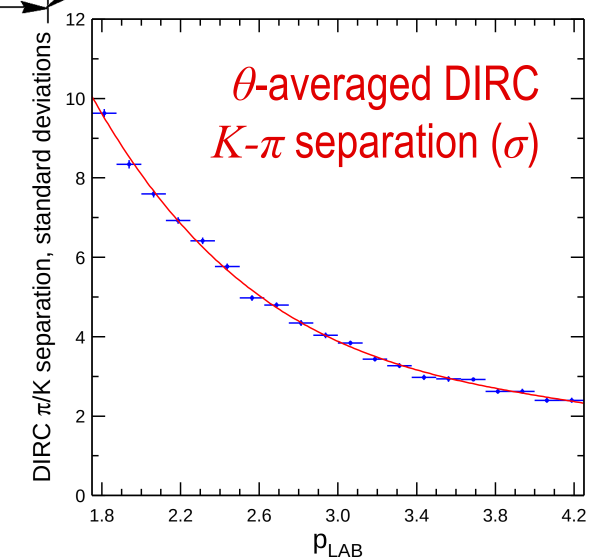
DIRC: 144 quartz bars; 0.84 x 4π coverage; 97% eff. @ 3 GeV/c; Better than 2.4σ π/K separation at all p

EMC: 6580 CsI(Tl) crystals; 0.90 x 4π coverage; 0.25 X_0 in front of the EMC (at 90°); σ_E/E = 2.3% x $E^{-1/4} \oplus$ 1.9%

IFR: Endcaps: 16-18 RPC layers; Barrel: 19 RPC or 12 LST layers; muon and K_L identification



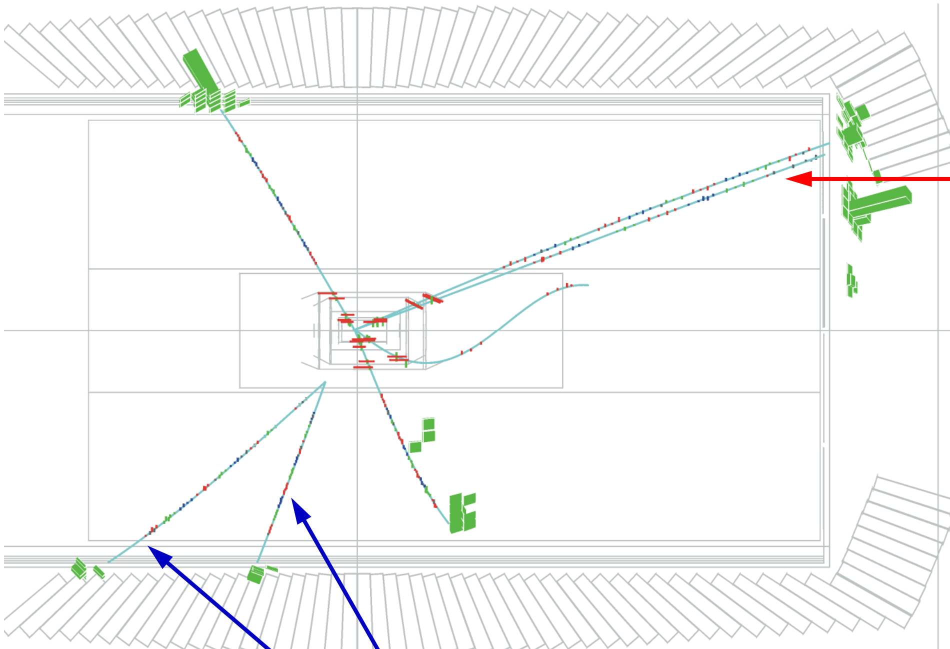




B. Aubert *et al.* [*BaBar* Collaboration], Nucl. Instrum. Meth. A **479**, 1-116 (2002)

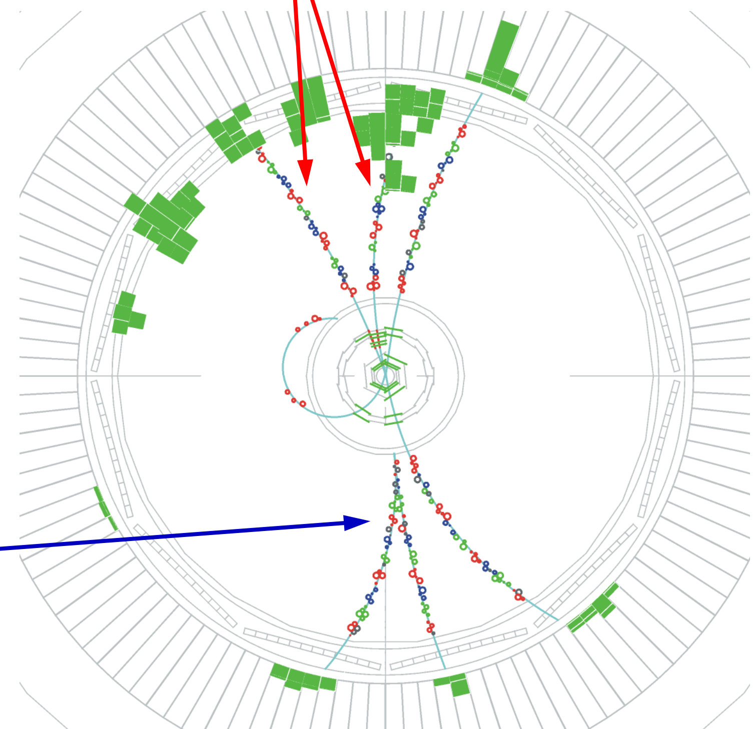
Example of a *B*-decay event in data: $B^0 \to \varphi K_S$ at *BaBar*

only the hits that correspond to reconstructed tracks and neutral candidates are shown (noise hits are removed)



$\varphi \to K^+K^-$

$K_S \to \pi^+\pi^-$

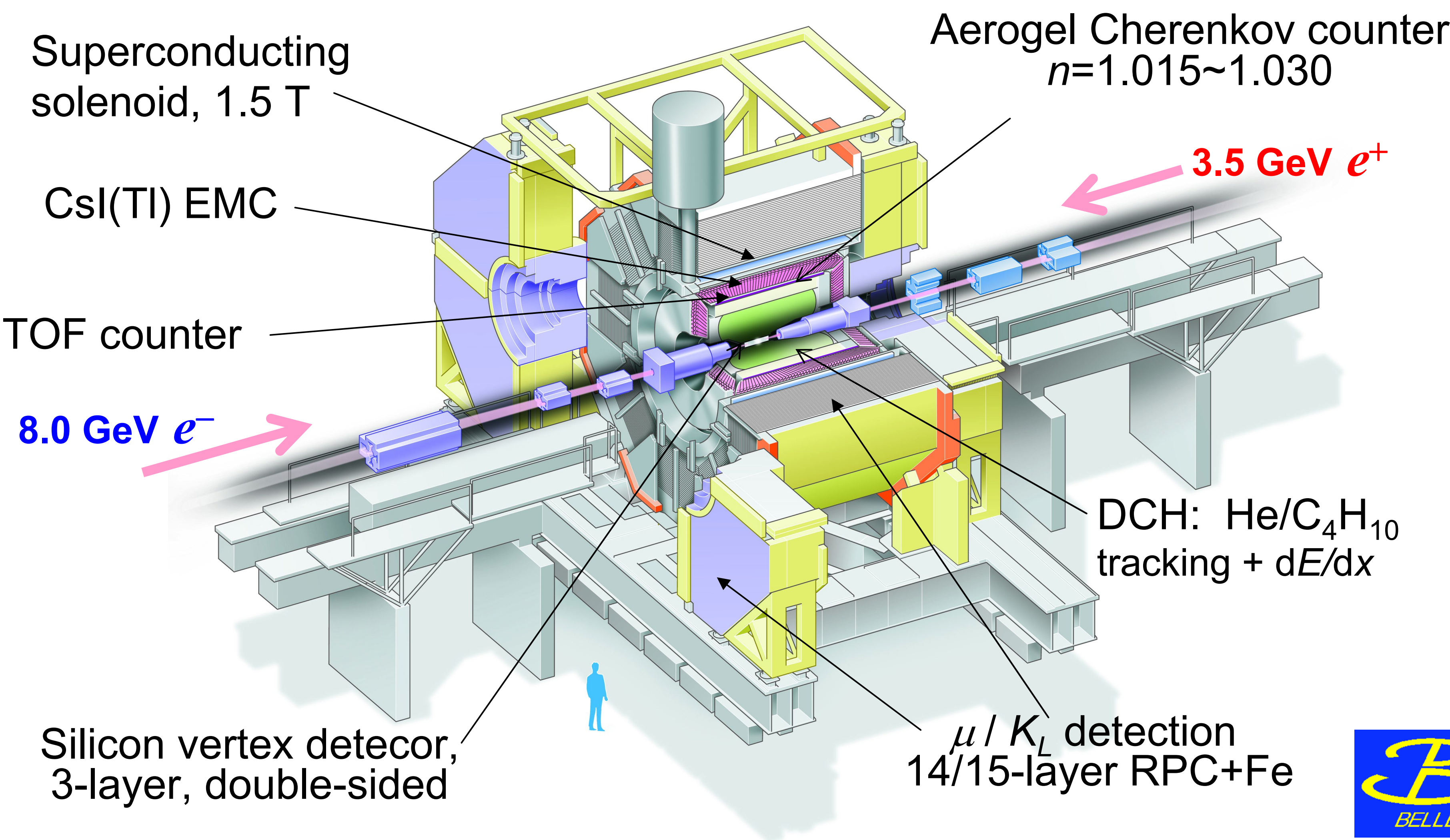


BABAR

Run 29368, event hexID 249a4b/d610dd73 (June 27, 2002)
*From the dataset used in Phys.Rev.D **69**:011102, 2004*

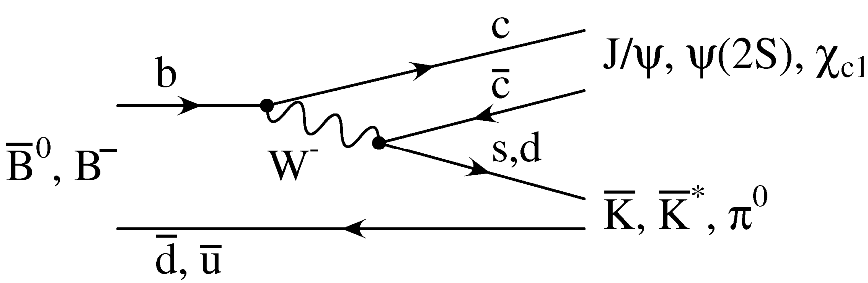
The Belle Detector

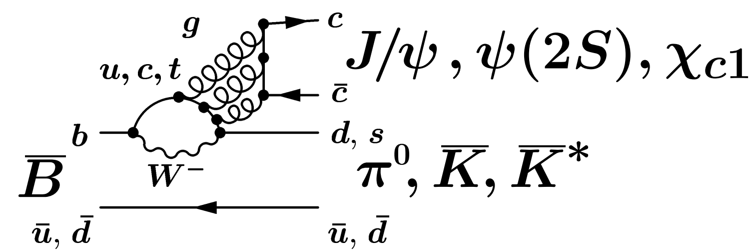
A. Abashian *et al.* [Belle Collaboration], Nucl. Instrum. Meth. A **479**, 117-232 (2002)



$\sin 2\beta$ in "golden" modes:

The highest-precision test of the CKM mechanism of *CP* violation in the Standard Model





"Golden" modes: color-suppressed tree dominates; the *t*-quark penguin has the same weak phase as the tree. In SM, therefore,

$$S_{\text{golden}} = \eta_{CP} \times \sin 2\beta, \quad C_{\text{golden}} = 0 \quad (\eta_{CP} = \pm 1)$$

Theoretical uncertainties:

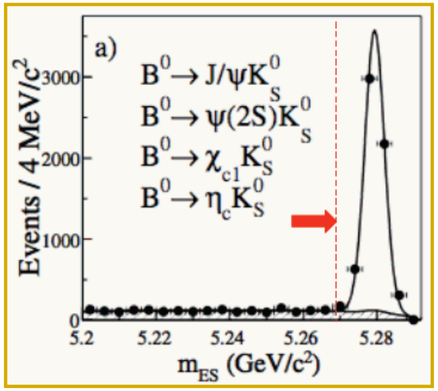
M. Ciuchini, M. Pierini, L. Silvestrini, Phys. Rev. Lett. **95**, 221804 (2005)

- example of a model-independent, data-driven calculation: assuming $SU(3)_{\text{flavor}}$ invariance, use $B^0 \to J/\psi\pi^0$ data to constrain penguin pollution in $J/\psi K^0$ $\Rightarrow$ $\Delta S_{J/\psi K^0} = S_{J/\psi K^0} - \sin 2\beta = 0.000 \pm 0.012$
- theoretical estimates of the biases due to u- and c-quark penguins, etc.:
  - $\Delta S_{J/\psi K^0} = S_{J/\psi K^0} - \sin 2\beta \sim O(10^{-3})$ H. Li, S. Mishima, hep-ph/0610120
  - $\Delta S_{J/\psi K^0} = S_{J/\psi K^0} - \sin 2\beta \sim O(10^{-4})$ H. Boos et al., Phys. Rev. **D** 73, 036006 (2006)

$\sin 2\beta$ in "golden" modes: *BaBar* ICHEP 06 (preliminary)

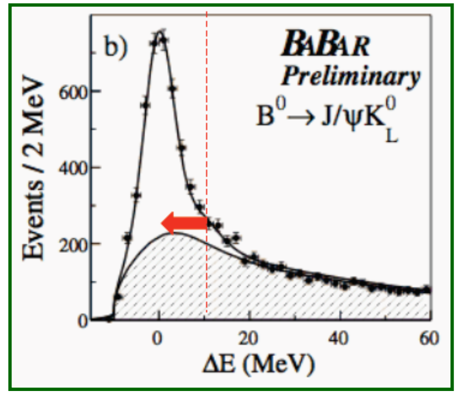
Over ***11300*** signal events

hep-ex/0607107



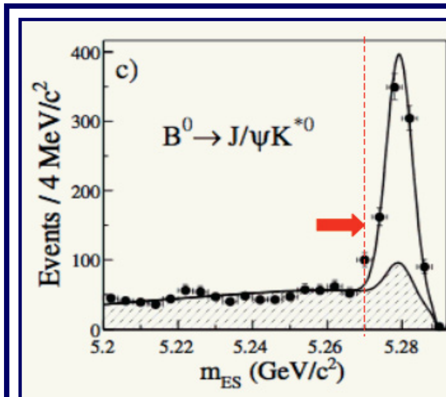
$(cc)K_S$ ($\eta_{CP} = -1$)

$N^{tag}_{ev} = 6028$
purity = 92%



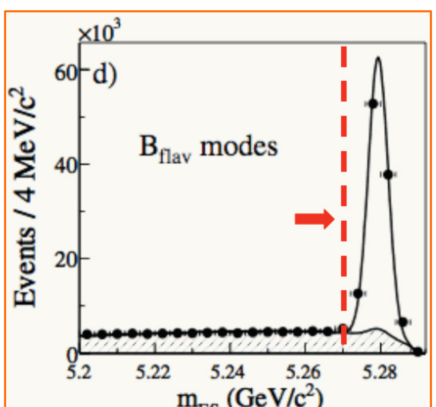
$(cc)K_L$ ($\eta_{CP} = +1$)

$N^{tag}_{ev} = 4323$
purity = 55%



$(cc)K^{0*}(K_S\pi^0)$
($\eta_{CP} = -1/+1$ admixture)

$N^{tag}_{ev} = 965$
purity = 68%

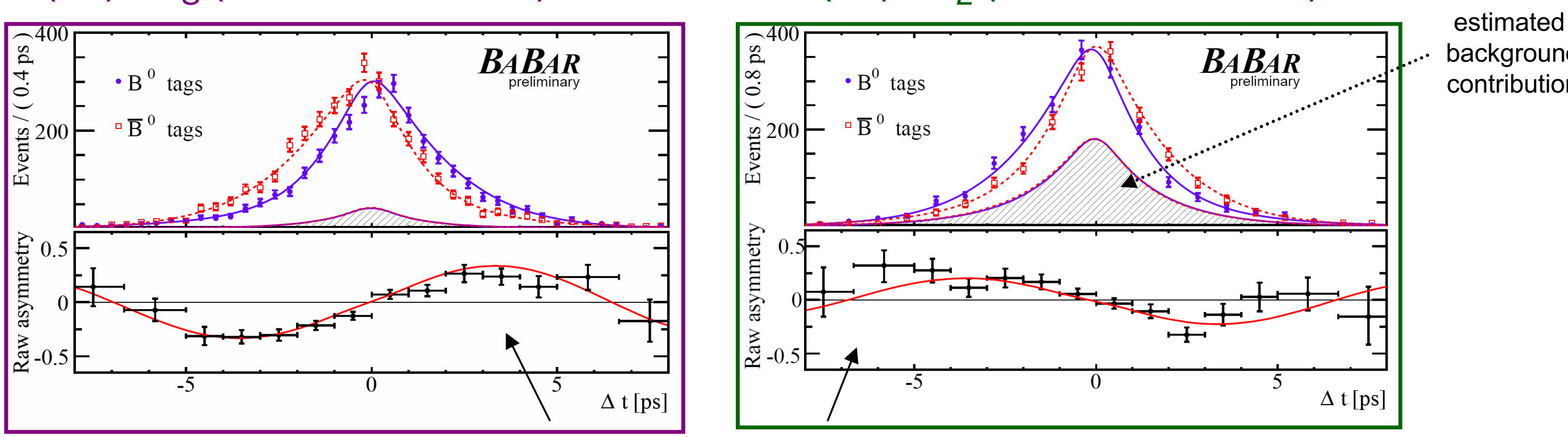


- Fully reconstructed flavor eigenstates (B_{flav} sample):
  - $D^{(*)}\, a_1/\rho/\pi$
  - $J/\psi K^{*0}(K^+\pi^-)$
- Use to determinate tagging and resolution parameters

$N^{tag}_{EV} = 112878$
purity = 83%

- Simultaneous fit to *CP* and B_{flav} samples to extract $\sin 2\beta$, λ_{golden}, tagging and resolution parameters

($c\bar{c}$) K^0_S (*CP*-odd modes) ($c\bar{c}$) K^0_L (*CP*-even mode)



raw asymmetry $\frac{N(\overline{B}^0) - N(B^0)}{N(\overline{B}^0) + N(B^0)}$ as function of Δt

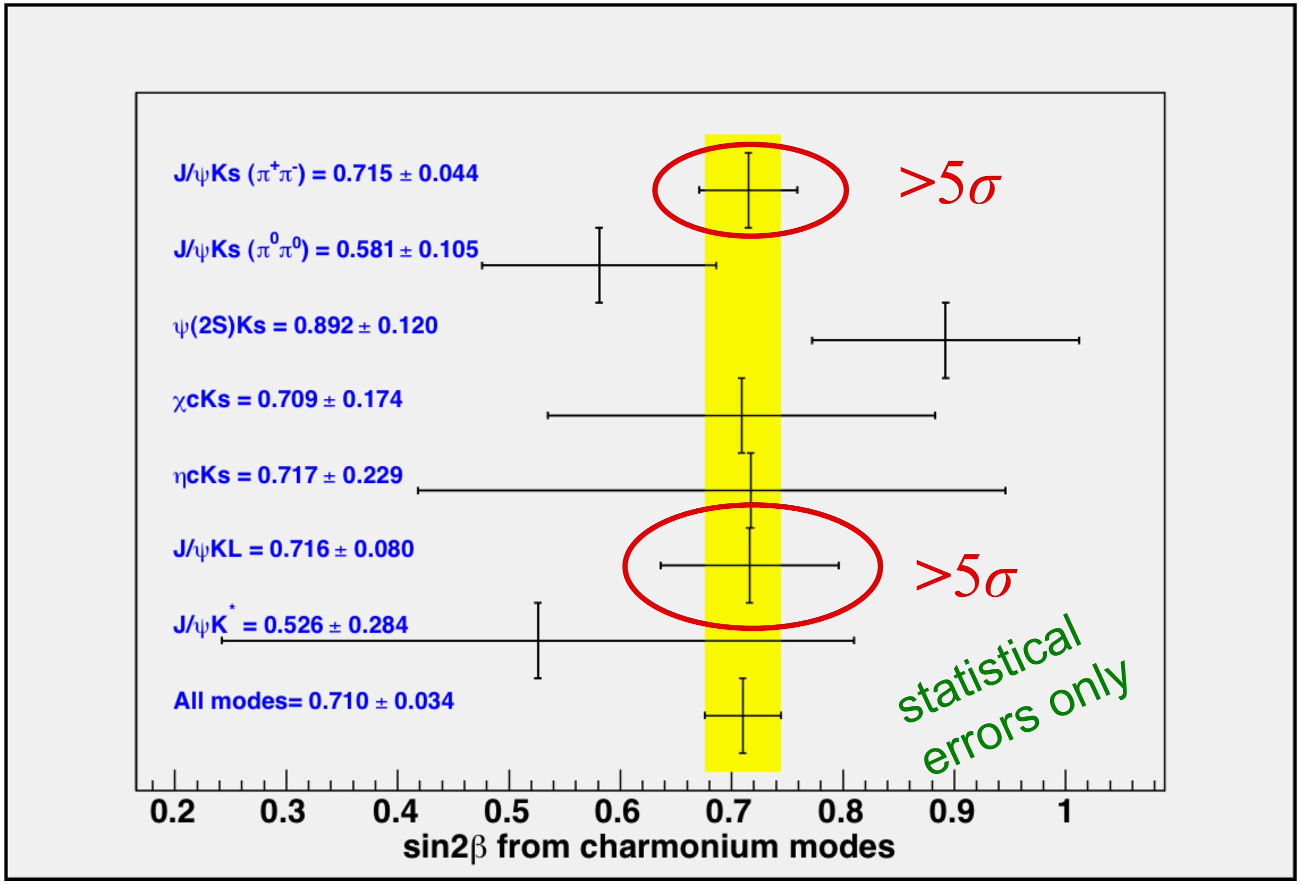
Preliminary with 316 fb^{-1}:

$\sin 2\beta = 0.710 \pm 0.034$ (stat) ± 0.019 (syst)
$|\lambda| = 0.932 \pm 0.026$ (stat) ± 0.017 (syst)

@ 205 fb^{-1} (Phys.Rev.Lett. 94 (2005), 161803) was:
$\sin 2\beta = 0.722 \pm 0.040 \pm 0.023$
$|\lambda| = 0.950 \pm 0.031 \pm 0.013$

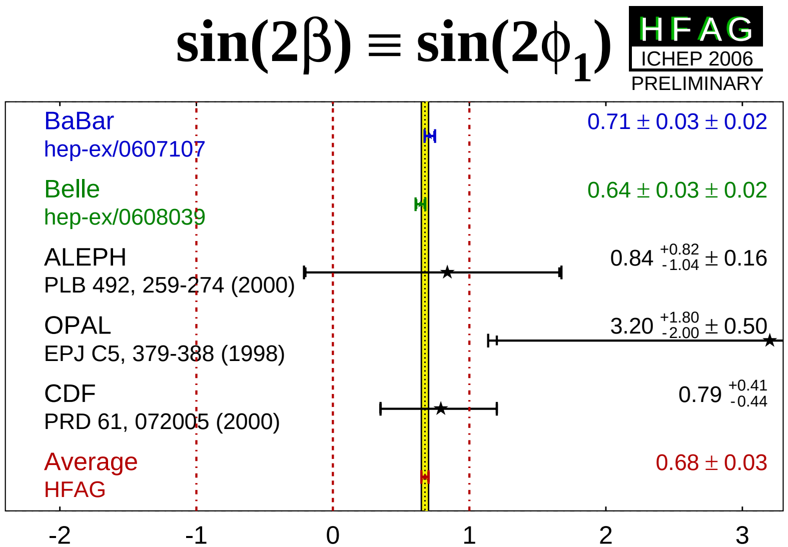
sin2β in "golden" modes: *BaBar* ICHEP 06 (preliminary)

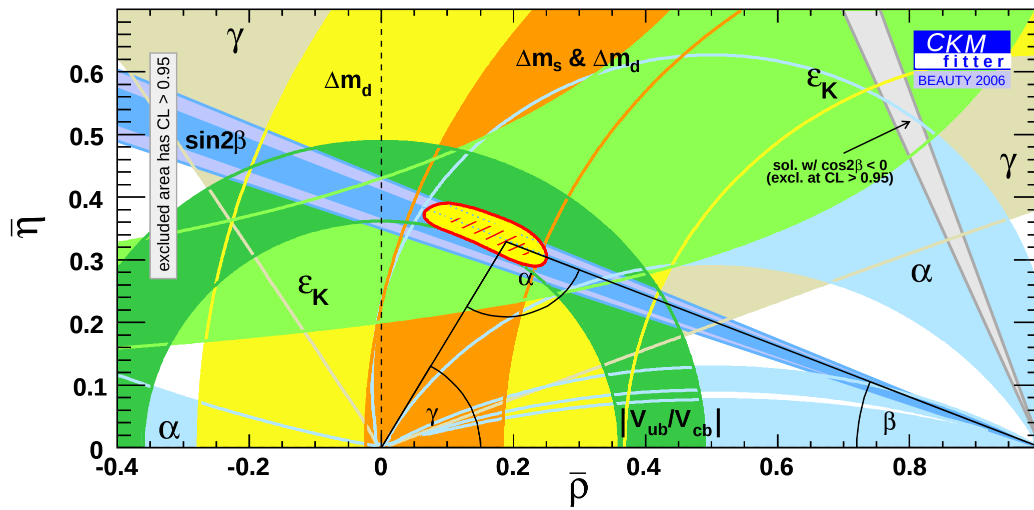
hep-ex/0607107

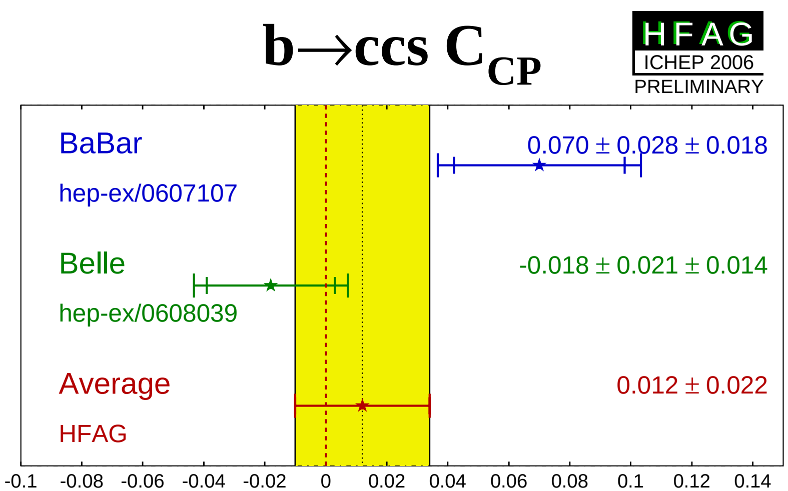


sin2β in "golden" modes:

Excellent agreement with global SM fit







Measurements of S in $B^0 \to J/\psi K^0$ by *BaBar* and Belle were the **first** observations of *CP* violation in *B* mesons (2002)

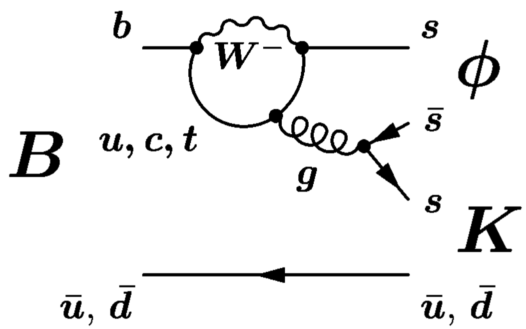
http://www.slac.stanford.edu/xorg/hfag/

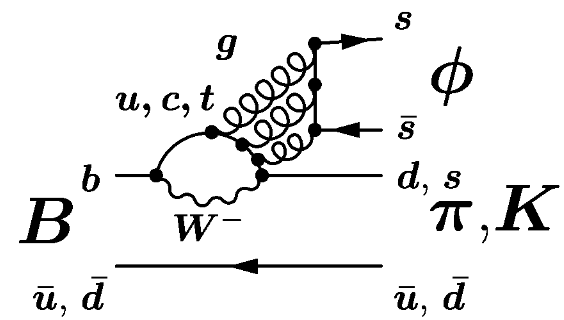
CKMfitter Group (J. Charles et al.), Eur. Phys. J. ***C41****:1-131 (2005)*

Decays dominated by gluonic penguins:
$B^0 \to \eta' K^0$, φK^0, $K^+K^-K_S$, $K_S\pi^0$, $K_SK_SK_S$, ωK_S, f_0K_S, etc.

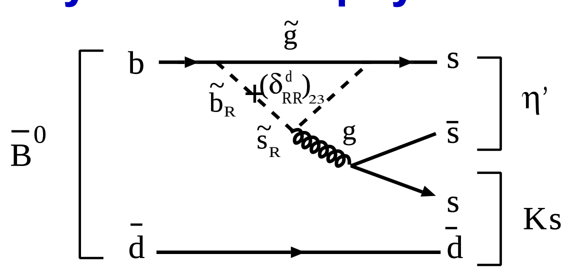
For example, consider
$B^0 \to \varphi K^0$ or $K_S K_S K_S$

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





- **Tree-level SM contributions are absent!**
- All other SM contributions are strongly suppressed
- SM penguins dominated by top-quark loops
  - ⇒ in SM, direct *CP* violation is small, ~1%
  - ⇒ and time-dependent *CP* violation is the same as in the "golden" charmonium-K^0 modes
- **Great sensitivity to non-SM physics in the loops!**



Decays dominated by gluonic penguins:

Indirect limits on the squark mixing matrix elements

B-meson factories

$$\begin{pmatrix} m^2_{\tilde{d}_L} & m_d(A_d - \mu \tan\beta) & (\Delta^d_{12})_{LL} & (\Delta^d_{12})_{LR} & (\Delta^d_{13})_{LL} & (\Delta^d_{13})_{LR} \\ & m^2_{\tilde{d}_R} & (\Delta^d_{12})_{RL} & (\Delta^d_{12})_{RR} & (\Delta^d_{13})_{RL} & (\Delta^d_{13})_{RR} \\ & & m^2_{\tilde{s}_L} & m_s(A_s - \mu \tan\beta) & (\Delta^d_{23})_{LL} & (\Delta^d_{23})_{LR} \\ & & & m^2_{\tilde{s}_R} & (\Delta^d_{23})_{RL} & (\Delta^d_{23})_{RR} \\ & & & & m^2_{\tilde{b}_L} & m_b(A_b - \mu \tan\beta) \\ & & & & & m^2_{\tilde{b}_R} \end{pmatrix}$$

LHC

Assuming all Δ's small and squarks nearly degenerate, we can use mass insertion approximation (MIA):

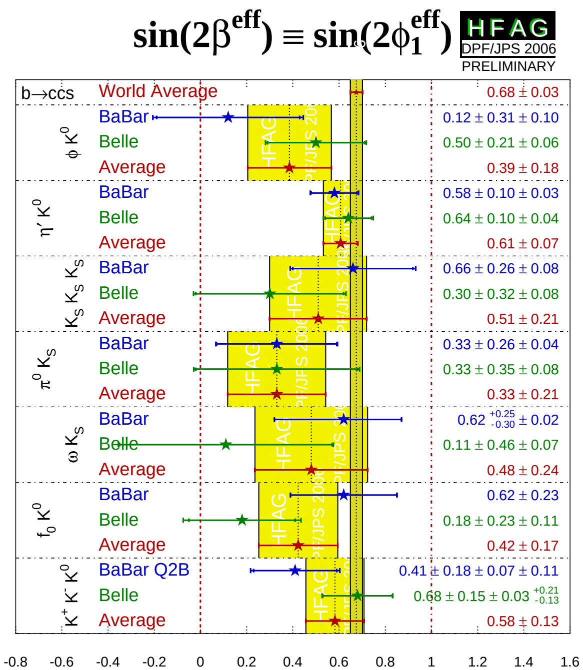
$$(\delta^d_{ij})_{AB} = \frac{(\Delta^d_{ij})_{AB}}{\tilde{m}^2}$$

Complementarity with the LHC is part of the physics case for a "Super *B* Factory"

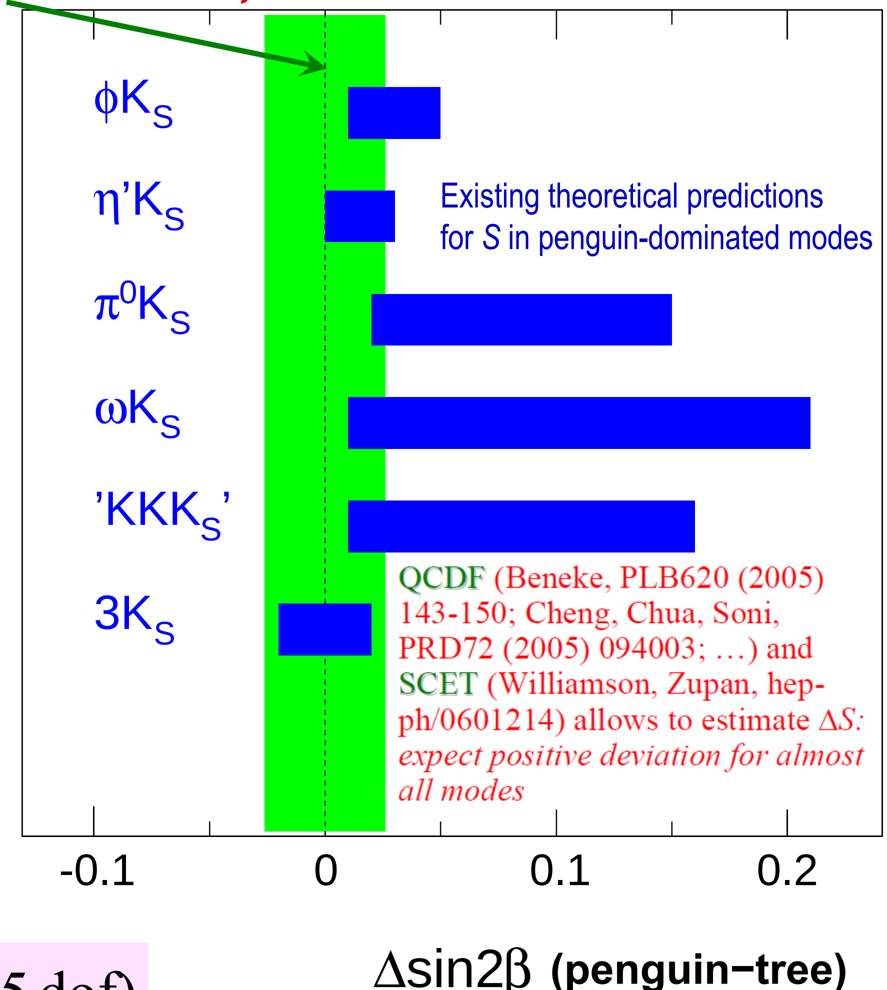
The world-average sin2β in penguin modes is 2.6σ less than in the "golden" modes

$$\left\langle \sin 2\beta_{\text{golden}} \right\rangle = 0.674 \pm 0.026$$

In 2004, the difference was 3.7σ…



experimental average

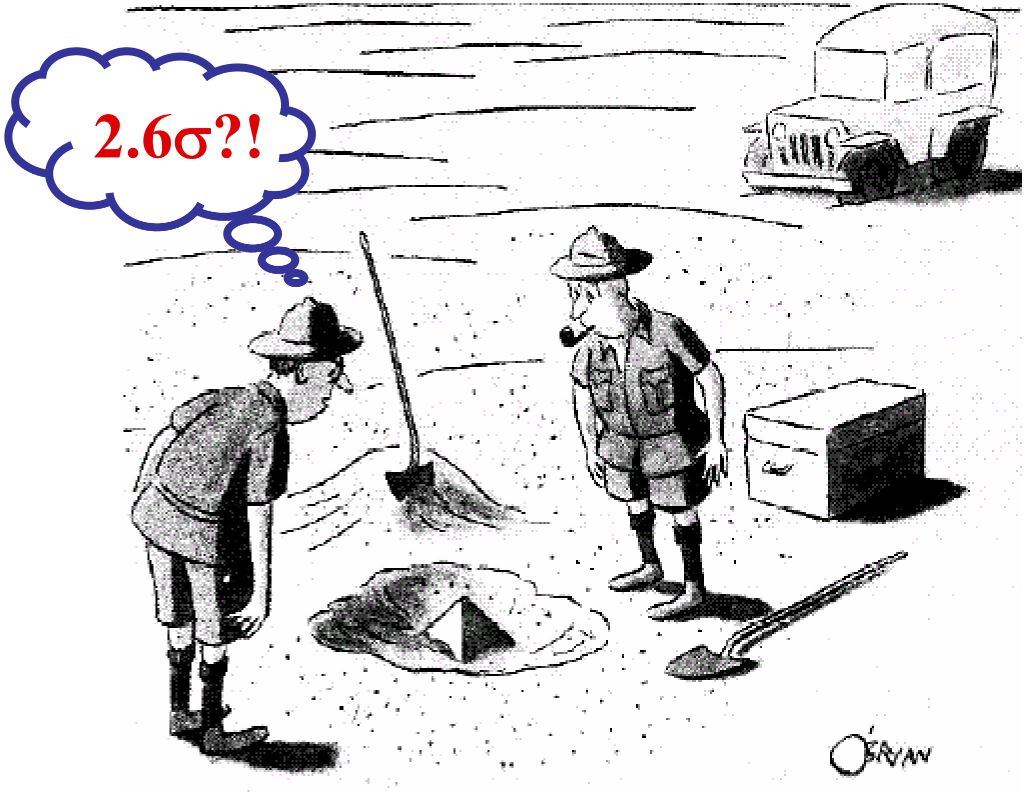


This is a very naive average

$$\left\langle \sin 2\beta_{\text{peng}} \right\rangle_{\text{naive}} = 0.53 \pm 0.05 \,(\chi^2 = 13/15\ \text{dof})$$

http://www.slac.stanford.edu/xorg/hfag/triangle/ichep2006/index.shtml

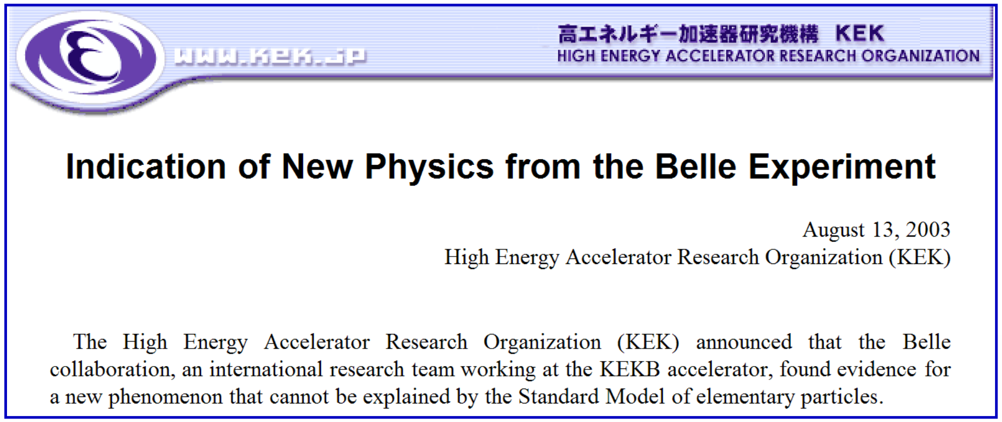
What do we make of this discrepancy?



"This could be the greatest discovery of the century. Depending, of course, on how far down it goes…"

$S_{\varphi K^0}$: another lesson on not getting too excited about 3σ-ish effects…

BaBar: hep-ex/0607112
Belle: hep-ex/0608039

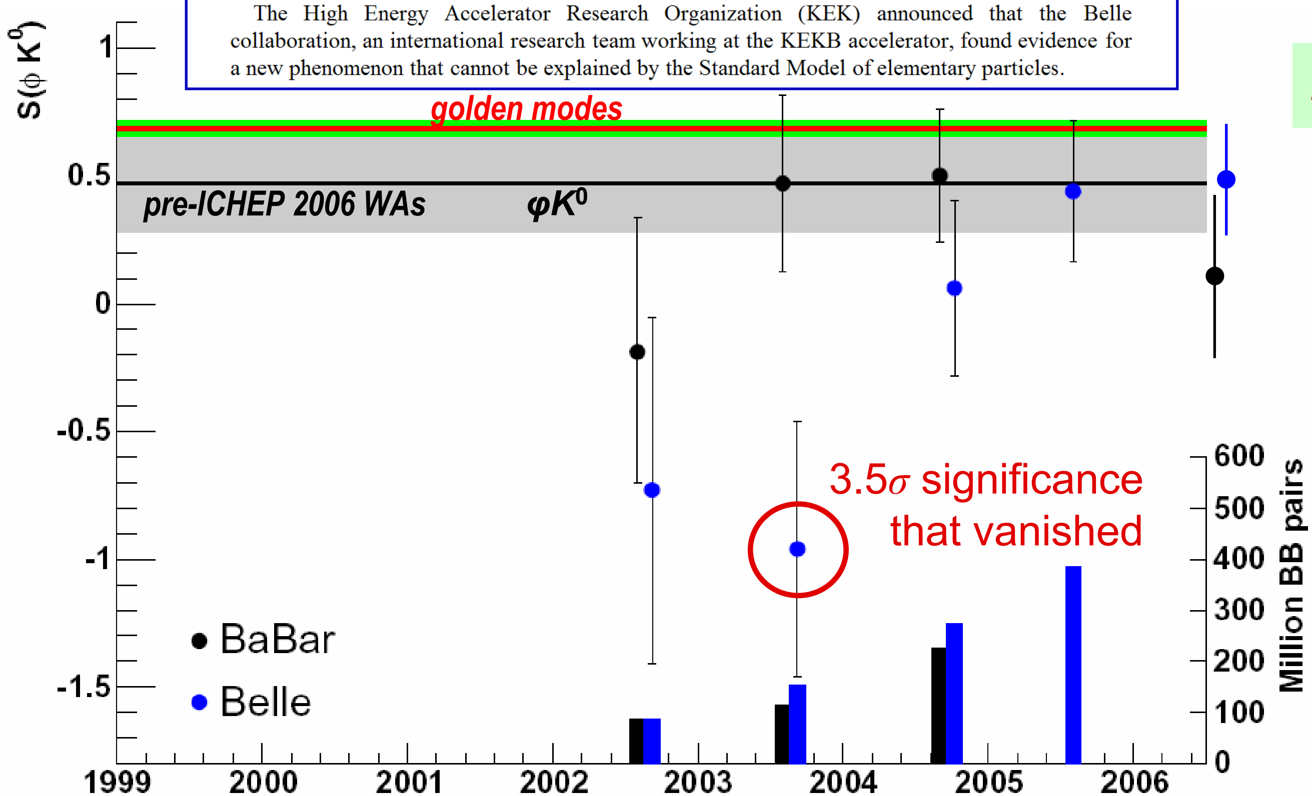


高エネルギー加速器研究機構 KEK
HIGH ENERGY ACCELERATOR RESEARCH ORGANIZATION
www.kek.jp

Indication of New Physics from the Belle Experiment

August 13, 2003
High Energy Accelerator Research Organization (KEK)

The High Energy Accelerator Research Organization (KEK) announced that the Belle collaboration, an international research team working at the KEKB accelerator, found evidence for a new phenomenon that cannot be explained by the Standard Model of elementary particles.



http://www.kek.jp/press/2003/belle3e.html

Currently, *BaBar:*

$$S_{\varphi K} = +0.12 \pm 0.31 \pm 0.10$$

Belle*:*

$$S_{\varphi K} = +0.50 \pm 0.21 \pm 0.06$$

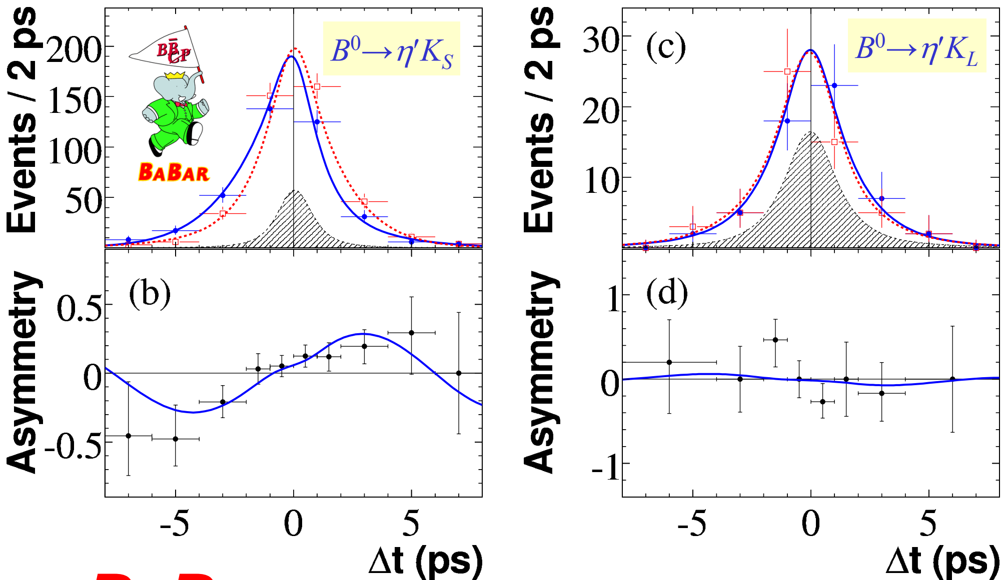
Both are consistent with the "golden" modes

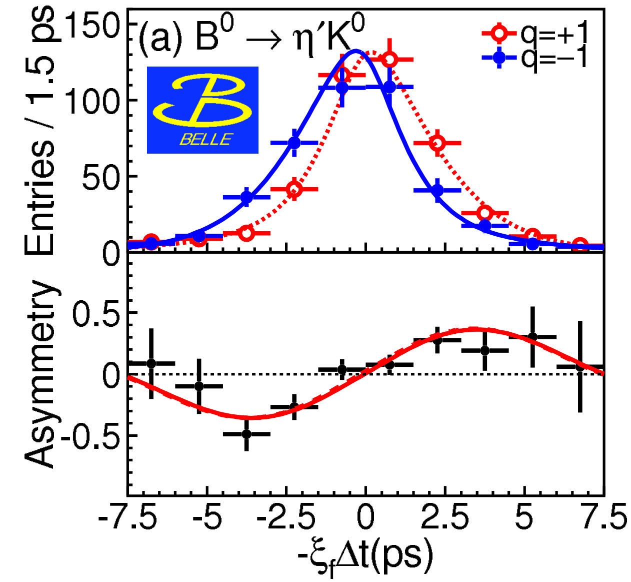
This happens to everyone…

This is one of the reasons two experiments is better than one

and the Phys. Rev. criterion for claiming "observation" is **5** standard deviations

CP violation in $B^0 \to \eta' K^0$





BaBar

$S_{\eta' K^0} = +0.58 \pm 0.10 \pm 0.03$ (5.5 σ)

$C_{\eta' K^0} = -0.16 \pm 0.07 \pm 0.03$

Belle

$S_{\eta' K^0} = +0.64 \pm 0.10 \pm 0.04$ (5.6 σ)

$C_{\eta' K^0} = +0.01 \pm 0.07 \pm 0.05$

Measurements of S in $B^0 \to \eta' K^0$ by *BaBar* and then Belle are the **second** observations of *CP* violation in *B* mesons (Fall 2006)

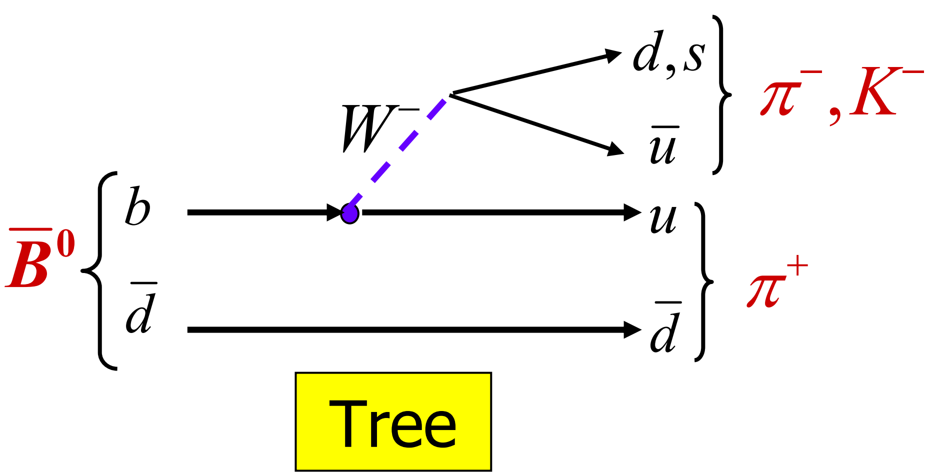
What's next?

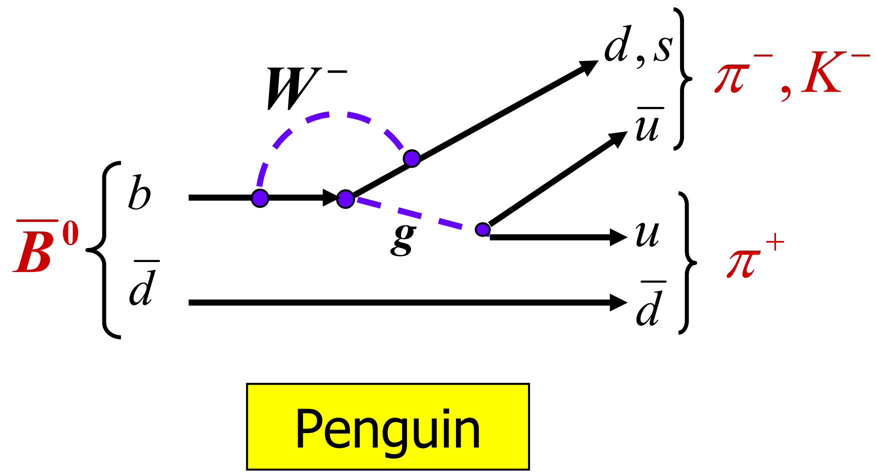
Measuring α with $B^0 \to \pi^+\pi^-$

$\mathcal{A}_{CP}(t)$ in $b \to u\bar{u}d$ decay to a *CP* eigenstate *at the tree level* :

Measure $180° - \beta - \gamma = \alpha \equiv \arg\left[\frac{-V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right]$ (in SM)

Penguins: $\mathcal{A}_{CP}(t) \Rightarrow \sin(2\alpha_{\text{eff}})$; $\alpha_{\text{eff}} = \alpha - \Delta\alpha$; direct $\mathcal{A}_{CP} \neq 0$

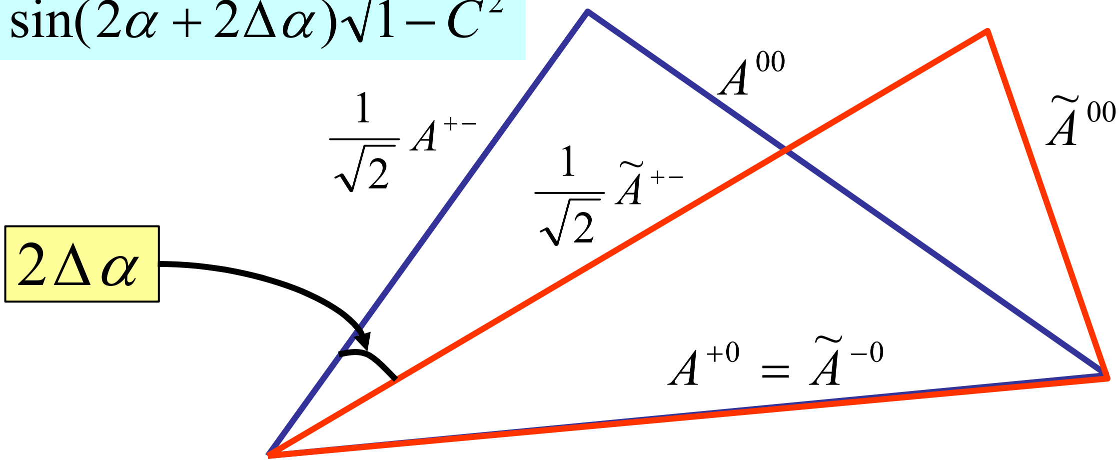




Isospin analysis in $B \to \pi\pi, \rho\rho$

M. Gronau, D. London, Phys. Rev. Lett. ***65****, 3381 (1990)*

$$S = \sin(2\alpha + 2\Delta\alpha)\sqrt{1 - C^2}$$



$$A^{+-} = A(B^0 \to \pi^+\pi^-)$$
$$\tilde{A}^{+-} = A(\overline{B}^0 \to \pi^+\pi^-)$$
$$A^{00} = A(B^0 \to \pi^0\pi^0)$$
$$\tilde{A}^{00} = A(\overline{B}^0 \to \pi^0\pi^0)$$
$$A^{+0} = A(B^+ \to \pi^+\pi^0)$$
$$\tilde{A}^{-0} = A(B^- \to \pi^-\pi^0)$$

In $B \to \rho\rho$, there are 3 such relations (one for each polarization)

6 unknowns, 6 observables in $\pi\pi$ (there is no vertex to measure $S_{\pi^0\pi^0}$)

5 observables in $\rho\rho$ (or 7, when both $C_{\rho^0\rho^0}$ and $S_{\rho^0\rho^0}$ are measured)

4-fold ambiguity in $2\Delta\alpha$: either triangle can flip up or down

$$A^{+0} = \frac{1}{\sqrt{2}} A^{+-} + A^{00}$$
$$\tilde{A}^{-0} = \frac{1}{\sqrt{2}} \tilde{A}^{+-} + \tilde{A}^{00}$$

$$A_{hh} = e^{+i\gamma}T + e^{-i\beta}P$$
$$\tilde{A}_{hh} = e^{-i\gamma}T + e^{+i\beta}P$$

Neglecting EW penguins, ±0 is a pure tree mode, and so the two triangles share a common side:

$$A(B^+ \to h^+h^0) = \tilde{A}(B^- \to h^-h^0)$$

The "classic" $B^0 \to h^+h^-$ analysis

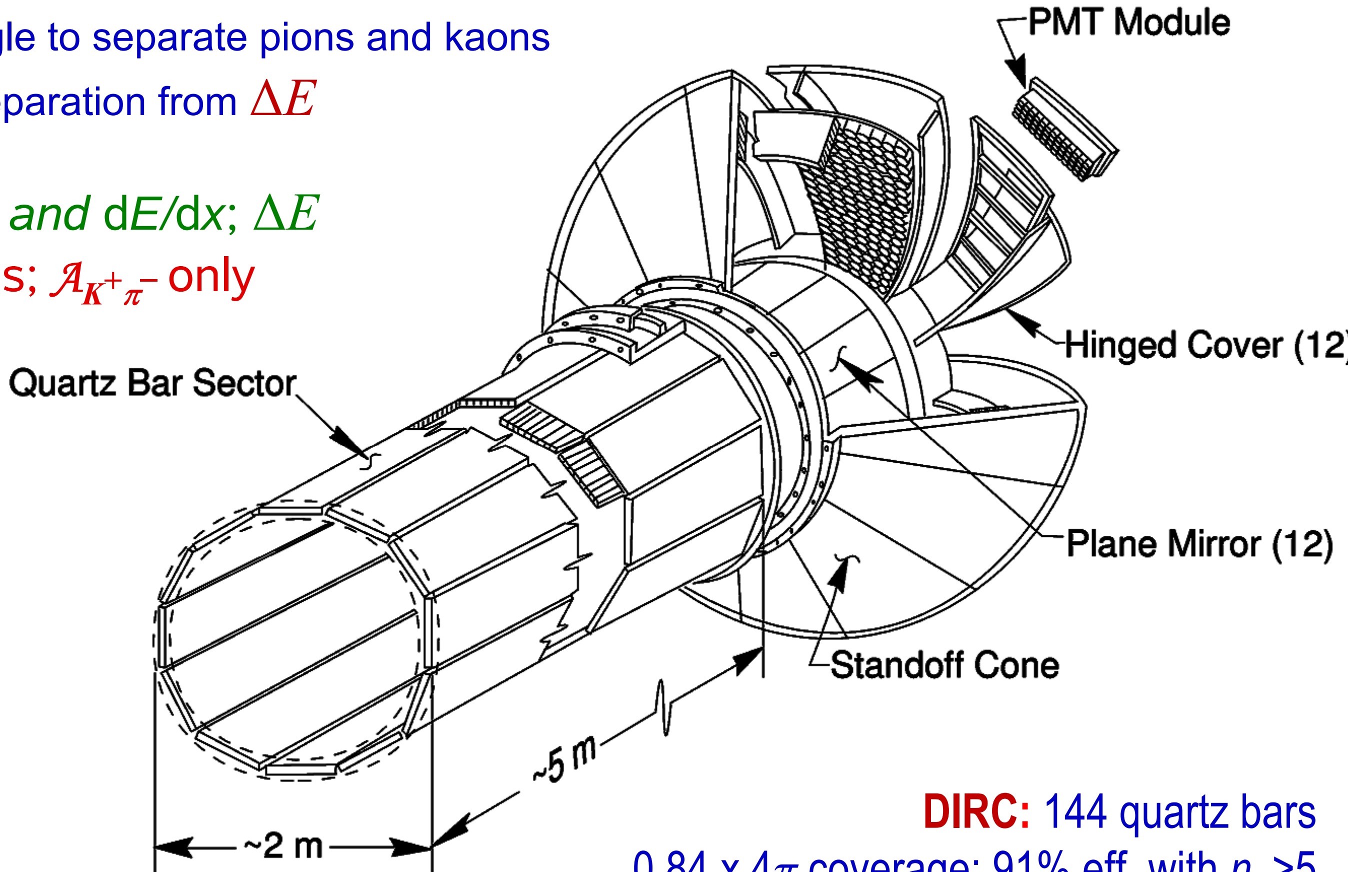
Simultaneous ML fit to $B^0 \to \pi^+\pi^-, K^+\pi^-, \pi^+K^-, K^+K^-$

Using DIRC Cherenkov angle to separate pions and kaons

Additional $\pi\pi / K\pi / KK$ separation from ΔE

Belle: PID with aerogel and dE/dx; ΔE

CDF: dE/dx and *B* mass; $\mathcal{A}_{K^+\pi^-}$ only



DIRC: 144 quartz bars

0.84 x 4π coverage; 91% eff. with n_γ>5

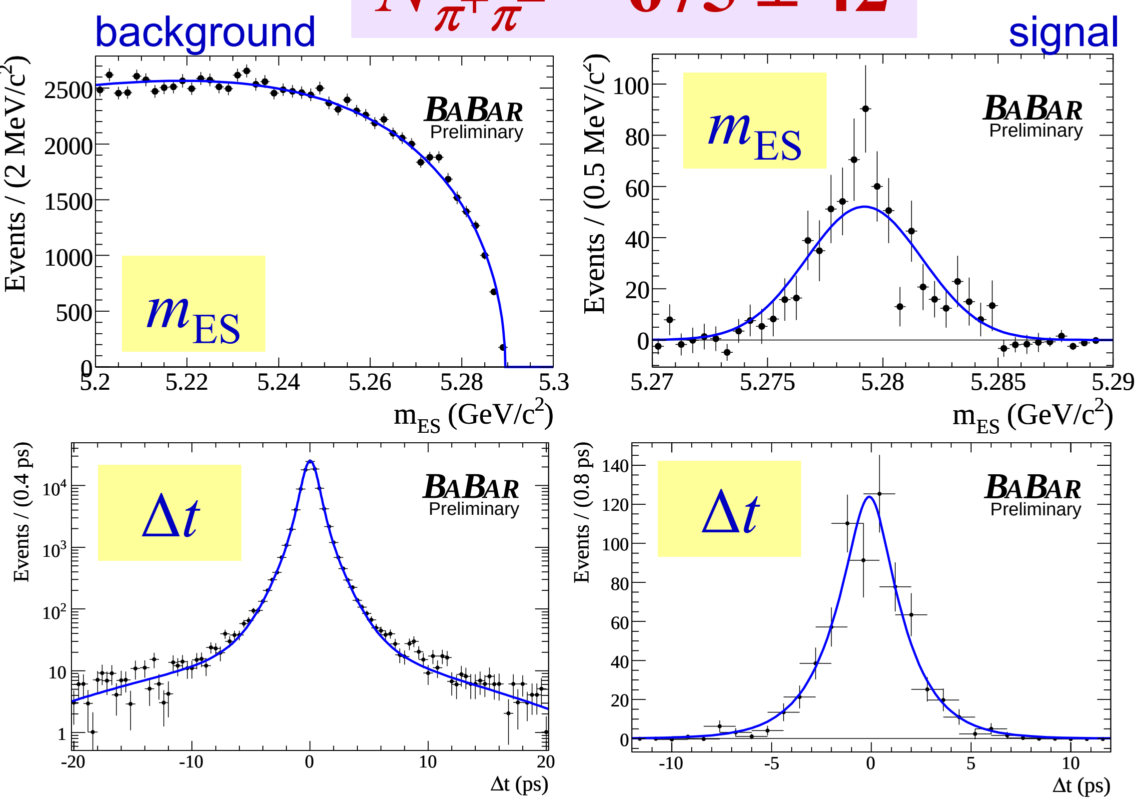
13σ π/K separation at 1.5 GeV/*c*, 2.5σ at 4.5 GeV/*c*

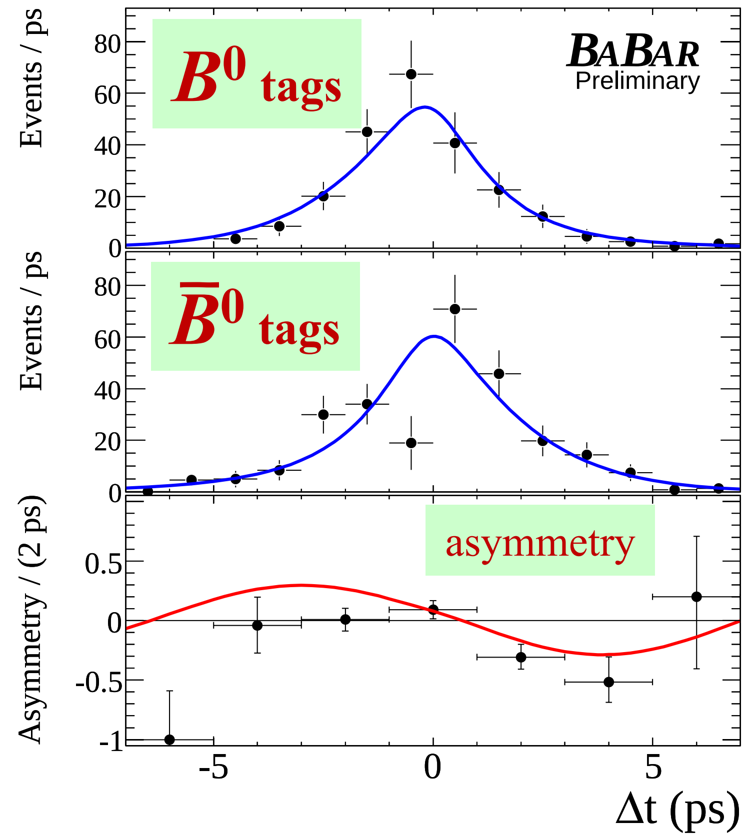
Calibration sample: $B^- \to \pi^- D^0$, $D^0 \to \pi^+ K^-$

ICHEP'06 *BaBar* results: $B^0 \rightarrow \pi^+\pi^-$ (1)

BaBar-CONF-06/039 (hep-ex/0607106)

$$N_{\pi^+\pi^-} = 675 \pm 42$$





${}_s\mathcal{P}lot$: Builds a histogram of x excluding it from the Maximum-Likelihood fit, assigning a weight to each event, keeping all signal events, getting rid of all background events, and keeping track of the statistical errors in each x bin

M. Pivk and F. R. Le Diberder,
"sPlot: a statistical tool to unfold data distributions,"
*Nucl. Instrum. Meth. A **555**, 356 (2005)*
[arXiv:physics/0402083].

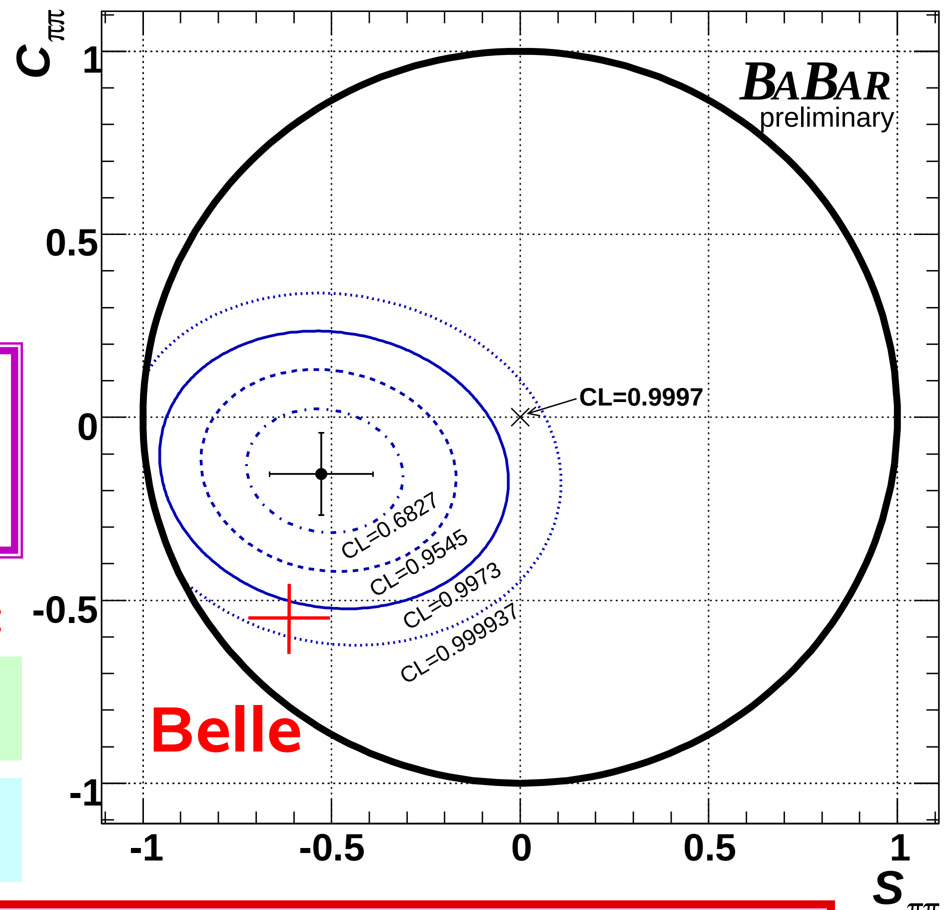
ICHEP'06 results: $B^0 \to \pi^+\pi^-$ (2)

BaBar: hep-ex/0607106; Belle: hep-ex/0608035

BaBar **has observed a 3.6 σ evidence for *CP* violation in $B^0 \to \pi^+\pi^-$**

$$S_{\pi\pi} = -0.53 \pm 0.14 \pm 0.02$$

$$C_{\pi\pi} = -0.16 \pm 0.11 \pm 0.03$$



Nota bene: (keep in mind for now)

BaBar: 347 million $B\bar{B}$ pairs, 675 ± 42 $\pi^+\pi^-$
Belle: 535 million $B\bar{B}$ pairs, 1464 ± 65 $\pi^+\pi^-$
Belle has x1.4 more $\pi^+\pi^-$ per fb^{-1} than *BaBar*!

Belle (updated and submitted to PRL):

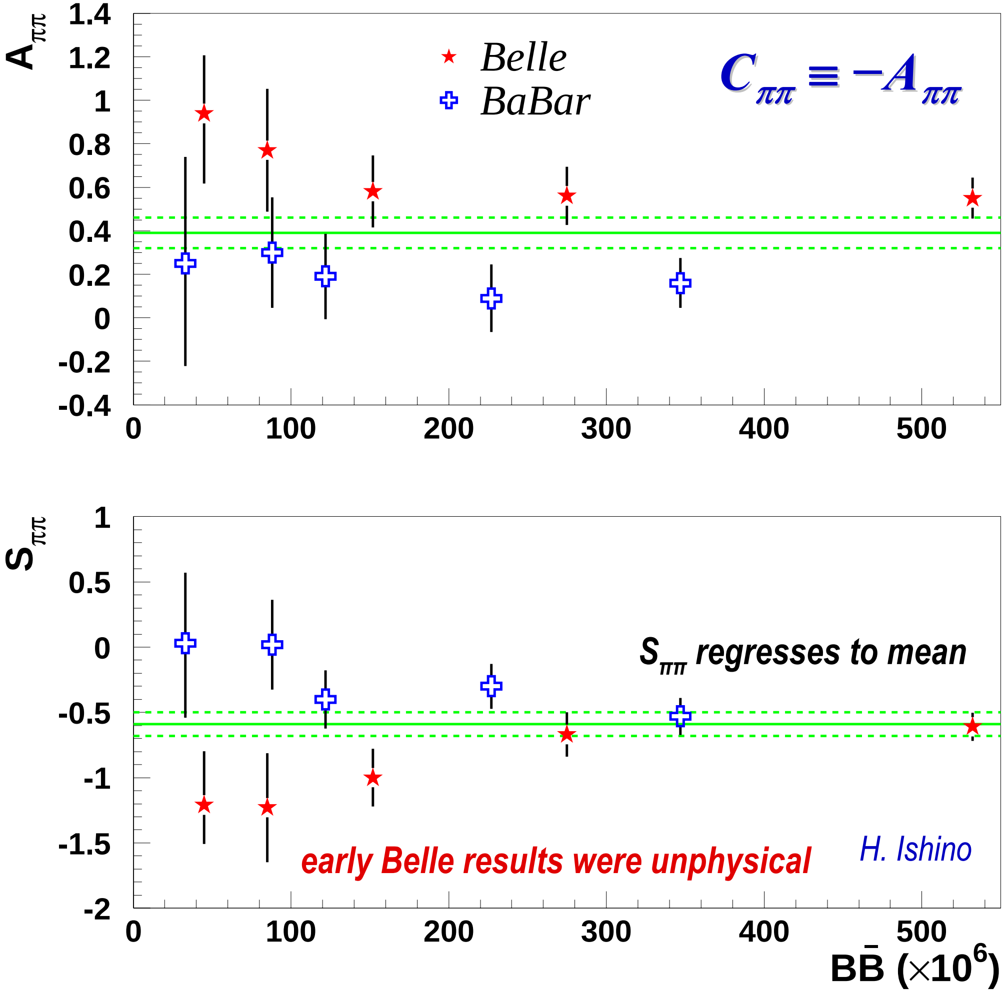
$$S_{\pi\pi} = -0.61 \pm 0.10 \pm 0.04 \quad (5.3\,\sigma)$$

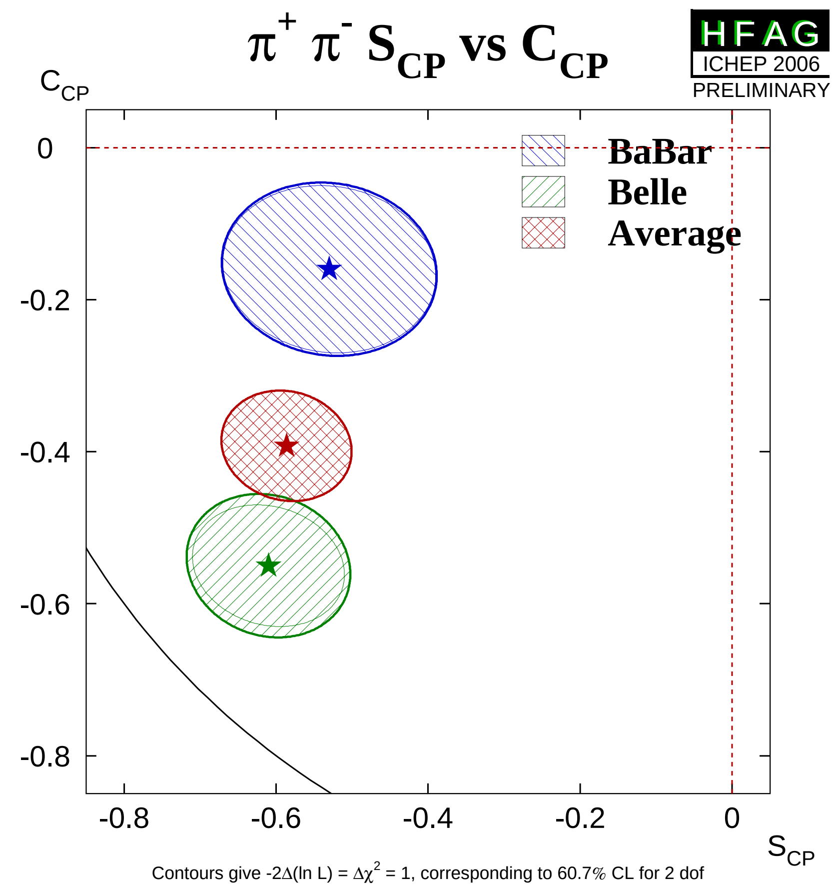
$$C_{\pi\pi} = -0.55 \pm 0.08 \pm 0.05 \quad (5.5\,\sigma)$$

Belle recently claimed observations of both S and C in $B^0 \to \pi^+\pi^-$

History of $B^0 \to \pi^+\pi^-$ results

There exists a history of disagreement between Belle and *BaBar* on $B^0 \to \pi^+\pi^-$
A 2.3σ difference is still here as of Summer 2006





The $B \to \pi^{\pm}\pi^0, \pi^0\pi^0$ analysis

Simultaneous fit to $B^0 \to \pi^+\pi^0, K^+\pi^0$ (using DIRC Cherenkov angle to separate pions and kaons)
$B^0 \to \pi^0\pi^0$: branching fraction and time-integrated direct *CP* asymmetry

NEW in 2006: in addition to $\pi^0 \to \gamma\gamma$, *we use merged* π^0 *and* $\gamma \to e^+e^-$ *conversions*

⇒ 10% efficiency increase per π^0 (4% from merged π^0, 6% from γ conversions)

merged π^0 **:**

the two photons are too close to one another in the EMC to be reconstructed individually; can be recovered using

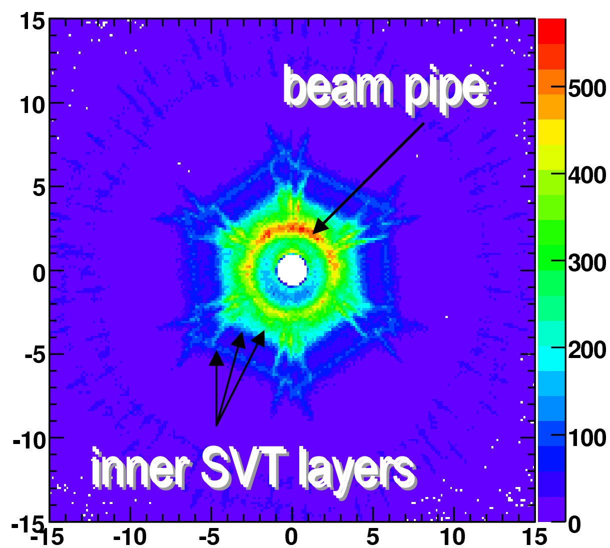
$$M^2_{\pi^0} \approx E^2_{\pi^0}(S_{\pi^0} - S_\gamma),$$

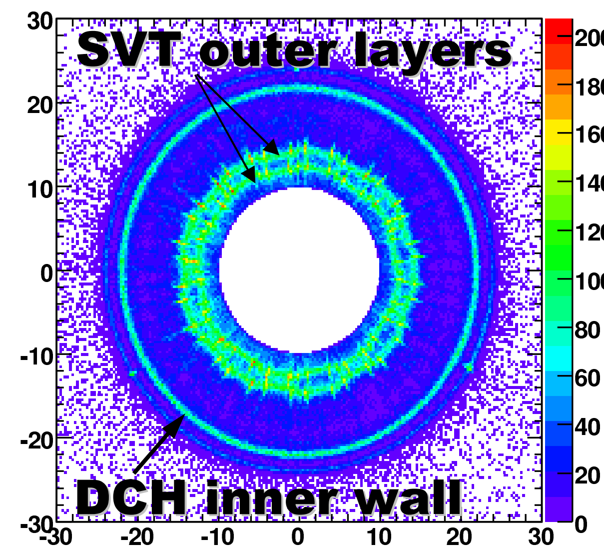
where *S* is the second EMC moment of the merged $\pi^0 \to \gamma\gamma$

The control sample: $\tau \to \rho\nu$

$\gamma \to e^+e^-$ **conversions:**

result from interactions with detector elements



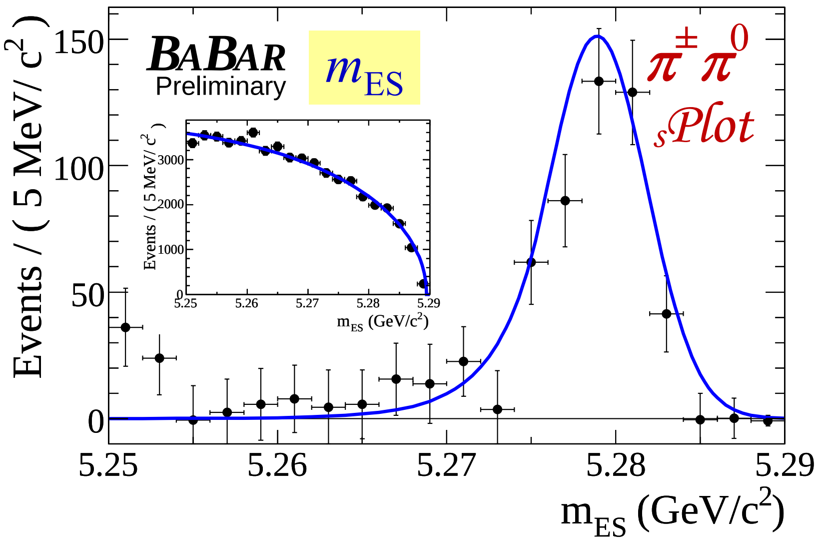


in a Super *B factory*, one can imagine measuring $S_{\pi^0\pi^0}$ with conversions!

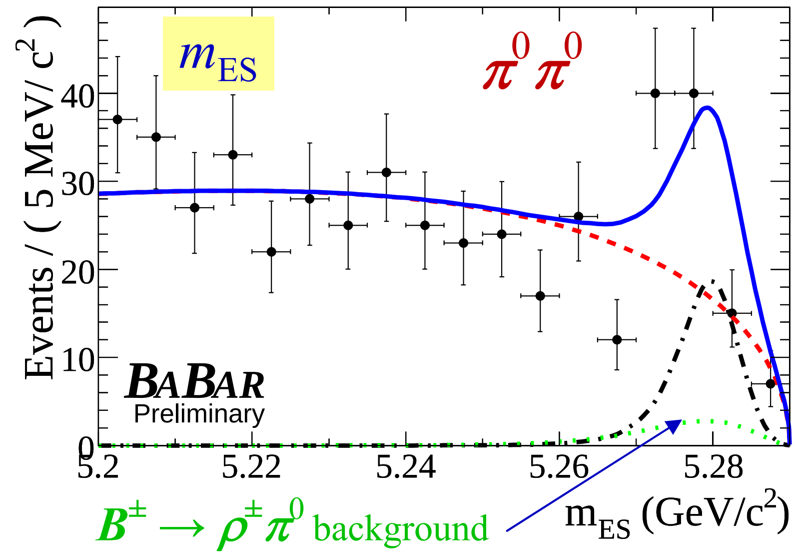
New *BaBar* results: $B \to \pi^{\pm}\pi^{0}, \pi^{0}\pi^{0}$

hep-ex/0607106

$N_{\pi^{\pm}\pi^{0}} = 572 \pm 53$



$N_{\pi^{0}\pi^{0}} = 140 \pm 25$



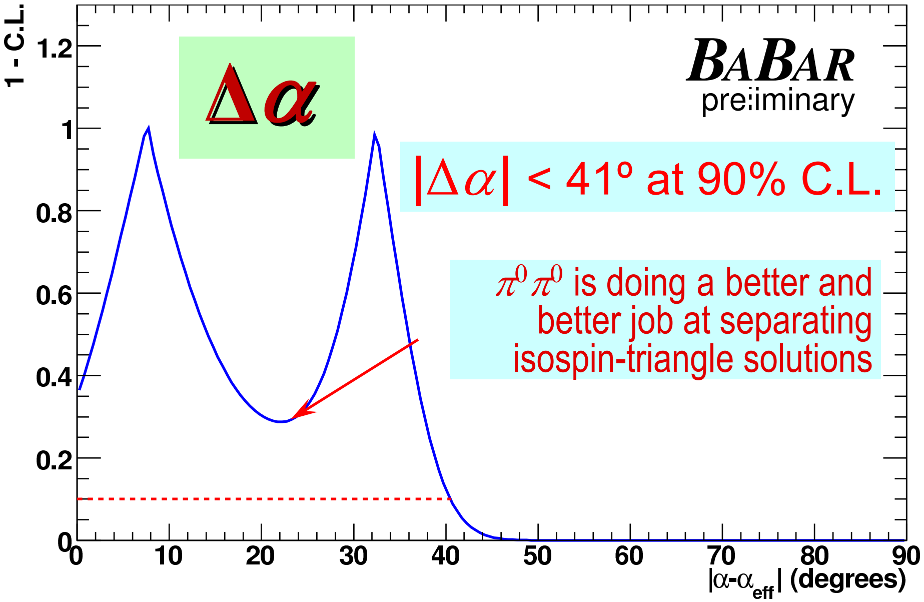
$\mathcal{B}r_{\pi^{\pm}\pi^{0}} = (5.12 \pm 0.47 \pm 0.29) \times 10^{-6}$

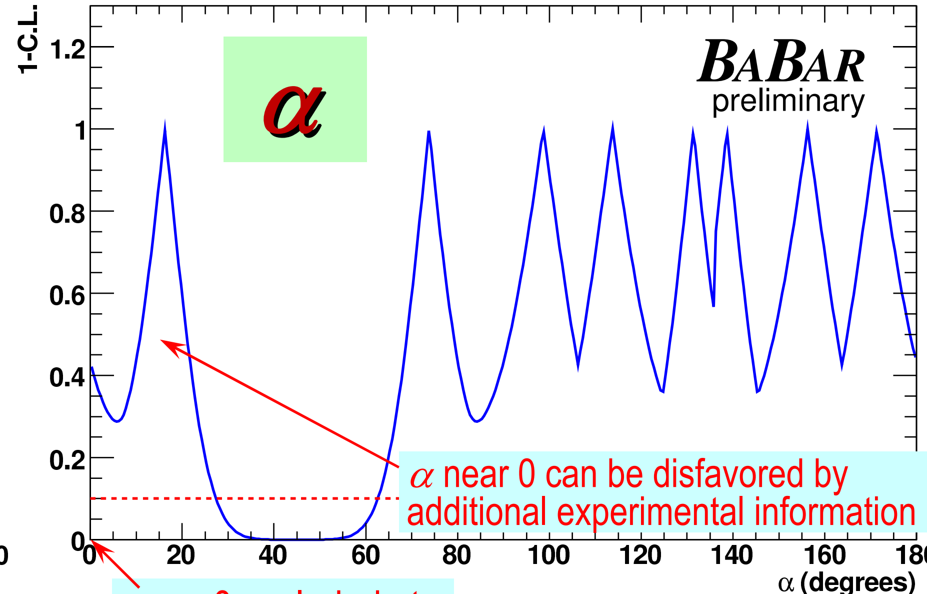
$\mathcal{B}r_{\pi^{0}\pi^{0}} = (1.48 \pm 0.26 \pm 0.12) \times 10^{-6}$

$C_{\pi^{0}\pi^{0}} = -0.33 \pm 0.36 \pm 0.08$

An interpretation of *BaBar* ICHEP'06 $B \to \pi\pi$ results

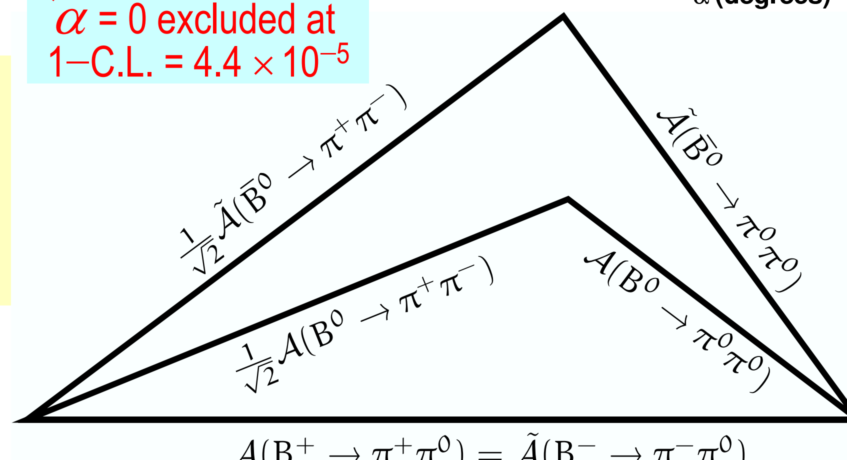
hep-ex/0607106





This is a <u>frequentist</u> interpretation: we use only the $B \to \pi\pi$ isospin-triangle relations in arriving at these constraints on $\Delta\alpha = \alpha - \alpha_{eff}$ and on α itself

Here is one of the possible solutions to the Gronau-London isospin triangle in $B \to \pi\pi$ according to the central values of the Summer 2006 BaBar results:

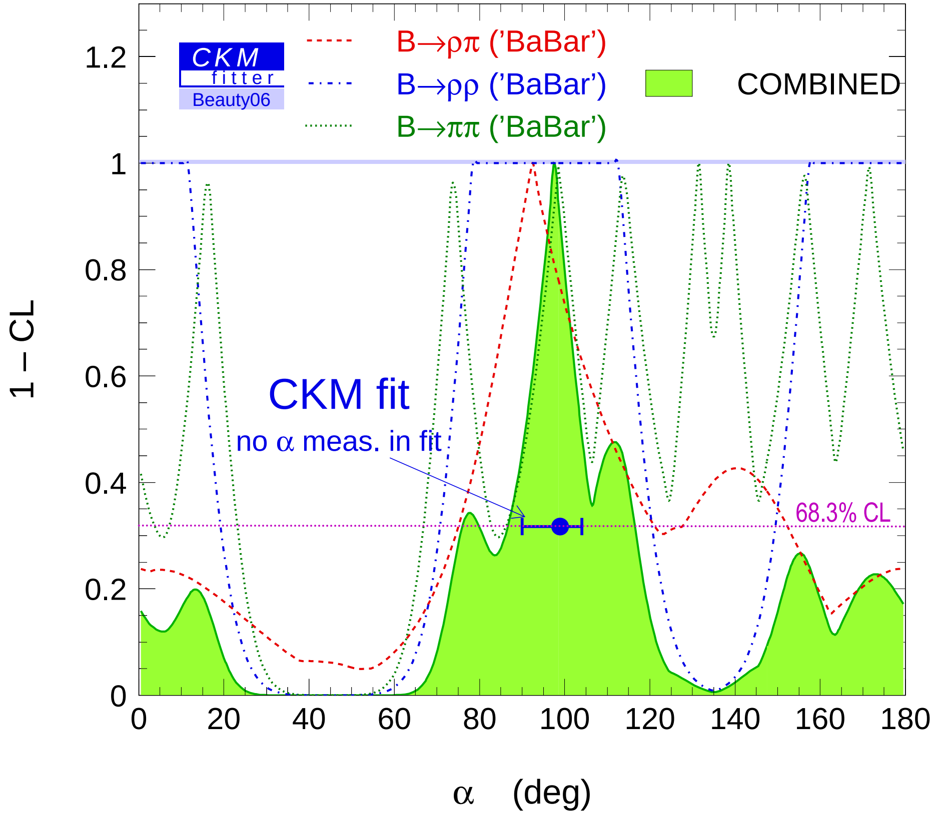


Global fits for the value of α

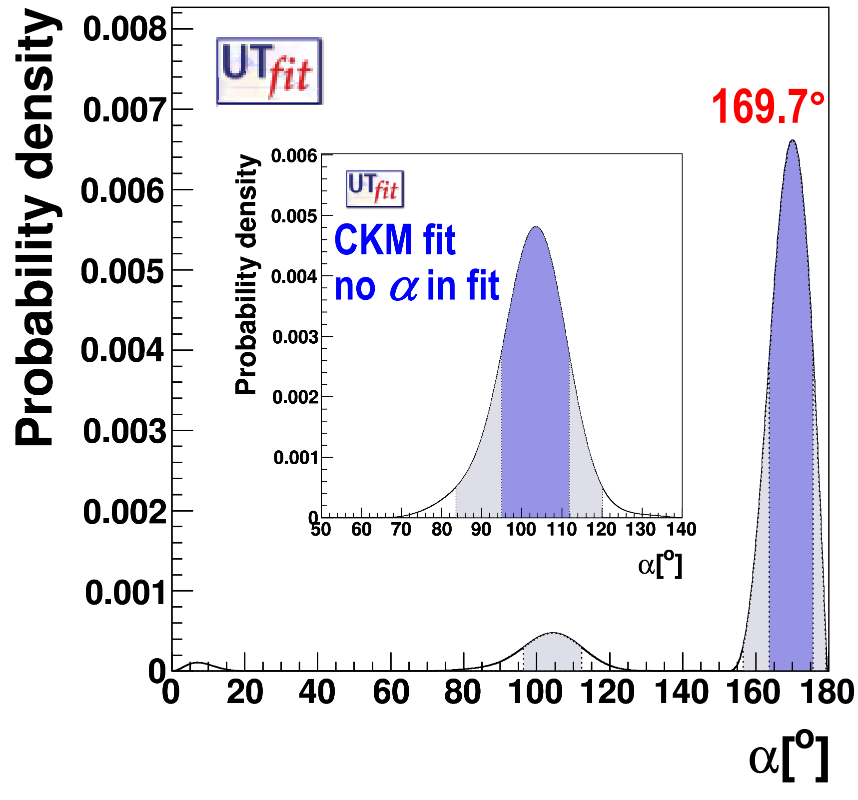
BaBar only, ICHEP'06

Two interpretations currently exist that convert the $B \rightarrow \pi\pi, \rho\pi, \rho\rho$ measurements to constraints on α:

Frequentist, only the isospin triangle relations used



Baesian, various model-dependent choices of priors



CKMfitter Group (J. Charles et al.), Eur. Phys. J. C**41**, 1-131 (2005), [hep-ph/0406184],
updated results and plots available at http://ckmfitter.in2p3.fr

M. Ciuchini, G. D'Agostini, E. Franco, V. Lubicz, G. Martinelli, F. Parodi, P. Roudeau, A. Stocchi, JHEP **0107** (2001) 013 [hep-ph/0012308],
updated results and plots available at http://utfit.roma1.infn.it

2006 preliminary results: $B^0 \to K^+\pi^-$

BaBar: hep-ex/0607106; Belle: ICHEP'06; CDF: DPF'06

BaBar: $\mathcal{A}_{K^+\pi^-} = -0.108 \pm 0.024 \pm 0.008$ *(ICHEP'06)*

Belle: $\mathcal{A}_{K^+\pi^-} = -0.093 \pm 0.018 \pm 0.008$ *(ICHEP'06)*

CDF: $\mathcal{A}_{K^+\pi^-} = -0.086 \pm 0.023 \pm 0.009$ *(DPF'06)*

$$\mathcal{A}_{K^+\pi^-}(\mathrm{WA}) = -0.095 \pm 0.013 \ (>7\sigma)$$

no single-experiment 5σ observation yet

Predicted to be ≈ $\mathcal{A}_{K^+\pi^0}(\mathrm{WA}) = +0.047 \pm 0.026$

4.8 σ difference: an "$\mathcal{A}_{K\pi}$ puzzle"

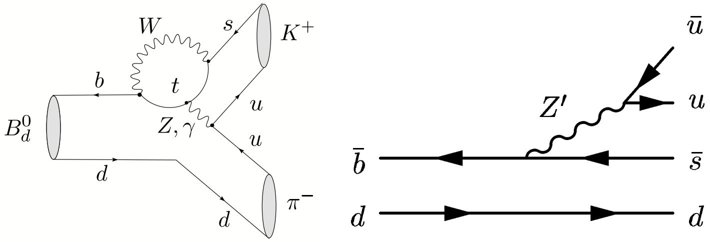
– Could be due to hadronic effects, not New Physics
(see R. Fleischer, hep-ph/0701217)

Looking for New Physics in $B^0 \to \pi^+\pi^-$, $B^0 \to K^+\pi^-$

This is just an example!

R. Fleischer, hep-ph/0701217, hep-ph/0608010; V. Barger et al., hep-ph/0406126

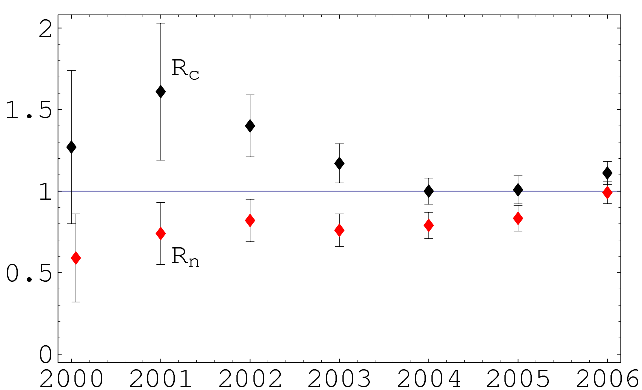
New Physics can enter through loops or even trees (e.g., FCNC Z')

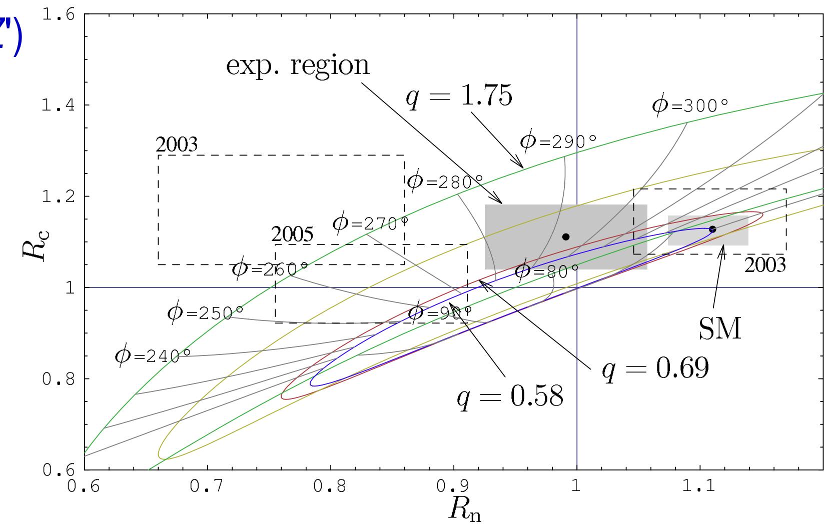


From Standard Model using *SU*(3), the ratio of the EW penguin and tree amplitudes *q* = 0.60 and their relative phase φ = 0.

$$R_c \equiv 2\left[\frac{\mathrm{BR}(B^\pm \to \pi^0 K^\pm)}{\mathrm{BR}(B^\pm \to \pi^\pm K^0)}\right] \stackrel{\text{exp}}{=} 1.11 \pm 0.07$$

$$R_n \equiv \frac{1}{2}\left[\frac{\mathrm{BR}(B_d \to \pi^\mp K^\pm)}{\mathrm{BR}(B_d \to \pi^0 K^0)}\right] \stackrel{\text{exp}}{=} 0.99 \pm 0.07$$





Before ICHEP 06 preliminary results:

$$q = 0.99\,^{+0.66}_{-0.70}, \quad \phi = -(94\,^{+16}_{-17})^\circ$$

Now the situation is much better:

$$q = 0.65^{+0.39}_{-0.35}, \quad \phi = -(52^{+21}_{-50})^\circ$$

Agrees with global SM fit and α, β measurements:

$$\gamma = \left(70.0^{+3.8}_{-4.3}\right)^\circ$$

Also predicted by *SU*(3):

$$C_{\pi\pi} = 2.5 \times \mathcal{A}_{K^+\pi^-} = -0.24$$

π/K separation with DCH dE/dx:

Catching up with Belle's $B^0 \to h^+h^-$ reconstruction efficiency

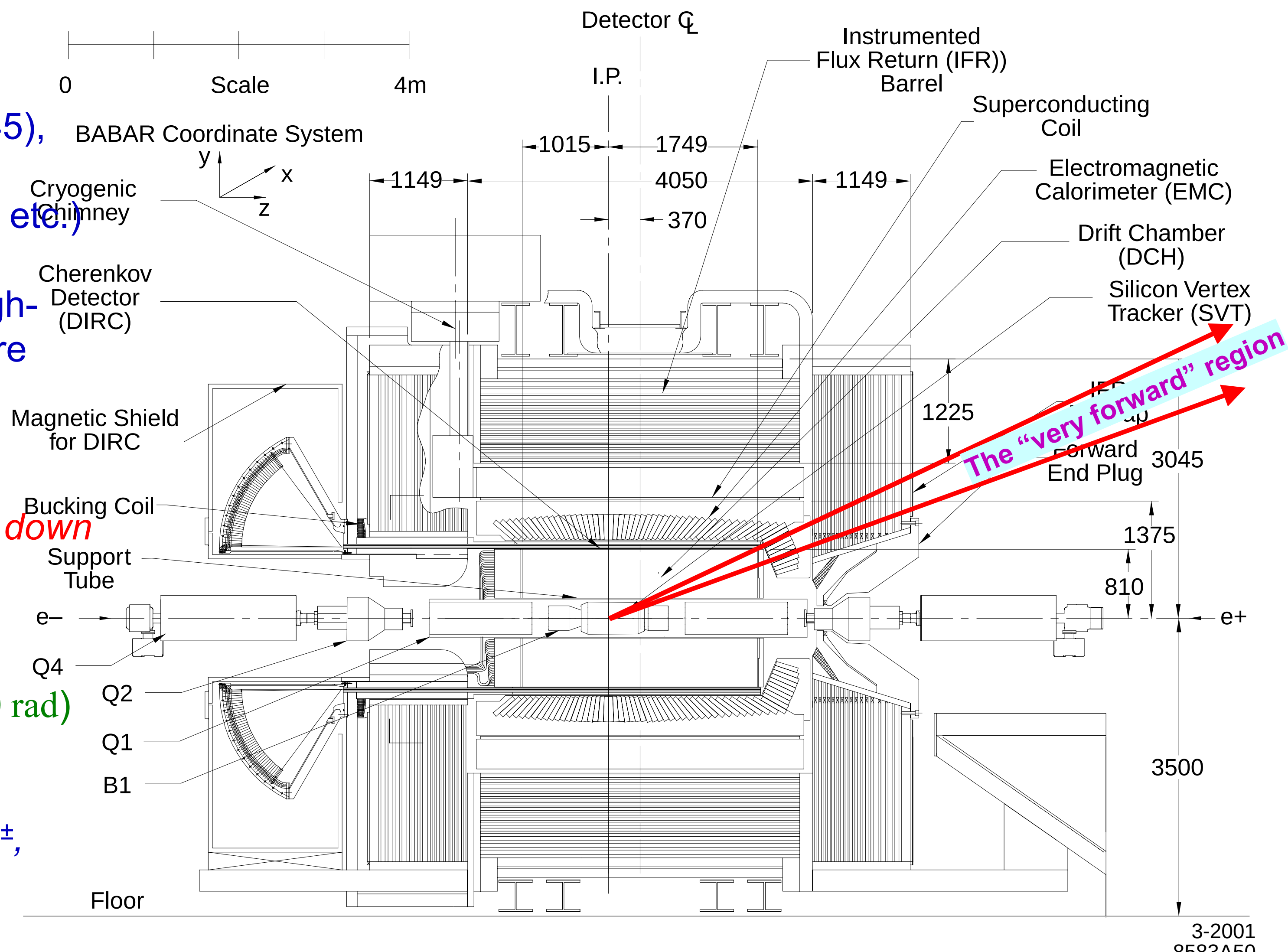
In the <u>barrel</u> (θ>0.445), the DIRC is ~9.3% inefficient (φ cracks, etc.)

Another ~12% of high-momentum tracks are outside the DIRC acceptance in θ.

We use DCH tracks down to θ = 0.35 rad

($J/\psi \to \mu^+\mu^-$ in sin2β analysis: down to 0.30 rad)

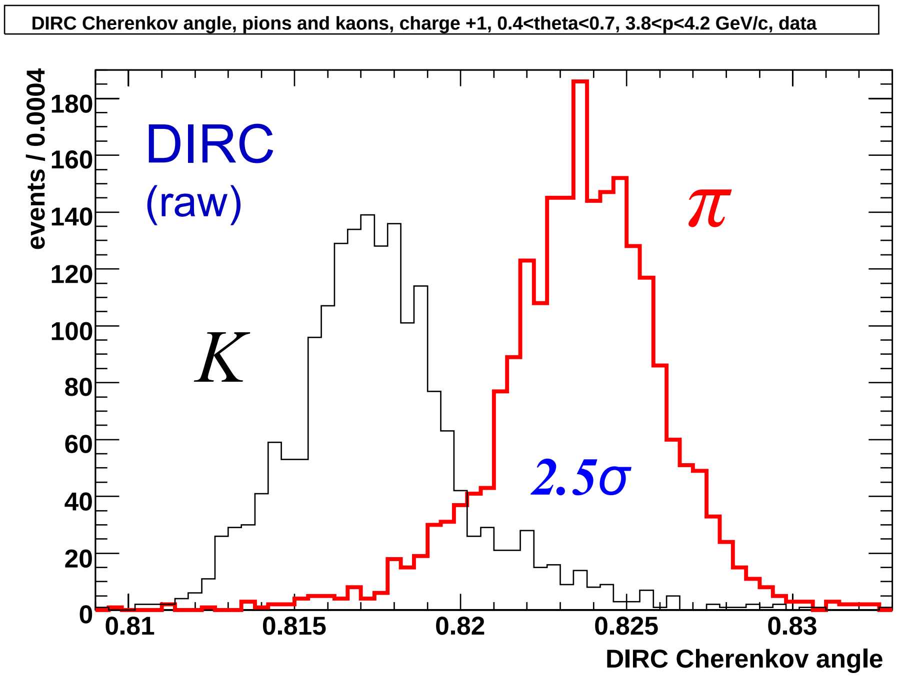
→16% event-yield increase for $B \to Xh^{\pm}$, 35% for $B^0 \to h^+ h^-$

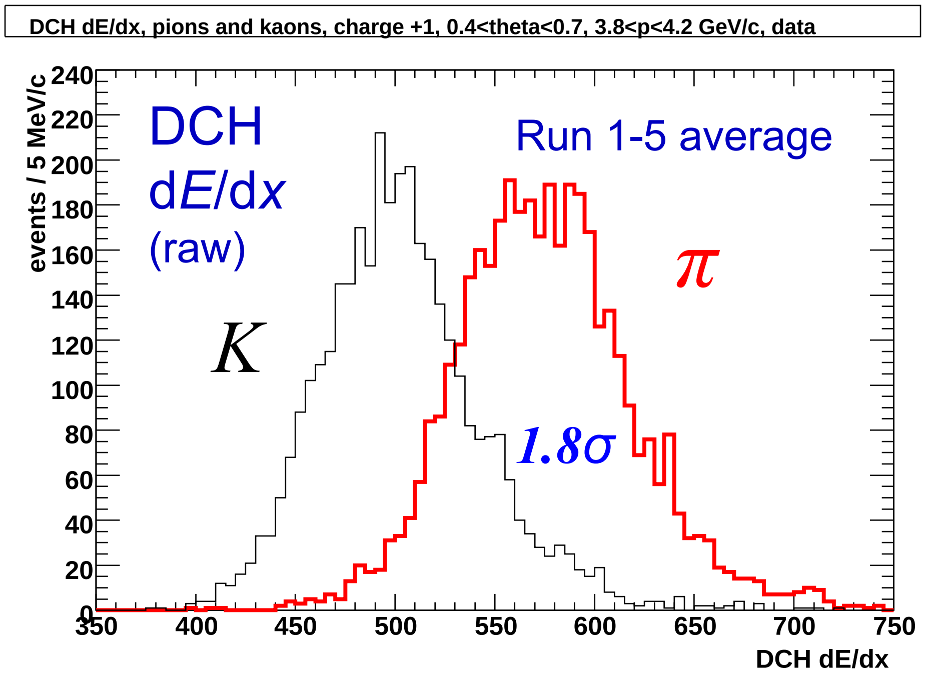


DCH d*E*/d*x* vs. DIRC

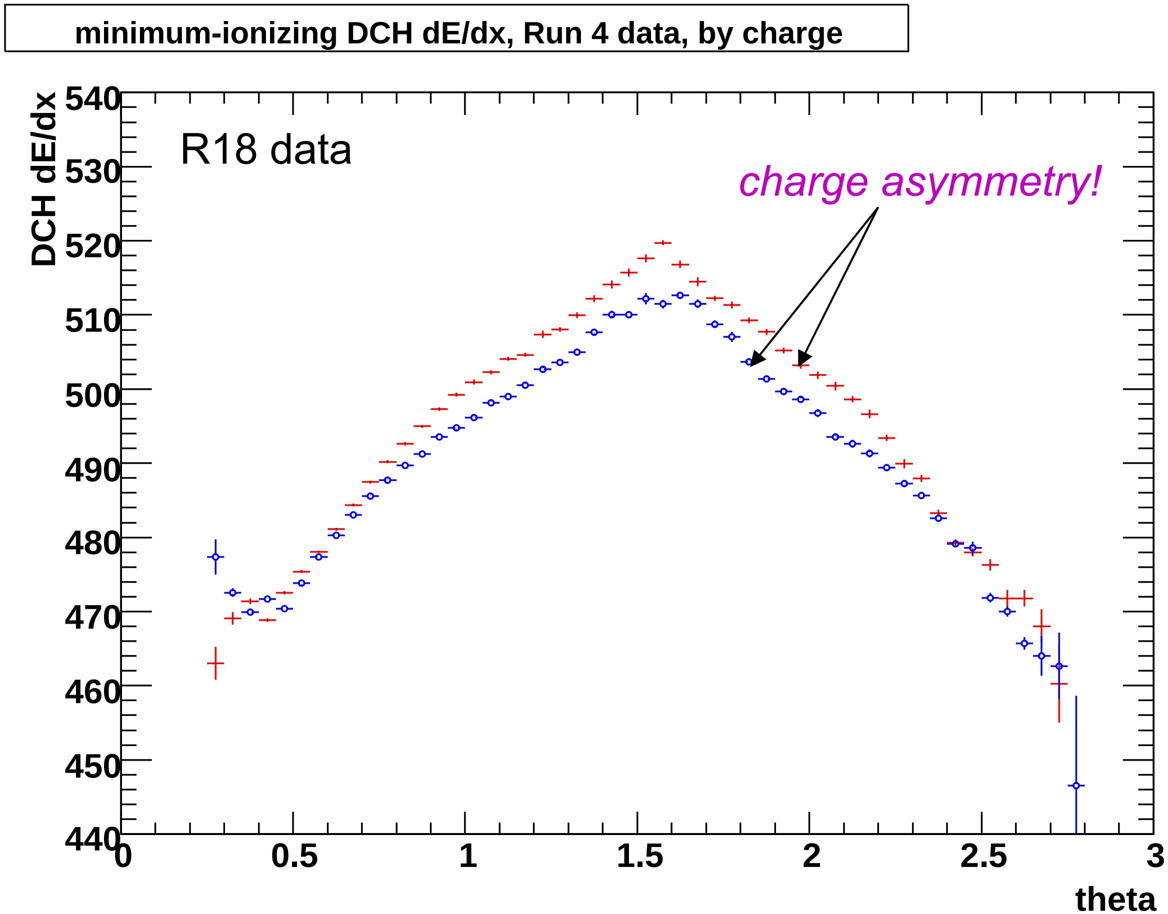
Indeed, in the forward region, DCH d*E*/dx is not much worse than the DIRC—and is 100% efficient!

$0.4 < \theta < 0.7$, $3.8 < p < 4.2$ GeV/c



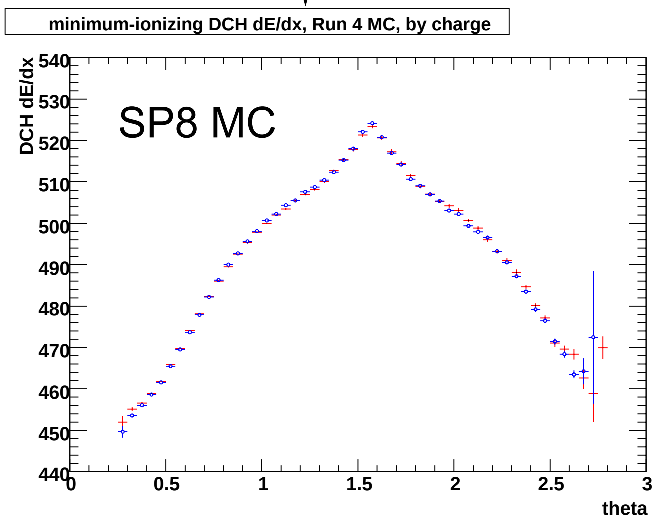


There are <u>many</u> reasons in the past DCH d*E*/dx failed to work in likelihood-based $B \to Xh^{\pm}$ analyses



Variations with the polar angle that are comparable with the DCH d*E*/dx resolution

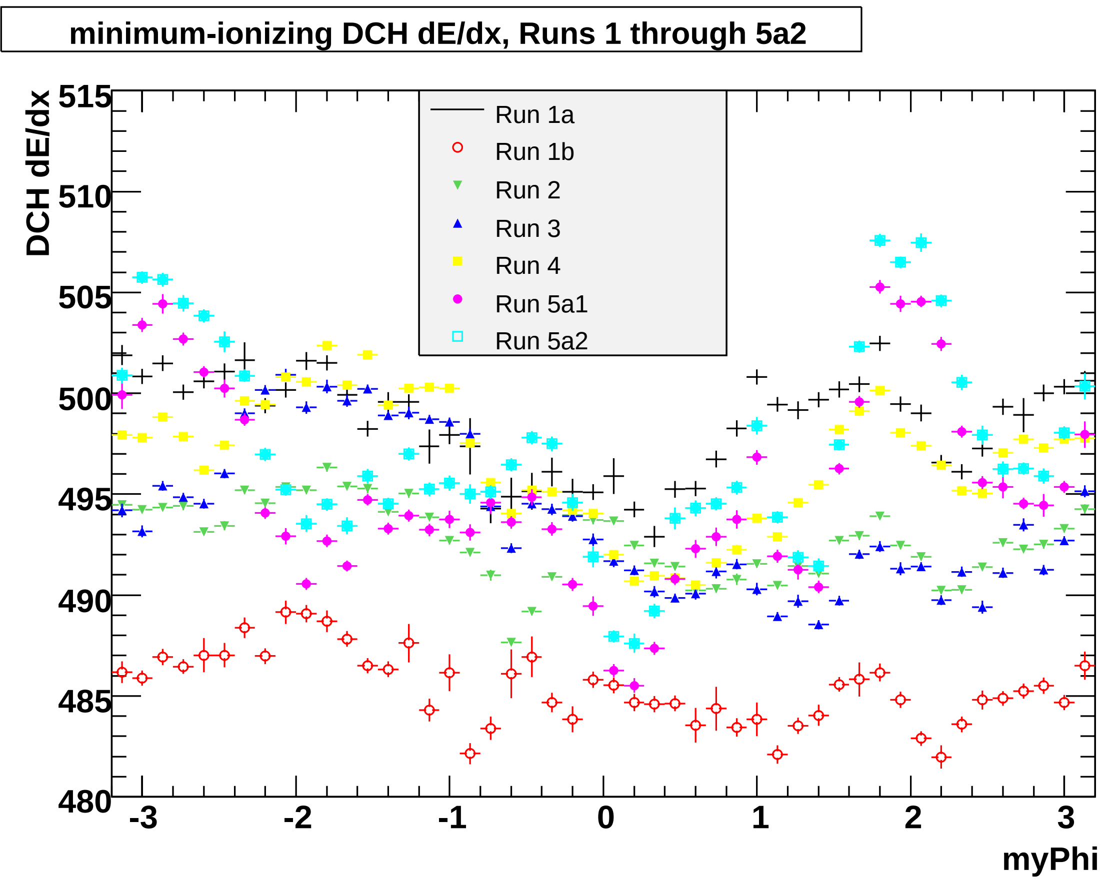
x2 larger in MC than in data

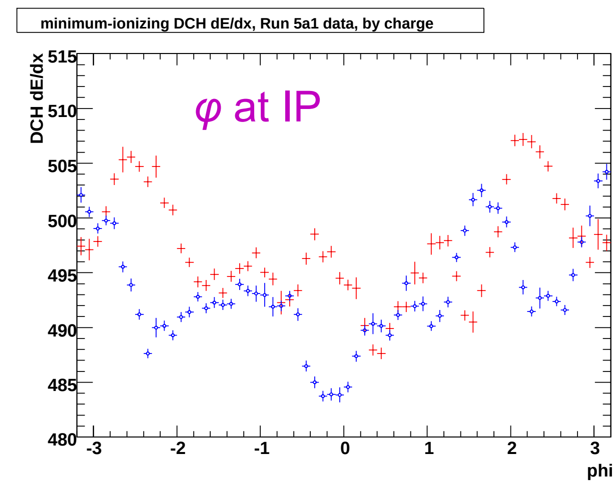


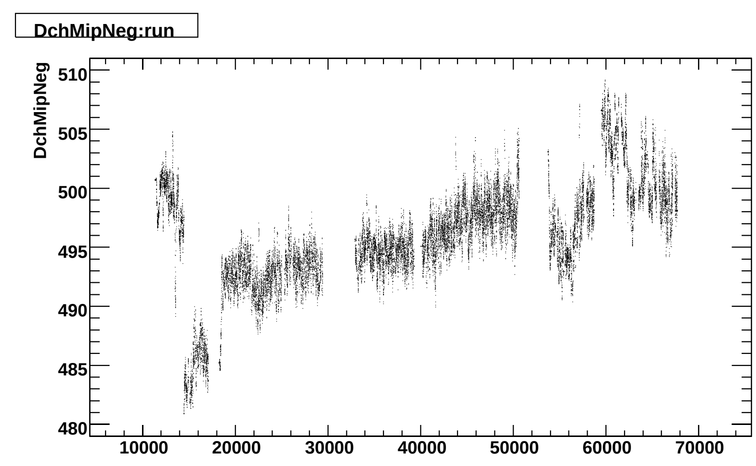
plus: inadequate calibration sample, binning in time, neglecting the data/MC discrepancies, variations in φ

There are many reasons all previous attempts to use DCH dE/dx in $B^0 \to Xh^\pm$ have failed…

DCH d*E*/dx also varies with time and the azimuthal angle *φ*







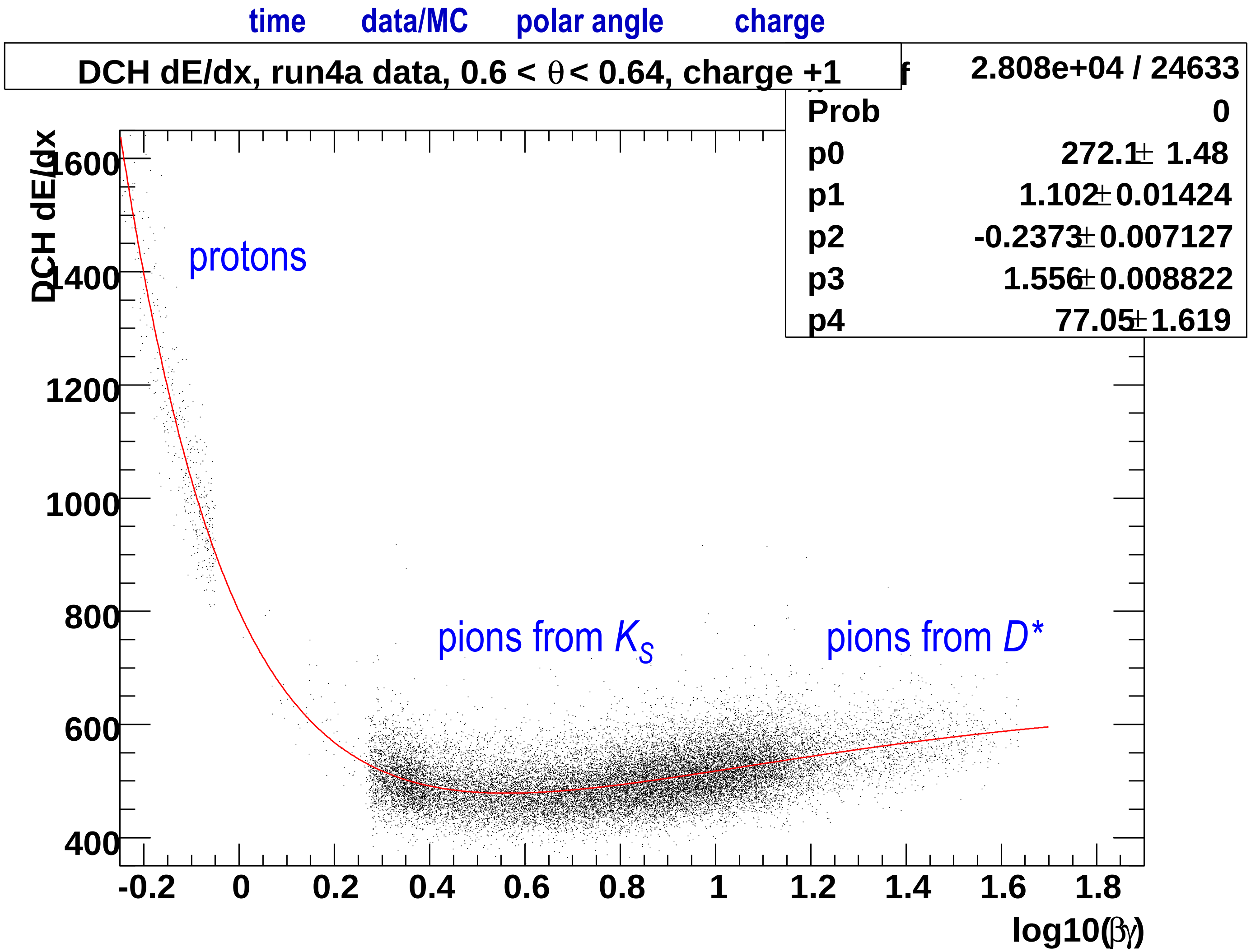
The DCH d*E*/dx fits — step 1

Done in bins of polar angle, charge, time

Note that this is unbinned fit with background subtraction.

A background-subtraction technique for *TGraphErrors* was developed

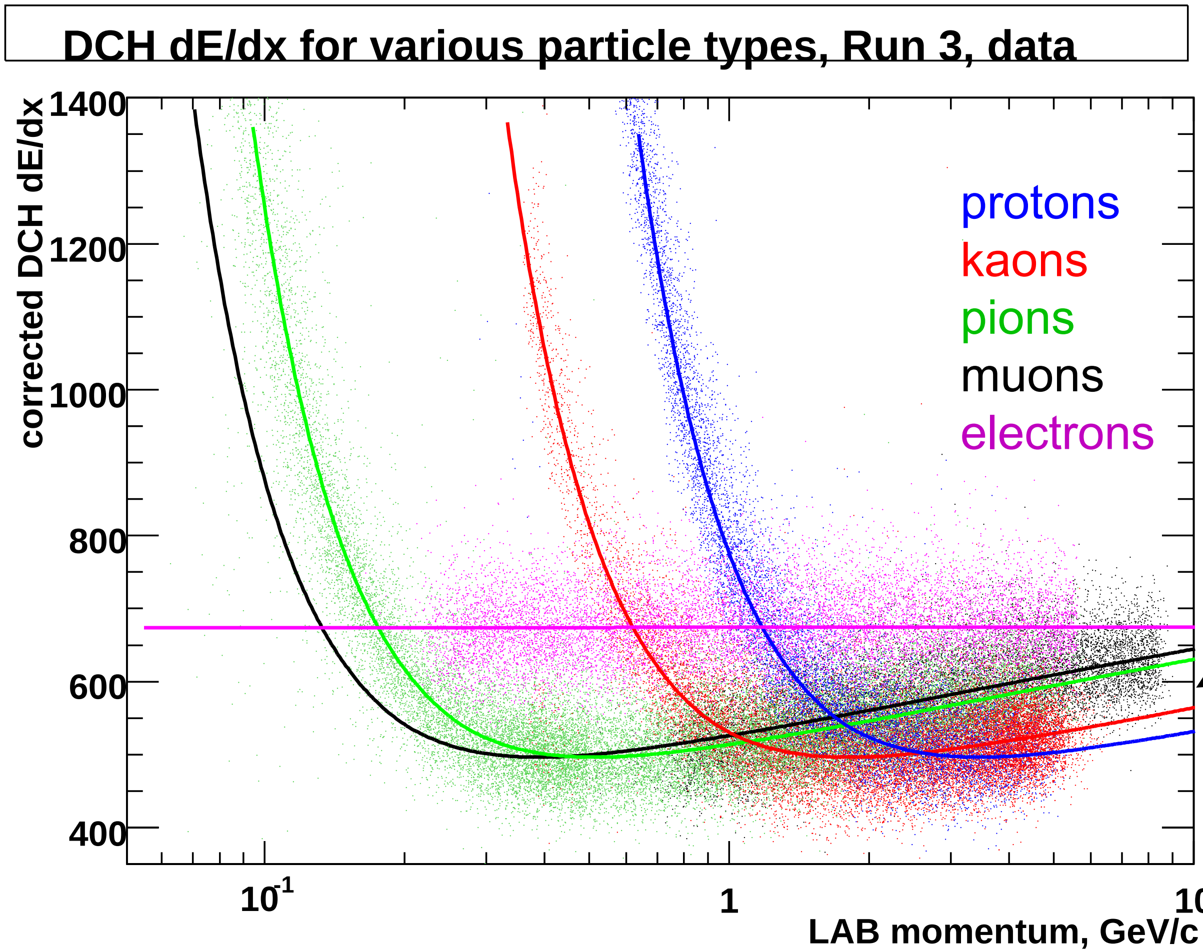
P0 is the scale,
P1 is the linear slope
P2<0 is the bend
(this is not the mass effect!
P3 and P4 are the modifiec
$1/\beta^2$ term to take into account the gain saturation effect

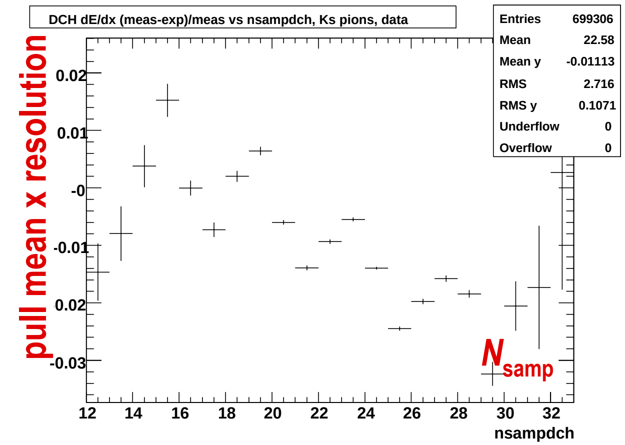


Then, azimuthal-angle corrections are done and resolutions vs N_{samp} tabulated

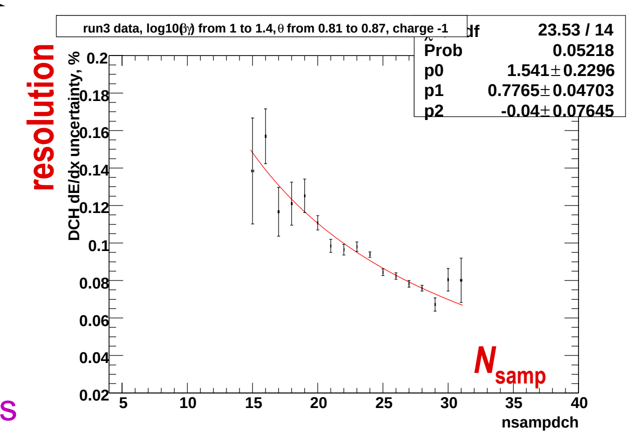
dE/dx in DCH

This is what DCH dE/dx looks like <u>after</u> the new calibration





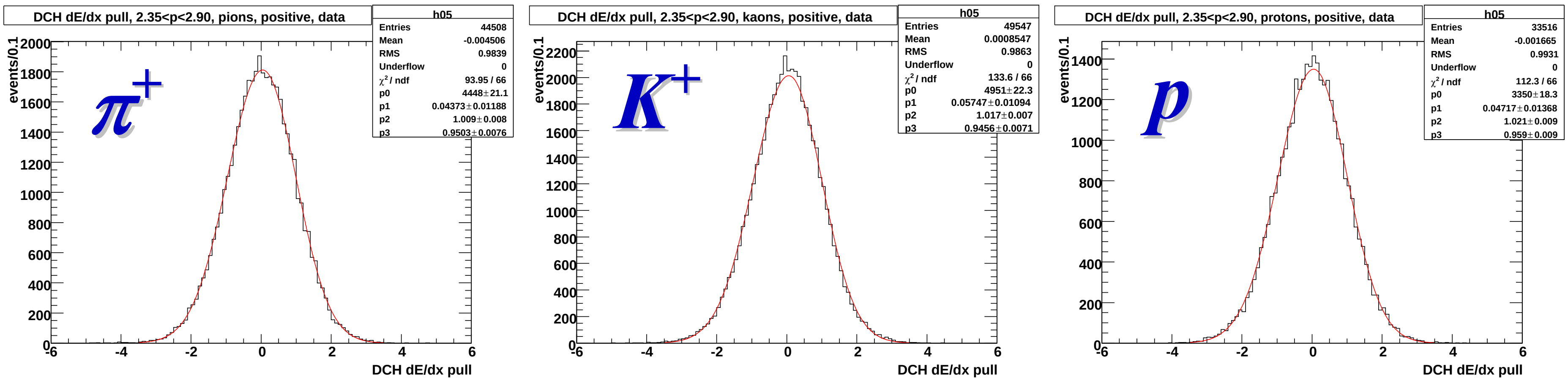
up to 1.9σ
π/K separation



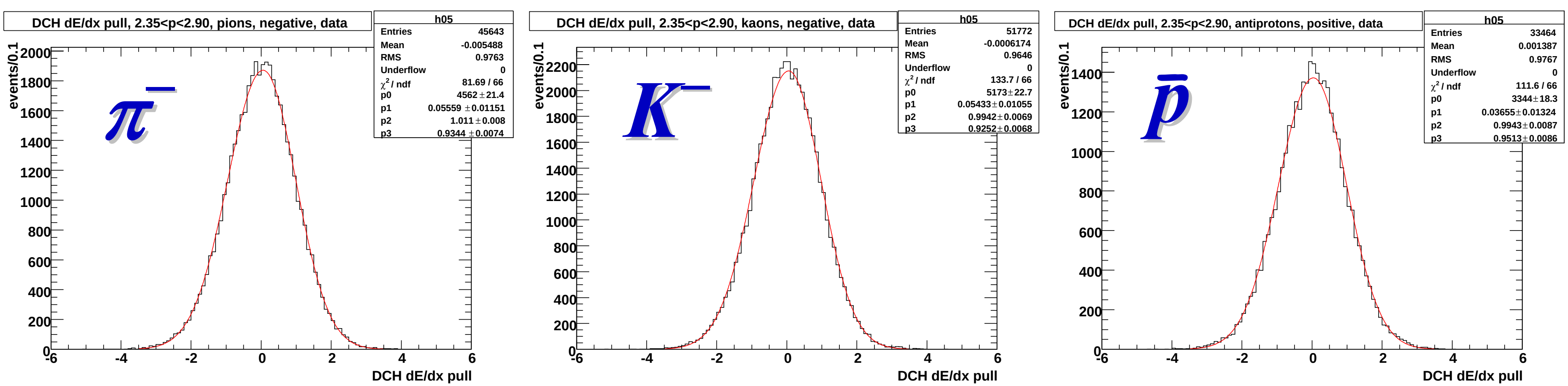
DCH d*E*/dx varies with the number of d*E*/dx samples

New, detailed DCH dE/dx parametrization:

"Two-body" π, K, p pulls

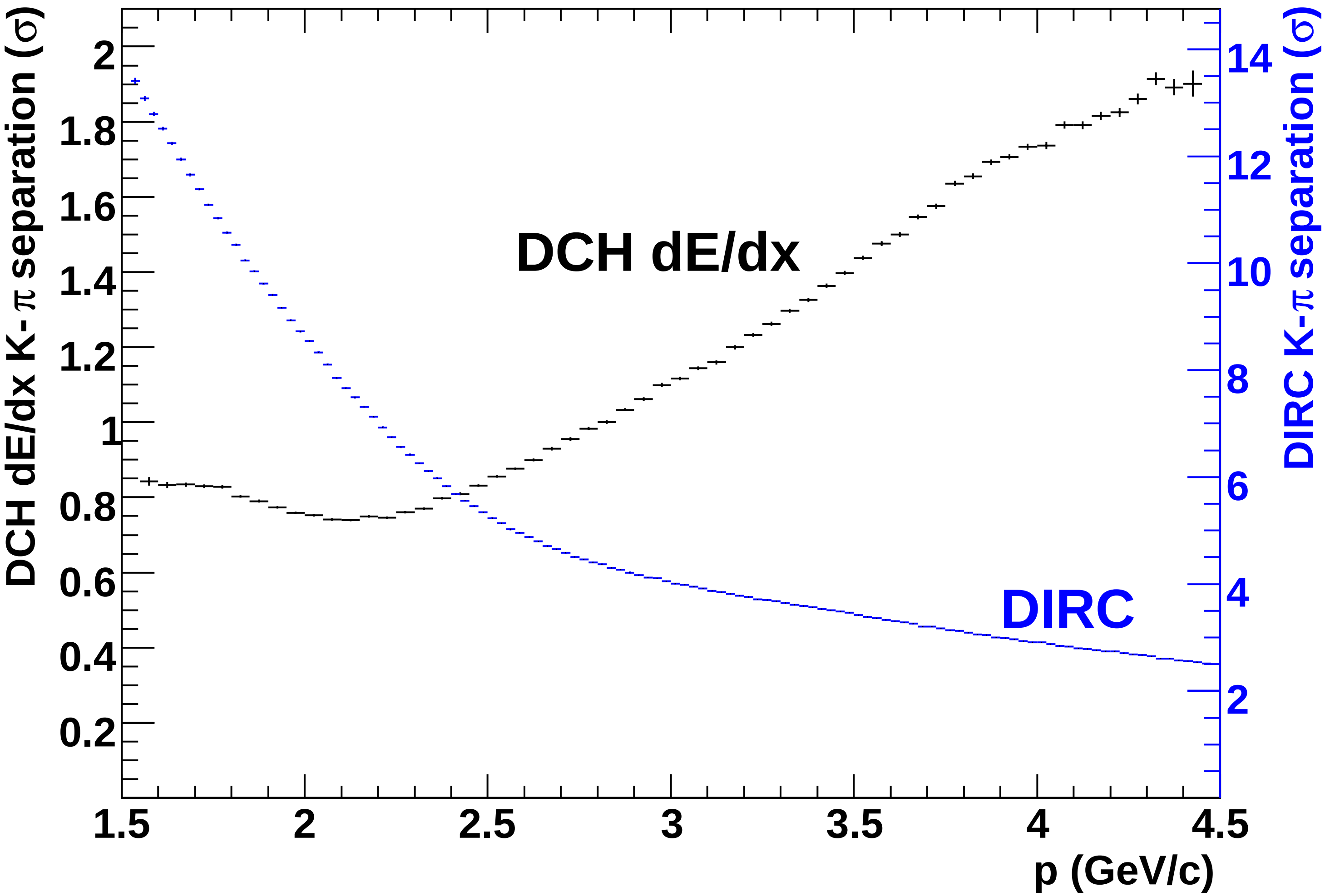


Pulls are controlled at a <1% level; non-Gaussian tails are absent by construction



"Two-body" DCH dE/dx K-π separation

complementary to DIRC



Validation of DCH dE/dx and DIRC PDFs

The sample: $D^{*+} \to \pi^{+}_{\text{slow}} D^0,\ D^0 \to \pi^+ K^-$

Flavor of the D^0 tagged by the π^{+}_{slow} charge (DCSD negligible)

$e^+e^- \to c\bar{c}$ *only:* $p_{\text{CM}}(D^0) > 2.5\ \text{GeV}/c$

$\mathcal{A}_{\text{FB}}$ *minimized:* $1.251 < \theta_{\text{CM}}(D^0) < 1.891\ \text{rad}$

Validation completed: $\mathcal{A}_{K^+\pi^-}$ bias that is due to PID PDFs is negligible

$\mathcal{A}_{K^+\pi^-}$ bias due to material interactions determined and cross-checked using several independent approaches

1) Detailed GEANT4 v7.1-based simulation
2) From material accounting and material properties + cross sections tabulated in PDG-RPP

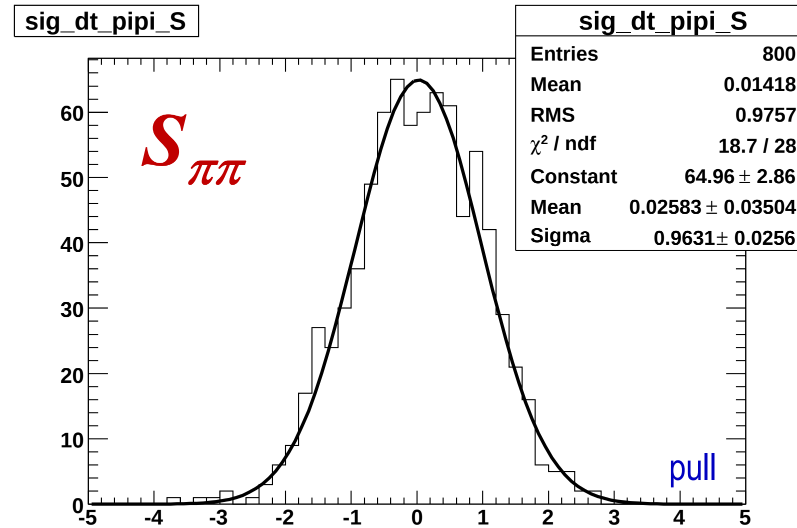
Material type	comment	density	λ_T	thickness	in λ_T	$\int \lambda_T$ from IP
Au	beam pipe	19.3	113.9	4 μm	0.07×10^{-3}	
Be	beam pipe	1.848	55.8	1.36 mm	4.50×10^{-3}	
H_2O	beam pipe	1.000	60.1	1.48 mm	2.46×10^{-3}	0.703%
Si	SVT modules	2.33	70.6	1.7 mm	5.61×10^{-3}	
Kapton + glue	SVT fanouts	1.4	60.3	0.50 mm	1.16×10^{-3}	
Cu + Cr	SVT fanouts	9.0	85.6	24 μm	0.25×10^{-3}	
Au	SVT fanouts	19.3	113.9	5 μm	0.09×10^{-3}	
Air	SVT	0.001205	62.0	20 cm	0.39×10^{-3}	
C	support tube	2.265	60.2	1.5 mm	5.57×10^{-3}	
Be	inner DCH wall	1.848	55.8	1.00 mm	3.31×10^{-3}	2.34%
80% He, 20% C_4H_{10}	25 cm of DCH	0.000615	51.2	25 cm	0.30×10^{-3}	
Total (IP to DCH)	90° GTL track					2.37% λ_T
80% He, 20% C_4H_{10}	the rest of DCH	0.000615	51.2	32 cm	0.38×10^{-3}	
C	DCH outer wall	2.265	60.2	3.8 mm	14.3×10^{-3}	
Al	DCH outer wall	2.70	70.6	125 μm	0.48×10^{-3}	
Al	DRC before SiO_2	2.70	70.6	3.2 mm	12.3×10^{-3}	
Total IP to DIRC	90° track					5.1% λ_T

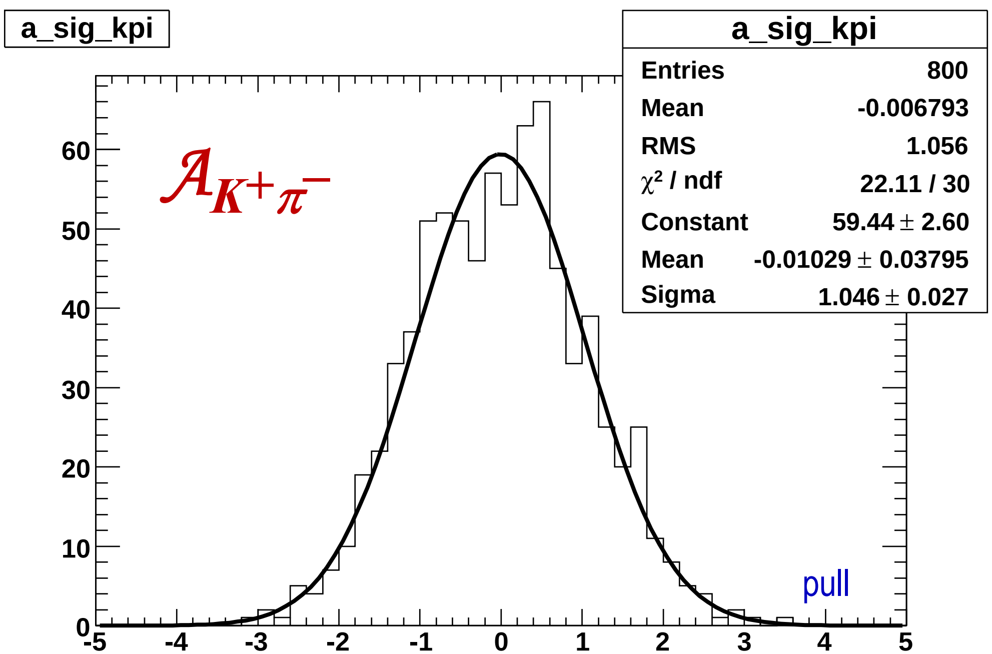
3) Asymmetry in the continuum background is consistent with these predictions

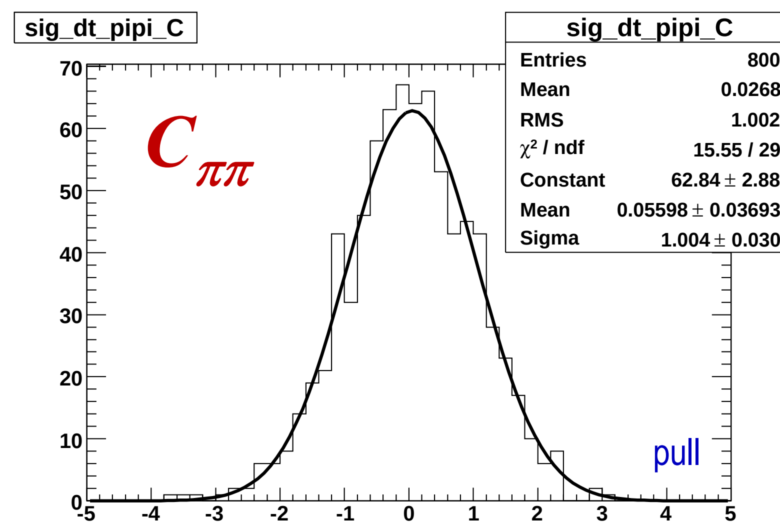
Fitter internal consistency check (1)

“Pure toy” MC generated with PDFs and sample sizes representative of the full 1999-2006 dataset, including d*E*/dx PDFs.

There are no biases



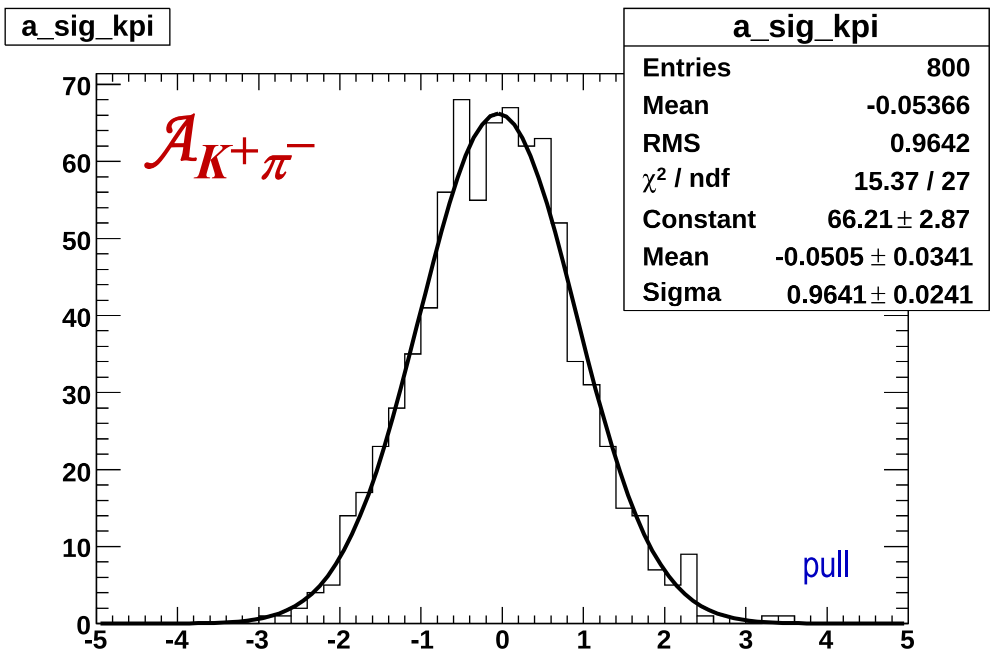


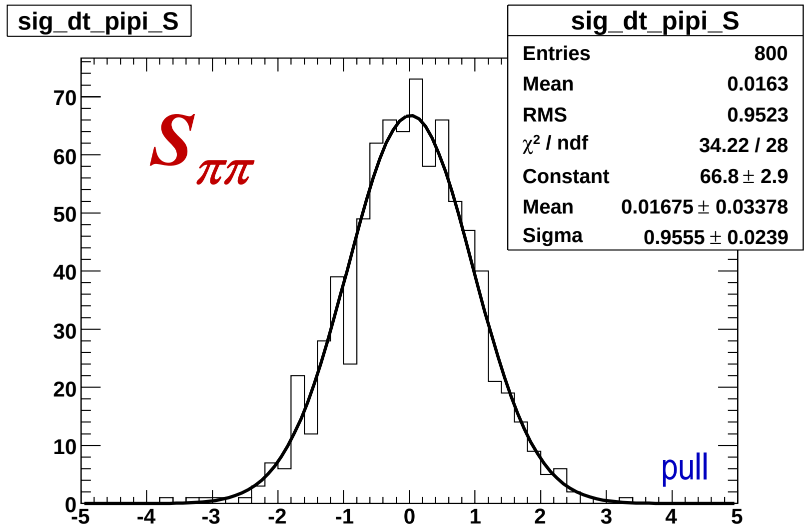


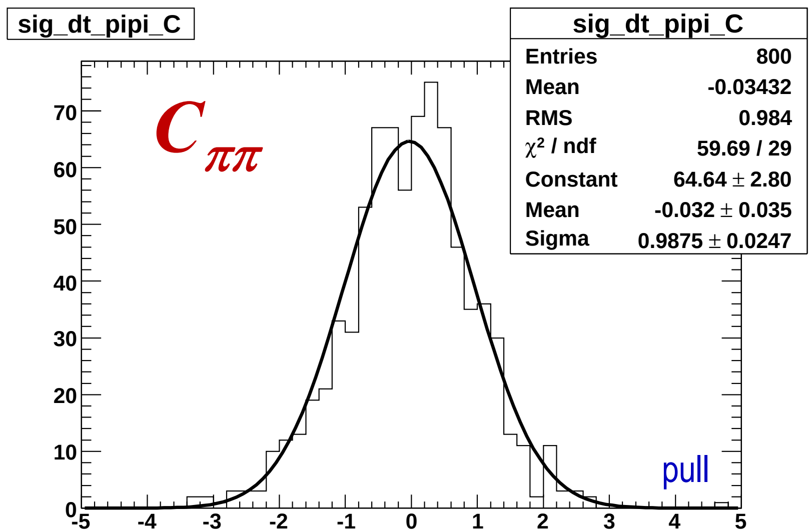
Fitter internal consistency check (2)

Embedded toy MC generated with fully simulated signal and a “toy” background, with sample sizes representative of the full 1999-2006 dataset, including d*E*/dx PDFs.

There are no biases

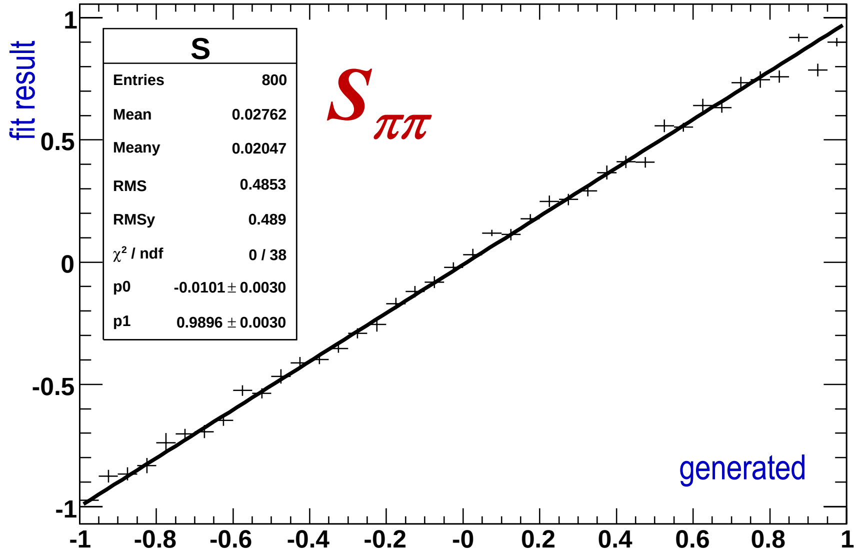




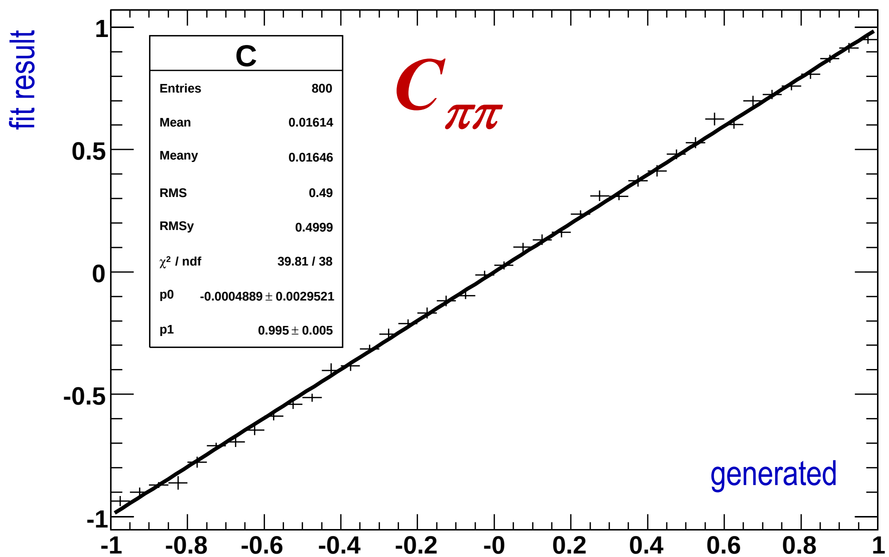


Fitter internal consistency check (3)

sig_dt_pipi_S_fit vs. sig_dt_pipi_S_gen



sig_dt_pipi_C_fit vs. sig_dt_pipi_C_gen



Status of the $B^0 \to h^+h^-$ *CPV* analysis

Analysis and PRL draft entered Collaboration-wide Review on President's Day, which means that I am not allowed to tell you any numbers or results yet except this:

Effective lumi gain from d*E*/d*x* is 31-35%

Stay tuned!

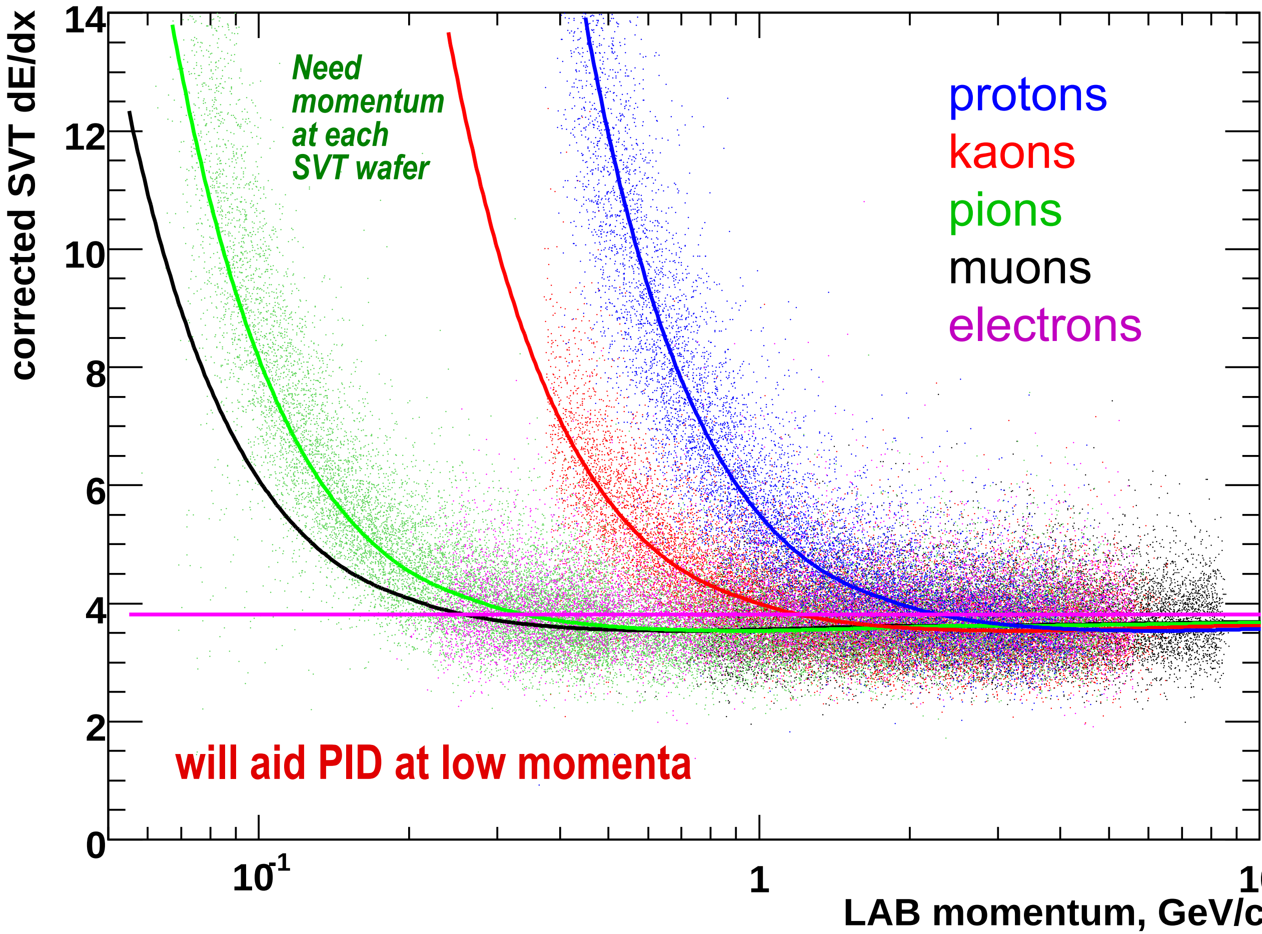
We still continue to improve *BaBar* !

Here are a few examples

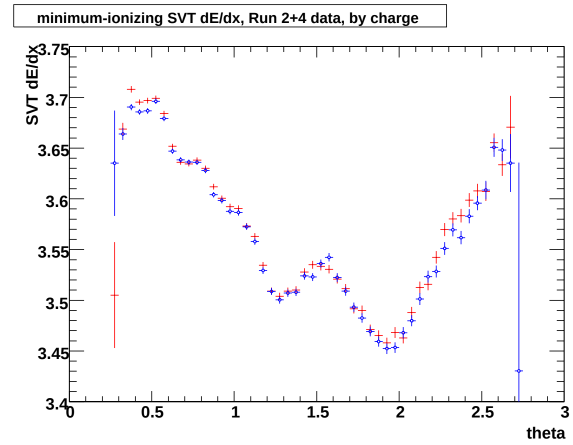
d*E*/dx in Silicon Vertex Tracker:
π/e, *K*/e separation; stand-alone SVT tracking

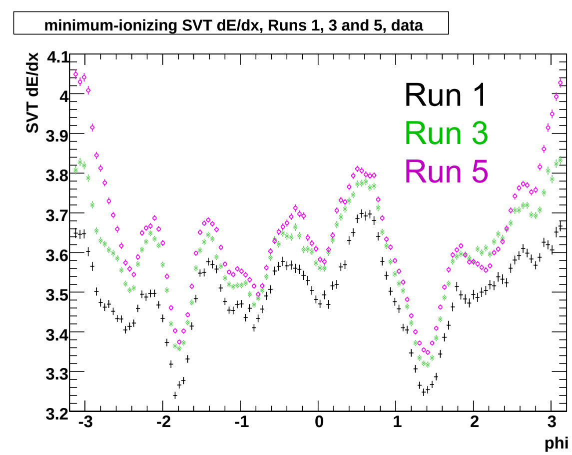
This is what SVT dE/dx looks like <u>after</u> the new detailed calibration

SVT dE/dx for various particle types, Run 3, data



Suffers from the same systematics as DCH d*E*/dx, only worse





Problems with RPCs

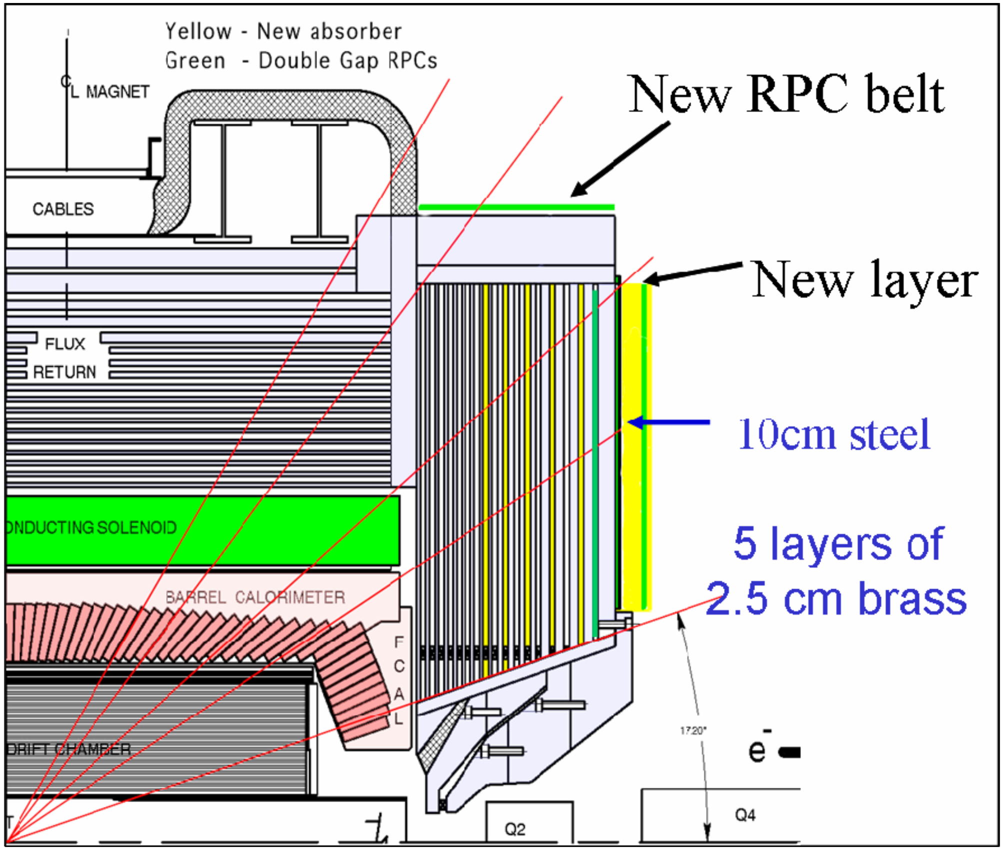
• The only major problem with the BaBar detector, known since 1999: RPC efficiency deteriorating at ~10-20%/year.

• Good muon and K_L identification efficiency essential in many searches for New Physics at BaBar.

• Forward End Cap upgraded in 2002:

• The Barrel has 5.1 λ_{int} with Layer 19 RPCs (dying, inaccessible), 4.5 λ_{int} without – marginal for a muon system.

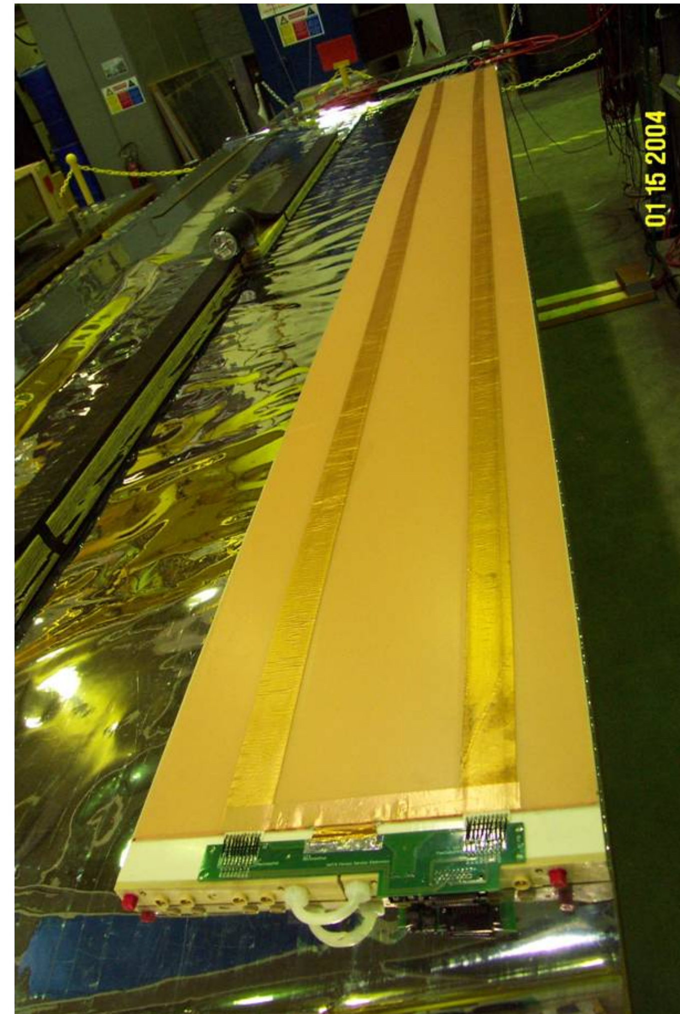
• Adding six 2.2 cm layers of brass increases barrel thickness to 5.3 λ_{int}.



• The technology chosen for Barrel RPC replacement is the **Limited Streamer Tube** (LST). Installed in 2004-06

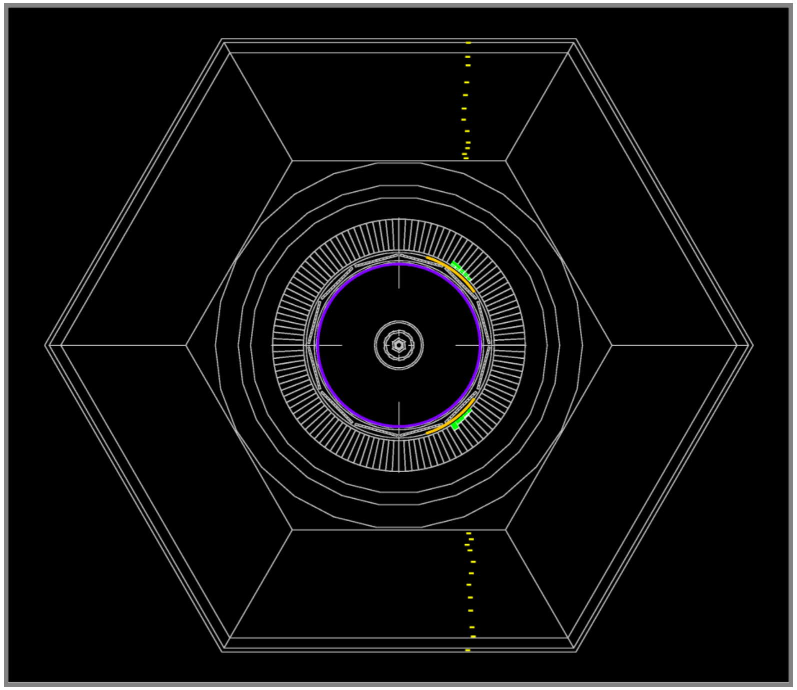
LST technology

- LST is a wire chamber operating in the self-limiting streamer mode, so
- Signal does not depend on the amount of initial ionization.
- Non-flammable gas (CO_2/ i-C_4H_{10}/Ar).
- 17x15 mm cells with three walls covered with conductive paint (graphite/PVAC).
- Tubes with 7 or 8 cell, 13 to 20 tubes per layer.
- phi position read off the wires (4 channels per tube), 94% eff., multiplicity mostly 1.
- Z strips span the entire width of a layer.

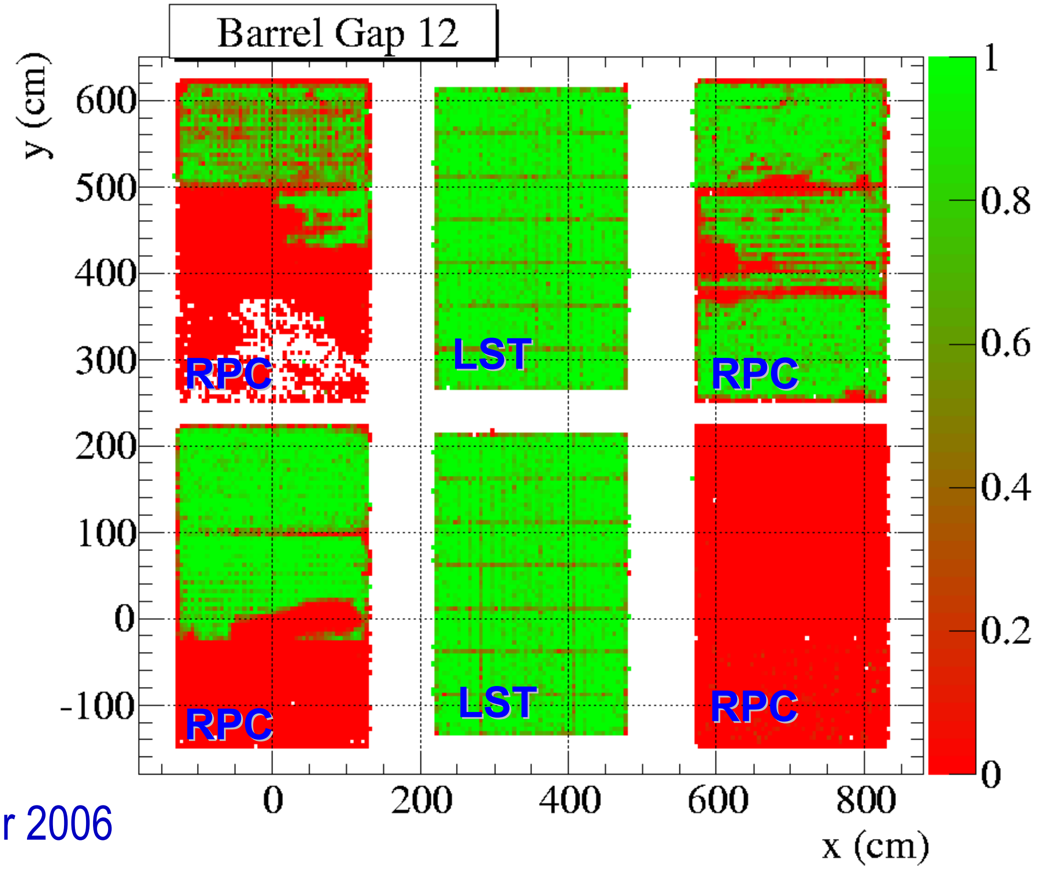


LST performance

First cosmics: run 50769, event 50170, Sep 28, 2004



Example of single-layer efficiency, May 2005

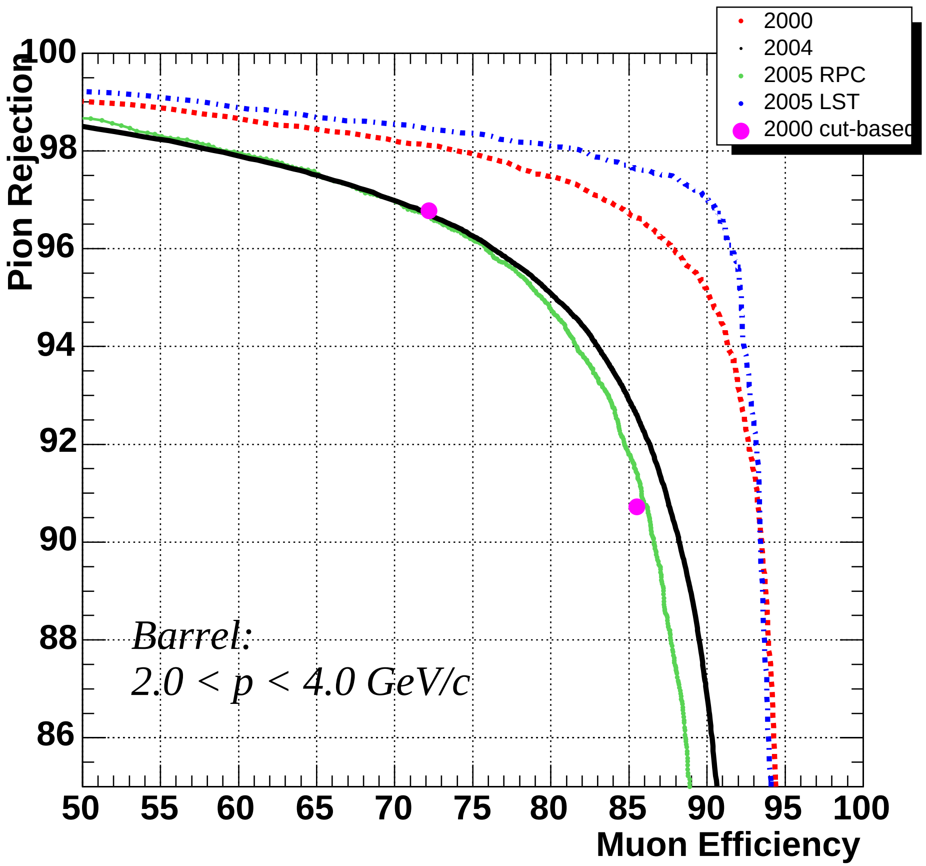


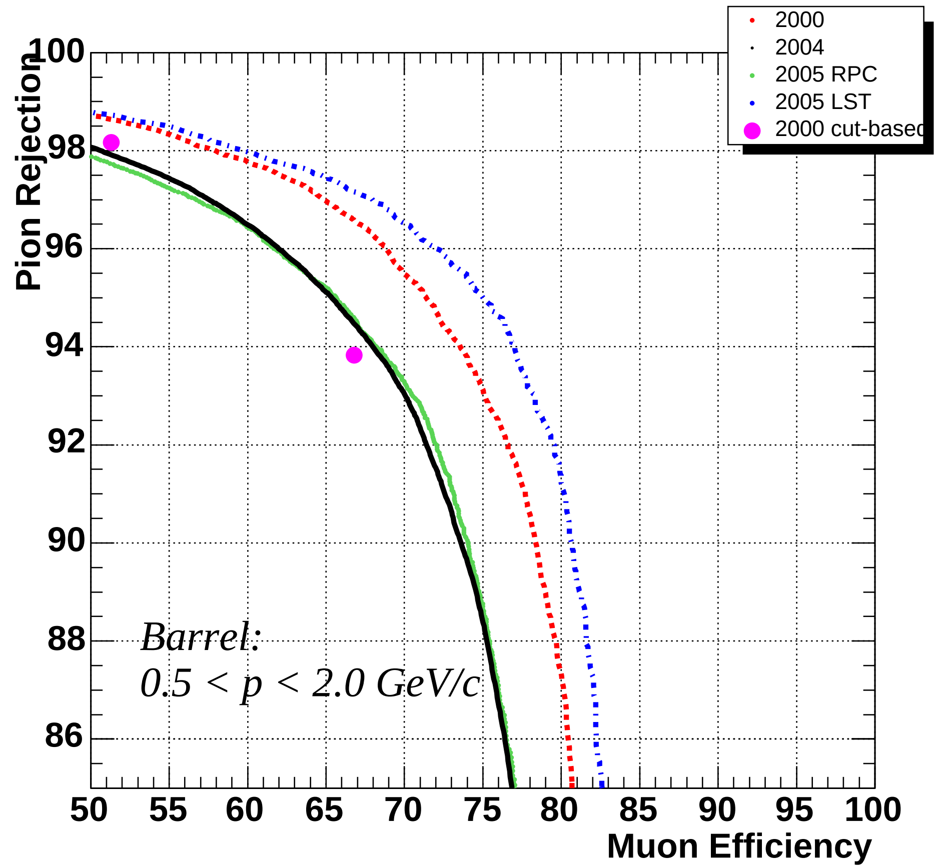
Upgrade of entire barrel completed in October 2006

Where we stand on muon ID

before many further improvements

We are already doing better than RPCs ever did!



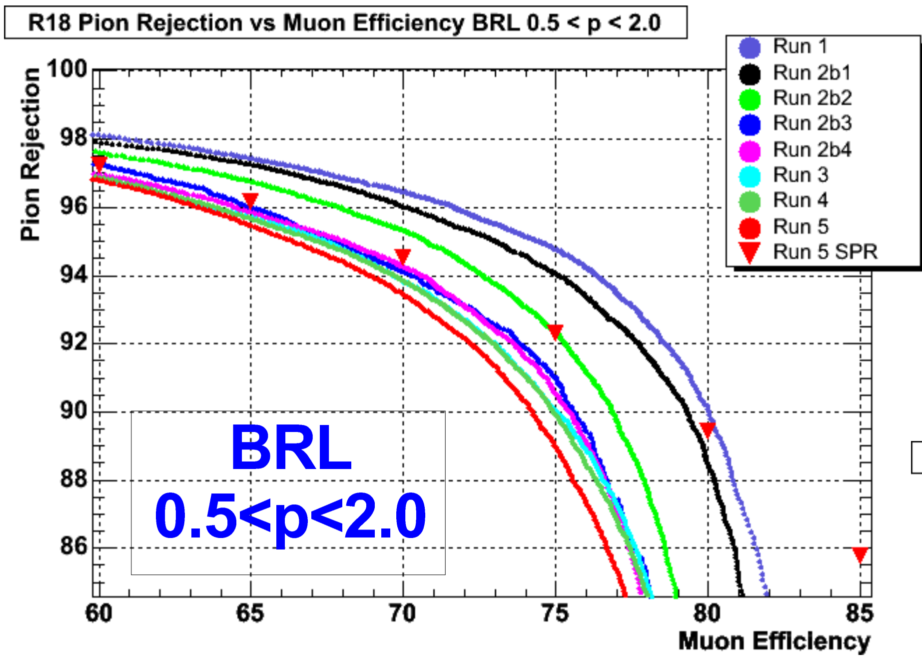


"In the pipeline" for Particle ID: better DCH and SVT d*E*/d*x*; more EMC information; boosted decision trees; …

Muon ID performance

Neural Net vs. Decision Trees

very preliminary



The more heterogeneous the inputs, the greater the advantage of Decision Trees over Neural Nets