Recent progress in *CP* violation:

New Physics under siege

High Energy Seminar
University of Pennsylvania

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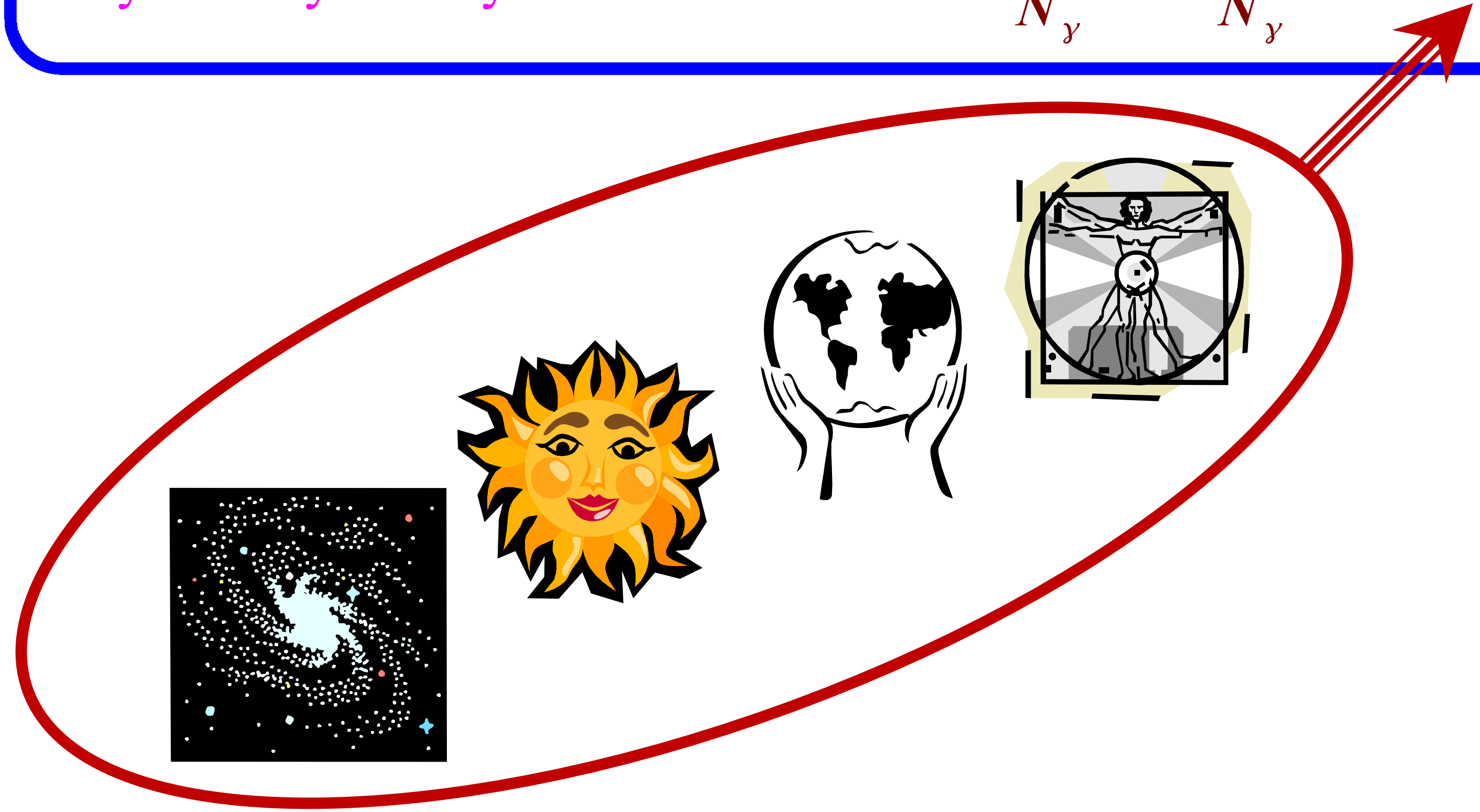
Matter-Antimatter Asymmetry the Universe

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

Baryonic asymmetry of the Universe: $\frac{N_{\mathrm{B}} - N_{\bar{\mathrm{B}}}}{N_\gamma} \simeq \frac{N_{\mathrm{B}}}{N_\gamma} \simeq 5\times10^{-10}$



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

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

This is by far the strongest argument for existence of sources of *CP* violation in nature

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

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:

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

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

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

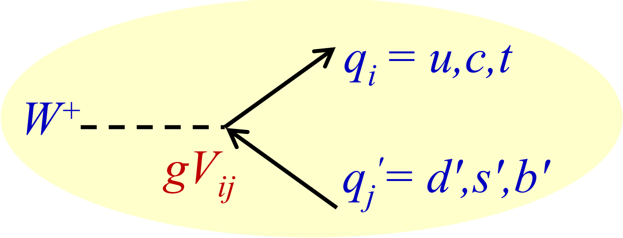
<u>the</u> "unitarity triangle"

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

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

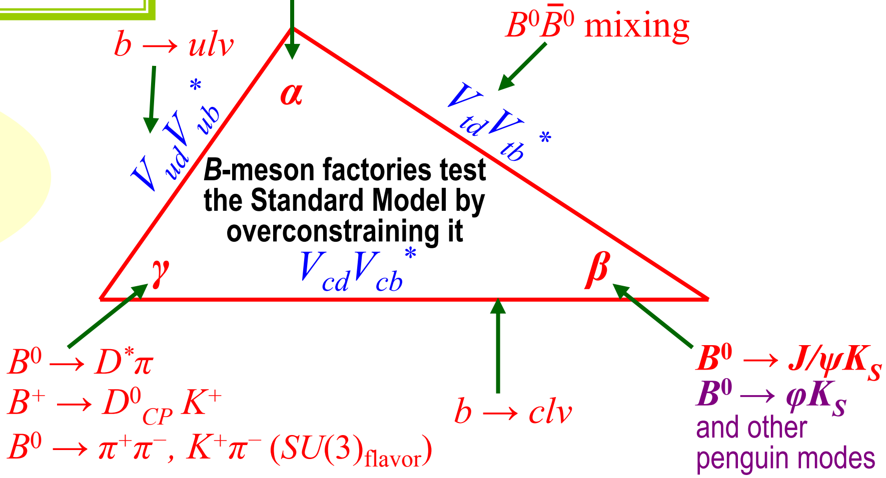
$$\gamma \equiv \arg\left[-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right]$$

In Kobayashi-Maskawa theory, a single phase is responsible for <u>all</u> *CP* violation in meson decays, making it testable



Supersymmetry (SUSY): dozens of independent phases, mostly in flavor-changing couplings; effects could be seen in loops

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



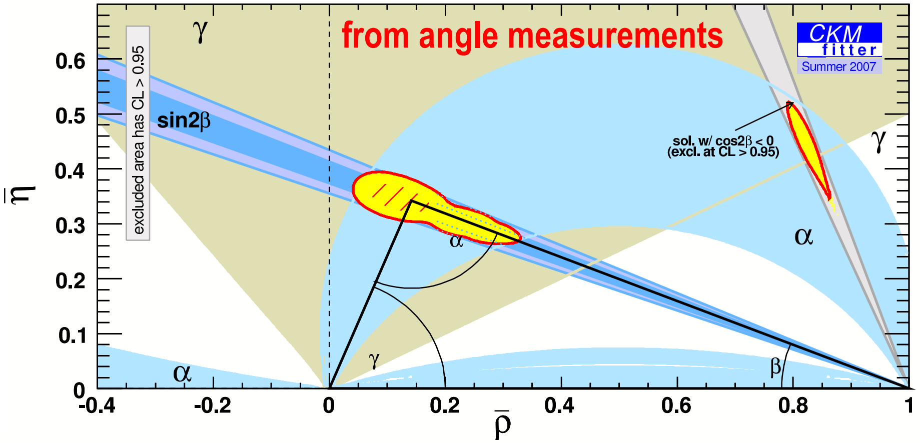
*CKM matrix overview: Review of Particle Physics, W.-M. Yao et al. [Particle Data Group], J. Phys. G **33**, 1 (2006)*

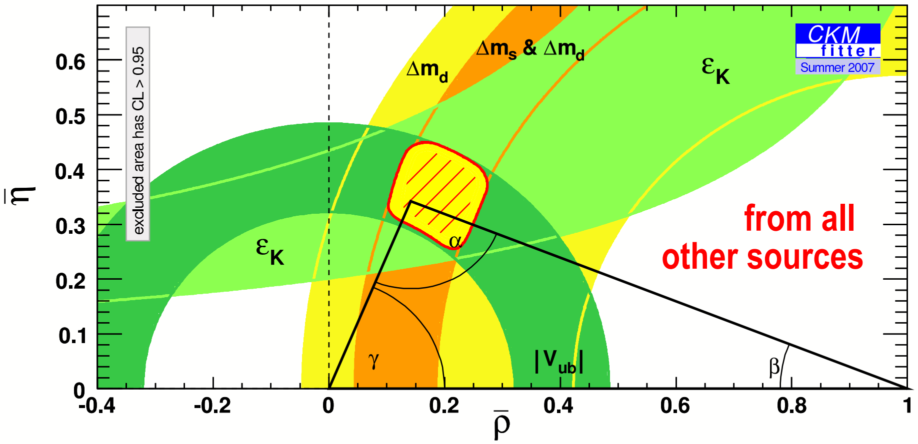
Current knowledge of the Unitarity Triangle

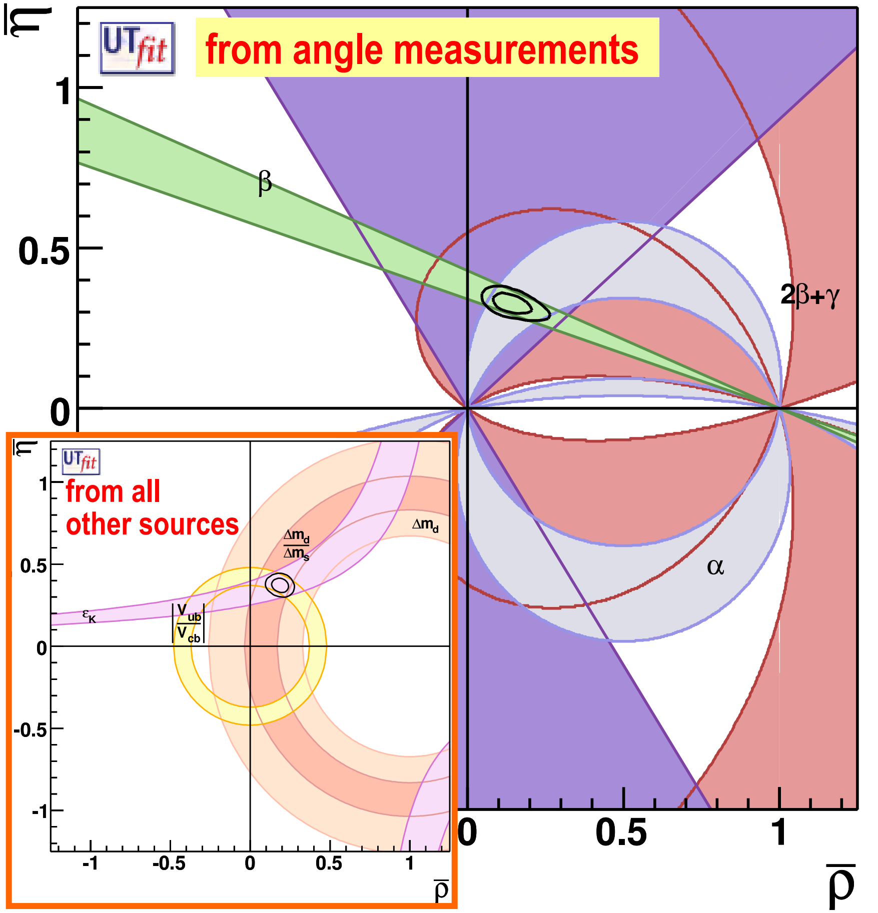
Important: all measurements are still statistics-limited

A frequentist interpretation

A Bayesian interpretation, with 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

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):

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

where

S and C is what we measure

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

from mixing, $\approx e^{-2i\beta}$

a_f is the time-evolution asymmetry:

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

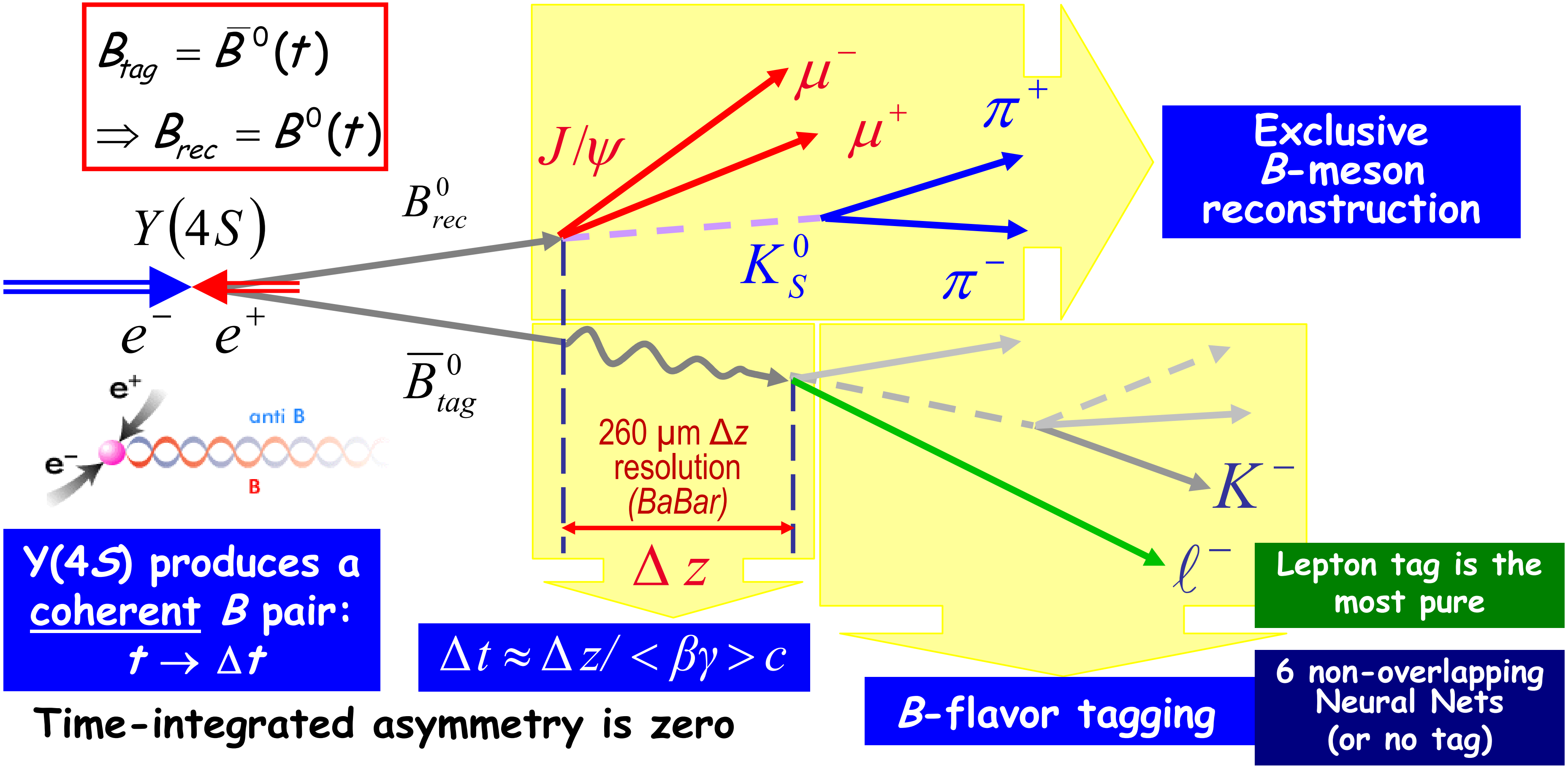
If f is a *CP* eigenstate, f_{CP}, we have *CP* violation if $\lambda_f \neq \pm 1$:

- $|q/p| \neq 1$ (*CP* violation in mixing, very small) ⟵ ***B. Aubert et al. (BaBar Collaboration) Phys. Rev. Lett. 96, 251802 (2006)***
- $|\overline{A}_{\overline{f}}/A_f| \neq 1$ (direct *CP* violation, small in $b \to c\overline{c}s$)
- **Im(λ_f) ≠ 0 (interference between mixing and decay)**

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

$B_{tag} = \bar{B}^0(t)$

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



Exclusive *B*-meson reconstruction

Y(4*S*) produces a <u>coherent</u> *B* pair: *t* → Δ*t*

$\Delta t \approx \Delta z / < \beta\gamma > c$

Lepton tag is the most pure

***B*-flavor tagging**

6 non-overlapping Neural Nets (or no tag)

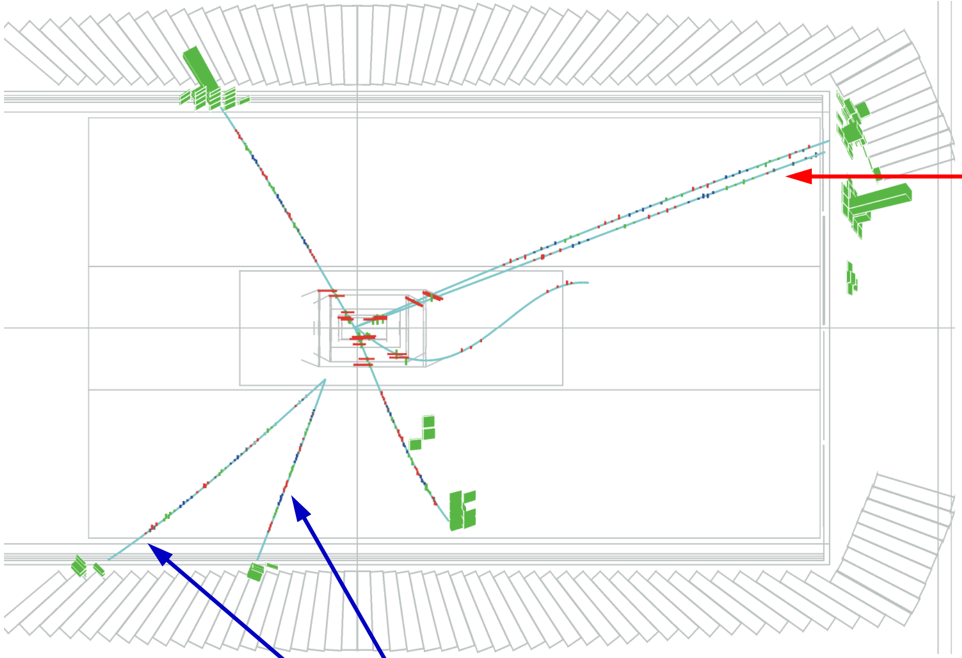
Time-integrated asymmetry is zero

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

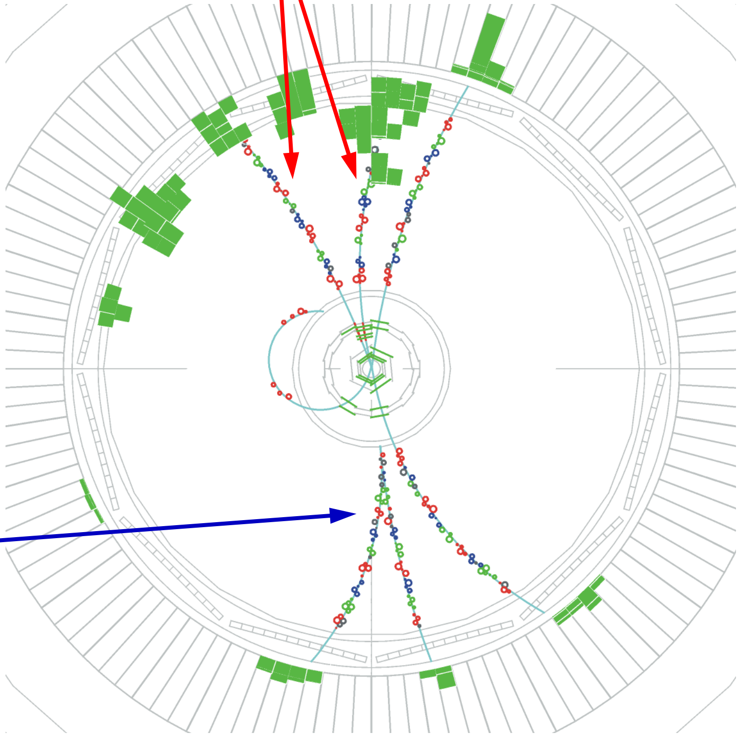
$B^0_{rec} = B^0_{CP}$ (*CP* eigenstates) ➡ *CP* analysis

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)



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



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

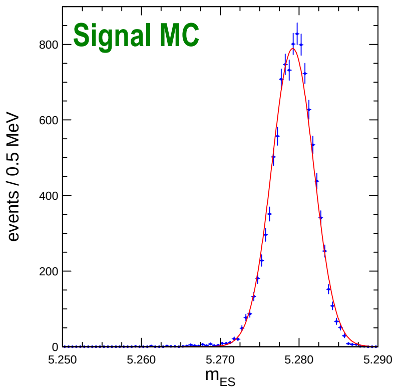
Run 29368, event hexID 249a4b/d610dd73 (June 27, 2002)
*From the dataset used in Phys.Rev.D **69**:011102, 2004*

Common discriminating variables: kinematics

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

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

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

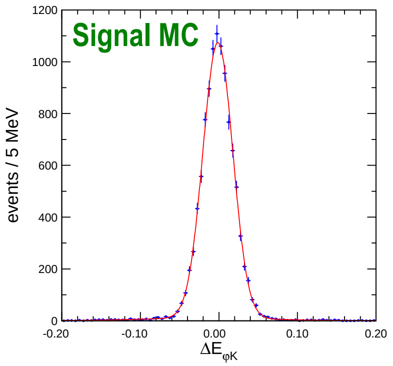


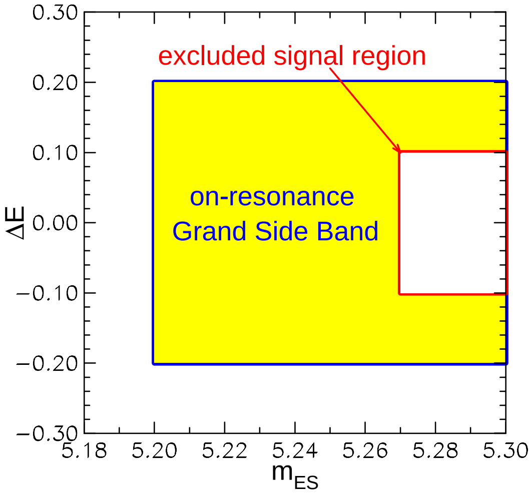
resolution ~2.6 MeV/c^2

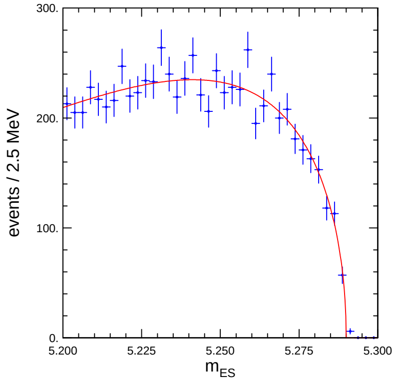
determined by the beam energy spread

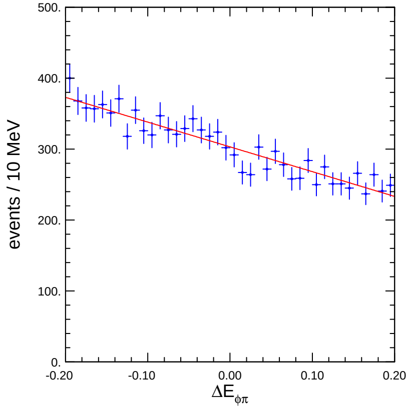
resolution ~15–80 MeV

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





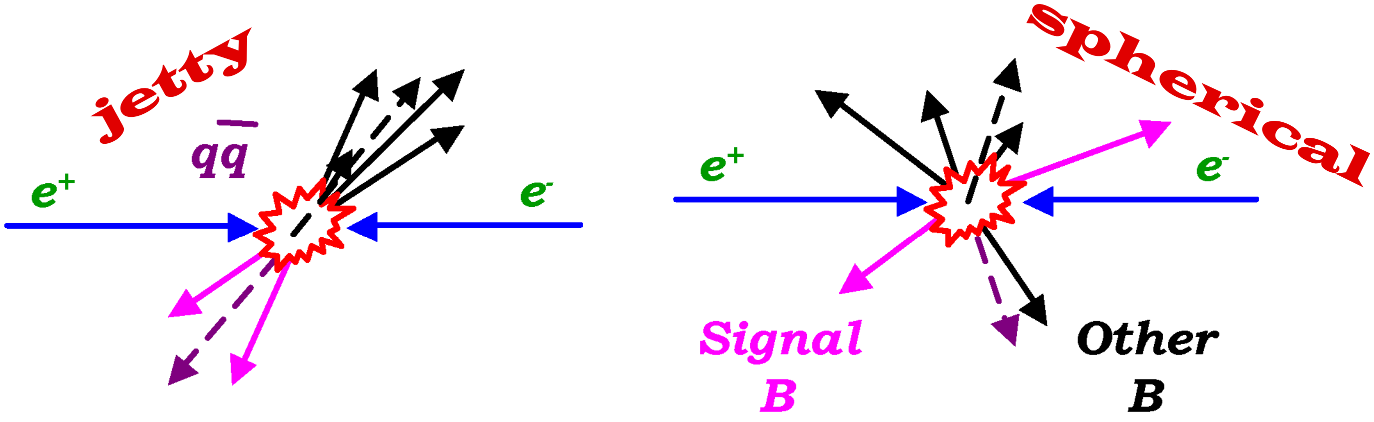




continuum background in the Grand Side Band

Common 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 *Y*(4*S*)
  - *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

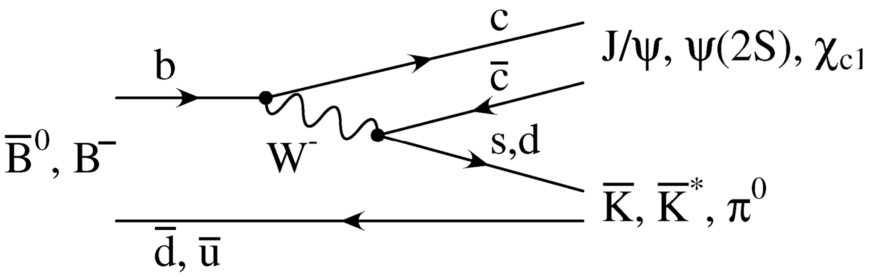


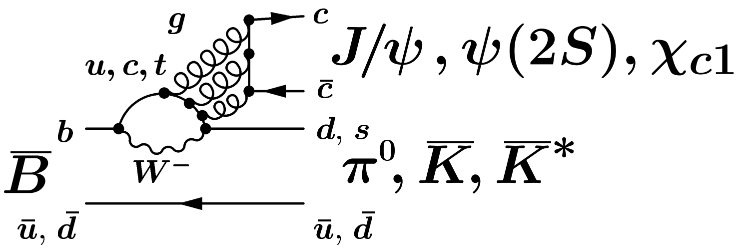
Analyses are <u>blind</u> until the methodology has been finalized and frozen

$\sin 2\beta$ in “golden” modes:

The highest-precision test of the KM mechanism of *CP* violation in meson decays

branching fractions $O(10^{-3})$





“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:

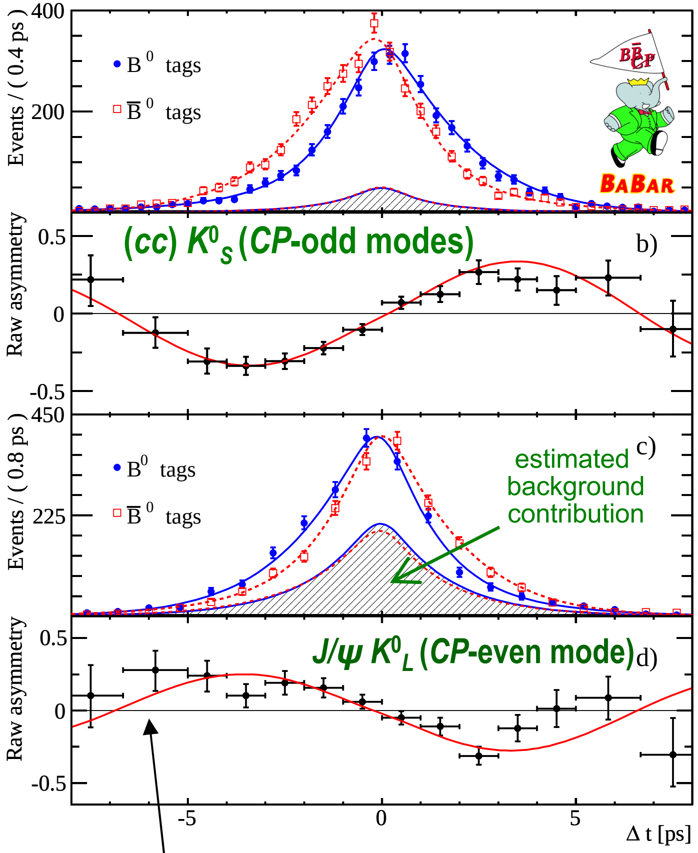
- *an example* of a model-independent, data-driven calculation:
  assuming $SU(3)_{\text{flavor}}$ invariance, use $B^0 \rightarrow J/\psi\pi^0$ data to constrain penguin pollution in $J/\psi K^0$ $\Rightarrow$ $\Delta S_{J/\psi K^0} = S_{J/\psi K^0} - \sin 2\beta = 0.000 \pm 0.012$

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

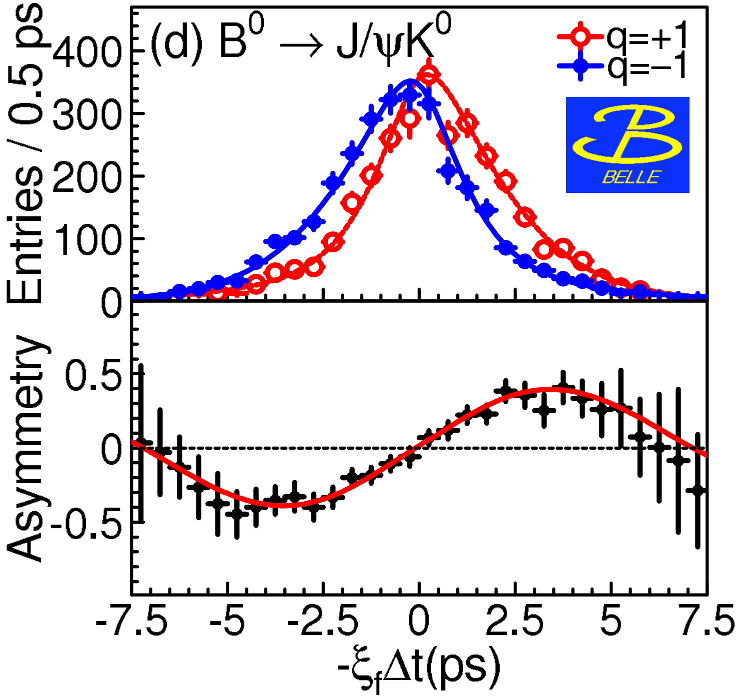
- theoretical estimates of the biases due to *u*- and *c*-quark penguins, etc.:
  - $\Delta S_{J/\psi K^0} = S_{J/\psi K^0} - \sin 2\beta \sim O(10^{-3})$ H. Li, S. Mishima, hep-ph/0610120
  - $\Delta S_{J/\psi K^0} = S_{J/\psi K^0} - \sin 2\beta \sim O(10^{-4})$ H. Boos et al., Phys. Rev. **D** 73, 036006 (2006)

$\sin 2\beta$ in “golden” modes: latest from *BaBar* and Belle

PRL 99, 171803 (2007) First observed in 2001 PRL 98, 031802 (2007)



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



***CP* violation in Standard Model is not small, it is *O*(1).**
Smallness of *CPV* in kaon decays is due to flavor suppression.

***CP*-violating phases in New Physics can also be *O*(1).**

BaBar with 384×10^6 *BB* pairs:

$\sin 2\beta = 0.714 \pm 0.032$ (stat) ± 0.018 (syst)

Belle with 535×10^6 *BB* pairs:

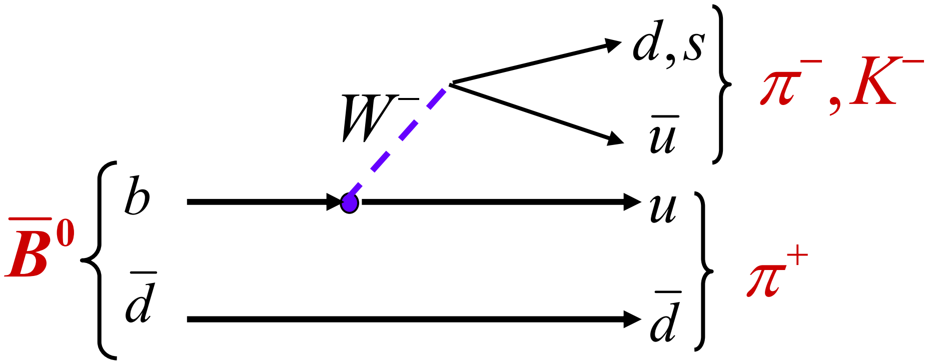
$\sin 2\beta = 0.642 \pm 0.031$ (stat) ± 0.017 (syst)

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* :

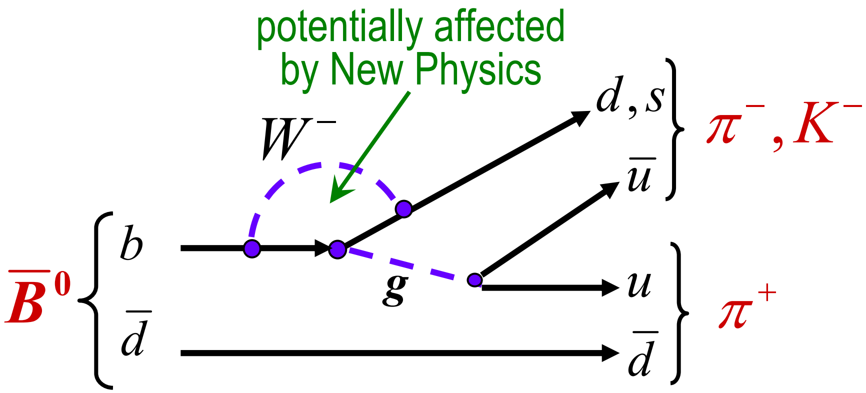
Measure $180° - \beta - \gamma = \alpha \equiv \arg\left[\frac{-V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right]$ (in SM)

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



Tree

Tree and penguin amplitudes have different weak and strong phases



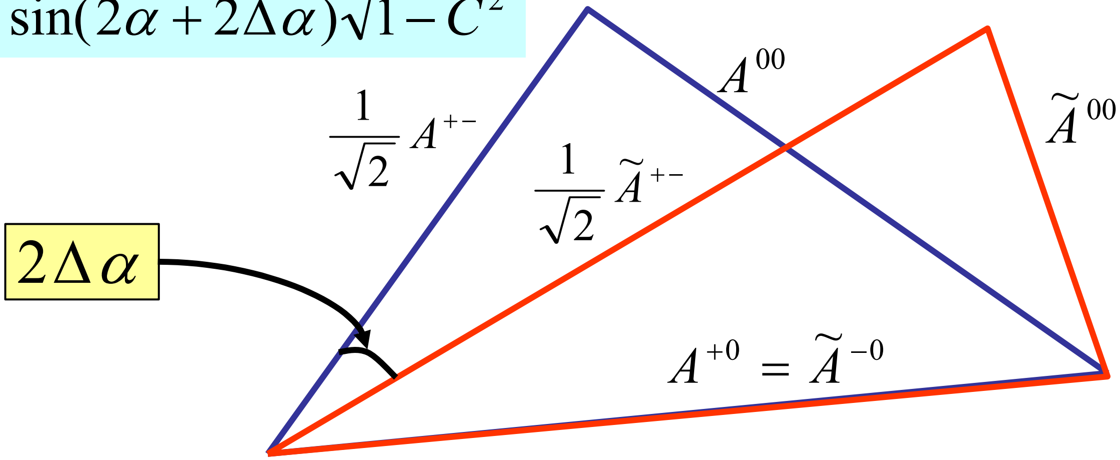
Penguin

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

Determines relative phase between *B* mixing and the tree, independent of the EW model

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:

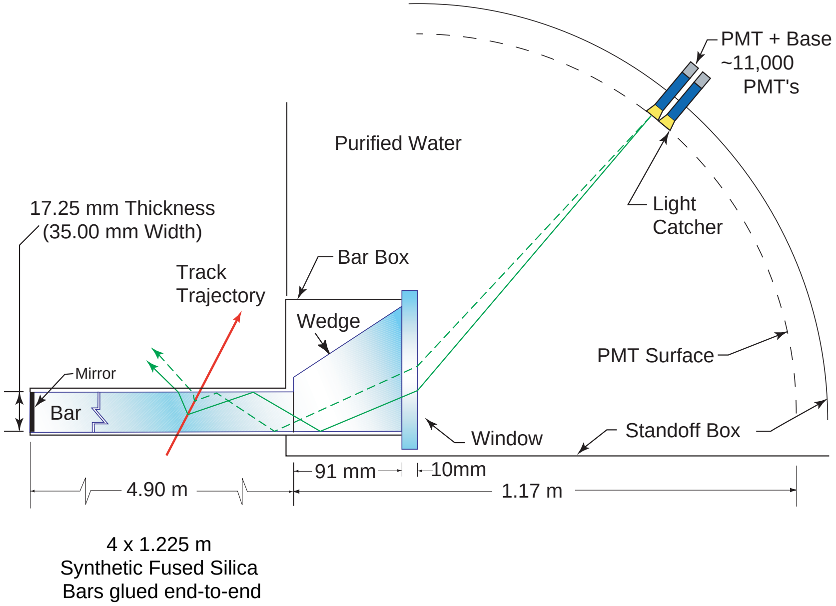
$$A(B^+ \to h^+h^0) = \tilde{A}(B^- \to h^-h^0)$$

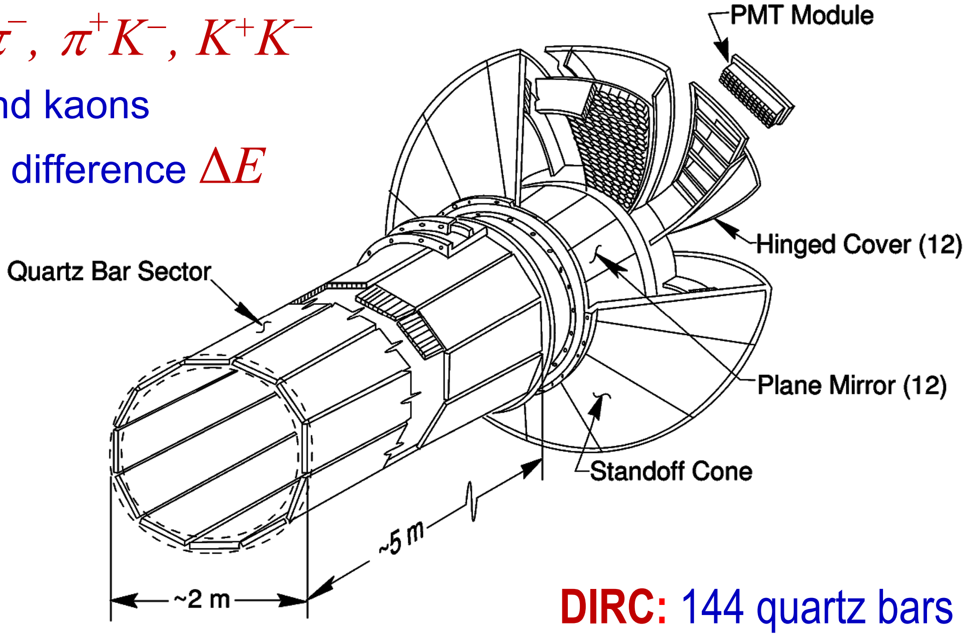
The "classic" $B^0 \to h^+h^-$ analysis

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

Using DIRC Cherenkov angle to identify pions and kaons

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





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

Belle: π/K separation with aerogel (threshold Cherenkov) and $\mathrm{d}E/\mathrm{d}x$; ΔE

Due to higher particle ID acceptance, Belle had x1.4 more h^+h^- per fb^{-1} than *BaBar*

CDF: $\mathrm{d}E/\mathrm{d}x$ and B mass; $\mathcal{A}_{K^+\pi^-}$ only

π/K separation with DCH dE/dx:

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

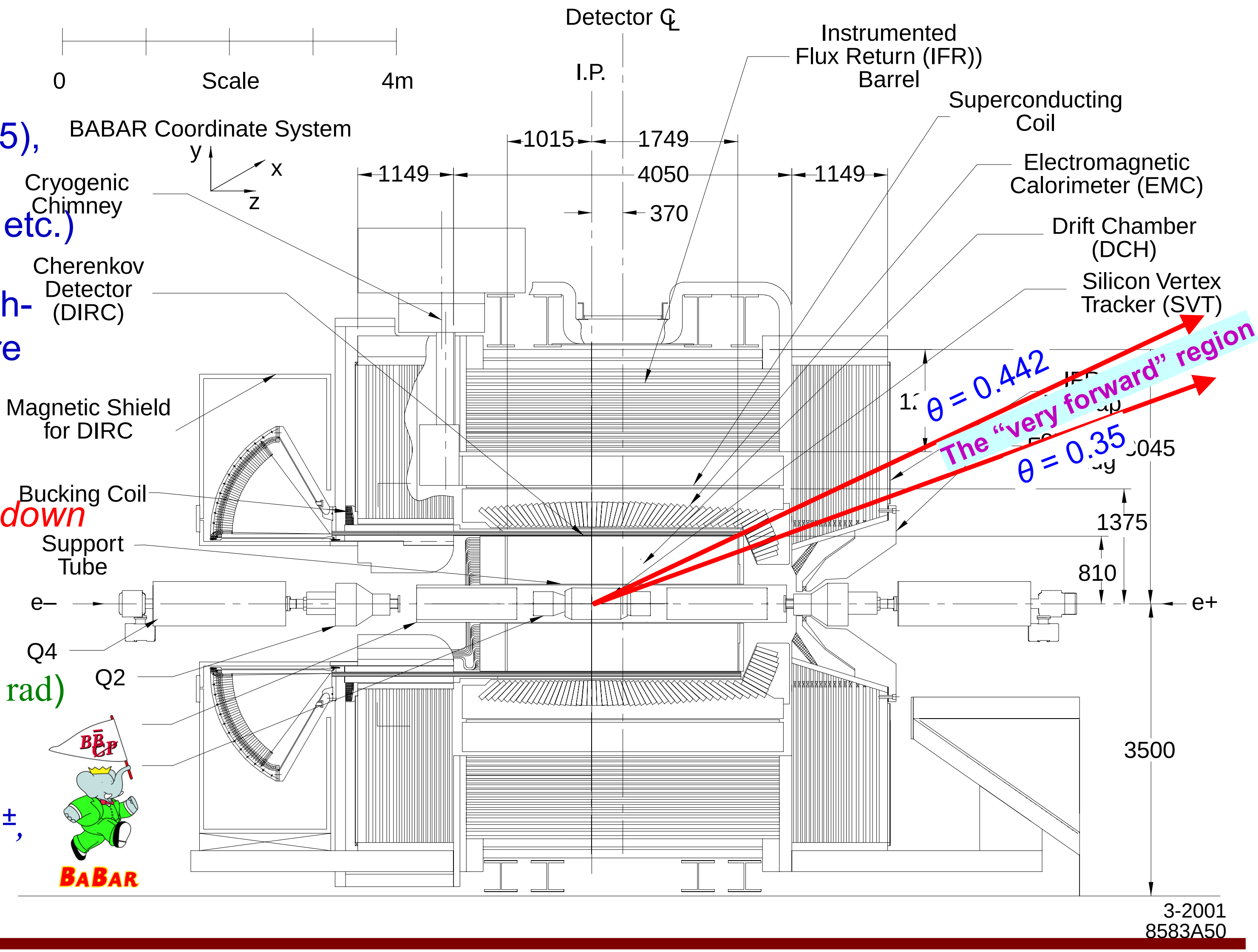
In the barrel (θ>0.445), the DIRC is ~9.3% inefficient (φ cracks, etc.)

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

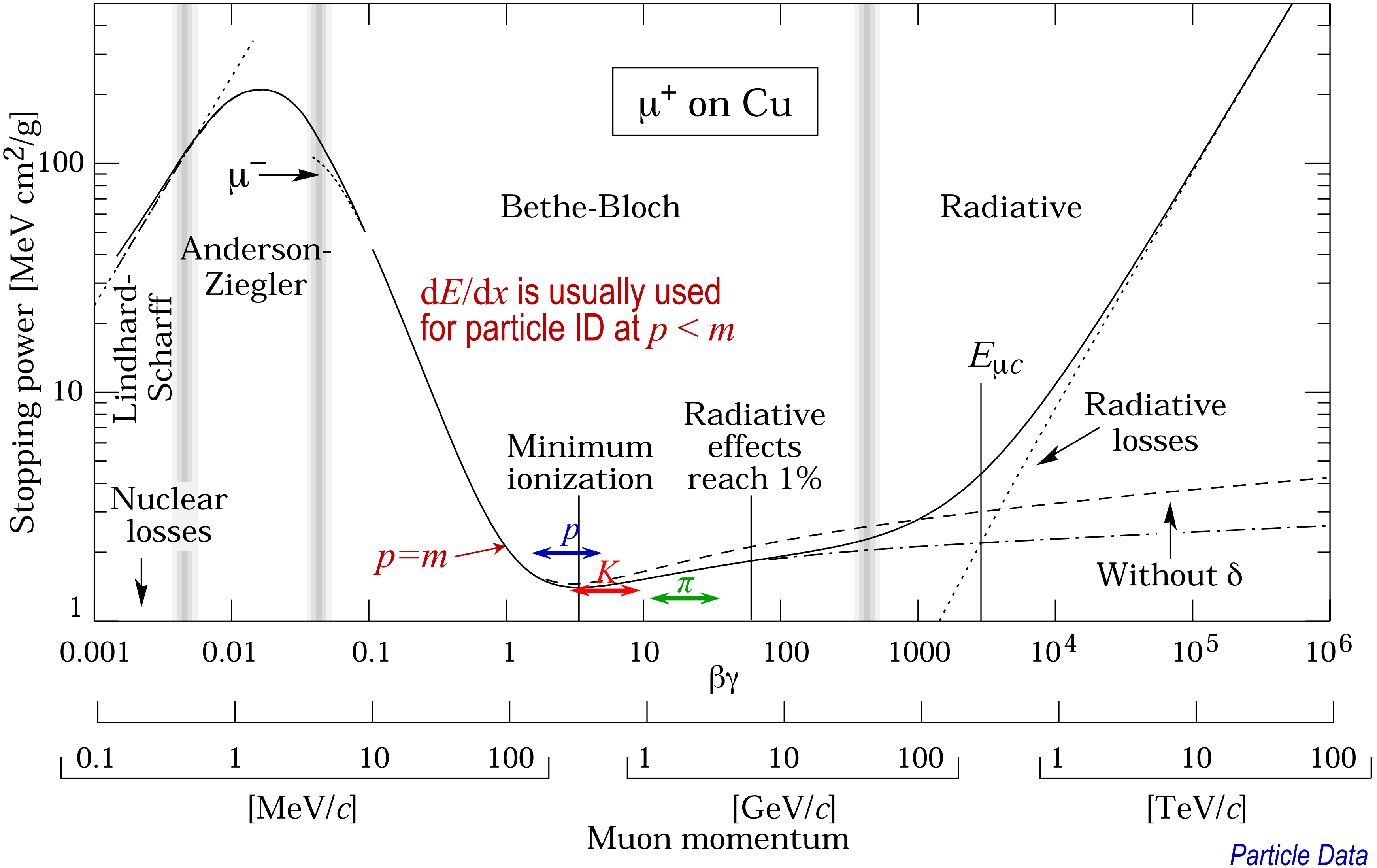
We use DCH tracks down to θ = 0.35 rad

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

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



Ionization energy loss for $B \to Xh^{\pm}$



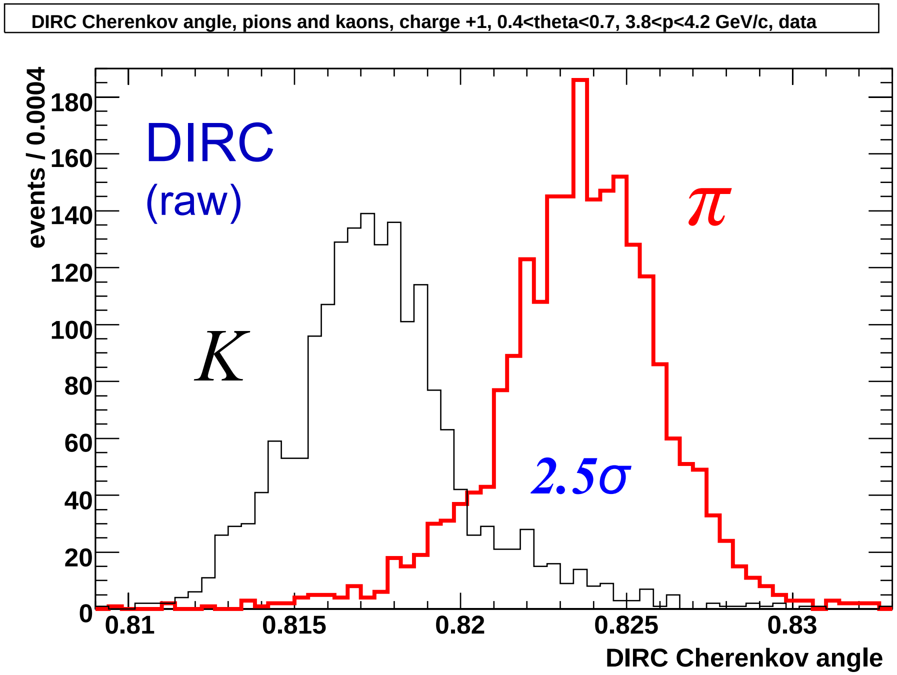
dE/dx is usually used for particle ID at $p < m$

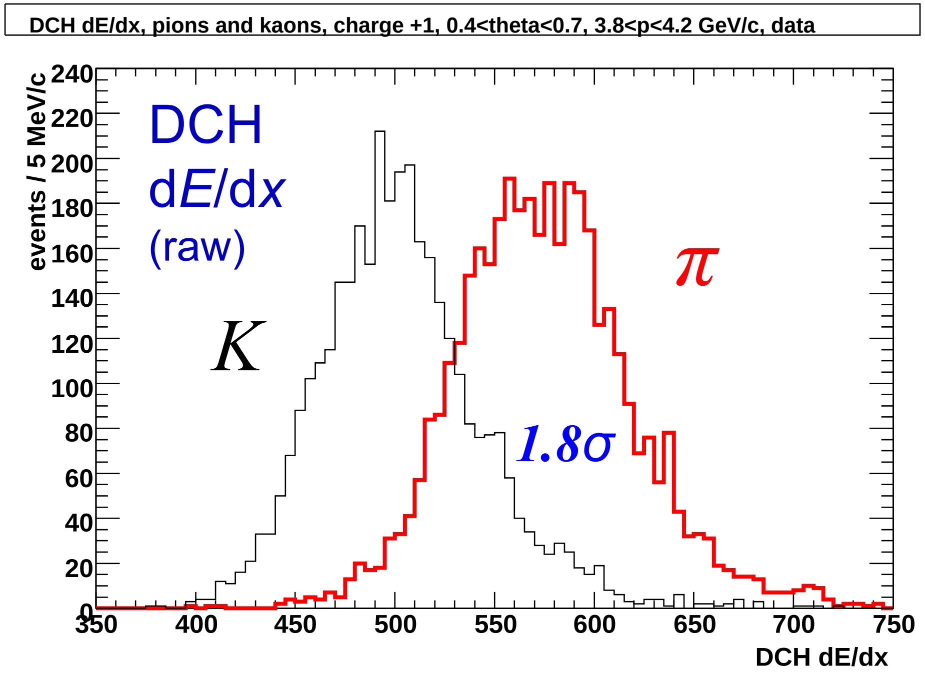
Particle Data Group

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

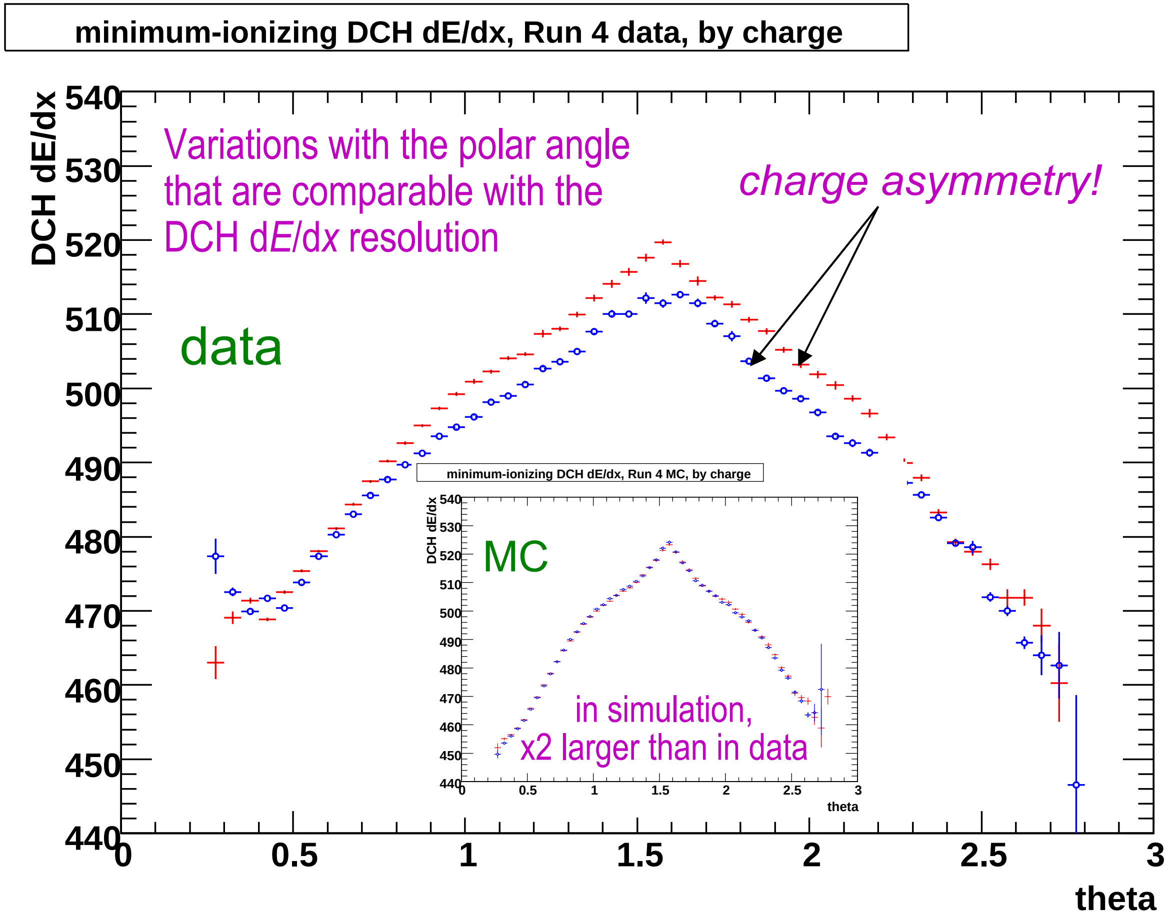
In the forward region, DCH d*E*/dx is not much worse than the DIRC—and is 100% efficient!

$0.4 < \theta < 0.7$, $3.8 < p < 4.2$ GeV/*c*
1999-2006 data





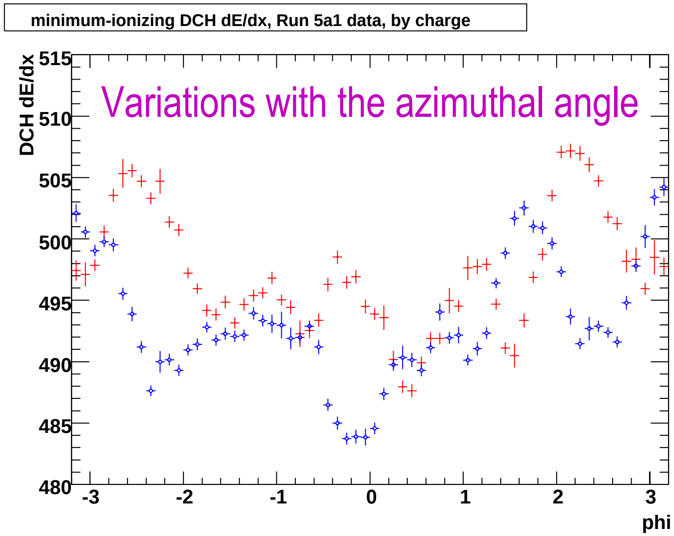
There were *many* reasons DCH dE/dx failed to work in likelihood-based $B \to Xh^{\pm}$ analyses in the past



Variations with the polar angle that are comparable with the DCH dE/dx resolution

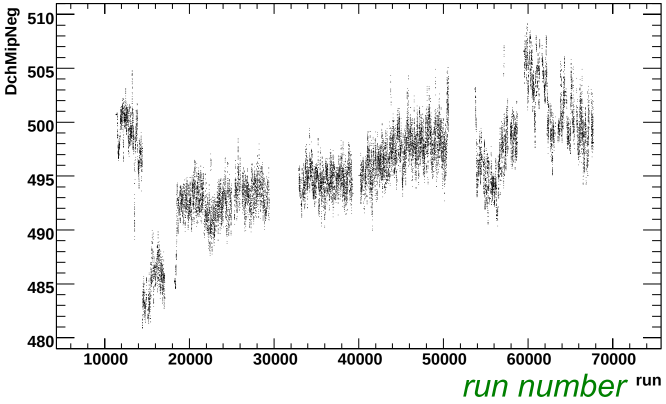
charge asymmetry!

in simulation, x2 larger than in data



Variations with the azimuthal angle

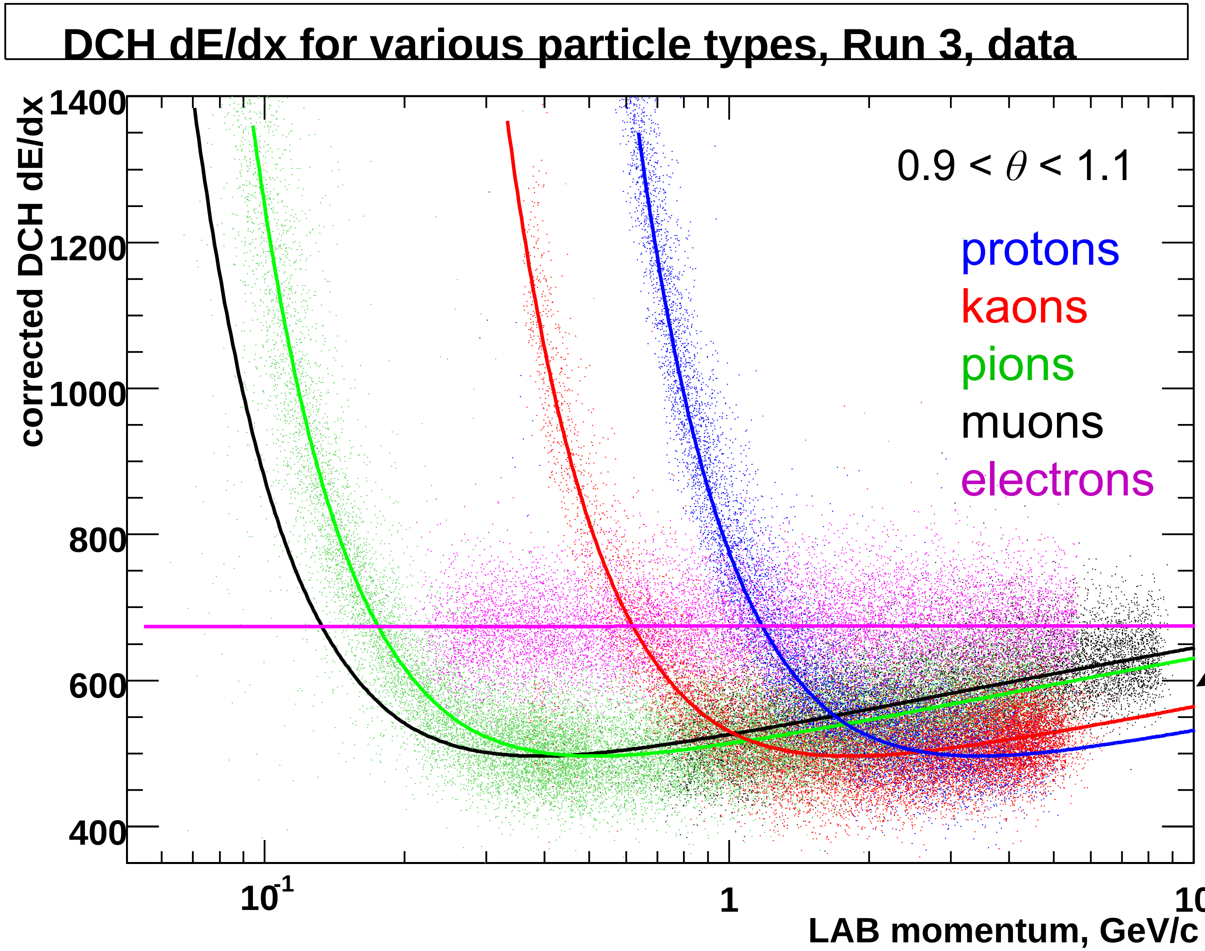
Minimum-ionizing DCH dE/dx vs. time

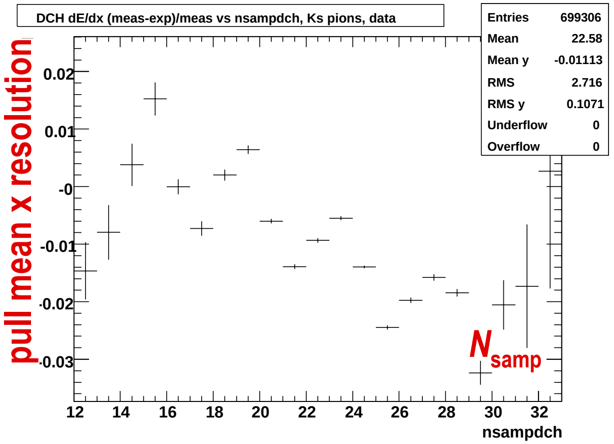


run number

dE/dx in DCH

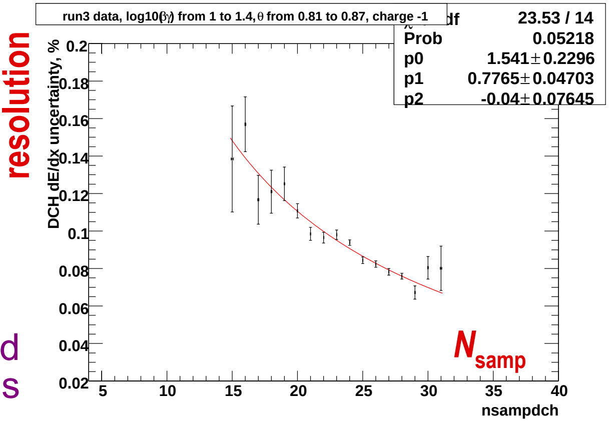
This is what DCH dE/dx looks like after the new calibration





up to 1.9σ

π/K separation

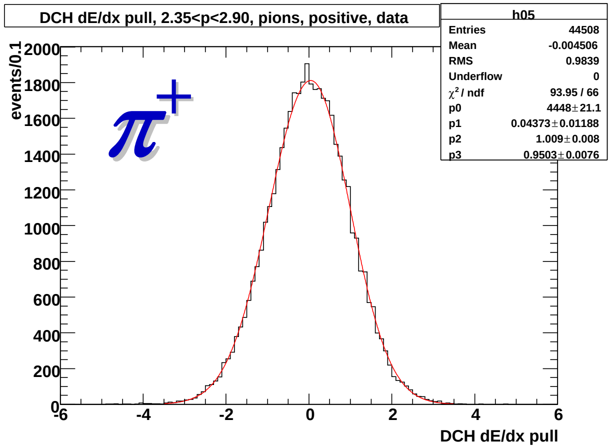


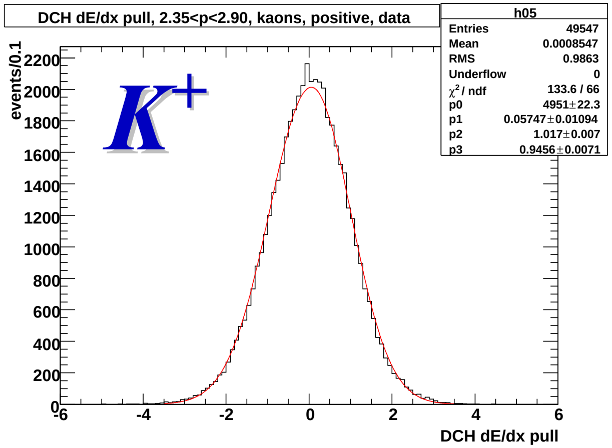
DCH dE/dx mean and resolution also depend on the number of dE/dx samples

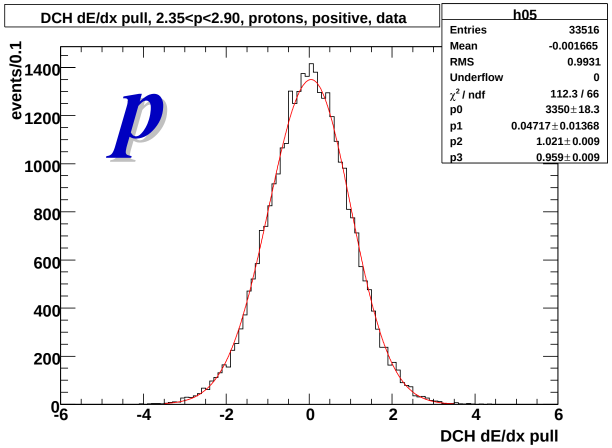
New, detailed DCH dE/dx parametrization: π, K, p pulls for $B \to Xh^{\pm}$ track momenta

pull ≡ (measured − expected) / error

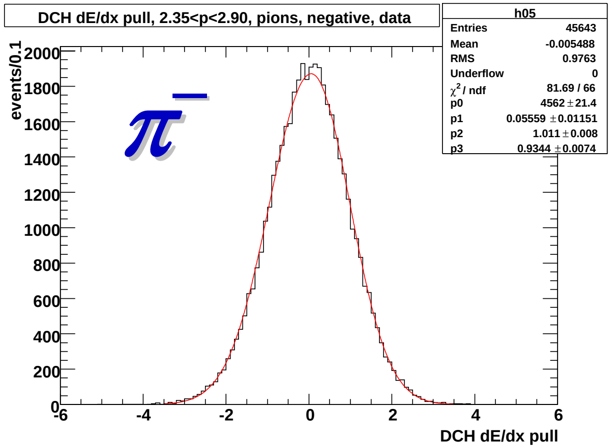
“measured” values in these plots are taken from appropriate calibration samples

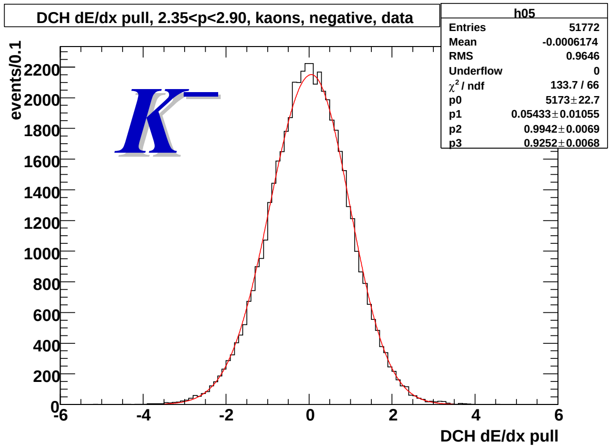

DCH dE/dx pull, 2.35<p<2.90, pions, positive, data

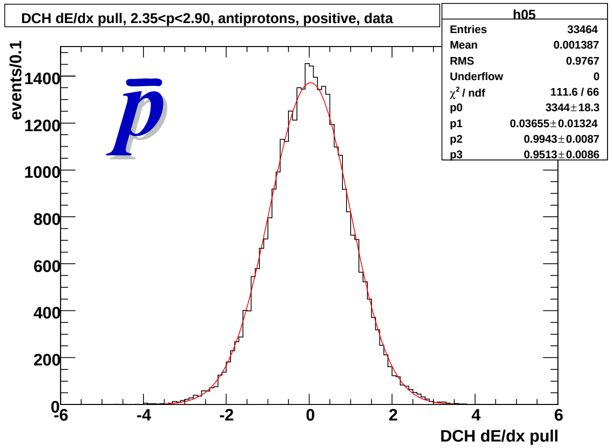

DCH dE/dx pull, 2.35<p<2.90, kaons, positive, data


DCH dE/dx pull, 2.35<p<2.90, protons, positive, data

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

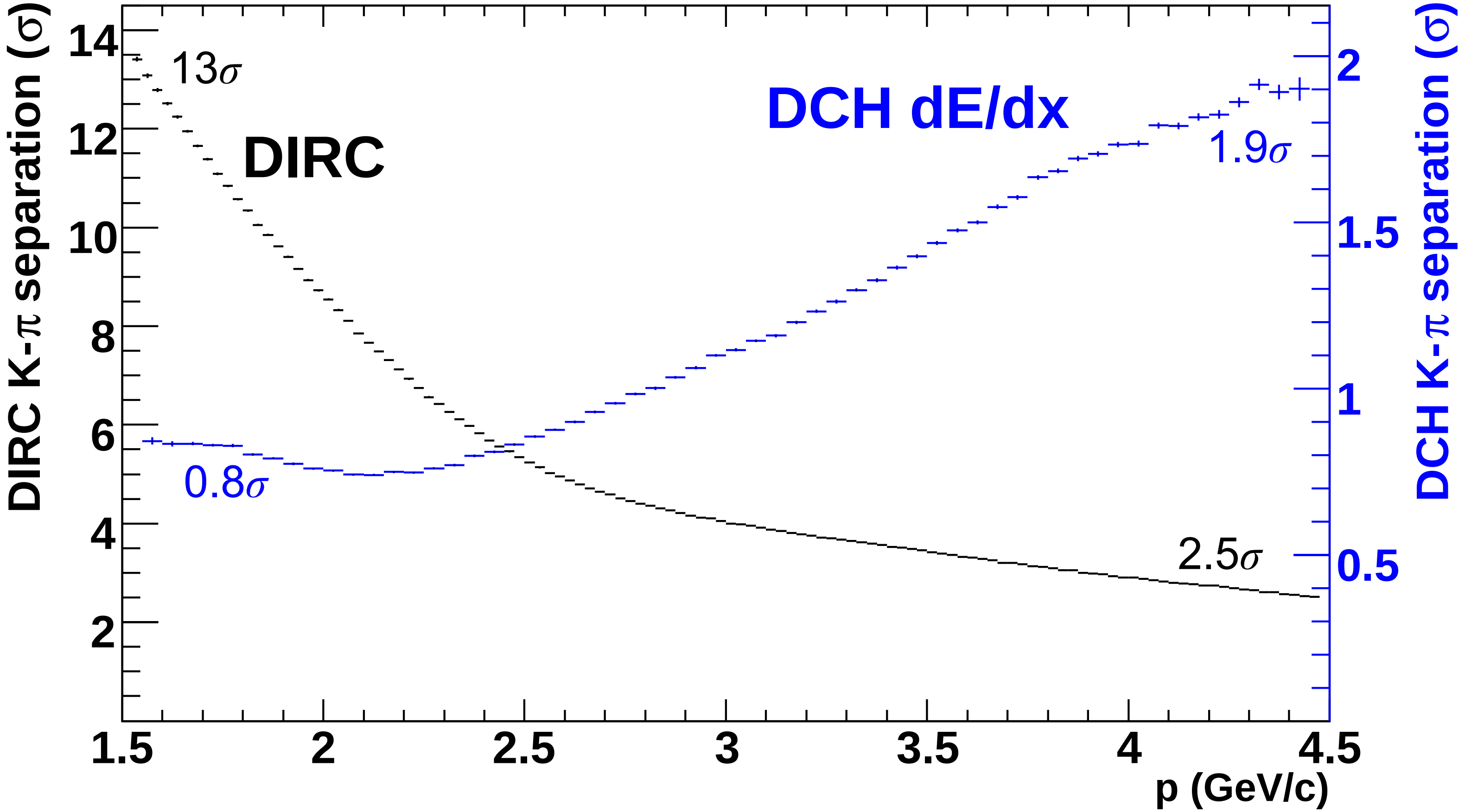

DCH dE/dx pull, 2.35<p<2.90, pions, negative, data


DCH dE/dx pull, 2.35<p<2.90, kaons, negative, data


DCH dE/dx pull, 2.35<p<2.90, antiprotons, positive, data

DCH dE/dx K-π separation in $B \to Xh^{\pm}$

complementary to DIRC



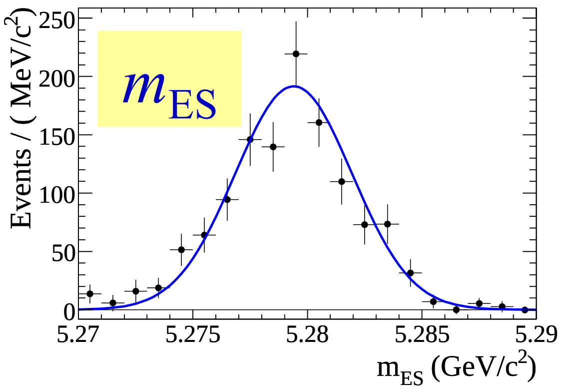
(for tracks that have good DIRC information, we use both DIRC and dE/dx)

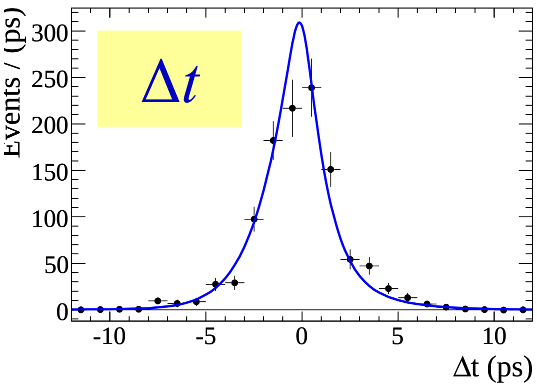
Our new result: $B^0 \to \pi^+\pi^-$

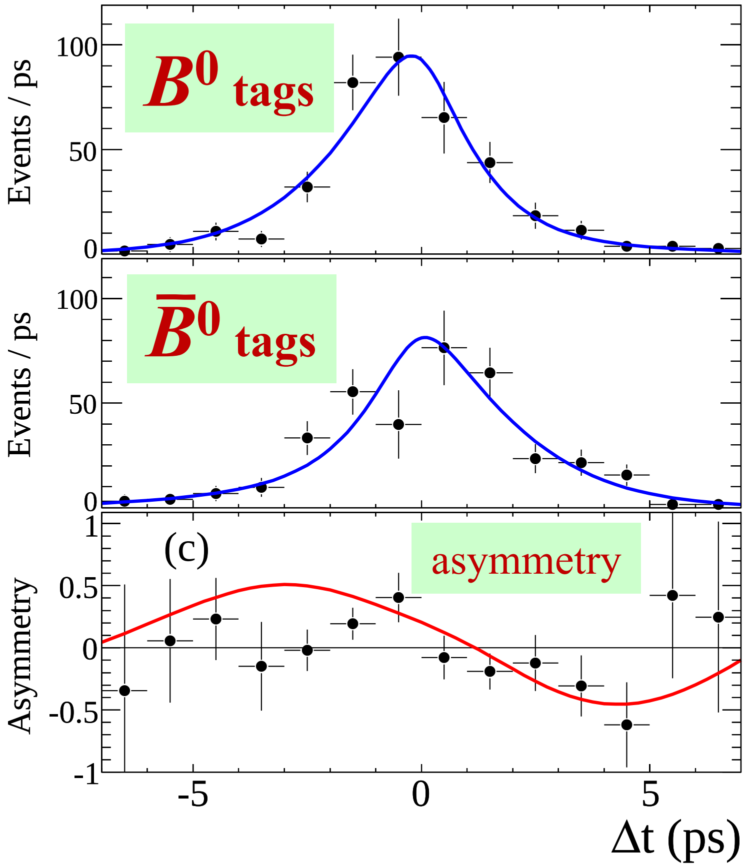
$$N_{\pi^+\pi^-} = 1139 \pm 49$$

52% overall increase
in signal reconstruction efficiency:

35% from DCH $\mathrm{d}E/\mathrm{d}x$,
13% mainly from reoptimizing the event-shape $|\cos\theta_{\mathrm{spher}}|$ cut







$_s\mathcal{P}lot$: 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]

PRL **99,** 021603 (2007) PHYSICAL REVIEW LETTERS week ending 13 JULY 2007

Observation of CP Violation in $B^0 \to K^+\pi^-$ and $B^0 \to \pi^+\pi^-$

BaBar **has made a 5.4σ observation of CP violation in $B^0 \to \pi^+\pi^-$**

$$S_{\pi\pi} = -0.60 \pm 0.11 \pm 0.03\ (5.1\sigma)$$

$$C_{\pi\pi} = -0.21 \pm 0.09 \pm 0.02\ (2.3\sigma)$$

BaBar: 383 million $B\bar{B}$ pairs, 1139 ± 49 $\pi^+\pi^-$

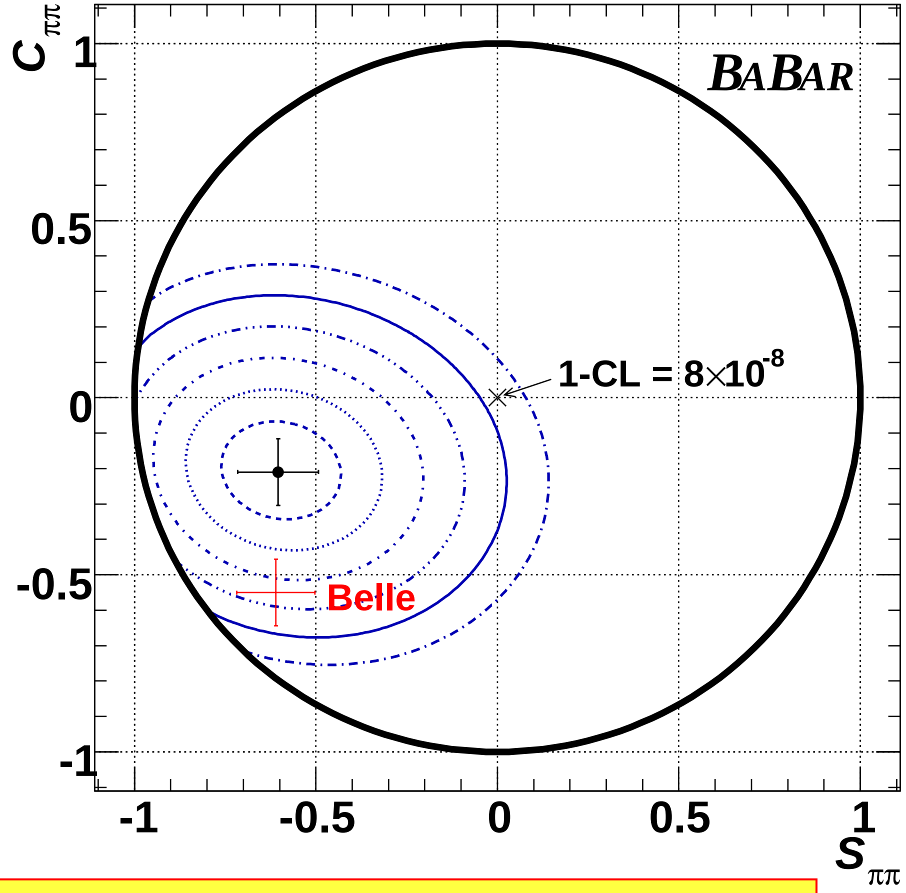
Belle: 535 million $B\bar{B}$ pairs, 1464 ± 65 $\pi^+\pi^-$

BaBar now has 9% more $\pi^+\pi^-$ per fb^{-1} than *Belle*

Belle PRL 98, 211801 (2007)

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

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

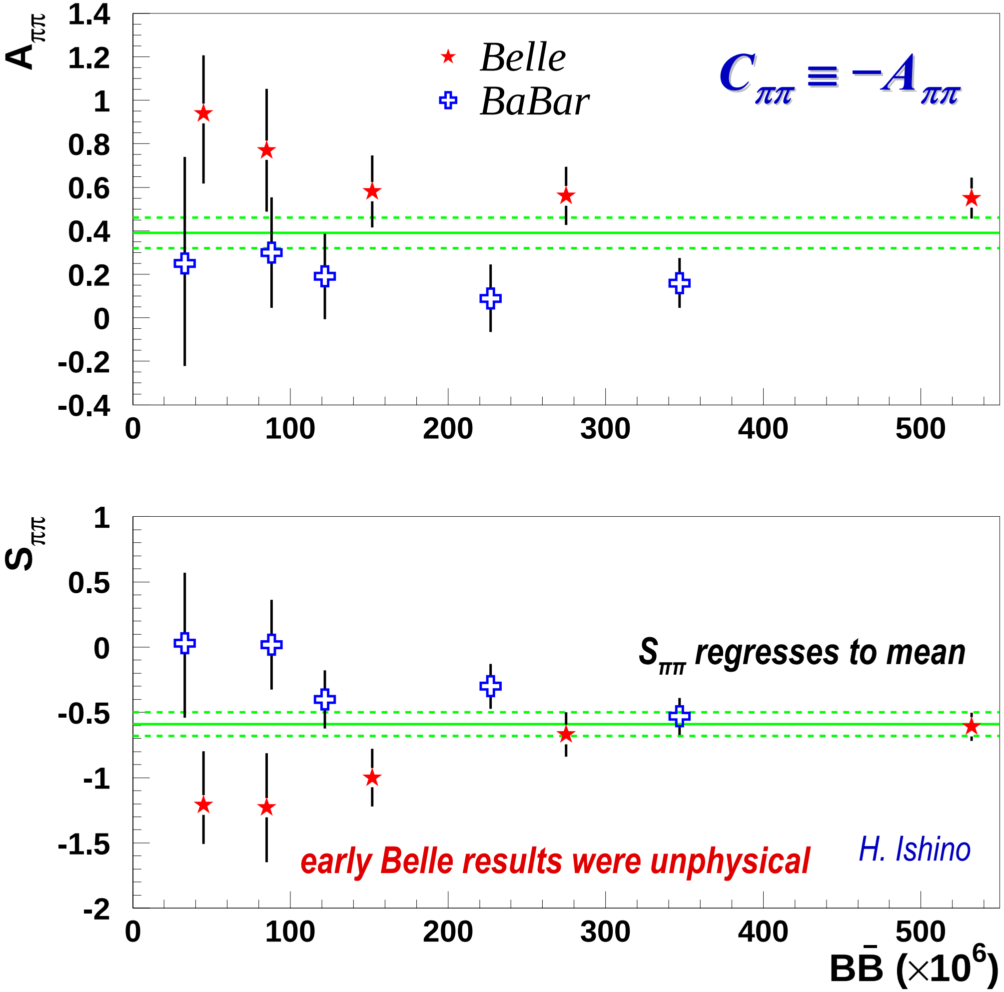


also: $$\mathcal{A}_{K^+\pi^-} = -0.107 \pm 0.018\ {}^{+0.007}_{-0.004}\ \ (5.5\sigma)$$

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 2.6σ difference is still present, in $C_{\pi\pi}$

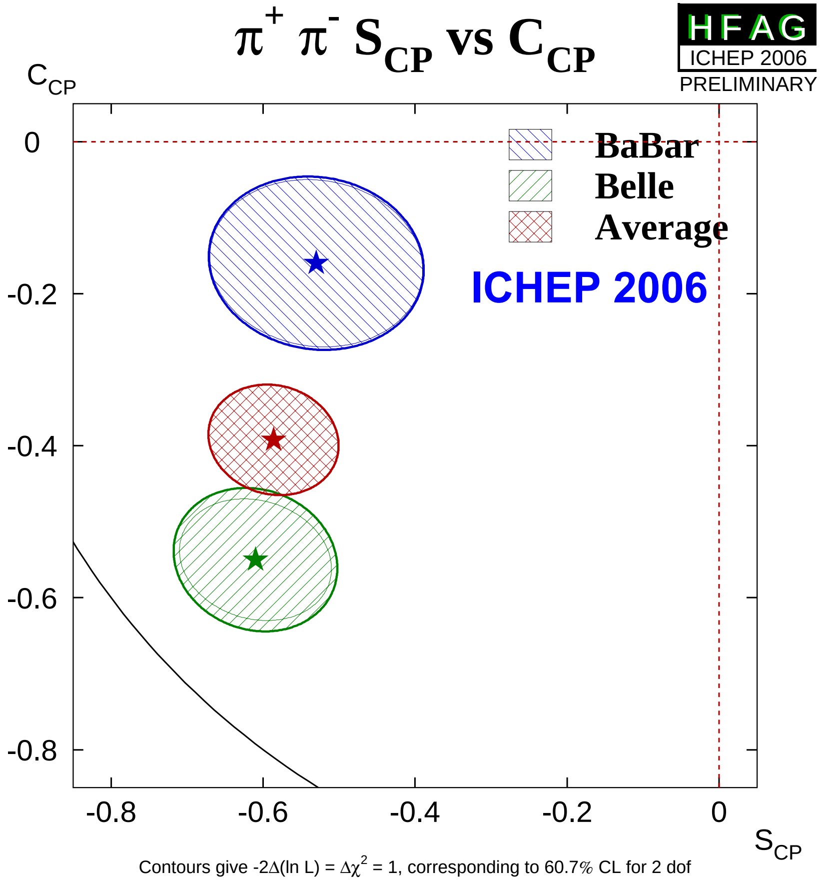


$C_{\pi\pi} \equiv -A_{\pi\pi}$

$S_{\pi\pi}$ regresses to mean

early Belle results were unphysical

H. Ishino



Contours give $-2\Delta(\ln L) = \Delta\chi^2 = 1$, corresponding to 60.7% CL for 2 dof

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

$\Rightarrow$ *10% efficiency increase per* π^0 (4% from merged π^0, 6% from γ conversions)

At a Super *B-meson* factory, $\gamma \to e^+e^-$ conversions would make $S_{\pi^0\pi^0}$ determination possible!

merged π^0 :

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

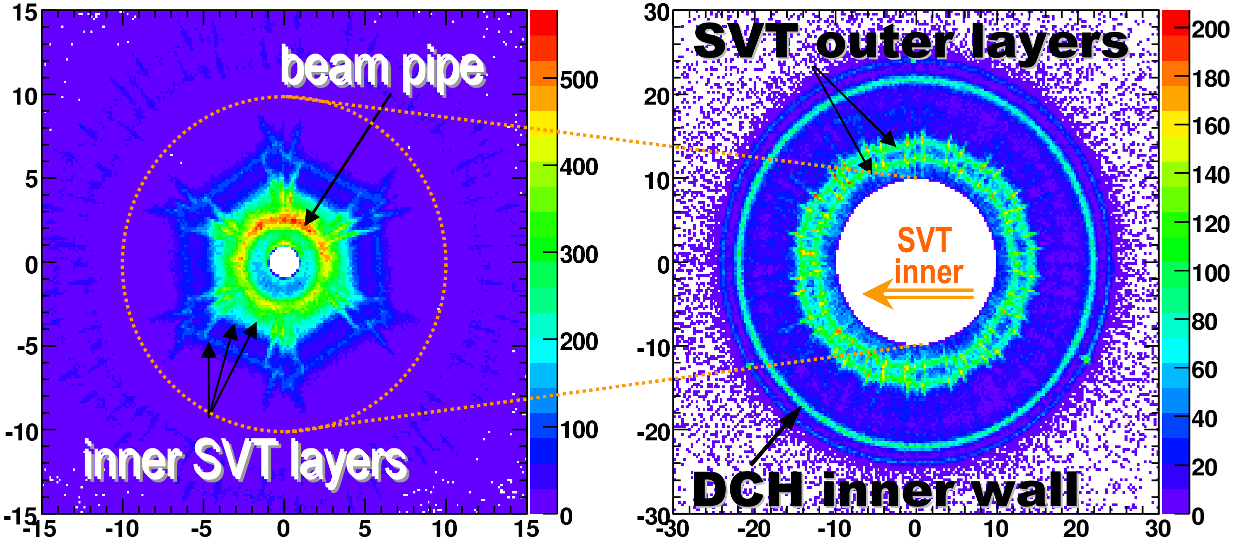
$$M^2_{\pi^0} \approx E^2_{\pi^0}(S_{\pi^0} - S_\gamma),$$

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

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

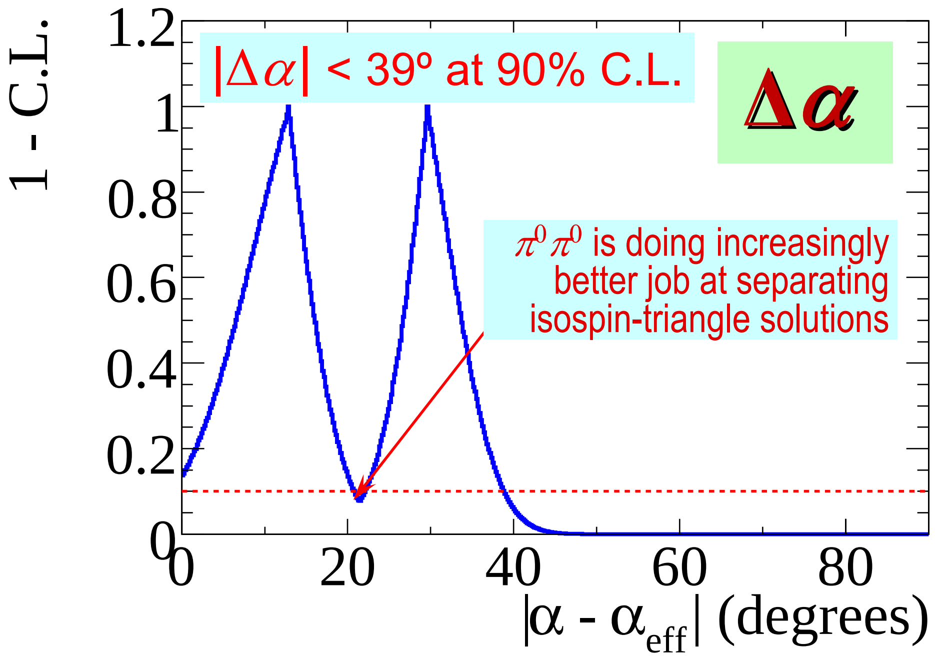
$\gamma \to e^+e^-$ conversions:

result from interactions with detector elements



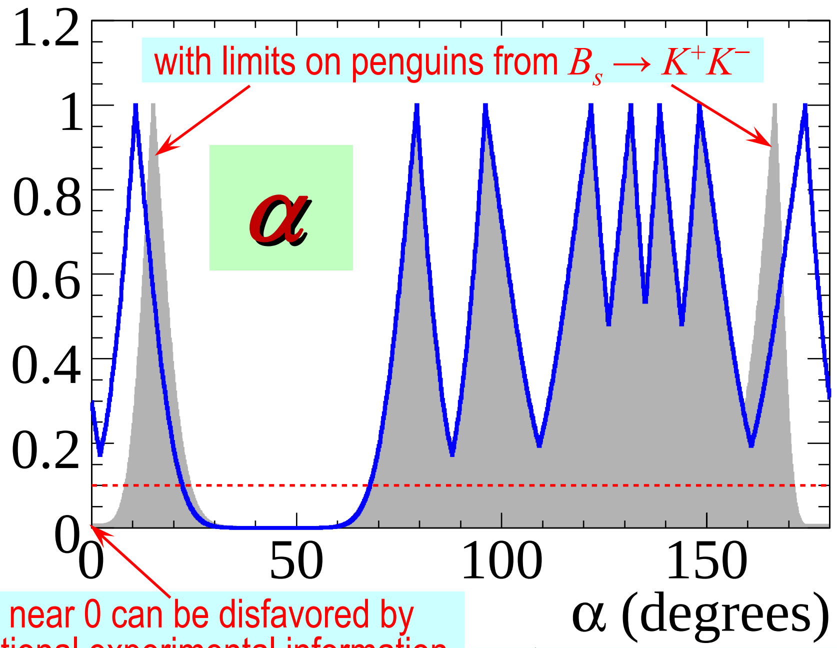
An interpretation of our new $B \to \pi\pi$ results

PRD 76, 091102 (2007)



$|\Delta\alpha|$ < 39° at 90% C.L.

$\pi^0\pi^0$ is doing increasingly better job at separating isospin-triangle solutions

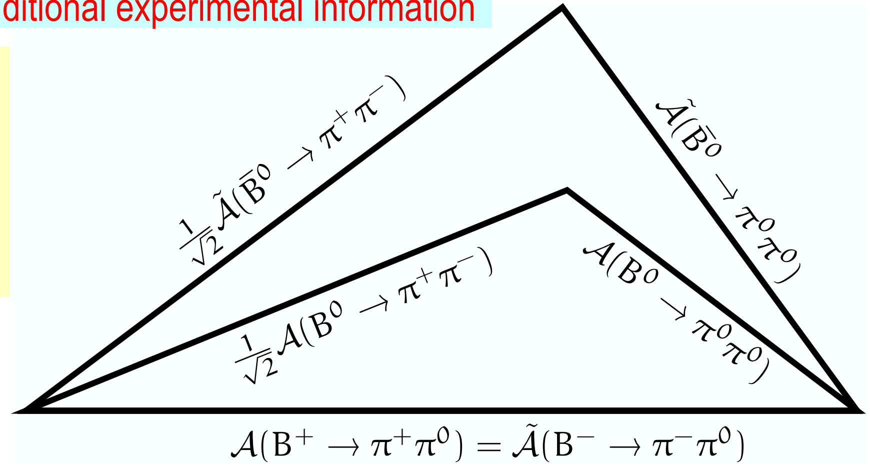


with limits on penguins from $B_s \to K^+K^-$

α near 0 can be disfavored by additional experimental information

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



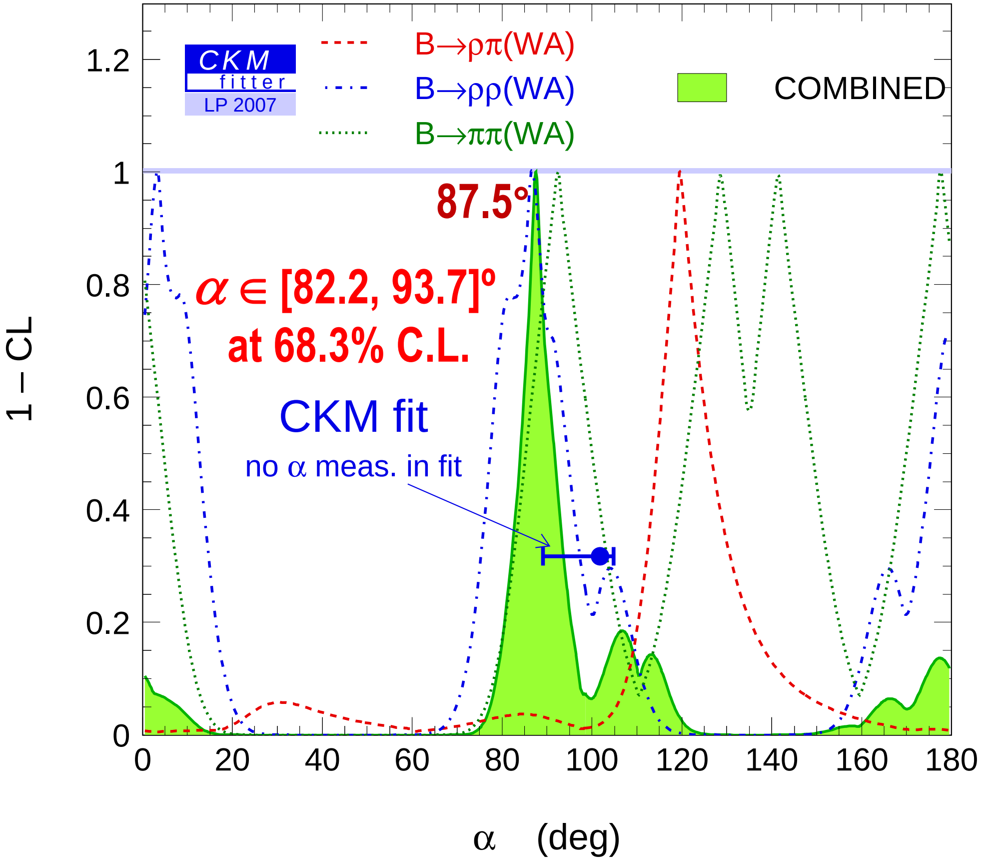
Global fits for the value of α

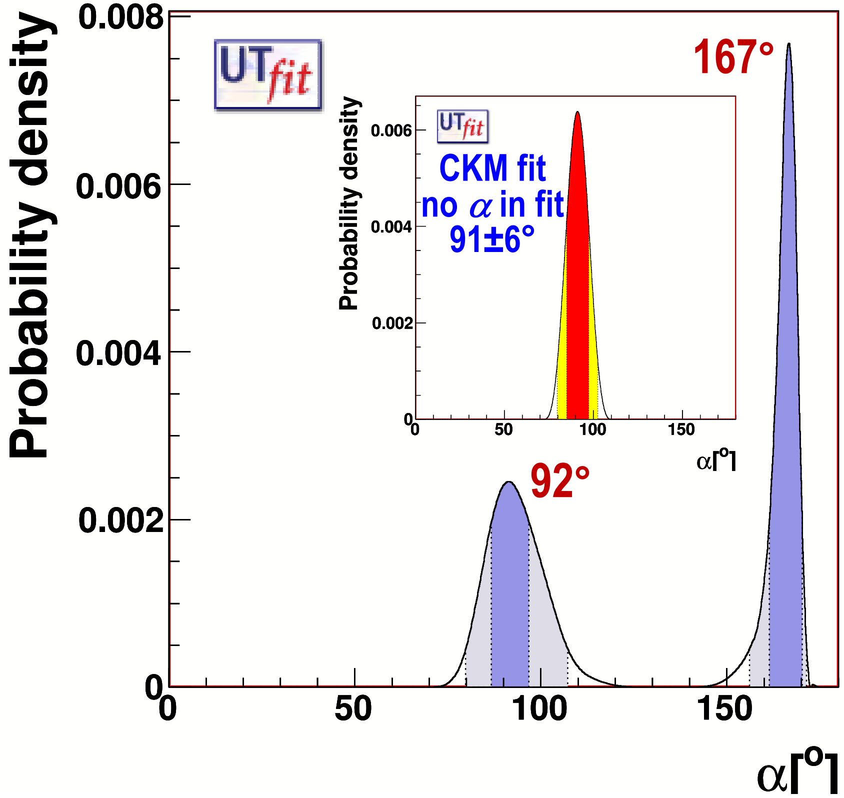
The <u>second-highest-precision</u> test of the KM mechanism of *CP* violation in meson decays

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

A frequentist interpretation

A Bayesian interpretation, with 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://www.utfit.org

Our new result: $B^0 \to K^+\pi^-$

the first >5σ observation of $\mathcal{A}_{K^+\pi^-}$ (direct *CP* violation)

BaBar: $\mathcal{A}_{K^+\pi^-} = -0.107 \pm 0.018\,^{+0.007}_{-0.004}$ *published in PRL 99, 021603 (2007)*

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

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

$$\mathcal{A}_{K^+\pi^-}(\text{World Average}) = -0.097 \pm 0.012 \ (8\sigma \text{ from } 0)$$

Predicted to be $\approx \mathcal{A}_{K^+\pi^0}(\text{WA}) = +0.051 \pm 0.025$

5.4σ difference: an "$\mathcal{A}_{K\pi}$ puzzle"

− Could be due to hadronic effects, not New Physics (e.g., see R. Fleischer, hep-ph/0608010, hep-ph/0701217)

assuming unbroken $SU(3)_{\text{flavor}}$:

$$C_{\pi\pi} = 3 \times \mathcal{A}_{K^+\pi^-}$$

with factorizable $SU(3)_{\text{flavor}}$-breaking corrections:

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

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

1) Detailed GEANT4 v7.1-based simulation: bias of −0.005

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 (uncorrected): −0.011 ± 0.004 (stat)

$\mathcal{A}_{K^+\pi^-}$ bias correction: $\boxed{+0.005^{+0.006}_{-0.003}}$

conservative

bias cannot be zero

Summary and outlook

By gaining a better, more detailed and precise understanding of BaBar detector performance, we have:

- Found ways to increase the $B^0 \to h^+h^-$ reconstruction efficiency by 52%
- Observed *CP* violation the time distribution of $B^0 \to \pi^+\pi^-$ decays
- Observed *CP* violation the charge asymmetry of $B^0 \to K^+\pi^-$ decays

  The first single-experiment 5-sigma observation of direct *CP* violation in a process where direct *CP* violation is not tightly coupled to another type of *CP* violation (as in ε' or $C_{\pi\pi}$). *CPV* in decay rules out "superweak" models.

The Kobayashi-Maskawa phase has been demonstrated to be the dominant source of *CP* violation in meson decays.

Constraints on the CKM Unitarity Triangle from angle measurements are comparable with constraints from all other sources – and mutually consistent.

The absence of a statistically significant incompatibility between them contains a wealth of information about the New Physics that we can be expected at the TeV scale. In particular, it pushes up the scale of new *CP*-violating physics in most models.

We continue to improve *BaBar* !

Problems with Resistive-Plate Muon Chambers

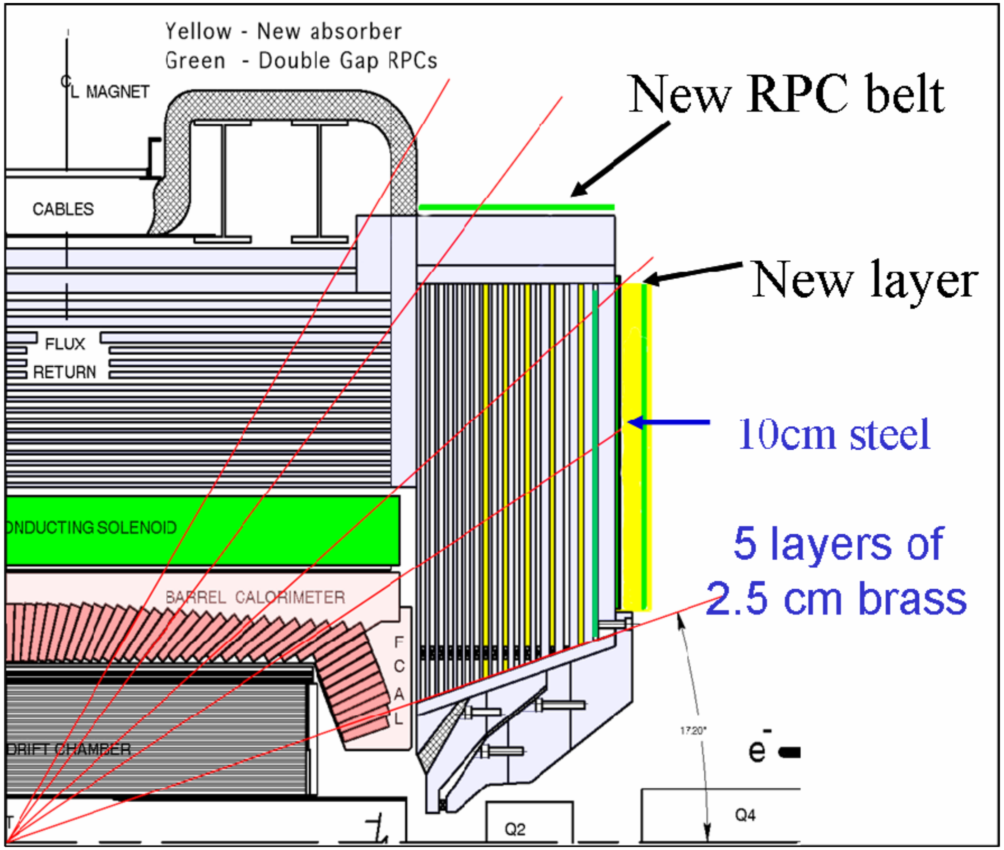
- The only major problem with the *BaBar* detector, known since 1999: RPC efficiency deteriorating at ~10-20%/year.

- 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.

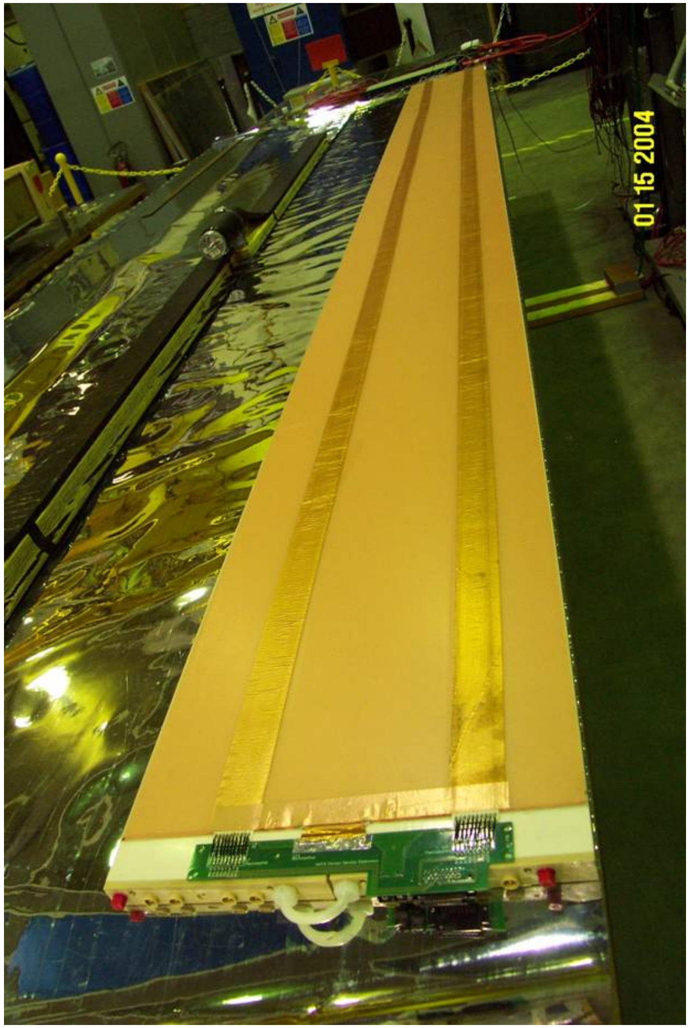
- Adding six 2.2 cm layers of brass increases barrel thickness to 5.3 λ_{int}.



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

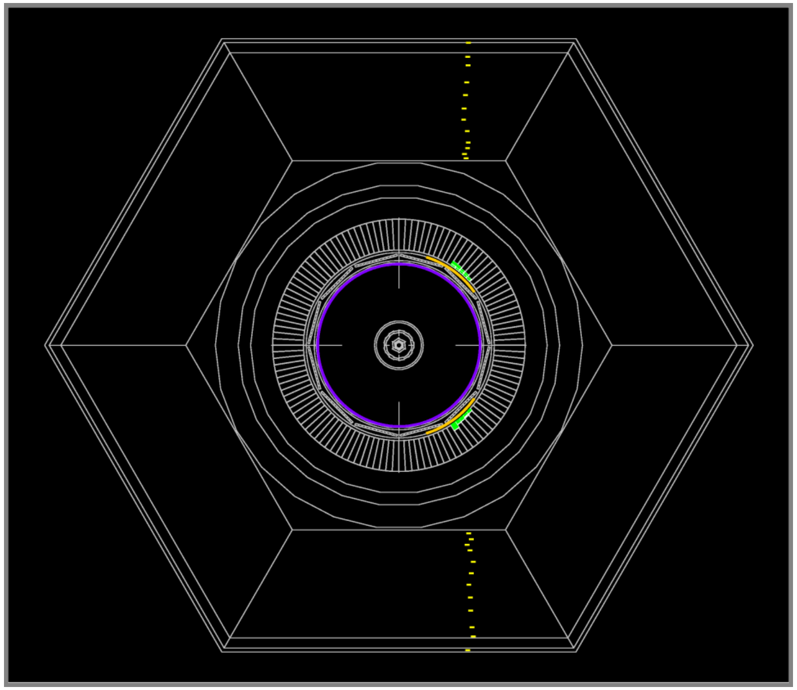
LST technology

- 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.

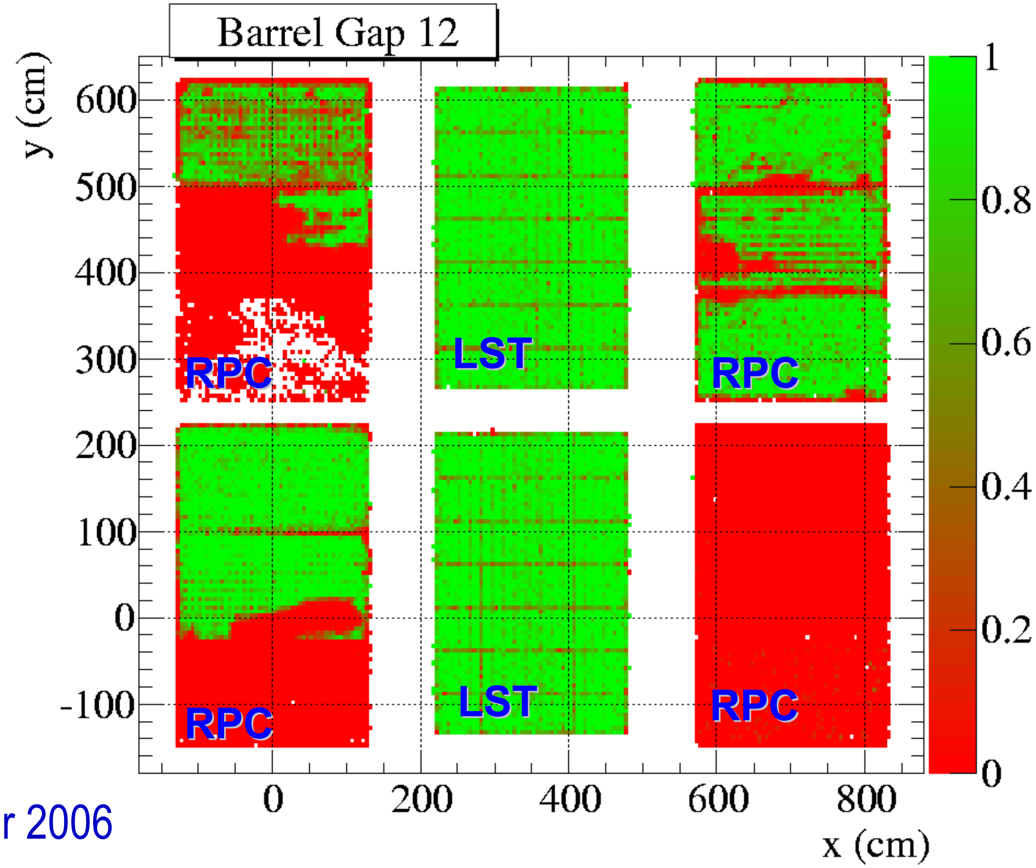


LST performance

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



Example of single-layer efficiency, May 2005

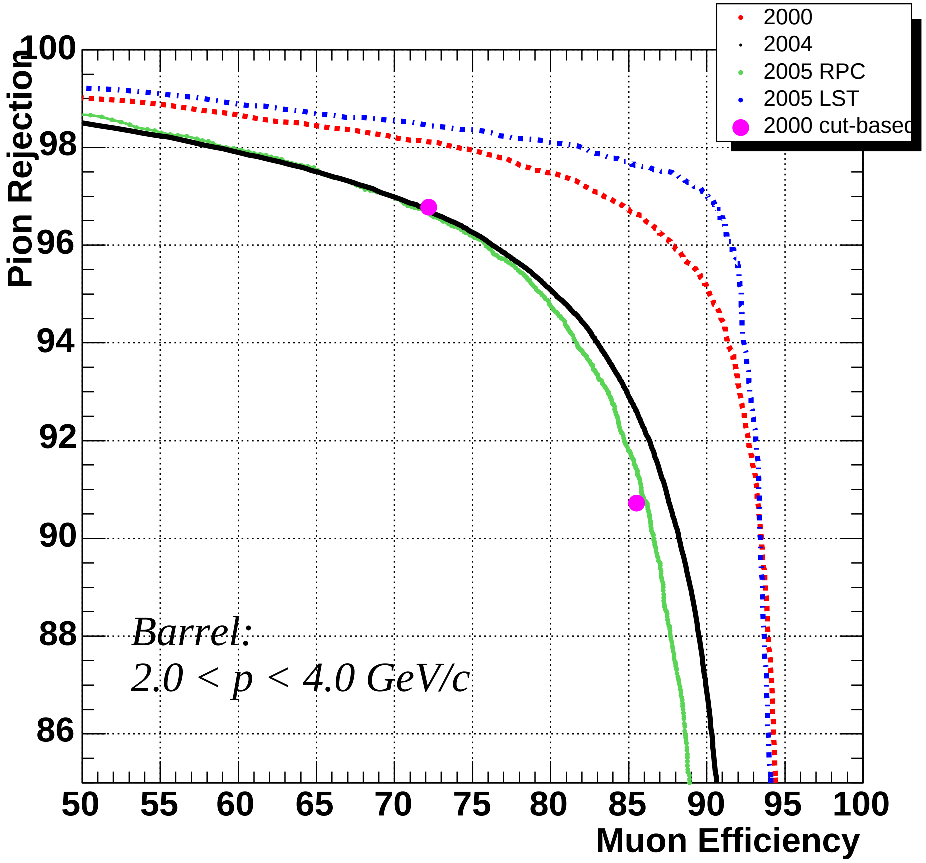


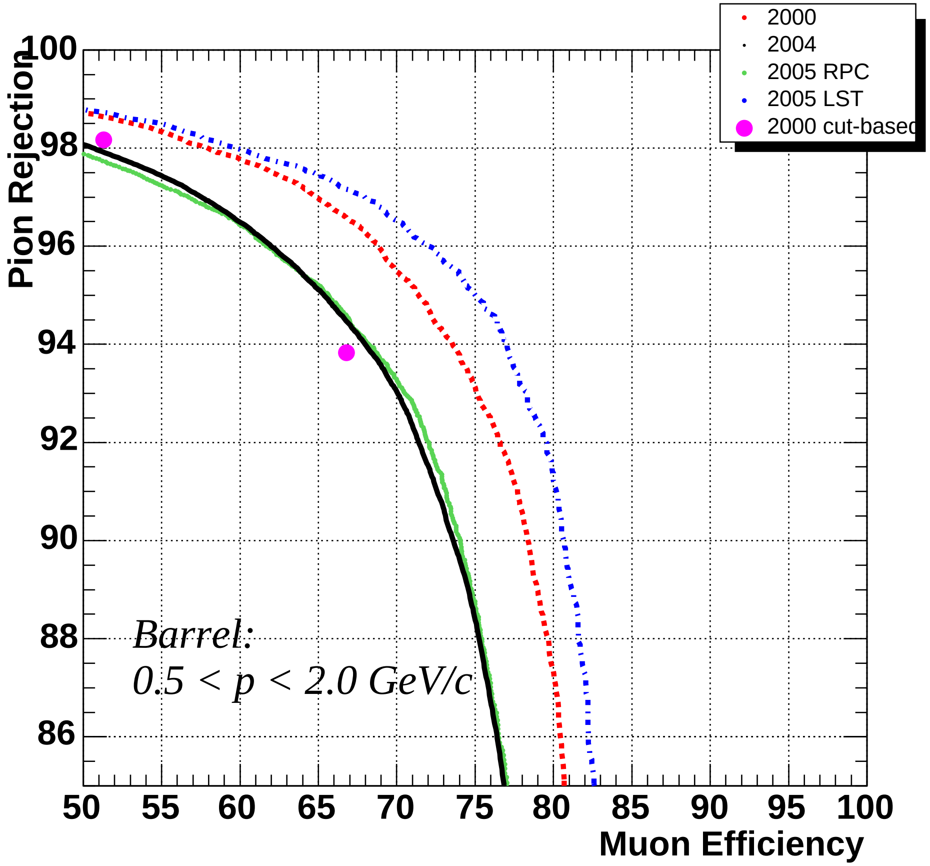
Upgrade of entire barrel completed in October 2006

Muon ID with LSTs

before many further improvements

LSTs were immediately doing better than RPCs ever did!



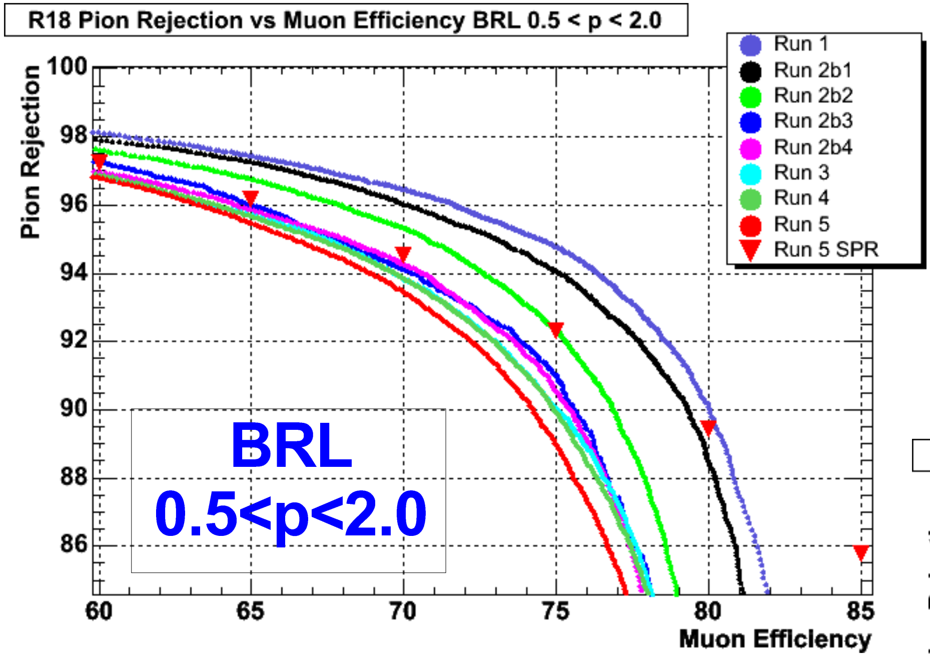


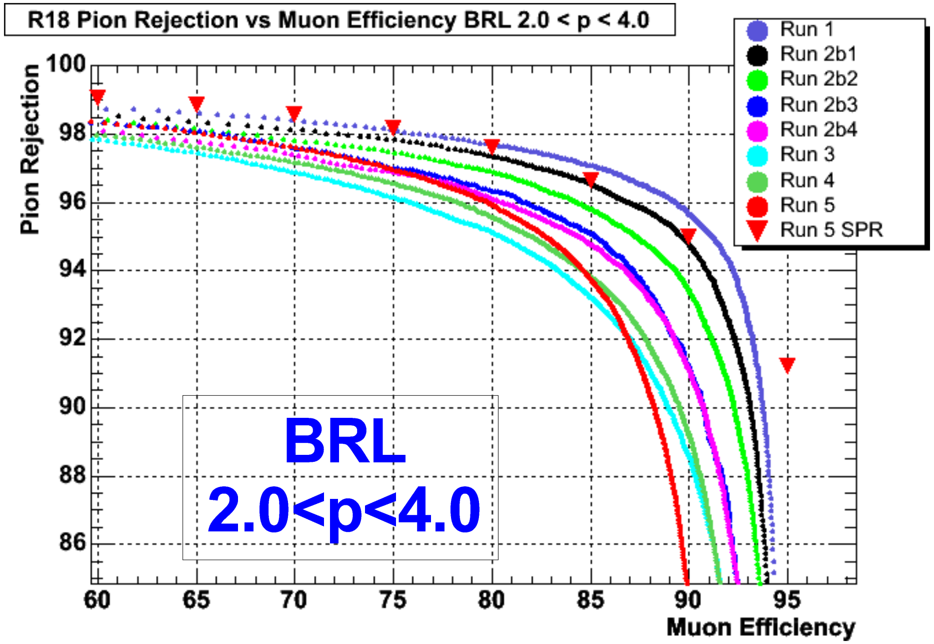
Muon ID idea:

Neural Net vs. Bagged Decision Trees

First try, some time in 2005… (Ilya Narsky, Caltech, CMS)

The more heterogeneous the inputs and/or the number of discriminating variables, the greater the advantage of Decision Trees over Neural Nets





Where does the room for improvement come from ?

1) Better parameterization of detector response:

- DCH d*E*/dx significantly improved
- SVT d*E*/dx greatly improved

Existing likelihood-based selectors will benefit “automatically” from the new d*E*/dx

First physics publications to use the new d*E*/dx parameterizations:

“Observation of *CP* Violation in $B^0 \to K^+\pi^-$ and $B^0 \to \pi^+\pi^-$”, PRL 99, 021603 (2007)

“Evidence for D^0-anti-D^0 Mixing”, PRL 98, 211802 (2007)

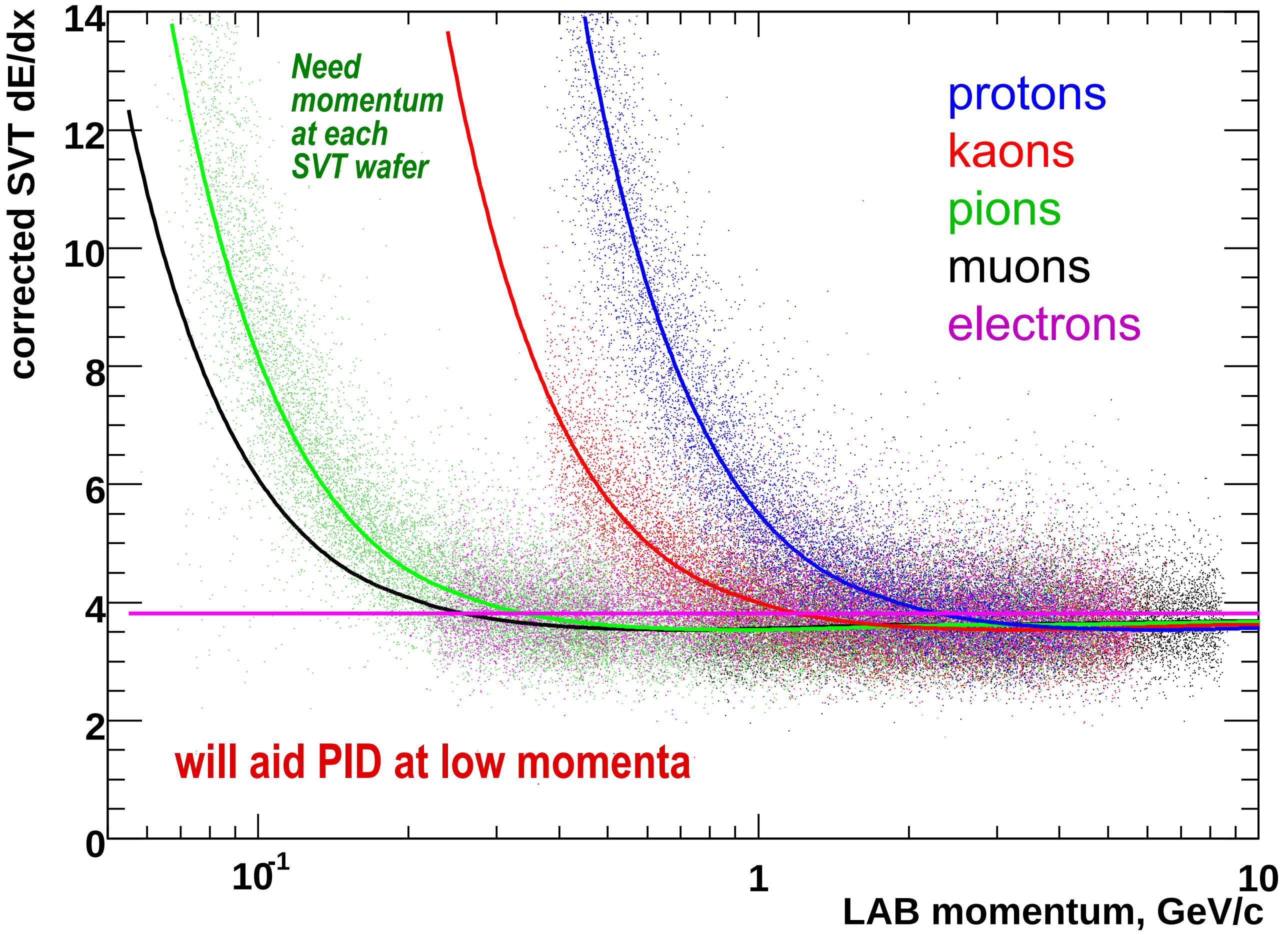
“Search for D^0-anti-D^0 mixing using doubly flavor tagged semileptonic decay modes”, PRD 76, 014018 (2007)

More analyses in the pipeline: all $\tau \to KX$, all charm-mixing with a D^{*+}, $B^+ \to K_S h^+$, …

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

This is what SVT dE/dx looks like __after__ the new detailed calibration

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

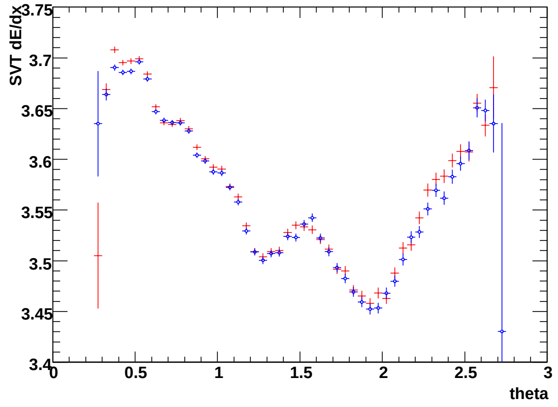


Need momentum at each SVT wafer

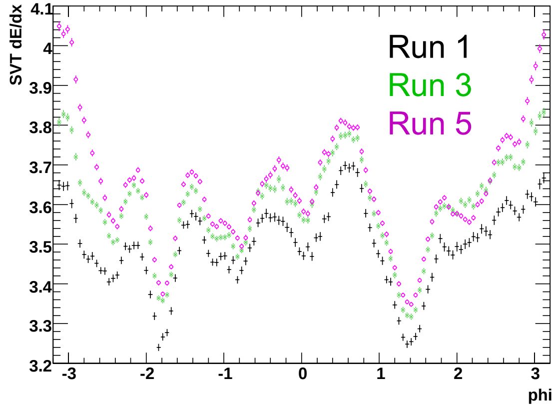
will aid PID at low momenta

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

minimum-ionizing SVT dE/dx, Run 2+4 data, by charge



minimum-ionizing SVT dE/dx, Runs 1, 3 and 5, data



Where does the room for improvement come from ?

2) previously unused quantities (“weak classifiers”), e.g.:

- number of signal and background photons in the DIRC (in a non-”binary” fashion)
- last layer hit in DCH (for kaon and pion decays in flight)
- DIRC and DCH d*E*/dx for muon ID
- full set of EMC quantities for all particle types
- SVT d*E*/dx for electron ID
- Flattening of the training-sample spectra in theta, phi and charge allows the use of these variables as input parameters

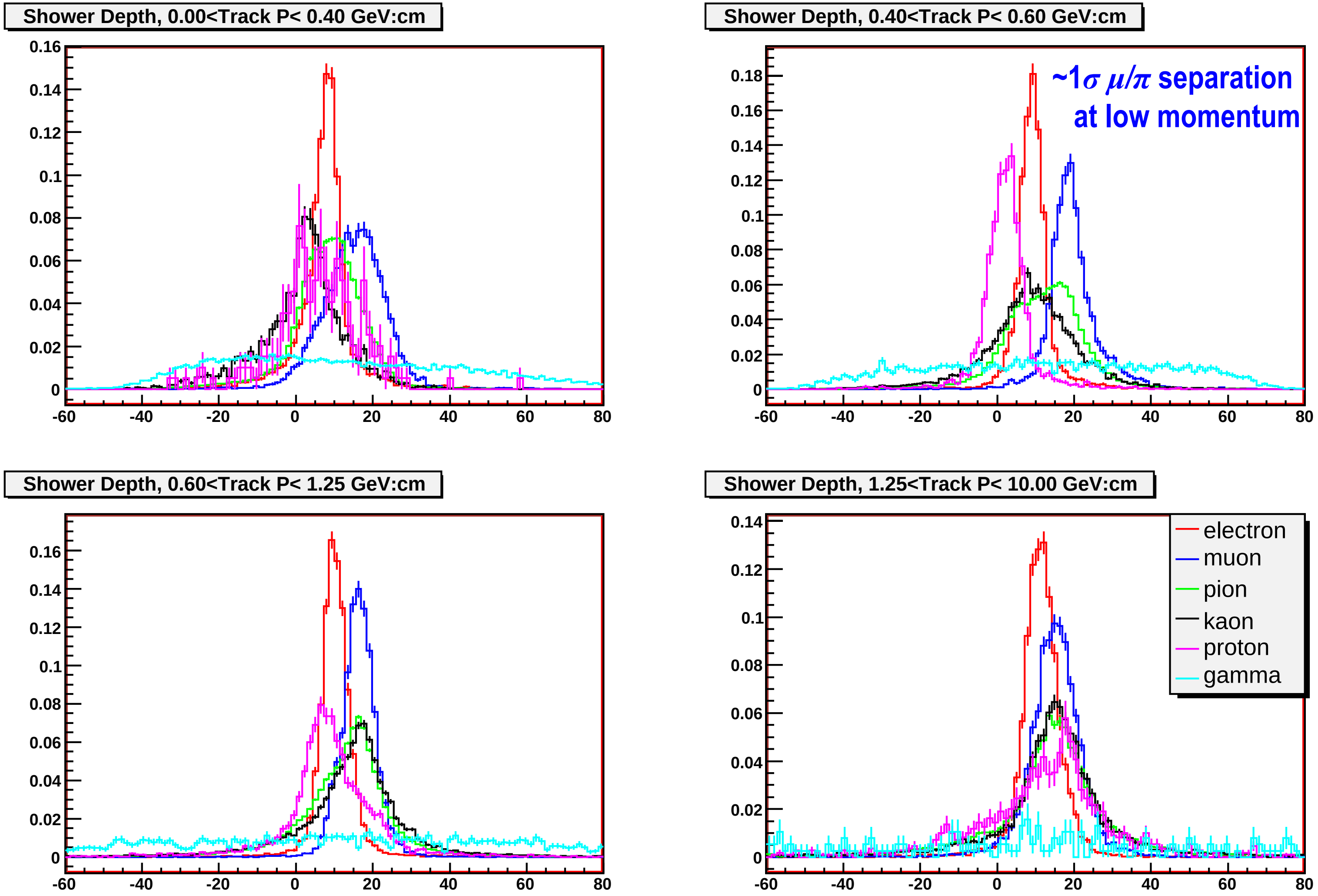
3) new quantities:

- longitudinal EMC shower depth
- using geometry to predict “dead spots” in detector acceptance

4) advanced statistical techniques from StatPatternRecognition

- SPR developed by Ilya Narsky (Caltech), SourceForge SPR V06-00-02
- we use SPR Boosted Decision Trees (muonBDT and kaonBDT selectors)
- and SPR multi-class learner (electron/pion/kaon/proton “KM” selectors)

EMC longitudinal shower depth



Shower Depth, 0.00<Track P< 0.40 GeV:cm

Shower Depth, 0.40<Track P< 0.60 GeV:cm

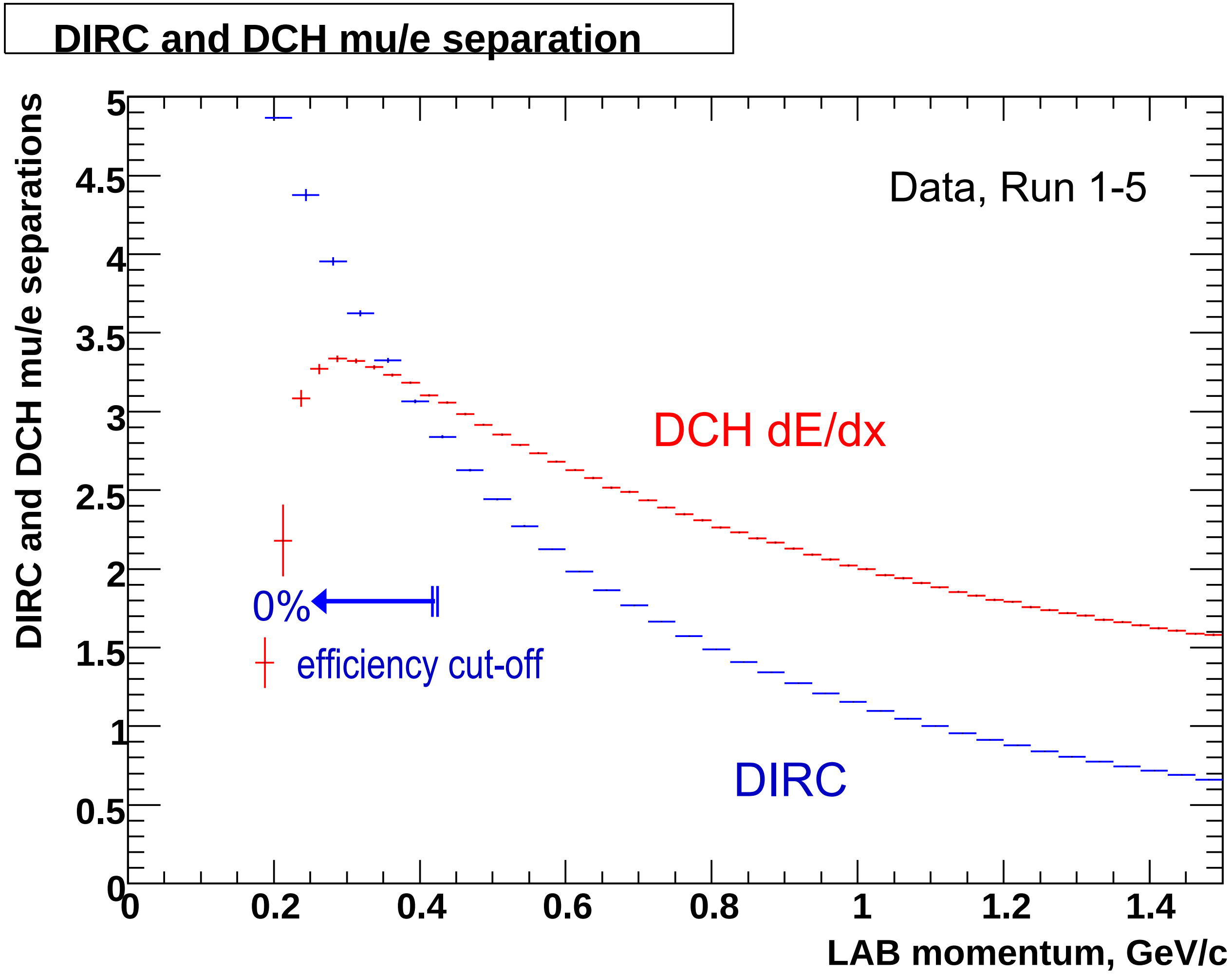
Shower Depth, 0.60<Track P< 1.25 GeV:cm

Shower Depth, 1.25<Track P< 10.00 GeV:cm

~1σ μ/π separation at low momentum

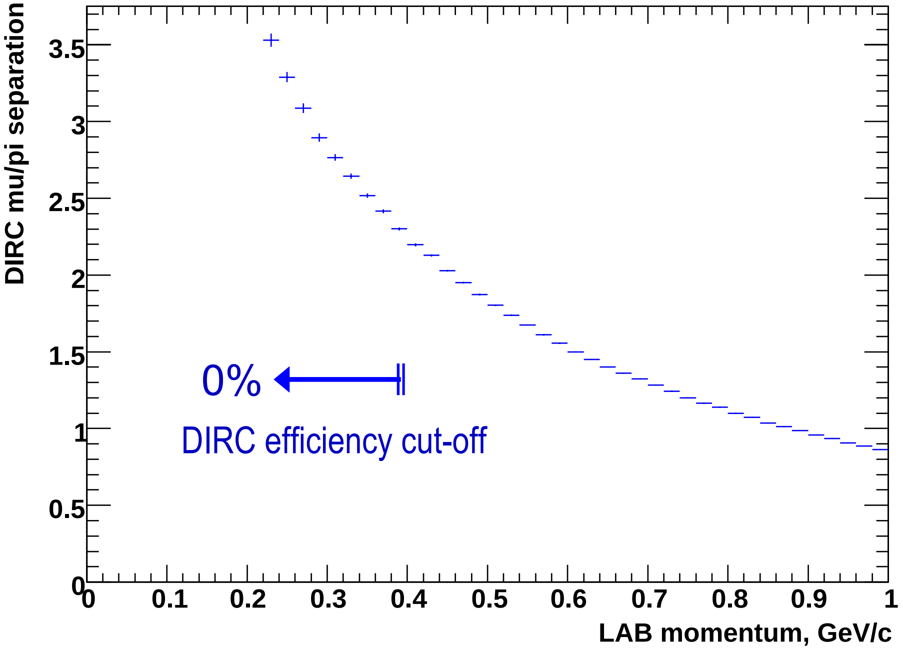
a NIM paper is planned

DCH dE/dx π,μ/e separation



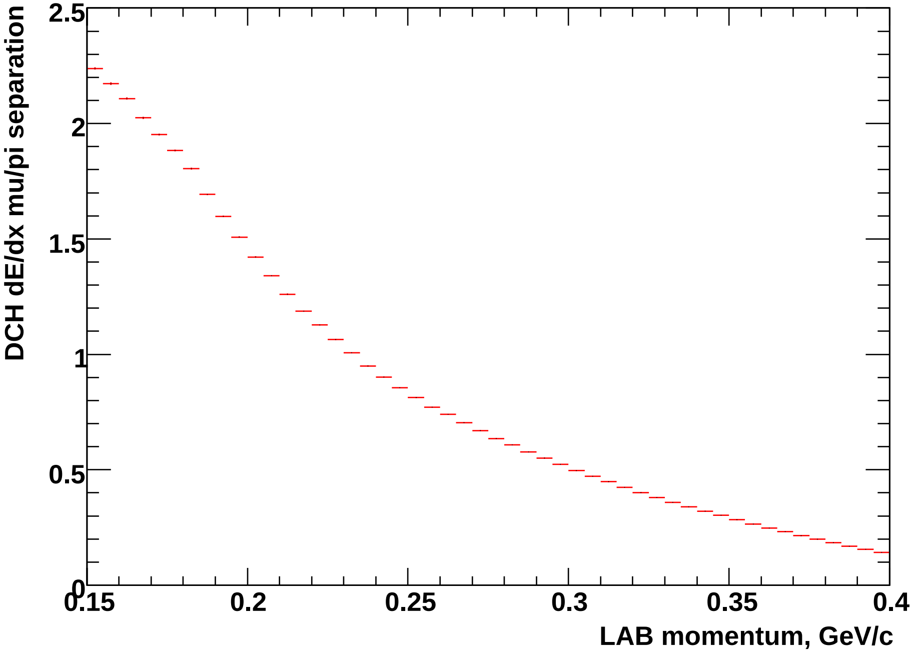
DIRC and DCH d*E*/dx π/μ separation

DIRC mu/pi separation, data

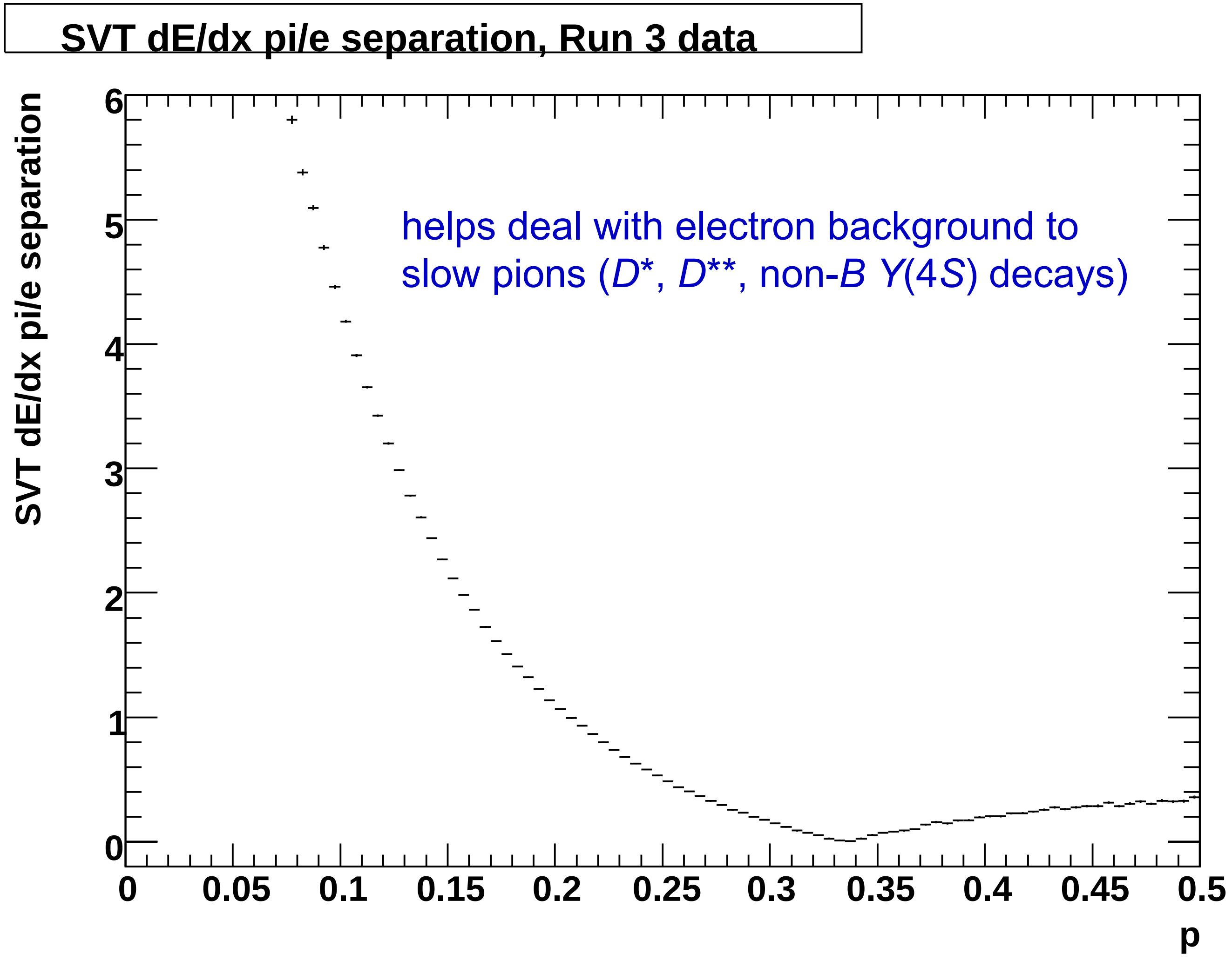


Muons below ~0.9 GeV/*c* do not have enough energy to punch through the IFR;
Until now, neither the DIRC nor the DCH were used in the muon selectors, nor a full set of EMC quantities

DCH dE/dx mu/pi separation, data

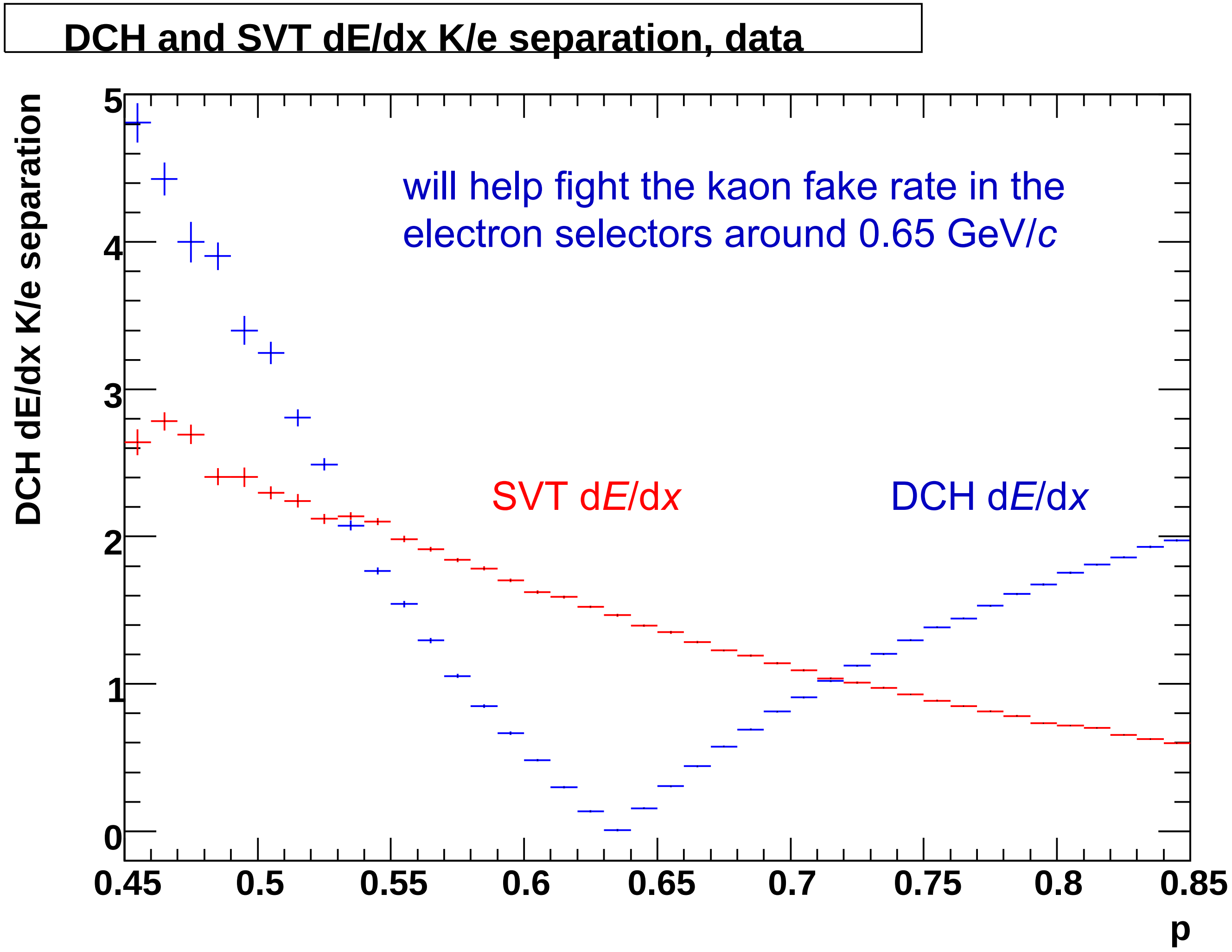


SVT d*E*/dx π/e separation



helps deal with electron background to slow pions (*D**, *D***, non-*B* *Y*(4*S*) decays)

SVT d*E*/dx *K*/*e* separation

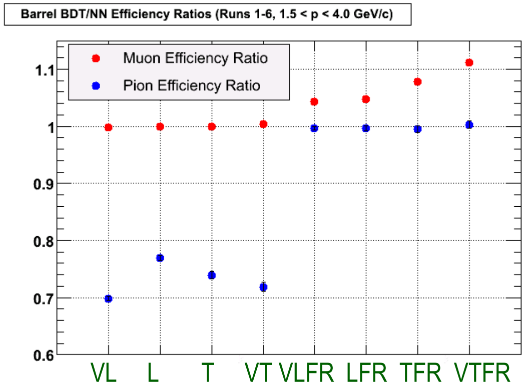


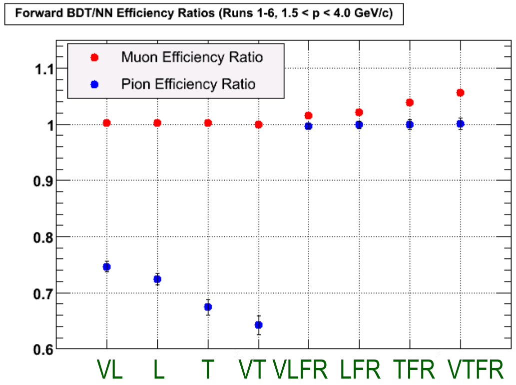
will help fight the kaon fake rate in the electron selectors around 0.65 GeV/*c*

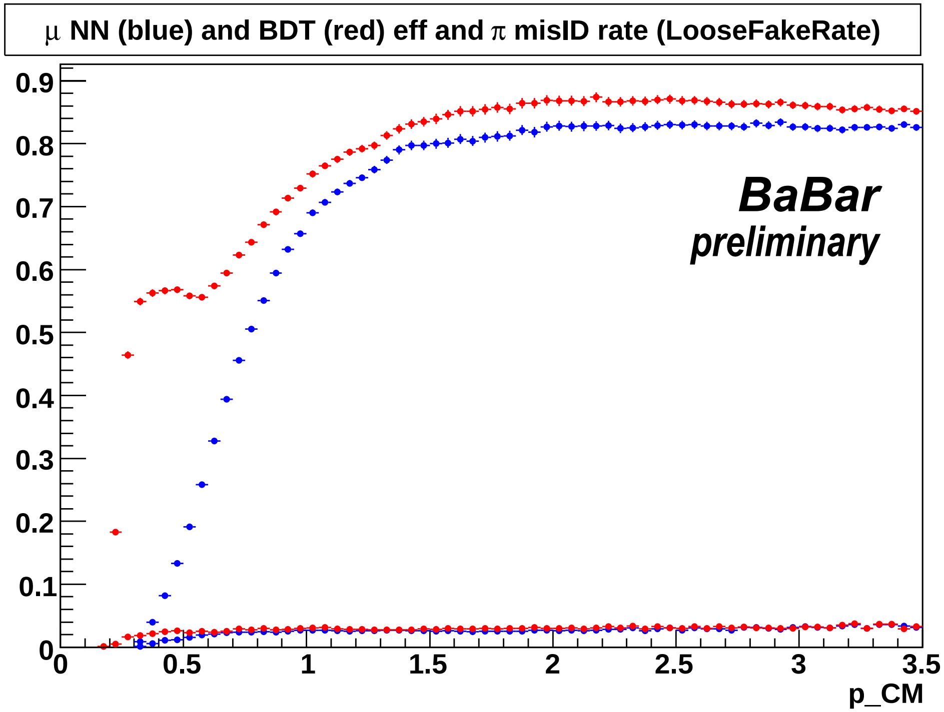
“Ultimate” muon ID now:

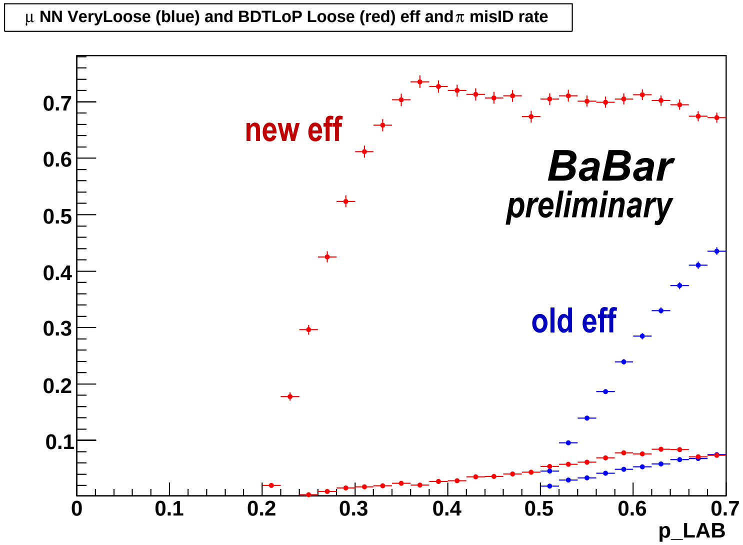
30 discriminating variables used

- p
- theta
- charge
- ifrns
- ifrmatchchi2
- ifrfitchi2
- ifrcont
- ifrsigmu
- ifrmeasintlen
- ecal
- lmom
- zmom20
- zmom42
- ncry
- s1s9
- s9s25
- secmom
- dEdxdchPullmu
- drcmuprob
- smsdrcmuprob
- emcdepth
- date
- drcpiprob
- drckprob
- nphot
- ndch
- lhit
- lfrcrackphi
- deltalambda
- ecaldivp

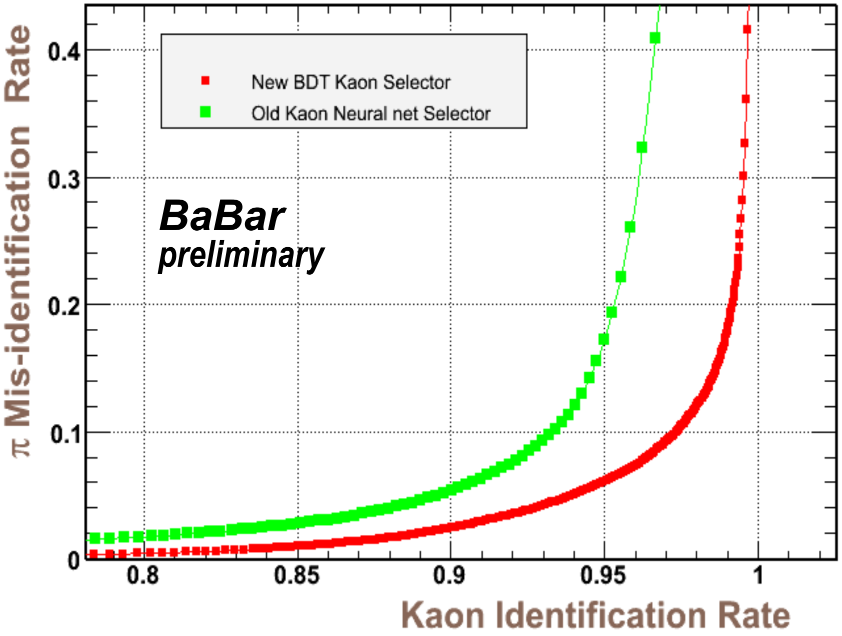

Barrel BDT/NN Efficiency Ratios (Runs 1-6, 1.5 < p < 4.0 GeV/c)


Forward BDT/NN Efficiency Ratios (Runs 1-6, 1.5 < p < 4.0 GeV/c)


μ NN (blue) and BDT (red) eff and π misID rate (LooseFakeRate)

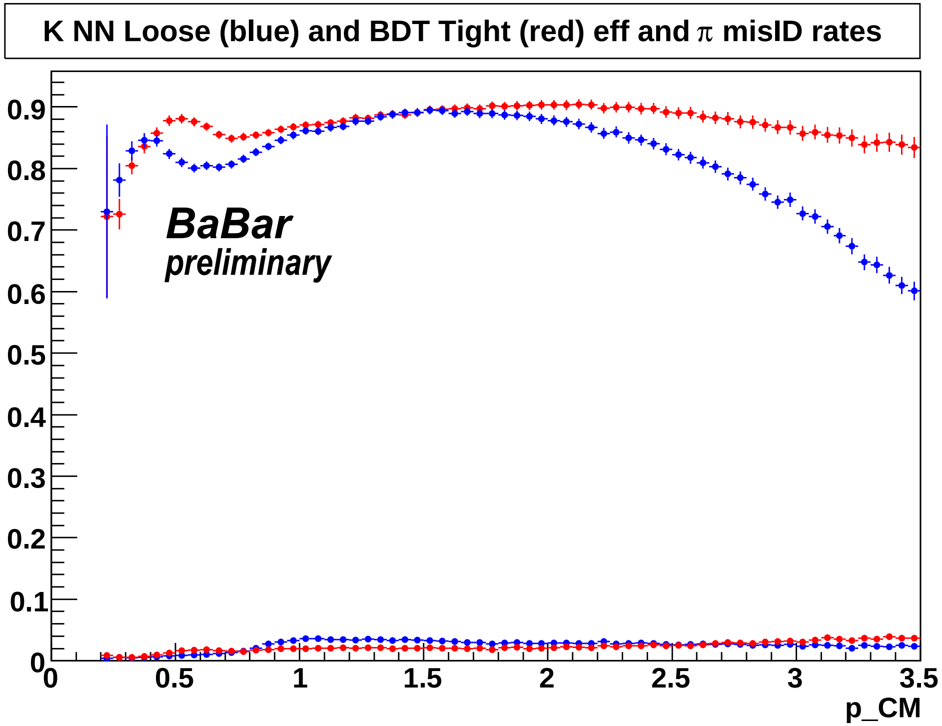

μ NN VeryLoose (blue) and BDTLoP Loose (red) eff and π misID rate

kaonBDT selector: replacement for kaonNN



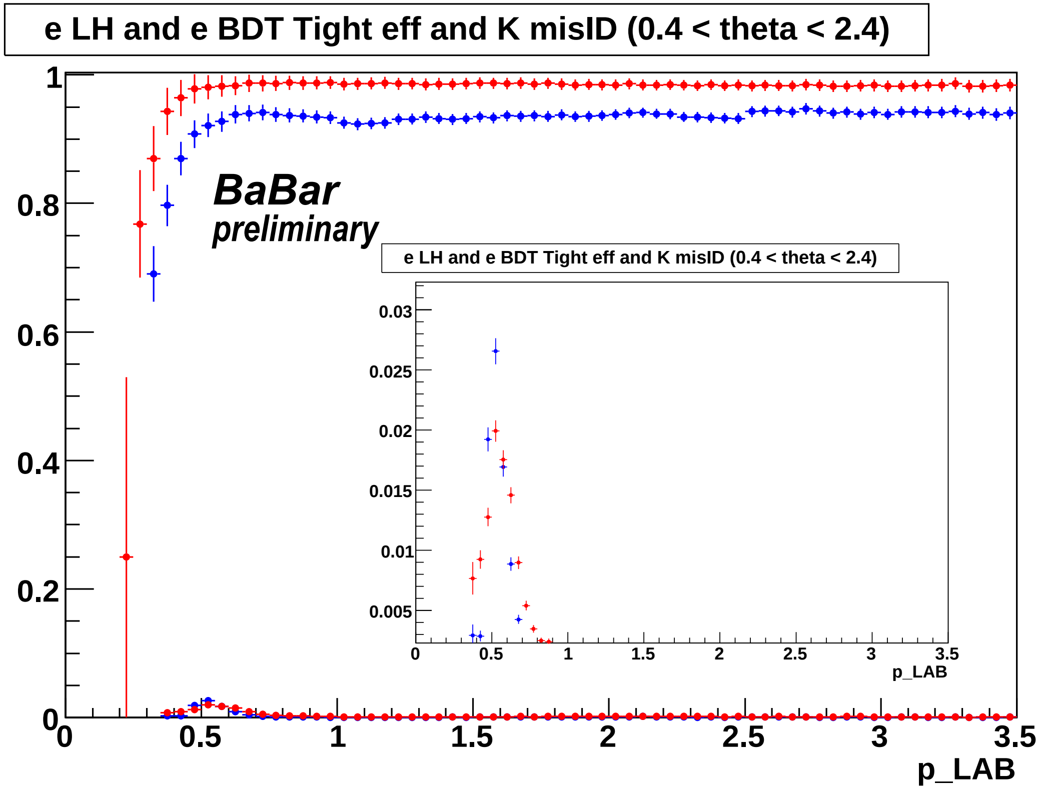
Plot made for D^* pion and kaon spectra, relevant to B^0 flavor tagging

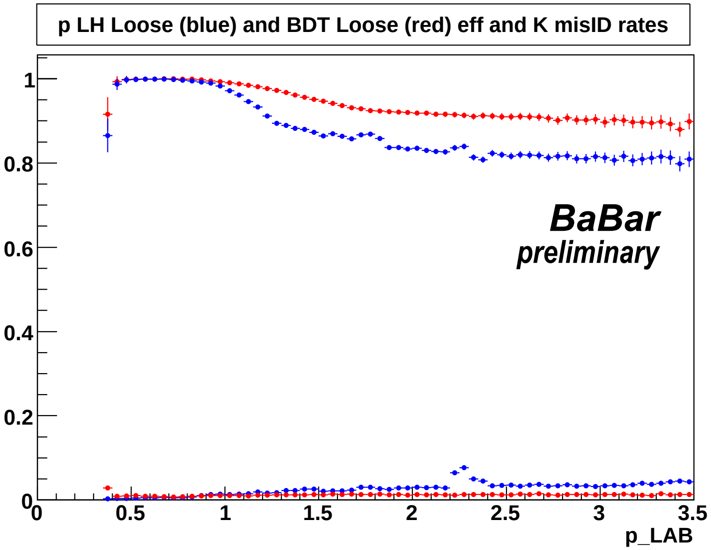
To be presented on February 11 at
Caltech workshop on multivariate analysis

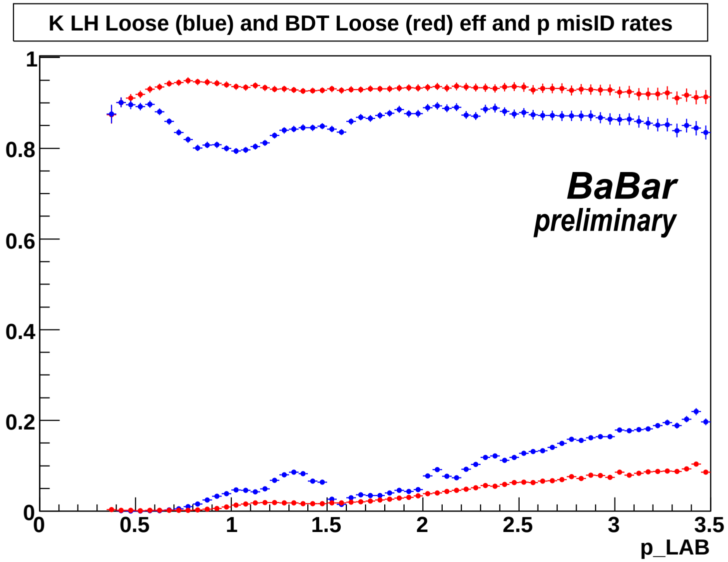


More new selectors

How much would you pay for 6% more electrons? ☺







The Motto

Make impossible measurements possible
and make the possible measurements first
(or the best)
by gaining detailed understanding
of your detector;
Make it in a way the entire Collaboration would benefit

The future:
physics at the Large Hadron Collider

There is little doubt that previously unseen phenomena will be observed at LHC.

My primary goal for the next several years is to make important contributions to measurements that are key to establishing a pattern among these new phenomena.

So, we see something that could be a Higgs. What is it that we see?

- Is it responsible for the Electro-Weak Symmetry Breaking? Are the WWh and ZZh couplings SM-like, ~$O(1)$? Important: $h \rightarrow \gamma\gamma, bb, WW^*$.

- Are there other particles (Higgses?) responsible for the large top-quark mass? Does the tth coupling agree with SM? Important: $h \rightarrow \gamma\gamma, bb$.

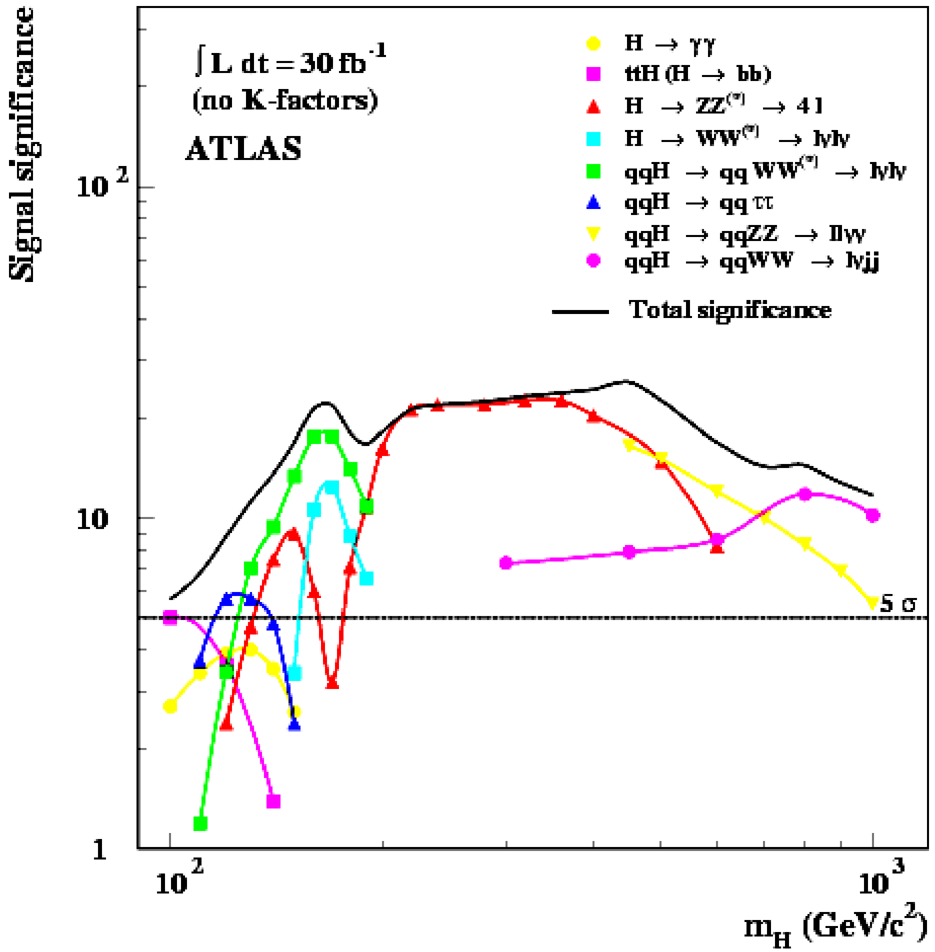
- Are there other Higgses? $H/A \rightarrow \tau^+\tau^-$? $H^+ \rightarrow tb$?

How can we use constraints on New Physics from B, B_s, K, D decays to be smart about the searches we focus on?

Answering these questions will be a challenge

Excellent understanding of the detector and sophisticated tools will be required

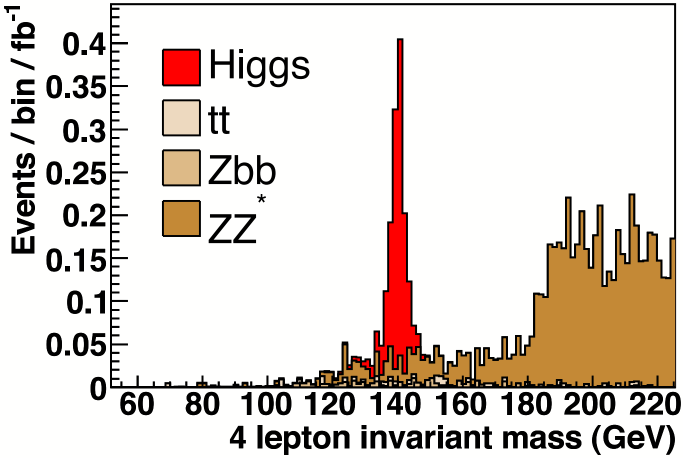
alignment
tracking
muons
electrons
b jets
τ jets
momentum scale
etc.

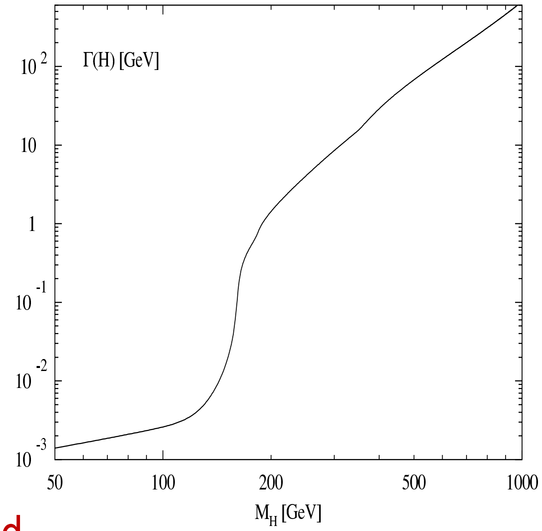


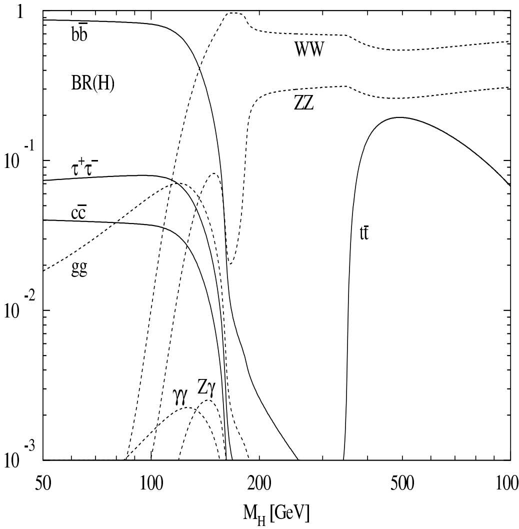
Muons at ATLAS: not merely a discovery tool!

$$H \rightarrow ZZ^{(*)} \rightarrow e^+e^-\mu^+\mu^-$$

If Nature is kind, LHC may be able to make a precision measurement of Higgs mass, and perhaps even width







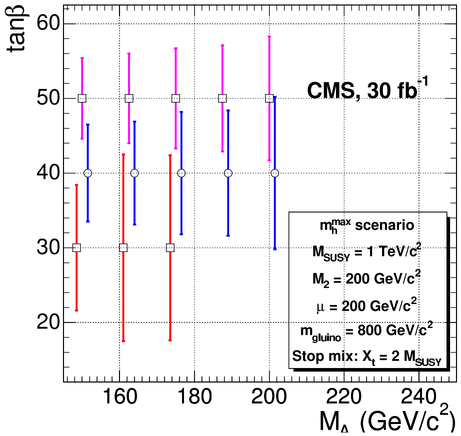
Excellent muon isolation/identification and momentum determination will be essential:

alignment
magnetic field map
unbiased momentum determination
multivariate "particle ID" (suppression of fakes)?

$$\Gamma(H/A \rightarrow \mu^+\mu^-):$$

Calibration sample:

$$Z \rightarrow \mu^+\mu^-$$



Not to mention scenarios with a *Z'* or other dimuon resonances…