B Physics and Quarkonia

Urs Langenegger
(ETH Zurich)

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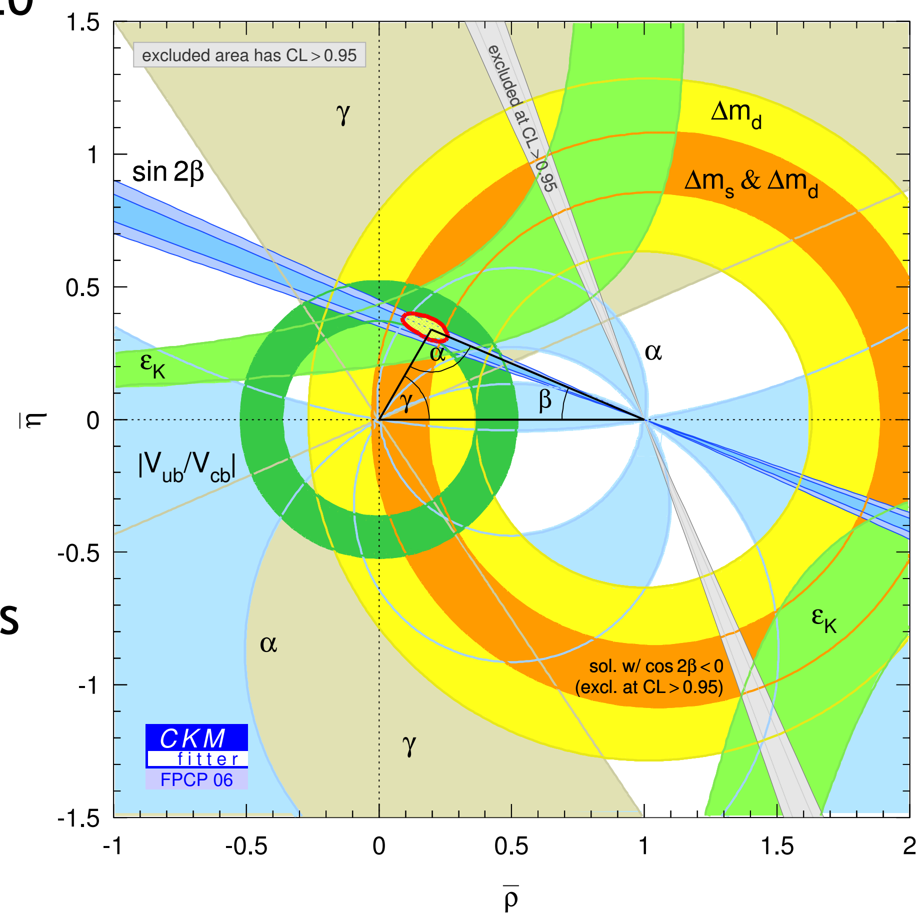
- Part I
  - ▷ Introduction
  - ▷ B-factories: CP violation
  - ▷ Tevatron: B_s mixing
- Part II
  - ▷ Semileptonic Decays
  - ▷ Radiative and Some Rare Decays
  - ▷ Heavy Quarkonia



Executive Summary I

- B physics
  - ▷ Quantitative tests of SM $\longrightarrow$ overconstraining 'the' unitarity triangle
  - ▷ Search for new physics $\longrightarrow$ 'delayed gratification'
  - ▷ Flood of data and new ideas $\longrightarrow$ spin-offs

- Time-dependent and CP-violating physics
  - ▷ CP-violation by B-factories

$$\beta = 21.7\,^{+1.3}_{-1.2}\,^\circ \quad \alpha = 100.2\,^{+15.0}_{-8.0}\,^\circ \quad \gamma = 62\,^{+35}_{-25}\,^\circ$$

$$\beta = \beta \text{ in b} \rightarrow \text{s penguins(?)}, \quad \alpha + \beta + \gamma = 186\,^{+38}_{-27}\,^\circ$$

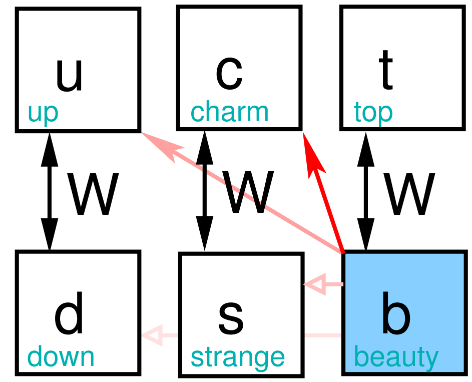
$$\text{direct } CP\text{−violation in } B^0 \rightarrow K^+\pi^-$$

  - ▷ B_s mixing measured by CDF

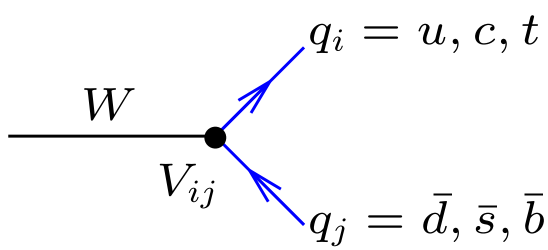
$$\Delta m_s = 17.31^{+0.33}_{-0.18}(\text{stat}) \pm 0.07(\text{syst})\,\text{ps}^{-1}$$

$$\frac{|V_{td}|}{|V_{ts}|} = 0.208^{+0.001}_{-0.002}(\text{exp})^{+0.008}_{-0.006}(\text{theo})$$

Cabibbo-Kobayashi-Maskawa Matrix



- Weak interactions of quarks
  - ▷ mass eigenstates $\neq$ weak eigenstates
  - ▷ flavor-changing quark decays



- Mixing described by complex unitary CKM matrix:

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

- Wolfenstein parametrization (to $\mathcal{O}(\lambda^4)$, $\lambda = \sin\theta_C \sim 0.22$)
  - ▷ illustrates hierarchical structure
  - ▷ describes all flavor changing quark transitions in SM
  - ▷ η is the only source for CP violation in SM (in quark sector)

'The' Unitarity Triangle

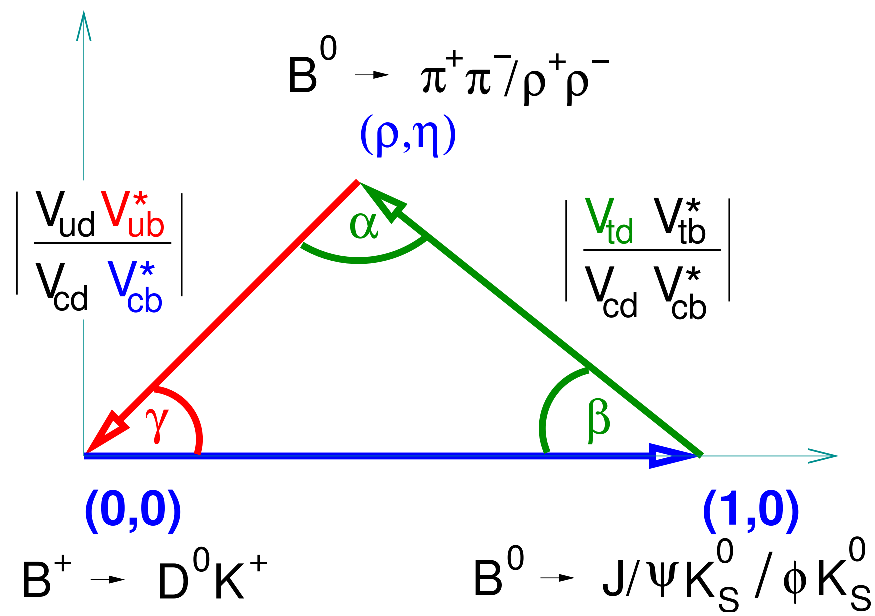
- Unitarity of CKM matrix implies

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

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

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

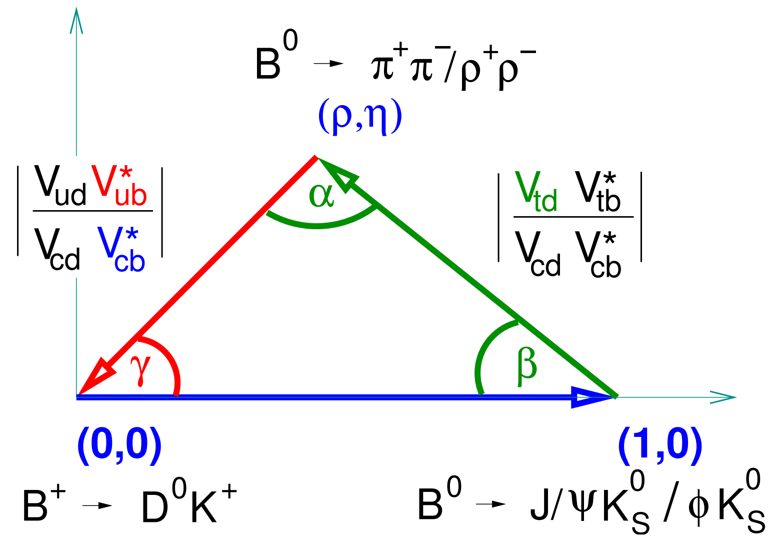
$$\alpha \equiv \arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right) = \pi - \beta - \gamma$$



- Access to Unitarity Triangle
  - ▷ CP violating asymmetries → angles
  - ▷ tree-level weak decays → sides
  - ▷ $B_{d,s}$ oscillations and loop-induced FCNC → sides

  \+ theory (models) and lattice QCD!

The Dream



Flavor physics is about overconstraining the Unitarity Triangle

- ▷ Comparison of experiment to clean theoretical expectations
- ▷ Same angle in different decays? $B^0 \to J/\psi K_S^0 \Longleftrightarrow B^0 \to \phi K_S^0$
- ▷ $\alpha + \beta + \gamma = 180°$?
- ▷ Sides vs. angles
- ▷ Same sides in different processes? $B^0 \to K^{(*)}/\rho\gamma \Longleftrightarrow B_{d,s}$ oscillations

$\longrightarrow$ 'See' New Physics before the LHC!

Characteristics of b-Mesons

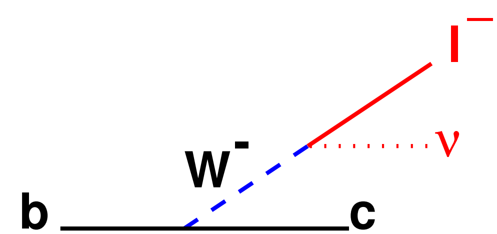
- b-hadron contents/naming convention:

$$
\begin{aligned}
|B^0\rangle &= |\bar{b}d\rangle & |\bar{B}^0\rangle &= |b\bar{d}\rangle \\
|B^+\rangle &= |\bar{b}u\rangle & |B^-\rangle &= |b\overline{u}\rangle \\
|B_s\rangle &= |\bar{b}s\rangle & |\bar{B}_s\rangle &= |b\overline{s}\rangle
\end{aligned}
$$

- Key numbers

Characteristics	Units	B^+	B^0	B_s	Remarks
Mass	MeV	5279.0 ± 0.5	5279.4 ± 0.5	5367.5 ± 1.8	hard scale: theory, $p_\perp$
Lifetime	ps	1.638 ± 0.011	1.530 ± 0.009	1.466 ± 0.059	secondary vertices
$c\tau$	μm	491	459	439	measureable if $\beta\gamma$ big
Hadronization	%	39.8 ± 1.1	39.8 ± 1.1	10.4 ± 1.3	b-baryons: 9.9 ± 2.0

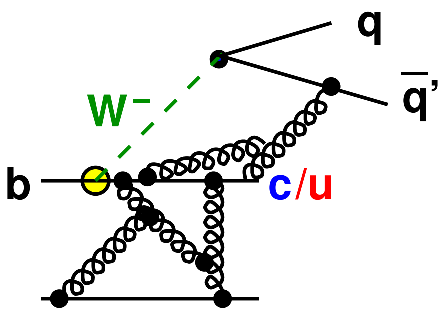
- Decay features
  - ▷ Enormous number of decay channels
  - ▷ Decays: hadronic, leptonic, semileptonic
  - ▷ Decay products allow (often) distinction between b or $\bar{b}$: 'flavor tagging'

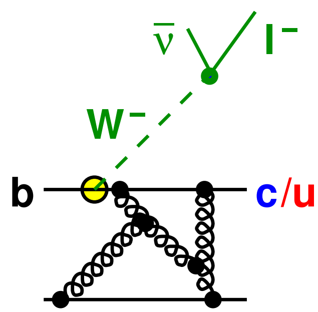


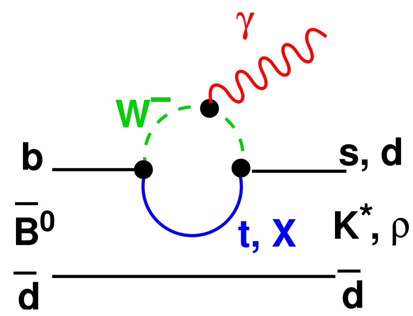
Nomenclature

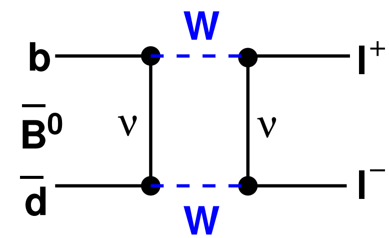
Decays

- Hadronic
- Semileptonic
- Penguin
- Leptonic



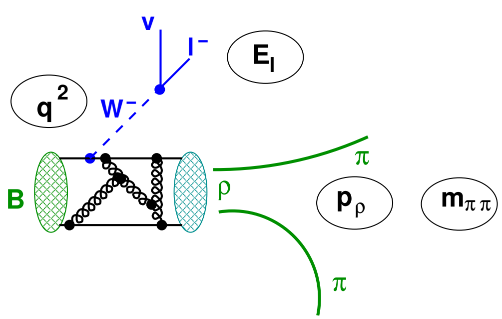


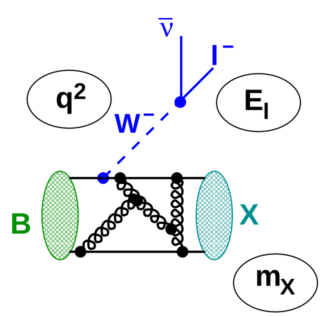


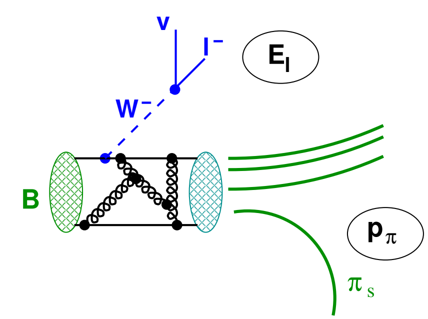


Decay reconstruction

- Exclusive
- Inclusive
- Partial



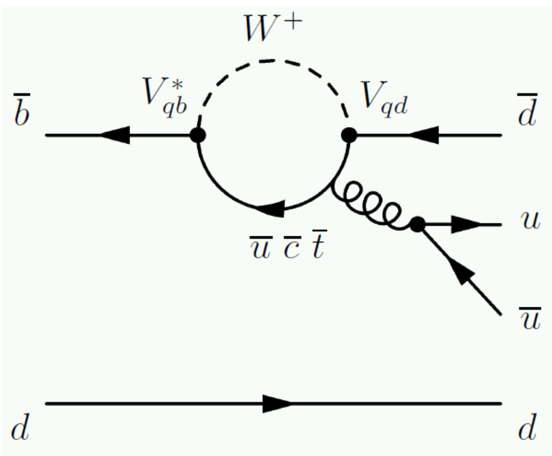


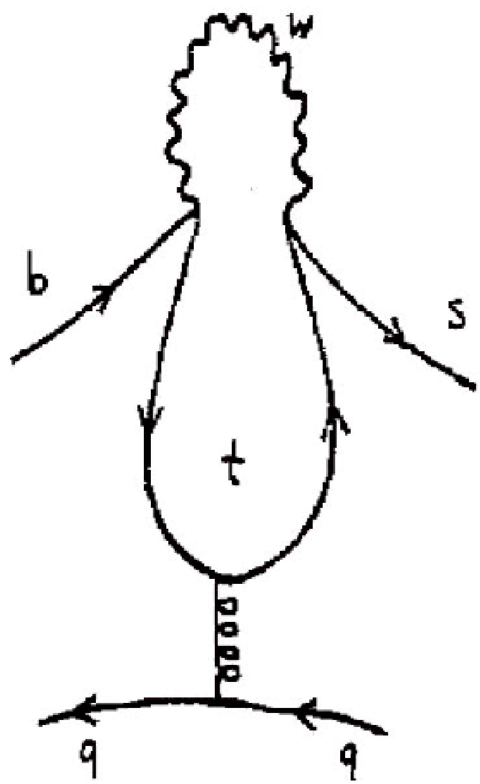


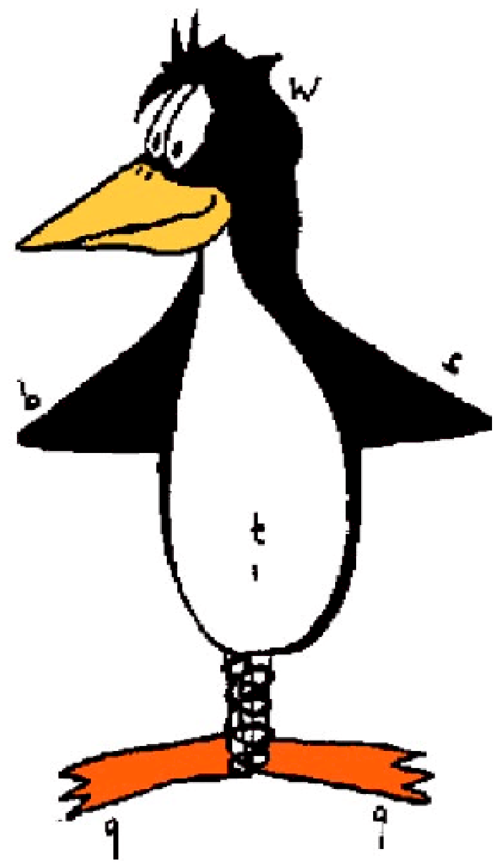
Penguins??

- The aftermath of bad habits
  - betting
  - substance abuse
  - working late at night

and the combination is



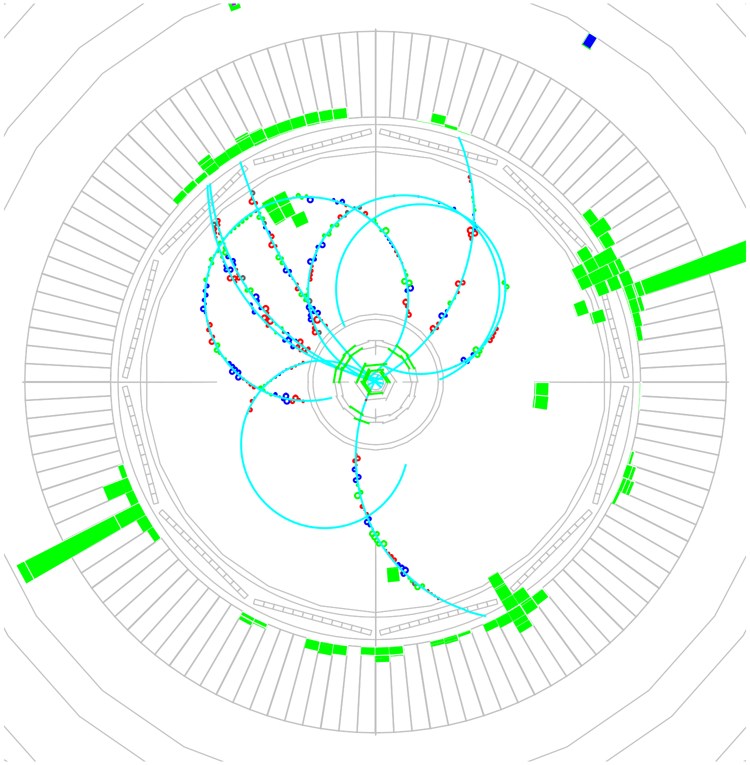




Quid licet Iovis, non licet bovis

Experimental Remarks

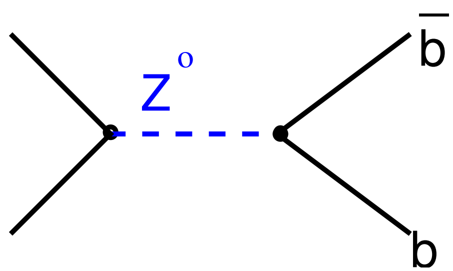
- Reconstruction of particle momentum and energy
  - ▷ charged $\longrightarrow$ tracking detectors
  - ▷ neutrals $\longrightarrow$ calorimeters
  - ▷ decay vertices $\longrightarrow$ silicon vertex detectors
  - ▷ neutrinos $\longrightarrow$ 4π detectors



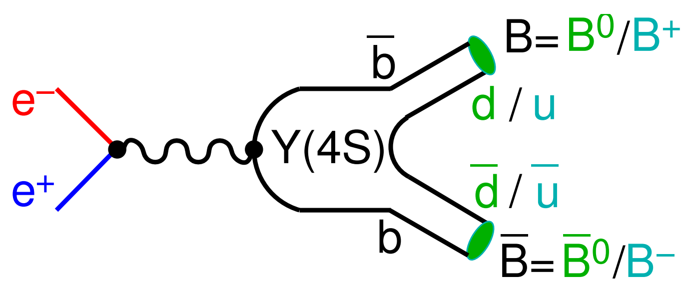
- Particle identification
  - ▷ All do leptons: $\mathcal{B}(\bar{B} \to X\ell\bar{\nu}) \sim 10\%$
    (note: $\ell \in \{e, \mu\}$; average, not sum!)
  - ▷ ECAL + tracker: Electrons
  - ▷ Flux return: Muons
  - ▷ Cherenkov detectors: K/π separation
  - ▷ Time-of-flight detectors: K/π separation
- Quantitative understanding of performance
  - ▷ maximal purity and resolution
  - ▷ optimal efficiency vs. misidentification

Production of b-Hadrons

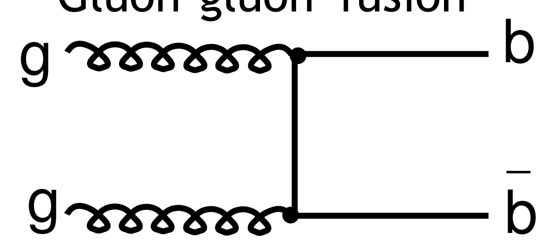
- Hadron colliders
  - ▷ hadronization $\longrightarrow$ all types
- Electron machines: Z decays
  - ▷ hadronization $\longrightarrow$ all types
  - ▷ $\mathcal{B}(Z \to b\bar{b}) = 15\%$



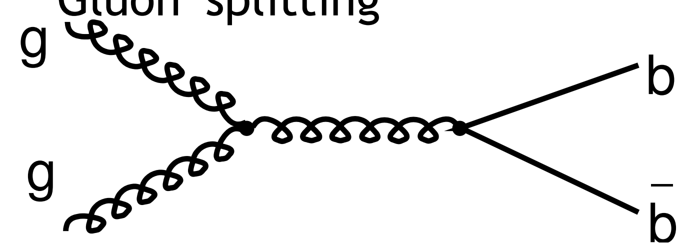
- Electron machines: $\Upsilon(4S)$ decays
  - ▷ $\mathcal{B}(\Upsilon(4S) \to B\bar{B}) \sim 100\%$



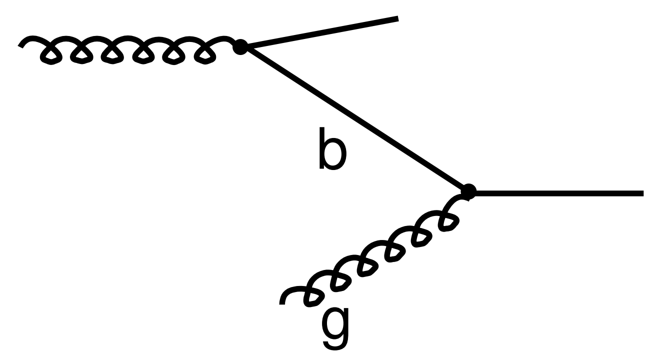
Gluon-gluon fusion



Gluon splitting



Flavor excitation



The colliders

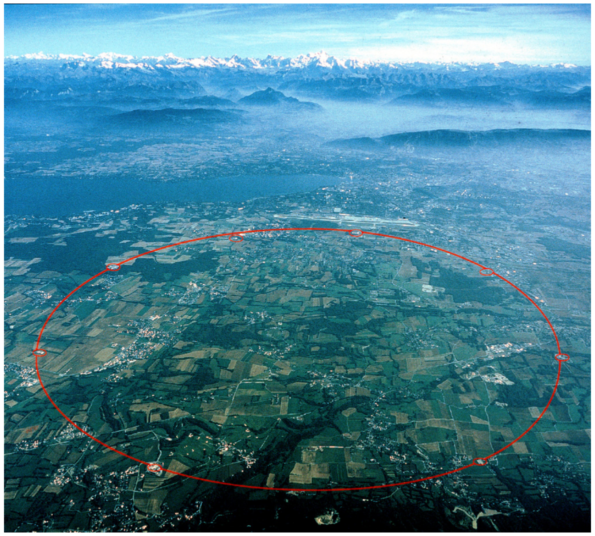
LHC

$\sqrt{s} = 14$ TeV

LEP

$\sqrt{s} = 91 \ldots$

209 GeV

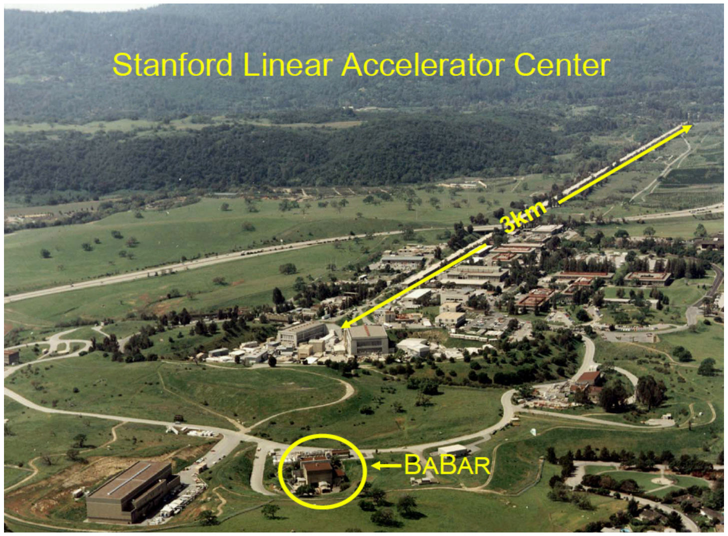


SLC

$\sqrt{s} = m_Z$

PEP-II

$\sqrt{s} = m_{\Upsilon(4S)}$



Tevatron

$\sqrt{s} = 2$ TeV

KEKB

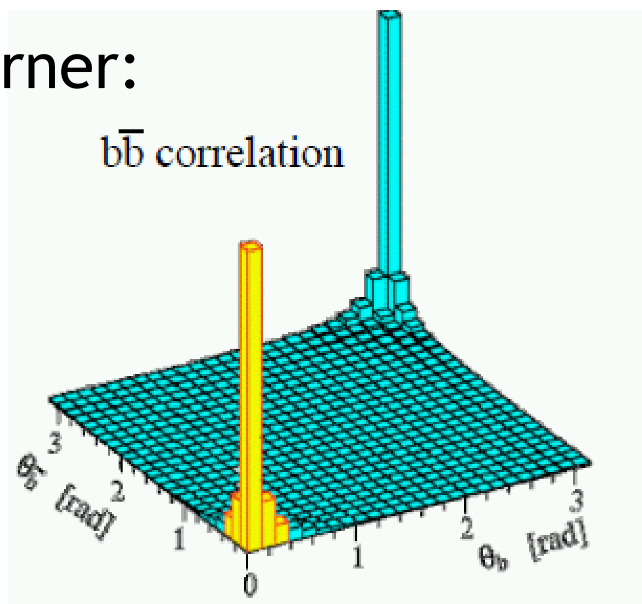
$\sqrt{s} = m_{\Upsilon(4S)}$

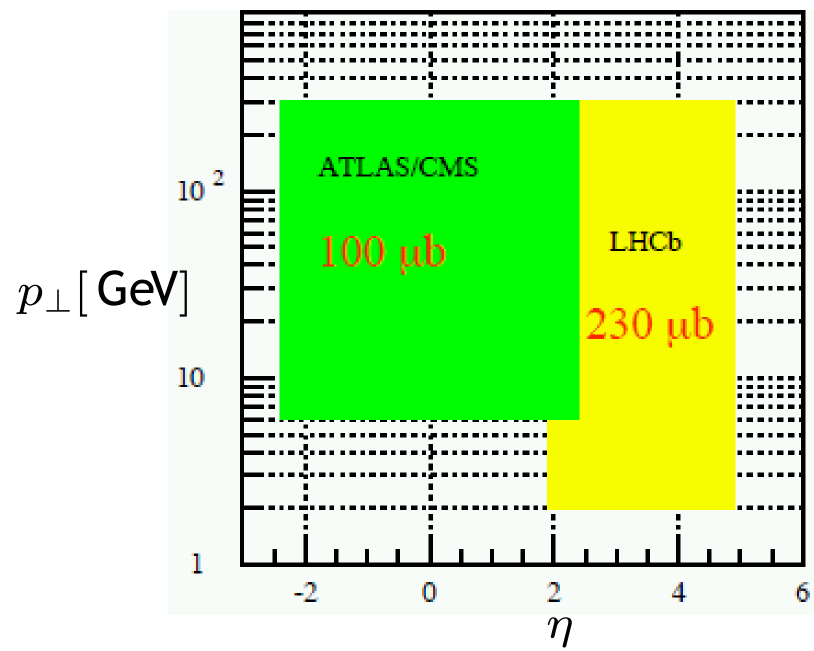
b Production Cross-sections

- Colliders: Approximate production cross-sections for $b\bar{b}$ quarks

Collider		$\sqrt{s}$ [GeV]	$\sigma(b\bar{b})$ [nb]	$\mathcal{L}$ [fb^{-1}]	S/B	b-types	Notes
HERA	γp	200	20	0.1	10^{-3}	all	QCD only
Tevatron	$p\bar{p}$	2000	50×10^3	$1 - 10$	10^{-3}	all	Trigger: ℓ, m, V
LHC	pp	14000	500×10^3	$2 - 100$	10^{-2}	all	Trigger: ℓ. LHCb
SLC/LEP	e^+e^-	91.2	6	0.1	0.20	all	45 GeV: boost!
B factories	e^+e^-	10.58	1	≥ 500	0.25	B^+, B^0	entangled

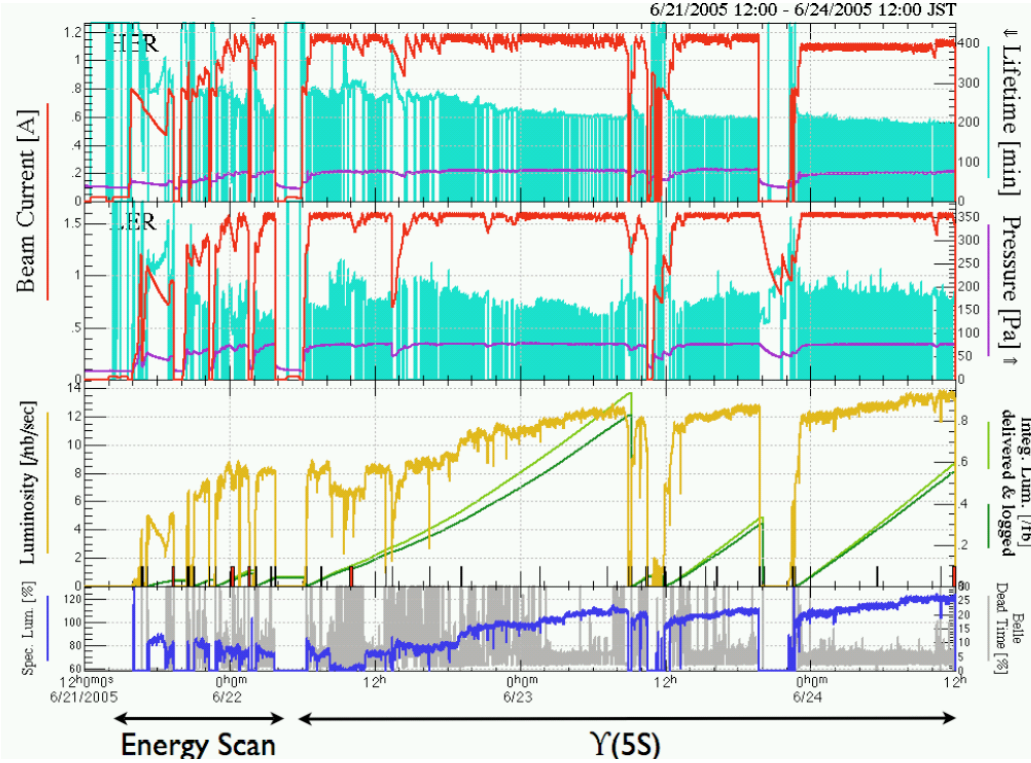
- LHCb's corner:





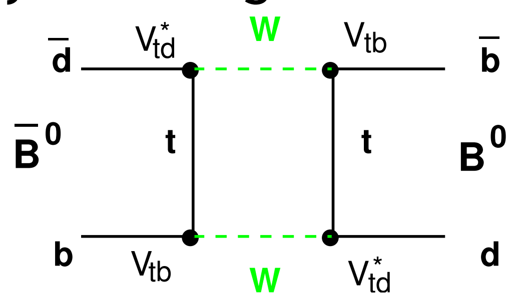
Advantages and Constraints

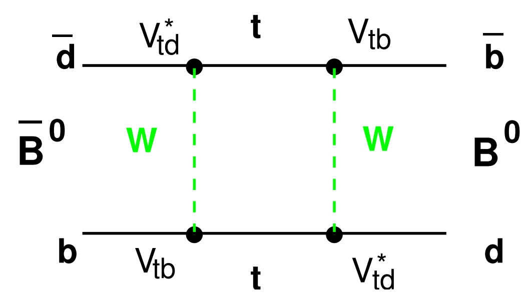
- Hadron machines
  - $+$ production cross section
  - $\pm$ hadronization: all flavors, but not mono-energetic
  - $-$ trigger (hadronic decays channels)
  - $-$ competition for bandwidth . . .
  - $-$ Particle ID
- Electron machines at $\Upsilon(4S)$
  - $+$ well-defined initial state
  - $+$ entangled state
  - $+$ neutrals!
  - $+$ S/B
  - $-$ cross section
  - $-$ only B^0 and B^+
- KEK-B is outstanding
  - ▷ $\Upsilon(5S) : 1.9\,\text{fb}^{-1}$ in 2.5 days!
  - ▷ $\Upsilon(3S)$: $3\,\text{fb}^{-1}$ recently!



Reminder on Neutral Meson Mixing

- Multiple Bases
  - ▷ Strong interaction creates quarks in flavor eigenstates
  - ▷ Time evolution given by mass eigenstates
  - ▷ weak interaction:





  - ▷ Box diagrams induce mixing of $M^0 \leftrightarrow \bar{M}^0, M^0 \in \{K^0, D^0, B^0, B_s\}$

- Consider initial superposition of M^0 and $\bar{M}^0$

$$|\psi(t=0)\rangle \quad = \quad a(0)|M^0\rangle + b(0)|\bar{M}^0\rangle$$

will evolve into

$$|\psi(t)\rangle \quad = \quad a(t)|M^0\rangle + b(t)|\bar{M}^0\rangle + c_1(t)\underbrace{|f_1\rangle}_{decay} + c_2(t)\underbrace{|f_2\rangle}_{decay} + \ldots$$

  - ▷ Weisskopf-Wigner approximation
    (time scales $\gg$ strong interaction times)

Effective Hamiltonian

- Time evolution

$$i\frac{d}{dt}\begin{pmatrix} a \\ b \end{pmatrix} = \mathbf{H}\begin{pmatrix} a \\ b \end{pmatrix} = \left(\mathbf{M} - \frac{i}{2}\mathbf{\Gamma}\right)\begin{pmatrix} a \\ b \end{pmatrix}$$

  - ▷ Hamiltonian H is not hermitian (decays), but $\mathrm{M} = \mathrm{M}^\dagger$ and $\Gamma = \Gamma^\dagger$
  - ▷ M off-shell (dispersive) intermediate states
  - ▷ Γ on-shell (absorptive) intermediate states

$$\mathrm{H} = \begin{pmatrix} \langle M^0|H|M^0\rangle & \langle M^0|H|\bar{M}^0\rangle \\ \langle \bar{M}^0|H|M^0\rangle & \langle \bar{M}^0|H|\bar{M}^0\rangle \end{pmatrix} = \begin{pmatrix} M - \frac{i}{2}\Gamma & M_{12} - \frac{i}{2}\Gamma_{12} \\ M_{12}^* - \frac{i}{2}\Gamma_{12}^* & M - \frac{i}{2}\Gamma \end{pmatrix}$$

- Eigenvectors of H have well defined masses and decays widths

$$\begin{aligned} |M_H\rangle &= p|M^0\rangle - q|\bar{M}^0\rangle \\ |M_L\rangle &= p|M^0\rangle + q|\bar{M}^0\rangle \\ \omega_H &= m_H - (i/2)\Gamma_H \\ \omega_L &= m_L - (i/2)\Gamma_L \end{aligned}$$

$$\begin{aligned} \Delta m &\equiv m_H - m_L & x &\equiv \Delta m/\Gamma \\ \Delta\Gamma &\equiv \Gamma_H - \Gamma_L & y &\equiv \Delta\Gamma/(2\Gamma) \\ \Gamma &\equiv (\Gamma_H + \Gamma_L)/2 & m &\equiv (m_H + m_L)/2 \\ \gamma_H &\equiv i m_H + \Gamma_H/2 & \gamma_L &\equiv i m_L + \Gamma_L/2 \end{aligned}$$

$$\mathrm{Note:}\quad \Delta m_B > 0, \qquad \Delta\Gamma_K > 0$$

Time-dependence

- Time evolution is trivial in mass basis

$$|M_H(t)\rangle = e^{-\gamma_H t}|M_H(0)\rangle = e^{-im_H t-\frac{1}{2}\Gamma_H t}|M_H(0)\rangle$$
$$|M_L(t)\rangle = e^{-\gamma_L t}|M_L(0)\rangle = e^{-im_L t-\frac{1}{2}\Gamma_L t}|M_L(0)\rangle$$

- Time evolution for flavor eigenstates more complicated
  - ▷ Initially pure flavor eigenstates evolve as $|M^0_{phys}(t)\rangle$ and $|\bar{M}^0_{phys}(t)\rangle$:

$$\psi_{M^0_{phys}}(t) = \frac{1}{2}\left\{|M^0\rangle\left(e^{-\gamma_h t}+e^{-\gamma_l t}\right)-\frac{q}{p}|\bar{M}^0\rangle\left(e^{-\gamma_h t}-e^{-\gamma_l t}\right)\right\}$$
$$\psi_{\bar{M}^0_{phys}}(t) = \frac{1}{2}\left\{|\bar{M}^0\rangle\left(e^{-\gamma_h t}+e^{-\gamma_l t}\right)-\frac{p}{q}|M^0\rangle\left(e^{-\gamma_h t}-e^{-\gamma_l t}\right)\right\}$$

  - ▷ Time-dependent probability to observe $\bar{M}^0$ after $M^0(t=0)$

$$P(M^0\to\bar{M}^0;t) = |\langle\bar{M}^0|\psi_{M^0_{phys}}(t)\rangle|^2 = \frac{1}{4}\left|\frac{q}{p}\right|^2\left\{e^{-\Gamma_h t}+e^{-\Gamma_l t}-2e^{-\Gamma t}\cos(\Delta m t)\right\}$$
$$P(M^0\to M^0;t) = |\langle M^0|\psi_{M^0_{phys}}(t)\rangle|^2 = \frac{1}{4}\left|\frac{p}{q}\right|^2\left\{e^{-\Gamma_h t}+e^{-\Gamma_l t}+2e^{-\Gamma t}\cos(\Delta m t)\right\}$$

Time-dependent Asymmetries

- Time-dependent flavor asymmetry:

$$A(t) = \frac{P(M^0 \to M^0;t) - P(M^0 \to \bar{M}^0;t)}{P(M^0 \to M^0;t) + P(M^0 \to \bar{M}^0;t)}$$

$$= \frac{\cos(\Delta m t) + (|p|^2 - |q|^2)\cosh(\frac{\Delta\Gamma t}{2})}{\cosh(\frac{\Delta\Gamma t}{2}) + (|p|^2 - |q|^2)\cos(\Delta m t)}$$

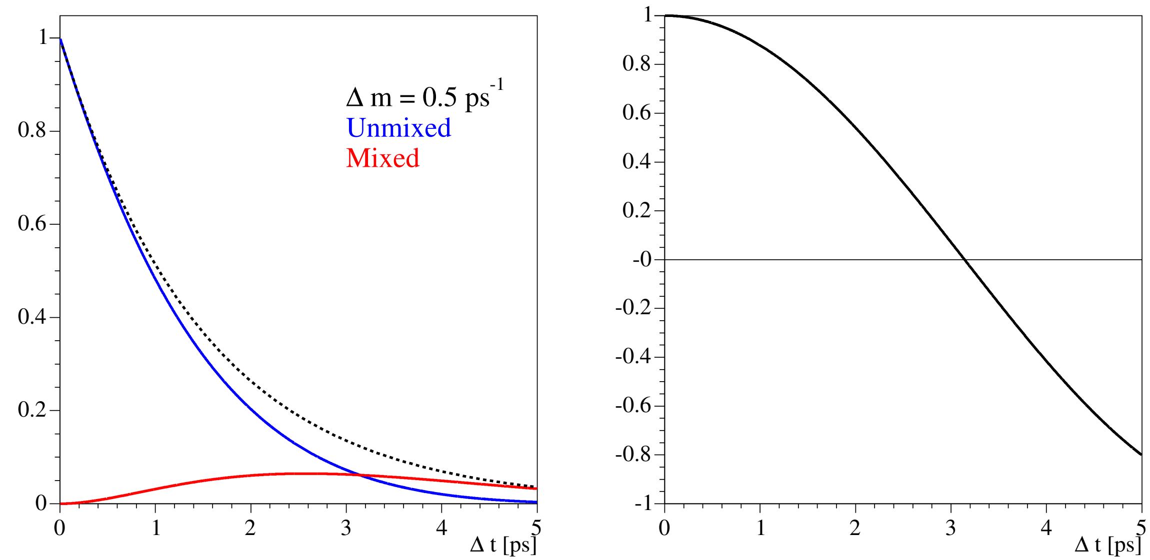
- Simplifications in the B systems
  - ▷ B^0 and B_s: CP violation in mixing small $\to$ $|q/p| = 1$
    (HFAG: $|q/p| = 1.0013 \pm 0.0034$)
  - ▷ B^0: $\Gamma \equiv \Gamma_H = \Gamma_L$
    (D0: $\Delta\Gamma_s = 0.15 \pm 0.10^{+0.03}_{-0.04}\,\text{ps}^{-1}$, CDF: $\Delta\Gamma_s = 0.47\,^{+0.19}_{-0.24} \pm 0.01\,\text{ps}^{-1}$)

$\to$ Asymmetry

$$A(t) = \frac{P(B^0B^0) - P(B^0\bar{B}^0)}{P(B^0B^0) + P(B^0\bar{B}^0)} = \cos(\Delta m t)$$

Illustration

- B_d system



- B_s system

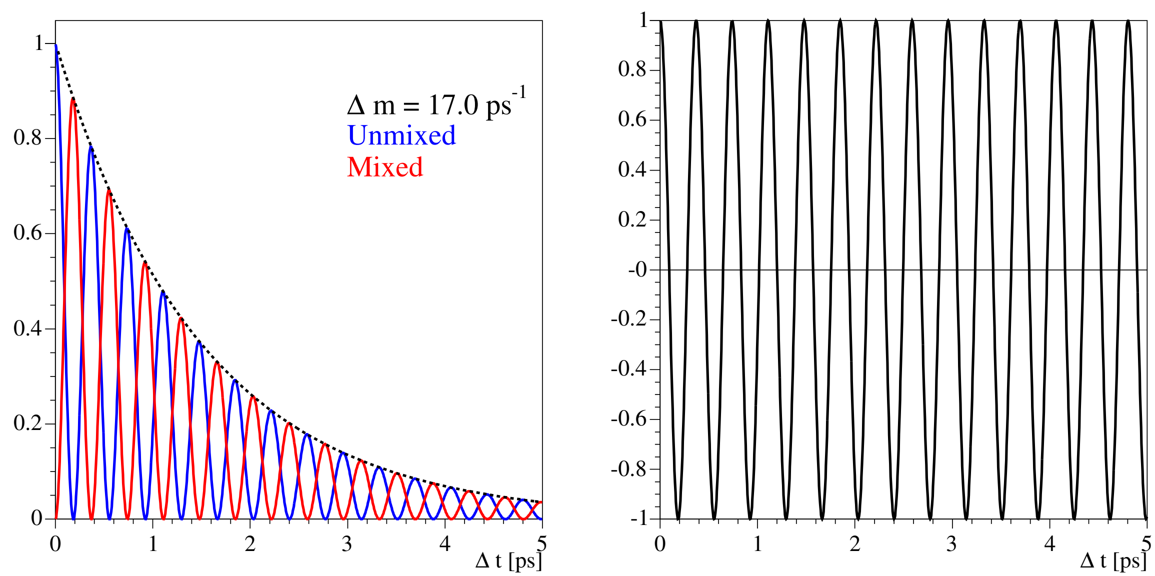
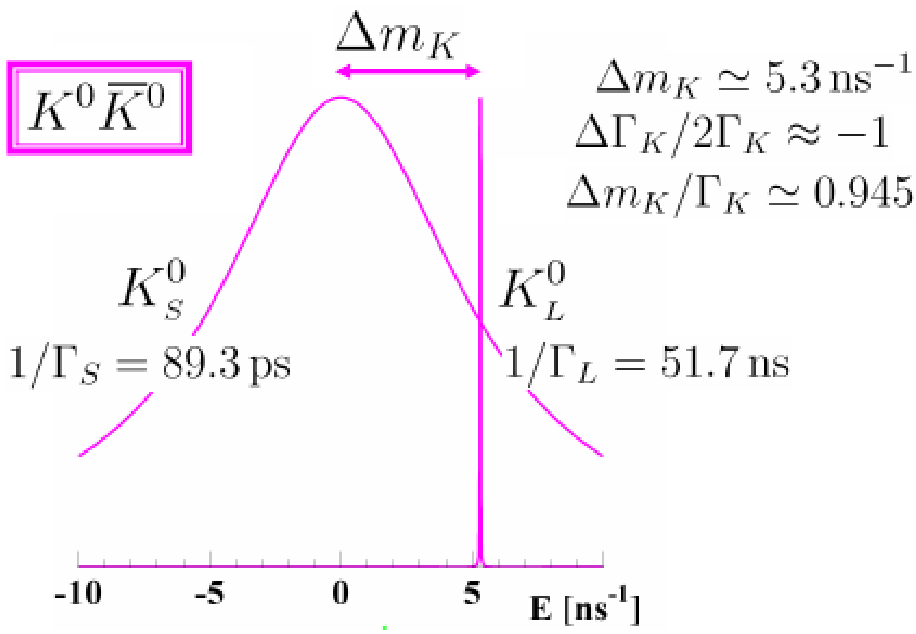
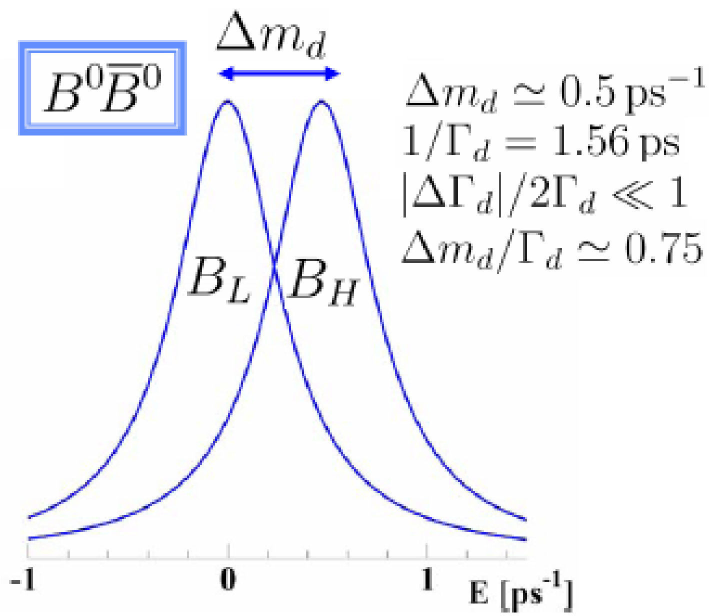
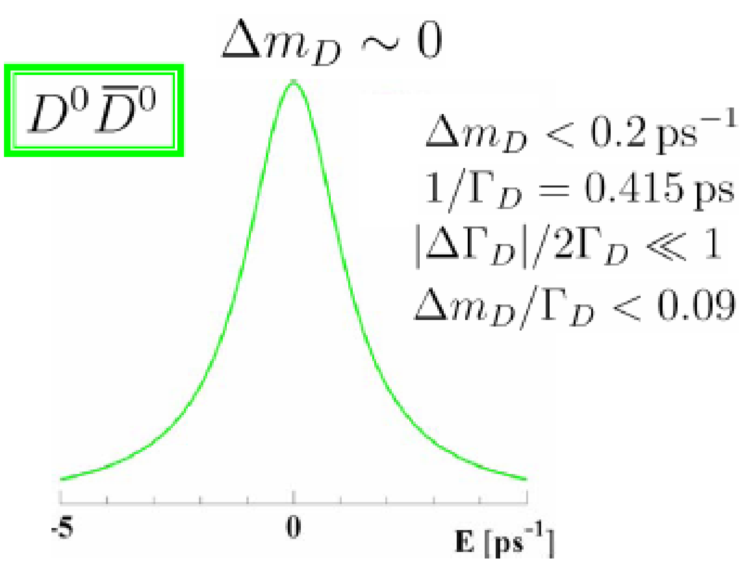
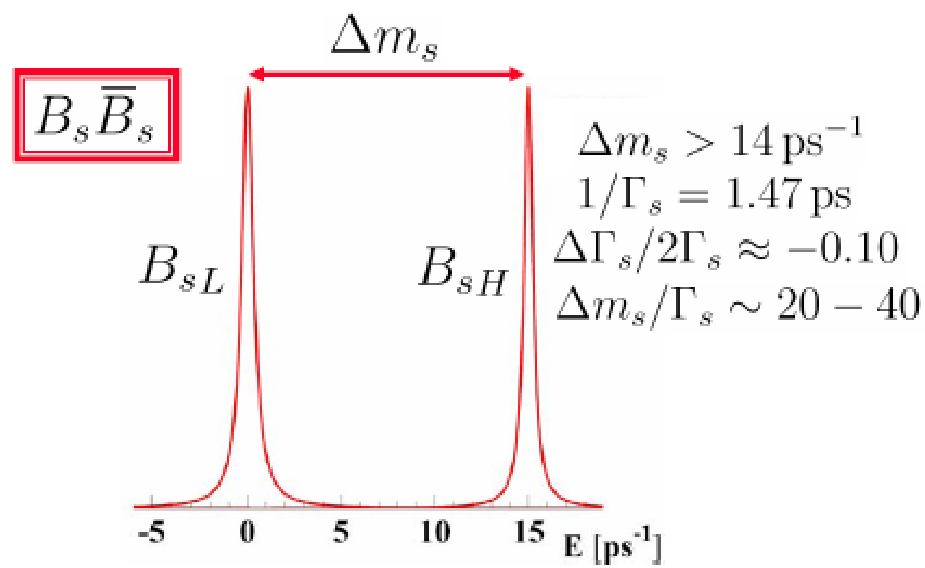


Illustration II









Time-dependent Decay Rates

- Decay amplitudes
  - ▷ $A_f = \langle f|H|M\rangle,\ A_{\bar f} = \langle \bar f|H|M\rangle,\ \bar A_f = \langle f|H|\bar M\rangle,\ \bar A_{\bar f} = \langle \bar f|H|\bar M\rangle,$
    $\lambda_f \equiv \frac{q}{p}\frac{\bar A_f}{A_f}$ $\longrightarrow$ interference in decays w/ and w/o mixing
- Back to general case (no requirements $|q/p| = 1,\ \Gamma_L = \Gamma_H$)

$$\frac{d\Gamma(M^0 \to f;t)\Delta t}{e^{-\Gamma t}N_f} = \left(|A_f|^2 + |\frac{q}{p}\overline{A}_f|^2\right)\cosh(y\Gamma t) + \left(|A_f|^2 - |\frac{q}{p}\overline{A}_f|^2\right)\cos(x\Gamma t)$$
$$+2\Re\left\{\frac{q}{p}A_f^*\overline{A}_f\right\}\sinh(y\Gamma t) - 2\Im\left\{\frac{q}{p}A_f^*\overline{A}_f\right\}\sin(x\Gamma t)$$

and similar for $d\Gamma(\bar M^0 \to f;t)/dt$ and $d\Gamma(M^0, \bar M^0 \to \overline{f};t)/dt$

- Terms
  - ▷ $\propto |A_f|^2$ and $\propto |\bar A_f|^2$ — decays without net oscillation
  - ▷ $\propto |\frac{q}{p}\overline{A}_f|^2$ and $\propto |\frac{p}{q}A_f|^2$ — decays after net oscillation
  - ▷ $\propto \sinh(y\Gamma t)$ and $\propto \sin(x\Gamma t)$ — interference between the two

Time-dependent CP-asymmetry

- Decay amplitudes are functions of phase space variables
  - Dalitz plot interference
- The asymmetry in decay to common final state

$$A_{f_{CP}}(t) = \frac{\Gamma(\bar{M}^0_{phys} \to f_{CP};t) - \Gamma(M^0_{phys} \to f_{CP};t)}{\Gamma(\bar{M}^0_{phys} \to f_{CP};t) + \Gamma(M^0_{phys} \to f_{CP};t)} = S_f \sin(\Delta m t) - C_f \cos(\Delta m t)$$

where (assuming $\Delta\Gamma = 0$ and $|q/p| = 1$)

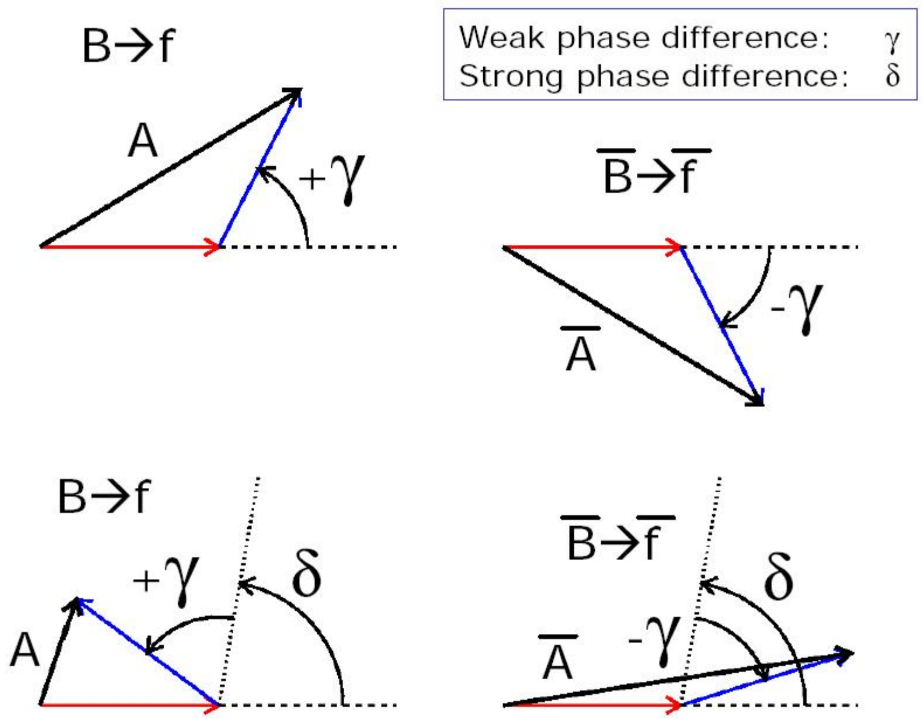
$$S_f \equiv \frac{2\Im(\lambda_f)}{1+|\lambda_f|^2} \quad \text{and} \quad C_f \equiv \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2} \qquad \text{and} \quad \lambda_f \equiv \frac{q}{p}\frac{\bar{A}_f}{A_f}$$

- For f_{CP} a CP-eigenstate and with one weak phase dominating
  - Asymmetry $A_{f_{CP}}$ measures weak phase cleanly
  - Asymmetry $A_{f_{CP}} = \eta_{CP} A_{\overline{f}_{CP}}$ where η_{CP} is CP-eigenvalue of f

$$\to C_{f_{CP}} = 0, \quad S_{f_{CP}} = \Im\{\lambda_{f_{CP}}\} = \sin(\arg \lambda_{f_{CP}})$$

$3 \times CP$ Violation

- **Decay**, aka 'direct'
  - ▷ $|\bar{A}_{\bar{f}}/A_f| \neq 1$
    where A_f amplitude for $B^0 \to f$
  - ▷ Example: $B^0 \to K^+\pi^-$
- **Mixing**
  - ▷ $|q/p| \neq 1$
    where $|B_\pm >= q|B^0 > \pm p|\bar{B}^0 >)$
  - ▷ Example: $K^0_L \to \pi^+\pi^-$
- **Interference of decay and mixing**
  - ▷ $\Im(\lambda_f) \neq 0, \lambda_f \equiv (\frac{q}{p}) \times \left(\frac{\bar{A}_f}{A_f}\right)$
  - ▷ Example: Time-dependent CP asymmetries at B factories



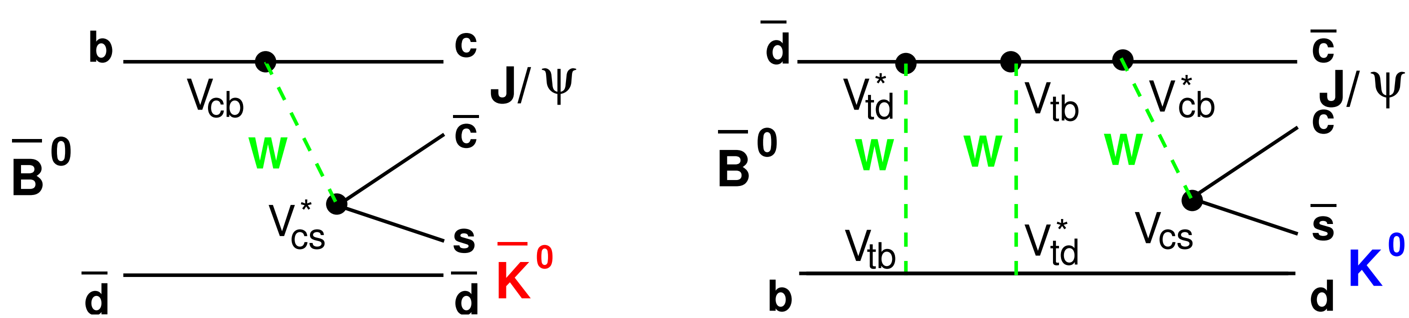
- Beauty beats strangeness for the study of CP violation
  - ▷ Many more decay modes
  - ▷ Smaller theoretical uncertainties
  - ▷ CP violation larger

The Golden Channel

- CP asymmetries in $B^0 \to J/\psi K^0$ and $\bar{B}^0 \to J/\psi \bar{K}^0$
  - ▷ Decay dominated by one weak phase
  - ▷ Subleading decay with same weak phase
  - ▷ common final state only with $K^0\bar{K}^0$ mixing

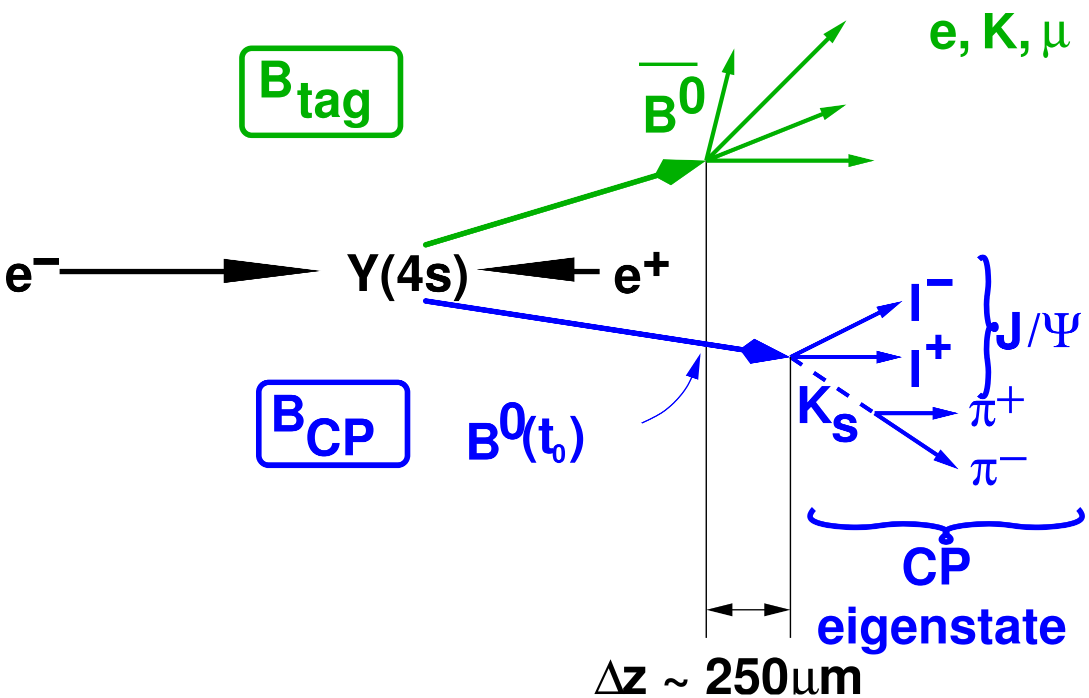
$$\begin{aligned}\lambda_{J/\psi K_{S,L}} &= \mp \left(\frac{q}{p}\right)_B \left(\frac{V_{cb}V_{cs}^*}{V_{cb}^*V_{cs}}\right) \left(\frac{q}{p}\right)_K \\ &= \mp \left(\frac{V_{tb}^*V_{td}}{V_{tb}V_{td}^*}\right) \left(\frac{V_{cb}V_{cs}^*}{V_{cb}^*V_{cs}}\right) \left(\frac{V_{cs}V_{cd}^*}{V_{cs}^*V_{cd}}\right) \\ &= \mp e^{-2i\beta}\end{aligned}$$

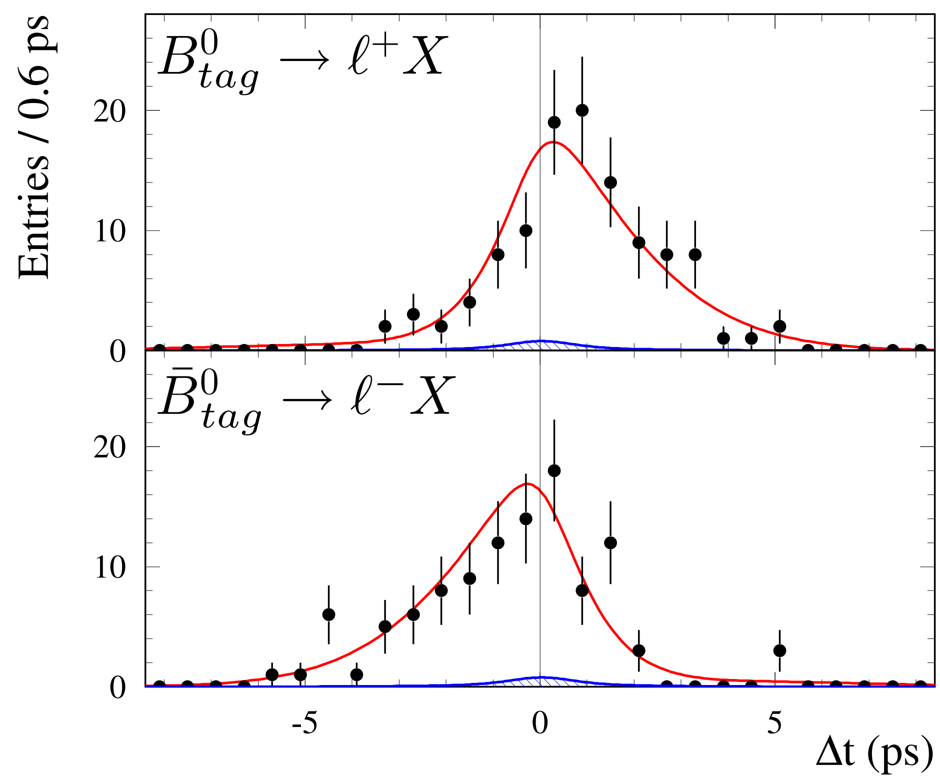
$\rightarrow$ $S_f = \eta_f \sin 2\beta$



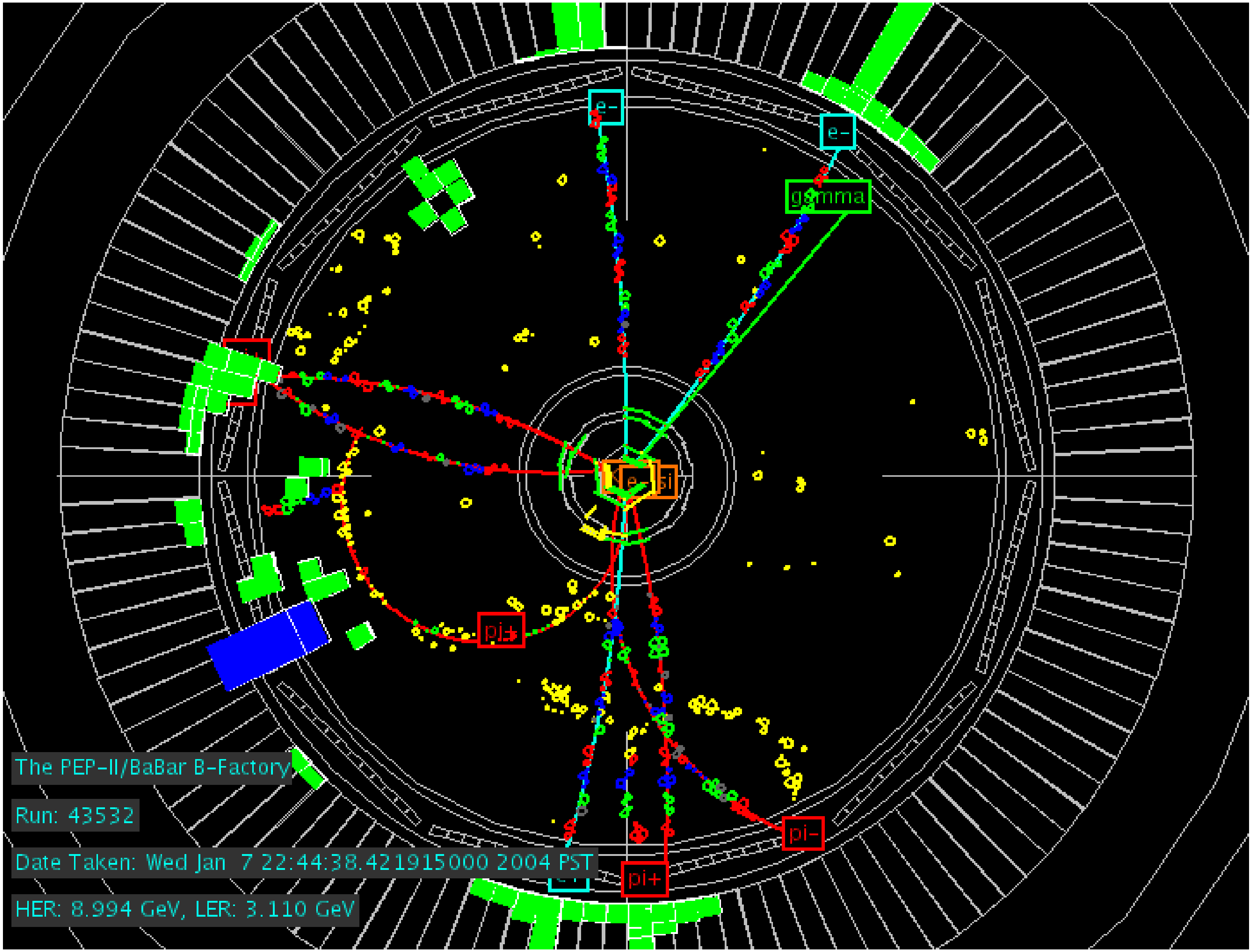
'Pure Gold'

- Produce many $\Upsilon(4S) \to B^0\bar{B}^0$ decays in entangled state
- Determine, at time t_0, B^0 or $\bar{B}^0$ in event as 'tag'
- Measure time difference to decay of other B^0 (or $\bar{B}^0$) into CP eigenstate, e.g. $B^0 \to J/\psi K^0_S$
- Compare B^0 and $\bar{B}^0$ $\to$ time-dependent CP asymmetry



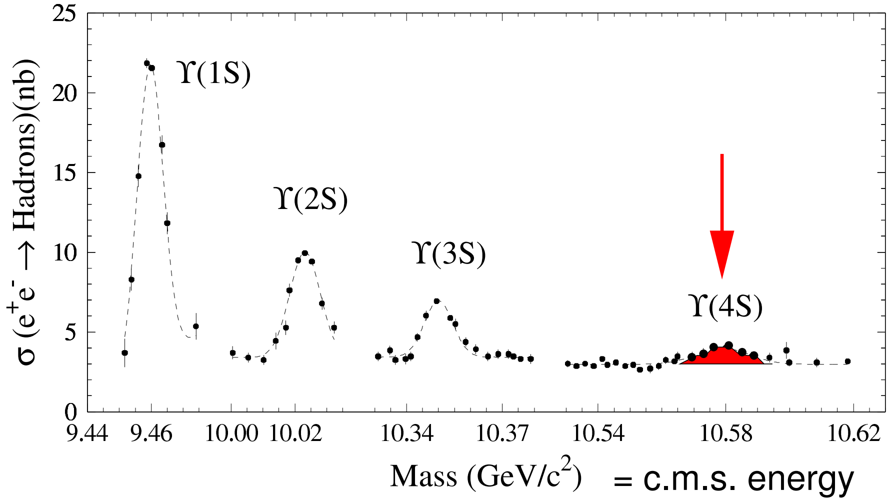


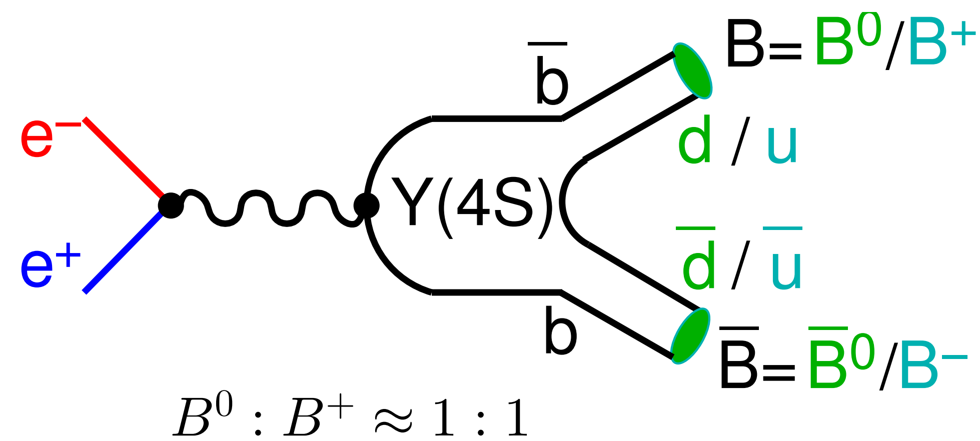
Experimental Heaven (close enough)



The $\Upsilon(4S)$

- Experimentally $\Upsilon(4S) \to B^0\bar{B}^0$ excellent source of B^0 mesons





$B^0 : B^+ \approx 1 : 1$

- Hadronic cross sections at $\sqrt{s} = 10.58$ GeV:

h	σ[nb]
b	1.05
c	1.3
d,s	0.3
u	1.4

- Threshold production
  - ▷ $m(\Upsilon(4S)) = 10.58$ GeV
  - ▷ final state

    $2 \times m_B = 2 \times 5.279$ GeV

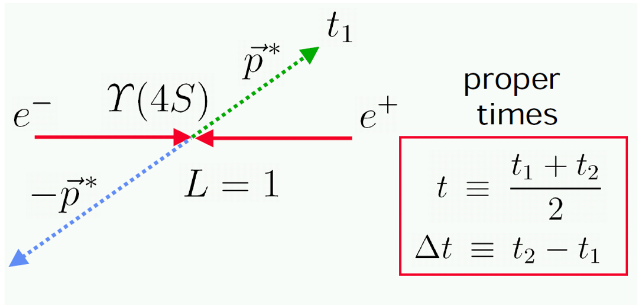
    $= 10.558$ GeV

- Fixed B momentum ($\Upsilon(4S)$ cms)

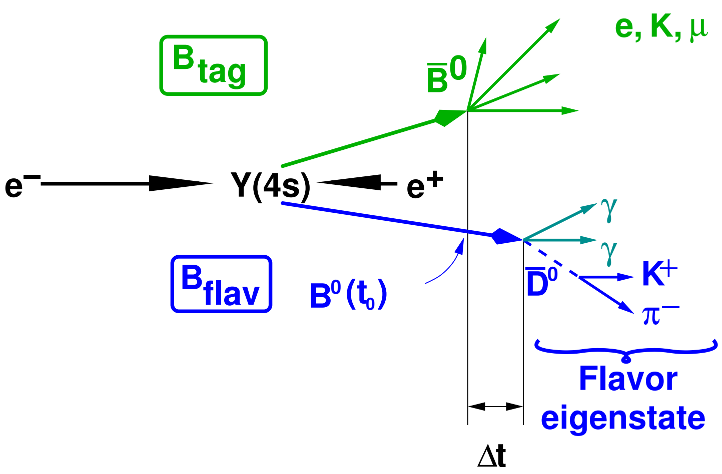
  $p_B = 0.34$ GeV

Time at $\Upsilon(4S)$

- $e^+e^- \to \Upsilon(4S) \to B^0\bar{B}^0 \;\; (J^{PC} = 1^{--})$
  - ▷ C-odd (two pseudoscalars in P-wave)
  - ▷ anti-symmetric wavefunction for $B\bar{B}$ state: $|\Upsilon(4S) \to B^0\bar{B}^0\rangle \sim |B^0, \vec{p^*}\rangle|\bar{B}^0, -\vec{p^*}\rangle - |\bar{B}^0, \vec{p^*}\rangle|B^0, -\vec{p^*}\rangle$



- Coupled time-evolution of entangled state
  - ▷ Einstein-Podolski-Rosen
- Mixing/oscillation in (anti-)phase
  - ▷ no B^0 B^0 or $\bar{B}^0$ $\bar{B}^0$
- Once B_1 decays, e.g. $\bar{B}_1 \to D^{*+}\ell^-\bar{\nu}$
  - ▷ specific flavor-tagging state
  - ▷ flavor of B_2 is fixed to B at that moment
  - ▷ time evolution of B_2 starts as described
  - ▷ decay time difference Δt is relevant
- Signed quantity Δt



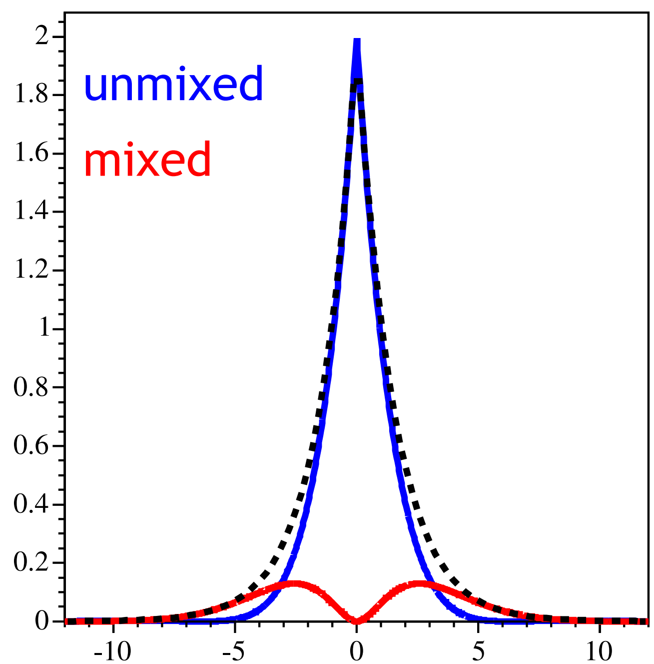
Mixing at $\Upsilon(4S)$

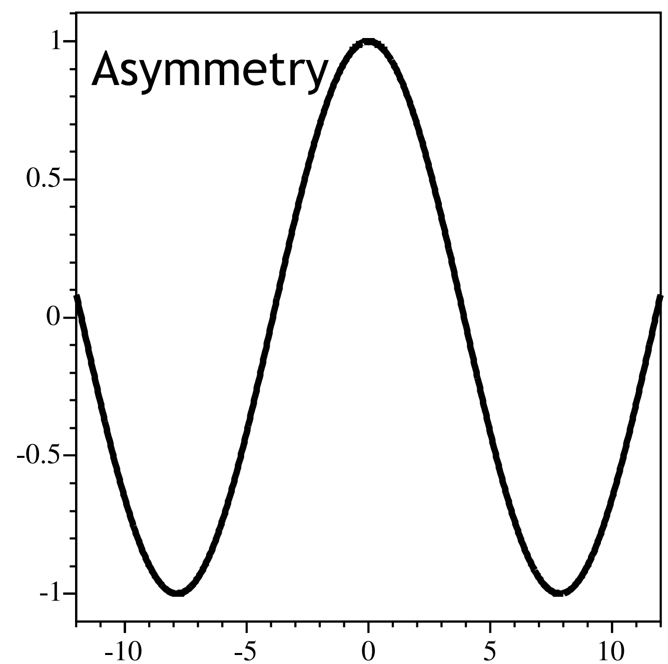
- At time $t = t_1$: First B^0 decay, *e.g.*, $B^0 \to D^{*-}\ell^+\nu$

$\Rightarrow$ Second B meson is $\bar{B}^0$

$$\psi_2(t_2) \quad = \quad |\bar{B}^0\rangle \left\{ e^{-\gamma_h(t_2-t_1)} + e^{-\gamma_l(t_2-t_1)} \right\} - \frac{p}{q}|B^0\rangle \left\{ e^{-\gamma_h(t_2-t_1)} - e^{-\gamma_l(t_2-t_1)} \right\}$$

- Function of Δt only $\rightarrow$ also in asymmetry

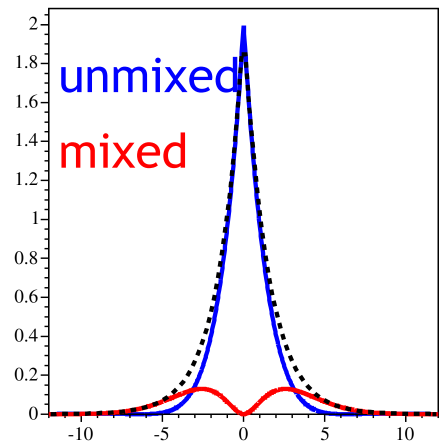


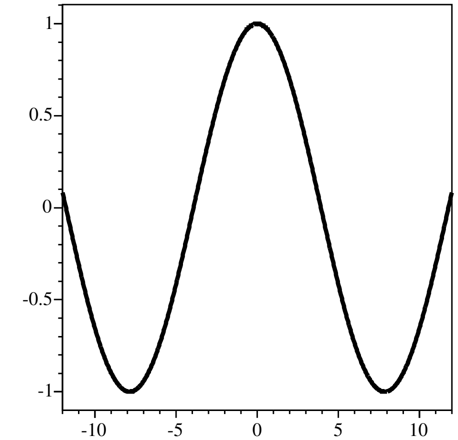


Time-independent Measurements

- Δt is algebraic quantity $\longrightarrow$ for time-integrated measurements:
  - ▷ Δt-even quantities are non-zero
  - ▷ Δt-odd quantities are zero
    (for finite integration range)
- Flavor-mixing is Δt-even

$$a_{mix}(\Delta t) \quad \sim \quad \cos(\Delta m \Delta t)$$

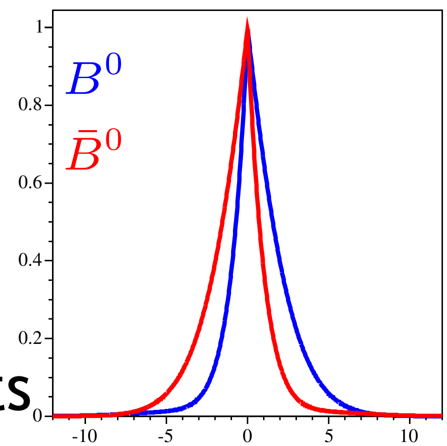


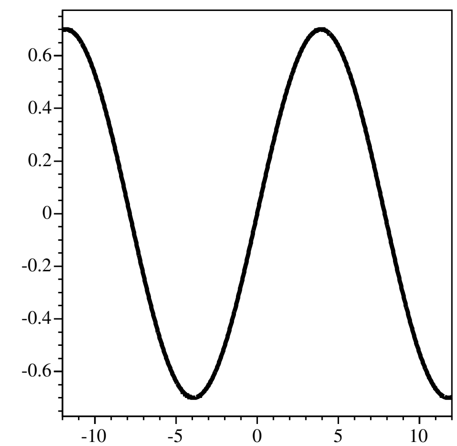


- CP-asymmetries are Δt-odd

$$a_{CP}(\Delta t) \quad \sim \quad \sin(\Delta m \Delta t)$$

(for golden channels, at least)

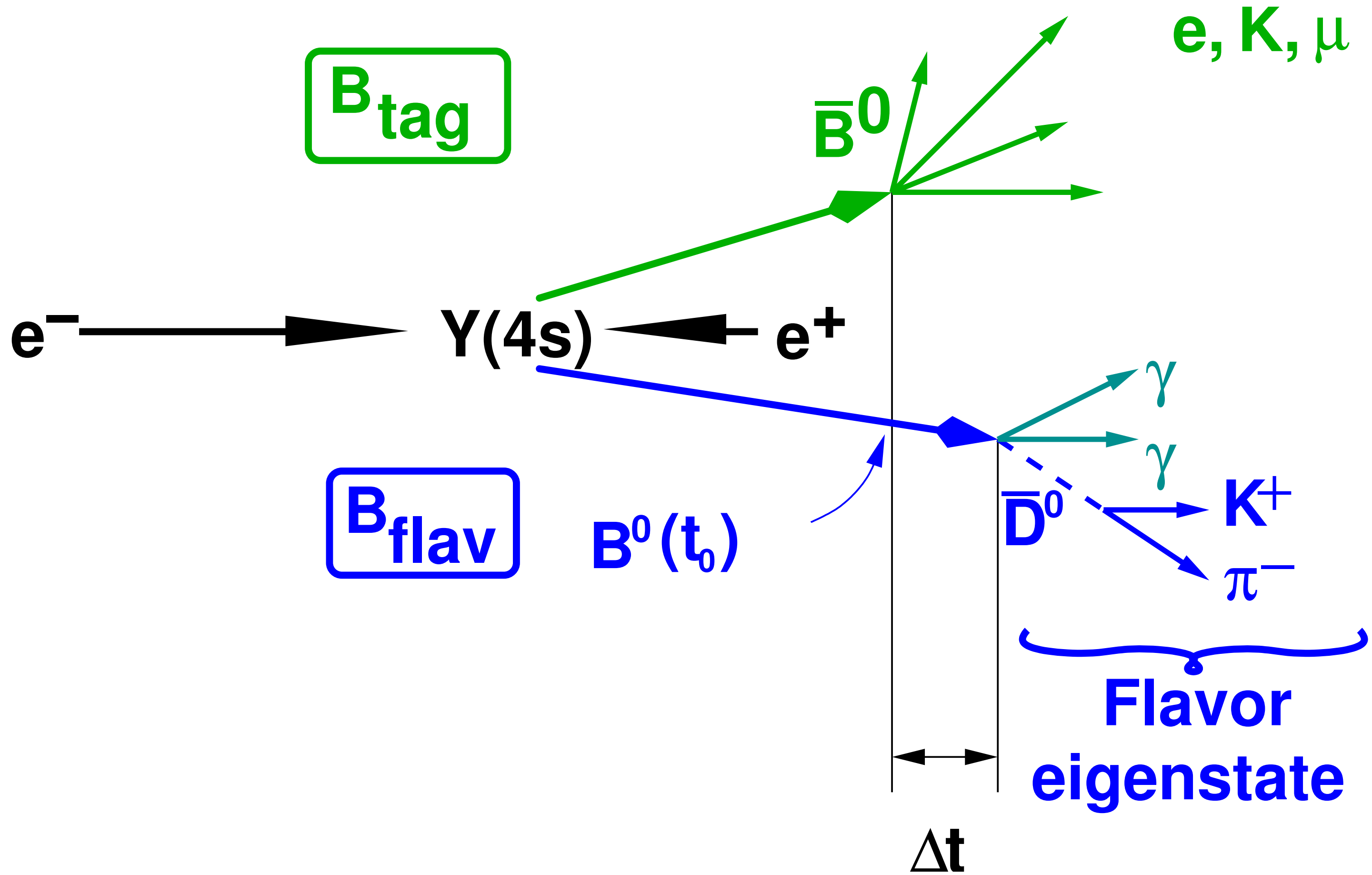




$\Rightarrow$ Time-dependent measurements

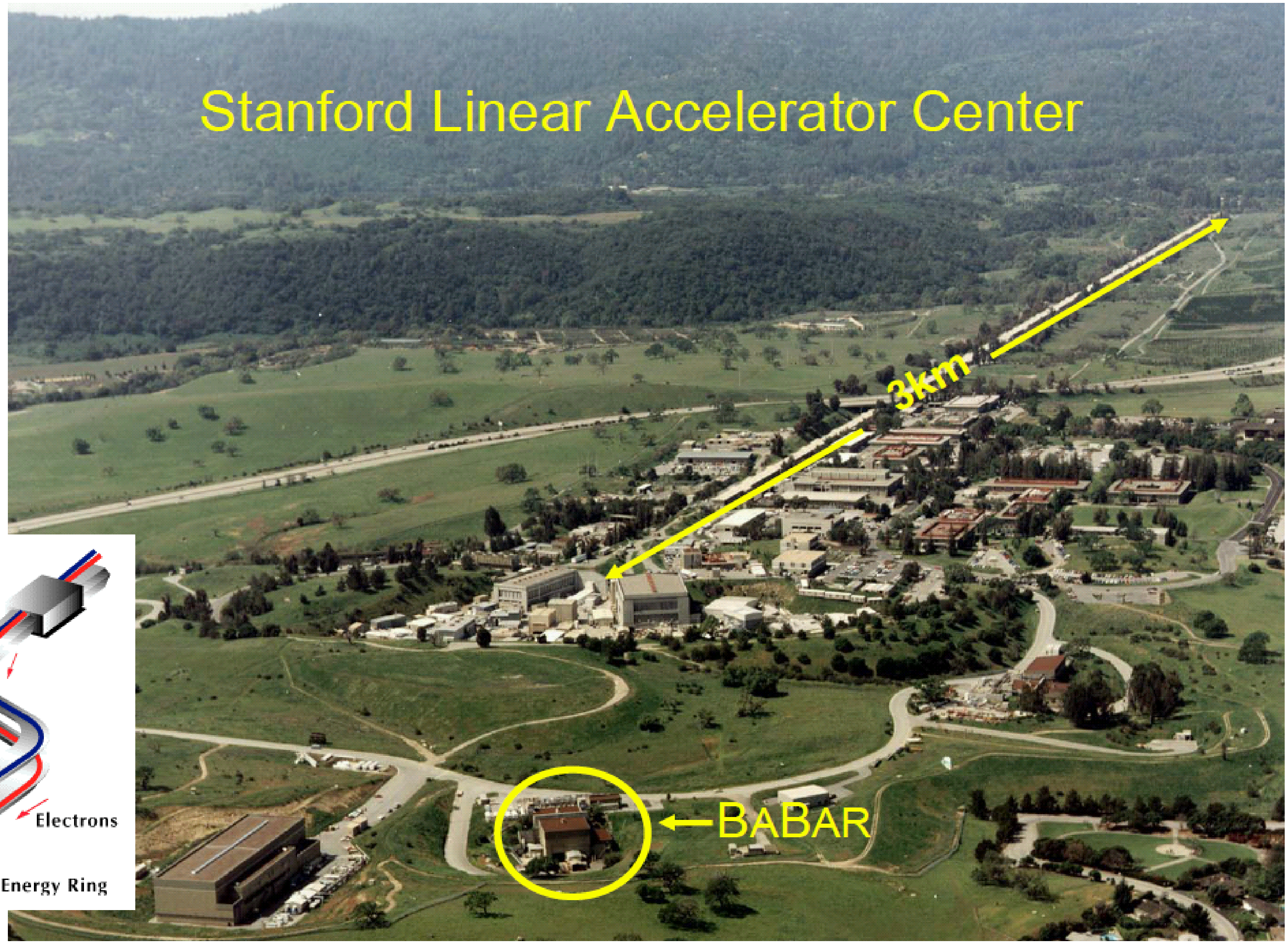
Time-dependent $\Upsilon(4S)$ decays

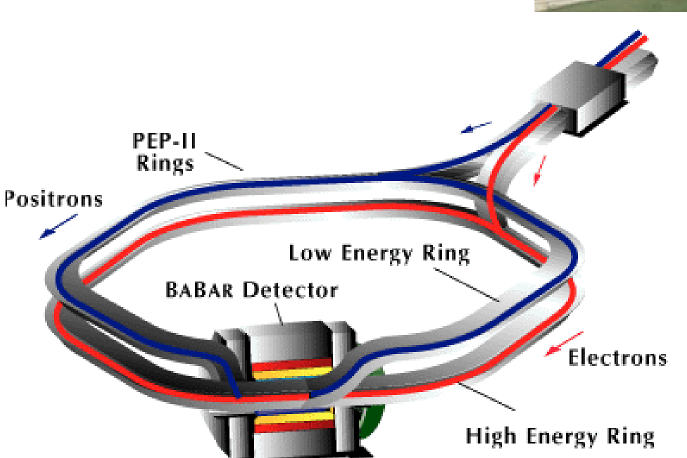
- Essential ingredients for time-dependent measurements
  - ▷ Tracking $\longrightarrow$ B reconstruction
  - ▷ Vertexing $\longrightarrow$ $\Delta z \approx \Delta t \beta\gamma$
  - ▷ Particle identification $\longrightarrow$ tagging



SLAC: BABAR and PEP-II

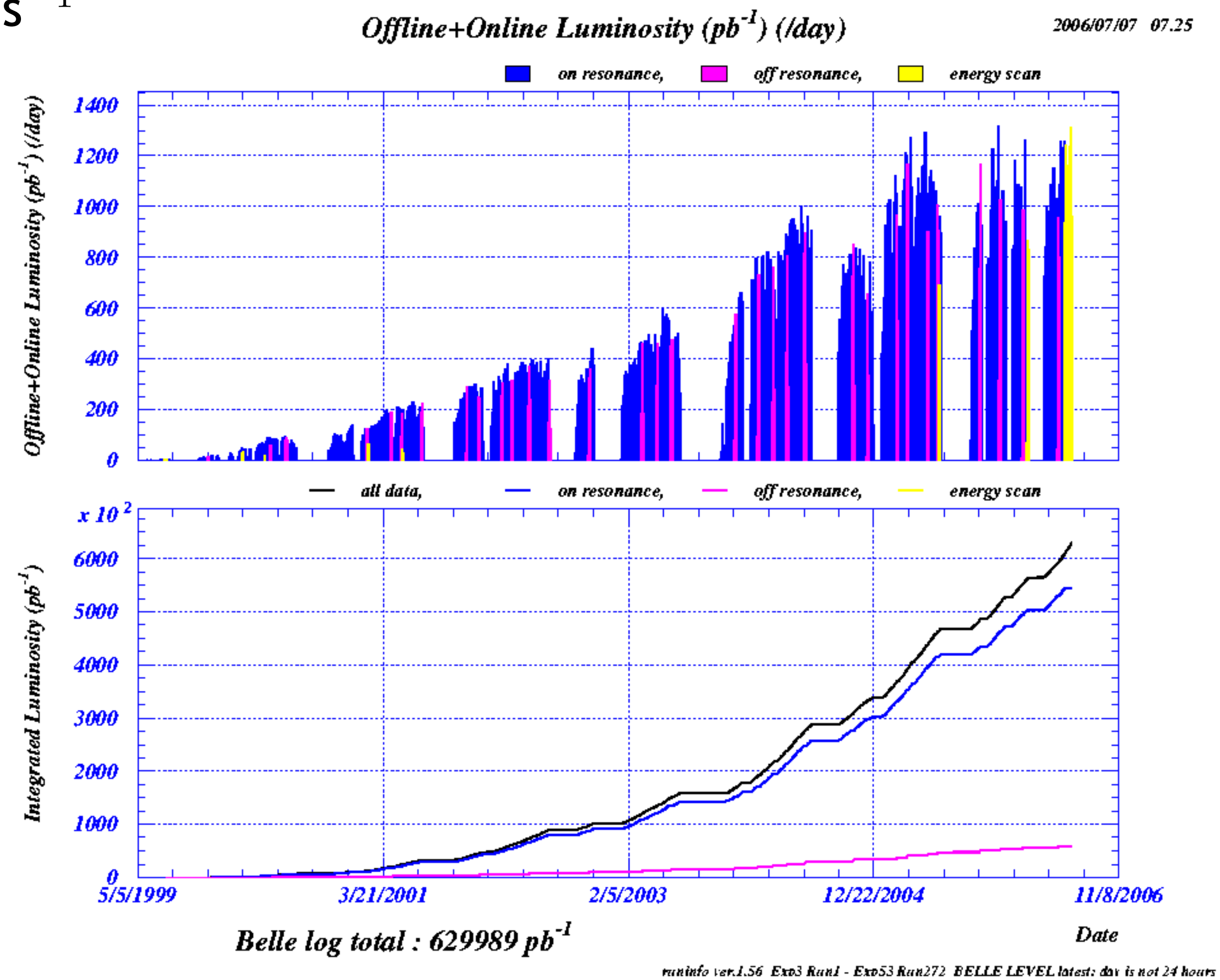
- Head-on collisions (no crossing angle)
  $e^-(9\,\text{GeV})$
  $e^+(3.1\,\text{GeV})$
  $\rightarrow \beta\gamma = 0.55$
- 2 rings
- Data-taking efficiency $> 99\%$!
- $\sim 10 B\bar{B}/\text{s}$



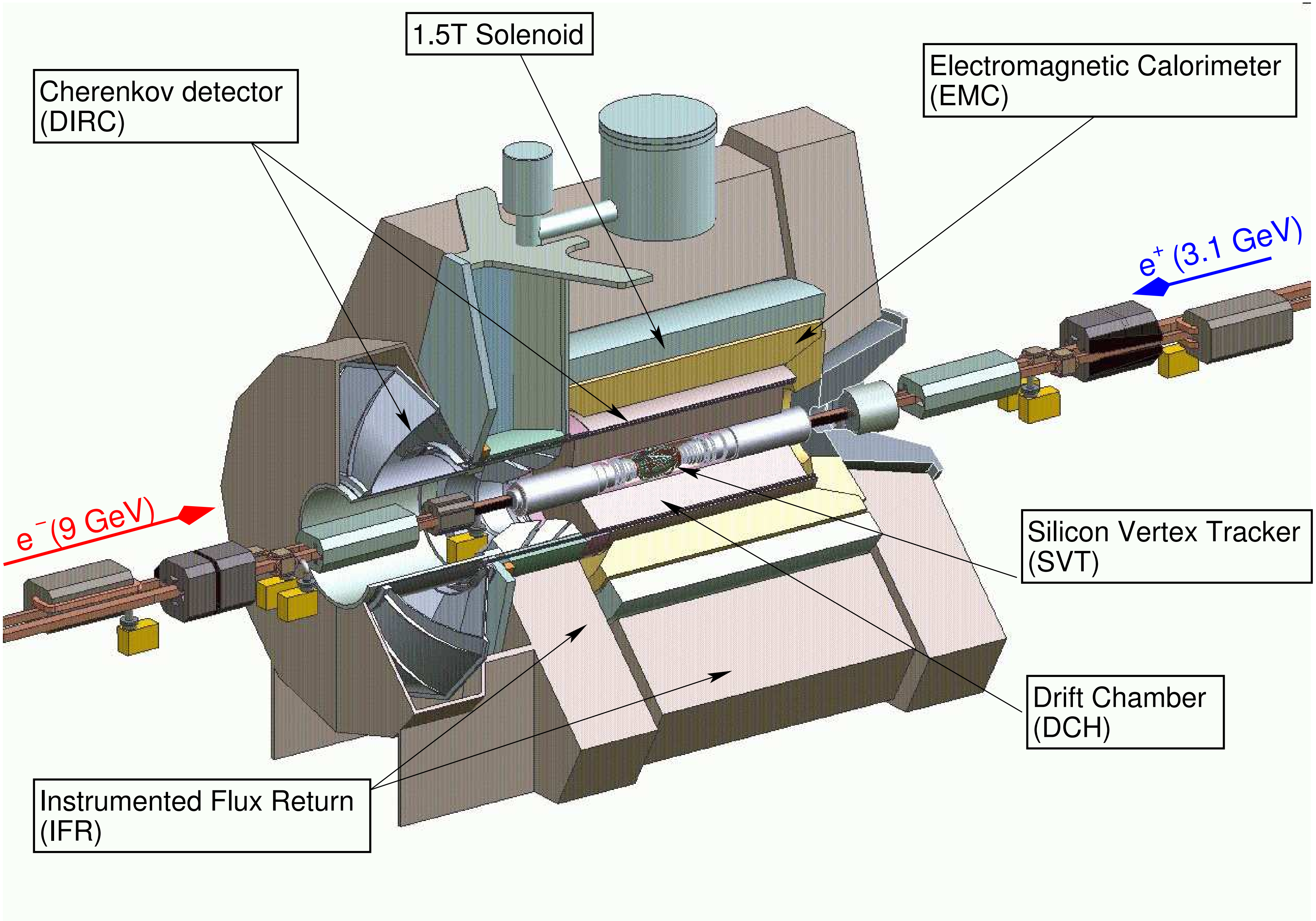


KEKB and Belle

- KEK-B vastly outperforms PEP-II
  - ▷ Belle is only slowly starting to exploit this
  - ▷ $16.52 \times 10^{33}\,\text{cm}^{-2}\,\text{s}^{-1}$
  - ▷ $629\,\text{fb}^{-1}$

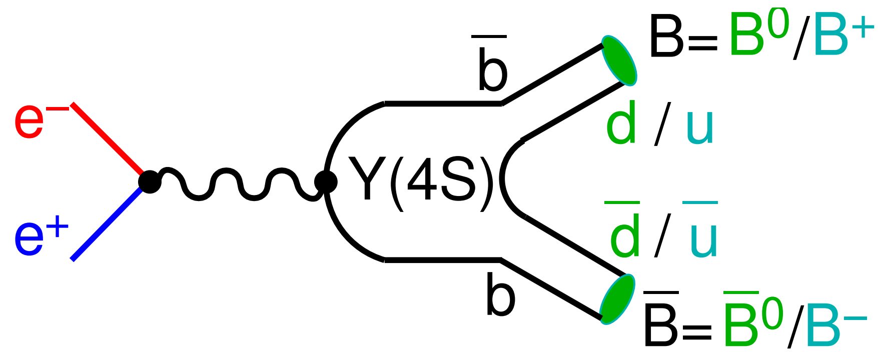


The *BABAR* Detector



B reconstruction

- Make use of
  - ▷ precisely known beam energies
  - ▷ no hadronization: $E_B = E_{\Upsilon(4S)}/2$ (in $\Upsilon(4S)$ restframe)



- Reconstruction of B mesons
  - ▷ lab: $p_B = (E, \vec{p})$
  - ▷ cms: $p_B^* = (E^*, \vec{p^*})$ (boost into restframe)

- Two analysis variables

$$
\begin{aligned}
m_{ES} &= \sqrt{E_{beam}^{*\,2} - \vec{p_B^*}^{\,2}} \\
\Delta E &= E_B^* - E_{beam}^*
\end{aligned}
$$

- Error propagation

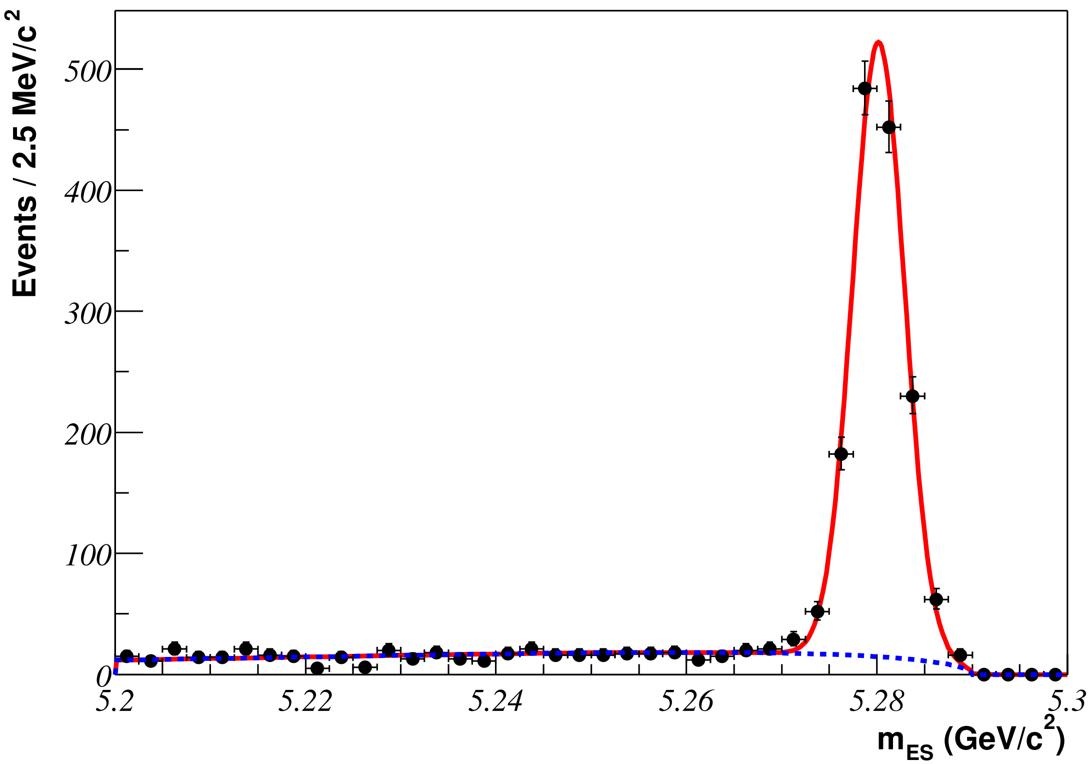
$$
\begin{aligned}
\sigma^2_{m_{ES}} &= \frac{1}{4}\sigma^2_{\sqrt{s}} + \left(\frac{p_B^*}{m_B}\right)^2 \sigma^2_{p^*} \approx \frac{1}{4}\sigma^2_{\sqrt{s}} \\
\sigma^2_{\Delta E} &= \frac{1}{4}\sigma^2_{\sqrt{s}} + \sigma^2_{E^*} \approx \sigma^2_{E^*}
\end{aligned}
$$

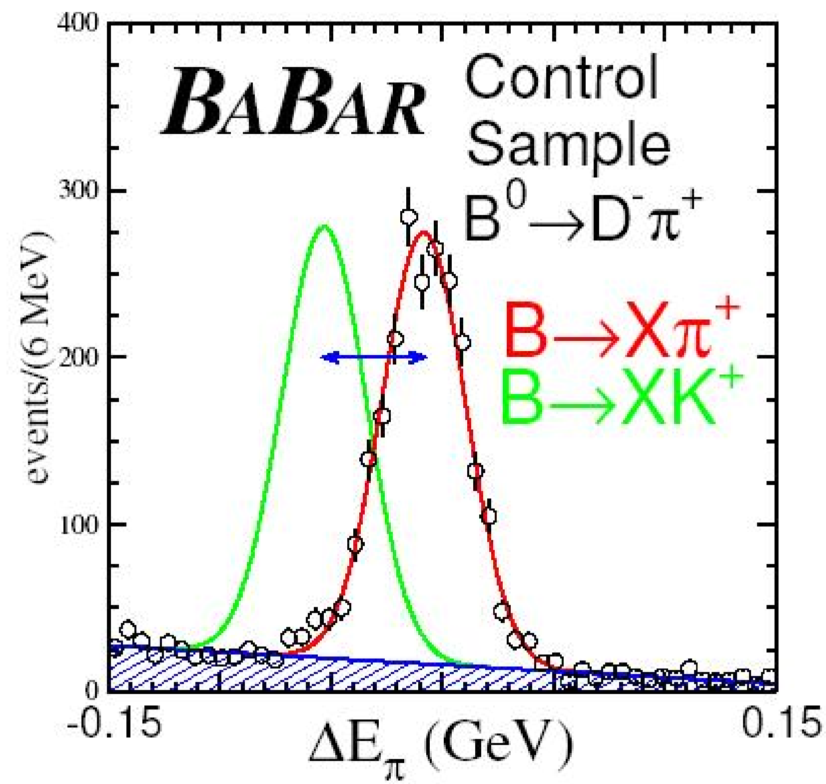
- Limitations
  - ▷ m_{ES}: beam energy spread $(E^*_{beam} = \sqrt{s}/2)$
  - ▷ ΔE: energy measurement (tracking)

m_{ES} and ΔE

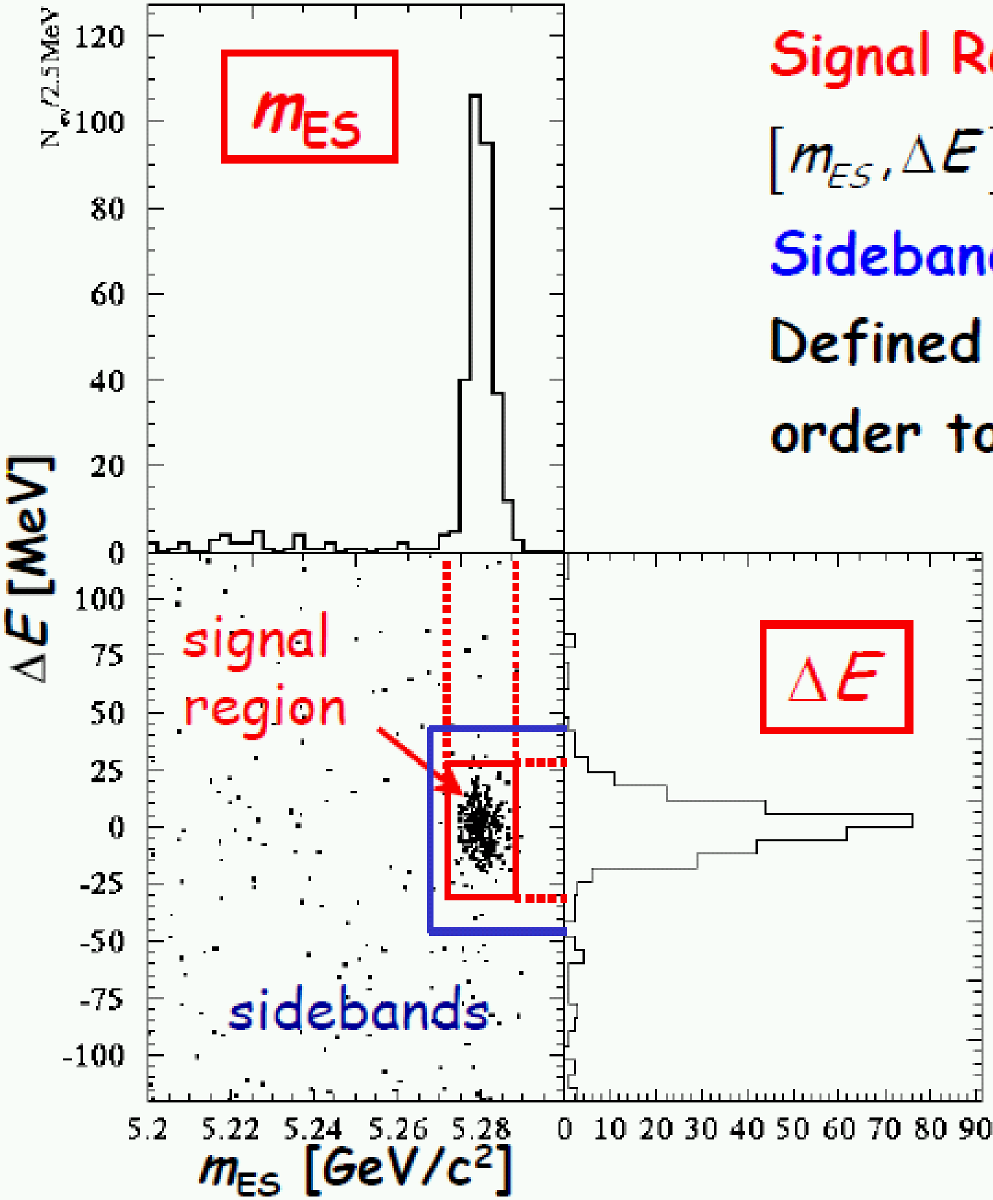
- Resolutions
  - ▷ m_{ES}: $2.5 - 3$ MeV
  - ▷ ΔE: $\sim 10 - 40$ MeV depending on n_{π^0} in final state
- m_{ES} background: phenomenological parametrization ('ARGUS')

$$dN/dm \propto m\sqrt{1-(m^2/E^2_{beam})} \times \exp[\alpha(1-(m^2/E^2_{beam}))]$$





m_{ES} and ΔE II



Signal Region:

$$[m_{ES}, \Delta E] = [m_B \pm 3\sigma_{m_{ES}}, 0 \pm 3\sigma_{\Delta E}]$$

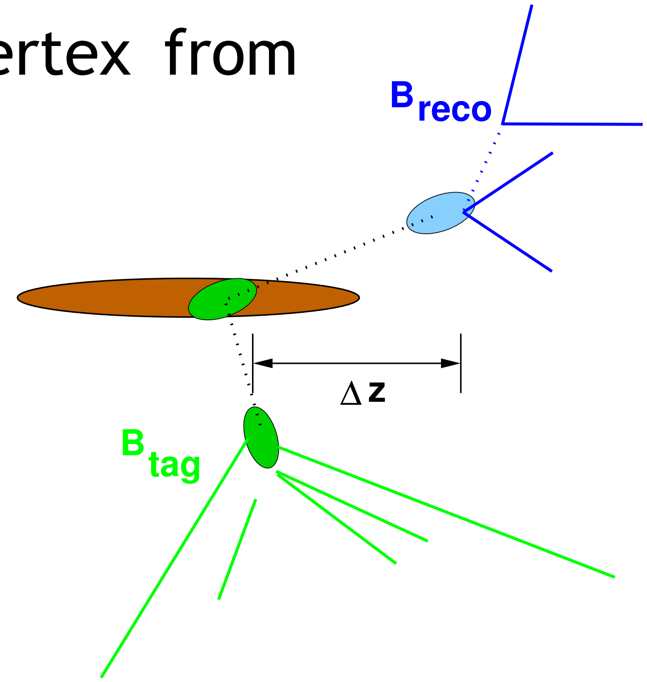
Sideband Region:

Defined outside signal region in order to estimate backgrounds

$B^0 \to J/\psi K_S$

Time Measurement: Vertexing

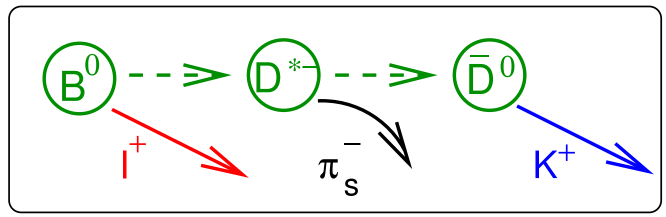
- Reconstruct B_{reco} and its decay vertex from
  - ▷ daughters
- Reconstruct B_{tag} direction from
  - ▷ B_{reco} vertex and momentum
  - ▷ beam spot
  - ▷ $\Upsilon(4S)$ momentum (pseudotrack)
- Reconstruct B_{tag} vertex from
  - ▷ Pseudotrack
  - ▷ Other consistent tracks
- Convert $\Delta z \rightarrow \Delta t \approx \Delta z / \beta\gamma c$

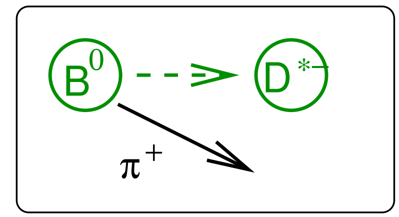


- Performance
  - ▷ Tracks: $\sigma_{IP} \sim 30\,\mu$m
  - ▷ Beamspot: $\sigma_{BS} \sim (150, 5, 10^4)\,\mu$m
  - ▷ B_{reco}: $\sigma_z \sim 65\,\mu$m
  - ▷ $B_{\rm tag}$: $\sigma_z \sim 110\,\mu$m
  - ▷ Δz: $\sigma_z \sim 180\,\mu$m

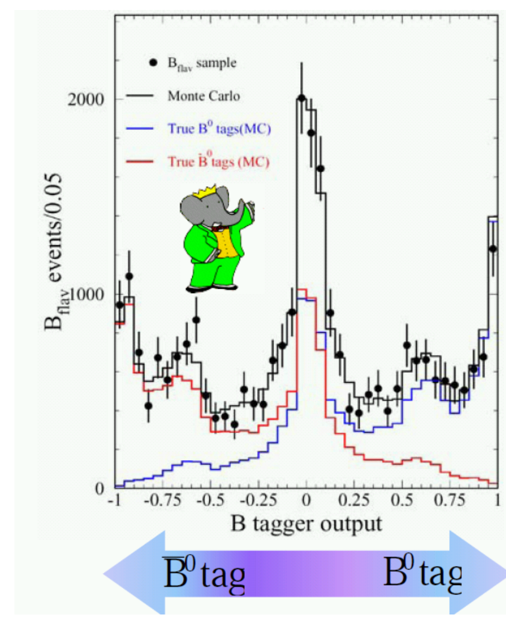
Tagging

- Tagging: flavor of 'other' B
  - and by coherence: 'this' B too (strictly!)
- Exploit charge correlations
  - Primary leptons
  - Kaons from charm decays
  - soft/fast pions





- Combine with neural networks, categories in terms of
  - physics (BABAR) and NN output (Belle)
- Performance
  - $Q = 30.5\%$
  - phenomenal compared to hadron machines:
  - CDF and LHCb: $1 \sim 4\%$
- Tagging at Hadron colliders
  - same-side vs. opposite-side
  - jet charge, kaons, . . .



Tagging Performance

- The figure of merit
  $Q = \varepsilon(1-2\omega)^2 = \varepsilon D^2$
  Mistag probability w
  Dilution $D = \frac{R-W}{R+W} = 1 - 2w$
- $A_{meas} = D \times A_{true}$
  - ▷ by definition of the dilution
- Statistical error on asymmetry

Category	ε(%)	ω(%)	Q(%)
Lepton	8.6±0.1	3.2±0.4	7.5±0.2
Kaon I	10.9±0.1	4.6±0.5	9.0±0.2
Kaon II	17.1±0.1	15.6±0.5	8.1±0.2
K-π	13.7±0.1	23.7±0.6	3.8±0.2
Pion	14.5±0.1	33.9±0.6	1.7±0.1
Other	10.0±0.1	41.1±0.8	0.3±0.1
Total	**74.9±0.2**		**30.5±0.4**

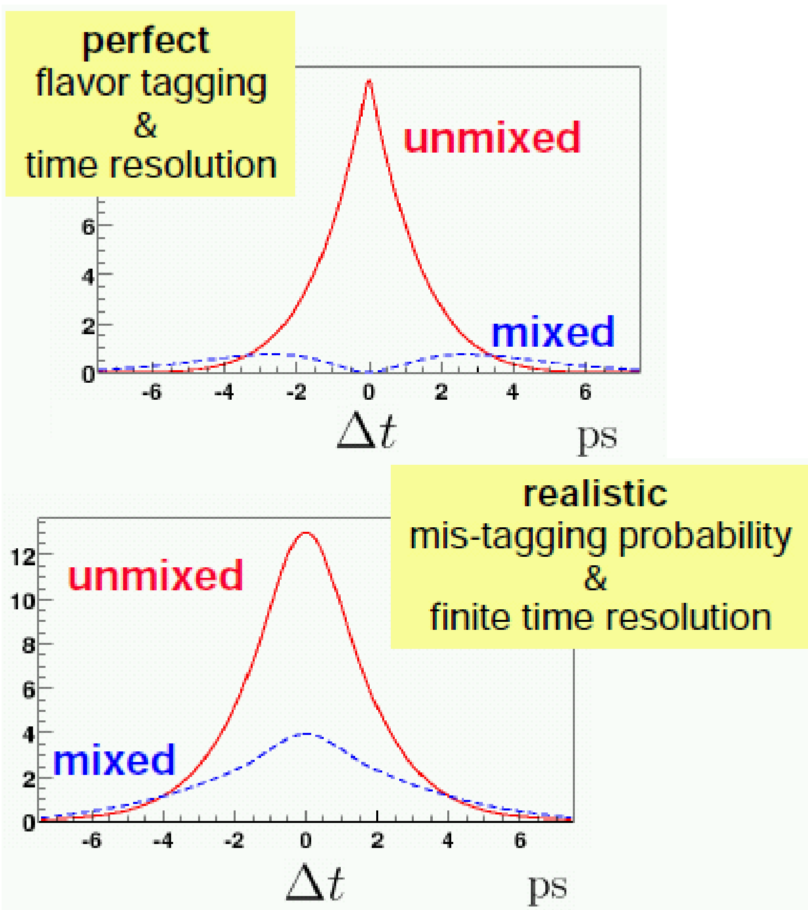
$$\sigma(A_{true}) = \sqrt{\frac{1 - D^2 A_{true}^2}{\varepsilon D^2 N}}$$

N is the total number of events

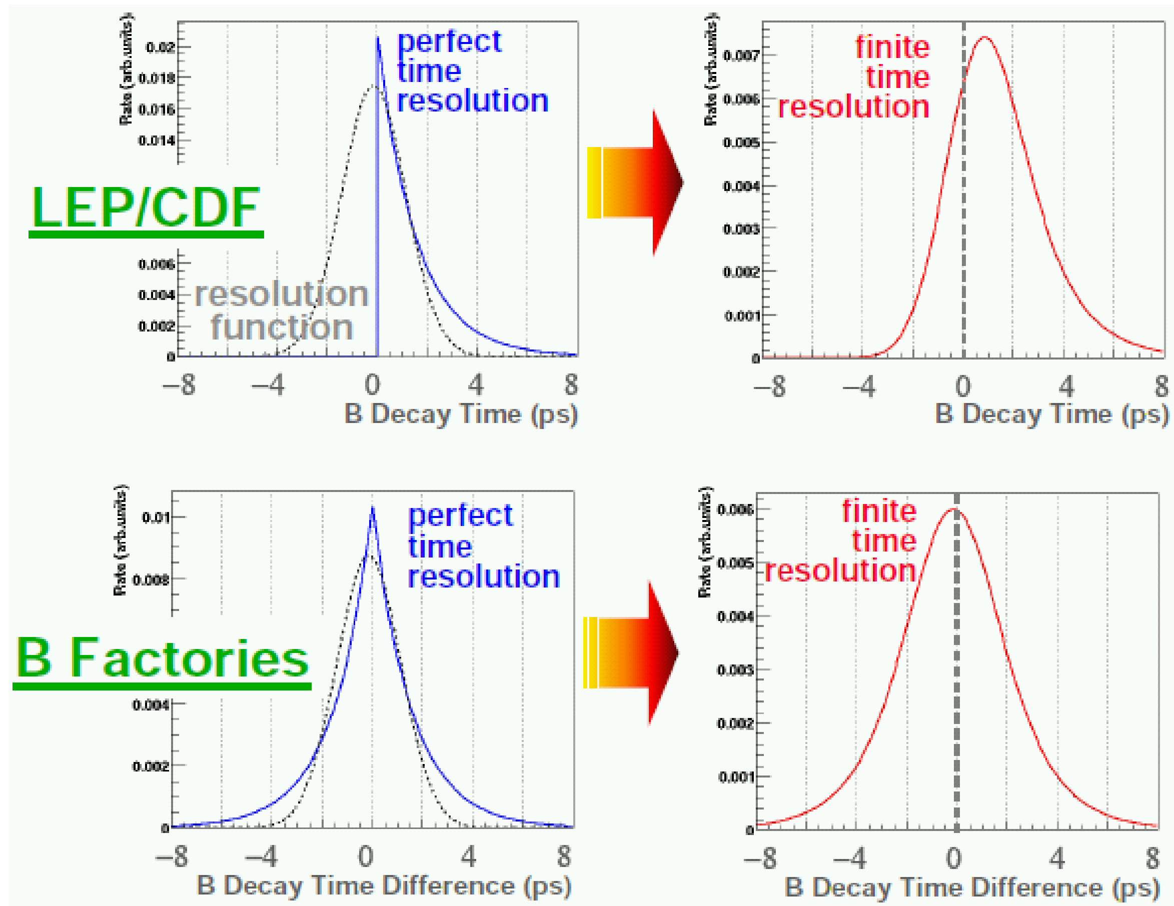
- ▷ numerator is effective statistics of sample
- ▷ equivalent to perfectly tagged

Experimental Imperfections

- B-factories



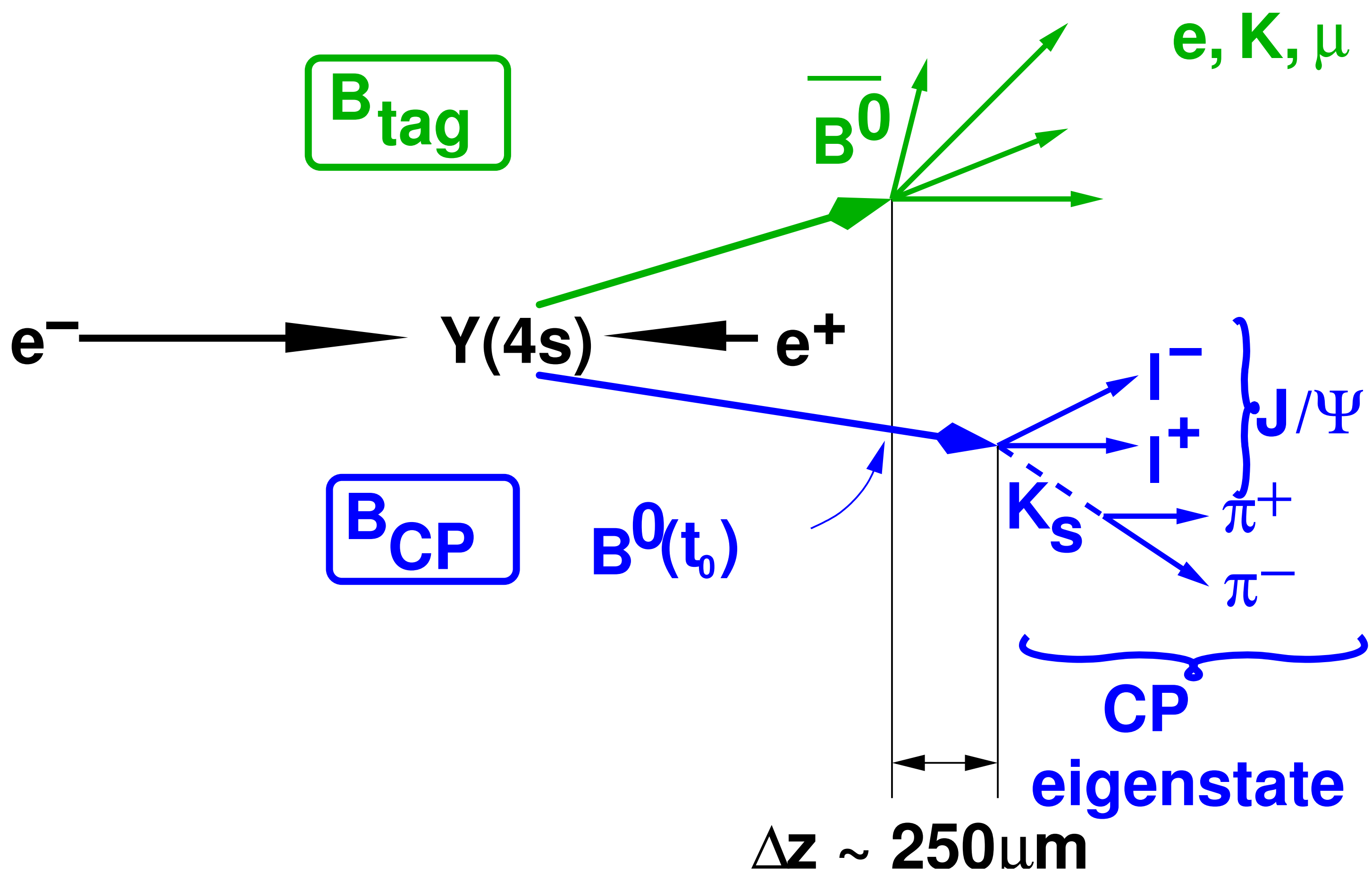
- LEP/Tevatron



- Mistagging will reduce amplitude
- Time resolution less a problem for B_d

The principle

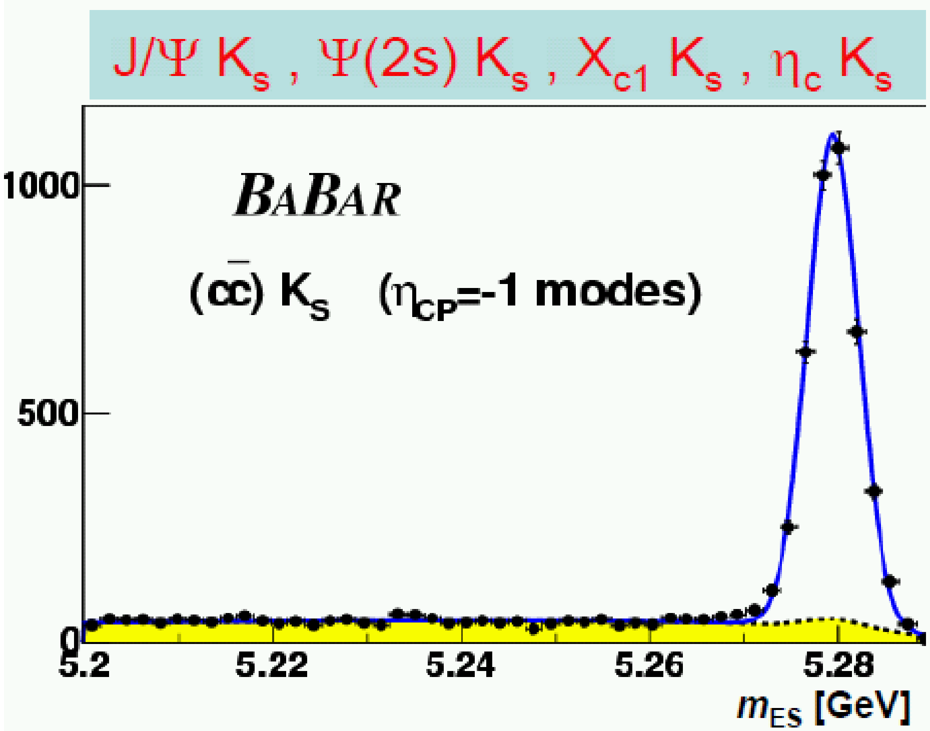
- Time-dependent mixing and CP analyses similar
  - mixed vs. unmixed
  - B^0 vs. $\bar{B}^0$

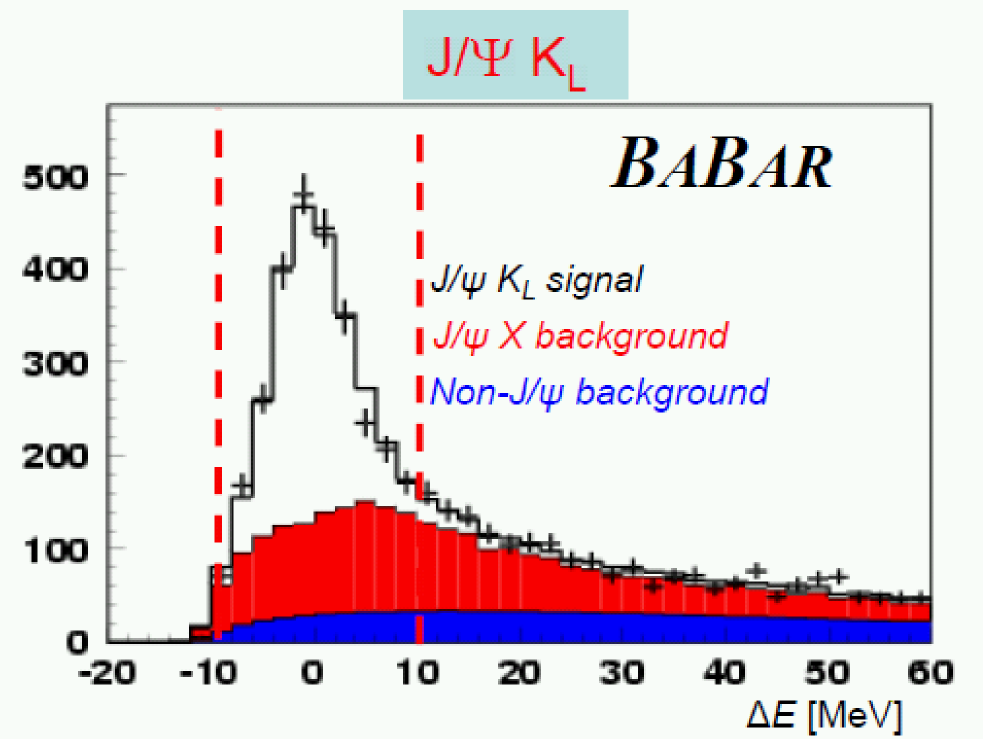


The latest BABAR Measurement

- Luminosity: ca. $210\,\mathrm{fb}^{-1}$, $N_{B\bar{B}} = 227 \times 10^6$
- Excellent reconstruction
  - ▹ Leptons
  - ▹ small (total) branching fractions

Mode	$\mathcal{B}$
$B \to J/\psi K_S$	4.2×10^{-4}
$J/\psi \to \ell^+\ell^-$	5.9×10^{-2}
$K_S \to \pi^+\pi^-$	69×10^{-2}



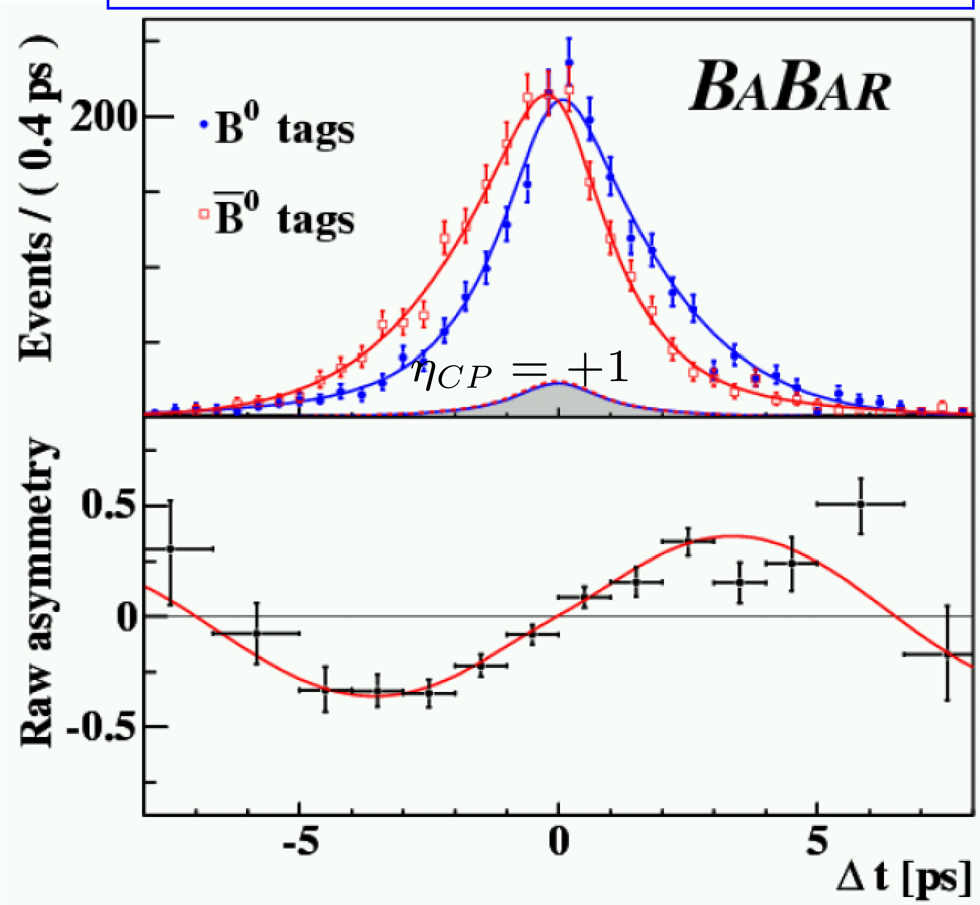


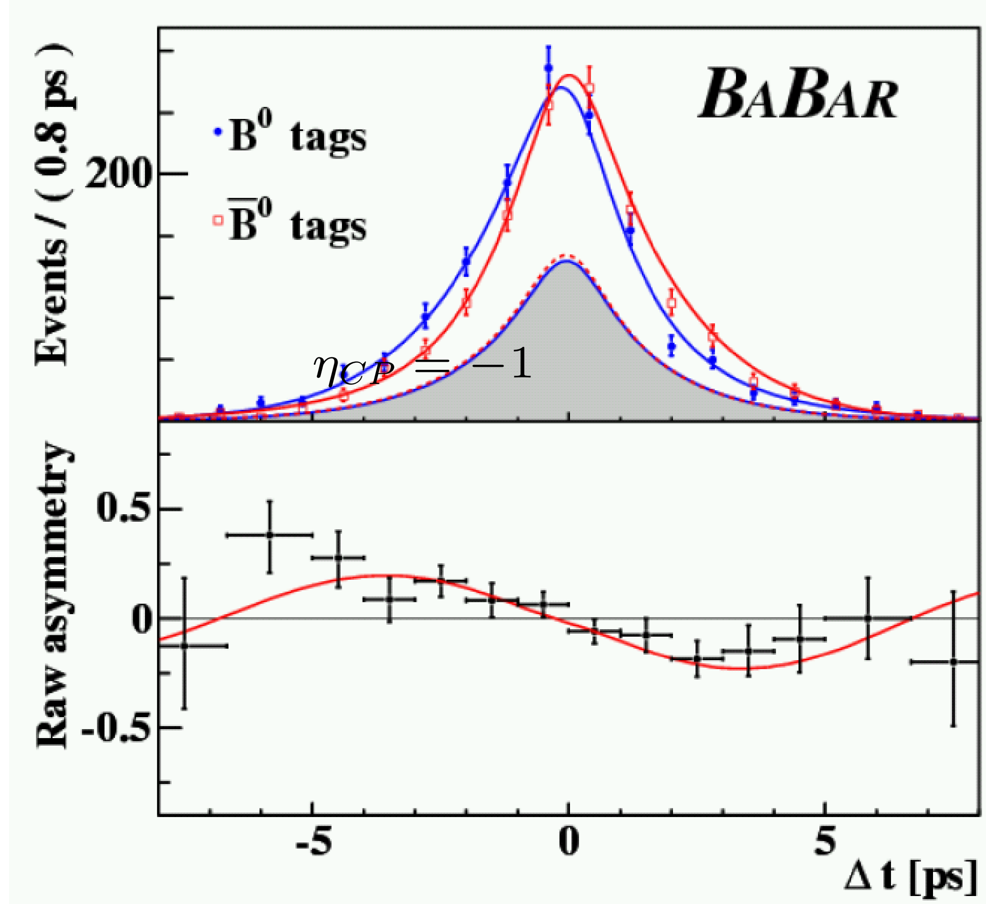
Results

- Calibration measurement

$$\sin 2\beta = 0.722 \pm 0.040 \pm 0.023$$
$$\beta = 23.1 \pm 1.6 \pm 0.9^\circ$$
$$\beta_{CKM} = 24.4^{+2.6\,\circ}_{-1.5}$$

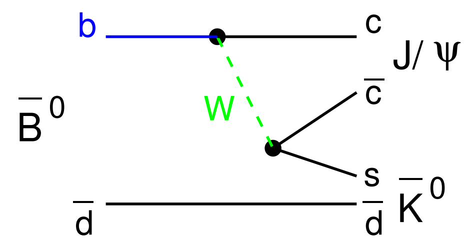
Channel	N(Tag)	Purity	η_{CP}	sin(2β)
$J/\Psi K_s(\pi+\pi-)$	2751	96%	-1	0.79±0.05
$J/\Psi K_s(\pi^0\pi^0)$	653	88%	-1	0.65±0.13
$\Psi(2S)K_s(\pi+\pi-)$	485	87%	-1	0.87±0.14
$\chi_{c1}K_s(\pi+\pi-)$	194	85%	-1	0.69±0.23
$\eta_c K_s(\pi+\pi-)$	287	74%	-1	0.17±0.25
Total (CP=-1)	4370			
$J/\Psi K^{*0}$	572	77%	+0.5	0.96±0.32
$J/\Psi K_L$	2788	56%	+1	0.57±0.09
Total	7730	78%		



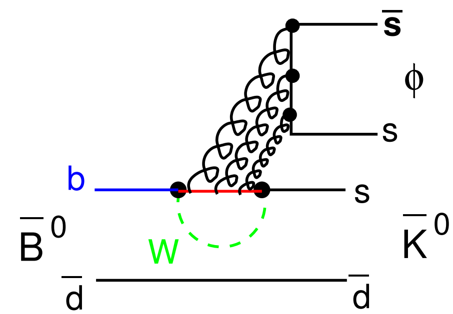


β: Penguins and New Physics

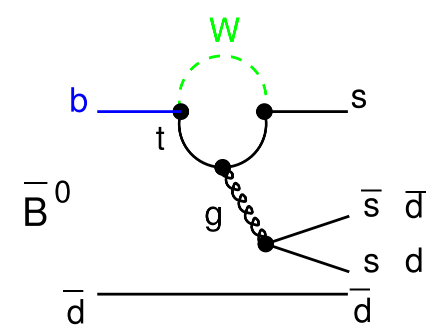
- 'New Physics' in CP violation
  - ▷ Loop diagrams: SM suppressed
  - ▷ Sensitive to heavy particles
  - ▷ Loop diagrams leading order: $b \to s$ penguins



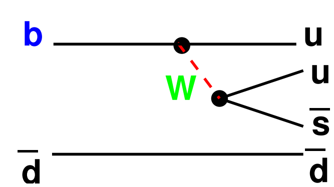
- Golden vs. penguin modes
  - ▷ $b \to c\bar{c}s$: T (suppressed P, with equal weak phase)
  - ▷ $b \to s$: P (suppressed T, not same weak phase, not all P with same weak phase)



- Uncertain 'tree pollution' major problem
  - ▷ $\mathcal{O}(5\%)$: $B^0 \to \phi K_S$, $B^0 \to K^+K^-K_S$
  - ▷ $\mathcal{O}(10\%)$: $B^0 \to \eta', f_0 K_S$
  - ▷ $\mathcal{O}(20\%)$: $B^0 \to \pi^0, \rho^0, \omega K_S$

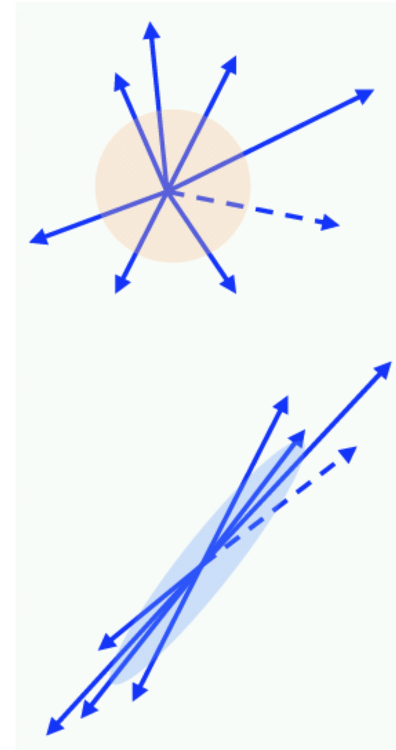


- Analysis proceeds as for golden modes
  - ▷ More $q\bar{q}$ continuum background (no leptons)
  - ▷ PID more challenging (high-momentum K ID)
  - ▷ Smaller statistics ($\mathcal{B}$ 20× smaller)

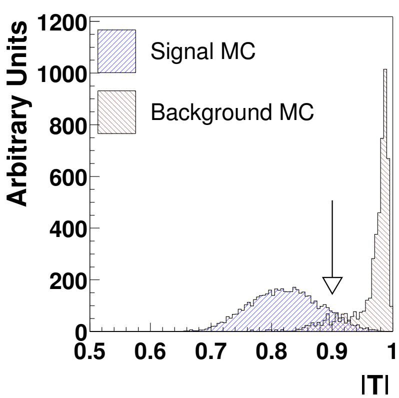


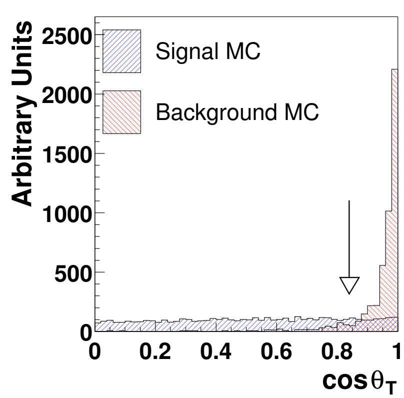
Background Reduction

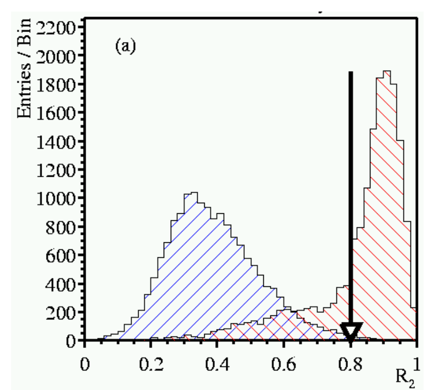
- $B\bar{B}$ events 'more' spherical than continuum
  - ▷ B decays at rest
  - ▷ Continuum events: $e^+e^- \to q\bar{q}(q = u, d, s, c)$
  - ▷ Severe background for final states without leptons

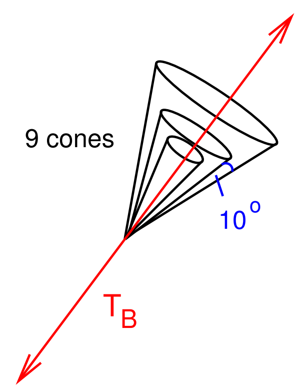


- Analysis possibilities ''event shape''
  - ▷ Fox-Wolfram moment $R_2 = H_2/H_0$
    with $H_l = \sum_{i,j} |\vec{p}_i||\vec{p}_j|P_l(\cos\alpha_{ij})/\sqrt{s}$
  - ▷ Thrust (-axis), $|\vec{T}| = \max\sum_i \vec{p}_i \cdot \vec{T}/|\vec{p}_i|$
    $|\cos\angle(\vec{T}_B, \vec{T}_{ROE})| < 0.8$
  - ▷ Sphericity, 'energy flow' in cones around B, . . .









$b \to s$ Penguin: $B^0 \to \phi K_S$

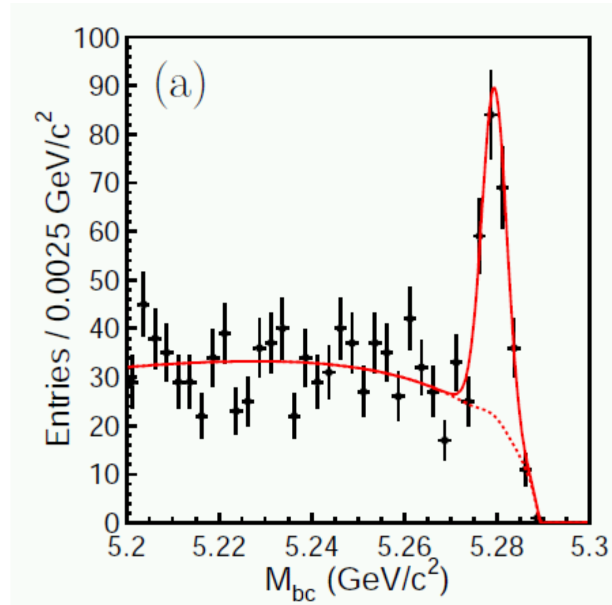
- Reconstruction more difficult
  - ▷ Kaons instead of leptons
  - ▷ ϕ lighter than J/ψ

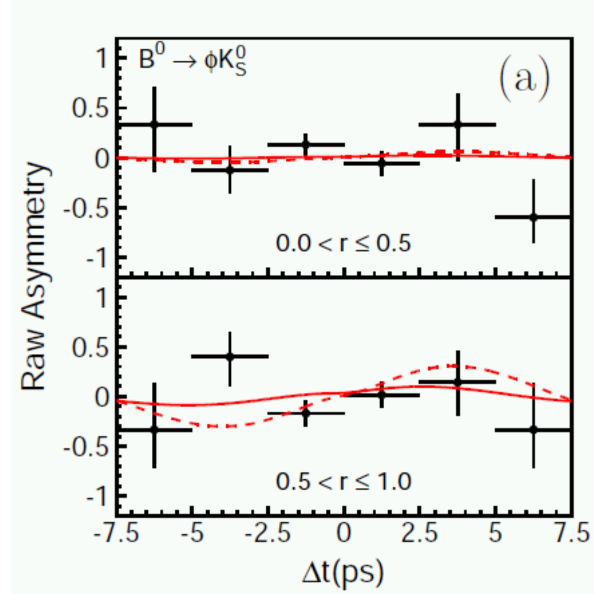
  $\to$ ϕ faster $\to$ vertexing less precise

- Belle 386MB

$$
\begin{aligned}
S_{\phi K^0} &= +0.44 \pm 0.27 \pm 0.05 \\
C_{\phi K^0} &= -0.14 \pm 0.17 \pm 0.07
\end{aligned}
$$

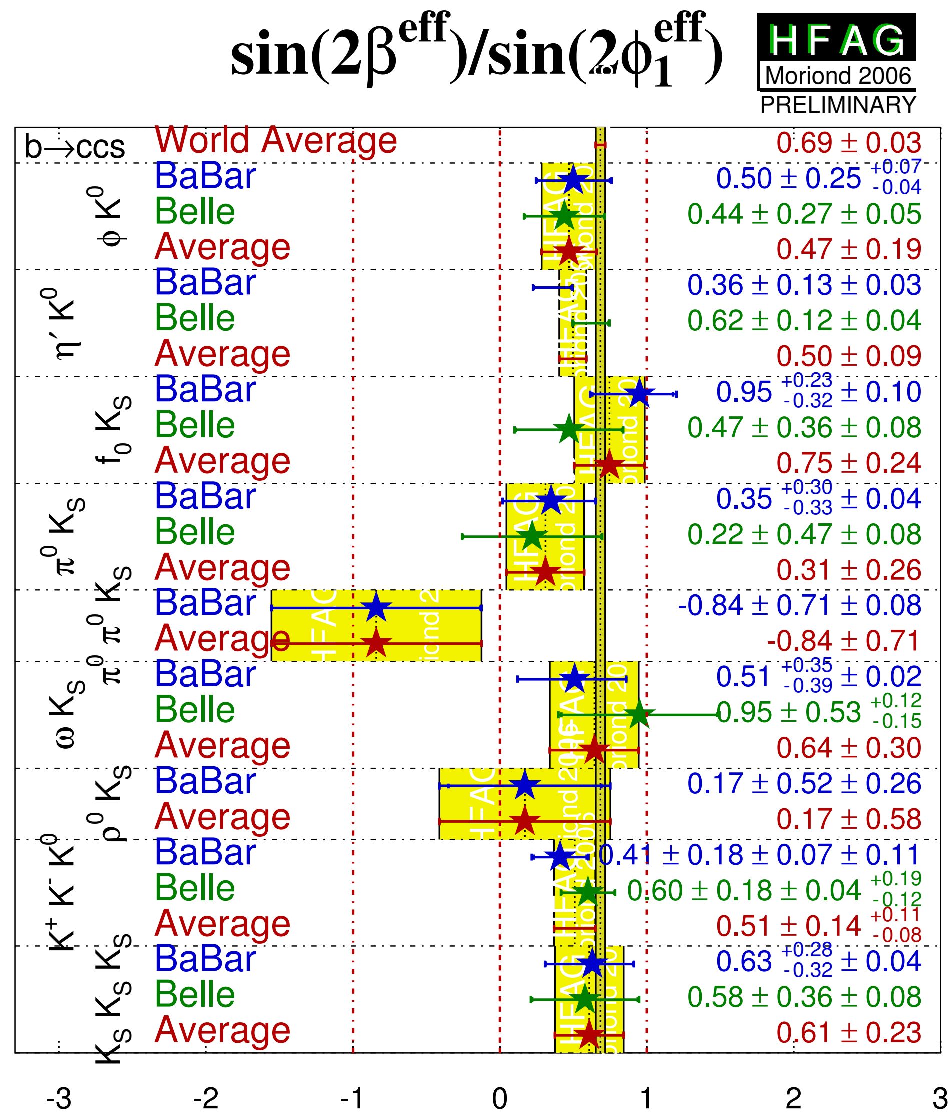
- Difference to golden modes?
  $\Delta S = \sin 2\beta_{\psi K_S} - \sin 2\beta_{\phi K_S}$
  - ▷ Naive loop/tree suppression:
    $\Delta S \sim 0.06 \pm 0.??$
  - ▷ Flavor SU(3):
    $\Delta S < 0.22$
  - ▷ QCD factorization:
    $\Delta S \sim 0.025 \pm 0.014$ (?)





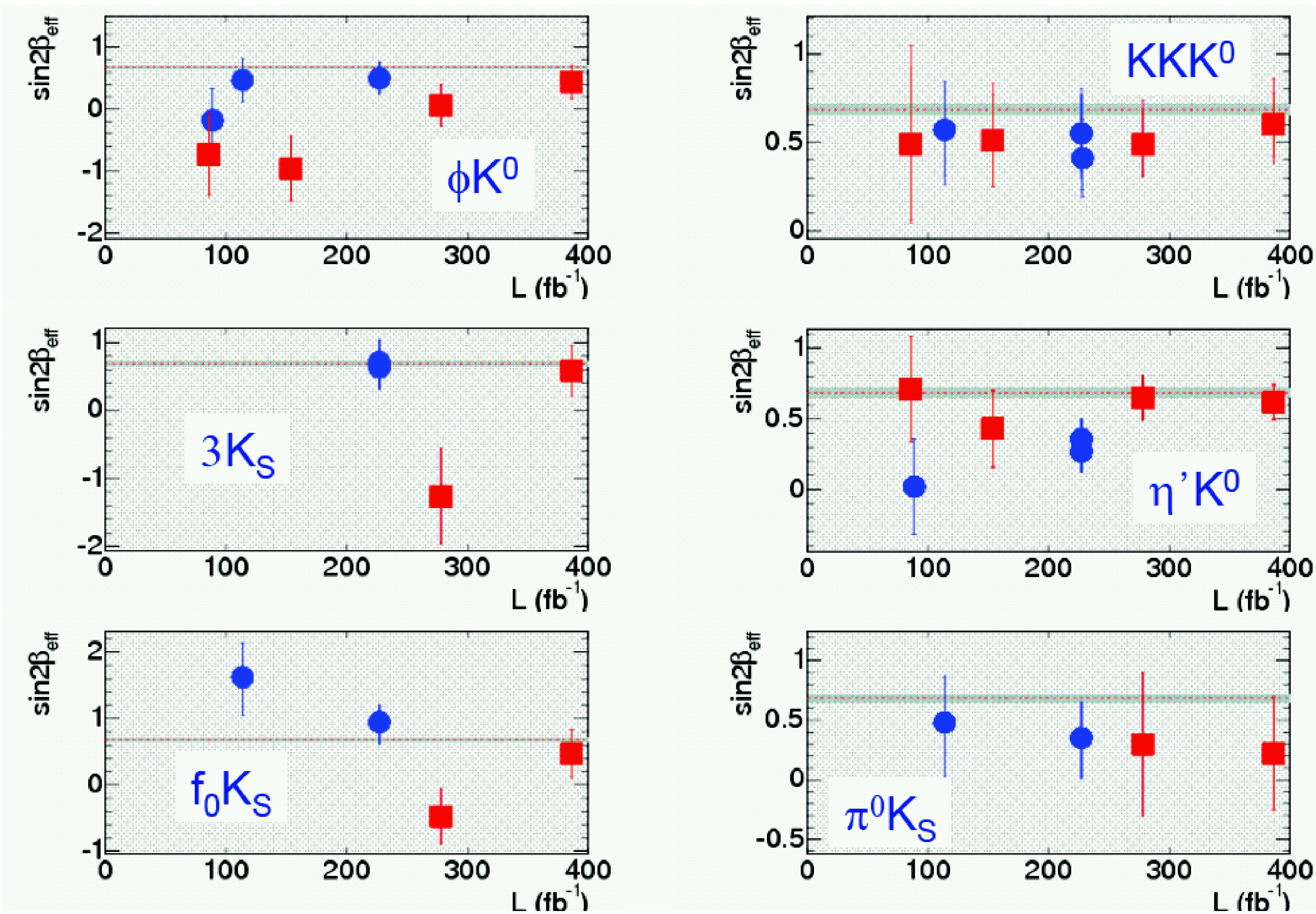
$c\bar{c}s$ vs. $b \to s$ Penguins

- Naive $b \to s$ penguin average of modes with smallest $\sigma_{\rm theo}$
  - ▷ $\phi K^0, \eta' K^0, K^0 \bar{K}^0 K^0$
  - $\to$ $\sin 2\beta_{\rm eff} = 0.50 \pm 0.06$
- 2.2σ from charmonium
  - ▷ Had been much more exciting last year, the year before, . . .
- Errors
  - ▷ theoretical
  - ▷ correlated experimental



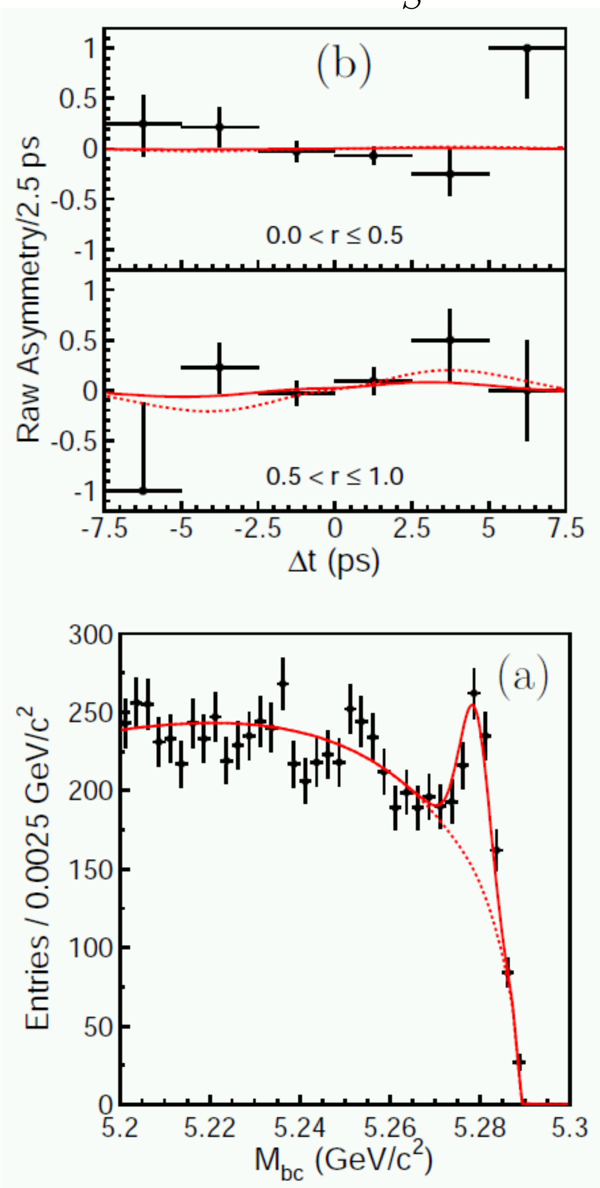
New Physics?

- Time-dependent CP-violation
  - ▷ in more than one sense?

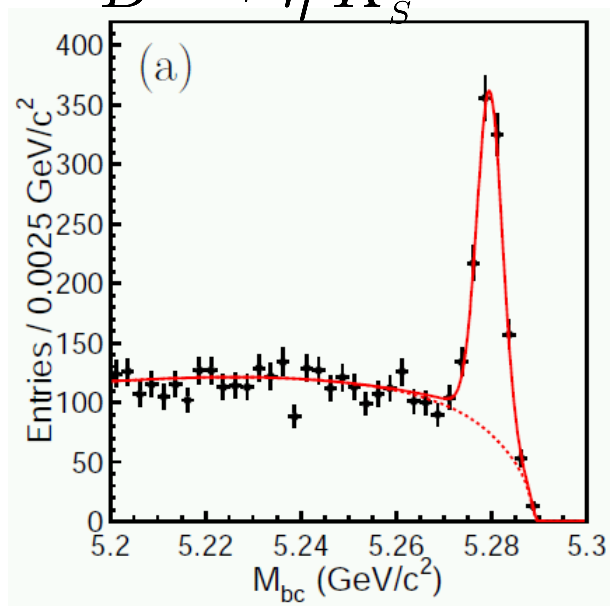


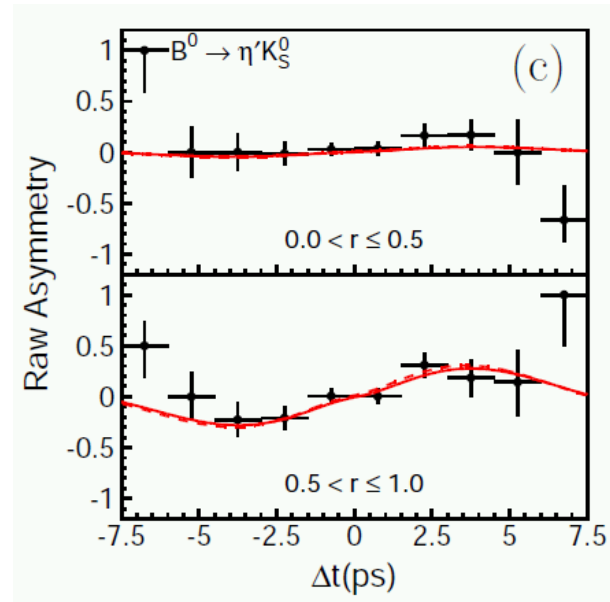
Some more examples

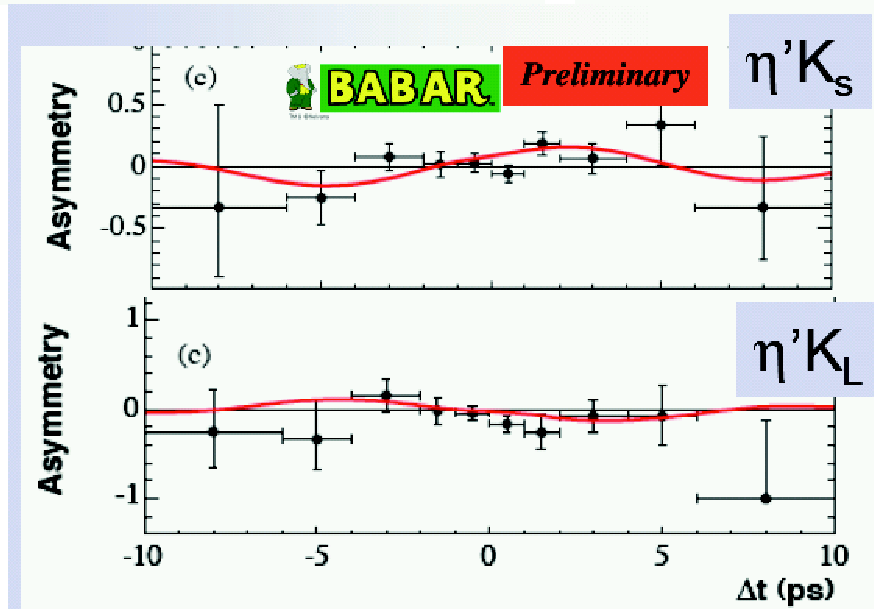
$B^0 \to \pi^0 K_S^0$



$B^0 \to \eta' K_S^0$







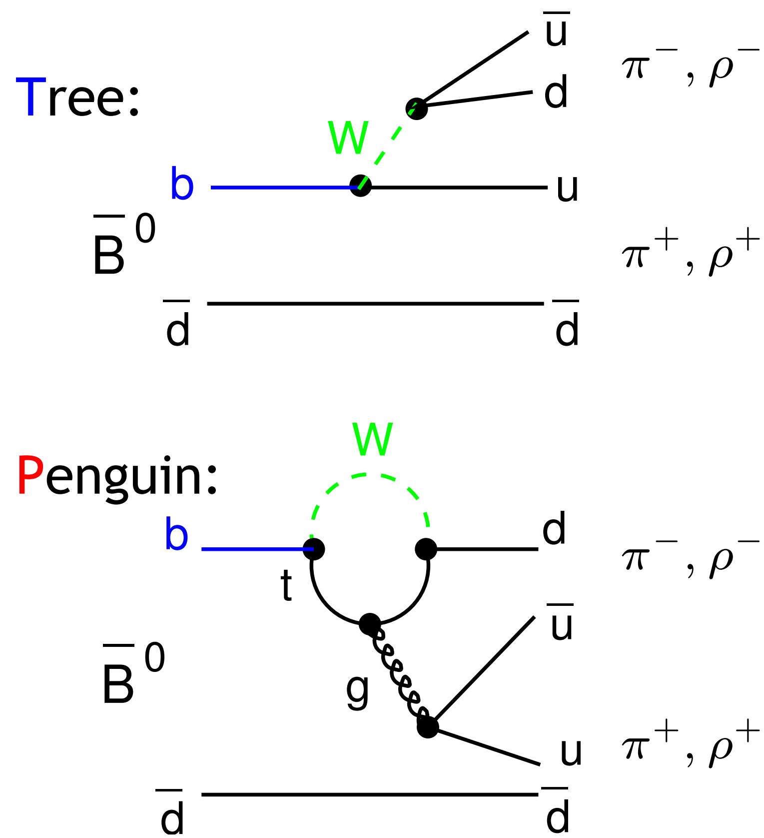
Determinations of α

- $b \to u$ decay into (CP eigenstate) $B^0 \to \pi^+\pi^-, \rho^\pm\pi^\mp, \rho^\pm\rho^\mp$
  - ▷ Mixing and $b \to u$ decay (for one decay amplitude!)

$$\lambda = e^{-i2\beta}e^{-i2\gamma} = e^{i2\alpha}$$
$$S = \sin 2\alpha, \quad C = 0$$

  - ▷ But: In addition to tree amplitudes, there are penguin processes $\to$ access to α complicated!

$$\lambda = e^{i2\alpha}\frac{T + Pe^{+i\gamma}e^{i\delta}}{T + Pe^{-i\gamma}e^{i\delta}}$$
$$C \propto \sin\delta \neq 0$$
$$S = \sqrt{1 - C^2}\,\sin 2\alpha_{\rm eff}$$



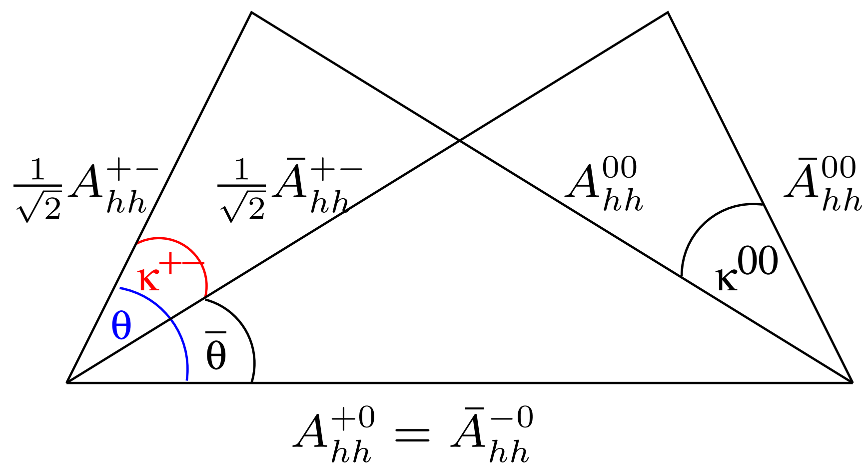
- How large is P/T?
  - ▷ Models, e.g, QCD factorization
  - ▷ Isospin analysis

Penguin vs. Tree

- Isospin relations allow estimation of penguin contribution
  - Two isospin relations (for B and $\bar{B}$ decays)

$$A(B^+ \to h^+h^0) \quad = \quad \frac{1}{\sqrt{2}} A(B^0 \to h^+h^-) + A(B^0 \to h^0h^0)$$

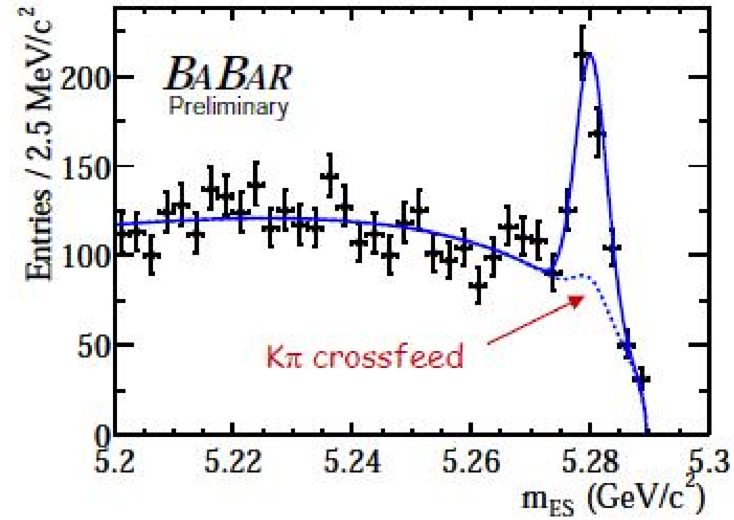
  - Neglecting ew penguins, $A(B^+ \to h^+h^0)$ is pure tree
  - Triangles with common base side
  - Determination of shift $\to$ $\kappa^{+-} = 2(\alpha_{\rm eff} - \alpha)$
  - A^{00} and $\bar{A}^{00}$ small $\to$ κ^{+-} small



CP Asymmetries in $B^0 \to \pi^+\pi^-$

- Same analysis methodology as always
  - ▷ $\mathcal{B}(B^0 \to \pi^+\pi^-) = 5.0 \times 10^{-6}$

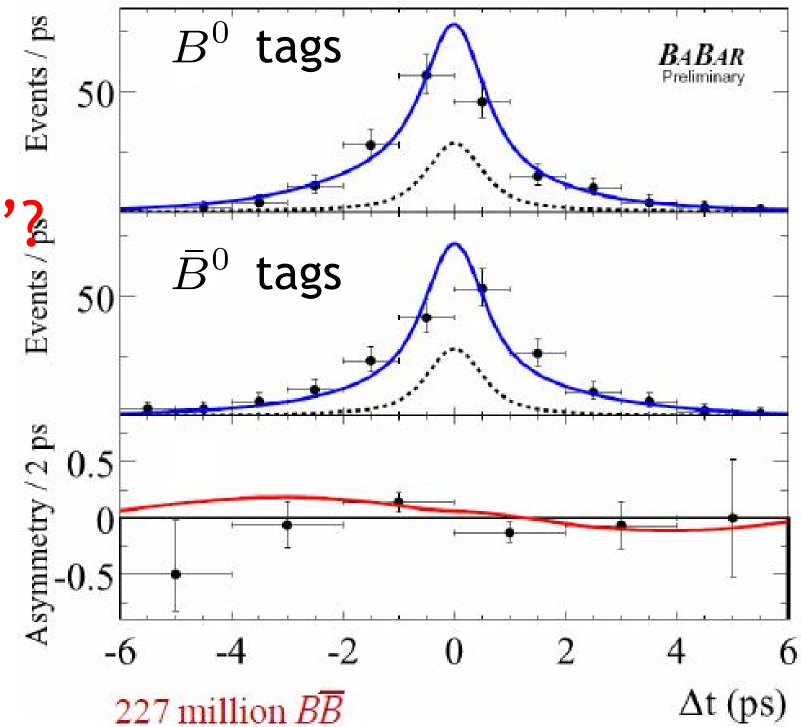
$$\begin{aligned} N_{sig} &= 467 \pm 33 \\ S_{\pi\pi} &= -0.30 \pm 0.17 \pm 0.03 \\ C_{\pi\pi} &= -0.09 \pm 0.15 \pm 0.04 \end{aligned}$$



- From this extract

$$\alpha_{\rm eff} = 99\,^{+5}_{-2}\,{}^\circ$$

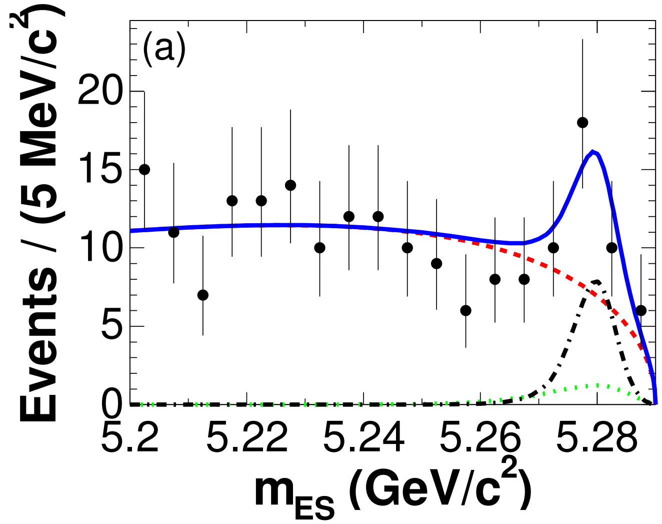
- How large is ‘penguin contribution’?
  - ▷ $P/T \sim 30\%$



$B^0 \to \pi^0\pi^0$: Penguins in $B^0 \to \pi^+\pi^-$

- Observation of 'large' signal (5.0σ)

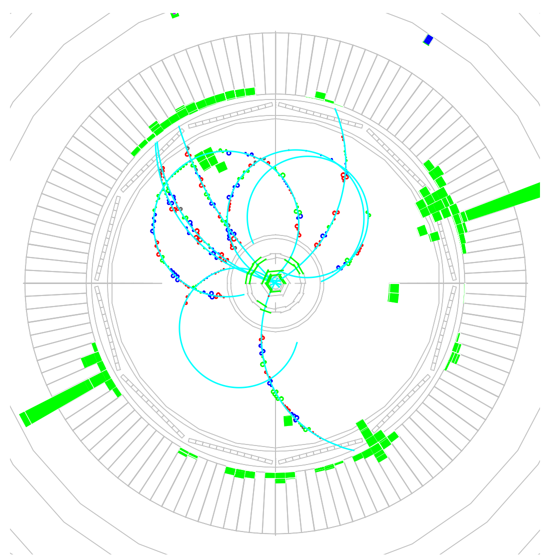
$$N_{sig} = 61 \pm 17$$
$$\mathcal{B}(B^0 \to \pi^0\pi^0) = (1.17 \pm 0.32 \pm 0.10) \times 10^{-6}$$

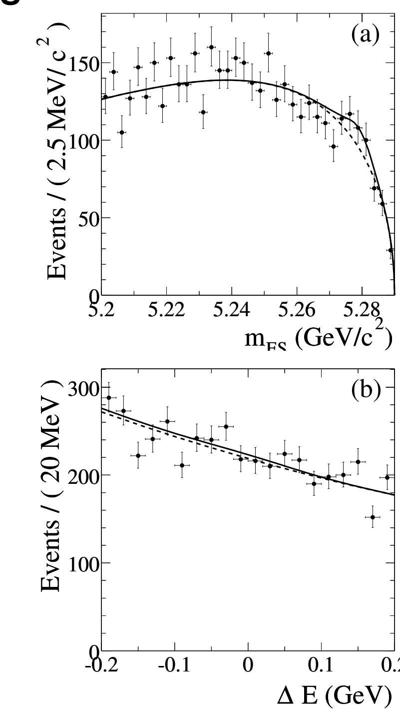


- This is unfortunate
  - ▷ too large for useful bound
  - ▷ too small for isospin analysis

$\Rightarrow$ Penguins substantial
  - ▷ See also later in $B^0 \to K^+\pi^-$

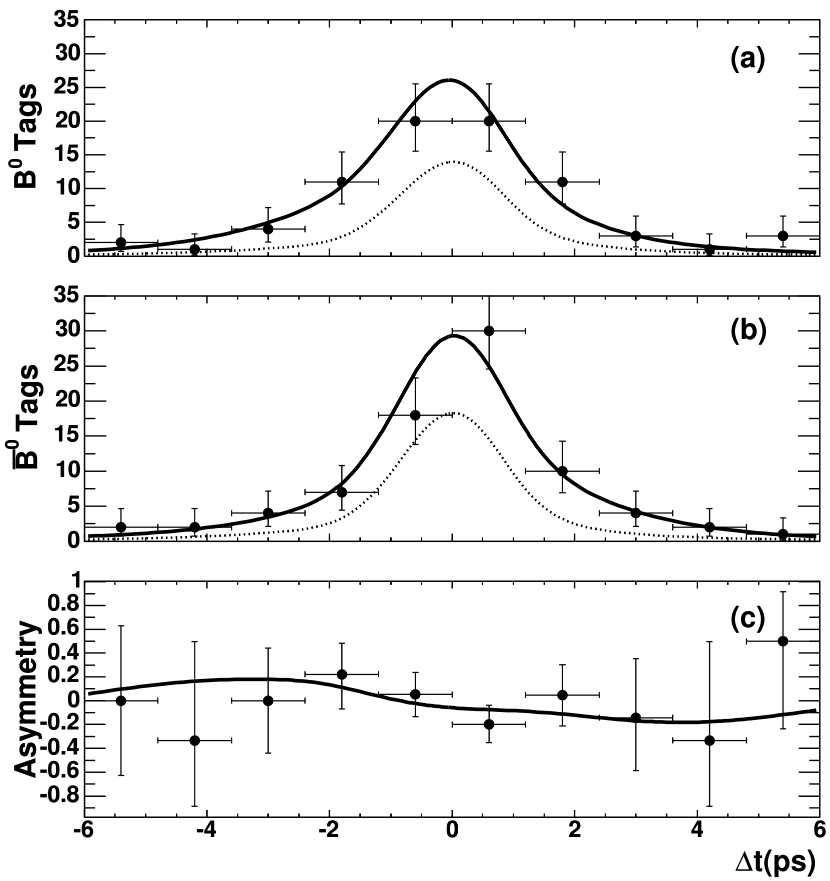
$\Rightarrow$ Experimental problems
  - ▷ Merged π^0
  - ▷ Radiative Bhabhas 'afterglow'





α from $B \to \rho^+\rho^-$?

- At quark level, same diagrams like $B \to \pi^+\pi^-$
  - ▷ ρ is vector particle (π pseudoscalar)
  - ▷ Decays: $\rho^0 \to \pi^+\pi^-$, $\rho^+ \to \pi^+\pi^0$
  - ▷ Larger branching fractions $\mathcal{B}(B^0 \to \rho^+\rho^-) = 26.2 \times 10^{-6}$
  - ▷ More difficult charged measurements: $B^0 \to \pi^+\pi^-$ vs. $B^0 \to \rho^+\rho^-$
  - ▷ Easier neutral measurements: $B^0 \to \pi^0\pi^0$ vs. $B^0 \to \rho^0\rho^0$



- Complications:
  - ▷ Penguins large?

    $\longrightarrow$ measure $\mathcal{B}(B^0 \to \rho^0\rho^0)$
  - ▷ Vector-Vector final state: Not a CP eigenstate a priori (Dilution of asymmetry)

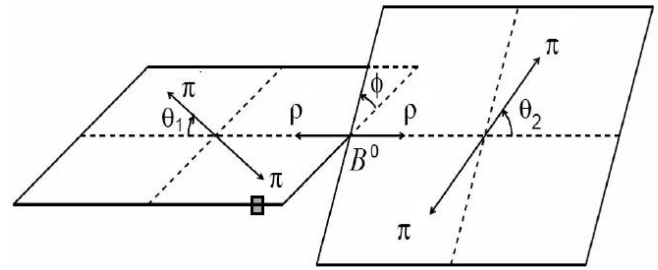
    $\longrightarrow$ measure polarization

α from $B \to \rho^+\rho^-$!

- Angular analysis to determine CP contents

$$f_L(\rho^+\rho^-) \quad = \quad 0.978 \pm 0.014\,^{+0.021}_{-0.029}$$

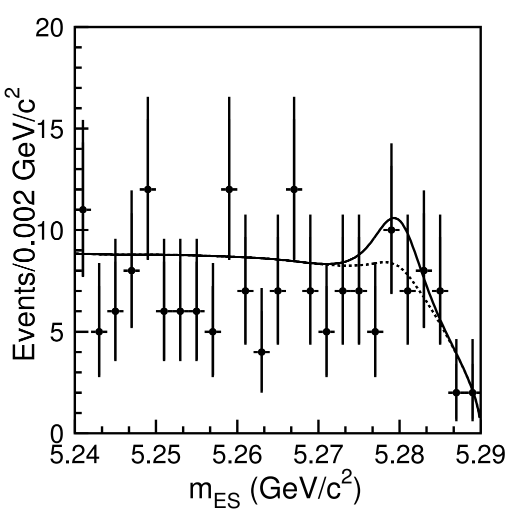
Pure CP-even final state

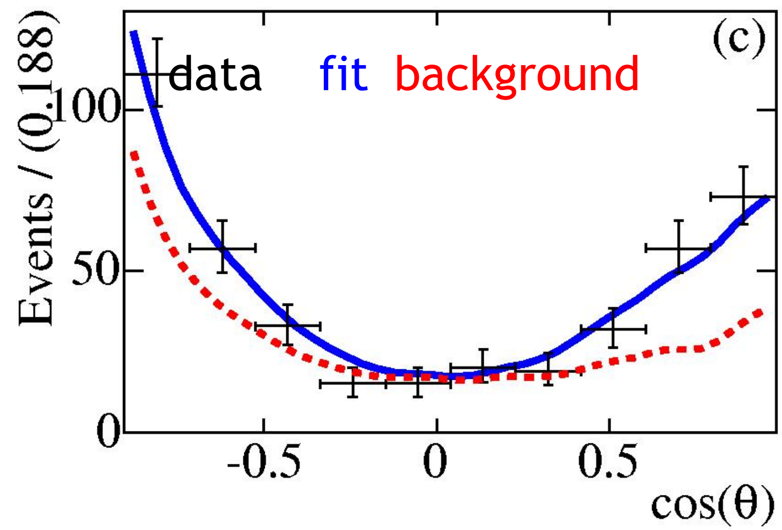


$$\frac{d^2N}{d\cos\theta_1 d\cos\theta_2} \propto f_L \cos^2\theta_1 \cos^2\theta_2 + \tfrac{1}{4}(1 - f_L)\sin^2\theta_1 \sin^2\theta_2$$

- Search for $B^0 \to \rho^0\rho^0$

$$\mathcal{B}(B^0 \to \rho^0\rho^0) \quad = \quad (0.54\,^{+0.36}_{-0.32} \pm 0.19) \times 10^{-6}$$
$$< \quad 1.1 \times 10^{-6} \quad (90\%\mathrm{CL})$$

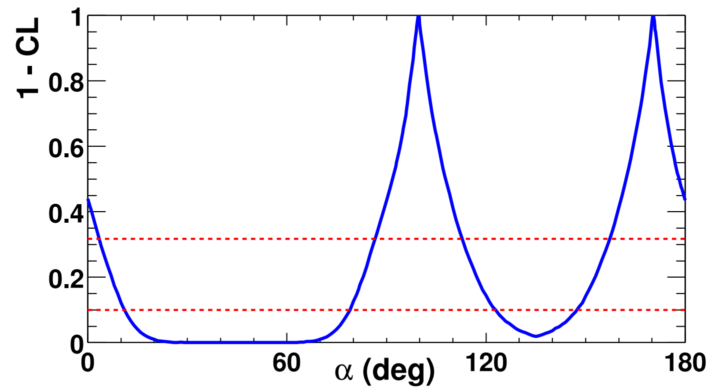




α: Results

- Penguins

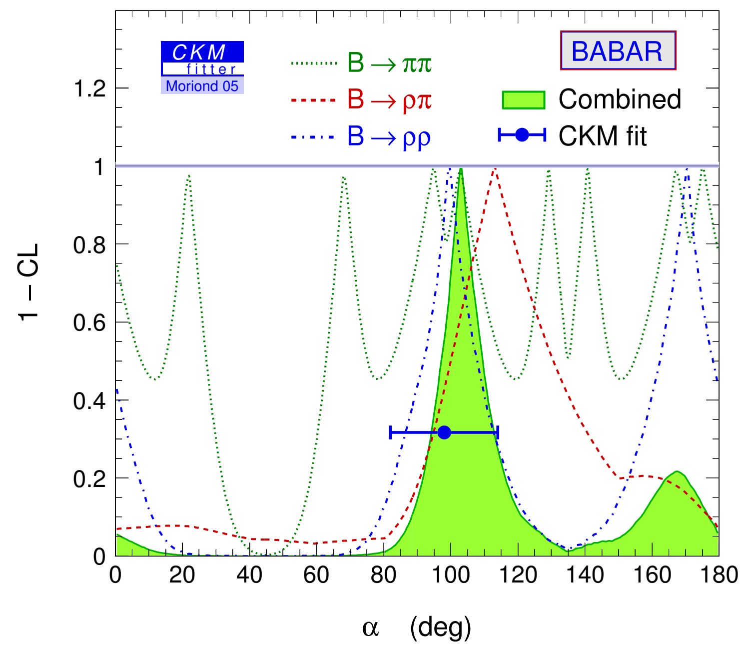
$$|P/T| = 0.07^{+0.14}_{-0.07}$$
$$|\alpha - \alpha_{\rm eff}| < 11^\circ (90\% \rm CL)$$



- Result

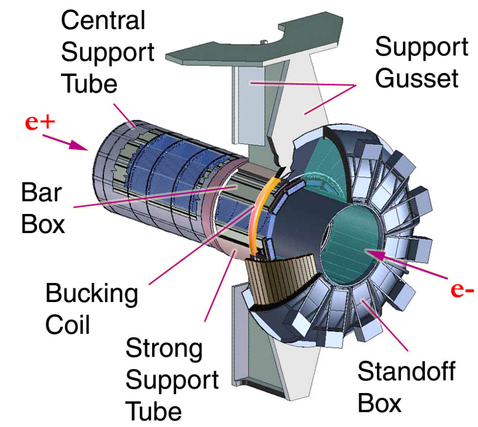
$$\alpha = 100 \pm 13^\circ$$

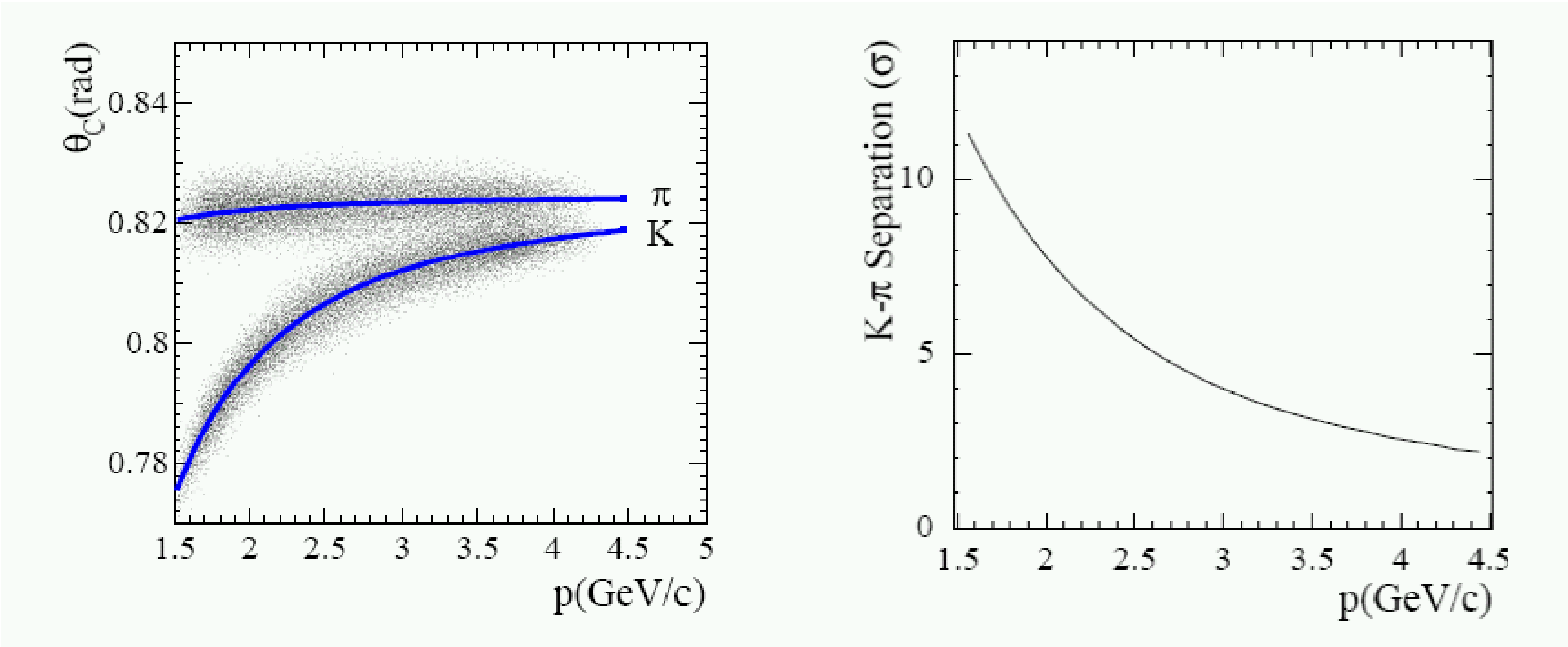
- Error dominated by 11° penguin uncertainty from $\mathcal{B}(B^0 \to \rho^0\rho^0)$
  - ▷ Will improve with more data and measurement of $B^0 \to \rho^0\rho^0$
- Variations on α
  - ▷ Combined α: $\alpha = 100^{+10}_{-11}{}^\circ$
  - ▷ CKM fit: $\alpha = 98 \pm 16^\circ$
  - ▷ CKM + combined: $\alpha = 99^{+6}_{-7}{}^\circ$



Hadronic Particle Identification

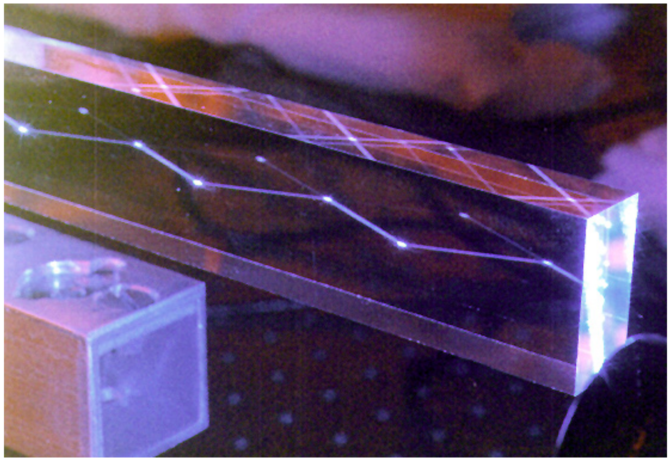
- Discrimination between K^+ and π^+ essential
- Cherenkov radiation $\longrightarrow$ DIRC
  - ▷ $\cos\theta_C = 1/n\beta$
  - ▷ 'Detection of internally reflected Cherenkov' light
- Driftchamber dE/dx

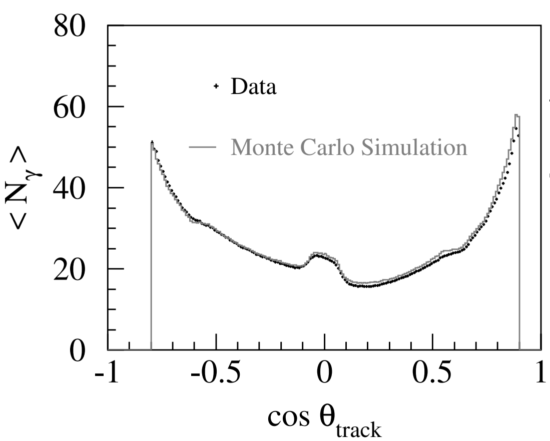


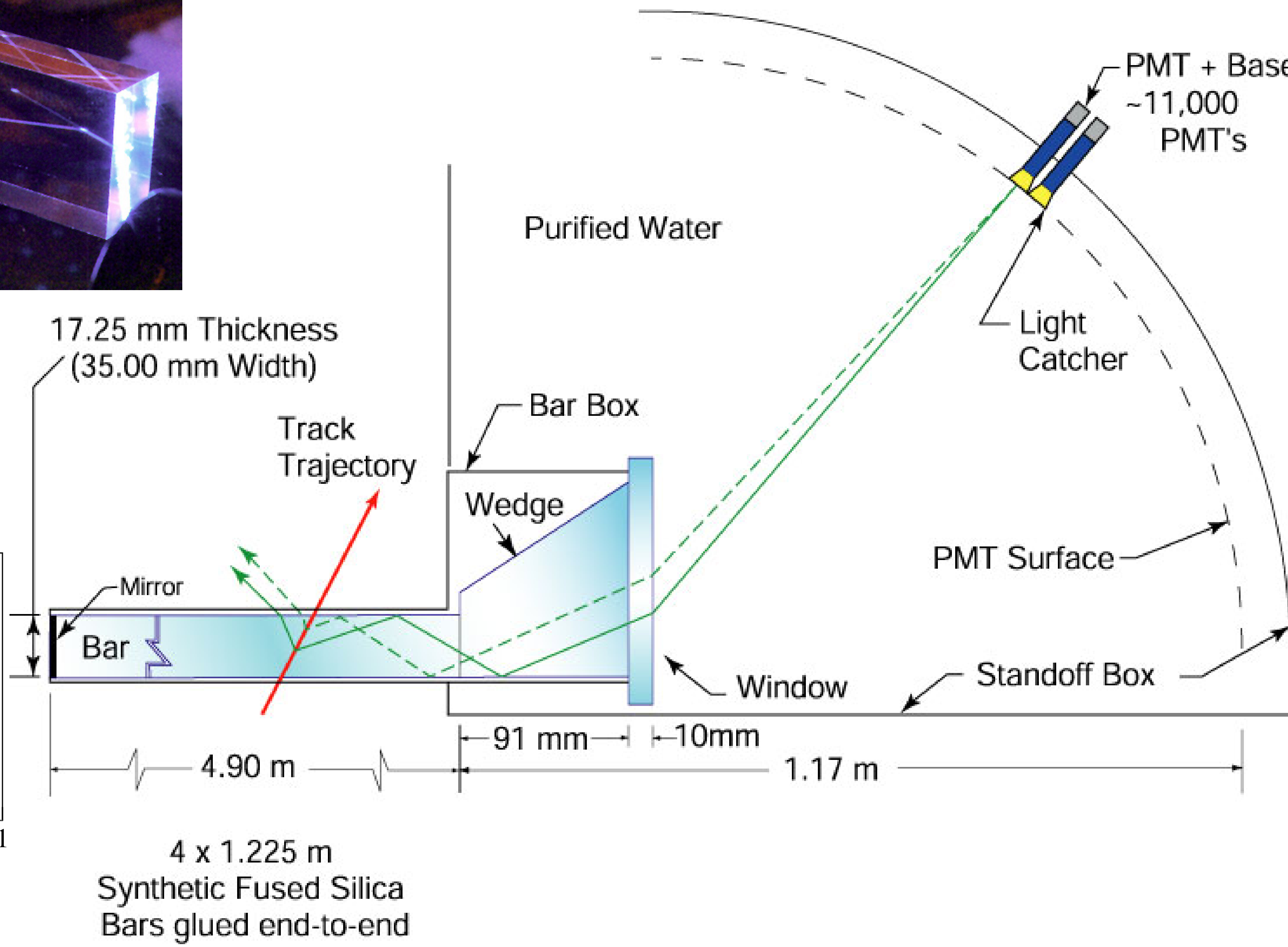


The DIRC

NIM A 538 (2005) 281

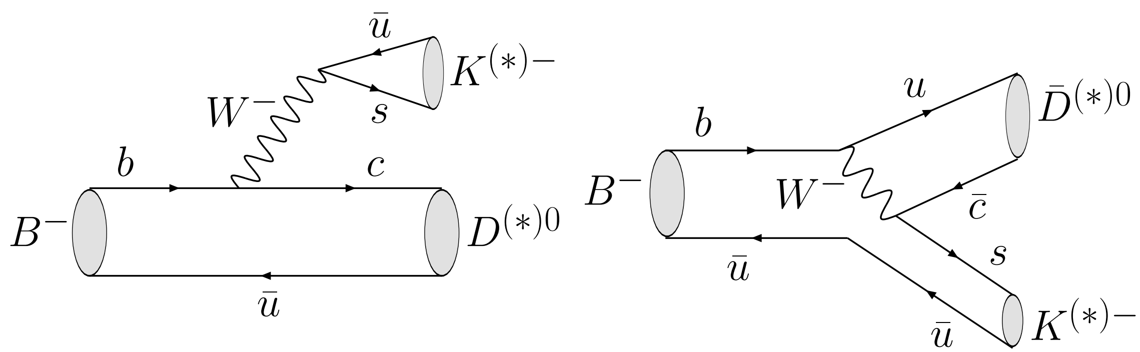






The Determination of γ

- At B-factories, (at least) two avenues to γ:
  - ▷ $B^0 \to D^+\pi^-$: $A_{CP} \propto r \sin(2\beta + \gamma)$
  - ▷ $B^- \to D^0 K^-$: $A_{CP} \propto r_B \sin\gamma \sin\delta_B$
- Time-independent: direct CP violation in B^+ decays
  - ▷ Tree decays!



  - ▷ with relative amplitude r_B, weak phase γ, strong phase δ_B
- For interference, choose decays where $D^0, \bar{D}^0 \to f$
- Critical parameter $r_B = \frac{A(b\to u)}{A(b\to c)}$
  - ▷ CKM and color suppression

If r_B small $\to$ little sensitivity to γ

Gronau, London, PLB 253, 483
Gronau, Wyler, PLB 265, 172

GLW — Gronau, London, Wyler

- Theoretically very clean (no penguins)
  - ▷ reconstruction of $D \to K^+K^-, \pi^+\pi^-$ $(CP = +1)$
    $D \to K_S\pi^0, K_S\omega, K_S\phi$ $(CP = -1)$
  - $\longrightarrow$ small effective branching fractions $\mathcal{O}(10^{-7})$
- 4 observables: Asymmetries and ratio of branching fracions

$$R_{CP\pm} = \frac{\Gamma(B^- \to D_\pm K^-) + \Gamma(B^+ \to D_\pm K^+)}{(\Gamma(B^- \to D^0 K^-) + \Gamma(B^+ \to \bar{D}^0 K^+))/2} = 1 + r_B^2 \pm 2 r_B \cos\delta_B \cos\gamma$$

$$A_{CP\pm} = \frac{\Gamma(B^- \to D_\pm K^-) - \Gamma(B^+ \to D_\pm K^+)}{\Gamma(B^- \to D^0 K^-) + \Gamma(B^+ \to \bar{D}^0 K^+)} = \frac{\pm 2 r_B \sin\delta_B \sin\gamma}{R_{CP\pm}}$$

  - ▷ Three are independent $(A_{CP+}R_{CP+} = -A_{CP-}R_{CP-})$
- Not enough statistics yet

  $N_{CP+} = 37.6 \pm 7.4$
  $N_{CP-} = 14.8 \pm 5.9$

GGSZ, PR, D68, 054018 (2003)

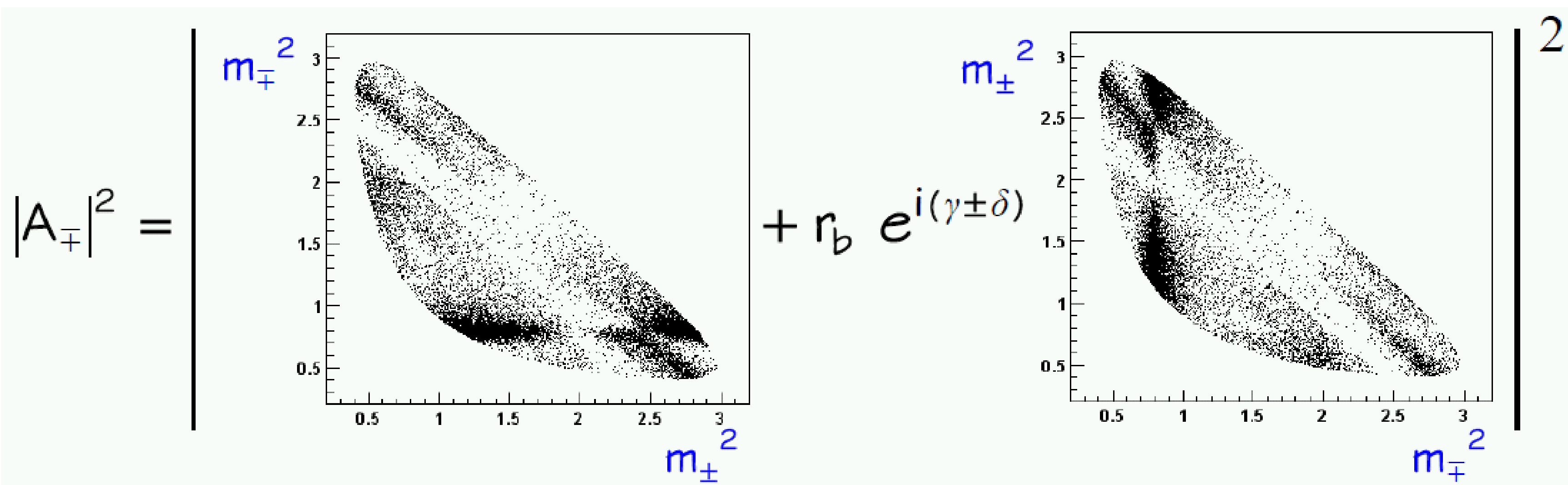
Time-dependent $D^0 K_S$ Dalitz Analysis

- In $B^+ \to D^0 K^+$ decays: study $D^0 \to K^0_S \pi^+ \pi^-$
- The amplitudes for B decay are written as

$$A(B^\pm) = \underbrace{f(m^2_\pm, m^2_\mp)}_{b\to c} + \underbrace{r_B e^{i(\delta \pm \gamma)} f(m^2_\mp, m^2_\pm)}_{b\to u}$$

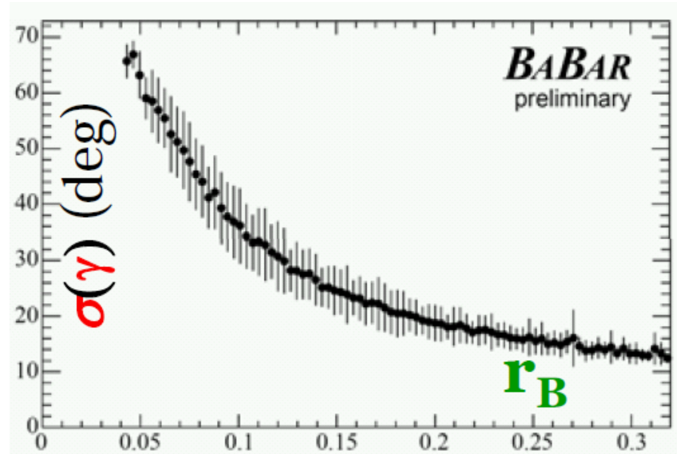
  - ▷ $f(m^2_\pm, m^2_\mp)$ decay amplitude $A(\bar{D}^0 \to K_S \pi^+ \pi^-)$
  - ▷ Dalitz variables $m^2_\pm = m^2_{K_S \pi^\pm}$

- Symbolically:



γ: Results

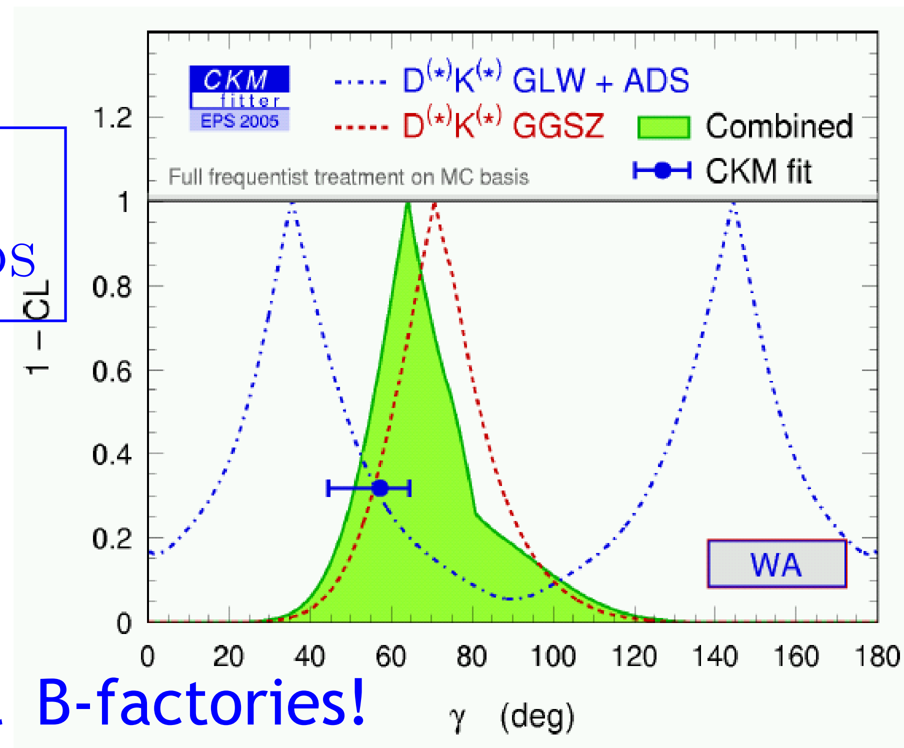
- More statistics than for GLW:
  - $B^- \to D^0 K^-$: $N_{\rm SIG} = 282 \pm 20$
  - $B^- \to D^{*0} K^-$: $N_{\rm SIG} = 133 \pm 14$



- Complications:
  - form of D^0 decay models
  - error depends on r_B
  - BABAR: $r_B = 0.12 \pm 0.08$
    BELLE: $r_B = 0.21 \pm 0.08$

$$\gamma = 67 \pm 28 \pm 13 \pm 11^\circ \quad \text{GGSZ}$$
$$= 51^{+23}_{-18}{}^\circ \quad \text{GGSZ + GLW + ADS}$$

- Combination of
  - BABAR GGSZ
  - GLW/ADS World average
- Expect $\sigma(\gamma) \sim 10^\circ$ in 2008
- No average by HFAG yet



- Very remarkable: Not foreseen at B-factories!

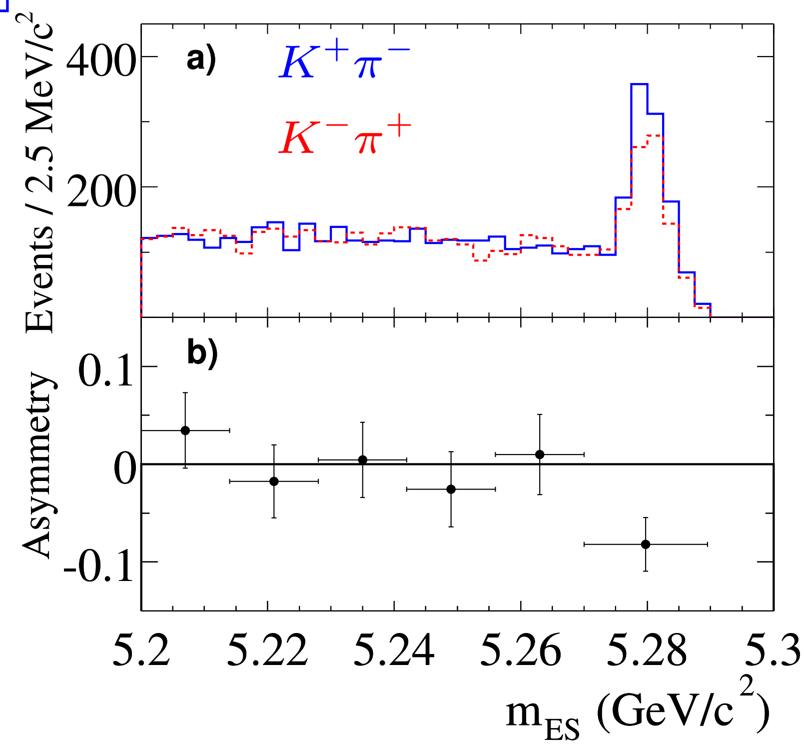
γ: An Alternative?

- Observation (4.2σ) of direct CP-violation in $B^0 \to K^+\pi^-$

$$A_{CP}^{K\pi} = \frac{n_{K^-\pi^+} - n_{K^+\pi^-}}{n_{K^-\pi^+} + n_{K^+\pi^-}} = -0.133 \pm 0.030 \pm 0.009 (BABAR) = -0.115 \pm 0.018 (W.A.)$$

- Simple counting experiment
  - ▷ once you understand charge-dependence of PID
- Sensitive to γ:
  - ▷ $A_{CP}^{K\pi} \propto \sin\gamma \sin\delta$
- For strong phase δ use
  - ▷ $\mathcal{B}(B^+ \to \pi^+ K_S)$
  - ▷ $\mathcal{B}(B^+ \to \pi^0 K^+)$
  - ▷ $\mathcal{B}(B^+ \to \pi^+ \pi^0)$

  and some theoretical input. But: Errors??



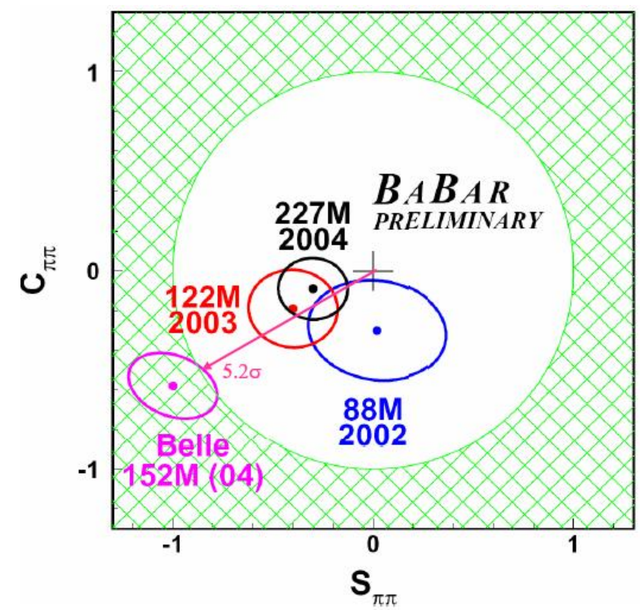
Direct CP violation: Another instance

- Belle claimed

$$S_{\pi\pi} = -1.00 \pm 0.21 \pm 0.07$$
$$C_{\pi\pi} = -0.58 \pm 0.15 \pm 0.07$$

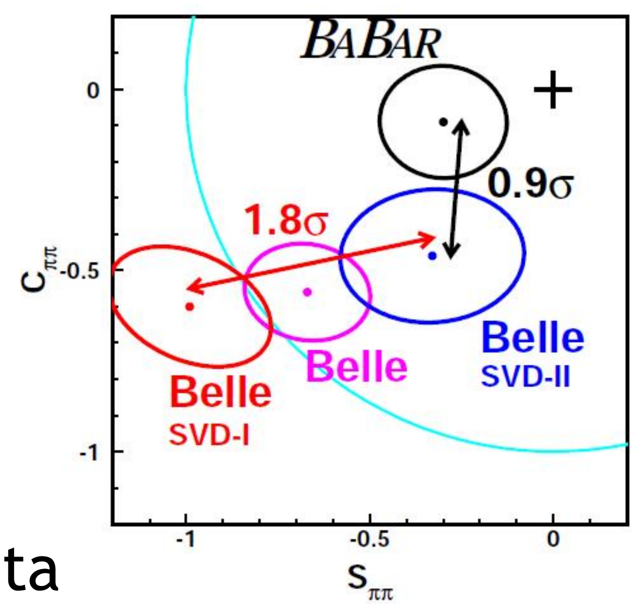
and recently

$$S_{\pi\pi} = -0.67 \pm 0.16 \pm 0.06$$
$$C_{\pi\pi} = -0.56 \pm 0.12 \pm 0.06$$



- This implies
  - ▷ large $|P/T| \sim 1$
  - ▷ large strong phases
  - ▷ possibly new physics

- *BABAR* sees nothing of this
  - ▷ New Belle measurement more consistent with *BABAR* result than with old Belle result

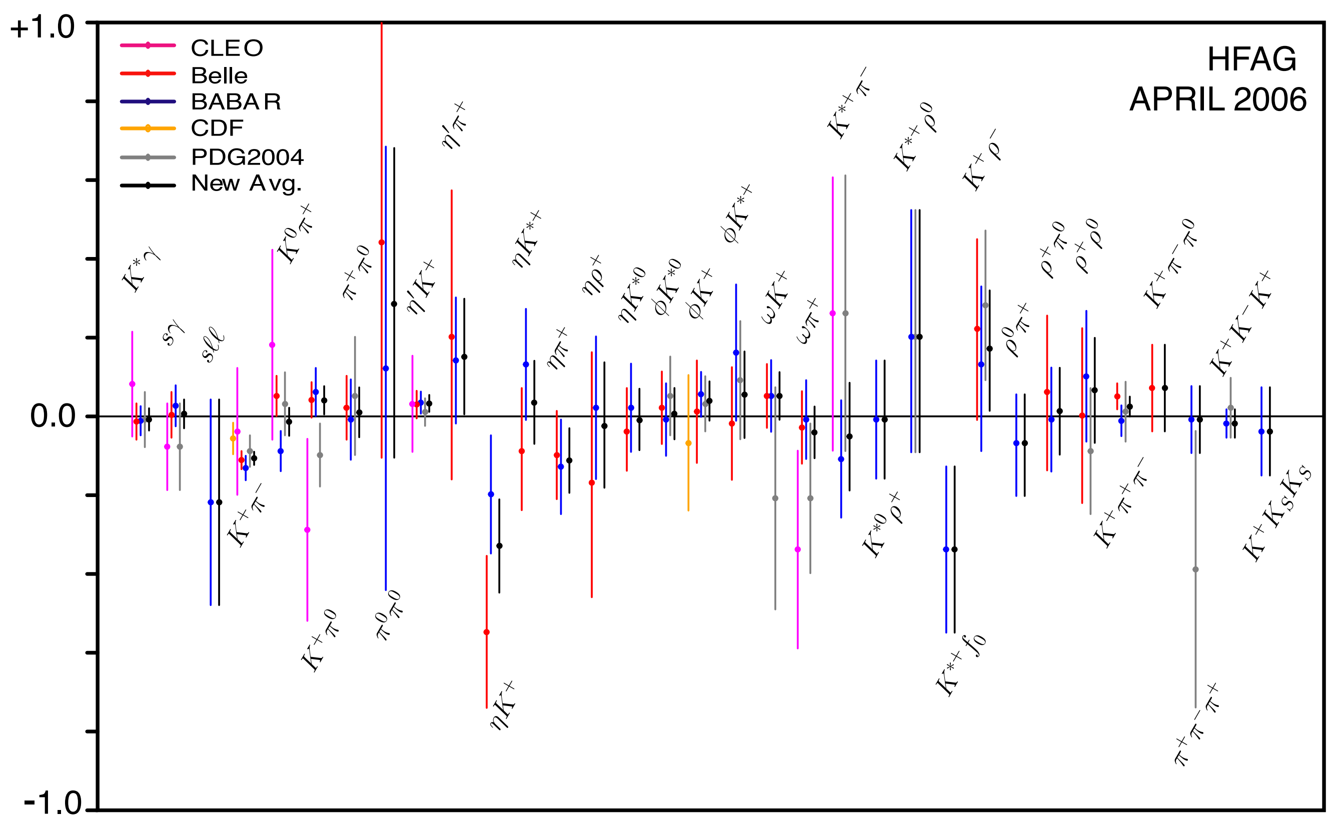


- Discrepancy at 3σ . . . need more data

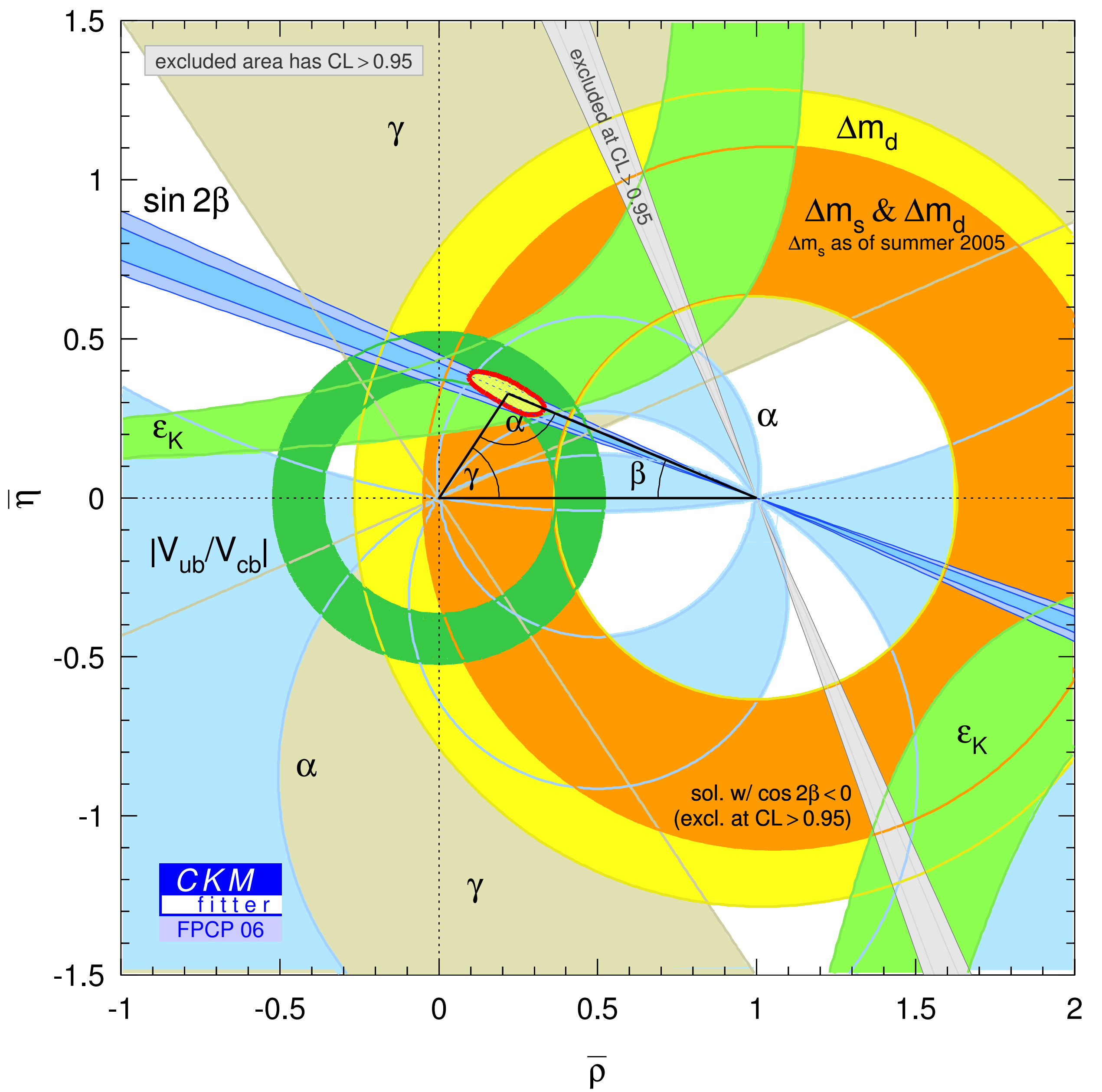
Even more CP-Asymmetries

- No extraction of weak phase
- Probe for new physics in modes with small SM expectation
  - ▷ decays dominated by one weak phase, *e.g.*, the Penguin-dominated decays $b \to s\gamma$, $B \to K^{(*)}\ell^+\ell^-$

CP Asymmetry in Charmless B Decays

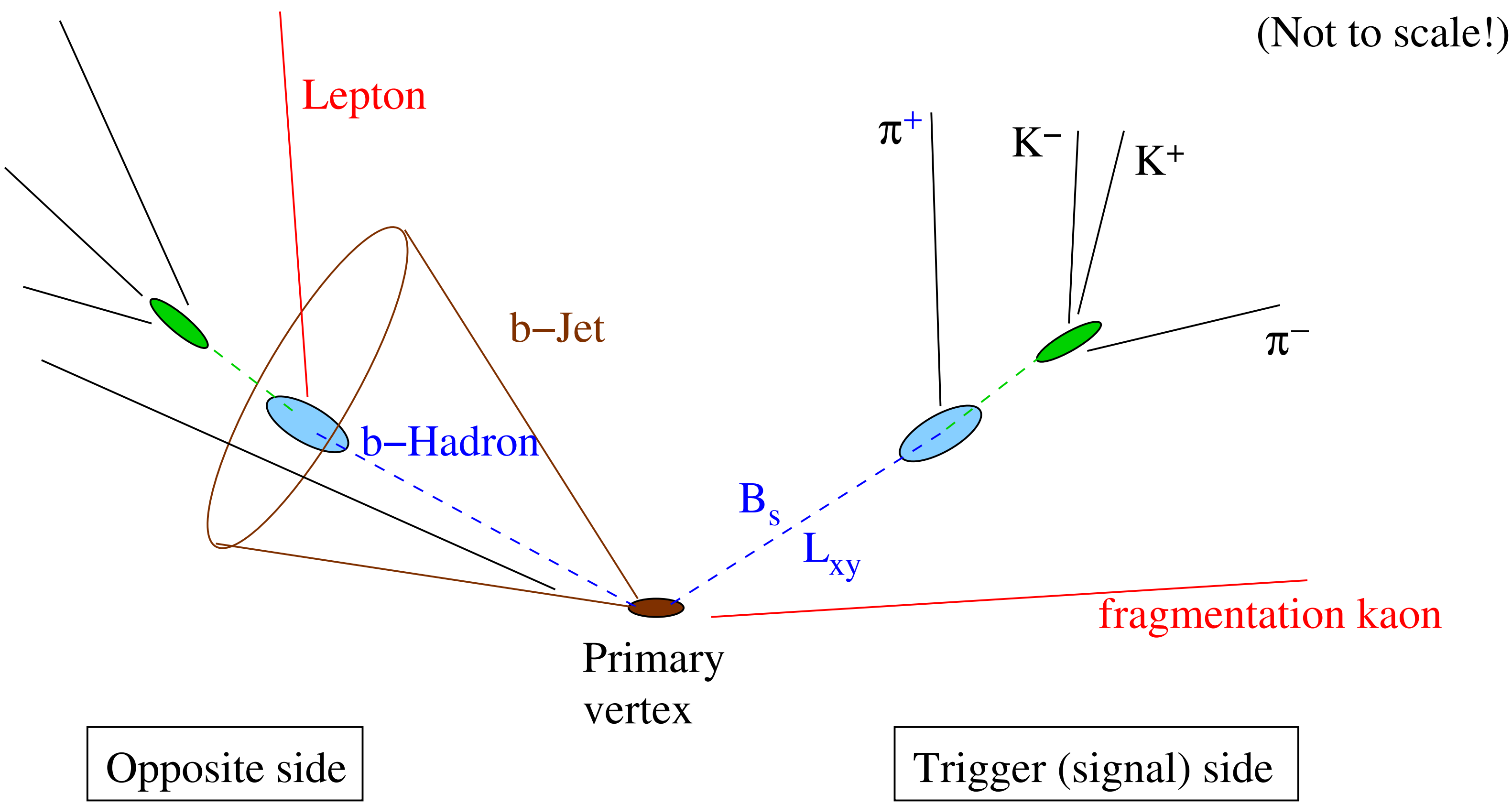


The big picture



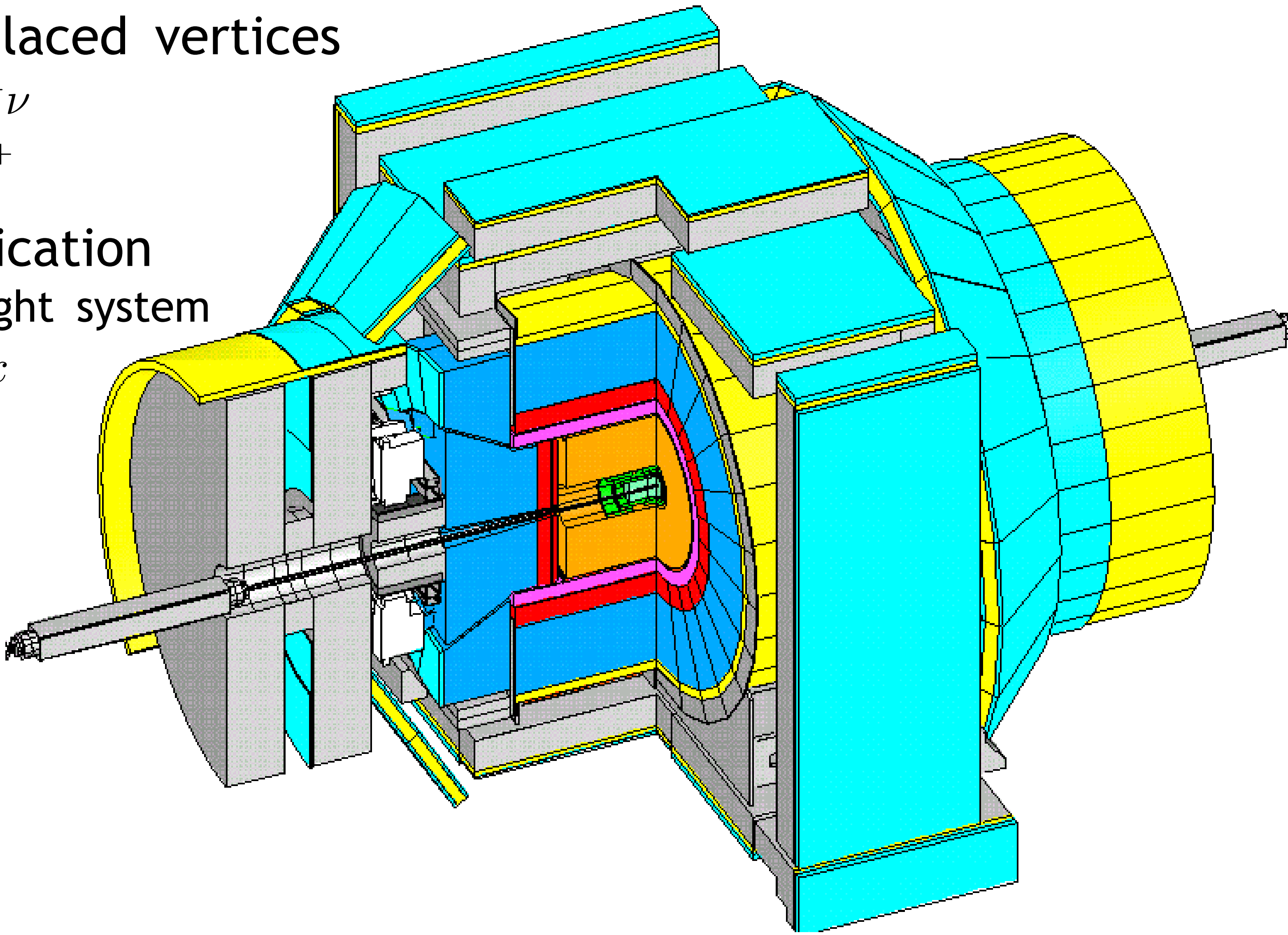
B_s Mixing Measurement Principle

- Measure B_s decay
  - $\longrightarrow$ decay flavor from decay products
  - $\longrightarrow$ decay length $l = t_{lab}\beta c = t\beta\gamma c = t\frac{p}{m}$
- Determine B_s production flavor



CDF Detector

- Luminosity $\mathcal{L} > 1\,\text{fb}^{-1}$
- Trigger: displaced vertices
  - ▷ $B_s \to D_s^+ \ell^+ \nu$
  - ▷ $B_s \to D_s^+ \pi^+$
- Kaon identification
  - ▷ Time-of-Flight system
  - ▷ DCH dE/dx
  - ▷ $p \leq 1.5\,$GeV



Mixing Measurement Significance

- The significance

$$\frac{1}{\sigma} \propto \sqrt{\frac{S}{S+B}} \sqrt{\frac{\varepsilon D^2}{2}} e^{-\sigma_t^2 \Delta m_s/2}$$

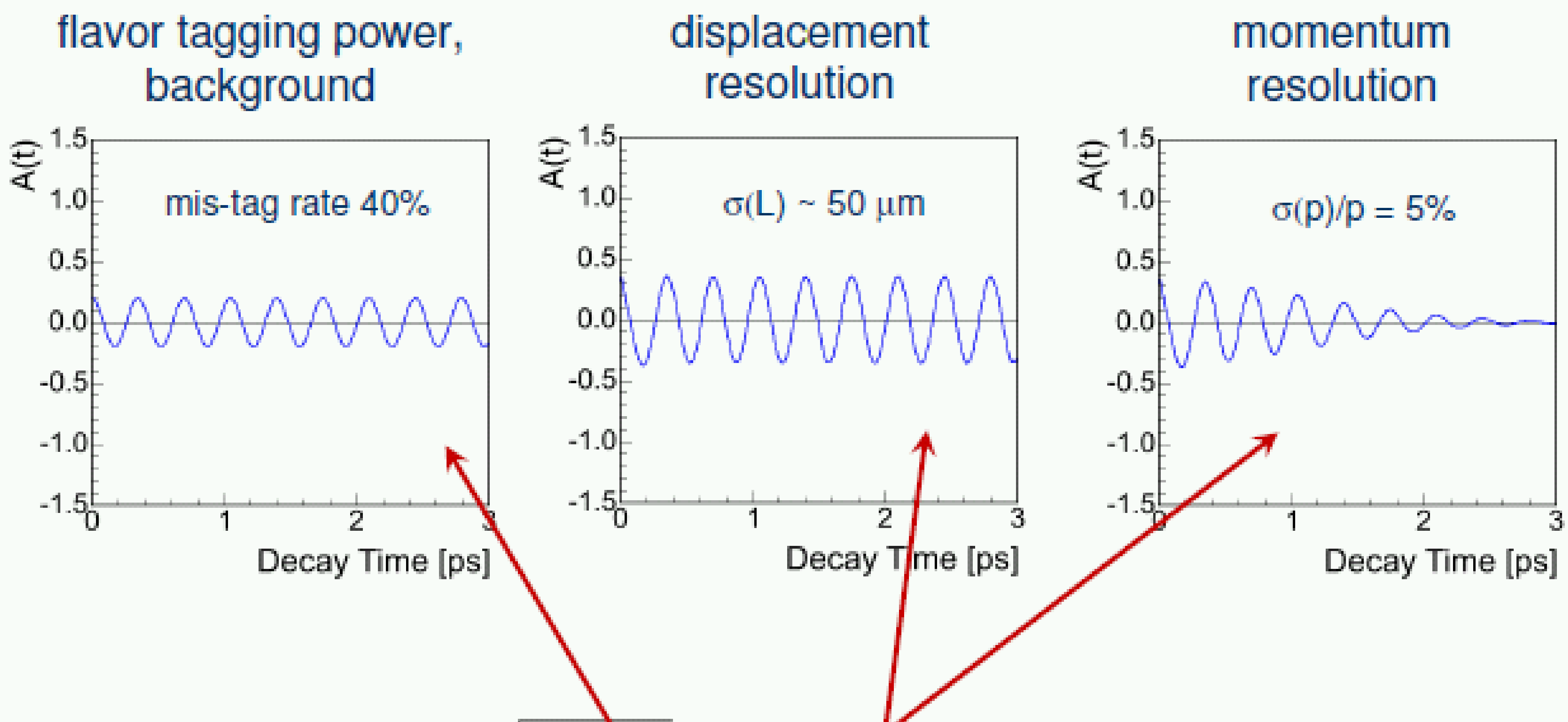
- Statistical power of flavor tagging εD^2
  - ▷ Tagging efficiency ε and dilution $D = 1 - 2w$ (w: mistag probability)

$$\varepsilon = \frac{\text{correct tags} + \text{incorrect tags}}{\text{all events}} \qquad D = \frac{\text{correct tags} - \text{incorrect tags}}{\text{all tags}}$$

  - ▷ Dilution D measures purity: $D = 0(1) \rightarrow$ random (perfect) tagging
  - ▷ Dilution attenuates observed oscillations

$$P(B^0 \to B^0, \bar{B}^0; t) \propto e^{-\Gamma t}(1 \pm D \cos \Delta m t)$$

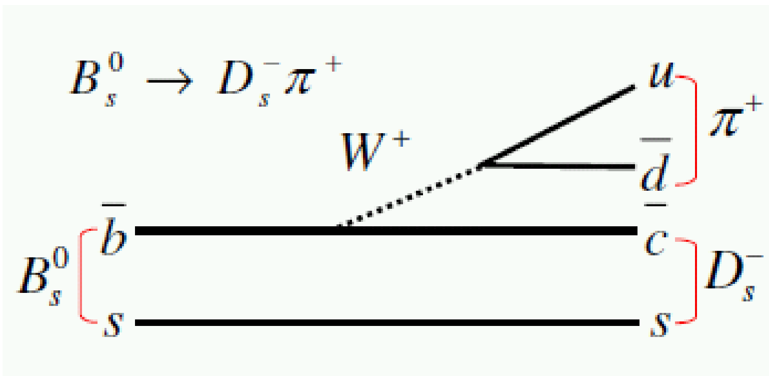
Detector Effects



$$\frac{1}{\sigma} = \sqrt{\frac{S\epsilon D^2}{2}} e^{-\frac{(\Delta m_s \sigma_t)^2}{2}} \sqrt{\frac{S}{S+B}}$$

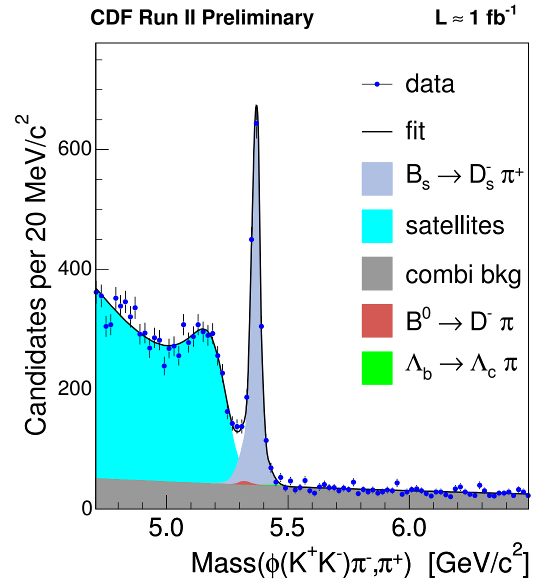
B_s Reconstruction: Hadronic Modes

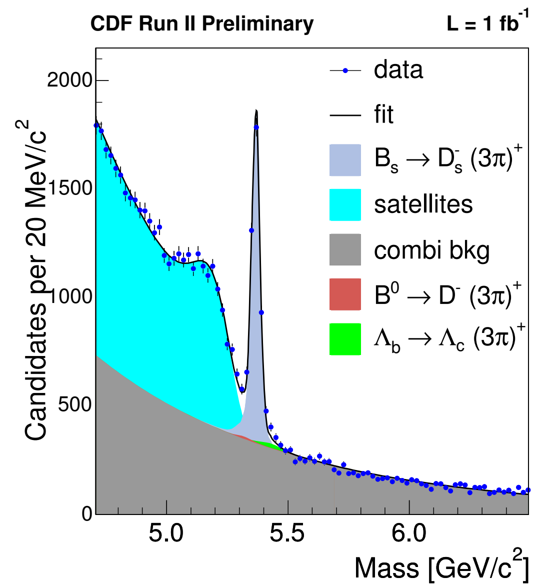
- Hadronic decays
  - ▷ excellent resolution: $p_\perp{}^B$ and vertexing



  - ▷ small statistics

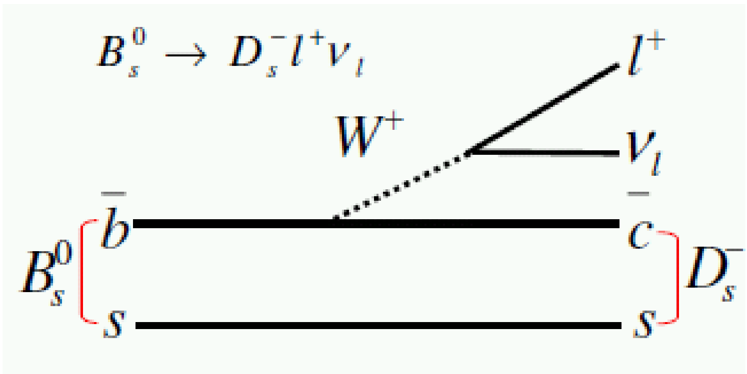
	Yield
$B_s \to D_s\pi$ ($\phi\pi$)	1600
$B_s \to D_s\pi$ ($K^* K$)	800
$B_s \to D_s\,\pi$ (3π)	600
$B_s \to D_s 3\pi$ ($\phi\,\pi$)	500
$B_s \to D_s 3\pi$ ($K^* K$)	200
Total	3700





Semileptonic B_s Reconstruction

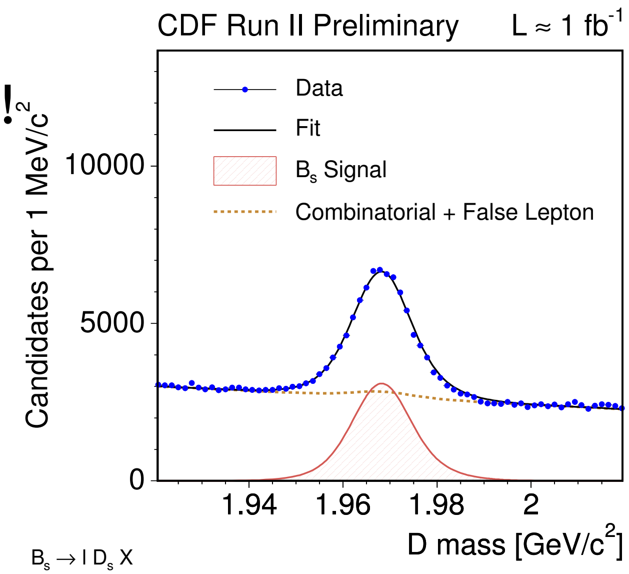
- Semileptonic decays
  - ▷ missing neutrino $\longrightarrow$ unknown B_s momentum!

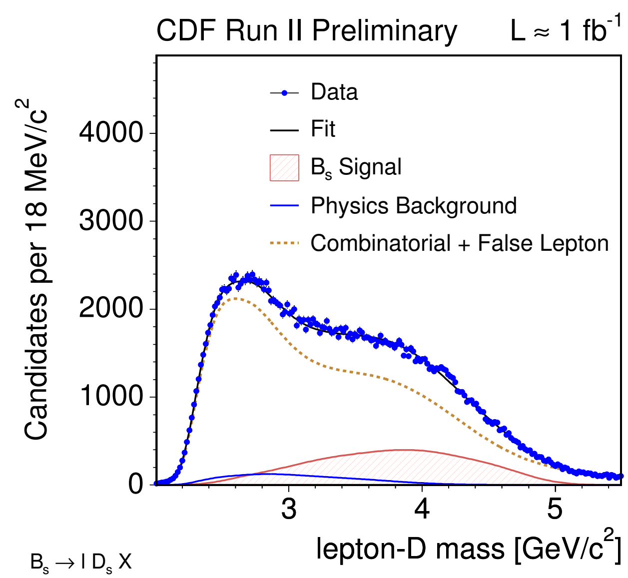


  - ▷ large statistics

ℓD_s: $D_s \to \phi\pi$	32 K
ℓD_s: $D_s \to K^*K$	11 K
ℓD_s: $D_s \to \pi\pi\pi$	10 K

ℓD^0: $D^0 \to K\pi$	540 K
ℓD^{*-}: $D^0 \to K\pi$	75 K
ℓD^-: $D^- \to K\pi\pi$	300 K

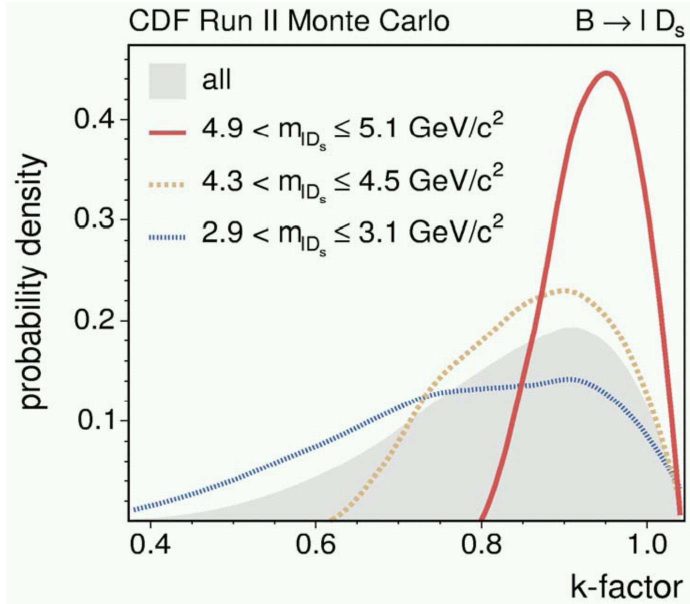




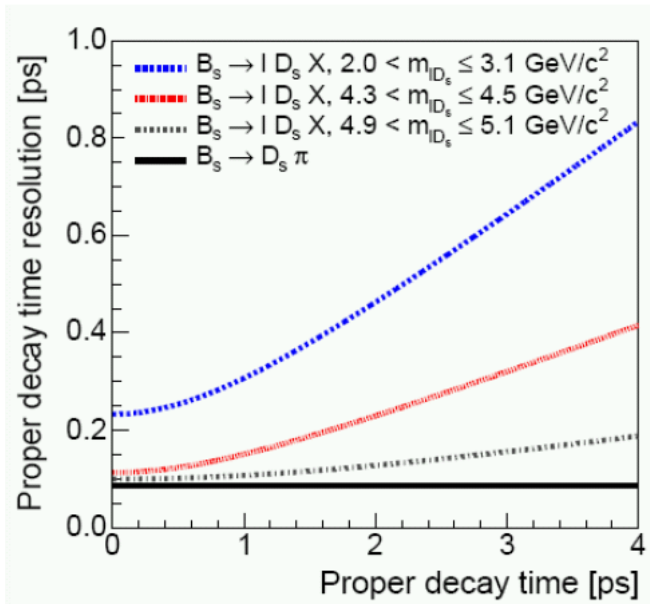
Lifetime Reconstruction

- Lifetime from (proper) decay length
  - ▷ $\vec{p}_B$: daughter tracks 3-momentum
  - ▷ flight length from secondary vertex
  - ▷ in transverse plane
- Semileptonic decays:
  - ▷ Correction with MC-derived k factor

$$t = l_{xy}^{D\ell} \frac{m_B}{p_\perp^{D\ell}} \times k_{MC} \qquad k_{MC} = \frac{l_{xy}^{B}}{l_{xy}^{D\ell}} \frac{p_\perp^{D\ell}}{p_\perp^{B}}$$

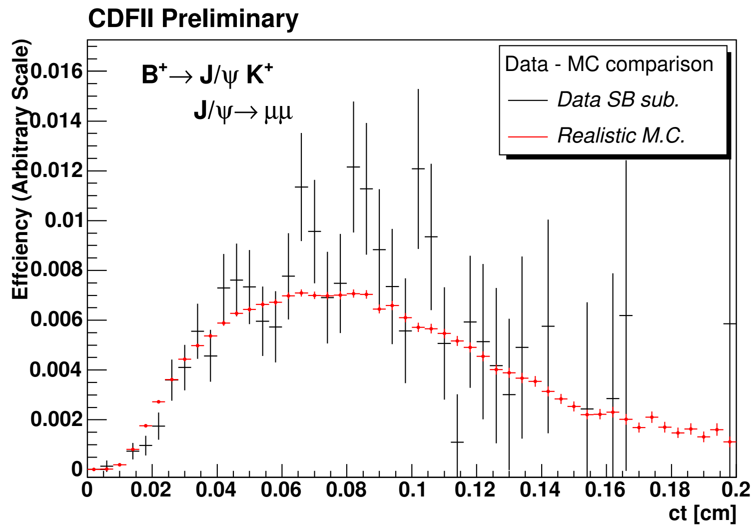


- Decay length resolution
  - ▷ not an issue for lifetime measurements
  - ▷ critical for B_s mixing!



Lifetime Reconstruction II

- Significant distortion of proper time distributions



- Unbinned maximum likelihood fit for τ
  - ▷ signal pdf:

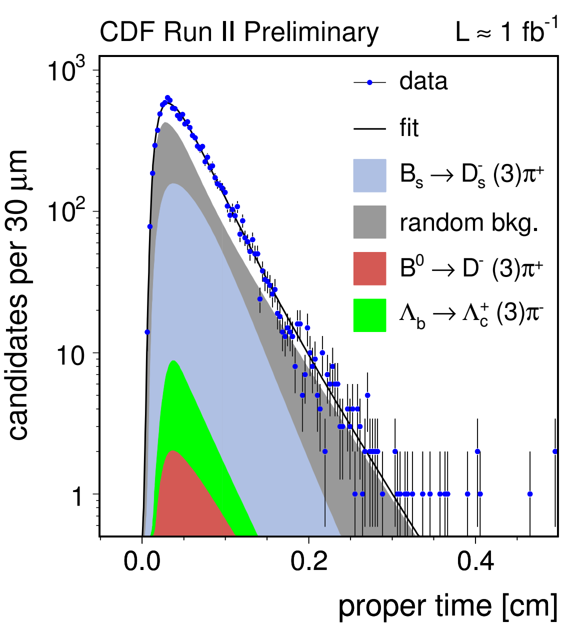
$$P(t) \sim e^{-t'/\tau} \otimes R(t', t) \times \varepsilon(t')$$

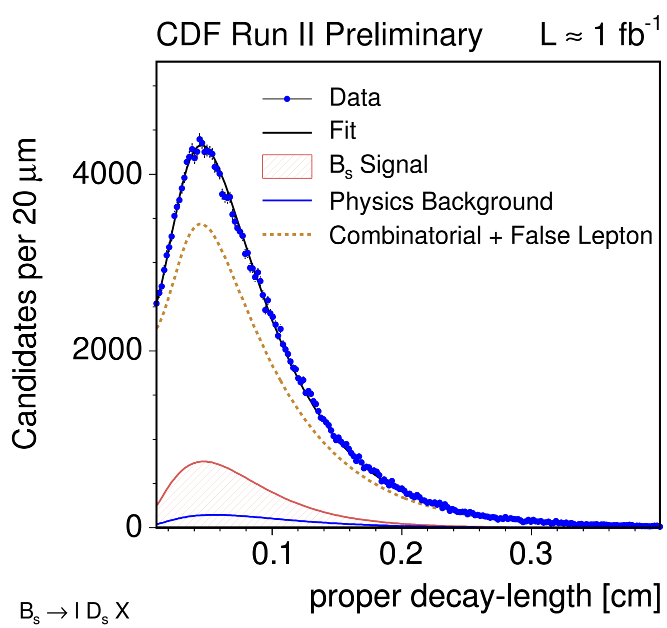
  - ▷ background pdf from data
    sidebands
    wrong-sign decays

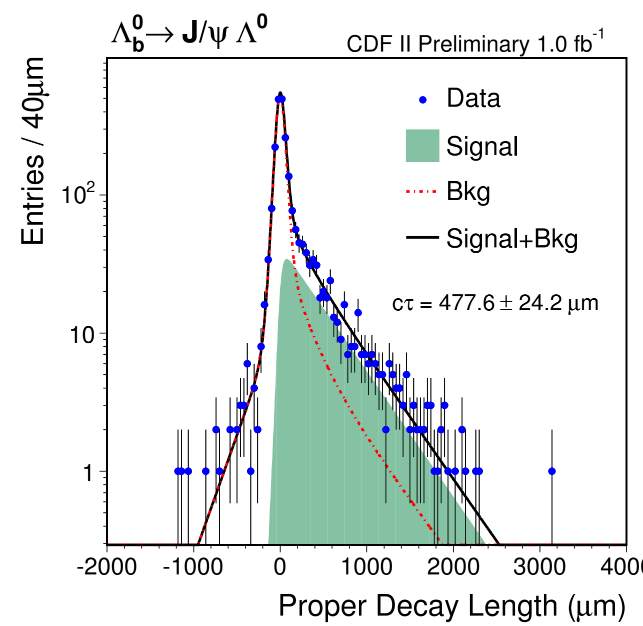
Lifetime Results

- All species can be measured at Tevatron

Mode	CDF [ps]	D0 [ps]
$B_s \to D_s^- \ell^+ \nu$	$1.381 \pm 0.055 \pm 0.050$	$1.398 \pm 0.044 \,^{+0.028}_{-0.025}$
$\Lambda_b \to J/\psi \Lambda$	$1.593 \pm 0.080 \pm 0.033$	$1.22 \pm 0.20 \pm 0.04$
$B_c \to J/\psi e^+ \nu$	$0.463 \pm 0.070 \pm 0.036$	$0.448 \pm 0.115 \pm 0.121$

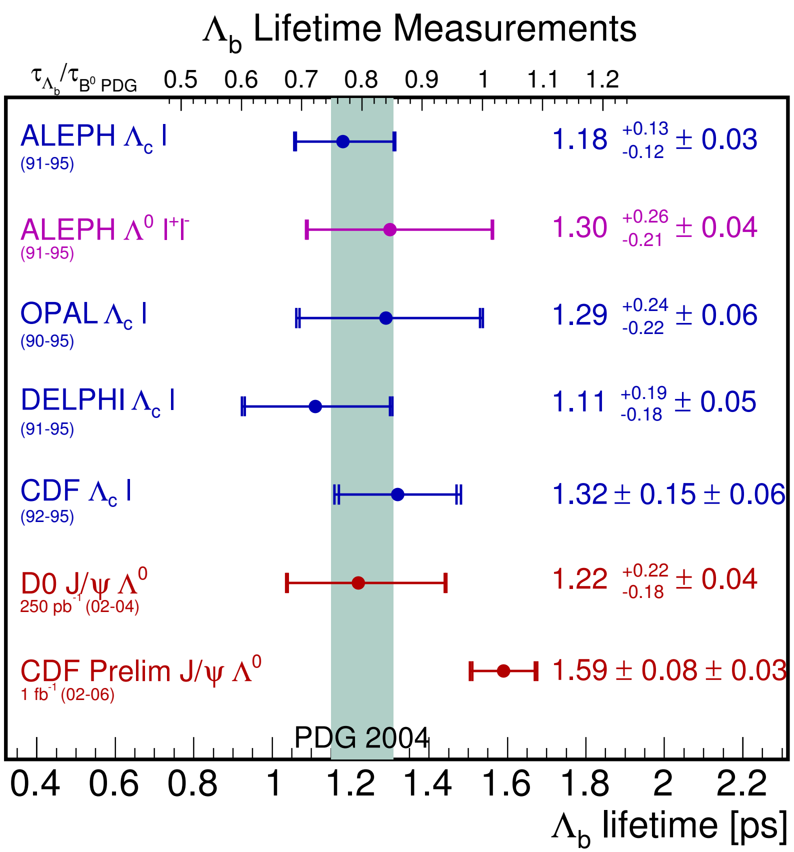


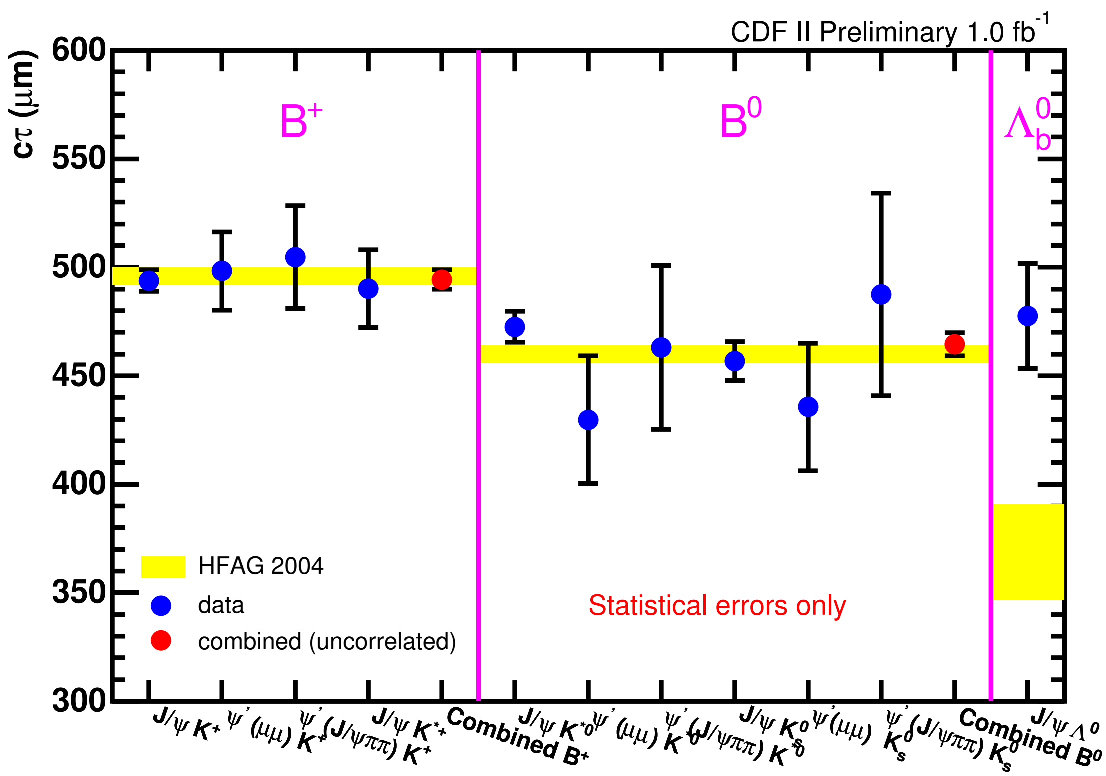




Lifetime Results in Context

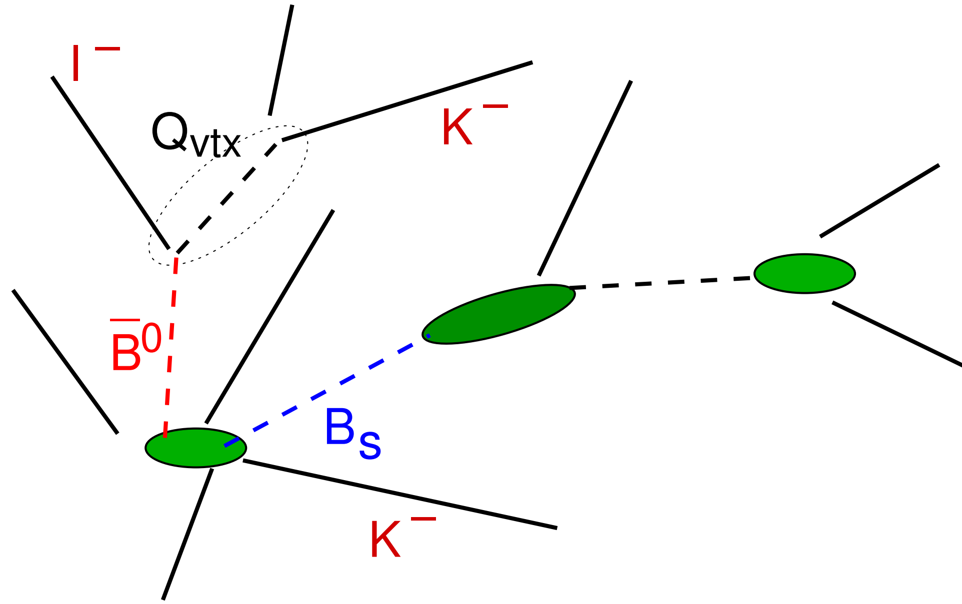
- Very competitive measurements
  - ▷ most analyses use only subset of data

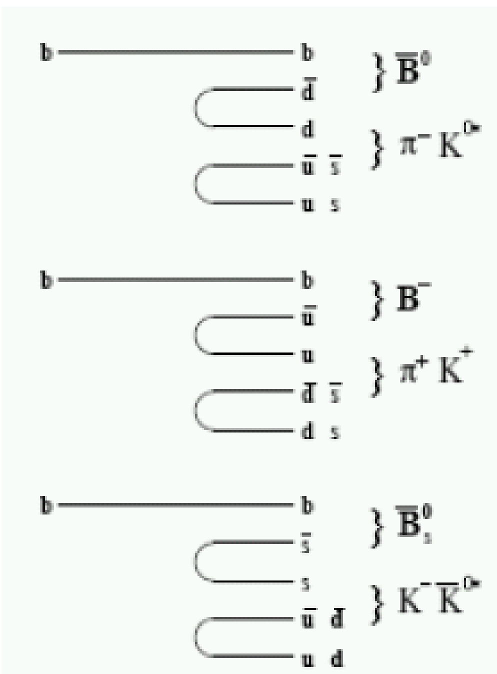




Hadron Collider Flavor Tagging

- Opposite side
  - ▷ SLT — soft lepton tagger
  - ▷ JETQ — jet charge tagger
- Same side
  - ▷ SS(K)T — same side (kaon) tagger





- Total Performance:

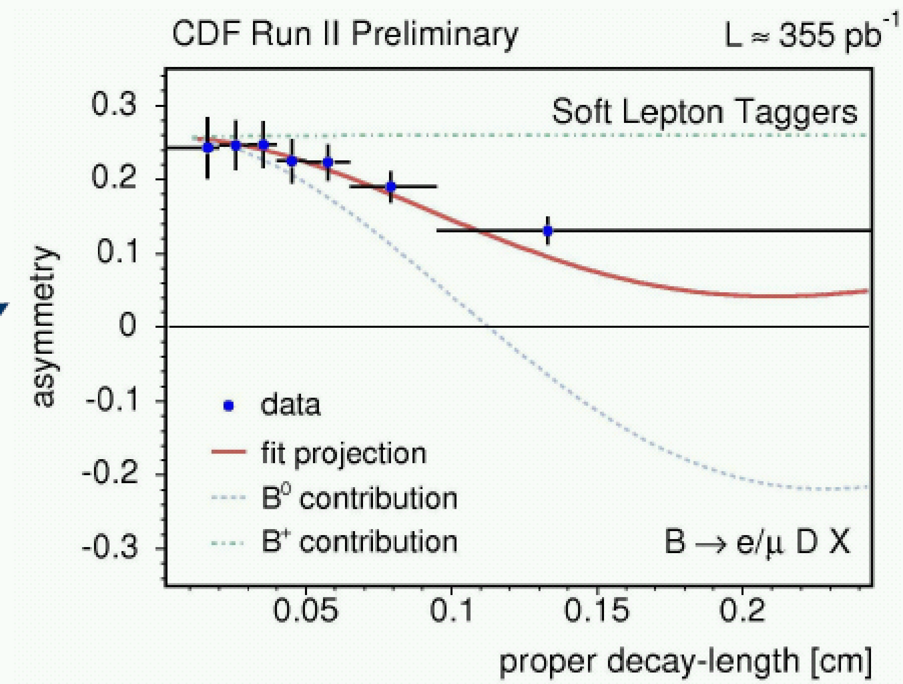
	εD² Hadronic (%)	εD² Semileptonic (%)
Muon	0.48 ± 0.06 (stat)	0.62± 0.03 (stat)
Electron	0.09 ± 0.03 (stat)	0.10 ± 0.01 (stat)
JQ/Vertex	0.30 ± 0.04 (stat)	0.27 ± 0.02 (stat)
JQ/Prob.	0.46 ± 0.05 (stat)	0.34 ± 0.02 (stat)
JQ/High p_T	0.14 ± 0.03 (stat)	0.11 ± 0.01 (stat)
Total OST	1.47 ± 0.10 (stat)	1.44 ± 0.04 (stat)
SSKT	3.42 ± 0.49 (syst)	4.00 ± 0.56 (syst)

Verification of Tagging

- Measure B_d mixing (precisely known from B-factories)
  - ▷ Does not work for same-side tagging

- fit separately in hadronic and semileptonic sample
- per sample, simultaneously measure
  - tagger performance
  - Δm_d
- projection incorporates several classes of tags

semileptonic, ID^-, muon tag



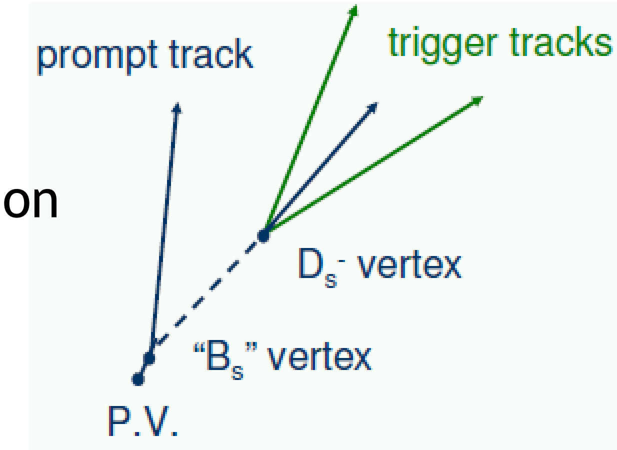
hadronic: $\Delta m_d = 0.536 \pm 0.028\ \text{(stat)} \pm 0.006\ \text{(syst)}\ \text{ps}^{-1}$

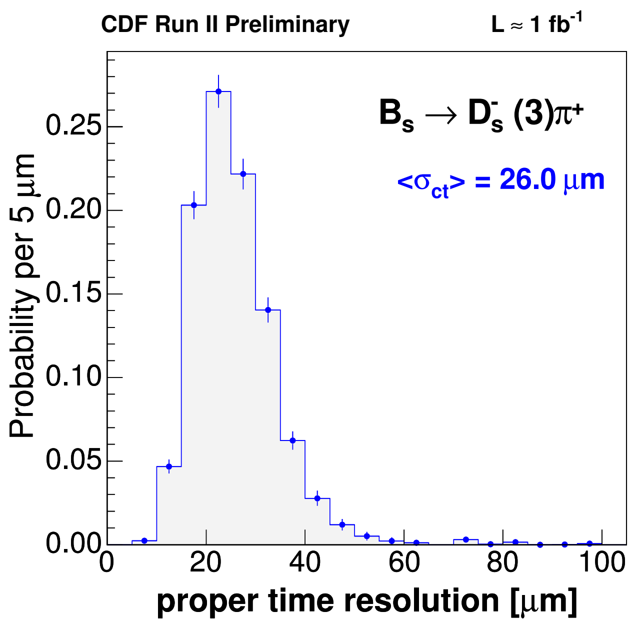
semileptonic: $\Delta m_d = 0.509 \pm 0.010\ \text{(stat)} \pm 0.016\ \text{(syst)}\ \text{ps}^{-1}$

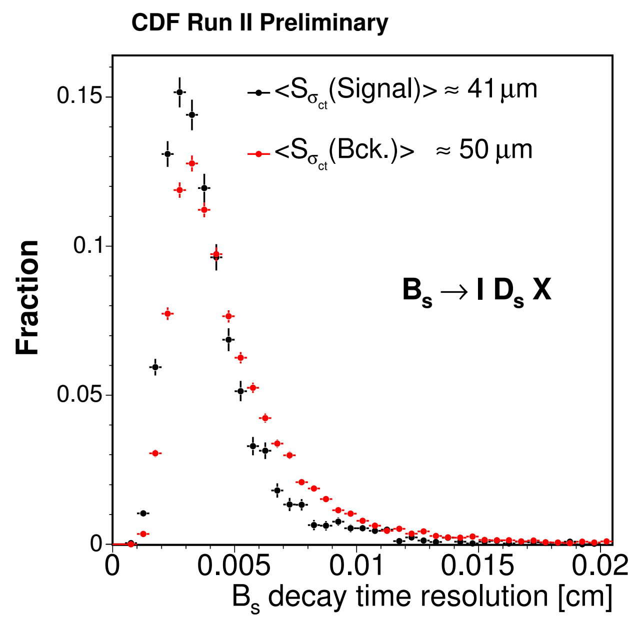
world average: $\Delta m_d = 0.507 \pm 0.005\ \text{ps}^{-1}$

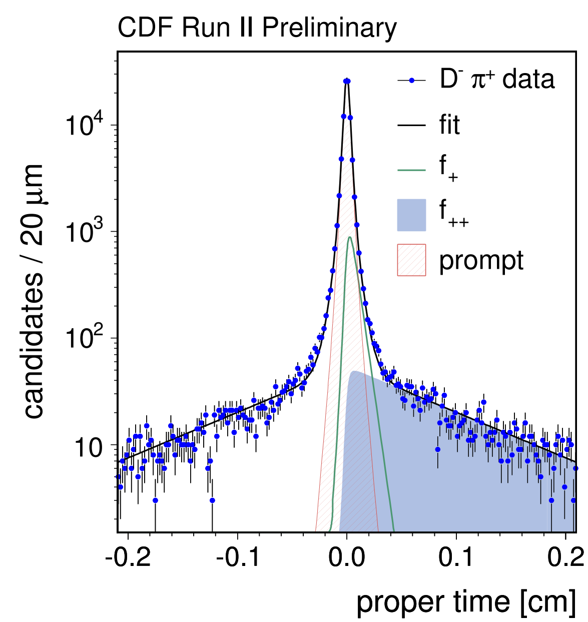
Proper Time Resolution

- Eminently important for B_s oscillations
  - ▷ Smears out asymmetry $\rightarrow$ dilution
  - ▷ Lifetime measurements provide no calibration
  - ▷ UML needs to correctly account for it
- Prompt D plus prompt track
  - ▷ quasi B_s particle
  - ▷ fit 'lifetime' $\longrightarrow$ resolution calibration



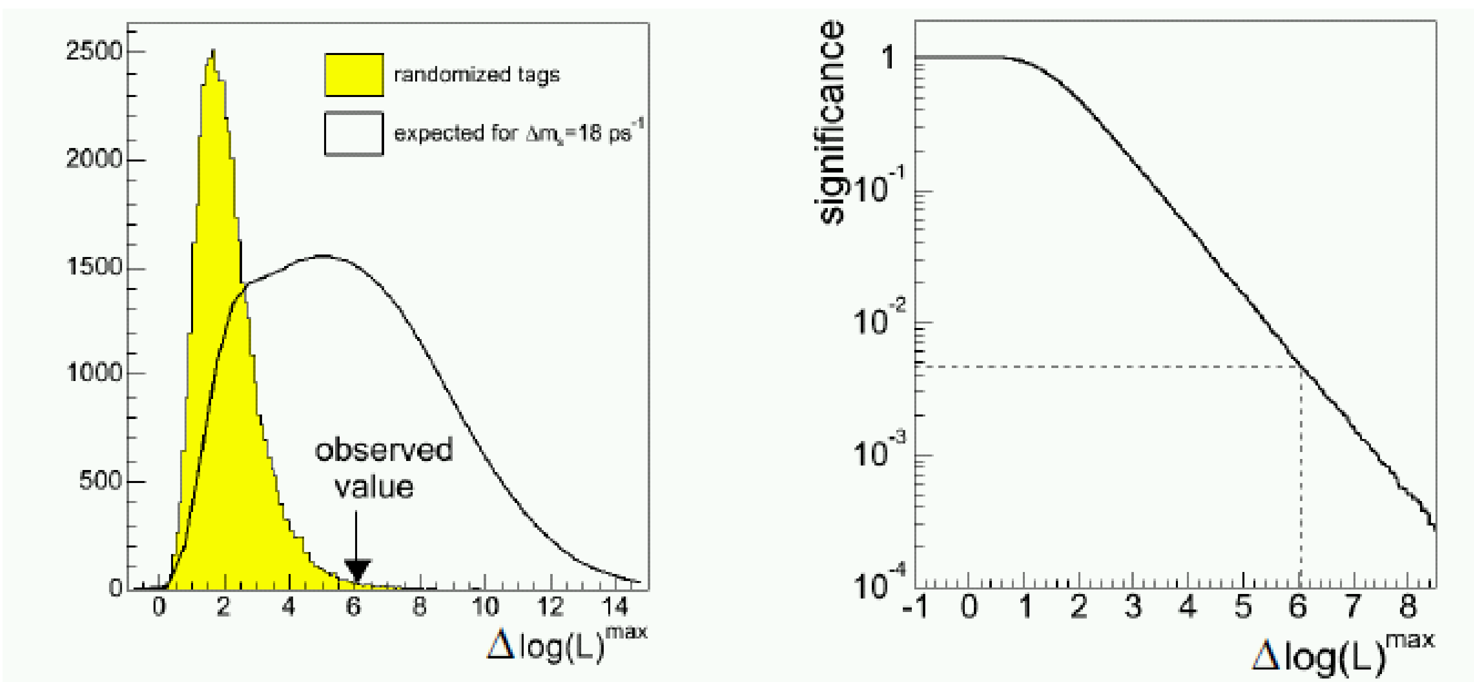






The Procedure

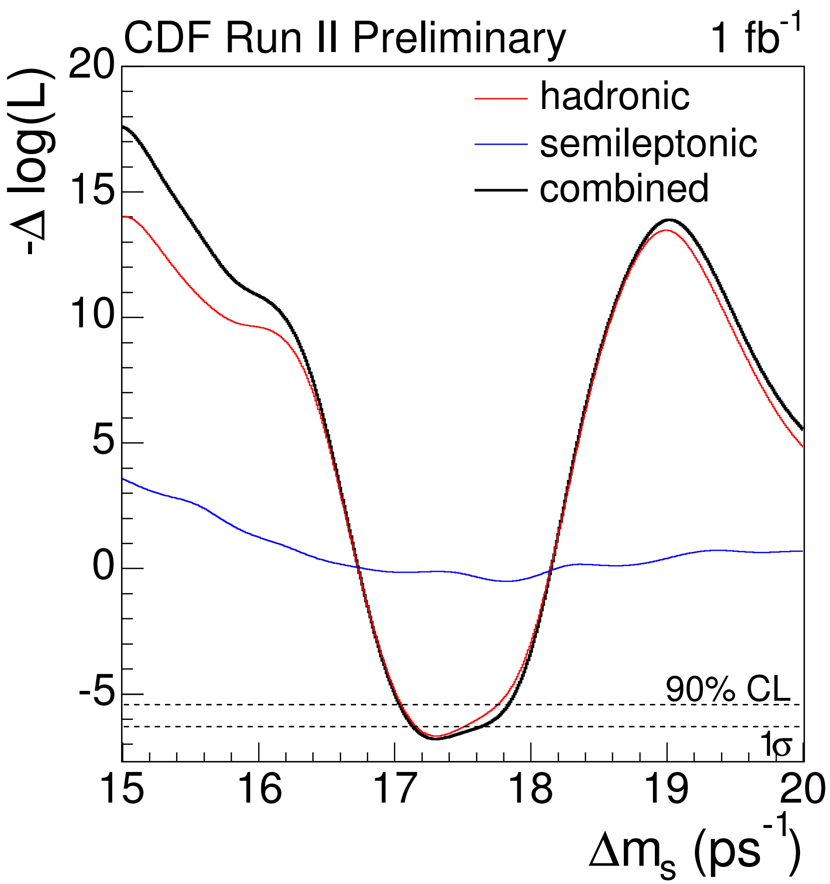
- Determination of oscillation in
  - ▷ time domain: fit frequency Δm_s in $\mathcal{L} \propto 1 \pm D \cos \Delta m_s t$
  - ▷ frequency domain: fit amplitude A in $\mathcal{L} \propto 1 \pm AD \cos \Delta m_s t$
- Decide beforehand whether to set UL or do measurement
  - ▷ p-value: probability that observed effect is from bg fluctuation
  - ▷ $p > 0.01$: Determine upper limit, $p < 0.01$: Measure Δm_s
- 228/50000 toy experiments: $\Delta \log(\mathcal{L}) \geq 6.06 \rightarrow p = 0.5\%$

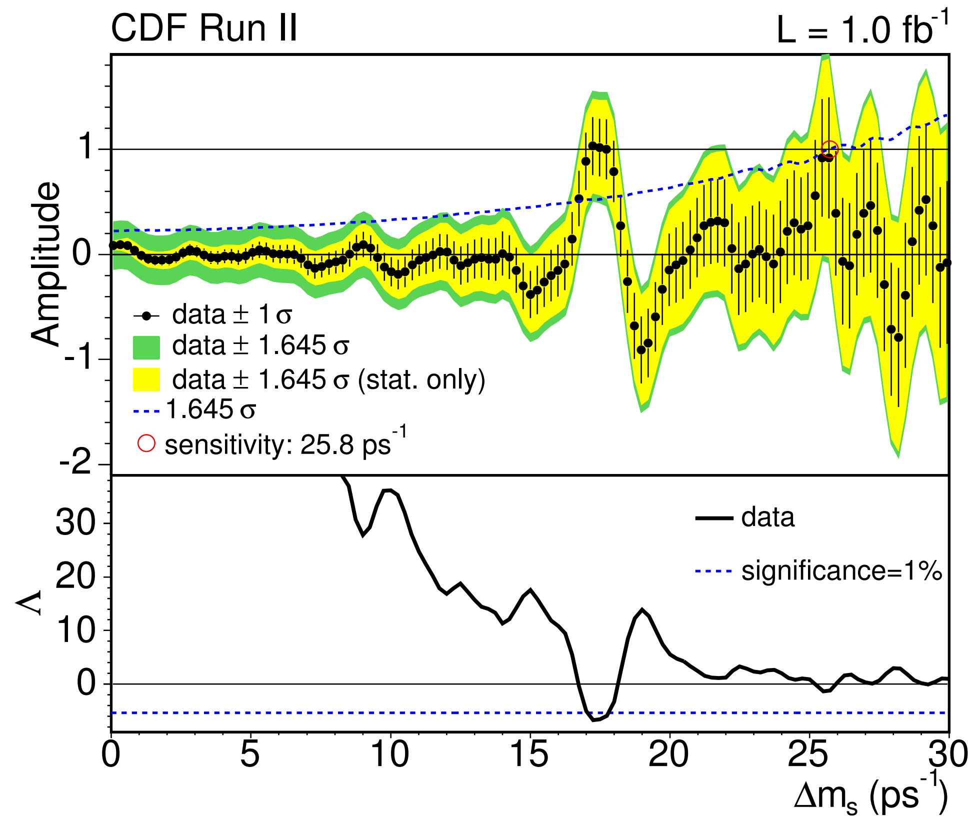


Determination of Δm_s

$\Delta m_s = 17.33^{+0.33}_{-0.18} \pm 0.07\,\text{ps}^{-1}$

(SM: $21.7\,^{+5.9}_{-4.2}\,\text{ps}^{-1}$)





- Interpretation help for amplitude plots
  - ▷ $A + 1.645\sigma(A) < 1$: excluded at 95%CL
  - ▷ $1.645\sigma(A) = 1$: measurement sensitivity

Impact of Measurement

- Independent measurement of

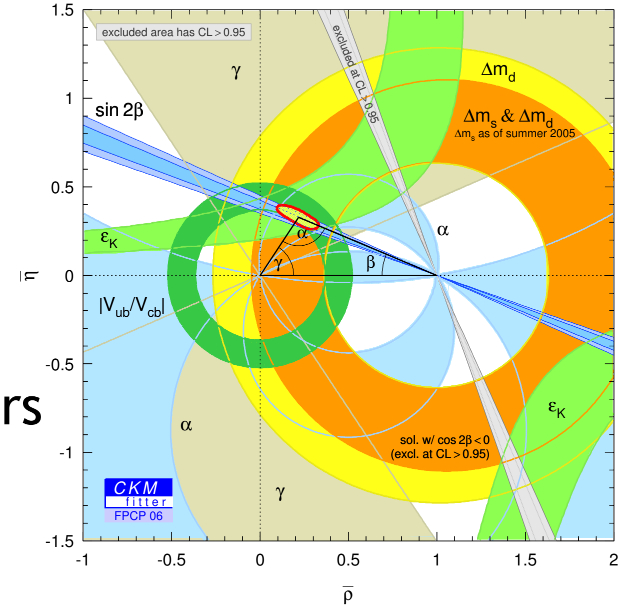
$$\frac{\Delta m_s}{\Delta m_d} = \frac{m_{B_s}}{m_{B_d}} \xi^2 \frac{|V_{ts}|^2}{|V_{td}|^2}$$

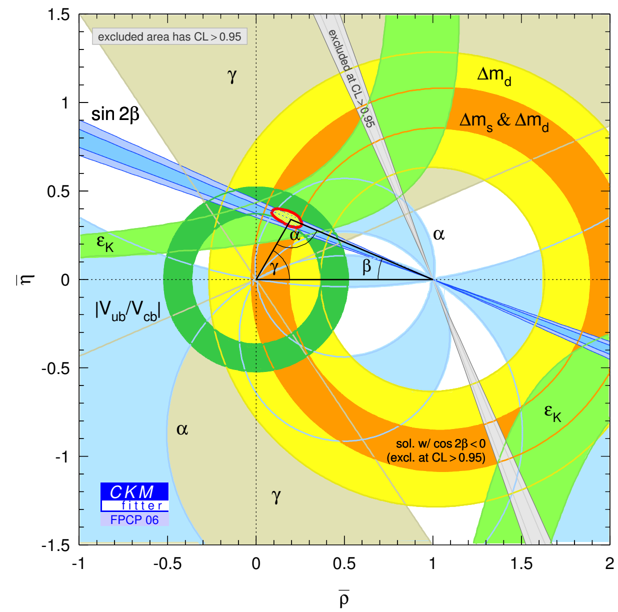
Ratio of decay constants and bag parameters

$\xi = 1.21^{+0.047}_{-0.035}$ from lattice, rest from PDG

$$\frac{|V_{td}|}{|V_{ts}|} = 0.208^{+0.008}_{-0.007}$$

- Consistent with $|V_{td}|/|V_{ts}|$ in Penguins
  - ▷ cf. tomorrow!
  - ▷ (more precise)





B_s in the future: LHCb

- Δm_s is only a first step
  - future experimental program at LHCb
- Mixing phase β_s
  - $\sin 2\beta_s$ from time-dependent asymmetries in $B_s \to J/\psi\,\phi$
  - $\sin 2\beta_s = 0.0365 \pm 0.0021$ predicted in SM
- γ

Decay Channel	Method	# events/y	Estimated error
$B_s \to D_s K$	time-dep. asymmetry	5400	14°
$B_s \to D^0 K^{*0}$	6 BF (triangles)	500-3400	8°
$B_s \to K^+K^-$	vs. $B^0 \to \pi^+\pi^-$	37k-26k	5°

- α and β

Decay Channel	Method	# events/y	Estimated error
$B^0 \to \pi^+\pi^-\pi^0$	time-dep. Dalitz	14k	10°_{stat}
$B^0 \to J\psi K^0_S$	time-dep. asymmetry	240k	$0.02(\sin 2\beta)$

Executive Summary I

- B physics
  - ▷ Quantitative tests of SM $\longrightarrow$ overconstraining 'the' unitarity triangle
  - ▷ Search for new physics $\longrightarrow$ 'delayed gratification'
  - ▷ Flood of data and new ideas $\longrightarrow$ spin-offs

- Time-dependent and CP-violating physics
  - ▷ CP-violation by B-factories

$$\beta = 21.7\,^{+1.3}_{-1.2}\,^\circ \quad \alpha = 100.2\,^{+15.0}_{-8.0}\,^\circ \quad \gamma = 62\,^{+35}_{-25}\,^\circ$$

$$\beta = \beta \text{ in b} \rightarrow \text{s penguins(?)}, \quad \alpha + \beta + \gamma = 186\,^{+38}_{-27}\,^\circ$$

$$\text{direct } CP\text{−violation in } B^0 \rightarrow K^+\pi^-$$

  - ▷ B_s mixing measured by CDF

$$\Delta m_s = 17.31^{+0.33}_{-0.18}(\text{stat}) \pm 0.07(\text{syst})\,\text{ps}^{-1}$$

$$\frac{|V_{td}|}{|V_{ts}|} = 0.208^{+0.001}_{-0.002}(\text{exp})^{+0.008}_{-0.006}(\text{theo})$$