Hadronic Physics at *BABAR*

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representing the *BABAR* Collaboration
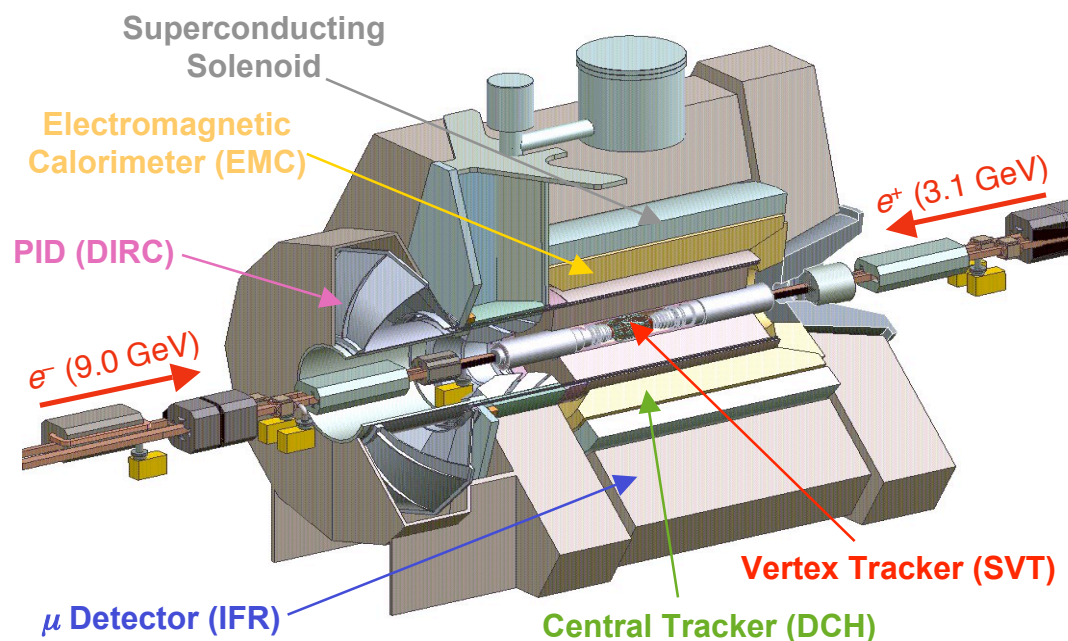
Hadronic physics at *BABAR*

❏ Traditionally, main focus of *BABAR* measurements is the electroweak sector:

    – "Standard Model" *CP* violation in *B* mesons;

    – angles and sides of the Unitarity Triangle

Superconducting Solenoid

Electromagnetic Calorimeter (EMC)

PID (DIRC)

e^+ (3.1 GeV)

e^- (9.0 GeV)

μ Detector (IFR)

Central Tracker (DCH)

Vertex Tracker (SVT)

❏ But the huge amount of data recorded ($\int \mathcal{L}\, dt$ = 477 fb^{-1}) allows a wealth of measurements related to hadronic physics:

    – quark masses, form factors in hadronic, semileptonic and radiative *B* and $D_{(s)}$ decays;

    – spectroscopy of charm mesons, quarkonium, light mesons, charmed baryons;

    – search for exotics;

    – cross sections, form factors, vacuum polarization from $e^+e^- \to$ hadrons
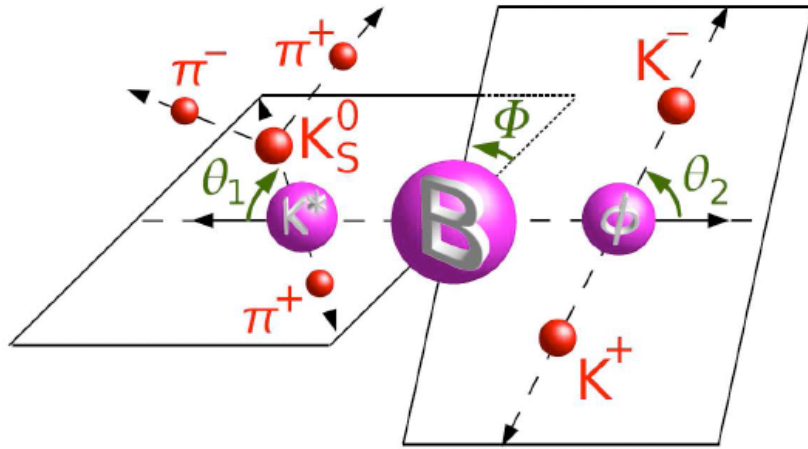
Outline

❏ Selection of a few recent results with broad range of involved hadronic models/parameters and very different experimental techniques:

- hadronic B decays (to charmless or charmonium states);

- hadron production in e^+e^- annihilation;

- D meson mixing;

- charmed baryon properties

❏ Many more details (and more results) in the 13 parallel talks and in the "new states" plenary talk

❏ In Standard Model occurs through $b \to s$ penguin

❏ Three amplitudes contribute, corresponding to helicity $\lambda = -1, 0, +1$ of the vector mesons:

$$\frac{d^3\Gamma}{d\cos\theta_1\, d\cos\theta_2\, d\Phi} \propto \left| \sum_{\lambda=-1,0,+1} A_\lambda Y_1^\lambda(\theta_1,\Phi) Y_1^{-\lambda}(\pi-\theta_2,0) \right|^2$$

❏ Weak interaction *V-A* structure, helicity conservation in strong interactions, *s*-quark spin flip suppression in penguin decays

$\Rightarrow |A_0| >> |A_+| >> |A_-|$ $(A_\pm \equiv (A_\| \pm A_\perp)/\sqrt{2})$

❏ Models have been proposed which violate this:

– within the SM: annihilation mechanism (Phys. Lett. B 601, 151), QCD rescattering (Phys. Rev. D 70, 054015);

– New Physics: scalar interaction, SuSy particles in loop

# Amplitude analysis of $B^\pm \rightarrow \phi K^{*\pm}$

❑ Both $K^*(892)^\pm \rightarrow K_S \pi^\pm$ and $K^*(892)^\pm \rightarrow K^\pm \pi^0$ are reconstructed

❑ 12 polarization-related quantities measured, including 6 *CP*-violating parameters:

- $\mathcal{B}(B^\pm \rightarrow \phi K^{*\pm}) = (11.2 \pm 1.0 \pm 0.9) \times 10^{-6}$

- $f_L \equiv |A_0|^2 / \Sigma|A_\lambda|^2 = 0.49 \pm 0.05 \pm 0.03 \Rightarrow |A_0|^2 \approx |A_+|^2 + |A_-|^2$

- $f_\perp \equiv |A_\perp|^2 / \Sigma|A_\lambda|^2 = 0.21 \pm 0.05 \pm 0.03$

- $\phi_{||} - \pi \equiv \arg(A_{||}/A_0) - \pi = (-0.67 \pm 0.20 \pm 0.07)$ rad

- $\phi_\perp - \pi \equiv \arg(A_\perp/A_0) - \pi = (-0.45 \pm 0.20 \pm 0.03)$ rad

- no evidence of *CP* violation

❑ Discrete ambiguity in the determination of $\phi_{||}$, $\phi_\perp$:

- $\phi_\perp \approx \phi_{||} - \pi \Rightarrow A_\perp \approx -A_{||} \Rightarrow |A_+|^2 << |A_-|^2$
- $\phi_\perp \approx \phi_{||} \Rightarrow A_\perp \approx A_{||} \Rightarrow |A_+|^2 >> |A_-|^2$

❑ The ambiguity is solved by studying interference of *S* and *P* waves in the $K\pi$ system: only $\phi_\perp \approx \phi_{||}$ acceptable $\Rightarrow |A_0| \approx |A_+| >> |A_-|$

S-P interference
no *S-P* interference

350 fb^{-1}
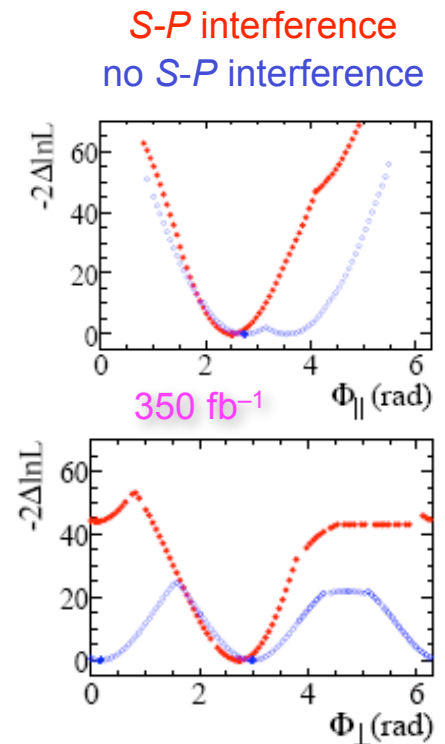
0705.1798 [hep-ex]

$B \to \eta_c K^*, \eta_c \gamma K^{(*)}$

❏ *B* decays to singlet states of charmonium much less known than decays to triplet (J/ψ, $\psi(2S)$, χ_{c1})

❏ NRQCD predicts *B* decays to *P* states of charmonium to occur at similar rates (Phys. Rev. D 51, 125):

– indeed $\mathcal{B}(B \to \chi_{c1} K) \sim \mathcal{B}(B \to \chi_{c0} K) \sim 10^{-4}$;

– but $B \to \chi_{c2} K$, $B \to h_c K$ as yet unobserved: current limit $< 10^{-5}$

❏ Search for $B^0 \to \eta_c K^{*0}$, $B^0 \to h_c K^{*0}$, $B^\pm \to h_c K^\pm$, with $\eta_c \to K_S K^+ \pi^-$, $K^+ K^- \pi^0$ and $h_c \to \eta_c \gamma$:
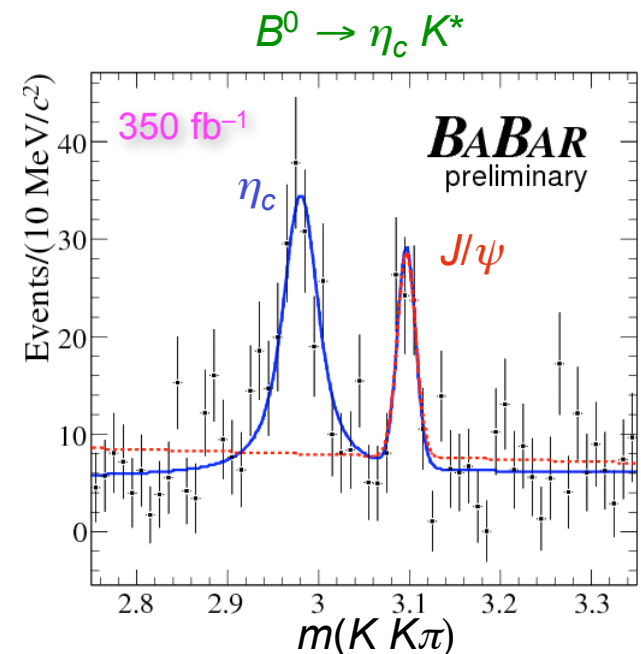
– $\mathcal{B}(B^0 \to \eta_c K^{*0}) = (6.1 \pm 0.8 \pm 1.1) \times 10^{-4}$ (factor 2 improvement over WA);

– no signal for h_c:
$\mathcal{B}(B^\pm \to h_c K^\pm) \cdot \mathcal{B}(h_c \to \eta_c \gamma) < 5.2 \times 10^{-5}$ (90% C.L.)
$\mathcal{B}(B^0 \to h_c K^{*0}) \cdot \mathcal{B}(h_c \to \eta_c \gamma) < 2.4 \times 10^{-4}$ (90% C.L.)

0707.2843 [hep-ex]

❏ More on charmless hadronic *B* decays in Heavy Meson Spectroscopy session:

  – G. Mohanty (12/10)

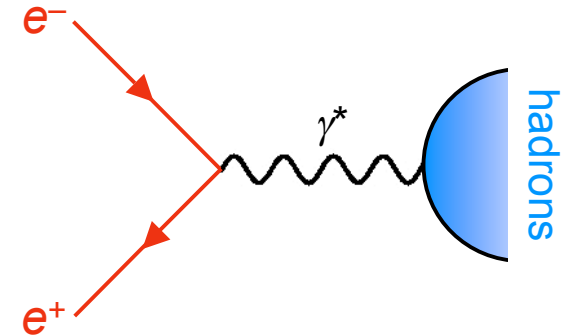# Hadron production in e^+e^- annihilations

❏ $\sigma(e^+e^- \rightarrow$ hadrons) ~ 3 nb $(\sigma(e^+e^- \rightarrow b\,\bar{b})$ ~ 1 nb) $\Rightarrow$ huge amount of data with $\mathcal{L}$ ~ 500 fb^{-1}

❏ Only some quantum numbers and helicity values are allowed in final state

❏ Non-perturbative quantities:

  – $e^+e^- \rightarrow h\bar{h}\ \Rightarrow$ form factor;

  – $e^+e^- \rightarrow \gamma P\ \Rightarrow$ transition form factor

❏ Broad e^+e^- energy range available via radiative return (Initial State Radiation, or ISR):

  – invariant mass spectrum up to 4-5 GeV in the same experiment $\Rightarrow$ same conditions, same analysis tools, same systematic errors;

  – high acceptance and high transverse momentum of hadrons
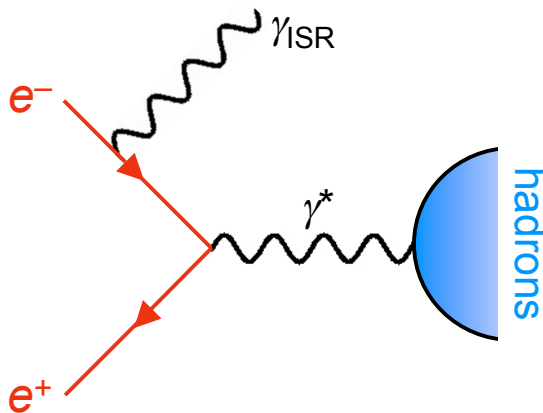
Correlated baryon-antibaryon production

❏ Baryon production in e^+e^- interactions:

– primary correlation: a diquark-antidiquark pair is produced in the interaction ⇒ the baryons resulting from hadronization share two flavors and have large rapidity gap $|\Delta y|$

– local correlation: a baryon-antibaryon pair is produced "locally" in the hadronization cascade from the initial quark or antiquark ⇒ small $|\Delta y|$
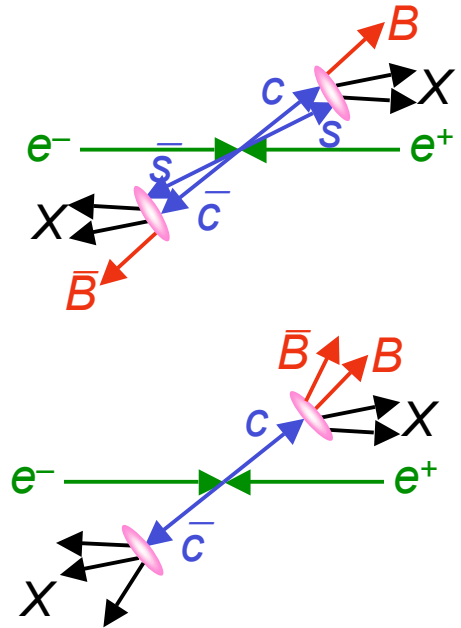
❏ Experimentally, $|\Delta y|$ peaks at low values
⇒ no evidence for primary production

– Several generators, with very different production models, are tuned to data for observed baryons and accompanying mesons distributions

❏ However, CLEO reported a 3.5-fold excess of events with both Λ_c^+ and $\overline{\Lambda}_c^-$ at $\sqrt{s}$ = 10.6 GeV/c^2 with respect to expectations from local correlation

– Given the energy and masses, the two charmed baryons must be leading hadrons from $e^+e^- \rightarrow c\,\bar{c}$ process

Correlated baryon-antibaryon production

- ❏ Λ_c reconstructed in $\Lambda_c^+ \to p\,K^-\,\pi^+$, $p\,K_S$
  - $\Upsilon(4S)$ decays rejected by $p^* > 2.3$ GeV/c
- ❏ $N(\Lambda_c^+\,\overline{\Lambda}_c^-) = 649 \pm 31$
  - if production uncorrelated $\Rightarrow$ 155 events expected
 - $\Rightarrow$ 4.2-fold excess, consistent with CLEO
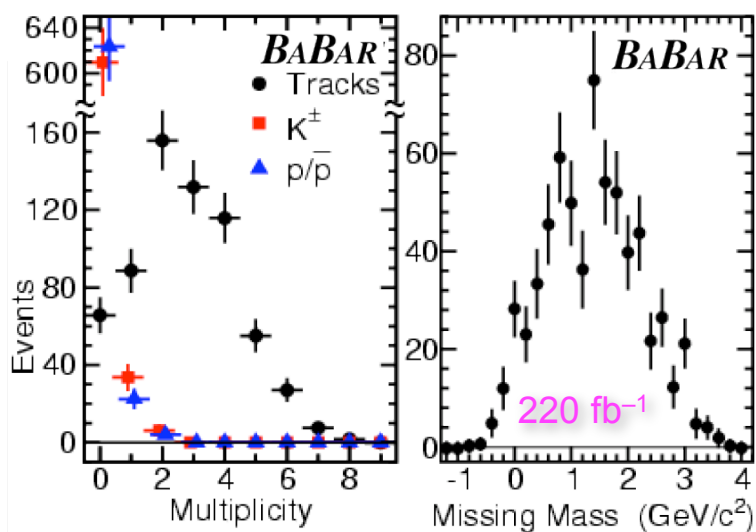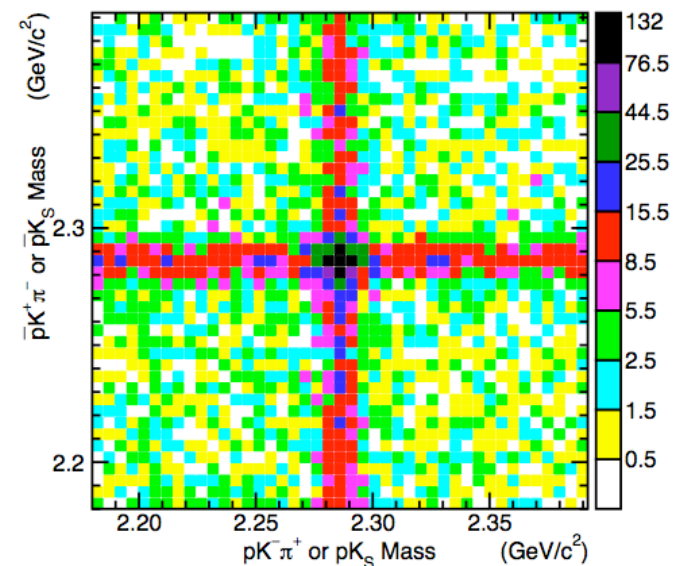
- ❏ Additional tracks:
  - low multiplicity: $<N_{tracks}> = 2.6 \pm 0.2$;
  - mostly pions;
  - no evidence for $e^+e^- \to \Lambda_c^+\,\overline{\Lambda}_c^-$
- ❏ Missing mass distribution:
  - low-peaking $\Rightarrow$ suppressed $n\bar{n}$ production
- ❏ Four-baryon events: $N_{4\text{-bar}} = 13 \pm 8$

to be submitted to PRL

Measurements with Initial State Radiation

❑ Why extending measurements of hadronic cross sections at low $\sqrt{s}$?

– hadronic contributions to $\alpha_\mu = g_\mu - 2$ and α_{QED} are calculated from hadronic cross section (in particular, α_μ^{had} sensitive to $\sqrt{s} < 2$ GeV contribution);

– form factors (e.g. proton form factors from $e^+e^- \to p\bar{p}$);

– light meson spectroscopy;
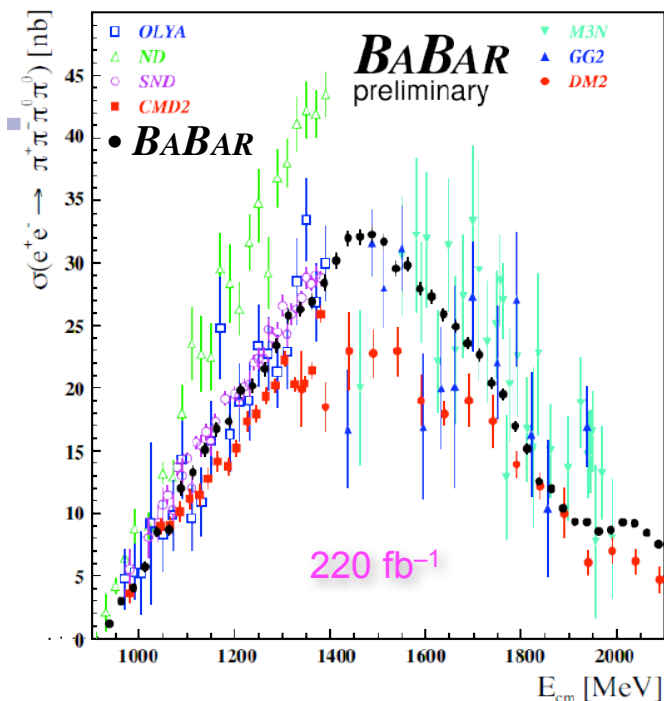
– charmonium and bottomonium spectroscopy.
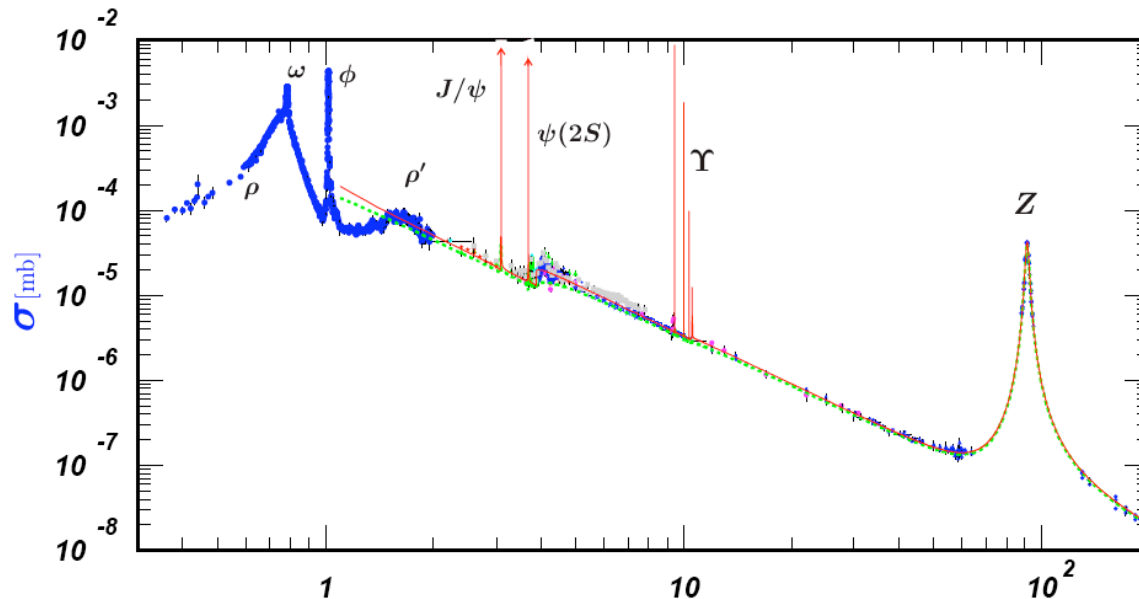
❑ Technique:

– detection of ISR photon can either be required or not;

– specific identified final set of particles;
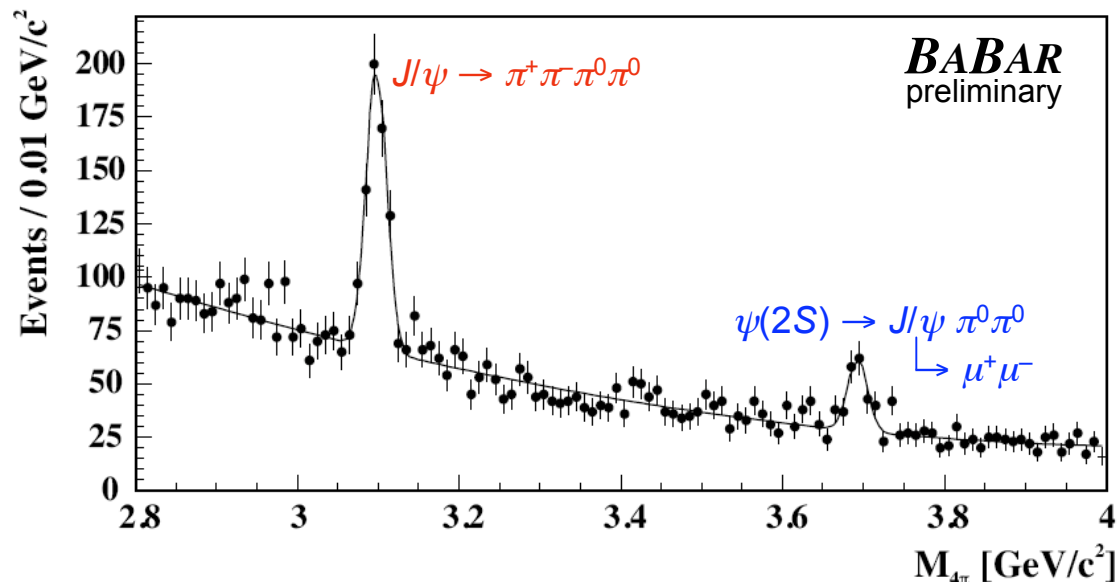
– kinematic fits

$e^+e^- \rightarrow \pi^+\pi^-\pi^0\pi^0$

220 fb^{-1}

❑ Charmonium region:
- first measurement of
$\mathcal{B}(J/\psi \rightarrow \pi^+\pi^-\pi^0\pi^0)$ =
$(5.74 \pm 0.74) \times 10^{-3}$

❑ Precision measurement important for α_μ, α_{QED}
- currently 8% at peak;
- improved accuracy over existing measurements

❑ Events selected requiring γ_{ISR}

❑ Several structures seen:
- $\omega\,\pi^0$, $a_1(1260)\,\pi$, $\rho^+\rho^-$, $f_0(980)\,\rho^0$

Λ form factor

❏ $e^+e^- \to \Lambda \bar{\Lambda} \, \gamma_{\text{ISR}}$ events selected requiring γ_{ISR}

❏ Production cross session as function of $m(\Lambda\bar{\Lambda})$:

$$\sigma_{\Lambda\bar{\Lambda}}(m) = \frac{4\pi\alpha^2\beta}{3m^2}\left[\left|G_M(m)\right|^2 + \frac{1}{2\tau}\left|G_E(m)\right|^2\right]$$

$$\left(\begin{array}{c} \tau = m^2/4m_\Lambda^2 \\ \beta = \sqrt{1-1/\tau} \end{array} \right) \qquad \frac{2\tau+1}{2\tau}\left|F(m)\right|^2 \leftarrow \text{effective form factor}$$

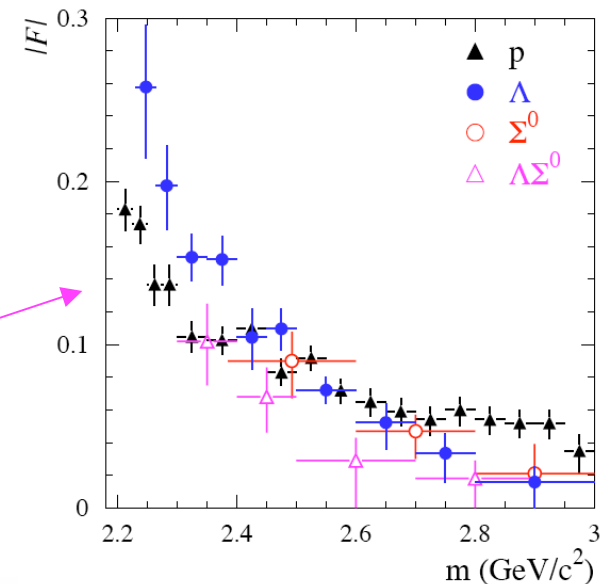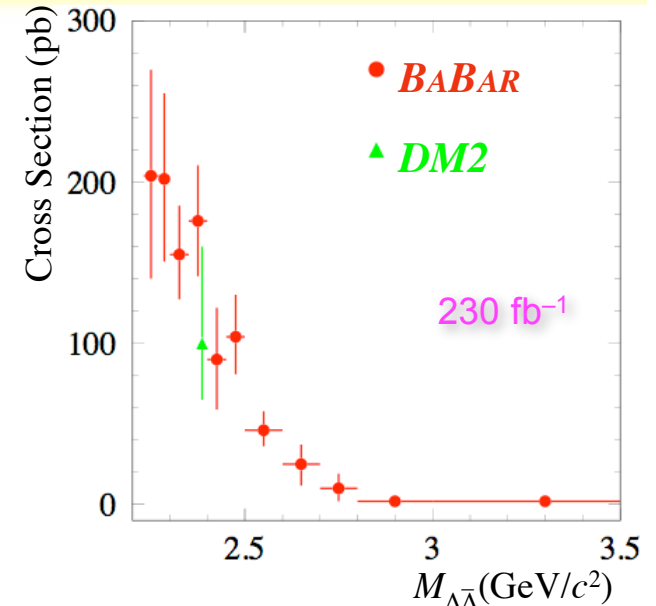❏ Both Λ reconstructed in $\Lambda \to p\,\pi^-$, with at least one proton identified

❏ Different angular distributions for E and M contributions

  – statistics too low to conclude on $|G_E|/|G_M|$

❏ Also analyzed $e^+e^- \to \Sigma^0 \bar{\Sigma}^0 \, \gamma_{\text{ISR}}$, $e^+e^- \to \Lambda \bar{\Sigma}^0 \, \gamma_{\text{ISR}}$ ($\Sigma^0 \to \Lambda \, \gamma$)

  – limited statistic

0709.1988 [hep-ex]
(to appear on PRD)

❏ More on e^+e^- hadron production in Light Meson Spectroscopy session:

– D. Muller: quasi-two-body $e^+e^- \rightarrow X\,Y$ at 10.6 GeV (12/10);

– W. Wang: inclusive and exclusive $e^+e^- \rightarrow$ hadrons in ISR (12/10);

– S. Serednyakov: exclusive $e^+e^- \rightarrow$ baryons or charmed mesons in ISR (12/10);

Contributions to *D*-mixing

❑ Like in the case of the *B* meson system, initially produced D^0, $\bar{D}^0$ flavour eigenstates evolve in time as two D_1, D_2 mass eigenstates:

  – $|D_{1,2}> = p\,|D^0\rangle \pm q\,|\bar{D}^0\rangle$;

  – $\Delta M = m_1 - m_2$; $\Delta\Gamma = \Gamma_1 - \Gamma_2$; $\Gamma = (\Gamma_1 + \Gamma_2)/2$; $x \equiv \Delta M/\Gamma$; $y \equiv \Delta\Gamma/2\Gamma$

❑ But unlike for *B*, the heaviest quark in the box loop is *b* (instead of *t*) and vertices are strongly CKM-suppressed.

  – short distance contribution (electroweak sector): GIM cancellation, destructive interference between LO and NLO $\Rightarrow x_{SD} \sim 10^{-6}$, $y_{SD} \sim 10^{-8}$;

  – long distance contribution (QCD): real states contribute to *x* and *y*, virtual states to *x* only; *x* more model-dependent, *y* more sensitive to quark-hadron duality
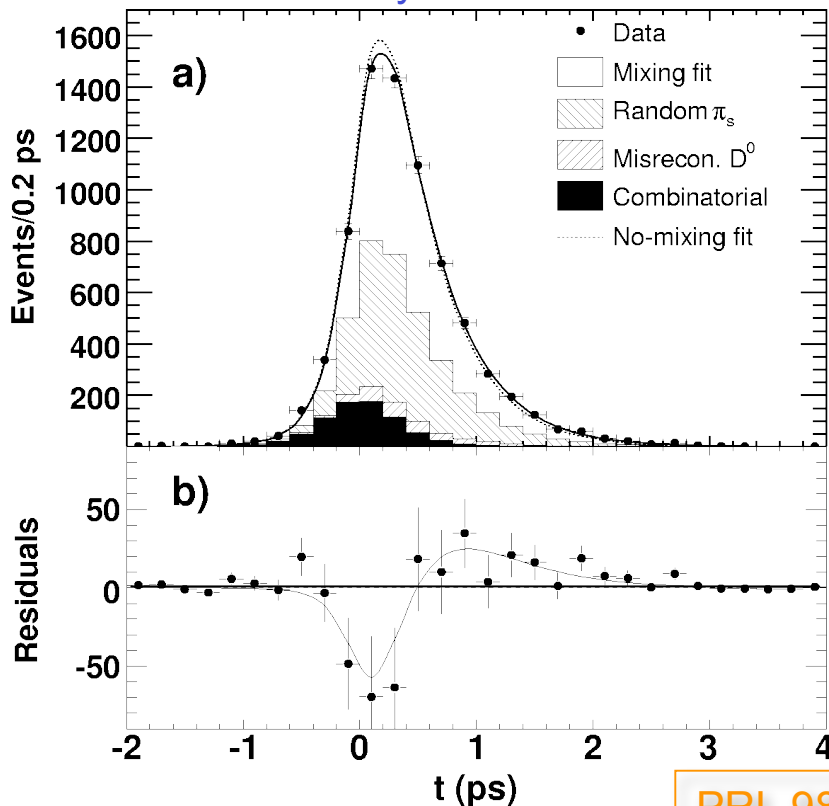 $\Rightarrow x_{LD} \sim y_{LD} \sim 10^{-3} - 10^{-2}$

short distance contribution   long distance contribution
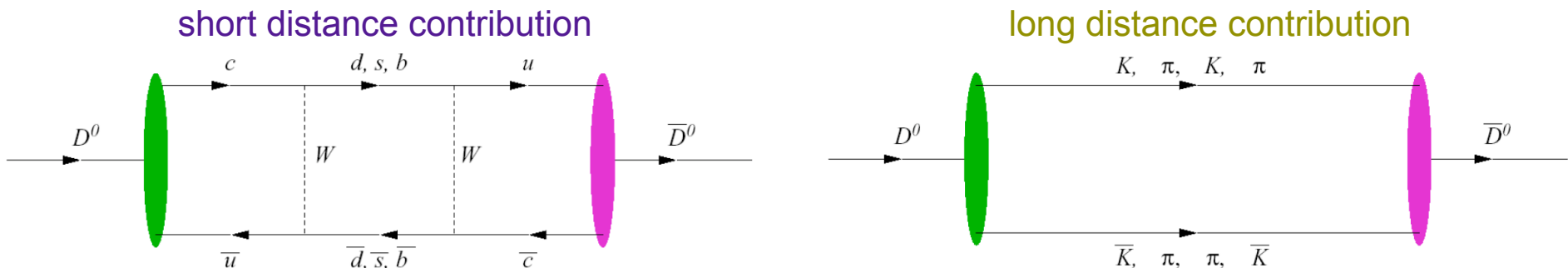
D-mixing results

- ❏ At *BaBar*, the *D* sample is produced in $e^+e^- \to c\bar{c}$ events ($\sigma \sim 1.3$ nb)
  - – $D^{*+} \to D^0\pi^+$, $D^{*-} \to \bar{D}^0\pi^-$ decays are used to tag the D^0 flavour

- ❏ $D \to K\pi$: fit "wrong sign" ($D^0 \to K^+\pi^-$) decay time distribution:
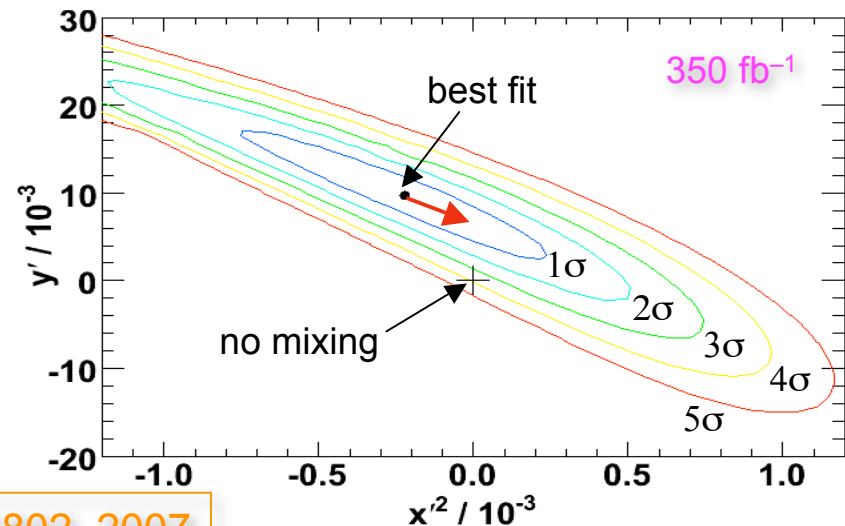
WS decay time distribution

- – $x' \equiv x\cos\delta_{K\pi} + y\sin\delta_{K\pi}$;
  $y' \equiv y\cos\delta_{K\pi} - x\sin\delta_{K\pi}$
- – $x'^2 = (-0.22 \pm 0.30 \pm 0.21) \times 10^{-3}$;
  $y' = (9.7 \pm 4.4 \pm 3.1) \times 10^{-3}$
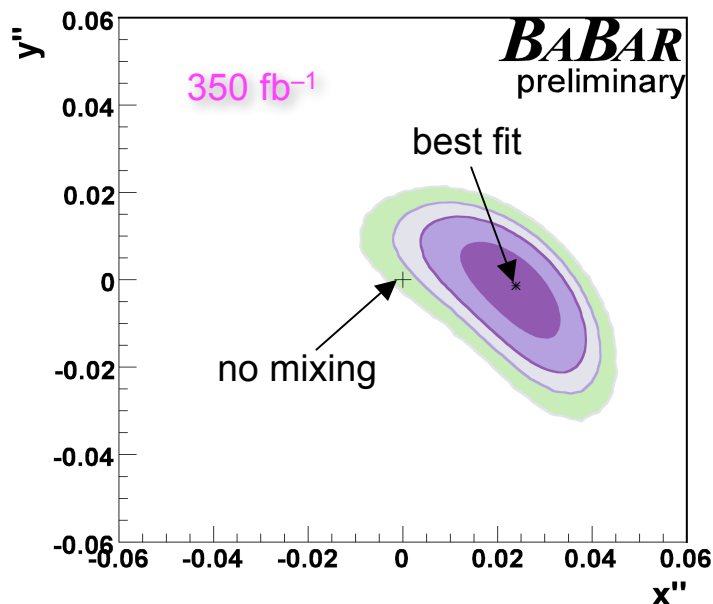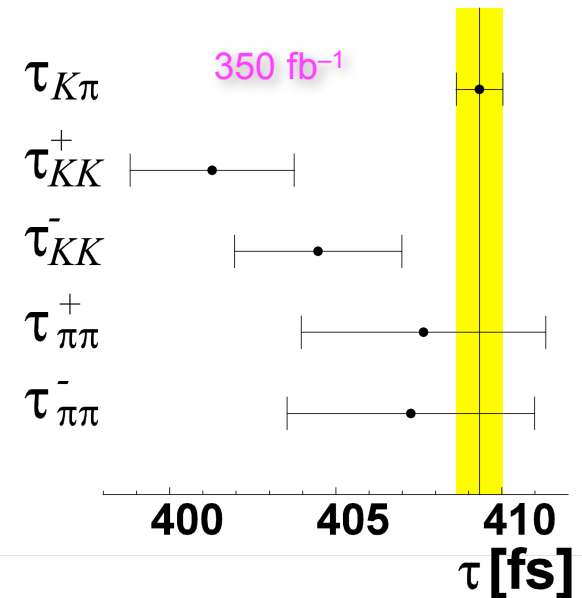 ⇒ 3.9 σ away from no mixing

PRL 98:211802, 2007

D-mixing results

❏ Lifetime ratio in $D^0 \to h^+ h^-$ ($h = K, \pi$):

   – *D*-mixing affects the decay time to *CP* eigenstates: the distributions can be fitted with effective lifetimes;

   – difference from $D^0 \to K^- \pi^+$ lifetime is evidence for *D* mixing

   – fit distributions for all modes simultaneously

  ⇒ 3.0 σ away from no mixing

subm. to PRD-RC

❏ Analysis of $D^0 \to K^- \pi^+ \pi^0$ Dalitz plot:

   – amplitudes extracted from time-independent Dalitz plot analysis of "right sign" sample;

   – "wrong sign" decay time distribution varies across Dalitz plot: fit with proper amplitudes and phases
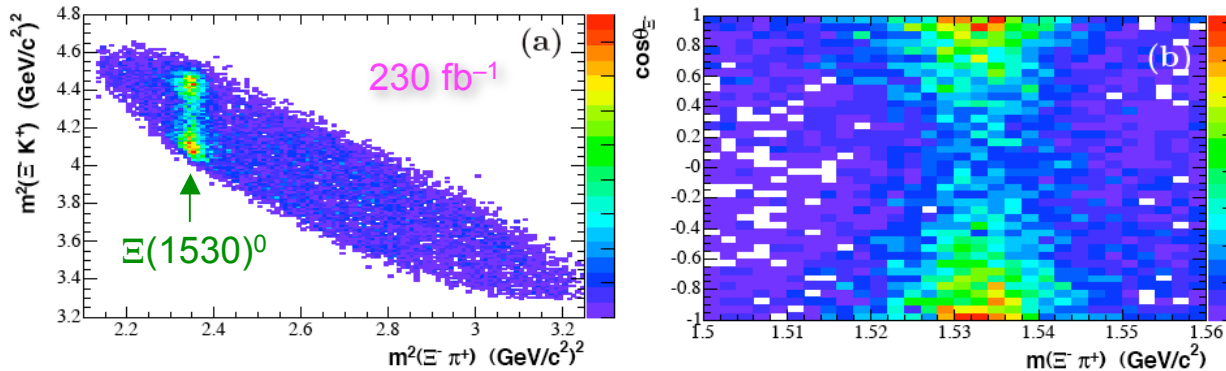
  ⇒ no mixing excluded at 99% C.L.

❏ More on *D* mixing in Heavy Meson Spectroscopy session:

   – R. Andreassen (9/10)

Measurement of the Ξ(1530)⁰ spin
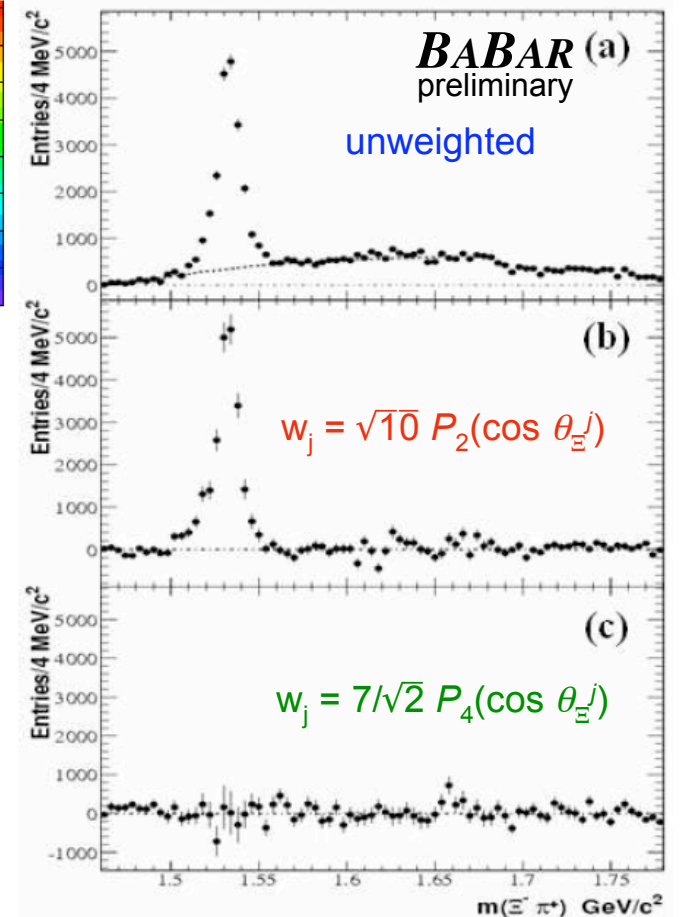
❏ From $K^-p \to \Xi(1530)^{0,-}\pi^{0,+}$ data $\Rightarrow J^P(\Xi(1530)^0) = 3/2^+$ or $J^P = 5/2^-$

❏ $\Xi(1530)^0$ seen as resonant $\Xi^-\pi^+$ structure in $\Lambda_c^+ \to \Xi^-\pi^+K^+$ decays

❏ Angular distribution:

$$\frac{dN}{d\cos\theta_{\Xi^-}} = N\sum_{l=0}^{l_{max}} \langle P_l \rangle P_l(\cos\theta_{\Xi^-}) \ , \ l_{max} = 2J - 1$$

❏ In any mass interval, the number of event has contributions from relevant l: by weighting each event with $P_l(\cos\theta_\Xi)$, only P_2 contribution survives $\Rightarrow J^P(\Xi(1530)^0) = 3/2^+$

And more…

❑ Heavy meson spectroscopy: quarkonium, charmed mesons and baryons:

   – A. G. Mokhtar: charmonium spectroscopy (Quarkonia States, 8/10);

   – V. Poireau: charm spectroscopy (Heavy Meson Spectroscopy, 9/10);

   – K. Mishra: charm Dalitz plot analyses (Heavy Meson Spectroscopy, 9/10)

❑ Semileptonic, leptonic and radiative penguins *B* decays:

   – M. Mazur: semileptonic decays (Heavy Meson Spectroscopy, 9/10);

   – E. Salvati: leptonic decays (Heavy Meson Spectroscopy, 12/10);

   – M. Lu: radiative penguins decays (Heavy Meson Spectroscopy, 12/10);

   – K. Tackman: determination of non-perturbative parameters (Heavy Meson Spectroscopy, 12/10)

❑ Angles of the Unitarity Triangle from hadronic *B* decays:

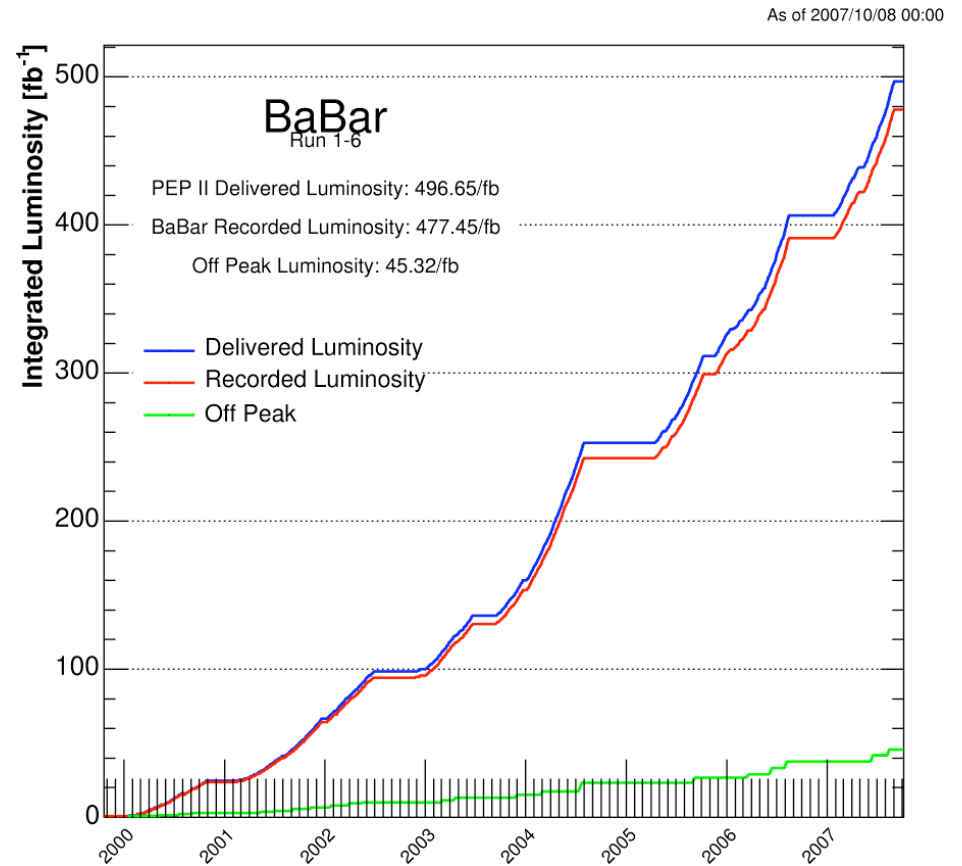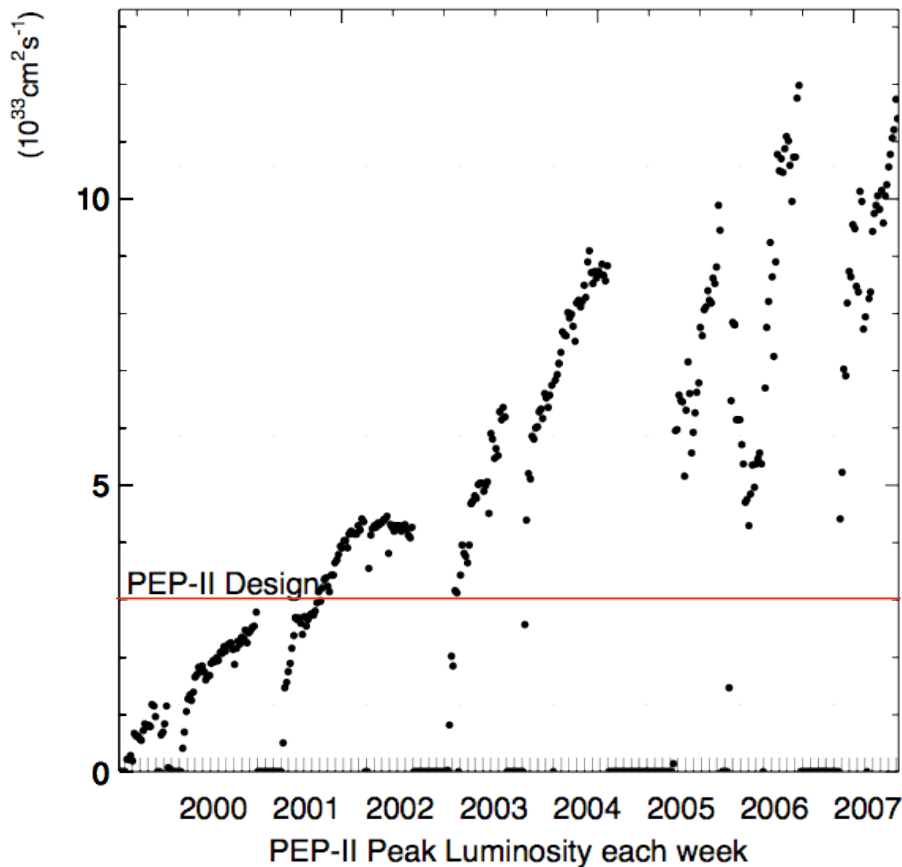   – S. Emery: UT angles (Heavy Meson Spectroscopy, 12/10)

Back-up slides

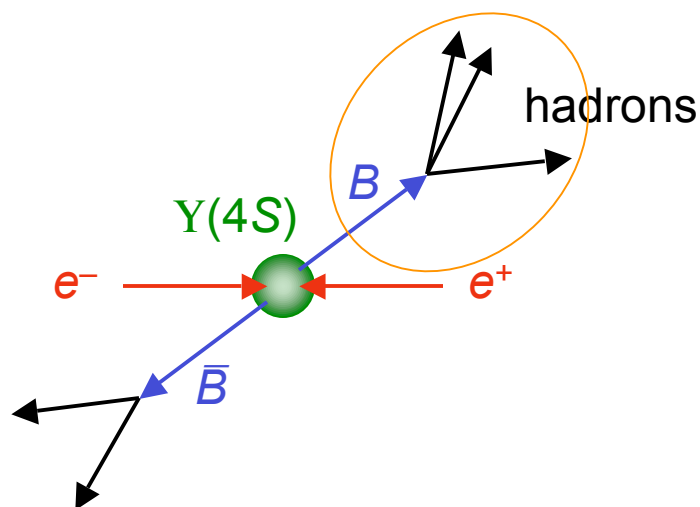# The BABAR data sample

Maximum instantaneous luminosity:

$\mathcal{L}_{max}$ = 1.2 × 10^{34} cm^{-2}s^{-1}

Total integrated luminosity:

$\int \mathcal{L}\, dt$ = 477 fb^{-1} (45 fb^{-1} off-peak)
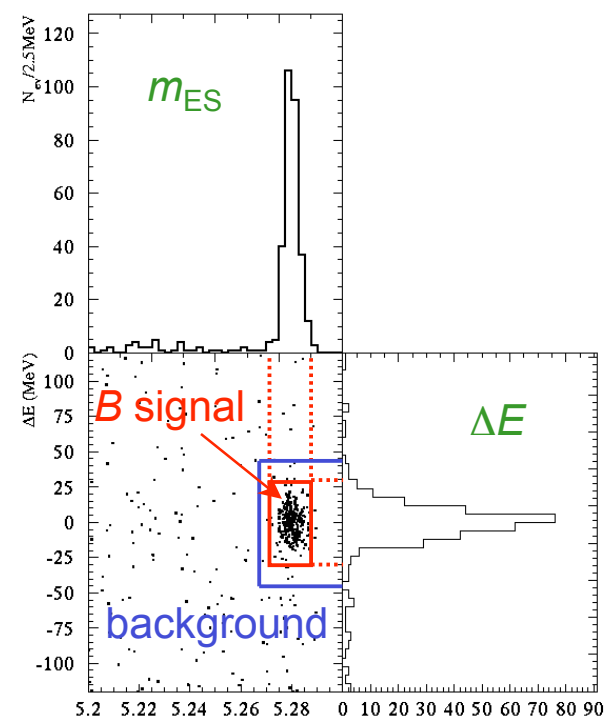
Reconstruction of *B* decays

□ A *B*-*B̄* meson pair is produced in the decay of the $\Upsilon(4S)$ formed in e^+e^- annihilation

□ Final products of the *B* decays are reconstructed and identified in the detector

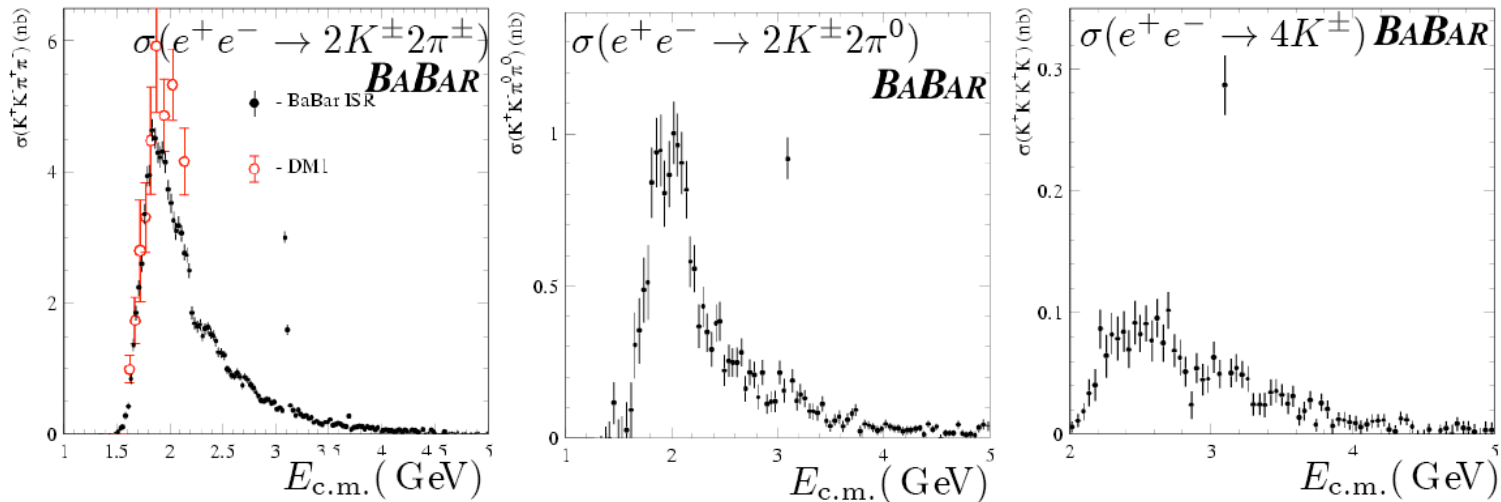□ A *B* candidate is reconstructed through a given decay chain

□ After continuum background reduction, *B*-decay events are selected by means of a pair of nearly uncorrelated variables, such as:

$$m_{ES} = \sqrt{(s/2 + \mathbf{p}_\Upsilon \cdot \mathbf{p}_B)^2 / E_\Upsilon - \mathbf{p}_B^2}$$

$$\Delta E = (E_\Upsilon E_B - \mathbf{p}_\Upsilon \cdot \mathbf{p}_B - s/2)/\sqrt{s}$$

$e^+e^- \to K^+K^-\pi^+\pi^-,\ K^+K^-\pi^0\pi^0,\ K^+K^-K^+K^-$

❑ Several intermediate states observed:

– $K^+K^-\pi^+\pi^-$: $K^{*0}K\,\pi$, $\phi\,\pi^+\pi^-$, $\phi\,f_0(980)$;

– $K^+K^-\pi^0\pi^0$: $K^{*\pm}K\,\pi^0$, $\phi\,\pi^0\pi^0$, $\phi\,f_0(980)$;

– $K^+K^-K^+K^-$: $\phi\,K^+K^-$

❑ Search for $Y(4260) \to \phi\,\pi\,\pi$ (large rate if glueball): no evidence

❑ Structure in $K\,K\,\pi\,\pi$ consistent with new state at 2.175 GeV/c^2