Rare Decays and Exotic States at *BABAR*

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Les Rencontres de Physique de la Vallée d'Aoste
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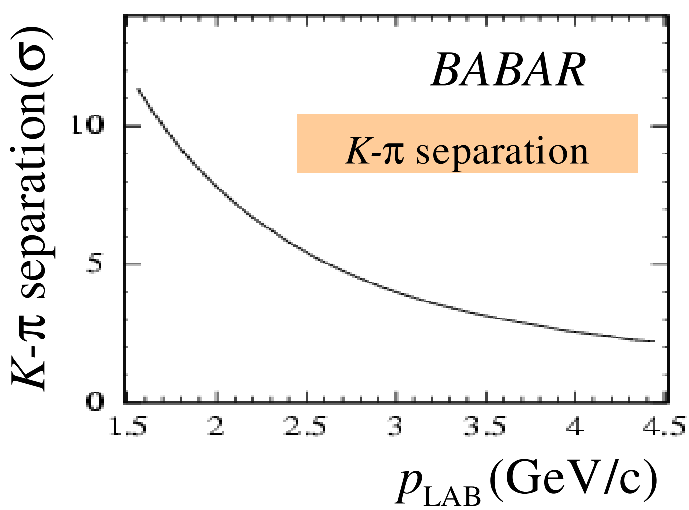
Outline

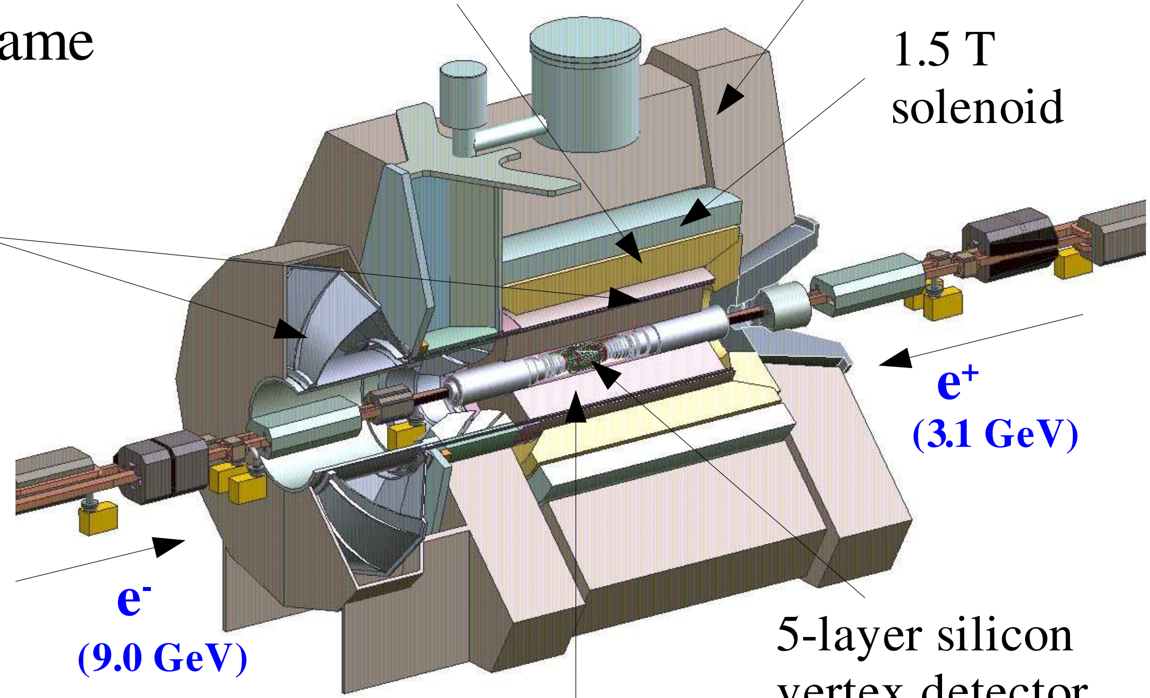
- *BABAR* overview
- $B^0 \to l^+ l^-$ (and $D^0 \to l^+ l^-$)
- $B \to (\rho,\omega)\gamma$
- $B^+ \to K^+ \nu \bar{\nu}$ and $B^+ \to \pi^+ \nu \bar{\nu}$
- Lepton flavour violation: $\tau^+ \to \mu^+ \gamma$
- Pentaquark searches: $\Theta(1540)^+$ and $\Xi_5(1860)$
- Summary

All results are preliminary unless otherwise specified

The *BABAR* experiment

- Operating at centre of mass energy of 10.58 GeV for Y(4S) → BB
- Asymmetric beam energies produce boost of β=0.56 in lab frame

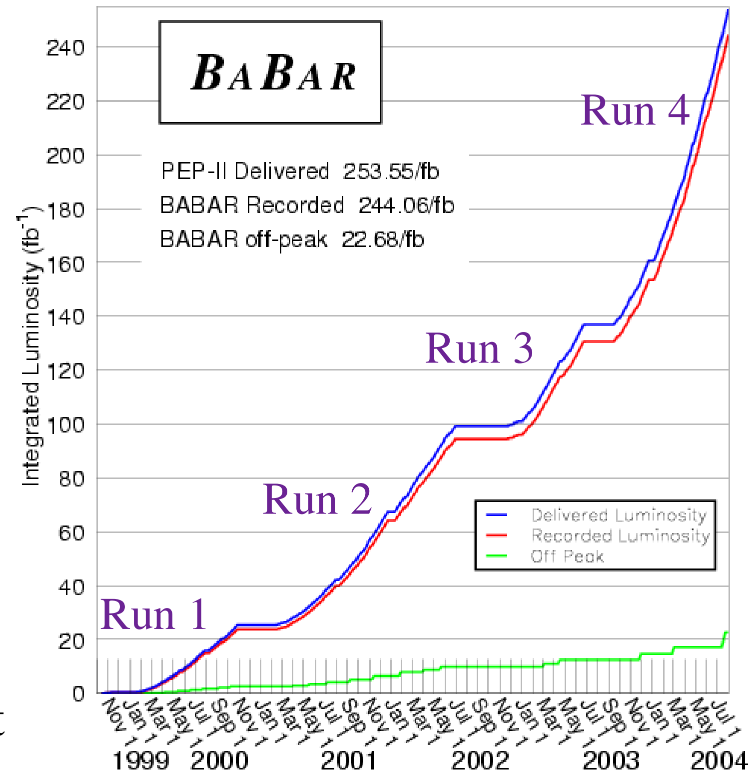




$\sigma_{p_T}/p_T = (0.13 \cdot p_T/[\mathrm{GeV}/c] + 0.45)\%$

BABAR performance

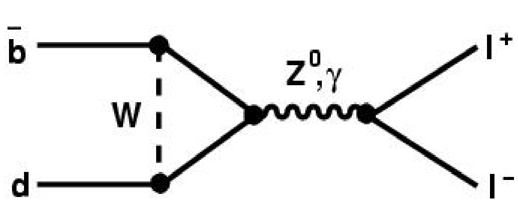
- 244 fb^{-1} of data since startup in 1999
  - ~**245 million BB pairs** plus an additional ~23 fb^{-1} of off-resonance data
- Two sextants of upgraded muon system (LST based) installed during summer 2004
- Anticipate startup in mid-March
  - "Run 5" startup originally scheduled for Oct 2004 delayed by an electrical accident and subsequent investigation
  - run extended until **summer 2006**, with target luminosity of **500fb^{-1}**
  - remainder of muon system upgrade deferred until 2006 shutdown

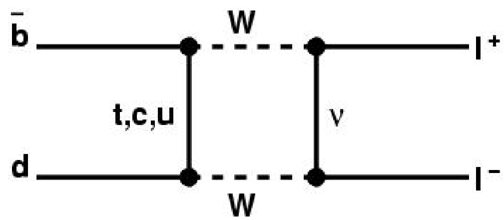


Process	effective σ (nb)
bb	1.1
cc	1.3
other qq	~2.1
ττ	0.89

Rare decays: $B^0 \to l^+ l^-$

- Theoretically very clean: within SM only non-vanishing operator is O_{10} (axial-current) and hadronic matrix element is f_B





SM predictions

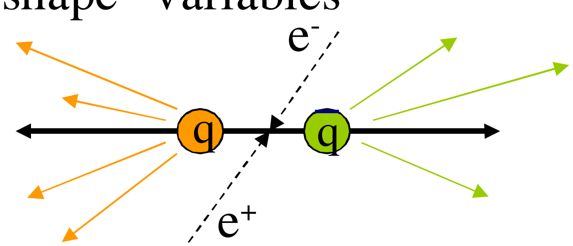
$Br(B^0 \to e^+e^-) \approx 10^{-15}$

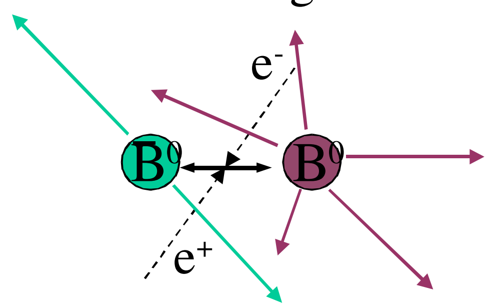
$Br(B^0 \to \mu^+\mu^-) \approx 10^{-10}$

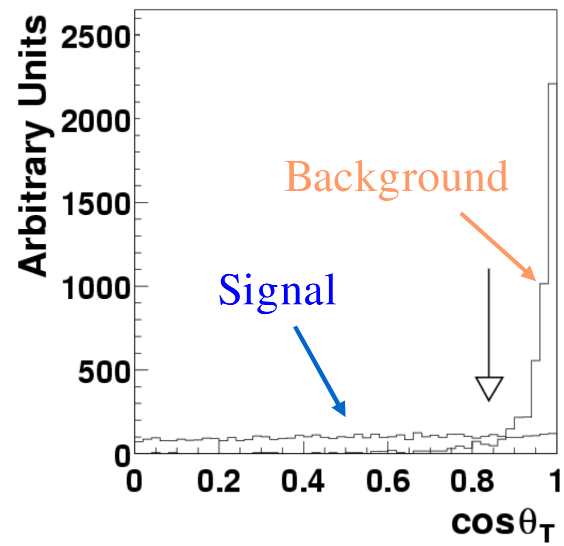
$Br(B^0 \to \tau^+\tau^-) \approx 10^{-8}$

  – New Physics can enhance rate by factor ~100 or more

- Experimentally very straightforward:
  – Distinguish B decays from continuum using "event shape" variables



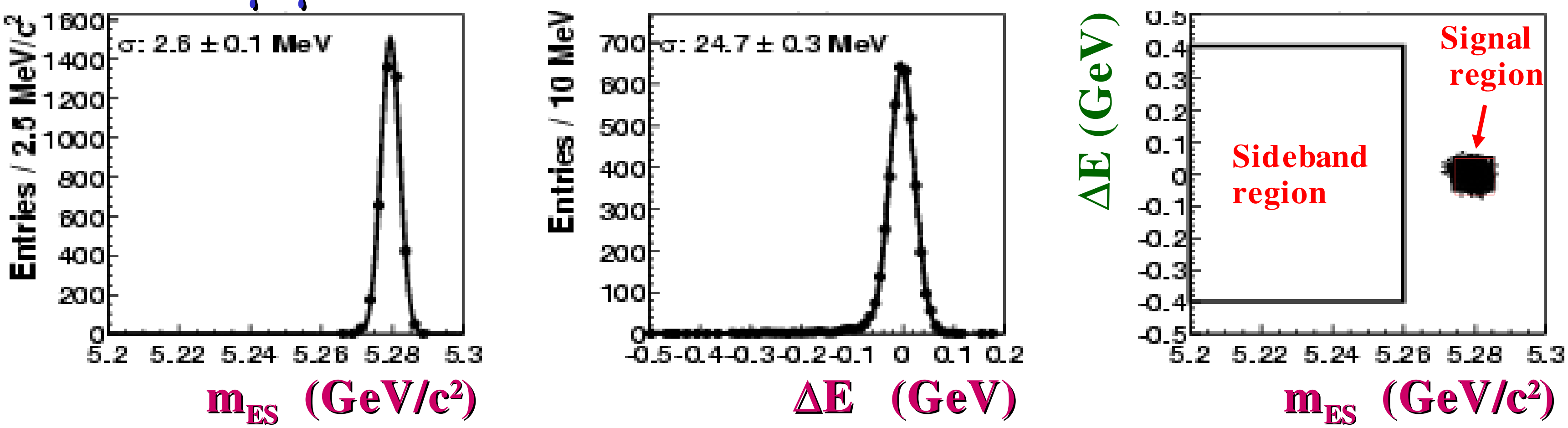




Then contrain kinematics of identified leptons to be consistent with a B meson parent...

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

$B^0 \to \mu^+\mu^-$ simulation

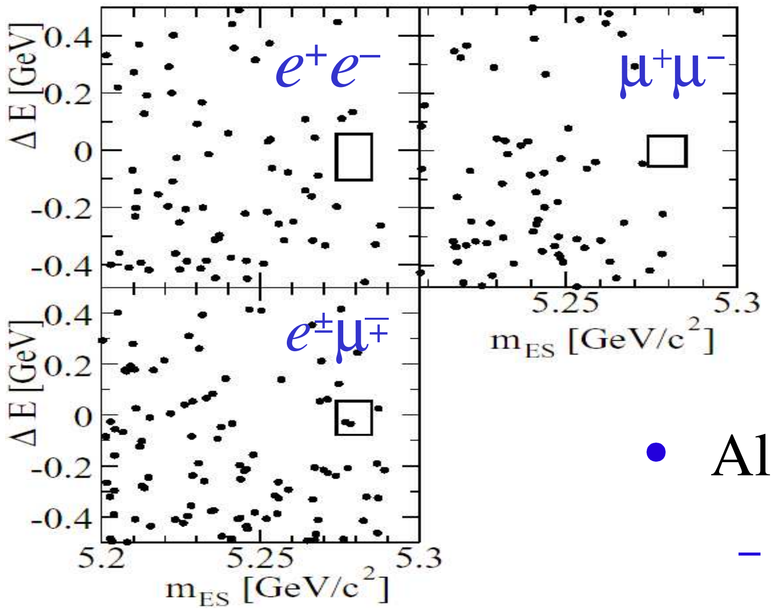


- Signal efficiencies obtained from MC
  - efficiency systematics of 5.7%, 7.1% and 6.8% (for ee, μμ, eμ) due to m_{ES} and ΔE shapes, tracking and PID
- Backgrounds estimated by extrapolating sideband regions in data into signal region
- Limits obtained from unblinded signal yields in data using modified frequentist method

$$m_{ES} \equiv \sqrt{E^{*2}_{\rm beam} - p^{*2}_{B}}$$
$$\Delta E^* \equiv E^*_B - E^*_{\rm beam}$$

channel	$N_{\rm obs}$	$N^{\rm bg}_{\rm exp}$	$\varepsilon[\%]$
$B^0 \to e^+e^-$	0	0.71 ± 0.31	21.8 ± 1.2
$B^0 \to \mu^+\mu^-$	0	0.72 ± 0.26	15.9 ± 1.1
$B^0 \to e^\pm\mu^\mp$	2	1.29 ± 0.44	18.1 ± 1.2

$B^0 \to l^+ l^-$ and $D^0 \to l^+ l^-$

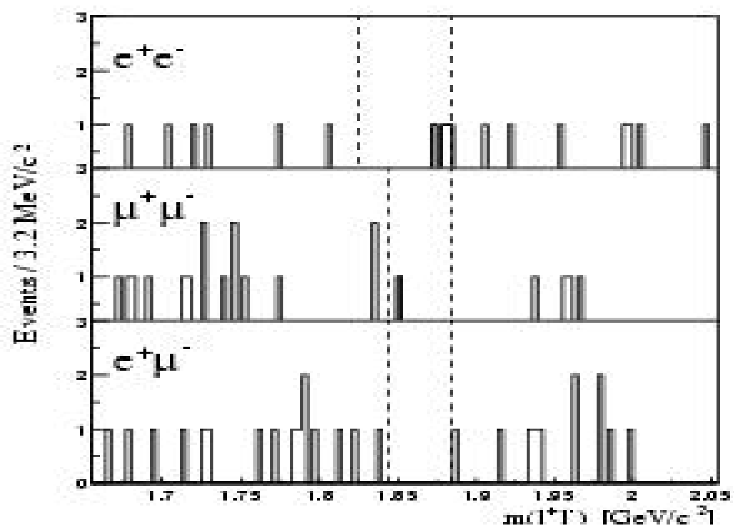


Based on 111 fb^{-1} :

$B(B^0 \to e^+e^-)$	$< 6.1 \times 10^{-8}$	at 90% C.L
$B(B^0 \to \mu^+\mu^-)$	$< 8.3 \times 10^{-8}$	hep-ex/0408096
$B(B^0 \to e^\pm\mu^{-+})$	$< 18 \times 10^{-8}$	(submitted to PRL)

***BABAR* Preliminary!**

- Also published limits on $D^0 \to l^+l^-$
  - sensitive to NP couplings to up-type quarks
  - Veto D^0 produced in B decays $P_D > 2.4$GeV/c and require $D^{*+} \to D^0\pi^+$ to reduce combinatorial backgrounds

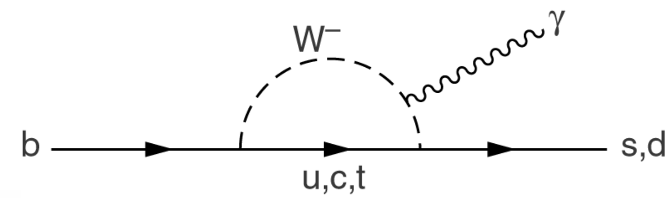


Based on 122 fb^{-1} (incl. offpeak)

$B(D^0 \to e^+e^-)$	$< 1.2 \times 10^{-6}$	at 90% C.L.
$B(D^0 \to \mu^+\mu^-)$	$< 1.3 \times 10^{-6}$	PRL 93:191801, 2004
$B(D^0 \to e^\pm\mu^{-+})$	$< 0.81 \times 10^{-6}$	(hep-ex/0408023)

$B \to \rho(770)\,\gamma$ and $B \to \omega(782)\,\gamma$

- FCNC processes proceed via EM penguin processes in SM with top quark in the loop



- Rates related by spectator quark model

$$\bar{\mathcal{B}}[B \to (\rho,\omega)\,\gamma] \equiv \frac{1}{2}\left\{\mathcal{B}(B^+ \to \rho^+\gamma) + \frac{\tau_{B^+}}{\tau_{B^0}}\left[\mathcal{B}(B_d^0 \to \rho^0\gamma) + \mathcal{B}(B_d^0 \to \omega\gamma)\right]\right\}$$

  - SM **$B[B \to (\rho,\omega)\,\gamma] \sim (0.9 - 1.8) \times 10^{-6}$** but also possible New Physics contributions

- Analysis on full dataset searches for modes **$B^+ \to \rho^+\gamma$, $B^0 \to \rho^0\gamma$** and **$B^0 \to \omega\gamma$**

  - select $\rho^0 \to \pi^+\pi^-$, $\rho^+ \to \pi^+\pi^0$, $\omega \to \pi^+\pi^-\pi^0$ candidates from combinations of pions with **$630 < m(\pi\pi) < 940$** MeV/c^2 and **$764 < m(\pi^+\pi^-\pi^0) < 795$** MeV/$c^2$
  - background primarily from $ee \to qq$ with energetic photon from ISR or π^0/η decays, or from other radiative B decays
  - photons candidates required to survive a $\pi^0(\eta)$ mass window "veto" in which they are combined with other photons with $E > 30(250)$ MeV

B→ (ρ,ω) γ results

- Additional bg rejection using neural net based on ROE (R2, cos $\theta^*_{\gamma\text{-}T}$, moments etc.) and Fisher based on signal (θ^*_B , θ_H etc.)
- Yield extracted from 4-dimensional extended maximum likelihood fit:

Based on 191 fb^{-1} :

$B(B^+ \to \rho^+\gamma) < 1.8 \times 10^{-6}$

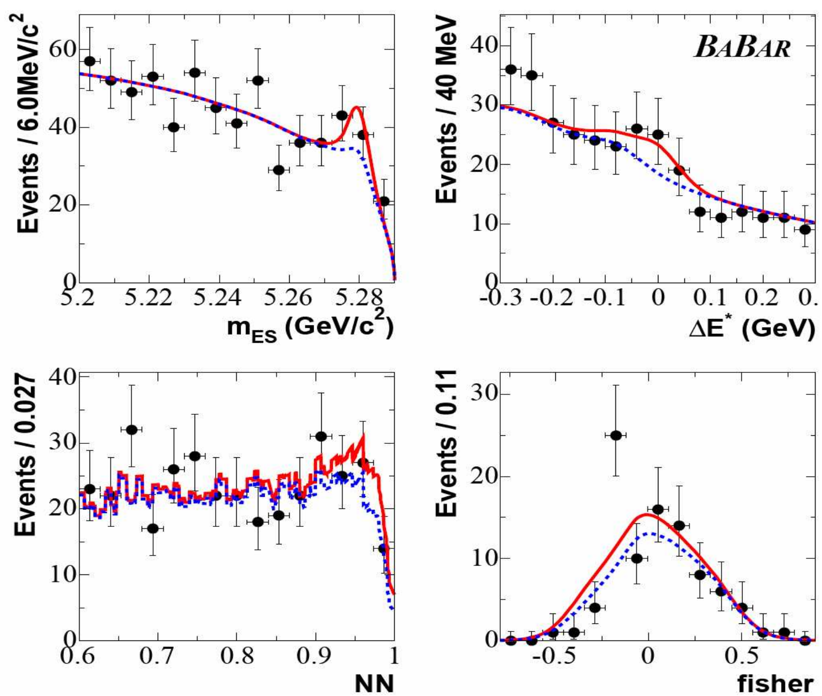
$B(B^0 \to \rho^0\gamma) < 0.4 \times 10^{-6}$

$B(B^0 \to \omega\gamma) < 1.0 \times 10^{-6}$

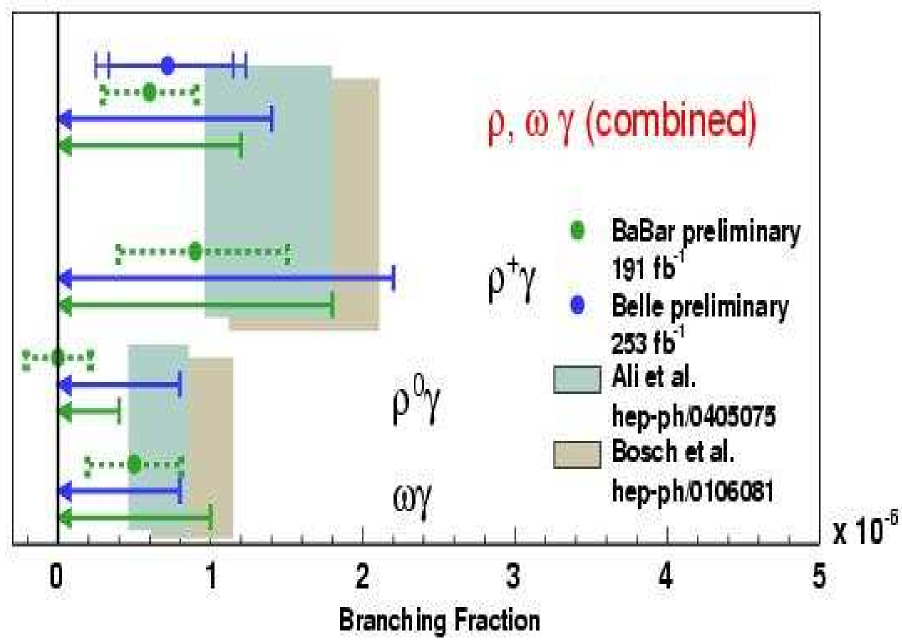
$B[B \to (\rho,\omega)\gamma] < 1.2 \times 10^{-6}$

at 90% C.L

B. Aubert et al., PRL 94,011801 (2005)



Combined (ρ,ω) γ fit



Unitarity triangle constraints

- Ratio of **b→ dγ** to **b→ sγ** modes constrains ratio of the CKM elements $|V_{td}|/|V_{ts}|$:

Ali et al. hep-ph/0405075

$$\frac{\overline{\mathcal{B}}[B \to (\rho/\omega)\gamma]}{\mathcal{B}(B \to K^*\gamma)} = \left|\frac{V_{td}}{V_{ts}}\right|^2 \left(\frac{1 - m_\rho^2/M_B^2}{1 - m_{K^*}^2/M_B^2}\right)^3 \zeta^2[1 + \Delta R]$$

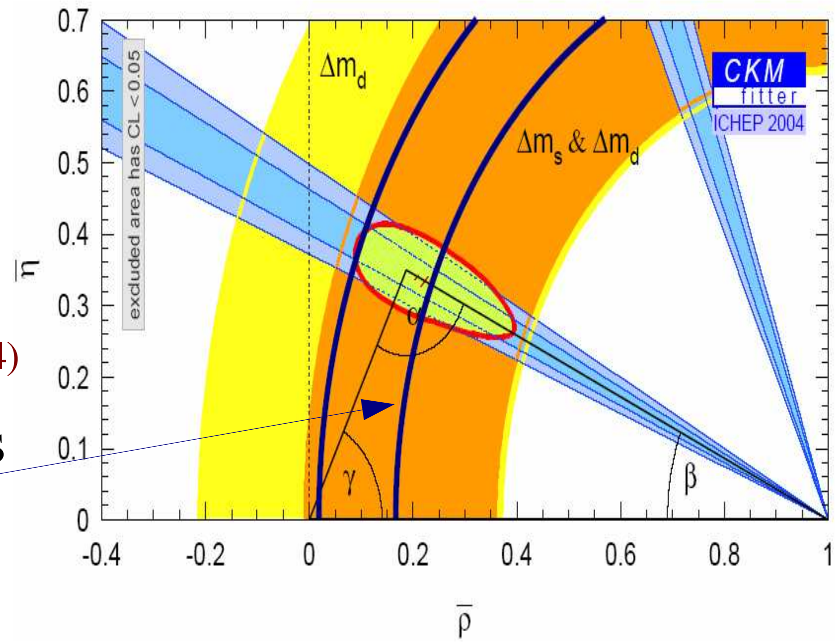
flavour SU(3) breaking $\zeta^2 = 0.85 \pm 0.10$

weak annihilation correction $\Delta R = 0.1 \pm 0.1$

- Using **B[B→ (ρ,ω)γ]** and BABAR measurement of **B→ K*γ**, obtain limit of <0.029 (90% C.L.) on the ratio of branching fractions

B. Aubert et al., PRD 70, 112006 (2004)

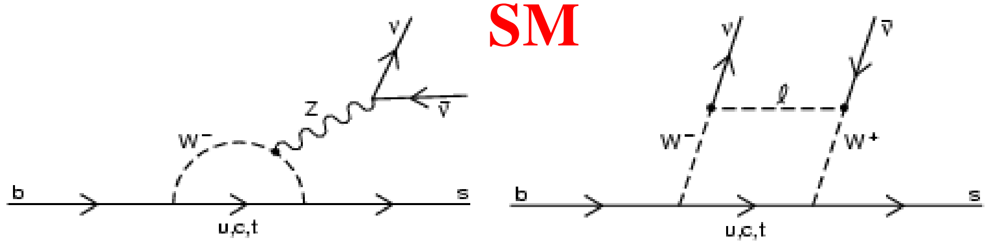
- Neglecting theoretical uncertainties yields $|V_{td}|/|V_{ts}| < 0.19$



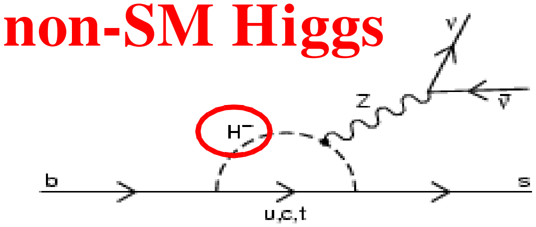
$B^+ \to K^+ \nu \bar{\nu}$ (and $\pi^+ \nu \bar{\nu}$)

- $b \to s \nu \bar{\nu}$ branching fraction theoretically clean and potentially sensitive to New Physics
  - No photonic penguin (only Z penguin) and a single Wilson coefficient (C_{10}); no long distance contributions

SM



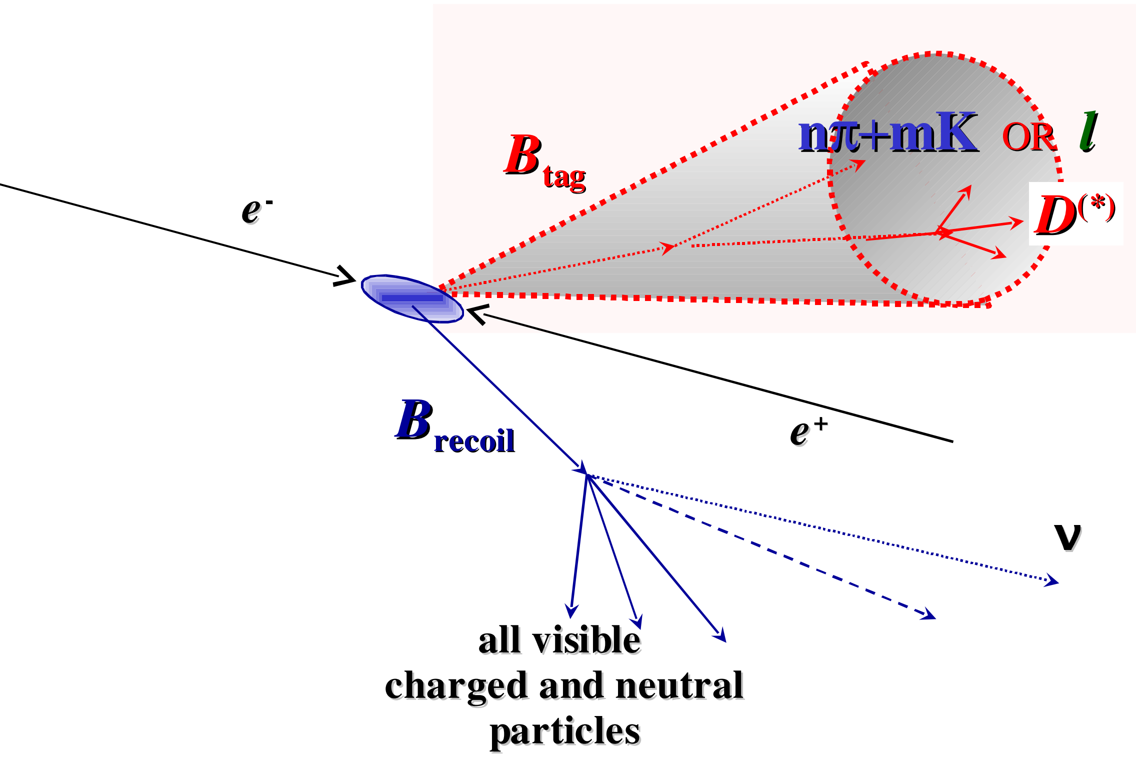
non-SM Higgs

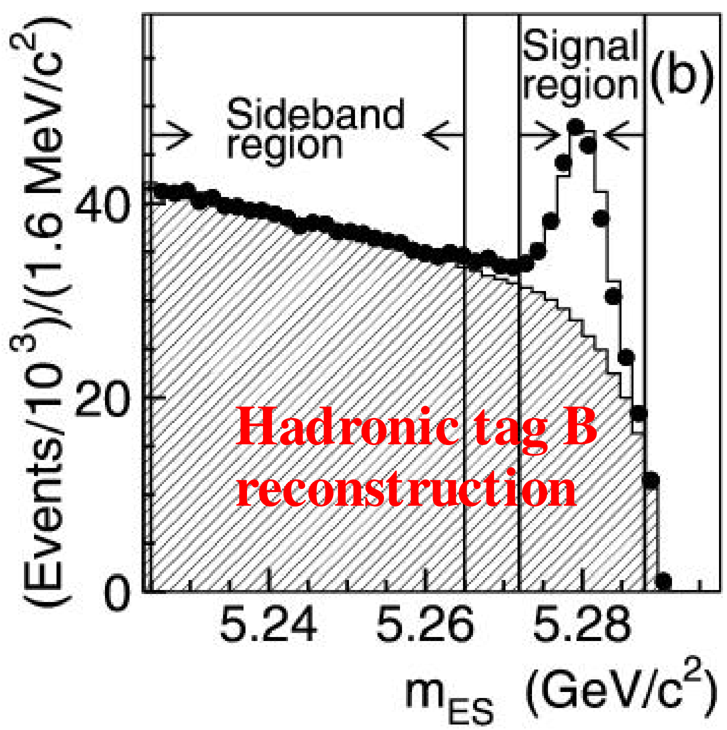


- Experimental limits can constrain everything from charged Higgs and SUSY to scalar dark matter couplings (Bird et al., PRL 93,201803 (2004))
- Presence of neutrinos in the final state makes experimental search challenging, hence search only for exclusive decays
  - Standard model: $B(B^+ \to K^+\nu\nu) \sim 4 \times 10^{-6}$

Recoil method

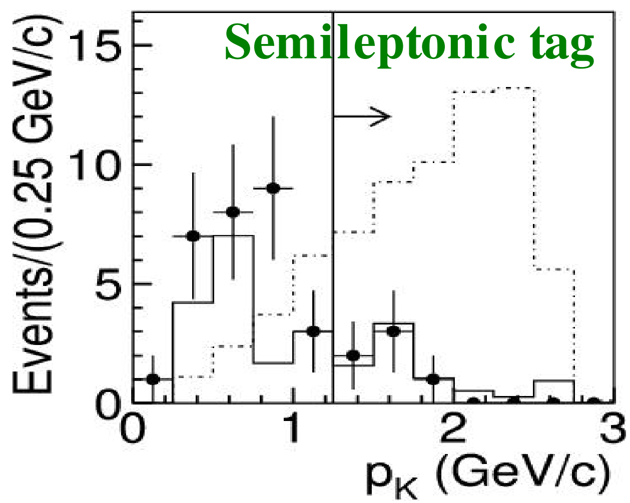
- Physics with a single-B "beam" (a.k.a. "recoil analysis")
  - exclusively reconstruct the decay of one B from Y(4S)→ BB in either a hadronic or semileptonic decay mode
  - **Hadronic B reconstruction** efficiency of ~0.2% yields **~2000** charged-B "tags" per fb^{-1} ; **Semileptonic** reconstruction yields **~5000** per fb^{-1}

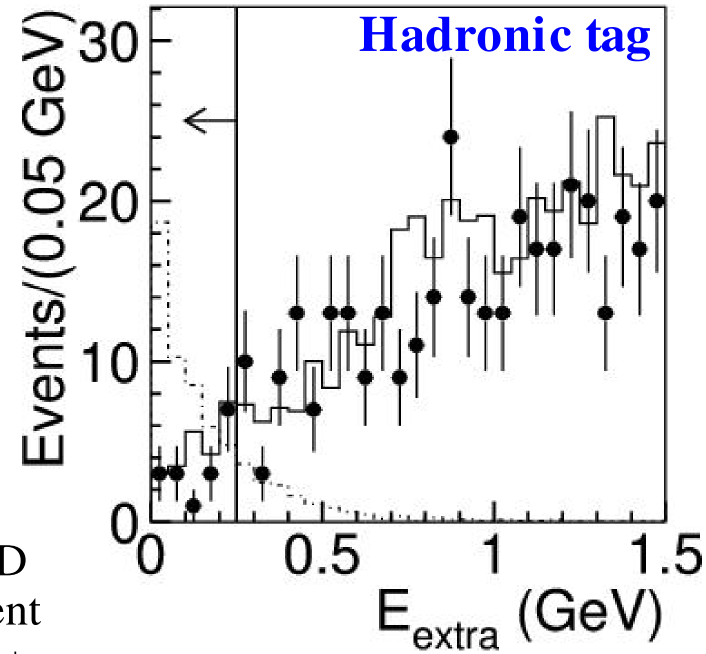




$B^+ \to K^+ \nu \bar{\nu}$ (had+SL recoil)

- Require only a single charged track ($K^\pm$ with $p_K > 1.25$ GeV/c) and little or no additional calorimeter energy ($E_{extra} < 250$ MeV)





reverse PID requirement for $B^+ \to \pi^+\nu\nu$ search

Tag	Hadronic	Semileptonic
Efficiency (%)	0.055 ± 0.005	0.115 ± 0.009
Background	3.9 ±1.1	3.4 ±1.2 *
Observed events	3	6

(*non-peaking only)

Based on 82 fb^{-1} :

$B(B^+ \to K^+\nu\nu) < 5.2 \times 10^{-5}$

$B(B^+ \to \pi^+\nu\nu) < 10 \times 10^{-5}$

at 90% C.L.

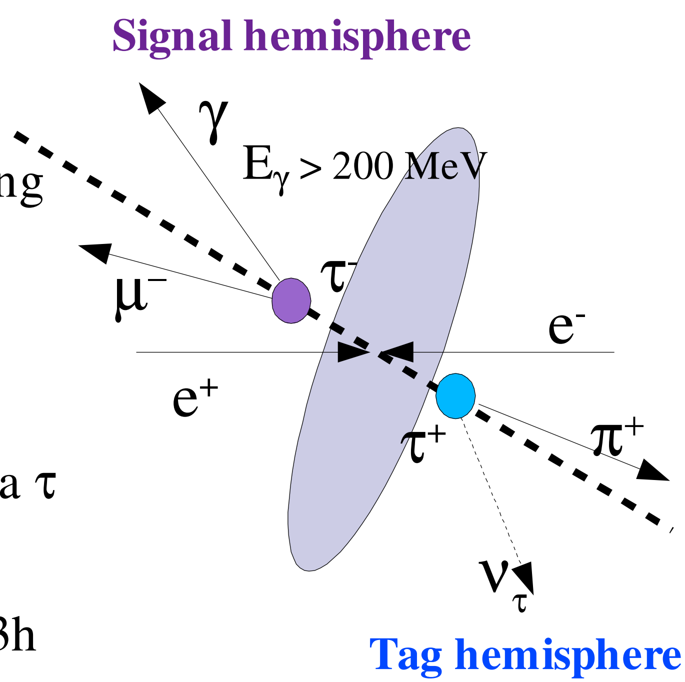
hep-ex/0411061

(accepted by PRL)

Neutrinoless τ decays (LFV)

- Lepton flavour violation in τ decays among the most theoretically clean signatures of New Physics
  - Occurs at level of $\sim 10^{-54}$ in the SM (with non-zero neutrino mass)
  - NP models predict enhancements up to current experimental limits and enhancements in τ decays relative to μ decays (very model specific!)

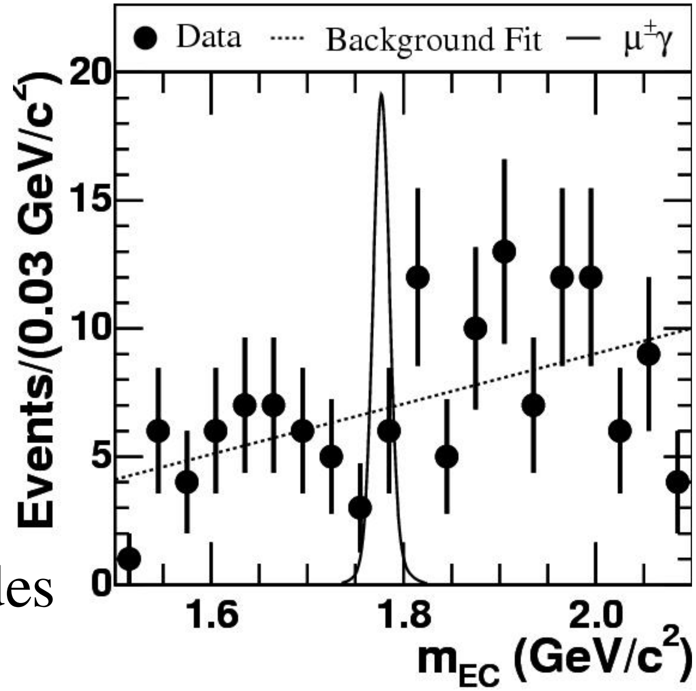
- $\tau^+ \rightarrow \mu^+ \gamma$
  - 232 fb^{-1} (on and off peak data) corresponding to 2.07×10^8 $e^+e^- \rightarrow \tau^+\tau^-$ events
  - Divide events into "signal" and "tag" hemispheres (based on thrust axis)
  - Look for $\mu-\gamma$ combination consistent with a τ parent in events with 1-1 or 1-3 topologies
  - Include additional tag modes: e, μ, h and 3h



$\tau^+ \rightarrow \mu^+ \gamma$ results

BABAR **Preliminary!**

- Define signal region as 2σ ellipse in:
  - $\Delta E = E_{\mu\gamma} - \sqrt{s}/2$
  - m_{EC} = invariant mass resulting from $\mu\gamma$ kinematic fit with $E_{\mu\gamma}$ constrained to $\sqrt{s}/2$
- Additional bg rejection from neural net (m_{miss}, p^T_{miss} , p^{tag}_{max}, $\cos\theta_H$, m_ν^2)
- Total of 4 events observed in all tag modes (expect 6.2 ± 0.5 background)
  - signal efficiency ~7.4%
  - Dominant backgrounds are $e^+e^- \rightarrow \mu^+\mu^-$ (66%) and $e^+e^- \rightarrow \tau^+\tau^-$ (27%)
  - Limits extracted from extended ML fit to m_{EC}



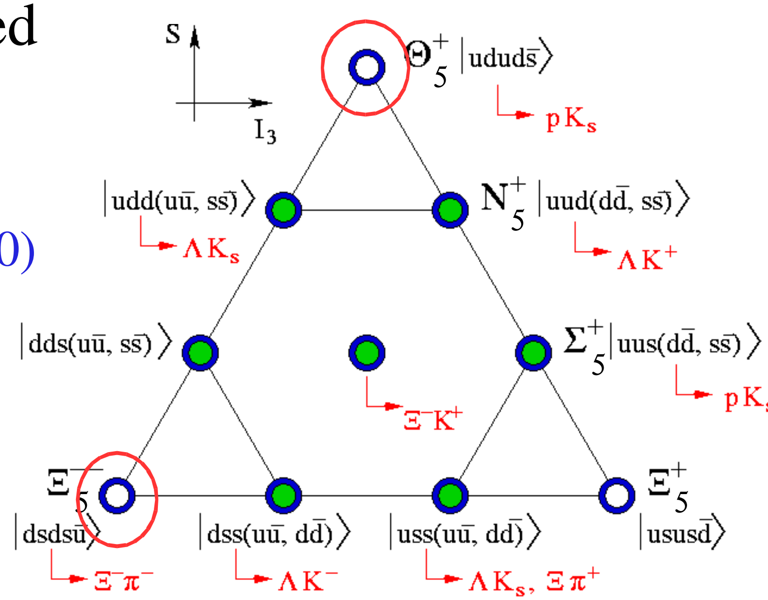
Based on 232 fb^{-1} :
$B(\tau^+ \rightarrow \mu^+\gamma) < 6.8 \times 10^{-8}$
at 90% C.L.
hep-ex/0502032
(submitted to PRL)

- Also BABAR limits on $\tau \rightarrow$ lll & lhh PRL 92:121801, 2004 and hep-ex/0409036

Pentaquark searches

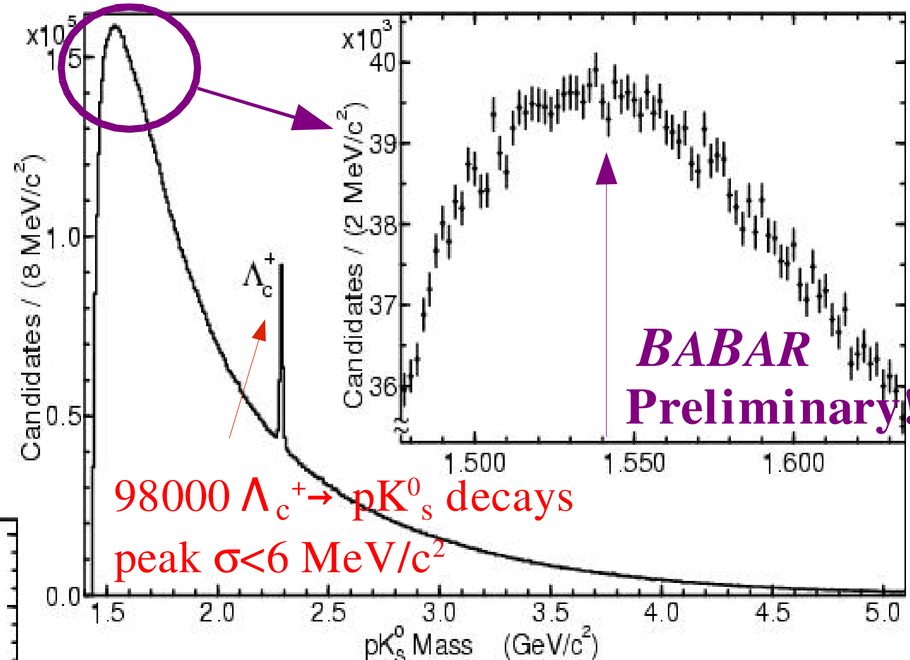
- Recent pentaquark frenzy triggered by paper by D.Diakonok, V. Petrov and M. Polyakov Z.Phys. A 359 (1997) 305., and evidence for $\Theta^+(1540)$ from several experimental groups
  - Chiral soliton model with $N^+(1710)$ as input, and mass splitting of ~180MeV
  - "Exotic" $\Theta^+(1540)$ would have to have minimal quark content of $udud\bar{s}$

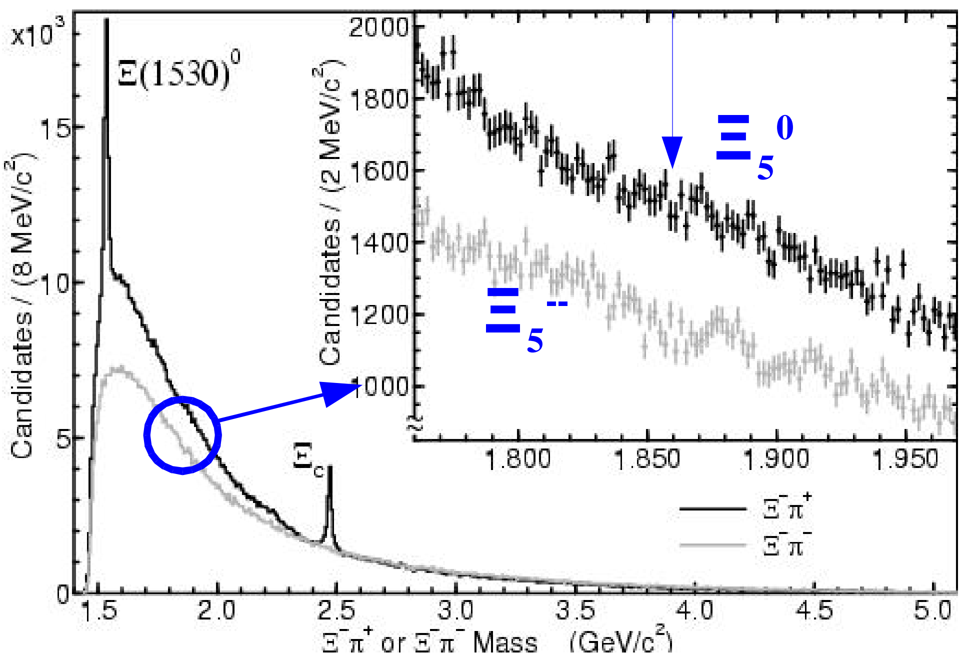
- BABAR preliminary results presented at ICHEP 04 (hep-ex/0408064; BABAR-CONF-04/36)
  - Search for $\Theta^+(1540)$, $\Xi^{--}(1860)$, $\Xi^0(1860)$ as well as other members of the antidecuplet and corresponding octet
- Results recently submitted to PRL



$\Theta(1540)^{+}$, $\Xi_5(1860)^{--}$ and $\Xi_5(1860)^{0}$

- Search for $\Theta^+ \rightarrow p K^0_s \, (K^0_s \rightarrow \pi^+\pi^-)$
  - Use all events accepted by trigger (>99% efficient for $ee \rightarrow qq$)
  - Reconstructed invariant mass resolution ranges from 2 – 8 MeV/c depending on mode and momentum.



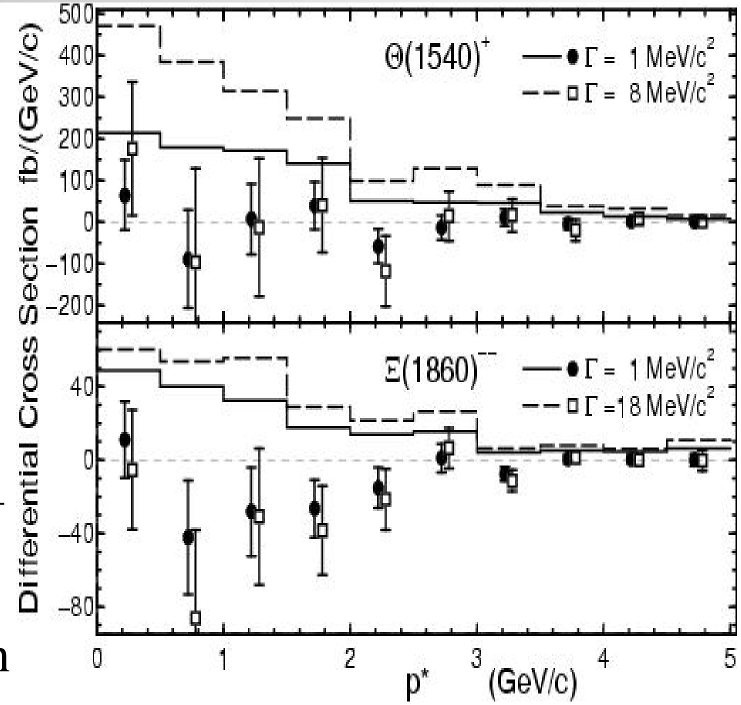


- $\Xi_5^{--} \rightarrow \Xi^- \pi^-$ and $\Xi_5^{0} \rightarrow \Xi^- \pi^+$ with $\Xi^- \rightarrow \Lambda^0\pi^-$, $\Lambda^0 \rightarrow p\pi^-$
  - observe 290000 Ξ^- candidates with S:B of 23:1 in $\Lambda^0 p^-$ mass
  - signal efficiency of 6.5% (low p*) to 12% (high p*)

Pentaquark results

BABAR **Preliminary!**

- No evidence for $\Theta(1540)^+$ or $\Xi_5(1860)$
- Production mechanism not known:
  - model-independent limits derived on inclusive production rates by fitting mass spectra in bins of p*
  - signal width varied from 1 MeV/c^2 up to natural widths of 8(18) MeV/c^2 for $\Theta(1540)^+$ ($\Xi(1860)^{--}$) reported by other experiments
  - yields quoted relative to total number of both ee → qq and Y(4S) events

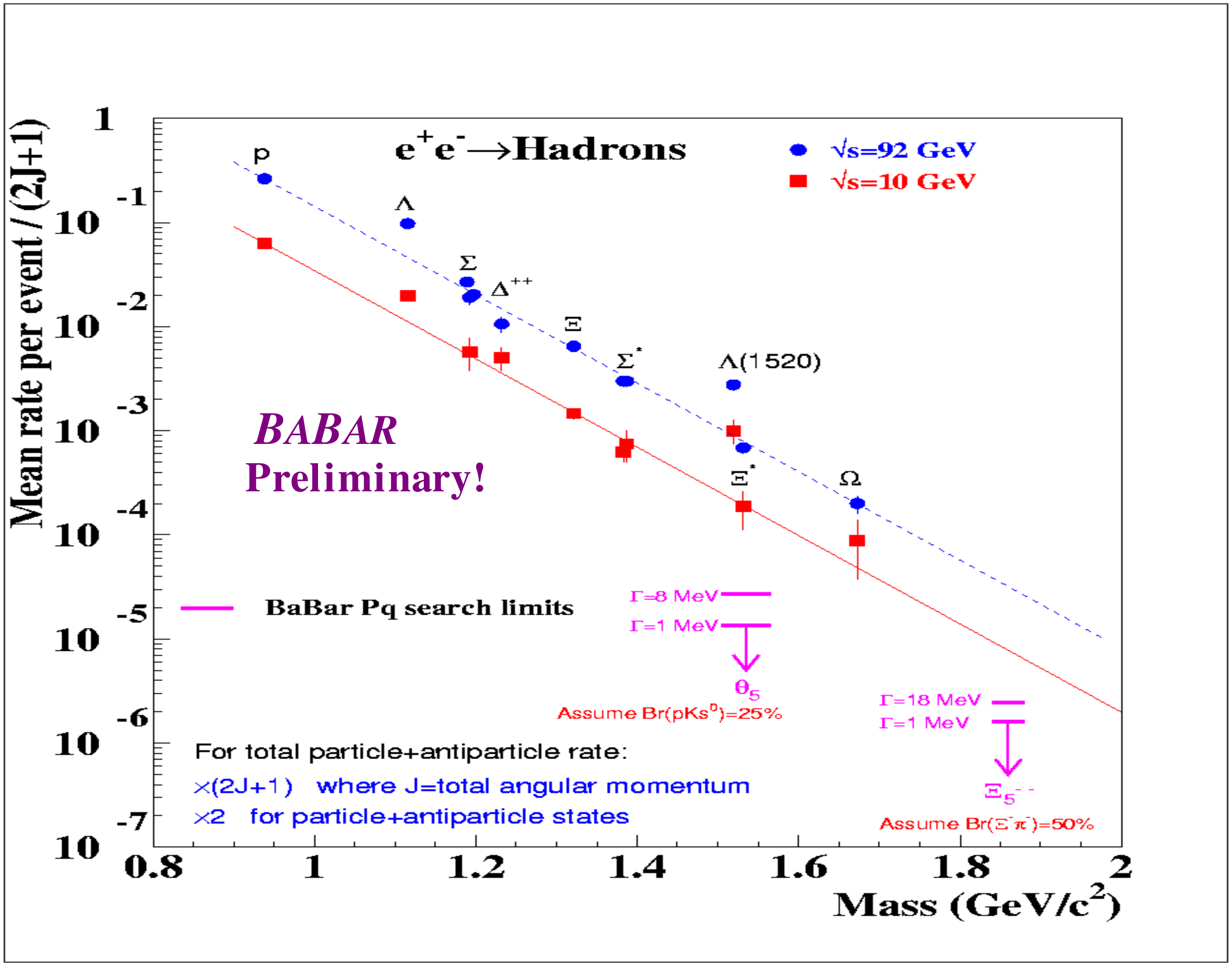


- If $\Theta(1540)^+$ or $\Xi_5(1860)^{--}$ pentaquarks exist, they are suppressed in e^+e^- → qq relative to ordinary baryons of similar mass by at least factors of 8 and 4 respectively

Pentaquark state	Cross-section UL (fb)	$e^+e^- \to$ qq yield UL (10^{-5}/event)
$\Theta^+ + \Theta^-$	171 (363)	5 (11)
$\Xi_5^{--} + \Xi_5^{++}$	25 (36)	0.74 (1.1)

Γ = 1 MeV/c^2 (Γ=natural width)
Based on 123 fb^{-1} of BABAR data
hep-ex/0502004 (submitted to PRL)

Baryon production rates in e^+e^-



Summary

- Present *BABAR* data set has permitted sensitive searches for rare B, τ and charm decays as well as exotic processes
  - currently ~240 fb^{-1} recorded; anticipate doubling by summer 2006
- Stringent (and interesting) limits on EW penguin processes
  - $B \to \rho/\omega\,\gamma$, $B \to K/\pi\,\nu\nu$, $B^0 \to l^+l^-$, $D^0 \to l^+l^-$
  - "Recoil method" analyses now have $O(10^6)$ reconstructed (hadronic + semileptonic) B decays, giving interesting sensitivity to modes with otherwise intractable backgrounds (e.g. $B \to K\nu\nu$)
- Comprehensive limits on LFV in τ decays
- No evidence for pentaquark production in e^+e^-

Backup slides

τ decay LFV results

Based on 91.5 fb^{-1} :

$B(\tau^- \to e^- e^+ e^-) < 1.4 \times 10^{-7}$ at 90% C.L.

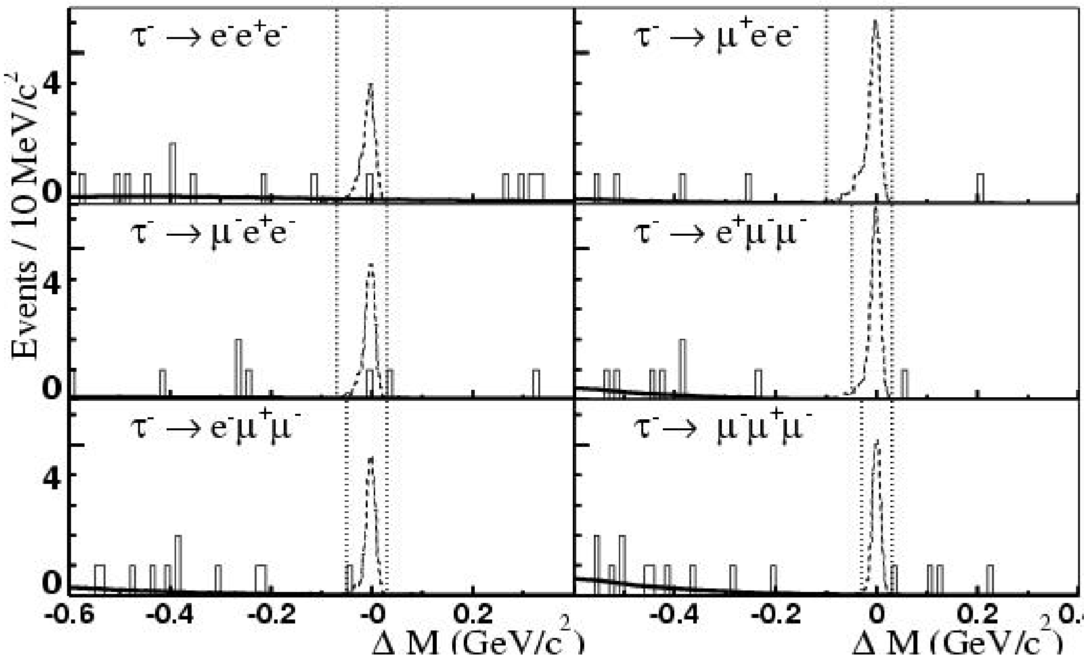
$B(\tau^- \to \mu^+ e^- e^-) < 1.4 \times 10^{-7}$

$B(\tau^- \to \mu^- e^+ e^-) < 1.4 \times 10^{-7}$ PRL 92:121801, 2004

$B(\tau^- \to e^+ \mu^- \mu^-) < 1.4 \times 10^{-7}$ (hep-ex/0312027)

$B(\tau^- \to e^- \mu^+ \mu^-) < 1.4 \times 10^{-7}$

$B(\tau^- \to \mu^- \mu^+ \mu^-) < 1.4 \times 10^{-7}$



Based on 221 fb^{-1} :

$B(\tau^- \to e^- K^+ K^-) < 1.4 \times 10^{-7}$

$B(\tau^- \to e^- K^+ \pi^-) < 1.7 \times 10^{-7}$

$B(\tau^- \to e^- \pi^+ K^-) < 3.2 \times 10^{-7}$

$B(\tau^- \to e^- \pi^+ \pi^-) < 1.2 \times 10^{-7}$

$B(\tau^- \to \mu^- K^+ K^-) < 2.5 \times 10^{-7}$

$B(\tau^- \to \mu^- K^+ \pi^-) < 3.2 \times 10^{-7}$

$B(\tau^- \to \mu^- \pi^+ K^-) < 2.6 \times 10^{-7}$

$B(\tau^- \to \mu^- \pi^+ \pi^-) < 2.9 \times 10^{-7}$

$B(\tau^- \to e^- K^+ K^-) < 1.5 \times 10^{-7}$

$B(\tau^- \to e^- K^+ \pi^-) < 1.8 \times 10^{-7}$

$B(\tau^- \to e^- \pi^+ \pi^-) < 2.7 \times 10^{-7}$

$B(\tau^- \to \mu^- K^+ K^-) < 4.8 \times 10^{-7}$

$B(\tau^- \to \mu^- K^+ \pi^-) < 2.2 \times 10^{-7}$

$B(\tau^- \to \mu^- \pi^+ \pi^-) < 0.7 \times 10^{-7}$

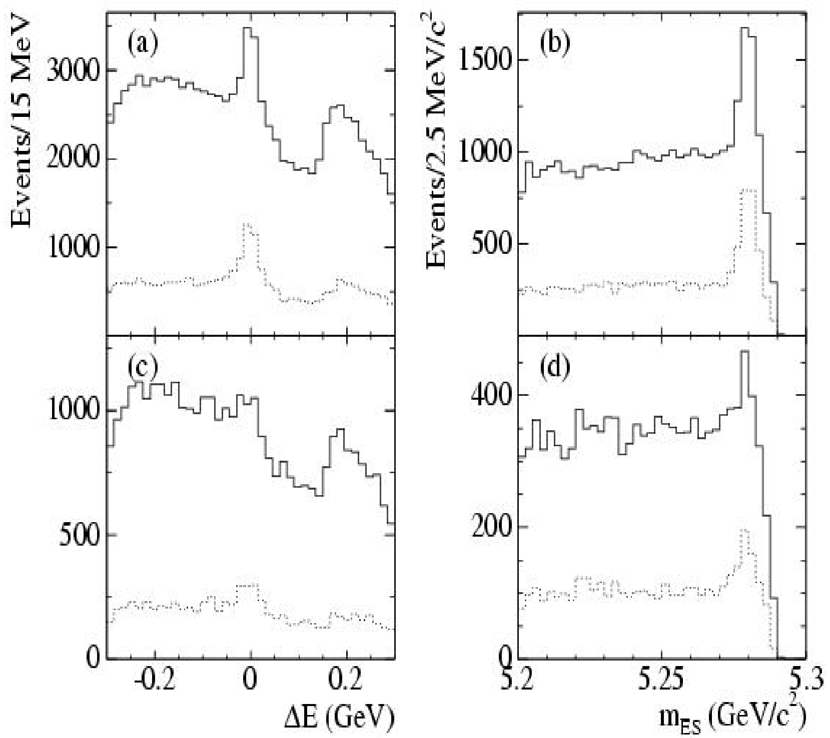
at 90% C.L.

hep-ex/0409036 (presented ar TAU04)

Charged partner of the X(3872)

- Narrow $J/\psi\ \pi^+\pi^-$ resonance observed in $B^- \rightarrow X K^-$ decays by Belle and confirmed by other experiments including BABAR (hep-ex/0406022)
  - kinematic distribution of $\pi^+\pi^-$ consistent with $\rho^0 \rightarrow \pi^+\pi^-$ hence might expect isospin partner decay $X^- \rightarrow J/\Psi\ \rho^-$

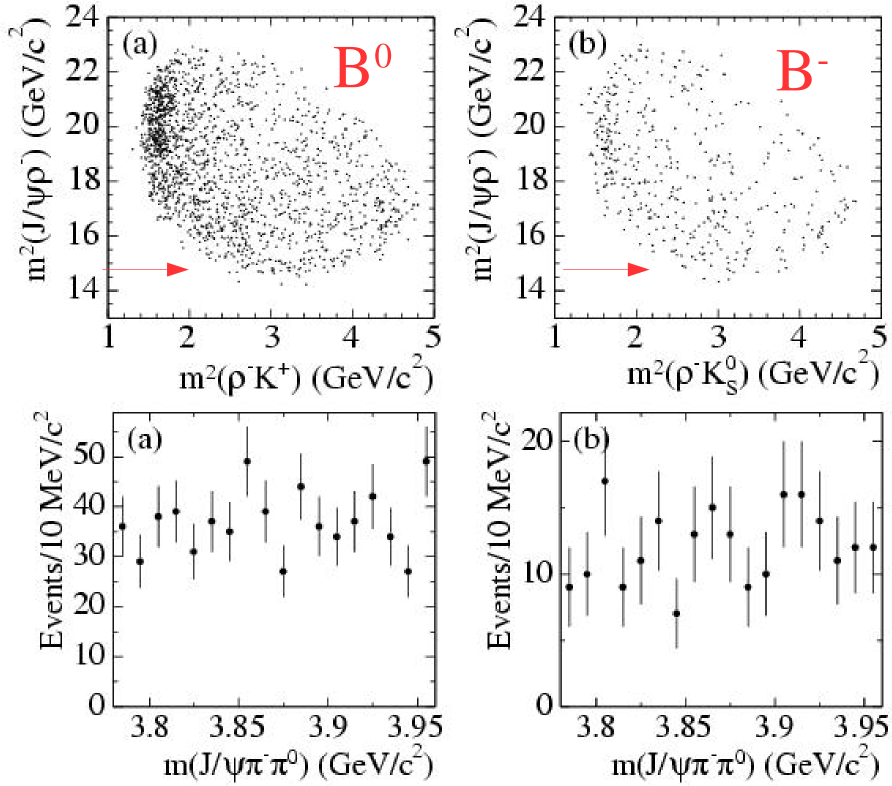
- Reconstruct $B^0 \rightarrow X^- K^+$ and $B^- \rightarrow X^- K^0_s$ with $X^- \rightarrow J/\Psi\ \pi^- \pi^0$
  - $J/\Psi \rightarrow e^+e^-, \mu^+\mu^-$; $K^0_s \rightarrow \pi^+\pi^-$
  - Retain B candidates with $|m_{ES}-m_B| < 5$ MeV/c^2 and $\Delta E < 20$ MeV
  - $0.67 < m(\pi^+\pi^0) < 0.78$ MeV/c^2



X^- results

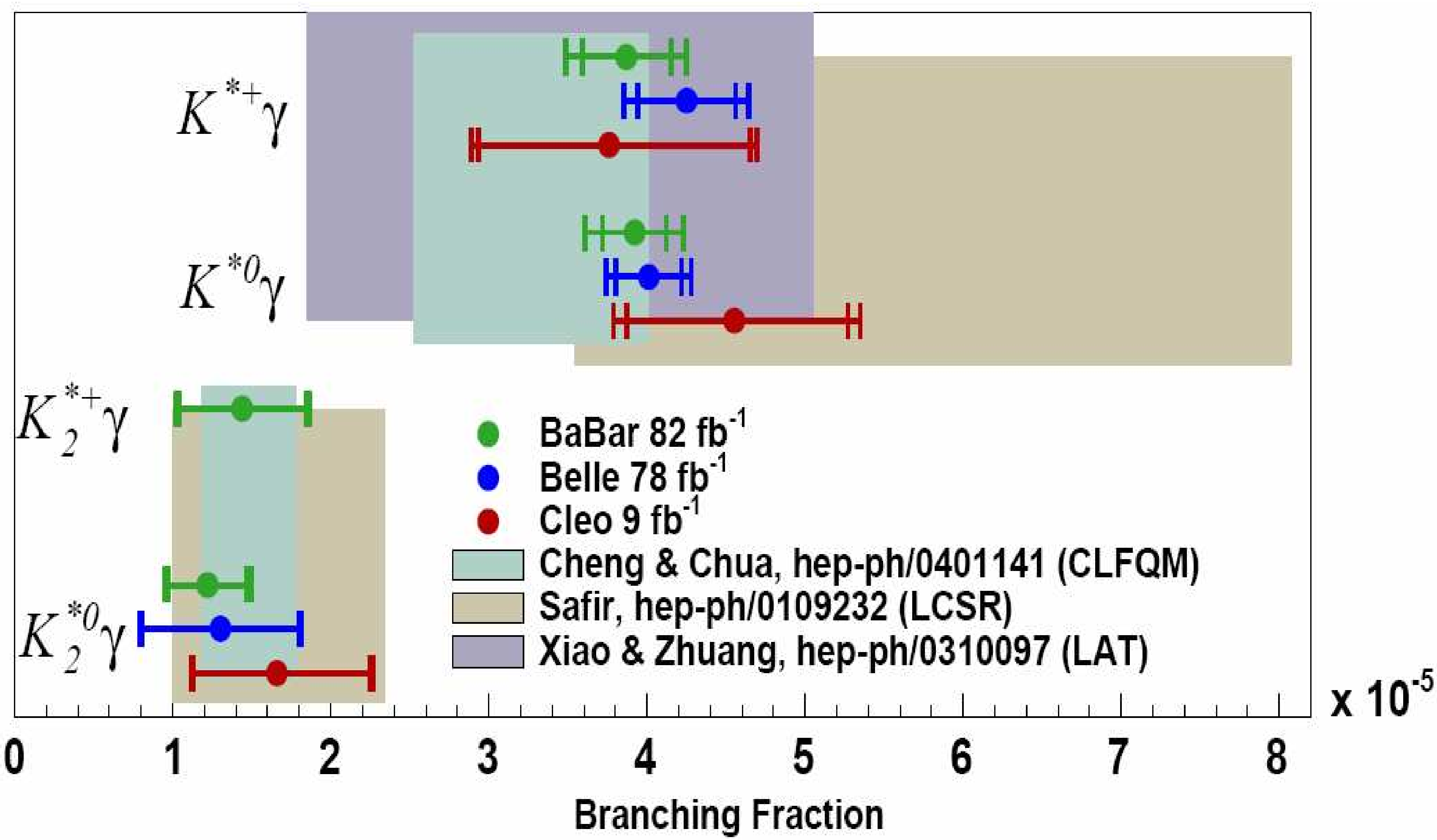
BABAR
Preliminary!

- No evidence of signal apparent either in Dalitz plots or in $m(J/\Psi\ \pi^+\pi^0)$ distributions
- Isovector signal hypothesis predicts:
  $B(B \to X^- K,\ X^- \to J/\Psi\ \pi^+\pi^0) =$
  $2 \times B(B \to X(3872) K,\ X \to J/\Psi\ \pi^+\pi^-)$
- comparison of X^- limits with BABAR X(3872) result excludes isovector-X hypothesis
  - (likelihood ratio favours null hypothesis by factor 1.1×10^4)

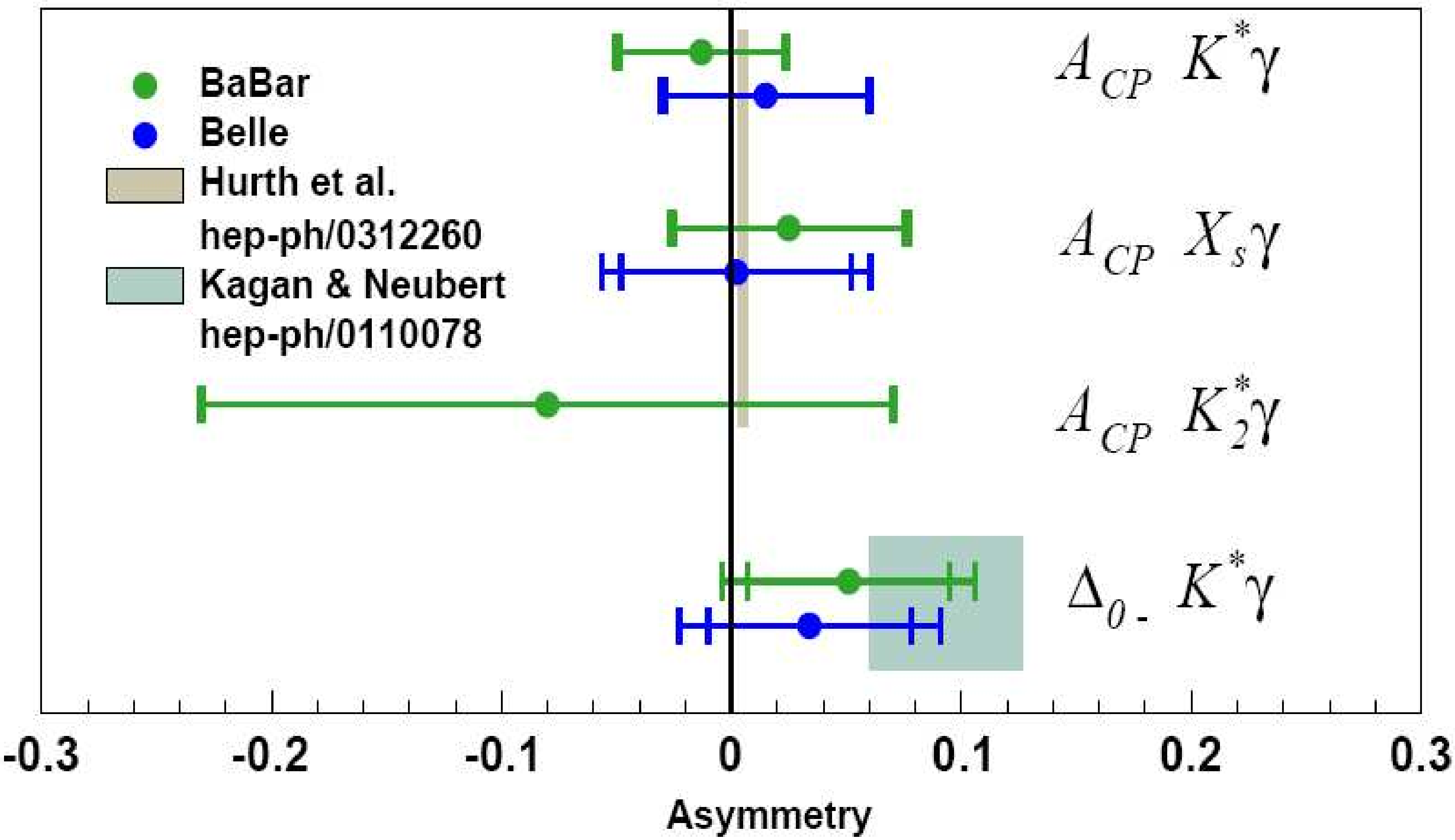


Based on 212 fb^{-1} :
$B(B^0 \to X^- K^+, X^- \to J/\Psi\ \pi^-\pi^0) < 5.4 \times 10^{-6}$
$B(B^0 \to X^- K^0,\ X^- \to J/\Psi\ \pi^-\pi^0) < 22 \times 10^{-6}$
at 90% C.L.
hep-ex/0412051 (submitted to PRD-RC)

B(B→ K*γ) results

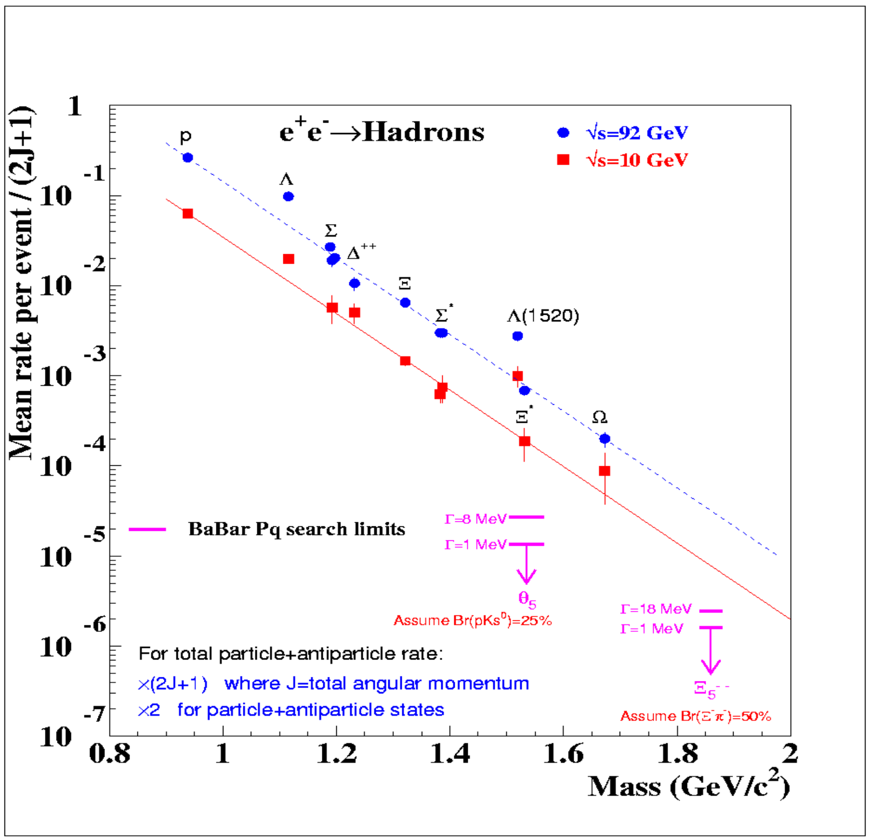


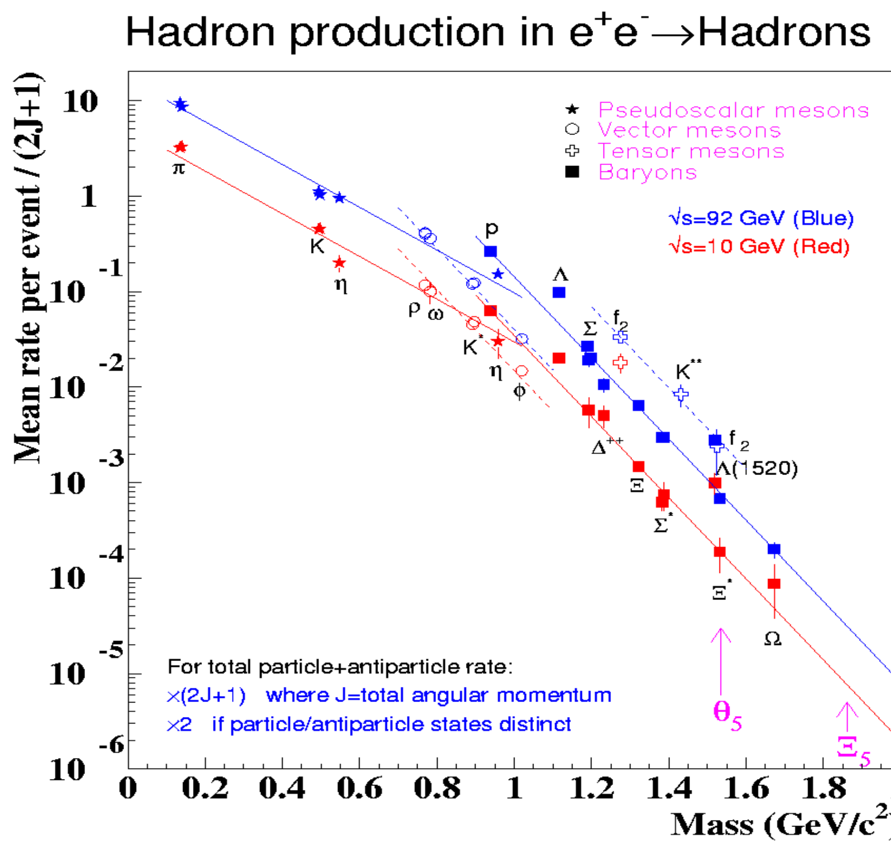
$B \rightarrow K^*\gamma$ CP asymmetry



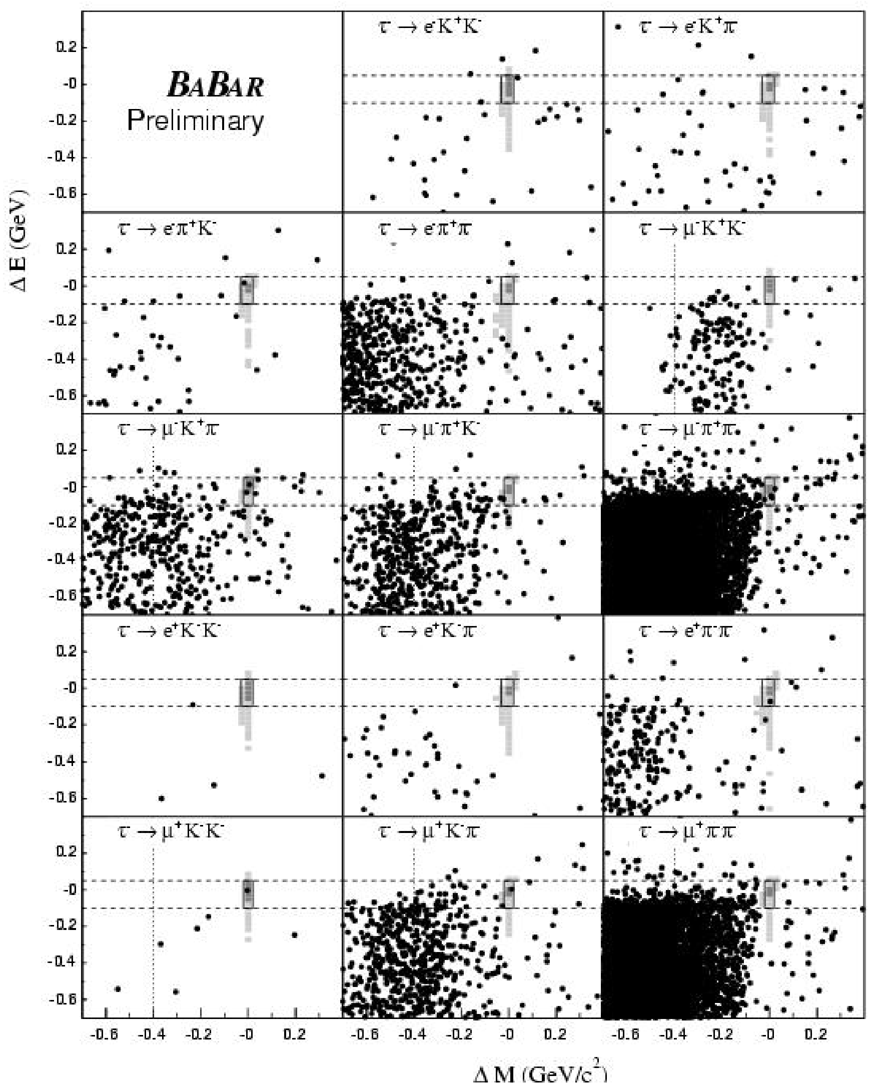
Hadron production rates in e+e-

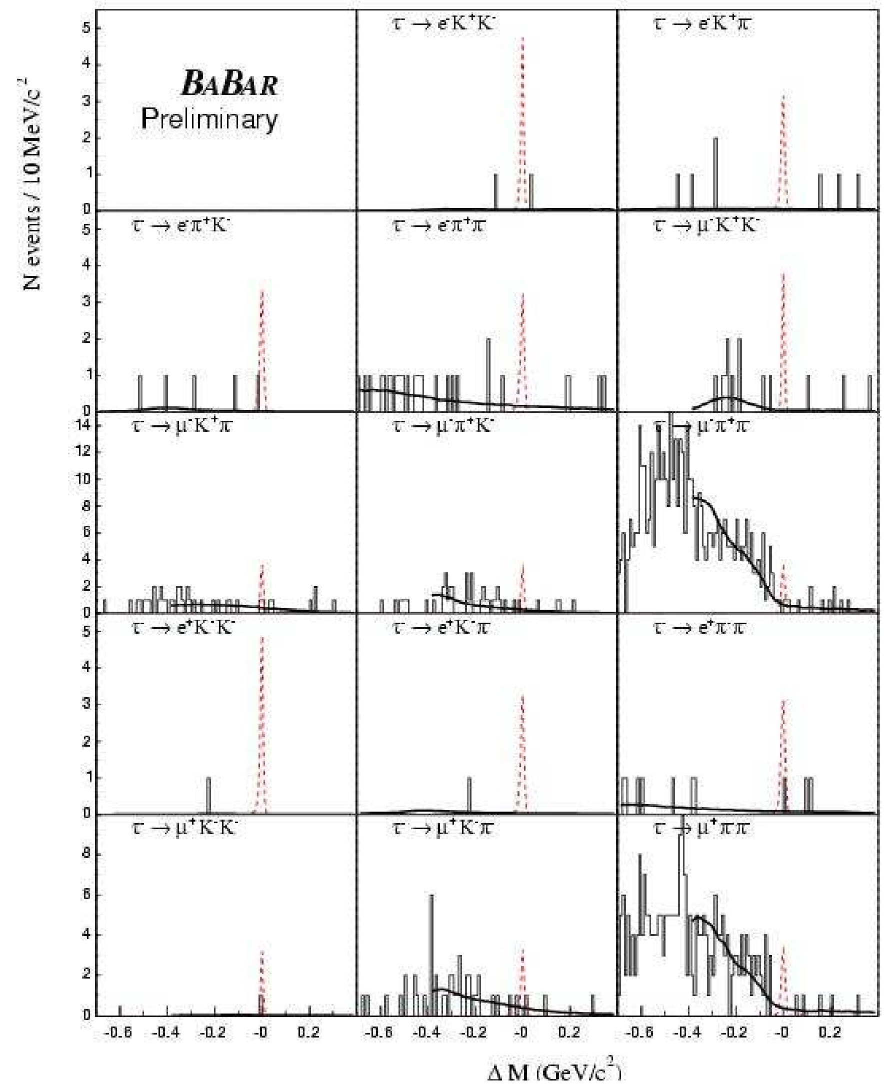
- Adapted from PDG, K.Hagiwara et at., Phys. Rev. D 66, 010001 (2002)



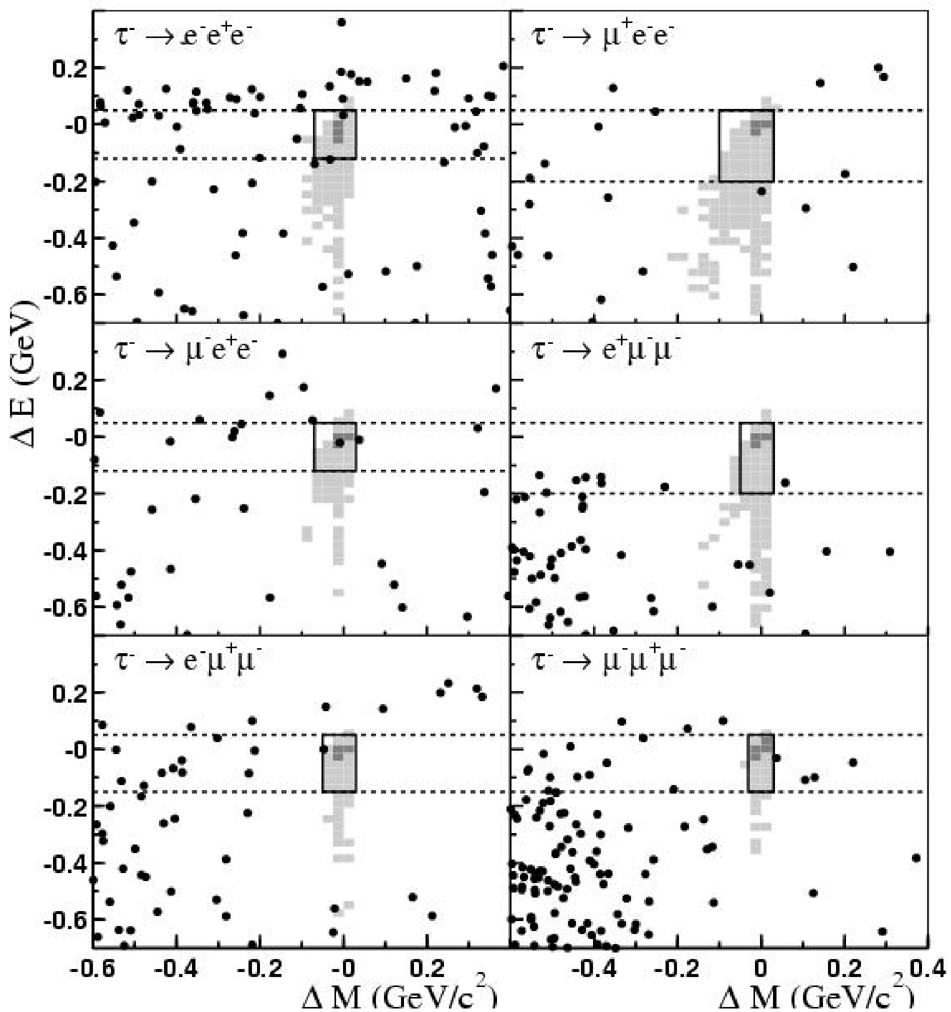


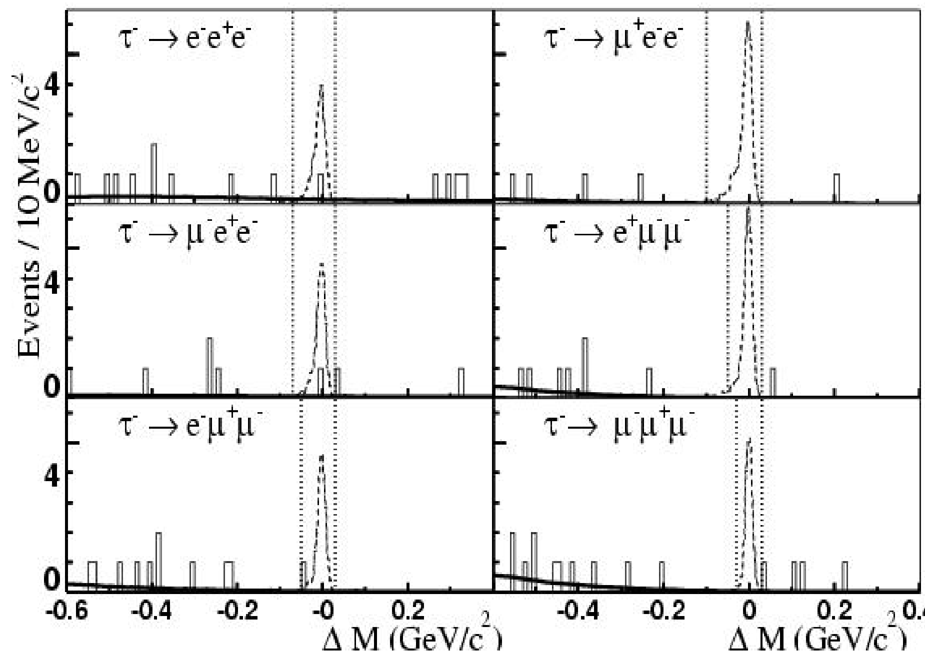
$\tau^+ \rightarrow l^+ h^- h^+$



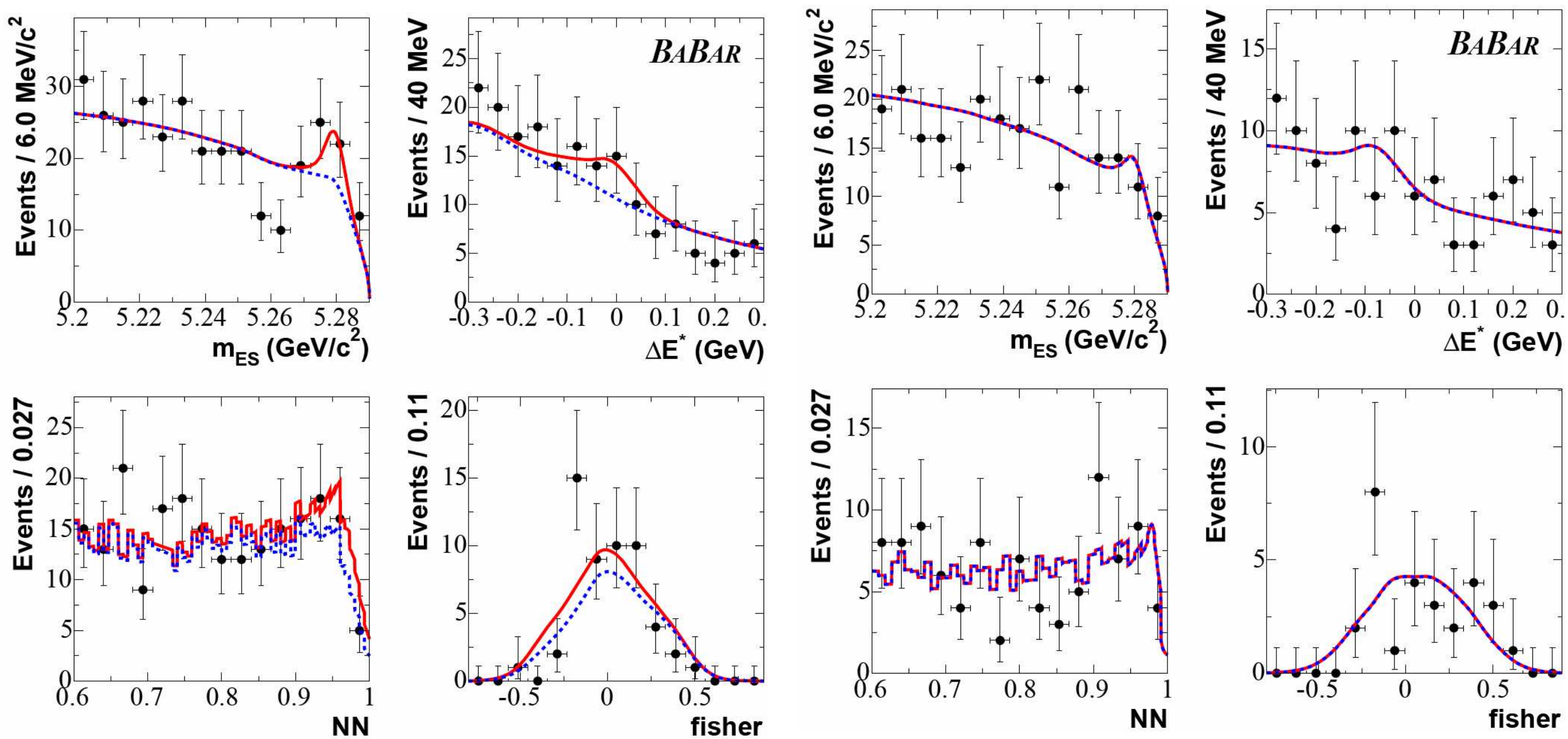


$\tau^+ \rightarrow l^+ h^- h^+$

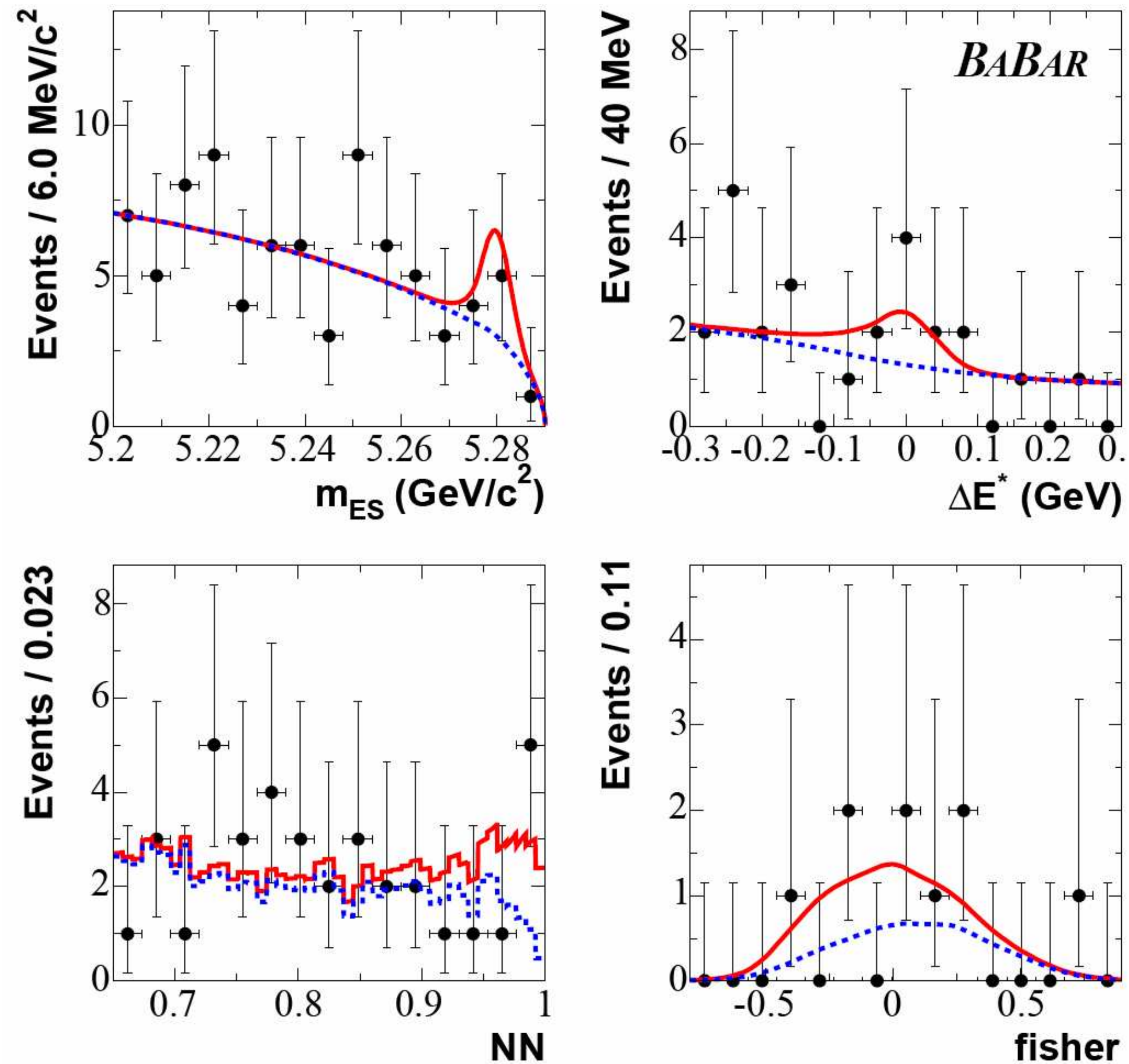




$B^+ \to \rho^+\gamma$ and $B^0 \to \rho^0\gamma$



B→ ωγ



Events / 6.0 MeV/c²
m_ES (GeV/c²)
Events / 40 MeV
BABAR
ΔE* (GeV)
Events / 0.023
NN
Events / 0.11
fisher

$B^0 \to \phi \gamma$