Results from BaBar on the Rare Exclusive Decays $B \to K \ell^+\ell^-$ and $B \to K^* \ell^+\ell^-$

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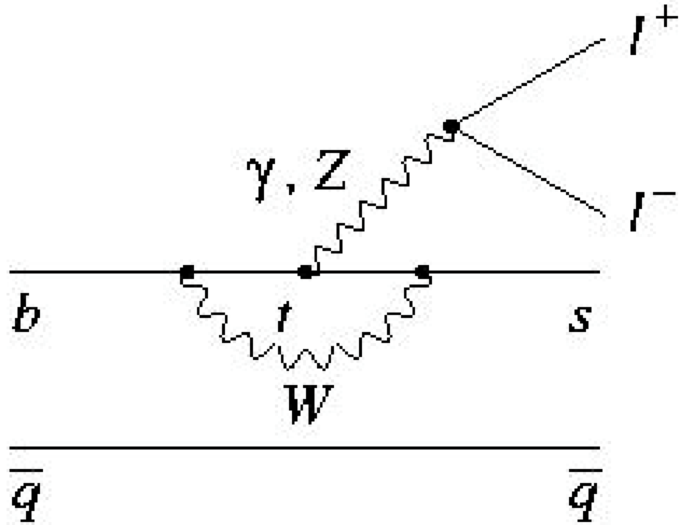
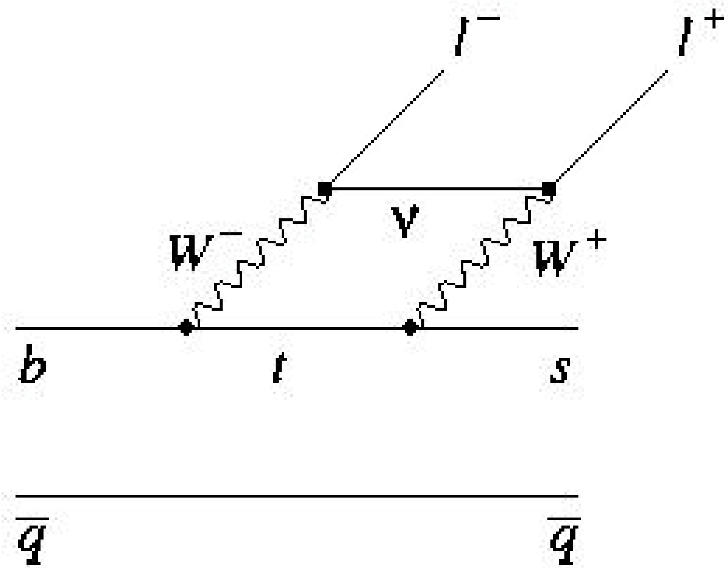
$B \rightarrow K^{(*)} l^+ l^-$ in the SM and Beyond





- **Flavor changing neutral current (*b* to *s*): proceeds via "penguin" or box diagrams in the SM.**
- **New physics at the EW scale (SUSY, technicolor, 4th generation quarks, etc.) can compete with small SM rate.**
- **Complementary to studying *b* to *s* γ due to presence of W and Z diagrams.**

Branching Fraction Predictions in the Standard Model

Authors	$\mathcal{B}(B \to K l^+ l^-)$ $/10^{-6}$	$\mathcal{B}(B \to K^* \mu^+ \mu^-)$ $/10^{-6}$	$\mathcal{B}(B \to K^* e^+ e^-)$ $/10^{-6}$
Ali *et al.* 2000	$0.57^{+0.17}_{-0.10}$	$1.9^{+0.5}_{-0.4}$	$2.3^{+0.7}_{-0.5}$
Ali *et al.* 2001 (NNLO)	0.35 ± 0.12	1.19 ± 0.39	1.58 ± 0.49
Colangelo *et al.*	0.3	1.0	
Melikhov *et al.*	0.44	1.15	1.50
Aliev *et al.*	0.31 ± 0.09	1.4	
Geng and Kao	0.5	1.4	

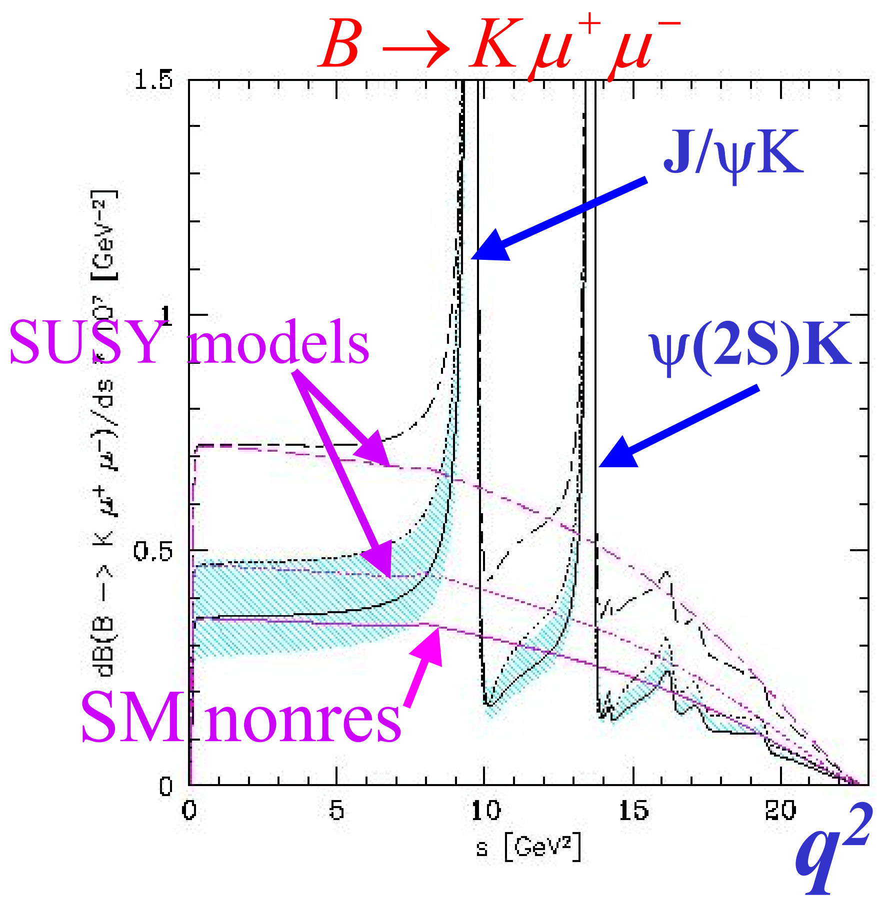
New Ali *et al.* predictions lower by 30-40%

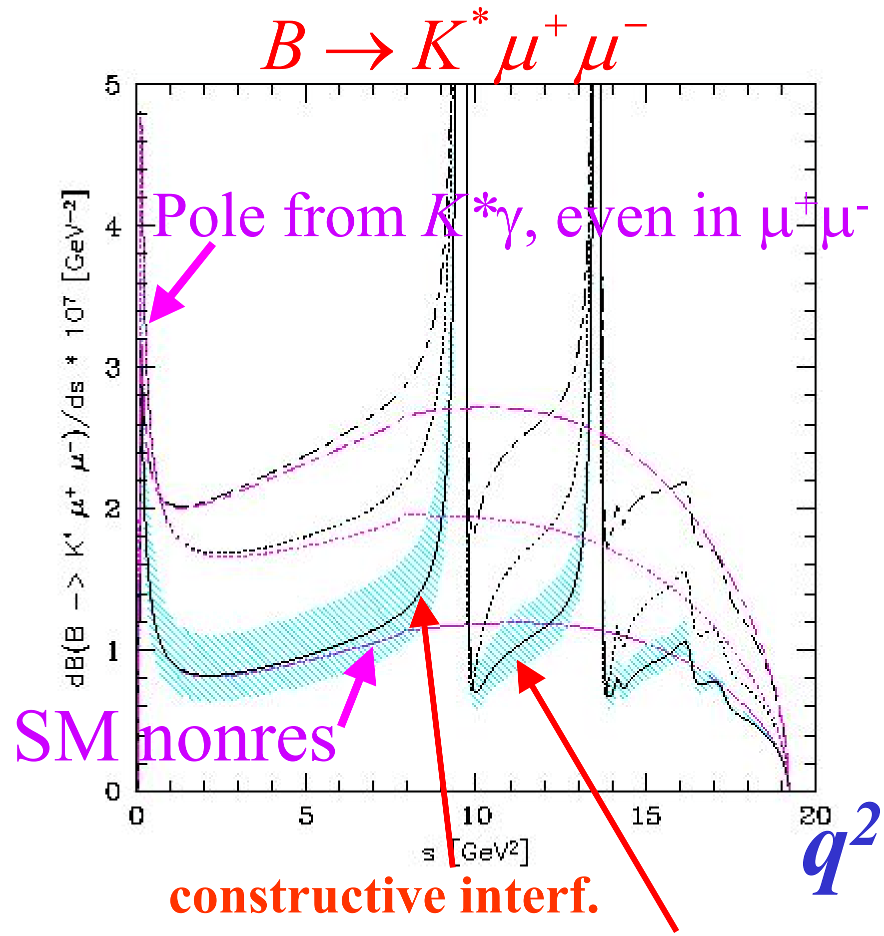
- $\mathcal{B}(B \to K \ell^+ \ell^-) =$
  $(0.35 \pm 0.11(\text{form fac.}) \pm 0.04(\mu_b) \pm 0.02(m_{t,\text{pole}}) \pm 0.0005(m_c/m_b)) \times 10^{-6}$
  [Ali, Lunghi, Greub, Hiller, hep-ph/0112300, 2001]

- $\mathcal{B}(B \to X_s \mu^+ \mu^-) = (4.15 \pm 0.70) \times 10^{-6}$
  $\mathcal{B}(B \to X_s e^+ e^-) = (6.89 \pm 1.01) \times 10^{-6}$

long-distance contribution from ψ resonances excluded

Decay rate vs. q^2 in the SM and SUSY





- Solid line+blue bands: SM range (±35%); Ali *et al.* form factors
- Dotted line: SUGRA model ($R_7 = -1.2$, $R_9 = 1.03$, $R_{10} = 1$; $R_i = C_i/C_i^{\rm SM}$)
- Long-short dashed line: SUSY model ($R_7 = -0.83$, $R_9 = 0.92$, $R_{10} = 1.61$)

$K^{(*)}ll$ Results from BaBar, J. Berryhill, DPF-2002

Recent Experimental Results

- **Belle: K*ll* observed in 2001 (29.1 fb^{-1}, PRL 88, 021801 (2002))**

$$B(B \to K l^+ l^-) = (0.75^{+0.25}_{-0.21} \pm 0.09) \times 10^{-6}$$

$$B(B \to K \mu^+ \mu^-) = (0.99^{+0.40+0.13}_{-0.32-0.14}) \times 10^{-6}$$

$$B(B \to K^* \mu^+ \mu^-) < 3.1 \times 10^{-6}$$

$$B(B \to K^* e^+ e^-) < 5.6 \times 10^{-6}$$

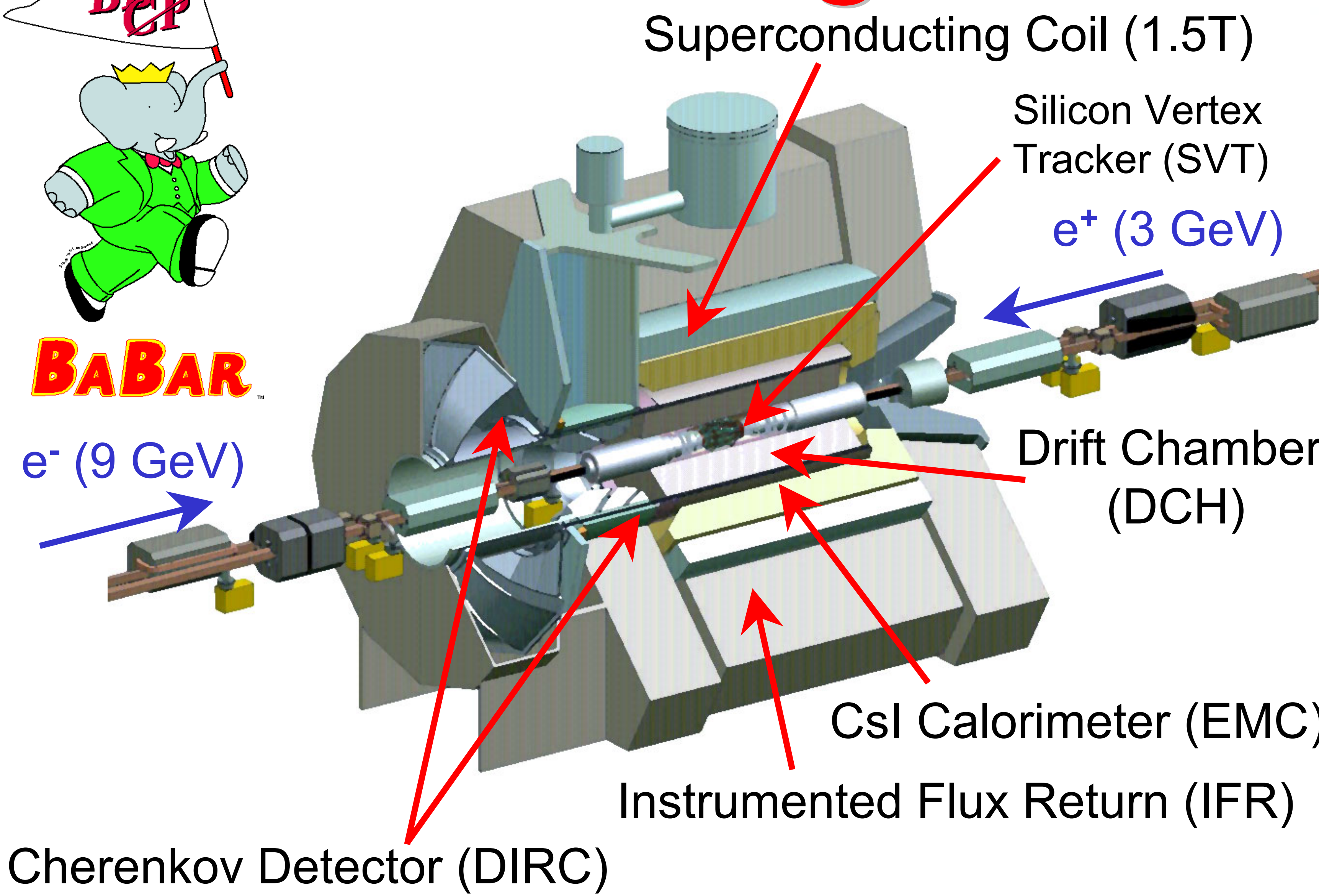
- **BaBar "Run 1" upper limit (20.7 fb^{-1}, accepted by PRL):**

$$B(B \to K l^+ l^-) < 0.51 \times 10^{-6} \quad 90\% \text{ C.L.}$$

$$B(B \to K^* l^+ l^-) < 3.1 \times 10^{-6} \quad 90\% \text{ C.L.}$$

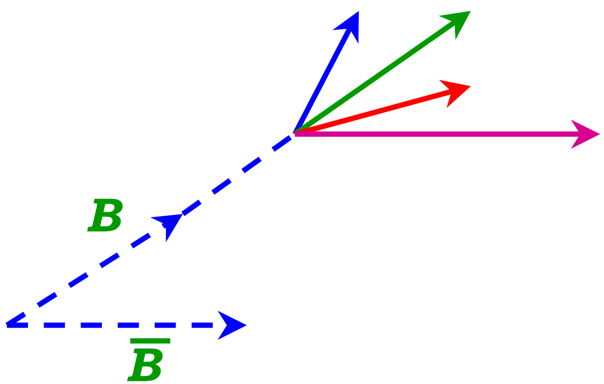
- **Belle K*ll* central value = BaBar Run 1 96% C.L. upper limit**
- **This result: "Run 1+Run 2" update (56.4 fb^{-1}, preliminary).**

BaBar Detector @ PEP II



B Meson Reconstruction at Υ(4s)

$$e^+e^- \to \Upsilon(4S) \to B\overline{B}$$



$$m_{ES} = \sqrt{{E^*_{beam}}^2 - (\sum_i p^*_i)^2}$$

$$\Delta E = \sum_i \sqrt{{p^*_i}^2 + m_i^2} - E^*_{beam}$$

Typical resolutions:

$\sigma(m_{ES}) \approx$ 2.5 MeV

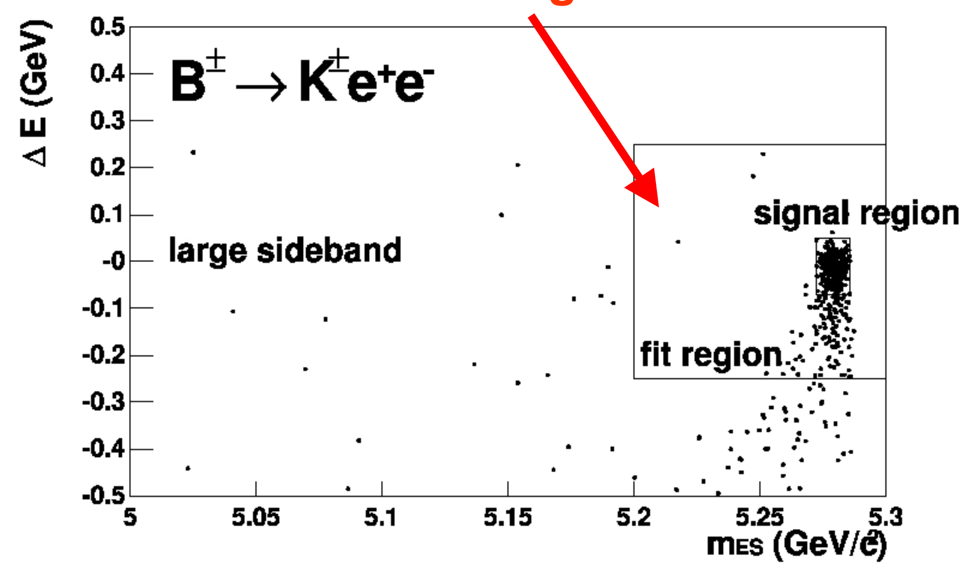
$\sigma(\Delta E) \approx$ 25 - 40 MeV

(*) ≡ measured in Υ(4S) rest frame

$E_i \longleftrightarrow E^*_{beam}$ ➔ Improve resolution

- **Define 3 regions in ΔE, m_{ES} plane:**
  - A – Signal region
  - B – Fit region
  - C – Large Sideband region

full fit region is blind



$K^{(*)}ll$ Results from BaBar, J. Berryhill, DPF-2002

Analysis Strategy: Event Selection

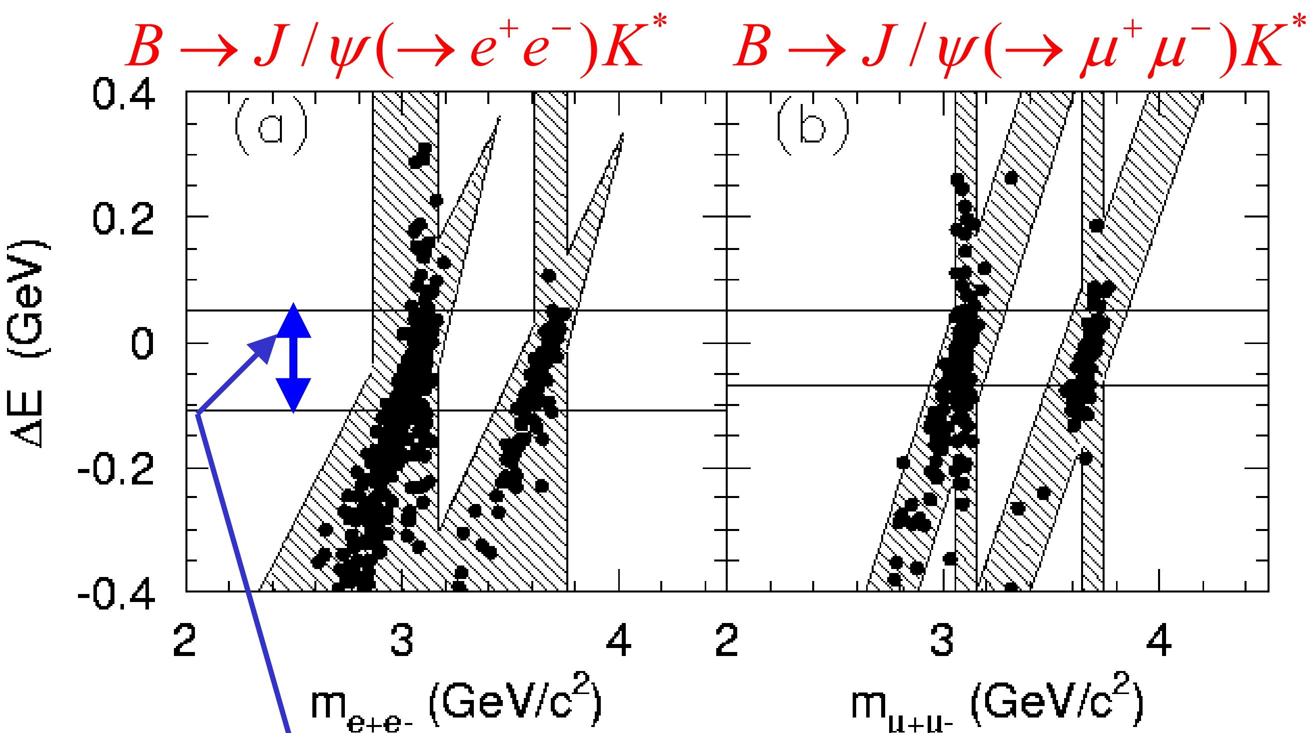
- **Reconstruct candidates** for the different decay modes with appropriate particle ID requirements:
  - $B^+ \to K^+ l^+ l^-$, where l is either e or μ
  - $B^0 \to K^0 l^+ l^-$, where $K^0 \to K^0_s \to \pi^+\pi^-$
  - $B^+ \to K^{*+} l^+ l^-$, where $K^{*+} \to K^0_s\pi^+$ and $K^0_s \to \pi^+\pi^-$
  - $B^0 \to K^{*0} l^+ l^-$, where $K^{*0} \to K^+\pi^-$
- **Backgrounds suppressed** using more detailed aspects of the event
  - Continuum events – event shape
  - BB events – vertexing, E_{miss}
  - $B \to J/\psi(\to l^+ l^-)K(*)$ decays – exclude regions in ΔE / $m(l^+ l^-)$ plane
  - Peaking backgrounds (small)
- **Signal/background optimization** with signal simulation and "large sideband" data. **All candidates in the fit region "blinded" until selection criteria are finalized.**

Analysis Strategy: Signal Fitting

- 2-D fit in the m_{ES} / ΔE plane estimates signal and background yield in the fit region.
  - Background shape and yield float for each decay mode
  - Signal shape fixed from signal MC and J/ψ K(*) data
  - Small residual peaking background fixed from MC.
- Signal branching fractions obtained from simulated signal efficiencies, total # of BB pairs produced.
- Control samples in the data check signal efficiencies and background characteristics :
  - B to J/ψ K(*) candidates
  - "Large sideband" region in m_{ES} / ΔE plane
  - $K^{(*)}e^{-}\mu^{+}$ combinations

$B \to J/\psi(\to l^+ l^-)K(*)$ Background

- These decays do not give us information about the short-distance physics and must be removed explicitly by a veto in the ΔE vs. $M(l^+l^-)$ plane.



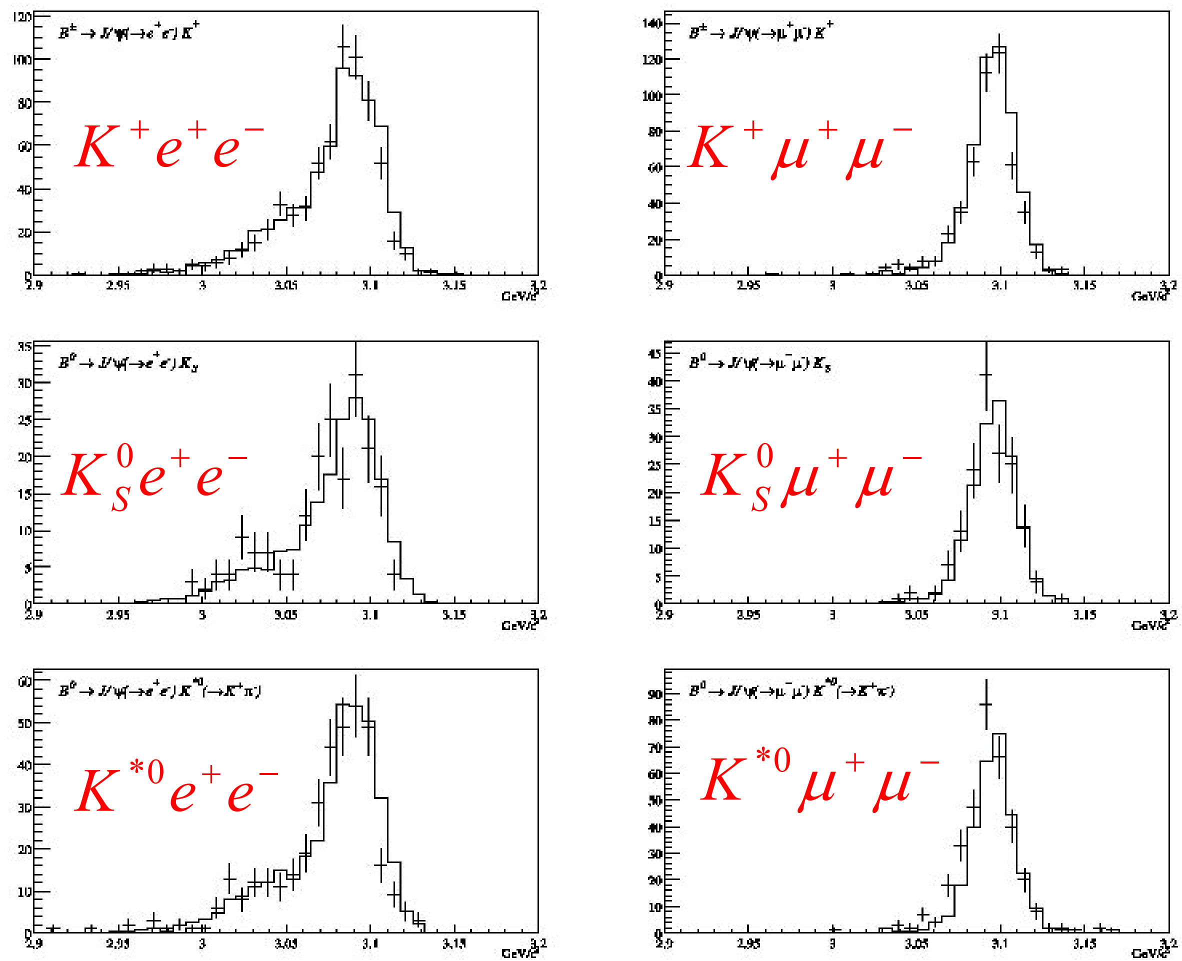
Nominal signal region

- When the leptons from $J/\psi \to l^+l^-$ *radiate* or are *mismeasured*, the event shifts in both $m(\psi)$ and in ΔE.
- Remove these events from BG region as well: simplify fit in m_{ES} vs. ΔE plane

$B \to J/\psi(\to l^+l^-)K(*)$: Control Sample

- Kinematics very similar to the signal
- Verifies efficiencies of essentially all selection criteria
- Excellent agreement btwn. Data and MC for rates and distributions

E.g. study tails in $M(l^+l^-)$ distribution



$M(l^+l^-)$

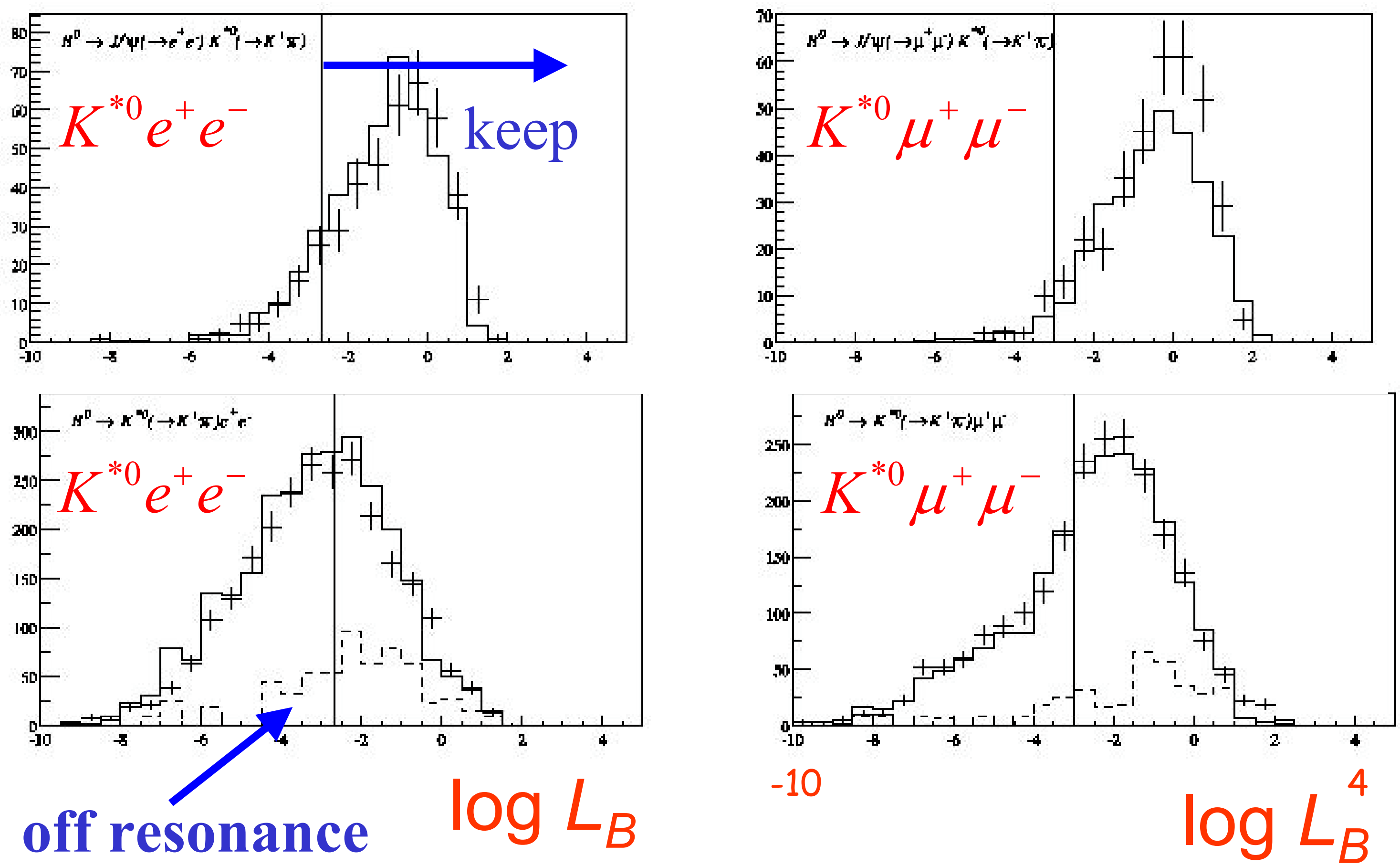
Points: data
Histo: MC

$K^{(*)}ll$ Results from BaBar, J. Berryhill, DPF-2002

J/ψ and Large Sideband Control Sample Study: *B* Likelihood Variable

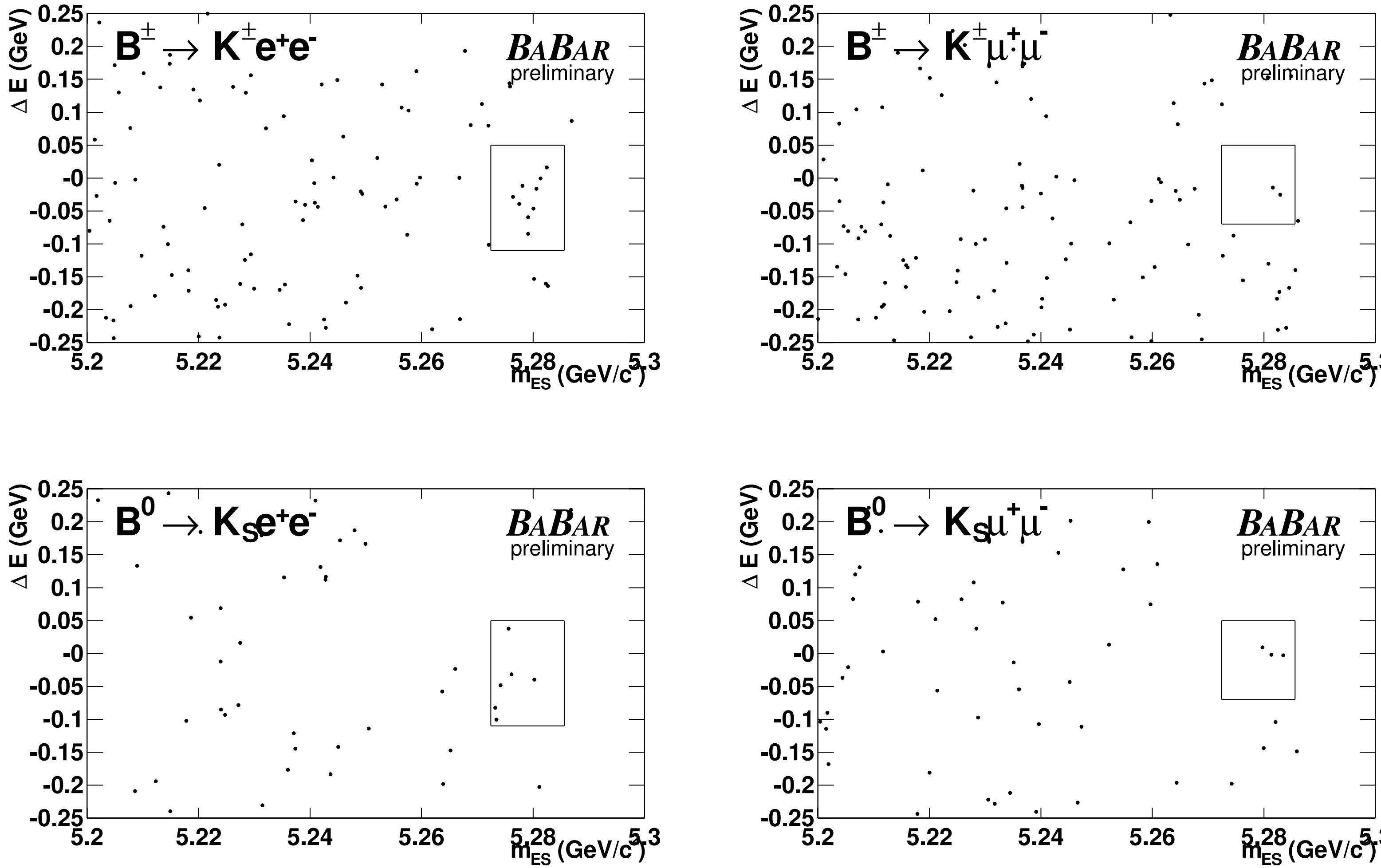
J/ψ Sample: signal-like

Large SB Sample: background-like



Kl^+l^- Fit Regions, Unblinded Run 1+2 data (56.4 fb-1)

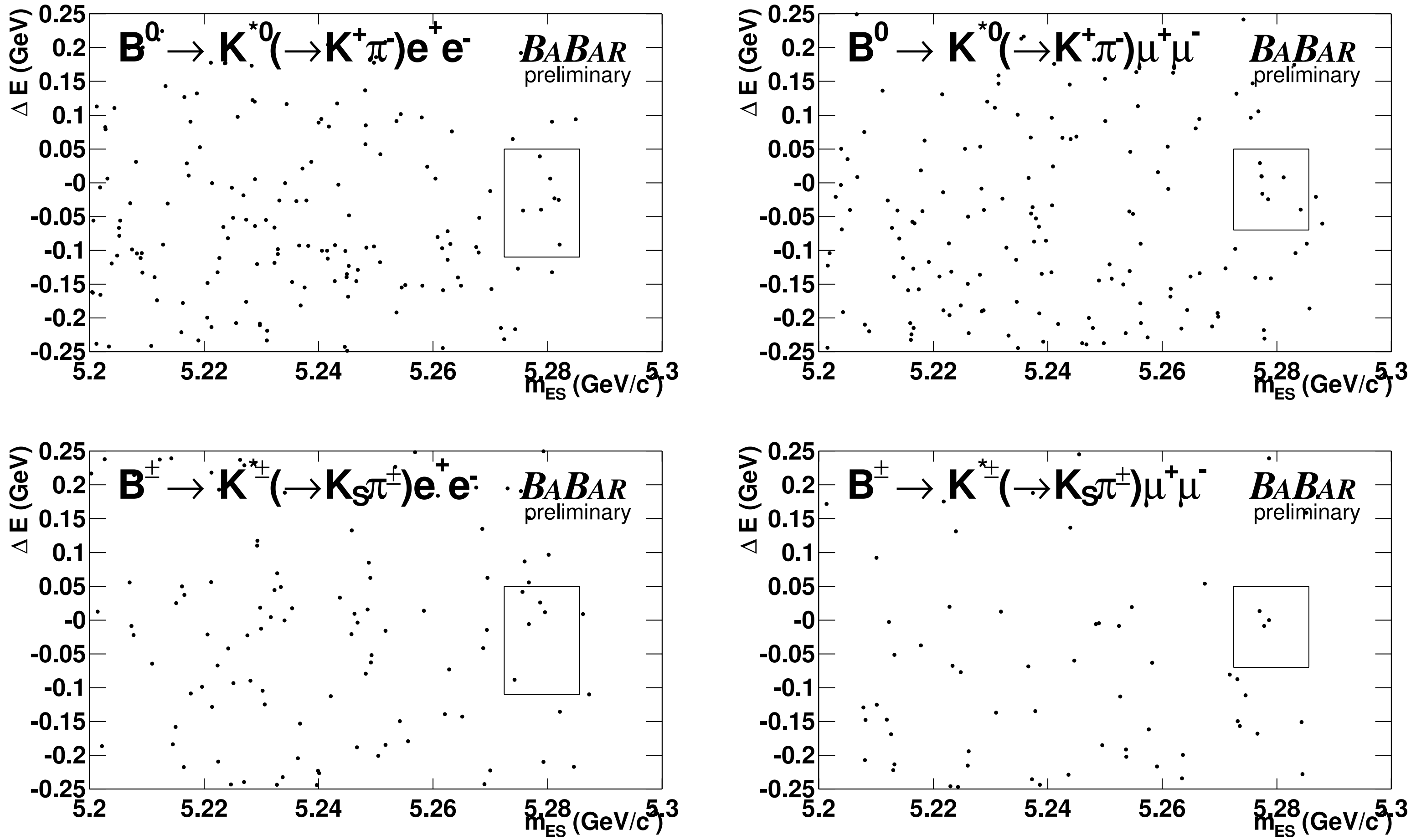
ΔE



m_{ES}

$K^* l^+ l^-$ Fit Regions, Unblinded Run 1+2 data (56.4 fb^{-1})

ΔE

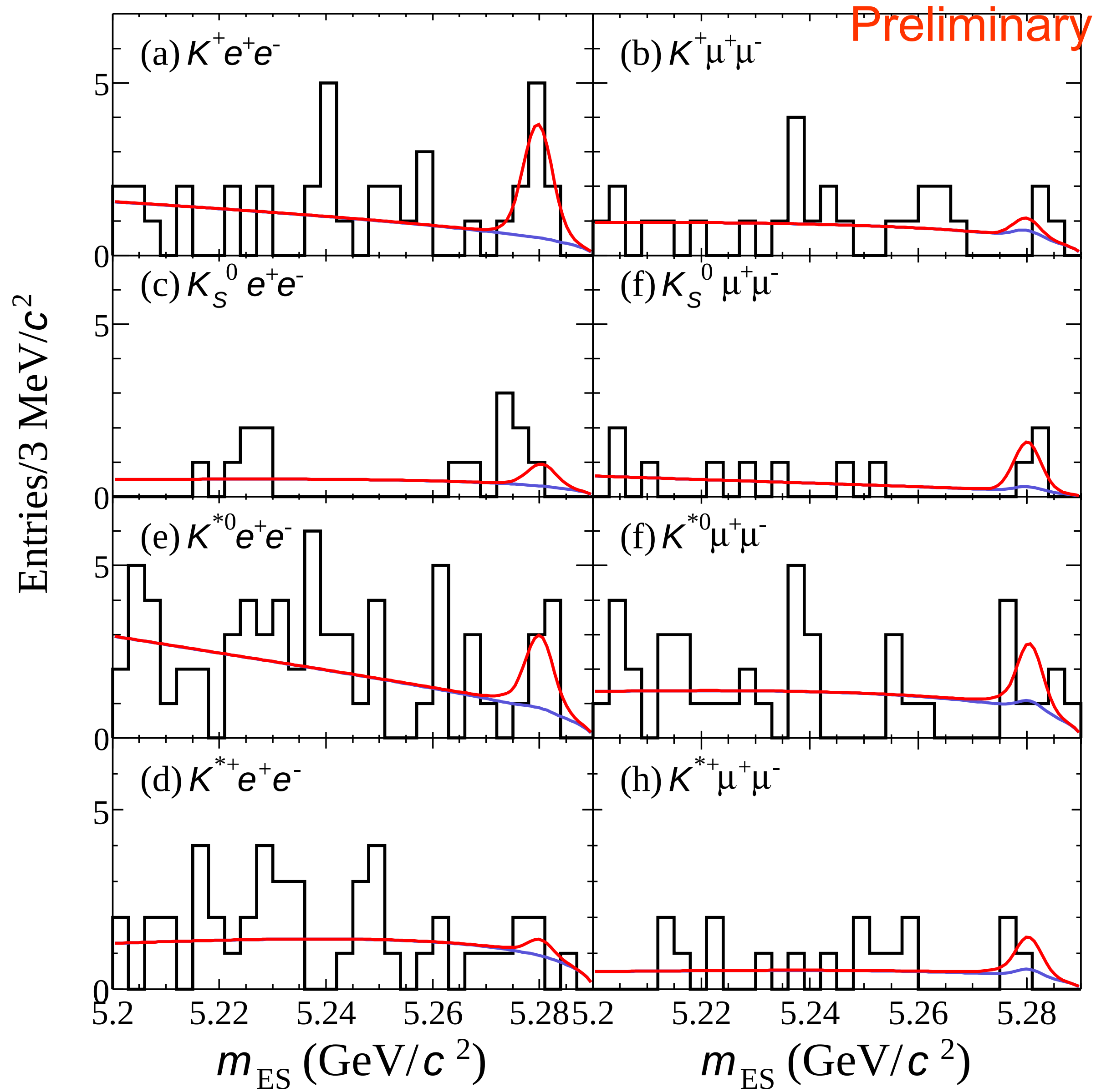


m_{ES}

Run 1+2 Unblinded: m_{ES}

2D fit projections after ΔE cut:

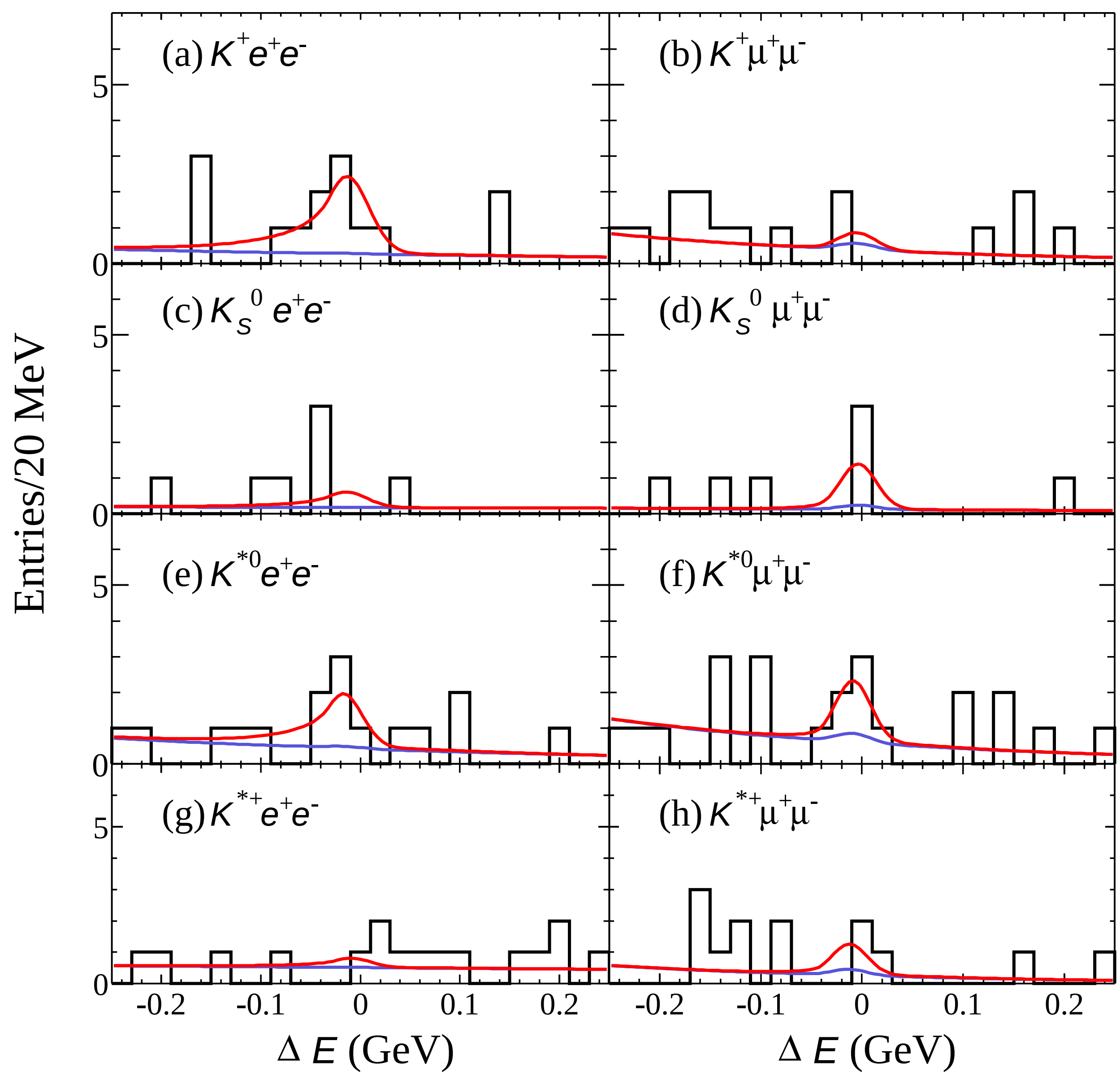
e: -110<ΔE<50 MeV
μ: -70<ΔE<50 MeV



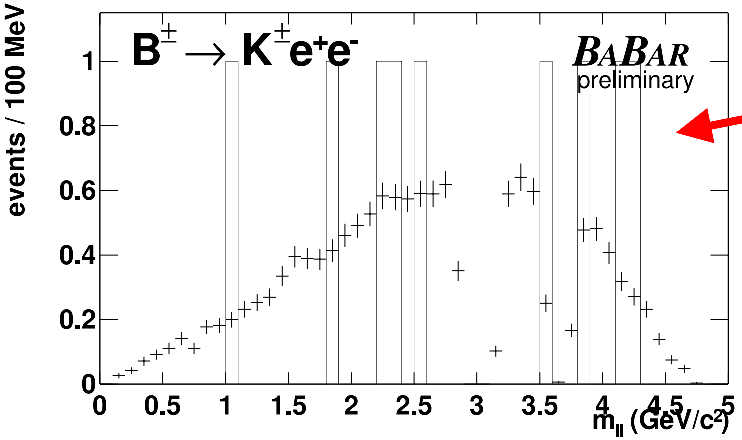
Run 1+2 Unblinded: ΔE

2D fit projections after m_{ES} cut

$5.2724 < m_{ES} < 5.2856$ GeV



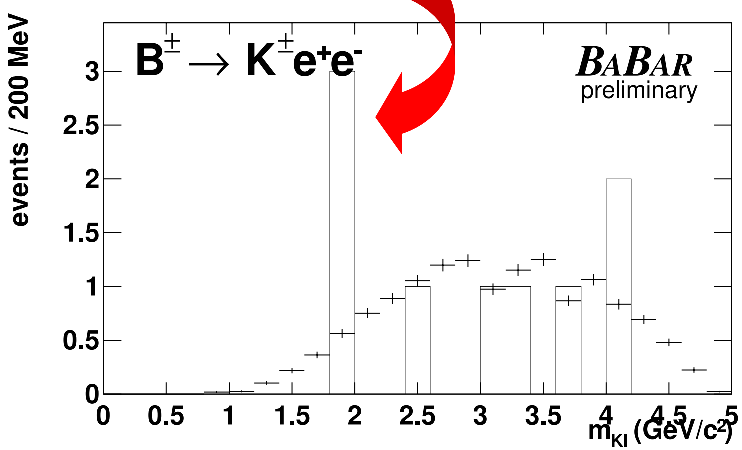
Signal Candidate Properties



- M(ll) – no apparent pileup near the J/ψ vetoes

Preliminary

2 of these consistent with D mass



- M(Kl) – possible background from B $\to D\pi$, $D \to K\pi$, both π's mis-id'd as electrons. (Note, this peaking BG is explicitly vetoed in K$\mu\mu$ channel).
- Simulation predicts 0.06 events of this background for this channel
- Studies of electron mis-id probabilities show no indication of problem.
- Nevertheless, include systematic error to account for possibility that 2 of these events are BG.

Fit Results I

Preliminary

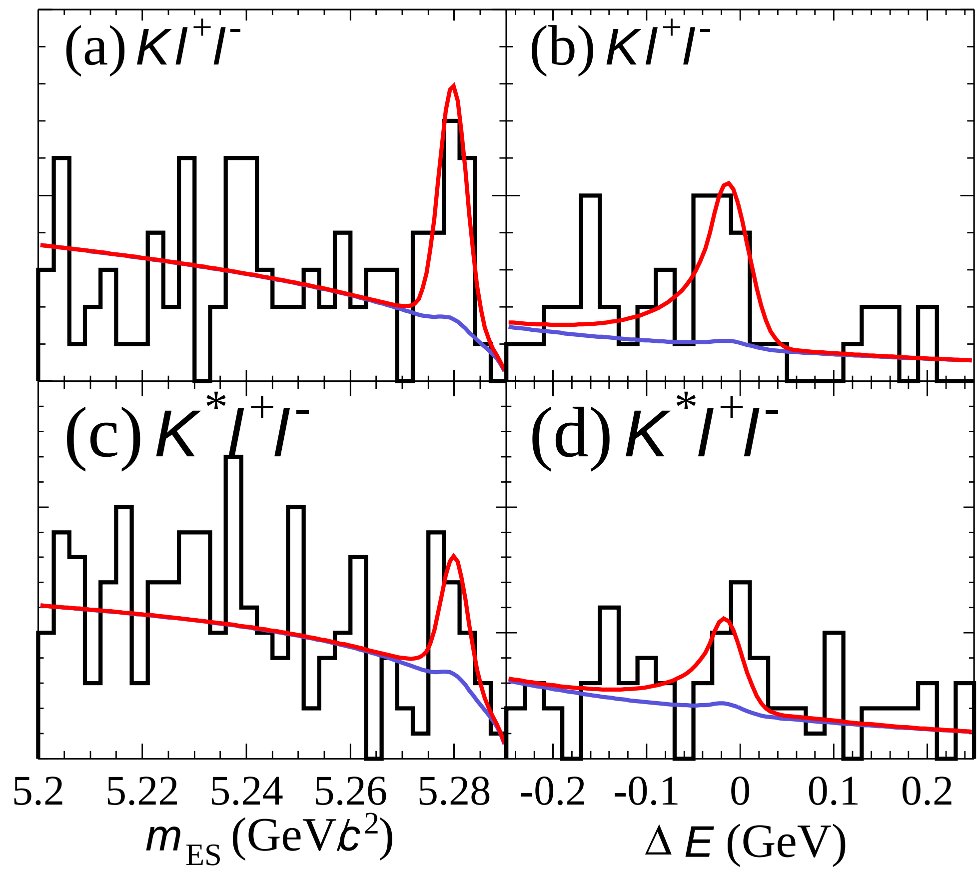
- **Unbinned max. likelihood fit in ΔE–m_{ES} plane for the 8 decay modes**

Mode	Signal yield	Eff. bkgd	ε (%)	$(\Delta B/B)_\varepsilon$ (%)	$(\Delta B)_{fit}$ (10^{-6})	B (10^{-6})
$B^+ \to K^+ e^+ e^-$	$9.6^{+4.6}_{-3.3}$	1.9	17.1	± 6.8	$^{+0.11}_{-0.23}$	$0.91^{+0.42+0.13}_{-0.32-0.24}$
$B^+ \to K^+ \mu^+ \mu^-$	$0.8^{+2.5}_{-1.3}$	1.2	9.9	± 6.8	± 0.10	$0.13^{+0.37}_{-0.23} \pm 0.10$
$B^0 \to K^0 e^+ e^-$	$1.8^{+2.8}_{-1.3}$	1.1	18.1	± 8.0	± 0.35	$0.47^{+0.69}_{-0.39} \pm 0.35$
$B^0 \to K^0 \mu^+ \mu^-$	$2.9^{+2.7}_{-1.5}$	0.4	10.3	± 7.8	± 0.22	$1.34^{+1.16}_{-0.78} \pm 0.25$
$B^0 \to K^{*0} e^+ e^-$	$7.3^{+4.7}_{-3.5}$	3.4	10.2	± 7.7	± 0.48	$1.66^{+1.08}_{-0.83} \pm 0.50$
$B^0 \to K^{*0} \mu^+ \mu^-$	$4.6^{+4.2}_{-2.9}$	2.3	6.6	± 9.3	± 0.39	$1.68^{+1.57}_{-1.09} \pm 0.42$
$B^+ \to K^{*+} e^+ e^-$	$1.5^{+4.0}_{-2.0}$	4.9	9.8	± 9.7	$^{+1.04}_{-1.06}$	$1.07^{+2.86+1.04}_{-1.51-1.06}$
$B^+ \to K^{*+} \mu^+ \mu^-$	$2.8^{+3.5}_{-2.0}$	1.5	5.4	± 11.1	± 1.82	$3.68^{+4.39}_{-2.88} \pm 1.86$

Fit Results II

Preliminary

- **Combining channels: m_{ES} and ΔE projections for K*ll* and K**ll***



B(B→K*ee)/B(B→K*μμ)=1.21 from Ali, *et al*, is used in combined K*ll fit.

$$B(B \to K\ell^+\ell^-) = (0.84^{+0.30+0.10}_{-0.24-0.18}) \times 10^{-6}$$

$$B(B \to K^*\ell^+\ell^-) = (1.89^{+0.84}_{-0.72} \pm 0.31) \times 10^{-6}$$

Systematic Uncertainties

Systematic errors on the efficiency

Largest sources:
- **Trk eff.**
- **Model dependence**

~ 7 – 11 % total per mode

Systematic errors on the # of signal events in the fit

- **Signal shape variation**
- **Background shape variation**
  - **includes peaking background uncertainty**

~ 0.5 – 2.0 events per mode

Signal Statistical Significance

- What is the probability that background alone would fluctuate to produce the observed signal?
  - Consider change in ln L when fixing the signal component to zero in fit.
  - For Kl^+l^-, equivalent to 5.0σ fluctuation; if systematic uncertainties in signal yield included $\Rightarrow$ still > 4σ
  - For $K^*l^+l^-$, equivalent to 3.5σ fluctuation
- The Kl^+l^- signal yield constitutes a significant observation of this decay.
- The $K^*l^+l^-$ signal yield is not conclusively significant, and we place an upper limit for this channel:

$$B(B \to K^* \ell^+ \ell^-) < 3.5 \times 10^{-6} \quad 90\% \text{ C.L.}$$

Preliminary

Comparison with Run 1 Result

- **Run 1:**

$$B(B \to K l^+ l^-) < 0.51 \times 10^{-6} \quad 90\% \text{ C.L.}$$

$$B(B \to K^* l^+ l^-) < 3.1 \times 10^{-6} \quad 90\% \text{ C.L.}$$

- **Run 1+2:**

$$B(B \to K \ell^+ \ell^-) = (0.84^{+0.30+0.10}_{-0.24-0.18}) \times 10^{-6}$$

$$B(B \to K^* \ell^+ \ell^-) < 3.5 \times 10^{-6} \quad 90\% \text{ C.L.}$$

Preliminary

- **All data fully reprocessed for Run 1+2 results: improvements in tracking, vertex detector alignment, etc. ⇒ resulted in migration of events in/out of signal region. Sensitivity of this analysis is mostly unchanged by the reprocessing (some improvement in K_s modes).**
- **Migration of events into/out of signal region checked with control samples ⇒ results are compatible**
- **The probability for a Kll branching fraction at our new value to give our Run 1 result is at the 2-3% level.**

Conclusions

- **We have studied the channels $B \to K l^+ l^-$ and $B \to K^* l^+ l^-$ using 56.4 fb^{-1} of data at the BaBar experiment at PEP-II.**
- **We obtain the following results:**

Preliminary

$$B(B \to K\ell^+\ell^-) = (0.84^{+0.30+0.10}_{-0.24-0.18}) \times 10^{-6}$$

$$B(B \to K^*\ell^+\ell^-) < 3.5 \times 10^{-6}$$

- **The statistical significance for $B \to K l^+ l^-$ is computed to be > 4σ including systematic uncertainties.**

Peaking Backgrounds

- Usually due to particle mis-idenficiation, e.g.:

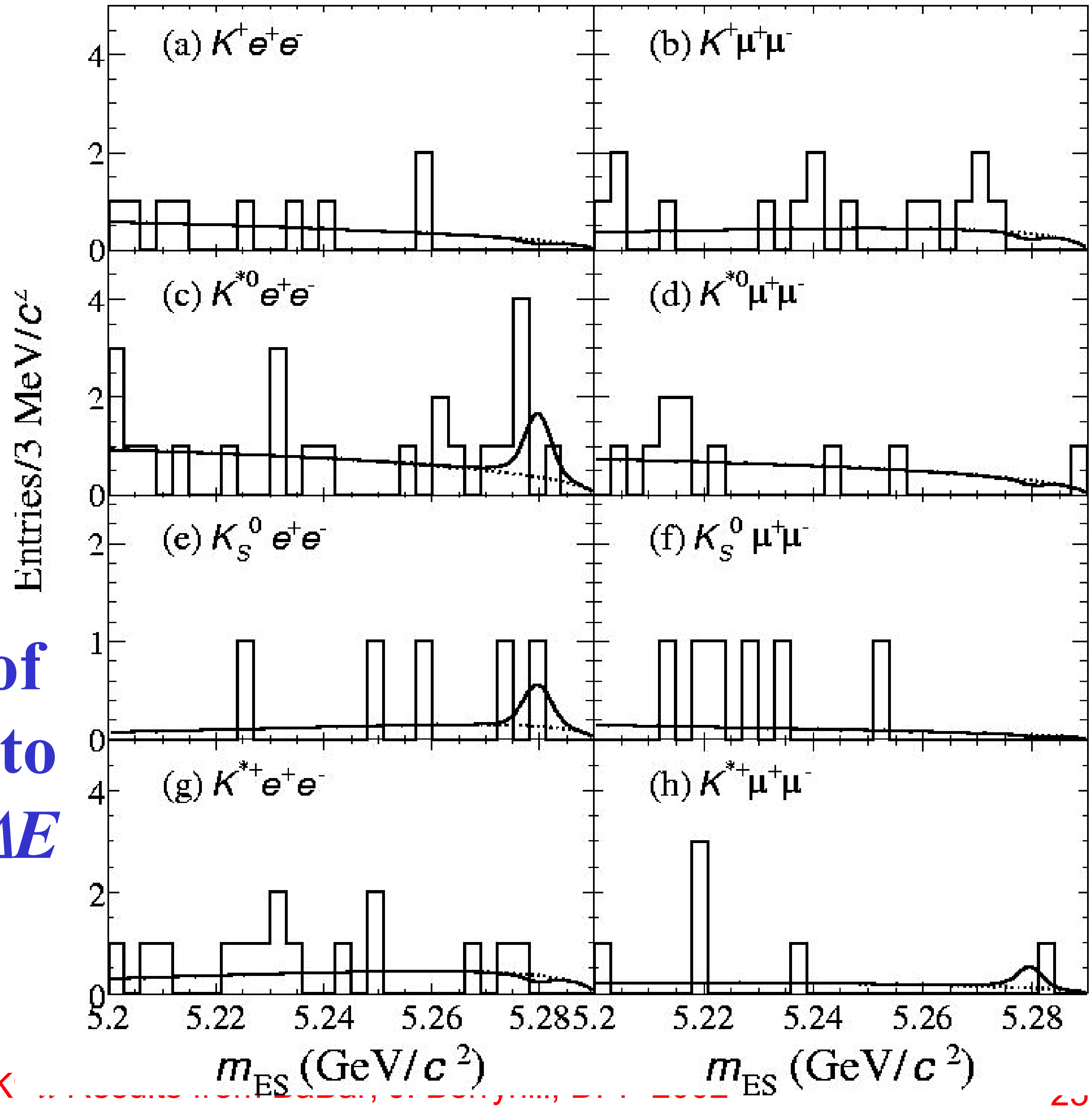
$$B \to D\pi$$
$$\hookrightarrow K\pi$$

Mis-id'd as muons ⇒ Kμμ background

- Since mis-id probability is higher for muons than for electrons, **explicit vetoes are applied for the muon modes.**
- Summary of peaking backgrounds as obtained from high statistics Monte Carlo sample.
- These are included in fit to extract signal.

Mode	Peaking background
$B^\pm \to K^\pm e^+ e^-$	$0.06^{+0.7}_{-0.06}$
$B^\pm \to K^\pm \mu^+ \mu^-$	0.5 ± 0.5
$B^0 \to K^0_S e^+ e^-$	$0.0^{+0.1}_{-0.0}$
$B^0 \to K^0_S \mu^+ \mu^-$	0.3 ± 0.3
$B^0 \to K^{*0} e^+ e^-$	0.3 ± 0.3
$B^0 \to K^{*0} \mu^+ \mu^-$	0.8 ± 0.8
$B^\pm \to K^{*\pm} e^+ e^-$	$0.05^{+0.3}_{-0.05}$
$B^\pm \to K^{*\pm} \mu^+ \mu^-$	0.7 ± 0.7

BaBar Run 1 Analysis (20.7 fb^{-1})



Projections of the 2D fit onto m_{ES} after a ΔE cut.

Belle results (29.1 fb^{-1})

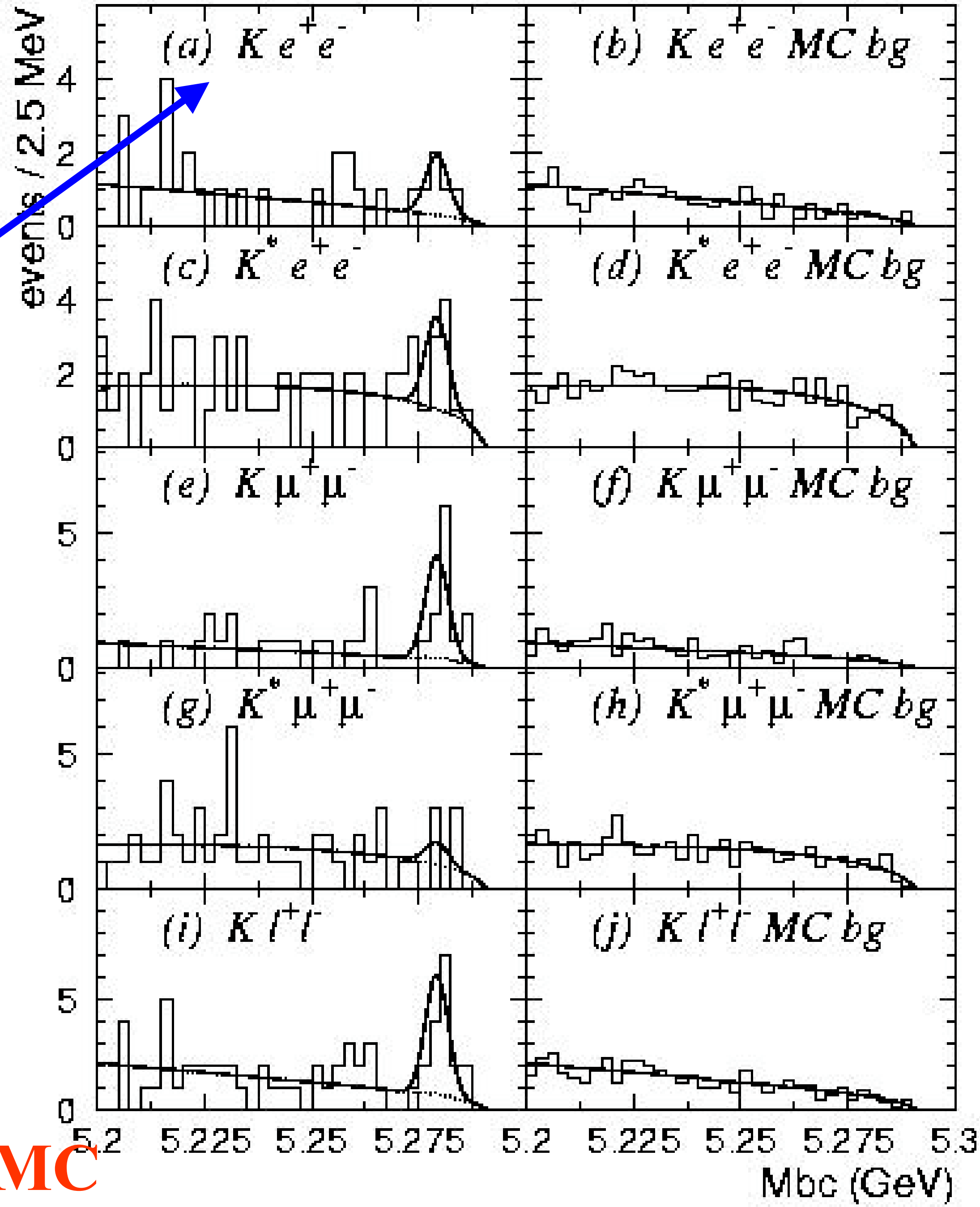
$4.1^{+2.7+0.6}_{-2.1-0.8}$ evts

$6.3^{+3.7+1.0}_{-3.0-1.1}$ evts

$9.5^{+3.8+0.8}_{-3.1-1.0}$ evts

$2.1^{+2.9+0.9}_{-2.1-1.0}$ evts

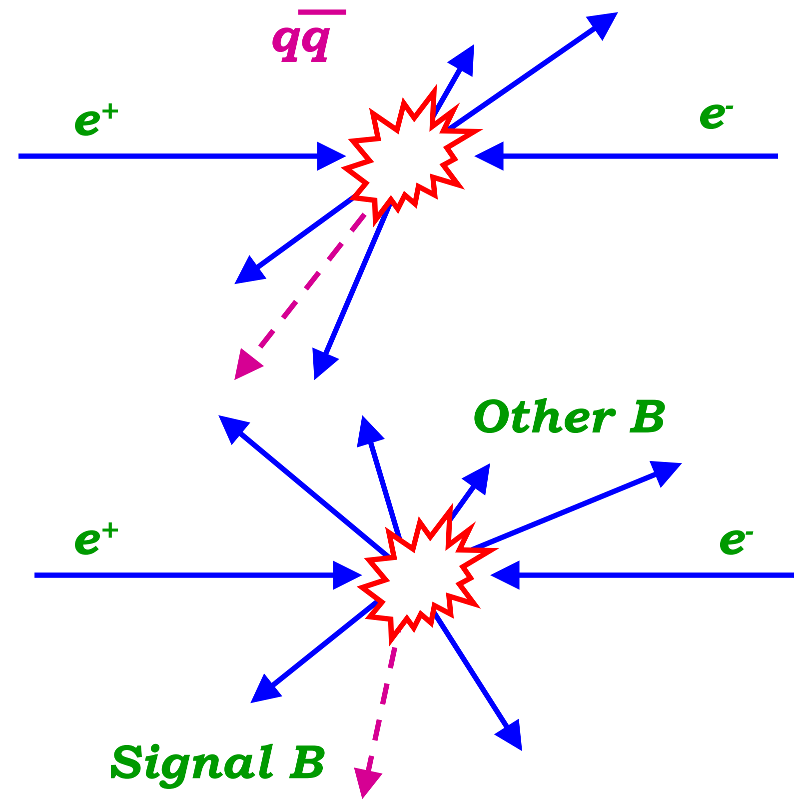
$13.6^{+4.5+0.9}_{-3.8-1.1}$ evts



Bkgd shape fixed from MC

Continuum Background Suppression

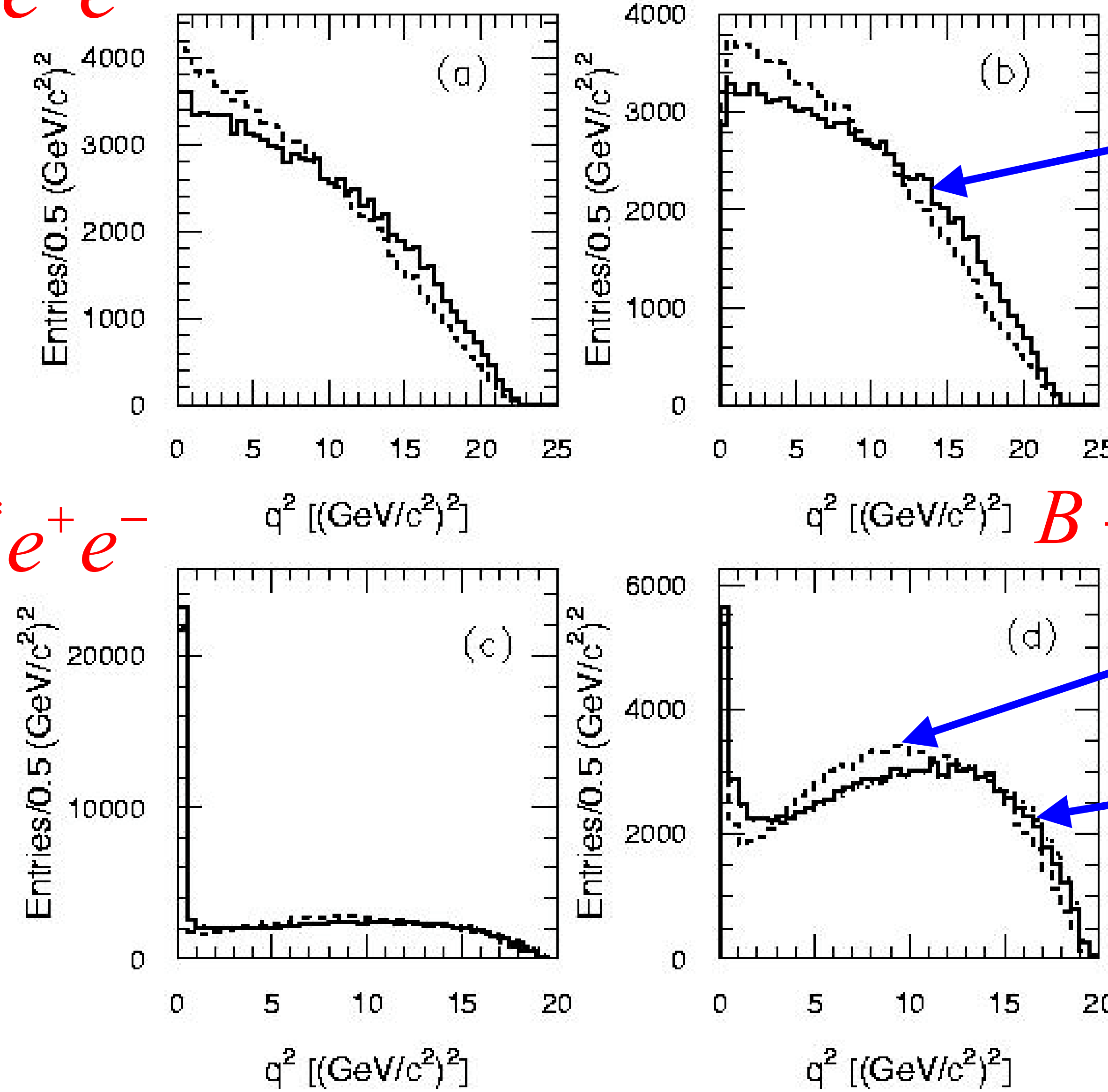
- **Continuum suppression: exploit fact that continuum events are more jet-like than BB events**
  - R_2: W-F 2nd moment
  - Cos θ_{thrust}: angle of candidate thrust axis
  - Cos θ_B : angle of B in CM
  - m_{Kl} : Kl invariant mass
- **Combine optimally using Fisher discriminant**
- **Put plot here.**



Generator-level q^2 Distributions from Form-Factor Models

$B \to K e^+ e^-$ $B \to K \mu^+ \mu^-$

$B \to K^* e^+ e^-$ $B \to K^* \mu^+ \mu^-$



Ali et al. 2000 (solid line)

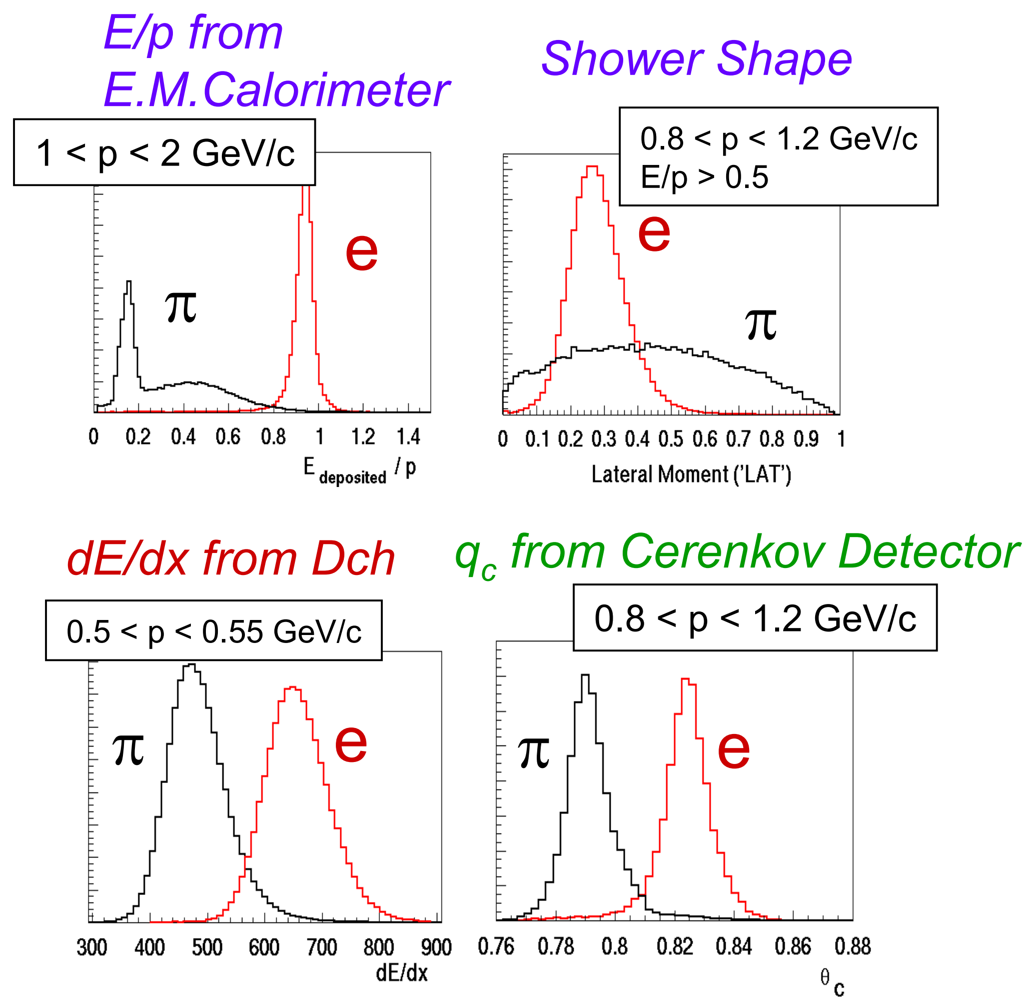
Colangelo 1999 (dashed line)

Melikhov 1997 (dotted line)

Shapes are very similar!

Particle Identification

- Electrons – p* > 0.5 GeV
  - shower shapes in EMC
  - E/p match
- Muons – p* > 1 GeV
  - Penetration in iron of IFR
- Kaons
  - dE/dx in SVT, DCH
  - θ_C in DRC



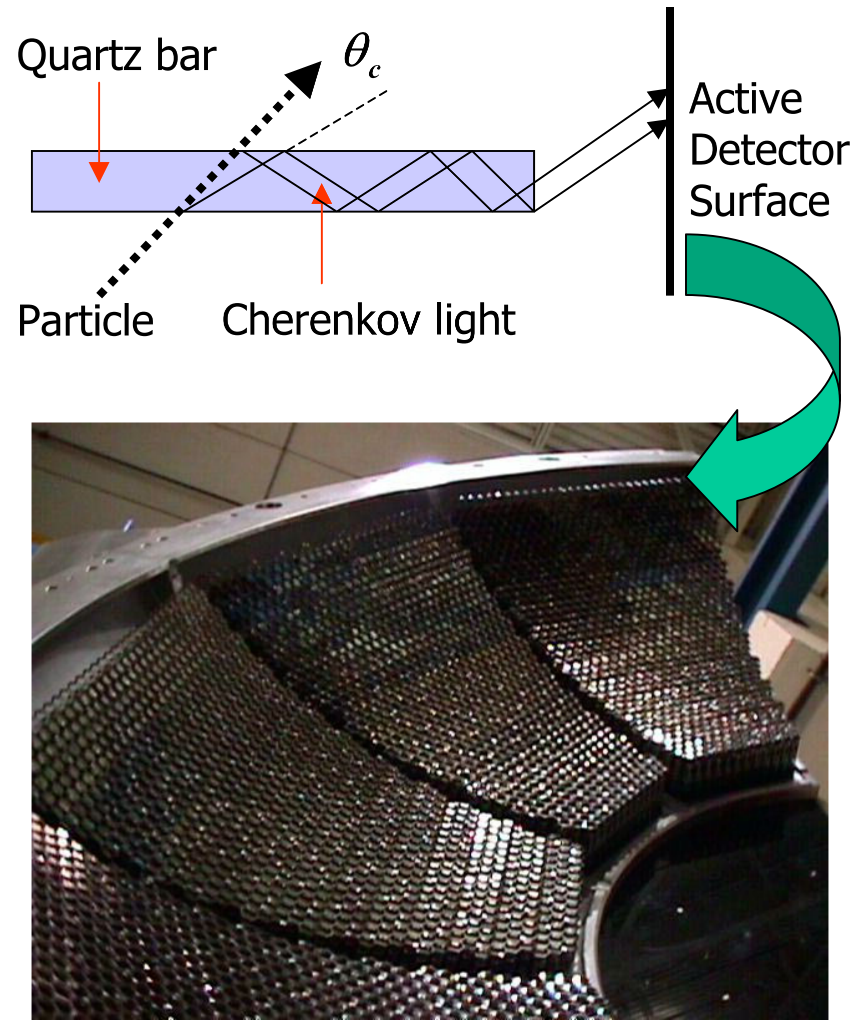
Kaons with DIRC

- The DIRC is able to identify particles via a measurement of the cone angle of their emitted Cherenkov light in quartz

$$\cos\theta_c = 1/n\beta$$

$$p = m\beta\gamma$$

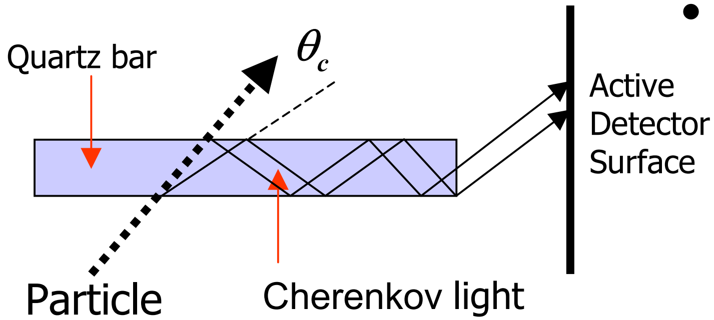
DCH → p; DIRC → $\beta\gamma$



- Provides **good π/K separation** for wide momentum range (up to ~4 GeV/c)

Particle Identification (DIRC)

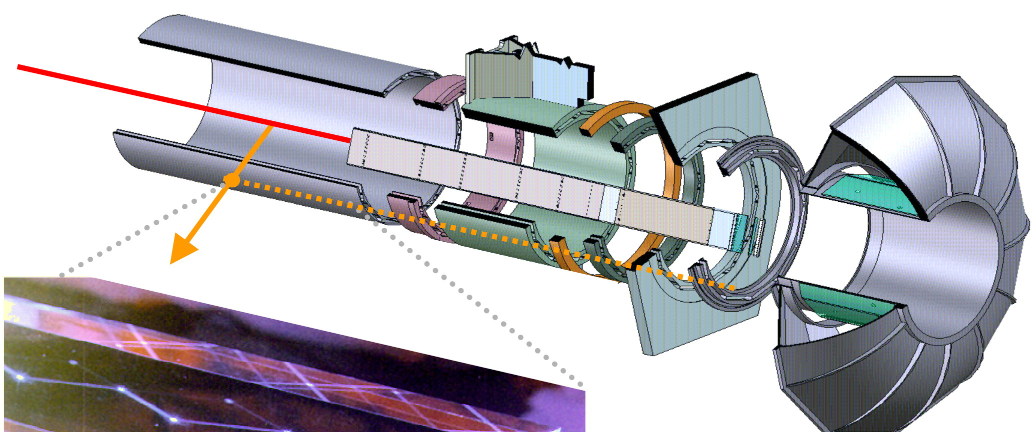
(Detector of Internally Reflected Cherenkov Light)

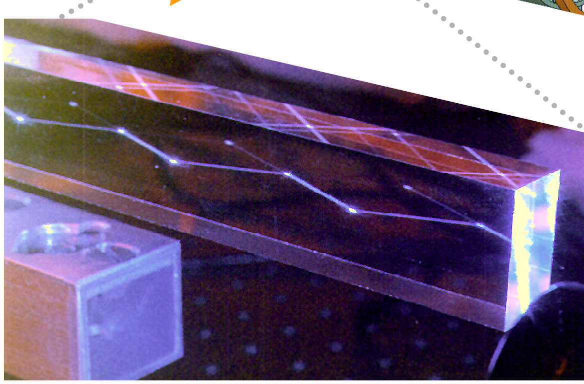


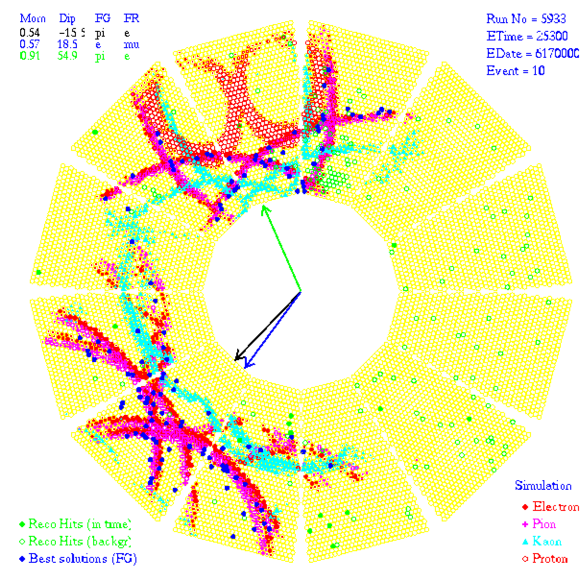
- Measure Angle of Cherenkov Cone in quartz

$$\cos\theta_c = 1/_{n\beta},\ p = m\beta\gamma$$

  - Transmitted by internal reflection
  - Detected by PMTs



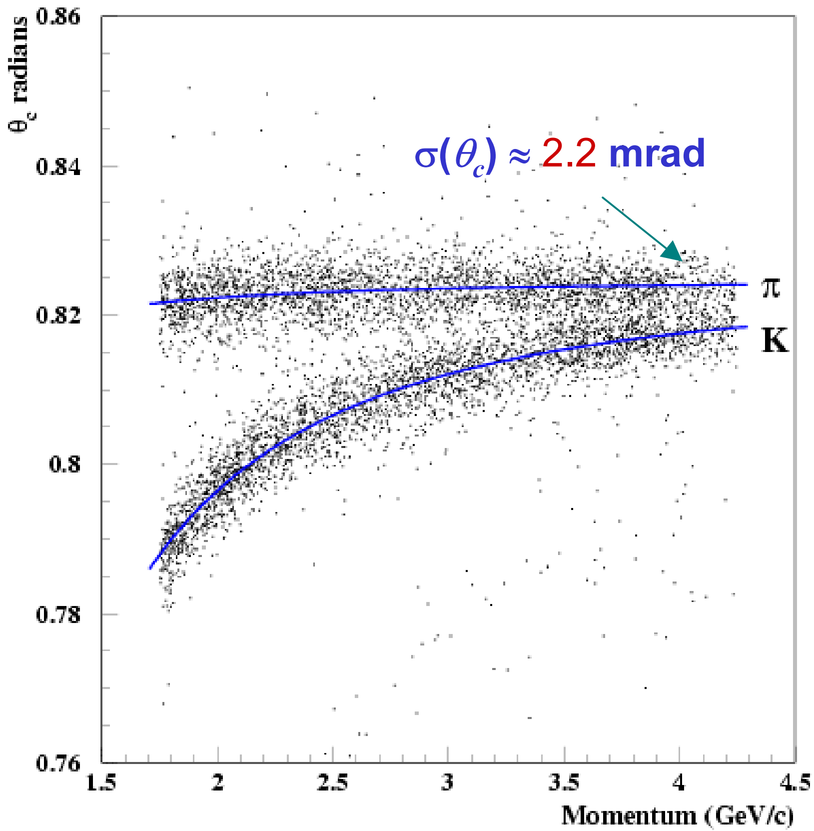


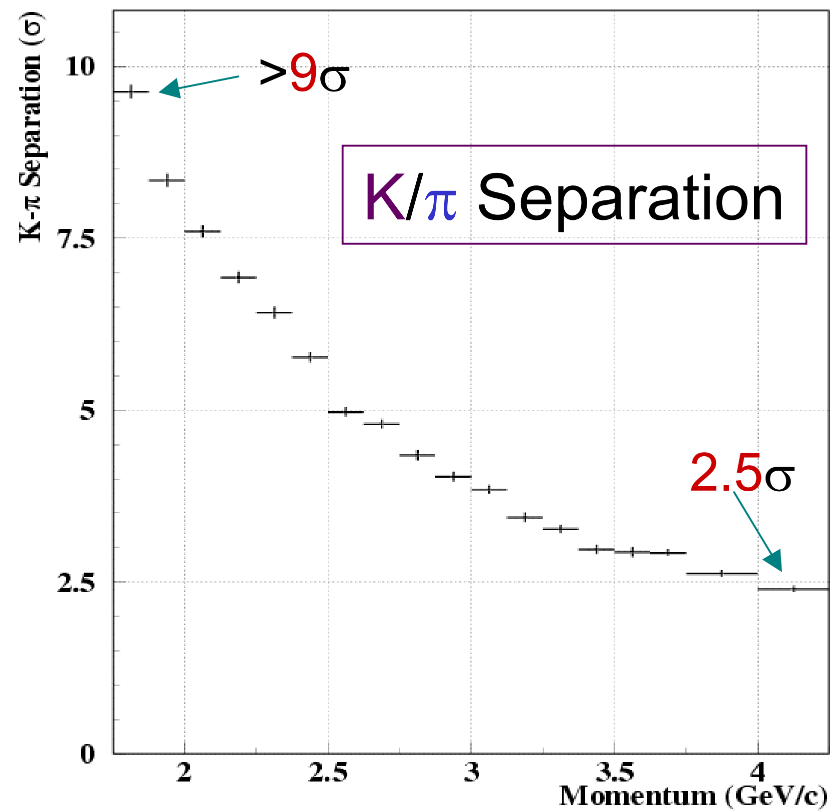


$K^{(*)}ll$ Results from BaBar, J. Berryhill, DPF-2002

Particle Identification (DIRC) cont'.

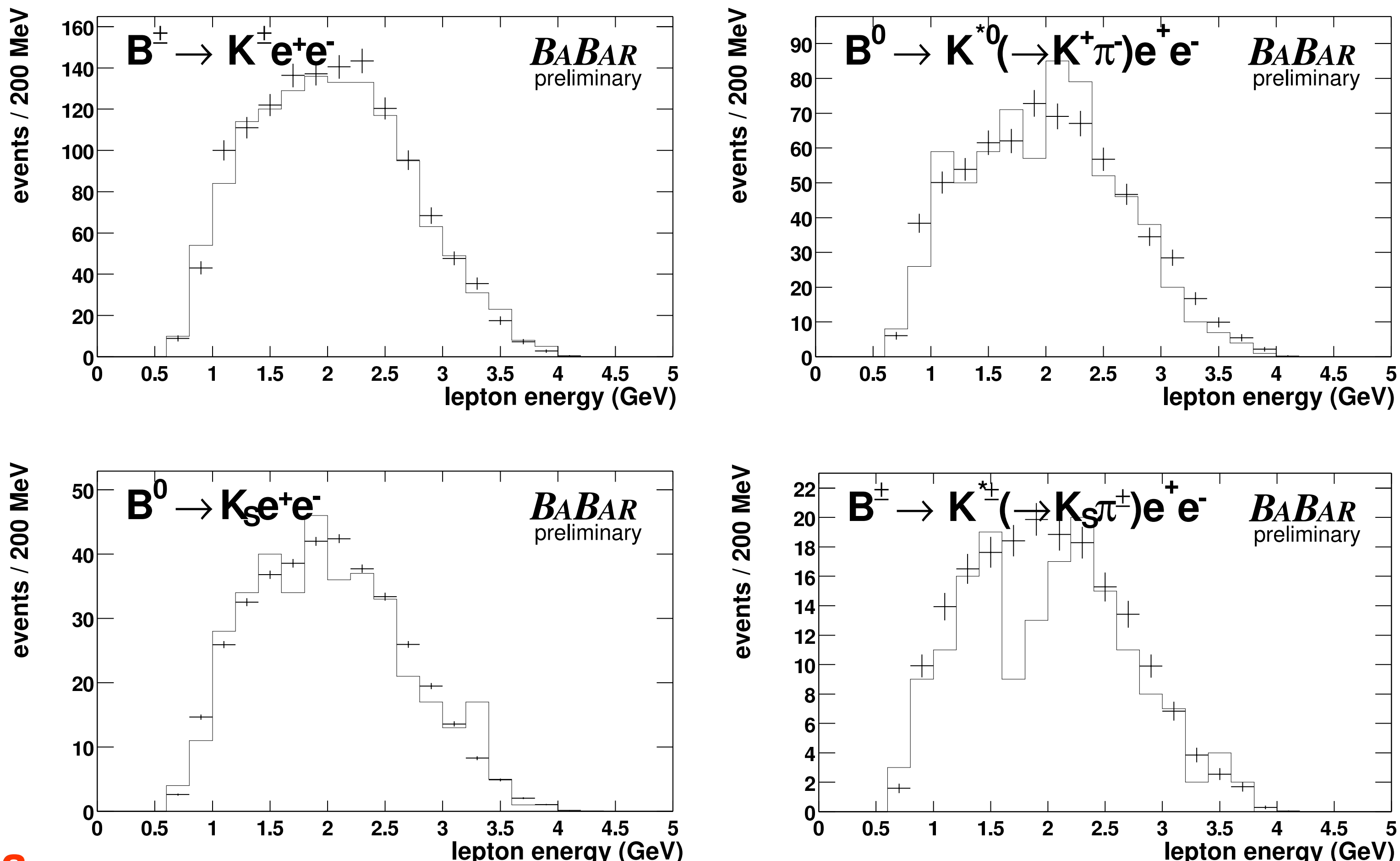
- DIRC θ_c resolution and K-π separation measured in data $\Rightarrow D^{*+} \to D^0\pi^+ \to (K^-\pi^+)\pi^+$ decays





J/ψ Control Samples: Lepton energy distributions

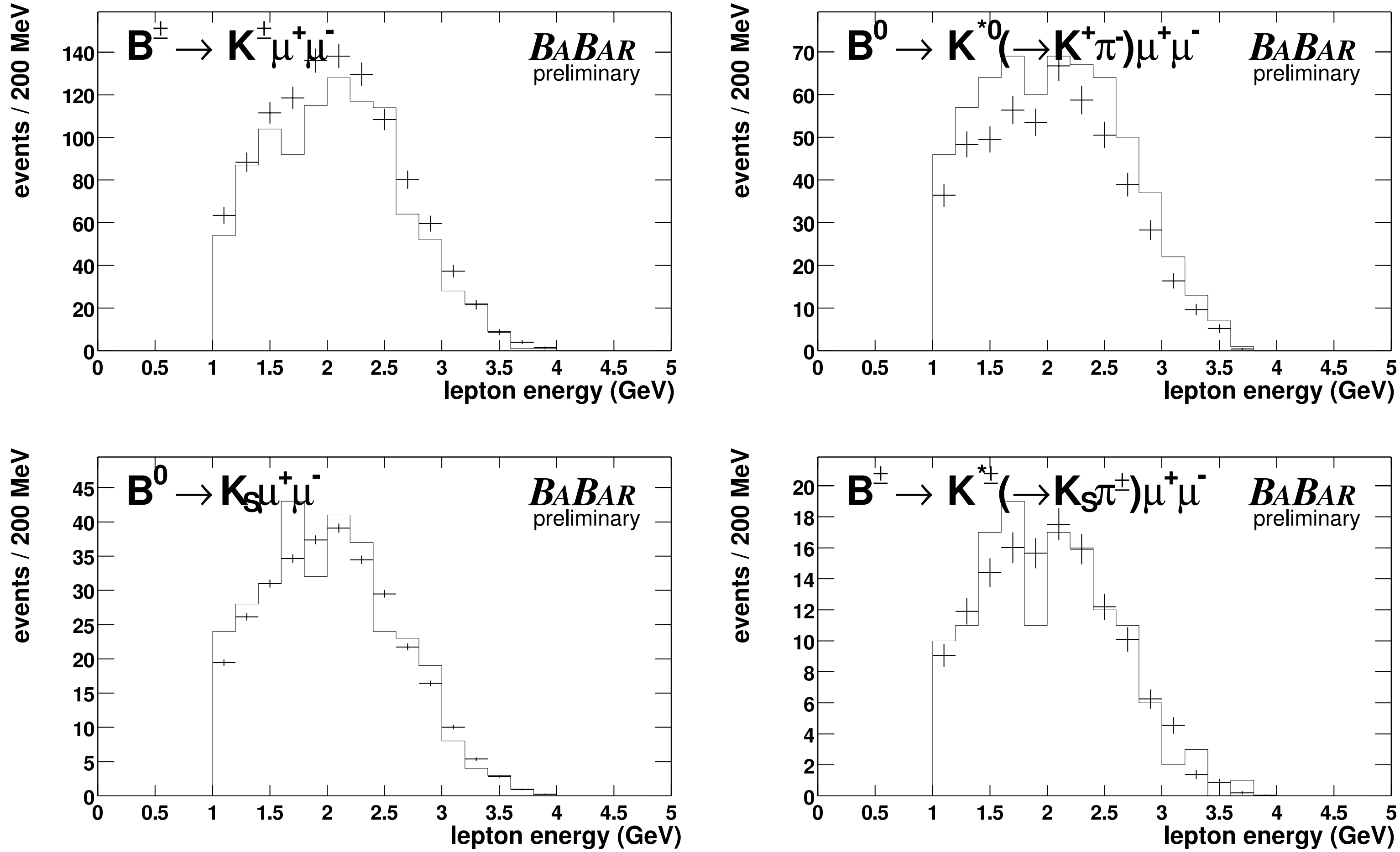
Electron channels



Points: data
Histo: MC

J/ψ Control Samples: Lepton energy distributions

Muon channels



Points: data
Histo: MC

Data Sample

- $e^+ e^- \rightarrow \Upsilon(4s) \rightarrow B\bar{B}$ data used for this talk

Run 1: 20.6 fb^{-1} (1999-2000)

23 million BB events

Run 2: 55 fb^{-1} (2001-2002)

60 million BB events

(so far)

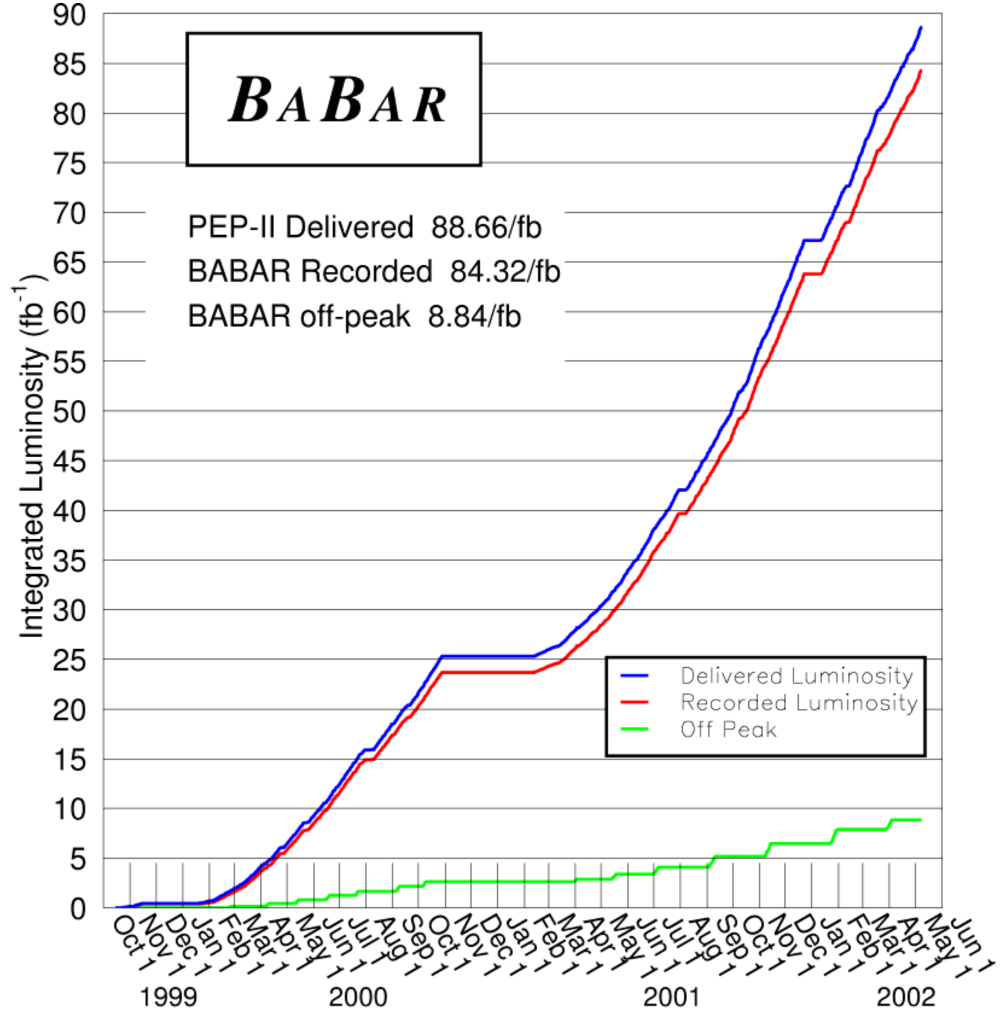
- $e^+ e^-$ annihilation

40 MeV below $\Upsilon(4s)$

Run 1: 2.6 fb^{-1}

Run 2: 6.2 fb^{-1}

This talk: 56.4 fb^{-1} on peak



Outline

- Introduction
- Analysis Overview
- Control Samples
- Results

Charmonium Control Samples: Yields in Data vs. Simulation

Mode	ϵ (%)	MC Yield	Data Yield	Data/MC (%)
$B^+ \to K^+e^+e^-$	18.0	669	660	98.6 ± 4.3
$B^+ \to K^+\mu^+\mu^-$	15.9	553	502	90.8 ± 4.5
$B^0 \to K^0e^+e^-$	18.4	191	190	99.4 ± 7.3
$B^0 \to K^0\mu^+\mu^-$	16.0	157	161	102.6 ± 8.2
$B^0 \to K^{*0}e^+e^-$	12.3	375	367	97.9 ± 5.6
$B^0 \to K^{*0}\mu^+\mu^-$	10.2	293	343	117.3 ± 7.1
$B^+ \to K^{*+}e^+e^-$	9.5	114	102	89.6 ± 9.2
$B^+ \to K^{*+}\mu^+\mu^-$	7.8	88	89	101.7 ± 11.2
$B \to K^+\ell^+\ell^-$ $(e+\mu)$		1222	1162	95.0 ± 3.1
$B \to K^0\ell^+\ell^-$ $(e+\mu)$		348	351	100.9 ± 5.4
$B \to K^{*0}\ell^+\ell^-$ $(e+\mu)$		667	710	106.4 ± 4.4
$B \to K^{*+}\ell^+\ell^-$ $(e+\mu)$		201	191	94.9 ± 7.1
All e^+e^- modes		1349	1319	97.8 ± 2.8
All $\mu^+\mu^-$ modes		1090	1095	100.5 ± 3.2
All modes		2439	2414	99.0 ± 2.1

$K^{(*)}ll$ Results from BaBar, J. Berryhill, DPF-2002