Evidence for the Flavor Changing Neutral Current Decays $B \to K l^+ l^-$ and $B \to K^* l^+ l^-$

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for the

BaBar Collaboration

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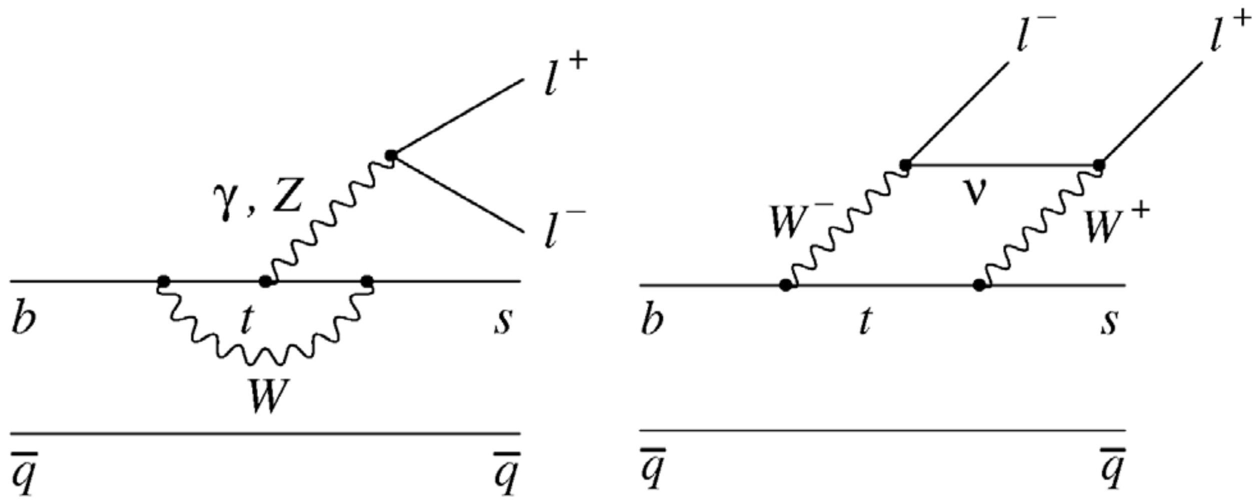
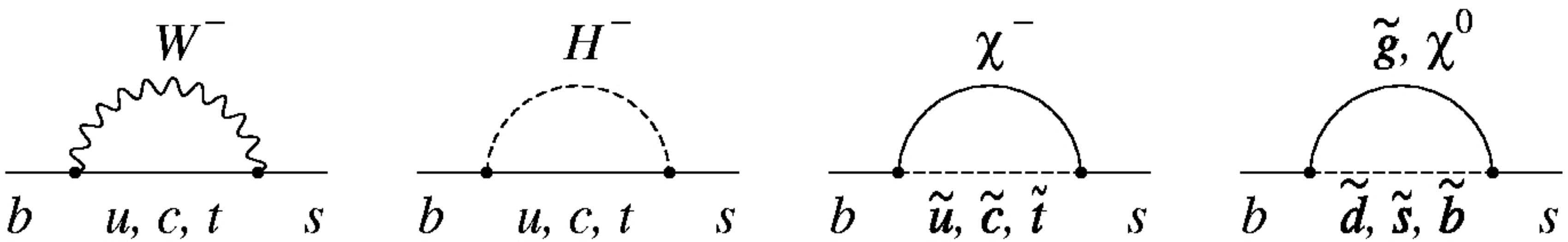
Outline

- Theoretical predictions
- Experimental status
- *B* reconstruction procedure, backgrounds, and event selection
- Fits and results
- Conclusions

Theory predictions: the standard model and beyond



- $B \to K^{(*)} l^+ l^-$: **sensitive to Wilson coefficients C_7, C_9, C_{10} in OPE**
- $B \to K^* \gamma$: **depends almost entirely on $|C_7|$**
- **New, heavy particles can affect the rate (2X) and decay distribs.**



Theoretical predictions based on 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
Aliev *et al.* (1997)	0.31 ± 0.09	1.4	
Colangelo *et al.* (1996)	0.3	1.0	
Faessler *et al.* (2002)	0.55	0.81	
Geng and Kao (1996)	0.5	1.4	
Melikhov *et al.* (1998)	0.44	1.15	1.50
Zhong *et al.* (2002)	$0.69^{+0.28}_{-0.25}$	$1.98^{+0.66}_{-0.71}$	$2.01^{+0.65}_{-0.73}$

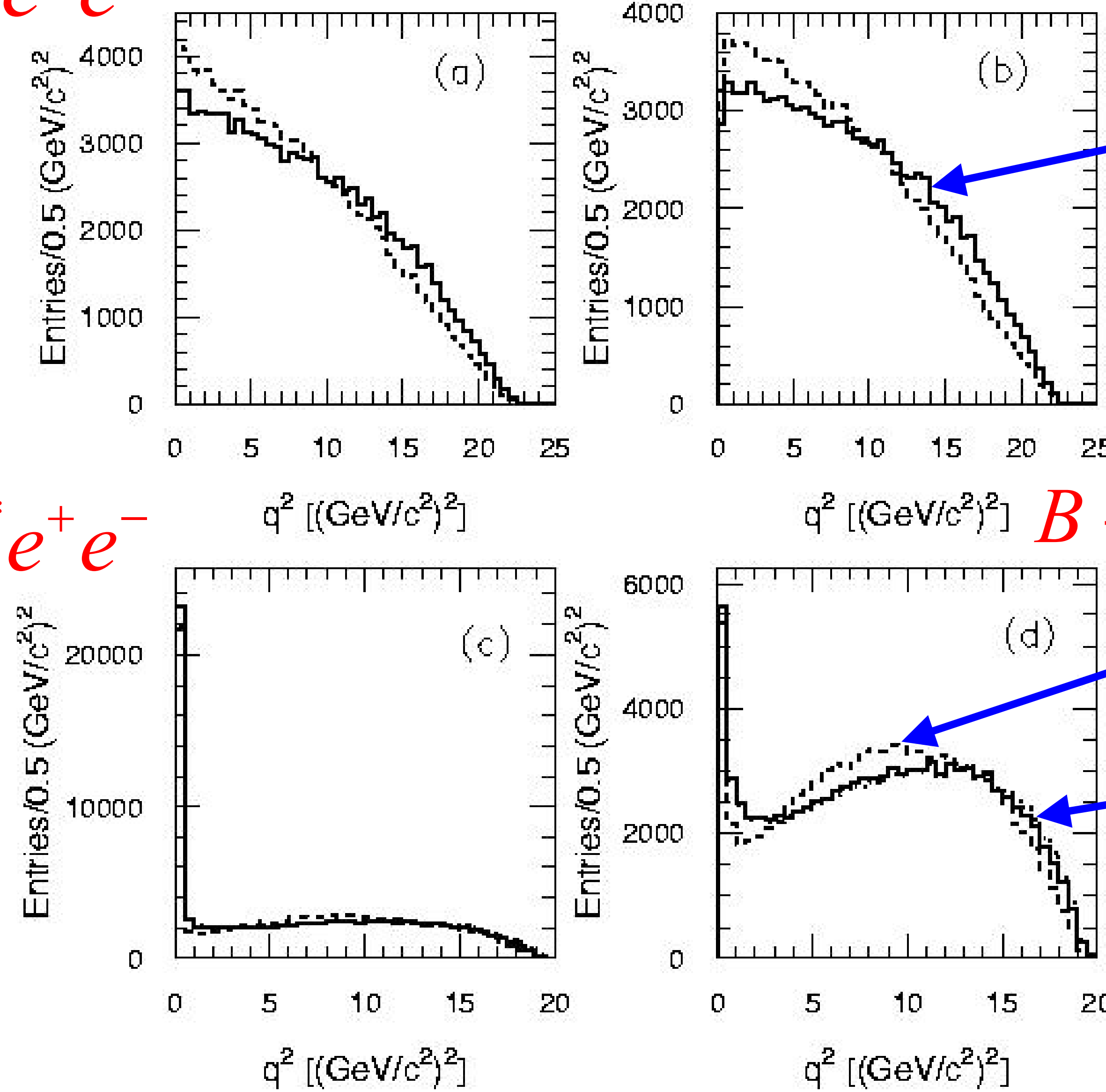
- $\mathcal{B}(B\to K\ell^+\ell^-) =$ **dominant uncertainty: form factors**
  $(0.35 \pm 0.11(\text{form fac.}) \pm 0.04(\mu_b) \pm 0.02(m_{t,\text{pole}}) \pm 0.0005(m_c/m_b)) \times 10^{-6}$
  [Ali, Lunghi, Greub, Hiller, hep-ph/0112300, 2001]

New calculations of QCD corrections predict too high a rate for B->K*γ; the necessary adjustment of T_1 form factor lowers the prediction for *B->K*l+l-*.

Generator-level distributions of $q^2 = m^2_{l^+l^-}$ from form-factor models

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

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



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

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

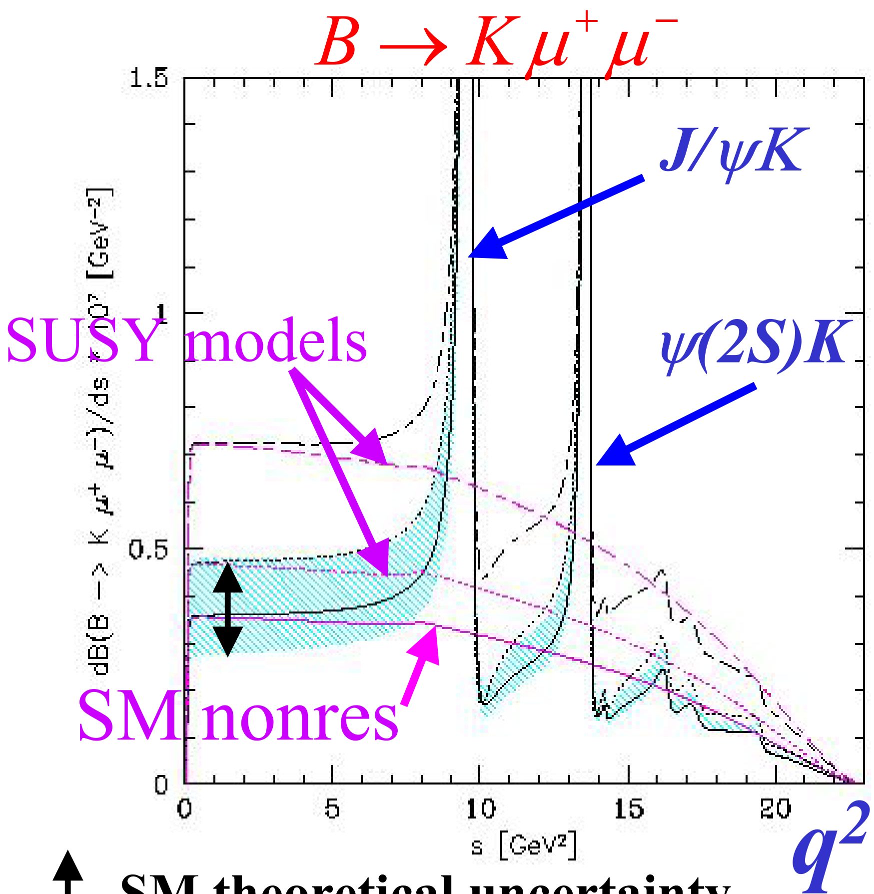
Ali et al. 2000 (solid line)

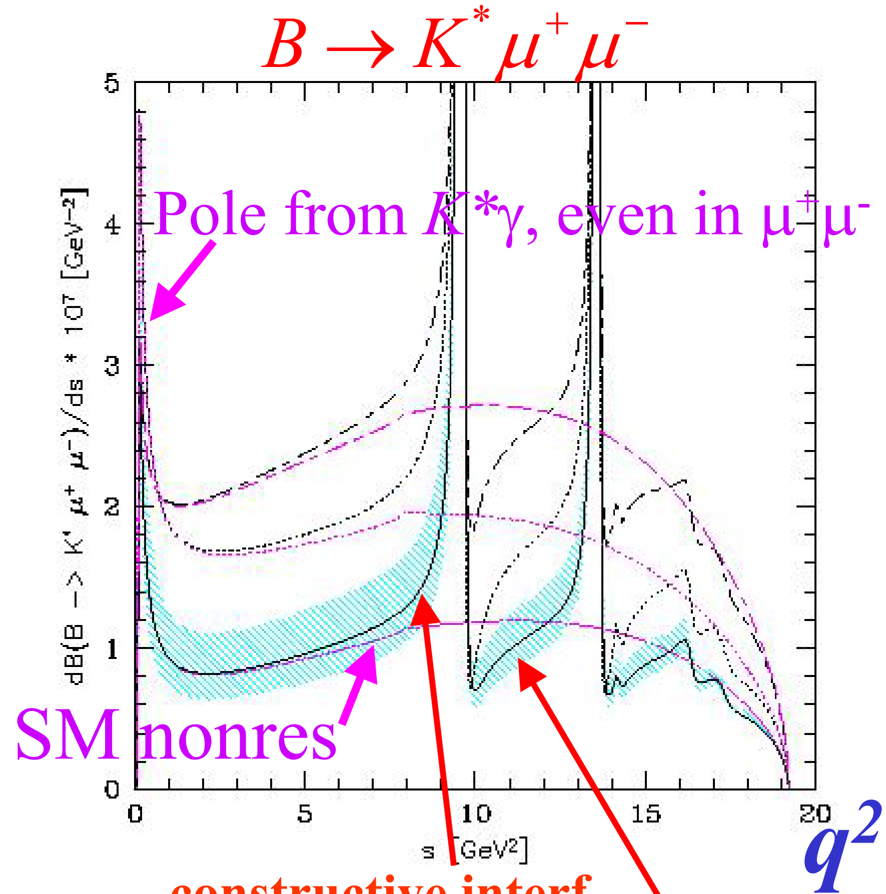
Colangelo 1999 (dashed line)

Melikhov 1997 (dotted line)

Shapes are very similar!

Decay rate vs. $q^2 = m^2_{l^+l^-}$ in the SM and SUSY





↕ **SM theoretical uncertainty**

- 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 ($R_7 = -0.83$, $R_9 = 0.92$, $R_{10} = 1.61$)

Recent experimental results

- **Belle (29.1 fb^{-1}) [K. Abe *et al.*, PRL 88, 021801 (2002).]**

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

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

- ***BABAR* (20.7 fb^{-1})[B. Aubert *et al.*, PRL 88, 241801 (2002).]**

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

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

- ***BABAR* (56.4 fb^{-1}) [FPCP, DPF conferences]**

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

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

- **Today: Run 1+2 prelim. result (77.8 fb^{-1} => 84.4 M $B\overline{B}$)**

Decay modes and final states

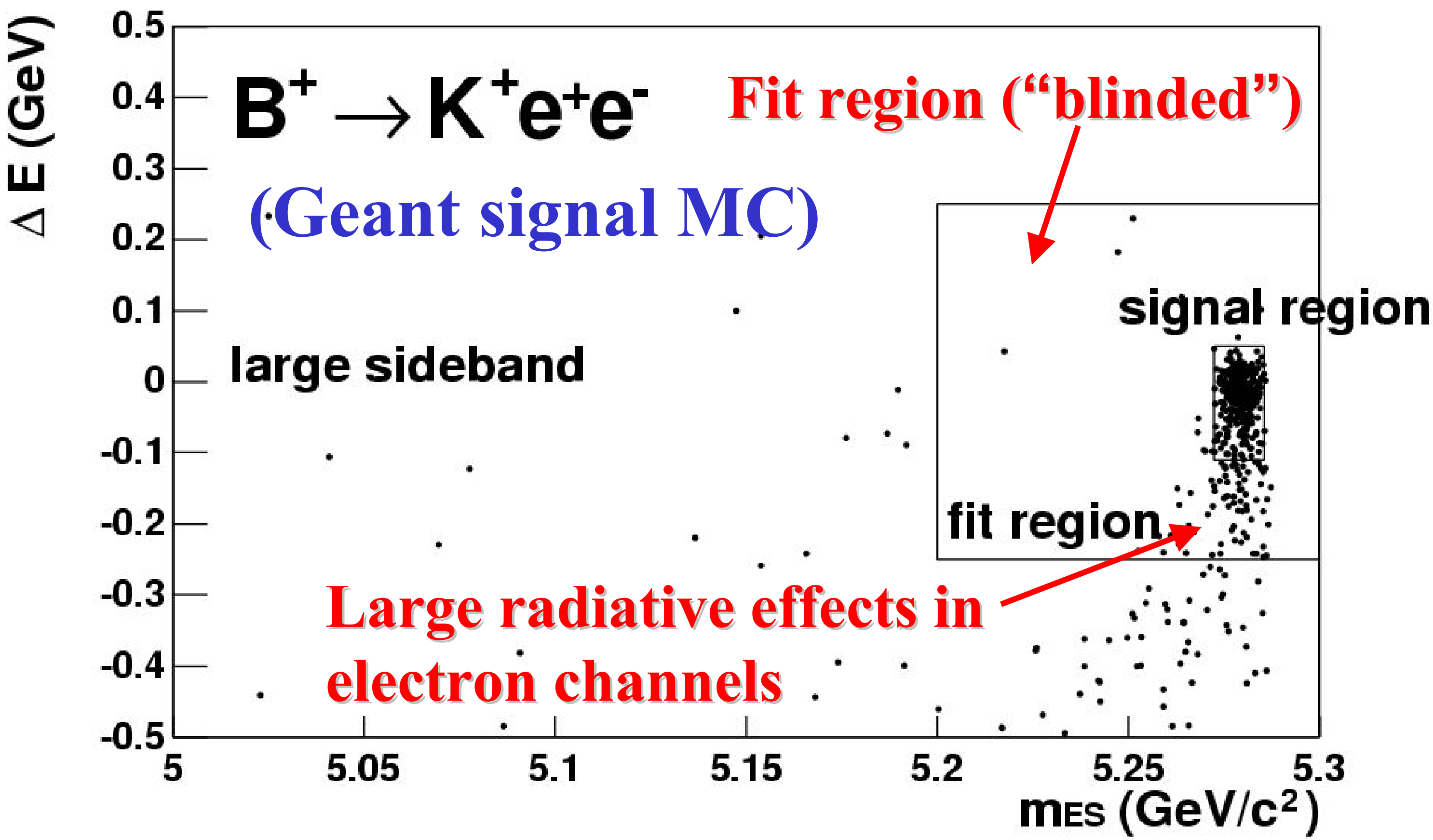
$B^+ \to K^+ e^+ e^-$	$B^+ \to K^+ \mu^+ \mu^-$
$B^0 \to K^0 e^+ e^-$	$B^0 \to K^0 \mu^+ \mu^-$
$B^+ \to K^{*+} e^+ e^-$	$B^+ \to K^{*+} \mu^+ \mu^-$
$B^0 \to K^{*0} e^+ e^-$	$B^0 \to K^{*0} \mu^+ \mu^-$

We reconstruct $K^0 \to K^0_s \to \pi^+ \pi^-$, $K^{*0} \to K^+ \pi^-$, and $K^{*+} \to K^0 \pi^+$.

B reconstruction with $e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\overline{B}$

$$m_{\text{ES}} = \sqrt{{E^*_{\text{beam}}}^2 - \left(\sum_{i=\text{daughters}} \vec{p}_i^{\,*}\right)^2} \qquad \Delta E = \sum_i \sqrt{\left(\vec{p}_i^{\,*}\right)^2 + m_i^2} - E^*_{\text{beam}}$$

Typical resolutions: $\sigma(m_{\text{ES}}) \approx$ 2.5 MeV, $\sigma(\Delta E) \approx$ 25 - 40 MeV



Backgrounds and event selection

$B \to J/\psi K^{(*)},\ \psi(2S)K^{(*)}$ with $\psi \to l^+ l^-$

Veto charmonium mass regions and J/ψK->K*l^+l^- feedup

$B\overline{B}$ combinatorics, especially from $B \to l^+,\ \overline{B} \to l^-$

Combine E_{miss} , vertex information, and B production angle into a "B likelihood" variable.

Continuum: $e^+e^- \to q\overline{q}$ (especially $c\overline{c}$), 2-photon

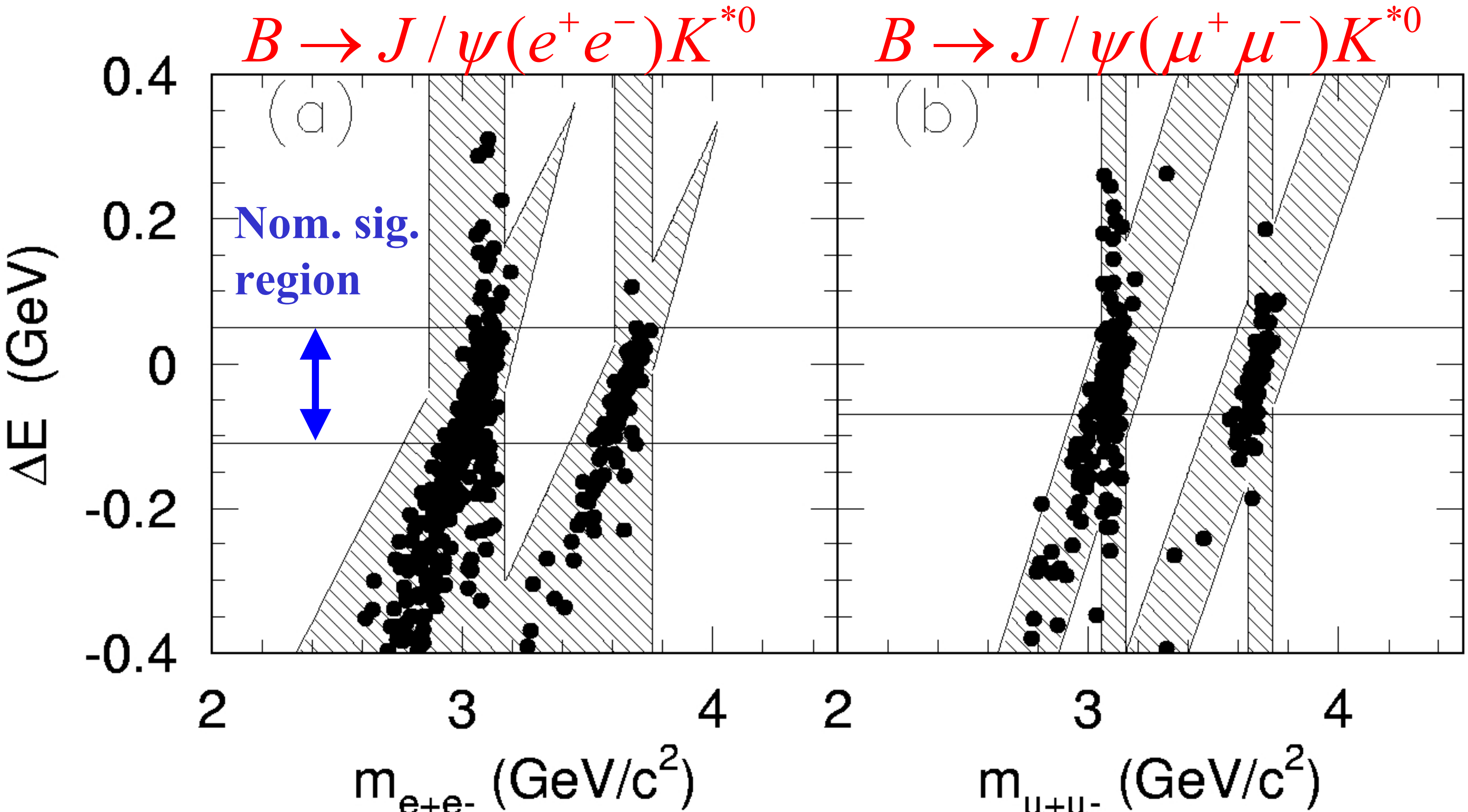
Jet-like event shape and $M(Kl)$ [$D \to Kl\nu$] into Fisher variable

Peaking backgrounds: $B^+ \to D^0\pi^+ (D^0 \to K^-\pi^+)$;

$B^- \to K^-\pi^+\pi^-;\ B \to K^*\gamma_{\mathrm{conv}}$

Veto and/or include in fit.

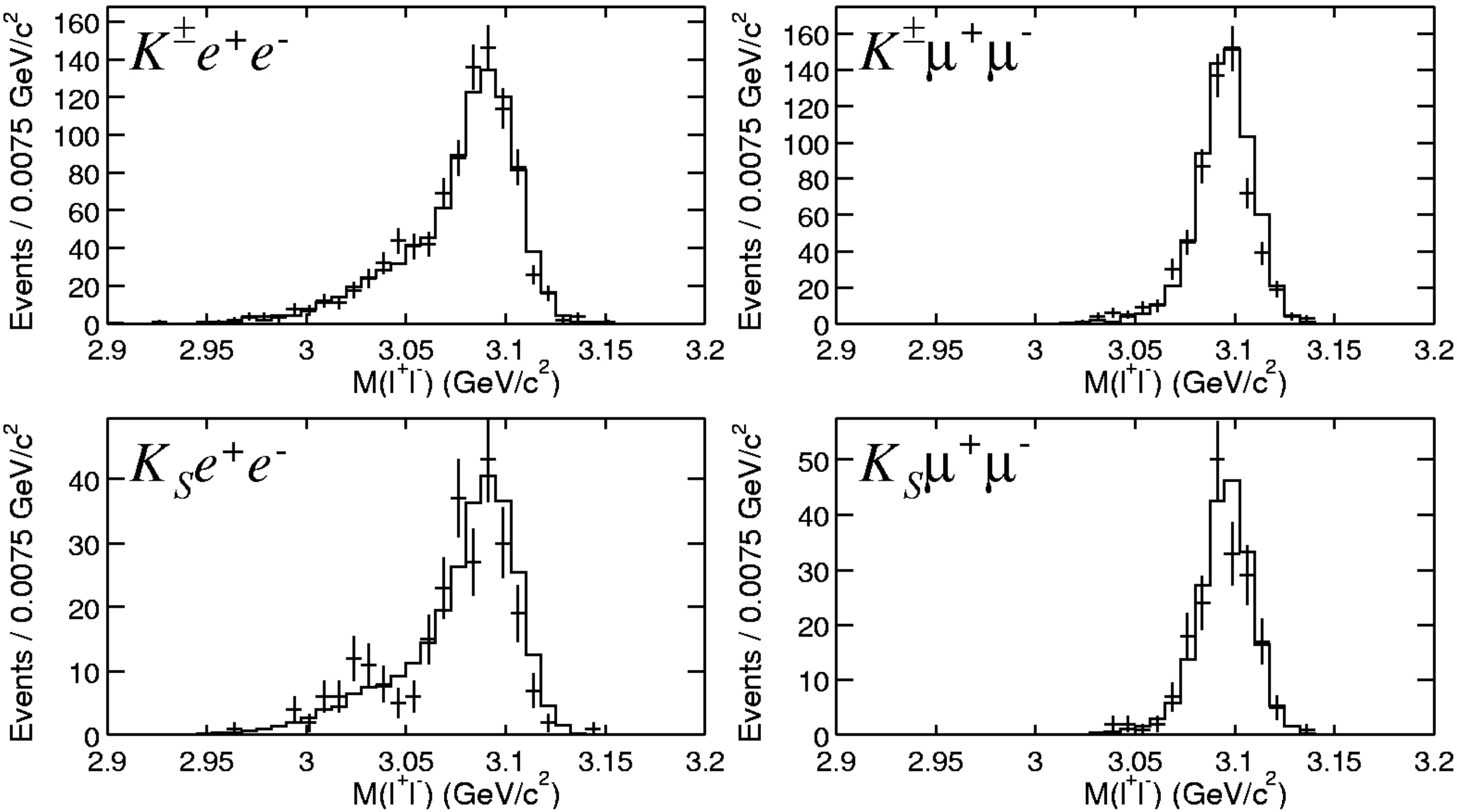
Charmonium veto regions in ΔE vs. m_{ll} (Monte Carlo simulation)



Radiation can pull m_{l+l-} below the J/ψ mass, but ΔE becomes negative!

Check of charmonium tails in m_{l+l-}

Data=Points with error bars; MC=histogram *BABAR preliminary*



➔ The MC simulates bremsstrahlung effects reasonably well.

Charmonium control sample yields

Mode ($J/\psi \to \ell^+\ell^-$)	MC Yield	Data Yield	Data/MC(%)
Combined by hadron final state			
$B^\pm \to K^\pm \ell^+\ell^-$	1580.9	1562	98.8±2.8
$B^0 \to K^0_s \ell^+\ell^-$	466.5	456	97.7±4.6
$B^0 \to K^{*0} \ell^+\ell^-$	848.2	935	110.2±3.9
$B^\pm \to K^{*\pm} \ell^+\ell^-$	264.9	255	96.3±6.2
Combined by lepton final state			
e^+e^- modes	1836.4	1871	101.9±2.6
$\mu^+\mu^-$ modes	1324.1	1337	101.0±3.0
All modes	3160.5	3208	101.5±1.9

➔ MC normalization based on published *BABAR* measurements.

$B \to D\pi^-$ vetoes in $B \to K^{(*)}\mu^+\mu^-$

- **Double fake**

μ^-

$$B \to D\pi^-$$

μ^+

$$D \to K^{(*)}\pi^+$$

Reassign particle masses and veto D region in $M(K\pi)$ and $M(K^*\pi)$ in muon channels.

- **Triple fake**

K^-

$$B^- \to D^0\pi^-$$

μ^+

$$D^0 \to K^-\pi^+$$

μ^-

Typical mis-ID probabilities (momentum dependent):

P(π ➔ e)=0.1%-0.3%; P(π ➔ μ)=1.3%-2.7%

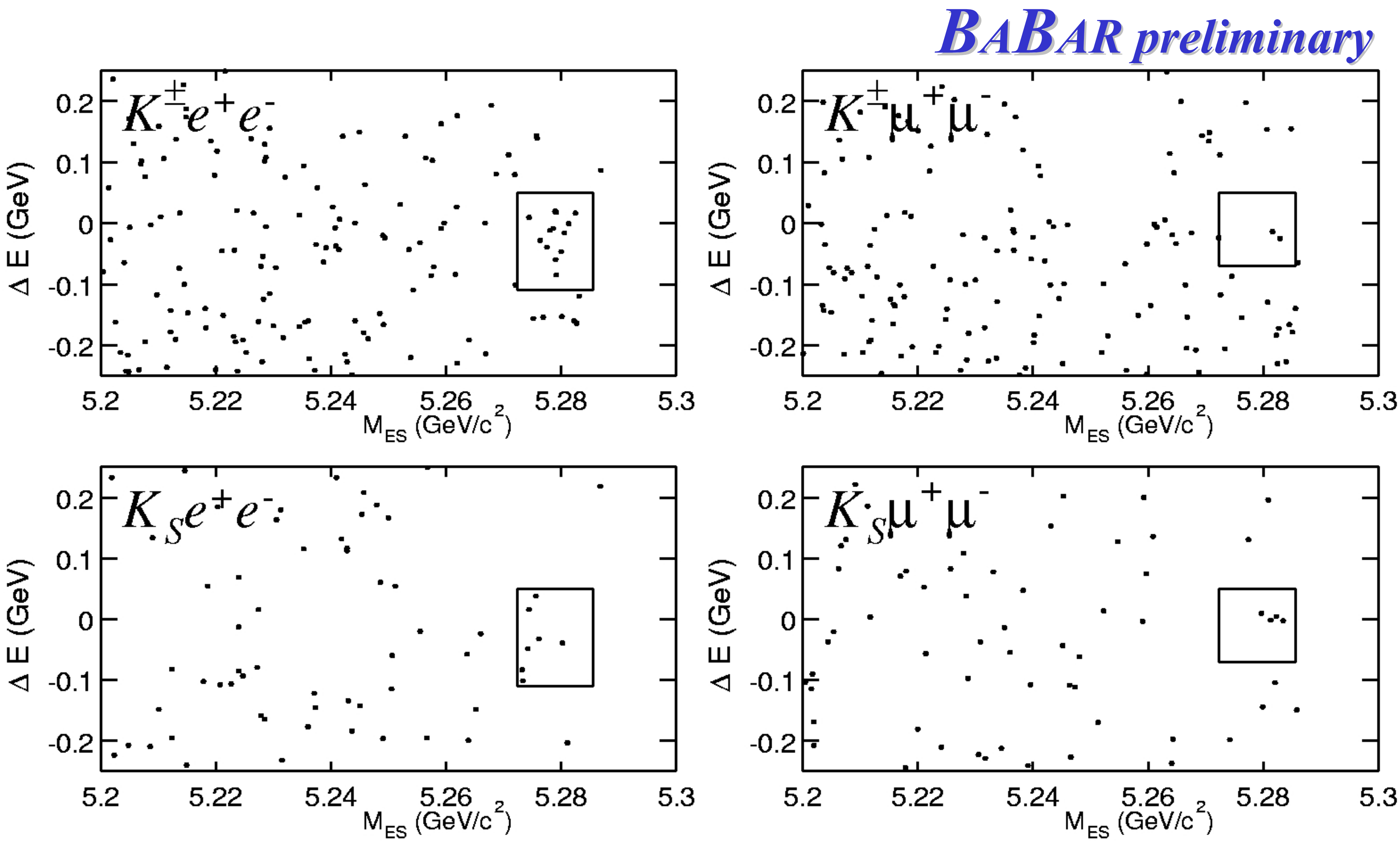
Estimates of remaining peaking backgrounds

Mode	Peaking background (events)
$B^{\pm} \to K^{\pm} e^{+} e^{-}$	$0.0^{+1.0}_{-0.0}$
$B^{\pm} \to K^{\pm} \mu^{+} \mu^{-}$	0.7 ± 0.7
$B^{0} \to K^{0}_{s} e^{+} e^{-}$	$0.0^{+0.1}_{-0.0}$
$B^{0} \to K^{0}_{s} \mu^{+} \mu^{-}$	0.5 ± 0.5
$B^{0} \to K^{*0} e^{+} e^{-}$	$0.2^{+0.5}_{-0.2}$
$B^{0} \to K^{*0} \mu^{+} \mu^{-}$	1.2 ± 1.2
$B^{\pm} \to K^{*\pm} e^{+} e^{-}$	$0.1^{+0.4}_{-0.1}$
$B^{\pm} \to K^{*\pm} \mu^{+} \mu^{-}$	1.0 ± 1.0

➔ Except for contribution from *B*->*K**γ, these backgrounds are computed by applying measured hadron->lepton fake rates to a MC sample 9X the data. Peaking backgrounds are not negligible in the muon channels.

Data: ΔE vs. m_{ES} for $B \to K l^+ l^-$ modes

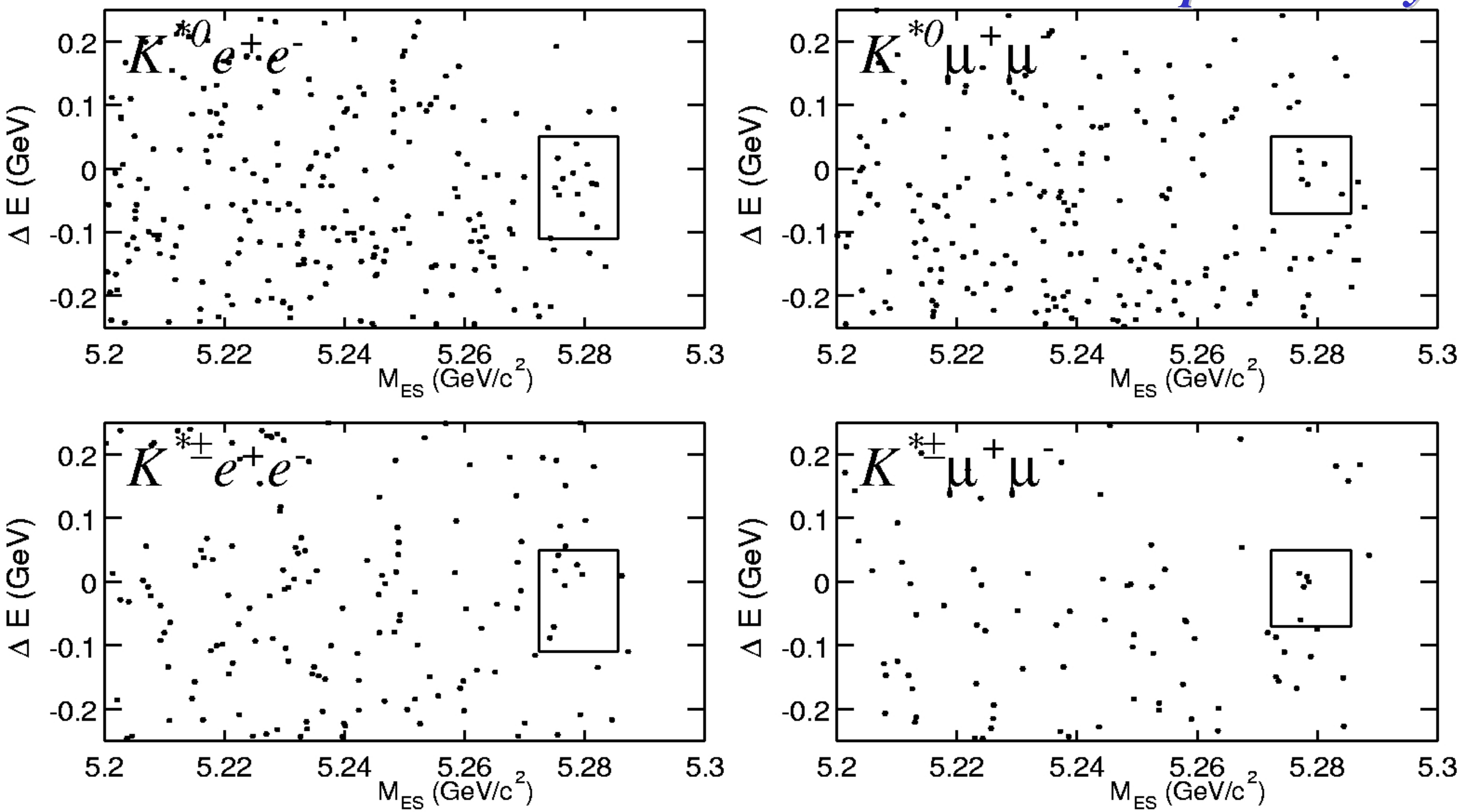
Full area= fit region   Small rectangle=nominal signal region



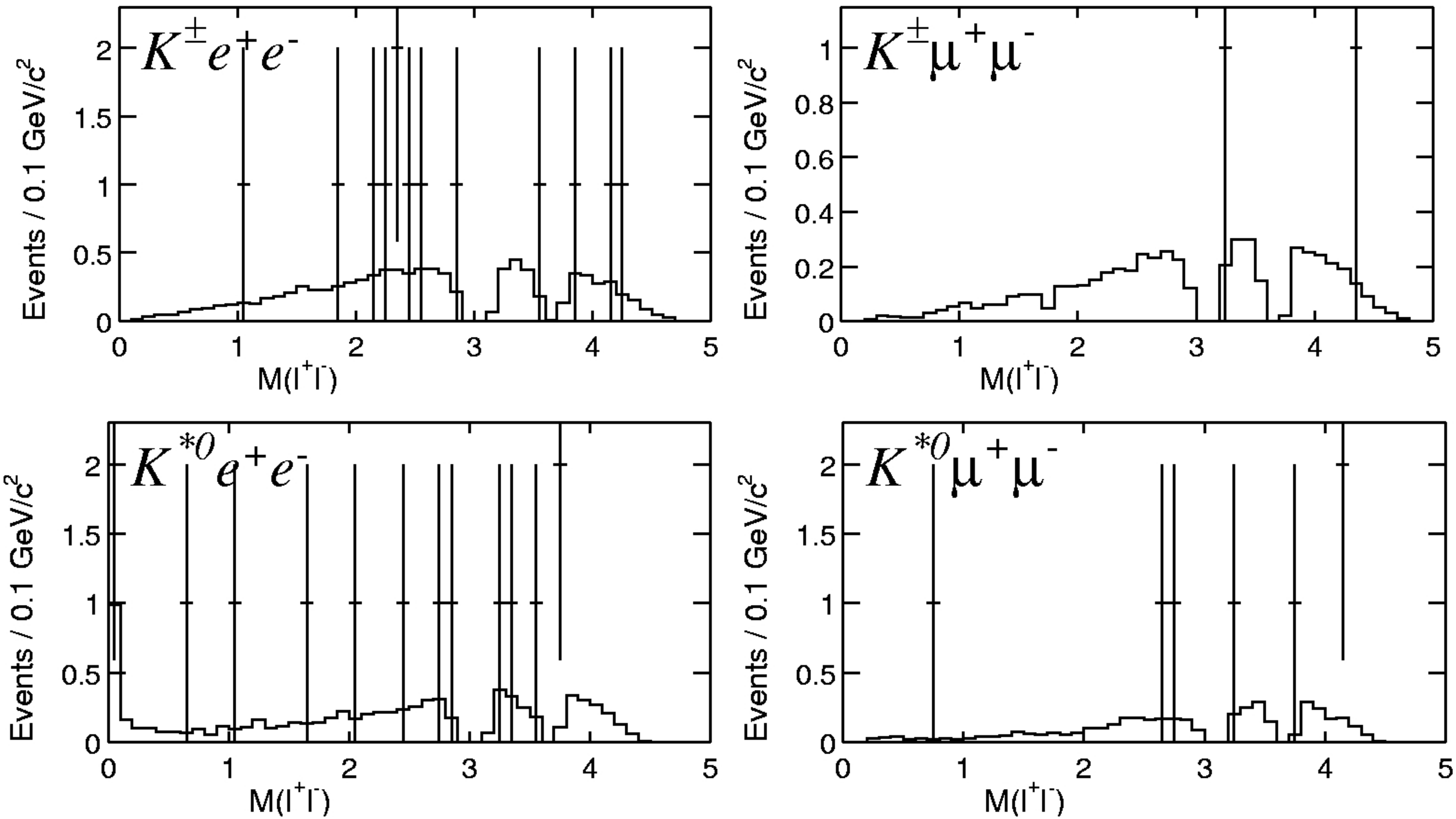
Data: ΔE vs. m_{ES} for $B \to K^* l^+ l^-$ modes

Full area= fit region   Small rectangle=nominal signal region

BABAR preliminary



m_{l+l-} for events in nominal signal region (includes some background)



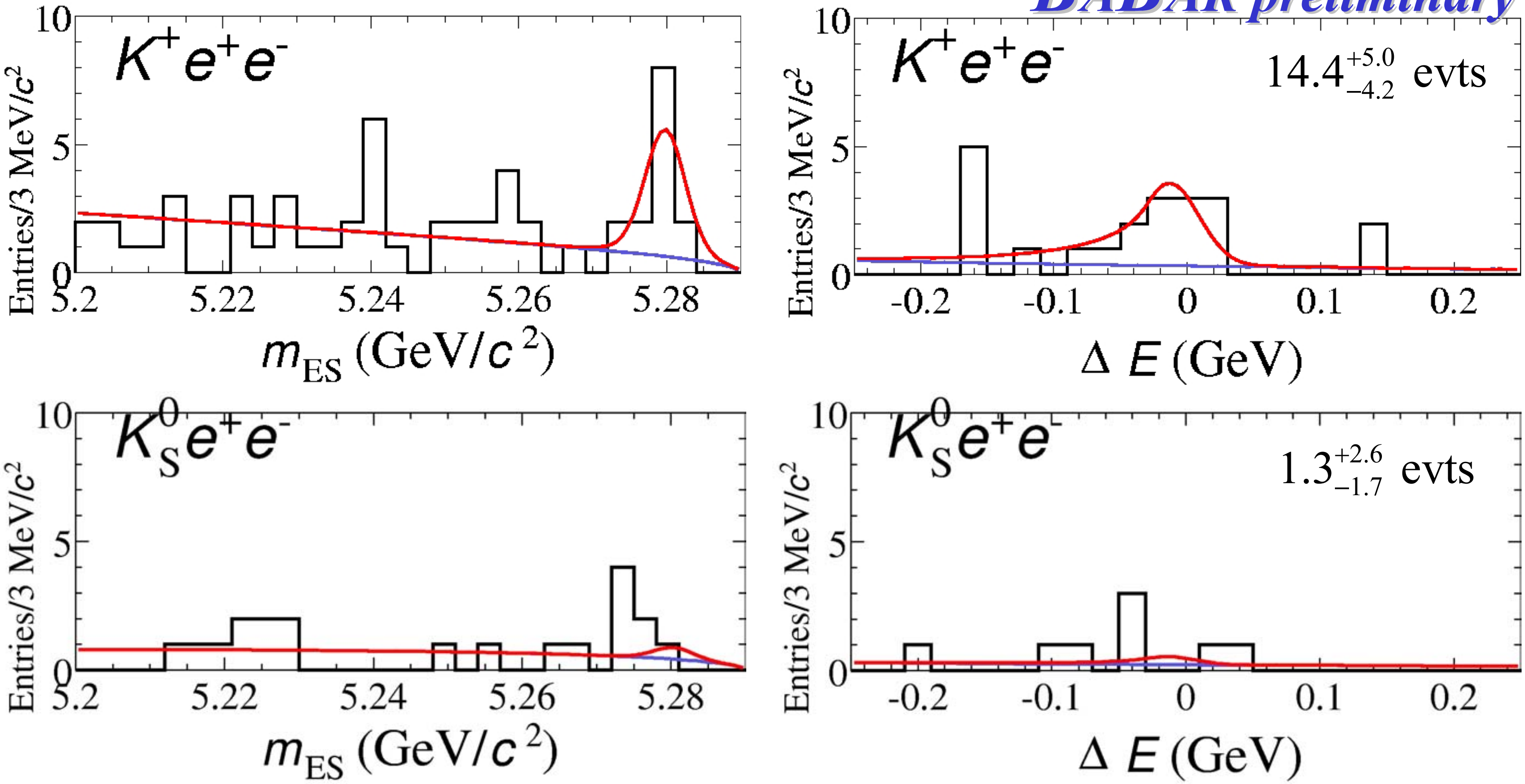
➔ Events do not cluster on veto boundaries.

Fit method

- 2-dim, unbinned maximum likelihood fit in m_{ES} vs. ΔE
- Signal shape:
  - Use Geant MC with shifts from $J/\psi K(*)$ samples; Crystal Ball parametrization.
- Background shape: ARGUS shape in m_{ES}; exponential in ΔE. Possible correlation is considered in evaluation of systematic error.
- The background normalization and shape parameters float in the fit.

Data: fit projections onto m_{ES} and ΔE for $B^+ \to K^+ e^+ e^-$ and $B^+ \to K_S^0 e^+ e^-$

BABAR preliminary

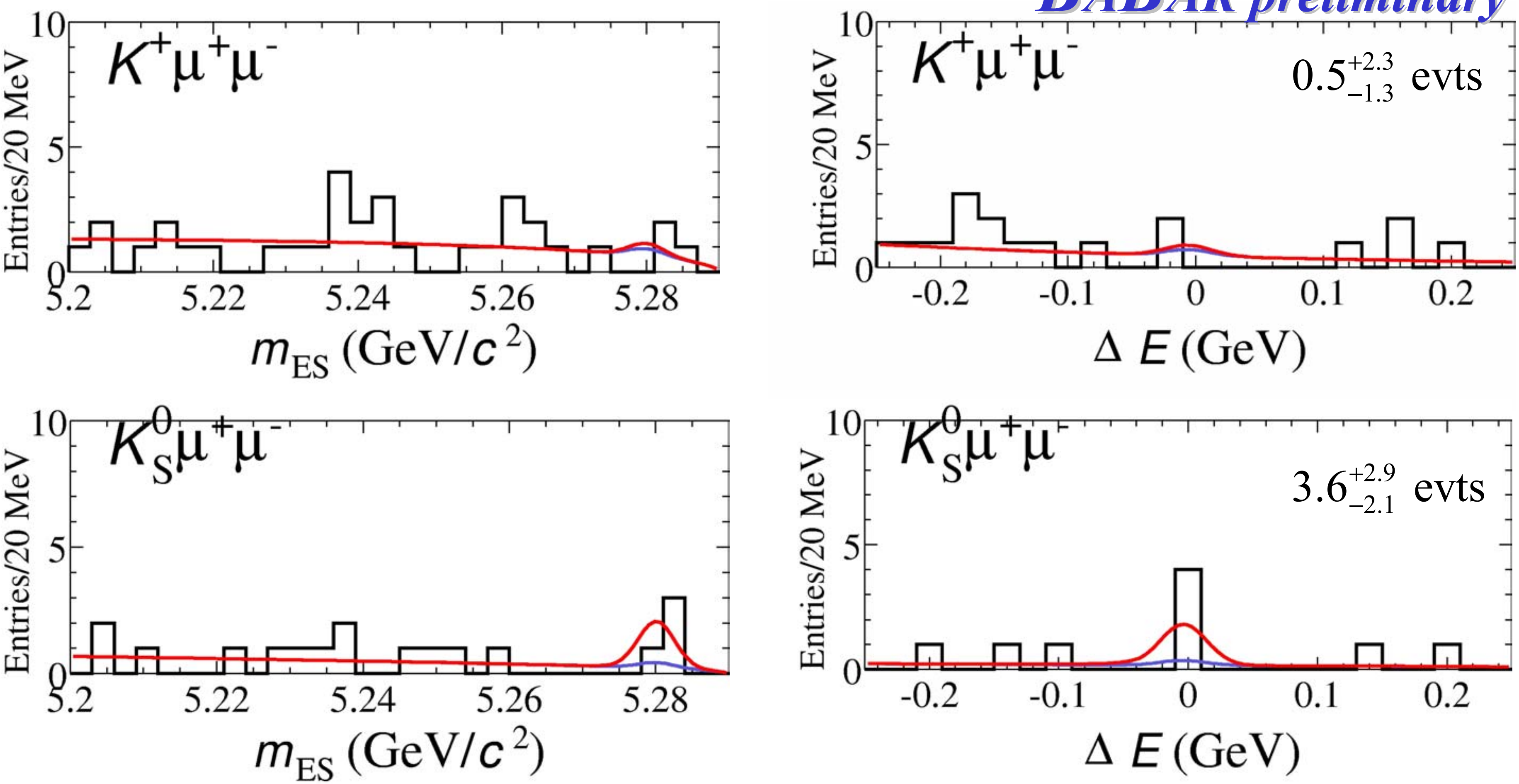


$-0.11 < \Delta E < 0.05$ GeV

$5.2725 < m_{ES} < 5.2856$ GeV/c^2

Data: fit projections onto m_{ES} and ΔE for $B^+ \to K^+\mu^+\mu^-$ and $B^+ \to K_S^0\mu^+\mu^-$

BABAR preliminary

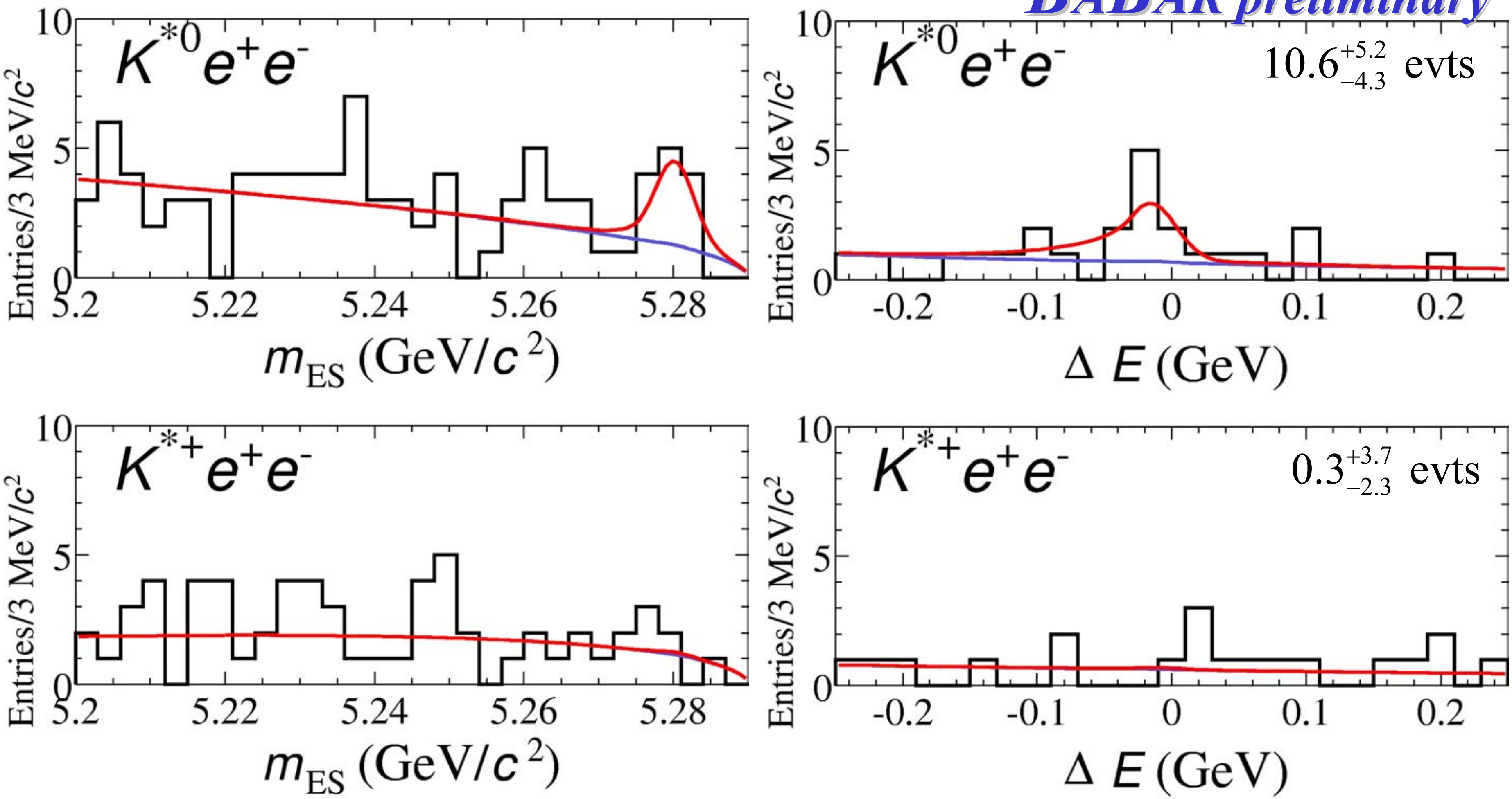


$-0.07 < \Delta E < 0.05$ GeV

$5.2725 < m_{ES} < 5.2856$ GeV/c^2

Data: fit projections onto m_{ES} and ΔE for $B^+ \to K^{*0} e^+ e^-$ and $B^+ \to K^{*+} e^+ e^-$

BABAR preliminary

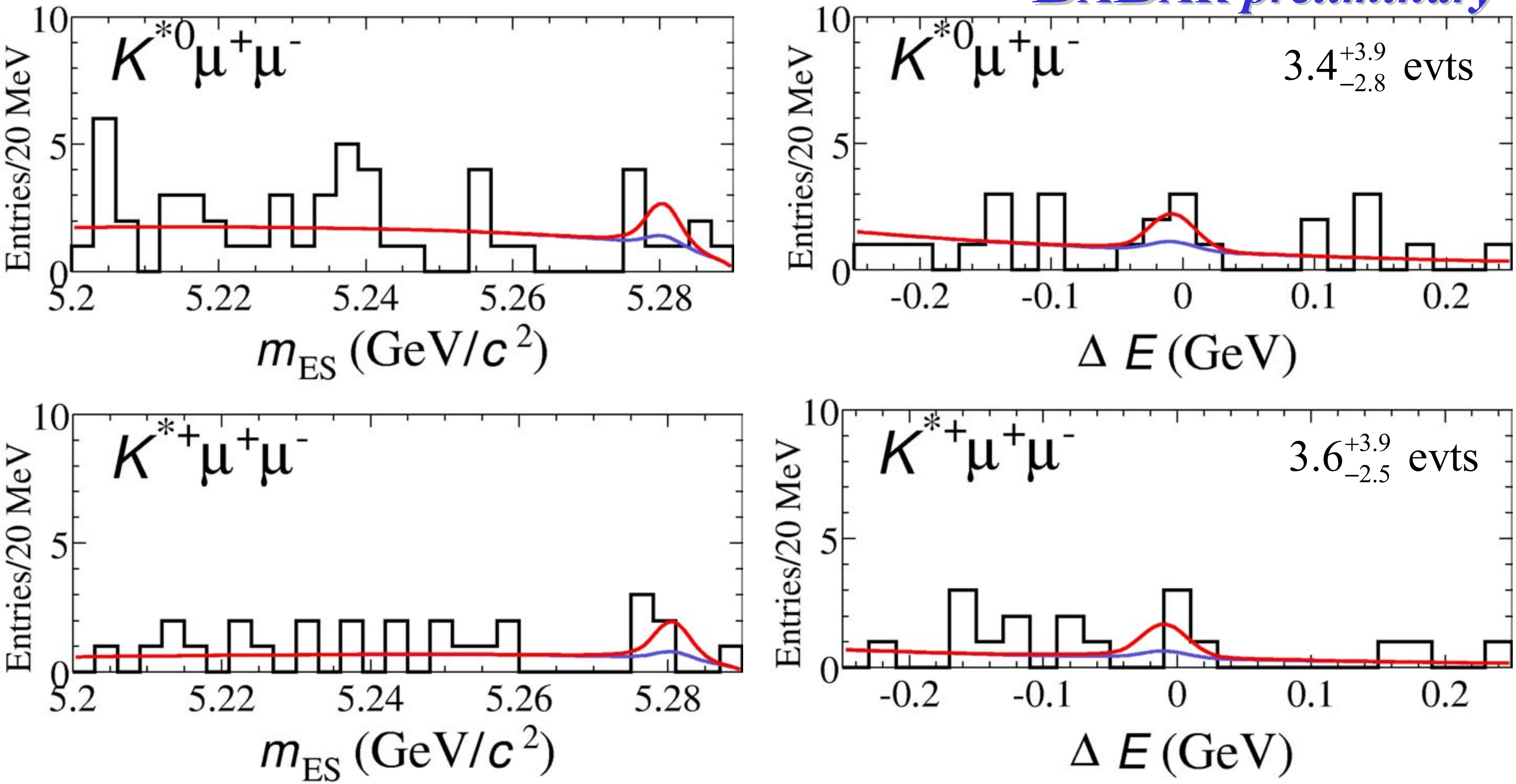


$-0.11 < \Delta E < 0.05$ GeV

$5.2725 < m_{ES} < 5.2856$ GeV/c^2

Data: fit projections onto m_{ES} and ΔE for $B^+ \to K^{*0}\mu^+\mu^-$ and $B^+ \to K^{*+}\mu^+\mu^-$

BABAR preliminary



$-0.07 < \Delta E < 0.05$ GeV

$5.2725 < m_{ES} < 5.2856$ GeV/c^2

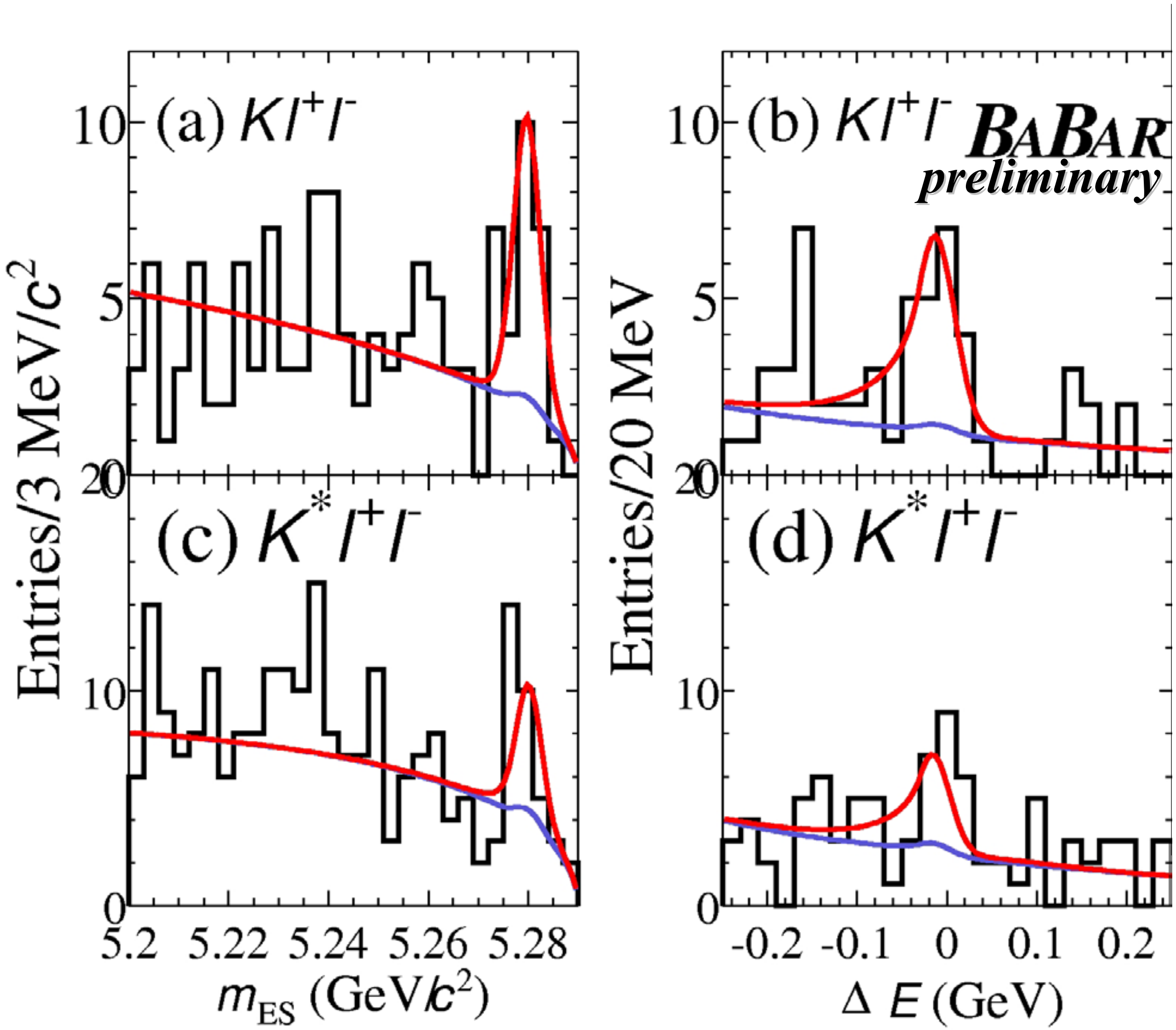
Yields, efficiencies, systematic errors, and branching fractions

BABAR preliminary

Mode	Signal Yield	ϵ (%)	$(\Delta\mathcal{B}/\mathcal{B})_\epsilon$ (%)	$(\Delta\mathcal{B})_{\rm fit}$ $(/10^{-6})$	$\mathcal{B}$ $(/10^{-6})$
$B^+ \to K^+ e^+ e^-$	$14.4^{+5.0}_{-4.2}$	17.5	± 6.8	$^{+0.14}_{-0.21}$	$0.98^{+0.34+0.16}_{-0.28-0.22}$
$B^+ \to K^+ \mu^+ \mu^-$	$0.5^{+2.3}_{-1.3}$	9.2	± 6.6	$^{+0.09}_{-0.08}$	$0.06^{+0.30+0.09}_{-0.17-0.08}$
$B^0 \to K^0 e^+ e^-$	$1.3^{+2.6}_{-1.7}$	18.6	± 7.9	± 0.14	$0.24^{+0.49+0.14}_{-0.32-0.15}$
$B^0 \to K^0 \mu^+ \mu^-$	$3.6^{+2.9}_{-2.1}$	9.4	± 7.7	± 0.24	$1.33^{+1.07}_{-0.78} \pm 0.26$
$B^0 \to K^{*0} e^+ e^-$	$10.6^{+5.2}_{-4.3}$	10.6	± 7.6	$^{+0.46}_{-0.47}$	$1.78^{+0.87+0.48}_{-0.72-0.49}$
$B^0 \to K^{*0} \mu^+ \mu^-$	$3.4^{+3.9}_{-2.8}$	6.1	± 9.3	± 0.38	$0.99^{+1.14}_{-0.82} \pm 0.39$
$B^+ \to K^{*+} e^+ e^-$	$0.3^{+3.7}_{-2.3}$	10.3	± 9.5	$^{+0.69}_{-0.72}$	$0.15^{+1.87+0.69}_{-1.16-0.72}$
$B^+ \to K^{*+} \mu^+ \mu^-$	$3.6^{+3.9}_{-2.5}$	5.2	± 11.1	± 1.80	$3.61^{+3.91}_{-2.51} \pm 1.84$

Low muon system efficiencies ➔ install replacement detectors

Combined fits: all channels



Significance:

4.4σ

2.8σ

To combine the K^*ll modes, we assume $K^*ee/K^*\mu\mu$=1.2 (Ali *et al.*).

Combine channel fits

$$\mathrm{B}(B \to K l^+ l^-) = (0.78^{+0.24+0.11}_{-0.20-0.18}) \times 10^{-6}$$

$$\mathrm{B}(B \to K^* l^+ l^-) = (1.68^{+0.68}_{-0.58} \pm 0.28) \times 10^{-6}$$

$$< 3.0 \times 10^{-6} \quad 90\% \ \mathrm{C.L.}$$

- **The combined significance of the B->*Kll* channels is 4.4σ (including systematic errors).**
- **There is an indication of a signal in *B->K*ll*, but the significance is only 2.8σ (including systematic errors).**
- **This result is consistent with our result from 56.4 fb^{-1} (and is somewhat higher than our original upper limit based on 20.7 fb^{-1}).**

Conclusions

- **We have updated our analysis with a sample of 84.4 M $B\bar{B}$ events, about four times the size of our original sample.**
- **We observe a $B\text{->}Kl^+l^-$ signal (4.4σ) with branching fraction**

$$\mathrm{B}(B \to K l^+ l^-) = (0.78^{+0.24+0.11}_{-0.20-0.18}) \times 10^{-6}$$

- **The central value is higher than most theoretical predictions based on the SM, but the uncertainties are large (both expt and theory), so there is no inconsistency.**

Conclusions (cont.)

- **We observe events consistent with a *B->K*l⁺l⁻* signal, but the significance is only 2.8σ**

$$\mathrm{B}(B \to K^{*} l^{+} l^{-}) = (1.68^{+0.68}_{-0.58} \pm 0.28) \times 10^{-6}$$

$$< 3.0 \times 10^{-6} \quad 90\% \ \text{C.L.}$$

- **These modes will be studied for many years to come. We can expect**
  - **better measurements and predictions for branching fractions**
  - **studies of kinematic distributions, which will provide additional sensitivity to new physics with less model dependence.**

Backup Slides

Multiplicative systematic errors: efficiencies and event sample

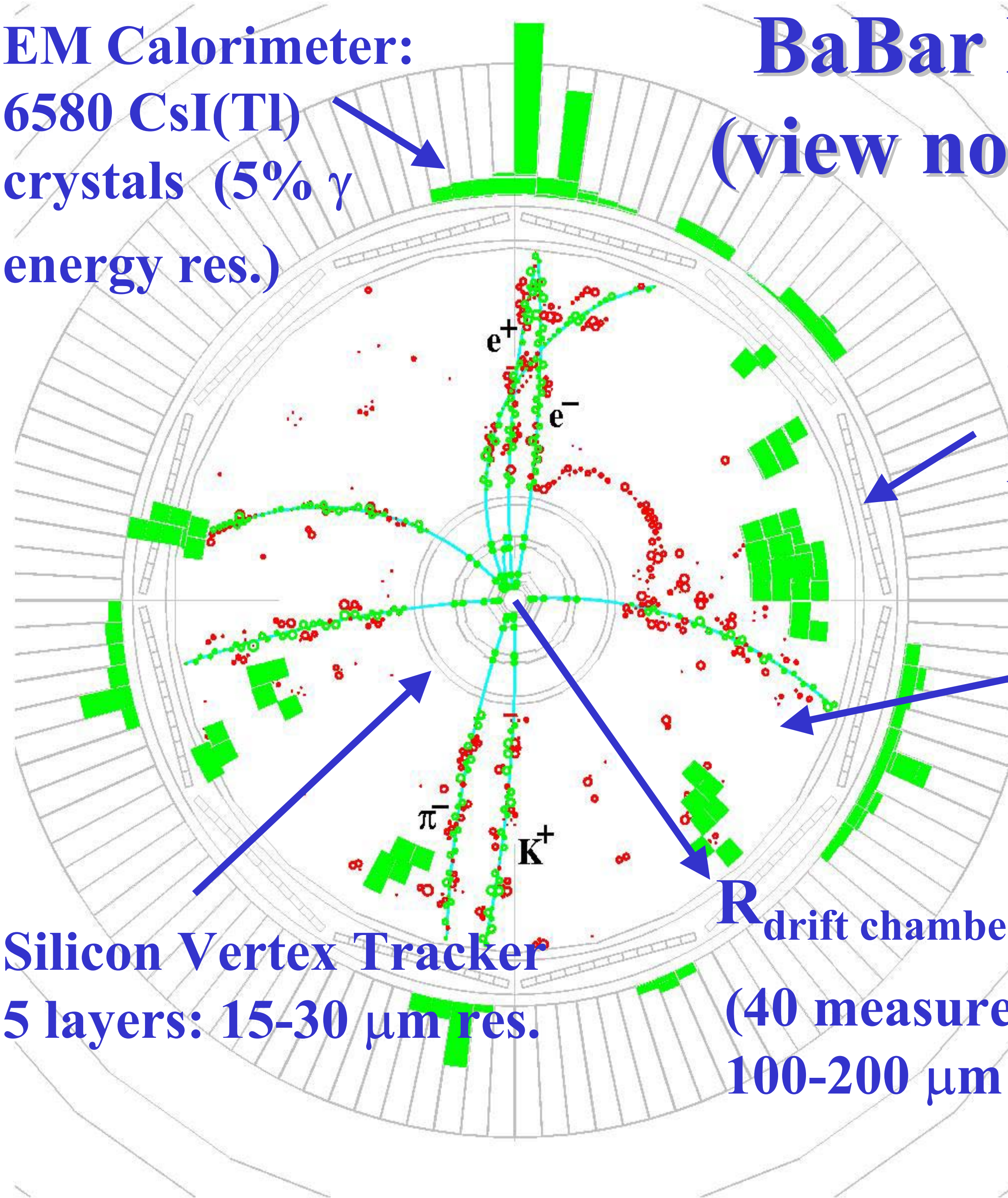
Systematic	$K^+e^+e^-$	$K^+\mu^+\mu^-$	$K_Se^+e^-$	$K_S\mu^+\mu^-$
Trk eff. (e,μ)	±1.6	±1.6	±1.6	±1.6
Electron ID	±2.7	-	±2.7	-
Muon ID	-	±2.0	-	±2.0
K,π ID	±2.0	±2.0	-	-
Trk eff. (K,π)	±1.3	±1.3	±2.6	±2.6
K_S^0 eff.	-	-	±3.2	±3.2
$B\overline{B}$ Counting	±1.1	±1.1	±1.1	±1.1
Fisher	±1.5	±1.5	±1.5	±1.5
$B\overline{B}$ likelihood	±2.5	±2.5	±2.5	±2.5
Model dep.	±4.0	±4.0	±4.0	±4.0
MC statistics	±1.1	±1.1	±1.1	±1.1
Total	±6.8	±6.6	±7.9	±7.7

Systematic errors on the fit yields

Mode	Signal Shape	Comb. Background Shape	Peaking Background
$K^+e^+e^-$	±0.3	±1.8	$^{+0.0}_{-1.0}$
$K^+\mu^+\mu^-$	±0.0	±0.1	±0.7
$K^0_Se^+e^-$	±0.3	±0.7	$^{+0.0}_{-0.1}$
$K^0_S\mu^+\mu^-$	±0.1	±0.3	±0.5
$K^{*0}e^+e^-$	±0.4	±2.6	$^{+0.2}_{-0.5}$
$K^{*0}\mu^+\mu^-$	±0.2	±0.3	±1.2
$K^{*+}e^+e^-$	±0.4	±1.3	$^{+0.1}_{-0.4}$
$K^{*+}\mu^+\mu^-$	±0.3	±1.4	±1.0

- Signal shape: allow 50% larger radiative tail; vary m_{ES} , ΔE means from control sample values to MC values.
- Combinatorial background shape: fix m_{ES} slopes to MC values; allow m_{ES} slope to have quadratic dependence on ΔE.
- Peaking background estimates: typically 100% uncertainties.

BaBar Event Display (view normal to beams)



EM Calorimeter: 6580 CsI(Tl) crystals (5% γ energy res.)

Cerenkov ring imaging detectors: 144 quartz bars (measure *velocity*)

Tracking volume: B=1.5 T

Silicon Vertex Tracker 5 layers: 15-30 μm res.

$R_{\text{drift chamber}}$=80.9 cm

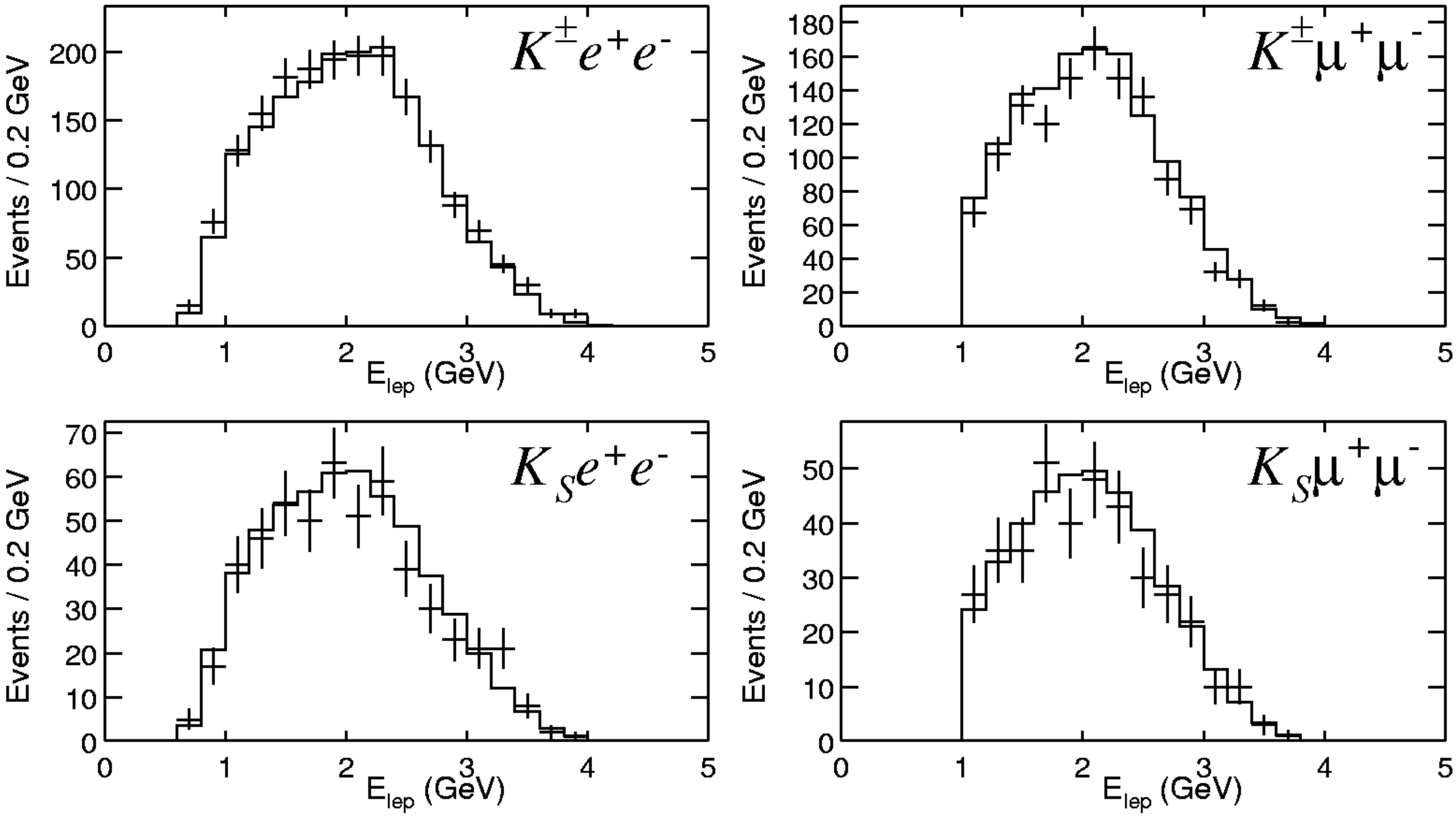
(40 measurement points, each with 100-200 μm res. on charged tracks)

Control samples

- **We make extensive use *control samples* in the data to check the MC, both for signal and background.**
  - ***Decays to charmonium.*** **Each final state has a "signal-like" control sample that is identical except for the restricted range of q^2. Checks MC predictions for cut efficiencies.**
  - ***"Large sideband"*** **in m_{ES} vs. ΔE plane: checks combinatorial background**
  - ***$Ke\mu$*: monitors combinatorial background**

Check of E_{lep} distributions using $J/\psi K(*)$ samples

Data=Points with error bars; MC=histogram *BABAR preliminary*

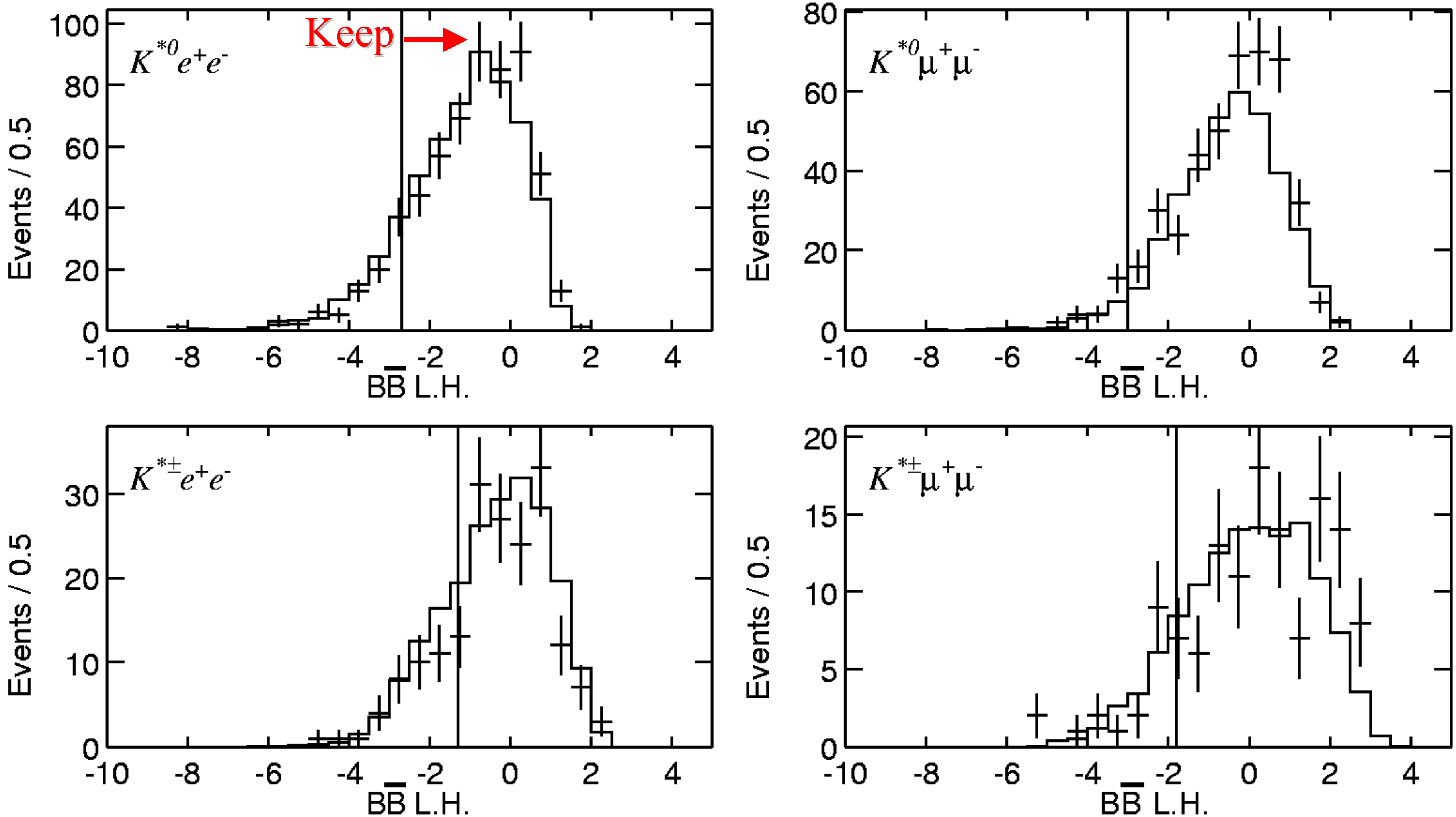


➔ We understand lepton ID efficiencies vs. lepton momentum.

Check of *B likelihood* distributions using *J/ψK(*)*

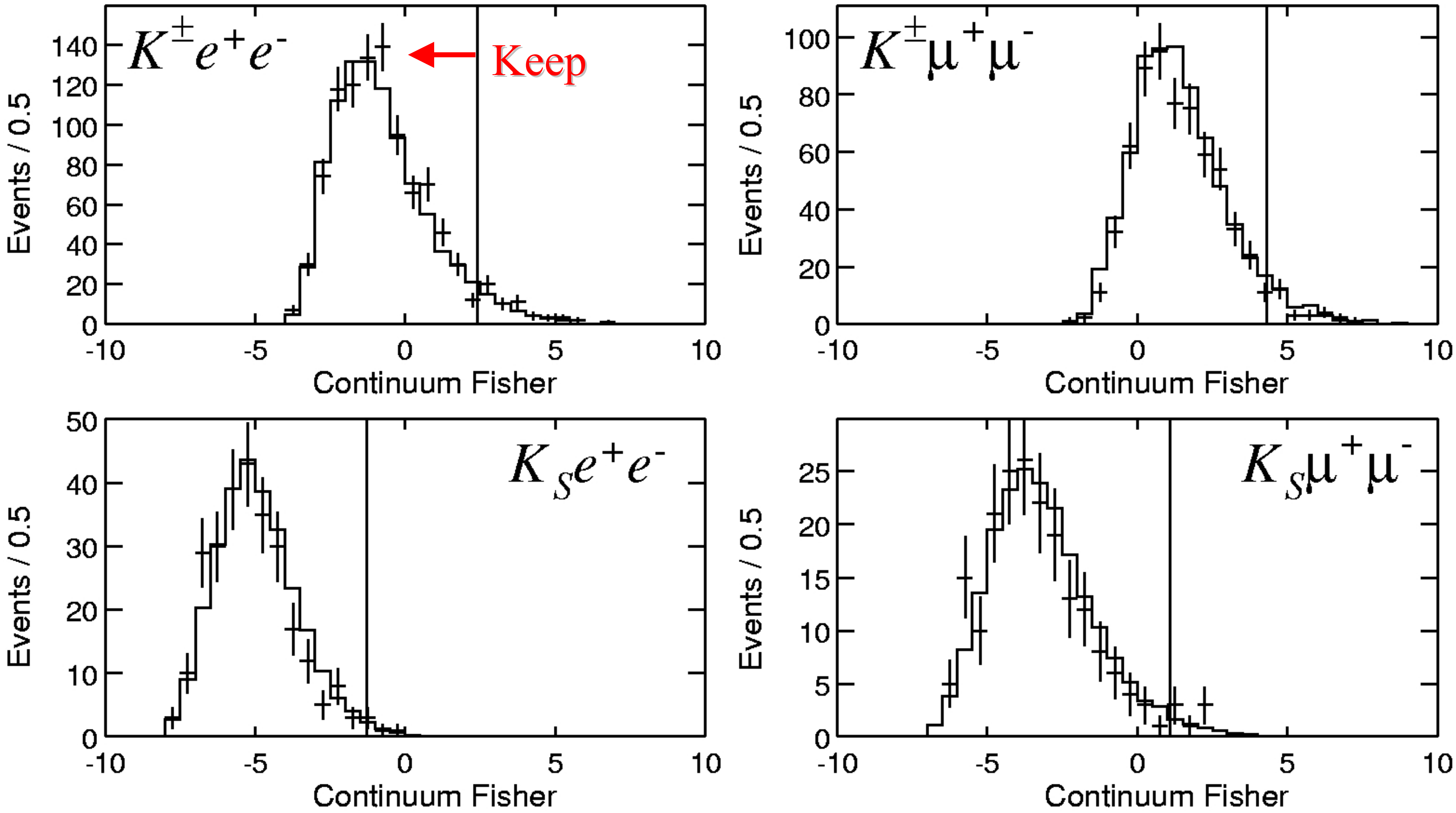
Data=Points with error bars; MC=histogram

BABAR preliminary



➔ Use this comparison to evaluate systematic errors on efficiencies.

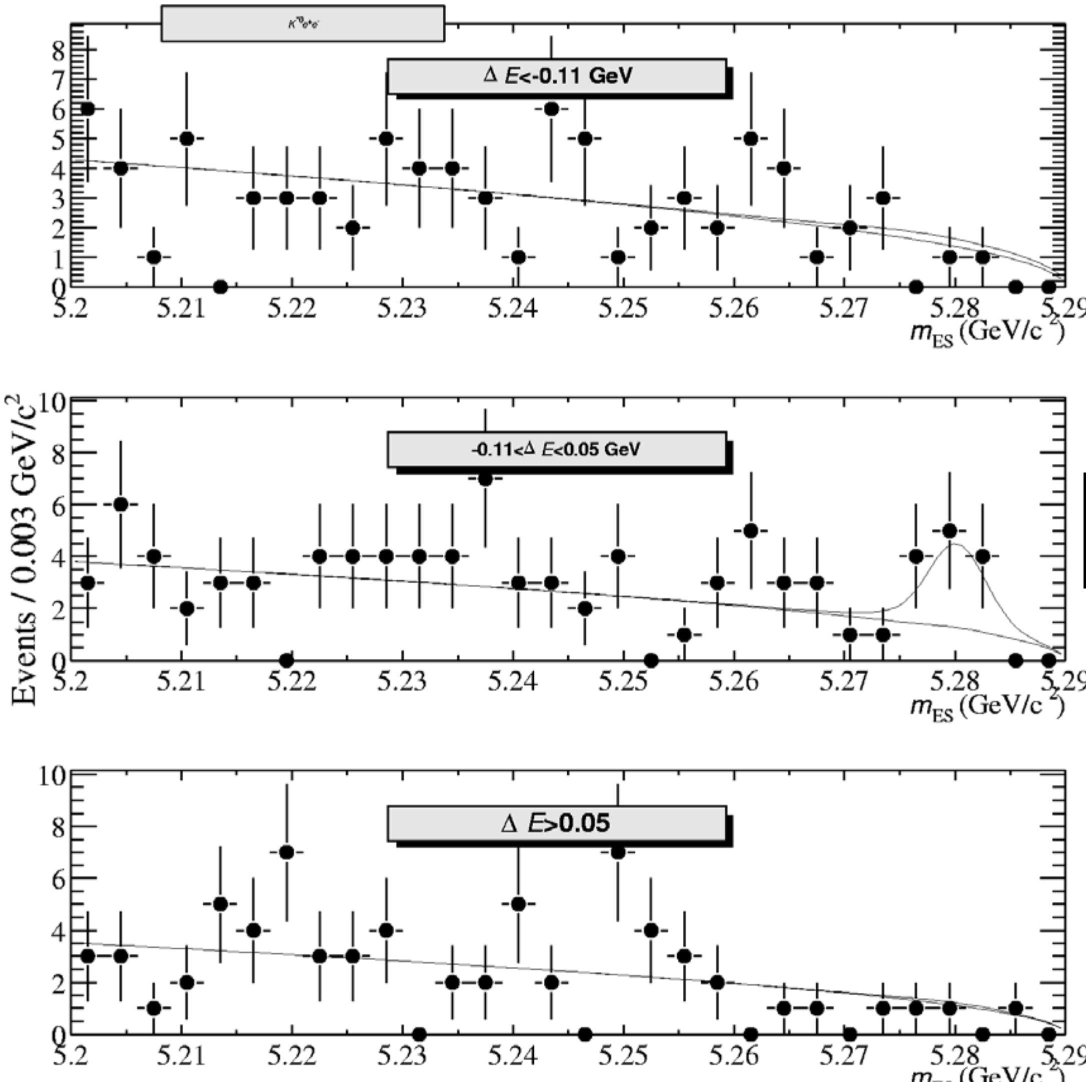
Check of Fisher variable (continuum suppression) distributions using *J/ψK(*)*



➔ Use this comparison to evaluate systematic errors on efficiencies.

Fit example: projections onto m_{ES} slices

$B^+ \to K^{*0} e^+ e^-$ ***BABAR preliminary***



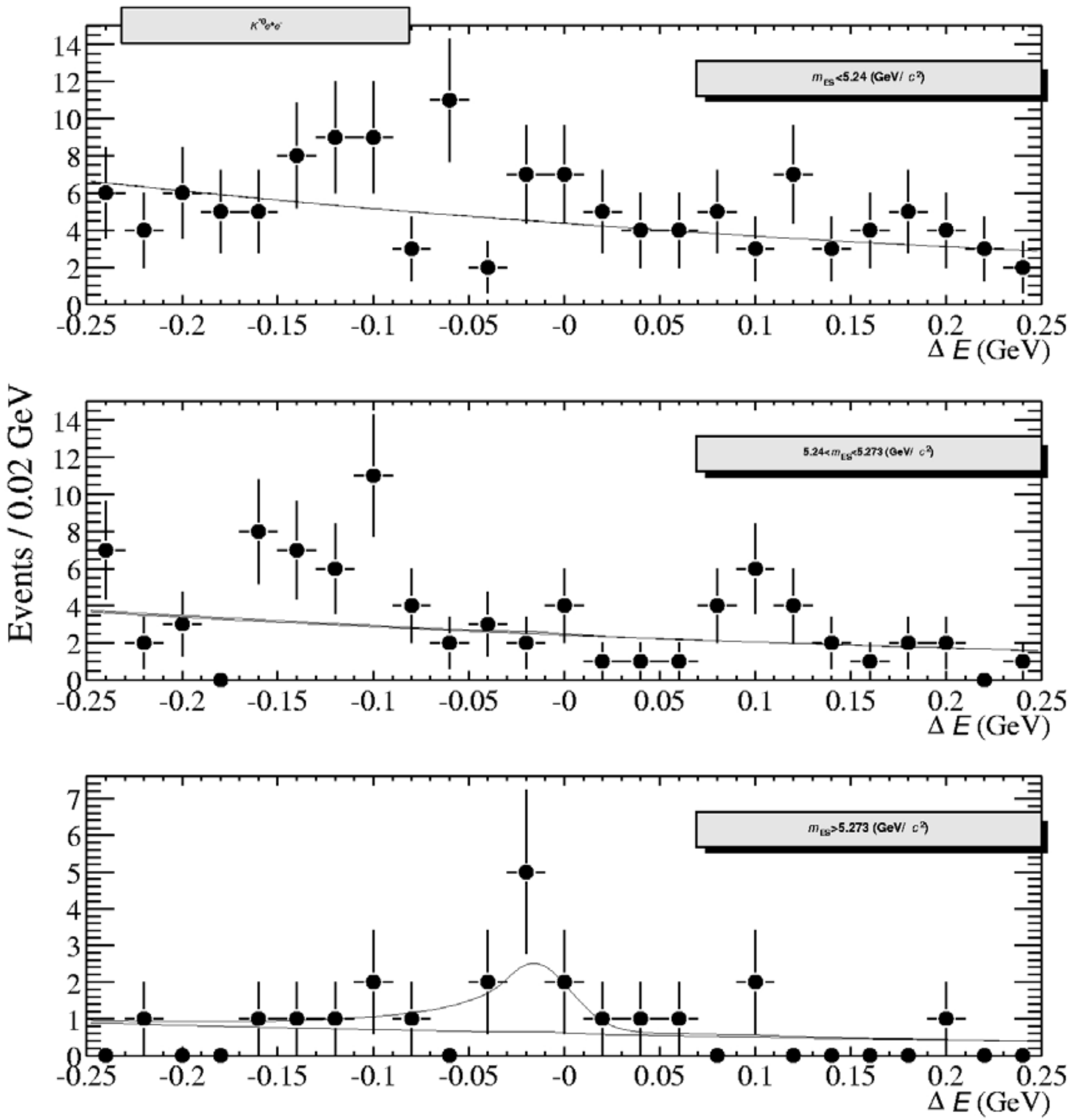
$\Delta E < -0.11$ GeV

$-0.11 < \Delta E < 0.05$ GeV

$\Delta E > 0.05$ GeV

Data: fit projections onto ΔE slices

$$B^+ \to K^{*0} e^+ e^-$$

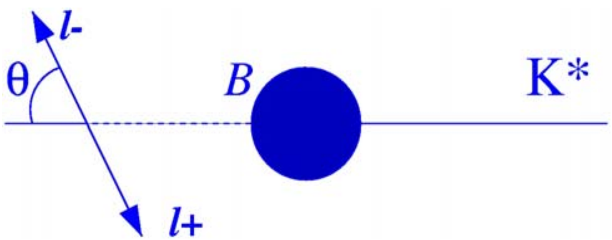


m_{ES}<5.24 GeV/c^2

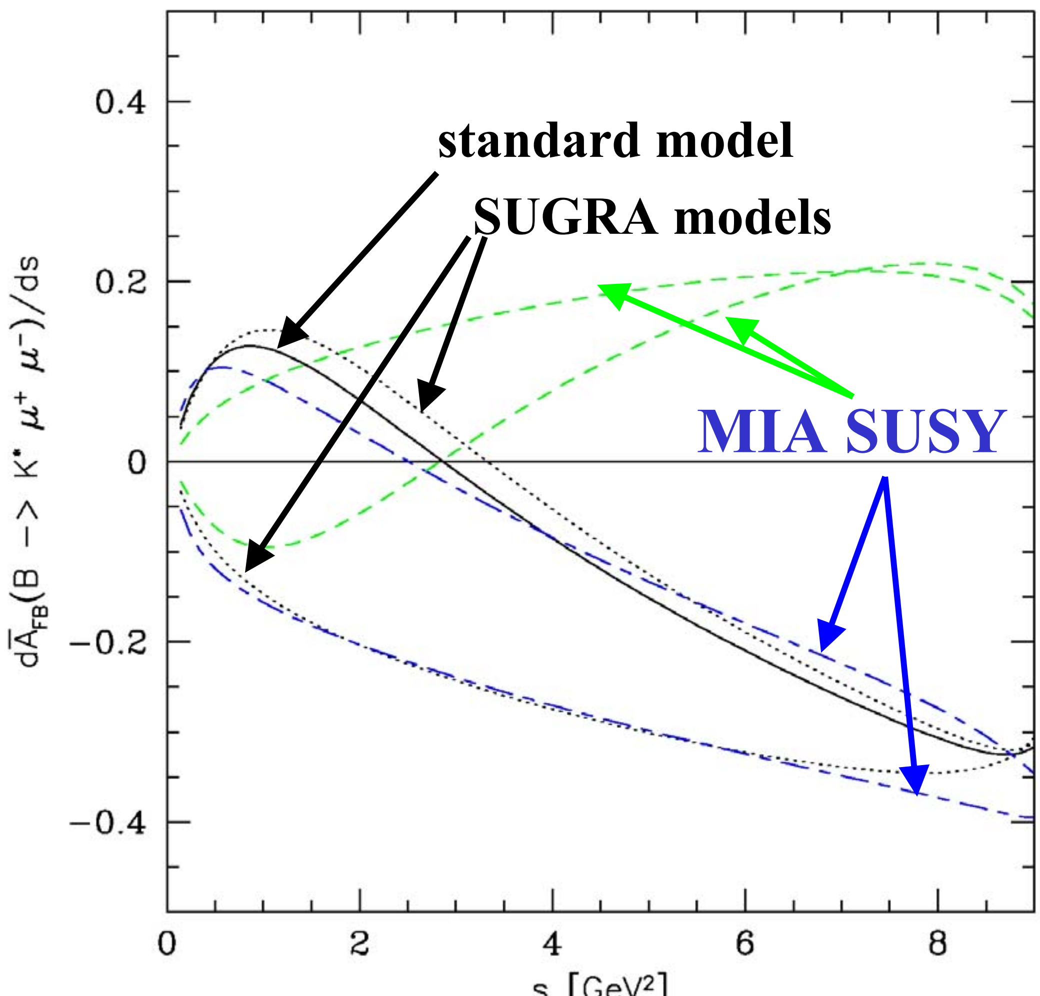
5.24<m_{ES}<5.273 GeV/c^2

m_{ES}>5.273 GeV/c^2

Forward-backward asymmetry vs. q^2



Polar angle of lepton in dilepton rest frame.



q^2 (GeV^2)

A. Ali *et al.*, PRD 61, 074024 (2000).