Radiative and Electroweak Penguin Decays of *B* Mesons

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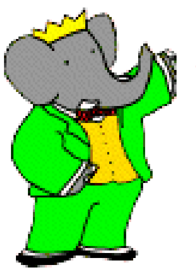


11th International Conference on *B* Physics at Hadron Machines
Oxford, Sept. 28, 2006

Outline

- Overview: a little history, physics goals, and challenges.
- $B^+ \to \rho^+ \gamma$, $B^0 \to \rho^0 \gamma$, $B^0 \to \omega \gamma$ and measurement of $|V_{td}/V_{ts}|$
- $B \to K\, l^+ l^-$ and $B \to K^*\, l^+ l^-$: search for new physics using the lepton forward-backward asymmetry
- Inclusive $B \to X_s\, \gamma$: branching fraction measurements and extraction of heavy-quark expansion parameters from the E_γ spectrum.
- Conclusions

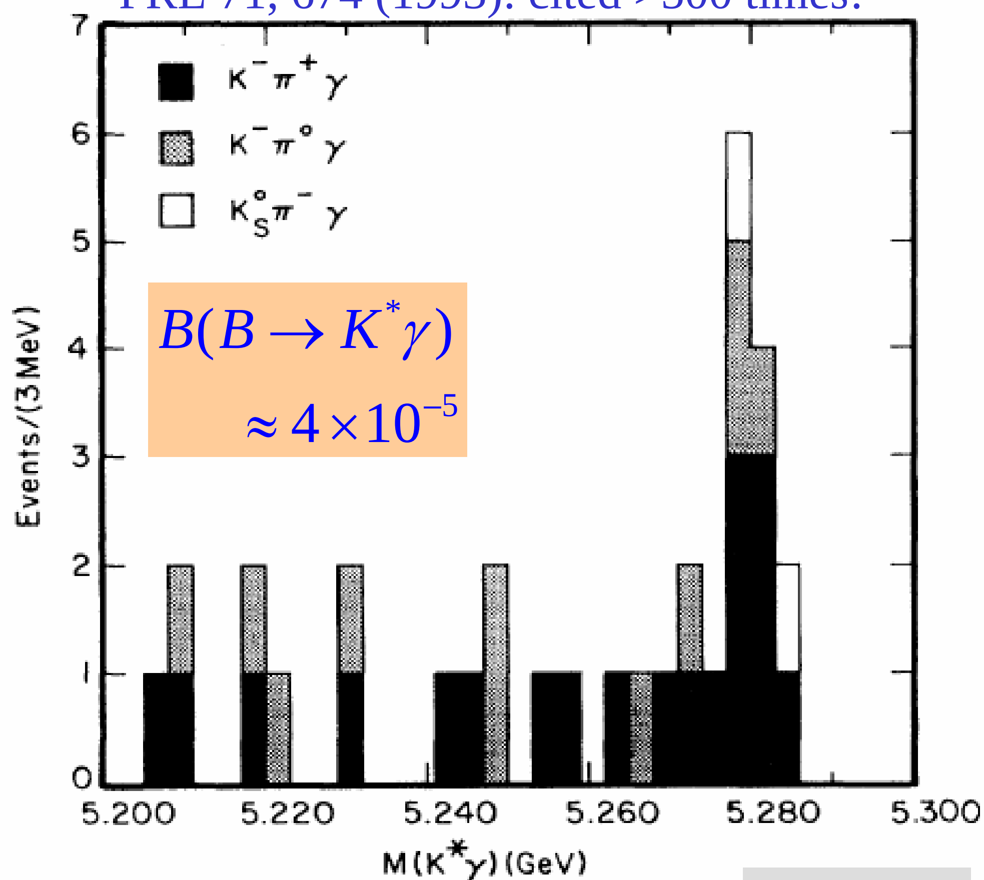
My apologies for not covering all results on radiative/electroweak penguin decays in this talk!

Radiative penguin decays of B mesons

Observation of $B \rightarrow K^* \gamma$

CLEO II (1993): *Loops* in B decays!

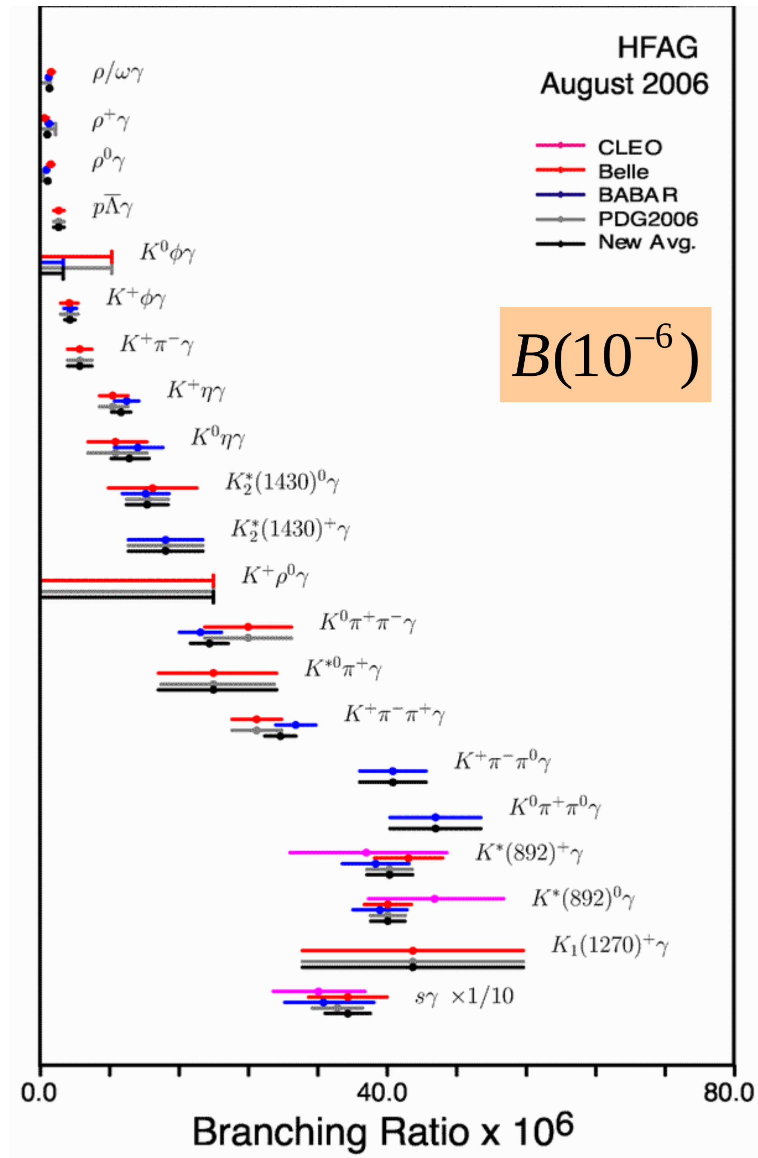
PRL 71, 674 (1993): cited >500 times!



$M(K^*\gamma)$

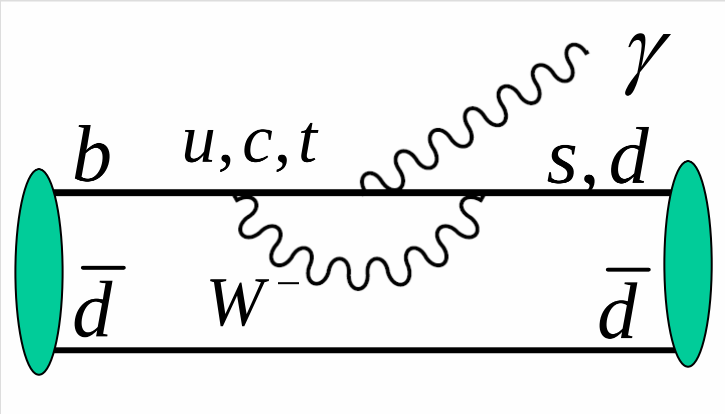
Rare, but not all that rare!

Now it's a physics program!

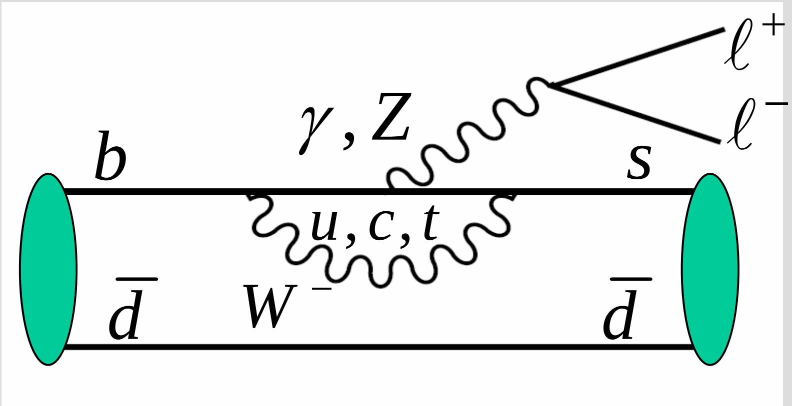


What can we learn from *b→s, d* transitions?

- **Flavor-changing neutral currents probe SM at 1-loop level.**

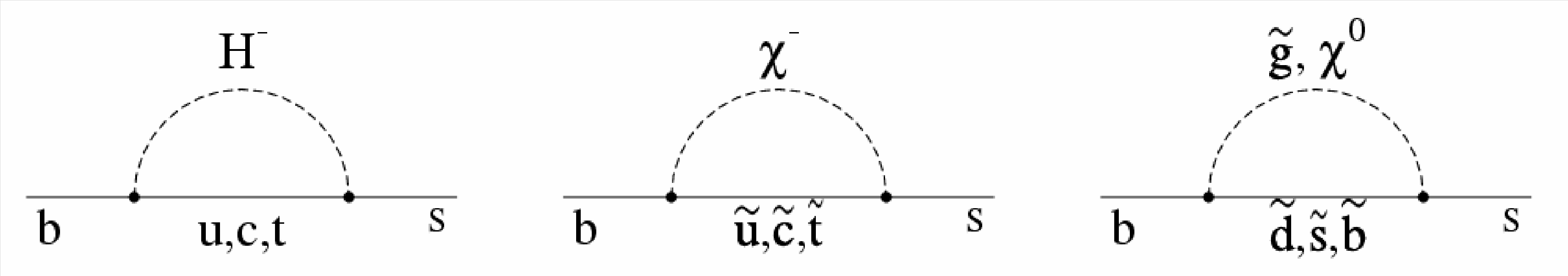


(dominated by *t* quark)



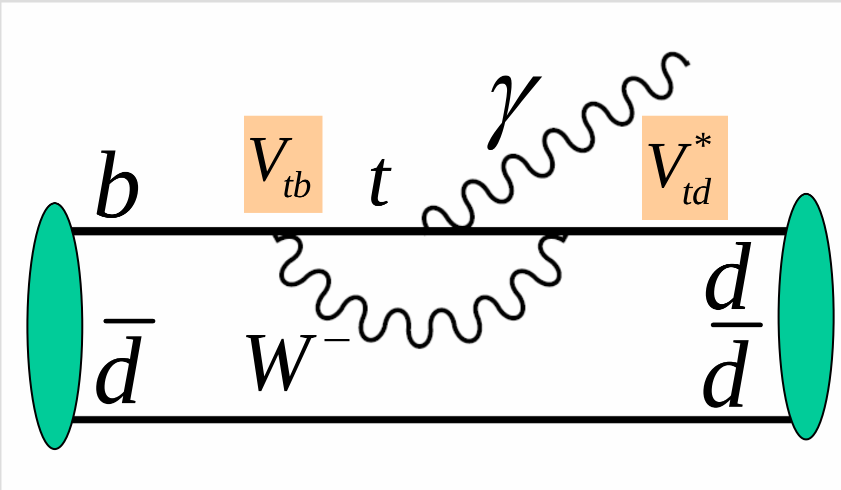
(+ W^+W^- box diagram)

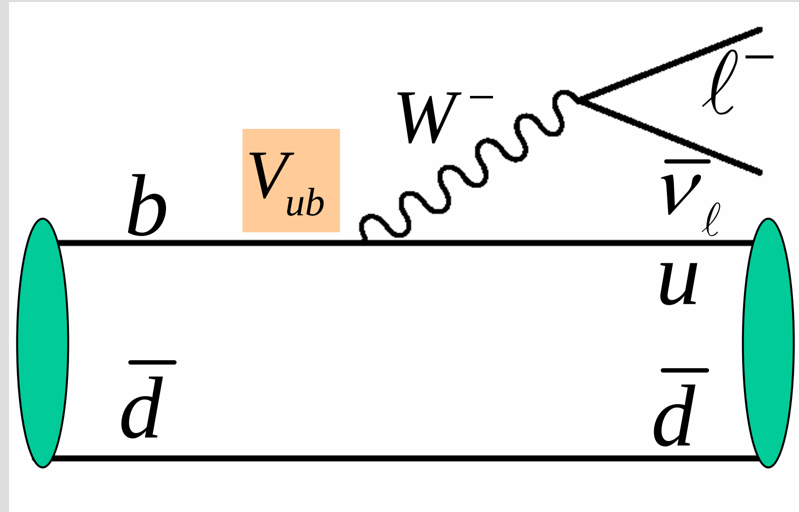
- **New physics can affect the amplitudes at leading order!**



- **As for *b→c* or *b→u* semileptonic decays, the amplitude in EM/EW penguins is factorizable (only one hadronic current).**

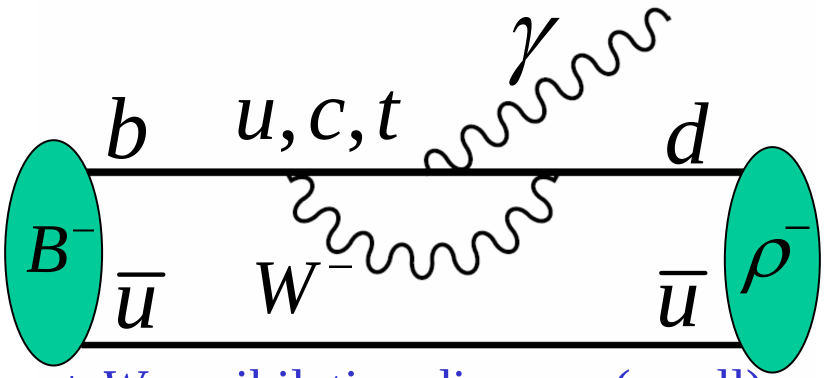
What can we learn from $b \to s,d$ transitions?



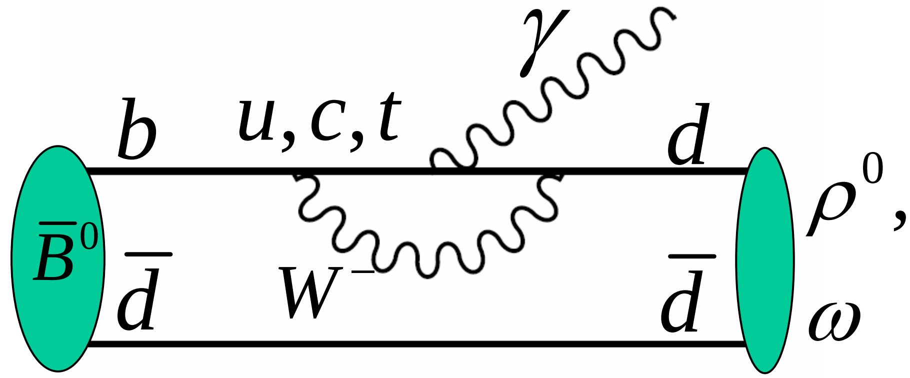


- **Presence of only single hadronic current allows us to isolate non-perturbative QCD parameters in well-defined way. Can be related to same parameters for other decays.**
  - **Exclusive decays: decay form factors $f_i(q^2)$. $b \to s$ transition is similar to $b \to u$ (heavy to light)**
  - **Inclusive decays: parameters of heavy-quark expansion (m_b, μ_π^2,…)**
- **Can extract information on CKM elements if info on hadronic parameters is available from data, theory, or both.**

Observation of $b \to d\,\gamma$ and Measurement of $|V_{td}/V_{ts}|$



+ W annihilation diagram (small)



$$\frac{B(B\to\rho\gamma)}{B(B\to K^*\gamma)} = \left|\frac{V_{td}}{V_{ts}}\right|^2 \frac{\left(m_B^2 - m_\rho^2\right)^3}{\left(m_B^2 - m_{K^*}^2\right)^3} \underbrace{\left(\frac{T_1^\rho(0)}{T_1^{K^*}(0)}\right)^2}_{1/\xi^2} (1+\Delta R)$$

$$\xi \equiv \frac{T_1^{K^*}(0)}{T_1^\rho(0)} = 1.17 \pm 0.09$$

Ball and Zwicky, JHEP 0604, 046 (2006)

$$\Delta R = 0.1 \pm 0.1$$

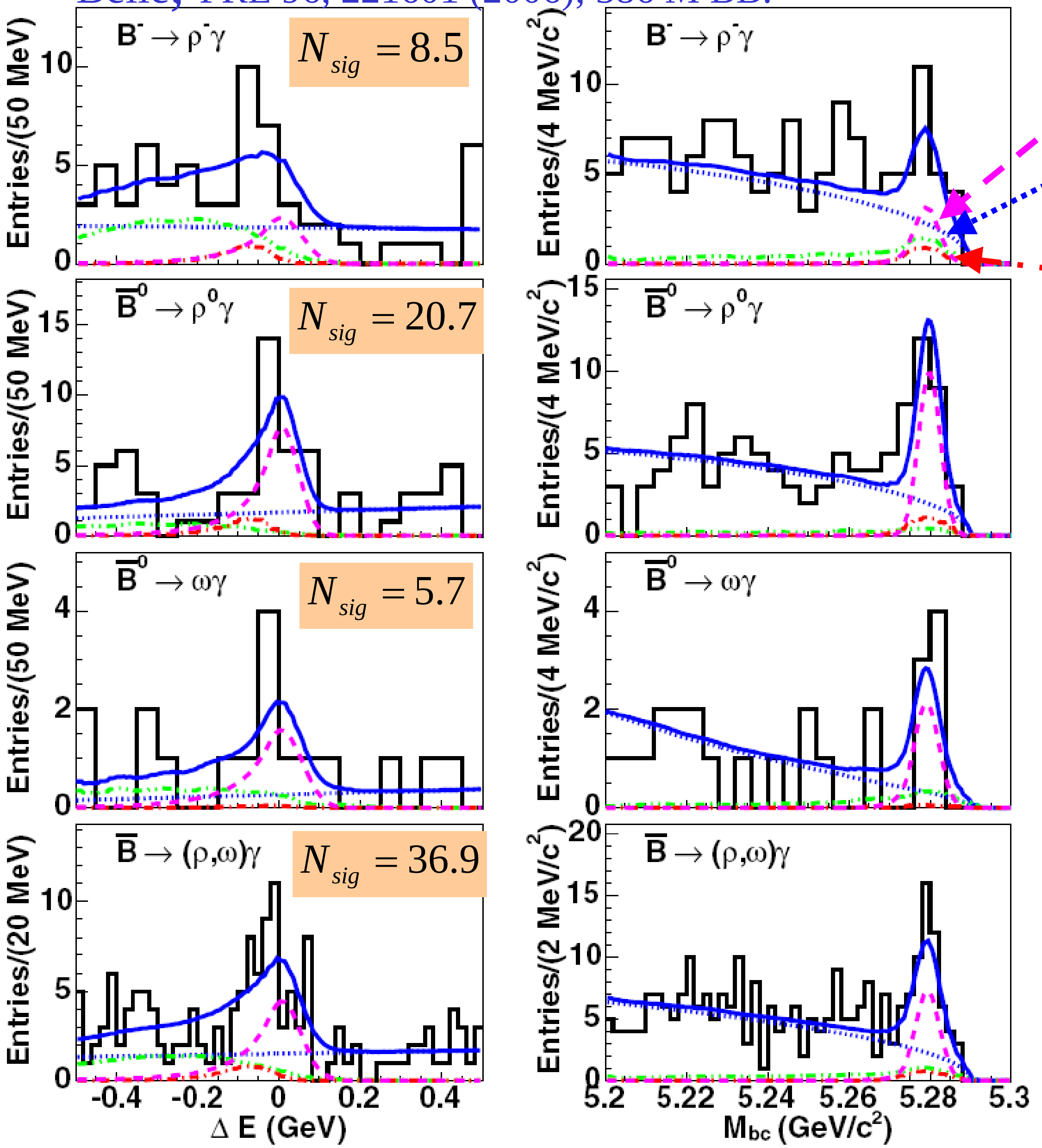
Ali, Lunghi, Parkhomenko, PLB 595, 323 (2004)

$$\Gamma\left(B^- \to \rho^-\gamma\right) = 2\Gamma\left(\bar{B}^0 \to \rho^0\gamma\right) \simeq 2\Gamma\left(\bar{B}^0 \to \omega\gamma\right)$$

I-spin (ρ), quark model (ω). Expect small I-spin violation: (1.1+/-3.9)%.

Measurement of $b \to d\,\gamma$ Decays (Belle)

Belle, PRL 96, 221601 (2006); 386 M $B\bar{B}$.

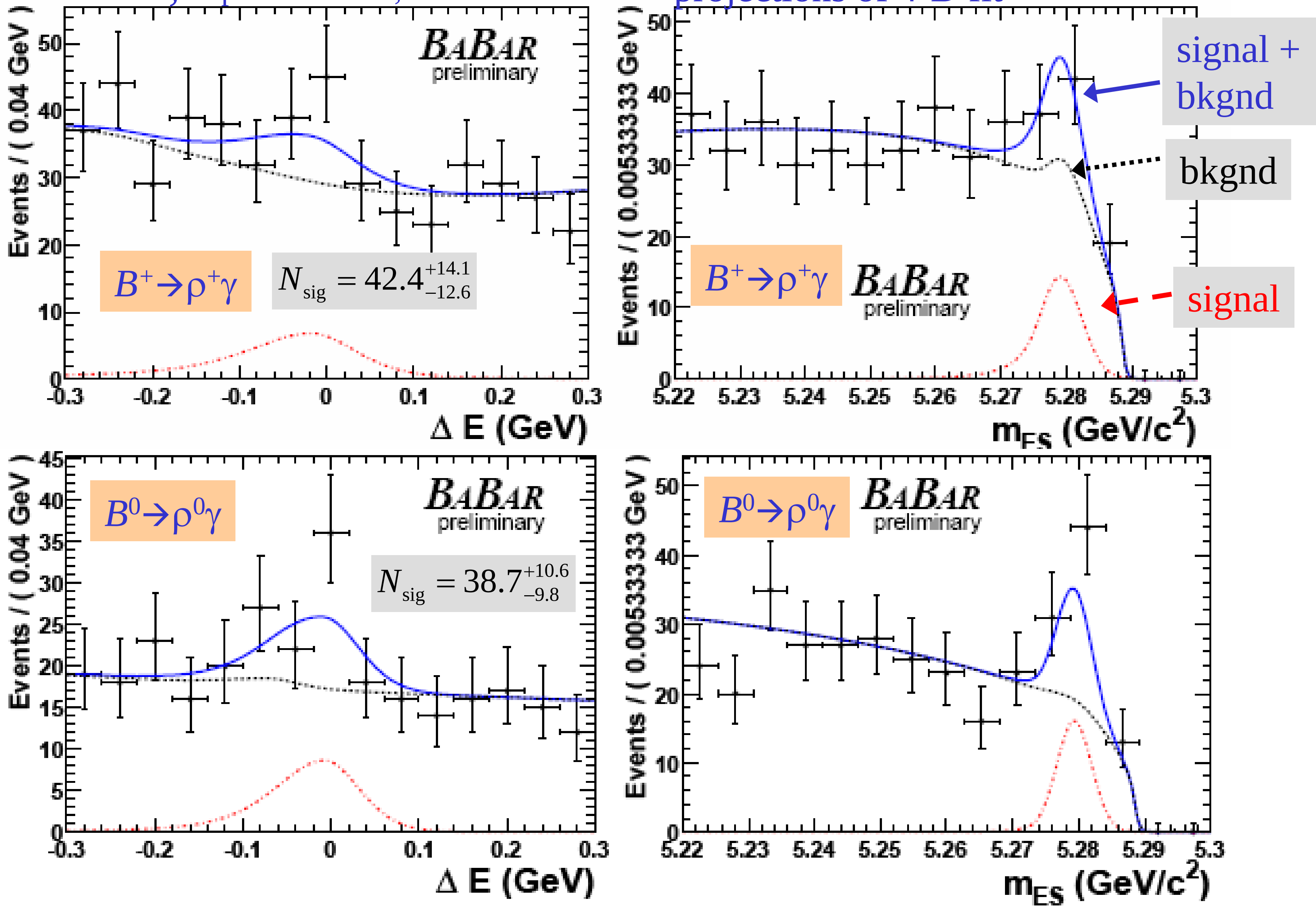


Good particle ID is critical in this measurement to suppress $B \to K^*\gamma$ feed-down.

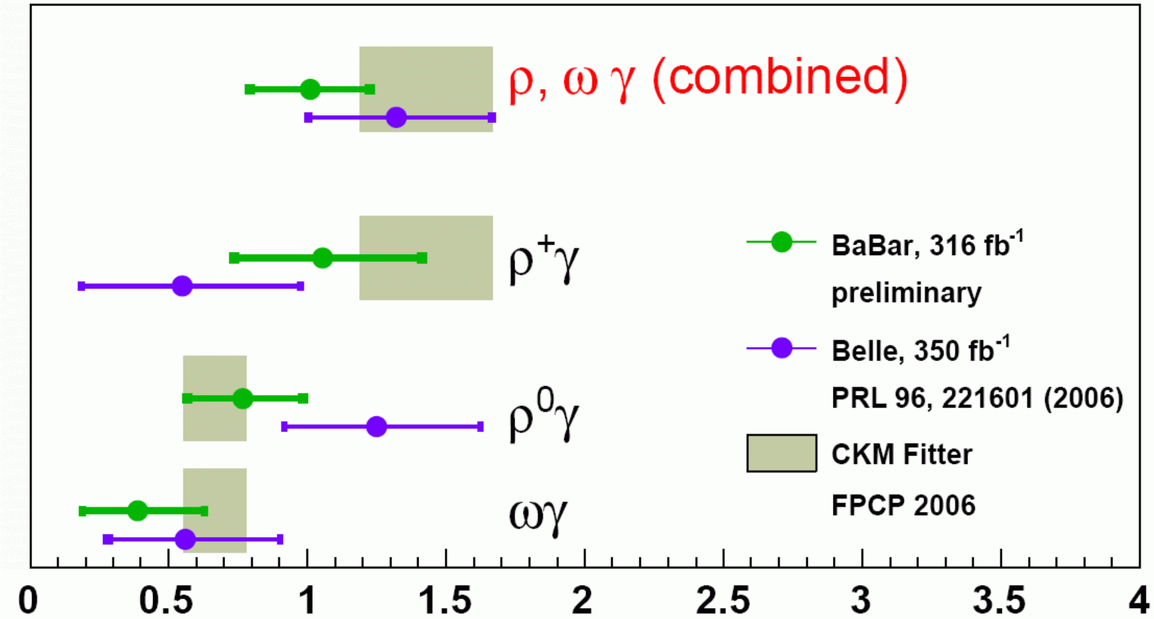
Mode	$\mathcal{B}\ (10^{-6})$
$B^- \to \rho^- \gamma$	$0.55^{+0.42+0.09}_{-0.36-0.08}$
$\bar{B}^0 \to \rho^0 \gamma$	$1.25^{+0.37+0.07}_{-0.33-0.06}$
$\bar{B}^0 \to \omega \gamma$	$0.56^{+0.34+0.05}_{-0.27-0.10}$
$\bar{B} \to (\rho, \omega)\gamma$	$1.32^{+0.34+0.10}_{-0.31-0.09}$

Measurement of $b \to d\,\gamma$ Decays (*BABAR*)

BABAR, hep-ex/0607099, 347 M $B\bar{B}$ projections of 4-D fit



Comparison of $b \to d\,\gamma$ Branching Fractions



(10^{-6})

CKM fitter includes CDF B_s mixing result.
Error on CKM Fitter prediction includes uncert. on $B \to V\gamma$ form-factor ratio.

I-spin consistency?

Mode	*BABAR* (10^{-6}) (6.3 σ signif.) preliminary; hep-ex/0607099	Belle (10^{-6}) (5.1σ signif.) PRL 96, 221601 (2006).
$B^+ \to \rho^+\gamma$	$1.06^{+0.35}_{-0.31} \pm 0.09$	$0.55^{+0.43+0.12}_{-0.37-0.11}$
$B^0 \to \rho^0\gamma$	$0.77^{+0.21}_{-0.19} \pm 0.07$	$1.17^{+0.35+0.09}_{-0.31-0.08}$
$B^0 \to \omega\gamma$	< 0.84 (90% C.L.)	$0.58^{+0.34+0.14}_{-0.31-0.10}$
$B \to (\rho^+, \rho^0, \omega)_{I\text{-avg}}\gamma$	$1.01 \pm 0.21 \pm 0.08$	$1.32^{+0.34+0.10}_{-0.31-0.09}$

Extracting $|V_{td}/V_{ts}|$ from $b \rightarrow d\,\gamma$ Decays

Belle, PRL 96, 221601 (2006).

$$\left|\frac{V_{td}}{V_{ts}}\right| = 0.199^{+0.026+0.018}_{-0.025-0.015}$$

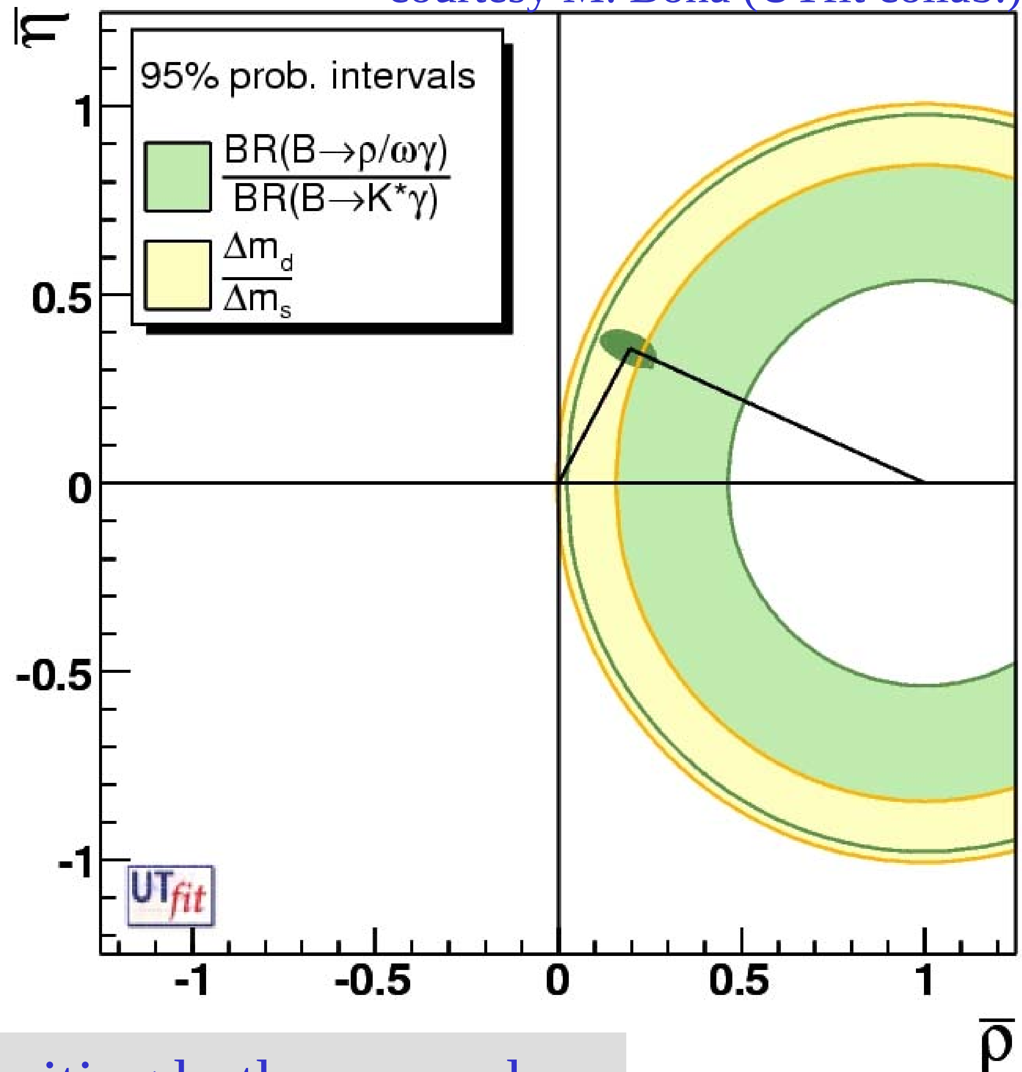
BABAR, hep-ex/0607099 (preliminary)

$$\left|\frac{V_{td}}{V_{ts}}\right| = 0.171^{+0.018+0.017}_{-0.021-0.014}$$

CDF, hep-ex/0606027 (preliminary)

$$\left|\frac{V_{td}}{V_{ts}}\right| = 0.208^{+0.001+0.008}_{-0.002-0.006}$$

courtesy M. Bona (UTfit collab.)

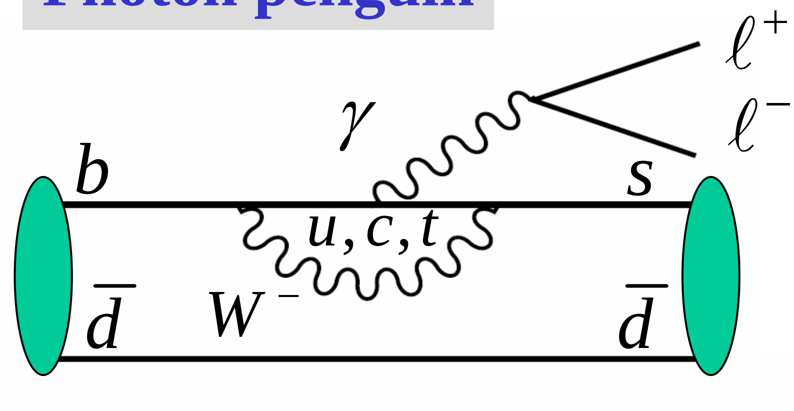


Consistent within errors.

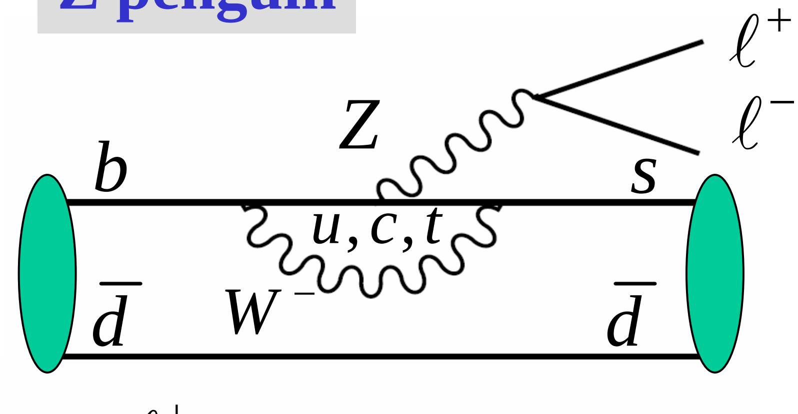
Theoretical uncertainties limiting both approaches.

$B \rightarrow K l^+ l^-$ and $B \rightarrow K^* l^+ l^-$ in the SM and Beyond

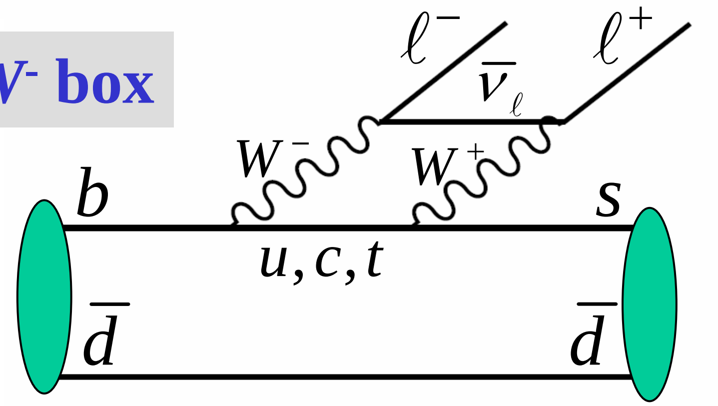
Photon penguin



Z penguin



W^+W^- box



- Dependence on kinematic variables in 3-body decays can be used to study the different amplitudes and their interference effects.
- The mode $B \rightarrow K l^+ l^-$ is allowed as well as $B \rightarrow K^* l^+ l^-$ ($B \rightarrow K\gamma$ forbidden by conservation of angular momentum).

Amplitude for $B \to K^* l^+ l^-$

$$M(B \to K^* \ell^+ \ell^-) = \frac{G_F \alpha_{EM}}{\sqrt{2}\pi} V_{ts}^* V_{tb} \Big\{ \Big[C_9^{eff} \langle K^* | \bar{s} \gamma_\mu P_L b | B \rangle$$

$$- 2 \frac{m_b}{q^2} C_7^{eff} \langle K^* | \bar{s} i \sigma_{\mu\nu} q^\nu P_R b | B \rangle \Big] (\bar{\ell} \gamma^\mu \ell)$$

$$+ C_{10} \langle K^* | \bar{s} \gamma_\mu P_L b | B \rangle (\bar{\ell} \gamma^\mu \gamma_5 \ell) \Big\}$$

photon penguin dom. at v. low q^2

mix of Z-penguin, W^+W^- box

Kruger and Matias; PRD 71, 094009 (2005)

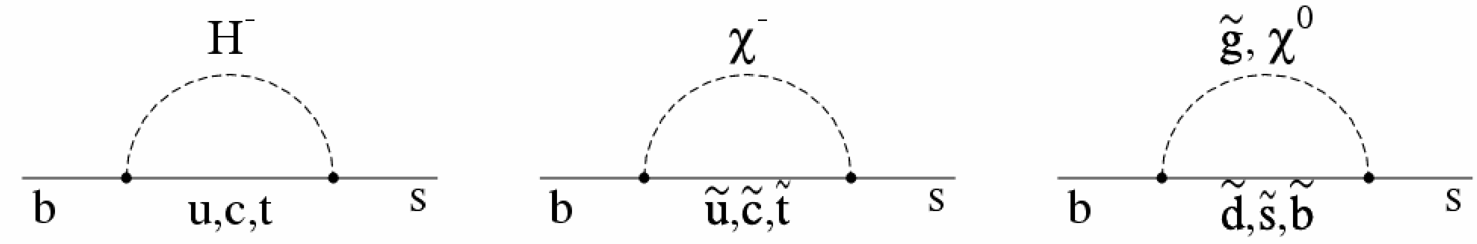
Short-distance physics encoded in C_i's (Wilson coefficients); calculated at NNLO in SM:

$$C_7^{eff} \simeq -0.3 \quad C_9 \simeq +4.3 \quad C_{10} \simeq -4.7$$

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

C_9, C_{10} generate asymm. in lepton angular distribution over most of q^2.

C_i's can be affected by new physics, which enters at same order as SM

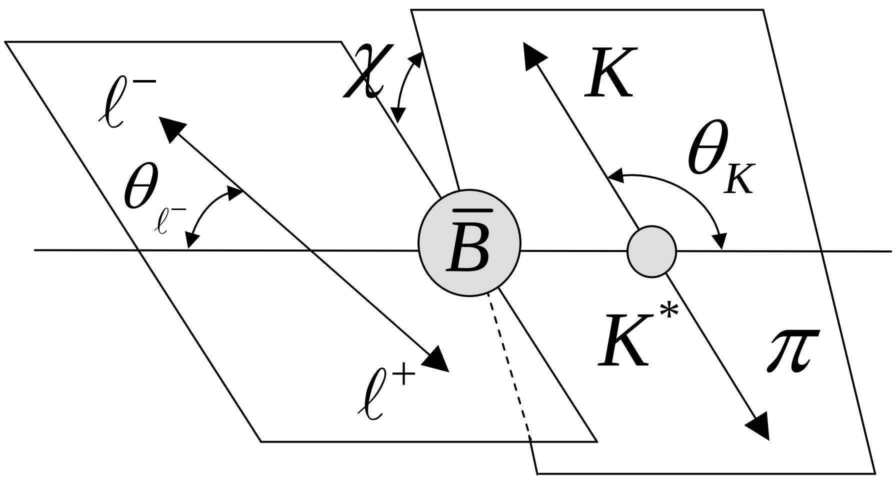


Form Factors and Observables

Long distance QCD physics is mainly described in terms of form factors, which are functions of $q^2 = (p_{\ell^+} + p_{\ell^-})^2$

- 4 semileptonic form factors: A_1, A_2, V, A_0 (similar to $B \to D^* l\nu$, $B \to \rho l \nu$)
- 3 penguin form factors: T_1, T_2, T_3

Form factor uncertainies → 35% uncertainty in rate predictions.



$$A_{FB} \equiv \frac{\int_0^1 \frac{d\Gamma}{d\cos\theta_\ell} d\cos\theta_\ell - \int_{-1}^0 \frac{d\Gamma}{d\cos\theta_\ell} d\cos\theta_\ell}{\int_0^1 \frac{d\Gamma}{d\cos\theta_\ell} d\cos\theta_\ell + \int_{-1}^0 \frac{d\Gamma}{d\cos\theta_\ell} d\cos\theta_\ell}$$

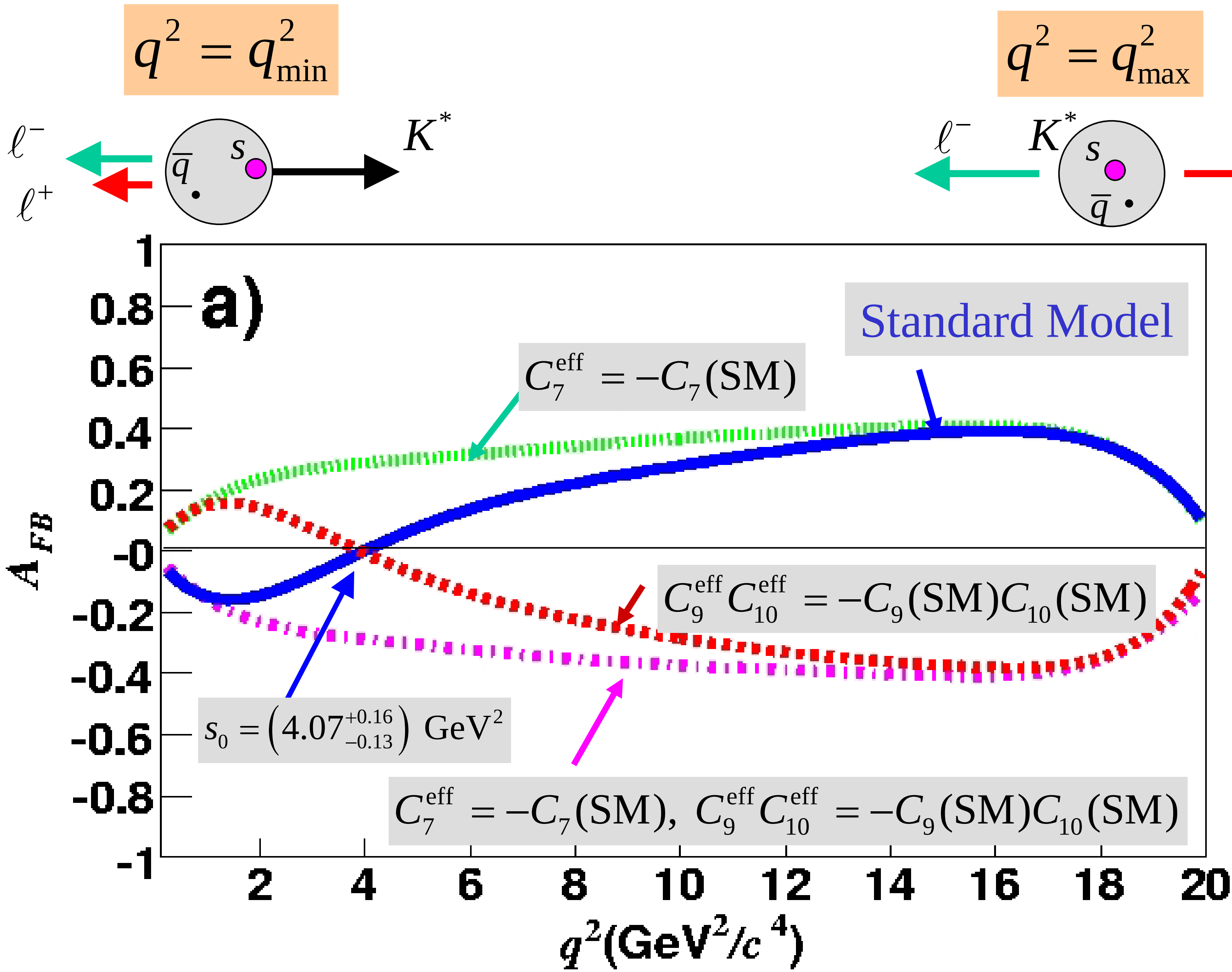
$$(s \equiv q^2)$$

$$\frac{dA_{FB}}{ds} \propto -C_{10} \left\{ \mathrm{Re}\left(C_9^{eff}\right) V A_1 + \frac{m_b m_B}{s} C_7^{eff} \left[V T_2 \left(1 - \frac{m_{K^*}}{m_B}\right)(1 - \hat{m}_{K^*}) + A_1 T_1 \left(1 + \frac{m_{K^*}}{m_B}\right) \right] \right\}$$

$$s_0 = \left(4.07^{+0.16}_{-0.13}\right)\ \mathrm{GeV}^2$$

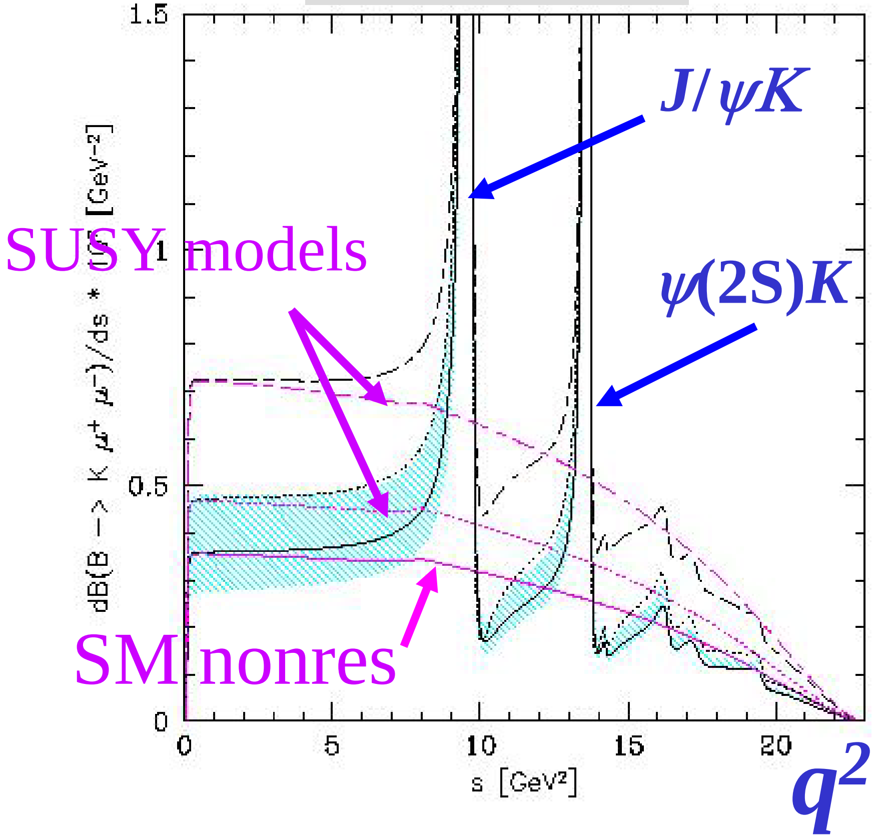
Precise SM prediction due to ff cancellation.

Predictions for A_{FB} in $B \to K^* l^+ l^-$: SM and beyond

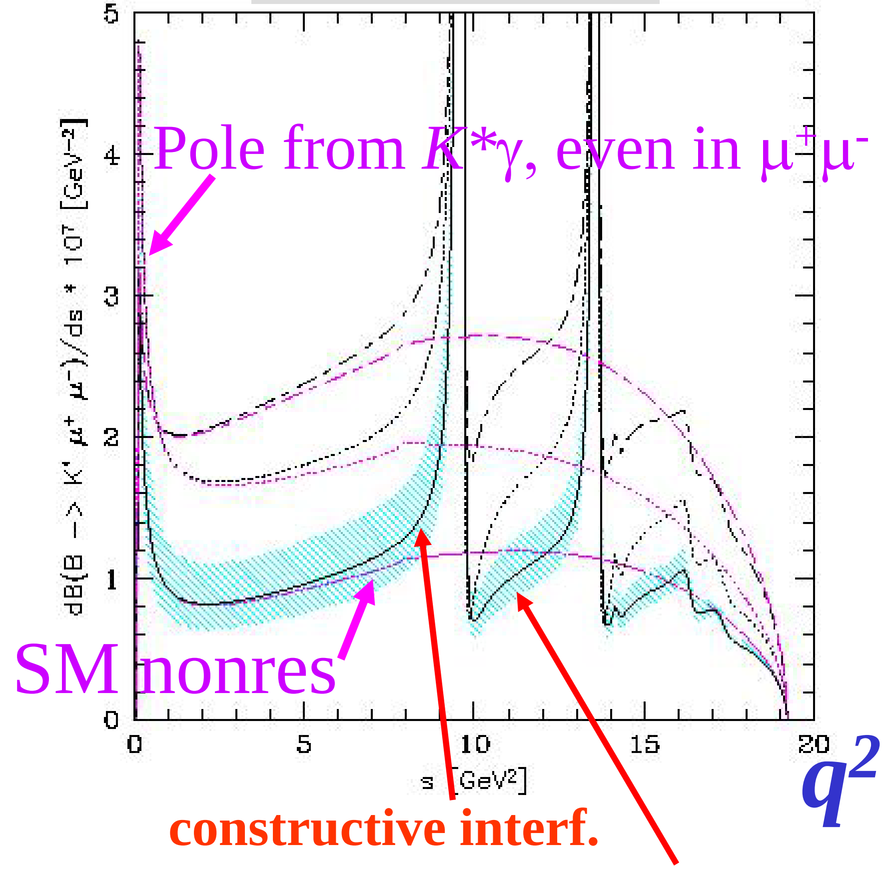


$B \to K l^+ l^-$ and $B \to K^* l^+ l^-$: q^2 distributions

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



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

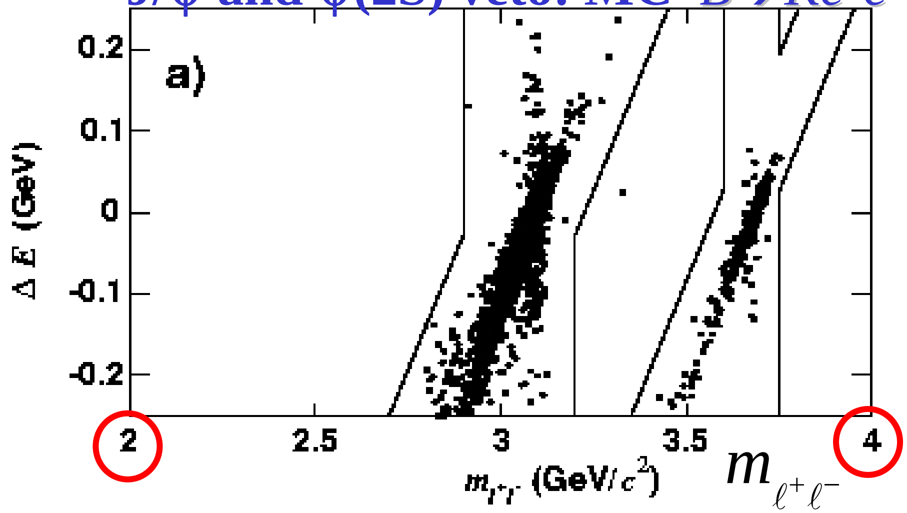


- Solid line+blue bands: SM range (±35%); Ali *et al.* form factors
- Dotted line: SUGRA model ($R_7 = -1.2$, $R_9 = 1.03$, $R_{10} = 1$; $R_i = C_i / C_i^{\rm SM}$)
- Long-short dashed line: SUSY model ($R_7 = -0.83$, $R_9 = 0.92$, $R_{10} = 1.61$)

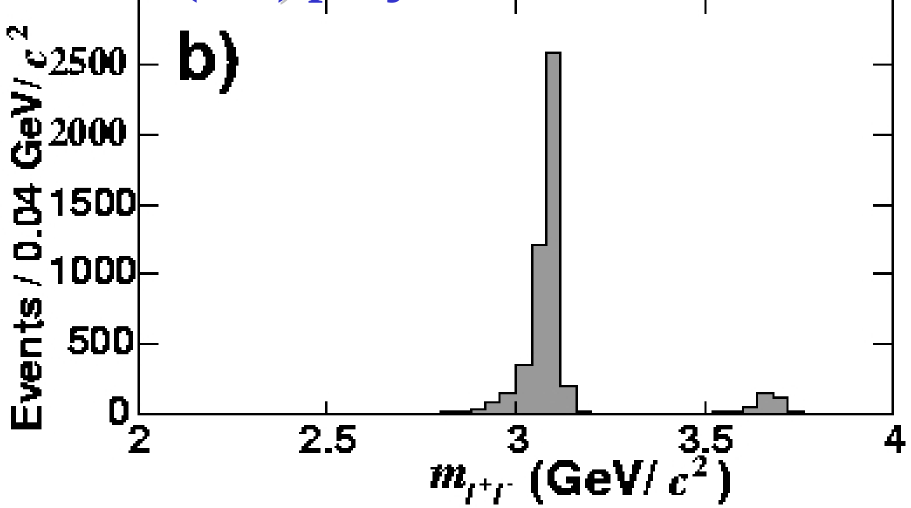
$B \to K l^+ l^-$ and $B \to K^* l^+ l^-$: the J/ψ veto

- The decays $B \to J/\psi K$ and $B \to J/\psi K^*$ are huge backgrounds and must be carefully removed (also $B \to \psi(2S)K$, $\psi(2S)K^*$).
- These backgrounds are restricted in q^2, but there is a tail due to bremsstrahlung in the electron modes.
- But $B \to J/\psi K$ and $B \to J/\psi K^*$ are valuable control samples; use them to study efficiency of almost any analysis cut.
- Ali, Kramer, Zhu: $\mathcal{B}(B \to K^* \ell^+ \ell^-; 1 \le q^2 \le 7\ \mathrm{GeV}^2) = (2.92^{+0.67}_{-0.61}) \times 10^{-7}$

J/ψ and $\psi(2S)$ veto: MC $B \to K e^+ e^-$

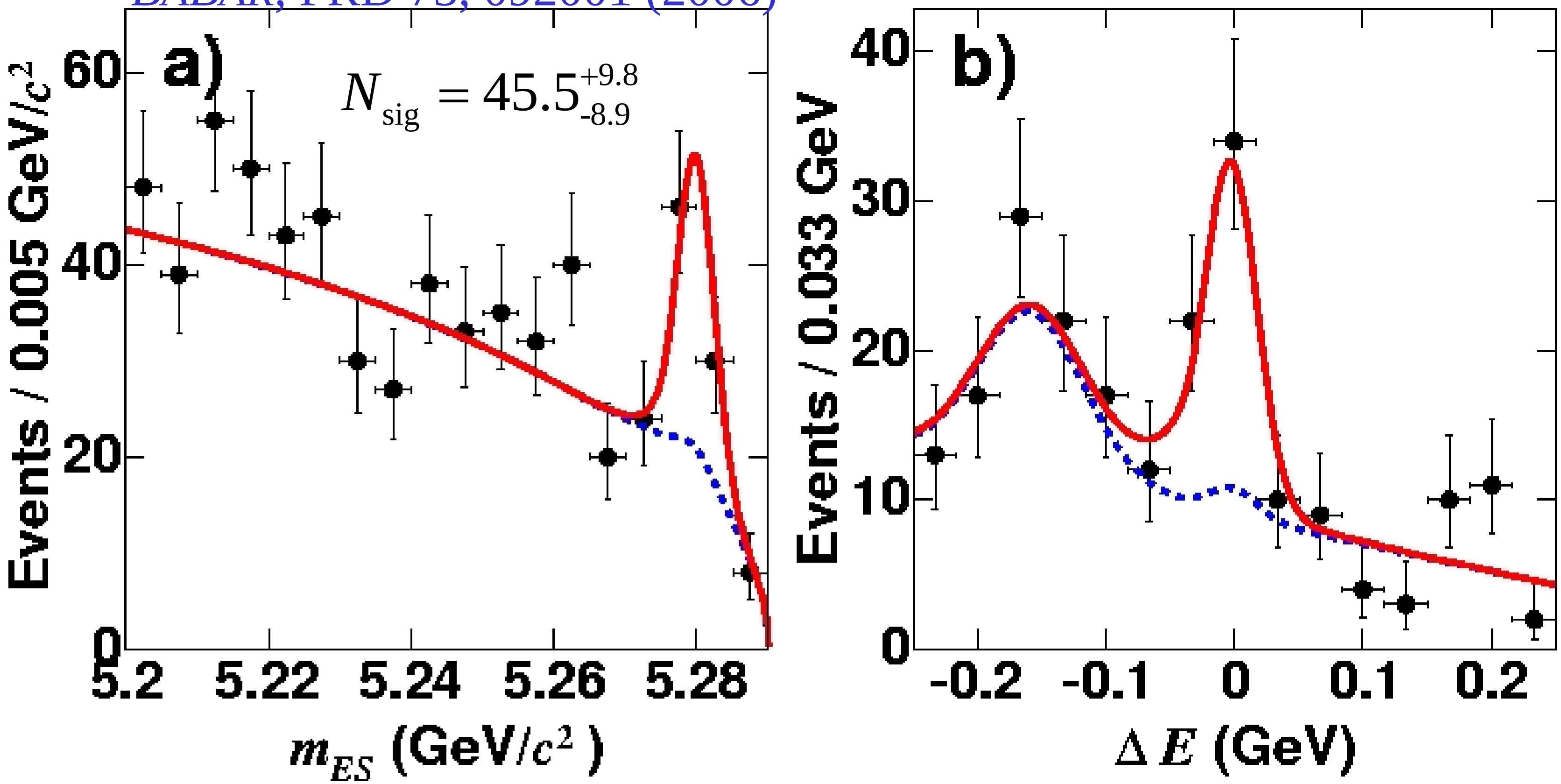


$m(e^+e^-)$ projection: MC $B \to K e^+ e^-$



$B \rightarrow K l^+ l^-$ Signal from *BABAR*

BABAR, PRD 73, 092001 (2006)



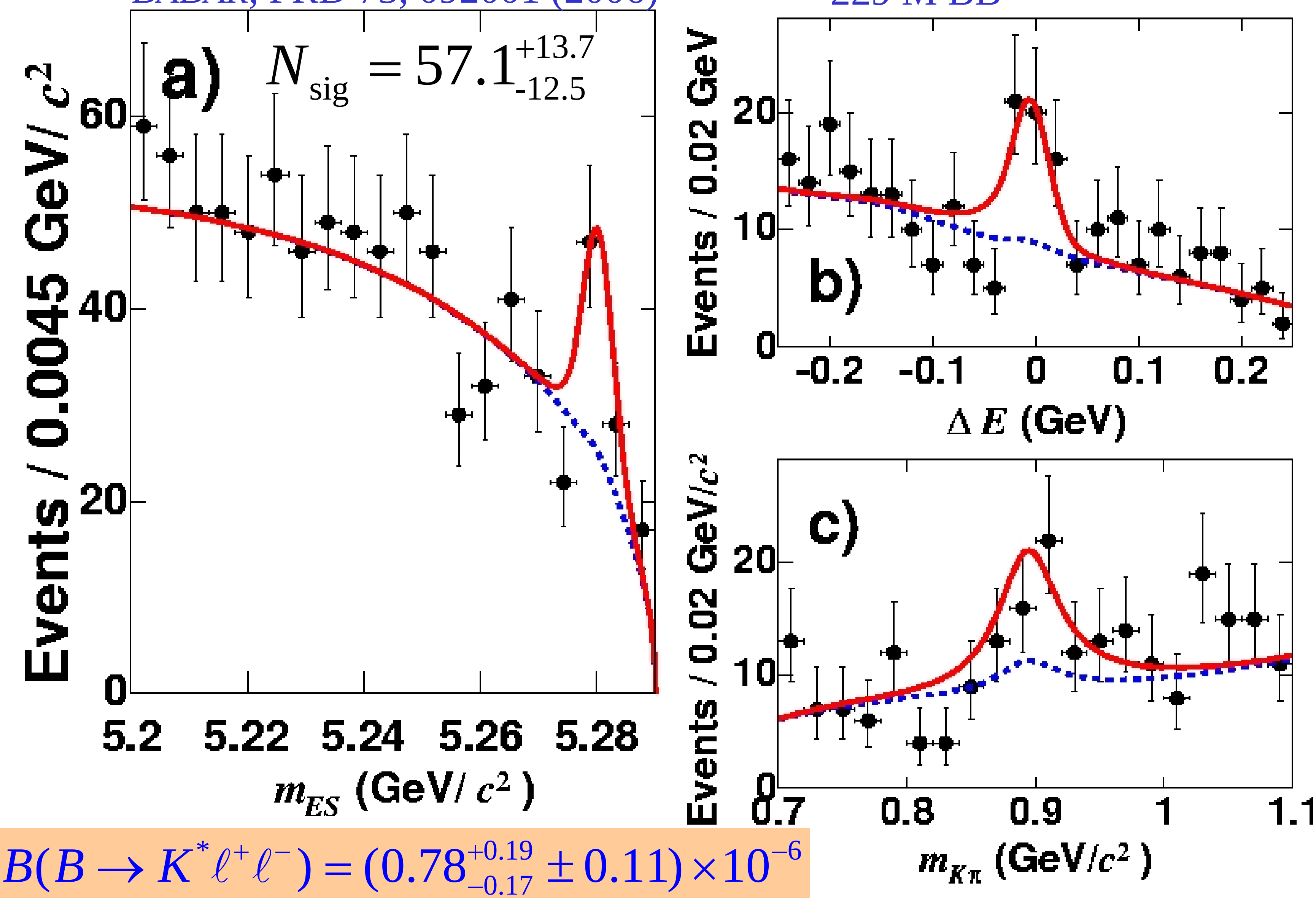
- summed over all $K\, l^+ l^-$ modes ($K^+ e^+ e^-$, $K^+ \mu^+ \mu^-$ $K_S\, e^+ e^-$, $K_S\, \mu^+ \mu^-$)
- significance 6.6 σ; rarest observed B decay

$$B(B \to K \ell^+ \ell^-) = (0.34 \pm 0.07 \pm 0.02) \times 10^{-6}$$

(averaged)

$B \to K^* l^+ l^-$ Signal from *BABAR*

BABAR, PRD 73, 092001 (2006) 229 M $B\bar{B}$

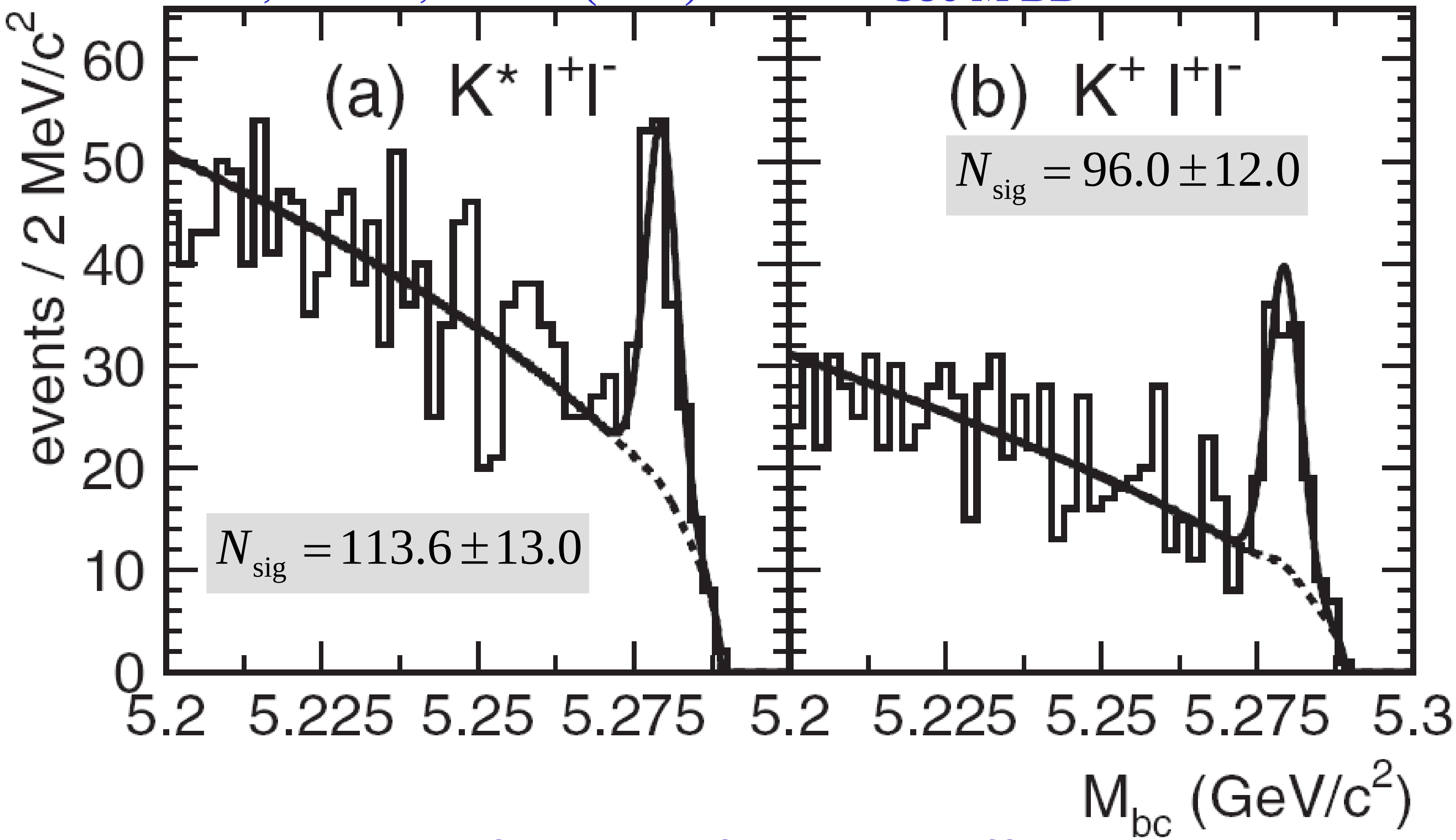


$$B(B \to K^* \ell^+ \ell^-) = (0.78^{+0.19}_{-0.17} \pm 0.11) \times 10^{-6}$$

$B \to K^{(*)} l^+ l^-$ Signals from Belle

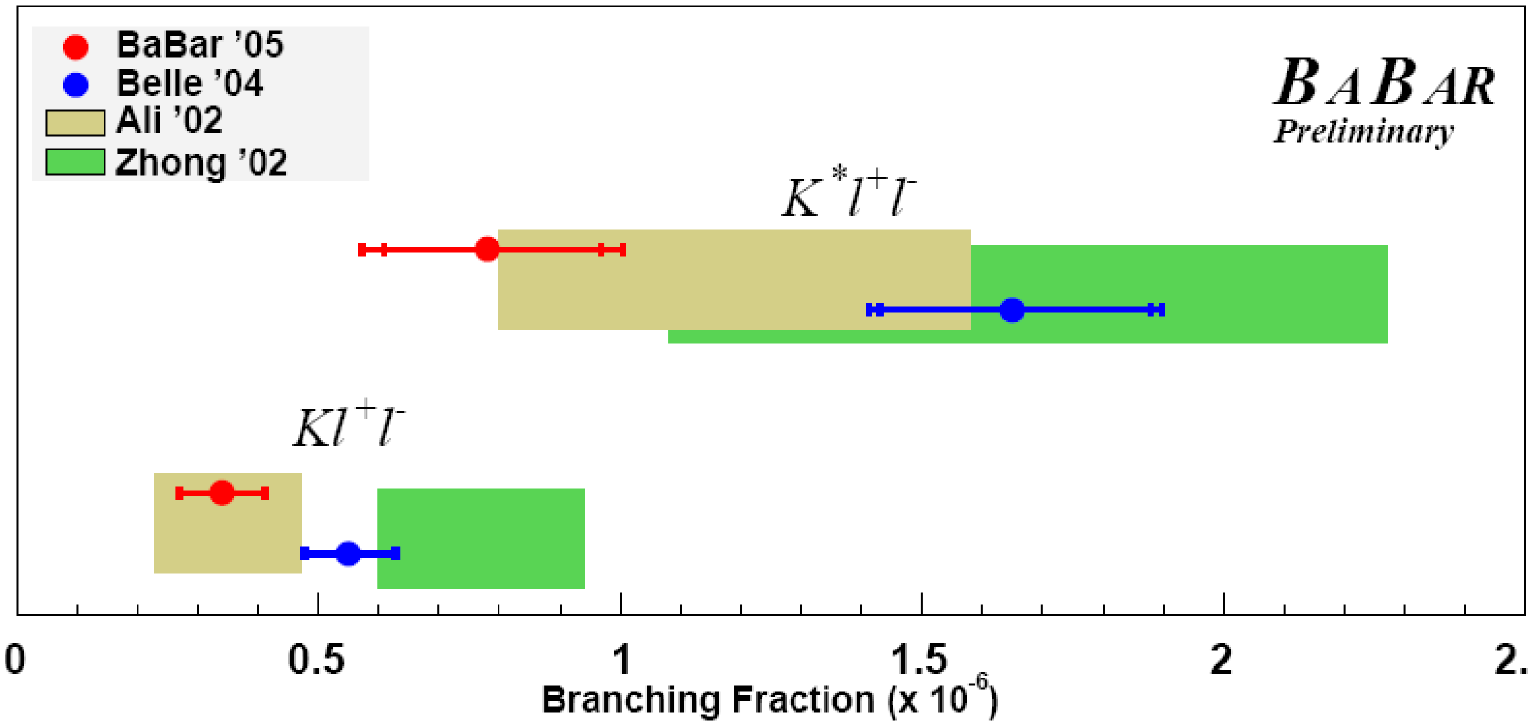
Belle, PRL 96, 251801 (2006)

386 M $B\bar{B}$



(data sample used for study of Wilson coefficients)

$B \to K l^+ l^-$ and $B \to K^* l^+ l^-$ branching fractions



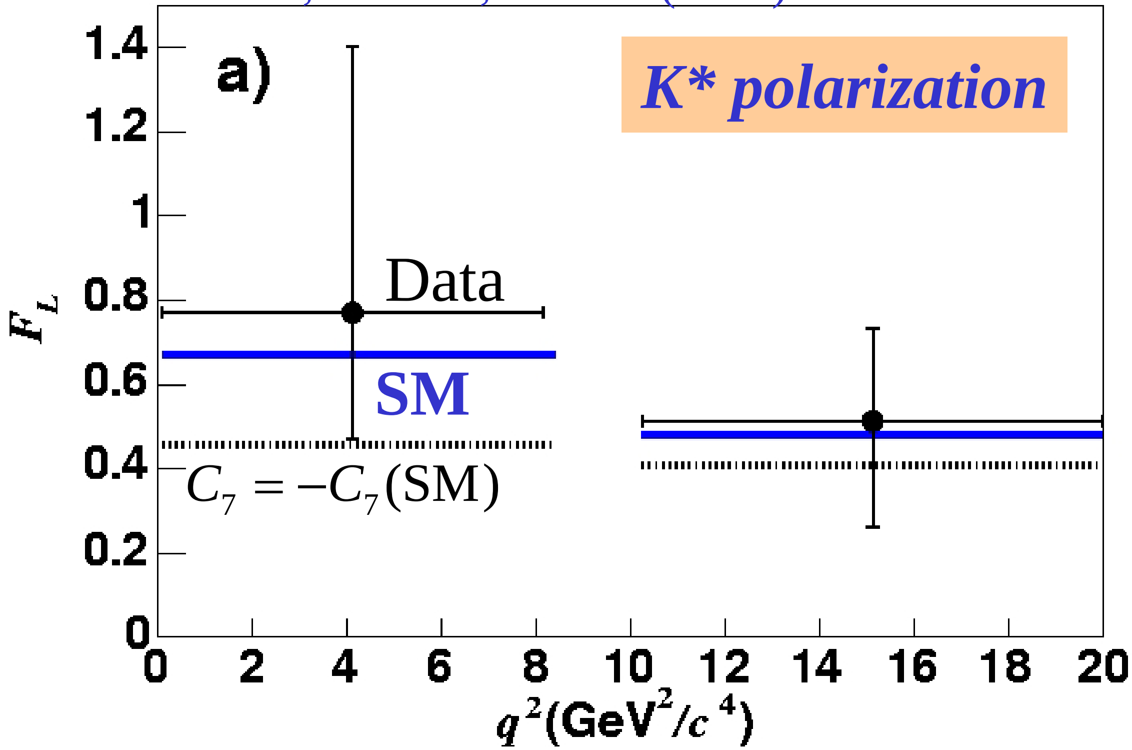
Mode	BABAR (10^{-6}) PRD 73, 092001 (2006)	Belle (10^{-6}) preliminary
$B \to K \ell^+ \ell^-$	$0.34^{+0.07}_{-0.07} \pm 0.02$	$0.550^{+0.075}_{-0.070} \pm 0.027$
$B \to K^* \ell^+ \ell^-$	$0.78^{+0.19}_{-0.17} \pm 0.11$	$1.65^{+0.23}_{-0.22} \pm 0.11$

$B \to K^* l^+ l^-$: *BABAR* results on *K** polarization and A_{FB}

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_K} = \frac{3}{2}F_L\cos^2\theta_K + \frac{3}{4}(1-F_L)\sin^2\theta_K$$

use in 2 bins of q^2

BABAR, PRD 73, 092001 (2006)



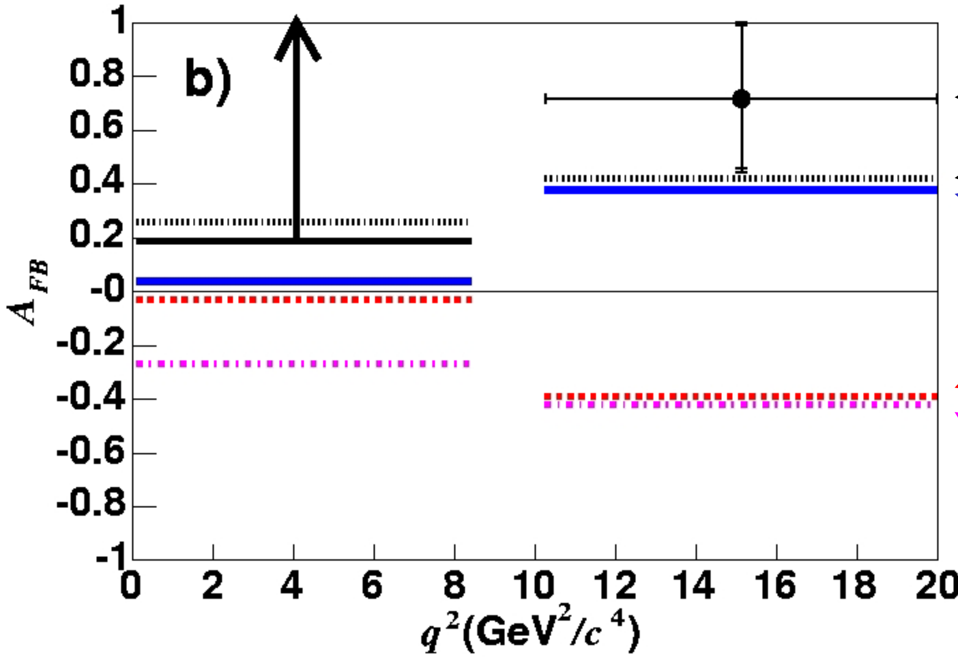
Polarization consistent with SM, but doesn't discriminate against new physics scenarios with current data sample.

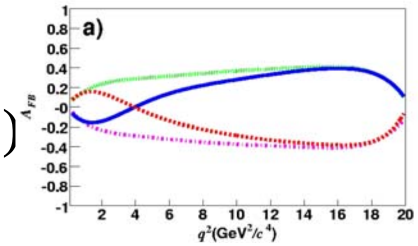
Theory predictions in graphs: Ali et al., PRD 66, 034002 (2002); Ball and Zwicky, PRD 71, 014029 (2005).

$B \to K^* l^+ l^-$: *BABAR* results on A_{FB} and Γ_L

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_l^*} = \frac{3}{4}F_L \sin^2\theta_l^* + \frac{3}{8}(1-F_L)(1+\cos^2\theta_l^*) + A_{FB}\cos\theta_l^*$$

use in 2 bins of q^2





Data

$C_7 = -C_7(\mathrm{SM})$

SM

$C_9^{\mathrm{eff}} C_{10}^{\mathrm{eff}} = -C_9(\mathrm{SM})C_{10}(\mathrm{SM})$

$\begin{cases} C_7^{\mathrm{eff}} = -C_7(\mathrm{SM}), \\ C_9^{\mathrm{eff}} C_{10}^{\mathrm{eff}} = -C_9(\mathrm{SM})C_{10}(\mathrm{SM}) \end{cases}$

excluded at 3.6σ!

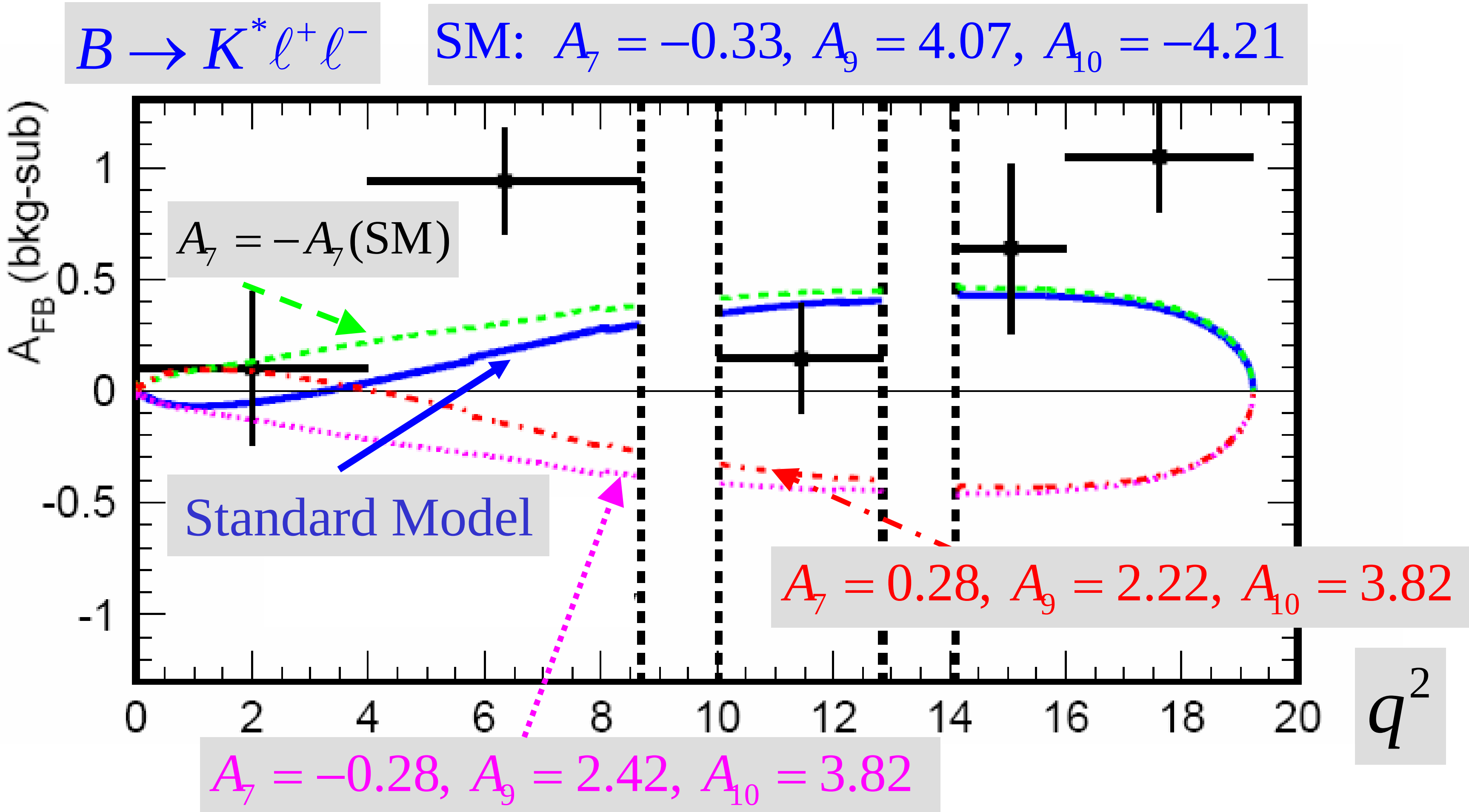
Any $A_{FB}<0$ excluded at >2.7σ

q^2 range (GeV^2)	A_{FB}	F_L
$0.1-8.41$	>0.19 (95% C.L.)	$0.77^{+0.63}_{-0.30} \pm 0.07$
>10.42	$0.72^{+0.28}_{-0.26} \pm 0.08$	$0.51^{+0.22}_{-0.25} \pm 0.08$

$A_{FB}\left(B \to K\ell^+\ell^-\right) = 0.15^{+0.21}_{-0.23} \pm 0.08 \quad \left(q^2 > 0.1\ \mathrm{GeV}^2\right)$

(A_{FB}=0 in SM and many BSM)

Belle results on A_{FB} for $B \to K^{(*)} l^+ l^-$



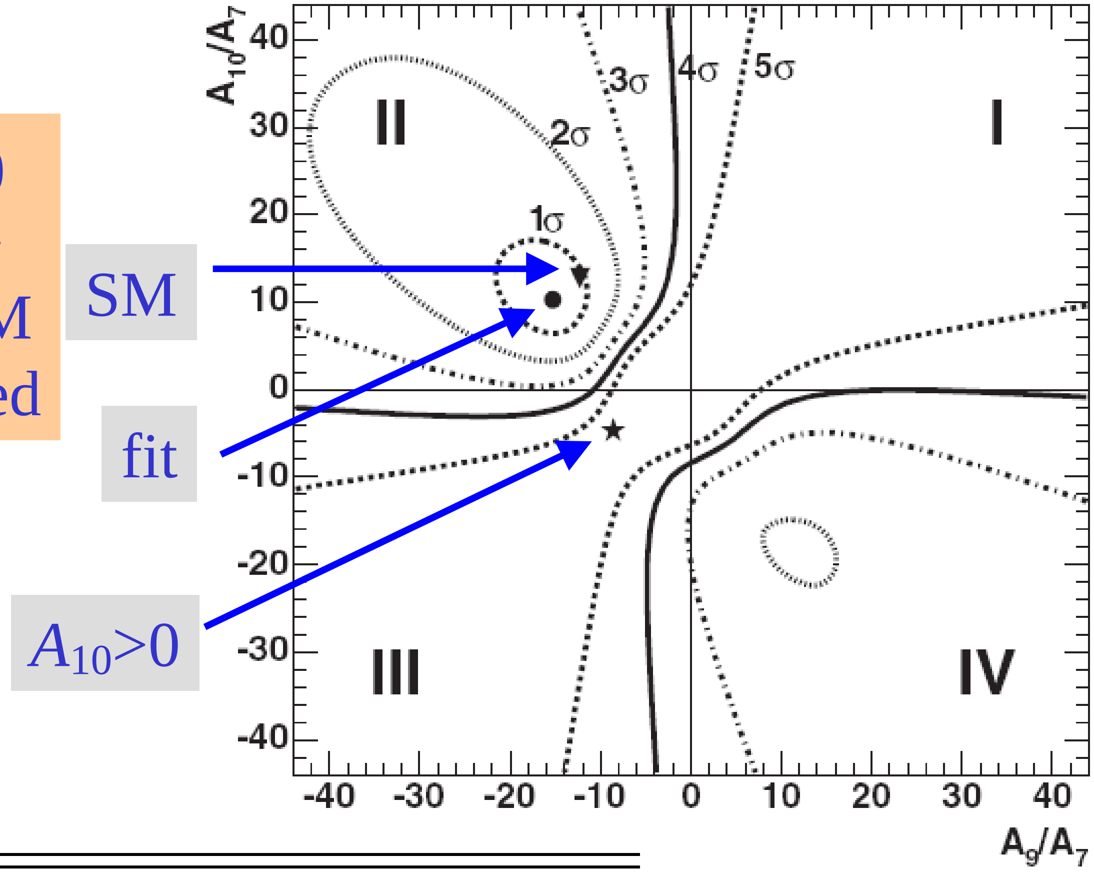
$$A_{FB}\left(B \to K^* \ell^+ \ell^-\right) = 0.50 \pm 0.15 \pm 0.02$$

$$A_{FB}\left(B \to K \ell^+ \ell^-\right) = 0.10 \pm 0.14 \pm 0.01$$

Belle, PRL 96, 251801 (2006)

Belle results on Wilson coefficients for $B \to K^{(*)} l^+ l^-$

- fix $|A_7|$ to SM ($B \to X_s \gamma$)
- fit for A_9/A_7 and A_{10}/A_7
- data consistent with SM
- quadrants II, IV allowed



	SM	$A_7 = -0.330$	$A_7 = +0.330$
A_9/A_7	−12.3	$-15.3^{+3.4}_{-4.8} \pm 1.1$	$-16.3^{+3.7}_{-5.7} \pm 1.4$
A_{10}/A_7	12.8	$10.3^{+5.2}_{-3.5} \pm 1.8$	$11.1^{+6.0}_{-3.9} \pm 2.4$

$$-1400 < \frac{A_9 A_{10}}{A_7^2} < -26.4 \quad 95\% \text{ C.L.}$$

→ $A_9 A_{10} < 0$ excludes quadrants I,III at 98.2% C.L.

Inclusive $B \to X_s \gamma$

- Canonical process for studying $b \to s$ transition. Theory uncertainties currently at 10% level (NLO); pushing toward 5% (NNLO).
- Huge theoretical effort to predict branching fractions & photon energy spectrum.
- Branching fraction measures $|C_7|$; spectrum is insensitive to new physics but is sensitive to m_b and Fermi motion of b-quark ("shape function").

$$E_\gamma > 1.6\ \text{GeV}$$

T. Hurth, E. Lunghi, W. Porod, Nucl. Phys. B 704, 56 (2005).

$$B(\bar{B} \to X_s \gamma) = \left(3.61\ {}^{+0.24}_{-0.40}\Big|_{m_c/m_b} \pm 0.02_{\text{CKM}} \pm 0.24_{\text{param}} \pm 0.14_{\text{scale}}\right) \times 10^{-4}$$

$$A_{CP}(\bar{B} \to X_s \gamma) = (0.42 \pm 0.08_{m_c/m_b} \pm 0.03_{\text{CKM}}\ {}^{+0.15}_{-0.08}\Big|_{scale})\%$$

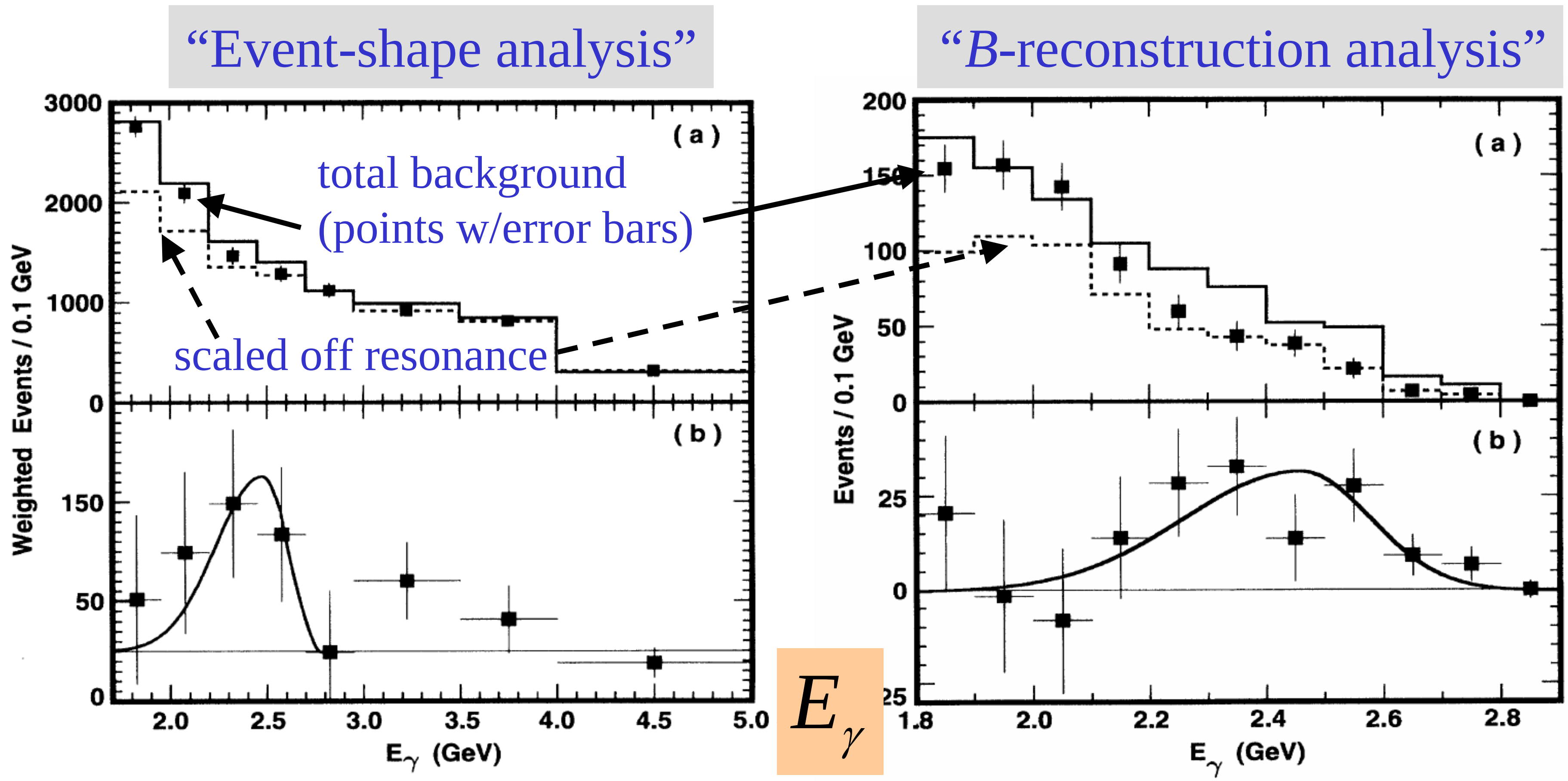
M. Neubert, Eur. Phys. J. C 40, 165 (2005).

$$B(\bar{B} \to X_s \gamma) = \left(3.47\ {}^{+0.33}_{-0.41}\Big|_{\text{pert}}\ {}^{+0.32}_{-0.29}\Big|_{\text{param}}\right) \times 10^{-4}$$

Inclusive $B \to X_s \gamma$: some history

CLEO, PRL 74, 2885 (1995); 2.01 fb^{-1} on $\Upsilon(4S)$, 0.96 fb^{-1} below $\Upsilon(4S)$

Backgrounds: B decays, continuum, $e^+e^- \to q\bar{q}\gamma$ (ISR), $e^+e^- \to q\bar{q} \to \pi^0 X$



$$B(B \to X_s \gamma) = (2.32 \pm 0.57\ (\text{stat.}) \pm 0.35\ (\text{sys.})) \times 10^{-4}$$

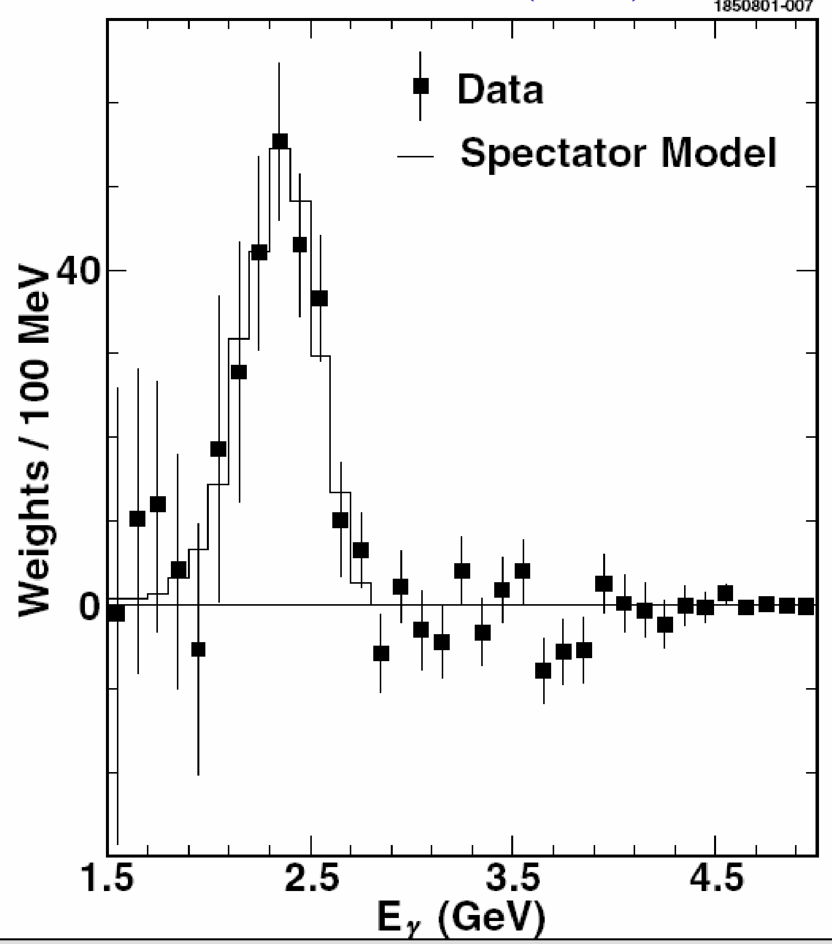
Challenges of inclusive $B \rightarrow X_s \gamma$

- Weak experimental signature: single high-energy photon + event-shape cuts. Lots of background from π^0's and η's! Fully inclusive analysis is not able to exploit the kinematic constraints (m_B, ΔE).
- Difficult to carry analysis down to $E_\gamma < 2.0$ GeV.
- Want to push toward 5% precision to match the expected precision of NNLO calculations. (It's amazing that you can do this analysis at all!)
- Two methods have evolved from initial CLEO approaches.

Method	Advantages	Disadvantages
Fully inclusive don't reconstruct X_s	**Closest correspondence to inclusive $B(B \rightarrow X_s \gamma)$.**	**Large background; limited sensitivity at low E_γ .**
Sum of exclusive $B \rightarrow K\, n(\pi)\, \gamma$	**Less background due to additional kinematic constraints. Better E_γ resolution.**	**More model dependence due to finite set of explicitly reconstructed $B \rightarrow X_s \gamma$ decays.**

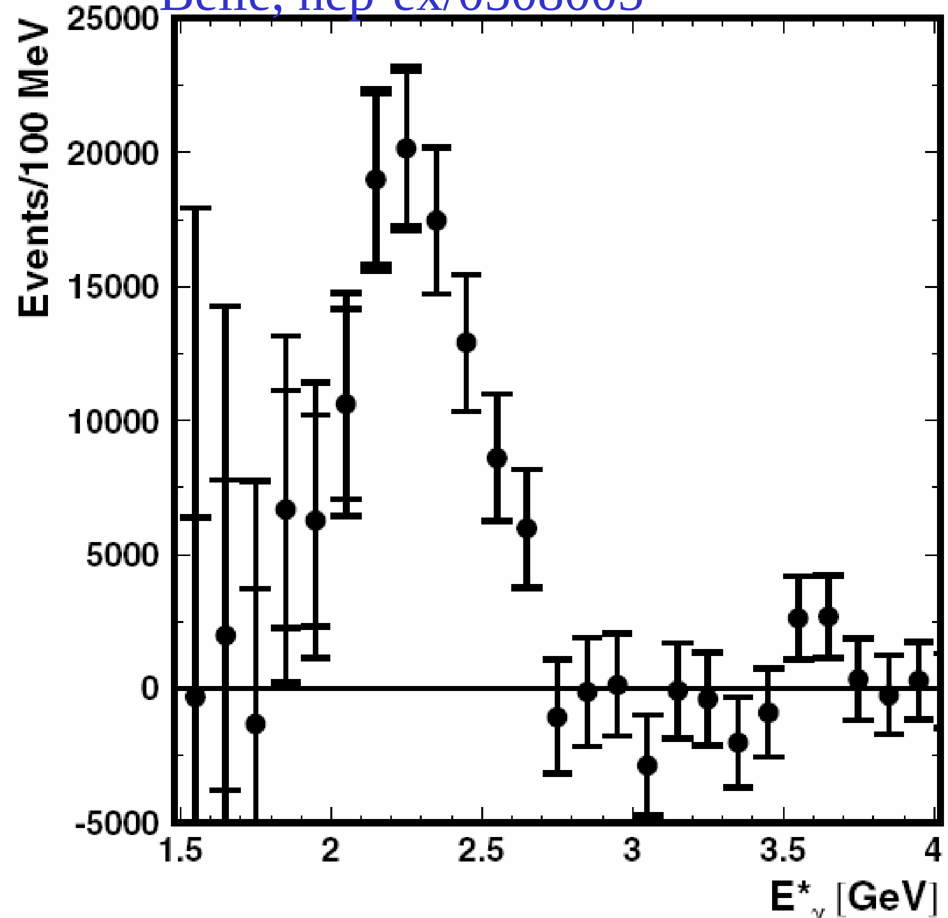
Fully inclusive $B \to X_s \gamma$: pushing down the energy threshold

CLEO, PRL 87, 215807 (2001), 9.1 fb-1



Belle, PRL 87, 061803 (2004), 140 fb^{-1}

Belle, hep-ex/0508005



$$BF = (3.21 \pm 0.43 \pm 0.27^{+0.18}_{-0.10}) \times 10^{-4}$$

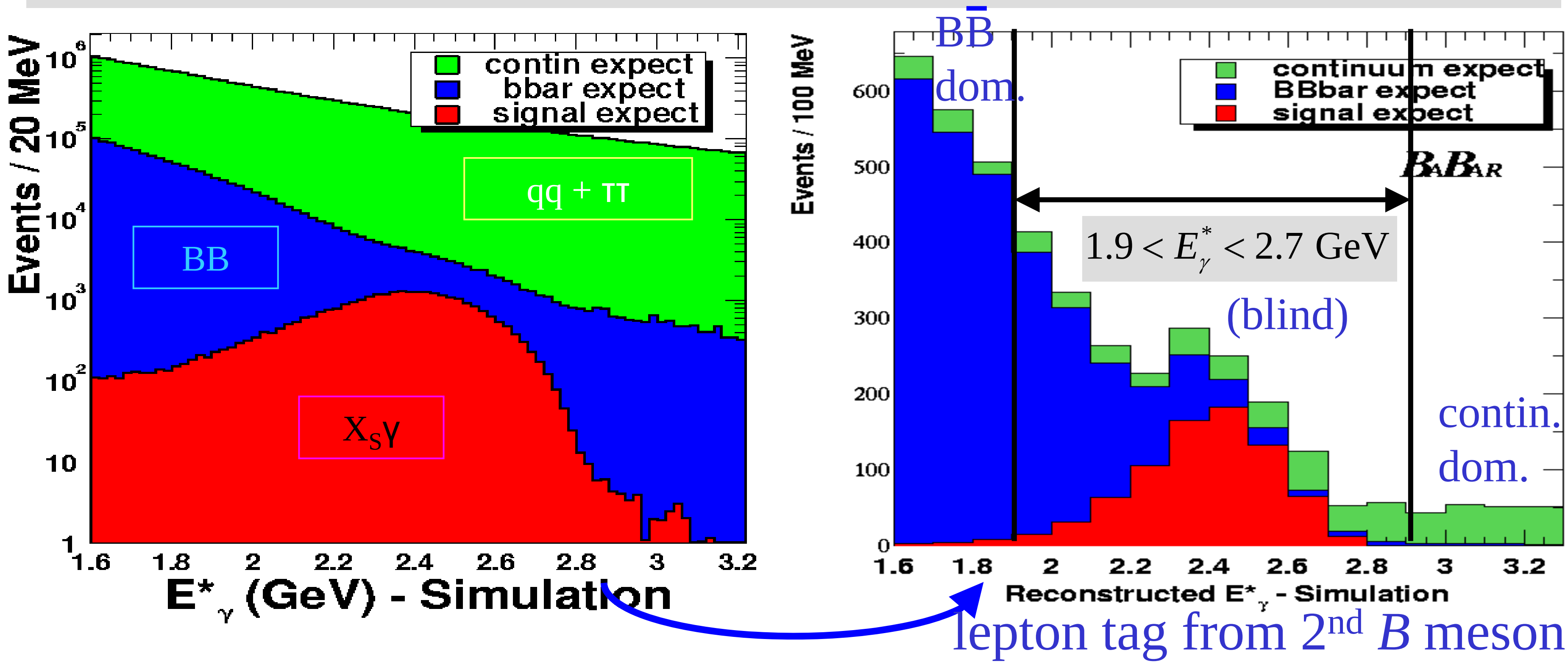
Measure for E_γ>2.0; extrap. to E_γ>0.25 GeV

$$BF = (3.55 \pm 0.32^{+0.30+0.11}_{-0.31-0.07}) \times 10^{-4}$$

Measure for E_γ>1.8 GeV; extrap. to full

Fully inclusive, lepton-tagged $B \rightarrow X_s \gamma$ (*BABAR*)

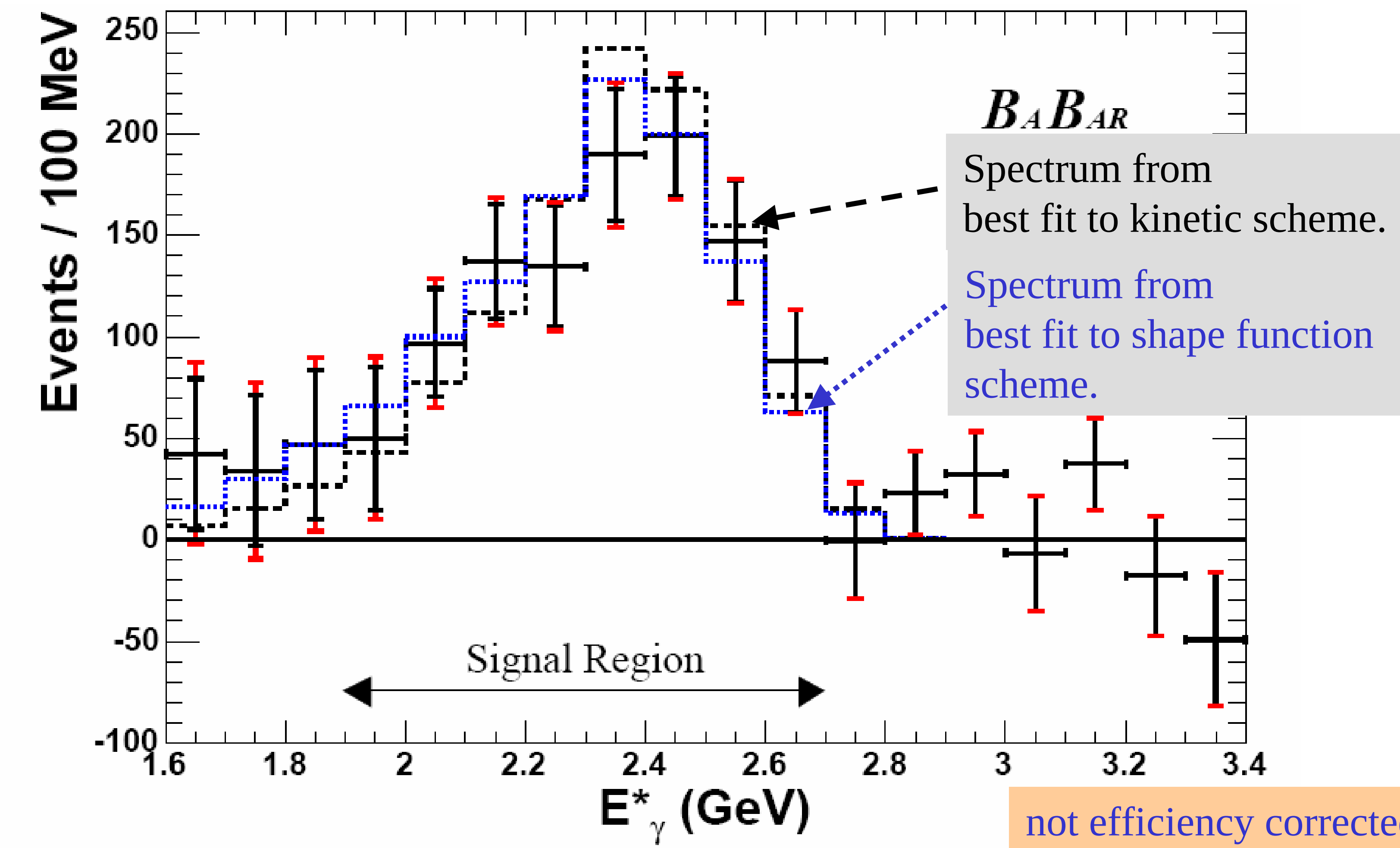
- Want to suppress large continuum background.
- Strengthen signature for signal by using decay of 2nd *B* in event.
- Require high energy lepton: $p_e^* > 1.25$ GeV, $p_\mu > 1.9$ GeV in addition to event-shape cuts.
- Tag does not compromise inclusiveness of X_s selection.



BABAR Fully Inclusive $B \to X_s\, \gamma$, w/lepton tag

hep-ex/0607071 (preliminary, submitted to PRL)

88.5×10^6 $B\overline{B}$ events



not efficiency corrected

$$B(B \to X_s \gamma) = (3.67 \pm 0.29 \pm 0.34 \pm 0.29) \times 10^{-4}$$

$E_\gamma > 1.9$ GeV (measured)

$$B(B \to X_s \gamma) = (3.94 \pm 0.31 \pm 0.36 \pm 0.21) \times 10^{-4}$$

$E_\gamma > 1.6$ GeV (extrapolated, kinetic scheme)

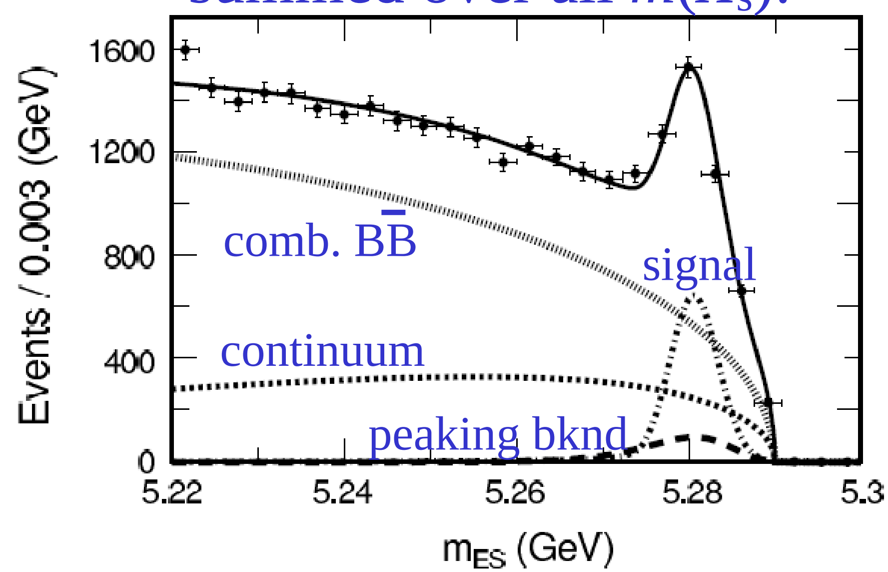
BABAR $B \rightarrow X_s\,\gamma$ with Sum of Exclusive Final States

Reconstruct 38 exclusive modes

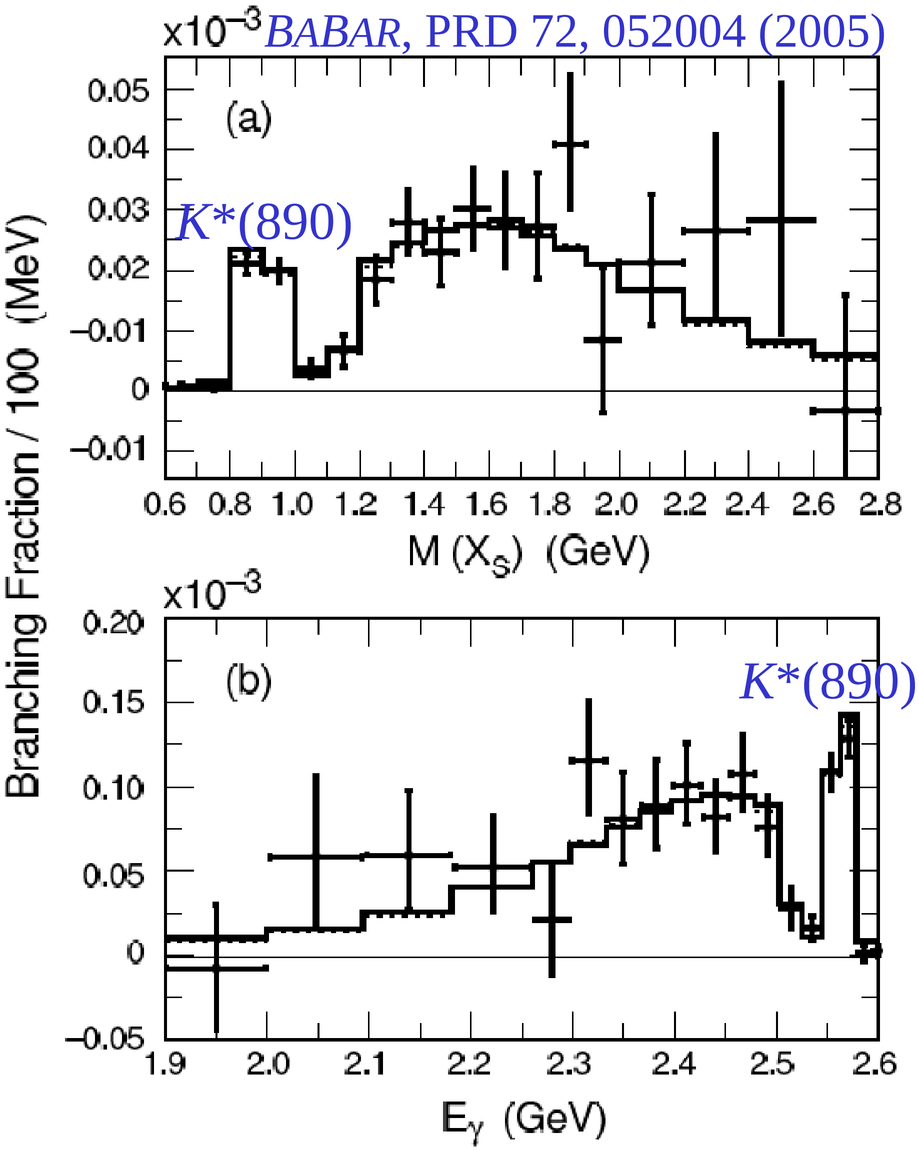
Final States	
$K^-\pi^+$, $K^0_S\,\pi^-$ $K^-\pi^0$, $K^0_S\,\pi^0$	$K^{(+,-,0)}$ $+(\leq 4\pi)$
$K^-\pi^+\,\pi^-$, $K^0_S\,\pi^+\,\pi^-$ $K^-\pi^+\,\pi^0$, $K^0_S\,\pi^-\,\pi^0$	
$K^-\pi^+\,\pi^-\,\pi^+$, $K^0_S\,\pi^+\,\pi^-\,\pi^-$ $K^-\pi^+\,\pi^-\,\pi^0$, $K^0_S\,\pi^+\,\pi^-\,\pi^0$	
$K^-\pi^0\,\pi^0$, $K^0_S\,\pi^0\,\pi^0$ $K^-\pi^+\,\pi^0\,\pi^0$, $K^0_S\,\pi^-\,\pi^0\,\pi^0$	
$K^-\pi^+\,\pi^-\,\pi^+\,\pi^-$, $K^0_S\,\pi^+\,\pi^-\,\pi^+\,\pi^-$ $K^-\pi^+\,\pi^-\,\pi^+\,\pi^0$, $K^0_S\,\pi^+\,\pi^-\,\pi^-\,\pi^0$ $K^-\pi^+\,\pi^-\,\pi^0\,\pi^0$, $K^0_S\,\pi^+\,\pi^-\,\pi^0\,\pi^0$	
$K^-\eta$, $K^0_S\,\eta$, $K^-\eta\,\pi^+$ $K^0_S\,\eta\,\pi^-$, $K^-\eta\,\pi^0$, $K^0_S\,\eta\,\pi^0$ $K^-\eta\,\pi^+\,\pi^-$, $K^0_S\,\eta\,\pi^+\,\pi^-$ $K^-\eta\,\pi^+\,\pi^0$, $K^0_S\,\eta\,\pi^-\,\pi^0$	$K^{(+,-,0)}$ $+\eta$ $+(\leq 2\pi)$
$K^-K^+K^-$, $K^-K^+K^0_S$ $K^-K^+K^-\pi^+$, $K^-K^+K^0_S\,\pi^-$ $K^-K^+K^-\pi^0$, $K^-K^+K^0_S\,\pi^0$	$3K^{(+,-,0)}$ $+(\leq 1\pi)$

- $|\Delta E|<40$ MeV
- Fit m_{ES} distrib. in bins of $m(X_s)$
- Correct for efficiency of each mode and missing modes fraction (→model dependence)

summed over all $m(X_s)$:



BABAR $B \rightarrow X_s \gamma$ with Sum of Exclusive Final States



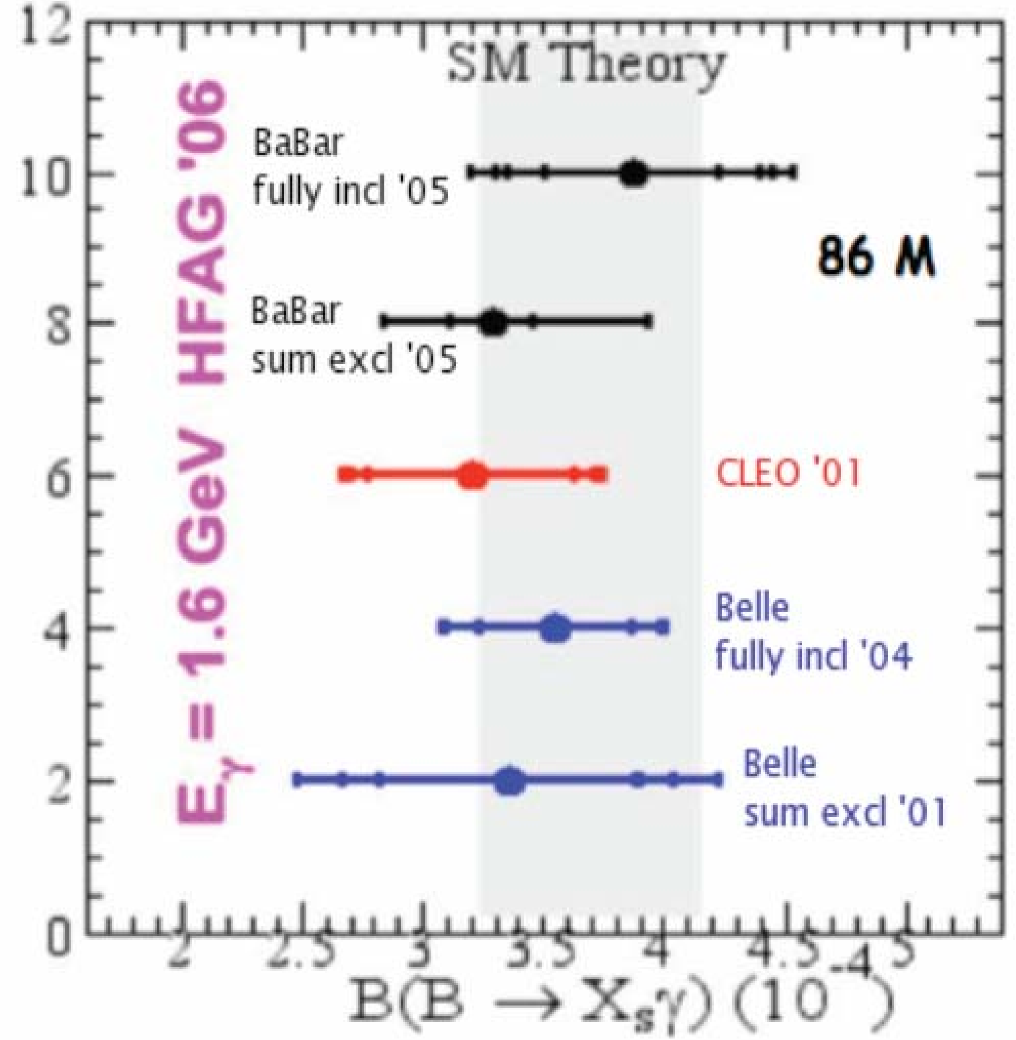
Energy Range	Branching Fraction (10^{-4})
E_γ >1.9 GeV	$3.27 \pm 0.18^{+0.55+0.04}_{-0.40-0.09}$
E_γ >1.6 GeV (extrapolated)	$3.35 \pm 0.19^{+0.56+0.04}_{-0.41-0.09}$

- averages over two shape-function schemes
- errors: stat, sys, variation of shape fcn params

E_γ Moments	Value (GeV or GeV^2)
$\langle E_\gamma \rangle$	$2.321 \pm 0.038^{+0.017}_{-0.038}$
$\langle E_\gamma^2 \rangle - \langle E_\gamma \rangle^2$	$0.0253 \pm 0.0101^{+0.0041}_{-0.0028}$

- E_γ (min) = 1.897 GeV

Summary of $B \to X_s \gamma$ Branching Fraction Measurements



$$B(B \to X_s \gamma) = (3.55 \pm 0.24^{+0.09}_{-0.10} \pm 0.03) \times 10^{-4}$$

HFAG average

Extraction of heavy-quark expansion parameters from $B \rightarrow X_s \gamma$

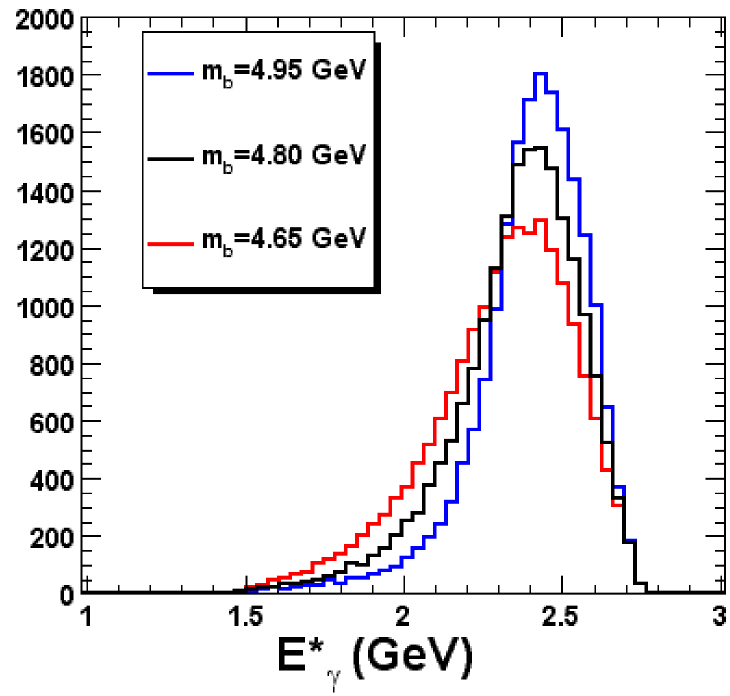
Using heavy-quark expansion (HQE), moments of inclusive *B* decay distributions can be expressed in terms of non-perturbative QCD parameters and quark masses.

- $B \rightarrow X_s \gamma$ inclusive E_γ spectrum
- $B \rightarrow X_c l \nu$ inclusive E_l spectrum and $M(X_c)$ hadron mass distrib.
- m_b now determined to about 1% and $|V_{cb}|$ is determined to <2%.

$$\langle E_\gamma \rangle \approx \frac{m_b}{2}$$

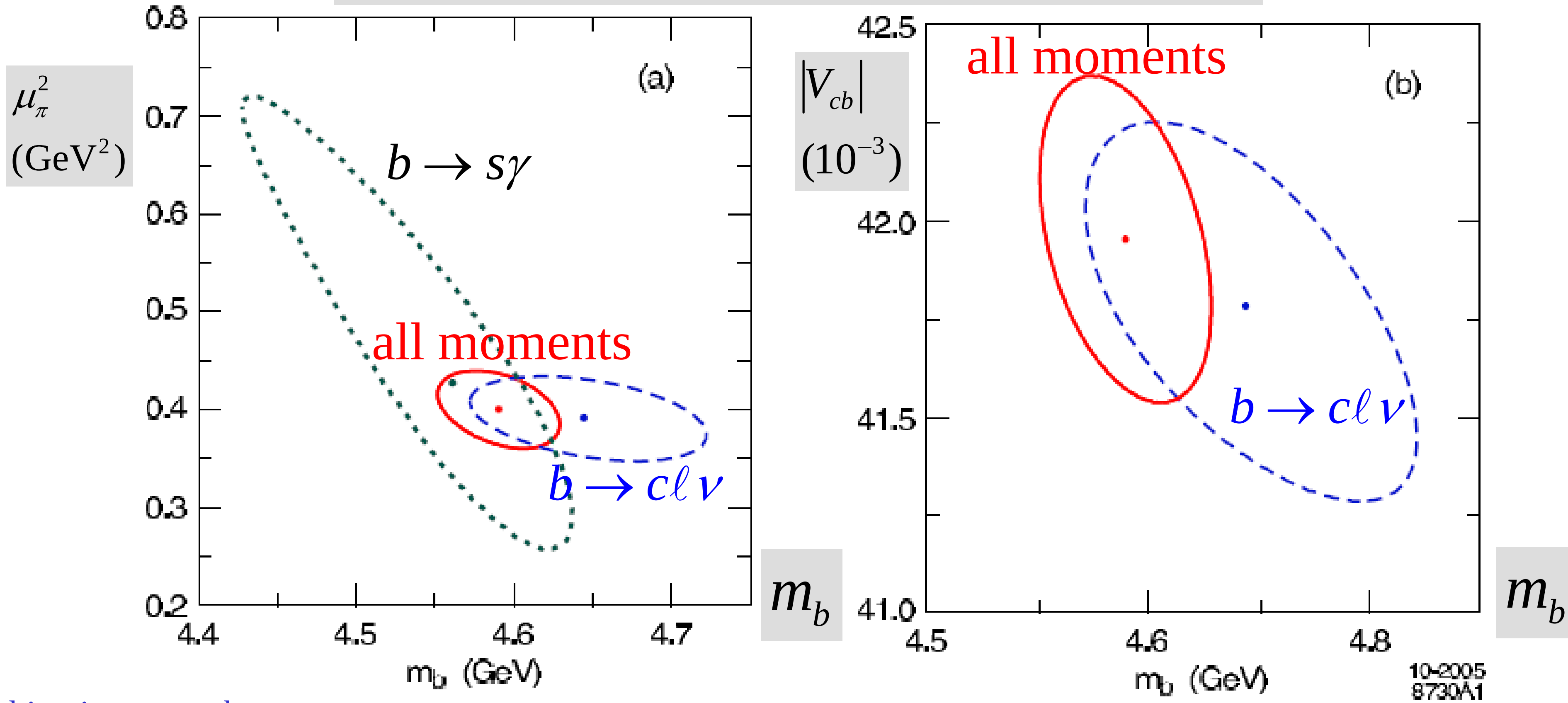
$$\left\langle \langle E_\gamma^2 \rangle - \langle E_\gamma \rangle^2 \right\rangle \approx g(m_b, \mu_\pi^2, \ldots)$$

(kinetic energy squared of *b*-quark)



Fits to moments of inclusive $B \rightarrow X_c\, l\, \nu$ and $B \rightarrow X_s\, \gamma$ distributions

Buchmüller and Flächer, PRD 73, 073008 (2006);
Data from BaBar, Belle, CDF, CLEO, & DELPHI



kinetic mass scheme

$$m_b = (4.590 \pm 0.025_{\text{exp}} \pm 0.030_{\text{HQE}})\ \text{GeV}$$

$$\mu_\pi^2 = (0.401 \pm 0.019_{\text{exp}} \pm 0.035_{\text{HQE}})\ \text{GeV}^2$$

$$|V_{cb}| = (41.96 \pm 0.23_{\text{exp}} \pm 0.35_{\text{HQE}} \pm 0.59_{\Gamma_{sl}}) \times 10^{-3}$$

m_b used for $|V_{ub}|$ (7.5% error!)

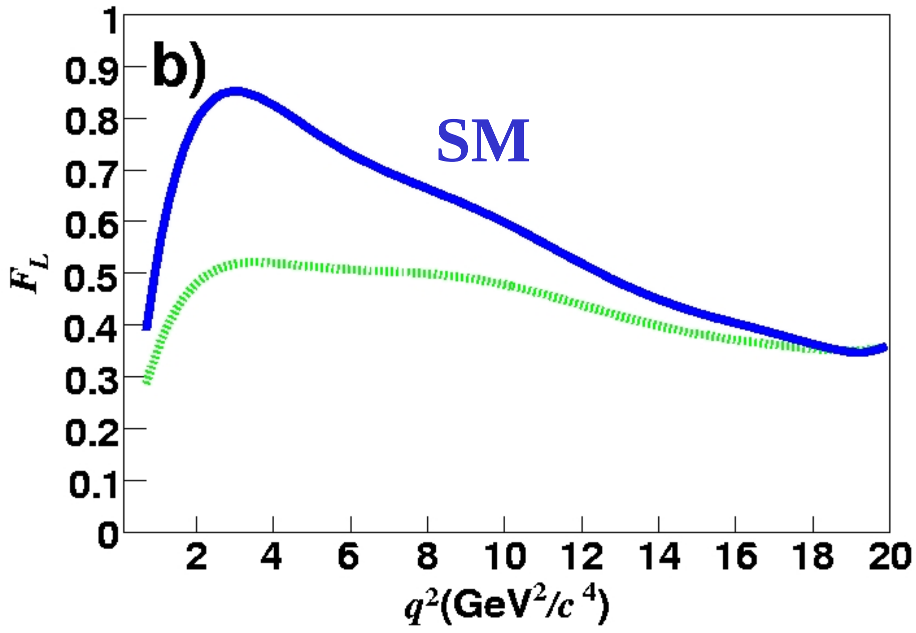
Conclusions

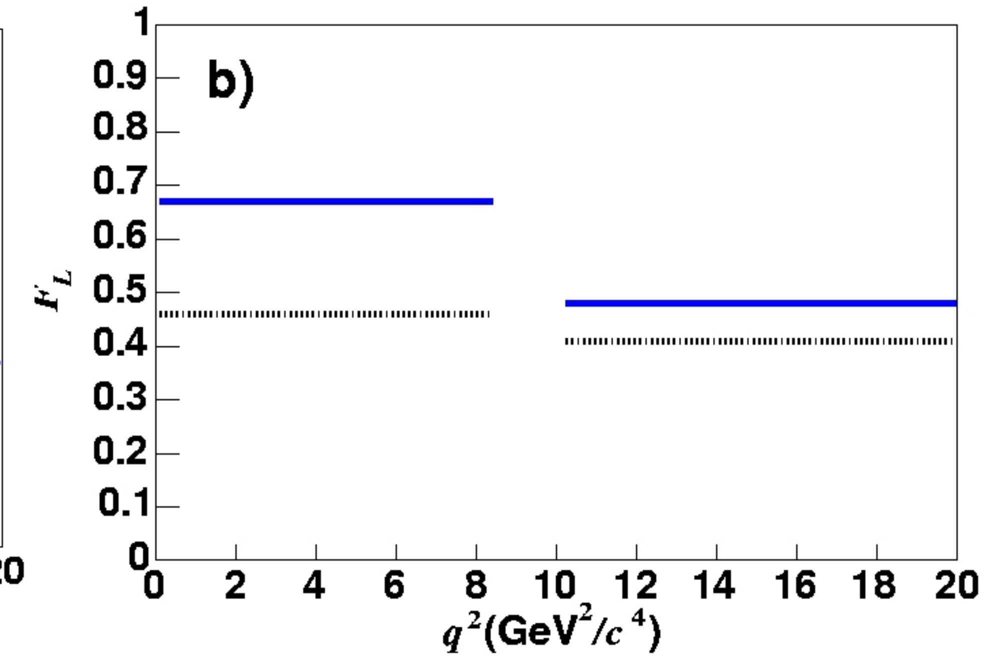
Studies of radiative/electroweak penguins have moved far beyond $B \to K^*\gamma$.

- Observation of exclusive $b \to d\,\gamma$ decays: $B \to (\rho^0, \rho^+, \omega)\,\gamma$
- Use to extract $|V_{td}/V_{ts}|$; consistent with value from B_s mixing. Precision limited by theoretical uncertainties.
- Electroweak penguins decays $B \to K\, l^+\, l^-$, $B \to K^*\, l^+\, l^-$, and $B \to X_s\, l^+\, l^-$ have been measured. First studies of decay distributions have been performed and exclude some non-SM scenarios. Much more data needed to exploit full potential.
- Inclusive $B \to X_s\,\gamma$ measurements provide information on m_b and non-pert. QCD parameters and help improve precision on $|V_{cb}|$ and $|V_{ub}|$. Difficult issues with systematic errors, but goal si to achieve 5% uncertainty on branching fraction.
- Much more to learn about penguins; we will study them for many years to come at BaBar, Belle, and LHC-b!

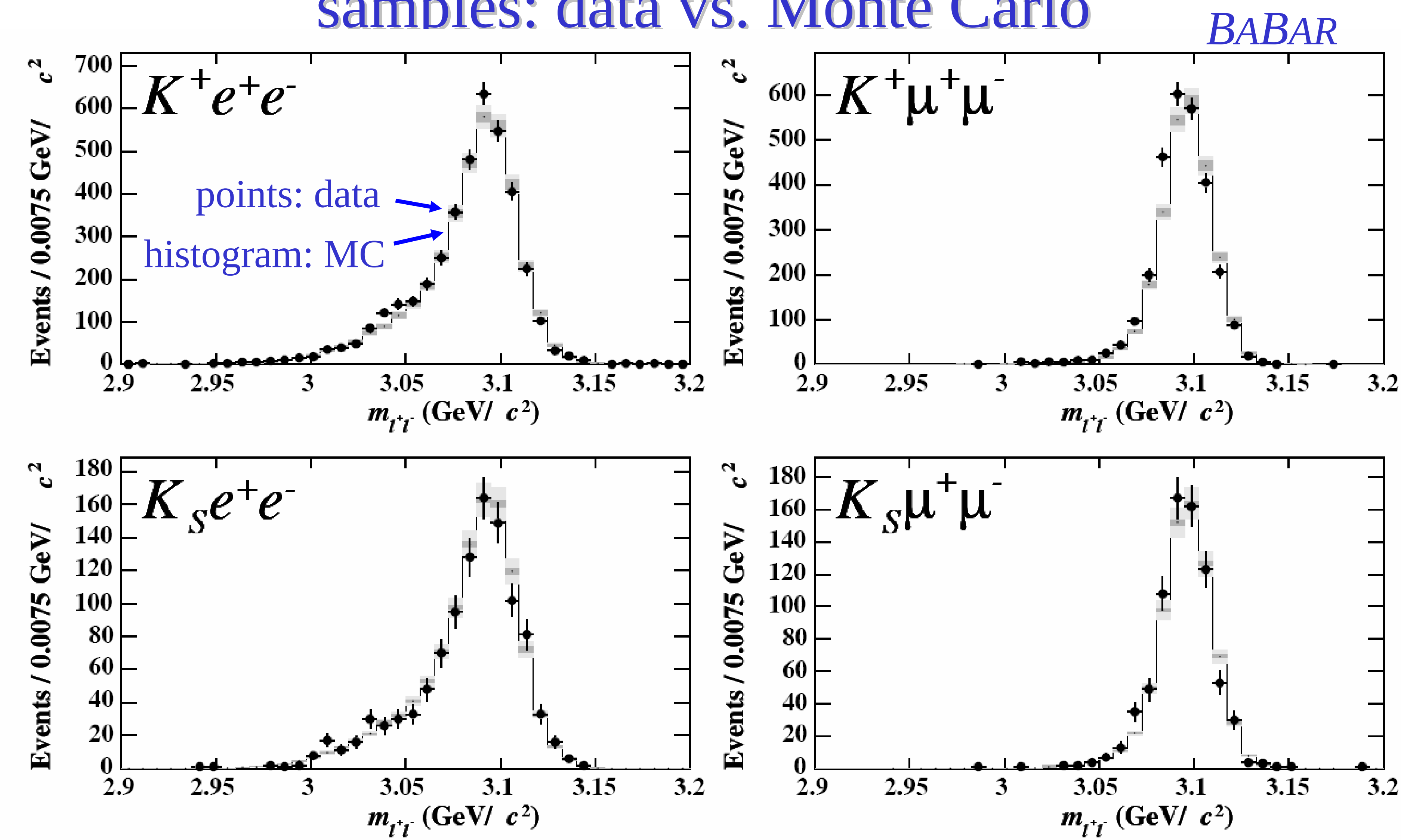
Backup slides

$B \rightarrow K^* l^+ l^-$: K^* polarization vs. q^2





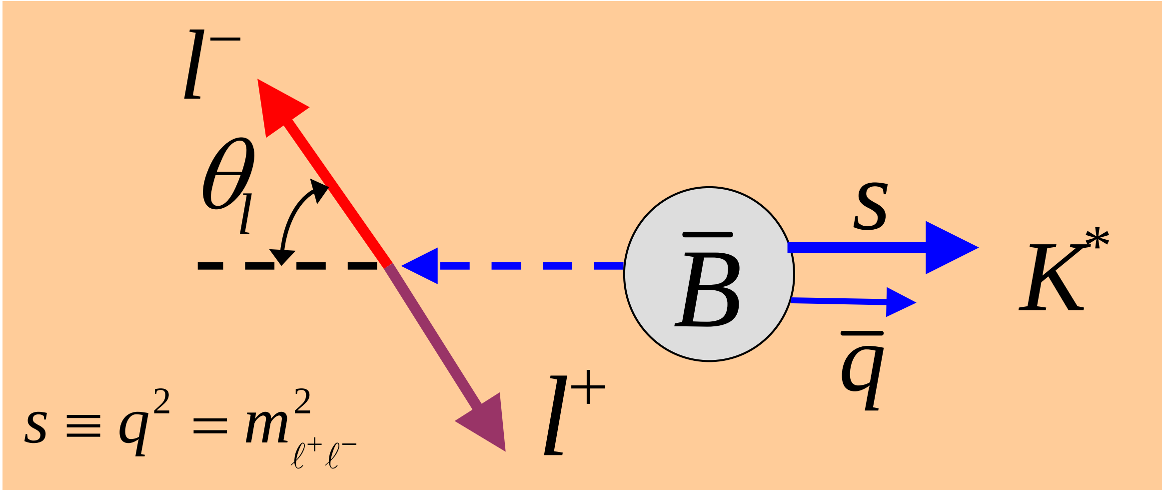
$M(l^+l^-)$ distributions from B→J/ψ K^+ control samples: data vs. Monte Carlo



absolute normalization

Bremsstrahlung tails well described by MC.

Lepton angular distribution in $l^+ l^-$ rest frame



use l^- if $\bar{B}$
use l^+ if B

$$\frac{dA_{FB}}{ds} \propto -C_{10}\left\{\mathrm{Re}\left(C_9^{eff}\right)VA_1 + \right.$$

$$\left. + \frac{m_b m_B}{s} C_7^{eff}\left[VT_2\left(1-\frac{m_{K^*}}{m_B}\right)(1-\hat{m}_{K^*}) + A_1 T_1\left(1+\frac{m_{K^*}}{m_B}\right)\right]\right\}$$

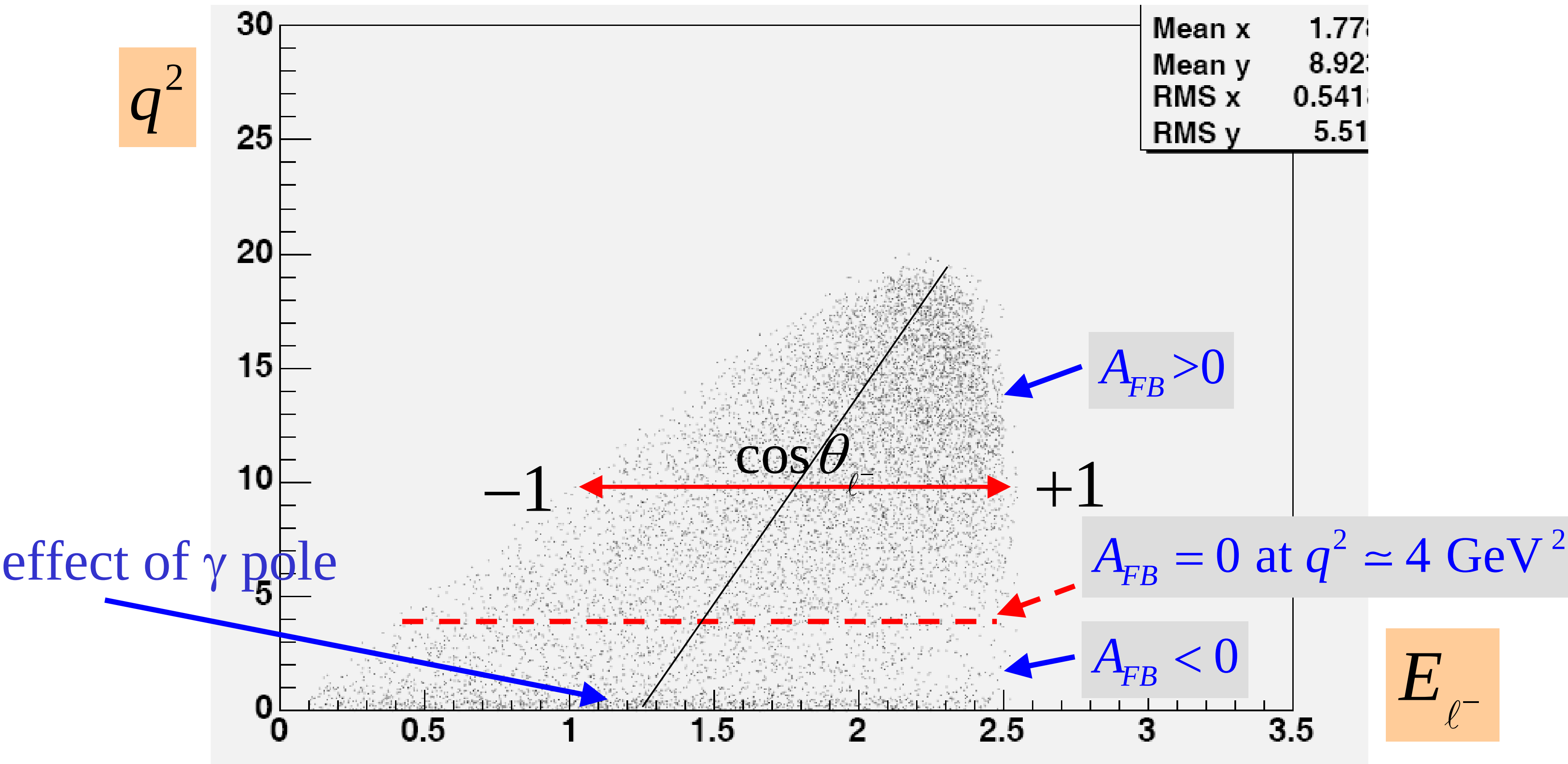
$$\frac{s_0}{m_B^2} = -\frac{m_b}{m_B}\frac{C_7^{eff}}{\mathrm{Re}\left(C_9^{eff}(s_0)\right)}\left\{\frac{T_2(s_0)}{A_1(s_0)}\left(1-\frac{m_{K^*}}{m_B}\right) + \frac{T_1(s_0)}{V(s_0)}\left(1+\frac{m_{K^*}}{m_B}\right)\right\}$$

$$s_0 = \left(4.07^{+0.16}_{-0.13}\right)\ \mathrm{GeV}^2$$

Ali, Kramer, Zhu, hep-ph/0601034

$B \rightarrow K^* l^+ l^-$ Dalitz plot

Can see A_{FB} behavior and q^2 dependence from the Dalitz plot



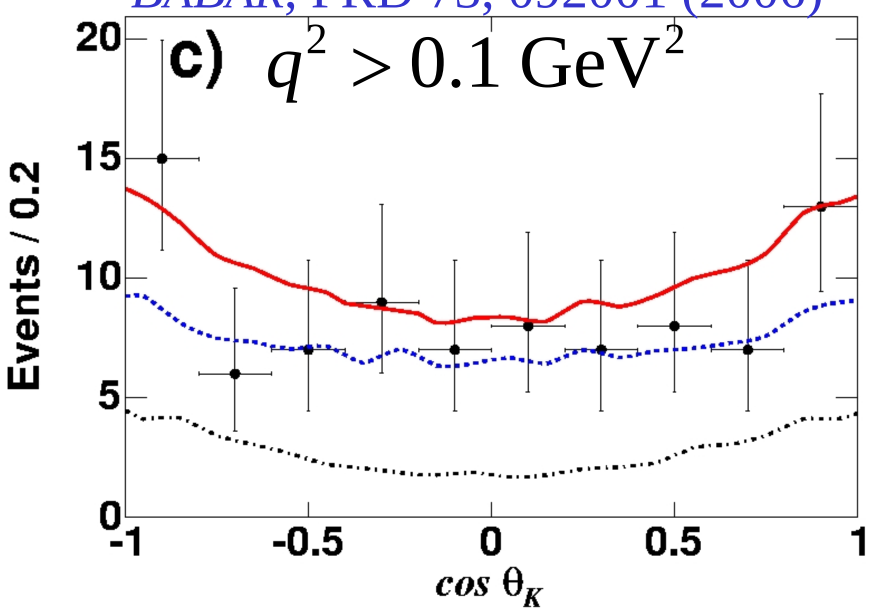
Note: $B \rightarrow K l^+ l^-$ is expected to have very small A_{FB}, even in presence of new physics; effectively provides a crosscheck.

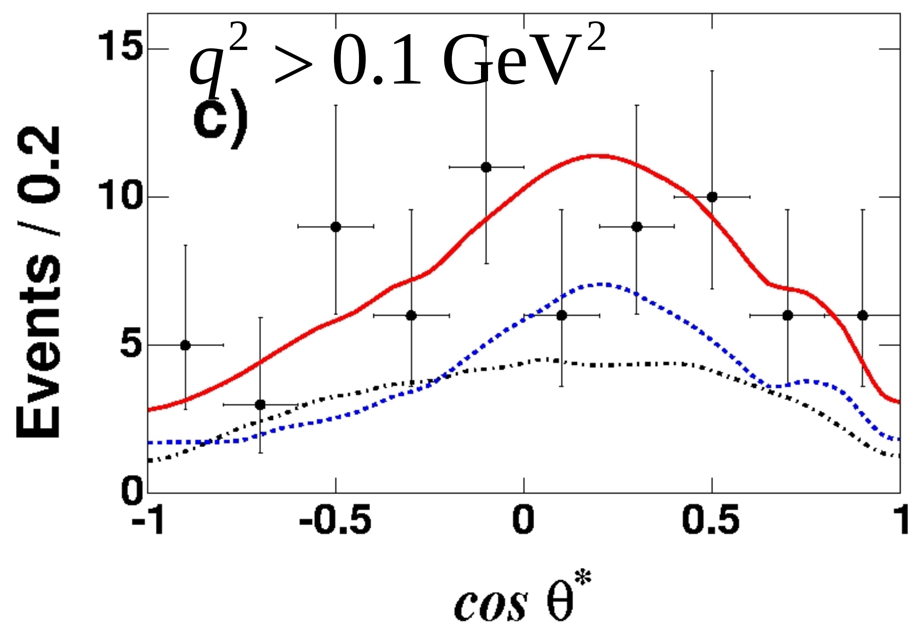
Extracting A_{FB} and F_L in bins of q^2

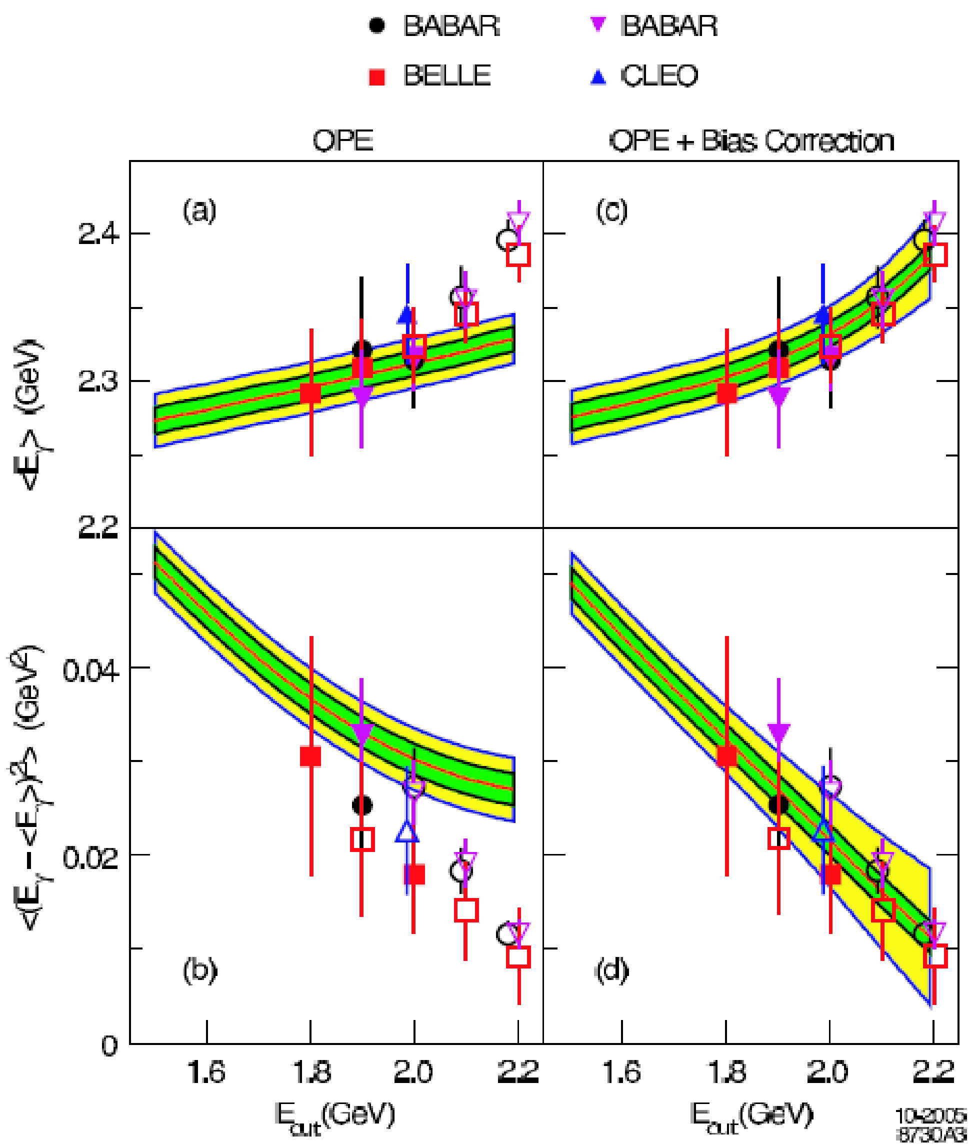
$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_K} = \frac{3}{2}F_L\cos^2\theta_K + \frac{3}{4}(1-F_L)\sin^2\theta_K$$

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_l^*} = \frac{3}{4}F_L\sin^2\theta_l^* + \frac{3}{8}(1-F_L)(1+\cos^2\theta_l^*) + A_{FB}\cos\theta_l^*$$

BABAR, PRD 73, 092001 (2006)







BABAR
BABAR
BELLE
CLEO
OPE
OPE + Bias Correction
(a)
(b)
(c)
(d)
$<E_\gamma>$ (GeV)
$<(E_\gamma - <E_\gamma>)^2>$ (GeV^2)
E_{cut}(GeV)
E_{cut}(GeV)
10-2005
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