Radiative and Electroweak Penguin Decays of *B* Mesons

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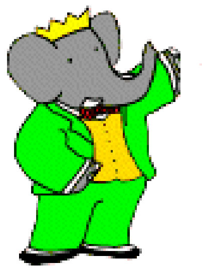
BABAR Collaboration



$$\begin{bmatrix} u \\ \ \end{bmatrix}\begin{bmatrix} c \\ s \end{bmatrix}\begin{bmatrix} \ \\ b \end{bmatrix}$$

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 the extraction 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 (including m_b) using the E_γ spectrum
- Conclusions

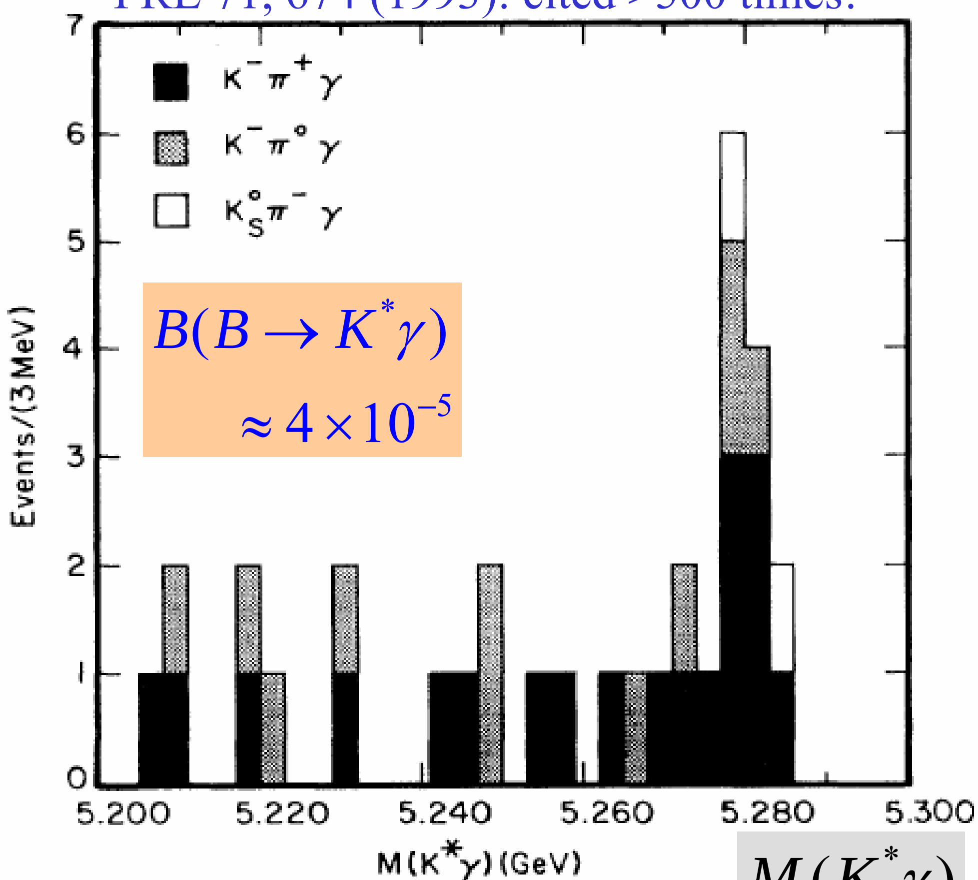
Apologies for not covering all results on radiative/electroweak penguin decays in this talk!

Radiative penguin decays of *B* mesons

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

CLEO II (1993): <u>*Loops* in *B* decays!</u>

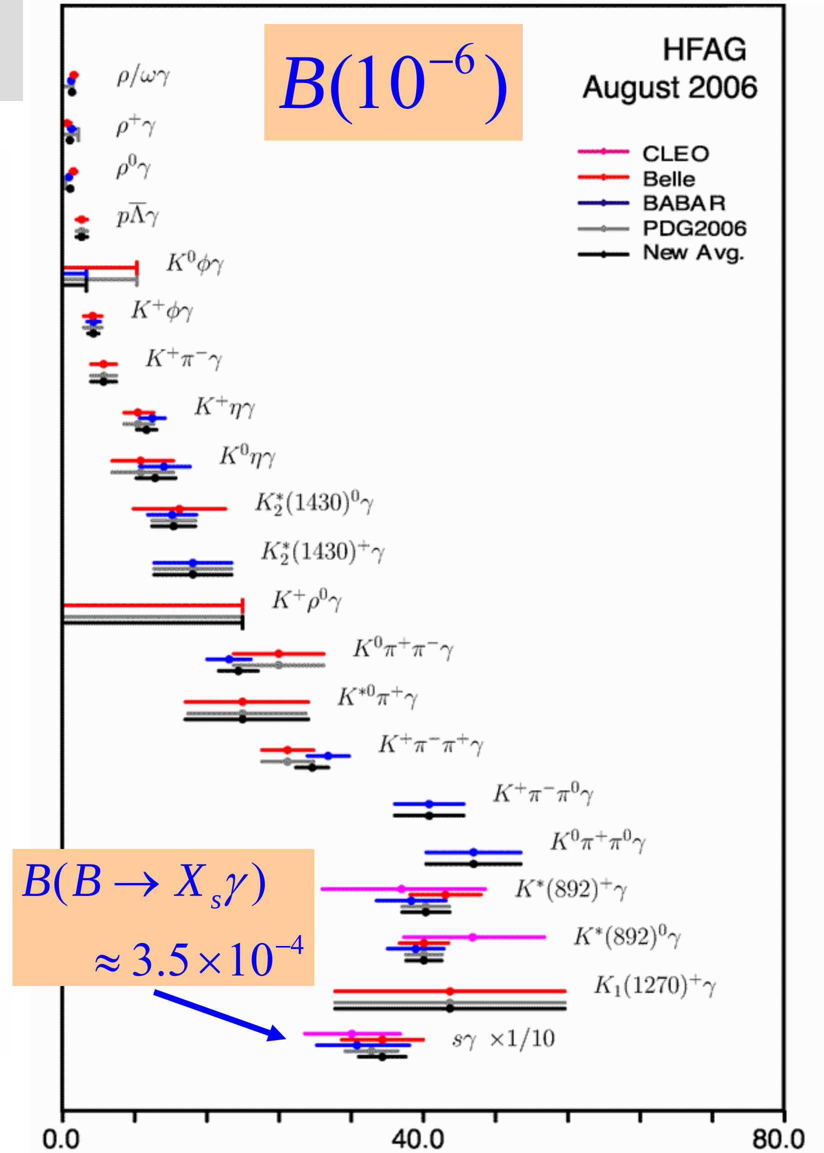
PRL 71, 674 (1993): cited >500 times!



$M(K^*\gamma)$

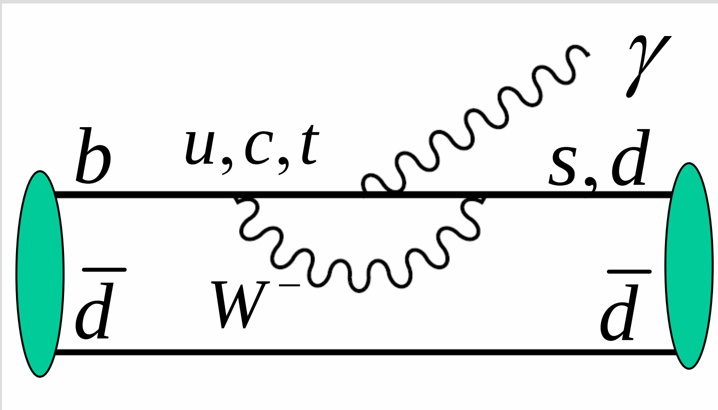
Rare, but not all that rare!

Now it's a physics program!

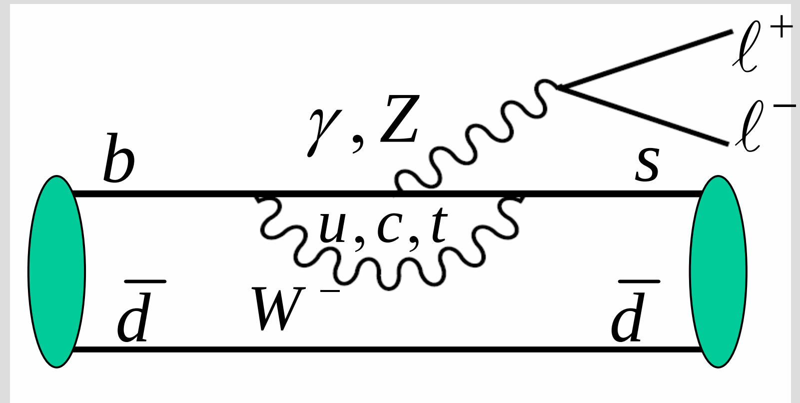


What can we learn from *b*→*s*, *d* transitions?

- **<u>Probe SM at 1-loop level</u> (flavor-changing neutral currents)**

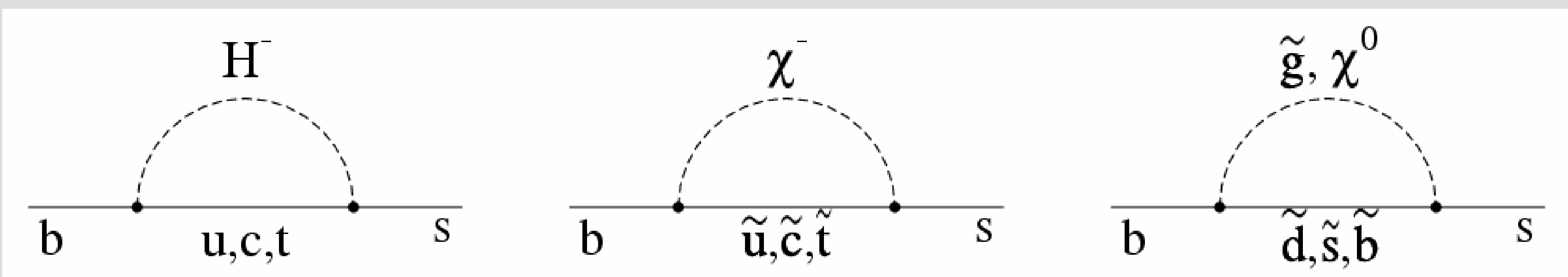


(dominated by *t* quark)



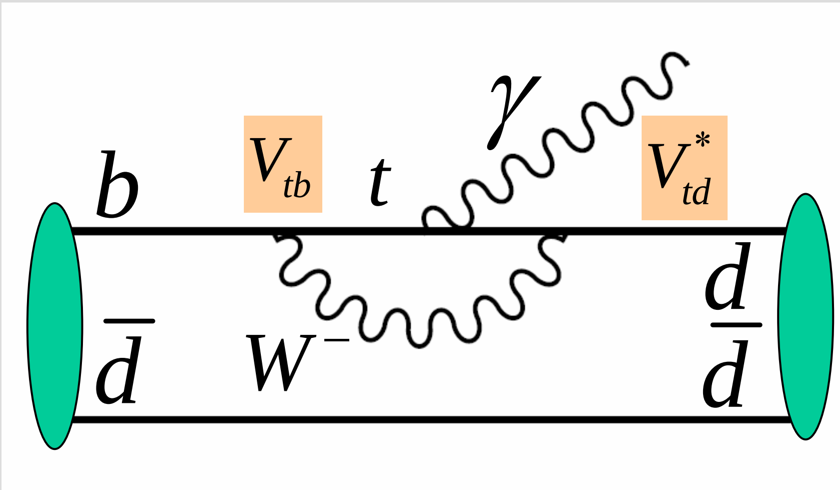
(+ W^+W^- box diagram)

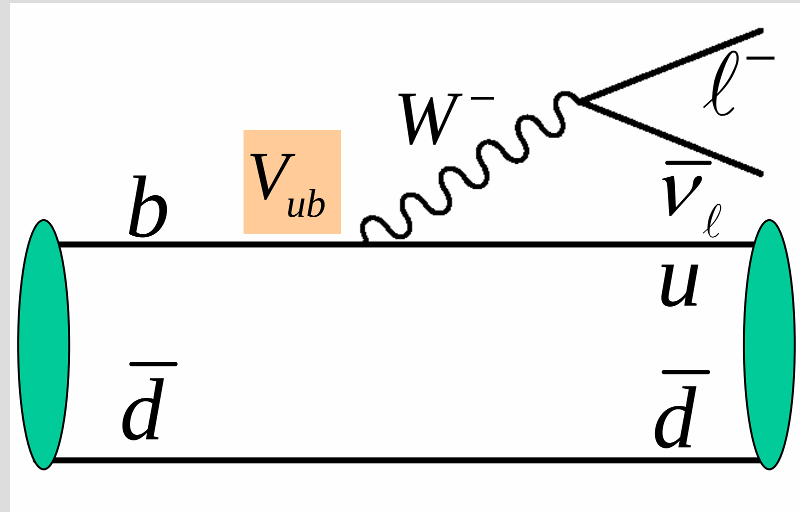
- **<u>Search for new physics:</u> can affect amplitudes at leading order**



- **As for semileptonic decays, the amplitude in EM/EW penguins involves only one hadronic current → factorizes.**

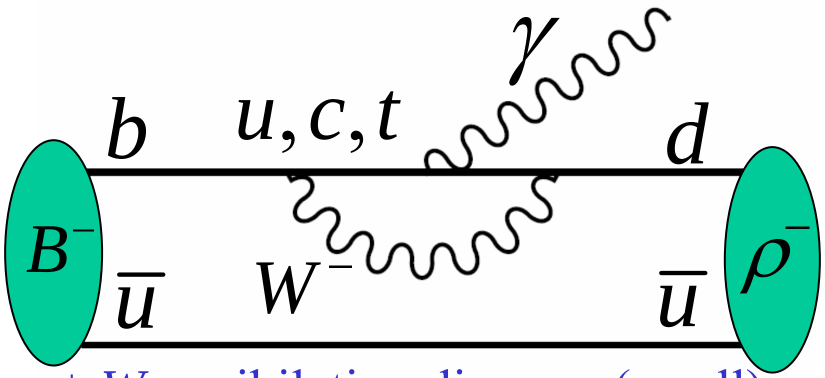
What can we learn from $b \to s,d$ transitions?

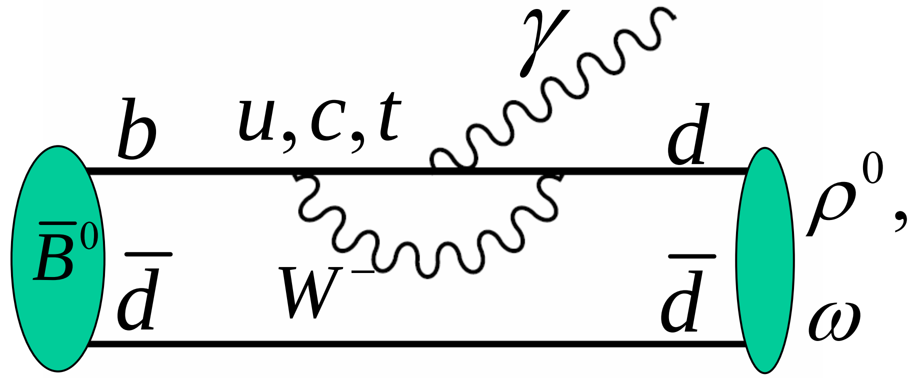




- **<u>Understand QCD dynamics:</u> single hadronic current allows us to isolate non-perturbative parameters in well-defined way. Can be related to same/similar parameters for other decays.**
  - **Exclusive decays: decay form factors $f_i(q^2)$. $b \to s$ transition is similar to $b \to u$ (heavy-to-light decays)**
  - **Inclusive decays: parameters of heavy-quark expansion (m_b, μ_π^2,…); important input for $|V_{ub}|$, $|V_{cb}|$ extractions.**
- **<u>Measure/constrain CKM elements</u> ($|V_{td}/V_{ts}|$): 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)
Ball and Zwicky, hep-ph/0603232

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

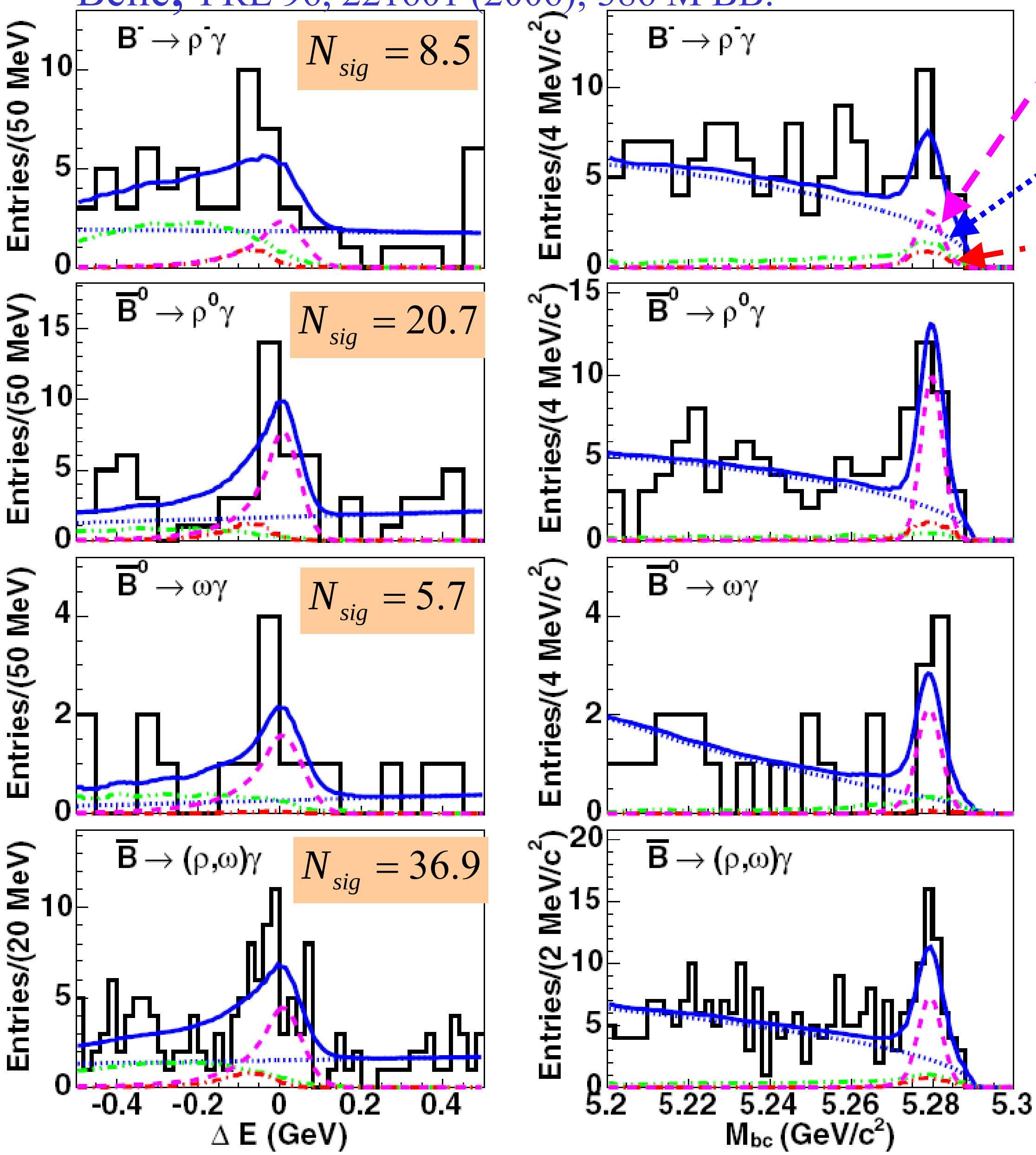
Ali, Lunghi, Parkhomenko, PLB 595, 323 (2004) [for I-spin avg.]

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

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 $B\bar{B}$.



Signal

continuum background

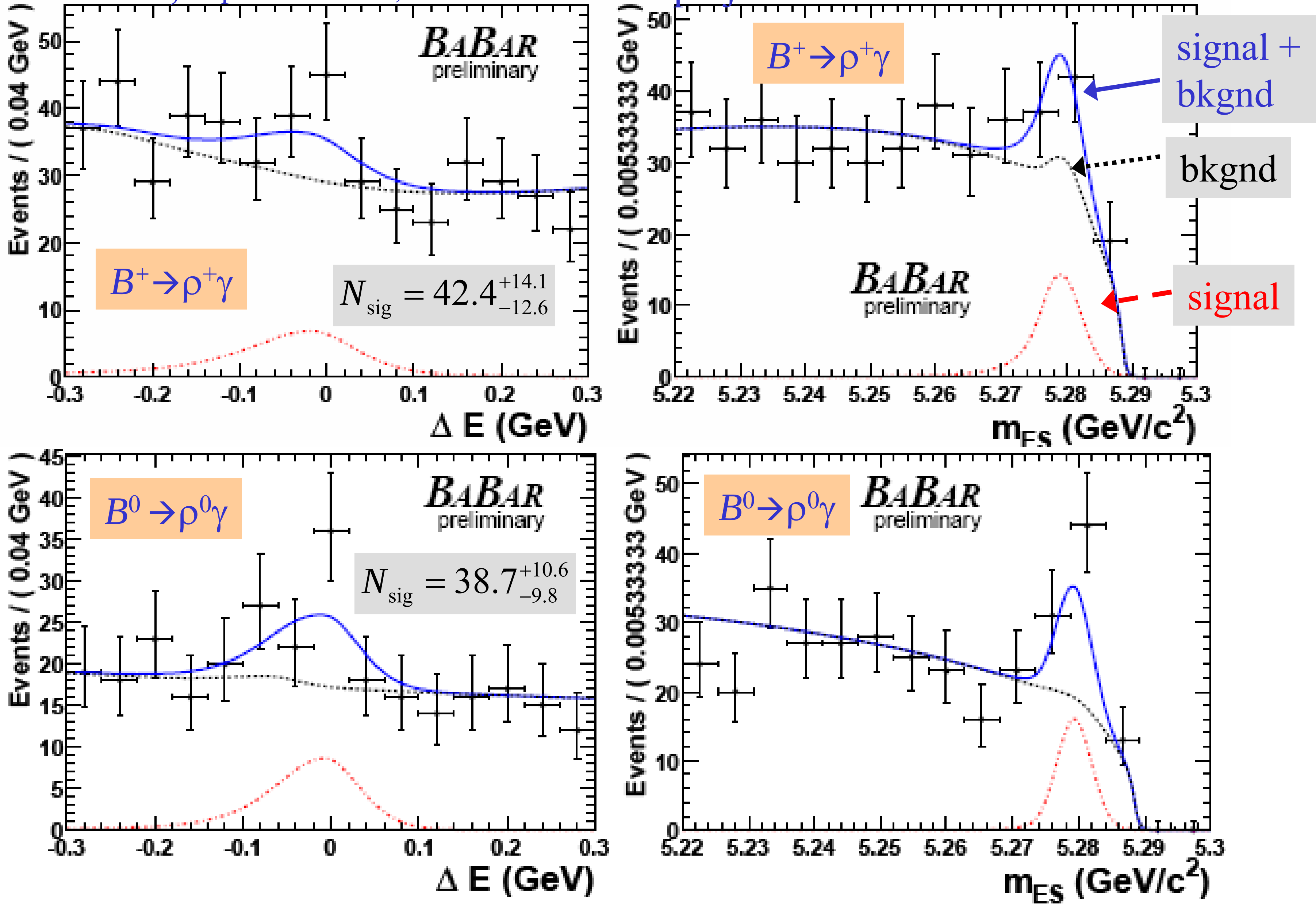
$B \to K^*\gamma$ $(BF \simeq 4\times10^{-5})$

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

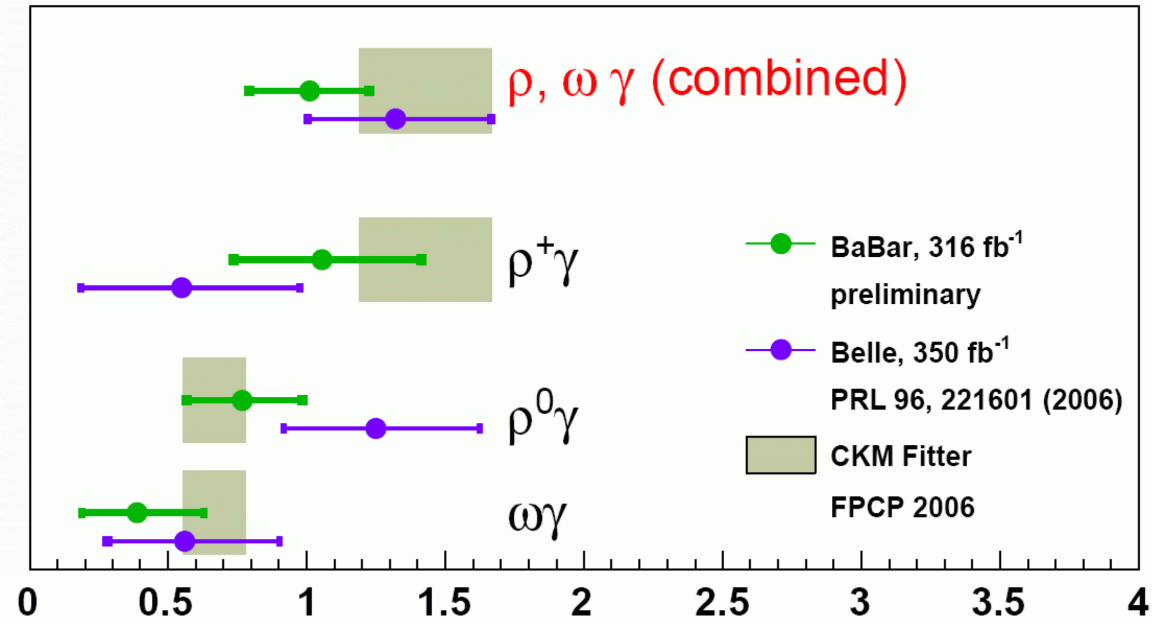
Mode	$\mathcal{B}$ (10^{-6})
$B^- \to \rho^-\gamma$	$0.55^{+0.42+0.09}_{-0.36-0.08}$
$\bar{B}^0 \to \rho^0\gamma$	$1.25^{+0.37+0.07}_{-0.33-0.06}$
$\bar{B}^0 \to \omega\gamma$	$0.56^{+0.34+0.05}_{-0.27-0.10}$
$\bar{B} \to (\rho,\omega)\gamma$	$1.32^{+0.34+0.10}_{-0.31-0.09}$

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



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?

(10^{-6})

Mode	*BABAR* (10^{-6}) (6.3 σ signif.) preliminary; hep-ex/0607099		Belle (10^{-6}) (5.1σ signif.) PRL 96, 221601 (2006).	
$B^+ \to \rho^+\gamma$	$1.06^{+0.35}_{-0.31} \pm 0.09$	4.1σ	$0.55^{+0.42+0.09}_{-0.36-0.08}$	1.6σ
$B^0 \to \rho^0\gamma$	$0.77^{+0.21}_{-0.19} \pm 0.07$	5.2σ	$1.25^{+0.37+0.07}_{-0.33-0.06}$	5.2σ
$B^0 \to \omega\gamma$	$0.39^{+0.24}_{-0.20} \pm 0.03$	2.3σ	$0.56^{+0.34+0.05}_{-0.27-0.10}$	2.3σ
$B \to (\rho^+, \rho^0, \omega)_{I\text{-avg}}\gamma$	$1.01 \pm 0.21 \pm 0.08$		$1.32^{+0.34+0.10}_{-0.31-0.09}$	

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

Belle, PRL 96, 221601 (2006).

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

expt thy

BABAR, hep-ex/0607099 (preliminary)

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

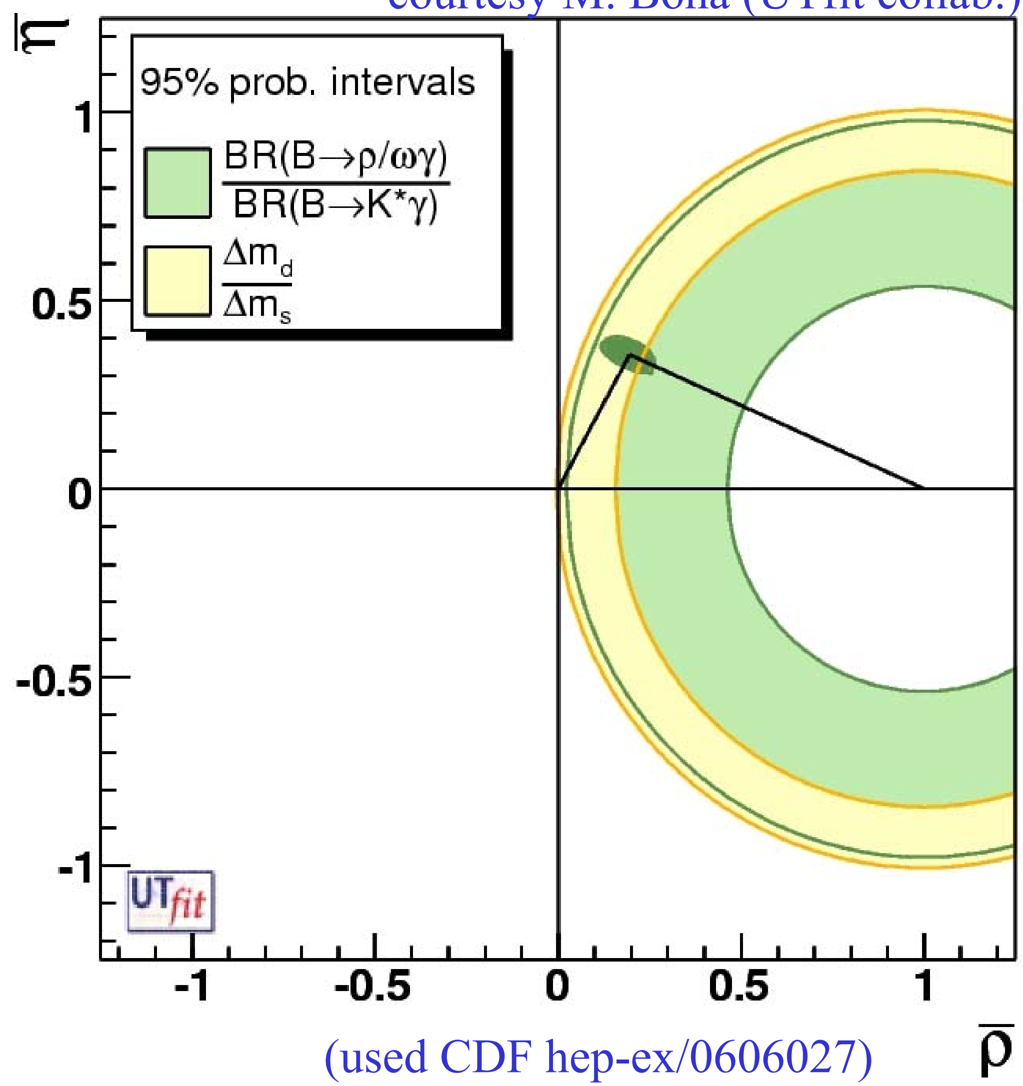
expt thy

CDF, hep-ex/0609040 (preliminary)

$$\left|\frac{V_{td}}{V_{ts}}\right| = 0.2060 \pm 0.0007^{+0.0081}_{-0.0060}$$

expt thy

courtesy M. Bona (UTfit collab.)



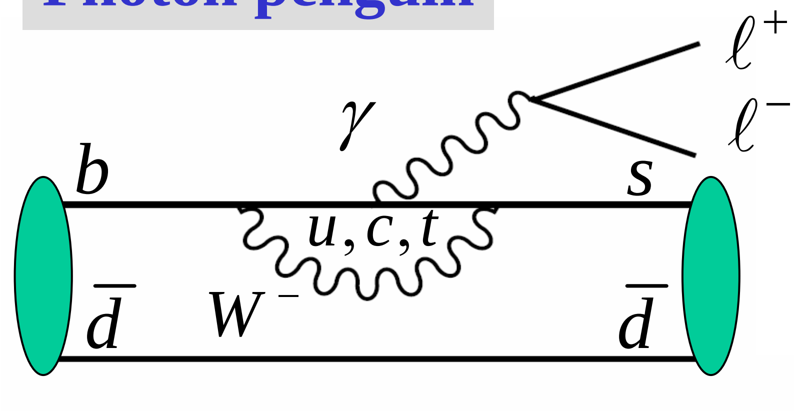
(used CDF hep-ex/0606027)

Consistent within errors!

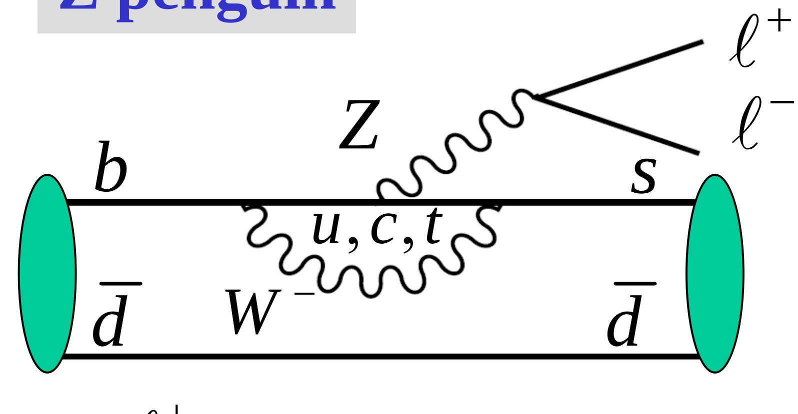
Theoretical uncertainties already or soon limiting both approaches.

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

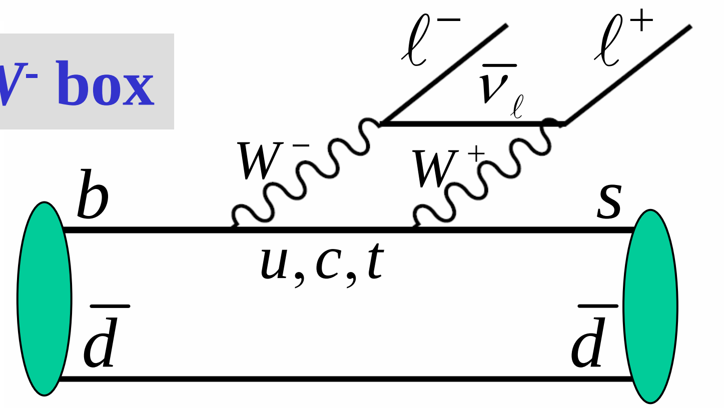
Photon penguin



Z penguin



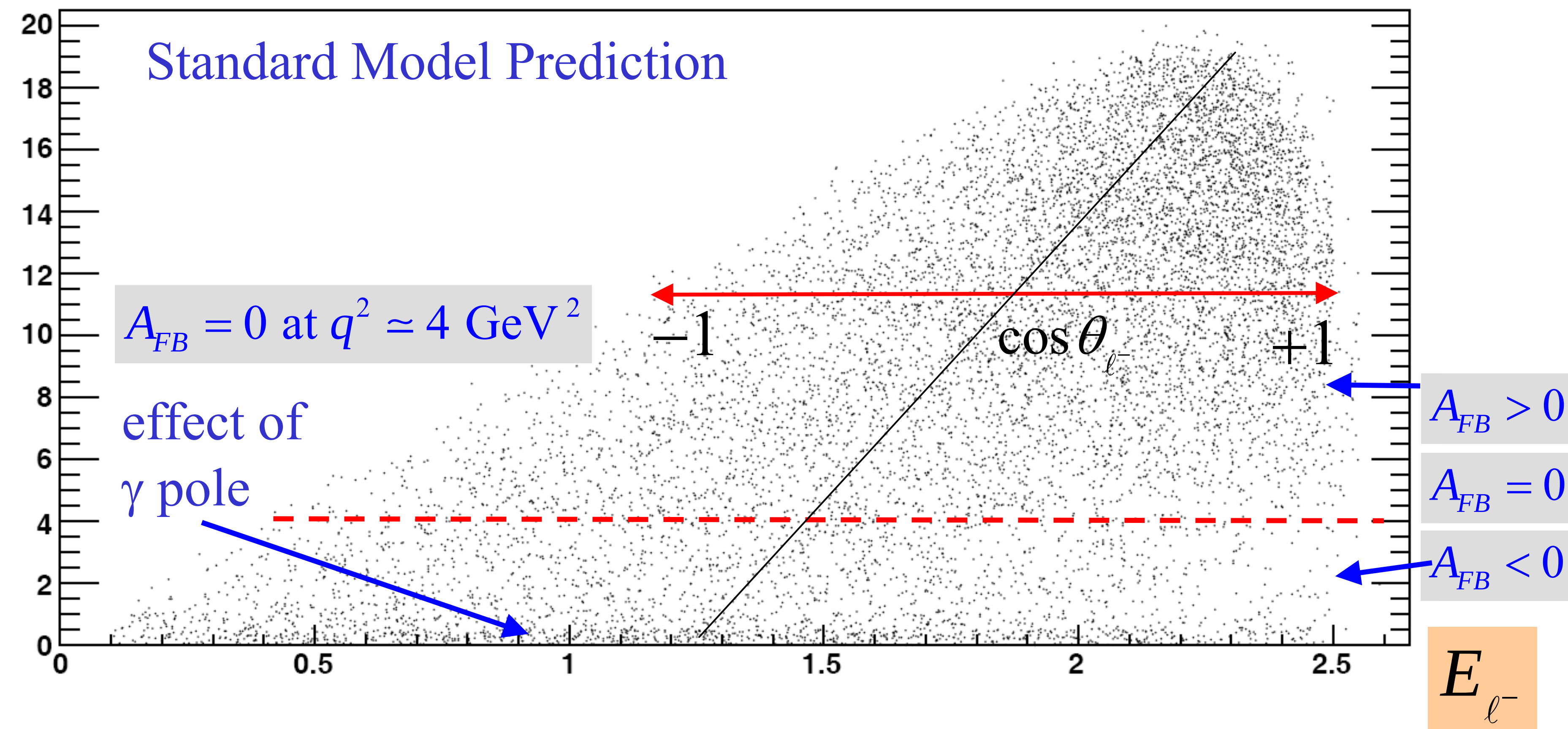
W^+W^- box



- 3-body decays → dependence of rate on kinematic variables 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).

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

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



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

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

$$M(B \to K^* \ell^+ \ell^-) = \frac{G_F \alpha_{EM}}{\sqrt{2}\pi} V_{ts}^* V_{tb} \left\{ \left[C_9^{eff} \langle K^* | \bar{s} \gamma_\mu P_L b | B \rangle - 2 \frac{m_b}{q^2} C_7^{eff} \langle K^* | \bar{s} i \sigma_{\mu\nu} q^\nu P_R b | B \rangle \right] \left(\bar{\ell} \gamma^\mu \ell \right) + C_{10} \langle K^* | \bar{s} \gamma_\mu P_L b | B \rangle \left(\bar{\ell} \gamma^\mu \gamma_5 \ell \right) \right\}$$

photon penguin dom. at v. low q^2 (C_7^{eff} term)

mix of Z-penguin, W^+W^- box (C_9^{eff} and C_{10} terms)

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)

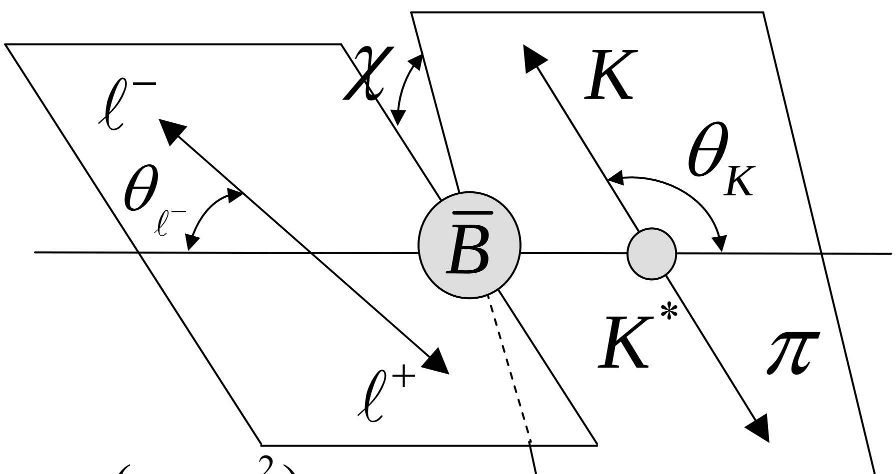
- Interference terms generate asymmetries in lepton angular distribution over most of q^2 range.
- C_i's can be affected by new physics; enters at same order as SM amp.

Form Factors and Observables

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

- 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 uncertainties → 35% uncertainty in rate predictions.



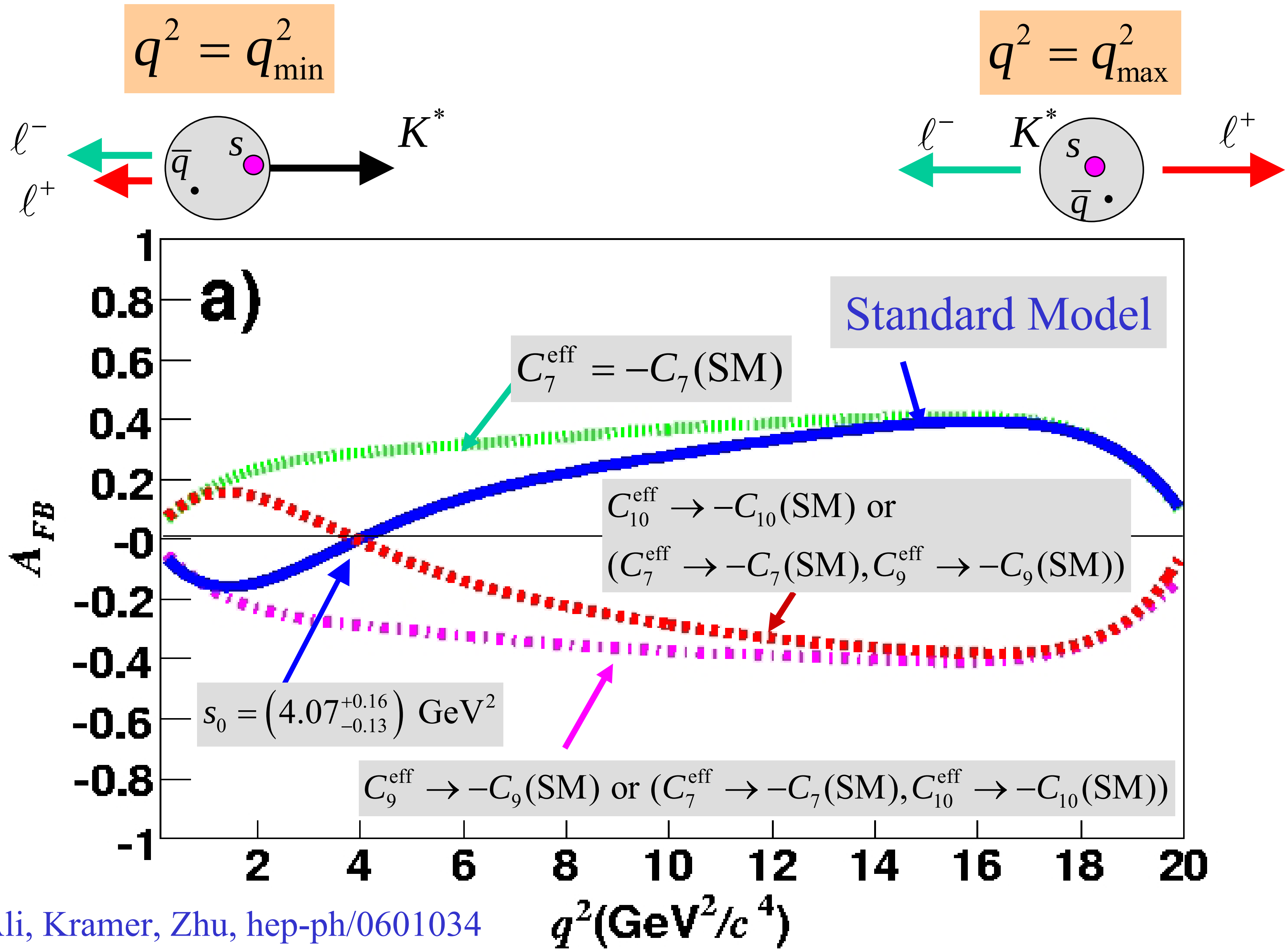
$(s \equiv q^2)$

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

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

$$\frac{dA_{FB}}{ds} \propto \underbrace{-C_{10}\left\{\mathrm{Re}\left(C_9^{eff}\right)VA_1}_{\text{large } s} + \frac{m_b m_B}{s} C_7^{eff}\left[VT_2\left(1 - \frac{m_{K^*}}{m_B}\right) + A_1 T_1\left(1 + \frac{m_{K^*}}{m_B}\right)\right]\right\}$$

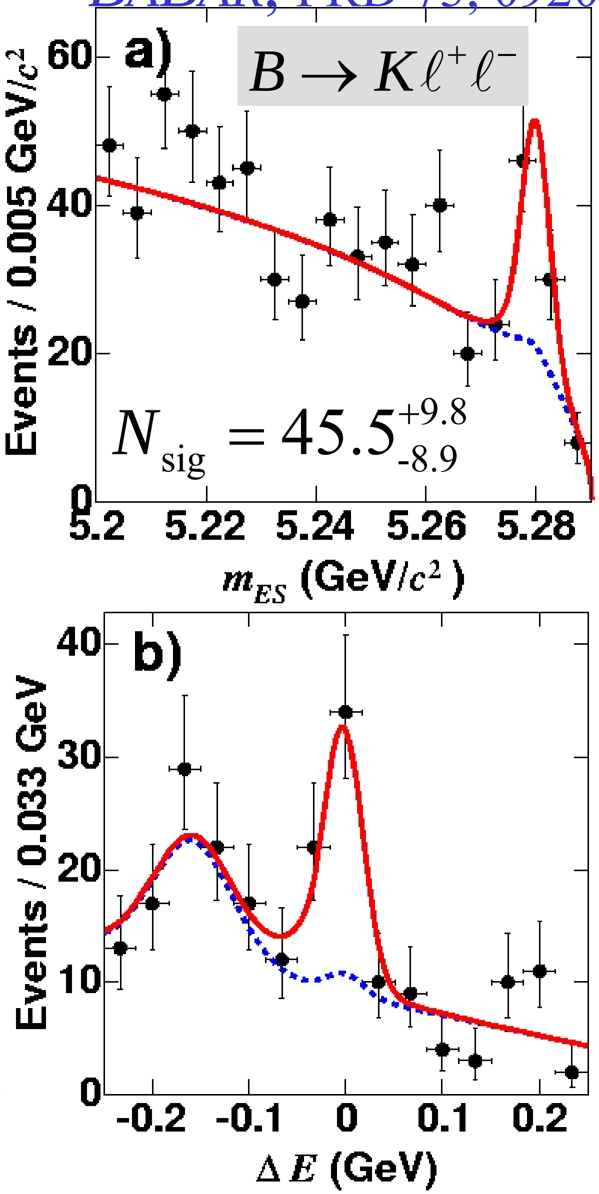
Predictions for A_{FB} in $B \rightarrow K^* l^+ l^-$: SM and beyond

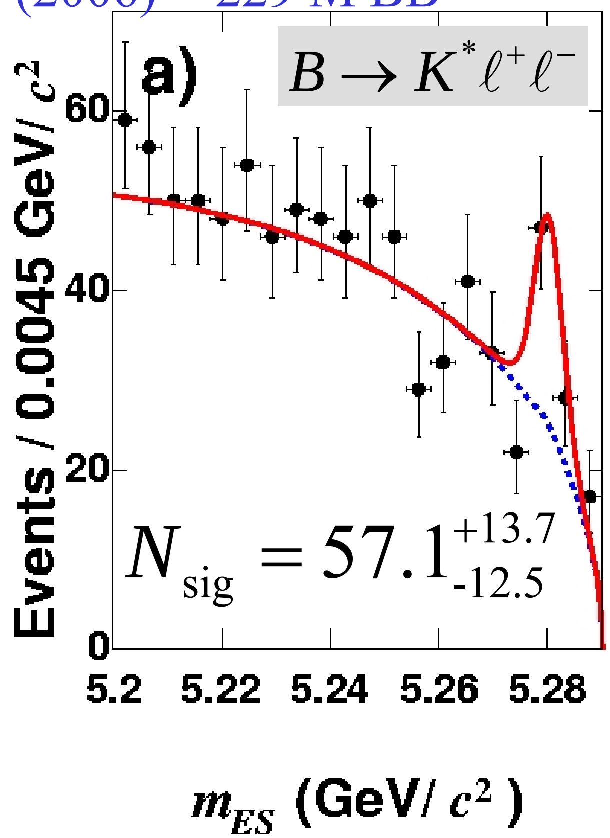


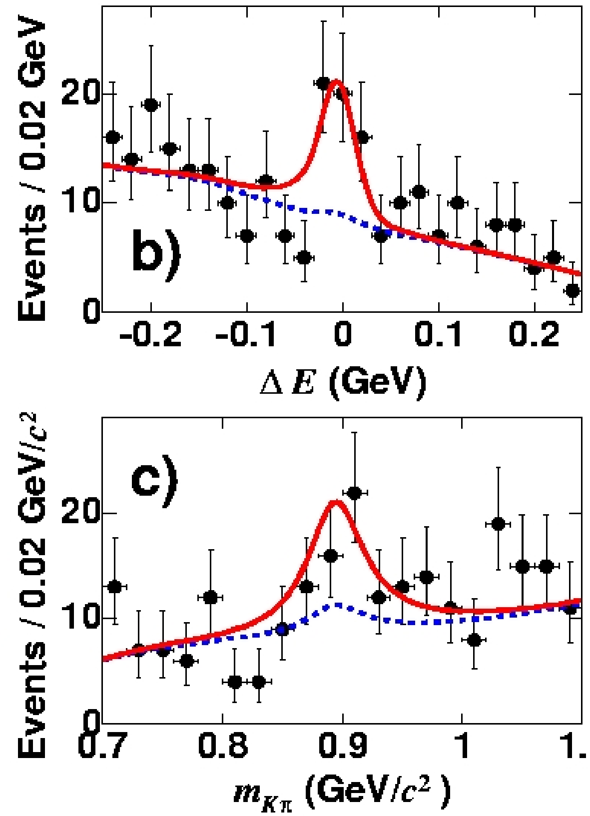
s_0: Ali, Kramer, Zhu, hep-ph/0601034

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

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







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

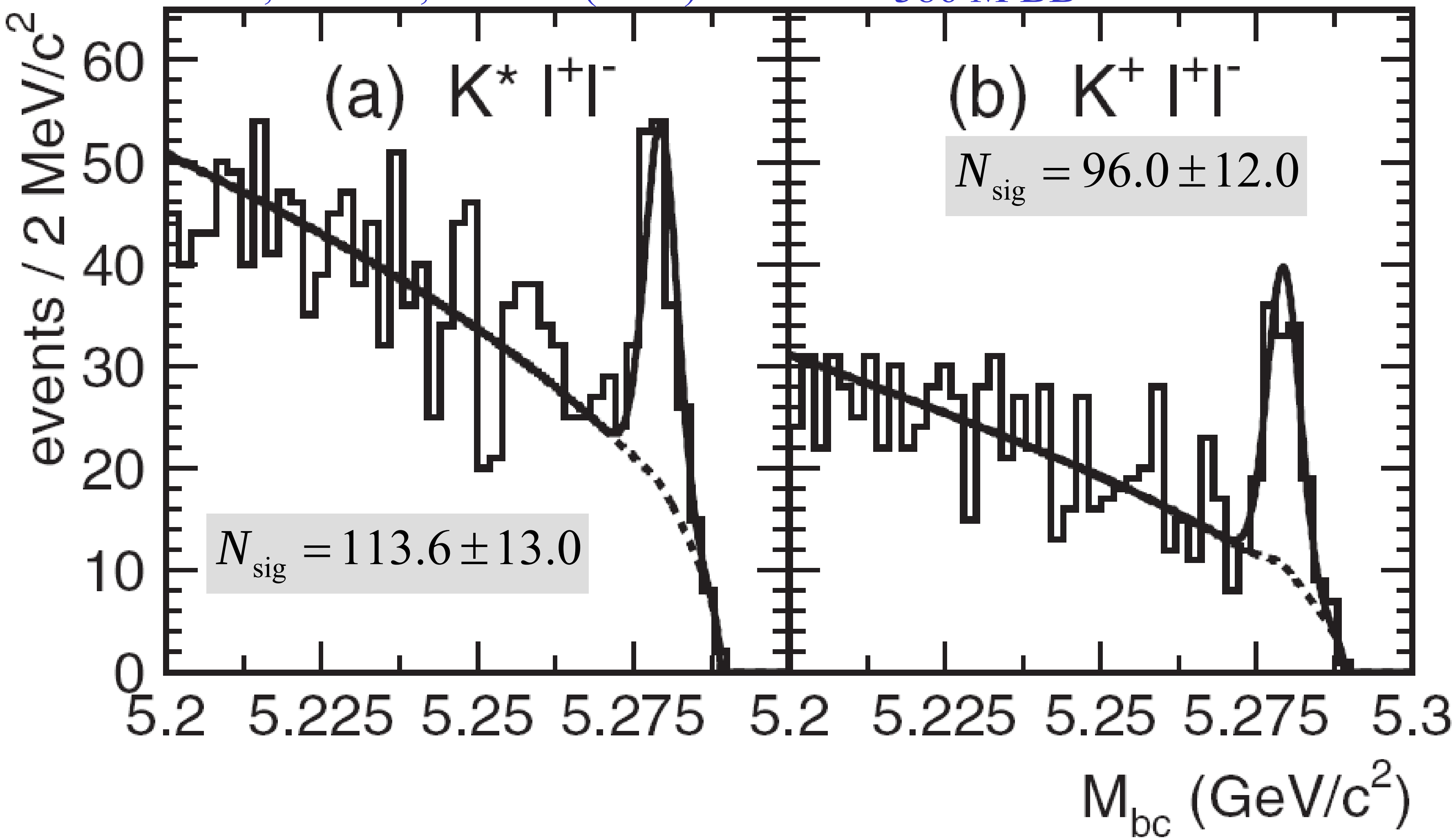
(6.6 σ, rarest observed B decay)

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

(5.7 σ)

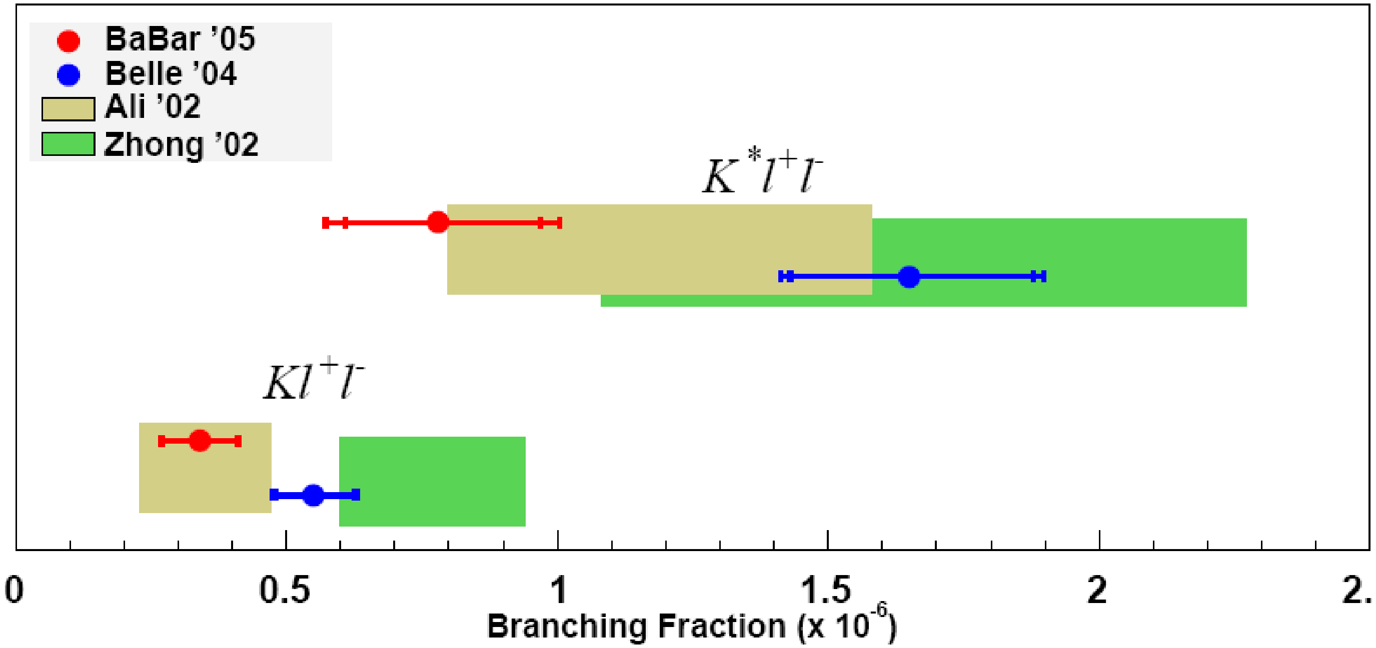
$B \to K^{(*)} l^+ l^-$ Signals from Belle

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}) [208 fb^{-1}] PRD 73, 092001 (2006)	Belle (10^{-6}) [253 fb^{-1}] preliminary, hep-ex/0410006
$B \to K \ell^+ \ell^-$	$0.34^{+0.07}_{-0.07} \pm 0.02$	$0.550^{+0.075}_{-0.070} \pm 0.027$
$B \to K^* \ell^+ \ell^-$	$0.78^{+0.19}_{-0.17} \pm 0.11$	$1.65^{+0.23}_{-0.22} \pm 0.11$

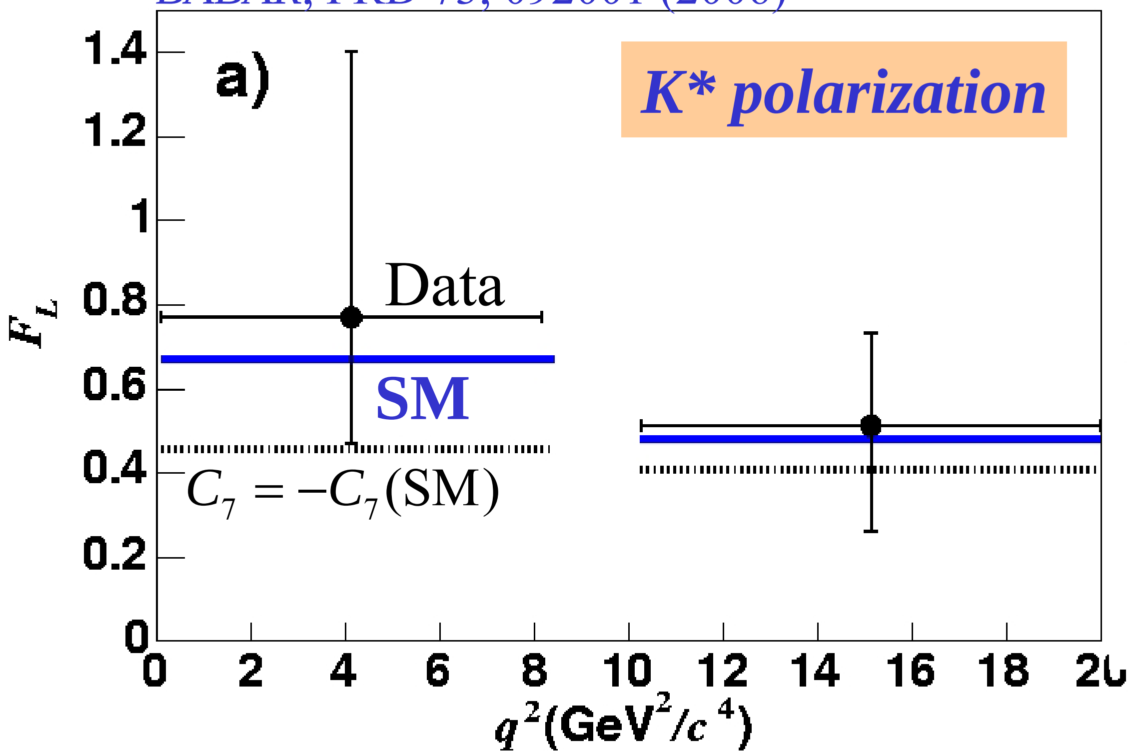
Inclusive: $B(B \to X_s \ell^+ \ell^-) = \left(4.50^{+1.03}_{-1.01}\right) \times 10^{-6}$ HFAG avg.

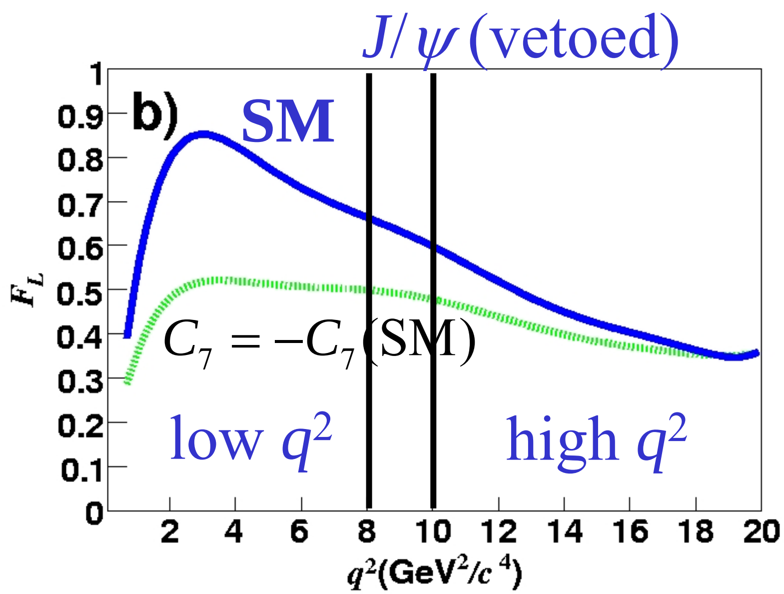
$B \to K^* l^+ l^-$: BABAR results on K^* polarization

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

apply in 2 bins of q^2

BABAR, PRD 73, 092001 (2006)





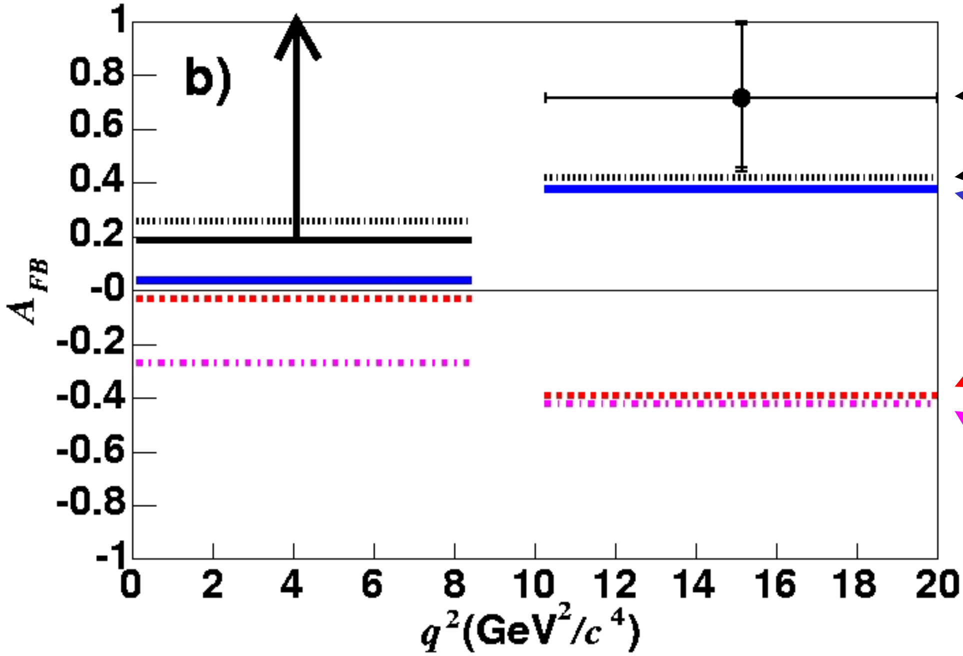
Polarization consistent with SM, but doesn't discriminate against new physics scenarios with current data sample.

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

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

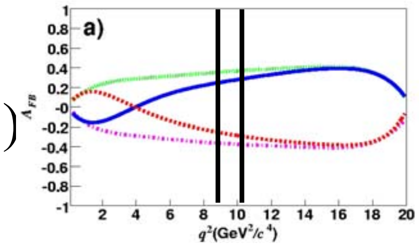
use in 2 bins of q^2



Data

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

SM



$C_{10}^{\text{eff}} \to -C_{10}(\text{SM})$ or $(C_7^{\text{eff}} \to -C_7(\text{SM}), C_9^{\text{eff}} \to -C_9(\text{SM}))$

$C_9^{\text{eff}} \to -C_9(\text{SM})$ or $(C_7^{\text{eff}} \to -C_7(\text{SM}), C_{10}^{\text{eff}} \to -C_{10}(\text{SM}))$

excluded at 3.6σ!

Any $A_{FB}<0$ excluded at $>2.7\sigma$

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	$0.72^{+0.28}_{-0.26} \pm 0.08$	$0.51^{+0.22}_{-0.25} \pm 0.08$

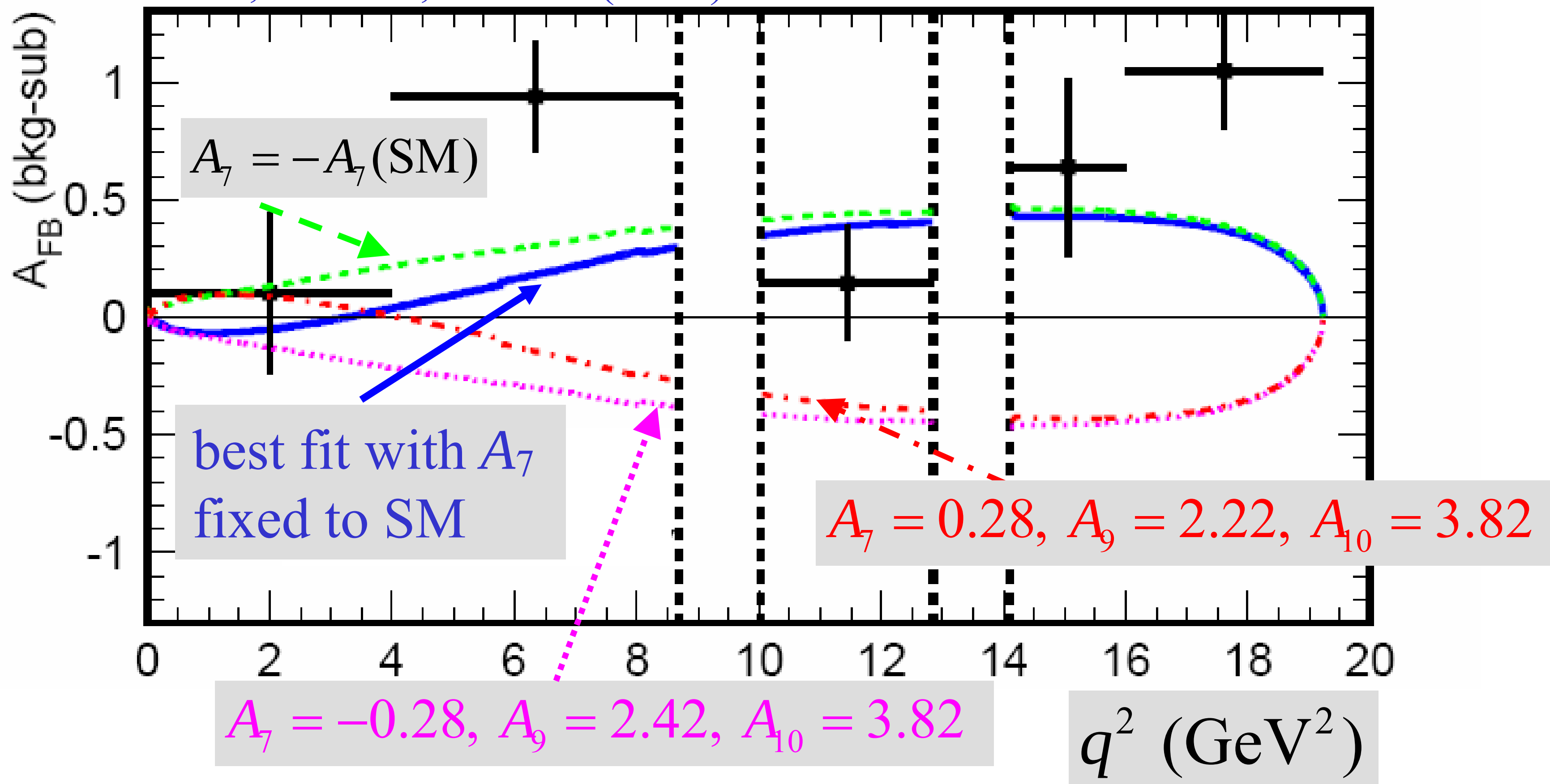
$A_{FB}\left(B \to K\ell^+\ell^-\right) = 0.15^{+0.21}_{-0.23} \pm 0.08 \quad \left(q^2 > 0.1\ \text{GeV}^2\right)$

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

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

Belle, PRL 96, 251801 (2006)

$A_i \simeq C_i$



for reference:

SM: $A_7 = -0.33,\ A_9 = 4.07,\ A_{10} = -4.21$

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

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

$B \to K^* l^+ l^-$: Belle results on Wilson coefficients

Fit q^2 and $\cos\theta_l$ for $A_i \simeq C_i$

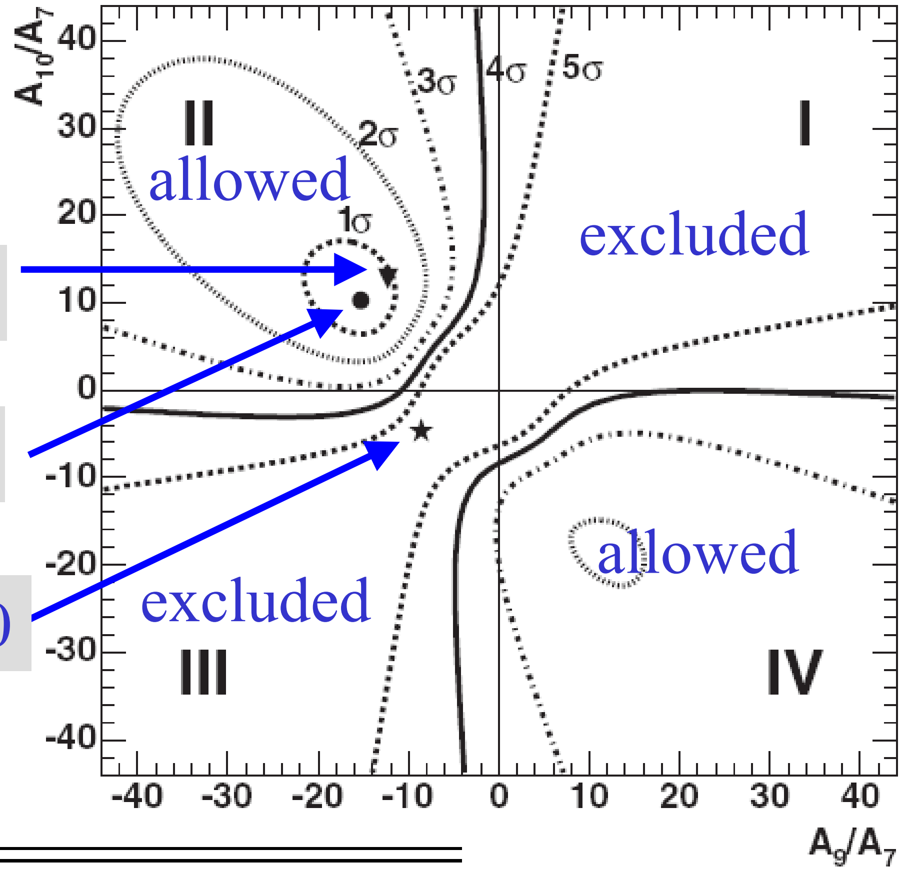
(A_i are real and constant; q^2 dep. corrections fixed to theory)

- 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 I, III excluded at 98.2% C.L.

SM

fit

$A_{10}>0$



	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	$10.3^{+5.2}_{-3.5} \pm 1.8$	$11.1^{+6.0}_{-3.9} \pm 2.4$

need $A_9A_{10}<0$ to get $A_{FB}>0$ in upper q^2 region

$$-1400 < \left(A_9 A_{10} / A_7^2\right) < -26.4 \quad 95\% \text{ C.L.}$$

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 fraction & photon energy spectrum. Also predictions for CP and I-spin violation.
- Spectrum is insensitive to new physics but is sensitive to m_b and Fermi motion of *b*-quark ("shape function").

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

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

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

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

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

M. Misiak and M. Steinhauser, hep-ph/0609241 NNLO

$$B(\bar{B} \to X_s \gamma) = (3.15 \pm 0.23) \times 10^{-4}$$

New!

all for $E_\gamma > 1.6$ GeV

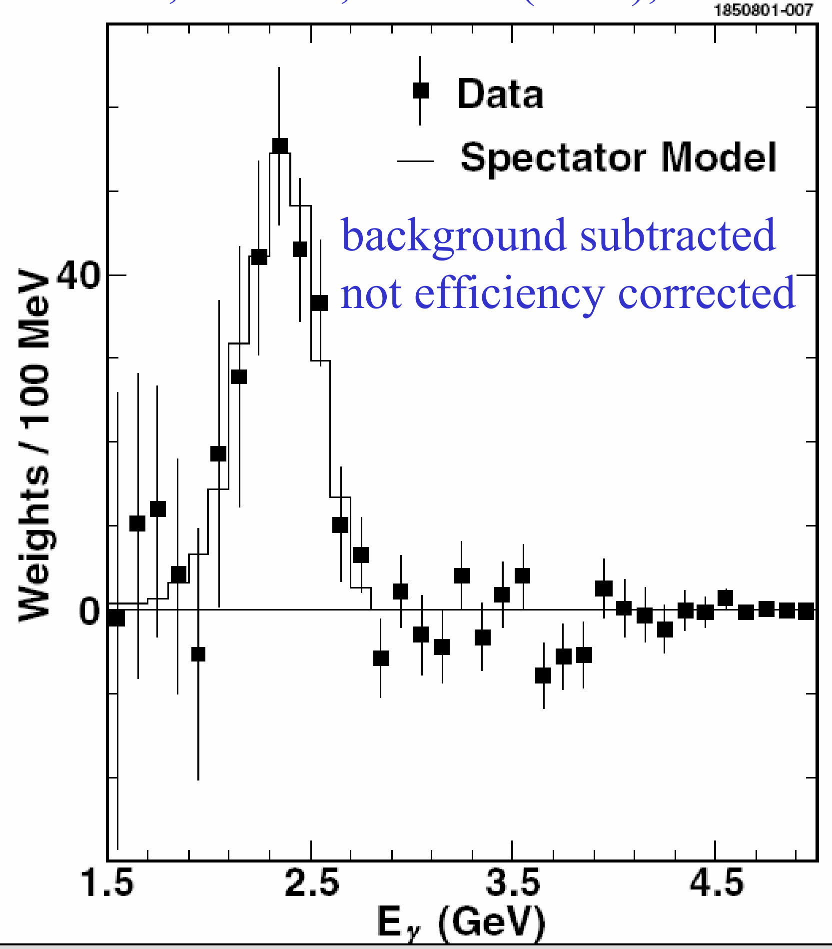
Challenges of measuring inclusive $B \rightarrow X_s \gamma$

- Weak experimental signature: single high-energy photon + event-shape cuts. Huge background from π^0's and η's!
- 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.

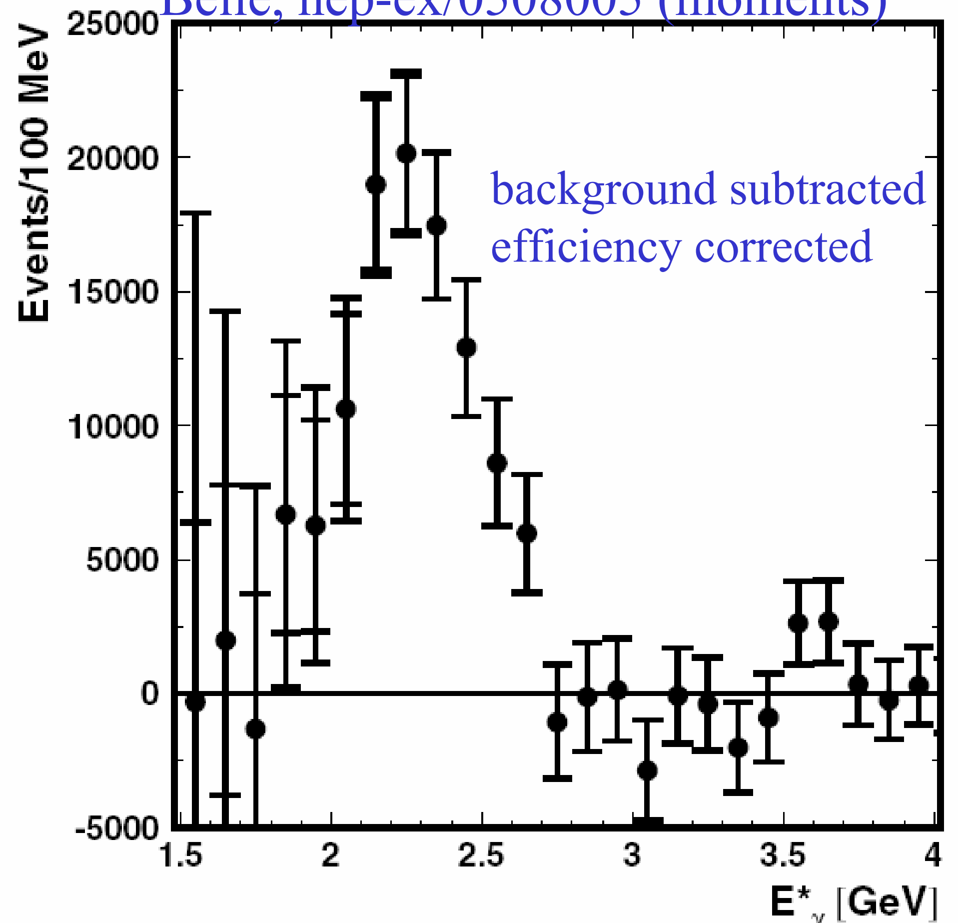
Method	Advantages	Disadvantages
Fully inclusive **Don't reconstruct X_s**	**Closest correspondence to inclusive $\mathcal{B}(B \rightarrow X_s \gamma)$.**	**Weak kinematic constraints $\rightarrow$ larger background** **E_γ known in Υ(4S) frame, not B frame (smearing).** **$\sigma(E_\gamma)$=50 MeV**
Sum-of-exclusive ***e.g., BABAR:* 38 modes!** $K+(\leq 4\pi)$, $K+\eta+(\leq 2\pi),\ 3K+(\leq 1\pi)$	**Less background due to additional kinematic constraints (m_{ES}, ΔE).** **Better E_γ resolution.**	**More model dependence due to finite set of explicitly reconstructed $B \rightarrow X_s \gamma$ decays.**

Fully inclusive $B \to X_s\, \gamma$

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



Belle, PRL 93, 061803 (2004), 140 fb^{-1}
Belle, hep-ex/0508005 (moments)



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

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

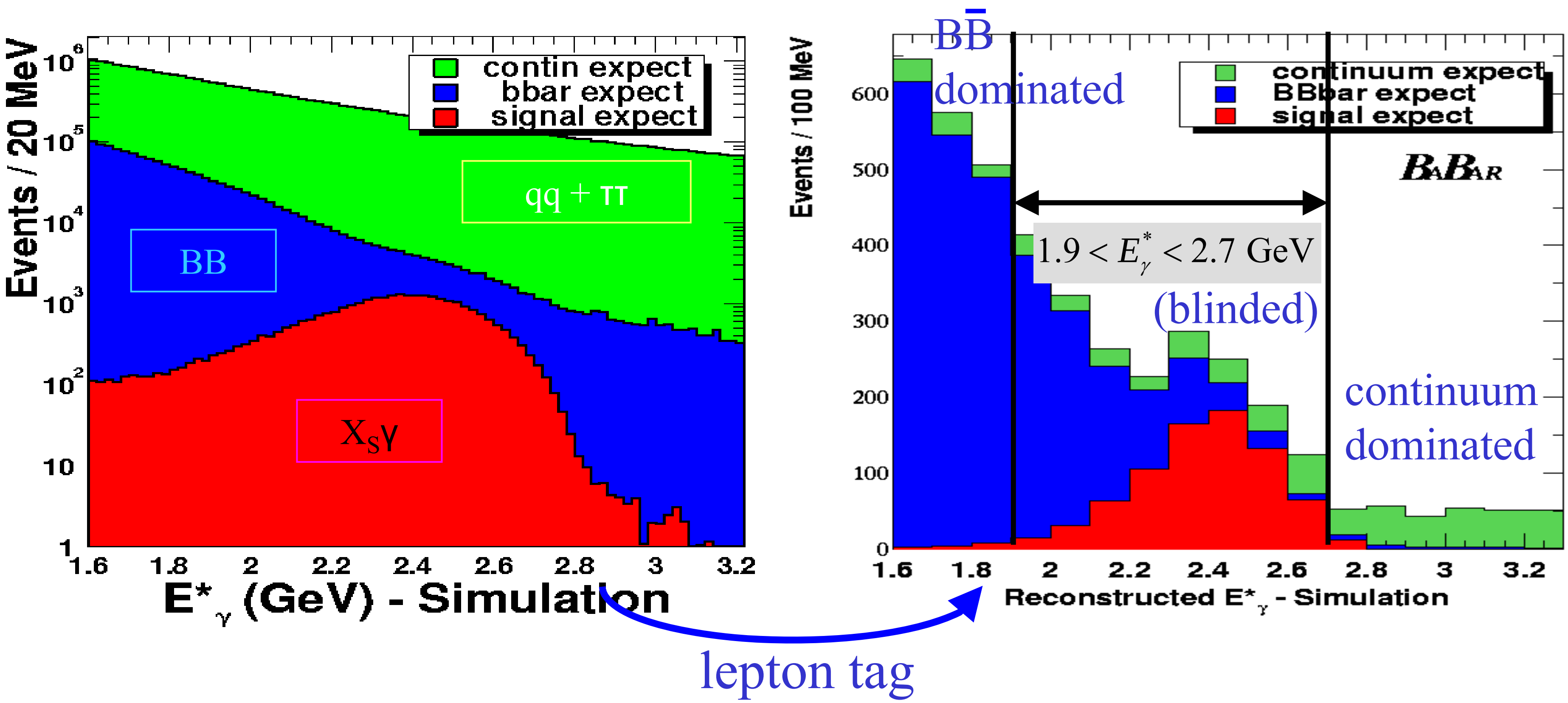
$$BF = (3.55 \pm 0.32^{+0.30+0.11}_{-0.31-0.07}) \times 10^{-4}$$

Measure for E_γ>1.8 GeV; extrap. to full

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

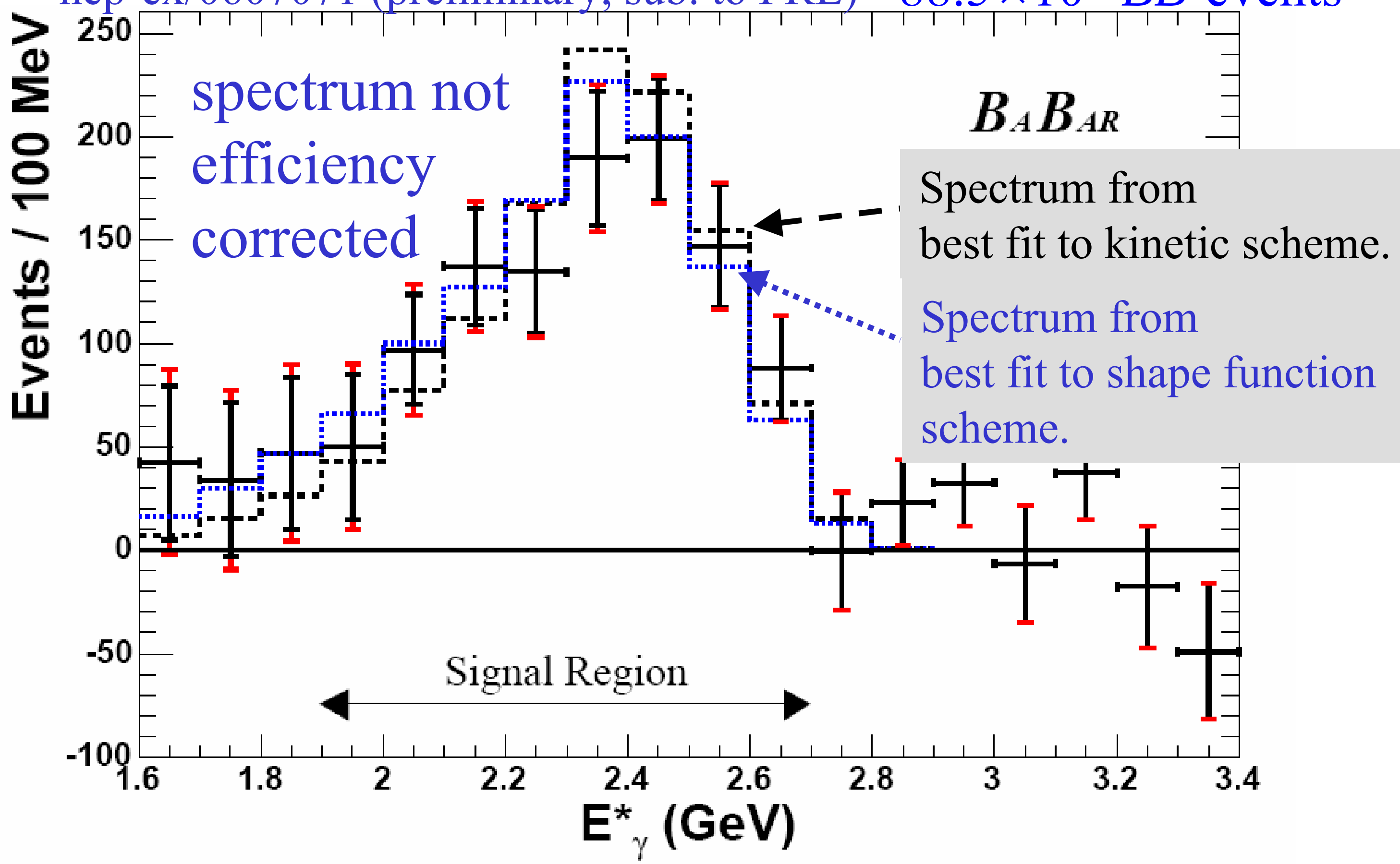
hep-ex/0607071 (preliminary, submitted to PRL)

Suppress large continuum background using
- Event-shape cuts (continuum has jet topology)
- Lepton tag: high energy lepton from <u>2nd B in event</u> ($B \rightarrow X_c\, l\, \nu$)



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

hep-ex/0607071 (preliminary, sub. to PRL) $88.5\times10^{6}\ B\bar{B}$ events



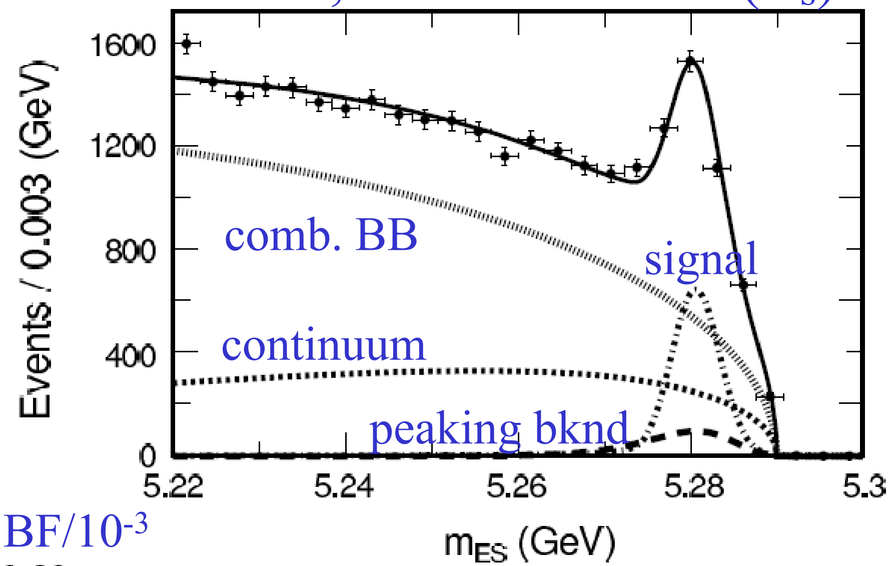
$B(B\rightarrow X_s\gamma) = (3.67 \pm 0.29 \pm 0.34 \pm 0.29)\times10^{-4}$ (stat, sys, model) $E_\gamma > 1.9$ GeV (measured)

$B(B\rightarrow X_s\gamma) = (3.94 \pm 0.31 \pm 0.36 \pm 0.21)\times10^{-4}$ $E_\gamma > 1.6$ GeV (extrapolated, kinetic scheme)

$A(CP) = -0.110 \pm 0.115 \pm 0.017$

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

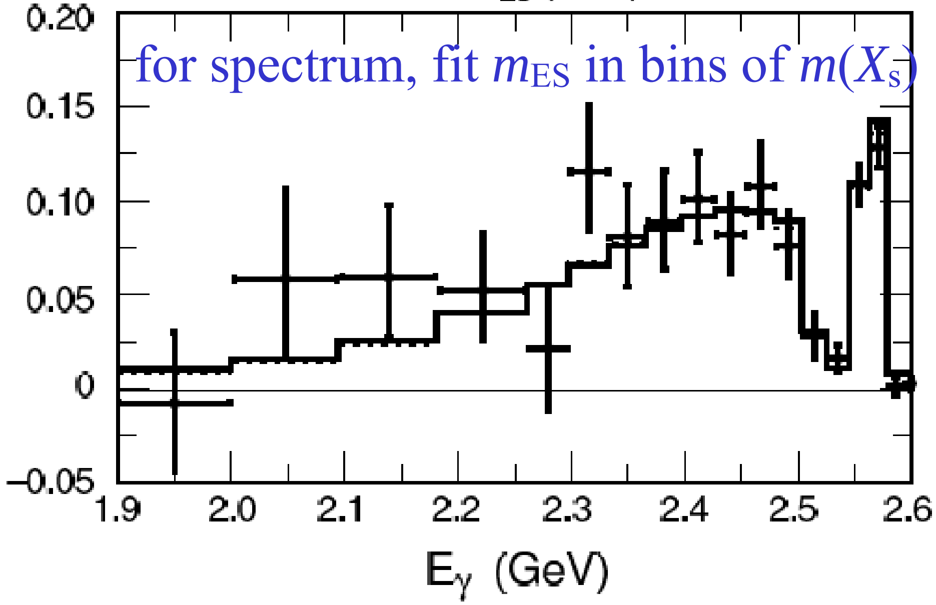
for BF, sum over all $m(X_s)$:



BABAR, PRD 72, 052004 (2005) 88.5M $B\bar{B}$

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

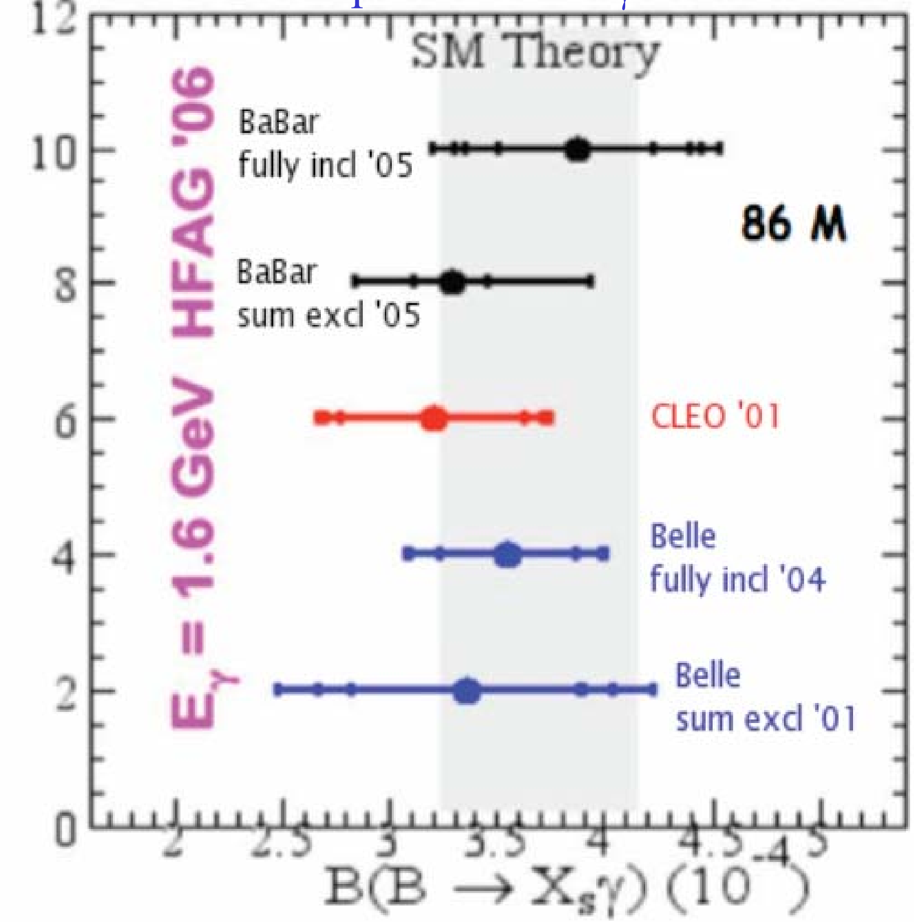


E_γ Moments	Value (GeV or GeV^2)
$\langle E_\gamma \rangle$	$2.321 \pm 0.038^{+0.017}_{-0.038}$
$\langle E_\gamma^2 \rangle - \langle E_\gamma \rangle^2$	$0.0253 \pm 0.0101^{+0.0041}_{-0.0028}$

- E_γ (min) = 1.897 GeV

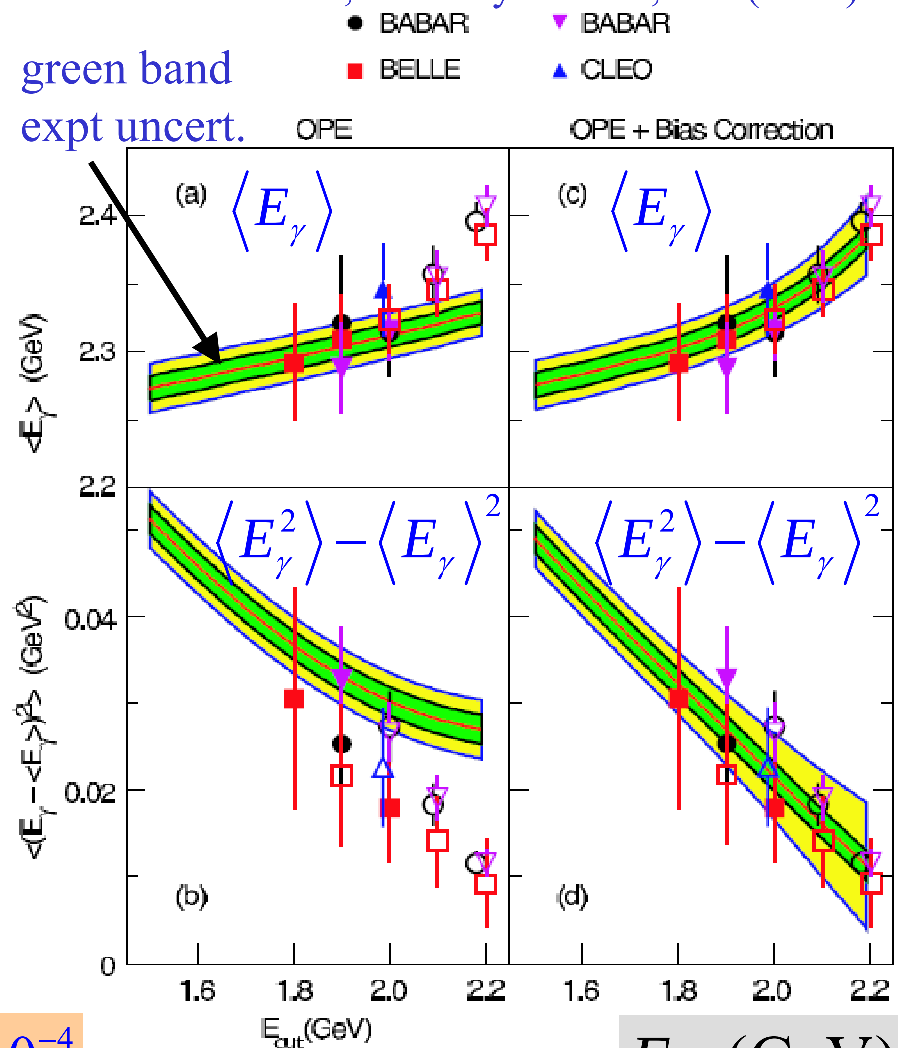
Summary: $B \to X_s\, \gamma$ Branching Fraction & Moments

HFAG 2006: common corrections to for BFs for extrapolations to E_γ=1.6 GeV.



Buchmüller and Flächer, PRD 73, 073008 (2006)
Gambino and Uraltsev, Eur. Phys. J C34, 181 (2004)

green band expt uncert.



$E_{\text{cut}}\,(\text{GeV})$

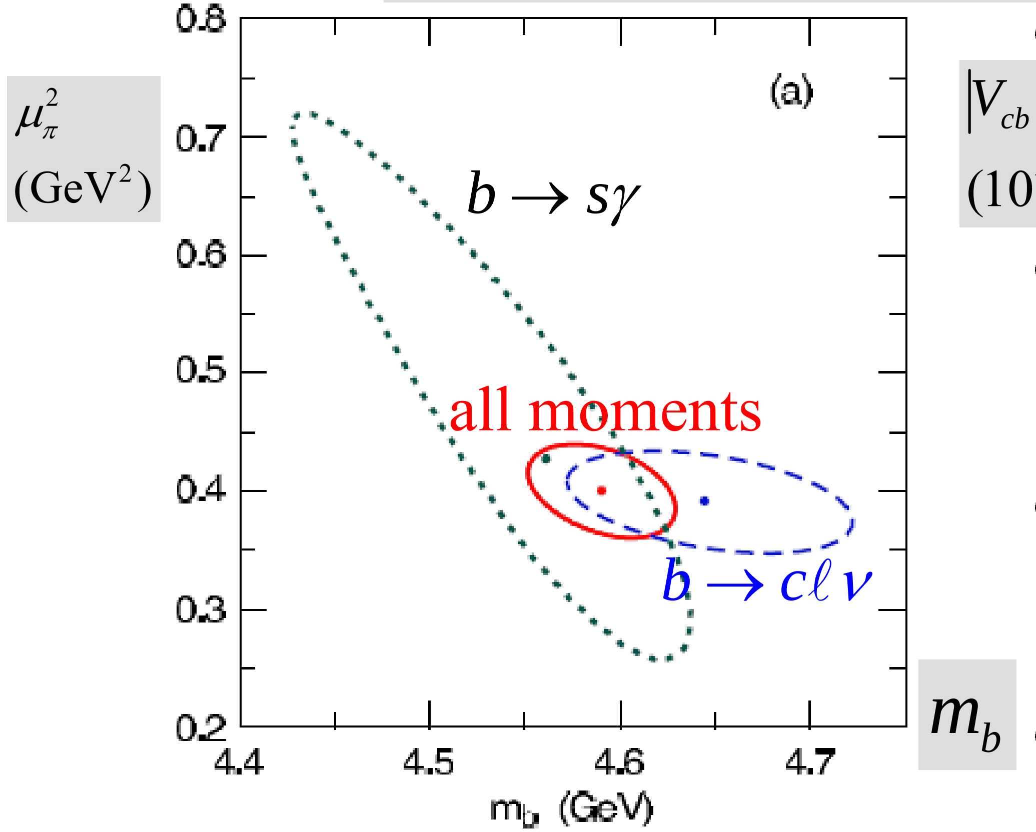
average

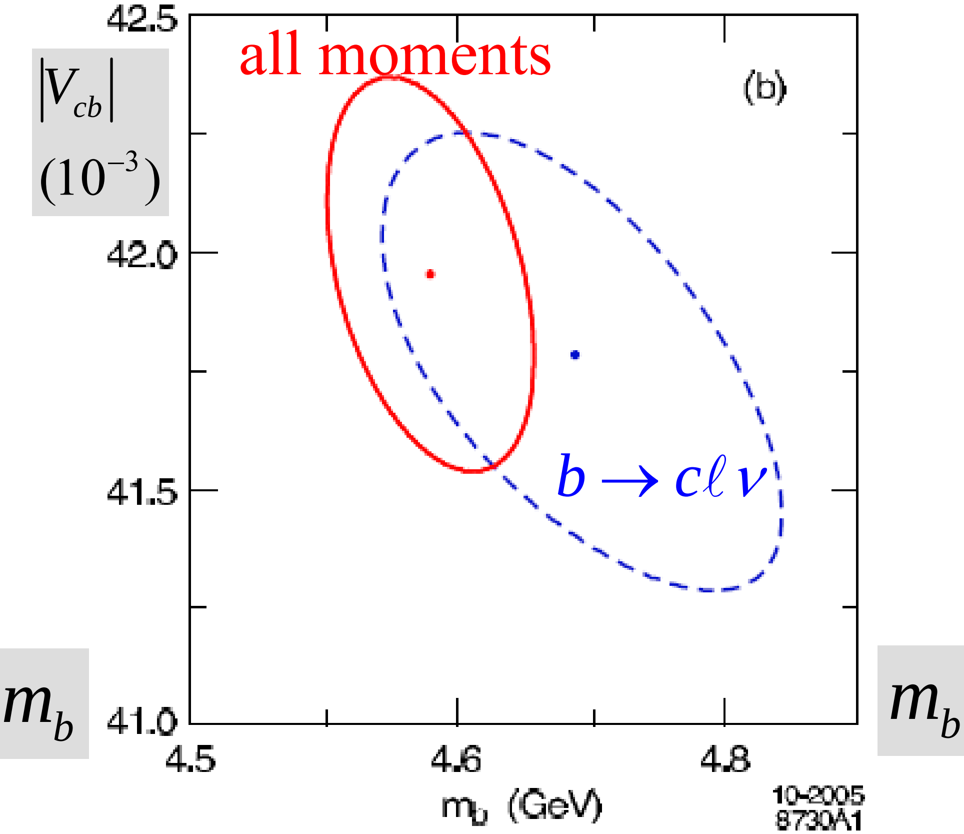
$$B(B \to X_s\gamma) = (3.55 \pm 0.24^{+0.09}_{-0.10} \pm 0.03) \times 10^{-4}$$

stat+sys shape fcn b→dγ frac

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

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





kinetic mass scheme

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

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

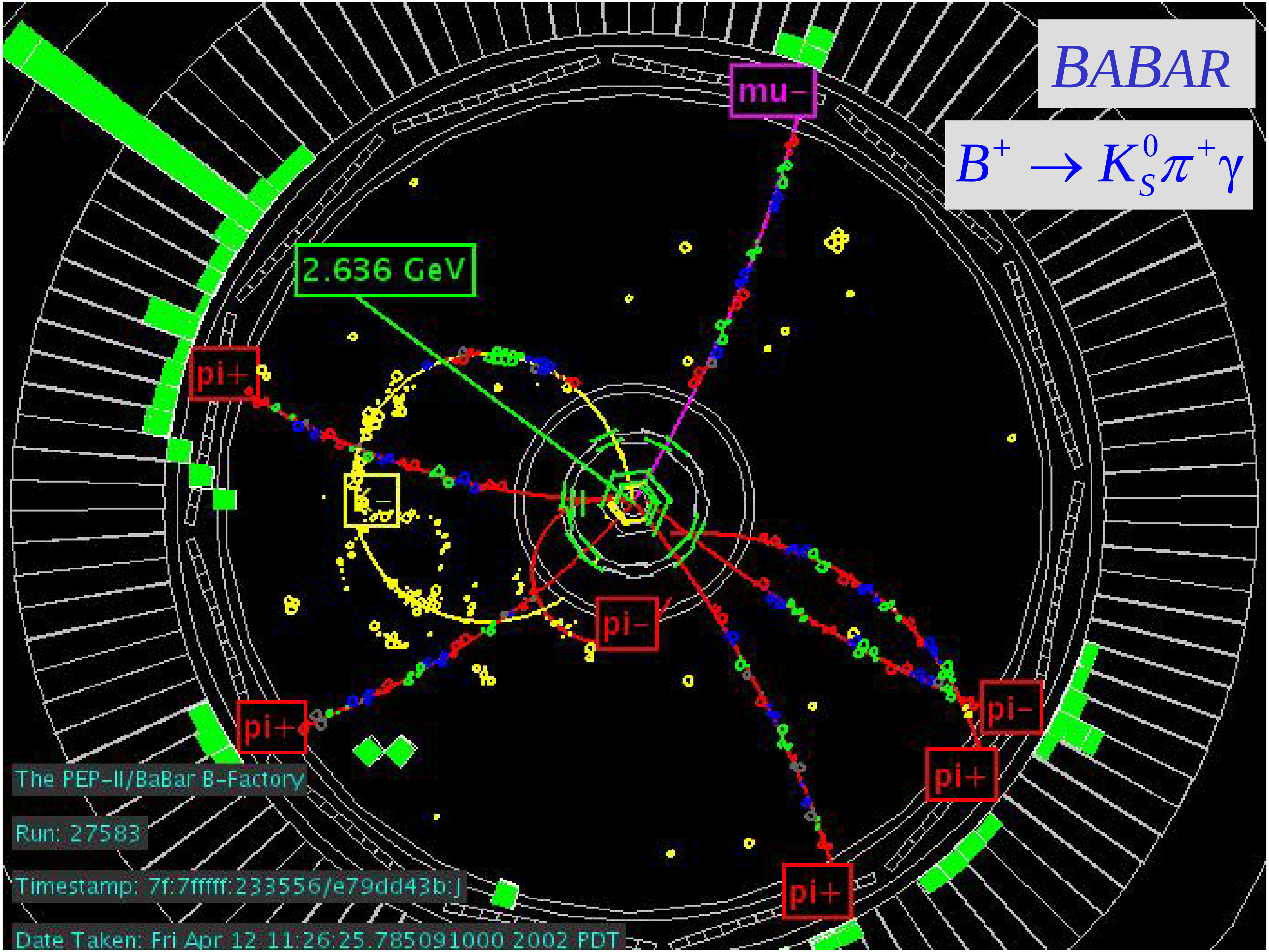
$|V_{cb}| = (41.96 \pm 0.23_{\text{exp}} \pm 0.35_{\text{HQE}} \pm 0.59_{\Gamma_{sl}}) \times 10^{-3}$

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 soon to be 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. 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 is to achieve 5% uncertainty on branching fraction.
- We will study radiative/EW penguins for many years to come at BaBar, Belle, and LHC-b!


BABAR
$B^+ \rightarrow K_S^0 \pi^+ \gamma$
mu-
2.636 GeV
pi+
K-
pi-
pi+
pi-
pi+
pi+
The PEP-II/BaBar B-Factory
Run: 27583
Timestamp: 7f:7fffff:233556/e79dd43b:J
Date Taken: Fri Apr 12 11:26:25.785091000 2002 PDT

Backup slides

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

Belle, PRL 96, 221601 (2006).

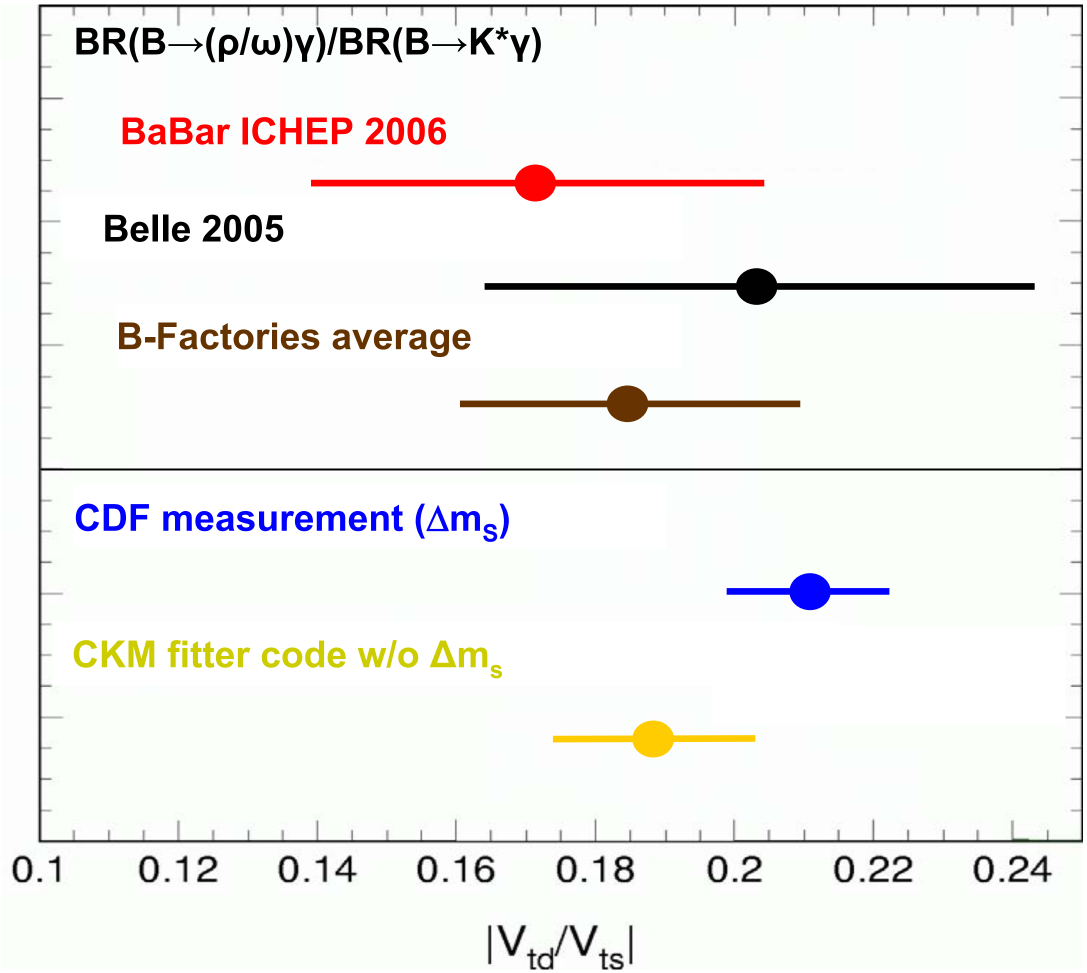
$$\left|\frac{V_{td}}{V_{ts}}\right| = 0.199^{+0.026+0.018}_{-0.025-0.015}$$

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)

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

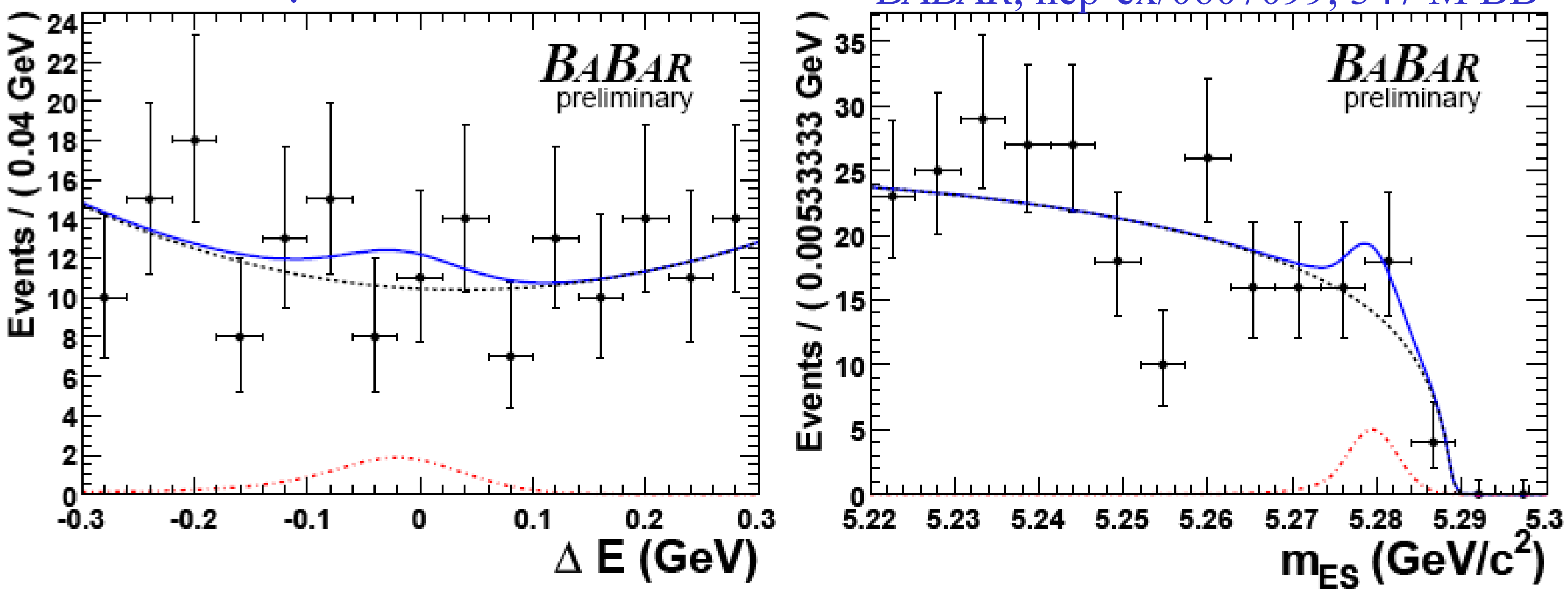


Consistent within errors.

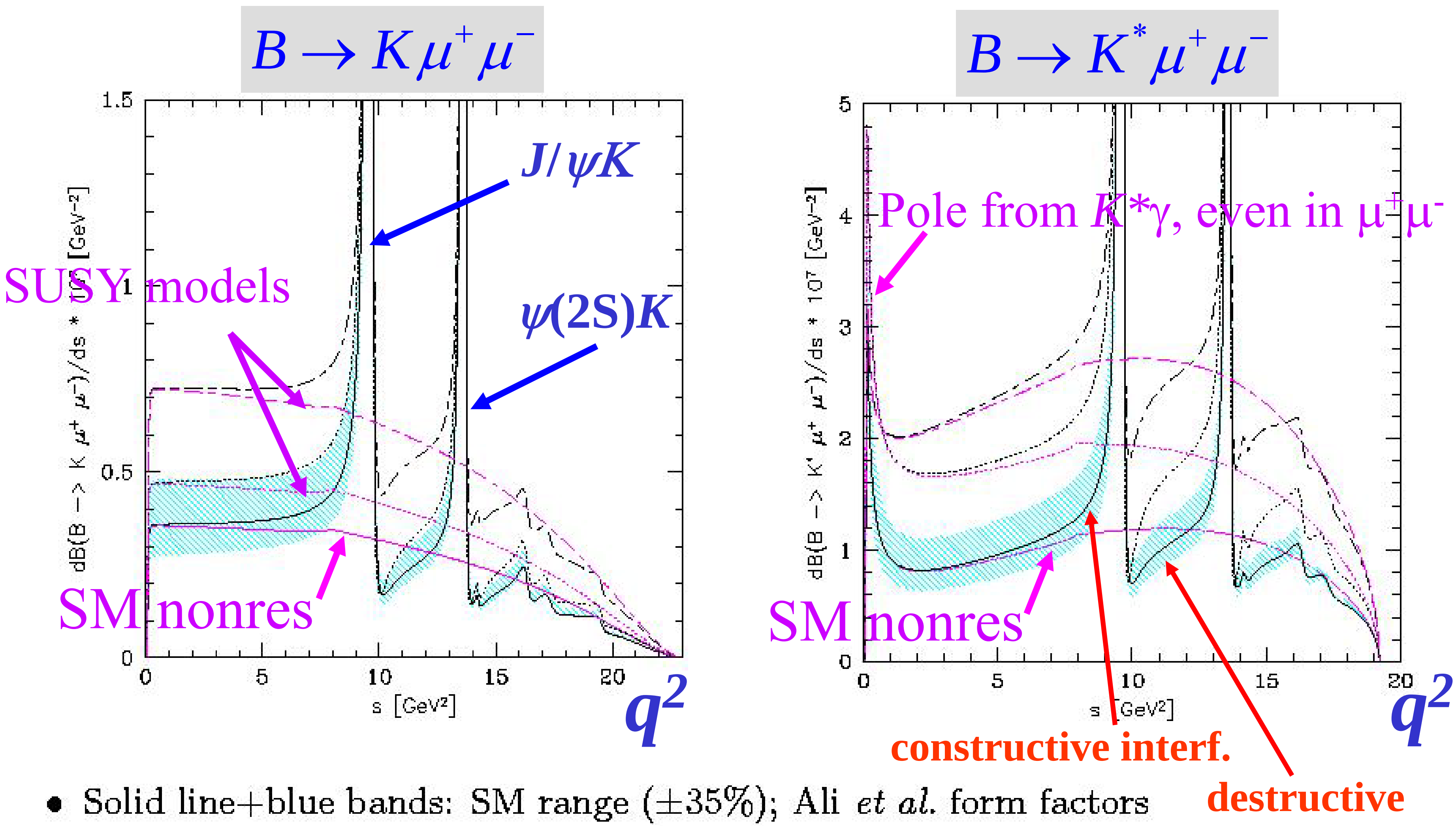
Theoretical uncertainties limiting both approaches.

$B^0 \to \omega\gamma$

BABAR, hep-ex/0607099, 347 M $B\bar{B}$



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

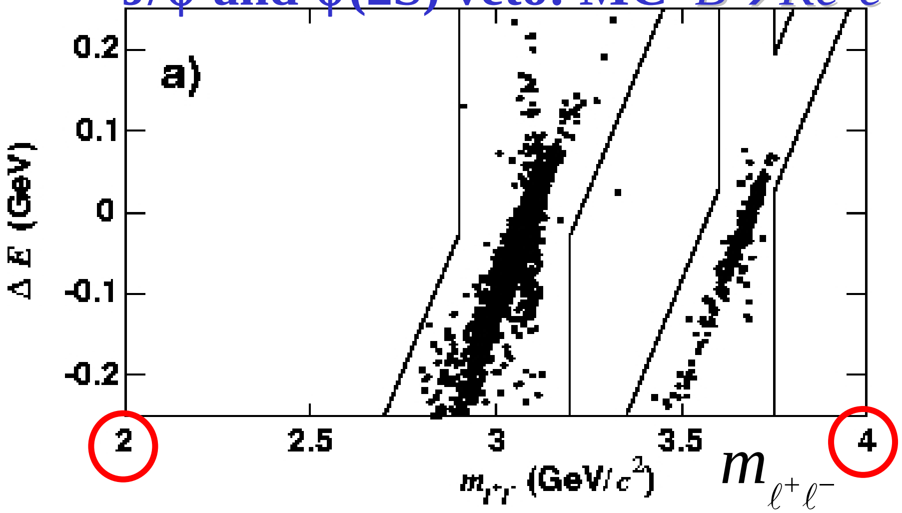


- Solid line+blue bands: SM range (±35%); Ali *et al.* form factors
- Dotted line: SUGRA model ($R_7 = -1.2$, $R_9 = 1.03$, $R_{10} = 1$; $R_i = C_i / C_i^{\rm SM}$)
- Long-short dashed line: SUSY model ($R_7 = -0.83$, $R_9 = 0.92$, $R_{10} = 1.61$)

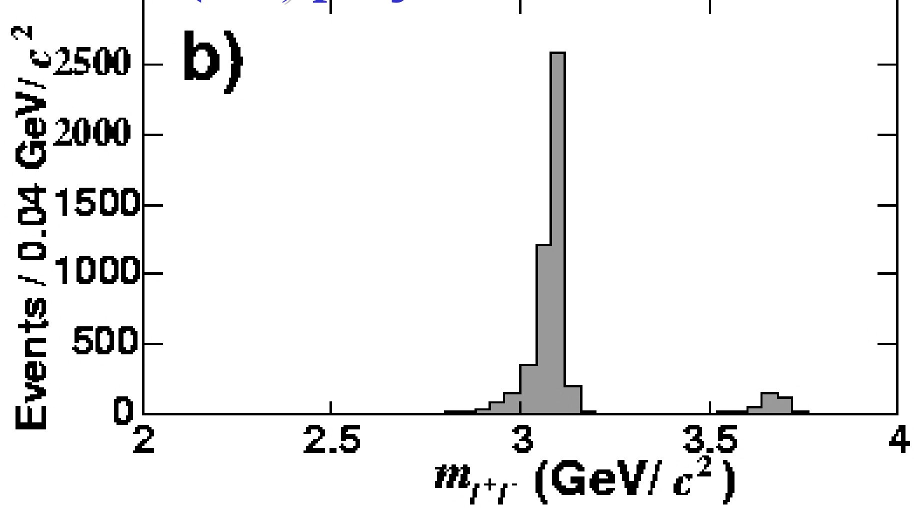
$B \to K l^+ l^-$ and $B \to K^* l^+ l^-$: the J/ψ veto

- 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: $B(B \to K^* \ell^+ \ell^-; 1 \le q^2 \le 7 \text{ GeV}^2) = (2.92^{+0.67}_{-0.61}) \times 10^{-7}$

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

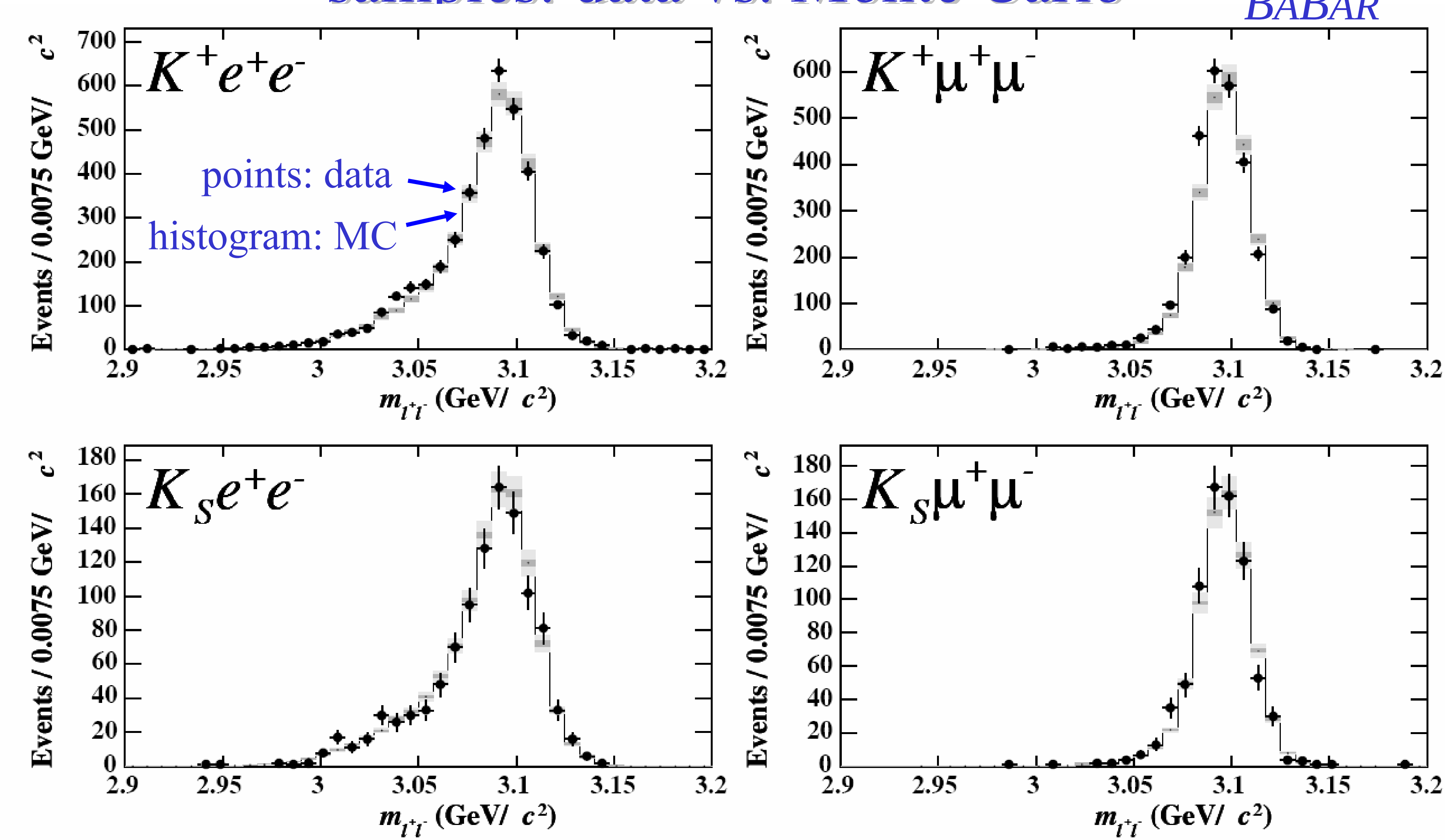


$m(e^+e^-)$ projection: MC $B \to K e^+ e^-$



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

BABAR

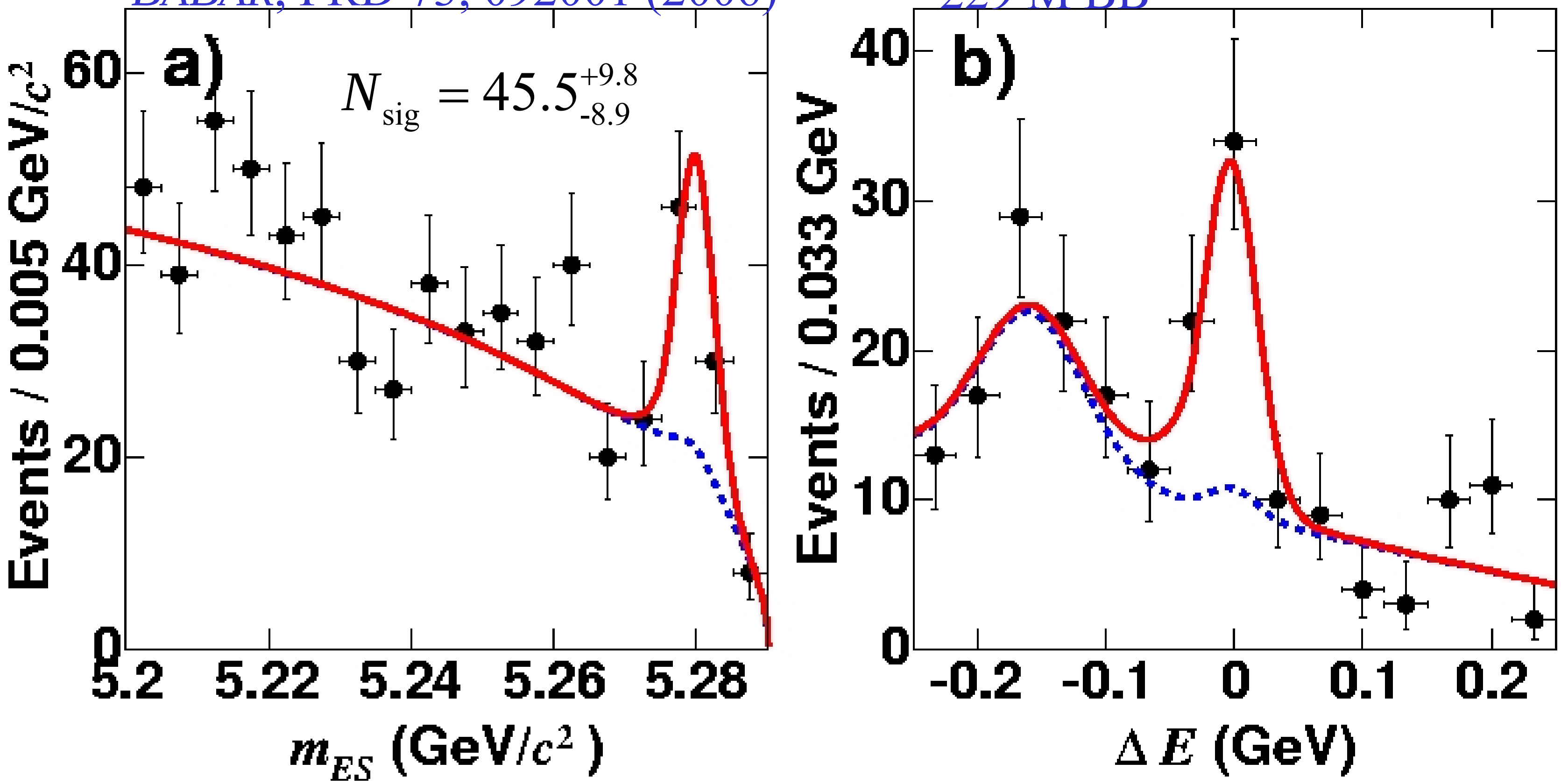


absolute normalization

Bremsstrahlung tails well described by MC.

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

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



- 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

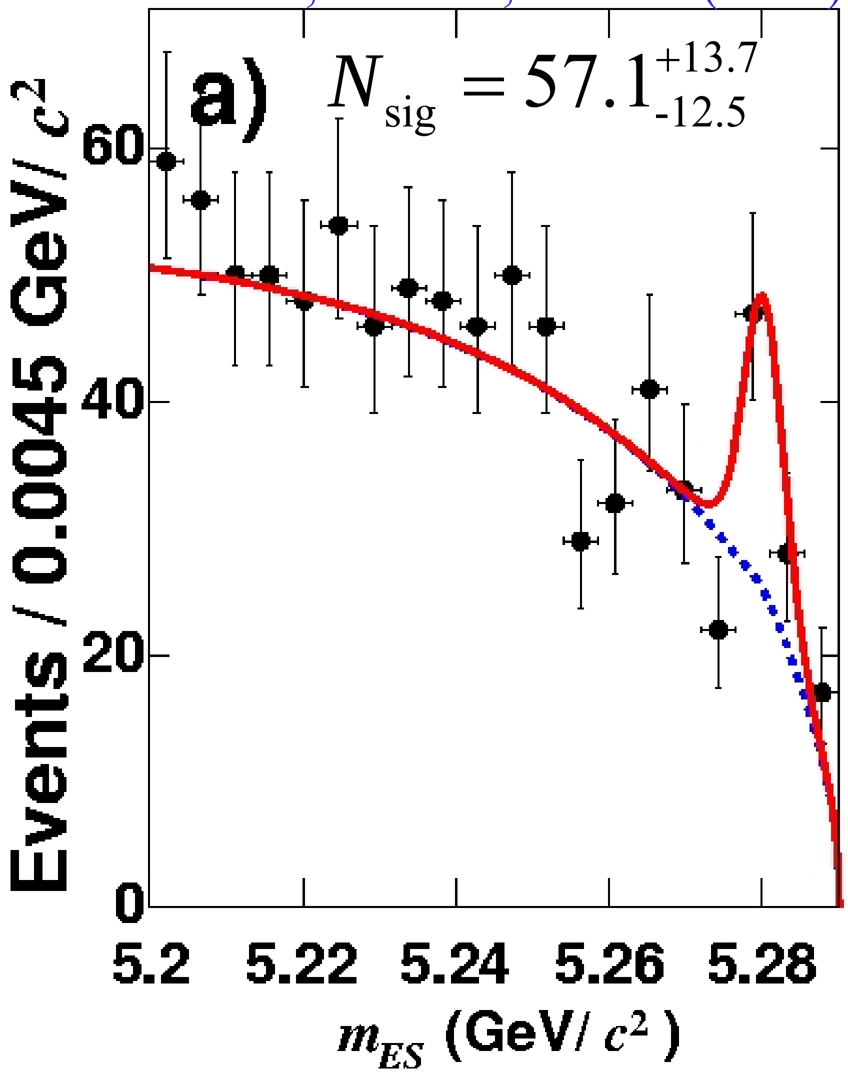
$$B(B \to K\ell^+\ell^-) = (0.34 \pm 0.07 \pm 0.02) \times 10^{-6}$$

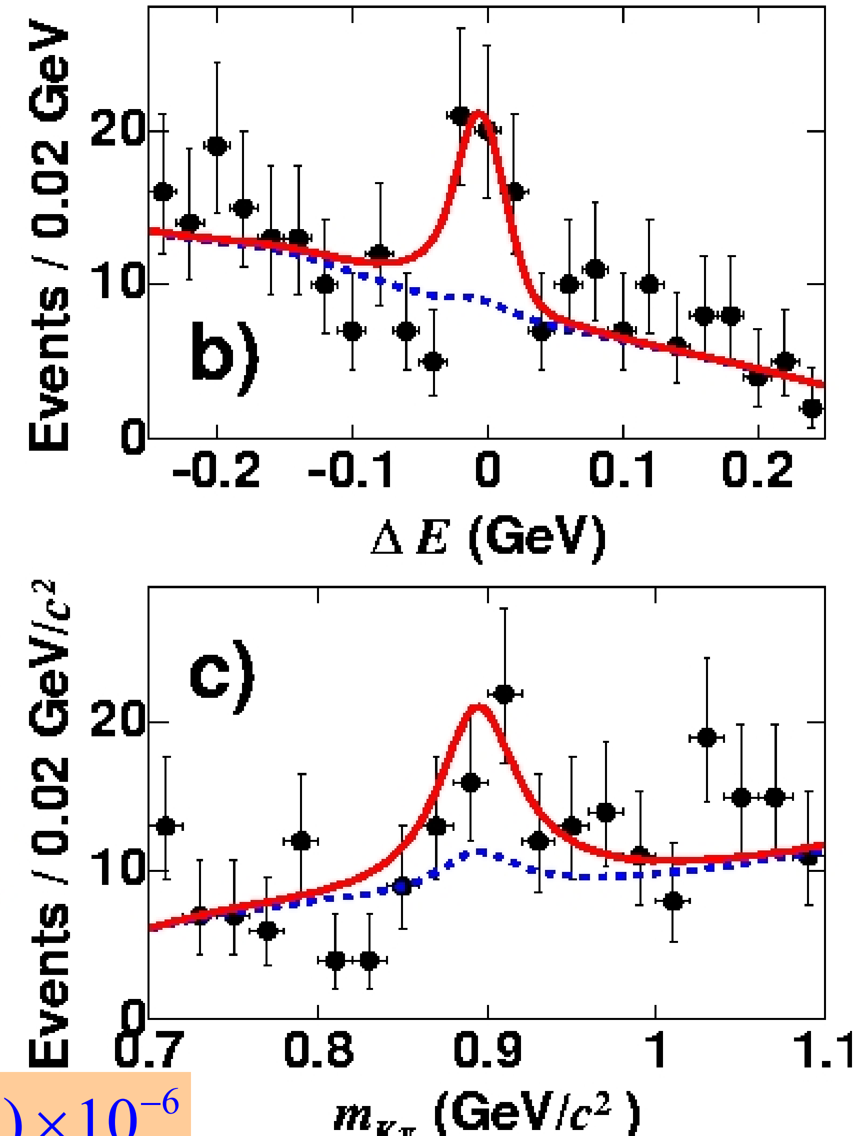
(averaged)

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

BABAR, PRD 73, 092001 (2006)

229 M $B\bar{B}$

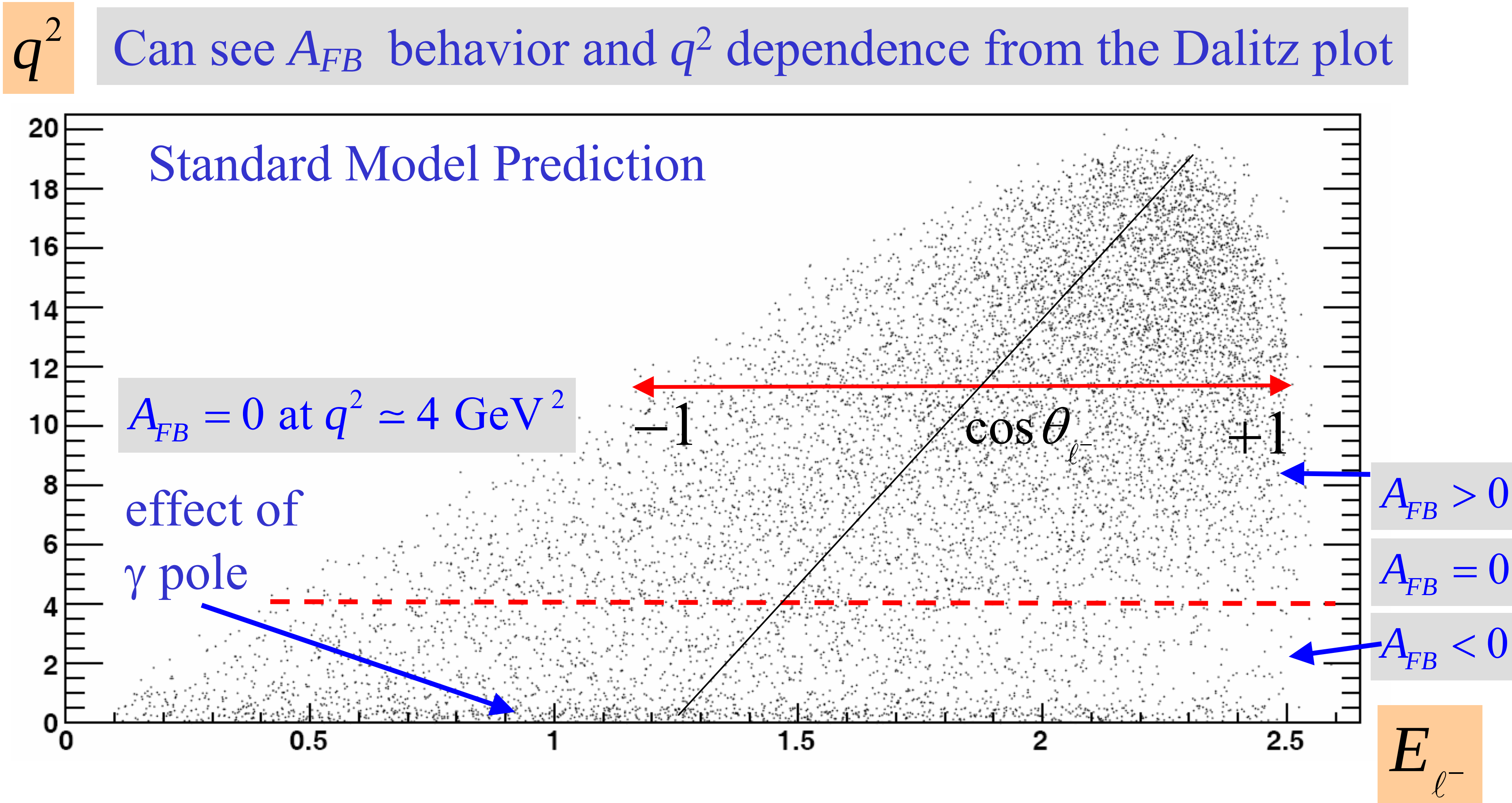




$$B(B \rightarrow K^{*}\ell^{+}\ell^{-}) = (0.78^{+0.19}_{-0.17} \pm 0.11) \times 10^{-6}$$

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

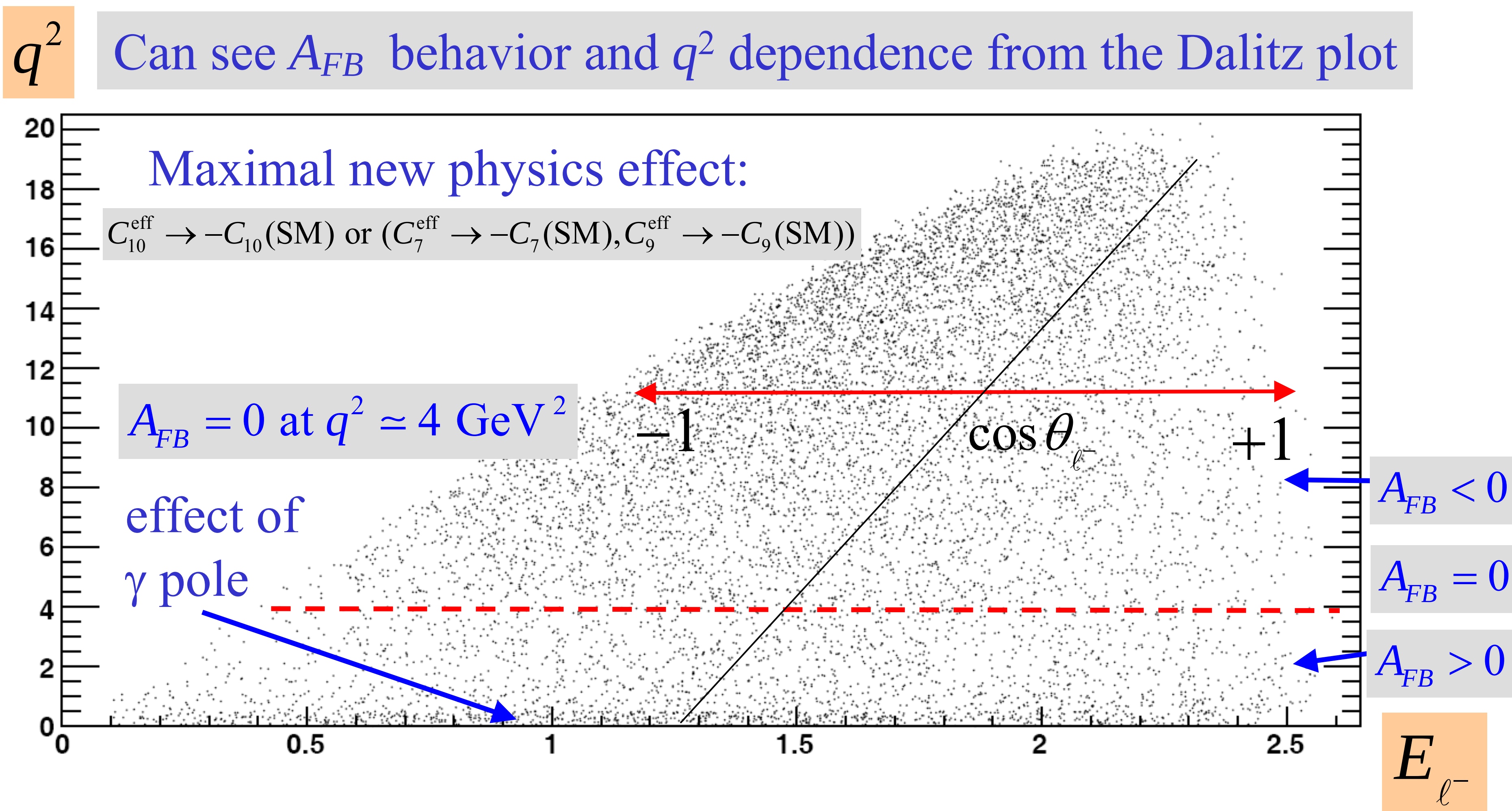
Can see A_{FB} behavior and q^2 dependence from the Dalitz plot



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

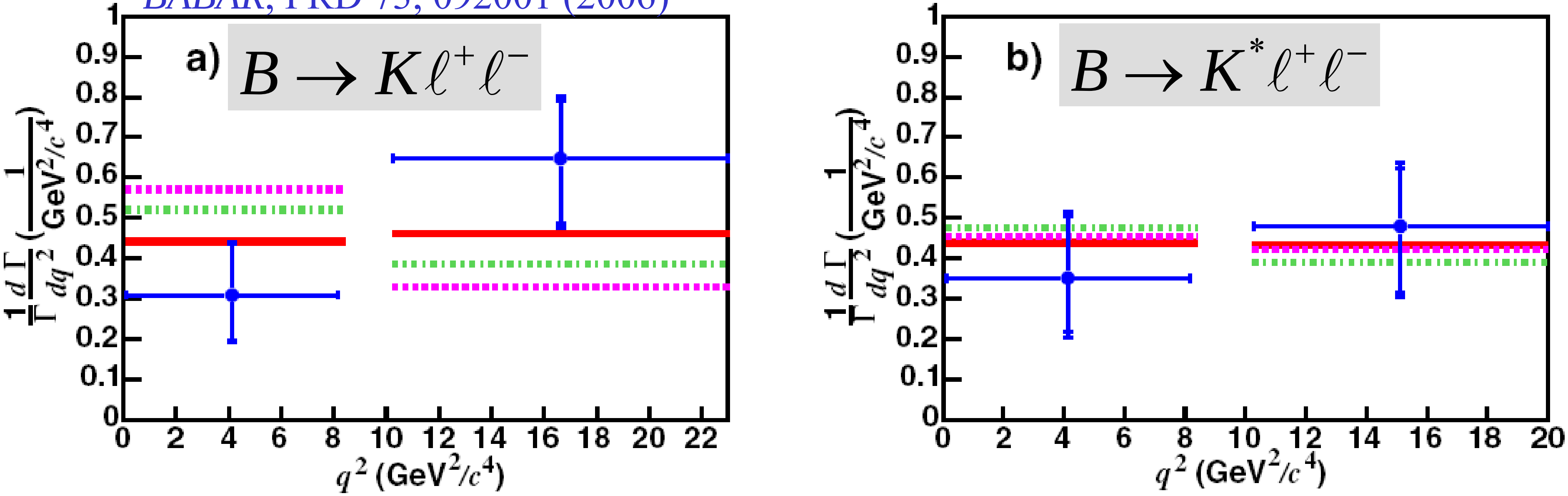
$B \to K^* l^+ l^-$ Dalitz plot

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



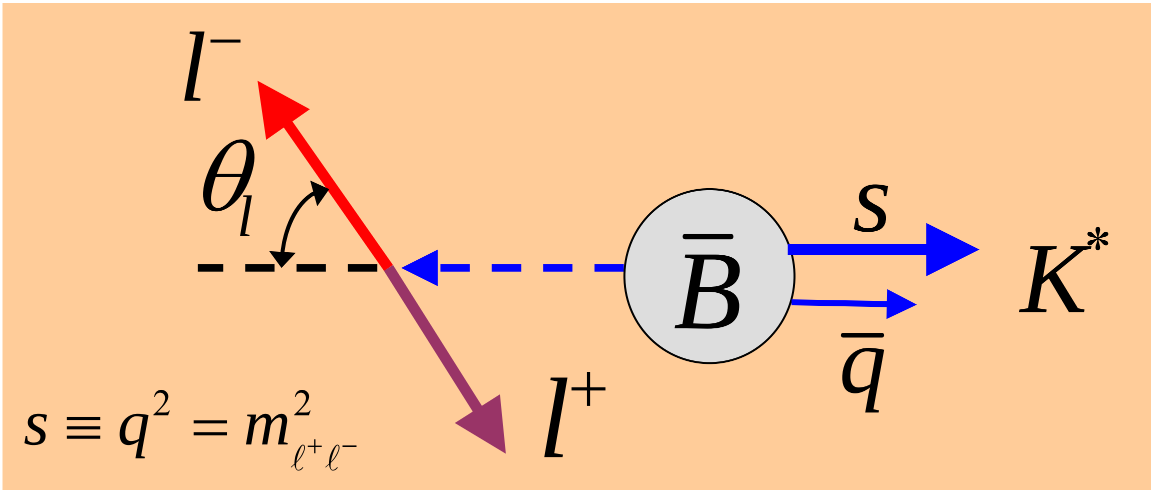
$B \to K^* l^+ l^-$: *BABAR* results on q^2 distribution

BABAR, PRD 73, 092001 (2006)



	$B \to K^*\ell^+\ell^-$		
q^2 (GeV$^2/c^4$)	$\mathcal{B}$ (10^{-6})	F_L	A_{FB}
0.1 − 8.41	$0.27^{+0.12}_{-0.10} \pm 0.05$	$0.77^{+0.63}_{-0.30} \pm 0.07$	>0.19 (95%CL)
>10.24	$0.37^{+0.13}_{-0.11} \pm 0.05$	$0.51^{+0.22}_{-0.25} \pm 0.08$	$0.72^{+0.28}_{-0.26} \pm 0.08$
>0.1	$0.73^{+0.20}_{-0.18} \pm 0.11$	$0.63^{+0.18}_{-0.19} \pm 0.05$	>0.55 (95%CL)
	$B \to K\ell^+\ell^-$		
q^2 (GeV$^2/c^4$)	$\mathcal{B}$ (10^{-6})	F_S	A_{FB}
0.1 − 8.41	$0.10^{+0.04}_{-0.04} \pm 0.01$	0	$-0.49^{+0.51}_{-0.99} \pm 0.18$
>10.24	$0.22^{+0.05}_{-0.05} \pm 0.02$	0	$0.26^{+0.23}_{-0.24} \pm 0.03$
>0.1	$0.34^{+0.07}_{-0.07} \pm 0.02$	$0.81^{+0.58}_{-0.61} \pm 0.46$	$0.15^{+0.21}_{-0.23} \pm 0.08$

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



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

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

$$\left. +\frac{m_b m_B}{s}C_7^{eff}\left[VT_2\left(1-\frac{m_{K^*}}{m_B}\right)(1-\hat{m}_{K^*}) + A_1T_1\left(1+\frac{m_{K^*}}{m_B}\right)\right]\right\}$$

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

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

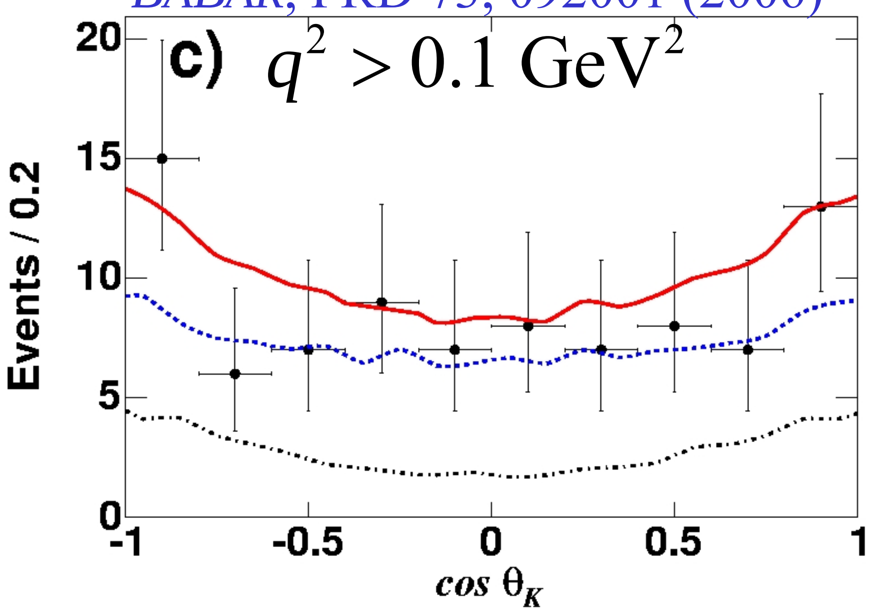
Ali, Kramer, Zhu, hep-ph/0601034

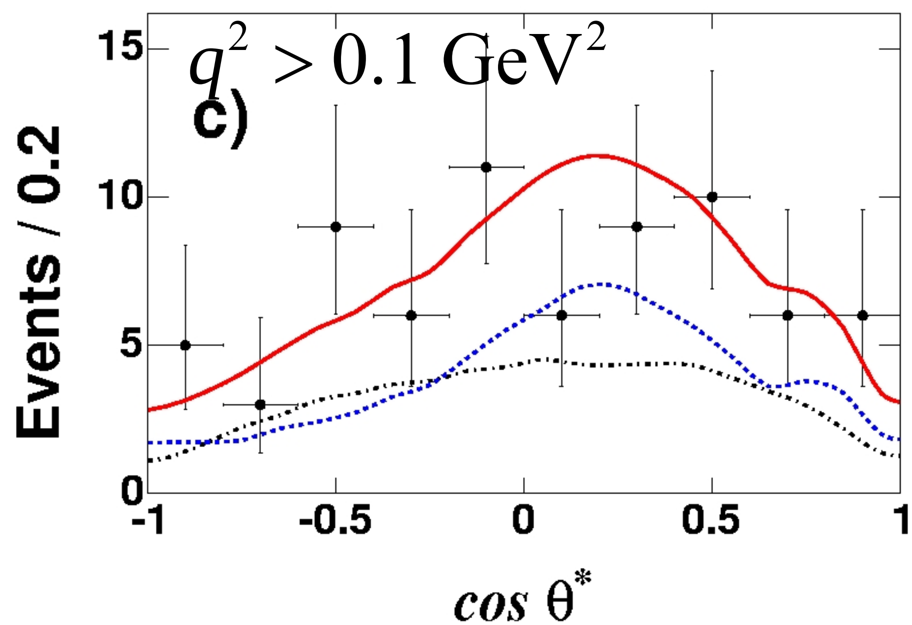
Extracting A_{FB} and F_L in bins of q^2

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

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

BABAR, PRD 73, 092001 (2006)





Belle, hep-ex/041006

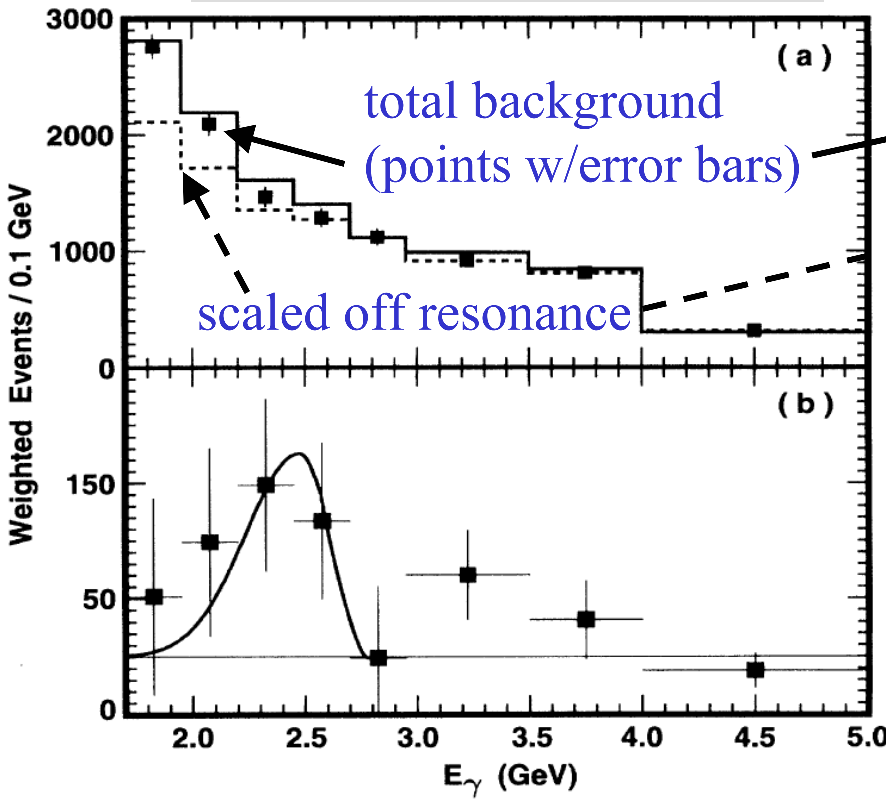
Mode	Signal yield	Efficiency [%]	$\mathcal{B}$ [$\times 10^{-7}$]	U.L.[$\times 10^{-7}$]	Signif.
$K^0 e^+ e^-$	$-1.0^{+1.8+0.2}_{-1.2-0.4}$	$5.10 \pm 0.29 \pm 0.20$	$-0.70^{+1.29+0.14}_{-0.82-0.28} \pm 0.03$	3.0	0.0
$K^+ e^+ e^-$	$28.6^{+6.7+0.5}_{-6.0-0.7}$	$16.3 \pm 0.7 \pm 0.1$	$6.40^{+1.50+0.29}_{-1.34-0.31} \pm 0.05$	-	6.4
$K e^+ e^-$	$26.6^{+6.8+0.6}_{-6.1-0.8}$	$10.7 \pm 0.5 \pm 0.1$	$4.54^{+1.16+0.22}_{-1.04-0.24} \pm 0.06$	-	5.5
$K^{*0} e^+ e^-$	$22.0^{+6.6+0.9}_{-5.9-0.7}$	$4.32 \pm 0.22 \pm 0.36$	$18.5^{+5.5}_{-4.9} \pm 1.1 \pm 1.5$	-	4.4
$K^{*+} e^+ e^-$	$6.2^{+4.1+0.3}_{-3.4-0.6}$	$1.42 \pm 0.08 \pm 0.06$	$16.0^{+10.4+1.2}_{-8.7-1.8} \pm 0.7$	37	1.7
$K^* e^+ e^-$	$28.9^{+7.6}_{-6.9} \pm 0.9$	$2.87 \pm 0.15 \pm 0.21$	$18.4^{+4.8}_{-4.4} \pm 1.1 \pm 1.3$	-	4.8
$K^0 \mu^+ \mu^-$	$11.6^{+4.0+0.1}_{-3.4-0.3}$	$6.76 \pm 0.41 \pm 0.04$	$6.26^{+2.17+0.38}_{-1.81-0.41} \pm 0.04$	-	5.1
$K^+ \mu^+ \mu^-$	$39.9^{+7.6+0.5}_{-6.9-0.7}$	$23.2 \pm 1.1 \pm 0.5$	$6.28^{+1.19+0.30}_{-1.08-0.31} \pm 0.13$	-	8.3
$K \mu^+ \mu^-$	$51.5^{+8.4+0.5}_{-7.8-0.7}$	$15.0 \pm 0.7 \pm 0.2$	$6.26^{+1.03+0.31}_{-0.64-0.32} \pm 0.10$	-	9.7
$K^{*0} \mu^+ \mu^-$	$40.7^{+7.6+0.5}_{-6.9-0.6}$	$8.01 \pm 0.43 \pm 0.14$	$18.5^{+3.5}_{-3.1} \pm 1.0 \pm 0.3$	-	8.4
$K^{*+} \mu^+ \mu^-$	$11.4^{+4.5+0.2}_{-3.8-0.6}$	$2.55 \pm 0.14 \pm 0.08$	$16.3^{+6.4+0.9}_{-5.4-1.2} \pm 0.5$	-	3.5
$K^* \mu^+ \mu^-$	$52.5^{+8.7+0.5}_{-8.0-0.8}$	$5.28 \pm 0.29 \pm 0.03$	$18.1^{+3.0}_{-2.8} \pm 1.1 \pm 0.1$	-	9.1
$K^0 \ell^+ \ell^-$	$10.7^{+4.4+0.2}_{-3.7-0.5}$	$5.95 \pm 0.36 \pm 0.11$	$3.28^{+1.34+0.21}_{-1.13-0.25} \pm 0.06$	-	3.5
$K^+ \ell^+ \ell^-$	$68.6^{+9.9+0.8}_{-9.3-1.0}$	$19.8 \pm 0.9 \pm 0.2$	$6.32^{+0.92}_{-0.85} \pm 0.29 \pm 0.06$	-	9.4
$K \ell^+ \ell^-$	$78.5^{+10.7+0.8}_{-10.0-1.1}$	$13.0 \pm 0.6 \pm 0.4$	$5.50^{+0.75}_{-0.70} \pm 0.27 \pm 0.02$	-	11.0
$K^{*0} \ell^+ \ell^-$	$63.8^{+9.9}_{-9.2} \pm 0.9$	$6.88 \pm 0.37 \pm 0.30$	$16.9^{+2.6}_{-2.4} \pm 0.9 \pm 0.7$	-	9.4
$K^{*+} \ell^+ \ell^-$	$16.3^{+5.6+0.5}_{-4.9-0.8}$	$2.22 \pm 0.13 \pm 0.02$	$13.4^{+4.6+0.9}_{-4.0-1.0} \pm 0.1$	-	3.7
$K^* \ell^+ \ell^-$	$82.2^{+11.4+1.0}_{-10.7-1.1}$	$4.55 \pm 0.24 \pm 0.12$	$16.5^{+2.3}_{-2.2} \pm 0.9 \pm 0.4$	-	10.1

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

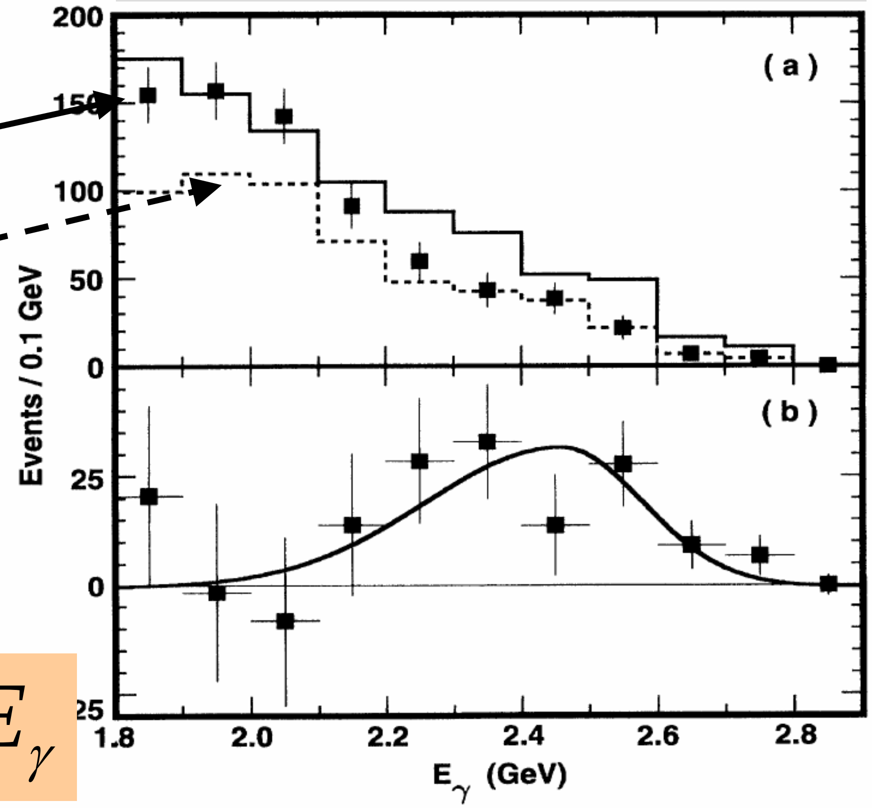
CLEO, PRL 74, 2885 (1995); 2.01 fb^{-1} on Υ(4S), 0.96 fb^{-1} below Υ(4S)

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

"Event-shape analysis"



"B-reconstruction analysis"



E_γ

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

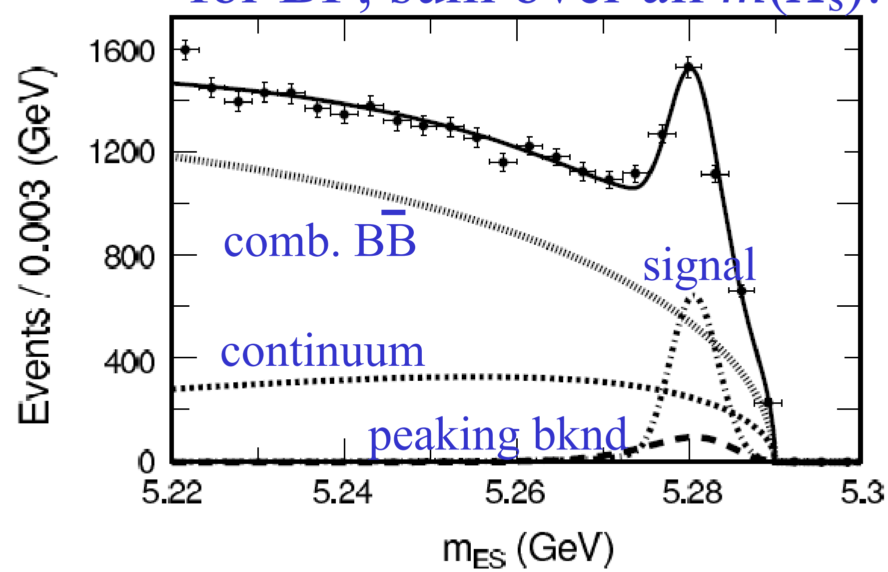
BABAR $B \rightarrow X_s \gamma$ with Sum of Exclusive Final States

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
- For E_γ spectrum, fit m_{ES} distrib. in bins of $m(X_s)$
- Correct for efficiency of each mode and missing modes fraction ($\rightarrow$model dependence)

for BF, sum over all $m(X_s)$:



Systematic Errors on $B \rightarrow X_s \gamma$

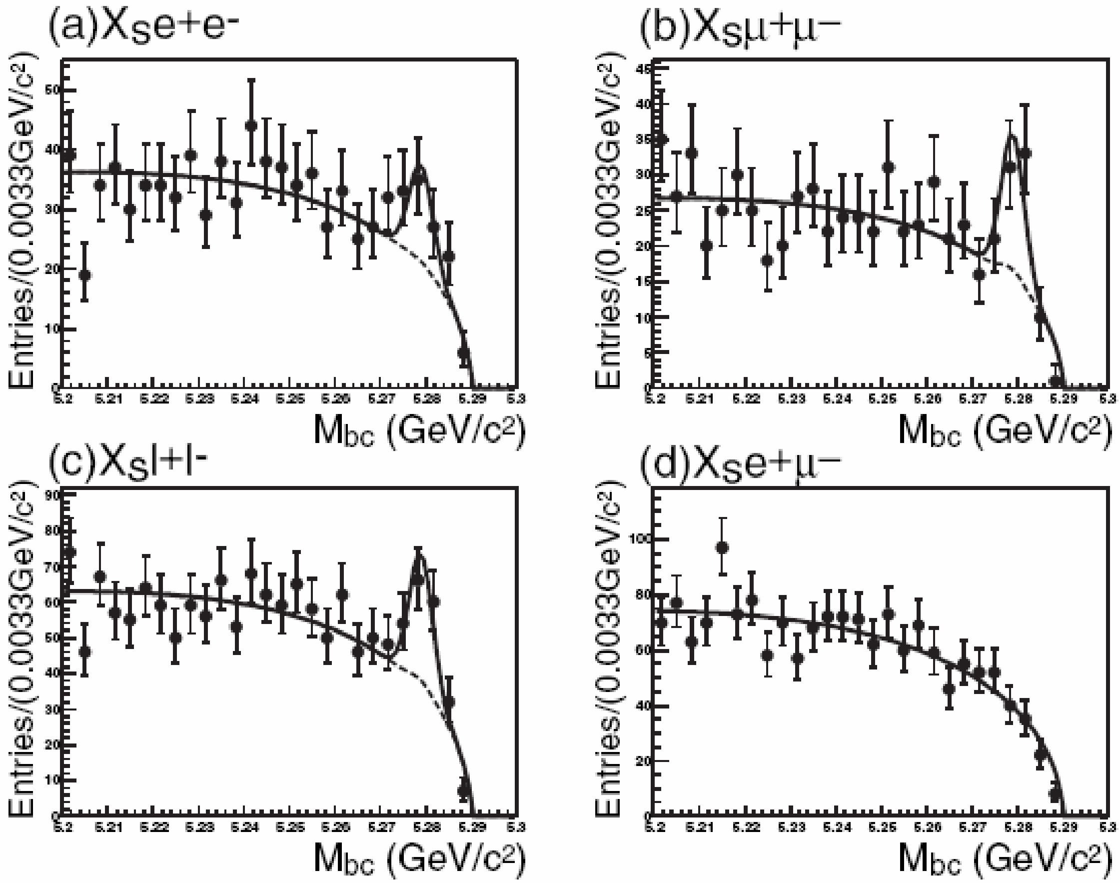
Belle, PRL 93, 061803 (2004)

TABLE I. Overview of systematic errors.

Source of systematic error	$\times 10^{-4}$
Raw branching fraction	3.51 ± 0.32
Data/MC efficiency ratio fits	± 0.208
Choice of fitting functions	± 0.048
Number of $B\bar{B}$ events	$^{+0.139}_{-0.160}$
ON-OFF data subtraction	± 0.026
Other $B\bar{B}$ photons	± 0.054
η veto efficiency on η	± 0.008
Signal MC	± 0.089
Photon detection efficiency	± 0.072
Energy leakage	$^{+0.035}_{-0.000}$
Total error for partial $\mathcal{B}(b \to q\gamma)$	$^{+0.282}_{-0.291}$

Belle: $B \to X_s\, l^+ l^-$

Belle, PRL 72, 092005 (2006)



$$B(B \to X_s \ell^+ \ell^-) = (4.11 \pm 0.83^{+0.85}_{-0.81}) \times 10^{-6}$$

5.4σ

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

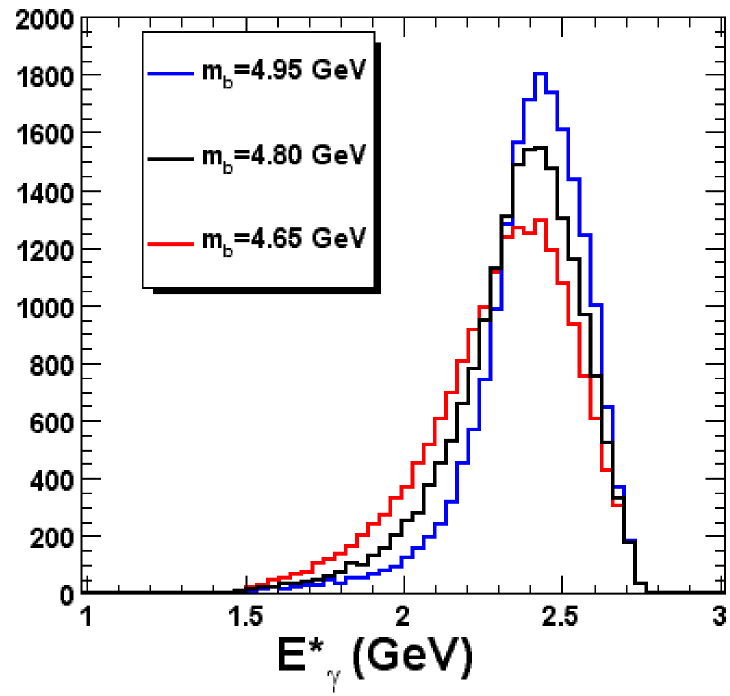
Using heavy-quark expansion (HQE), moments of inclusive *B* decay distributions can be expressed in terms of non-perturbative QCD parameters and quark masses.

- $B \rightarrow X_s \gamma$ 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%.

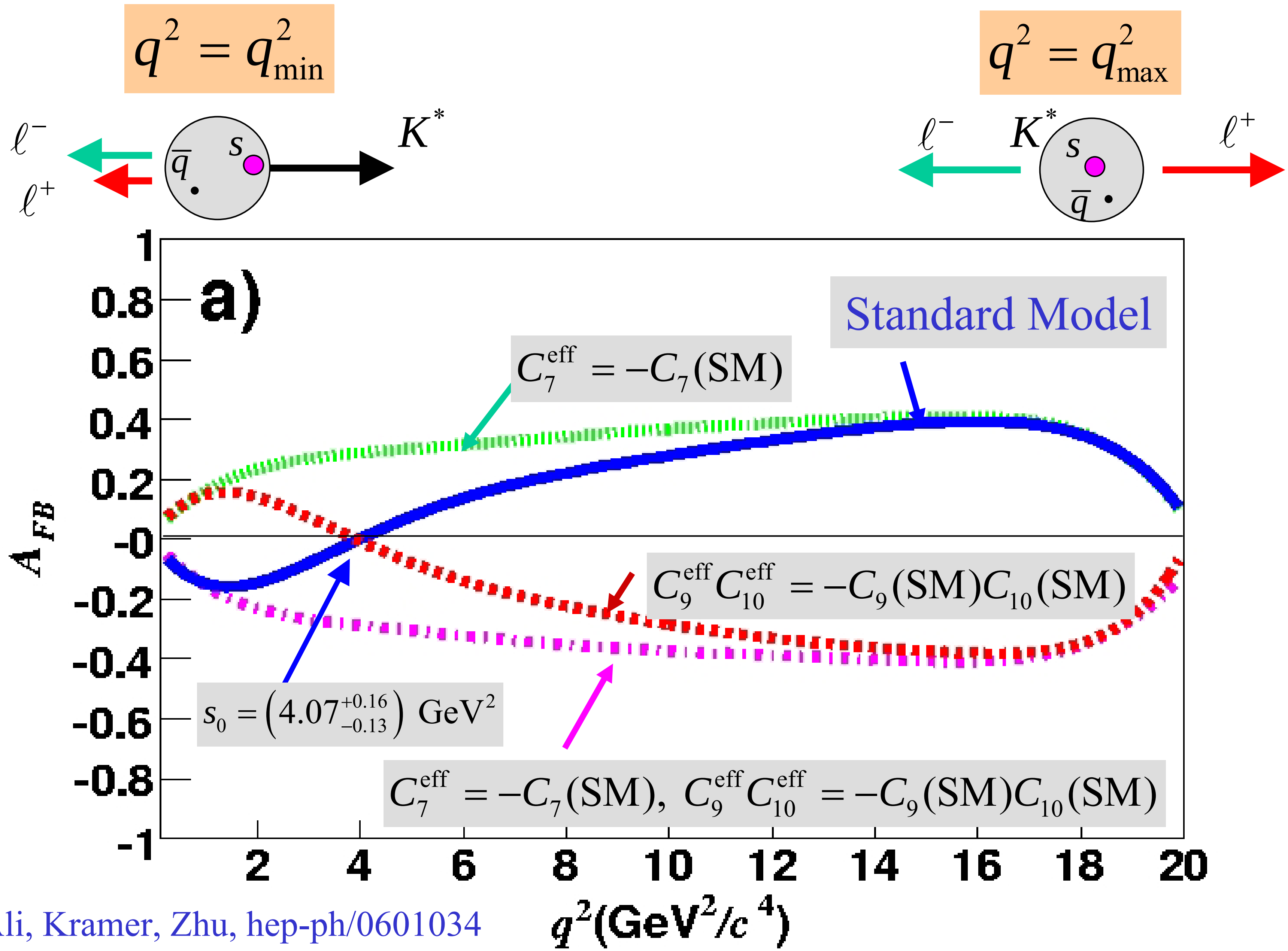
$$\langle E_\gamma \rangle \approx \frac{m_b}{2}$$

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

(measures kinetic-energy-squared of *b*-quark)



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

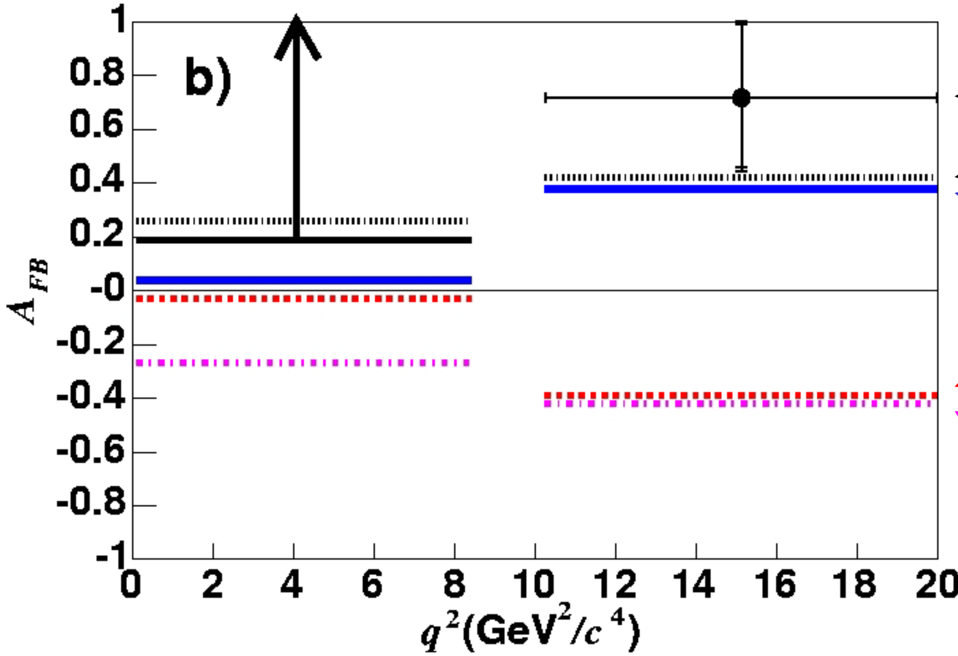


s_0: Ali, Kramer, Zhu, hep-ph/0601034

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

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

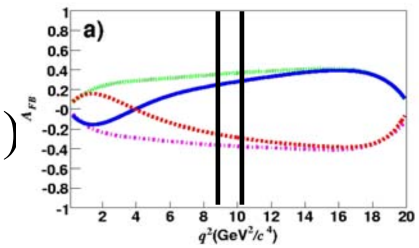
use in 2 bins of q^2



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)