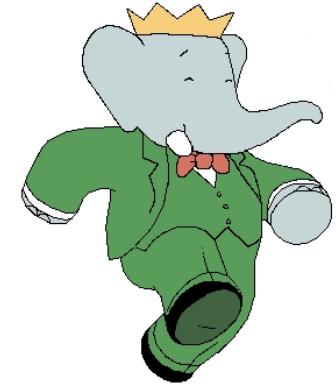
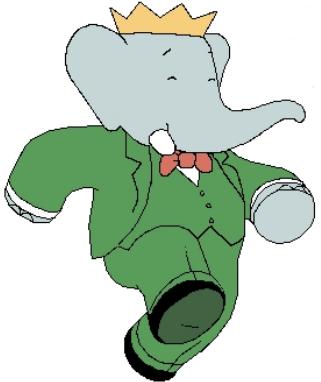




Recent studies of $b \rightarrow s\gamma$ transitions with the BaBar detector



Fergus Wilson

Rutherford Appleton Laboratory
For the BaBar collaboration
SUSY 2016

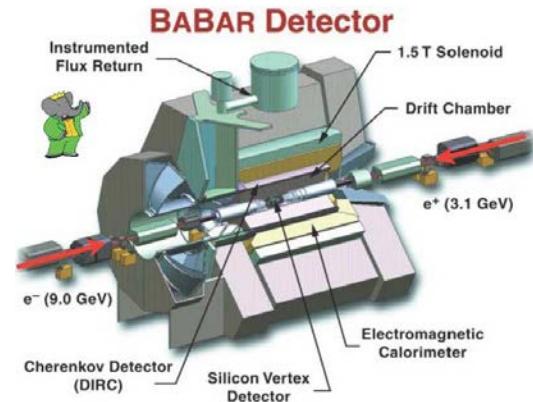


Outline

1. Time-dependent CP asymmetries in $B^0 \rightarrow K_s^0 \pi^- \pi^+ \gamma$
 - [PRD 93 052013 \(2016\)](#)
2. Angular asymmetries in the decays $B \rightarrow K^* l^+ l^-$
 - [PRD 93 052015 \(2016\)](#)
3. Lepton Universality in $B \rightarrow K l^+ l^-$
 - Update to [PRD 86 032012 \(2012\)](#)
 - To be submitted to PRD
- Search for $B^+ \rightarrow K^+ \tau^+ \tau^-$
 - [arXiv:1605.09637](#)



BaBar and PEP-II : $e^+e^- \rightarrow Y(nS) \rightarrow BB$

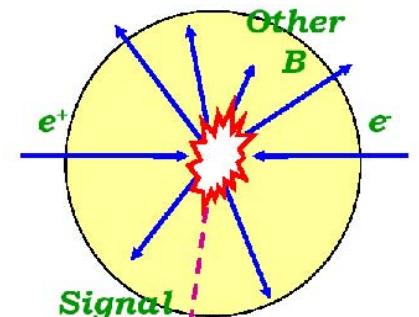
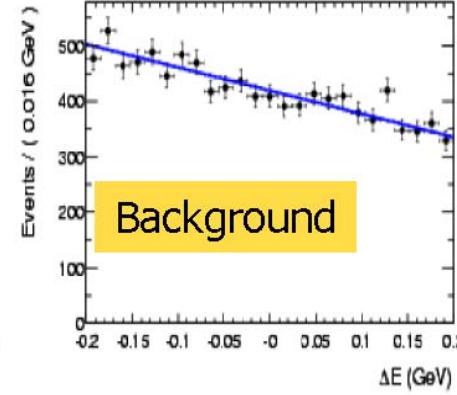
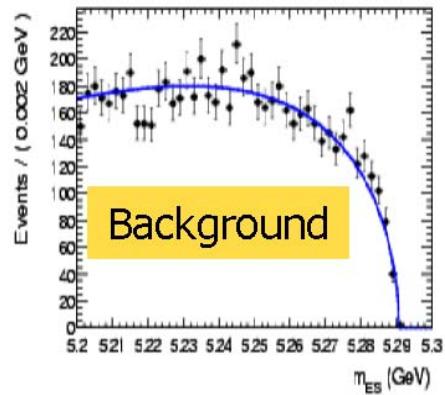
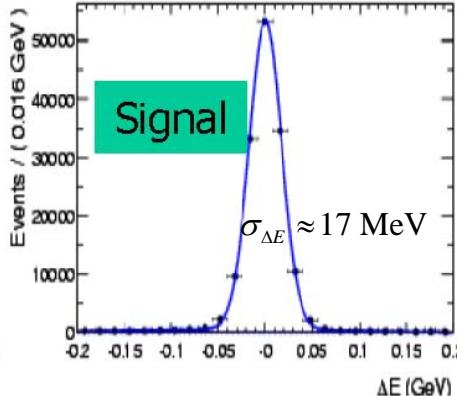
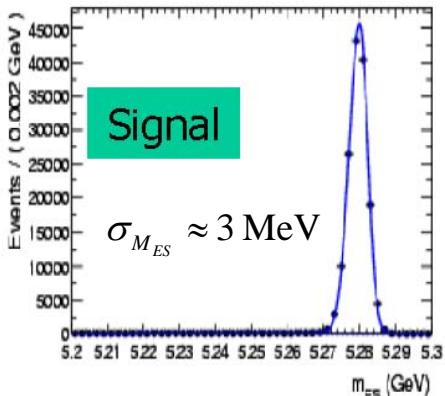


$$m_{ES} = \sqrt{E_{beam}^{*2} - p_B^{*2}}$$

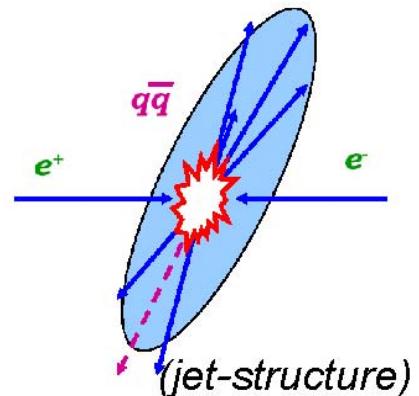
$$\Delta E = E_B^* - E_{beam}^*$$

Event Topology

	Lumi	BB Events
$\Upsilon(4S)$	424 fb^{-1}	471×10^6
$\Upsilon(3S)$	28 fb^{-1}	121×10^6
$\Upsilon(2S)$	14 fb^{-1}	99×10^6
$\tau^+\tau^-$		$\sim 450 \times 10^6$



(spherical)

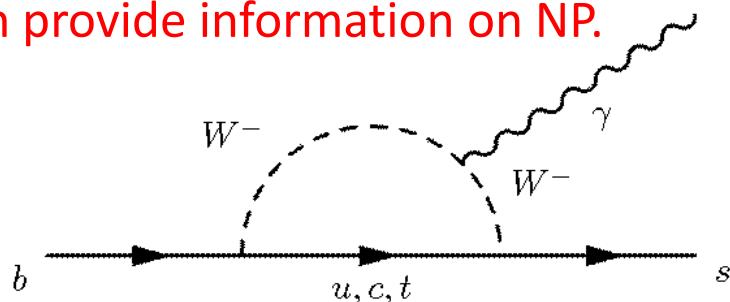


Plus: blinded analysis, multivariate discriminants, Maximum Likelihood (ML) fits



Time-dependent CP asymmetries in $B^0 \rightarrow K_s^0 \pi^- \pi^+ \gamma$

- The V-A structure of the Standard Model (SM) weak interactions yields predominantly left-handed γ in $b \rightarrow s\gamma$ decays ($B \rightarrow s\gamma_{RH}, \bar{B} \rightarrow \bar{s}\gamma_{LH}$).
- Implies mixing-induced CP asymmetry in $B \rightarrow f_{CP}\gamma$ is small in the SM.
- New Physics (NP) processes with an opposite-helicity γ may be possible without contradicting SM branching fraction predictions
 - $B(B \rightarrow X_s \gamma) = (3.43 \pm 0.21 \pm 0.07) \times 10^{-4}$ ([HFAG](#))
 - $B(B \rightarrow X_s \gamma) = (3.36 \pm 0.23) \times 10^{-4}$ ([SM prediction](#))
- Some models have a right-handed process comparable in magnitude to left-handed processes e.g. PRD 49, 5890 (1994); PRL B333, 196 (1994); PRD 49, 5894 (1994)
 - Measuring CP asymmetry can provide information on NP.**

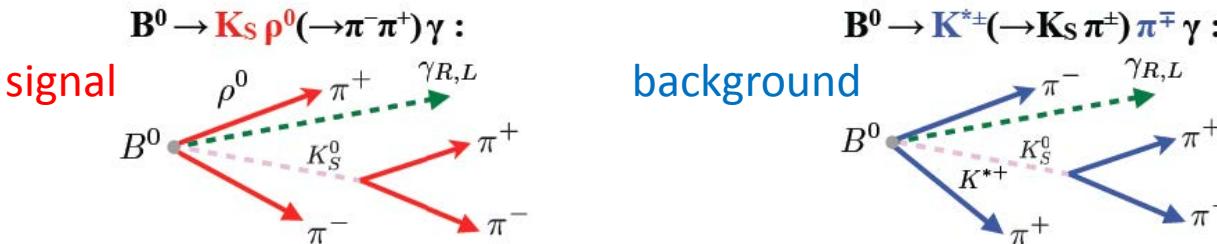


- Some previous results:
 - $B^0 \rightarrow K_s^0 \rho^0 \gamma$ ([Belle PRL101, 251601 \(2008\)](#)), $B^0 \rightarrow K_s^0 \pi^0 \gamma$ ([BaBar PRD78, 071102 \(2008\)](#)); [Belle PRD74, 111104 \(2006\)](#): no evidence for NP, CP compatible with SM.
 - $B^+ \rightarrow K^+ \pi^- \pi^+ \gamma$: non-zero value (5.2σ) of photon polarisation ([LHCb PRL 112, 161801 \(2014\)](#))



$B^0 \rightarrow K_s^0 \pi^- \pi^+ \gamma$ Analysis Method

- Time-dependent mixing-induced CP asymmetry parameters $S_{K0\text{sp}y}$ and $C_{K0\text{sp}y}$ in $B^0 \rightarrow K_s^0 \rho^0 \gamma$
- Problem 1: background from $B^0 \rightarrow K^{*\pm} \pi^\mp \gamma$ dilutes $S_{K0\text{sp}y}$ from $B^0 \rightarrow K_s^0 \rho^0 \gamma$



- Problem 2: not enough $B^0 \rightarrow K_s^0 \rho^0 \gamma$ for amplitude analysis
 - Perform amplitude analysis of $B^+ \rightarrow K^+ \pi^- \pi^+ \gamma$ to identify resonances and amplitudes A .
 - Use isospin relations[§] to relate $B^+ \rightarrow K^+ \pi^- \pi^+ \gamma$ amplitudes to $B^0 \rightarrow K_s^0 \pi^- \pi^+ \gamma$.
 - Calculate dilution factor from these amplitudes:

$$D_{K_s^0 \rho \gamma} \equiv \frac{S_{K_s^0 \pi^+ \pi^- \gamma}}{S_{K_s^0 \rho \gamma}} = \frac{\int \left[\left| A_{K_s^0 \rho} \right|^2 - \left| A_{K^{*+} \pi^-} \right|^2 - \left| A_{(K\pi)_0^{*+} \pi^-} \right|^2 + 2\Re(A_{K_s^0 \rho}^* A_{K^{*+} \pi^-}) + 2\Re(A_{K_s^0 \rho}^* A_{(K\pi)_0^{*+} \pi^-}) \right] dm^2}{\int \left[\left| A_{K_s^0 \rho} \right|^2 + \left| A_{K^{*+} \pi^-} \right|^2 + \left| A_{(K\pi)_0^{*+} \pi^-} \right|^2 + 2\Re(A_{K_s^0 \rho}^* A_{K^{*+} \pi^-}) + 2\Re(A_{K_s^0 \rho}^* A_{(K\pi)_0^{*+} \pi^-}) \right] dm^2}$$

- Use ML fit to proper time distribution of $B^0 \rightarrow K_s^0 \pi^- \pi^+ \gamma$ to extract C and diluted S :

$$P_{sig}^i(\Delta t, \rho_\Delta; q_{tag}, c) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{2\tau_{B^0}} \left[1 + q_{tag} \left(\frac{\Delta D_c}{2} + \langle D \rangle_c (S \sin(\Delta m_d \Delta t) - C \cos(\Delta m_d \Delta t)) \right) \right] \otimes R_{sig}^c(\Delta t, \rho_\Delta)$$

- Correct S by dilution factor to produce $S_{K0\text{sp}y}$

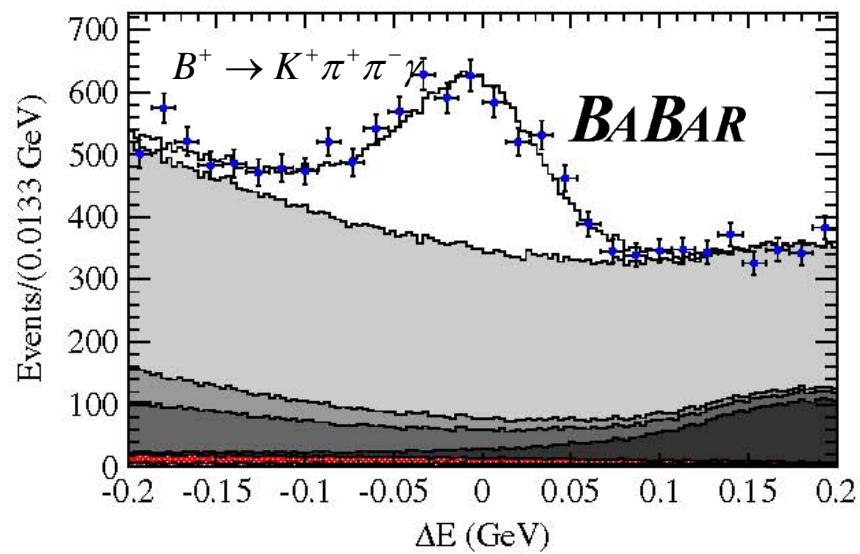
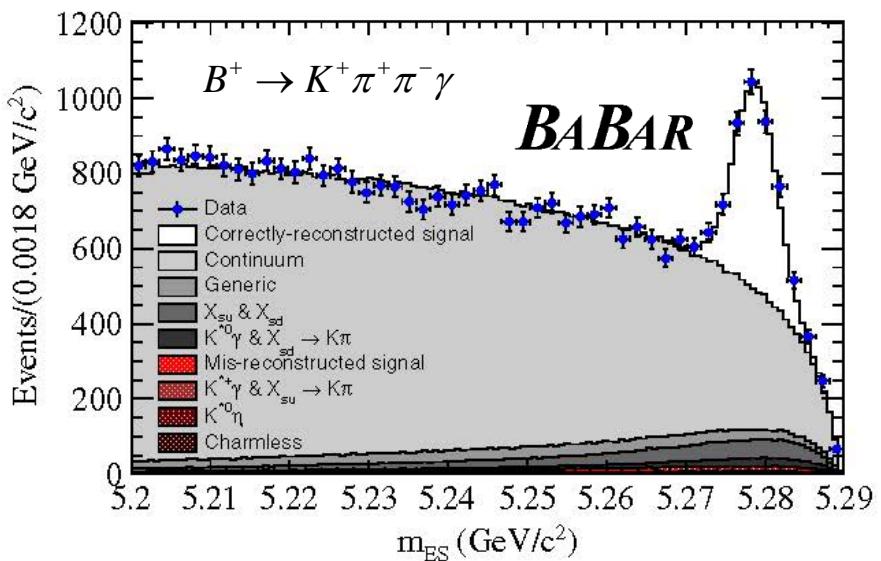
§= Hebinger, Kou and Yu, [LAL-15-75](#)



$B^+ \rightarrow K^+ \pi^- \pi^+ \gamma$ Results

[PRD 93, 052013 \(2016\)](#)

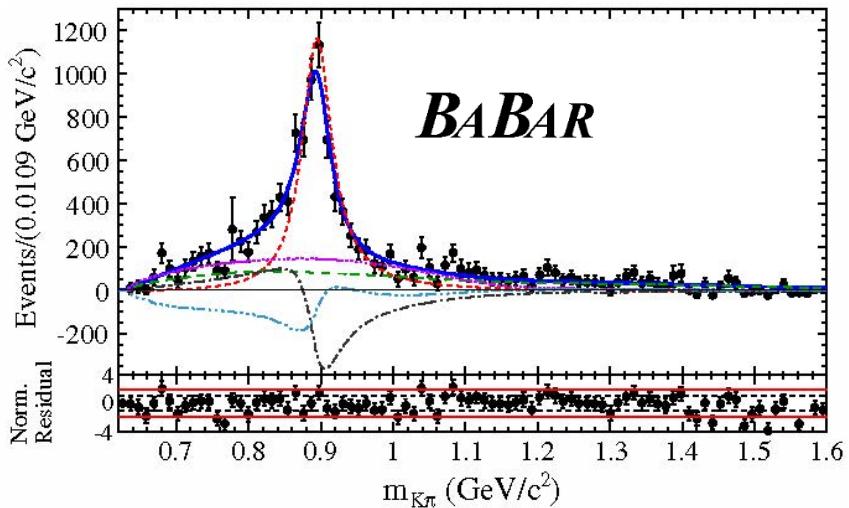
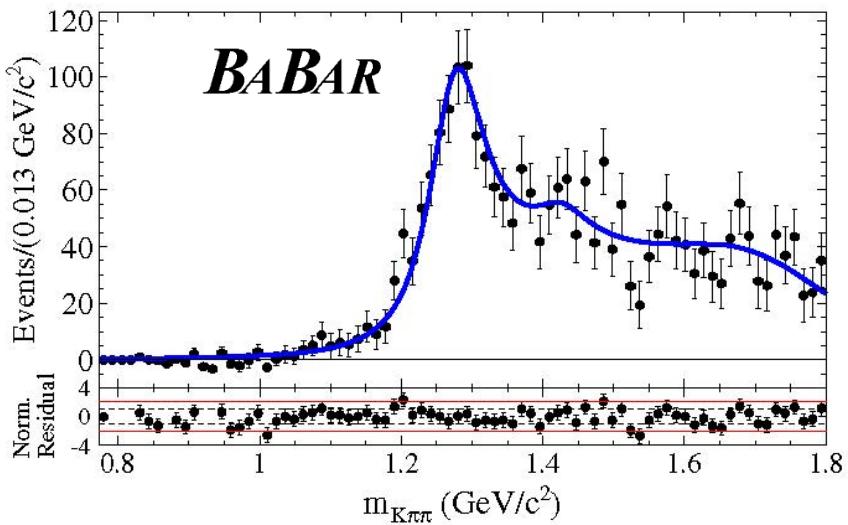
- B^+ yield extracted from ML fit to ΔE , m_{ES} , and Fisher Discriminant (F).
- Amplitude analysis performed over full Dalitz plane to identify resonances.
- Dilution extracted in optimized region $0.6 < m_{\pi\pi} < 0.9$ GeV, $m_{K\pi} < 0.845$ or $m_{K\pi} > 0.945$ GeV.





$B^+ \rightarrow K^+ \pi^- \pi^+ \gamma$ Amplitudes

[PRD 93, 052013 \(2016\)](#)



Mode	$B(B^+ \rightarrow \text{Mode}) \times 10^{-6}$	Previous WAs
$B^+ \rightarrow K^+ \pi^+ \pi^- \gamma$	$24.5 \pm 0.9 \pm 1.2$	27.6 ± 2.2
$K_1(1270)^+ \gamma$	$44.1^{+6.3+3.6}_{-4.4-3.6} \pm 4.6$	43 ± 13
$K_1(1400)^+ \gamma$	$9.7^{+4.6+2.8}_{-2.9-2.3} \pm 0.6$	< 15
$K^*(1410)^+ \gamma$	$27.1^{+5.5+5.2}_{-4.4-2.6} \pm 2.7$	n/a
$K_2^*(1430)^+ \gamma$	$8.7^{+7.0+8.7}_{-5.3-10.4} \pm 0.4$	14 ± 4
$K^*(1680)^+ \gamma$	$66.7^{+9.3+13.5}_{-7.8-10.0} \pm 5.4$	< 1900

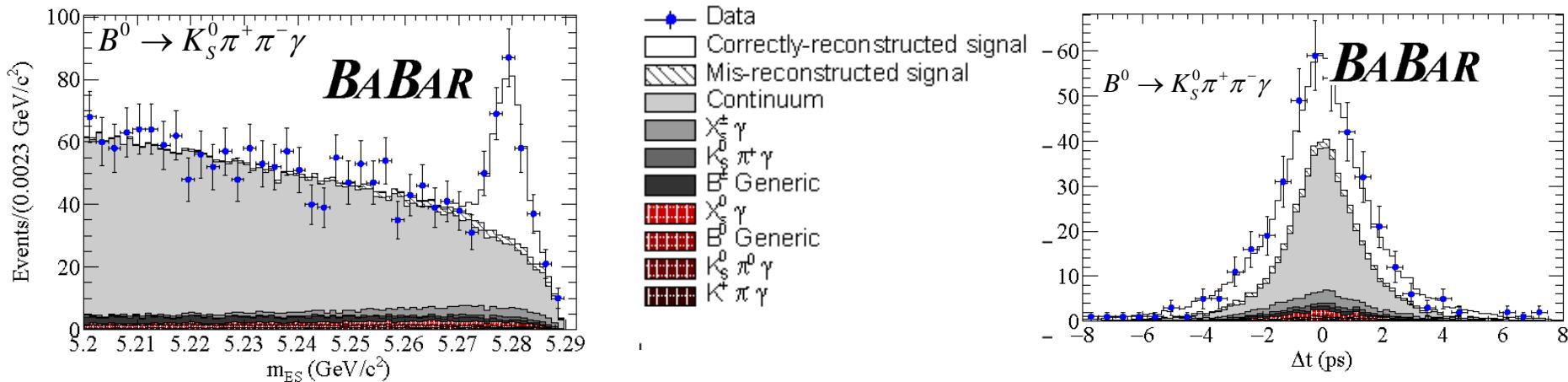
Mode	$B(B^+ \rightarrow \text{Mode}) \times 10^{-6}$	Previous WAs
$K^*(892)^0 \pi^+ \gamma$	$23.4 \pm 0.9^{+0.8}_{-0.7}$	20^{+7}_{-6}
$K^+ \rho(770)^0 \gamma$	$8.2 \pm 0.4 \pm 0.8 \pm 0.02$	< 20
$(K\pi)_0^0 \pi^+ \gamma$ (NR)	$9.9 \pm 0.7^{+1.5}_{-1.9}$	< 9.2
$K_0^*(1430)^0 \pi^+ \gamma$	$1.32^{+0.09+0.20}_{-0.10-0.26} \pm 0.14$	n/a



$B^0 \rightarrow K_s^0 \pi^- \pi^+ \gamma$ Results

B^0 yield and CP from time-dependent ML fit to $(\Delta E, m_{ES}, F, \Delta t, \sigma_t; q_{tag}, c)$.

PRD 93, 052013 (2016)



$$B(B^0 \rightarrow K^0 \pi^+ \pi^- \gamma) = (24.0 \pm 2.4^{+1.7}_{-1.8}) \times 10^{-6}$$

$$S_{K_s^0 \pi^+ \pi^- \gamma} = +0.14 \pm 0.25 \pm 0.03$$

$$C_{K_s^0 \pi^+ \pi^- \gamma} = -0.39 \pm 0.20^{+0.03}_{-0.02}$$

$$D_{K_s^0 \rho^0 \gamma} = -0.78^{+0.19}_{-0.17}$$

$$S_{K_s^0 \rho^0 \gamma} = -0.18 \pm 0.32^{+0.06}_{-0.05}$$

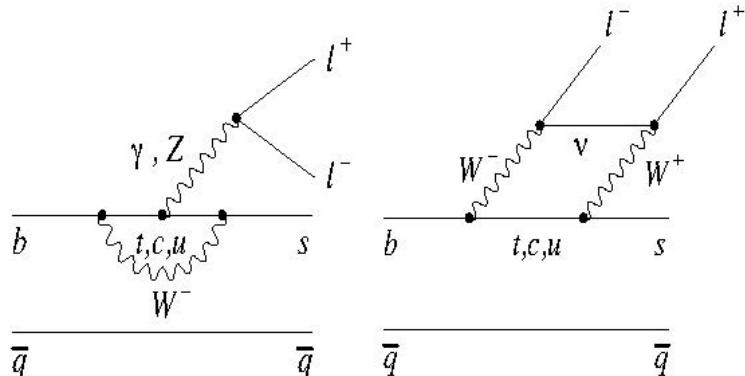
Results consistent with Belle [PRL 101, 251601 (2008)]
 CP asymmetries consistent with zero and SM.



Angular analysis of the decays $B \rightarrow K^* l^+ l^-$



PRD 93, 052015 (2016)



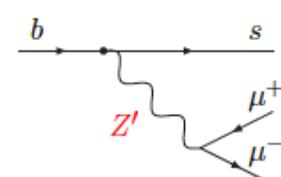
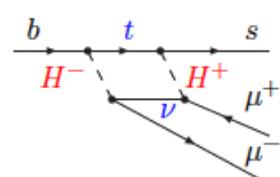
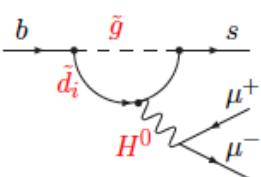
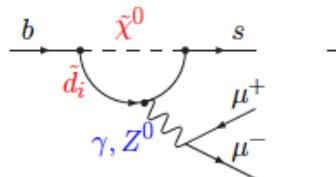
Effective Hamiltonian can be expressed via Operator Product Expansion (OPE) in terms of operators O and calculable Wilson coefficients C .

$$H_{eff} = -\frac{4G_F}{\sqrt{2}} V_{tq}^* V_{tb} \sum_{i=1} C_i^{(\ell)}(\mu) O_i^{(\ell)}(\mu) + \sum_i \frac{C_i^{NP}}{\Lambda^2} O_i^{NP}$$

$i = 1, 2$	Tree
$i = 3-6, 8$	Gluon Penguin
$i = 7$	Photon Penguin
$i = 9$	EW Penguin (axial)
$i = 10$	EW Penguin (vector)
$i = S$	Scalar Penguin
$i = P$	Pseudoscalar Penguin

New Physics (NP) can enter via new particles in loops

- Potentially modifies magnitude and phase of SM C_i
- Probes new couplings and NP at a scale \sim few TeV.
- Angular distributions as a function of q^2 sensitive to NP





Angular analysis of the decays $B \rightarrow K^* l^+ l^-$

PRD 93, 052015 (2016)

- Extract yield with ML to (m_{ES} , ΔE , BDT probability)
- The $B \rightarrow K^* l^+ l^-$ angular distribution depends on:
 - θ_K between K^+ & B^0 in K^* rest frame
 - θ_l between $l^+(l^-)$ & $B(B\bar{B})$ in l^+l^- rest frame
 - ϕ between the di-lepton and $K\pi$ planes

- Not enough events for full angular analysis, so integrate over two angles to find longitudinal polarisation F_L and lepton forward-backward asymmetry, A_{FB} :

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

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

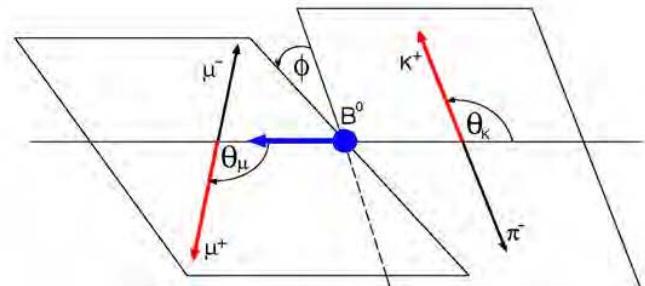
$$P_2 = -2A_{FB}/(3(1 - F_L))$$

- Perform F_L , A_{FB} fit in 6 q^2 bins with 5 final states

$$B^+ \rightarrow K^{*+} (\rightarrow K^+ \pi^0) e^+ e^- \quad B^+ \rightarrow K^{*+} (\rightarrow K_S^0 \pi^+) \mu^+ \mu^-$$

$$B^+ \rightarrow K^{*+} (\rightarrow K_S^0 \pi^+) e^+ e^- \quad B^0 \rightarrow K^{*0} (\rightarrow K^+ \pi^-) \mu^+ \mu^-$$

$$B^0 \rightarrow K^{*0} (\rightarrow K^+ \pi^-) e^+ e^-$$

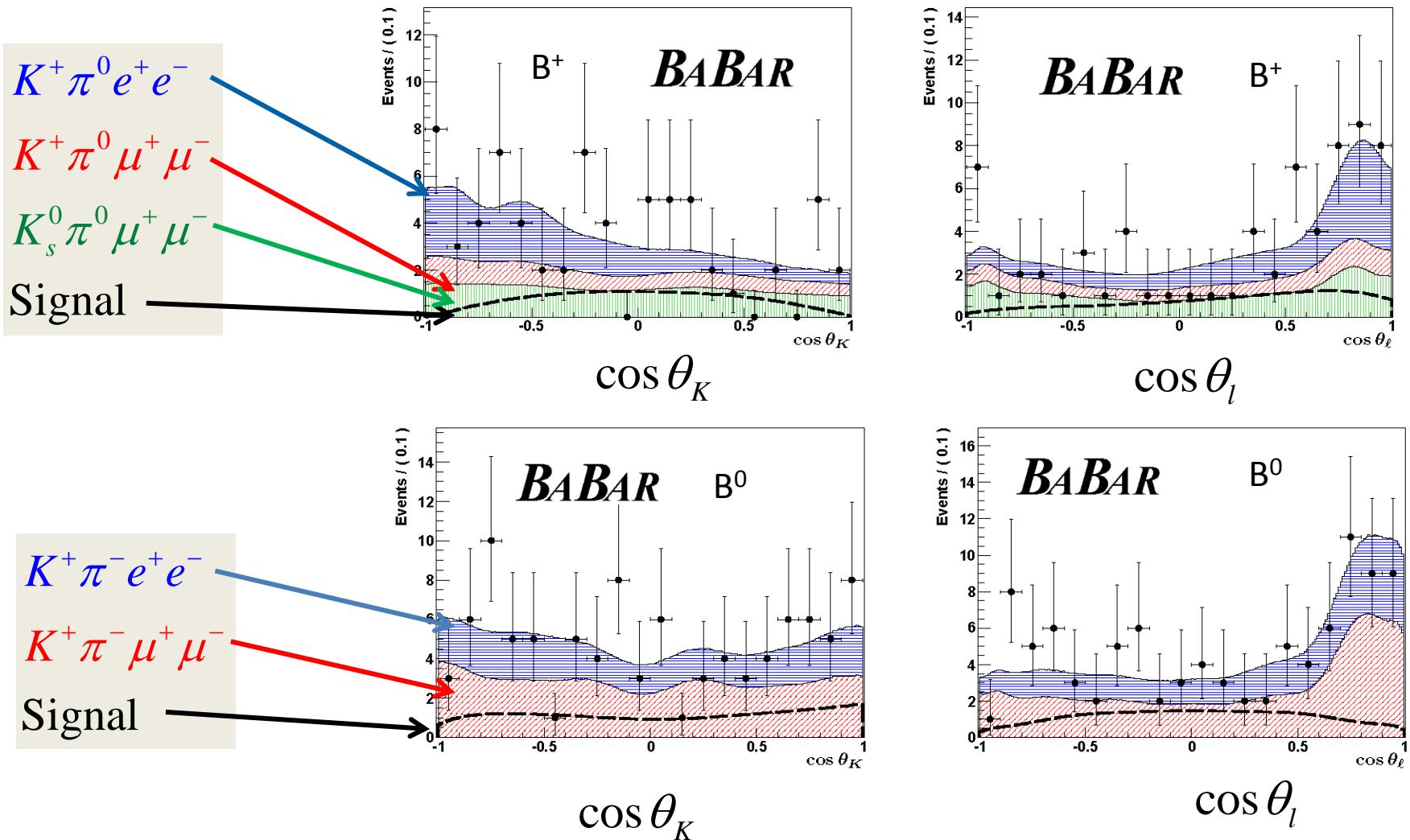


q^2 bin	Range (GeV^2/c^4)
q_1^2	0.10 – 2.00
q_2^2	2.00 – 4.30
q_3^2	4.30 – 8.12
q_4^2	10.11 – 12.89
q_5^2	14.21 – $(m_B - m_{K^*})^2$
q_0^2	1.00 – 6.00

$B \rightarrow K^* l^+ l^-$ results for bin $q^2_0 \quad 1 < q^2 < 6 \text{ GeV}^2$

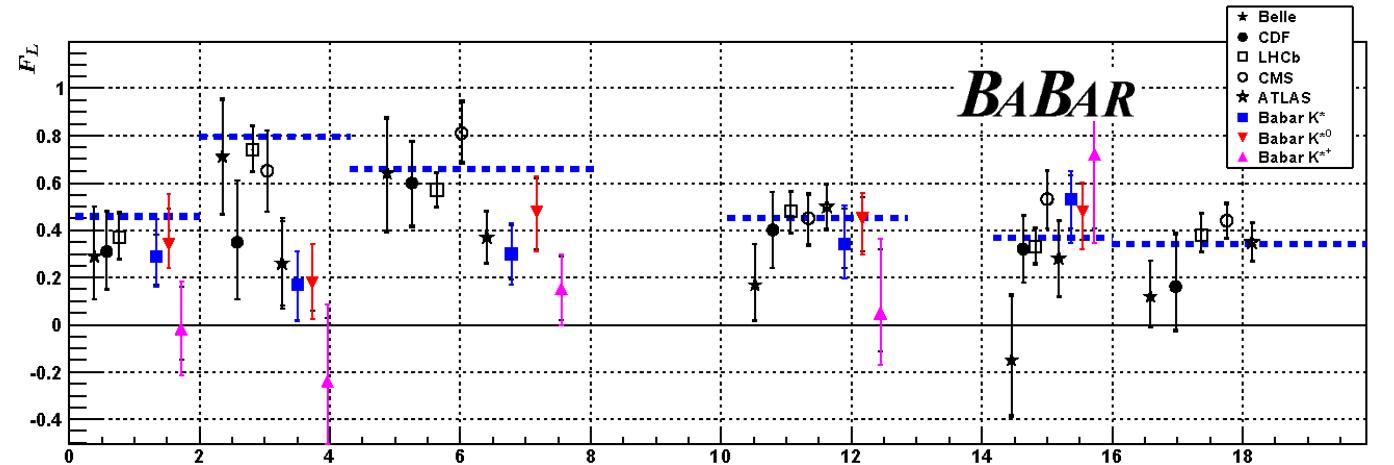


PRD 93, 052015 (2016)



The shaded distributions include signal and background

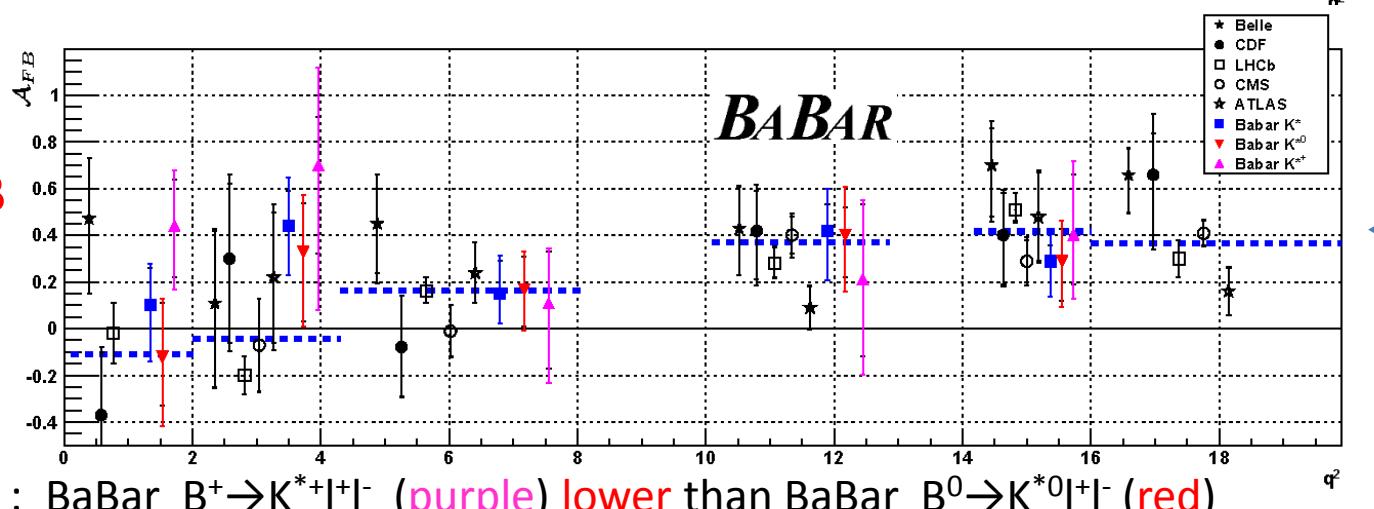
F_L and A_{FB} versus q^2



PRD 93, 052015 (2016)



SM (with $\pm 5\text{-}7\%$ uncertainty)



A_{FB}

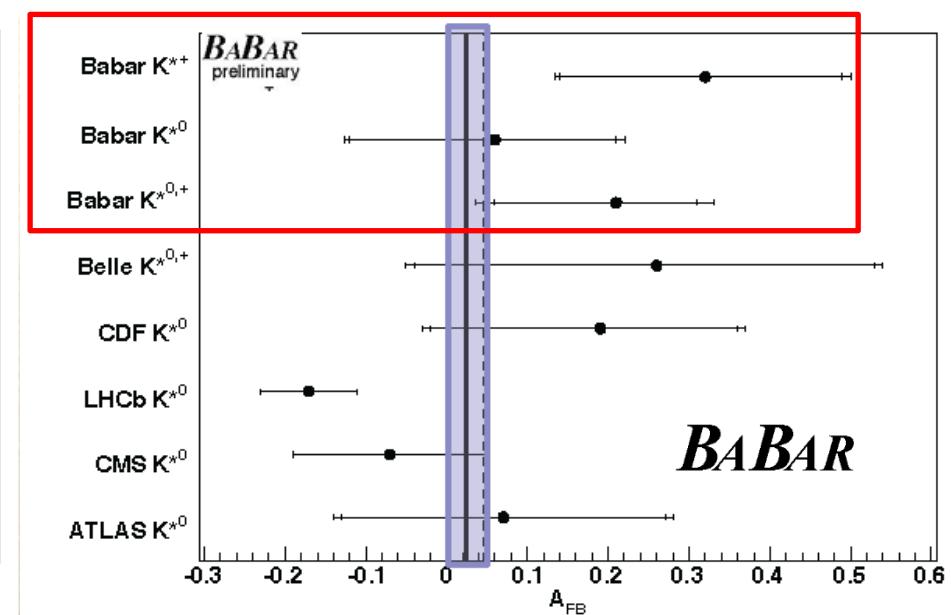
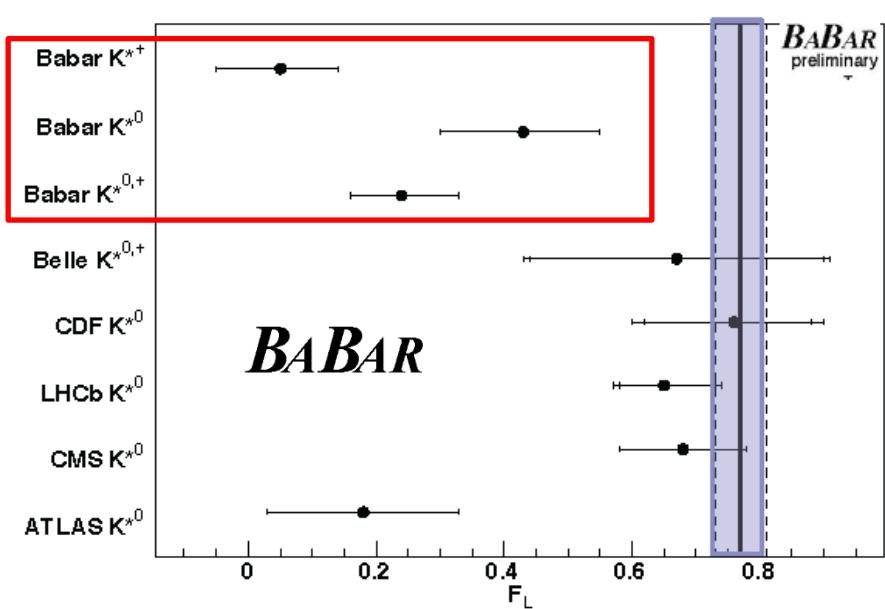
- F_L : BaBar $B^+ \rightarrow K^{*+} l^+ l^-$ (purple) lower than BaBar $B^0 \rightarrow K^{*0} l^+ l^-$ (red)
- F_L : BaBar $B \rightarrow K l^+ l^-$ (blue) agrees with SM except $q^2_2 (>3\sigma)$ and $q^2_3 (>2\sigma)$
- A_{FB} : BaBar $B^+ \rightarrow K^{*+} l^+ l^-$ agrees with BaBar $B^0 \rightarrow K^{*0} l^+ l^-$
- A_{FB} : BaBar $B \rightarrow K l^+ l^-$ agrees with SM except $q^2_2 (>2\sigma)$. Other bins agree with SM and other experiments.



F_L and A_{FB} between $1.0 < q^2 < 6.0 \text{ GeV}^2$

PRD 93, 052015 (2016)

- $1.0 < q^2 < 6.0 \text{ GeV}^2$ region less susceptible to theoretical uncertainties e.g. charmonia.
- BaBar F_L **lower** than SM prediction ($> 3\sigma$)
- BaBar A_{FB} **agrees** with SM and experiments.



Belle: PRL 103, 171801 (2012); LHCb: JHEP 08 (2013) 131; ATLAS: ATLAS-CONF 2013-038 (2013); CDF: PRL 108, 081808 (2012); CMS: PLB 727, 77 (2013)

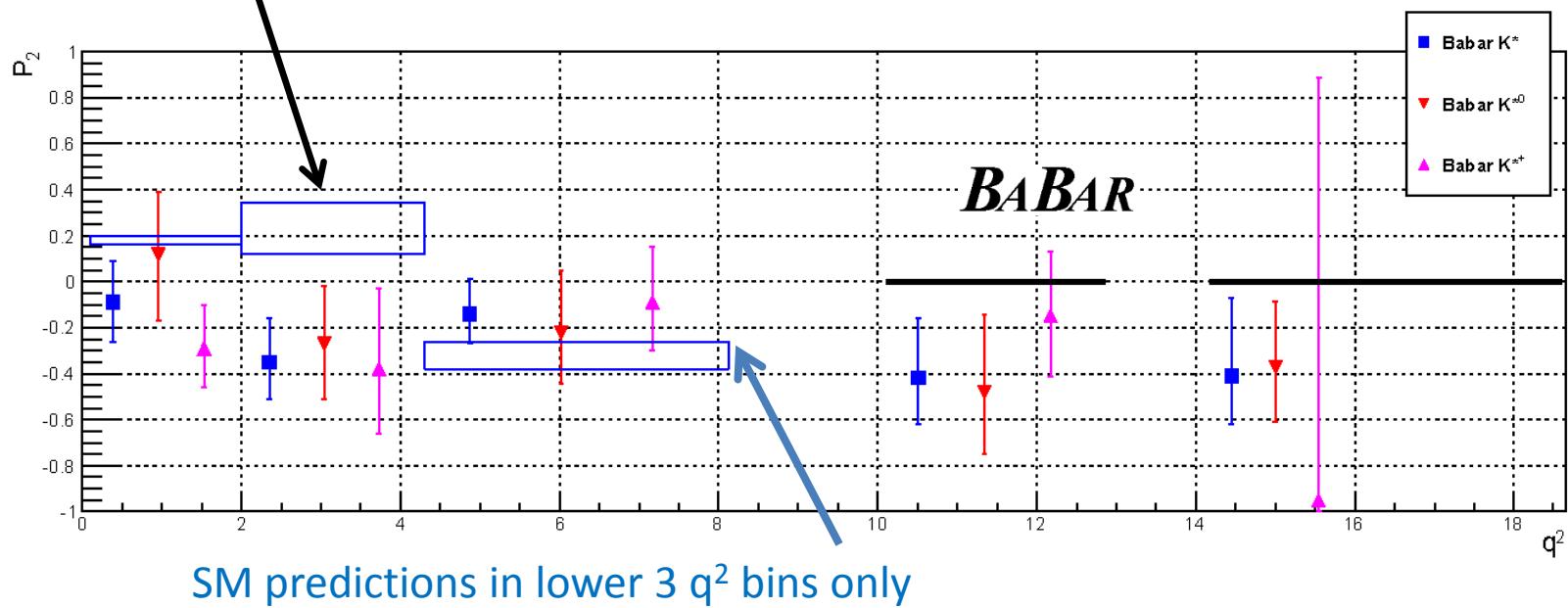


Results for P_2

PRD 93, 052015 (2016)

- P_2 less susceptible to theoretical uncertainties
- Between $1.0 < q^2 < 6.0 \text{ GeV}^2$: $P_2 = 0.11 \pm 0.10$
- In $q^2 > 2$, see $>2\sigma$ discrepancy with the SM

$$P_2 = -\frac{2}{3} \frac{A_{FB}}{(1 - F_L)}$$



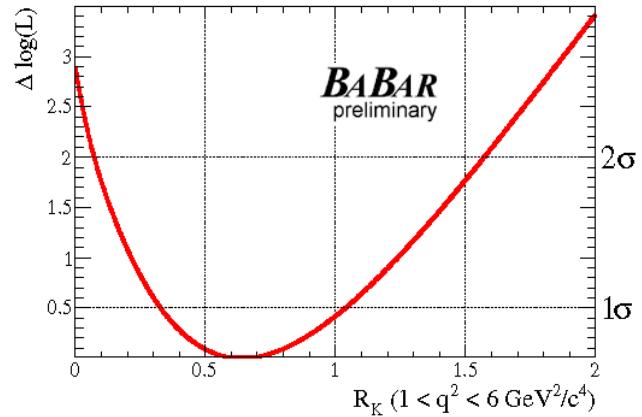
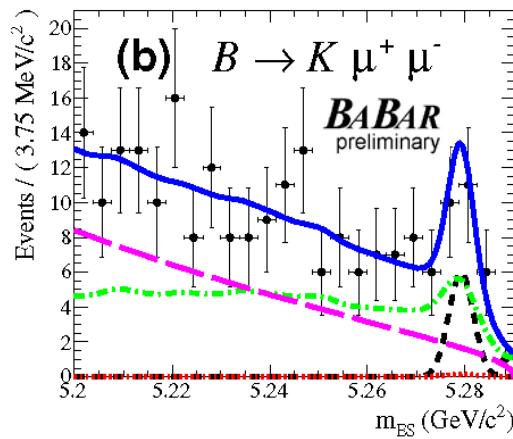
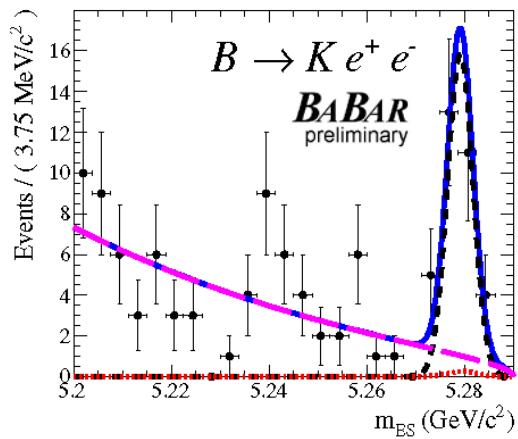


Lepton Universality in $B \rightarrow K l^+ l^-$

To be submitted to PRD

- Very similar motivation, selection, and data as previous topic.
- Update to [PRD 86, 032012 \(2012\)](#) using new q^2 range.
- Combine B^0 and B^+ decays.
- Use $1.0 < q^2 < 6.0 \text{ GeV}^2$ region where theory uncertainties are lowest.
- SM prediction $R_K \approx 1.0 \pm (0.001-0.01)$

$$R_K = \frac{B(B \rightarrow K \mu^+ \mu^-)}{B(B \rightarrow K e^+ e^-)}$$



$$R_K = 0.64^{+0.39}_{-0.30} \pm 0.06 \text{ [this result]}$$

$(1 < q^2 < 6 \text{ GeV}^2)$

$$R_K = 0.74^{+0.40}_{-0.31} \pm 0.06 \text{ [BaBar PRD 86, 032012 (2012)]} \quad (0.1 < q^2 < 8.1 \text{ GeV}^2)$$

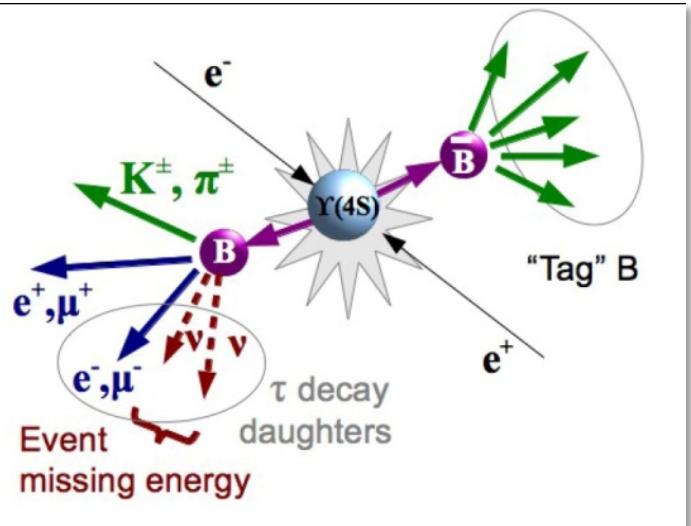
$$R_K = 0.745^{+0.090}_{-0.074} \pm 0.036 \text{ [LHCb PRL 113, 151601 (2014)]} \quad (1 < q^2 < 6 \text{ GeV}^2)$$

Consistent with previous BaBar result, SM and LHCb

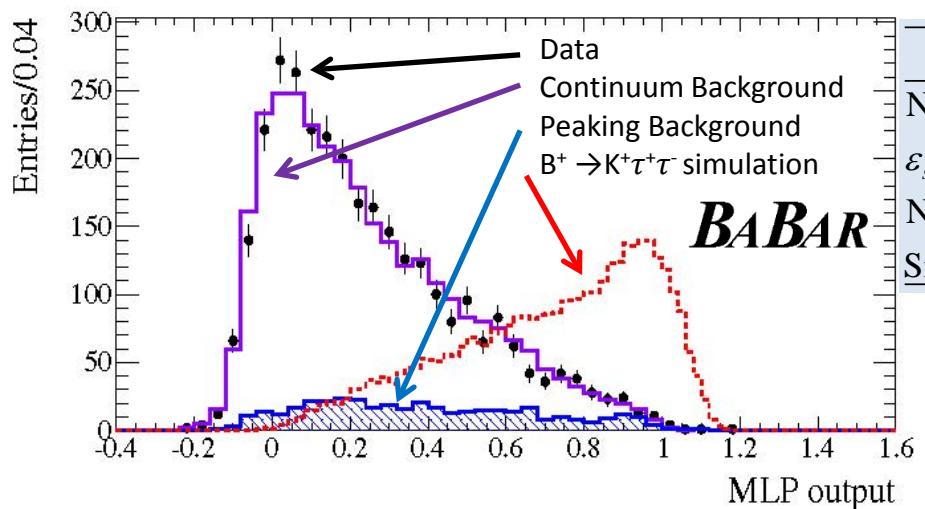


Search for $B^+ \rightarrow K^+\tau^+\tau^-$

arXiv:1605.09637



- NP coupling could be different to e^- or μ^- .
- Consider only $\tau^+ \rightarrow \mu^+ \nu_\mu \bar{\nu}_\tau$ and $\tau^+ \rightarrow e^+ \nu_e \bar{\nu}_\tau$ decays.
- Fully reconstruct one $B_{\text{tag}} \rightarrow SX$ through its hadronic decays:
 - S: $D^{(*)0}, D^{(*)\pm}, D_s^{*\pm}, J/\psi$
 - X: ≤ 5 kaons+pions
 - Constrains direction of signal B decay.
- Look for missing energy.
- Counting experiment, N_{obs} .
- N_{bkg} from simulation and data.



	e^+e^-	$\mu^+\mu^-$	$e^+\mu^-$
N_{bkg}	$49.4 \pm 2.4 \pm 2.9$	$45.8 \pm 2.4 \pm 3.2$	$59.2 \pm 2.8 \pm 3.5$
$\varepsilon_{\text{sig}} (\times 10^{-5})$	$1.1 \pm 0.2 \pm 0.1$	$1.3 \pm 0.2 \pm 0.1$	$2.1 \pm 0.2 \pm 0.2$
N_{obs}	45	39	92
Significance (σ)	-0.6	-0.9	3.7

$$B(B^+ \rightarrow K^+\tau^+\tau^-) = (1.31^{+0.66+0.35}_{-0.61-0.25}) \times 10^{-3}$$

$$B(B^+ \rightarrow K^+\tau^+\tau^-) < 2.25 \times 10^{-3} \text{ (90% CL UL)}$$



Conclusion

- BaBar continues to produce measurements of $b \rightarrow s\gamma$ transitions:
 1. Time-dependent CP asymmetries in $B^0 \rightarrow K_s^0 \pi^-\pi^+\gamma$
 2. Angular asymmetries in the decays $B \rightarrow K^* l^+l^-$ (first measurement in charged B mode).
 3. Lepton Flavour Ratio in $B \rightarrow K l^+l^-$
 4. First measurement of for $B^+ \rightarrow K^+\tau^+\tau^-$
- Results (including any tensions with SM) are compatible with measurements from other experiments.