Rare *B* decays at *BABAR*

Wolfgang Gradl

on behalf of the *BABAR* collaboration

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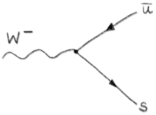
SFB 1044
THE LOW-ENERGY FRONTIER OF THE STANDARD MODEL

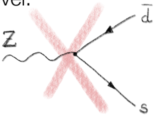
JG|U
JOHANNES GUTENBERG UNIVERSITÄT MAINZ

PRISMA

Flavour-changing neutral currents



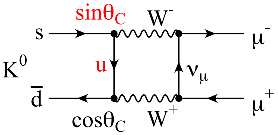
Quark flavour changed by interaction with W boson:
elementary vertices $qq'W$

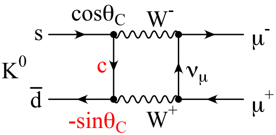


Standard model forbids flavour-changing neutral currents (FCNC) at tree level:
no elementary vertex bsZ or $bs\gamma$
GIM mechanism provides exact cancellation

Loops can induce FCNC, but they are suppressed by the GIM mechanism
amplitude $\propto$ mass squared difference of quarks

e.g. $K^0 \to \mu^+\mu^-$



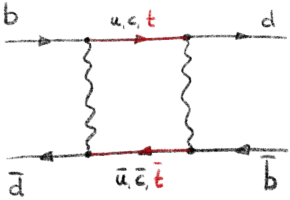


$$\mathcal{B}(K_L^0 \to \mu^+\mu^-) = (6.84 \pm 0.11) \times 10^{-9}$$

FCNC through loops

Loops can contain off-shell particles $\Rightarrow$ sensitivity to much larger mass/energy scales

Example: B^0-$\bar{B}^0$ oscillation proceeds mainly via loop containing t quark
observation of B^0-$\bar{B}^0$ oscillation at ARGUS in the late 1980's (handful of events of the type $e^+e^- \to \Upsilon(4S) \to B^0B^0$ or $\bar{B}^0\bar{B}^0$) immediately led to lower limit on $m_t > 50\,\mathrm{GeV}/c^2$

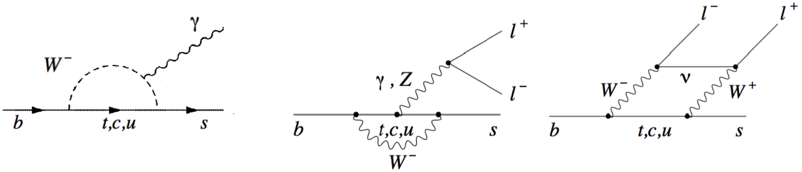


Parameters	Comments
$r > 0.09$ (90%CL)	this experiment
$x > 0.44$	this experiment
$B^{1/2} f_B \approx f_\pi < 160$ MeV	B meson ($\approx$pion) decay constant
$m_b < 5\ \mathrm{GeV}/c^2$	b-quark mass
$\tau < 1.4 \times 10^{-12}$s	B meson lifetime
$\lvert V_{td} \rvert < 0.018$	Kobayashi–Maskawa matrix element
$\eta_{QCD} < 0.86$	QCD correction factor [a)]
$m_t > 50\ \mathrm{GeV}/c^2$	t quark mass

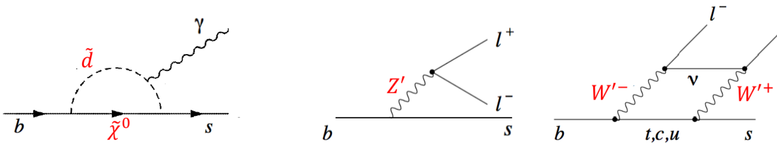
ARGUS, Phys. Lett. B **192**, 245 (1987)

FCNC in the SM and beyond

Standard model contributions



Sensitive to new physics, e.g.



Effective couplings

”Integrate out” heavy degrees of freedom (like Fermi theory of neutron β decay)

Effective Hamiltonian expressed via Operator Product Expansion (OPE) in terms of operators $\mathcal{O}_i$ and calculable *Wilson coefficients* C_i

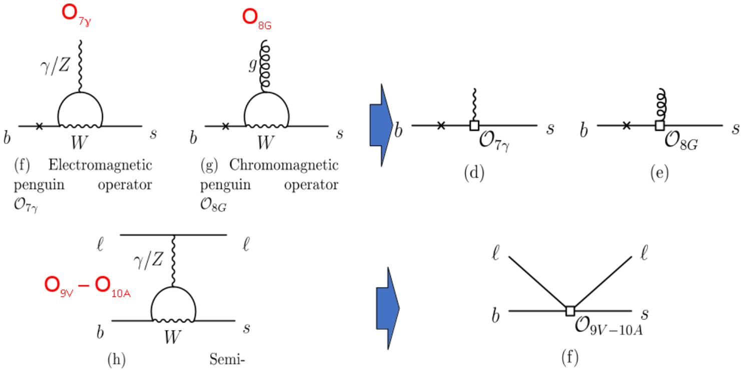
$$H_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tq}^* V_{tb} \sum_i C_i(\mu)\mathcal{O}_i(\mu) + \sum_i \frac{C_i^{NP}}{\Lambda^2}\mathcal{O}_i^{NP}$$

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

- potentially modifies phase and magnitude of SM C_i
- angular distributions as function of q^2 sensitive to NP
- probes new couplings and NP at a scale of a few TeV

For decays $b \to s\gamma$, $b \to s\ell^+\ell^-$:
relevant operators $\mathcal{O}_{7\gamma}, \mathcal{O}_{9,10}$

Effective couplings: $b \to s\ell^+\ell^-$



(f) Electromagnetic penguin operator $\mathcal{O}_{7\gamma}$

(g) Chromomagnetic penguin operator $\mathcal{O}_{8G}$

(h) Semi-leptonic operators $\mathcal{O}_{9V-10A}$

The *BABAR* experiment

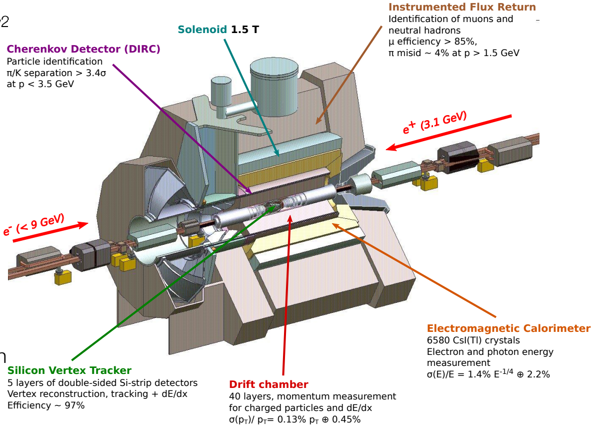
- PEP-II: e^+e^- collider, $3.1 \times 9\ \text{GeV}^2$
  $\sqrt{s} = 10.58\,\text{GeV}\ [\Upsilon(4S)]$

- Asymmetric beam energies
  c.m. lab boost $\beta\gamma = 0.56$

- Asymmetric detector
  - acceptance in c.m.
    $-0.9 \lesssim \cos\theta^* \lesssim 0.85$

- excellent performance
  - Good tracking, mass resolution
  - Good γ, π^0 reco.
  - Full PID for e, μ, π, K, p

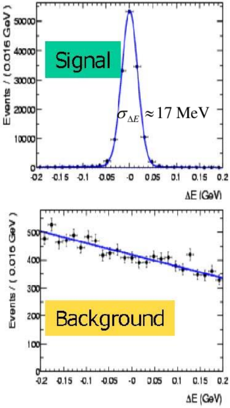
- in operation 1999 – 2008
  collaboration still active



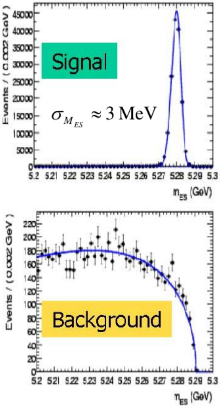
- High luminosity
  - $\mathcal{L}_{\text{peak}} = 12.069 \times 10^{33}\,\text{cm}^{-2}\,\text{s}^{-1}$
  - $426\,\text{fb}^{-1}$ on $\Upsilon(4S)$
    471 million $B\bar{B}$ pairs

Reconstructing B mesons

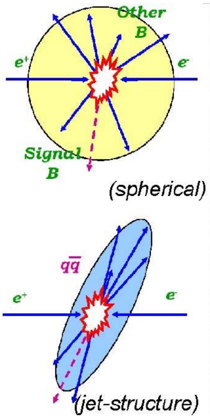
$$\Delta E = E_B^* - E_{beam}^*$$



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



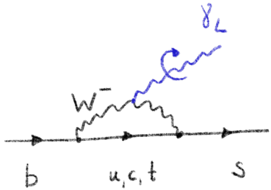
Event "shape"

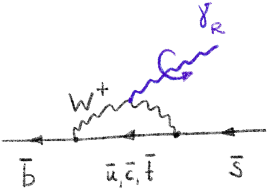


Blind analysis, multivariate discriminants, maximum likelihood fits

$B \to K\pi\pi\gamma$ overview

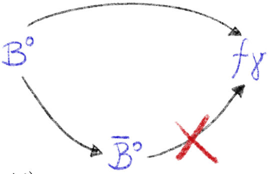
In the SM: left-handed quarks, right-handed anti-quarks ($V - A$ structure)
produce left-handed photons in $b \to s\gamma$ transition
opposite helicity suppressed by $\sim m_s/m_b \approx 0.02$





Therefore, $\bar{B}^0 \to s\gamma_L$ and $B^0 \to \bar{s}\gamma_R$

$B \to K\pi\pi\gamma$ overview



γ_L and γ_R in principle distinguishable
$\Rightarrow$ no interference between final state without and with mixing
$\Rightarrow$ no CP violation in interference

$$\mathcal{A}_{CP}(\Delta t) = S_{f_{CP}} \sin(\Delta m \Delta t) - C_{f_{CP}} \cos(\Delta m \Delta t)$$

SM prediction: $S_{f_{CP}\gamma} \sim 0.02$

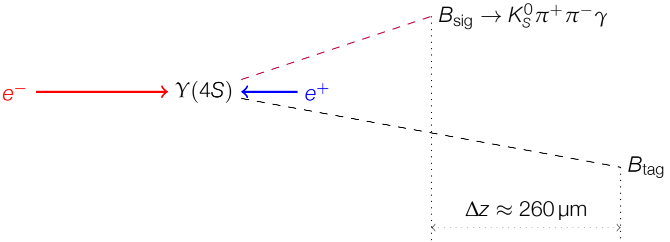
NP models with large right-handed contributions are allowed, within branching fractions, and can lead to large CP violation

Previous results:

- $B^0 \to K^0_S \rho^0 \gamma$ Belle Phys. Rev. Lett. **101**,251601 (2008),
  $B^0 \to K^0_S \pi^0 \gamma$ BABAR Phys. Rev. D **78**, 071102 (2008); Belle Phys. Rev. D **74**, 111104 (2006)
  CPV compatible with SM; no evidence for NP
- $B^+ \to K^+ \pi^+ \pi^- \gamma$ LHCb Phys. Rev. Lett. **112**, 161801 (2014)
  photon polarisation non-zero (5.2σ)

$B^0 \to K_S^0 \pi^+ \pi^- \gamma$ analysis strategy

BABAR, Phys. Rev. D **93**, 052103



B meson decay-time distribution in presence of CP violation:

$$\propto \exp\left(\frac{|\Delta t|}{\tau_{B^0}}\right)\left[1 + q_{\text{tag}}\left\{\frac{\Delta D}{2} + D\left(S\sin(\Delta t \Delta m) - C\cos(\Delta t \Delta m)\right)\right\}\right] \otimes R(\Delta t)$$

q_{tag}	$= 1(-1)$ for $B_{\text{tag}} = B^0(\bar{B}^0)$
$\Delta D, D$	Mistag probabilities
S	CPV in interference (suppressed in SM: $\sim m_s/m_b$)
C	direct CPV (0 in SM for CP-eigenstate final state)

$B^0 \to K_S^0\pi^+\pi^-\gamma$ analysis strategy

1. problem: background from $B \to K^{*\pm}\pi^{\mp}\gamma$ dilutes $S_{K_S\rho\gamma}$ from $B^0 \to K_S^0\rho^0\gamma$
   need to perform full amplitude analysis to obtain dilution factor
   $D_{K_S\rho\gamma} \equiv S_{K_S\pi\pi\gamma}/S_{K_S\rho\gamma}$
2. problem: not enough $B^0 \to K_S^0\pi^+\pi^-\gamma$ to perform amplitude analysis
   - Perform amplitude analysis on $B^+ \to K^+\pi^+\pi^-\gamma$ to identify resonances and amplitudes
   - Use isospin relations to relate $B^+ \to K^+\pi^+\pi^-\gamma$ to $B^0 \to K_S^0\pi^+\pi^-\gamma$
     Hebinger, Kou, and Yu, LAL-15-75
   - Calculate dilution factor from these amplitudes

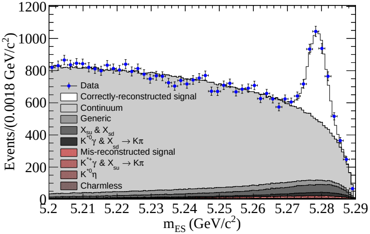
$$D_{K_S\rho\gamma} = \frac{\int \left[|\mathcal{A}_{K_S\rho}|^2 - |\mathcal{A}_{K^{*+}\pi^-}|^2 - |\mathcal{A}_{(K\pi)_0^+\pi^-}|^2 + 2\Re(\mathcal{A}^*_{K_S\rho}A_{K^{*+}\pi^-}) + 2\Re(\mathcal{A}^*_{K_S\rho}A_{(K\pi)_0^+\pi^-}) \right] \mathrm{d}m^2}{\int \left[|\mathcal{A}_{K_S\rho}|^2 + |\mathcal{A}_{K^{*+}\pi^-}|^2 + |\mathcal{A}_{(K\pi)_0^+\pi^-}|^2 + 2\Re(\mathcal{A}^*_{K_S\rho}A_{K^{*+}\pi^-}) + 2\Re(\mathcal{A}^*_{K_S\rho}A_{(K\pi)_0^+\pi^-}) \right] \mathrm{d}m^2}$$

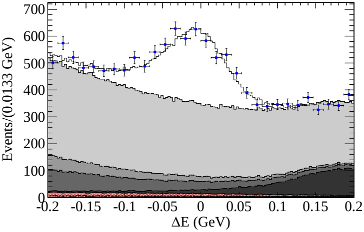
Use full phase space to determine amplitudes
Determine dilution factor in optimised region

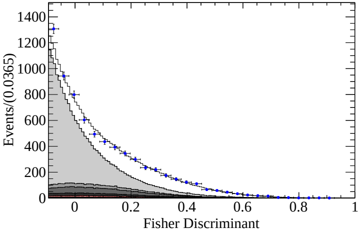
$0.6 < m_{\pi^+\pi^-} < 0.9$ GeV, $m_{K\pi} < 0.845$ GeV or $m_{K\pi} > 0.945$ GeV

$B^+ \to K^+\pi^+\pi^-\gamma$ results

Determine B^+ yield from ML fit to m_{ES}, ΔE, and event-shape Fisher discriminant

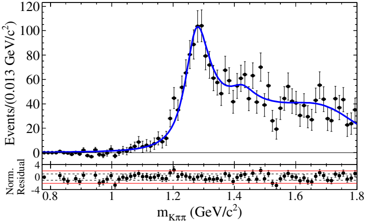




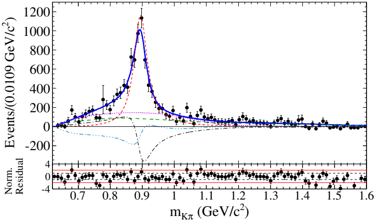


$B^+ \to K^+\pi^+\pi^-\gamma$ amplitudes

Use sPlot technique to produce background-subtracted mass spectra
perform 1D fits (not enough statistics)



Mode	$\mathcal{B}(B^+ \to \text{Mode})[10^{-6}]$	Previous WA $[10^{-6}]$
$K_1(1270)^+\gamma$	$44.1^{+6.3+3.6}_{-4.4-3.6} \pm 4.6$	43 ± 13
$K_1(1400)^+\gamma$	$9.7^{+4.6+2.8}_{-2.9-2.3} \pm 0.6$	< 15
$K^*(1410)^+\gamma$	$27.1^{+5.4+5.2}_{-4.8-2.6} \pm 2.7$	n/a
$K^*_2(1430)^+\gamma$	$8.7^{+7.0+8.7}_{-5.3-10.4} \pm 0.4$	14 ± 4
$K^*(1680)^+\gamma$	$66.7^{+9.3+13.3}_{-7.8-10.0} \pm 5.4$	< 1900

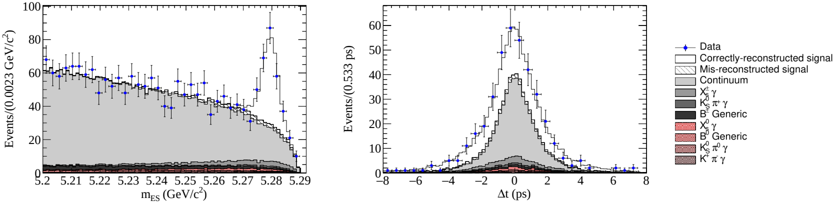


Mode	$\mathcal{B}(B^+ \to \text{Mode})[10^{-6}]$	Previous WA $[10^{-6}]$
$K^*(892)^0\pi^+\gamma$	$23.4 \pm 0.9^{+0.8}_{-0.7}$	20^{+7}_{-6}
$K^+\rho(770)^0\gamma$	$8.2 \pm 0.4 \pm 0.8 \pm 0.02$	< 20
$(K\pi)^0_0\pi^+\gamma$ (NR)	$9.9 \pm 0.7^{+1.5}_{-1.9}$	< 9.2
$K^*_0(1430)^0\pi^+\gamma$	$1.32^{+0.09+0.20}_{-0.10-0.26}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

$B^0 \to K_S^0 \pi^+ \pi^- \gamma$ results

BABAR, Phys. Rev. D **93**, 052103

B^0 yield and CP parameters from time-dependent ML fit



Results:

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

$$S_{K_S\pi^+\pi^-\gamma} = +0.14 \pm 0.25 \pm 0.03 \qquad D_{K_S\rho\gamma} = -0.78^{+0.19}_{-0.17}$$

$$C_{K_S\pi^+\pi^-\gamma} = -0.39 \pm 0.20^{+0.03}_{-0.02} \qquad S_{K_S\rho\gamma} = -0.18 \pm 0.32^{+0.06}_{-0.05}$$

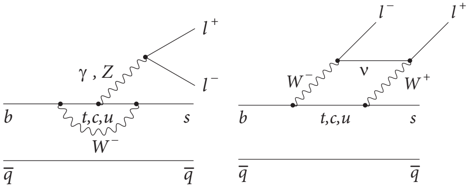
Consistent with Belle Phys. Rev. Lett. **101**, 251601 (2008)

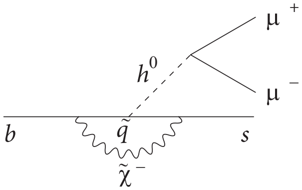
Several new amplitudes observed

CP asymmetries consistent with zero and the SM

Angular analysis of $B \to K^* \ell^+ \ell^-$

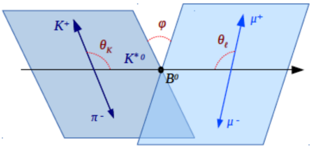
BABAR, Phys. Rev. D **93**, 052105





$B \to K^* \ell^+ \ell^-$ angular distribution depends on

- θ_K between K and B in K^* rest frame
- θ_ℓ between ℓ^+ and B (ℓ^- and $\bar{B}$) in $\ell^+\ell^-$ rest frame
- ϕ between di-lepton and $K\pi$ planes



$q^2 \equiv m^2(\ell^+\ell^-)$

Test operators $\mathcal{O}_{7\gamma}, \mathcal{O}_{9V}, \mathcal{O}_{10A}$

Angular analysis of $B \to K^* \ell^+ \ell^-$

BABAR, Phys. Rev. D **93**, 052105

Extract yield with ML fit to (m_{ES}, ΔE, BDT probability)

Not enough events to perform full angular analysis: integrate over two angles to find longitudinal polarisation F_L and lepton forward-backward asymmetry $\mathcal{A}_{FB}$

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

$$\frac{1}{\Gamma(q^2)} \frac{\mathrm{d}\Gamma}{\mathrm{d}\cos\theta_\ell} = \frac{3}{4} F_L(q^2) \sin^2\theta_\ell + \frac{3}{8}(1 - F_L(q^2))(1 + \cos^2\theta_\ell) + \mathcal{A}_{FB}(q^2) \cos\theta_\ell$$

Use 5 final states

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

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

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

and 6 bins in q^2, excluding charmonium states J/ψ and $\psi(2S)$

New: electron mode for B^0; first measurement for B^+ decays

Results for bin q_0^2: $1 < q^2 < 6\ \mathrm{GeV}^2$

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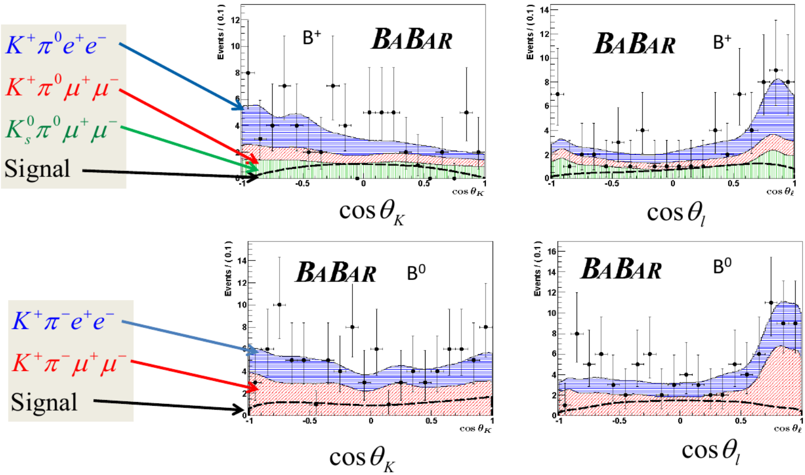

shaded distributions include signal and background

F_L and $\mathcal{A}_{FB}$ versus q^2

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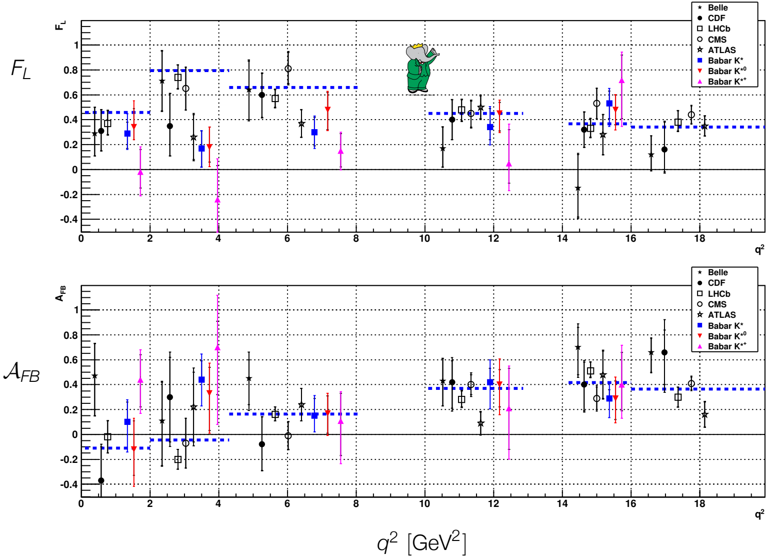
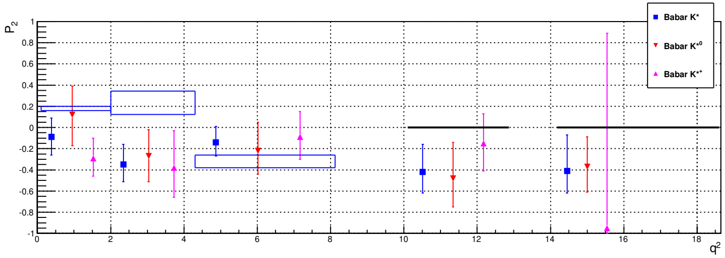


Observable P_2

Less susceptible to theoretical uncertainties than F_L, $\mathcal{A}_{FB}$ alone:

$$P_2 \equiv -\frac{2}{3}\frac{\mathcal{A}_{FB}}{1-F_L}$$

For $1 \leq q^2 \leq 6\text{GeV}^2$: $P_2^{SM} = 0.11 \pm 0.10$ Descotes-Genon *et al.*, JHEP12(2014)125



In bin q_2^2, see discrepancy $> 2\sigma$ with SM

Summary

- *BABAR* continues to produce measurements of $b \to s\gamma$ transitions:
  Time-dependent *CP* asymmetries in $B^0 \to K^0_S \pi^+\pi^-\gamma$
  Angular asymmetries in the decays $B \to K^*\ell^+\ell^-$
  first measurements in charged *B* mode
- Results (including any tensions with SM) compatible with measurements from other experiments
- Much more statistics needed to improve precision
  (LHCb; Belle II, see Riccardo's talk yesterday)