

Prospects for

$$B_d \rightarrow K^{*0} \mu^+ \mu^-$$

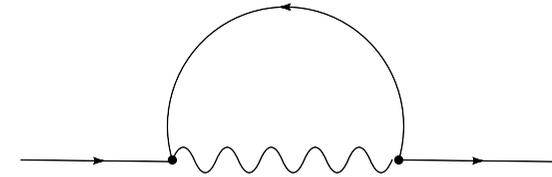
at LHCb

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Imperial College London

Physics at the LHC, 3rd October 2008

Introduction



- FCNC $b \rightarrow s$ quark transitions occur via a loop
- New physics (NP) can enter the loop
- Treat with Operator Product Expansion $\mu = m_b$
 - Model independent approach

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} \mathbf{V}_{tb} \mathbf{V}_{ts}^* \sum_{i=1}^{10} [\mathbf{C}_i(\mu) \mathcal{O}_i(\mu) + \mathbf{C}'_i(\mu) \mathcal{O}'_i(\mu)]$$

- Wilson Coefficients give short range Physics
 - Measure to discover or exclude entire classes of NP

$$B_d \rightarrow K^{*0} \mu^+ \mu^-$$

- First observed at Belle

- $Br(B_d \rightarrow K^{*0} \mu^+ \mu^-) = (1.22_{-0.32}^{+0.38}) \times 10^{-6}$

- Particles in Loop

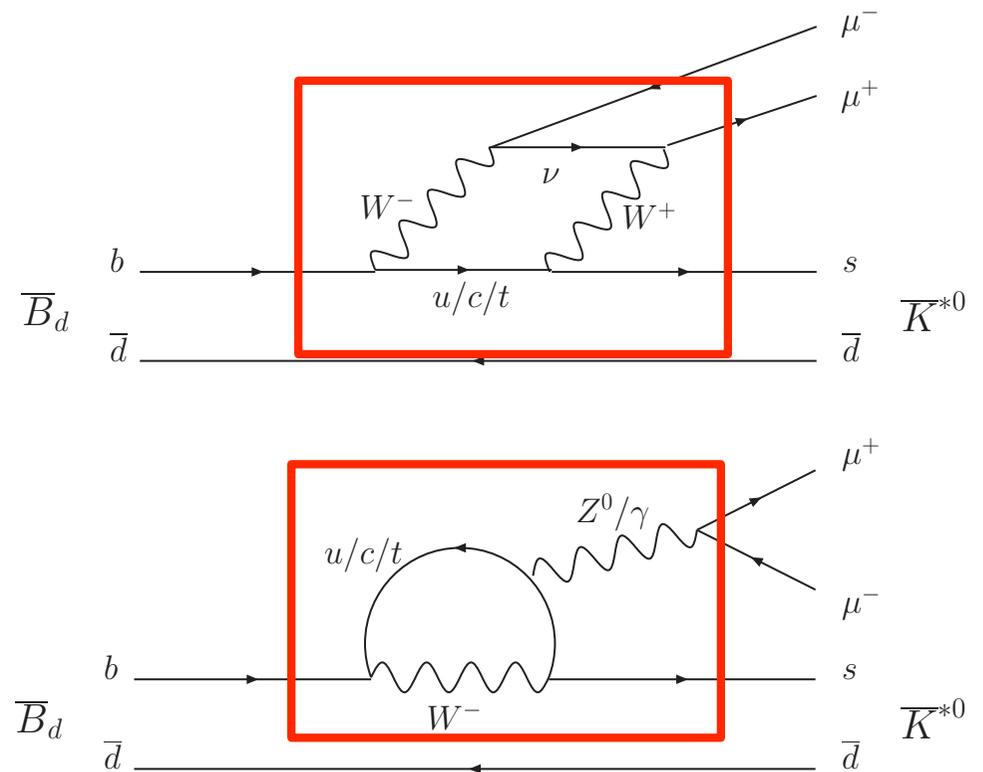
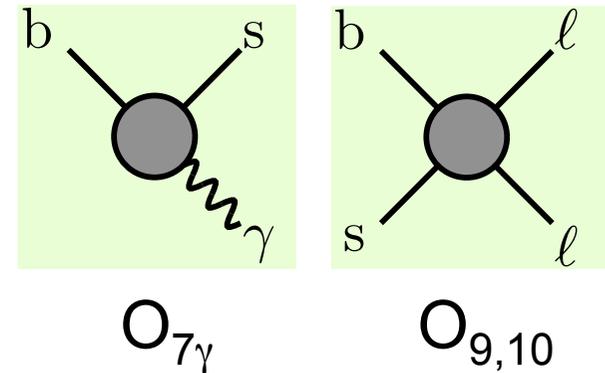
- Both neutral and charged NP (replace $W^\pm, Z^0/\gamma, u/c/t$)

- Sensitive to NP

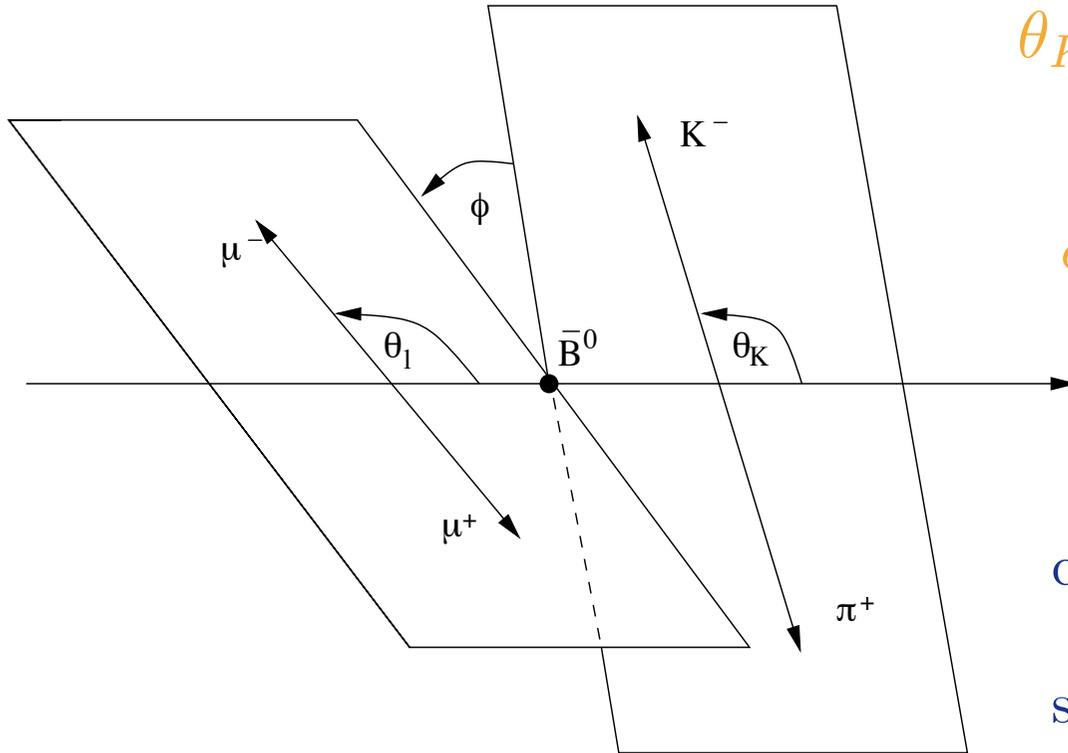
- Dominated by C_7, C_9, C_{10}
 - Studied with NP from SUSY, Littlest Higgs, Randall-Sundrum, Universal Extra Dimensions etc

- Laboratory for Studying NP

- Complementary to direct searches
 - Offers NP model discrimination for any LHC discoveries



Decay Kinematics



θ_l : Angle between μ^- and B in $\mu\mu$ rest frame

θ_K : Angle between K^- and the \bar{B} in the \bar{K}^{*0} rest frame

ϕ : Angle between the \bar{K}^{*0} and $\mu\mu$ decay planes

See e.g. arXiv: 0807.2589

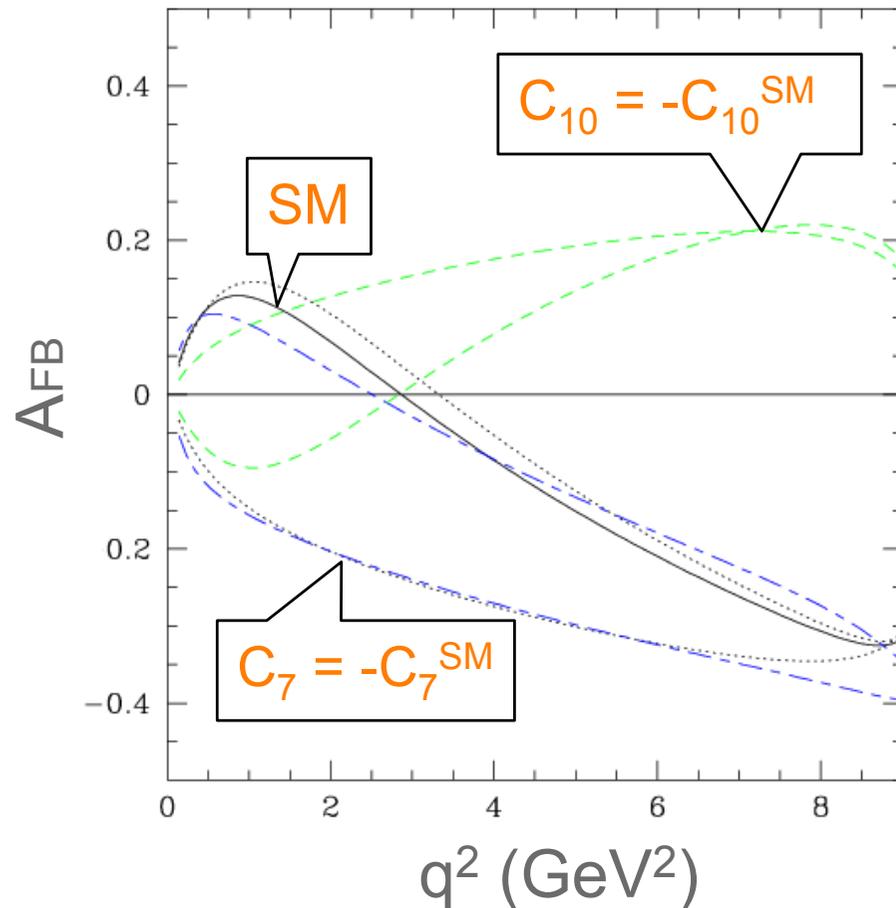
$$\cos \theta_l = \frac{q_\mu \cdot e_z}{|q_{\mu^-}|} \quad \cos \theta_K = \frac{r_{K^-} \cdot e_z}{|r_{K^-}|}$$

$$\sin \phi = (e_l \times e_K) \cdot e_z \quad \cos \phi = e_K \times e_l$$

- Decay in terms of 3 Angles and 1 Invariant Mass
 - θ_l, θ_K, ϕ and q^2 , the invariant mass squared of μ pair

$$e_z = \frac{p_{K^-} + p_{\pi^+}}{|p_{K^-} + p_{\pi^+}|}, e_l = \frac{p_{\mu^-} \times p_{\mu^+}}{|p_{\mu^-} \times p_{\mu^+}|}, e_K = \frac{p_{K^-} \times p_{\pi^+}}{|p_{K^-} \times p_{\pi^+}|}$$

What to Measure?



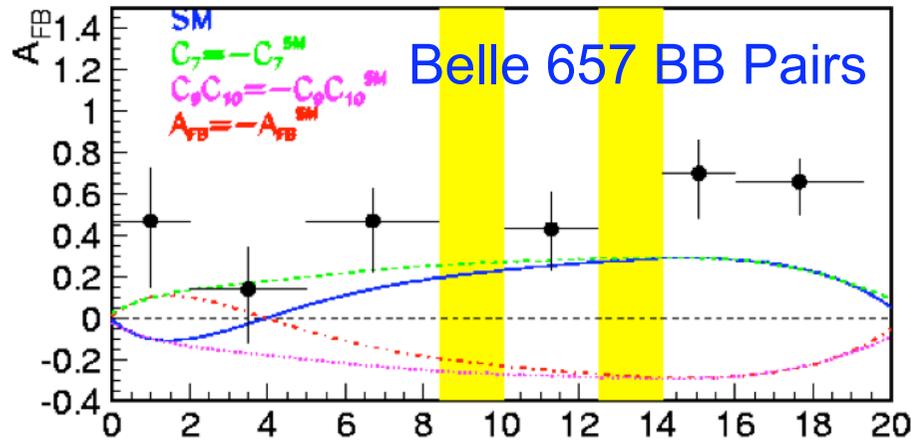
Ali *et al*, PR **D61**:074024 (2000)

- Angular observables
 - Small theory error
 - Experimentally accessible
- E.g. forward-backward asymmetry of $\mu\mu$
 - Sensitive to interference between C_7 , C_9 & C_{10}
- Plausible NP models
 - Large deviations
- Zero crossing point (q^2_0)
 - Accessible with small integrated luminosities ($\sim 0.5\text{fb}^{-1}$)
 - Form factors cancel at leading order

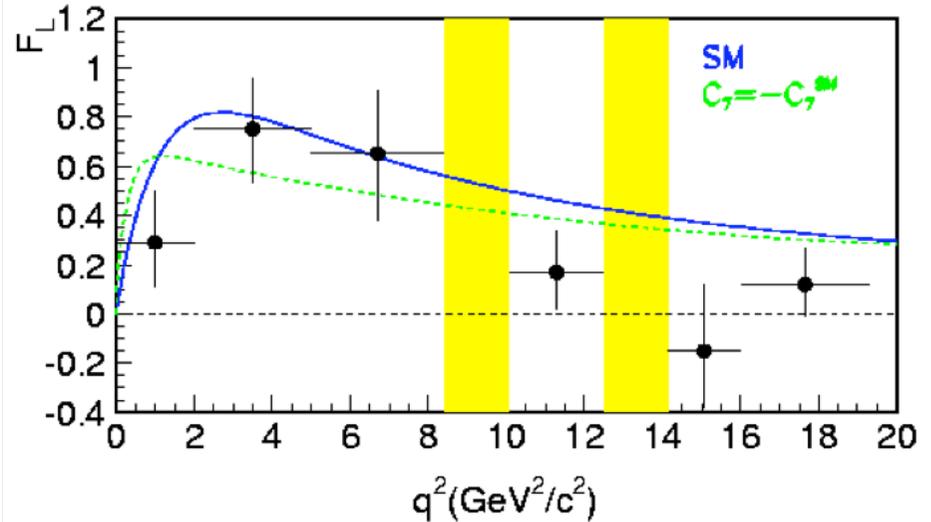
Current Status – Interesting Hints?

Belle (2008) - ICHEP

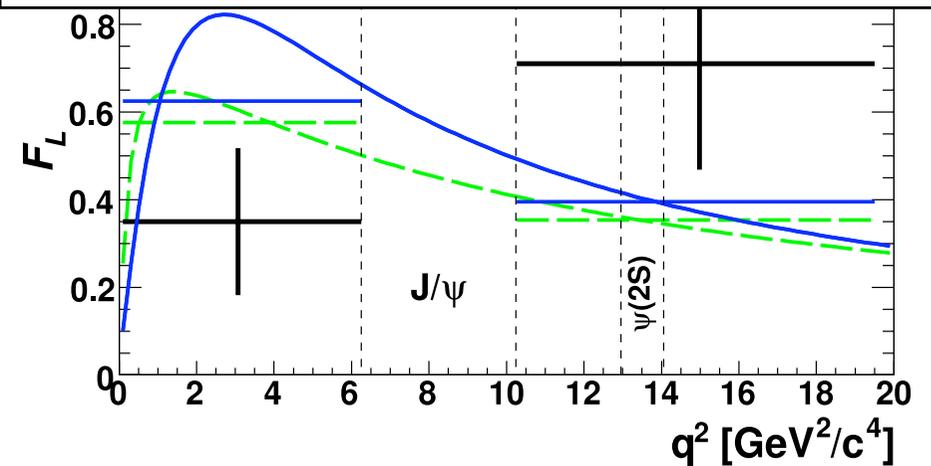
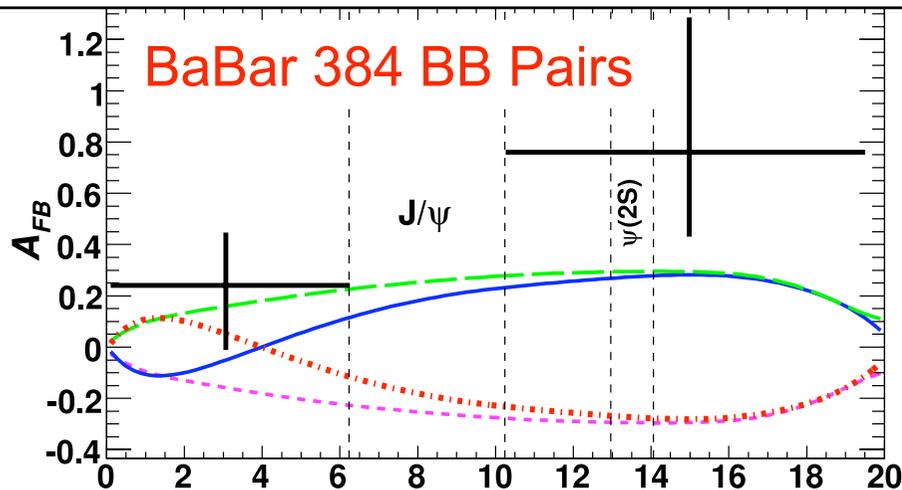
BaBar (2008) – 0804.4412



Opposite sign convention w.r.t. LHCb



F_L – longitudinal polarization of the K^*

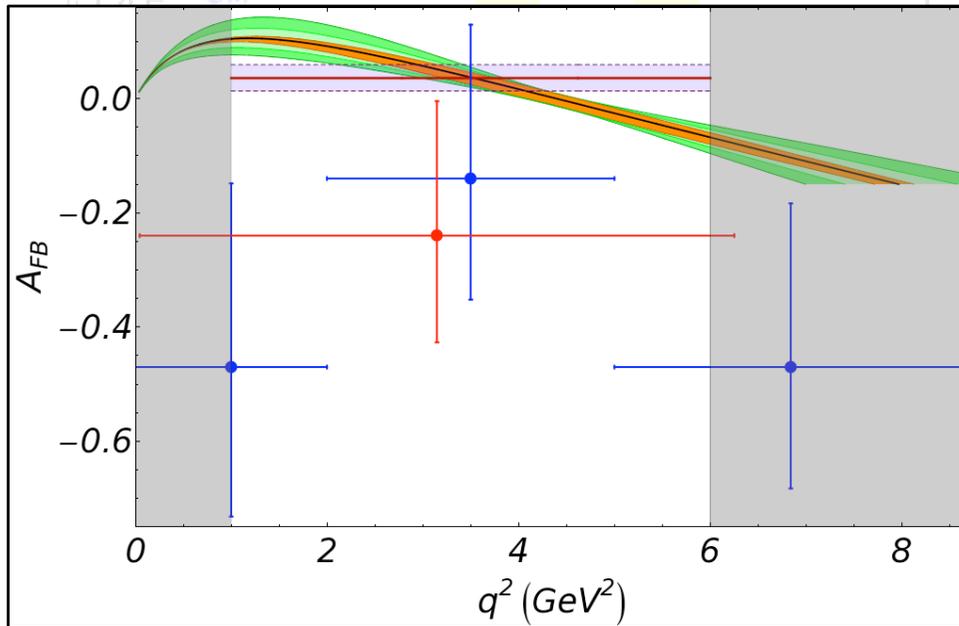


Current Status – Zooming In

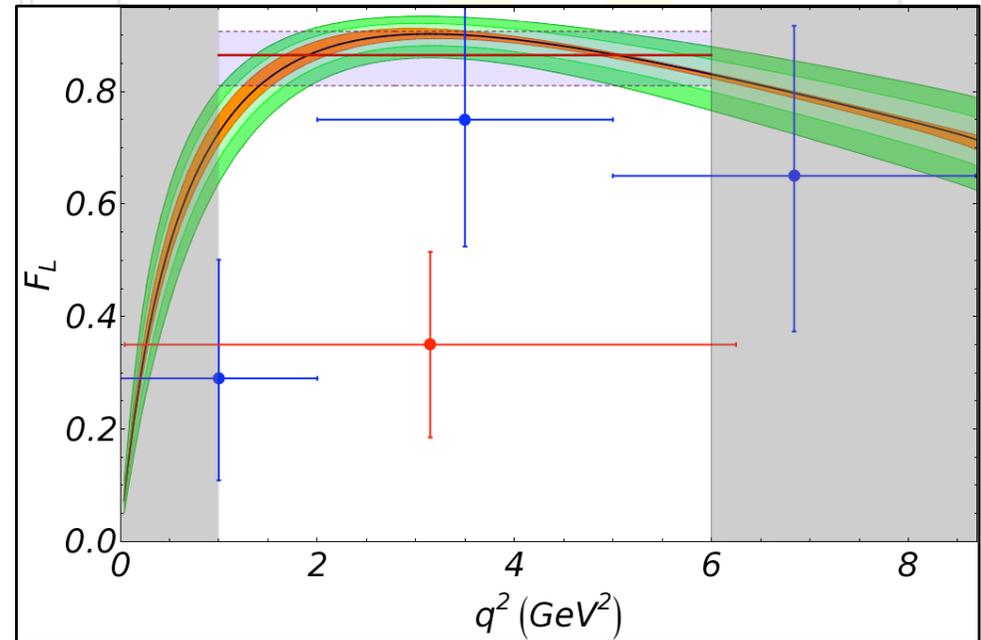
Belle (2008) - ICHEP

BaBar (2008) – 0804.4412

AFB



FL



Observables only reliably calculable in q^2 region 1-6 GeV^2/c^4

Up to LHCb to see what is really going on!

(SM + Errors from arXiv: 0807.2589)

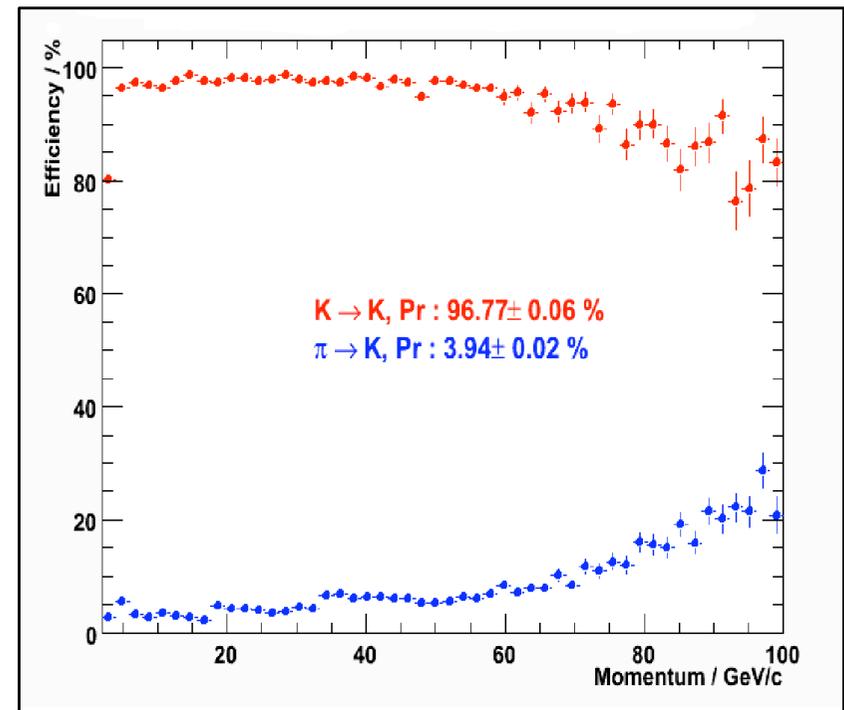
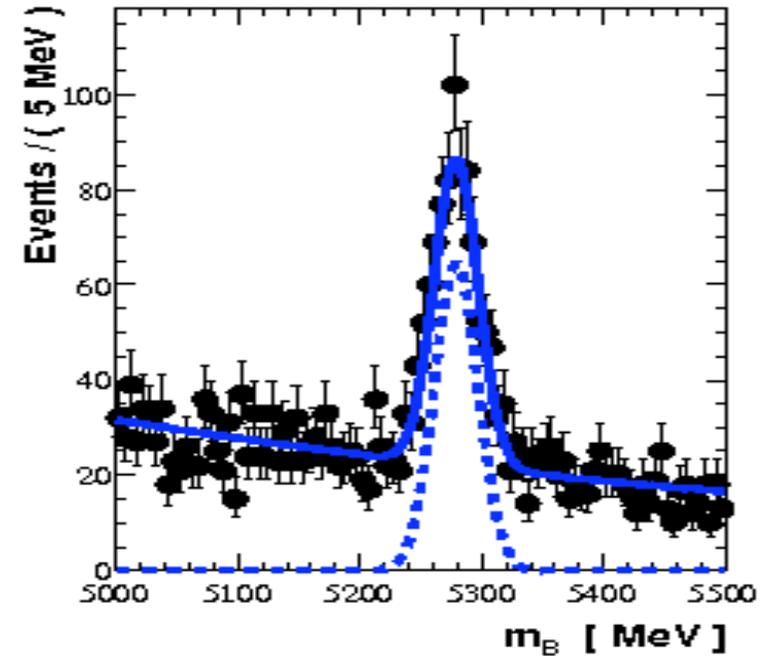
BaBar (2008) ~100 events, Belle (2008) ~ 200 events

Less than 0.1fb^{-1} will give same statistics as currently available

LHCb (2fb^{-1}) ~ 7.2k events

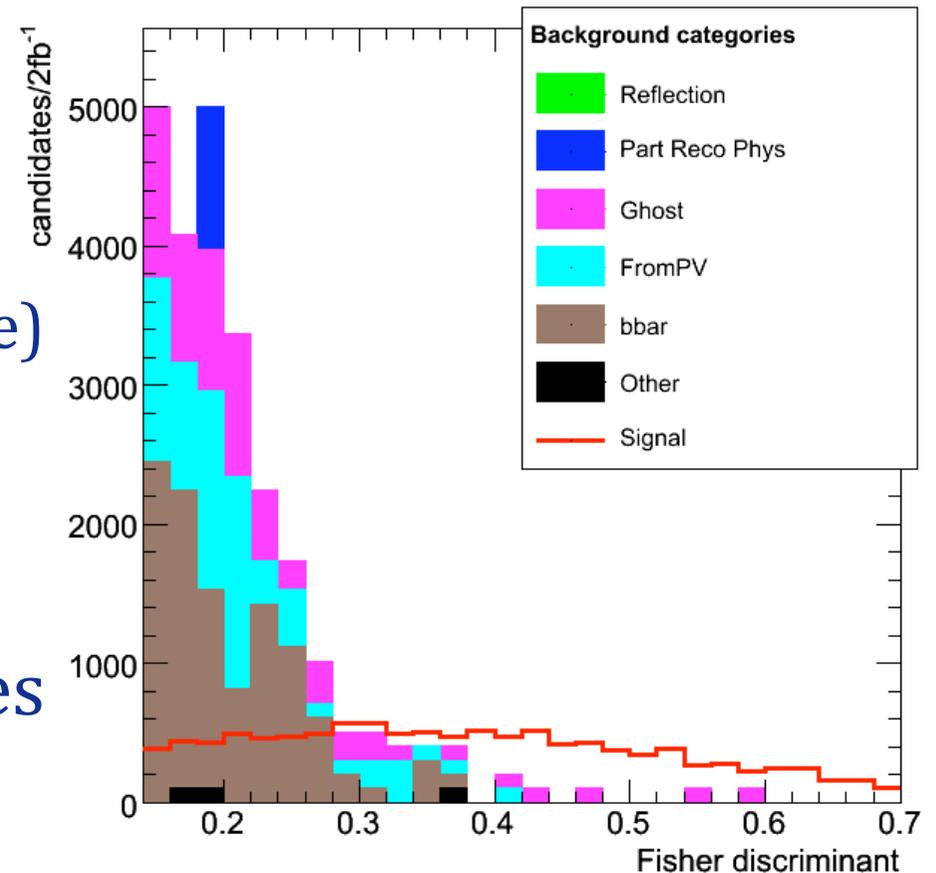
Selecting the Signal at LHCb

- Challenging Environment
 - LHCb Optimized for B-physics
- L0 μ trigger
 - μ p_T threshold $\sim 1\text{GeV}$
- B_d vertex res. $\sim 130\mu\text{m}$
- Track momentum $\sim 0.5\%$
 - B_d mass res. $\sim 18\text{ MeV}$
- Good μ ID performance key
- π/K separation from RICHs



Signal Yields

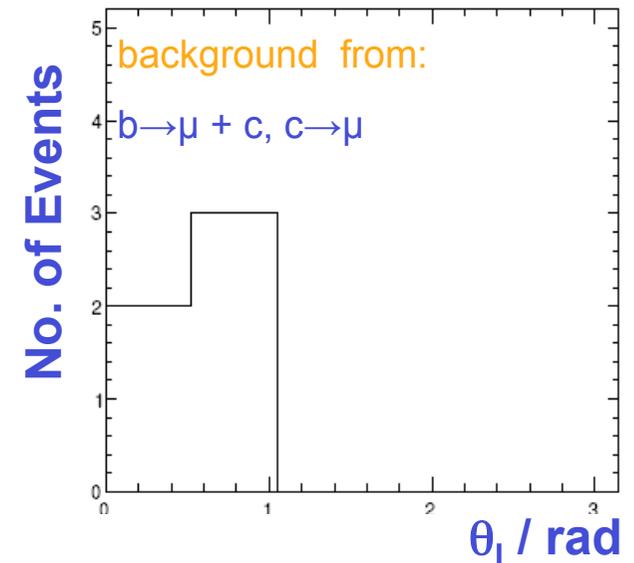
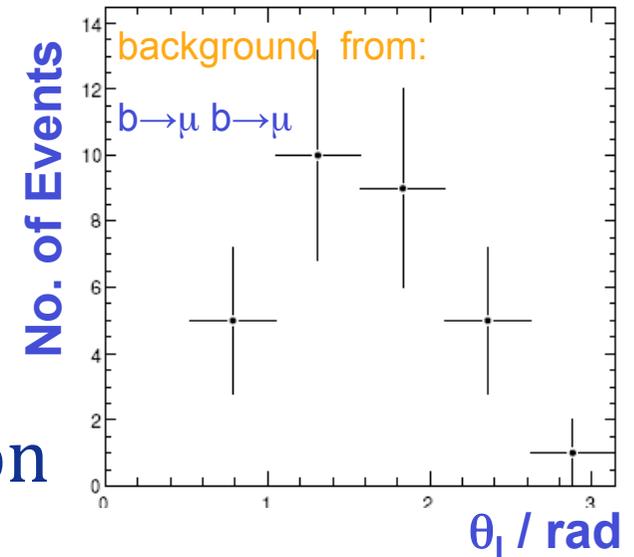
- Latest full MC studies:
 - Total selection eff. 1.1%
 - $\sim 7.2\text{k}$ per 2fb^{-1} (full q^2 range)
 - $\sim 3.7\text{k}$ per 2fb^{-1} ($q^2 < m_{J/\psi}^2$)
 - $\sim 1.1\text{k}$ of background events
 - See CERN-LHCb-2007-038
- Use multivariate techniques
 - B_d flight distance, IP, PID likelihoods



2fb^{-1} is the expected integrated luminosity for one nominal year of smooth LHCb data taking

Background at LHCb

- Dominated by genuine μ from B_d
 - Little μ mis-ID in MC
- $b \rightarrow \mu, b \rightarrow \mu$ dominant contribution
 - Symmetric in θ_1 , scales A_{FB} observed
- $b \rightarrow \mu + c, c \rightarrow \mu$ significant
 - Asymmetric in θ_1 , affects A_{FB}
- Non-resonant $B_d \rightarrow K \pi \mu \mu$ thought to be small
 - Limits set from $B \rightarrow K^* \gamma$
 - Will measure in data

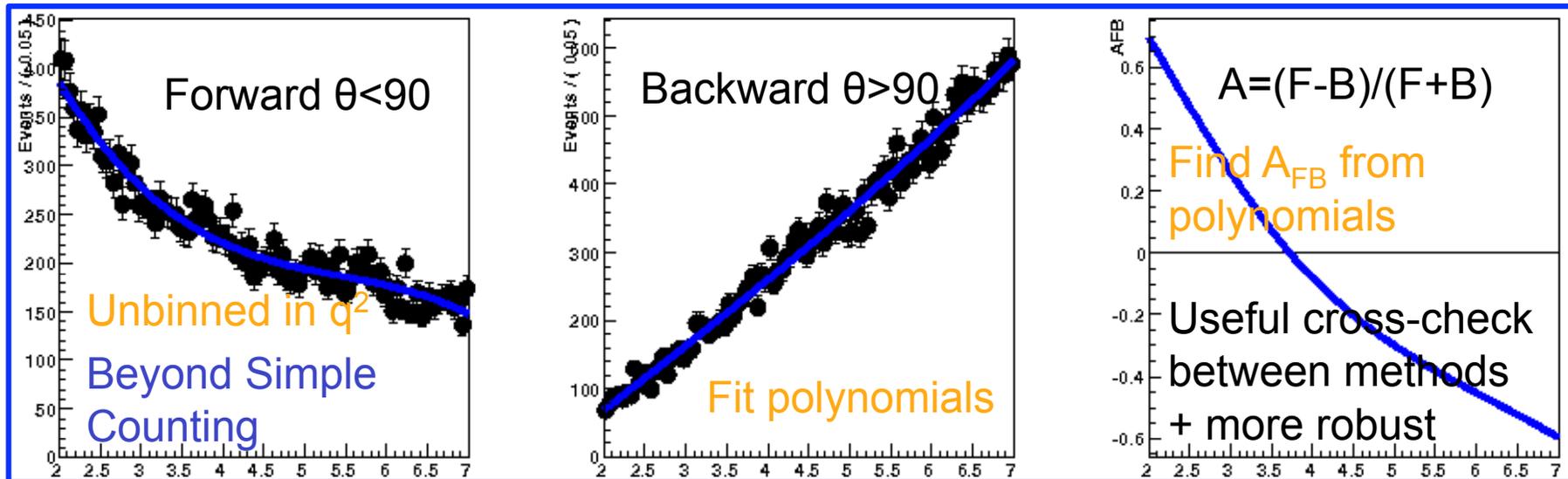
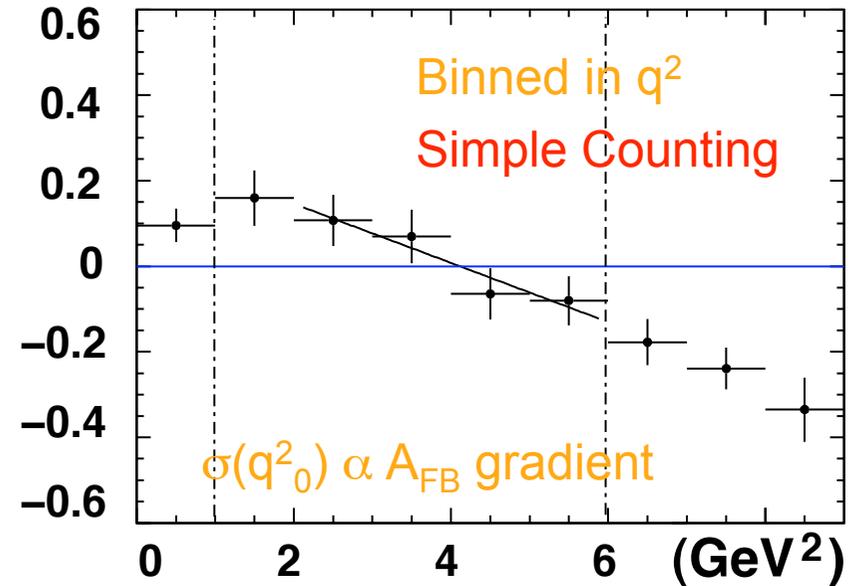


Analysis Timeline (2fb^{-1} means 1 nominal year!)

- A_{FB} first – can do a counting experiment $0.5 - 2 \text{fb}^{-1}$
 - Zero crossing also accessible
 - CERN-LHCb-2007-039
- Perform fits to decay angles $\rightarrow F_L, A_T^{(2)}$ $2 - 4 \text{fb}^{-1}$
 - Fit just to θ_1 or all three angles
 - CERN-LHCb-2007-057
- Full angular analysis
 - Many observables + improved resolution $3 - 10 \text{fb}^{-1}$
- Steps limited by understanding not statistics

Counting Experiments for AFB

- Can extract A_{FB} by counting forward and backward μ
 - Relatively simple
 - Requires only small integrated luminosity
- Allows zero-crossing extraction
 - $\sigma(q^2_0) \sim 0.8 \text{ GeV}^2/c^4 (0.5 \text{ fb}^{-1}), 0.5 \text{ GeV}^2/c^4 (2 \text{ fb}^{-1})$



Projection Fits

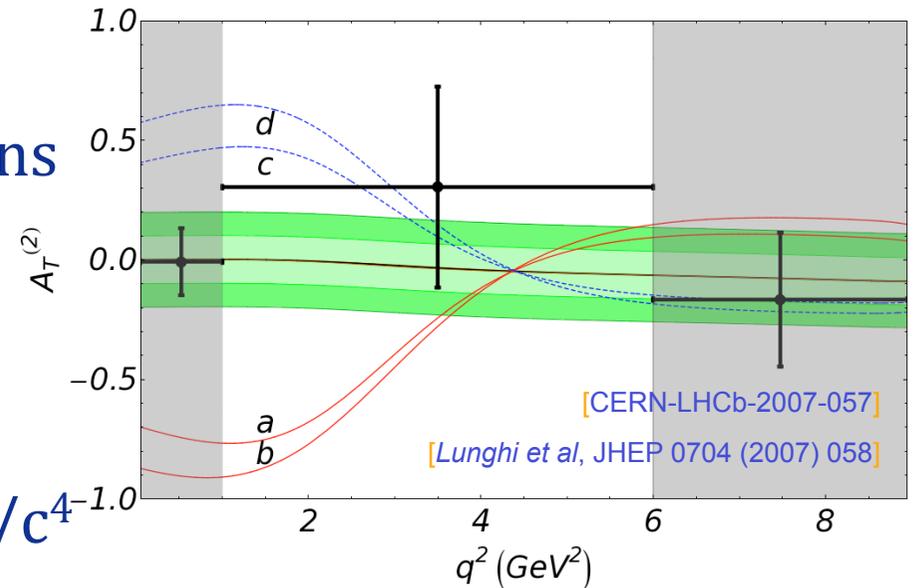
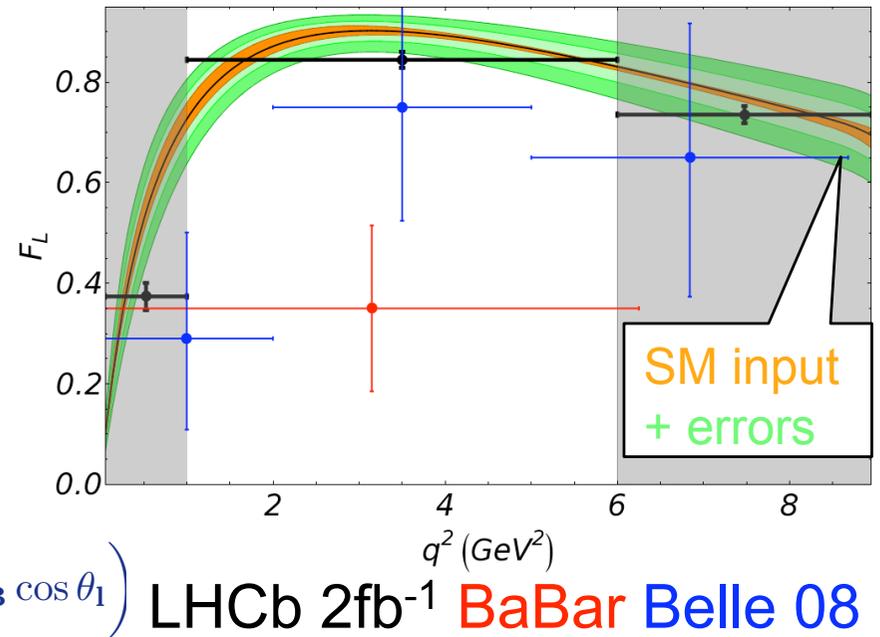
- Three decay angles \rightarrow beyond θ_1
 - Angular projections of θ_1, ϕ, θ_K dist.

$$\frac{d\Gamma'}{d\phi} = \frac{\Gamma'}{2\pi} \left(1 + \frac{1}{2}(1 - F_L)A_T^{(2)} \cos 2\phi + A_{Im} \sin 2\phi \right)$$

$$\frac{d\Gamma'}{d \cos \theta_1} = \Gamma' \left(\frac{3}{4}F_L \sin^2 \theta_1 + \frac{3}{8}(1 - F_L)(1 + \cos^2 \theta_1) + A_{FB} \cos \theta_1 \right)$$

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

- Perform simultaneous fit in q^2 bins
- Improve precision on A_{FB} by ~ 2
- F_L precision also improved
- Measure new observable $A_T^{(2)}$ with poor resolution in 1-6 GeV^2/c^4 region due to $(1-F_L)$ suppression



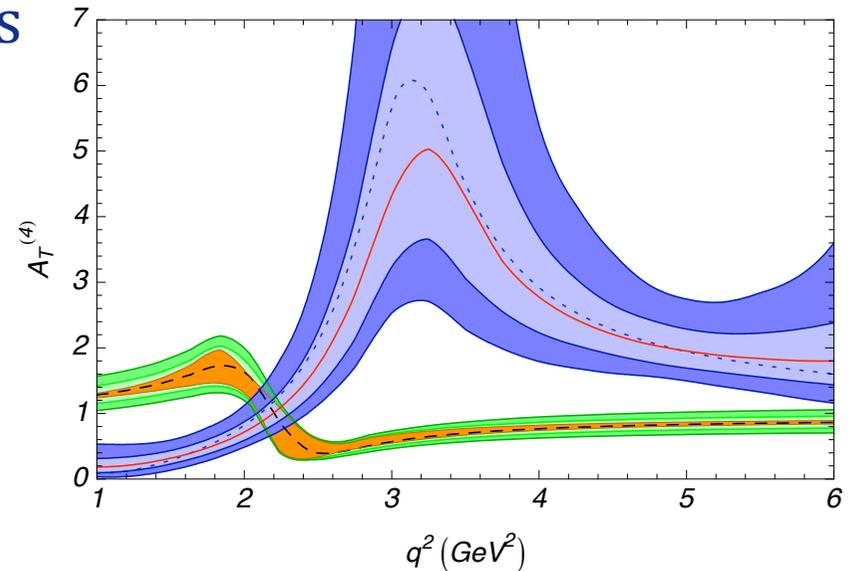
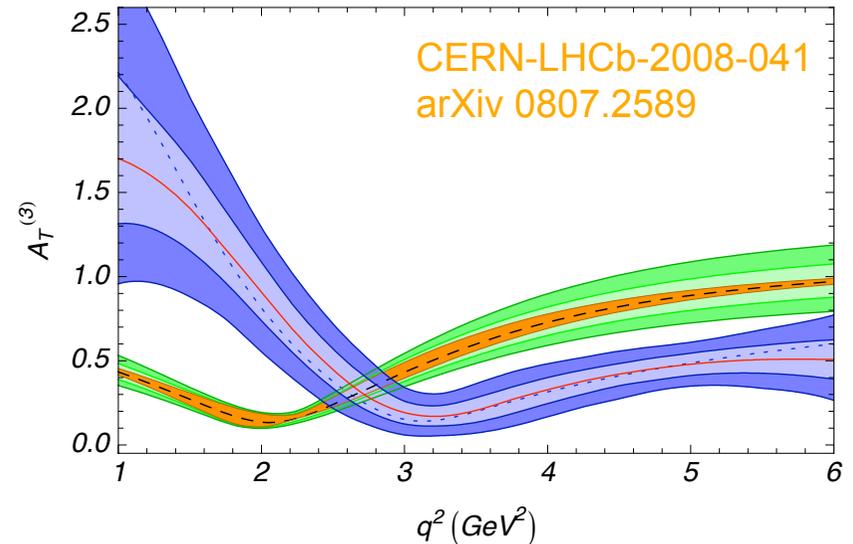
Full Angular Analysis

$$d^4\Gamma$$

- $\frac{d^4\Gamma}{dq^2 d\theta_1 d\theta_K d\phi}$ parameterized by K^* spin amplitudes
 - $A_{\perp L,R}, A_{\parallel L,R}, A_{0L,R}$
- Perform fit for amplitudes
 - Assume polynomial q^2 variation
- Calc. observables from amplitudes
 - New observables $A_T^{(3)} A_T^{(4)}$

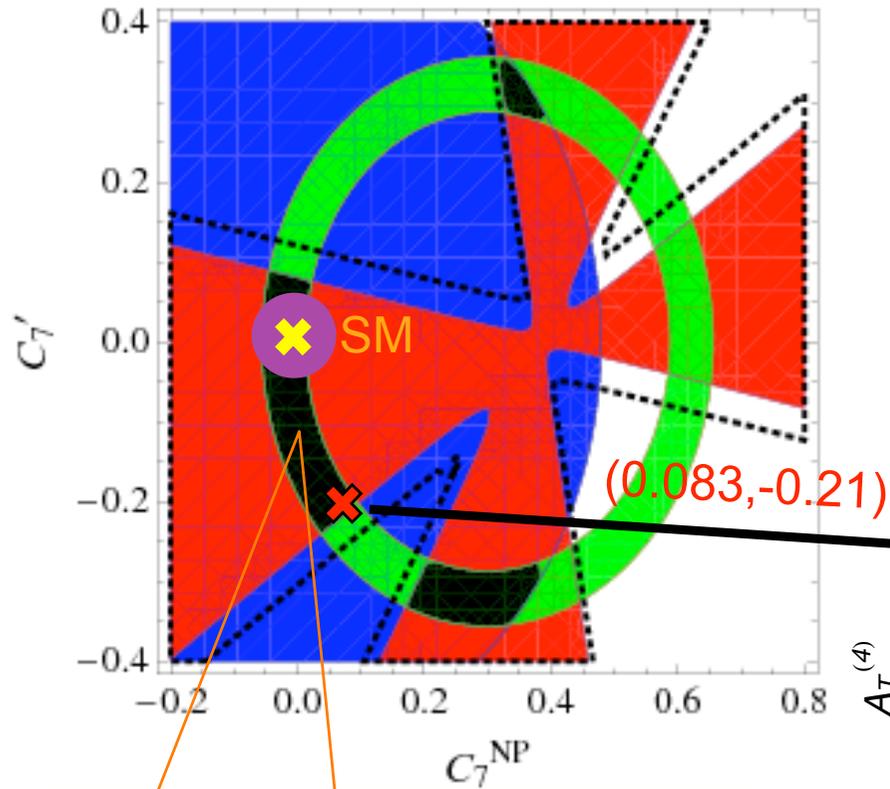
$$A_T^{(3)} = \frac{|A_{0L}A_{\parallel L}^* - A_{0R}^*A_{\parallel R}|}{\sqrt{|A_0|^2 \times |A_{\perp}|^2}} \quad A_T^{(4)} = \frac{|A_{0L}A_{\perp L}^* - A_{0R}^*A_{\perp R}|}{|A_{0L}^*A_{\parallel L} + A_{0R}A_{\parallel R}^*|}$$

- 10fb⁻¹ sensitivities for SUSY input
 - JHEP 0704 (2007) 058 - model 'b'
- MC Fits converge with 2fb⁻¹
 - Acceptance a challenge

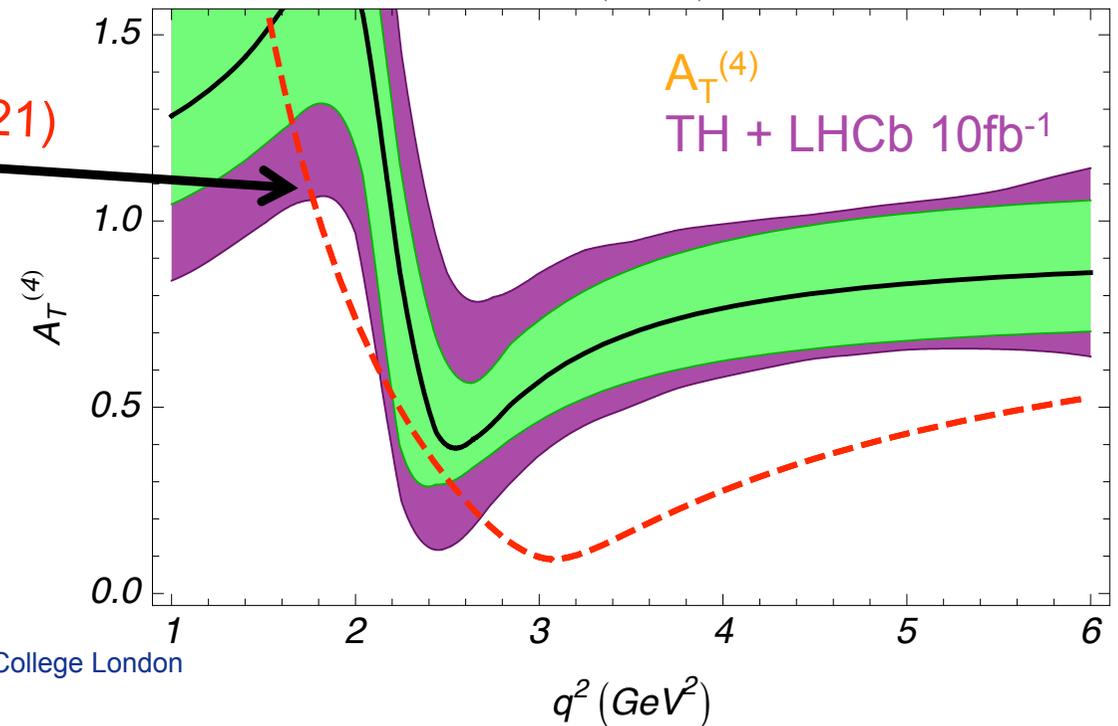
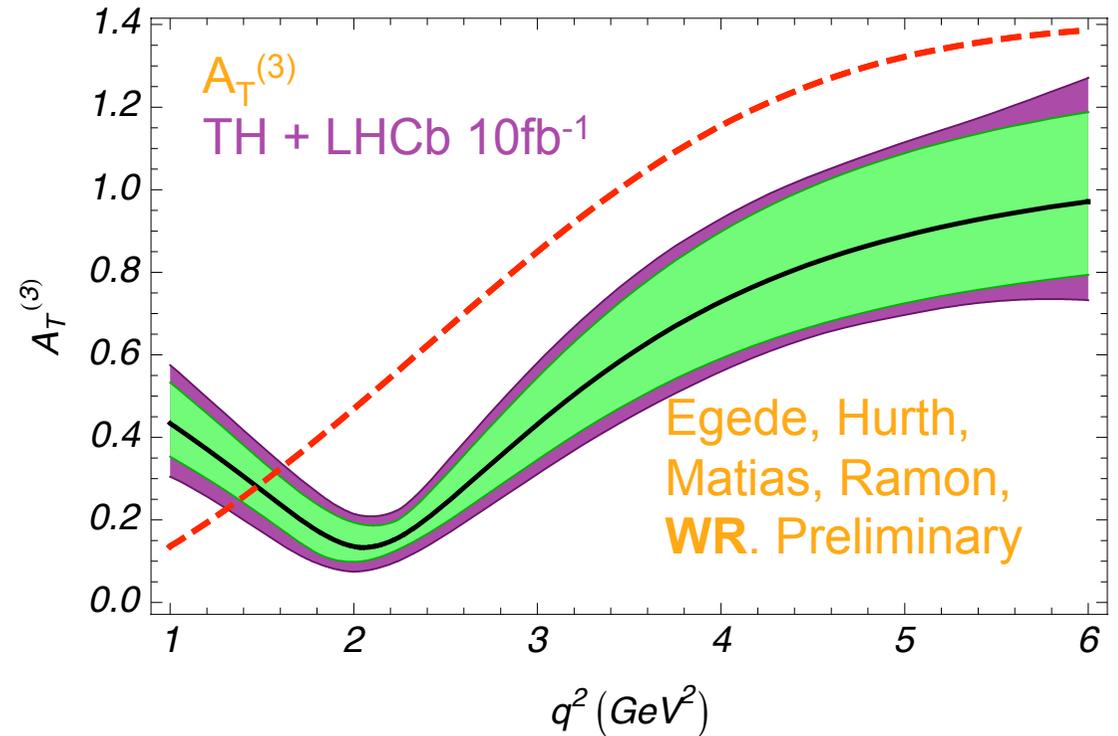


Finding NP in C_7

$S_{K\pi\gamma}$ $\mathcal{B}_{[1,6]}$
 $b \rightarrow s\gamma$ Intersection



Allowed regions - C_7 real
 JHEP 0807:106,2008
 After 10fb^{-1} FA analysis?



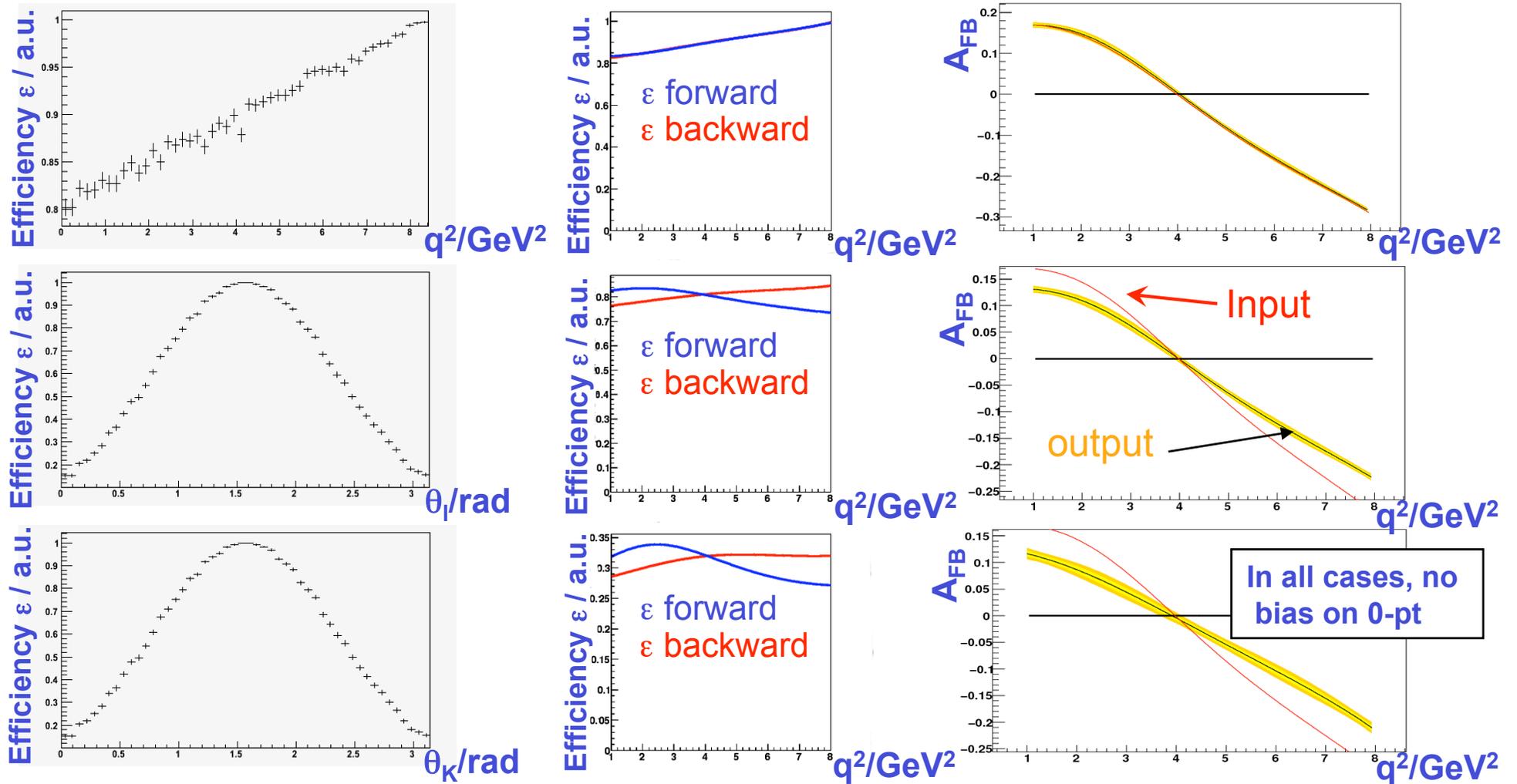
Summary $\bar{B}_d \rightarrow \bar{K}^{*0} \mu^+ \mu^-$

- Excellent prospects for discovery of NP
 - Hints from B-factories + theory
- Expect 7.2k signal events per year over whole q^2 range
- Exciting Physics program
- Many observables to study
 - Counting experiments, projections, full angular
 - Real discriminating power for NP
- Exciting times ahead!

BACK UP SLIDES



Acceptance Effects for A_{FB}



- Take toy efficiencies for q^2 , θ_l , θ_K
 - θ_K biases A_{FB} even though are only using θ_l directly

Outside the Theoretically Clean Region

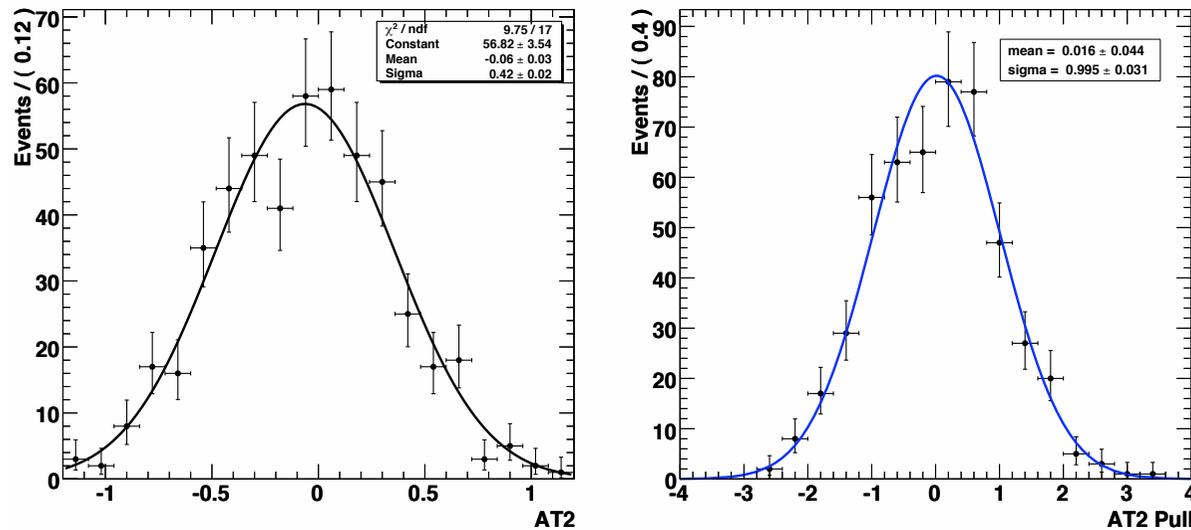
- $B \rightarrow$ Vector form factors large source of theoretical uncertainty
 - Dominated by low energy effects
 - 7 independent functions of q^2 – $V, T_{1,2,3}, A_{0,1,2}$
- Use SCET to reduce $7 \rightarrow 2$ at Leading Order
 - Only valid in range 1-6 GeV^2/c^4
 - Can not handle resonances or low q^2 region
- Observables where 2 remaining FF cancel
 - $A_T^{(2,3,4)}$ and AFB zero-crossing point
- Uncertainties outside region much greater
- See Beneke et al, Nucl. Phys. B612 (2001) 26-58

Projection Fit Resolutions

- Results from CERN-LHCb-2007-057

| q^2 region (GeV^2/c^4) | A_{FB} | | $A_T^{(2)}$ | | F_L | |
|--|---------------------|----------------------|---------------------|----------------------|---------------------|----------------------|
| | 2 fb^{-1} | 10 fb^{-1} | 2 fb^{-1} | 10 fb^{-1} | 2 fb^{-1} | 10 fb^{-1} |
| 0.05 – 1.00 | 0.034 | 0.017 | 0.14 | 0.07 | 0.027 | 0.011 |
| 1.00 – 6.00 | 0.020 | 0.008 | 0.42 | 0.16 | 0.016 | 0.007 |
| 6.00 – 8.95 | 0.022 | 0.010 | 0.28 | 0.13 | 0.017 | 0.008 |

Table 1: The expected resolution for measurements of the parameters A_{FB} , $A_T^{(2)}$ and F_L for the $\bar{B}_d \rightarrow \bar{K}^{*0} \mu^+ \mu^-$ decay at LHCb in regions of the squared di-muon mass q^2 with 2 and 10 fb^{-1} of integrated luminosity.



Observables

$$A_{\text{FB}} = \frac{3}{2} \frac{\text{Re}(A_{\parallel L} A_{\perp L}^*) - \text{Re}(A_{\parallel R} A_{\perp R}^*)}{|A_0|^2 + |A_{\parallel}|^2 + |A_{\perp}|^2}$$

$$F_L(q^2) = \frac{|A_0|^2}{|A_0|^2 + |A_{\parallel}|^2 + |A_{\perp}|^2},$$

$$A_T^{(2)} = \frac{|A_{\perp}|^2 - |A_{\parallel}|^2}{|A_{\perp}|^2 + |A_{\parallel}|^2}$$

$$A_T^{(3)} = \frac{|A_{0L} A_{\parallel L}^* - A_{0R}^* A_{\parallel R}|}{\sqrt{|A_0|^2 |A_{\perp}|^2}},$$

and

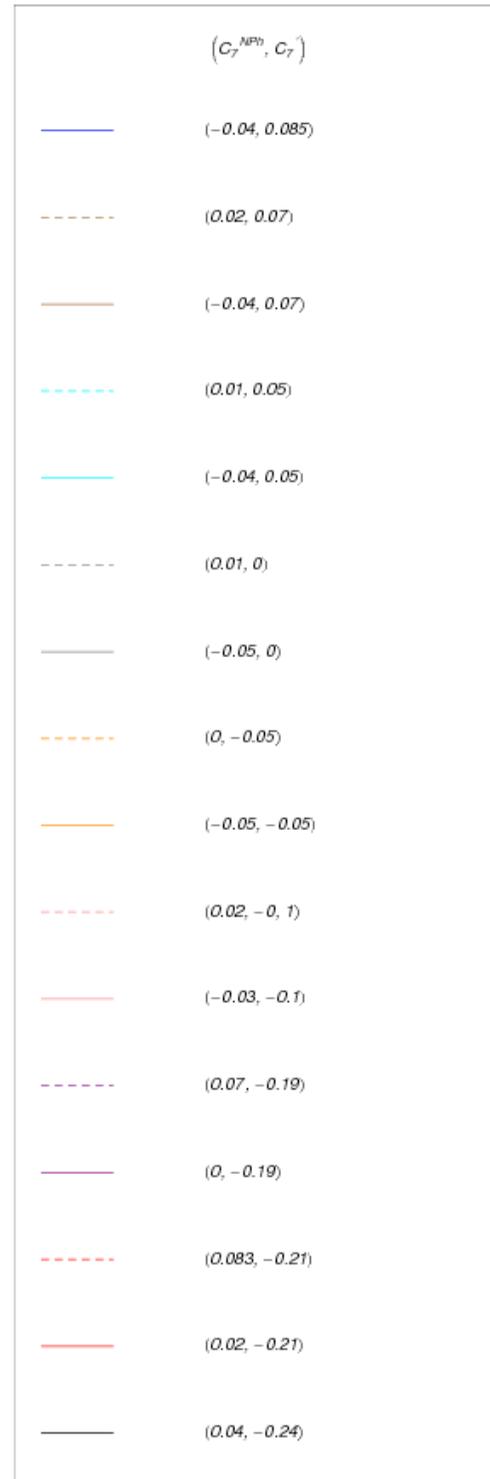
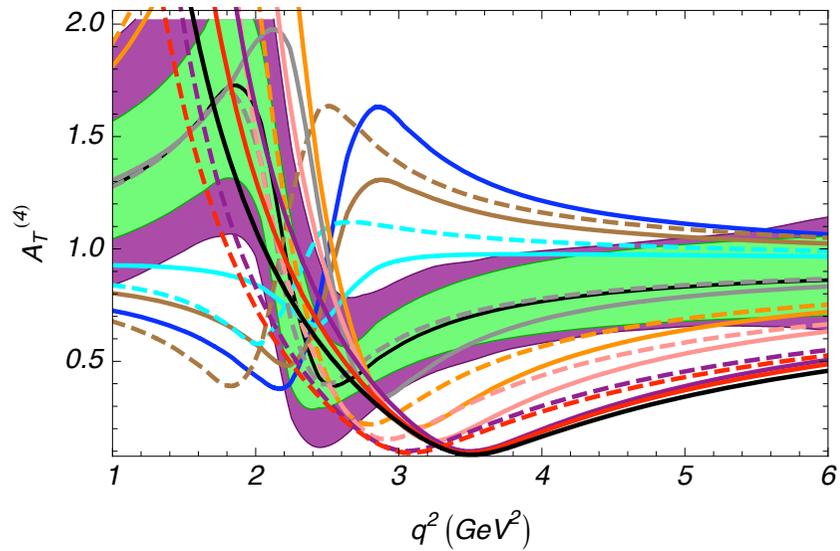
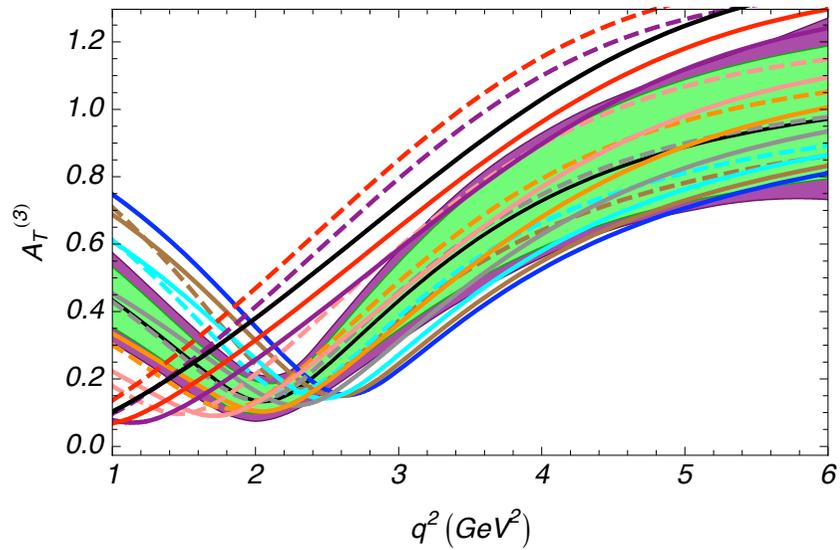
$$A_T^{(4)} = \frac{|A_{0L} A_{\perp L}^* - A_{0R}^* A_{\perp R}|}{|A_{0L}^* A_{\parallel L} + A_{0R} A_{\parallel R}^*|},$$

$$A_i A_j^* \equiv A_{iL}(q^2) A_{jL}^*(q^2) + A_{iR}(q^2) A_{jR}^*(q^2) \quad (i, j = 0, \parallel, \perp).$$

Drell-Yan Backgrounds

- Not significant background at LHCb
- Full simulation study:
 - $b\bar{b}$ decays dominant source of $\mu\mu$ in mass range
 - Drell-Yan production much lower
- Reconstruction Efficiency:
 1. Fake signal \rightarrow need a K^* from elsewhere
 2. Wrongly associate this with $\mu\mu$ vertex
 3. Miss-ID rate should be very low

NP in C_7 Legend



Selection Cuts from LHCb-2007-038

| Particle | Cut variable | Selection cut value | Preselection cut value |
|-----------|-----------------------------------|--|---------------------------|
| B_d | mass window | $\pm 50 \text{ MeV}/c^2 (3.6\sigma)^b$ | $\pm 500 \text{ MeV}/c^2$ |
| | p_r | $> 250 \text{ MeV}/c$ | $> 250 \text{ MeV}/c$ |
| | vertex χ^2 | < 20 | < 50 |
| | $\cos \theta$ | > 0.99975 | > 0.99 |
| | flight-significance | > 6 | - |
| | sIPS | < 5 | < 8 |
| | Vertex Isolation ^c | < 11 | - |
| K^* | mass window | $\pm 100 \text{ MeV}/c^2 (2 \times \text{FWHM})^d$ | $\pm 300 \text{ MeV}/c^2$ |
| | p_r | $> 300 \text{ MeV}/c$ | $> 300 \text{ MeV}/c$ |
| | vertex χ^2 | < 30 | < 30 |
| | flight-significance | > 1 | - |
| | sIPS | > 1.5 | > 1.5 |
| K^\pm | p | $> 2000 \text{ MeV}/c$ | $> 2000 \text{ MeV}/c$ |
| | p_r | $> 400 \text{ MeV}/c$ | $> 250 \text{ MeV}/c$ |
| | sIPS | > 3.0 | > 1.5 |
| π^\pm | p | $> 2000 \text{ MeV}/c$ | $> 2000 \text{ MeV}/c$ |
| | p_r | $> 250 \text{ MeV}/c$ | $> 250 \text{ MeV}/c$ |
| | sIPS | > 3.0 | > 1.5 |
| $\mu\mu$ | J/ Ψ (1S, 2S) mass-rejection | 2900 - 3200 MeV/c^2 3650 - 3725 MeV/c^2 | - - |
| | χ^2 | < 15 | - |
| | flight-distance | $> 1 \text{ mm}$ | - |
| μ^\pm | p | $> 4000 \text{ MeV}/c$ | $> 4000 \text{ MeV}/c$ |
| | p_r | $> 500 \text{ MeV}/c$ | $> 300 \text{ MeV}/c$ |
| | sIPS | > 2.0 | > 0.5 |

Angular Distribution

$$\frac{d^4\Gamma_{\bar{B}_d}}{dq^2 d\theta_l d\theta_K d\phi} = \frac{9}{32\pi} I(q^2, \theta_l, \theta_K, \phi) \sin \theta_l \sin \theta_K ,$$

$$I = I_1 + I_2 \cos 2\theta_l + I_3 \sin^2 \theta_l \cos 2\phi + I_4 \sin 2\theta_l \cos \phi + I_5 \sin \theta_l \cos \phi + I_6 \cos \theta_l \\ + I_7 \sin \theta_l \sin \phi + I_8 \sin 2\theta_l \sin \phi + I_9 \sin^2 \theta_l \sin 2\phi.$$

$$I_1 = \frac{3}{4} (|A_{\perp L}|^2 + |A_{\parallel L}|^2 + (L \rightarrow R)) \sin^2 \theta_K + (|A_{0L}|^2 + |A_{0R}|^2) \cos^2 \theta_K \\ \equiv a \sin^2 \theta_K + b \cos^2 \theta_K,$$

$$I_2 = \frac{1}{4} (|A_{\perp L}|^2 + |A_{\parallel L}|^2) \sin^2 \theta_K - |A_{0L}|^2 \cos^2 \theta_K + (L \rightarrow R) \\ \equiv c \sin^2 \theta_K + d \cos^2 \theta_K,$$

$$I_3 = \frac{1}{2} \left[(|A_{\perp L}|^2 - |A_{\parallel L}|^2) \sin^2 \theta_K + (L \rightarrow R) \right] \equiv e \sin^2 \theta_K,$$

$$I_4 = \frac{1}{\sqrt{2}} \left[\text{Re}(A_{0L} A_{\parallel L}^*) \sin 2\theta_K + (L \rightarrow R) \right] \equiv f \sin 2\theta_K,$$

$$I_5 = \sqrt{2} \left[\text{Re}(A_{0L} A_{\perp L}^*) \sin 2\theta_K - (L \rightarrow R) \right] \equiv g \sin 2\theta_K,$$

$$I_6 = 2 \left[\text{Re}(A_{\parallel L} A_{\perp L}^*) \sin^2 \theta_K - (L \rightarrow R) \right] \equiv h \sin^2 \theta_K,$$

$$I_7 = \sqrt{2} \left[\text{Im}(A_{0L} A_{\parallel L}^*) \sin 2\theta_K - (L \rightarrow R) \right] \equiv j \sin 2\theta_K,$$

$$I_8 = \frac{1}{\sqrt{2}} \left[\text{Im}(A_{0L} A_{\perp L}^*) \sin 2\theta_K + (L \rightarrow R) \right] \equiv k \sin 2\theta_K,$$

$$I_9 = \left[\text{Im}(A_{\parallel L} A_{\perp L}^*) \sin^2 \theta_K + (L \rightarrow R) \right] \equiv m \sin^2 \theta_K.$$

Physics Sensitivity to K^* Spin Amplitudes

$$A_{\perp L,R} = N\sqrt{2}\lambda^{1/2} \left[(\mathcal{C}_9^{(\text{eff})} \mp \mathcal{C}_{10}) \frac{V(s)}{m_B + m_{K^*}} + \frac{2m_b}{q^2} (\mathcal{C}_7^{(\text{eff})} + \mathcal{C}_7'^{(\text{eff})}) T_1(q^2) \right], \quad (3.5)$$

$$A_{\parallel L,R} = -N\sqrt{2}(m_B^2 - m_{K^*}^2) \left[(\mathcal{C}_9^{(\text{eff})} \mp \mathcal{C}_{10}) \frac{A_1(q^2)}{m_B - m_{K^*}} + \frac{2m_b}{q^2} (\mathcal{C}_7^{(\text{eff})} - \mathcal{C}_7'^{(\text{eff})}) T_2(q^2) \right], \quad (3.6)$$

$$A_{0L,R} = -\frac{N}{2m_{K^*}\sqrt{q^2}} \left[(\mathcal{C}_9^{(\text{eff})} \mp \mathcal{C}_{10}) \left\{ (m_B^2 - m_{K^*}^2 - q^2)(m_B + m_{K^*}) A_1(q^2) - \lambda \frac{A_2(q^2)}{m_B + m_{K^*}} \right\} + 2m_b(\mathcal{C}_7^{(\text{eff})} - \mathcal{C}_7'^{(\text{eff})}) \left\{ (m_B^2 + 3m_{K^*}^2 - q^2) T_2(q^2) - \frac{\lambda}{m_B^2 - m_{K^*}^2} T_3(q^2) \right\} \right] \quad (3.7)$$

where $\lambda = m_B^4 + m_{K^*}^4 + q^4 - 2(m_B^2 m_{K^*}^2 + m_{K^*}^2 q^2 + m_B^2 q^2)$ and

$$N = \left[\frac{G_F^2 \alpha^2}{3 \cdot 2^{10} \pi^5 m_B^3} |V_{tb} V_{ts}^*|^2 q^2 \lambda^{1/2} \left(1 - \frac{4m_t^2}{q^2} \right)^{1/2} \right]^{1/2}. \quad (3.8)$$

Experimental Constraints for C7 Plot

| observable | SM | data |
|--|--------------------------------------|---|
| $\mathcal{B}(\bar{B} \rightarrow X_s \gamma)^a$ | $(3.15 \pm 0.23) \cdot 10^{-4}$ [34] | $(3.52 \pm 0.25) \cdot 10^{-4}$ [3] |
| $S_{K^* \gamma}^b$ | $(-2.8_{-0.5}^{+0.4}) \cdot 10^{-2}$ | -0.19 ± 0.23 [3, 31] |
| $\mathcal{B}(\bar{B} \rightarrow X_s \bar{l}l) _{[1,6]}$ | $(1.59 \pm 0.11) \cdot 10^{-6}$ [35] | $(1.60 \pm 0.51) \cdot 10^{-6}$ [33] |
| $\mathcal{B}(\bar{B} \rightarrow X_s \bar{l}l) _{>0.04}$ | $(4.15 \pm 0.70) \cdot 10^{-6}$ [21] | $(4.5 \pm 1.0) \cdot 10^{-6}$ [24] |
| $\langle A_{FB} \rangle_{[high\ q^2]}^c$ | < 0 | $-(0.76_{-0.32}^{+0.52} \pm 0.07)$ [6], also [4, 5] |
| $\mathcal{B}(\bar{B}_s \rightarrow \bar{\mu}\mu)$ | $\simeq 3 \cdot 10^{-9}$ | $< 4.7 \cdot 10^{-8}$ at 90% C.L. [32] |

Table 3: Relevant $b \rightarrow s\gamma$ and $b \rightarrow s\bar{l}l$ observables. ^aWith photon energy cut $E_\gamma > 1.6$ GeV. ^bSM value obtained with $m_s = 0.12$ GeV. ^cNote the different lepton angle convention between [5, 6] and this work.