$B \to K^* \mu\mu$ in the SM and Beyond

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based on arXiv:0811.1214

Lancaster, Nov 12 2008

University of Durham

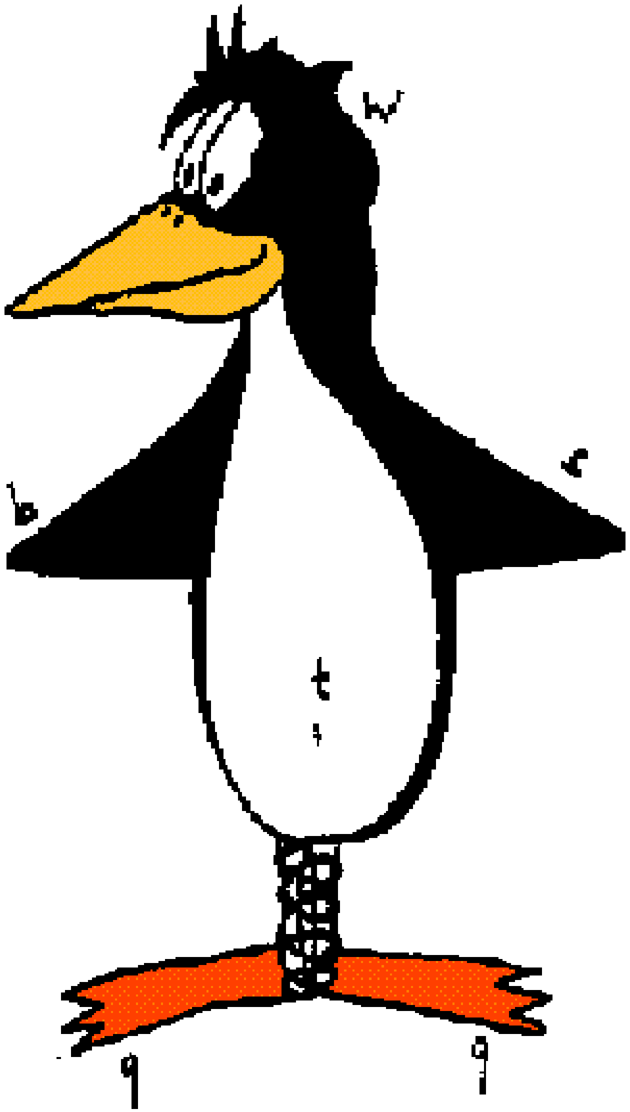
Anything wrong with $b \longrightarrow s$?

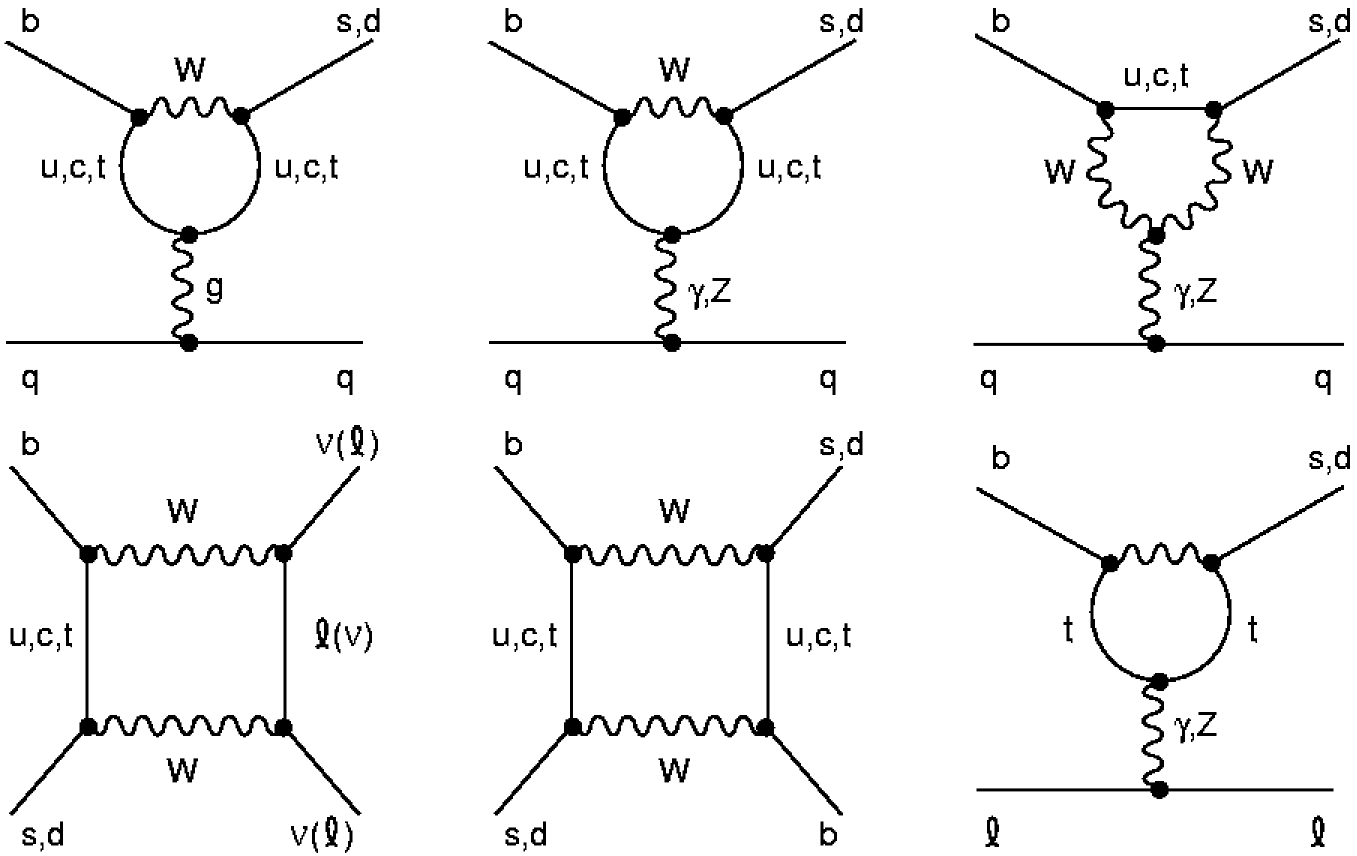
- time-dependent CP asymmetry in $b \to s$: $S_{\Phi K} \neq S_{J/\psi K}$
- hints at large B_s mixing phase from Tevatron

If there are BSM sources for the above, they will be found at the LHC:

- B_s mixing phase
- $B_s \to \mu^+\mu^-$
- $\boxed{B \to K^*\mu^+\mu^-}$

$B \to K^* \mu\mu$ – Diagrams





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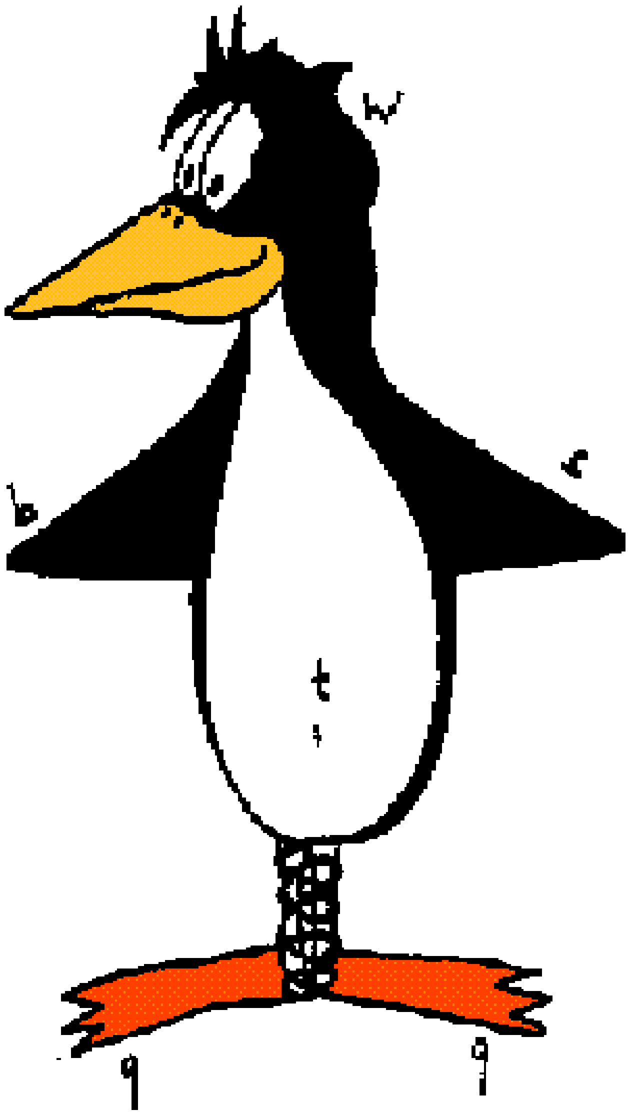

- $b \to s\ell^+\ell^-$ is FCNC (flavour-changing neutral current) – forbidden at tree-level in the SM
- in the SM induced by one-loop penguin and one-loop box diagrams
- new physics also at one loop (e.g. MSSM) or possibly tree-level (e.g. FC neutral Higgs) [heavily suppressed]
- related decay $b \to s\gamma$ extensively studied at B factories
  - also FCNC, but with less sensitivity to BSM than $b \to s\ell^+\ell^-$ (less operators in effective Hamiltonian, less observables)
  - difficult at the LHC because of γ; $\mu^+\mu^-$ has better detection efficiency

$B \to K^* \mu\mu$ – Data

Current status (ICHEP 08) at B factories and Tevatron:

Experiment	BaBar	Belle	CDF
$\mathcal{B}(B \to K^* \mu^+ \mu^-) \times 10^7$	$11.1 \pm 1.9 \pm 0.7$	$10.8^{+1.0}_{-1.0} \pm 0.9$	$8.1 \pm 3.0 \pm 1.0$
# of events	? (ca. 1/2 of Belle)	$230(!)$	?

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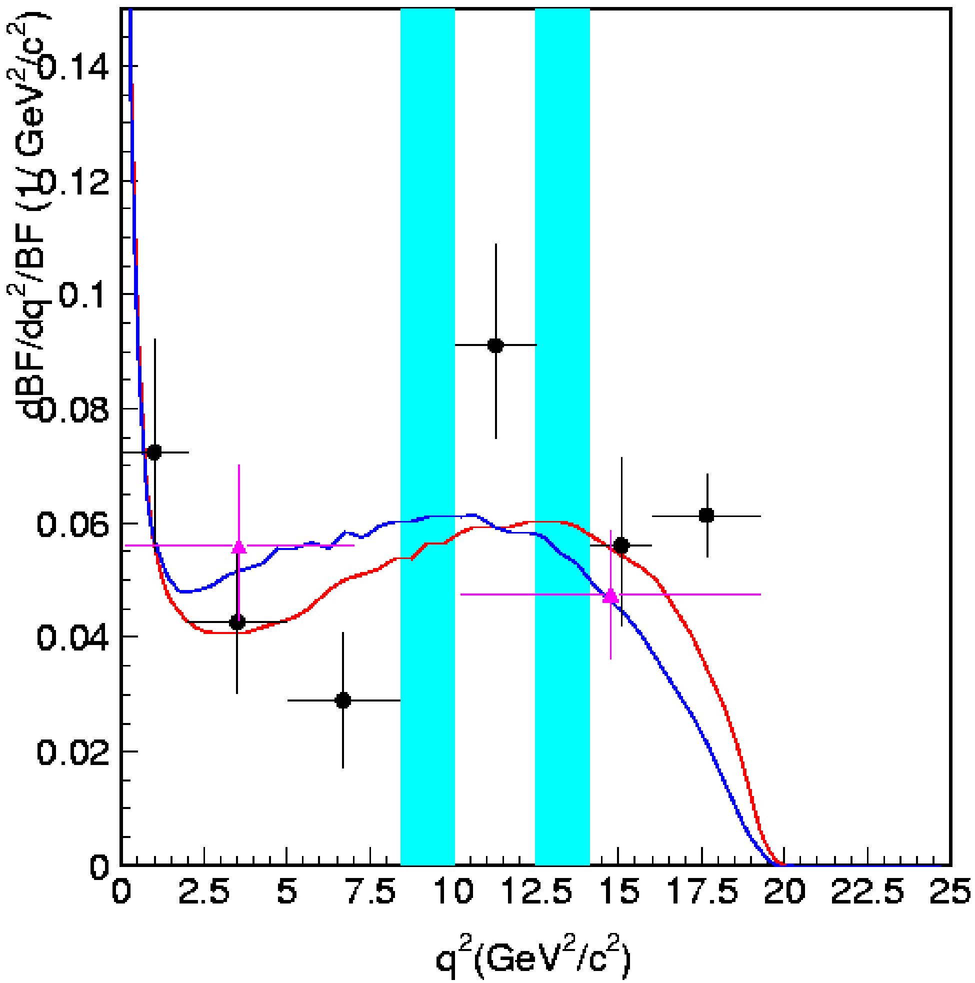
Current (Belle) measurement of di-lepton mass spectrum (230 events):



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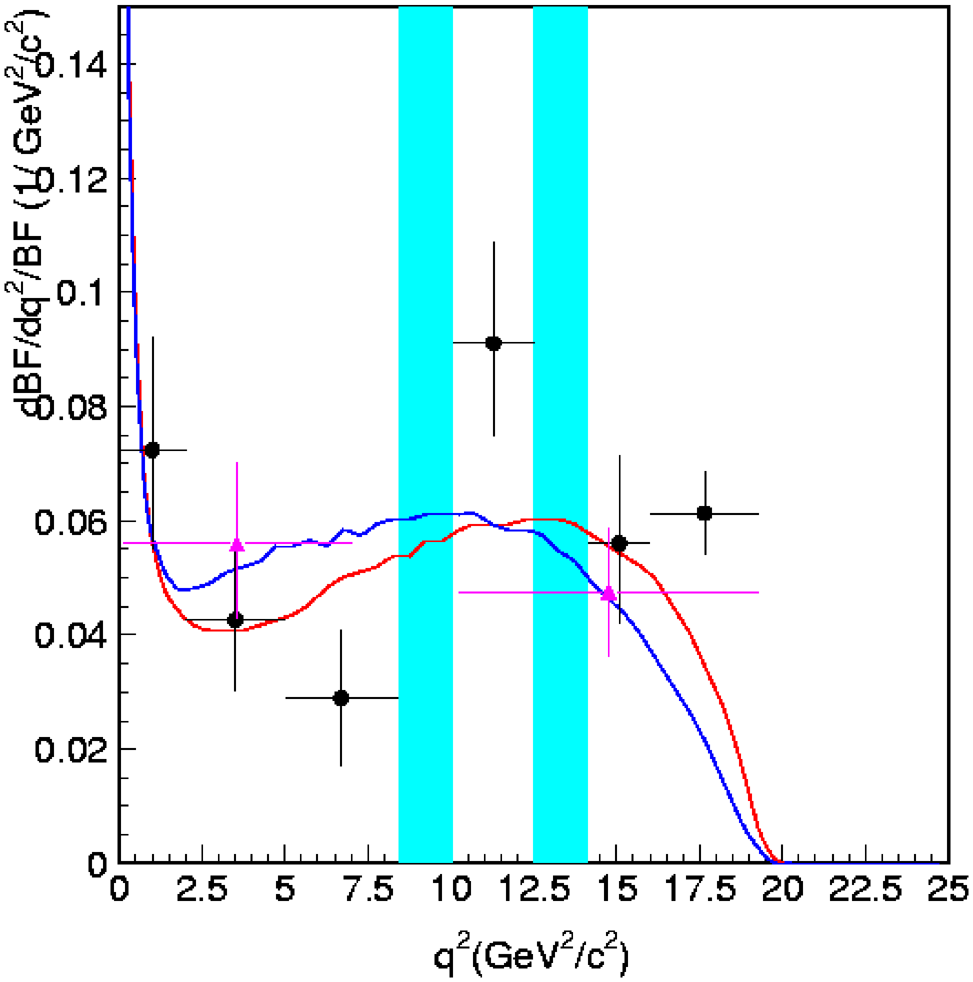
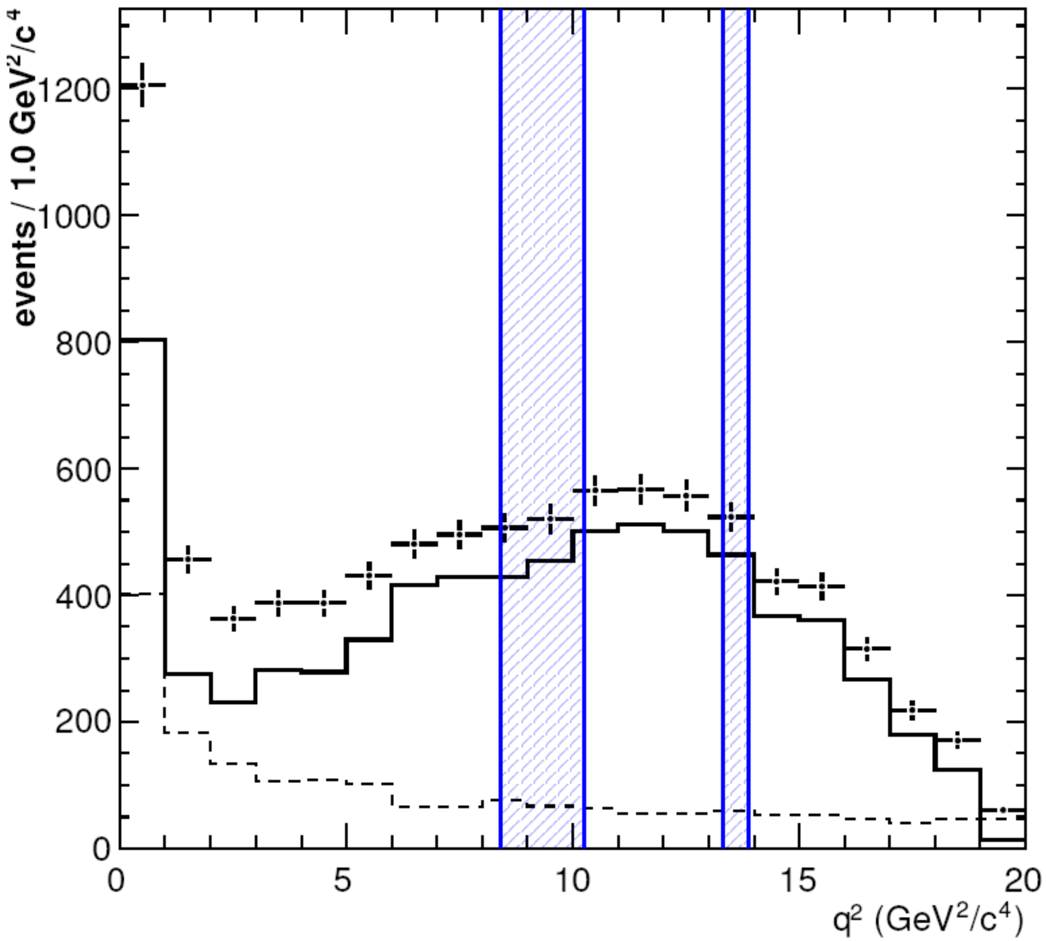


Projection: LHCb with 7200 events (2 fb^{-1}, i.e. 1y of running)



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The usual suspects:

- branching ratio
- dilepton mass spectrum
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More than you think!

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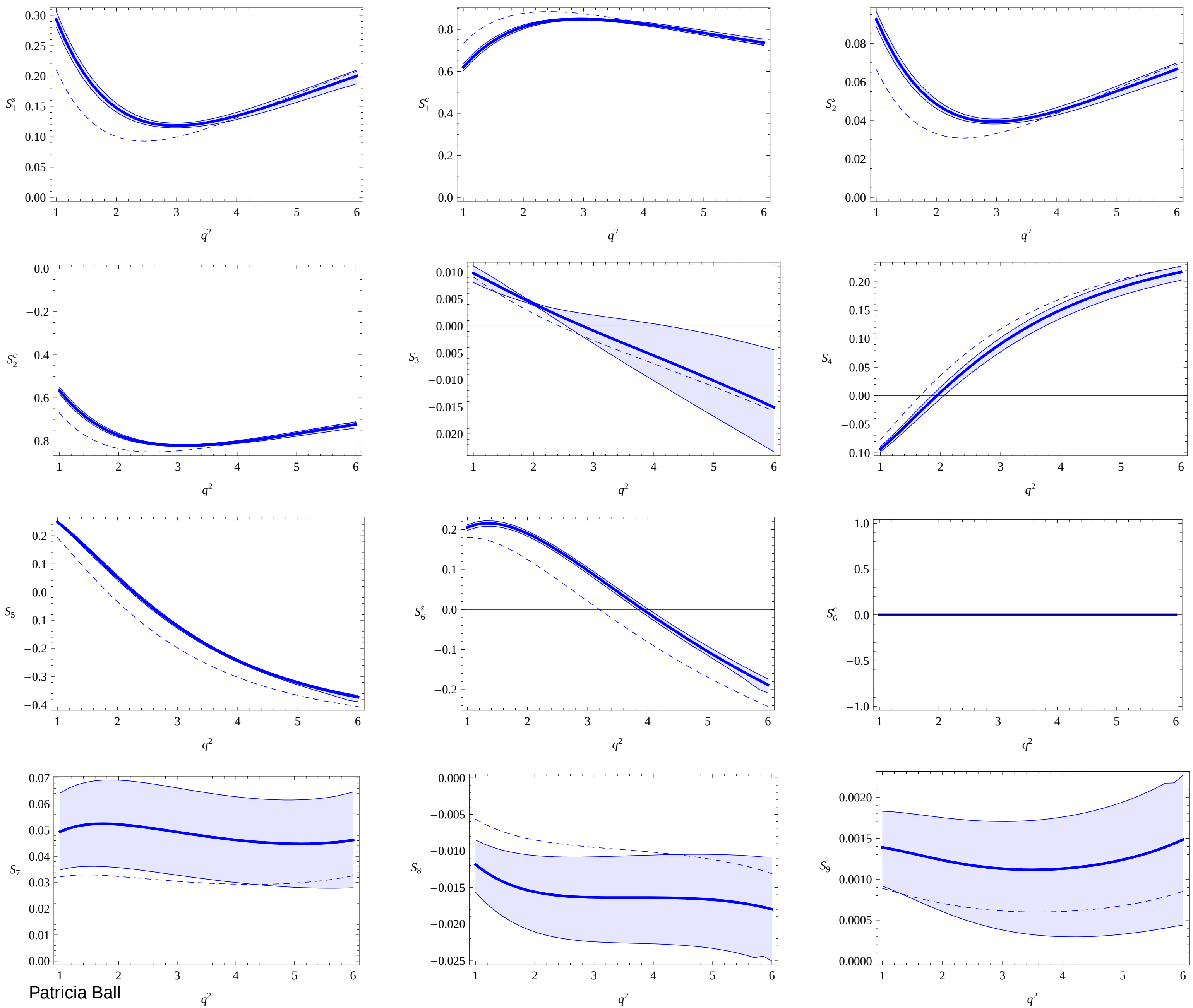

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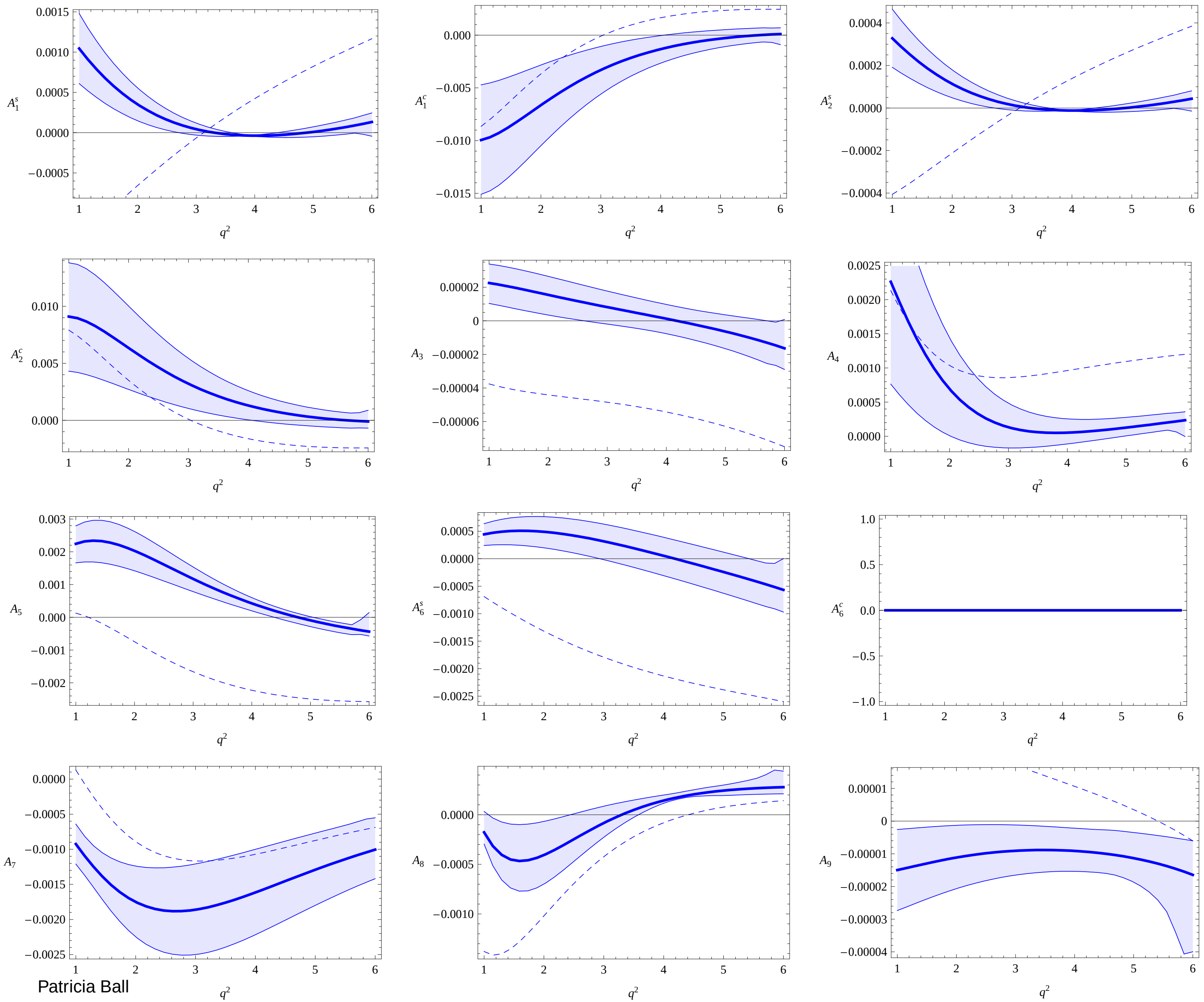

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- how to define observables
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The big questions:

- how to calculate $B \to K^* \mu^+ \mu^-$ decays $\to$ this talk
- how to define observables $\to$ this talk
- how to find new physics $\to$ next talk (A. Bharucha)

How to calculate

The B Physicist’s Toolbox

For exclusive decays:

- effective field theories
  - disentangle physics governed by different mass scales (SM: $m_W, m_t \gg m_b \gg \Lambda_{\rm QCD}$)
  - evolution between scales governed by renormalisation group equations (known to 3-loop accuracy for $b \to s\ell^+\ell^-$)

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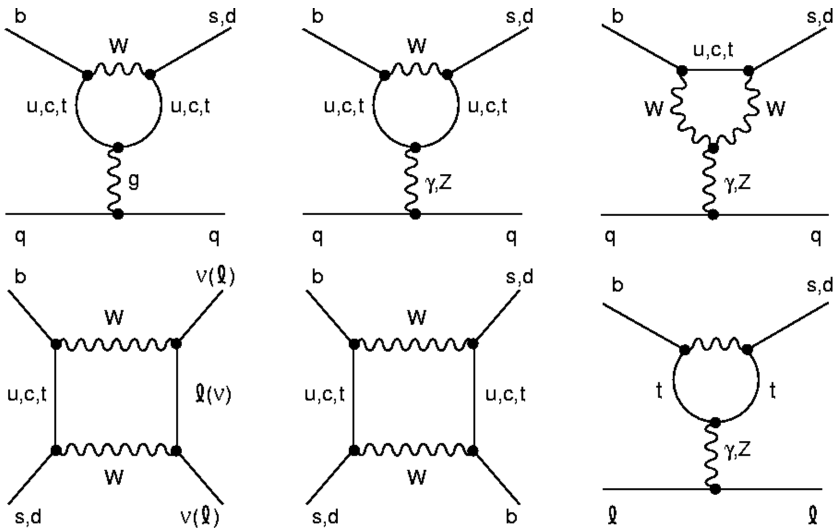
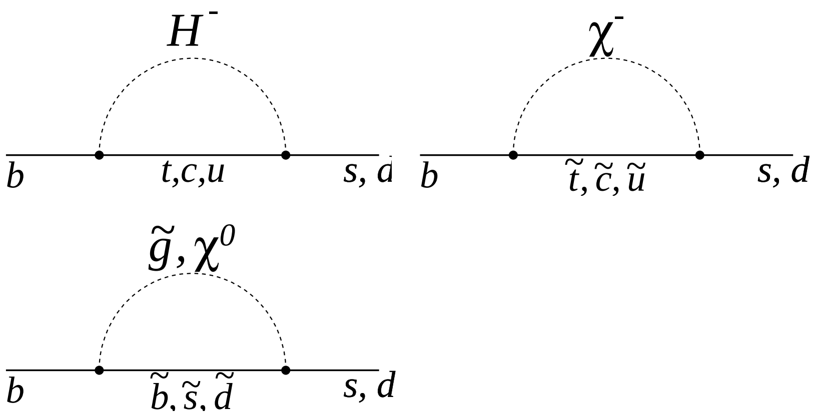
- hard spectator effects etc.: QCD factorization

The Effective Hamiltonian



Possible BSM diagrams (MSSM):



- calculate diagrams in full theory (SM or BSM)
- match to effective Hamiltonian

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} \times \text{CKM} \times \sum_i C_i(\mu)\mathcal{O}_i(\mu)$$

  with Wilson coefficients C_i and (e.g. 4-quark) operators $\mathcal{O}_i$
- μ is renormalisation scale. Matching done at $\mu \approx m_W$. For B physics, need to know C_i at $\mu \approx m_b$: solve RG equations

$$\mu \frac{d}{d\mu}\vec{C}(\mu) = \gamma^T \vec{C}(\mu)$$

- anomalous dimensions γ known to 3-loop accuracy (Gorbahn/Haisch/Misiak 04+05)
- initial conditions $C_i(m_W)$ known to 2-loop accuracy (Bobeth/Misiak/Urban 99)

Form Factors

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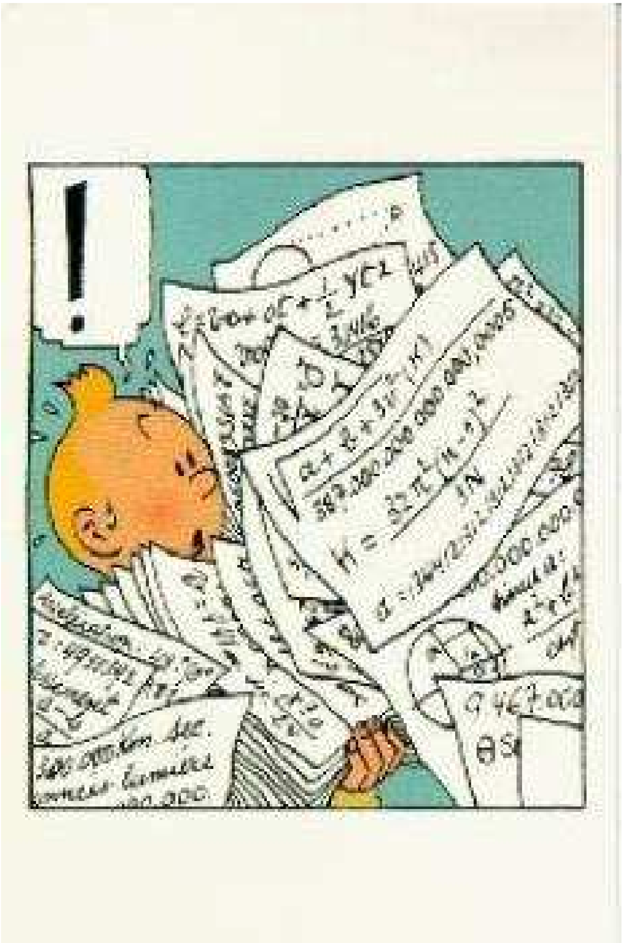
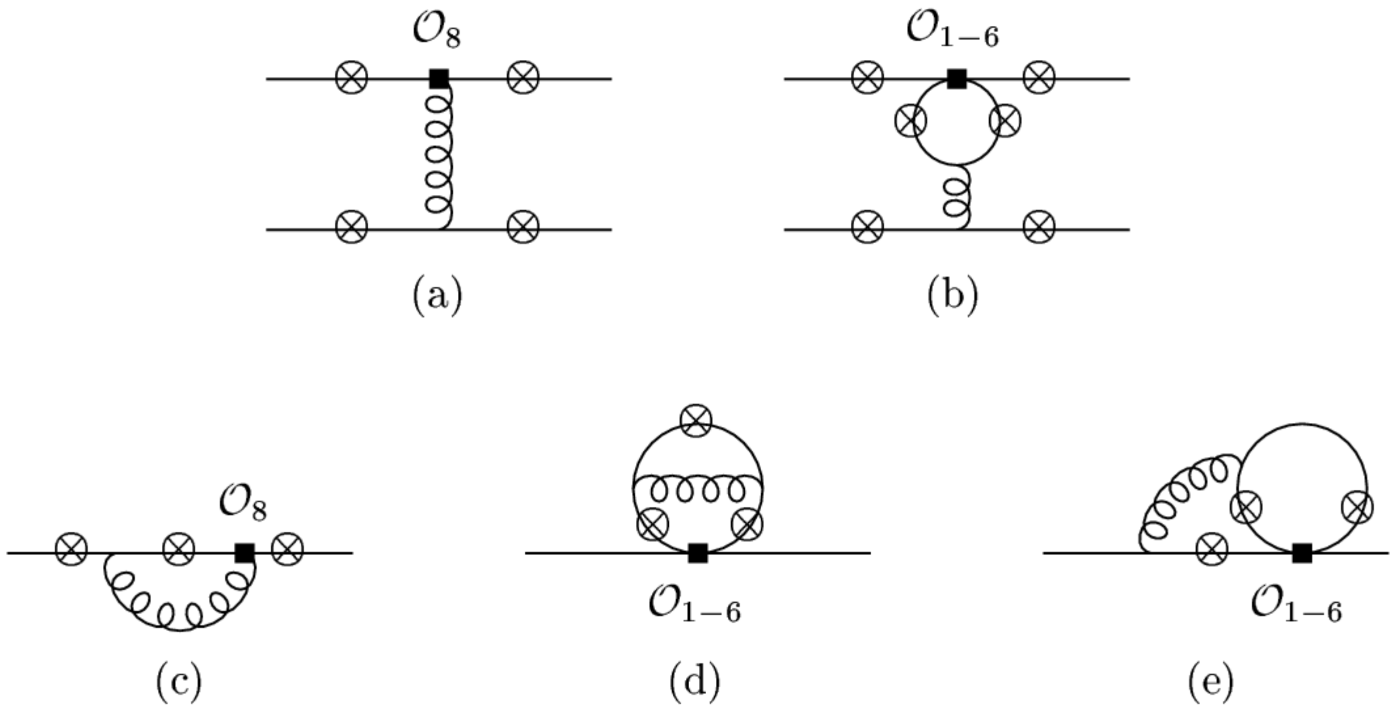


QCD Factorisation

(Beneke/Feldmann/Seidel 01+04)



$\otimes$ = emission of photon

Include matrix elements of operators which are not related to form factors.

- mostly $O(\alpha_s)$ corrections
- plus weak annihilation: diagrams with quarks in B meson annihilating

How we differ from our competitors

Recent analyses: Bobeth/Hiller/Piranishvili 08, Egede et al. 08

We use:

- full set of 7 form factors with correlated errors
  (instead of 2 form factors in heavy quark limit)
- full analysis of *all* observables
- large set of BSM models

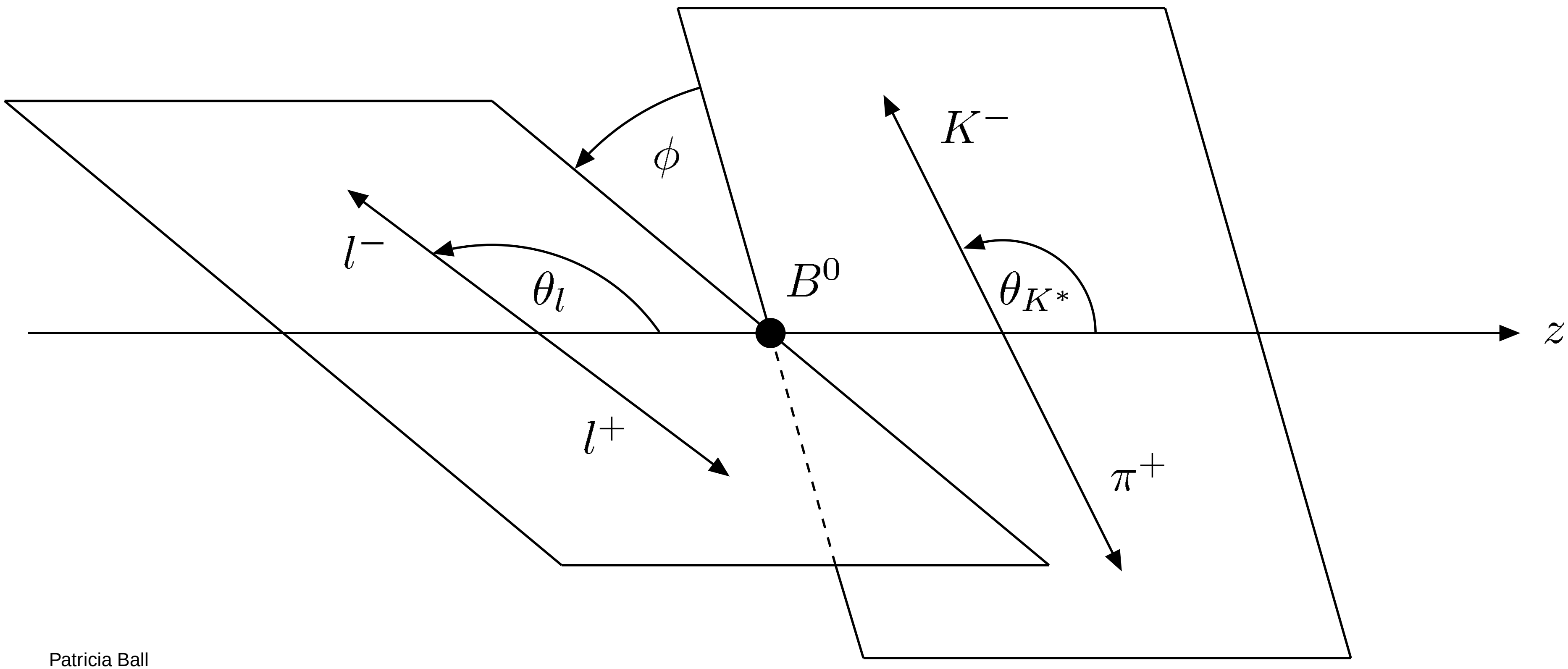
How to define observables

Kinematics

K^* decays to $K\pi$ ($\approx$100 %). Angular distribution of $K\pi$ indicative for polarisation of K^*.

Full angular spectrum:

$$\frac{d^4\Gamma}{dq^2\, d\cos\theta_l\, d\cos\theta_{K^*}, d\phi} = \frac{9}{32\pi} I(q^2, \theta_l, \theta_{K^*}, \phi)$$



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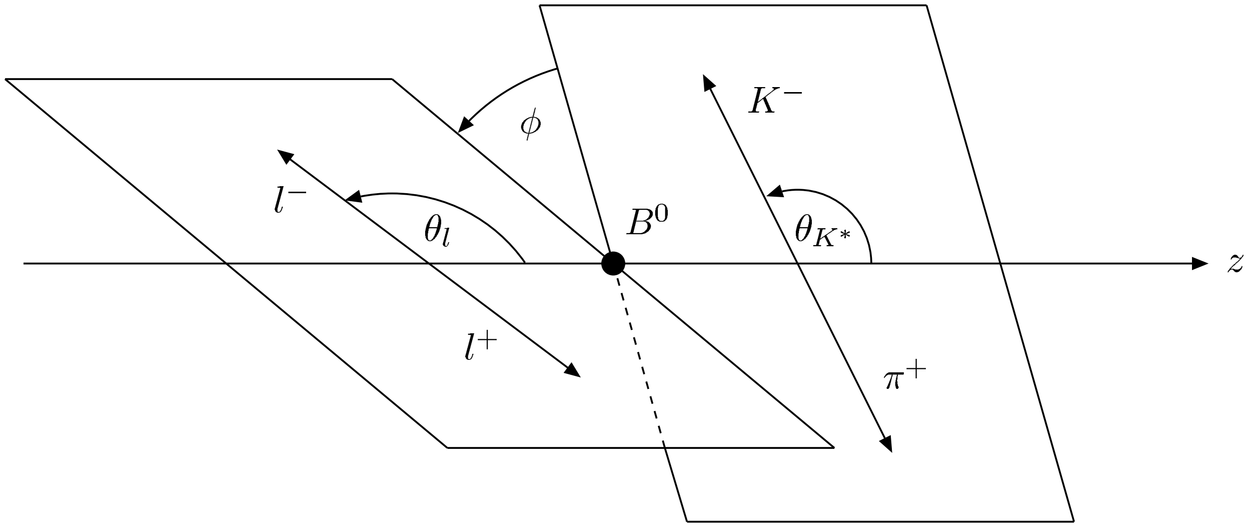
$$\begin{aligned} I(q^2, \theta_l, \theta_{K^*}, \phi) \quad = \quad & I_1^s \sin^2\theta_{K^*} + I_1^c \cos^2\theta_{K^*} + (I_2^s \sin^2\theta_{K^*} + I_2^c \cos^2\theta_{K^*}) \cos 2\theta_l \\ & + I_3 \sin^2\theta_{K^*} \sin^2\theta_l \cos 2\phi + I_4 \sin 2\theta_{K^*} \sin 2\theta_l \cos\phi \\ & + I_5 \sin 2\theta_{K^*} \sin\theta_l \cos\phi \\ & + (I_6^s \sin^2\theta_{K^*} + I_6^c \cos^2\theta_{K^*}) \cos\theta_l + I_7 \sin 2\theta_{K^*} \sin\theta_l \sin\phi \\ & + I_8 \sin 2\theta_{K^*} \sin 2\theta_l \sin\phi + I_9 \sin^2\theta_{K^*} \sin^2\theta_l \sin 2\phi. \end{aligned}$$

I_j: experimental observables: angular correlations

$\rightarrow$ complete information on $B \rightarrow K^* \mu\mu$



I_j and Form Factors/Wilson Coefficients

Relation between observables I_j and $\langle K^*\mu\mu|\mathcal{H}_{\rm eff}|B\rangle$ given in terms of transversity amplitudes $A_{\|,\perp,0,t}$, e.g.

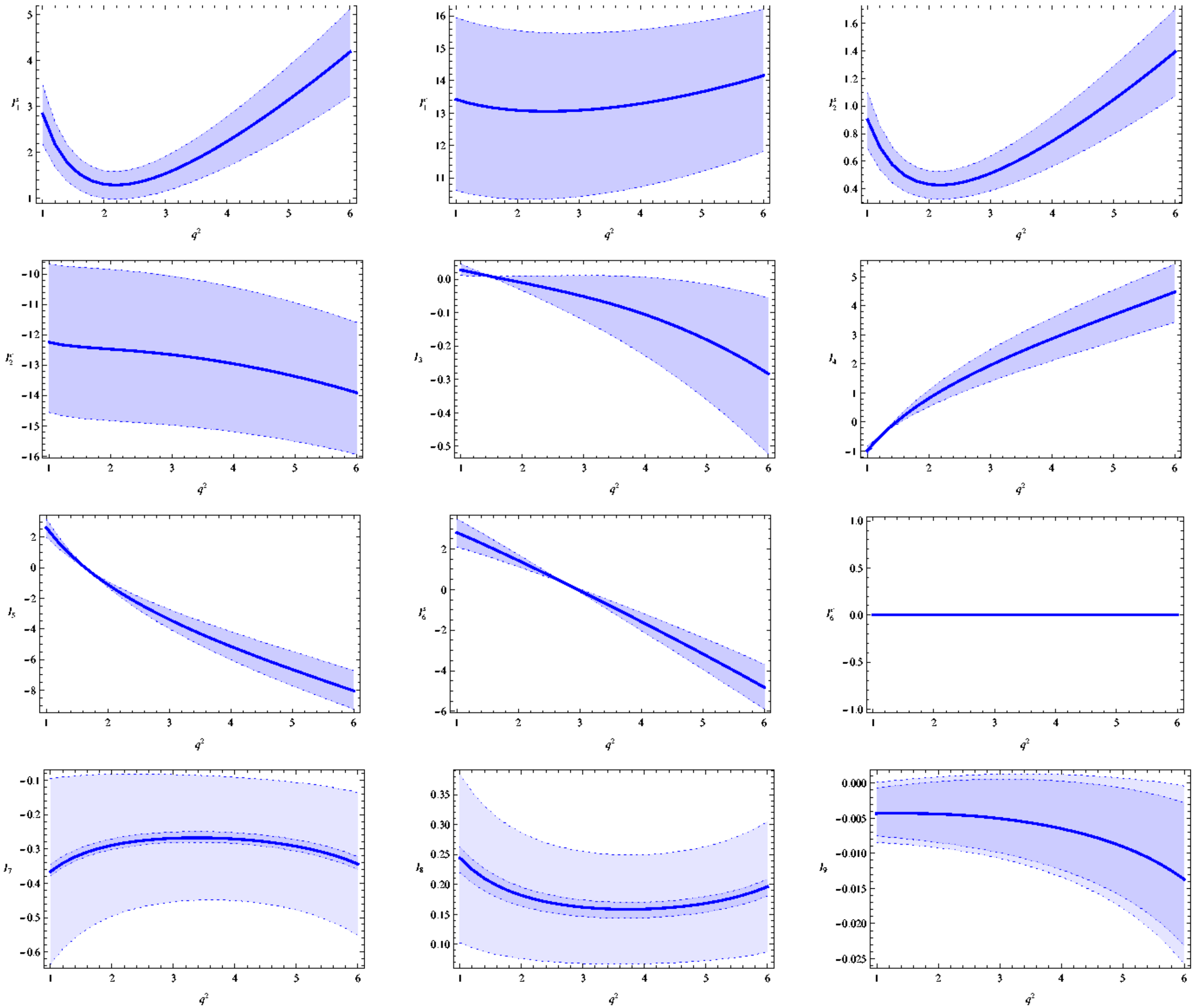
$$I_6^s = 2\beta_\ell\left[\text{Re}(A_\|^L A_\perp^{L\,*}) - (L\to R)\right],$$

with

$$A_{\perp L,R} = N\sqrt{2}\lambda^{1/2}\Bigg[\left[(C_9^{\rm eff}+C_9^{\rm eff\prime})\mp(C_{10}+C_{10}')\right]\frac{V(q^2)}{m_B+m_{K^*}} + \frac{2m_b}{q^2}(C_7^{\rm eff}+C_7^{\rm eff\prime})T_1(q^2)\Bigg]$$

$$A_{\| L,R} = -N\sqrt{2}(m_B^2-m_{K^*}^2)\left[(C_9^{\rm eff}-C_9^{\rm eff\prime})\mp(C_{10}-C_{10}')\right]\frac{A_1(q^2)}{m_B-m_{K^*}} + \frac{2m_b}{q^2}(C_7^{\rm eff}-C_7^{\rm eff\prime})T_2(q^2)\Bigg]$$

A few comments on I_j



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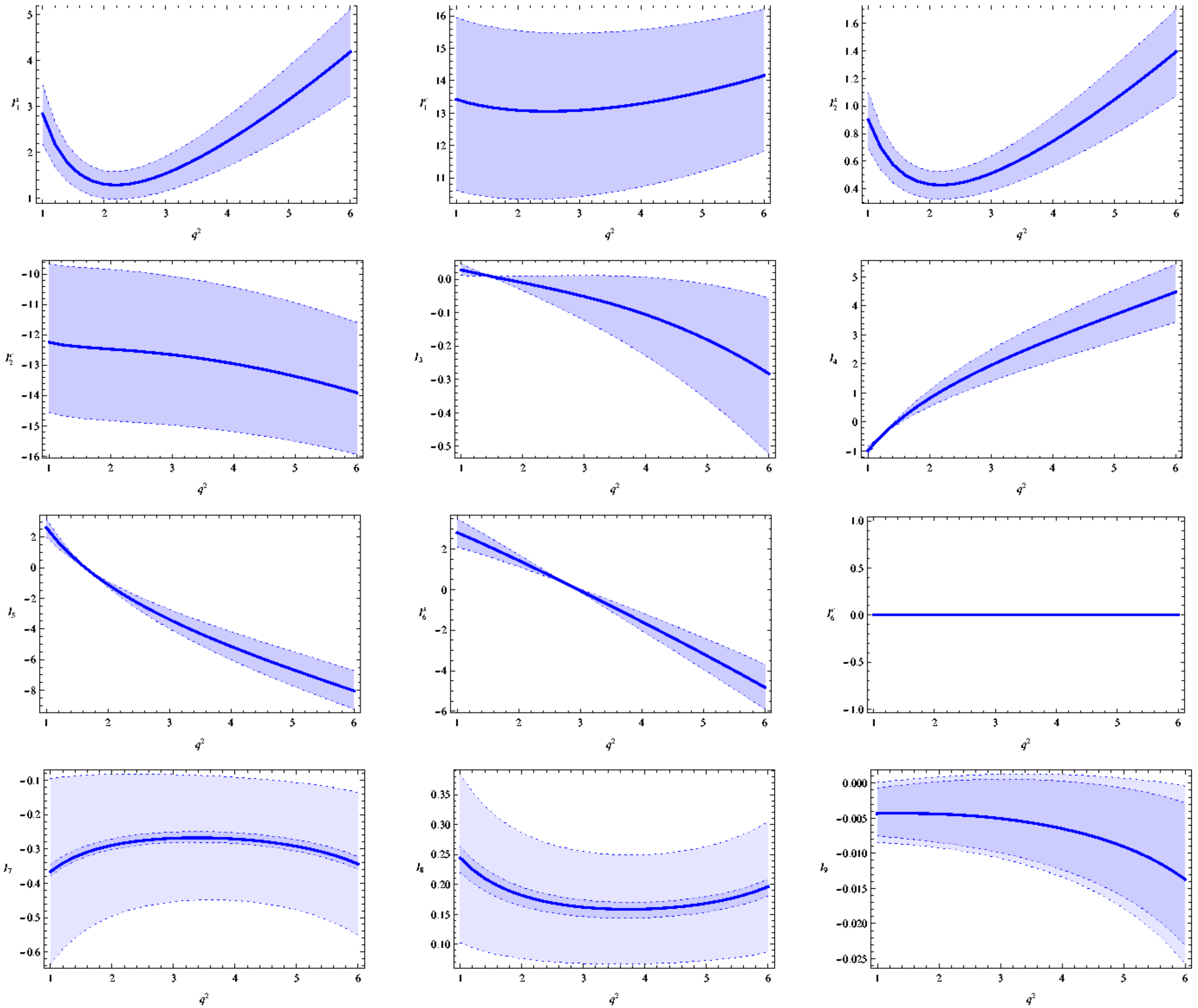

- I_j contain complete information to be extracted from the decay
- for massless leptons, $I_1^s = 3I_2^s$ and $I_1^c = -I_2^c$
- $I_6^c = 0$ in SM; a non-zero value is due to contributions from scalar operators and $m_l \neq 0$. Potentially good observable for extended Higgs sector!

Observables

- order principle: behaviour under CP trafos: I_j from b ($\bar{B}^0$) decay, $\bar{I}_j$ from $\bar{d}$ (B^0) decay
  - CP-even (CP-averaged) $I_j + \bar{I}_j$, CP-odd $I_j - \bar{I}_j$
- normalize by $d(\Gamma + \bar{\Gamma})/dq^2$ (q^2: invariant dilepton mass)
- new standard observables: symmetries S_j and asymmetries A_j:

$$S_j = \frac{I_j + \bar{I}_j}{d(\Gamma + \bar{\Gamma})/dq^2}, \qquad A_j = \frac{I_j - \bar{I}_j}{d(\Gamma + \bar{\Gamma})/dq^2}$$

  Taking ratios reduces theory errors!

- advantage symmetries: increased statistics
- advantage asymmetries: sensitivity to new CP-violating phases induced by BSM (all A_j very close to 0 in SM)

Relation to Known Observables

Forward-backward asymmetry:

$$A_{\rm FB} = \frac{3}{8}\,(2S_6^s + S_6^c)$$

Transverse asymmetries: (Krüger/Matias)

$$A_T^{(2)} = \frac{S_3}{2\,S_2^s}$$

$$A_T^{(3)} = \left(\frac{4\,S_4^2 + S_7^2}{-2\,S_2^c\,(2\,S_2^s + S_3)}\right)^{1/2}$$

$$A_T^{(4)} = \left(\frac{S_5^2 + 4\,S_8^2}{4\,S_4^2 + S_7^2}\right)^{1/2}$$

Note: while all S_i and A_i are well-behaved, the $A_T^{(i)}$ can, in principle, have (highly-theory dependend) peaks from small denominators.

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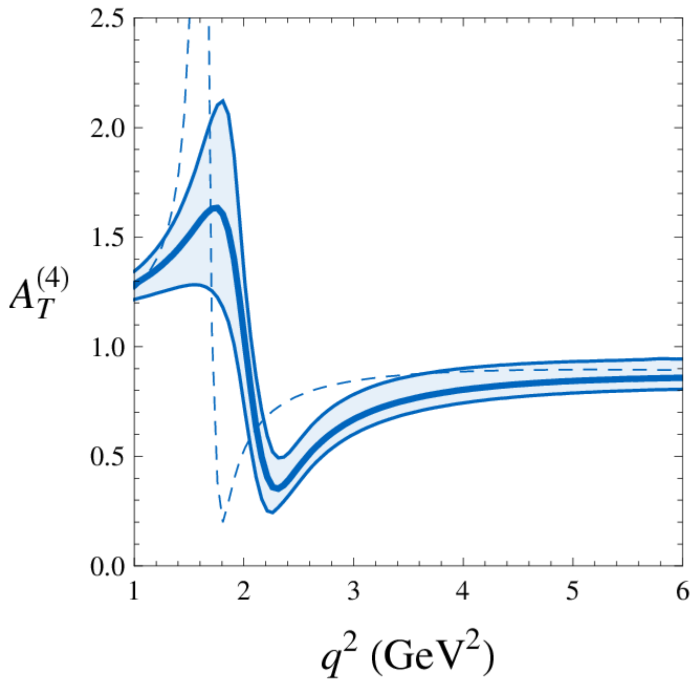

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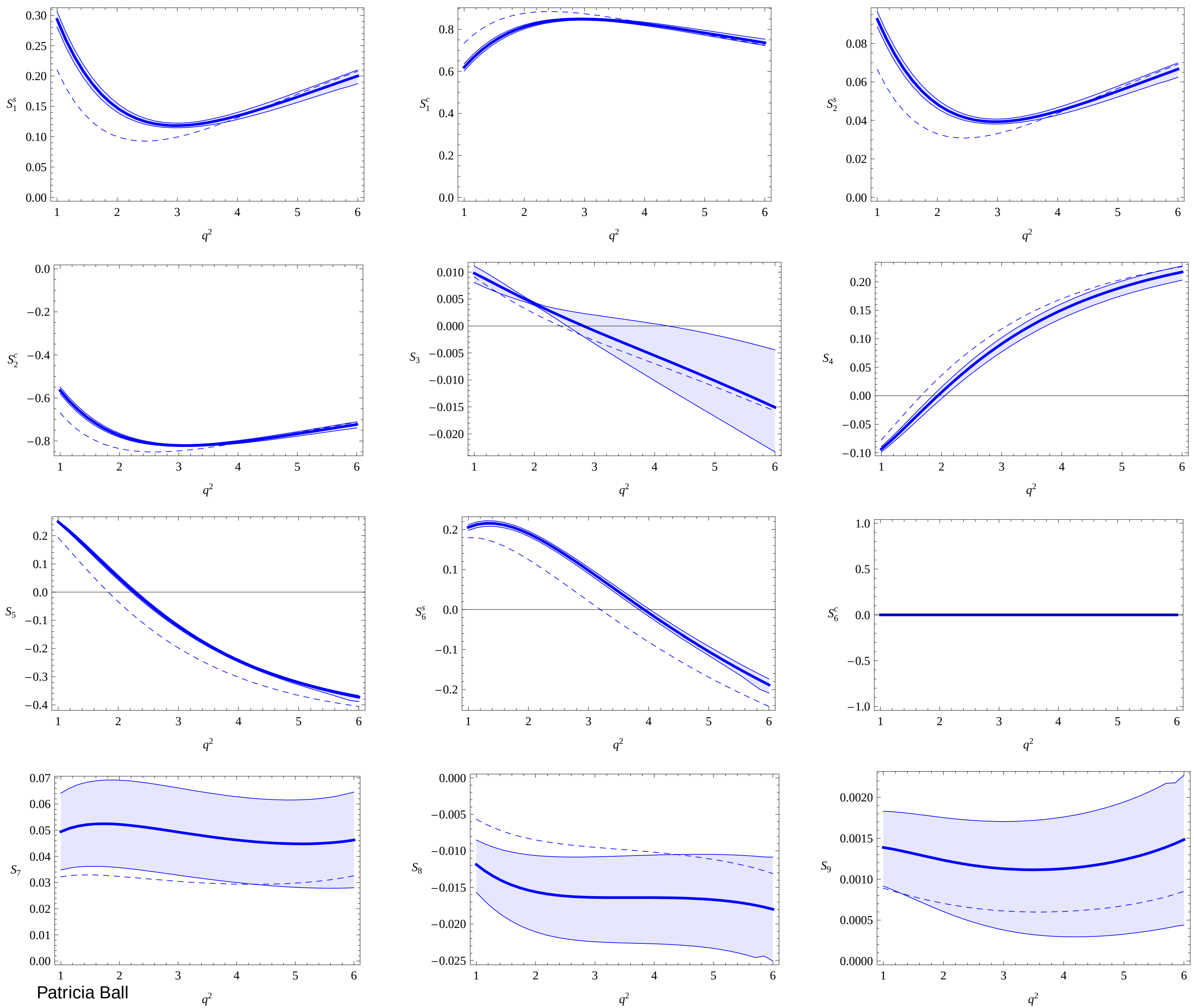

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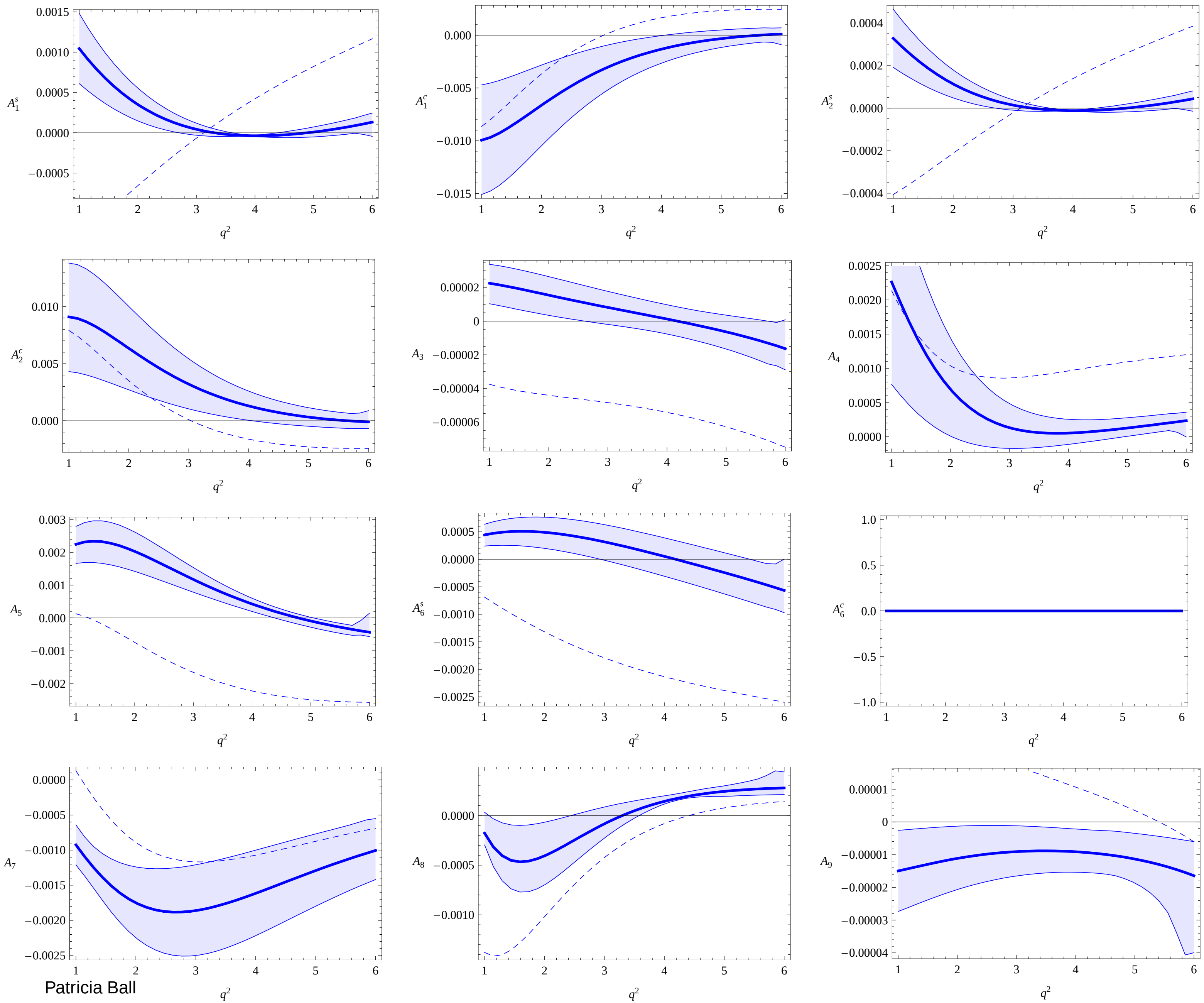

How to measure S_i and A_i?

- full angular spectrum
- or: suitable integrals
  - if observable is smooth in q^2:

$$S_i(q^2) \to \langle S_i \rangle \equiv \int_{1\,\mathrm{GeV}^2}^{6\,\mathrm{GeV}^2} dq^2\, S_i(q^2)$$

    (QCD factorization only valid for small q^2: choose interval $1\,\mathrm{GeV}^2 \leq q^2 \leq 6\,\mathrm{GeV}^2$ below (theory) charm threshold $4m_c^2$)

  - for S_5, e.g., only need small number of bins in angles:

$$\begin{aligned} S_5 \;&=\; -\frac{4}{3}\left[\int_{\pi/2}^{3\pi/2} - \int_0^{\pi/2} - \int_{3\pi/2}^{2\pi}\right] d\phi \left[\int_0^1 - \int_{-1}^0\right] d\cos\theta_K \\ &\quad \times \frac{d^3(\Gamma - \bar{\Gamma})}{dq^2\, d\cos\theta_K d\phi} \Bigg/ \frac{d(\Gamma + \bar{\Gamma})}{dq^2} \end{aligned}$$

Features to look for in S_i and A_i

- zeros in S_i
  - in S_6 (forward-backward asymmetry), also in $S_{4,5}$
  - correlation between zeros and BR$(B \to X_s\gamma)$
- large A_i (larger than $O(1\%)$)
  - due to **new CP-violating phases**
- non-zero S_6^c: evidence for **BSM scalar operators**

How to find New Physics

$\longrightarrow$ Aoife Bharucha's talk

Summary

- $B \to K^* \mu\mu$ is an ideal channel to find new physics in the flavour sector at the LHC
- high sensitivity to new CP-violating phases
- alternatively, with mass scales of NP fixed by Atlas/CMS, the decay can help to constrain NP couplings
- theoretical description based on
  - effective Hamiltonian: known to NNLL accuracy in SM, plus one-loop NP effects (complete MSSM, MSSM with various constraints, little Higgs model) (Buras et al., 200x)
  - form factors: QCD sum rules on the light-cone (Ball/Zwicky 04, Ball 08)
  - QCD factorisation (Beneke/Feldmann/Seidel 01+04)
- theoretical uncertainty well under control as only ratios (symmetries + asymmetries) considered
- LHC will collect enough data to allow analysis of full angular spectrum (may need upgrade?)