EXCLUSIVE $B \to K^{\star}\ell\ell$ WITH HIGH STATISTICS

Will Reece (CERN)

Introduction

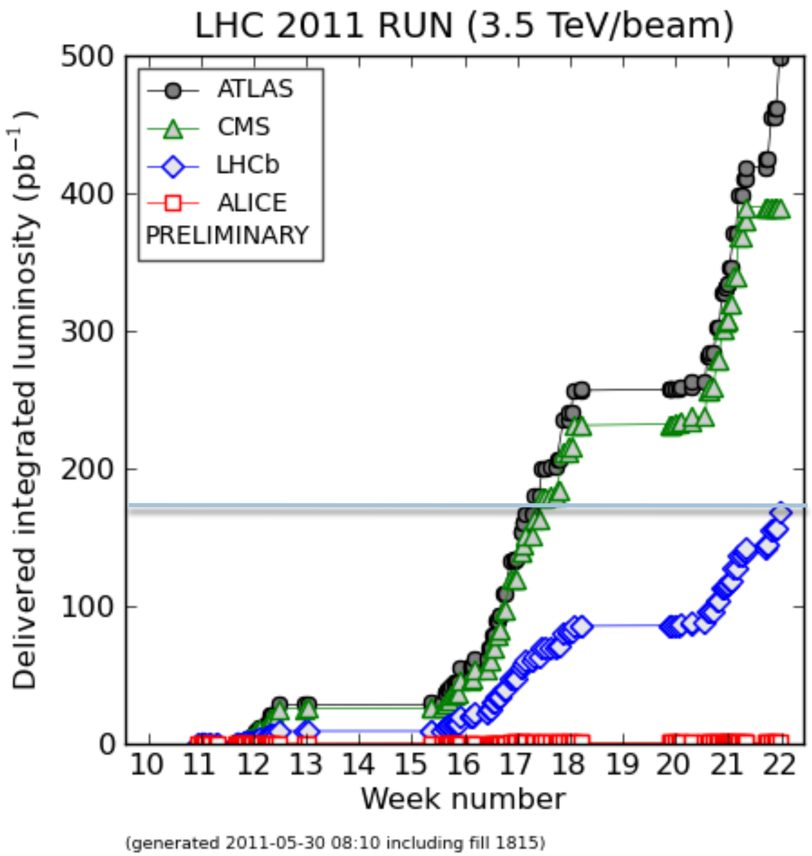
- Rare decays a hot topic at the LHC
  - Core part of LHCb physics program (arXiv:0912.4179)
  - Sensitive to new physics in $b \to s$ loops
- Two targets of particular interest
  - $B_s \to \mu\mu$ and $B_d \to K^\star \ell\ell$
  - Orthogonal and complementary views on NP
  - Gives access to C_7, C_9, C_{10}, C_S, C_P & Primes
- Will focus on $B_d \to K^* \mu\mu$ at LHCb
  - Not a member of collaboration so will concentrate on phenomenology results and interesting measurements

Note on Yields

- Public LHCb MC studies:
  - Full simulation at 14 TeV
  - Use $\sigma_{b\bar{b}} = 500$ µb
  - 2fb^{-1} per nominal year
- 2011 LHC Run:
  - 7TeV with pile-up
  - Measure (arXiv:1009.2731):

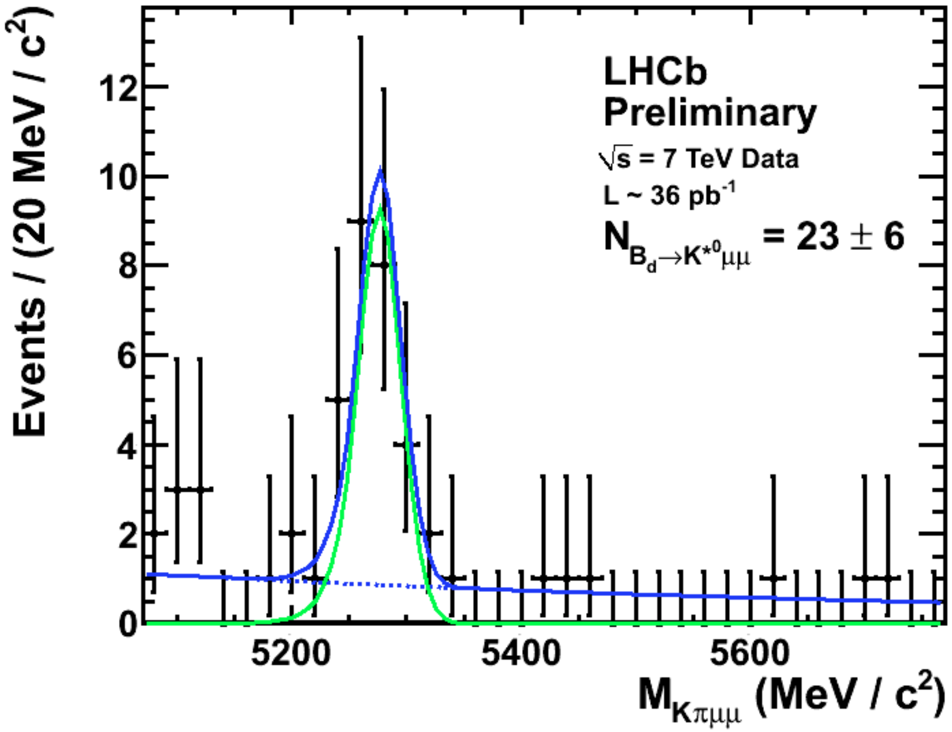
$$\sigma(pp \to b\bar{b}X) = (284 \pm 20 \pm 49)\mu\text{b}$$

- Stick to official MC yields here:
  - Mentally scale by ~0.6!



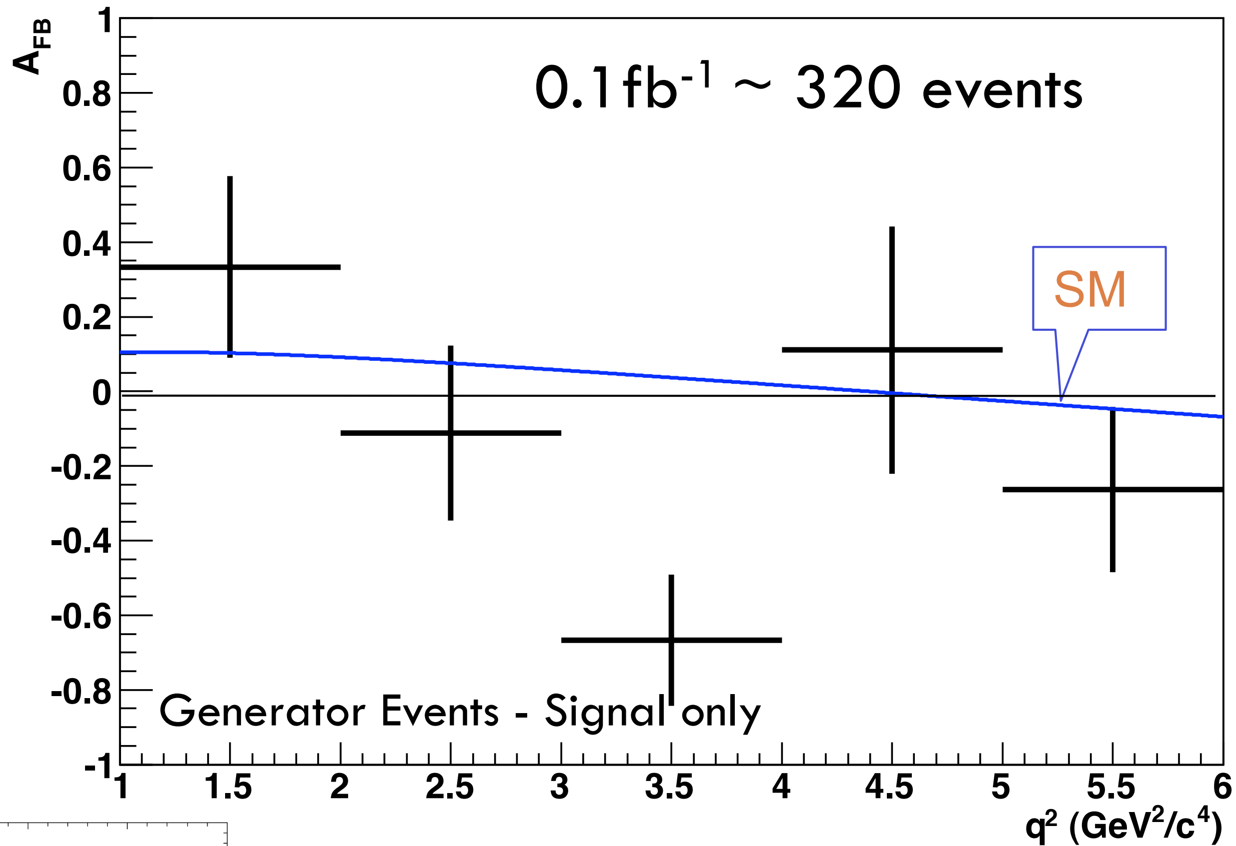
LHCb Analysis Status

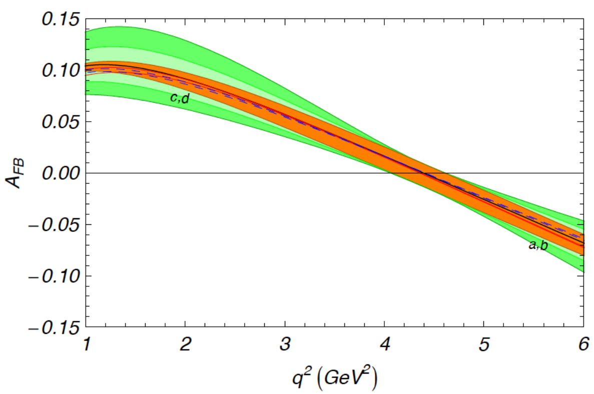
- Selection tuned on $B \to K^{\star} J/\psi$ events
- Clean signal sample
  - Results only for $36pb^{-1}$
- 23±6 evts; B/S = 0.2
  - BaBar: 60 0.3
  - Belle: 230 0.25
  - CDF: 100 0.4
- LHCb at planned lumi now
  - ~$200pb^{-1}$ on tape in 2011



LHCb 2010 LHC Run data:
B/S = 0.2; Selected with MVA
B/S = 1 gives 50% more events

A Possible (Near) Future at the LHC





$$A_{FB} = \frac{\int_0^1 \frac{\partial^2\Gamma}{\partial q^2 \cos\theta_l} d\cos\theta_l - \int_{-1}^0 \frac{\partial^2\Gamma}{\partial q^2 \cos\theta_l} d\cos\theta_l}{\int_0^1 \frac{\partial^2\Gamma}{\partial q^2 \cos\theta_l} d\cos\theta_l + \int_{-1}^0 \frac{\partial^2\Gamma}{\partial q^2 \cos\theta_l} d\cos\theta_l}$$

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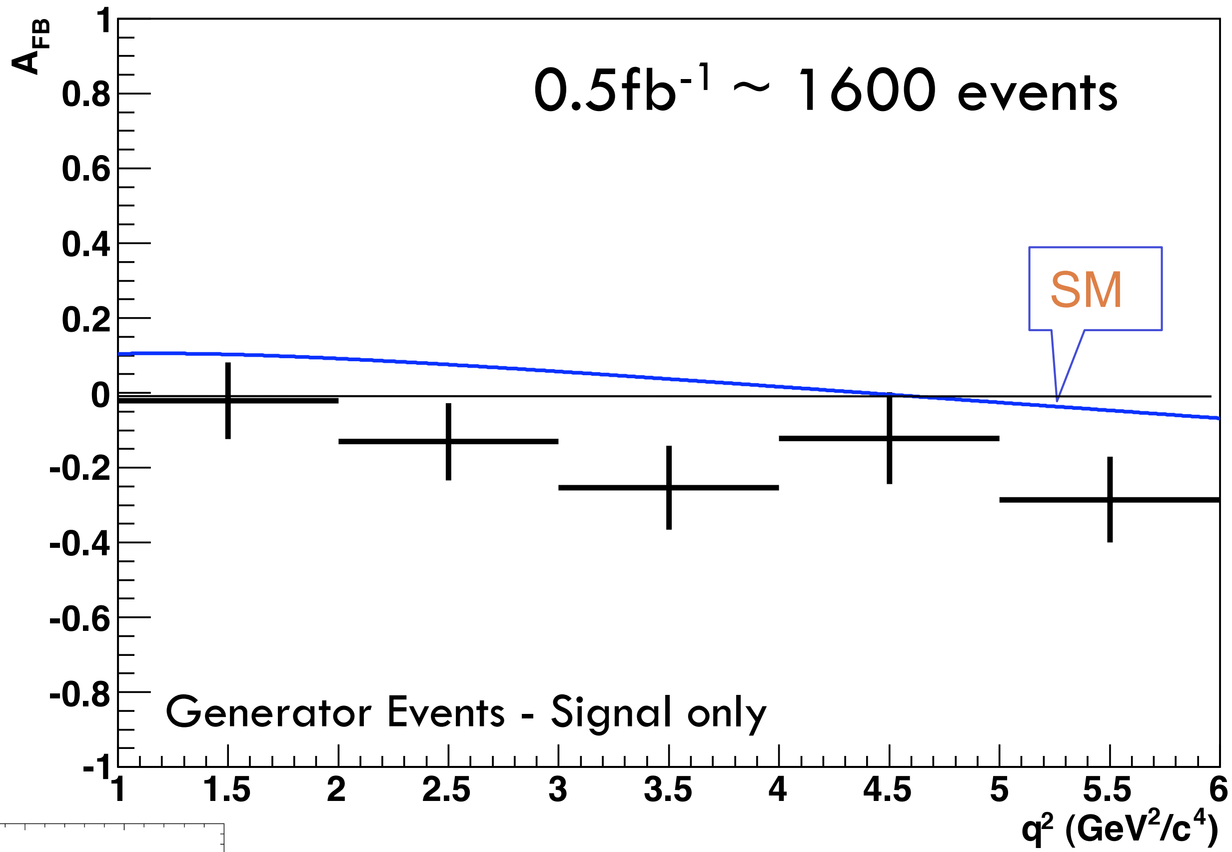

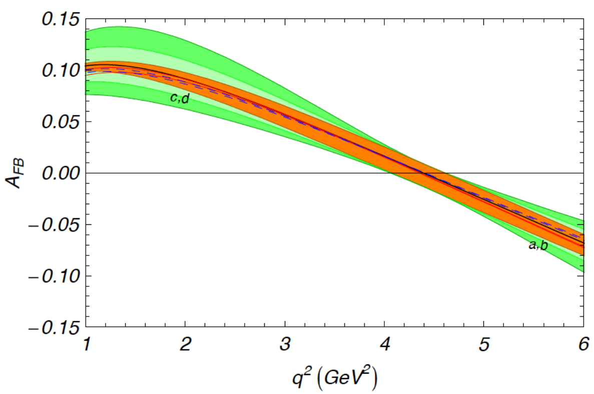

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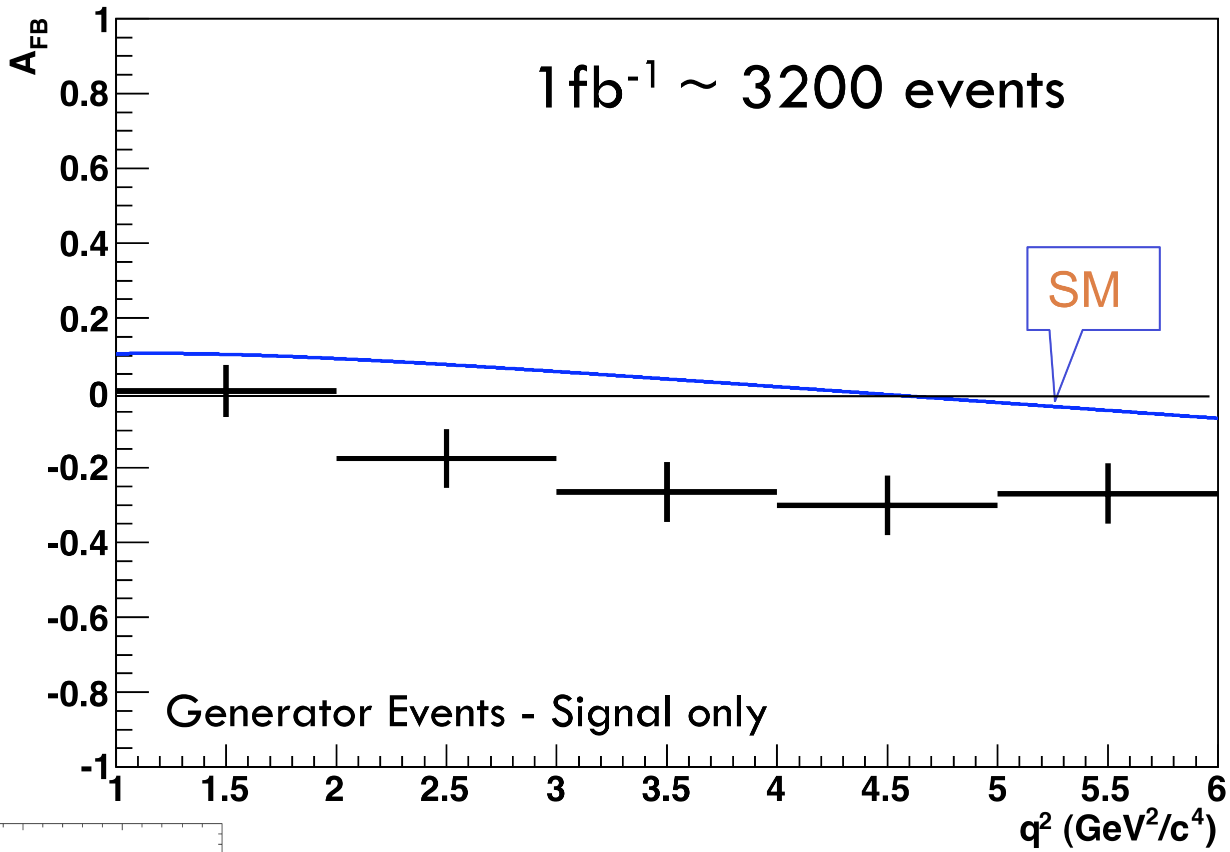
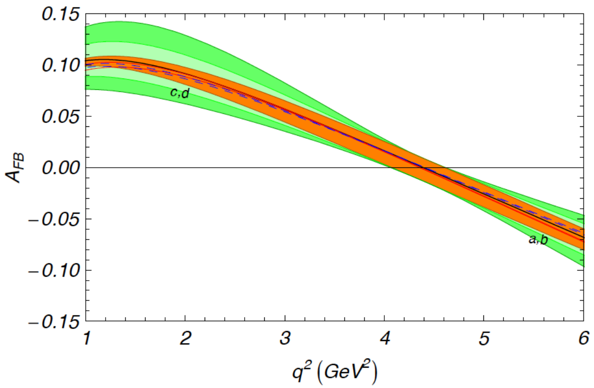
A Possible (Near) Future at the LHC





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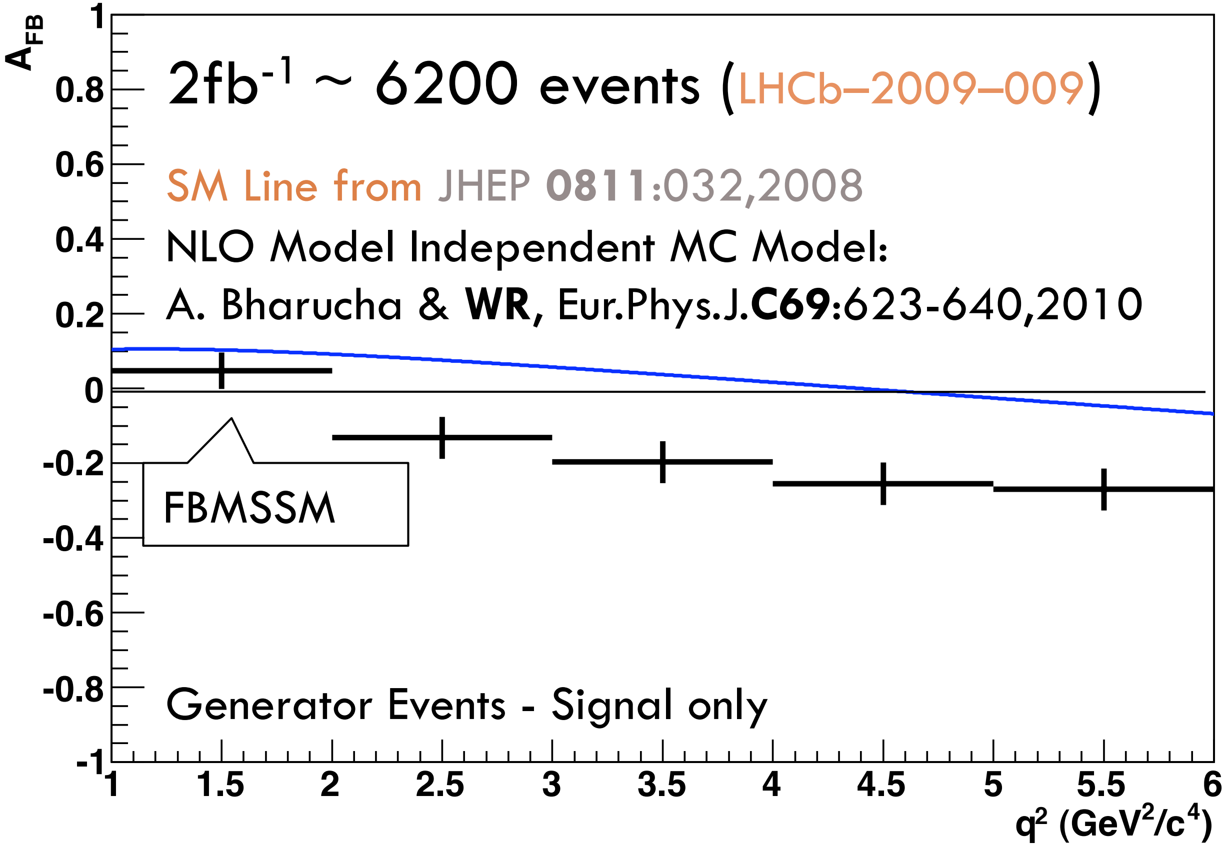
A Possible (Near) Future at the LHC

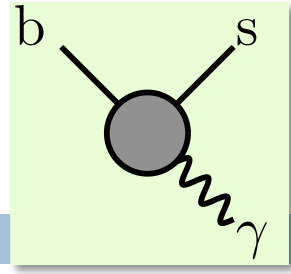


Generated with FBMSSM

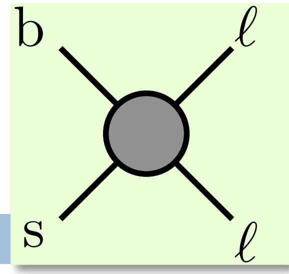
[Altmannshofer, Ball, Bharucha, Buras, Straub, Wick, (JHEP **0901**:019,2009)]

(LHCb would have already observed $B_s \rightarrow \mu\mu$ in this scenario)

$B_d \to K^* \mu^+ \mu^-$



$O_{7\gamma}$

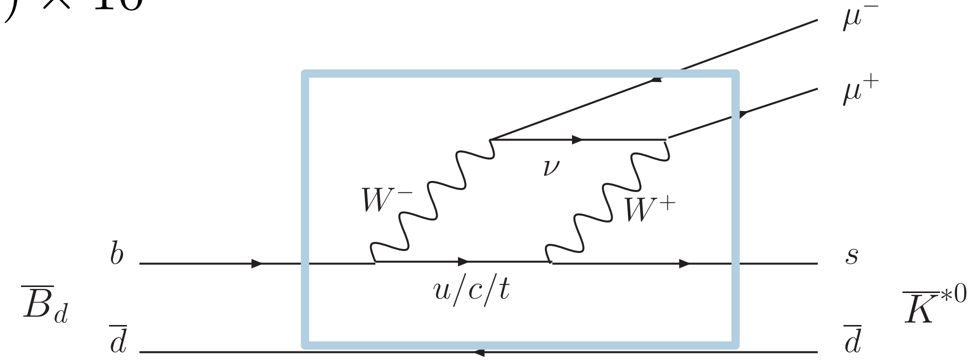


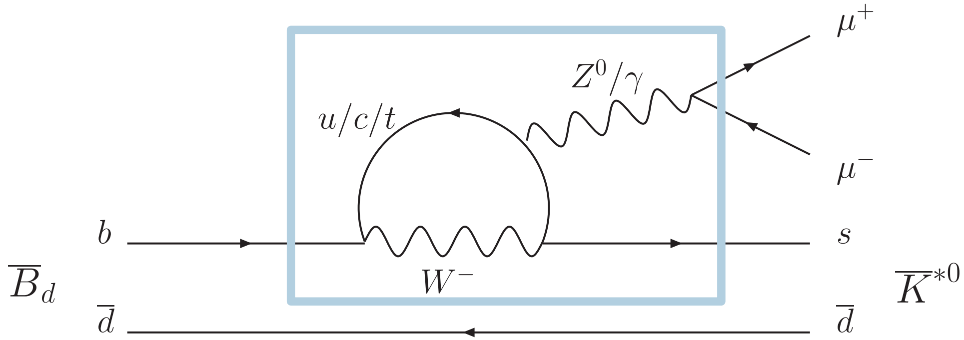
$O_{9,10}$

- First observed at Belle
  - $Br(B_d \to K^\star \mu^+ \mu^-) = (11.5\ ^{+0.16}_{-0.15}) \times 10^{-7}$
- Particles in Loop
  - Both neutral and charged NP (replace $W^\pm$, Z^0/γ, u/c/t)
- Sensitive to NP in loops
  - Use OPE: Model independent

$$\mathcal{H}_{\text{eff}} \propto \sum_{i=1}^{10} [C_i \mathcal{O}_i + C_i' \mathcal{O}_i']$$

- Dominated by C_7, C_9, C_{10} in SM
  - Enhance other operators with NP
- Measure Wilson coefficients
  - Discover or limit NP in $b \to s$ loop

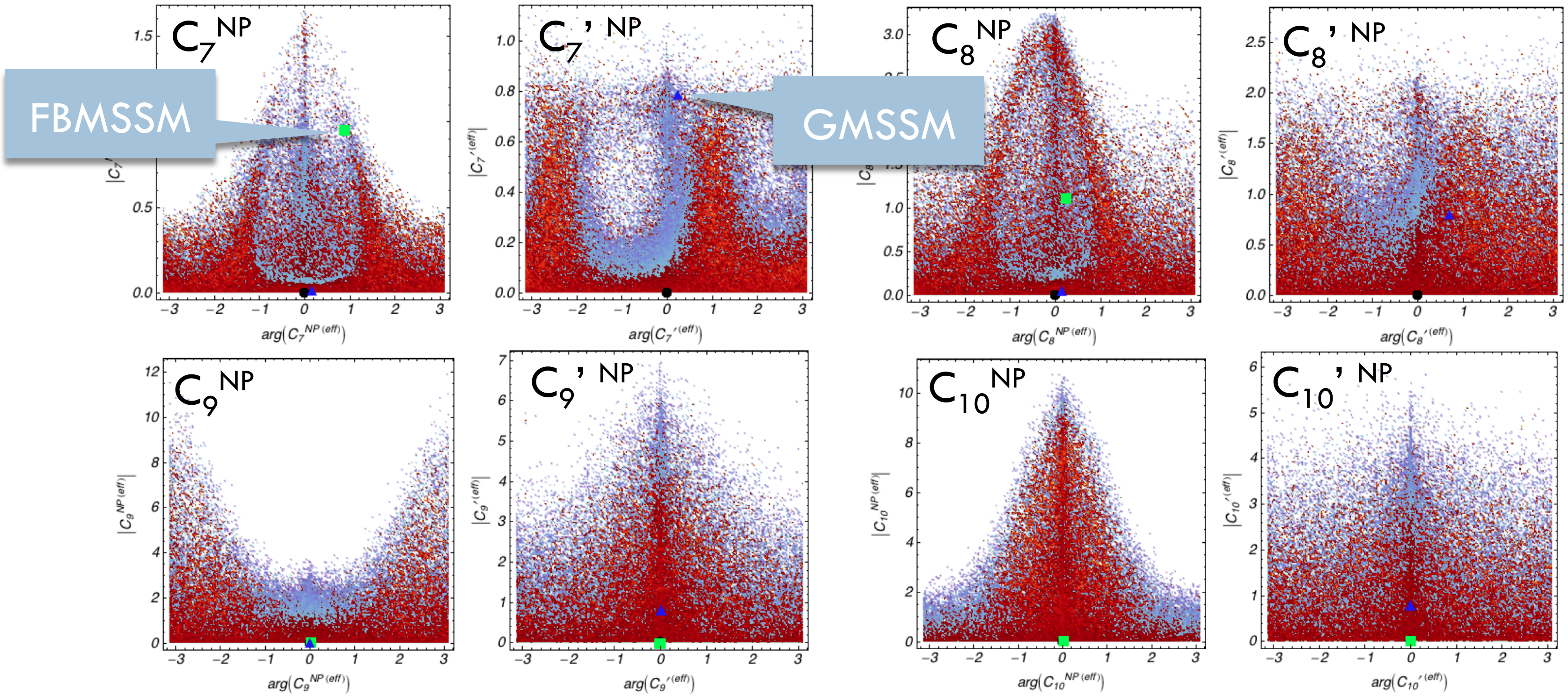




Wilson Coefficients

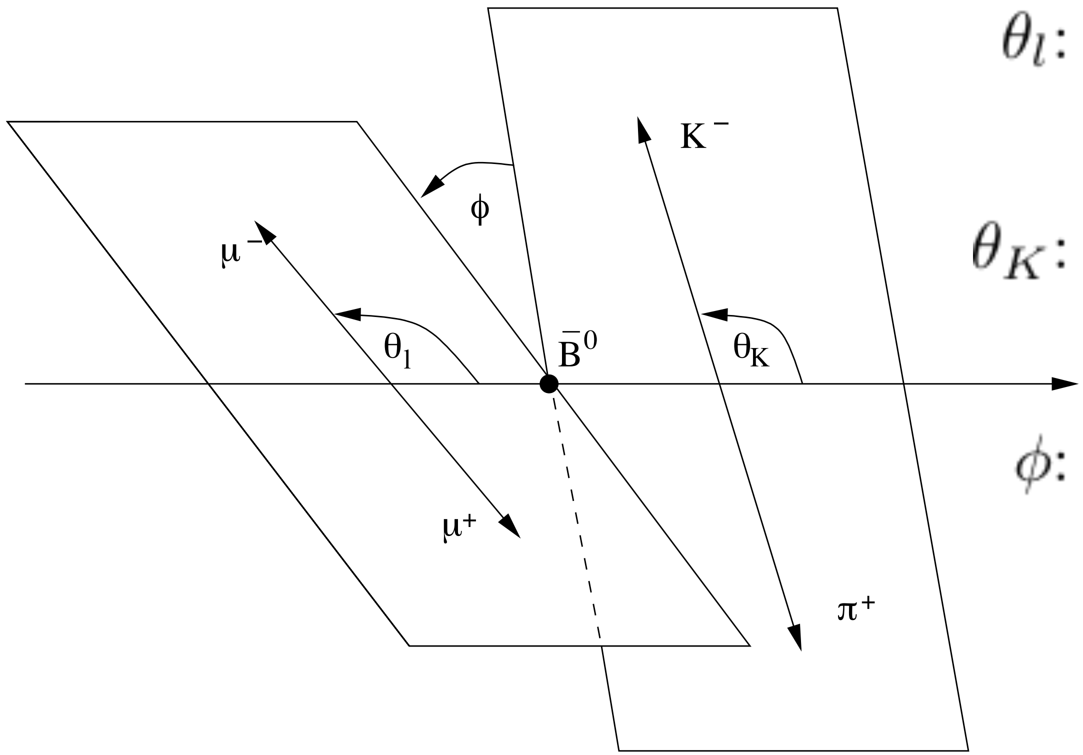
Red: 68%; Blue 95%
Values shown at M_W
SM at (0,0)

A. Bharucha & **WR**, Eur.Phys.J.**C69**:623-640,2010



- MCMC scan over C_7, C_8, C_9, C_{10}, C_S, C_P + primes
- Phases left free, uses 2010 constraints (see backup)
  - High-q^2 constraints in A_{FB}, F_L not considered (affects C_{10})

Decay Kinematics



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

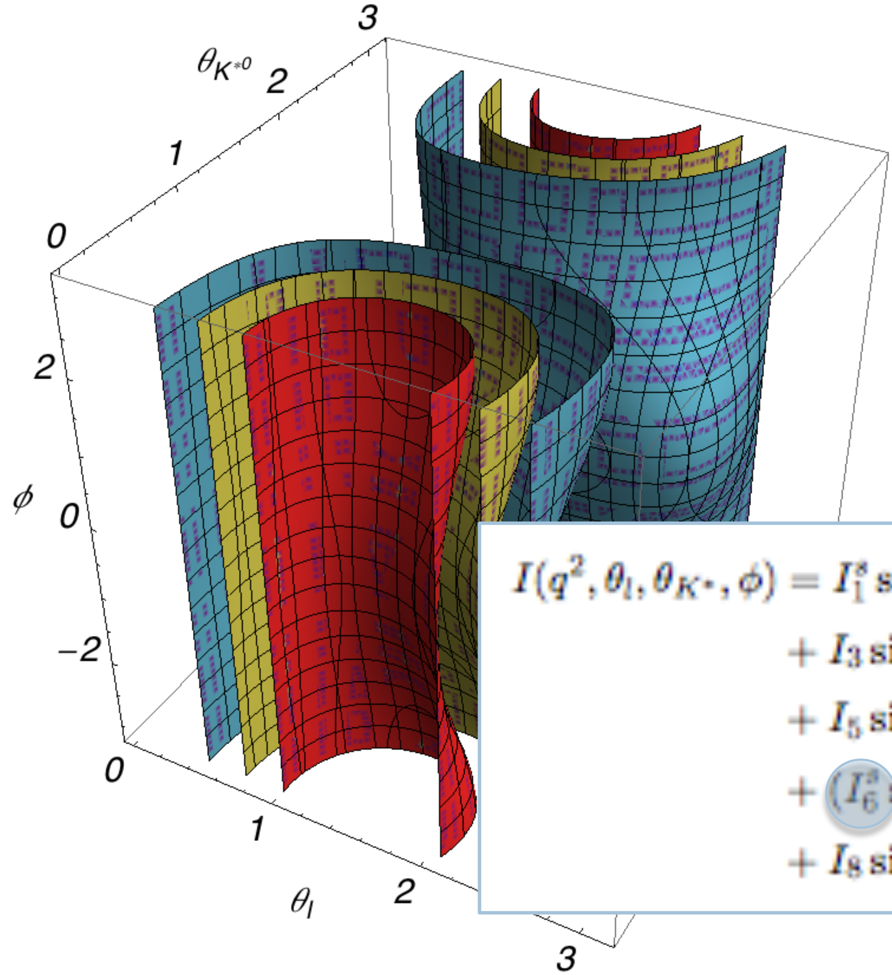
θ_K: Angle between K^- and the $\bar{B}$ in the $\bar{K}^{*0}$ rest frame

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

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

Angular Distribution

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

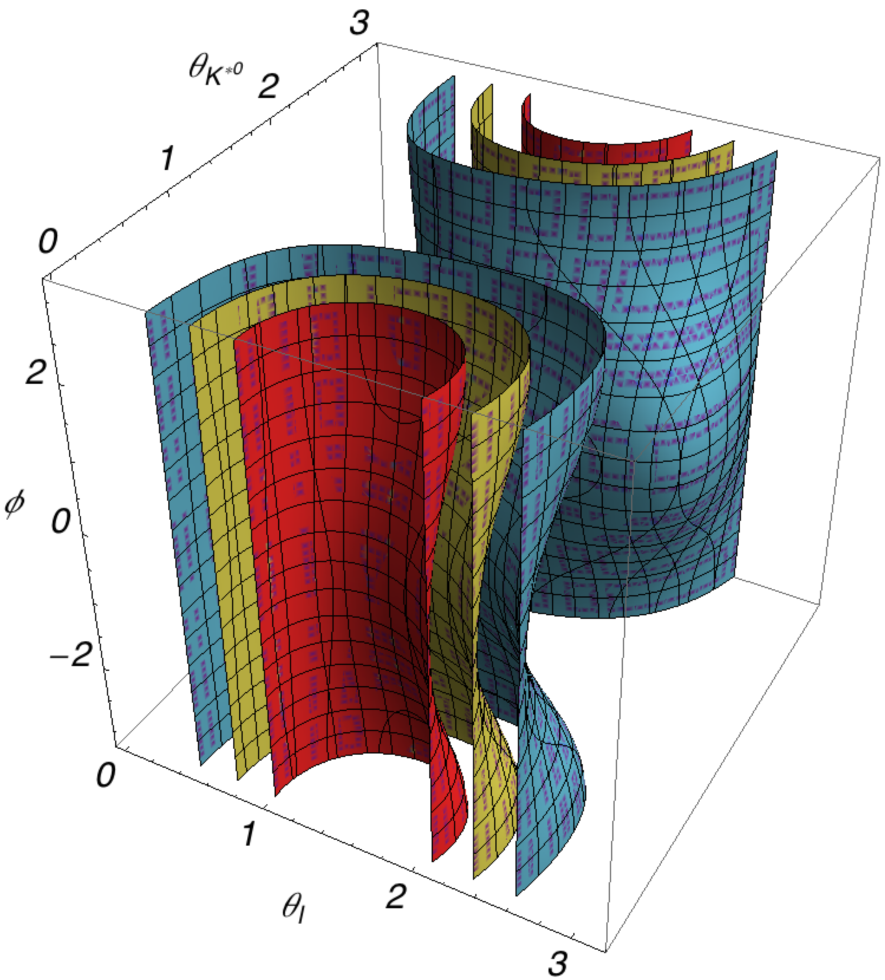


SM Distribution for $q^2 = 3.5$ GeV^2

- SM agreement with BF OK
  - 2009 update pulls more
- P→VV Final state:
  - More observables to study
  - Angular variables interesting

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

Angular Distribution (Experimental)



SM Distribution for q^2 = 3.5 GeV^2

- Resolution: q_2, θ_l, θ_K, ϕ good
- Decay distribution symmetries:
  - Important for fitting

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

- Number events in sample
  - Proportional to decay amplitude
  - Larger coefficients → more events → smaller uncertainties on given I_n
- Balance with theory errors
  - Many nice observables proposed

Landscape

$$S_i^{(a)} = \left(I_i^{(a)} + \bar{I}_i^{(a)}\right) \Big/ \frac{d(\Gamma + \bar{\Gamma})}{dq^2}$$

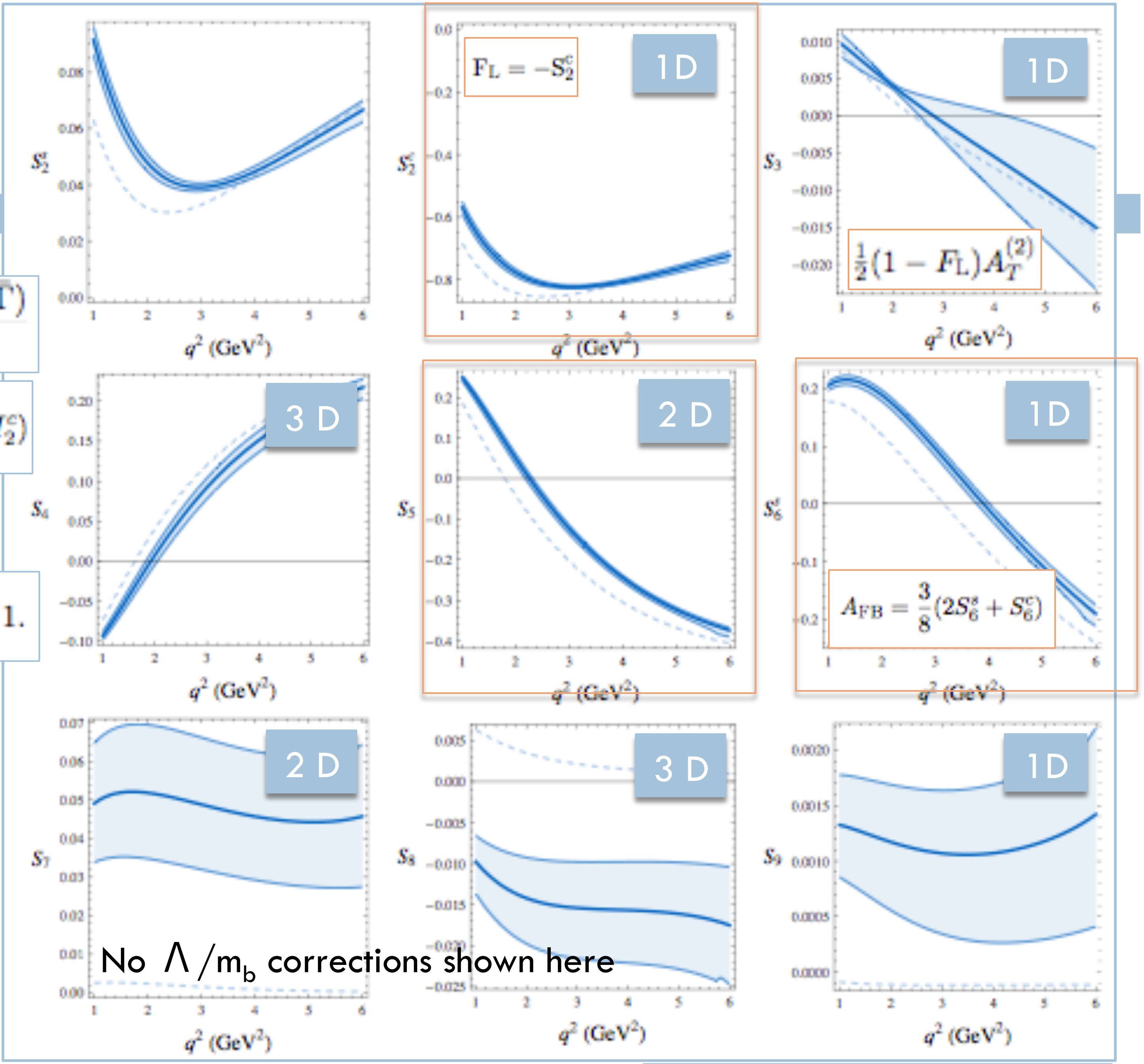
$$\frac{d\Gamma}{dq^2} = \frac{3}{4}(2\,I_1^s + I_1^c) - \frac{1}{4}(2\,I_2^s + I_2^c)$$

$$\frac{3}{4}(2\,S_1^s + S_1^c) - \frac{1}{4}(2\,S_2^s + S_2^c) = 1.$$

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

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

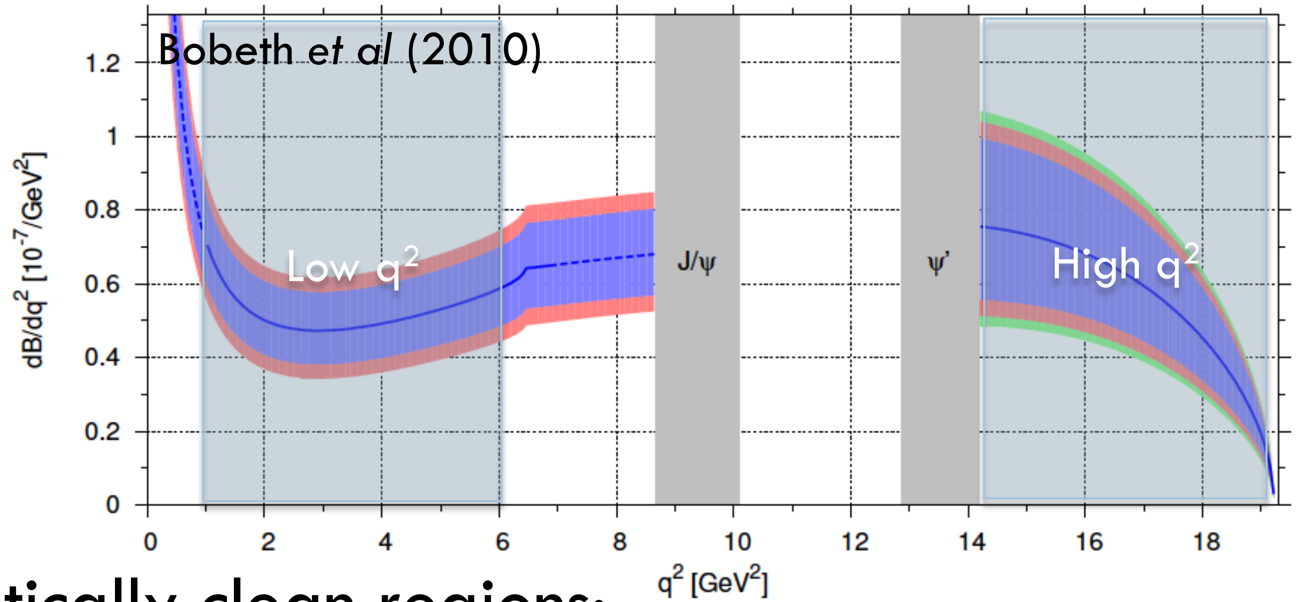
$$A_T^{(4)} = \left(\frac{S_5^2 + 4\,S_8^2}{4\,S_4^2 + S_7^2}\right)^{1/2}.$$



$$A_T^{(5)}\Big|_{m_\ell=0} = \frac{\sqrt{16 J_1^{s\,2} - 9 J_6^{s\,2} - 36(J_3^2 + J_9^2)}}{8 J_1^s}$$

SM Predictions, Altmannshofer et al, JHEP **0901**:019,2009

Landscape – q^2



- Theoretically clean regions:
  - Large recoil ($1<q^2<6$ GeV^2) – e.g. Kruger, Matias, Phys.Rev.**D71**:094009,2005
  - Low recoil ($14<q^2<19.2$ GeV^2) - Bobeth et al, JHEP **1007**:098,2010
- Belle measures signal yields in both regions
  - Ratio low/high: 0.35 ± 0.1

What to measure?

- Consider three phases: low, medium, high statistics
- Low statistics (~100s): 1D projections
  - A_{FB}, F_L, BF, ($A_T^{(2)}$, S_9)
- Medium statistics (~1000s): Can use 2D projections
  - A_{FB} (+ Zero), S_5 (+ Zero), $A_T^{(2)}$, CP asymmetries
- High statistics (>5000): Full-angular analysis
  - Can measure everything!
  - Many theoretically clean variables for low and high q^2
  - May be able to possible to reduce required yields?

Low Statistics

$$H_T^{(3)} = \frac{\mathrm{Re}(A_\parallel^L A_\perp^{L*} - A_\parallel^{R*} A_\perp^R)}{\sqrt{(|A_\parallel^L|^2 + |A_\parallel^R|^2)(|A_\perp^L|^2 + |A_\perp^R|^2)}} = \frac{\beta_l J_6}{2\sqrt{(2J_2^s)^2 - J_3^2}}.$$

- Limited to 1D distributions – project over angles

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

$A_{IM} = S_9$

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

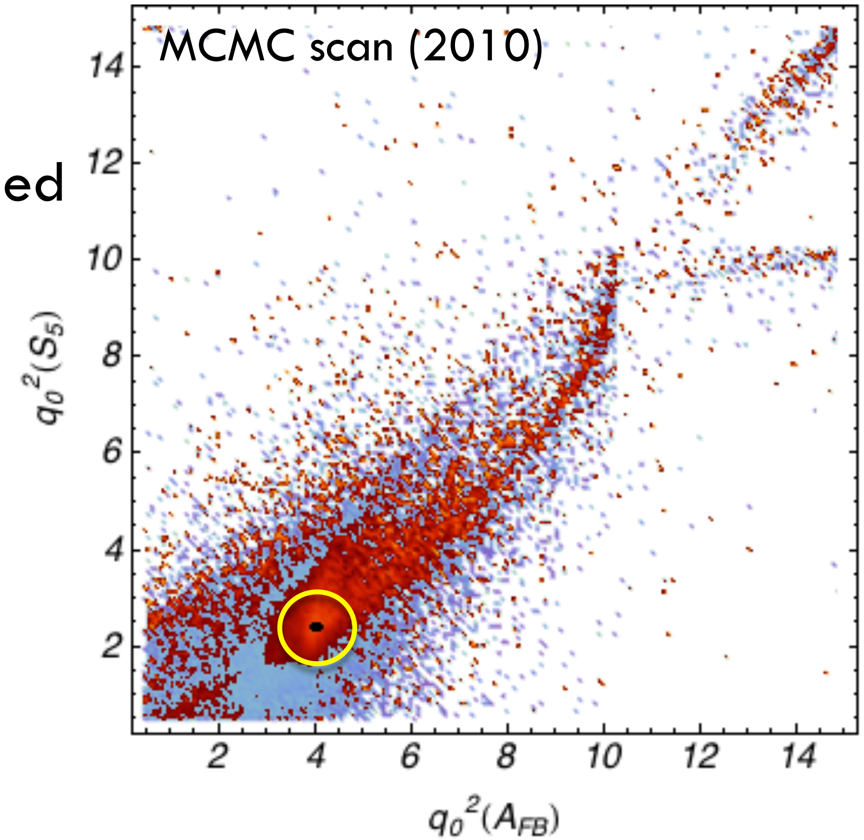
$$\frac{\mathbf{d\Gamma'}}{\mathbf{d}\cos\theta_\mathbf{K}} = \frac{\mathbf{3\Gamma'}}{\mathbf{4}}\left(\mathbf{2F_L}\cos^\mathbf{2}\theta_\mathbf{K} + (\mathbf{1} - \mathbf{F_L})\sin^\mathbf{2}\theta_\mathbf{K}\right)$$

- Try simultaneous fit – 3x1D (LHCb-PUB-2007-057)
- Sensitivity to $A_T^{(2)}$ poor in low q^2 region (F_L large)
  - In high q^2 region, F_L smaller so expect much better results
    - C.F. Very low q^2 $B \rightarrow K^*ee$ analysis (LHCb-PUB-2009-008)
- Excellent prospects for $H_T^{(3)}$ at this stage

Medium Statistics

$$H_T^{(2)} = \frac{\mathrm{Re}(A_0^L A_\perp^{L*} - A_0^{R*} A_\perp^R)}{\sqrt{(|A_0^L|^2 + |A_0^R|^2)(|A_\perp^L|^2 + |A_\perp^R|^2)}} = \frac{\beta_l J_5}{\sqrt{-2J_2^c(2J_2^s + J_3)}}$$

- 2D distributions + zeros
  - S_5, S_7 become available
  - CP asym (A_9), $A_T^{(2)}$ more constrained
- Zeros experimental uncertainty:
  - Proportional to gradient
- A_{FB} and S_5 zeros clean
  - Form factors cancel at LO
- Gradient for S_5 often large
  - Get ~2 times sensitivity
- Ratio $A_{FB}^{\{1,2\}}/A_{FB}^{\{4,6\}}$ may help
  - See Lunghi, Soni, JHEP **1011**:121,2010
- $H_T^{(2)}$ could prove powerful here



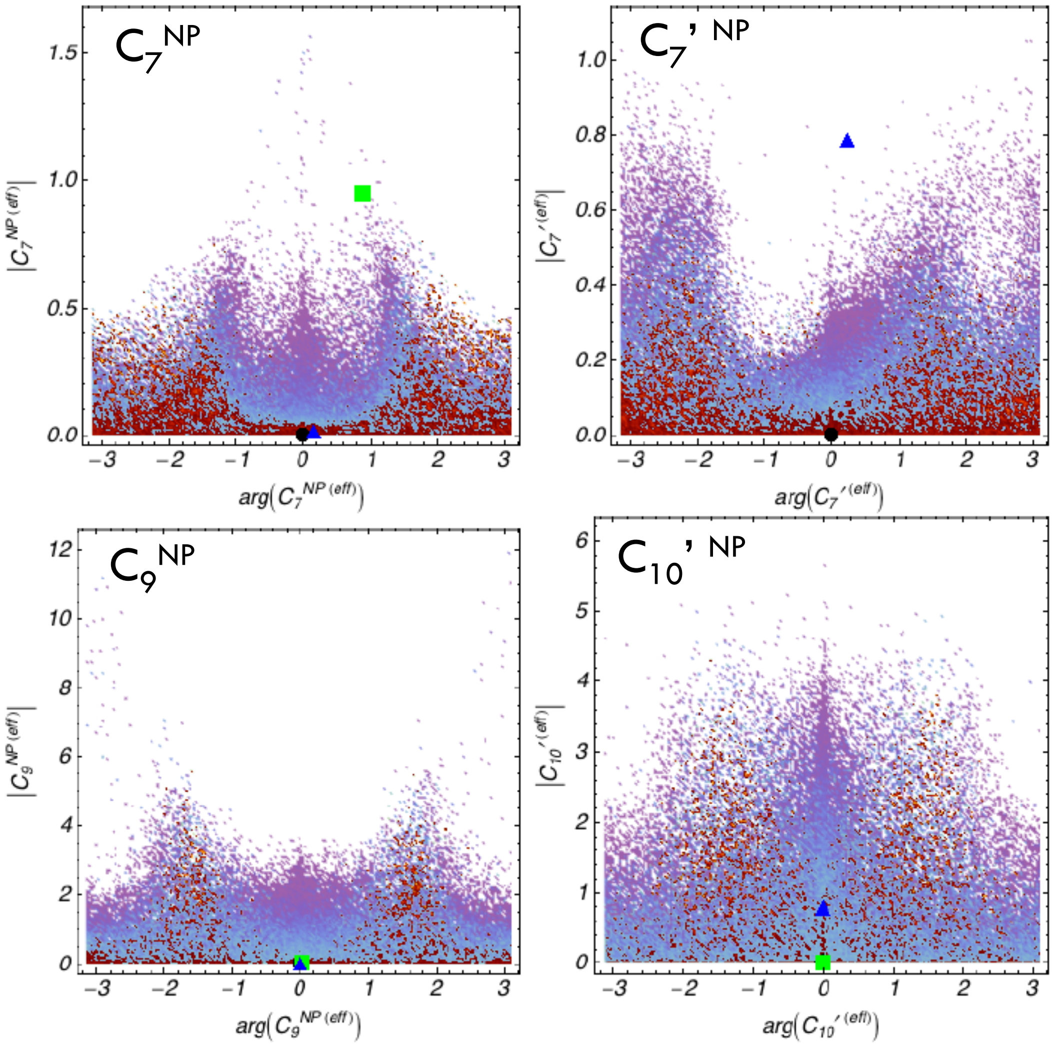
$$\frac{G_0(S_5)}{G_0(A_{\mathrm{FB}})} \approx 1.75$$

Comparing Observables

Observable	2 fb^{-1}	1 fb^{-1}	0.5 fb^{-1}	LHCb 2 fb^{-1}	Ref.
$q_0^2(A_{\mathrm{FB}})$	$^{+0.56}_{-0.94}$	$^{+1.27}_{-0.97}$	–	0.42	[128]
$q_0^2(S_5)$	$^{+0.27}_{-0.25}$	$^{+0.53}_{-0.40}$	–	–	
$\langle A_{\mathrm{FB}}\rangle_{1-6\,\mathrm{GeV}^2}$	$^{+0.03}_{-0.04}$	$^{+0.05}_{-0.03}$	$^{+0.08}_{-0.06}$	0.020	[107]
$\langle F_{\mathrm{L}}\rangle_{1-6\,\mathrm{GeV}^2}$	$^{+0.02}_{-0.02}$	$^{+0.04}_{-0.03}$	$^{+0.04}_{-0.06}$	0.016	[107]
$\langle S_5\rangle_{1-6\,\mathrm{GeV}^2}$	$^{+0.07}_{-0.08}$	$^{+0.09}_{-0.11}$	$^{+0.16}_{-0.15}$	–	
$\langle A_9\rangle_{1-6\,\mathrm{GeV}^2}$	$^{+0.08}_{-0.07}$	$^{+0.11}_{-0.11}$	$^{+0.22}_{-0.14}$	0.015	[2][a]

- Use simple counting experiments (non-optimal)
  - Compare sensitivities (official LHCb numbers shown in box)
  - See CERN-THESIS-2010-095 for more details

Effects on Parameter Space ($2fb^{-1}$)



- What if LHCb $2fb^{-1}$ results were at SM?
  - See previous table
  - A_9 not considered
- Parameter space much reduced at 68%
  - High-q^2 will help further
  - CP asymmetries

High q^2 Estimates: (q^2 > 14GeV)

My (**unofficial**) high-q^2 estimates:

A_{FB}:	±0.01
F_L:	±0.01
$A_T^{(2)}$:	±0.2
$H_T^{(3)}$:	±0.1

Based on CERN-LHCB-2007-057

Observable	$2\,\mathrm{fb}^{-1}$	$1\,\mathrm{fb}^{-1}$	$0.5\,\mathrm{fb}^{-1}$	LHCb $2\,\mathrm{fb}^{-1}$	Ref.
				0.42	[128]
				—	
				0.020	[107]
				0.016	[107]
				—	
				0.015	[2][a]

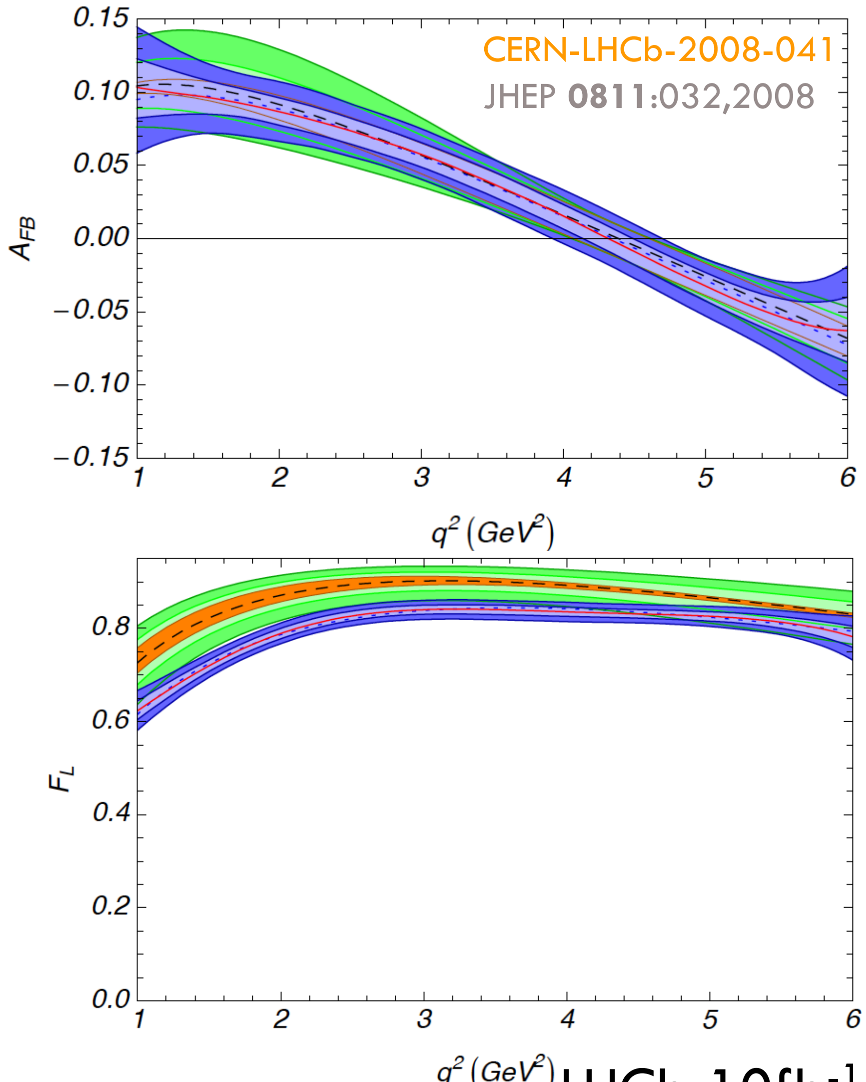
- Increased statistics in high-q^2 bin: Factor of 2-3
  - Selection efficiencies, trigger, acceptance easier?
- F_L suppression of $A_T^{(2)}$ reduced: Take 25% effect here

High Statistics

SM Theory Distribution

Toy fits to SUSY **model b** (C'_7 != 0) 1, 2σ

- Perform full-angular analysis
  - Fit for spin amplitudes
  - $A_{\perp L,R}, A_{||L,R}, A_{0L,R}$
  - Assume polynomial q^2 variation
- Calculate <u>any</u> observable from amplitudes
  - New observables $A_T^{(3)}$ $A_T^{(4)}$ optimized for C_7' sensitivity
  - $10fb^{-1}$ sensitivities for SUSY input
    - JHEP 0704 (2007) 058 – model 'b'
    - Allowed by experimental constraints
- MC Fits converge with $2fb^{-1}$
- Separate fit in high-q^2 region → $H_T^{(1)}$
- All CP asymmetries now available



LHCb $10fb^{-1}$

High Statistics

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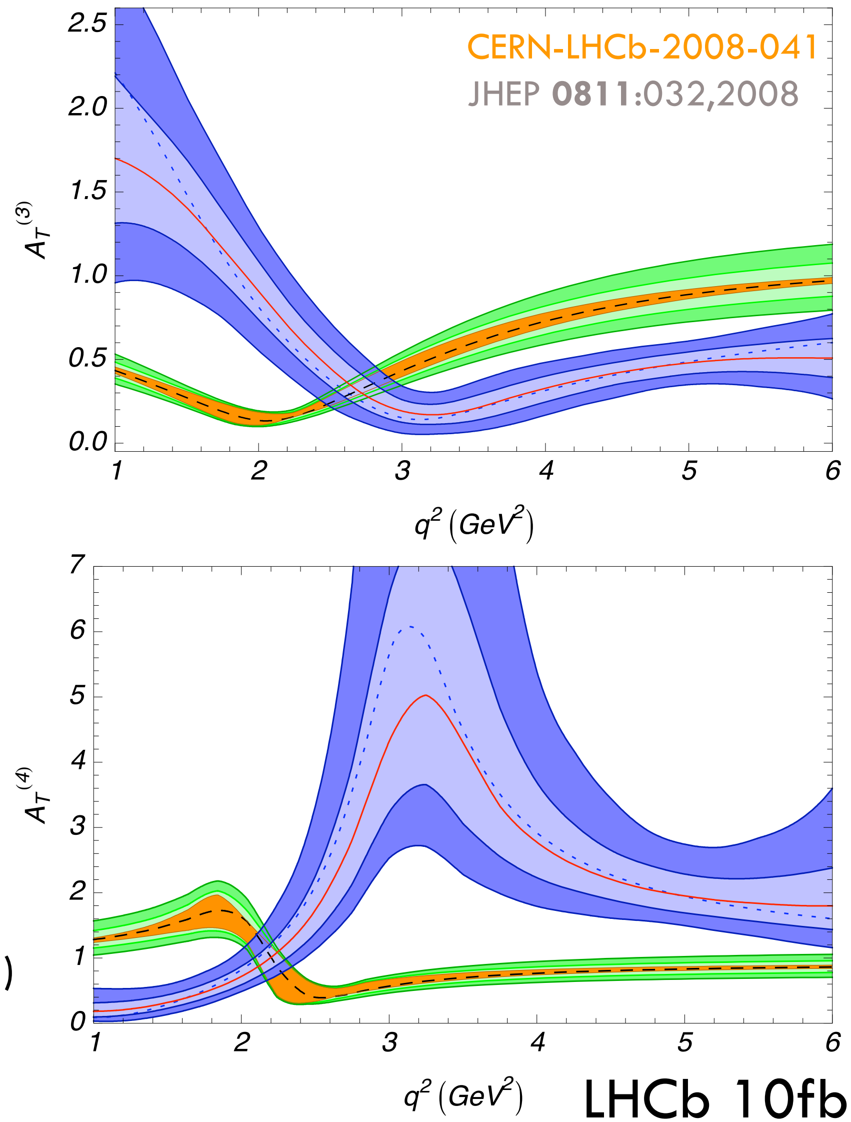


LHCb $10fb^{-1}$

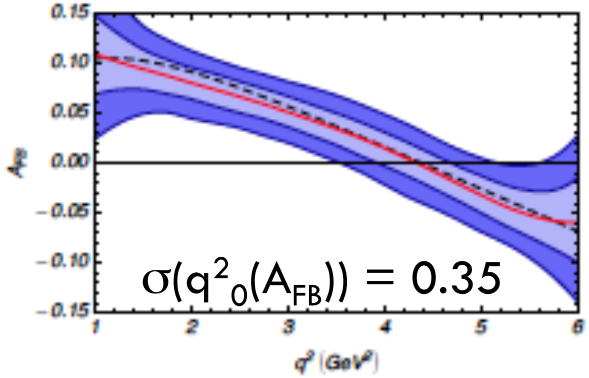
Note on Symmetries

Case	Coefficients	Dependencies	Amplitudes	Symmetries
$m_\ell = 0,\ A_S = 0$	11	3	6	4
$m_\ell = 0$	11	2	7	5
$m_\ell > 0,\ A_S = 0$	11	1	7	4
$m_\ell > 0$	12	0	8	4

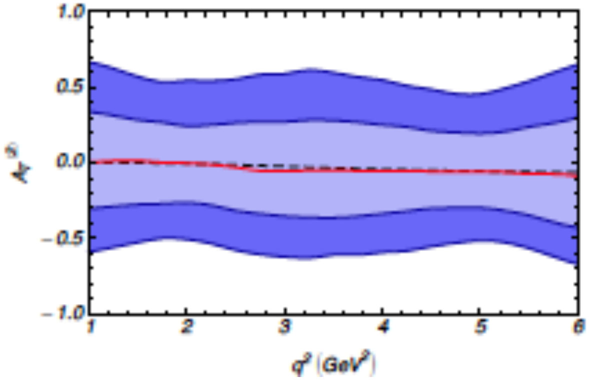
- Angular distribution has symmetries
  - Must be removed before fitting (under-constrained)
- All observables must be invariant
  - Many in literature are not! E.g. $A_T^{(1)}$
- Massless leptons case: 3 trivial + 1 non-trivial
  - Independent L and R phase rotations
  - Two L-R rotations: One real, one complex
  - See Egede *et al*, JHEP **1010**:056,2010

Full Angular Fit Sensitivities (SM)

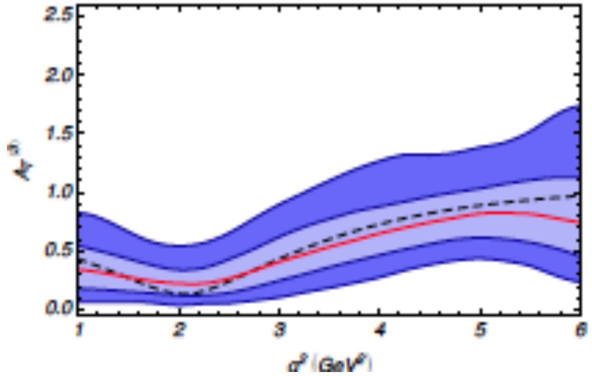
LHCb $2fb^{-1}$ A_{FB}



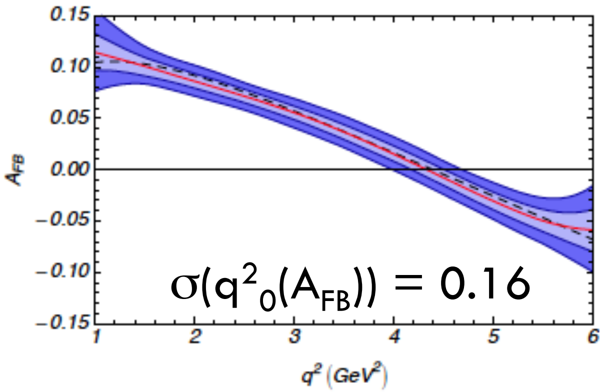
$A_T^{(2)}$



$A_T^{(3)}$



LHCb $10fb^{-1}$ A_{FB}



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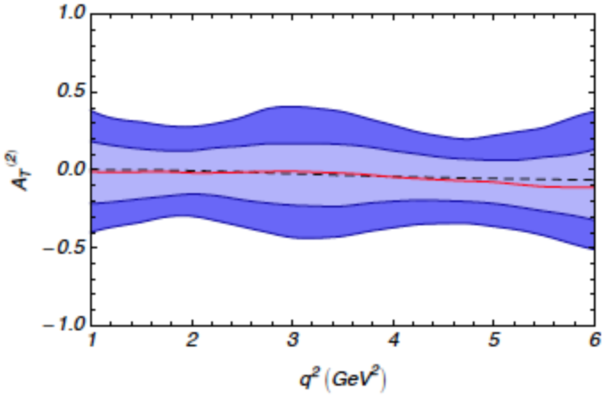
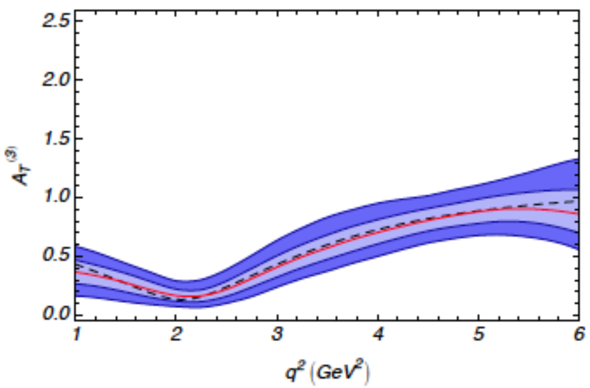
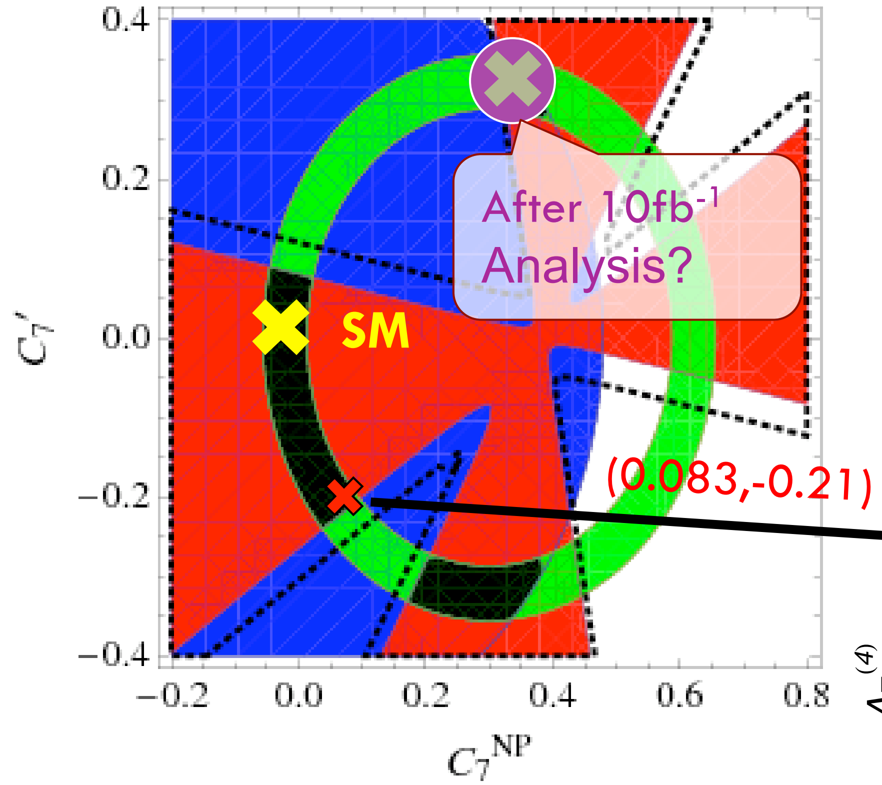


$A_T^{(3)}$

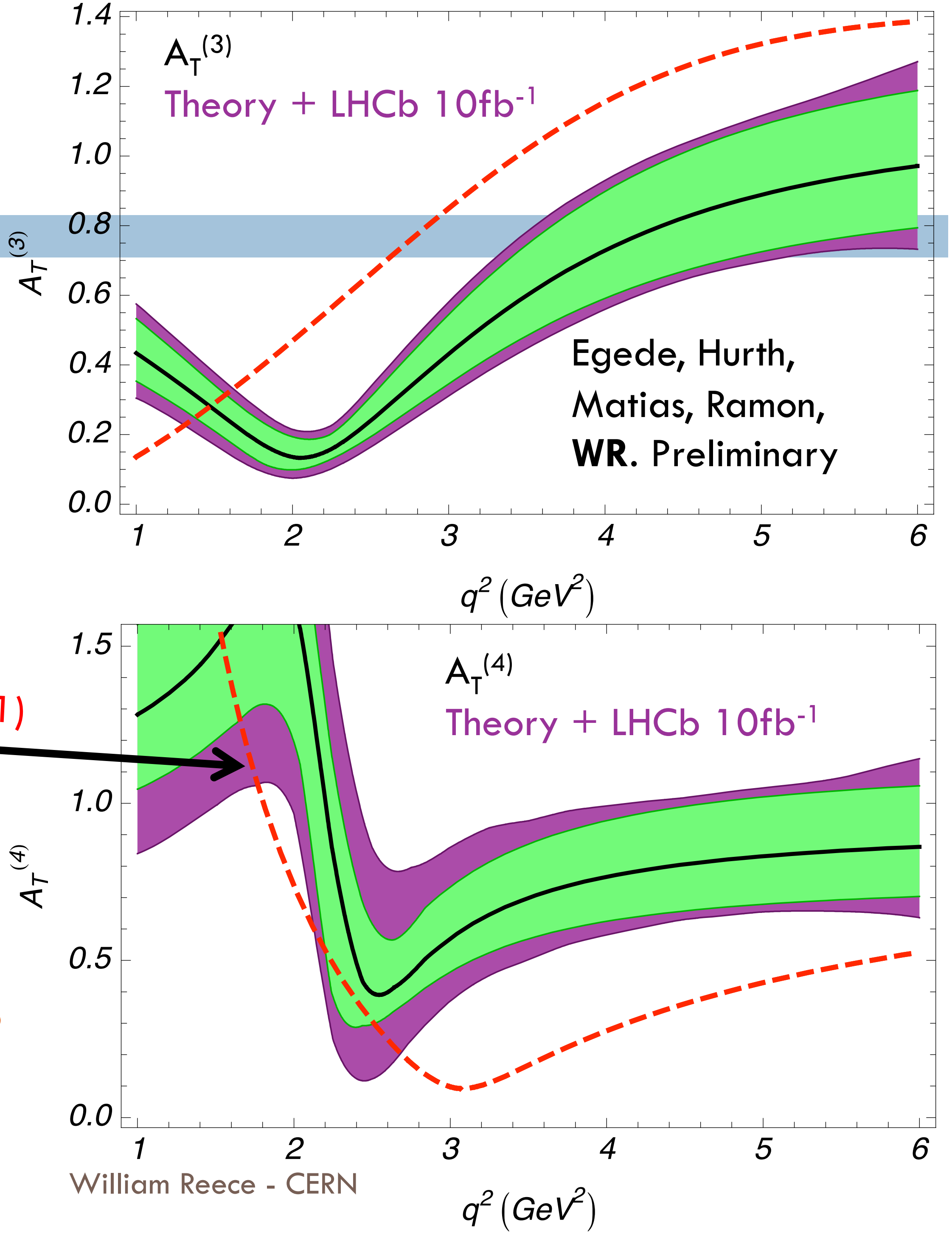


NP in C_7



Bobeth *et al*, JHEP **0807**:106,2008

$C_7 = C_7^{SM} + C_7^{NP}$



Summary

- Three eras of $B \to K^{\star}\mu\mu$ measurements at LHCb
  - Each has interesting observables to study
  - Must balance experimental and theoretical uncertainties
- Should really cut into allowed regions
  - Severe limits or explore structure of NP
- High-q^2 region little studied so far by experimentalists
  - Looks pretty promising
- Full-angular analysis will be key
  - Most interesting area for comparison with SuperB

BACKUP

Comparisons with Theory (2010)

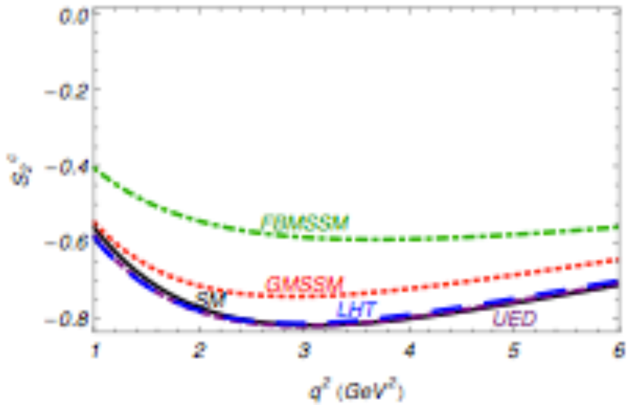
Belle Update (2009)
0.99\pm 0.2 \pm 0.9
Hiroyuki Nakayama, (Tokyo U.) . Dec 2009. 142pp. Ph.D. Thesis

Observable	Experiment	SM Theory
$\mathcal{B}(B_s \to \mu^+\mu^-)$	$3.6 \cdot 10^{-8}$ [57]	$(3.70 \pm 0.31) \cdot 10^{-9}$
$\mathcal{B}(B \to X_s l^+ l^-)_{1\text{-}6\,\mathrm{GeV}^2}$	$(1.60 \pm 0.51) \cdot 10^{-6}$ [14]	$(1.97 \pm 0.11) \cdot 10^{-6}$
$\mathcal{B}(B \to X_s \gamma)$	$(3.52 \pm 0.23 \pm 0.09) \cdot 10^{-4}$ [56]	$(3.28 \pm 0.25) \cdot 10^{-4}$
$S(B \to K^* \gamma)$	$(-1.6 \pm 2.2) \cdot 10^{-1}$ [56]	$(-0.26 \pm 0.05) \cdot 10^{-1}$
$\langle A_{\mathrm{FB}} \rangle_{1\text{-}6\,\mathrm{GeV}^2}$	-0.26 ± 0.29 [8]	0.04 ± 0.03
$\langle F_L \rangle_{1\text{-}6\,\mathrm{GeV}^2}$	0.67 ± 0.24 [8]	0.76 ± 0.08

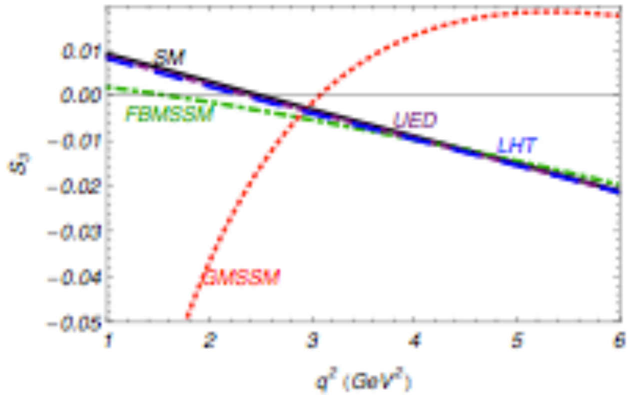
Table 8: Experimental measurements used as constraints, along with theoretical predictions in the SM.

A. Bharucha & **WR**, Eur.Phys.J.**C69**:623-640,2010

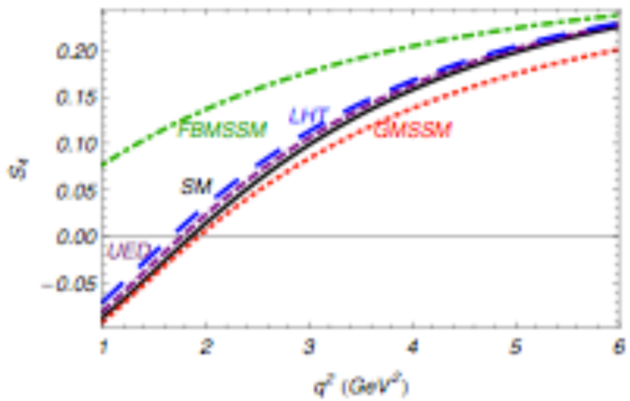
Landscape with NP



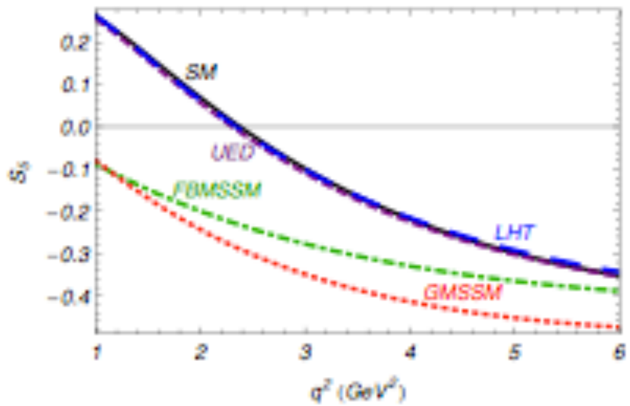
(a) S_2^c



(b) S_3

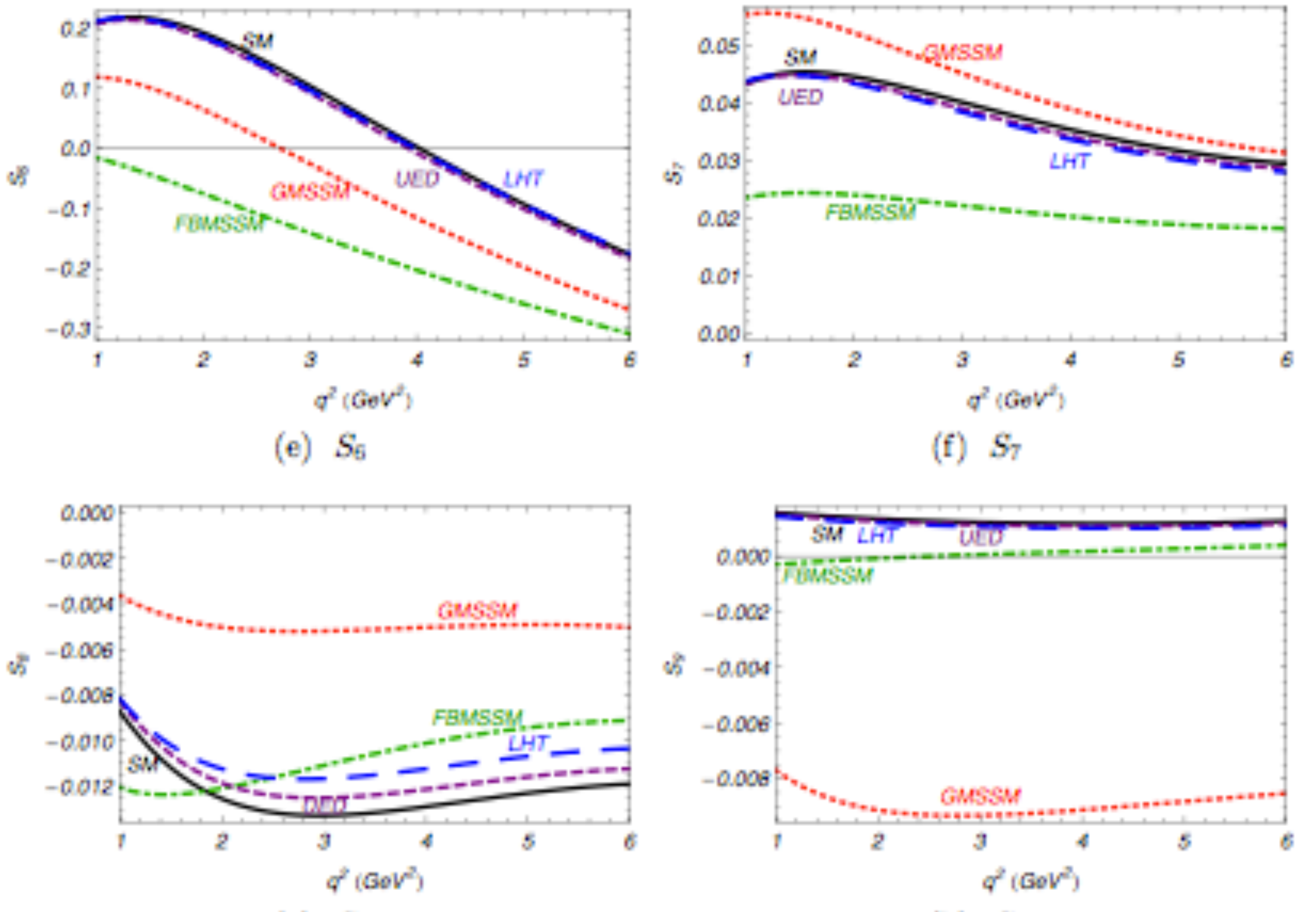


(c) S_4



(d) S_5

Landscape with NP



(e) S_6 (f) S_7

(g) S_8 (h) S_9

Massless symmetries

Left-handed phase rotation

$$A'_{\perp L} = e^{i\phi_L} A_{\perp L},\ A'_{\parallel L} = e^{i\phi_L} A_{\parallel L},\ A'_{0L} = e^{i\phi_L} A_{0L}$$

Right-handed phase rotation

$$A'_{\perp R} = e^{i\phi_R} A_{\perp R},\ A'_{\parallel R} = e^{i\phi_R} A_{\parallel R},\ A'_{0R} = e^{i\phi_R} A_{0R}$$

Continuous L-R global rotation

$$\begin{aligned}
A'_{\perp L} &= +\cos\theta A_{\perp L} + \sin\theta A^*_{\perp R} \\
A'_{\perp R} &= -\sin\theta A^*_{\perp L} + \cos\theta A_{\perp R} \\
A'_{0L} &= +\cos\theta A_{0L} - \sin\theta A^*_{0R} \\
A'_{0R} &= +\sin\theta A^*_{0L} + \cos\theta A_{0R} \\
A'_{\parallel L} &= +\cos\theta A_{\parallel L} - \sin\theta A^*_{\parallel R} \\
A'_{\parallel R} &= +\sin\theta A^*_{\parallel L} + \cos\theta A_{\parallel R}.
\end{aligned}$$

Continuous L-R global rotation

$$\begin{aligned}
A''_{\perp L} &= +\cosh i\phi A_{\perp L} + \sinh i\phi A^*_{\perp R} \\
A''_{\perp R} &= +\sinh i\phi A^*_{\perp L} + \cosh i\phi A_{\perp R} \\
A''_{0L} &= +\cosh i\phi A_{0L} - \sinh i\phi A^*_{0R} \\
A''_{0R} &= -\sinh i\phi A^*_{0L} + \cosh i\phi A_{0R} \\
A''_{\parallel L} &= +\cosh i\phi A_{\parallel L} - \sinh i\phi A^*_{\parallel R} \\
A''_{\parallel R} &= -\sinh i\phi A^*_{\parallel L} + \cosh i\phi A_{\parallel R}.
\end{aligned}$$