SUSY 2015 - Flavor Violation Theory & Experiment

# $B \to K^* \mu\, \mu$

## Charming Penguins strike back again ?

M.Ciuchini, M.Fedele, E.Franco, S.Mishima, A.Paul, L.Silvestrini, M.V. (in preparation)

INFN

M. Valli

SISSA

Lake Tahoe (USA), August 24 2015

Supported by:

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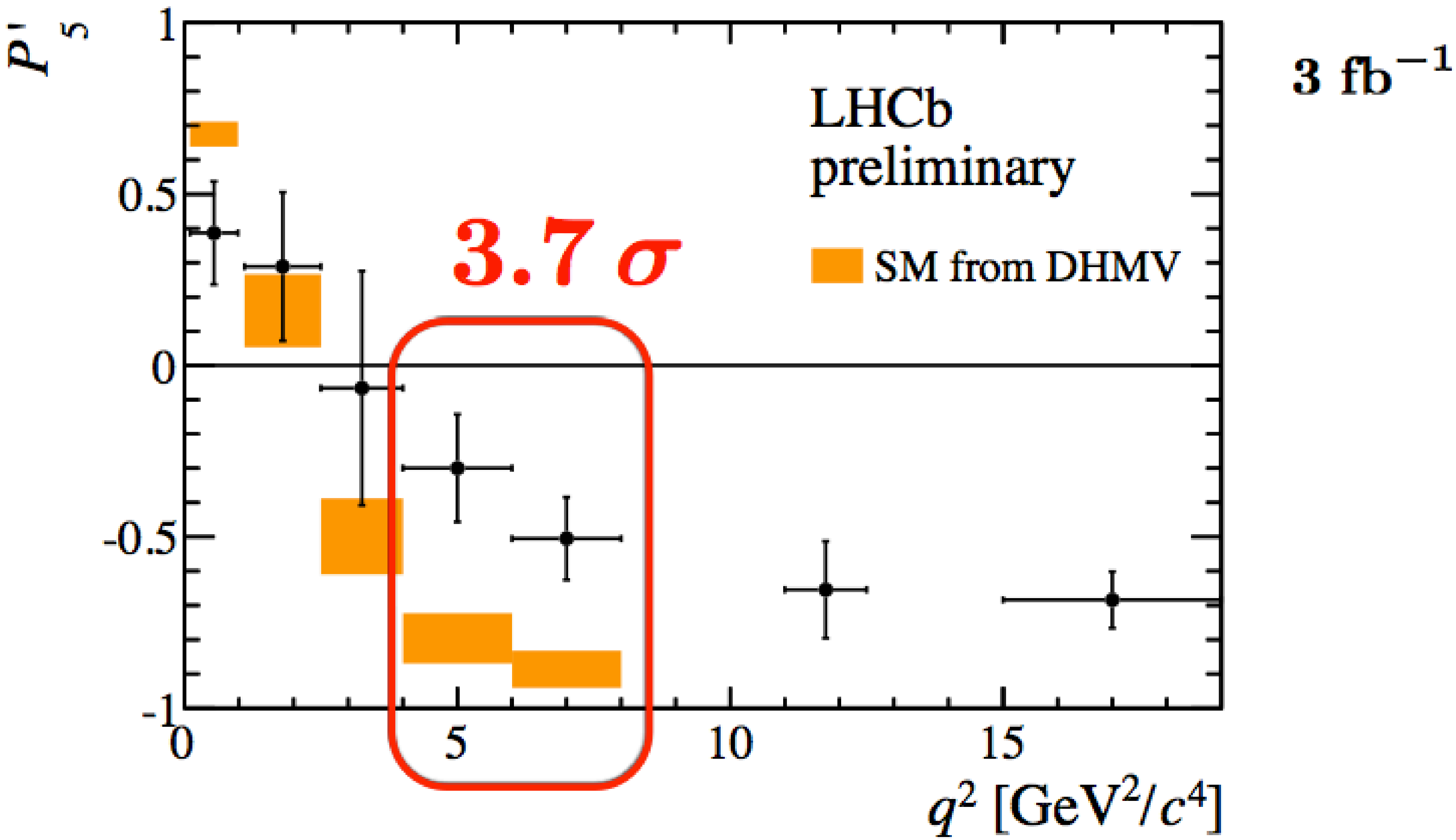
# The $P'_5$ anomaly




S. Descotes-Genon, L. Hofer, J. Matias, and J. Virto

**JHEP 1412 (2014) 125, arXiv:1407.8526**

# B to $K^*\mu^+\mu^-$ generalities

In the Standard Model (SM), FCNCs arise only @ loop-level

→ NP can sizably contribute to these rare processes

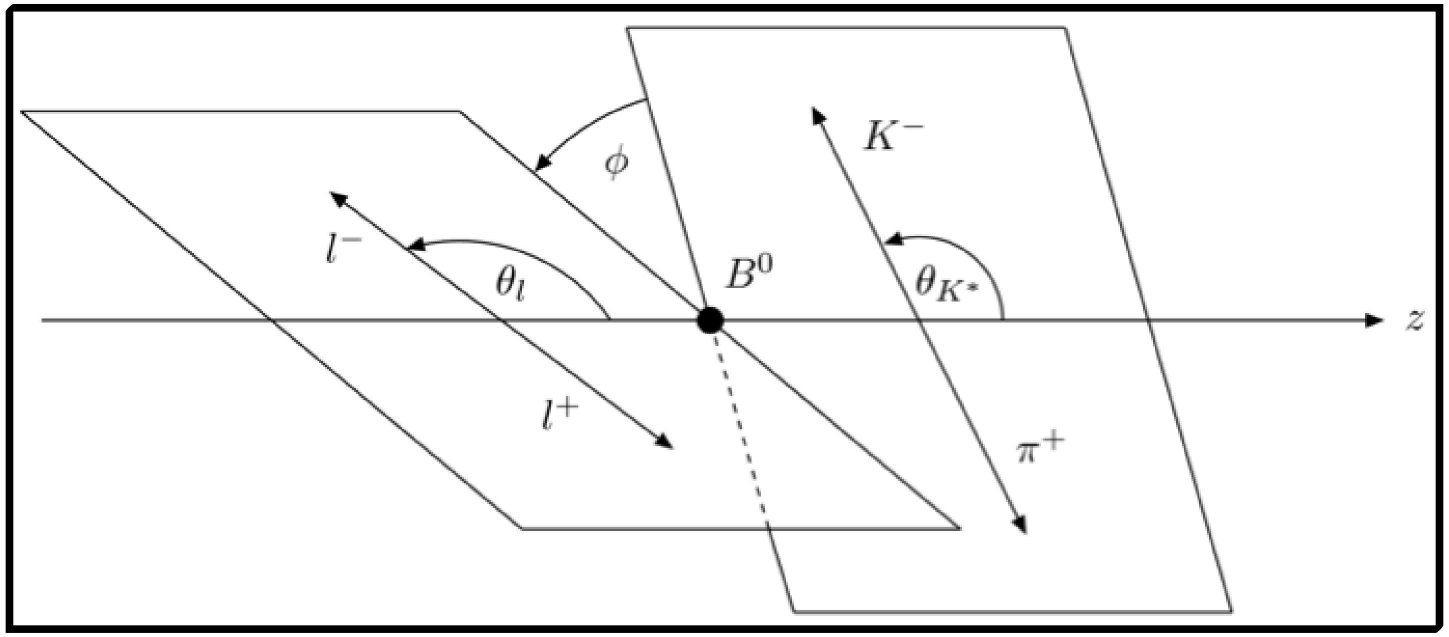
## Angular Analysis

$\theta_K$ in $K^*$ rest frame

$\theta_l$ in dilepton CM frame

$\phi$ boost-invariant w.r.t. z-axis

$q^2 \equiv$ invariant dilepton mass




$$\frac{d^{(4)}\Gamma}{dq^2\, d(\cos\theta_l) d(\cos\theta_k) d\phi} = \frac{9}{32\,\pi}$$
$$\times \Big( I_1^s \sin^2\theta_k + I_1^c \cos^2\theta_k + (I_2^s \sin^2\theta_k + I_2^c \cos^2\theta_k) \cos 2\theta_l$$
$$+ I_3 \sin^2\theta_k \sin^2\theta_l \cos 2\phi + I_4 \sin 2\theta_k \sin 2\theta_l \cos\phi$$
$$+ I_5 \sin 2\theta_k \sin\theta_l \cos\phi + (I_6^s \sin^2\theta_k + I_6^c \cos^2\theta_K) \cos\theta_l$$
$$+ I_7 \sin 2\theta_k \sin\theta_l \sin\phi + I_8 \sin 2\theta_k \sin 2\theta_l \sin\phi$$
$$+ I_9 \sin^2\theta_k \sin^2\theta_l \sin 2\phi \Big)$$

$$S_i = \left( I_i^{(s,c)} + \bar{I}_i^{(s,c)} \right) / \, \Gamma'$$

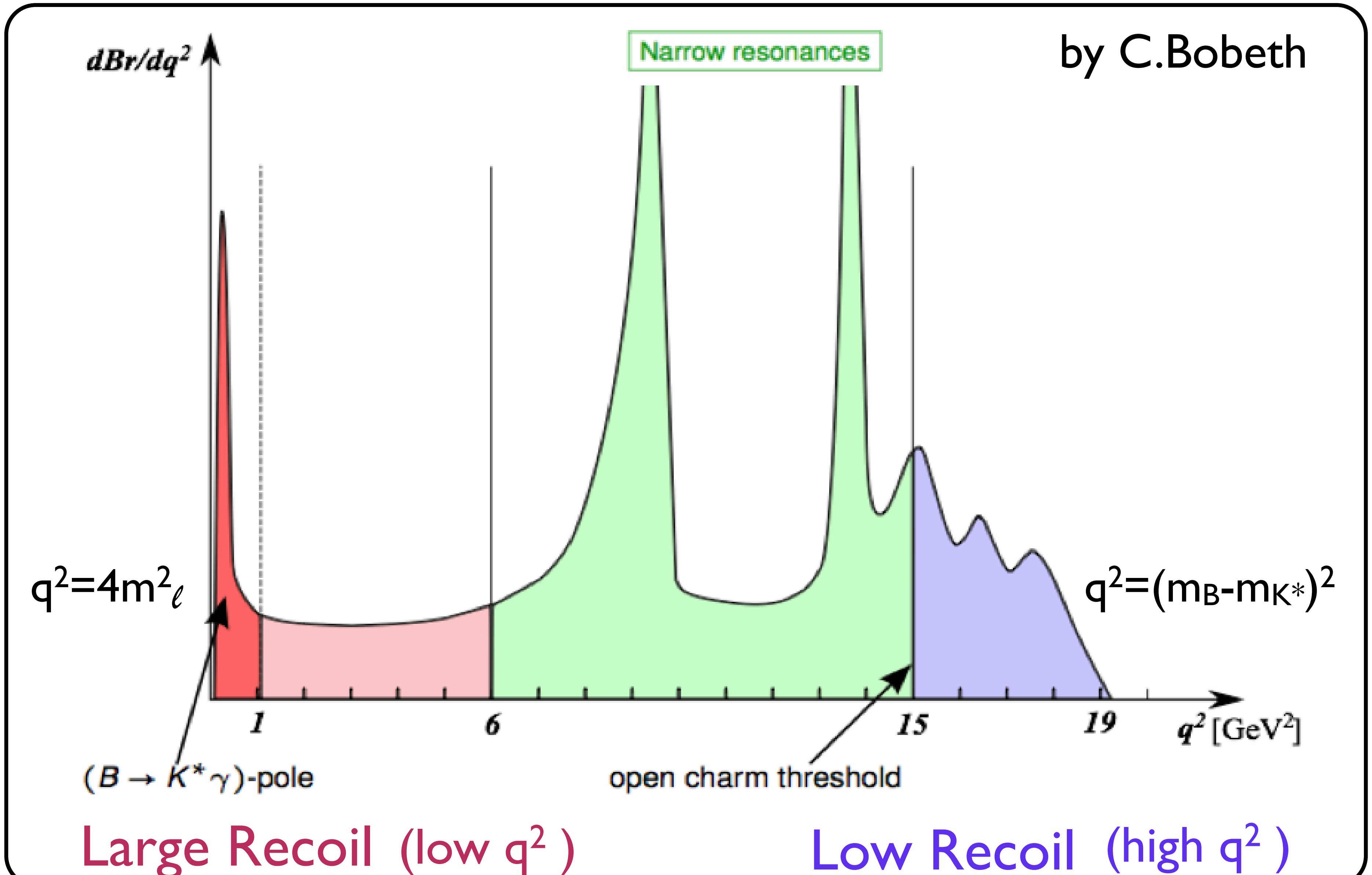
$$\left( 2\,\Gamma' \equiv d\Gamma/dq^2 + d\bar{\Gamma}/dq^2 \right)$$

**8 CP-AVERAGED OBSERVABLES**

$$\boxed{F_L, A_{FB}, S_{3,4,5,7,8,9}}$$

State-of-the art experimental cuts and event reconstruction allow an angular analysis in bins of $q^2$: $\langle I_i^{(c,s)} \rangle = \int_{q^2_{min}}^{q^2_{max}} dq^2 \; I_i^{(c,s)}(q^2)$

## 3 distinct regions in the dilepton mass spectrum:




Experimental binning from latest data release, LHCb-CONF-2015-002:

[0.1, 0.98], [1.1, 2.5], [2.5, 4.0] [4.0, 6.0], [6.0, 8.0], [1.1,6.0]

[15.0, 17.0] ,[17.0, 19.0], [15.0, 19.0]

[ $GeV^2$ ]

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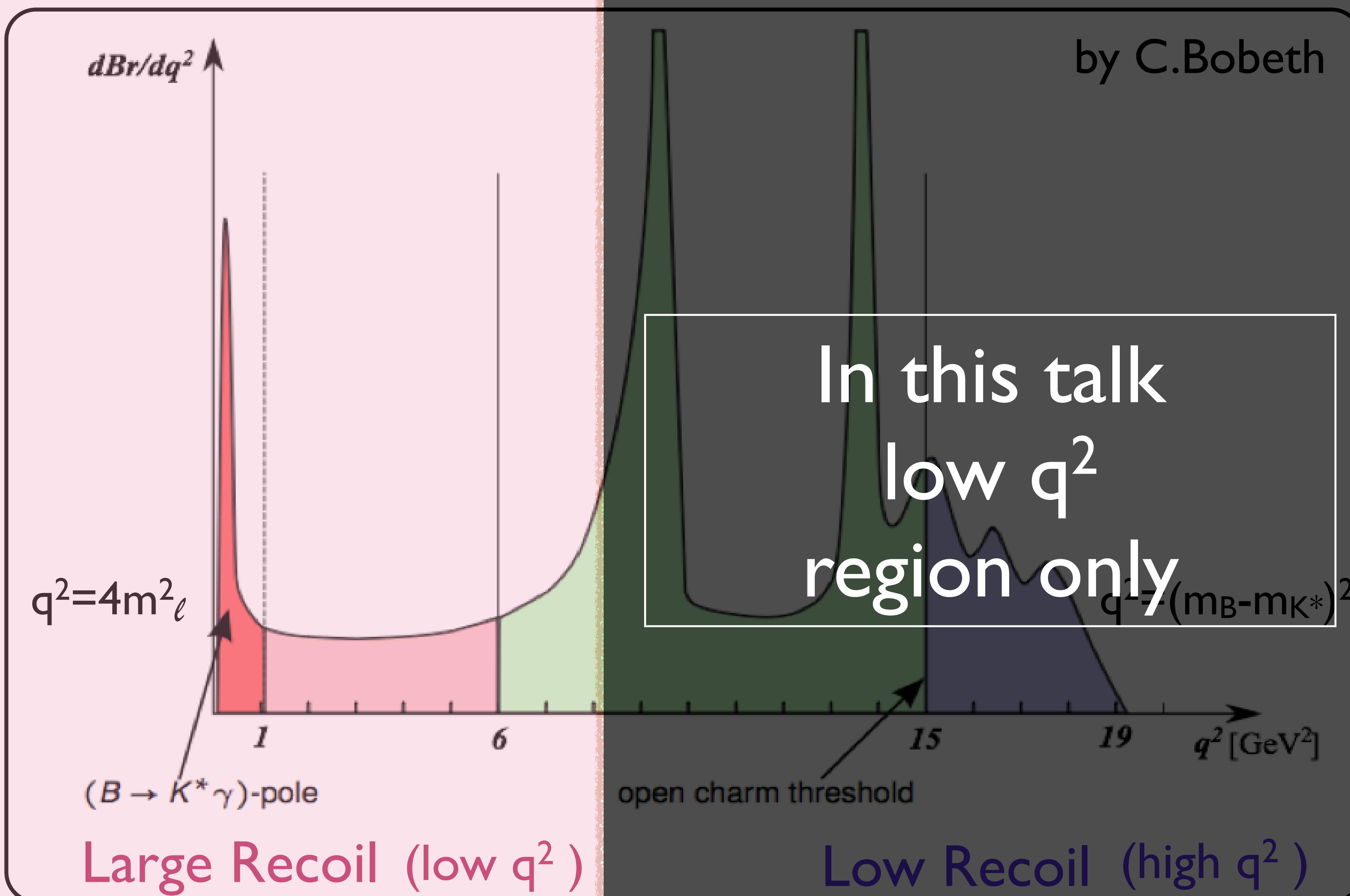


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[ GeV² ]

# The decay in the Standard Model

B to K* μμ decay belongs to b→ s transitions

$$\boxed{\mathcal{H}_{\rm eff}^{\Delta B=1} = \mathcal{H}_{\rm eff}^{\rm had} + \mathcal{H}_{\rm eff}^{\rm sl}}$$

@ dimension 6, 10 operators

$$Q_1^{q=u,c} = (\bar{s}_L \gamma_\mu T^a q_L)(\bar{q}_L \gamma^\mu T^a b_L)$$

$$Q_2^{q=u,c} = (\bar{s}_L \gamma_\mu q_L)(\bar{q}_L \gamma^\mu b_L)$$

$$P_3 = (\bar{s}_L \gamma_\mu b_L) \sum\nolimits_q (\bar{q}\gamma^\mu q)$$

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$$P_5 = (\bar{s}_L \gamma_{\mu 1}\gamma_{\mu 2}\gamma_{\mu 3} b_L) \sum\nolimits_q (\bar{q}\gamma^{\mu 1}\gamma^{\mu 2}\gamma^{\mu 3} q)$$

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$$Q_{8g} = \frac{g_s}{16\pi^2} m_b \bar{s}\sigma_{\mu\nu} P_R G^{\mu\nu} b$$

$$Q_{7\gamma} = \frac{e}{16\pi^2} m_b \bar{s}\sigma_{\mu\nu} P_R F^{\mu\nu} b$$

$$Q_{9V} = \frac{\alpha_{em}}{4\pi} (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell)$$

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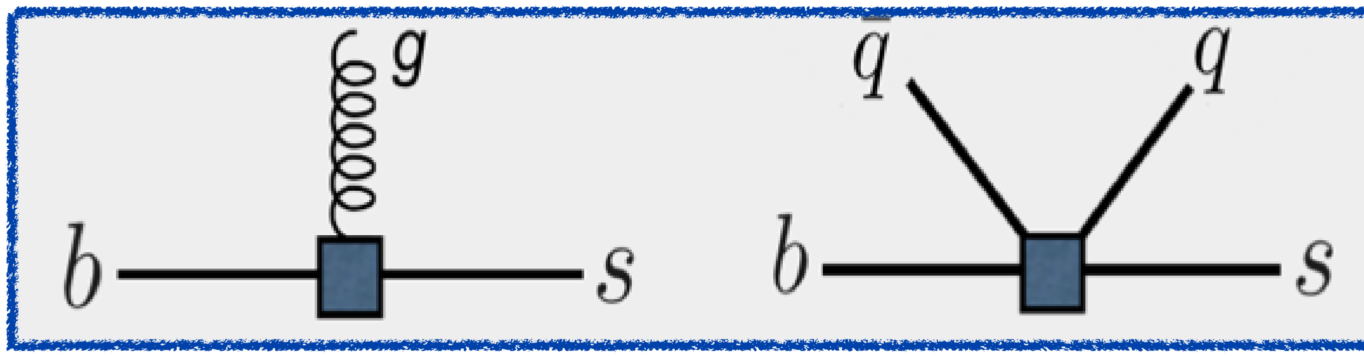

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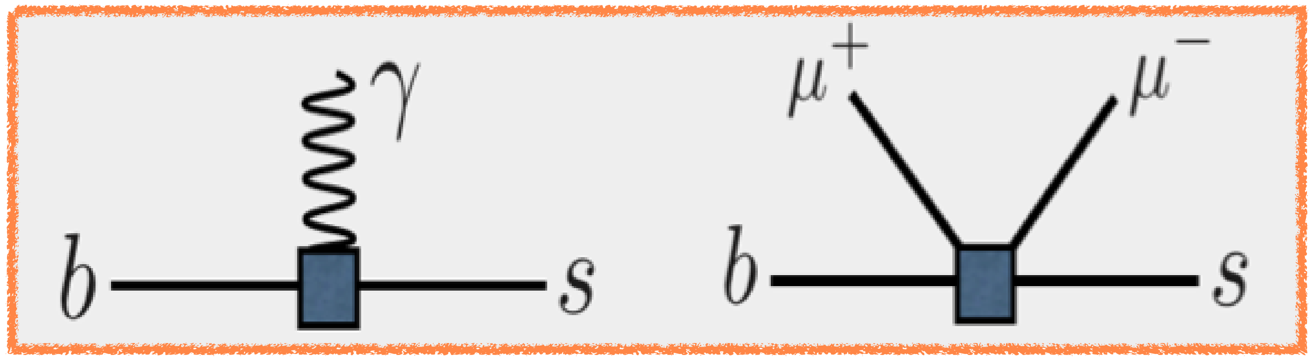

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@ dimension 6, 10 operators

$$\mathcal{H}_{\text{eff}}^{\Delta B=1} \sim \sum_i C_i \, \mathcal{O}_i$$

Short-distance physics:

- 2-loop QCD matching
- 3-loop 10 x 10 ADM

Running from $m_W$ down to $m_b$ :

$C_1$ = - 0.26, $C_2$ = 1.01, $C_7$ = - 0.3

$C_8$ = - 0.17, $C_9$ = 4.21, $C_{10}$ = - 4.1

and all the rest < 0.01.

In the SM, $\langle M\,\ell\,\ell|\mathcal{H}_{\rm eff}^{\rm sl}|\bar{B}\rangle$ corresponds to the following helicity amplitudes:

$$\boxed{\begin{aligned} &H_V(\lambda) \propto C_9 \tilde{V}_{L\lambda} + \frac{2m_b m_B}{q^2} C_7 \tilde{T}_{L\lambda} \\ &H_A(\lambda) \propto C_{10} \tilde{V}_{L\lambda} \qquad\qquad\qquad (\lambda = 0, \pm) \\ &H_P \propto \frac{2m_l m_B}{q^2} C_{10} \left(1 + \frac{m_s}{m_B}\right) \widetilde{S} \end{aligned}}$$

The angular coefficients $I^{(c,s)}$ are functions of these amplitudes, as well as the CP averaged observables we are ultimately interested in.

For example,

$$I_1^c = F\left(\frac{1}{2}\left(|H_V^0|^2 + |H_A^0|^2\right) + |H_P^0|^2 + \frac{2m_l^2}{q^2}\left(|H_V^0|^2 - |H_A^0|^2\right)\right),$$

$$I_1^s = F\left(\frac{\beta^2+2}{8}\left(|H_V^+|^2 + |H_V^-|^2 + |H_A^+|^2 + |H_A^-|^2\right) + \frac{m_l^2}{q^2}\left(|H_V^+|^2 - |H_V^-|^2 - |H_A^+|^2 + |H_A^-|^2\right)\right)$$

where:

$$F = \frac{\lambda^{1/2}\beta q^2}{3\times 2^5 \pi^3 m_B^3} \mathrm{BR}(K^* \to K\pi), \quad \beta = \sqrt{1 - \frac{4m_l^2}{q^2}},$$

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

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→ 7 $q^2$-dependent form factors to be computed

At low $q^2$, most recent determination in Bharucha, Straub, Zwicky (1503.05534), through QCD Sum Rules on the Light-Cone (LCSR).

$$F^{(i)}(q^2) = \sum_k \alpha_k^{(i)} \frac{\left[z(q^2) - z(0)\right]^k}{1 - \left(q/m_R^{(i)}\right)^2}$$

given up to k=2

$$z(t) = \frac{\sqrt{t_+ - t} - \sqrt{t_+ - t_0}}{\sqrt{t_+ - t} + \sqrt{t_+ - t_0}}$$

where $t_\pm = (m_B \pm m_{K^*})^2$ and

$t_0 = t_+(1 - \sqrt{1 - t_-/t_+})$.

Low recoil region

1501.00367

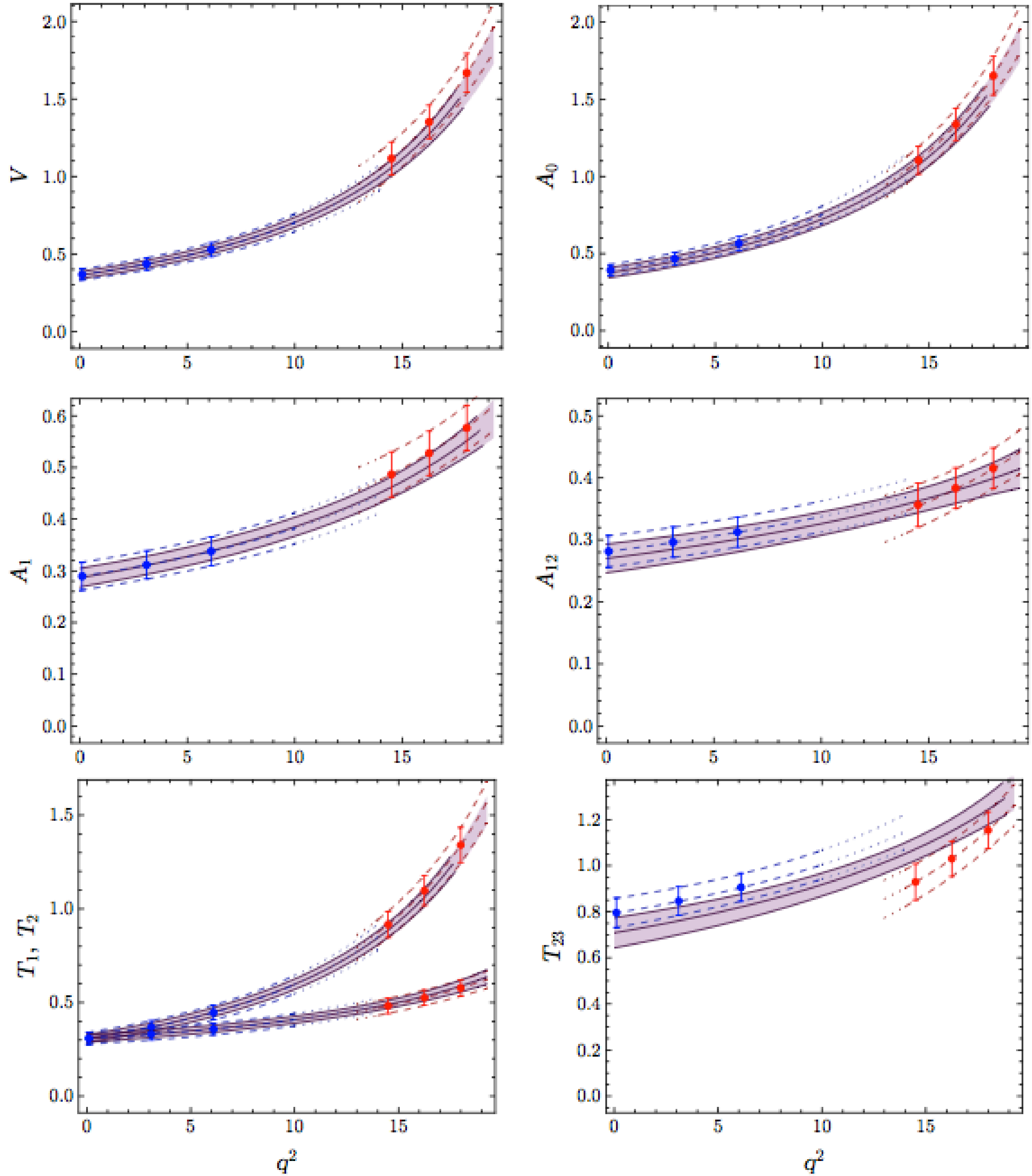
Lattice

VS

LCSR

1503.05534

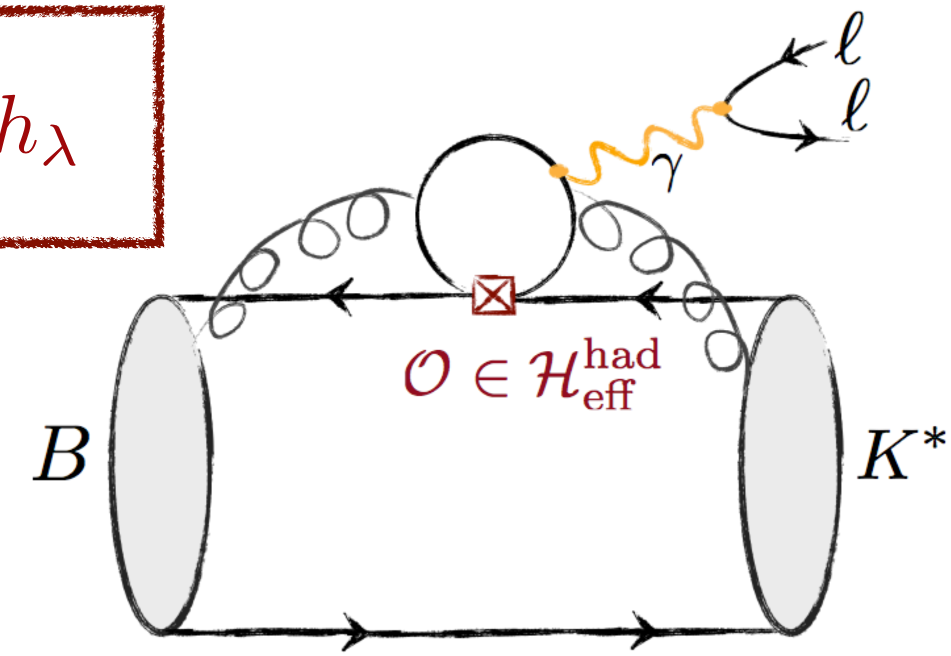
Large recoil region



What about the hadronic part of the effective Hamiltonian?

It can contribute to $H_V(\lambda)$ through the insertion of E.M. currents!

$$\boxed{H_V(\lambda) \propto C_9 \tilde{V}_{L\lambda} + \frac{2 m_b m_B}{q^2} C_7 \tilde{T}_{L\lambda} - \frac{16\pi^2 m_B^2}{q^2} h_\lambda}$$




where the above hadronic contribution reads:

$$h_\lambda(q^2) = \frac{\epsilon_\mu^*(\lambda)}{m_B^2} \int d^4x e^{iqx} \langle \bar{K}^* | T\{ j_{\text{em}}^\mu(x) \mathcal{H}_{\text{eff}}^{\text{had}}(0) \} | \bar{B} \rangle$$

This correlator is the weakest part of the theoretical prediction.

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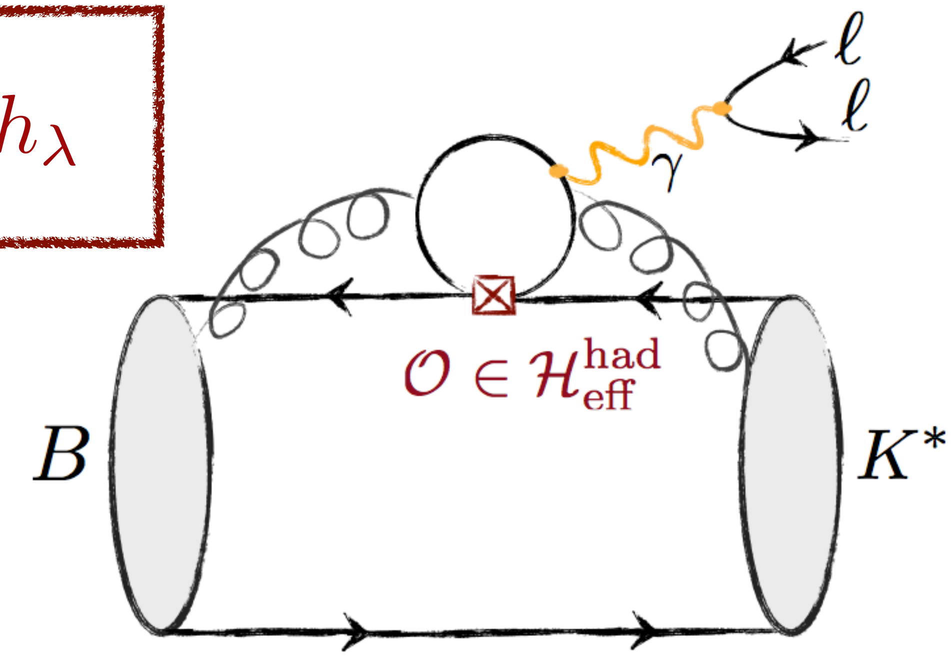


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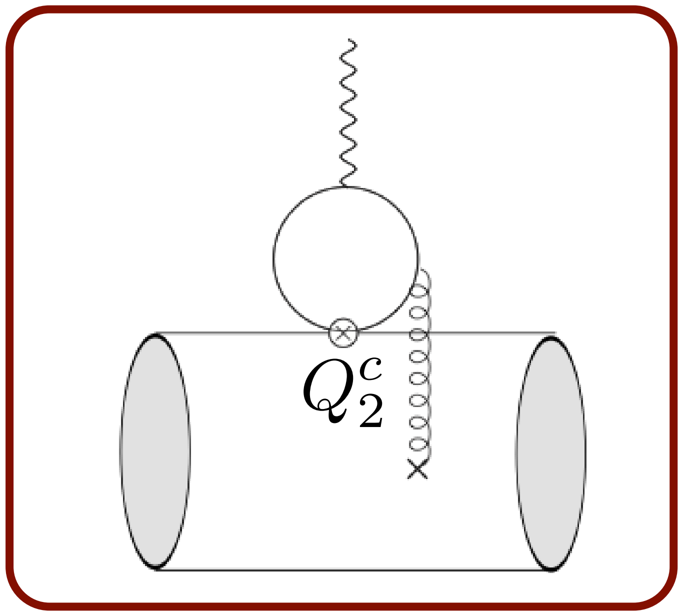
**This correlator is the weakest part of the theoretical prediction.**

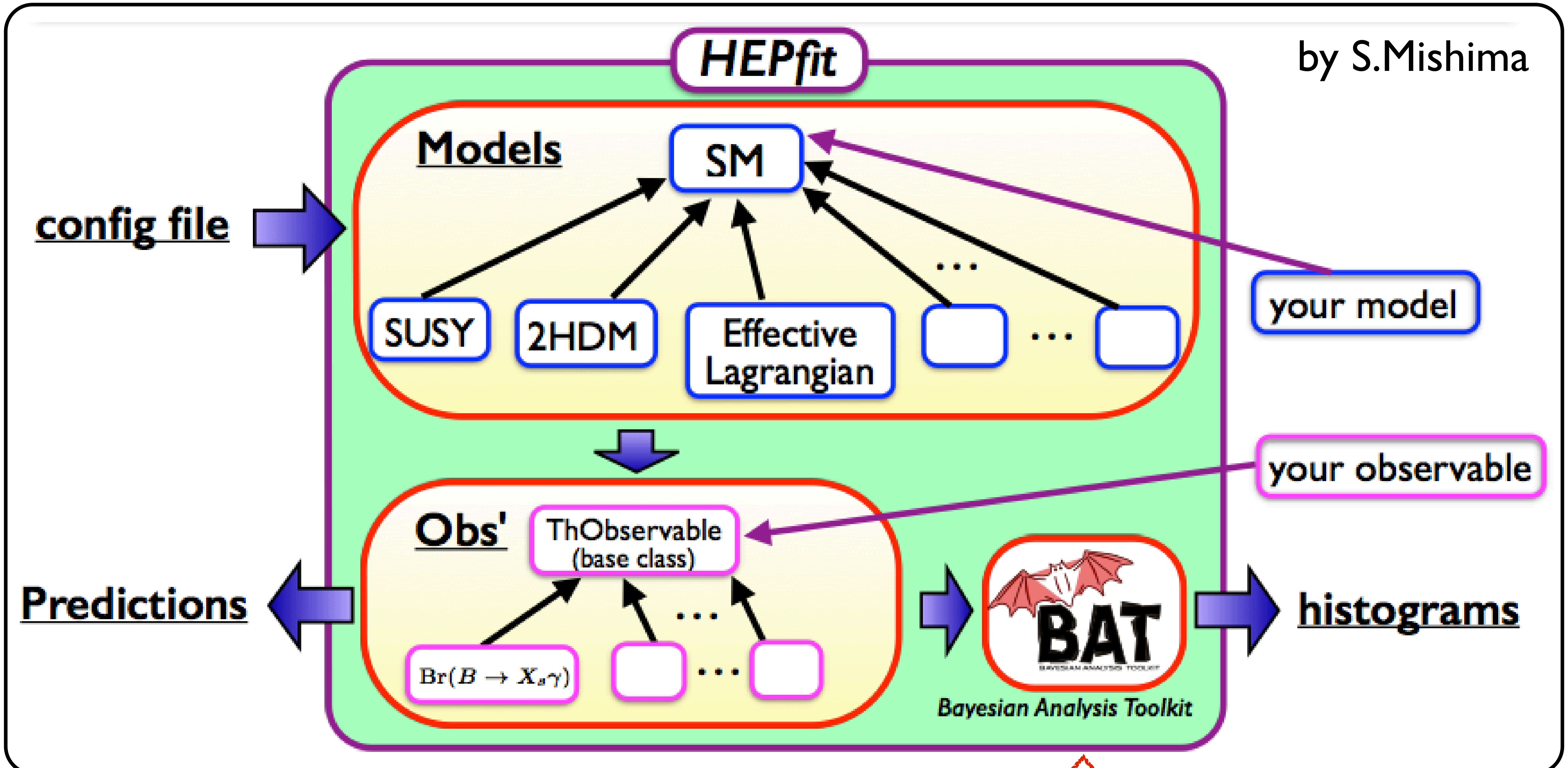
A big effort has been done by **Khodjamirian et al.**, 1006.4945, where the charm-loop + single soft gluon emission was computed.




DRAWBACKS:

- still partial estimate of the effect, valid for $q^2 \lesssim 1\,\mathrm{GeV}^2$ only
- multiple soft gluon emission suppressed as far as $q^2 << 4\, m_c^2$

# HEPfit: Our weapon of choice

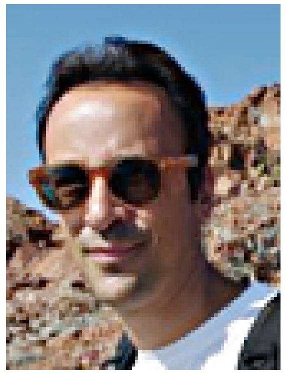


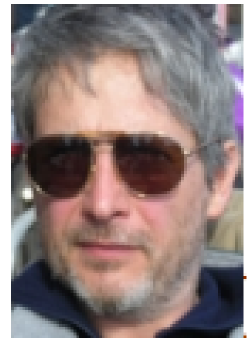

Full-fledged statistical data analysis in this work carried out by means of Bayes Theorem

$$P(\lambda|D) \propto P(D|\lambda) \, P_0(\lambda)$$

$\lambda$ posterior likelihood $\lambda$ prior

the HEPfit group:
@present


L.Silvestrini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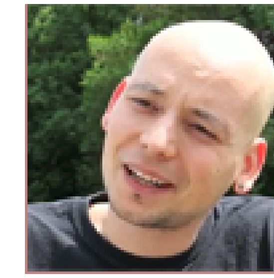
M.Pierini

+ 7 postdocs
+ 4 PhD students

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HEPfit is a framework for cal… …bles (Flavour, EWPT, Higgs) in the SM and Beyond, cons… …eter space with a global fit

Do not miss tomorrow's talk of A.Paul!

---

It is a **public code** written … …MPI parallelization, with GSL, Boost, ROOT and Bayes… …ysis Toolkit (BAT) dependencies.

---

HEPfit will be officially released with a user friendly cross-platform CMake + a detailed documentation of the code (technical paper + Doxygen!)

**First official release soon!**

Developer version already available @ https://github.com/silvest/HEPfit

# Our Analysis in the low $q^2$ region

## MAIN THEORY INPUT:

For the form factors, LCSR state-of-the-art estimate in 1503.05534:

# parameters: 3 x 7 - 2 = 19 (with 19x19 correlation matrix)

Following Jager & Camalich'14, 1412.3183, we parametrized the non-factorizable hadronic contribution as:

$$h_\lambda(q^2) = h_\lambda^{(0)} + h_\lambda^{(1)} q^2 + \underline{h_\lambda^{(2)} q^4} \ , \ (\lambda = 0, \pm)$$

TO PROVIDE A MORE RELIABLE DESCRIPTION ABOVE FEW GeV $^2$

# parameters: 3 x 3 x 2 = 18

to which we assigned a generous prior (all flatly distributed in ± 2 x $10^{-4}$ ).

## EXPERIMENTAL INFO EXPLOITED:

LHCb-CONF-2015-002

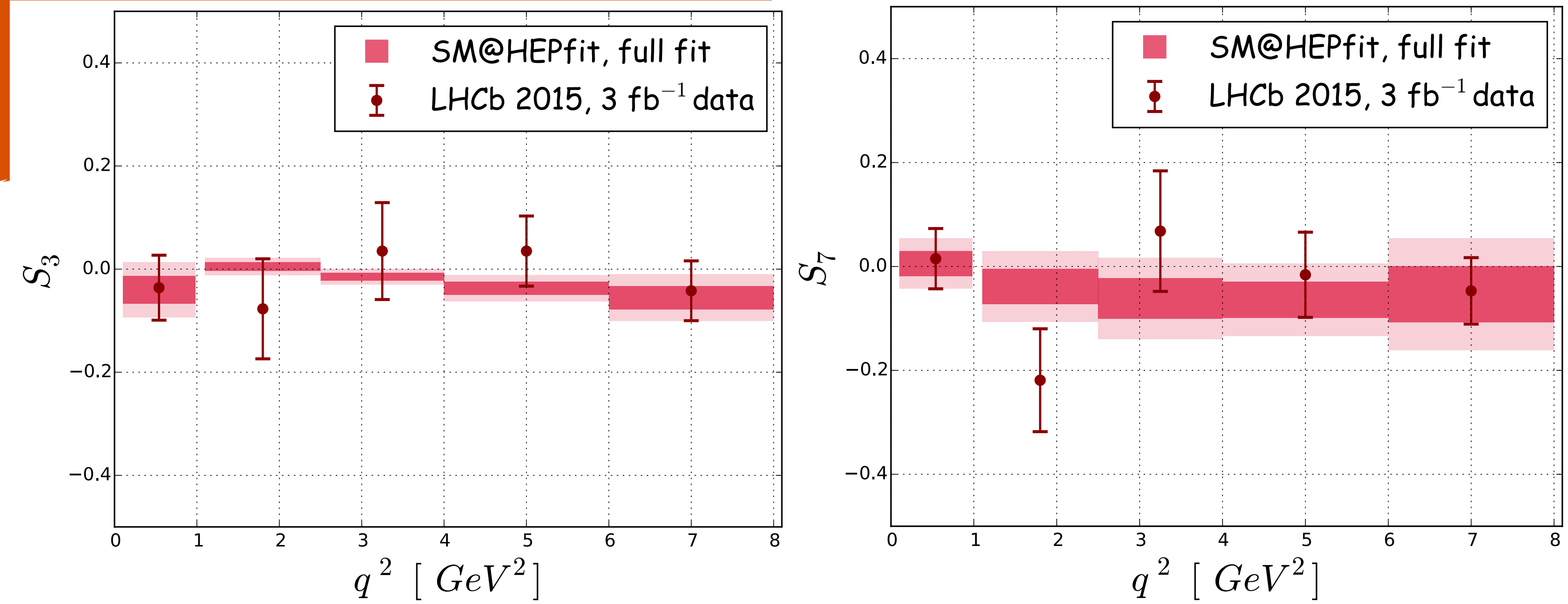
$$\boxed{F_L, A_{FB}, S_{3,4,5,7,8,9}}$$

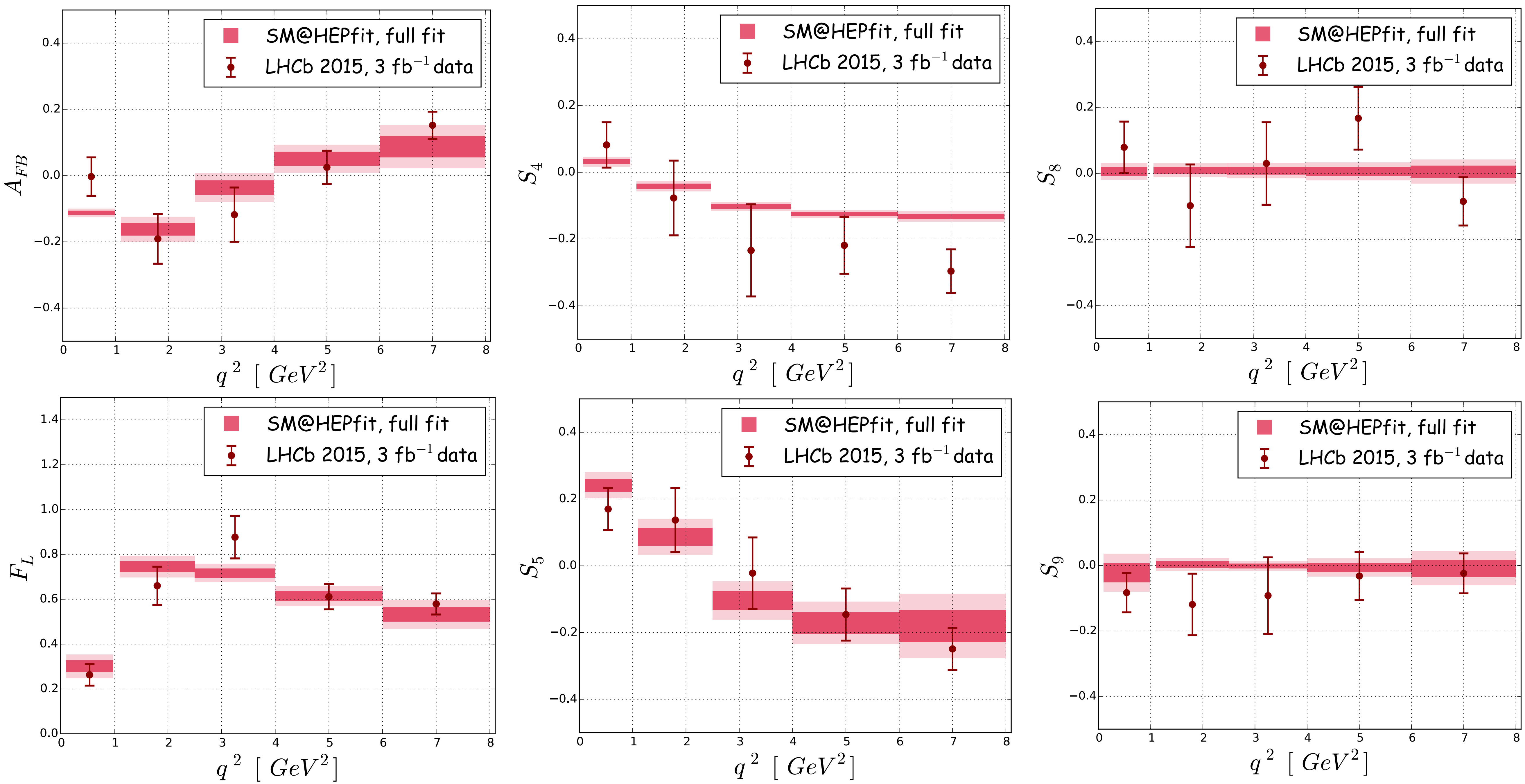
8 x 6 = 48 (with 8x8 correlation matrix per bin)

$\mathcal{B}(B \to K^* \mu\mu)$ 1 x 4 --> 52 , $\mathcal{B}(B \to K^* \gamma)$ --> 53

HEPfit

*full fit*



Switching off one observable per time, one can fit again and look @

# The PULL of the FIT

$$\frac{\mathcal{O}_{th} - \mathcal{O}_{exp}}{\sqrt{\sigma_{th}^2 + \sigma_{exp}^2}}$$

| **Bin** $\mathbf{q^2}$ $[GeV^2/c^4]$ | $\mathbf{A_{FB}}$ | $\mathbf{F_L}$ | $\mathbf{S_3}$ | $\mathbf{S_4}$ | $\mathbf{S_5}$ | $\mathbf{S_7}$ | $\mathbf{S_8}$ | $\mathbf{S_9}$ |
|---|---|---|---|---|---|---|---|---|
| $[0.1, 0.98]$ | $1.9$ | $-0.9$ | $0.0$ | $0.7$ | $-1.2$ | $0.1$ | $0.9$ | $-1.2$ |
| $[1.1, 2.5]$ | $-0.6$ | $-0.9$ | $-0.8$ | $-0.3$ | $0.7$ | $-2.0$ | $-0.8$ | $-1.3$ |
| $[2.5, 4]$ | $-1.3$ | $1.8$ | $0.6$ | $-1.0$ | $0.7$ | $0.5$ | $0.2$ | $-0.8$ |
| $[4, 6]$ | $-0.6$ | $0.5$ | $1.1$ | $-1.1$ | $-0.4$ | $-0.1$ | $1.7$ | $-0.5$ |
| $[6, 8]$ | $0.7$ | $1.4$ | $0.3$ | $-2.5$ | $-1.5$ | $-0.3$ | $-1.2$ | $0.4$ |
| $[1.1, 6]$ | $-1.3$ | $0.6$ | $0.9$ | $-1.0$ | $0.4$ | $-0.8$ | $0.5$ | $-0.7$ |

No statistically significant deviation from the angular observables.

(the result concerning the branching ratios is good as well)

# Cleaness of the "clean" P'5

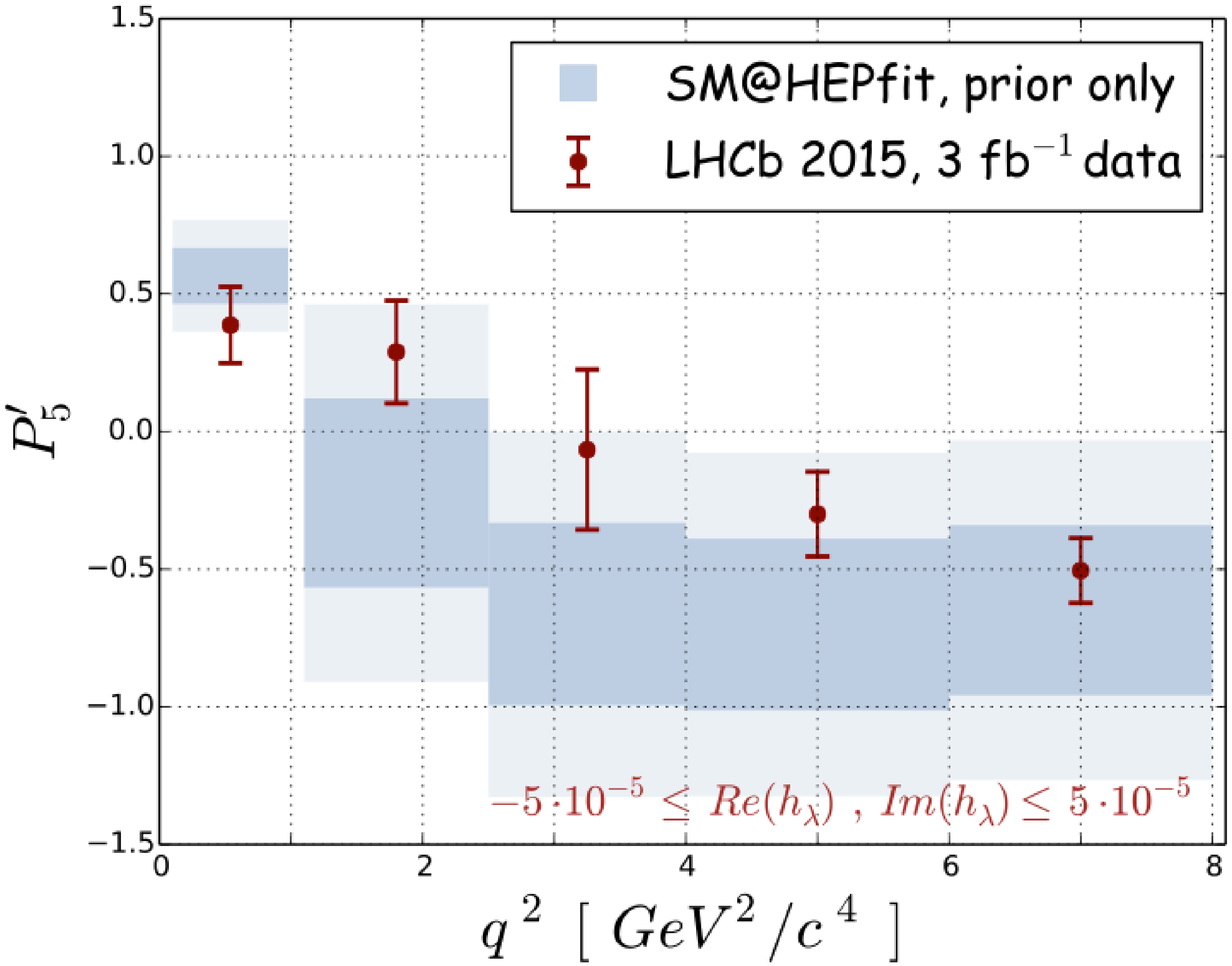
Some peculiar ratios of observables have been proposed with the aim of exploiting possible form factor/hadronic uncertainty cancellations.

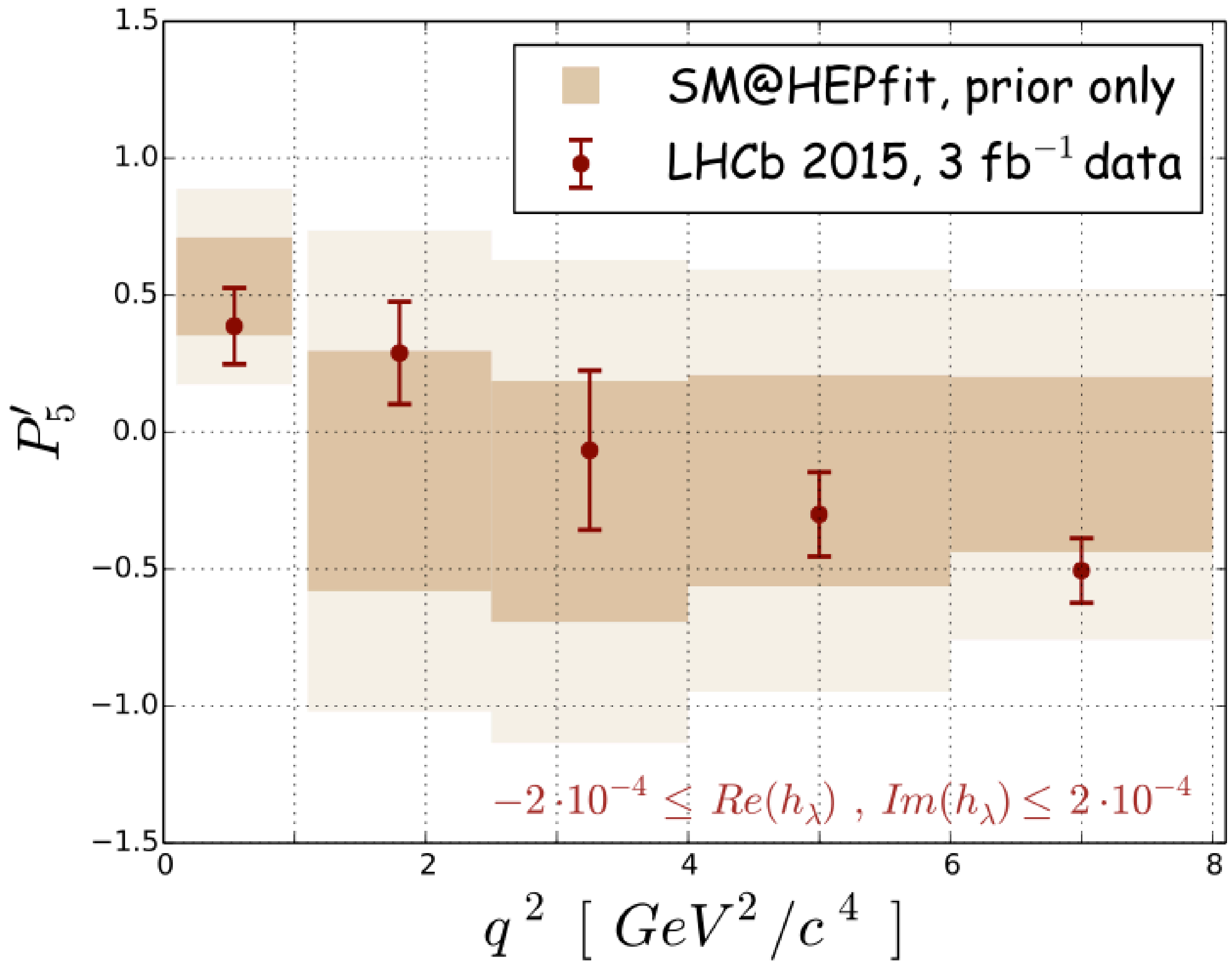
(see Descotes-Genon et al.'13 and ref. therein)

One example on top of some others:

$$P'_5 \equiv \frac{S_5}{\sqrt{F_L(1-F_L)}}$$

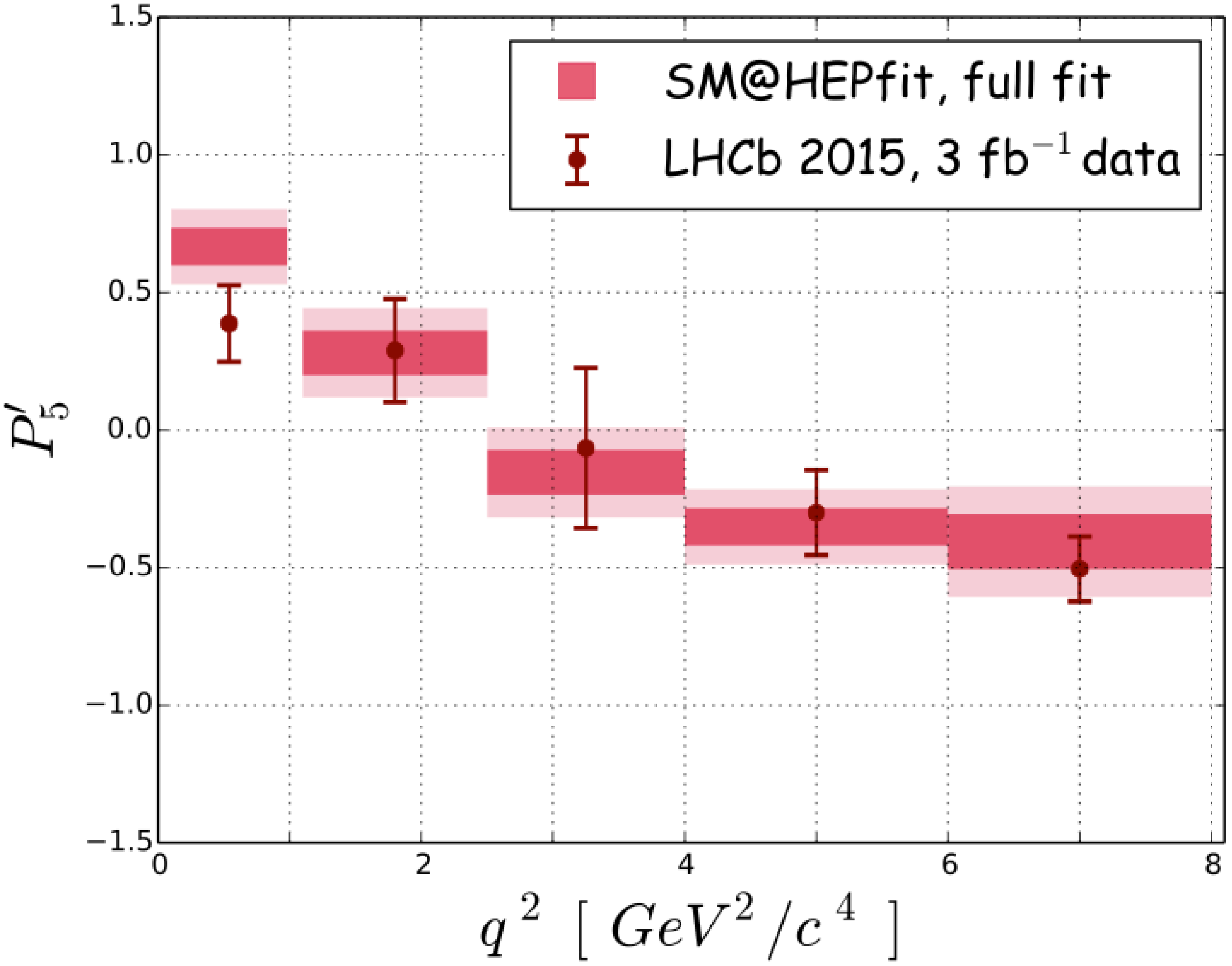
($q^2 \gtrsim m^2_\mu$)

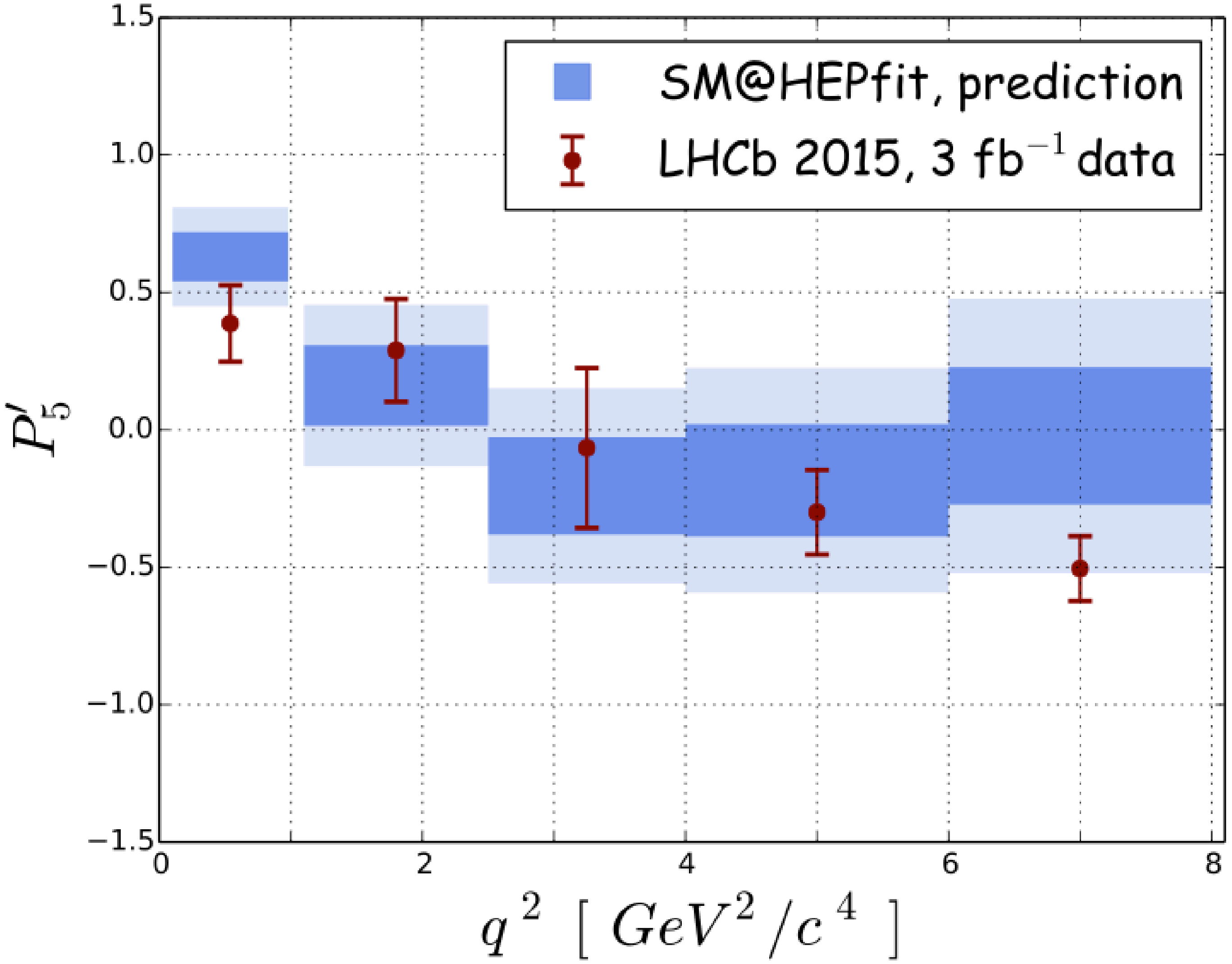



Our data-blind analysis with large hadronic contributions clearly shows a large shift in both the central values + inflation of errors!

# Fit & Prediction of $P'_5$

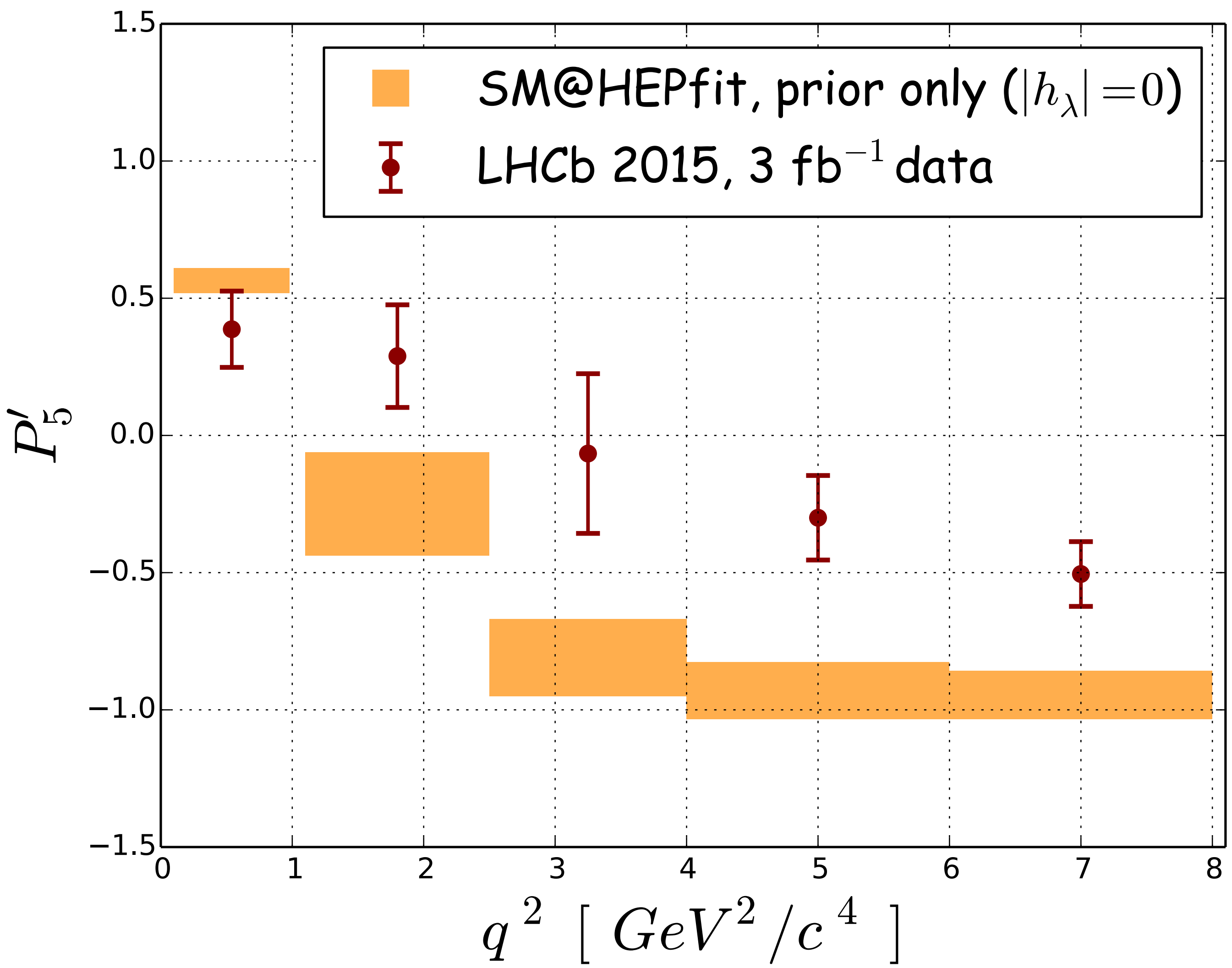


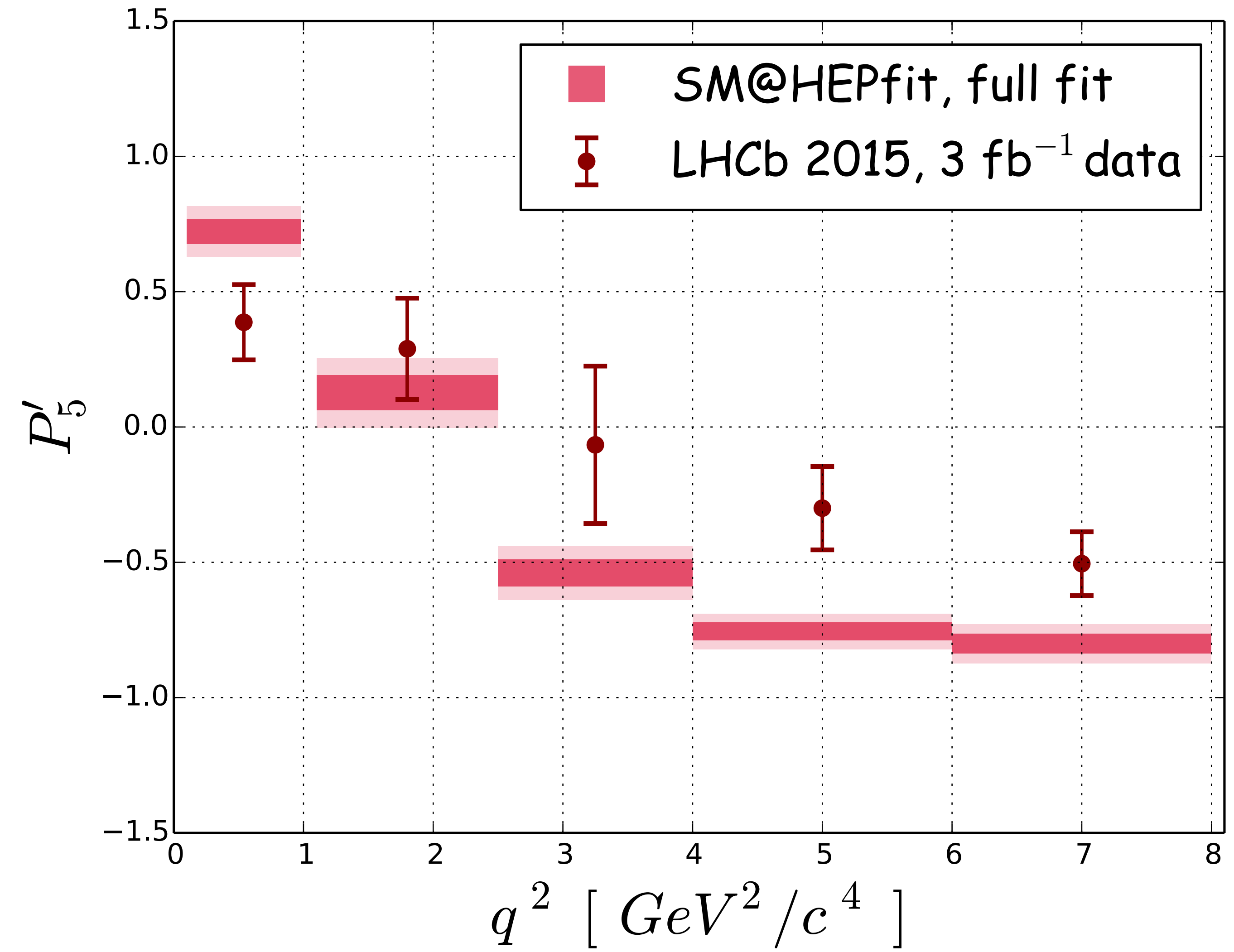




(computed from the helicity amplitudes, i.e. not from fit result of $S_5$ and $F_L$)

(switching off $S_5$ and $F_L$ together )

# How to get the Anomaly




Data-blind estimation.
No "charm-loop effect".
(1 sigma band here entirely due to LCSR form factors uncertainties)

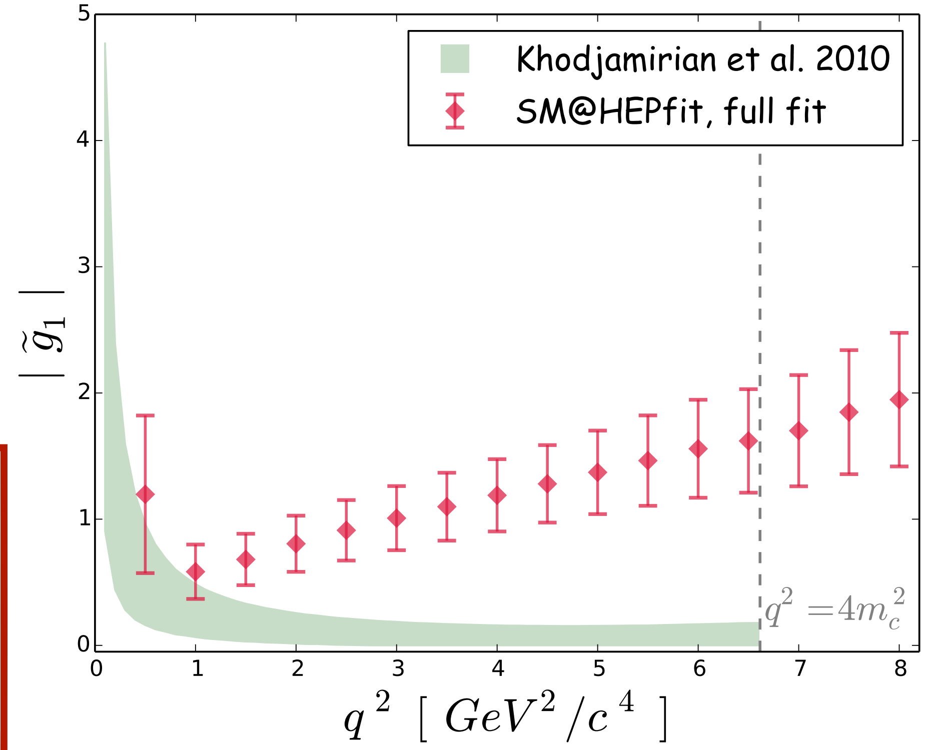
Fit with **Khodjamirian et al.** estimate imposed in the whole $q^2$ range [0.98,8] $GeV^2$.

# Face to face with hadronic contributions

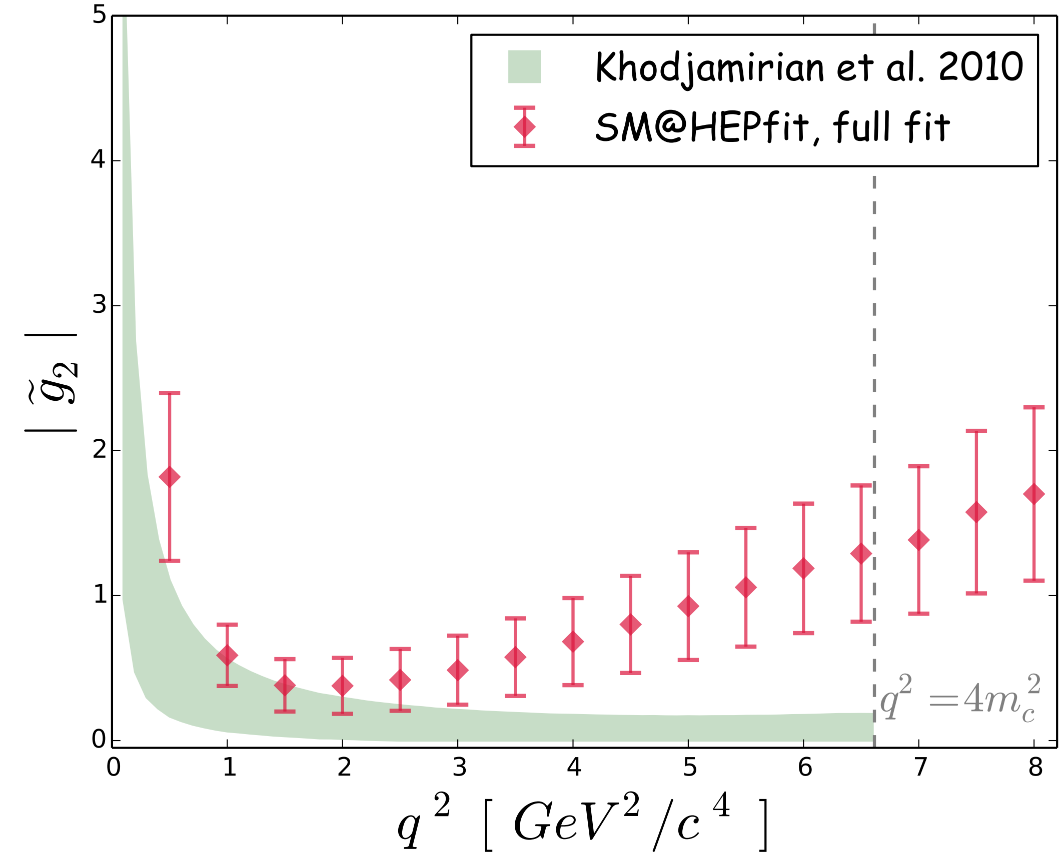
One can easily read the size of the hadronic contribution $h_\lambda$ as a shift in $C_9$ .

Eventually, to compare with the literature:

$$\tilde{g} \equiv \Delta C_9^{(\text{non pert.})}/(2C_1)$$

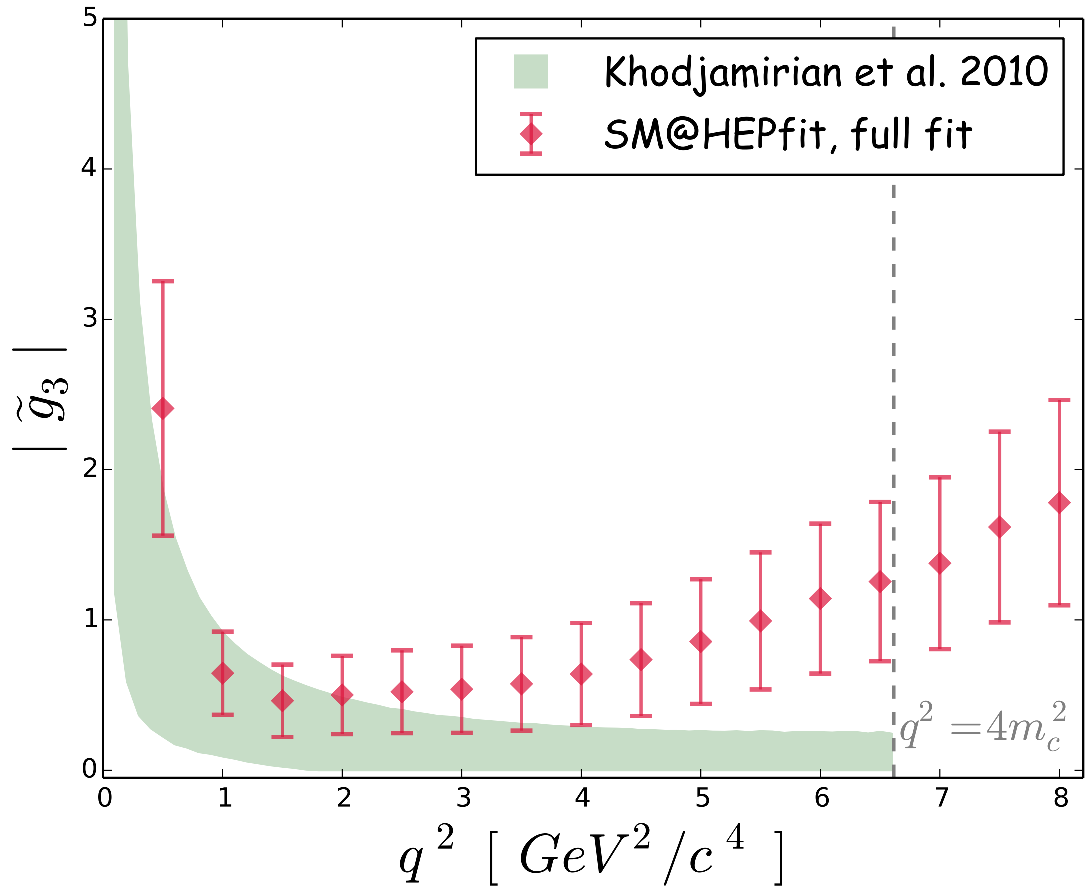



hadronic contribution extracted is compatible with theory estimate order of magnitude for $q^2 \lesssim 1\,\mathrm{GeV}^2$ and grows for larger $q^2$ towards charm resonances ... it goes as expected!




DISCLAIMER:

Generic NP contribution in a Wilson coefficient would not bring any $q^2$ dependence.



CERN. July 10th 2015.

by A.Paul

# ANOMALY

anomaly |əˈnɒm(ə)li|
noun (pl.**anomalies**)
: something that deviates from what is standard, normal, or expected
: *there are a number of anomalies in the present system*

Hadronic (charm) effects can sizably affect your prediction.

This is what one could expect to find in B to K*ll.

That is what we were able to extract from available data.

At present, no anomaly can be possibly claimed.

Thank You!