Rare B Decays: Theory and Experiment 2016

B to K*ll in the Standard Model

and other exclusive b to s transitions

INFN

M. Fedele

SAPIENZA UNIVERSITÀ DI ROMA

based on arXiv:1512.07157 in collaboration with:

M.Ciuchini, E.Franco, S.Mishima, A.Paul, L.Silvestrini & M.Valli

UAB Universitat Autònoma de Barcelona

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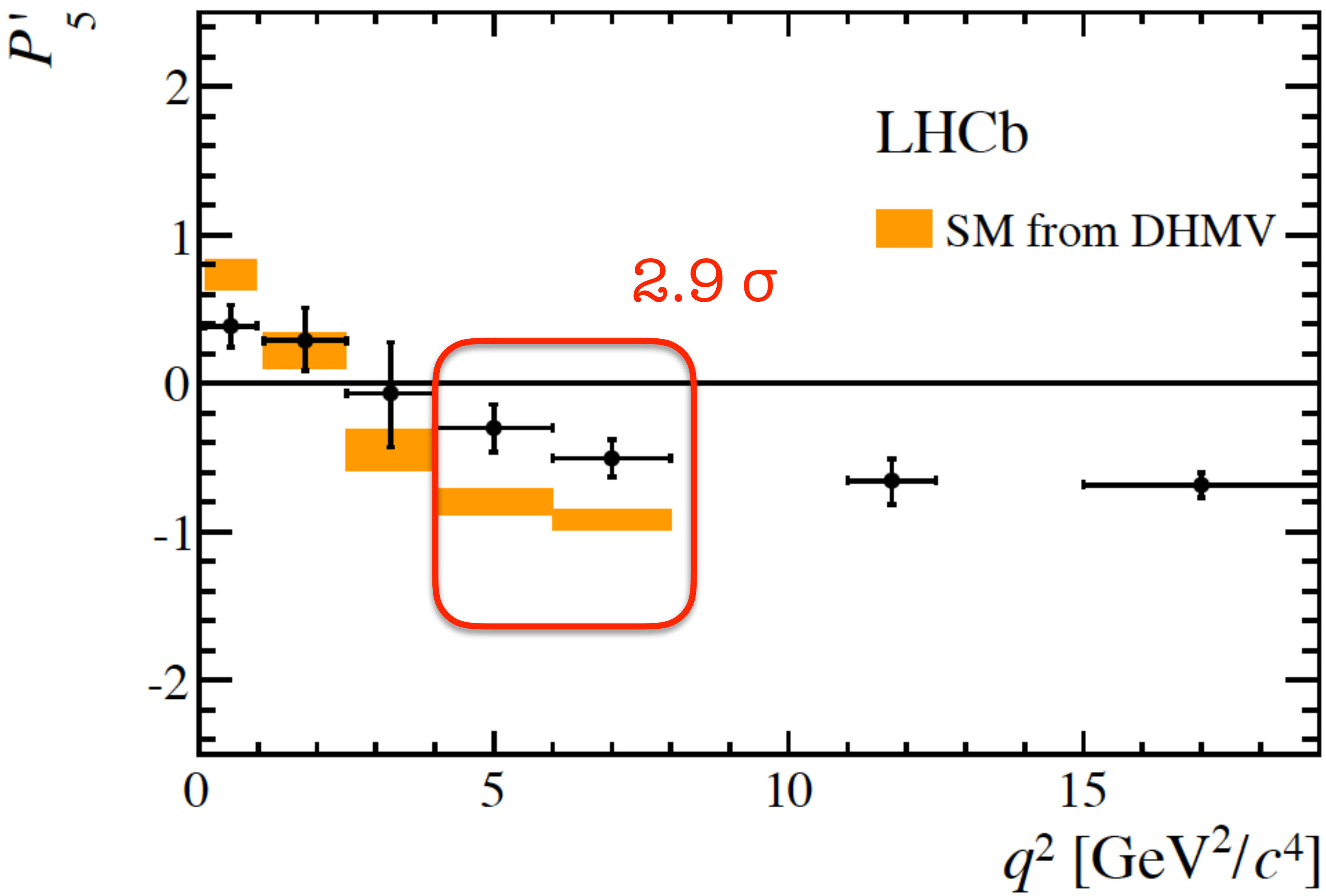
erc European Research Council Funding for top researchers from anywhere in the world

The P'_5 anomaly



LHCb
arXiv:1512.04442

Is NP the responsible for this anomaly? Many think so…

F.Beaujean et al. arXiv:1310.2478 W.Altmannshofer, D.M.Straub arXiv:1411.3161 S. Descotes-Genon et al. arXiv:1510.04239 T.Hurt et al. arXiv:1603.00865 A.Karan et al. arXiv:1603.04355 …

The aim of my talk

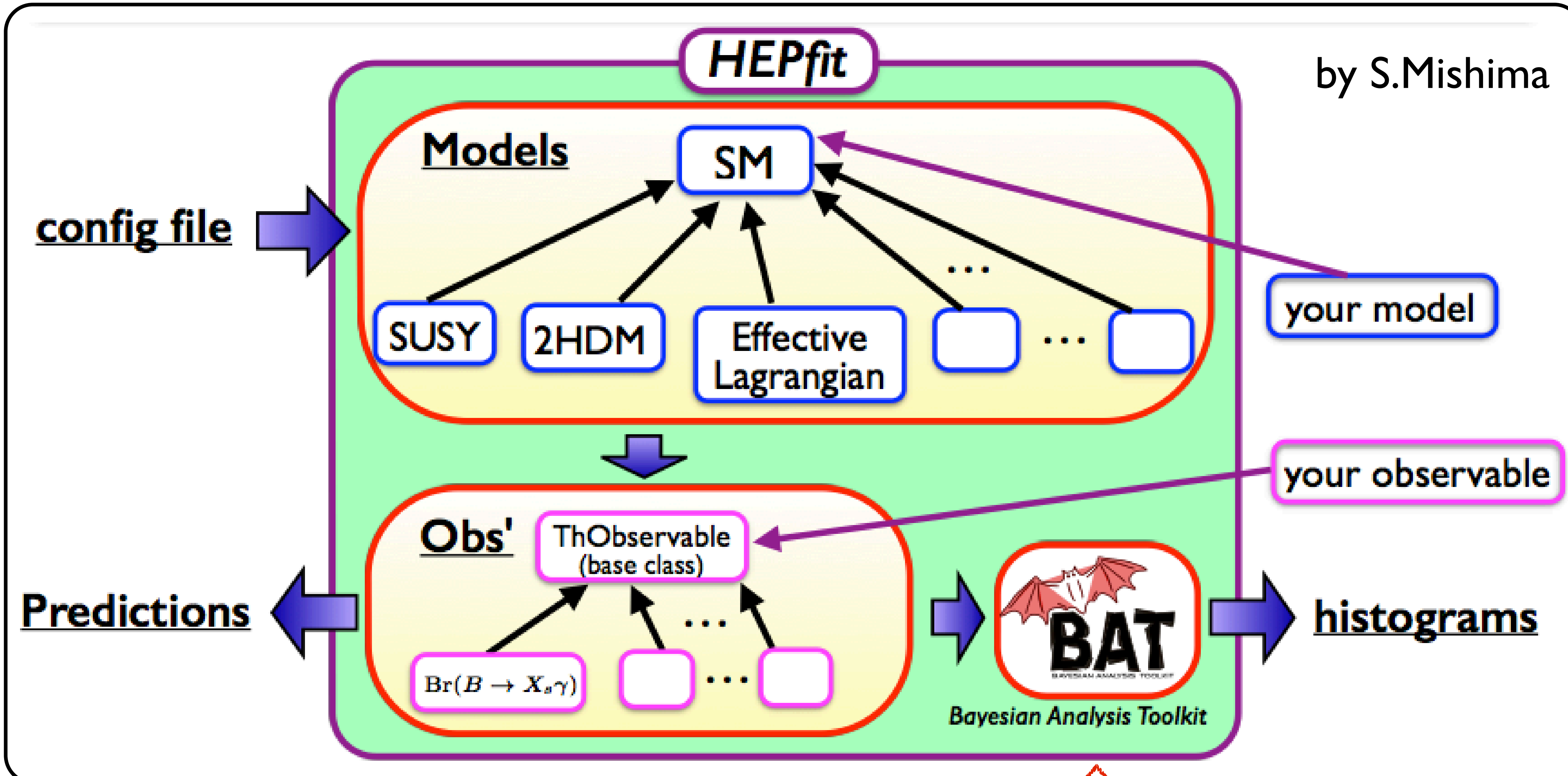
*Can we be **sure** that the anomaly **is due to NP**, or there is still a **chance that SM can reproduce** the experimental results? Is it even legit to ask…? **YES!***

On the theoretical side, we still don't know how to properly take into account non-perturbative hadronic contributions in the whole phenomenological region

- *Are the hadronic contributions **properly estimated** in the anomaly bins?*
- *How **sensitive** is the SM prediction **to hadronic contributions**?*

*To address this questions, we will **extract** by means of a **Bayesian analysis** the **hadronic contributions***

HEPfit : a new tool for SM physics & Beyond

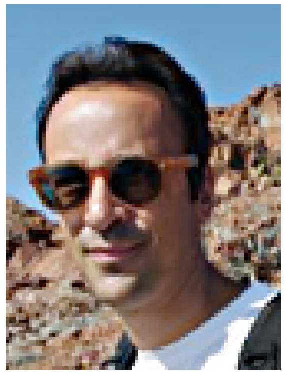


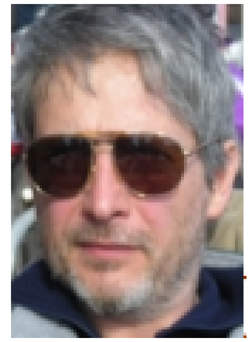
*Full-fledged statistical data analysis **in this work** carried out by means of **Bayes Theorem***

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

λ posterior — likelihood — λ prior

the HEPfit group:
@present

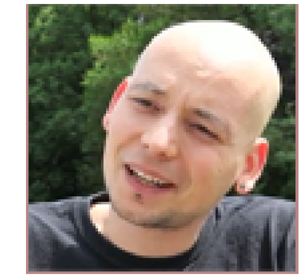

L.Silvestrini


M.Ciuchini


S.Mishima


E.Franco


L.Reina


M.Pierini

+ 5 postdocs
+ 3 PhD students

HEPfit is a framework for calculating observables (Flavour, EWPT, Higgs) in the SM and Beyond, constraining model parameter space with a global fit

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It is a **public code** written in C++, supporting MPI parallelization, with GSL, Boost, ROOT and Bayesian Analysis Toolkit (BAT) dependencies

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HEPfit v1.0 release candidate available @ http://hepfit.roma1.infn.it/ with a user friendly cross-platform CMake + a detailed Doxygen documentation of the code (user manual coming out soon!)

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

The large- recoil region in HEPfit

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

- *NNLO matching and evolution of Wilson coefficients for Q_{1-10}*

- *7 Form Factors from LCSRs*

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

$$+$$

19 x 19 correlation matrix

A.Bharucha, D.M.Straub and R.Zwicky *arXiv:1503.05534*

- *Hard gluon exchanges from QCD factorization*

  S.W.Bosch and G.Buchalla *arXiv:0106081*

  M.Beneke, T.Feldmann and D.Seidel *arXiv:0106067*

- *Soft gluon exchanges ($u\bar{u}$, $c\bar{c}$ loops, Q_{8g} and WA)*

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

by M.Valli

We followed the helicity amplitude formalism :

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

$$H_V(\lambda) \propto C_9 \tilde{V}_{L\lambda} + \frac{2m_b m_B}{q^2} C_7 \tilde{T}_{L\lambda} - \frac{16\pi^2 m_B^2}{q^2} h_\lambda \qquad (\lambda = 0, \pm)$$

$$H_A(\lambda) \propto C_{10} \tilde{V}_{L\lambda} \quad , \quad H_P \propto \frac{2m_l m_B}{q^2} C_{10} \left(1 + \frac{m_s}{m_B}\right) \widetilde{S}$$

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IN OUR BAYESIAN FIT

- LHCb binned angular observables (including correlations) and BRs for $B \to K^* \mu^+ \mu^-,\ K^* e^+ e^-,\ K^* \gamma$

  arXiv:1502.04442, 1304:6325

  arXiv:1501.03038, 1304:3035

  HFAG2014

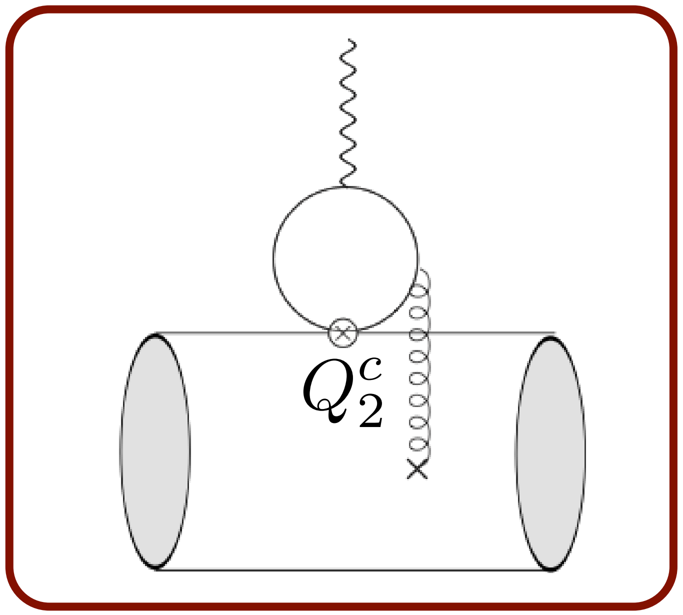
- Half-normal distribution (σ=0.2) for helicity amplitude suppression factor $\left| \frac{h_+^{(0)}}{h_-^{(0)}} \right|$

  S.Jaeger and J.M.Camalich *arXiv:1212.2263*

- Flat prior for the non-perturbative hadronic contribution :

$$\left| h_{0,\pm}^{(0,1,2)} \right| \in \left[0, 2 \cdot 10^{-3}\right] \quad , \quad Arg\left(h_{0,\pm}^{(0,1,2)}\right) \in \left[0, 2\pi\right]$$

Regarding soft-gluon emission, *we can exploit an extra constraint in our fit taking into account the* **order of magnitude estimate from LCSR** *(*A.Khodjamirian, T.Mannel, A.A.Pivovarov and Y.M.Wang *arXiv: 1006.4945)* **as a gaussian weight on** *the* **absolute values of h_λ**



DISCLAIMER

Effect estimated in the single-soft gluon approximation

Each additional soft-gluon *exchange is* **suppressed** *by a factor* $1/(q^2 - 4m_c^2)$ *hence this approximations holds* **only for very low** q^2 *and worsens at higher* q^2 **breaking down exactly where the "anomaly bins" sit**

- Constraints (when applied) implemented only for $q^2 \lesssim 1$ GeV^2

Results are different from the ones we put on arXiv due to a wrong factor in S_4. We thank Joaquim Matias to point us to an inconsistency in our results due to this wrong factor.

The SM@HEPfit analysis, case 1

EXPERIMENTAL WEIGHTS :

q² experimental binning

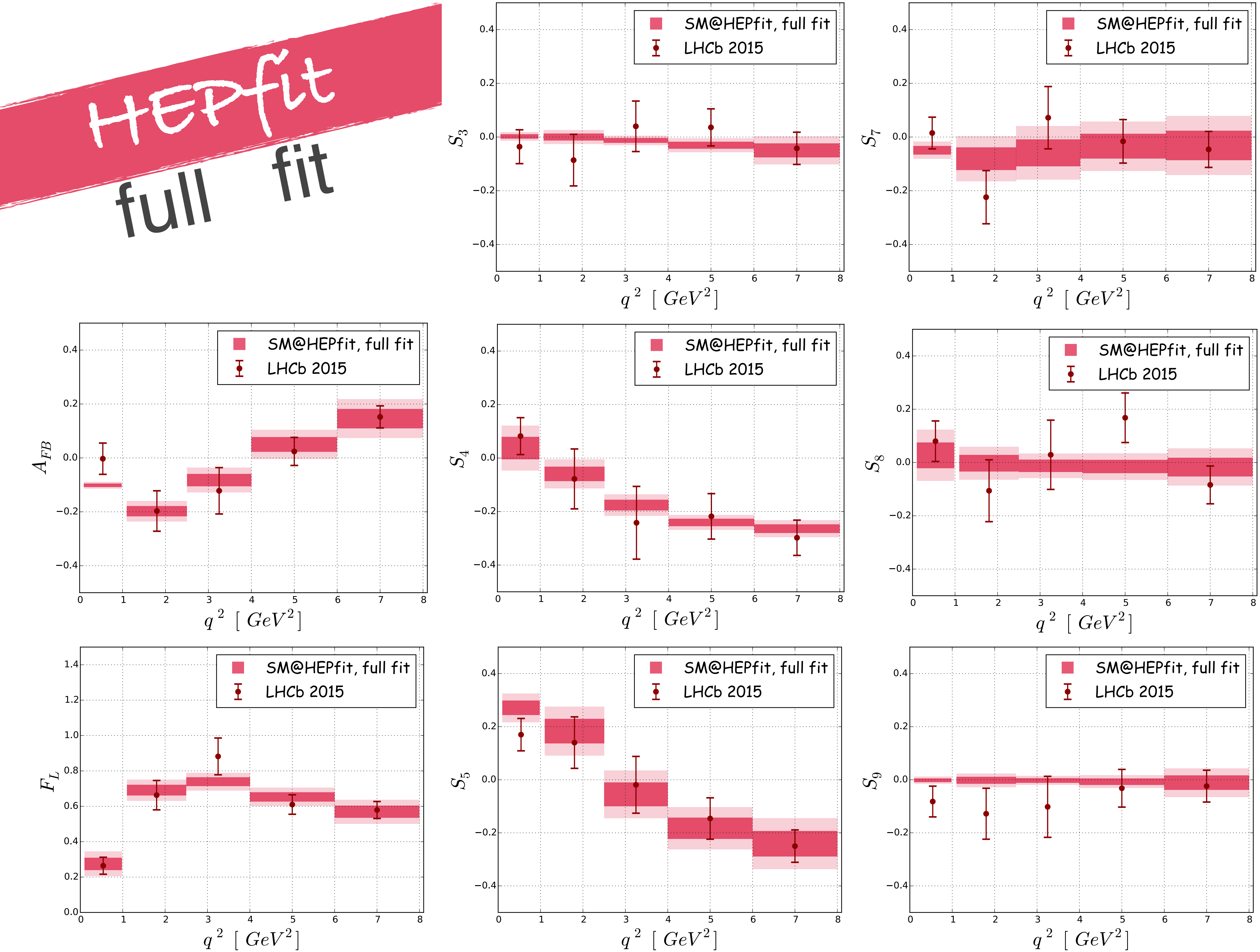
$F_L, A_{FB}, S_{3,4,5,7,8,9}$ *correlated in each bin of q²*	[0.1, 0.98], [1.1, 2.5], [2.5, 4.0] [4.0, 6.0], [6.0, 8.0]
$\mathcal{B}(B \to K^* \mu\mu)$	[0.1, 2], [2, 4.3], [4.3, 8.68]
$\mathcal{B}(B \to K^* \gamma)$	kinematical endpoint
$\mathcal{B}(B \to K^* ee), F_L, P_{1,2,3}$	[0.03, 1], [0.002, 1.12]

THEORY WEIGHTS :

LCSR FFs with correlation matrix for low q^2 region only

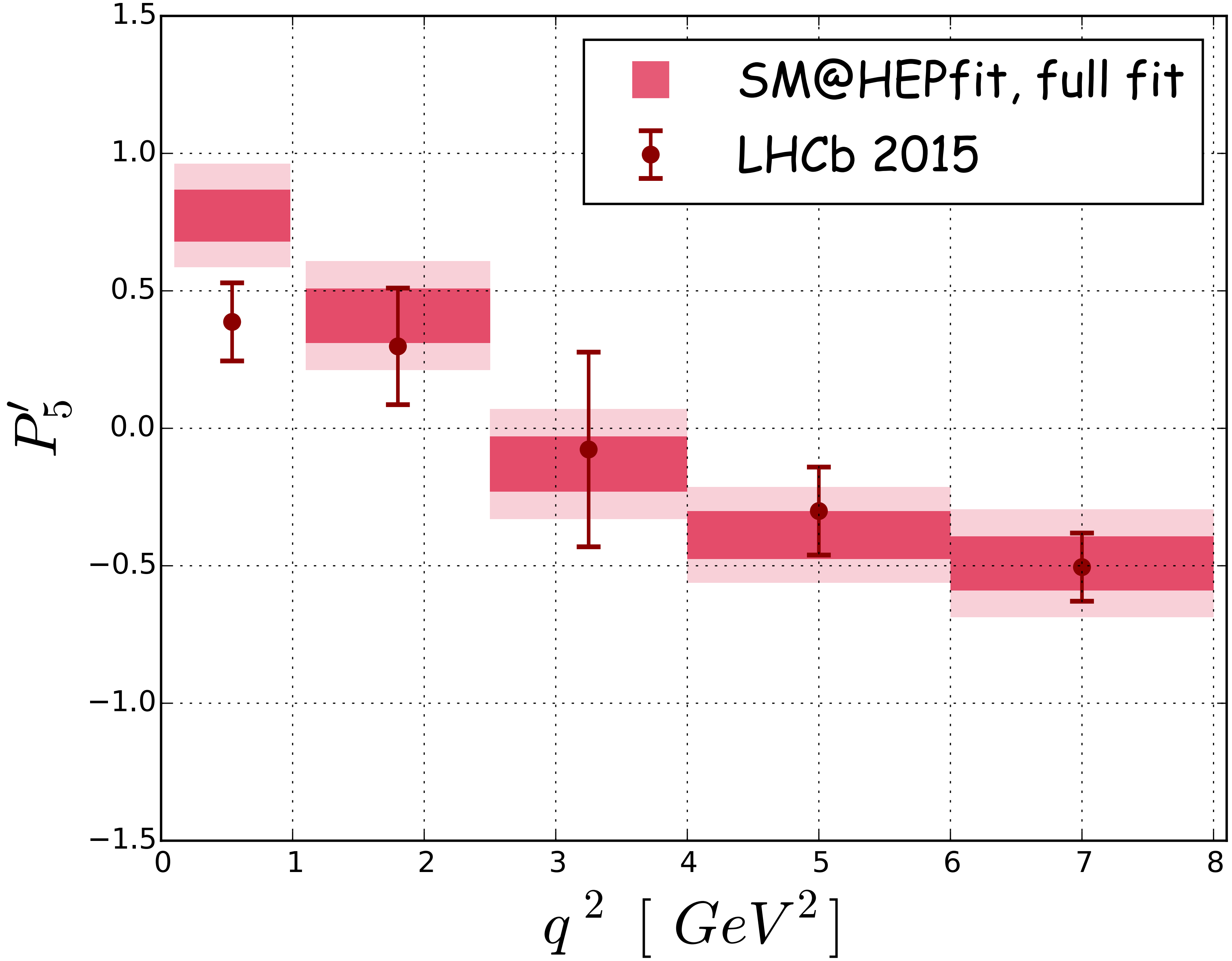
Amplitude helicity suppression at kinematical endpoint

Khodjamirian et al. constraint **ONLY for $q^2 \lesssim 1$ GeV²**



HEPfit
full fit
SM@HEPfit, full fit
LHCb 2015
S_3
S_7
A_{FB}
S_4
S_8
F_L
S_5
S_9
q^2 [GeV^2]

WHAT ABOUT THE OPTIMIZED OBSERVABLES … ?



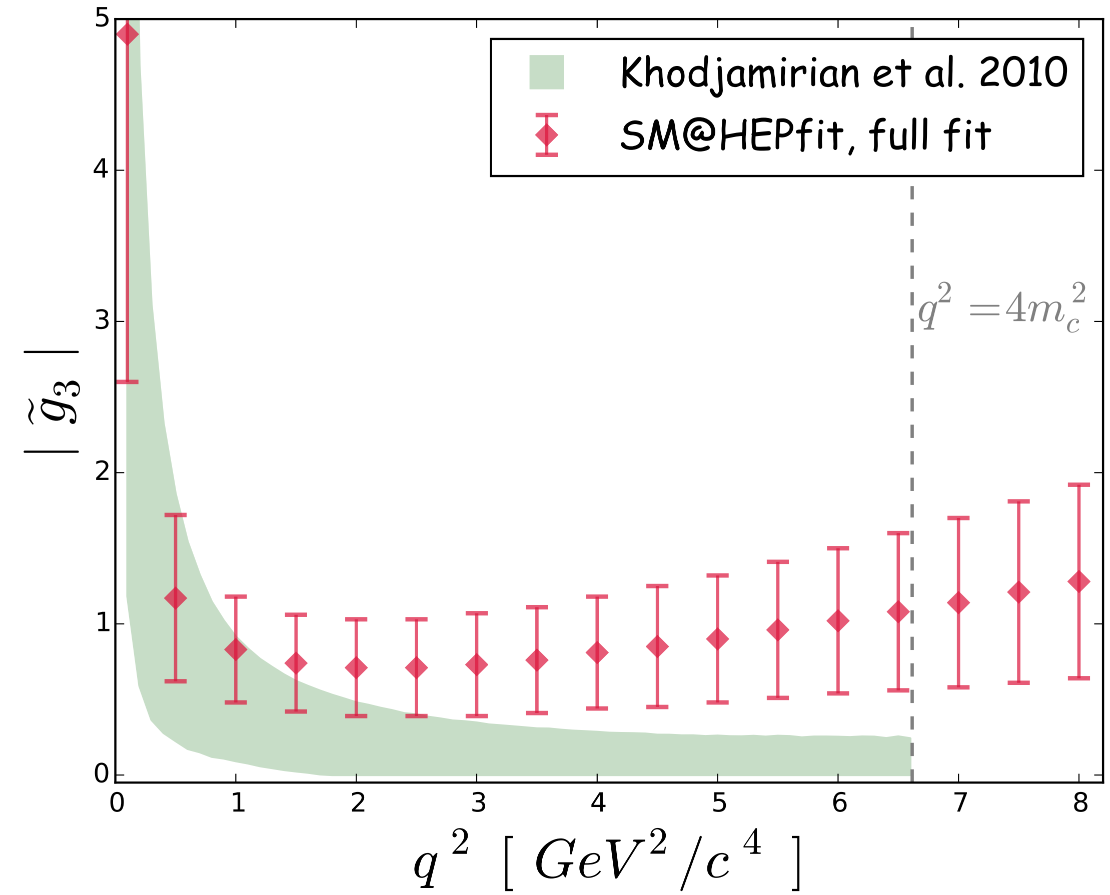
$$P'_5 = \frac{S_5}{\sqrt{F_L(1 - F_L)}}$$

No anomalies in P'_5 …!

EXTRACTING THE NON-PERTURBATIVE HADRONIC CONTRIBUTION

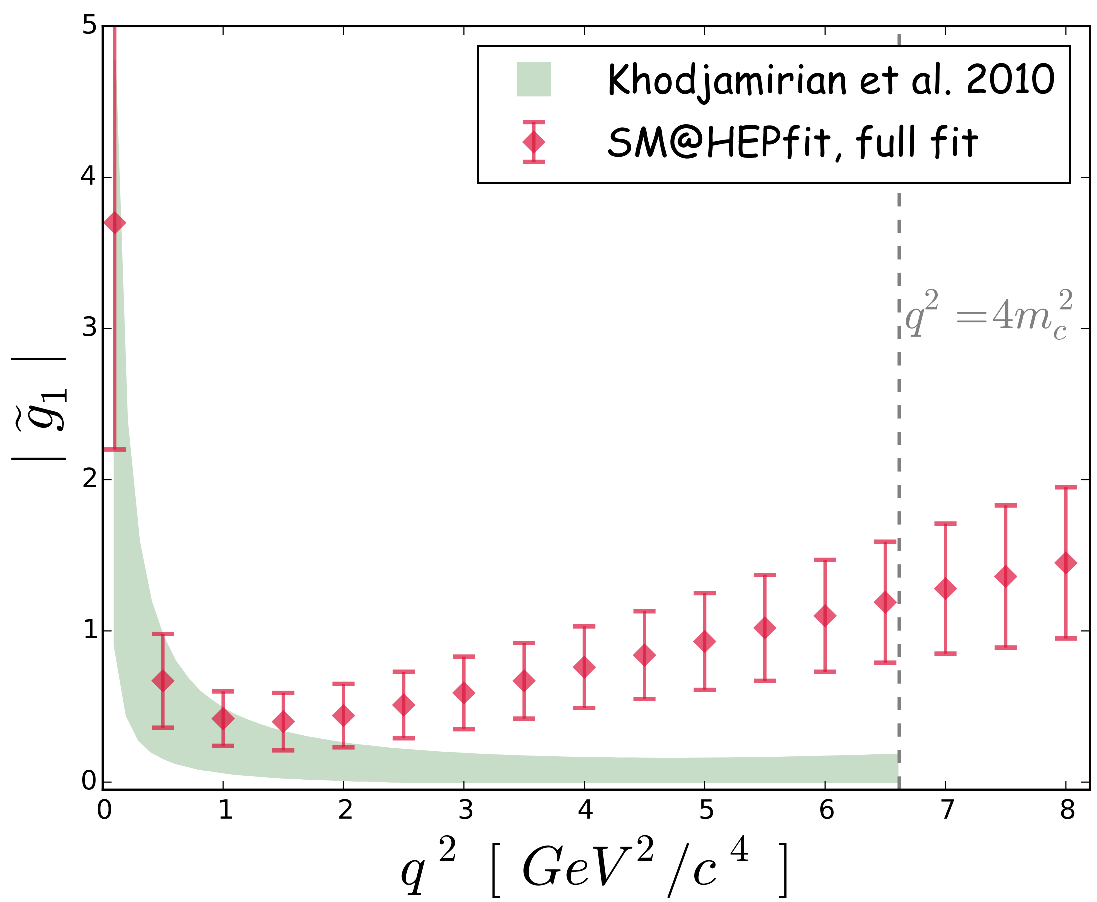
$$\tilde{g} \equiv \Delta C_9^{(\text{non pert.})} / (2C_1)$$

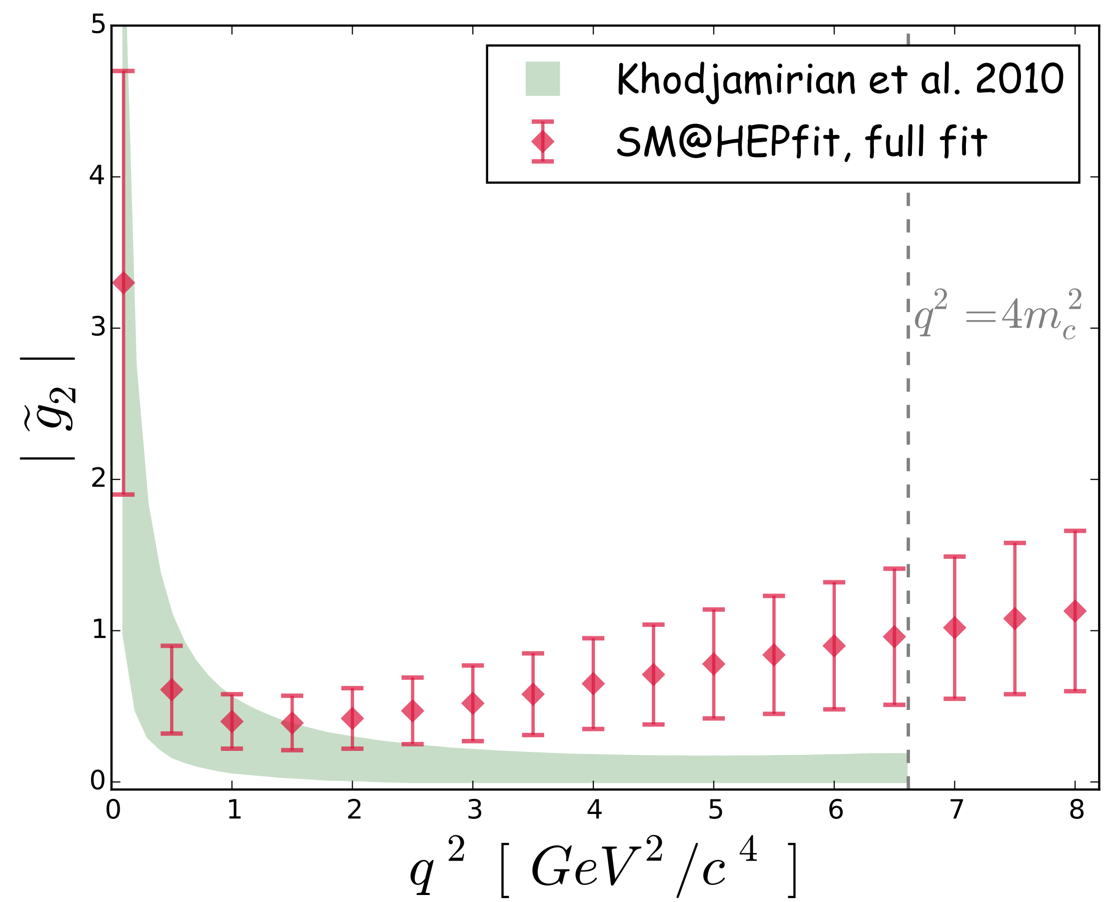
see *arXiv:1006.4945*



DISCLAIMER

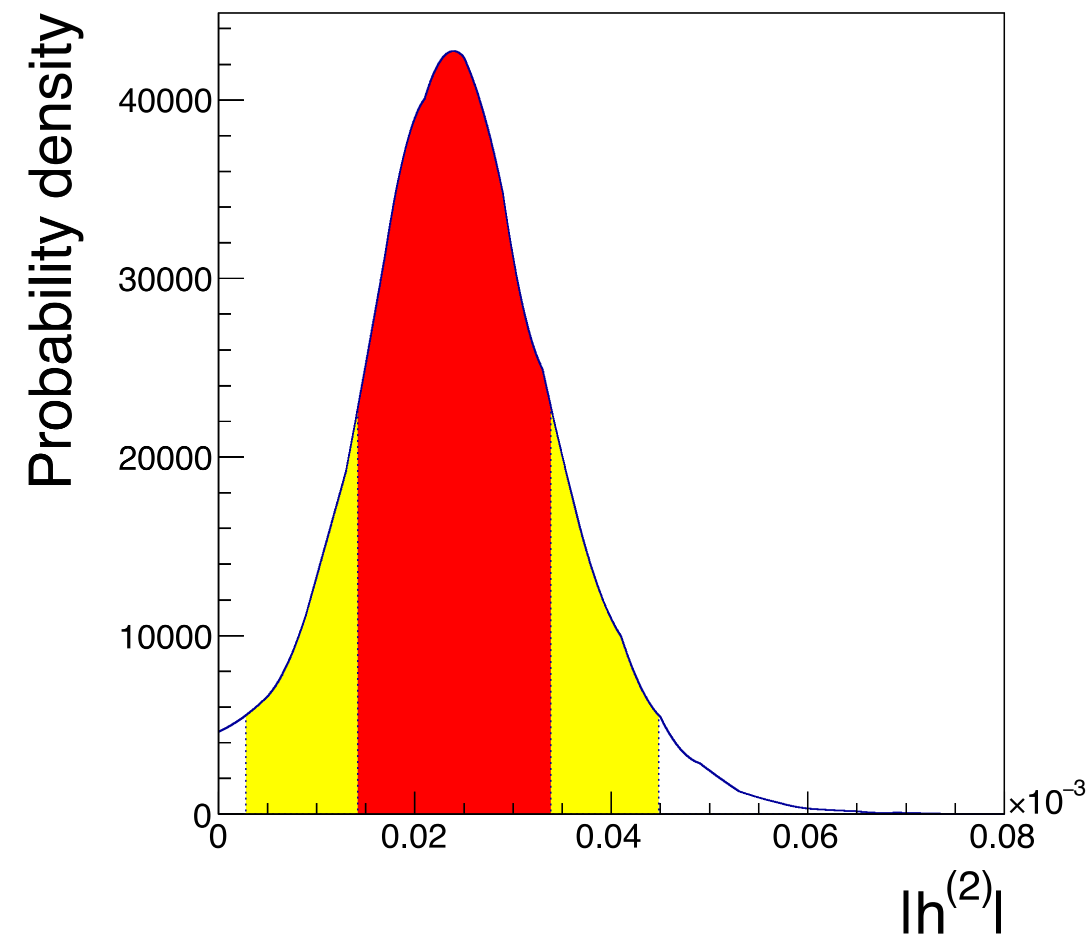
NP contribution in C_7 and/or C_9 cannot reproduce such a q^2 behaviour





RESULTS FOR THE HADRONIC PARAMETERS h_λ

Parameter	**Absolute value**	**Phase** (rad)
$h_0^{(0)}$	$(5.7 \pm 2.0) \cdot 10^{-4}$	3.57 ± 0.55
$h_0^{(1)}$	$(2.3 \pm 1.6) \cdot 10^{-4}$	0.1 ± 1.1
$h_0^{(2)}$	$(2.8 \pm 2.1) \cdot 10^{-5}$	-0.2 ± 1.7
$h_+^{(0)}$	$(7.9 \pm 6.9) \cdot 10^{-6}$	0.1 ± 1.7
$h_+^{(1)}$	$(3.8 \pm 2.8) \cdot 10^{-5}$	-0.7 ± 1.9
$h_+^{(2)}$	$(1.4 \pm 1.0) \cdot 10^{-5}$	3.5 ± 1.6
$h_-^{(0)}$	$(5.4 \pm 2.2) \cdot 10^{-5}$	3.2 ± 1.4
$h_-^{(1)}$	$(5.2 \pm 3.8) \cdot 10^{-5}$	0.0 ± 1.7
$h_-^{(2)}$	$(2.5 \pm 1.0) \cdot 10^{-5}$	0.09 ± 0.77



$|h_-^{(2)}|$ *differs from zero* **at more than 95.45% probability,**
thus **disfavouring** *the interpretation of the hadronic correction*
as **NP contributions in C_7 and/or C_9**

The SM@HEPfit analysis, case II

EXPERIMENTAL WEIGHTS :

q² experimental binning

$F_L, A_{FB}, S_{3,4,5,7,8,9}$ *correlated in each bin of q^2*	[0.1, 0.98], [1.1, 2.5], [2.5, 4.0] [4.0, 6.0], [6.0, 8.0]
$\mathcal{B}(B \to K^* \mu\mu)$	[0.1, 2], [2, 4.3], [4.3, 8.68]
$\mathcal{B}(B \to K^* \gamma)$	kinematical endpoint
$\mathcal{B}(B \to K^* ee), F_L, P_{1,2,3}$	[0.03, 1], [0.002, 1.12]

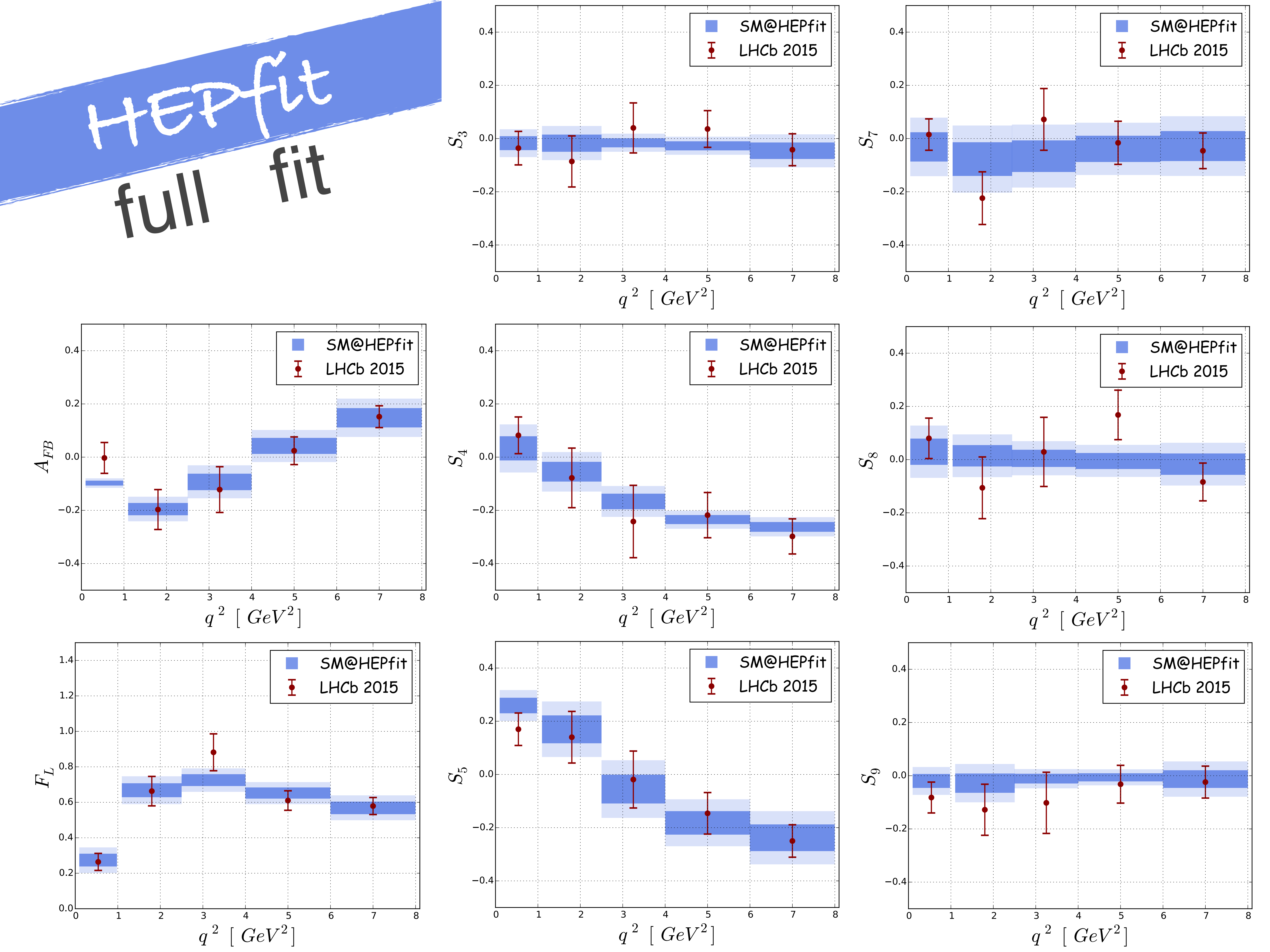
THEORY WEIGHTS :

LCSR FFs with correlation matrix for low q^2 region only

Amplitude helicity suppression at kinematical endpoint

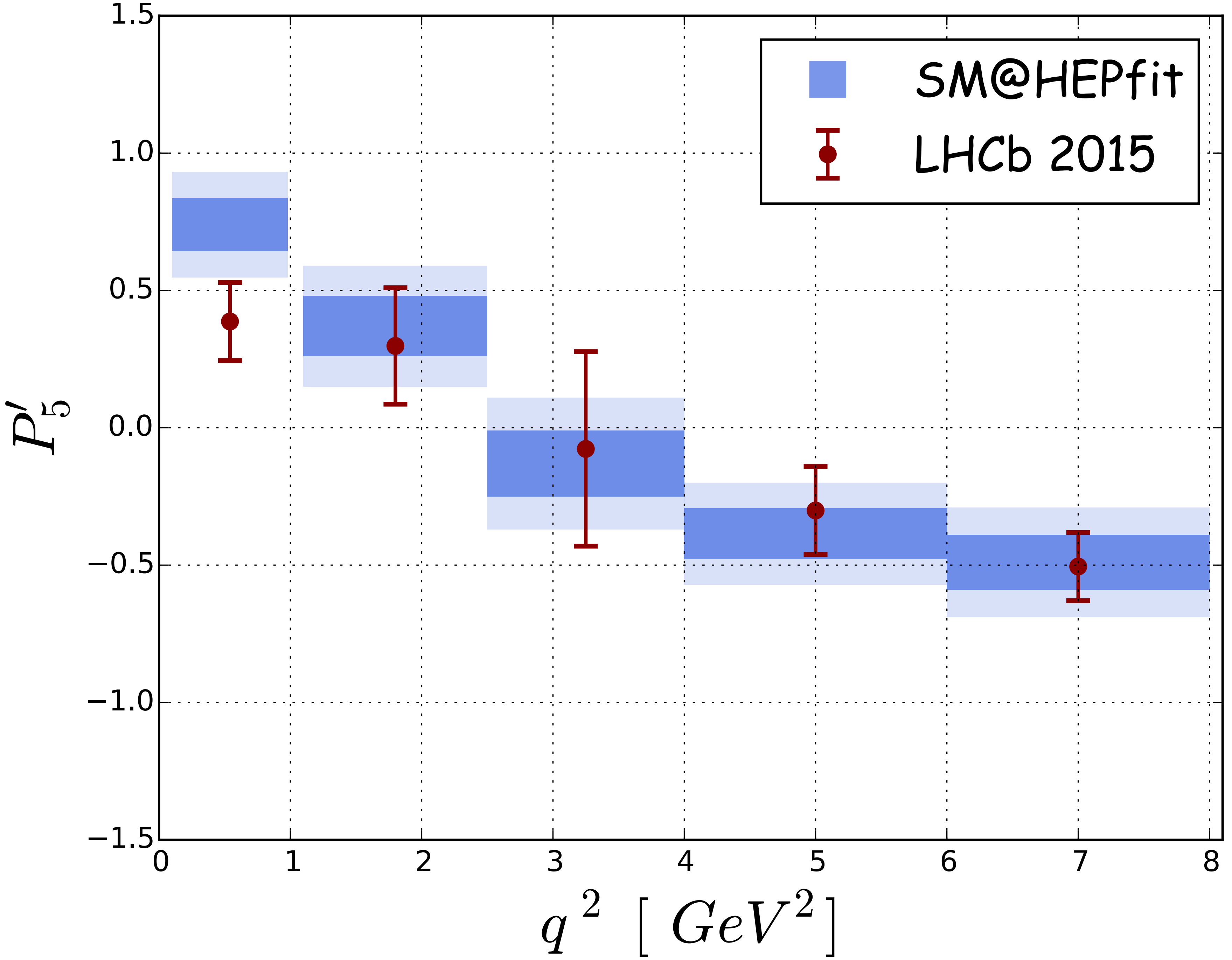
No theoretical info on h_λ

DATA-DRIVEN



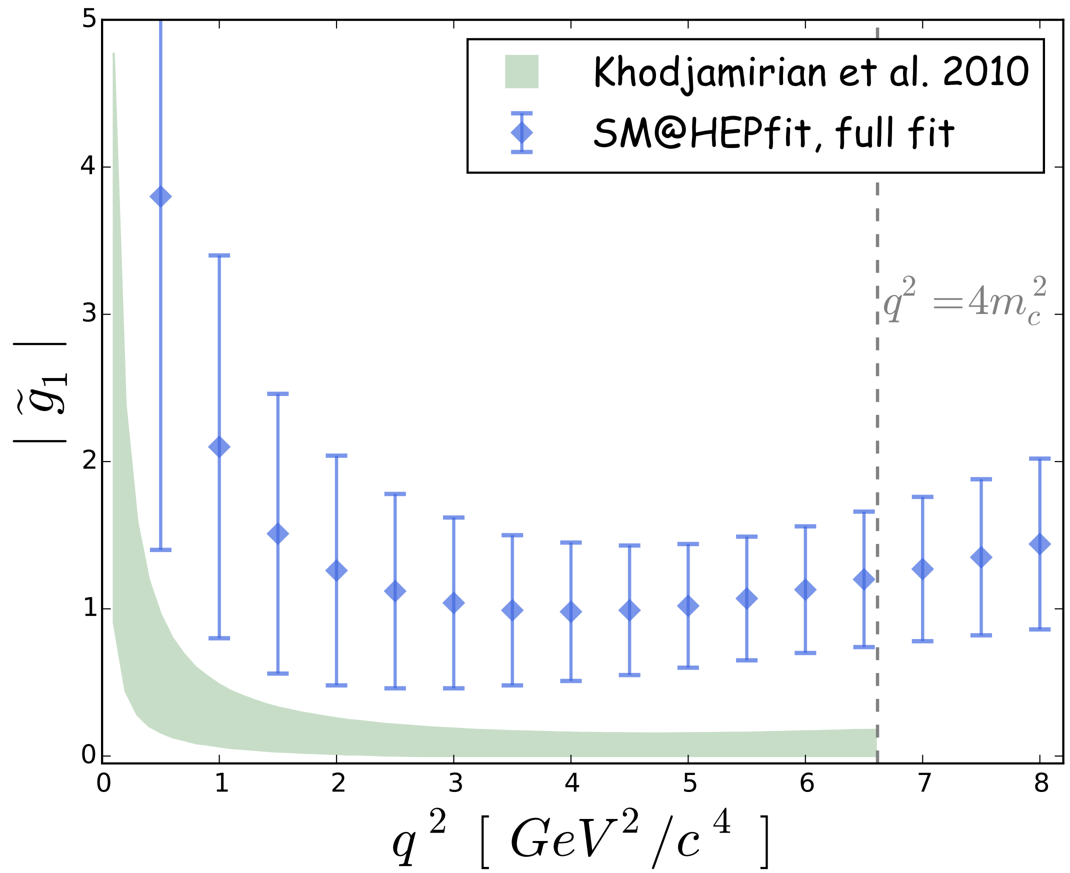
HEPfit
full fit
SM@HEPfit
LHCb 2015
S_3
S_7
A_{FB}
S_4
S_8
F_L
S_5
S_9
q^2 [GeV^2]

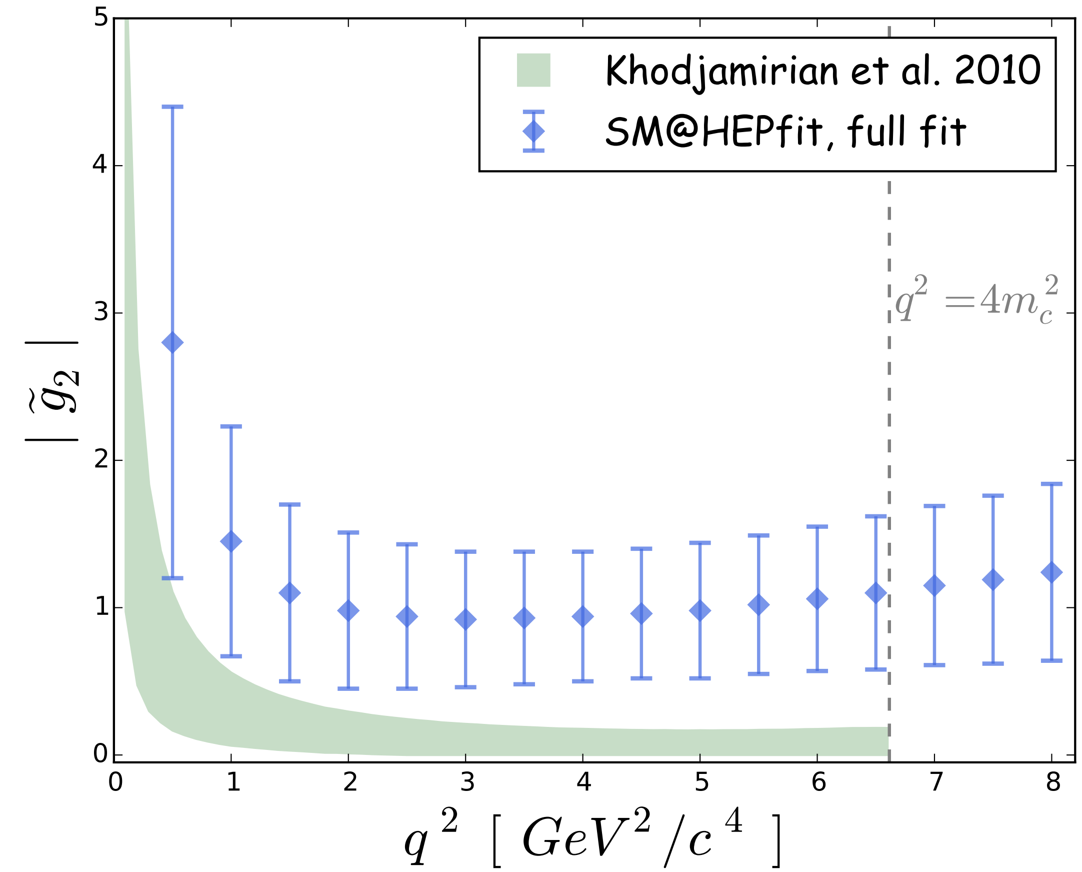
WHAT ABOUT THE OPTIMIZED OBSERVABLES … ?



Still no anomalies in P'_5 …!

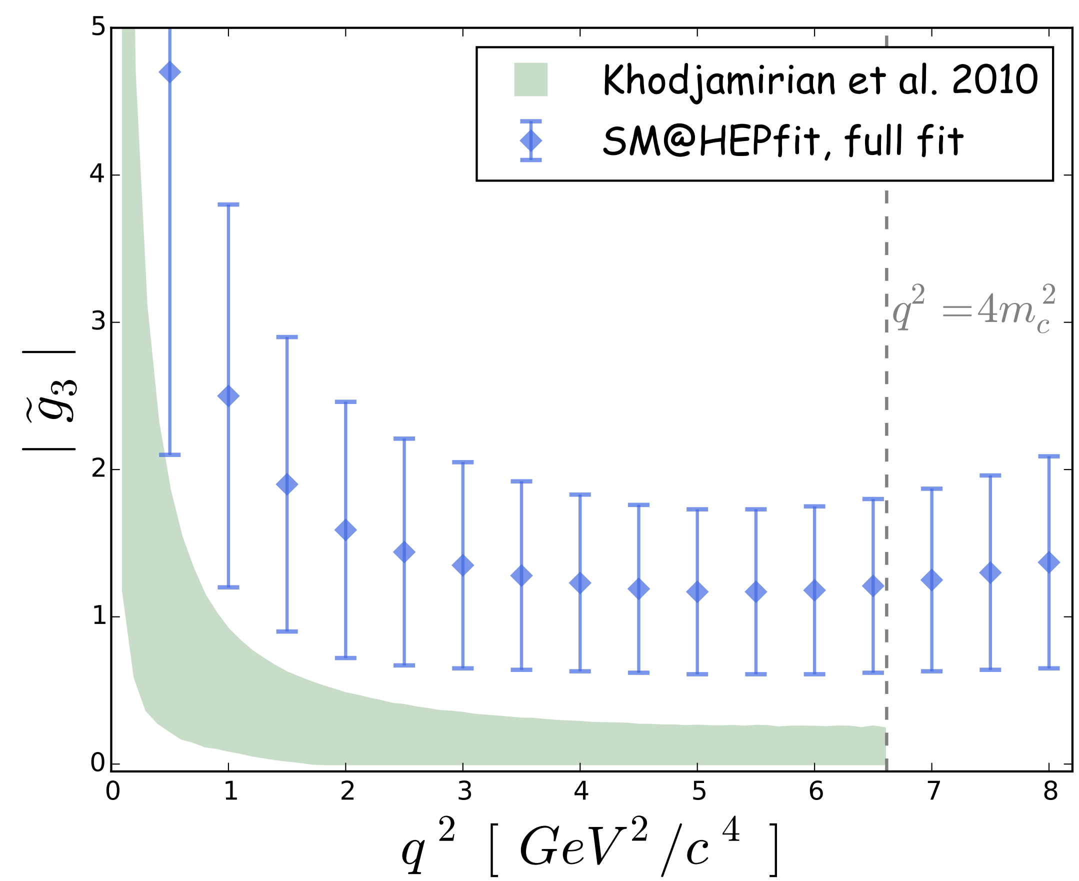
EXTRACTING (again) THE NON-PERTURBATIVE HADRONIC CONTRIBUTION





A data-driven extraction leads to an **inflated contribution with respect to LCSR** *estimate with unavoidable* **larger errors**

No firm conclusions on q^2 behaviour



RESULTS FOR THE HADRONIC PARAMETERS h_λ (again)

Parameter	**Absolute value**	**Phase** (rad)
$h_0^{(0)}$	$(5.8 \pm 2.1) \cdot 10^{-4}$	3.54 ± 0.56
$h_0^{(1)}$	$(2.9 \pm 2.1) \cdot 10^{-4}$	0.2 ± 1.1
$h_0^{(2)}$	$(3.4 \pm 2.8) \cdot 10^{-5}$	-0.4 ± 1.7
$h_+^{(0)}$	$(4.0 \pm 4.0) \cdot 10^{-5}$	0.2 ± 1.5
$h_+^{(1)}$	$(1.4 \pm 1.1) \cdot 10^{-4}$	0.1 ± 1.7
$h_+^{(2)}$	$(2.6 \pm 2.0) \cdot 10^{-5}$	3.8 ± 1.3
$h_-^{(0)}$	$(2.5 \pm 1.5) \cdot 10^{-4}$	$-1.53 \pm 0.75 \cup 1.85 \pm 0.45$
$h_-^{(1)}$	$(1.2 \pm 0.9) \cdot 10^{-4}$	$-0.90 \pm 0.70 \cup 0.80 \pm 0.80$
$h_-^{(2)}$	$(2.2 \pm 1.4) \cdot 10^{-5}$	0.0 ± 1.2

$|h_-^{(2)}|$ *differs from zero* **at more than 68.3% probability,** *thus* **no firm conclusion** *on the interpretation of the hadronic correction* **can be drawn**

The SM@HEPfit analysis, case III

EXPERIMENTAL WEIGHTS :

q^2 experimental binning

$F_L, A_{FB}, S_{3,4,5,7,8,9}$ *correlated in each bin of q^2*	[0.1, 0.98], [1.1, 2.5], [2.5, 4.0] [4.0, 6.0], [6.0, 8.0]
$\mathcal{B}(B \to K^* \mu\mu)$	[0.1, 2], [2, 4.3], [4.3, 8.68]
$\mathcal{B}(B \to K^* \gamma)$	kinematical endpoint
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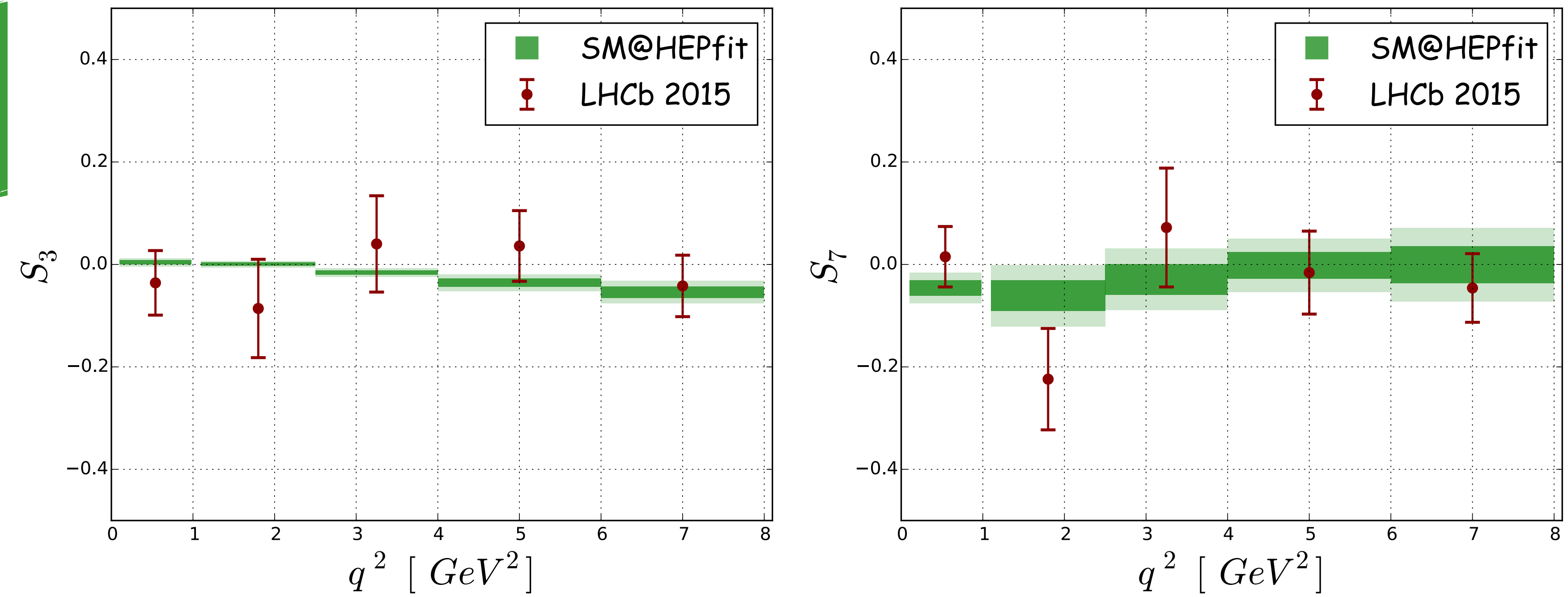
THEORY WEIGHTS :

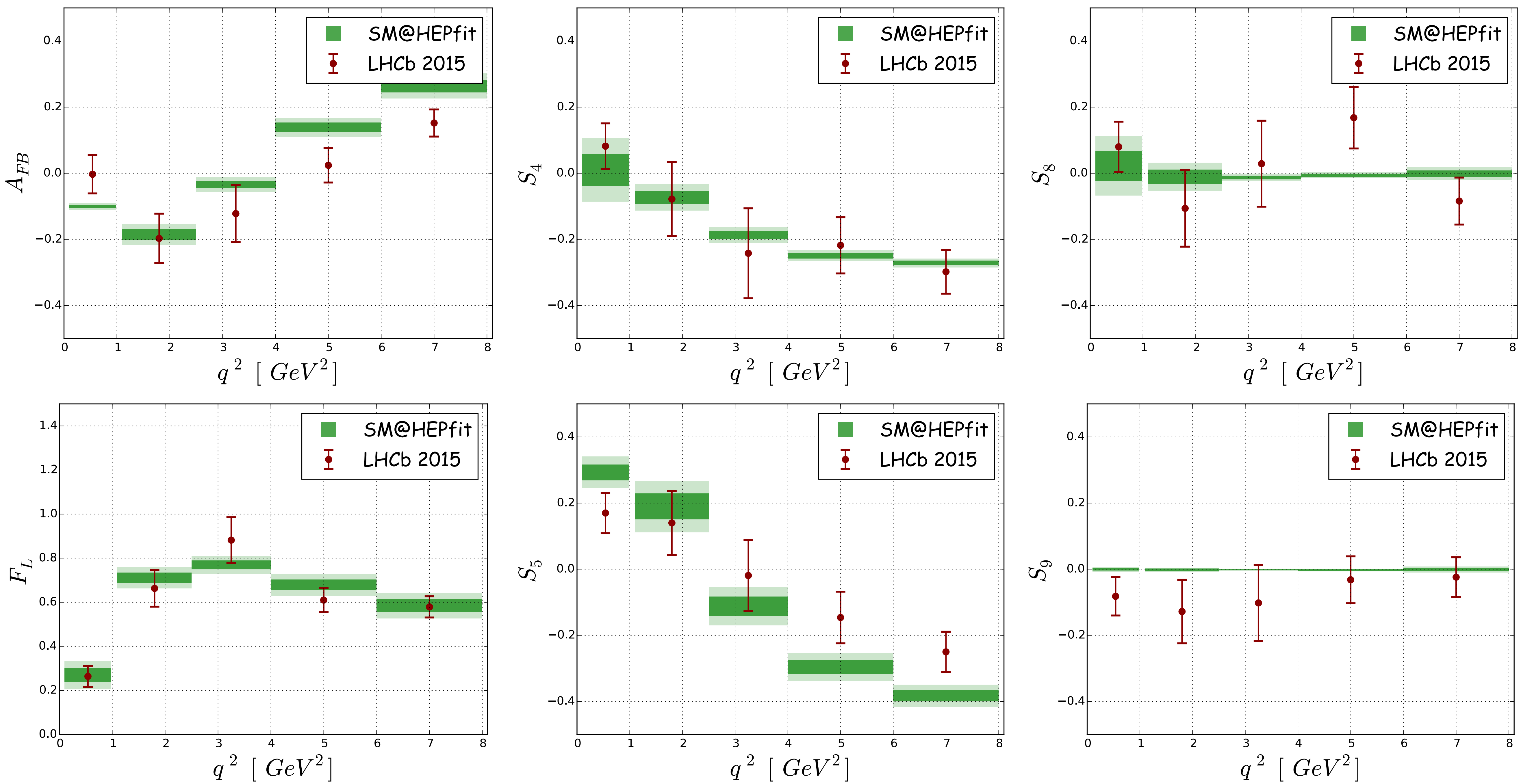
LCSR FFs with correlation matrix for low q^2 region only

Amplitude helicity suppression at kinematical endpoint

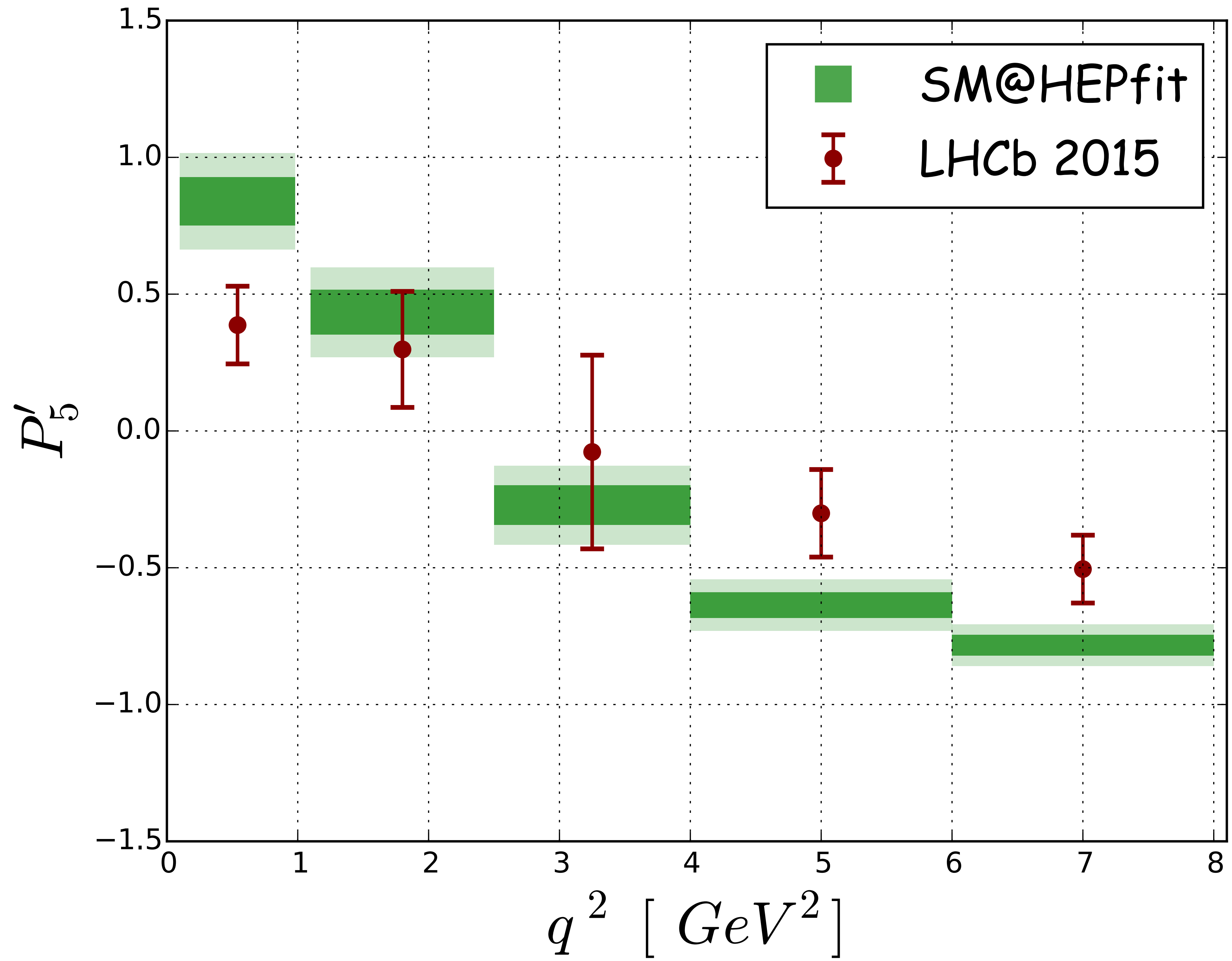
Khodjamirian et al. constraint **for "all" q^2**

HEPfit
“Full” Khodj.





WHAT ABOUT THE OPTIMIZED OBSERVABLES … ?



Anomaly strikes back in P'_5 …!

COMPARING THE FITS

To **compare** *different scenarios we used the* **information criterion**, defined as

$$IC = -2\overline{\log L} + 4\sigma^2_{\log L}$$

The **first term** *measures the* **goodness of the fit**, *while the* **second** *is a* **penalty term** *counting the number of* **effective parameters**

Better models have smaller IC

No constraints *on power corrections:*	IC = 72
Khodjamirian et al. only for $q^2 \lesssim 1$ **GeV^2**:	IC = 78
Same as above, but **no q^4 term**:	IC = 81
Khodjamirian et al. for **all q^2**:	IC = 111

FINAL REMARKS

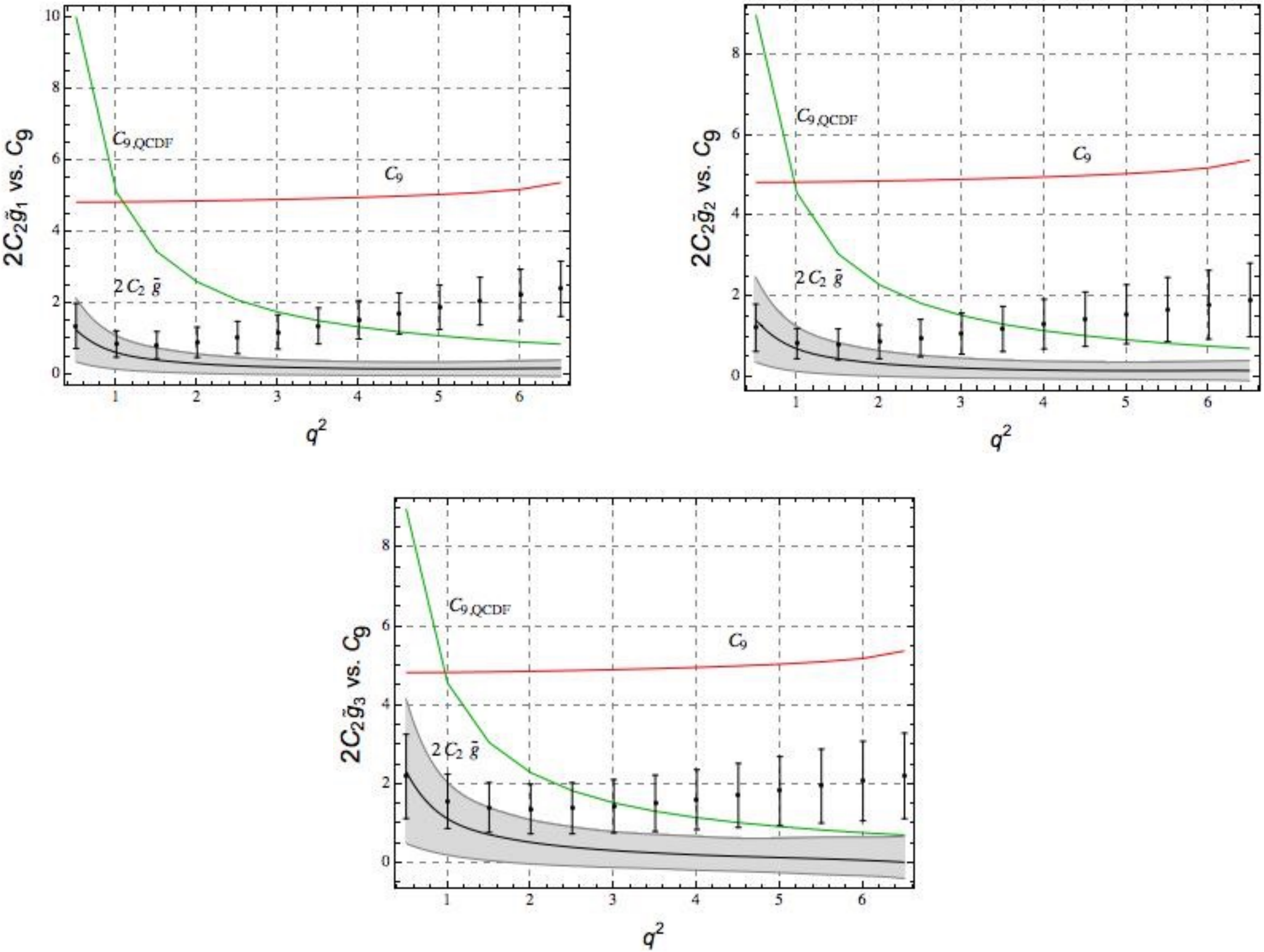
In our ***Bayesian analysis*** *of B to K* μμ we* ***do not hit the anomalies****,* ***provided we use the current LCSR estimates*** *for the non-factorizable hadronic contribution only in the reliable regime, i.e.* $\boldsymbol{q^2 \lesssim 1\ \mathrm{GeV}^2}$

The extracted hadronic contribution displays an ***expected growth*** *in respect to the current LCSR estimates for* ***higher*** $\boldsymbol{q^2}$*, showing a* ***behaviour that would hardly resemble*** *contribution mainly due to* ***NP***

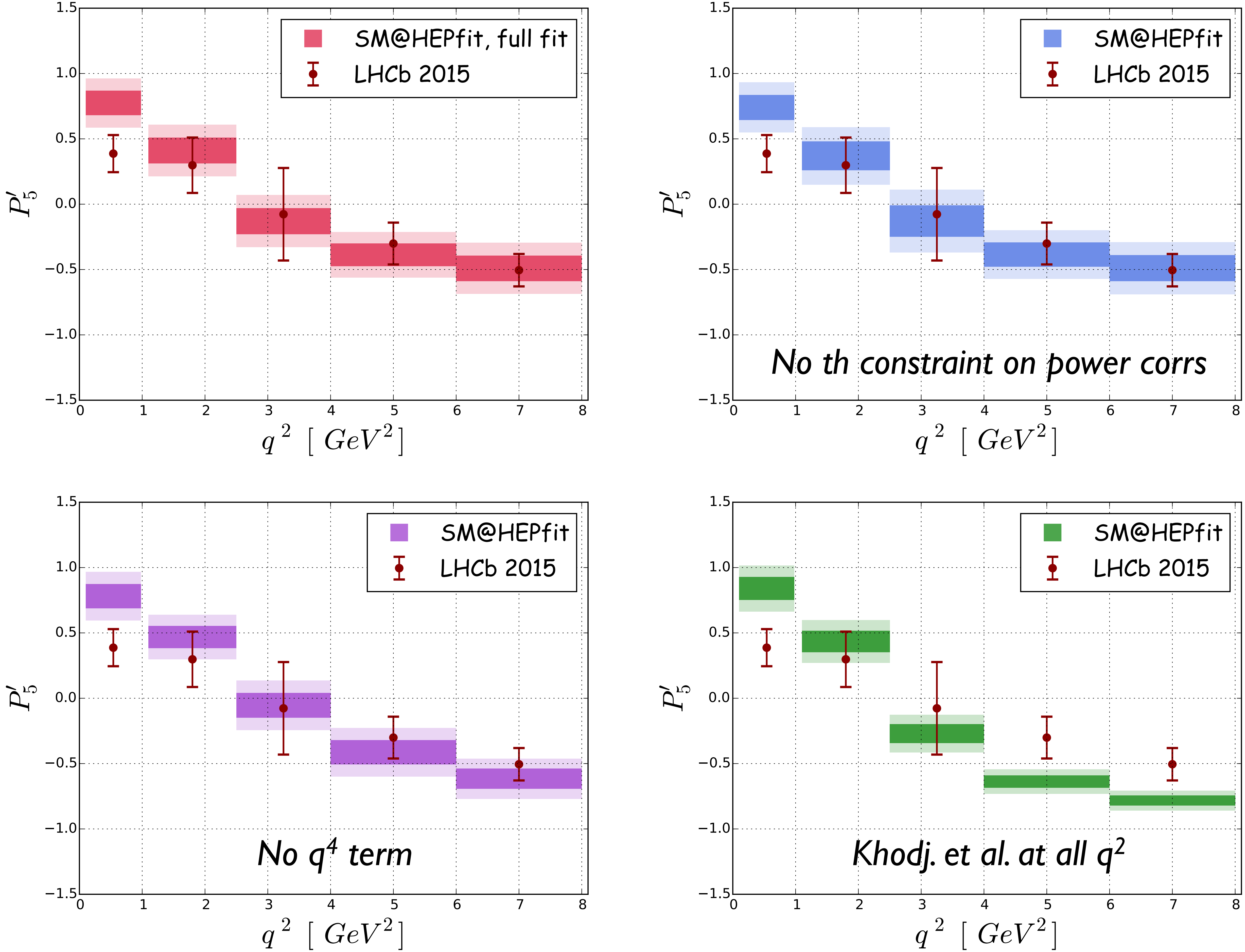
The ***Data-Driven*** *scenario shows that* ***experimental information*** *at hand is* ***not sufficient*** *to discriminate a definitive* q^2 *behaviour*

We need either ***more statistics from LHCb data*** *or a* ***theoretical breakthrough*** *in the* ***estimate of non-factorizable hadronic contribution*** *before being able to probe NP looking at B to K* μμ alone*

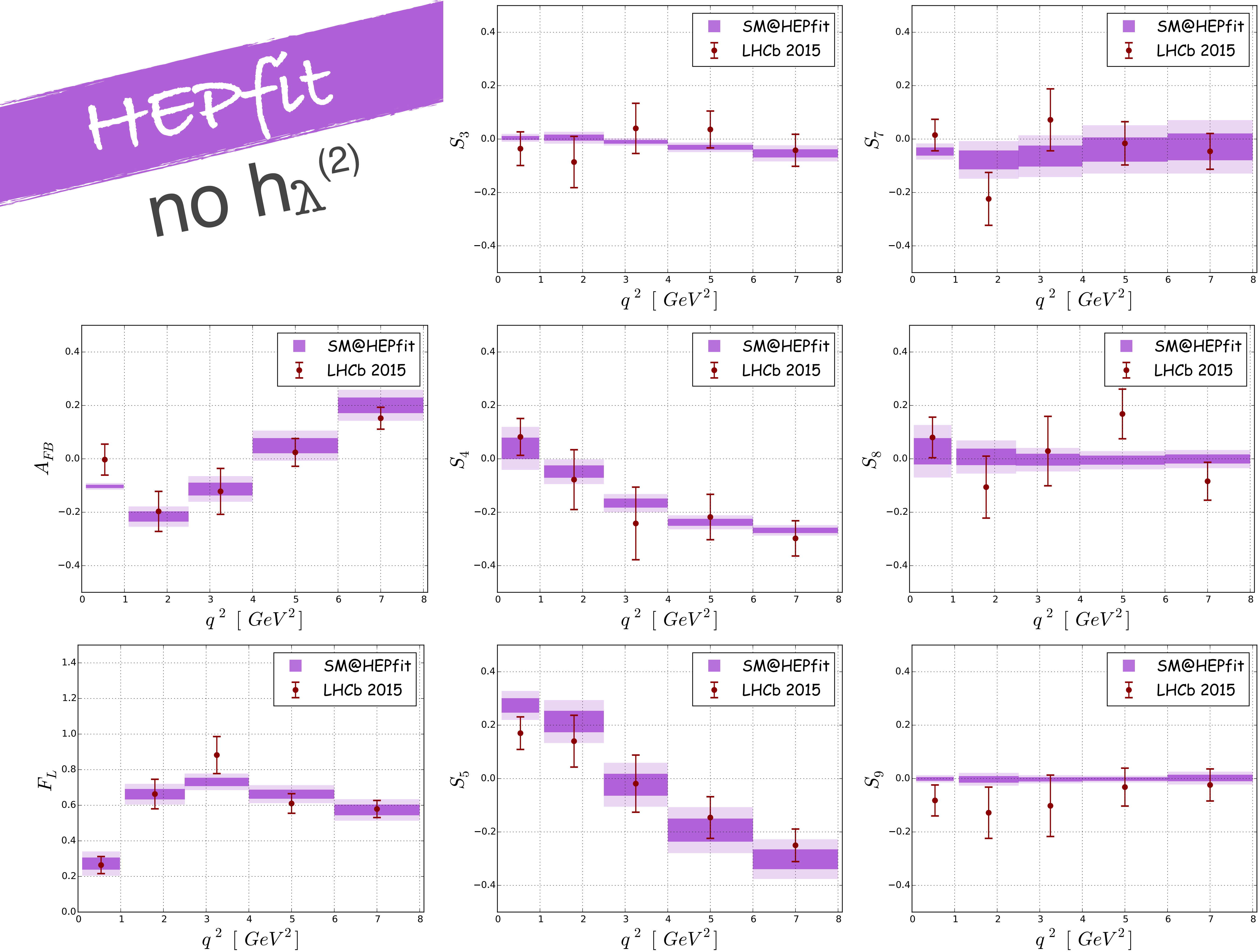
Backup slides



$2C_2\tilde{g}_1$ vs. C_9
$C_{9,\text{QCDF}}$
C_9
$2\,C_2\;\tilde{g}$
q^2
$2C_2\tilde{g}_2$ vs. C_9
$C_{9,\text{QCDF}}$
C_9
$2\,C_2\;\tilde{g}$
q^2
$2C_2\tilde{g}_3$ vs. C_9
$C_{9,\text{QCDF}}$
C_9
$2\,C_2\;\tilde{g}$
q^2



SM@HEPfit, full fit
LHCb 2015
P_5'
q^2 [GeV^2]
SM@HEPfit
LHCb 2015
No th constraint on power corrs
P_5'
q^2 [GeV^2]
SM@HEPfit
LHCb 2015
No q^4 term
P_5'
q^2 [GeV^2]
SM@HEPfit
LHCb 2015
Khodj. et al. at all q^2
P_5'
q^2 [GeV^2]


HEPfit
no $h_\lambda^{(2)}$
SM@HEPfit
LHCb 2015
S_3
S_7
A_{FB}
S_4
S_8
F_L
S_5
S_9
q^2 [GeV^2]