Universität Zürich[UZH]

Experimental approaches to disentangle long-distance contributions to $b \to s\, l^+ l^-$

R. Silva Coutinho + A. Mauri + K. Petridis

Universität Zürich - SNF Ambizione

7th Workshop on Rare semileptonic B decays
September 4th, 2019

Funded by

FNSNF Swiss National Science Foundation

From BFs to the “(in)famous” P’$_5$

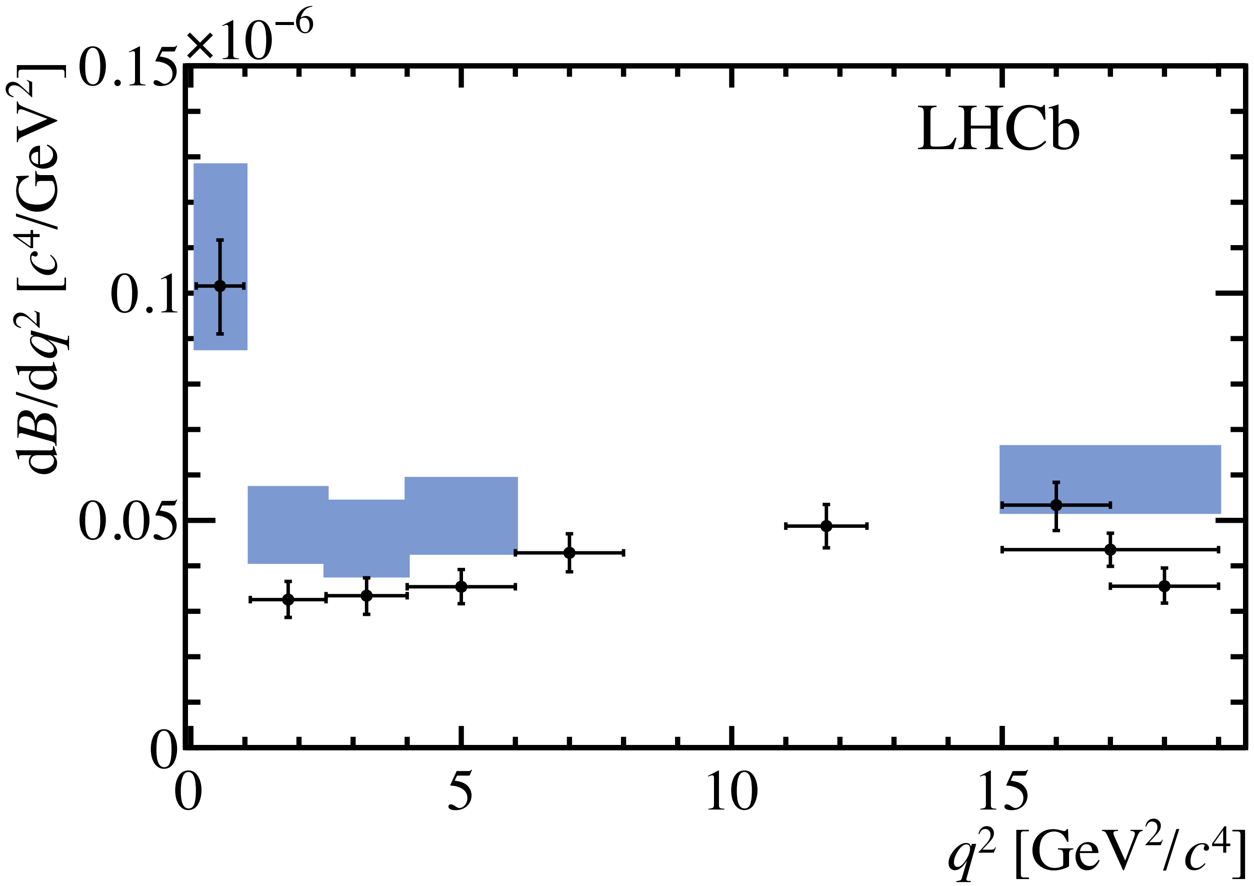
[JHEP 04 (2017) 142, JHEP 02 (2016) 104]

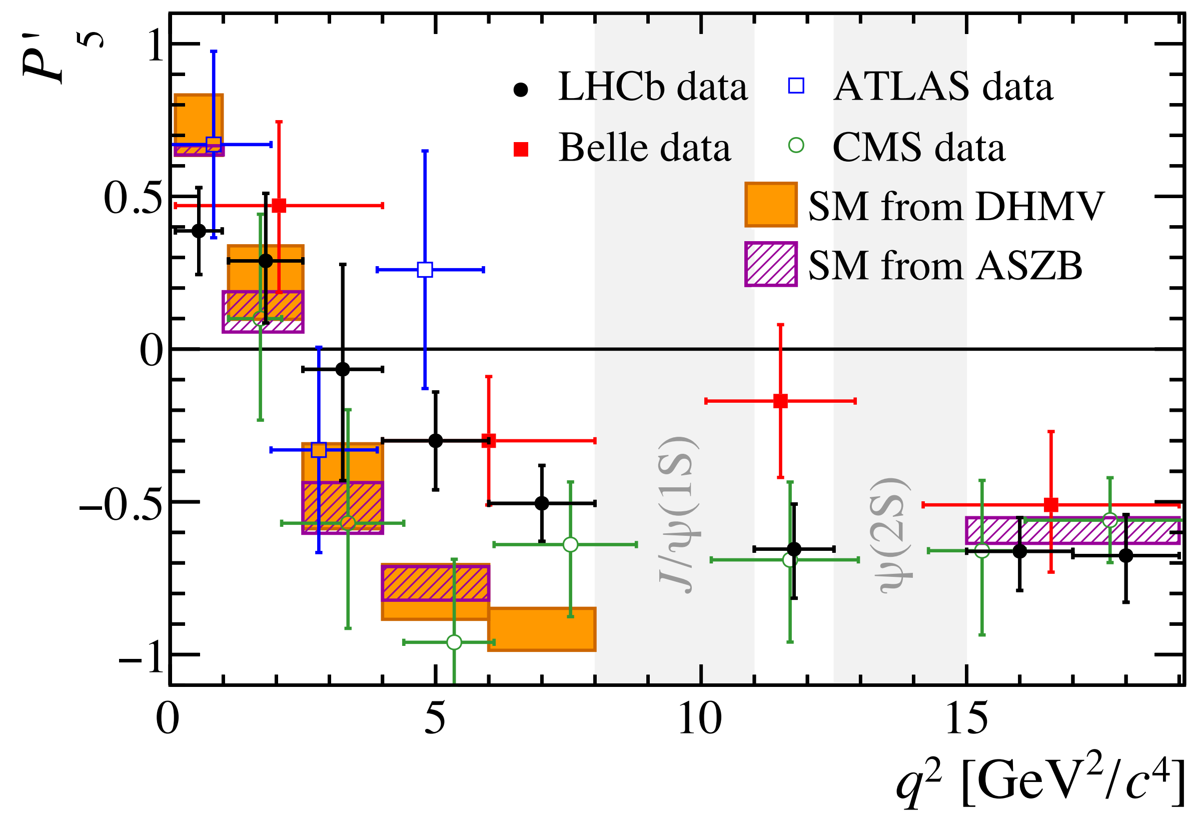
Coherent picture for muonic channels indicating tensions with the SM

Key element: how to reliably model the q^2 distribution with long-distance effects?

$$P_5' = \frac{S_5}{\sqrt{F_L(1-F_L)}}$$

[JHEP 1204 (2012) 104]

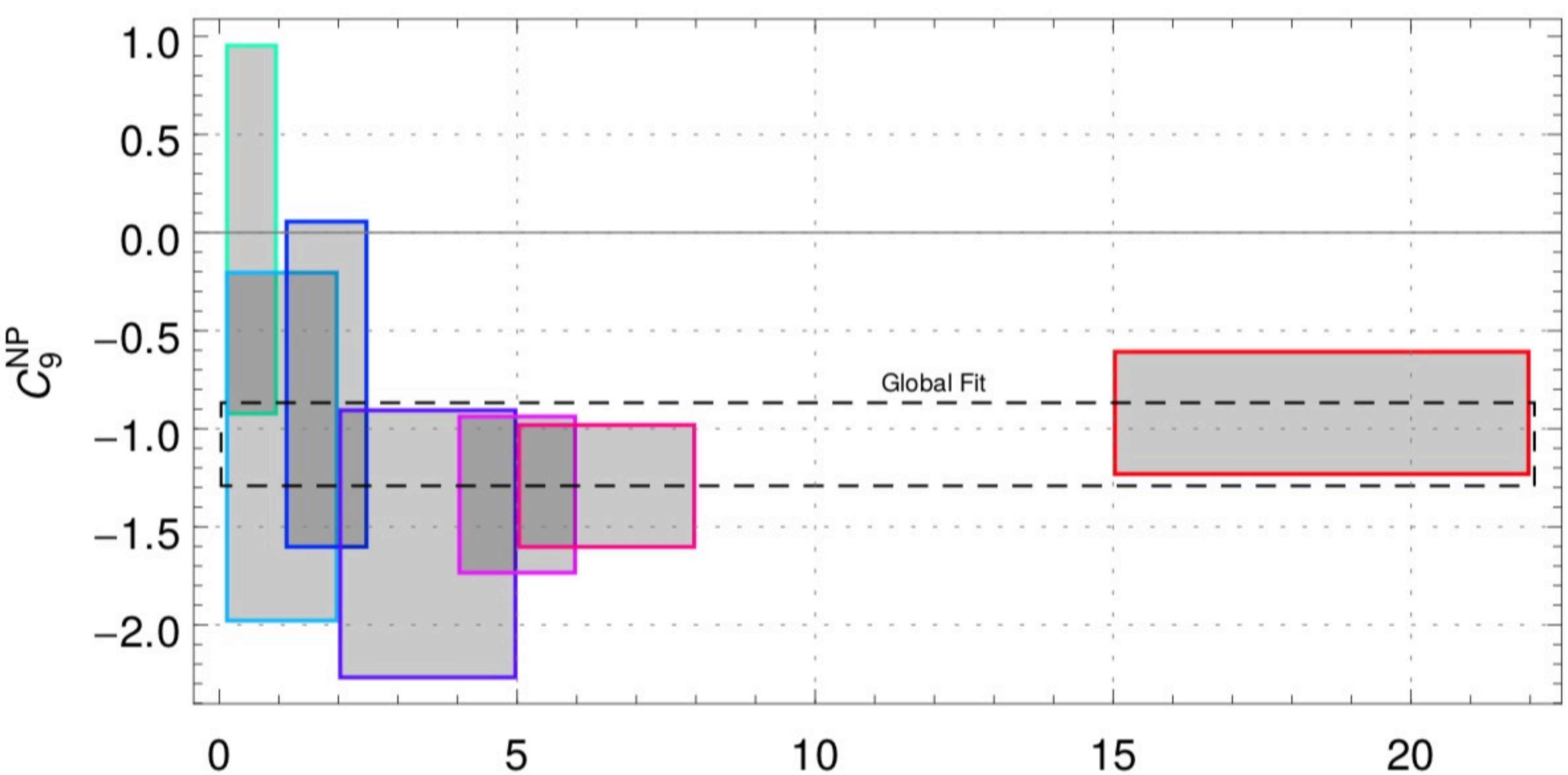




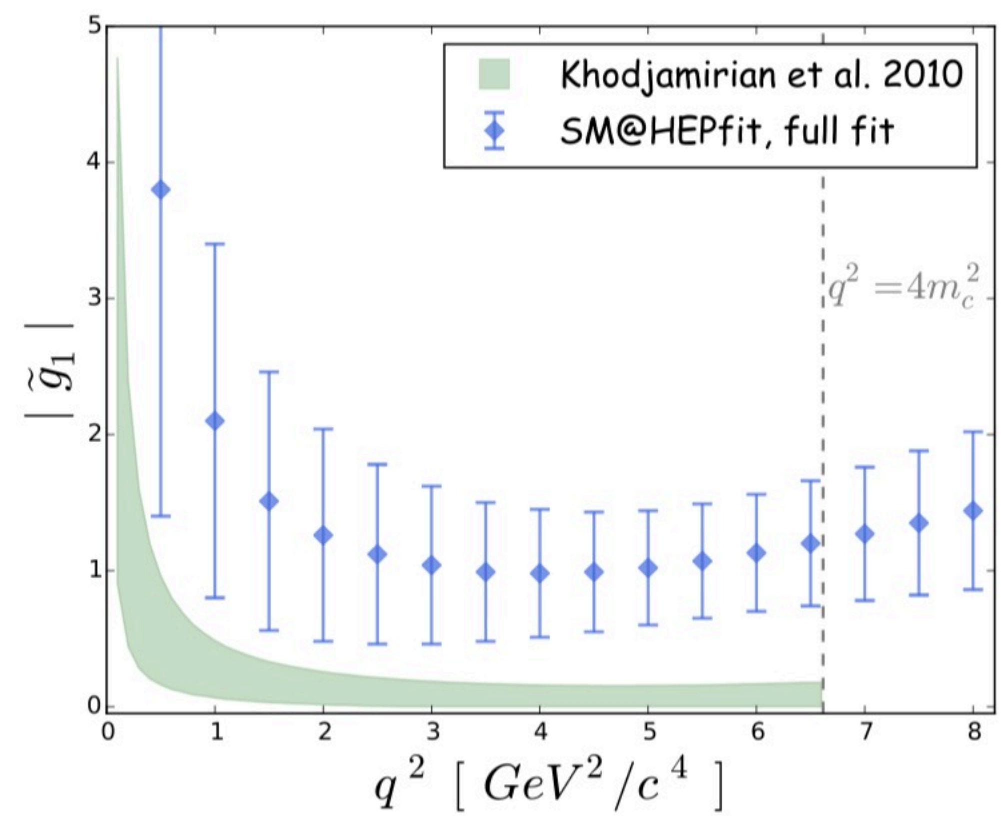
What we can learn from data?

If we are underestimating $c\bar{c}$ contributions then naively expect to see the shift in C_9 get larger closer to the narrow charmonium resonances.

[Decotes-Genon et al JHEP 06 (2016) 092]



[M. Chiuchini et al JHEP 06 (2016) 116]



No clear evidence for a rise in the data (but more data is needed)

What comes Next?

LHCb results: `Run-II` dataset

Direct fits to Wilson Coefficients

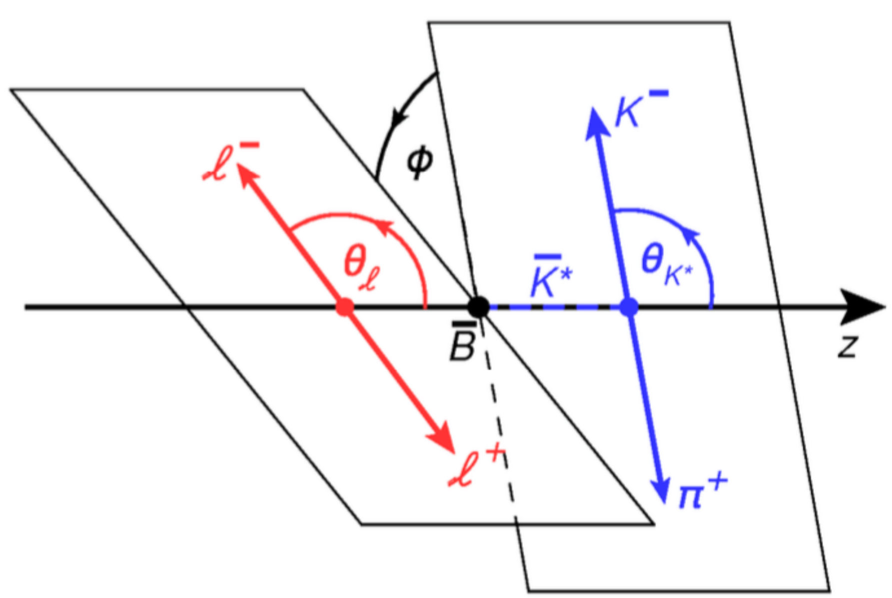
[Eur. Phys. J. C (2018) 78: 453]
[Eur. Phys. J. C, 78 6 (2018) 451, arXiv:1805.06378]

What about electrons?

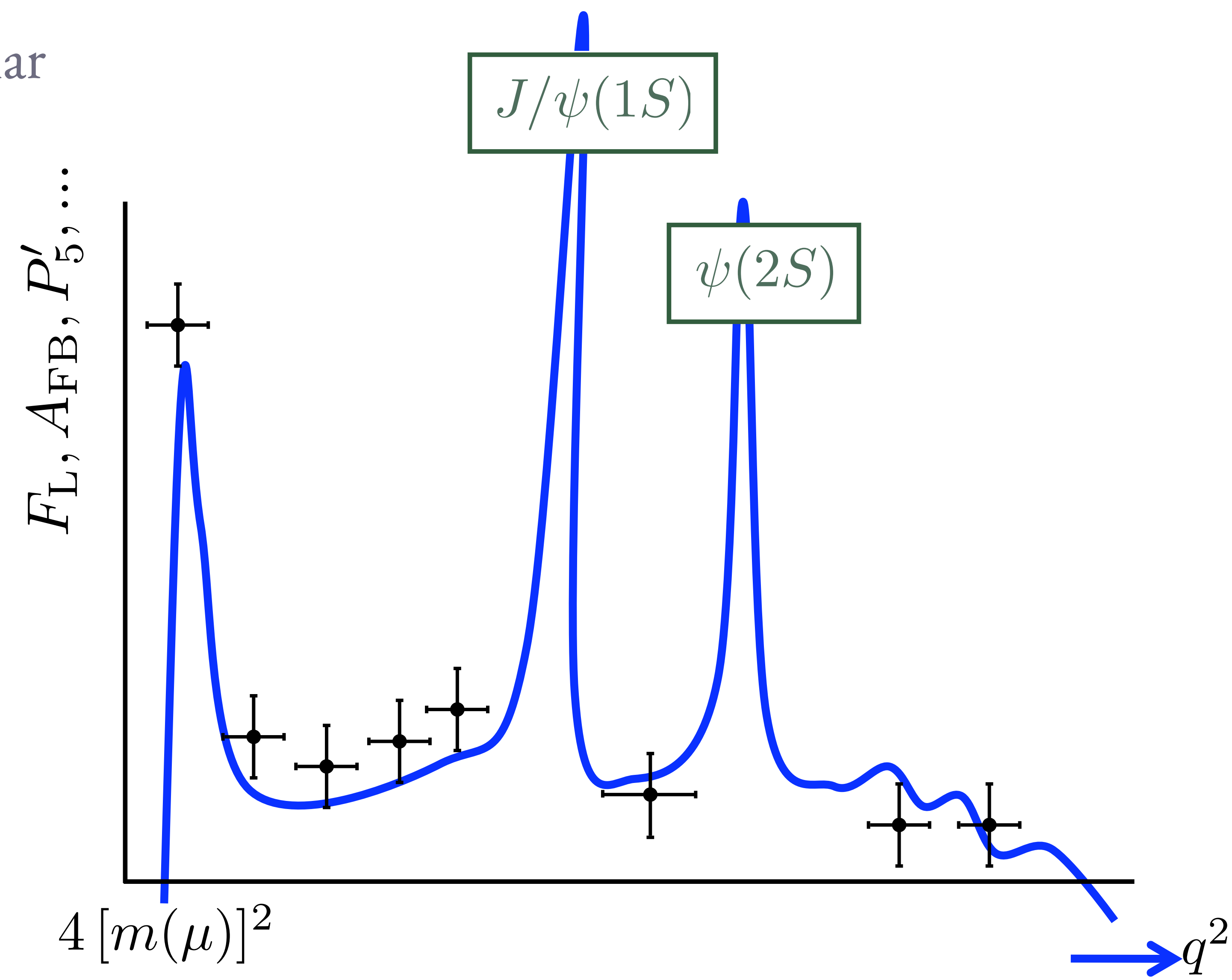
[Phys. Rev. D 99, 013007 (2019)]

The rare decay $B^0 \rightarrow K^{*0}[K^+\pi^-]\mu^+\mu^-$

Large number of observables: BF fractions, CP asymmetries and angular observables (5-dimension)



[Binned approach]



di-muon invariant mass squared, q^2

Amplitude analyses of $B^0 \to K^{*0}\mu^+\mu^-$

Observables integrated in q^2 bins are largely theory independent, so important information is lost

- Determination of long-distance contributions
- Improve sensitivity in the measurement

Two approaches at LHCb, e.g. for $B^0 \to K^{*0}\mu^+\mu^-$ ($\lambda = \perp, \parallel, 0$):

$$\mathcal{A}_\lambda^{(\ell)\,L,R} = \mathcal{N}_\lambda^{(\ell)} \left\{ \boxed{(C_9^{(\ell)} \mp C_{10}^{(\ell)})}\boxed{\mathcal{F}_\lambda(q^2)} + \frac{2m_b M_B}{q^2}\left[\boxed{C_7^{(\ell)}}\boxed{\mathcal{F}_\lambda^T(q^2)} - 16\pi^2 \frac{M_B}{m_b}\boxed{\mathcal{H}_\lambda(q^2)}\right]\right\}$$

- Wilson coefficients [observables]
- Form factors
- Non-local hadronic contributions

["Isobar"-like approach]

LHCb, Eur. Phys. J. C (2017) 77: 161,
Blake et al, Eur. Phys. J. C (2018) 78: 453

[z-expansion approach]

Eur. Phys. J. C, 78 6 (2018) 451,
arXiv:1805.06378

Guinea pig (isobar): $B^+ \rightarrow K^+\mu^+\mu^-$ decays

[EPJ C77 (2017) 161]

Fit to full di-muon mass spectrum including: ρ, ω, φ, Jψ, ψ(2S), ψ(3770), ψ(4040), ψ(4160), ψ(4415)

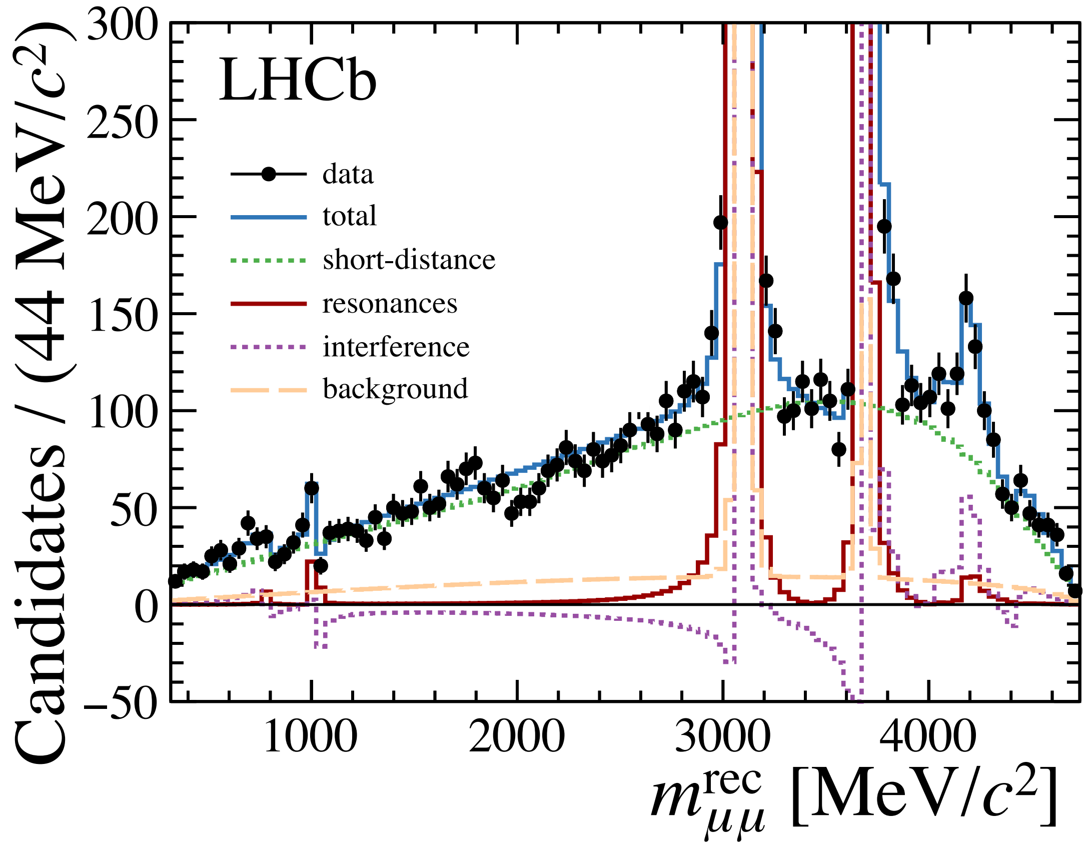
$$\frac{\mathrm{d}\Gamma}{\mathrm{d}q^2} = \frac{G_F^2\alpha^2|V_{tb}V_{ts}^*|^2}{128\pi^5}|\boldsymbol{k}|\beta\left\{\frac{2}{3}|\boldsymbol{k}|^2\beta^2\left|\mathcal{C}_{10}f_+(q^2)\right|^2 + \frac{4m_\mu^2(m_B^2-m_K^2)^2}{q^2m_B^2}\left|\mathcal{C}_{10}f_0(q^2)\right|^2 + |\boldsymbol{k}|^2\left[1-\frac{1}{3}\beta^2\right]\left|\mathcal{C}_9f_+(q^2)+2\mathcal{C}_7\frac{m_b+m_s}{m_B+m_K}f_T(q^2)\right|^2\right\}$$

Breit-Wigners

$$\mathcal{C}_9^{\mathrm{eff}} = \mathcal{C}_9 + \sum_j \eta_j e^{i\delta_j} A_j^{\mathrm{res}}(q^2)$$

Magnitude and phase of each resonance relative to C₉

Fit suggested J/ψ has little impact outside the region



[isobar] approach in a nutshell

[EPJ C78 (2018) 453]

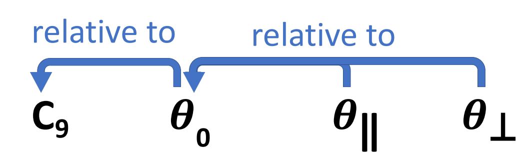
$$\mathcal{A}_\lambda^{(\ell)\,L,R} = \mathcal{N}_\lambda^{(\ell)} \left\{ (C_9^{(\ell)} \mp C_{10}^{(\ell)})\mathcal{F}_\lambda(q^2) + \frac{2m_b M_B}{q^2}\left[C_7^{(\ell)} \mathcal{F}_\lambda^T(q^2) - 16\pi^2 \frac{M_B}{m_b} \mathcal{H}_\lambda(q^2) \right] \right\}$$

$\mathcal{G}_\lambda(q^2)$

$$\mathcal{G}_0 = \frac{m_b}{m_B + m_{K^*}} T_{23}(q^2) \zeta^0 e^{i\omega^0} + A_{12}(q^2) \sum_j \eta_j^0 e^{i\theta_j^0} A_j^{\rm res}(q^2),$$

$$\mathcal{G}_\parallel = \frac{2m_b}{q^2} T_2(q^2) \zeta^\parallel e^{i\omega^\parallel} + \frac{A_1(q^2)}{m_B - m_{K^*}} \sum_j \eta_j^\parallel e^{i\theta_j^\parallel} A_j^{\rm res}(q^2),$$

$$\mathcal{G}_\perp = \frac{2m_b}{q^2} T_1(q^2) \zeta^\perp e^{i\omega^\perp} + \frac{V(q^2)}{m_B + m_{K^*}} \sum_j \eta_j^\perp e^{i\theta_j^\perp} A_j^{\rm res}(q^2),$$



Magnitude and phase of non-local contribution to dipole form factor

Sum over all resonances

Magnitude and phase for each resonance

BW Amplitudes

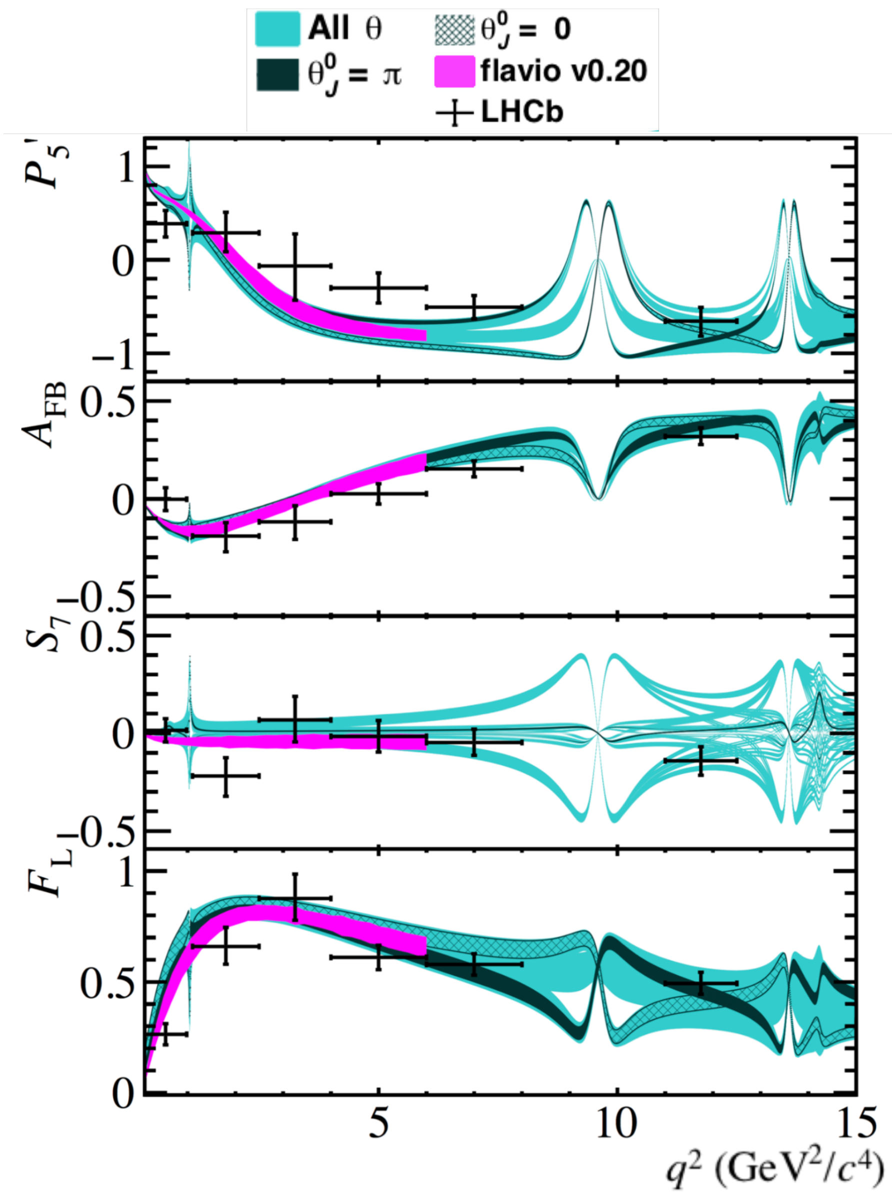
e.g.: $\rho^0, \phi(1020), J/\psi, \psi(2S), \psi(3770), \psi(4040), \psi(4160)$

Existing angular analyses and BFs of $B \to VK^{*0}$ can constrain two phases and all magnitudes

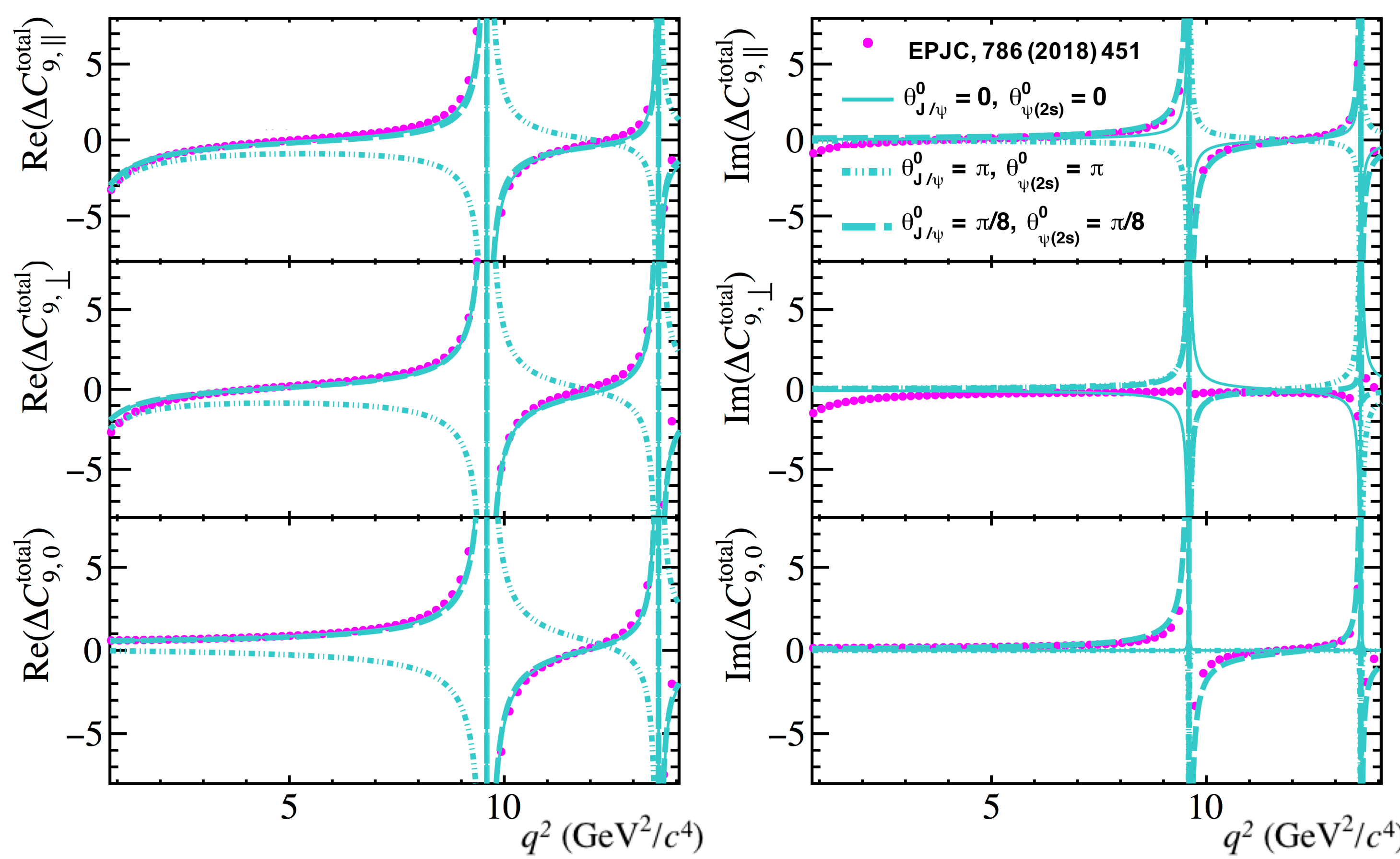
[isobar] visualising the model

[EPJ C78 (2018) 453]

Angular observables can also discriminate between different phases



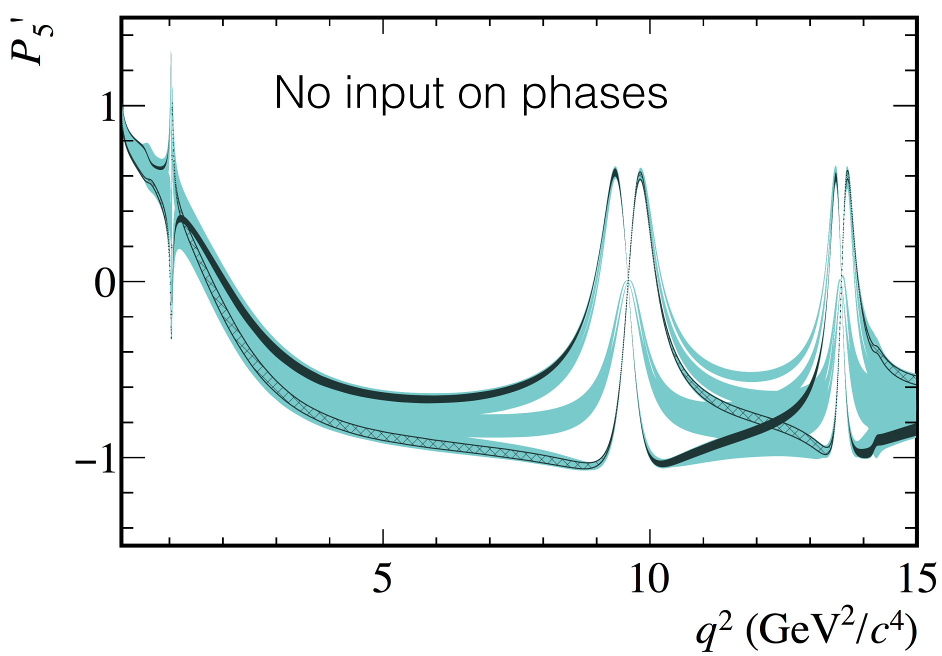
Useful validation: compatibility between "Isobar" and z-parametrisation" approaches

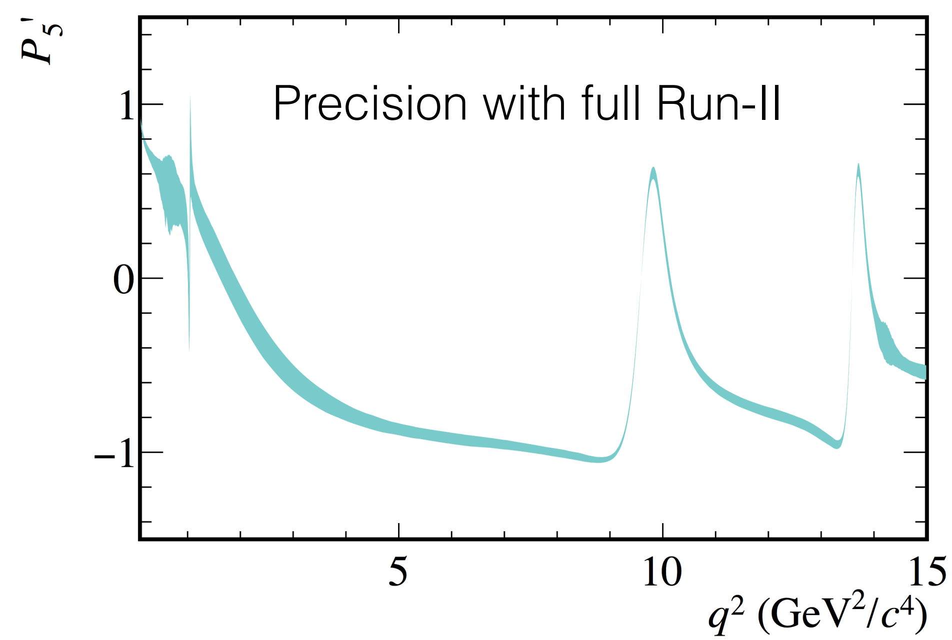


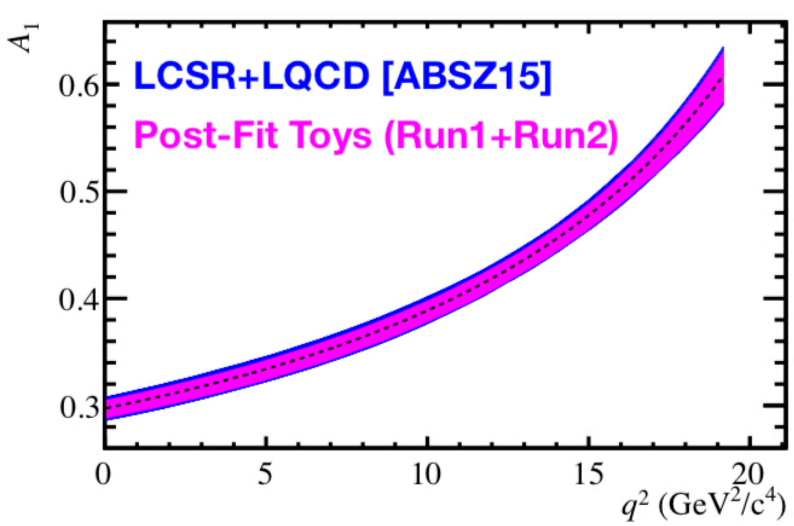
[isobar] controlling hadronic paramaters

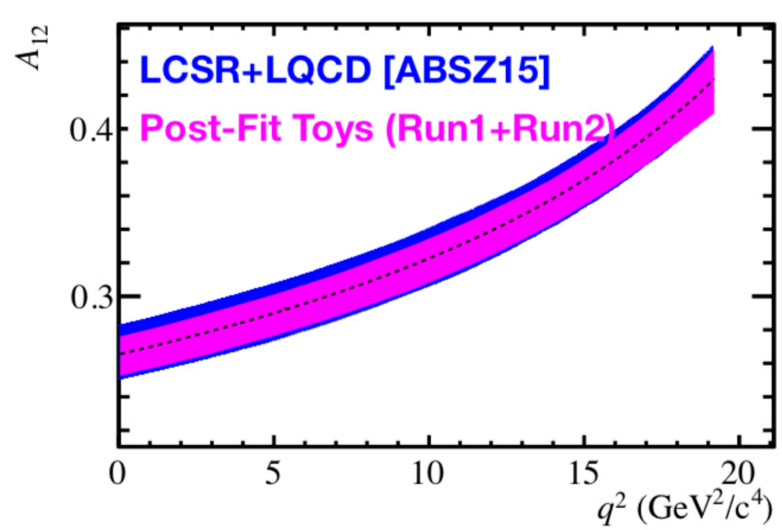
[EPJ C78 (2018) 453] [Preliminary, U. Egede, M. Hecker, P. Owen, G. Pomery, K. Petridis]

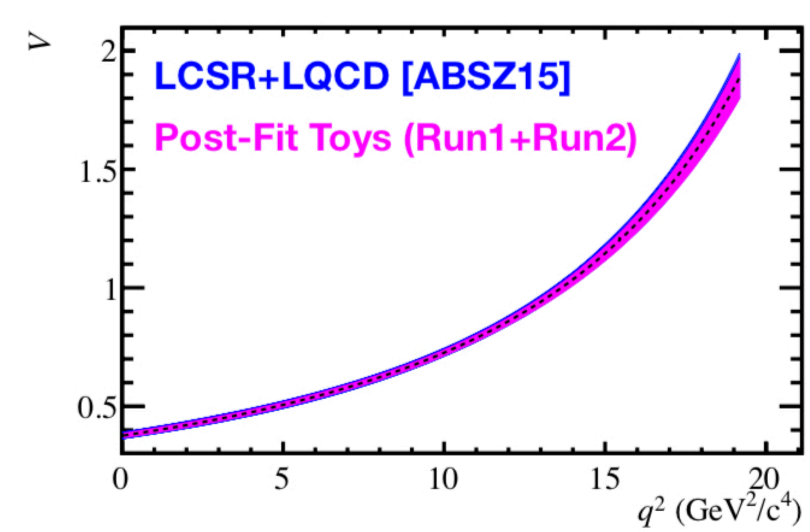
Run-II dataset will provide strong constraint on phases, but no improvements on FFs









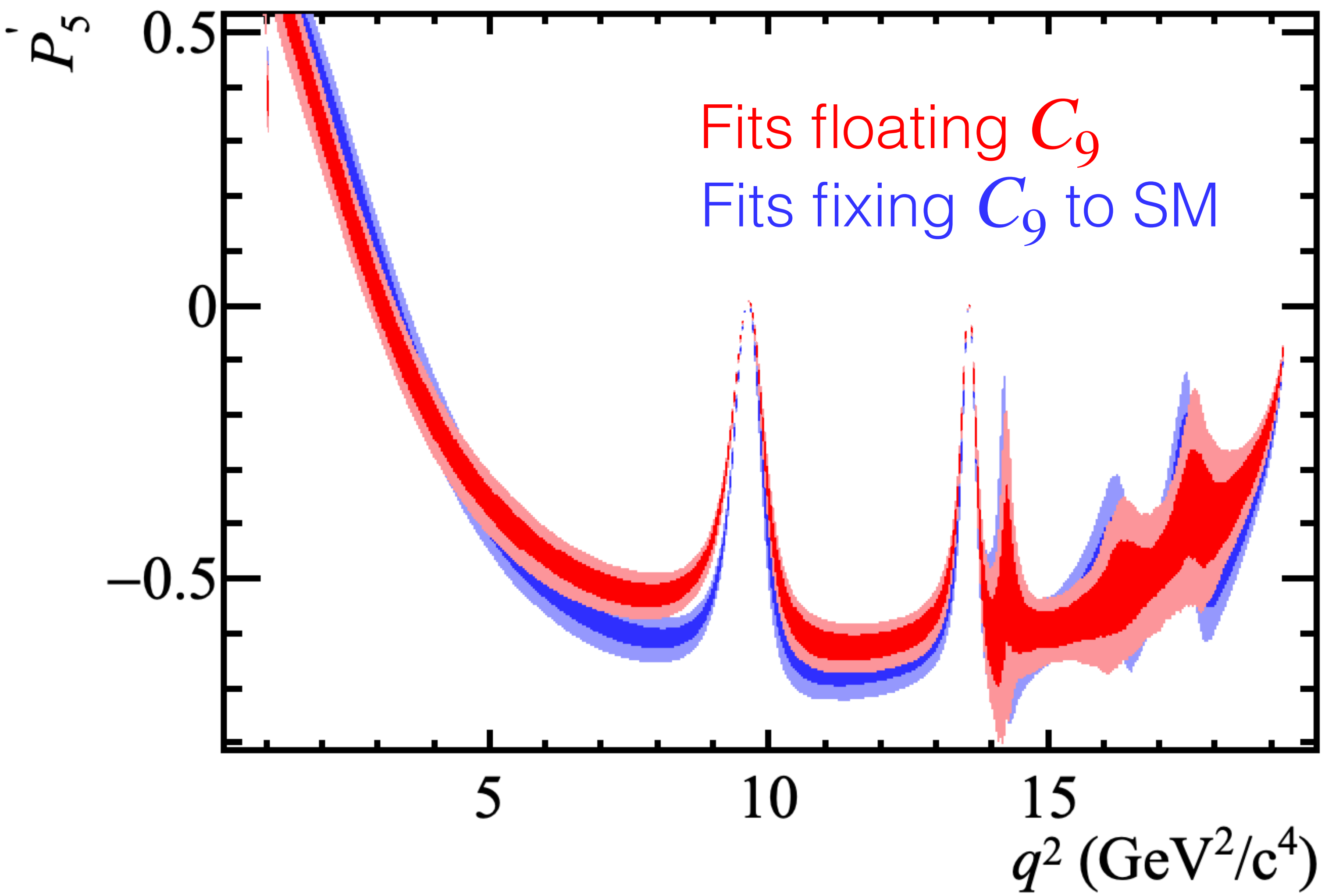


[isobar] controlling hadronic paramaters

[Preliminary, U. Egede, M. Hecker, P. Owen, G. Pomery, K. Petridis]

In the presence of New Physics, the model of non-local contribution cannot describe data with expected Run-II statistics

Generate toys with $C_9^{NP} = -1.5$



[z-parametrisation] $B^0 \to K^{*0}\mu^+\mu^-$ decays

Universität Zürich[UZH]

Parametrisation suggested in [Eur. Phys. J. C, 78 6 (2018) 451]:

$$\mathcal{A}_\lambda^{(\ell)\,L,R} = \mathcal{N}_\lambda^{(\ell)} \left\{ \boxed{(C_9^{(\ell)} \mp C_{10}^{(\ell)})} \boxed{\mathcal{F}_\lambda(q^2)} + \frac{2 m_b M_B}{q^2} \left[\boxed{C_7^{(\ell)}} \boxed{\mathcal{F}_\lambda^T(q^2)} - 16\pi^2 \frac{M_B}{m_b} \boxed{\mathcal{H}_\lambda(q^2)} \right] \right\}$$

Non-local hadronic contributions

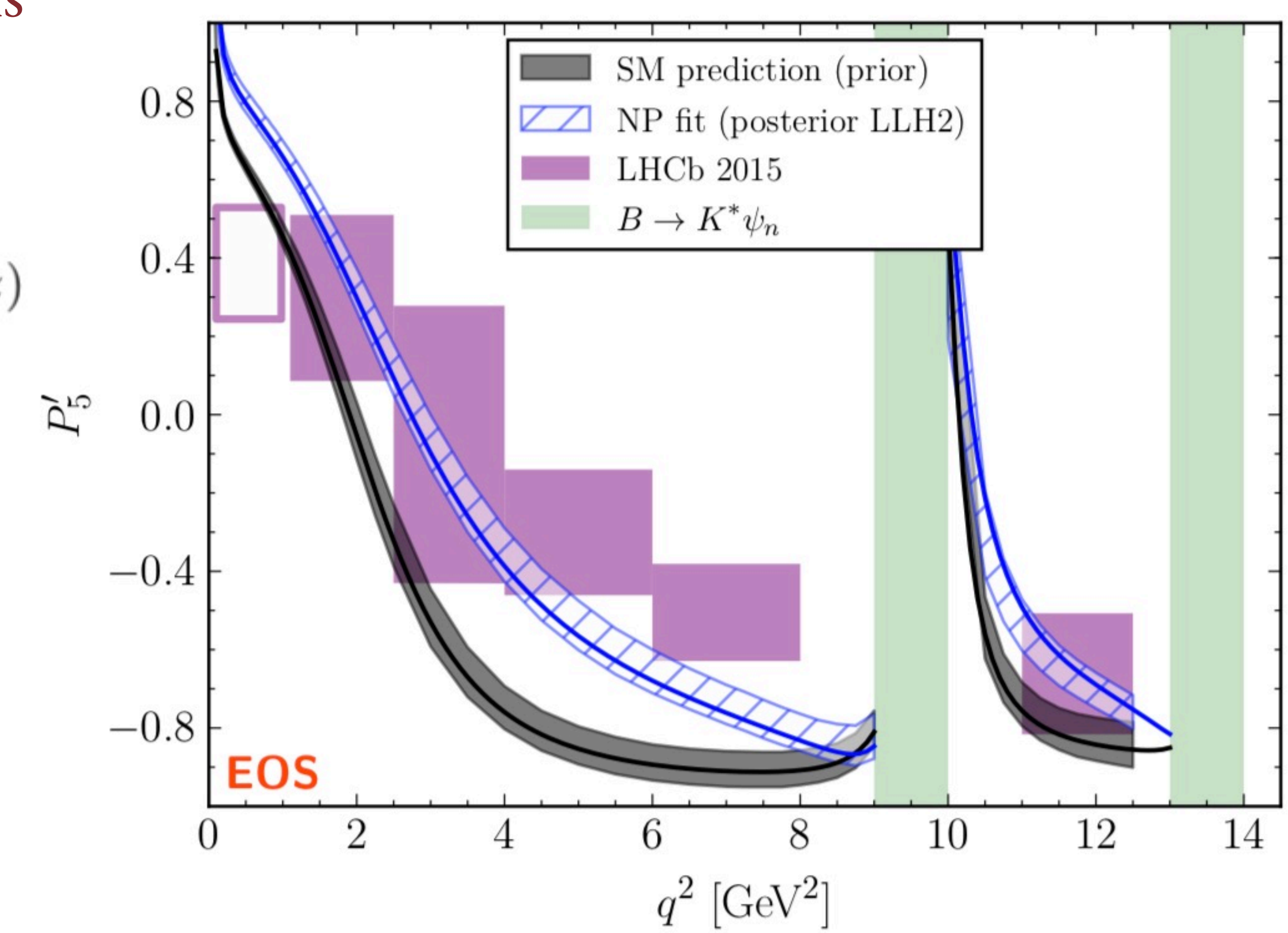
mapping: $q^2 \to z(q^2)$

$$\mathcal{H}_\lambda(z) = \frac{1 - z z_{J/\psi}^*}{z - z_{J/\psi}} \frac{1 - z z_{\psi(2S)}^*}{z - z_{\psi(2S)}} \hat{\mathcal{H}}_\lambda(z)$$

extract the poles

$$\hat{\mathcal{H}}_\lambda(z) = \left[\sum_k \alpha_k^{(\lambda)} z^k \right] \mathcal{F}_\lambda(z)$$

- Analytic within $|z|=1$
- Cut-off os series at z^2

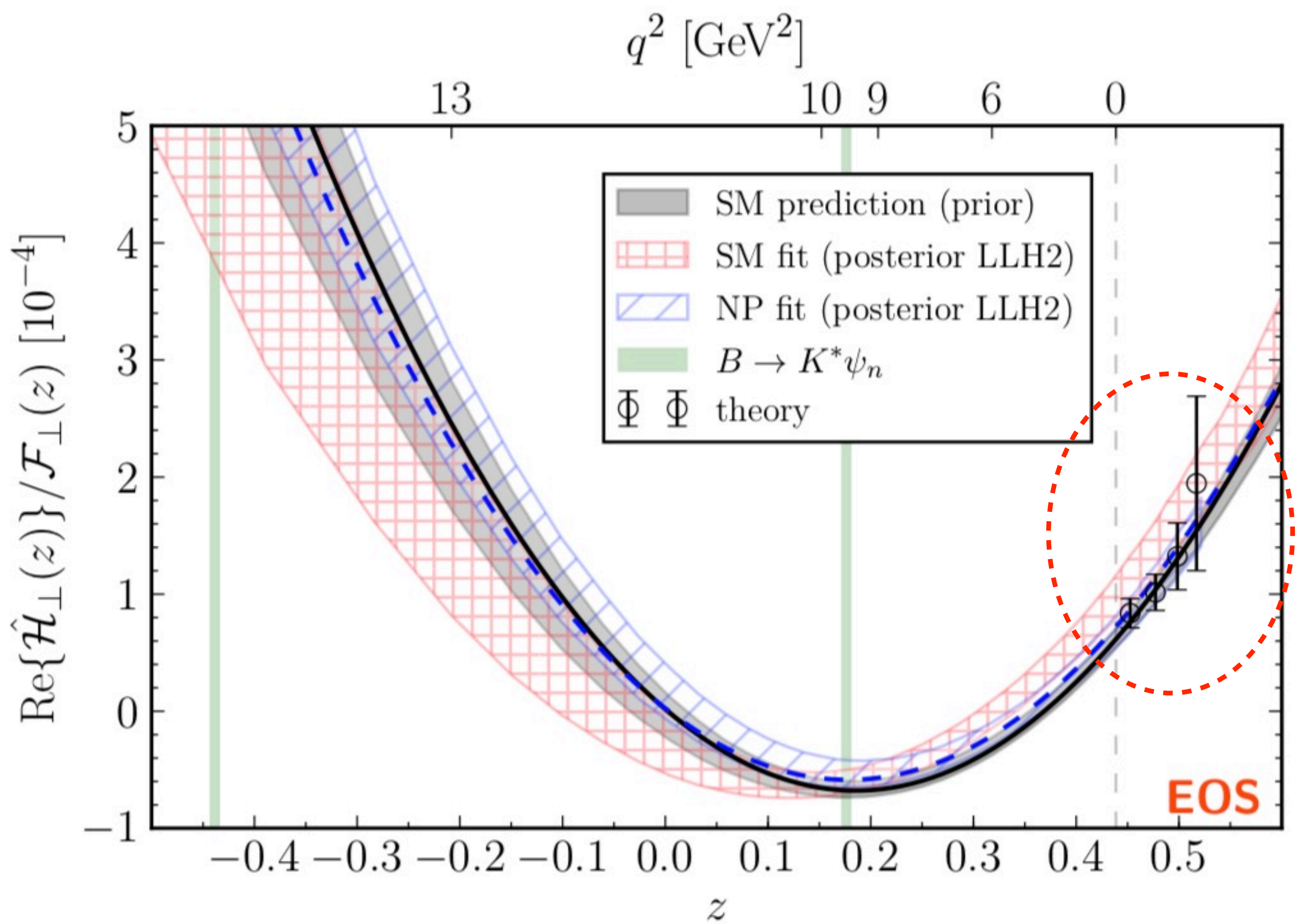


[z-parametrisation] $B^0 \to K^{*0}\mu^+\mu^-$ decays

[arXiv:1805.06378]

SM predictions from Eur. Phys. J. C, 78 6 (2018) 451 are made with a z^2 cut

[Note that the true order of z is a priori unknown - same problem is shared among other approaches]



Theory points at negative q^2

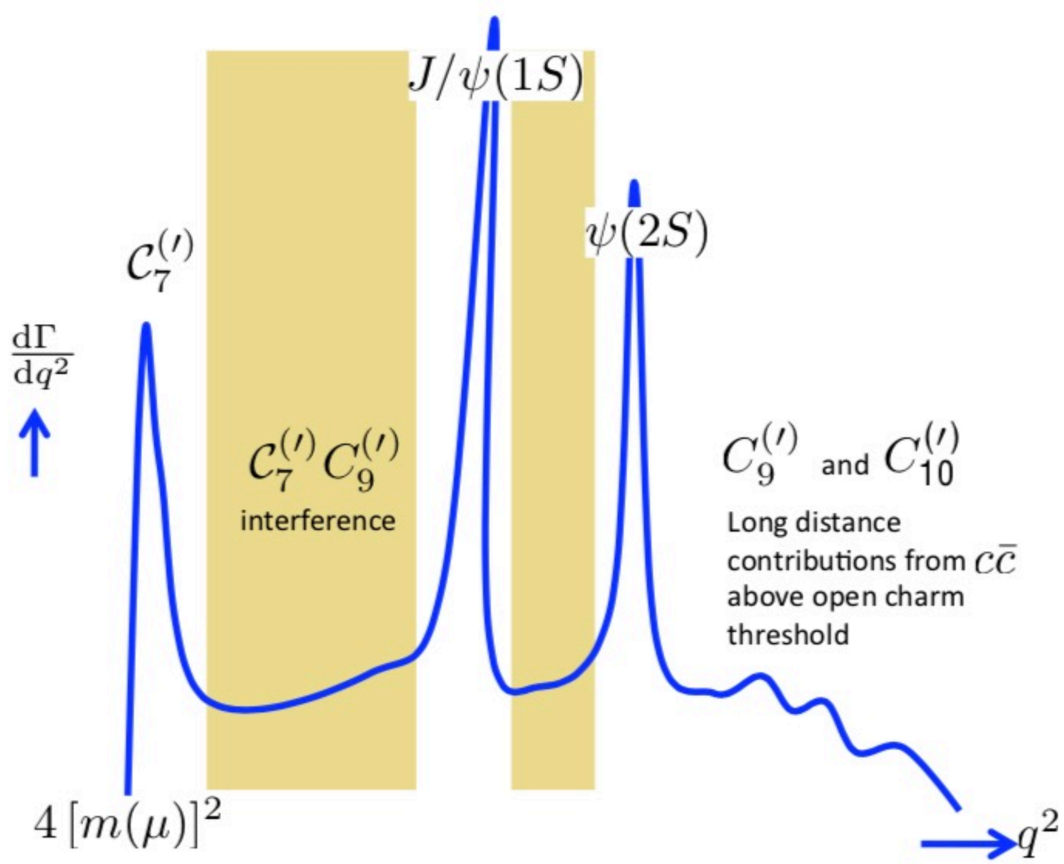
BF and angular analysis of $B \to K^*\{J/\psi, \psi(2S)\}$decays (3 amplitudes + 2 relative phases)

[z-parametrisation] $B^0 \to K^{*0}\mu^+\mu^-$ decays

[arXiv:1805.06378]

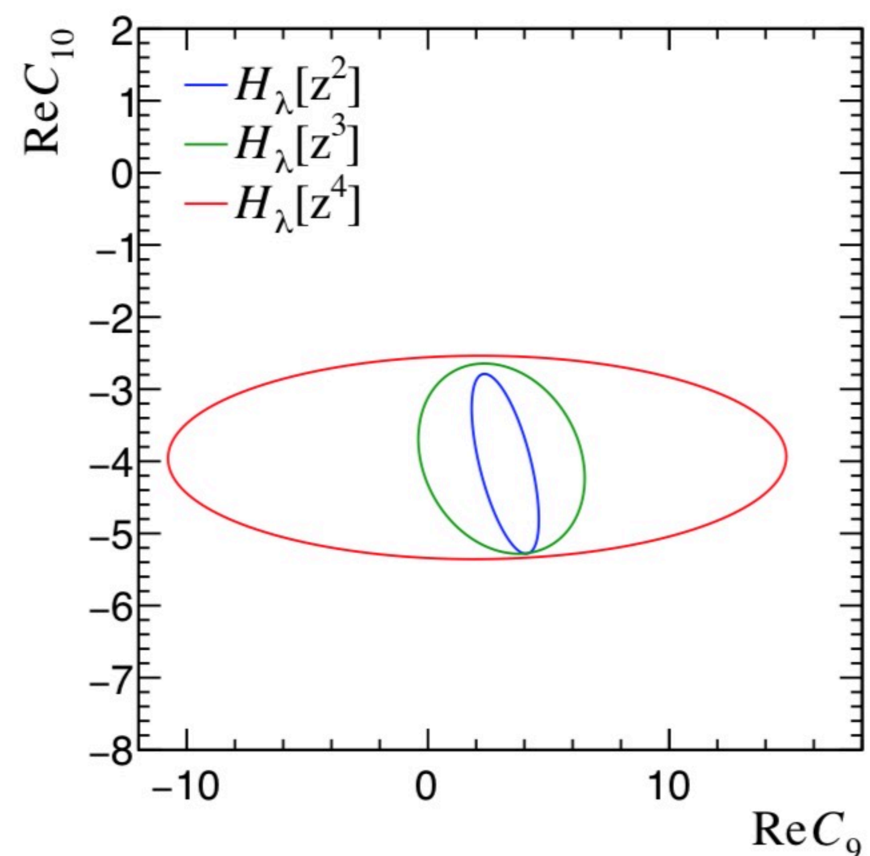
First attempt to study the effect of the theory constraints cut-off

- Signal yield related to the BR
- CKM/FF are floating/gaussian constrained parameters and **H are free**



[1.1, 9.0] & [10.0, 13.0] GeV^2

Strong dependence on the cut-off of the *z*-expansion…



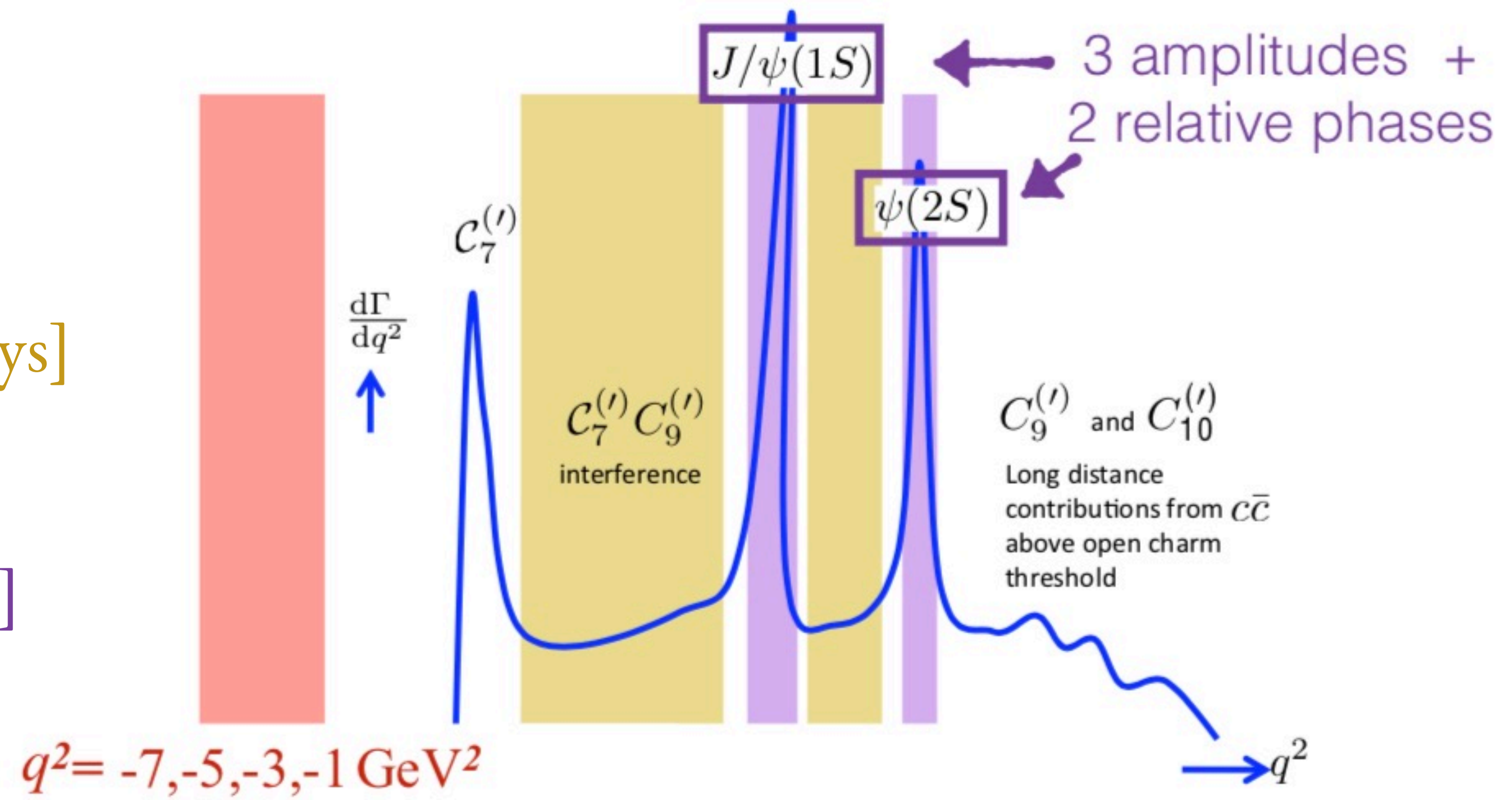
[z-parametrisation] $B^0 \to K^{*0}\mu^+\mu^-$ decays

Combined amplitude fit:

[semi-muonic $B \to K^*\mu\mu$ decays]

[theory points at negative q^2]

[hadronic $B \to K^*\{J/\psi, \psi(2S)\}$]



	LHCb Upgrade [50 fb^{-1}]	
	Re C_9^{NP} mean	Re C_9^{NP} sigma
z^2 fit	-0.996 ± 0.003	0.060 ± 0.002
z^3 fit	-1.015 ± 0.006	0.124 ± 0.004
z^4 fit	-1.012 ± 0.007	0.146 ± 0.005
z^5 fit	-0.983 ± 0.008	0.157 ± 0.006

- unbiased central value
- statistical uncertainty slightly increasing
  - effect strongly mitigated by the introduction of the theory constraints

studying the behaviour of the series expansion at different order allows to access in a quantitative way this model-dependency

[z-parametrisation] $B^0 \to K^{*0}\mu^+\mu^-$ decays

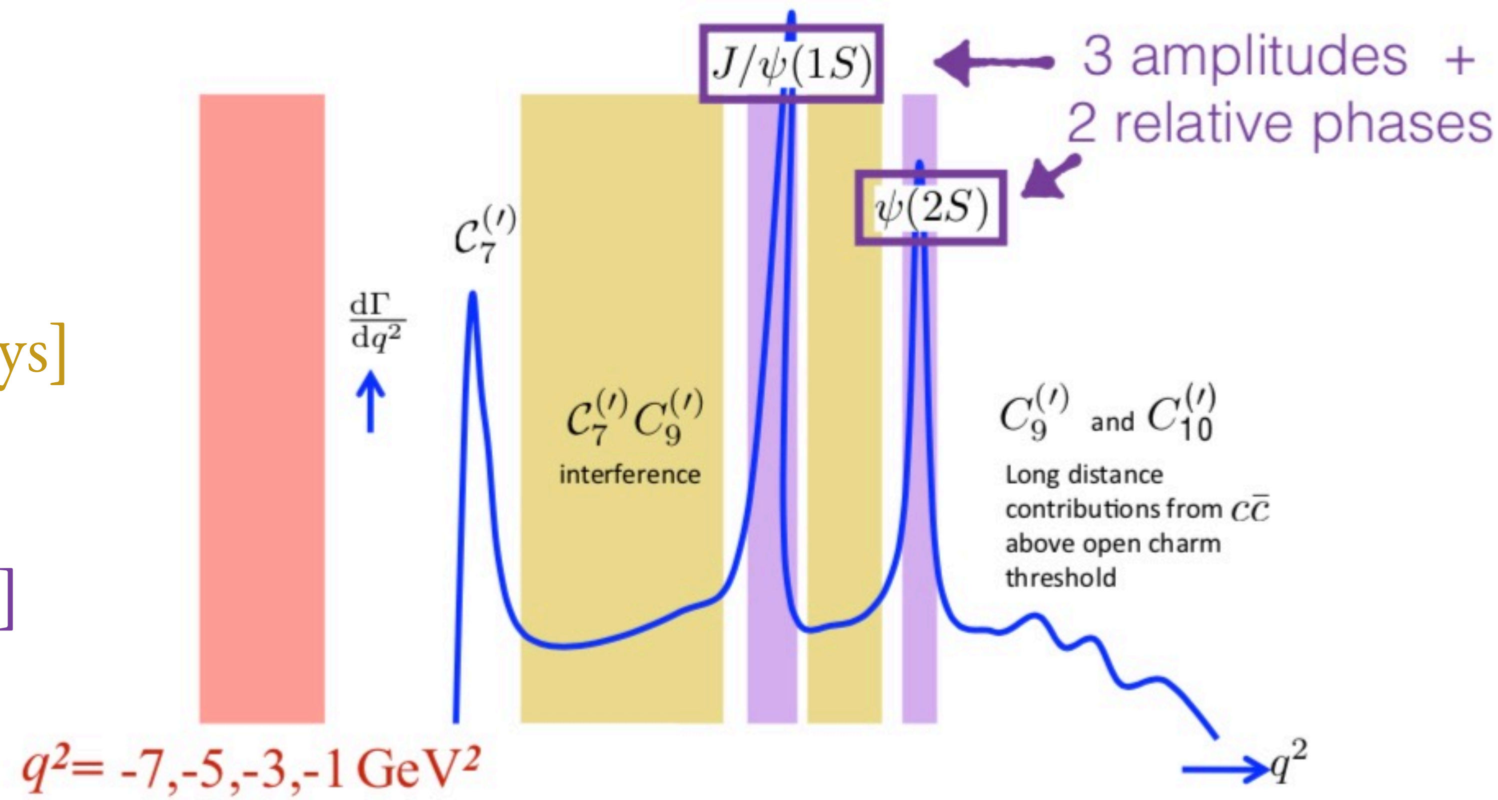
Universität Zürich[UZH]

Combined amplitude fit:

[semi-muonic $B \to K^*\mu\mu$ decays]

[theory points at negative q^2]

[hadronic $B \to K^*\{J/\psi, \psi(2S)\}$]



Generating at z^4 order:

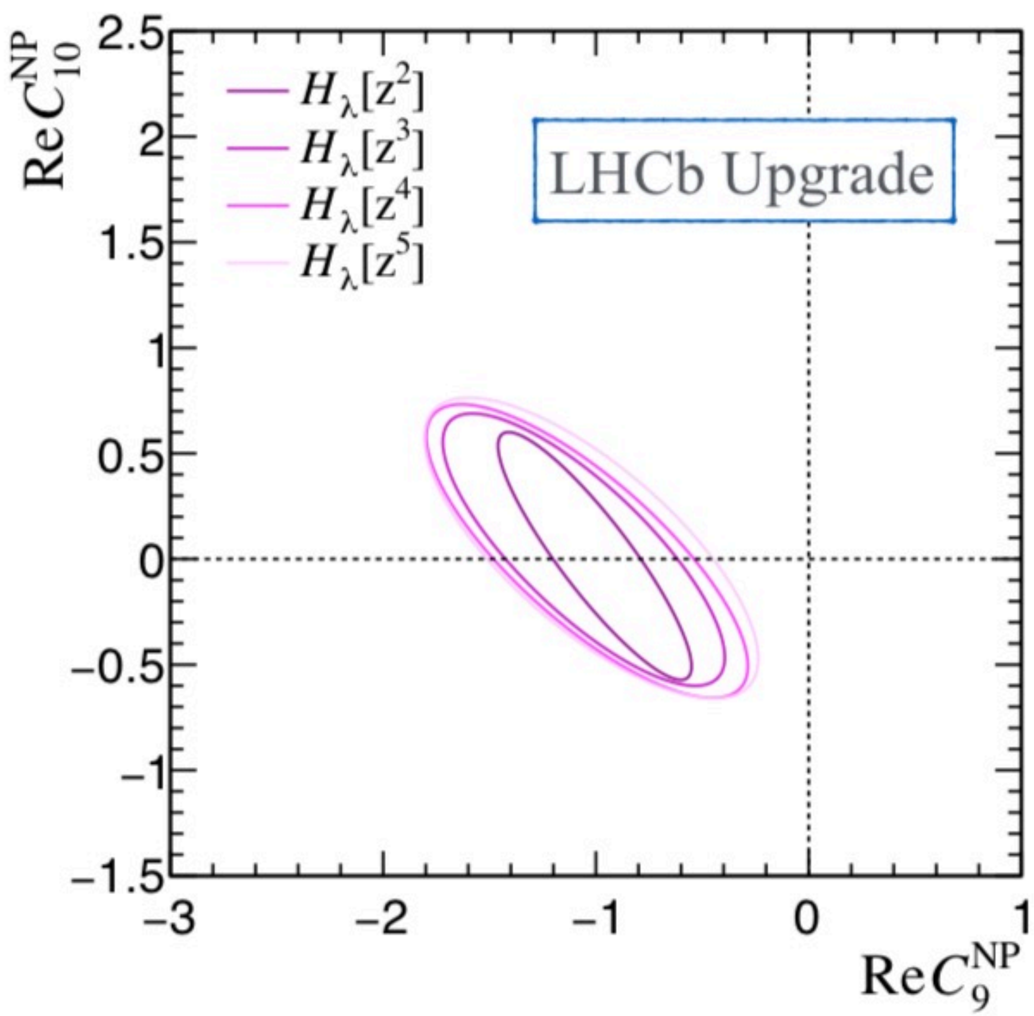
gen. C_9^{NP} = -1	LHCb Upgrade [50 fb^{-1}] Re C_9^{NP} mean	Re C_9^{NP} sigma
z^2 fit	$\boxed{-1.824}$ ± 0.003	0.063 ± 0.002
z^3 fit	$\boxed{-1.188}$ ± 0.005	0.103 ± 0.004
z^4 fit	$\boxed{-1.018}$ ± 0.006	0.119 ± 0.004
z^5 fit	$\boxed{-0.985}$ ± 0.007	0.141 ± 0.005

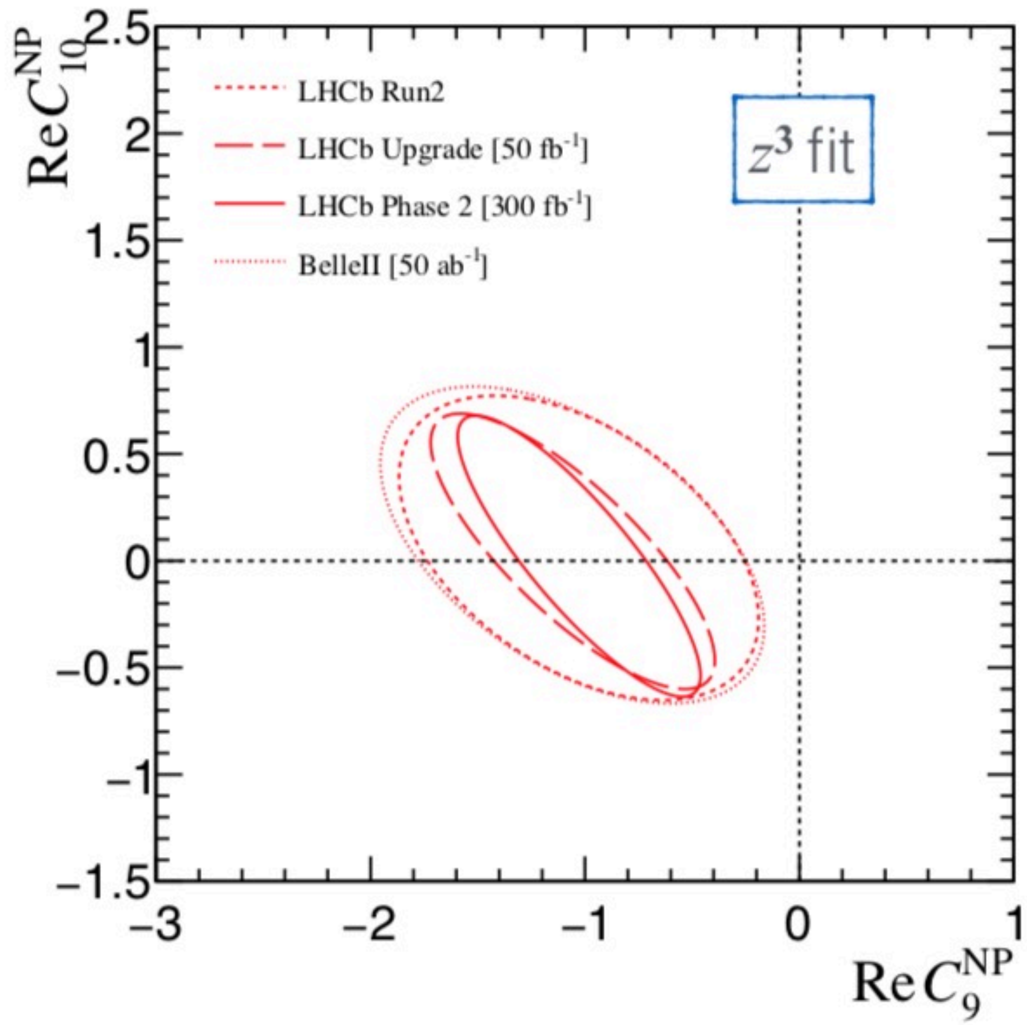
wrong order → C_9^{NP} is biased!!!

right order or higher → mean OK

Simultaneous fit to C_9 and C_{10}

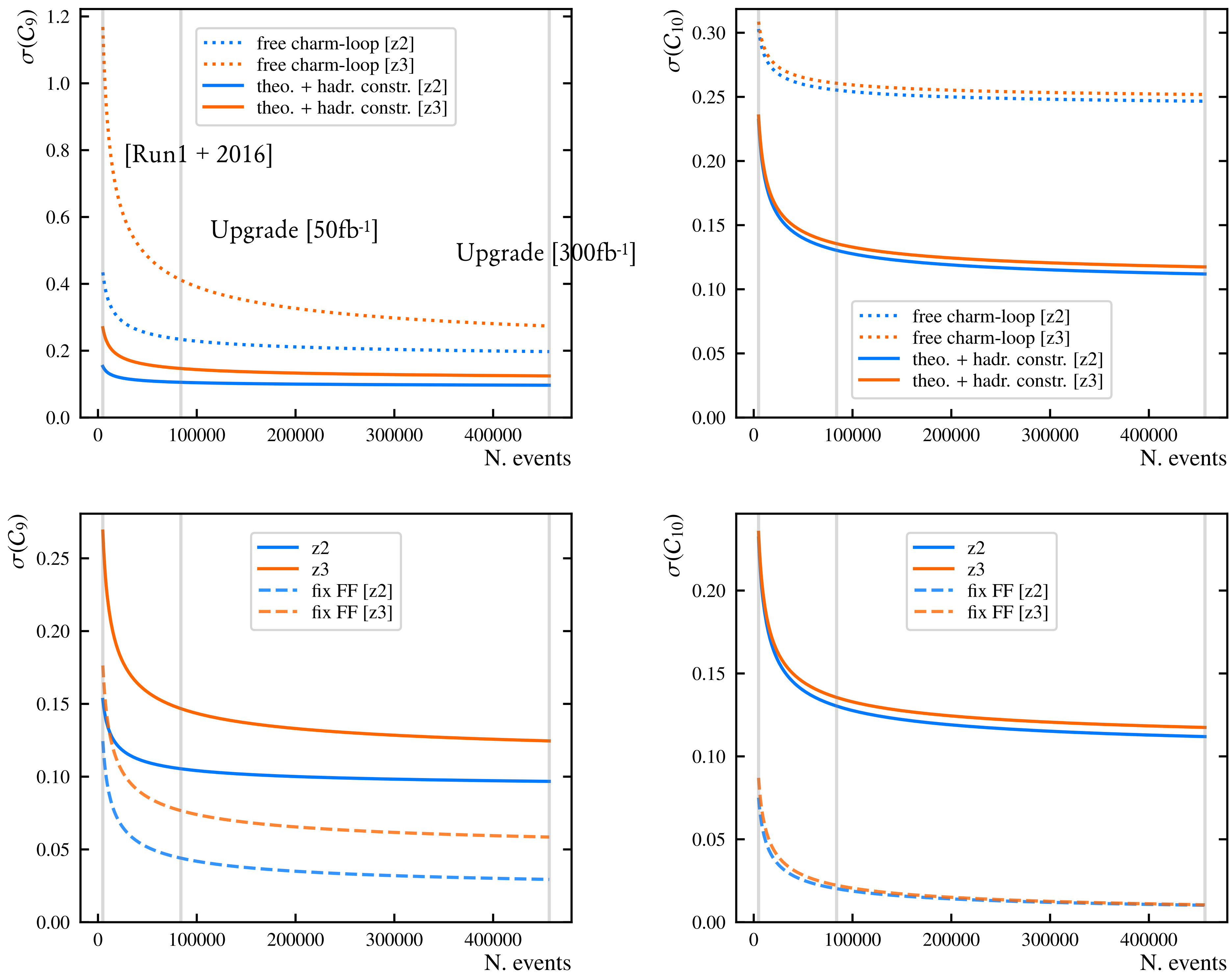
[A. Mauri PhD Thesis]





- uncertainty slightly increase for fit with order higher than z^3
- uncertainty saturates due to the form factors after LHCb Upgrade

C_9 and C_{10} vs FF and charm-loop interplay

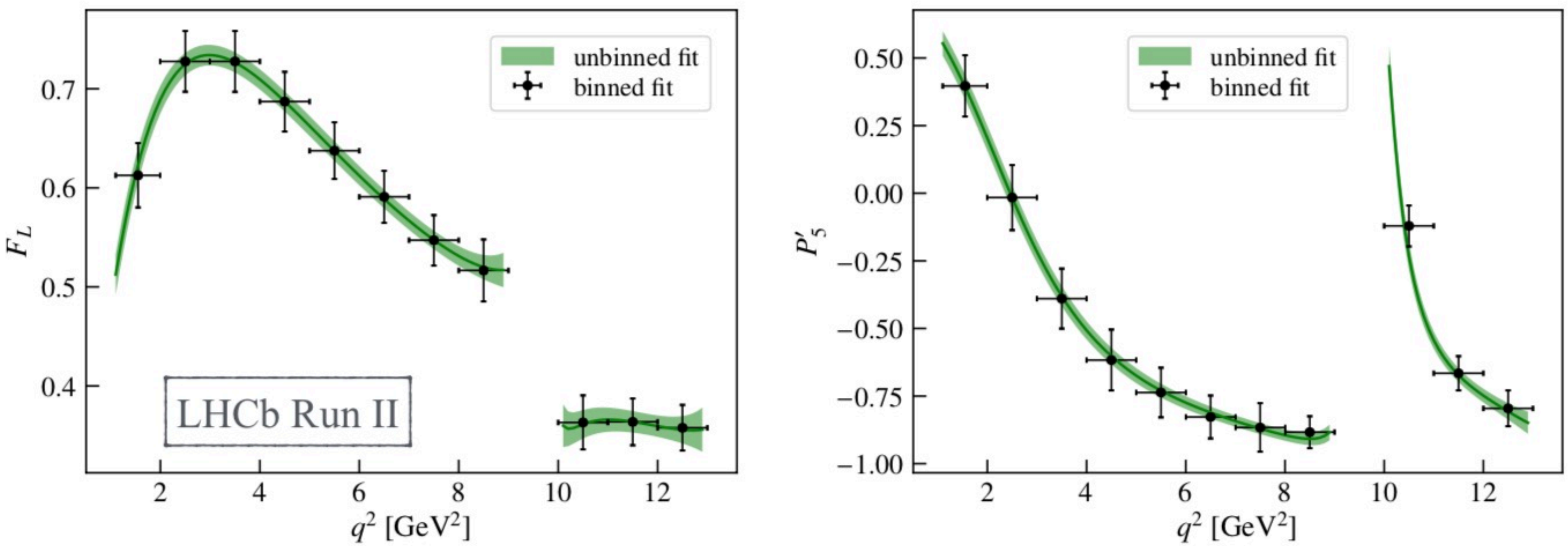


Angular observables

[arXiv:1805.06378]

The classical angular observables can be a posteriori calculate

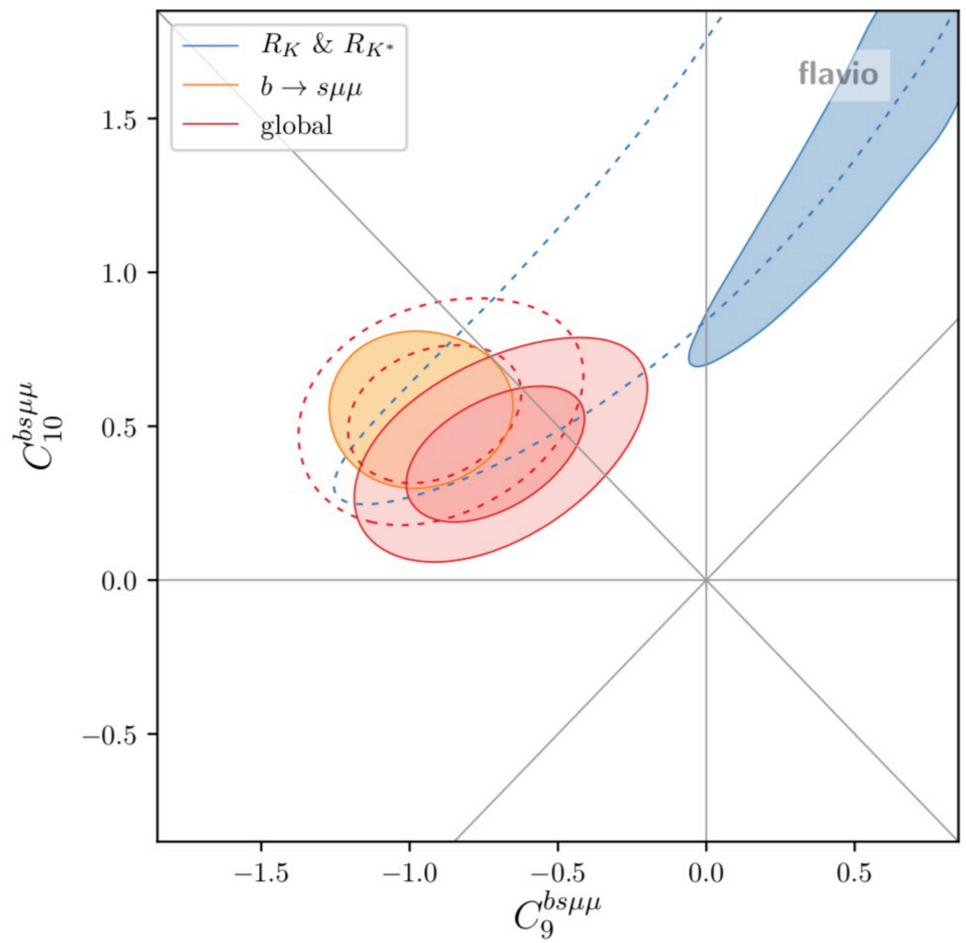
- Signal only ToyMC (no background, acceptance or systematics)
- Sensitivity significantly improve wrt the binned approach
- **Independent on the the truncation of the *z*-expansion!**



How to explore the full LFU information?

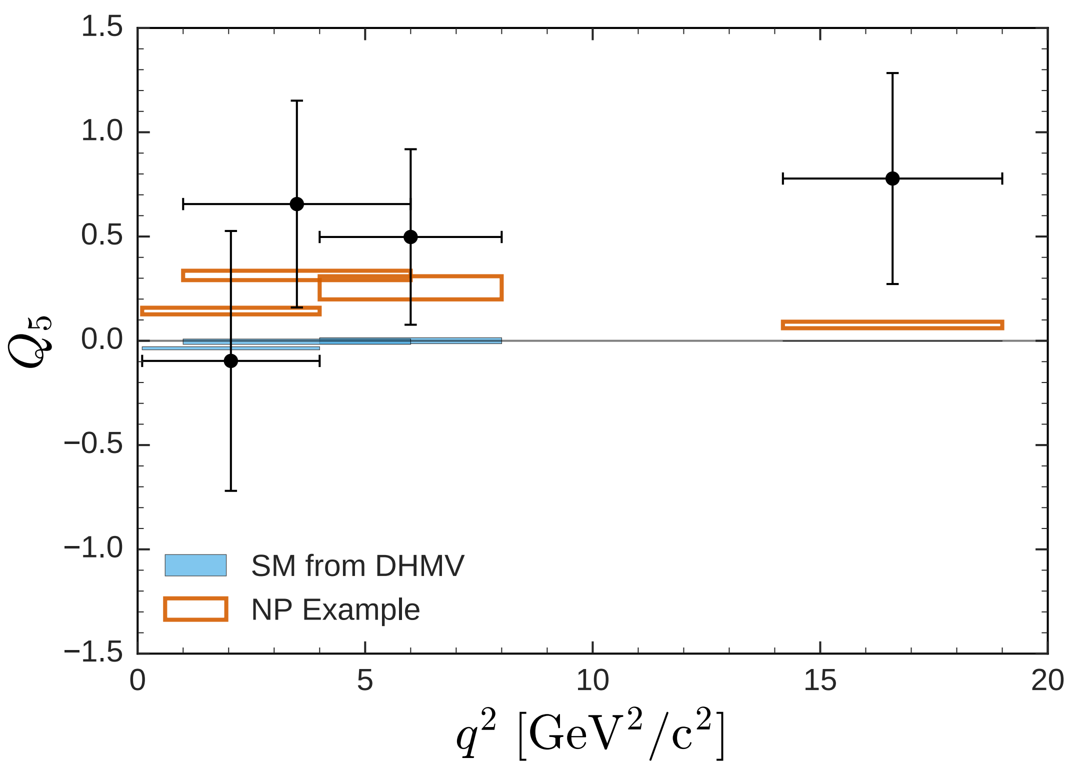
One of the interesting features of the anomalous pattern seen in FCNC transitions is the connection between P'$_5$ and R$_{K^*}$

Currently, this link is *only* visualised in global fit analyses



First steps towards an experimental direct connection, *i.e.* probes of LFU in observables

[Belle, PRL 118 (2017) no.11, 111801]



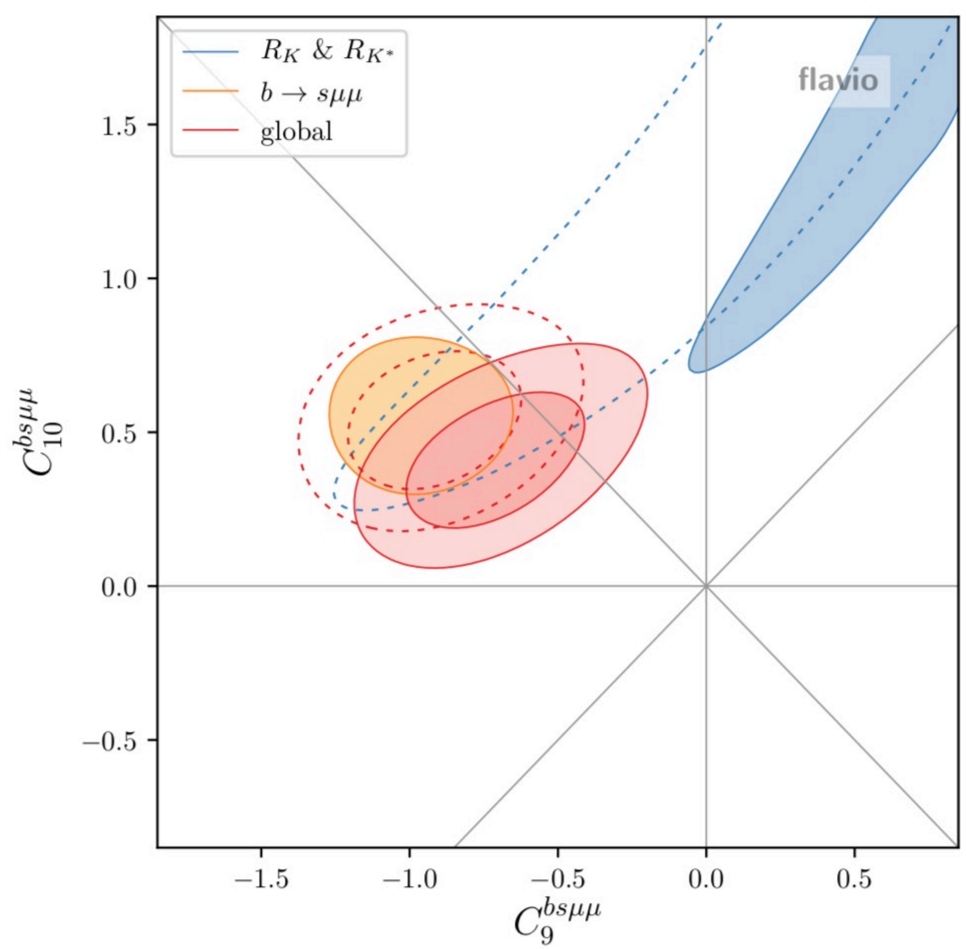
$$Q_5 = P_5'(\mu\mu) - P_5'(ee)$$

[JHEP 10 (2016) 075]

How to explore the full LFU information?

One of the interesting features of the anomalous pattern seen in FCNC transitions is the connection between P'_5 and R_{K^*}

Currently, this link is *only* visualised in global fit analyses



First steps towards an experimental direct connection, or combining both angular and branching ratio information

$$D_i(q^2) \equiv \frac{d\mathcal{B}^{(e)}}{dq^2} S_i^{(e)}(q^2) - \frac{d\mathcal{B}^{(\mu)}}{dq^2} S_i^{(\mu)}(q^2)$$

[PRD 95, 035029 (2017)]

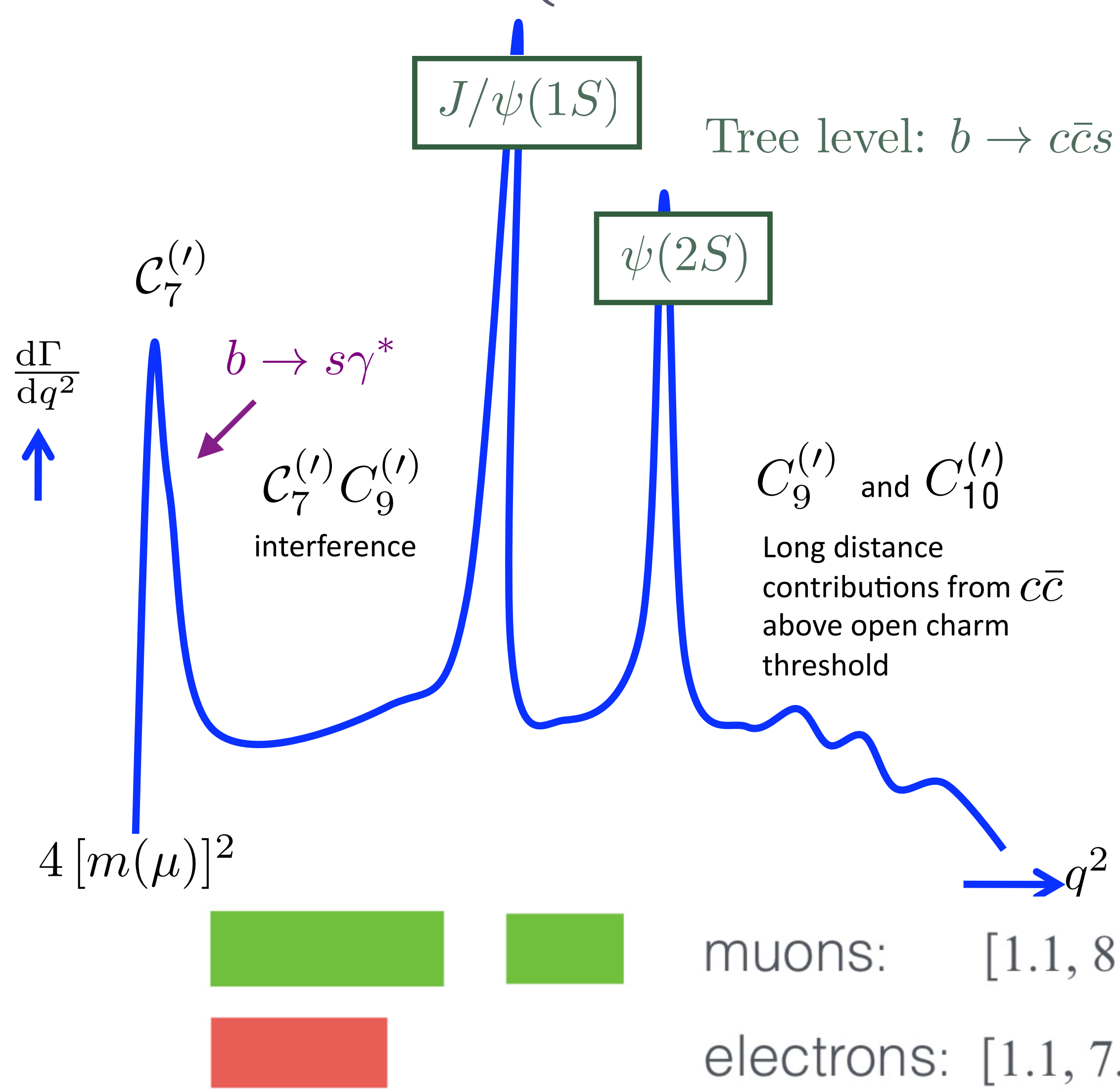
- Still limited to the individual μ/e analyses (*e.g.* cannot share F_L observable)
- Provide set of independent observables, e.g. related to P'_5 and A_{FB}, that can be combined and provide higher sensitivity

Universität Zürich UZH

[A. Mauri *et al*, PRD 99 (2019) 013007]

Simultaneous unbinned analysis of $B^0 \to K^{*0}\mu^+\mu^-$ and $B^0 \to K^{*0}e^+e^-$

$$\mathcal{A}_\lambda^{(\ell)\,L,R} = \mathcal{N}_\lambda^{(\ell)} \left\{ \boxed{(C_9^{(\ell)} \mp C_{10}^{(\ell)})} \boxed{\mathcal{F}_\lambda(q^2)} + \frac{2m_b M_B}{q^2} \left[\boxed{C_7^{(\ell)}} \boxed{\mathcal{F}_\lambda^T(q^2)} - 16\pi^2 \frac{M_B}{m_b} \boxed{\mathcal{H}_\lambda(q^2)} \right] \right\}$$



muons: [1.1, 8.0] & [11.0, 12.5] GeV^2

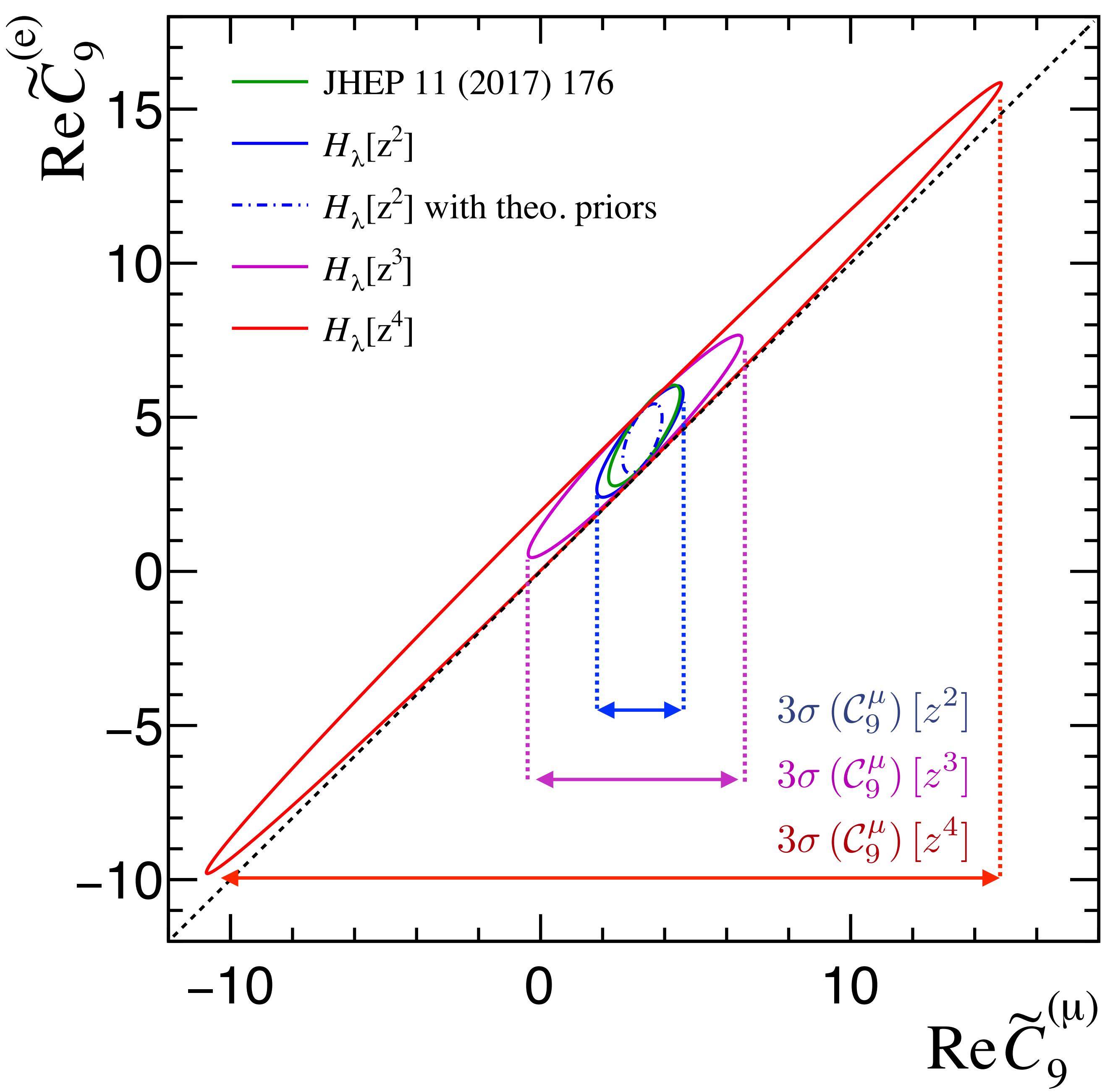
electrons: [1.1, 7.0] GeV^2

- All nuisance parameters are shared between electron and muons, *i.e.* CKM and (non) local hadronic
- Extended maximum-likelihood fit, **i.e. includes R_{K^*} information**

The correlation bound that enables LFU tests

[A. Mauri *et al*, PRD 99 (2019) 013007]

$$\mathcal{C}_9^{(e)} = \mathcal{C}_9^{\rm SM} = \mathcal{C}_9^{(\mu)} + 1$$



$C_i^{(\ell)}$ **: strongly dependent on the model assumption (renamed for simplicity)**

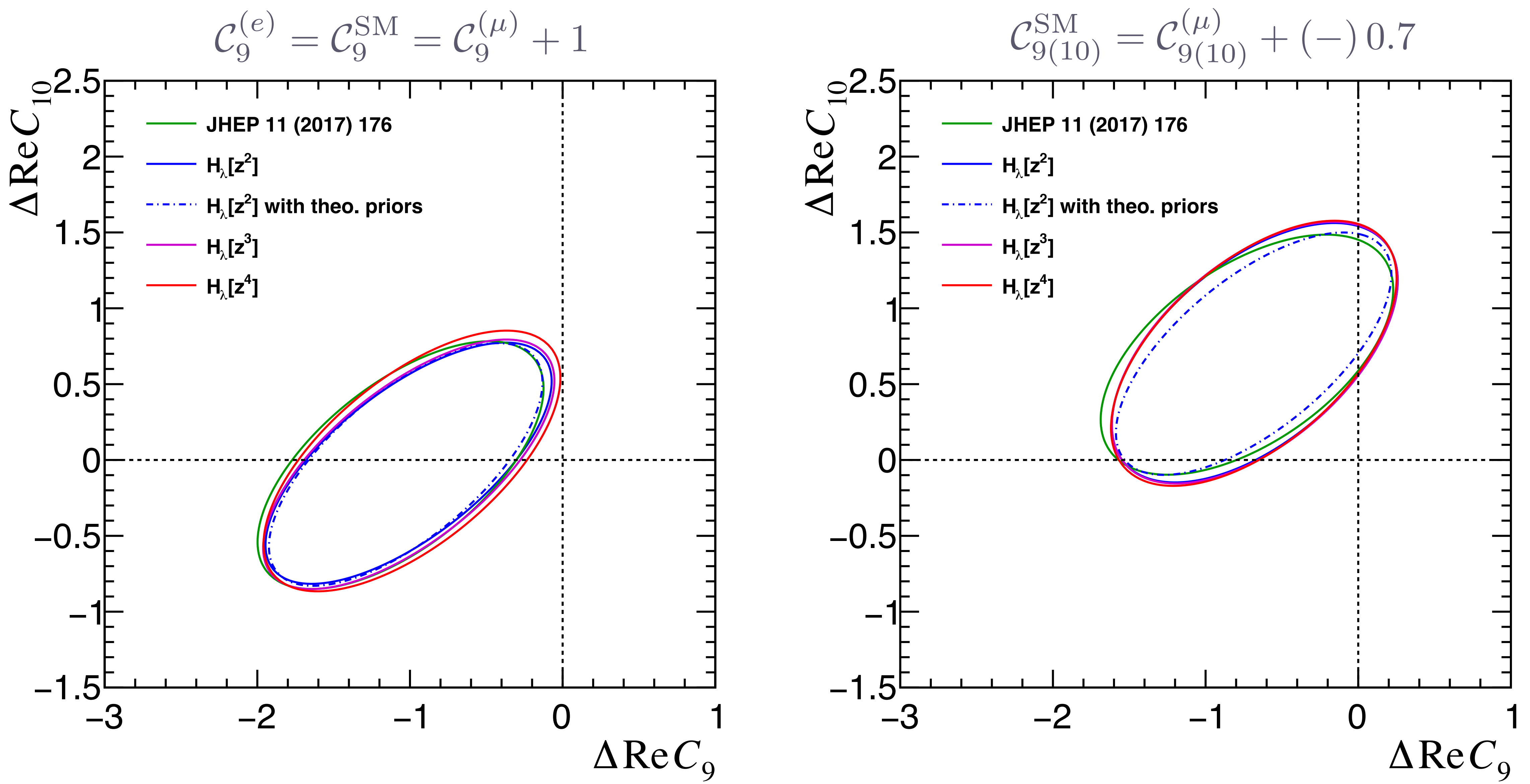
Key feature: model-independent determination of the difference between electron and muons WCs

$$\Delta\mathcal{C}_i = \widetilde{\mathcal{C}}_i^{(\mu)} - \widetilde{\mathcal{C}}_i^{(e)}$$

- **Insensitive to the parametrisation of the non-local contributions**
- **Significance wrt LFU hypothesis is unbiased**

Sensitivity to LFU breaking with LHCb Run II

[A. Mauri *et al*, PRD 99 (2019) 013007]

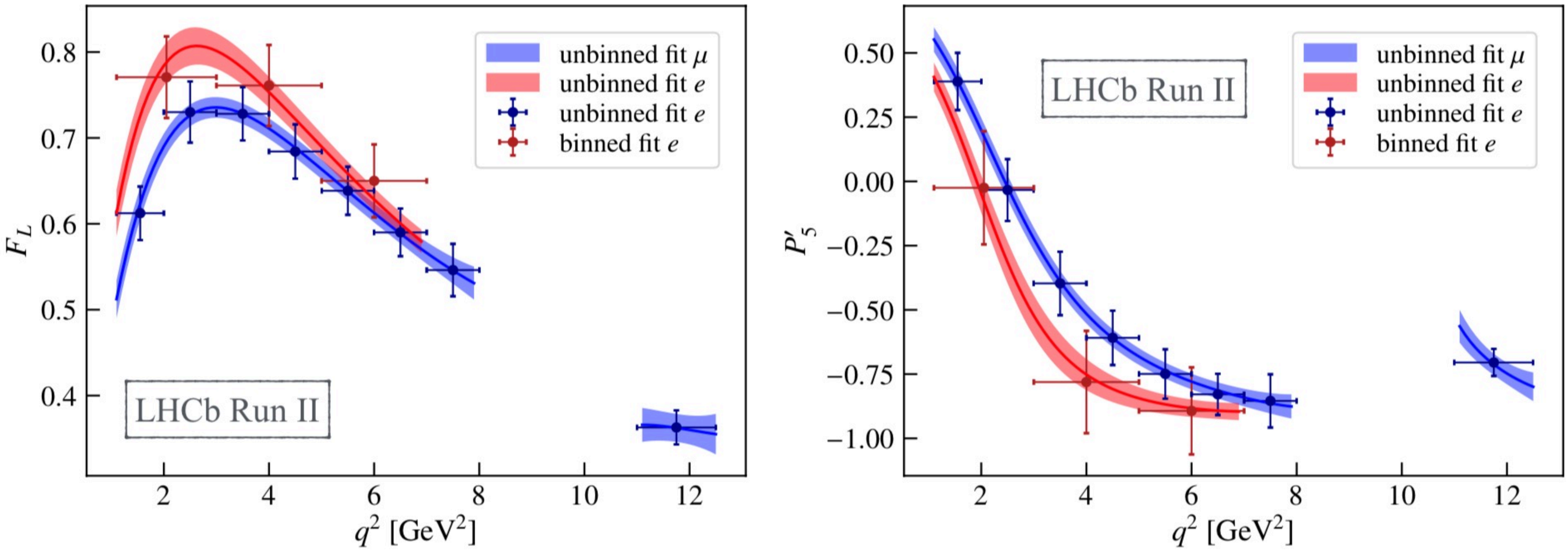


Determination of ΔC_i is stable and model-independent → early first observation of LFU violation can be obtained with LHCb Run II dataset in $B \to K^* l^+ l^-$ decays

Features of the proposed LFU observable

[A. Mauri *et al*, PRD 99 (2019) 013007]

Notice that the classical binned observables can also be retrieved by this method



Similar to the muonic case this analysis will provide more precise results

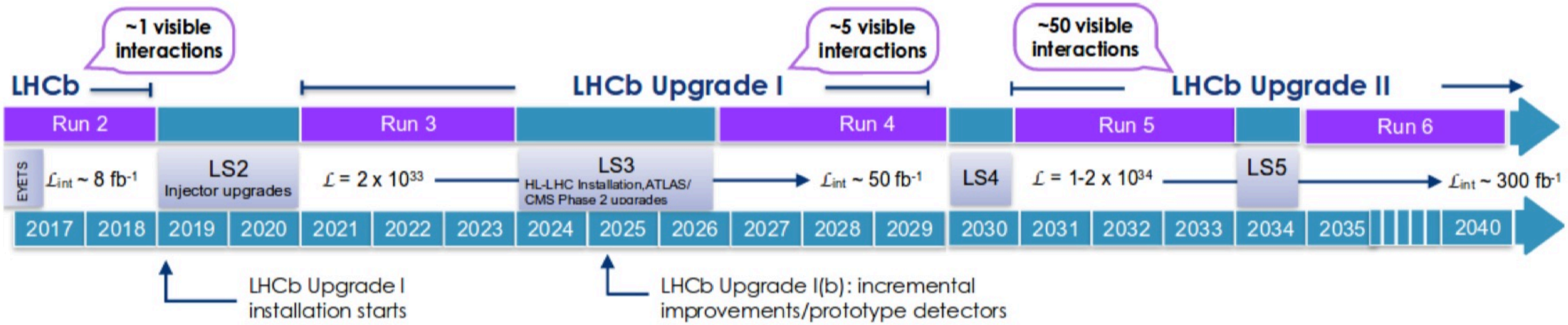
Universität Zürich[UZH]

What comes Next-to-Next?

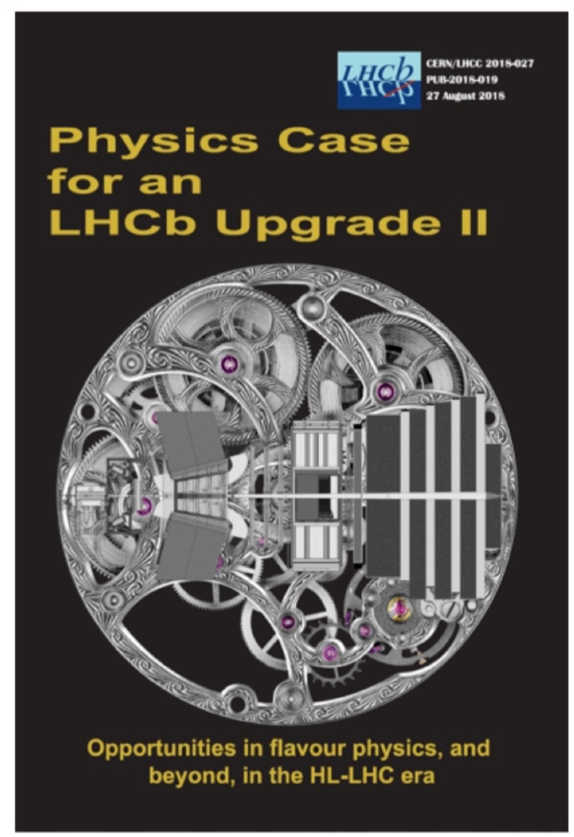
LHCb: from Run I+II to $50 - 300\,\mathrm{fb}^{-1}$

Novel ideas (opportunities) to investigate at LHCb

LHCb upgrades



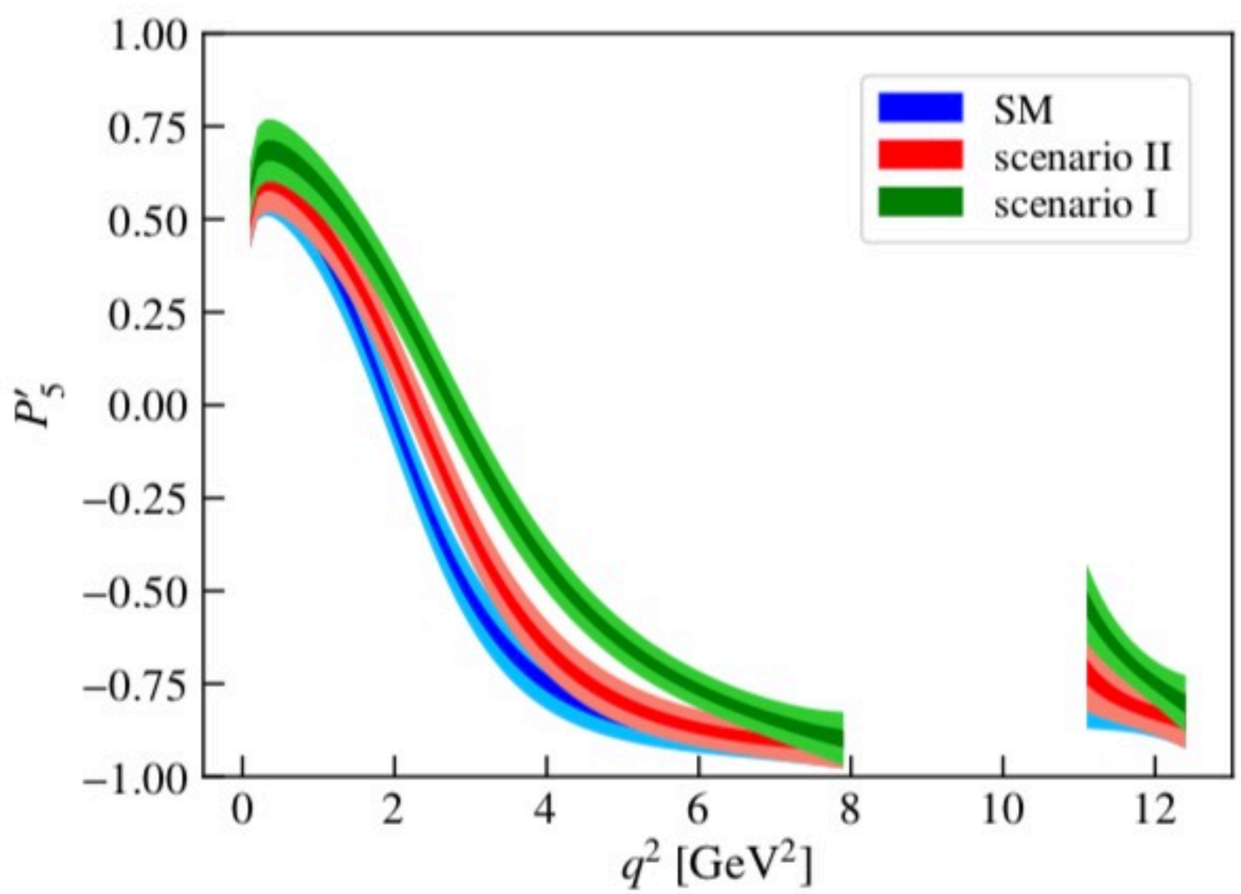
- Upgrade of the LHCb detector during LS2
  - All trigger decision software
  - Expect to collect 50 fb^{-1}
- LHCb phase-II
  - Further major upgrade in LS4 to profit from the HL-LHC program
  - Increase dataset up to 300 fb^{-1}

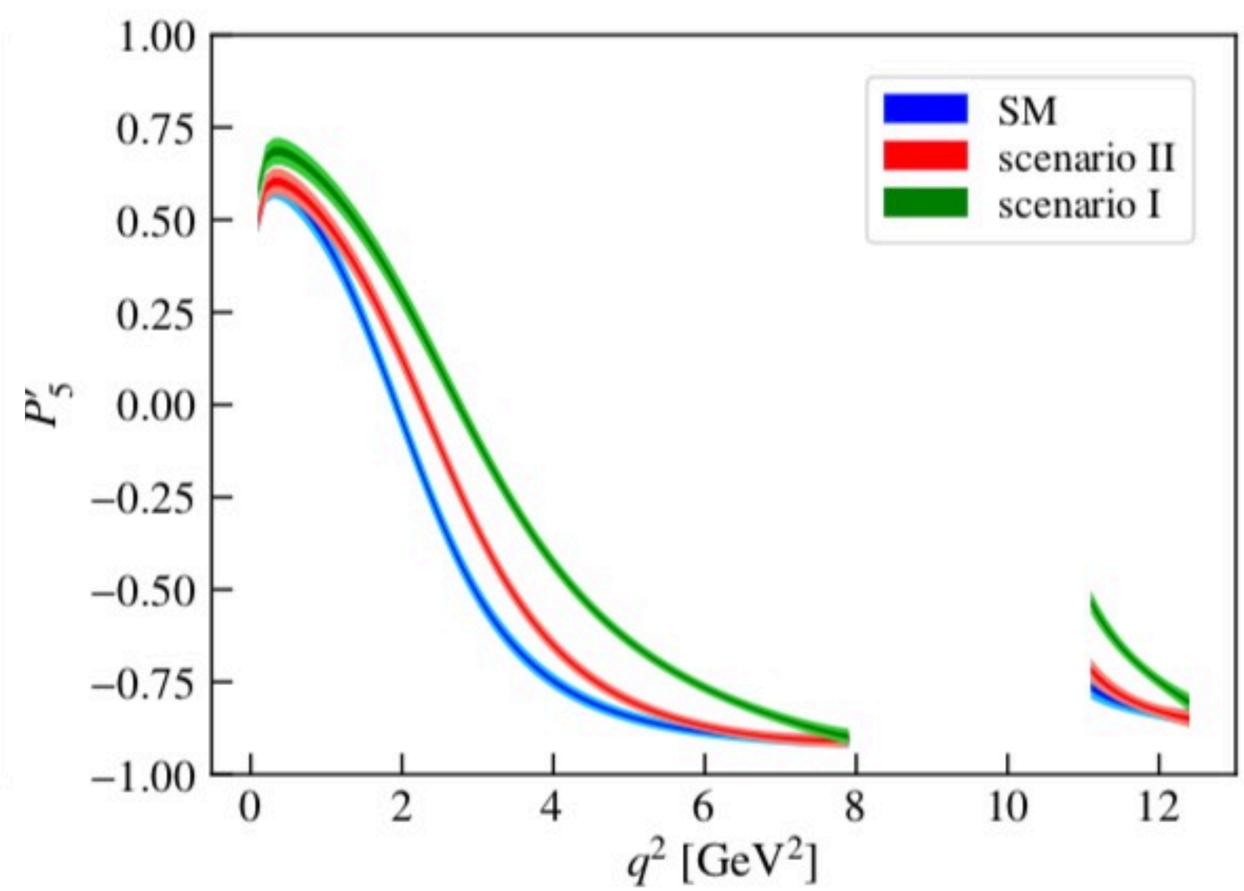


Sensitivities for the LHCb Upgrade

[arXiv:1812.07638]

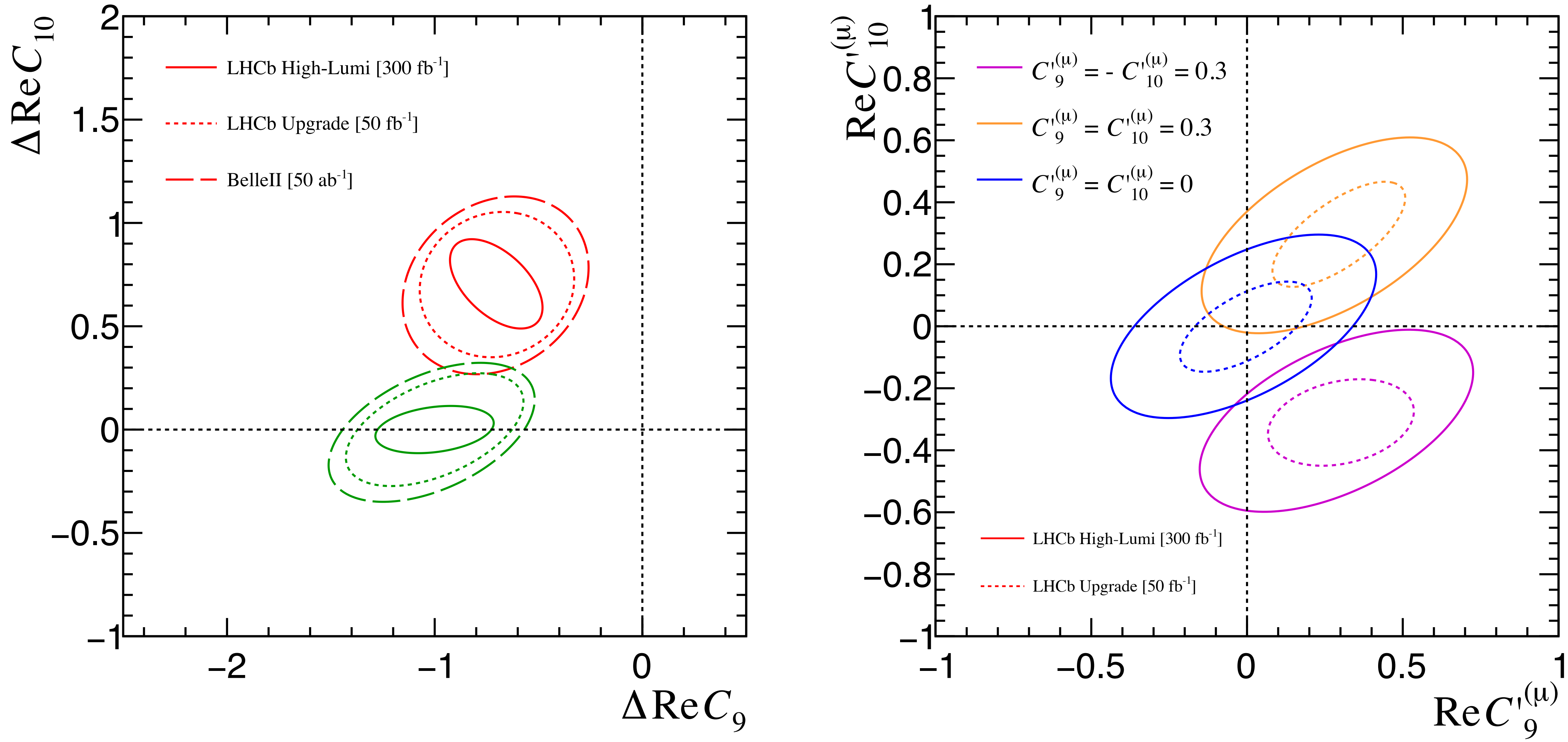
scenario	C_9^{NP}	C_{10}^{NP}
I	-1.4	0
II	-0.7	0.7





[A. Mauri *et al*, PRD 99 (2019) 013007]

$$\mathcal{C}_9^{(e)} = \mathcal{C}_9^{\mathrm{SM}} = \mathcal{C}_9^{(\mu)} + 1$$



Interesting opportunities to disentangle different NP hypotheses even with a single measurement

How to use the available data in the future?

Release nothing and proceed anyway.

No risk of data mis-use.

No extra work.

Cannot update when hadronic information improves

Ultimate sensitivity is lost.

Release background-subtracted data.

Not much work.

Full flexibility given.

Difficult to use, big risk of mis-use.

Will people accept this before data is fully exhausted?

Allow for reinterpretation behind an API.

Hide experimental details.

Flexibility can be defined.

A lot of work.

Relies on some level of consistency between analyses.

By. P. Owen

How to use the available data in the future?

There are three well known packages for fitting observables and generating SM data

http://superiso.in2p3.fr/ SuperIso

https://eos.github.io/ EOS

https://flav-io.github.io/ flavio

Perhaps we should sort a simpler synergy between experiment and theory, *e.g.* create a simple formalism (API) from the experimental side

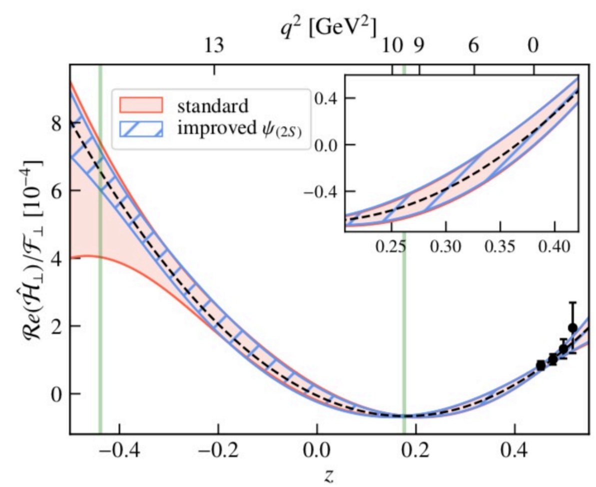
Example:

[Fitter]

zfit

https://github.com/zfit/zfit

[Model]



["Published" data]

TensorFlow Hub

Summary

- Amplitude analyses is a very “flavourful” road to probe NP at LHCb (still a large number of physics to explore)
- Much progress is being made on the understanding of the short/long distance effects → synergy between theory and experiment is paramount
- Measurements of C_{10} might be an interesting venue to explore experimentally to confirm NP ... but improvements on form factors are essential!!
- **The road ahead?** More measurement, new observables (e.g. $\Delta C_{9,10}$) and LHCb upgrade!

S-wave contribution

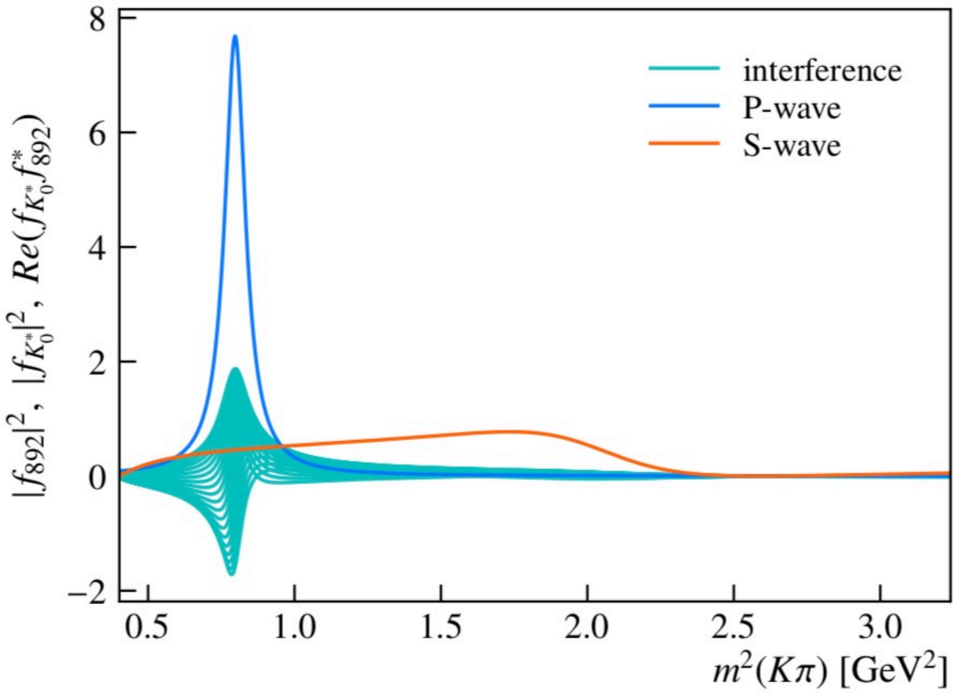
[arXiv:1805.06378]

Since we fully fit the q² dependence, this has also to be extended to the S-wave

$$\mathcal{A}^{L,R}_{S0} = -N_0 \frac{\sqrt{\lambda_{K_0^*}}}{M_B\sqrt{q^2}} \left\{ \left[(C_9 - C_9') \mp (C_{10} - C_{10}') \right] f_+(q^2) + \frac{2m_b M_B}{q^2} \left[(C_7 - C_7') f_T(q^2) - 16\pi^2 \frac{M_B}{m_b} \mathcal{H}_{S0}(q^2) \right] \right\}$$

$$\mathcal{A}_{St} = -2N_0 \frac{M_B^2 - M_{K_0^*}^2}{M_B\sqrt{q^2}} (C_{10} - C_{10}') f_0(q^2)$$

Form factors are gaussian constrained from [Nucl. Phys. B868 (2013) 368] and hadronic and H parameters are free in the fit



Simultaneous fit to C_9 and C_{10}

[A. Mauri PhD Thesis]

Considering all experimental effects the sensitivity for the Wilson coefficients are not significantly affected

$\mathcal{C}_9^{NP}$ mean	$\mathcal{C}_9^{NP}$ sigma	$\mathcal{C}_{10}^{NP}$ mean	$\mathcal{C}_{10}^{NP}$ sigma	correlation $\mathcal{C}_9^{NP}$- $\mathcal{C}_{10}^{NP}$
Signal only (P-wave)				
-0.96 ± 0.01	0.22 ± 0.01	0.05 ± 0.01	0.29 ± 0.01	-0.52 ± 0.03
P + S-waves				
-0.94 ± 0.01	0.23 ± 0.01	0.07 ± 0.02	0.31 ± 0.01	-0.54 ± 0.04
P-wave + Acc. + Bkg.				
-0.96 ± 0.01	0.23 ± 0.01	0.09 ± 0.02	0.33 ± 0.01	-0.45 ± 0.05
Full fit				
-0.93 ± 0.01	0.24 ± 0.01	0.08 ± 0.01	0.34 ± 0.01	-0.44 ± 0.03