FPCapri 2018 - 8-10 June 2018

On hadronic uncertainties polluting the NP hunt in b -> s transitions

M. Fedele

based on JHEP 06 (2016) 116 and Eur. Phys. J. C77 (2017) 688 in collaboration with:

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

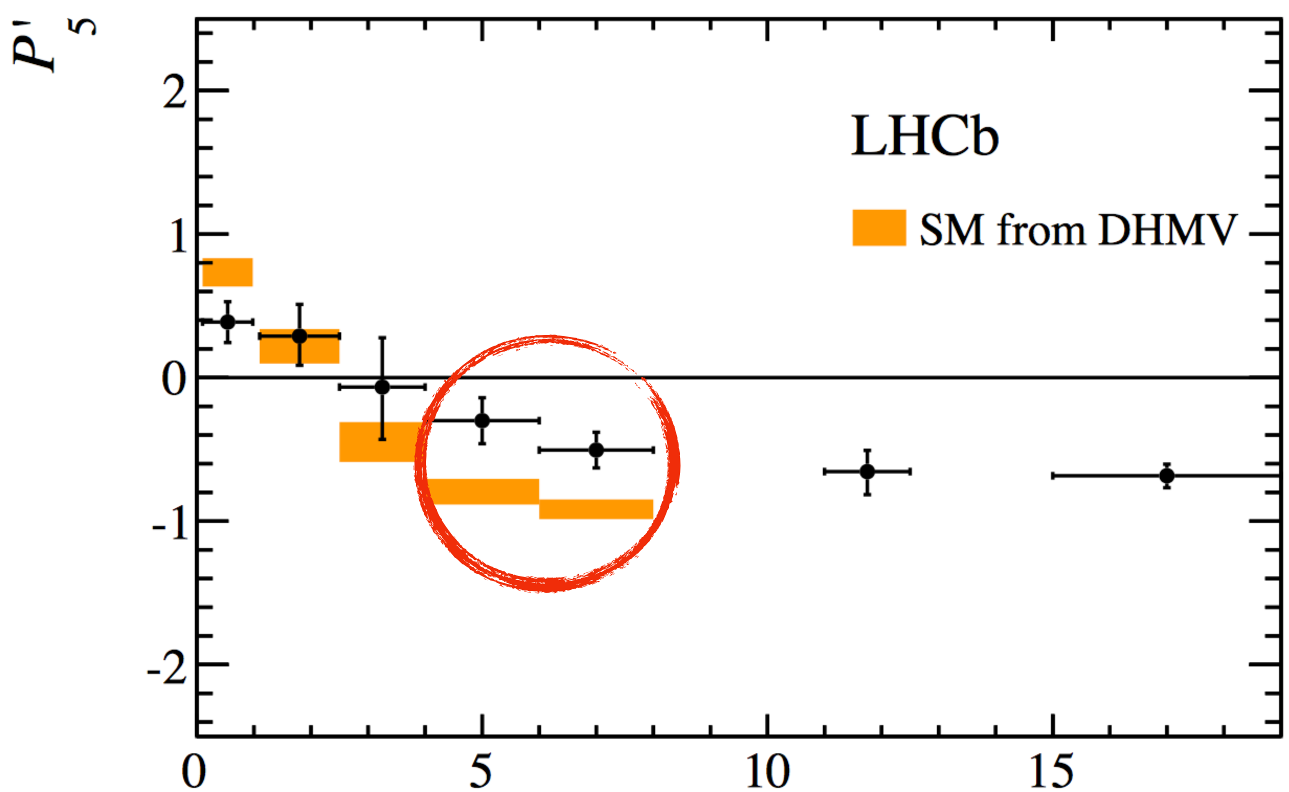
OPPORTUNITIES WITH SEMI-LEPTONIC B DECAYS

No tree-level flavour changing neutral currents (FCNC) in the Standard Model (SM).

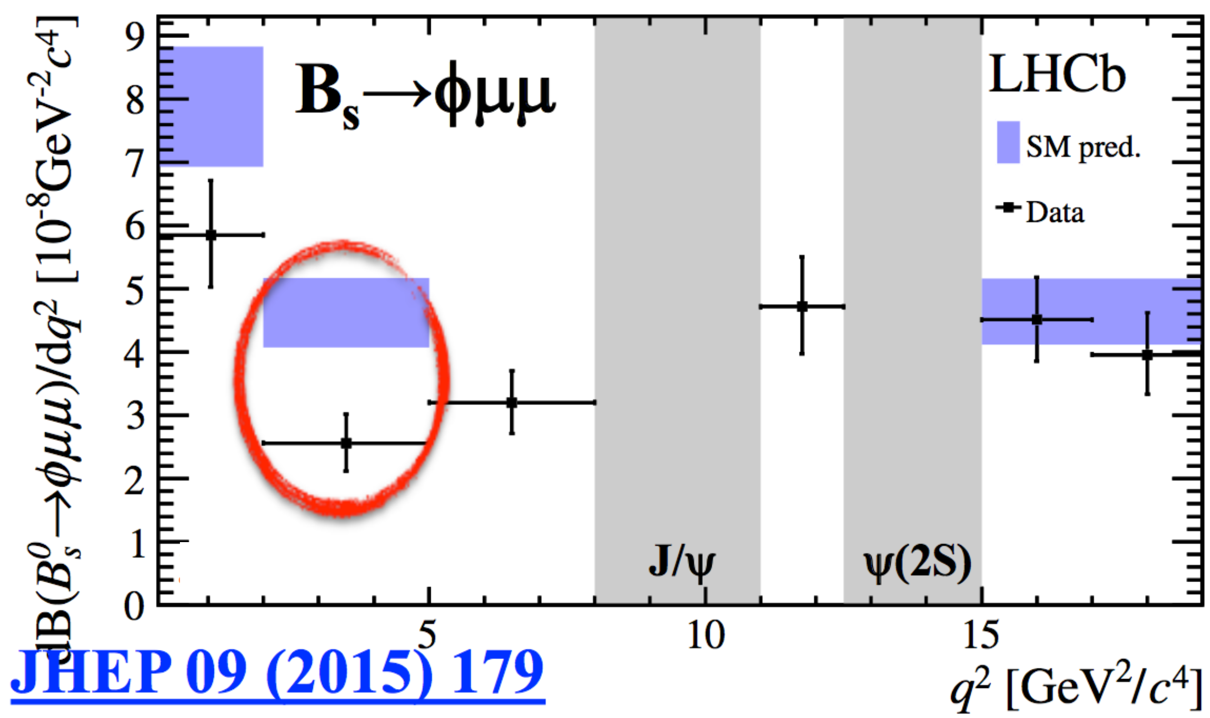
⇨ New Physics (NP) may sizably contribute in FCNC amplitudes

E.g.: b to s ll transitions

INTRIGUING SET OF "ANOMALIES" IN DATA OF EXCLUSIVE B RARE DECAYS



JHEP 1602 (2016) 104



JHEP 09 (2015) 179

~ 3.5 σ

Angular analysis of $B \longrightarrow K^*\mu\mu$ for small dilepton mass, $4 < q^2 / \text{GeV}^2 < 8$.

~ 2.5 σ

Br of $B_s \longrightarrow \phi\mu\mu$

Opportunities with Semi-Leptonic B Decays

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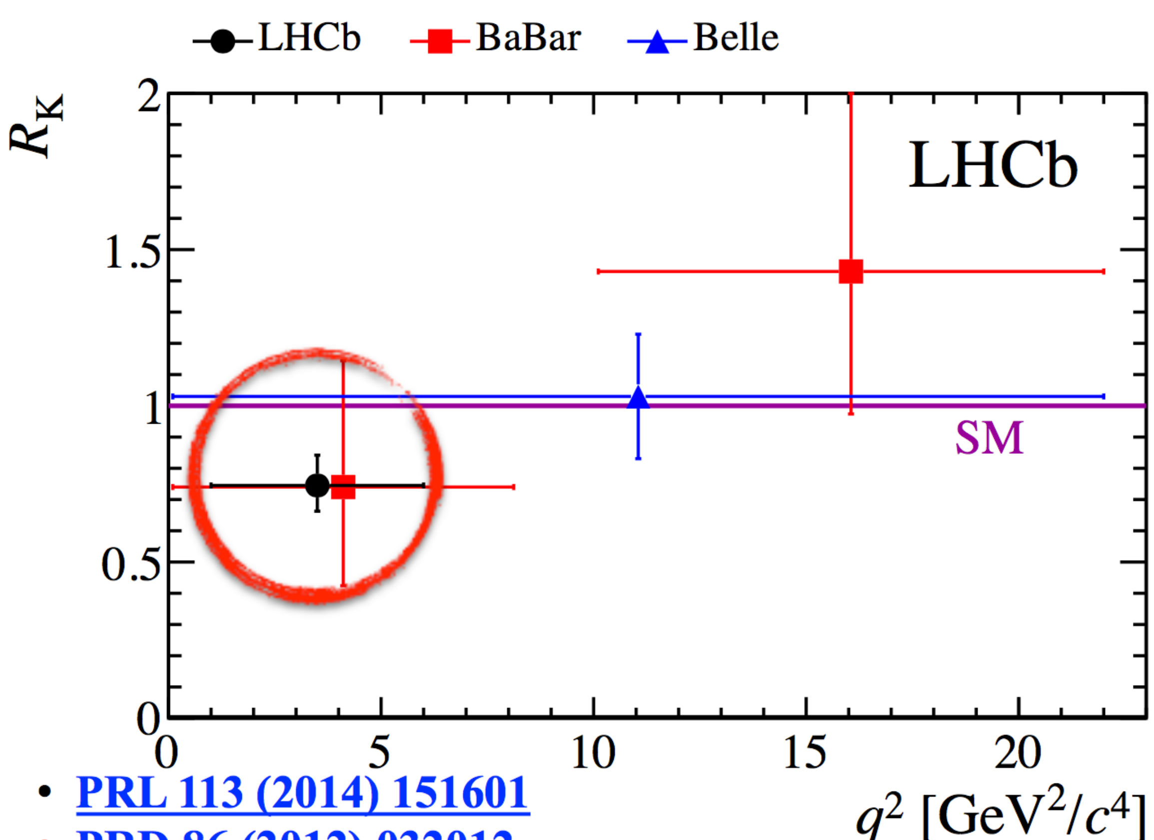

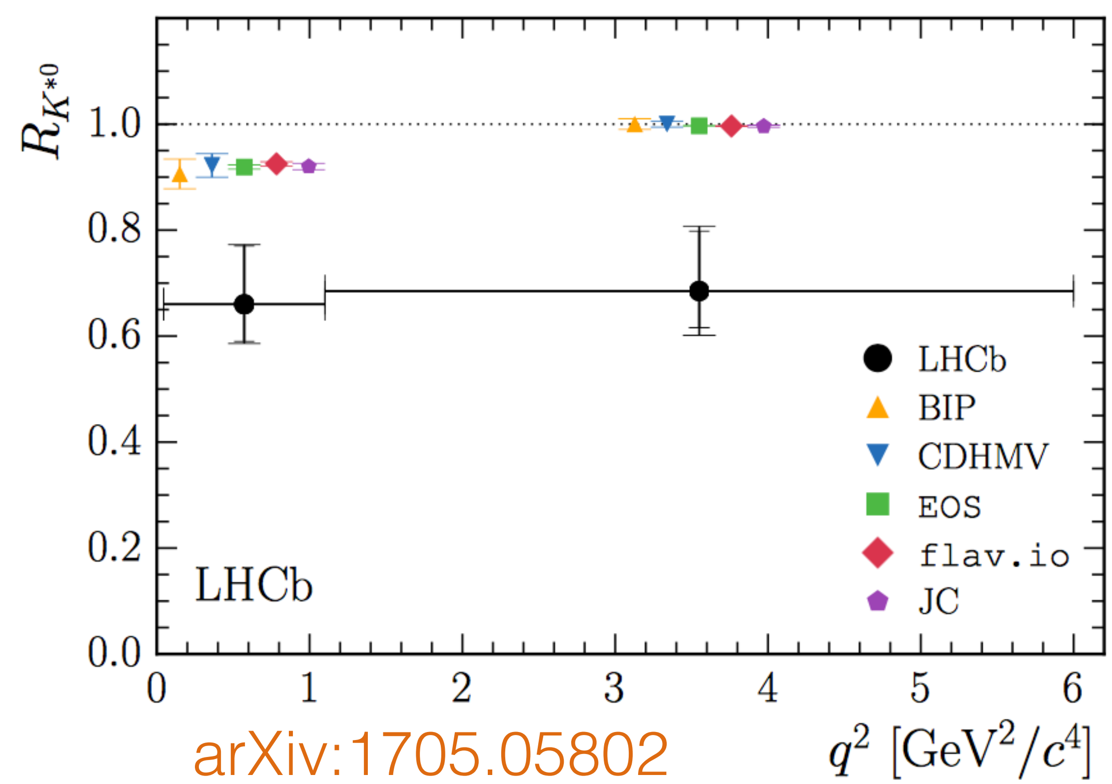

arXiv:1705.05802

- PRL 113 (2014) 151601
- PRD 86 (2012) 032012
- PRL 103 (2009) 171801

~ 2.5 σ

$R_{K^{(*)}} = Br(B \longrightarrow K^{(*)}ee) / Br(B \longrightarrow K^{(*)}\mu\mu)$

The B -> V(P)ll decay channel: the Hamiltonian

$$H_{eff}^{\Delta B=1} = H_{eff}^{had} + H_{eff}^{sl+\gamma}$$

$$H_{eff}^{had} = \frac{4G_F}{\sqrt{2}} \sum_{p=u,c} \lambda_p \Big[C_1 P_1^p + C_2 P_2^p + \sum_{i=3,\ldots,6} C_i P_i + C_{8g} Q_{8g} \Big]$$

$$H_{eff}^{sl+\gamma} = \frac{4G_F}{\sqrt{2}} \lambda_t \Big[C_7^{(\prime)} Q_{7\gamma}^{(\prime)} + C_9^{(\prime)} Q_{9V}^{(\prime)} + C_{10}^{(\prime)} Q_{10A}^{(\prime)} + C_S^{(\prime)} Q_S^{(\prime)} + C_P^{(\prime)} Q_P^{(\prime)} \Big]$$

$$\begin{aligned}
P_1^p &= (\bar{s}_L \gamma_\mu T^a p_L)(\bar{p}_L \gamma^\mu T^a b_L) \\
P_2^p &= (\bar{s}_L \gamma_\mu p_L)(\bar{p}_L \gamma^\mu b_L) \\
P_3 &= (\bar{s}_L \gamma_\mu b_L) \sum\nolimits_q (\bar{q} \gamma^\mu q) \\
P_4 &= (\bar{s}_L \gamma_\mu T^a b_L) \sum\nolimits_q (\bar{q} \gamma^\mu T^a q) \\
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P_6 &= (\bar{s}_L \gamma_{\mu 1} \gamma_{\mu 2} \gamma_{\mu 3} T^a b_L) \sum\nolimits_q (\bar{q} \gamma^{\mu 1} \gamma^{\mu 2} \gamma^{\mu 3} T^a q)
\end{aligned}$$

$$\begin{aligned}
Q_{7\gamma} &= \frac{e}{16\pi^2} \hat{m}_b \bar{s} \sigma_{\mu\nu} P_R F^{\mu\nu} b \\
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Matrix elements of quark currents from $Q_{7,9,10,S,P}$ naively factorize:

$$\mathcal{A} \sim \langle \ell^+ \ell^- | J_{\rm lep} | 0 \rangle \langle V(P) | J_{had} | \overline{B} \rangle$$

Not possible for the hadronic Hamiltonian!

$$\tilde{h}_\lambda(q^2) \sim \epsilon_{\lambda,\mu} \int d^4x \, e^{iqx} \langle V(P) | T\{ J^{\mu,e.m.}_{had}(x) \mathcal{H}^{eff}_{had}(0) \} | B \rangle$$

The B -> V(P)ll decay channel: the amplitudes

The amplitudes, in the helicity basis, are proportional to

$$H^V_\lambda(q^2) \propto (C_9 - C_9')\tilde{V}_\lambda(q^2) + \frac{2m_b m_B}{q^2}(C_7 - C_7')\tilde{T}_\lambda(q^2) - 16\pi^2 \frac{m_B^2}{q^2}\tilde{h}_\lambda(q^2)$$

$$H^A_\lambda(q^2) \propto (C_{10} - C_{10}')\tilde{V}_\lambda(q^2)$$

$$H^S(q^2) \propto \frac{m_b}{m_W}(C_S - C_S')\tilde{S}(q^2)$$

$$H^P(q^2) \propto \frac{m_b}{m_W}(C_P - C_P')\tilde{S}(q^2) + \frac{2m_\ell m_B}{q^2}(C_{10} - C_{10}')\left(1 + \frac{m_s}{m_b}\right)\tilde{S}(q^2)$$

$$(\lambda = 0, \pm)$$

The main sources of uncertainties are coming from the form factors and from the hadronic parameters

The B -> V(P)ll decay channel: the form factors

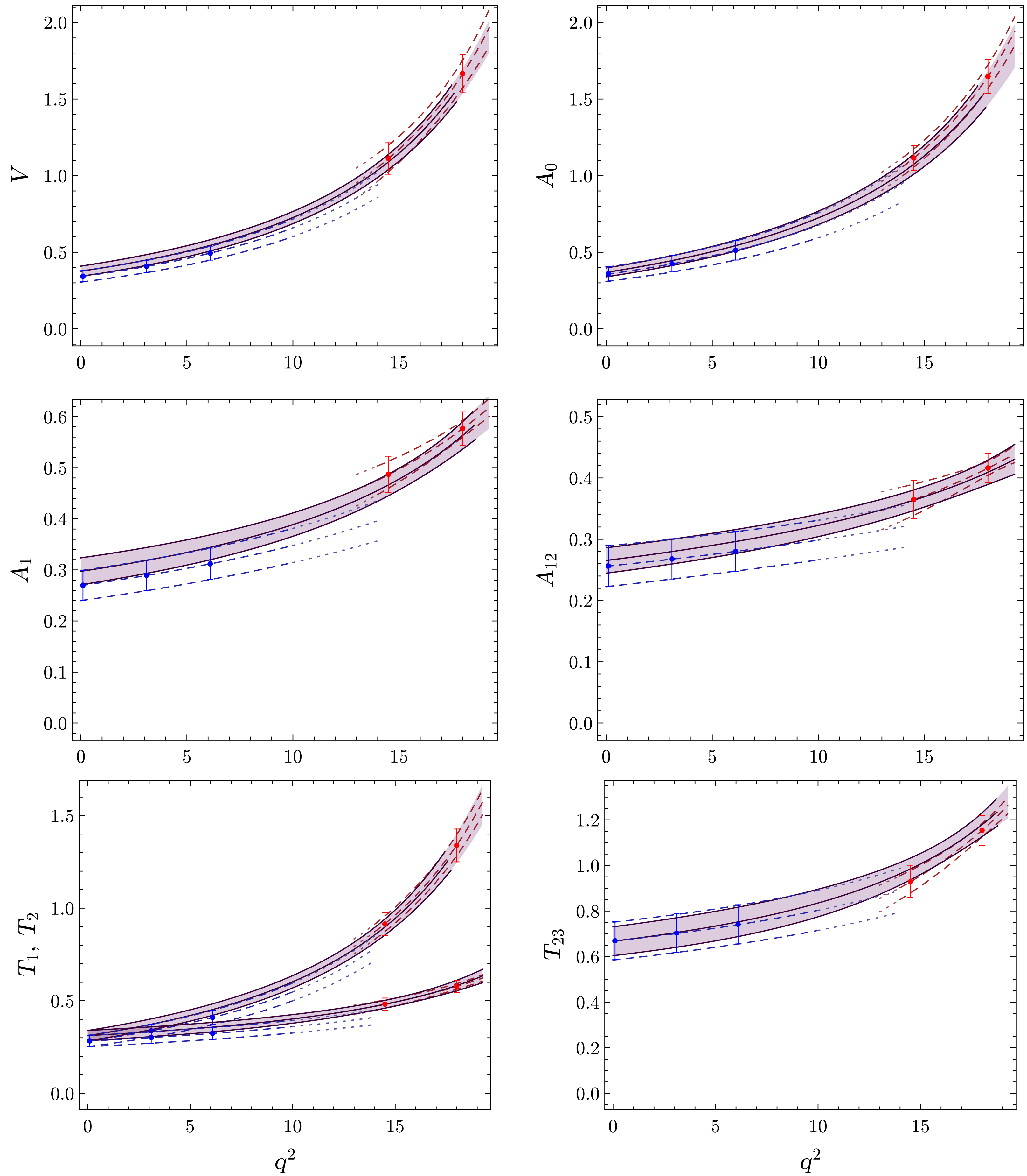
Low recoil region (Lattice, Pos Lattice2014 (2015) 372)

vs.

Large recoil region (LCSR, JHEP 08 (2016) 098)

⇓

Full form factors, together with the *correlation matrix*, have become a reliable option



The B -> V(P)ll decay channel: the hadronic parameter

At first order in α_{em} we can get a contribution from current-current quark operators & QCD penguins

Loop suppressed amplitude, can be enhanced by non-perturbative QCD effects!

In particular, **charm current-current insertion not further parametrically suppressed.**

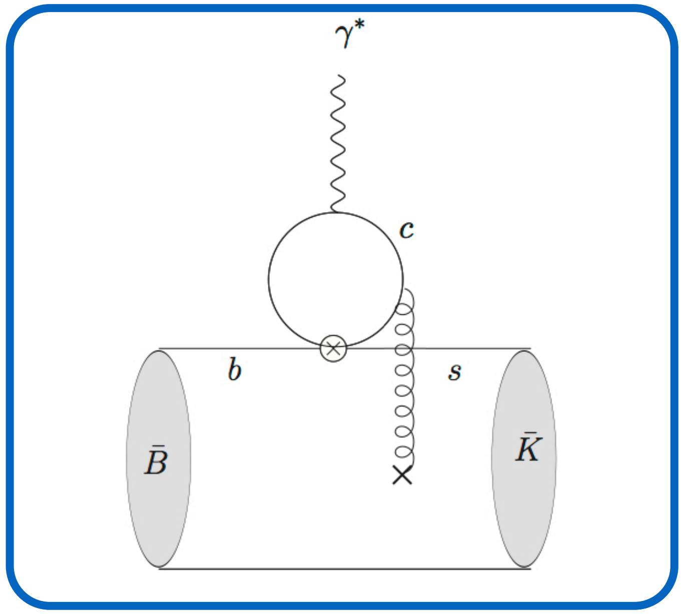
Soft gluon emission from cc-loop estimated for P = K and V = K* with LCSR + dispersion relation. **Sizable effect in K***

A.Khodjamirian et al., **JHEP 1009 (2010) 089**

$\Rightarrow$ Correlator expanded on the light-cone: **LCSR estimate based on small q^2** .

$\Rightarrow$ **Dispersion relation** in order **to extrapolate LCSR result** up to charm resonances.

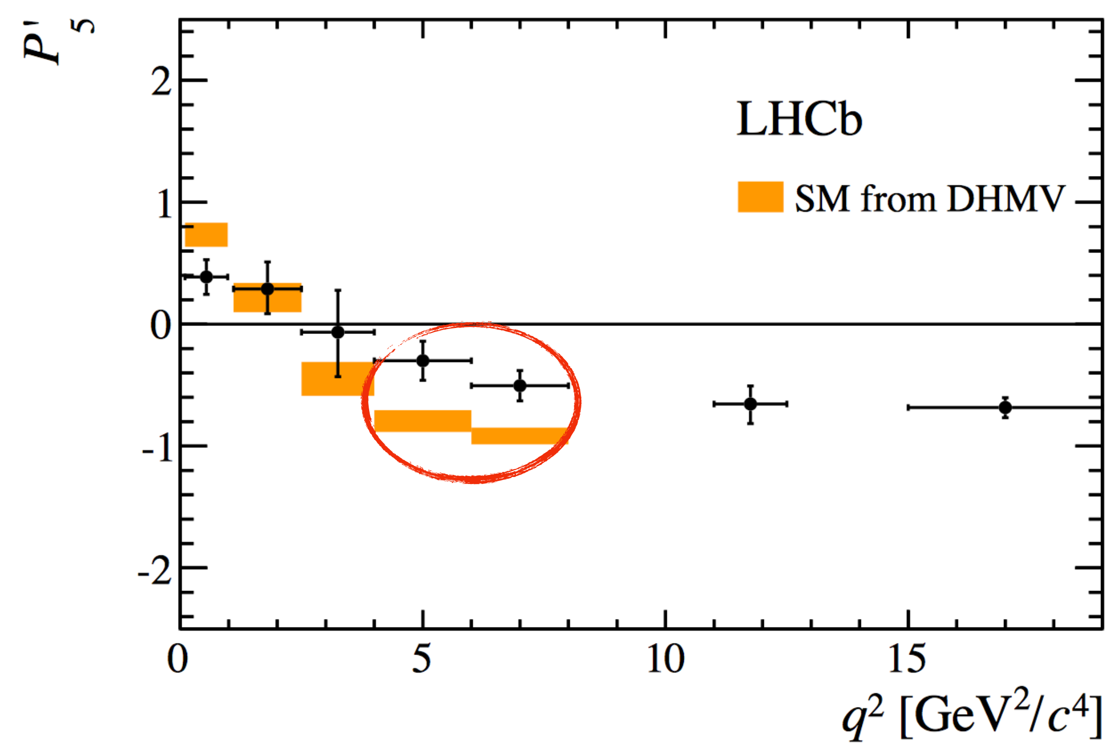
$\Rightarrow$ **Single soft gluon approximation**: strictly valid only for $q^2 \ll 4m_c^2$!



Results recently corroborated by: Bobeth et al. `17 Blake et al. `17

A different analysis: why?

The first analyses addressing the *B* —> *K*μμ* angular anomaly were performed employing the **LCSR estimate** for the hadronic contribution



Single soft gluon approximation: strictly valid only for $\mathbf{q^2 << 4 m^2_c}$!

$\Rightarrow$ Analysis of the *B* —> *K*μμ* decay channel only, aiming to extract the hadronic contribution from data and compare it with LCSR estimate (update of Ciuchini et al, '15)

$\Rightarrow$ Global fit of the *b* —> *s* anomalies, without forgetting what we learnt from the previous analysis (update of Ciuchini et al, '17)

Parametrizing the hadronic contributions: The Phenomenological Data Driven (PDD) approach

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

We parametrized the hadronic contribution in order to have terms that cannot be reinterpreted as a NP contribution, hence potential discriminators

$$\tilde{h}_\lambda(q^2) = \sum_i \tilde{h}_\lambda^{(i)} \left(\frac{q^2}{GeV^2}\right)^i$$

$$i = 0 \leftrightarrow C_7^{NP}$$

$$i = 1 \leftrightarrow C_9^{NP}$$

$$\left\{\left(C_9^{\rm eff} + h_-^1\right) V_{L-} + \frac{m_B^2}{q^2}\left[\frac{2m_b}{m_B}\left(C_7^{\rm eff} + h_-^0\right) T_{L-} - 16\pi^2 h_-^2 q^4\right]\right\}$$

$$\left\{\left(C_9^{\rm eff} + h_-^1\right) \tilde{V}_{L0} + \frac{m_B^2}{q^2}\left[\frac{2m_b}{m_B}\left(C_7^{\rm eff} + h_-^0\right) \tilde{T}_{L0} - 16\pi^2 \left(\tilde{h}_0^0 + \tilde{h}_0^1 q^2\right)\right]\right\}$$

$$\left\{\left(C_9^{\rm eff} + h_-^1\right) V_{L+} + \frac{m_B^2}{q^2}\left[\frac{2m_b}{m_B}\left(C_7^{\rm eff} + h_-^0\right) T_{L+} - 16\pi^2 \left(h_+^0 + h_+^1 q^2 + h_+^2 q^4\right)\right]\right\}$$

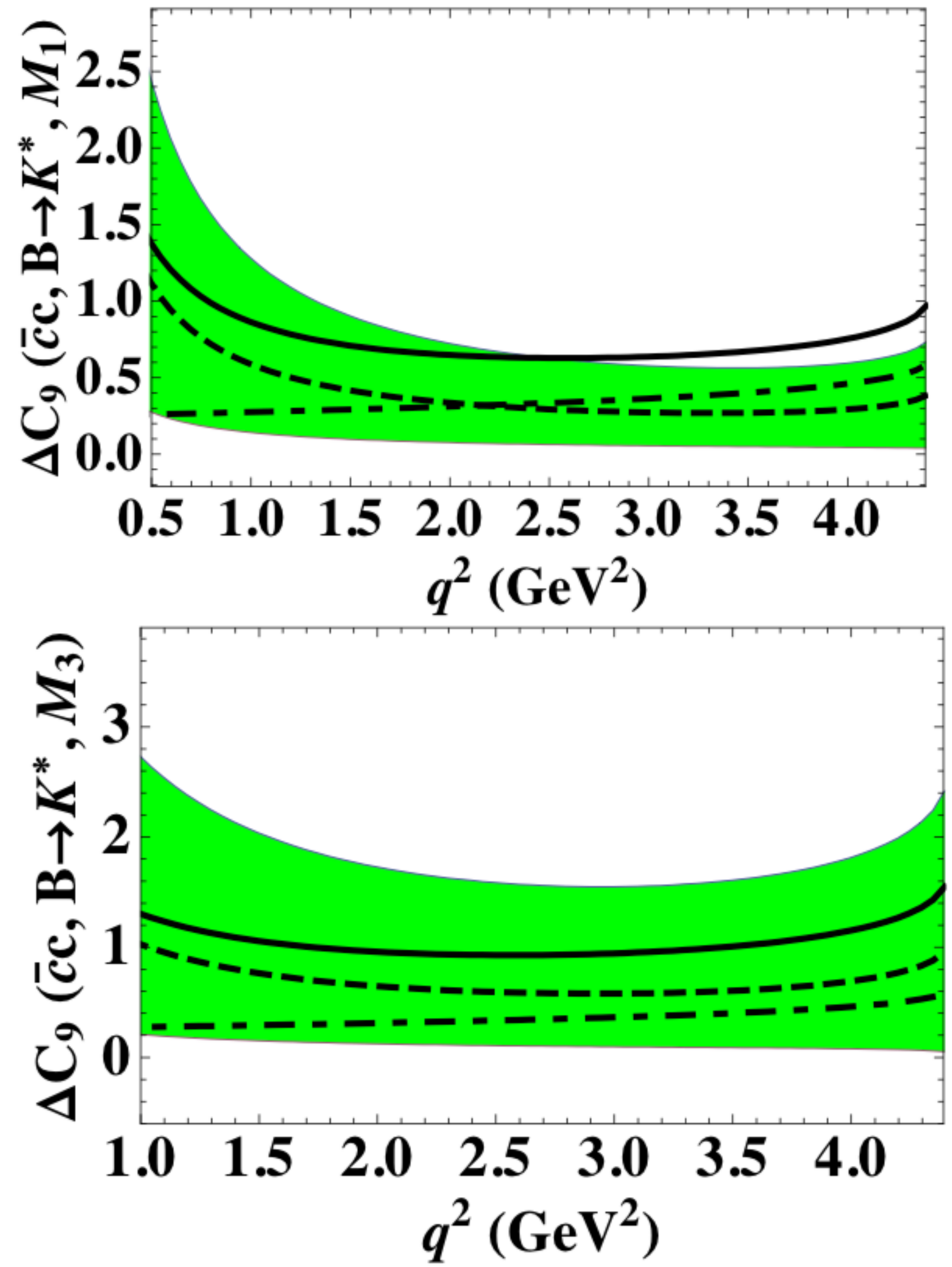
We impose the LCSR estimate only up to q^2 = GeV^2

New Parametrization!

Parametrizing the hadronic contributions: The Phenomenological Model Driven (PMD) approach

We employ the LCSR computation + dispersion relation adopting the given parametrization, using it as a prior on the absolute value (and allowing for a phase factor)

$$\Delta C_{9,i}^{(c\bar{c})}(q^2) = \frac{r_{1,i}\left(1-\frac{\bar{q}^2}{q^2}\right) + \Delta C_{9,i}^{(c\bar{c})}(\bar{q}^2)\frac{\bar{q}^2}{q^2}}{1 + r_{2,i}\frac{\bar{q}^2 - q^2}{m_{J/\psi}^2}}$$



A.Khodjamirian et al., **JHEP 1009 (2010) 089**

Results recently corroborated by: Bobeth et al. `17 Blake et al. `17

How do we compare?

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

Fit results

Phenomenological
Model Driven **(PMD)**

IC = 125

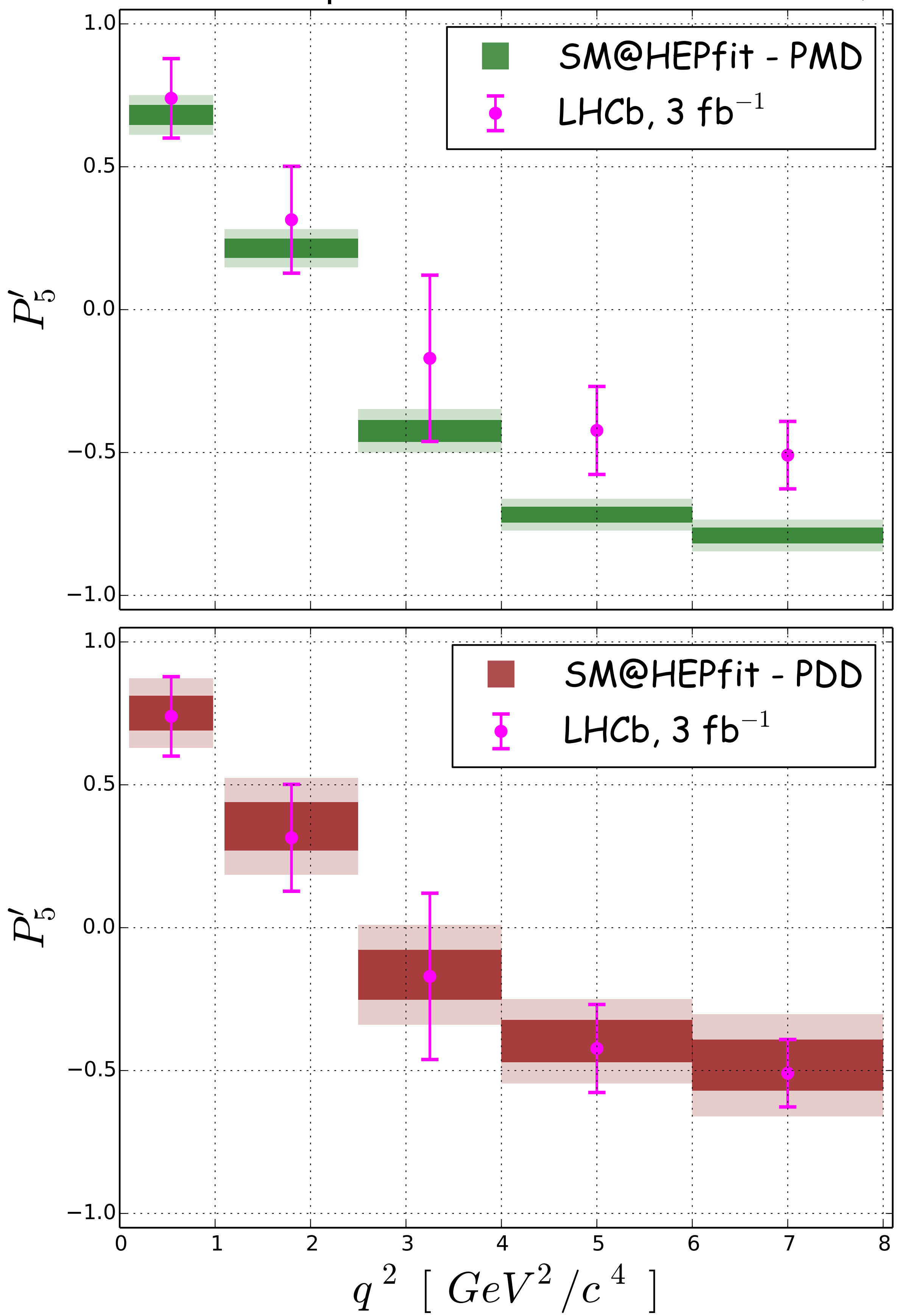
$$P'_5 = \frac{S_5}{\sqrt{F_L(1-F_L)}}$$

Matias et al. \`12

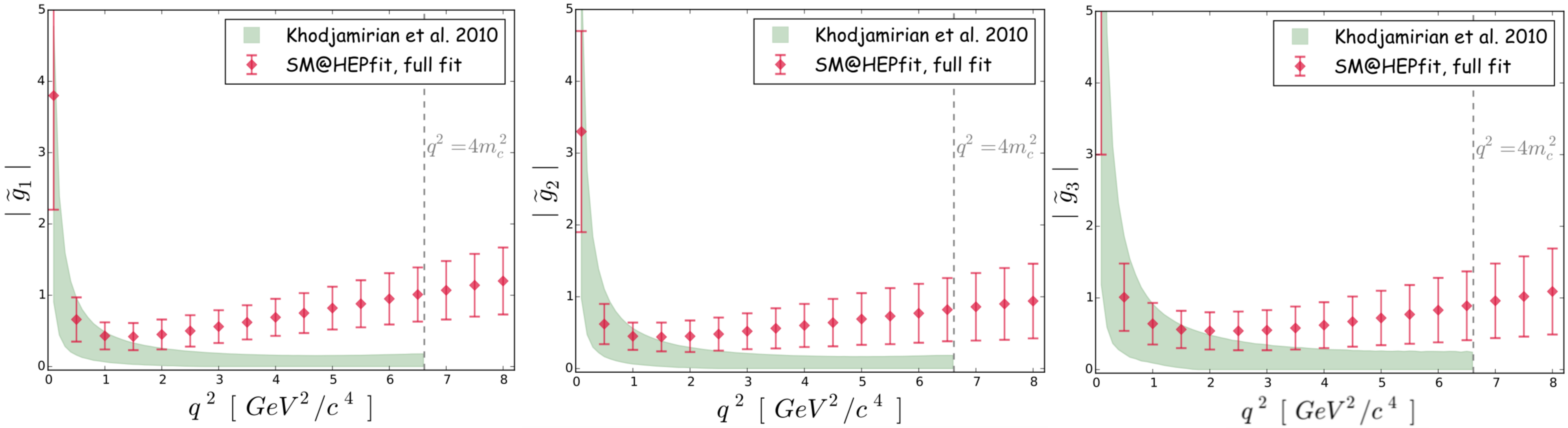
Phenomenological
Data Driven **(PDD)**

IC = 101

update of Ciuchini et al, ’15

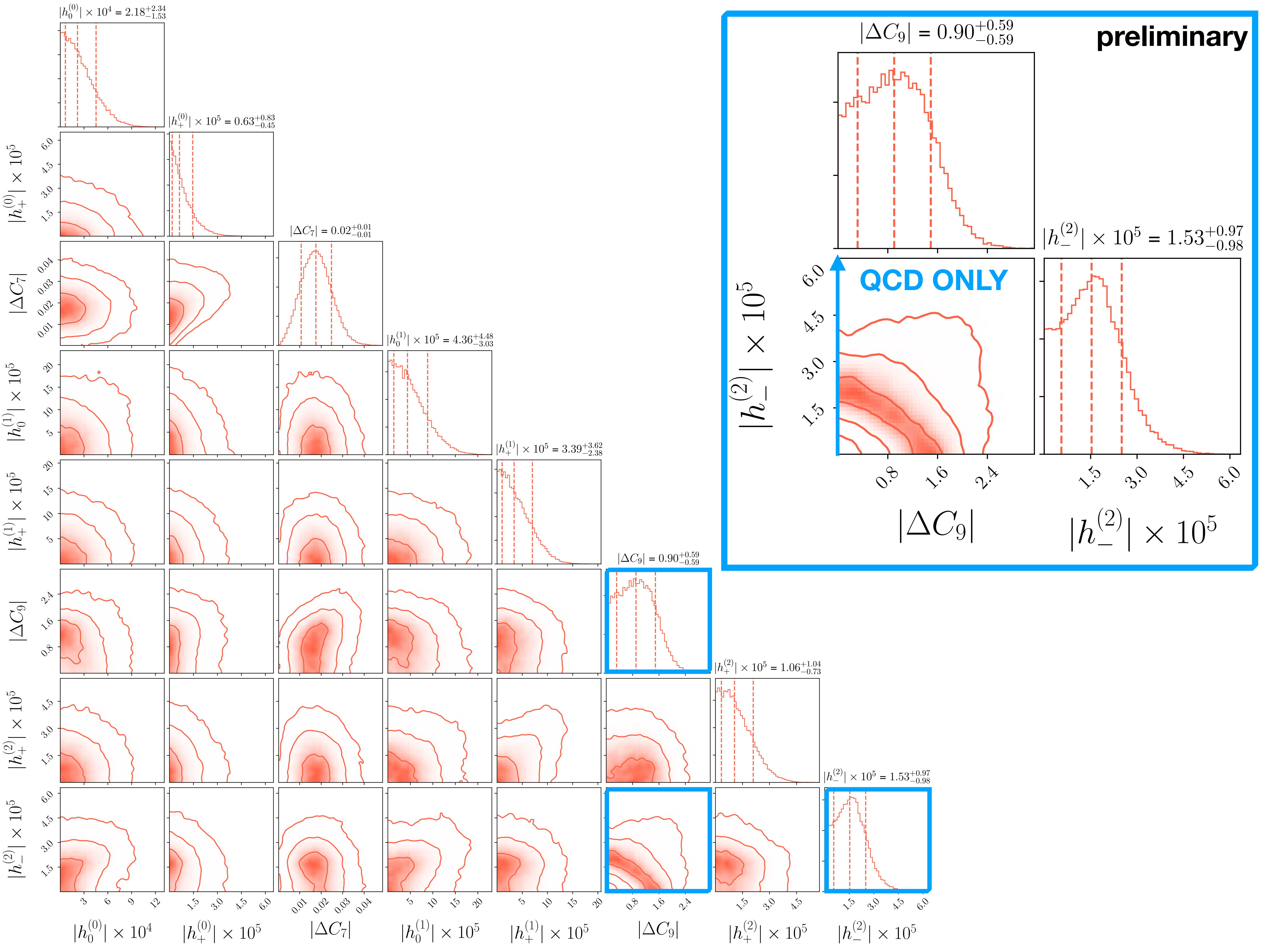


PDD: Results for the hadronic contributions



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

Expected growth of the had. contributions in the region where multiple soft gluon emission is no longer negligible, however obtaining results in the same ballpark of the ones obtained applying dispersion relations to the LCSR estimates



$|h_0^{(0)}| \times 10^4 = 2.18^{+2.34}_{-1.53}$
$|h_+^{(0)}| \times 10^5 = 0.63^{+0.83}_{-0.45}$
$|\Delta C_7| = 0.02^{+0.01}_{-0.01}$
$|h_0^{(1)}| \times 10^5 = 4.36^{+4.48}_{-3.03}$
$|h_+^{(1)}| \times 10^5 = 3.39^{+3.62}_{-2.38}$
$|\Delta C_9| = 0.90^{+0.59}_{-0.59}$
$|h_+^{(2)}| \times 10^5 = 1.06^{+1.04}_{-0.73}$
$|h_-^{(2)}| \times 10^5 = 1.53^{+0.97}_{-0.98}$
$|h_0^{(0)}| \times 10^4$
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$|\Delta C_7|$
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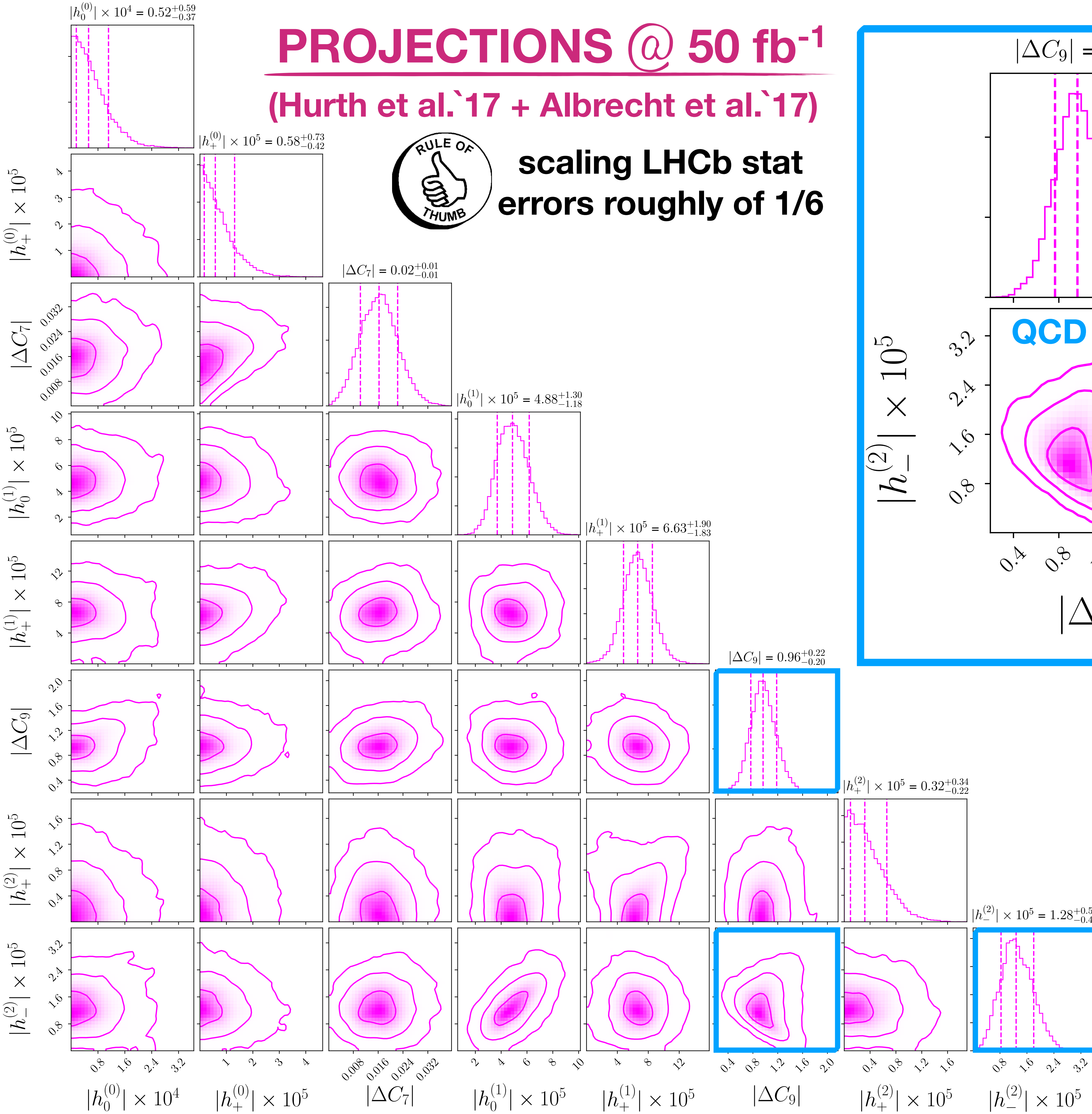
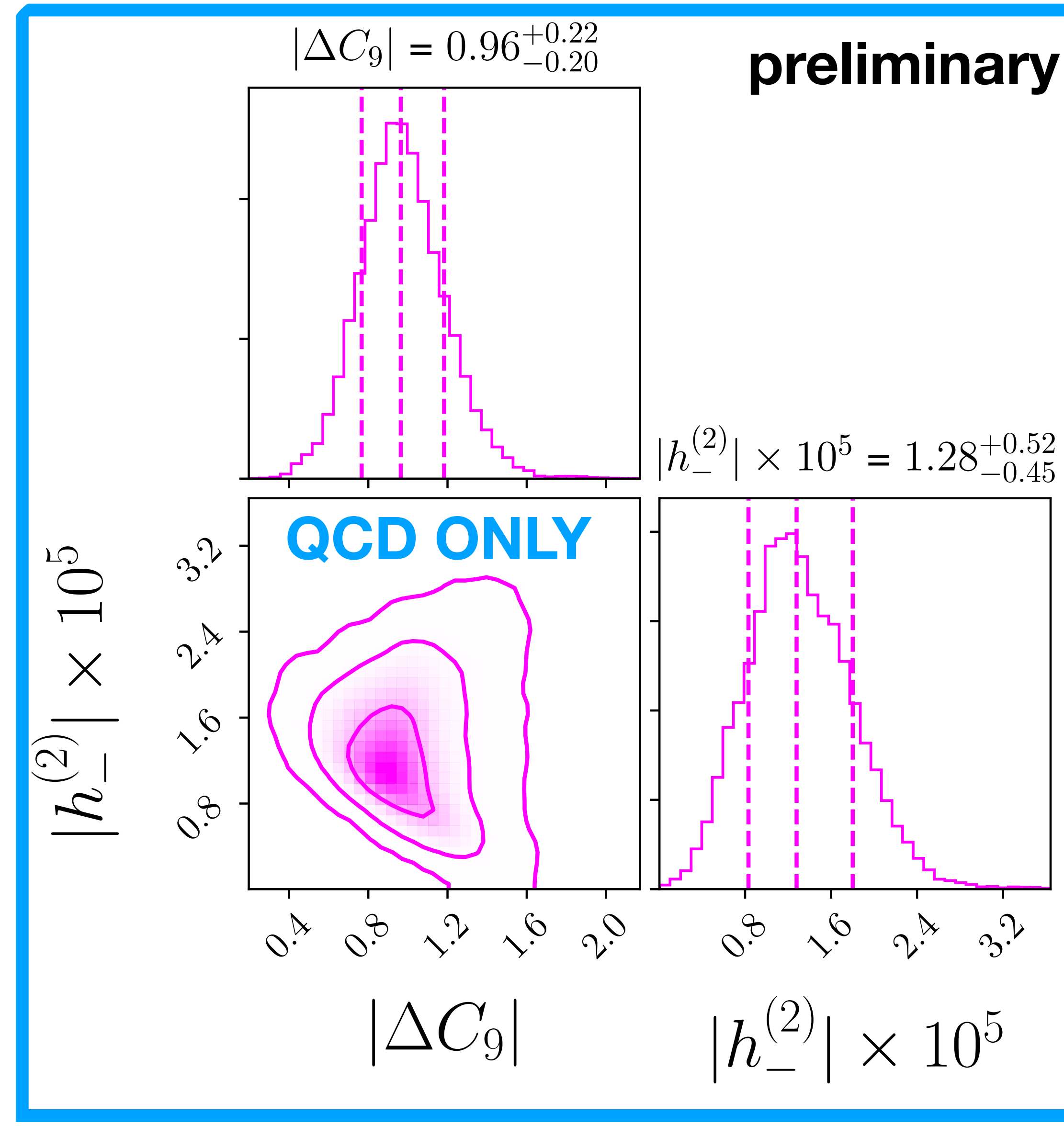
$|h_+^{(2)}| \times 10^5$
$|h_-^{(2)}| \times 10^5$
preliminary
QCD ONLY

PROJECTIONS @ 50 fb^{-1}

(Hurth et al.`17 + Albrecht et al.`17)

scaling LHCb stat errors roughly of 1/6





What did we learn so far?

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.* $\boldsymbol{q^2 \lesssim 1}$ ***GeV***$\boldsymbol{^2}$

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***

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*

About NP and b —> s ll Global Analyses

TANTALIZING

LHCb measurement of $R_{K^{(*)}}$ may be the most convincing call for NP in b —> s ll.

Hiller & Kruger, PRD 69 (2004) 074020

COMBINE THESE TWO WITH P'_5 ANOMALY + ALL OTHER AVAILABLE DATA

Need of global analyses of state-of-the-art b —> s ll measurements.

Evidence for NP contributions at the 5σ level.
Origin of these effects commonly associated to Q_9 .

$C_{9\mu}^{NP}$

Stat significance robust against QCD power corrections?

Data unambiguously suggest NP in muonic vectorial current?

Altmannshofer, W. et al. ‘17
Capdevila, B. et al. ‘17
Ciuchini, M. et al. ‘17
D’Amico, G. et al. ‘17
Geng, L.-S. et al. ‘17
Hiller & Nisandzic ‘17

Set of measurements included in our global analysis

LHCb	$F_L, A_{FB}, S_{3,4,5,7,8,9}$ i.e. available angular info for $K^{(*)}, \phi$ modes $\mathcal{B}(B \to K^{(*)}\ell\ell, \gamma)$ $\mathcal{B}(B_s \to \phi\,\mu\mu, \gamma)$ $R_{K,[1,6]}, R_{K^*,[0.045,1.1],[1.1,6]}$	JHEP 1611 (2016) 047 JHEP 1602 (2016) 104 JHEP 1509 (2015) 179 JHEP 1504 (2015) 064 Nucl.Phys. B867 (2013) 1-18 PRL 113 (2014) 151601 arXiv:1705.05802
ATLAS	$F_L, A_{FB}, S_{3,4,5,7,8}$	ATLAS-CONF-2017-023
CMS	$P_1, P_5', F_L, A_{FB}, \mathcal{B}(B \to K^*\mu\mu)$	CMS-PAS-BPH-15-008 twiki.cern/…/CMSPublic/…
Belle	$P'_{5\,(\mu,e)}$	PRL 118 (2017) 111801

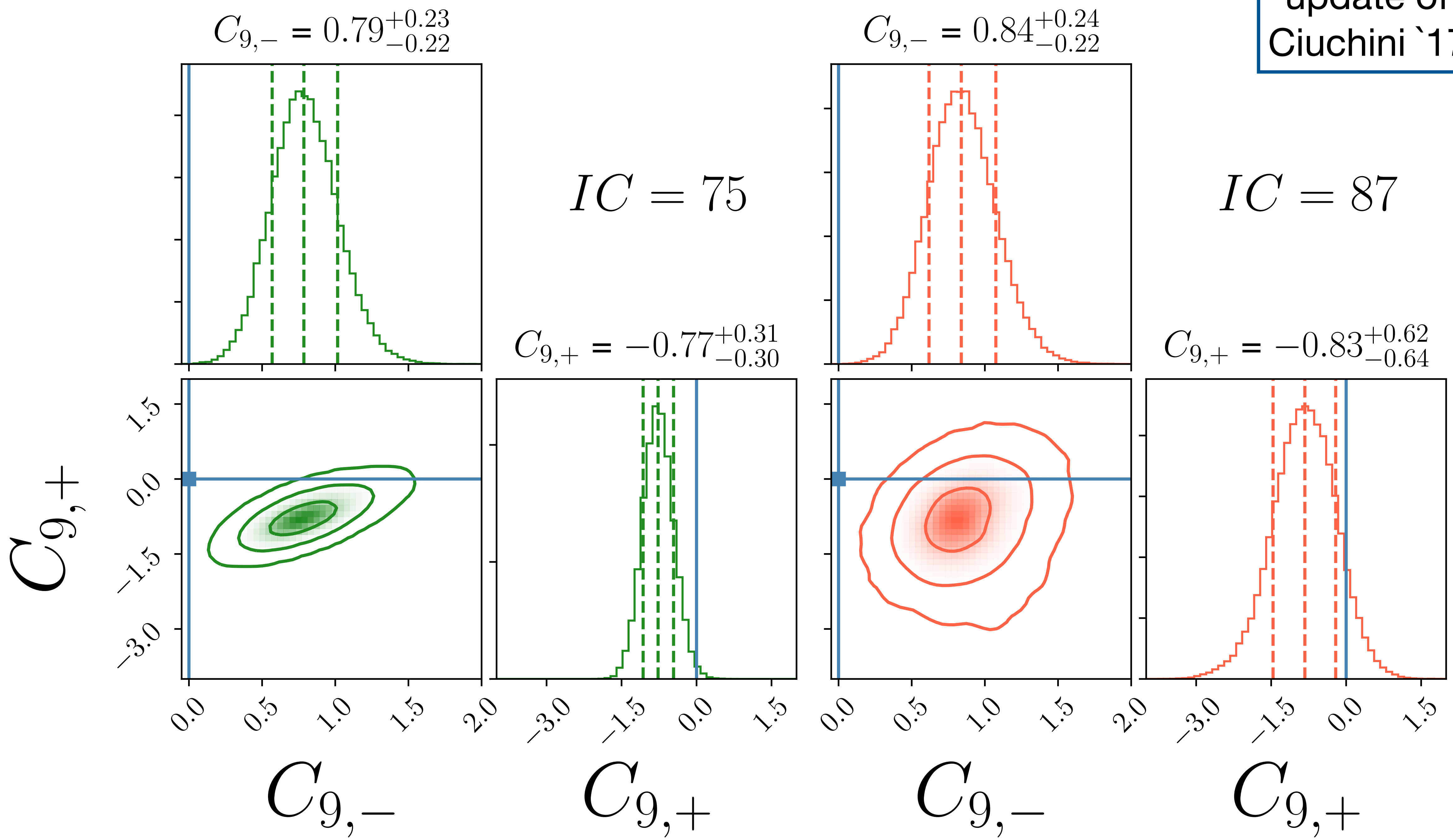
We use data in the large recoil region only, i.e. where anomalies show up.

We always take into account theory/experimental correlations when provided.

LHCb, HFLAV	$\mathcal{B}(B_s \to \mu\mu), \mathcal{B}(B \to X_s\gamma)$	LHCB-PAPER-2017-001 FERMILAB-PUB-16-611-ND

Vectorial NP Scenario

preliminary update of Ciuchini `17

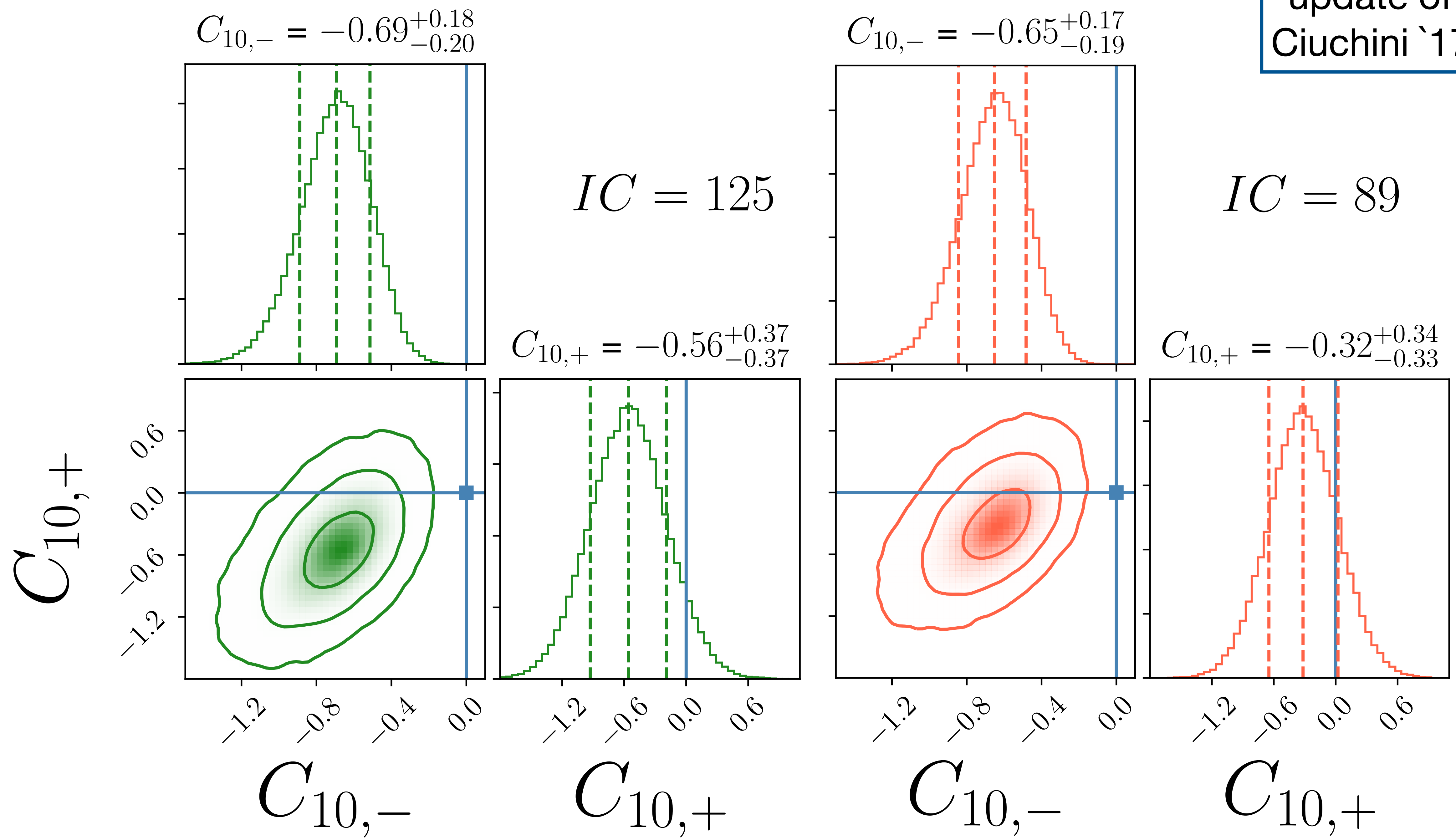


Minus coefficient is probed by LUV obs.
Minimality currently rewards PMD

$$C_{9,\pm}^{NP} = \frac{1}{2}\left(C_{9,\mu}^{NP} \pm C_{9,e}^{NP}\right)$$

Axial NP Scenario

preliminary update of Ciuchini `17

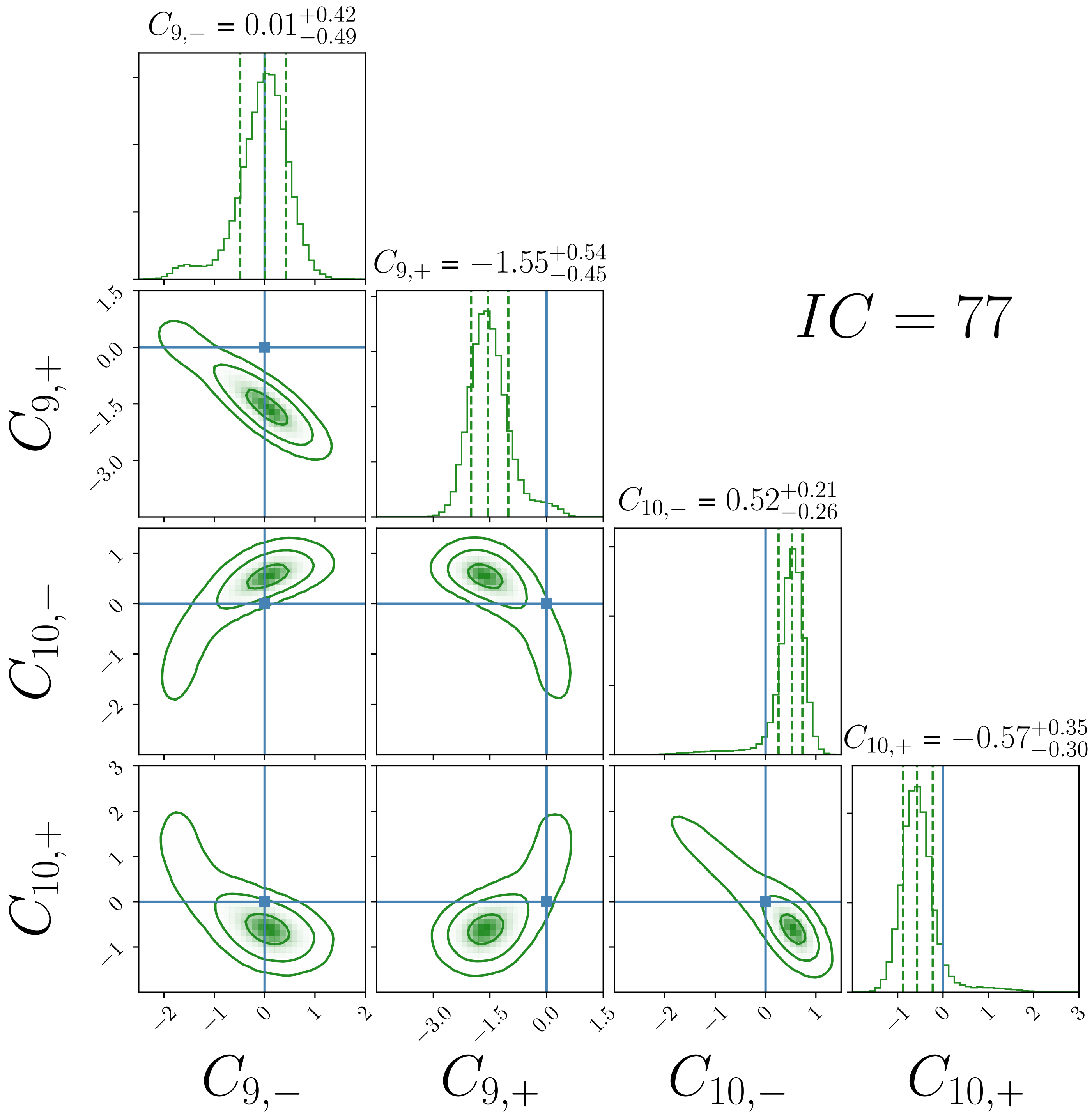


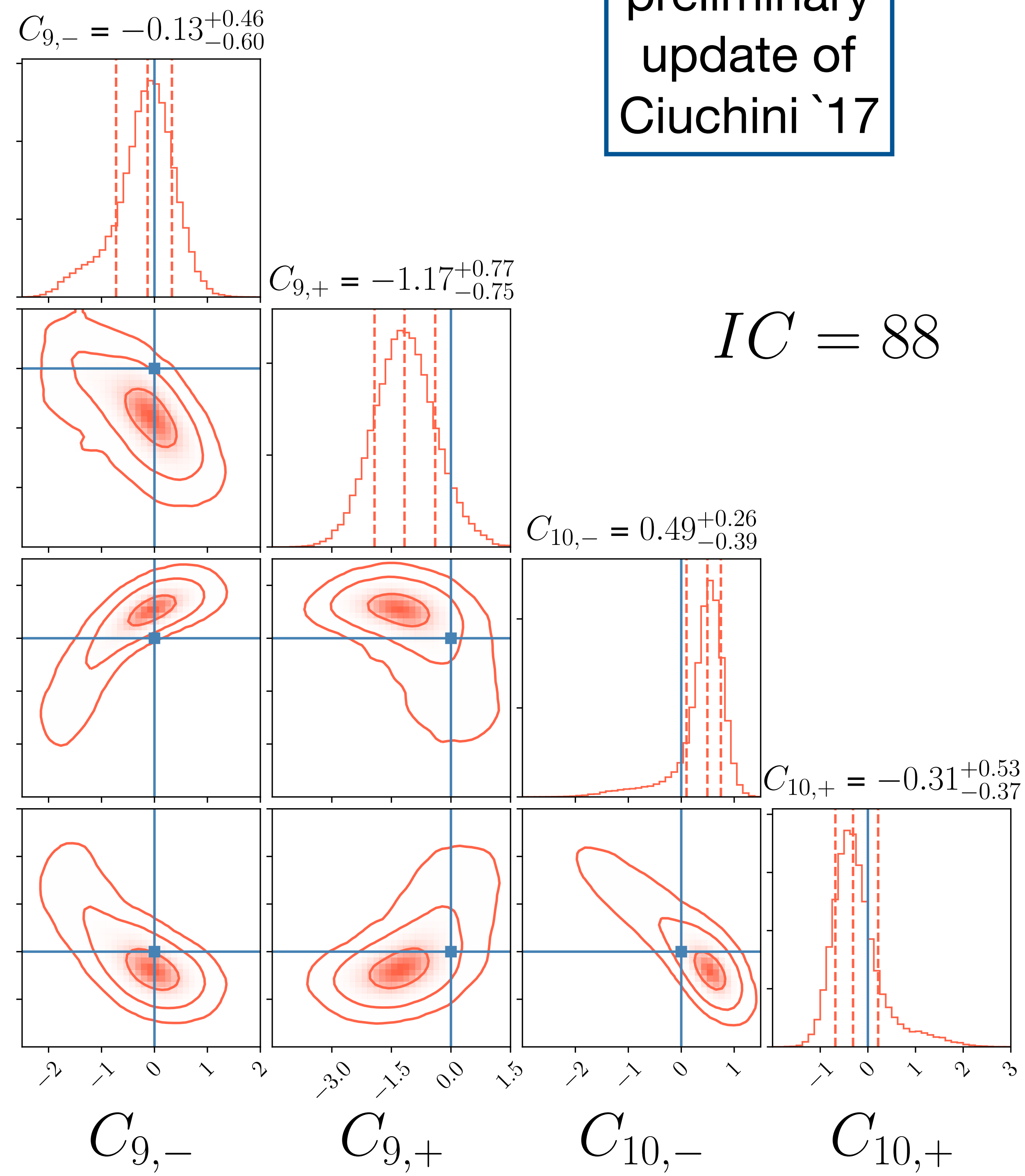
Minus coefficient is again probed by LUV obs.
In PDD the axial sol. is as viable as the vectorial

$$C^{NP}_{10,\pm} = \frac{1}{2}(C^{NP}_{10,\mu} \pm C^{NP}_{10,e})$$

Vectorial & Axial NP Scenario

preliminary
update of
Ciuchini `17

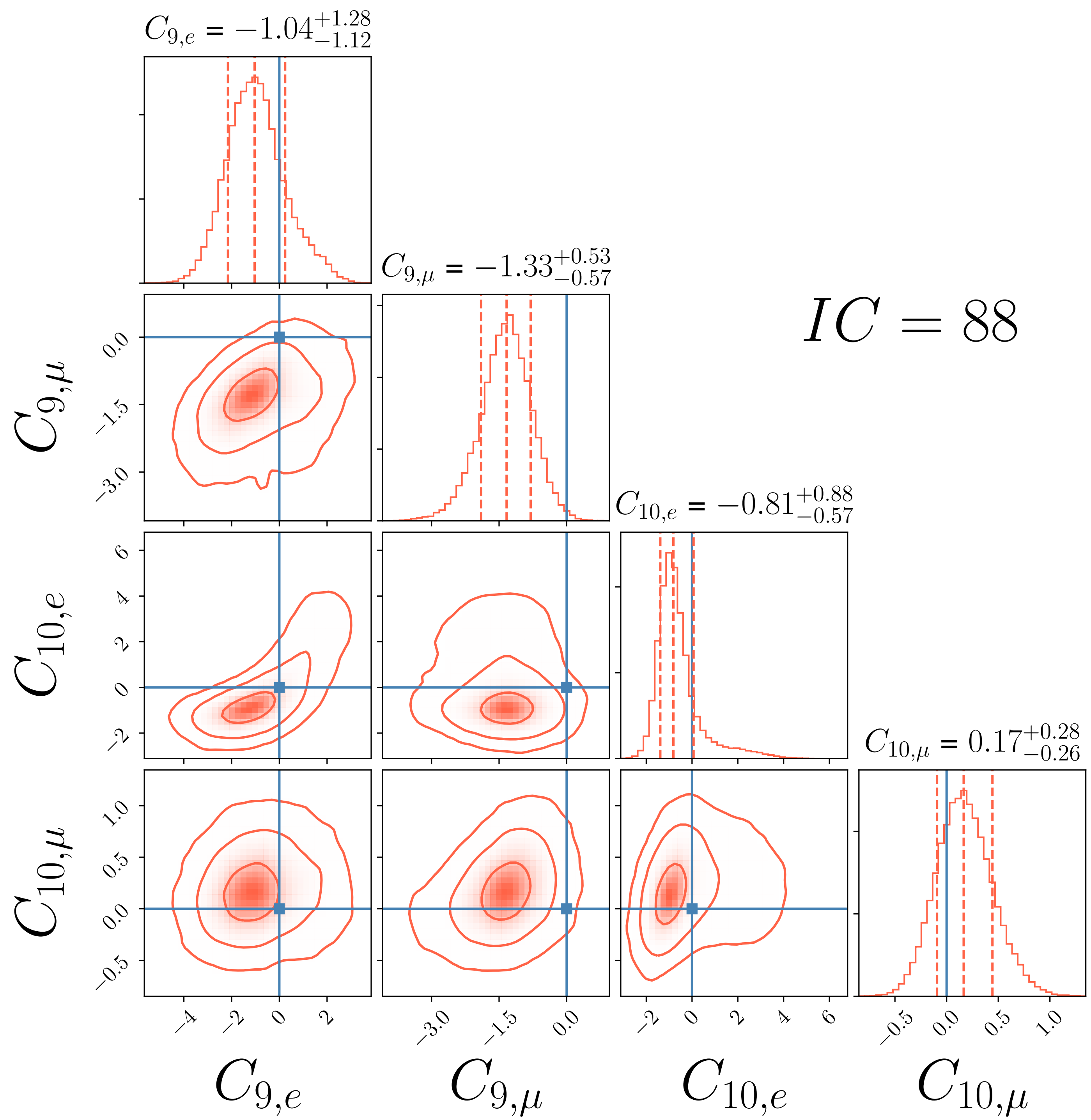




"Polluted" plus-direction in C9 is selected by data
in strong correlation with the axial coefficients

VECTORIAL & AXIAL NP SCENARIO

preliminary update of Ciuchini `17

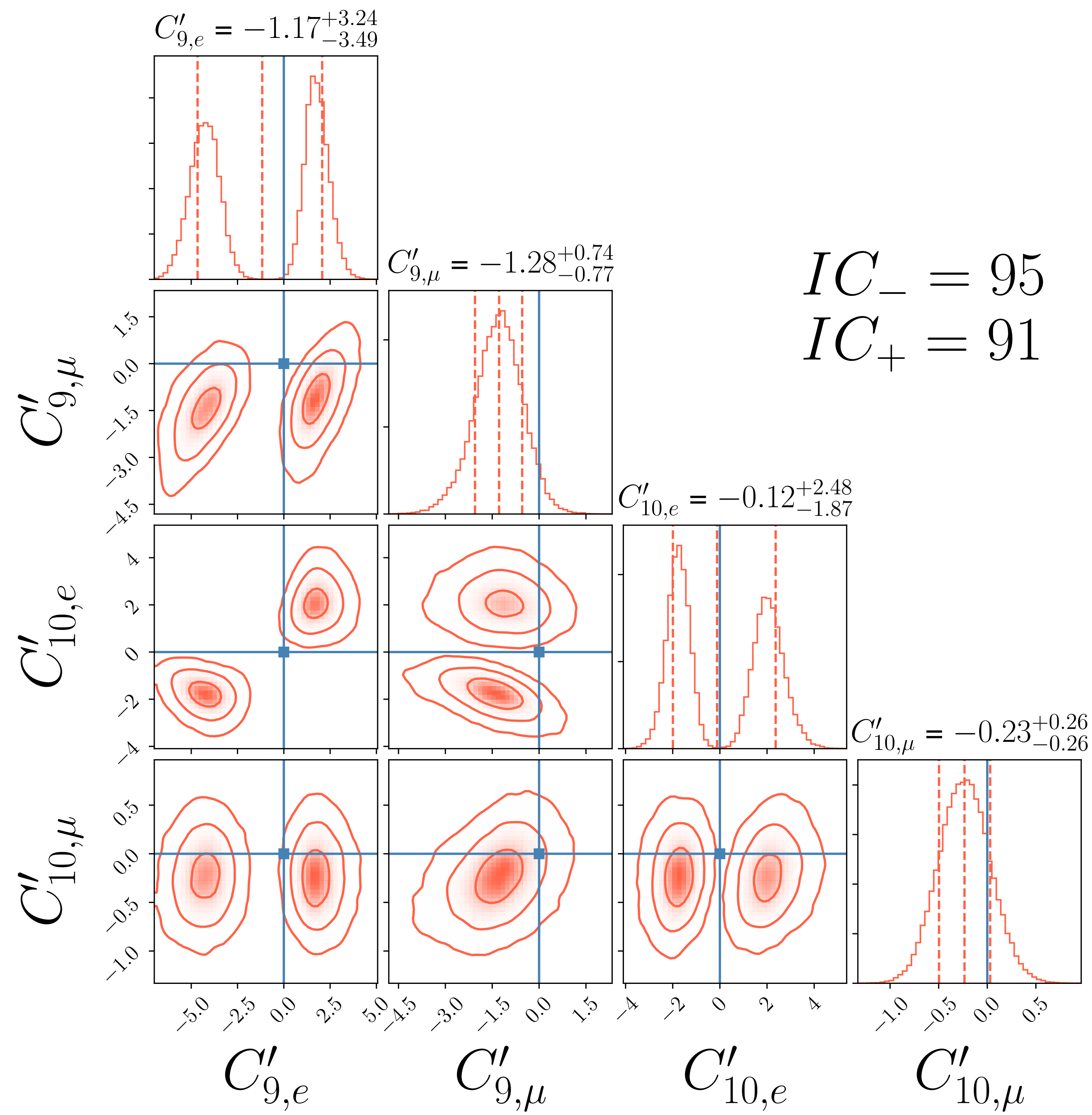


$IC = 88$

Back in the lepton-flavored basis, such correlations point towards a preferred scenario with muonic vectorial NP

(Vectorial & Axial)' NP Scenario

preliminary update of Ciuchini `17



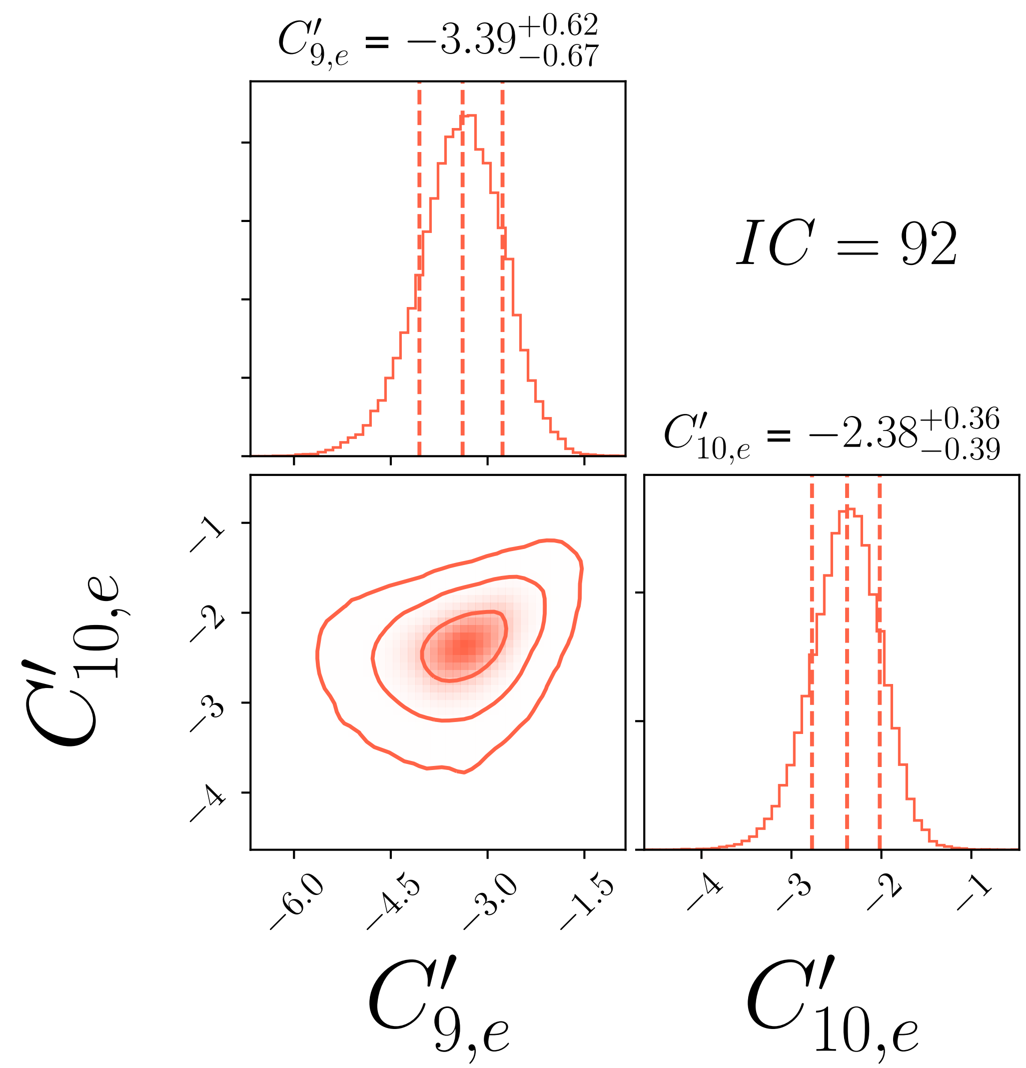
$$IC_- = 95$$
$$IC_+ = 91$$

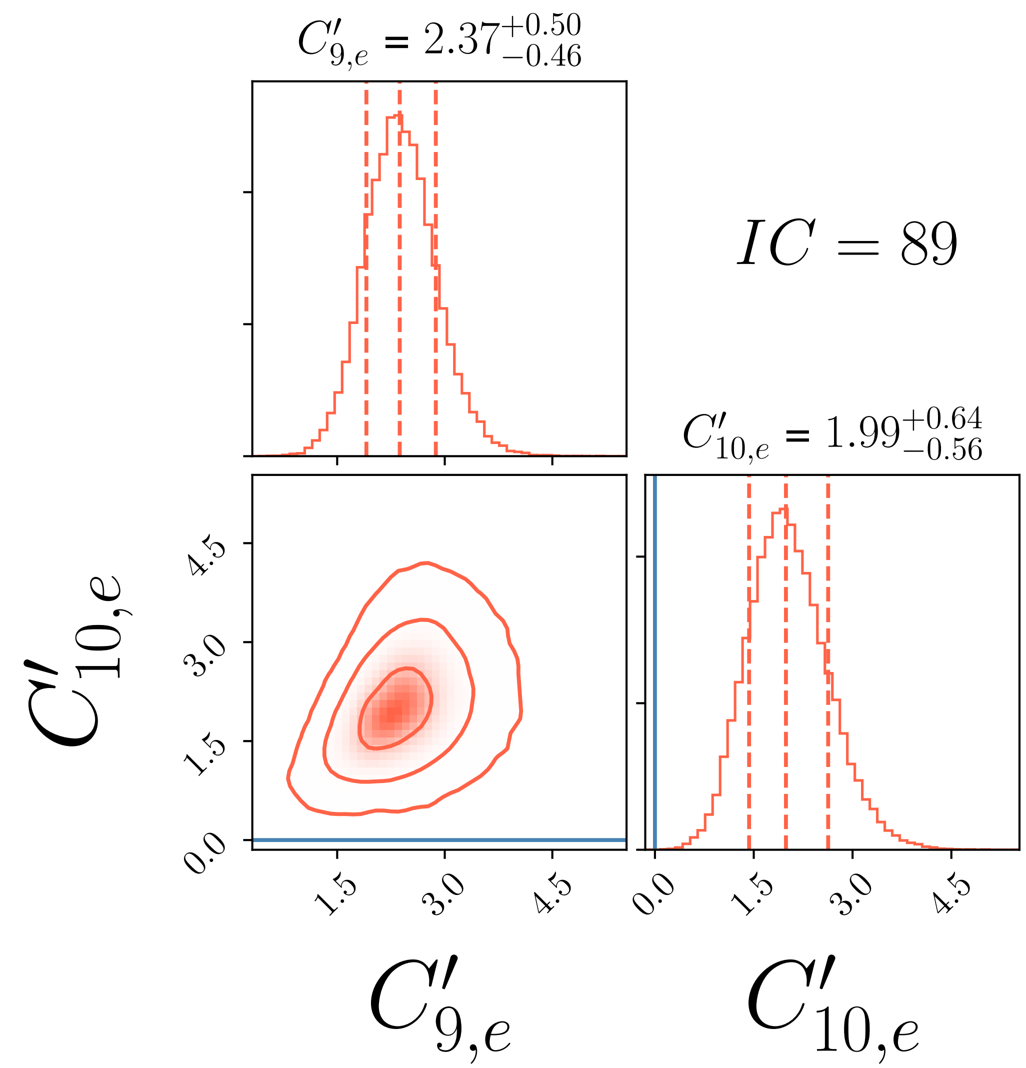
The right-handed scenario points towards a preferred electron scenario
However, even in PDD, these solutions are (a bit) disfavored

(Vectorial & Axial)' NP Scenario

Bimodality driven by Belle data, can be studied separately

preliminary update of Ciuchini `17





The right-handed scenario points towards a preferred electron scenario

However, even in PDD, these solutions are (a bit) disfavored

Summary & Conclusions

- **Hadronic contributions are important in B to V ll amplitude.**
  —> present estimate of "charm-loop effect" limited to $q^2 << 4m^2_c$.

- **Unknown QCD power corrections may also mimic NP effects.**
  —> hard to call for NP in standalone study of $K^*\mu\mu$ angular obs!

Evidence for q² dependence beyond the first order in a power expansion in q² of the hadronic correlator

$$\tilde{h}_\lambda(q^2) \sim \epsilon_{\lambda,\mu} \int d^4x \, e^{iqx} \langle \overline{V}(\overline{P}) | T\{J^{\mu,e.m.}_{had}(x) \mathcal{H}^{eff}_{had}(0)\} | \overline{B} \rangle$$

may definitely discriminate genuine NP effects with the advent of more data from LHCb / Belle2.

- $R_{K^{(*)}}$ **anomalies** (if not stat fluke/exp issue) undoubtedly **require NP.**

A conservative approach to hadronic effects in b —> s ll global fits impacts significances + leaves room for different NP interpretations of current data.