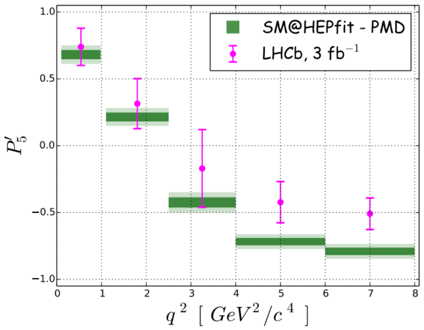
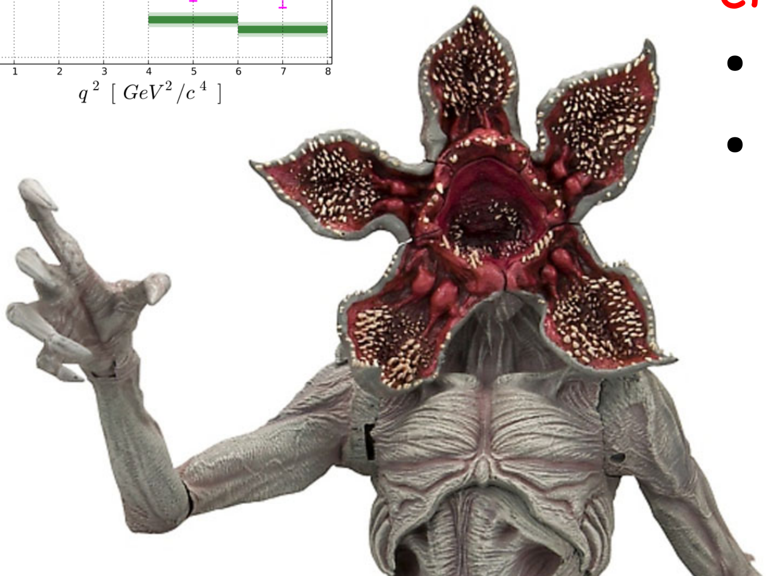
Charm-loop effects

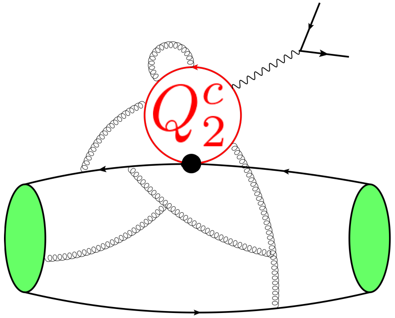


Marco Ciuchini

INFN ROMA TRE

- charm loop in B → K*ℓℓ decays
  - theoretical estimates
  - phenomenological approaches





LHCP Bologna 2018

Angular analysis of B → K*μμ

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

angular analysis

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

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

8 CP-AVERAGED OBSERVABLES

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

In the helicity amplitude formalism $(m_\ell \sim 0)$, we need to compute few helicity amplitudes: $H^\lambda_{V,A}$ $\quad \lambda = 0, \pm$

$$I_1^c = -I_2^c = \frac{F}{2}\left(|H_V^0|^2 + |H_A^0|^2\right),$$

$$I_1^s = 3 I_2^s = \frac{3}{8} F \left(|H_V^+|^2 + |H_V^-|^2 + |H_A^+|^2 + |H_A^-|^2\right),$$

$$I_3 = -\frac{F}{2} \mathrm{Re}\left[H_V^+ (H_V^-)^* + H_A^+ (H_A^-)^*\right],$$

$$I_4 = \frac{F}{4} \mathrm{Re}\left[(H_V^+ + H_V^-)(H_V^0)^* + (H_A^+ + H_A^-)(H_A^0)^*\right],$$

$$I_5 = \frac{F}{4} \mathrm{Re}\left[(H_V^- - H_V^+)(H_A^0)^* + (H_A^- - H_A^+)(H_V^0)^*\right],$$

$$I_6^s = F \mathrm{Re}\left[H_V^- (H_A^-)^* - H_V^+ (H_A^+)^*\right],$$

$$I_6^c = 0,$$

$$I_7 = \frac{F}{2} \mathrm{Im}\left[(H_A^+ + H_A^-)(H_V^0)^* + (H_V^+ + H_V^-)(H_A^0)^*\right],$$

$$I_8 = \frac{F}{4} \mathrm{Im}\left[(H_V^- - H_V^+)(H_V^0)^* + (H_A^- - H_A^+)(H_A^0)^*\right],$$

$$I_9 = \frac{F}{4} \mathrm{Im}\left[H_V^+ (H_V^-)^* + H_A^+ (H_A^-)^*\right].$$

$$H_V{}^{\lambda} = \frac{4iG_F m_B}{\sqrt{2}}\frac{\alpha_e}{4\pi}\lambda_t\left\{C_9^{\rm eff}\tilde{V}_{L\lambda} + \frac{m_B^2}{q^2}\left[\frac{2m_b}{m_B}C_7^{\rm eff}\tilde{T}_{L\lambda} - 16\pi^2 h_\lambda\right]\right\},$$

$$H_A{}^{\lambda} = \frac{4iG_F m_B}{\sqrt{2}}\frac{\alpha_e}{4\pi}\lambda_t C_{10}\tilde{V}_{L\lambda}. \qquad \lambda = 0, \pm$$

NNLO Wilson coefficients from the ΔB=1, ΔS=1 effective Hamiltonian:

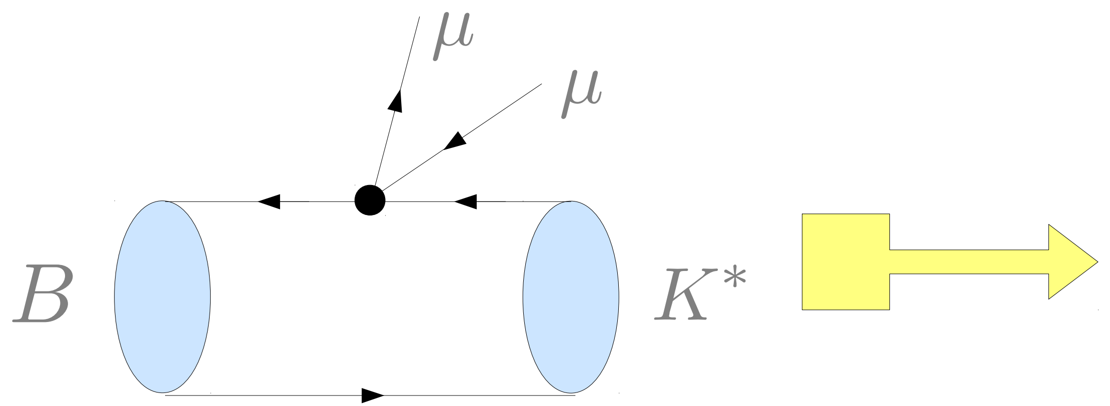
$$\mathcal{H}_{\rm eff}^{\Delta B=1} = \mathcal{H}_{\rm eff}^{sl+\gamma} + \mathcal{H}_{\rm eff}^{had}$$

$$\mathcal{H}_{\rm eff}^{sl+\gamma} = -\frac{4G_F}{\sqrt{2}}\lambda_t\left(C_7 Q_{7\gamma} + C_9 Q_{9V} + C_{10}Q_{10A}\right)$$

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

$$Q_{9V} = \frac{\alpha_e}{4\pi}(\bar{s}_L\gamma_\mu b_L)(\bar{\ell}\gamma^\mu \ell)\,,$$

$$Q_{10A} = \frac{\alpha_e}{4\pi}(\bar{s}_L\gamma_\mu b_L)(\bar{\ell}\gamma^\mu\gamma^5 \ell)\,.$$



Hadronic matrix elements of quark currents: FORM FACTORS*

*not discussed here

Charm loop in the effective theory

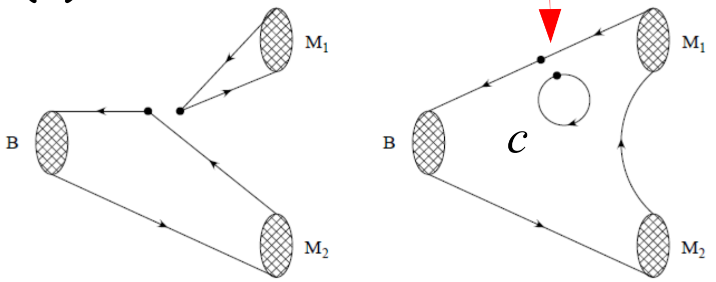
$$\mathcal{H}_{\rm eff}^{\rm had} = \frac{4G_F}{\sqrt{2}}\left\{\lambda_u\left[C_1\left(Q_1^u - Q_1^c\right) + C_2\left(Q_2^u - Q_2^c\right)\right] - \lambda_t\left[C_1 Q_1^c + C_2 Q_2^c + \sum_{i=3}^{6} C_i Q_i + C_8 Q_{8g}\right]\right\}$$

top loops in the SM give rise to penguin operators

- non-perturbative matrix elements of local operators
- α_s suppressed matching conditions, small Wilson coefficients

charm (and up) loops appear as Wick contractions in the MEs

- dominated by the insertion of $Q_{1,2}$, namely O(1) Wilson coefficients
- easily produce intermediate real states, i.e. rescattering, non-local contributions, strong phases, etc.



BUT 4-quark operators also contribute to the ME. In the helicity amplitude formalism, they appear in

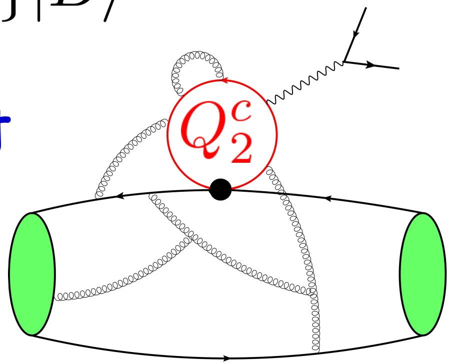
Jäger, Camalich, arXiv:1212.2263; Melikhov, Nikitin, Simula, hep-ph/9807464

$$\mathrm{H}_V{}^{\lambda} = \frac{4iG_F m_B}{\sqrt{2}} \frac{e^2}{16\pi^2} \lambda_t \left\{ C_9^{\mathrm{eff}} \tilde{V}_{L\lambda} + \frac{m_B^2}{q^2} \left[\frac{2m_b}{m_B} C_7^{\mathrm{eff}} \tilde{T}_{L\lambda} - 16\pi^2 h_\lambda \right] \right\}$$

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

- At small values of $q^2 = m_{\ell\ell}{}^2$, the H^{had} matrix element factorizes in the infinite mass limit

Beneke, Feldmann, Seidel, hep-ph/0106067

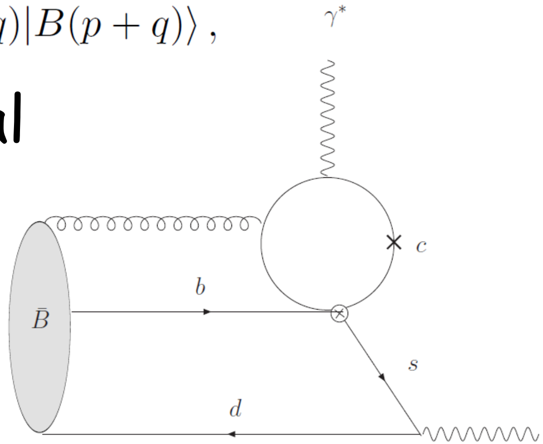


- Yet the "charming penguin" issues are present:
  → how large is the genuine power-suppressed contribution?
  → how much does it increase approaching the resonant region where factorization badly fails?

An estimate in 2 steps:

Khodjamirian, Mannel, Pivovarov, Wang, arXiv:1006.4945

1. at $q^2 \ll 4m_c^2$ the charm loop is dominated by light-cone dynamics. One can write the ME $\left[\mathcal{H}_\mu^{(B\to K^{(*)})}(p,q)\right]_{nonfact} = 2C_1\langle K^{(*)}(p)|\widetilde{\mathcal{O}}_\mu(q)|B(p+q)\rangle\,,$ where $\widetilde{\mathcal{O}}_\mu(q) = \int d\omega\, I_{\mu\rho\alpha\beta}(q,\omega)\bar{s}_L\gamma^\rho\delta[\omega - \frac{(in_+\mathcal{D})}{2}]\widetilde{G}_{\alpha\beta}b_L$ is a non-local operator representing the first subleading term of an expansion in $\Lambda^2/(4m_c^2-q^2)$ (single soft gluon approximation), whose ME is computed using light-cone sum rules



step 1 estimate of the hadronic contribution at small $q^2 <$ few GeV^2
but large uncertainties (100%? more?)
no hard gluons, no phases, no scale and scheme dependence, …

2. extend the previous result to larger q^2 using a dispersion relation, modeling the spectral function (2 physical $\Psi^{(')}$ + effective poles)

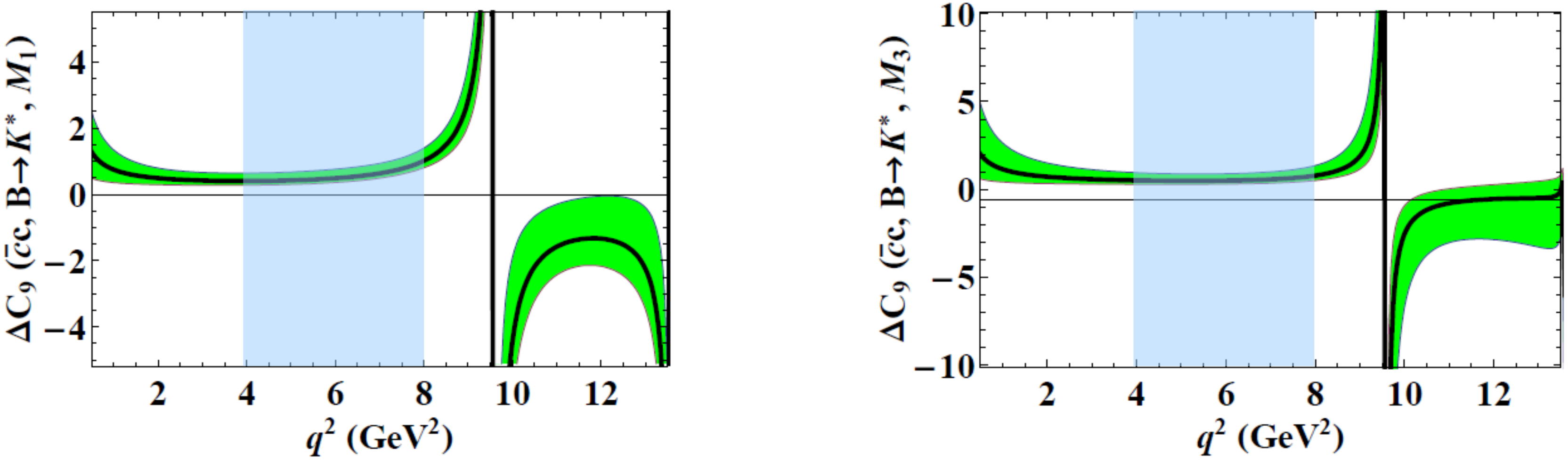
step 2

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

$r_{1,i}$	$r_{2,i}$
$0.10^{+0.02}_{-0.00}$	$1.13^{+0.00}_{-0.01}$
$0.09^{+0.01}_{-0.00}$	$1.12^{+0.00}_{-0.01}$
$0.06^{+0.04}_{-0.10}$	$1.05^{+0.05}_{-0.04}$

but model dependence, duality violation, no pert. gluons, no phases: uncertainty?

Khodjamirian, Mannel, Pivovarov, Wang, arXiv:1006.4945



2010 → today

Step 1: no new non-perturbative calculation. However an hierarchy among contributions in the helicity basis has been found

Jäger, Camalich, arXiv:1212.2263

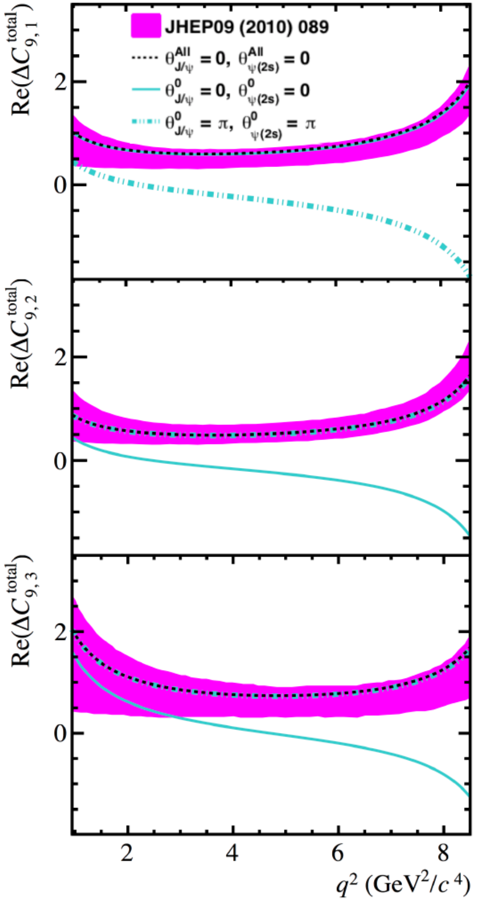
$$h_+ \sim \mathcal{O}\left(\frac{\Lambda}{m_b}\right) h_-$$

Step 2: recent attempts to gain more control over the q^2 dependence improving the dispersion relation approach

1. new phenomenological model using resonance data over the full dimuon spectrum
   Blake, Egede, Owen, Pomery, Petridis, arXiv:1709.03921
2. replace the dispersion relation with a z-expansion of h_λ, constraining the coefficients using analiticity and
   Bobeth, Chrzaszcz, van Dyk, Virto, arXiv:1707.07305
   1. resonant $B \to \Psi^{(n)}K^*$ data (masses and amplitudes)
   2. LCSR + QCDF theoretical results at small/negative q^2

empirical model

Blake, Egede, Owen, Pomery, Petridis, arXiv:1709.03921
see also LHCb collaboration, arXiv:1612.06764



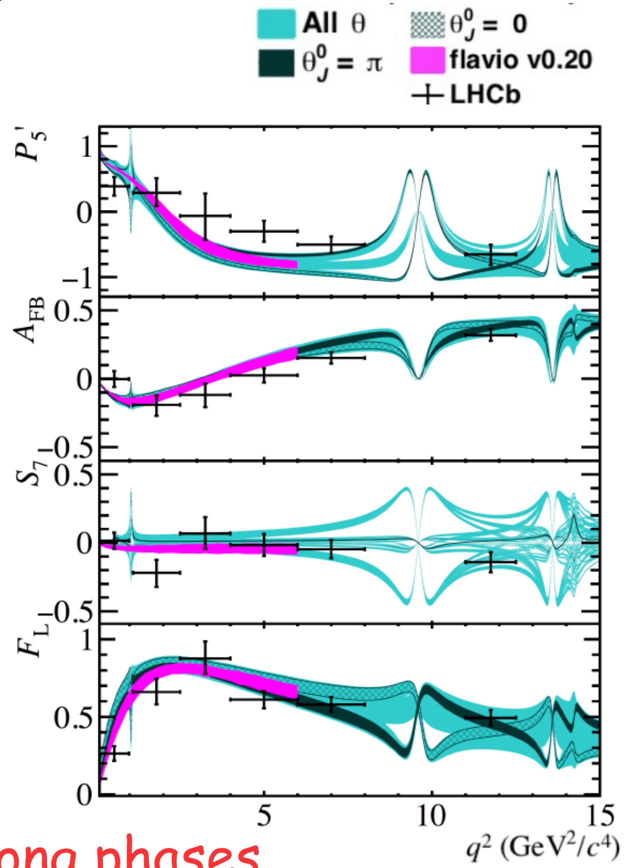
The hadronic contribution is modeled as the sum of 1⁻⁻ resonances given by relativistic Breit-Wigner functions

$$\Delta C^{\rm had}_{9\ \lambda}(q^2) = \sum_j \eta^\lambda_j e^{i\theta^\lambda_j} A^{\rm res}_j(q^2)$$

$$A^{\rm res}_j(q^2) = \frac{m_{{\rm res}\,j}\Gamma_{{\rm res}\,j}}{(m^2_{{\rm res}\,j} - q^2) - i m_{{\rm res}\,j}\Gamma_j(q^2)}$$

Open issues:

Why should it work far from the resonances? What about double counting? How large is the model uncertainty?



Illustrate nicely the importance of strong phases

c loop from analyticity

Bobeth, Chrzaszcz, van Dyk, Virto, arXiv:1707.07305

Features:

- get rid of DD branch-cut modeling by mapping it at the boundary of the expansion region
- exploits the $\psi^{(\prime)}$ resonance data to constrain the expansion

Open issues:

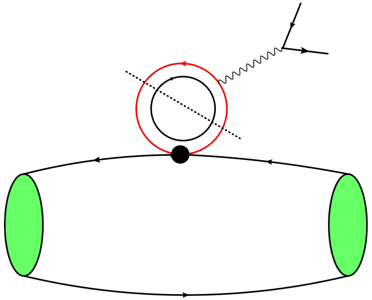
- strong phases related to the DD_s cut in p^2 are taken from LCSR and QCDF calculations. Are they reliable?

k	0	1	2
$\mathrm{Re}[\alpha_k^{(\perp)}]$	-0.06 ± 0.21	-6.77 ± 0.27	18.96 ± 0.59
$\mathrm{Re}[\alpha_k^{(\parallel)}]$	-0.35 ± 0.62	-3.13 ± 0.41	12.20 ± 1.34
$\mathrm{Re}[\alpha_k^{(0)}]$	0.05 ± 1.52	17.26 ± 1.64	–
$\mathrm{Im}[\alpha_k^{(\perp)}]$	-0.21 ± 2.25	1.17 ± 3.58	-0.08 ± 2.24
$\mathrm{Im}[\alpha_k^{(\parallel)}]$	-0.04 ± 3.67	-2.14 ± 2.46	6.03 ± 2.50
$\mathrm{Im}[\alpha_k^{(0)}]$	-0.05 ± 4.99	4.29 ± 3.14	–

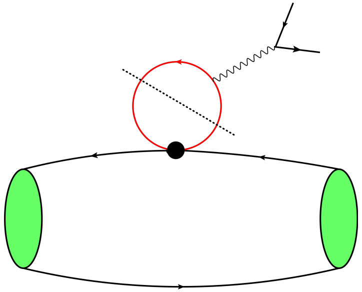
- z expansion: no sign of convergence for the typical values |z|~ 0.2-0.4

NB: expansion of FF's at much smaller z values

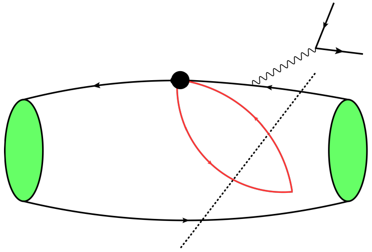
$D\bar{D}$



$\psi^{(n)}$



DD_s



Parametrizing the charm loop

Jäger, Camalich, arXiv:1212.2263
MC, Fedele, Franco, Mishima, Paul, Silvestrini, Valli, arXiv:1512.07157
+ preliminary update

$$
\begin{aligned}
H_V^- &= -iN\left\{\left(C_9^{\text{eff}}+h_-^1\right)V_{L-}+\frac{m_B^2}{q^2}\left[\frac{2m_b}{m_B}\left(C_7^{\text{eff}}+h_-^0\right)T_{L-}-16\pi^2 h_-^2\, q^4\right]\right\}\\
H_V^0 &= -iN\left\{\left(C_9^{\text{eff}}+h_-^1\right)\tilde{V}_{L0}+\frac{m_B^2}{q^2}\left[\frac{2m_b}{m_B}\left(C_7^{\text{eff}}+h_-^0\right)\tilde{T}_{L0}-16\pi^2\left(\tilde{h}_0^0+\tilde{h}_0^1\, q^2\right)\right]\right\}\\
H_V^+ &= -iN\left\{\left(C_9^{\text{eff}}+h_-^1\right)V_{L+}+\frac{m_B^2}{q^2}\left[\frac{2m_b}{m_B}\left(C_7^{\text{eff}}+h_-^0\right)T_{L+}-16\pi^2\left(h_+^0+h_+^1\, q^2+h_+^2\, q^4\right)\right]\right\}
\end{aligned}
$$

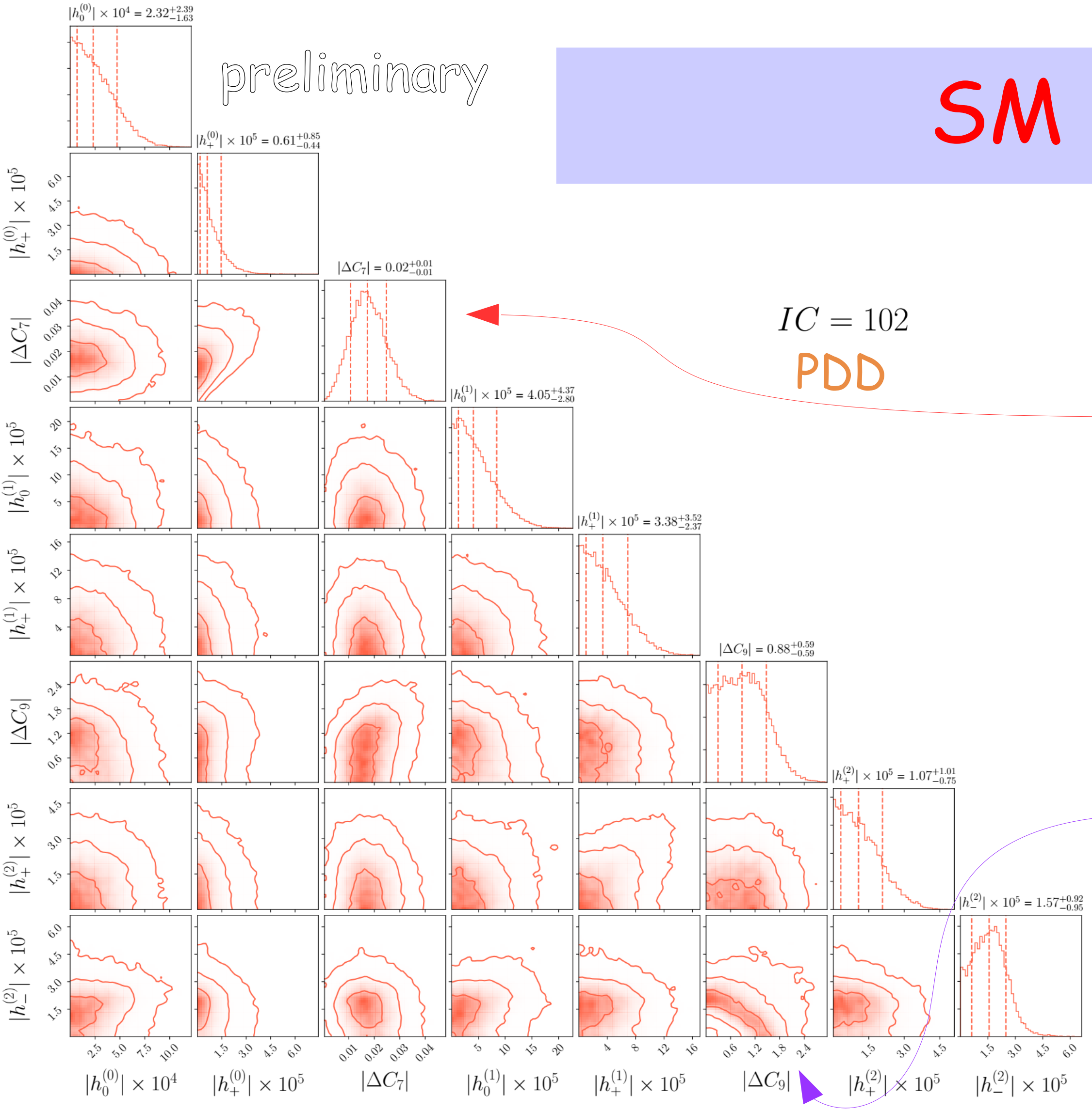
$\Delta C_7^{(cc)} = h_-^0$ and $\Delta C_9^{(cc)} = h_-^1$ shift the corresponding Wilson coefficients (as NP contributions do), while the other parameters have no short-distance counterparts

Fitting hadronic parameters

- compute all amplitudes using QCD factorization and form factors from LQCD (Bailey et al. '15) and LCSR (Bharucha, Straub & Zwicky '15)
- add hadronic parameters and
  - use LCSR calculation from KMPW at low q^2 (0 and 1 GeV^2) only (**PDD**)

    or
  - extrapolate LCSR calculation to larger q^2 using KMPW (**PMD**)
- fit all available experimental data using the HEPfit code
- compare different hadronic models using $IC = -2\overline{\log L} + 4\sigma^2_{\log L}$

SM fit of the h_λ's



preliminary

$IC = 102$

PDD

$B \to K^*\ell\ell$ data accounted for by the hadronic contributions

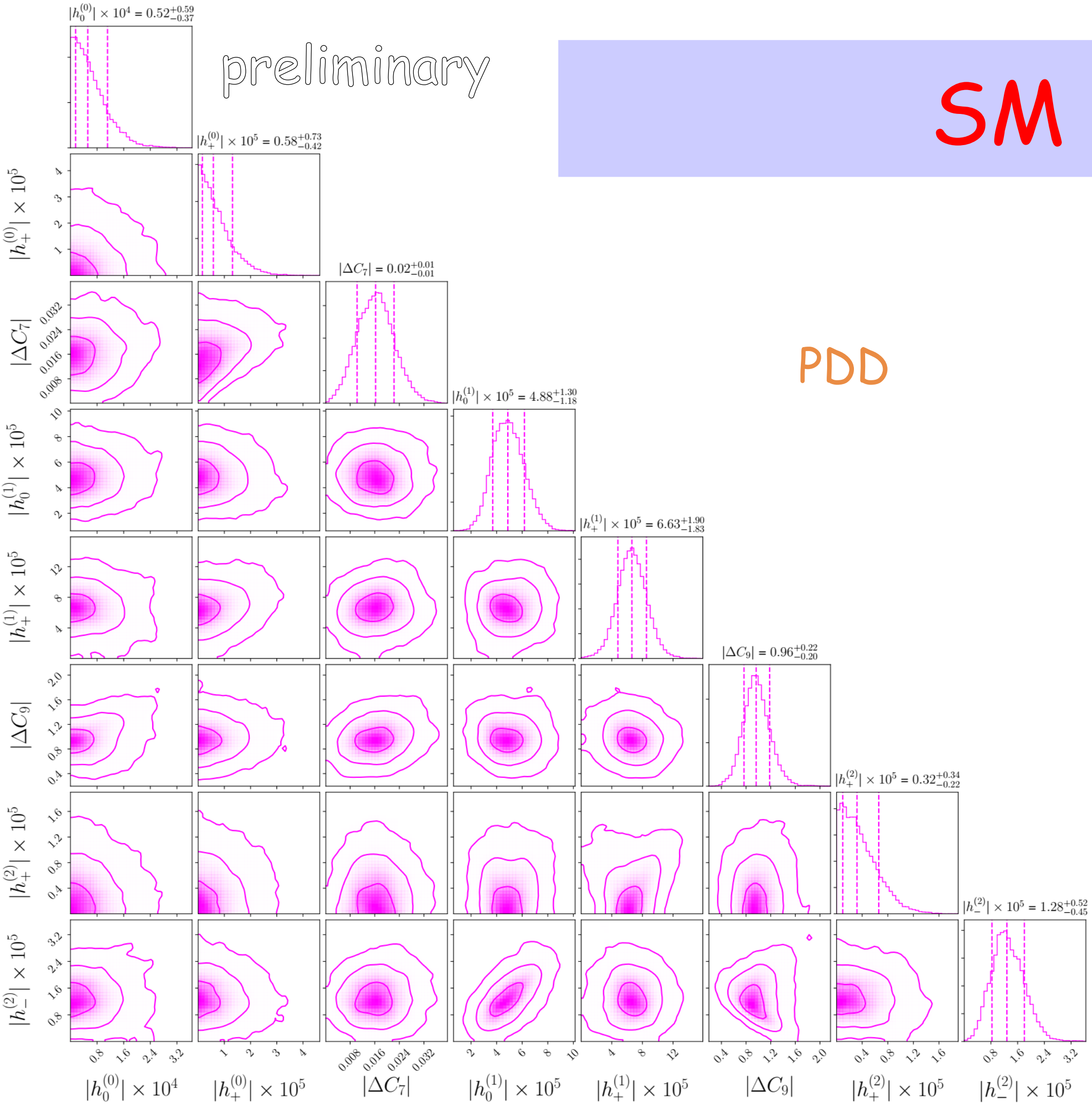
$|\Delta C_7|$ fixed by the KMPW value at $q^2 = 0$

No clear evidence for other non-vanishing hadronic parameters but interesting correlation $|\Delta C_9|$ - $h_-^{(2)}$

Future experimental uncertainties will be able to pin down the $h^{(2)}$'s

MC, Coutinho, Fedele, Franco, Paul, Silvestrini, Valli, in preparation

SM fit projection



PDD

Central values fixed to the present fit global mode

Experimental errors reduced by a factor of 6 (202?)

Many coefficient can be measured, even in the presence of NP (barring ΔC_7 and ΔC_9)

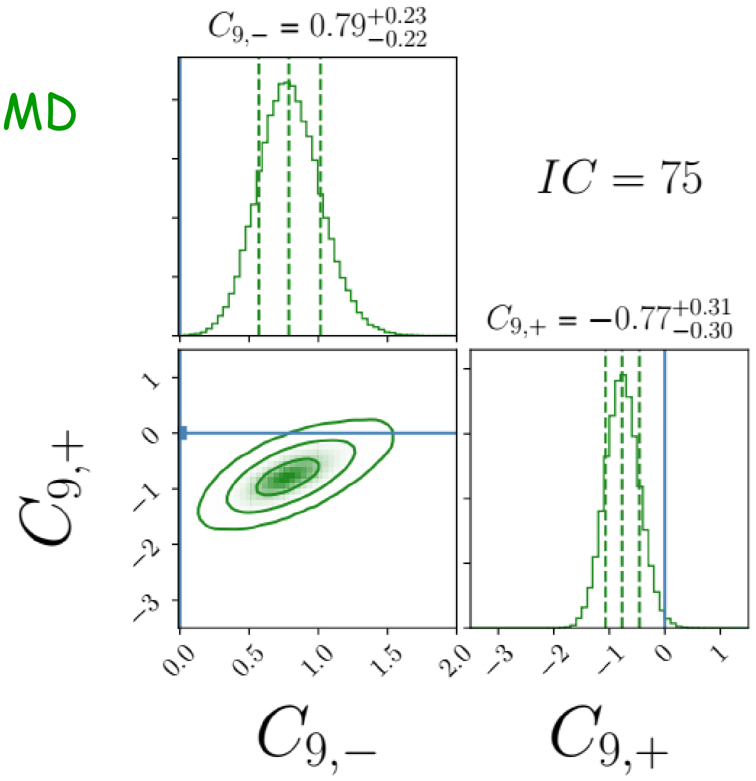
MC, Coutinho, Fedele, Franco, Paul, Silvestrini, Valli, in preparation

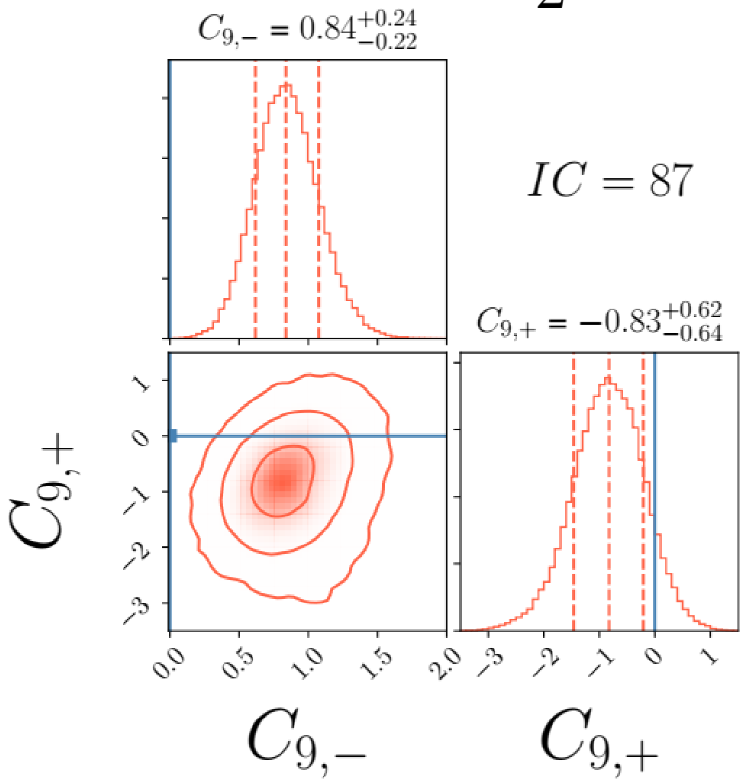
NP in C_9^μ and C_9^e

MC, Coutinho, Fedele, Franco, Paul, Silvestrini, Valli, arXiv:1704.05447 + work in progress

LFUV hints are not affected by hadronic parameters… $C_{9,\pm} = \frac{1}{2}(C_{9,\mu} \pm C_{9,e})$

PMD





PDD

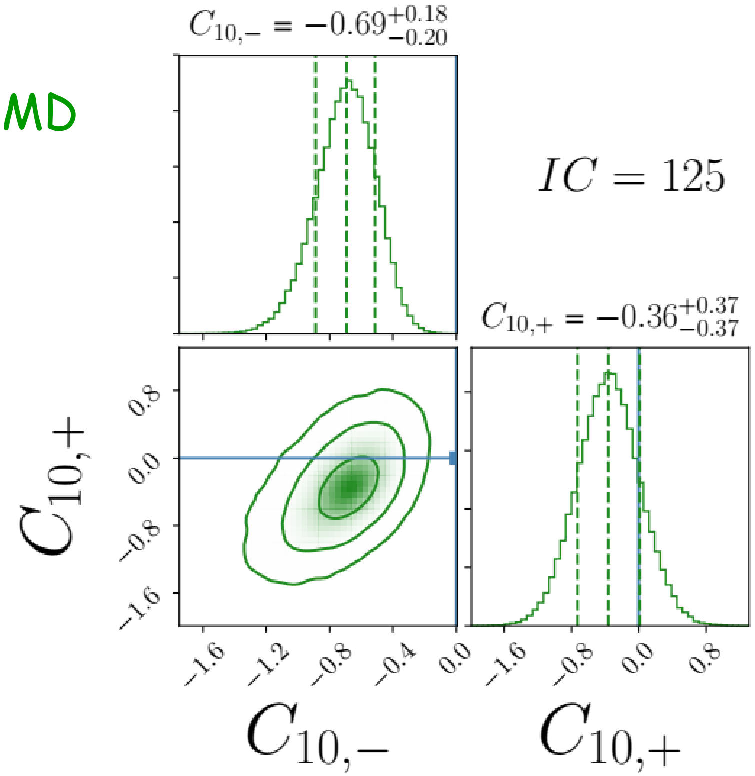
NP in C_{10}^{μ} and C_{10}^{e}

MC, Coutinho, Fedele, Franco, Paul, Silvestrini, Valli, arXiv:1704.05447 + work in progress

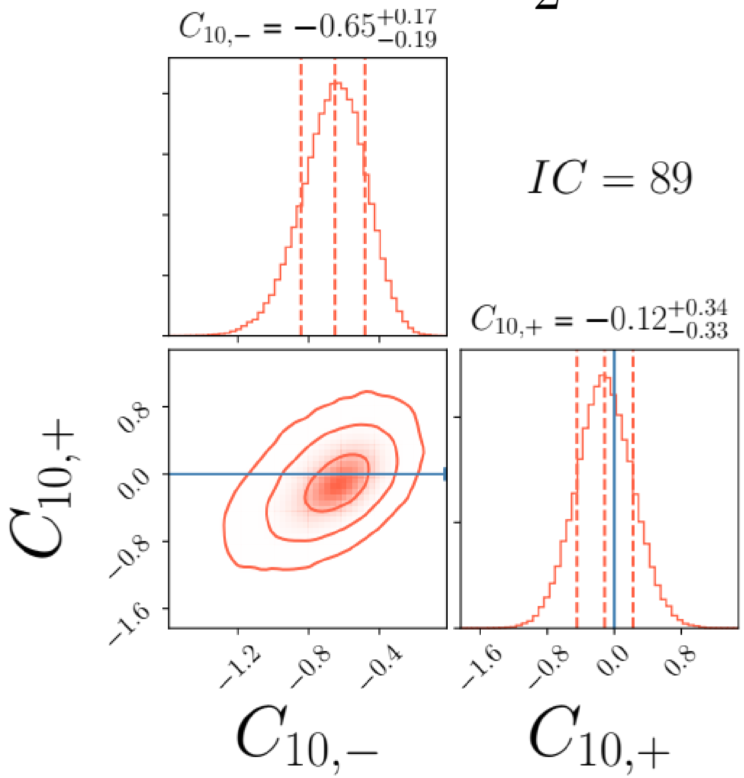
… BUT the viable NP scenarios ARE!

$$C_{10,\pm} = \frac{1}{2}\left(C_{10,\mu} \pm C_{10,e}\right)$$

PMD



PDD



Charm loop: dangerous or  harmless?

A clear-cut non-perturbative calculation is not available yet

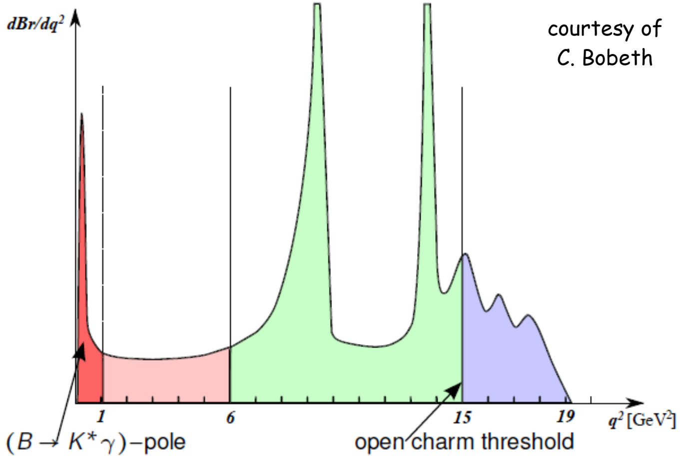
Combinations of QCDF, LCSR, analiticity and unitarity point to a moderate effect with a flat q^2 dependence in the region of interest. Yet their ability to fully describe c-loop rescattering is questionable

Future data could be able to pin down hadronic contributions with no short-distance counterparts (all but ΔC_7 and ΔC_9)

LFUV signals are not affected, but their interpretation may be

Backup

Charm loop in B→K*ℓℓ



$$\mathcal{H}_{\text{eff}}^{b\to s\ell\ell} = \mathcal{H}_{\text{eff}}^{sl+\gamma} + \mathcal{H}_{\text{eff}}^{\text{had}}$$

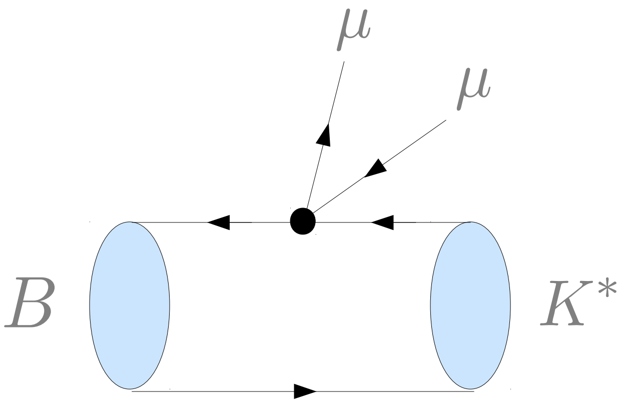
$$\mathcal{H}_{\text{eff}}^{sl+\gamma} = -\frac{4G_F}{\sqrt{2}}\lambda_t\left(C_7 Q_{7\gamma} + C_9 Q_{9V} + C_{10} Q_{10A}\right)$$

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

$$Q_{9V} = \frac{\alpha_e}{4\pi}(\bar{s}_L\gamma_\mu b_L)(\bar{\ell}\gamma^\mu\ell)\,,$$

$$Q_{10A} = \frac{\alpha_e}{4\pi}(\bar{s}_L\gamma_\mu b_L)(\bar{\ell}\gamma^\mu\gamma^5\ell)\,.$$

Semileptonic decays have simpler hadronic MEs



Hadronic matrix elements of quark currents: FORM FACTORS*

Angular analysis of B → K*μμ

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

angular analysis

$$S_i = \left(I_i^{(s,c)} + \bar{I}_i^{(s,c)} \right) / \Gamma'$$
$$(2\,\Gamma' \equiv d\Gamma/dq^2 + d\bar{\Gamma}/dq^2)$$

8 CP-AVERAGED OBSERVABLES

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

In the helicity amplitude formalism $(m_\ell \sim 0)$, we need to compute few helicity amplitudes: $H^\lambda_{V,A}$ $\lambda = 0, \pm$

$$I_1^c = -I_2^c = \frac{F}{2}\left(|H_V^0|^2 + |H_A^0|^2\right),$$
$$I_1^s = 3I_2^s = \frac{3}{8}F\left(|H_V^+|^2 + |H_V^-|^2 + |H_A^+|^2 + |H_A^-|^2\right),$$
$$I_3 = -\frac{F}{2}\mathrm{Re}\left[H_V^+(H_V^-)^* + H_A^+(H_A^-)^*\right],$$
$$I_4 = \frac{F}{4}\mathrm{Re}\left[(H_V^+ + H_V^-)(H_V^0)^* + (H_A^+ + H_A^-)(H_A^0)^*\right],$$
$$I_5 = \frac{F}{4}\mathrm{Re}\left[(H_V^- - H_V^+)(H_A^0)^* + (H_A^- - H_A^+)(H_V^0)^*\right],$$
$$I_6^s = F\mathrm{Re}\left[H_V^-(H_A^-)^* - H_V^+(H_A^+)^*\right],$$
$$I_6^c = 0,$$
$$I_7 = \frac{F}{2}\mathrm{Im}\left[(H_A^+ + H_A^-)(H_V^0)^* + (H_V^+ + H_V^-)(H_A^0)^*\right],$$
$$I_8 = \frac{F}{4}\mathrm{Im}\left[(H_V^- - H_V^+)(H_V^0)^* + (H_A^- - H_A^+)(H_A^0)^*\right],$$
$$I_9 = \frac{F}{4}\mathrm{Im}\left[H_V^+(H_V^-)^* + H_A^+(H_A^-)^*\right].$$

Charm loop in the effective theory

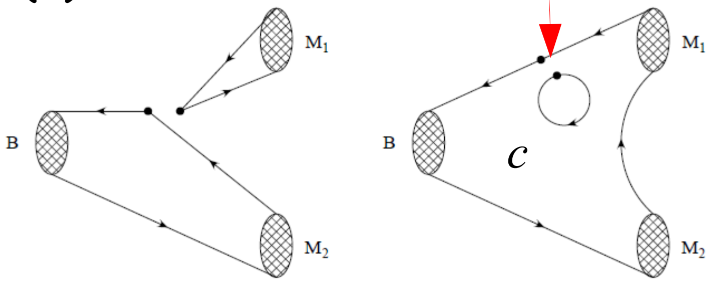
$$\mathcal{H}_{\rm eff}^{\rm had}(\Delta S=1)=\frac{4G_F}{\sqrt{2}}\left\{\lambda_u\left[C_1\left(Q_1^u-Q_1^c\right)+C_2\left(Q_2^u-Q_2^c\right)\right]-\lambda_t\left[C_1Q_1^c+C_2Q_2^c+\sum_{i=3}^{6}C_iQ_i+C_8Q_{8g}\right]\right\}$$

top loops in the SM give rise to penguin operators

- non-perturbative matrix elements of local operators
- α_s suppressed matching conditions, small Wilson coefficients

charm (and up) loops appear as Wick contractions in the MEs

- dominated by the insertion of $Q_{1,2}$, namely O(1) Wilson coefficients
- easily produce intermediate real states, i.e. rescattering, non-local contributions, strong phases, etc.



Non-leptonic $b \to s$ decays: "charming" penguins

Colangelo, Nardulli, Paver, Riazuddin, Z.Phys. C45 (1990) 575
MC, Franco, Martinelli, Pierini, Silvestrini, hep-ph/9703353

Charm penguin is doubly Cabibbo-enhanced in $b \to s\bar{u}u$ transitions

- Threatened factorization of non-leptonic B decays in the infinite mass limit → tamed

  Beneke, Buchalla, Neubert, Sachrajda, arXiv:0902.4446
  see also Bauer, Pirjol, Rothstein, Stewart, hep-ph/0502094
- Questioned the extraction of the CKM angle γ from $B \to K\pi$ decays (but helped to account for the $K\pi$ and $\pi\pi$ BRs and CP asymmetries)
- Challenged claims of NP sensitivity of various non-leptonic B decays

  → still to be tamed

  MC, Franco, Martinelli, Pierini, Silvestrini, hep-ph/0208048
  Beneke, Buchalla, Neubert, Sachrajda, hep-ph/0104110
  Fleischer, Matias, hep-ph/9906274, …

Form factors

Six (seven) form factors need to be computed: $\tilde{V}_{L\lambda}, \tilde{T}_{L\lambda}, (\tilde{S}_L)$

or, in the transversity basis, $V, A_{(0),1,2}, T_{0,1,2}$

Two main approaches:

Isgur, Wise; J. Charles et al., hep-ph/9812358; Grinstein, Pirjol, hep-ph/0201298

Heavy quark symmetry

- 7 FF's → 2 soft functions in the infinite mass limit
- useful to define optimized observables (FF-independent for $m_b \to \infty$)
- symmetry breaking corrections still require a dynamical approach

Non-perturbative QCD approaches

- 2+1 lattice QCD calculations at low recoil - uncertainty ~ 5-10%

  Horgan, Liu, Meinel, Wingate, arXiv:1310.3722

- light-cone sum rules at large recoil - uncertainty ~ 10-15%

  Bharucha, Straub, Zwicky, arXiv:1503.05534

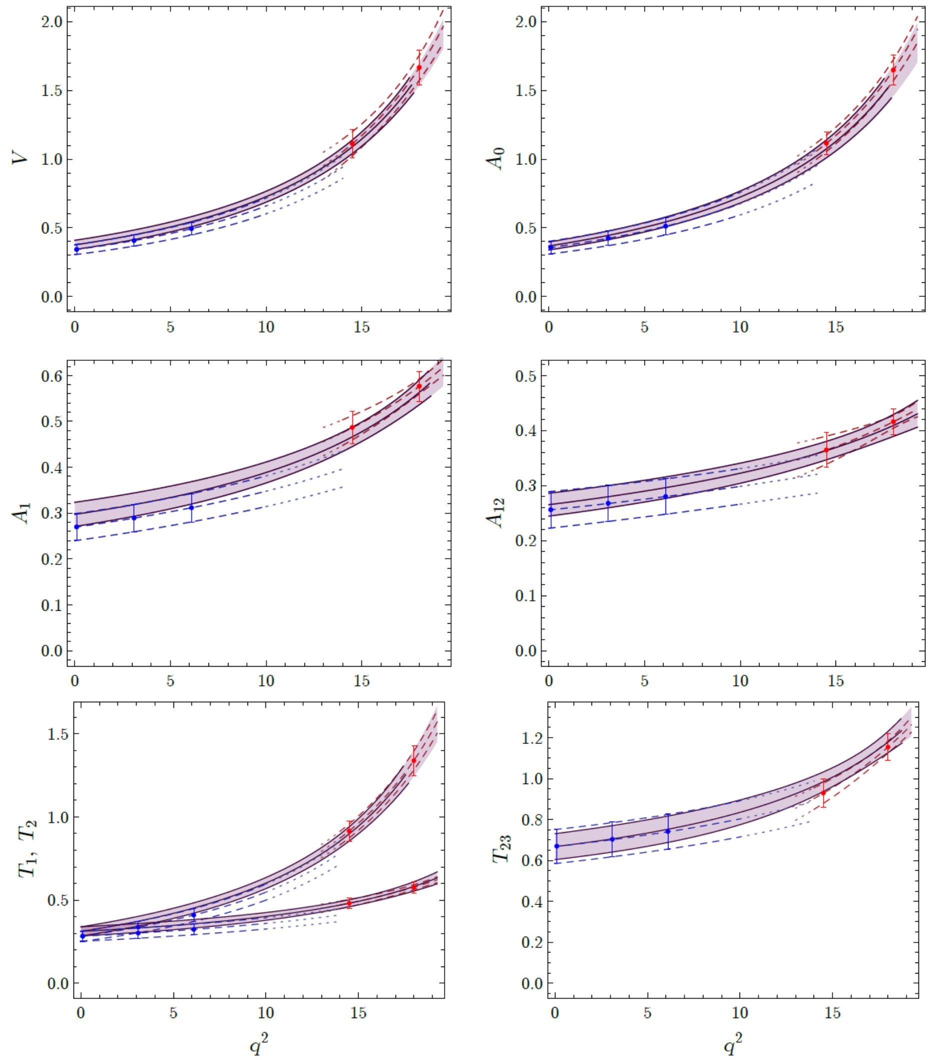
Results given in terms of the coefficients of a z-expansion

$$F^{(i)}(q^2) = \sum_k \alpha_k^{(i)} \frac{\left(z(q^2) - z(0)\right)^k}{1 - q^2/m_{R,i}^2}$$

Correlations induced by the HQ symmetry accounted for by the provided correlation matrix

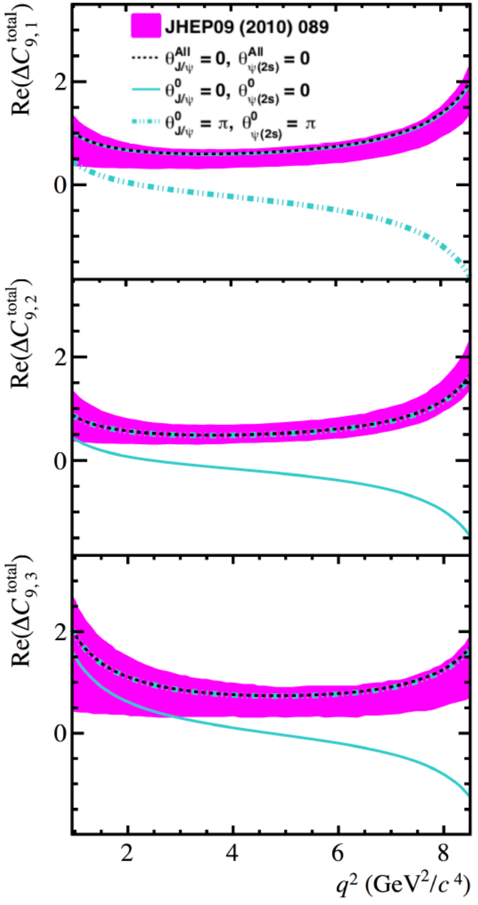
In the low q^2 region, one has to rely on LCSR results, yet the extrapolation to high q^2 matches quite well lattice QCD

Bharucha, Straub, Zwicky, arXiv:1503.05534v3



empirical model

Blake, Egede, Owen, Pomery, Petridis, arXiv:1709.03921
see also LHCb collaboration, arXiv:1612.06764



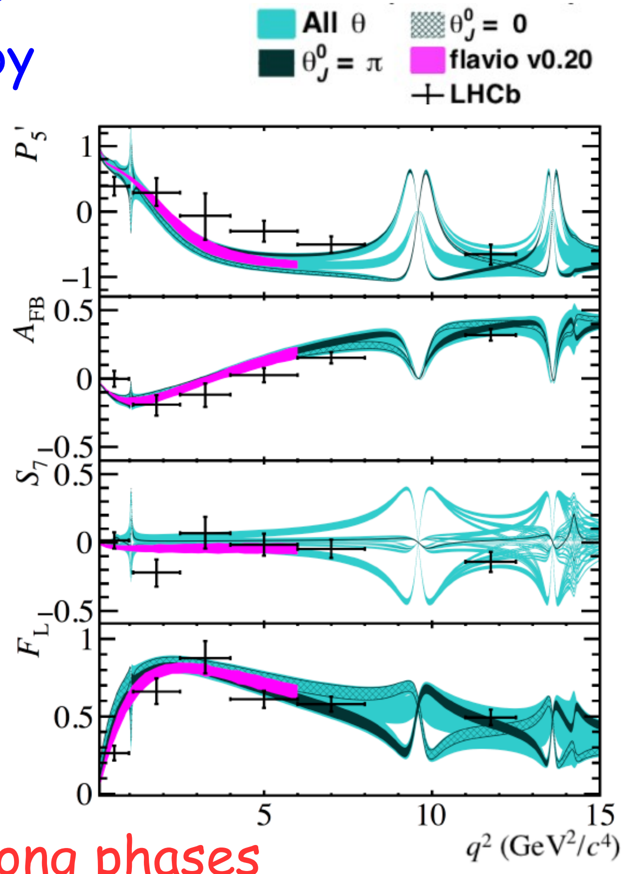
The hadronic contribution is modeled as the sum of 1^{--} resonances represented by relativistic Breit-Wigner functions

$$\Delta C_{9\,\lambda}^{\text{had}}(q^2) = \sum_j \eta_j^\lambda e^{i\theta_j^\lambda} A_j^{\text{res}}(q^2)$$

$$A_j^{\text{res}}(q^2) = \frac{m_{\text{res}\,j}\Gamma_{\text{res}\,j}}{(m_{\text{res}\,j}^2 - q^2) - i m_{\text{res}\,j}\Gamma_j(q^2)}$$

Open issues:

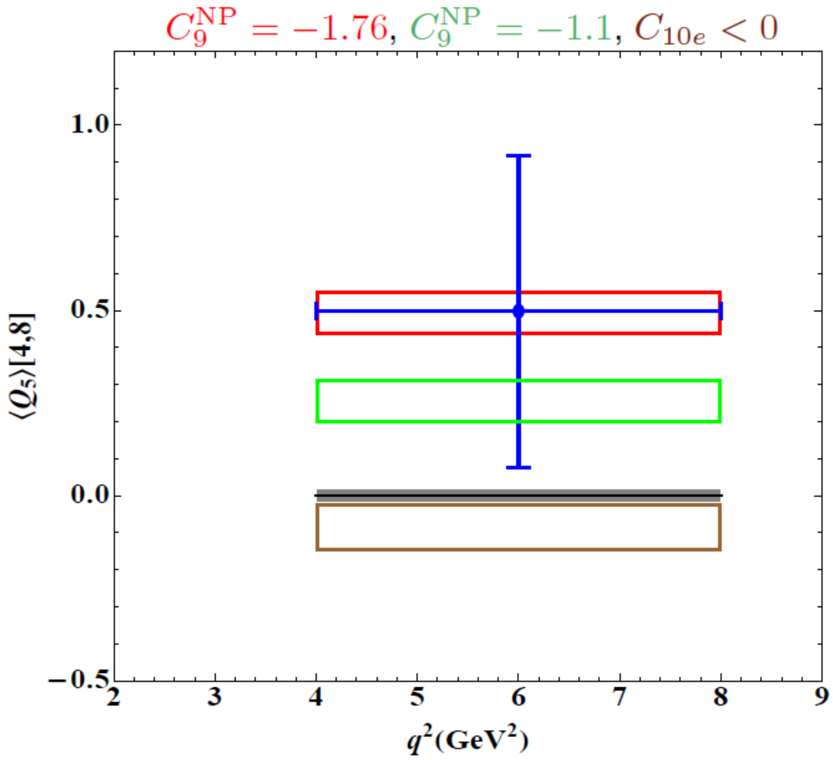
Why should it work far from the resonances? What about double counting? How large is the model uncertainty?

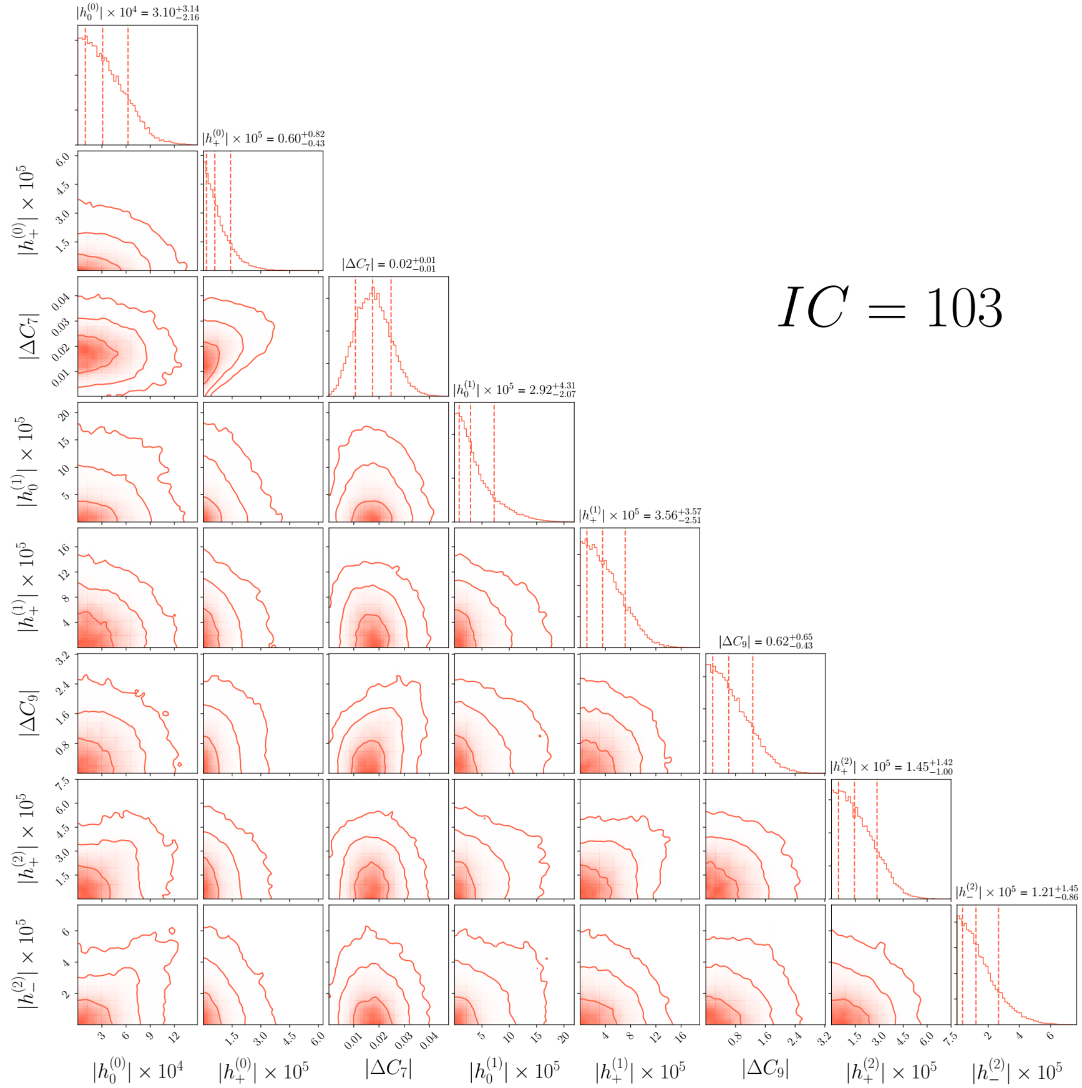


Illustrate nicely the importance of strong phases

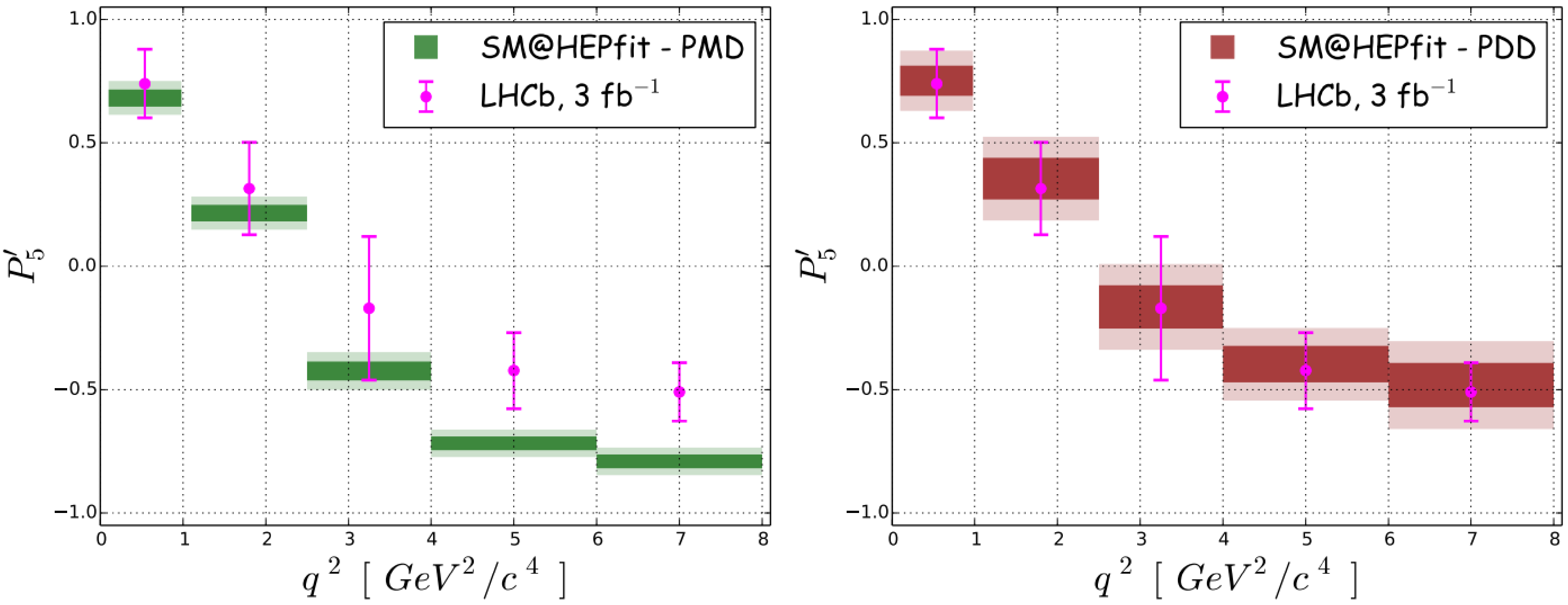
Alguero, Capdevila, Decotes-Genon, Matias, in preparation

Belle data [S. Wehle @ Belle Col.]




$|h_0^{(0)}| \times 10^4 = 3.10^{+3.14}_{-2.16}$
$|h_+^{(0)}| \times 10^5 = 0.60^{+0.82}_{-0.43}$
$|\Delta C_7| = 0.02^{+0.01}_{-0.01}$
$|h_0^{(1)}| \times 10^5 = 2.92^{+4.31}_{-2.07}$
$|h_+^{(1)}| \times 10^5 = 3.56^{+3.57}_{-2.51}$
$|\Delta C_9| = 0.62^{+0.65}_{-0.43}$
$|h_+^{(2)}| \times 10^5 = 1.45^{+1.42}_{-1.00}$
$|h_-^{(2)}| \times 10^5 = 1.21^{+1.45}_{-0.86}$
$|h_0^{(0)}| \times 10^4$
$|h_+^{(0)}| \times 10^5$
$|\Delta C_7|$
$|h_0^{(1)}| \times 10^5$
$|h_+^{(1)}| \times 10^5$
$|\Delta C_9|$
$|h_+^{(2)}| \times 10^5$
$|h_-^{(2)}| \times 10^5$

$IC = 103$


SM@HEPfit - PMD
LHCb, 3 fb^{-1}
P_5'
1.0
0.5
0.0
−0.5
−1.0
0
1
2
3
4
5
6
7
8
q^2 [GeV^2/c^4]
SM@HEPfit - PDD
LHCb, 3 fb^{-1}

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

angular analysis

$$S_i = \left(I_i^{(s,c)} + \bar{I}_i^{(s,c)} \right) / \, \Gamma'$$
$$(2\,\Gamma' \equiv d\Gamma/dq^2 + d\bar{\Gamma}/dq^2)$$

8 CP-AVERAGED OBSERVABLES

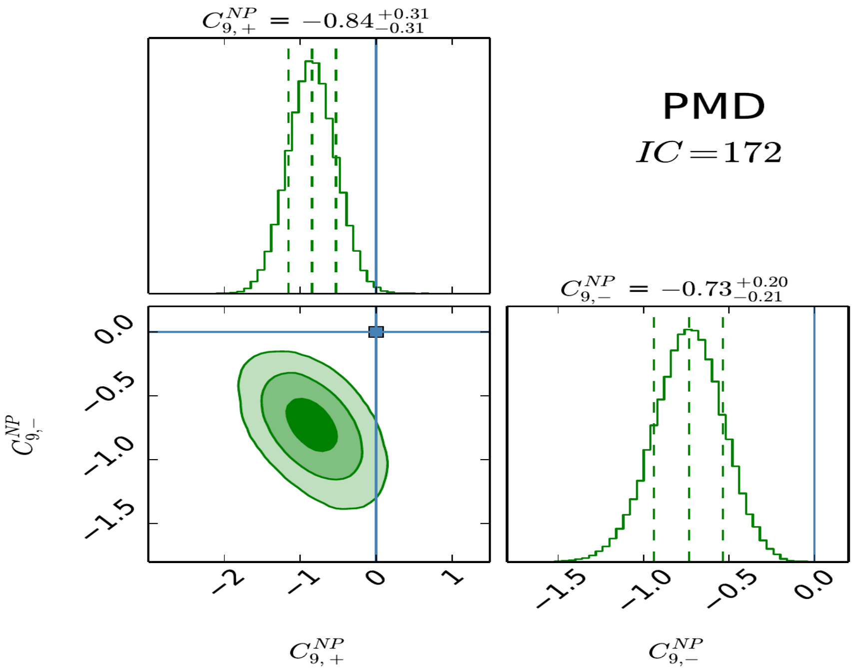
$$F_L,\, A_{FB},\, S_{3,4,5,7,8,9}$$

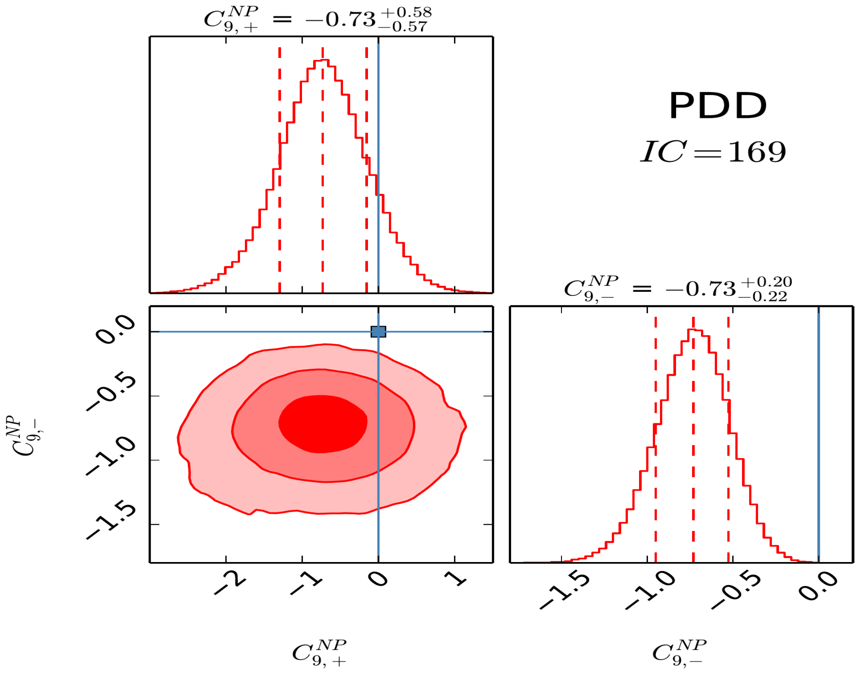
In the helicity amplitude formalism: $(m_\ell \sim 0)$

$$I_1^c = -I_2^c = \frac{F}{2}\left(|H_V^0|^2 + |H_A^0|^2\right),$$
$$I_1^s = 3 I_2^s = \frac{3}{8} F \left(|H_V^+|^2 + |H_V^-|^2 + |H_A^+|^2 + |H_A^-|^2\right),$$
$$I_3 = -\frac{F}{2} \mathrm{Re}\left[H_V^+ (H_V^-)^* + H_A^+ (H_A^-)^*\right],$$
$$I_4 = \frac{F}{4} \mathrm{Re}\left[(H_V^+ + H_V^-)(H_V^0)^* + (H_A^+ + H_A^-)(H_A^0)^*\right],$$
$$I_5 = \frac{F}{4} \mathrm{Re}\left[(H_V^- - H_V^+)(H_A^0)^* + (H_A^- - H_A^+)(H_V^0)^*\right],$$
$$I_6^s = F \mathrm{Re}\left[H_V^- (H_A^-)^* - H_V^+ (H_A^+)^*\right],$$
$$I_6^c = 0,$$
$$I_7 = \frac{F}{2} \mathrm{Im}\left[(H_A^+ + H_A^-)(H_V^0)^* + (H_V^+ + H_V^-)(H_A^0)^*\right],$$
$$I_8 = \frac{F}{4} \mathrm{Im}\left[(H_V^- - H_V^+)(H_V^0)^* + (H_A^- - H_A^+)(H_A^0)^*\right],$$
$$I_9 = \frac{F}{4} \mathrm{Im}\left[H_V^+ (H_V^-)^* + H_A^+ (H_A^-)^*\right].$$

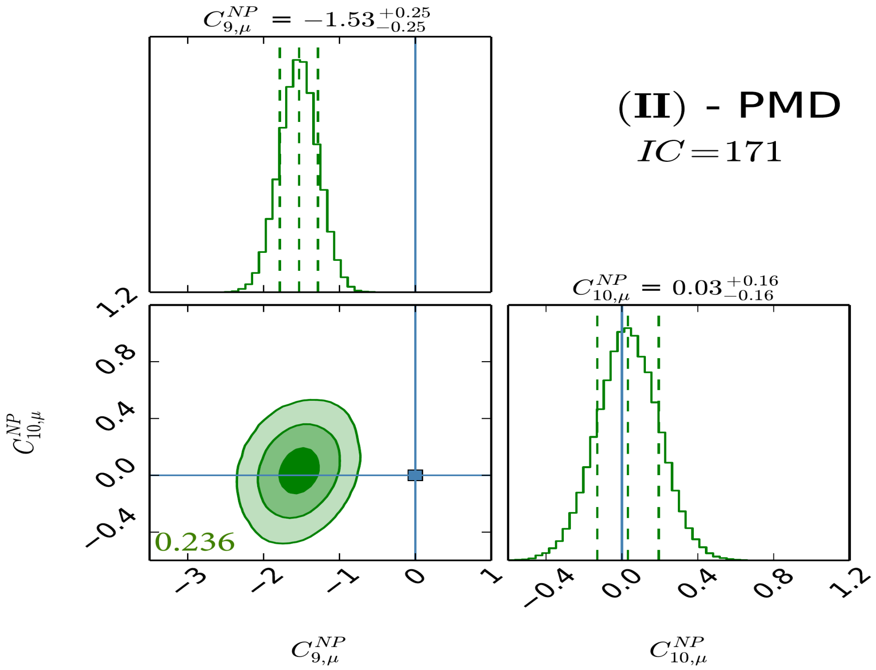
We need to compute few helicity amplitudes: $H^{\lambda}_{V,A}$ $\quad \lambda = 0, \pm$

NP IN C_9^μ AND C_9^e

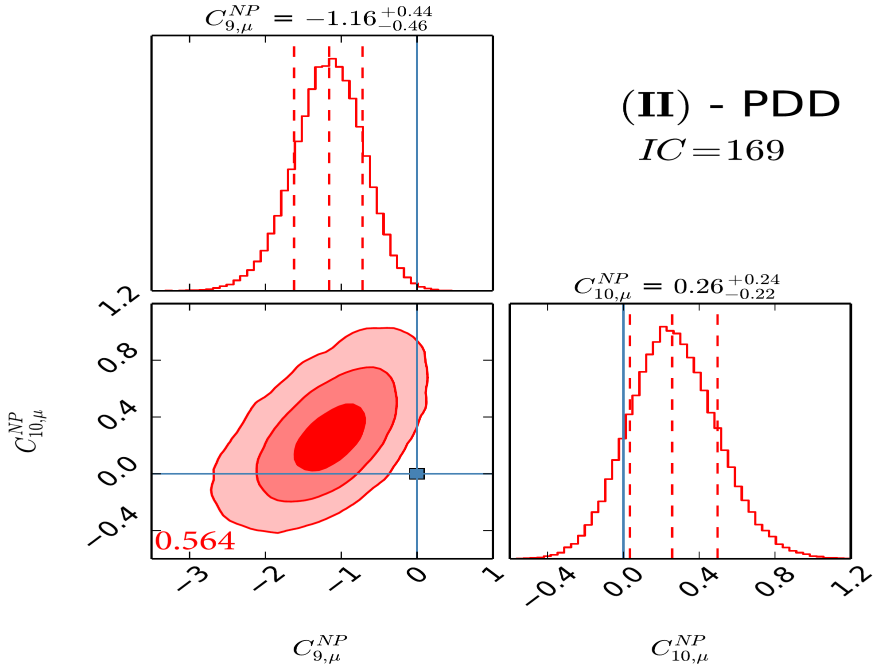




NP IN C_9^μ AND C_{10}^μ

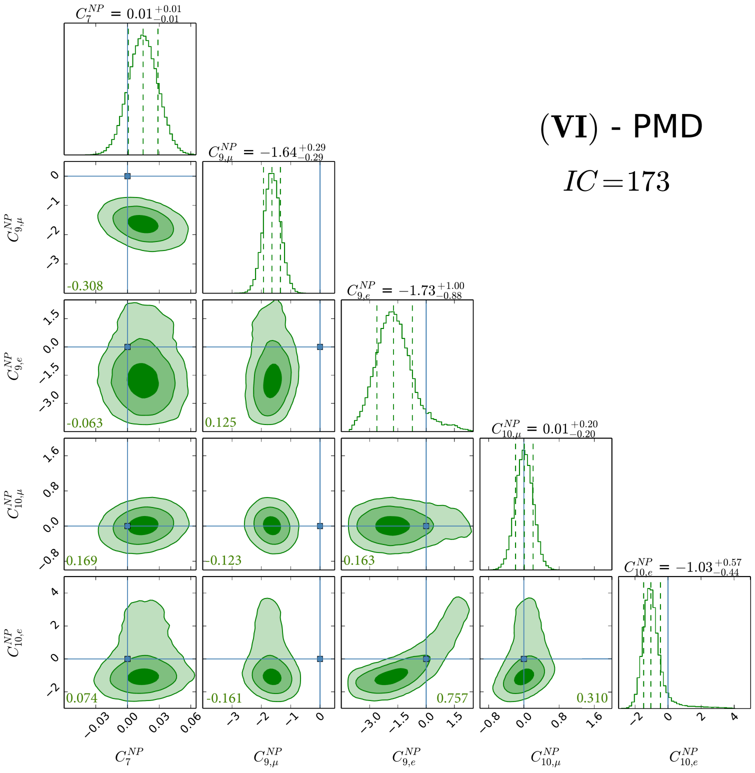


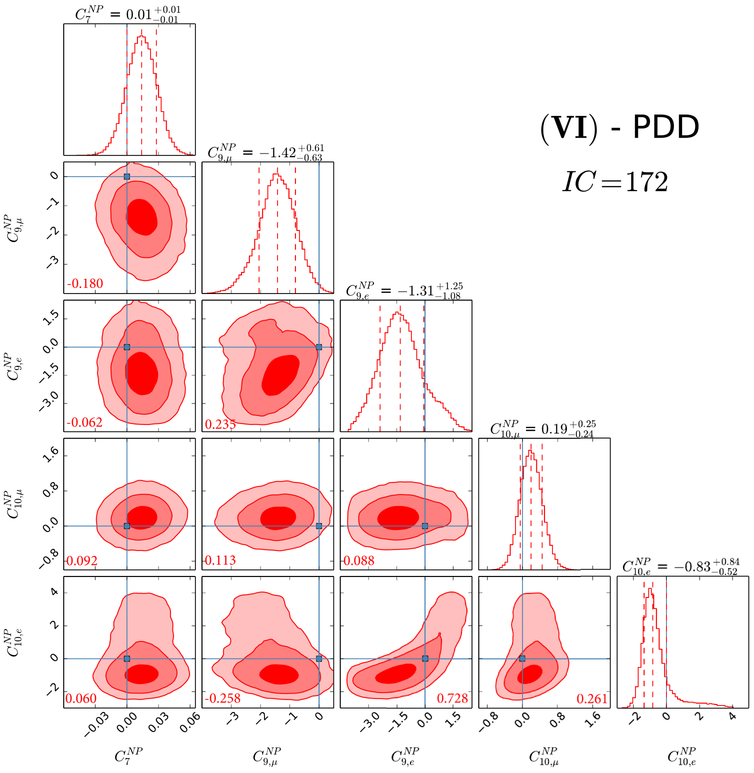
(II) - PMD
$IC = 171$



(II) - PDD
$IC = 169$

NP IN C_7, $C_{9,10}^{e,\mu}$



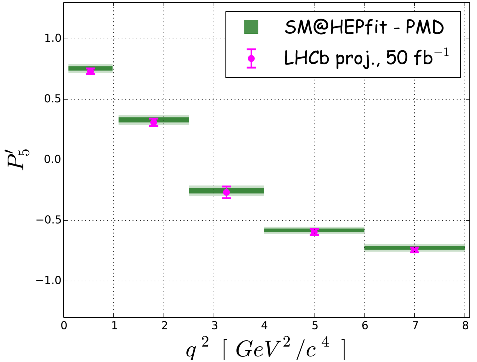


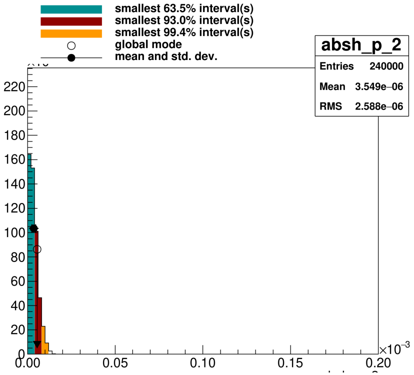
FUTURE PROJECTIONS

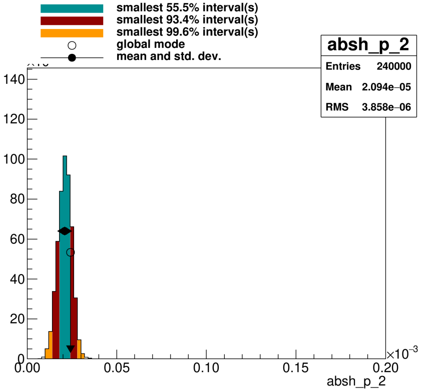
- Choose a theory setup (SM or NP; rising or non-rising charm loop)
- Generate experimental results from current best fit point in the given setup
- Assume future exp errors scaling LHCb statistical errors to 50/fb (roughly /6) and including BelleII estimates
- Fit parameters from generated data

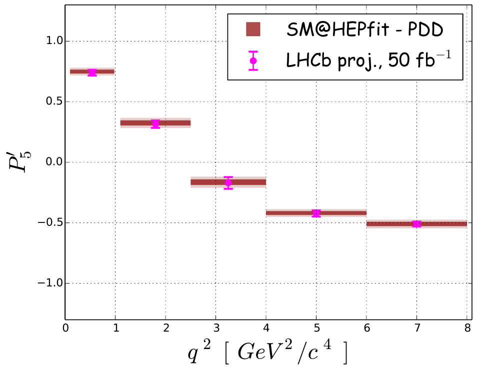
See also Hurth, Mahmoudi, Martinez Santos & Neshatpour '17; Albrecht, Bernlochner, Kenzie, Reichert, Straub, Tully '17

SM PROJECTION



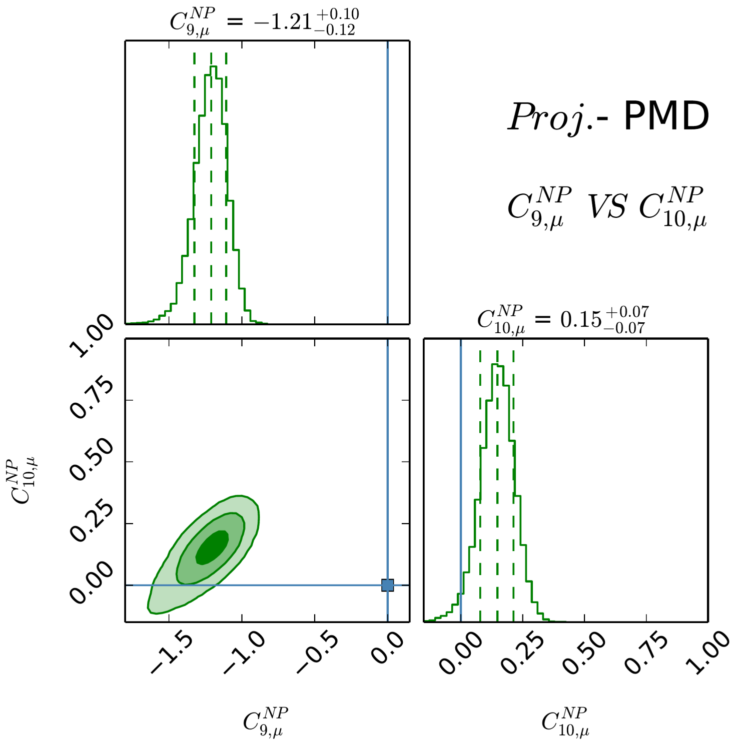






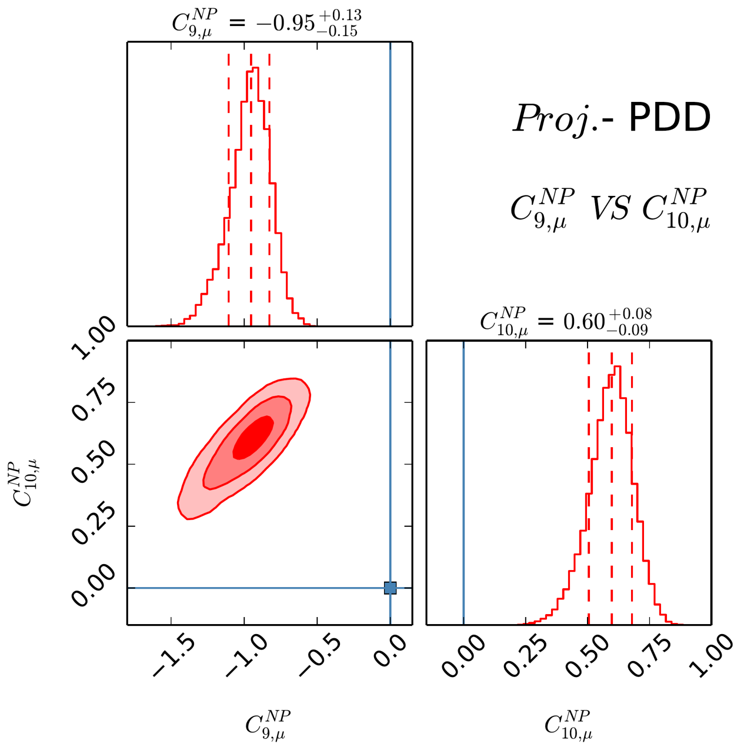
PRELIMINARY!

NP PROJECTION



Proj.- PMD

$C^{NP}_{9,\mu}$ VS $C^{NP}_{10,\mu}$

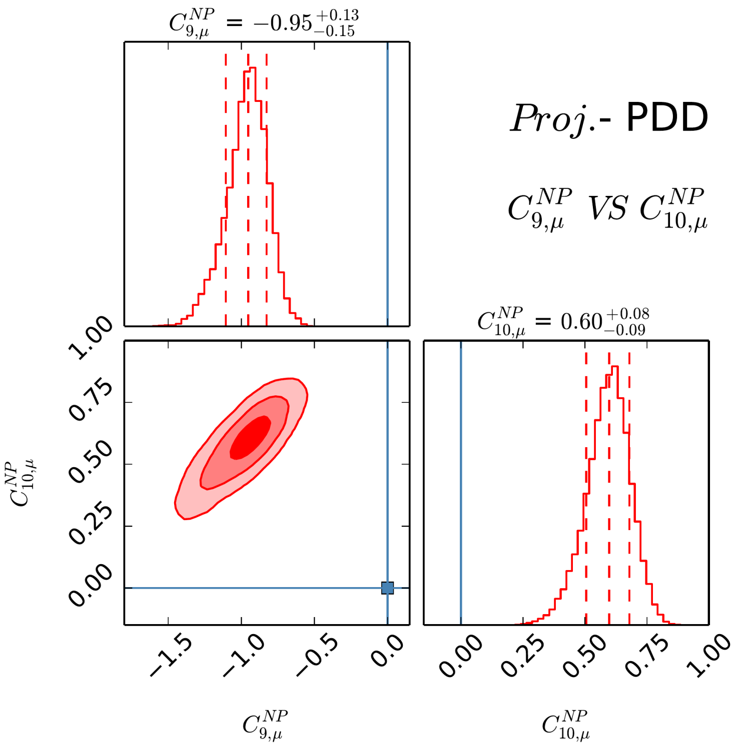


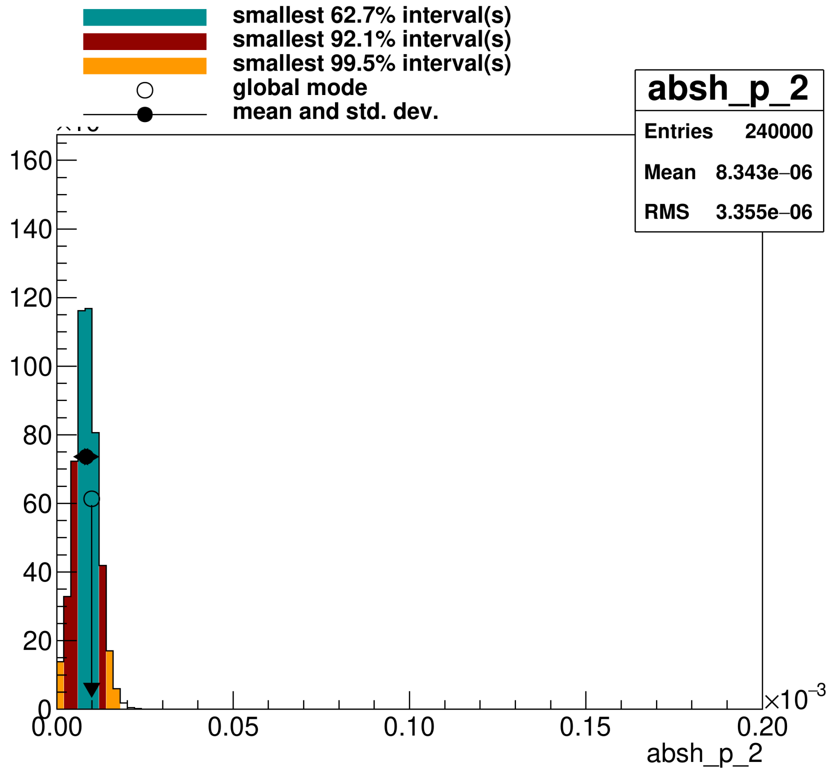
Proj.- PDD

$C^{NP}_{9,\mu}$ VS $C^{NP}_{10,\mu}$

PRELIMINARY!

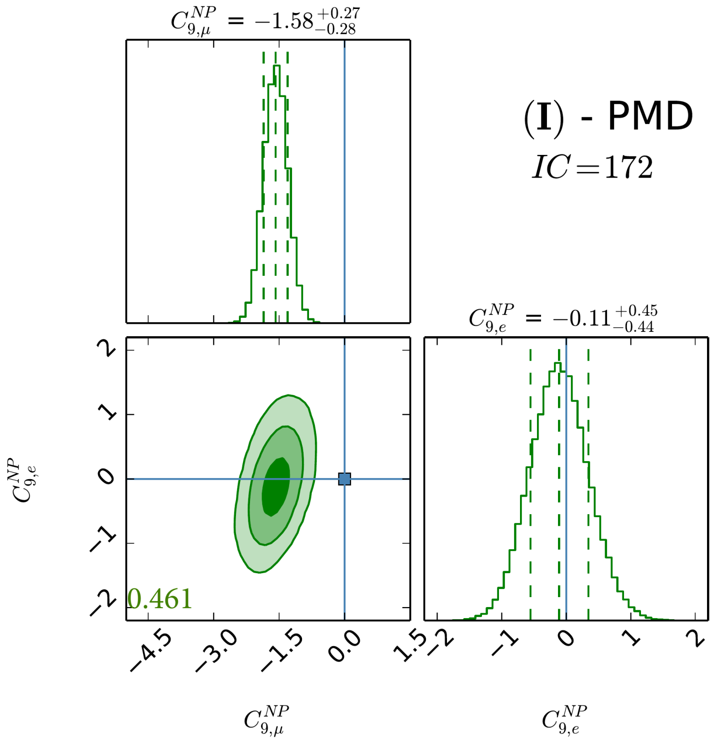
NP PROJECTION

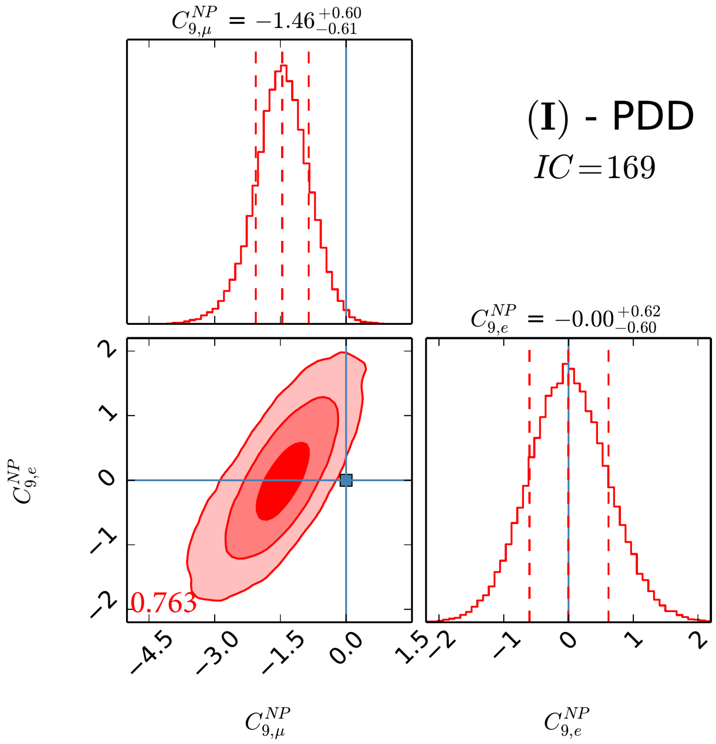




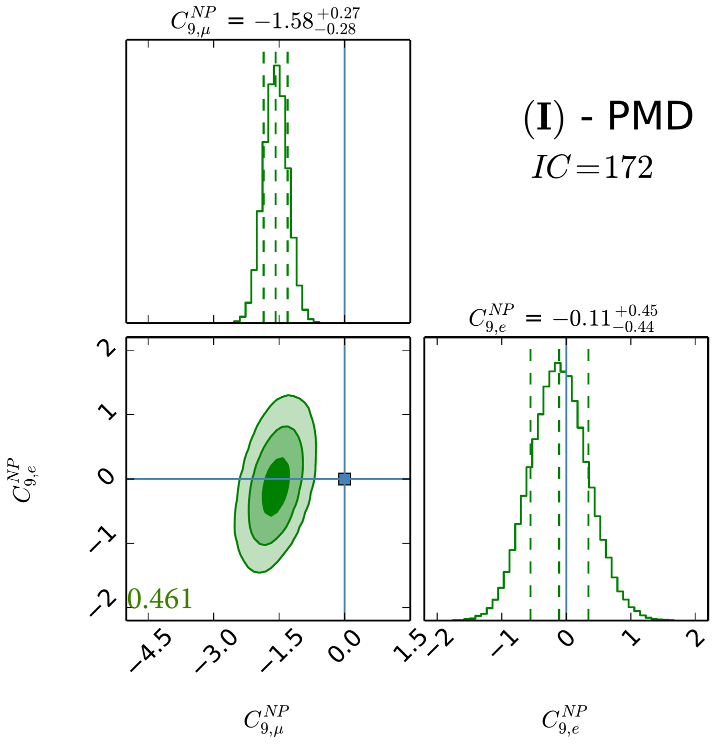
PRELIMINARY!

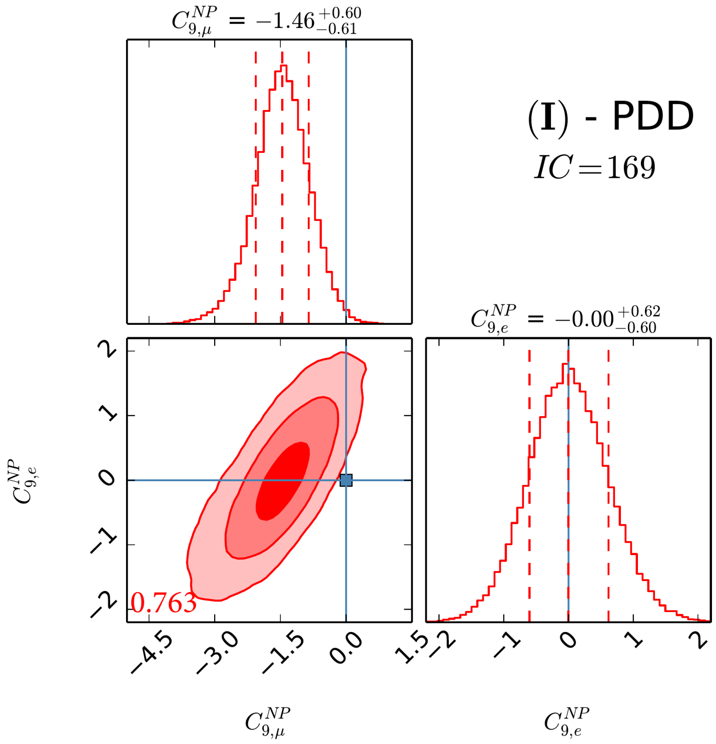
NP IN C_9^μ AND C_9^e



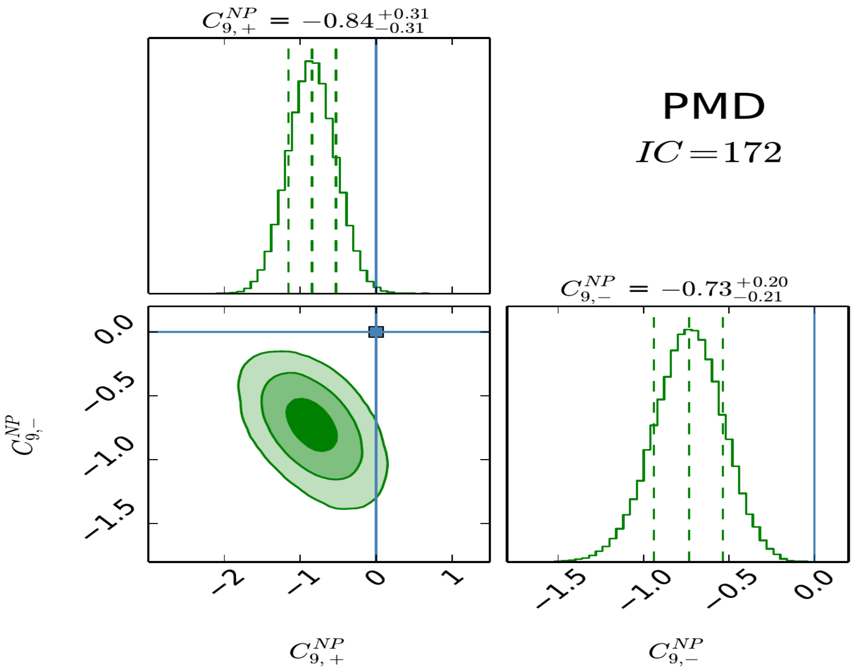


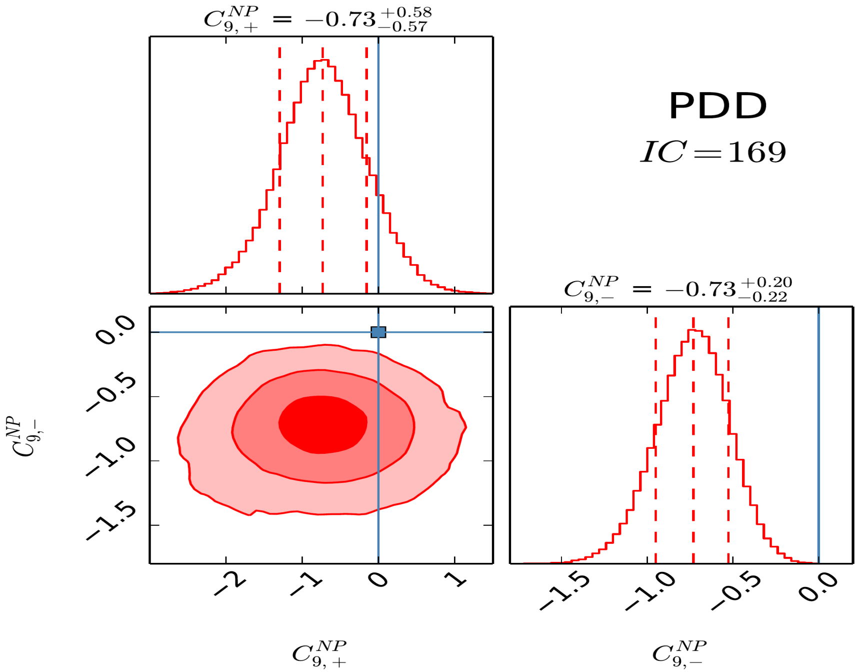
NP IN C_9^μ AND C_9^e



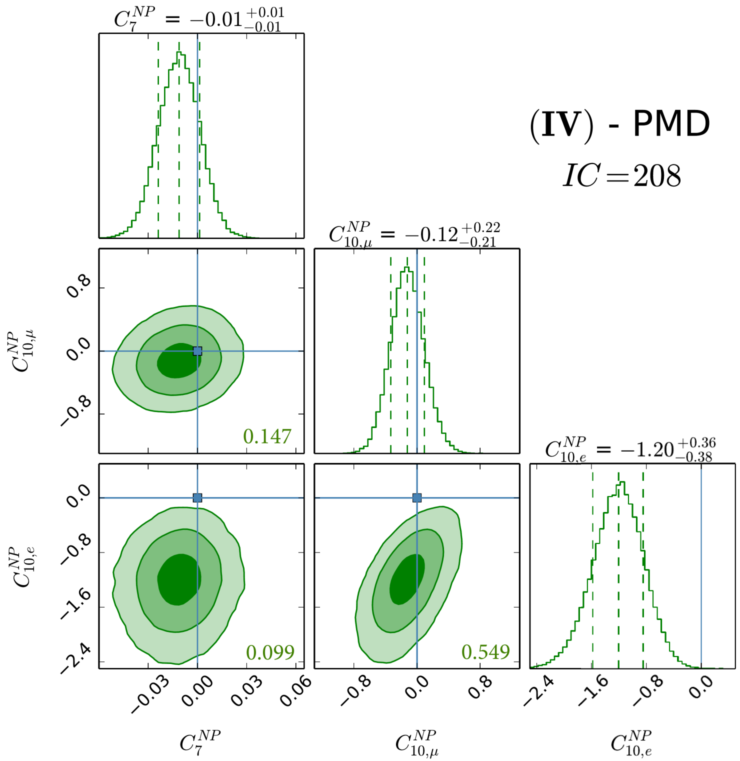


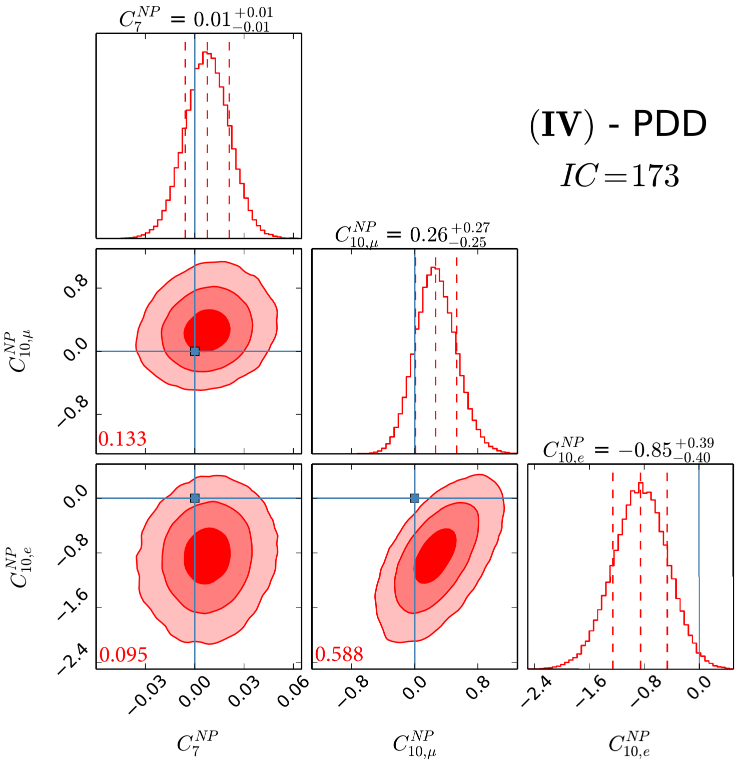
NP IN C_9^μ AND C_9^e





NP IN C_7, C_{10}^{μ} AND C_{10}^{e}





Taming the charm-loop monster…