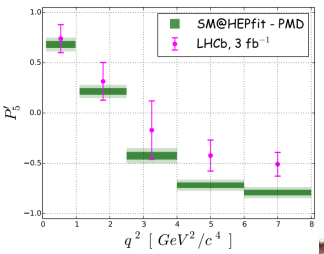
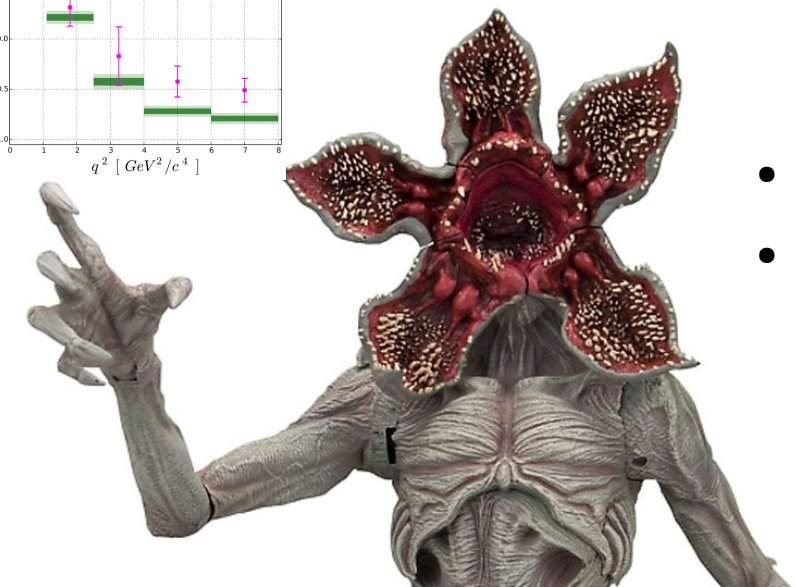
Charm-loop effects





Marco Ciuchini

INFN ROMA TRE

- charm loops in B decays: a short history
- charm loops in semileptonic B decays
  - Theoretical estimates
  - Phenomenological approach

Towards the Ultimate Precision in Flavour Physics

University of Warwick, 16-18 April 2018

Charm loop in the effective theory

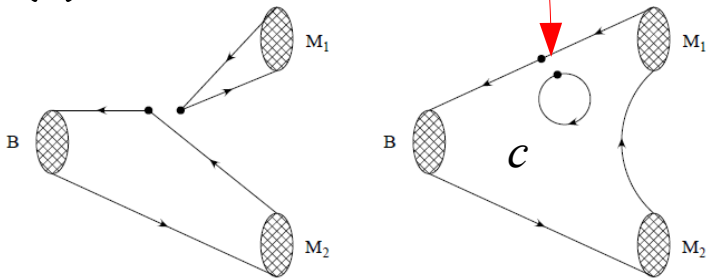
$$\mathcal{H}_{\rm eff}^{\rm had}(\Delta S=1)=\frac{4G_F}{\sqrt{2}}\left\{\lambda_u\left[C_1\left(Q_1^u-Q_1^c\right)+C_2\left(Q_2^u-Q_2^c\right)\right]-\lambda_t\left[C_1Q_1^c+C_2Q_2^c+\sum_{i=3}^{6}C_iQ_i+C_8Q_{8g}\right]\right\}$$

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→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→sūu transitions

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

Beneke, Buchalla, Neubert, Sachrajda, hep-ph/0411171
see also Bauer, Pirjol, Rothstein, Stewart, hep-ph/0401188

- Questioned the extraction of the CKM angle γ from B → Kπ decays (but helped to account for the Kπ and $\pi\pi$ BRs and CP asymmetries)
- Challenged claims of NP sensitivity of various non-leptonic B decays

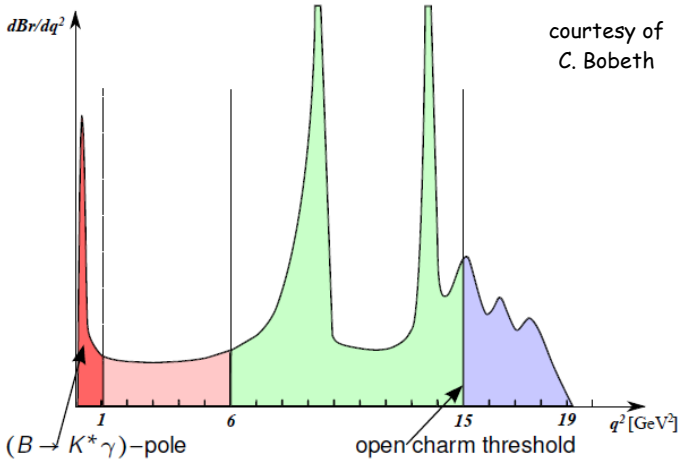
→ still to be tamed

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

Charm loop in B→K*ℓℓ

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

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

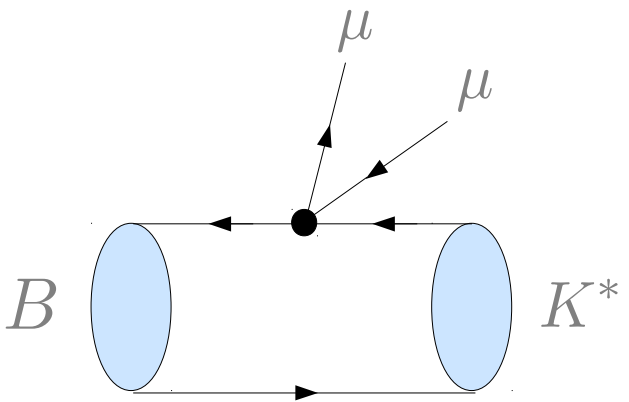


Semileptonic decays have simpler hadronic MEs

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

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

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



Hadronic matrix elements of quark currents: **FORM FACTORS***

*not discussed here

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

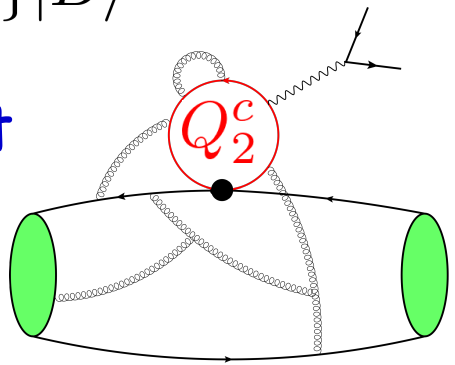
Jäger, Camalich, arXiv:1212.2263;
Melikhov, Nikitin, Simula, hep-ph/9807464

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

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

- 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?

Taming the charm-loop monster…

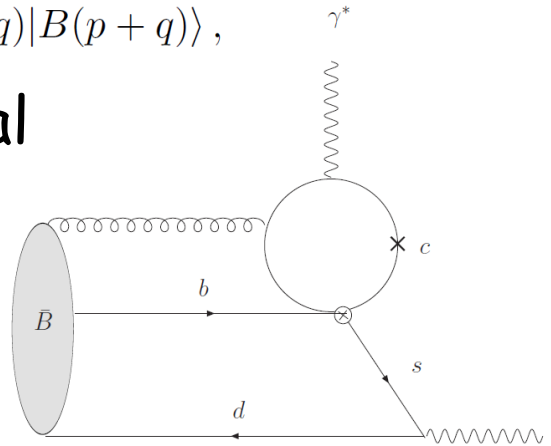
An estimate in 2 steps:

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 $\left[\mathcal{H}_\mu^{(B\to K^{(*)})}(p,q)\right]_{non\,fact} = 2C_1\langle K^{(*)}(p)|\widetilde{\mathcal{O}}_\mu(q)|B(p+q)\rangle\,,$

   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 $\Psi^{(\prime)}$ + effective poles)

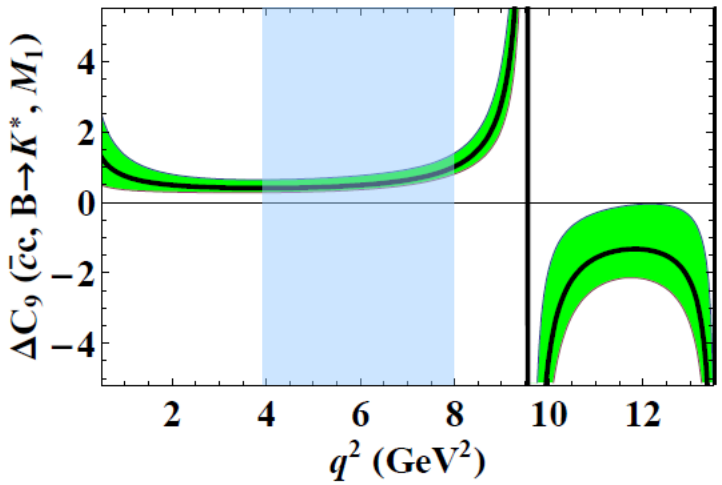
step 2

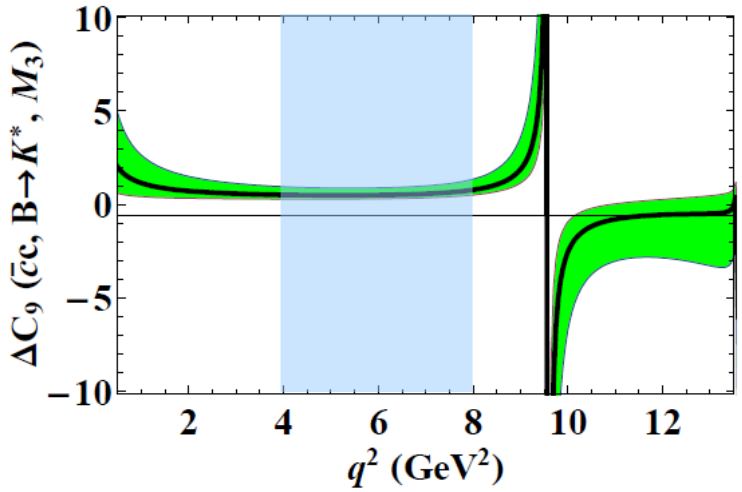
$$\Delta C_{9,i}^{(c\bar{c})}(q^2) = \frac{r_{1,i}\left(1-\frac{\bar{q}^2}{q^2}\right) + \Delta C_{9,i}^{(c\bar{c})}(\bar{q}^2)\frac{\bar{q}^2}{q^2}}{1 + r_{2,i}\frac{\bar{q}^2-q^2}{m_{J/\psi}^2}}$$

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

but model dependence, no pert. gluons and 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,
   see next talk

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

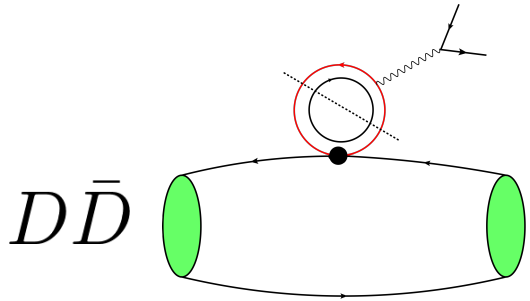
   1. resonant $B \to \Psi^{(n)} K^*$ data (masses and amplitudes)
   2. LCSR + QCDF theoretical results at small/negative q^2

c-loop from analyticity

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

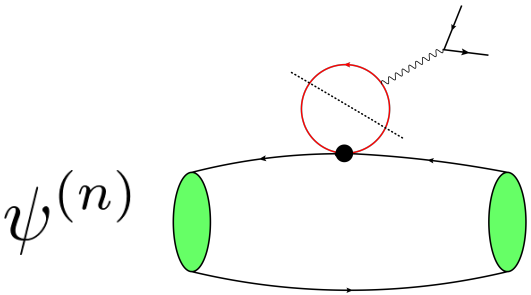
Features:

- 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



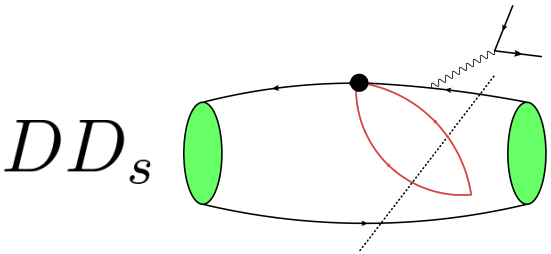
Open issues:

- 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 $|z| \sim 0.2$-0.4
  NB: z expansion of FF at much smaller values



Parametrizing the charm loop

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

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

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

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

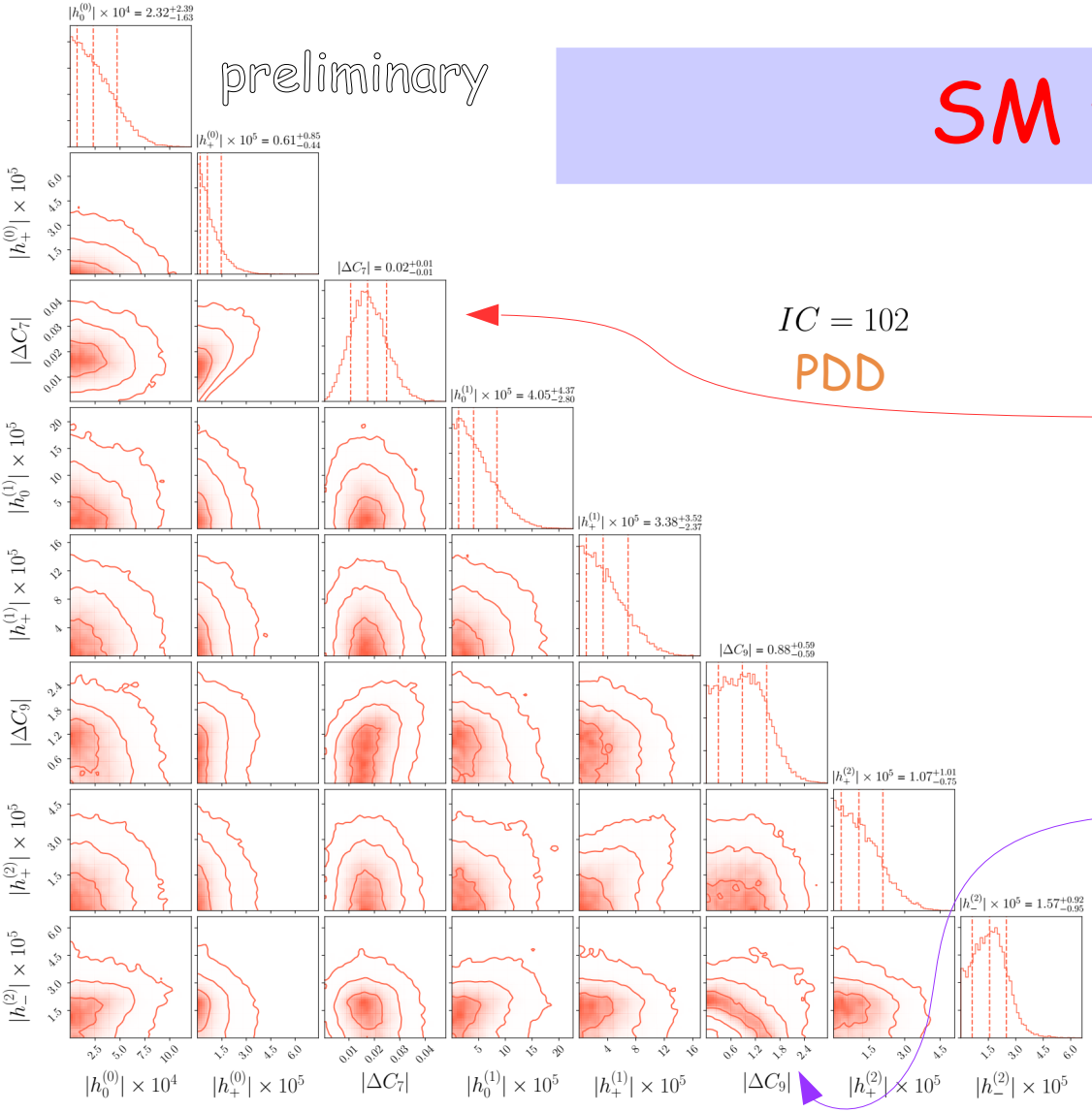
$\Delta C_7^{(cc)} = h_-^0$ and $\Delta C_9^{(cc)} = h_-^1$ shift the corresponding Wilson coefficients (as NP contributions do), while the other parameters have no short-distance counterparts

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

SM fit of the h_λ's



$IC = 102$

PDD

B→K*ℓℓ data accounted for by the hadronic contributions

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

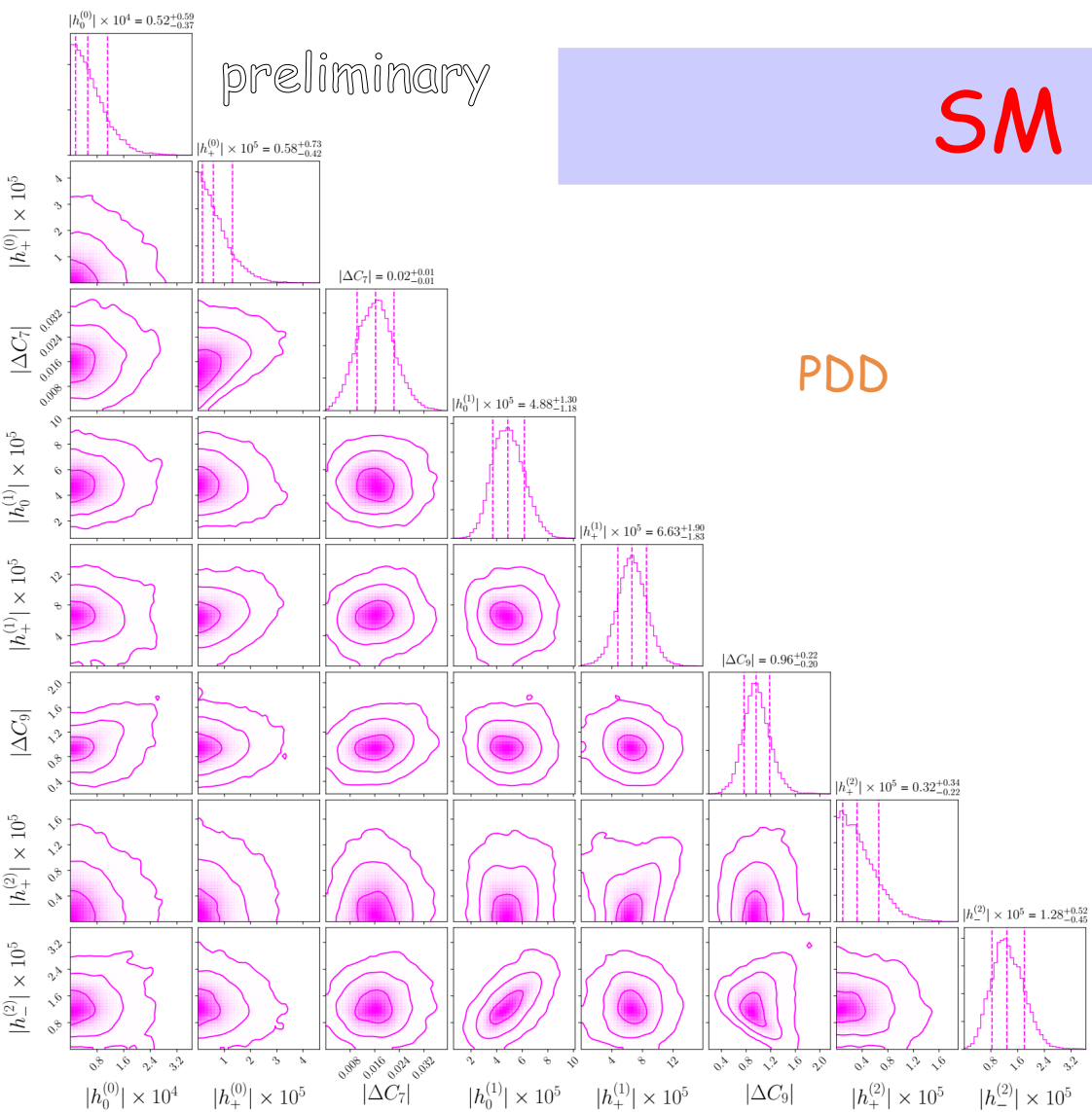
No clear evidence for other non-vanishing hadronic parameters but interesting correlation $|\Delta C_9|$ - $h_-^{(2)}$

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

preliminary



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)

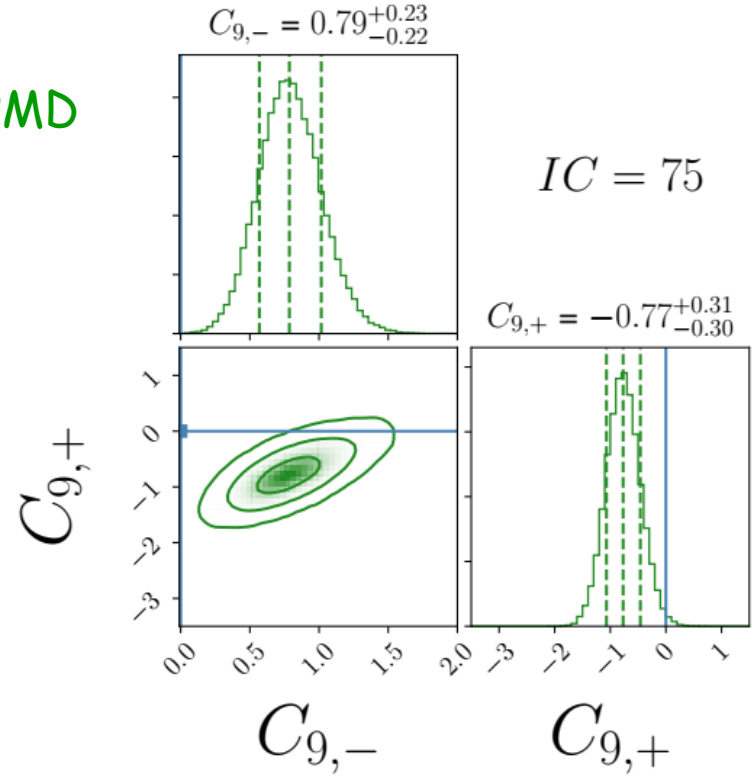
MC, Coutinho, Fedele, Franco, Paul, Silvestrini, Valli, in preparation

NP in C_9^μ and C_9^e

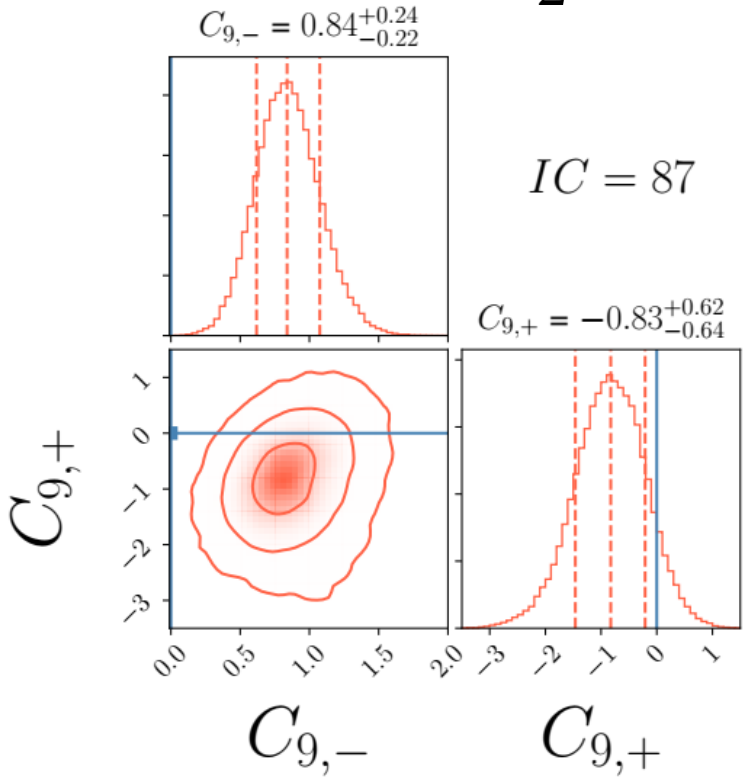
MC, Coutinho, Fedele, Franco, Paul, Silvestrini, Valli, arXiv:1704.05447 + work in progress

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

PMD



PDD



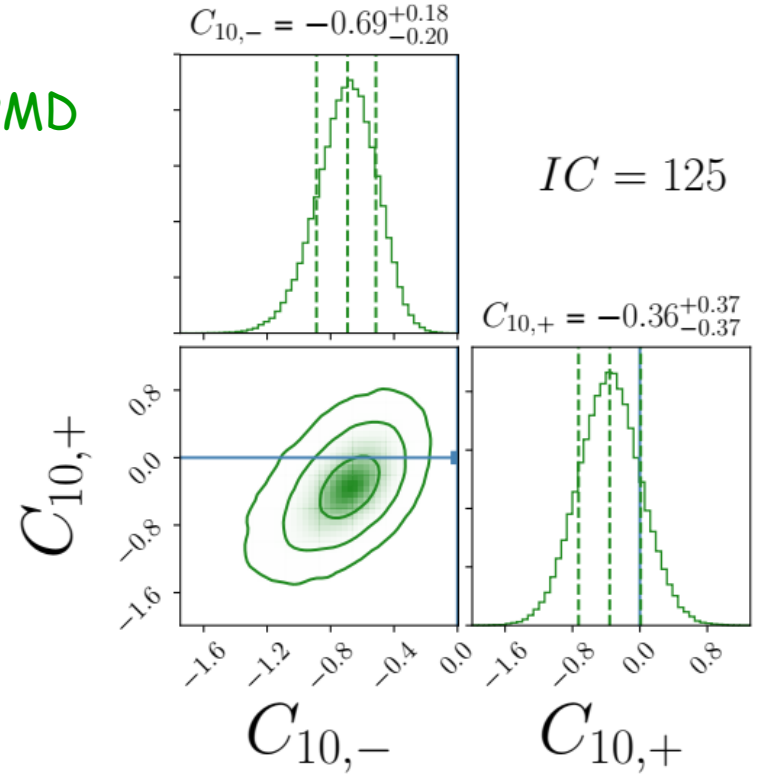
NP in C_{10}^{μ} and C_{10}^{e}

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

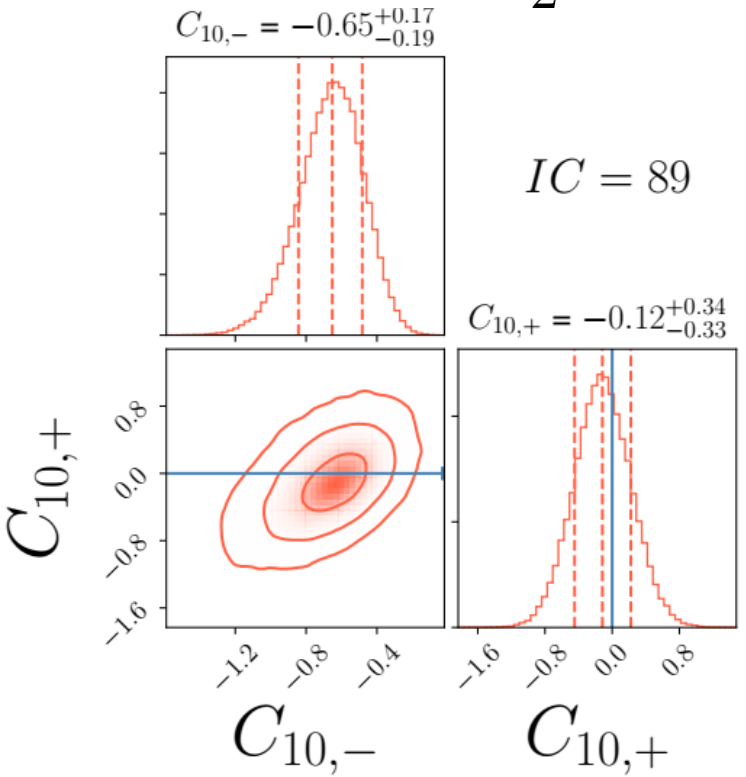
… BUT the viable NP scenarios ARE!

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

PMD



PDD



Charm loop: dangerous or harmless?

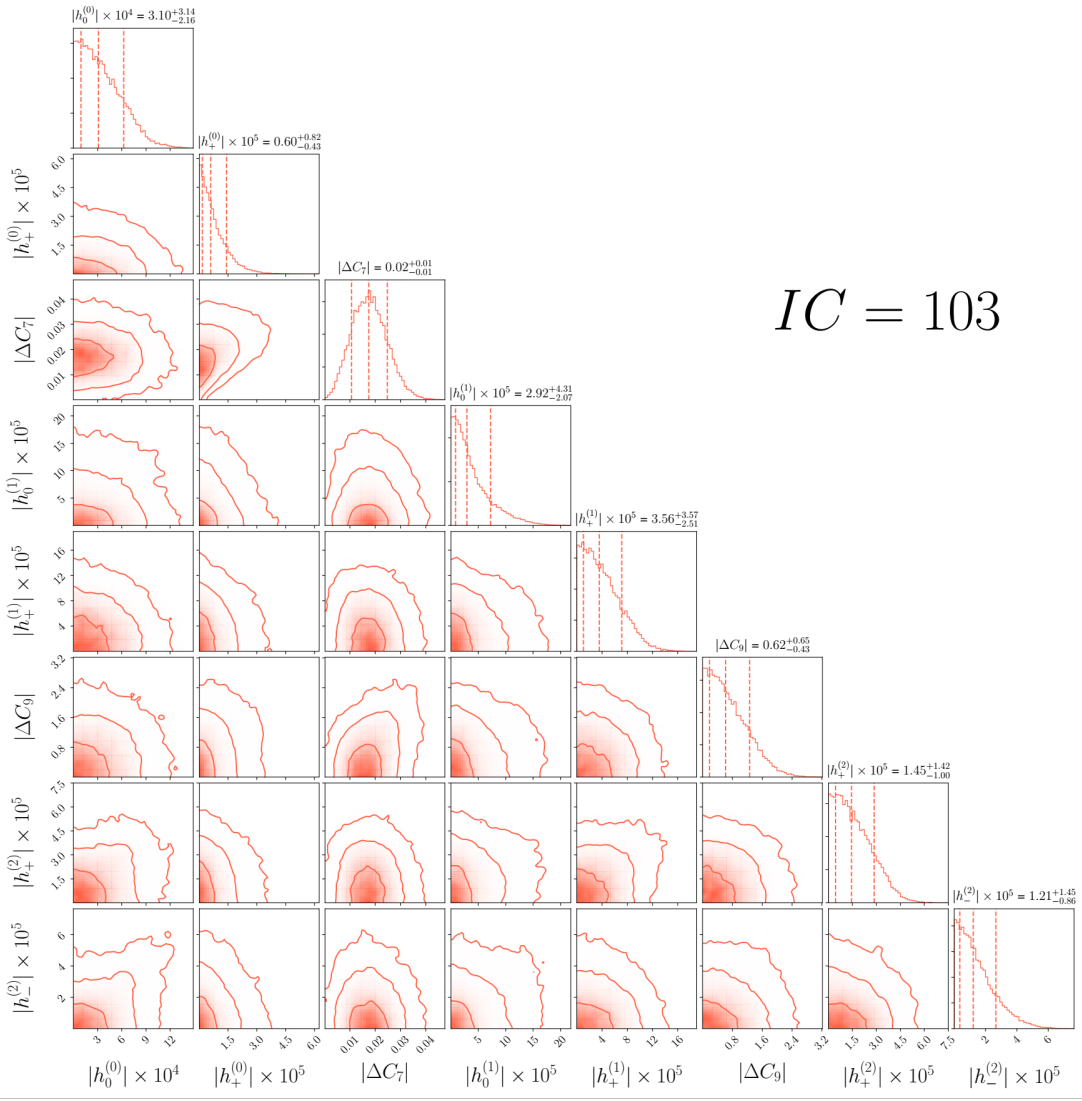
A clear-cut non-perturbative calculation is not available yet

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

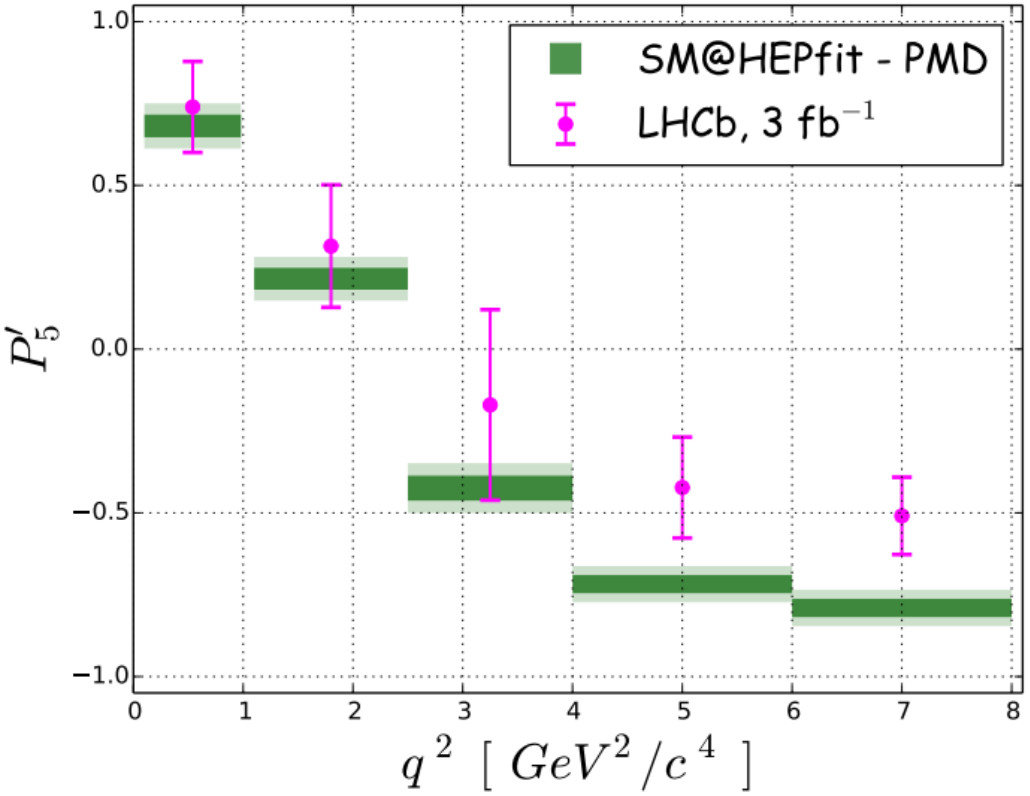
Future data could be able to pin down hadronic contributions with no short-distance counterparts (all but ΔC_7 and ΔC_9)

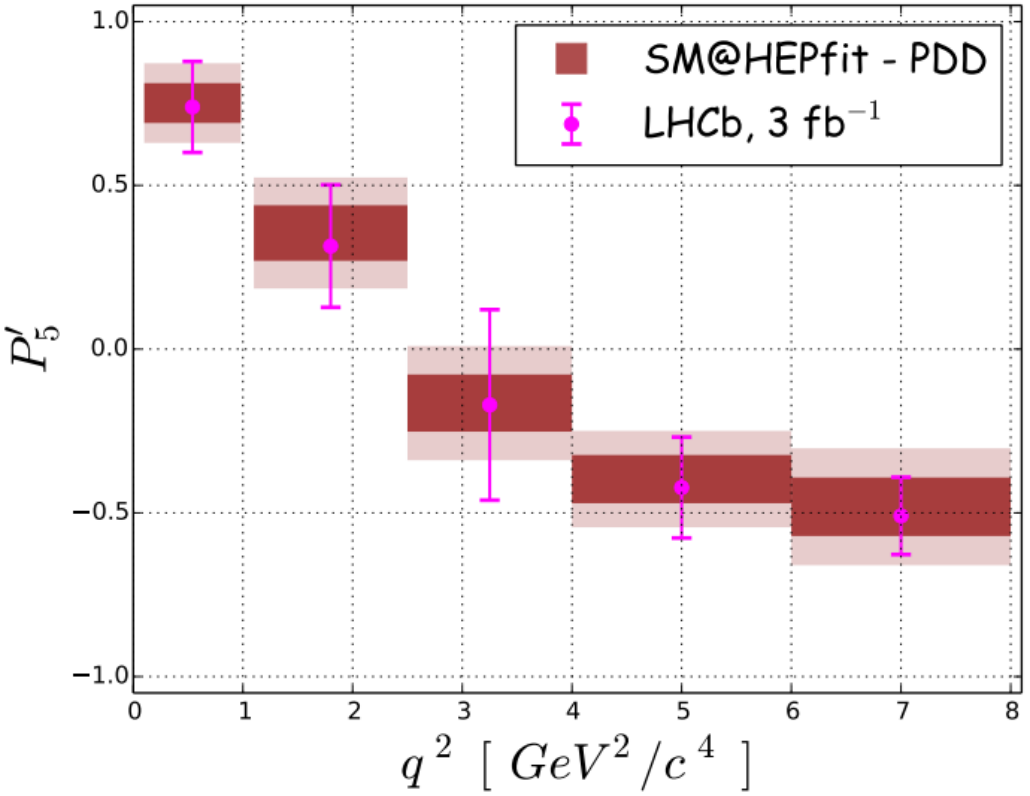
LFUV signals are not affected, but their interpretation may be

Backup


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

$$IC = 103$$


SM@HEPfit - PMD
LHCb, 3 fb^{-1}
P_5'
q^2 [GeV^2/c^4]


SM@HEPfit - PDD
LHCb, 3 fb^{-1}
P_5'
q^2 [GeV^2/c^4]

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

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

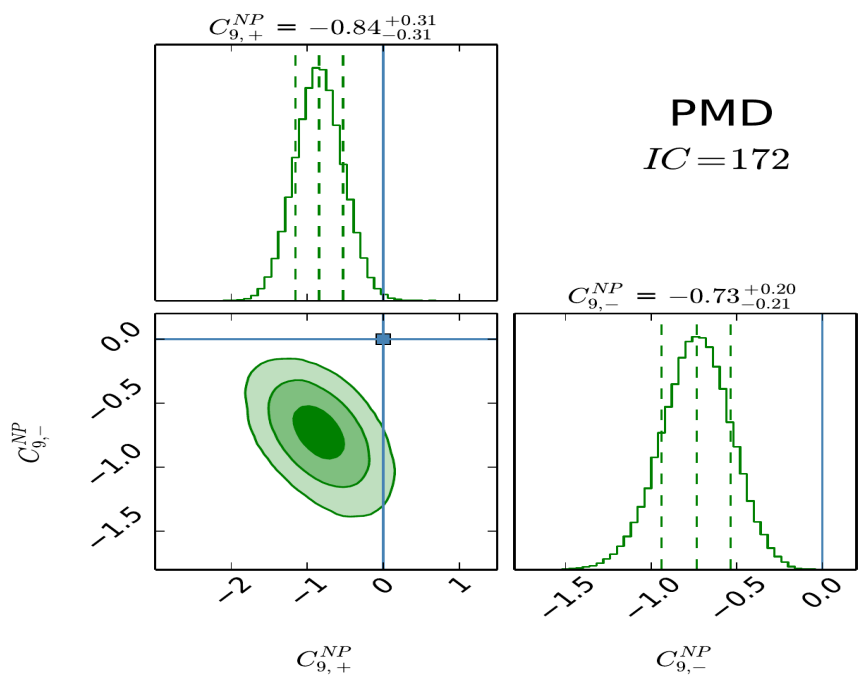
$$F_L, A_{FB}, S_{3,4,5,7,8,9}$$

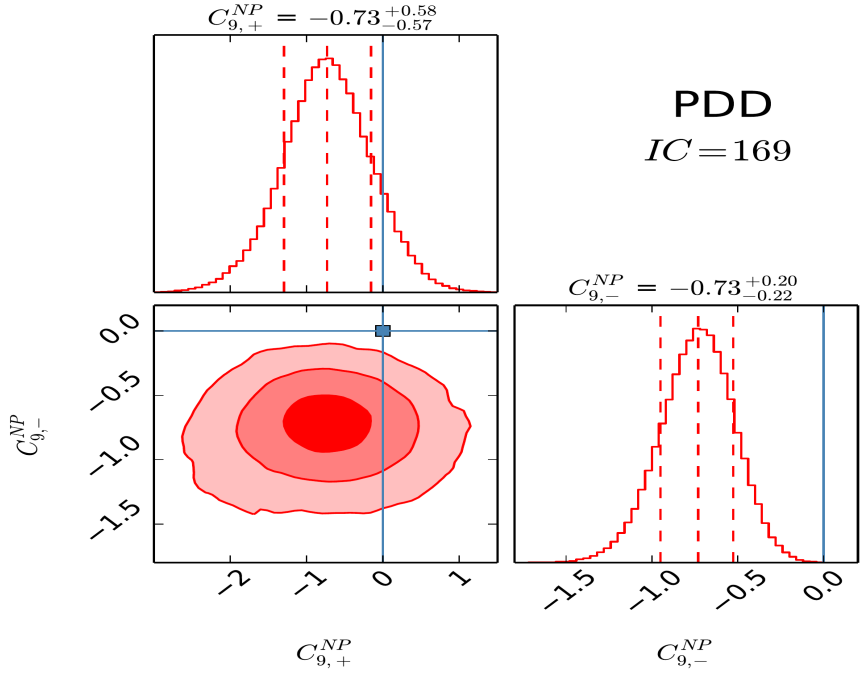
In the helicity amplitude formalism: $(m_\ell \sim 0)$

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

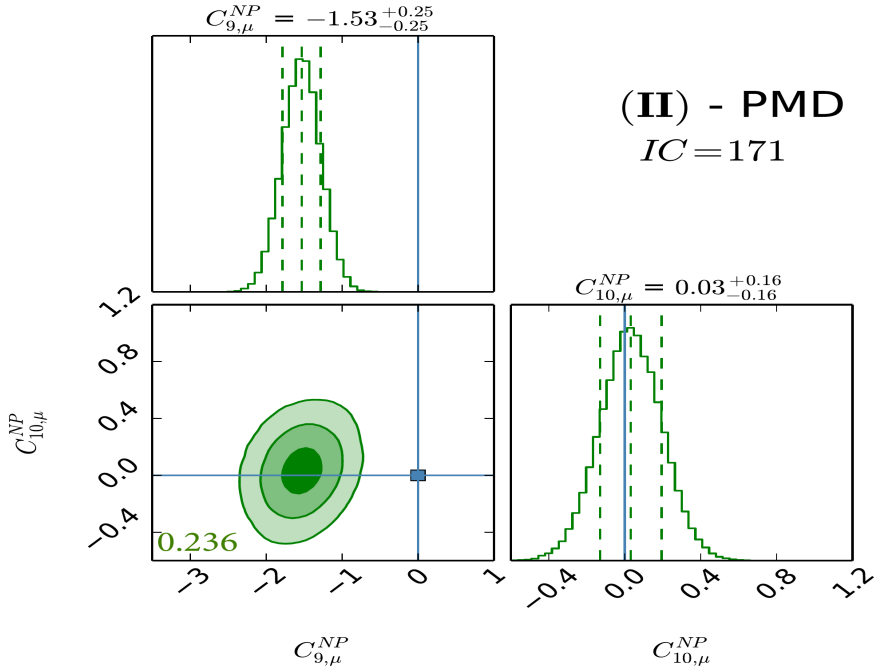
We need to compute few helicity amplitudes: $H_{V,A}^{\lambda}$ $\lambda = 0, \pm$

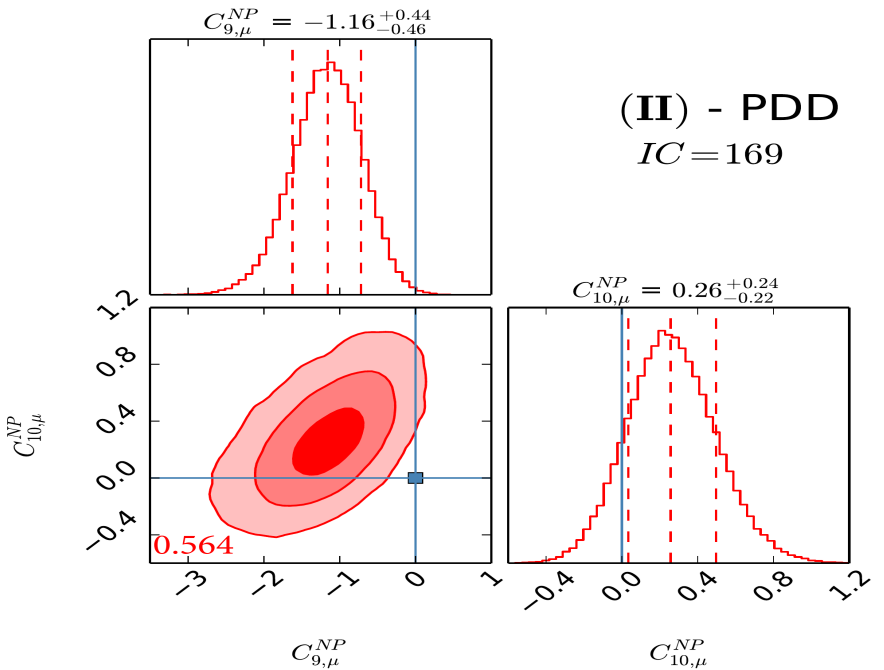
NP IN C_9^{μ} AND C_9^{e}



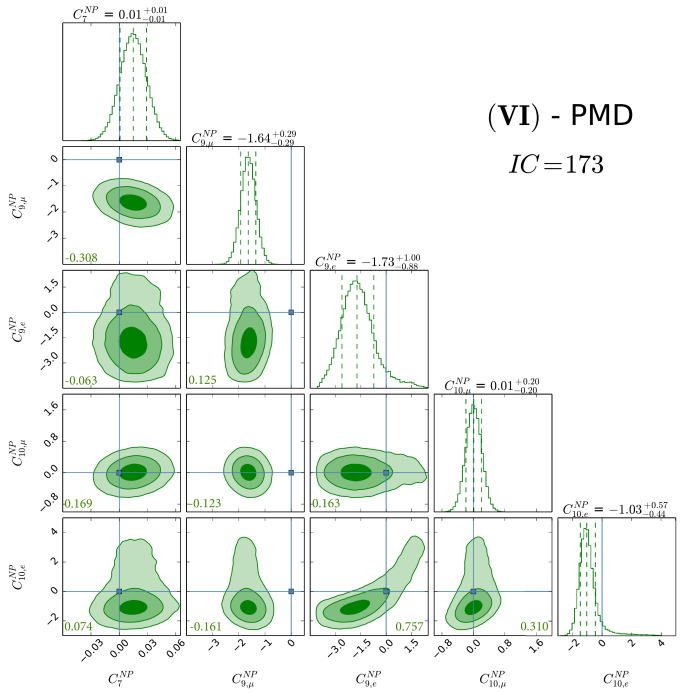


NP IN C_9^μ AND C_{10}^μ



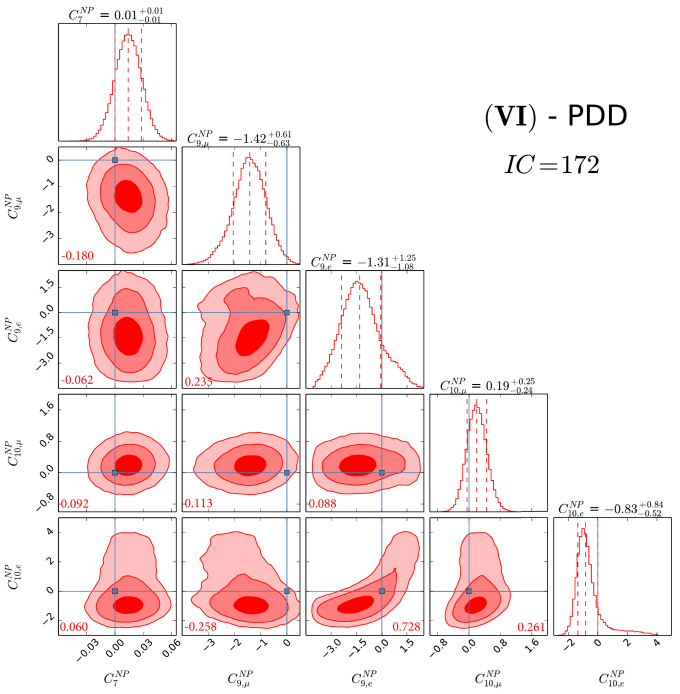


NP IN C_7, $C_{9,10}^{e,\mu}$



(**VI**) - PMD

$IC = 173$



(**VI**) - PDD

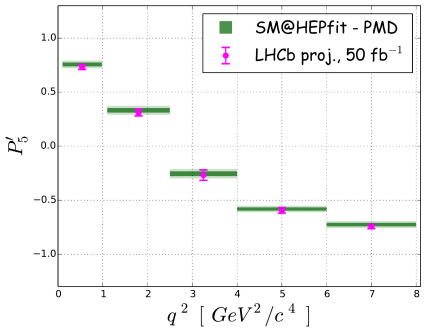
$IC = 172$

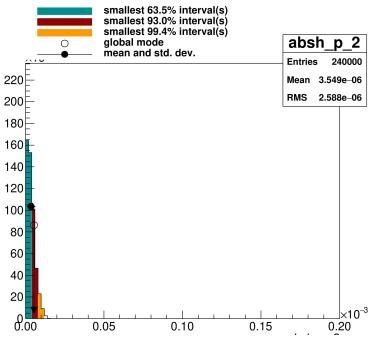
FUTURE PROJECTIONS

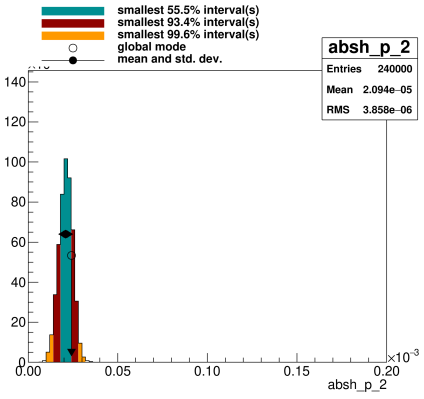
- Choose a theory setup (SM or NP; rising or non-rising charm loop)
- Generate experimental results from current best fit point in the given setup
- Assume future exp errors scaling LHCb statistical errors to 50/fb (roughly /6) and including BelleII estimates
- Fit parameters from generated data

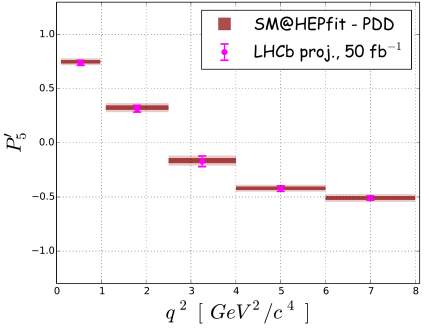
See also Hurth, Mahmoudi, Martinez Santos & Neshatpour '17;
Albrecht, Bernlochner, Kenzie, Reichert, Straub, Tully '17

SM PROJECTION



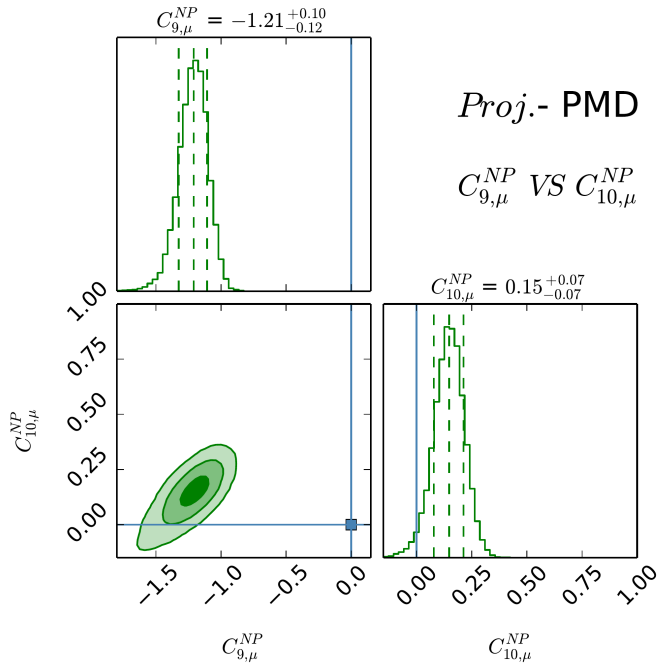






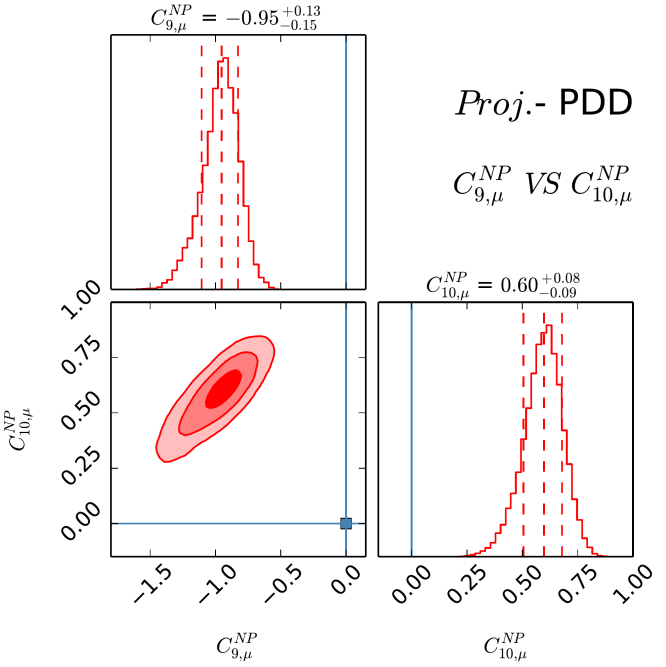
PRELIMINARY!

NP PROJECTION



Proj.- PMD

$C_{9,\mu}^{NP}$ *VS* $C_{10,\mu}^{NP}$

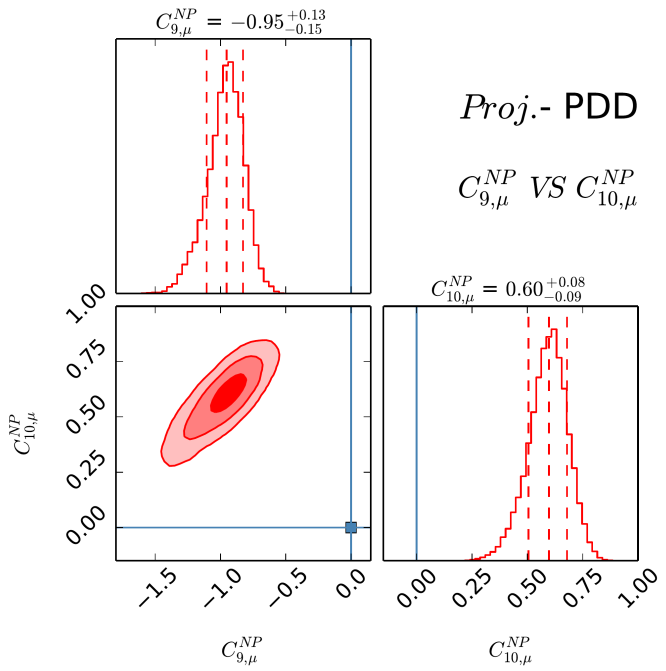


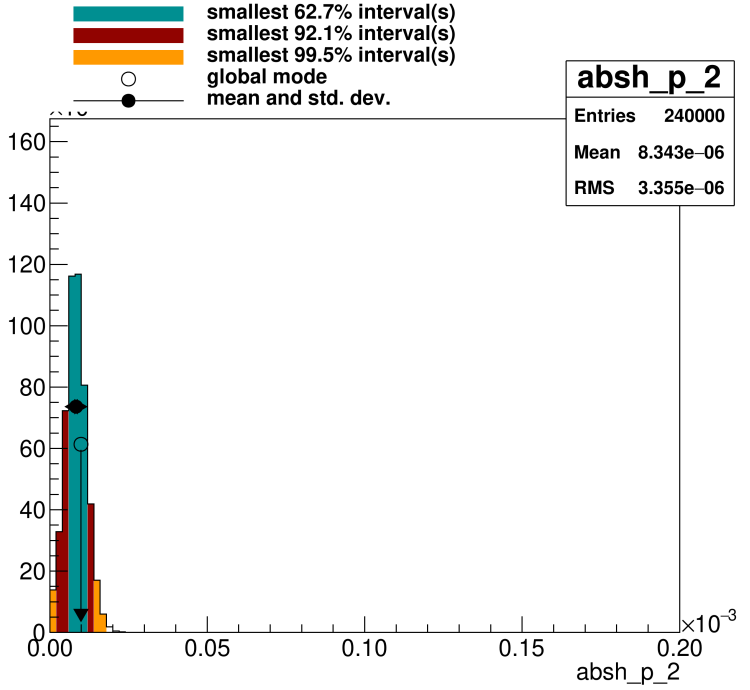
Proj.- PDD

$C_{9,\mu}^{NP}$ *VS* $C_{10,\mu}^{NP}$

PRELIMINARY!

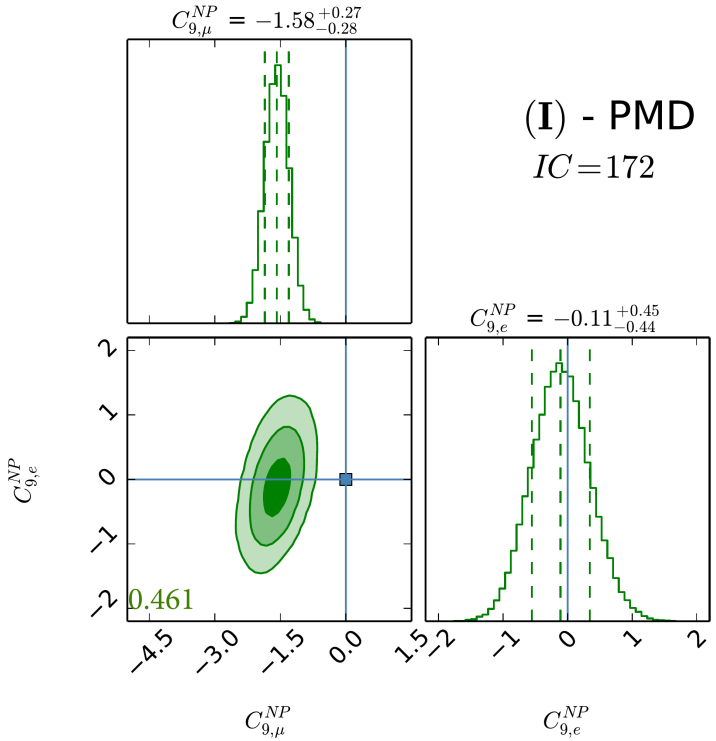
NP PROJECTION





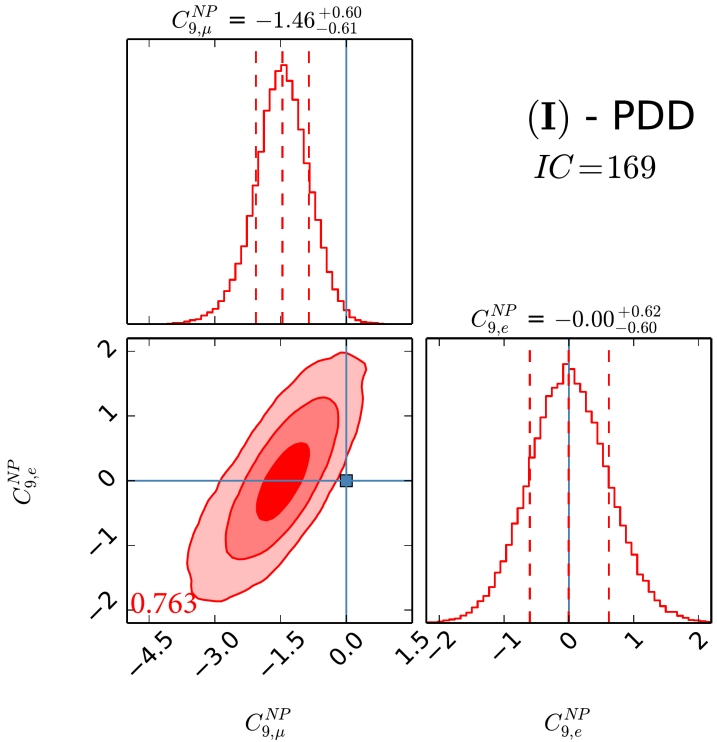
PRELIMINARY!

NP IN C_9^μ AND C_9^e



(I) - PMD

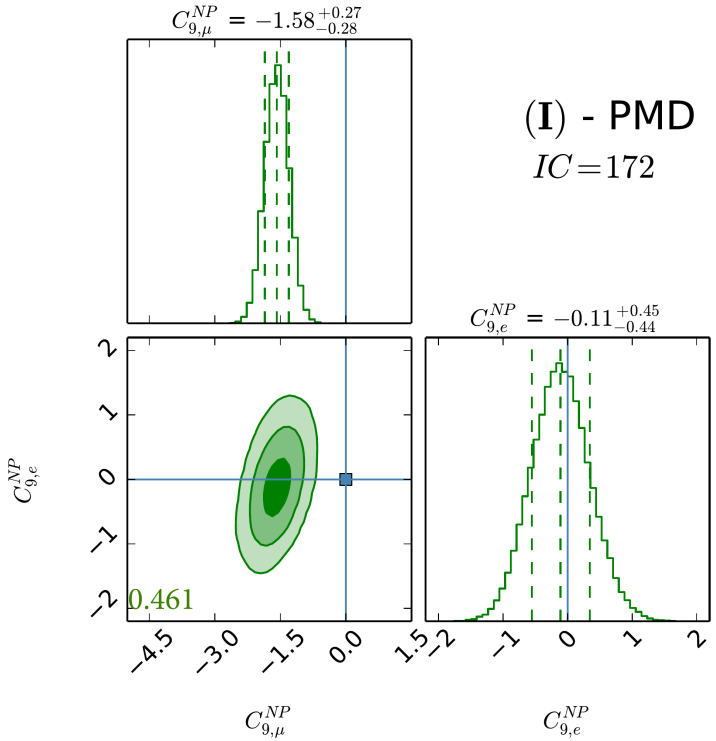
$IC = 172$



(I) - PDD

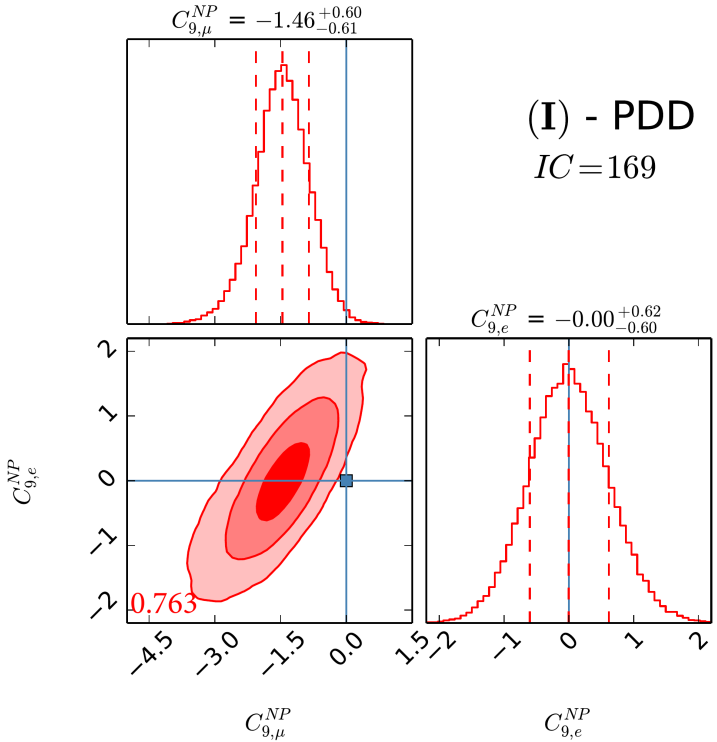
$IC = 169$

NP IN C_9^μ AND C_9^e



(I) - PMD

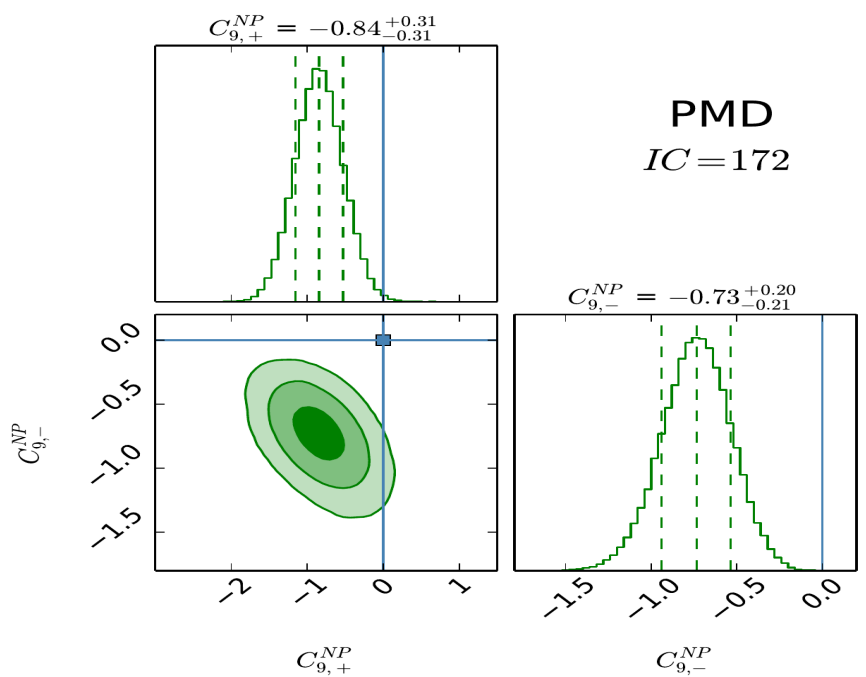
$IC = 172$

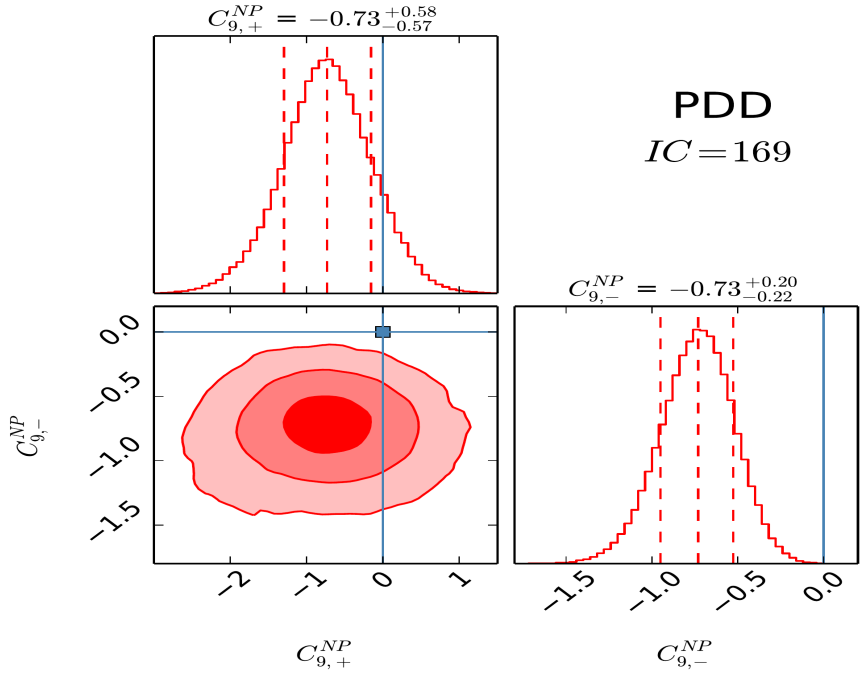


(I) - PDD

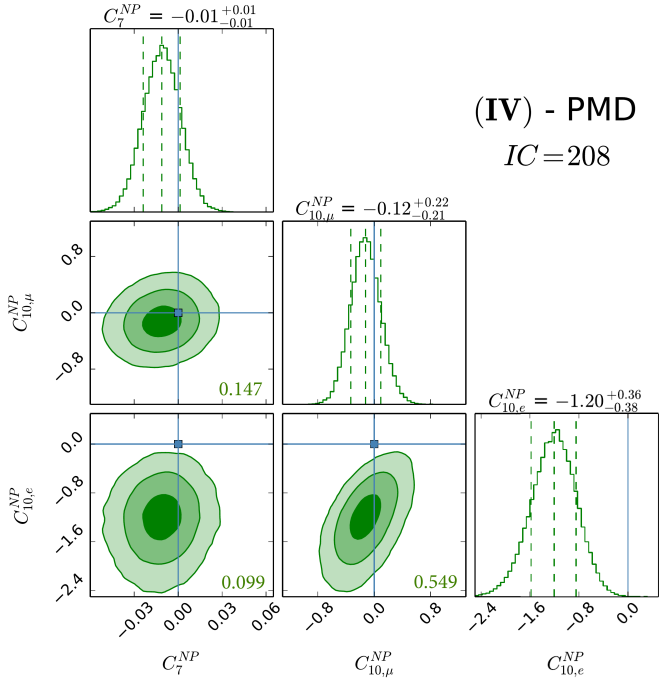
$IC = 169$

NP IN C_9^{μ} AND C_9^{e}



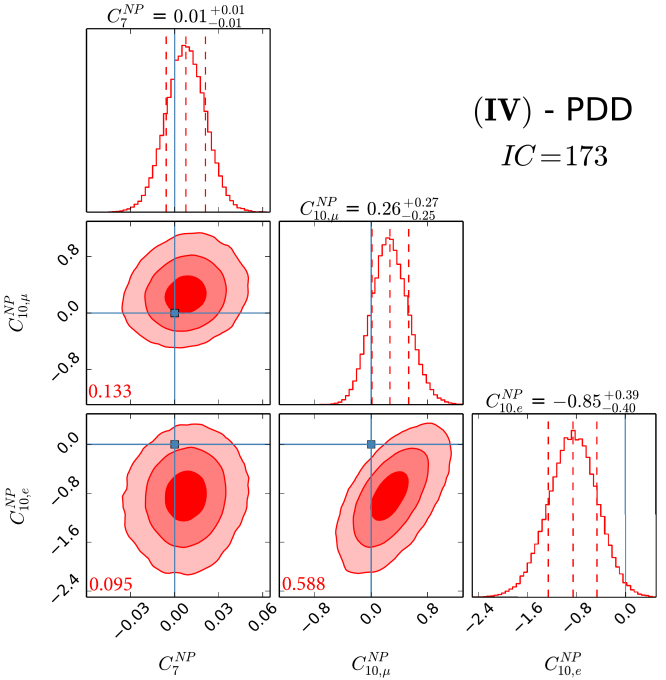


NP IN C_7, C_{10}^{μ} AND C_{10}^{e}



(**IV**) - PMD

$IC = 208$



(**IV**) - PDD

$IC = 173$