TENSIONS IN FLAVOUR PHYSICS

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- Introduction
- Unitarity triangle analysis and CP violation
- CP violation in K decays
- Rare B decays
- Lepton Flavour Universality violation
- Outlook

Many thanks to M. Bona!

INTRODUCTION

- What is the scale Λ of NP?
  - consider the SM as an effective theory valid up to the NP scale Λ:

$$\mathcal{L} = \mathcal{L}_{SM} + \Lambda^2 |\phi|^2 + \mathcal{L}_5/\Lambda + \mathcal{L}_6/\Lambda^2 + \ldots$$

determines the EW scale

break SM accidental symmetries

- NP effects best probed in transitions forbidden or highly suppressed in the SM: GIM suppression of FCNC, smallness of J

Unitarity Triangle Analysis

- All flavour mixing in the SM described by four CKM parameters, e.g. λ, A, ρ, η
- CKM unitarity implies triangular relations: $(V^\dagger V)_{db}=0 \Leftrightarrow$ triangle with apex (ρ, η)
  - Test the consistency of the SM both "visually" and quantitatively
  - Compare CP-conserving and CP-violating obs.
  - Get constraints on deviations from the SM

V_{cb} and V_{ub}

New HFAG (HFLAV) @CKM16

$|V_{cb}|$ *(excl)* = $(38.88 \pm 0.60)\ 10^{-3}$

$|V_{cb}|$ *(incl)* = $(42.19 \pm 0.78)\ 10^{-3}$

New HFAG @CKM16

~3.3σ discrepancy

New HFAG @CKM16

$|V_{ub}|$ *(excl)* = $(3.65 \pm 0.14)\ 10^{-3}$

$|V_{ub}|$ *(incl)* = $(4.50 \pm 0.20)\ 10^{-3}$

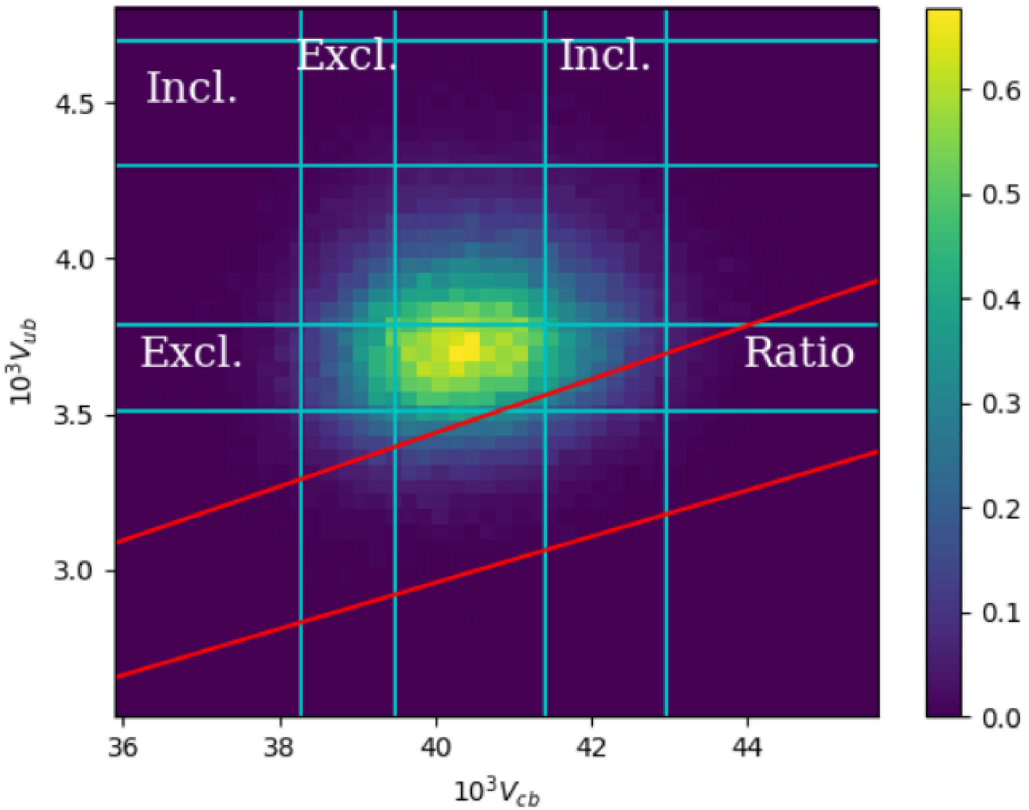
New HFAG @CKM16

~3.4σ discrepancy

$|V_{ub} / V_{cb}|$ *(LHCb)* = $(8.0 \pm 0.6)\ 10^{-2}$

Updated value

updated for LHCP17



Model-Independent Extraction of $|V_{cb}|$ from $\bar{B} \to D^* \ell \overline{\nu}$, cont'd

- New Belle analysis released: **Abdesselam *et al* (Belle) 1702.01521**
  - Unfolded data, full correlation matrix
  - Large dataset, energy and angular distributions
  - CLN: $|V_{cb}| = (37.4 \pm 1.3) \times 10^{-3}$
- Two independent analyses using BGL:
  - Very consistent fits:

$$|V_{cb}| = (41.7\ ^{+2.0}_{-2.1}) \times 10^{-3}$$

Bigi, Gambino & Schacht, 1703.06124

$$|V_{cb}| = (41.9\ ^{+2.0}_{-1.9}) \times 10^{-3}$$

BG & Kobach, 1703.08170

  - Robust: different numerical inputs
  - Likely culprit: independent form factors (no HQET symmetry)

$$\begin{aligned} \langle D^*(\varepsilon, p')|\bar{c}\gamma^\mu b|\bar{B}(p)\rangle &= ig\epsilon^{\mu\nu\alpha\beta}\varepsilon^*_\nu p_\alpha p'_\beta, \\ \langle D^*(\varepsilon, p')|\bar{c}\gamma^\mu\gamma^5 b|\bar{B}(p)\rangle &= f\varepsilon^{*\mu} + (\varepsilon^* \cdot p)[a_+(p+p')^\mu + a_-(p-p')^\mu], \end{aligned}$$

Recall: BGL introduced z-parametrization, eg,

$$g(z) = \frac{1}{P_g(z)\phi_g(z)} \sum_{n=0}^{N} a_n z^n \quad \text{with} \quad \sum_n a_n^2 \le 1 \quad \text{and} \quad 0 \le z \le z_{\max} = 0.056$$

with calculable outer function ϕ and Blaschke factor P

  - CLN uses BGL technique, but imposes HQET conditions

Work ahead:

- Experiments: release unfolded data
- Experiments' next best alternative: do BGL fits
- Global analysts: do BGL fits, others (*e.g.*, polynomail in q^2)?
- Theorists: Λ/m_c effects?
- Theorists: Is BGL better than polynomial for independent form factors?
- Can this affect $B \to D^{(*)}\tau\nu$
- ...

If I may be so bold: *problem solved*

- Retrospect: What went wrong?
  - The probelm was sociological!

Also: FF calculations only on MILC configurations
$\Rightarrow$need confirmation with different methods

V_{cb} and V_{ub}

updated for LHPC17

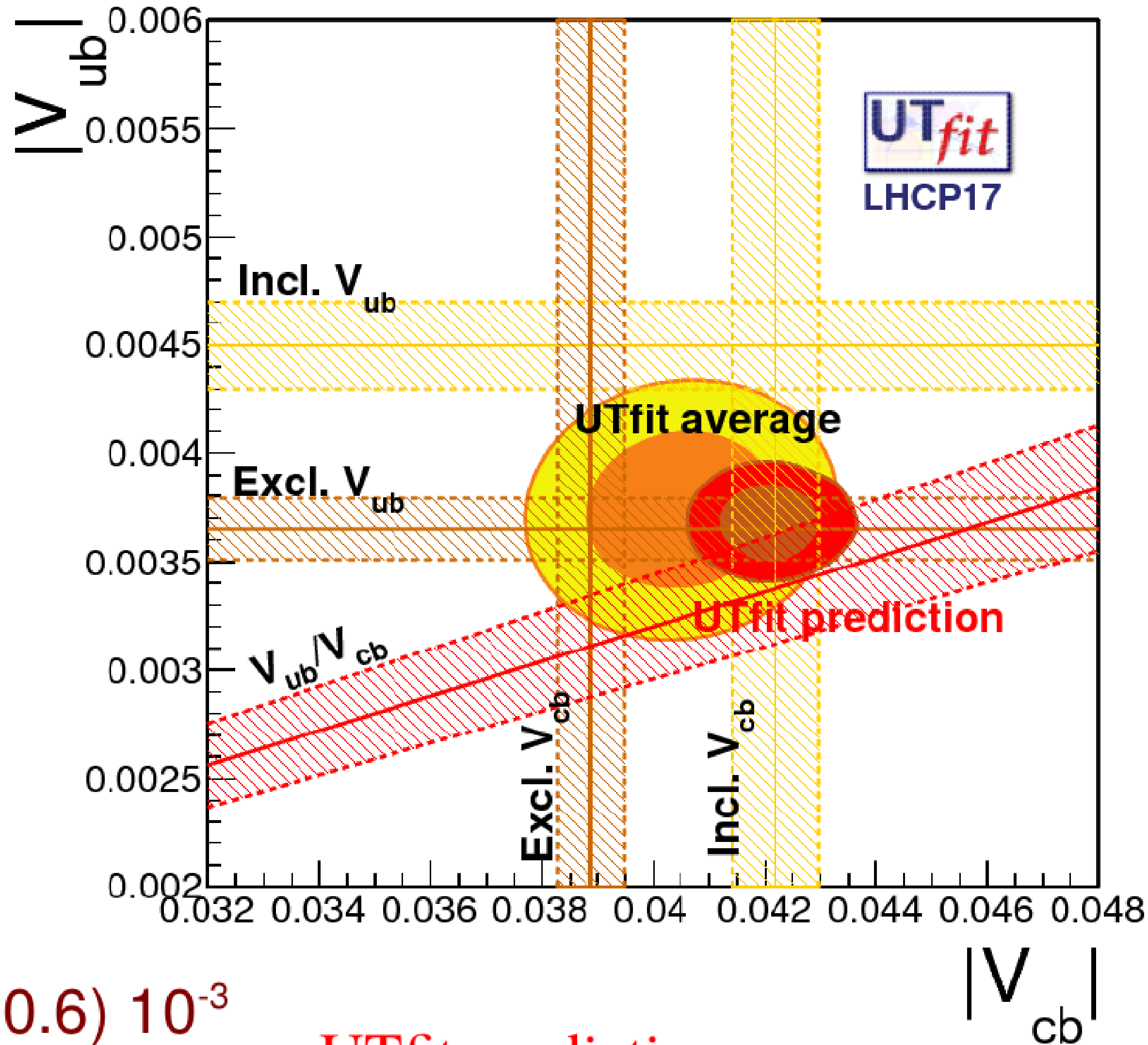
2D average inspired by D'Agostini skeptical procedure (hep-ex/9910036) with σ=1. Very similar results obtained from a 2D a la PDG procedure.

$|V_{cb}| = (40.5 \pm 1.1)\ 10^{-3}$

uncertainty ~ 2.4%

$|V_{ub}| = (3.74 \pm 0.23)\ 10^{-3}$

uncertainty ~ 5.6%

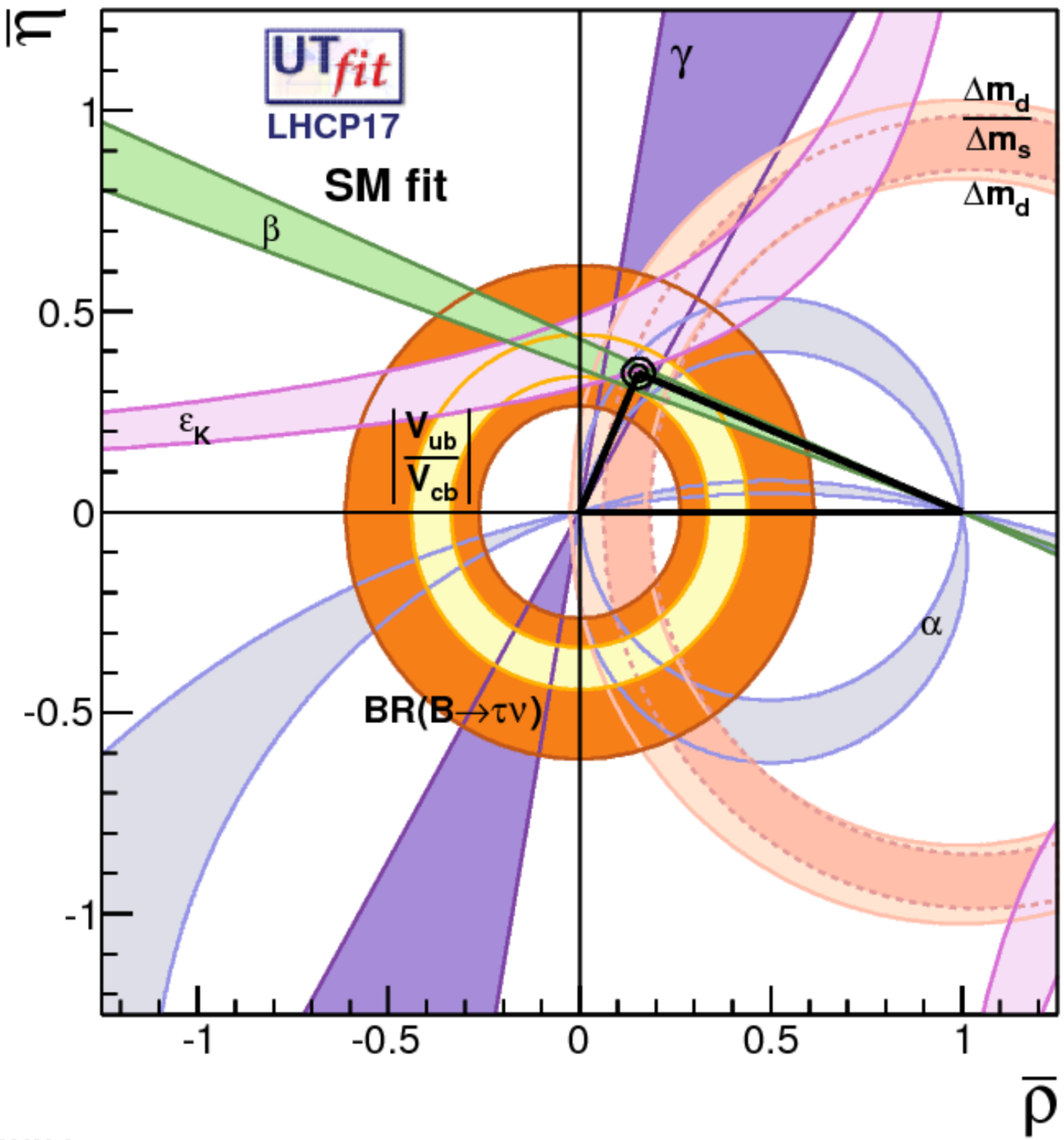


$|V_{cb}| = (42.1 \pm 0.6)\ 10^{-3}$

$|V_{ub}| = (3.68 \pm 0.11)\ 10^{-3}$

UTfit predictions

Unitarity Triangle analysis in the SM:



levels @ 95% Prob

~10 %

$\bar{\rho} = 0.154 \pm 0.015$

$\bar{\eta} = 0.346 \pm 0.013$

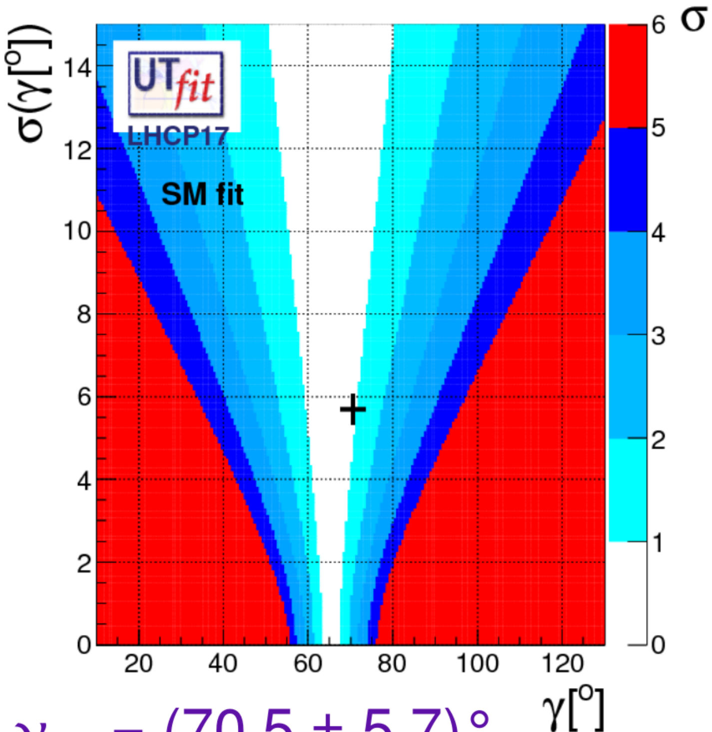
~4%

compatibility plots

A way to "measure" the agreement of a single measurement with the indirect determination from the fit using all the other inputs: test for the SM description of the flavour physics

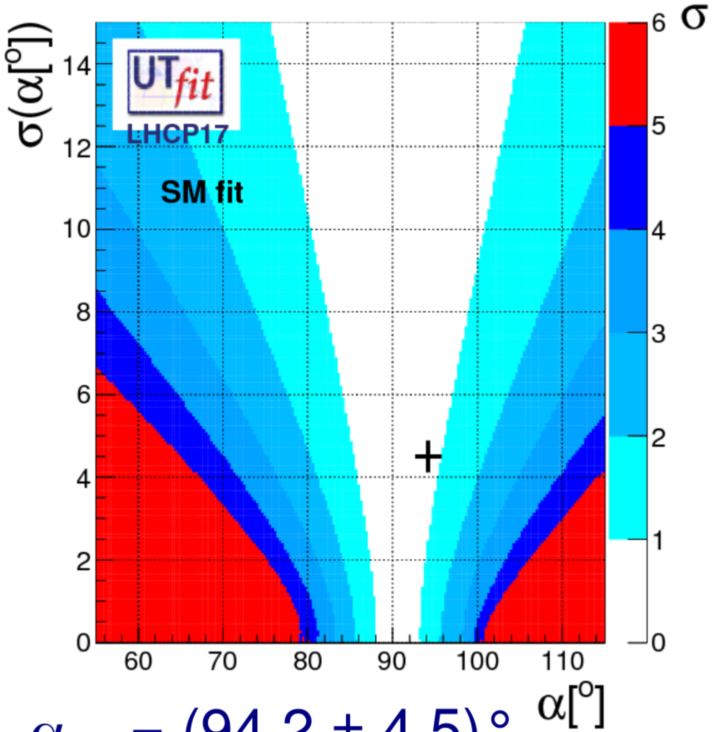
Color code: agreement between the predicted values and the measurements at better than 1, 2, ...nσ

The cross has the coordinates (x,y)=(central value, error) of the direct measurement



γ_{exp} = (70.5 ± 5.7)°

γ_{UTfit} = (65.5 ± 2.1)°



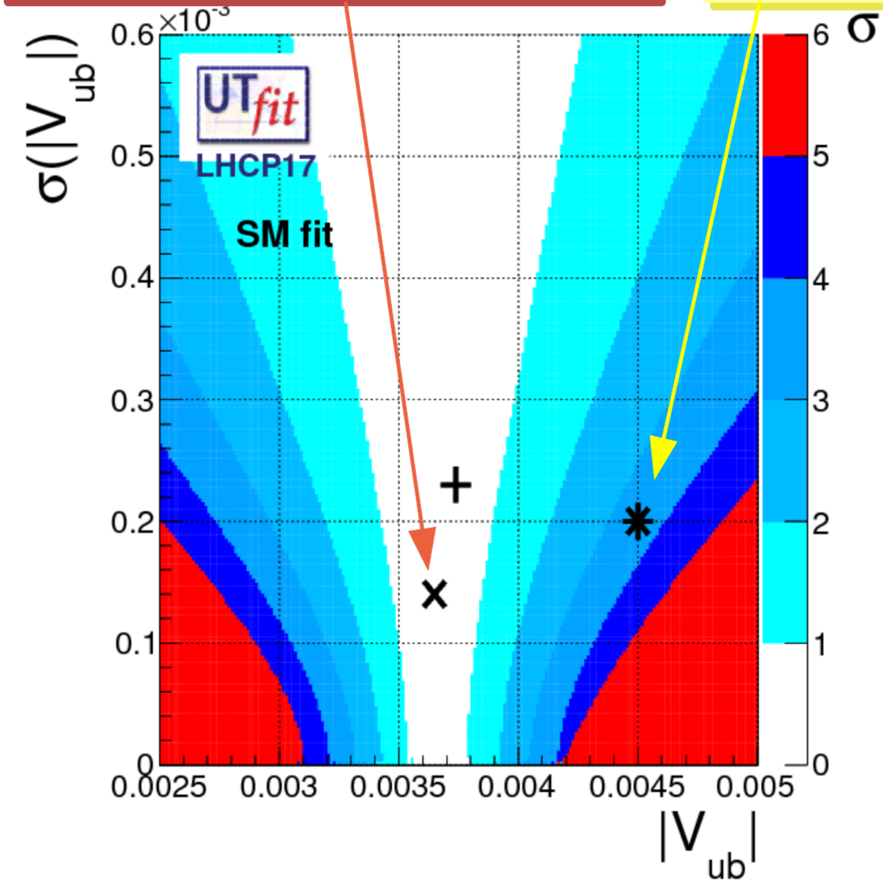
α_{exp} = (94.2 ± 4.5)°

α_{UTfit} = (90.6 ± 2.5)°

tensions? not really.. still that V_{ub} inclusive

V_{ub} *(excl)* = $(3.65 \pm 0.14)\ 10^{-3}$

Vub (incl) = (4.50 ± 0.20) 10-3



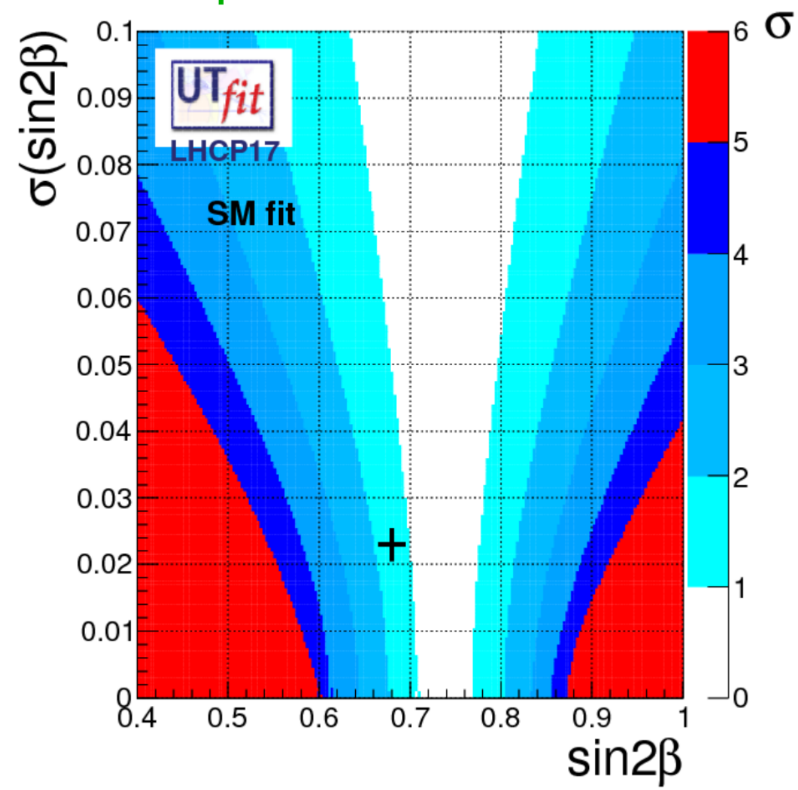
$Vub_{exp} = (3.74 \pm 0.23) \cdot 10^{-3}$

$Vub_{UTfit} = (3.66 \pm 0.13) \cdot 10^{-3}$

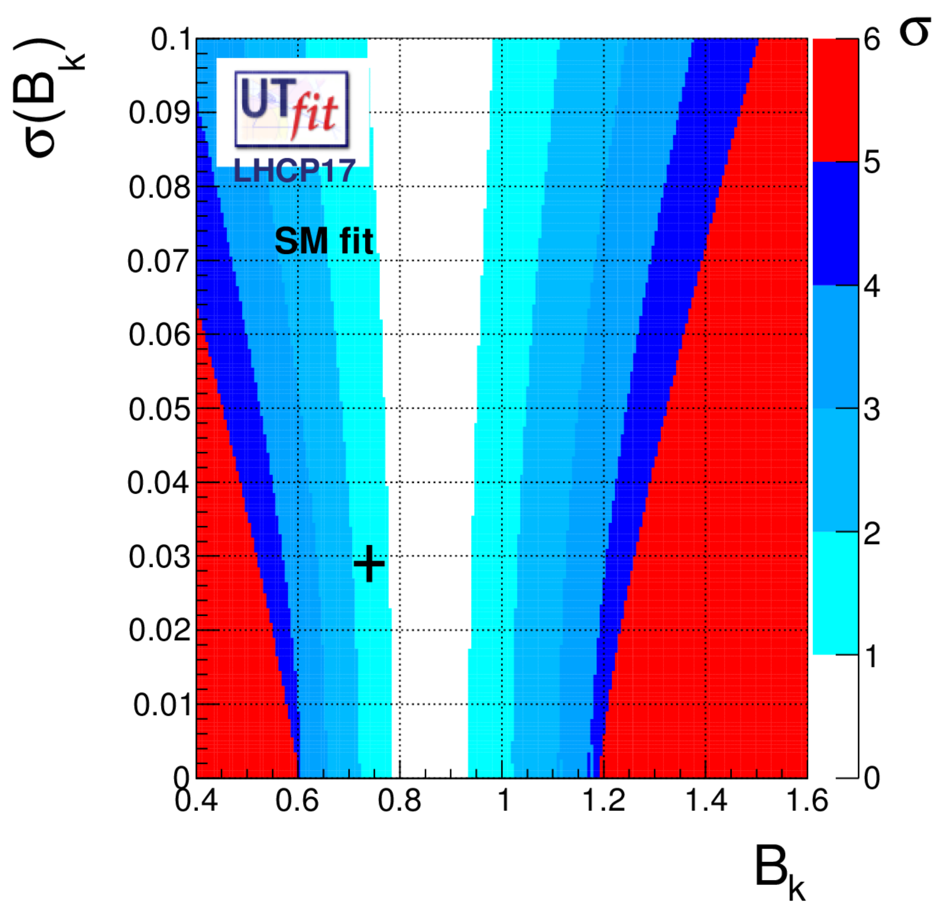
~1.4σ

$\sin 2\beta_{exp} = 0.680 \pm 0.023$

$\sin 2\beta_{UTfit} = 0.737 \pm 0.031$



COMPATIBILITY PLOT FOR ε_K



- Currently no tension in ε_K
- Theoretical improvements needed to fully exploit NP sensitivity: long-distance contributions, B-parameter, D=8 operators...

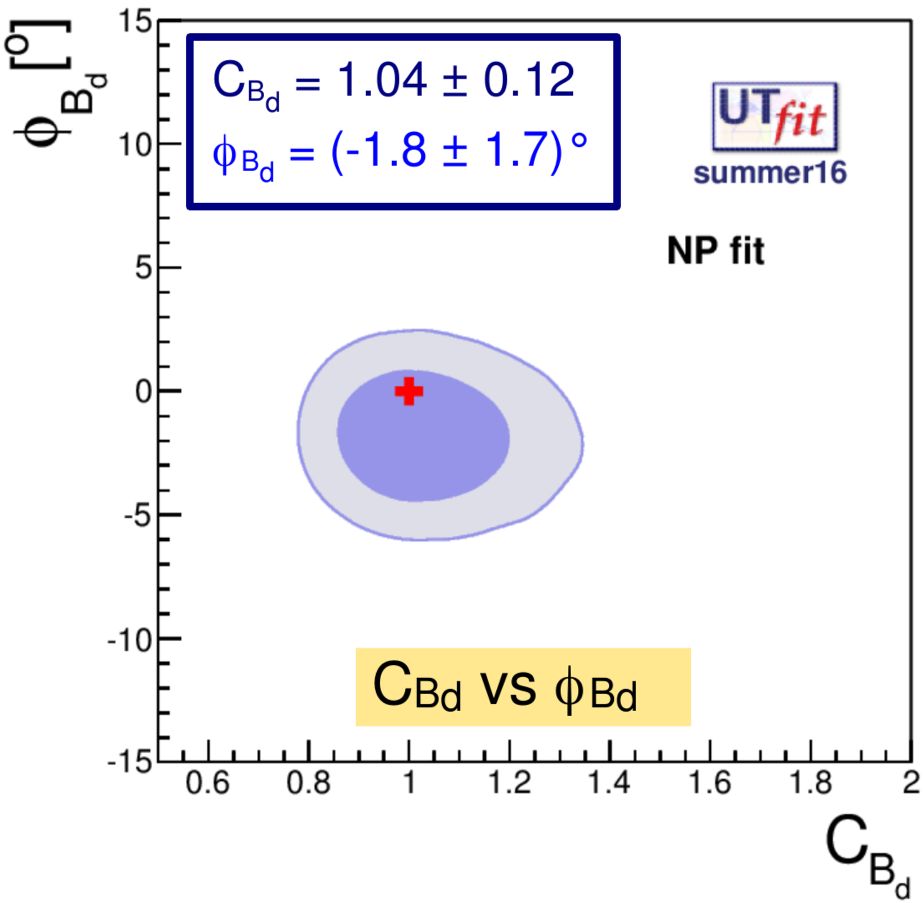
NP parameter results

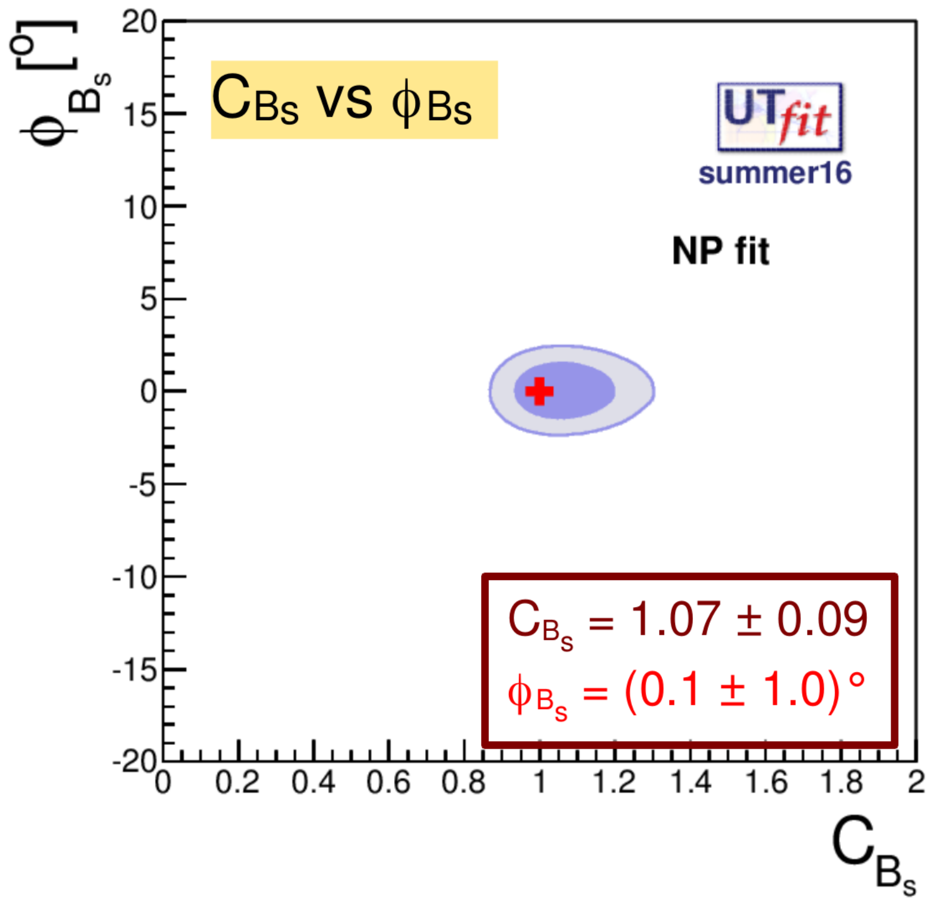
dark: 68%
light: 95%
SM: red cross

K system

$C_{\varepsilon_K} = 1.05 \pm 0.11$

$$A_q = C_{B_q} e^{2i\phi_{B_q}} A_q^{SM} e^{2i\phi_q^{SM}}$$

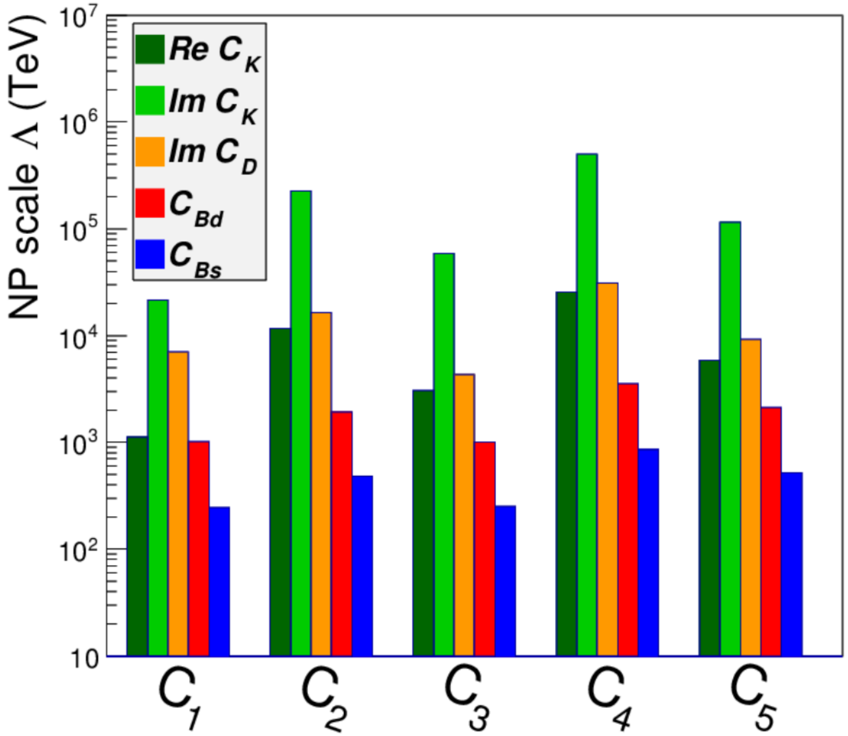




results from the Wilson coefficients

Generic: $C(\Lambda) = \alpha/\Lambda^2$, F_i~1, arbitrary phase

α ~ 1 for strongly coupled NP



Lower bounds on NP scale (in TeV at 95% prob.)

Non-perturbative NP
$\Lambda > 5.0\ 10^5$ TeV

To obtain the lower bound for loop-mediated contributions, one simply multiplies the bounds by α_s (~ 0.1) or by α_W (~ 0.03).

$\alpha \sim \alpha_W$ in case of loop coupling through weak interactions

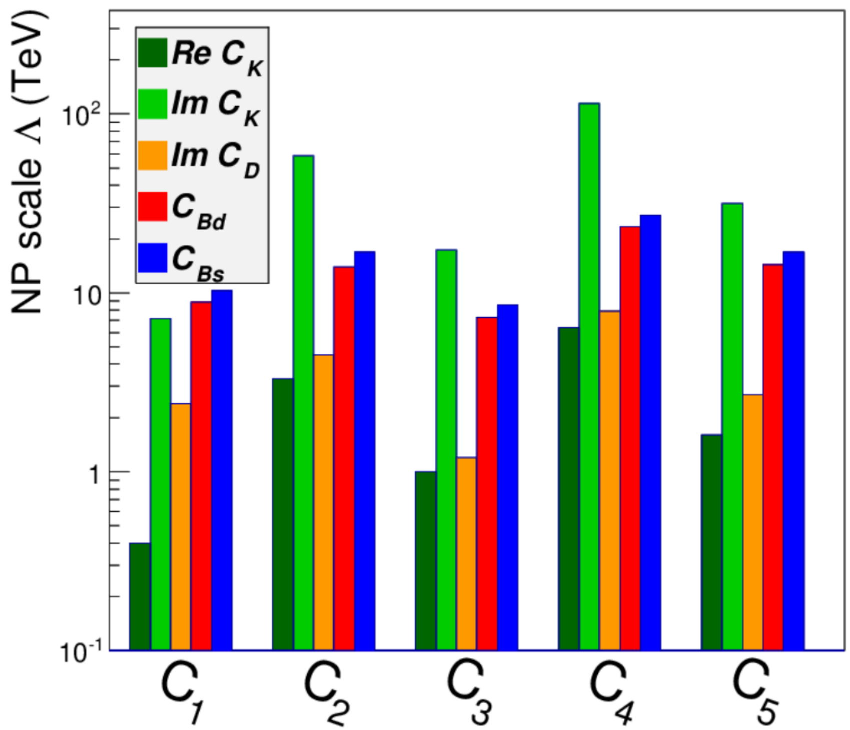
NP in α_W loops
$\Lambda > 1.5\ 10^4$ TeV

Best bound from ε_K
  dominated by CKM error
CPV in charm mixing follows,
  exp error dominant
Best CP conserving from Δm_K,
  dominated by long distance
B_d and B_s behind,
  errors from both CKM and B-parameters

results from the Wilson coefficients

NMFV: $C(\Lambda) = \alpha \times |F_{SM}|/\Lambda^2$, $F_i \sim |F_{SM}|$, arbitrary phase

$\alpha \sim 1$ for strongly coupled NP



Lower bounds on NP scale
(in TeV at 95% prob.)

Non-perturbative NP
$\Lambda > 114$ TeV

To obtain the lower bound for loop-mediated contributions, one simply multiplies the bounds by α_s (~ 0.1) or by α_W (~ 0.03).

$\alpha \sim \alpha_W$ in case of loop coupling through weak interactions

NP in α_W loops
$\Lambda > 3.4$ TeV

- If new chiral structures present, ε_K still leading
- $B_{(s)}$ mixing provides very stringent constraints, especially if no new chiral structures are present
- Constraining power of the various sectors depends on unknown NP flavour structure.

CP VIOLATION IN K DECAYS

- RBC-UKQCD accomplished for the first time a consistent lattice calculation of $K \to \pi\pi$ matrix elements. Formidable task:
  - Renormalization
  - Chirality
  - Final state interactions
  - Disconnected diagrams
- Independent check needed!

RBC-UKQCD RESULTS

- ΔI=1/2 rule from cancellations in the 3/2 amplitude rather than penguin enhancement
  - 3/2 cancellation consistent with ΔS=2 and D, B decays: deviations from VIA small in B, sizable in D (1/N~0), large in K (negative 1/N) Carrasco, Lubicz & LS '13
  - also consistent with large N models Buras, Gerard & Bardeen '86, '14

$$\frac{\mathrm{Re}(A_0)}{\mathrm{Re}(A_2)} = 31.1(11.2)$$ RBC-UKQCD, PRD 91, 074502 (2015)

RBC-UKQCD RESULTS II

- evaluation of ε'/ε even more challenging:

$$\mathrm{Re}\left(\frac{\varepsilon'}{\varepsilon}\right) = \mathrm{Re}\left\{\frac{i\omega e^{i(\delta_2-\delta_0)}}{\sqrt{2}\varepsilon}\left[\frac{\mathrm{Im}A_2}{\mathrm{Re}A_2} - \frac{\mathrm{Im}A_0}{\mathrm{Re}A_0}\right]\right\}$$

- cancellation between 3/2 and ½ makes it very sensitive to even small relative uncertainties in the two contributions

- resulting ε'/ε small wrt exp (16.6±2.3)10^{-4}

$$\mathrm{Re}\left(\frac{\varepsilon'}{\varepsilon}\right) = 1.38(5.15)(4.59) \times 10^{-4}$$

RBC-UKQCD, PRL 115, 212001 (2015)

(see also Buras et al '15, Kitahara, Nierste & Temper '16)

NP IN K DECAYS?

- Need improved lattice numbers & independent confirmation (not soon…)
- Cancellation between A_2 and A_0 makes ε'/ε even more sensitive to NP: modified Z couplings, Z' models, SUSY, trojan EWP, etc… $\Rightarrow$ effects in other observables (dedicated session tomorrow morning)

RARE B DECAYS I: P_5'

- $b \to s l^+ l^-$ FCNC transitions generated by

Z-penguins, boxes and photon penguins

arise at the EW scale

arise at all scales – low-energy contributions

- Exclusive transitions require infinite mass limit + form factors + estimate of power corrections (charm loop + ...)

$B \to K^* l^+ l^-$ AT LOW q^2

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

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

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

- "clean" observables have been introduced to minimize FF dependence in the limit $m_b \to \infty$

Kruger & Matias '05; ...

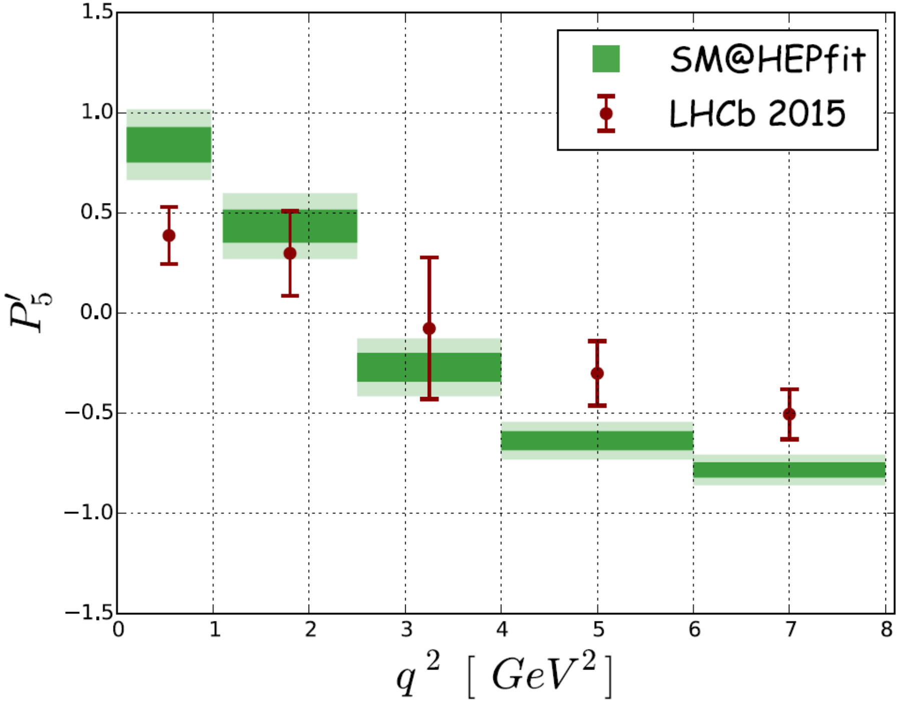
- they are not clean wrt power corrections!

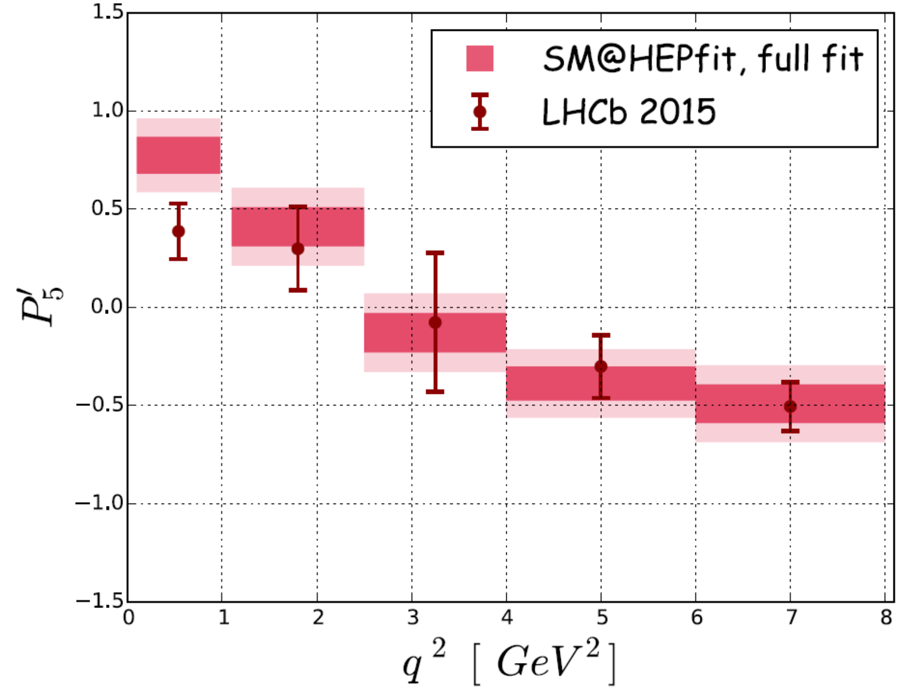
Jäger & Camalich '13, '14

THE CHARM LOOP

- Need some nonperturbative method to evaluate the correction to factorization (notice that $\Lambda/m_b \gtrsim \alpha_s/4\pi$)
- Currently only one LCSR estimate available, valid for $q^2 \sim 0$ (LC), $q^2 \ll 4m_c^2$ (single gluon) Khodjamirian et al '10
- Common approach is to extrapolate smoothly to J/ψ
- Expect charm loop to grow for q^2 close to the charm threshold Lyon & Zwicky '14
- Quark-hadron duality breakdown at J/ψ BBNS '09

IMPACT OF CHARM LOOP





"Optimistic" evaluation of nonfactorizable contributions

Conservative evaluation of nonfactorizable contributions

RARE B DECAYS II: $R_{K(*)}$

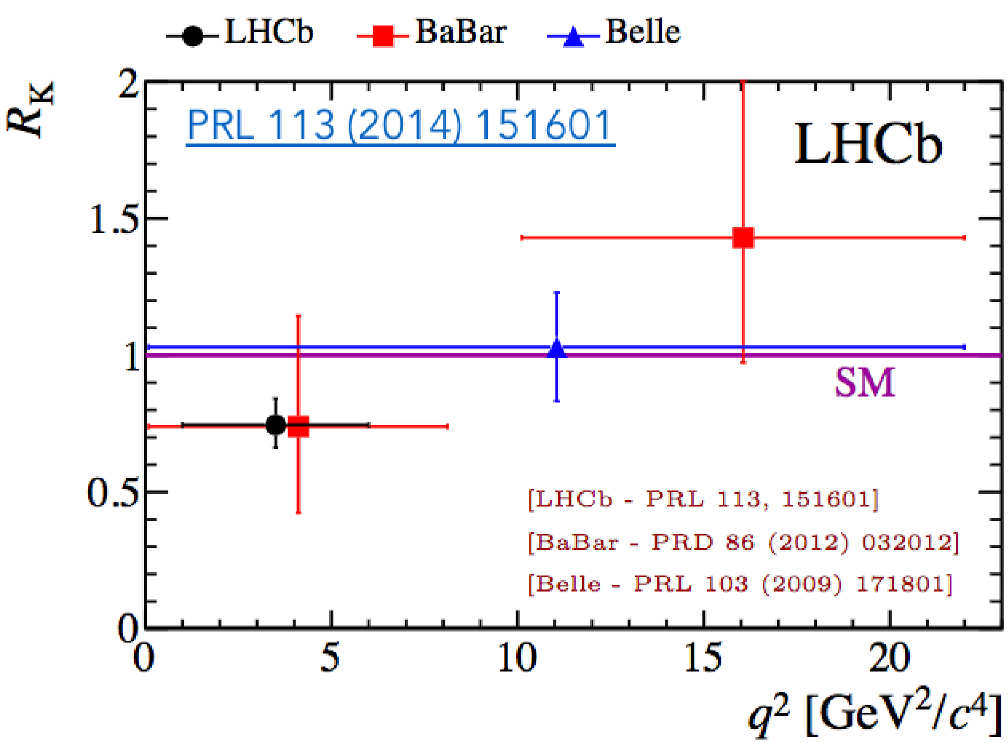
- Hadronic uncertainties drop in μ/e ratios

Hiller & Kruger '03

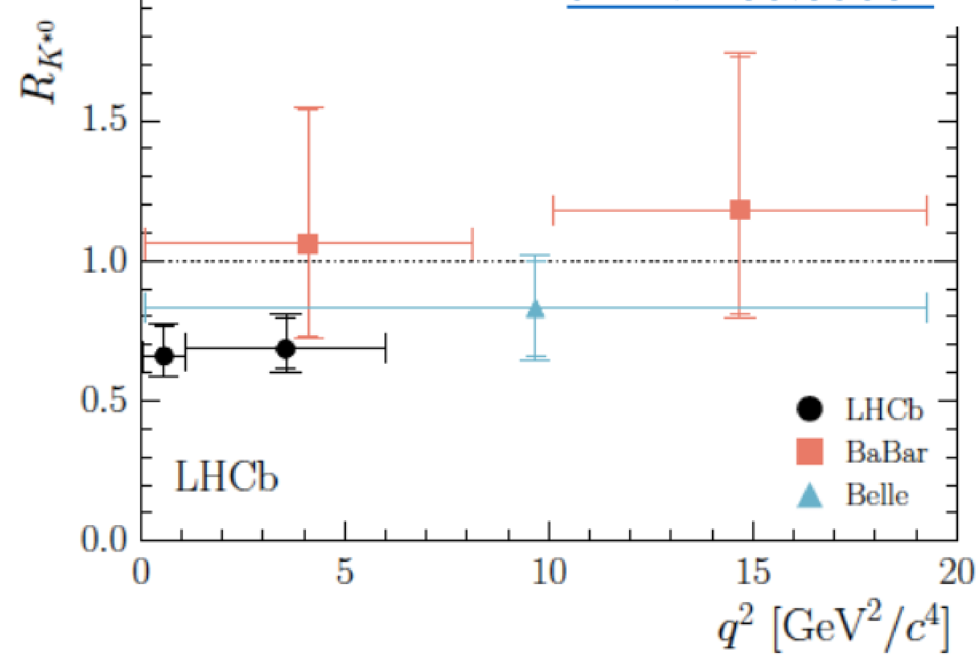
Summary

- PRD 86 (2012) 032012
- PRL 103 (2009) 171801

PRL 113 (2014) 151601



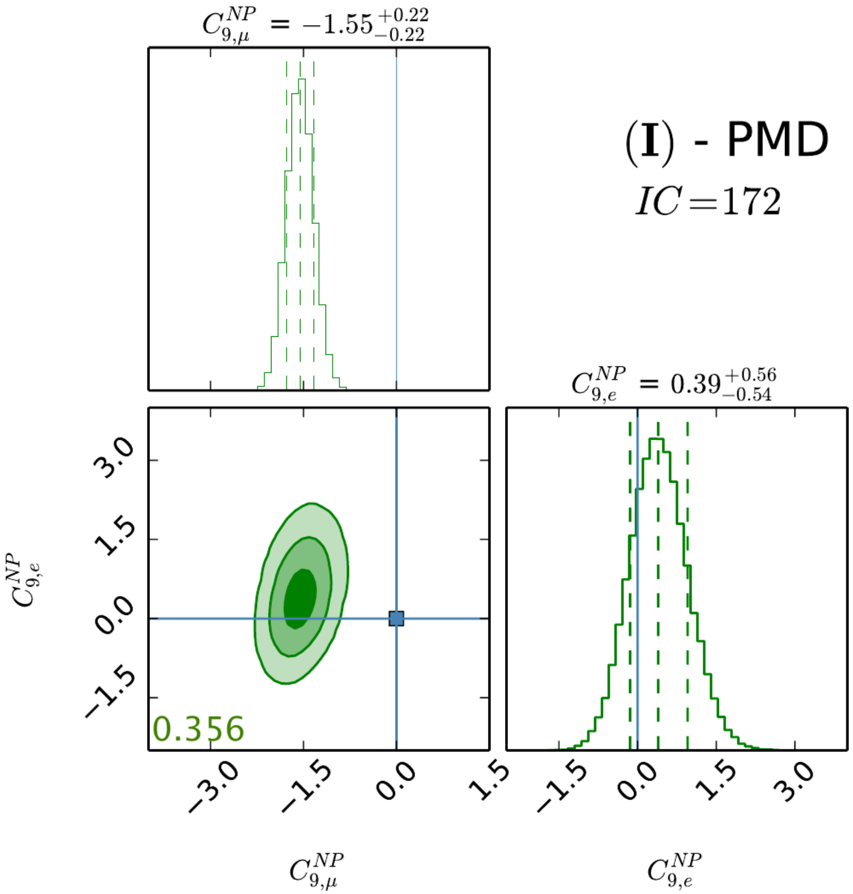
arXiv:1705.05802

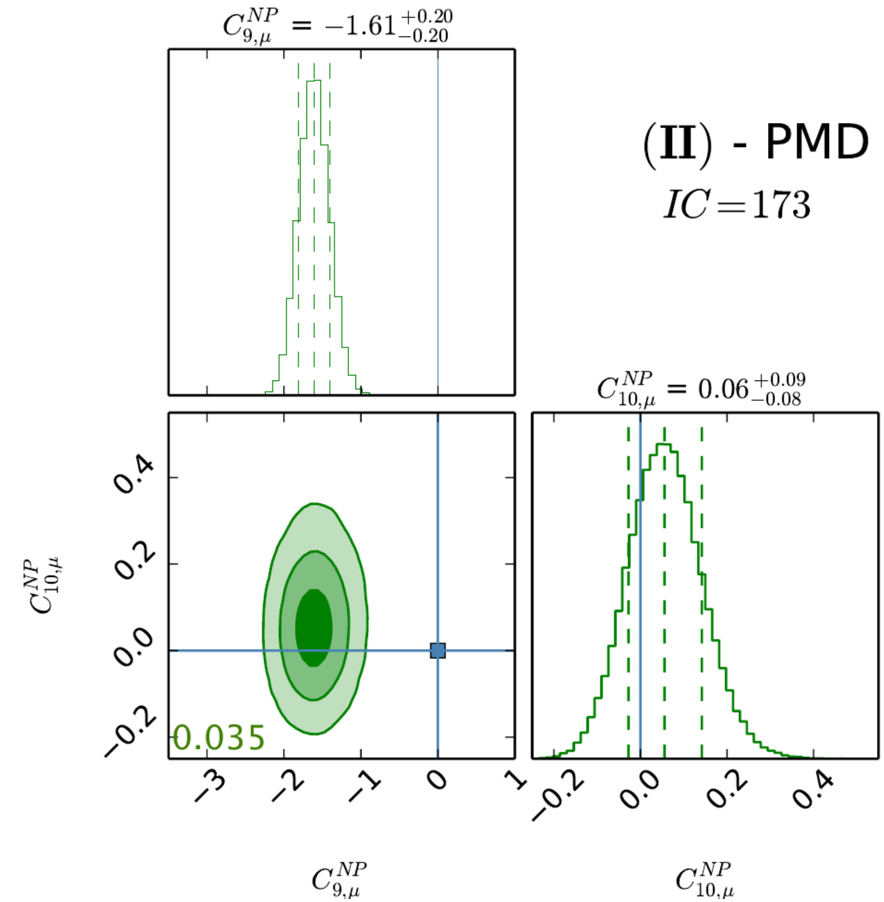


M-H Schune, CERN Instant Workshop

NP IN $b \to sl^+l^-$?

- $R_{K(*)}$ (if not statistics/systematic driven) call for NP in $b \to sl^+l^-$
- tempting to combine this with P_5' and all other exp data
- result of the combination strongly depends on estimate of hadronic uncertainties (mainly charm loop)

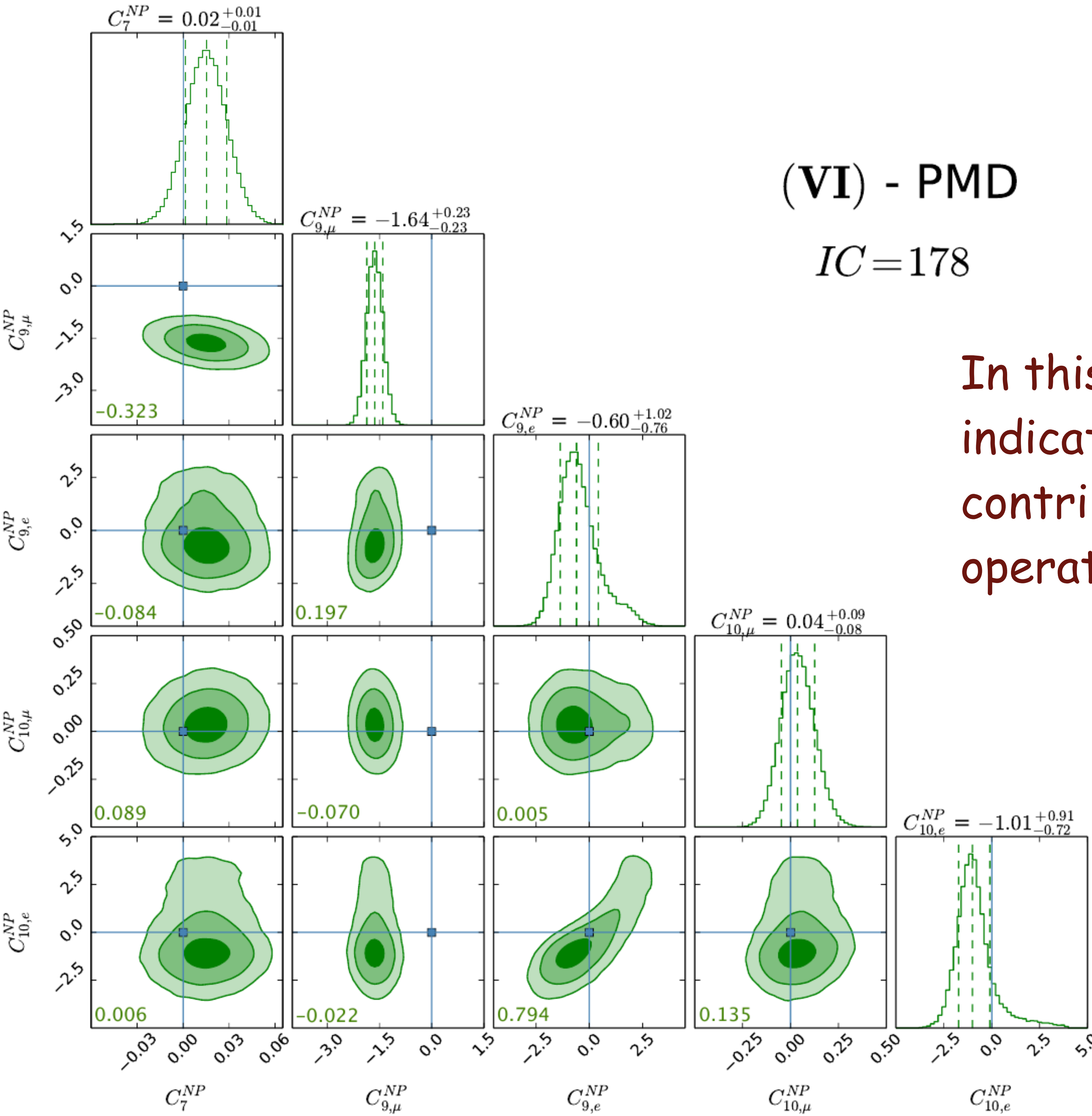




Trusting Khodjamirian et al over the full q^2 range clearly points to $C_{9\mu}^{NP} \sim -1.6$ @ 7σ, due to $R_{K(*)}$ & P_5'

($C_{9(10)} \Leftrightarrow$ (axial) vector lepton current)

Ciuchini et al. '17; Capdevila et al. '17; Altmannshofer, Stangl & Straub '17



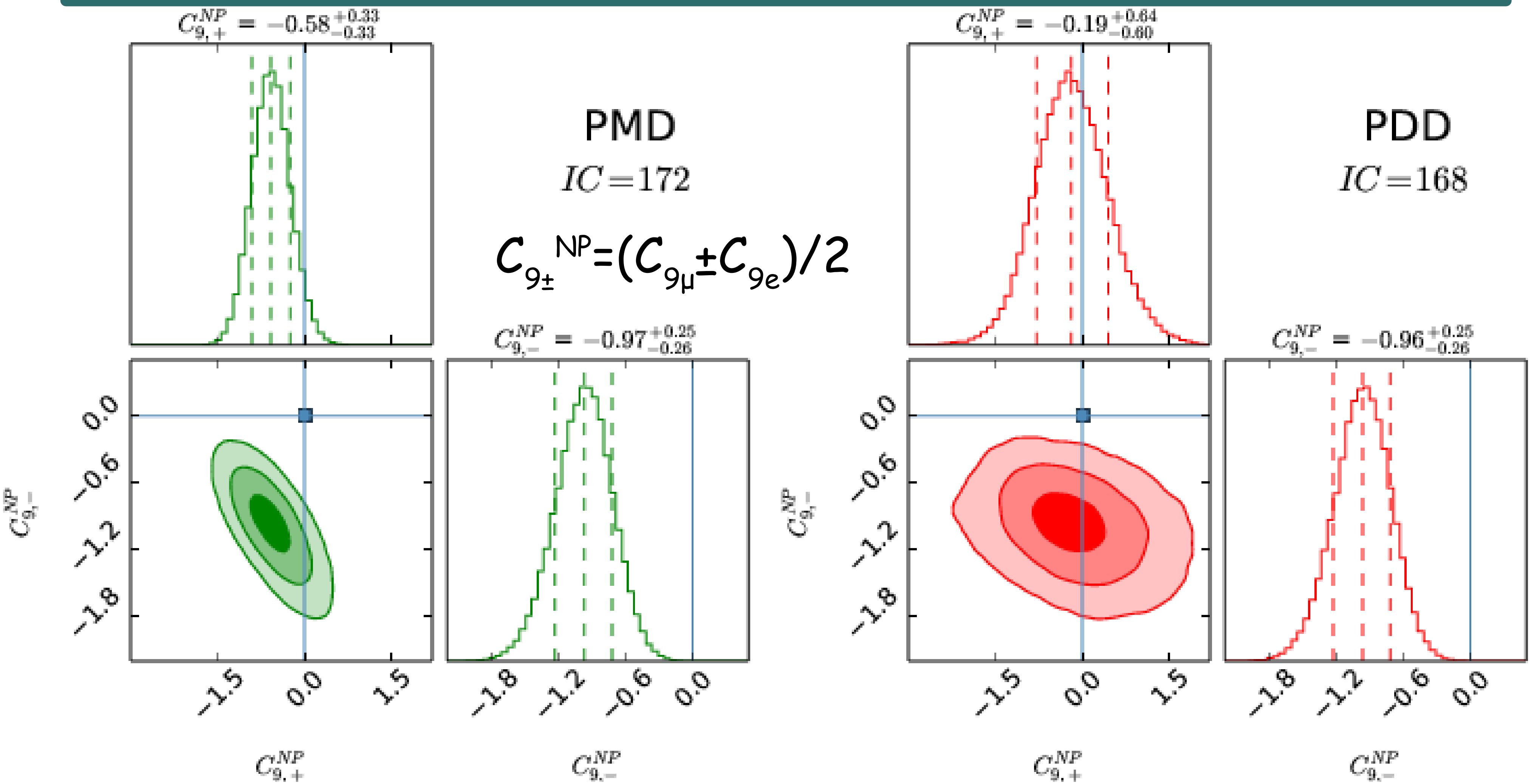
(VI) - PMD

$IC = 178$

In this approach, no indication of NP contributions to other operators.

Ciuchini et al. '17

IS $C_{9\mu}^{NP}$ ROBUST?

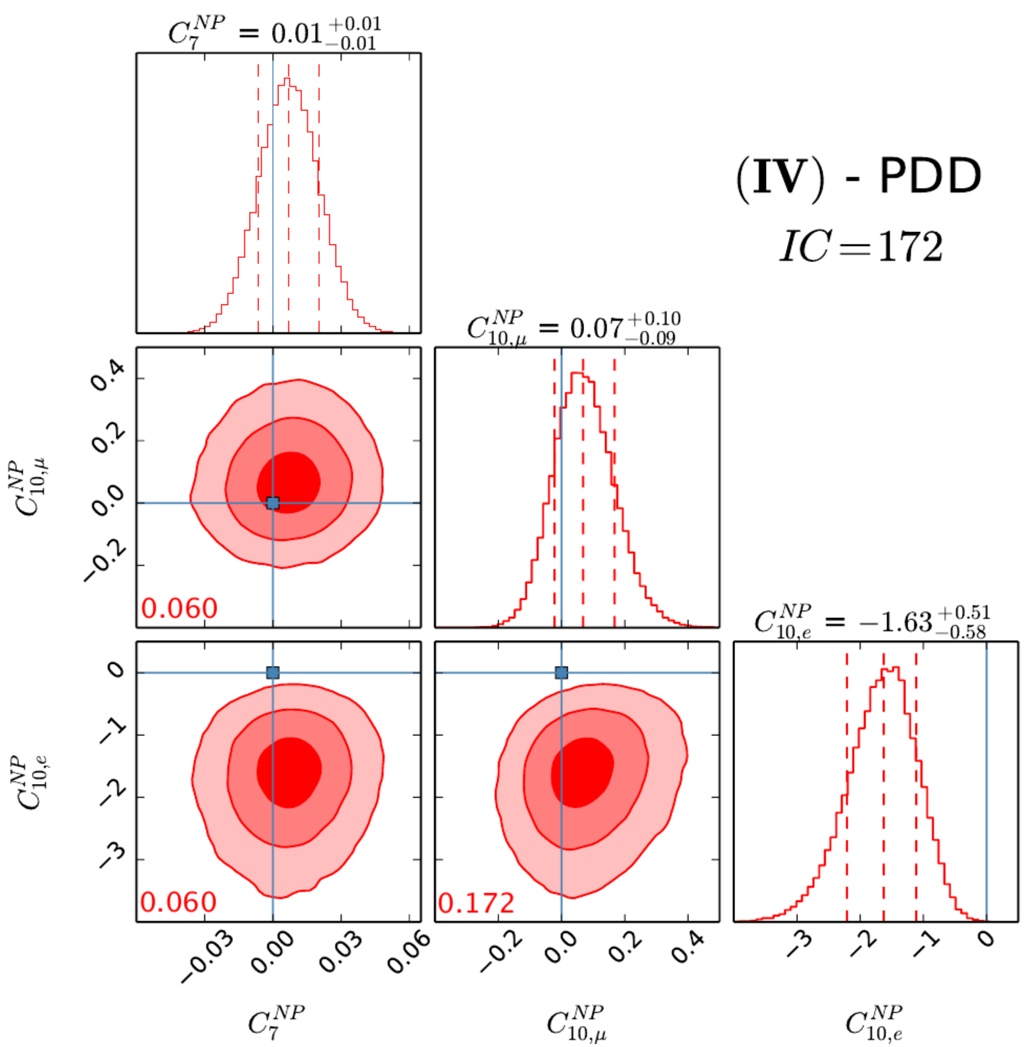


$C_{9\pm}^{NP} = (C_{9\mu} \pm C_{9e})/2$

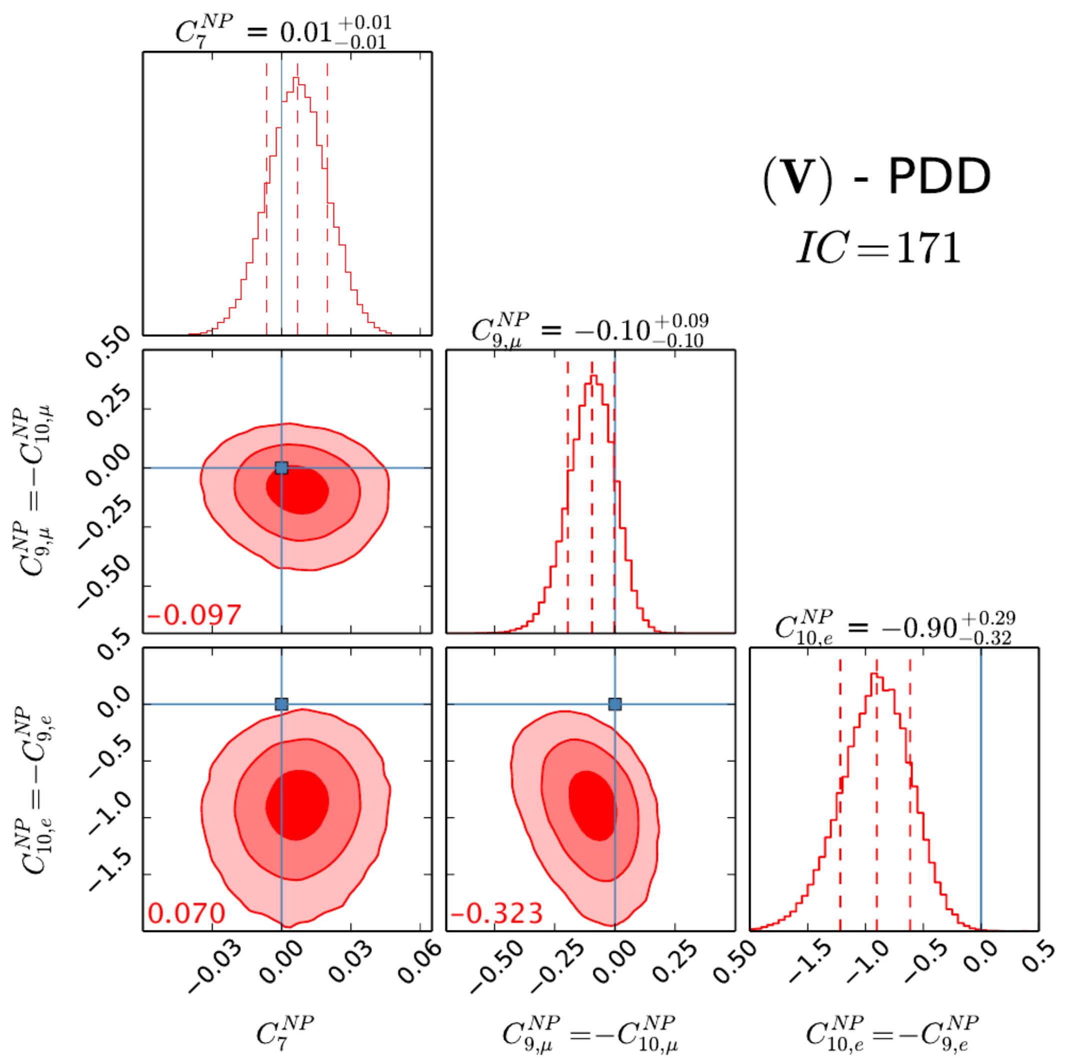
~4σ evidence of C_{9-}^{NP} ~ -1 is stable, ~2σ indication of C_{9+}^{NP} fully depends on assumptions on charm loop (which contributes to C_9)

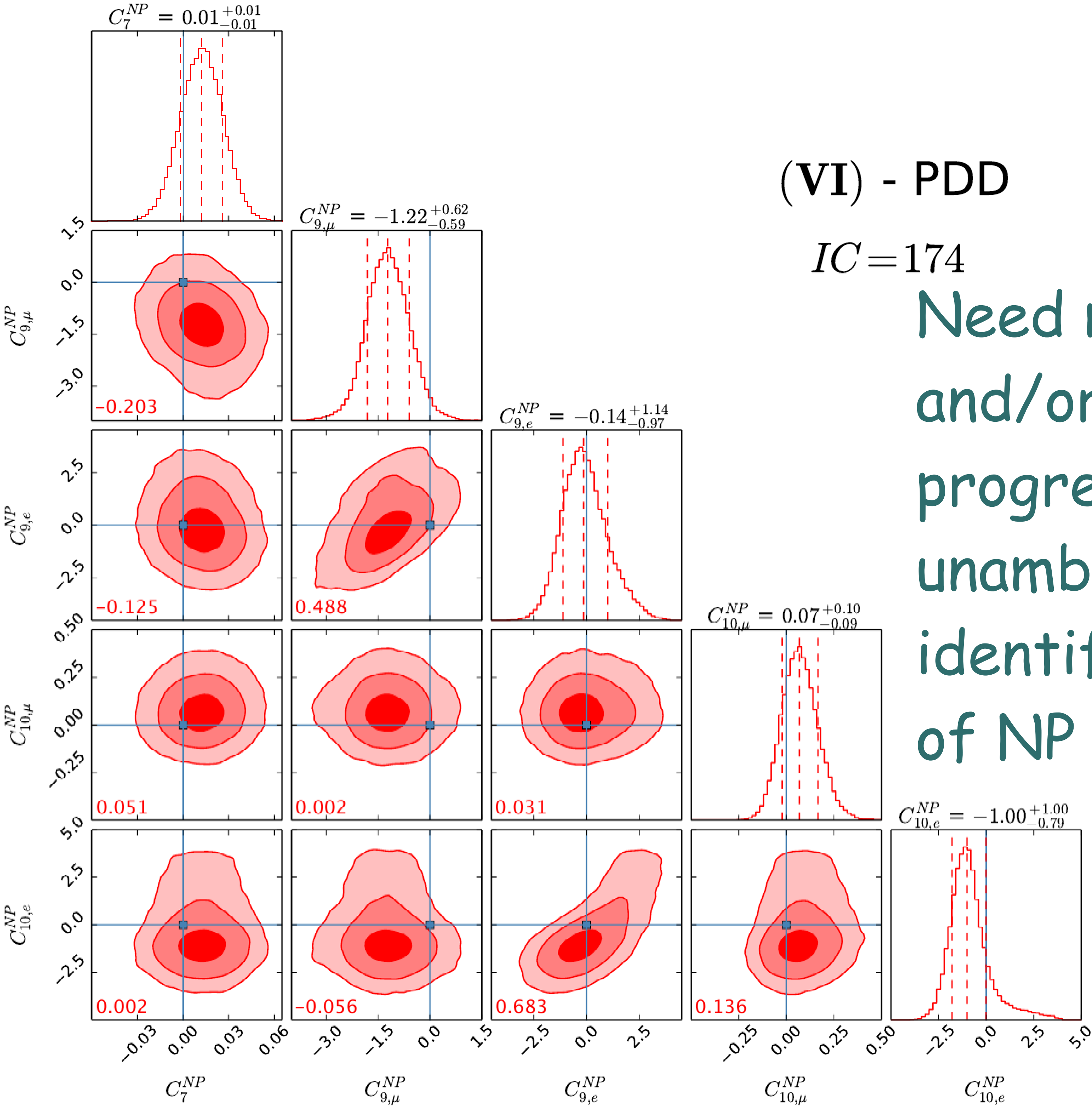
OTHER NP SCENARIOS VIABLE

$C_{10e}^{NP} \neq 0$



$C_{10e}^{NP} = -C_{9e}^{NP} \neq 0$





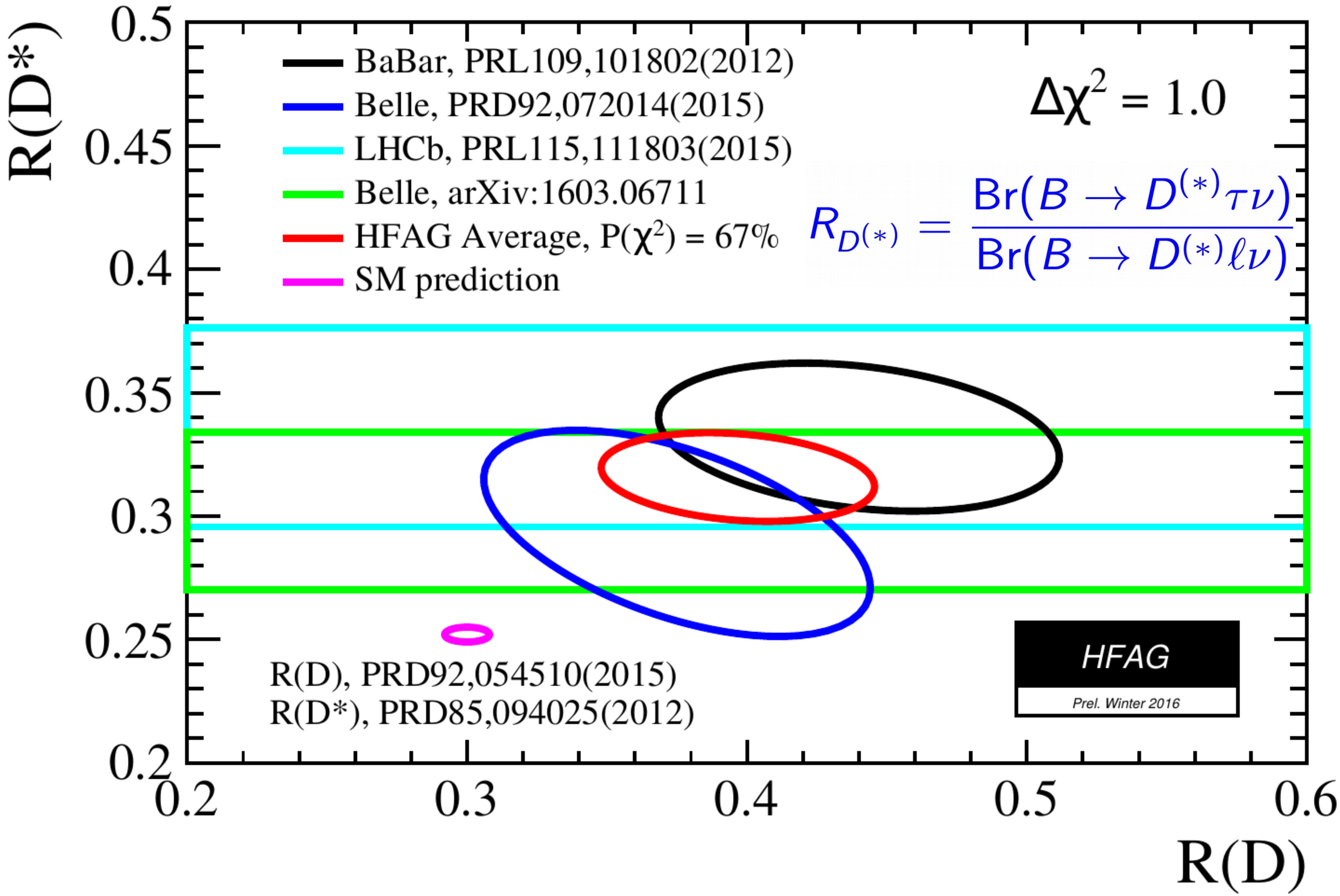
(VI) - PDD

$IC = 174$

Need more data and/or theoretical progress to unambiguously identify pattern of NP contributions

See also Alonso et al. '17, ...

LUV IN B→D(*)lν



BaBar, PRL109,101802(2012)
Belle, PRD92,072014(2015)
LHCb, PRL115,111803(2015)
Belle, arXiv:1603.06711
HFAG Average, P(χ²) = 67%
SM prediction
Δχ² = 1.0
$R_{D^{(*)}} = \frac{Br(B \to D^{(*)}\tau\nu)}{Br(B \to D^{(*)}\ell\nu)}$
R(D), PRD92,054510(2015)
R(D*), PRD85,094025(2012)
HFAG
Prel. Winter 2016
R(D*)
R(D)
0.2
0.25
0.3
0.35
0.4
0.45
0.5
0.6

INTERPRETING $R(D^{(*)})$

- SM prediction seems clean, but:
  - if NP is present in $B \to D^{(*)} \mu \nu_\mu$ and/or in $B \to D^{(*)} e \nu_e$, use of exp spectrum to extrapolate FF's to whole q^2 region may be inconsistent
  - need evaluation of FF's from more groups
  - same caveats on use of CLN as in V_{cb} extractions apply
  - more on this later (S. Schacht)

INTERPRETING $R(D^{(*)})$

- Main difference wrt $R_{K^{(*)}}$: here NP contribution comparable to tree-level SM amplitude needed, as opposed to NP contribution comparable to one-loop SM one
- Required NP scale smaller:
  - good for direct detection
  - must keep other effects under control

High-energy effective Lagrangian

- **A simultaneous explanation of both $R_K^{\mu/e}$ and $R_D^{\tau/\ell}$ anomalies naturally selects a left-handed operator $(\bar{c}_L\gamma_\mu b_L)(\bar{\tau}_L\gamma_\mu\nu_L)$ which is related to $(\bar{s}_L\gamma_\mu b_L)(\bar{\mu}_L\gamma_\mu\mu_L)$ by the $SU(2)_L$ gauge symmetry** [Bhattacharya et al., '14].

- **Global fits** of $B \to K^*\ell\ell$ data favour (not exclusively) an effective 4-fermion operator involving left-handed currents $(\bar{s}_L\gamma_\mu b_L)(\bar{\mu}_L\gamma_\mu\mu_L)$, i.e. the $C_9 = -C_{10}$ solution [Hiller et al., '14, Hurth et al.,'14, Altmannshofer and Straub '14, Descotes-Genon et al., '15, ...].

- **This picture can work only if NP couples much more strongly to the third generation than to the first two.** Two interesting scenarios are:

  - **Lepton Flavour Violating case:** NP couples in the interaction basis only to third generations. Couplings to lighter generations are generated by the misalignment between the mass and the interaction bases [Glashow, Guadagnoli and Lane, '14] .

  - **Lepton Flavour Conserving case:** NP couples dominantly to third generations but LFV does not arise if the groups $U(1)_e \times U(1)_\mu \times U(1)_\tau$ are unbroken [Alonso et al., '15].

See the talks by Crivellin, Isidori and Straub for an exhaustive account of models.

LFU violation in $\tau \to \ell\bar{\nu}\nu$

- **LFU breaking effects in $\tau \to \ell\bar{\nu}\nu$**

$$R_\tau^{\tau/e} = \frac{\mathcal{B}(\tau \to \mu\nu\bar{\nu})_{\rm exp}/\mathcal{B}(\tau \to \mu\nu\bar{\nu})_{\rm SM}}{\mathcal{B}(\mu \to e\nu\bar{\nu})_{\rm exp}/\mathcal{B}(\mu \to e\nu\bar{\nu})_{\rm SM}}$$

$$R_\tau^{\tau/\mu} = \frac{\mathcal{B}(\tau \to e\nu\bar{\nu})_{\rm exp}/\mathcal{B}(\tau \to e\nu\bar{\nu})_{\rm SM}}{\mathcal{B}(\mu \to e\nu\bar{\nu})_{\rm exp}/\mathcal{B}(\mu \to e\nu\bar{\nu})_{\rm SM}}$$

- $R_\tau^{\tau/\ell}$: experiments vs. theory

$$R_\tau^{\tau/\mu} = 1.0022 \pm 0.0030\,, \quad R_\tau^{\tau/e} = 1.0060 \pm 0.0030$$ [HFAG, '14]

$$R_\tau^{\tau/\ell} \approx 1 + \frac{0.01\, C_3}{\Lambda^2(\rm TeV)}\, \lambda^u_{33}\lambda^e_{33}$$

- $R_{D^{(*)}}^{\tau/\ell}$: experiments vs. theory

$$R_D^{\tau/\ell} = 1.37 \pm 0.17, \qquad R_{D^*}^{\tau/\ell} = 1.28 \pm 0.08$$

$$R_{D^{(*)}}^{\tau/\ell} \approx 1 - \frac{0.12\, C_3}{\Lambda^2(\rm TeV)}\left(1 + \frac{\lambda^d_{23}}{V_{cb}}\right)\lambda^e_{33}$$

Feruglio, Paradisi & Pattori

Strong tension between $R_\tau^{\tau/\ell}$ and $R_D^{\tau/\ell}$

EXPLAINING $R(D^{(*)})$ & $R_{K^{(*)}}$

- Possible to get a consistent EFT picture based on U(2) flavour symmetry, but some tuning required by B_s mixing and LFU in $\tau \to l\nu\nu$

Bordone, Isidori, Trifinopoulos '17

- Two broad classes of explicit models:
  - vector triplet — Greljo, Isidori, Marzocca '15; Boucenna et al '16
  - leptoquarks — ...
- More in the next talks (Marco Nardecchia)

OUTLOOK

- In an overall SM-consistent picture of flavour and CP violation, we see some tensions:
- SM prediction for ε'/ε too low
  - need independent confirmation of matrix elements from LQCD
  - very sensitive to NP - effect can arise from very high scales

OUTLOOK II

- Hints of Lepton Universality Violation in $b \to s l^+ l^-$ decays $R_{K(*)}$
  - theoretically very clean
  - sensitive to NP - effect can arise from scales up to tens of TeV
  - possibility of NP effects also in angular observables very interesting, but too early to give up other NP scenarios with SM explanation of P_5'

OUTLOOK III

- Intriguing hints of LUV also in charged current $B \to D^{(*)} l \nu$ decays
  - theoretically clean, with some caveats
  - not particularly sensitive to NP: need NP at the TeV scale
  - requires some gymnastics to avoid current bounds
  - something else should be seen soon

OUTLOOK IV

- Very exciting times ahead, with Belle II and LHCb upgrade forthcoming
- If tensions confirmed, expect other indirect/direct signals of NP
- Experimental program so broad that other even more interesting tensions may arise soon!