New Physics in Inclusive $B \to X_c \ell \bar{\nu}$

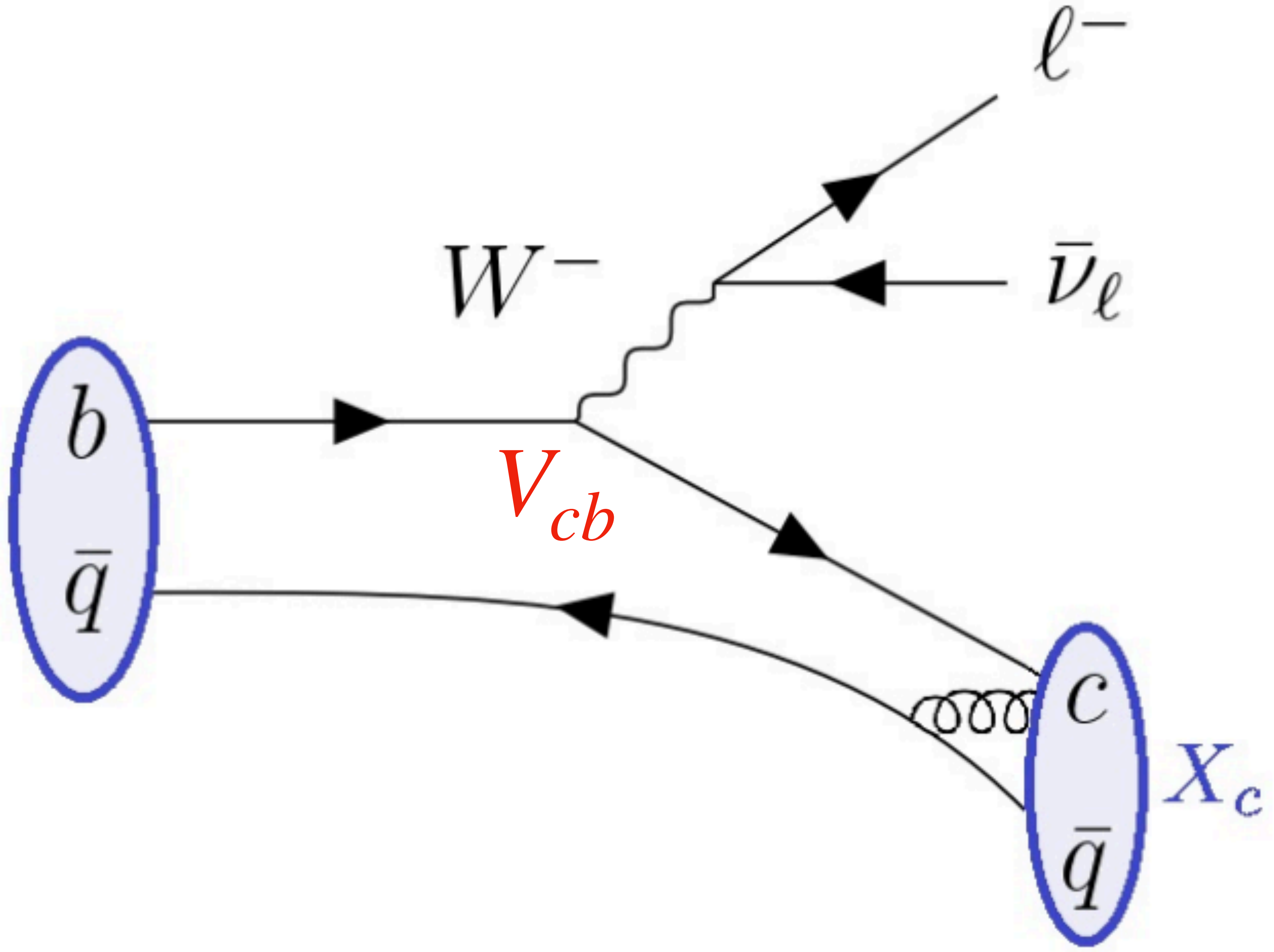
Based on 2507.22123, AC, G. Finauri, P. Gambino, M. Jung, S. Mächler

Taming hadronic uncertainties in and beyond the Standard Model

24/10/2025 - IJClab, Orsay

Alexandre Carvunis - Università di Torino

Exclusive vs Inclusive determination of Vcb



$$\Gamma(b \to c\ell\bar{\nu}) \propto |V_{cb}|^2$$

$$\bar{B} \to X_c \ell \bar{\nu}$$

$X_c = D, D^*, D^{**}, D\pi, \ldots$

Inclusive decay rate

Measurement in B factories (BaBar, Belle, Belle II,…)

Prospects for $\Lambda_b \to X_c \ell \bar{\nu}$ at LHCb

TH input: HQE + optical theorem

$$\bar{B}_{(s)} \to D^{(*)}_{(s)} \ell \bar{\nu}$$

Exclusive decay rate

$\bar{B} \to D^{(*)} \ell \bar{\nu}$ measurements from B factories

$\bar{B}_s \to D_s^{(*)}$ by LHCb

TH input: lattice/HQE+exp/LCSR

Consistency tests of both SM predictions and measurements

See Marzia’s talk

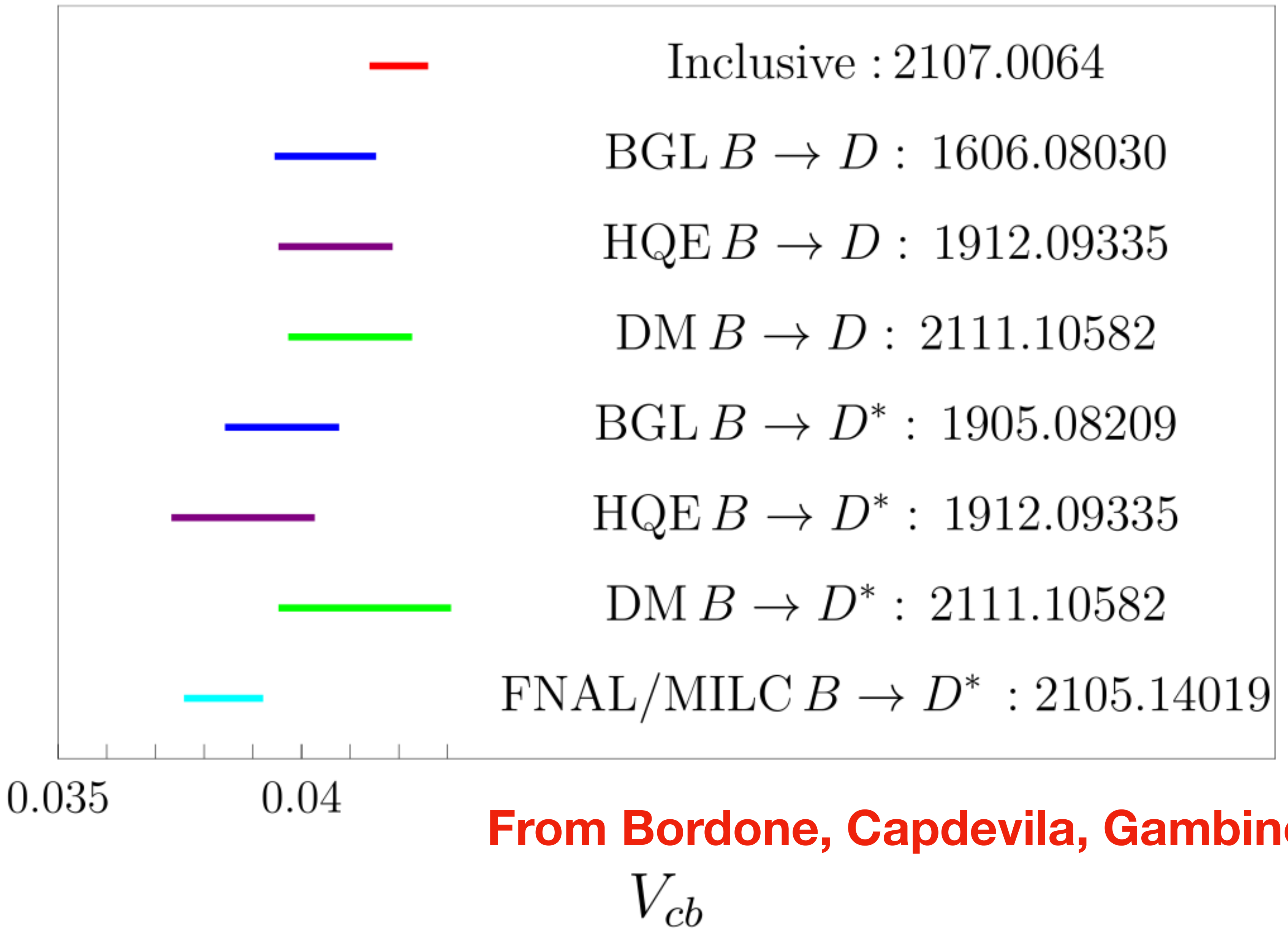
The Vcb Puzzle

Exclusive

$$|V_{cb}^{\rm excl}| = (39.62 \pm 0.47) \times 10^{-3}$$

Average by HFLAV 2023

Large variability between determinations using different processes, FF parameterization, lattice input, etc… See next slides



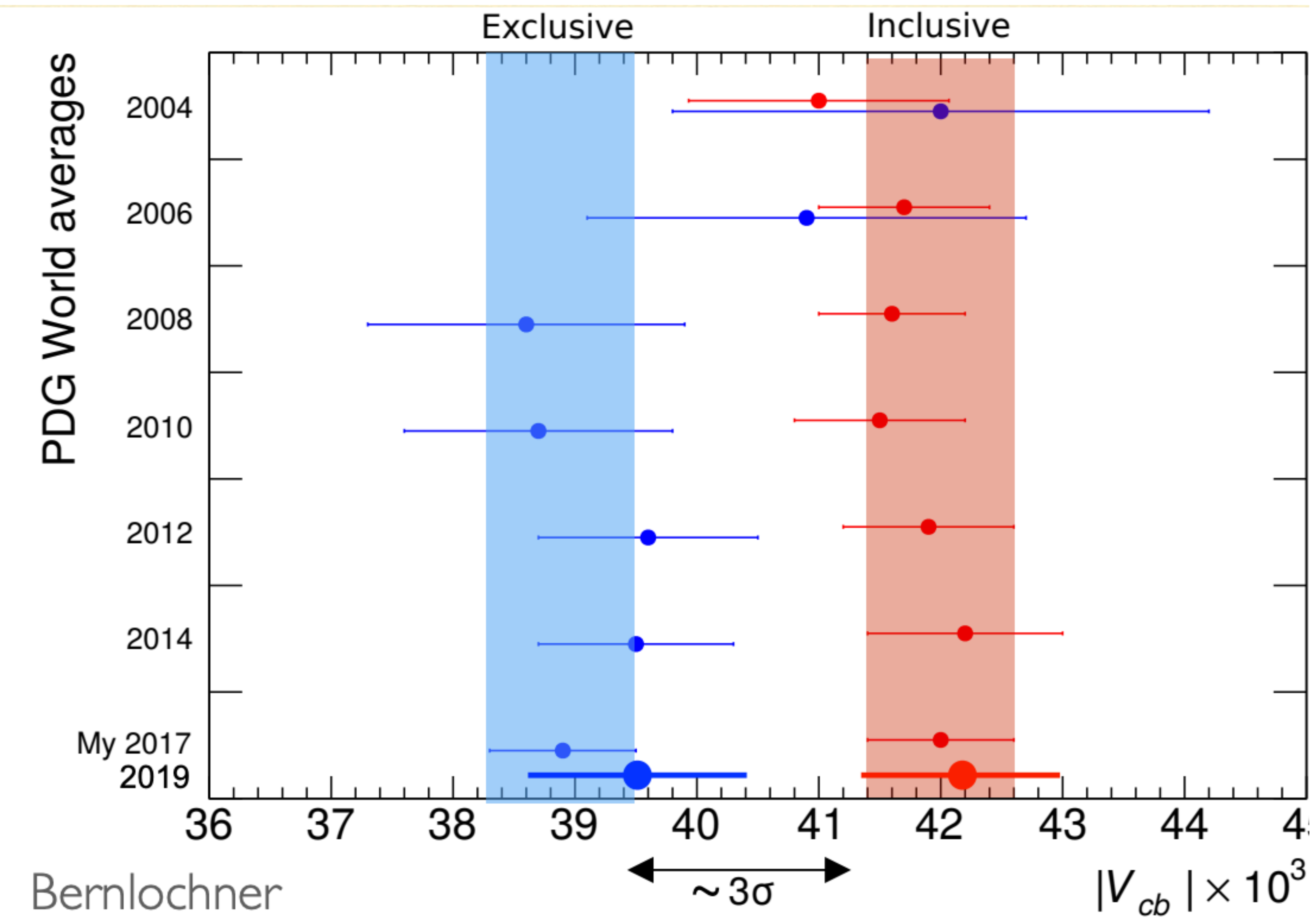
From Bordone, Capdevila, Gambino ‘21

Almost 4σ

Inclusive

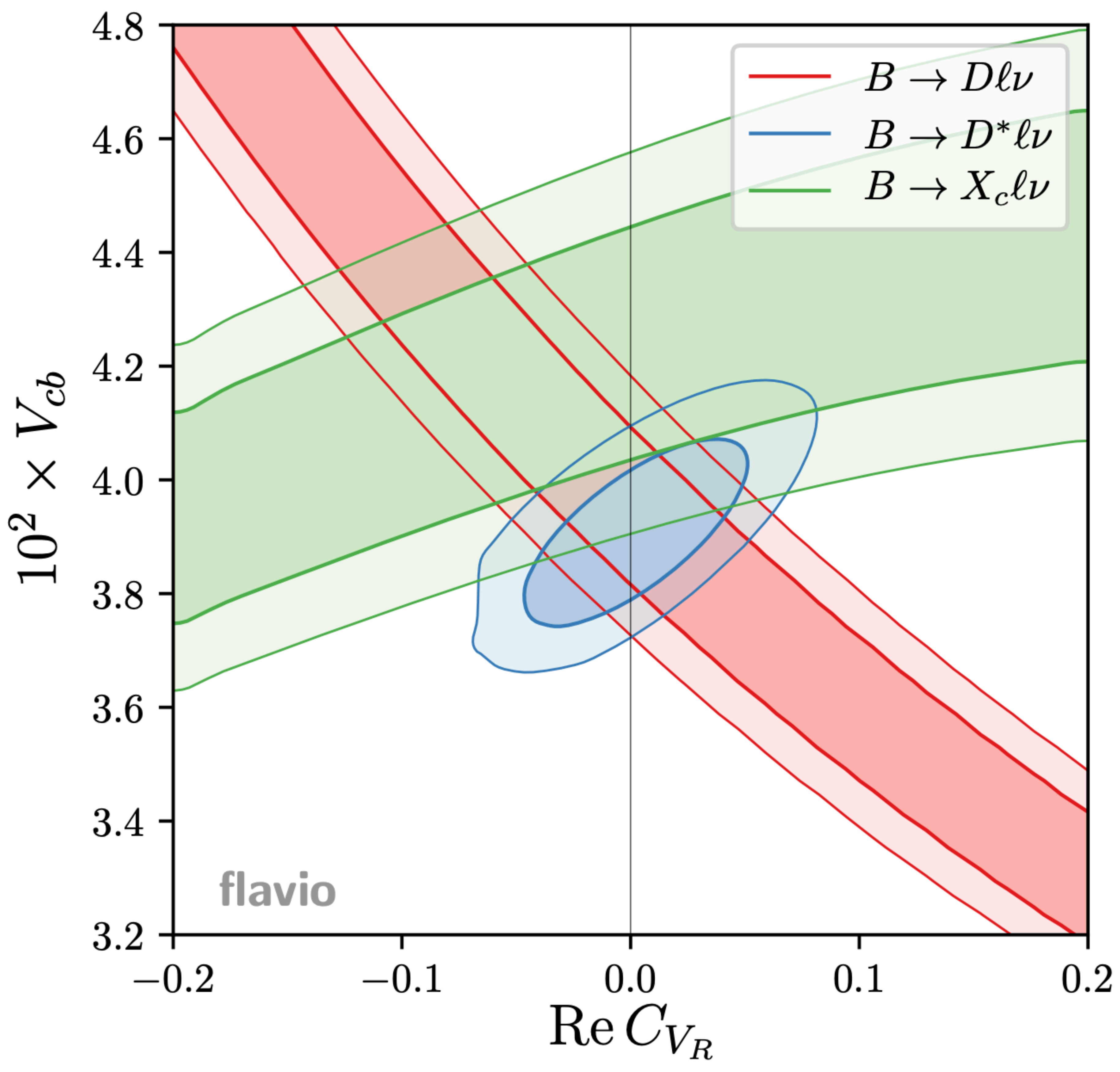
$$|V_{cb}^{\rm incl}| = (41.97 \pm 0.48) \times 10^{-3}$$

Finauri Gambino ‘23



Why look for New Physics in $B \to X_c \ell \bar{\nu}$?

- There are ***still*** anomalies in some semileptonic B decays, e.g. $BR(B \to K^{(*)}\ell\ell)$ (+ang.), and $R(D^{(*)})$
  See Martino's talk
- Can the V_{cb} puzzle in exclusive vs inclusive $b \to c\ell\bar{\nu}$ $(\ell = e, \mu)$ be explained by NP? [Crivellin et al. 1407.1320] says no but performed a 'zeroth order analysis' only
- Observables in inclusive and exclusive decays have different sensitivities to NP
- Measurements of inclusive $B \to X_c \ell \bar{\nu}$ observables use different analysis techniques from exclusive decays. Independent data + different systematics



M. Jung, D. Straub (1801.01112)

$B \to X_c \ell \bar{\nu}$ in the SM

At the b scale:

$$H_W = \frac{4G_F}{\sqrt{2}} V_{cb} (\bar{c}\gamma^\mu P_L b)(\bar{\ell}\gamma_\mu P_L \nu_\ell) = \frac{4G_F}{\sqrt{2}} V_{cb} (J_q^\mu \times J_{\ell,\mu})$$

$$d\Gamma(\bar{B} \to X_c \ell \bar{\nu}_\ell) \propto \sum_{X_c} |\langle X_c \ell \bar{\nu}_\ell | H_W | \bar{B} \rangle|^2 \propto |V_{cb}|^2 L_{\mu\nu} W^{\mu\nu} + \mathcal{O}(\alpha_{em})$$

$$L_{\mu\nu} \propto \sum_{\text{spins}} \left\langle \bar{\nu}_\ell \ell | J_{\mu,\ell} | 0 \right\rangle \left\langle \bar{\nu}_\ell \ell | J_{\nu,\ell} | 0 \right\rangle^\dagger$$

known exactly

$$W^{\mu\nu} \propto \sum_{X_c} \left\langle X_c | J_q^\mu | \bar{B} \right\rangle \left\langle X_c | J_q^\nu | \bar{B} \right\rangle^\dagger$$

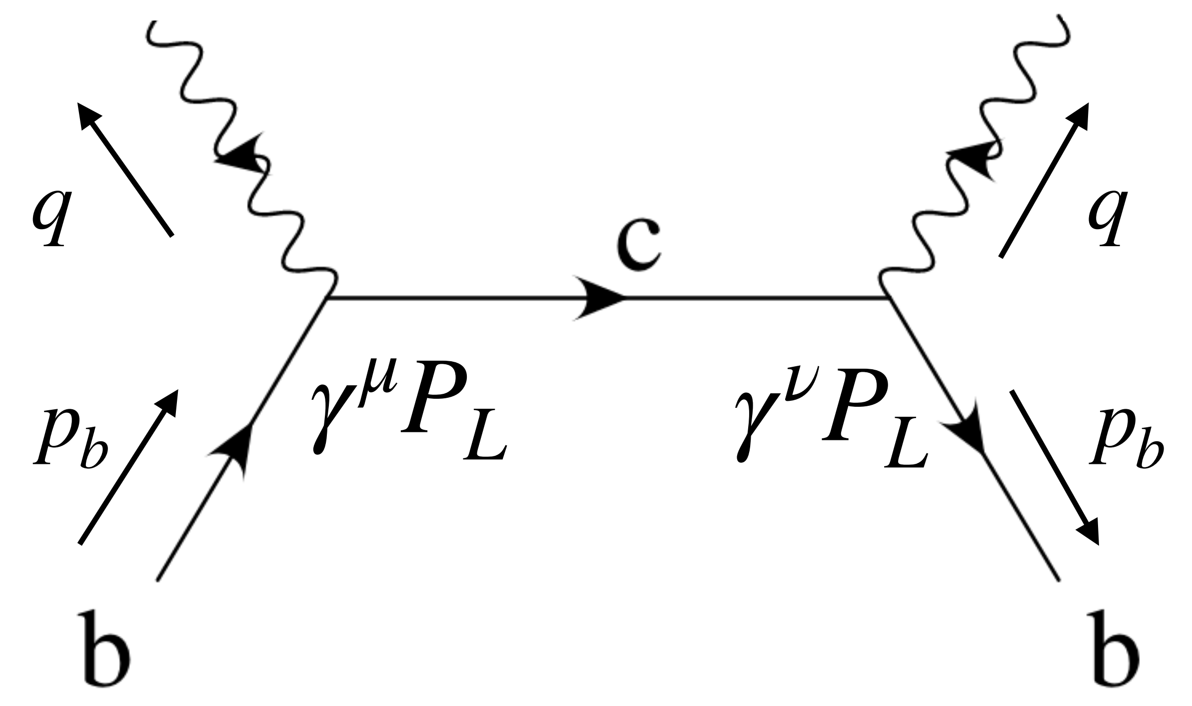
Optical Theorem

$$W^{\mu\nu} = -\frac{1}{\pi} \mathrm{Im} T^{\mu\nu}$$

$$2m_B T^{\mu\nu}(q) = -i \int d^4x e^{-i(p_b - q)x} \left\langle \bar{B} \left| T\left[J_q^\nu(x)^\dagger J_q^\mu(0) \right] \right| \bar{B} \right\rangle$$

Calculable via OPE in Heavy Quark Effective Theory (HQET)

$T^{\mu\nu} =$



$+ \mathcal{O}(\alpha_s)$

OPE of the forward scattering amplitude

$$T^{\mu\nu}(q) = \frac{i}{2m_B}\int d^4x e^{i(m_b v - q)\cdot x}\langle \bar{B}|\bar{b}_v(x)\gamma^\mu P_L S_{\mathrm{BGF}}(x,0)\gamma^\nu P_L b_v(0)|\bar{B}\rangle\,,$$

$$S_{\mathrm{BGF}}(x,0) = i\int \frac{d^4p}{(2\pi)^4}e^{-ip\cdot x}\frac{\not{p}+m_c}{p^2-m_c^2+i\eta}\sum_{n=0}^{\infty}(-1)^n\left[i\not{D}\frac{\not{p}+m_c}{p^2-m_c^2+i\eta}\right]^n.$$

D3 (exact)

$$\langle \bar{B}|\bar{b}\gamma^\mu b|\bar{B}\rangle = 2m_B v^\mu\,,$$

$$\langle \bar{B}|\bar{b}\gamma^\mu\gamma^5 b|\bar{B}\rangle = 0\,,$$

D4

related to higher dimensional parameters through EOM

D5: 2 parameters

$$2m_B\boxed{\mu_\pi^2} = -\langle \bar{B}|\bar{b}_v iD_\perp^\mu iD_{\perp\mu} b_v|\bar{B}\rangle\,,$$

$$2m_B\boxed{\mu_G^2} = \frac{1}{2}\langle \bar{B}|\bar{b}_v[iD_\perp^\mu, iD_\perp^\nu](-i\sigma_{\mu\nu})b_v|\bar{B}\rangle$$

D6: 2 parameters

$$2m_B\boxed{\rho_D^3} = \frac{1}{2}\langle \bar{B}|\bar{b}_v\left[iD_\perp^\mu,\left[iv\cdot D, iD_{\perp\mu}\right]\right]b_v|\bar{B}\rangle\,,$$

$$2m_B\boxed{\rho_{LS}^3} = \frac{1}{2}\langle \bar{B}|\bar{b}_v\left\{iD_\perp^\mu,\left[iv\cdot D, iD_\perp^\nu\right]\right\}(-i\sigma_{\mu\nu})b_v|\bar{B}\rangle\,.$$

D7: 9 independent parameters

D8: 18 (!)

Mannel,Turczyk,Uraltsev 2010
Mannel,Milutin,Vos 2023
Finauri 2025

Only 4 unknown HQE ME at order Λ_{QCD}^3/m_b^3 !

What can this calculation do?

- We obtain an expression for the triple differential decay rate:

$$\frac{d\Gamma}{dE_\ell dE_\nu dq^2} = |V_{cb}|^2 G_F^2 \frac{m_b^5}{16\pi^3}\left[f_{LP} + f_{NLP}^{\mu_\pi}\frac{\mu_\pi{}^2}{m_b^2} + f_{NLP}^{\mu_G}\frac{\mu_G^2}{m_b^2} + f_{NNLP}^{\rho_{LS}}\frac{\rho_{LS}^3}{m_b^3} + f_{NNLP}^{\rho_D}\frac{\rho_D^3}{m_b^3} + \mathcal{O}(\Lambda_{QCD}^4/m_b^4)\right]$$

$$\mu_\pi \sim \mu_G \sim \rho_D \sim \rho_{LS} \sim \Lambda_{QCD} \qquad \Lambda_{QCD}/m_b \sim 0.1$$

- $\mathcal{O}(\Lambda_{QCD}^n/m_b^n)$ terms $\propto \delta^{(n-1)}[(m_b v - q)^2 - m_c^2] \rightarrow \frac{d\Gamma}{dE_\ell dE_\nu dq^2}$ *is not physical.*
- The HQE is only valid for observables integrated over a range $\Delta E_\ell, \Delta E_\nu, \Delta q^2 \gg \Lambda_{QCD}^{(2)}$ (smearing). Higher power contributions are enhanced if the integration range is too small.

See Raynette talk's for critical assessment of the experimental results at Belle (II)

GAP

Observables

$$\mathscr{M}_n = \langle X^n \rangle = \frac{\int dX \, \frac{d\Gamma}{dX} X^n}{\int dX \, \frac{d\Gamma}{dX}}, X = E_\ell, q^2, m_{X_c}^2$$

with lower cuts on E_ℓ, q^2. Ratio independent of V_{cb}. In practice central moments are used to reduce systematic errors $\equiv \langle (X - \langle X \rangle)^n \rangle$ for $n \geq 2$. TH error explodes for $n \geq 4$. We use all moments with $n \leq 3$.

- Lepton energy and hadronic mass moments from Babar, CLEO, DELPHI, CDF, Belle
- q^2 moments from Belle and Belle II
- We also include $R^*(E_{\ell\mathrm{cut}}) = \frac{\int_{E_{\ell\mathrm{cut}}}^{E_{\ell\max}} dE_\ell \frac{d\Gamma}{dE_\ell}}{\int_0^{E_{\ell\max}} dE_\ell \frac{d\Gamma}{dE_\ell}}$

Measured by Babar and Belle

Fitted

$$\mathcal{B}_{\mathrm{cut}}(E_{\ell\mathrm{cut}}) = \mathcal{B}(\bar{B} \to X_c \ell \bar{\nu}) R^*(E_{\ell\mathrm{cut}})$$

Fit strategy

1. Extract HQE matrix elements by fitting the kinematic moments and R^*

   Fit parameters: m_b, m_c(constrained), $\mu_\pi^2, \mu_G^2, \rho_{LS}^3, \rho_D^3$, BR $_{c\ell\nu}$

2. Extract $|V_{cb}|$ from the total decay rate using the result of the fit

$$\Gamma_{B\to X_c\ell\nu} = |V_{cb}|^2 f(m_b, m_c, \mu_\pi^2, \mu_G^2, \rho_{LS}^3, \rho_D^3) = \frac{\mathrm{BR}_{c\ell\nu}}{\tau_B}$$

State-of-the-art SM calculation

	dE_ℓ	dm_X^2	dq^2	Γ
1	α_s^2 [Melnikov 2008]	α_s^2 [Pak, Czarnecki 2008]	α_s^2 [Fael, Herren 2024]	α_s^3 [Fael, Schönwald, Steinhauser 2020]
$1/m_b^2$	α_s	α_s [Alberti, Ewerth, Gambino, Nandi 2012, 2013]	α_s	α_s
$1/m_b^3$	1	1 [Gremm, Kapustin 1997]	α_s [Mannel, Moreno Pivovarov 2021]	α_s [Mannel, Pivovarov 2019]
$1/m_b^{4,5}$ $1/(m_b^3 m_c^2)$	1	1 [Mannel, Turczyk, Uraltsev 2010]	1 [Mannel, Milutin, Vos 2023]	1 [Mannel, Turczyk, Uraltsev 2010]

[............... Updated in GF 2501.09090.....................]

Slide by Gael Finauri

SM result

m_b [GeV]	m_c [GeV]	μ_π^2 [GeV^2]	μ_G^2 [GeV^2]	ρ_D^3 [GeV^3]	ρ_{LS}^3 [GeV^3]	BR$_{c\ell\bar{\nu}}$ [%]	$10^3 \lvert V_{cb} \rvert$
4.574	1.090	0.435	0.278	0.164	-0.090	10.62	41.64
0.012	0.010	0.040	0.048	0.018	0.089	0.15	0.47
1	0.390	-0.229	0.560	-0.022	-0.181	-0.064	-0.421
	1	0.015	-0.238	-0.028	0.084	0.034	0.071
		1	-0.097	0.535	0.266	0.144	0.346
			1	-0.261	0.004	0.001	-0.271
				1	-0.014	0.025	0.172
					1	-0.010	0.056
						1	0.694
							1

New result! 2507.22123

Updates:

- Inclusion of α_s^2 corrections in the q^2-moments
- α_{em} in the total decay width

$B \to X_c \ell \bar{\nu}$ with New Physics

- Assuming $\Lambda_{NP} \gg m_W$, no LFV, no RH neutrinos, dim 6 operators, the Hamiltonian is:

$$H_W^{NP} = \frac{4G_F}{\sqrt{2}} V_{cb} \Big[(1+C_{VL})[\bar{c}\gamma^\mu P_L b][\bar{\ell}\gamma_\mu P_L \nu_\ell] + C_{V_R}[\bar{c}\gamma^\mu P_R b][\bar{\ell}\gamma_\mu P_L \nu_\ell] + C_T[\bar{c}\sigma^{\mu\nu} P_L b][\bar{\ell}\sigma_{\mu\nu} P_L \nu_\ell]$$

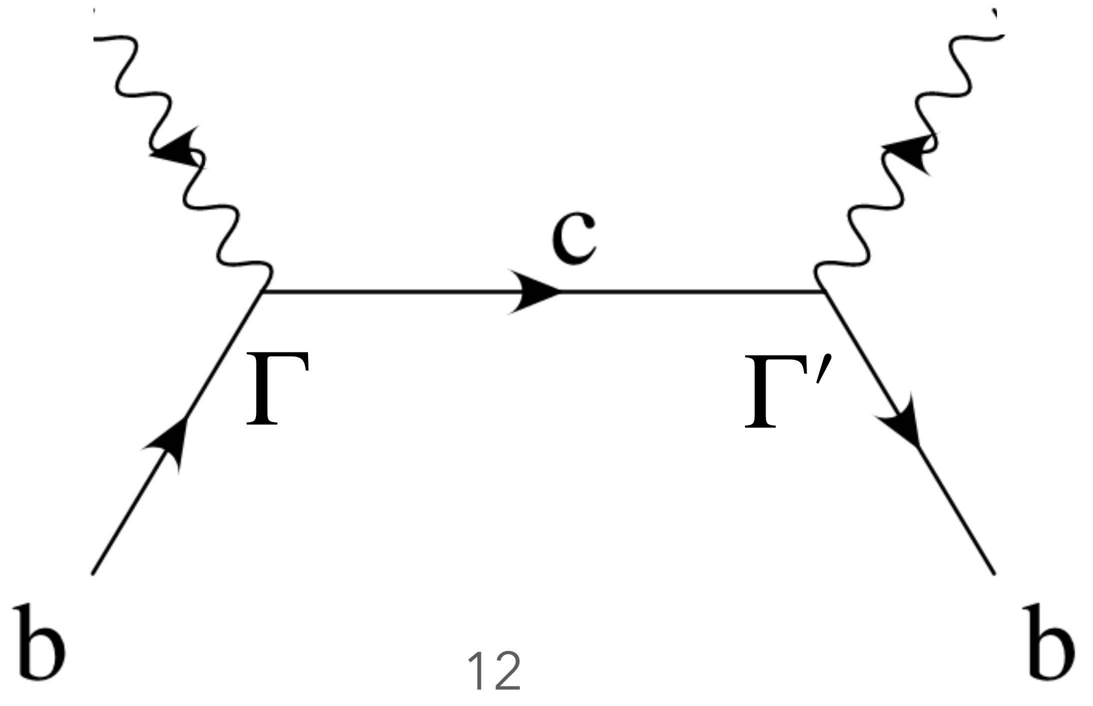
$$+ C_S[\bar{c}b][\bar{\ell}P_L\nu_\ell] + C_P[\bar{c}\gamma_5 b][\bar{\ell}P_L\nu_\ell] \Big]$$

$$\boxed{\tilde{V}_{cb} \equiv V_{cb}(1 + C_{VL}),\ \tilde{C}_X \equiv C_X/(1 + C_{V_L})}$$

- This introduces new terms to compute in the hadronic tensor OPE

$$2m_B T_{\Gamma\Gamma'} = -i \int d^4x e^{-iqx} \left\langle \bar{B} \,|\, \left[J_{\Gamma'}(x)^\dagger J_\Gamma(0) \right] |\, \bar{B} \right\rangle \qquad \Gamma, \Gamma' \in \left\{ \gamma^\mu P_L, \gamma^\mu P_R, \sigma^{\mu\nu} P_L, \mathbf{1}, \gamma_5 \right\}$$

$T_{\Gamma\Gamma'} =$



$+\mathcal{O}(\alpha_s)$

$B \to X_c \ell \bar{\nu}$ with New Physics

- Schematically, the result of the OPE looks like:

$$\frac{d\Gamma(B \to X_c \ell \bar{\nu})}{dq^2 dE_\nu dE_\ell} \propto \sum_{\Gamma,\Gamma'} W_{\Gamma\Gamma'} L_{\Gamma\Gamma'}$$

$$\boxed{\begin{aligned} W_{\Gamma\Gamma'} = \frac{C_\Gamma C^*_{\Gamma'}}{m_b}\Big[& (\ldots) + (\ldots)\frac{\mu_\pi^2}{m_b^2} + (\ldots)\frac{\mu_G^2}{m_b^2} + (\ldots)\frac{\rho_D^3}{m_b^3} + (\ldots)\frac{\rho_{LS}^3}{m_b^3} + \ldots \\ & \alpha_s\Big[(\ldots) + (\ldots)\frac{\mu_\pi^2}{m_b^2} + \ldots\Big] + \\ & \alpha_s^2[\ldots] + \ldots\Big] \end{aligned}}$$

- The SM only interferes with C_{VR}: only NP that contributes linearly to $d\Gamma$
- We work with the following power counting: $C_\Gamma^i \times \alpha_s^j$, $i + j \leq 2$ and up to order $\dfrac{1}{m_b^3}$
  - SM : $\mathcal{O}(1/m_b^3) + \mathcal{O}(\alpha_s/m_b^2) + \mathcal{O}(\alpha_s^2)$, for Γ_{tot} : $\mathcal{O}(1/m_b^3) + \mathcal{O}(\alpha_s/m_b^3) + \mathcal{O}(\alpha_s^3)$
  - C_{V_R} : $\mathcal{O}(1/m_b^3) + \mathcal{O}(\alpha_s)$ [Blok et al. 9307247],[Manohar et al. 9308246],[Feger et al. 1003.4022], [Kamali 1811.07393]
  - Other NP : $\mathcal{O}(1/m_b^3)$ [Grossman et al. 9403376],[Colangelo et al. 1611.07387],[Fael et al. 2208.04282]

Fit setup

- 14 free parameters in the fit:
  - $\mathrm{BR}_{c\ell\bar{\nu}}$
  - Quark masses: m_b, m_c
  - HQE matrix elements: $\mu_\pi^2, \mu_G^2, \rho_{LS}^3, \rho_D^3$
  - NP Wilson coefficients: $a_{V_R}, a_T, a_P, a_S, c(\delta_{V_R}), c(\delta_S), c(\delta_P)$

For $m_\ell = 0$ only 3 interference terms:

$\mathrm{Re}(C_{V_R}^* C_{V_L}), \mathrm{Re}(C_S^* C_T), \mathrm{Re}(C_P^* C_T)$

$$\boxed{\frac{C_X}{1 + C_{V_L}} \equiv a_X e^{i\delta_X}}$$

- **This is the first global fit for inclusive B decays with New Physics**

Fit Results

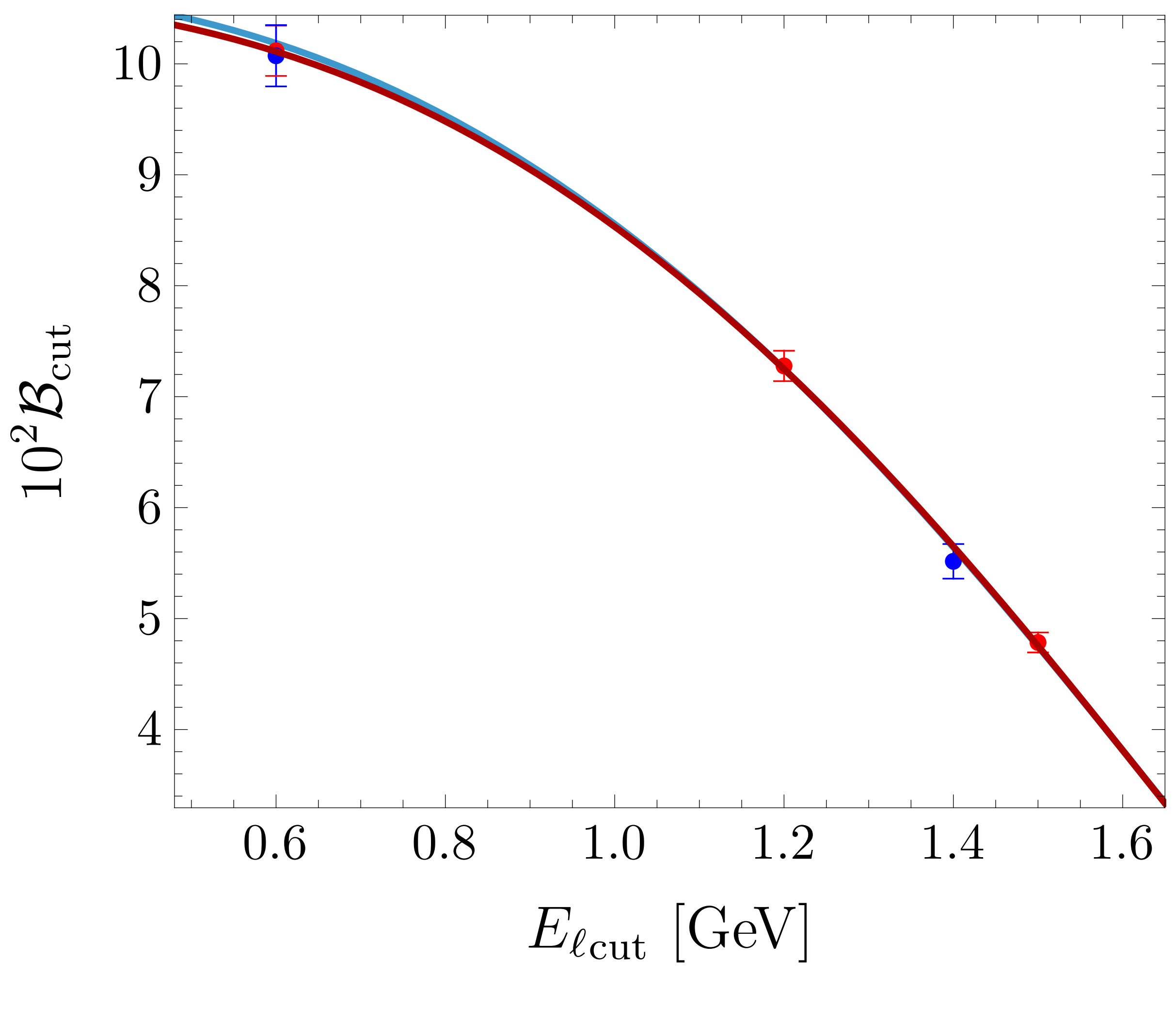
With agnostic New Physics

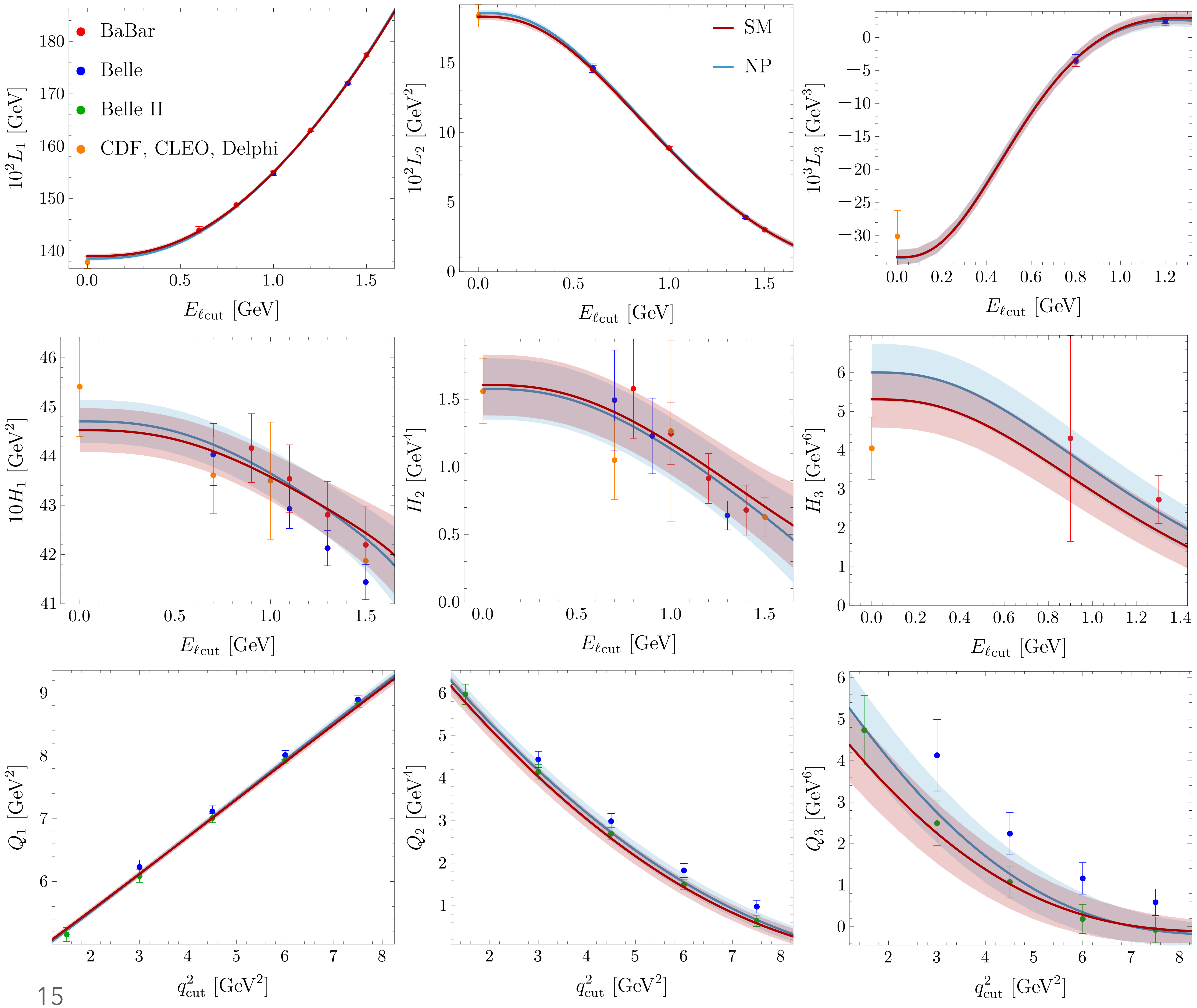
$$\chi^2_{SM}/\text{d.o.f.} = 42.58/74$$

$$\downarrow$$

$$\chi^2_{NP}/\text{d.o.f.} = 36.08/67$$

SM compatible with the NP fit at the 0.7σ level. No preference for NP.



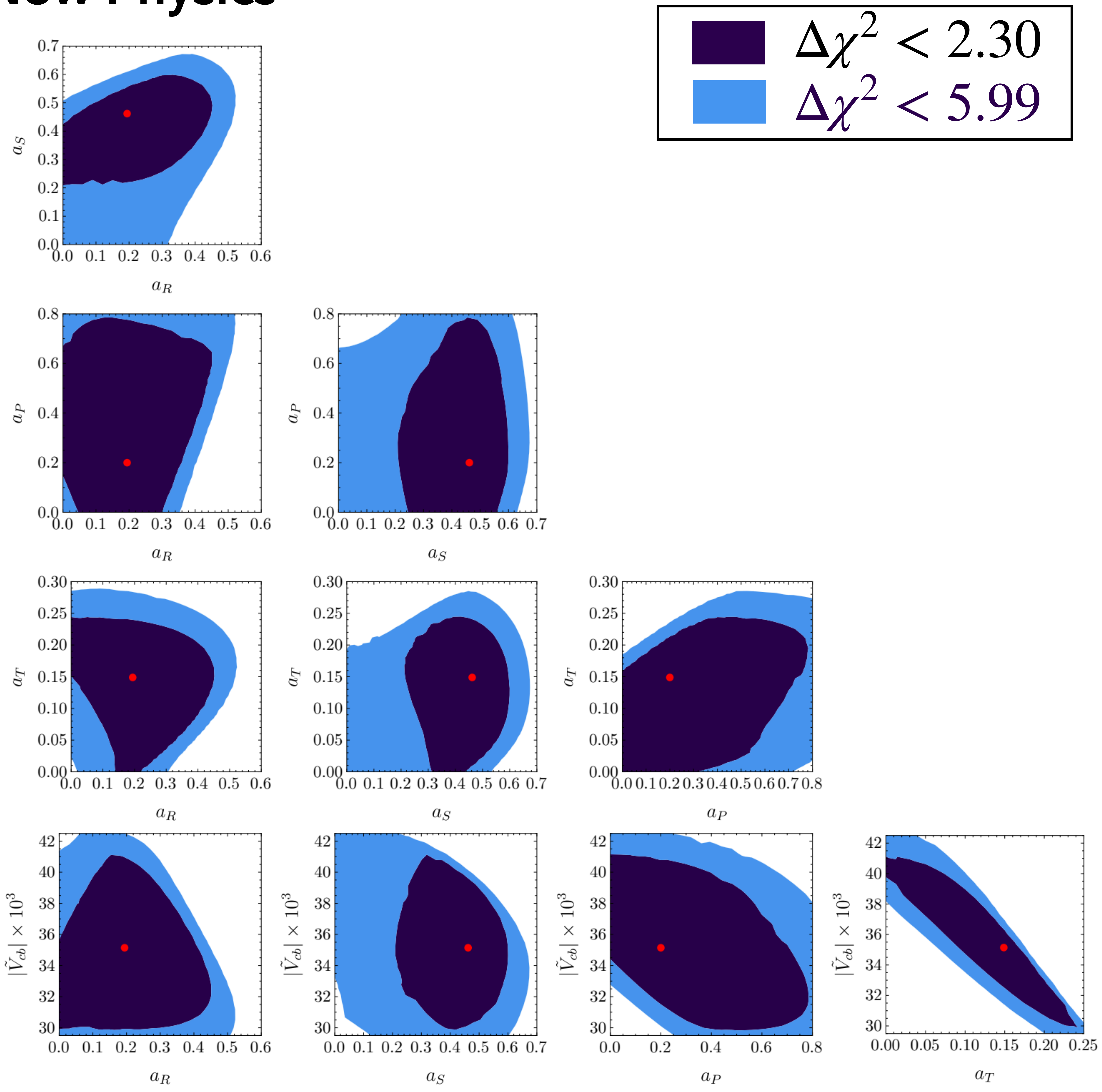


Fit Results

With agnostic New Physics

- HQE parameters are SM-like
- All single NP WCs are compatible with zero within the 68 % C.L. interval (< 95 % for a_S)
- Upper bounds competitive with bounds from exclusive decays
- Important correlation between a_T and $\tilde{V}_{cb}$ gives the profiled $\tilde{V}_{cb}$ a large uncertainty:

$$\boxed{|\tilde{V}_{cb}| = 35.3^{+4.4}_{-3.6} \cdot 10^{-3}}$$



Why is the error on $\tilde{V}_{cb}$ so large?

Here we take:

$m_b^{\rm kin}(\mu_k)$	4.573 GeV
$\overline{m}_c(\mu_c)$	1.090 GeV
$\mu_\pi^2(\mu_k)$	0.454 GeV^2
$\mu_G^2(\mu_k)$	0.288 GeV^2
$\rho_D^3(\mu_k)$	0.176 GeV^3
$\rho_{LS}^3(\mu_k)$	-0.113 GeV^3

The predictions for each observables can be written as a quartic polynomial in NP WC:

$$\xi = \xi_{\rm SM} + a_{V_R} c(\delta_{V_R})\xi_{LR} + a_{V_R}^2\xi_{RR} + a_S^2\xi_{SS} + a_P^2\xi_{PP} + a_T^2\xi_{TT} + a_{V_R}^2 c(\delta_{V_R})^2\xi_{LR^2} + a_S a_T c(\delta_S)\xi_{ST} + a_P a_T c(\delta_P)\xi_{PT}\,,$$

Total decay rate

	$10\times\Gamma/\Gamma_0$
$\tilde\Gamma_{SM}$	$6.580\ -0.461_{\rm pow}\ -0.560_{\alpha_s}\ -0.009_{\alpha_s/m_b^2} - 0.034_{\alpha_s/m_b^3} - 0.105_{\alpha_s^2} + 0.003_{\alpha_s^3}$
$\tilde\Gamma_{RR}$	$6.580\ -0.461_{\rm pow}\ -0.560_{\alpha_s}$
$\tilde\Gamma_{LR}$	$-4.280\ +0.634_{\rm pow}\ +0.464_{\alpha_s}$
$\tilde\Gamma_{TT}$	$78.964\ -7.865_{\rm pow}$
$\tilde\Gamma_{SS}$	$5.430\ +0.240_{\rm pow}$
$\tilde\Gamma_{PP}$	$1.150\ -0.118_{\rm pow}$

$< E_\ell >$ with $E_\ell^{cut} = 1$ GeV

	L_1 $[10^{-2}$ GeV$]$
ξ_{SM}	$157.276\ -1.676_{\rm pow}\ -0.312_{\alpha_s}\ -0.463_{\frac{\alpha_s}{m_b^2}}\ +0.084_{\alpha_s^2}$
ξ_{RR}	$-9.760\ +1.114_{\rm pow}\ +0.208_{\alpha_s}$
ξ_{LR}	$-0.368\ +0.606_{\rm pow}\ -0.197_{\alpha_s}$
ξ_{LR^2}	$-0.247\ +0.427_{\rm pow}\ -0.128_{\alpha_s}$
ξ_{TT}	$-78.076\ +9.286_{\rm pow}$
ξ_{SS}	$0.184\ +3.006_{\rm pow}$
ξ_{PP}	$-0.184\ +0.191_{\rm pow}$
ξ_{ST}	$-19.519\ -2.147_{\rm pow}$
ξ_{PT}	$19.519\ -0.025_{\rm pow}$

« Flat direction » in the fit for $a_S \sim 3a_T$ and $c(\delta_S) = -1$ which allow for large shifts in a_S, a_T and $|\tilde{V}_{cb}|$
$a_P \sim 3a_T$ $\quad c(\delta_P) = 1$ $\quad a_P$

Single Mediator NP models

- We also investigate 5 single-mediator scenarios which only contribute to some of the 5 WCs in the WET Hamiltonian

SMEFT $\mu = \Lambda_{NP} = 1$ TeV	running and matching to WET $\longrightarrow$	WET $\mu = 5$ GeV

(Vector-like quark doublet) $\rightarrow \{\hat{C}_{V_R}\}\,,$ (I)

Charged scalar $\{$ $(H^{\pm}) \rightarrow \{\hat{C}_{S_L}, \hat{C}_{S_R}\}\,,$ (II)

Leptoquarks
$$\begin{cases} (S_1) \rightarrow \{\hat{C}_T, \hat{C}_{S_L} = -4\hat{C}_T\}\,, & \text{(III)} \\ (R_2) \rightarrow \{\hat{C}_T, \hat{C}_{S_L} = 4\hat{C}_T\}\,, & \text{(IV)} \\ (U_1, V_2) \rightarrow \{\hat{C}_{S_R}\}\,, & \text{(V)} \end{cases}$$

	I	II	III	IV	V
C_{V_R}	$0.689[\hat{C}_{V_R}]_3$	0	0	0	0
C_S	0	$-0.57([\hat{C}_{S_L}]_3 + [\hat{C}_{S_R}]_3)$	$2.34[\hat{C}_T]_3$	$-2.18[\hat{C}_T]_3$	$-0.57[\hat{C}_{S_R}]_3$
C_P	0	$0.57([\hat{C}_{S_L}]_3 - [\hat{C}_{S_R}]_3)$	$-2.34[\hat{C}_T]_3$	$2.18[\hat{C}_T]_3$	$-0.57[\hat{C}_{S_R}]_3$
C_T	0	$0.003[\hat{C}_{S_L}]_3$	$-0.65[\hat{C}_T]_3$	$-0.63[\hat{C}_T]_3$	0

Fit Results

Legend:

I - Vector-like quark (C_{V_R})

II - Charged scalar (C_S, C_P)

III - S_1 LQ ($C_T, C_{S_L} = -7C_T$)

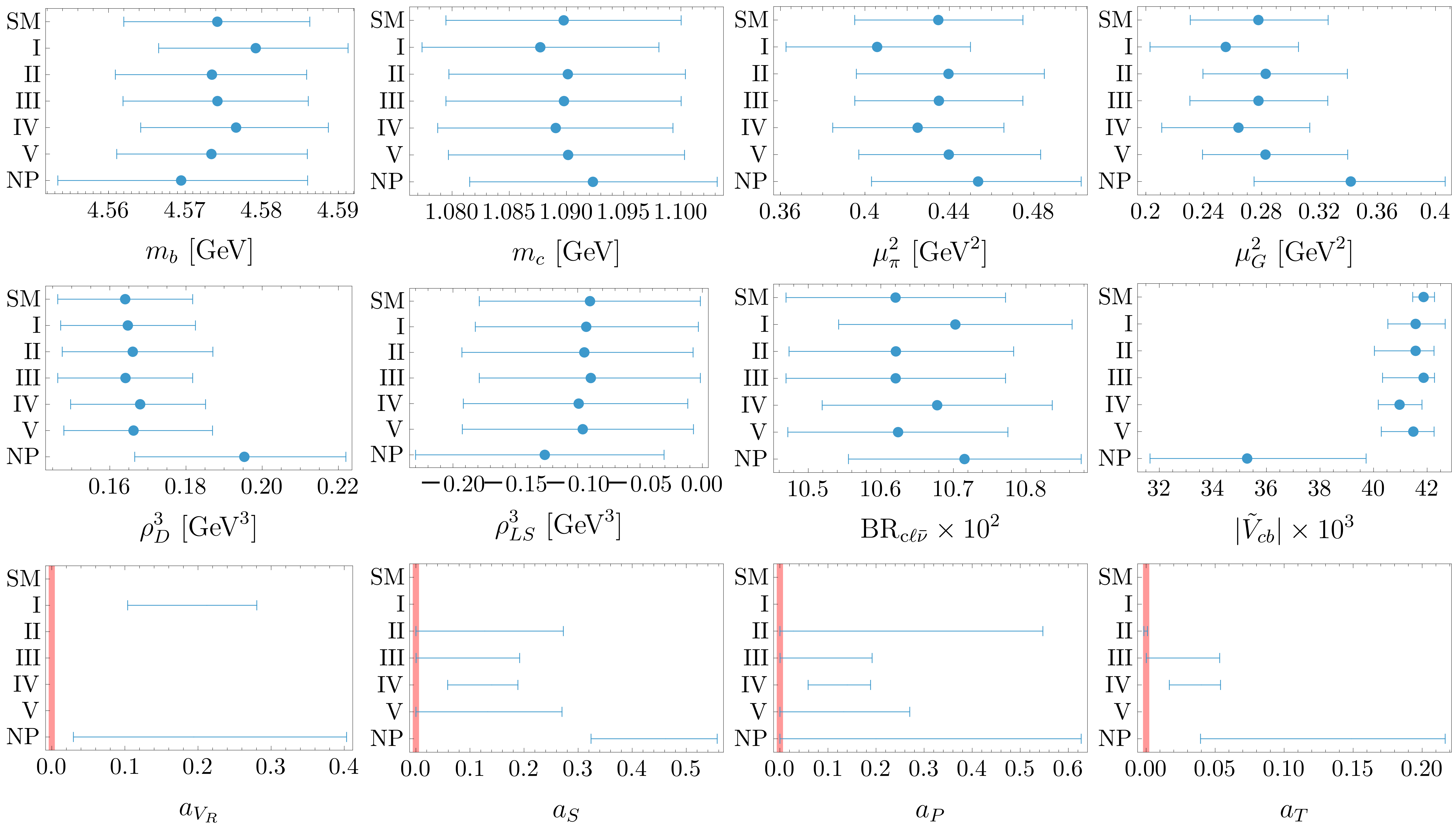
IV - R_2 LQ ($C_T, C_{S_L} = 7C_T$)

V - U_1, V_2 LQ (C_{S_R})

NP - All WCs

68% C.L. interval

Best-fit point

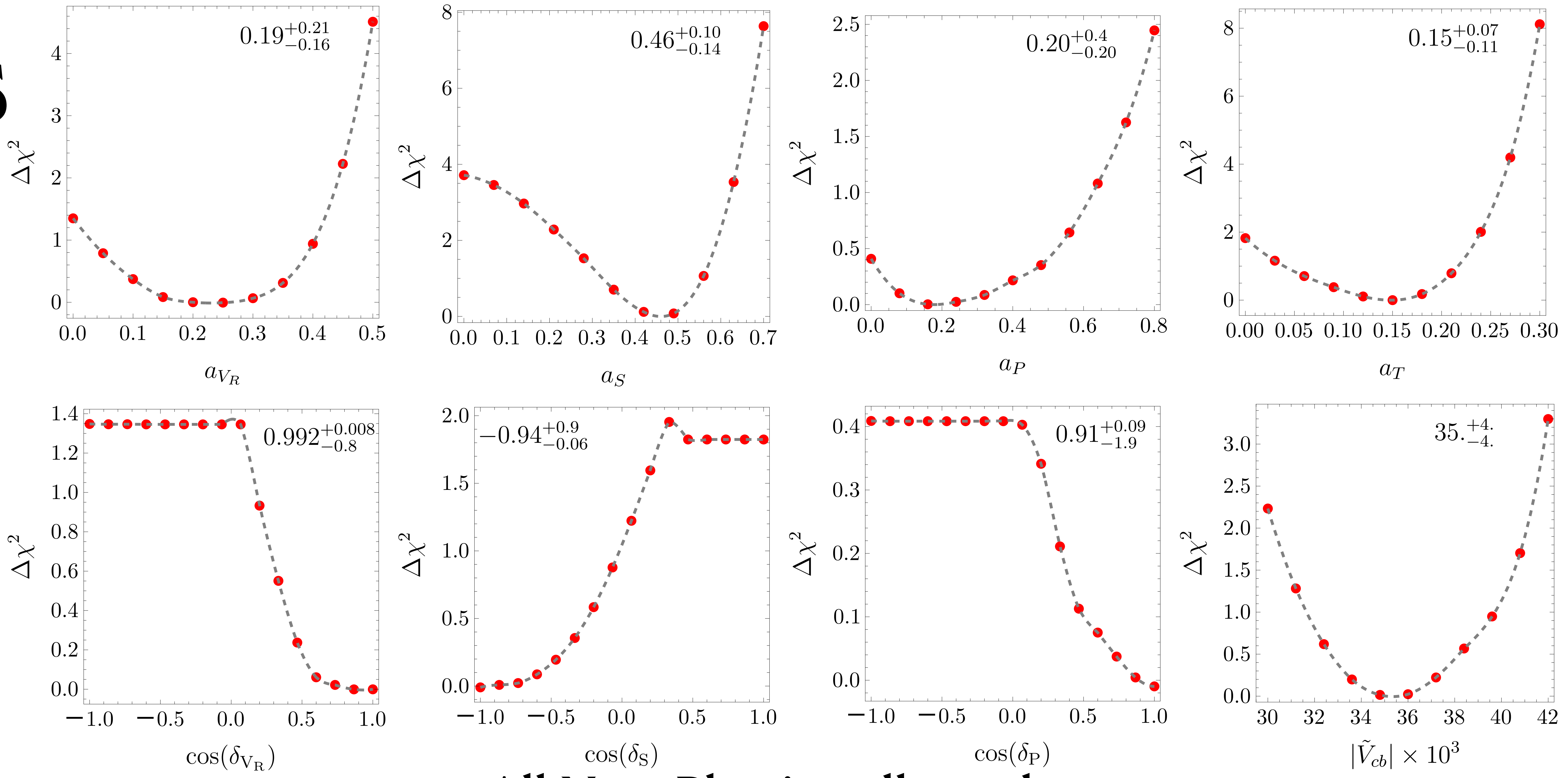


« Flat direction » in the fit for $a_S \sim 3a_T$ and $c(\delta_S) = -1$ found at the best fit point for a_S, a_T in 'NP'

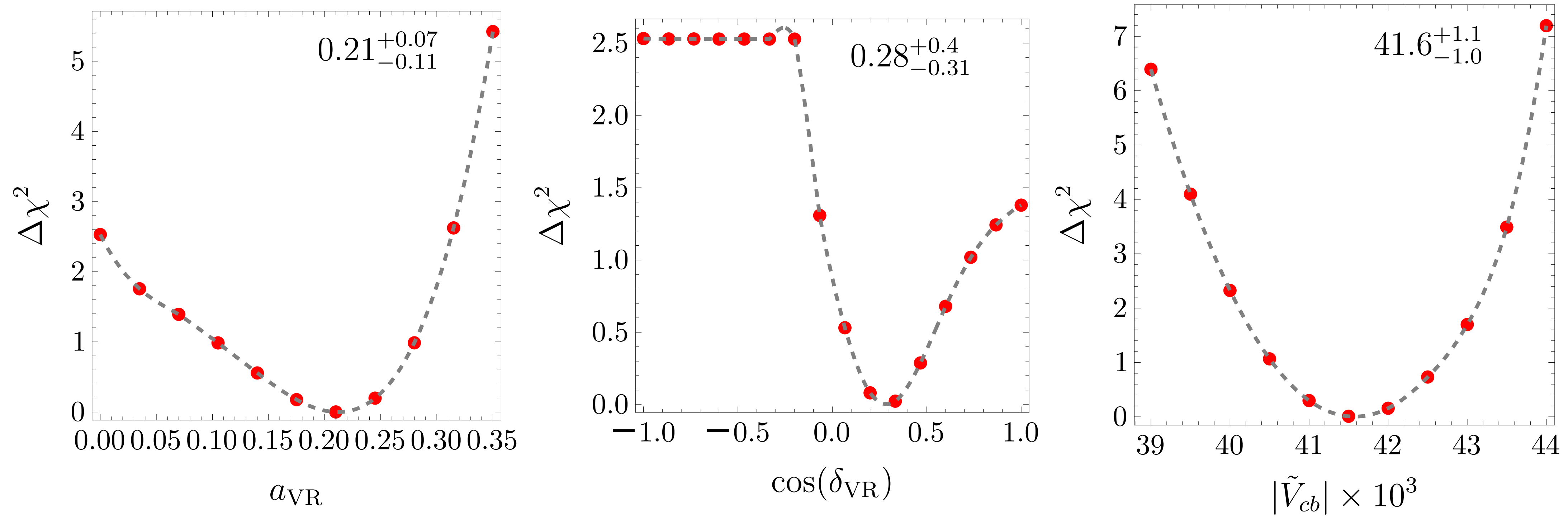
Most distributions are non-Gaussian

1D profile likelihoods

- 1D profile likelihoods of WCs are non-Gaussian
- E.g. a_S (a_{V_R}) is compatible with 0 at the 2σ level in 'NP' (I),
- $|\tilde{V}_{cb}|$ is moderately affected in single mediator models
- Only scenario I (slightly) prefers a complex NP WC (C_{V_R})



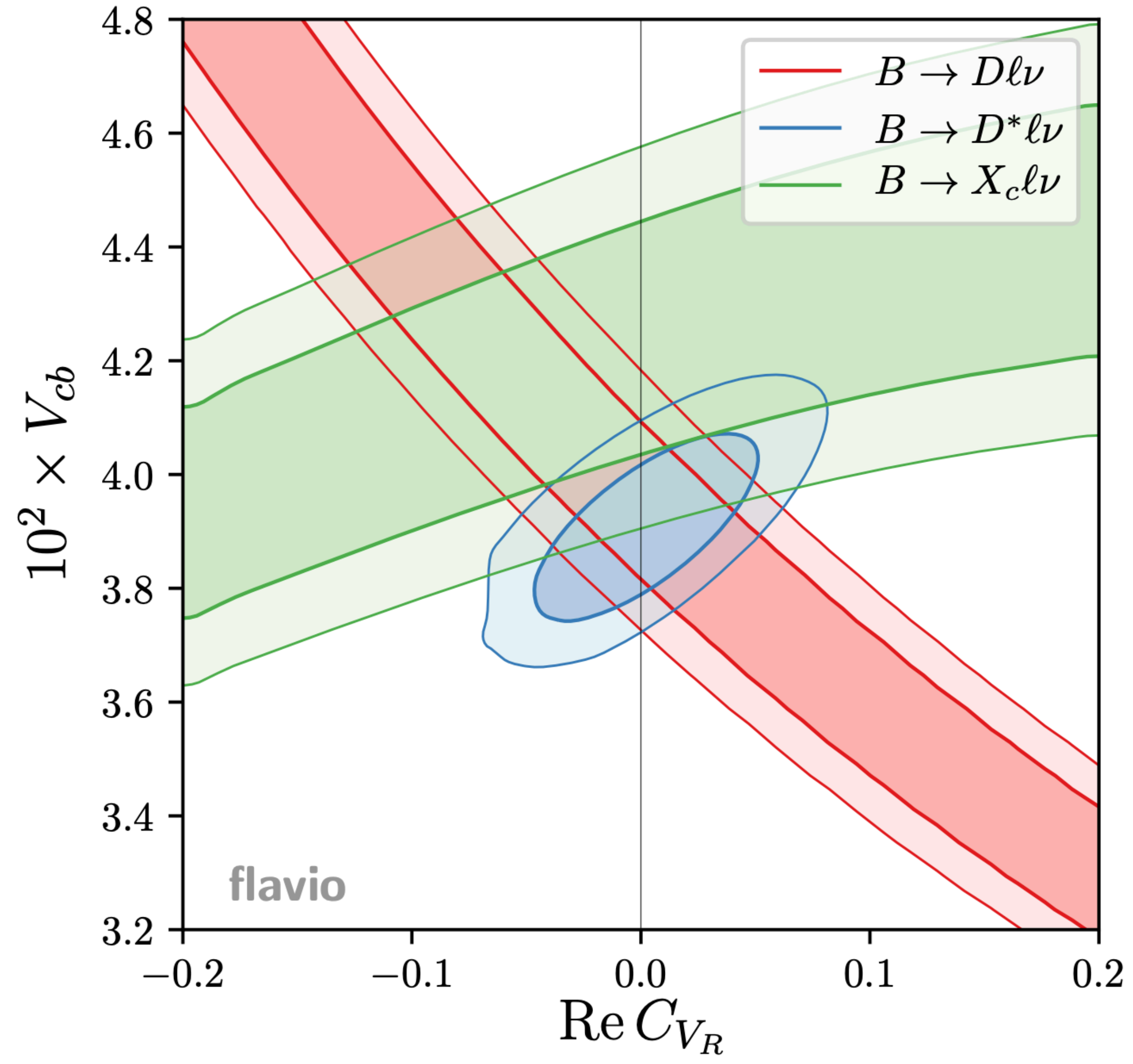
All New Physics allowed



Scenario I

Back to the Vcb puzzle

E.g. for NP in $Re(C_{V_R})$



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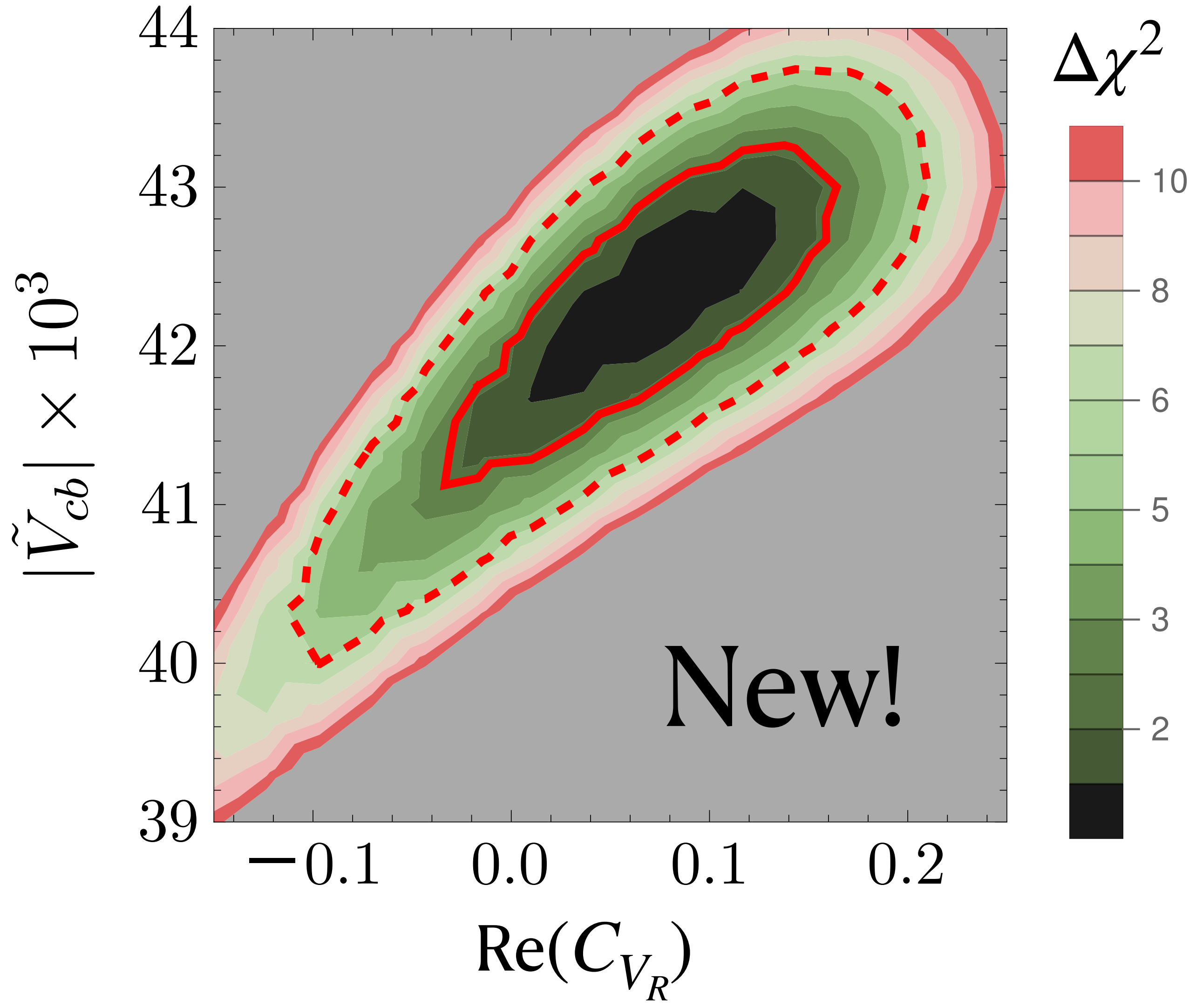
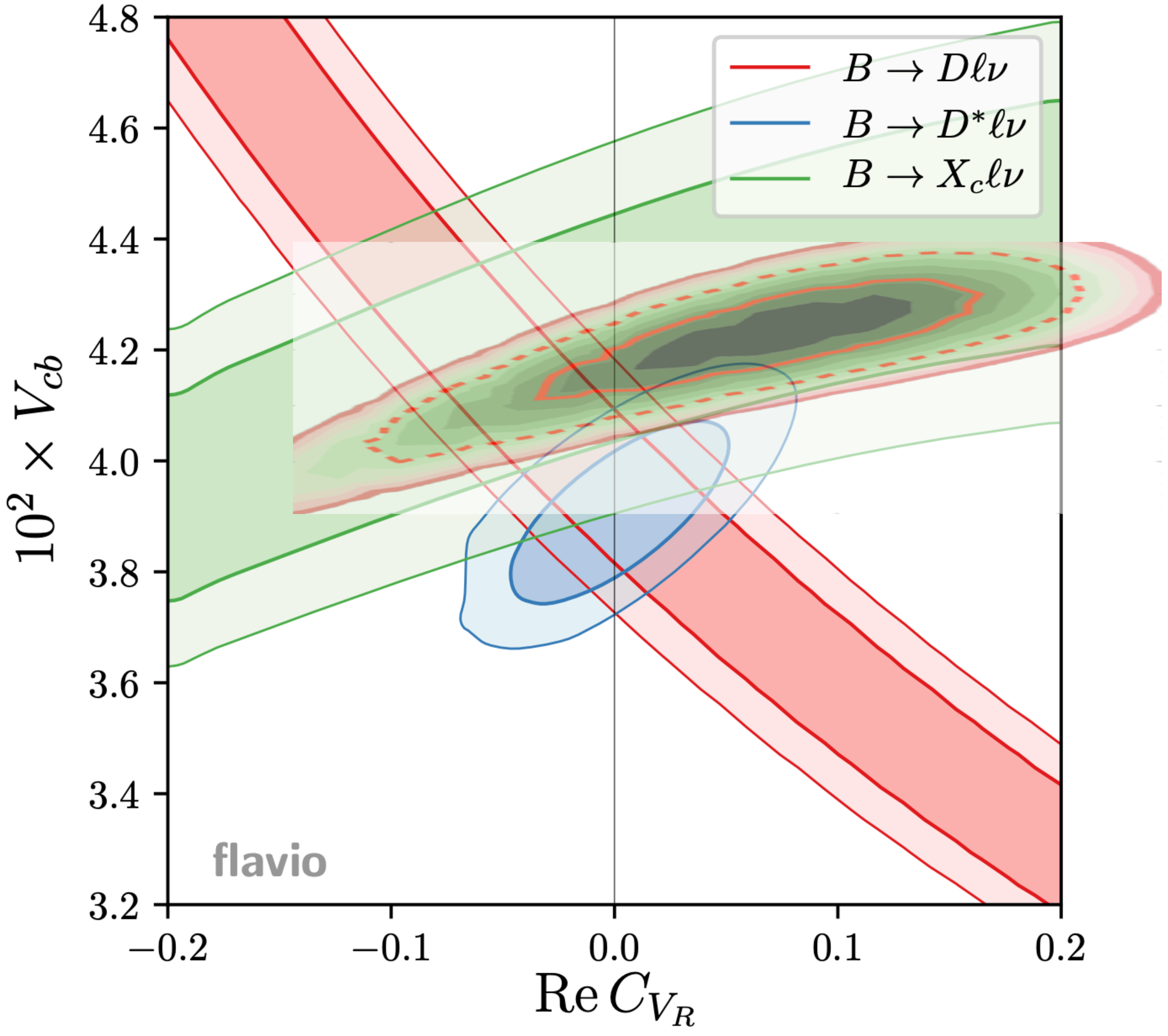


68 % C.L.

95 % C.L.



Exclusive bounds need to be updated and included in a global fit!

Outlook

- We perform a state-of-the-art calculation of $B \to X_c \ell \bar{\nu}$ with New Physics
  - First global fit of inclusive $B \to X_c \ell \bar{\nu}$ with model-independent New Physics
  - Provide new and competitive constraints on New Physics in $b \to c \ell \bar{\nu}$ transitions
- Perspectives:
  - $\mathcal{O}(\alpha_s)$ radiative corrections to all New Physics contributions (very soon)
  - Global fit including exclusive $b \to c \ell \bar{\nu}$ decays
  - Implementation in flavio/EOS/other?

Thank you!

Appendix

Exclusive Vcb: Theory prediction of $d\Gamma/dw(\bar{B} \to D^*\ell\bar{\nu})$

$$\frac{d\Gamma}{dw}\left(\bar{B} \to D^*\ell\bar{\nu}_\ell\right) = \frac{G_F^2 m_B^5}{48\pi^3}\left|V_{cb}\right|^2\left(w^2-1\right)^{1/2} P(w)\left(\eta_{\mathrm{ew}}\mathscr{F}(w)\right)^2$$

Phase space factor

EW corrections

Form Factor

$w = v \cdot v'$ product of initial and final velocities

FF definition:

$$\frac{\langle D^*(v',\epsilon)|\bar{c}\gamma^\mu b|B(v)\rangle}{\sqrt{m_B m_{D^*}}} = h_V(w)\,\varepsilon^{\mu\nu\rho\sigma} v_{B,\nu} v_{D^*,\rho}\epsilon^*_\sigma,$$

$$\frac{\langle D^*(v',\epsilon)|\bar{c}\gamma^\mu\gamma^5 b|B(v)\rangle}{\sqrt{m_B m_{D^*}}} = i h_{A_1}(w)\,(1+w)\epsilon^{*\mu} - i\left[h_{A_2}(w)v_B^\mu + h_{A_3}(w)v_{D^*}^\mu\right]\epsilon^*\cdot v_B$$

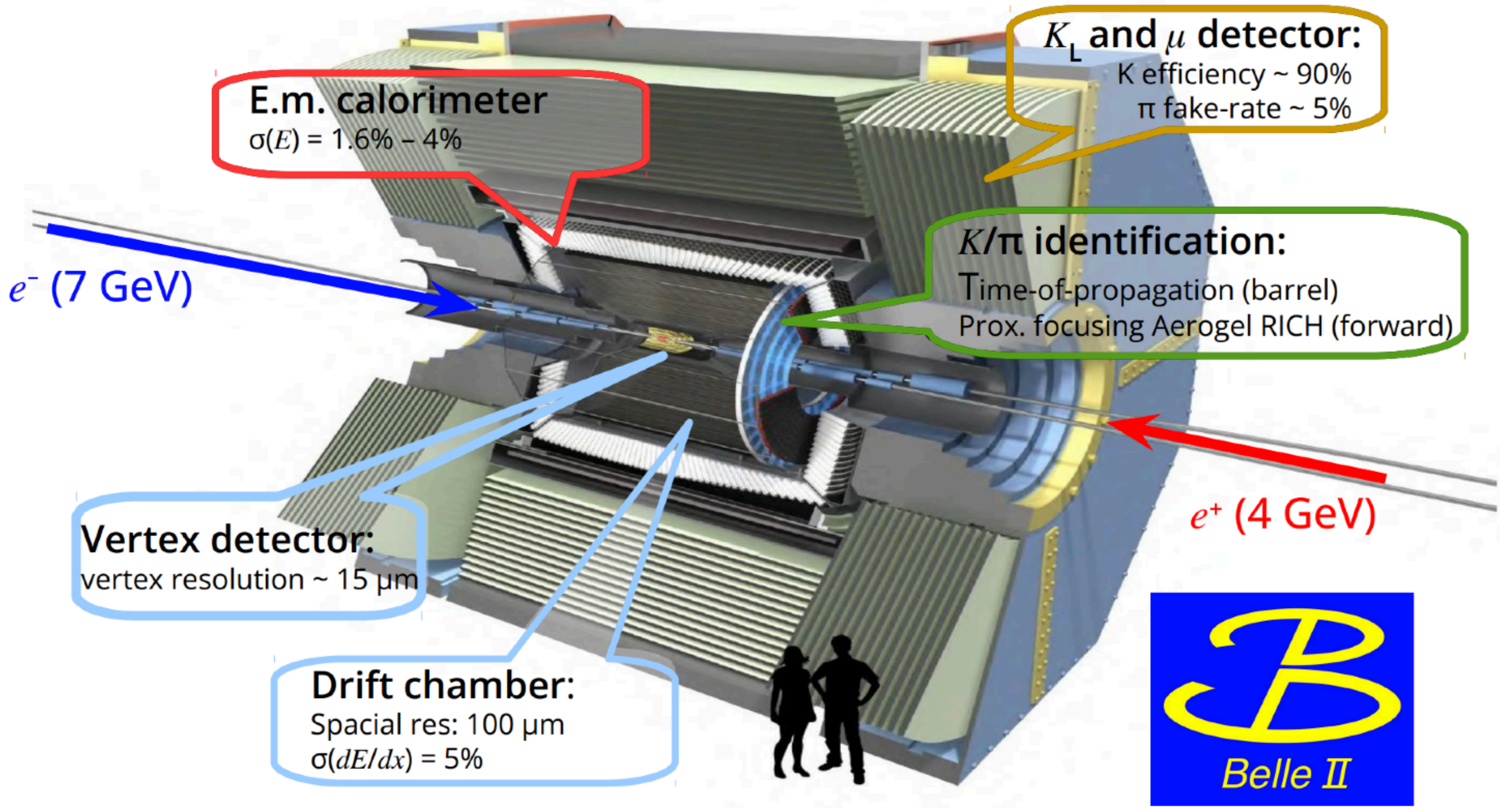
3 ways to obtain the FFs :

- HQET + experiment + lattice for normalization
- Lattice only (In tension with the experiment driven determination)
- Light-Cone Sum Rules (not very accurate for $b \to c$ decays)

Measurement of $B \to X_c \ell \bar{\nu}$

At B factories - e.g. Belle II at SuperKEKB

- B factories: $e^+e^- \to \Upsilon(4S) \to \bar{B}B$
  - High hermeticity detector
  - Low background and no pile up
  - Excellent PID
- BUT fewer B produced compared to p-p collider:
  - ~390M $B\bar{B}$ pairs at SuperKEKB/Belle II
  - $>10^{12}$ b-hadrons produced at LHCb
- Open questions (non-exhaustive):
  - Experimental correlation between moments is currently unknown (but non-zero)
  - 'Gap' between sum of inclusive modes (used to generate simulated events) and measured total decay rate



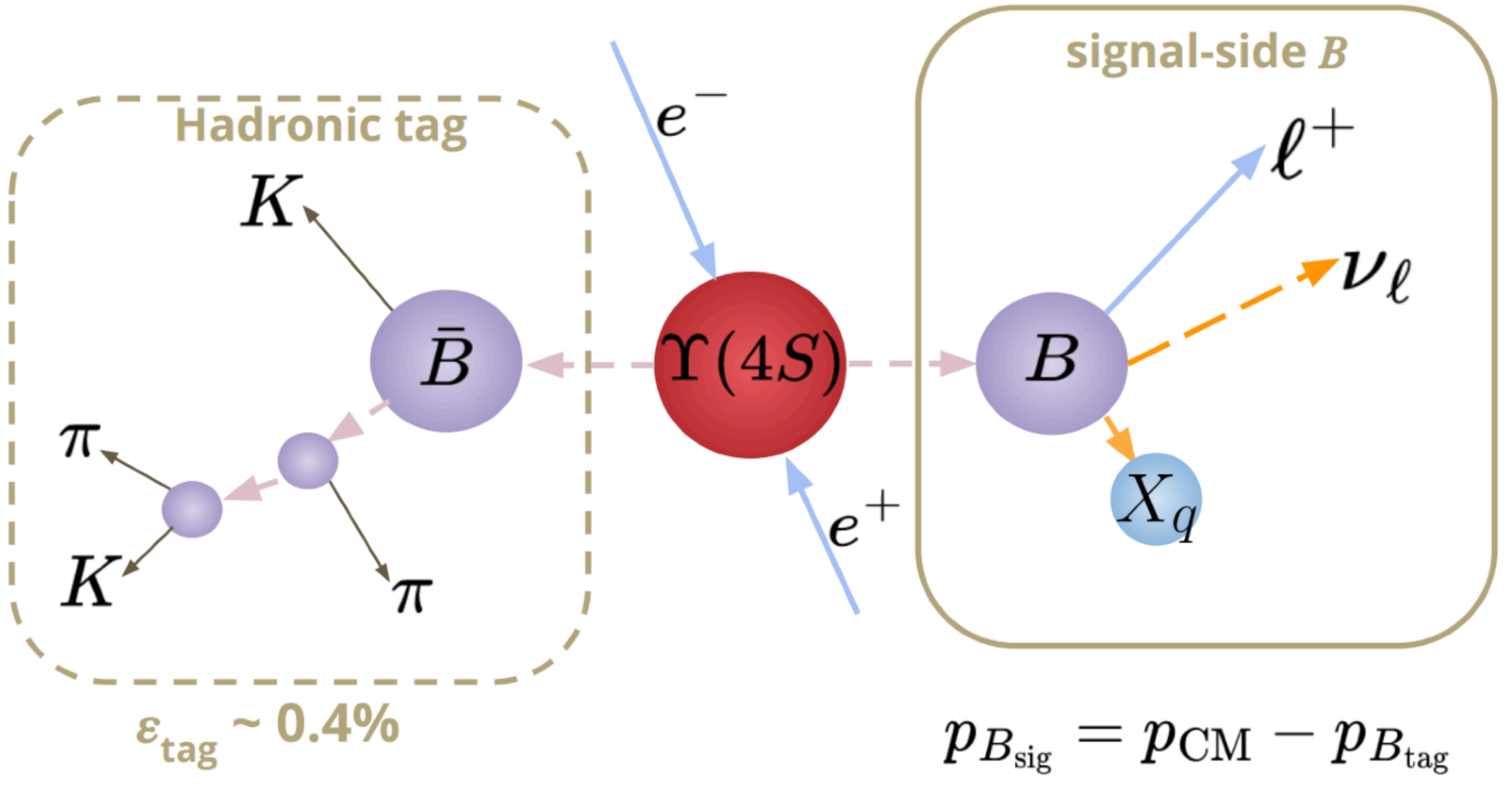


Image credit: Stefano Moreta

Total reconstruction, then subtraction of $B \to X_u \ell \bar{\nu}$

$$\left|\frac{V_{ub}}{V_{cb}}\right|^2 \sim 0.8\,\%$$

$\tilde{V}_{cb}$ vs complex C_{V_R}