PAUL SCHERRER INSTITUT

Rare B decays & new physics

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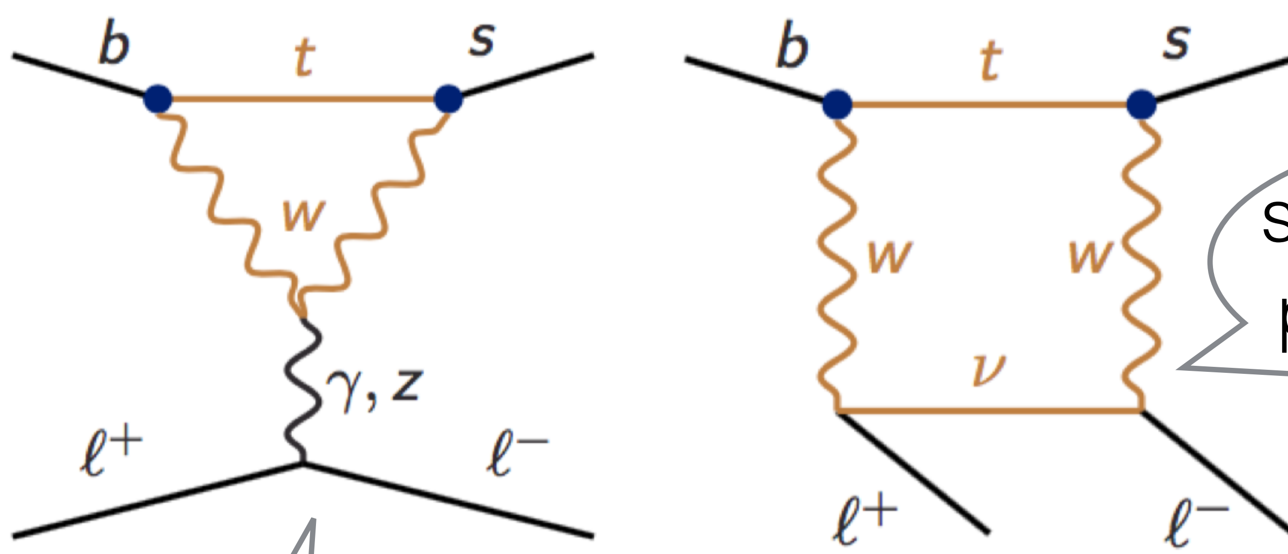
Outline

- Introduction
- Rare semileptonic mode $B \to K^* \ell^+ \ell^-$
  - Model independent framework
  - Evidence of new physics
- Lepton flavor non-universality
- Summary

Introduction

loop and CKM suppressed
SM amplitude



sensitive to new
particle in loop

large no. of experimentally
accessible observables

valuable probe for indirect
search of NP

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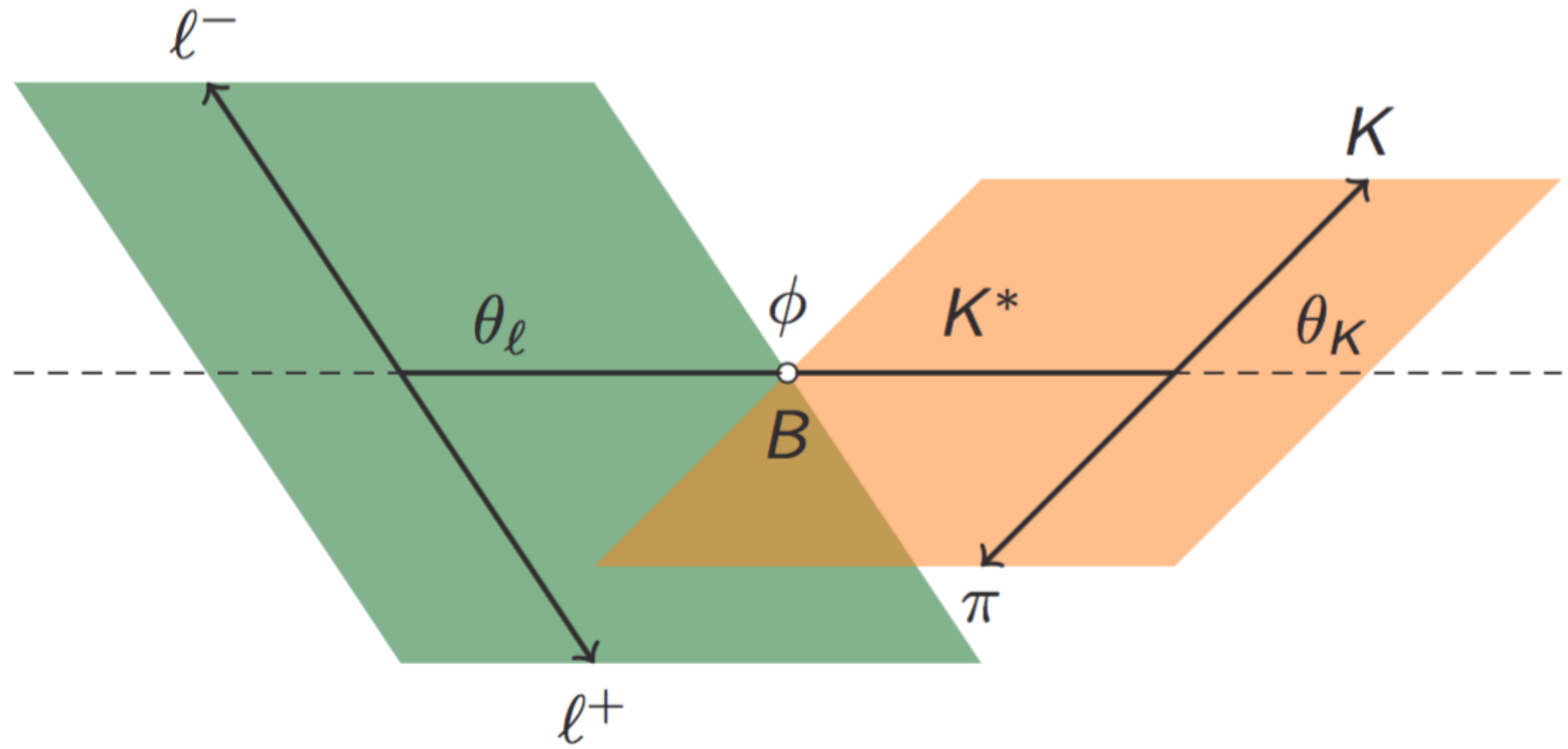
Introduction

Angular analysis in well known helicity frame [Kruger, Sehgal, Sinha, Sinha '99]



The differential distribution $\dfrac{d^4\Gamma(B \to K^* \ell^+ \ell^-)}{dq^2\, d\cos\theta_l\, d\cos\theta_k\, d\phi}$

$$= \frac{9}{32\pi} \Big[I_1^s \sin^2\theta_K + I_1^c \cos^2\theta_K + (I_2^s \sin^2\theta_K + I_2^c \cos^2\theta_K)\cos 2\theta_l + I_3 \sin^2\theta_K \sin^2\theta_l \cos 2\phi$$

$$+ I_4 \sin 2\theta_K \sin 2\theta_l \cos\phi + I_5 \sin 2\theta_K \sin\theta_l \cos\phi + I_6^s \sin^2\theta_K \cos\theta_l$$

$$+ I_7 \sin 2\theta_K \sin\theta_l \sin\phi + I_8 \sin 2\theta_K \sin 2\theta_l \sin\phi + I_9 \sin^2\theta_K \sin^2\theta_l \sin 2\phi \Big]$$

Motivation

- $I_i =$ short distance + long distance

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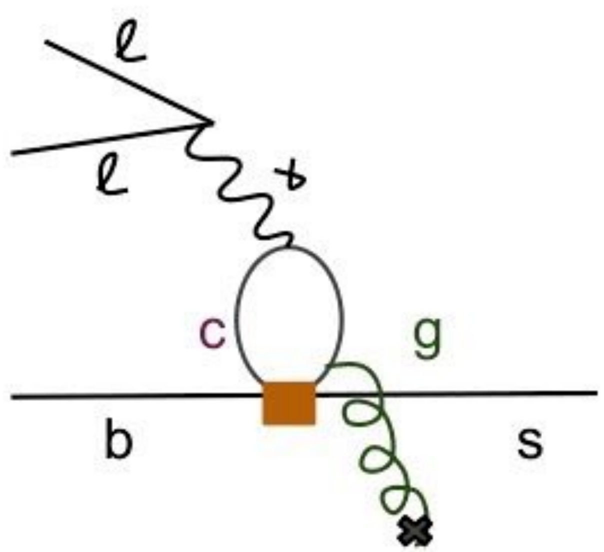
Non-factorizable
contributions:



no quantitative computation

- Challenge: either estimate accurately or *eliminate*

Model Independent Framework

- The amplitude $\mathcal{A}\left(B(p) \to K^*(k)\ell^+\ell^-\right)$ [RM, Sinha, Das '14]

$$= \frac{G_F\alpha}{\sqrt{2}\pi} V_{tb}V_{ts}^* \Bigg[\Bigg\{ C_9 \left\langle K^* | \bar{s}\gamma^\mu P_L b | \bar{B} \right\rangle - \frac{2C_7}{q^2} \left\langle K^* | \bar{s} i \sigma^{\mu\nu} q_\nu (m_b P_R + m_s P_L) b | \bar{B} \right\rangle$$

$$- \frac{16\pi^2}{q^2} \sum_{i=\{1-6,8\}} C_i \mathcal{H}_i^\mu \Bigg\} \bar{\ell}\gamma_\mu \ell + C_{10} \left\langle K^* | \bar{s}\gamma^\mu P_L b | \bar{B} \right\rangle \bar{\ell}\gamma_\mu\gamma_5 \ell \Bigg]$$

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Wilson coefficients

non-local operator
for non factorization contributions

lorentz & gauge invariance allow general parametrization with form-factors $\mathcal{X}_j$, $\mathcal{Y}_j$

$$\mathcal{H}_i^\mu \sim \left\langle K^* | i \int d^4x\, e^{iq\cdot x} T\{ j_{em}^\mu(x), \mathcal{O}_i(0) \} | \bar{B} \right\rangle$$

$\Rightarrow$ parametrize with 'new' form-factors $\mathcal{Z}_j^i$

[Khodjamirian *et. al* '10]

Model Independent Framework

- Absorbing factorizable & non-factorizable contributions into

$$C_9 \longrightarrow \widetilde{C}_9^{(j)} = C_9 + \Delta C_9^{(\text{fac})}(q^2) + \underbrace{\Delta C_9^{(j),(\text{non-fac})}(q^2)}_{\sim \sum_i C_i \, \mathcal{Z}_j^i / \mathcal{X}_j}$$

$$\frac{2(m_b+m_s)}{q^2} C_7 \, \mathcal{Y}_j \longrightarrow \widetilde{\mathcal{Y}}_j = \frac{2(m_b+m_s)}{q^2} C_7 \, \mathcal{Y}_j + \cdots$$

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- Most general parametric form of amplitude in SM

$$\mathcal{A}_\lambda^{L,R} = (\widetilde{C}_9^\lambda \mp C_{10})\mathcal{F}_\lambda - \widetilde{\mathcal{G}}_\lambda \qquad \mathcal{A}_t\Big|_{m_\ell=0} = 0$$

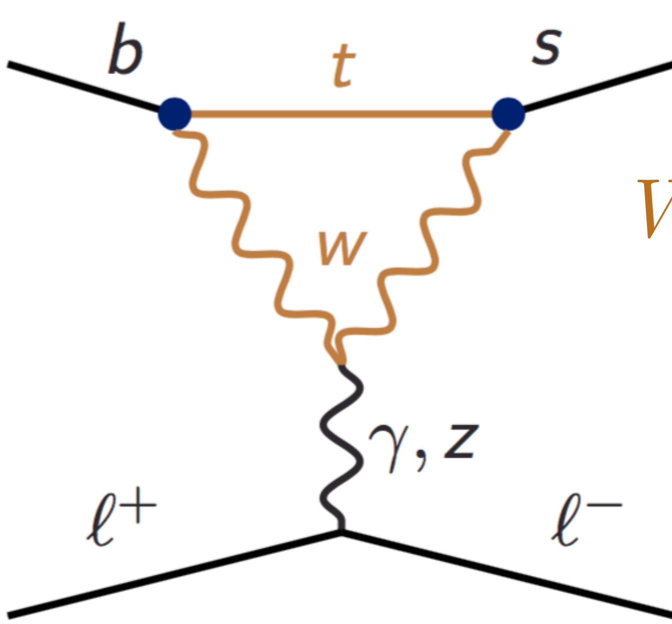
Form-factors: $\mathcal{F}_\lambda \equiv \mathcal{F}_\lambda(\mathcal{X}_j)$ and $\widetilde{\mathcal{G}}_\lambda \equiv \widetilde{\mathcal{G}}_\lambda(\widetilde{\mathcal{Y}}_j)$

Right-Handed Current

- Chirality flipped operators $\mathcal{O} \Leftrightarrow \mathcal{O}'$

$$\bar{s}\gamma_\mu P_L b \quad \Longleftrightarrow \quad \bar{s}\gamma_\mu P_R b$$

$$\bar{s} i\sigma_{\mu\nu} P_R b \quad \Longleftrightarrow \quad \bar{s} i\sigma_{\mu\nu} P_L b$$



$W_L \Leftrightarrow W_R$

- In presence of right-handed gauge boson or other kind of new particles like leptoquarks etc..

RH Current

- Amplitudes $\mathcal{A}_{\perp}^{L,R} = ((\widetilde{C}_9^{\perp} + C_9') \mp (C_{10} + C_{10}'))\mathcal{F}_{\perp} - \widetilde{\mathcal{G}}_{\perp}$

  $\mathcal{A}_{\|,0}^{L,R} = ((\widetilde{C}_9^{\|,0} - C_9') \mp (C_{10} - C_{10}'))\mathcal{F}_{\|,0} - \widetilde{\mathcal{G}}_{\|,0}$

- Notation $r_\lambda = \dfrac{\mathrm{Re}(\widetilde{\mathcal{G}}_\lambda)}{\mathcal{F}_\lambda} - \mathrm{Re}(\widetilde{C}_9^\lambda) \qquad \xi = \dfrac{C_{10}'}{C_{10}} \qquad \xi' = \dfrac{C_9'}{C_{10}}$

- Variables $R_\perp = \dfrac{\frac{r_\perp}{C_{10}} - \xi'}{1+\xi}, \; R_\| = \dfrac{\frac{r_\|}{C_{10}} + \xi'}{1-\xi}, \; R_0 = \dfrac{\frac{r_0}{C_{10}} + \xi'}{1-\xi}.$

- HQET limit $\dfrac{\widetilde{\mathcal{G}}_\|}{\mathcal{F}_\|} = \dfrac{\widetilde{\mathcal{G}}_\perp}{\mathcal{F}_\perp} = \dfrac{\widetilde{\mathcal{G}}_0}{\mathcal{F}_0} = -\kappa \dfrac{2 m_b m_B C_7}{q^2},$ [Grinstein, Prijol '04] [Bobeth *et. al* '10]

⇨ $r_0 = r_\| = r_\perp \equiv r$ ignoring non-factorisable corrections

⇨ $R_0 = R_\| \neq R_\perp$ *in presence of RH currents*

RH Current

At kinematic endpoint → ☑ exact HQET limit
☑ polarization independent non-factorisable correction

- Observables $F_L(q^2_{\text{max}}) = \frac{1}{3}, F_{\|}(q^2_{\text{max}}) = \frac{2}{3}, A_4(q^2_{\text{max}}) = \frac{2}{3\pi},$

$$F_\perp(q^2_{\text{max}}) = 0,\ \ A_{\text{FB}}(q^2_{\text{max}}) = 0,\ \ A_{5,7,8,9}(q^2_{\text{max}}) = 0.$$

[Hiller, Zwicky '14]

- Taylor series expansion around $\delta \equiv q^2_{\text{max}} - q^2$

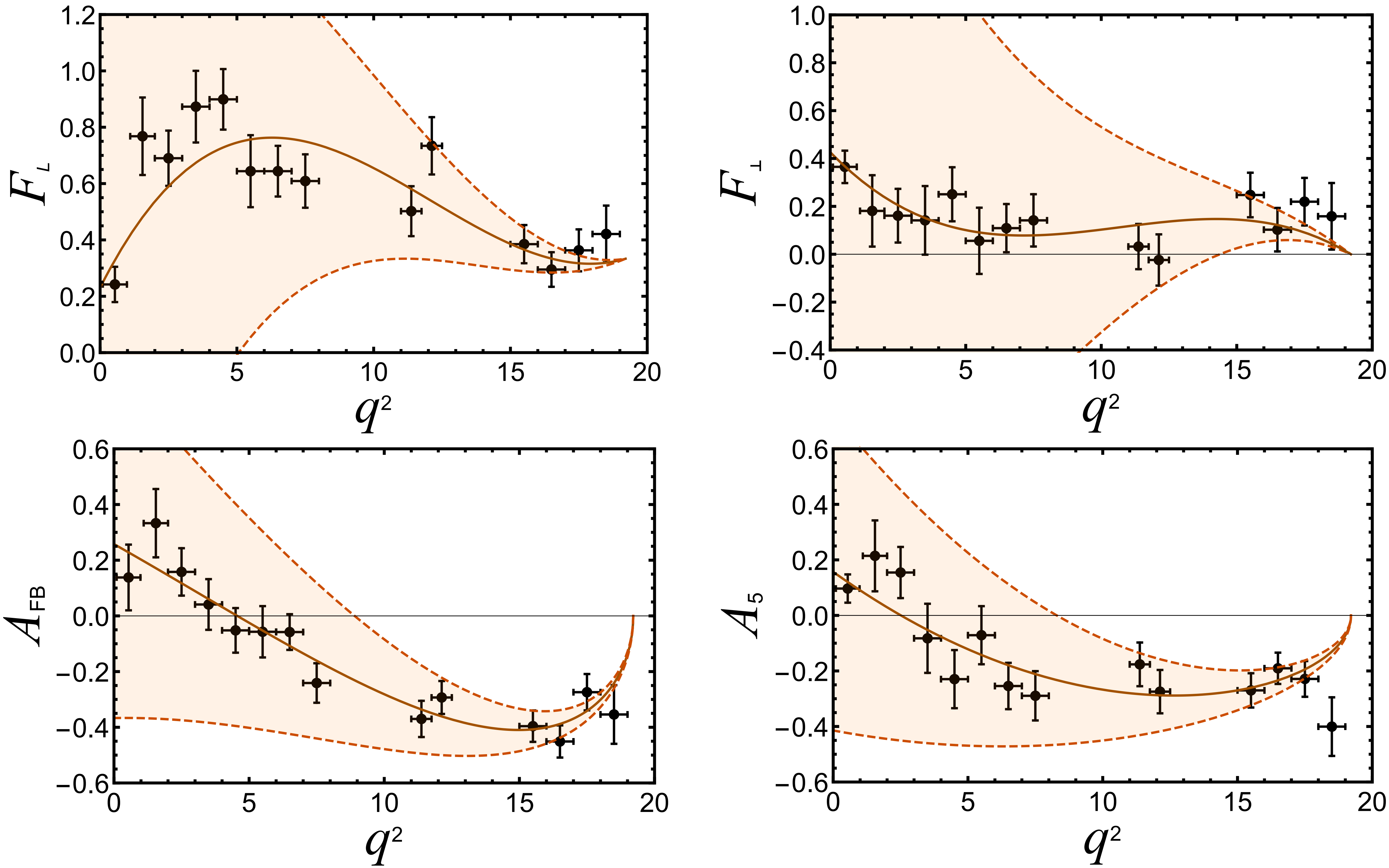
$$F_L = \frac{1}{3} + F_L^{(1)}\delta + F_L^{(2)}\delta^2 + F_L^{(3)}\delta^3$$

$$F_\perp = F_\perp^{(1)}\delta + F_\perp^{(2)}\delta^2 + F_\perp^{(3)}\delta^3$$

$$A_{\text{FB}} = A_{\text{FB}}^{(1)}\delta^{\frac{1}{2}} + A_{\text{FB}}^{(2)}\delta^{\frac{3}{2}} + A_{\text{FB}}^{(3)}\delta^{\frac{5}{2}}$$

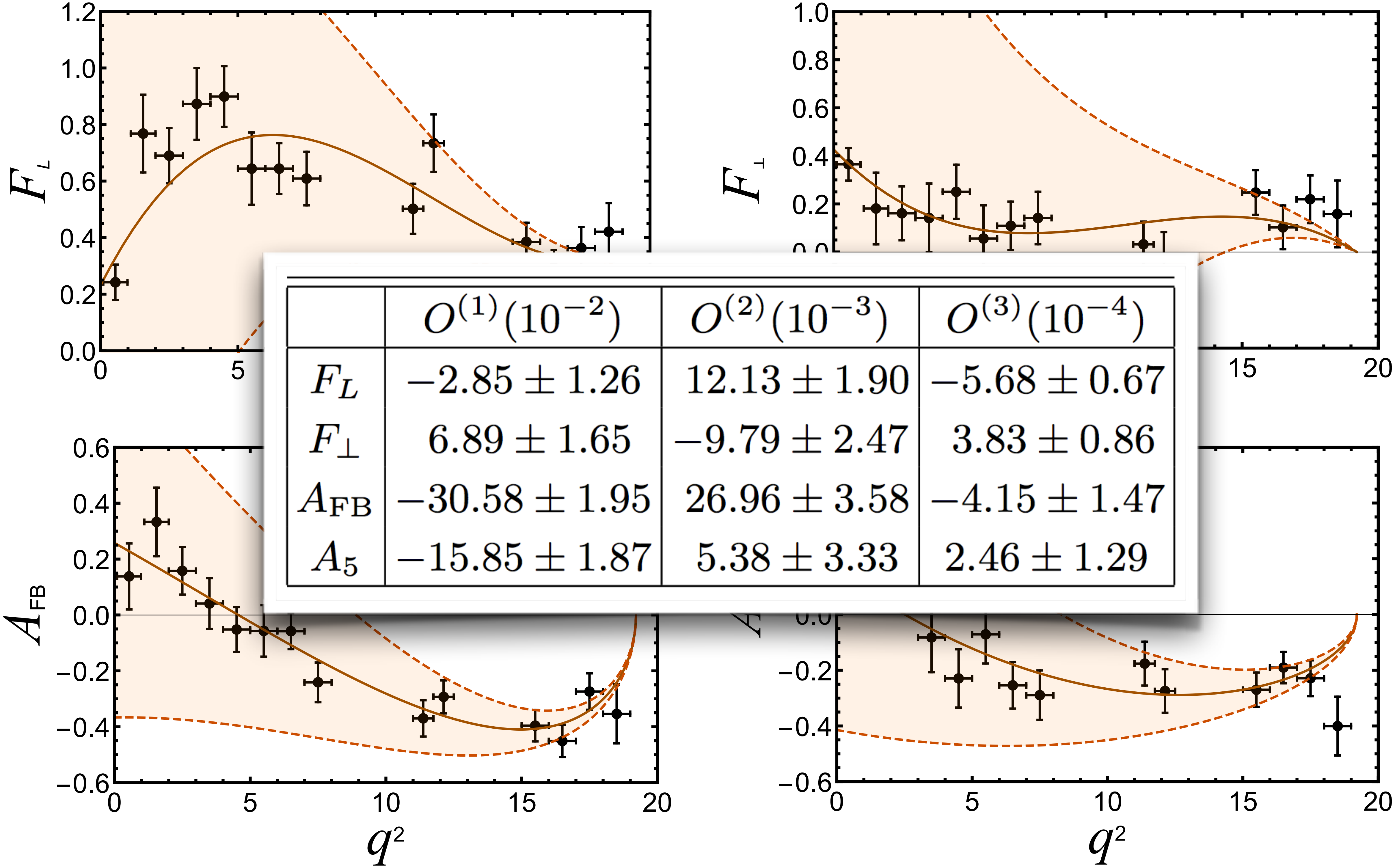
$$A_5 = A_5^{(1)}\delta^{\frac{1}{2}} + A_5^{(2)}\delta^{\frac{3}{2}} + A_5^{(3)}\delta^{\frac{5}{2}},$$

RH Current



Fit to 14 bin LHCb data including correlation among observables

RH Current



	$O^{(1)}(10^{-2})$	$O^{(2)}(10^{-3})$	$O^{(3)}(10^{-4})$
F_L	-2.85 ± 1.26	12.13 ± 1.90	-5.68 ± 0.67
$F_\perp$	6.89 ± 1.65	-9.79 ± 2.47	3.83 ± 0.86
$A_{\rm FB}$	-30.58 ± 1.95	26.96 ± 3.58	-4.15 ± 1.47
A_5	-15.85 ± 1.87	5.38 ± 3.33	2.46 ± 1.29

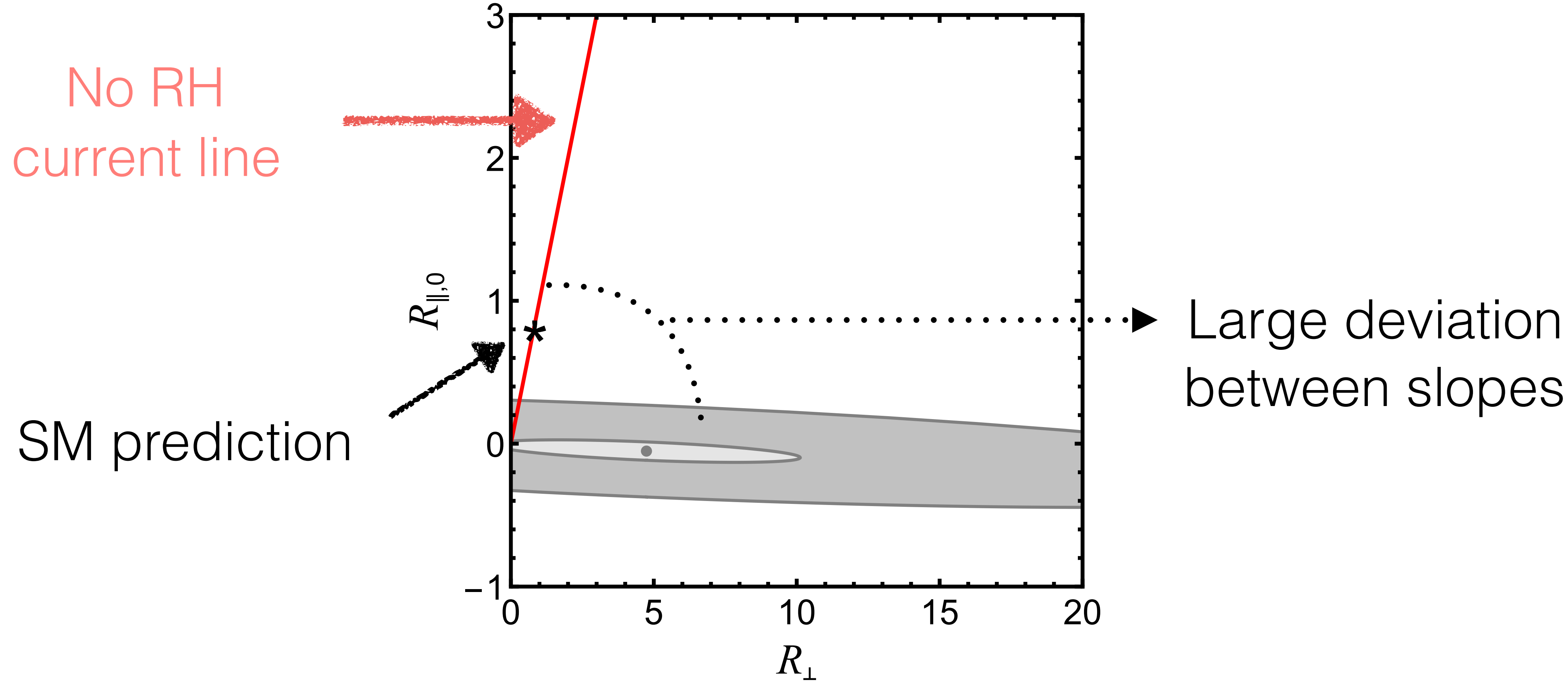
Fit to 14 bin LHCb data including correlation among observables

RH Current

- Limiting analytic expressions

$$R_\perp(q^2_{\rm max}) = \frac{\omega_2 - \omega_1}{\omega_2\sqrt{\omega_1 - 1}}, \quad R_\parallel(q^2_{\rm max}) = \frac{\sqrt{\omega_1 - 1}}{\omega_2 - 1} = R_0(q^2_{\rm max})$$

$$\omega_1 = \frac{3}{2}\frac{F_\perp^{(1)}}{A_{\rm FB}^{(1)\,2}} \;\text{ or }\; \frac{3}{8}\frac{F_\perp^{(1)}}{A_5^{(1)\,2}} \;\text{ and }\; \omega_2 = \frac{4\left(2A_5^{(2)} - A_{\rm FB}^{(2)}\right)}{3\,A_{\rm FB}^{(1)}\left(3F_L^{(1)} + F_\perp^{(1)}\right)} \;\text{ or }\; \frac{4\left(2A_5^{(2)} - A_{\rm FB}^{(2)}\right)}{6\,A_5^{(1)}\left(3F_L^{(1)} + F_\perp^{(1)}\right)}$$



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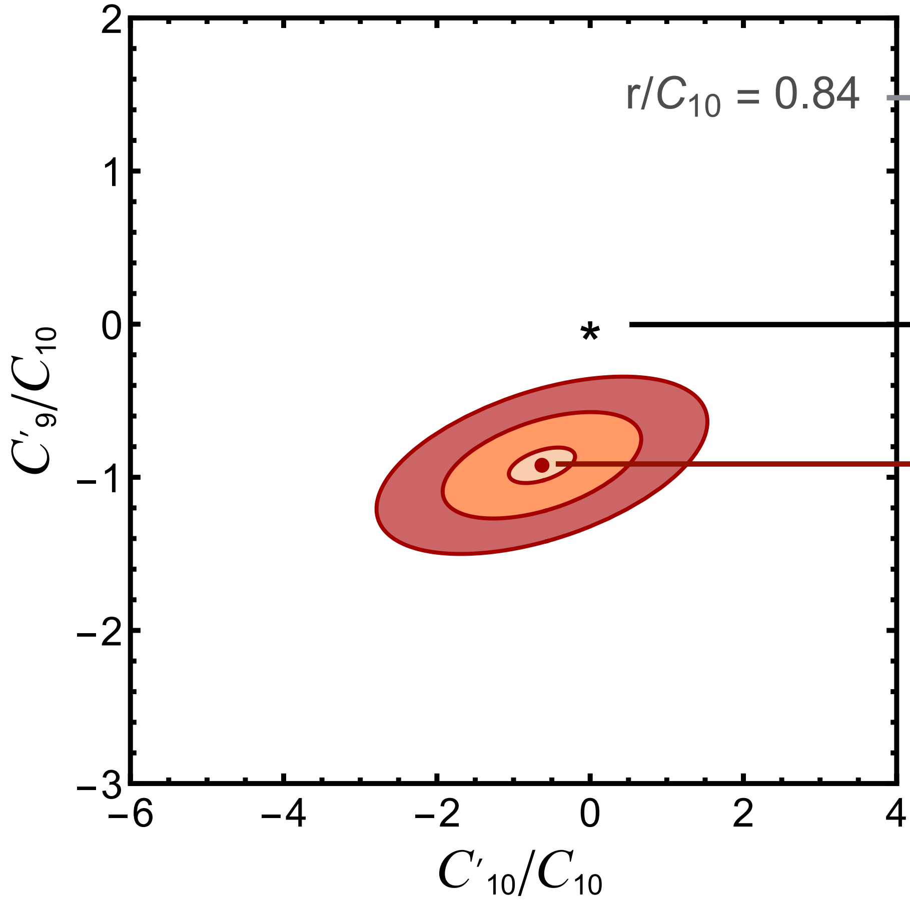
Results in $C'_{10}/C_{10} - C'_9/C_{10}$



SM input

More than 5σ deviation

$$C'_{10}/C_{10} = -0.63 \pm 0.43$$

$$C'_9/C_{10} = -0.92 \pm 0.10$$

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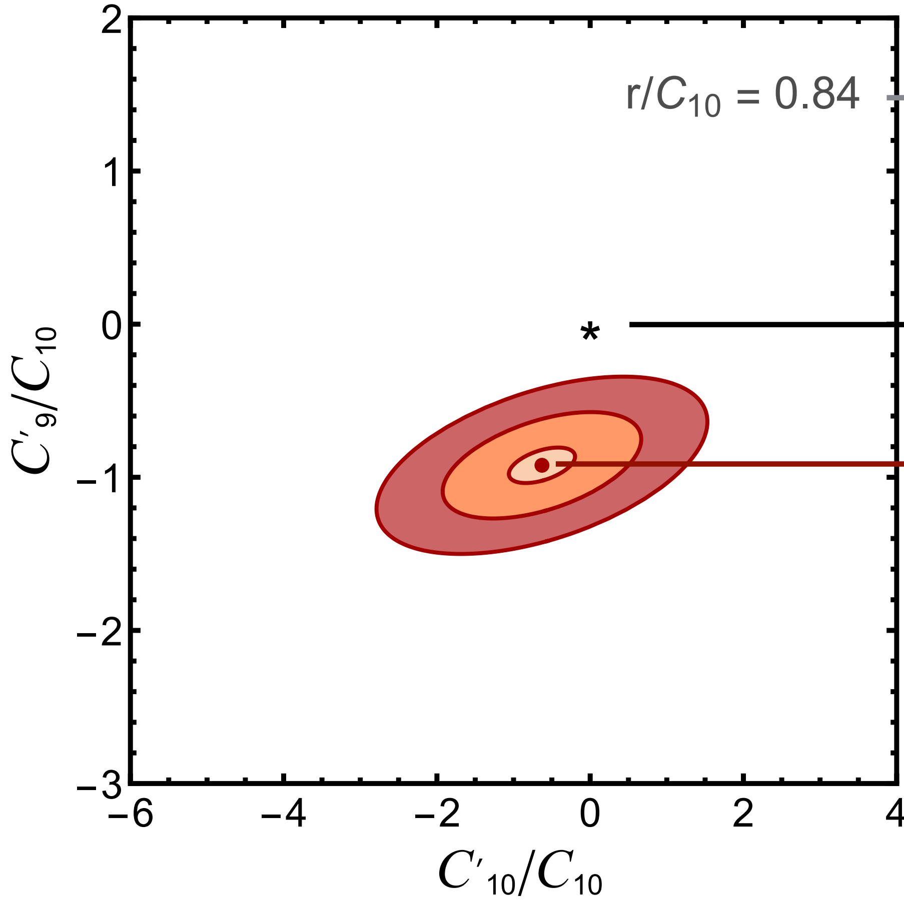

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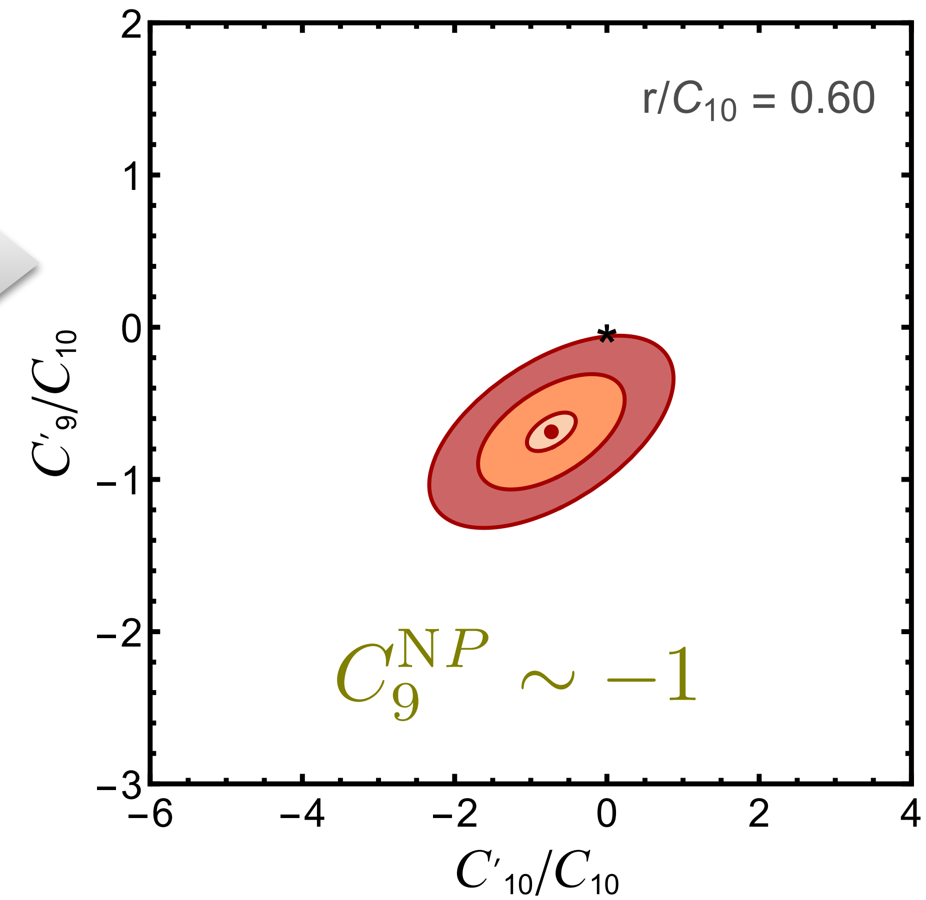
reduced significance of deviation for lowered r/C_{10} value

Other kind of NP like Z' as hinted in global fits

[Altmannshofer, Straub '14]



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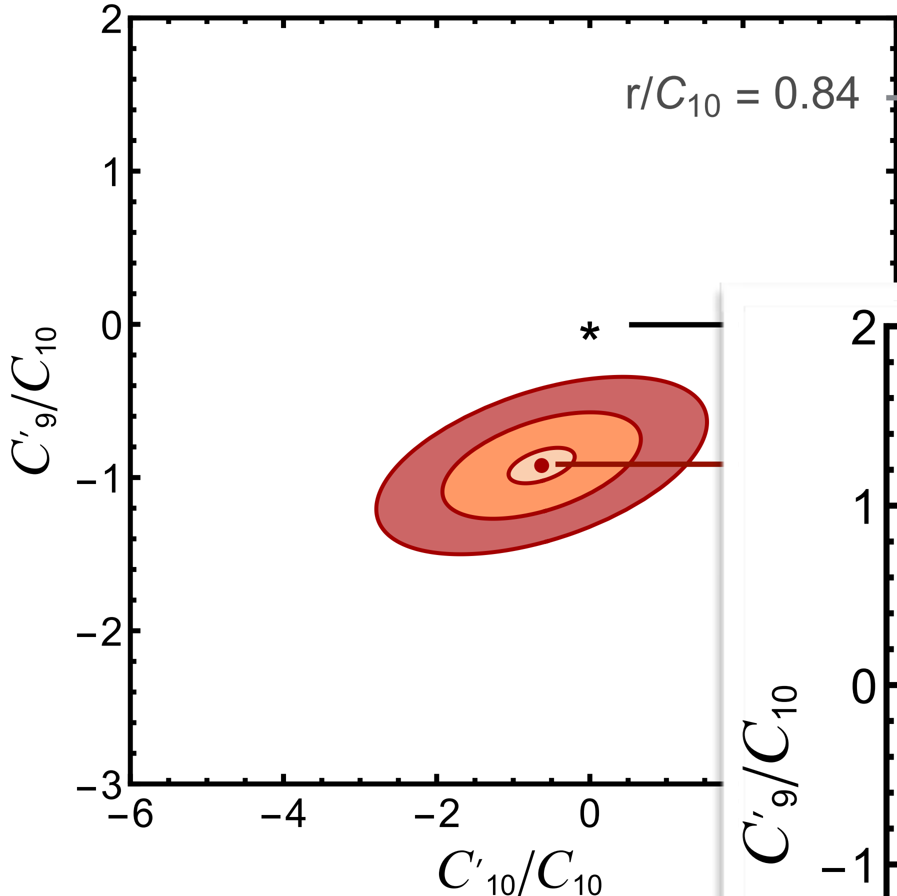

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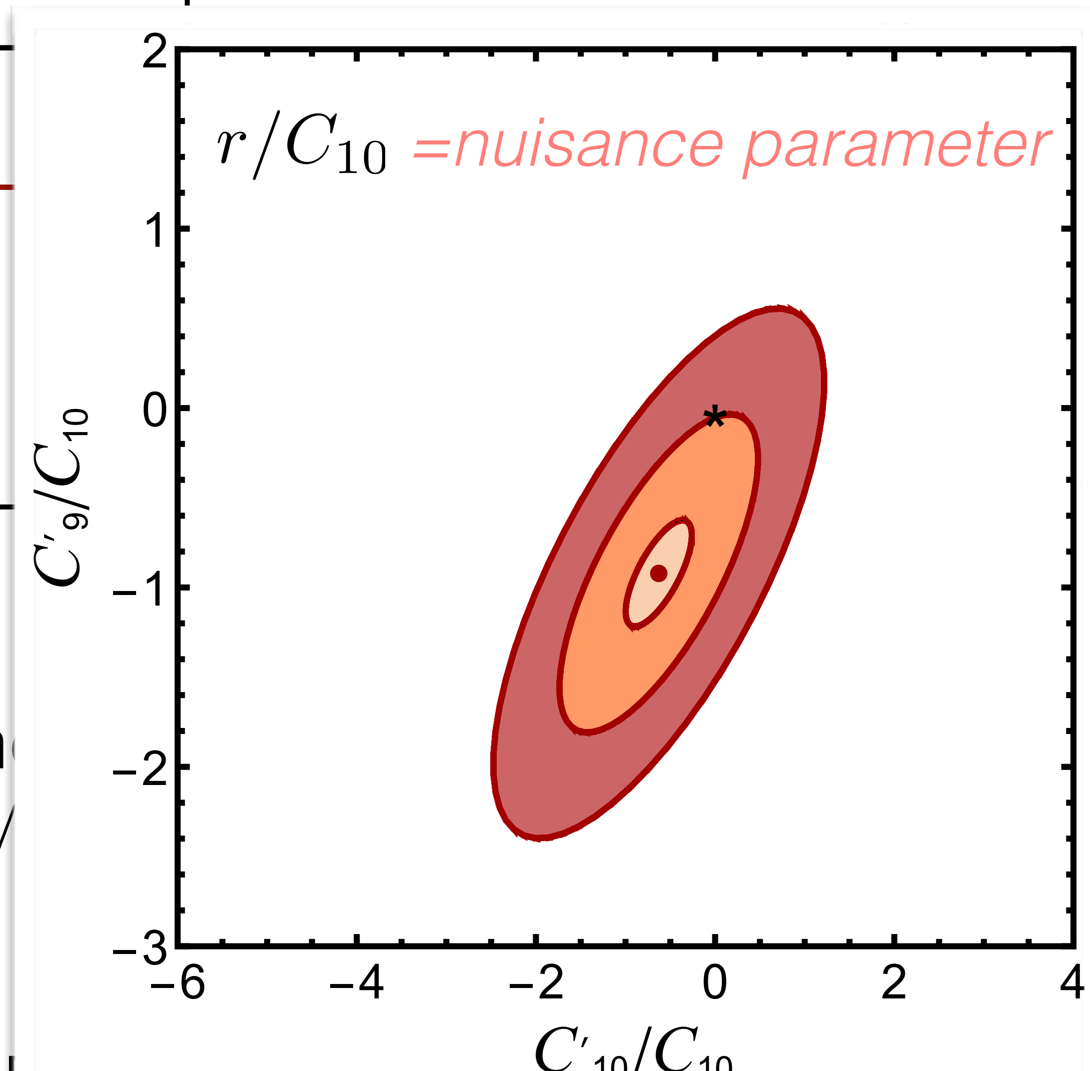
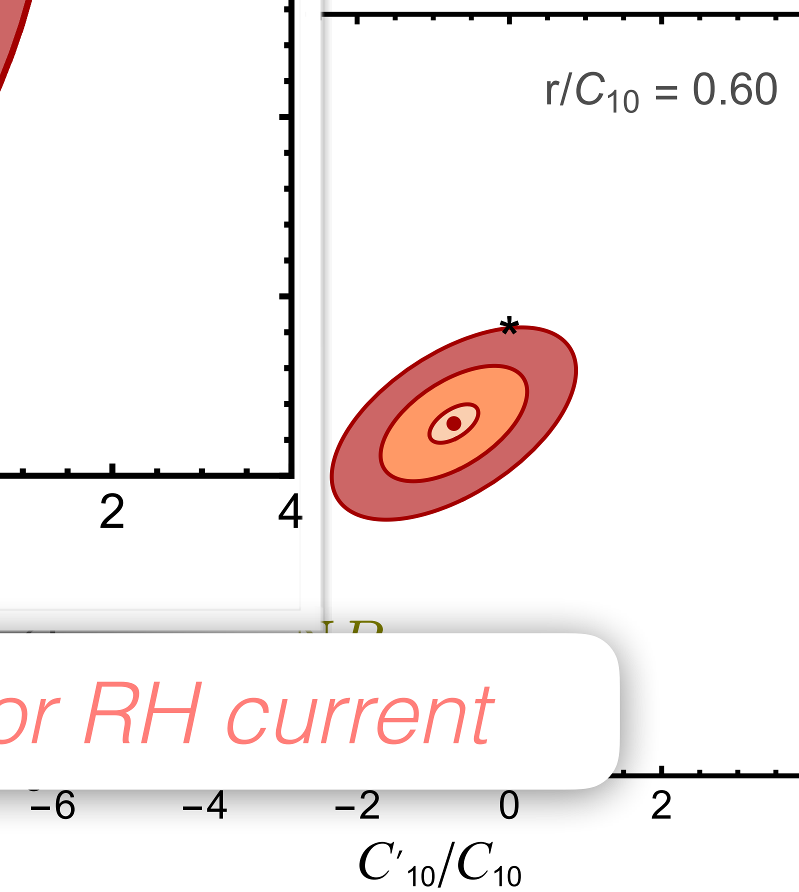


0.43

0.10



reduced significan
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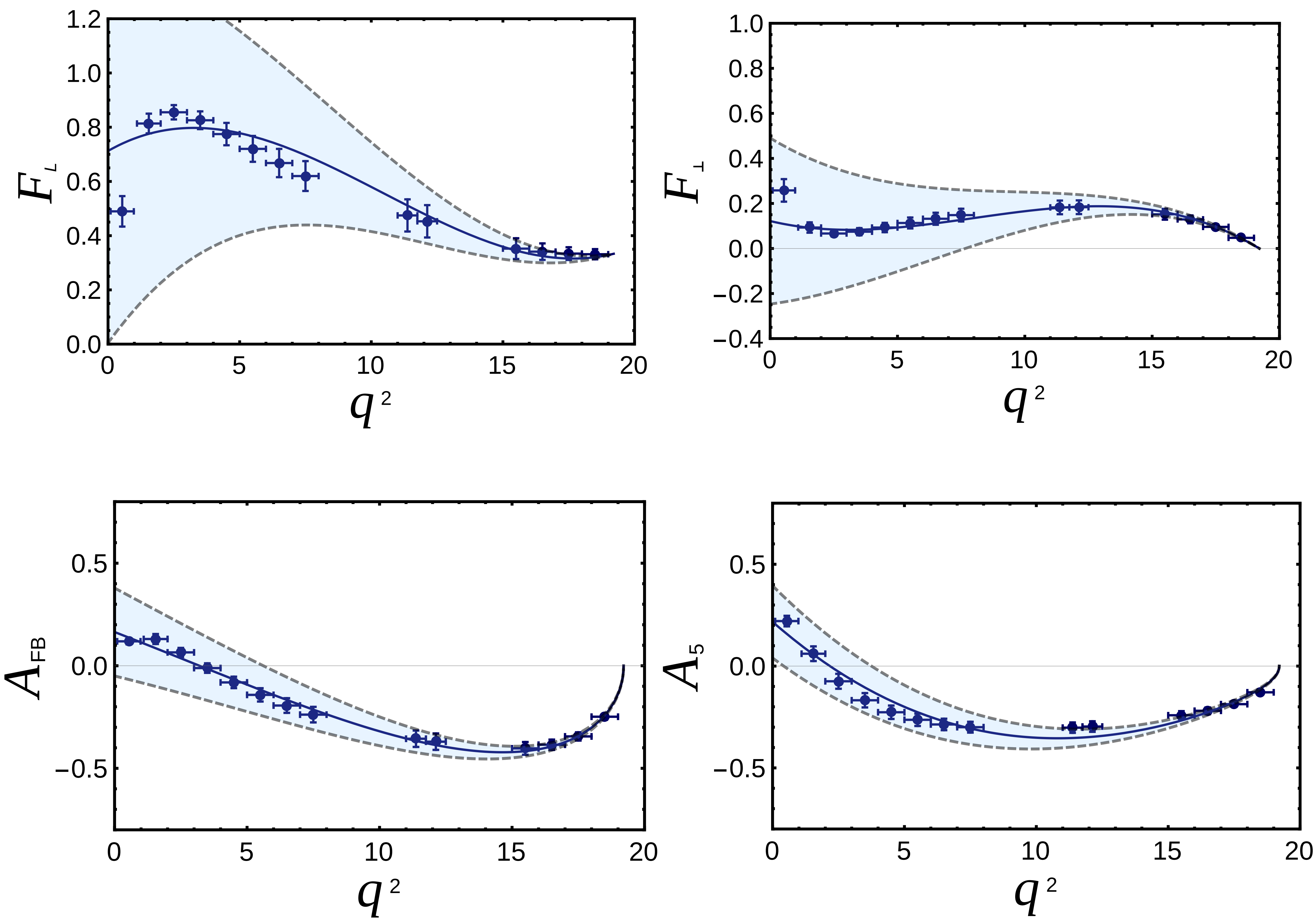
Other kind of NP
as hinte

Minimal significance for RH current

[Altmannshofer, Straub '14]

Fit to form factor observables



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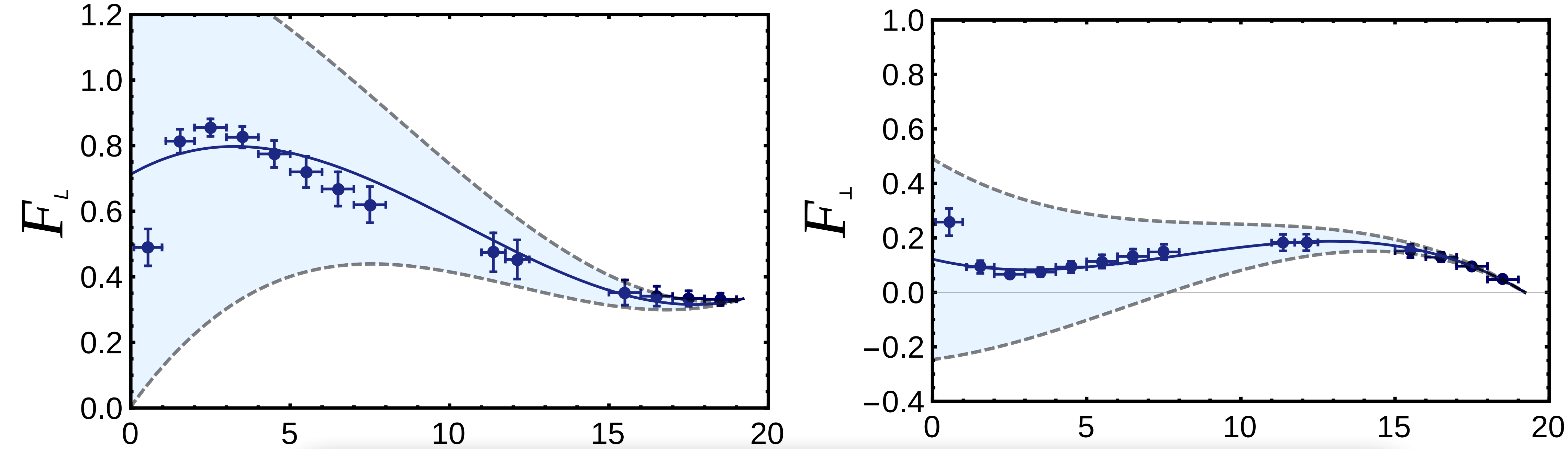
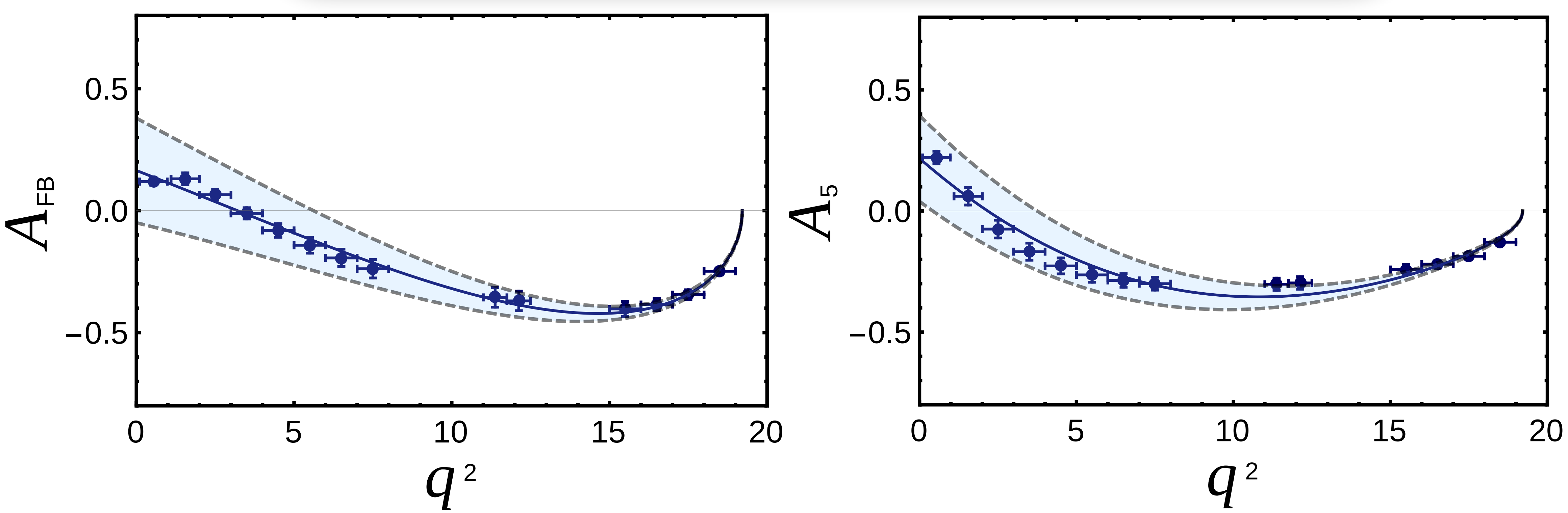
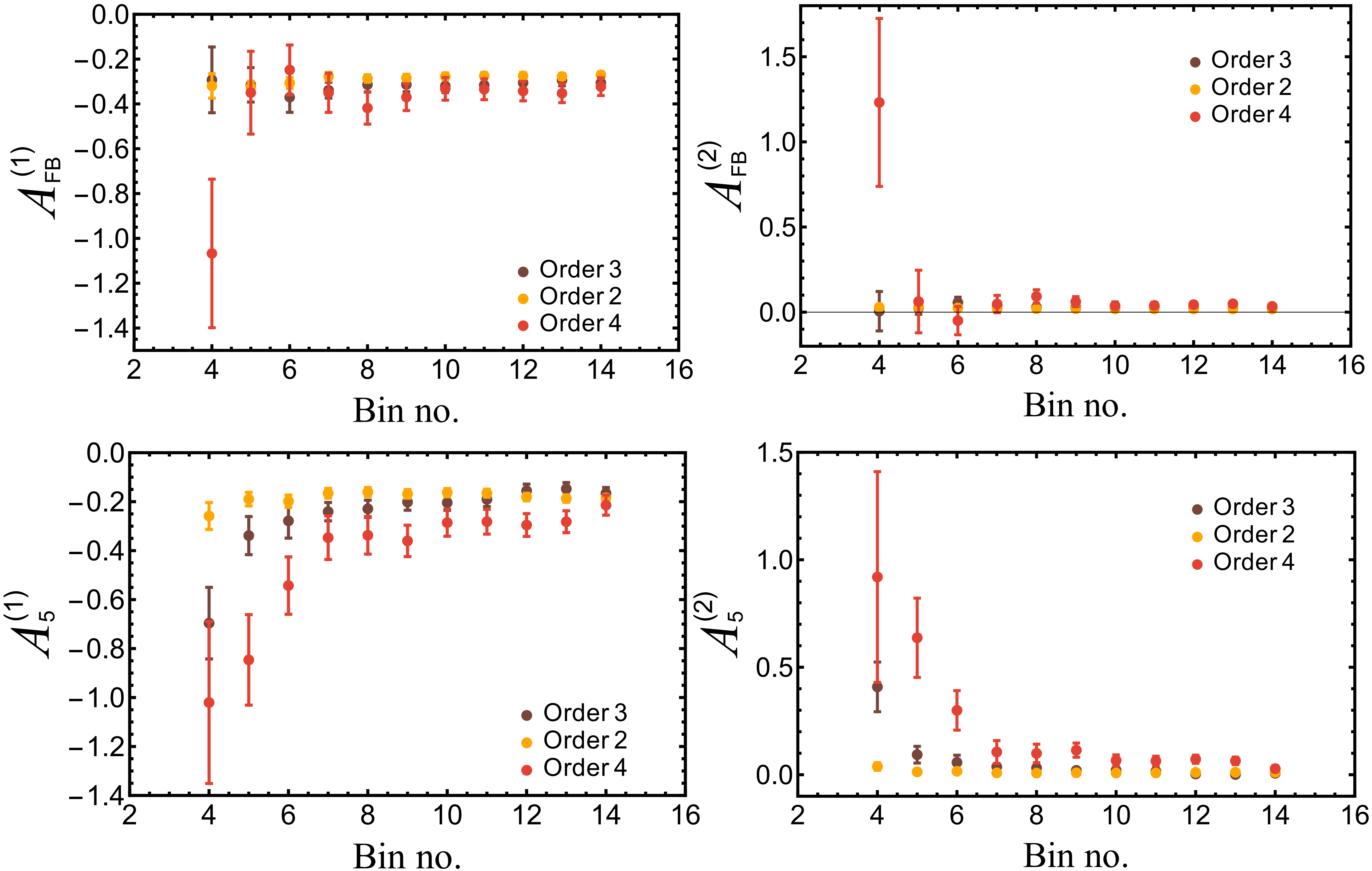


nicely explained by 3rd order polynomial



Convergence of coefficients



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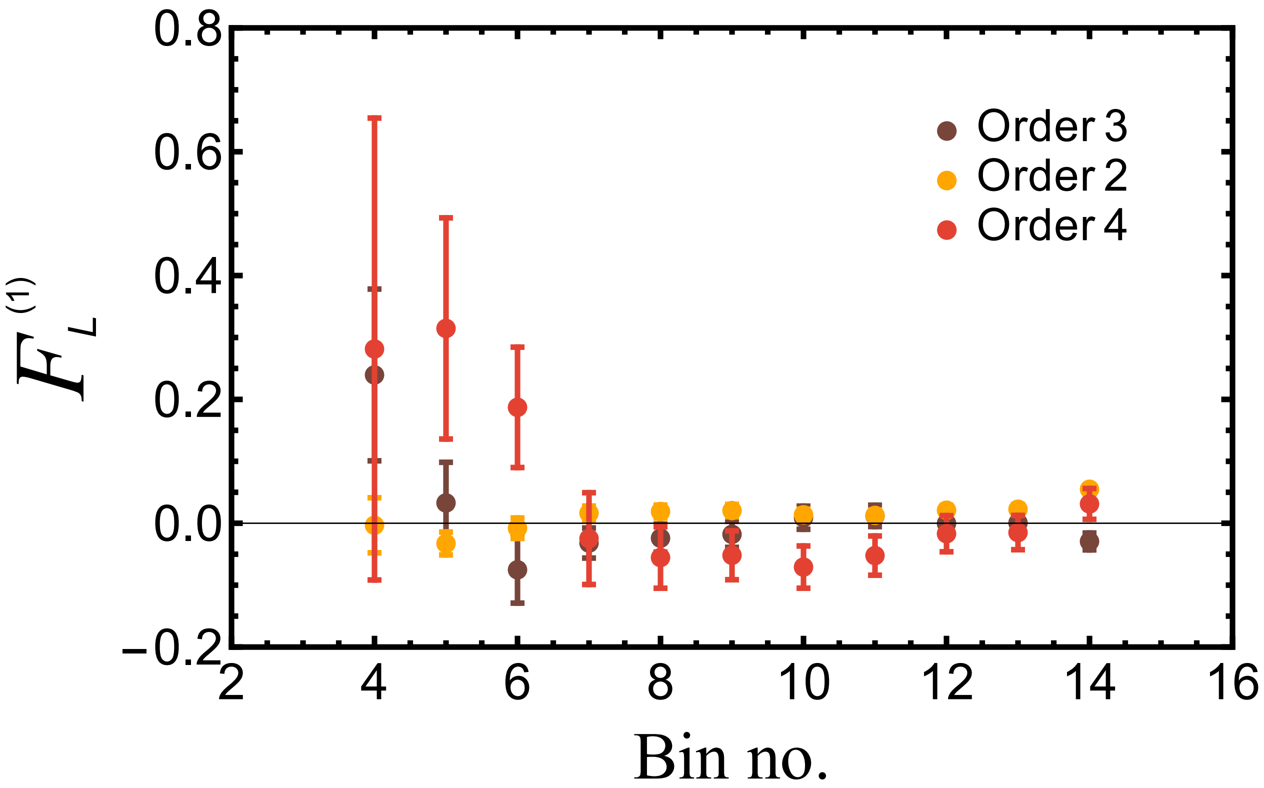
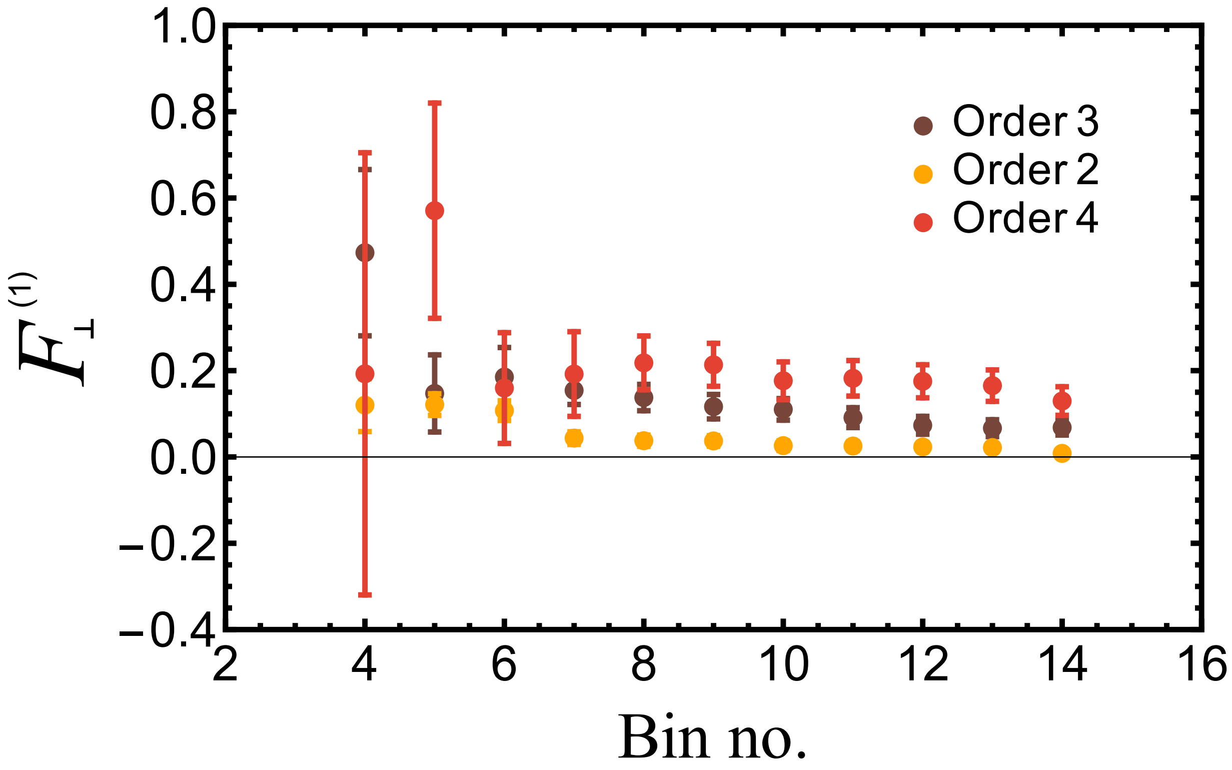


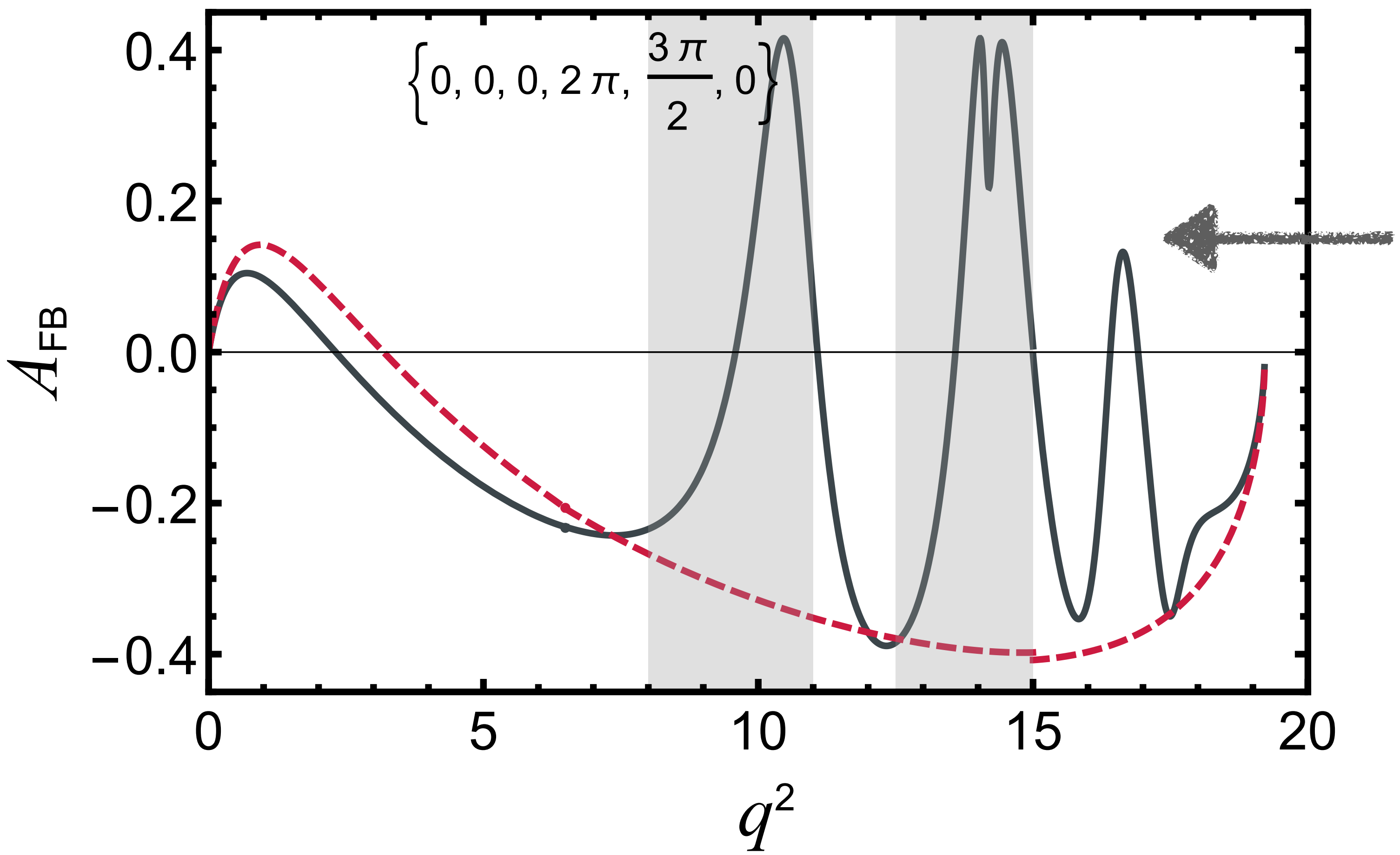


Shows a good convergence with variation in polynomial order & no. of bins used for the data fit

Resonances

$c\bar{c}$ bound states added: J/ψ, $\psi(2S)$, $\psi(3770)$, $\psi(4040)$, $\psi(4160)$, $\psi(4415)$.

Observable $=$ Form-factors $+$ Kruger & Sehgal parametrization



Asymmetries decrease in high q^2 region

makes observable ω_1 unphysical

Random variation of each strong phases

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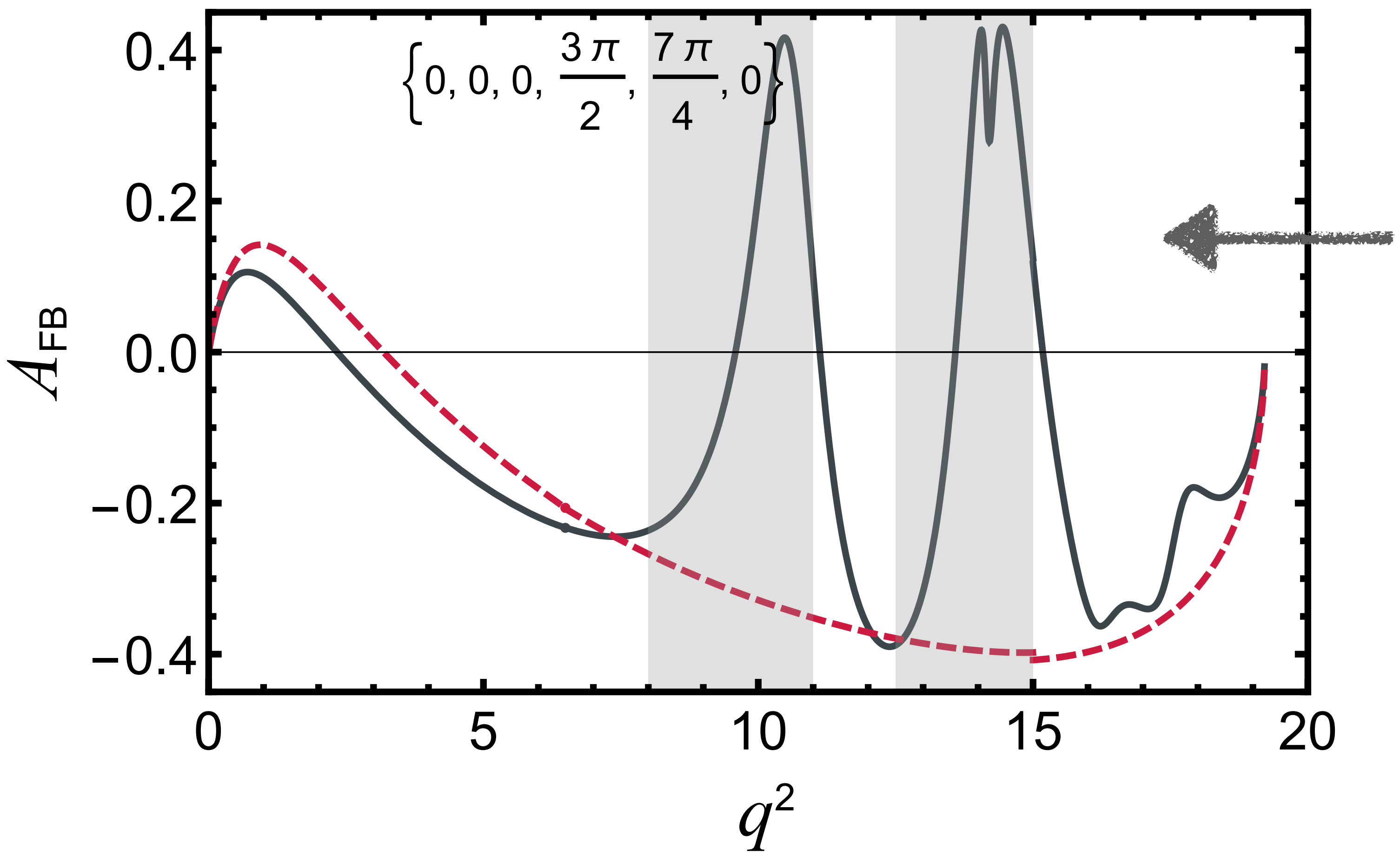

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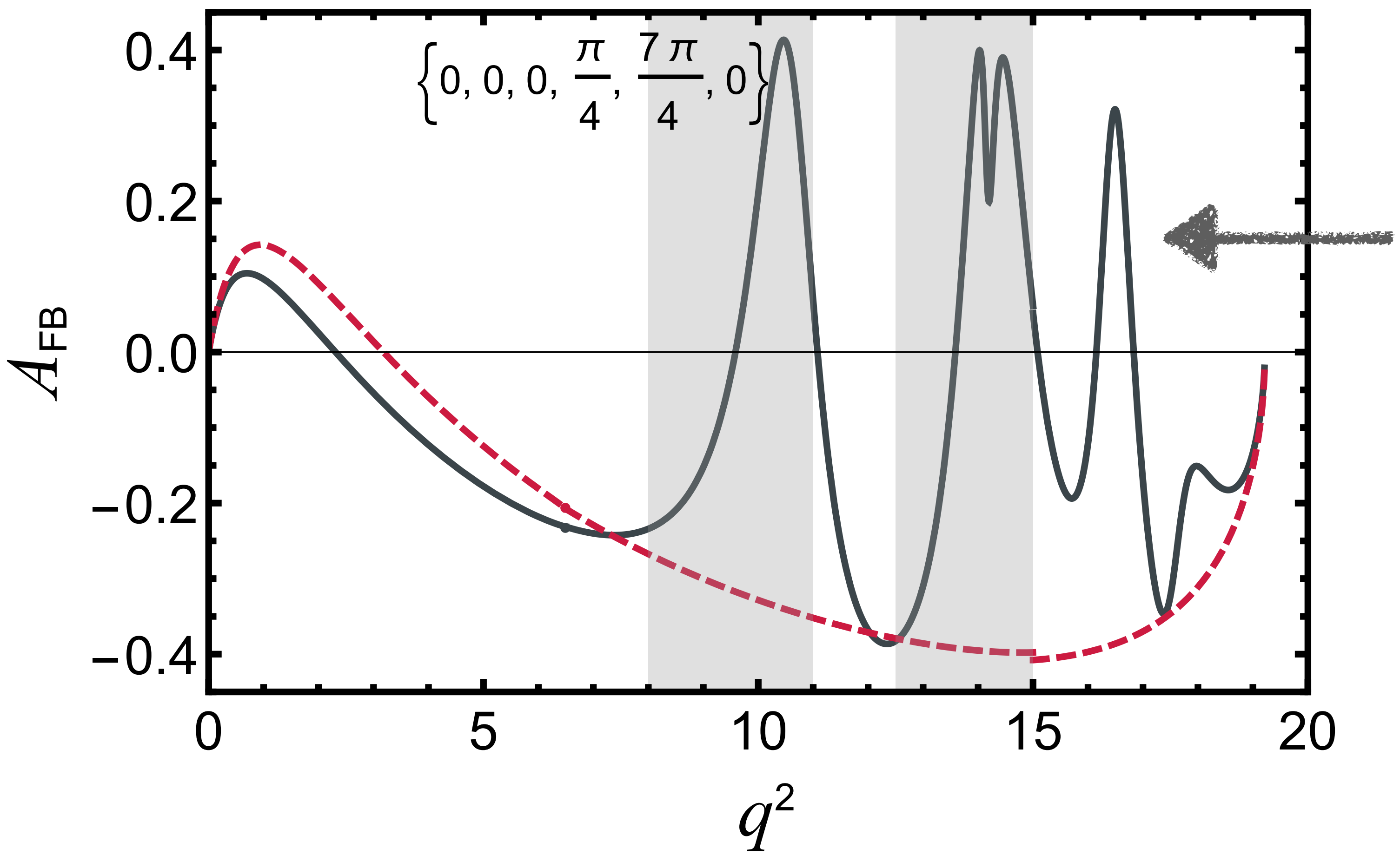

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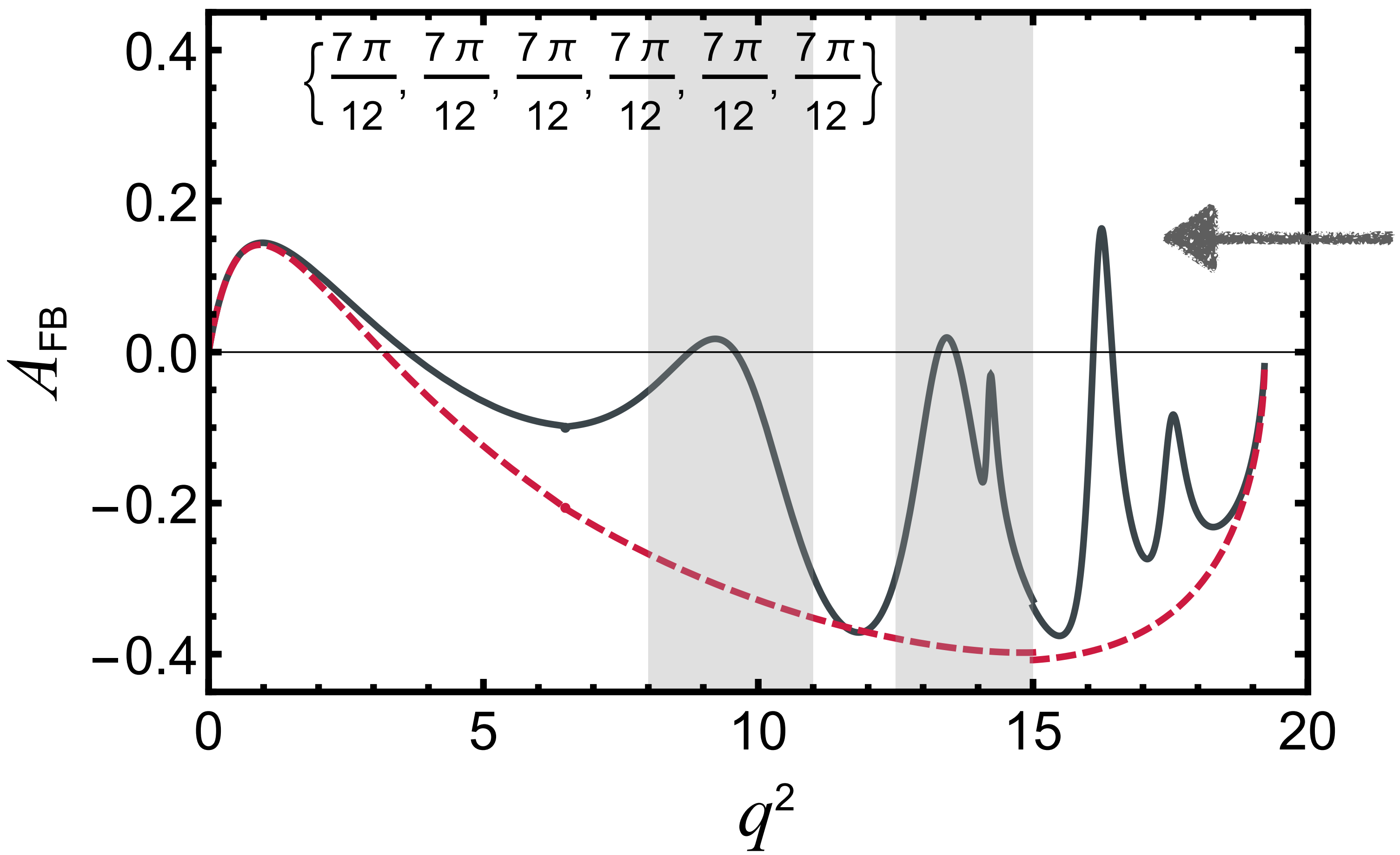

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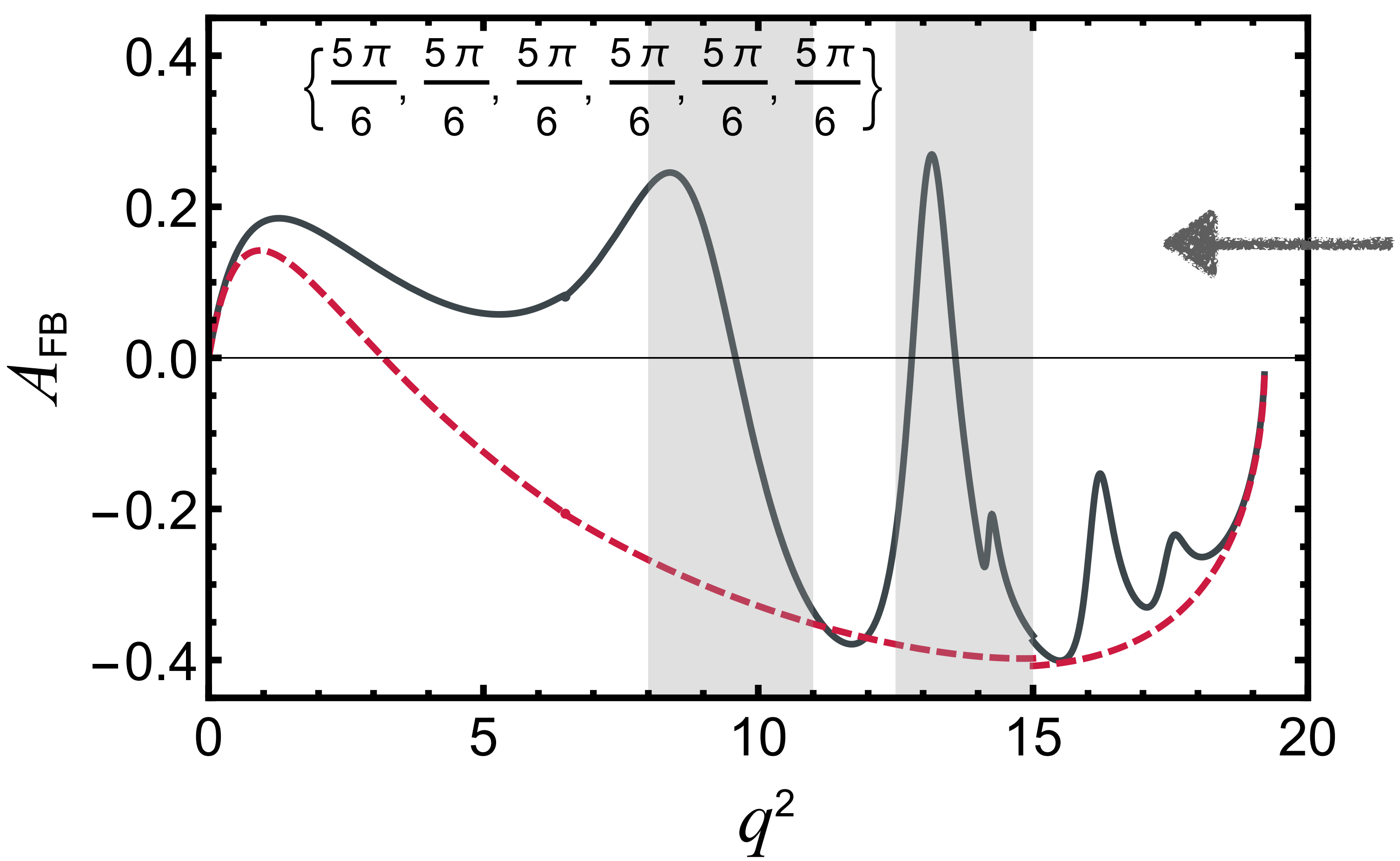

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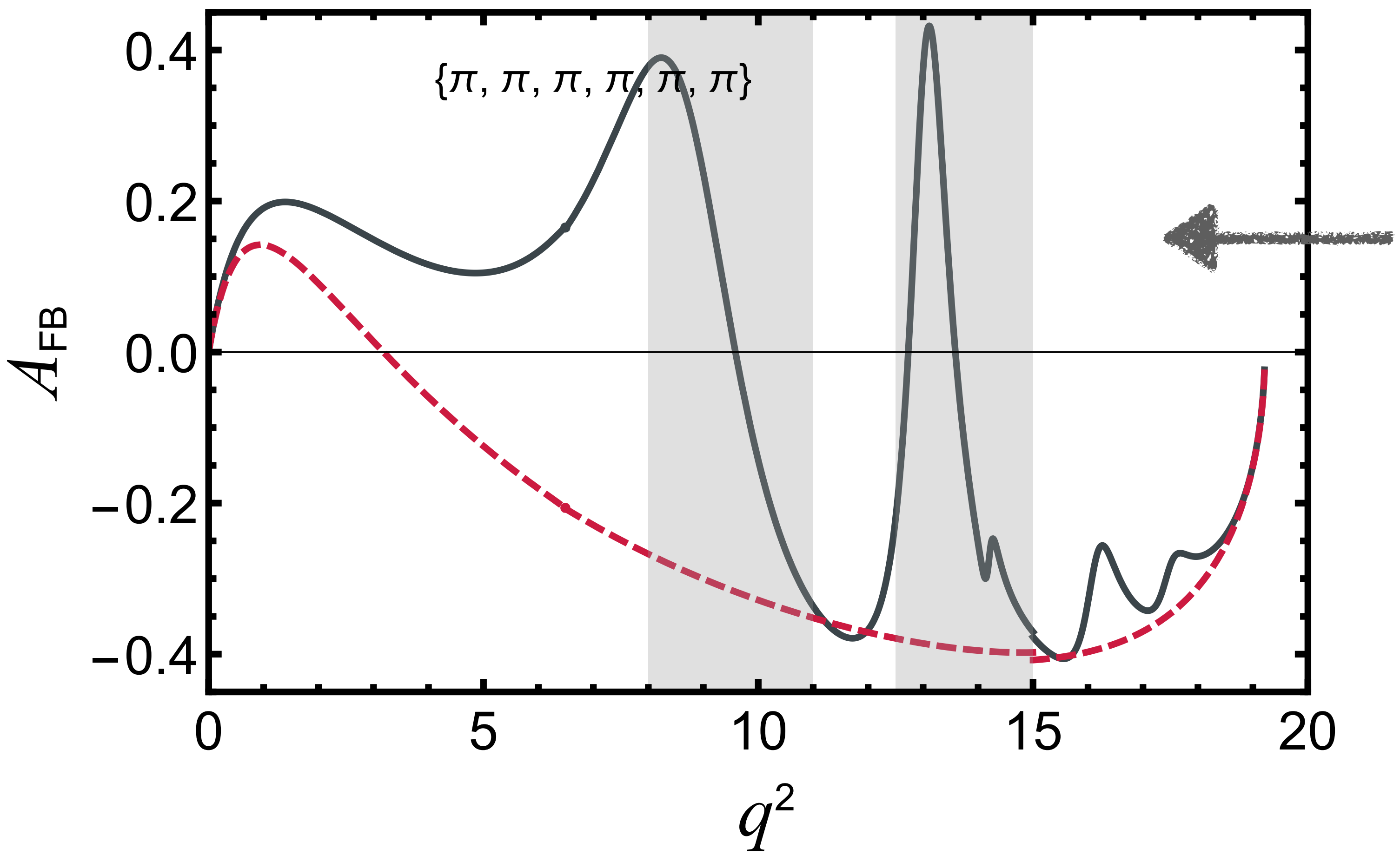

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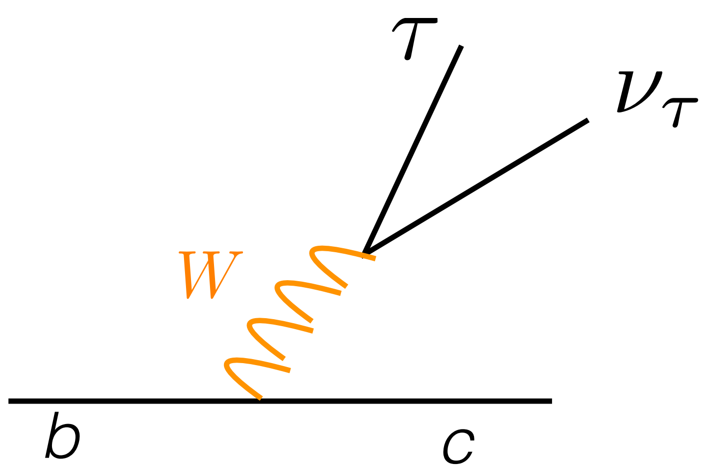
Random variation of each strong phases

Lepton non-universality

- Exciting discrepancies observed in charged current B decays



$$\mathcal{H}^{\text{eff}} = \frac{4G_F}{\sqrt{2}} V_{cb} \left(1 + C^{\text{NP}}\right) \, (\bar{c}_L \gamma_\mu b_L)(\bar{\tau}_L \gamma^\mu \nu_{\tau L})$$

$$R(D^{(*)}) \equiv \frac{\text{BR}(B \to D^{(*)} \tau\nu)}{\text{BR}(B \to D^{(*)} \ell\nu)} \,, \quad \ell \in \{e, \mu\}$$

$$R(D) = (1.34 \pm 0.17\,) \times R(D)_{\text{SM}}, \quad R(D^*) = (1.23 \pm 0.07\,) \times R(D^*)_{\text{SM}}$$

2.2σ $\qquad$ 3.3σ

combined deviation $\sim 4\sigma$

Lepton non-universality

- Discrepancies in neutral current B decays also

$$R_{K^{(*)}} \equiv \frac{\text{BR}(B \to K^{(*)}\mu\mu)}{\text{BR}(B \to K^{(*)}ee)}$$

$$R_K = 0.745^{+0.090}_{-0.074} \pm 0.036 \qquad q^2 \in [1:6]\,\text{GeV}^2 \longrightarrow 2.6\sigma$$

$$R_{K^*}^{\text{low}} = 0.660^{+0.110}_{-0.070} \pm 0.024 \qquad q^2 \in [0.045:1.1]\,\text{GeV}^2 \longrightarrow 2.1\sigma$$

$$R_{K^*}^{\text{cntr}} = 0.685^{+0.113}_{-0.069} \pm 0.047 \qquad q^2 \in [1.1:6]\,\text{GeV}^2 \longrightarrow 2.4\sigma$$

$$\Phi \equiv d\,\text{BR}(B_s \to \phi\mu\mu)/dq^2\Big|_{q^2\in[1:6]\,\text{GeV}^2}$$

$$= \left(2.58^{+0.33}_{-0.31} \pm 0.08 \pm 0.19\right) \times 10^{-8}\ \text{GeV}^{-2} \quad \text{(exp)}$$

$$= (4.81 \pm 0.56) \times 10^{-8}\ \text{GeV}^{-2} \quad \text{(SM)}$$

3σ

Lepton non-universality

- Constraints from other modes

$$\mathrm{BR}(B_s \to \mu\mu) = \begin{array}{l} (3.0 \pm 0.6^{+0.3}_{-0.2}) \times 10^{-9} \quad (\mathrm{exp.}) \\ (3.65 \pm 0.23) \times 10^{-9} \quad (\mathrm{SM}) \end{array}$$

well in agreement

$$\mathrm{BR}(B \to K^{(*)}\nu\bar{\nu}) < 1.6\,(2.7) \times 10^{-5}$$

$$\mathrm{BR}(B^+ \to K^+\mu^\pm\tau^\mp) < 4.5\,(2.8) \times 10^{-5}$$

$$\mathrm{BR}(B_s \to \tau\tau) < 6.8 \times 10^{-3}$$

Quite challenging to explain all anomalies together by evading all the bounds.

Lepton non-universality

- NP operators with 2nd & 3rd generation fields

$$\mathcal{H}^{\rm NP} = A_1\,(\bar{Q}_{2L}\gamma_\mu L_{3L})\,(\bar{L}_{3L}\gamma^\mu Q_{3L}) + A_2\,(\bar{Q}_{2L}\gamma_\mu Q_{3L})\,(\bar{\tau}_R\gamma^\mu \tau_R)$$

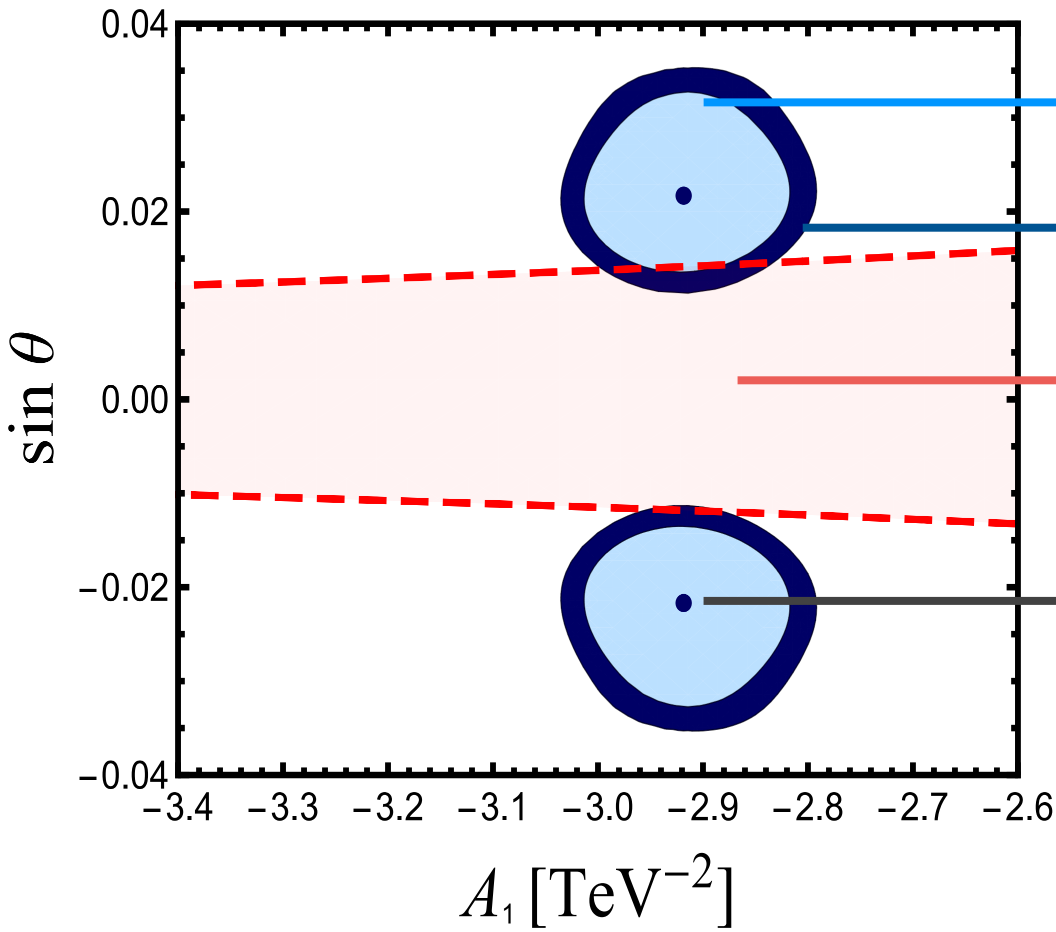
- Directly contributes to $R(D^{(*)})$

- Diagonalisation of Hamiltonian for lepton part through small mixing angle θ : interaction basis → mass basis

$$\tau = \cos\theta\,\tau' + \sin\theta\,\mu'$$

Contribution to $b \to s\mu\mu$ is generated

Lepton non-universality



95% C.L.

99% C.L.

Allowed by $B^+ \to K^+ \mu^- \tau^+$

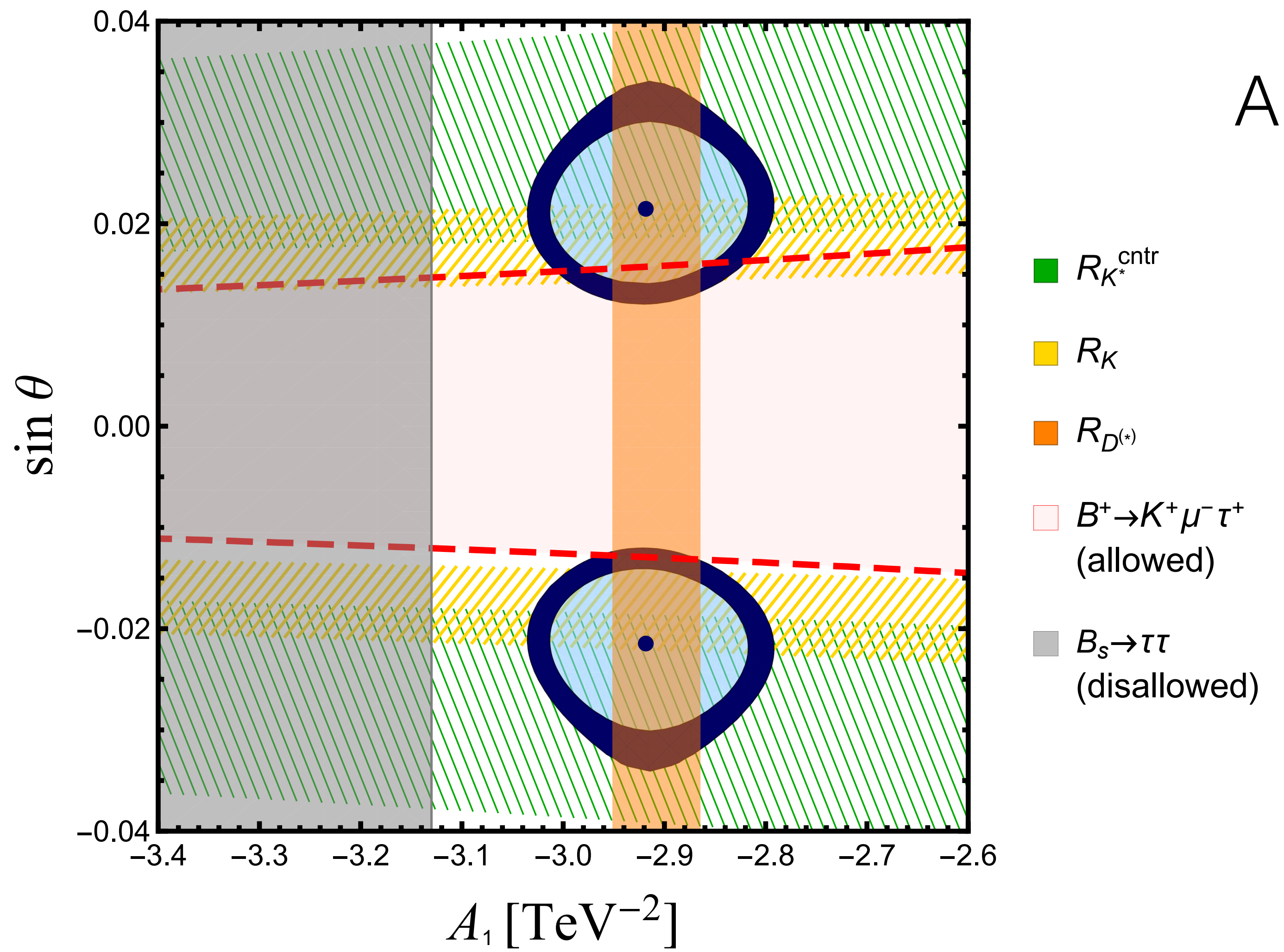
$$A_1 (= A_2) = -2.92\,\mathrm{TeV}^{-2}$$
$$\sin\theta = \pm 0.022$$

$\chi^2_{\rm SM} \simeq 46$ → $\chi^2_{\rm allowed\ region} \simeq 15$

✓ agreement within 2σ level

$$R_K \simeq 0.86,\ \ R_{K^*}{}^{\rm cntr} \simeq 0.88,\ \ R_{K^*}^{\rm low} \simeq 0.90,$$
$$R_{D^{(*)}} \simeq 1.25,\ \ \Phi \simeq 4.1 \times 10^{-8}\mathrm{GeV}^{-2}.$$

Lepton non-universality



Allowing 20% breaking

$$A_2 = 4A_1/5$$

from quantum corrections or unknown dynamics of the UV completion of the model

$$\chi^2_{\rm SM} \simeq 46 \quad \Rightarrow \quad \chi^2_{\rm allowed\ region} \simeq 10$$

$$R_K \simeq 0.80,\ \ R_{K^*}{}^{\rm cntr} \simeq 0.83,\ \ R_{K^*}^{\rm low} \simeq 0.88,$$

$$R_{D^{(*)}} \simeq 1.24,\ \ \Phi \simeq 3.8 \times 10^{-8} {\rm GeV}^{-2}.$$

agreement within 1σ level

Summary

Popular approaches	Our approach
☑ Combine all $b \to s$ transitions	☑ Most general parametric form of SM amplitude
↓	$+$
many decay modes i.e observables	$B \to K^* \ell^+ \ell^-$ observables
$+$	$+$
more hadronic uncertainties	eliminate hadronic uncertainties
$+$	↓
conservative assumption of non-factorisable contributions	no/minimal dependency on form-factors & independent of non-factorisable contributions
☑ Focusing on low q^2 region	☑ Conclusion derived at endpoint

Summary

- ☑ Formalism developed to include all possible effects within SM

- ☑ Strong evidence of RH currents derived at endpoint limit —
  - systematics studied by varying polynomial order & bin no.
  - finite K^* width effect is considered
  - resonance effects increase the deviation

Summary

- Several hints of lepton non universality are observed by various experimental groups

- In terms of effective operators we show a possible explanation to all the anomalies together

    - The model has only two new parameters
    - It predicts some interesting signatures both in the context of B decays as well as high-energy collisions

- Opens up way to construct UV complete theory

- Fluctuation? Wait for more data to be accumulated!

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