Searching new physics in B decays

Rusa Mandal
IFIC, Universitat de Valencia-CSIC

On Phys. Rev. D 95, 114006 (2017),
Phys. Rev. Lett. 119, 151801 (2017)

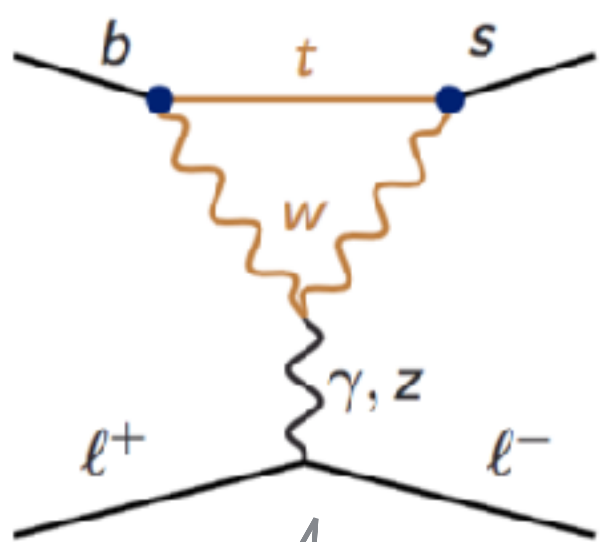
June 27, 2018

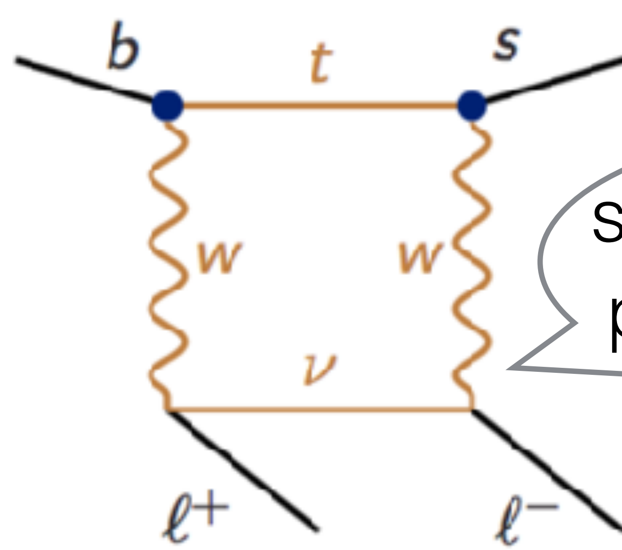
Outline

- 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





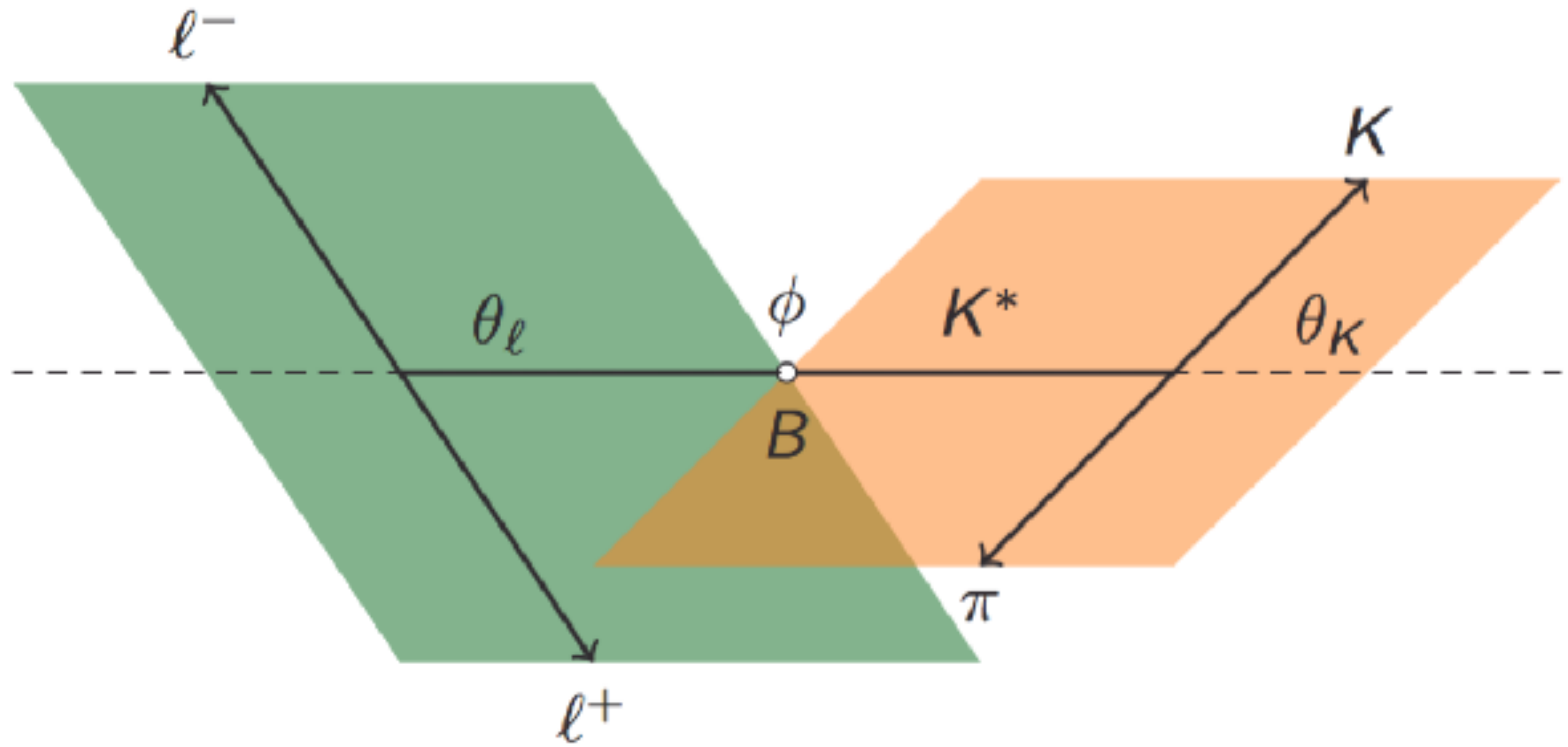
sensitive to new particle in loop

large no. of experimentally accessible observables

valuable probe for indirect search of NP

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

Motivation

- $I_i =$ short distance + long distance

Wilson coefficients:
perturbatively calculable

Motivation

- $I_i =$ short distance + long distance

Wilson coefficients:
perturbatively calculable

Form-factors:
non-perturbative estimates
from LCSR, HQET, Lattice …
tremendous effort since past

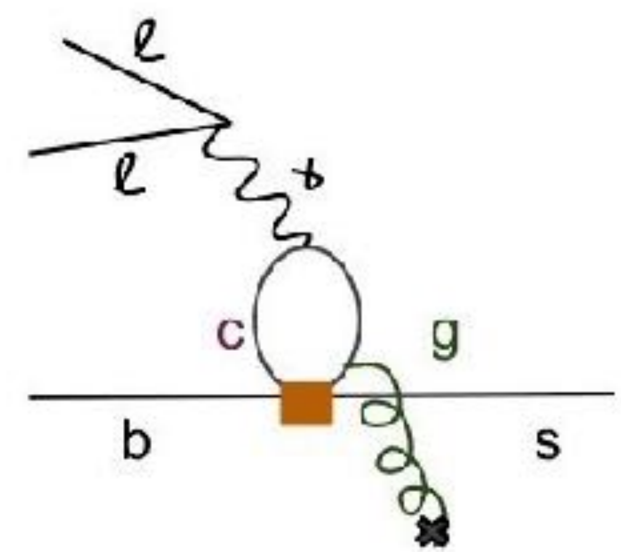
Motivation

- $I_i =$ short distance + long distance

Wilson coefficients:
perturbatively calculable

Form-factors:
non-perturbative estimates
from LCSR, HQET, Lattice …
tremendous effort since past

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]

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

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

Model Independent Framework

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

$$
= \frac{G_F \alpha}{\sqrt{2}\pi} V_{tb} V_{ts}^* \Bigg[\Bigg\{ C_9 \langle K^* | \bar{s}\gamma^\mu P_L b | \bar{B} \rangle - \frac{2C_7}{q^2} \langle K^* | \bar{s} i \sigma^{\mu\nu} q_\nu (m_b P_R + m_s P_L) b | \bar{B} \rangle
- \frac{16\pi^2}{q^2} \sum_{i=\{1-6,8\}} C_i \mathcal{H}_i^\mu \Bigg\} \bar{\ell}\gamma_\mu \ell + C_{10} \langle K^* | \bar{s}\gamma^\mu P_L b | \bar{B} \rangle \bar{\ell}\gamma_\mu\gamma_5 \ell \Bigg]
$$

Wilson coefficients

Model Independent Framework

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

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

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

Wilson coefficients

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

Model Independent Framework

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

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

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

Wilson coefficients

non-local operator
for non factorization contributions

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

$$\mathcal{H}_i^\mu \sim \left\langle K^*|i\int d^4x\, e^{iq\cdot x}T\{j^\mu_{em}(x), \mathcal{O}_i(0)\}|\bar{B}\right\rangle \Rightarrow$$ parametrize with 'new' form-factors $\mathcal{Z}_j^i$

[Khodjamirian *et. al* '10]

Model Independent Framework

- Absorbing factorizable & non-factorizable contributions into

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

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

Model Independent Framework

- Absorbing factorizable & non-factorizable contributions into

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

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

- Most general parametric form of amplitude in SM

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

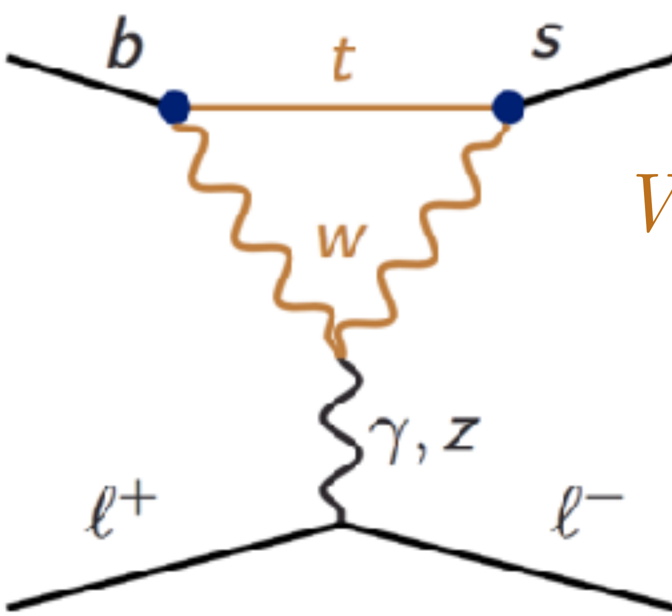
Form-factors: $\mathcal{F}_\lambda \equiv \mathcal{F}_\lambda(\mathcal{X}_j)$ and $\widetilde{\mathcal{G}}_\lambda \equiv \widetilde{\mathcal{G}}_\lambda(\widetilde{\mathcal{Y}}_j)$

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..

Rusa Mandal, IFIC

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

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

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

$\Rightarrow$ $\boxed{R_0 = R_\| \neq R_\perp}$ *in presence of RH currents*

RH Current

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

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

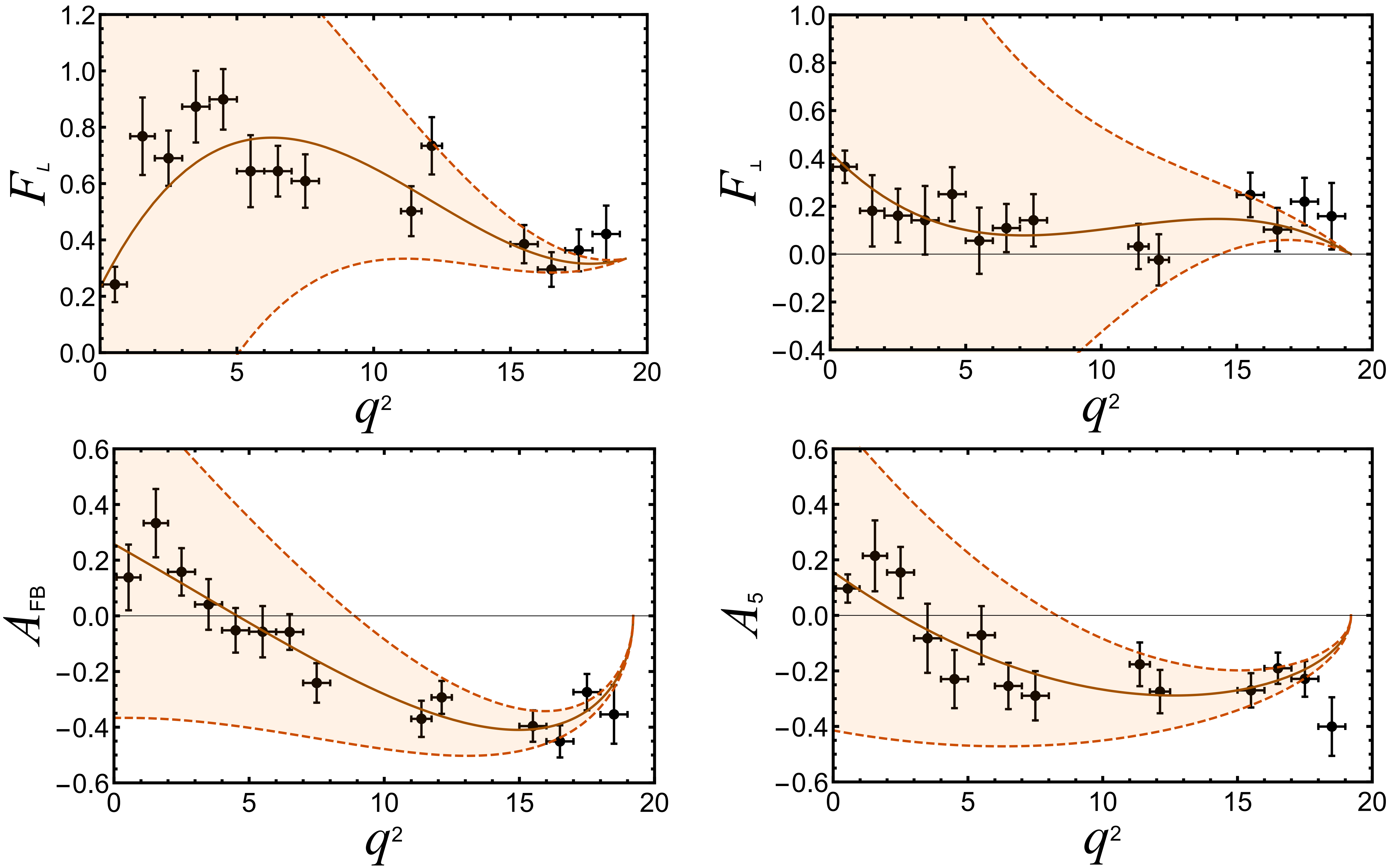
$$F_{\perp}(q^2_{\rm max}) = 0,\; A_{\rm FB}(q^2_{\rm max}) = 0,\; A_{5,7,8,9}(q^2_{\rm max}) = 0.$$

[Hiller, Zwicky '14]

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

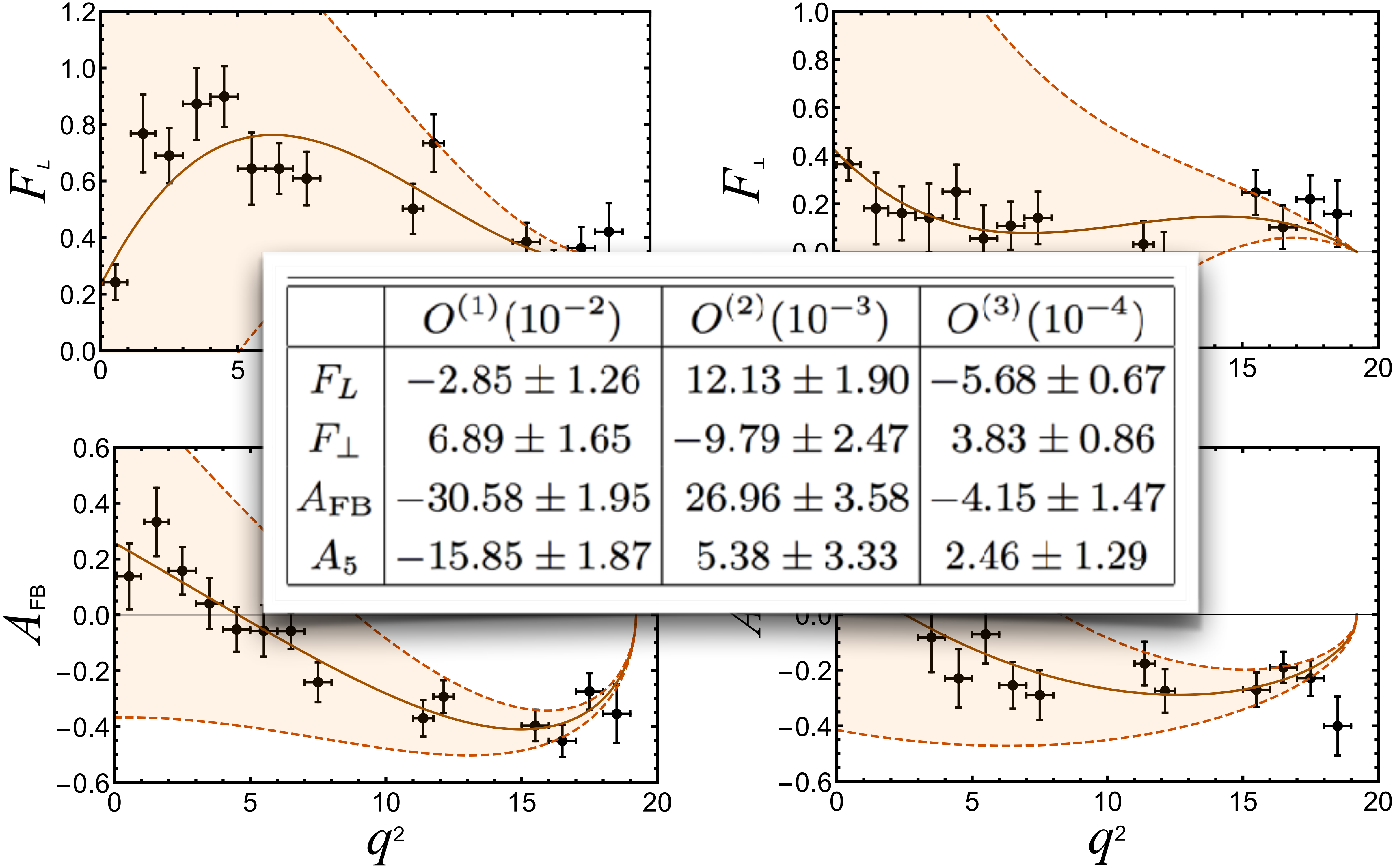
$$\begin{aligned}
F_L &= \frac{1}{3} + F_L^{(1)}\delta + F_L^{(2)}\delta^2 + F_L^{(3)}\delta^3 \\
F_{\perp} &= F_{\perp}^{(1)}\delta + F_{\perp}^{(2)}\delta^2 + F_{\perp}^{(3)}\delta^3 \\
A_{\rm FB} &= A_{\rm FB}^{(1)}\delta^{\frac{1}{2}} + A_{\rm FB}^{(2)}\delta^{\frac{3}{2}} + A_{\rm FB}^{(3)}\delta^{\frac{5}{2}} \\
A_5 &= A_5^{(1)}\delta^{\frac{1}{2}} + A_5^{(2)}\delta^{\frac{3}{2}} + A_5^{(3)}\delta^{\frac{5}{2}},
\end{aligned}$$

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

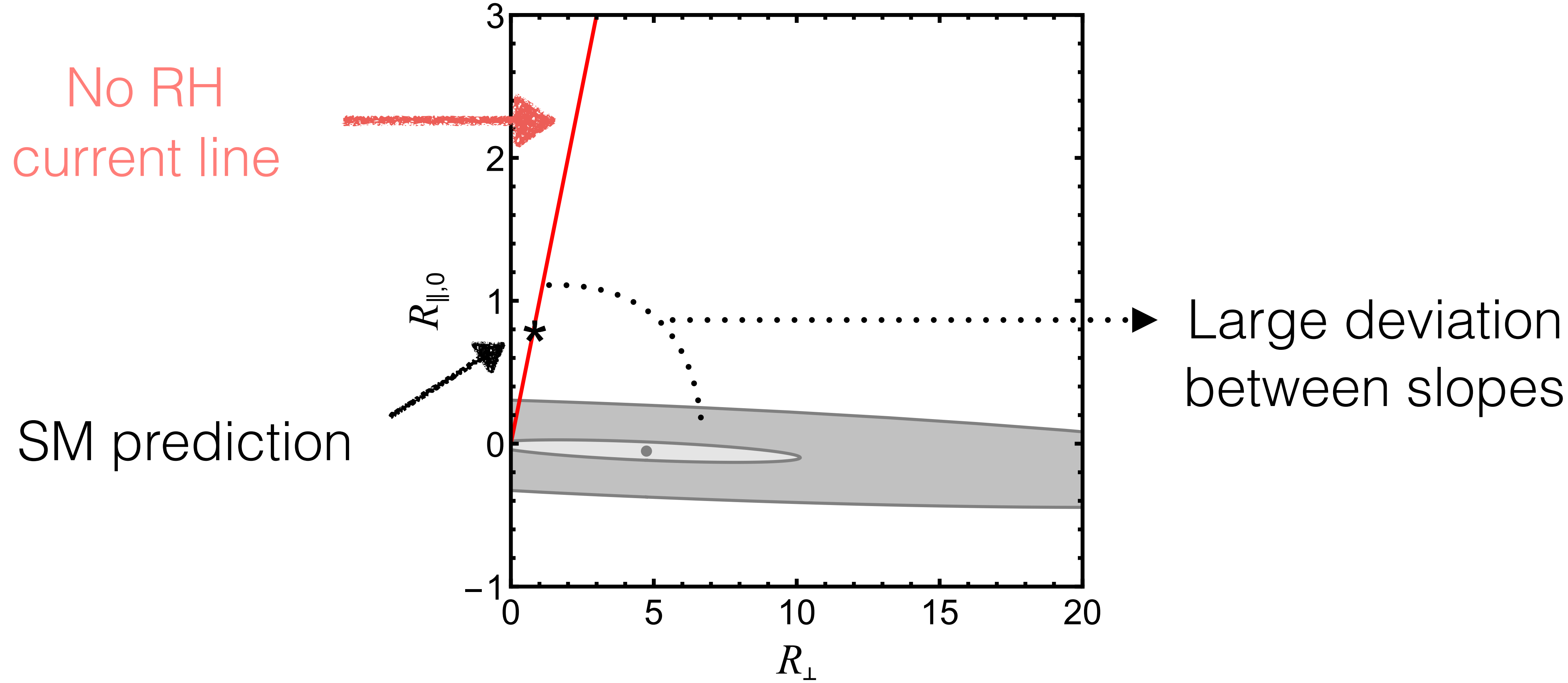
Fit to 14 bin LHCb data including correlation among observables

RH Current

- Limiting analytic expressions

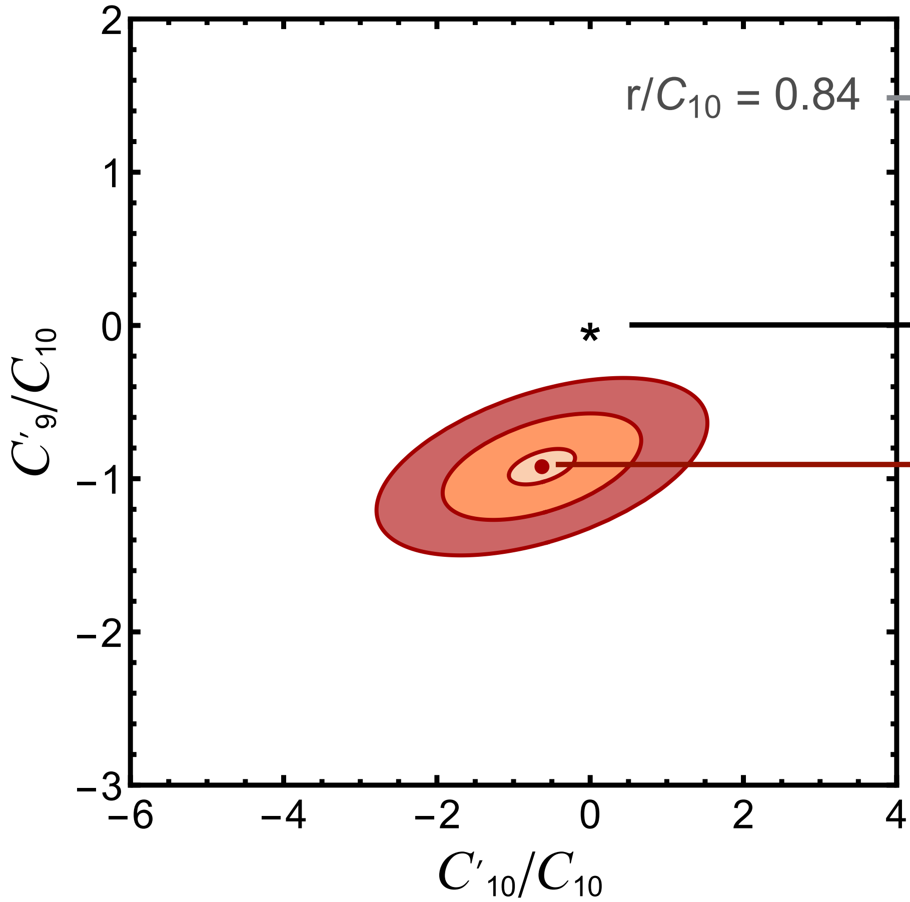
$$R_\perp(q^2_{\rm max}) = \frac{\omega_2 - \omega_1}{\omega_2\sqrt{\omega_1 - 1}}, \quad R_\parallel(q^2_{\rm max}) = \frac{\sqrt{\omega_1 - 1}}{\omega_2 - 1} = R_0(q^2_{\rm max})$$

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



Rusa Mandal, IFIC

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



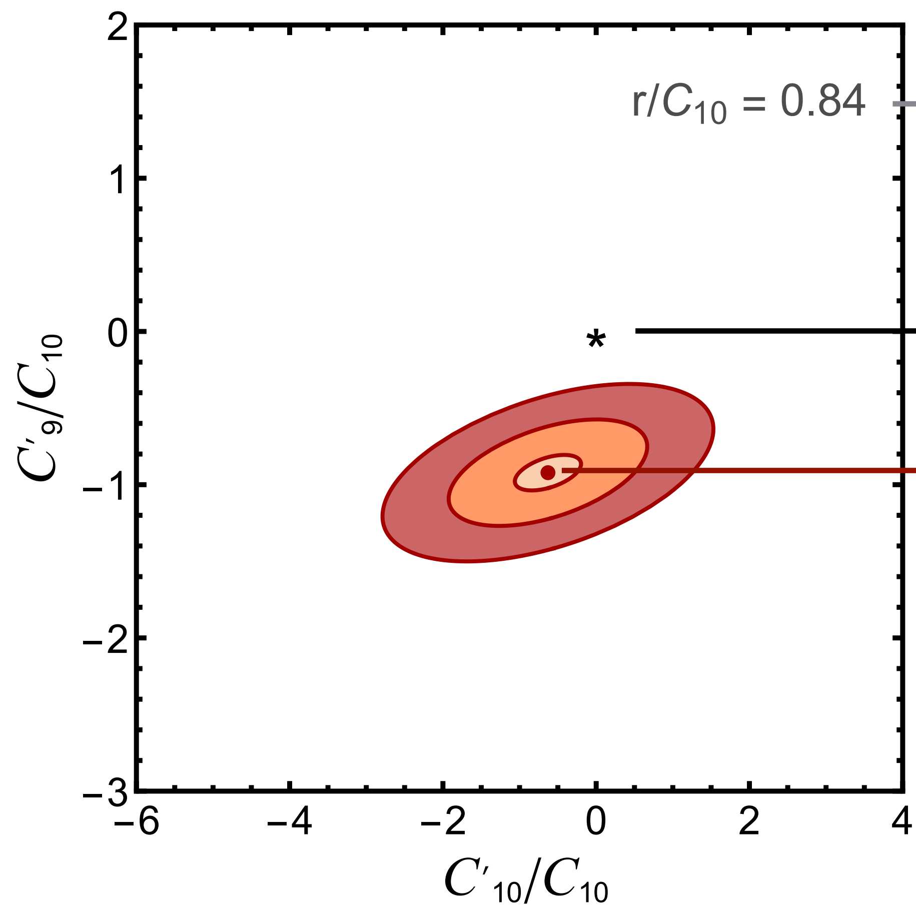
SM input

More than 5σ deviation

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

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

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



SM input

More than 5σ deviation

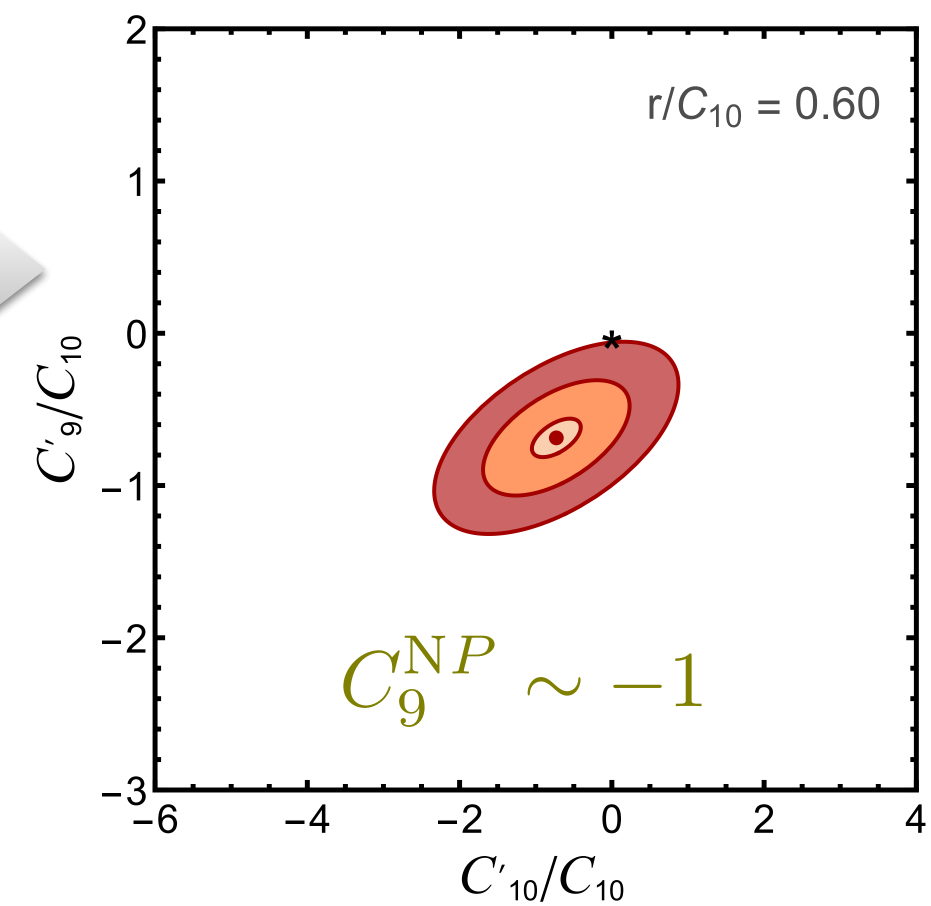
$$C'_{10}/C_{10} = -0.63 \pm 0.43$$

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

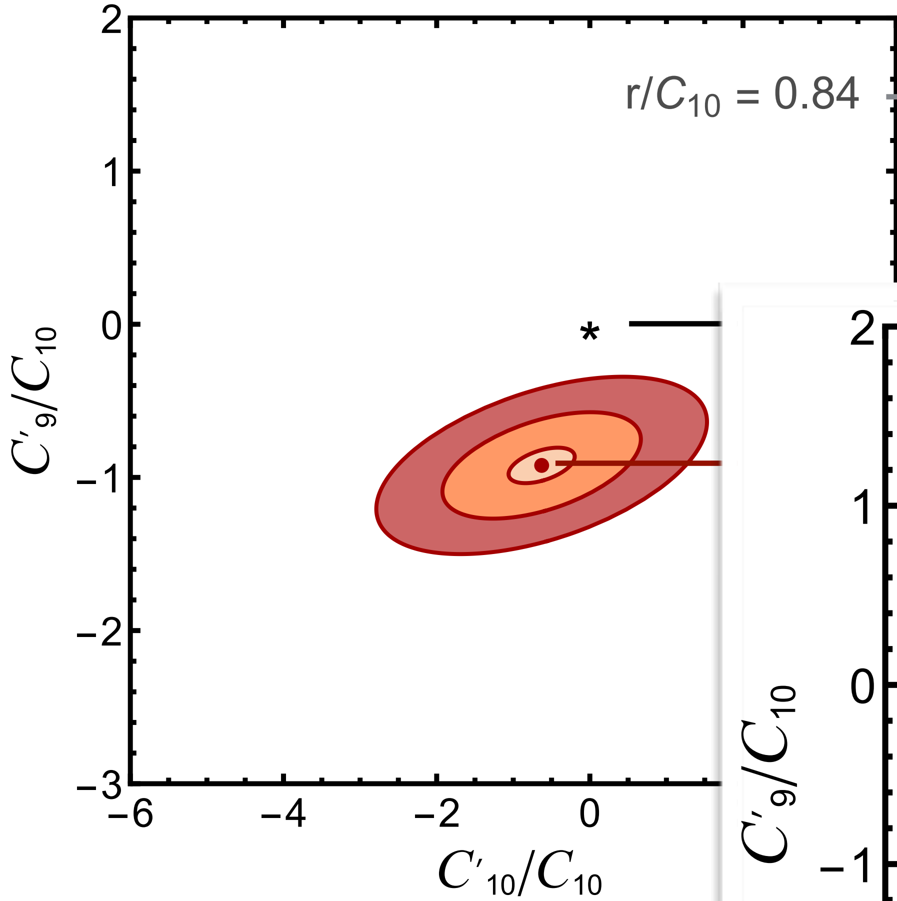
reduced significance of deviation for lowered r/C_{10} value

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

[Altmannshofer, Straub '14]



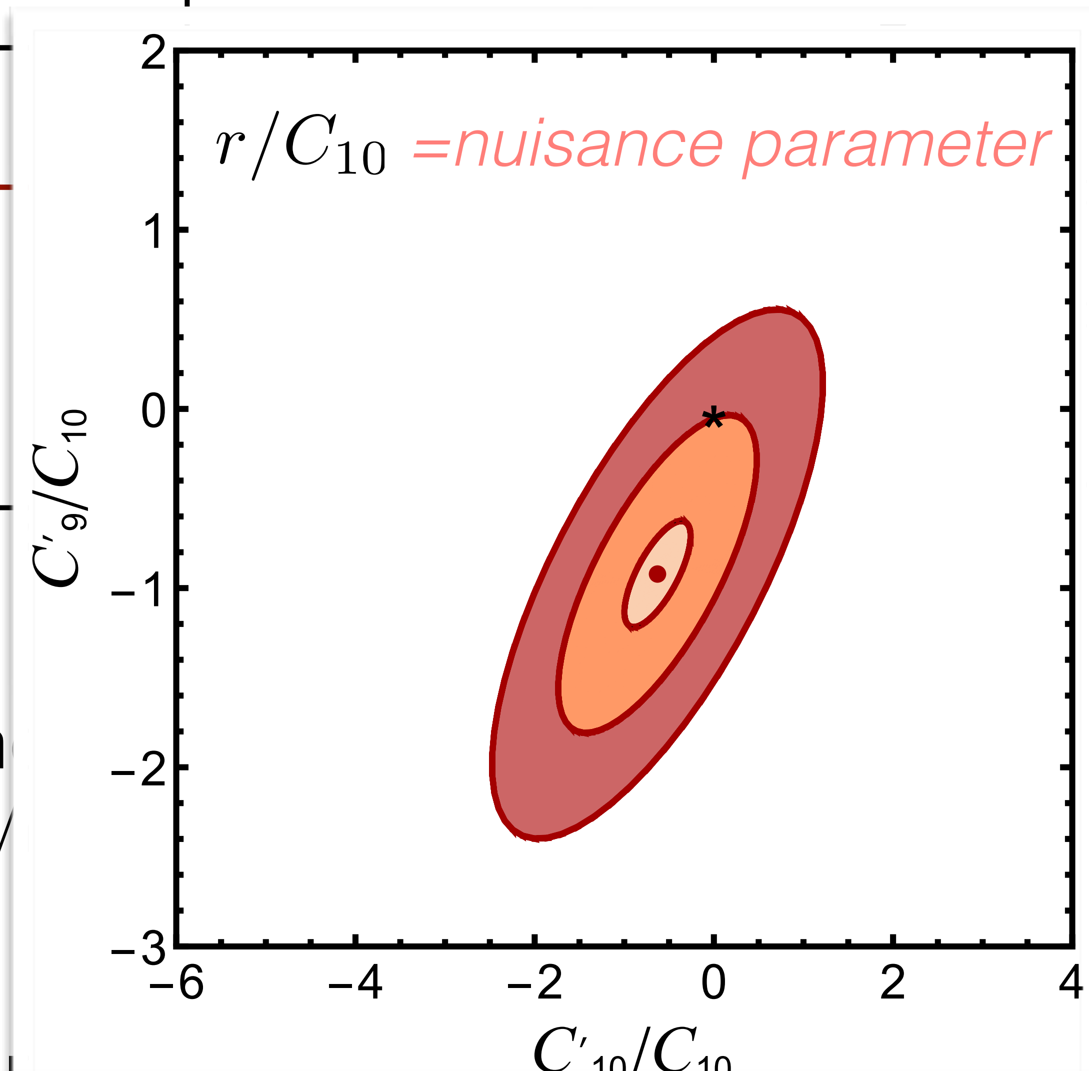
Results in $C'_{10}/C_{10} - C'_9/C_{10}$

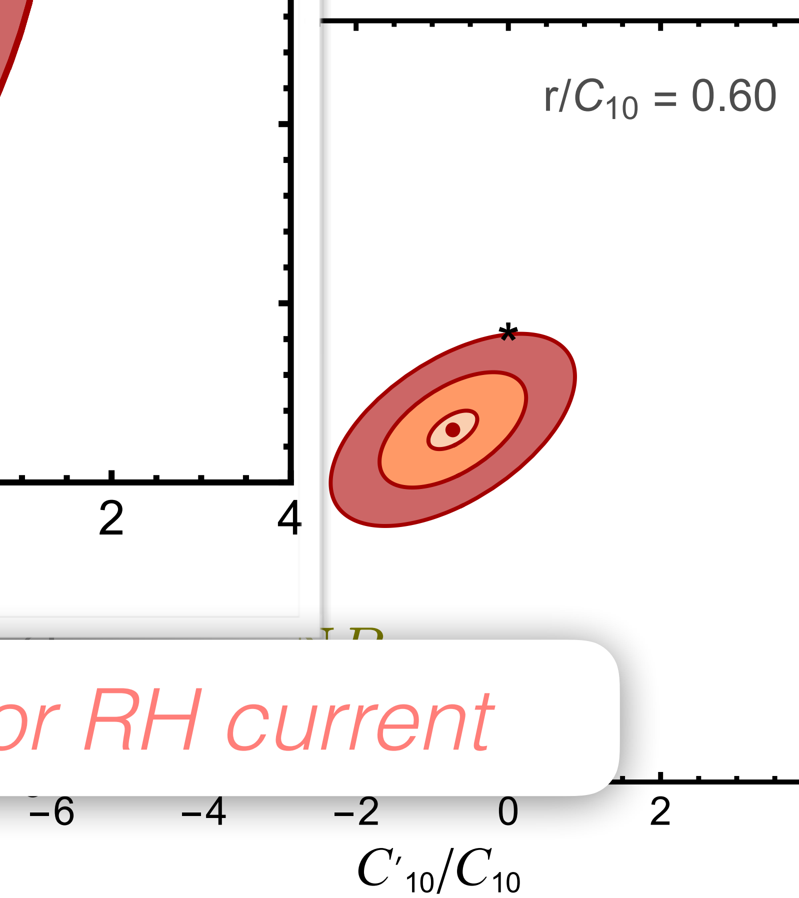


SM input

0.43

0.10





reduced significan

for lowered $r/$

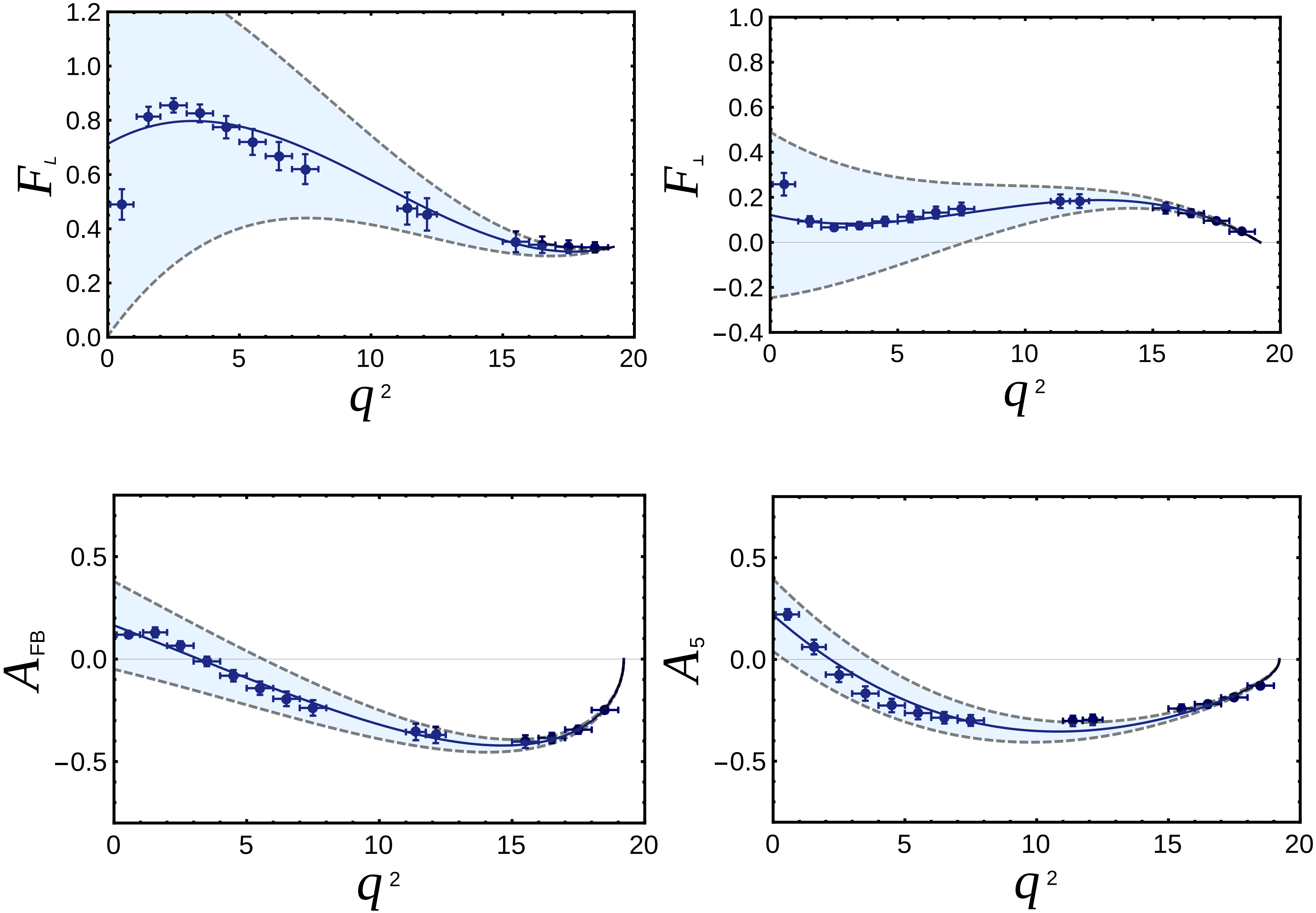
Other kind of NI

as hinte

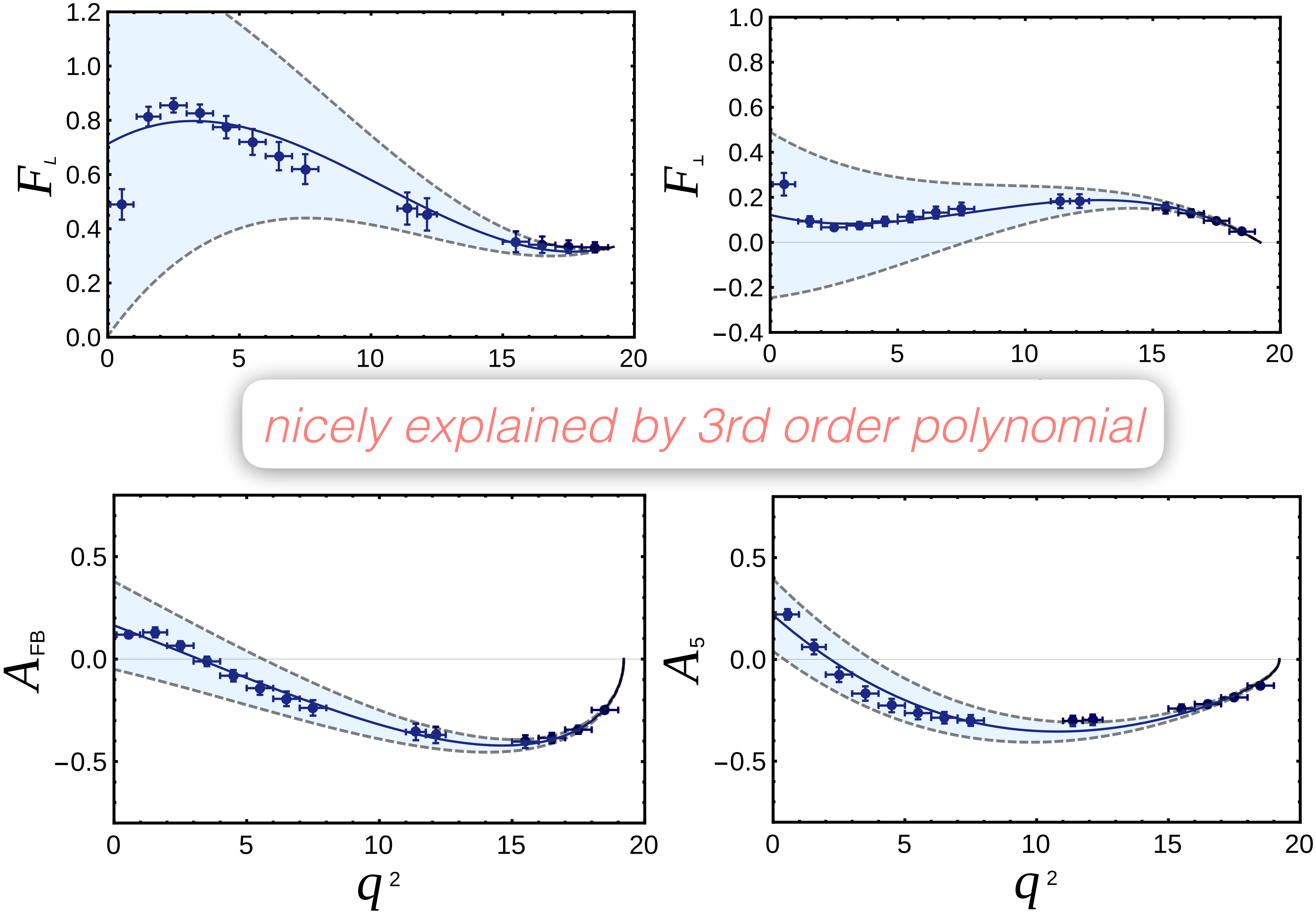
[Altmannshofer, Straub '14]

Minimal significance for RH current

Fit to form factor observables

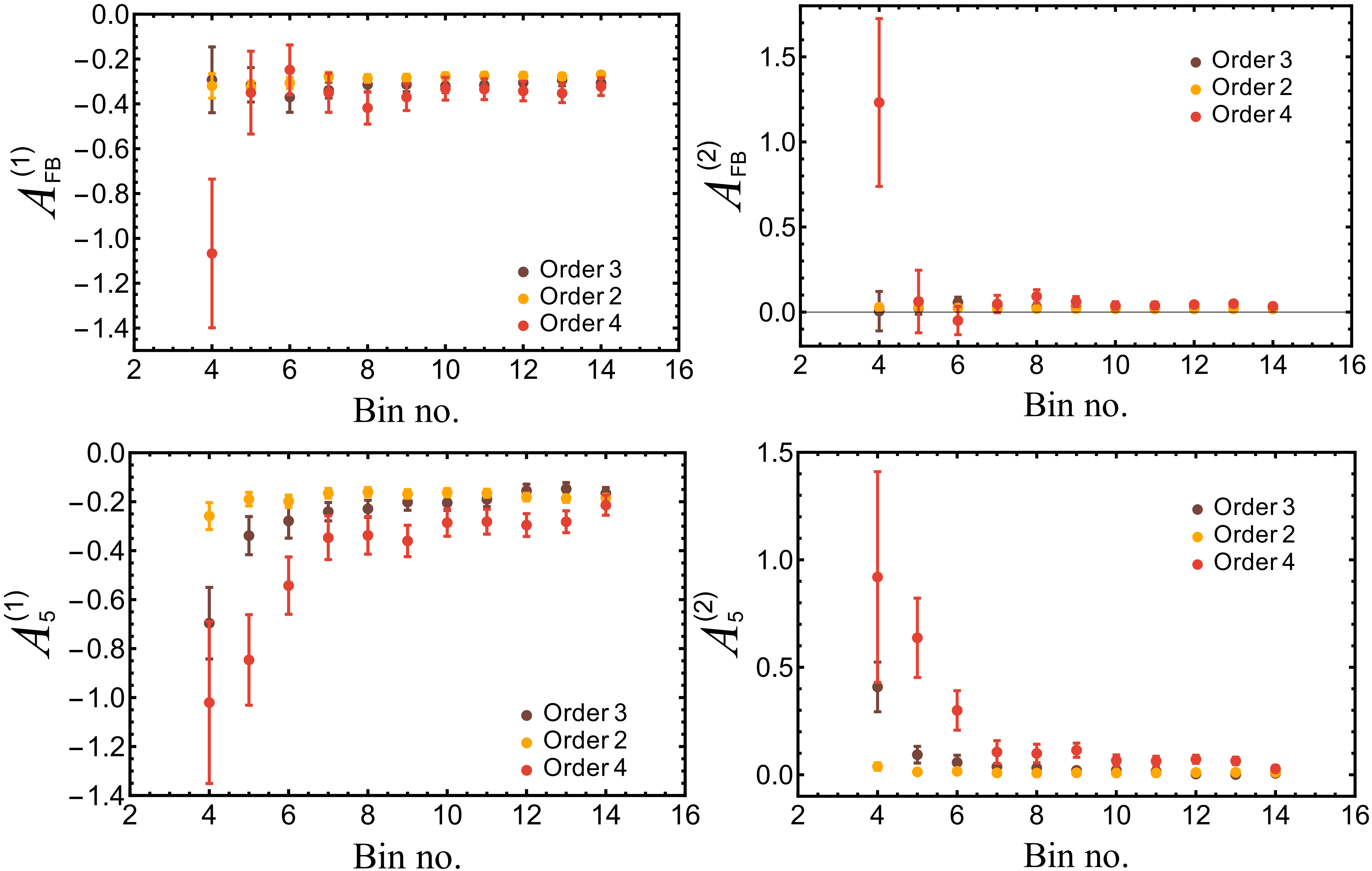


Fit to form factor observables

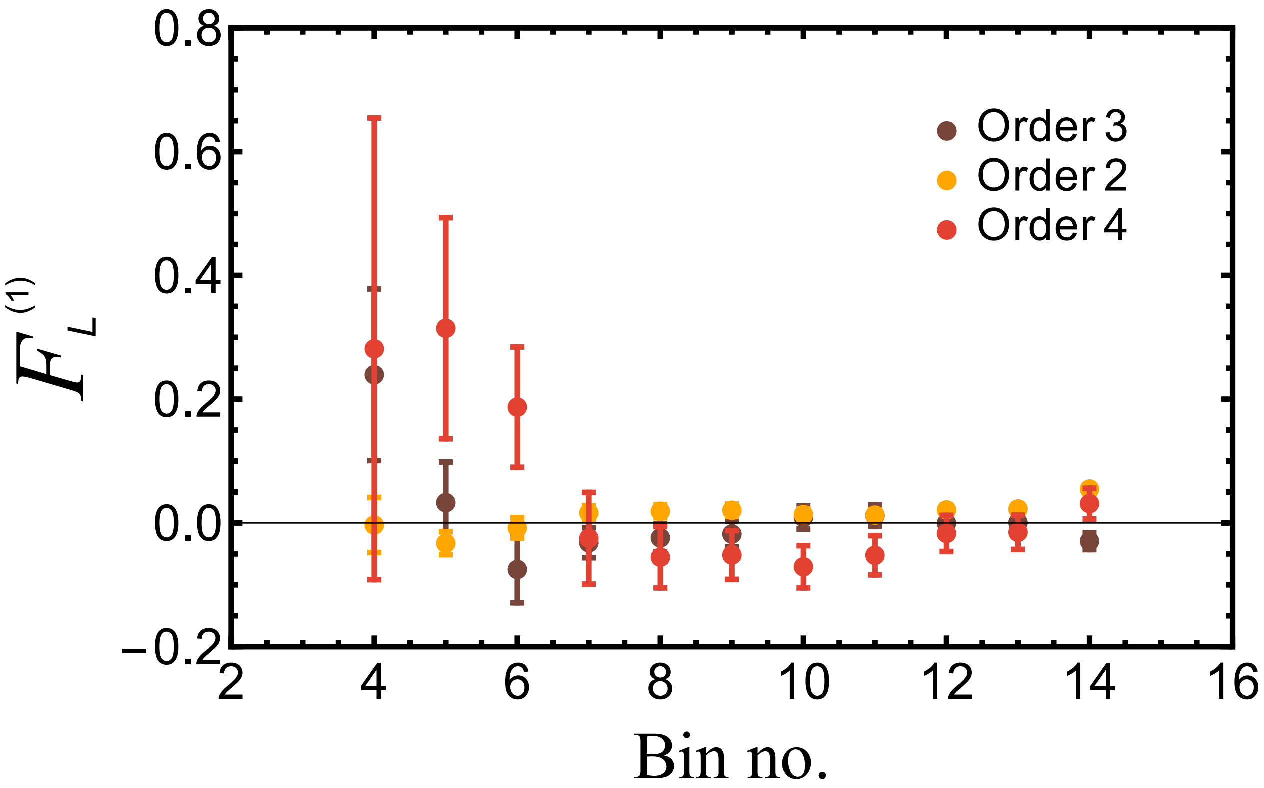


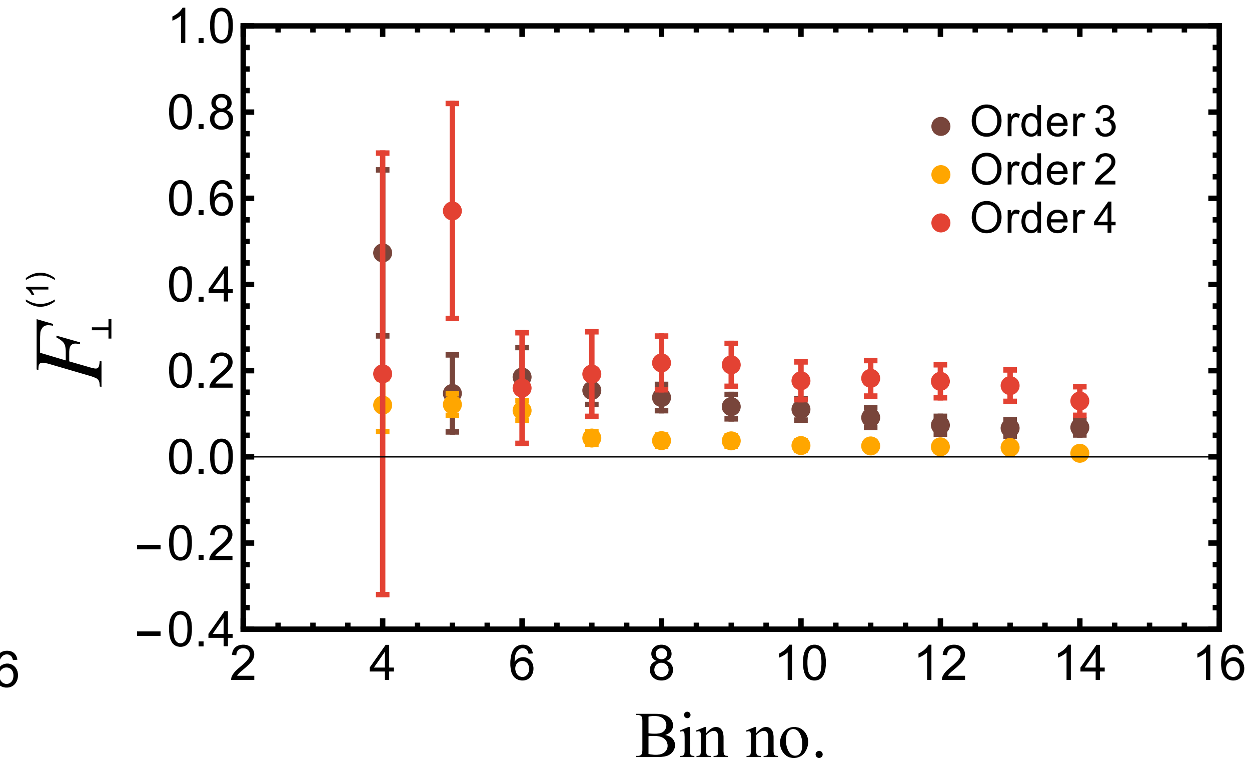
nicely explained by 3rd order polynomial

Convergence of coefficients



Convergence of coefficients



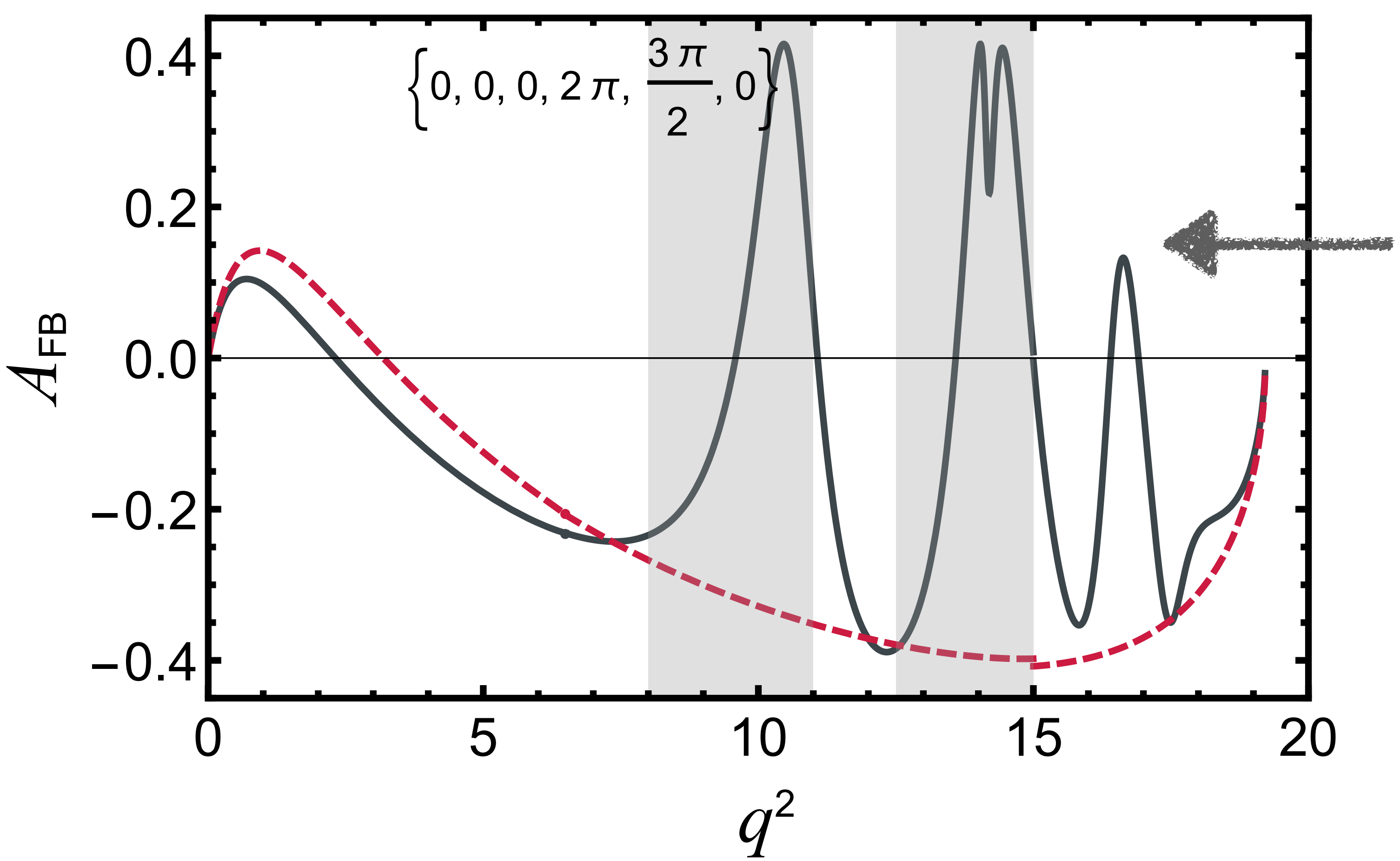


Shows a good convergence with variation in polynomial order & no. of bins used for the data fit

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

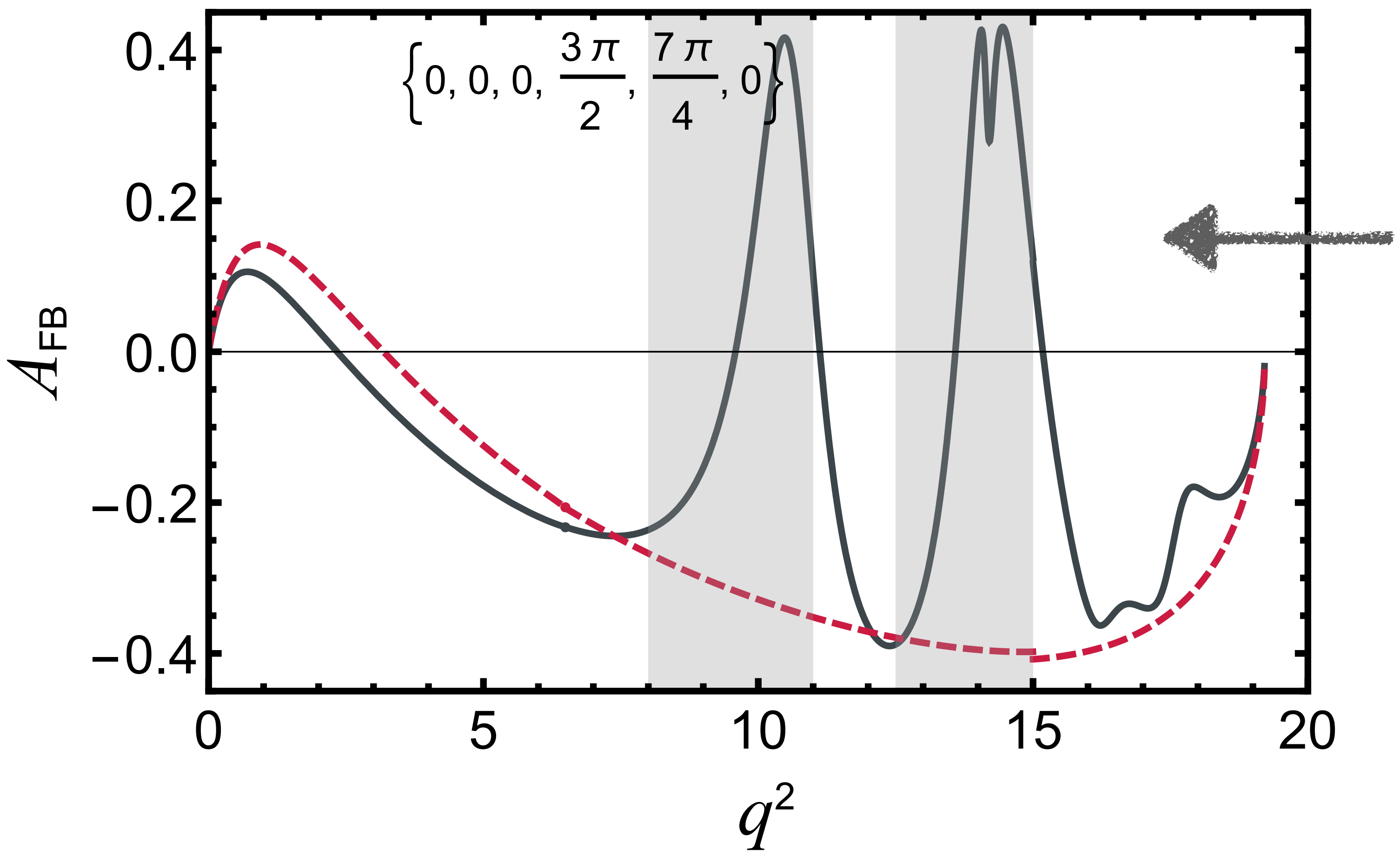
makes observable ω_1 unphysical

Random variation of each strong phases

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

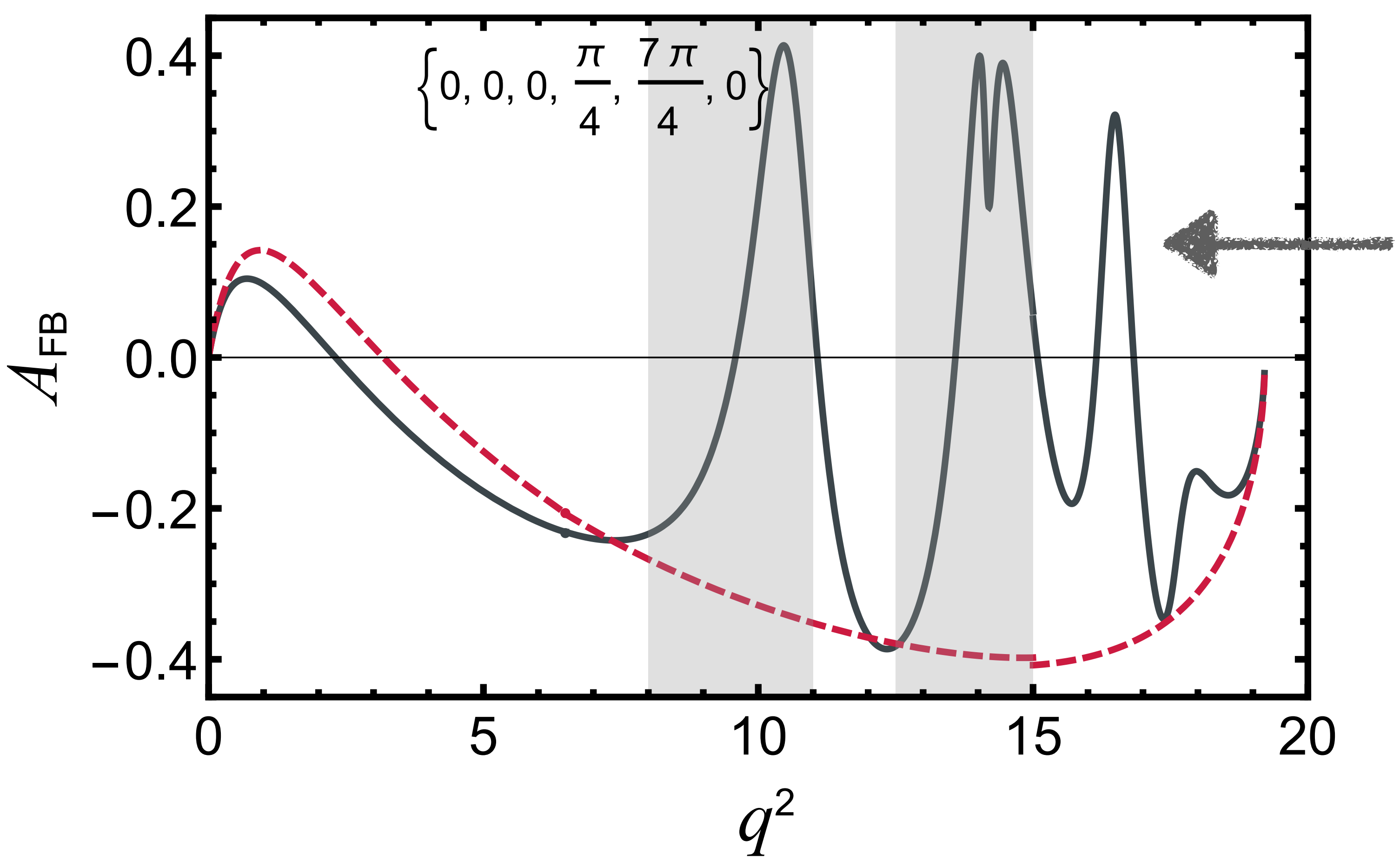
makes observable ω_1 unphysical

Random variation of each strong phases

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

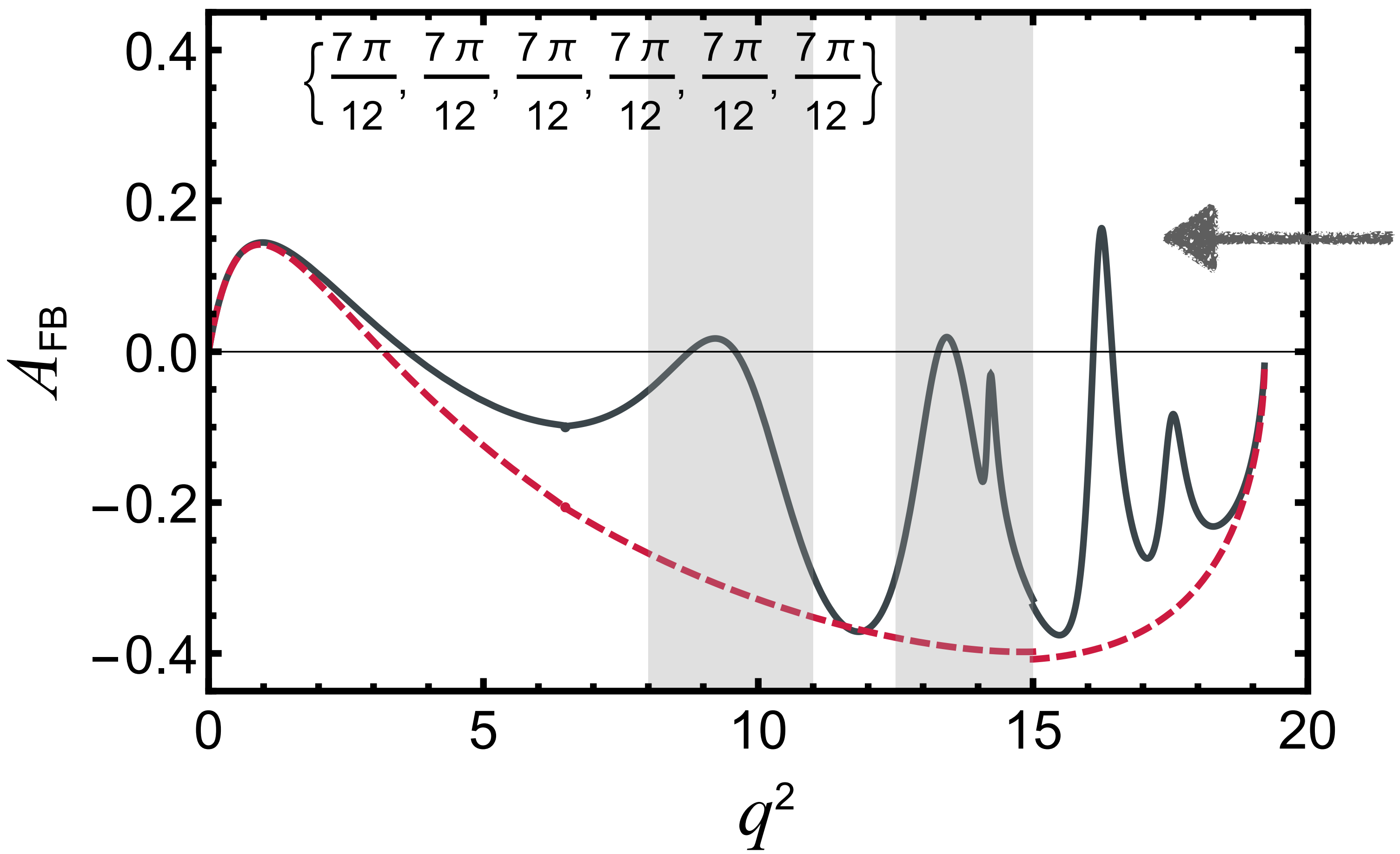
makes observable ω_1 unphysical

Random variation of each strong phases

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

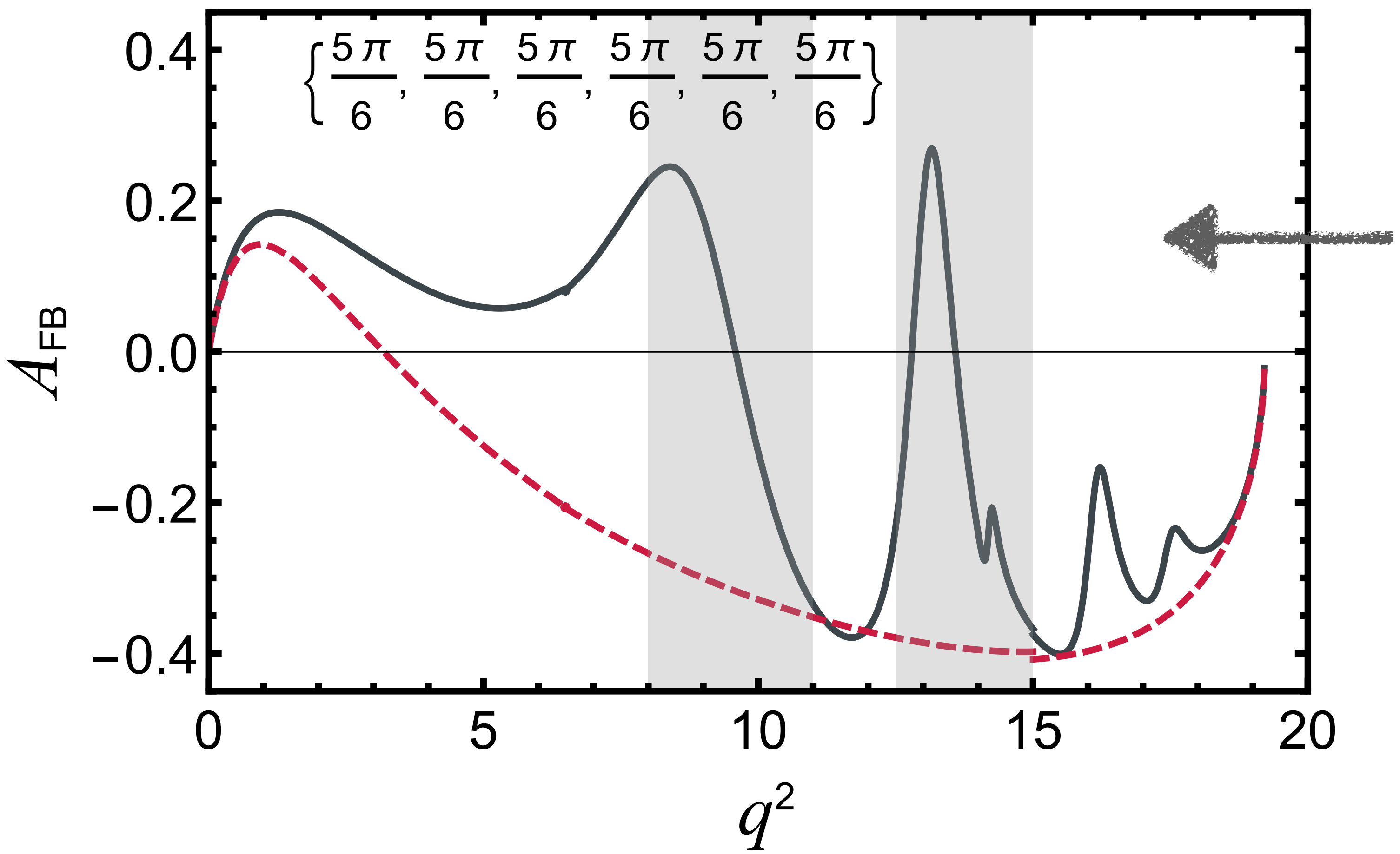
makes observable ω_1 unphysical

Random variation of each strong phases

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



Random variation of each strong phases

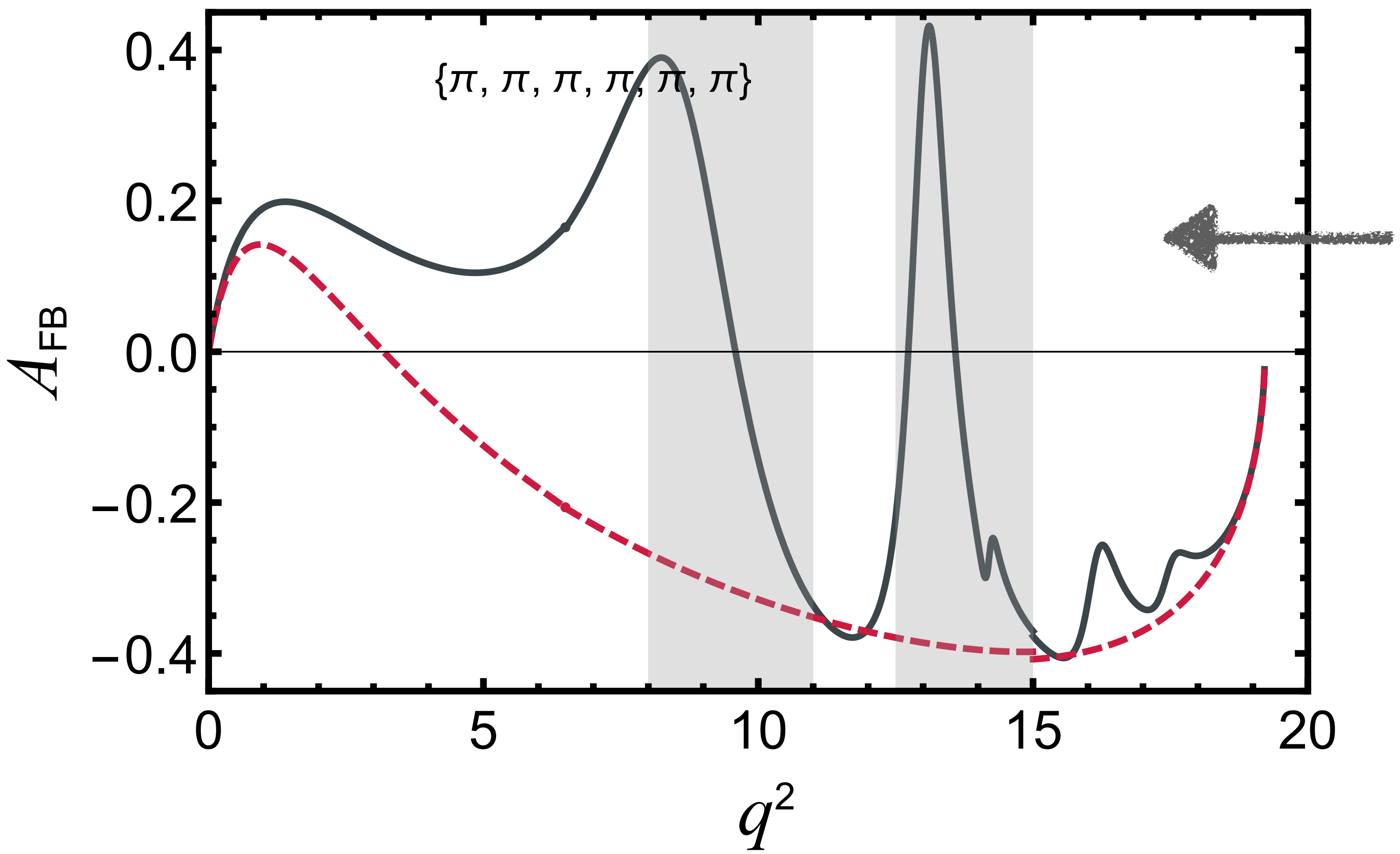
Asymmetries decrease in high q^2 region

makes observable ω_1 unphysical

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

Lepton non-universality

- Discrepancies in neutral current B decays

$$R_{K^{(*)}} \equiv \frac{\mathrm{BR}(B \to K^{(*)}\mu\mu)}{\mathrm{BR}(B \to K^{(*)}ee)} = 1 \text{ in SM}$$

[LHCb '14,'17]

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

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

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

[LHCb '15]

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

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

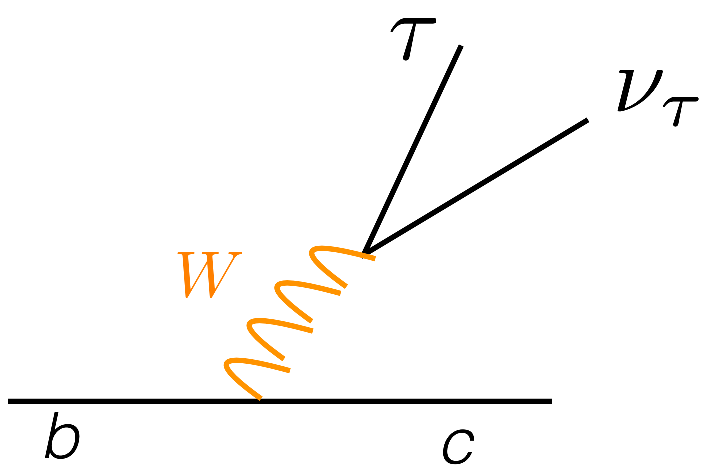
$$= (4.81 \pm 0.56) \times 10^{-8}\ \mathrm{GeV}^{-2} \quad (\mathrm{SM})$$

3σ

Rusa Mandal, IFIC

Lepton non-universality

- Exciting discrepancies observed in charged current B decays



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

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

$$R(D) = \underbrace{(1.34 \pm 0.17\,)}_{2.2\sigma} \times R(D)_{\text{SM}}\,, \quad R(D^*) = \underbrace{(1.23 \pm 0.07\,)}_{3.3\sigma} \times R(D^*)_{\text{SM}}$$

[HFAG]

combined deviation
$\sim 4\sigma$

Lepton non-universality

- Constraints from other modes [LHCb '17]

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

well in agreement

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

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

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

$$\mathrm{BR}(B_c^- \to \tau^- \bar{\nu}) \lesssim 5\%$$ [Grinsten *et.al* '16]

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

Lepton non-universality

- NP operators with 2nd & 3rd generation fields

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

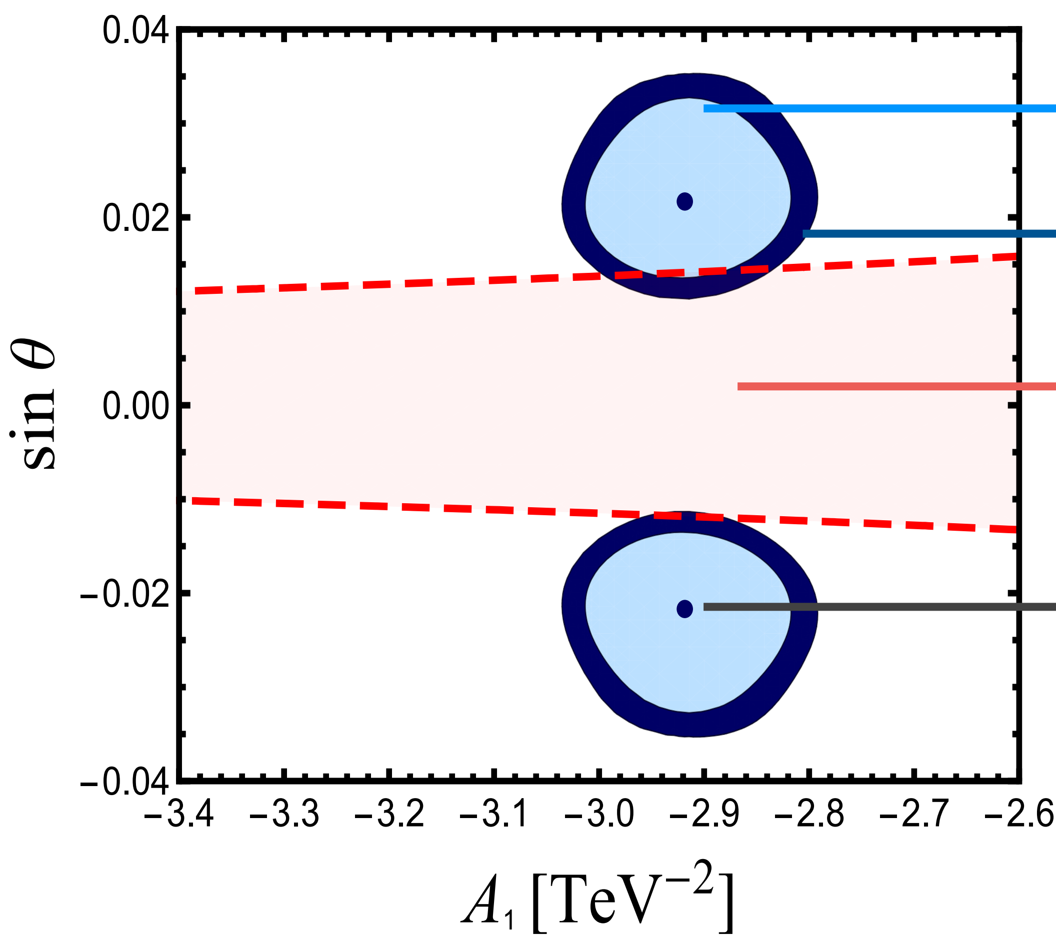
- Directly contributes to $R(D^{(*)})$

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

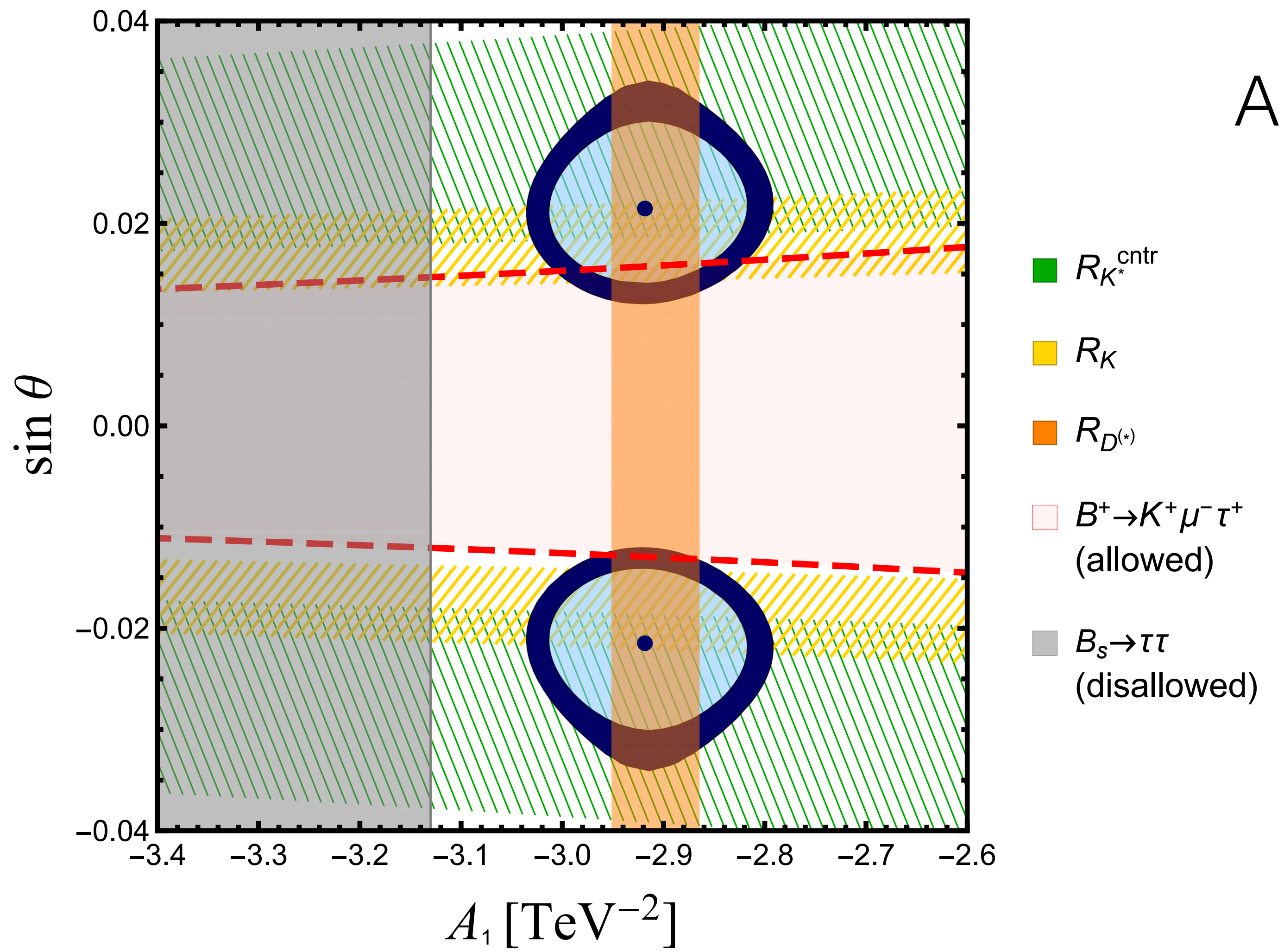
$$A_1 (= A_2) = -2.92\,\mathrm{TeV}^{-2}$$
$$\sin\theta = \pm 0.022$$

$$\chi^2_{\rm SM}/\mathrm{d.o.f} \simeq 6.6 \quad \Rightarrow \quad \chi^2_{\rm allowed\ \ region}/\mathrm{d.o.f} \simeq 3$$

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

✔ agreement within 2σ level

Lepton non-universality



Allowing 20% breaking

$$A_2 = 4A_1/5$$

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

$$\chi^2_{\text{SM}}/\text{d.o.f} \simeq 6.6 \quad \rightarrow \quad \chi^2_{\text{allowed region}}/\text{d.o.f} \simeq 2$$

$$R_K \simeq 0.80, \; R_{K^*}{}^{\text{cntr}} \simeq 0.83, \; R_{K^*}^{\text{low}} \simeq 0.88,$$
$$R(D^{(*)}) \simeq 1.24 \times R(D^{(*)})_{\text{SM}}, \Phi \simeq 3.8 \times 10^{-8}\text{GeV}^{-2}$$

✔ agreement within 1σ level

Lepton non-universality

- Another discrepancy at $b \to c$ charged current [LHCb '17]

$$R_{J/\psi} \equiv \frac{\mathrm{BR}(B_c \to J/\psi\, \tau\nu)}{\mathrm{BR}(B_c \to J/\psi\, \mu\nu)}$$

$$= (2.5 \pm 0.97\,) \times R_{J/\psi}^{\mathrm{SM}} \longrightarrow \; < 2\sigma$$

$\downarrow$

In the same direction as of $R(D^{(*)})$

$\Rightarrow$ considered operators can also explain

- $SU(2)_L$ triplet type operators are also explored [1712:01593]

Summary

Popular approaches	Our approach
☑ Combine all $b \to s$ transitions	☑ Most general parametric form of SM amplitude
$\Downarrow$	$+$
many decay modes i.e observables	$B \to K^* \ell^+ \ell^-$ observables
$+$	$+$
more hadronic uncertainties	eliminate hadronic uncertainties
$+$	$\Downarrow$
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

Rusa Mandal, IFIC

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 in the context of *B* decays such as $B_s \to \tau\tau,\ B \to K^{(*)}\mu\tau$

- Opens up way to construct UV complete theory

- Fluctuation? Wait for more data to be accumulated!

Summary

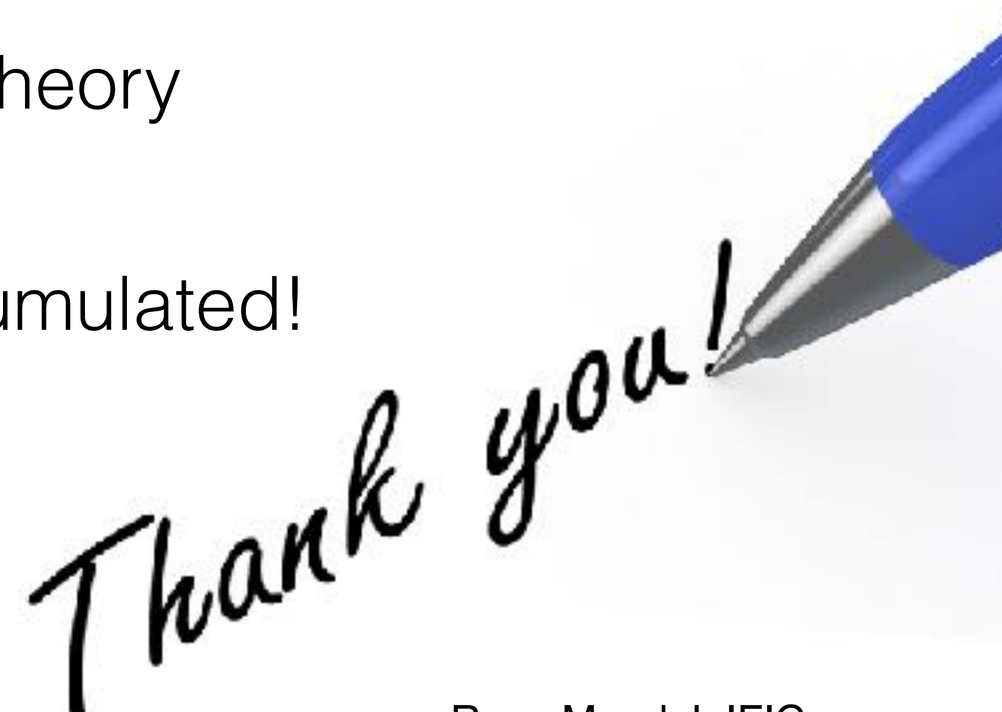
- Several hints of lepton non universality are observed by various experimental groups

- 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 in the context of *B* decays such as $B_s \to \tau\tau,\ B \to K^{(*)}\mu\tau$

- Opens up way to construct UV complete theory

- Fluctuation? Wait for more data to be accumulated!



Back Up

Complex part of amplitudes

- SM amplitude $\mathcal{A}_\lambda^{L,R} = (\widetilde{C}_9^\lambda \mp C_{10})\mathcal{F}_\lambda - \widetilde{\mathcal{G}}_\lambda$
- Complex part $\varepsilon_\lambda \equiv \mathrm{Im}(\widetilde{C}_9^\lambda)\mathcal{F}_\lambda - \mathrm{Im}(\widetilde{\mathcal{G}}_\lambda)$
- Iterative solutions

$$\varepsilon_\perp = \frac{\sqrt{2}\pi\Gamma_f}{(r_0 - r_\parallel)\mathcal{F}_\perp}\left[\frac{A_9 \mathrm{P}_1}{3\sqrt{2}} + \frac{A_8 \mathrm{P}_2}{4} - \frac{A_7 \mathrm{P}_1 \mathrm{P}_2 r_\perp}{3\pi \widehat{C}_{10}}\right],$$

$$\varepsilon_\parallel = \frac{\sqrt{2}\pi\Gamma_f}{(r_0 - r_\parallel)\mathcal{F}_\perp}\left[\frac{A_9 r_0}{3\sqrt{2} r_\perp} + \frac{A_8 \mathrm{P}_2 r_\parallel}{4\mathrm{P}_1 r_\perp} - \frac{A_7 \mathrm{P}_2 r_\parallel}{3\pi \widehat{C}_{10}}\right],$$

$$\varepsilon_0 = \frac{\sqrt{2}\pi\Gamma_f}{(r_0 - r_\parallel)\mathcal{F}_\perp}\left[\frac{A_9 \mathrm{P}_1 r_0}{3\sqrt{2}\mathrm{P}_2 r_\perp} + \frac{A_8 r_\parallel}{4 r_\perp} - \frac{A_7 \mathrm{P}_1 r_0}{3\pi \widehat{C}_{10}}\right].$$

Complex part of amplitudes

q^2 range in GeV^2	$\varepsilon_\perp/\sqrt{\Gamma_f}$	$\varepsilon_\parallel/\sqrt{\Gamma_f}$	$\varepsilon_0/\sqrt{\Gamma_f}$
$0.1 \leq q^2 \leq 0.98$	-0.048 ± 0.116	-0.047 ± 0.103	0.020 ± 0.111
$1.1 \leq q^2 \leq 2.5$	-0.010 ± 0.078	-0.010 ± 0.078	0.078 ± 0.172
$2.5 \leq q^2 \leq 4.0$	-0.009 ± 0.079	-0.008 ± 0.080	-0.025 ± 0.212
$4.0 \leq q^2 \leq 6.0$	-0.026 ± 0.097	0.014 ± 0.093	0.032 ± 0.234
$6.0 \leq q^2 \leq 8.0$	-0.011 ± 0.088	-0.046 ± 0.078	-0.132 ± 0.129
$11.0 \leq q^2 \leq 12.5$	-0.011 ± 0.050	0.038 ± 0.074	-0.078 ± 0.114
$15.0 \leq q^2 \leq 17.0$	-0.0003 ± 0.067	-0.027 ± 0.071	0.020 ± 0.072
$17.0 \leq q^2 \leq 19.0$	0.006 ± 0.076	-0.090 ± 0.090	-0.040 ± 0.088

$\dfrac{\varepsilon_\lambda}{\sqrt{\Gamma_f}}$ values with errors are consistent with zero

Resonances

Parametrization in Wilson coefficient C_9 [Kruger, Sehgal '96]

$$g(m_c,q^2) = -\frac{8}{9}\ln\frac{m_c}{m_b} - \frac{4}{9} + \frac{q^2}{3}\,P\int_{4\hat{m}_D^2}^{m_b^2} \frac{R_{\rm had}^{c\bar{c}}(x)}{x(x-q^2)}dx + i\frac{\pi}{3}R_{\rm had}^{c\bar{c}}(q^2)$$

$$R_{\rm had}^{c\bar{c}}(q^2) = R_{\rm cont}^{c\bar{c}}(q^2) + \sum_{V=J/\psi,\psi'\ldots} \frac{9q^2}{\alpha}\frac{{\rm Br}(V\to l^+l^-)\Gamma_{\rm total}^V\Gamma_{\rm had}^V}{(q^2-m_V^2)^2+m_V^2{\Gamma_{\rm total}^V}^2}e^{i\delta_V}$$

Solutions

$$R_\perp = \pm\frac{3}{2}\frac{\left(\frac{1-\xi}{1+\xi}\right)F_\perp + \frac{1}{2}\mathsf{P}_1 Z_1}{\mathsf{P}_1 A_{\rm FB}}$$

$$R_\parallel = \pm\frac{3}{2}\frac{\left(\frac{1+\xi}{1-\xi}\right)\mathsf{P}_1 F_\parallel + \frac{1}{2}Z_1}{A_{\rm FB}}$$

$$R_0 = \pm\frac{3}{2\sqrt{2}}\frac{\left(\frac{1+\xi}{1-\xi}\right)\mathsf{P}_2 F_L + \frac{1}{2}Z_2}{A_5}$$

$$\mathsf{P}_2 = \frac{\left(\frac{1-\xi}{1+\xi}\right)2\mathsf{P}_1 A_{\rm FB} F_\perp}{\sqrt{2}A_5\left(\left(\frac{1-\xi}{1+\xi}\right)2F_\perp + Z_1\mathsf{P}_1\right) - Z_2\mathsf{P}_1 A_{\rm FB}}$$

$$\begin{aligned}
F_\perp &= 2\zeta\,(1+\xi)^2(1+R_\perp^2)\\
F_\parallel \mathsf{P}_1^2 &= 2\zeta\,(1-\xi)^2(1+R_\parallel^2)\\
F_L \mathsf{P}_2^2 &= 2\zeta\,(1-\xi)^2(1+R_0^2)\\
A_{\rm FB}\mathsf{P}_1 &= 3\zeta\,(1-\xi^2)\big(R_\parallel + R_\perp\big)\\
\sqrt{2}A_5\mathsf{P}_2 &= 3\zeta\,(1-\xi^2)\big(R_0 + R_\perp\big)
\end{aligned}$$

$$Z_1 = \sqrt{4F_\parallel F_\perp - \frac{16}{9}A_{\rm FB}^2} \quad Z_2 = \sqrt{4F_L F_\perp - \frac{32}{9}A_5^2}$$

Effective operators

- Hamiltonian and relevant operators for $b \to s\mu\mu$

$$\mathcal{H}^{\text{eff}} = \frac{-4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i C_i(\mu)\mathcal{O}_i(\mu) \,,$$

$$\mathcal{O}_7 = \frac{e}{16\pi^2} m_b \,(\bar{s}\sigma_{\mu\nu} P_R b)\, F^{\mu\nu}$$

$$\mathcal{O}_9 = \frac{e^2}{16\pi^2} (\bar{s}\gamma_\mu P_L b)\,(\bar{\mu}\gamma^\mu \mu)$$

$$\mathcal{O}_{10} = \frac{e^2}{16\pi^2} (\bar{s}\gamma_\mu P_L b)\,(\bar{\mu}\gamma^\mu \gamma_5 \mu)$$

New contribution to (axial)vector currents

$$C_9 \to C_9 + C_9^{\text{NP}}$$

$$C_{10} \to C_{10} + C_{10}^{\text{NP}}$$