B-physics Anomalies: Theory

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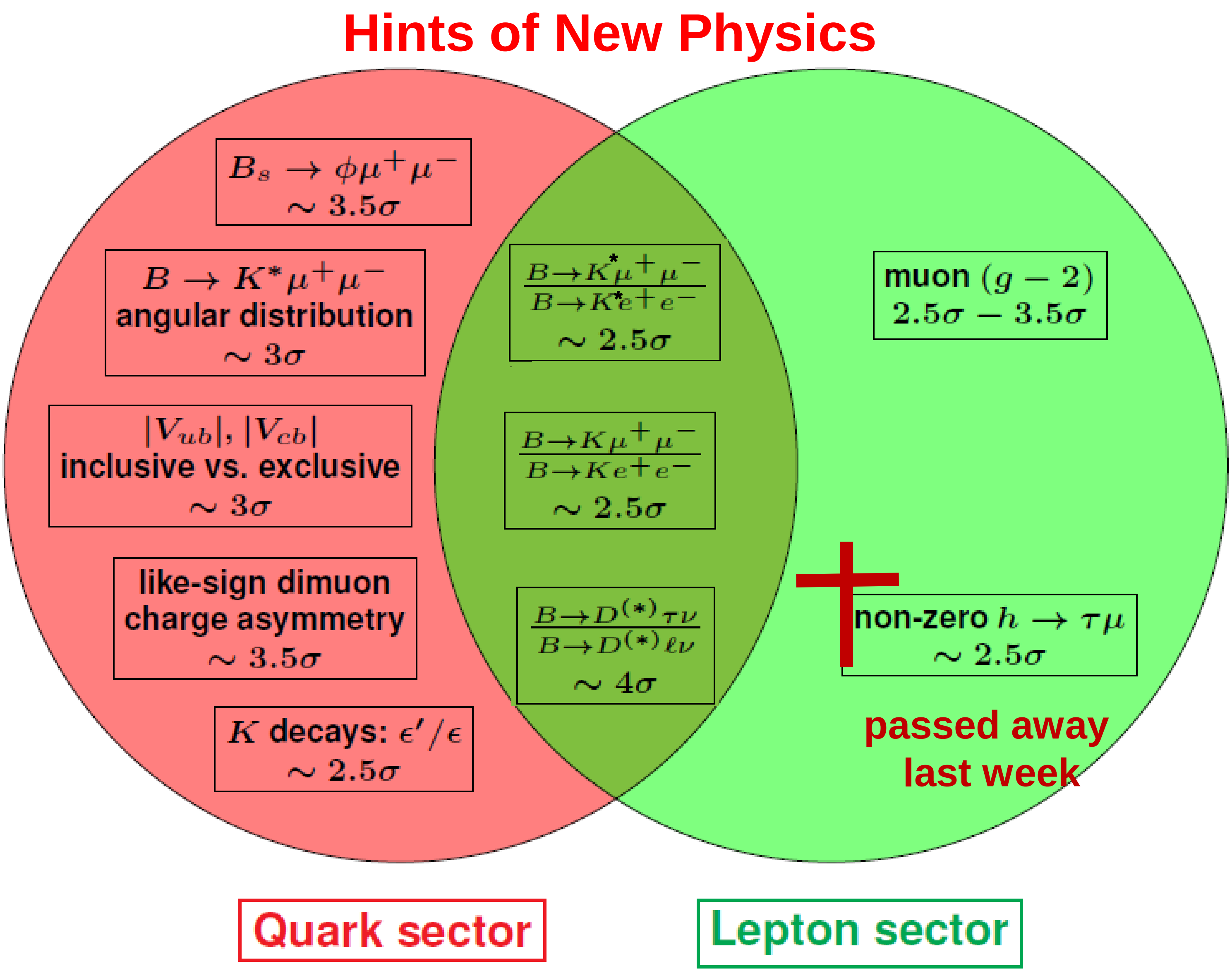
Outline:

- Status of Hadronic uncertainties for the *B*-Anomalies:

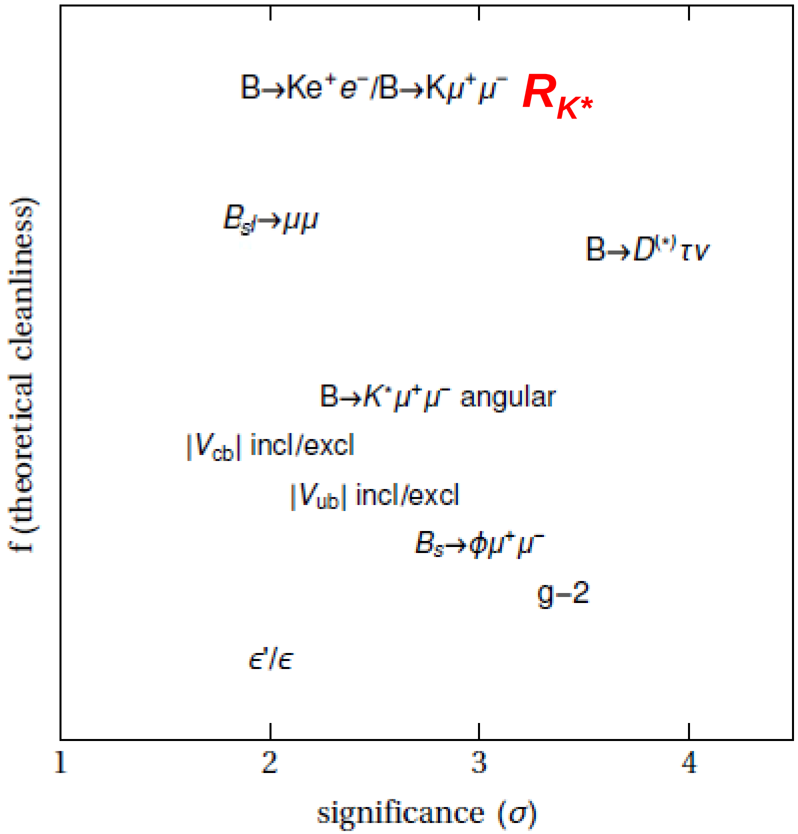
- Some emerging New Physics scenario:

**Flavour Physics at LHC run II,
Benasque, June 22-27 2017**

Flavour Anomalies up to now



Flavour Anomalies: First cleanliness.



Z. Ligeti, Moriond QCD 2016

- Some channels are very clean, only limited by present exp. statistics
- Other channels require careful assessment of the theoretical error:
  -> still useful in presence of NP correlations
- Very interesting pattern of anomalies…

B Anomalies

Hints of New Physics

$\frac{B\to K\mu^+\mu^-}{B\to K e^+ e^-}$ $\sim 2.5\sigma$

$\frac{B\to K^*\mu^+\mu^-}{B\to K^* e^+ e^-}$ $\sim 2.5\sigma$

$B\to K^*\mu^+\mu^-$ angular distribution $\sim 3\sigma$

$\frac{B\to D^{(*)}\tau\nu}{B\to D^{(*)}\ell\nu}$ $\sim 4\sigma$

- **New Physics effects at ~25% of the SM**

- **New Physics scales:**

1) *From $b \to s\mu\mu$*

$$\frac{g_{NP}^2}{\Lambda_{NP}^2} = G_F V_{tb} V_{ts}^* \frac{\alpha}{4\pi} C_{9,10}^{NP} \Rightarrow \frac{\Lambda_{NP}}{g_{NP}} = 35\text{ TeV}$$

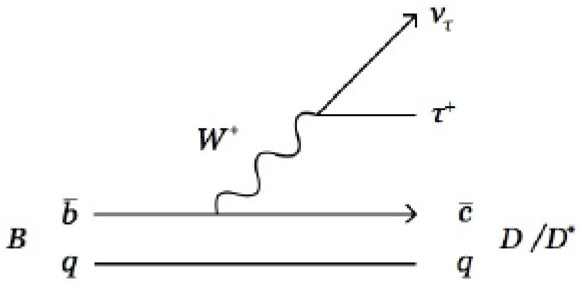
2) *From $b \to c\tau\nu$*

$$\frac{g_{NP}^2}{\Lambda_{NP}^2} = G_F V_{cb} C^{NP} \Rightarrow \frac{\Lambda_{NP}}{g_{NP}} = 3\text{ TeV}$$

- **“No problems” with Atlas/CMS direct searches**

B Anomalies: $b \to c\tau\nu$ and $b \to s\mu\mu$

1) Flavour Changing Charged Current $b \longrightarrow c\,\ell\,\nu_\ell$ $(B \to D^{(*)}\tau\nu, \ldots)$



2) Flavour Changing Neutral Current $b \longrightarrow s\ell\ell$

$$(B \to K^*\mu\mu, B \to \phi\mu\mu, R_K, \ldots)$$

B Anomalies: LFU - $b \to c\tau\nu$

$$R_{D^{(*)}} = \frac{\mathrm{Br}(B \to D^{(*)}\tau\nu)}{\mathrm{Br}(B \to D^{(*)}\ell\nu)}$$

$\ell = e, \mu$

- Once Upon a Time (2012) a tension from BaBar

$$R(D) = \begin{cases} 0.440 \pm 0.072 & \text{BaBar} \\ 0.297 \pm 0.017 & \text{SM} \end{cases} \quad 2.0\sigma$$

$$R(D^*) = \begin{cases} 0.332 \pm 0.030 & \text{BaBar} \\ 0.252 \pm 0.003 & \text{SM} \end{cases} \quad 2.7\sigma$$

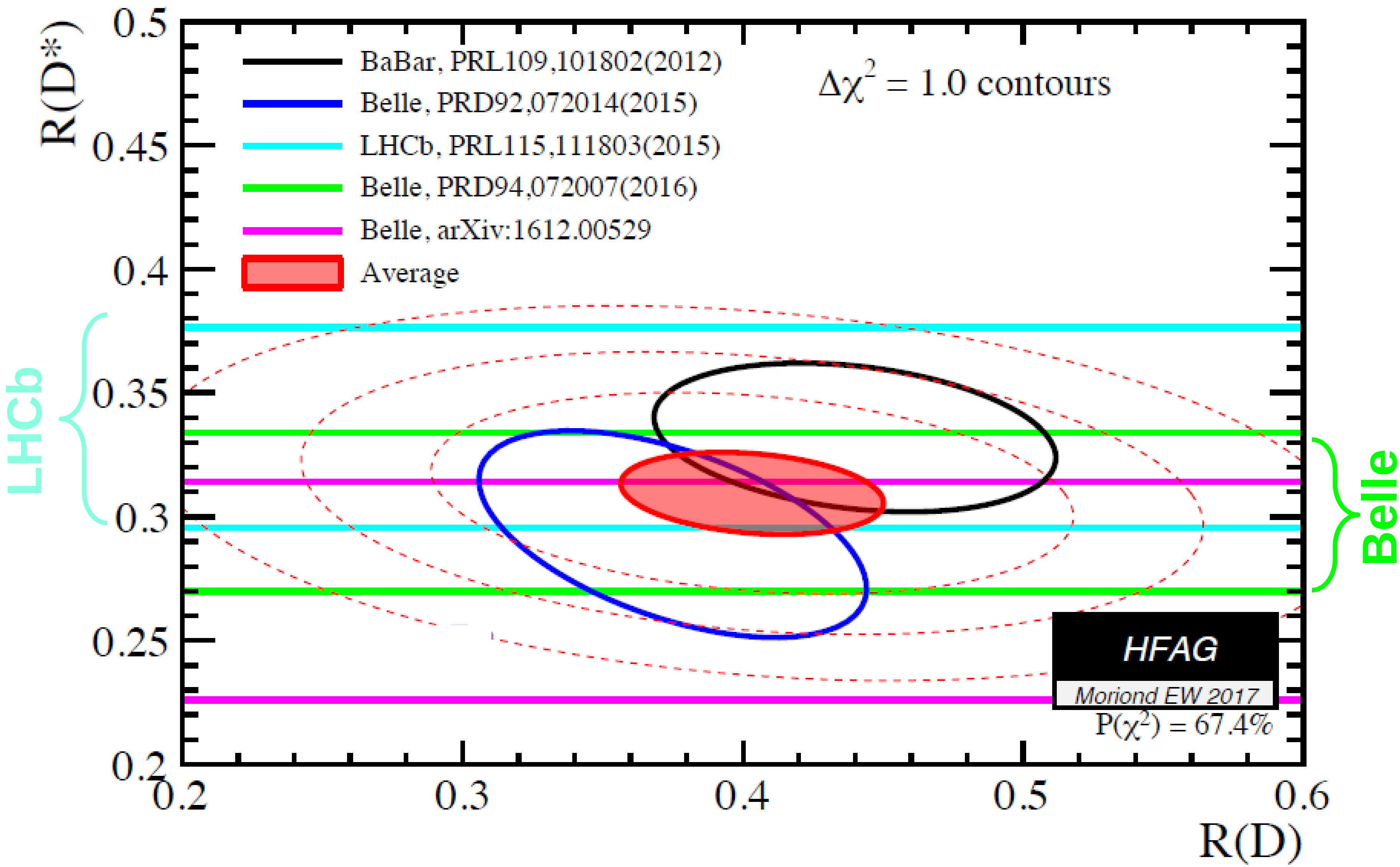
Combined: 3.4σ

- Recently, LHCb has measured R_{D^*}, confirming the 3.3σ tension

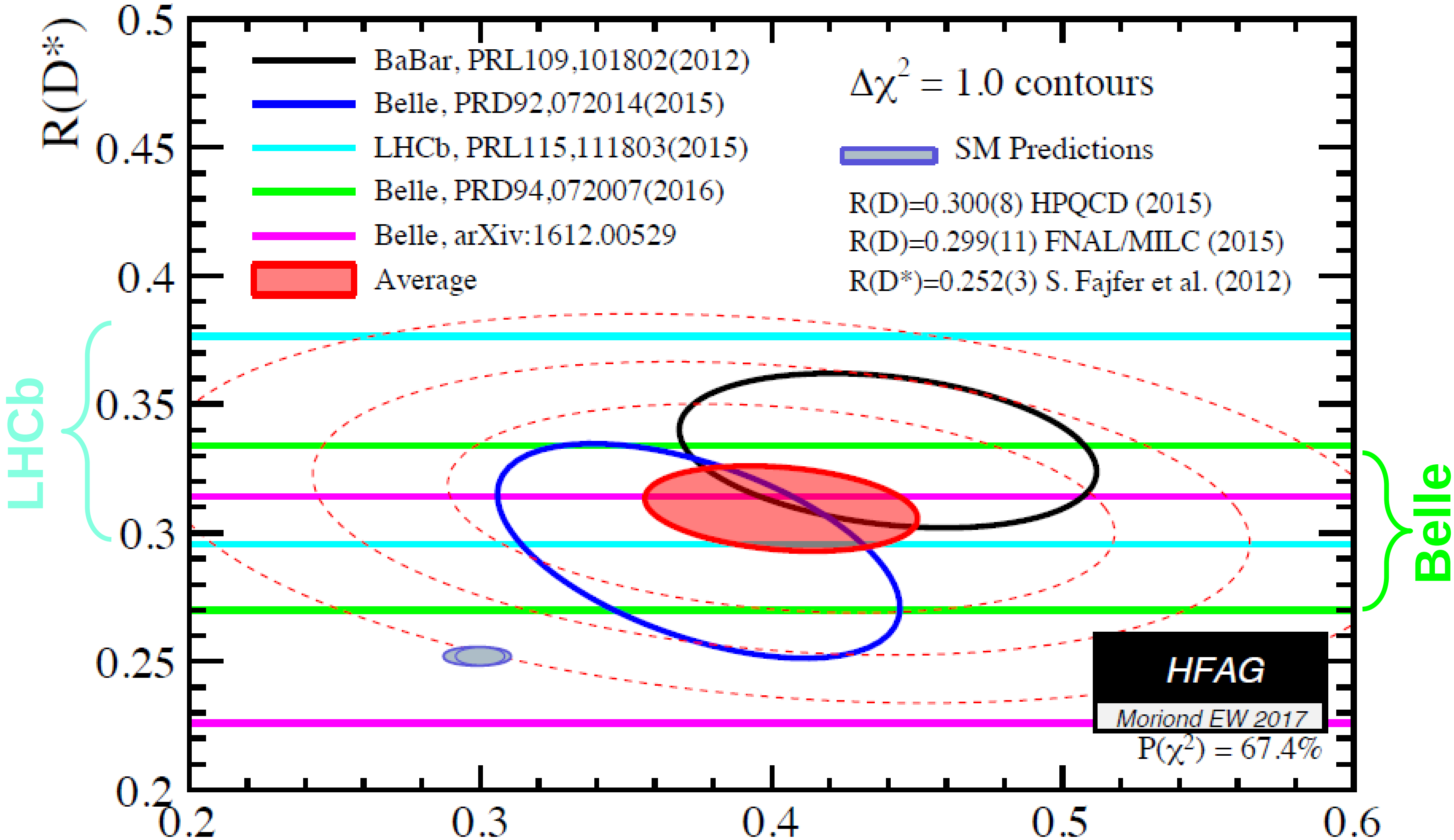
$$Heff = \frac{g_{NP}^2}{\Lambda_{NP}^2} \overline{b_L} \gamma^\mu c_L \bar{\tau} \gamma^\mu \nu$$

B Anomalies: LFU - $b \to c\tau\nu$

- HFAG 2017



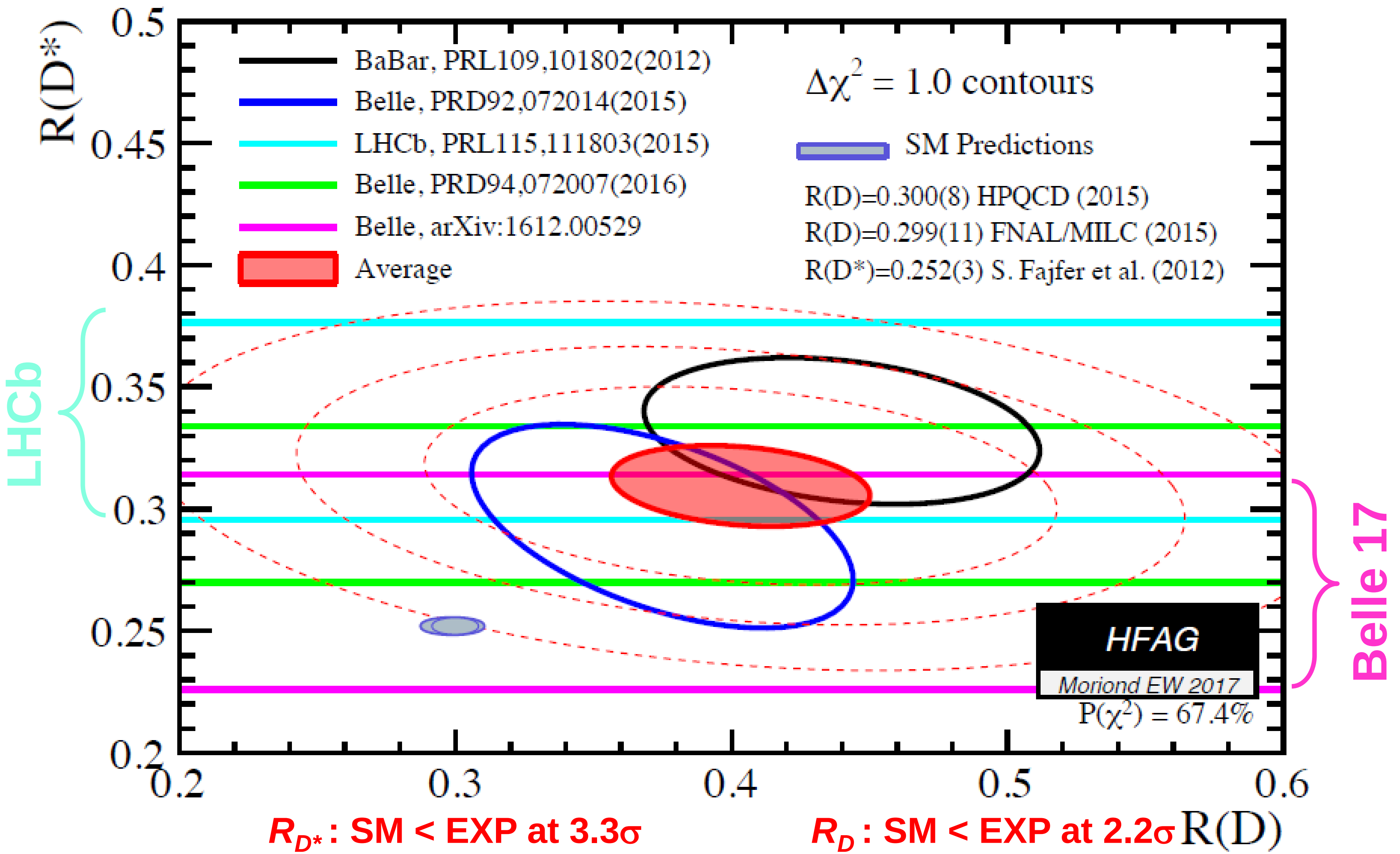
B Anomalies: LFU - $b \rightarrow c\tau\nu$



R_{D^*} : SM < EXP at 3.3σ R_D : SM < EXP at 2.2σ

- Combining the two observables, excess of about 4σ

B Anomalies: LFU - $b \to c\tau\nu$



- Combining the two observables, excess of about 4σ

B Anomalies: LFU - $b \to c\tau\nu$

$$R_{D^{(*)}} = \frac{\mathrm{Br}(B \to D^{(*)}\tau\nu)}{\mathrm{Br}(B \to D^{(*)}\ell\nu)}$$

ℓ =e, μ

❑ Issues that need to be understood

❖ **Hadronic uncertainties?**

Weak Matrix Elements: form factors

❖ **The τ is (experimentally) complicated?**

Talk by Fernando, L. Henry (Thur)

❖ **New Physics effects at tree-level?**

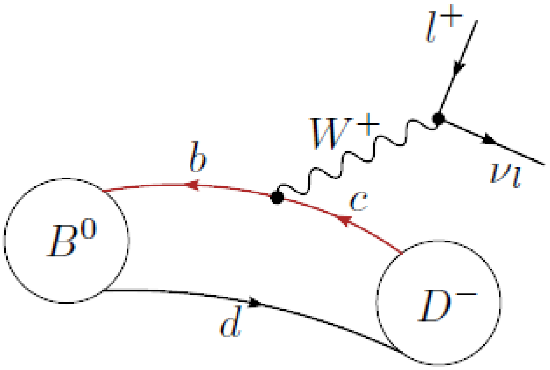
Talk by Nejc, Javier

30% τ enhancement of the SM amplitude

B Anomalies

$$R_{D^{(*)}} = \frac{\mathrm{Br}(B \to D^{(*)}\tau\nu)}{\mathrm{Br}(B \to D^{(*)}\ell\nu)}$$

❖ **Hadronic uncertainties: $B \to D$ Form Factors**



Form Factors are lepton universal:

$\to$ uncertainties largely cancel in R_D

$$\frac{d\Gamma(B \to Pl\nu)}{dq^2} = \frac{G_F^2 |V_{cb}|^2}{24\pi^3} \frac{(q^2 - m_l^2)^2 \sqrt{E_P^2 - m_P^2}}{q^4 m_{B_{(s)}}^2} \left[\left(1 + \frac{m_l^2}{2q^2}\right) m_{B_{(s)}}^2 (E_P^2 - m_P^2) |f_+(q^2)|^2 + \frac{3m_l^2}{8q^2} (m_{B_{(s)}}^2 - m_P^2)^2 |f_0(q^2)|^2 \right]$$

e,μ suppressed

For $B \to D$: High Precision LQCD calculations over the high-q^2 region

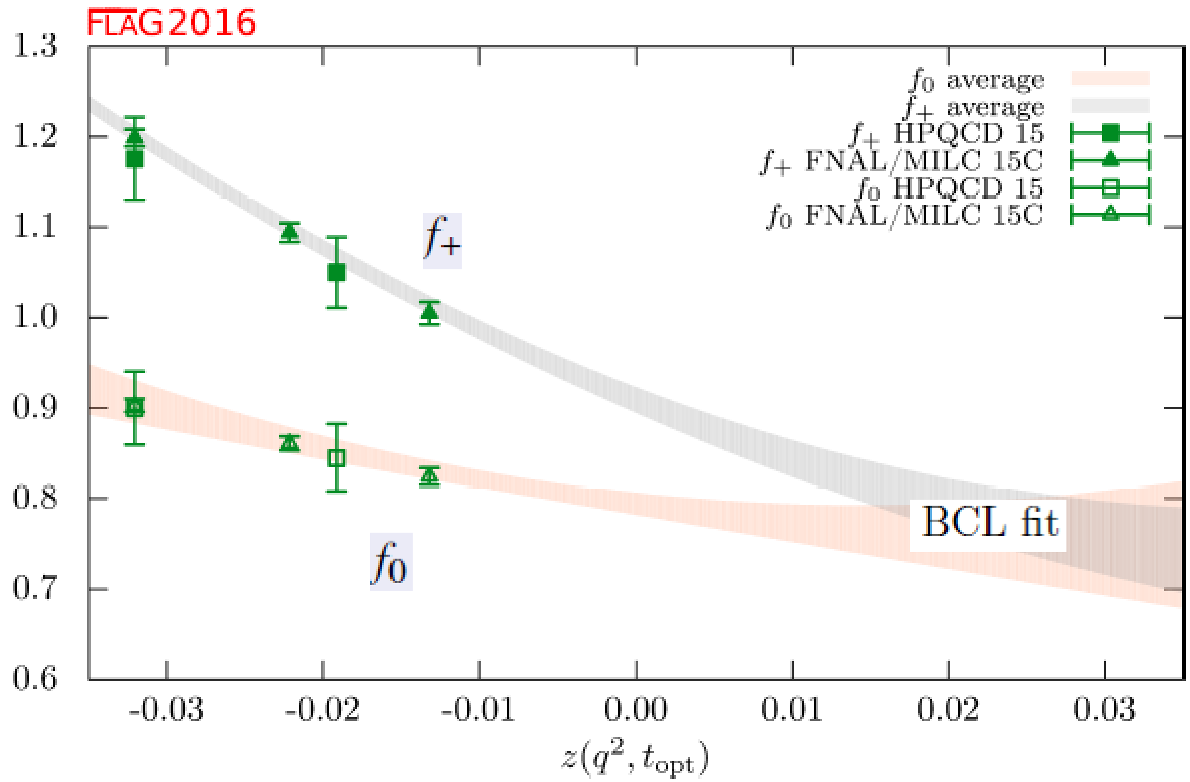
$$\langle P(p')|\bar{b}\gamma_\mu q|B_q(p)\rangle = f_+(q^2)\left(p_\mu + p'_\mu - \frac{m_{B_q}^2 - m_P^2}{q^2} q_\mu\right) + f_0(q^2) \frac{m_{B_q}^2 - m_P^2}{q^2} q_\mu$$

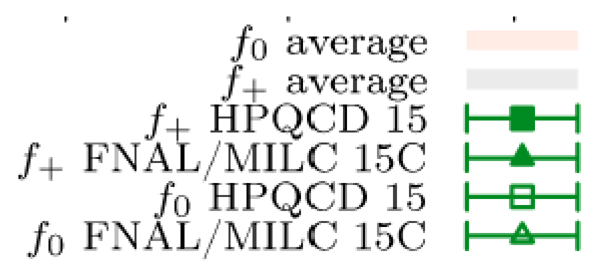
B Anomalies

$$R_{D^{(*)}} = \frac{\mathrm{Br}(B \to D^{(*)}\tau\nu)}{\mathrm{Br}(B \to D^{(*)}\ell\nu)}$$

❖ **Hadronic uncertainties: $B \to D$ Form Factors**

HPQCD (arXiv:1505.03925, PRD 2015)
FNAL/MILC (arXiv:1503.07237, PRD 2015)





- Form Factor errors ~10%
- Use NRQCD for m_b and m_c
- Systematic not fully studied

For $B \to D$: LQCD form factors from **high-q^2 region** + BCL/CLN q^2 model independent fit:

Boyd, Grinstein & Lebed '96, Caprini, Lellouch & Neubert'98

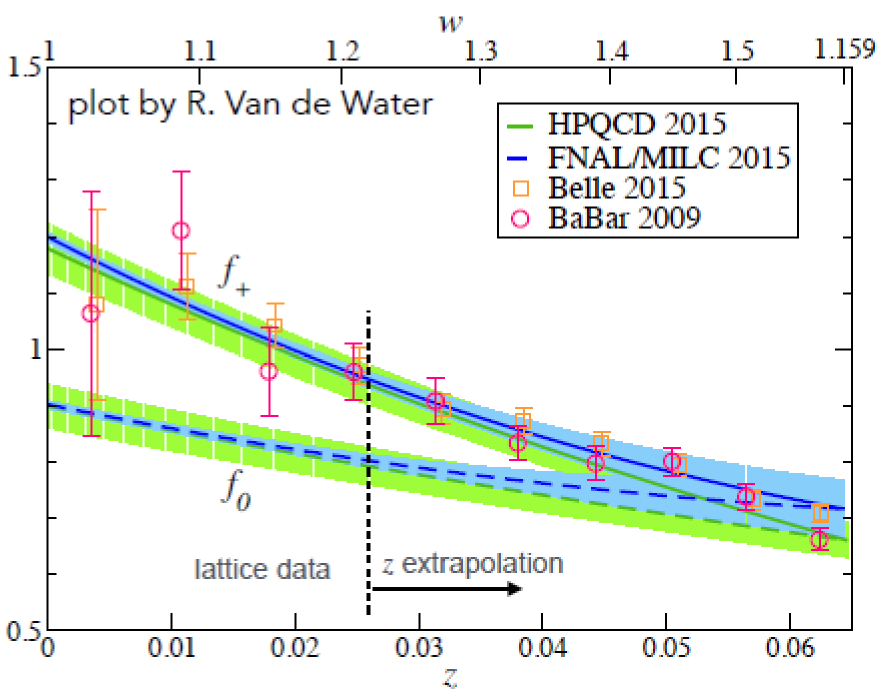
BCL

CLN

B Anomalies

$$R_{D^{(*)}} = \frac{\text{Br}(B \to D^{(*)}\tau\nu)}{\text{Br}(B \to D^{(*)}\ell\nu)}$$

❖ **Hadronic uncertainties: $B \to D$ Form Factors**



HPQCD (arXiv:1505.03925, PRD 2015) (E. Gamiz)
FNAL/MILC (arXiv:1503.07237, PRD 2015)

☆ LQCD form factor uncertainties (~1.2%) smaller than experiment.

Lattice: R_D = 0.300(10) : 3%

Exp: R_D = 0.388(47) : 12%

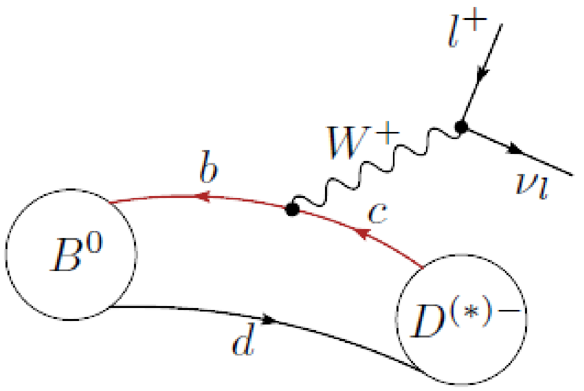
R_D : SM < EXP at 2.2σ

For $B \to D$: LQCD form factors from **high-q^2 region** + BCL/CLN q^2 model independent fit: ***shape in good agreement with exp.***

B Anomalies

$$R_{D^{(*)}} = \frac{\mathrm{Br}(B \to D^{(*)}\tau\nu)}{\mathrm{Br}(B \to D^{(*)}\ell\nu)}$$

- **Hadronic uncertainties: $B \to D^*$ Form Factors**



Form Factors are lepton universal:

$\to$ uncertainties largely cancel in R_{D^*}

$$\frac{\mathrm{d}\Gamma(B \to D^* l \nu_l)}{\mathrm{d}w} = \frac{G_F^2}{4\pi^3}(m_B - m_{D^*})^2(w^2-1)^{1/2}|\eta_{\mathrm{EW}}|^2\chi(w)\,|V_{cb}|^2\,|\mathcal{F}(w)|^2 \;+\; \mathcal{O}\left(\frac{m_l^2}{q^2}\right)$$

$$\frac{\langle D^*(p_{D^*},\epsilon^{(\alpha)})|A^\mu|B(p_B)\rangle}{\sqrt{M_B M_{D^*}}} = \frac{i}{2}\epsilon_\nu^{(\alpha)*}\left[g^{\mu\nu}(1+\omega)h_{A_1}(\omega) - v_B^\nu\left(v_B^\mu h_{A_2}(\omega) + v_{D^*}^\mu h_{A_3}(\omega)\right)\right]$$

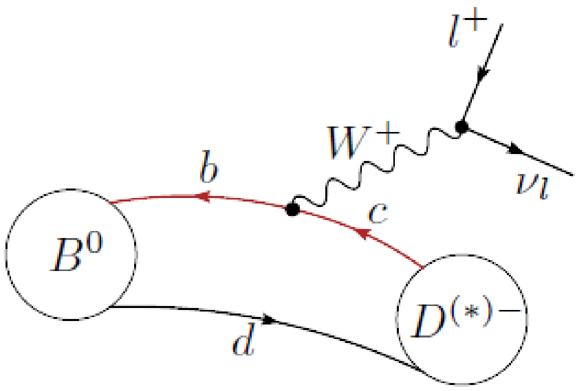
$$\frac{\langle D^*(p_{D^*},\epsilon^{(\alpha)})|V^\mu|B(p_B)\rangle}{\sqrt{M_B M_{D^*}}} = \frac{1}{2}\epsilon^{\mu\nu}{}_{\rho\sigma}\,\epsilon_\nu^{(\alpha)*}\,v_B^\rho v_{D^*}^\sigma\,h_V(\omega)$$

10%
in $B \to D^* \tau \nu$

B Anomalies

$$R_{D^{(*)}} = \frac{\mathrm{Br}(B \to D^{(*)}\tau\nu)}{\mathrm{Br}(B \to D^{(*)}\ell\nu)}$$

❖ **Hadronic uncertainties:** $B \to D^*$ **Form Factors**



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☹ **For $B \to D^*$:** No LQCD calculations for w<1:   only calculation at w=1!

New results expected at Lattice 2017, Granada (June 21-26)

B Anomalies: $b \to c\tau\nu$

New Results on $B \to D^* (D)$ at Granada

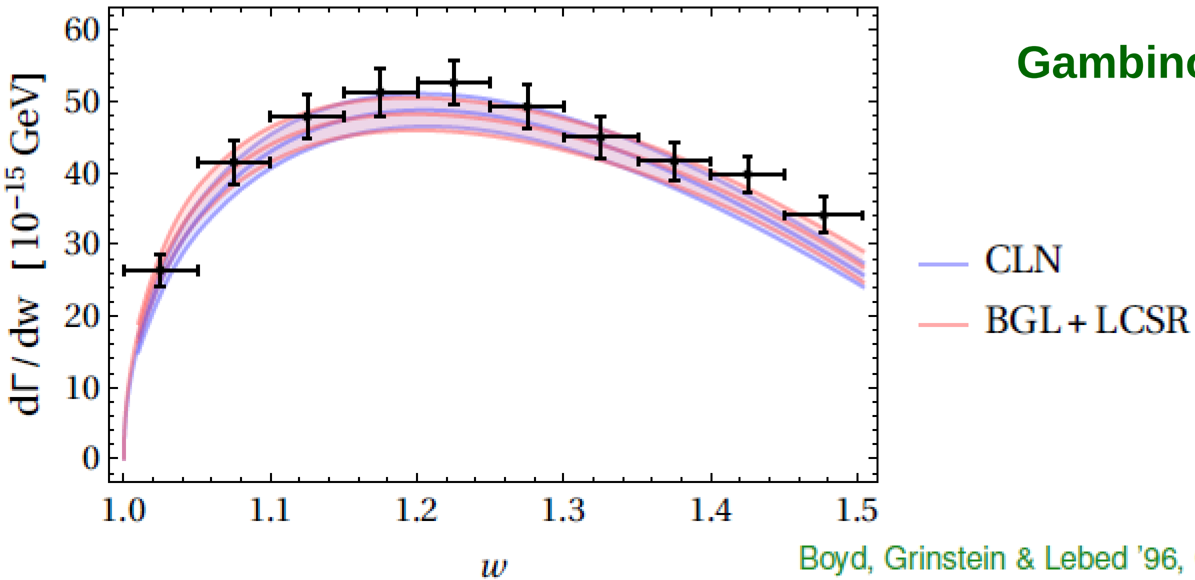
B Anomalies

$$R_{D^{(*)}} = \frac{\mathrm{Br}(B \to D^{(*)}\tau\nu)}{\mathrm{Br}(B \to D^{(*)}\ell\nu)}$$

❖ **Hadronic uncertainties:** $B \to D^*$ **Form Factors**

☹ **For** $B \to D^*$**:** No LQCD calculations for w<1

❑ *3 FFs from model-independent fit of* ***B → D* l ν*** *experimental data*
+ 1 scalar from HQET



Gambino et al. 17

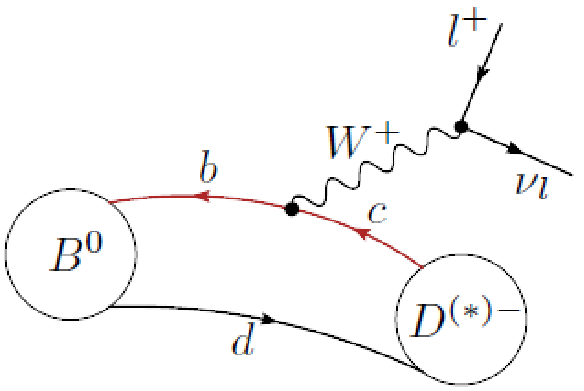
$$w = \frac{m_B^2 + m_{D^*}^2 - q^2}{2 m_B m_{D^*}},$$

Boyd, Grinstein & Lebed '96, Caprini, Lellouch & Neubert'98

B Anomalies

$$R_{D^{(*)}} = \frac{\mathrm{Br}(B \to D^{(*)}\tau\nu)}{\mathrm{Br}(B \to D^{(*)}\ell\nu)}$$

❖ **Hadronic uncertainties: $B \to D^*$ Form Factors**



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❑ *FFs from model-independent fit of **B → D* l v** experimental data + HQET*

Theory/Fit: R_{D^*} = 0.252(3): 1%

Exp: R_{D^*} = 0.321(21): 6%

S. Fajfer et. al, 12, Ligeti et, 17, Gambino et al. 17

R_{D^*} : SM < EXP at 3.3σ

B Anomalies

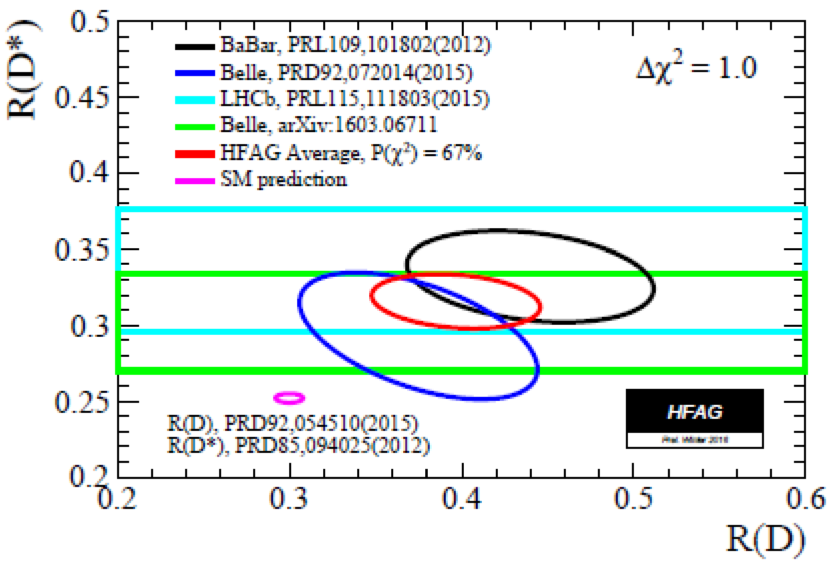
$$R_{D^{(*)}} = \frac{\mathrm{Br}(B \to D^{(*)}\tau\nu)}{\mathrm{Br}(B \to D^{(*)}\ell\nu)}$$

❖ Hadronic uncertainties?

- Form Factors are lepton universal:

$\to$ uncertainties largely cancel in R_D and R_{D*}

- SM predictions of R_{D*} and R_{D*} are well under control



➢ **Excesses observed at more than ~4σ**

	$R(D)$	$R(D^*)$
BaBar	$0.440 \pm 0.058 \pm 0.042$	$0.332 \pm 0.024 \pm 0.018$
Belle	$0.375^{+0.064}_{-0.063} \pm 0.026$	$0.293^{+0.039}_{-0.037} \pm 0.015$
LHCb		$0.336 \pm 0.027 \pm 0.030$
Exp. average	0.388 ± 0.047	0.321 ± 0.021
SM expectation	0.300 ± 0.010	0.252 ± 0.005
Belle II, 50 ab^{-1}	± 0.010	± 0.005

➢ **Tensions observed at three Experiments**

30% enhancement of the SM amplitude

B Anomalies

$$R_{D^{(*)}} = \frac{\text{Br}(B \to D^{(*)}\tau\nu)}{\text{Br}(B \to D^{(*)}\ell\nu)}$$

❖ **Hadronic uncertainties?**

- ***Form Factors are lepton universal:***
  $\rightarrow$ uncertainties largely cancel in R_D and R_{D*}

- ***SM predictions of R_{D*} and R_{D*} are well under control***

❖ **The τ is (experimentally) complicated**

Talk by Fernando, L. Henry (Thur)

❖ **New Physics effects at tree-level**

Talk by Nejc

B Anomalies: $b \to c\tau\nu$ and $b \to s\mu\mu$

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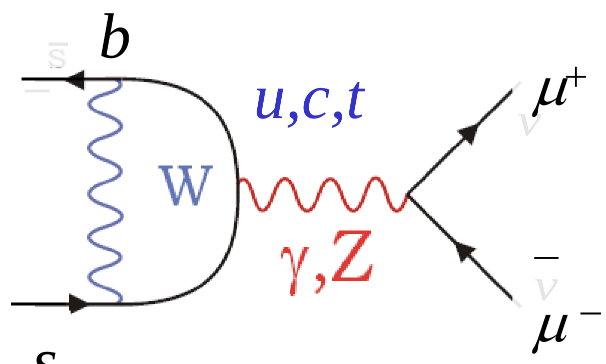


+ W box

At short-distance

$$Heff = \begin{cases} C_7 \times \bar{b}_R \sigma^{\mu\nu} s_L F_{\mu\nu} + \\ C_9 \times \bar{b}_L \gamma^{\mu} s_L \bar{l} \gamma^{\mu} l + \\ C_{10} \times \bar{b}_L \gamma^{\mu} s_L \bar{l} \gamma^{\mu} \gamma_5 l \end{cases}$$

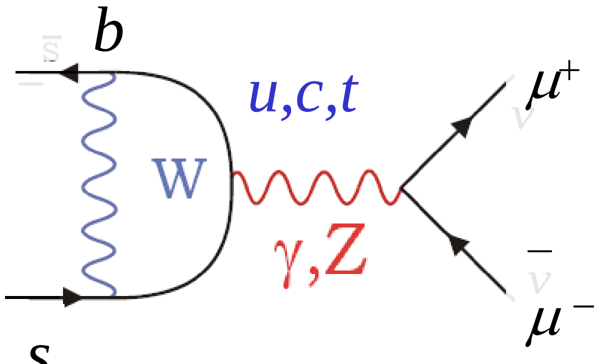
$Br(B_d \to X_s \gamma) \propto |C_7|$

$Br(B_s \to \mu^+ \mu^-) \propto C_{10}$

$A(B_d \to K l^+ l^-) \propto C_{7,9,10}$

$A(B_d \to K^* l^+ l^-) \propto C_{7,9,10}$

$b \to s$ transitions: $B_s \to \mu\mu$



$+ W\ box$

$$CVC : q^{\mu} \bar{\ell} \gamma^{\mu} \ell = 0$$

1) No γ interactions: no $C_{9,7}$

2) Only *Z* interactions: C_{10}

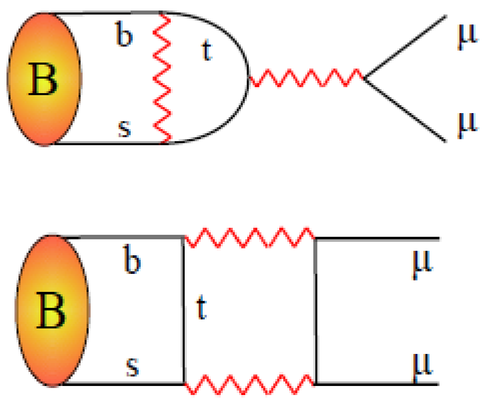
m_c, m_u GIM suppressed

3) Only t,W,Z contributions

To large extent, pure local interaction:

C_{10} *- short-distance couplings: q^2-independent!*

$b \to s$ transitions: $B_s \to \mu\mu$



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To large extent, pure local interaction:
C_{10} - short-distance couplings: q^2-independent!

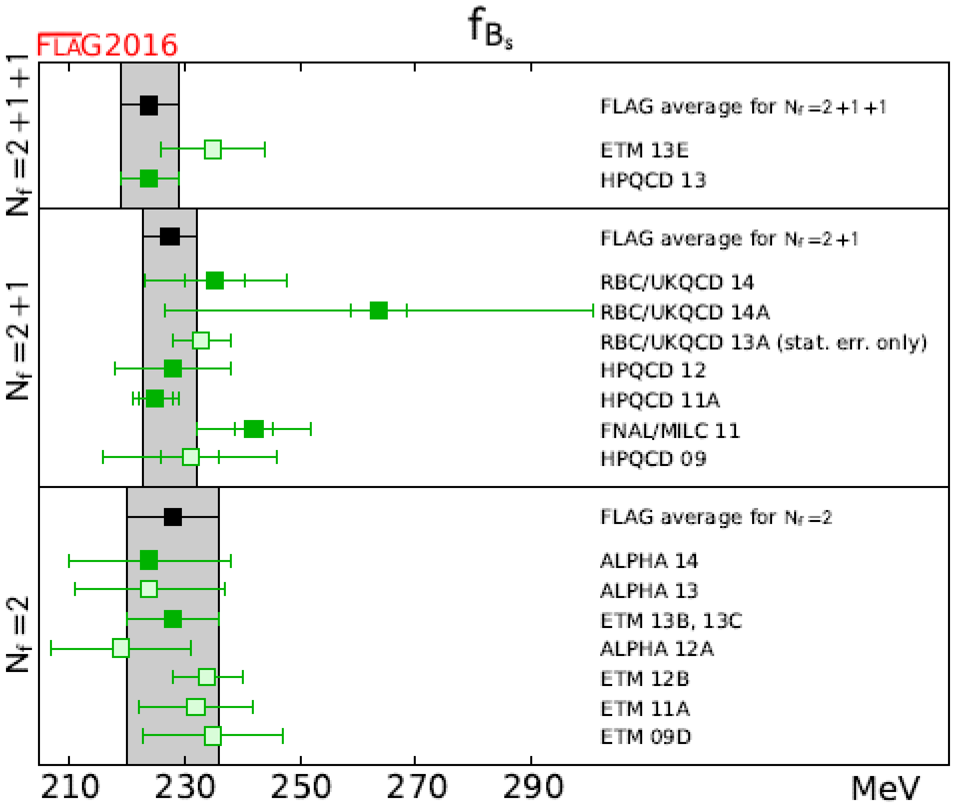
$$\Gamma\left(B_s^0 \to \mu^+\mu^-\right) \sim \frac{G_F^2 \alpha^2}{64\pi^3} m_{Bs}^2 f_{Bs}^2 \left|V_{tb} V_{ts}\right|^2 \left|2 m_\mu C_{10}\right|^2$$

Only one hadronic parameter: f_{Bs}

$$\langle 0 | \bar{b}\gamma^\mu \gamma_5 s | B_s^0 \rangle = i q^\mu f_{Bs}$$

❖hadronic uncertainties?

b→s transitions: $B_s \to \mu\mu$



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❖hadronic uncertainties under control

Lattice: ETMC, MILC, HPQCD

Practically a Miracle!

1) Continuum limit

2) different lattice approaches: NRQCD and Relativ. *b*

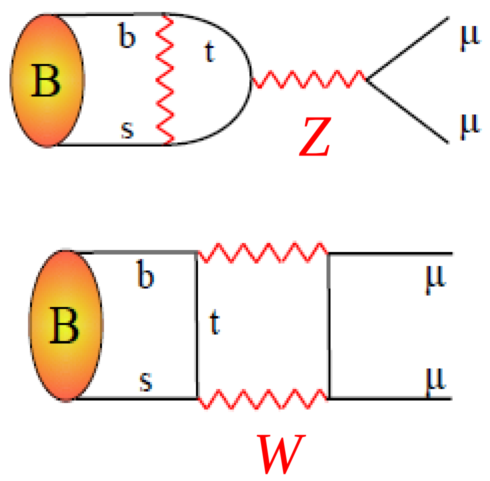
Only one hadronic parameter: f_{Bs}

$$\langle 0|\bar{b}\gamma^\mu\gamma_5 s|B_s^0\rangle = iq^\mu f_{Bs}$$

$$f_{Bs} = (228 \pm 4)\,\mathrm{MeV}$$

2% hadronic uncertainty

$b \to s$ transitions: $B_s \to \mu\mu$



$$\Gamma\left(B_s^0 \to \mu^+\mu^-\right) \sim \frac{G_F^2 \alpha^2}{64\pi^3} m_{Bs}^2 f_{Bs}^2 \left|V_{tb} V_{ts}\right|^2 \left|2 m_\mu C_{10}\right|^2$$

$$O_{10} = \left(\bar{b}\gamma_L^\mu s\right)\bar{\ell}\gamma^\mu\gamma_5\ell$$

2% hadronic uncertainty

✓ $\mathrm{Br}^{exp}(B_s \to \mu\mu) = (2.8 \pm 0.7)10^{-9}$ (25%)

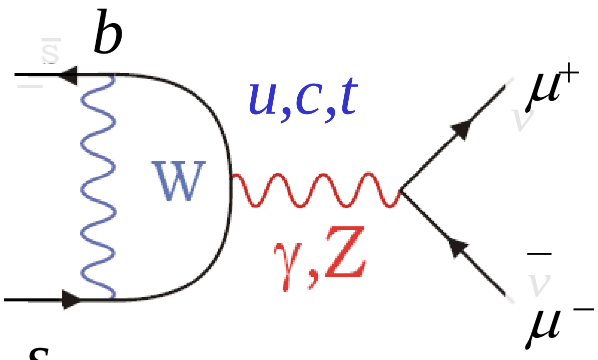
➲ $\mathrm{Br}^{SM}(B_s \to \mu\mu) = (3.65 \pm 0.23)10^{-9}$ (6%)

EXP 1.2 σ below SM

(small significance but ...)

C_{10} : short-distance coupling, q^2-independent!

B Anomalies: $b \to s\ \mu\mu$



+ W box

From W,Z, top

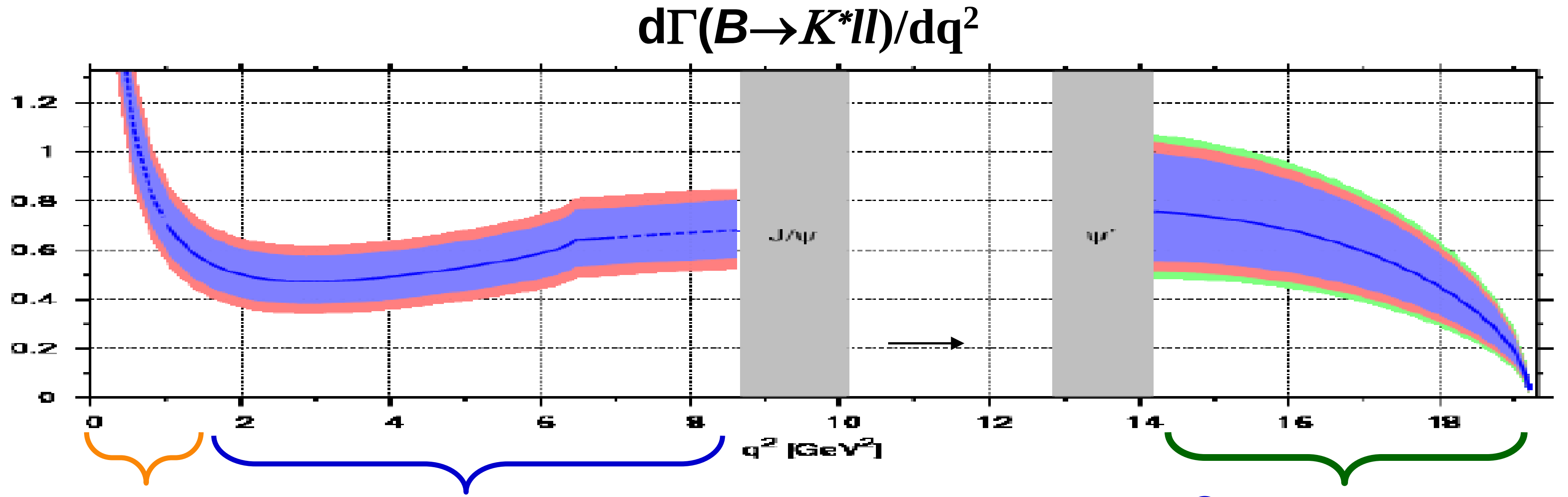
$$Heff = \begin{cases} C_7 \times \bar{b}_R \sigma^{\mu\nu} s_L F_{\mu\nu} + \\ C_9 \times \overline{b_L} \gamma^{\mu} s_L \bar{l} \gamma^{\mu} l + \\ C_{10} \times \bar{b}_L \gamma^{\mu} s_L \bar{l} \gamma^{\mu} \gamma_5 l \end{cases}$$

$B \to K\mu\mu$

$B \to K^{*}\mu\mu$

Complications by charm and chiral loops

$b \to s$ transitions: Example $B \to K^* \mu\mu$



☺ γ pole C_7: chiral loops

☺ large recoil range

$1\text{GeV}^2 < q^2 < 6\ \text{GeV}^2$

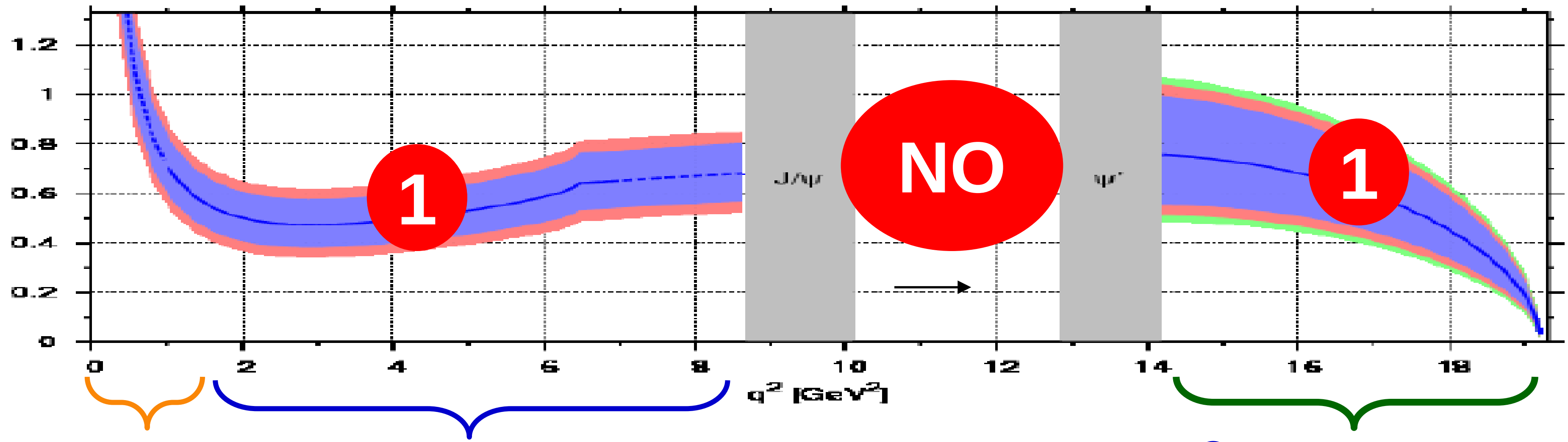
☹ J/ψ Resonances: (non-local) γ effects

☺low recoil region

$q^2 > 14.2\ \text{GeV}^2$

$b \to s$ transitions: $B \to K^* \mu\mu$

$d\Gamma(B \to K^* ll)/dq^2$



☺ **γ pole C_7:** chiral loops

☺ **large recoil range**
$C_{9,10}(Z, t, NP)$
$1\,\mathrm{GeV}^2 < q^2 < 6\,\mathrm{GeV}^2$

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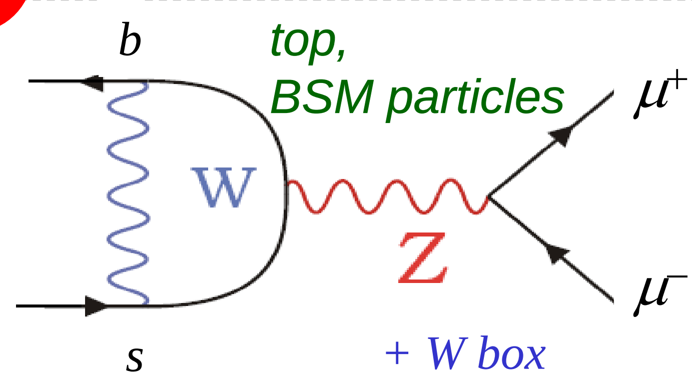
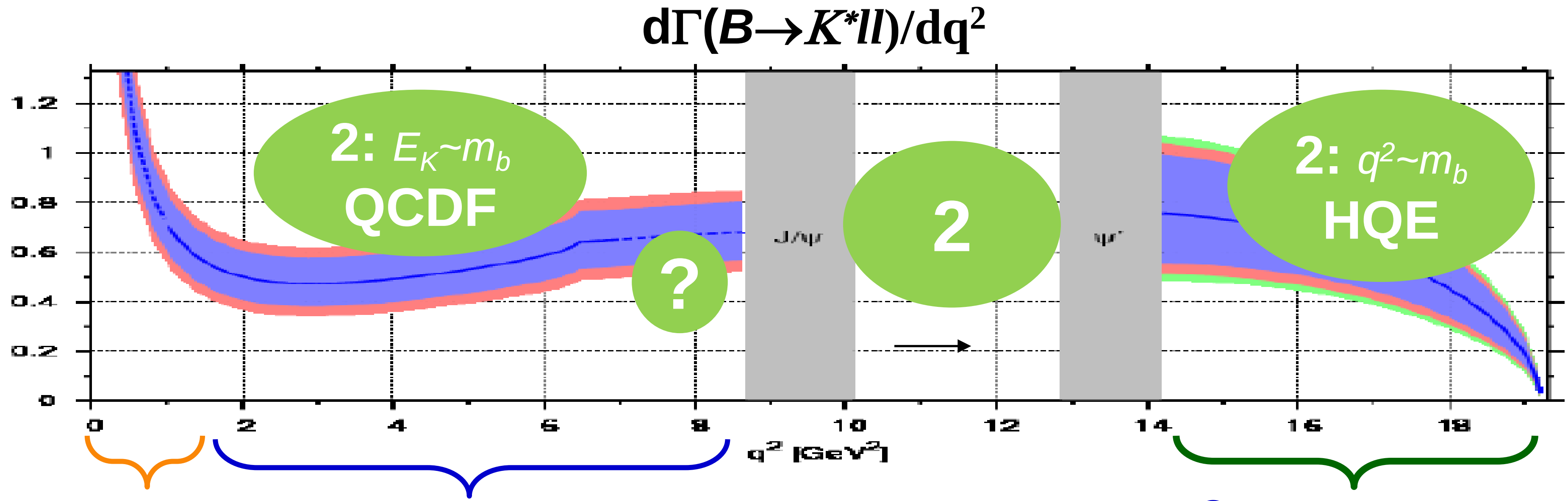
1



⇨

$$H_{SD}^{eff} = \begin{cases} C_7 \times \bar{b}\sigma^{\mu\nu} s F_{\mu\nu} \\ C_{10} \times \bar{b}\gamma_L^{\mu} s \bar{l}\gamma^{\mu}\gamma_5 l \\ C_9 \times \bar{b}\gamma_L^{\mu} s \bar{l}\gamma^{\mu} l \end{cases}$$

$b \to s$ transitions: $B \to K^* \mu\mu$



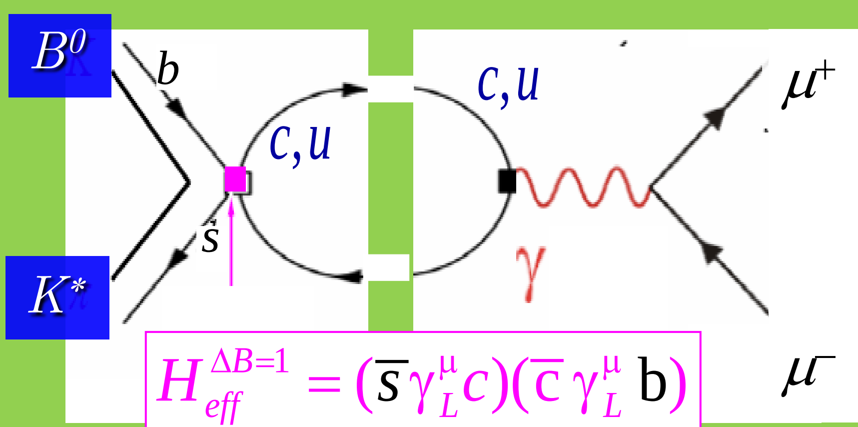
☺ γ pole C_7: chiral loops

😐 **large recoil range**
$C_{9,10}$(Z, t, NP) + LD γcc :
$1\,\mathrm{GeV}^2 < q^2 < 6\,\mathrm{GeV}^2$

☹ **J/ψ Resonances**:
(non-local) γ effects

☺ **low recoil region**
$C_{9,10}$ (Z, t, NP)
$q^2 > 14.2\,\mathrm{GeV}^2$

2



$$H_{eff}^{\Delta B=1} = (\bar{s}\gamma_L^{\mu} c)(\bar{c}\gamma_L^{\mu} b)$$

- **Non-local Interaction (LD)**

$$H_{LD} = \frac{\alpha_{em}}{q^2} \left\langle K^* \gamma \middle| T\left(H_{eff}^{\Delta B=1}(x) J_{\gamma}^{em}(0)\right) \middle| B \right\rangle$$

- "**Non-Factorizable Contributions**"

$$\langle K^* | H_{SD}^{eff} + H_{LD} | B \rangle = C_{7,9,10}^{SD} \langle K^* | Q_{7,9,10} | B \rangle + \langle K^* | H_{LD} | B \rangle$$

1 2

1 ***Hadronic Uncertainties:*** $\langle K^* | Q_{7,9,10} | B \rangle$?

Form Factors?

$$Q_7 = \frac{e^2 m_b}{16\pi^2} \bar{s}_L \sigma^{\mu\nu} b_R F_{\mu\nu} \qquad Q_9 = \frac{e^2}{16\pi^2} \bar{s}_L \gamma^\mu b_L \bar{l} \gamma_\mu l \qquad Q_{10} = \frac{e^2}{16\pi^2} \bar{s}_L \gamma^\mu b_L \bar{l} \gamma_5 \gamma_\mu l$$

2 ***Hadronic Uncertainties:*** $H_{LD} = \frac{\alpha_{em}}{q^2} \langle K^* \gamma | T(H_{eff}^{\Delta B=1}(x) J_\gamma^{em}(0)) | B \rangle$

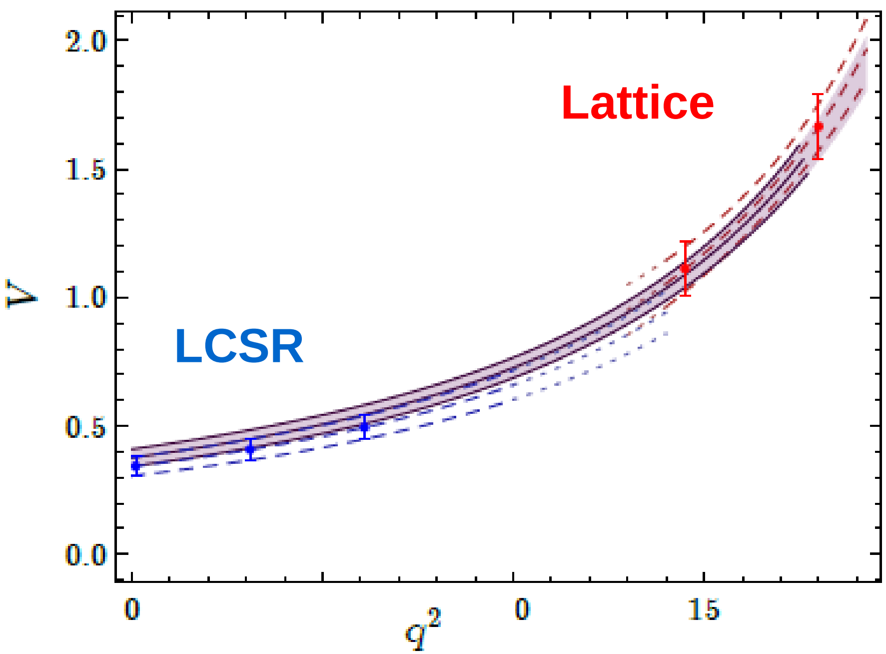
Non-local operators

$$H_{eff}^{\Delta B=1} \begin{cases} Q_1^c = (\bar{s}_L \gamma_\mu T^a c_L)(\bar{c}_L \gamma^\mu T^a b_L) & Q_2^c = (\bar{s}_L \gamma_\mu c_L)(\bar{c}_L \gamma^\mu b_L) \\ Q_3 = (\bar{s}_L \gamma_\mu b_L) \sum_q (\bar{q} \gamma^\mu q) & Q_4 = (\bar{s}_L \gamma_\mu T^a b_L) \sum_q (\bar{q} \gamma^\mu T^a q) \end{cases}$$

1

Form Factors Determinacions?

$B \to K^*$: 7 form factors in QCD: $V(q^2)$, $A_{0,1,2}(q^2)$, $T_{1,2,3}(q^2)$



LOW q^2: $E_{K^*} \sim m_b$

LCSR :

A. Bharucha et al. 2015

(*B* → *K:* Ball et al. 2004)

HIGH q^2: $q^2 \sim m_b^2$

Lattice:

Horgan et al. 2013

(*B* → *K:* E. Gamiz et al. 2016)

☺ **FFs by LCSR extrapolated at large q^2 are in agreement with the Lattice ones.**

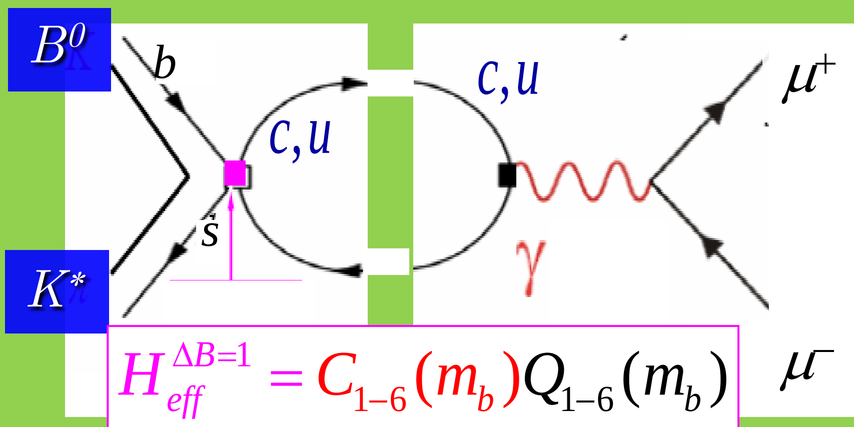
15% uncertainties -> tough to improve it

2

Non-Local operators: charm and chiral loops $[Q_{1-6}]$

$$Q_1^c = (\bar{s}_L \gamma_\mu T^a c_L)(\bar{c}_L \gamma^\mu T^a b_L) \qquad Q_2^c = (\bar{s}_L \gamma_\mu c_L)(\bar{c}_L \gamma^\mu b_L)$$

$$Q_3 = (\bar{s}_L \gamma_\mu b_L) \sum_q (\bar{q}\gamma^\mu q) \qquad Q_4 = (\bar{s}_L \gamma_\mu T^a b_L) \sum_q (\bar{q}\gamma^\mu T^a q)$$



$$H_{eff}^{\Delta B=1} = C_{1-6}(m_b) Q_{1-6}(m_b)$$

$$\longrightarrow \frac{\alpha_{em}}{q^2} \langle K^* \gamma | T(H_{eff}^{\Delta B=1}(x) J_\gamma^{em}(0)) | B \rangle$$

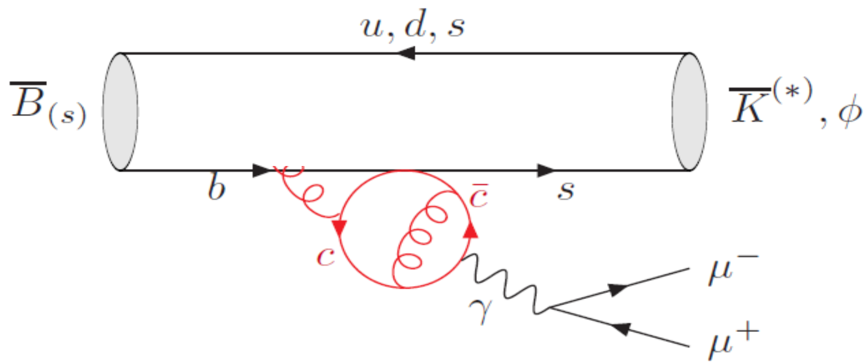
$$O_9 = (\bar{b}\gamma_L^\mu s)\bar{\ell}\gamma^\mu \ell$$

a) Easy Contributions: (no spectator effects): Factorisable effects: NLO QCDF

$$C_9^{tot} = C_9^{SD} + C_9^{cc-fact}(q^2)$$

SD: Z, t, NP
q^2-independent
~4.0

LD: charm
q^2-dependent
~0.4

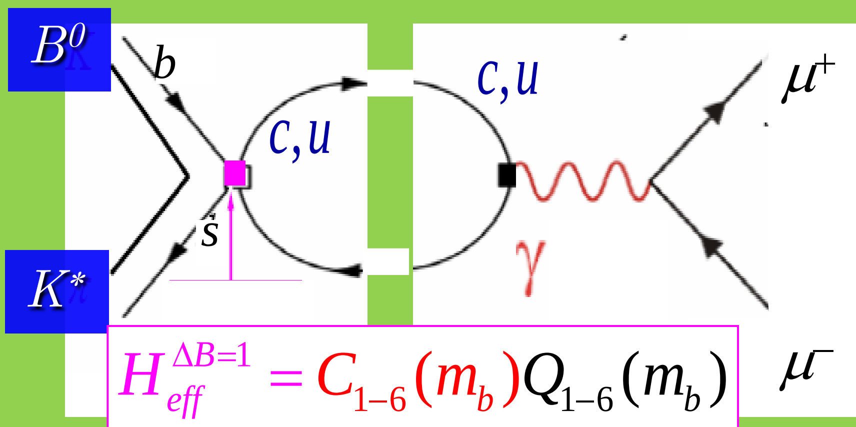


2

Non-Local operators: charm and chiral loops $[Q_{1-6}]$

$$Q_1^c = (\bar{s}_L \gamma_\mu T^a c_L)(\bar{c}_L \gamma^\mu T^a b_L) \qquad Q_2^c = (\bar{s}_L \gamma_\mu c_L)(\bar{c}_L \gamma^\mu b_L)$$

$$Q_3 = (\bar{s}_L \gamma_\mu b_L) \sum_q (\bar{q} \gamma^\mu q) \qquad Q_4 = (\bar{s}_L \gamma_\mu T^a b_L) \sum_q (\bar{q} \gamma^\mu T^a q)$$



$$H_{eff}^{\Delta B=1} = C_{1-6}(m_b) Q_{1-6}(m_b)$$

$$\longrightarrow \frac{\alpha_{em}}{q^2} \langle K^* \gamma | T(H_{eff}^{\Delta B=1}(x) J_\gamma^{em}(0)) | B \rangle$$

$$O_9 = (\bar{b} \gamma_L^\mu s) \bar{\ell} \gamma^\mu \ell$$

a) Easy Contributions: (no spectator effects): Factorisable effects: NLO QCDF

$$C_9^{tot} = \underline{C_9^{SD}} + \underline{C_9^{cc-fact}(q^2)}$$

SD: Z, t, NP
q^2-independent
~4.0

LD: charm
q^2-dependent
~0.4

$$C_{9,LO}^{cc-fact}(q^2) = C_3 + \frac{64}{9} C_5 + \frac{64}{27} C_6 - \frac{1}{2} h(q^2, 0) \left(C_3 + \frac{4}{3} C_4 + 16 C_5 + \frac{64}{3} C_6 \right)$$
$$+ h(q^2, m_c) \left(\frac{4}{3} C_1 + C_2 + 6 C_3 + 60 C_5 \right) - \frac{1}{2} h(q^2, m_b) \left(7 C_3 + \frac{4}{3} C_4 + 76 C_5 + \frac{64}{3} C_6 \right), \quad (4)$$

and $z = 4m_q^2/q^2$.

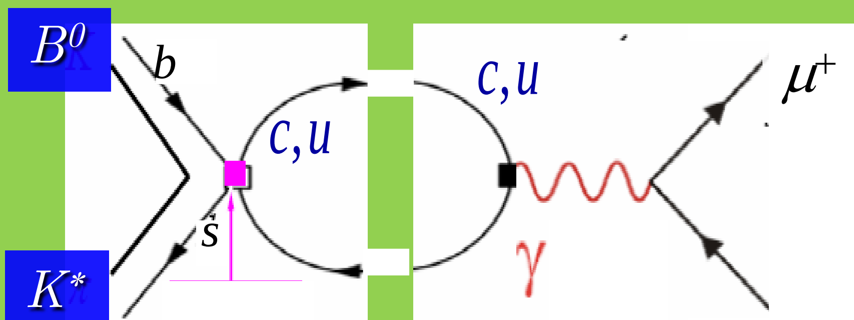
$$h(q^2, m_q) = -\frac{4}{9} \left(\ln \frac{m_q^2}{\mu^2} - \frac{2}{3} - z \right) - \frac{4}{9} (2 + z) \sqrt{|z - 1|} \times \begin{cases} \arctan \frac{1}{\sqrt{z-1}} & z > 1 \\ \ln \frac{1 + \sqrt{1-z}}{\sqrt{z}} - \frac{i\pi}{2} & z \le 1 \end{cases},$$

2

Non-Local operators: charm and chiral loops $[Q_{1-6}]$

$$Q_1^c = (\bar{s}_L \gamma_\mu T^a c_L)(\bar{c}_L \gamma^\mu T^a b_L) \qquad Q_2^c = (\bar{s}_L \gamma_\mu c_L)(\bar{c}_L \gamma^\mu b_L)$$

$$Q_3 = (\bar{s}_L \gamma_\mu b_L) \sum_q (\bar{q} \gamma^\mu q) \qquad Q_4 = (\bar{s}_L \gamma_\mu T^a b_L) \sum_q (\bar{q} \gamma^\mu T^a q)$$

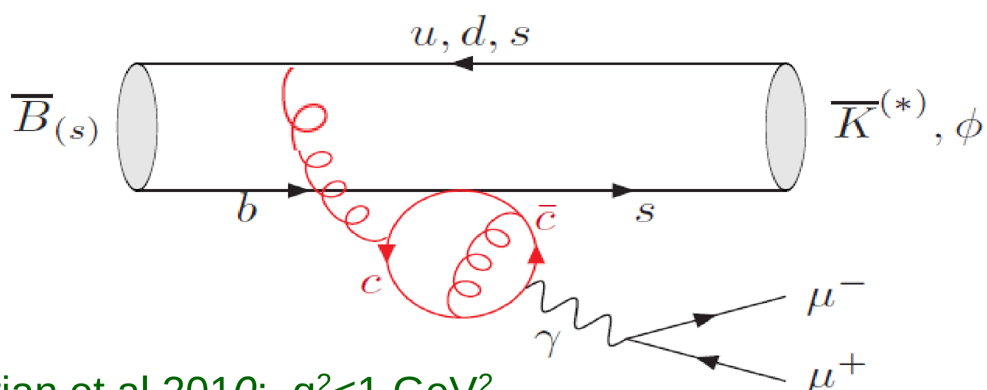


$$H_{eff}^{\Delta B=1} = C_{1-6}(m_b) Q_{1-6}(m_b)$$

$$\longrightarrow \frac{\alpha_{em}}{q^2} \langle K^* \gamma | T(H_{eff}^{\Delta B=1}(x) J_\gamma^{em}(0)) | B \rangle$$

$$O_9 = \left(\bar{b} \gamma_L^\mu s\right) \bar{\ell} \gamma^\mu \ell$$

b) Tough contractions: Non-factorizable power corrections (spectator effects)



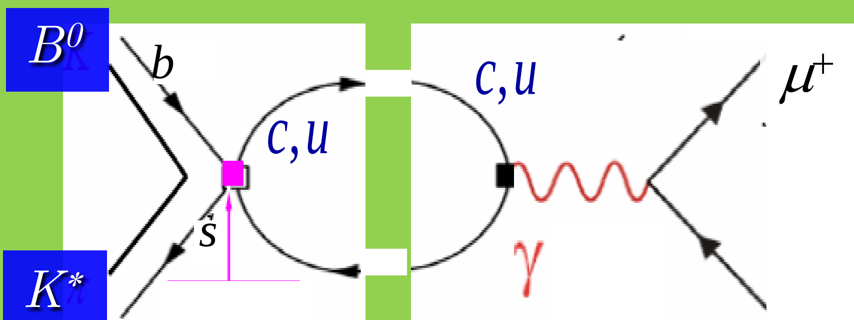
Khodjamirian et al,2010: $q^2 < 1$ GeV^2

2

Non-Local operators: charm and chiral loops $[Q_{1-6}]$

$$Q_1^c = (\bar{s}_L \gamma_\mu T^a c_L)(\bar{c}_L \gamma^\mu T^a b_L) \qquad Q_2^c = (\bar{s}_L \gamma_\mu c_L)(\bar{c}_L \gamma^\mu b_L)$$

$$Q_3 = (\bar{s}_L \gamma_\mu b_L) \sum_q (\bar{q}\gamma^\mu q) \qquad Q_4 = (\bar{s}_L \gamma_\mu T^a b_L) \sum_q (\bar{q}\gamma^\mu T^a q)$$



$$H_{eff}^{\Delta B=1} = C_{1-6}(m_b) Q_{1-6}(m_b)$$

$$\longrightarrow \frac{\alpha_{em}}{q^2} \langle K^* \gamma | T(H_{eff}^{\Delta B=1}(x) J_\gamma^{em}(0)) | B \rangle$$

$$O_9 = (\bar{b}\gamma_L^\mu s)\bar{\ell}\gamma^\mu \ell$$

b) Tough contractions: Non-factorizable power corrections (spectator effects)

$$C_9^{tot} = C_9^{SD} + C_9^{cc-fac}(q^2) + C_9^{ccNoF}(q^2)$$

Talk by Bernat

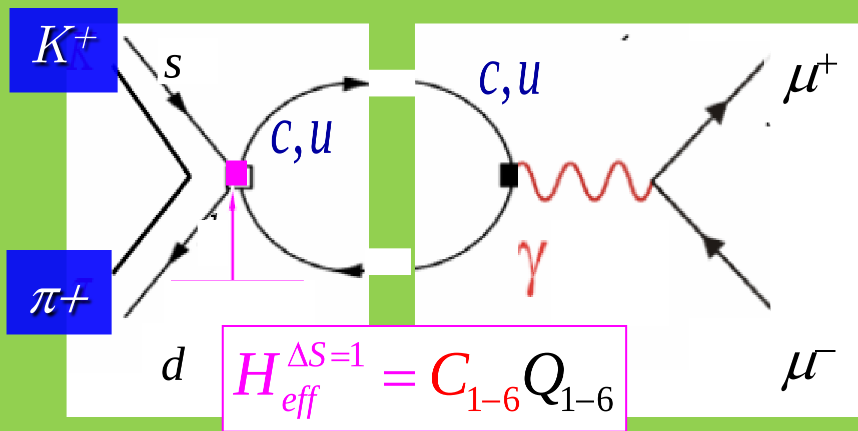
SD: Z, t, NP	LD-fact: charm	LD-no fact: charm
q^2-independent	q^2-dependent	q^2-dependent
~4.0	~0.4	*"golden test from data"*

2

Non-Local operators: charm and chiral loops $[Q_{1-6}]$

$$Q_1^c = (\bar{s}_L \gamma_\mu T^a c_L)(\bar{c}_L \gamma^\mu T^a d_L) \qquad Q_2^c = (\bar{s}_L \gamma_\mu c_L)(\bar{c}_L \gamma^\mu d_L)$$

$$Q_3 = (\bar{s}_L \gamma_\mu d_L) \sum_q (\bar{q} \gamma^\mu q) \qquad Q_4 = (\bar{s}_L \gamma_\mu T^a d_L) \sum_q (\bar{q} \gamma^\mu T^a q)$$



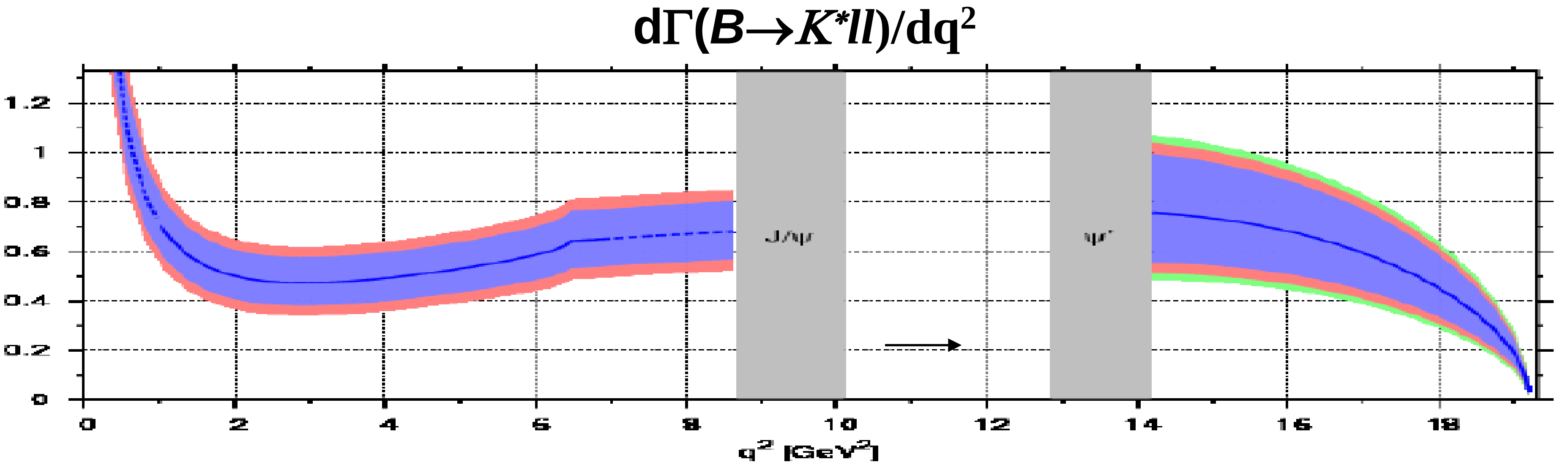
$$\longrightarrow \langle \pi | T(H_{eff}^{\Delta B=1}(x) J_\gamma^{em}(0)) | K \rangle$$

Non-factorizable Charm Loops from first principle.

N. Christ et al. **arXiv:1504.01170, arXiv:1602.01374**
Carrasco et al., **arXiv:1502.00257**

Only recently the same issue addressed in the Kaon physics by from the Lattice QCD.

$b \to s$ transitions: $B \to K^* \mu\mu$

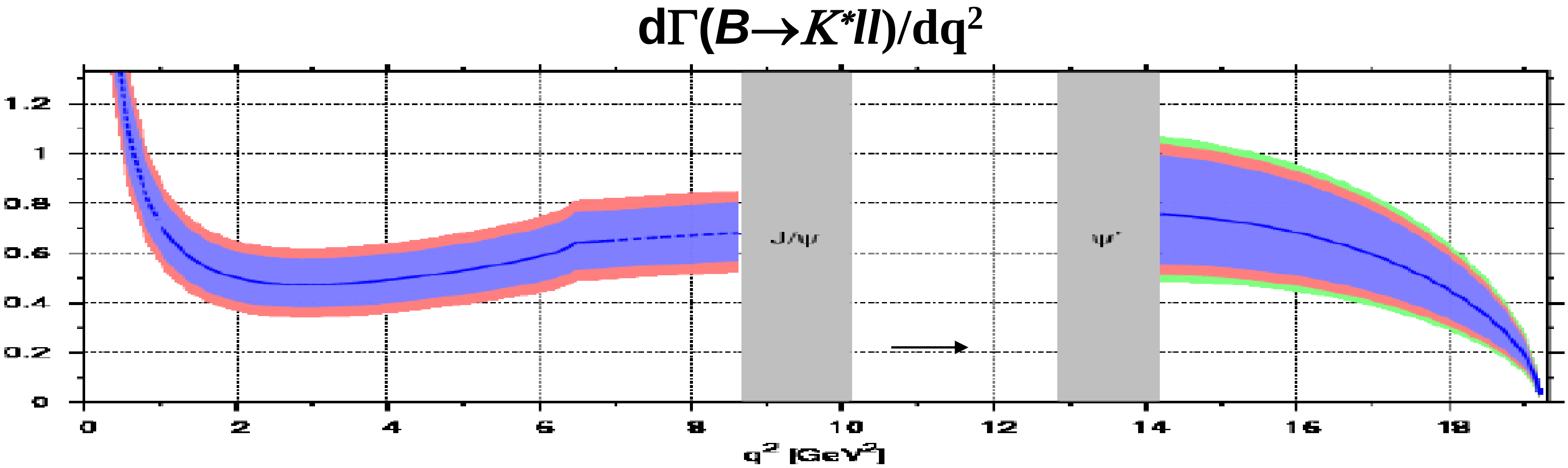


Two sources of QCD uncertainties

1) *Form-Factor s : "Factorizable power corrections"!*

2) *Non-Factorizable power corrections!*

$b \to s$ transitions: $B \to K^* \mu\mu$



NO PANIC

To large extent, uncertainties cancel in super-clean and clean observables

- $R_K = Br(B_d \to K\mu^+\mu^-)/Br(B_d \to K l^+ l^-)$
- $R_{K^*} = Br(B_d \to K^*\mu^+\mu^-)/Br(B_d \to K^* l^+ l^-)$
- **Angular Observables**: *P_5' anomalies*

F.Kruger, J.Matias '05; J. Matias et al. >2010

B Anomalies: LFU on b → s

- **Super-Clean observables**

Form Factors and Non-Factorizable effects are lepton universal

At q^2=[1,6] GeV2
$$R_K \equiv \frac{\mathrm{Br}\left(B^+ \to K^+\mu^+\mu^-\right)}{\mathrm{Br}\left(B^+ \to K^+e^+e^-\right)} = 1 + \mathcal{O}(10^{-4})$$

At q^2=[0.045,1.1] GeV2
$$R_{K^*} \equiv \frac{\Gamma\left(B^0 \to K^{*0}\mu^+\mu^-\right)}{\Gamma\left(B^0 \to K^{0*}e^+e^-\right)} = 0.91 +0.03$$

At q^2=[1.1,6.0]GeV2
$$R_{K^*} \equiv \frac{\Gamma\left(B^0 \to K^{*0}\mu^+\mu^-\right)}{\Gamma\left(B^0 \to K^{0*}e^+e^-\right)} = 1.00 +0.01$$

* EM corrections are lepton-dependent but at ∼ % level Bordone *et al.* EPJC76(2016),8,440

B Anomalies: LFU on $b \to s$

- **Super-Clean observables**

Form Factors and Non-Factorizable effects are lepton universal

$0.745 \pm 0.09_{\rm stat} \pm 0.036_{\rm syst}$

$$R_K \equiv \frac{\text{Br}\left(B^+ \to K^+\mu^+\mu^-\right)}{\text{Br}\left(B^+ \to K^+e^+e^-\right)} = 1 + \mathcal{O}(10^{-4})$$

$0.685^{+0.113}_{-0.069} \pm 0.047$

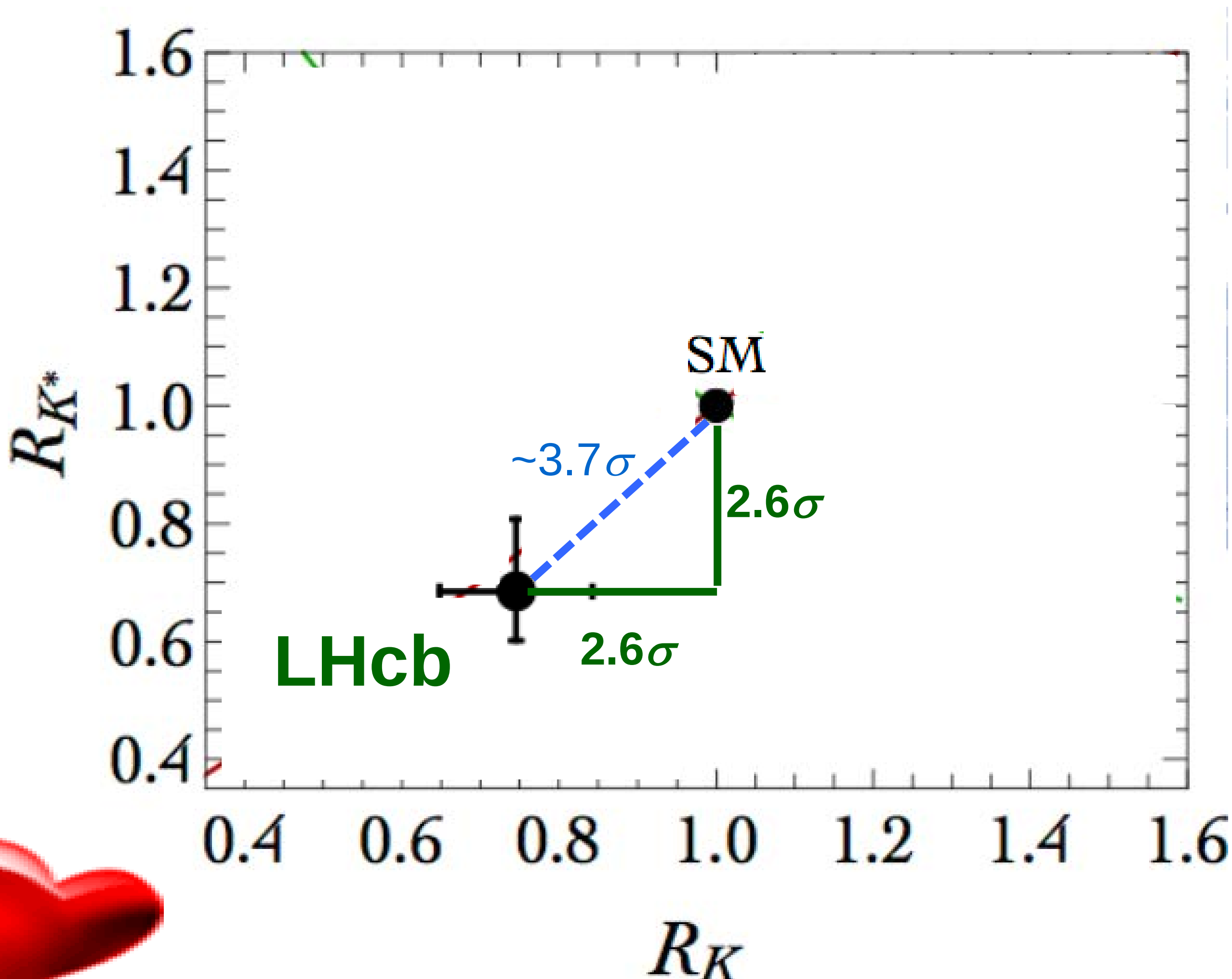
$$R_{K^*} \equiv \frac{\Gamma\left(B^0 \to K^{*0}\mu^+\mu^-\right)}{\Gamma\left(B^0 \to K^{0*}e^+e^-\right)} = 0.91 + 0.03$$

$0.660^{+0.110}_{-0.070} \pm 0.024$

$$R_{K^*} \equiv \frac{\Gamma\left(B^0 \to K^{*0}\mu^+\mu^-\right)}{\Gamma\left(B^0 \to K^{0*}e^+e^-\right)} = 1.00 + 0.01$$

LHcb 2.6σ below than the SM

B Anomalies: LFU on $b \to s$

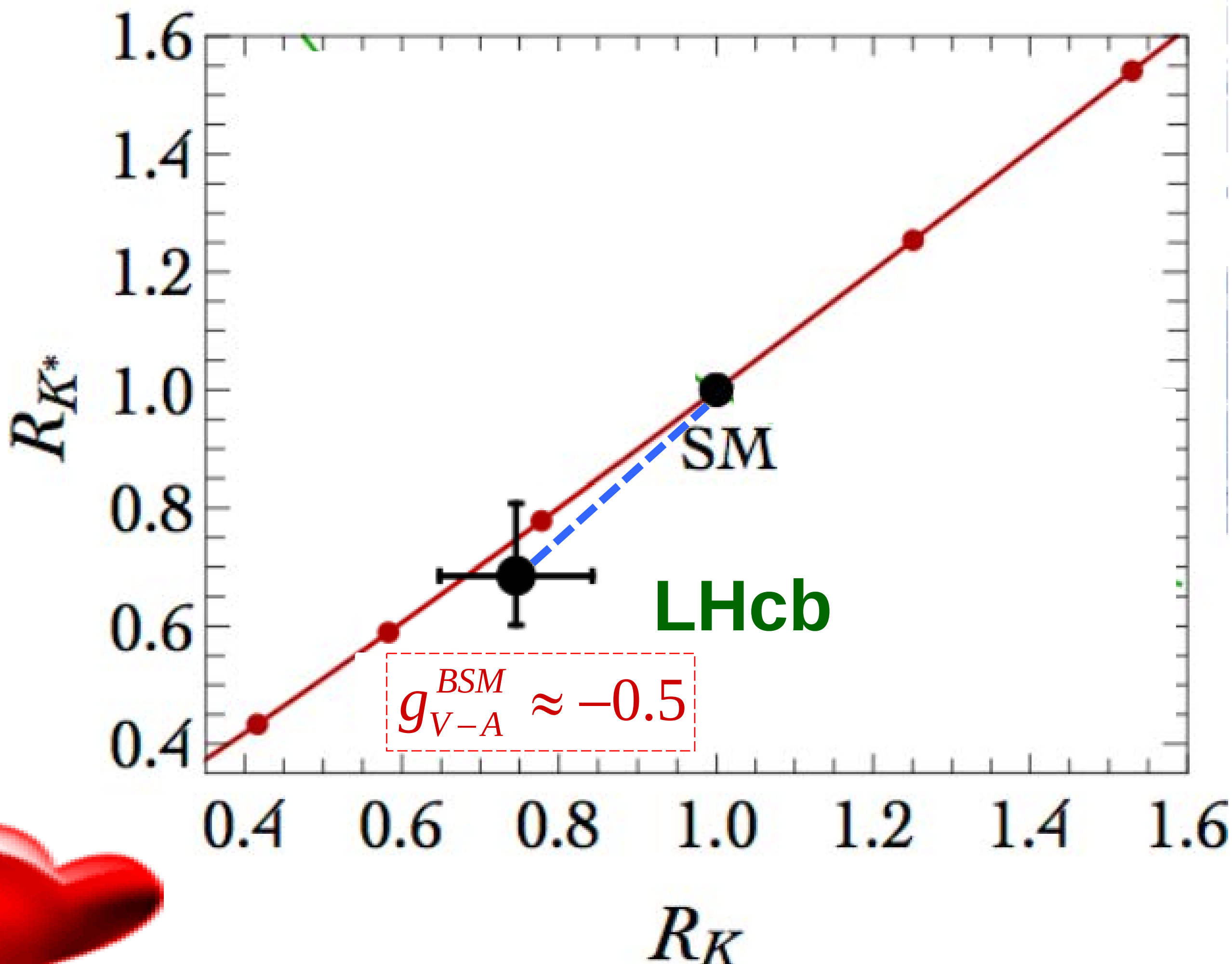


GOING STRAIGHT
~3.7σ
by Pitagora Theorem

At q^2=[1,6] GeV2

B Anomalies: LFU on $b \to s$

$$R_K = 1 + 0.23 g_{V-A}^{BSM} \longrightarrow R_{K^*} = R_K$$

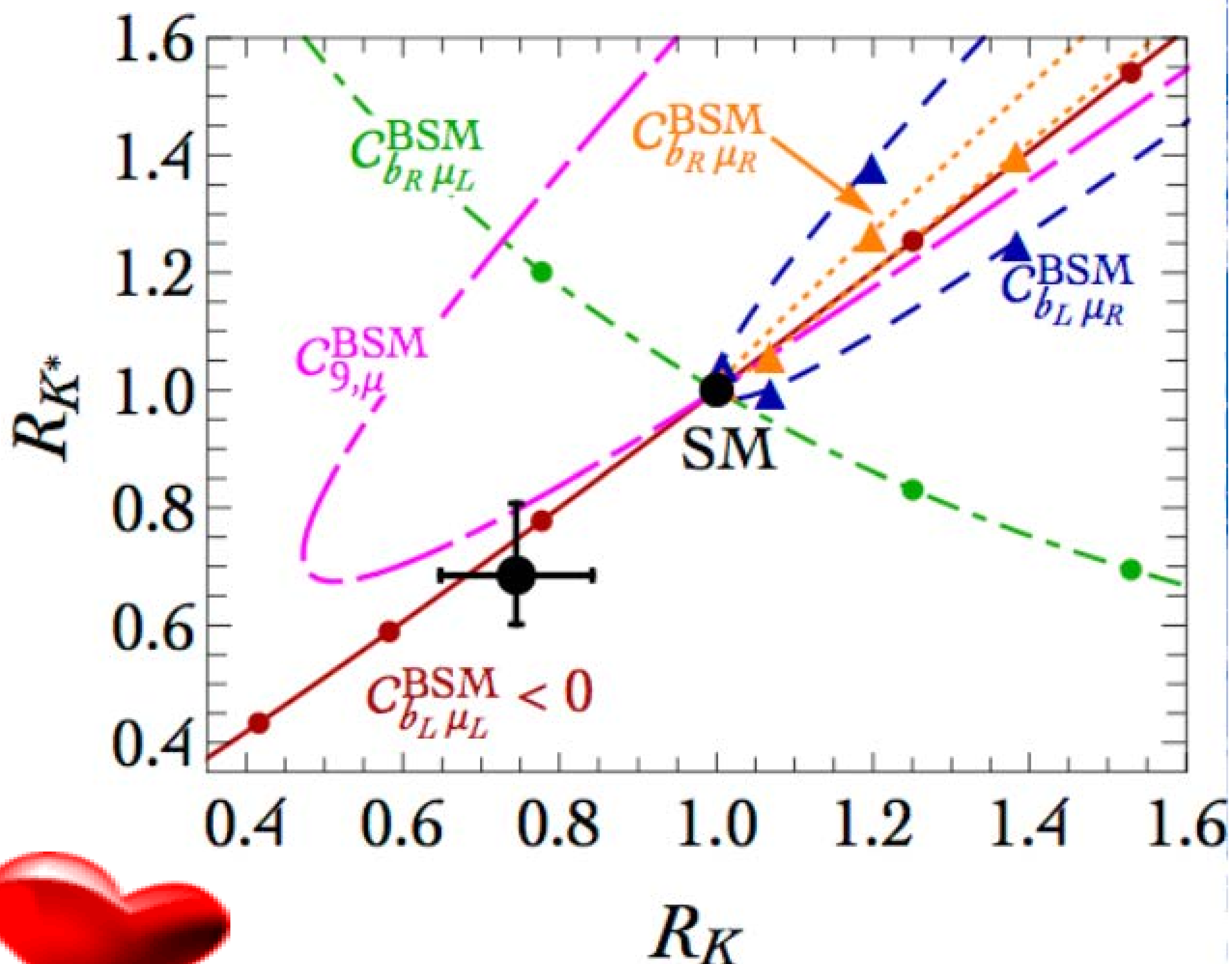


$$g_{V-A}^{BSM} = \frac{C_9^\mu - C_{10}^\mu}{2}$$

At q^2=[1,6] GeV2

B Anomalies: LFU on b → s

$$R_{K^*} \simeq R_K - 0.4\,\mathrm{Re}\left(C^{\mathrm{BSM}}_{b_R\mu_L} - C^{\mathrm{BSM}}_{b_R e_L}\right)$$



Talk by Bernat, Javier (Fri), P. Owen (Fri)

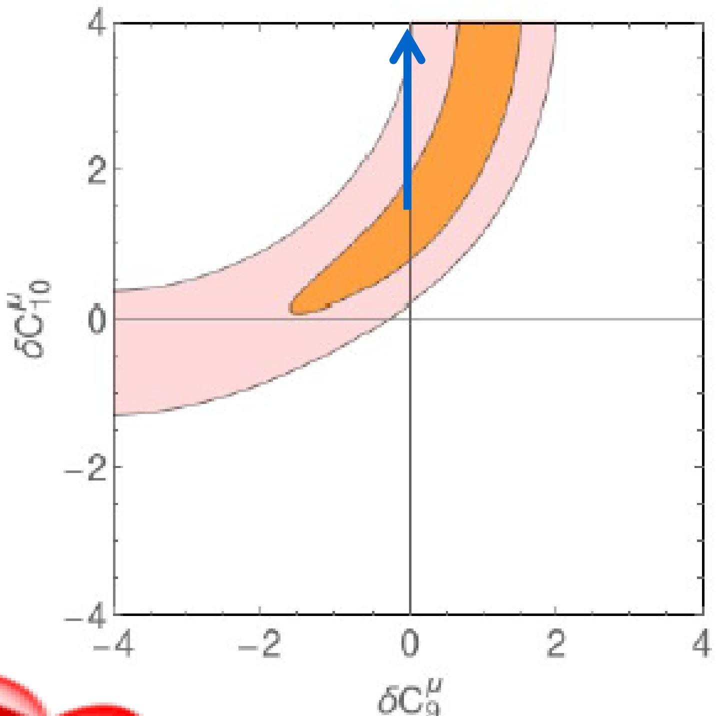
$$C_9^\mu = \frac{1}{2}\left(C_{b_L\mu_L} + C_{b_L\mu_R}\right)$$

$$C_{10}^\mu = \frac{1}{2}\left(C_{b_L\mu_R} - C_{b_L\mu_L}\right)$$

D'Amico et al.
B. Capdevila et al.
J. Camalich et al.
A. Celis, J. Fuentes-Martin.
D. Straub et. Al
M. Ciuchini et.

B Anomalies: LFU on $b \to s$

Obs.	Expt.	SM	$\delta C_L^\mu = -0.5$	$\delta C_9^\mu = -1$	$\delta C_{10}^\mu = 1$	$\delta C_9'^\mu = -1$
R_K [1, 6] GeV^2	0.745 ± 0.090	$1.0004^{+0.0008}_{-0.0007}$	$0.773^{+0.003}_{-0.003}$	$0.797^{+0.002}_{-0.002}$	$0.778^{+0.007}_{-0.007}$	$0.796^{+0.002}_{-0.002}$
R_{K^*} [0.045, 1.1] GeV^2	0.66 ± 0.12	$0.920^{+0.007}_{-0.006}$	$0.88^{+0.01}_{-0.02}$	$0.91^{+0.01}_{-0.02}$	$0.862^{+0.016}_{-0.011}$	$0.98^{+0.03}_{-0.03}$
R_{K^*} [1.1, 6] GeV^2	0.685 ± 0.120	$0.996^{+0.002}_{-0.002}$	$0.78^{+0.02}_{-0.01}$	$0.87^{+0.04}_{-0.03}$	$0.73^{+0.03}_{-0.04}$	$1.20^{+0.02}_{-0.03}$
R_{K^*} [15, 19] GeV^2	–	$0.998^{+0.001}_{-0.001}$	$0.776^{+0.002}_{-0.002}$	$0.793^{+0.001}_{-0.001}$	$0.787^{+0.004}_{-0.004}$	$1.204^{+0.007}_{-0.008}$



1) C_{10}(BSM)>0 suggested!!!

Only from Super-Clean observables:

J. Camalich et al.
D'Amico et al.
B. Capdevila et al.
A. Celis, J. Fuentes-Martin.
D. Straub et. Al
M. Ciuchini et.

B Anomalies: LFU on $b \to s$

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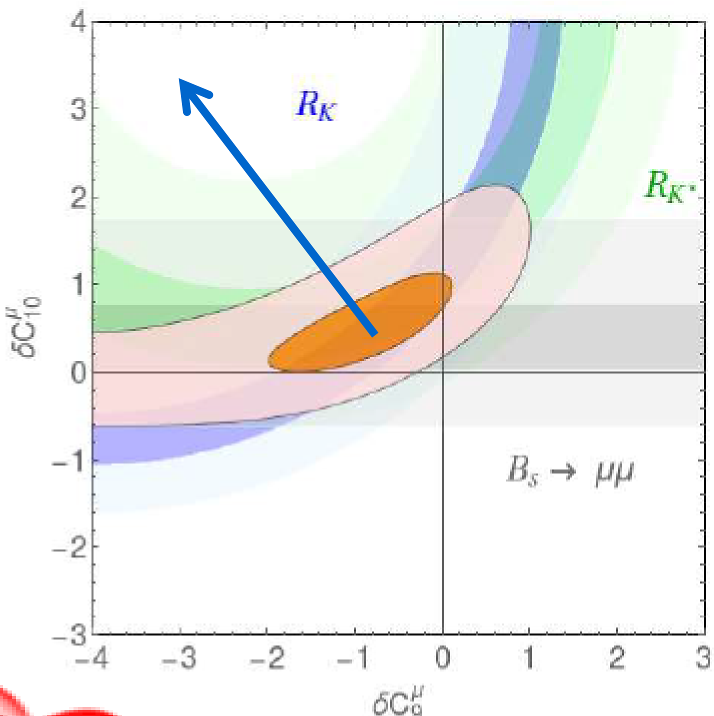


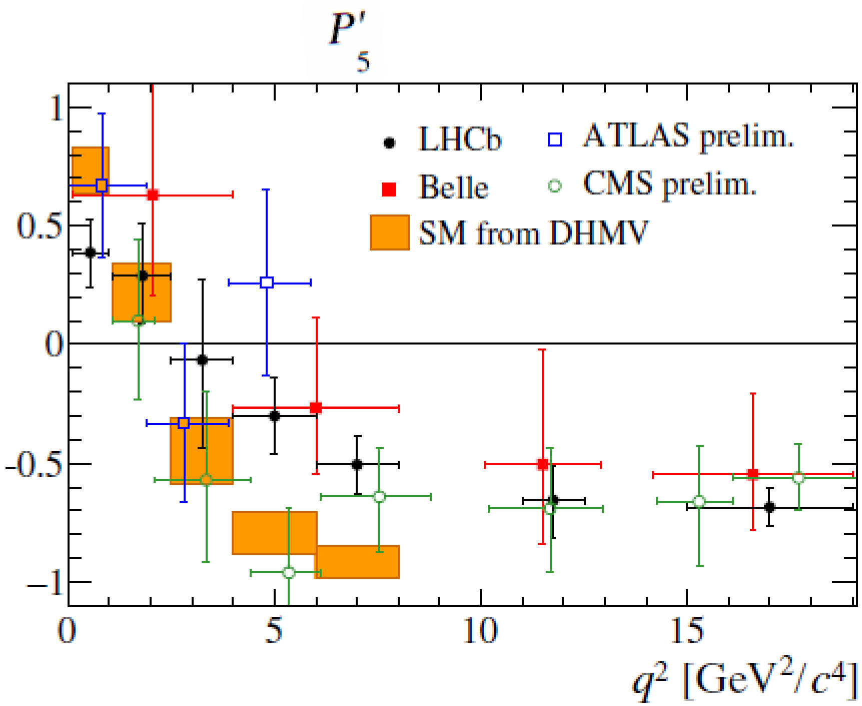
1) C_{10}(BSM)>0 suggested!!!

Fit suggests nonzero $C_L = (C_9 - C_{10})/2$

Only from Super-Clean observables:

J. Camalich et al.
D'Amico et al.
B. Capdevila et al.
A. Celis, J. Fuentes-Martin.
D. Straub et. Al
M. Ciuchini et.

B Anomalies: $B \to K^* (\to K\pi)\mu\mu$: P_5' *the clean*



$$\frac{1}{d\Gamma/dq^2}\frac{d^4\Gamma}{d\cos\theta_\ell\, d\cos\theta_K\, d\phi\, dq^2} =$$

$$\frac{9}{32\pi}\Big[\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_\ell$$
$$- F_L\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi$$
$$+ S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi + S_5\sin 2\theta_K\sin\theta_\ell\cos\phi$$
$$+ S_6\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\phi$$
$$+ S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big],$$

$$P'_{i=4,5,6,8} = \frac{S_{j=4,5,7,8}}{\sqrt{F_L(1-F_L)}}.$$

DHMV
JHEP 1301(2013)048

LHCb

2013: 1 fb^{-1} data
$3.7\,\sigma$ in $[4, 8.3]$

2015: 3 fb^{-1} data
$2.8\,\sigma$ in $[4, 6]$
$3.0\,\sigma$ in $[6, 8]$

Belle

2016: $P_5'^{\ell}$ $(\ell = \mu, e)$
$2.5\,\sigma$ in $[4, 8]$

Moriond 2017

Atlas: tension consistent with LHCb and Belle

CMS: consistent with SM

Talk by Bernat

B Anomalies: $B \to K^{(*)}$ Brs: going to dirty obs

Various measurements of branching ratios are low compared to the SM prediction

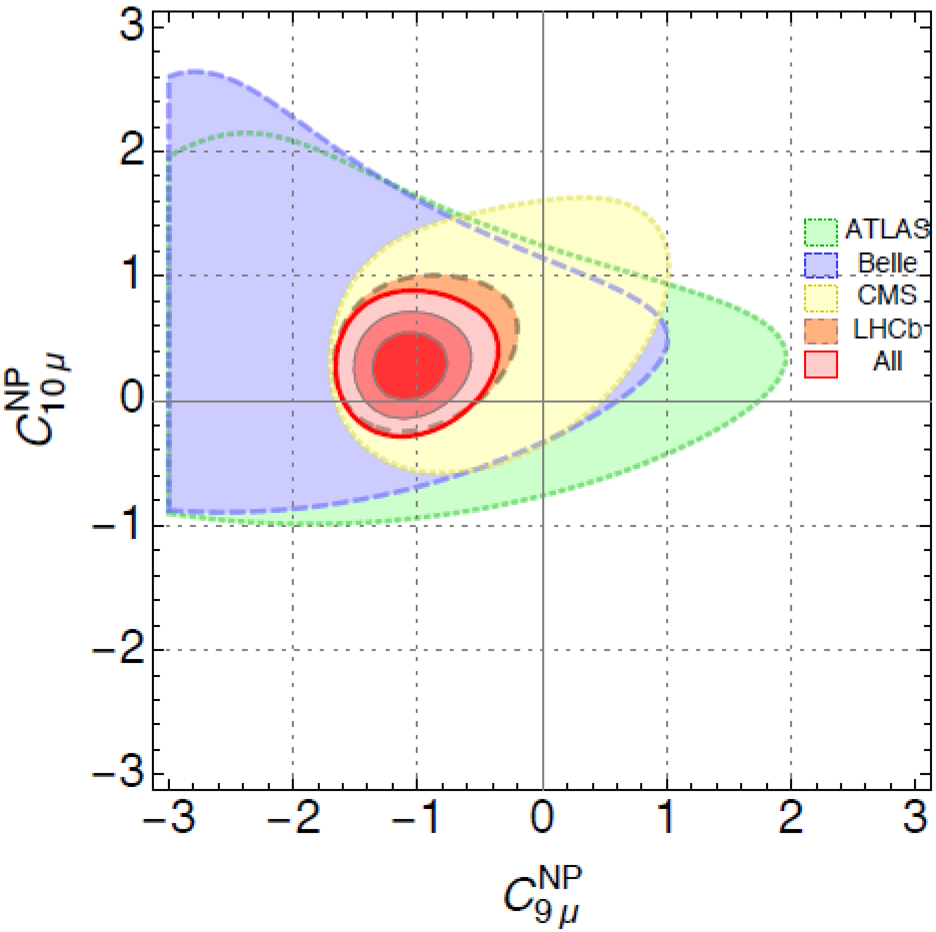
Decay	obs.	q^2 bin	SM pred.	measurement		pull
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	F_L	$[2, 4.3]$	0.81 ± 0.02	0.26 ± 0.19	ATLAS	$+2.9$
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	F_L	$[4, 6]$	0.74 ± 0.04	0.61 ± 0.06	LHCb	$+1.9$
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	S_5	$[4, 6]$	-0.33 ± 0.03	-0.15 ± 0.08	LHCb	-2.2
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	P_5'	$[1.1, 6]$	-0.44 ± 0.08	-0.05 ± 0.11	LHCb	-2.9
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	P_5'	$[4, 6]$	-0.77 ± 0.06	-0.30 ± 0.16	LHCb	-2.8
$B^- \to K^{*-}\mu^+\mu^-$	$10^7 \frac{dBR}{dq^2}$	$[4, 6]$	0.54 ± 0.08	0.26 ± 0.10	LHCb	$+2.1$
$\bar{B}^0 \to \bar{K}^0\mu^+\mu^-$	$10^8 \frac{dBR}{dq^2}$	$[0.1, 2]$	2.71 ± 0.50	1.26 ± 0.56	LHCb	$+1.9$
$\bar{B}^0 \to \bar{K}^0\mu^+\mu^-$	$10^8 \frac{dBR}{dq^2}$	$[16, 23]$	0.93 ± 0.12	0.37 ± 0.22	CDF	$+2.2$
$B_s \to \phi\mu^+\mu^-$	$10^7 \frac{dBR}{dq^2}$	$[1, 6]$	0.48 ± 0.06	0.23 ± 0.05	LHCb	$+3.1$
[recently updated, LHCB 1506.08777]				0.26 ± 0.04		$+3.5$

[Altmannshofer, Straub 1503.06199]

New Physics?

Talk by Bernat

B Anomalies: all together



super-clean observables
+ clean P_5
+ dirty obs (Br, …, F_L)

Overall fit still suggests a nonzero
$C_L = (C_9 - C_{10})/2$

From B. Capdevila et al.

Talk by Bernat

Flavour Anomalies: What Next

- Many tensions at <3 σ : *Thanks GOD!*

- Intriguing correlation is emerging: "*μ_L are ~15% less than expected*"

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  - New Physics?

Please, improve $B_s \to \mu\mu$

- Exp. error 3 times larger than the Theory one.
- Exp. central value 1.2 σ below the Theory one.
- strong and clean test of C_{10}
- C_{10} = SM -> NO extra V-A currents

⇒ *Then extra $U(1)_V$?*

Flavour Anomalies: What Next

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❖ Intriguing correlation is emerging: *"μ_L are ~15% less than expected"*

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	$\langle P_5' \rangle_{[4,6]}$
LHCb	-0.30 ± 0.16
SM	-0.82 ± 0.08

10%
Impossible to reduce QCD uncertainties from now on.

- New Physics?

- *Improve $B_s \to \mu\mu$*
- *Improve R_K and R_{K^*}*
- ***P_i obs still important***
- *R_D from Lhcb?*
  !!Anomaly arises from the R_D -R_{D^*} correlations!!

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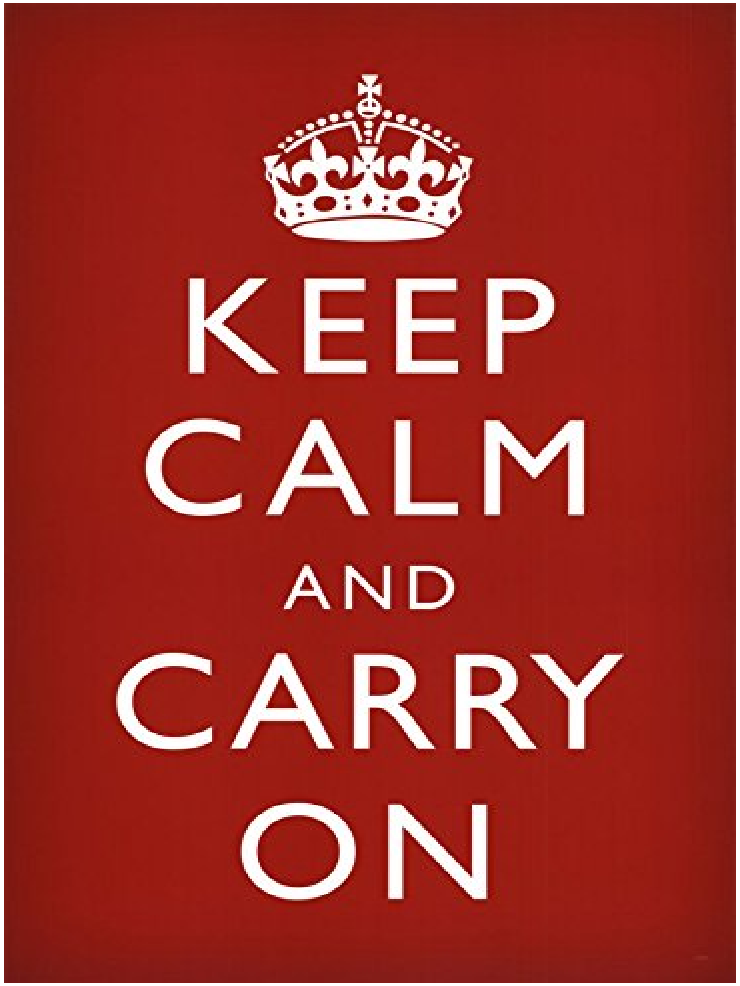
    !!Anomaly arises from the R_D -R_{D^*} correlations!!

Up to now,
very difficult to fit all the tensions in one model!

Flavour Anomalies: Conclusions



Thanks