$b \to s$ transitions and Lattice QCD

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✓ ***BIG News:*** *November 2012, first evidence of $B_s \to \mu^+ \mu^-$ from* LHCb

➲ *PANIC:* the measured $Br^{exp}(B_s \to \mu\mu) = (3.2 \pm 1.5)10^{-9}$ is close to the SM,
$Br^{SM}(B_s \to \mu\mu) = (3.3 \pm 0.3)10^{-9}$

✓ ***NEWS:*** *information from $B \to K\mu\mu$ and $B \to K^*\mu\mu$ soon available* BaBar & LHCb - 2012:

➲ *NO PANIC:* $Br(B \to K^{(*)}\mu\mu)$ and $Br(B_s \to \mu\mu)$ *sensitive to different "b-> s couplings"*

IV Workshop on Fermions and Extended Objects on the Lattice:
June 16-22 (2013), Benasque

✓ Introduction:

➲ *What is Flavor Physics in the Standard Model ?*

➲ *Status of Flavor Physics searches (Babar, Belle, Tevatron, LHcb):*

-> Today, it is fair to say: small deviations from the SM expected !

✓ Future perspectives: *b->s modes "unexplored corner"*

☺ *Tool: Eff. Hamiltonian for the full set of b->s processes!*

☹ **BIG CHALLENGE: hadronic uncertainties => Lattice QCD**

goal: control QCD at low energy at a few percent, by numerical simulation

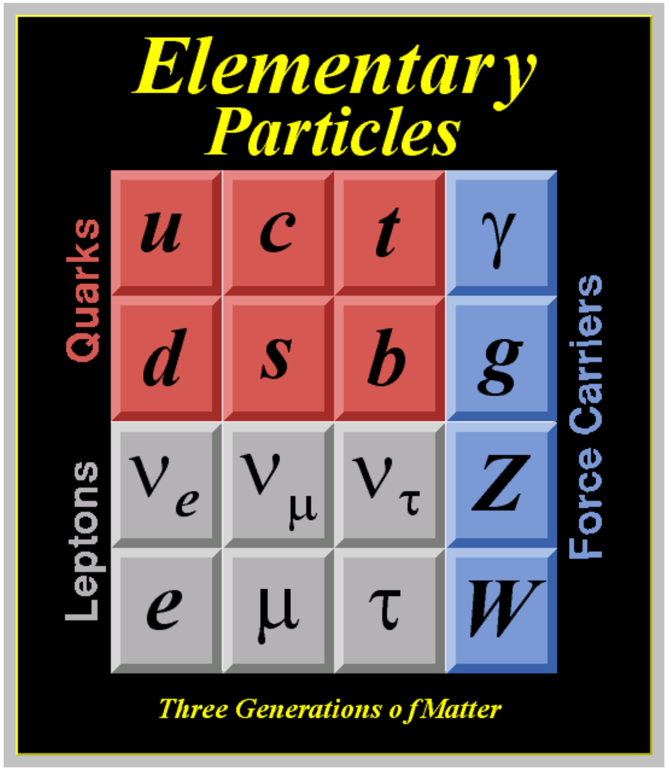
❖ *Potentialities of* $B\to K\mu\mu$ *vs* $B_s\to\mu\mu$

➲ *Theory and Exp. information on* $B\to K\mu\mu$ *is still poor!*

➲ *Complementary info also from* $B\to K^{*}\mu\mu$*: richer "b-> s couplings"*

✓Introduction:

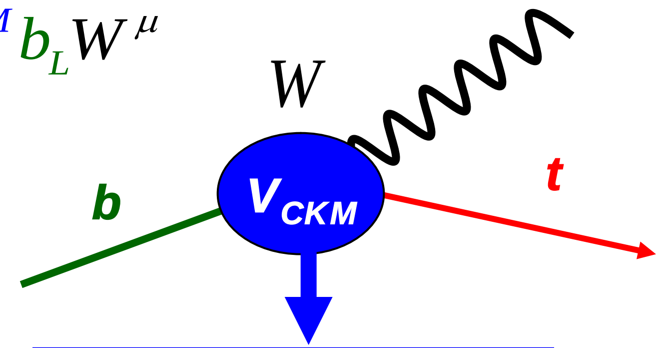
- *What is Flavor Physics in the Standard Model?*



- **Flavour Transitions:** **Weak interactions violate flavour: CKM matrix and CP violation**

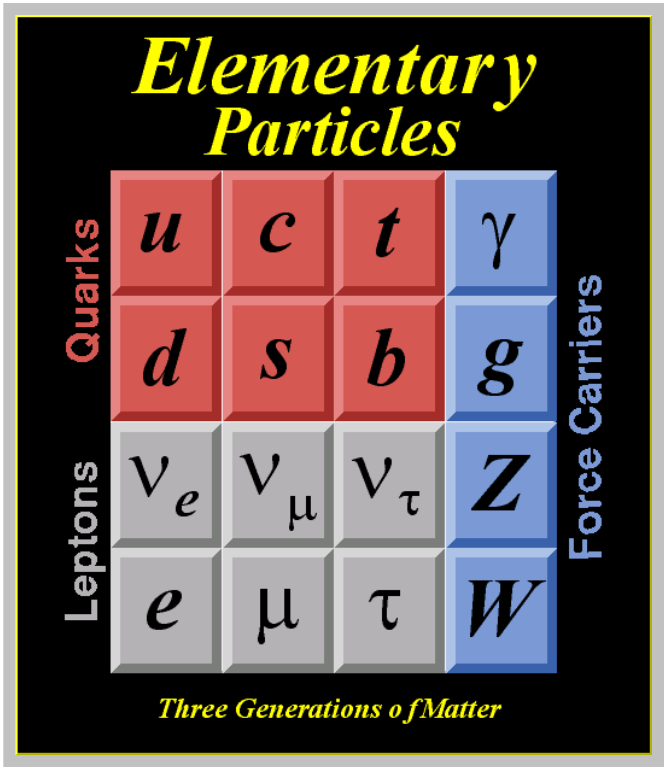
$$\mathcal{L}_{int} = \bar{t}_L \gamma_\mu V^{CKM} b_L W^\mu$$

...



$$V^{CKM} = \begin{pmatrix} \mathbf{V_{ud}} & \mathbf{V_{us}} & \mathbf{V_{ub}} \\ \pi \to l\nu & K \to \pi l\nu & B \to \pi l\nu \\ \mathbf{V_{cd}} & \mathbf{V_{cs}} & \mathbf{V_{cb}} \\ D \to \pi l\nu & D \to K l\nu & B \to D^{(*)} l\nu \\ D \to l\nu & D_s \to l\nu & \\ \mathbf{V_{td}} & \mathbf{V_{ts}} & \mathbf{V_{tb}} \\ \langle B_d|\overline{B}_d\rangle & \langle B_s|\overline{B}_s\rangle & \end{pmatrix}$$

=>3 angles and 1 Phase



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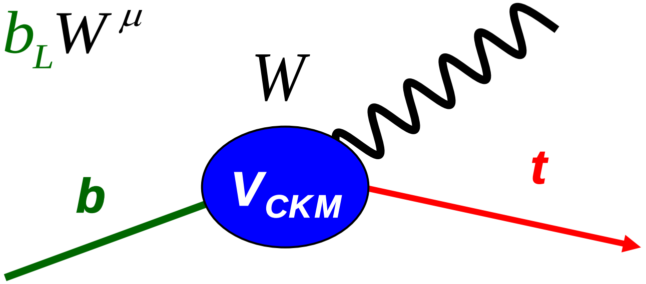
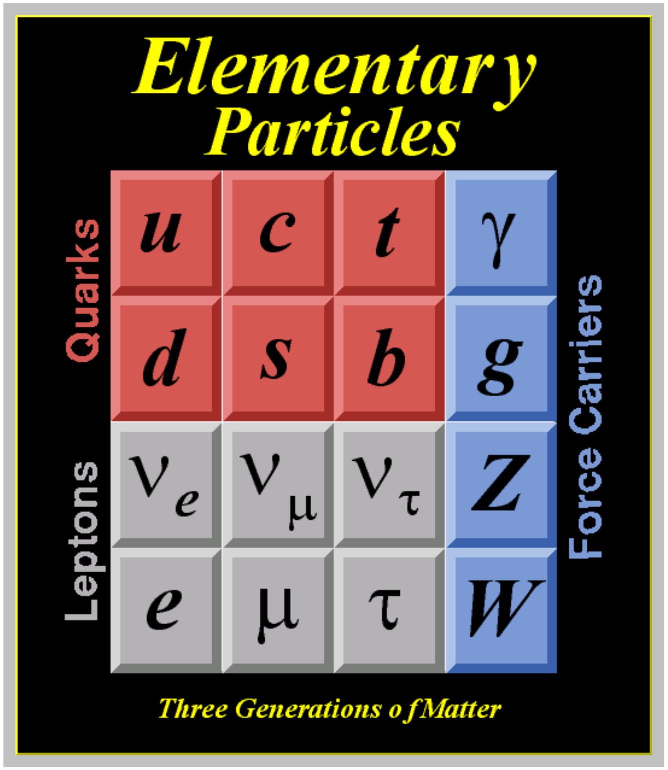


macroscopic picture
(effective couplings after ewsb)



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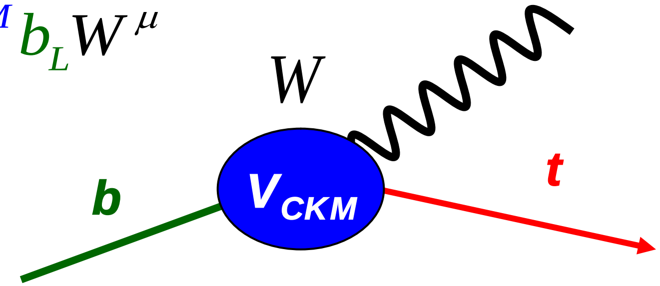
$$\mathcal{L}_{int} = \bar{t}_L \gamma_\mu V^{CKM} b_L W^\mu$$

$$\ldots$$



microscopic picture?

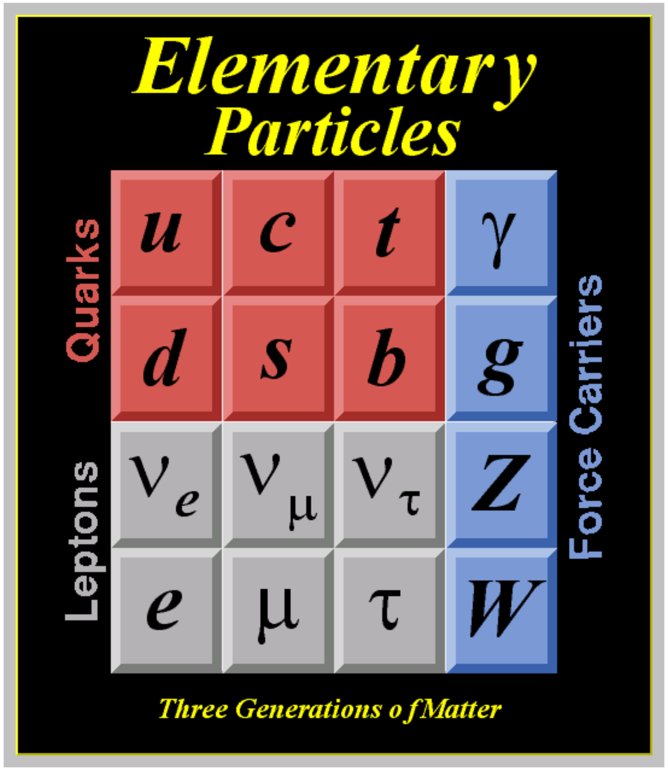
=>LHC job

the Higgs mechanism!

2 open options: *Linear or Non-Linear Higgs realisation?*

1HDM	**Techni C**
2HDM	**Little H.**
SUSY	**Extra D.**

ATLAS-CMS (2012): Higgs evidence!



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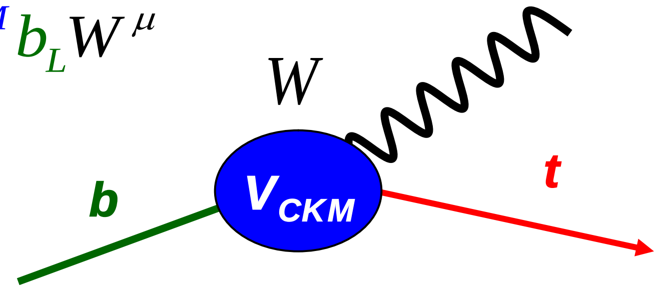


microscopic picture?

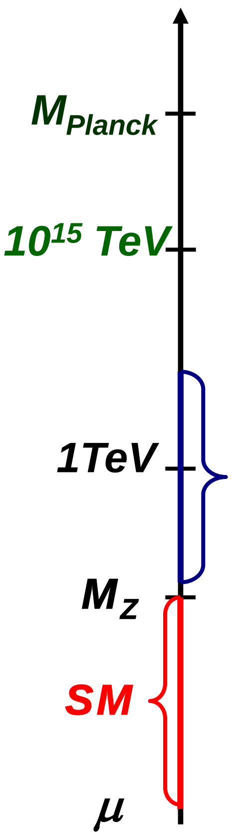
- ***ad hoc description in the SM***

$$\underbrace{D_\mu H^+ D^\mu H - V(H^+ H)}_{\text{ewsb sector}} + \underbrace{Y^{ij} H \overline{\psi}_L \psi_R}_{\text{flavour sector}} + \text{h.c}$$

1. not stable under radiative corrections;

$$\mathcal{L}_{\text{eff}}(\mu \le M_Z) = \overbrace{\mathcal{L}_{\text{gauge}}(A_i, \psi_i) \;+\; \mathcal{L}^{\Lambda_{UV}}_{\text{Higgs}}(H, A_i, \psi_i)}^{\text{Standard Model } \mathcal{L}_{SM}} + \underbrace{\frac{\mathcal{L}^{(5)}}{\Lambda_{UV}}}_{\text{see-saw}} + \underbrace{\frac{\mathcal{L}^{(6)}}{\Lambda_{UV}^2}}_{\text{EWPT, FCNC, CPV}} \cdots$$

BUT, as effective theory below M_{Planck}, *how large is the SM Λ_{UV} cut-off?*



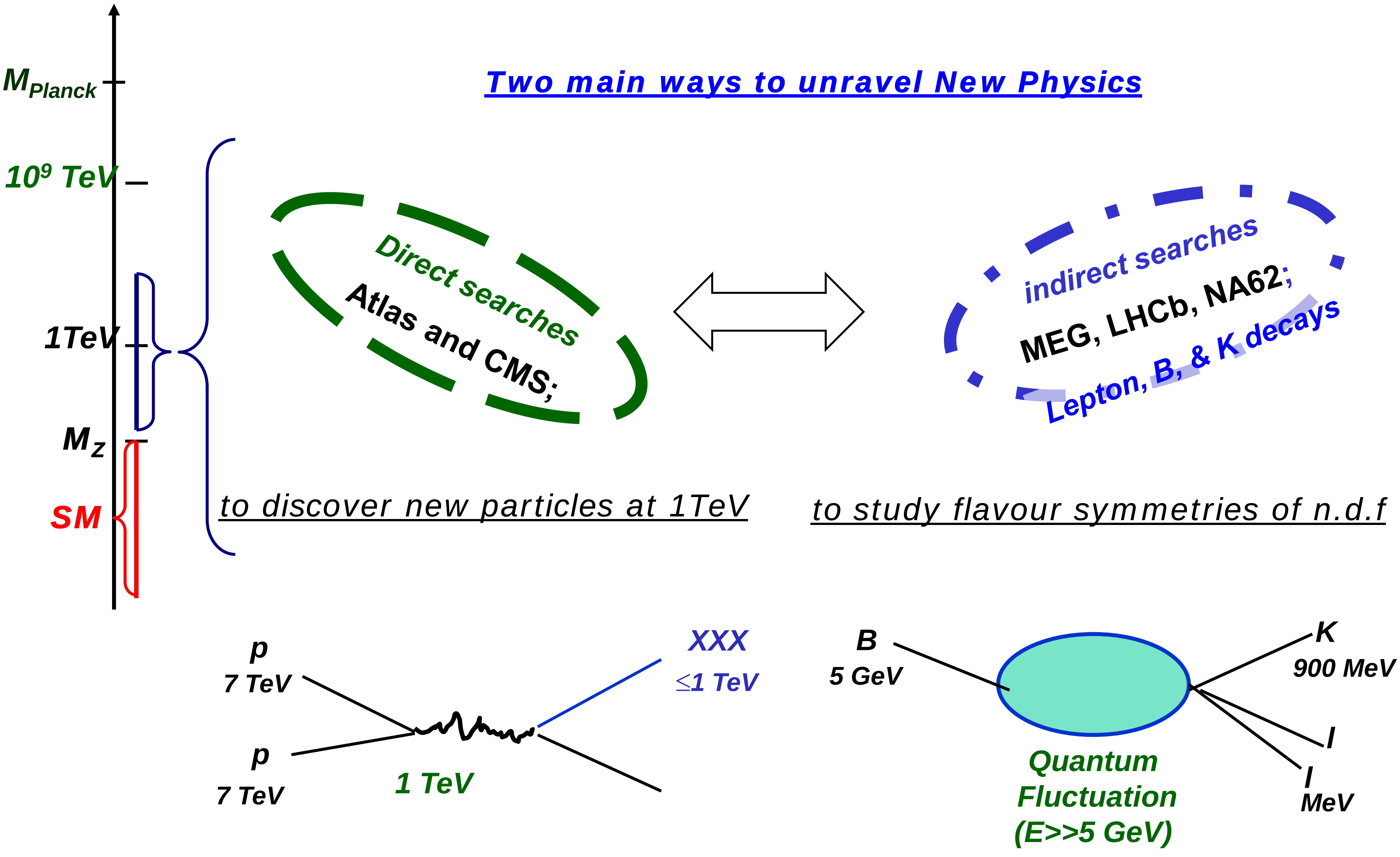
SuperKamiokande, WMAP ...

many *hints for* Beyond SM *physics*:

- gravity — $\Lambda_{UV} \sim 10^{19}$ TeV
- **neutrino oscillations** — $\Lambda_{UV} \sim 10^{15}$ TeV (see-saw)
- relic density — $\Lambda_{WIMP} \lesssim 1$ TeV, $\Lambda_{strong} \gtrsim 1$ TeV
- matter/anti-matter asymmetries

however no clear clues, because of large model dependence!

Naturalness of Higgs sector would require $\Lambda_{UV} \lesssim 1$ **TeV**

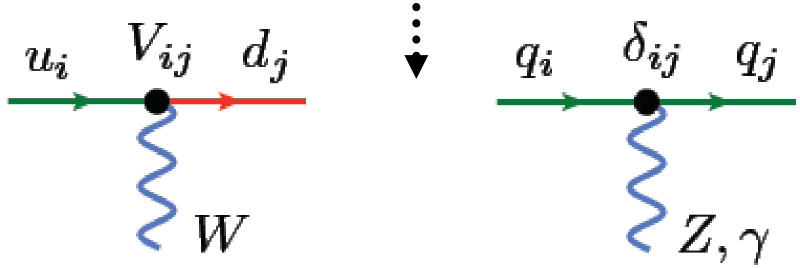

Two main ways to unravel New Physics
M_Planck
10^9 TeV
1TeV
M_Z
SM
Direct searches
Atlas and CMS;
indirect searches
MEG, LHCb, NA62;
Lepton, B, & K decays
to discover new particles at 1TeV
to study flavour symmetries of n.d.f
p
7 TeV
p
7 TeV
1 TeV
XXX
≤1 TeV
B
5 GeV
K
900 MeV
l
l
MeV
Quantum
Fluctuation
(E>>5 GeV)

✓Introduction:

➲*Status of Flavor Physics searches (Babar, Belle, Tevatron, LHCb):*

Flavor Physics 2013 (bd, sd):

$$\mathcal{L}_{SM} = \mathcal{L}_{gauge}(A_i, Q_i) + \overline{Q}_L Y_U U_R H + \overline{Q}_L Y_D D_R \tilde{H}$$



V: CKM matrix

δ: unit matrix

✓ Spectacular confirmation of the *CKM model as the dominant source of flavor and CP violation*

✓ Flavor-violating interactions encoded in *Yukawa coupling to Higgs boson*

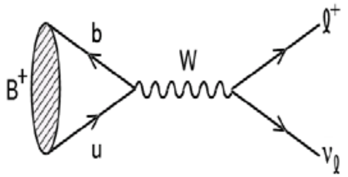
✓ Suppression of flavor-changing neutral currents (FCNCS) and CP violation in quark sector due to *unitarity of CKM matrix, small mixing angles, and GIM mechanism*.

$$\begin{array}{c} \\ \boldsymbol{V} \approx \end{array} \begin{array}{c} \begin{array}{ccc} d & s & b \end{array} \\ \begin{pmatrix} 1 & \lambda & \lambda^3 \\ -\lambda & 1 & \lambda^2 \\ -\lambda^3 & -\lambda^2 & 1 \end{pmatrix} \end{array} \begin{array}{c} \\ u \\ c \\ t \end{array}$$

$\lambda \approx 0.22$: Cabibbo angle

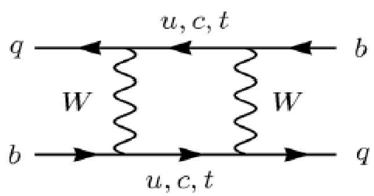
Flavour Physics and the quark sector in picture

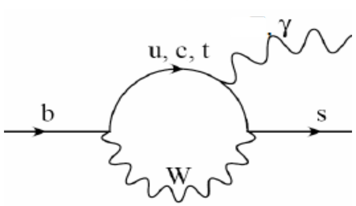
I. Remarkable consistency between tree-level processes



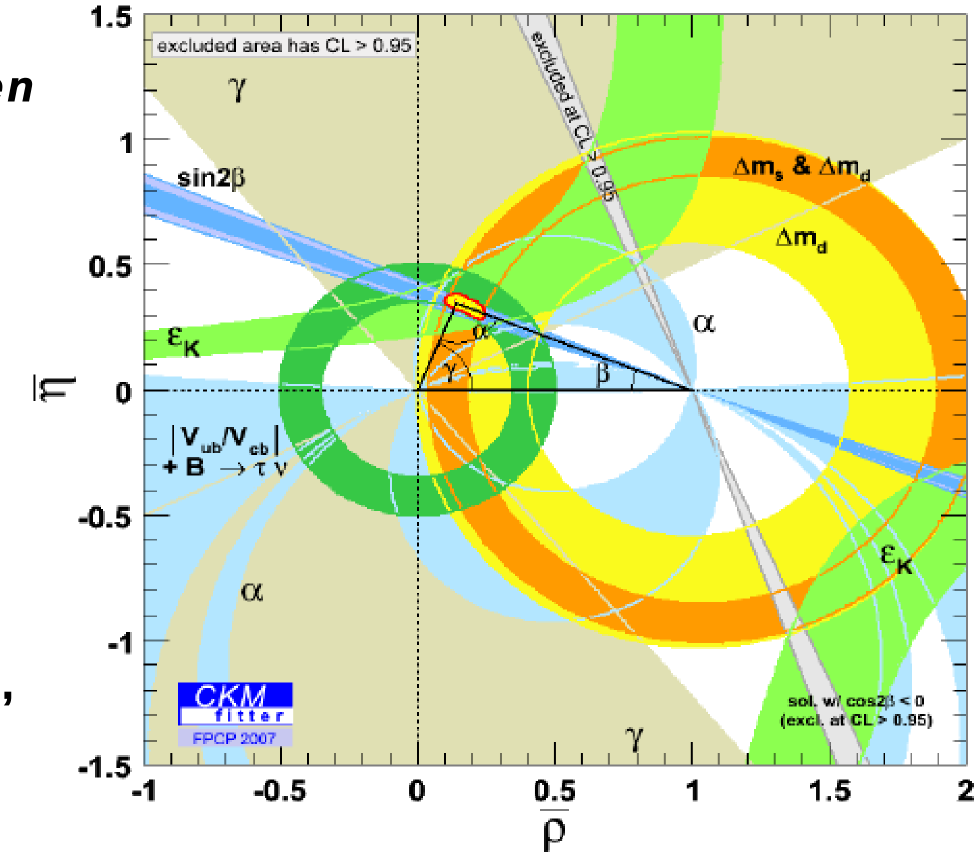
γ, α, V_{ub}, V_{cb}

and loop induced observables (FCNC)





$\sin(2\beta)$, Δm_{ds}, ε_K, $b \to s\gamma$ ...



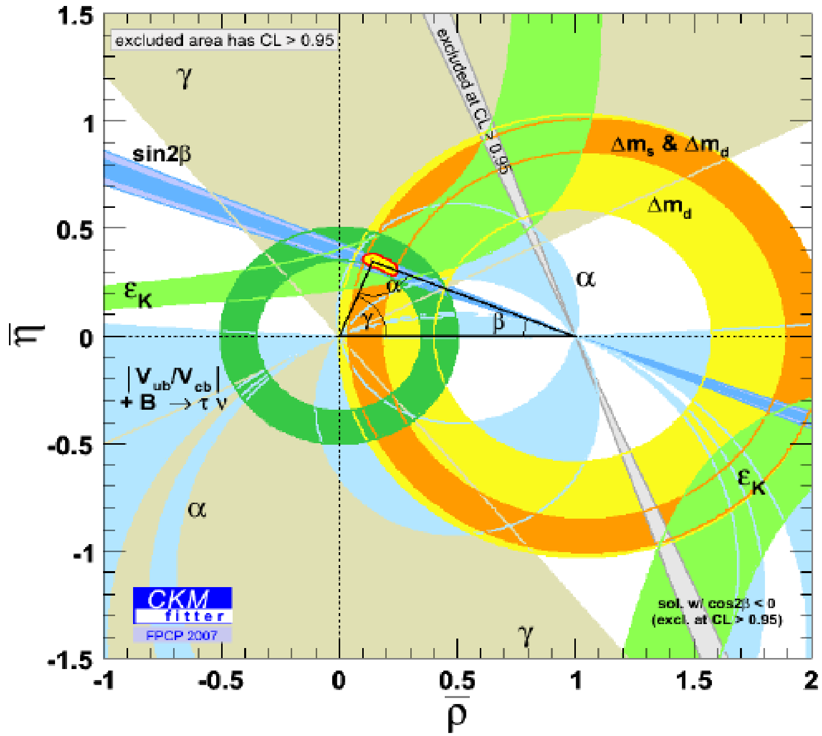
$$V_{cd}V_{cb}^{*} + V_{ud}V_{ub}^{*} + V_{td}V_{tb}^{*} = 0$$

II. Remarkable consistency between CPV and CPC observables

Nowadays, we have a good knowledge of the physical couplings of the quark Yukawa sector: (6 masses + 4 CKM angles)

What about BSM effects?

The absence of dominant New Physics signals in FCNCs implies strong constraints on flavour pattern BSM



Past studies are mostly on b->d (and s->d) FCNC transitions

☺ ***b->s transitions -> possible "rich" ground for new test!***

☹ ***Deal with QCD at low energy – no perturbation theory***

✓Future perspectives: FCNC *b->s modes “unexplored corner”*

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

th (7%): $(3.13 \pm 0.23) \times 10^{-4}$

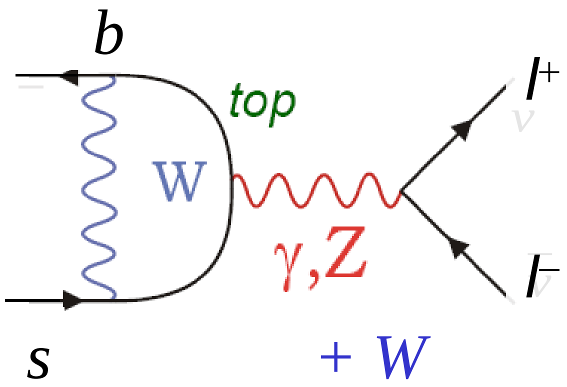
exp (7%): $(3.52 \pm 0.24) \times 10^{-4}$

Babar+Belle 1999-2007

$Br(B_d \to X_s l^+ l^-) \propto C_7 C_9 + |C_9| + |C_{10}| + |C_7|$

	exp (30%):	th (15-25%):
$[q^2 \in [0.04, 1.0]\ \mathrm{GeV}^2]$	$(0.6 \pm 0.5) \times 10^{-6}$	$(0.8 \pm 0.2) \times 10^{-6}$
$[q^2 \in [1.0, 6.0]\ \mathrm{GeV}^2]$	$(1.6 \pm 0.5) \times 10^{-6}$	$(1.6 \pm 0.1) \times 10^{-6}$
$[q^2 > 14.4\ \mathrm{GeV}^2]$	$(4.4 \pm 1.3) \times 10^{-7}$	$(2.4 \pm 0.8) \times 10^{-7}$

Babar+Belle 2007



+ W box

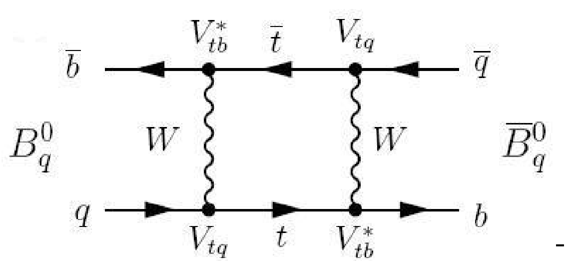
$$Heff = \begin{cases} C_7 \times \bar{b}_R \sigma^{\mu\nu} s_L F_{\mu\nu} + \\ C_9 \times \bar{b}_L \gamma^\mu s_L \bar{l} \gamma^\mu l + C_{10} \times \bar{b}_L \gamma^\mu s_L \bar{l} \gamma^\mu \gamma_5 l \\ C_S \times \bar{b}_L s_R \bar{l} l + C_P \times \bar{b}_L s_R \bar{l} \gamma_5 l + \\ C_T \times \bar{b}_R \sigma^{\mu\nu} s_L \bar{l} \sigma^{\mu\nu} l + C_{T5} \times \bar{b}_R \sigma^{\mu\nu} s_L \bar{l} \sigma^{\mu\nu} \gamma_5 l \\ +L \Leftrightarrow R : (C'_9, C'_{10}, C'_S, C'_P, C_{T5}) \end{cases}$$

SM Ops. (first two lines)

BSM Ops. (last three lines)

ΔM_s

$C_{box} \times \bar{b}_L \gamma^\mu s_L \bar{b}_L \gamma^\mu s_L$



Tevatron 2006

$Br(B_s \to \mu^+ \mu^-) \propto C^{(\prime)}_{9,10,S,P}$

$Br(B_d \to K^* \gamma) \propto |C^{(\prime)}_7|$

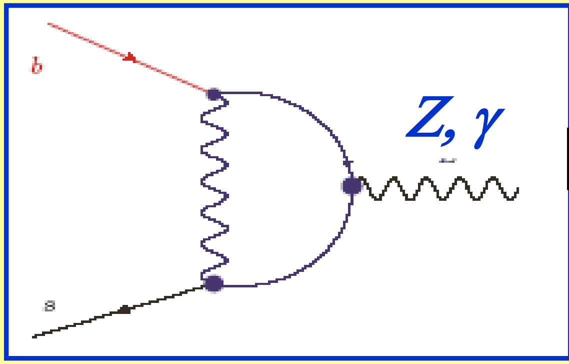
LHCb 2012

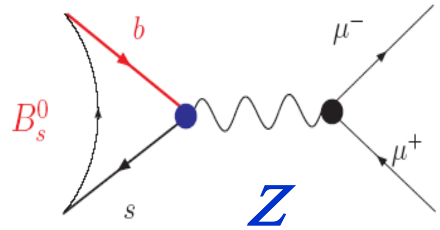
$Br(B_d \to K l^+ l^-) \propto C^{(\prime)}_{9,10,S,P,T}$

$B_d \to K^* l^+ l^- \propto C^{(\prime)}_{9,10,S,P,T}$

here, we expect theory and exp. progress

Theory: Effective lagrangian at $\mu \sim m_b$

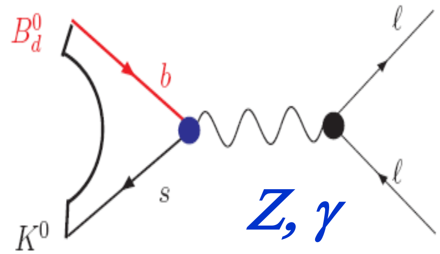




$B_s \to \mu\mu$ **(P=-1)**

$$\langle 0 | \bar{b}\Gamma\gamma_5 s | B_s^0 \rangle \neq 0, \langle 0 | \bar{b}\Gamma s | B_s^0 \rangle = 0$$

Br $\propto$ **($m_l^2(C_{10}-C'_{10})$, $C_{P,S}-C'_{P,S}$)**



$B \to K ll$ **(P=1)**

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

Br $\propto$ **($C_7+C'_7$, $C_9+C'_9$, $C_{10}+C'_{10}$, $C_{P,S}+C'_{P,S}$, C_T, C_{T5})**

+ $B \to X_s\gamma$ strongly constrains **$C_{7(8)}$**

$$L_{eff} = C_7 \bar{b}\sigma_L^{\mu\nu} s F_{\mu\nu} + C'_7 \bar{b}\sigma_R^{\mu\nu} s F_{\mu\nu} + C_9 \left(\bar{b}\gamma_L^\mu s\right)\bar{\ell}\gamma^\mu\ell + C'_9 \left(\bar{b}\gamma_R^\mu s\right)\bar{\ell}\gamma^\mu\ell$$
$$+ C_{10}\left(\bar{b}\gamma_L^\mu s\right)\bar{\ell}\gamma^\mu\gamma_5\ell + C'_{10}\left(\bar{b}\gamma_R^\mu s\right)\bar{\ell}\gamma^\mu\gamma_5\ell + C_S\left(\bar{b}Ls\right)\bar{\ell}\ell + C'_S\left(\bar{b}Rs\right)\bar{\ell}\ell$$
$$+ C_P\left(\bar{b}Ls\right)\bar{\ell}\gamma_5\ell + C'_P\left(\bar{b}Rs\right)\bar{\ell}\gamma_5\ell + C_T\left(\bar{b}\sigma_L^{\mu\nu}s\right)\bar{\ell}\sigma^{\mu\nu}\ell + C'_T\left(\bar{b}\sigma_R^{\mu\nu}s\right)\bar{\ell}\sigma^{\mu\nu}\ell$$

Theory: Hadronic Uncertainties

$Br(B_s \to \mu^+\mu^-) \propto C_{9,10,S,P}$

$Br(B_d \to K^{(*)} l^+ l^-) \propto C_{9,10,S,P,T}$

GOAL: calculate Matrix elements of 2-quark operators between hadrons (decay constants & Form factors)

SM operators

$$O_7 = \bar{b}_R \sigma^{\mu\nu} s_L F_{\mu\nu}$$

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

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

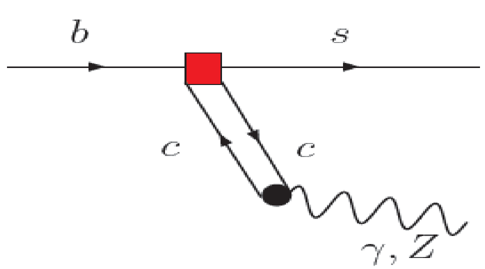
$$O_2 = \left(\bar{b}\gamma_L^\mu c\right)\left(\bar{c}\gamma_L^\mu s\right)$$

BSM operators

$$O_{S(P)} = \left(\bar{b}_R s_L\right)\bar{\ell}\ell_{S(P)},\ O_T = \left(\bar{b}_R \sigma^{\mu\nu} s_L\right)\bar{\ell}\sigma^{\mu\nu}\ell$$

$$+L \leftrightarrow R$$

Charm Loops



Under control (to some extent)
at low and large q^2, *out of resonance region*

Khodjamirian's talk

Theory: Hadronic Uncertainties

$B_s \to \mu\mu$

$$L_{eff} = C_7 \bar{b}\sigma_L^{\mu\nu} s F_{\mu\nu} + C_7' \bar{b}\sigma_R^{\mu\nu} s F_{\mu\nu} + C_9 \left(\bar{b}\gamma_L^{\mu} s\right)\bar{\ell}\gamma^{\mu}\ell + C_9' \left(\bar{b}\gamma_R^{\mu} s\right)\bar{\ell}\gamma^{\mu}\ell$$
$$+ C_{10}\left(\bar{b}\gamma_L^{\mu} s\right)\bar{\ell}\gamma^{\mu}\gamma_5\ell + C_{10}'\left(\bar{b}\gamma_R^{\mu} s\right)\bar{\ell}\gamma^{\mu}\gamma_5\ell + C_S\left(\bar{b}Ls\right)\bar{\ell}\ell + C_S'\left(\bar{b}Rs\right)\bar{\ell}\ell$$
$$+ C_P\left(\bar{b}Ls\right)\bar{\ell}\gamma_5\ell + C_P'\left(\bar{b}Rs\right)\bar{\ell}\gamma_5\ell + C_T\left(\bar{b}\sigma_L^{\mu\nu} s\right)\bar{\ell}\sigma^{\mu\nu}\ell + C_T'\left(\bar{b}\sigma_R^{\mu\nu} s\right)\bar{\ell}\sigma^{\mu\nu}\ell$$

$$\langle \mu\mu | L_{eff} | B_s^0 \rangle = \langle 0 | \bar{b}\Gamma s | B_s^0 \rangle \langle \mu\mu | \bar{\ell}\Gamma\ell | 0 \rangle$$

Hadronic Uncertainties
Lattice QCD

$B_s \to \mu\mu$

Only one hadronic parameter: f_{Bs}

$$\langle 0 | \bar{b}\gamma^{\mu}\gamma_5 s | B_s^0 \rangle = i p^{\mu} f_{Bs}$$
$$\langle 0 | \bar{b}\gamma_5 s | B_s^0 \rangle = -i f_{Bs} M_{Bs}^2 / m_b$$

$$f_{Bs} = (234 \pm 10)\,\mathrm{MeV}$$

4% hadronic uncertainty

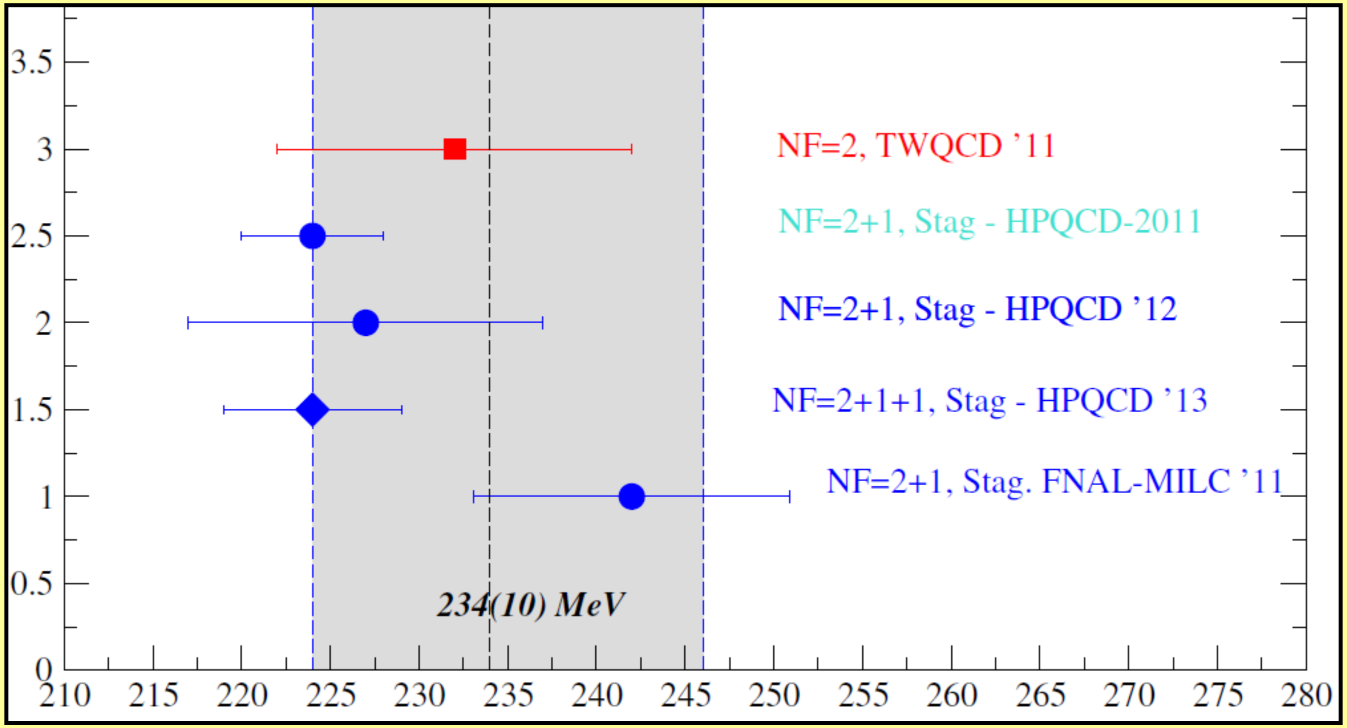
Lattice: ETMC, MILC, HPQCD

$Br(B_s \to \mu\mu)^{SM} = (3.3 \pm 0.3) \times 10^{-9}$ (6.5%)

Theory: Hadronic Uncertainties

$B_s \to \mu\mu$

f_{Bs}



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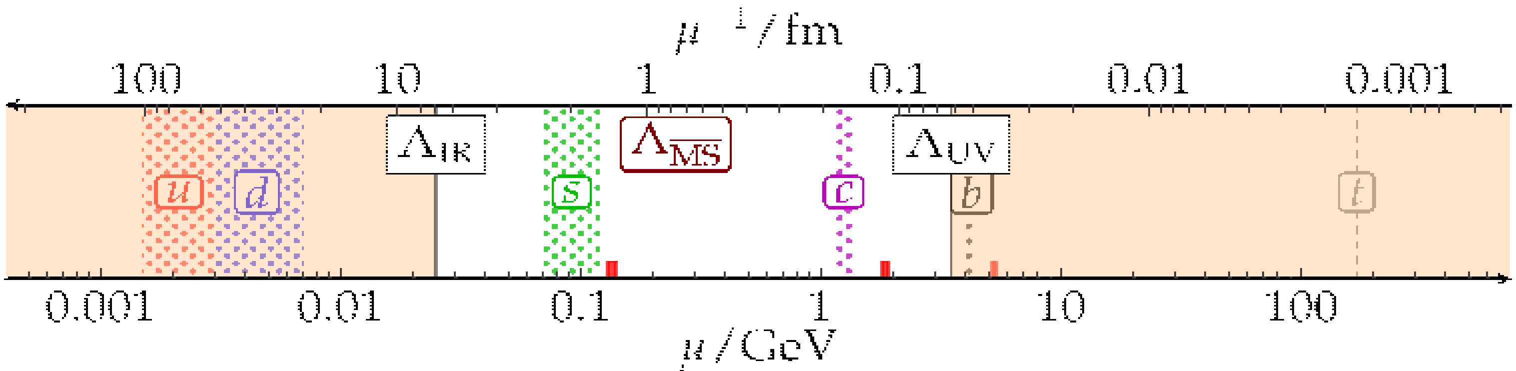
Challenge of B-physics: the multi scale-problem of QCD



hierarchy of disparate physical scales to be covered:

$$\Lambda_{IR} = L^{-1} \ll m_\pi, \ldots, m_D, m_B \ll a^{-1} = \Lambda_{UV}$$

$$\left\{ O(e^{-L m_\pi}) \Rightarrow \boxed{L \gtrsim \frac{4}{m_\pi} \sim 6\,\text{fm}} \right\} \curvearrowright \; L/a \gtrsim 120 \; \curvearrowleft \left\{ a m_D \lesssim \frac{1}{2} \Rightarrow \boxed{a \approx 0.05\,\text{fm}} \right\}$$

Currently a^{-1}<4 GeV, *b* quarks cannot be directly simulate at their physical mass due to large discretization errors ($a\, m_b$« 1)

- *effective theories: like NRQCD action*
- *simulate heavy quark in the charm region and extrapolate to the B + HQET.*

Comments:

- ***Discretized NRQCD action***

  ➢ *Quite Sophisticated procedure!*

  ➲ *larger set of 1/(am$_Q$) corrections on the lattice w.r.t the continuum*

  ➢ O[$\alpha_s^n/(am_Q)$] divergences to be subtracted to get the continuum limit

➢ *On the other hand, large experience from MILC/FNAL/HPQCD*

☺ ***Successful strategy for f_B comparing with unquenched results from other approaches***

Theory: Hadronic Uncertainties

$B \to K ll$

$B \to K ll$

Dominant uncertainties come from the form 3 factors: $f_+(q^2)$, $f_0(q^2)$, $f_T(q^2)$

$$\langle B(p)|\bar{b}\gamma^\mu s|K(k)\rangle = \left(p^\mu + k^\mu - \frac{m_B^2 - m_K^2}{q^2}q^\mu\right) f_+(q^2) + \frac{m_B^2 - m_K^2}{q^2} q^\mu f_0(q^2)$$

$$\langle B(p)|\bar{b}\sigma^{\mu\nu} s|K(k)\rangle = \frac{i f_T}{m_B + m_K}\left[(p^\mu + k^\mu)q^\nu - (p^\nu + k^\nu)q^\mu\right]$$

- $C_{9,10}^{(\prime)} \to f_+(q^2), f_0(q^2), C_{S,P}^{(\prime)} \to f_0/m_b \quad C_7^{(\prime)} \to f_T,$
- Wide range of $q^2=[0,(m_B-m_K)^2]$ -> **Opportunities for different nonperturbative techniques: Lattice QCD** – relative th. error 30% -> large room for improvement

$$\langle \mu\mu | L_{eff} | B_s^0\rangle = \langle K | \bar{b}\Gamma s | B_s^0\rangle \langle \mu\mu | \bar{\ell}\Gamma \ell | 0\rangle$$

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$B \to K ll$

Dominant uncertainties come from the form 3 factors: $f_+(q^2)$, $f_0(q^2)$, $f_T(q^2)$

$$\langle B(p)|\bar{b}\gamma^\mu s|K(k)\rangle = \left(p^\mu + k^\mu - \frac{m_B^2 - m_K^2}{q^2} q^\mu\right) f_+(q^2) + \frac{m_B^2 - m_K^2}{q^2} q^\mu f_0(q^2)$$

$$\langle B(p)|\bar{b}\sigma^{\mu\nu} s|K(k)\rangle = \frac{i f_T}{m_B + m_K}\left[(p^\mu + k^\mu) q^\nu - (p^\nu + k^\nu) q^\mu\right]$$

❖ $C_{9,10}^{(\prime)} \to f_+(q^2), f_0(q^2), C_{S,P}^{(\prime)} \to f_0/m_b \quad C_7^{(\prime)} \to f_T,$

❖ Wide range of $q^2=[0,(m_B-m_K)^2]$ -> **Opportunities for different nonperturbative techniques: Lattice QCD** – relative th. error 30% -> large room for improvement

*! LATTICE QCD: only approach to compute the full ff basis at **large** q^2:*
☺ no $O(\Lambda/m_b)$ uncertainty from Isgur-Wise relation at LO!

Theory: Hadronic Uncertainties

$B \to K^* \gamma$, $B \to K^* ll$

$$\langle V(p',\varepsilon)|\bar{q}\hat{\gamma}^\mu b|B(p)\rangle = \frac{2iV(q^2)}{m_B+m_V}\epsilon^{\mu\nu\rho\sigma}\varepsilon^*_\nu p'_\rho p_\sigma$$

$$\begin{aligned}\langle V(p',\varepsilon)|\bar{q}\hat{\gamma}^\mu\hat{\gamma}^5 b|B(p)\rangle = {} & 2m_V A_0(q^2)\frac{\varepsilon^*\cdot q}{q^2}q^\mu \\ & +(m_B+m_V)A_1(q^2)\left(\varepsilon^{*\mu}-\frac{\varepsilon^*\cdot q}{q^2}q^\mu\right) \\ & -A_2(q^2)\frac{\varepsilon^*\cdot q}{m_B+m_V}\left((p+p')^\mu-\frac{m_B^2-m_V^2}{q^2}q^\mu\right)\end{aligned}$$

$$q^\nu\langle V(p',\varepsilon)|\bar{q}\hat{\sigma}_{\mu\nu}b|B(p)\rangle = 2T_1(q^2)\epsilon_{\mu\rho\tau\sigma}\varepsilon^{*\rho}p^\tau p'^\sigma$$

$\longrightarrow$ $Br(B \to K^* \gamma)$ one ff. at $q^2=0$

$$\begin{aligned}q^\nu\langle V(p',\varepsilon)|\bar{q}\hat{\sigma}_{\mu\nu}\hat{\gamma}^5 b|B(p)\rangle = {} & iT_2(q^2)[\varepsilon^*_\mu(m_B^2-m_V^2)-(\varepsilon^*\cdot q)(p+p')_\mu] \\ & +iT_3(q^2)(\varepsilon^*\cdot q)\left[q_\mu-\frac{q^2}{m_B^2-m_V^2}(p+p')_\mu\right]\end{aligned}$$

$Br(B \to K^* ll)$: 7 form factors in QCD

*! LATTICE QCD: only approach to compute the full ff basis at **large** q^2:*
☺ no $O(\Lambda/m_b)$ uncertainty from Isgur-Wise relation at LO!

Studies of form-factor calculations on the Lattice:

$B \to K ll$

N_F=0: Quenched lattice QCD: **relativistic fermions**

- D. Becirevic, N. Kosnik, F. M., E. Schneider, 2012

N_F=2+1 staggered fermions: NRQCD

- FNAL/MILC, 2012
- HPQCD, June 2013
- Cambridge (***prelims***), 2012

→ $f_+(q^2)$, $f_+(q^2)$ $f_T(q^2)$

$B \to K^* ll$

N_F=0: Quenched lattice QCD: **relativistic fermions**

- D. Becirevic, V. Lubicz & F. M. 2007 → $T_{12}(q^2)$

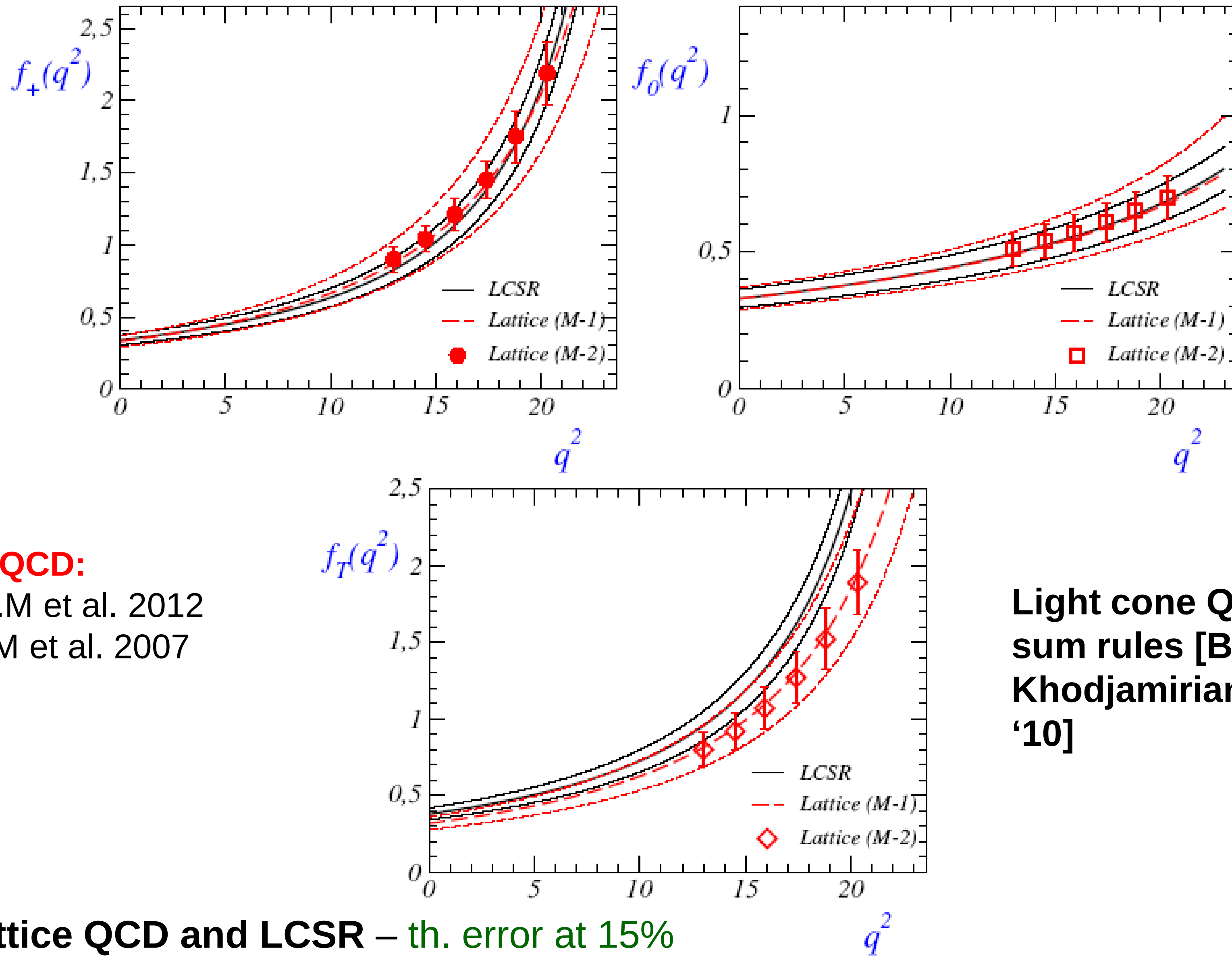
N_F=2+1 staggered fermions: **NRQCD**

- Cambridge (***prelims***), 2012 → $T_{12}(q^2)$ $V(q^2)$, $A_{012}(q^2)$

☹ *preliminary unquenched activities:*
overall agreement between Quenched and LCSR

☹ *q^2 dependence: further complication with respect to f_B or B_B*

$B \to K\ell^+\ell^-$ form factors



Lattice QCD:
***f_+, f_0* ->**F.M et al. 2012
***f_T* ->** F.M et al. 2007

Light cone QCD sum rules [Ball'05, Khodjamirian'07, '10]

1) **Lattice QCD and LCSR** – th. error at 15%
2) **Lattice points at large q^2**
3) **Agreement with LQSR**

☺ **helpful the HQET ffs at q^2_{max}**

Theory: Hadronic Uncertainties

$B \to K ll$

$B \to K ll$

Dominant uncertainties come from the 3 form factors: $f_+(q^2)$, $f_0(q^2)$, $f_T(q^2)$

$$\langle K | \bar{b}\gamma^\mu \gamma_5 s | B \rangle \Leftrightarrow f_{+,0}(q^2) \qquad \langle K | \bar{b}\sigma^{\mu\nu} s | B \rangle \Leftrightarrow f_T(q^2)$$

❖ $C_{9,10}^{(\prime)} \to f_+(q^2), f_0(q^2), C_{S,P}^{(\prime)} \to f_0/m_b \quad C_7^{(\prime)} \to f_T,$

❖ Wide range of q^2=[$0,(m_B-m_K)^2$] -> Opportunities for different nonperturbative techniques: Lattice QCD and LCSR – relative error 30%

$$\mathrm{Br}\left(B \to K\ell^+\ell^-\right)_{\mathrm{SM}} = \begin{cases} (7.5 \pm 1.4) \times 10^{-7} & \mathrm{LQCD}\,, \\ (6.8 \pm 1.6) \times 10^{-7} & \mathrm{LCSR}\,. \end{cases},$$

Lattice average

$$\mathrm{Br}\left(B \to K\ell^+\ell^-\right)_{\mathrm{SM}} = (7.0 \pm 1.8) \times 10^{-7}$$

still th. error large 30%

BaBar'12

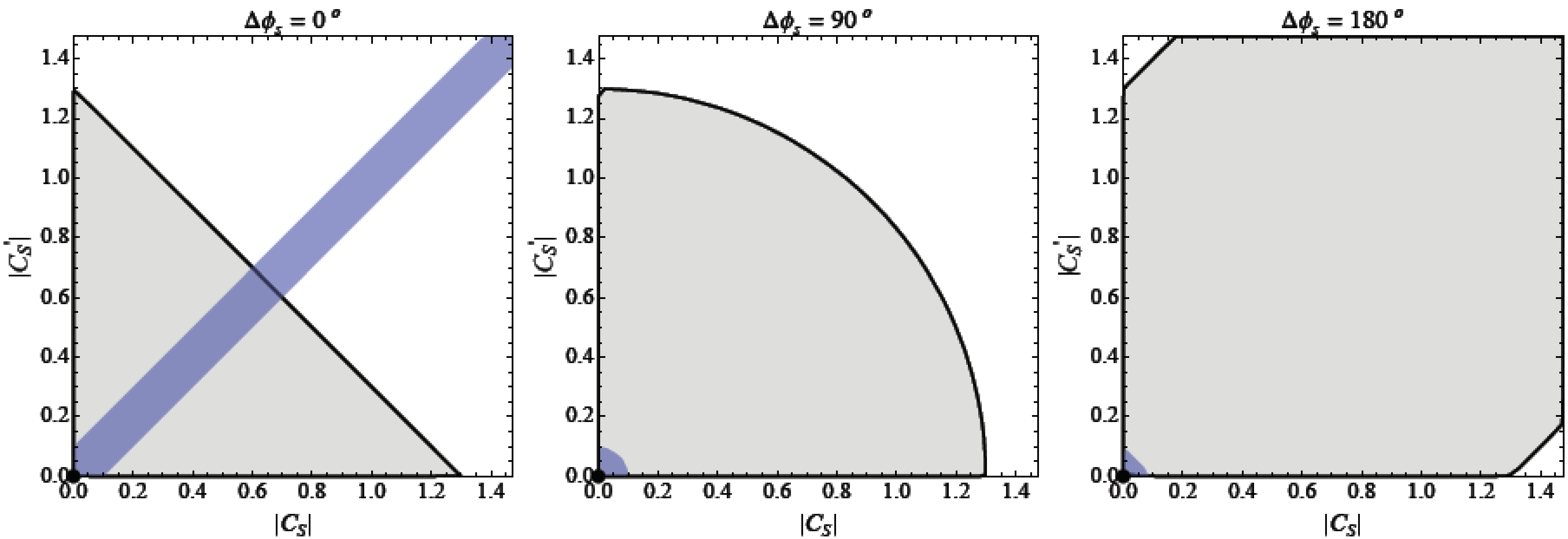
$\mathrm{Br}(B \to K\, ll) = (4.7 \pm 0.6) \times 10^{-7}$

LHCb'12

$\mathrm{Br}(B^+ \to K^+ \mu\mu) = (3.1 \pm 0.7) \times 10^{-7}$

New Physics: scalar scenario, SM + $C_S\left(\bar{b}(1-\gamma_5)s\right)\bar{\ell}\ell + C_S'\left(\bar{b}(1+\gamma_5)s\right)\bar{\ell}\ell$

- $B_s \to \mu^+\mu^- \longrightarrow |C_S - C_S'|$ NO helicity suppression
- $B \to K\mu^+\mu^- \longrightarrow |C_S + C_S'|$



- Constraints strongly depend on relative phase $\Delta\phi_S$

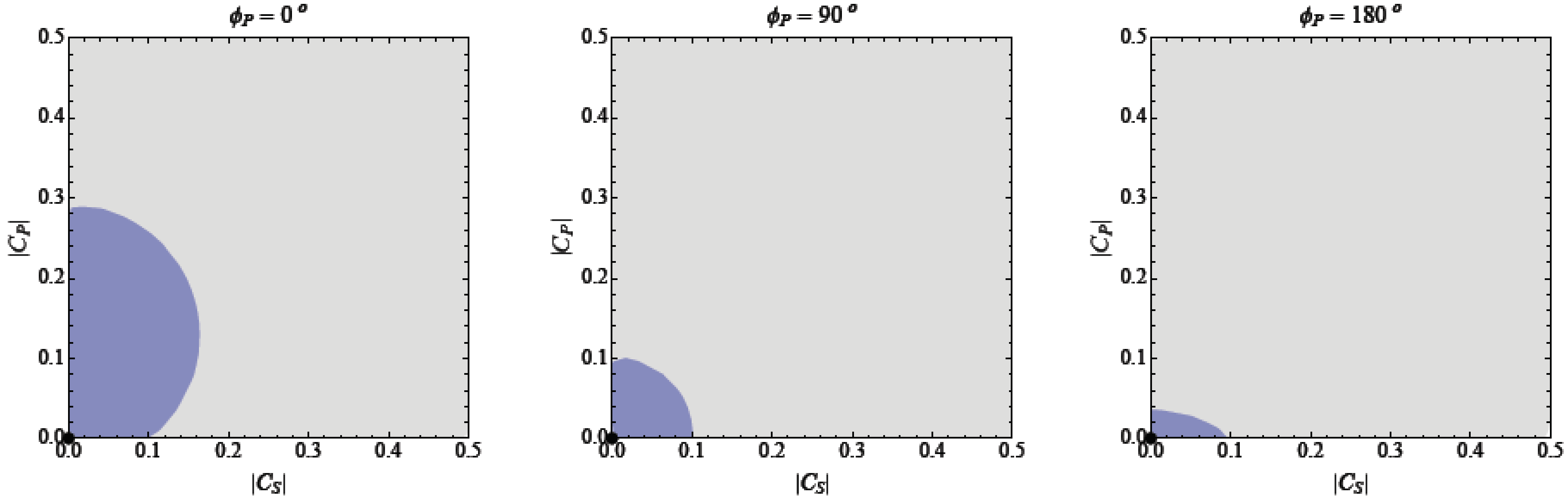
(**GREY** = $B \to K\mu^+\mu^-$, **BLUE** = $B_s \to \mu^+\mu^-$)

$$|C_S \pm C_S'|^2 = |C_S|^2 + |C_S'|^2 \pm 2\,|C_S|\,|C_S'|\cos(\Delta\phi_S)$$

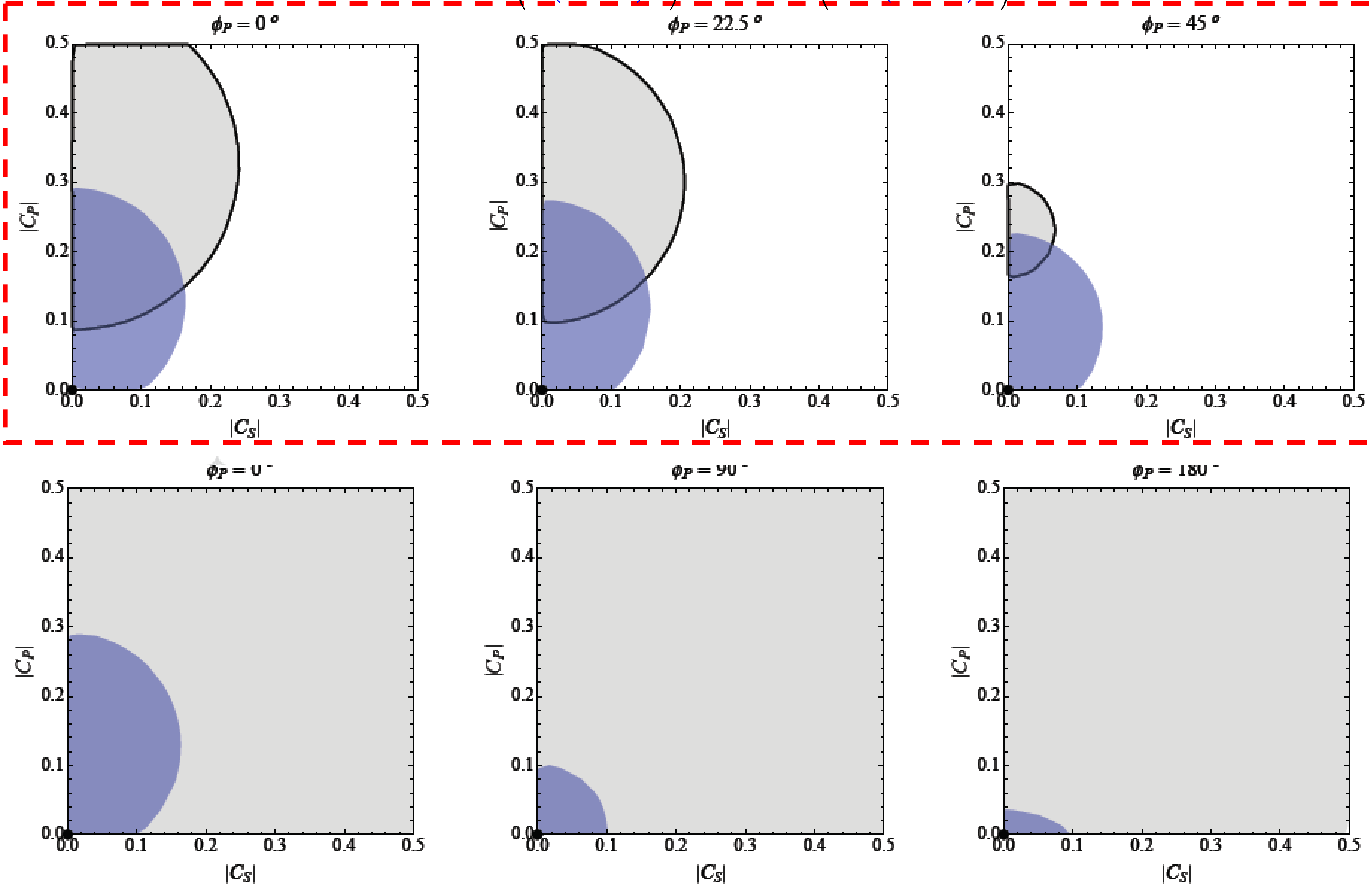
New Physics: **SM +** $C_S\left(\bar{b}(1-\gamma_5)s\right)\bar{\ell}\gamma_5\ell + C_P\left(\bar{b}\gamma_5(1-\gamma_5)s\right)\bar{\ell}\gamma_5\ell$

- $B_s \to \mu^+\mu^- \longrightarrow |C_S|, \quad |C_P + 2m_\ell/m_B C_{10}^{\rm SM}|$
- $B \to K\mu^+\mu^- \longrightarrow |C_S|, \quad |C_P + \# m_\ell/m_B C_{10}^{\rm SM}|$
- Phase of C_P enters

(**GREY** = $B \to K\mu^+\mu^-$, **BLUE** = $B_s \to \mu^+\mu^-$)

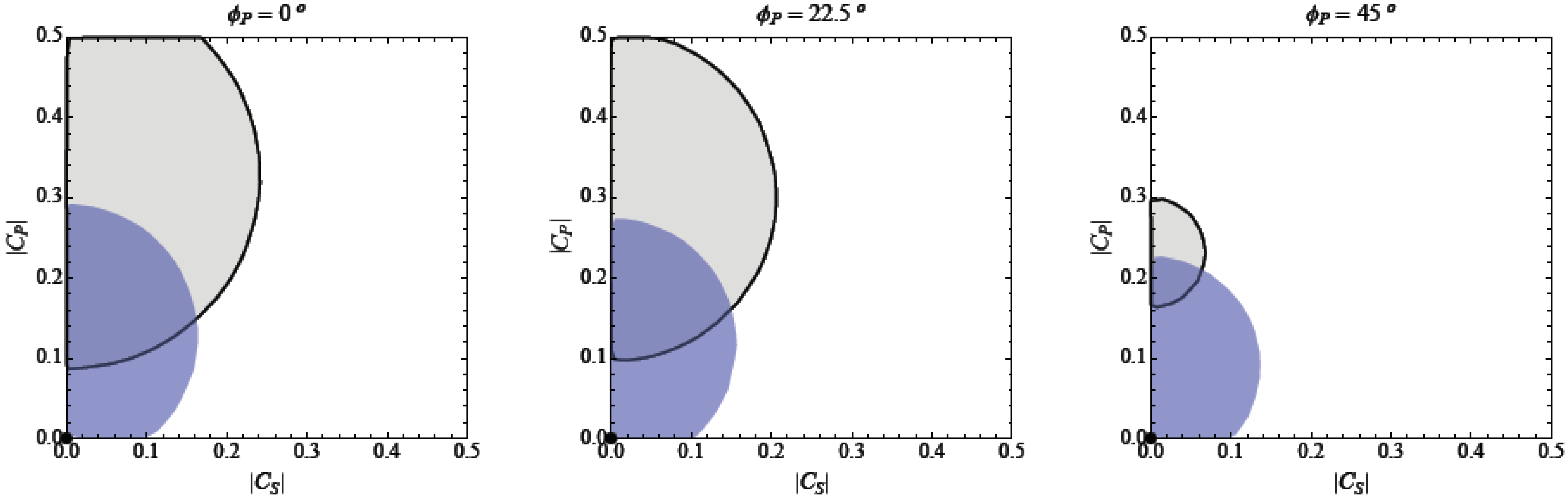


New Physics: SM + $C_S\left(\bar{b}(1-\gamma_5)s\right)\bar{\ell}\gamma_5\ell + C_P\left(\bar{b}\gamma_5(1-\gamma_5)s\right)\bar{\ell}\gamma_5\ell$



Lowering th. error on *B->Kll 20% smaller than now*

New Physics: **SM** + $C_S\left(\bar{b}\left(1-\gamma_5\right)s\right)\bar{\ell}\gamma_5\ell+C_P\left(\bar{b}\gamma_5\left(1-\gamma_5\right)s\right)\bar{\ell}\gamma_5\ell$



This "toy-scenario" would prefer nonzero C_P.

Lowering th. error on *B->Kll 20% smaller than now*

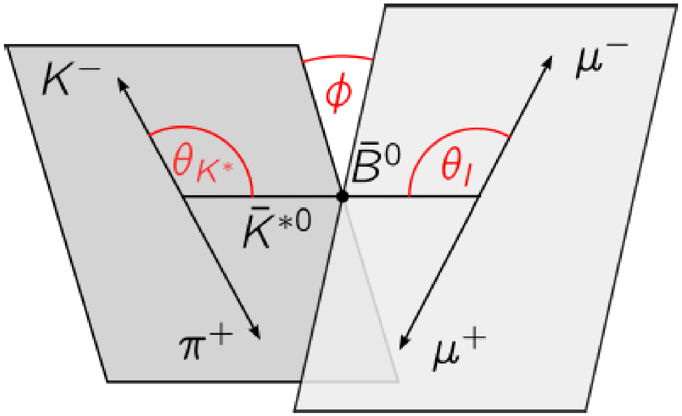
Observables in $B \to K^* ll$ process

$$\bar{B}^0 \to \bar{K}^{*0}(\to K^-\pi^+)\mu^+\mu^-$$

=> Exploiting the decay $K^* \to K\pi$: four-body analysis and access to the K^* polarisation:

$B \to K^*(\to K\pi)\mu^+\mu^-$ Angular Decay Distribution

$\bar{B}^0 \to \bar{K}^{*0}(\to K^-\pi^+)\mu^+\mu^-$



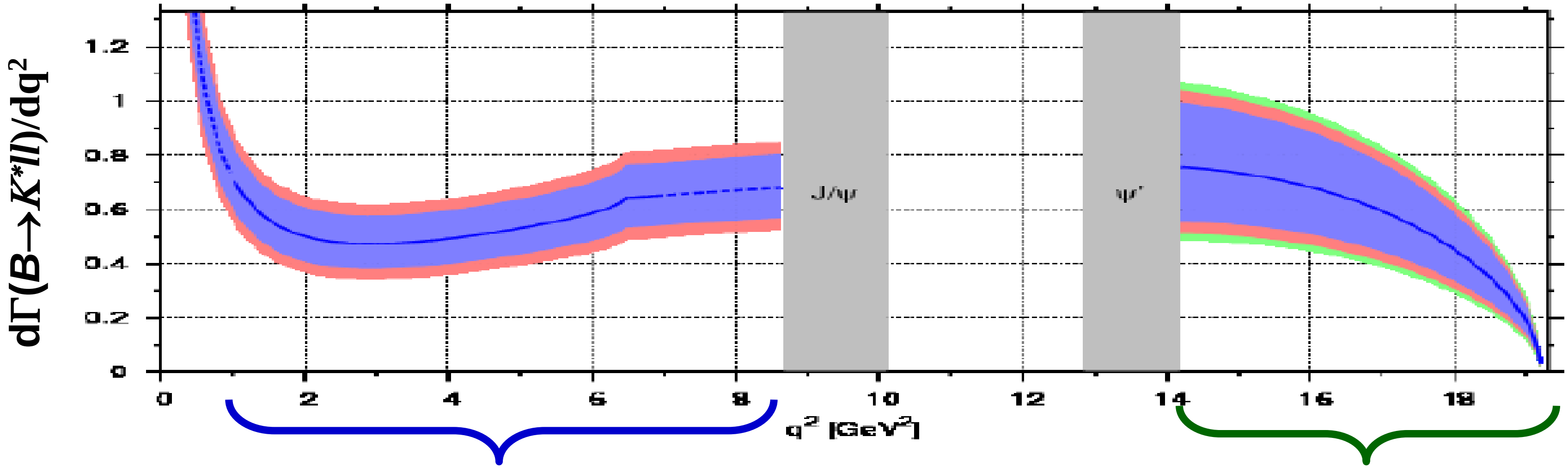
$$\frac{d^4\Gamma_{\bar{B}_d}}{ds\, d\theta_l\, d\theta_K\, d\phi} = \frac{9}{32\pi} I(s, \theta_l, \theta_K, \phi) \sin\theta_l \sin\theta_K$$

$$I = \mathbf{I}_1 + \mathbf{I}_2 \cos 2\theta_l + \mathbf{I}_3 \sin^2\theta_l \cos 2\phi + \mathbf{I}_4 \sin 2\theta_l \cos\phi + \mathbf{I}_5 \sin\theta_l \cos\phi + \mathbf{I}_6 \cos\theta_l + \mathbf{I}_7 \sin\theta_l \sin\phi + \mathbf{I}_8 \sin 2\theta_l \sin\phi + \mathbf{I}_9 \sin^2\theta_l \sin 2\phi.$$

11 independent angular coefficients, $\mathbf{I}_i$, for $\bar{B}^0 \to \bar{K}^{*0}(\to K^-\pi^+)\mu^+\mu^-$ **to measure!**

q^2 dep. unknown!
from form factor!large uncertainty.

*B→K*ll process*



large recoil region: 1GeV^2 <q^2<6 GeV^2

low recoil region: q^2>14.2 GeV^2

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

❑ $m_b \to \infty$, $E_{K^*} \to \infty$: low $q^2 \sim 0$

✓LEET + QCDF expansion:

➲ ***2 independent ffs: $V(q^2)$, $A_2(q^2)$***

☺ ***ffs by LCSR → ☺ at low q^2***

❑ **Satisfactory scenario at large recoil:** ☹ tough to improve!

❑ $m_b \to \infty$, $E_{K^*} \to 0$: large $q^2 \sim m_b$

✓HQET + OPE→ ☺ *$O(\Lambda^2/m_b^2)$ uncertainties* ☺

✓Isgur-Wise relations→ 😐 *$O(\Lambda/m_b)$ uncertainties* 😐

➲ ***3 independent ffs: $V(q^2)$, $A_{1,2}(q^2)$***

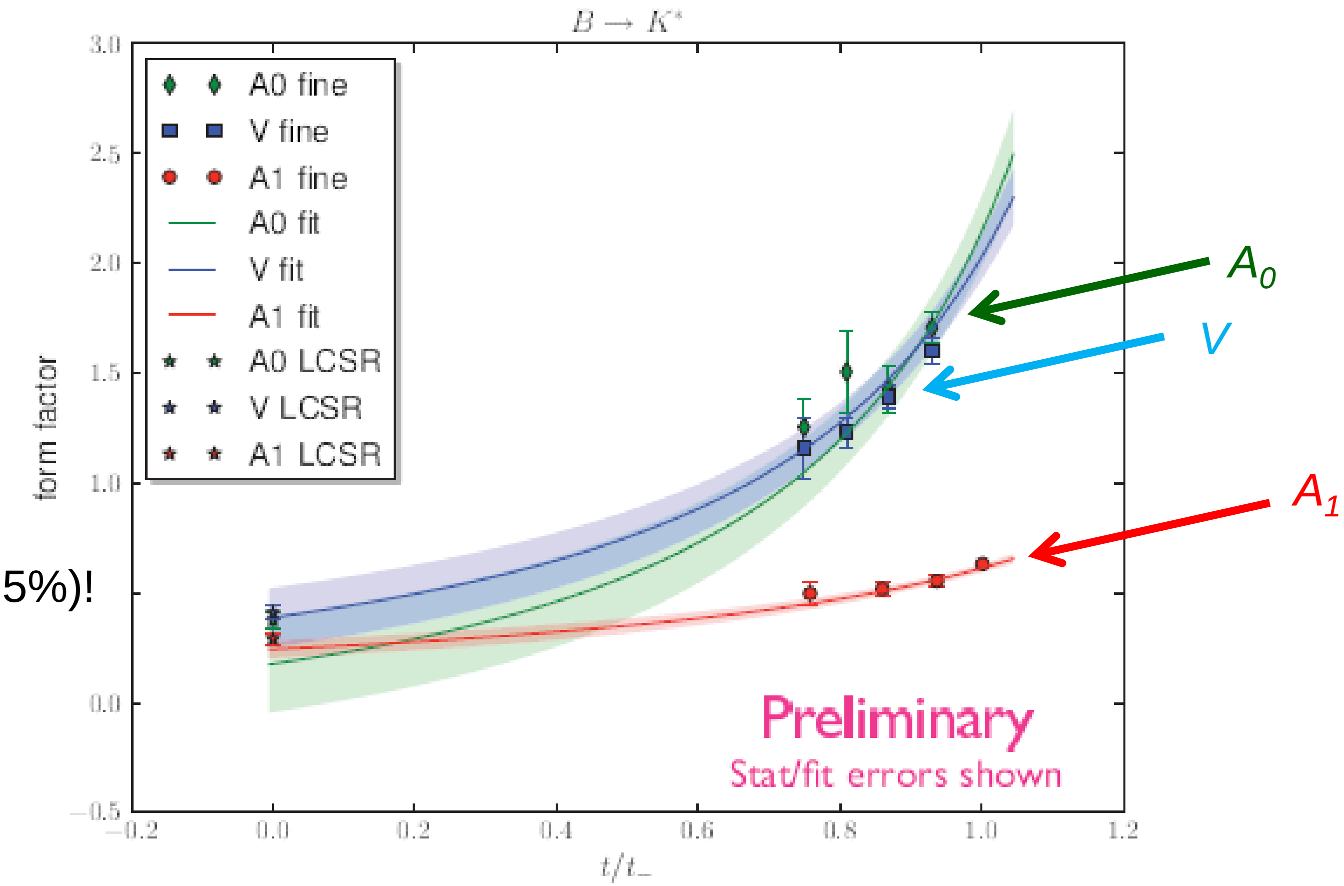
☹ ***ffs by LCSR extrapolated ☹ at large q^2***

☹ **Unsatisfactory scenario at low recoil**

☺ **But room to improve -> LATTICE QCD**

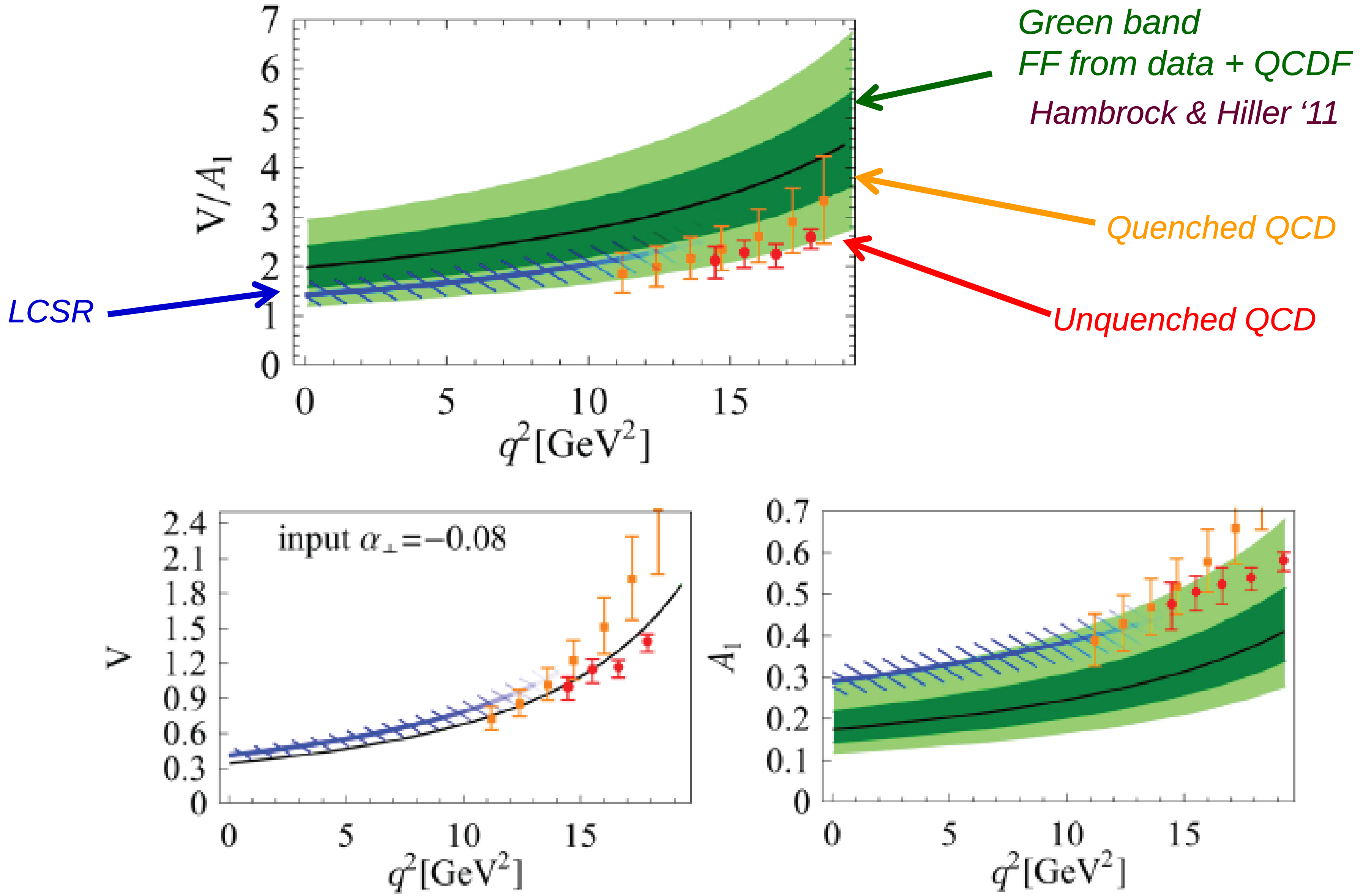
$B \to K^* ll$ form factors from Cambridge/W&M/Edinburgh.

- Only stats errors (at 5%)!
- Promising study



Preliminary results on $B \to K^* ll$ V, A_0, and A_1 vs. $q^2/q^2_{\rm max}$. (by M. Wingate at lattice 2012)

Comparison of $B \to K^* ll$ form factor calculations



Conclusions

- ***Br($B_s \to \mu\mu$) is genuinely sensitive to (pseudo)scalar operators***

$$O_S' = \left(\bar{b} P_{R,L} s\right) \bar{\ell}\ell, \text{ and } O_P = \left(\bar{b} P_{R,L} s\right) \bar{\ell}\gamma_5 \ell$$

  - Only one hadronic parameter enters, ***f_{Bs} -> small th. error***

- ***Br($B \to Kll$) & Br($B \to K^* ll$) is sensitive to (pseudo)scalar + vector operators (+ tensors)***
  - hadronic parameters, ***$f_{0,+T}$ form factors -> large th. error***
  - **With respect to $B_s \to \mu\mu$, it probes the effective Hamiltonian in an "orthogonal" direction!**
  - **Improvement of form factors calculation** would make the observables a high resolution probe of scalar operators
    - with tensor operators tested by $A_{FB}(B \to K^{(*)} ll)$
    - with vector ones by $B \to X_s ll$ spectrum and transverse asymmetries in $B \to K^* ll$

Conclusions:

LATTICE QCD -> touchable progress in recent years:

- reliable *unquenched simulations with pions close to the physical point =>* m_π=156 MeV (PACS-CS), m_π=190 MeV (BMW)

- f_K/f_π & f_B *paradigma of present lattice progress!*
- *promising studies at percent level on the way for B Physics ffs*

Still a long work to assess 1%-precision needed for B physics

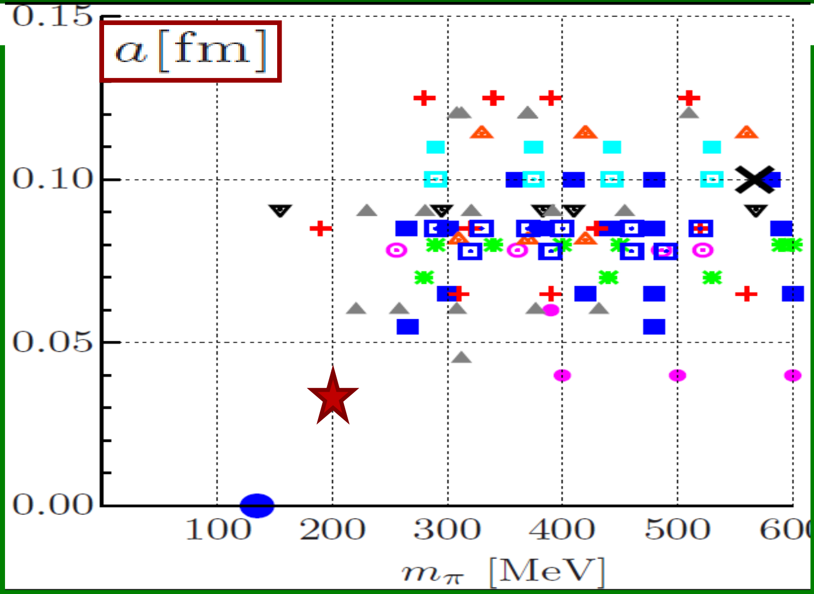
❶ ***discretization errors:*** $a * m_B << 1$

=> **a ∼ 0.033 fm** (6 GeV): ($a \geq 0.07$ fm)

❷ ***finite volume effects:*** $L * m_\pi >> 1$

=> **L ≥ 4.5 fm** ($L \leq 3$ fm)

❸ ***chiral regime*: 200 ≤ m_π ≤ 300 MeV**



courtesy of G. Herdoiza