Flavor-physics outlook

after LS1 and after LS2

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VI Meeting Italiano sulla Fisica p-p a LHC, Acquario di Genova

Taken from Acquario di Genova website

Flavor at the LHC: the LHCb reach

☑ Besides two general-purpose exp's, the LHC includes one exp dedicated to b- and c-hadron decays: LHCb

See LHCb "roadmap" doc, 0912.4179

LHCb physics objectives

- γ angle from tree-level decays — *can be determined entirely from $B \to DK$ tree decays, with negligible th. uncertainty $\Rightarrow$ standard candle*
  Talk by A. Carbone && P. Gambino
- $B_s \to \mu\mu$ — *very rare, ultra-clean decay, exquisite probe of Yukawa sector*
- mixing-induced CPV in $B_s \to J/\psi\ \phi$ — *tiny SM phase $\Rightarrow$ null test of SM CPV*
- charmless 2-body *B* decays — *test of direct (= in decay) CPV*
- $B^0 \to K^*\ \mu\mu$ — *fully angular analyses possible $\Rightarrow$ vast set of (CP-odd & CP-even) observables*
  Talk by Bona && Dinardo && Serra
- $B_s \to \phi\ \gamma$ and other radiatives — *sensitivity to magnetic ops; large $\Delta\Gamma_s$ offers sensitivity to γ polarization $\Rightarrow$ RH currents*
- CPV in charm — *unique observables for up-sector flavor & CPV; CPV = sole corner of charm physics w/ controlled QCD uncertainties*
  Talk by P. Paradisi && A. Di Canto

SM flavor violation: Within the SM, all of (quark) flavor violation is ruled by

two renormal. "Yukawa" interactions with one scalar doublet

$$L_{\mathrm{qY}} = \overline{Q}_L Y_u H^c u_R + \overline{Q}_L Y_d H d_R$$

Physical parameters:

- The Y's eigenvalues
- The relative "rotation" between the Y's

SM quark flavor patterns:

- The only entry in the Y's that is O(1) (in units of the SM Higgs vev and assuming one single vev) is $(Y_u)_{33}$
- The other eigenvalues are $\ll 1$
- The relative rotation (aka CKM) is close to the identity

Why we don't complain (much) about these patterns

- In the absence of these interactions (Y's → 0), the SM Lagrangian <u>recovers a large "chiral" group</u> of global (not local, to our knowledge) SU(3) transformations: one for each of Q_L, u_R, d_R

(In the presence of the Y's, this symmetry is used up to define a quark basis, e.g. the mass eigenbasis)

Why not a gauge flavor group?

Possible, but beware that:

- you need to ensure anomaly cancellation

  ⇨ add new fermions

- you have flavor gauge bosons

  ⇨ tree FCNCs

What's (potentially) interesting for theory progress

☑ Aside possibly from $(Y_u)_{33}$, the rest of the pattern may well be “accidental”.

So, it is likely NOT to be respected by non-SM physics, <u>however decoupled it may be</u>

Look for however small, but clear-cut (= separable from SM dynamics) in the above pattern

This qualifies especially:

☑ *Very rare, very clean decays*

☑ *CPV*

including by the way lepton flavor violation and its reach at MEG, Belle II, etc. (not covered in this talk)

Why pursuing CPV

- **Objection 1**

  By now established that the CKM phase explains the bulk of <u>low-energy</u> measured CPV

- **Objection 2**

  And the CKM phase is (arguably) insufficient to explain baryogenesis within the SM

All true, but

☞ even small deviations from the “CKM-phase-only scenario” may provide major hints on the high-scale CPV dynamics

☞ In several CPV observables, e.g. asymmetries, most of SM uncertainties cancel

⇨ especially clean tests

$B_s \rightarrow \mu\mu$

The $B_s \to \mu\mu$ decay within the SM: structure

See: Buchalla, Buras '93; Misiak, Urban '99

$BR[B_s \to \mu\mu]$ has the following structure

crucial: chiral suppression

$$BR[B_s \to \mu^+\mu^-] \simeq \frac{1}{\Gamma_s} \times \boxed{\left(\frac{G_F^2 \alpha_{\rm e.m.}^2}{16\pi^3 s_W^4}\right) \cdot |V_{tb}^* V_{ts}|^2} \cdot \boxed{f_{B_s}^2}\, m_{B_s} \cdot \boxed{m_\mu^2} \cdot \boxed{Y^2(m_t^2/M_W^2)}$$

short-distance function (aka Wilson coefficient)

couplings: gauge and CKM

hadronic matrix elem'

hadronic matrix element

Recall: the final state is purely leptonic

The only non-null matrix elem' is:

$$\langle 0 | \bar{b} \gamma^\alpha \gamma_5 s | B_s(p) \rangle = -i f_{B_s} p^\alpha$$

- f_{B_s} is among the simplest quantities for lattice QCD
- high-precision calculations possible, and in part already reality

See: Buchalla, Buras '93; Misiak, Urban '99

☑ **BR[$B_s \to \mu\mu$] has the following structure**

crucial: chiral suppression

$$BR[B_s \to \mu^+\mu^-] \simeq \frac{1}{\Gamma_s} \times \boxed{\left(\frac{G_F^2 \alpha_{\rm e.m.}^2}{16\pi^3 s_W^4}\right) \cdot |V_{tb}^* V_{ts}|^2} \cdot \boxed{f_{B_s}^2}\, m_{B_s} \cdot \boxed{m_\mu^2} \cdot \boxed{Y^2(m_t^2/M_W^2)}$$

short-distance function (aka Wilson coefficient)

couplings: gauge and CKM

hadronic matrix elem'

chiral suppression

- Easy to understand: take the B momentum p

  contract p with the lepton current, using p = p(μ^+) + p(μ^-)

  use e.o.m. for μ^+ and μ^-

- Masses' & couplings' dependence of the BR = "usual" FCNC-related suppression $\times \boxed{\dfrac{m_\mu^2}{M_W^2}}$

Additional "chiral" suppression: relative 10^{-6} factor

BR[$B_s \to \mu\mu$] error: parametric

- The main sources of error within the BR formula are:

$$BR[B_s \to \mu^+\mu^-] \simeq \frac{1}{\Gamma_s} \times \left(\frac{G_F^2 \alpha_{\rm e.m.}^2}{16\pi^3 s_W^4}\right) \cdot \left|V_{tb}^* V_{ts}\right|^2 \cdot f_{B_s}^2 m_{B_s} \cdot m_\mu^2 \cdot Y^2(m_t^2/M_W^2)$$

- Thus, one can write the following phenomenological expression for the BR

top "pole" mass here

$$BR[B_s \to \mu^+\mu^-] = 3.23 \cdot 10^{-9} \cdot \left(\frac{\tau_{B_s}}{1.466\,\mathrm{ps}}\right) \cdot \left(\frac{\mathrm{Re}(V_{tb}^* V_{ts})}{4.05 \cdot 10^{-2}}\right)^2 \cdot \left(\frac{f_{B_s}}{227\,\mathrm{MeV}}\right)^2 \cdot \left(\frac{M_t}{173.2\,\mathrm{GeV}}\right)^{3.07}$$

- Using this expression, one can easily work out the main error components as follows

	pdgLive	CKMfitter or UTfit	LQCD average (central value from C. Davies)	Tevatron average on 5.8/fb: 1107.5255
Input	$\tau_{B_s} = 1.466(31)\,\mathrm{ps}$	$\mathrm{Re}(V_{tb}^* V_{ts}) = 4.05(8) \cdot 10^{-2}$	$f_{B_s} = 227(8)\,\mathrm{MeV}$	$M_t = 173.2(0.9)\,\mathrm{GeV}$
Contribution to BR relative error	2%	4%	7%	1.6%

Total relative error expected for BR[$B_s \to \mu\mu$]: **about 8.5%**

D. Guadagnoli, Flavor outlook after LS1 & LS2

BR[$B_s \to \mu\mu$] systematics: soft radiation

Buras, Girrbach, DG, Isidori, EPJC 13

☑ Ideally, the final state is a μμ-pair such that $m_{\mu\mu} \approx m_{Bs}$. In practice, this final state may come with a number of soft, undetected, photons, so that what one is actually measuring is:

$$BR(B_s \to \mu\mu) + BR(B_s \to \mu\mu + n\gamma)\big|_{n\neq 0}$$

[(dominant) sub-leading e.m. correction to the BR]

Why should this correction be significant?

Correction included by LHCb
Atlas/CMS treatment?

Main physics argument

- A proper treatment of soft photons must sum up the contribution from an arbitrary number of:

real emitted soft photons + **virtual soft photons**

cutoff 1 $= \sum_i E_{\gamma i} = \underbrace{E_{\rm cut}}$

cutoff of exp origin:
minimum energy that one or more γ have to have to be detectable

cutoff 2 $= \Lambda \leq \underbrace{\frac{m_{B_s}}{2}}$

kinematic limit of the energy that a virtual γ can have

- Furthermore, the two contributions, separately, have each an IR cutoff.

Since the two UV cutoffs are (generally) vastly different, the correction may well be important – and in fact it is.

$$BR(B_s \to \mu\mu[+n\gamma])\big|_{\sum E_{\gamma i} \leq E_{\rm cut}} = \left(\frac{E_{\rm cut}}{m_{B_s}/2}\right)^{\frac{\alpha_{\rm e.m.}}{\pi}\#} \cdot BR(B_s \to \mu\mu)_{\rm th}$$

taking $E_{\rm cut}$ = 60 MeV [LHCb]
correction = 0.89

BR[$B_s \to \mu\mu$] systematics: the initial state oscillates

Pointed out in De Bruyn *et al.*, *PRL 12 & PRD 12*

- $B_s \to \mu\mu$ arises from the following sequence:

$b\,\bar{b}$ production → the b hadronizes into a $\bar{B}_s$ or the $\bar{b}$ hadronizes into a B_s at t = 0 → the $\bar{B}_s$ (t) or the B_s (t) evolves with time and decays into μμ

In practice, at the exp level:

- there is no flavor tagging: exp measures the sum of $B_s(t) \to \mu\mu$ and $\bar{B}_s(t) \to \mu\mu$
- the decay time info is (for the moment) not used either

What one is effectively measuring is:

$$\int dt \{\Gamma(B_s(t) \to \mu\mu) + \Gamma(\bar{B}_s(t) \to \mu\mu)\}$$

The exp-measured BR can be defined as follows:

$$BR(B_s \to \mu\mu)_{\mathbf{exp}} \equiv \int_0^\infty dt \frac{1}{2} \{\Gamma(B_s(t) \to \mu\mu) + \Gamma(\bar{B}_s(t) \to \mu\mu)\}$$

See:
Dunietz, Fleischer, Nierste
hep-ph/0012219, PRD

Continued: BR_{exp} vs. BR_{th}

See:
De Bruyn *et al.*
PRL 12

What exp measures

$$BR_{\mathbf{exp}} \equiv \int_0^\infty dt\, \frac{1}{2} \underbrace{\{\Gamma(B_s(t)\to\mu\mu)+\Gamma(\bar{B}_s(t)\to\mu\mu)\}}$$

Expressing $B_s(t)$ and $\bar{B}_s(t)$ in terms of the mass eigenstates, this sum can be rewritten as

$$= \int_0^\infty dt\, \frac{1}{2} \overbrace{\{R_H e^{-\Gamma_H t} + R_L e^{-\Gamma_L t}\}}$$

whence, integrating over t, one gets:

$$BR_{\mathbf{exp}} \equiv \tau_s \left(\frac{R_H+R_L}{2}\right) \frac{1}{1-\Delta\Gamma_s/2\Gamma_s}$$

Γ_s is the average between the $B_{s,H}$ and $B_{s,L}$ widths

Beware

This derivation assumes that exp efficiency ϵ be a constant with respect to *t*.

More rigorously, the (measured) $\epsilon(t)$ should be included in the above integral

What theory calculates

The theoretical BR discussed at the beginning is equivalent to:

$$BR_{\mathbf{th}} \equiv \frac{\tau_s}{2} \{\Gamma(B_s(t)\to\mu\mu)+\Gamma(\bar{B}_s(t)\to\mu\mu)\}\big|_{t=0}$$

Expressing $B_s(t)$ and $\bar{B}_s(t)$ as before, one gets:

$$BR_{\mathbf{th}} \equiv \tau_s \left(\frac{R_H+R_L}{2}\right)$$

The relation between BR_{exp} and BR_{th} is therefore

$$BR_{\mathbf{exp}} \equiv BR_{\mathbf{th}} \frac{1}{1-\Delta\Gamma_s/2\Gamma_s}$$

$$= BR_{\mathbf{th}} \boxed{\frac{1}{1-0.072}}$$

See:
- LHCb-CONF-2012-002
- latest HFAG average: 1207.1158

BR[$B_s \to \mu\mu$]: SM vs. exp

- More on theory systematics:

  incomplete knowledge of NLO EW corrections

  - *Implied syst. error comparable to f_{Bs} error*
  - *Impact on above central value arguably small (~ O(1%)) in appropriate scheme [see Buras, Girrbach, DG, Isidori, EPJC 13]*
  - *Final answer only from full calculation (**Gorbahn et al.**, in progress)*

- In short, the quantity to be compared with exp is therefore

$$BR[B_s \to \mu^+\mu^-]_{\text{SM pred.}} = \frac{(3.23 \pm 0.27)\cdot 10^{-9}}{1-0.072} = (3.48 \pm 0.29)\cdot 10^{-9}$$

- LHCb finds LHCb, PRL 13

$$BR[B_s \to \mu^+\mu^-]_{\text{LHCb}} = (3.2^{+1.5}_{-1.2})\cdot 10^{-9}$$

Outlook

Observable	Exp error 2018		Exp error w/ LHCb upgrade (50/fb)	SM error 2018
$BR[B_s \to \mu^+\mu^-]$	$\sim 10\,\%$	assumes 0.4 · 10⁻⁹ LHCb ⊕ 0.4 · 10⁻⁹ CMS	$0.15\cdot 10^{-9}$	small
$\dfrac{BR[B_d \to \mu^+\mu^-]}{BR[B_s \to \mu^+\mu^-]}$	$\sim 100\,\%$		$\sim 30\,\%$	small

$B_s \rightarrow \mu\mu$

and new physics

BR[$B_s \to \mu^+\mu^-$] beyond the SM

☑ **Model-independent approach:** effective operators

Beyond the SM,
a total of 6 operators can contribute:

(One may write also two tensor operators,
but their matrix elements vanish for this process.)

SM operator

$$O_A \equiv (\bar{b}\gamma_L^\alpha s)(\bar{\mu}\gamma_\alpha\gamma_5\mu) \qquad O'_A \equiv (\bar{b}\gamma_R^\alpha s)(\bar{\mu}\gamma_\alpha\gamma_5\mu)$$

$$O_S \equiv (\bar{b}P_L s)(\bar{\mu}\mu) \qquad O'_S \equiv (\bar{b}P_R s)(\bar{\mu}\mu)$$

$$O_P \equiv (\bar{b}P_L s)(\bar{\mu}\gamma_5\mu) \qquad O'_P \equiv (\bar{b}P_R s)(\bar{\mu}\gamma_5\mu)$$

☑ The very "delicate" structure of the SM prediction
is easily spoiled beyond the SM.

Credits: Gino Isidori

- Why is this actually plausible?

Observation: the $B_s \to \mu\mu$ amplitude remains a well-defined object in the limit where gauge interactions go to zero.

$$A_{B_s\to\mu\mu} \propto G_F \cdot \alpha_{e.m.} \cdot Y(M_t^2/M_W^2) \quad \text{with} \quad Y\left(\frac{M_t^2}{M_W^2}\right) \sim \frac{M_t^2}{M_W^2} \quad \text{because of GIM}$$

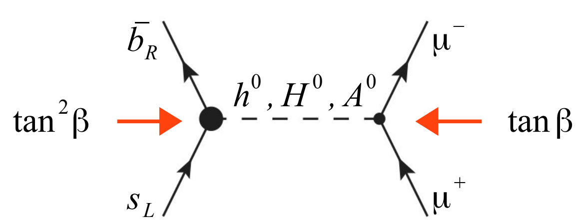
- Hence the relevant proportionality is:

$$A_{B_s\to\mu\mu} \propto \frac{1}{v^2} \cdot g^2 \cdot \frac{M_t^2}{M_W^2} \propto \frac{y_t^2}{v^2}$$

the g^2 dependence cancels out

So this process is a genuine probe
of Yukawa interactions
i.e. of the scalar-fermion sector

One famous example:
the MSSM with large tanß



Effectively tree-level diagrams:
Enhancement going as:

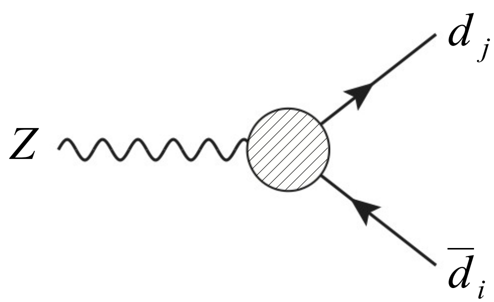
$$BR[B_s\to\mu^+\mu^-] \propto A_t^2\,\frac{\tan^6\beta}{M_A^4}$$

BR[$B_s \to \mu\mu$] as an EW precision test

DG, Isidori, 1302.3909

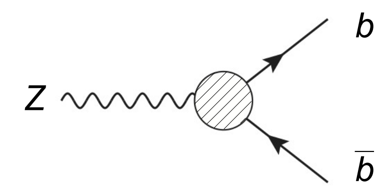
- $B_s \to \mu\mu$ is more than 'just' a probe of new scalars mediating FCNCs

Consider the Z-$\bar{d}_i$-d_j coupling:



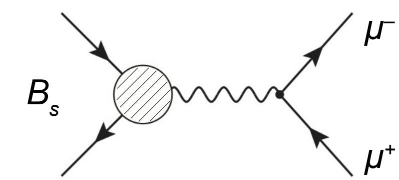
Flavor-diag: *i = j (= 3)*

Affects LEP-measured
$Z \to b\,\bar{b}$ observables: R_b, A_b, A^b_{FB}



Flavor-off-diag: *i ≠ j*

Affects Z-penguin-driven FCNCs,
in particular $B_s \to \mu\mu$



- At the Lagrangian leven, these coupling modifications may be parameterized as follows

$$L_{\rm eff}^{Zdd} = \frac{g}{c_W}\, Z_\mu\, \bar{d}^i \gamma^\mu \left[\left(g_L^{ij} + \delta g_L^{ij}\right) P_L + \left(g_R^{ij} + \delta g_R^{ij}\right) P_R \right] d^j$$

new-physics enters here

where:

SM couplings

$$g_L^{ii} = -\frac{1}{2} + \frac{1}{3} s_W^2 + \text{loops}$$

$$g_R^{ii} = \frac{1}{3} s_W^2 + \text{loops} \qquad g_{L,R}^{ij} = 0 + \text{loops}$$

Effective theory

DG, Isidori, 1302.3909

☑ Shifts in Zdd couplings can be implemented as contributions from effective operators (→ minimal model dep.)

The only operators relevant to the problem are of the form:

$$\text{Operators} \sim \left(\bar{d}_i \, \gamma^\mu \, \underbrace{X^{ij}}_{\text{flavor structure}} d_j\right) \underbrace{\left(H^\dagger D_\mu H\right)}_{\sim\, v^2 Z_\mu}$$

Comments

☑ Three such structures compatible with the SM gauge group

☑ Other operators yield negligible effects in either *Z*-peak obs or in $B_s \to \mu\mu$

- 4-fermion ops. negligible in Zbb
- ops. involving field-strength tensors negligible in $B_s \to \mu\mu$

☑ In this approach, there is a correlation between $Z \to b\bar{b}$ and $B_s \to \mu\mu$.

This correlation is fixed, after specifying the X^{ij} couplings.

Within frameworks as general (and motivated) as:

- Minimal Flavor Violation — See: D'Ambrosio *et al.*, NPB 02

or

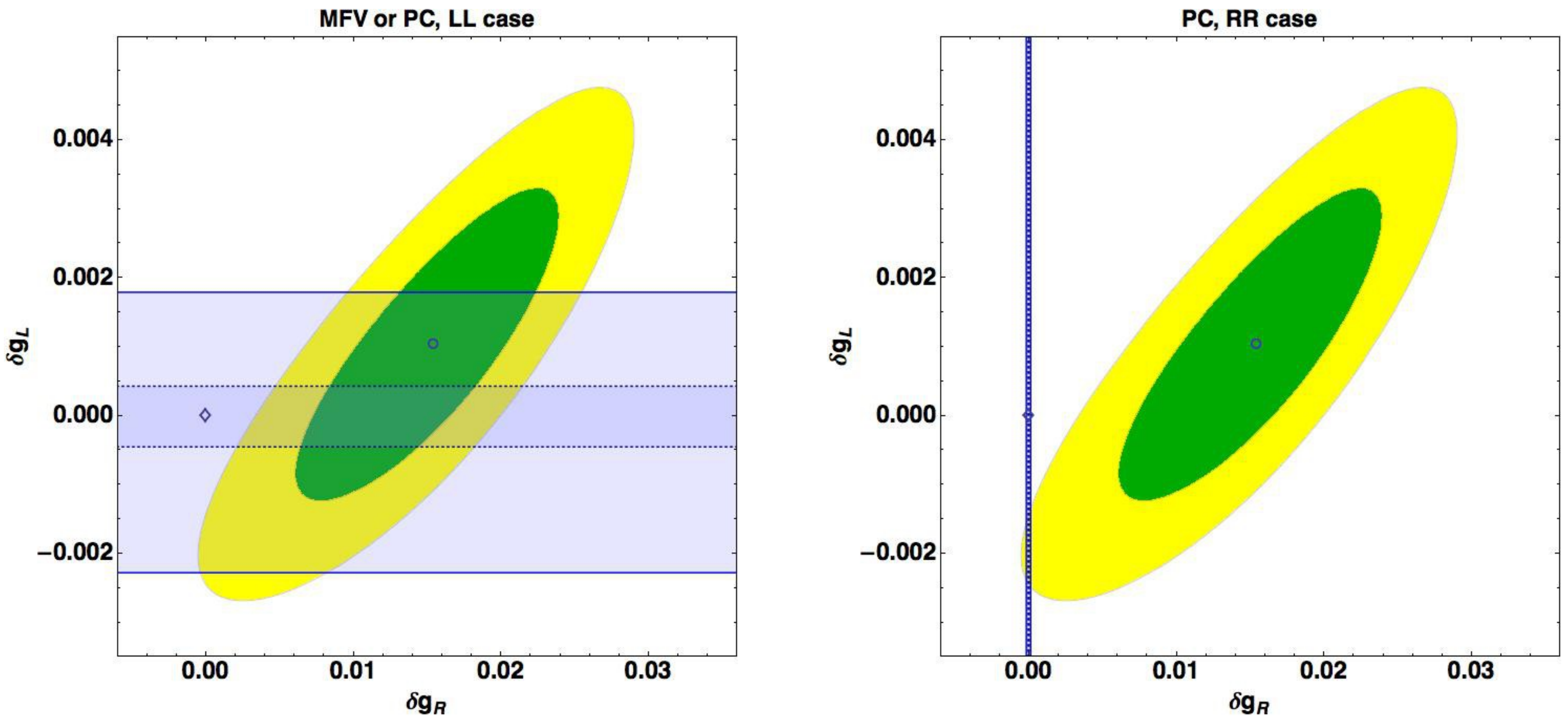
- Partial Compositeness — See: Davidson, Isidori, Uhlig, PLB 08; Rattazzi *et al.*, NPB 13

the X^{ij} can be fixed up to O(1) factors (that btw weigh equally between Zbb and $B_s \to \mu\mu$)

BR[$B_s \to \mu\mu$] as an EWPT: results

DG, Isidori, 1302.3909

☑ One can then compare the limits on $\delta g_{L,R}$ obtained from *Z*-peak obs with those obtained from $B_s \to \mu\mu$



with present $B_s \to \mu\mu$ exp error	$\lvert\delta g_L\rvert^{\text{MFV or PC}} < 2.3\times10^{-3}$	$\lvert\delta g_R\rvert^{\text{PC}} < 1.6\times10^{-4}$
with ~ 10% $B_s \to \mu\mu$ error	$\lvert\delta g_L\rvert^{\text{MFV or PC}} < 4.6\times10^{-4}$	$\lvert\delta g_R\rvert^{\text{PC}} < 3.3\times10^{-5}$

!

Mixing-induced CPV in B_s

Mixing-induced CPV in B_s: main channel(s)

☑ The "benchmark" B_s decay to explore mixing-induced CPV is:

$$B_s \left(\to \bar{B}_s\right) \to J/\psi \; \phi, \quad J/\psi \to \mu^+\mu^-, \quad \phi \to K^+K^-$$

Comments

☑ B_s-equivalent of $B_d \to J/\psi\, K_s$, benchmark mode for sin 2ß at B-factories

☑ Analysis needs to be:

- time-dependent (otherwise no sensitivity to $B_s - \bar{B}_s$)
- angular (to disentangle CP-even & CP-odd components in final state)

☑ **Theory systematics**

Main point:

<u>Provided</u> the (B_s or $\bar{B}_s$) decay amplitude doesn't introduce uncalculable phases, the process allows to determine the $B_s - \bar{B}_s$ mixing phase, ϕ_s

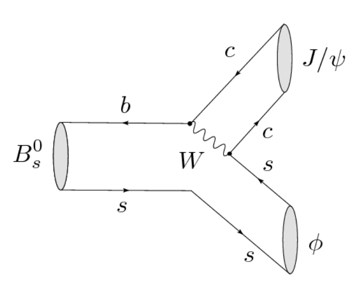
Within the SM:

$$\begin{aligned}\phi_s^{\mathrm{SM}} &= 2\arg\left(V_{ts}^* V_{tb}\right)\\ &= -0.036(2)\end{aligned}$$

Is this assumption fulfilled for this decay?

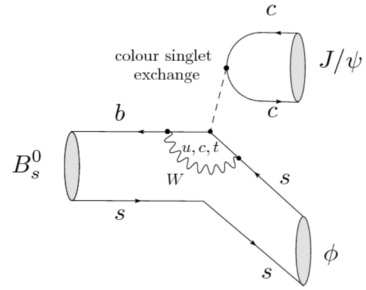
$$\mathrm{Ampl.}\left(B_s \to J/\psi\,\phi\right) =$$

tree



+

penguin



diags. stolen from 1303.5575 for simplicity

More comments

☑ If non-negligible the penguin ampl. needs to be fitted from data

☑ But in this decay:

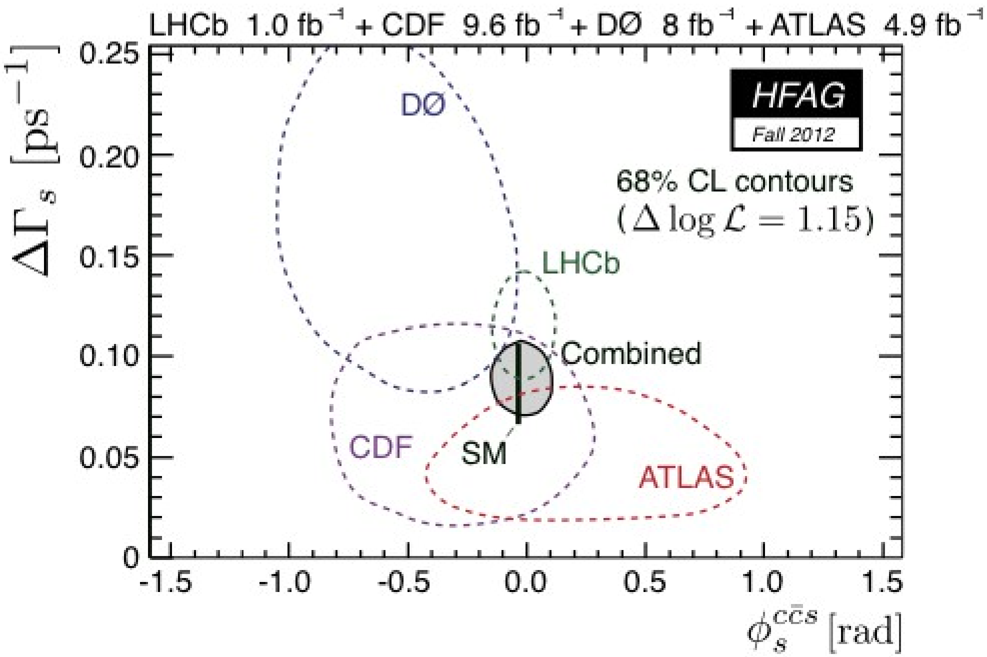
$$|\mathrm{penguin}/\mathrm{tree}| \propto \lambda^2_{\mathrm{Cabibbo}}$$

☑ So, with present accuracy, assumption is fulfilled

Mixing-induced CPV in B_s: results and outlook

☑ The state-of-the-art determination of ϕ_s is a global fit (HFAG) to $b \to c\bar{c}s$ data

It is dominated by the $B_s \to J/\psi\ \phi$ channel, that in fact is simultaneously sensitive to $\{\phi_s, \Delta\Gamma_s, \Gamma_s\}$



Comments

☑ Also $\Delta\Gamma_s$ sign resolved, via $B_s \to J/\psi\ K^+ K^-$

☑ Data (gray) and SM (vertical "line") show perfect consistency at current accuracy

No apparent sign of penguin pollution (as expected for these modes)

☑ With more data, also "penguin modes" $b \to qqs$ will be included.

Penguin contrib's (channel-dependent) will need to be parameterized and directly extracted from the fit

Outlook for ϕ_s

	Current, HFAG	**Exp error w/ LHCb upgrade (50/fb)**
	$\phi_s^{c\bar{c}s} = -0.013^{+0.083}_{-0.090}$	0.008
	$\left(\phi_s^{SM} = -0.036(2)\right)$	

- ϕ_s accuracy likely to remain limited by <u>statistics</u> (even after LHCb upgrade)
- *How small a phase can we eventually probe?*
  Suppose a model predicts ½ the SM phase.
  It will be testable at 3 σ

ϕ_s vs. $\Delta\Gamma_s$ via "effective" lifetimes

Pointed out in:
Fleischer, Knegjens
EPJC 11

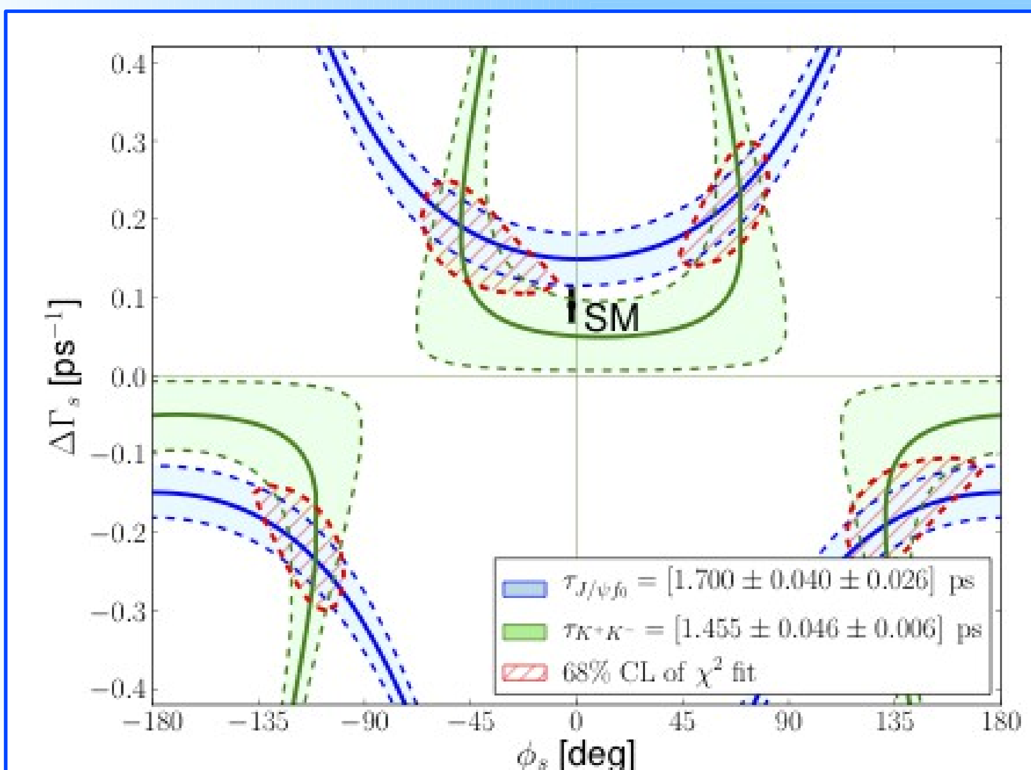
- Consider a generic B_s decay. As soon as time information is available, one can access the B_s "effective" lifetime for that decay, defined as:

$$\tau_f \equiv \frac{\int_0^\infty \left(\Gamma(B_s(t) \to f) + \Gamma(\bar{B}_s(t) \to f) \right) t \, dt}{\int_0^\infty \left(\quad " \quad \right) dt}$$

Note
flavor tagging not required

- By expressing $B_s(t)$ in terms of the mass eigenstates, and evolving them in t, it is clear that *each τ_f is sensitive to (a different combination of) the mixing phase ϕ_s and the width difference $\Delta\Gamma_s$*

- One can translate τ_f measurements into contours in the ϕ_s vs. $\Delta\Gamma_s$ plane.



Example (from Knegjens at Capri FP 12)

Uses eff. lifetime measurements in:

- $B_s \to K^+ K^-$
- $B_s \to J/\psi \ f_0(980)$

from LHCb 2011 data (1 / fb)

(More data exist from CDF as well)

Note

this determination is *robust with respect to hadronic penguin uncertainties*

CPV in B_s mixing and the D0 di-muon anomaly

- CPV in B_s mixing is described by $\phi_{12}^s \equiv \arg\left(-M_{12}^s/\Gamma_{12}^s\right) \overset{\text{SM}}{=} \boxed{3.8(1.0)\cdot 10^{-3}}$

  - tiny
  - rephasing-invariant
  - sensitive to (even smallish) NP shifts, in particular in M_{12} (boxes)

- **Exp:** this phase can be extracted from "wrong-charge" semilep. B_s decays

  "Wrong-charge" lepton ⇨ Oscillation must have occurred before decay

  measured quantity

$$a_{\rm sl}^s \equiv \frac{\Gamma[\bar{B}_s(t)\to l^+ X]-\Gamma[B_s(t)\to l^- X]}{+}$$

- **D0** measures several $a_{\rm sl}$ -related observables, among the others the "like-sign di-muon charge asymmetry"

  D0 PRD 11

$$A_{\rm sl}^{\mu\mu} = C_d\, a_{\rm sl}^d + C_s\, a_{\rm sl}^s = -0.787(172)(93)\cdot 10^{-2}$$

weigh the B_d vs. B_s production fractions & mixing probabilities

at face value ~ 4 σ away from zero

SM predicts — **Lenz+Nierste** CKM 2010

$$A_{\rm sl}^{\mu\mu} = -2.3(0.4)\cdot 10^{-4}$$

$$\left(a_{\rm sl}^s = 1.9(0.3)\cdot 10^{-5} \quad a_{\rm sl}^d = -4.1(0.6)\cdot 10^{-4}\right)$$

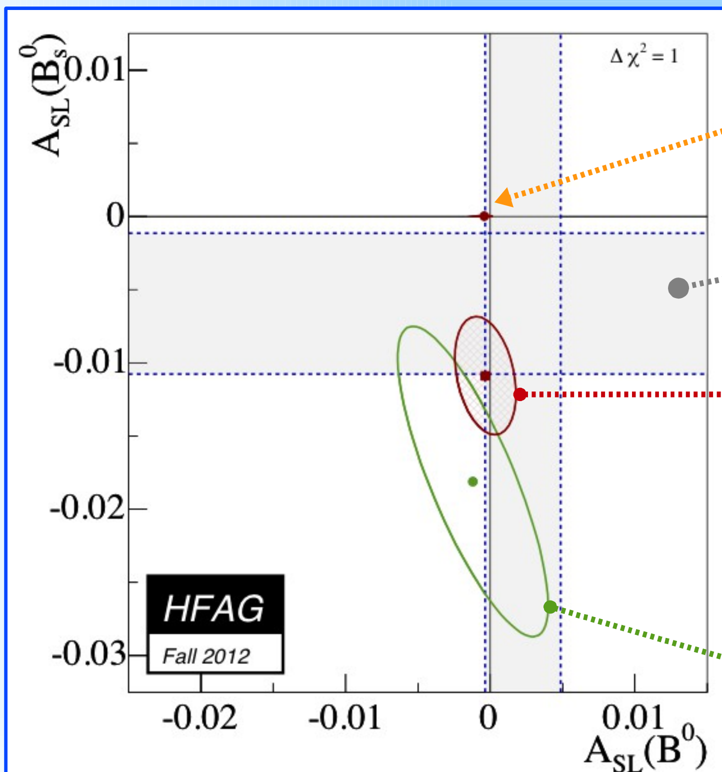
CPV in B_s mixing and the D0 di-muon anomaly

- LHCb does not confirm a non-zero asymmetry

LHCb ICHEP 2012

$$a_{sl}^{s} = -0.24(54)(33)\cdot 10^{-2}$$

- Combining with B_d data (especially from *B*-factories) HFAG finds



SM: next to {0,0}

gray bands:
B_d vs. B_s averages

full fit
yields 2.4 σ discrepancy

D0 di-muon

"Conclusion"

Issue not settled: eagerly awaiting more data, especially from LHCb

Direct (= in decay) CPV in B_s

LHCb breaking news:
First observation of direct CPV in B_s

- CP violation in decay occurs when the decay rate $M \to f$ differs from the decay rate involving the CP-conjugate states. One quantifies it by the asymmetry:

$$A_{CP}(M \to f) = \frac{\Gamma(\bar{M} \to \bar{f}) - \Gamma(M \to f)}{+}$$

- This can be measured in charmless, charged, 2-body B-meson decays. LHCb finds:

LHCb
1304.6173

$$A_{CP}(B_d \to K^+ \pi^-) = -0.080 \pm 0.007_{\text{stat}} \pm 0.003_{\text{syst}}$$

>10 σ: confirms B-factories' discovery

$$A_{CP}(B_s \to K^- \pi^+) = 0.27 \pm 0.04_{\text{stat}} \pm 0.01_{\text{syst}}$$

6.5 σ

Theory

- B_d figure from B-factories sparkled a debate on whether the effect was from SM or new physics
- Quantitative SM predictions notoriously challenging with ≥ 2 hadrons in the final state

Way out: collect several measurements + exploit approximate flavor symmetries among them to cancel unknowns

Lipkin, PLB 05

Observed DCPV in B_d is SM or NP?

Check SM prediction of equal violation in $B_s \to K^- \pi^+$

$$\Delta = \frac{A_{CP}(B_d \to K^+ \pi^-)}{A_{CP}(B_s \to K^- \pi^+)} + \frac{\text{BR}(B_s \to K^- \pi^+)}{\text{BR}(B_d \to K^+ \pi^-)} \frac{\tau_d}{\tau_s} \overset{\text{SM}}{=} 0$$

$$\Delta_{\text{exp}} = -0.02 \pm 0.06$$

Rare radiative and semileptonic B_s decays

Exclusive B decays: basics

- The crucial advantage of exclusive modes is that they offer several observables: angular & CPV obs.

  In several concrete scenarios (e.g. w/ RH currents) TeV-scale particles modify one or more of these obs.

- In fact, SM deviations can be constrained model-independently, adopting a fully general Hamiltonian:

operators:

$$\underbrace{O_7^{(\prime)}\ ,\quad O_8^{(\prime)}}_{\text{magnetic and chromomag.}}\ ,\quad \underbrace{O_9^{(\prime)}\ ,\quad O_{10}^{(\prime)}}_{\bar{q}q\bar{l}l \text{ vector-like operators}}\ ,\quad \underbrace{O_S^{(\prime)}\ ,\quad O_P^{(\prime)}}_{\bar{q}q\bar{l}l \text{ scalar operators}}$$

- **Radiative modes** (e.g. $B_s \to \phi\,\gamma$) mostly sensitive to magnetic operators: O_7, O_8, + primed (= parity-flipped)

  (Semi)lep. modes (e.g. $B \to K^*\,\mu\mu$, $B_s \to \phi\,\mu\mu$, $B \to K\,\mu\mu$, $B_s \to \mu\mu$) are, in principle, sensitive to all

- Set of operators constrained & sensitivity is different in different modes $\Rightarrow$ **typically, combined analysis**

Several such analyses.
Examples:

Bobeth, Hiller *et al.*
JHEP 12

Becirevic, Mescia *et al.*
PRD 12

Hurth, Mahmoudi
NPB 12

Altmannshofer, Paradisi, Straub, JHEP 12

An example in some detail: $B \to K^* \mu\mu$

Work from: Beneke, Buchalla, Neubert, Sachrajda; Bauer et al.; Feldmann; Egede et al.; Descotes, Matias et al.; Bobeth, Hiller et al.; Khodjamirian-Mannel; ...

Basic challenge: find kinematic regions where f.f. dependence either calculable or "simple" (= can be got rid of)

Such regions exist:

1 Large meson recoil

- The combined limit of heavy b & energetic K(*) allows for QCD factorization (BBNL) of the decay amplitude:

$$\text{Ampl.} \propto \underbrace{\xi_i}_{\text{process-indep. f.f.}} \times \underbrace{C_i}_{\text{perturbatively calculable q.ties}}$$

Main points

- Drastic simplification in the number of f.f.'s: 2 (K*) or 1 (K)
- **f.f. dependence is linear**
  Possible to devise observables where f.f. dep. cancels for all (low) $q_{\mu\mu}^2$
- **Downside:**
  No general method to estimate Λ_{QCD} / m_b corrections

- **Analysis:**
  Several observables proposed, in which ξ dependence cancels completely (modulo Λ_{QCD} / m_b corrections!)
  High sensitivity to O_7, O_9, O_{10} (& primed). Ideal probes of RH currents.

2 Large $q_{\mu\mu}^2$

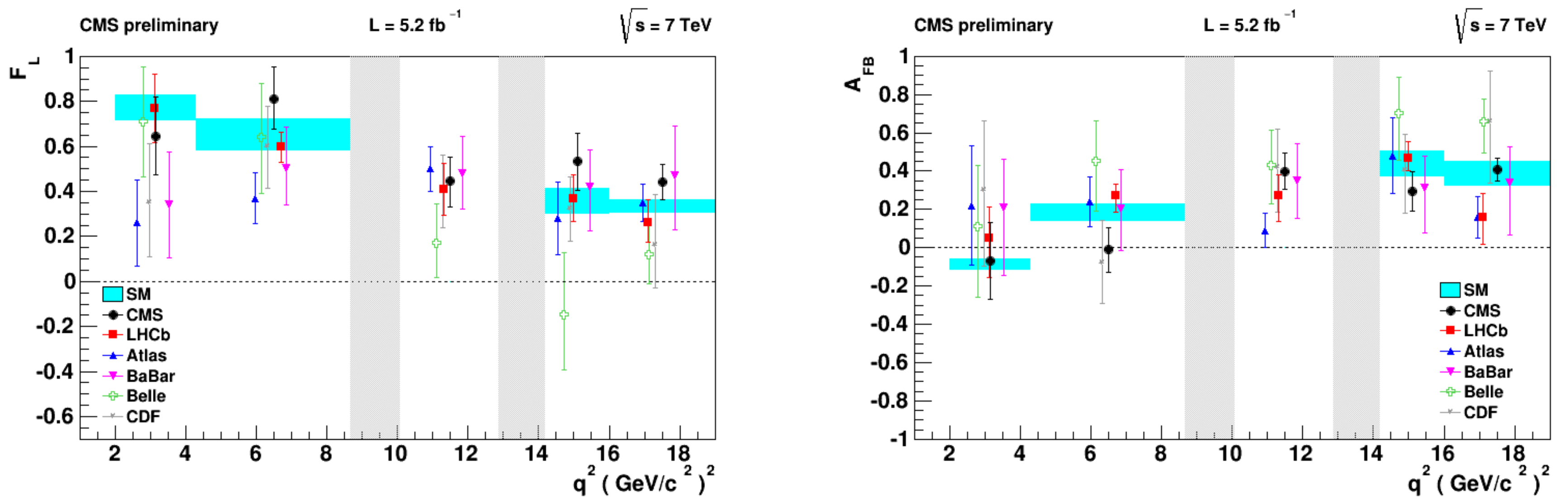
- Short: also theoretically well under control (for more technical circumstances)

- **Analysis:**
  Weaker dependence on O_7 (& primed) ⇨ Cleaner extraction of O_9 and O_{10} (& primed) contribs.

Data and outlook

- For decays like $B \to K^* \mu\mu$, the fully angular (in $q_{\mu\mu}^2$ and in 3 decay angles) distribution is in principle accessible. It consists of **12 angular terms, with coeff. functions $J_i(q_{\mu\mu}^2)$** [Krüger et al., PRD 00; Altmannshofer et al. JHEP 09]

- **The J_i offer plenty of observables:** symmetric (asymmetric) combinations ⇨ CP-averaged (CP-odd) quantities
  With current (limited) statistics: build partially integrated obs, with large bins:



Outlook

- **With 5 / fb at LHCb:** full angular analysis of $B \to K^* \mu\mu$. Ultimate exp aim: measure all the J_i & exploit in full NP sensitivity.

- In MFV models (and others), rare $b \to d$ transitions are such that $\mathrm{A}(b \to d)/\mathrm{A}(b \to s) \propto |V_{td}/V_{ts}|$
  First measurements exist (B-factories + LHCb). But full potential exploitable only with LHCb (and Belle!) upgrade.

For example: Possible a detailed comparison of $\boxed{|V_{td}/V_{ts}|_{\text{penguins}} \text{ vs. } |V_{td}/V_{ts}|_{\text{boxes}}}$

Conclusions

- ☑ Two wide classes of processes interesting for theory: rare and clean decays & CPV

  In both cases, LHCb well on its way towards interesting results

- ☑ **$B_s \to \mu\mu$**
  - *Theory (SM) ready to match experimental accuracy*
  - *Overall accuracy expected at ~ 10% by 2018 (dominated by exp)*
  - *One of the best existing probes of the Yukawa sector*
  - *Also exquisite probe of Zqq anomalous couplings.*

    Within general frameworks for BSM flavor breaking (MFV and generic partial compositeness) $B_s \to \mu\mu$ constraint typically stronger than Z-peak observables

- ☑ **Mixing & mixing-induced CPV in B_s**
  - *Clean "null test" of the SM, passed within present accuracies*
  - *With increased exp accuracy, mandatory to revise assumptions about penguin amplitudes*
  - *Effective lifetimes as a penguin-pollution-immune avenue to access the same observable*
  - *CPV in pure mixing: D0 dimuon anomaly not confirmed by LHCb, but still unresolved issue (2.4 σ)*

Conclusions

☑ Direct CPV in B_s

- *LHCb discovery in charmless two-body decays*
  Now possible to accurately test a SM sum rule where hadronic uncertainties cancel

☑ Rare radiative and semileptonic decays

- *Crucial advantage: lots of observables. New physics testable in a model-independent approach*
- *In appropriate kinematic regions, possible to construct observables where f.f. dependence nearly cancels. Several CP-averaged and CP-odd observables proposed*
- *Ideal probes of (even very suppressed) RH currents*
- *With 5 / fb: full NP potential of semileptonic channels will be exploited.*
- *Besides $b \to s$, important to also measure $b \to d$ channels. In this way one can test*

$$|V_{td}/V_{ts}|_{\text{penguins}} \text{ vs. } |V_{td}/V_{ts}|_{\text{boxes}}$$

☑ sin2ß vs. ϵ_K vs $B \to \tau\nu$ tensions: status

- *Currently below 2σ (sin2ß vs. ϵ_K). Disappeared in $B \to \tau\nu$*
- *Worthwhile to follow, especially after γ improvements (LHCb) and Belle II startup*

Some Topics for Discussion

☑ $B_s \to \mu\mu$

- *Error on B_s decay constant (f_{Bs}) crucial for BR error. Too aggressive f_{Bs} errors – and corresponding BR($B_s \to \mu\mu$) errors – should be taken cum grano salis*
- *The "large-$\Delta\Gamma_s$" factor (De Bruyn et al.) as well as the soft-photon correction factor should be estimated by convoluting in the time integral the (measured !) exp acceptance as a function of B_s decay time*
- *$B_d \to \mu\mu$ && $B_s \to \tau\tau$*

☑ Mixing & mixing-induced CPV in B_s

- *Prospects for "effective-lifetime" (= untagged but time-dependent BRs) measurements*
- *Whether the ϕ_s vs. $\Delta\Gamma_s$ determination with effective lifetimes will be competitive with the determination from the "benchmark" $B_s \to J/\psi\ \phi$, $J/\psi\ \pi\ \pi$ analysis*
- *Prospects on ϕ_s error from exps other than LHCb (for which the figure seems to be 0.008 w/ 50/fb)*
- *Strategies for understanding the D0 di-muon anomaly (if any)*

Some More Topics for Discussion

☑ Rare semileptonic & radiatives

- *According to "Implications Workshop" paper, only 5 / fb necessary for a fully angular analysis of $B \to K^* \mu\mu$. Does this mean measuring all of the (12) coefficient functions of this distribution?*
- *Prospects for $b \to d$ channels and for testing* $|V_{td}/V_{ts}|_{\text{penguins}}$ vs. $|V_{td}/V_{ts}|_{\text{boxes}}$

Additional material

Fixing the couplings. Case 1: MFV

- ☑ MFV is the statement that – even beyond the SM – the only structures that break the flavor symmetry are the SM Yukawa couplings

- ☑ This statement fixes the flavor structure of new operators.

  Example: operators with the bilinear $\bar{Q}^i_L \gamma^\mu X_{ij} Q^j_L \quad \Longrightarrow \quad X_{ij} = O(1) \times (Y_u Y_u^\dagger)_{ij}$

- ☑ This fixes the flavor structure of the $Z \bar{d}_i d_j$ coupling δg_L^{ij}

  E.g., in the basis where $Y_u = V^\dagger \hat{Y}_u$ and $Y_d = \hat{Y}_d$ one has: $\boxed{\delta g_L^{ij} \propto V^*_{ti} V_{tj}}$

Most relevantly, this fixes univocally the <u>correlation</u> between the flavor-off-diag. and the flavor-diag. coupling:

$$\boxed{\delta g_L^{32}} = \boxed{\frac{V^*_{tb} V_{ts}}{|V_{tb}|^2}} \boxed{\delta g_L}$$

shift in the Zbs coupling: affects $B_s \to \mu\mu$

flavor structure (fixed within the framework)

shift in $Z \to b\bar{b}$

Fixing the couplings. Case 2: Partial Compositeness

See e.g.: Davidson, Isidori, Uhlig, PLB 08

☑ **Basic observation #1.** Within the dim-4 part of the Lagrangian, two are the possible sources of flavor violation:

① Yukawa interactions (as known) and/or ② hierarchical kinetic terms for fermions (in a non-canonical wave-function normalization)

Restricting to dim-4 interactions, the two sources are interchangeable (→ only a matter of field-basis choice)

☑ **About source ②**

- Hierarchical kin. terms can arise in extra-dims as non-trivial profiles of fermion wave-functions in the extra-dims
- Hierarchies are then transmitted to the Yukawa interactions, once kin. terms are made canonical
- Before rotation to the canonical basis, Yukawa interactions can therefore be patternless, O(1) anarchic matrices

Example

$$\bar{Q}_L Z_Q^{-2} \gamma^\mu D_\mu Q_L$$

with $Z_Q = \mathrm{diag}(z_Q^{(1)}, z_Q^{(2)}, z_Q^{(3)})$

and $z_Q^{(1)} \ll z_Q^{(2)} \ll z_Q^{(3)}$

&& $Y_{u,d} = O(1)$ $\xrightarrow{\text{canonical basis}}$ $(Y_{u,d})_{ij} \propto z_Q^{(i)} z_{u,d}^{(j)}$

Fixing the couplings. Case 2: Partial Compositeness

See e.g.: Keren-Zur *et al.*, NPB 13

☑ Basic observation #2.

The *very same* $Y_{u,d}$ pattern as above arises in scenarios of Partial Compositeness.

The defining property of (fermion) Partial Compositeness is as follows.

At a cutoff scale *Λ*, the SM fermions f_i couple linearly to operators O_i of a confining sector:

$$\text{interactions} \quad = \epsilon_i \, f_i \, O_i$$

- the ϵ_i measure the degree of compositeness of f_i
- apart from an overall factor, *the ϵ_i can be identified with the z_i of the previous picture*

Main points

- The two pictures are completely equivalent – at least within our context
- From the second picture it is evident that the relevant low-energy d.o.f. are not f_i, but rather $\epsilon_i f_i$
  Building our EFT with $\epsilon_i f_i$ the flavor structure is fixed – apart from O(1) factors

Example

Flavor structure of the RH operator $O^{32}_{1R} \equiv i \left(\bar{b}_R \gamma^\mu s_R\right) H^\dagger D_\mu H$

Wilson coeff.

$$\propto z_d^{(3)} z_d^{(2)} = \frac{z_Q^{(3)} z_d^{(3)} \; z_Q^{(2)} z_d^{(2)}}{z_Q^{(3)} \, z_Q^{(2)}} \propto \frac{m_b \, m_s}{|V_{tb}||V_{ts}|} \quad \Rightarrow \quad \delta g_R^{32} = \frac{m_b m_s}{|V_{tb}||V_{ts}|} \frac{|V_{tb}|^2}{m_b^2} \, \delta g_R$$