Towards the Ultimate Precision in Flavour Physics

B decays to rare leptonic and semileptonic final states

- Flavour physics always at the frontier of testing the SM and looking for BSM

top 10 observables beyond $\mathcal{B}(b \to s\gamma)$

1. CP asymmetry $a_{CP}(b \to s\gamma)$; in SM direct CP violation in $b \to s$ is small: $a_{CP} = \frac{|A|^2-|\bar{A}|^2}{|A|^2+|\bar{A}|^2} \propto \alpha_s(m_b) Im \frac{V_{ub}V_{us}^*}{V_{tb}V_{ts}^*} \sim \alpha_s(m_b)\lambda^2 \lesssim \mathcal{O}(1\%)$
   $a_{CP} = (-0.079 \pm 0.108 \pm 0.022)(1 \pm 0.03)$ CLEO hep-ex/0010075
2. search for wrong helicity $\bar{s}_R \sigma_{\mu\nu} b_L$ in $b \to s\gamma$; in SM small $C_7' = m_s/m_b C_7$ e.g. with polarization studies in $\Lambda_b \to \Lambda\gamma$ at Tevatron, LHC, GigaZ hep-ph/0108074
3. $|\sin 2\beta_{(J/\Psi K)} - \sin 2\beta_{(\Phi K)}|$ is $\lesssim \mathcal{O}(\lambda^2)$ in SM; direct CPX in $b \to s\bar{s}s$
   $\mathcal{B}(B \to \Phi K_0)_{ave} = 8.8^{+2.7}_{-2.3} \cdot 10^{-6}$ Belle, Babar preliminary
   $\sigma_{\Phi K_s}(stat) = 0.56, 0.18$ with $0.1, 1ab^{-1}$ hep-ph/0112312
4. precision study in inclusive $b \to s\ell^+\ell^-$ branching ratio at NNLO for low dilepton inv mass below $c\bar{c}$ threshold hep-ph/0112300

Gudrun Hiller, SLAC — beach 2002 — Slide 15

top 10 observables beyond $\mathcal{B}(b \to s\gamma)$

5. For-Back-asymmetry $A_{FB}(B \to (X_s, K^*)\ell^+\ell^-)$ sign/shape
6. if it exists, what is the position of the A_{FB} zero in low q^2
7. Forward-Back-CP asymmetry $A_{FB}^{CP} \equiv \frac{A_{FB}+\bar{A}_{FB}}{A_{FB}-\bar{A}_{FB}} \sim \frac{Im(C_{10})}{Re(C_{10})}$ probes non-SM CP phase in sZb vertex; in SM $A_{FB}^{CP} < 10^{-3}$ hep-ph/0006136
8. $B_s - \bar{B}_s$ mixing, Z-penguins
9. $\mathcal{B}(B_{d,s} \to \mu^+\mu^-)$, sensitive to neutral higgs exchange
10. nEDMs, strong CP problem $\bar{\Theta} < 10^{-10}, \delta_{CKM} \sim O(1)$? sensitive to flavor blind CP violation if PQ-axion solution, if spontaneously broken CP tight constraints on flavor structure hep-ph/0201251

top 100: $b \to s\nu\bar{\nu}$, $K \to \pi\nu\bar{\nu}$, $D_0 - \bar{D}_0$, leptons, neutrinos

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Key topics 2002: CP, observation of rare B-decays, start of angular analysis, C_7, C_7', C_{10}, C_P ... and K, D physics

Key themes now: precision, CP, lepton nonuniversality ... and K, D

- **Community eagerly awaiting for new results**, particularly LU tests

Conclusions

- Crucial to follow different theoretical treatments (SFF or FF) and FF LCSR approaches.
- Improvements on theoretical side for $b \to s\mu\mu$:
  - Form Factors: KMPW $\mathcal{O}(\alpha_s)$ corrections, BSZ test error assessment, i.e., $f_{K^*}^T$.
    → Optimized observables in SFF more robust against changes in FF than non-optimized ones.
  - Non factorizable contributions: theory and experimental approach.
    → Data seems to point to absence of a relevant q^2 dependent in C_9 besides known ones.
- Disentangling scenarios with LFUV observables:
  - R_{K^*} very sensitive to hadronic uncertainties in presence of NP in particular to changes in FF.
  - R_K excellent probe in SM but also in NP due to simple structure.
  - Q_5 unique capacity to disentangle $C_9 = -C_{10}$ and C_9, but also size of possible hadronic contributions.
- An experimental improvement on R_K error by 40% assuming same cv:
  A fit with only LFUV will move above 5σ and near 7σ of complete fit.

SUMMARY: PLEASE PROVIDE R_K and Q_5!!!!!!!!!!

Joaquim Matias — Universitat Autònoma de Barcelona — *Directions for improvement in precision for P_i and LFUV observables*

- **Very large sample of b->s(d)ll decays will become available in (near) future**

Observable	Run 1 result	8 fb^{-1}	50 fb^{-1}	300 fb^{-1}
Yield $B^0 \to K^{*0}\mu^+\mu^-$	2398 ± 57 [74]	9175	70480	435393
Yield $B_s^0 \to \phi\mu^+\mu^-$	432 ± 24 [75]	1653	12697	78436
Yield $B^+ \to K^+\mu^+\mu^-$	4746 ± 81 [83]	18159	139491	861709
Yield $B^+ \to \pi^+\mu^+\mu^-$	93 ± 12 [84]	355	2725	16831
Yield $\Lambda_b^0 \to \Lambda\mu^+\mu^-$	373 ± 25 [85]	1426	10957	67688

Observable ($1.1 < q^2 < 6.0\,\mathrm{GeV}^2/c^4$)	Run 1 result	8 fb^{-1}	50 fb^{-1}	300 fb^{-1}
Yield $B^+ \to K e^+e^-$	254 ± 29	950	7500	45000
Yield $B^0 \to K^{*0}e^+e^-$	111 ± 14	400	3200	20000
Yield $B_s^0 \to \phi e^+e^-$	–	75	560	3500
Yield $\Lambda_b^0 \to pK e^+e^-$	–	200	1500	9400
Yield $B^+ \to \pi^+e^+e^-$	–	–	300	1800

- **Belle-II will very soon enter the game** (could improve precision on BR of normalisation modes used by LHCb?)

- How precise can **RK(*)** become?

Potentially irreducible systematics are bound by the limited knowledge of the modelling of bremsstrahlung effects

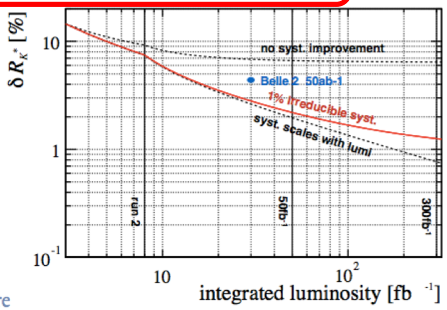
[i] Reconstruction of emitted-γ before the magnet

[ii] Ability to find the corresponding photons in the ECAL

[iii] Energy resolution

These features are compulsory for the design of the upgrade detector

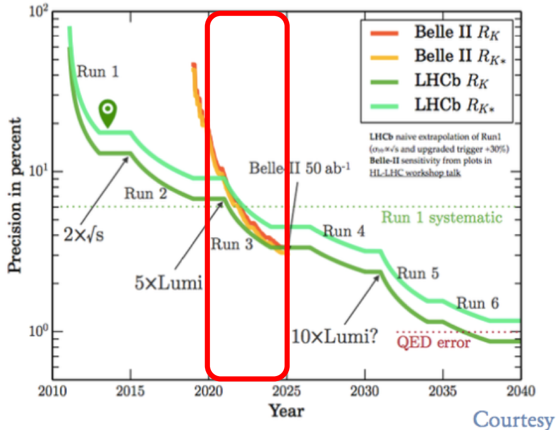
e.g. reduced amount of material before the magnet would reduce these factors



Courtesy of T. Blake

- Tight but healthy competition ahead

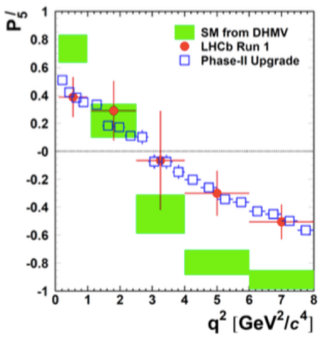
How is the interplay between LHCb/Belle-II ?

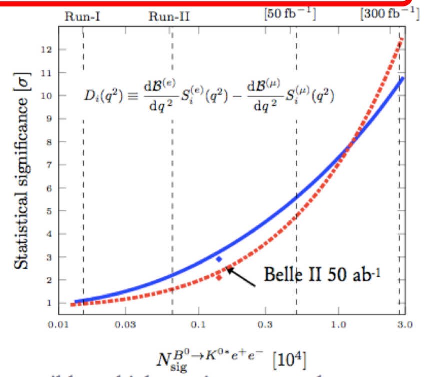


Courtesy of M. Borsato

- What about **angular observables**?

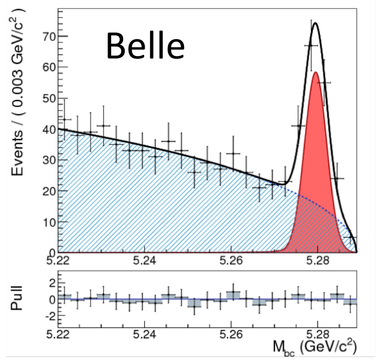
Limiting factors are hard to estimate prior to the first $B^0 \to K^{*0}e^+e^-$ angular analysis

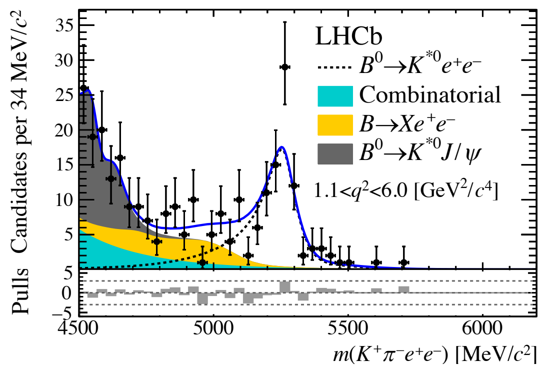




In particular, no "double-ratio" tricky is possible - which requires an even better control of the electron mode systematics

- Life at Belle-II easier with electrons





- Analyses must drive the design of the **LHCb Phase-II upgrade ECAL**

- Long-standing debate on whether not full control of charm-loops could explain the present anomalies
- **Sinergy between theory and experiments, but need more data**
- New ideas and continuous progress

Charm loop: dangerous or  harmless?

A clear-cut non-perturbative calculation is not available yet

Combinations of QCDF, LCSR, analiticity and unitarity point to a moderate effect with a flat q^2 dependence in the region of interest. Yet their ability to fully describe c-loop rescattering is questionable

Future data could be able to pin down hadronic contributions with no short-distance counterparts (all but ΔC_7 and ΔC_9)

LFUV signals are not affected, but their interpretation may be

- Fit to data reveals that the J/ψ has little impact outside the region.

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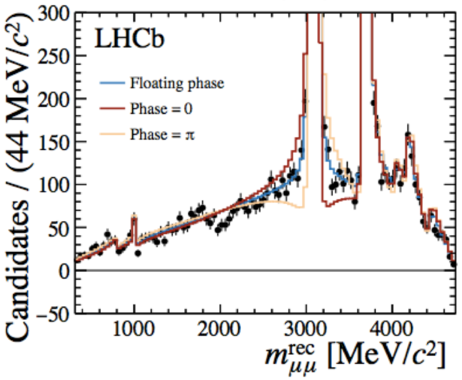
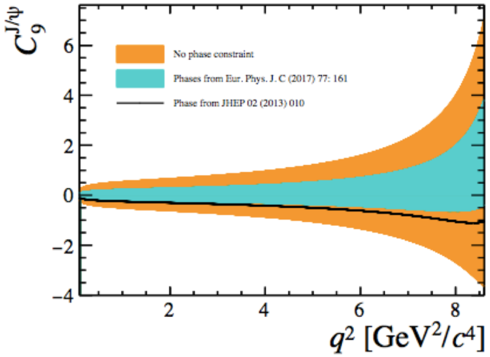


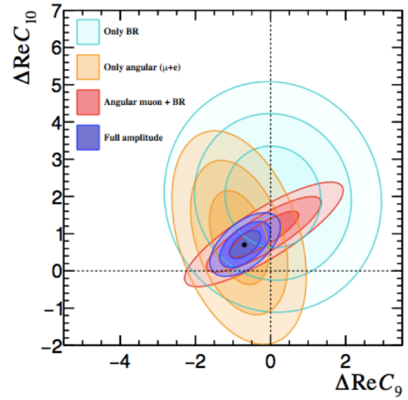


P.Owen

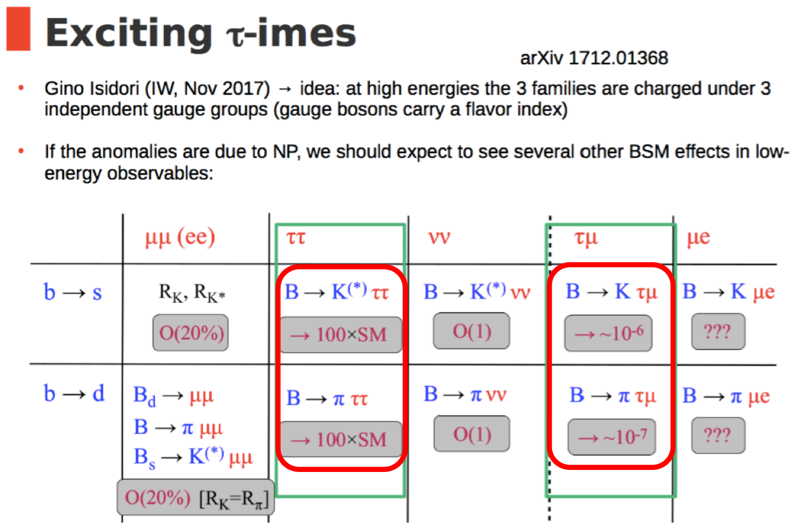
[A. Mauri *et al*, to appear in arXiv tomorrow]

Chapter [iv]: simultaneous unbinned analysis of $B^0 \to K^{*0}\mu^+\mu^-$ and $B^0 \to K^{*0}e^+e^-$

- All nuisance parameters are shared between electron and muons, i.e. CKM and (non) local hadronic
- Extended maximum-likelihood fit, i.e. includes R_{K^*} information



- Given hints of LU violation taus are attracting significant interest, particularly in **LF violating decays**



Exciting τ-imes

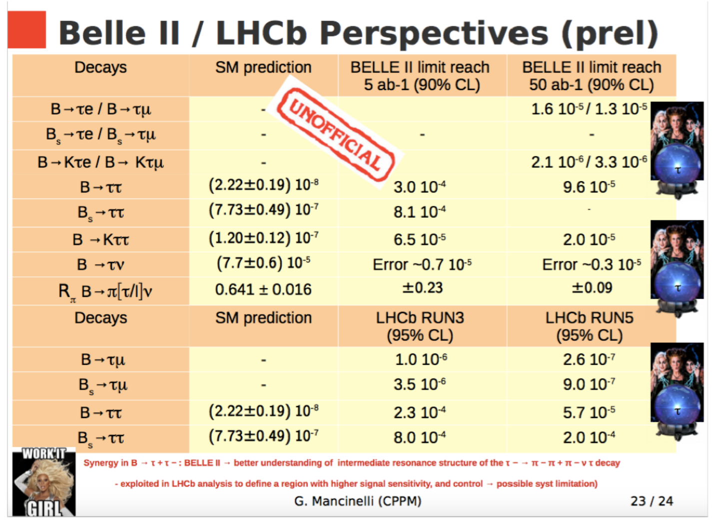
arXiv 1712.01368

- Gino Isidori (IW, Nov 2017) → idea: at high energies the 3 families are charged under 3 independent gauge groups (gauge bosons carry a flavor index)
- If the anomalies are due to NP, we should expect to see several other BSM effects in low-energy observables:

	μμ (ee)	ττ	νν	τμ	μe
$b \to s$	R_K, R_{K^*} O(20%)	$B \to K^{(*)} \tau\tau$ → 100×SM	$B \to K^{(*)} \nu\nu$ O(1)	$B \to K \tau\mu$ → ~10^{-6}	$B \to K \mu e$???
$b \to d$	$B_d \to \mu\mu$, $B \to \pi \mu\mu$, $B_s \to K^{(*)} \mu\mu$ O(20%) $[R_K = R_\pi]$	$B \to \pi \tau\tau$ → 100×SM	$B \to \pi \nu\nu$ O(1)	$B \to \pi \tau\mu$ → ~10^{-7}	$B \to \pi \mu e$???

- Tau reconstruction at Belle-II is facilitated compared to LHCb
- Analyses must drive the design of the **LHCb Phase-II upgrade**

- Larger datasets and analysis techniques constantly developing will make **increasingly stringent tests in future**



Belle II / LHCb Perspectives (prel)

Decays	SM prediction	BELLE II limit reach 5 ab-1 (90% CL)	BELLE II limit reach 50 ab-1 (90% CL)
$B \to \tau e$ / $B \to \tau\mu$	-		$1.6\ 10^{-5}$ / $1.3\ 10^{-5}$
$B_s \to \tau e$ / $B_s \to \tau\mu$	-	-	-
$B \to K\tau e$ / $B \to K\tau\mu$	-		$2.1\ 10^{-6}$ / $3.3\ 10^{-6}$
$B \to \tau\tau$	$(2.22 \pm 0.19)\ 10^{-8}$	$3.0\ 10^{-4}$	$9.6\ 10^{-5}$
$B_s \to \tau\tau$	$(7.73 \pm 0.49)\ 10^{-7}$	$8.1\ 10^{-4}$	-
$B \to K\tau\tau$	$(1.20 \pm 0.12)\ 10^{-7}$	$6.5\ 10^{-5}$	$2.0\ 10^{-5}$
$B \to \tau\nu$	$(7.7 \pm 0.6)\ 10^{-5}$	Error ~$0.7\ 10^{-5}$	Error ~$0.3\ 10^{-5}$
R_π $B \to \pi[\tau/l]\nu$	0.641 ± 0.016	± 0.23	± 0.09
Decays	**SM prediction**	**LHCb RUN3 (95% CL)**	**LHCb RUN5 (95% CL)**
$B \to \tau\mu$	-	$1.0\ 10^{-6}$	$2.6\ 10^{-7}$
$B_s \to \tau\mu$	-	$3.5\ 10^{-6}$	$9.0\ 10^{-7}$
$B \to \tau\tau$	$(2.22 \pm 0.19)\ 10^{-8}$	$2.3\ 10^{-4}$	$5.7\ 10^{-5}$
$B_s \to \tau\tau$	$(7.73 \pm 0.49)\ 10^{-7}$	$8.0\ 10^{-4}$	$2.0\ 10^{-4}$

Synergy in $B \to \tau^+\tau^-$: BELLE II → better understanding of intermediate resonance structure of the $\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$ decay

- exploited in LHCb analysis to define a region with higher signal sensitivity, and control → possible syst limitation)

G. Mancinelli (CPPM) 23 / 24

Improvements for tau leptons:

- Better Ecal → better neutral isolation algorithms
- Tracking stations in the magnet → ~30% more efficiency for $B \to \tau\tau$
- Hadronic trigger improvements (up to factors 2 for hadronic tau decays)
- Mass reconstruction methods depend heavily on the error on the primary and the tau decay vertices, hence any improvement in the tracking system will be highly valuable.