A propos de la brisure de la symétrie *CP* LHCb, Belle II et FCC-ee

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Disclaimers

- Three Physics-driven talks covering the very same experiments: CPV (this one), rare decays and spectroscopy. Specific comments of the expts assigned with a certain arbitrariness to each of the talk: current exp. landscape and timeline of future exp. in this talk, details on Belle II detector and operation in Justine's talk and specifics on the so-called LHCb upgrade II in Patrick's talk.

- The talks are focussing to collider physics but there is a strong interplay with low-energy experiments with muon beams, kaons, neutrons etc…

- There is a clear case for Flavours at large in the mid- and long-terms.

Outline

- Present experimental landscape for Flavours Physics at colliders.
- CPV: a state of the art and the lessons for the future.
- The projections towards the HL-LHC and the FCC-*ee* programs.
- Conclusions.

1) The present experimental landscape at colliders.

Two machines, four experiments

- LHC: hadron collider, three experiments addressing Flavour Physics. One dedicated, LHCb.
- SuperKEKB: asymmetric e+e- operated at the Upsilon(4S) threshold. One experiment, Belle II.
- Obvious complementarity: distinctive features, different experimental environments.
- Similar timelines from now on. LHCb and Belle II will take concurrently data for ~10 years. LHCb Upgrade at HL-LHC EoI→TDR. Belle coll. envisions as well an upgrade (5x50/ab).
- Let's note that a kaon Physics program is running as well in parallel - another view of the Unitarity from rare kaons $K \to \pi\nu\nu$.

2) CPV, a state of the art.

The observables relevant to the CKM profile (hence allowing predictions to be made):

- Chosen to be experimentally precise and theoretically clean (enough).
- The *CP*-conserving observables: neutral *B* meson oscillation frequencies (fully dominated by hadronic parameters - decay constants and bag factors), V_{ub} and V_{cb} matrix elements from semileptonic decays of *b*-hadrons.
- The clean *CP*-violating observables: CKM angles. Almost theory-free presently.
- The (less-clean) *CP*-violating asymmetry in the mixing of kaons.

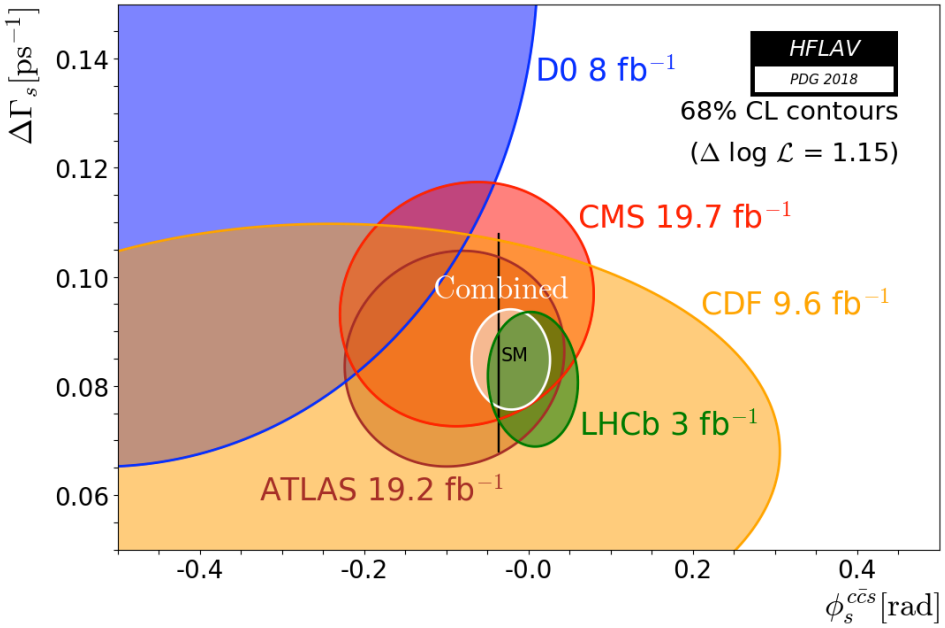
2) CPV, a state of the art.

A selection of *CP*-violating observables relevant to the null-tests of the SM:

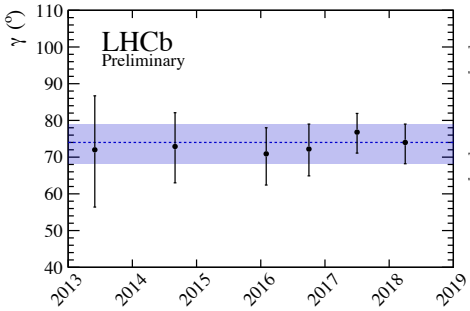
- Weak mixing phase of the Bs
- *CP*-violating (semileptonic) asymmetries in the *B* mixing.
- Mixing-induced *CP* violation in $\Delta B = 1$ transitions.
- *CP* asymmetries in charm mixing and decays.
- etc…
- … + many others about *CP*-conserving obs. , *e.g.* rare decays

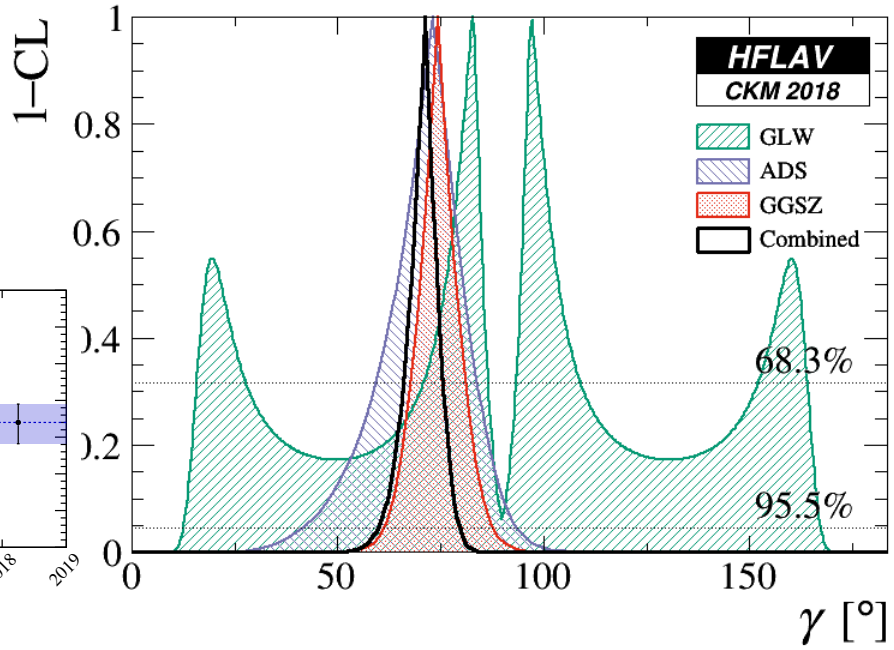
2) CPV, a state of the art

A selection of major recent achievements: weak *Bs* mixing phase, gamma combination



⇒ Powerful null-test of the SM

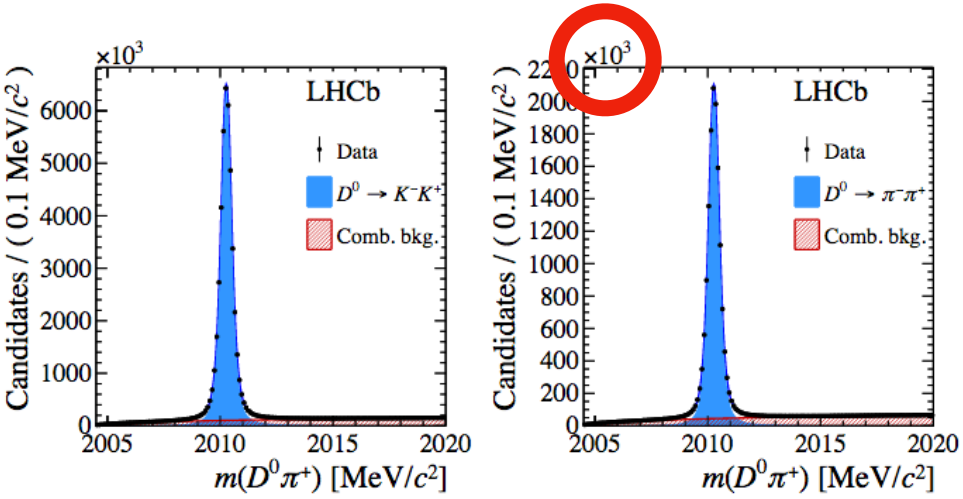




Precision era of the CKM profile ⇐

2) CPV, a state of the art

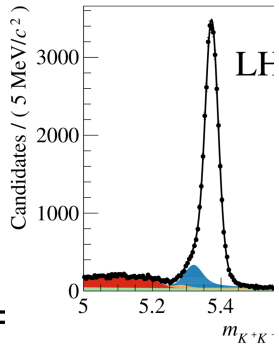
A selection of major recent achievements: *CP* violation in charm, time-dependent CPV in B_s systems,

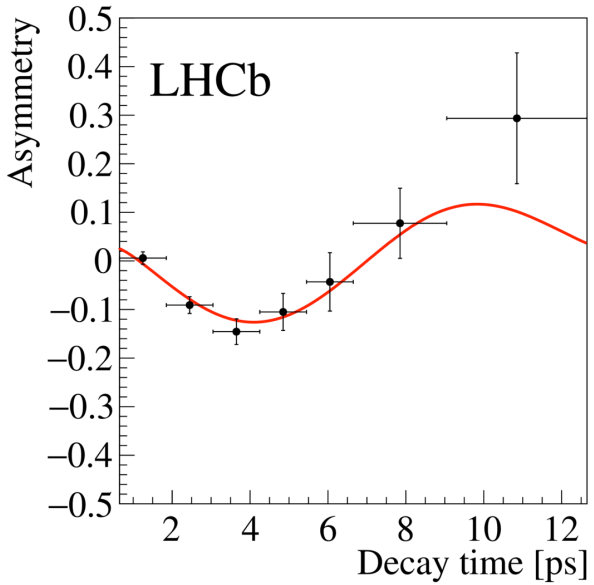


$$\Delta A_{CP} = (-15.4 \pm 2.9) \times 10^{-4}.$$

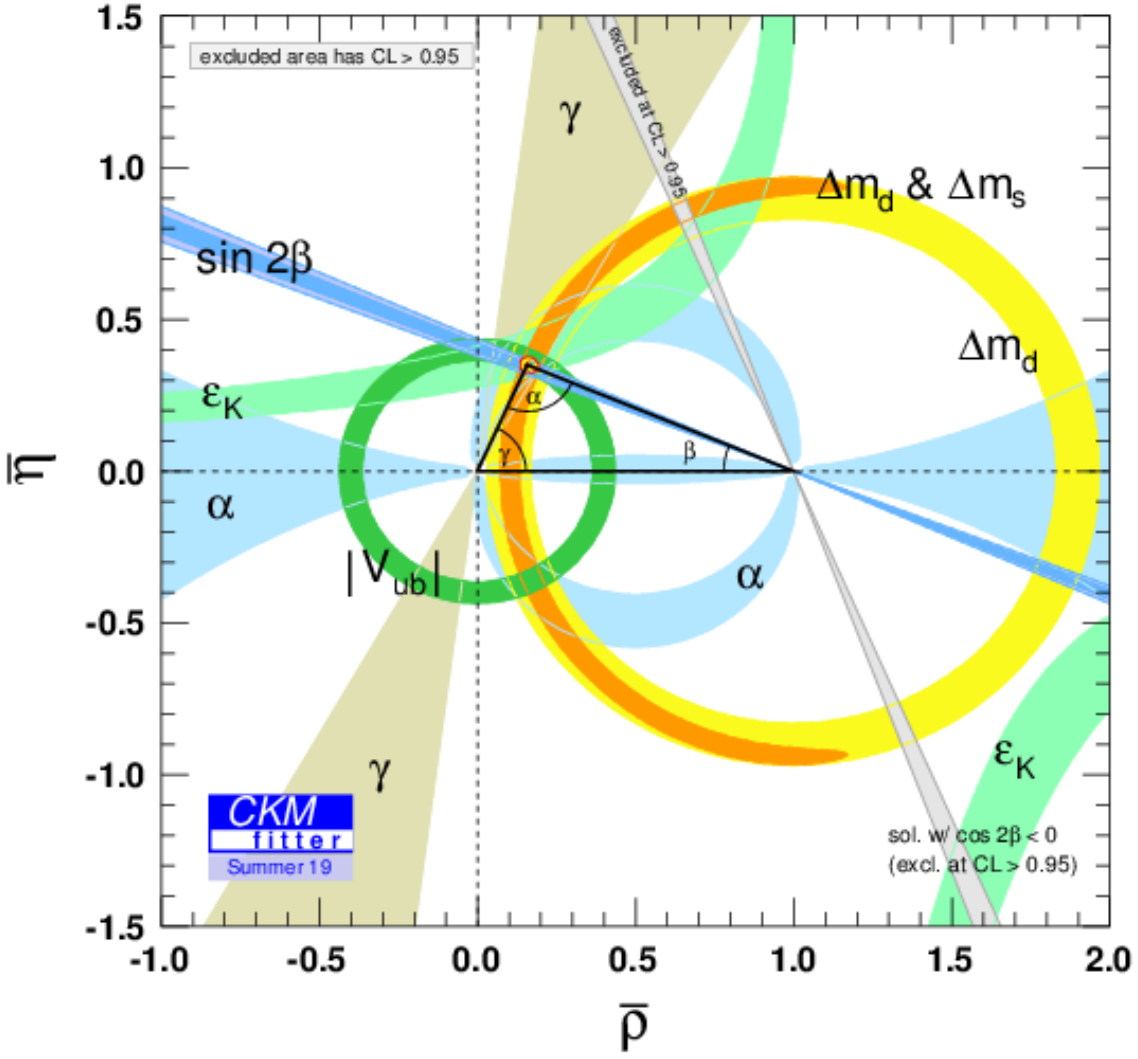
⇒ Powerful null-test of the SM, New territory

Precision era of the CKM profile ⇐

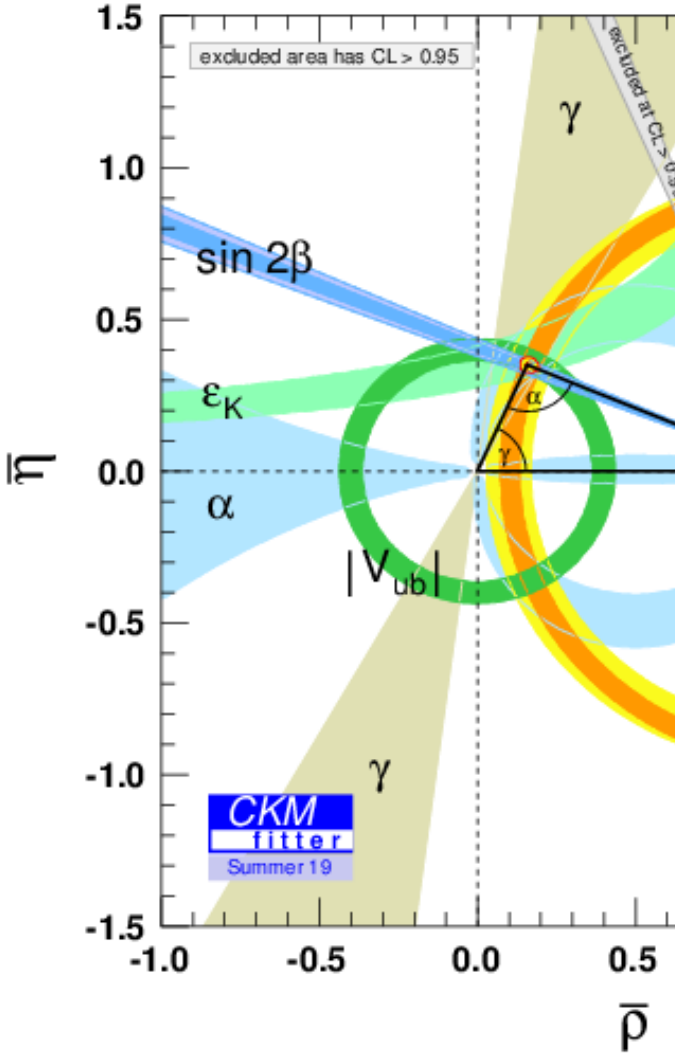




2) CPV, a state of the art, the broad picture



2) CPV, a state of the art, the broad picture

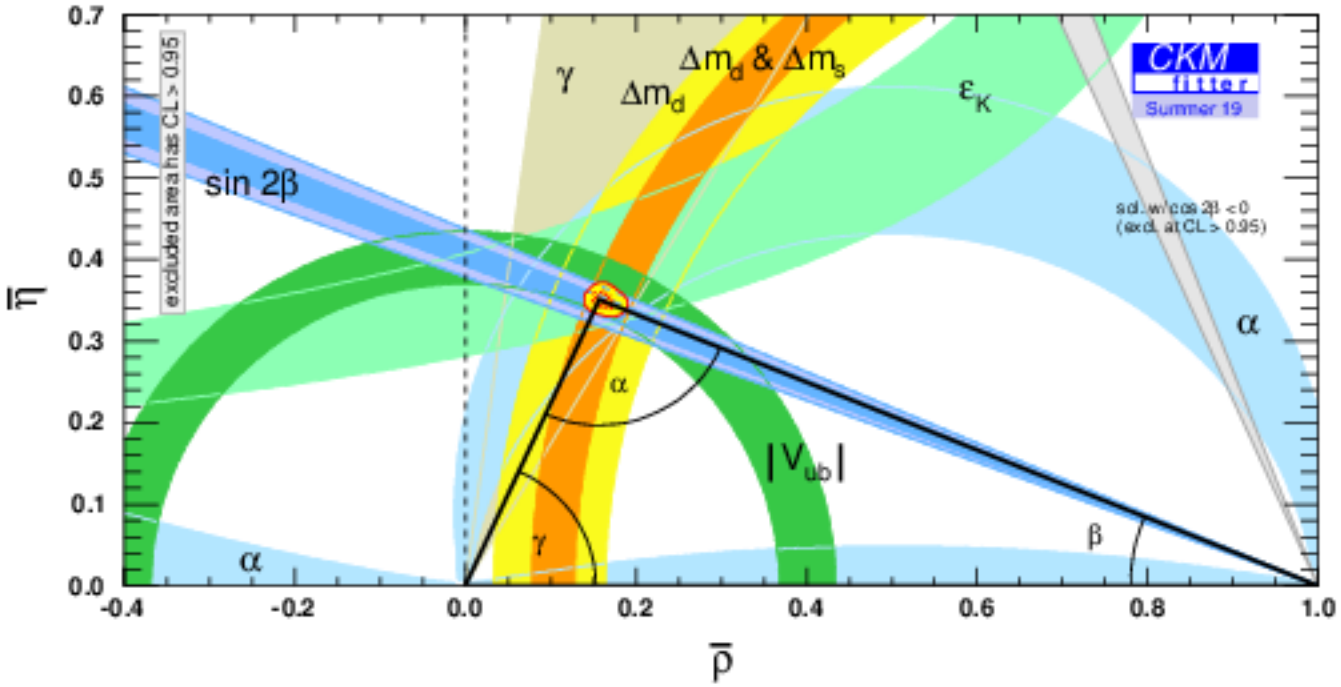


The second pillar of the SM :

- Remarkable consistency of all observables within the SM. The SM passes the test and one can do the metrology of its parameters.
- CKM is at work in charged EW currents.
- KM paradigm IS the dominant source of *CP* symmetry breaking.

2) CPV, a state of the art.

A closer look: the players

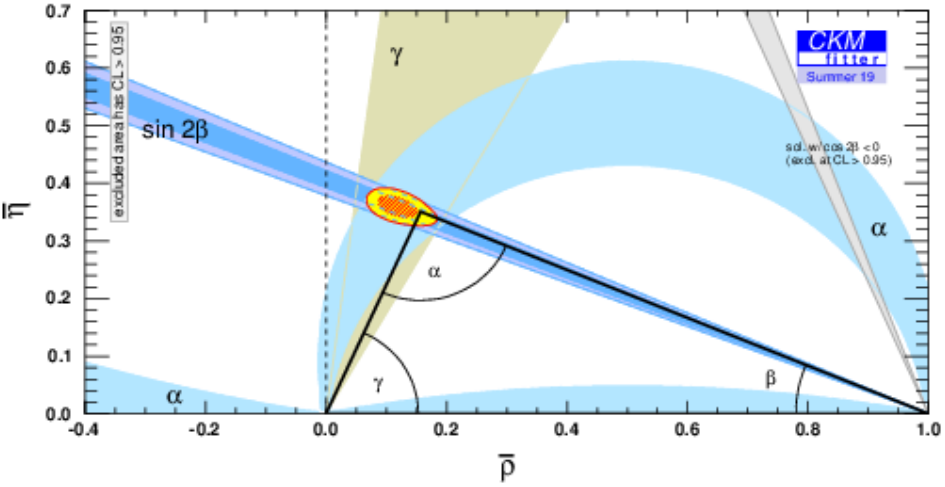


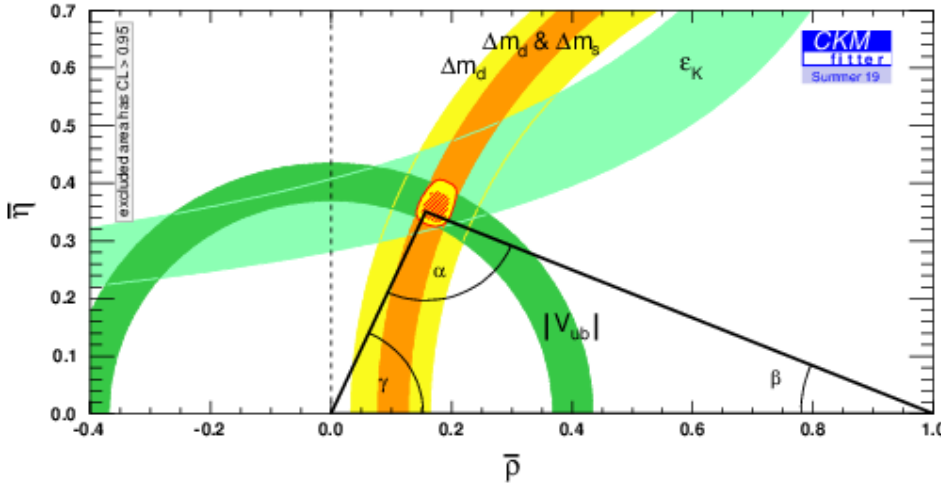
- The *B*-factory established most of this legacy.

- Yet, LHCb drives the gamma angle precision, and stepped in significantly in V_{ub} and V_{cb} matrix elements determination.

2) CPV, a state of the art.

A closer look: theory-free vs hadronic parameters.

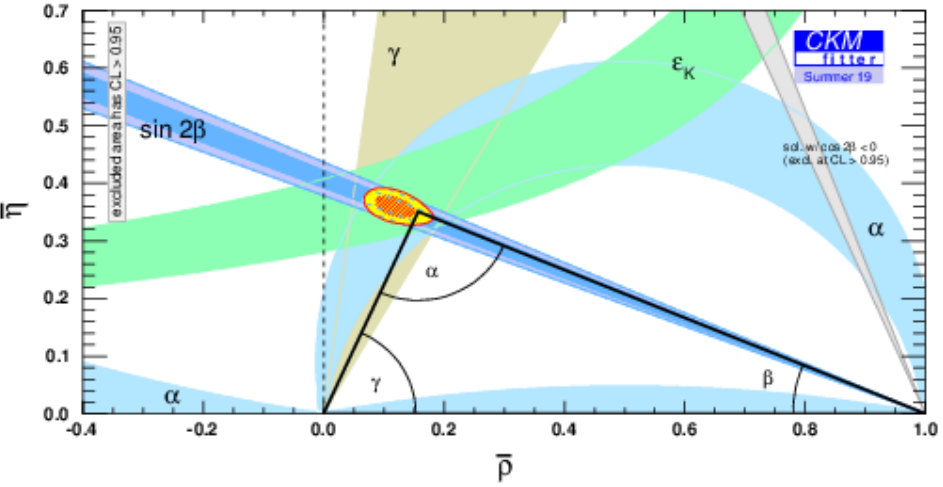


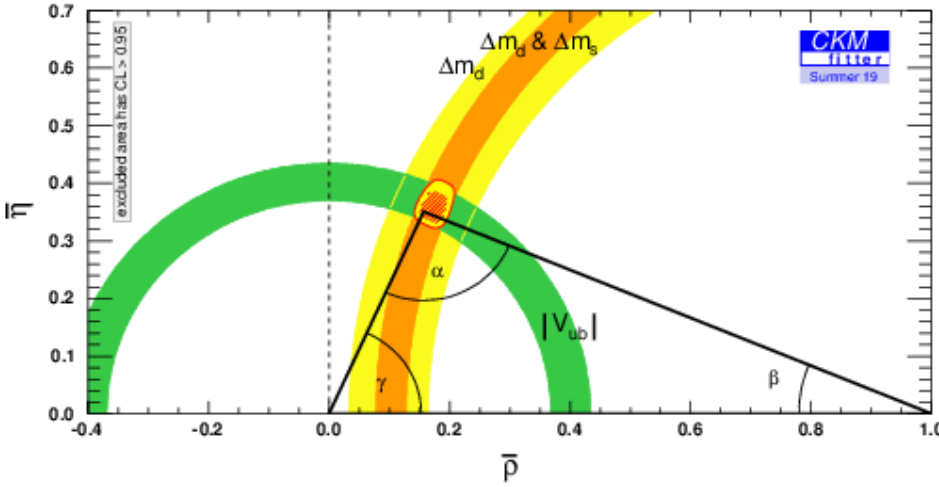


- Remarkable agreement.
- Acknowledgement of the progresses and successes of Lattice QCD to predict the hadronic parameters and the form factors.

2) CPV, a state of the art.

A closer look: *CP*-conserving vs *CP*-violating.

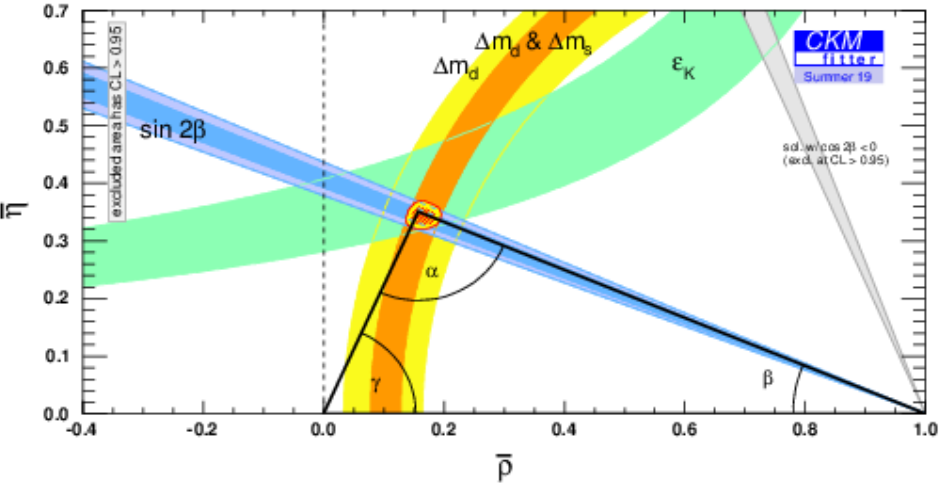


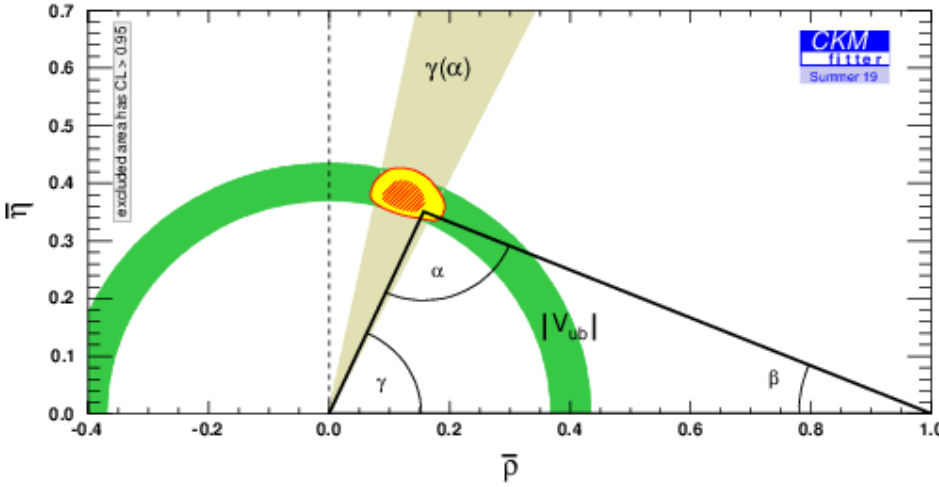


- Again remarkable agreement.
- Acknowledgement of the progresses made in LQCD (here semileptonic form factors, decay constants and bag factors).

2) CPV, a state of the art.

A closer look: loops vs trees.





- Again remarkable agreement.
- Obvious display of the importance / necessity of a more precise gamma. LHCb on its way. LHCb upgrade II in perspective.
- Same comment in order for the matrix element V_{ub}.

2) CPV, a state of the art, beyond the CKM profile

Quasi-model-independent constraints on BSM in in the mixings

- Fix the apex by considering (model-dependence is there) that four-fermions couplings are SM and 3x3 unitarity holds : main players are gamma and V_{ub} (V_{cb}).

$$|V_{ud}|,\ |V_{us}|,\ |V_{ub}|,\ |V_{cb}|,\ B^+ \to \tau^+ \nu_\tau \text{ and } \gamma$$

- Model the BSM contributions in mixing as a complex number multiplying the SM mixing hamiltonian matrix elements

$$\Delta_q = |\Delta_q| e^{i 2 \Phi_q^{\rm NP}}$$

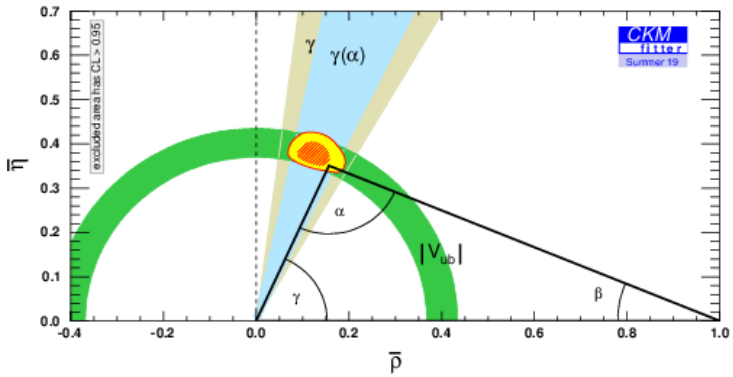
$$\begin{aligned} \left\langle B_q \left| \mathcal{H}_{\Delta B=2}^{\rm SM+NP} \right| \bar{B}_q \right\rangle &\equiv \left\langle B_q \left| \mathcal{H}_{\Delta B=2}^{\rm SM} \right| \bar{B}_q \right\rangle \\ &\times \left(\mathrm{Re}(\Delta_q) + i\, \mathrm{Im}(\Delta_q) \right) \end{aligned}$$

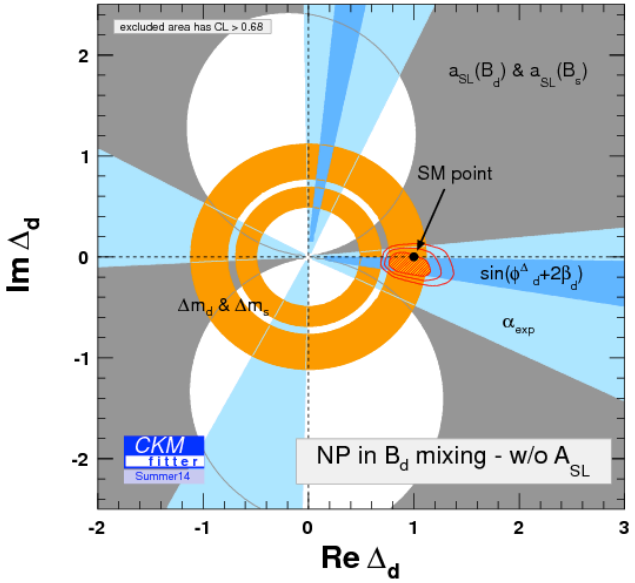
parameter	prediction in the presence of NP
Δm_q	$\lvert\Delta_q^{\rm NP}\rvert \times \Delta m_q^{\rm SM}$
2β	$2\beta^{\rm SM} + \Phi_d^{\rm NP}$
$2\beta_s$	$2\beta_s^{\rm SM} - \Phi_s^{\rm NP}$
2α	$2(\pi - \beta^{\rm SM} - \gamma) - \Phi_d^{\rm NP}$
$\Phi_{12,q} = \mathrm{Arg}[-\frac{M_{12,q}}{\Gamma_{12,q}}]$	$\Phi_{12,q}^{\rm SM} + \Phi_q^{\rm NP}$
A_{SL}^q	$\frac{\Gamma_{12,q}}{M_{12,q}^{\rm SM}} \times \frac{\sin(\Phi_{12,q}^{\rm SM} + \Phi_q^{\rm NP})}{\lvert\Delta_q^{\rm NP}\rvert}$
$\Delta\Gamma_q$	$2\lvert\Gamma_{12,q}\rvert \times \cos(\Phi_{12,q}^{\rm SM} + \Phi_q^{\rm NP})$

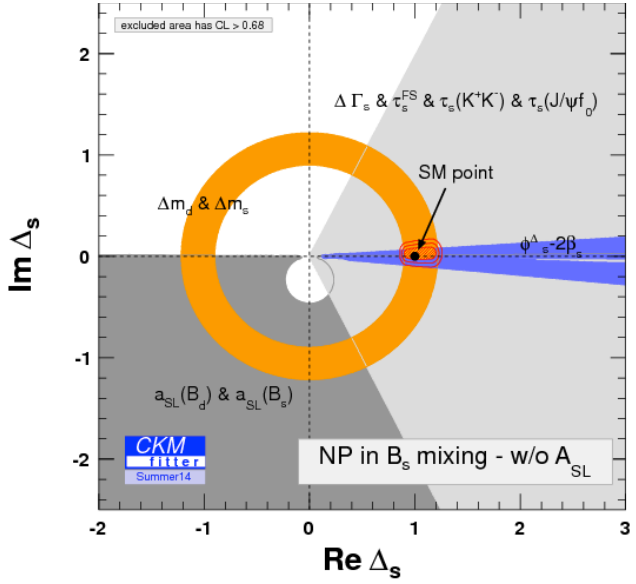
2) CPV, a state of the art, beyond the CKM profile

Model-independent constraints on BSM in in the mixings

- Fix the apex by considering (model-dependence is there) that four fermions couplings are SM : main players are gamma and V_{ub} (V_{cb}).





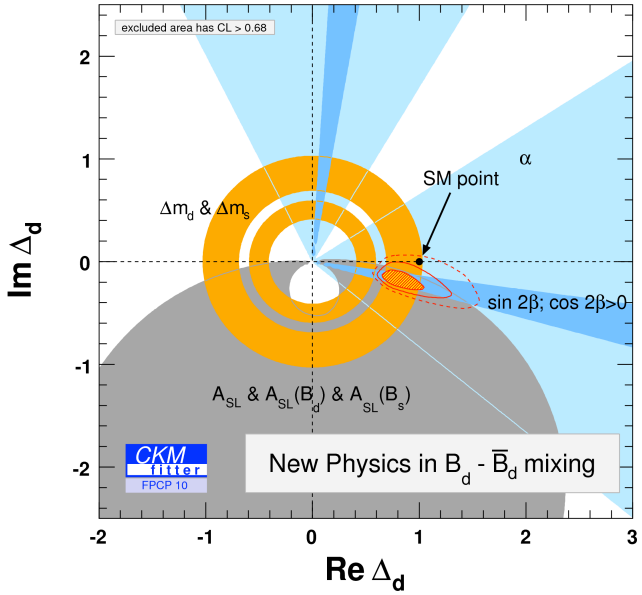


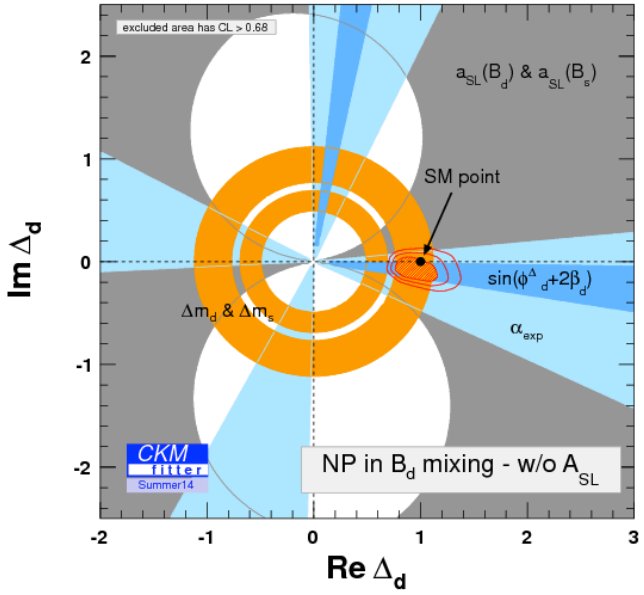
Sizeable NP is still allowed by the LHCb constraint in both B_d and B_s mixing.

2) CPV, a state of the art, aparté

Model-independent constraints on BSM in in the mixings

- Back at the beginning of the previous decade, Belle observed for the first time the decay $B^+ \to \tau^+ \nu$ (sensitive to V_{ub}) ith a quite high branching fraction.
- This favoured high values of sin2β in the SM. A new phase in the *Bd* mixing accomodated the SM $B^+ \to \tau^+ \nu$ vs sin2β discrepancy.





2) CPV, a state of the art, intermediate conclusions.

Take away messages:

#1 Tremendous success of the SM.

#2 Yet a single observation almost smashed the SM. If BSM is there and close, it could come as naturally as in the example I chose. Precision in order ! Remember the Russian experiment which stopped just at the edge of the observation of $K_L \to \pi\pi$.

#3 Normalisation matters: at the anticipated precisions of the relevant experiments to come (Belle II, LHCb upgrade II, FCC-*ee*), these explorations will likely be limited by the knowledge of V_{cb} and the LQCD uncertainties.

3) The future prospects

- Based on the documents:
  - LHCb upgrade II — https://arxiv.org/abs/1808.08865
  - HL-LHC — http://arxiv.org/abs/1812.07638
  - Belle II — https://arxiv.org/abs/1808.10567
  - FCC-ee — http://cds.cern.ch/record/2651294/

- Machine / Experiments distinctive characteristics:

Belle II / III — FCC-ee — LHCb

Quantum entanglement

Boost

Statistics

Experimental Cleanliness

All species of hadrons

3) The future prospects — Belle II in one slide.

- Belle II is approved, up and running.
- Belle II case for *CP* violation is obvious: *e.g.*

Table 8: Belle II Golden/Silver observables on the measurement of time dependent CP violation in B decays and the measurement of the UT angles ϕ_1 and ϕ_2. See the caption in Table 4 for more details.

	Process	Observable	Theory	Sys. dom. (Discovery) [ab^{-1}] vs LHCb	vs Belle	Anomaly	NP
●	$B \to J/\psi K^0_S$	ϕ_1	⋆⋆⋆	5-10	⋆⋆	⋆⋆	⋆	⋆
●	$B \to \phi K^0_S$	ϕ_1	⋆⋆	>50	⋆⋆	⋆⋆⋆	⋆	⋆⋆⋆
●	$B \to \eta' K^0_S$	ϕ_1	⋆⋆	>50	⋆⋆	⋆⋆⋆	⋆	⋆⋆⋆
●	$B \to \rho^\pm \rho^0$	ϕ_2	⋆⋆⋆	>50	⋆	⋆⋆⋆	⋆	⋆
●	$B \to J/\psi \pi^0$	ϕ_1	⋆⋆⋆	>50	⋆	⋆⋆⋆	-	-
●	$B \to \pi^0 \pi^0$	ϕ_2	⋆⋆	>50	⋆⋆⋆	⋆⋆⋆	⋆⋆	⋆⋆
●	$B \to \pi^0 K^0_S$	S_{CP}	⋆⋆	>50	⋆⋆⋆	⋆⋆⋆	⋆⋆	⋆⋆

- Relevant at many other places of the case.

3) The future prospects — LHCb Upgrade II in two.

- An Expression of Interest for an upgrade of the experiment in the times of teh HL-LHC has been submitted by the collaboration:

https://arxiv.org/abs/1808.08865

- In phase with the full exploitation of HL-LHC.

- The French LHCb groups have jointly introduced a contribution to this prospective supporting this upgrade:

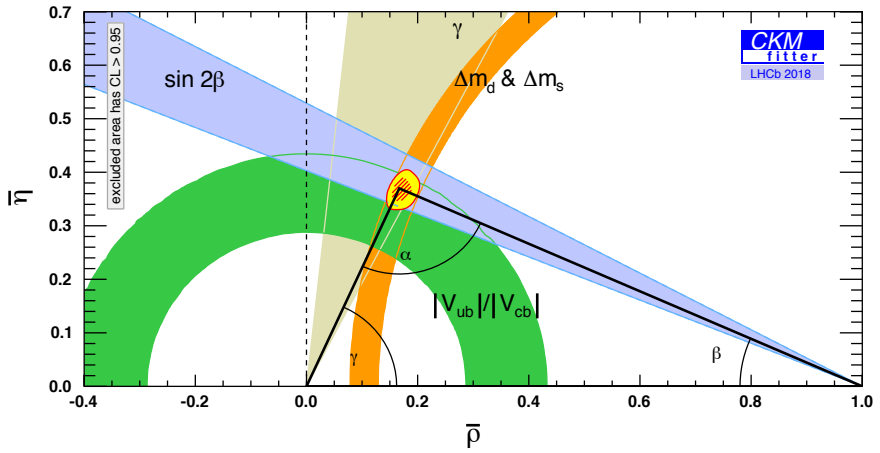
LHCb France input to the IN2P3 national prospects 2020-2030

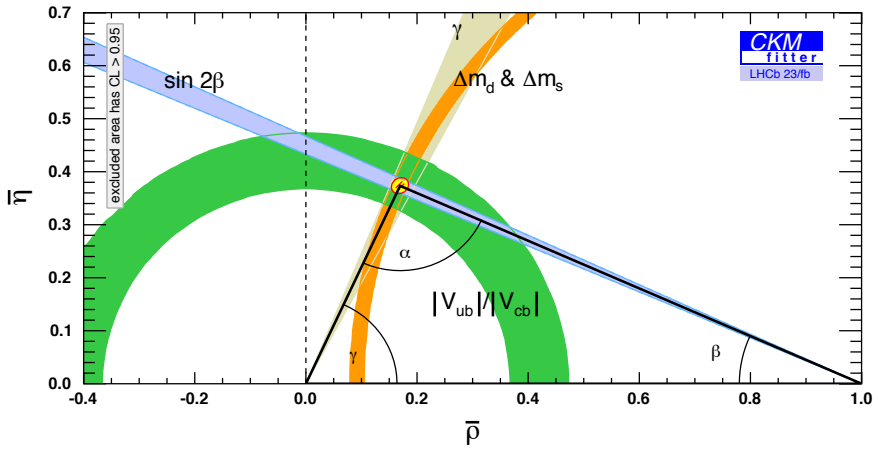
November 27, 2019

H. Afshamia[2], Z. Ajaltouni[2], Y. Amhis[4], E. Aslanides[3], V. Balagura[4,6], S. Barsuk[4], A. Bharucha[9] E. Ben-Haim[5], E. Bertholet[5], P. Billoir[5], J. Cerasoli[3], J. Charles[9], M. Charles[5], M. Chefdeville[1], J.A.B. Coelho[4], J. Cogan[3], E. Cogneras[2], D. Decamp[1], L. Del Buono[5], O. Deschamps[2], F. Desse[4], A. Downes[1], D. Fazzini[4], F. Fleuret[4,6], B. Fuks[8], F.A. Garcia Rosales[4], D. Gerstel[3], Ph. Ghez[1], V.V. Gligorov[5], T. Grammatico[5], D. Guadagnoli[7], M. Knecht[9], R. Le Gac[3], R. Lefèvre[2], L. Lellouch[9], O. Leroy[3], V. Lisovskyi[4], F. Machefert[4], F. Mahmoudi[10], G. Mancinelli[3], J.F. Marchand[1], C. Marin Benito[4], E. Maurice[4,6], C. Meaux[3], M.-N. Minard[1], S. Monteil[2], A.B. Morris[3], E.M. Niel[4], P. Perret[2], B. Pietrzyk[1], F. Polci[5], A. Poluektov[3], R. Quagliani[5] B. Quintana[2], R.I. Rabadan Trejo[3], M. Reboud[1], F. Reiss[5], P. Robbe[4], A. Robert[5], H. Sazak[2], M.H. Schune[4], S. T'Jampens[1], V. Tisserand[2], D.Y. Tou[5], A. Usachov[4], D. Vom Bruch[5], S. Weber[5], G. Wormser[4], S. Zafeiropoulos[9]

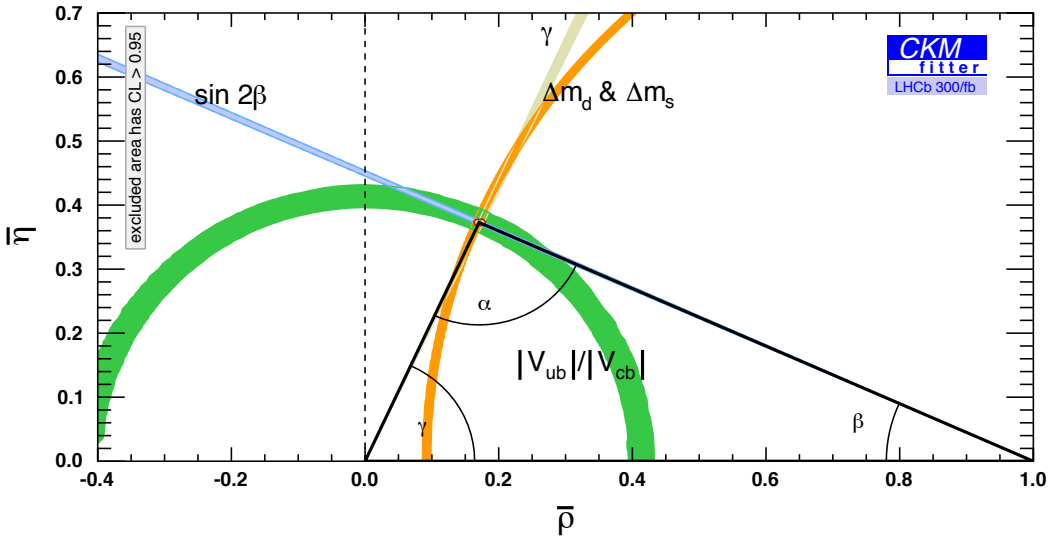
3) The future prospects — LHCb Upgrade II in two slides.

- Here is an extraction of the *CP* prospects for this experiment:





w/ LQCD extrapolations

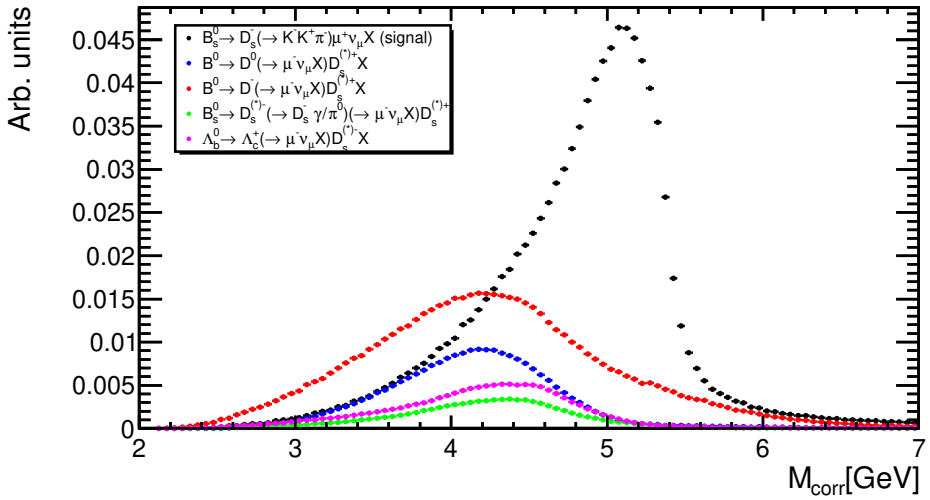


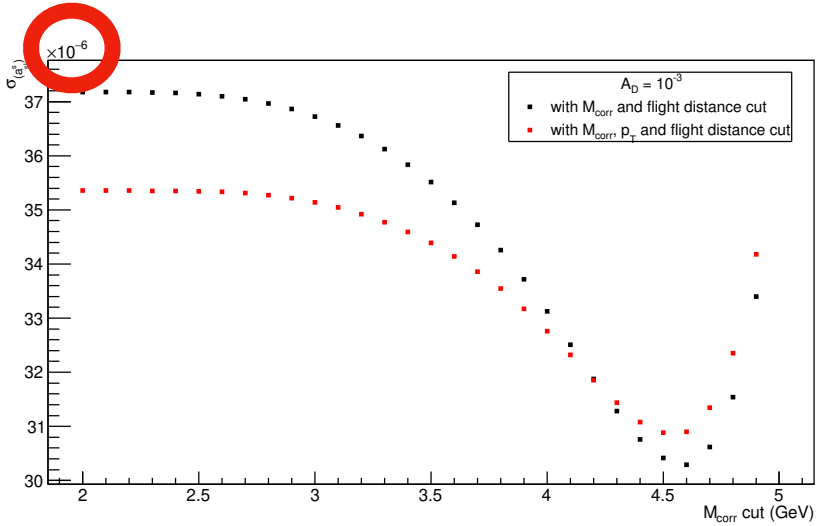
LHCb only

3) The future prospects — FCC-*ee* in two slides

- FCC-*ee* competes favourably with both Belle II and LHCb upgrade, as far as *CP* observables are concerned.

- One quantitative study (work in progress), to give the flavour of the possible precision. SM value of B_s semileptonic asymmetry is at reach !





- The systematic exploration is yet to perform.

3) The future prospects — FCC-*ee* in two slides

- FCC-*ee* competes favourably with both Belle II and LHCb upgrade, as far as *CP* observables are concerned.

- One of the main limitation of the analysis of NP in mixings is the normalisation of the CKM profile through V_{cb}.. The possibility of determining it at the *WW* threshold is a game changer.

- Flavour Physics and Electroweak precision tests are intertwined. The exclusive reconstruction tags, as pioneered in *B*-factories, can serve the precision of measurements as R_b or $A_{\rm FB}(bb)$.

- The design study explored territories where FCC-*ee* is unique.

- The comprehensive exploration is yet to perform.

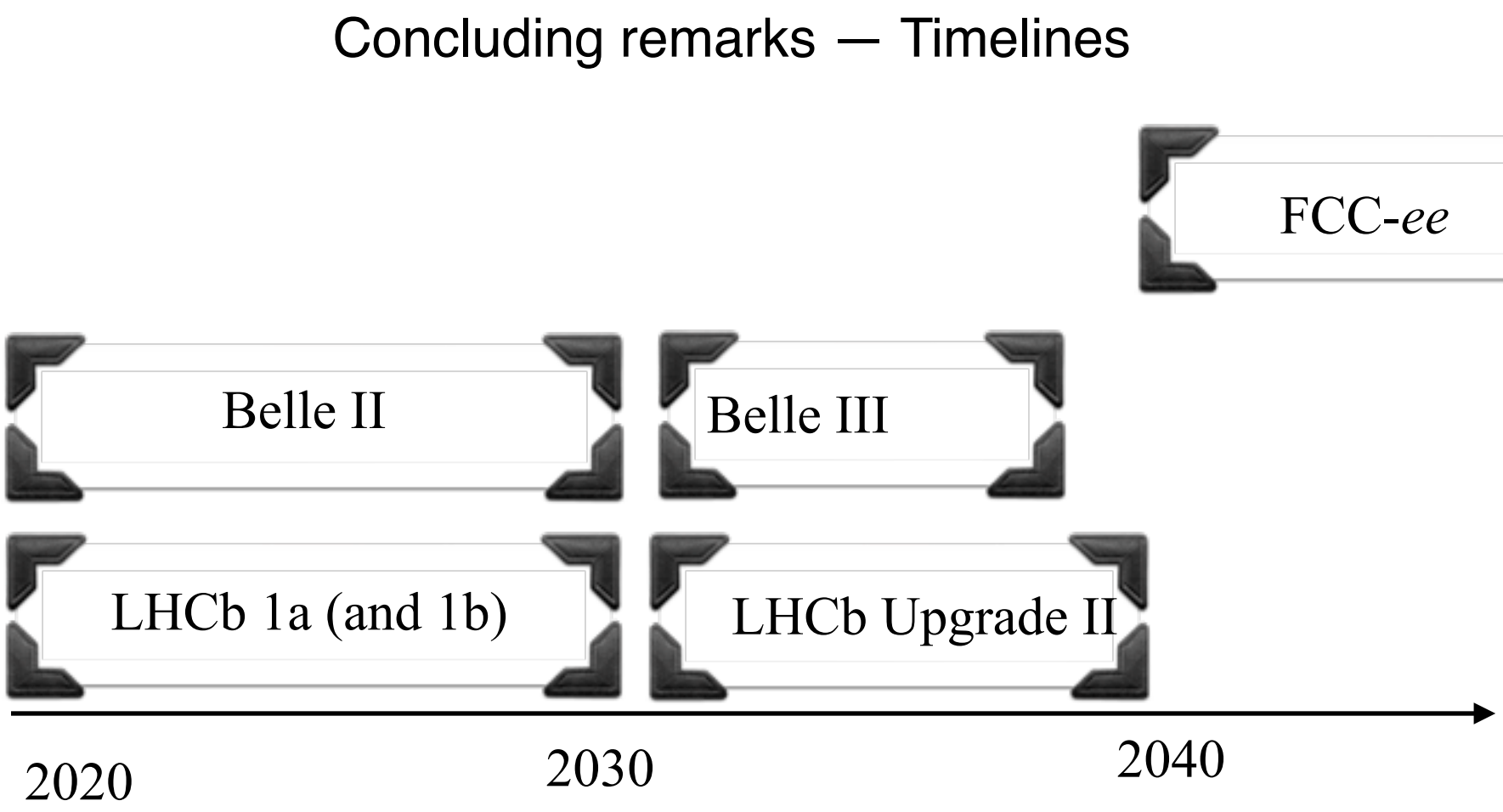
Concluding remarks — Physics.

- Remarkable consistency conveyed by all observables (*CP*-conserving and *CP*-violating) in *b*-, *c*-, *s*-flavoured particle systems. This significantly constrains BSM scenarii. It defines to some extent the Flavour problem.

- The study of *CP* violation in *b*-flavoured hadrons is entering an actual precision era with the LHCb upgrade and Belle II programs which are presently building on. Authentic complementarity, in *CP* studies, as for the rare-and less-rare decays. LHCb Upgrade II under consideration for the full exploitation of the HL-LHC program.

- FCC program has unique capabilities (mostly explored so far in rare decays — see next talk) and can be key (here also) for sorting out NP models.

4) Summary about CP breaking perspectives.



Seamlessly continuation of the Physics program

Concluding remarks - Community

- The GDR Intensity frontier community is the likely representative platform of the French Flavour experimental and theoretical communities.

- A poll was issued to measure how this community projects into future projects. Main outcomes for collider physics:

  - For the mid-term, LHCb Upgrade II is acclaimed. Actual work has started for most of the LHCb French groups.

  - For the long-term, FCC-*ee* is judged, with the same surface, as the natural continuation of this Physics program. Importance of at least 5 10^{12} Z decays.

4) Back-up


Belle II


FCC
hh ee he


LHCb
THCp