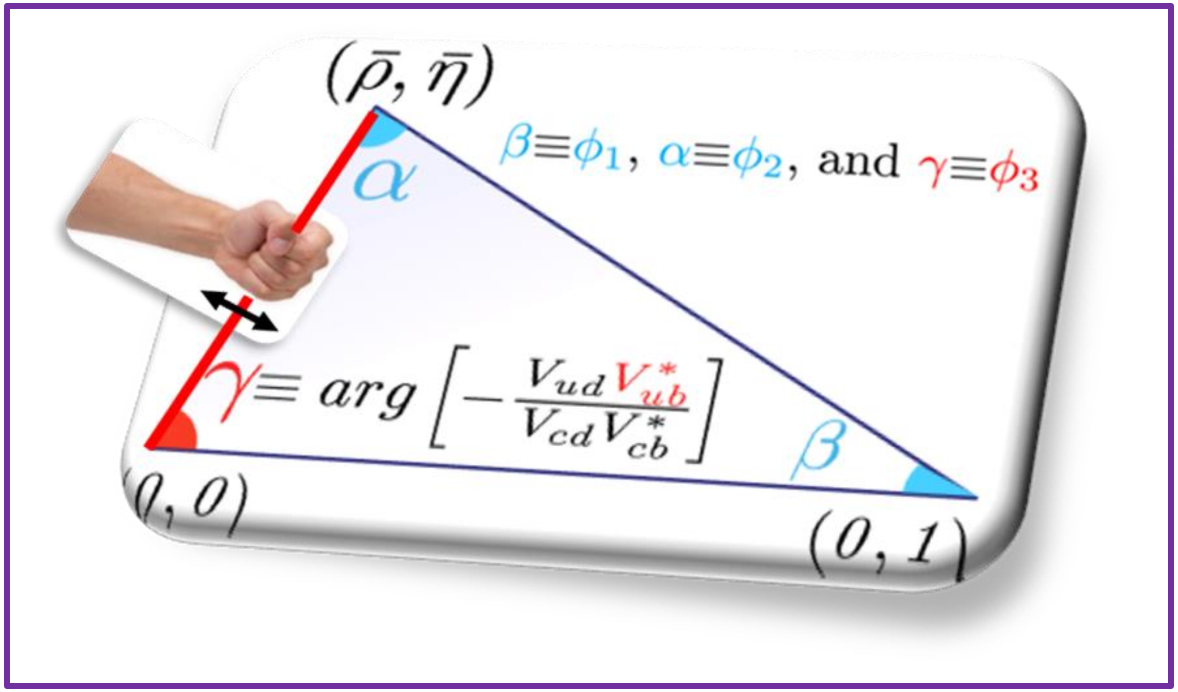
# Discrete Symmetries Overview part 1: CKM basics

V. Tisserand, LPC-Clermont Ferrand, France

Lyon St Joseph, Nov. 2nd 2022

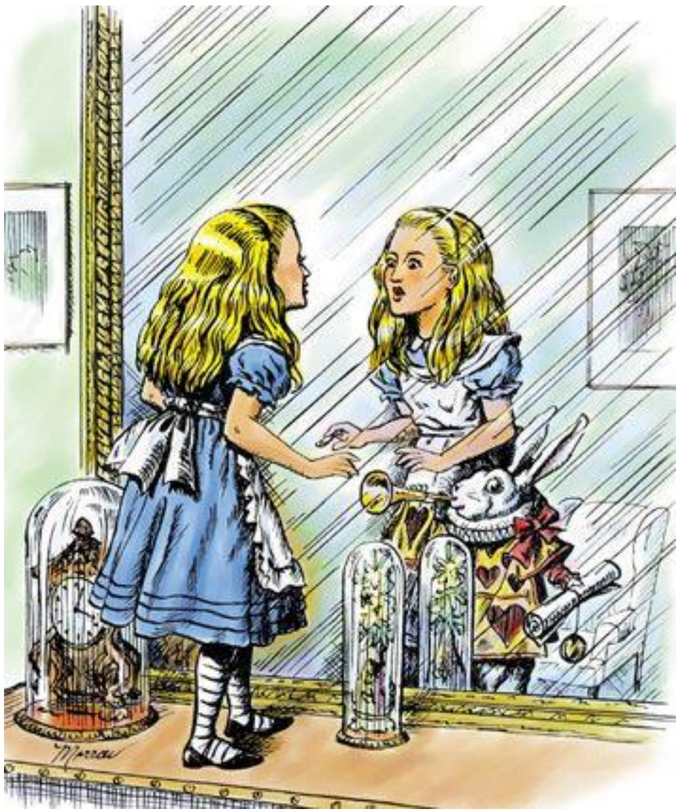




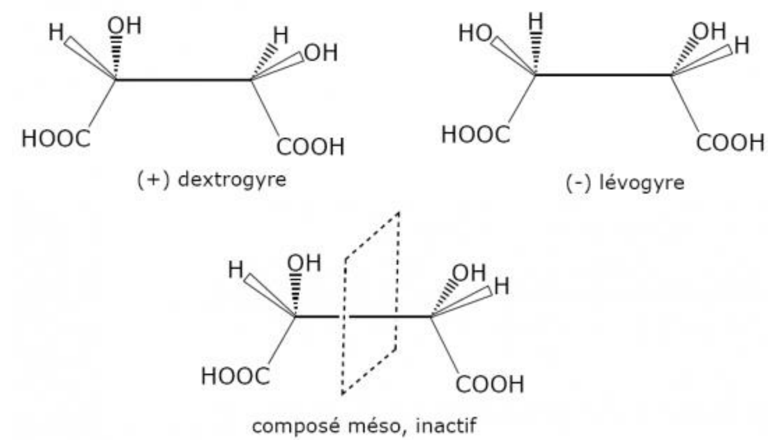
GDR-InF Annual Workshop 2022

# Discrete Symmetries (CPT)

- **Parity:** is an event seen in a mirror as realistic as the original one?
- **Time reversal:** watching the film of an event backwards results in a realistic event?
- **Charge conjugation:** can we distinguish matter from antimatter?



parity




**Lewis Carroll (1871)**
"Through the Looking-Glass, and What Alice Found There"

**Louis Pasteur** and the molecular chirality (1847-1856) [polarized light & crystallography]

# Discrete Symmetries (CPT)

- **Parity:** is an event seen in a mirror as realistic as the original one?
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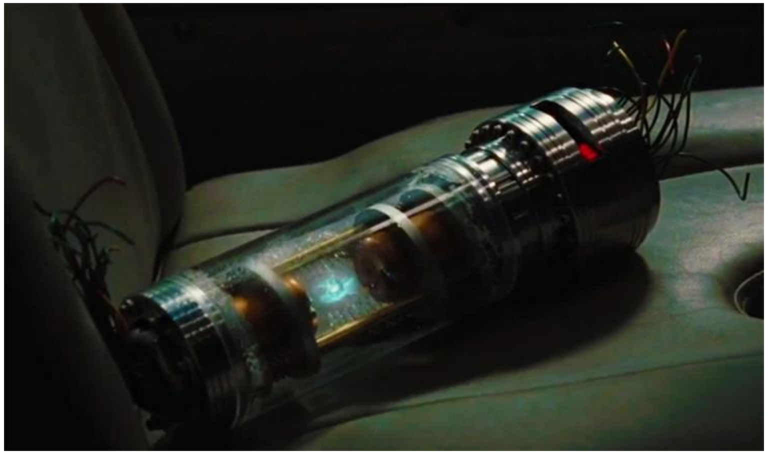
Anti-matter reactors/containers

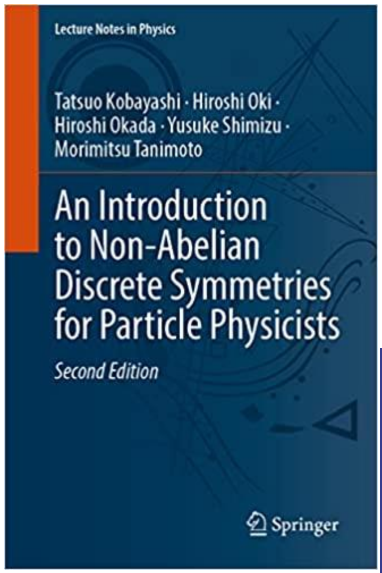


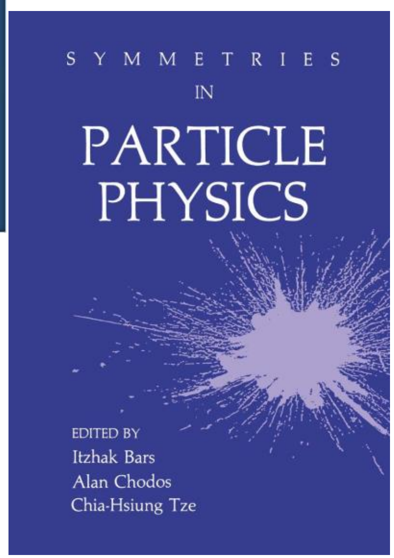
Time reversal machines


# Discrete Symmetries (CPT)

- Parity
- Time reversal
- Charge conjugation

## Some readings




arXiv:hep-ph/9807516v1 27 Jul 1998

### Discrete and Global Symmetries in Particle Physics


R. D. Peccei

Department of Physics and Astronomy, UCLA, Los Angeles, CA 90095-1547



**Abstract.** I begin these lectures by examining the transformation properties of quantum fields under the discrete symmetries of Parity, P, Charge Conjugation, C, and Time Reversal, T. With these results in hand, I then show how the structure of the Standard Model helps explain the conservation/violation of these symmetries in various sectors of the theory. This discussion is also used to give a qualitative proof of the CPT Theorem, and some of the stringent tests of this theorem in the neutral Kaon sector are reviewed. In the second part of these lectures, global symmetries are examined. Here, after the distinction between Wigner-Weyl and Nambu-Goldstone realizations of these symmetries is explained, a discussion is given of the various, approximate or real, global symmetries of the Standard Model. Particular attention is paid to the role that chiral anomalies play in altering the classical symmetry patterns of the Standard Model. To understand the differences between anomaly effects in QCD and those in the electroweak theory, a discussion of the nature of the vacuum structure of gauge theories is presented. This naturally raises the issue of the strong CP problem, and I present a brief discussion of the chiral solution to this problem and of its ramifications for astrophysics and cosmology. I also touch briefly on possible constraints on, and prospects for, having real Nambu-Goldstone bosons in nature, concentrating specifically on the simplest example of Majorons. I end these lectures by discussing the compatibility of having global symmetry in the presence of gravitational interactions. Although these interactions, in general, produce small corrections, they can alter significantly the Nambu-Goldstone sector of theories.


### Discrete Symmetries

*by*

Prof.dr Ing. J. F. J. van den Brand

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Amsterdam, The Netherlands
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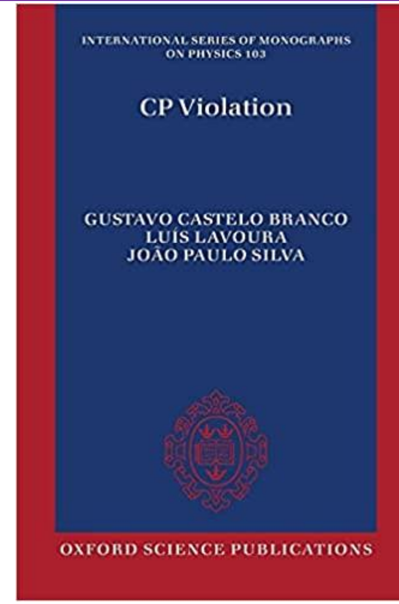
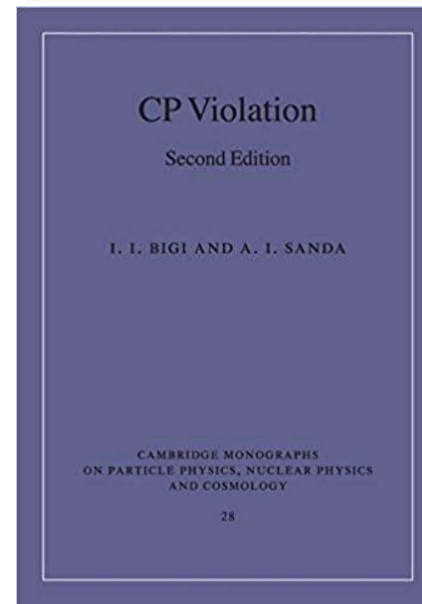
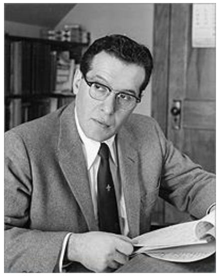


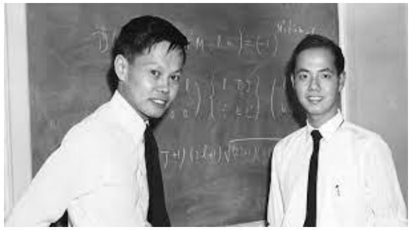



# Discrete Symmetries (CPT)

- E. Noether's first theorem (1915) states that every differentiable symmetry of the action of a physical system with conservative forces has a corresponding conservation law.

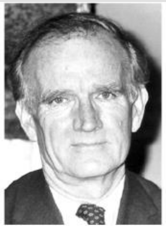


- ('32) C.D. Anderson & P.A.M. Dirac the positive electron (*positron*)
- CPT invariance theorem J. Wigner ('51) + G. Lüders & W. Pauli ('54) + J.S. Bell ('55)



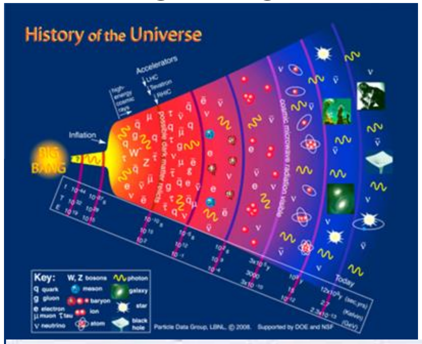
Just after T.-D.Yang & C.-N.Lee
The experiments of Particle-Nuclear physicist C.-S. Wu ('57) and M. Goldhaber ('58) proved that weak interactions are not P-invariant.

The Tau-Theta puzzle(60s), R.Dalitz, N. Cabibbo's mixing angle $\lambda$ ('63) & Evidence for CP violation in the decay of neutral K-mesons observed by J. Cronin & V. Fitch ('64)+ Christenson, Turlay



# Discrete Symmetries (CPT)

HEP Big-Bang




**A. Sakahrov conditions Cosmological baryongenesis ('67):**

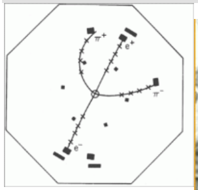
- Baryon number B violation.
- C-symmetry and CP-symmetry violation.
- Interactions out of thermal equilibrium.

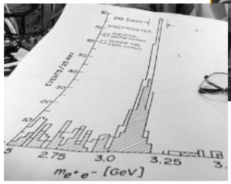
*+ Kuzmin, Rubakov, Shaposhnikov '85*

**GIM Mechanism ('70)**

**M.K. Gaillard & B.W. Lee rare kaons ('74)**

➔ a VIP (very important paper, a must read)





**The Charm of B. Richter and S. Ting ('74) J/ψ**

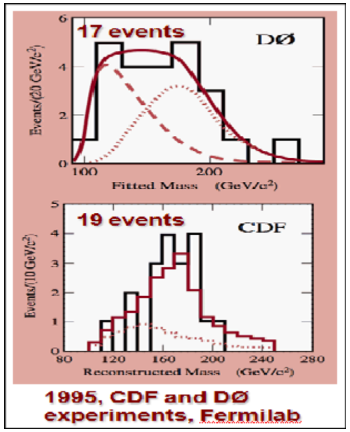
Strong CP problem

Axion ('77) Peccei-Quinn

**The beauty of Lederman ('77) Oups Leon: ϒ**

$B^0$-$B^0$bar oscillation

UA1 and Argus ('87): $\chi$ & $\Delta m_d$




The ('94) top discovery at FermiLab & CDF in 2006 measures the $B_s$ oscillation $\Delta m_s$

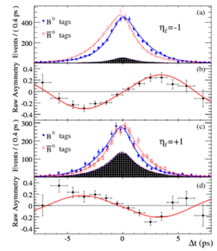
**Kobayashi & Maskawa ('73)**

# Discrete Symmetries (CPT)

**1956**
**Parity violation**
T. D. Lee,
C. N. Yang and
C. S. Wu *et al.*

**1963**
**Cabibbo Mixing**
N. Cabibbo

**1964**
**Strange particles:**
***CP* violation in *K* meson decays**
J. W. Cronin,
V. L. Fitch *et al.*



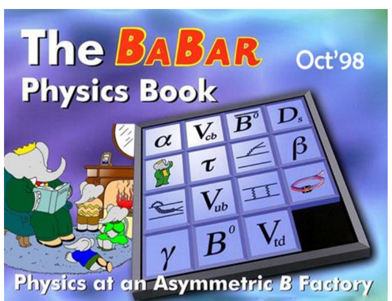
**1973**
**The CKM matrix**
M. Kobayashi and
T. Maskawa

**2001**
**Beauty particles:**
***CP* violation in $B^0$ meson decays**
BaBar and Belle collaborations

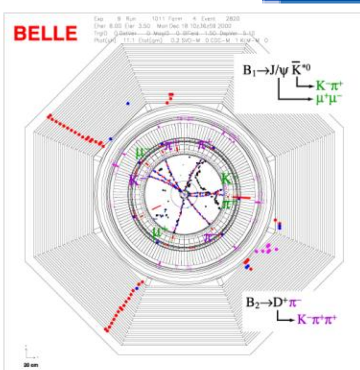
+ D oscillation BaBar 2007

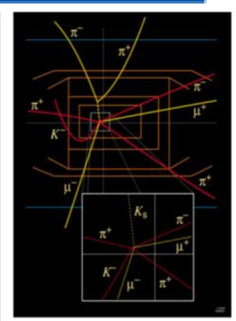
TODAY

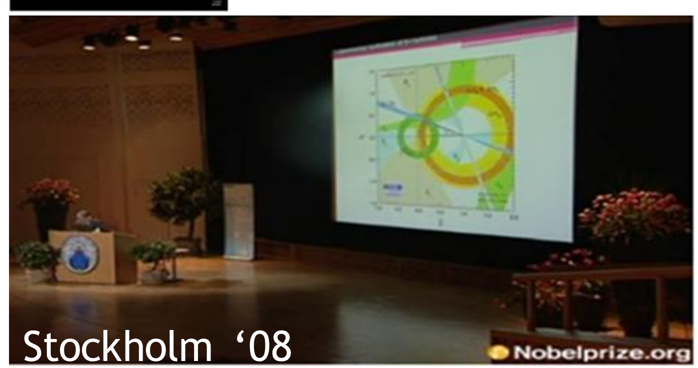
**2019**
**Charm particles:**
***CP* violation in $D^0$ meson decays**
LHCb collaboration



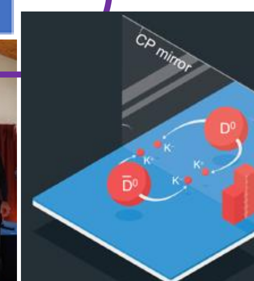


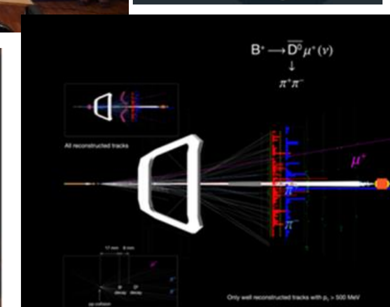






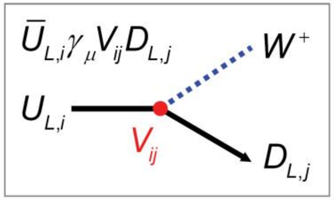


# The Standard Model (SM) & the Unitary CKM Matrix
# ➔ mixing of the 3 quarks families & CP violation

• the Higgs boson gives mass to elementary bosons & fermions (quarks, leptons) through Yukawa couplings, but there is not only that ! :

$$\mathcal{L}_{cc}^{\text{quarks}} = \frac{g}{2\sqrt{2}} W_\mu^\dagger \Big[\sum_{ij} \bar{u}_i(q_2)\gamma^\mu(1-\gamma^5) V_{ij} d_j\Big] + \text{h.c}$$




charged currents (EW) imply transitions between quark families : quarks decays [there are no neutral current changing flavour (FCNC) at tree level (i.e. GIM mechanism)].

$$V_{CKM} = \begin{array}{c} \\ u \\ c \\ t \end{array} \begin{array}{ccc} d & s & b \\ \hline \end{array}$$

$$V_{CKM} = \begin{array}{cc} & \begin{array}{ccc} d & s & b \end{array} \\ \begin{array}{c} u \\ c \\ t \end{array} & \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} \end{array}$$

$$+ \mathcal{O}(\lambda^4) \qquad (VV^\dagger = 1)$$

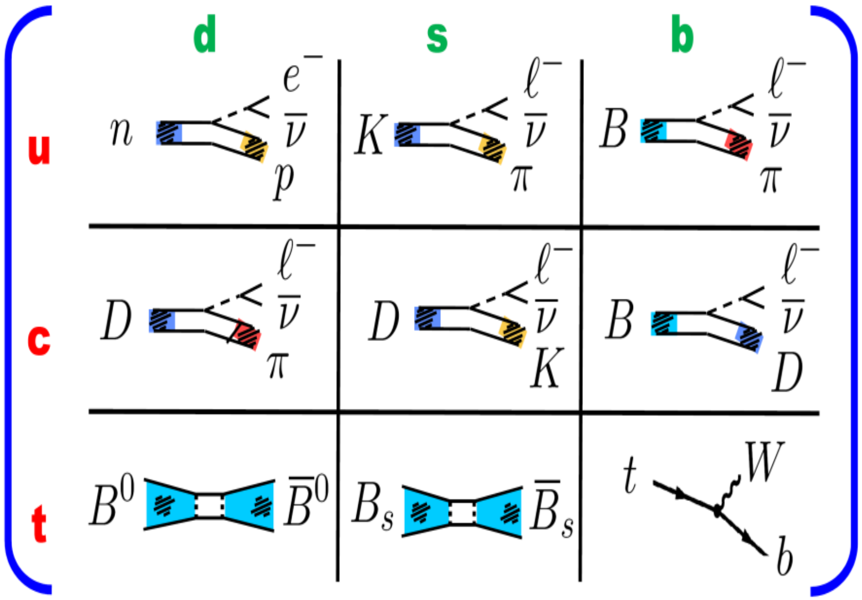
• strong hierarchy in EW $V_{ij}$ couplings for the 3 families (wrt diagonal couplings $\propto \lambda^N \approx (0.225)^N$ : ➔ Cabibbo angle).

• KM (Kobayashi-Maskawa) mechanism :

3 generations ➔ 4 parameters: A, $\lambda$, $\rho$ & 1 complex part $\eta$ which phase is the unique source of CPV in SM.

# The CKM Matrix : the unitary triangle & the very rich phenomenolgy of quark flavors

$V_{CKM}$ =

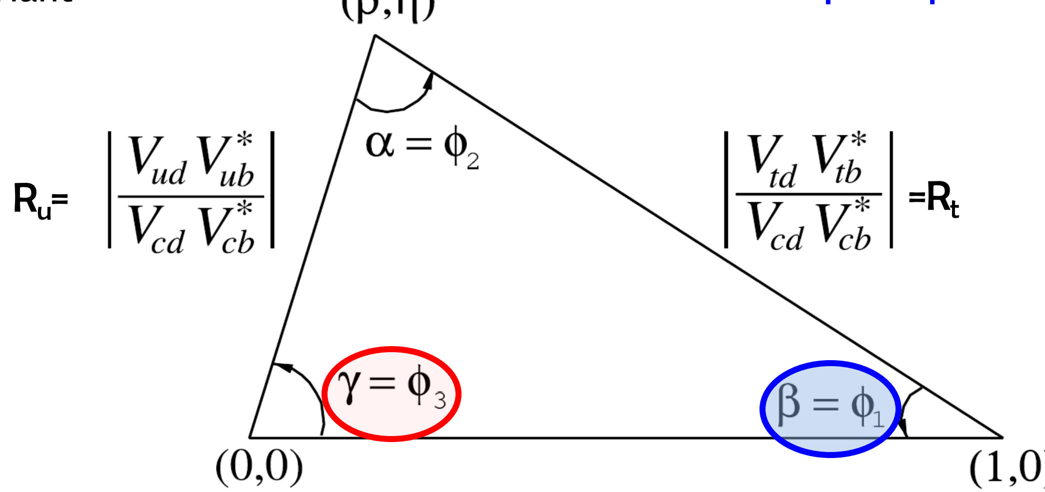



➔4 parameters (A, λ, ρ & η) to be obtained/tested wrt data: nucleons, K, D, $B_{(s)}$ & top quark physics.

➔ unitarity relation in $B_d$ system (1[rst] line/3[rd] column):

$$\boxed{\begin{array}{c}\dfrac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} + 1 + \dfrac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*} = 0 \\ O(1) + O(1) + O(1)\end{array}}$$

Unitarity triangle in the $(\bar{\rho},\bar{\eta})$ complex plane:




Parametrisation « à la Wolfenstein » phase invariant & valid at any orders in λ @ CKMfitter

***(EPJ C41, 1-131, 2005)*** :

$$\bar{\rho} + i\bar{\eta} = -\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}$$

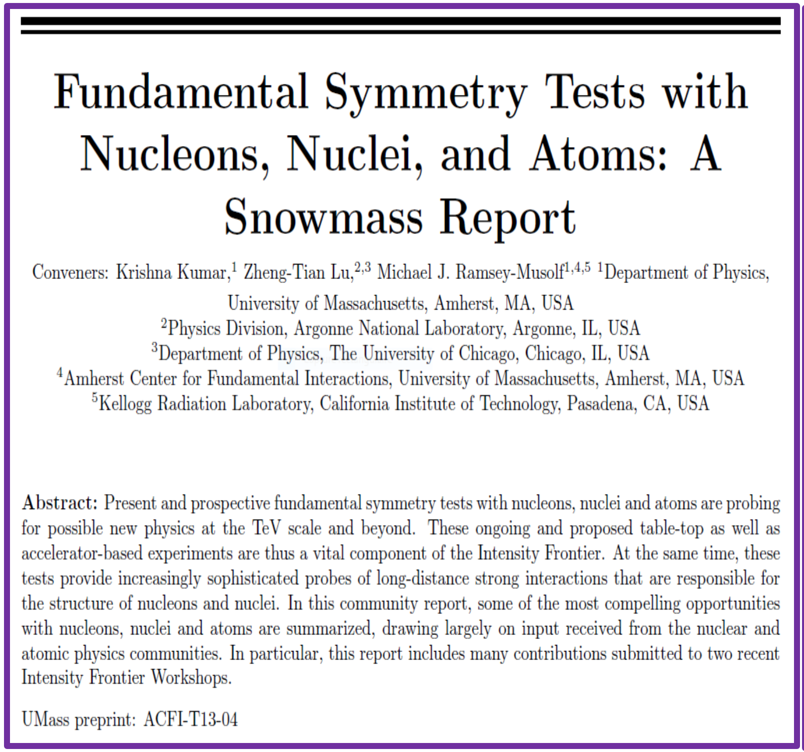
$$\lambda^2 = \frac{|V_{us}|^2}{|V_{ud}|^2 + |V_{us}|^2} \qquad A^2\lambda^4 = \frac{|V_{cb}|^2}{|V_{ud}|^2 + |V_{us}|^2}$$

# Discrete Symmetries Overview part 2:
# nEDM & nuclear β-decays

**See Maud Versteegen (CENBG), Guillaume Pignol (LPSC)**

**In a few minutes**

arXiv:1312.5416v1 [hep-ph] 19 Dec 2013

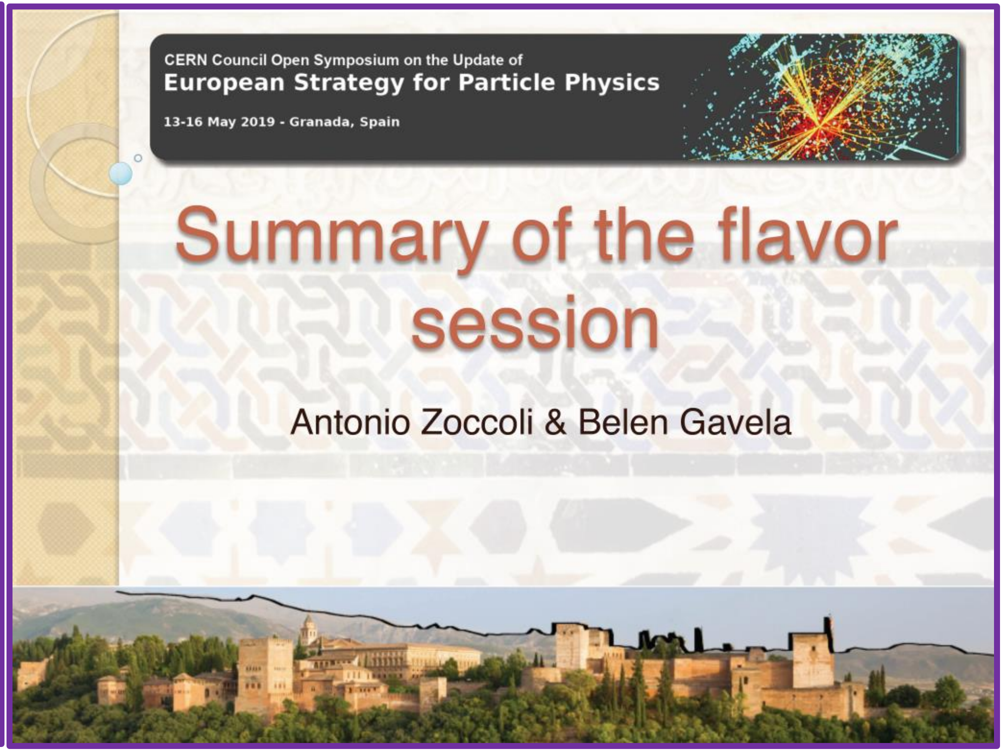


Fundamental Symmetry Tests with Nucleons, Nuclei, and Atoms: A Snowmass Report

Conveners: Krishna Kumar,[1] Zheng-Tian Lu,[2,3] Michael J. Ramsey-Musolf[1,4,5] [1]Department of Physics, University of Massachusetts, Amherst, MA, USA
[2]Physics Division, Argonne National Laboratory, Argonne, IL, USA
[3]Department of Physics, The University of Chicago, Chicago, IL, USA
[4]Amherst Center for Fundamental Interactions, University of Massachusetts, Amherst, MA, USA
[5]Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, CA, USA

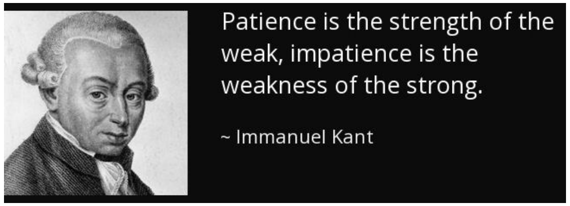
**Abstract:** Present and prospective fundamental symmetry tests with nucleons, nuclei and atoms are probing for possible new physics at the TeV scale and beyond. These ongoing and proposed table-top as well as accelerator-based experiments are thus a vital component of the Intensity Frontier. At the same time, these tests provide increasingly sophisticated probes of long-distance strong interactions that are responsible for the structure of nucleons and nuclei. In this community report, some of the most compelling opportunities with nucleons, nuclei and atoms are summarized, drawing largely on input received from the nuclear and atomic physics communities. In particular, this report includes many contributions submitted to two recent Intensity Frontier Workshops.

UMass preprint: ACFI-T13-04



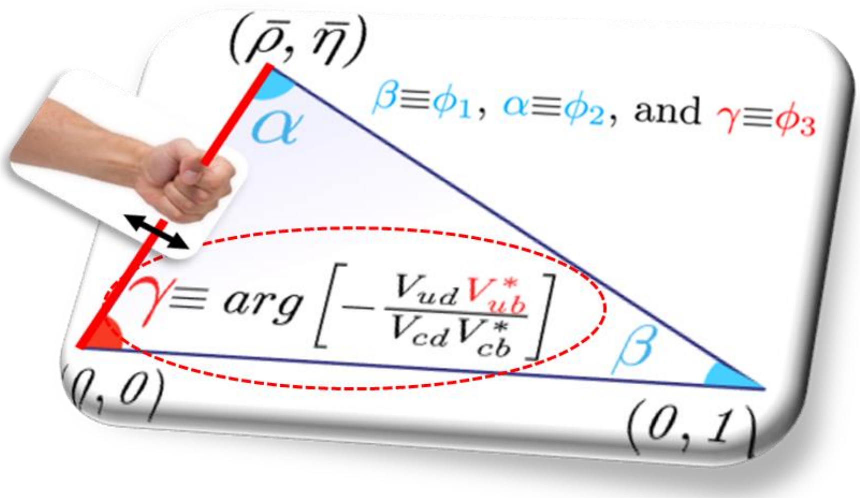

https://indico.cern.ch/event/808335/sessions/306785/#20190513

**I must confess that this is most of what I know about it + in CKMfitter [Phys.Rev. D91 (2015) 073007]()**



# ➔ The CKM angle γ is a fundamental parameter of the SM related to the complex phase in the KM mechanism responsible for CP violation in quark sector

Already 12 years ago after the B factories BaBar@SLAC and Belle@KEK we knew that

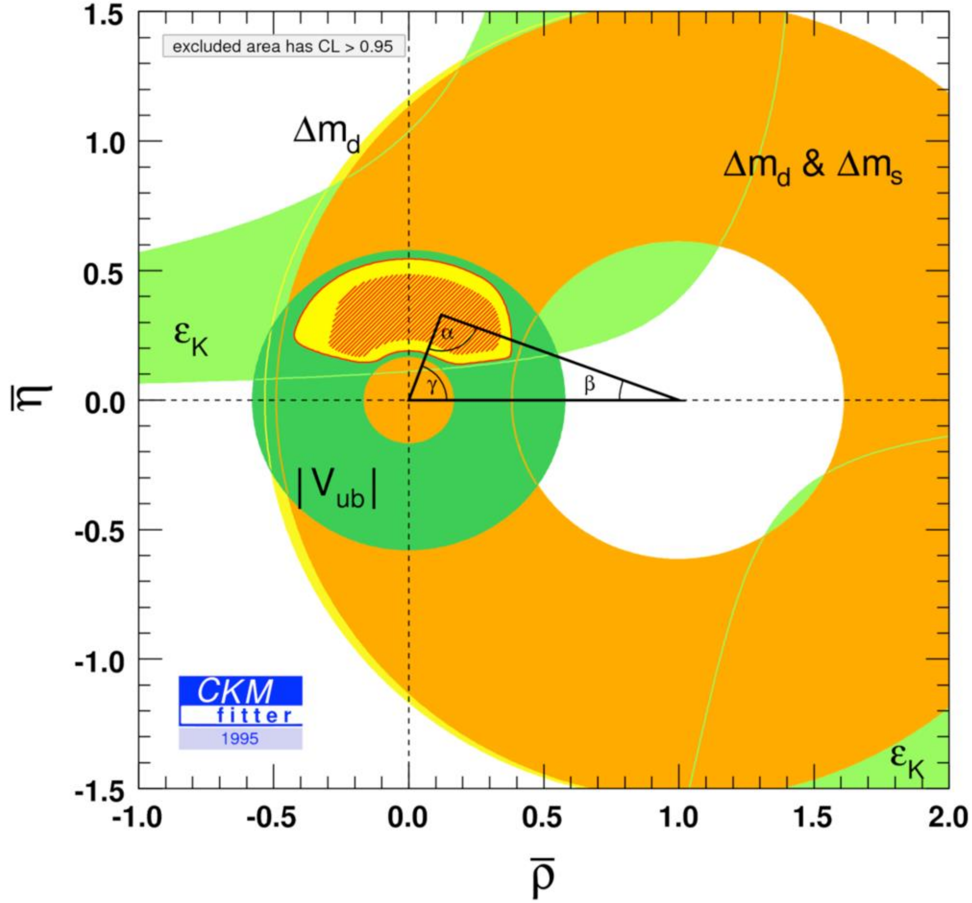



M. Kobayashi & T. Masakwa, Nobel prize of physics 2008

The KM mechanism is the main source of CPV at EW scale (i.e. @ $m_{W/Z}$) But there is still room for BSM physics

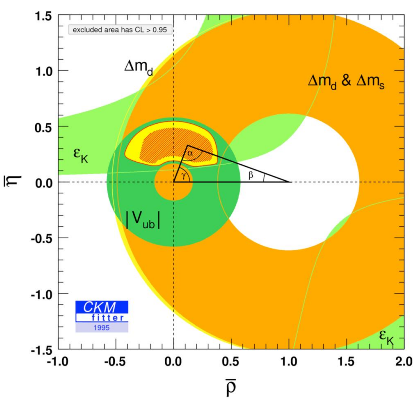
# Last 25 years have seen tremendous progresses on CKM metrology

## 1995 after LEP

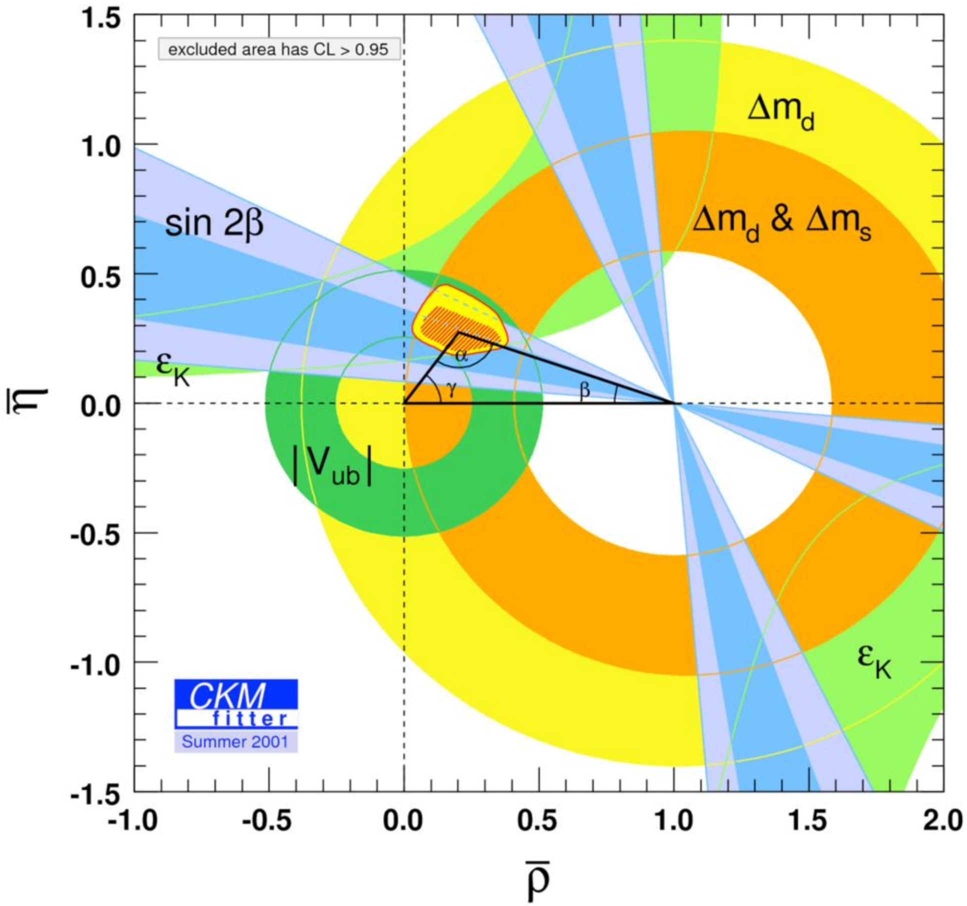


# Last 25 years have seen tremendous progresses on CKM metrology

1995

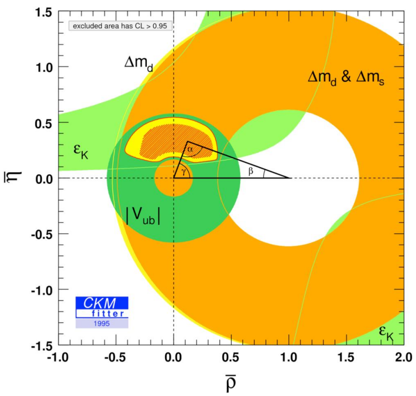



2001: B-factories at work

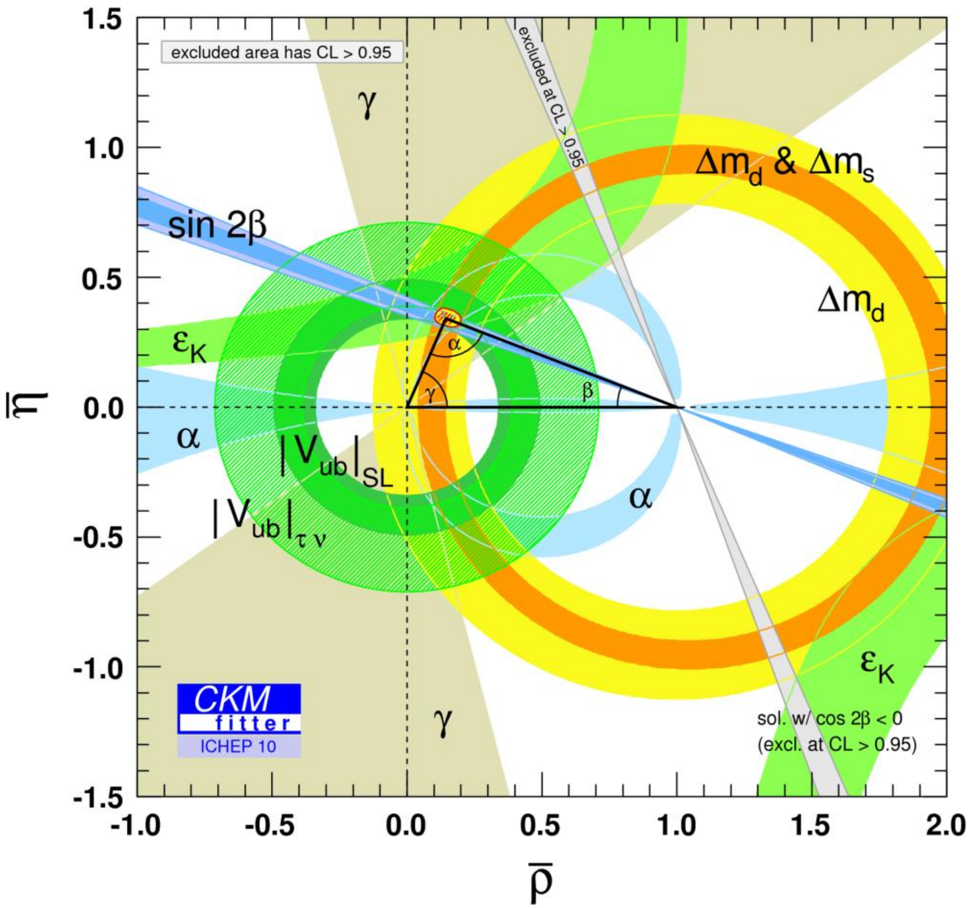


# Last 25 years have seen tremendous progresses on CKM metrology

1995

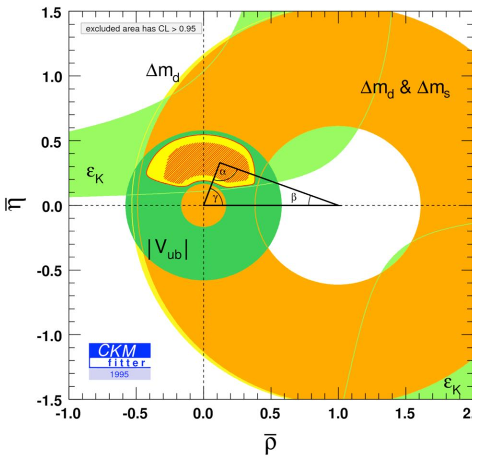



2010: B-factories legacy+CDF@TeVatron

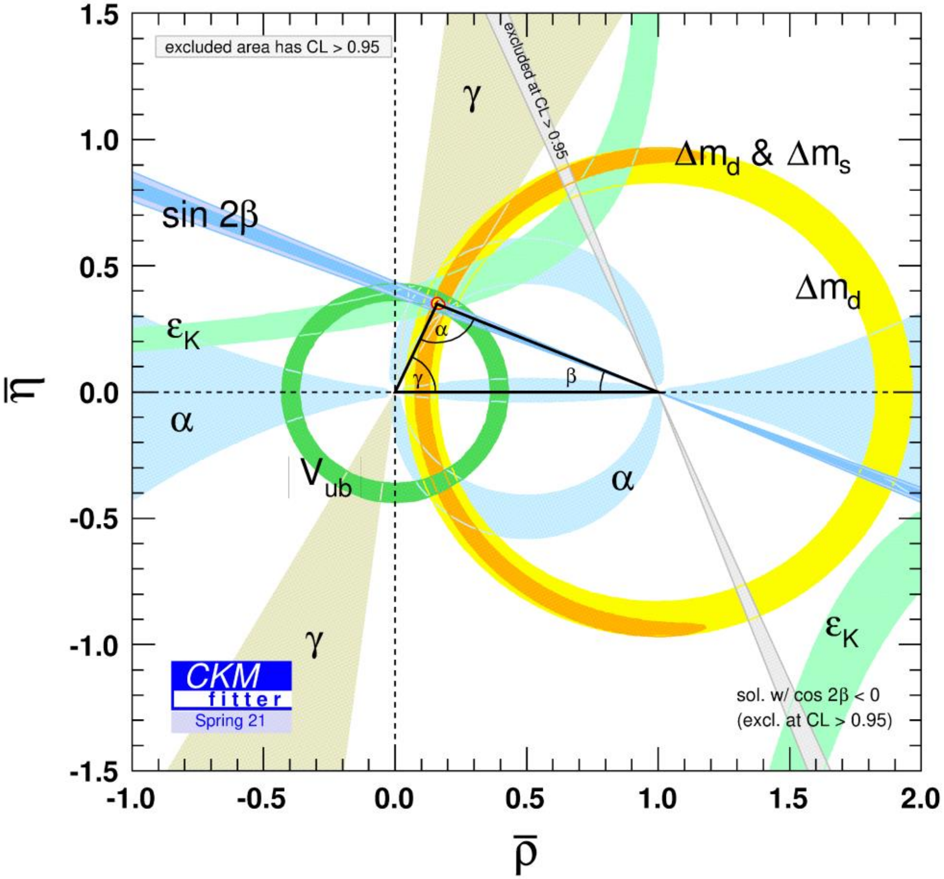


# Last 25 years have seen tremendous progresses on CKM metrology

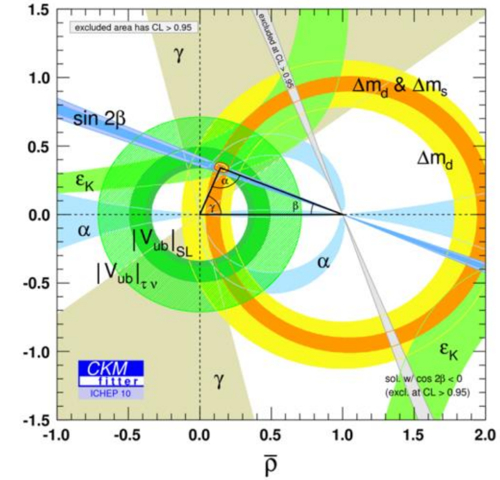
1995




Now after 10 years of LHCb

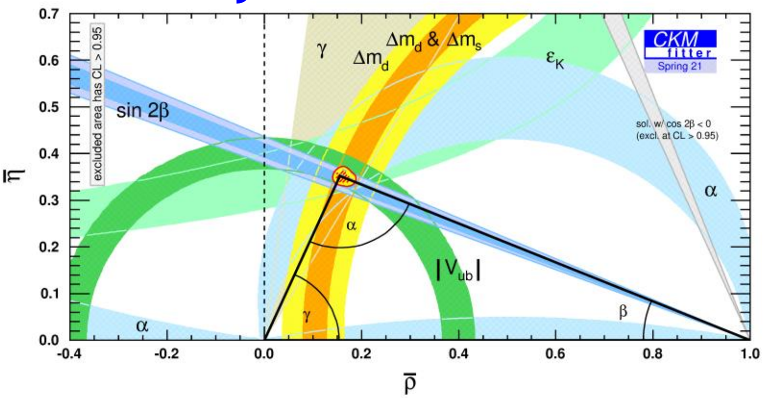



2010



# Intermezzo: CKM metrology the UT & the PMNS UT (CPV with neutrinos)

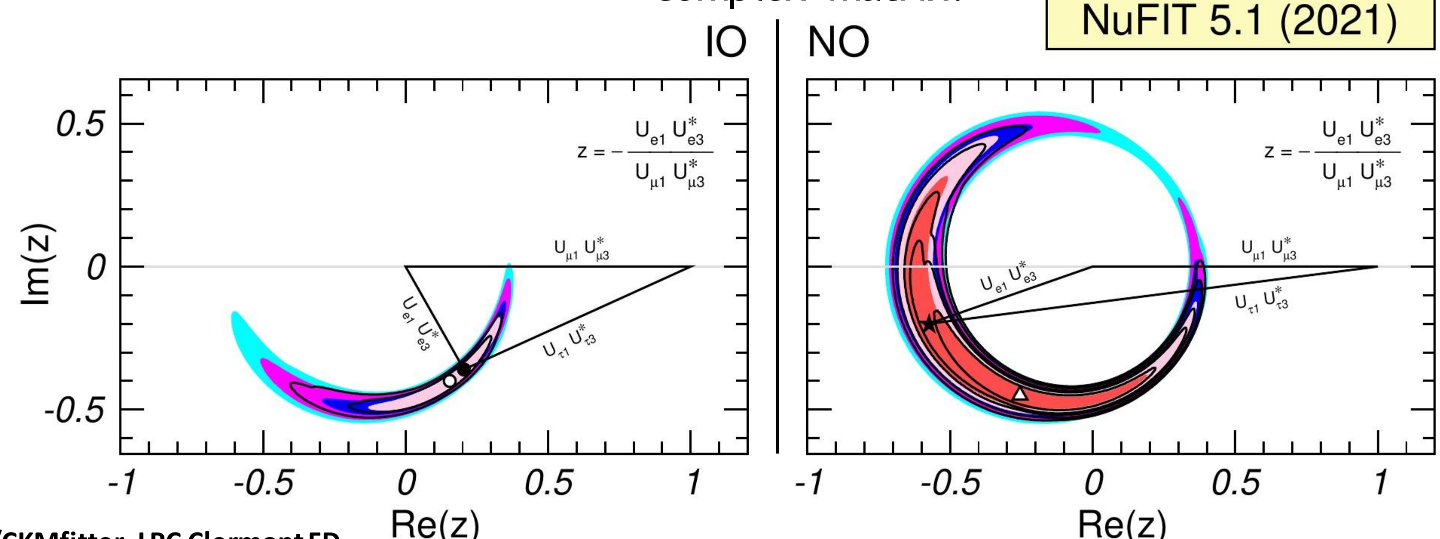
**after 10 years of LHCb 2021**



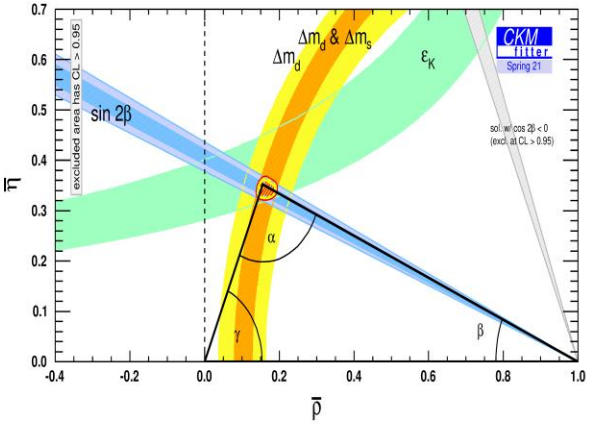

**The other UT**

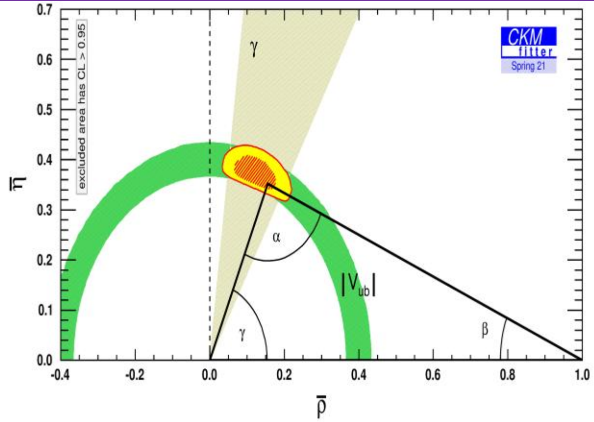
Pontecorvo ('57) solar neutrino problem : neutrinos oscillation! => explained by Sakata, Maki & Nakagawa ('62, the Nagoya school (+K.M.)) with a 3x3 unitary complex matrix!

NuFIT 5.1 (2021)



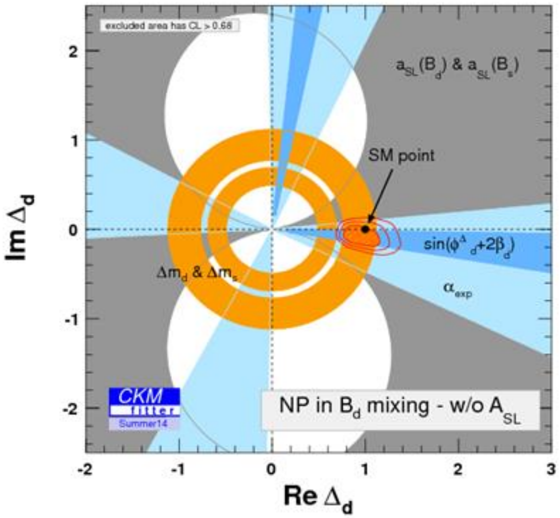
# Global coherence tests of CKM within/outside the SM

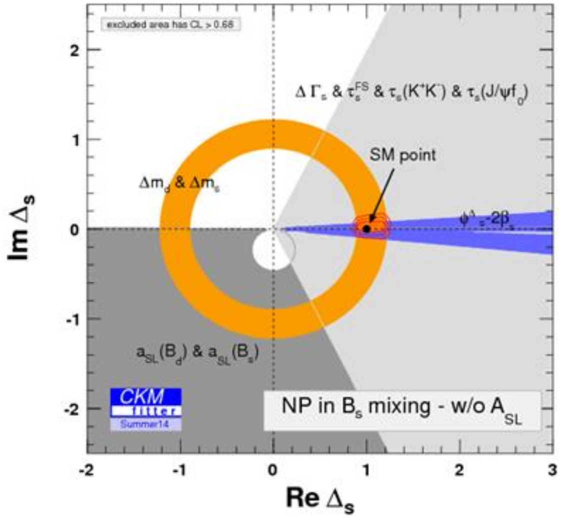



Now after 10 years of LHCb

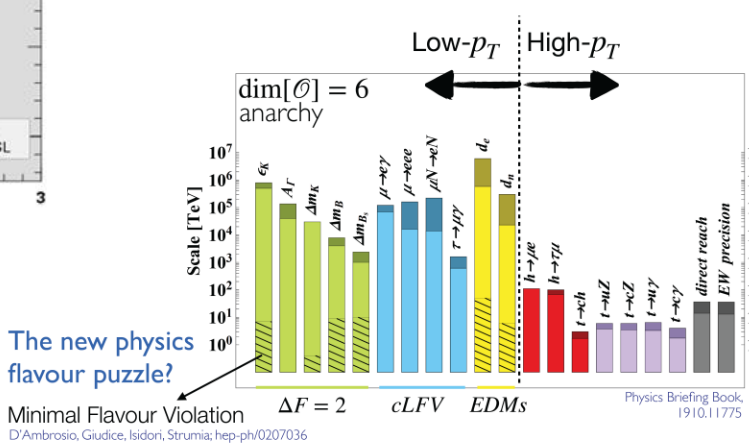
New physics or no New Physics yet seen ? When will we know ?

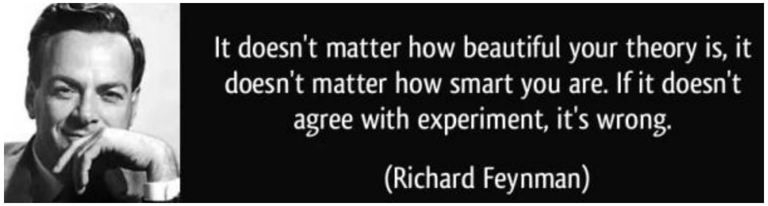



## *The importance of flavour data!*

- SMEFT at $\dim[\mathcal{O}] = 6$ - new sources of flavour violation
- Strong constraints from flavour experiments




A. Greljo ICHEP 22

# Ok this "old/boring guy" is keeping looking backwards… What's new then ?

« Un homme sans *passé* est plus pauvre qu'un homme sans *avenir*. » -*Elie Wiesel*.



# Charm CPV: discovery to characterization

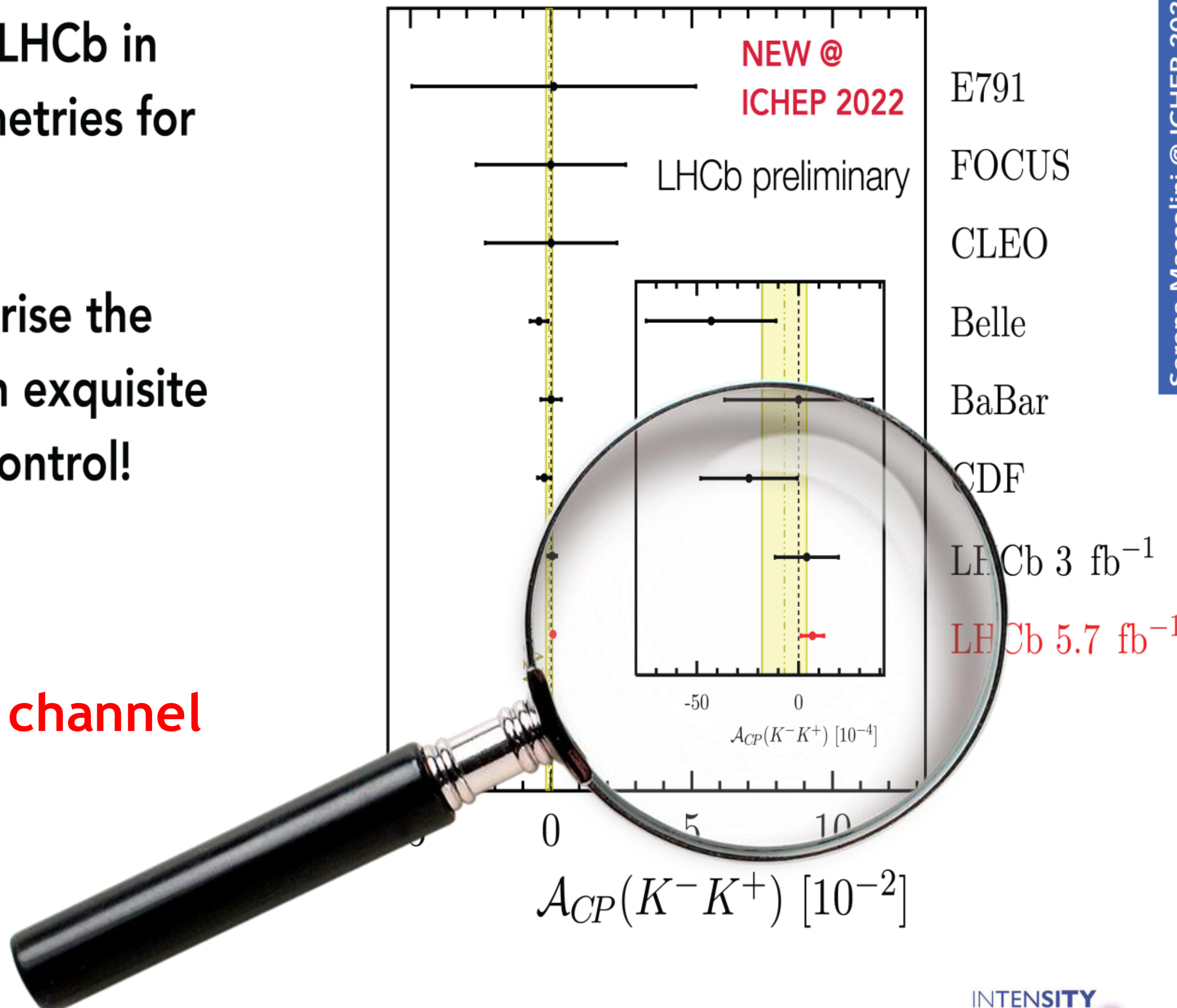
CPV in charm observed by LHCb in the difference of CP asymmetries for the $\pi\pi$ and KK final states

Now beginning to characterise the individual asymmetries with exquisite precision and systematics control!

V. Gligorov@ICHEP22

**First charm CPV in single channel**

But still unclear if SM or new dynamics in charm decays

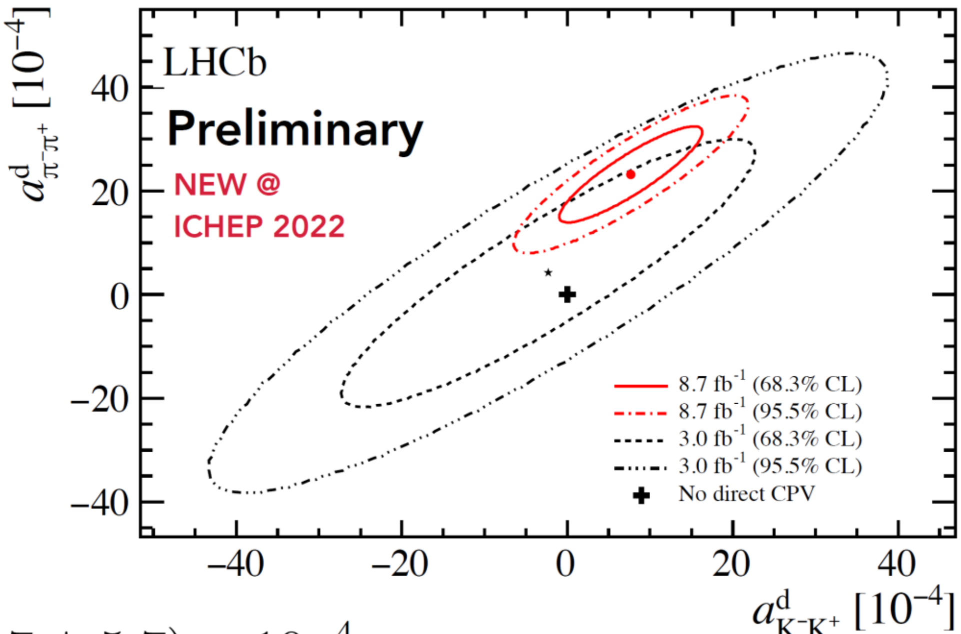



Serena Maccolini @ ICHEP 2022

# Charm CPV: discovery to characterization

Combination of the measurement of CP violation in the KK mode with the difference between KK and ππ leads to the first single-mode evidence (3.8σ) of CPV in ππ

Systematics controlled at the $10^{-4}$ level — essential to scale to $10^{-5}$




$$a^{d}_{K^-K^+} = (\ 7.7 \pm 5.7) \times 10^{-4}$$

$$a^{d}_{\pi^-\pi^+} = (23.2 \pm 6.1) \times 10^{-4}$$

with $\rho(a^{d}_{KK}, a^{d}_{\pi\pi}) = 0.88$

**Measurements limited by control mode yields — must collect all charm at the LHC with real-time analysis!**

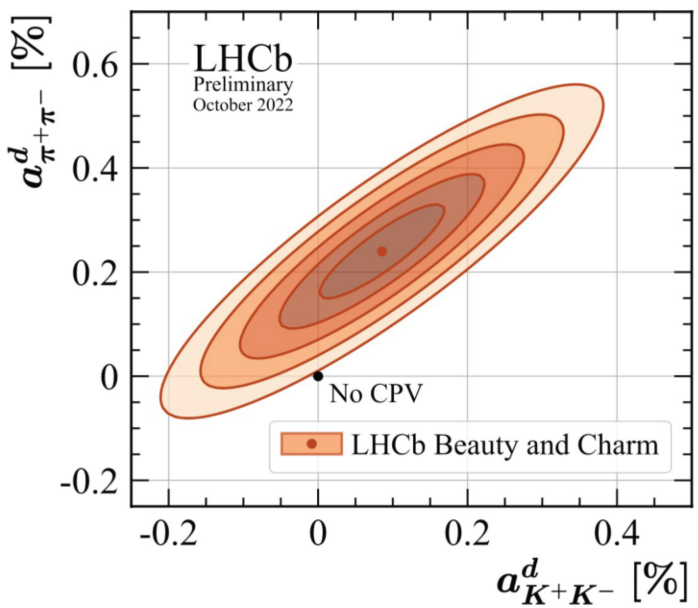
V. Gligorov@ICHEP22

## New charm combinations

[LHCb-CONF-2022-003]

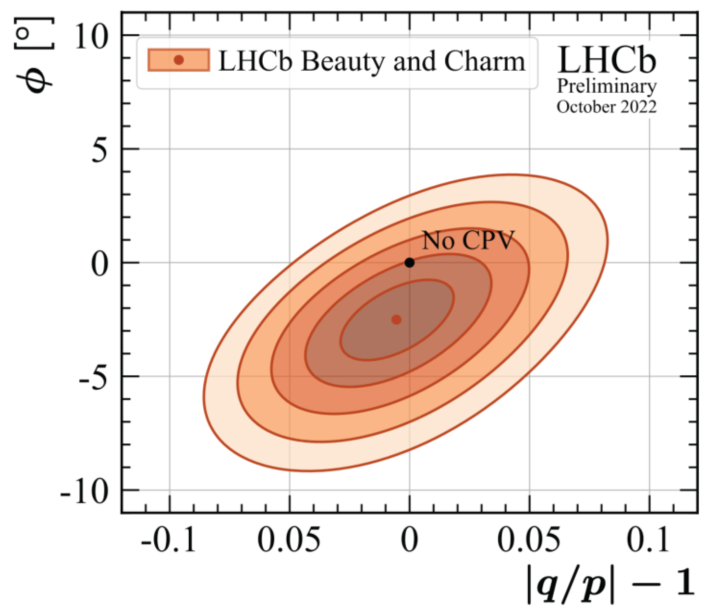
### Direct CPV

$$a^d_{K^+K^-} = (9.0 \pm 5.7)\times 10^{-4}$$
$$a^d_{\pi^+\pi^-} = (24.0^{+6.1}_{-6.2})\times 10^{-4}$$




### Indirect CPV

$$\phi = (-2.5 \pm 1.2)^\circ$$
$$|q/p| = 0.995^{+0.015}_{-0.016}$$

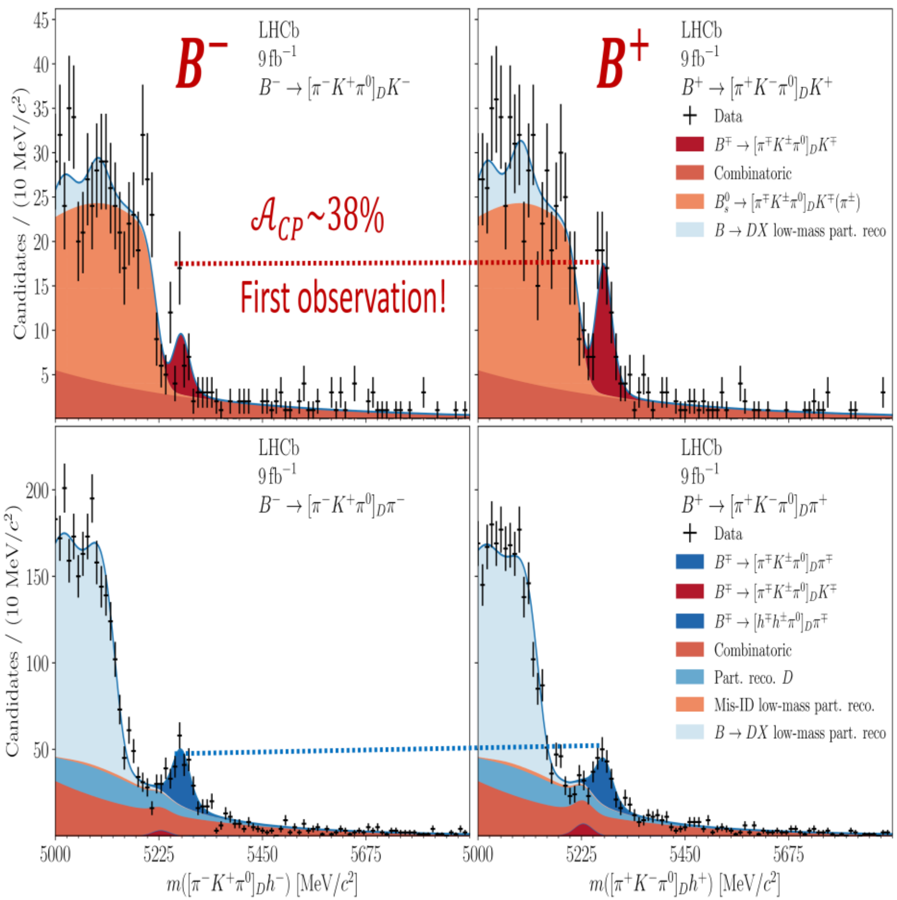





*Charm only results almost indistinguishable

# $B^{\pm} \to D(h^{\pm}h'^{\mp}\pi^{0})h^{\pm}$

arXiv:2112.10617 LHCb-PAPER-2021-036
JHEP03(22) 153




- B candidates $B^{\mp} \to DK^{\mp}$ and $B^{\mp} \to D\pi^{\mp}$ , where charm meson reconstructed in quasi-GLW and ADS method:

- $D \to \pi^+\pi^-\pi^0$
- $D \to K^+K^-\pi^0$
- $D \to K^+\pi^-\pi^0$
- **$D \to \pi^+K^-\pi^0$(suppressed)**

Phys. Lett. B 740 (2015) 1

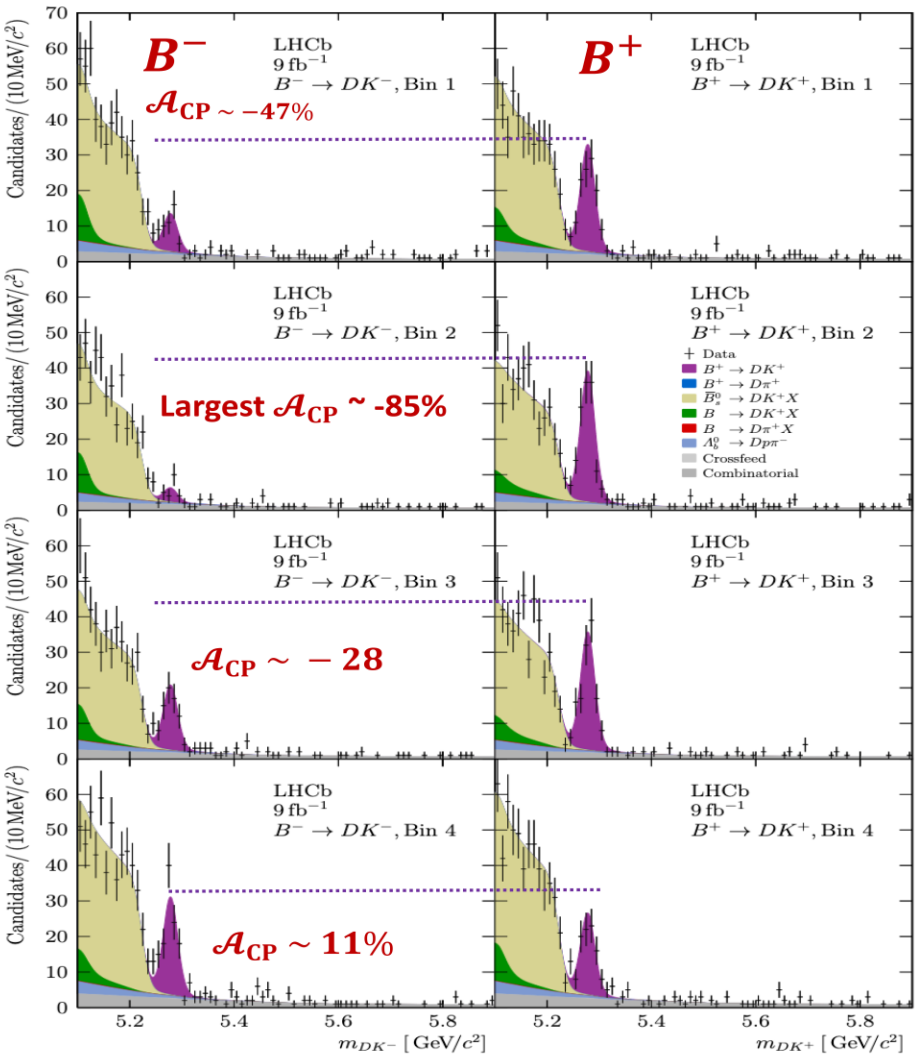
- $R_D$ Coherence factor ~1

Sensitivity to $\gamma$ yet limited:
$(56^{+24}_{-19})^{\circ}$

# Since 2021 Nov GDR Annual meeting : LHCb

## CKM angle $\gamma$ in $B^{\pm} \to D K^{\pm}$ with $D \to K^{\mp}\pi^{\pm}\pi^{\pm}\pi^{\mp}$

arXiv:2209.03692 LHCb-PAPER-2022-017




- Binned approach based on Improved sensitivity to the phase γ through binning D decay phase space PLB 802 (2020) T. Evans et al.
- Maximize the sensitivity the coherence factor $R_D$ is larger in Bin 2 and 3

  ➔ **Largest CPV ever seen !!!!!**

- D decay hadronic parameters from CLEO-C, BESIII JHEP 05 (21) 164

$$\gamma = \left(54.8 \,^{+6.0}_{-5.8} \,^{+0.6}_{-0.6} \,^{+6.7}_{-4.3}\right)^{\circ}$$

# Since 2021 Nov GDR Annual meeting : LHCb

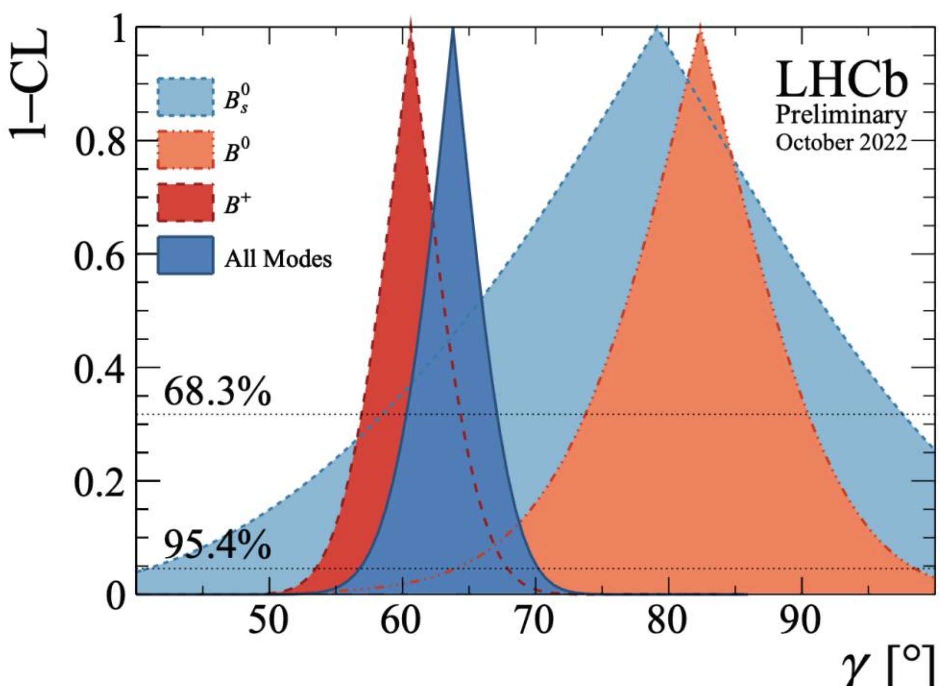
**New combination ($\gamma$ + D mixing parameters) shown few days ago at the LHCb Implication Workshop at CERN 19-21 Oct 22**

## Combination of LHCb measurements

LHCb-CONF-2022-003

- $\boxed{\gamma = (63.8^{+3.5}_{-3.7})^\circ,}$ $x_D = (0.398^{+0.050}_{-0.049})\%$, $y_D = (0.636^{+0.020}_{-0.019})\%$
  - * Improvements about 10% on $\gamma$ ($\sim$ 1 year data-taking), 6% on $x_D$ and 38% on $y_D$
  - $\gamma_{\rm UTFit} = (65.8 \pm 2.2)^\circ$, $\gamma_{\rm CKMFitter} = (65.5^{+1.1}_{-2.7})^\circ$
- Tension between different $B$ categories remains ($\sim 2\sigma$)

**With GammaCombo Package, i.e. a frequentist approach used with 173 observables to determine 52 parameters**



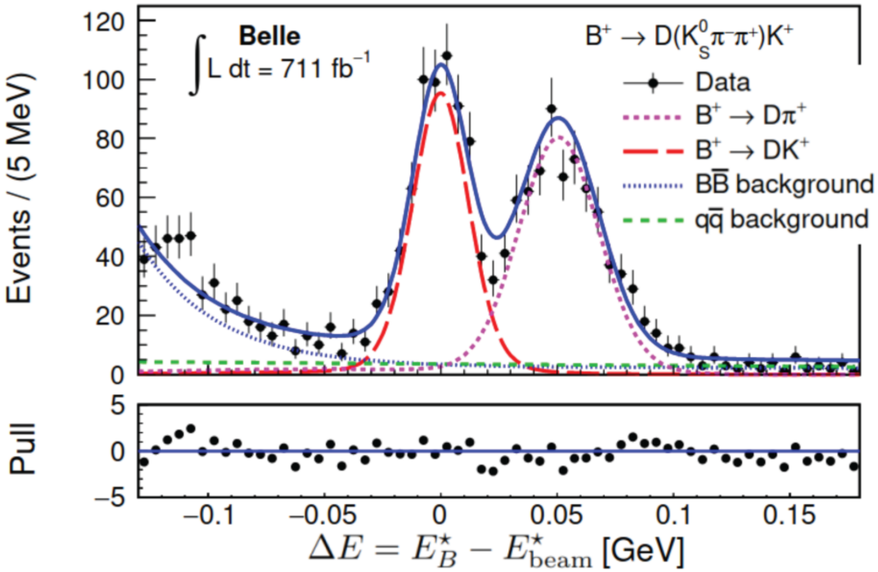


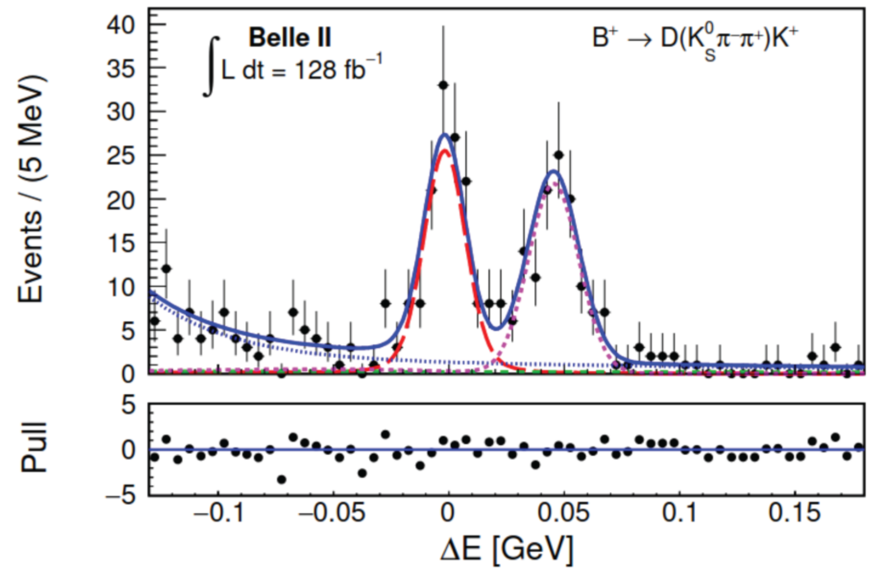
Ultimately: Aim for the sub-degree precision to challenge the global coherence of the CKM fit beyond the SM $\Lambda_{NP}$>15-20 TeV

Phys.Rev.D89:033016,2014
CKMfitter + Papucci/Ligeti

# Since 2021 Nov GDR Annual meeting : Belle II

## Belle II is also showing its capabilities




$$\gamma = (78.4 \pm 11.4\ \text{(stat.)}\ \pm 0.5\ \text{(syst.)}\ \pm 1.0\ \text{(ext.)})^\circ$$

**Joint analysis of B→D(Ksππ)K decays with Belle + Belle II data**
**Significantly improved the resolution ➔ DK wrt Dπ separation!**
**Not competitive yet, but stay tune if Super KEK delivers lumi**
**Belle II recorded only ~430/fb (almost like BaBar did)**

# Belle II is also showing its capabilities

**CKM angle $\phi_2/\alpha$**

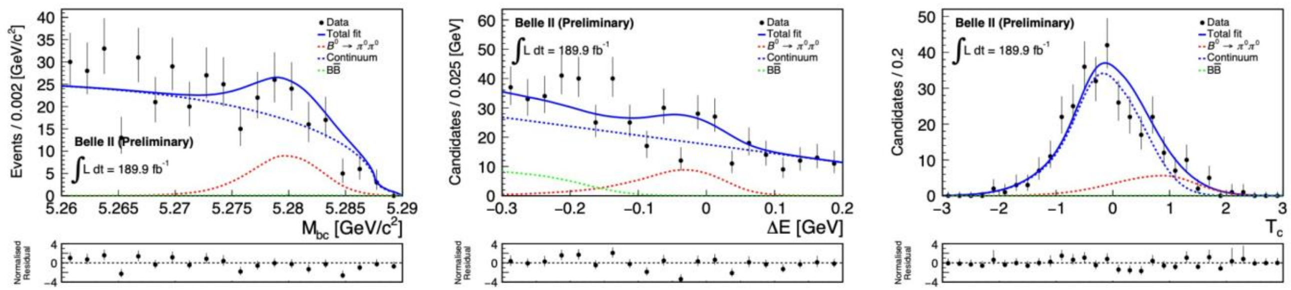
## $B^0 \to \pi^0\pi^0$ Result

New for ICHEP

Results competitive with Belle with a data set of less than one third!

$$\mathcal{A}^{CP} = 0.14 \pm 0.46\ \text{(stat)} \pm 0.07\ \text{(syst)}$$
$$\mathcal{B} = (1.27 \pm 0.25\ \text{(stat)} \pm 0.17\ \text{(syst)}) \cdot 10^{-6}$$

WA: $\mathcal{A}^{CP} = 0.33 \pm 0.22$, $\mathcal{B} = (1.59 \pm 0.26) \cdot 10^{-6}$




$N(\text{sig}) = 93 \pm 18$

- Results demonstrate Belle II's capability to measure decays with neutrals
  $\Rightarrow$ Belle II is ready to offer key contributions

# Belle II is also showing its capabilities

**T. Humair at Moriond EW 2022**

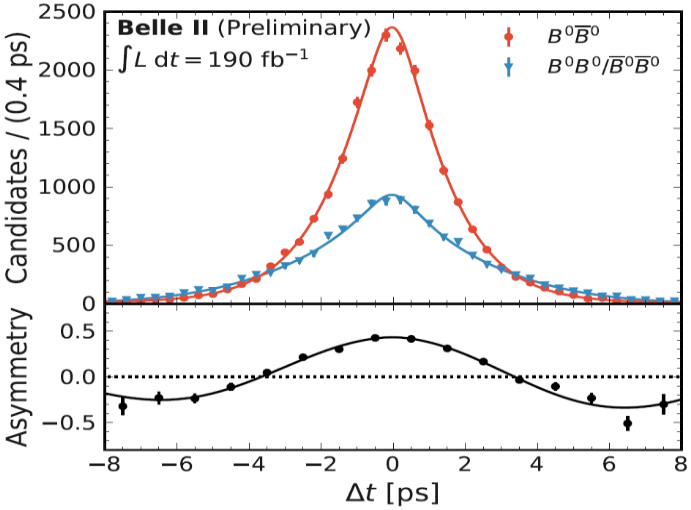
## New mixing and lifetime measurement: result

Belle II: $\varepsilon_{\text{tag}} = (30.0 \pm 1.3)\%$
Belle : $\varepsilon_{\text{tag}} = (30.1 \pm 0.4)\%$

arXiv:2110.00790

Result compatible with world average:

$$\tau_{B^0} = 1.499 \pm 0.013\,(\text{stat.}) \pm 0.008\,(\text{syst.})\text{ ps},$$
$$\Delta m_d = 0.516 \pm 0.008\,(\text{stat.}) \pm 0.005\,(\text{syst.})\text{ ps}^{-1}.$$




Compared to Belle and BaBar's best measurement:

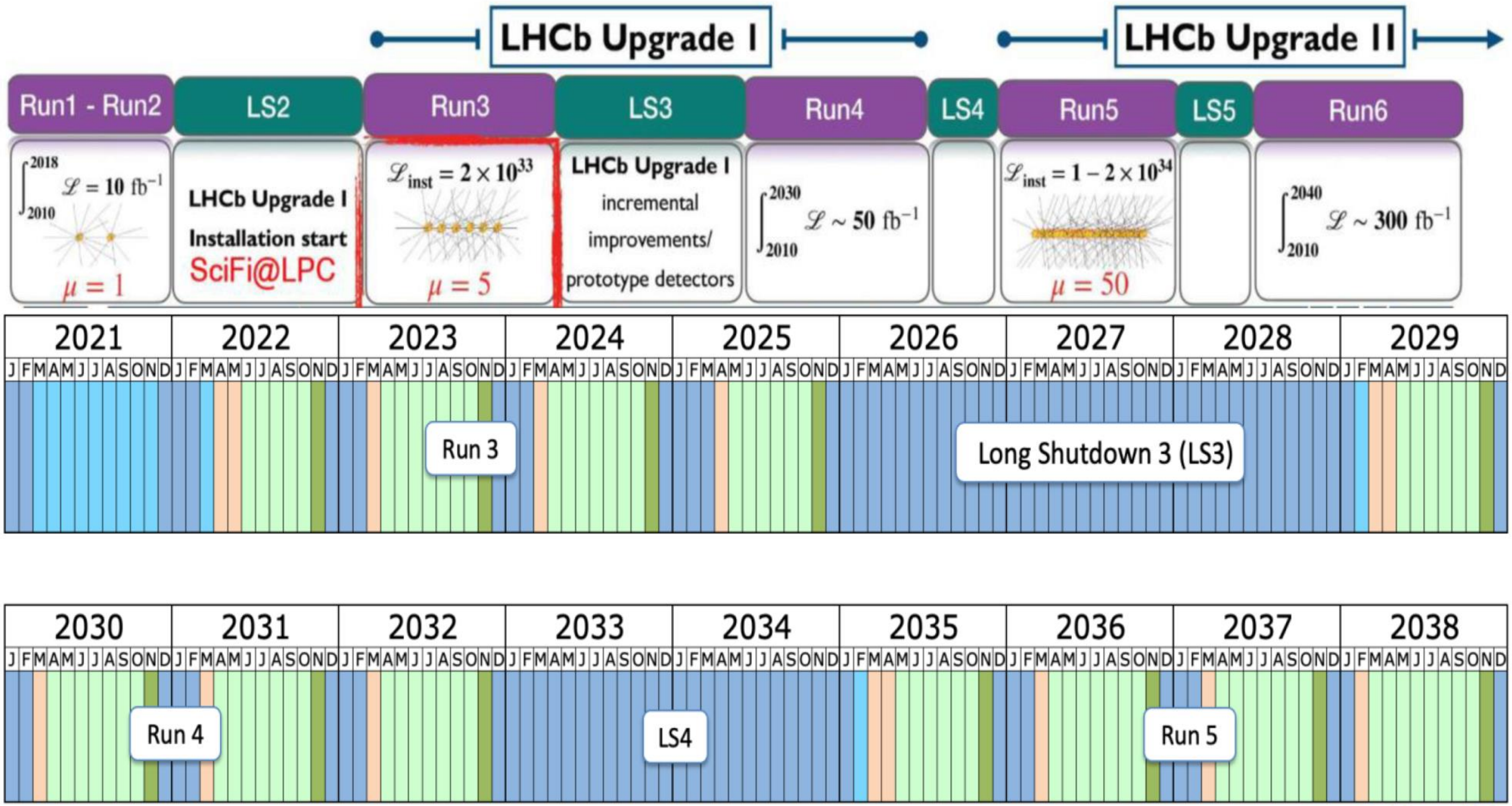
- Slightly worse stat. uncertainty because not using $B^0 \to D^{*-}\ell^+\nu$ modes yet.
- better alignment and background systematics.
- comparable resolution modelling systematics.

Milestone in Belle II program: we are fully ready for time dependent analyses!

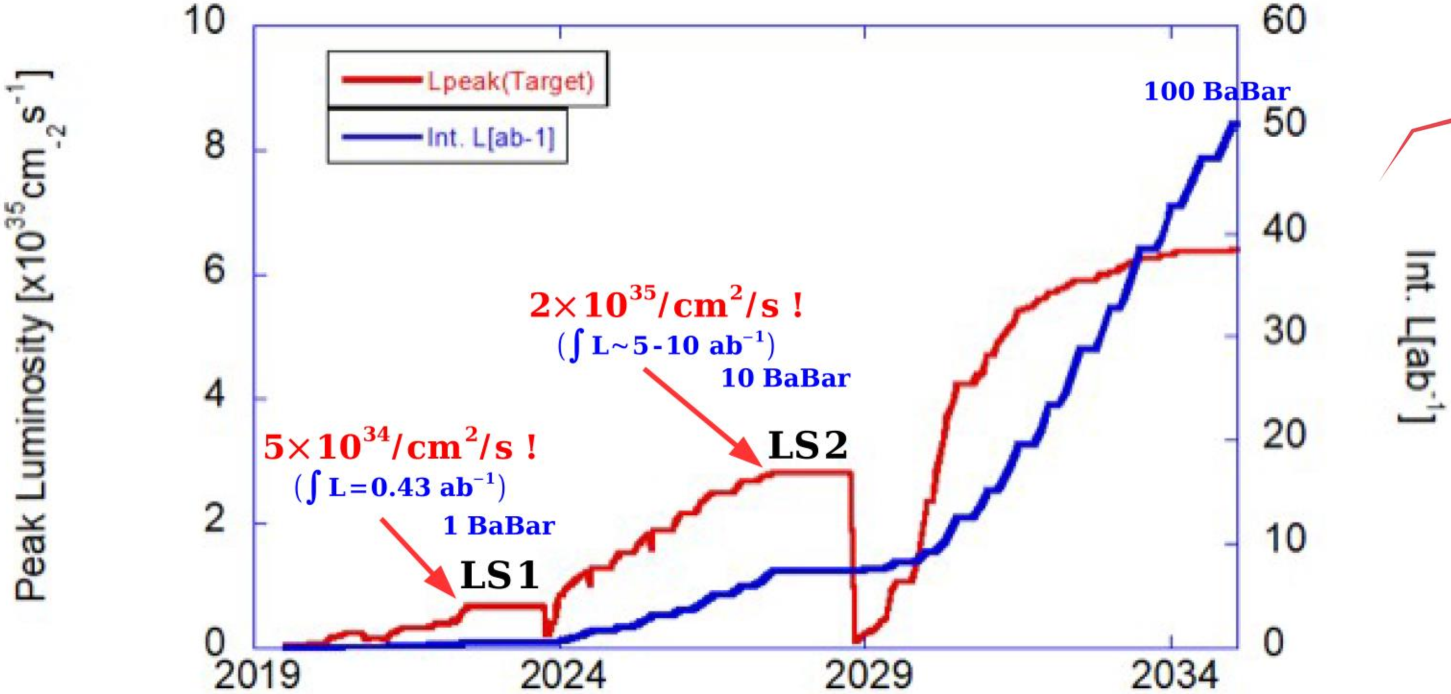
**Next steps:** $\tau$, $\Delta m_d$ with $B^0 \to D^{*-}\ell^+\nu$ and competitive $\sin 2\beta$ measurement.

**Note: $\sin 2\beta/\phi_1 = 0.72 \pm 0.06 \pm 0.02$ with 190/fb only**
**Current World average/with charmonium is $0.699 \pm 0.017$ (dominated by stat)**

# LOOKING FORWARD to the bright FUTURE




# Calendrier de Belle II




run 1 (→ juin 2022): luminosite integre ~0.43 ab$^{-1}$, $4-5\times10^{34}$/cm$^2$/s
PXD complet (2 couches) a installe durant LS1 (2022-2023)
(+beampipe + TOP PMTs)

run 2 (→ 2027): luminosite integre 5-10 ab$^{-1}$, $2\times10^{35}$/cm$^2$/s

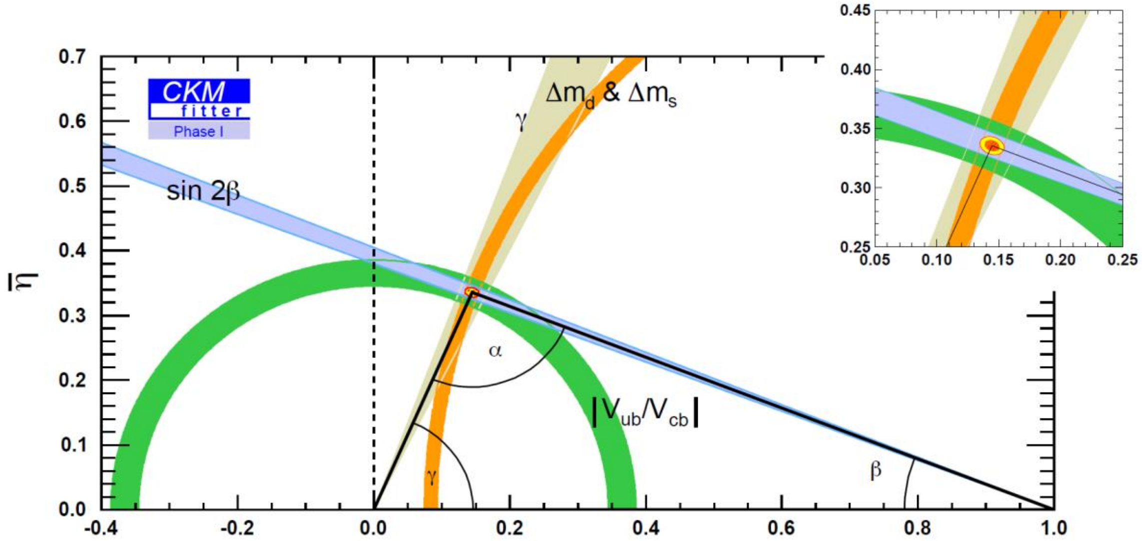
**2027 : collider upgrade (QCS+RF) → installation upgraded detector**

run 3 (→ > 2030): 50 ab$^{-1}$

K. Trabelsi @ CS IN2P3 27/10/2022

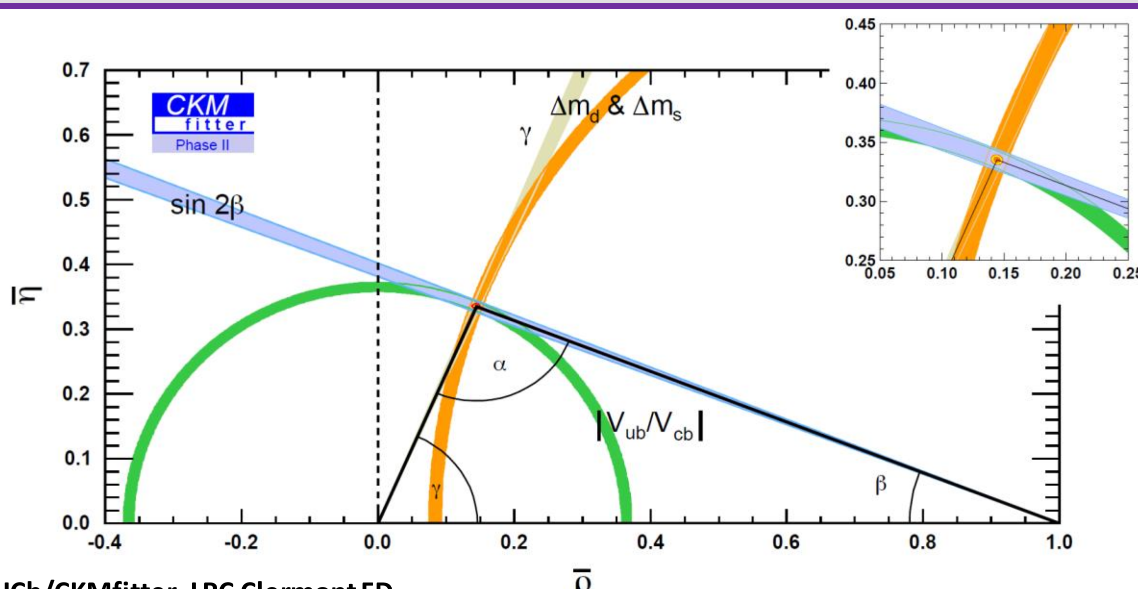
# LOOKING FORWARD!

## Phase I: LHCb at 23 $fb^{-1}$, CMS/ATLAS at 300 $fb^{-1}$, Belle II at 50 $ab^{-1}$.




~in about 10 years

## Phase II: LHCb at 300 $fb^{-1}$, CMS/ATLAS at 3000 $fb^{-1}$, and Belle II at 50 $ab^{-1}$.




~20 years