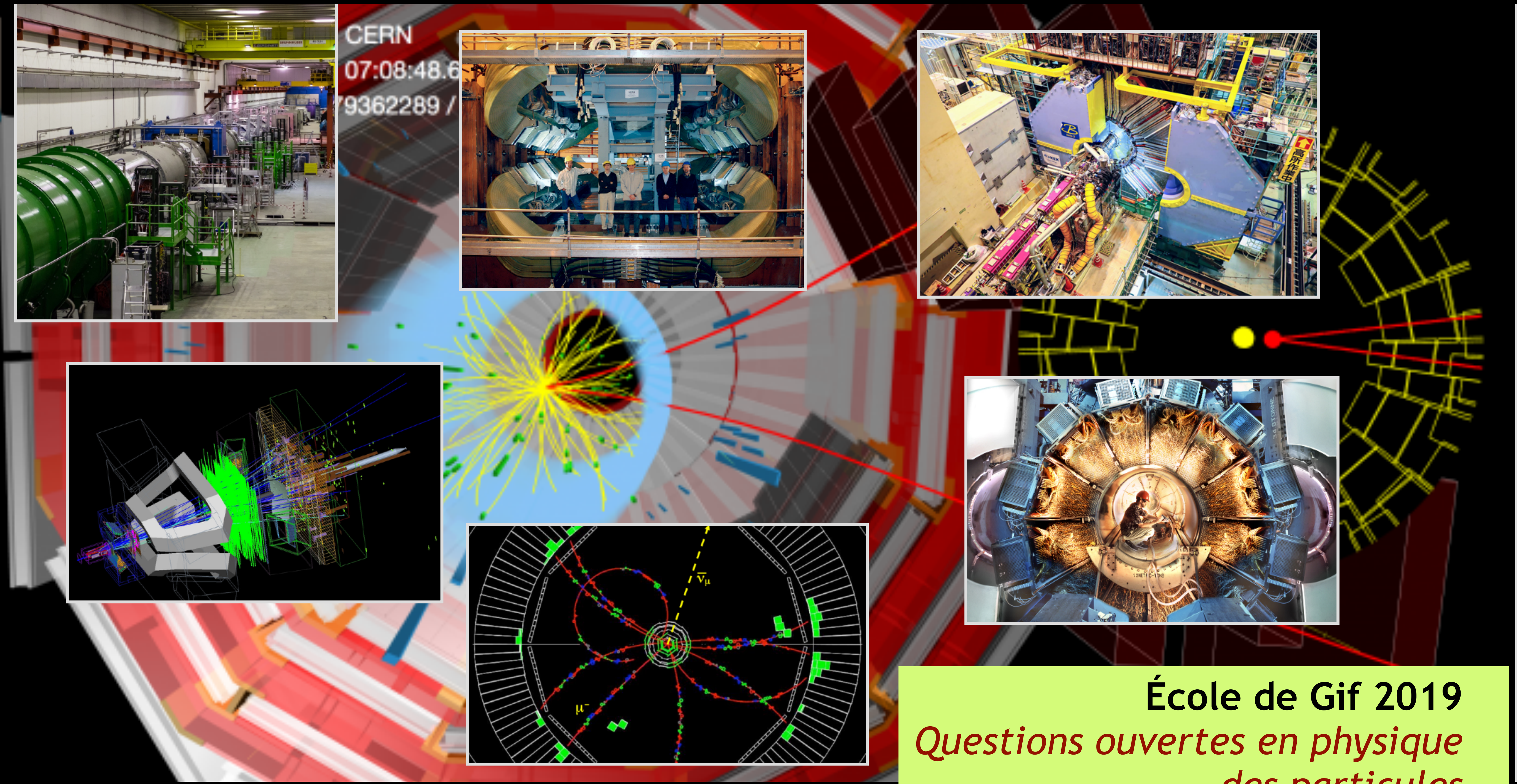
Les expériences du futur : potentiel de physique

Physique de la saveur



Gautier Hamel de Monchenault

École de Gif 2019

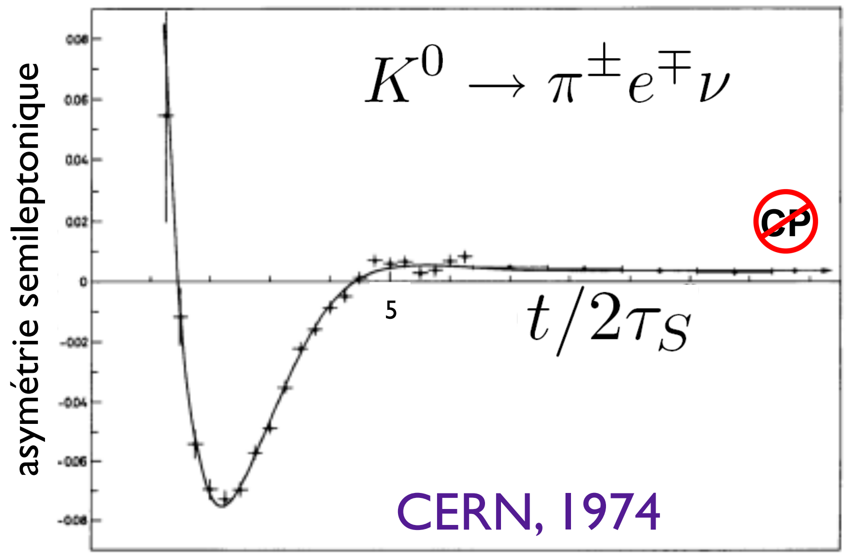
Questions ouvertes en physique des particules

2-6 septembre 2019

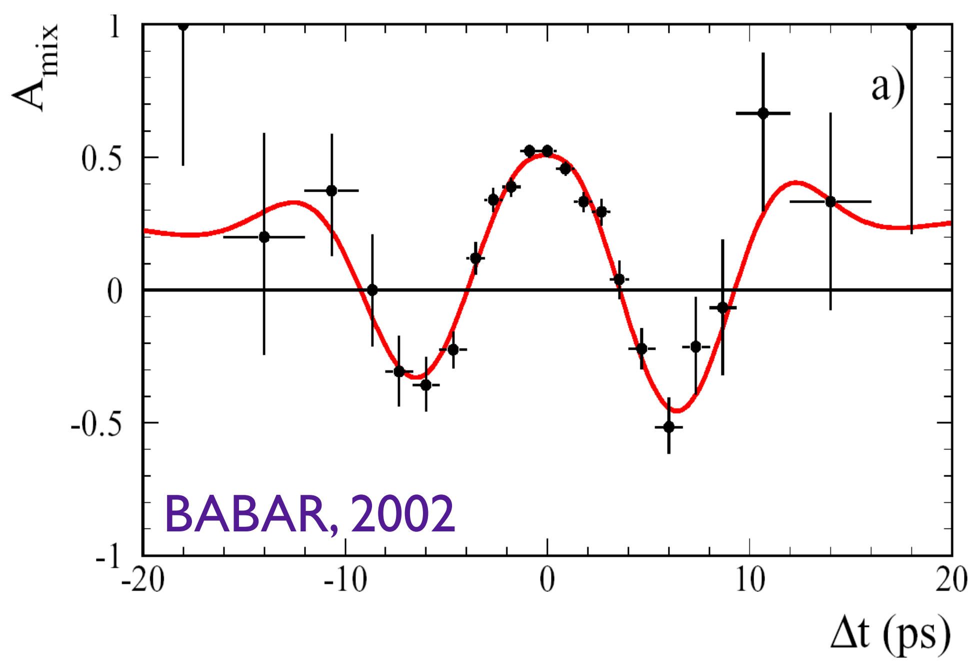
École polytechnique, Palaiseau

Flavour Oscillations

☛ in the neutral kaon system

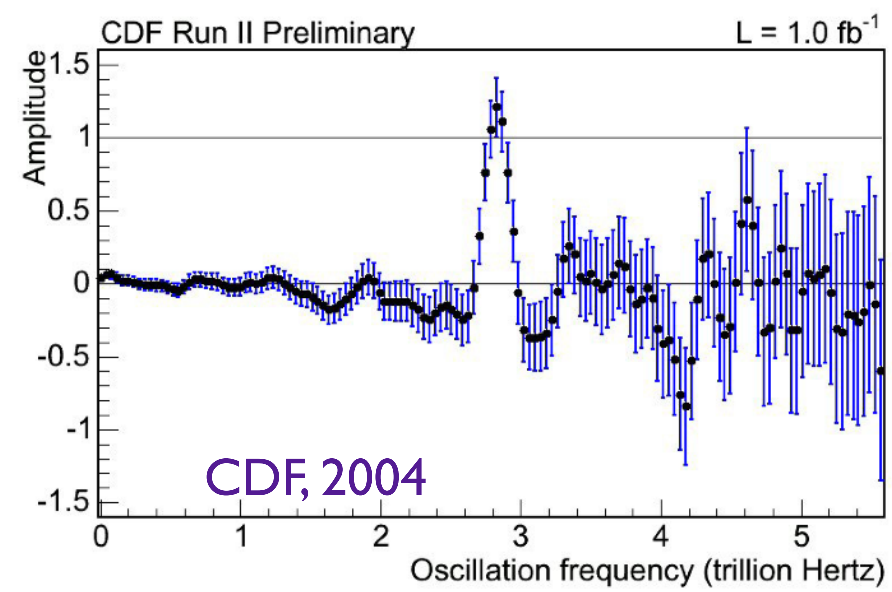


☛ in the B^0 meson system



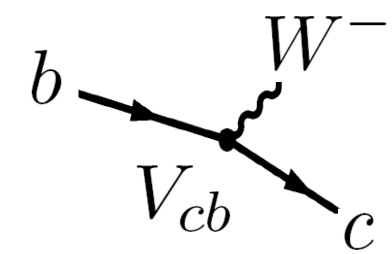
☛ in the B_s^0 meson system

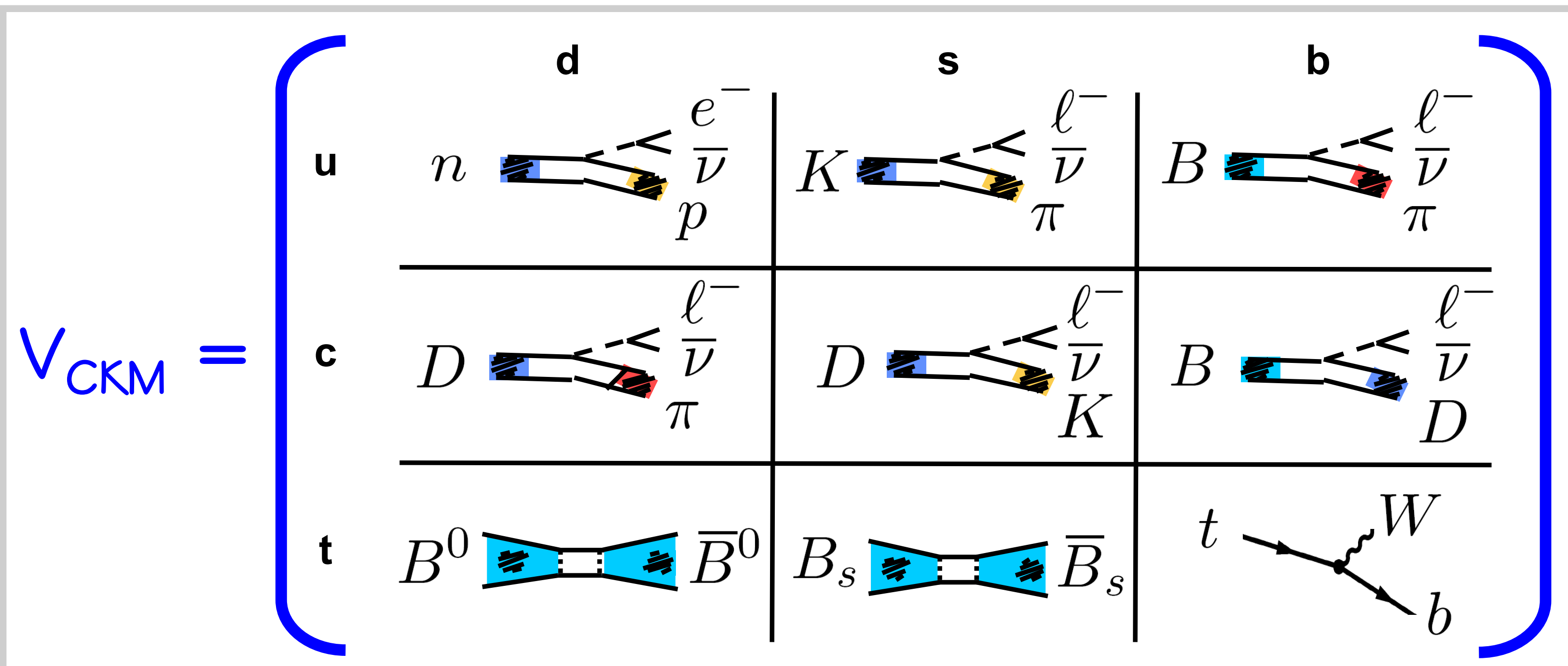
- observation



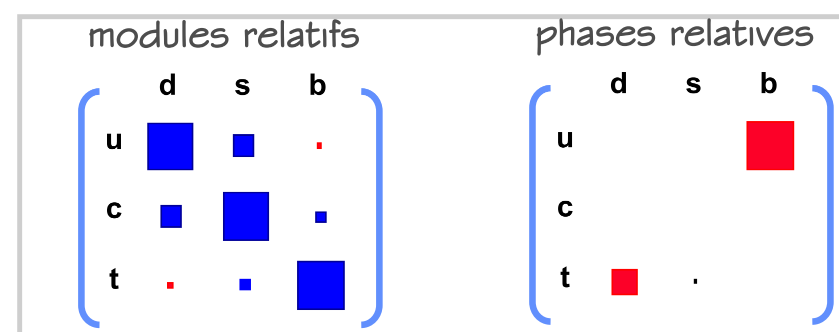
Quark Flavour Mixing

Cabibbo, Kobayashi-Maskawa (CKM) matrix
- complex, unitary dimension-3 (3 quark families)
- elements = coupling between up-type quarks and down-type quarks





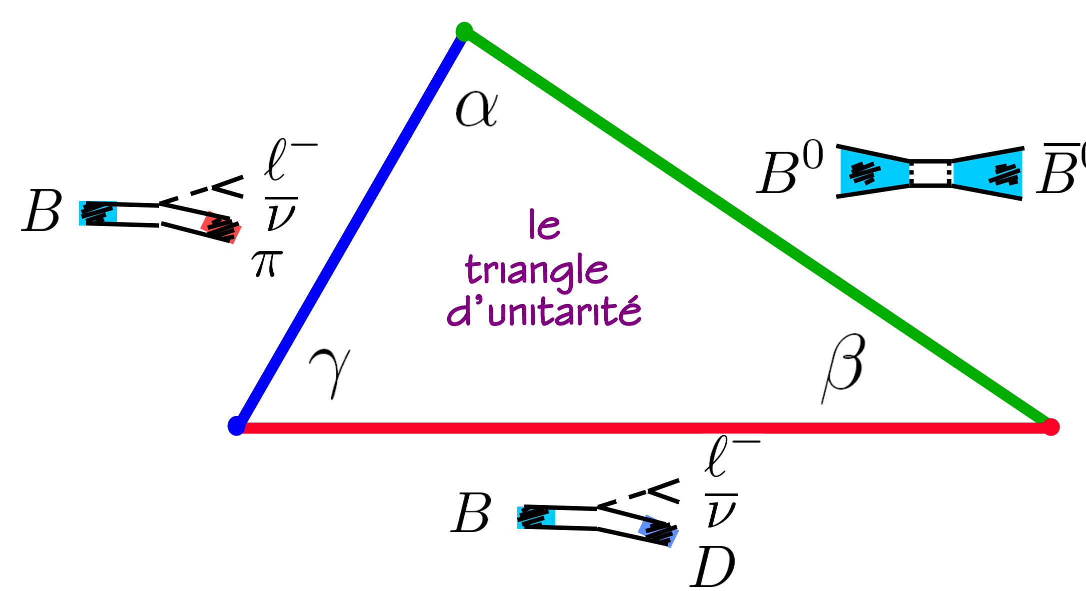
The CKM matrix is :
- almost diagonal
- quasi real



Unitarity = "conservation of probability"

➪ relations between CKM matrix elements

➪ equation of a triangle : the **Unitarity Triangle** (UT)



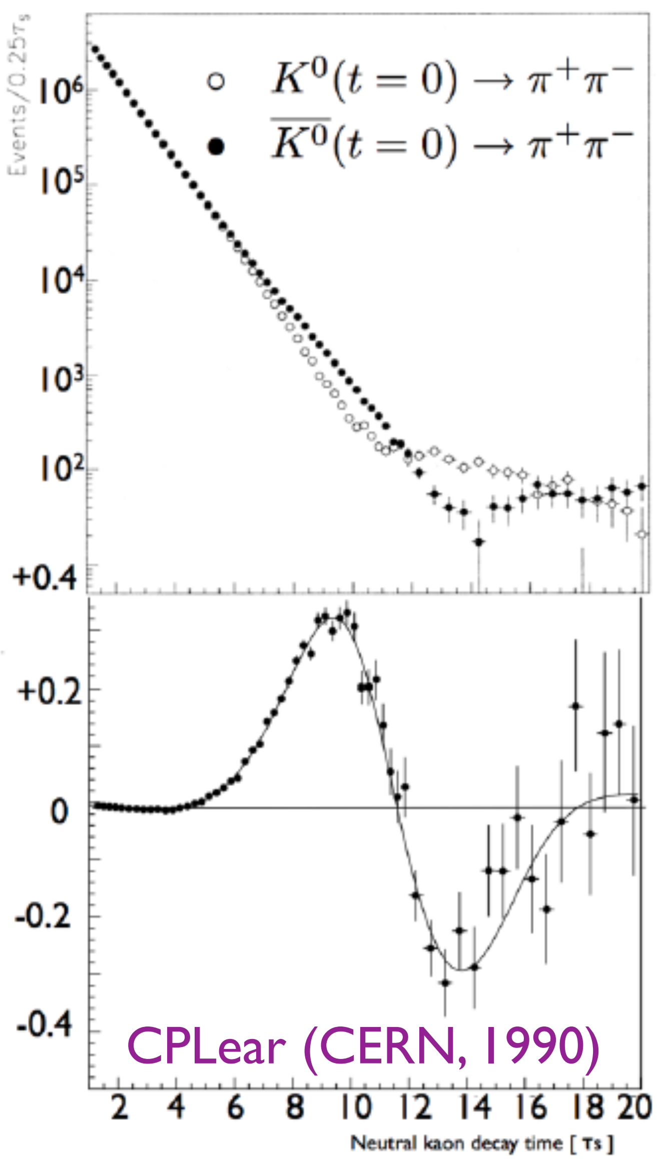
Origin of CP violation in the MS

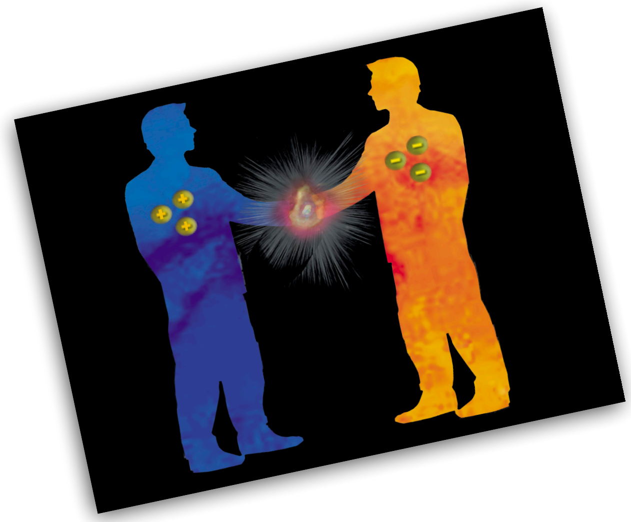
CP Violation

☛ B meson system
BABAR/Belle (years 2000), LHCb

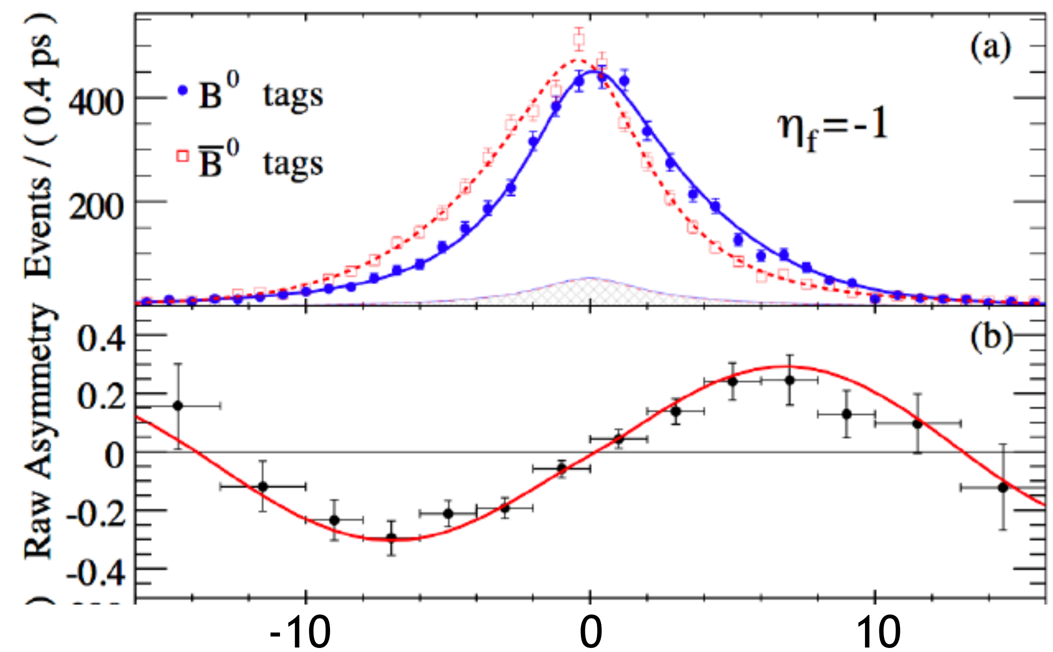
☛ neutral kaon system
(discovery : 1964)

- in flavour mixing
  (direct CP violation)



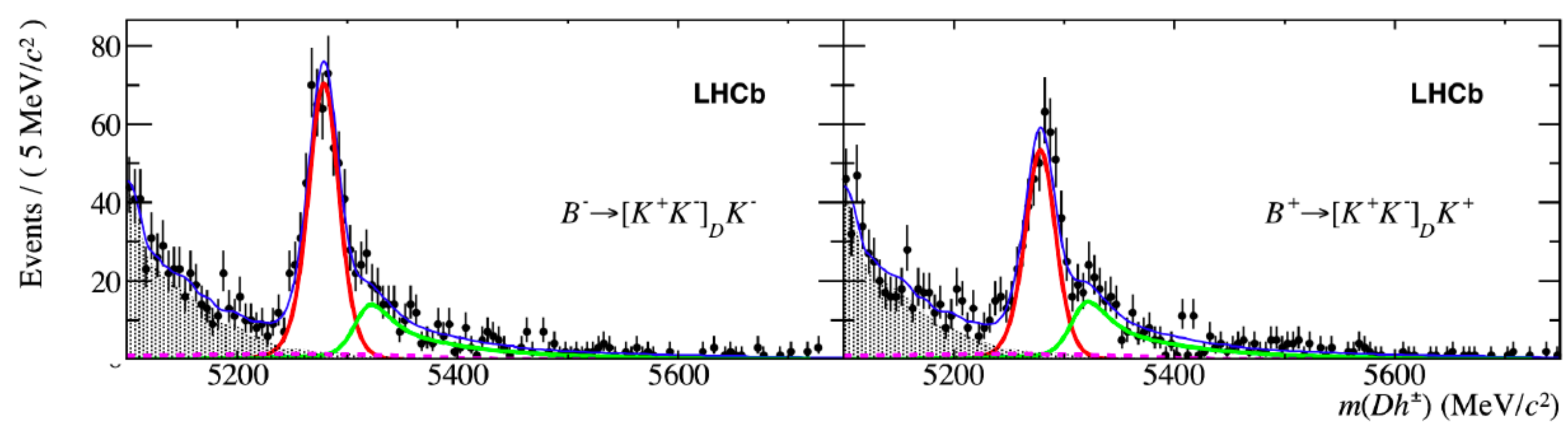


- in the interference mixing/decay
  (mixing-induced CP violation)



- in the decay
  (direct CP violation)

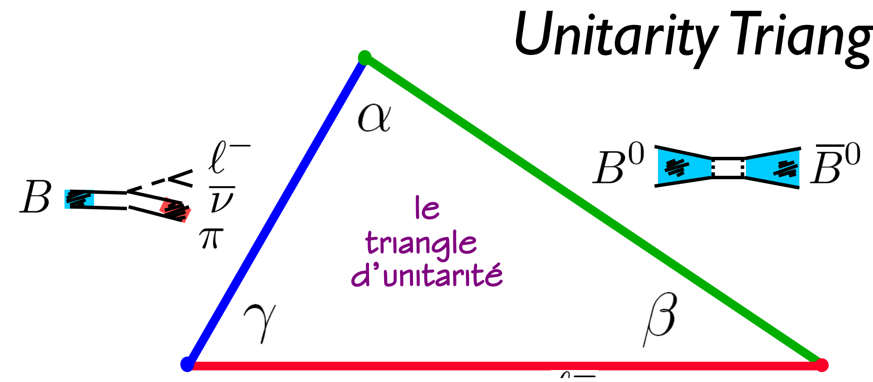
neutral kaons : NA48 (CERN, 1998)
B mesons : BABAR/Belle, LHCb



☛ charm meson system
LHCb (2019)

CP Violation

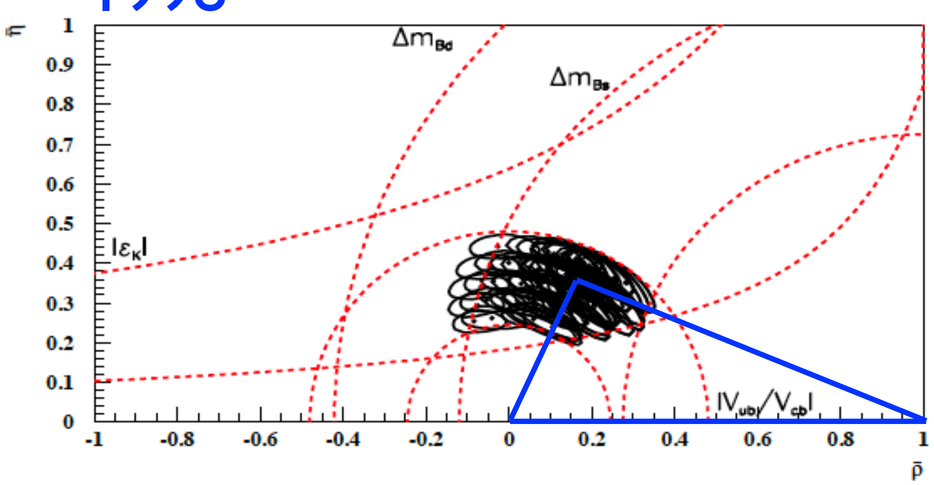
Test of KM model :
- *redundant* and *independent* measurements
- consistency of results



Experimentally
- length of sides

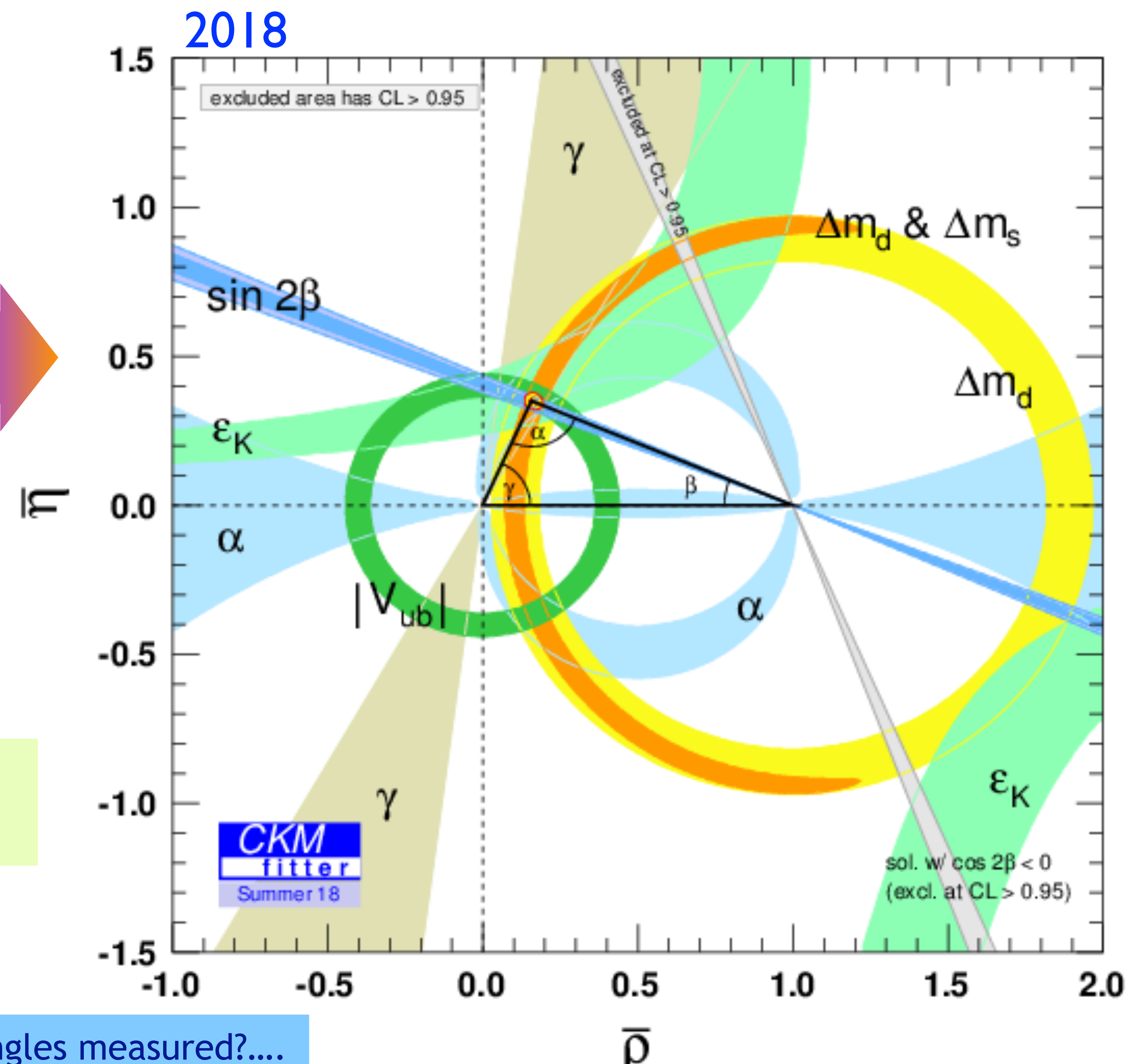
➪ constraints on the UT *apex*

1998



- years 2000 : BABAR and Belle
- since 2010 : LHCb
- 2020+ : LHCb and Belle-II

2018



Is CP violation in the quark sector sufficient to account for baryogenesis?

very very small Jarlskog invariant

$$J_{\rm CP}^{\rm CKM} = (3.0 \pm 0.2) \times 10^{-5}$$

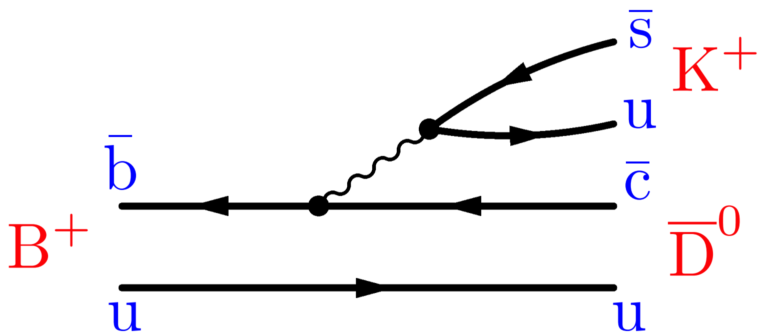
(see later)

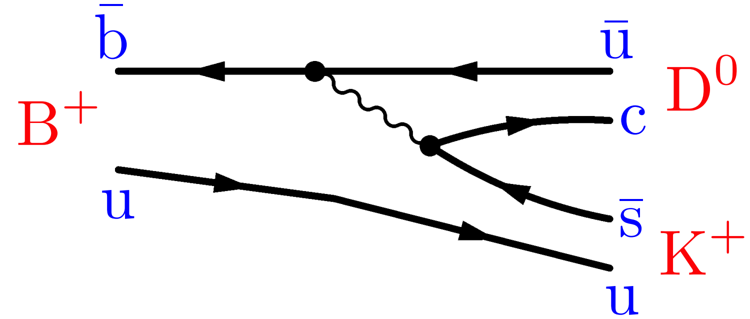
how are angles measured?....

Trees and Penguins

examples of interfering amplitudes
leading to CP violating effects

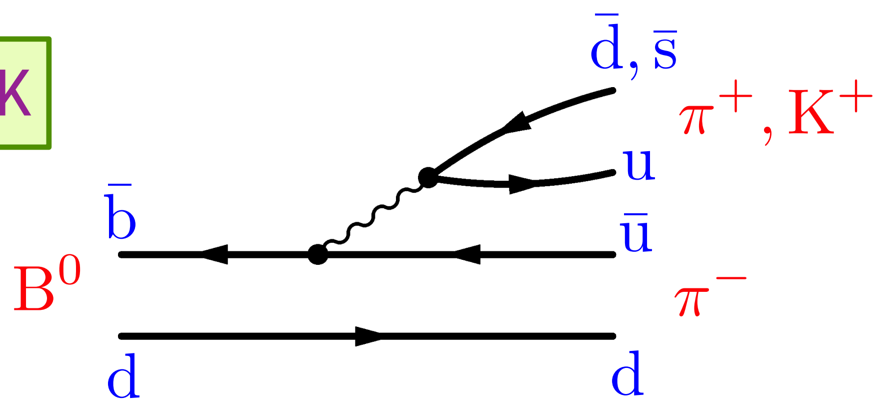
$B_u \to DK$

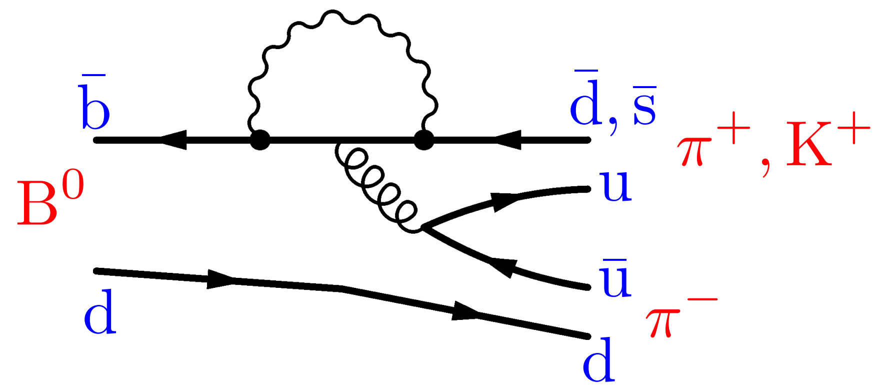




⇒ γ

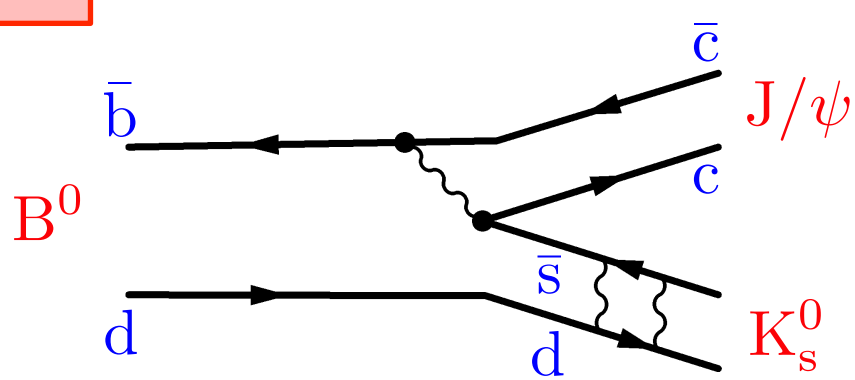
$B_d \to \pi K, KK$

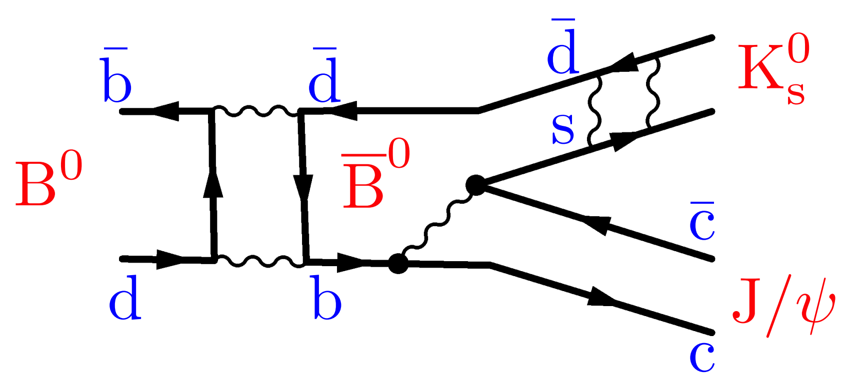




⇒ α, γ

$B_s \to J/\psi\ K_s$





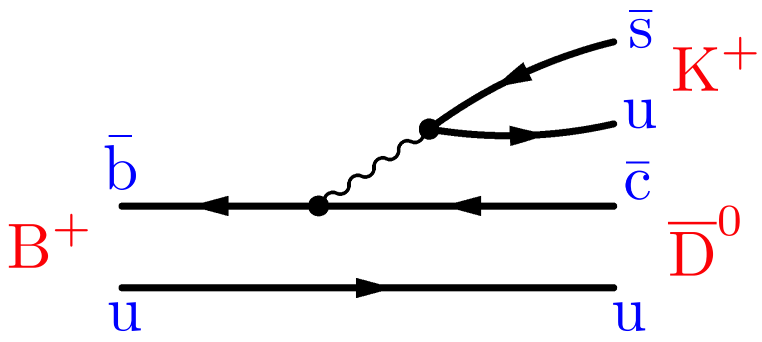
⇒ β

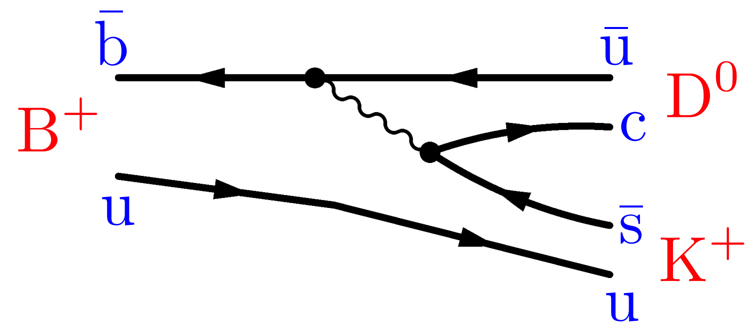
β = 22 deg

Trees and Penguins

examples of interfering amplitudes
leading to CP violating effects

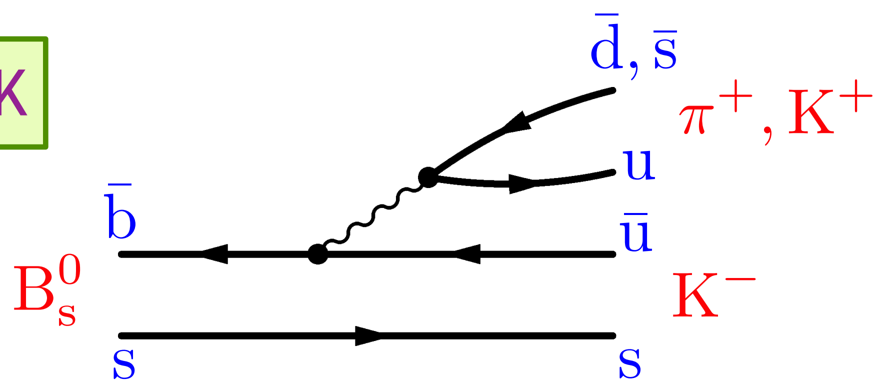
$B_u \to DK$

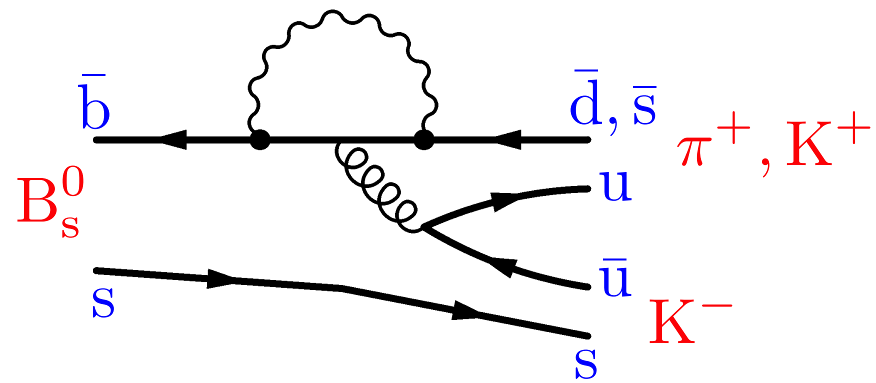




➠ γ

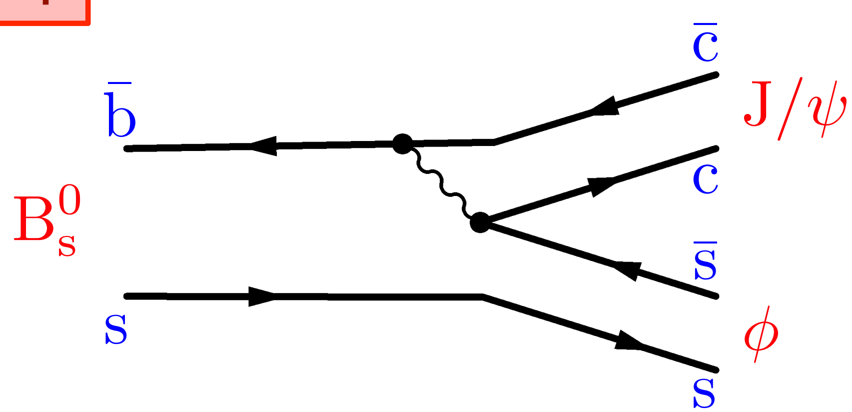
$B_s \to KK, \pi K$

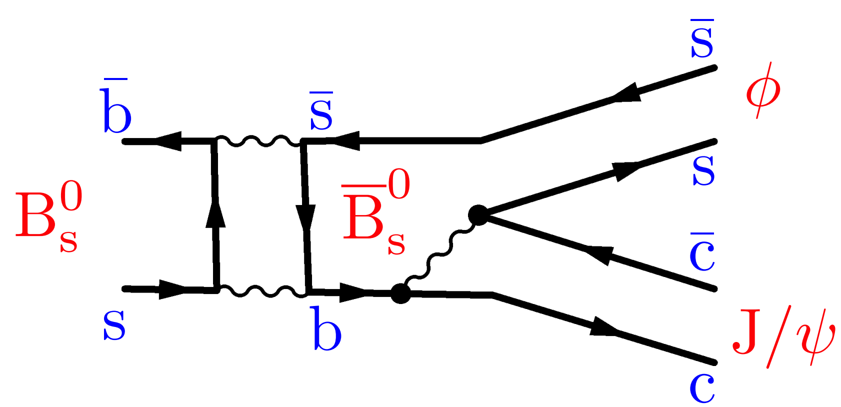




➠ α, γ

$B_s \to J/\psi\ \phi$



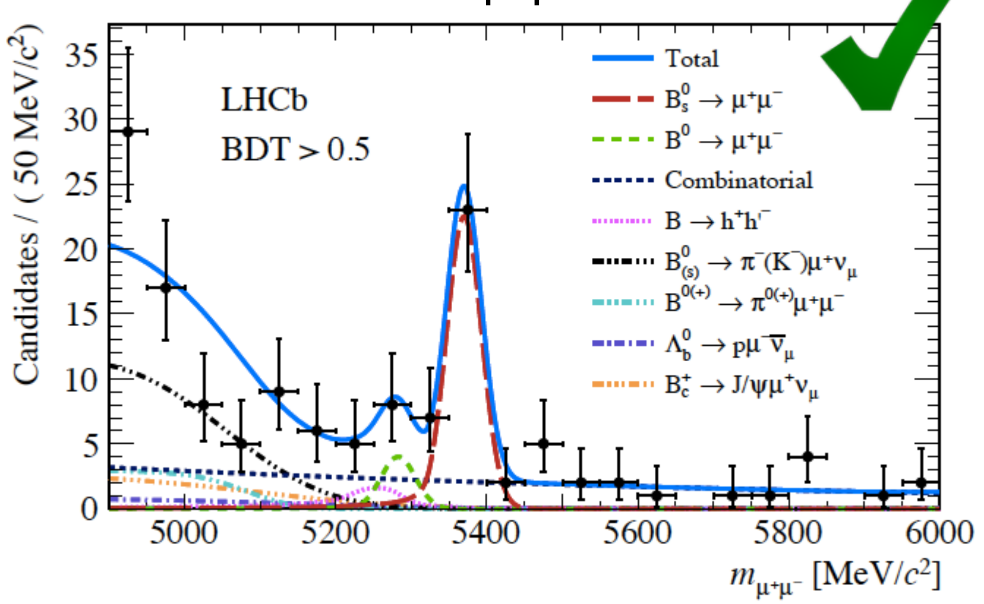


➠ ϕ_s

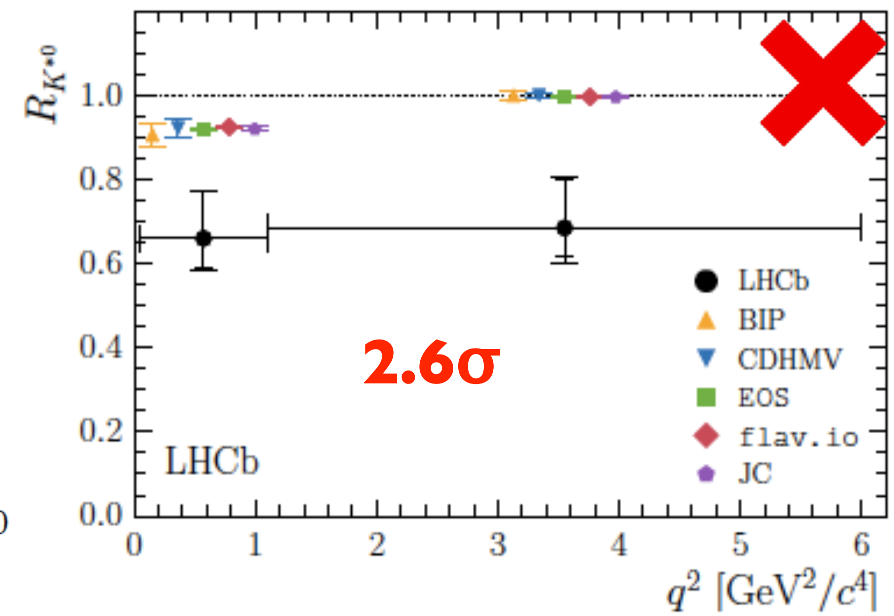
ϕ_s = 36 mrad

Anomalies in Flavour Physics

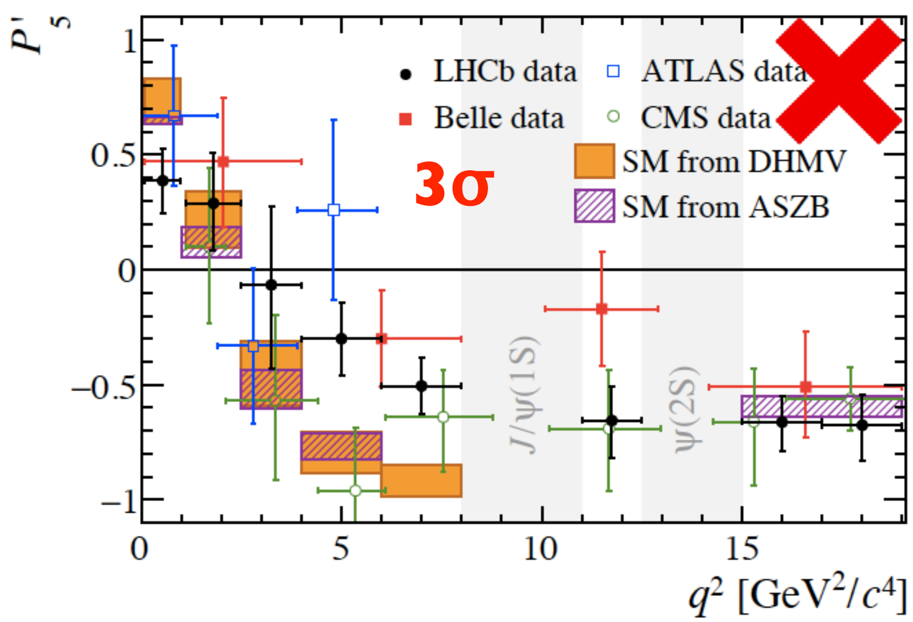
$B_s \to \mu^+\mu^-$



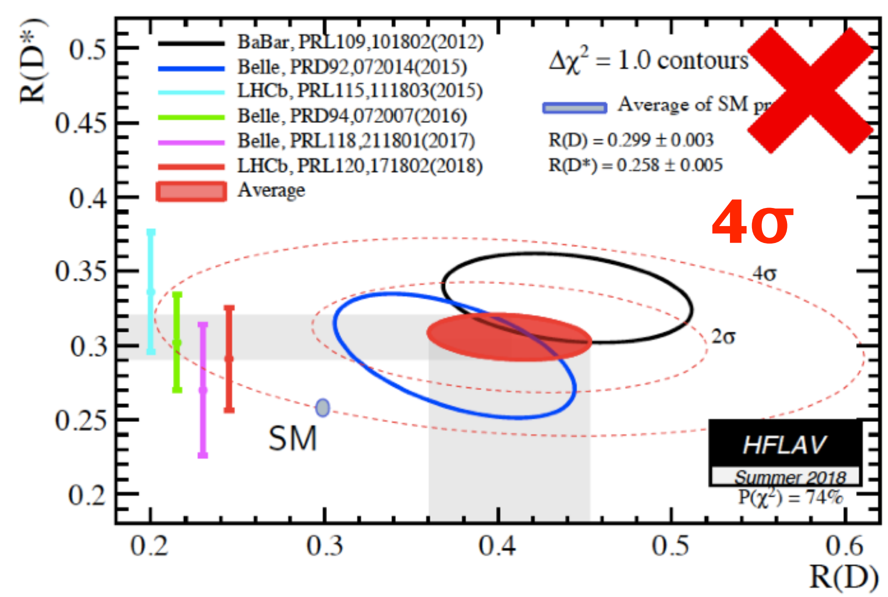
$R_{K^*} = B\to K^*\mu^+\mu^- / B\to K^*e^+e^-$



Distribution angulaire (P'₅) dans $B\to K^*\ell^+\ell^-$



$R(D^{(*)}) = B\to D^{(*)}\tau\nu / B\to D^{(*)}\mu\nu$



New physics in favour changing neutral currents (FCNC)?

Non-universality of leptonic flavour ?

Previous anomalies :

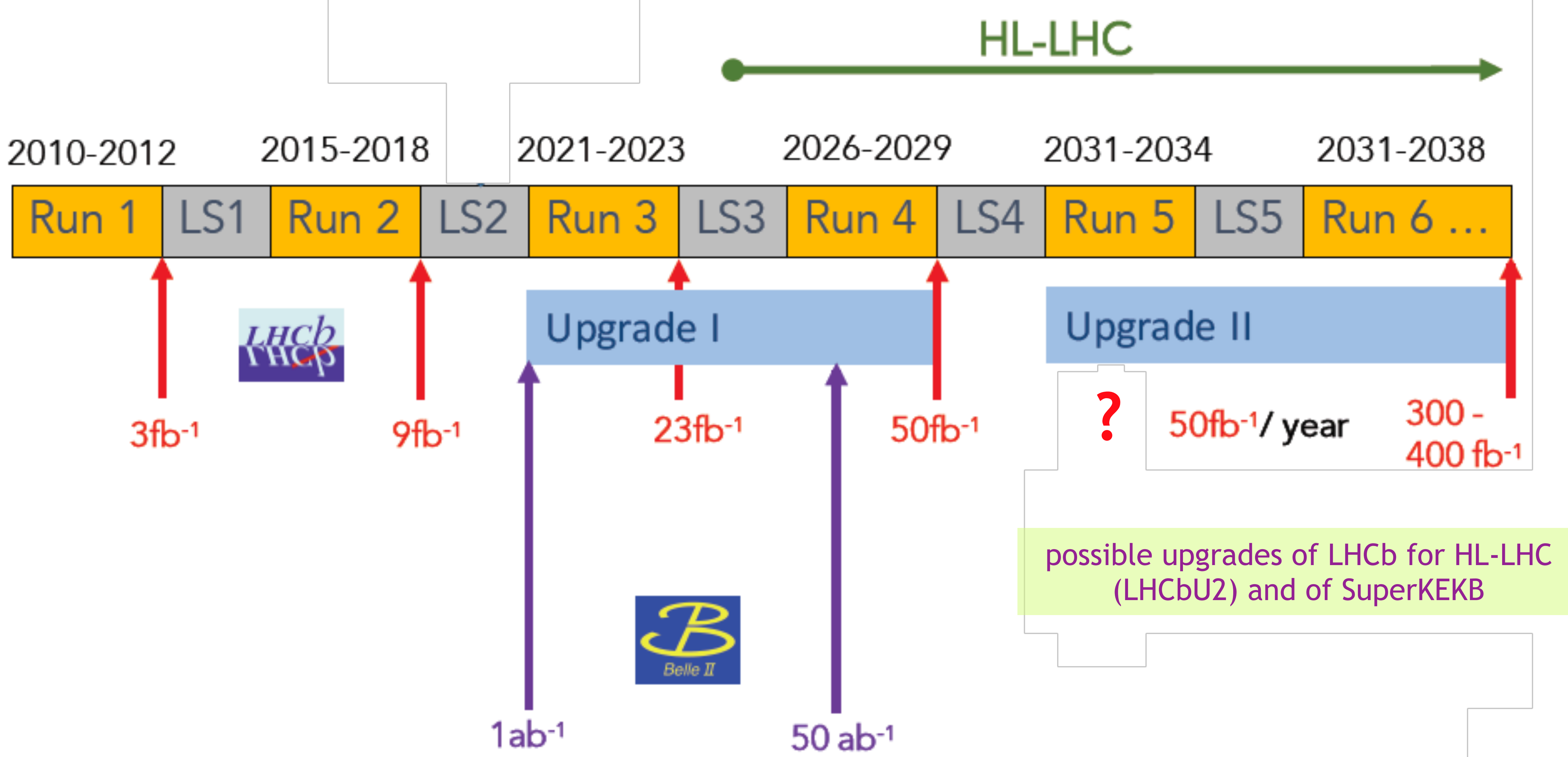
- tension between SLD/LEP LR/FB asym. (2.5σ)
- tension in N_ν (2σ)

and :

- μ(g-2) anomaly (4σ)
- suppression of Bs → $\phi\ell^+\ell^-$ (3σ)
- tensions between inclusive and exclusive $|V_{ub}|$ and $|V_{cb}|$ (3σ)

Flavour anomalies will be tested with high confidence at LHCb and BELLE-2 in the 5 years to come

Prospects in Flavour Physics



Belle-II ➠ Belle-III ?

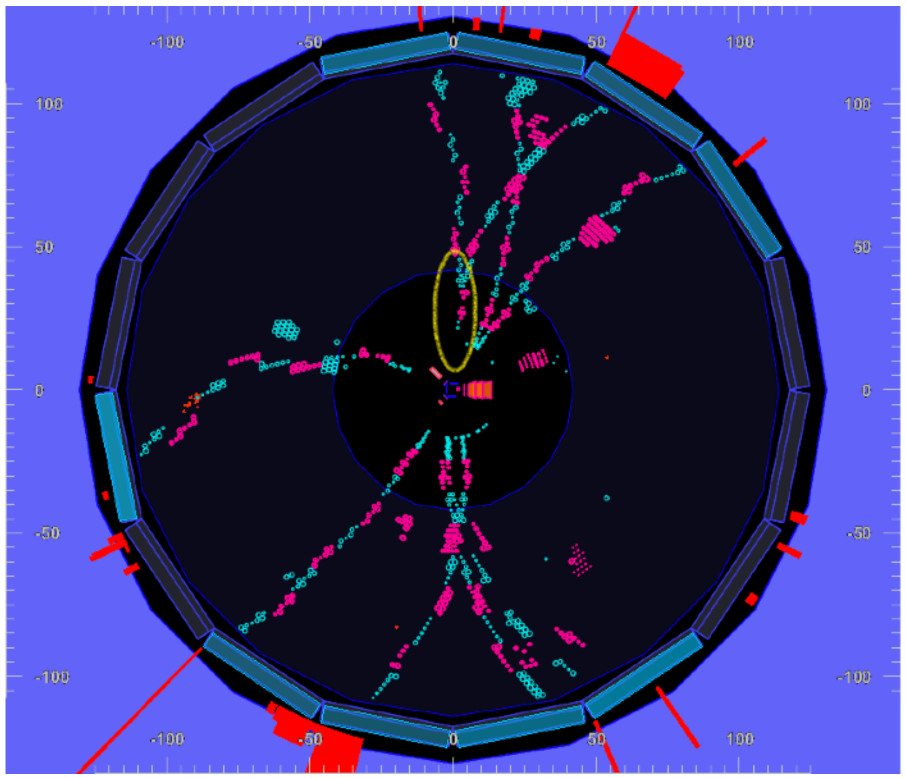
- goal = × 5 in peak luminosity
- detectors at $\mathscr{L}$ = 4 × 10^{36} $cm^{-2}s^{-1}$?
- physics case?

Z factories

- Peta-Z: FCC-ee, CEPC
- Tera-Z: ILC, CLIC (radiative return)

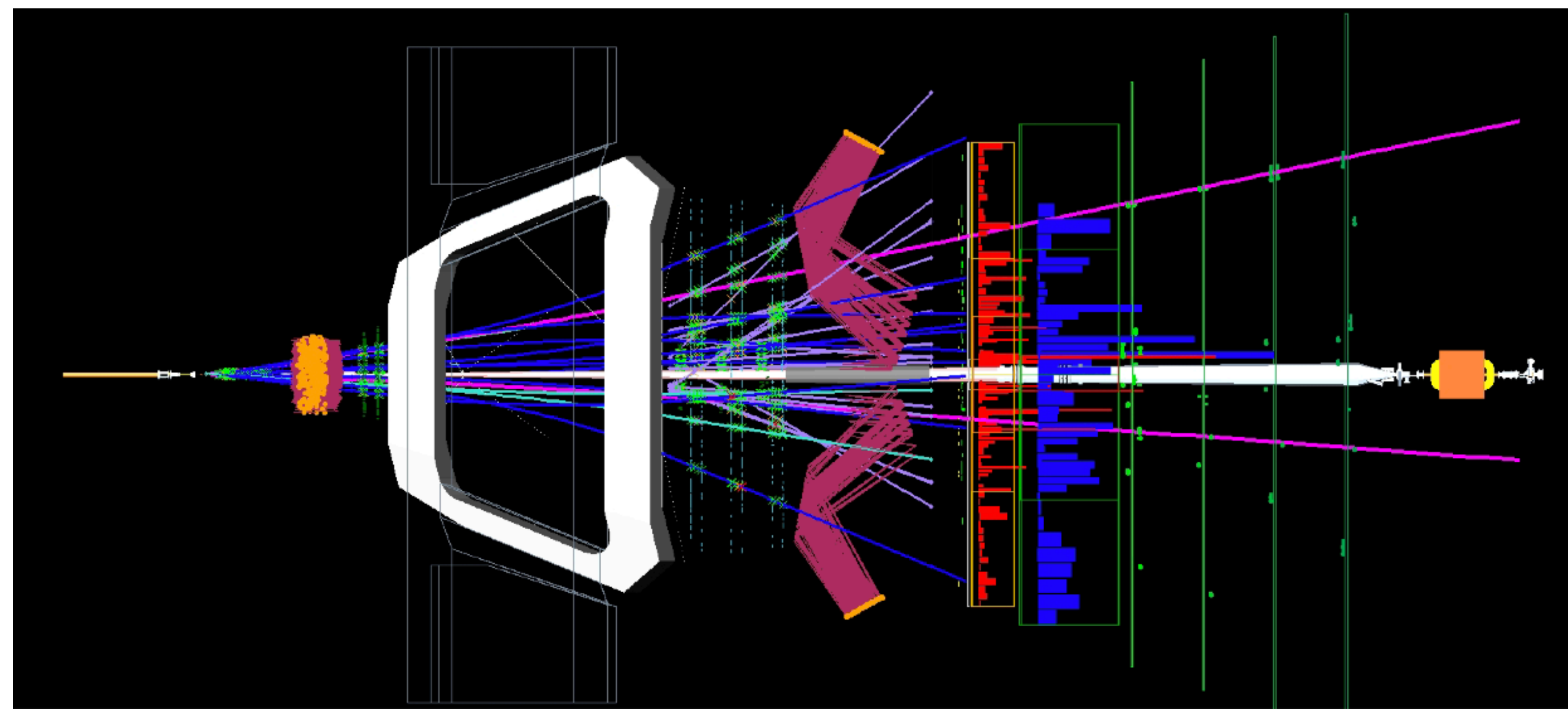
Complementarity in Flavour Physics

Belle-II



- fully efficient trigger on B events
- CP eigenstates with B mesons
- modes with neutral particles
- inclusive measurements

LHCb

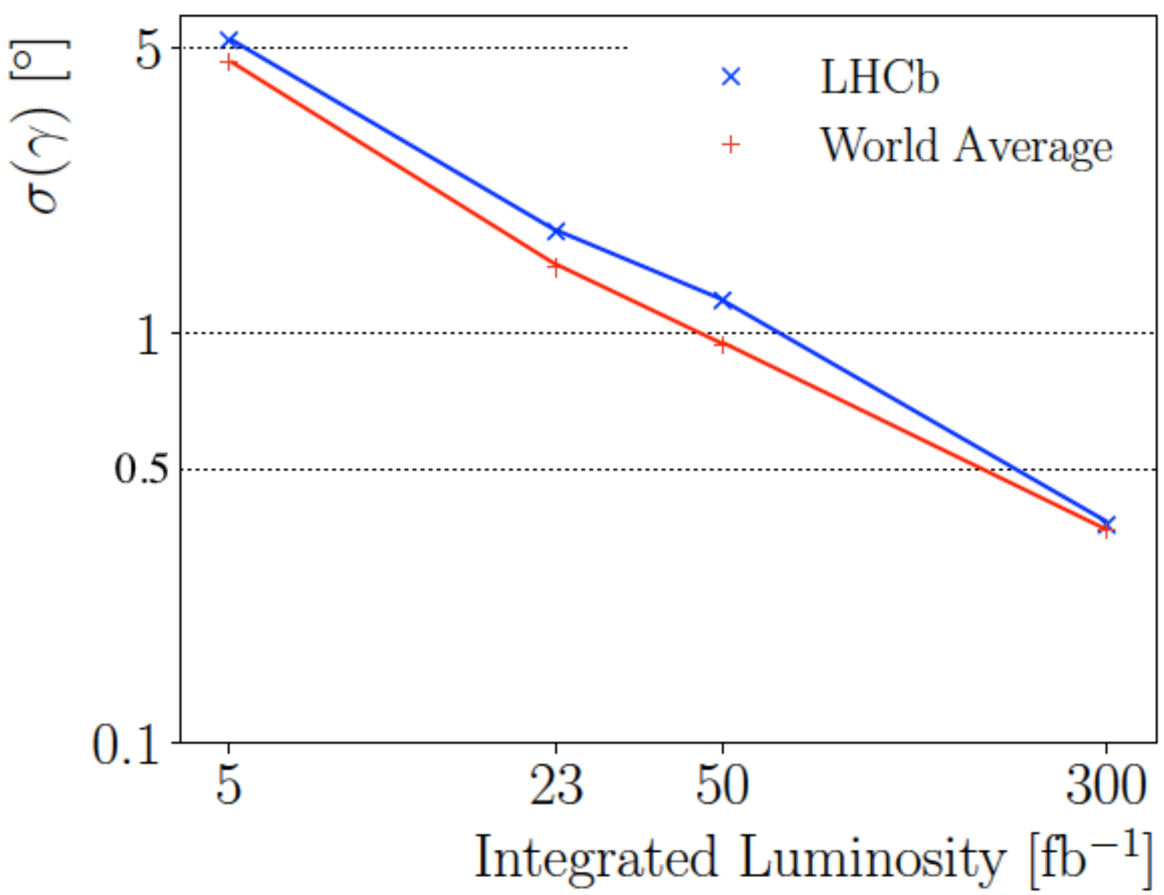


- access to all B hadrons
- fully-charged final states
- sensitivity to ultra-rare decays

☛ many dedicated flavour physics projects
- kaon physics
- lepton flavour violation
- muon g–2
- etc.

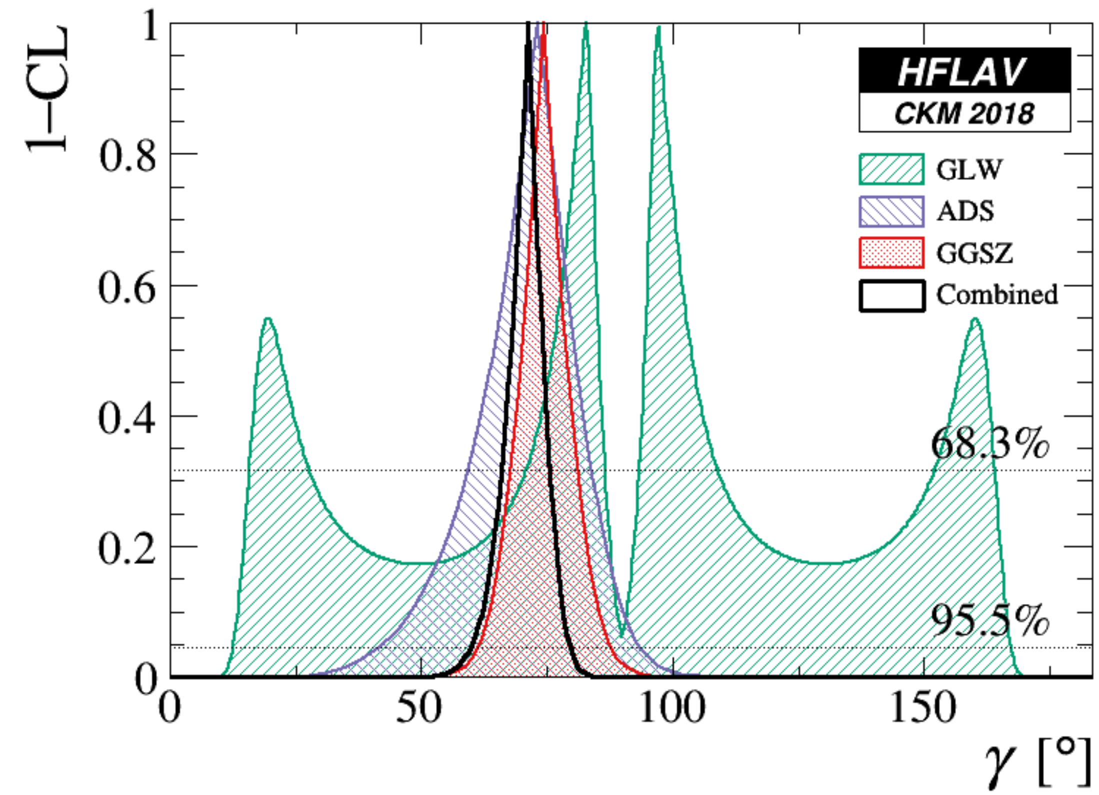
Measurement of Angle γ

from interference between
b → c and b → u tree-level transitions
➠ B → DK decay modes



$\gamma = (71.1^{+4.6}_{-5.3})^\circ$

dominated by LHCb

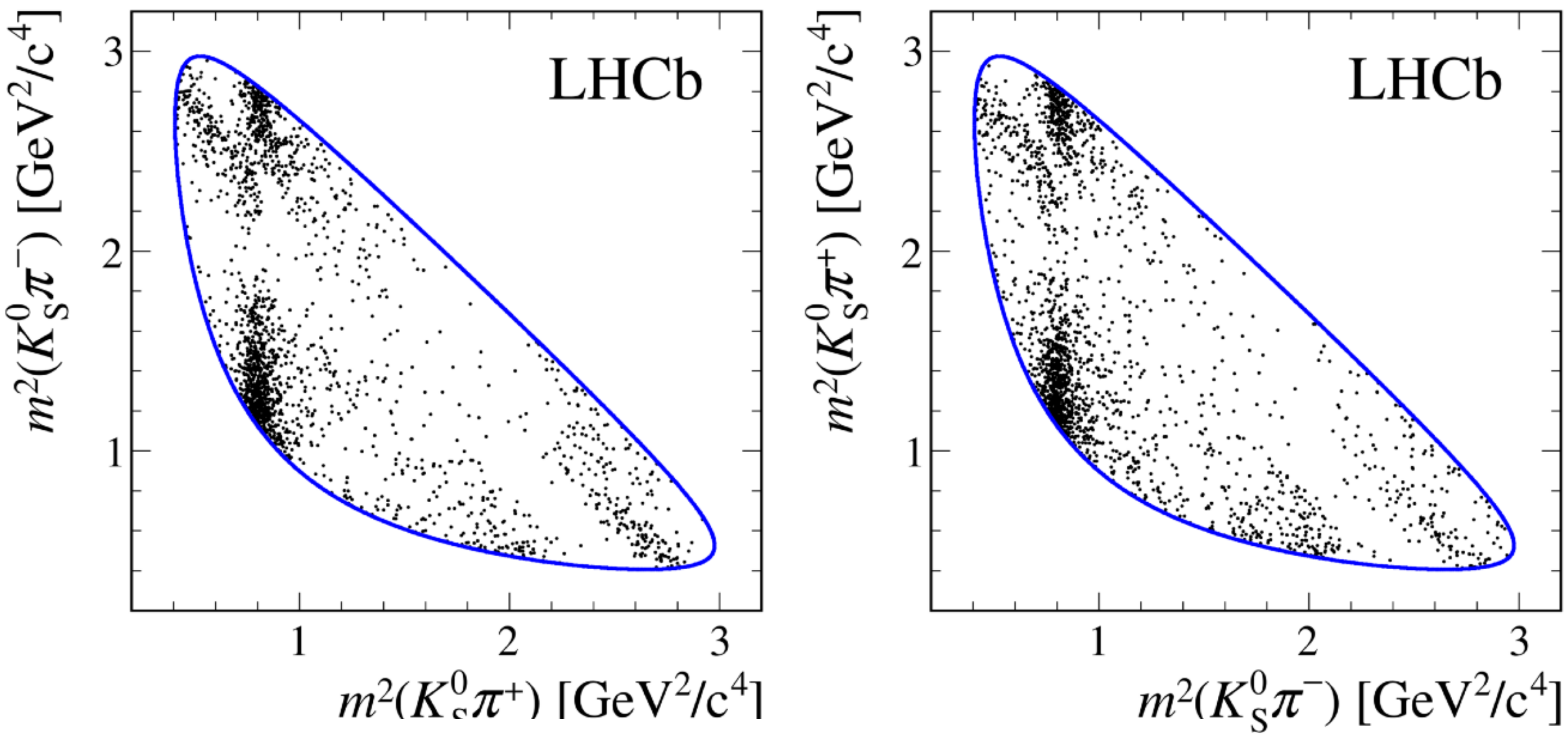


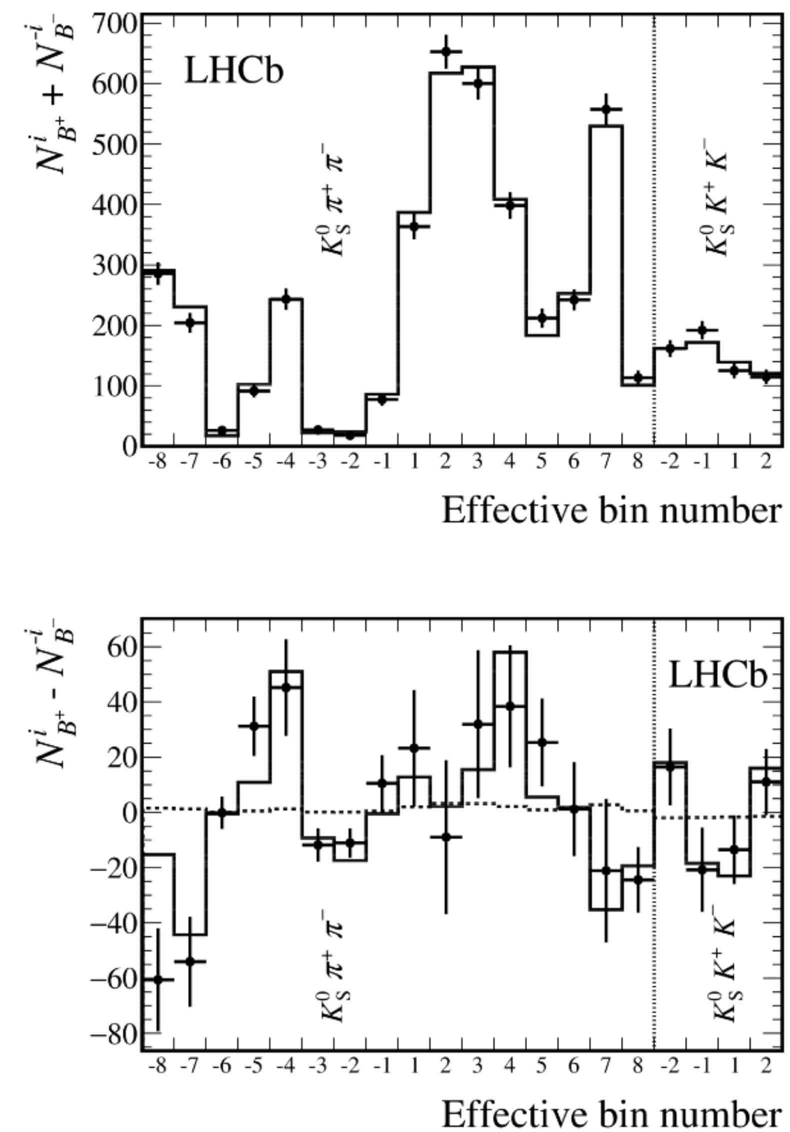
2030: LHCb-U1 (23 fb^{-1}) ≈ Belle-II ➠ 1.5 deg
2040: LHCb-U2 (300 fb^{-1}) ➠ < 0.5 deg

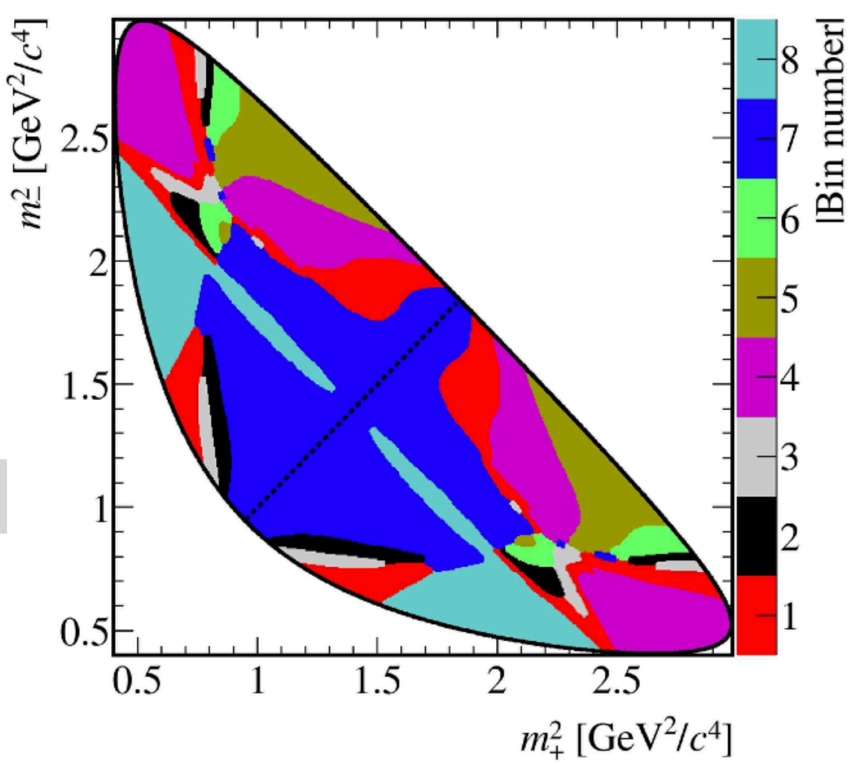
several methods, the most sensitive being ADS and GGSZ

Angle γ with GGSZ Method

GGSZ method







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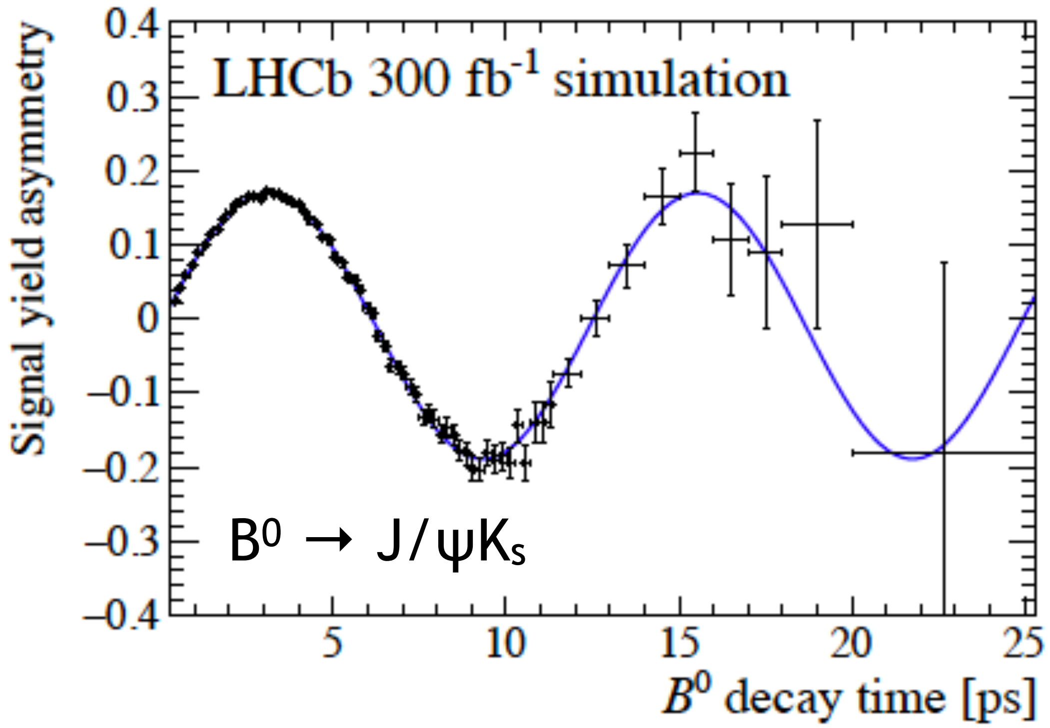
☛ Dalitz analyses necessitate high statistics

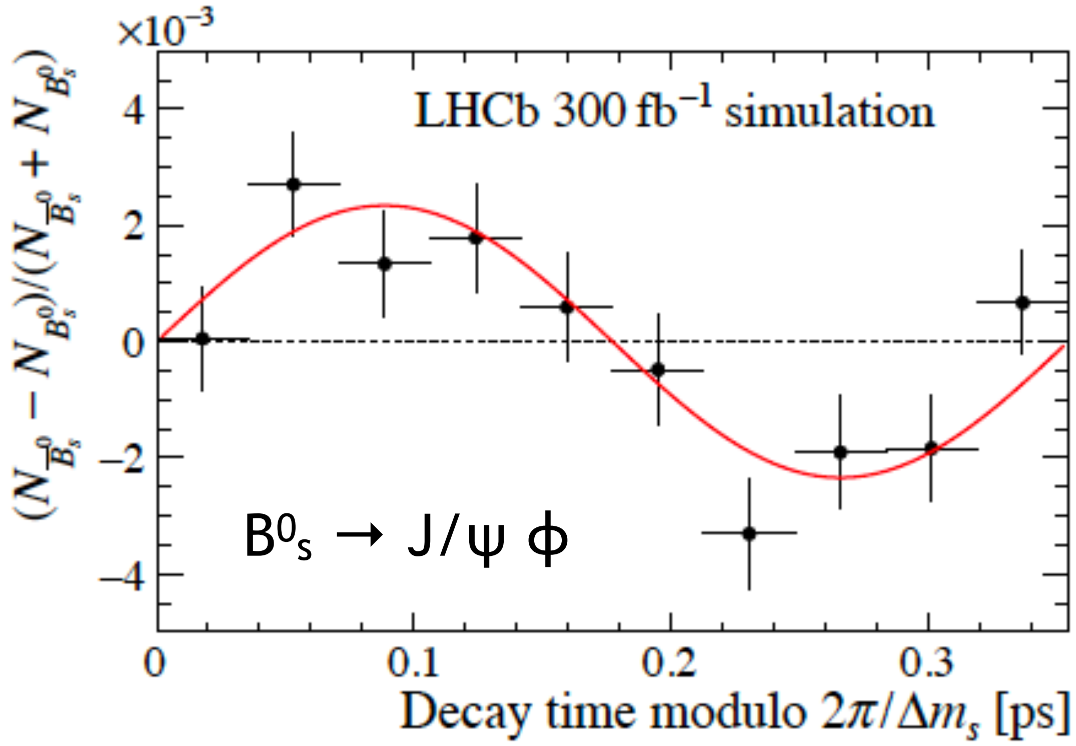
☛ ultimately, a precise knowledge of the D meson strong phases will be necessary

- importance of tau-charm factories (e.g., BES-III)

CP Violation in the Interference

Time-dependent CP violating asymmetries with 300 fb−1 of LHCb data





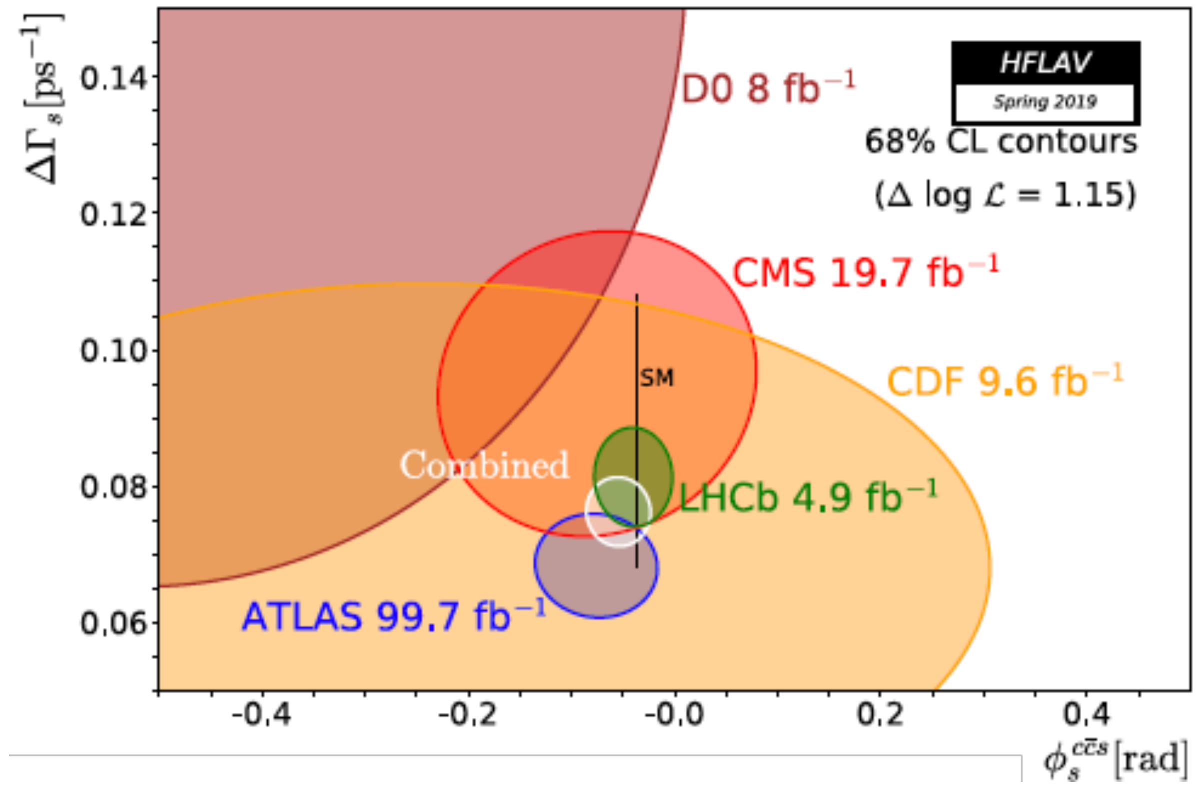
CP Violation in the Interference

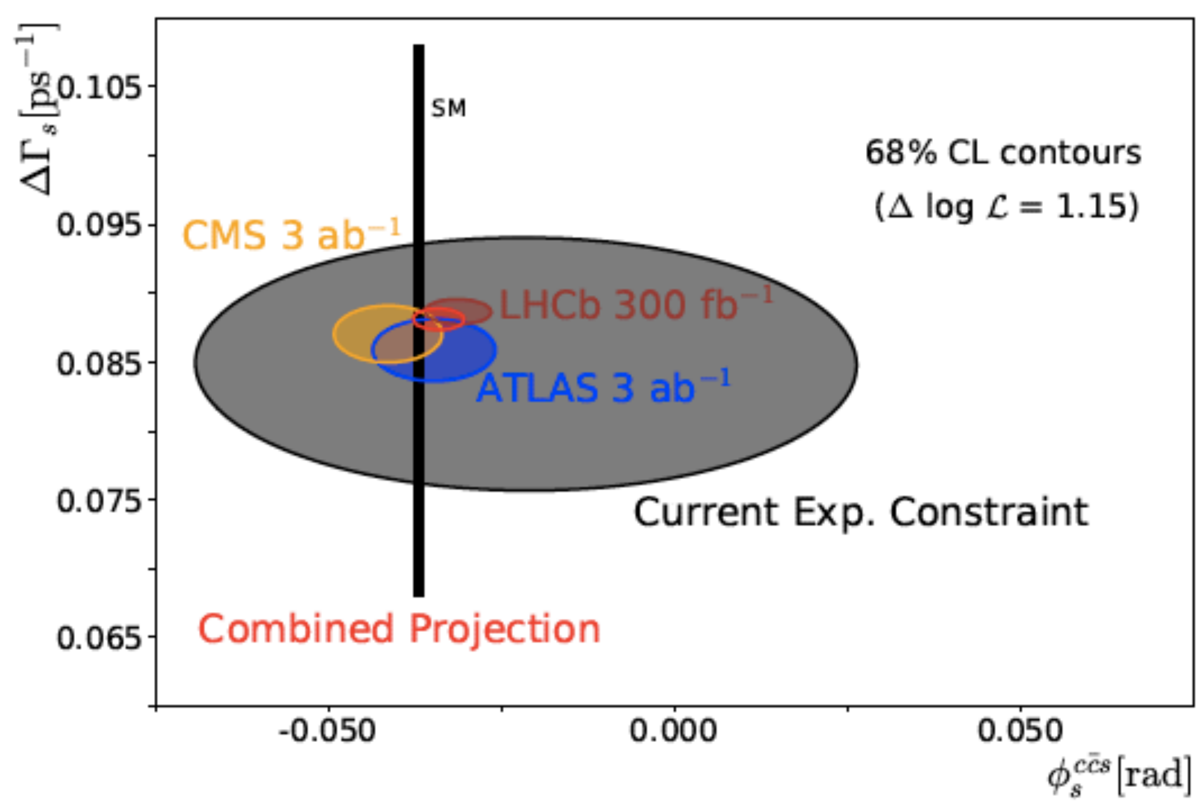
B_d system ➟ sin 2β
B_s system ➟ sin 2ϕ_s

mostly $B_s \to J/\Psi\ \phi$

needs
- initial B tagging
- decay time measurements
- angular analysis

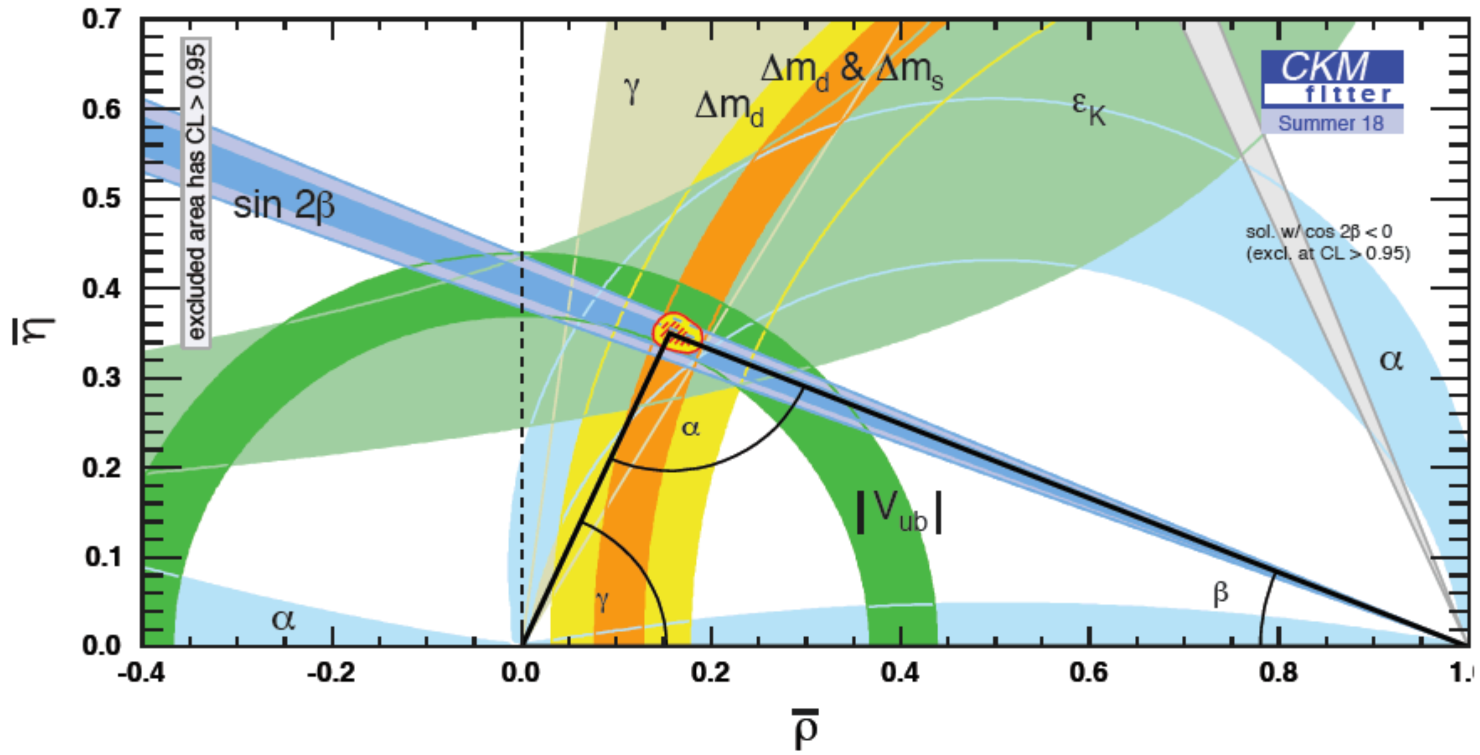
projections assume that the tagging performance can be maintained at HL-LHC



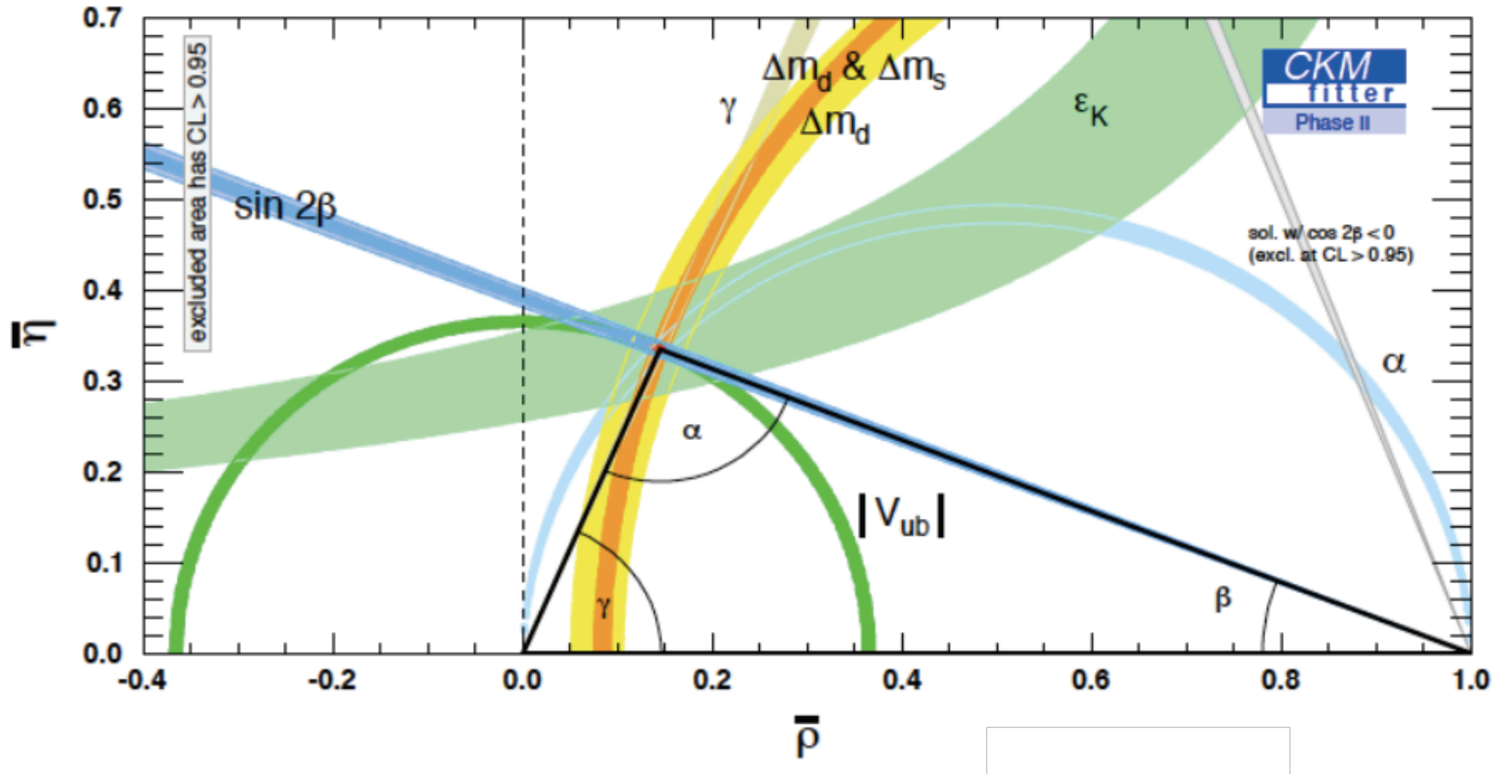


Ultimate Test of the KM Paradigm

2018



2035?

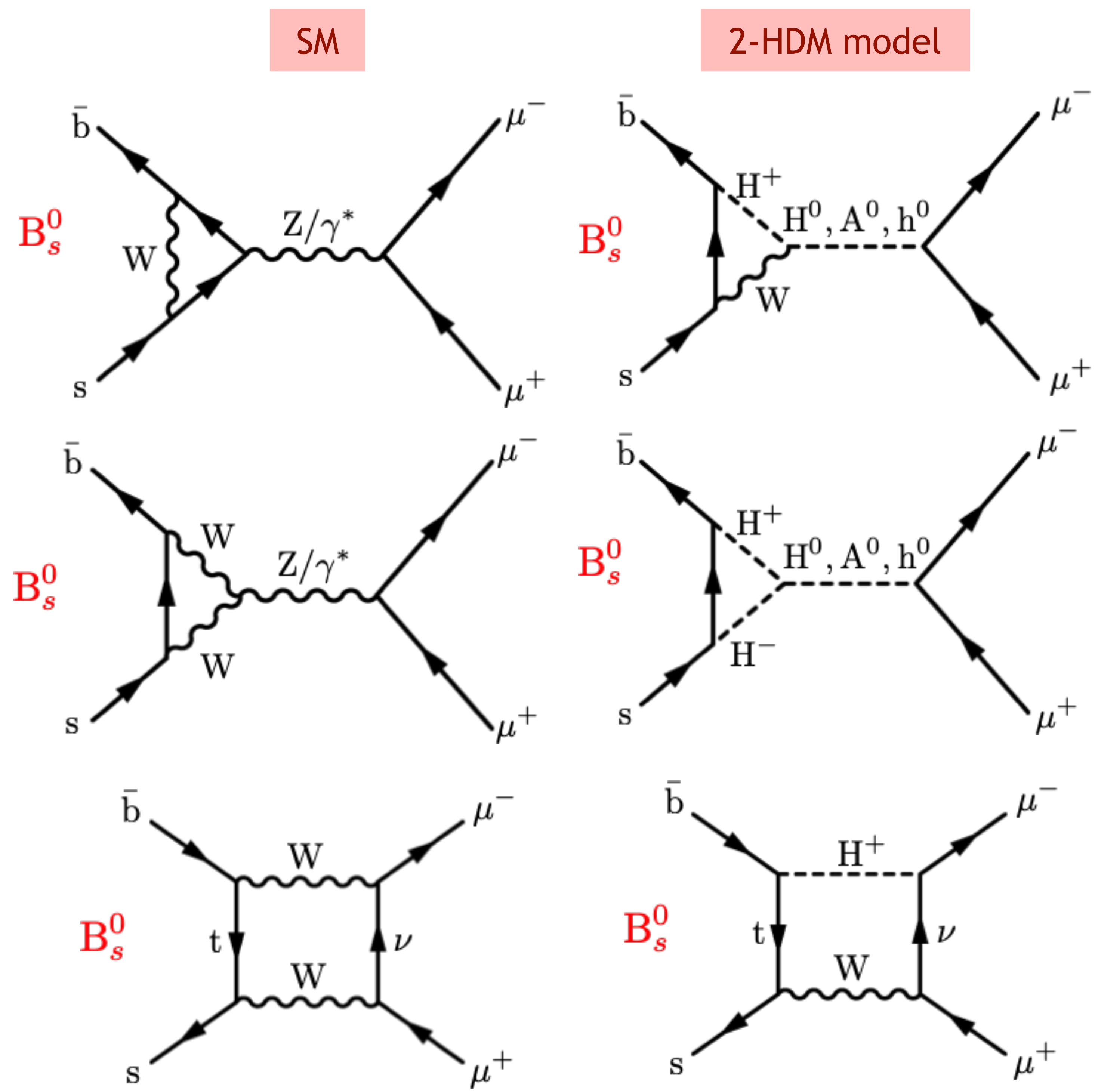


LHCb Upgrade-II
arxiv:1808.08865

$B_s^0 \to \mu\mu$

Very rare decay in the SM
(Cabibbo- and helicity-suppressed)

- very sensitive to new physics (extended Higgs sector, VQ)
- clean experimental signature

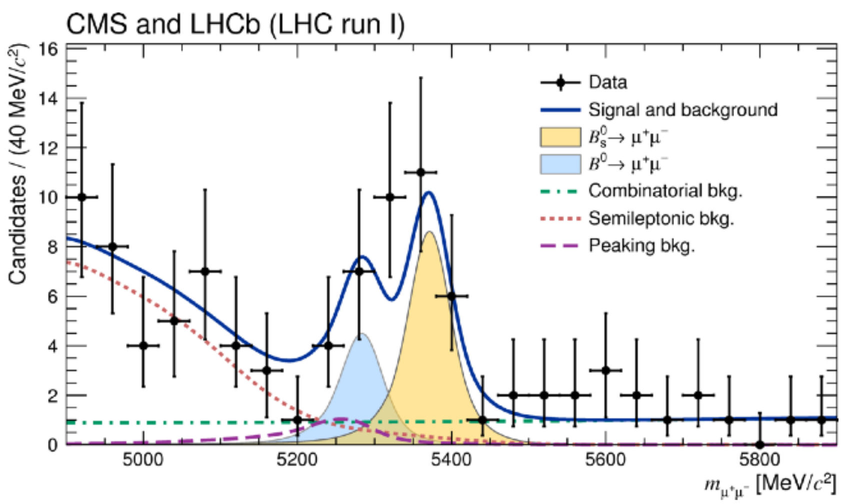


☛ Theory SM: limited by $|V_{cb}|$

- $B(B_s^0 \to \mu\mu) = (3.7 \pm 0.3) \times 10^{-9}$
- $B(B_d^0 \to \mu\mu) = (1.1 \pm 0.1) \times 10^{-10}$

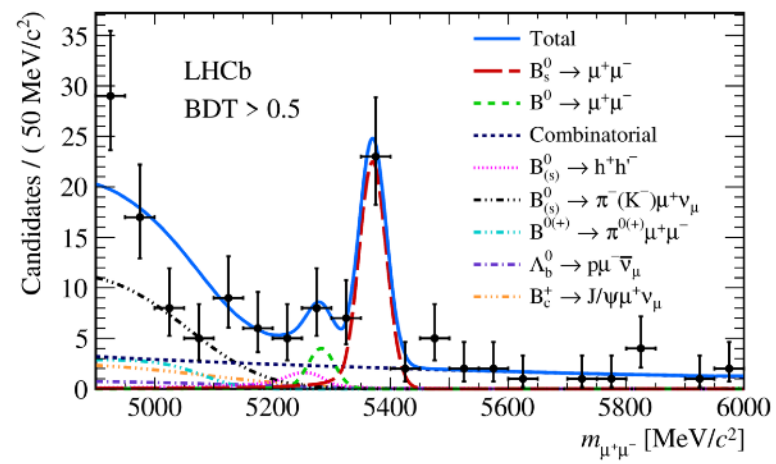
$B_s^0 \to \mu\mu$

LHCb+CMS Run-1



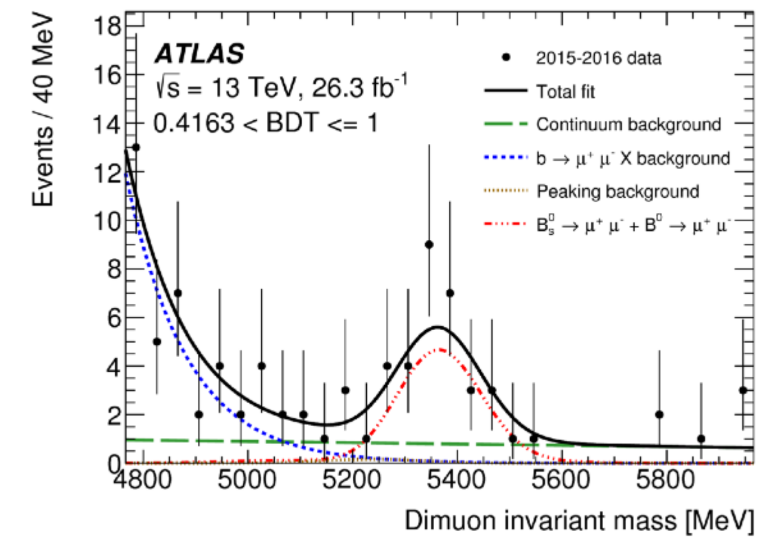
Nature (2015) 14474

LHCb 2016

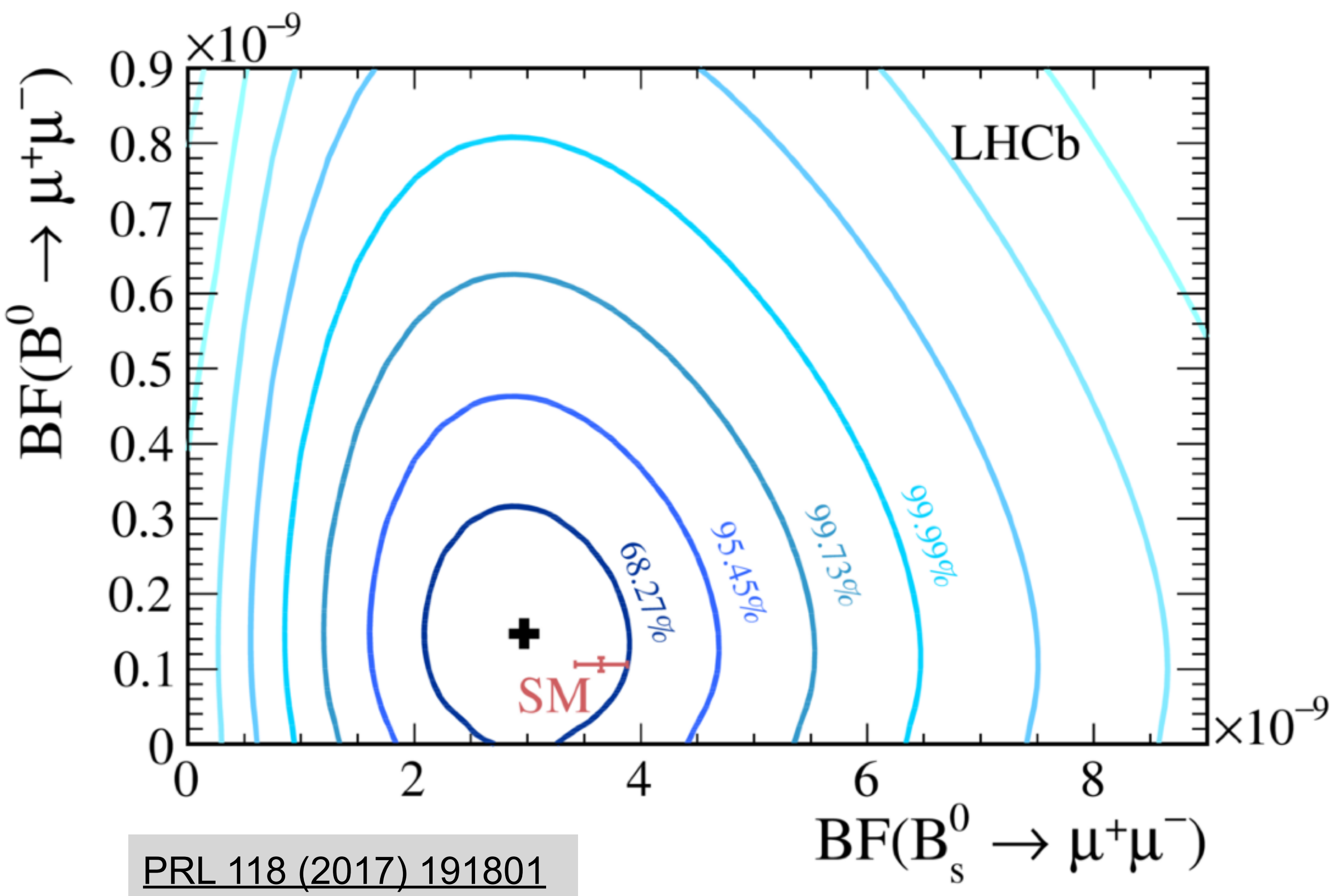


PRL 118 (2017) 191801

ATLAS 2016



JHEP 04 (2019) 098



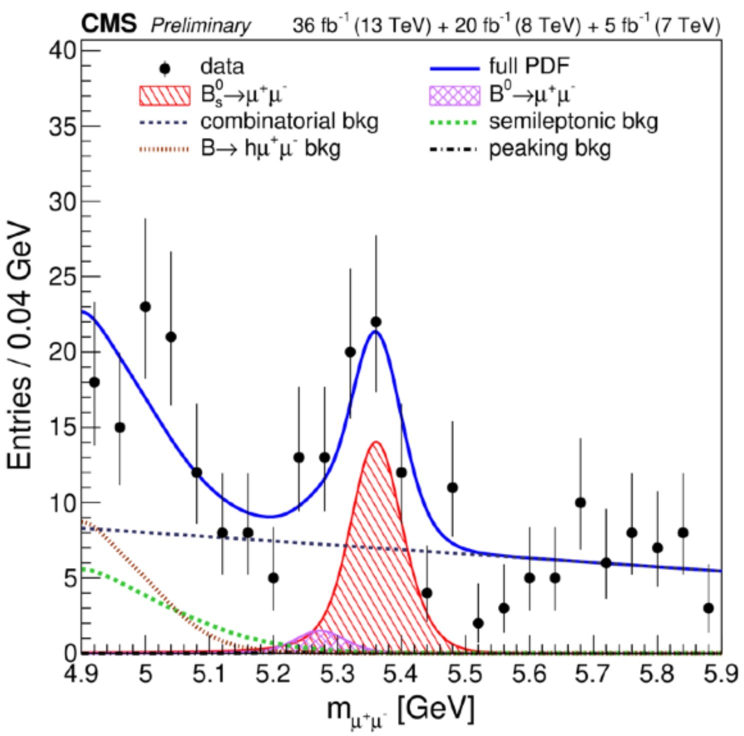
PRL 118 (2017) 191801

- ☛ Bs → μμ decay established at >6σ by LHCb+CMS (Run-1)
- now 7.8σ in LHCb and 5.6σ in CMS
- ☛ Measurement limited by f_s/f_d
- expect improvements from lattice QCD

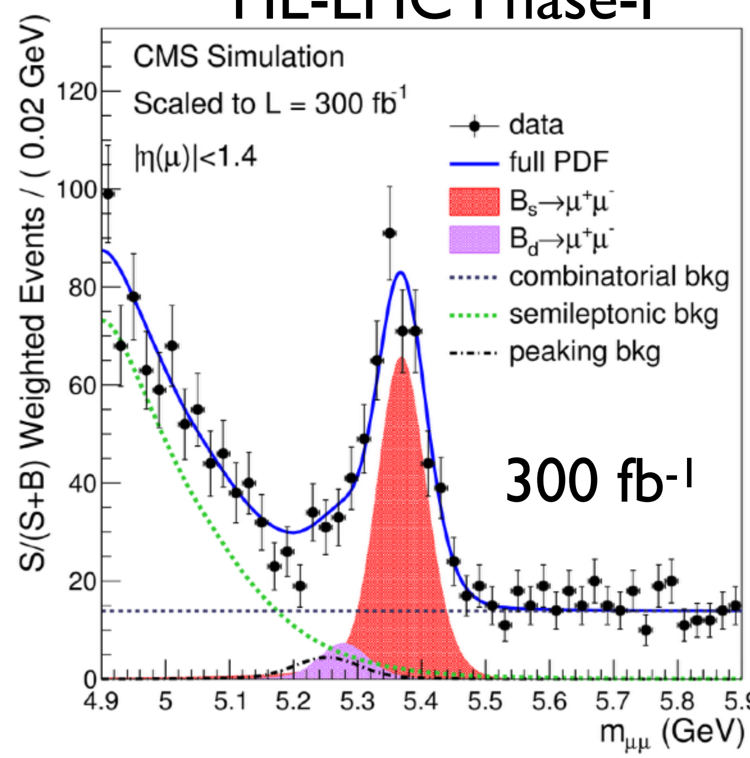
$B_s^0 \to \mu\mu$

Importance of the Phase-II tracking improvements for precision flavour physics

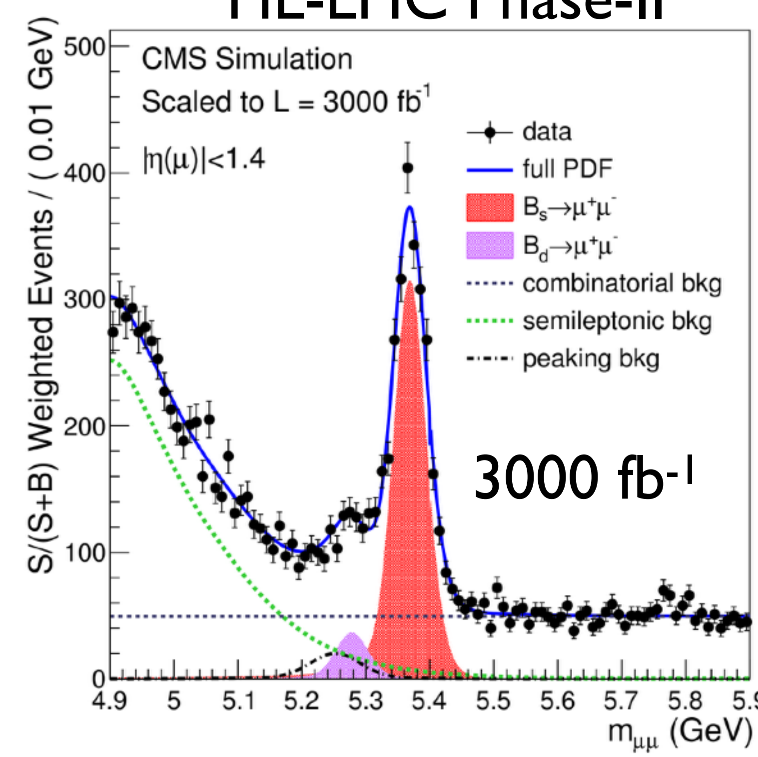
CMS 2016

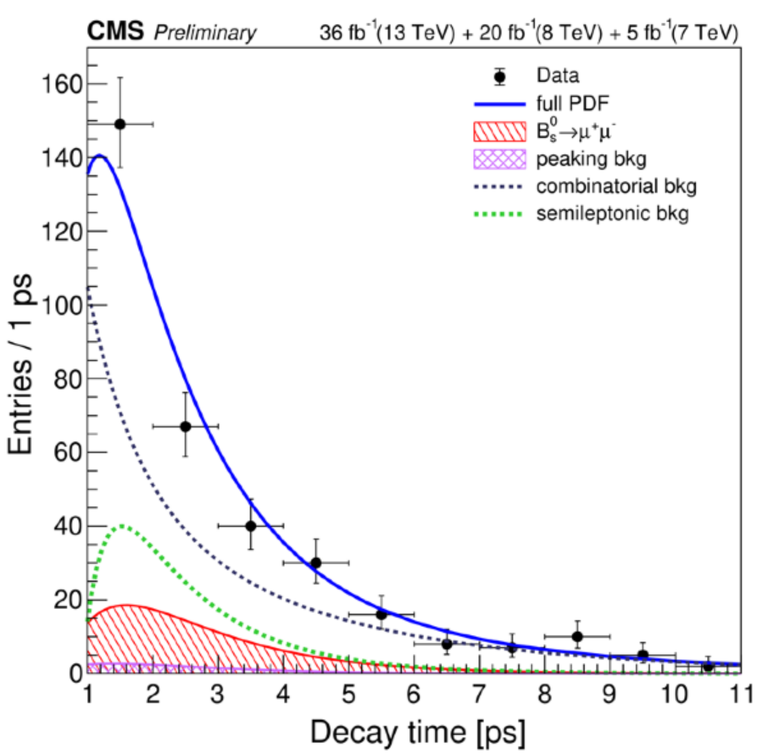


HL-LHC Phase-I



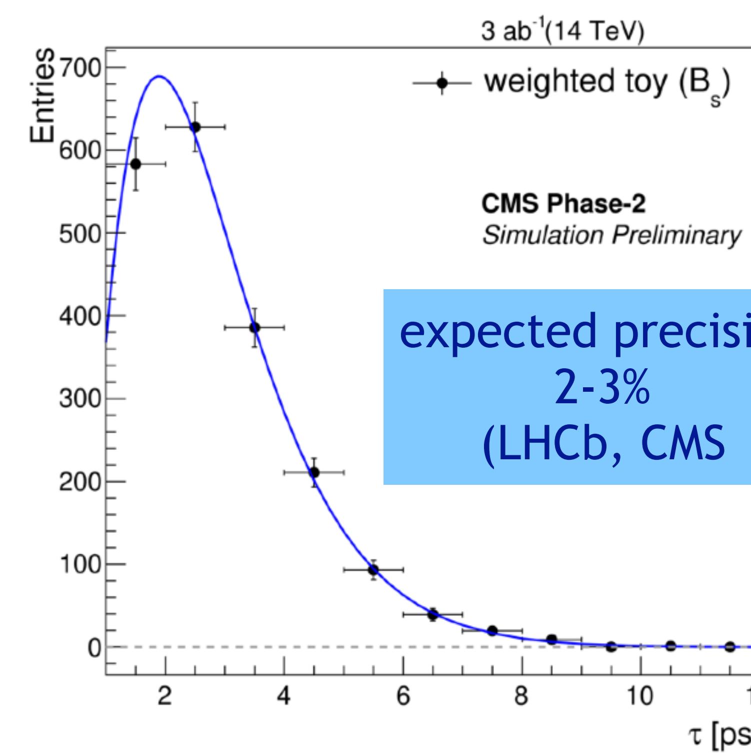
HL-LHC Phase-II





The branching fraction measures the difference between LH and RH couplings
the LH/RH coupling can be lifted by an effective lifetime measurement

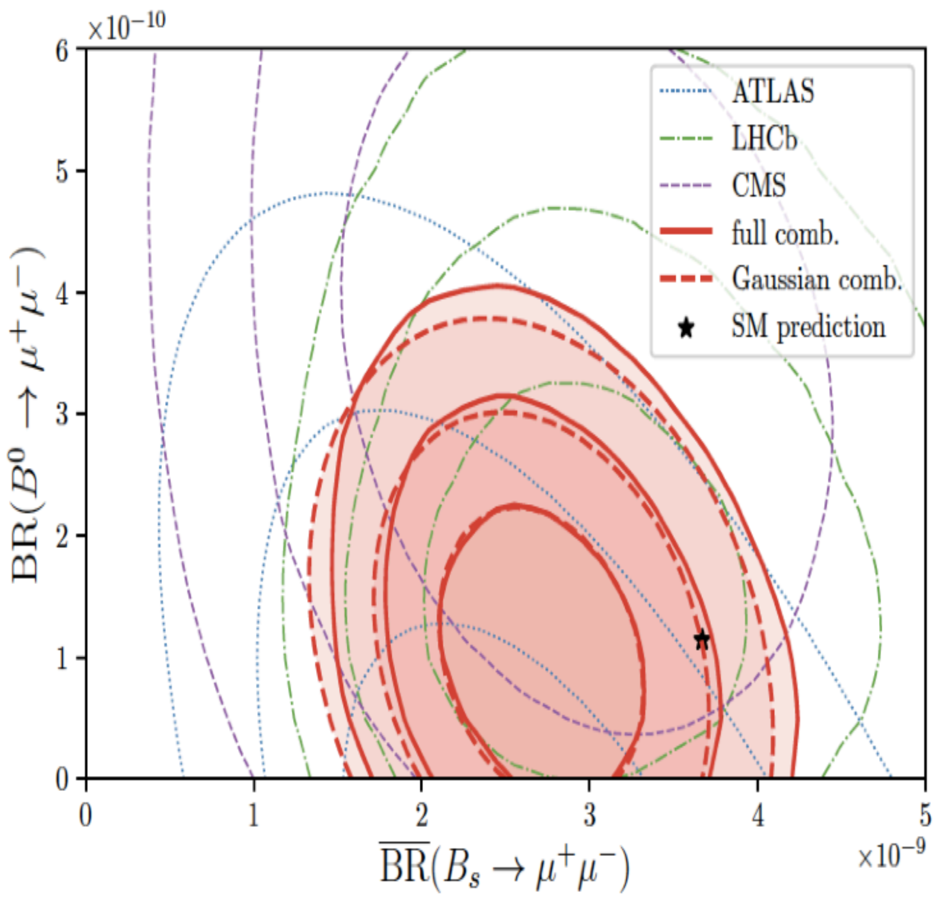
With 300 fb⁻¹, LHCb expects 100 perfectly tagged events for time-dependent CP measurement

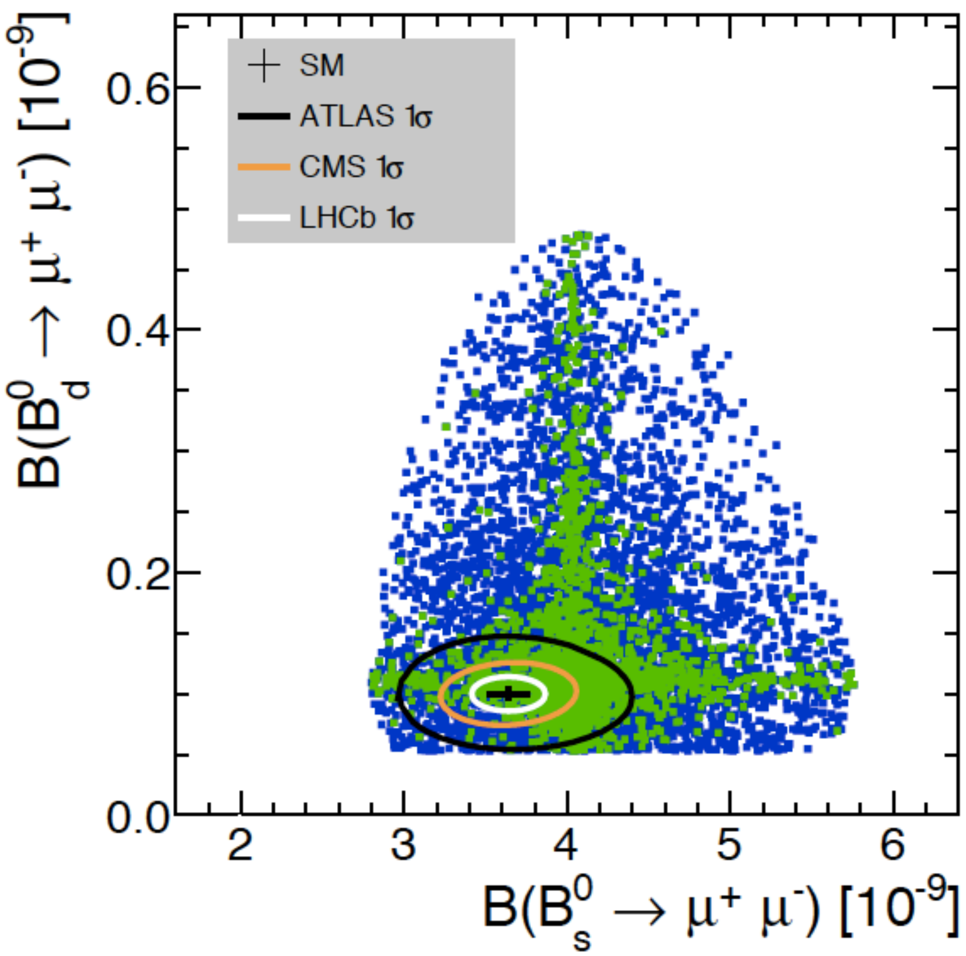


expected precision 2-3% (LHCb, CMS)

CMS-PAS-BPH-16-004

$B_{s,d}^0 \to \mu\mu$



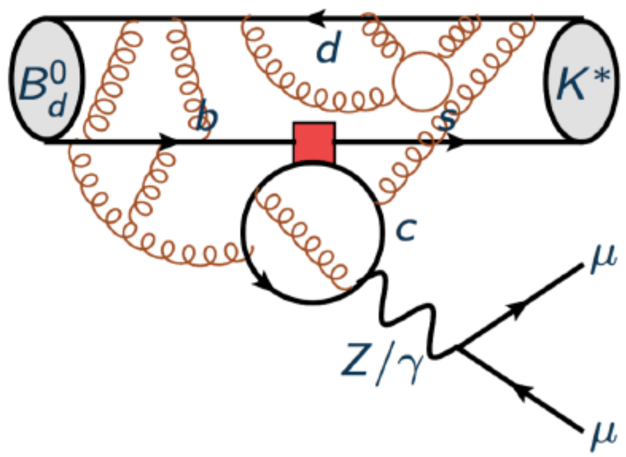


experimental sensitivity limited by systematics
close to SM uncertainty (CKM matrix elements, Bs decay constant)

other observables:

- effective lifetime
- time-dependent CP asymmetry (only accessible with full 300 fb−1 statistics)

$b \to s\ell\ell$ transitions

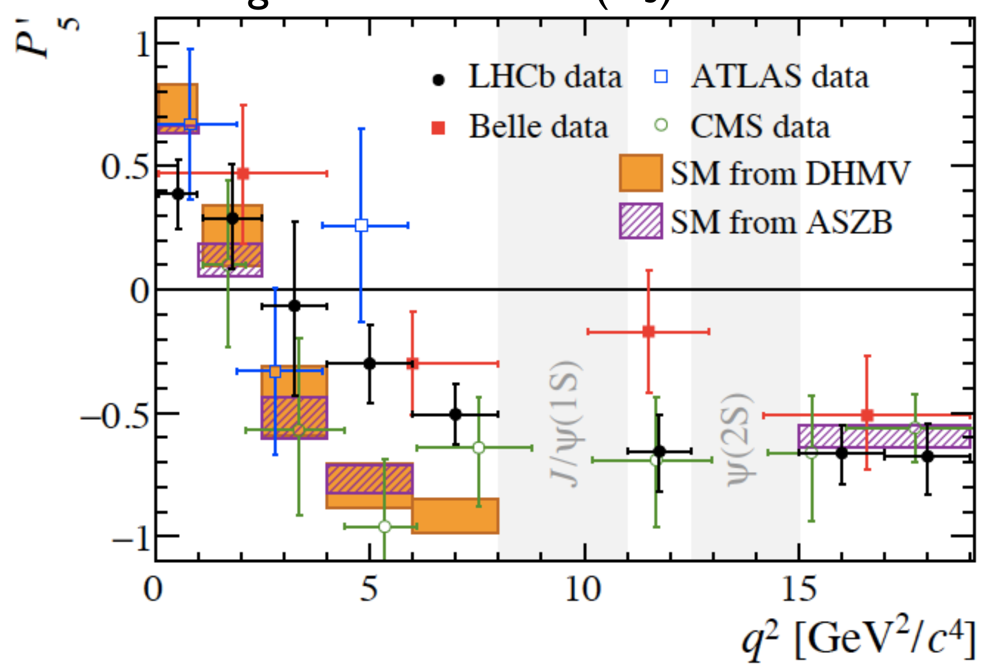


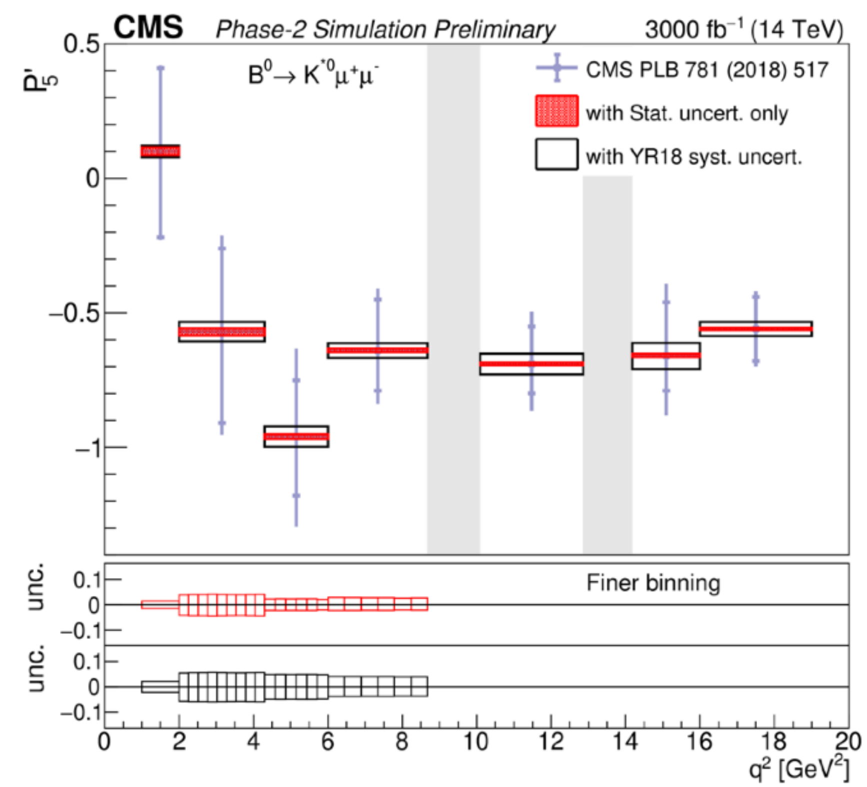
Very rich phenomenology
- large BF
- angular analysis
- access to many operators

- many $K^*\mu\mu$ observables are theoretically clean
- some have large uncertainties due to non-perturbative QCD

CMS-PAS-FTR-18-033

Angular distribution (P'_5) in $B \to K^*\ell^+\ell^-$





ATLAS, CMS and LHCb will significantly improve the sensitivity

ATL-PHYS-PUB-2019-003

expect of order 500k events/exp.

➠ better control of contribution from charmonium resonances, which contaminate theory interpretation

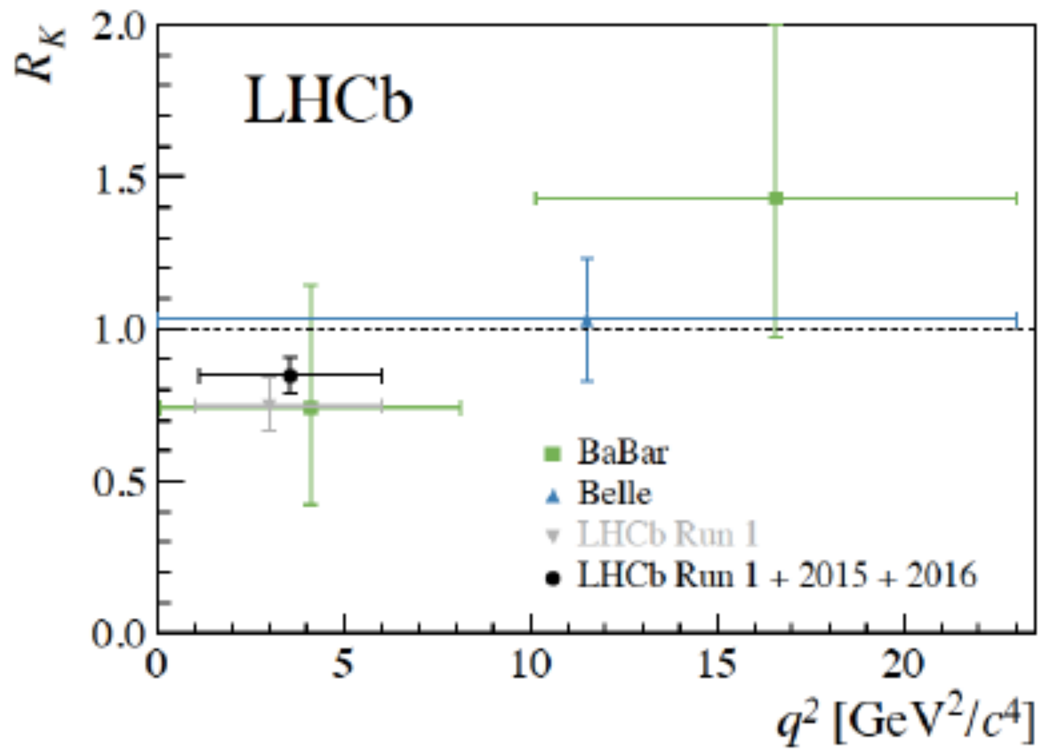
➠ in case of anomaly, discrimination of NP scenarios

Tests of Lepton Universality

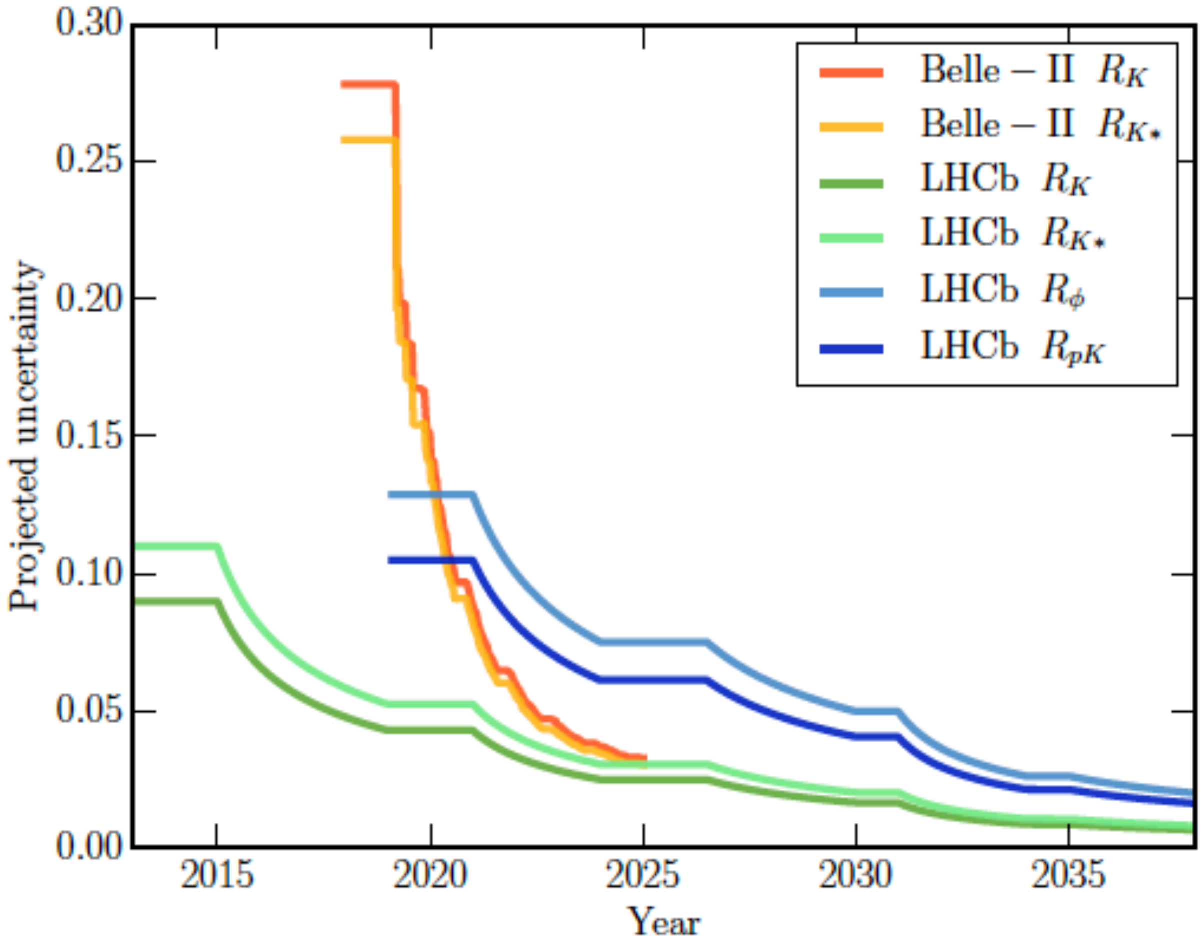
The R_{Hs} ratios: R_K, R_{K^*}, R_ϕ, R_{pK}

$$R_{\mathrm{Hs}} = \frac{\int_{\mathrm{bin}} \mathrm{H_b} \to \mathrm{H_s}\mu^+\mu^-}{\int_{\mathrm{bin}} \mathrm{H_b} \to \mathrm{H_s}\mathrm{e}^+\mathrm{e}^-}$$

R_{Hs} = 1 (at 10^{-3} QED corrections) in the SM



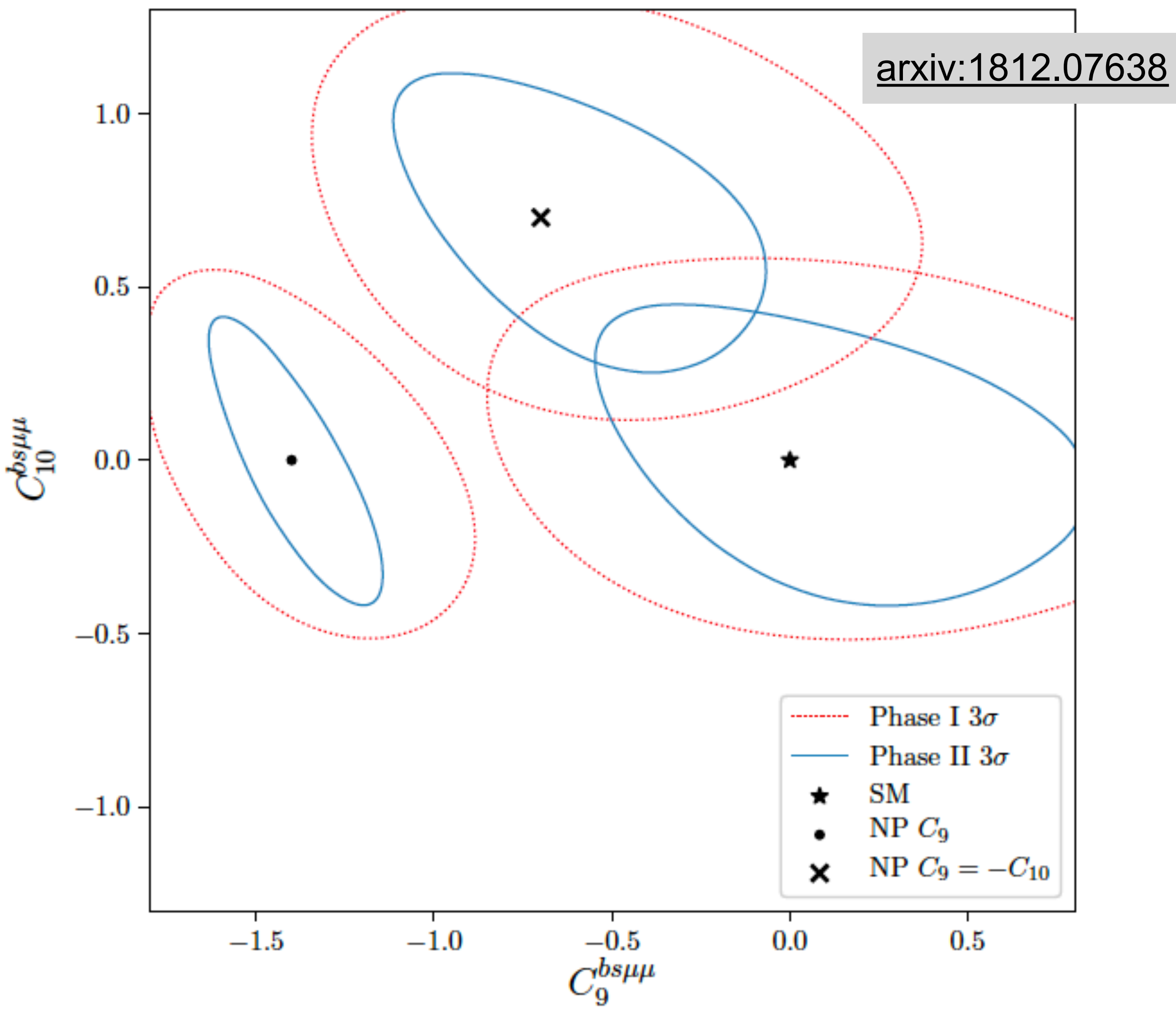
R_{Hs} precision in the 1-6 GeV² bin

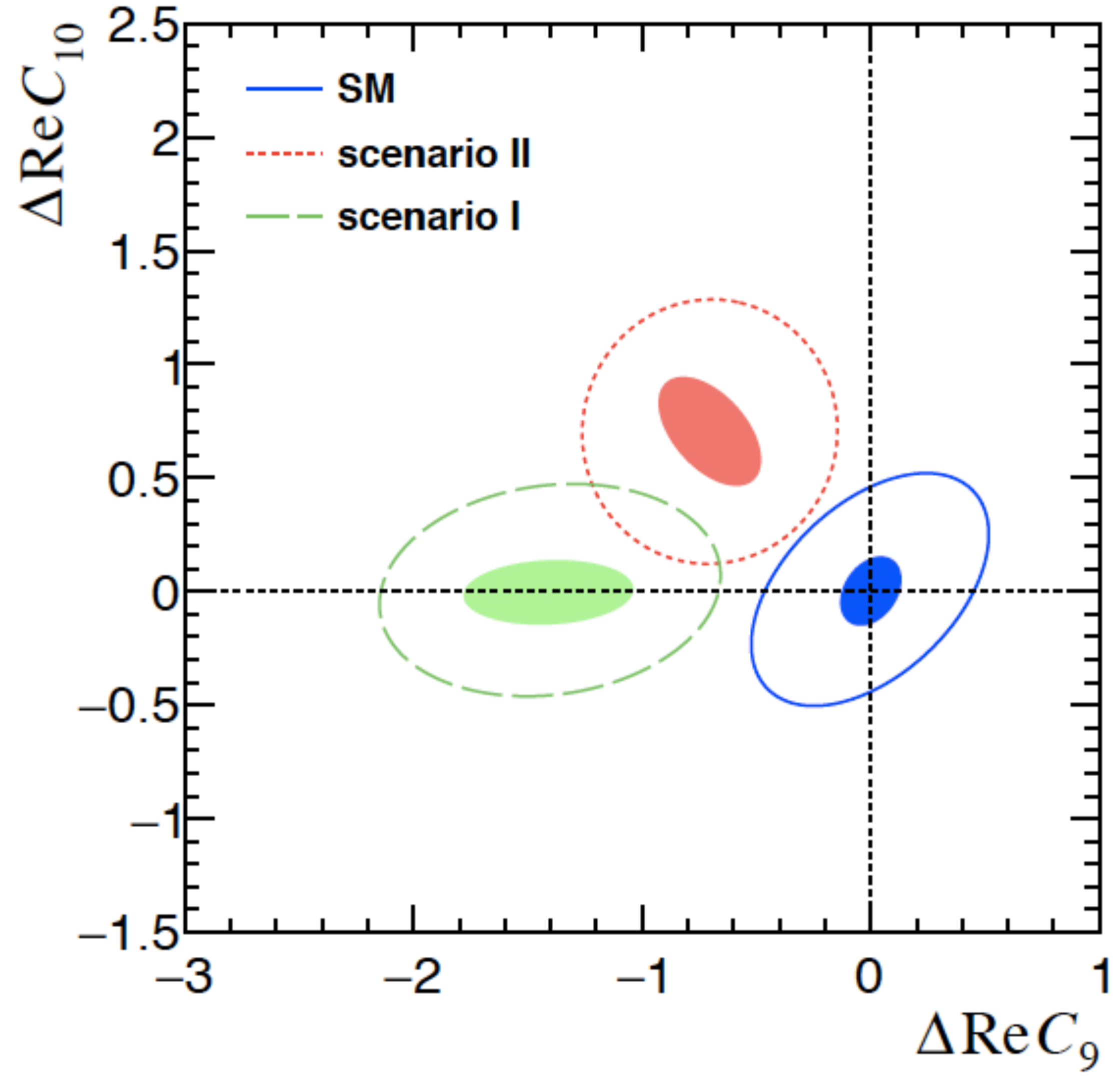


- Percent level with LHCb-U1
- LHCb-U2 needed to get sub-percent

  ➠ access to b → dℓℓ

Global Fits





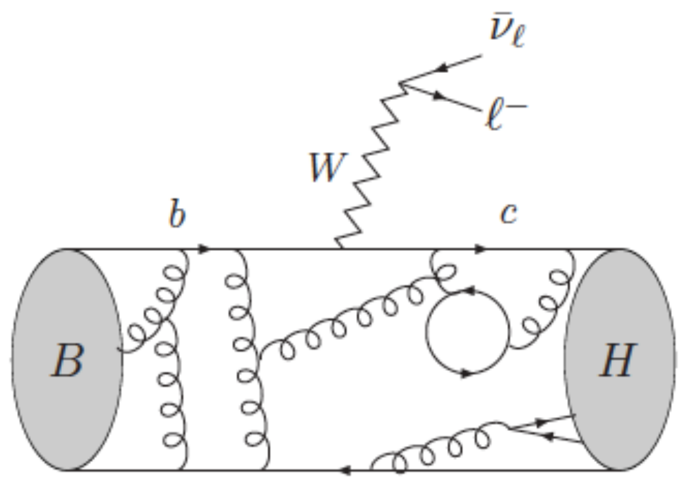
Example of global fit

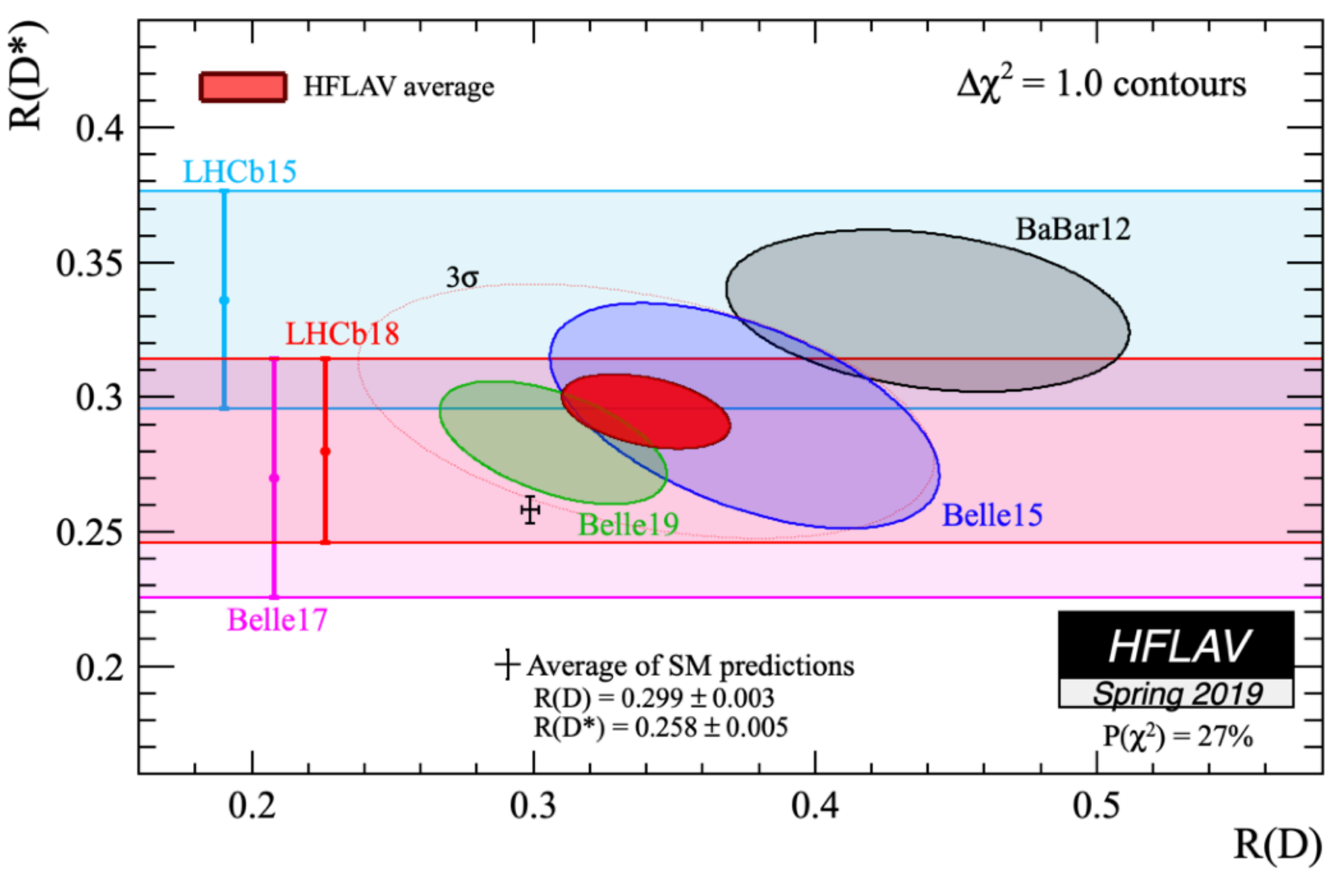
- $B_s^0 \to \mu\mu$ and $B^0 \to K^* \ell\ell$ angular analysis
- ATLAS/CMS (300 fb^{-1}) + LHCb (23 fb^{-1})
- ATLAS/CMS (3 ab^{-1}) + LHCb (300 fb^{-1})

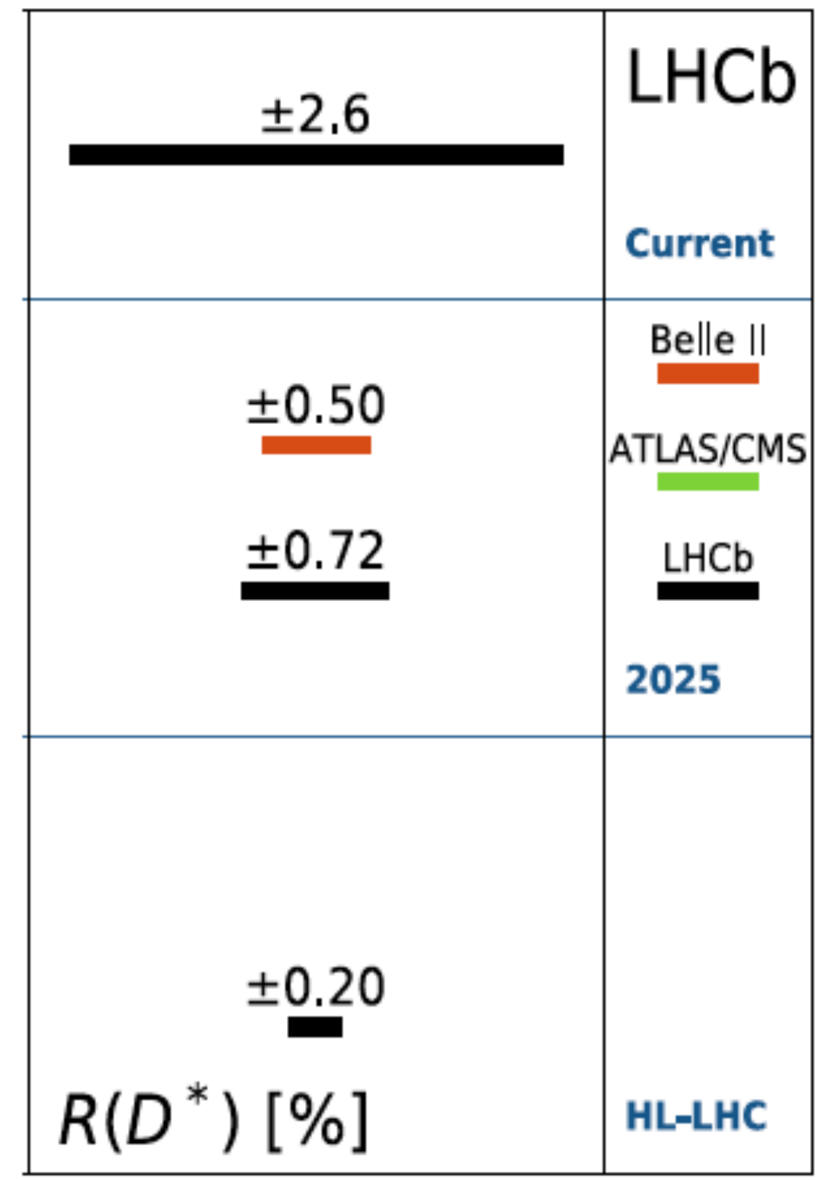
Global fit of $b \to s\ell\ell$ and R_{D^*}

scenario	C_9^{NP}	C_{10}^{NP}	C_9'	C_{10}'	
I	−1.4	0	0	0	$b \to s\ell\ell$
II	−0.7	0.7	0	0	$b \to s\ell\ell + R_{D^*}$

LU Tests in b → $c\ell\nu$







"compatibility" with the SM at the 3.1σ level

Flavour Physics at the FCC-ee (Z pole)

The ultimate e^+e^- beauty, charm and τ factory

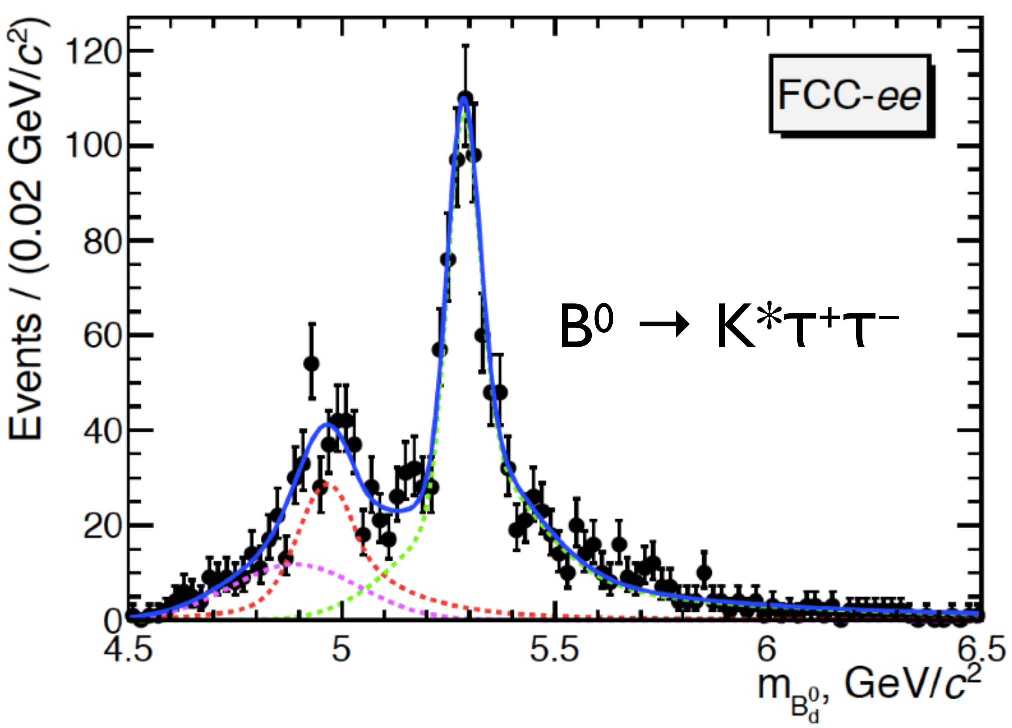
Complementarity with Belle-II and LHCb

☛ 10^{12} Z → bb
- access to B^0, B_s, B_c, B hadrons
- 100 000 $B_s \to \tau^+\tau^-$

Particle production (10^9)	B^0 / $\overline{B}^0$	B^+ / B^-	B^0_s / $\overline{B}^0_s$	Λ_b / $\overline{\Lambda}_b$	$c\overline{c}$	τ^-/τ^+
Belle II	27.5	27.5	n/a	n/a	65	45
FCC-*ee*	1000	1000	250	250	1000	500

☛ example

test of the $b \to s\ell^+\ell^-$ anomaly for $\ell = \tau$



Full reconstruction and angular analysis

☛ another example
- test of lepton flavour universality in BR($\tau \to e\nu\nu$) versus τ lifetime