Flavour and CP physics with b-hadrons

And one word on D physics

Marie-Hélène Schune
LAL, Orsay

No time to enter into any details … this talk does not give justice to the huge amount of results and studies performed

Context

CP violation

Rare decays ($B_{(s)} \to \mu\mu$ and $b \to s\ell\ell$)

Semileptonic decays

No time to discuss topics related to a better understanding of non-perturbative QCD (resonances, exotic states)

LHCb Upgrade II: arXiv:1808.08865
Flavours at HL-LHC: arXiv:1812.07638
Belle II physics book: arXiv 1808.10567
Inputs to Granada

Overall situation in particle physics

Observations

Higgs boson seems quite SM-like

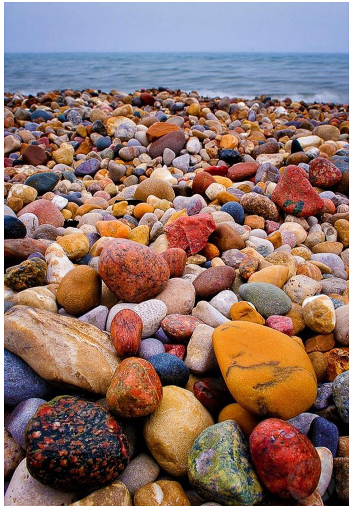
No sign of direct signals of NP particles (gap between SM and NP mass spectra)

A few open questions

Dark matter candidate ?
Baryon asymmetry generation ?

Which are the sources of flavour symmetry breaking we observed ?

No stone left unturned



Flavour physics !

CP violation and FCNC : sensitive probes of short distance physics

Probes scales >> 1 TeV (depending on c_{NP})

Many tests limited by statistics not by systematics nor theory

$$A(\psi_i \rightarrow \psi_j + X) = A_0 \left(\frac{c_{\mathrm{SM}}}{v^2} + \frac{\boldsymbol{c}_{\mathbf{NP}}}{\boldsymbol{\Lambda}_{\mathbf{NP}}^{\mathbf{2}}} \right)$$

NP scale and coupling

1964 $K_L \rightarrow \pi\pi$: CP violation
3 families

1987 B_d mixing $\sqrt{s}$=10 GeV (ARGUS)

$$\Delta m_d \sim 0.00002 \times \left(\frac{m_t}{\mathrm{GeV}/c^2} \right)^2 \mathrm{ps}^{-1} \sim 0.5\ \mathrm{ps}^{-1}$$

$\Rightarrow m_t$ >50 GeV

Experimental heavy flavours: a large and active community

Publications:
~ 50% from LHCb
BESIII and Belle
less from BaBar, ATLAS and CMS

HFLAV inputs

People in Europe:
61 groups on LHCb
36 in Belle II
17 on BESIII
+ ATLAS & CMS

+ theoretical community !

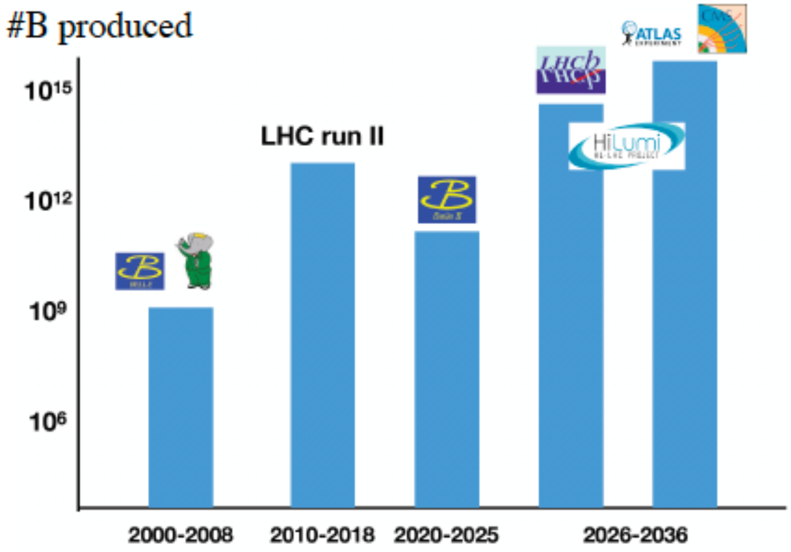
Where are we ? (since September 2012)
Where are we going ?

CP violation

Rare decays ($B_{(s)} \rightarrow \mu\mu$ and $b \rightarrow s\ell\ell$)

Semileptonic decays

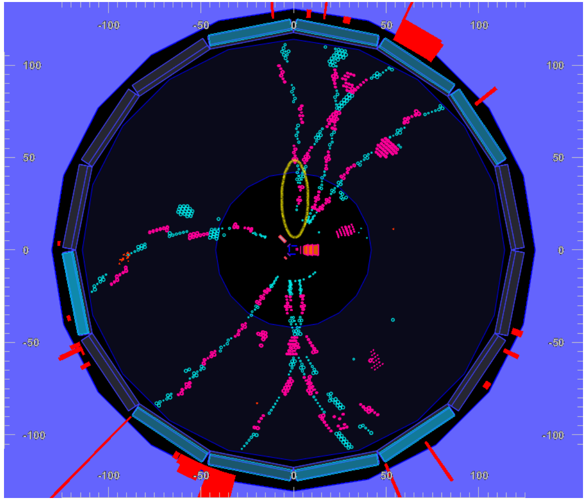
log scale !



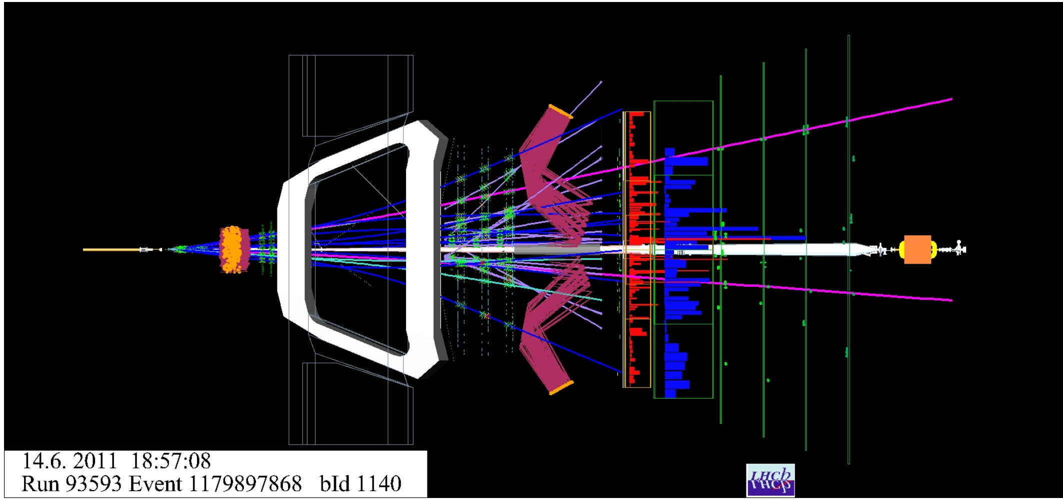
Patrick Owen at HL-HE LHC (March 2019)

Experimental environments

Belle-II



LHCb

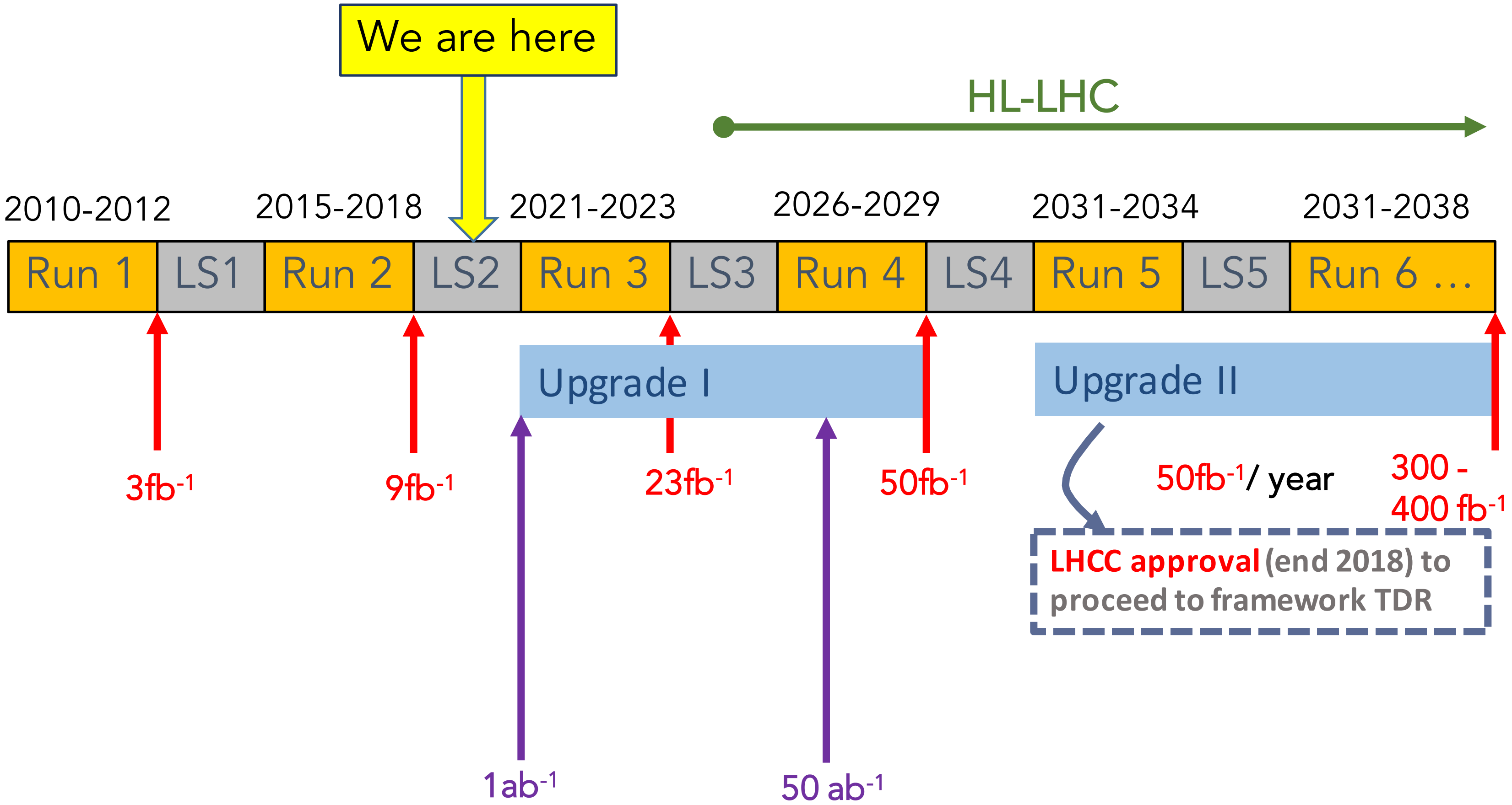


Immensely different environments ⇒ complementarity !

Trigger fully efficient on B events : modes with neutrals, inclusive measurements

Access to tiny BRs, all b-hadrons types

Where are we going ?



LHC

…but also:

Belle II+1= Belle III

Just started within Belle II

Goal: x5 increase in peak luminosity

- ❑ Doable from a machine perspective ?
- ❑ Detectors issues running at $4\ 10^{36}\ cm^{-2}\ s^{-1}$
- ❑ Physics case

Under study, more before the end of 2019

Z^0 factories

Goal: $10^{11} - 10^{12}\ Z^0$ (CEPC)
$5.\ 10^{12}\ Z^0$ (FCCee)
$BR(Z^0 \rightarrow b\bar{b}) = 15\%$

ILD-like detector + charged hadron PID.

FCC-pp a dedicated experiment (à la LHCb)

e^+e^- Super τ-charm factory (Novosibirsk)
E: 2 to 6 GeV.
Peak luminosity (> 4 GeV) $10^{35}\ cm^{-2}\ s^{-1}$

γ angle measurement

$\gamma = \arg\left(\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$

Interferences between b→c and b→u tree-level transitions: SM candle (and many modes to be used) : B→DK

NP in loops ?

Comparison with measurements in charmless B decays (loops)

γ vs $\gamma+\phi_s$

NP in mixing?

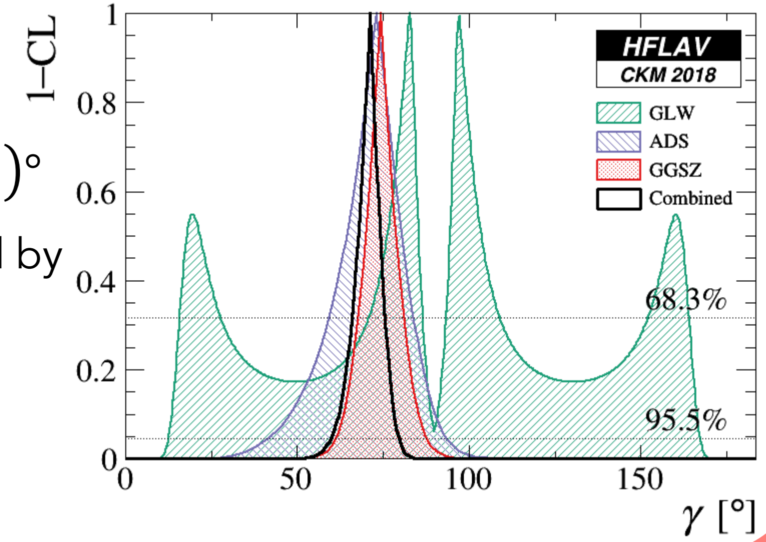
Time dependent measurement : $B_s \rightarrow D_sK$

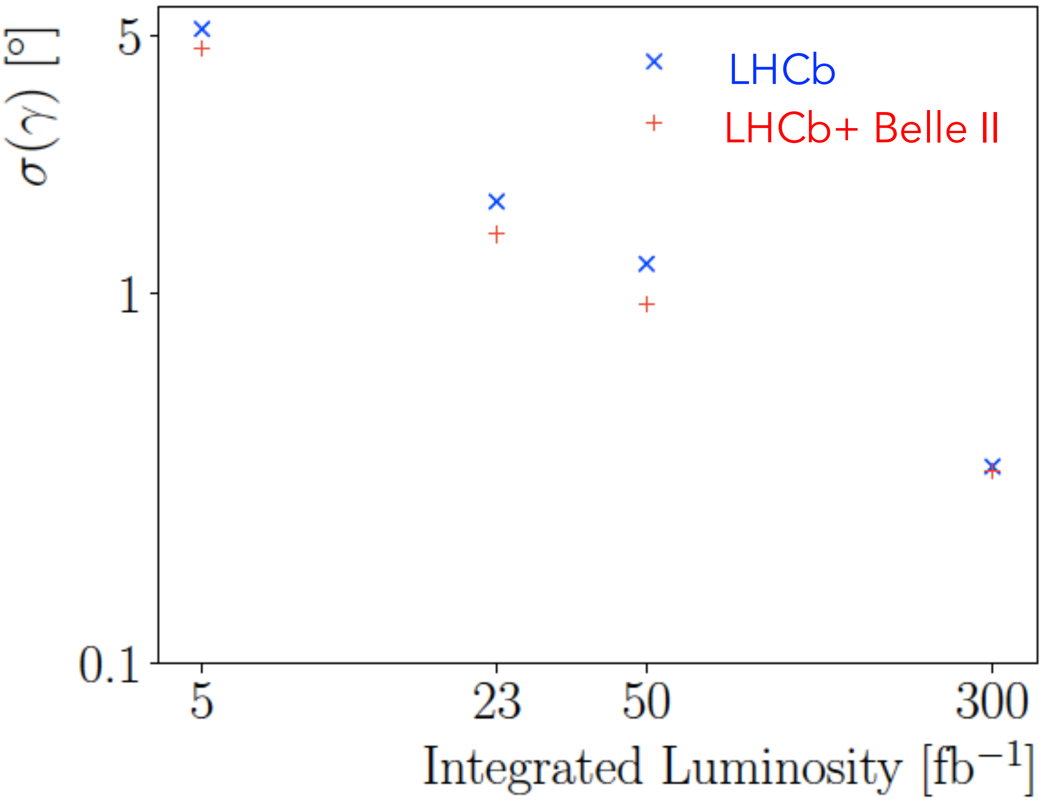
$\sigma_{2018} = \sigma_{2012}/2.5$

2018

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

Fully dominated by LHCb



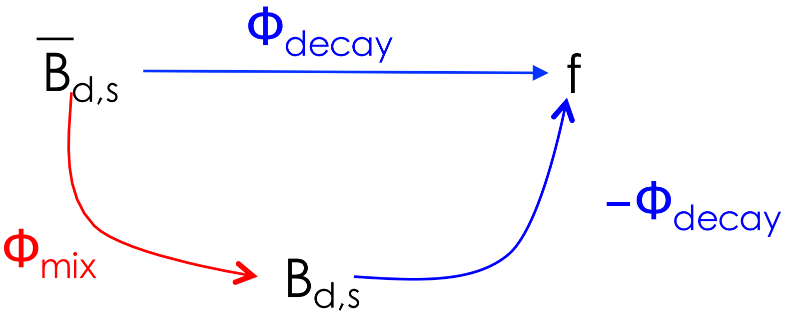


In ~ 2030 $\sigma_{LHCb\text{-}U1}$ ~ $\sigma_{Belle\text{-}II}$ = 1.5°

End of HL-LHC (LHCb-U2) : subdegree uncertainty

A precise knowledge of the D strong phases is mandatory (BES III, τ-charm)

CP violation in the interference between mixing and decay



$\Phi = \Phi_{mix} - 2\ \Phi_{decay}$

Mostly $B_s \rightarrow J/\psi\phi$ but not only
(LHCb analyzes $B_s \rightarrow J/\psi KK$, $J/\psi\pi\pi$)

Needs :

- Initial state tagging
- Decay time measurement
- (Angular analysis)

B_d system : 2β

B_s system : ϕ_s

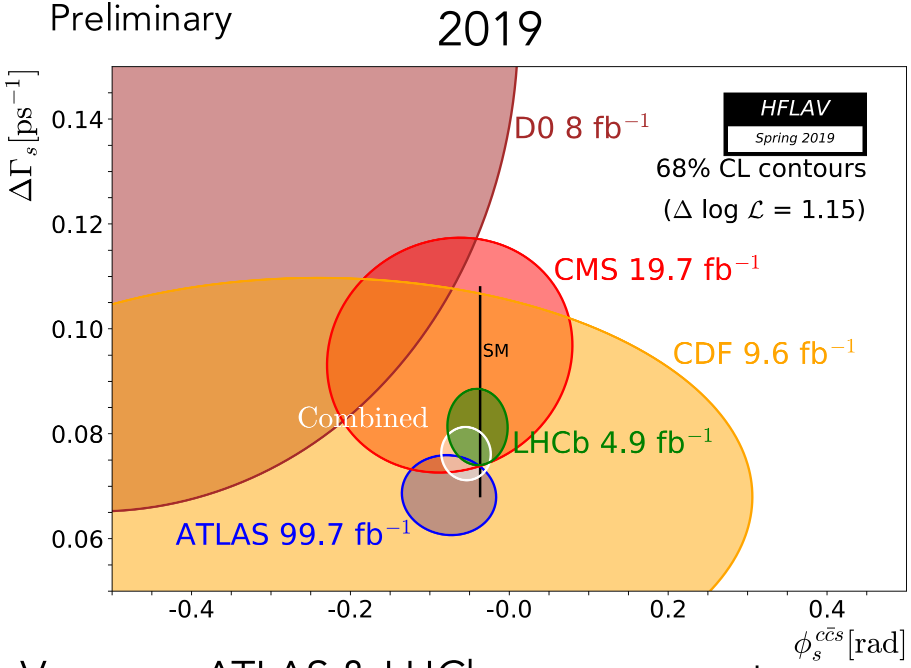
$$\varphi_s^{SM} = -0.03686^{+0.00096}_{-0.00068}\ \text{rad}$$

[CKMFitter]

$$\Phi = \Phi^{SM} + \Delta\Phi_{peng} + \Delta\Phi_{NP}$$

For the ultimate precision: non perturbative QCD (penguin pollution) : should be constraint from data

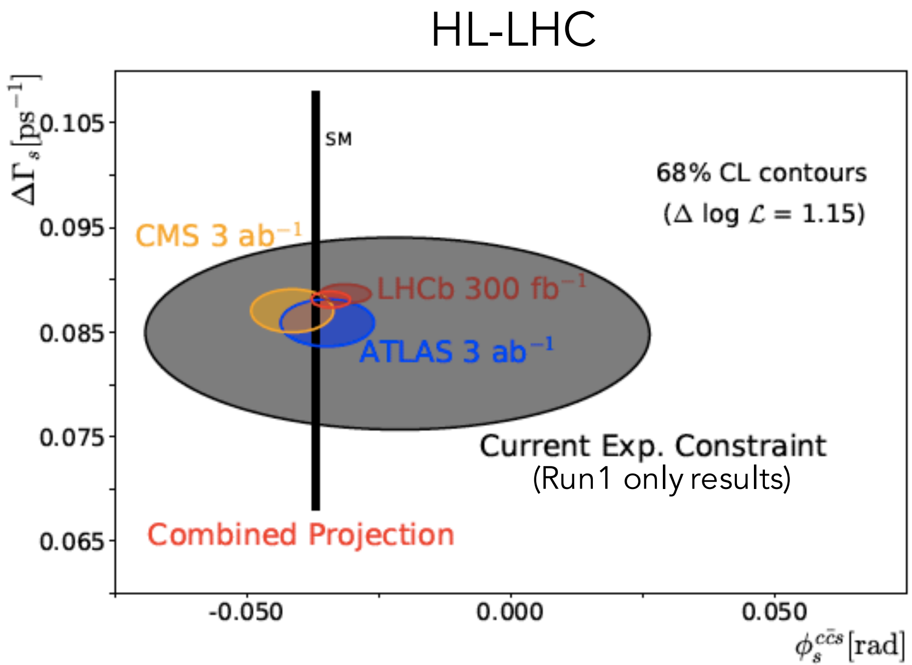
Preliminary



Mostly $B_s \to J/\psi\phi$ but not only (LHCb analyzes $B_s \to J/\psi KK$, $J/\psi\pi\pi$ D_sD_s)

Very new ATLAS & LHCb measurements

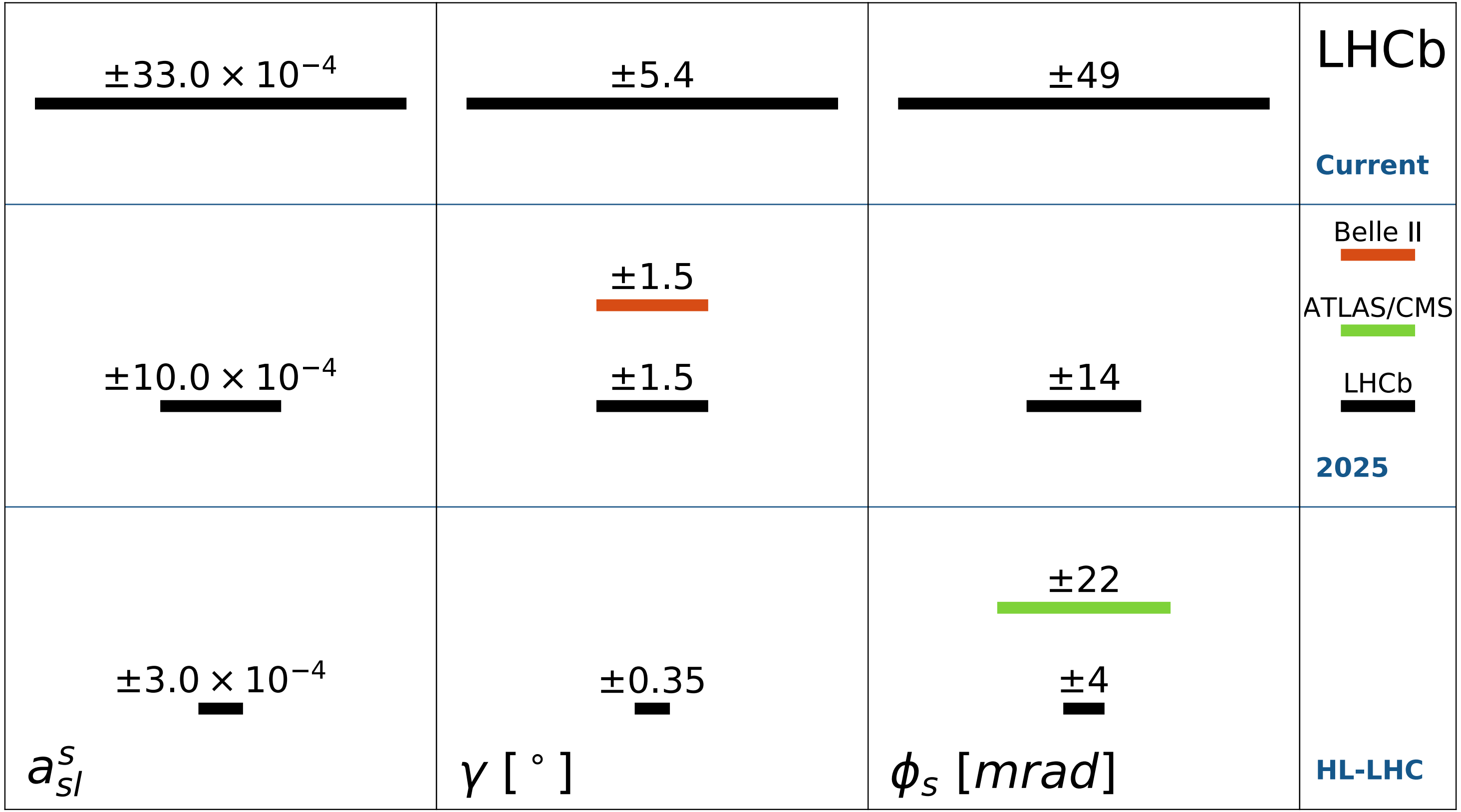
HL-LHC



Tagging performances to be maintained

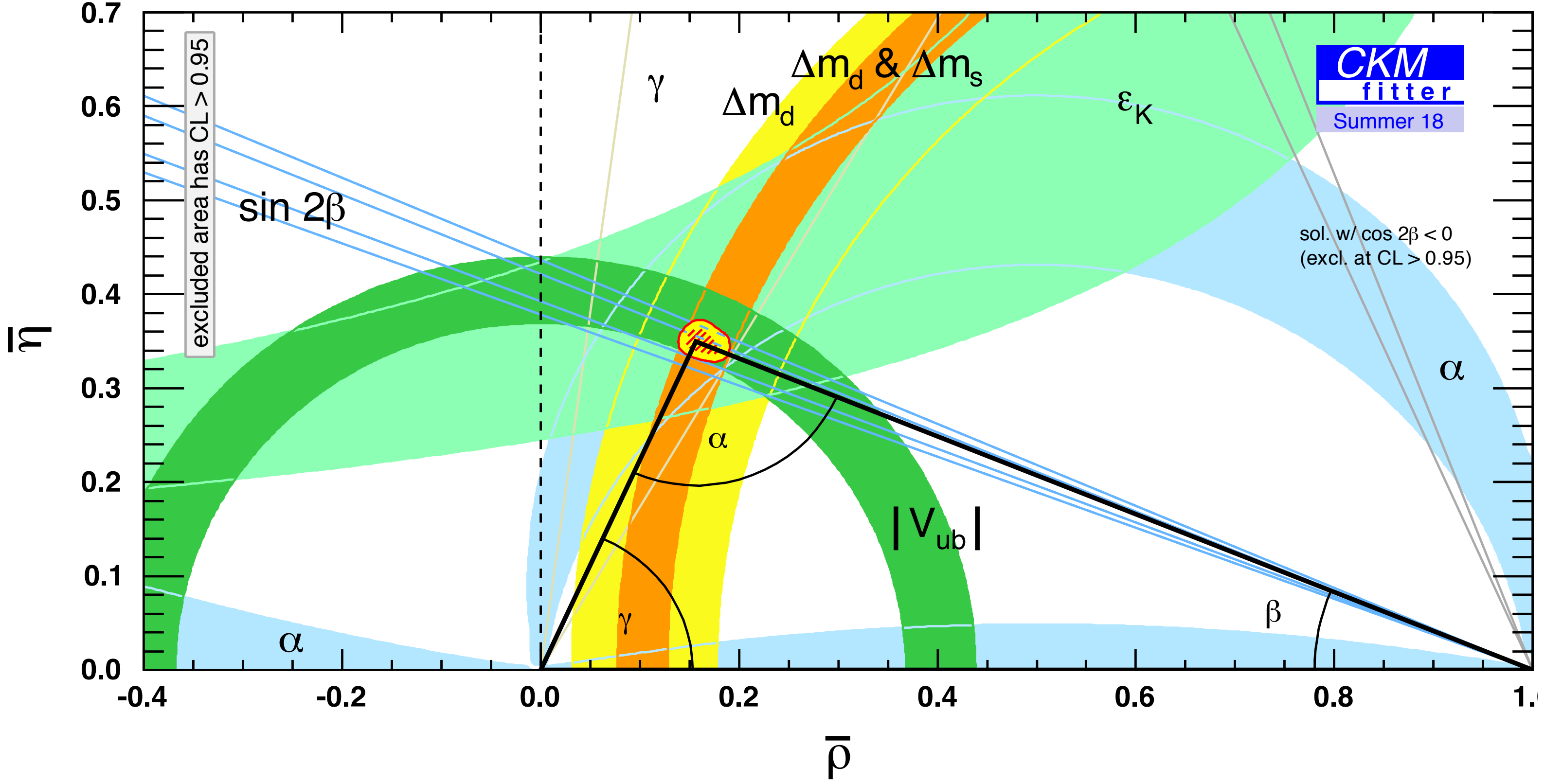
2018 projections for B mixing and CPV in one slide

arXiv:1808.08865



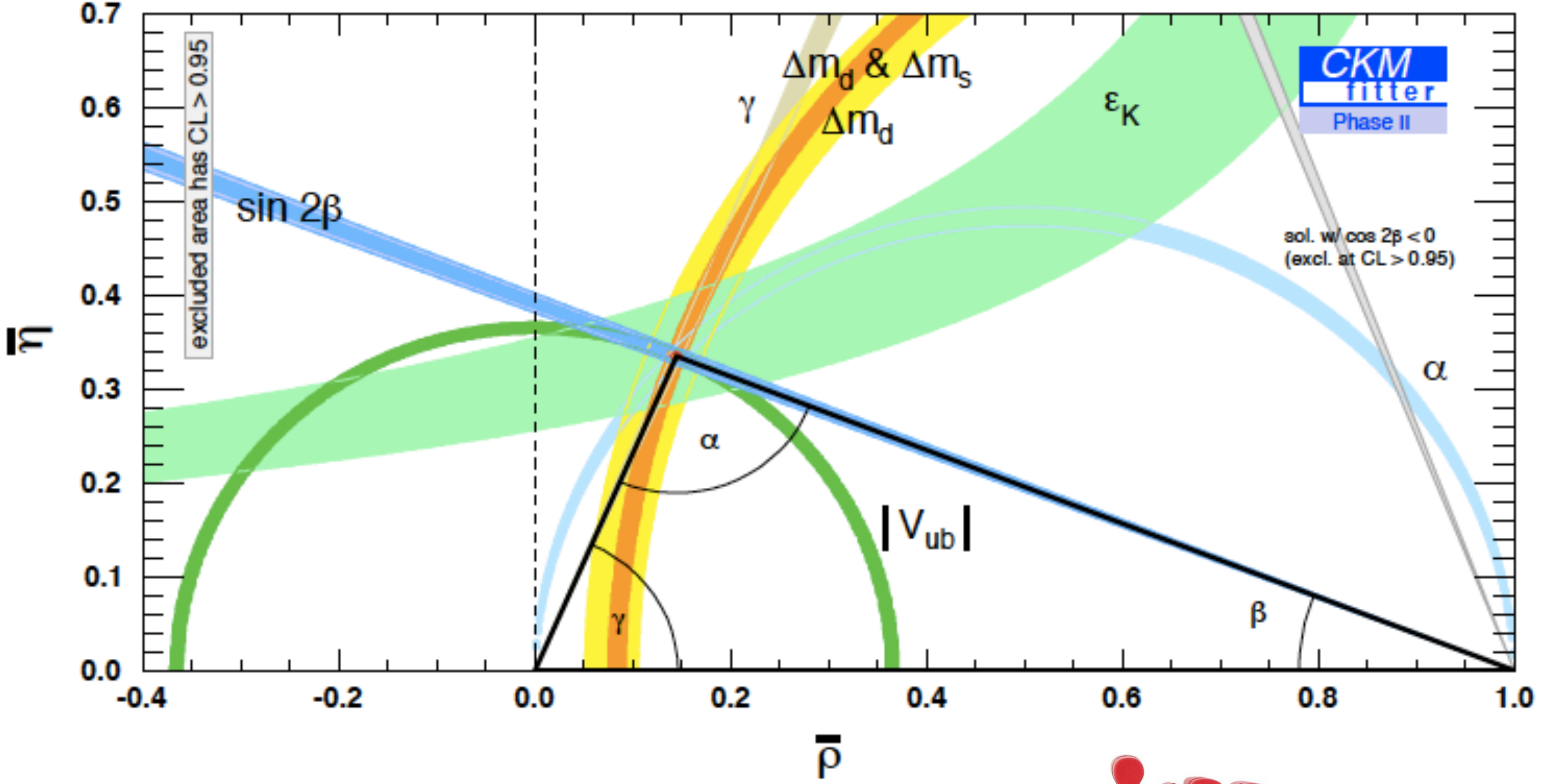
as of mid 2018

2018



0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
-0.4
-0.2
0.0
0.2
0.4
0.6
0.8
1.0
η̄
ρ̄
excluded area has CL > 0.95
sin 2β
γ
Δm_d
Δm_d & Δm_s
ε_K
CKM fitter
Summer 18
sol. w/ cos 2β < 0
(excl. at CL > 0.95)
α
α
α
γ
β
|V_ub|

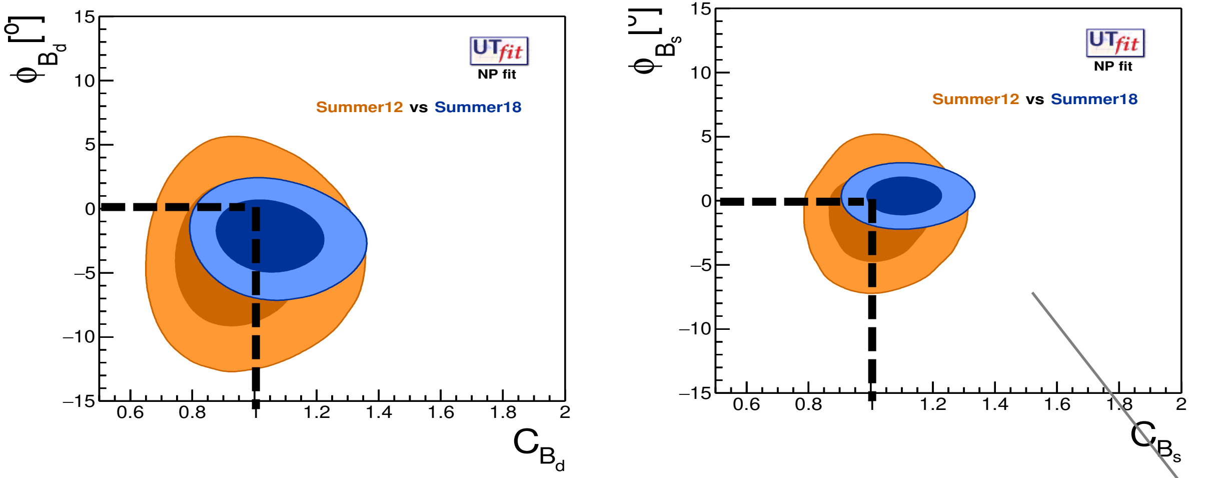
End of HL-LHC



Inconsistencies among measurements ?

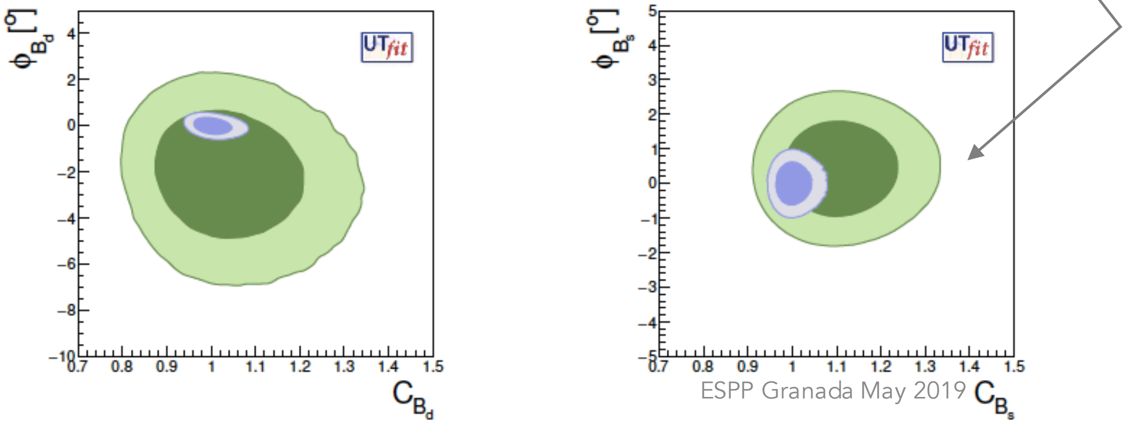
NP in |ΔF| = 2 transitions ?

$$C_{B_q}\, e^{2i\phi_{B_q}} = \frac{\langle B_q | H_{\rm eff}^{\rm full} | \bar{B}_q \rangle}{\langle B_q | H_{\rm eff}^{\rm SM} | \bar{B}_q \rangle}$$



Now: NP transition about an order of magnitude smaller than the SM-allowed one

blue becomes green
axes size changed



HL-LHC will allow to gain a factor 4

Discovery of CP violation in charm decays

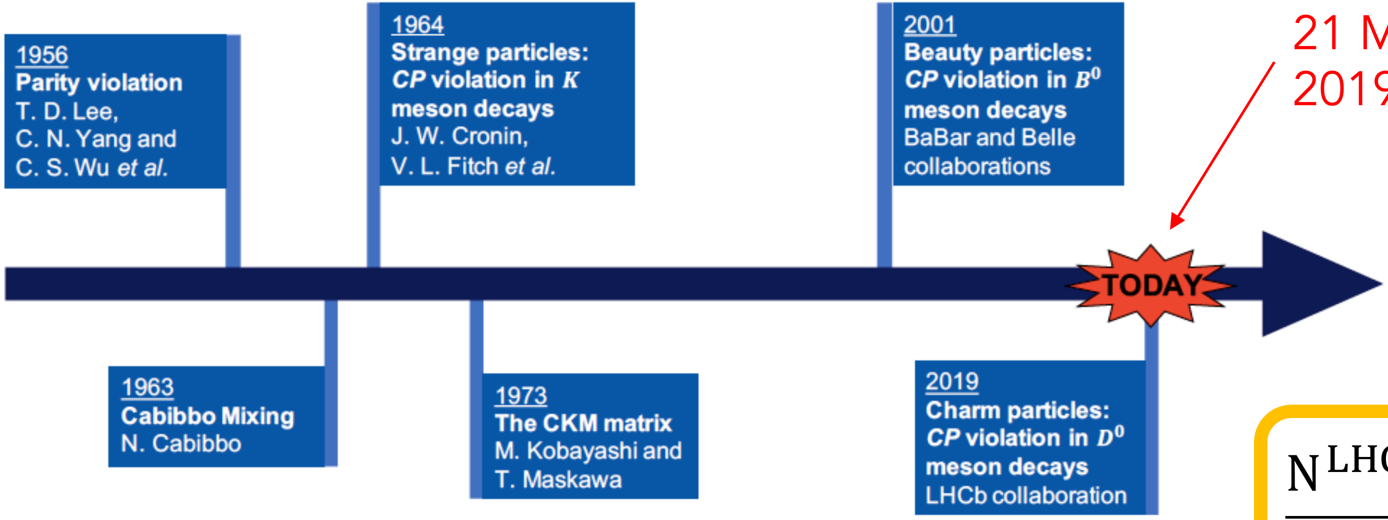
CP violation in up-type sector. SM expectations : 10^{-3} - 10^{-4}.

$\sigma_{cc} \simeq 20\sigma_{bb}$ at LHCb

Extremely large samples needed !

~ 80 10^6 signal events

21 March 2019



$$\frac{N^{\text{LHCb-Upgrade II}}}{N^{\text{Belle II}}} \sim 100$$

in key-channels

Experimentally: $A_{raw} = \frac{N(D^0 \to f) - N(\bar{D}^0 \to f)}{N(D^0 \to f) + N(\bar{D}^0 \to f)} = A_{CP} + A_D(\pi_s^+/\mu) + A_P(D^{*+}/D^0_{\text{from } B})$

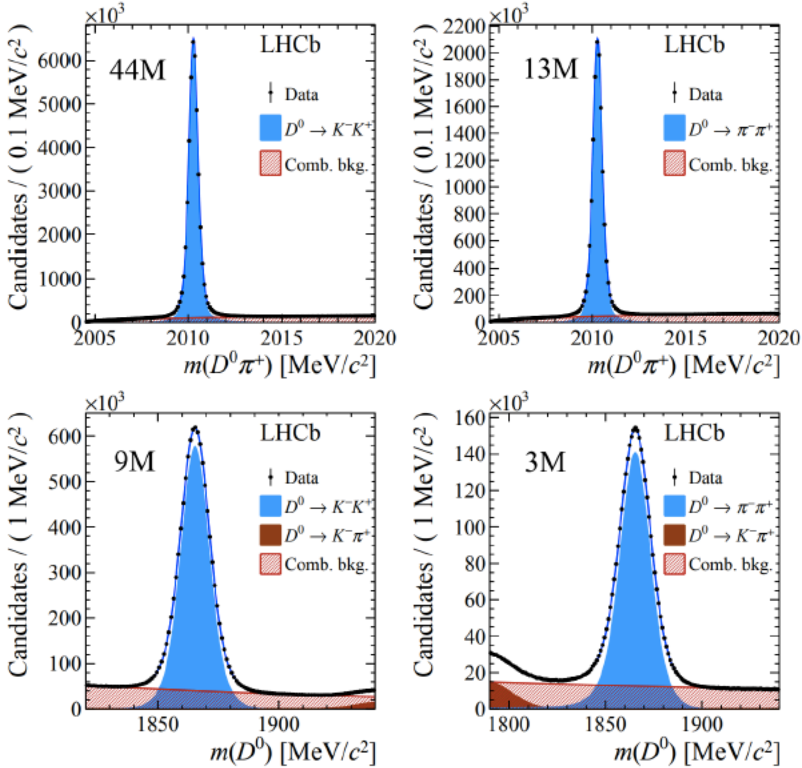
$D^0 \to KK$ or $\pi\pi$
charge symmetric

$$\Delta A_{CP} = A_{raw}(KK) - A_{raw}(\pi\pi) \cong A_{CP}(KK) - A_{CP}(\pi\pi)$$

Kinematical reweighting ⇒ production and detection asymmetries cancel

π tag

μ tag



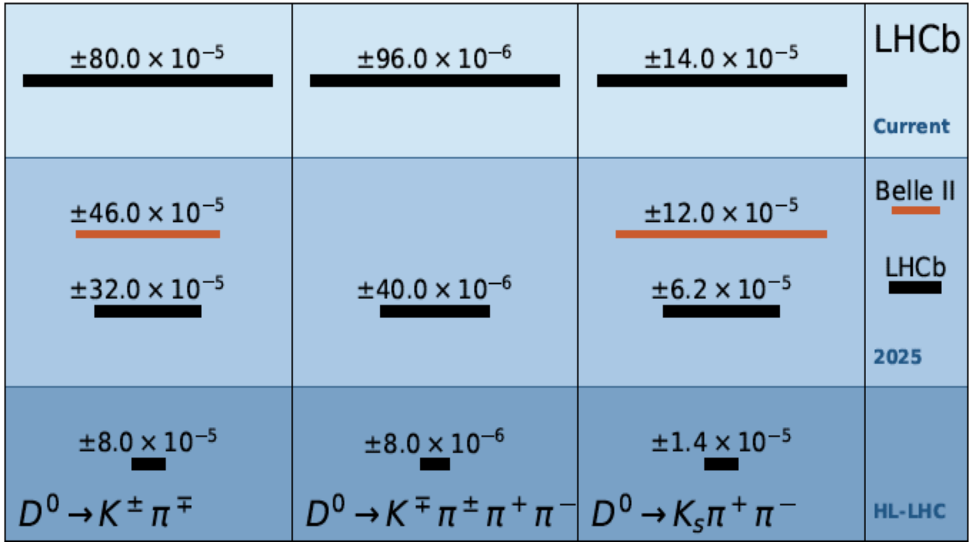
ΔA_{CP}=(-0.154±0.029)%
Observation of CP violation at 5.3 σ

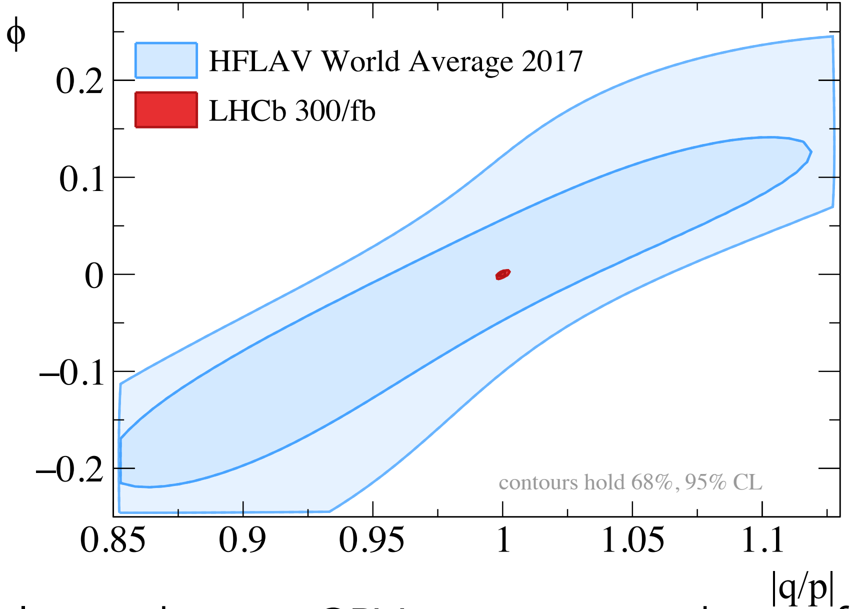
Run2 dataset (6 fb^{-1})

arXiv:1903.08726

2018 projections for D CPV in one slide

arXiv:1808.08865

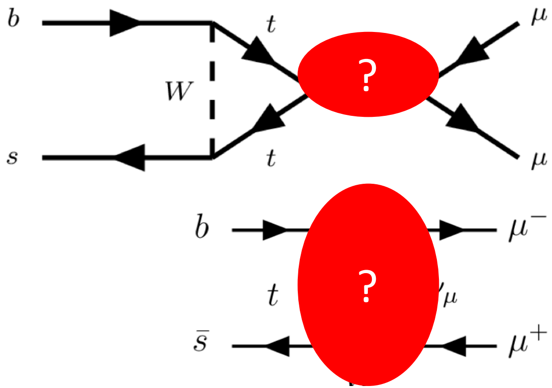




LHCb may well be the only experiment to be able to observe CPV in mixing in charm if there is no NP contribution

A joint program between experiments and theory to progress on the predictions

Challenges in the amount of data



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

SM: $\mathcal{B}(B_s \to \mu^+\mu^-)_{SM} = (3.64 \pm 0.11) \cdot 10^{-9}$,

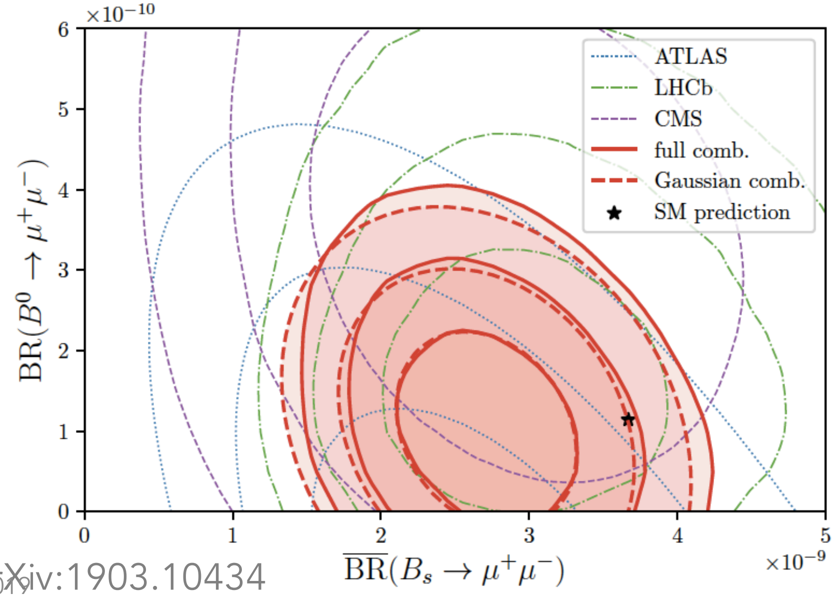
$\mathcal{B}(B_d \to \mu^+\mu^-)_{SM} = (1.00 \pm 0.03) \cdot 10^{-10}$.

arXiv:1812.07638 and refs therein

- SM : very rare (V_{tq}, helicity suppression)
- Very sensitive to NP (eg models with extended Higgs sector)
- Clean experimental signature
- Observed by LHCb, CMS and ATLAS

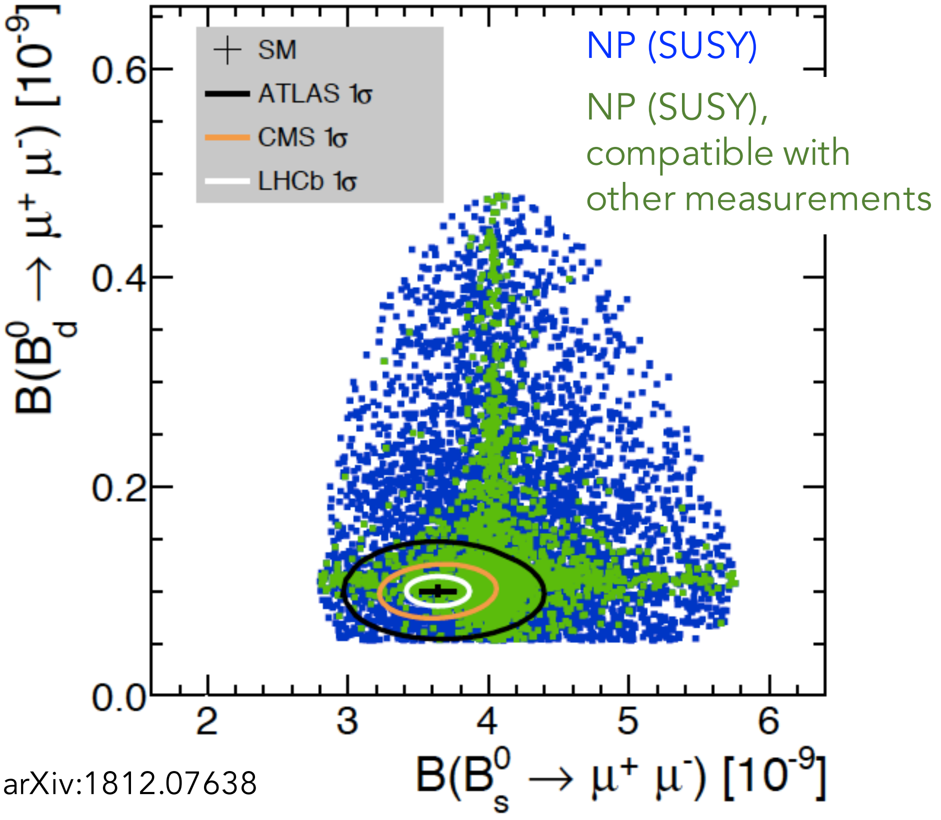
$$\overline{\mathrm{BR}}(B_s \to \mu^+\mu^-) = (2.67^{+0.45}_{-0.35}) \times 10^{-9}$$

Mass resolution is a key-ingredient



arXiv:1903.10434

Expected sensitivities at HL-LHC



arXiv:1812.07638

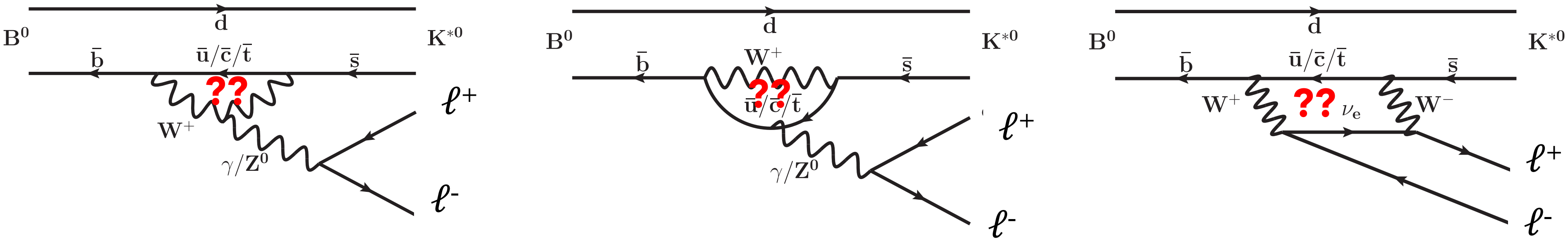
Experimental sensitivity:

- dominated by systematics (f_s/f_d)
- close to the SM uncertainty (CKM matrix elements, B_s decay constant)

Additional observables:

- effective lifetime (precision for LHCb : 8% for 23 fb^{-1} and 2 % with 300 fb^{-1})
- time dependent CP asymmetry (sensitive to NP phase) . Accessible only with 300 fb^{-1}

b→sℓℓ transitions

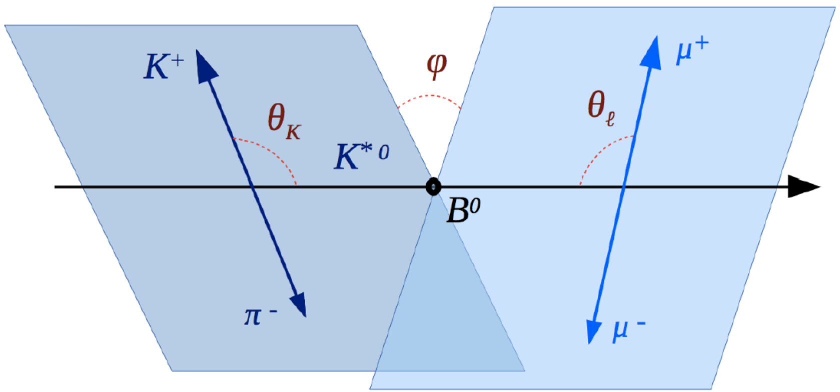


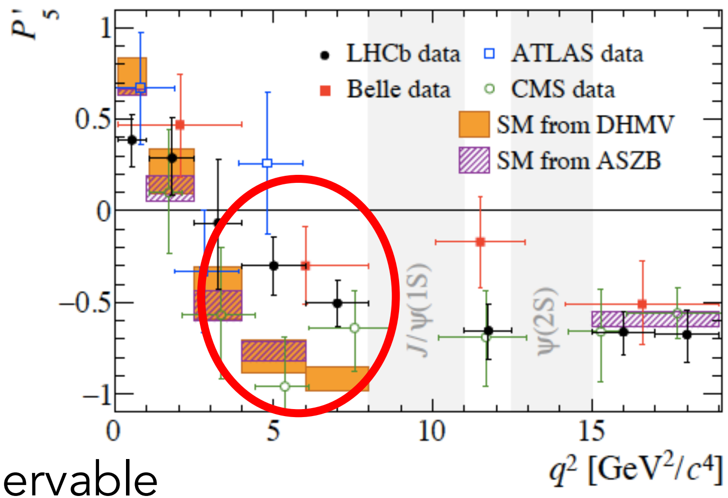
Relative importance of the different diagrams varies with $q^2 = M^2(\ell^+\ell^-)$

Rich phenomenology:

- BF (but large theoretical uncertainties due to non-perturbative QCD)
- Angular observables
- Ratios of BF (test of Lepton Universality)

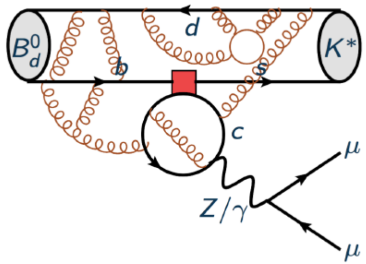
$B^0 \to K^{*0} \mu\mu$





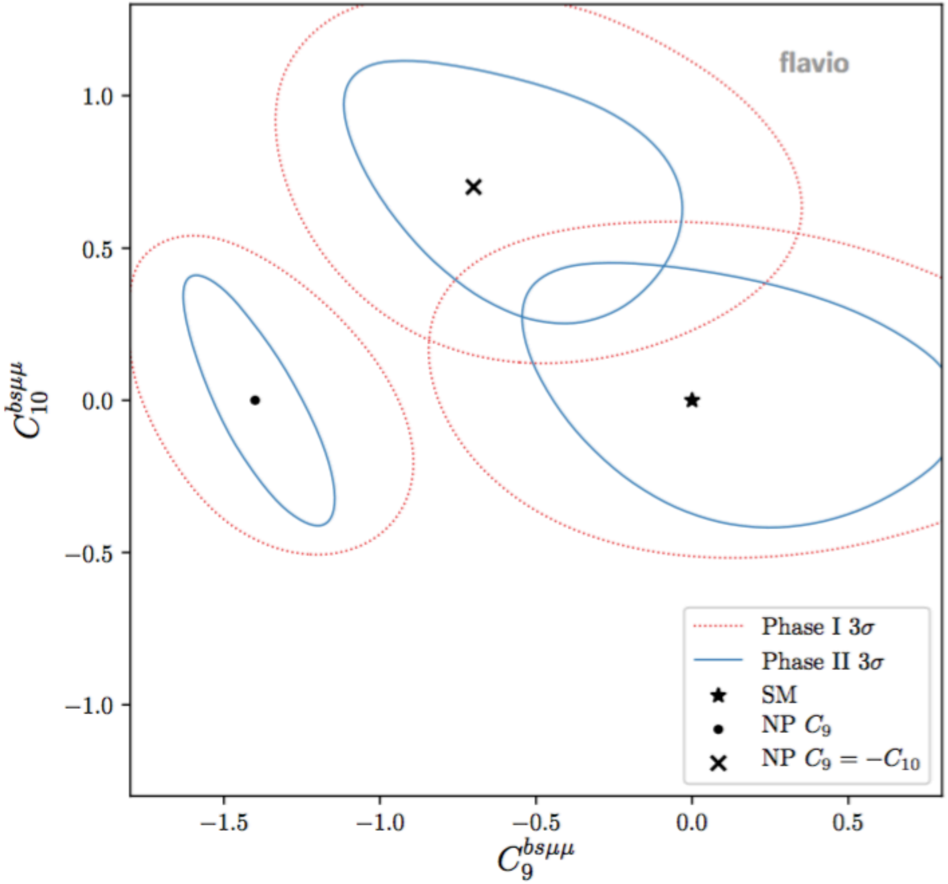
Tensions with the SM. Clearly exhibited in P'5 observable

LHCb JHEP 02(2016) 104
ATLAS JHEP 10 (2018) 047
CMS PLB 753 (2016) 424
Belle (PRL 118 (2017) no.11, 111801)



$c\bar{c}$ loops : theoretical debate about their impact

An example of global fit : $B_s \to \mu\mu$ + B→K* μμ angular analysis ATLAS, CMS & LHCb



3σ contours

23 fb^{-1} LHCb
300 fb^{-1} ATLAS and CMS

end of Run3

300 fb^{-1} LHCb
3000 fb^{-1} ATLAS and CMS

end of HL-LHC

Other measurements:

Belle II: measurements of the related $B \to K^{(*)} \nu\nu$ modes

LU tests in b →sℓℓ: the R_{Hs} ratios

$$R_{H_s} = \frac{\int_{q^2_{\min}}^{q^2_{\max}} \frac{d\Gamma(H_b\to H_s\mu^+\mu^-)}{dq^2}\, dq^2}{\int_{q^2_{\min}}^{q^2_{\max}} \frac{d\Gamma(H_b\to H_s e^+e^-)}{dq^2}\, dq^2}$$

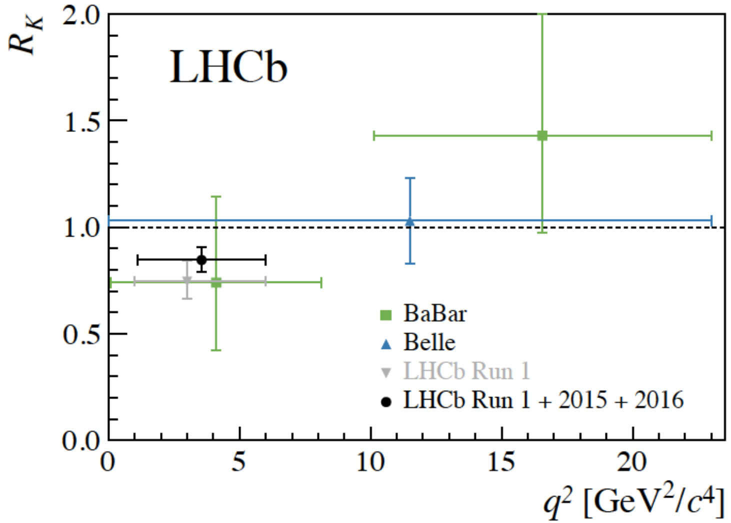
R_{Hs} =1 (at 10^{-3}) in the SM

QED effects ~ % arXiv:1605.07633

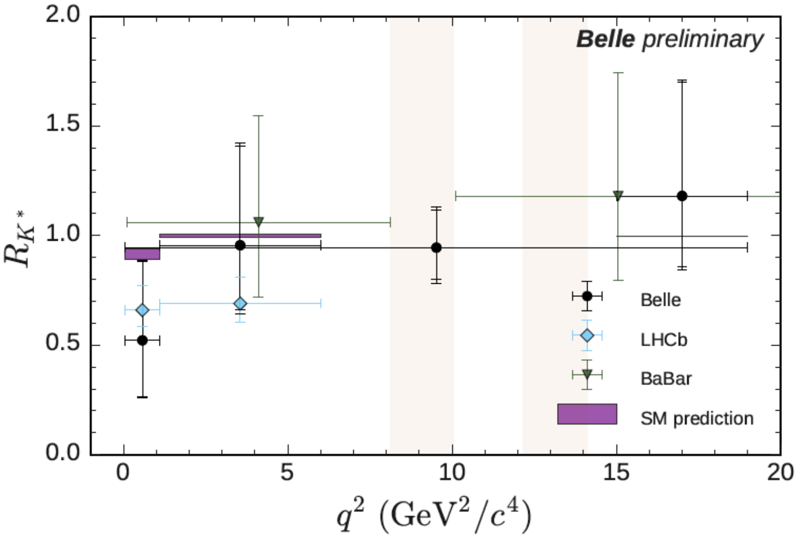
LU : an accidental symmetry of the SM

R_K , R_{K*} , R_ϕ , R_{pK} …

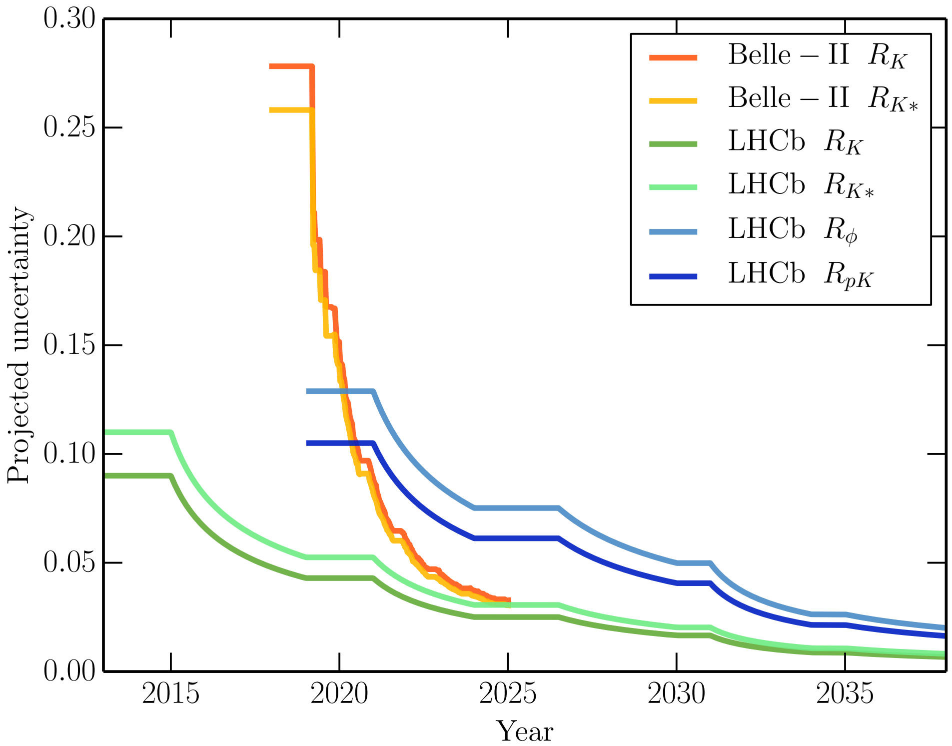
arXiv 1903.09252



Belle M. Prim Moriond 2019



R_{Hs} precision in the 1-6 GeV^2 bin



arXiv:1809.06229

Statistics only
systematics wall around 0.5 % ?

Belle II and LHCb (Upgrades) B→K$^{(*)}$ $\ell_1\ell_2$

With LHCb-Upgrade II unique access to b →dℓℓ

LHCb Upgrade I and Belle-II in ~ 2030: measurements at the few % level

LHCb-Upgrade II is needed to enter the sub-percent level to characterize the NP type

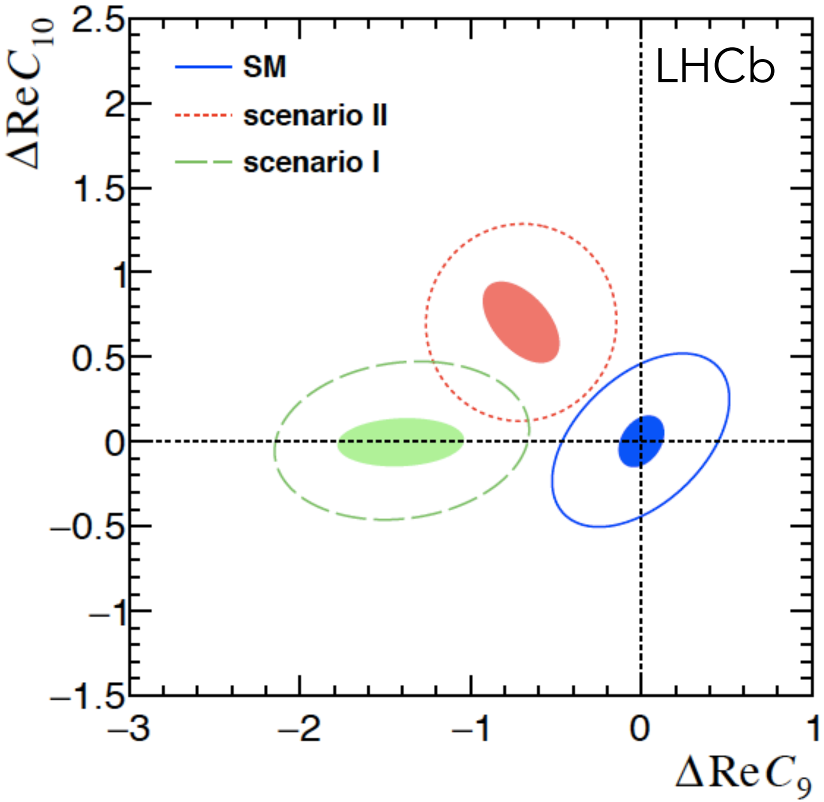
Do both !

Differences in the angular distributions of K*ee and K*μμ

Run3 (23 fb^{-1})

Upgrade II (300 fb^{-1})

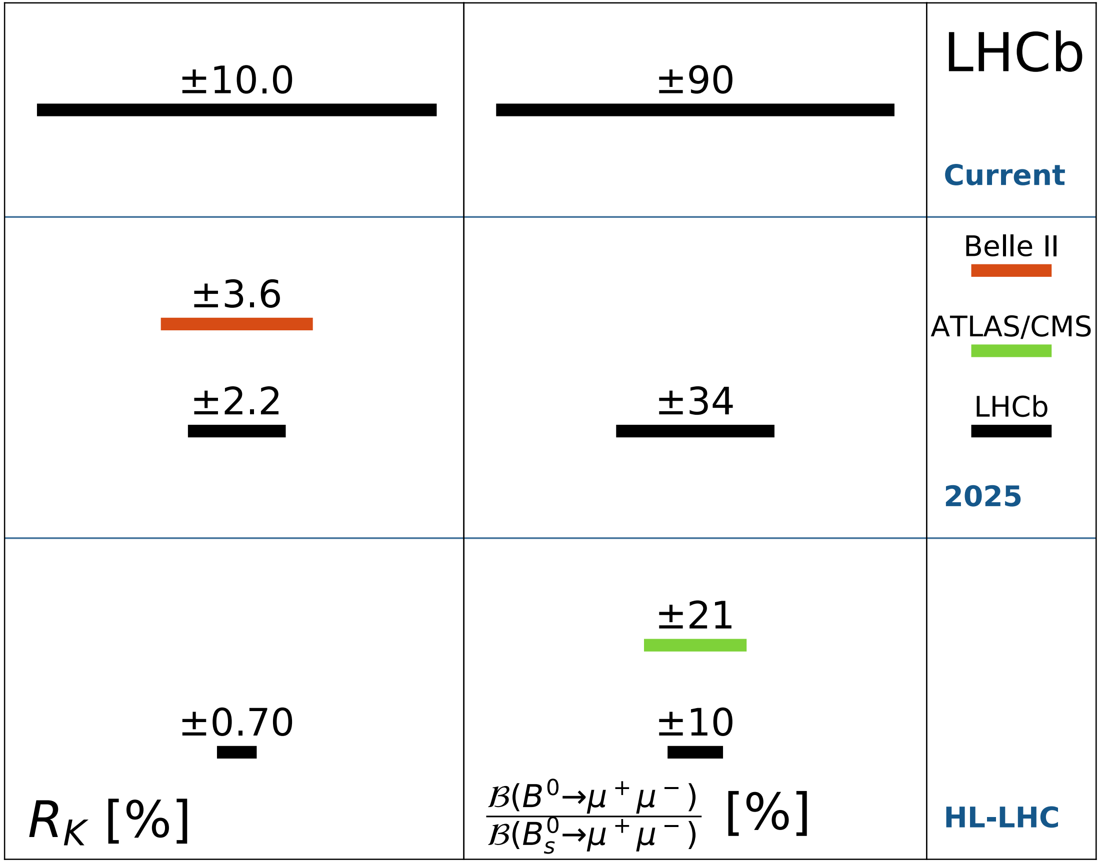
3σ contours



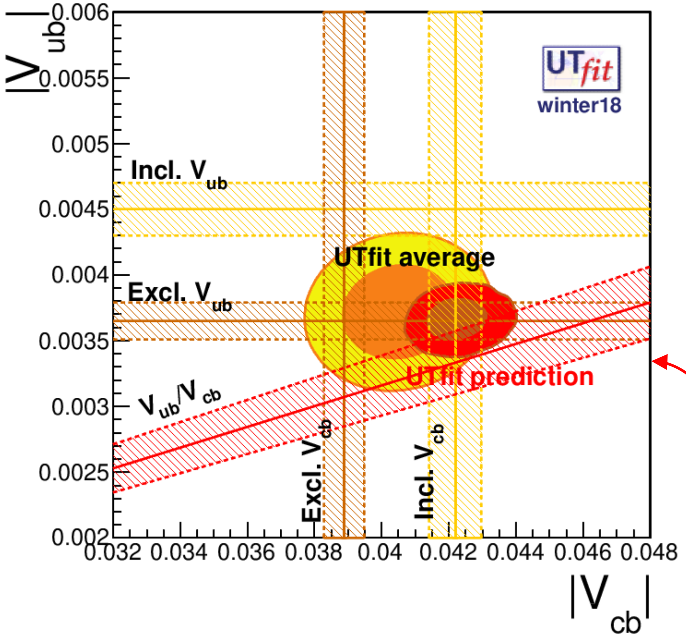
scenario	C_9^{NP}	C_{10}^{NP}	C'_9	C'_{10}	
I	−1.4	0	0	0	b→sll
II	−0.7	0.7	0	0	b→sll + R(D*)

2018 projections for rare decays in one slide

arXiv:1808.08865



b →cℓν and b →uℓν



Historically, mostly the domain of B-factories (but not fully)

Inclusive versus exclusive puzzle.
(call for publication of unfolded/efficiency corrected data)

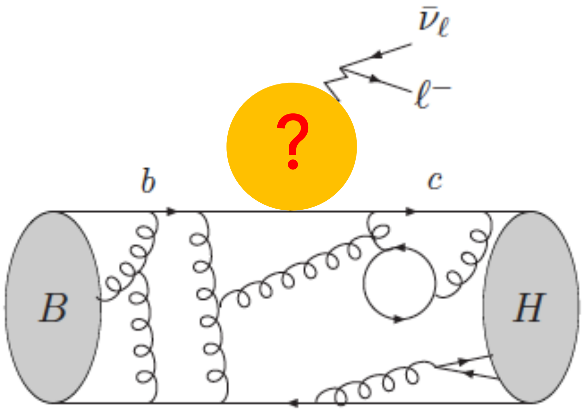
LHCb
$$\frac{|V_{ub}|^2}{|V_{cb}|^2} = \frac{\mathcal{B}(\Lambda_b^0 \to p\mu^-\overline{\nu}_\mu)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\mu^-\overline{\nu}_\mu)} R_{\rm FF}$$
Lattice QCD

Larger statistics will (hopefully) help clarifying the situation

$|V_{ub}|/|V_{cb}|$ precision :

LHCb today	LHCb 2025	Belle II 50 ab^{-1}	LHCb Upgrade II
6%	3%	1%	1%

LU tests with tree diagrams

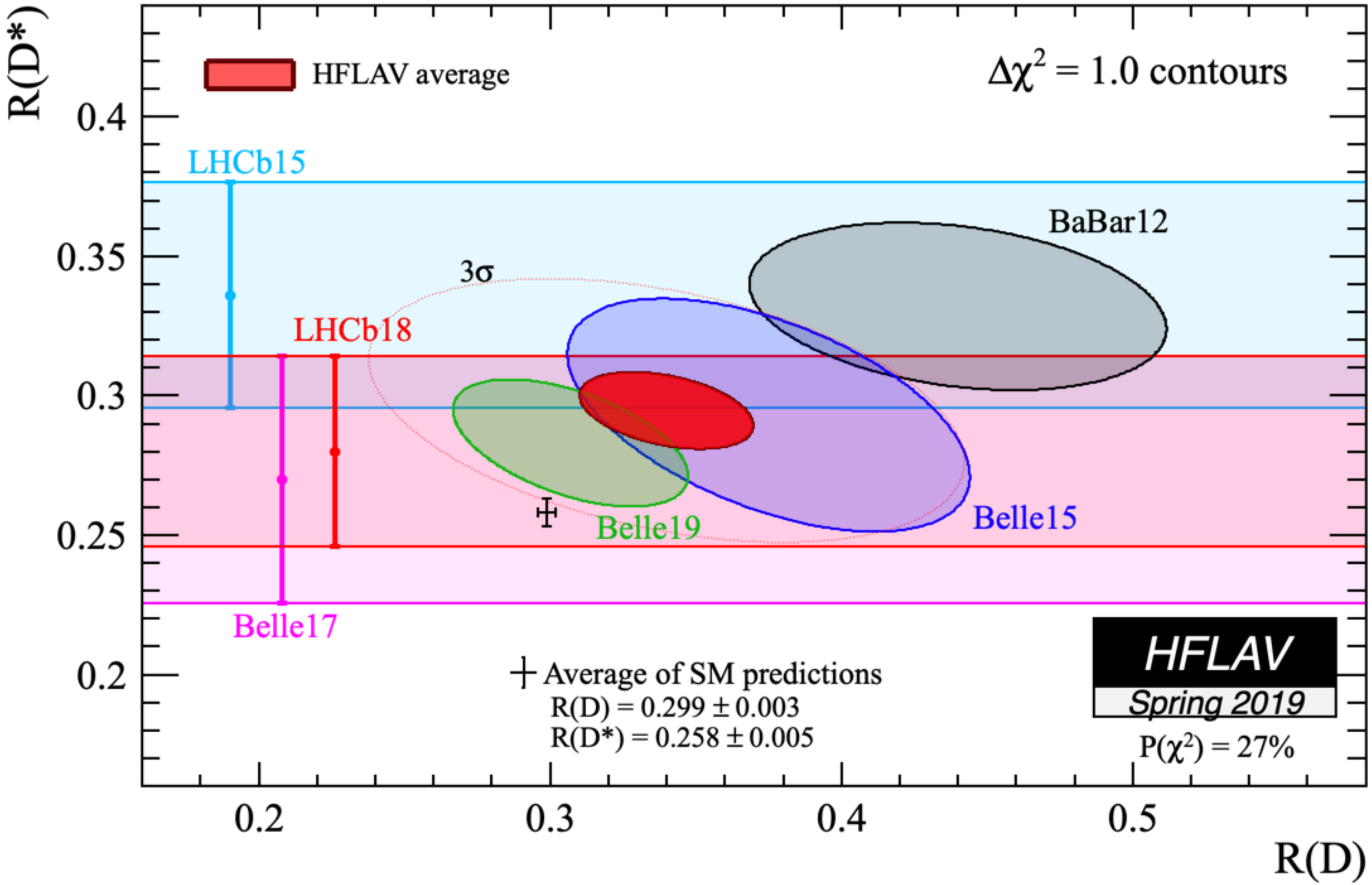


$$R_{H_c} = \frac{\mathcal{B}(H_b \to H_c\,\tau^-\overline{\nu}_\tau)}{\mathcal{B}(H_b \to H_c\,\ell'^-\overline{\nu}_{\ell'})}$$

e or μ

Need to "compensate" for the missing neutrino(s):

- rest of the event (B-Factories)
- information from large flight distance (LHCb)

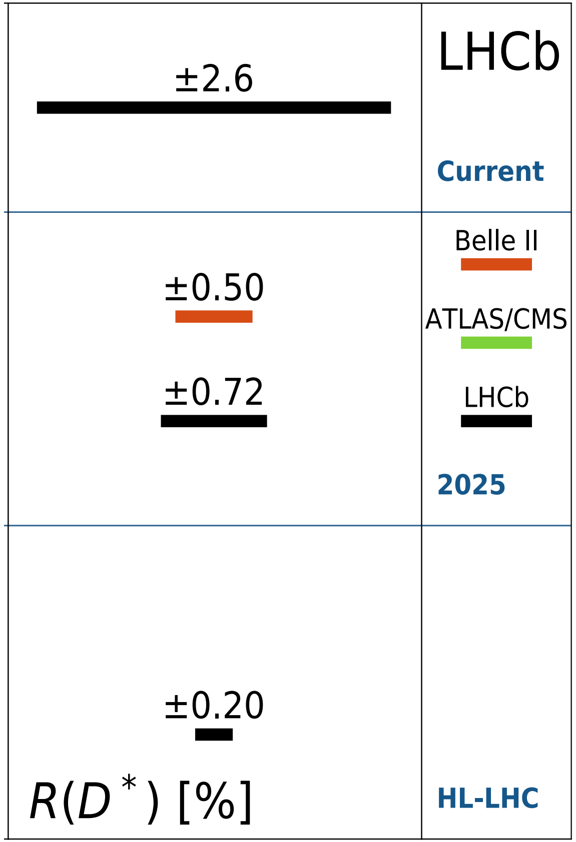


Compatibility with the SM at the level of 3.1 σ

Will greatly benefit from the two different experimental environments

2018 projections LU tests in $b \to c\ell\nu$ in one slide

arXiv:1808.08865



$R(D)$, $R(D^*)$

$R(D_s)$ $R(\Lambda_c)$, $R(J/\psi)$

theory predictions to be improved

And additional observables (τ polarization)

Summary

LHC:

- main results from LHCb
- ATLAS and CMS also contributing and are working to enlarge their flavour physics scope

A charged hadron PID is mandatory for a full physics program.

Important to have experiments in very different environments (pp and e^+e^-).

LHCb Upgrade II (x2 in Λ_{NP} wrt Upgrade I) $\Rightarrow$ LHCC framework TDR for beg. of 2021.

Complementarity/synergy with τ-charm factories results (BES III), and lower energy experiments

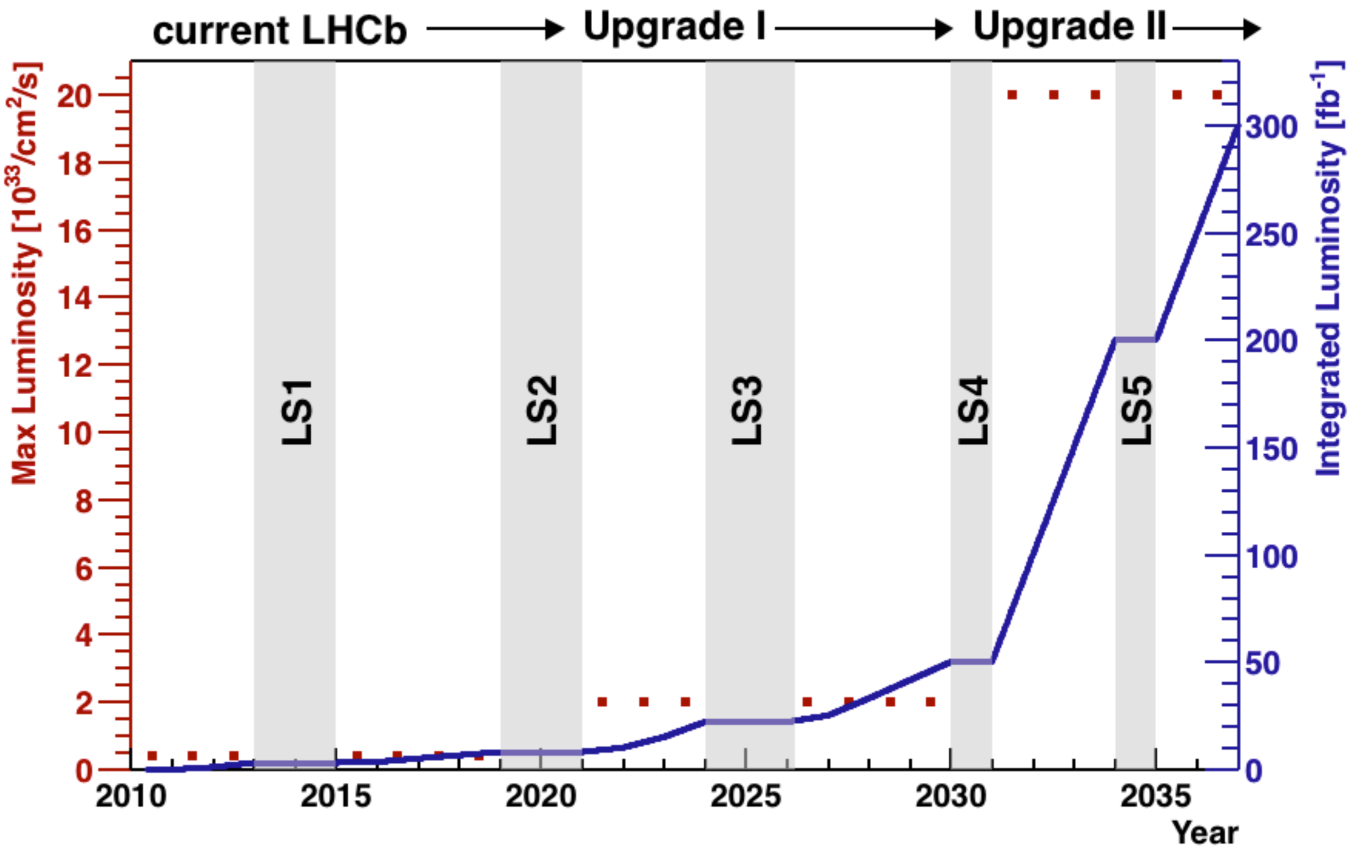
In order to benefit from the experimental precision, parallel effort on the reduction of theoretical uncertainties is required

In the longer term: « Z^0-factory » a fantastic tool for Flavour Physics

Critical for medium term:
preparation of LHCb Upgrade II, full exploitation of LHCb & Belle II data samples

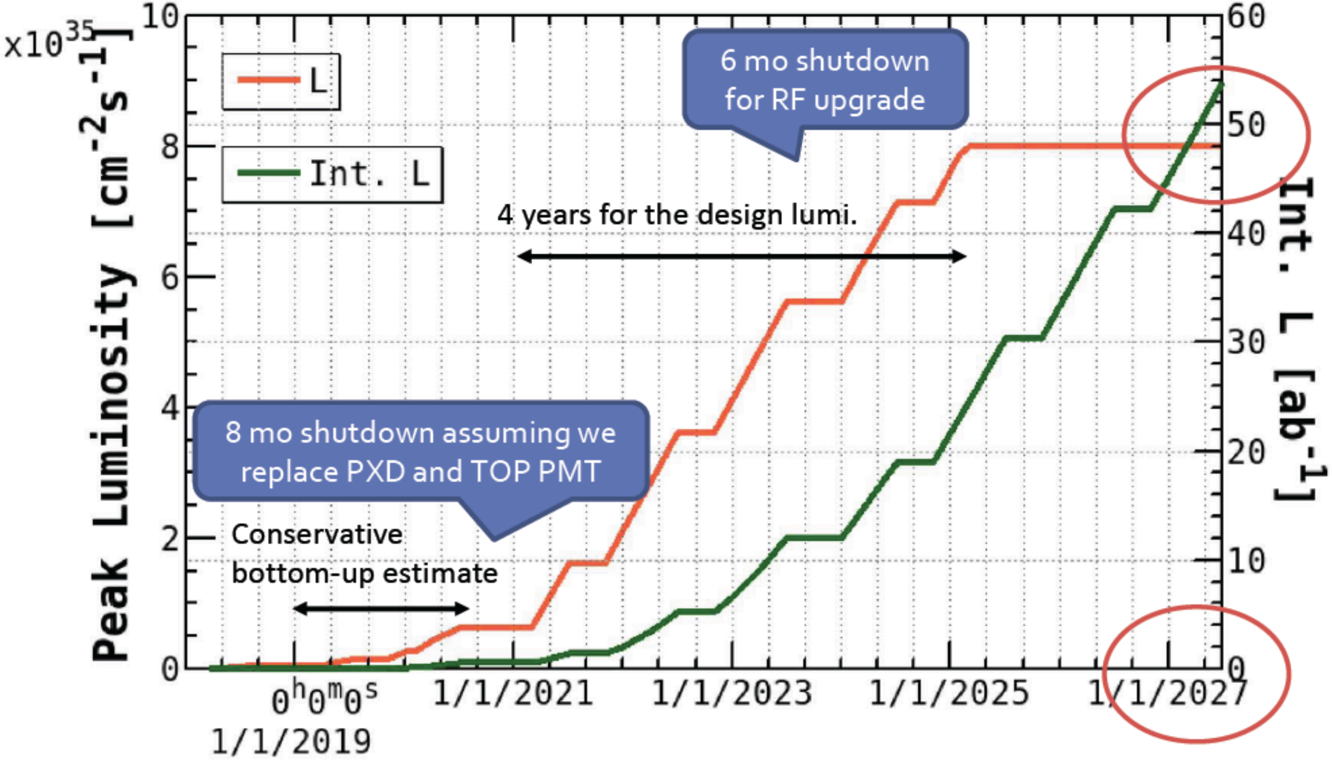
Backup slides

LHCb Upgrade II: Luminosity

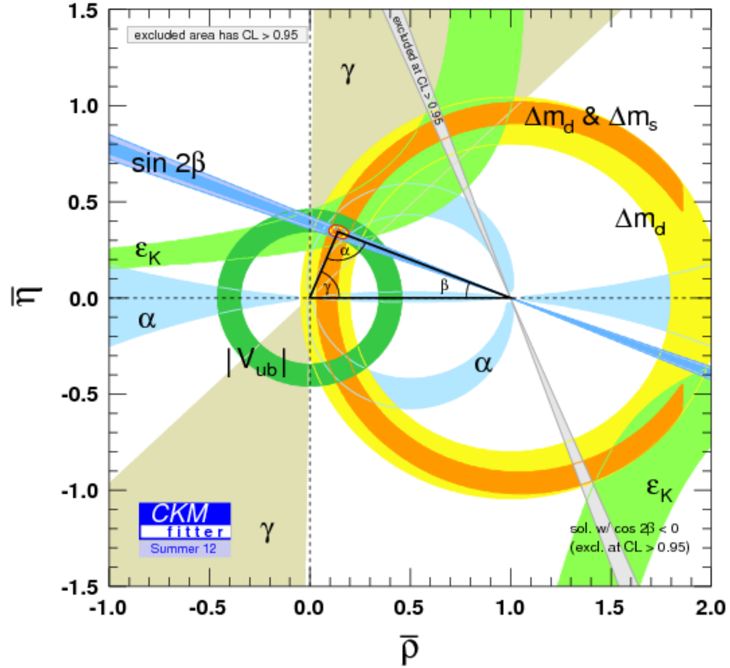


Belle-II luminosity

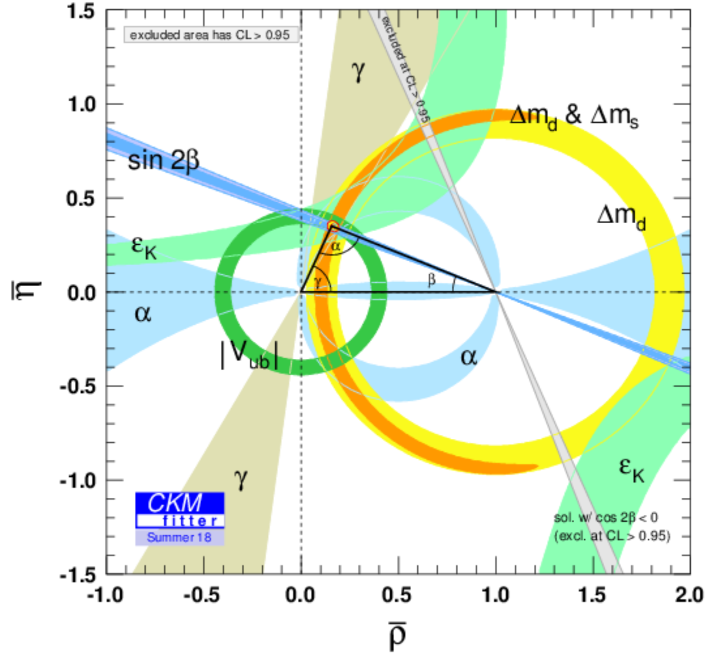
Expected (Integrated) Luminosity



2012



2018

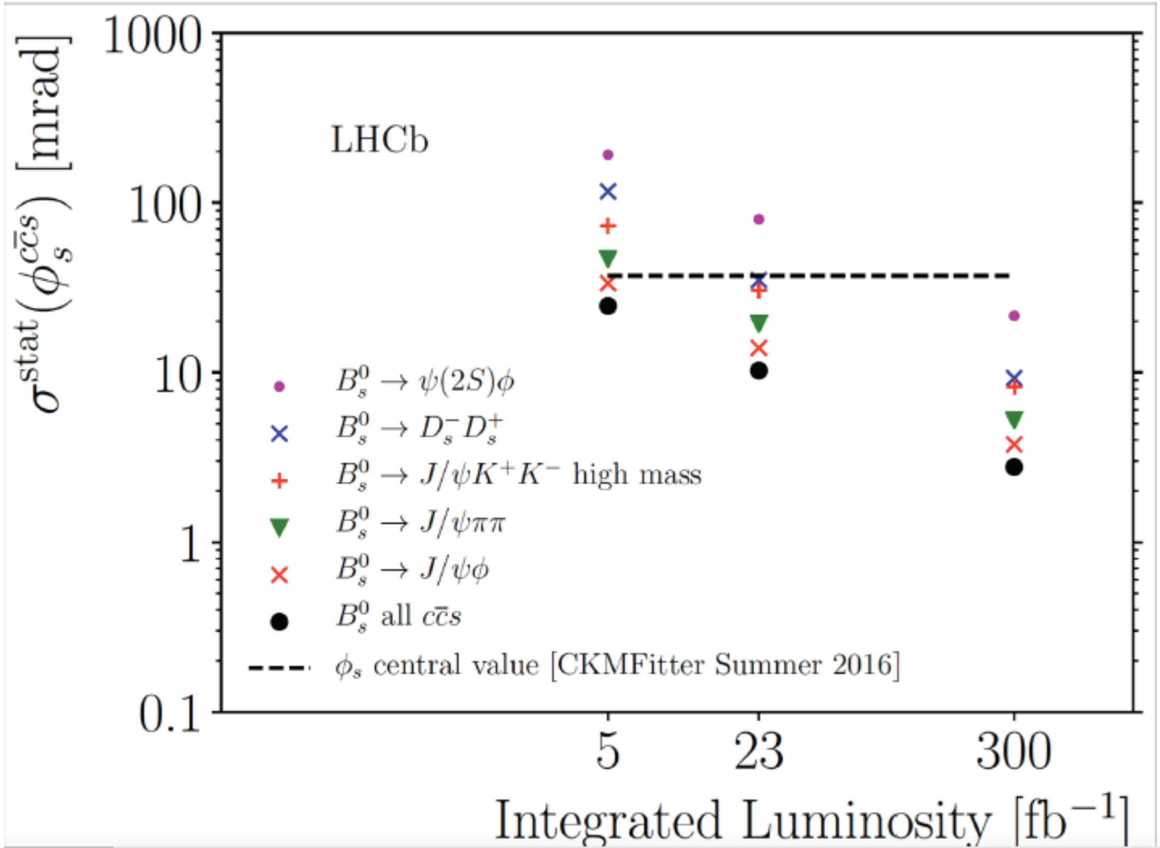


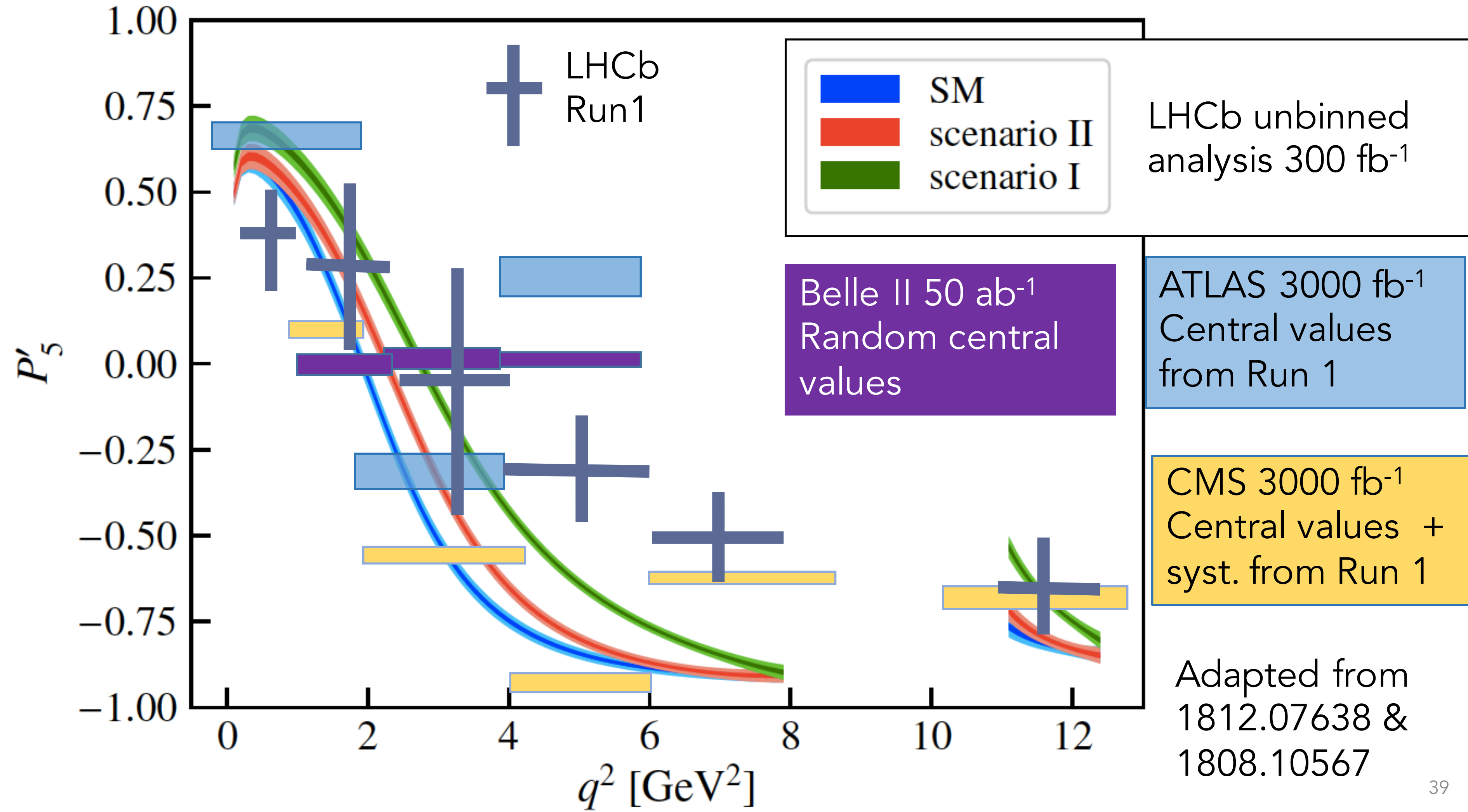
γ angle measurement factor 2.5 improvement

Δm_d , Δm_s as well as QCD parameters : factor 2 to 4

V_{ub} : factor 2 improvement but inclusive versus exclusive puzzle still present

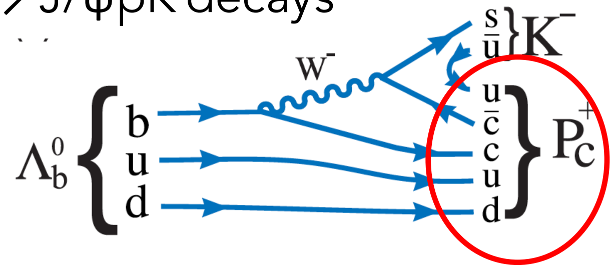
ϕ_s prospects (LHCb)



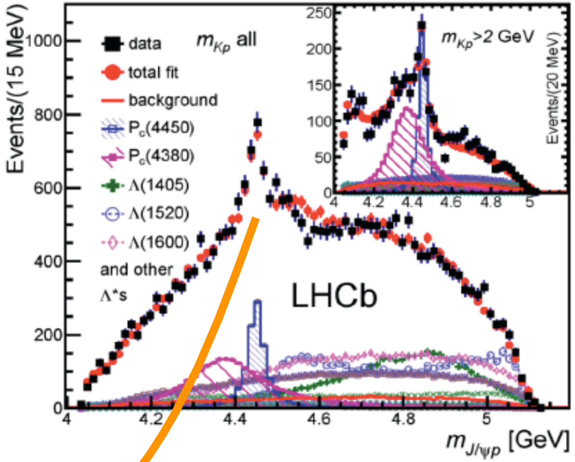

1.00
0.75
0.50
0.25
0.00
−0.25
−0.50
−0.75
−1.00
P'_5
0
2
4
6
8
10
12
q^2 [GeV^2]
LHCb Run1
SM
scenario II
scenario I
LHCb unbinned analysis 300 fb^{-1}
Belle II 50 ab^{-1} Random central values
ATLAS 3000 fb^{-1} Central values from Run 1
CMS 3000 fb^{-1} Central values + syst. from Run 1
Adapted from 1812.07638 & 1808.10567

Pentaquarks

$\Lambda_b \to J/\psi p K$ decays

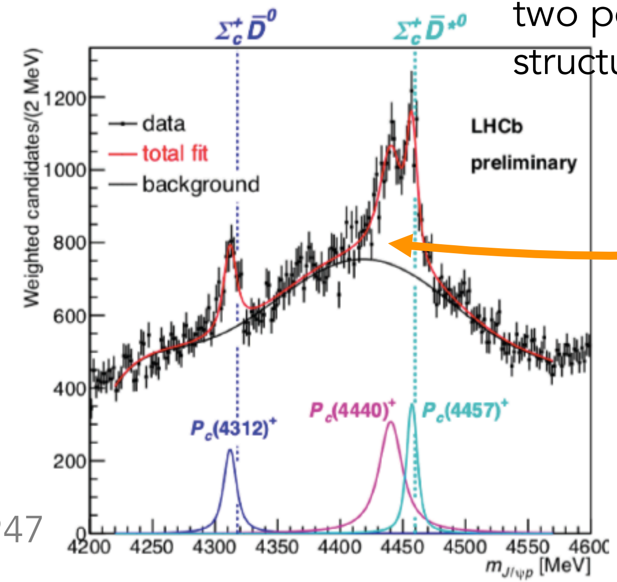


2015 PRL 115, 072001 (2015)

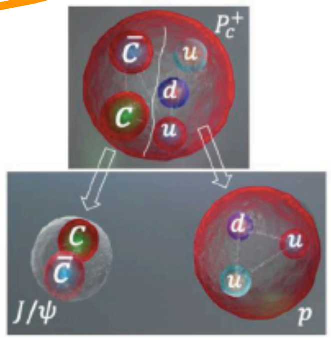


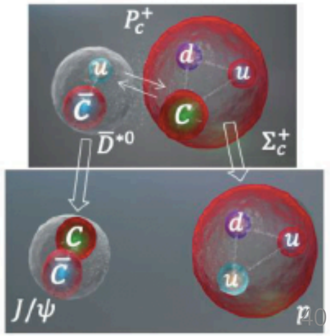
$P_c(4450)$: a two peaks structure !

2019:



tightly bound or molecular ?





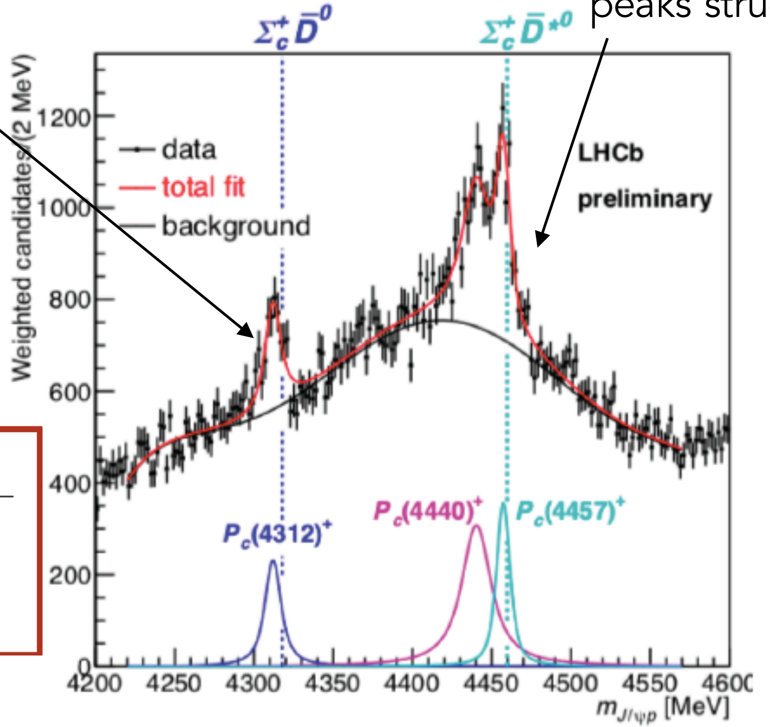
arXiv:1904.03947

Update using Run2 full statistics ⇒x 9 statistics of the published result !
(x2 selection , x3 integrated luminosity, x cross section changes with energy)

Narrow bump hunting analysis with empirical background shape

$P_c(4450)$: a two peaks structure !

New peak at 4312 MeV



Full amplitude analysis ongoing especially needed to confirm the broad $P_c(4380)$

State	M [MeV]	Γ [MeV]	(95% CL)	$\mathcal{R}$ [%]
$P_c(4312)^+$	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	$9.8 \pm 2.7^{+\ 3.7}_{-\ 4.5}$	(< 27)	$0.30 \pm 0.07^{+0.34}_{-0.09}$
$P_c(4440)^+$	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+\ 8.7}_{-10.1}$	(< 49)	$1.11 \pm 0.33^{+0.22}_{-0.10}$
$P_c(4457)^+$	$4457.3 \pm 0.6^{+4.1}_{-1.7}$	$6.4 \pm 2.0^{+\ 5.7}_{-\ 1.9}$	(< 20)	$0.53 \pm 0.16^{+0.15}_{-0.13}$

$$\mathcal{R} \equiv \frac{\mathcal{B}(\Lambda_b \to P_c^+ K^-)\mathcal{B}(P_c^+ \to J/\psi p)}{\mathcal{B}(\Lambda_b \to J/\psi p K^-)}$$

Table 9.1: Expected data samples at LHCb Upgrade II and Belle II for key decay modes for the spectroscopy of heavy flavoured hadrons. The expected yields at Belle II are estimated by assuming similar efficiencies as at Belle.

	LHCb			Belle II
Decay mode	$23\,\text{fb}^{-1}$	$50\,\text{fb}^{-1}$	$300\,\text{fb}^{-1}$	$50\,\text{ab}^{-1}$
$B^+ \to X(3872)(\to J/\psi\,\pi^+\pi^-)K^+$	14k	30k	180k	11k
$B^+ \to X(3872)(\to \psi(2S)\gamma)K^+$	500	1k	7k	4k
$B^0 \to \psi(2S)K^-\pi^+$	340k	700k	4M	140k
$B_c^+ \to D_s^+ D^0 \overline{D}^0$	10	20	100	—
$\Lambda_b^0 \to J/\psi\, pK^-$	340k	700k	4M	—
$\Xi_b^- \to J/\psi\,\Lambda K^-$	4k	10k	55k	—
$\Xi_{cc}^{++} \to \Lambda_c^+ K^-\pi^+\pi^+$	7k	15k	90k	<6k
$\Xi_{bc}^+ \to J/\psi\,\Xi_c^+$	50	100	600	—

R_X expected precision in the 1-6 q^2 bin

When ?	At hands	End of Run3 (2025)	2027 ?	End of Run4 (2030?)	End of HL-LHC
Int. Lumi	9 fb^{-1}	23 fb^{-1}	50 ab^{-1}	50 fb^{-1}	300 fb^{-1}
R_K	.043	.025	.036	.017	.007
R_{K*}	.052	.031	.032	.020	.008
R_ϕ	.13	.076	-	.050	.020
R_{pK}	.105	.061	-	.041	.016

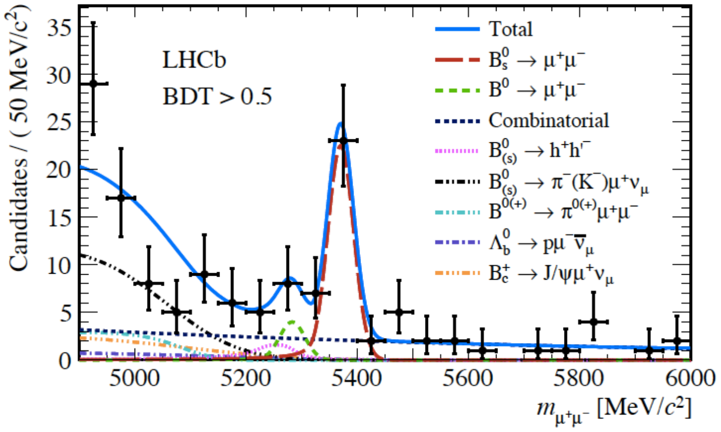
NB : Run1 + 2 fb^{-1} @ 13 TeV R_K achieved precision 7%

LHCb Ugrade I and Belle-II: measurements at the few % level

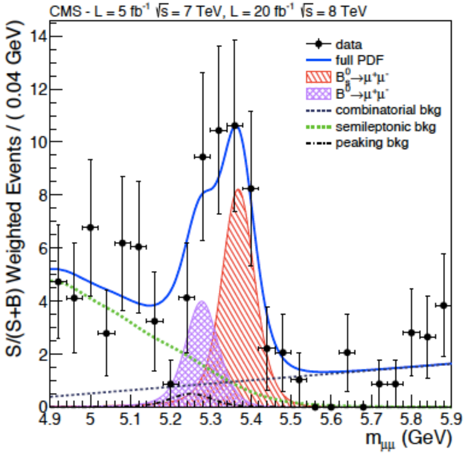
LHCb-Upgrade II is needed to enter the sub-percent level

$B_s \to \mu\mu$

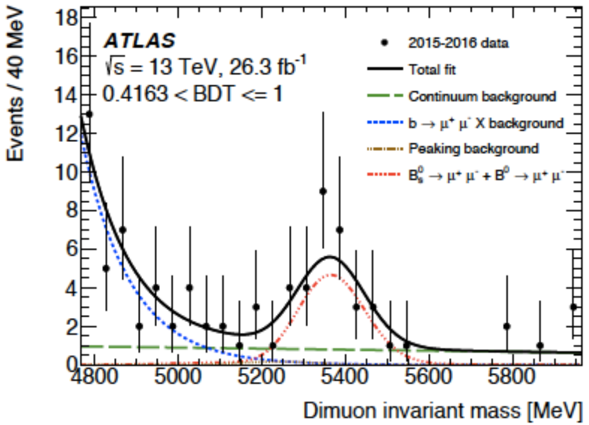
PRL. 118, 191801



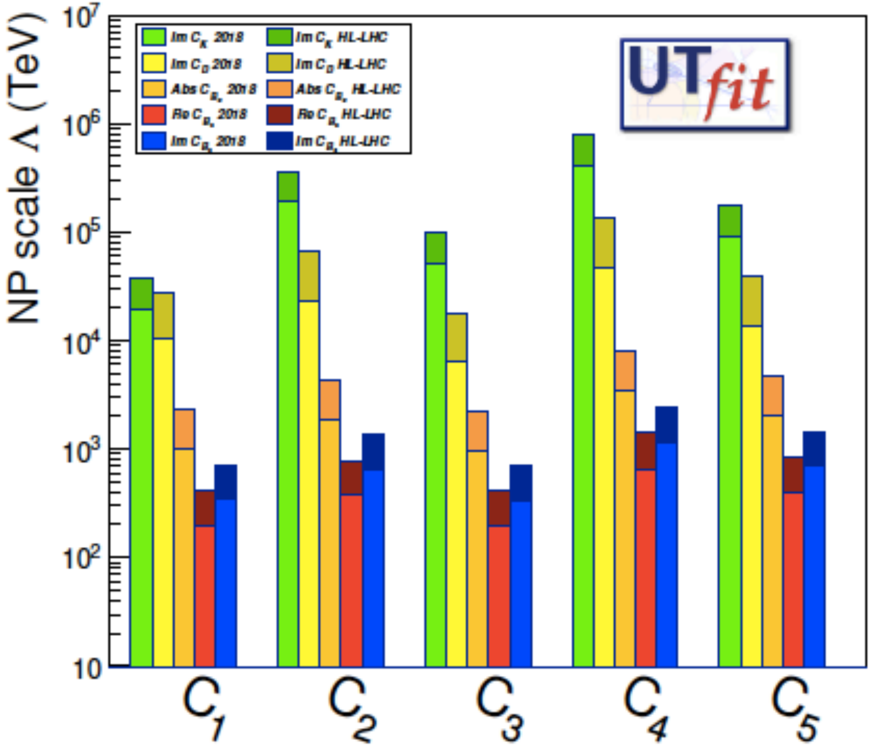
PRL 111 (2013) 101804



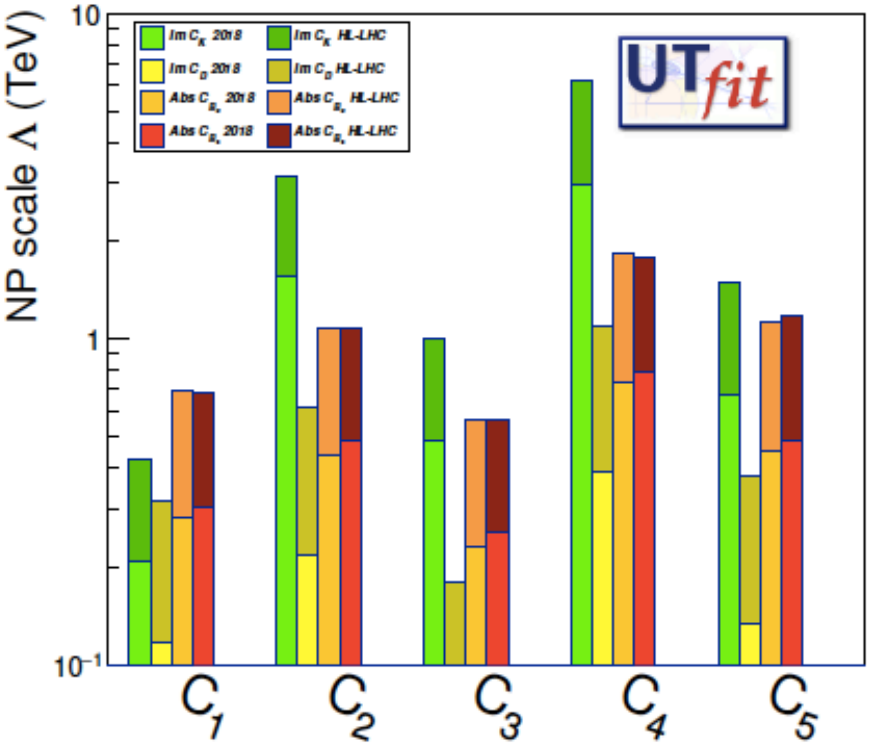
JHEP 04 (2019) 098



NP couplings = 1
tree level



NP is MFV coupling, contributes at the 1-loop level



After HL-LHC with LHCb Upgrade II increase by a factor 2 of the NP scale reach

[Upgrade II physics case, LHCb-PUB-2018-009]

Yield	Run 1 result	$9\,\mathrm{fb}^{-1}$	$23\,\mathrm{fb}^{-1}$	$50\,\mathrm{fb}^{-1}$	$300\,\mathrm{fb}^{-1}$
$B^+ \to K^+ e^+ e^-$	254 ± 29 [274]	1 120	3 300	7 500	46 000
$B^0 \to K^{*0} e^+ e^-$	111 ± 14 [275]	490	1 400	3 300	20 000
$B^0_s \to \phi e^+ e^-$	–	80	230	530	3 300
$\Lambda^0_b \to pK e^+ e^-$	–	120	360	820	5 000
$B^+ \to \pi^+ e^+ e^-$	–	20	70	150	900