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# Theory perspective for HL-LHC in flavor

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Workshop on the physics of HL-LHC – CERN, October 31, 2017

# Objective

The purpose is to address and discuss the question:

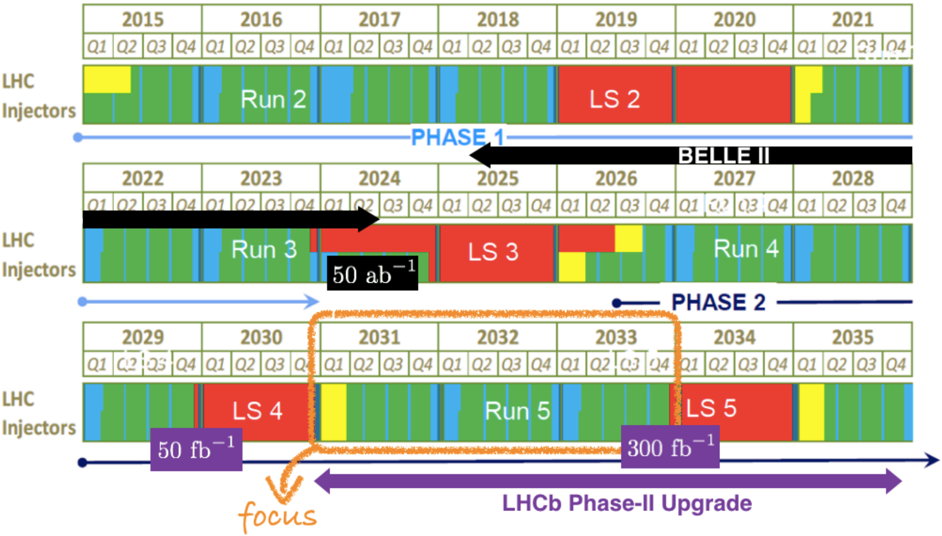
**Q :** What can HL-LHC do in the context of flavor for BSM ?

and collect ideas and suggestions for the corresponding contribution to the Yellow Report.

The answer to **Q** depends strongly on the status of flavor by the start of HL-LHC era
$\rightarrow$ after LHC Phase-1 and Belle II program completed
Thus one would need to consider various scenarios.

Note that LHCb plays the fundamental role in Flavor @ LHC, but ATLAS and CMS also contribute with important measurements.

# Time Stage




LHCb Phase-II upgrade to be able to benefit of HL.

# In the context of Flavor Anomalies

Today, the flavor anomalies occupy a central focus.

In this talk I will consider (by request of the conveners):

- LFNU in tree decays
- LFNU in FCNCs
- Penguin $B$ decays

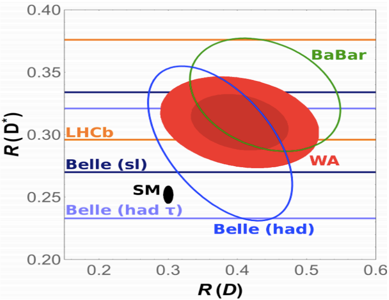
By 2030, the anomalies will be either confirmed or ruled-out independently by LHCb Phase-1 and Belle II. Albrecht et al, 1709.10308

Question **Q** must be addressed in this context

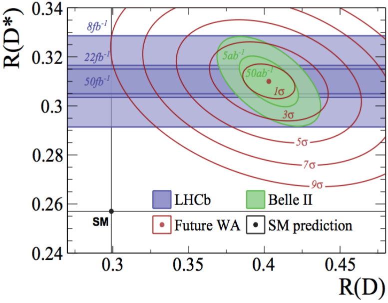
# LFNU in Charged Currents

## $R(D^{(\star)})$ : Present and Future

| Observ. | $\sigma(SM)$ | $\sigma^{2017}_{\mathrm{expWA}}$ | Belle II (50 $ab^{-1}$) | LHCb I (50 $fb^{-1}$) |
|---|---|---|---|---|
| $R(D)$ | 1% | 11.6% | 3.2% | ? |
| $R(D^\star)$ | 1% | 5.5% | 2.2% | 1.6% |



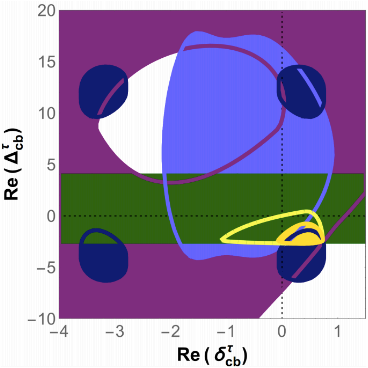

Celis, Jung, Li, Pich, 1612.07757




Albrecht et al, 1709.10308

# LFNU in Charged Currents

- 5 operators in the WET (for each lepton flavor, if no LFV)
- 6 ops in SMEFT (at tree level), 2 of them LFU ($O_{VR}$ is LFU up to $v^4/\Lambda^4$)
- New observables are already constraining the viable explanations for $R(D^{(\star)})$




Fit to scalar operators:

Dark blue : $R(D^{(\star)})$

Light blue : $d\Gamma(B \to D^{(\star)}\tau\nu)/dq^2$

Green : $B_c$ lifetime

Purple : $R(X_c)$

Dark yellow : Combined

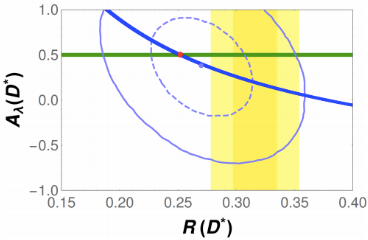
Yellow : Combined (complex)

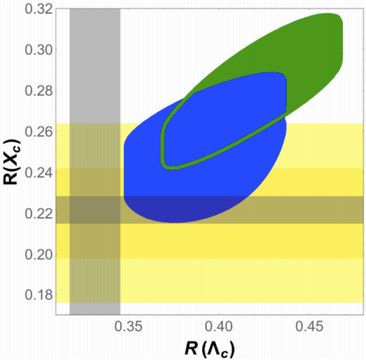
Celis, Jung, Li, Pich, 1612.07757

- New observables are also important to distinguish among different scenarios

V-A scenario
Scalar scenario

Celis, Jung, Li, Pich, 1612.07757




- $\tau$ Polarization, inclusive, baryonic...
- Angular distributions also very powerful Alonso et al 2006, Ligeti et al 2006
- Also FLAVOR: what about $b \to u\tau\nu$ and $c \to d(s)\tau\nu$?

# LFNU in Charged Currents : Prospects

Thanks to Greg Ciezarek

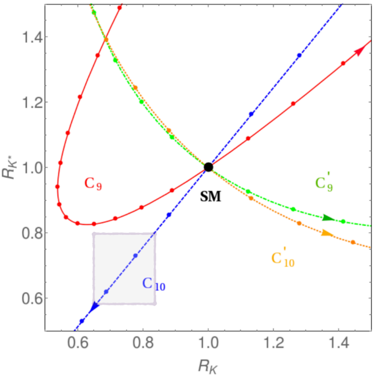
1. By Run 4, the measurements of $R_X$ with $X = \{D^{(*)}, \Lambda_c\}$ will have negligible statistical uncertainty, both for $\tau/\mu$ and $\mu/e$ non-universality ratios.
   There is no gain here from Phase-2 upgrade.
2. Phase-2 will make possible the measurement of $R_X$ with $X = \Lambda_c^*, \Omega_c, \Xi_c, \ldots$ and similar ratios of $B_s$, all at the few percent level CERN-LHCC-2017-003, LHCb EoI
3. Phase-2 allows $\tau/\mu$ universality ratios in $B_c$ decays.
4. Phase-2 will provide precise measurements of tau-polarization observables in $B \to D^{(*)}\tau\nu$. But what is the gain w.r.t. Run 4?
5. Full angular analyses of $B \to D^{(*)}\ell\nu$ already powerful by Run 4. Precise measurements of $\tau$ mode only possible in Phase-2.
6. $B_c \to \tau\nu$ is not competitive with the $B_c$ lifetime constraint.
   Improve theory and measurements of other decay modes.
7. Measurements of $B_s \to D_s^{(*)}\ell\nu$ are underway.
8. $b \to u\tau\nu$ and $c \to d(s)\tau\nu$ look difficult.
   Ongoing work on $B \to p\bar{p}\tau\nu$, but difficult for theory.

# LFNU in FCNCs : Current

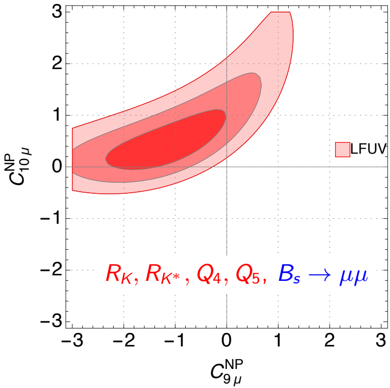
- Current tensions in $\frac{b\to s\mu\mu}{b\to see}$ combined up to $\sim 4\sigma$ (not only $R_{K^{(*)}}$)
- Constrain $\simeq (C_{i\mu}^{NP} - C_{ie}^{NP})$. But let's assume NP in $\mu$ only...

$$\mathcal{L}_{\text{eff}}^{NP} = -\frac{4G_F}{\sqrt{2}}\frac{\alpha_{\text{em}}}{4\pi}\left\{ C_{9\mu}^{NP}\,[\bar{s}\gamma_\nu P_L b][\bar{\mu}\gamma^\nu \mu] + C_{10\mu}^{NP}\,[\bar{s}\gamma_\nu P_L b][\bar{\mu}\gamma^\nu\gamma_5 \mu] + \cdots \right\}$$

Li-Sheng Geng *et al* 1704.05446

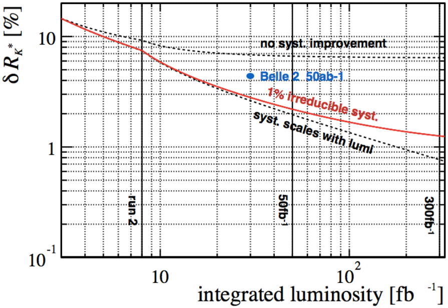



Capdevila *et al* 1704.05340



# LFNU in FCNCs : 2030

- ☐ Currently $\delta R_{K^{(\star)}} \sim 15\%$
- ☐ Prospects for $R_K$, $R_K^*$ from Phase-1 and Belle II are $\delta R_{K^{(\star)}} \sim$ few %

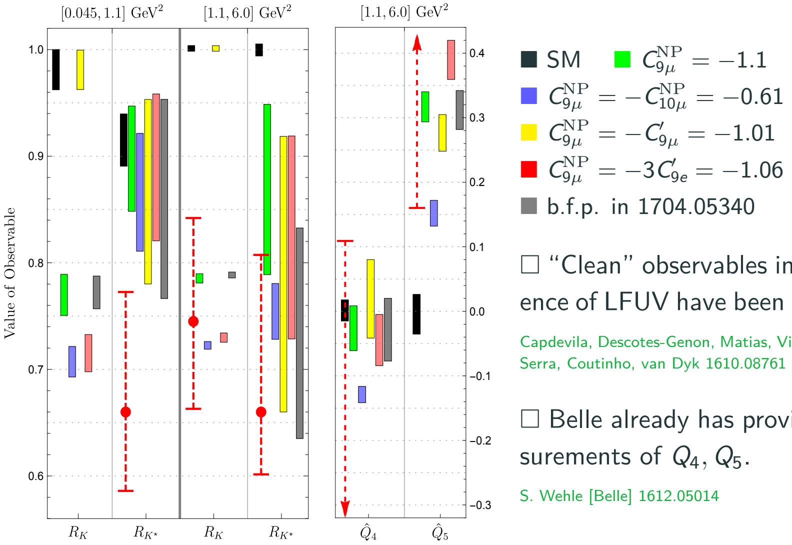



- ☐ Enough to establish NP (if central values stay put)
- ☐ Also other ratios measured with high precision, including angular obs

- ☐ Thus NP situation probably clear : $> 5\sigma$ in each observable ($R_{K,K^*,\phi,\Lambda_b}\ldots$)
- ☐ and some info about the patterns ($C_9$ vs $C_{10}$ vs RHCs)
- ☐ The question is to define the patterns precisely

# LFNU in FCNCs : NP-discrimination and hadronic effects

☐ In the presence of LFUV (SM or NP), hadronic uncertainties reappear.




Capdevila, Crivellin, Descotes-Genon, Matias, Virto 1704.05340

☐ "Clean" observables in the presence of LFUV have been proposed.

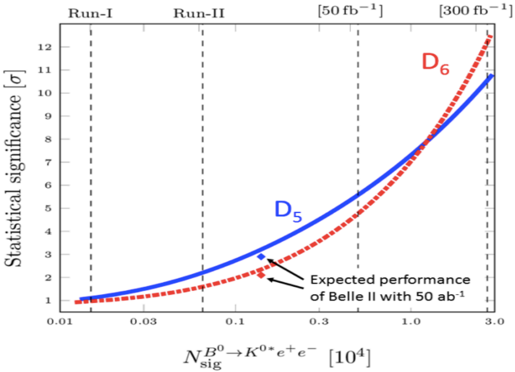
Capdevila, Descotes-Genon, Matias, Virto 1605.03156
Serra, Coutinho, van Dyk 1610.08761

☐ Belle already has provided measurements of $Q_4, Q_5$.

S. Wehle [Belle] 1612.05014

# LFNU in FCNCs : Clean observables

- ☐ Measurement of clean observables possible at Phase-1 and Belle II
- ☐ Phase-2 great potential CERN-LHCC-2017-003, LHCb EoI




$D_{5,6}$ defined in

Serra, Coutinho, van Dyk 1610.08761

Expect similar prospects for clean observables $Q_i$, $B_i$ in

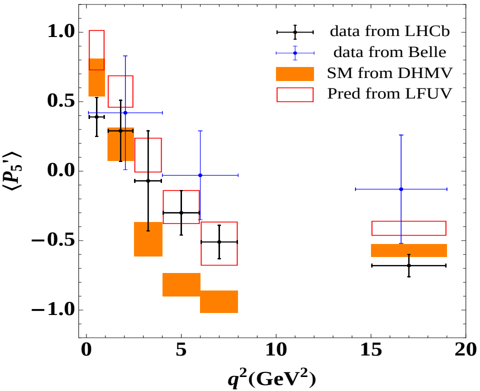
Capdevila, Descotes, Matias, JV 1605.03156

- ☐ Needed to confirm many LFNU tests
- ☐ Probing $\tau/\mu$ universality extremely difficult, see later

# New Physics in $b \to s\ell\ell$

☐ LFNU implies NP in $b \to s\mu\mu$ and/or $b \to see$.

☐ Currently effects in $\mu$ are preferred because of $b \to s\mu\mu$ anomalies.

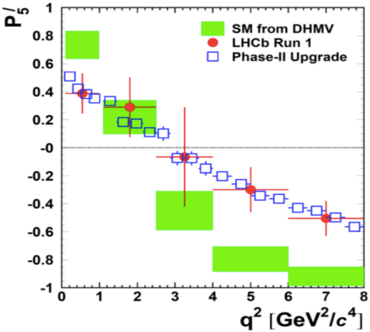



☐ These anomalies will be well probed experimentally before Phase-2.
(See e.g. Hurth, Mahmoudi, Martinez-Santos, Neshatpour 1705.06274, Albrecht et al 1709.10308)

# New Physics in $b \to s\ell\ell$

☐ But Phase-2 will put experimental errors to negligible levels

CERN-LHCC-2017-003, LHCb EoI




$P_5'$ defined in

Descotes-Genon, Matias, Ramon, JV 1207.2753

☐ Bottleneck is SM uncertainties:

Assuming vanishing exp uncertainties

$\text{Pull}(P_5'^{[2.5,4.0]}) = 3.5\sigma$

$\text{Pull}(P_5'^{[4.0,6.0]}) = 6.5\sigma$

$\text{Pull}(P_5'^{[6.0,8.0]}) = 5.4\sigma$

☐ Good motivation to improve on the theory (see later).

As Jure said: We have got 15 years to figure this out (not much really)

# New Physics in $b \to s\ell\ell$

□ For the moment diversity of measurements can serve.

□ Phase-2 will provide the a full spectrum of $b \to s\mu\mu$ and $b \to see$ including new observables in $B_s$ and $\Lambda_b$ (other baryons?).

□ All in all, full map of deviations in $b \to s\ell\ell$, $\ell = \{e, \mu\}$.

□ This will settle the $\mu$ vs e question

- Some models predict no effects in $e^+e^-$ (e.g. $U(1)_{L_\mu - L_\tau}$ Altmannhofer et al 1403.1269)
- Some models predict large effects in $e^+e^-$ (e.g. $U(2)$ flavor models Falkowski, Nardecchia, Ziegler 1509.01249)

# New Physics in $b \to s\ell\ell$ : Hadronic contributions

☐ Given the experimental prospects, theory is the bottleneck.
Two types of non-perturbative problems:

1. Form Factors
2. Non-local effects (e.g. long distance quark loops)

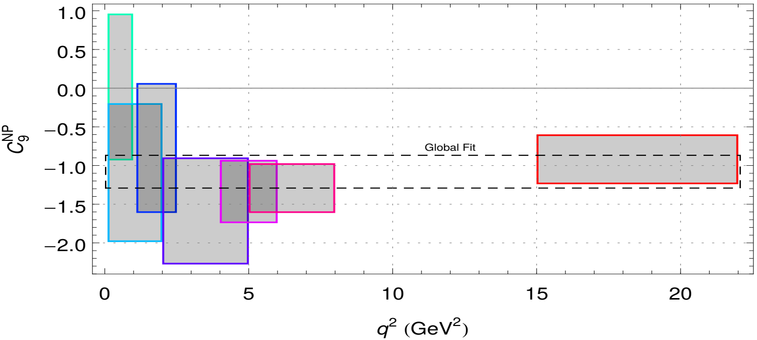
☐ Expected improvement of FFs from Lattice until 2030. (LCSRs already in the limit of their capacity).

☐ Non-local effects:

- Test the data through the fits:
  - Tests of $q^2$ dependence
  - Tests of $K^*$-helicity dependence
- Data driven determinations

# New Physics in $b \to s\ell\ell$ : Hadronic contributions

☐ Testing the data : $q^2$-dependence Descotes-Genon, Hofer, Matias, JV 1510.04239



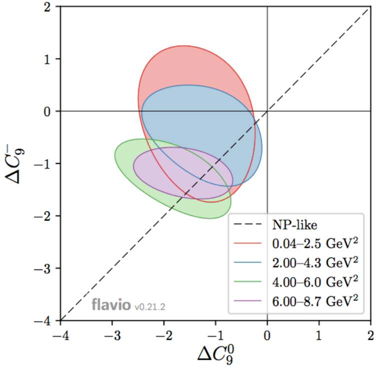

☐ Tiny uncertainites will allow to test hadronic contributions precisely

See also Altmannshofer, Straub 1503.06199, Ciuchini et al 1512.07157, Chobanova et al 1702.02234

# New Physics in $b \to s\ell\ell$ : Hadronic contributions

☐ Testing the data : $K^*$-helicity dependence

Altmannshofer, Niehoff, Stangl, Straub 1703.09189

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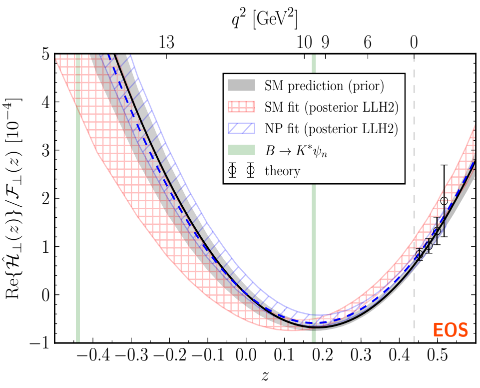
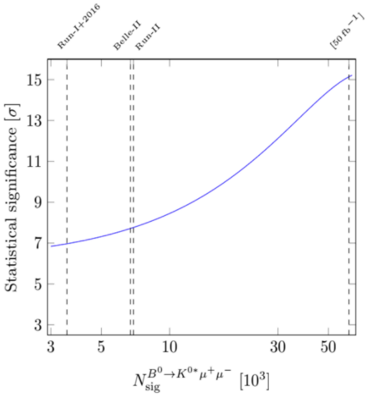
# New Physics in $b \to s\ell\ell$ : Hadronic contributions

☐ Data-driven determinations (with or w/o theory input)




Bobeth, Chrzaszcz, van Dyk, JV 1707.07305



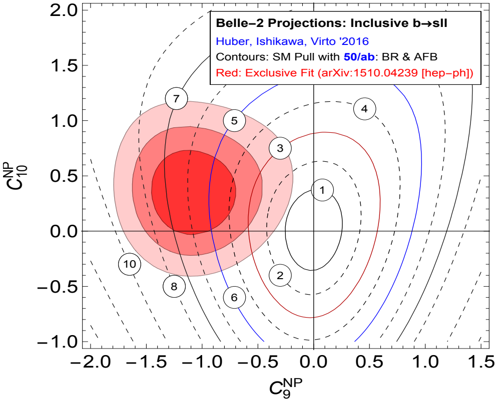

Chrzaszcz, Coutinho, Mauri, Serra, van Dyk w.i.p.

Essential input : $B \to K^*\psi_n$ (independent of $C_9$).

See also Blake, Egede, Owen, Pomery, Petridis 1709.03921

# New Physics in $b \to s\ell\ell$ : Hadronic uncertainties

☐ Also: Must be consistent with **inclusive** data



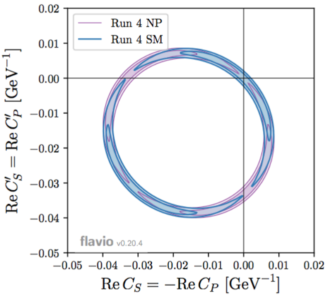

This is important (analogy with $V_{ub}$, $V_{cb}$).

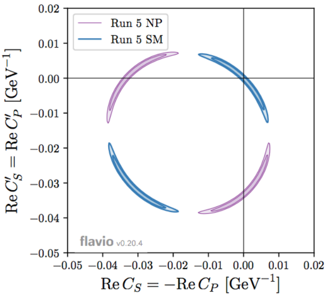
☐ Of course global fits also test global consistency (important wide range of $b$-hadron decay channels accessible in Phase-2).

**In summary**: with higher and higher experimental precision, consistency will make it harder and harder to be fooled by QCD effects.

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

- ☐ If $C_{10}$ plays a role, also $B_{d,s} \to \mu\mu$ is a clean confirmation. But this also very sensitive to scalar operators.
- ☐ Here LHCb + ATLAS + CMS combination important
- ☐ Current: $\sigma_{\mathrm{SM}}(BR) \simeq 5\%$, $\sigma_{\mathrm{exp}}(BR) \simeq 20\%$
- ☐ Future: $\sigma_{\mathrm{exp,Run4}}(BR) \simeq 5\%$, $\sigma_{\mathrm{exp,Run5}}(BR) \simeq 2.5\%$, and $A_{\Delta\Gamma}$!



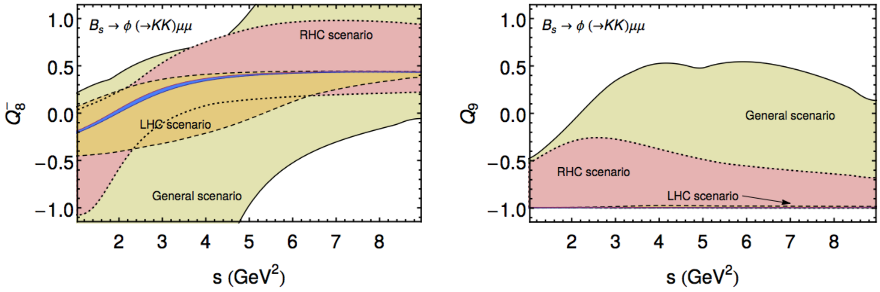

Altmannshofer, Niehoff, Straub 1702.05498

# New observables from Phase-2

**Time dependence in $B \to V\ell\ell$**

Descotes-Genon, JV 1502.05509

☐ Flavour-tagged t-dependent analysis of $B_s \to \phi\mu\mu$.

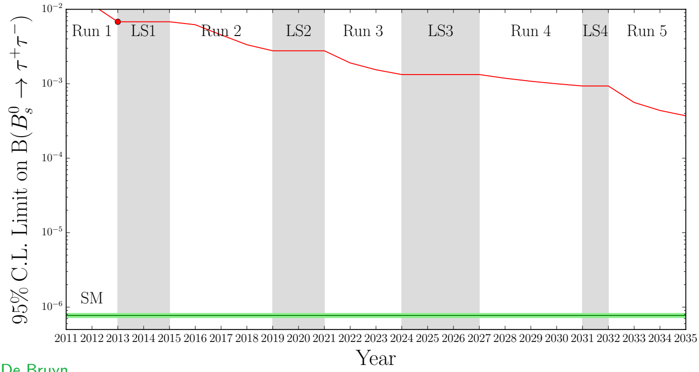



$$\frac{d\Gamma(B(t) \to f_{CP}) - d\Gamma(\bar{B}(t) \to f_{CP})}{ds\, d\cos\theta_\ell\, d\cos\theta_M\, d\phi} = \sum_i [J_i(t) - \widetilde{J}_i(t)]\; f_i(\theta_\ell, \theta_M, \phi)$$

$$J_i(t) - \widetilde{J}_i(t) = e^{-\Gamma t}\Big[(J_i - \widetilde{J}_i)\cos(x\Gamma t) - s_i \sin(x\Gamma t)\Big] \quad (Q_i \simeq \text{“clean”} s_i)$$

# New observables from Phase-2

- ☐ Full spectrum of $b \to d\ell\ell$. Better precision than $b \to s\ell\ell$ from Run 1.
- ☐ Time-dependence in $B \to \rho\mu\mu$
- ☐ Isospin tests in $B \to \rho\mu\mu$ and $B \to \pi\mu\mu$.
- ☐ Tau modes. Not looking good (but can constrain large effects!).



# Outlook

☐ If Anomalies are genuine, will be established by 2030

☐ Still Phase-2 crucial to sharpen the NP patterns, to bound QCD effects, and to study the flavor

☐ Need still some work to make all this more quantitative

☐ More focus on UV-complete models, and on interplay (CCs vs FCNCs)

☐ Also consider the 2030 scenario where anomalies have disappeared

☐ Of course there is also good physics case for other observables (CKM physics, LFV, non-leptonic decays (three-body decays), ... )

☐ It could also be that by 2030 new particles have been discovered...