Flavor in HL-LHC era

Comments on
Challenges & Open Questions

April 4, 2018

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University of Maryland

- A brief overview of where we are on the experimental side, and some of the open questions and plans for future.
- Material drawn from physics studies for Belle—II and LHCb Upgrade-I, and expression of interest for LHCb Upgrade-II. However, all mistakes and misinterpretations are mine.
- For deep and detailed talks on the subjects, please see the talks in Flavor sessions of the workshop

It's hazardous to comment on the "expected" physics of future experiments, as shown by the example below from a workshop (like this one) in 1981 on future of B physics :

" ....The last item on my list is on the nature of CP violation. This violation observed so far only in K^0 must show up in some other place. Our theoretical advice is that the size of the effects expected in B decay is very small, un-observably small......."

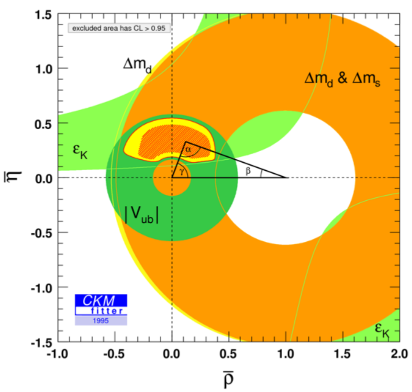
The pessimism somewhat justified given the accuracy of experiments then, and the dominant view at the time that m(top)~15 GeV.

"It's tough to make predictions, especially about the future"

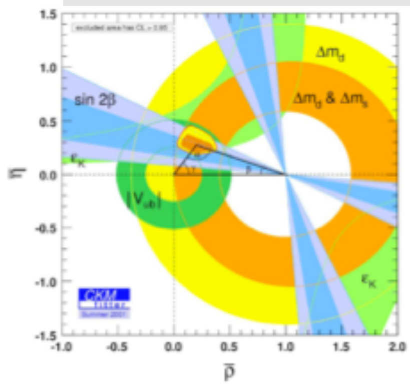
--Yogi Berra

It's safe to say that the era of Belle-II and LHCb-upgrades I & (II) will produce a much sharper picture of the physics of flavor.

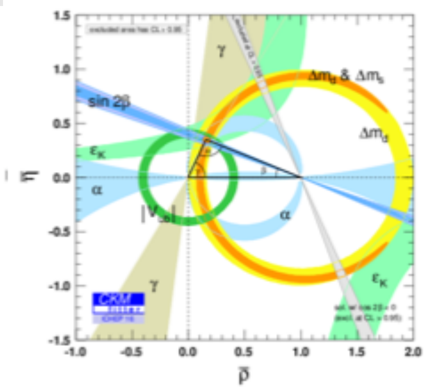
Last century



2001

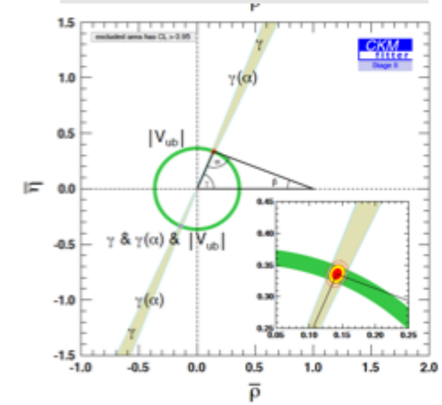


Today



Belle-II & LHCb upgrades

2025+



"There is no guarantee that this will reveal anything new, but there is some reason for optimism" (paraphrasing Ed Thorndike from the same workshop on "B Physics" in 1981).

Timeline of some of the key milestones

2040

2030

LHCb Upgrade I & Belle-II

2020

LHC & LHCb on the scene:
precise ϕ_s, γ $B_s \to \mu^+\mu^-$

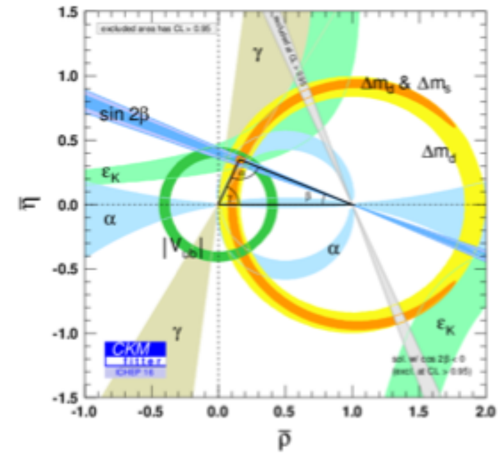
2010

Tevatron: B_s mixing & ϕ_s

D^0 mixing, $B \to \tau\nu$

Precision $\sin 2\beta$; α & γ
direct CPV in $B \to K\pi$.

CPV &
Standard Model



2001- CPV in B decays observed.

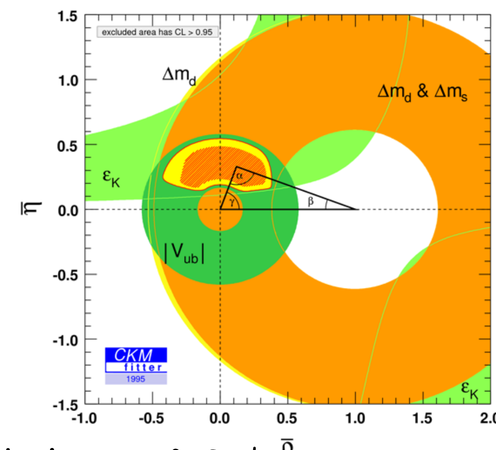
2000

1999- BaBar & Belle Running

1993- $b \to s\gamma$ observed ;

B factory projects launched.

1990



1987- B^0 mixing - anticipated heavy top B meson, lifetime, V_{cb} , V_{ub}

1980

Bottom

Charm

K decay, mixing & CPV with GIM & CKM anticipated charm & 3[rd] generation

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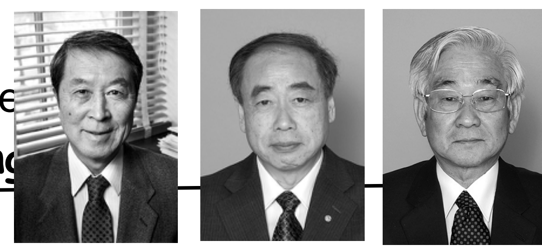
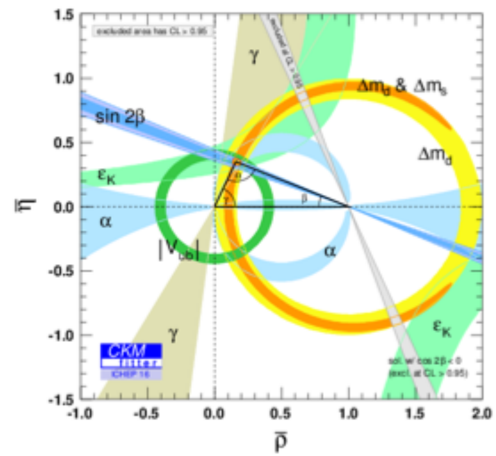
1999- BaBar & Belle Runnin

CKM is the dominant source of the observed CP violations effects.
2008 Nobel prize





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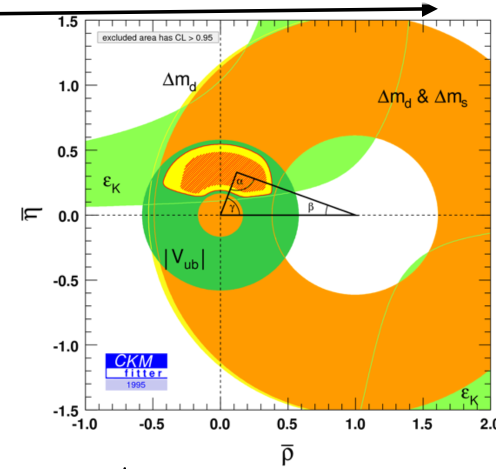

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CP Violation: Status

- Kaons and B hadrons are sole sources of CPV & T-Violation
    - No evidence for CPV in the charm system
    - No evidence for EDM
- CP Violation in the B meson system:
  - CPV measured in many channels, and beyond Mixing
    - Indirect CPV in interference of decay and mixing
    - Direct CPV in the decay amplitude
  - Time-Reversal (T) violation observed in the B system
    - In balance with observed CPV in B, supporting CPT invariance.
- CP Violation in SM does not account for Baryon asymmetry in universe
    - The CP question remains open & Flavor processes serve as probes of new sources of CPV, along with neutrinos

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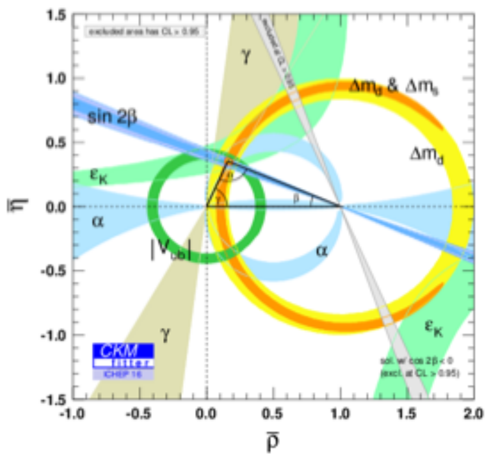
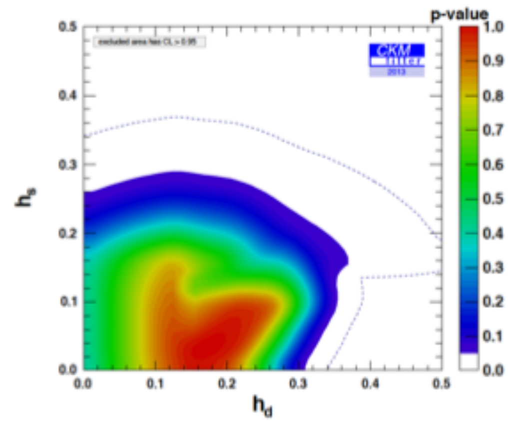
Charm
K decay, mixing & CPV with GIM & CKM anticipated charm & 3rd generation

Flavor & New Physics
How much NP can be accommodated?

$$M_{12} = M_{12}^{SM} \times \left(1 + h\, e^{2i\sigma}\right)$$





$A_{NP} < 0.3 A_{SM}$ $\propto \frac{|C|^2}{\Lambda_{NP}^2}$

$\Lambda_{NP} >>>$ TeV
For c~1

Constraint on NP/SM amplitude
See *(arXiv: 1309.2293)*

2040

Timeline of some of the key milestones

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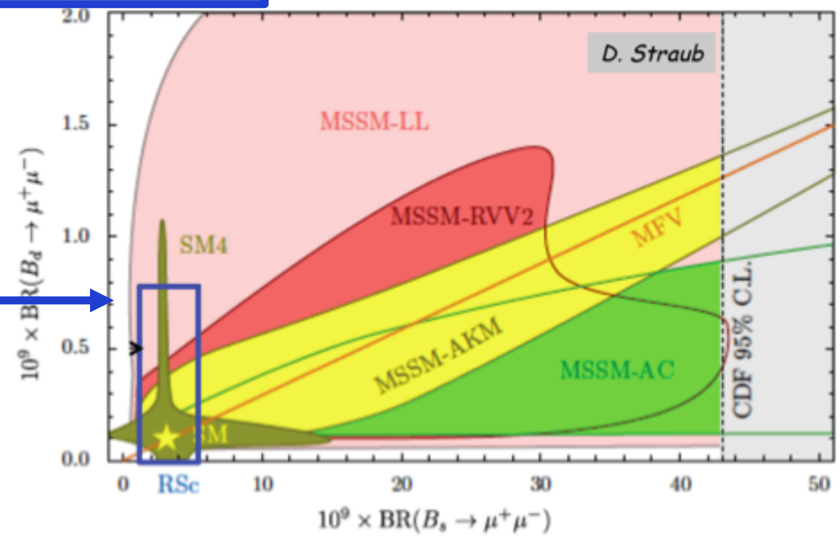
Flavor & New Physics

LHC & LHCb on the scene:
precise ϕ_s, γ $B_s \to \mu^+\mu^-$

For $\Lambda_{NP} \sim$ TeV



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Several Anomalies:

There are some areas of tension with SM & slowly growing; all in need of plausible SM explanations ..or (NP?)

- Lepton Flavor Universality
- Tensions in angular distribution of radiative decays, P'_5
- $K\pi$-puzzle
- V_{ub} and V_{cb} :Inclusive vs exclusive measurements
- $\sin 2\beta$ tension (direct vs CKM fit)
- Di-muon Asymmetry

Flavor Physics at HL-LHC:

The main questions remain open- albeit with different focus- and the primary venues for exploring them are far from exhausted:

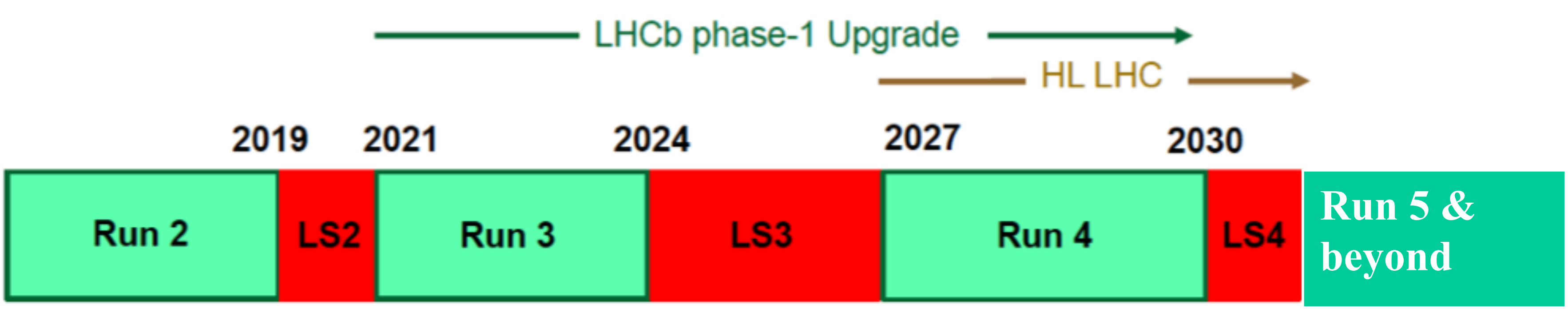
- CP violation
  - Focus is now on CPV beyond SM
- Footprint of New Physics in FCNC processes
- Charged Leptons:
  - Lepton Flavor Universality
  - Lepton Flavor Violation

Experimental Landscape

EOI

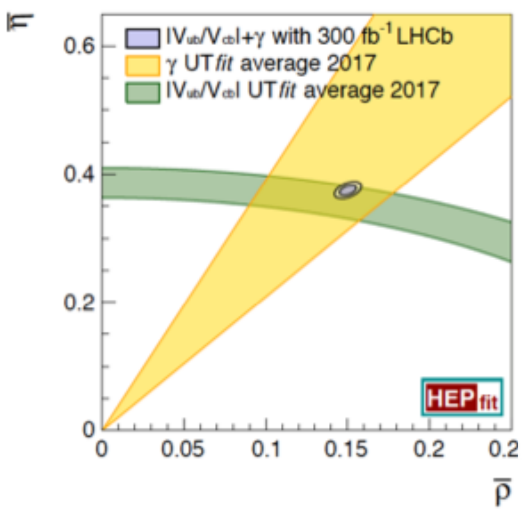
LHCb ~8 fb-1	Belle-II ~50 ab-1	&	LHCb Upgrade I ~50 fb-1	LHCb-Upgrade II ~300 fb-1

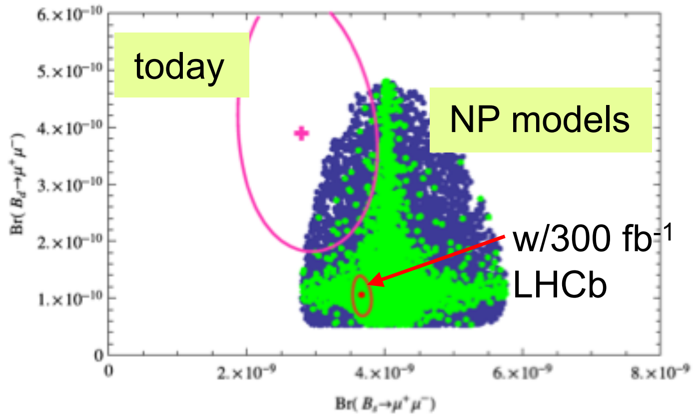
+ Data from CMS and ATLAS for some key channels



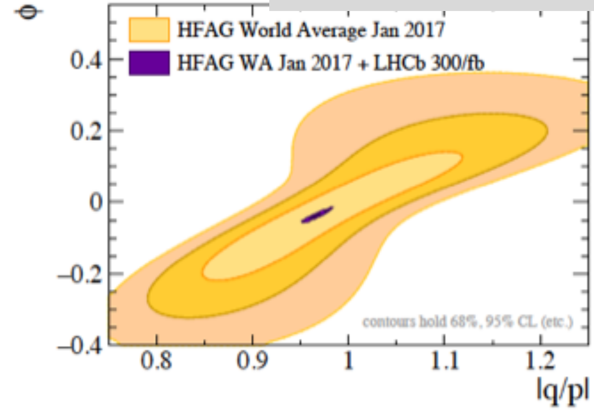
A much sharper picture to emerge

CERN-LHCC-2017-003

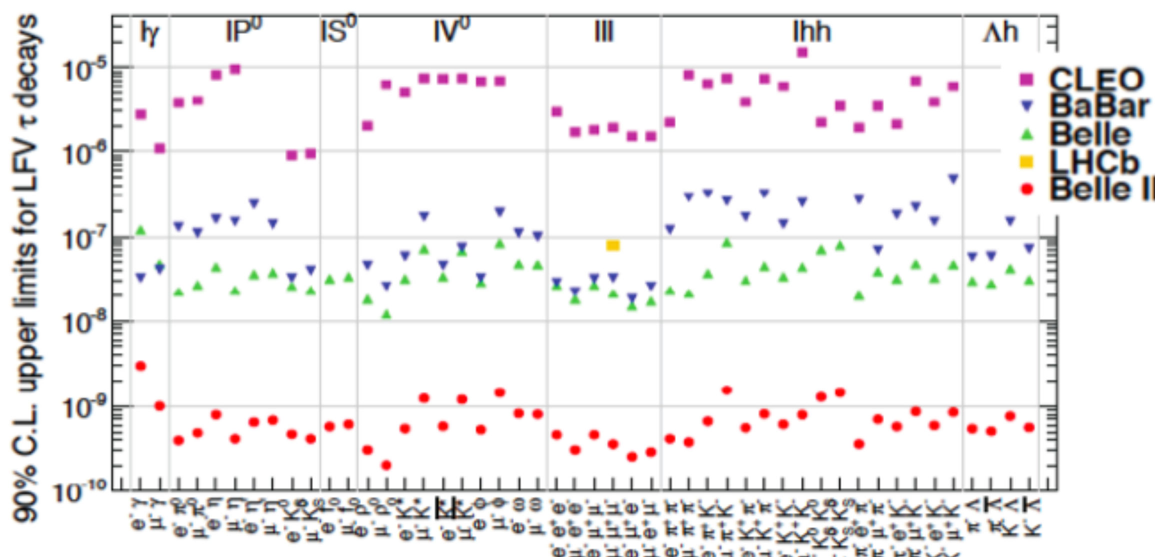




D0 mixing CPV



Sensitivity to lepton Flavor Violation in tau decays



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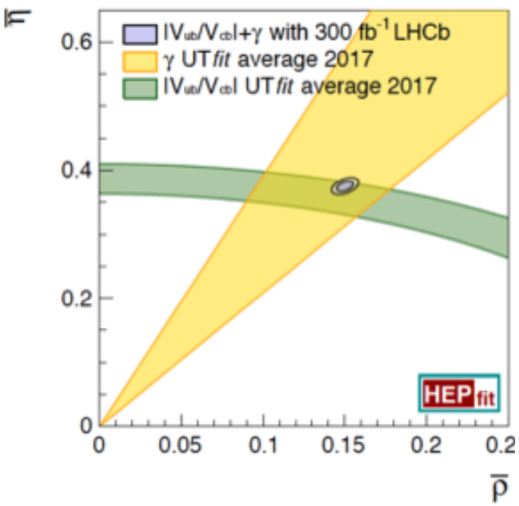

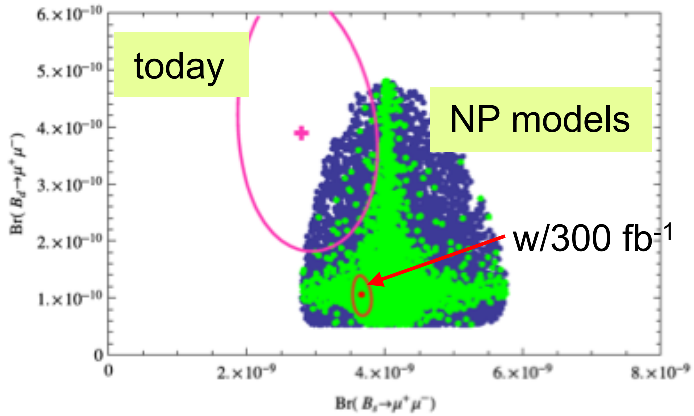

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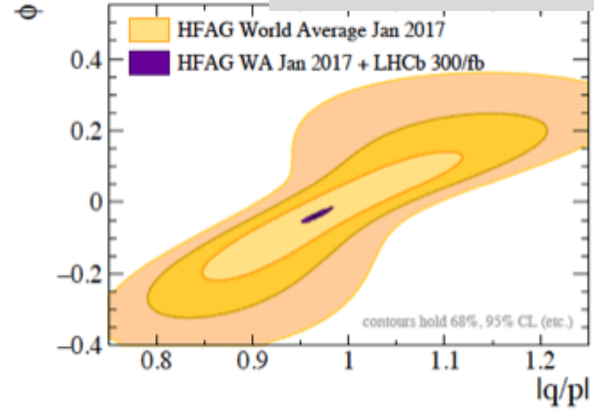


Expected precision of a few key observables

In some cases, reach or lower than (current) theory uncertainties – e.g. ϕ_s

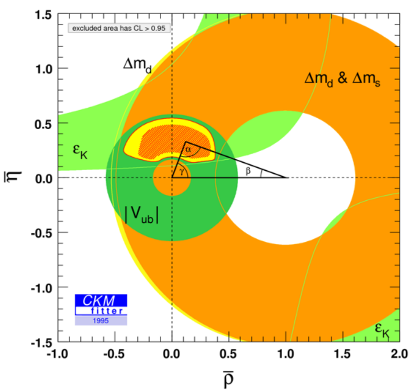
	Now	LHCb upgrade I	Belle-II	LHCb-Upgrade II
Data size		50 fb^{-1}	50 ab^{-1}	300 fb^{-1}
γ	5^o	1^o	1^o	0.4^o
ϕ_s	0.025	0.008	--	0.003
$B\to\mu\mu/B_s\to\mu\mu$	90%	~40%	--	~20%
$B\to K(*)\nu\nu$		--	~12%	--

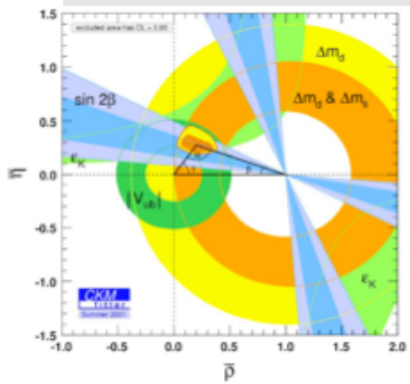
CKM metrology & NP:

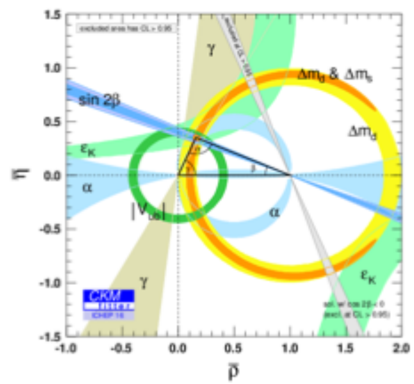
- Look for departure from the SM paradigm: all CP violation is governed by one parameter.
- Requires precise CKM metrology (α,β,γ, β_s, $|V_{ub}|$, $|V_{cb}|$,...)

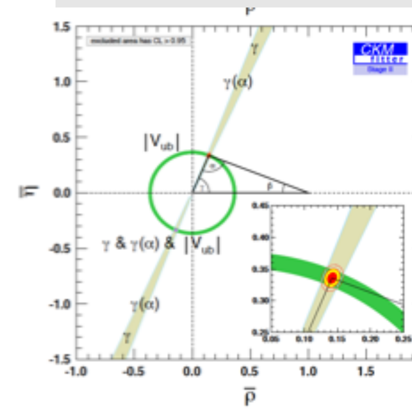
Belle-II & LHCb upgrades

Last century	2001	Today	2025+

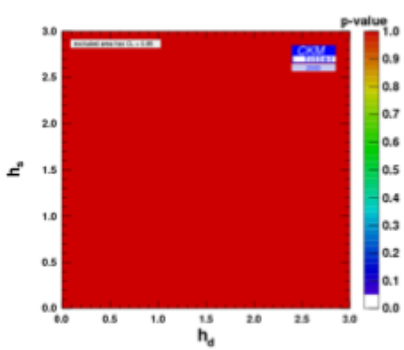


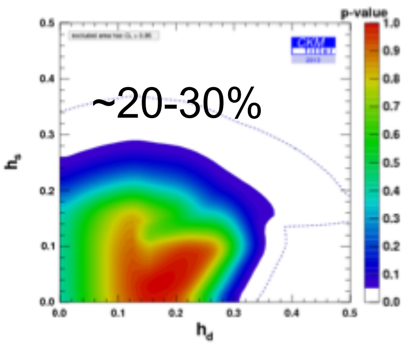


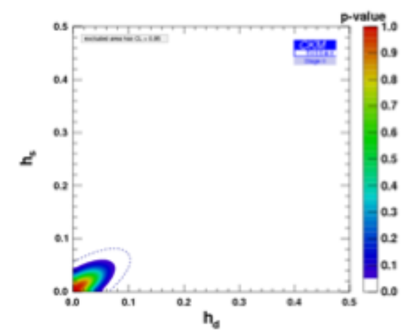




Constraint on NP/SM amplitude See *(arXiv: 1309.2293)*







A closer look at the numbers reveals some of the challenges ahead:

Constraint on NP/SM amplitude
See *(arXiv: 1309.2293)*

	2003	2013	Stage I		Stage II	
$\lvert V_{ud}\rvert$	0.9738 ± 0.0004	$0.97425 \pm 0 \pm 0.00022$	id		id	
$\lvert V_{us}\rvert$ $(K_{\ell 3})$	$0.2228 \pm 0.0039 \pm 0.0018$	$0.2258 \pm 0.0008 \pm 0.0012$	0.22494 ± 0.0006		id	
$\lvert \epsilon_K\rvert$	$(2.282 \pm 0.017) \times 10^{-3}$	$(2.228 \pm 0.011) \times 10^{-3}$	id		id	
Δm_d [ps^{-1}]	0.502 ± 0.006	0.507 ± 0.004	id		id	
Δm_s [ps^{-1}]	> 14.5 [95% CL]	17.768 ± 0.024	id		id	
$\lvert V_{cb}\rvert \times 10^3$ $(b \to c\ell\bar{\nu})$	$41.6 \pm 0.58 \pm 0.8$	$41.15 \pm 0.33 \pm 0.59$	42.3 ± 0.4	[17]	42.3 ± 0.3	
$\lvert V_{ub}\rvert \times 10^3$ $(b \to u\ell\bar{\nu})$	$3.90 \pm 0.08 \pm 0.68$	$3.75 \pm 0.14 \pm 0.26$	3.56 ± 0.10	[17]	3.56 ± 0.08	
$\sin 2\beta$	0.726 ± 0.037	0.679 ± 0.020	0.679 ± 0.016	[17]	0.679 ± 0.00	
α (mod π)	—	$(85.4^{+4.0}_{-3.8})^\circ$	$(91.5 \pm 2)^\circ$	[17]	$(91.5 \pm 1)^\circ$	[17]
γ (mod π)	—	$(68.0^{+8.0}_{-8.5})^\circ$	$(67.1 \pm 4)^\circ$	[17, 18]	$(67.1 \pm 1)^\circ$	[17, 18]
β_s		$0.0065^{+0.0450}_{-0.0415}$	0.0178 ± 0.012	[18]	0.0178 ± 0.004	[18]
$\mathcal{B}(B \to \tau\nu) \times 10^4$	—	1.15 ± 0.23	0.83 ± 0.10	[17]	0.83 ± 0.05	[17]
$\mathcal{B}(B \to \mu\nu) \times 10^7$	—	—	3.7 ± 0.9	[17]	3.7 ± 0.2	[17]
$A^d_{SL} \times 10^4$	10 ± 140	23 ± 26	-7 ± 15	[17]	-7 ± 10	[17]
$A^s_{SL} \times 10^4$	—	-22 ± 52	0.3 ± 6.0	[18]	0.3 ± 2.0	[18]
$\bar{m}_c$	$1.2 \pm 0 \pm 0.2$	$1.286 \pm 0.013 \pm 0.040$	1.286 ± 0.020		1.286 ± 0.010	
$\bar{m}_t$	167.0 ± 5.0	$165.8 \pm 0.54 \pm 0.72$	id		id	
$\alpha_s(m_Z)$	$0.1172 \pm 0 \pm 0.0020$	$0.1184 \pm 0 \pm 0.0007$	id		id	
B_K	$0.86 \pm 0.06 \pm 0.14$	$0.7615 \pm 0.0026 \pm 0.0137$	0.774 ± 0.007	[19, 20]	0.774 ± 0.004	[19, 20]
f_{B_s} [GeV]	$0.217 \pm 0.012 \pm 0.011$	$0.2256 \pm 0.0012 \pm 0.0054$	0.232 ± 0.002	[19, 20]	0.232 ± 0.001	[19, 20]
B_{B_s}	1.37 ± 0.14	$1.326 \pm 0.016 \pm 0.040$	1.214 ± 0.060	[19, 20]	1.214 ± 0.010	[19, 20]
f_{B_s}/f_{B_d}	$1.21 \pm 0.05 \pm 0.01$	$1.198 \pm 0.008 \pm 0.025$	1.205 ± 0.010	[19, 20]	1.205 ± 0.005	[19, 20]
B_{B_s}/B_{B_d}	1.00 ± 0.02	$1.036 \pm 0.013 \pm 0.023$	1.055 ± 0.010	[19, 20]	1.055 ± 0.005	[19, 20]
$\tilde{B}_{B_s}/\tilde{B}_{B_d}$	—	$1.01 \pm 0 \pm 0.03$	1.03 ± 0.02		id	
$\tilde{B}_{B_s}$	—	$0.91 \pm 0.03 \pm 0.12$	0.87 ± 0.06		id	

Belle II & LHCb-Upg I:
~2% Vub
~1% Vcb
γ at ~1°
& α at ~1°

This program requires a major advancement of theoretical-LQCD- inputs; Stage II counting on ~0.5% accuracy on lattice inputs & even more ambitious in HL-LHC era

Flavor Physics at HL-LHC:

- Footprint of New Physics in FCNC processes
  - They have a track record of spotting the presence of new particles and interactions before their direct observations.
  - Current measurements are largely consistent with SM but there are hints of tension

—

Example of theorist vision: *"DNA of flavor physics effects"*

by W. Altmannshofer, A.J. Buras, S. Gori, P. Paradisi D.M. Straub,

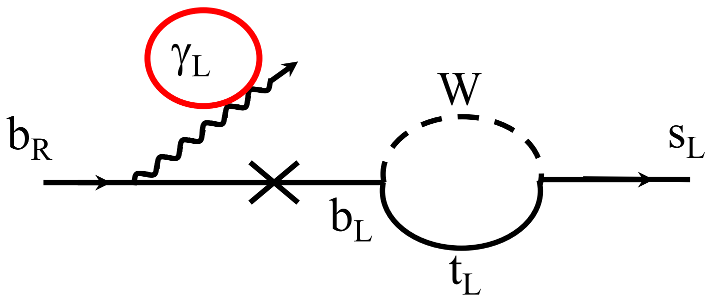
	AC	RVV2	AKM	δLL	FBMSSM	LHT	RS
$D^0-\bar{D}^0$	★★★	★	★	★	★	★★★	?
ϵ_K	★	★★★	★★★	★	★	★★	★★★
$S_{\psi\phi}$	★★★	★★★	★★★	★	★	★★★	★★★
$S_{\phi K_S}$	★★★	★★	★	★★★	★★★	★	?
$A_{\rm CP}(B\to X_s\gamma)$	★	★	★	★★★	★★★	★	?
$A_{7,8}(B\to K^*\mu^+\mu^-)$	★	★	★	★★★	★★★	★★	?
$A_9(B\to K^*\mu^+\mu^-)$	★	★	★	★	★	★	?
$B\to K^{(*)}\nu\bar{\nu}$	★	★	★	★	★	★	★
$B_s\to\mu^+\mu^-$	★★★	★★★	★★★	★★★	★★★	★	★
$K^+\to\pi^+\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$K_L\to\pi^0\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$\mu\to e\gamma$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
$\tau\to\mu\gamma$	★★★	★★★	★	★★★	★★★	★★★	★★★
$\mu+N\to e+N$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
d_n	★★★	★★★	★★★	★★	★★★	★	★★★
d_e	★★★	★★★	★★	★	★★★	★	★★★
$(g-2)_\mu$	★★★	★★★	★★	★★★	★★★	★	?

★★★ large effects

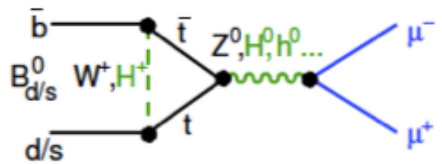
★★ visible but small effects

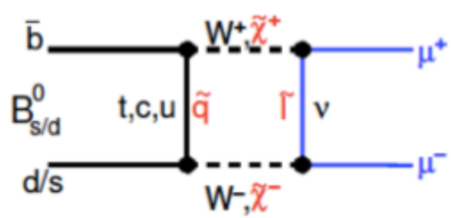
★ unobservable effects

A few have been extensively studied with major impact on NP searches



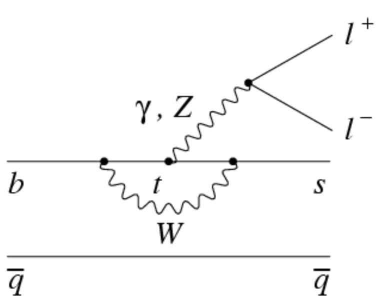
A key probe of NP in B decays
Observables: Rate, CPV, γ polarization-
Precision to reach theoretical limit..

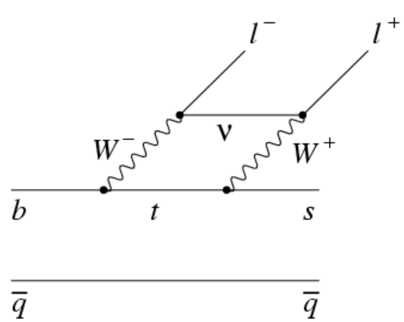




$$SM : Br(B_s^0 \to \mu^+\mu^-) = (3.66 \pm 0.23) \times 10^{-9}$$

Finally Seen (LHCb & CMS) – consistent with SM –additional observables will become accessible

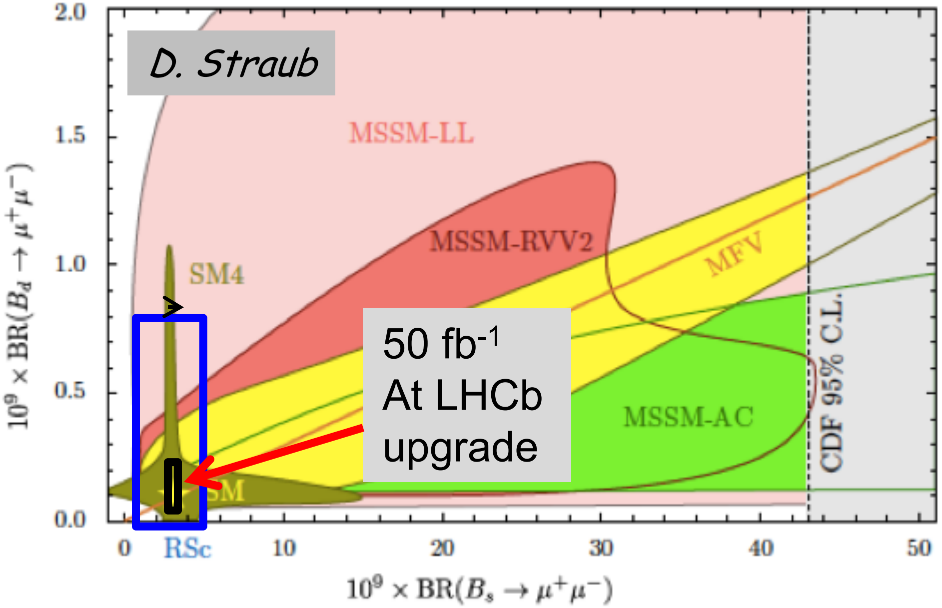




Recent precise measurements from LHCb show interesting hints of deviations from SM- including tests of Lepton Flavor Universality

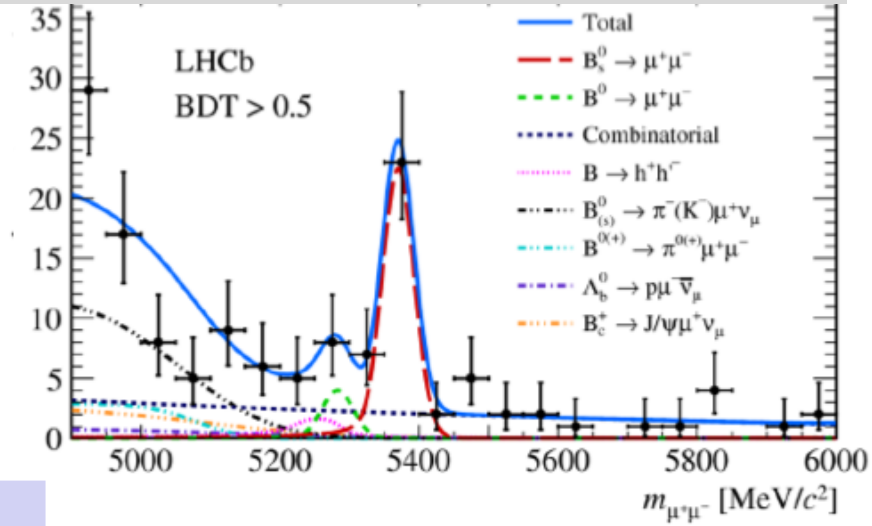
$B \rightarrow K^{(*)}\nu\nu$ at Belle-II to reach ~12% accuracy

$B \to \mu^+\mu^-$



Observed by LHCb & CMS

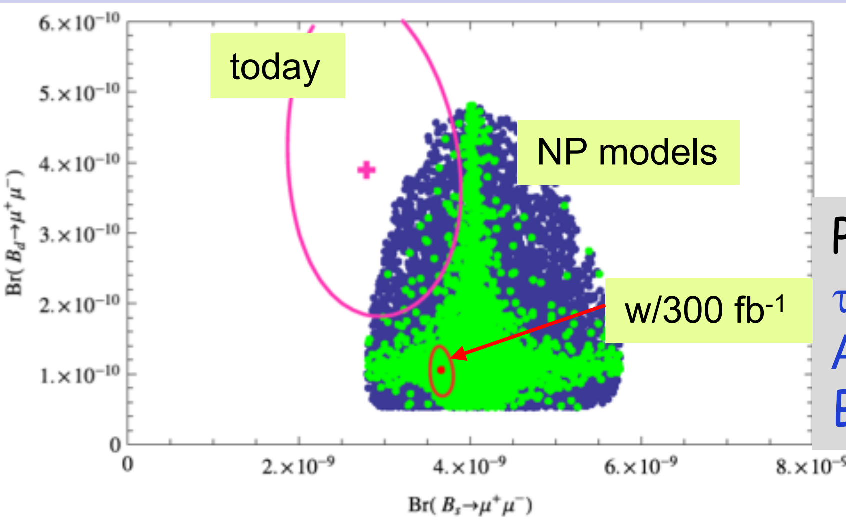
Recent result from LHCbRun1+ 1.4 fb^{-1} of Run 2



$$Br(B_s^0 \to \mu^+\mu^-) = (3.0 \pm 0.6^{+0.3}_{-0.2}) \times 10^{-9}$$

$$SM: Br(B_s^0 \to \mu^+\mu^-) = (3.66 \pm 0.23) \times 10^{-9}$$

Expected LHCb Sensitivity with 300 fb-1



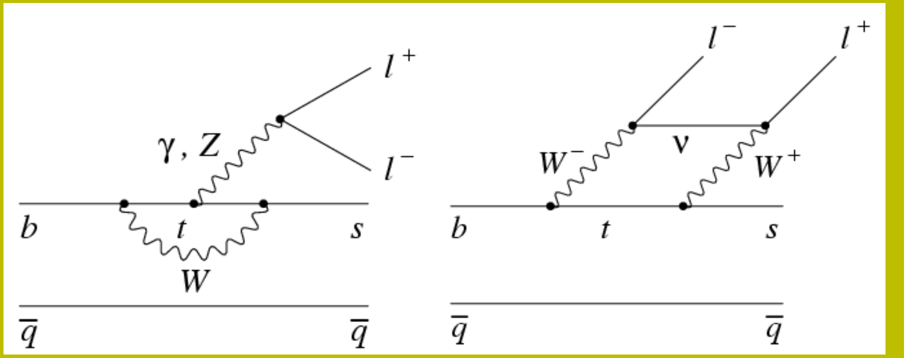
Precision of other accessible observables:

$\tau(B_s \to \mu\mu)$ to ~2%

A_{cp} $(B_s \to \mu\mu)$ to 0.2

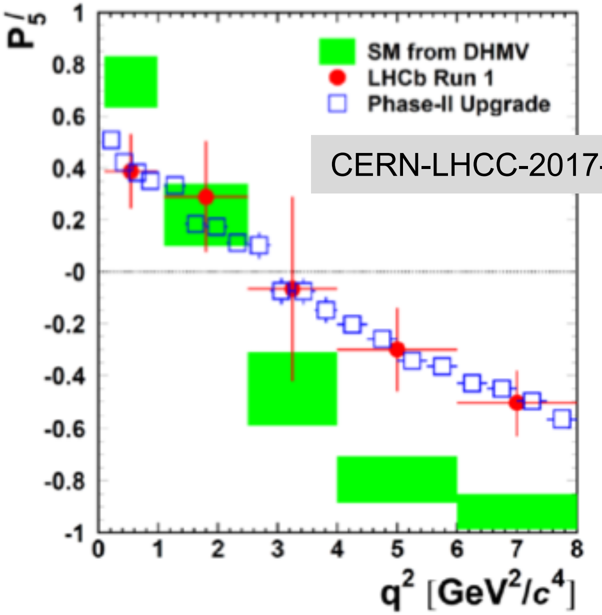
$B(B \to \mu\mu)/B(B_s \to \mu\mu)$ to ~15-20%

$B \to K^{(*)} l^+ l^-$



Several observables- sensitive to New Physics- extracted from differential rates.

Expected LHCb Sensitivity with 300 fb-1



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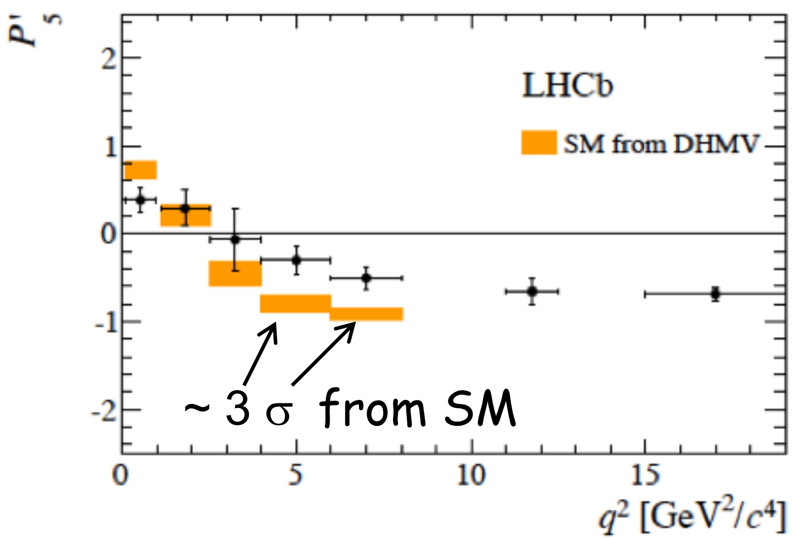


Flavor Physics at HL-LHC:

- Charged Leptons:
  - Lepton Flavor Universality (LFU)
    - Current measurements of Semileptonic decays show intriguing effects- hinting at LFU violation.
  - Lepton Flavor Violation

Tests of Lepton Flavor Universality in $B \to K^{(*)} l^+ l^-$

$$R_H = \frac{\int \frac{d\Gamma(B \to H\mu^+\mu^-)}{dq^2} dq^2}{\int \frac{d\Gamma(B \to He^+e^-)}{dq^2} dq^2}$$

Within SM: $R_{K(*)} \sim 1$

LHCb

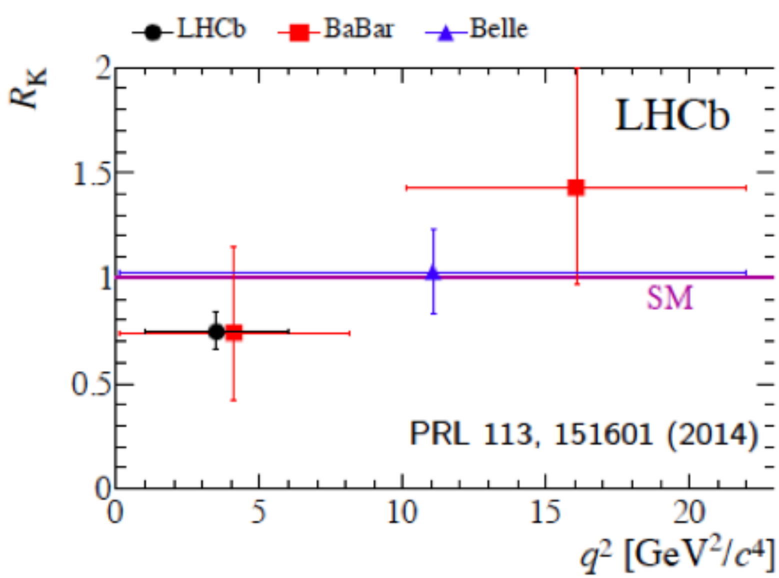
$$R_K = 0.745^{+0.090}_{-0.074} \pm 0.036$$

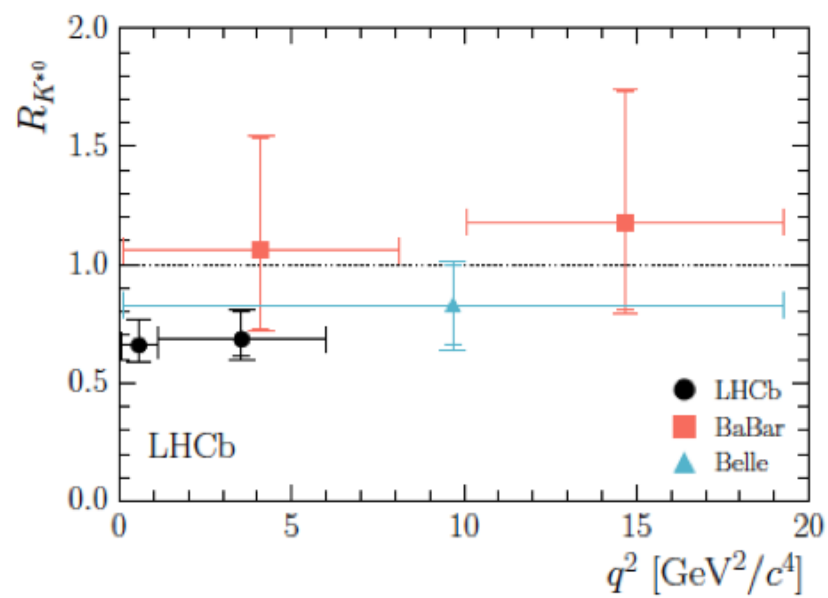
$$R_{K^*} = 0.660^{+0.110}_{-0.070} \pm 0.024 \ \ low-q^2$$

$$R_{K^*} = 0.685^{+0.113}_{-0.069} \pm 0.047 \ \ high-q^2$$

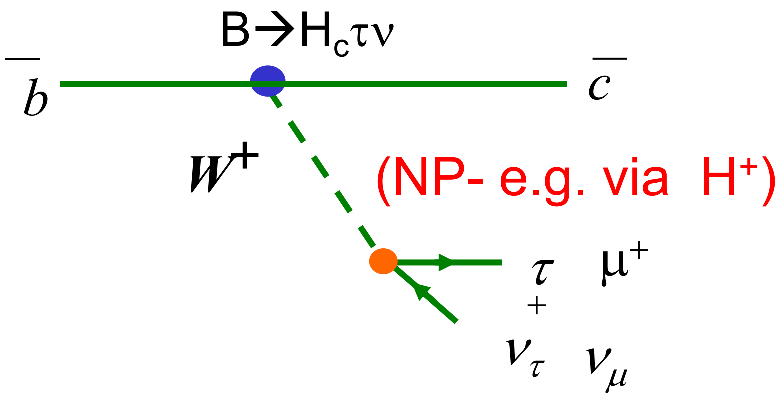
Within 2.6 σ of SM

Within 2.1-2.3 σ & 2.4-2.5 σ of SM





Tests of Lepton Flavor Universality (2)



In SM, decays to μ & τ differ only due to their mass differences

The key observables:

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

$$R(J/\psi) = \frac{B(B_c^+ \to J/\psi\tau^+\bar{\nu})}{B(B_c^+ \to J/\psi\mu^+\bar{\nu})}$$

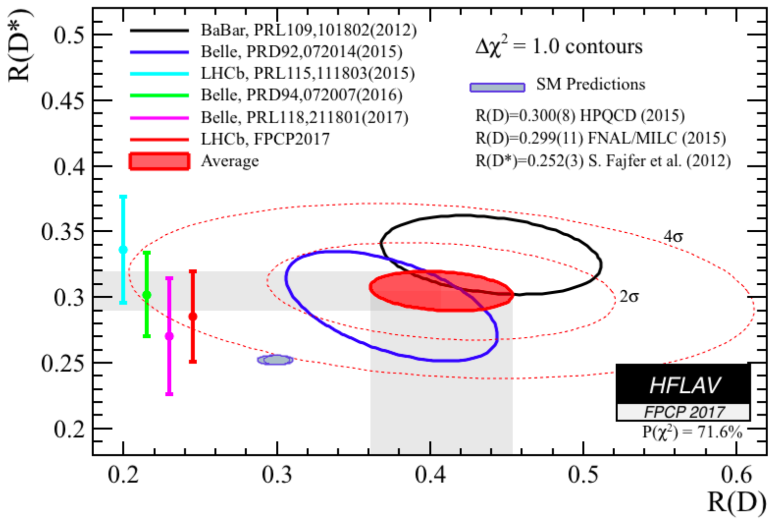
- These are theoretically very "clean"; computed in HQFT or LQCD
- Form-Factor Uncertainties largely cancel

$R(D) = 0.300 \pm 0.008$ H. Na et al., (LQCD)

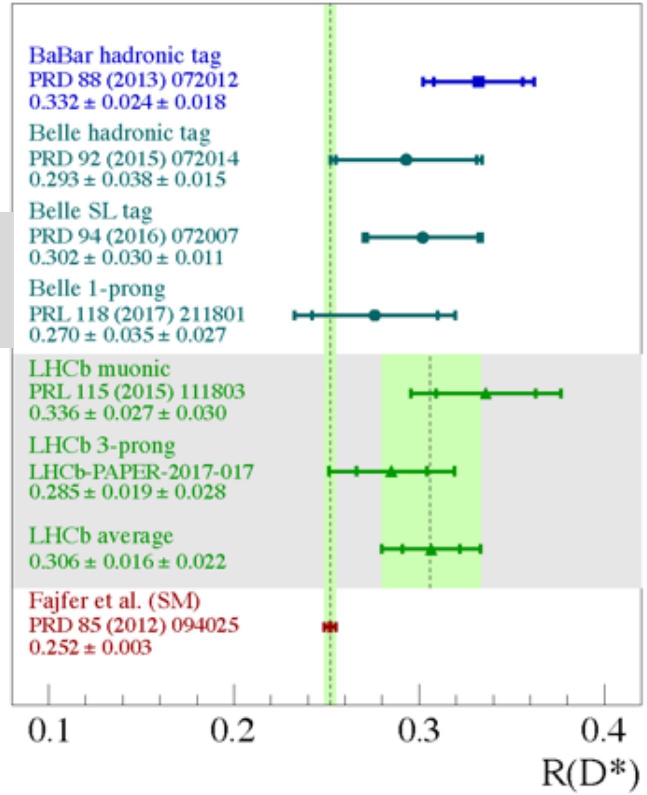
$R(D^*) = 0.252 \pm 0.003$ S. Fajfer et al (HQET)

$R(J/\psi) = 0.25 - 0.28$

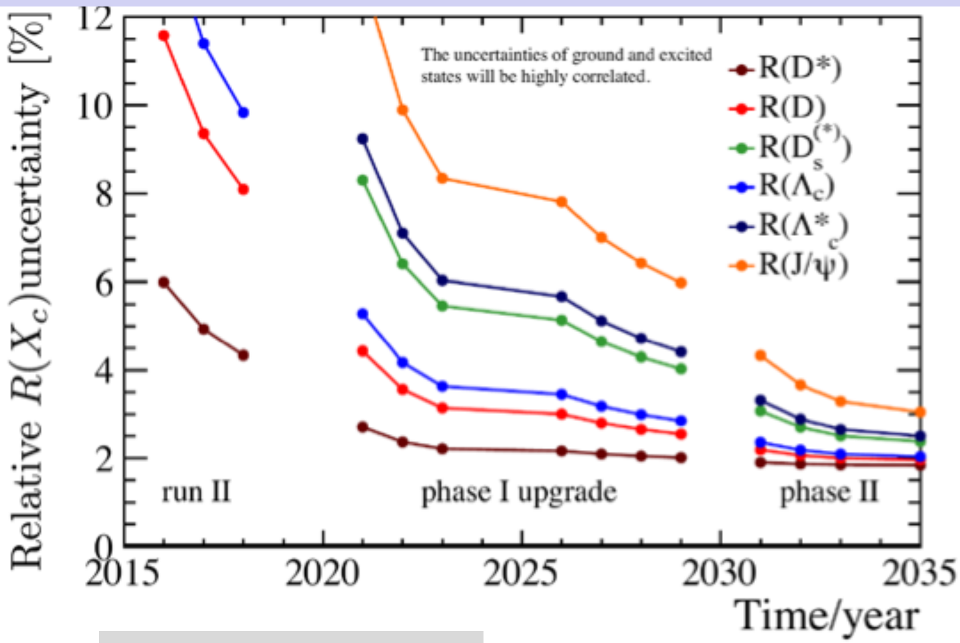
Uncertainties partly due to contribution of scalar form factors- helicity suppressed contributions that are negligible for e & μ channels

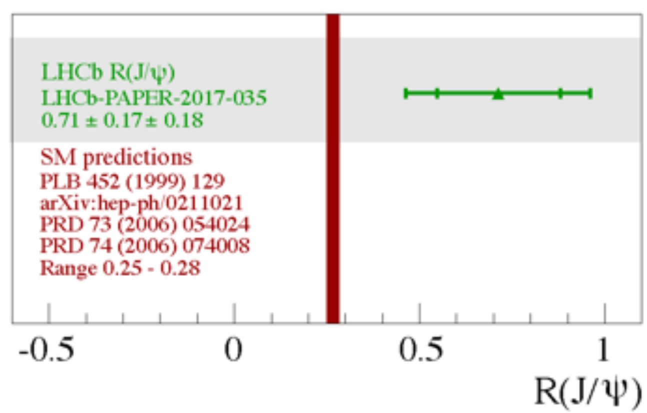


4.1 σ tension with LFU/SM



Evolution of LHCb Sensitivity up to 300 fb-1





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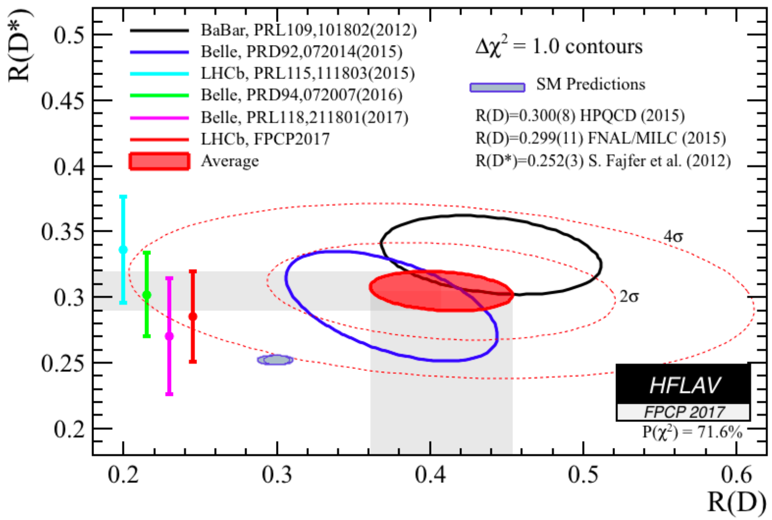
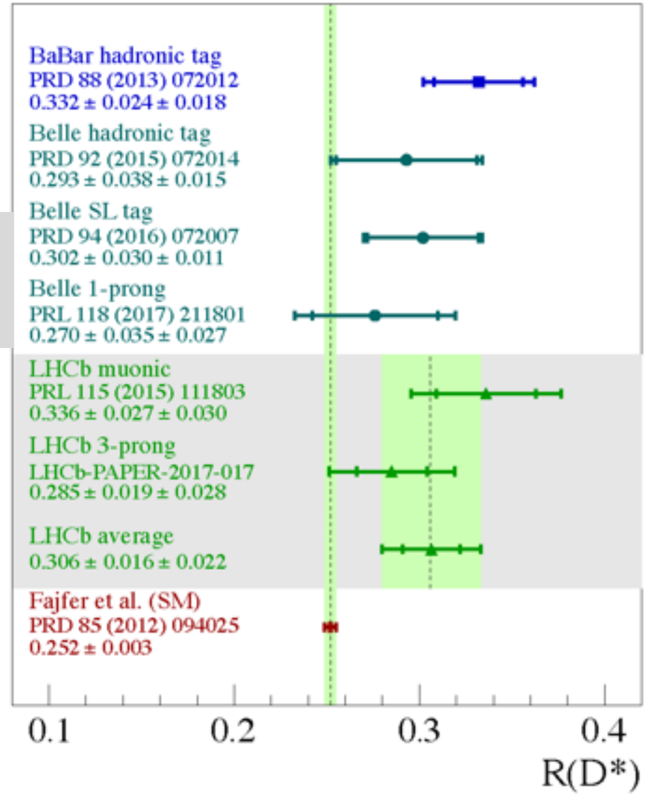
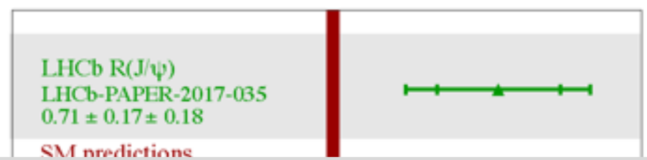
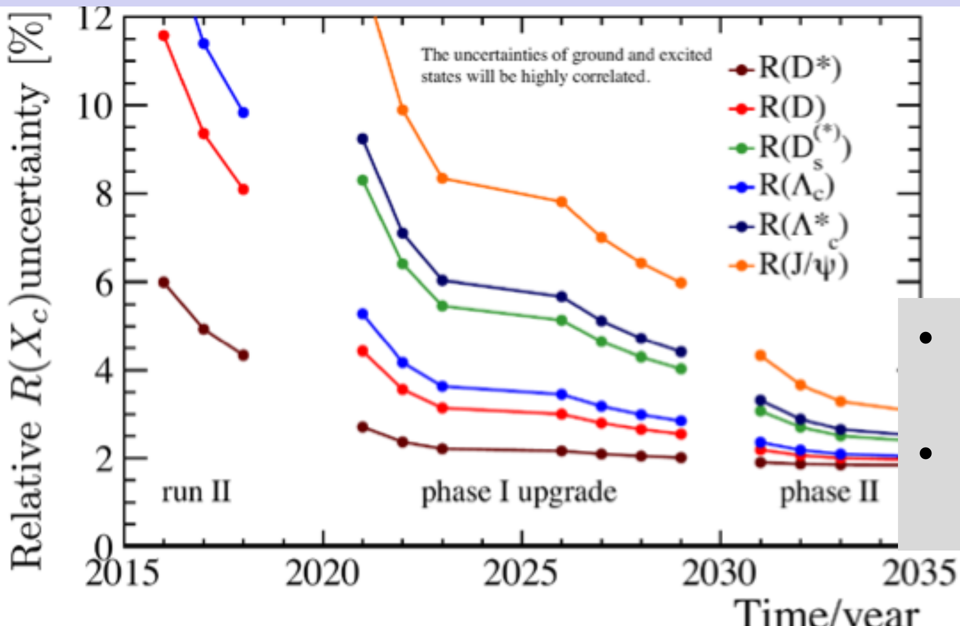


4.1 σ tension with LFU/SM





Evolution of LHCb Sensitivity up to 300 fb-1

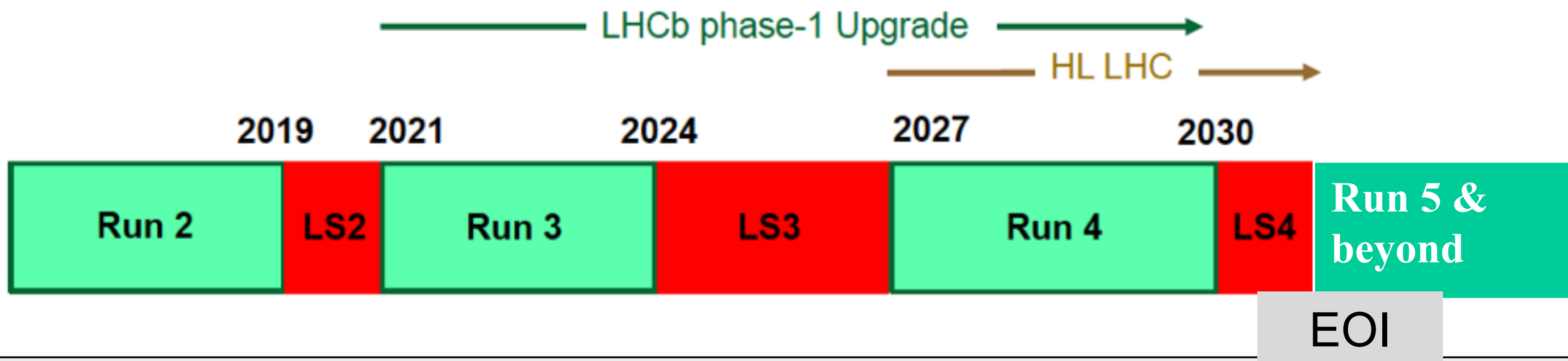


- Will need much improved Form Factor info for these measurements
- Will ultimately measure polarization and CPV effects

CERN-LHCC-2017-003

Experimental Challenges

Realization of three major instruments



LHCb
~8 fb-1

LHCb Upgrade I & Belle-II
50 fb-1 50 ab-1

LHCb-Upgrade II
300 fb-1

	LHC Run	Period of data taking	Maximum $\mathcal{L}$ $[\mathrm{cm}^{-2}\mathrm{s}^{-1}]$	Cumulative $\int \mathcal{L}\, dt$ $[\mathrm{fb}^{-1}]$	Pile up
Current detector	1 & 2	2010–2012, 2015–2018	4×10^{32}	8	1.1
Phase-1 Upgrade	3 & 4	2021–2023, 2026–2029	2×10^{33}	50	6
Phase-2 Upgrade	5 $\rightarrow$	2031–2033, 2035 $\rightarrow$	2×10^{34}	300	50

Super Flavor Experiments

<u>At LHC:</u> Endowed with large production cross section: its mostly about trigger & pile-up

σ_{cc}~6 mb (7 TeV) σ_{τ}~80 μb (7 TeV)
σ_{bb}~280 μb(7 TeV) (~500 at 13 TeV)
B_d, B_u, B_s, B_c, Λ_b,...
LHCb at $\mathcal{L}$~ $4\times10^{32}/cm^2/s$
Expect ~8/fb by 2018
LHCb upgrade-I: $\mathcal{L}$~$2\times10^{33}/cm^2/s$
Aiming for ~50/fb
LHCb upgrade-II: $\mathcal{L}$~$2\times10^{34}/cm^2/s$
Aiming for ~50/fb

- CMS and ATLAS players

in some key areas

- <u>e+e- Super B factory</u>
- Small cross-section; its mostly about luminosity (xsection ~1 nb)

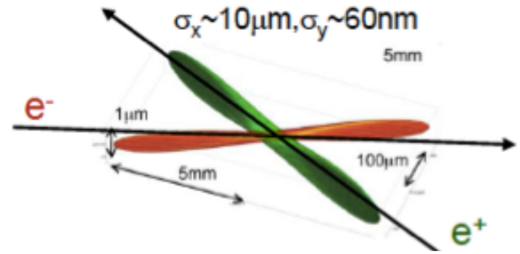
Asymmetric energy $e^+ + e^-$ colliders to operate in the $\Upsilon(4S)$ region as well as in the charm threshold region.

- Super KEKB in Japan- well underway
- At $\mathcal{L}$ ~8×10^{35} /cm^2/s

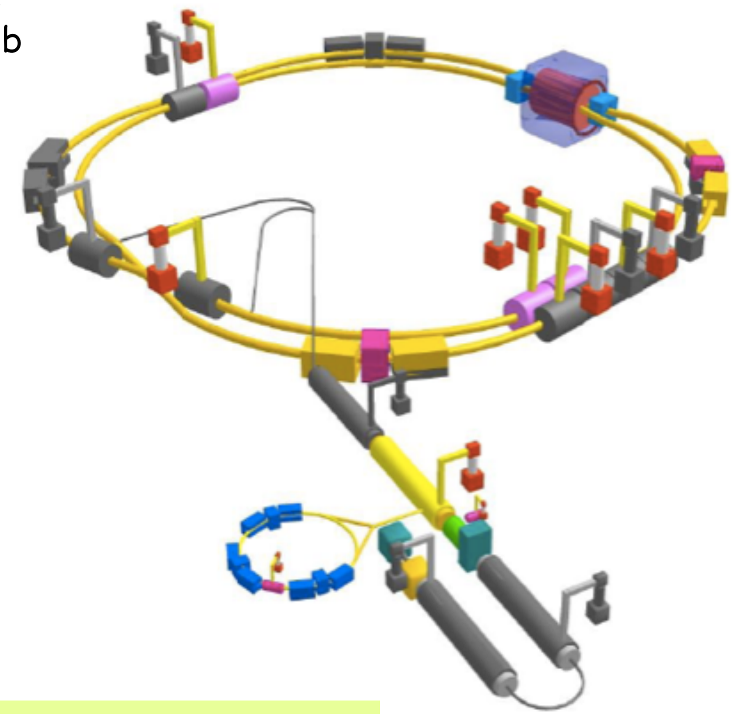
Aiming for a data set of ~ 50 /ab
- ~10^{11} B decays
- ~10^{11} tau decays
- ~10^{11} charm decays

Belle-II at SuperKEKB

Asymmetric Energy e+e- collider at goal peak Luminosity 8×10^{35} /cm^2/s aiming for <u>50 ab^{-1}</u>



Design based on Nano-beam scheme proposed by P. Raimondi (Frascati), tight focusing, larger crossing angle & higher I_b

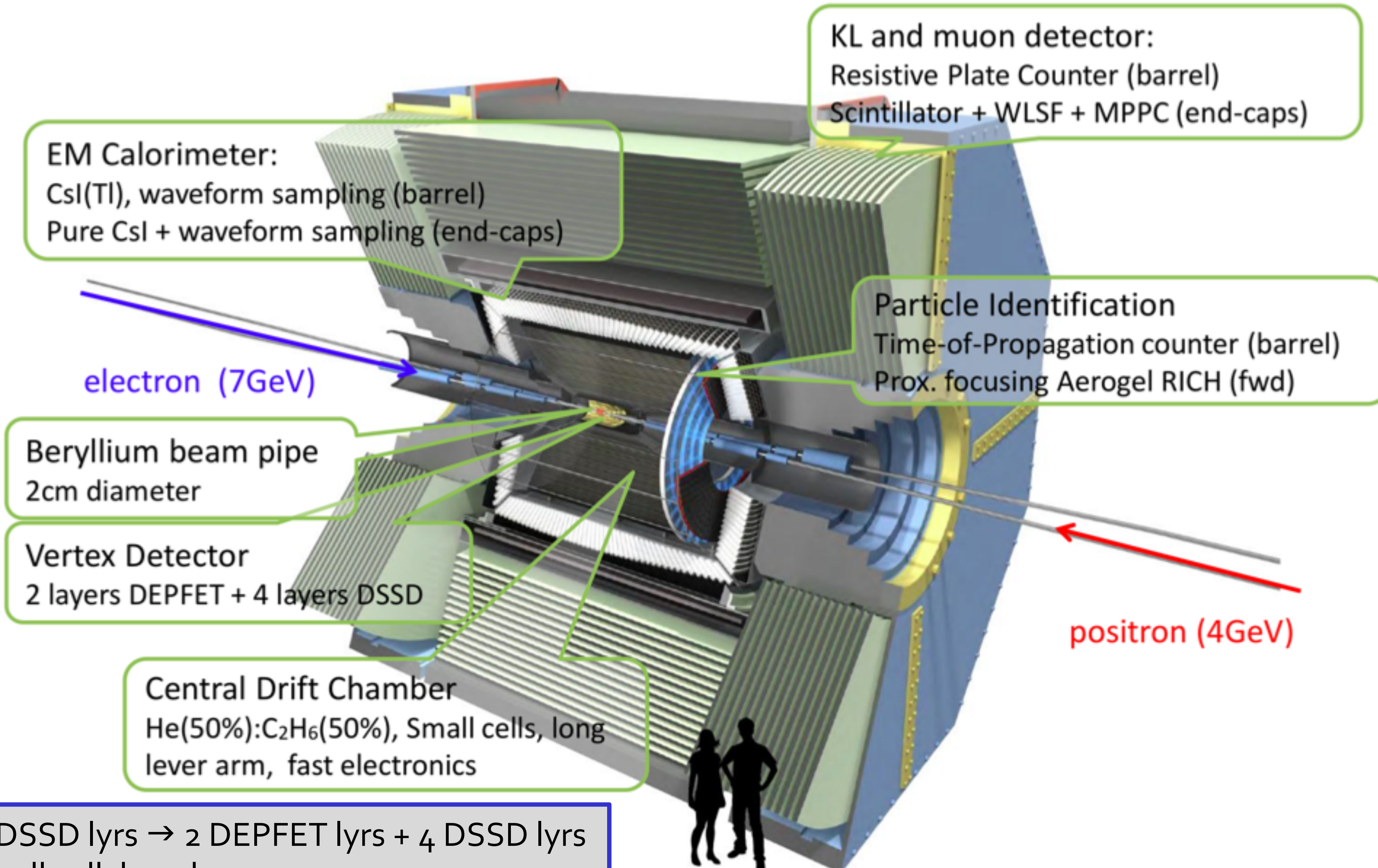


Accelerator Upgrade

- low emittance electron injector
- New positron damping ring
- New vacuum chambers
- New HER and LER lattice and long dipoles for low emittance
- New IR for low β^*
- Modified and additional RF for higher currents

March 21, 2018: Injected electrons in the ring
Next: positrons and collisions in few months
See Alan Schwartz's talk for more detail

Belle II Detector

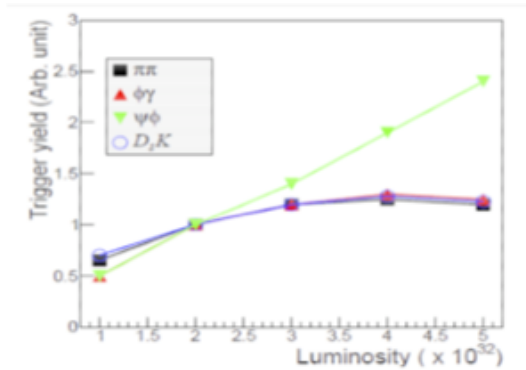


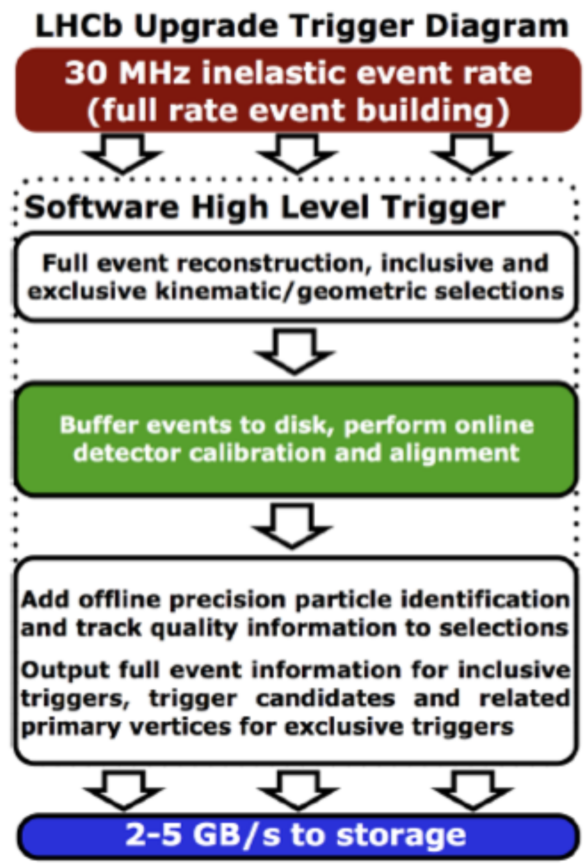
SVD: 4 DSSD lyrs → 2 DEPFET lyrs + 4 DSSD lyrs
CDC: small cell, long lever arm
ACC+TOF → TOP+A-RICH
ECL: waveform sampling, pure CsI for end-caps
KLM: RPC → Scintillator +SiPM (end-caps)

LHCb upgrade-I

- The upgrade is designed to run at luminosity of (1-2)x10^{33} $cm^{-2}s^{-1}$.

Saturation of yields with 1MHz L0 limit
Must raise P_T cut to stay below 1 MHz





➔ New Trigger Appoach:

- ➢Remove L0 (hardware) trigger
- ➢Readout the detector at the 40 MHz LHC clock rate
- ➢Move to a fully flexible software trigger

➔major upgrade of LHCb detector required:

- ❖Replace all FE electronics & DAQ system
- ❖Replace all Tracking sub-detectors
- ❖Upgrade of RICH photo-detectors and optics

Upgrade-I

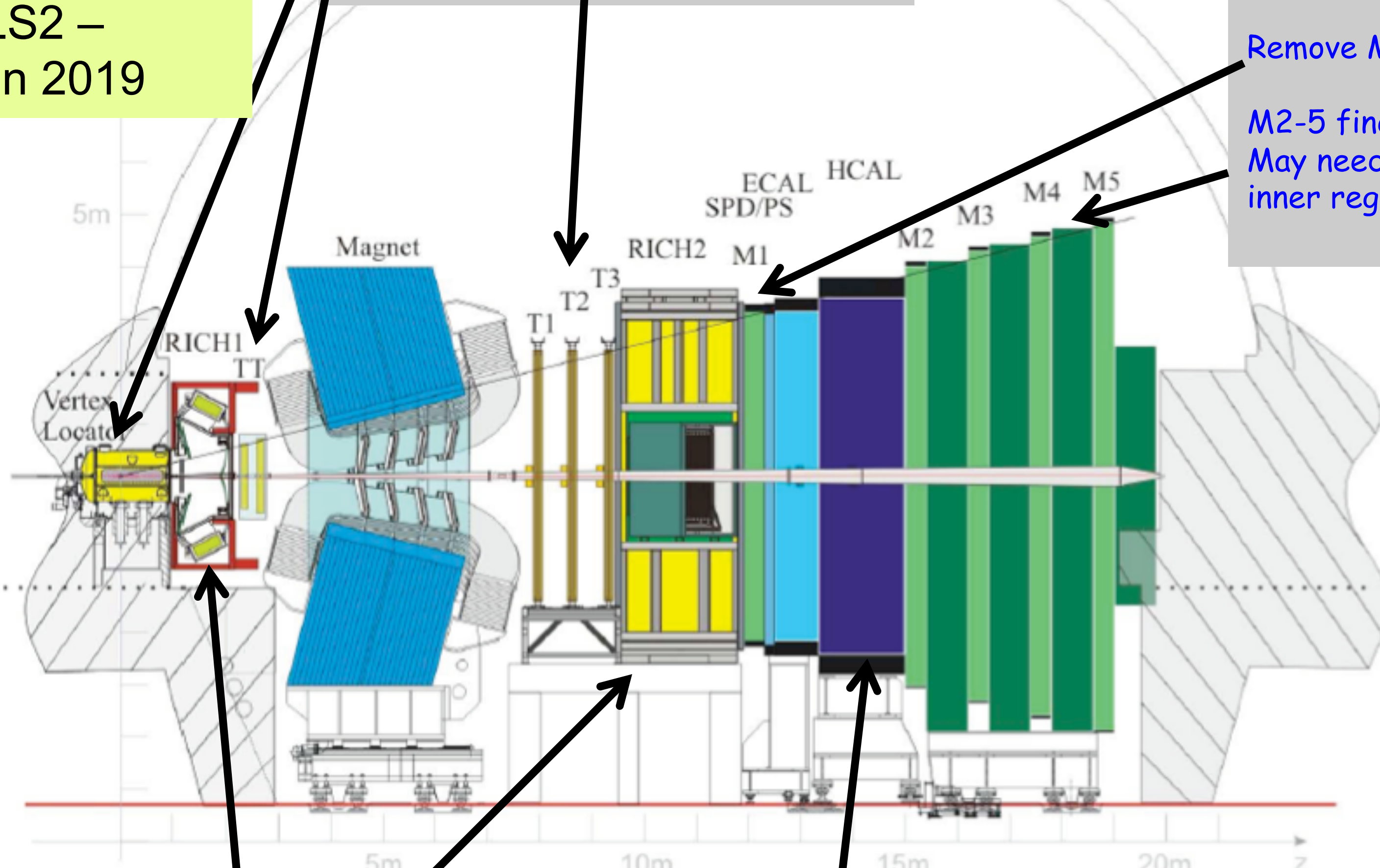
The assembly and installation to start in LHC LS2 – starting in 2019

Tracking system:
New VELO (Si strip → Pixel)
New upstream tracker (TT) (Si)
New downstream tracker (Sci Fiber)

Muon System:

Remove M1

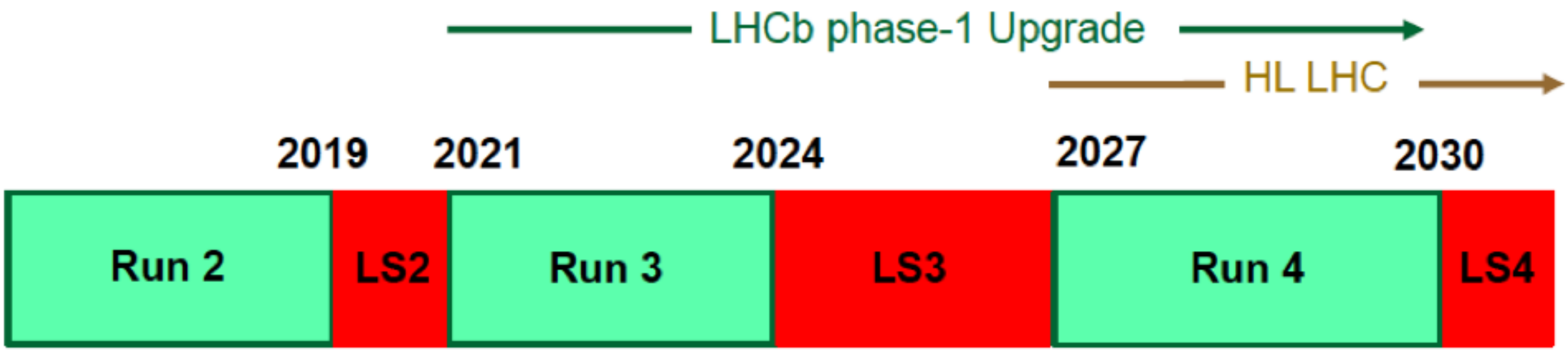
M2-5 fine for $1x10^{33}$
May need upgrade of inner region at $2x10^{33}$



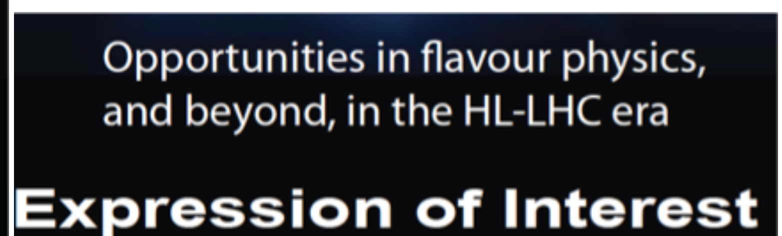
RICH 1 & RICH 2
HPD→ MaPMT
New 40 MHz R/O
RICH1: new optics
remove aerogel

Calorimeter:
New 40 MHz R/O
Lower PMT gain to reduce anode current
Remove SPD & PS

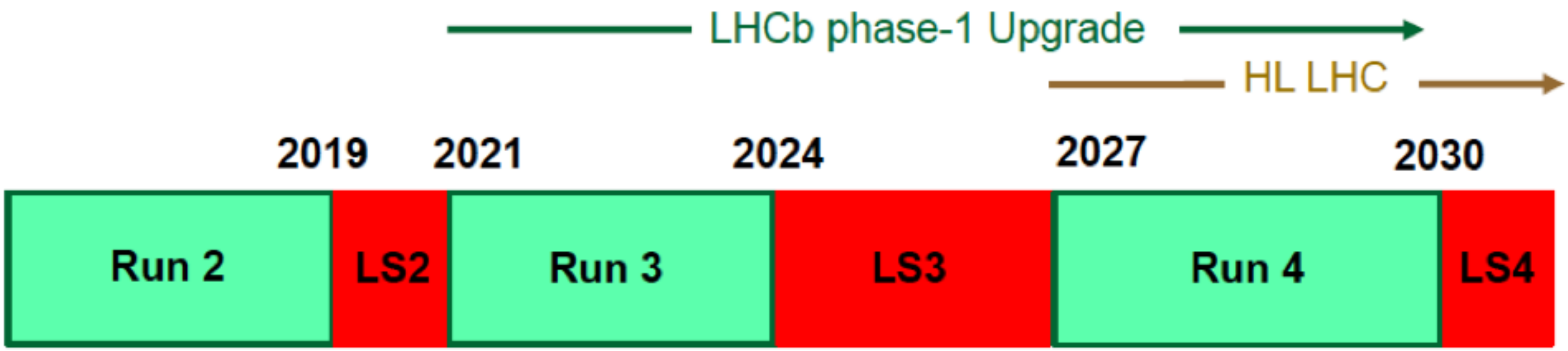
LHCb Upgrade-II



Expression-of-Interest submitted for LHCb Upgrade-II



LHCb Upgrade-II: Challenges



Major challenges for LHC & LHCb at peak Luminosity of 2×10^{34} /cm^2/s:

- Current studies indicate 2×10^{34} is possible with changes to IP optics (β^* reduction) & shielding. Triplet lifetime may limit integ. Lum. to ~ 300 fb^{-1}

- At Int/crossing ~50 (vs 1.1 now) & Track Multiplicity as high as 3500:
  - Will need a new tracking system & thinner pixels with finer granularity & time measurements in VELO
  - Improved PID & Calorimertery (with fine granularity- e.g. SiW)
  - Will need innovative solutions to enormous increase in data rate (>>ATLAS & CMS)

- Next: narrow the space of solutions and develop TDR

Summary comments

- Flavor physics remains one of the primary drivers of the search for New Physics beyond SM, and most scenarios of New Physics are expected to leave a footprint in flavor processes.
  - The current data is consistent with the Standard Model, setting severe constraints on scenarios of New Physics Beyond SM, but many stones remain unturned.
    - There are some areas of tensions with SM, waiting for more precise measurements. Lepton Flavor Universality is under the microscope.

- The next phase of the program-with Belle-II & LHCb-upgrades- will result in a much sharper picture of the physics of flavor- will resolve or solidify some of the current anomalies. *There is no guarantee that this will reveal anything new, but there is reason for optimism.*