Flavor Physics at LHCb

Status of the experiment
Selection of Physics
Future plans

US ATLAS meeting 2018
July 30, 2018

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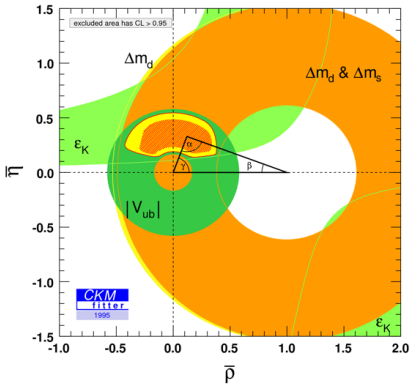
University of Maryland

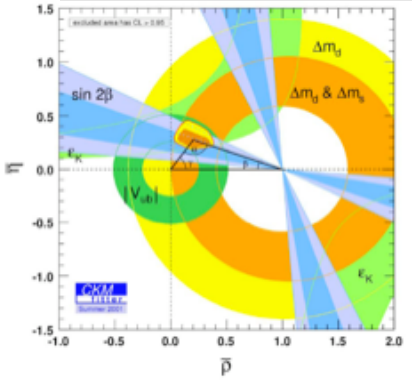
Why bother with more flavor physics?

The goal is a much sharper picture of flavor processes
=➔Improved sensitivity to footprints of new physics.

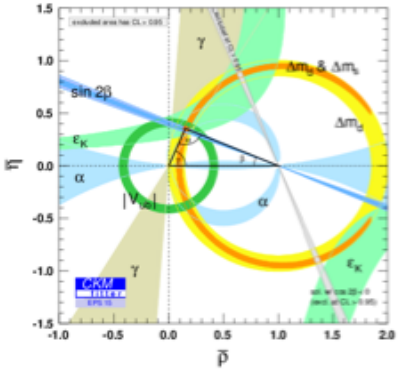
Last century



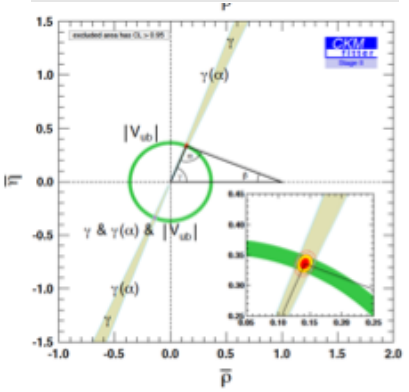
2001



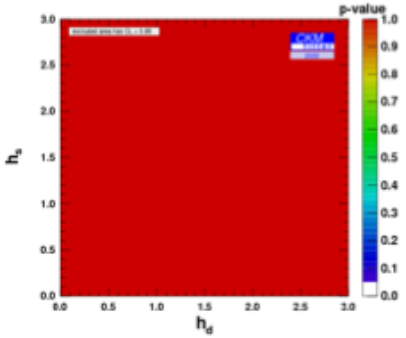
Today

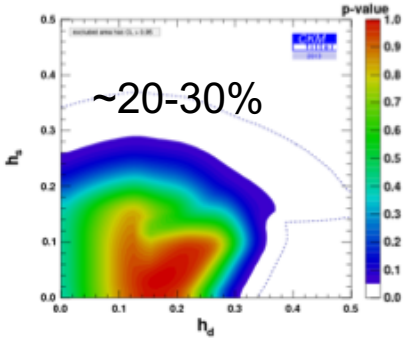


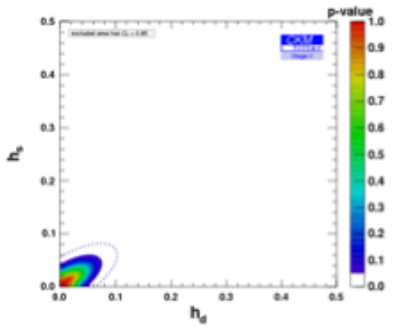
2025+



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







Why bother with more flavor physics?

CP Violation remains an open question

- CKM mechanism is the primary source of observed CPV
  - Kaons and B hadrons are the sole sources of CPV & T-Violation
    - No evidence for CPV in the charm system
    - No evidence for EDM
    - Time-Reversal (T) violation is observed in the B system- in balance with the observed CPV, supporting CPT invariance.

- Rare flavor processes remain good probes of new sources of CPV- present in most scenarios of new physics.
  - SM CP Violation is unable to account for baryon asymmetry in universe

Why bother with more flavor physics?

Some anomalies persist, and
the list is growing

- Hints of lepton flavor non-universality
- Tensions in angular distribution of radiative decays
- $K\pi$-puzzle
- V_{ub} and V_{cb} :Inclusive vs exclusive measurements
- Sin2β tension (direct vs CKM fit)

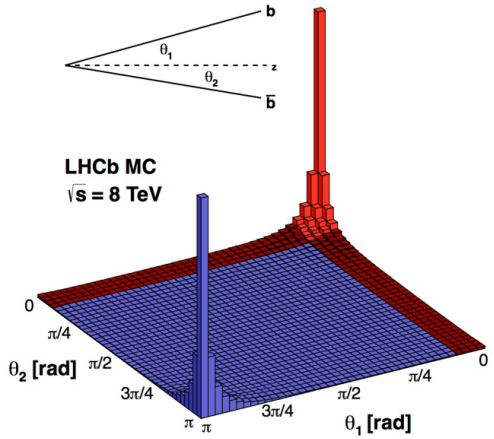
The LHCb Detector

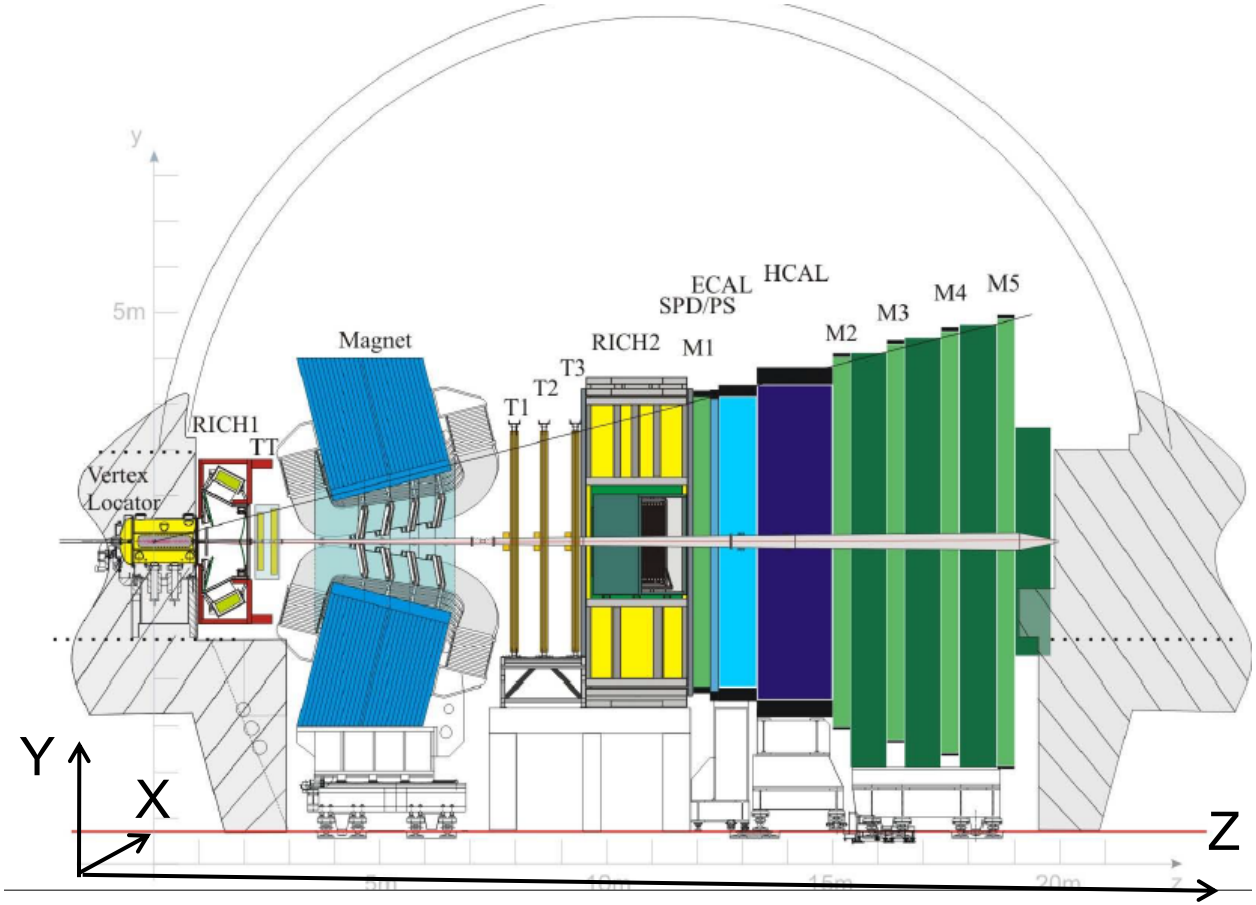
A Single Arm Spectrometer at LHC

Acceptance: $2 < \eta < 5$

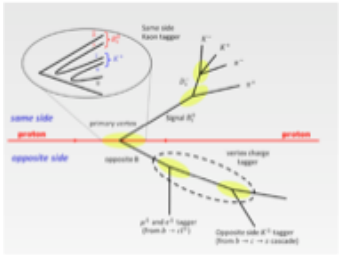
σ_{inel}~70-80 mb
σ_{cc}~6 mb (7 TeV)
σ_{τ}~80 μb (7 TeV)
σ_{bb}~280 μb (7 TeV)
σ_{bb}~500 μb (14 TeV)

$b\bar{b}$ peaked forward or backward with ~25% in detector acceptance





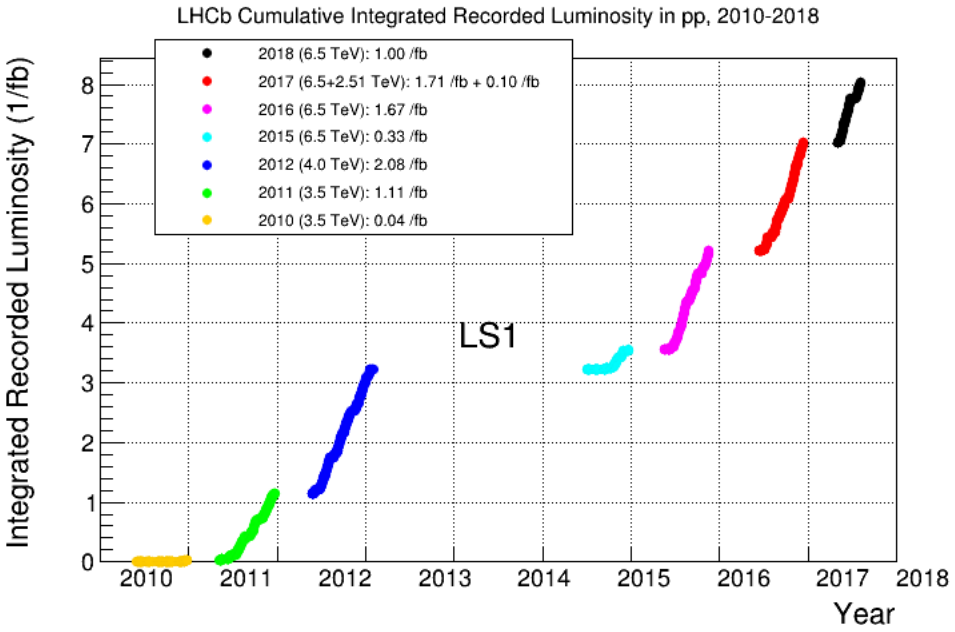
Access to all species of B hadrons

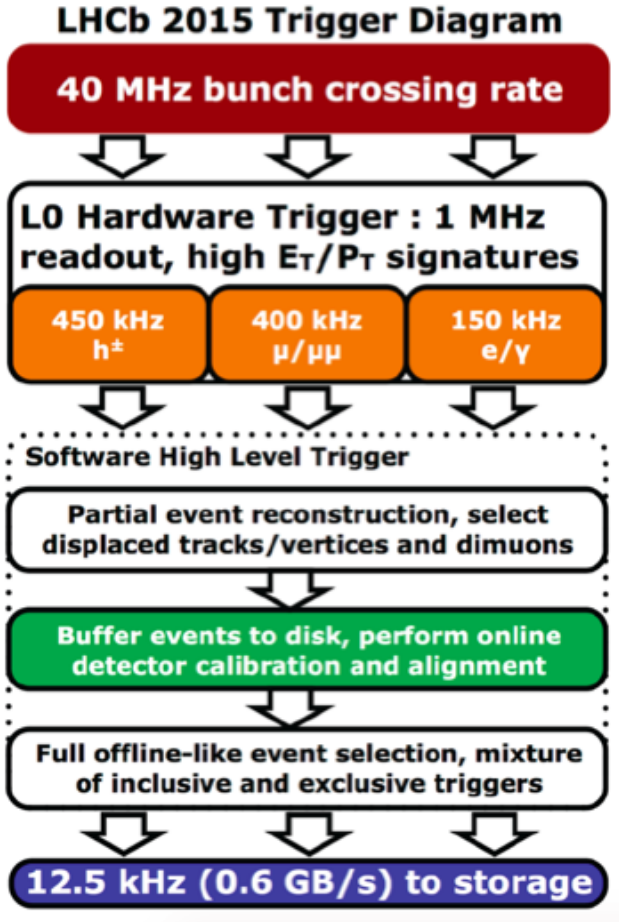


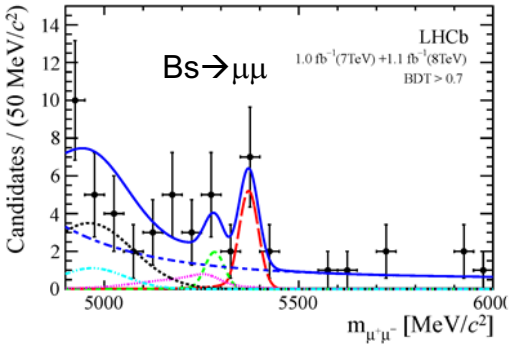
JINST 3 (2008) S08005.
Int. J. Mod. Phys. A30 (2015) 1530022.

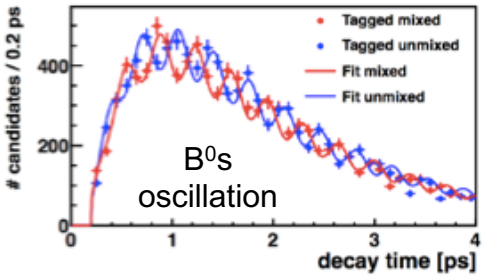
LHCb Status

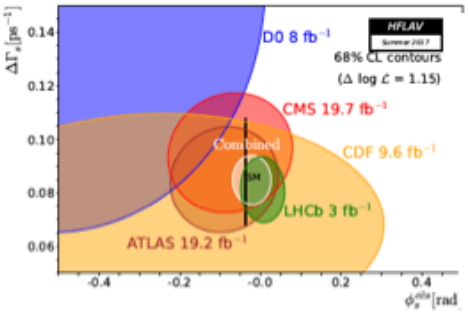
- Operates at Inst Luminosity ~4×10^{32} cm^{-2} s^{-1}
  - Beam separation is adjusted to keep the luminosity constant.
- In Run 2, mean number of visible collisions/beam-crossing ~1.1
- Recorded Luminosity ~ 8 fb-1

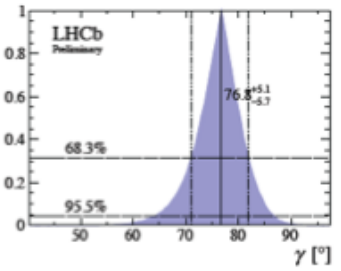


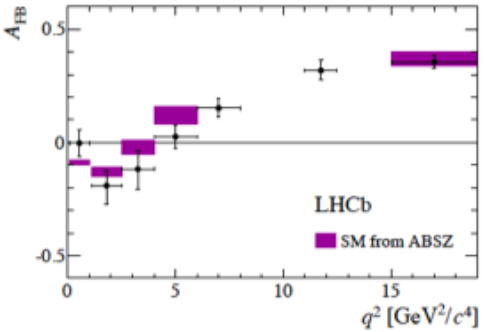


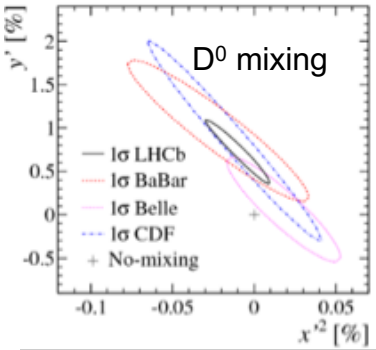


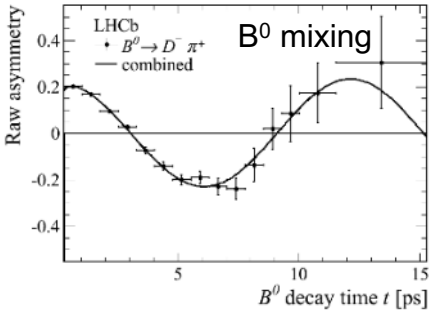


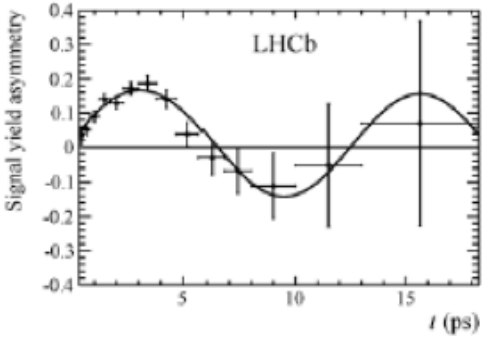


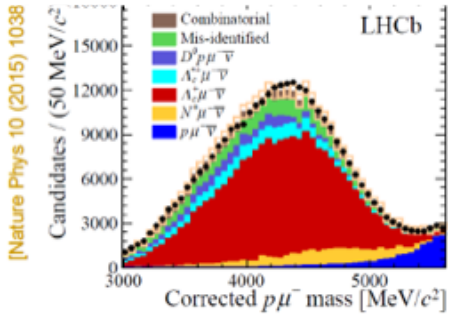






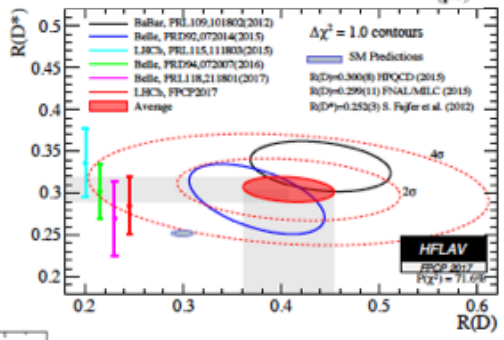


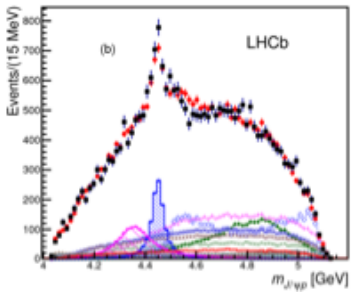


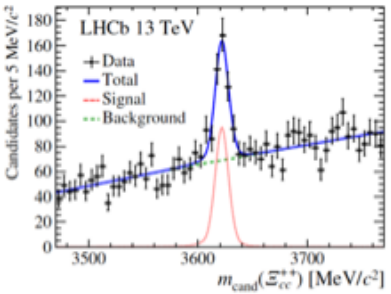


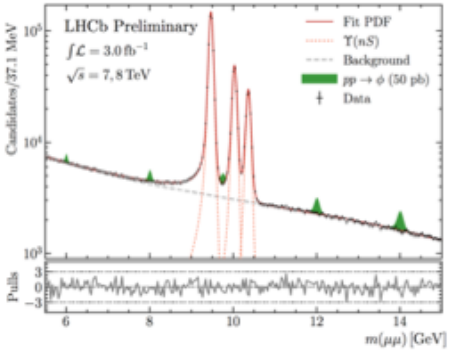
Bs→μμ
1.0 fb⁻¹(7TeV) +1.1 fb⁻¹(8TeV)
BDT > 0.7

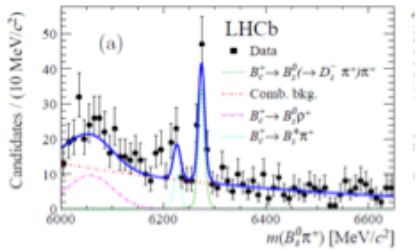
LHCb covers a very broad spectrum of physics, from Flavor to EW, DM search, QCD, pA…

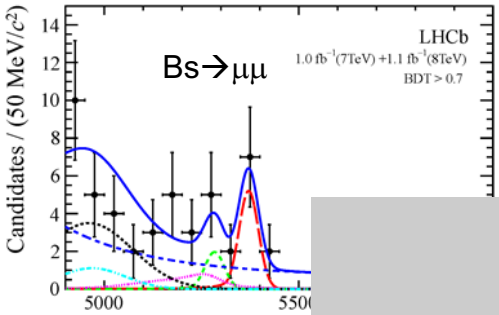


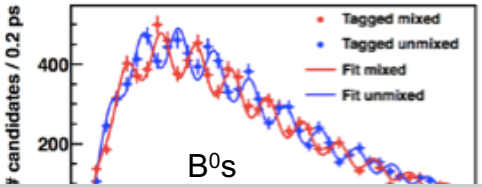


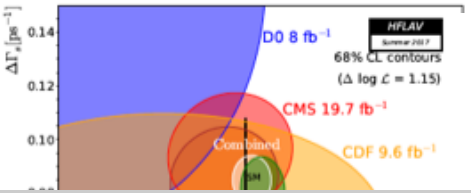


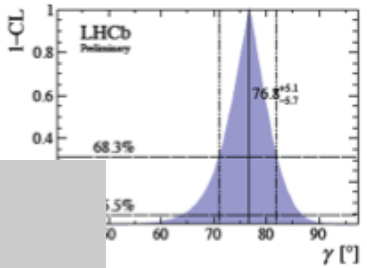






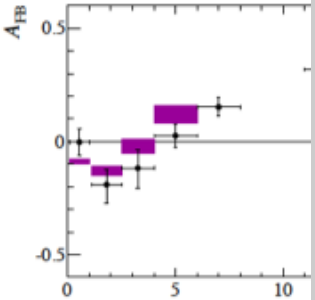


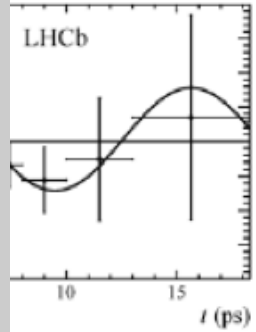


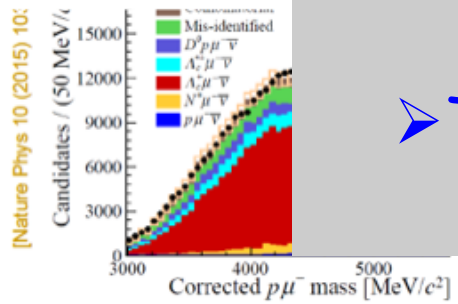


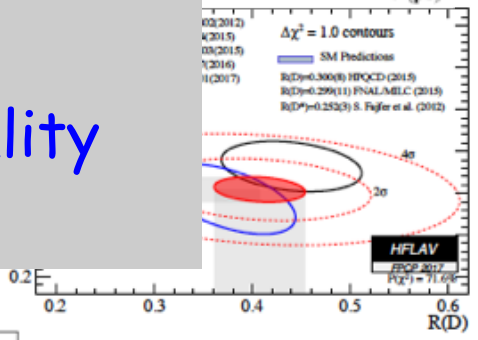
Comments on three areas

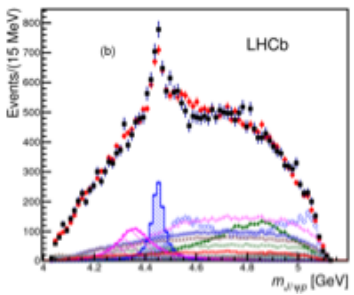
- New Physics search via CKM meterology
- New Physics search in FCNC processes:
  - Observation of $B \to \mu^+\mu^-$
  - Precise measurements of $B \to K^{(*)} l^+l^-$
- Tests of Lepton Flavor Universality

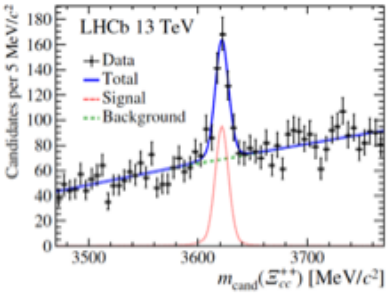


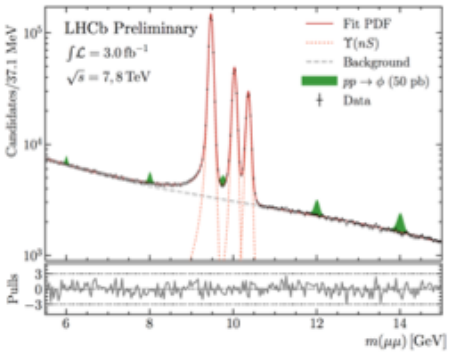


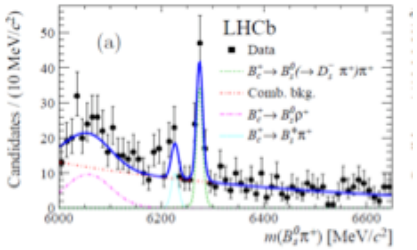












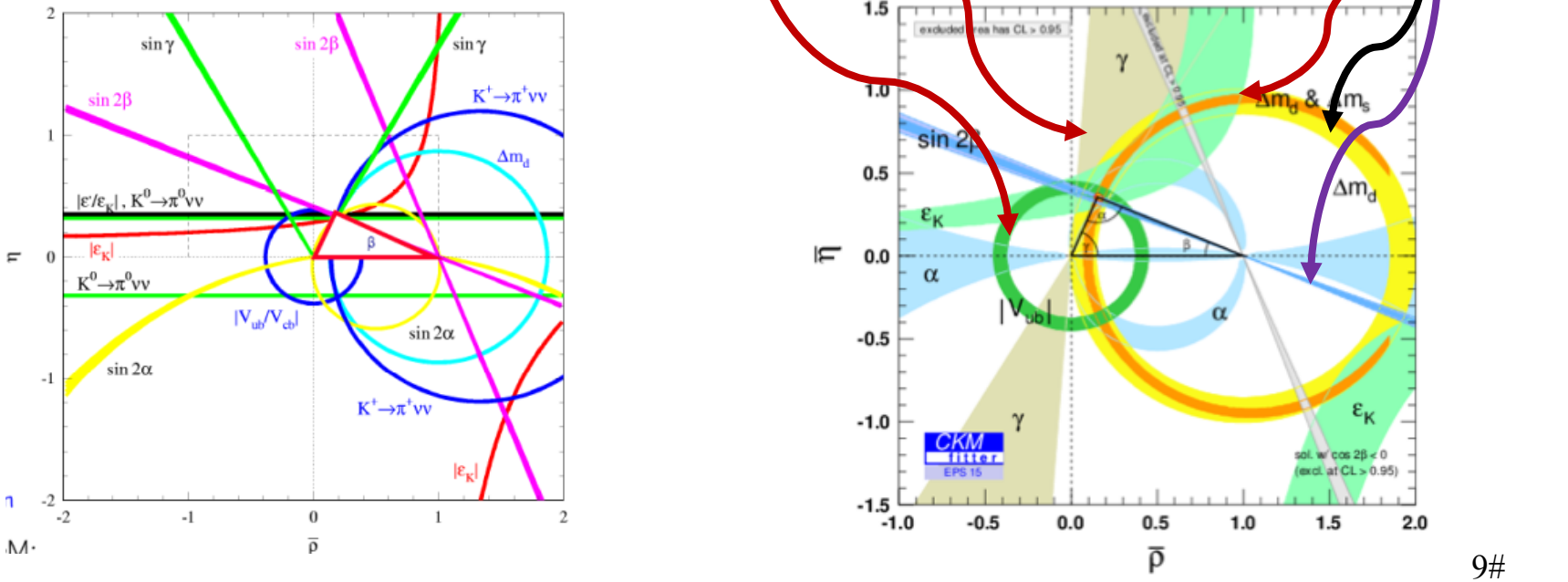
Continue to sharpen the CKM picture

The picture may be modified by the presence of New Physics (NP)

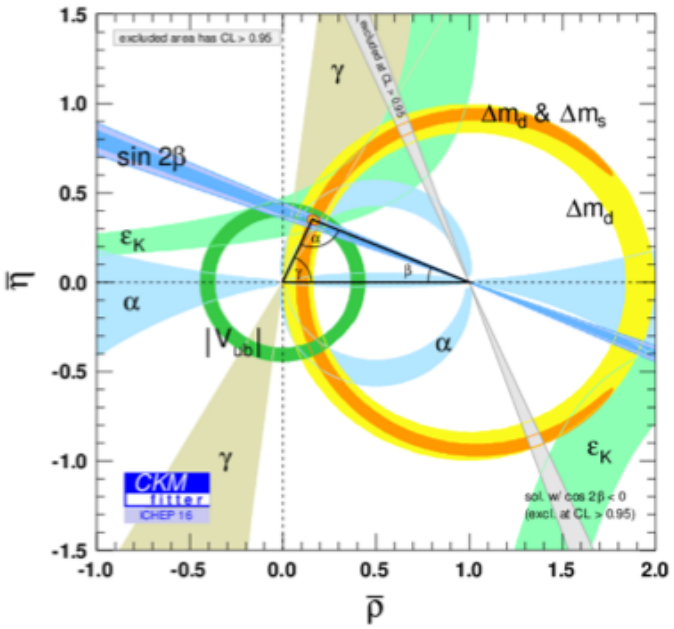
Observables involving $B^0 \Leftrightarrow \overline{B^0}$ *oscillation*

Bring in sensitivity to New Physics

NP free measurements -tree level processes: V_{ub} & γ



Status of CKM (2018)

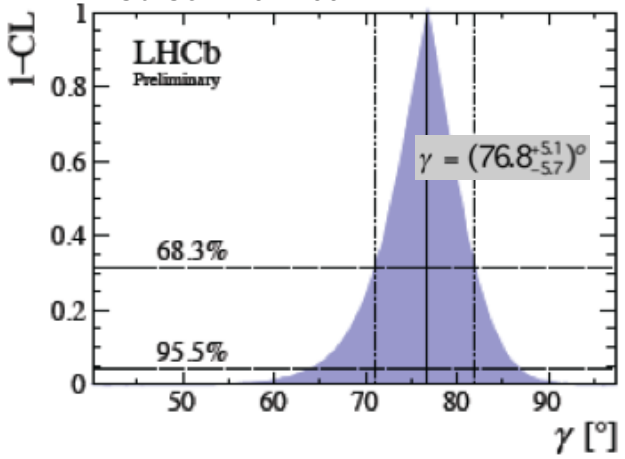


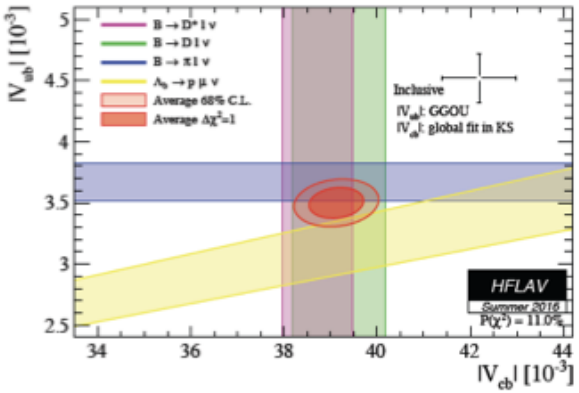
All is well with the CKM picture at O(10%) level:

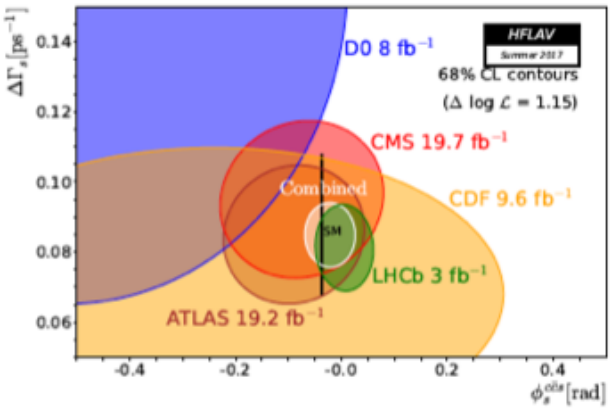
	Direct	CKM fit
α	$\left(87.6^{+3.5}_{-3.3}\right)^o$	$\left(92.1^{+1.5}_{-1.1}\right)^o$
β	$\beta = (22.2 \pm 0.7)^\circ$	$\left(23.74^{+1.13}_{-0.98}\right)^o$
γ	$\left(76.2^{+4.7}_{-5.0}\right)^o$	$\left(65.9^{+0.96}_{-2.54}\right)^o$
$-2\beta_s$	-0.021 ± 0.031	-0.0370 ± 0.0006

Some of the measurements at LHC

LHCb-Conf-2017-004







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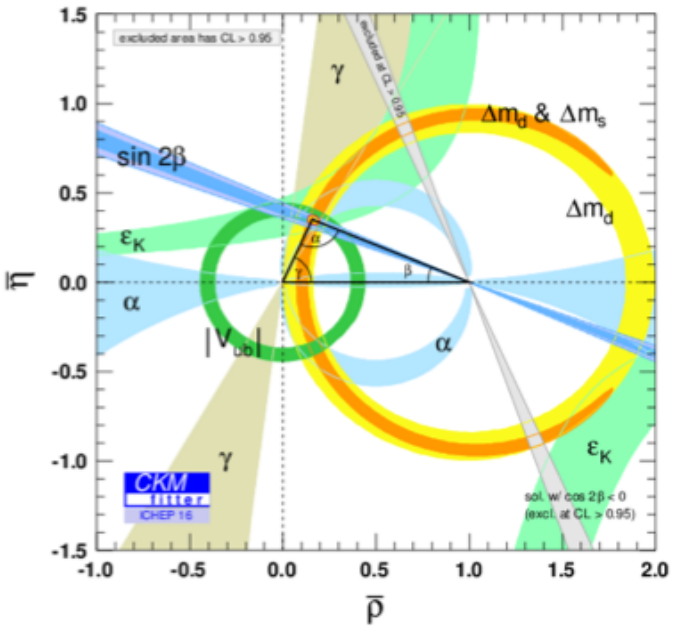

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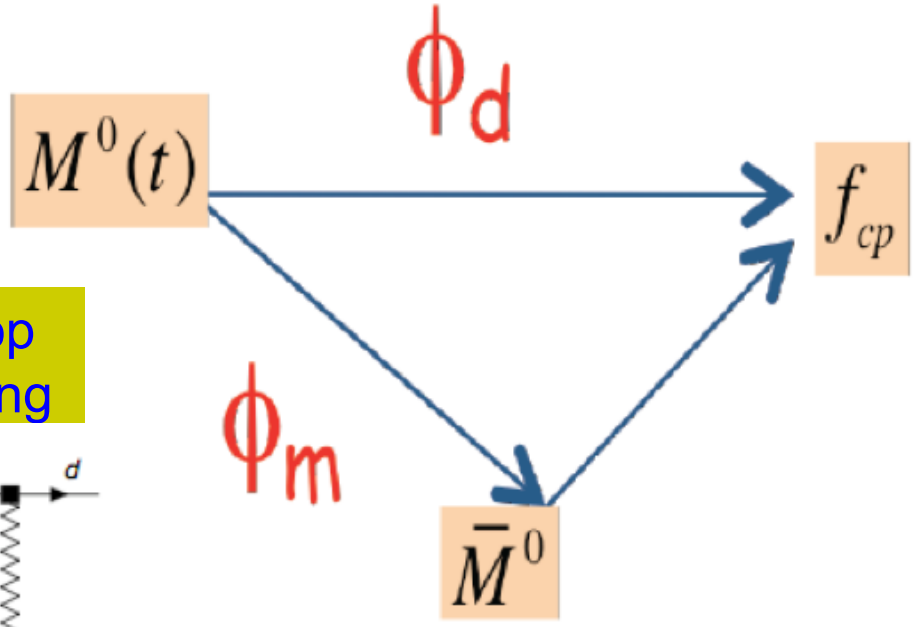
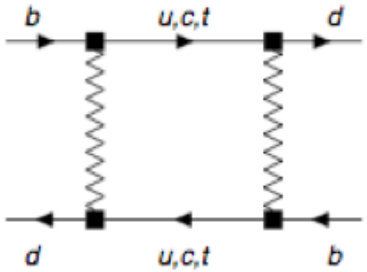
$-2\beta_s$	-0.021 ± 0.031	-0.0370 ± 0.0006

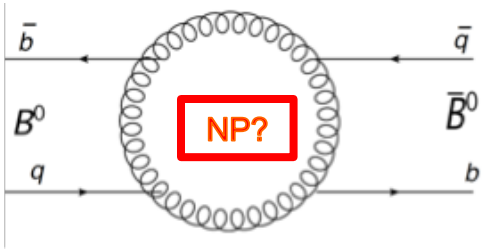
Is there room for New Physics?
CPV sources beyond SM?

New Physics Through Mixing



Through new loop diagrams in mixing

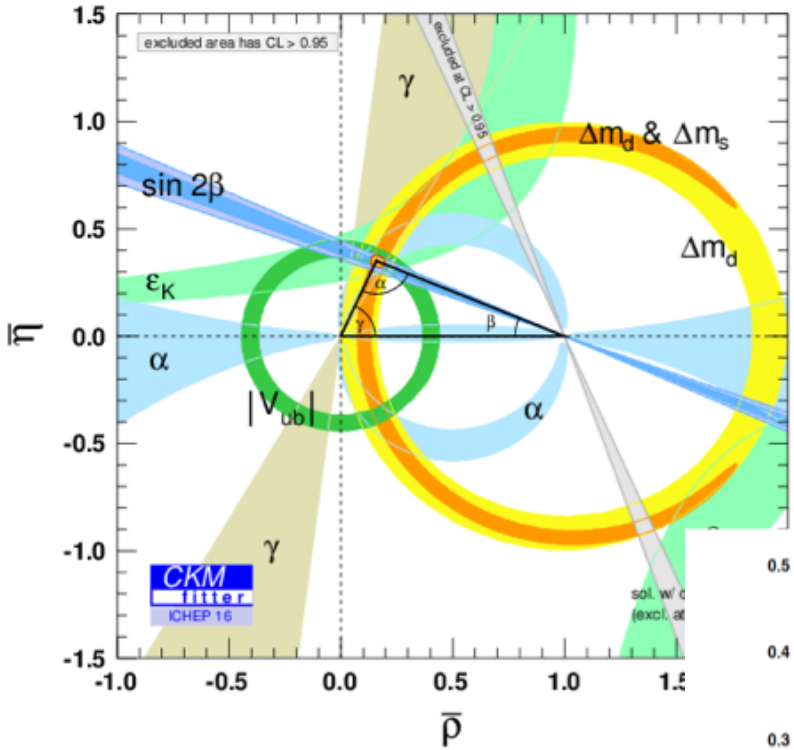


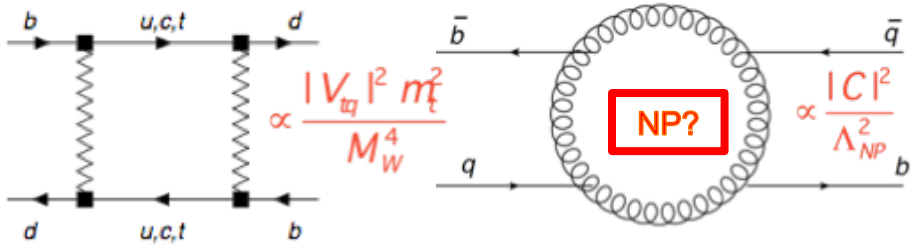


New Physics Through Mixing

All is well with the CKM picture at O(10%) level:

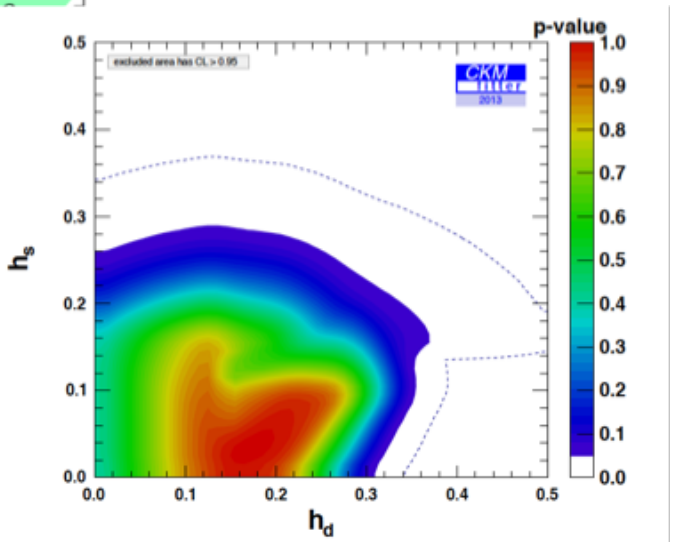
For New Physics through Mixing





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

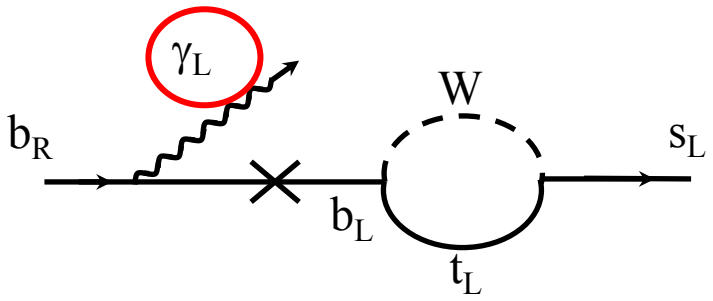
Constraint on NP/SM amplitude
See *(arXiv: 1309.2293)*



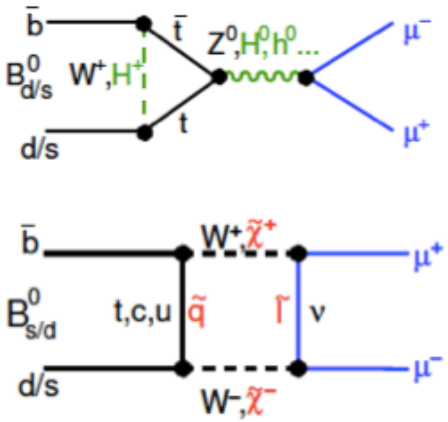
$A_{NP} < 0.3 A_{SM}$

$\Lambda_{NP} >> 10^2$ TeV
For c~1

Search for New Physics footprint in other FCNC Processes



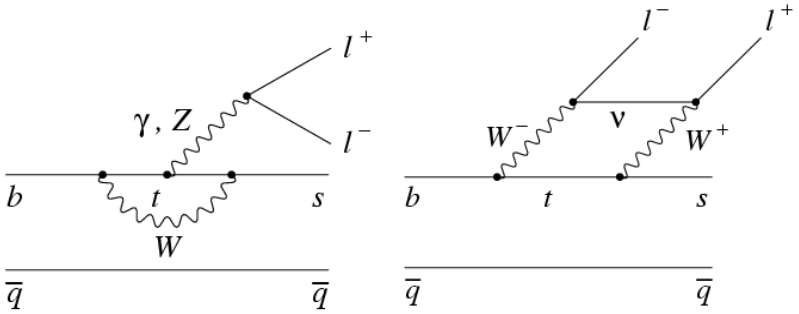
A key probe of NP in B decays
Observables: Rate, CPV, polarization of γ



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

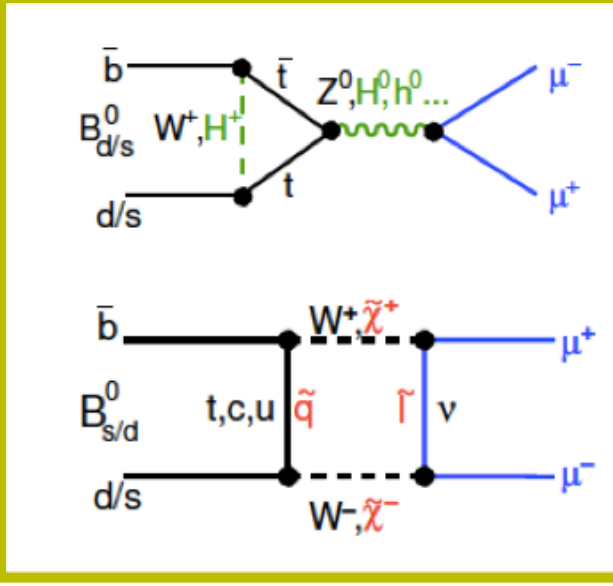
PRL 112, 101801

Finally seen (LHCb & CMS) – consistent with SM – sets severe constraints on BSM



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

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



Major success story at LHC

LHCb & CMS Run 1

$$Br(B_s^0 \to \mu^+\mu^-) = (2.8^{+0.7}_{-0.6}) \times 10^{-9} \quad 6.2\sigma$$

$$Br(B_s^0 \to \mu^+\mu^-) = (3.9^{+1.6}_{-1.4}) \times 10^{-10}$$

[arXiv:1411.4413, Nature 522 (2015) 68]

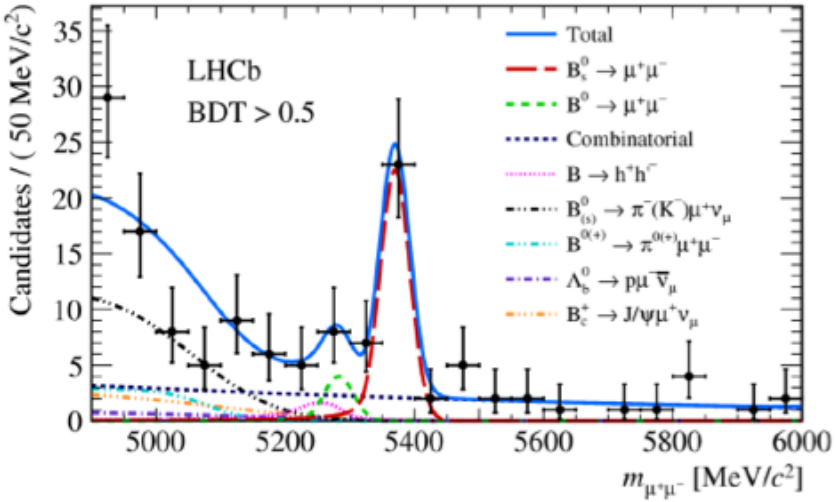
$$ATLAS: Br(B_s^0 \to \mu^+\mu^-) = (0.9^{+1.1}_{-0.8}) \times 10^{-9}$$

Eur. Phys. J. C76(2016) no. 9, 513

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

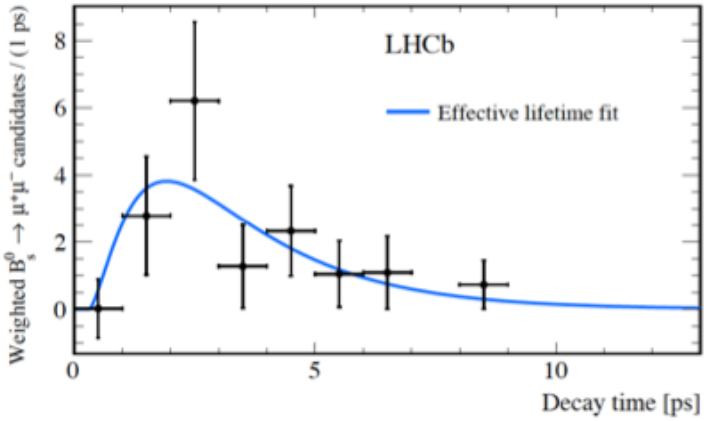
PRL 118, 191801 (2017)

LHCb Run1+ 1.4 fb^{-1} of Run 2



Effective lifetime consistent with SM:

$$\tau(B_s^0 \to \mu^+\mu^-) = 2.04 \pm 0.44 \pm 0.05 \text{ ps},$$



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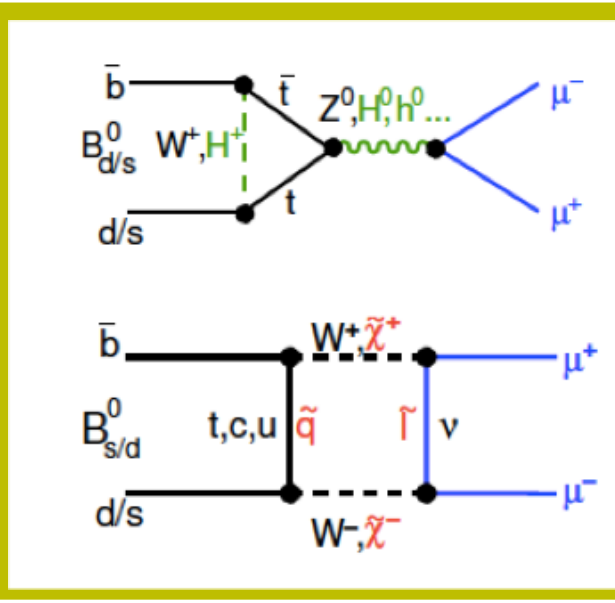

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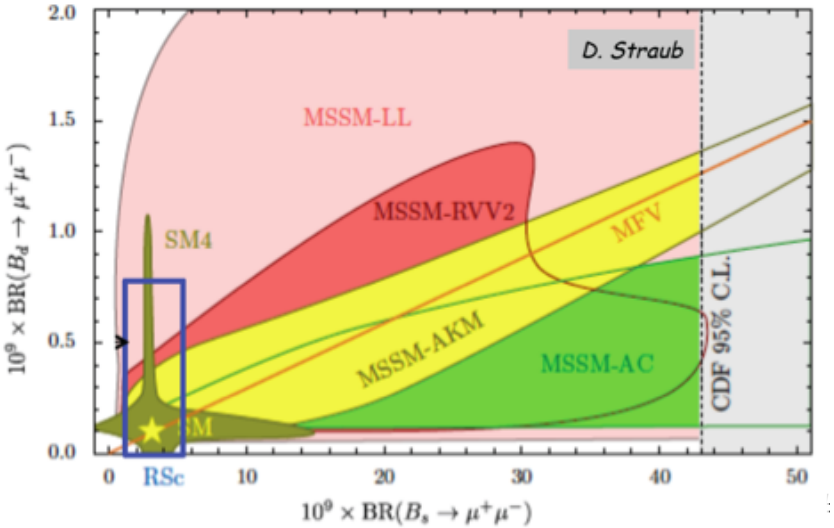
PRL 118, 191801 (2017)

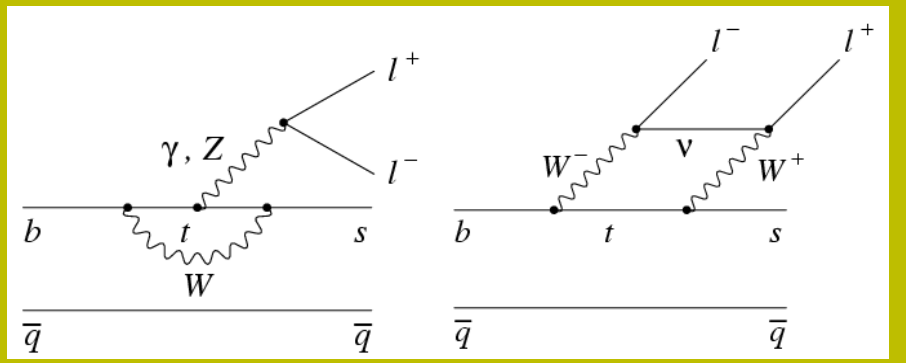
Consistent with SM

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

Severely constraining parameter space of new physics models



$B \rightarrow K^{(*)}\mu^+\mu^-$



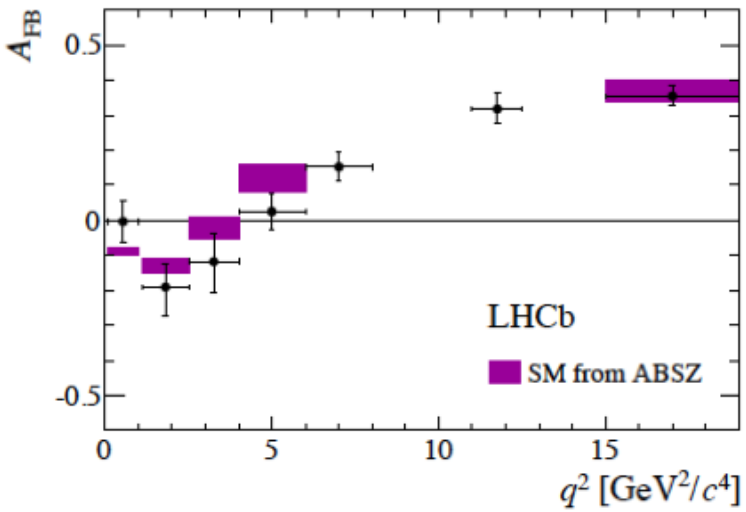
Several observables- sensitive to New Physics- extracted from differential rates.

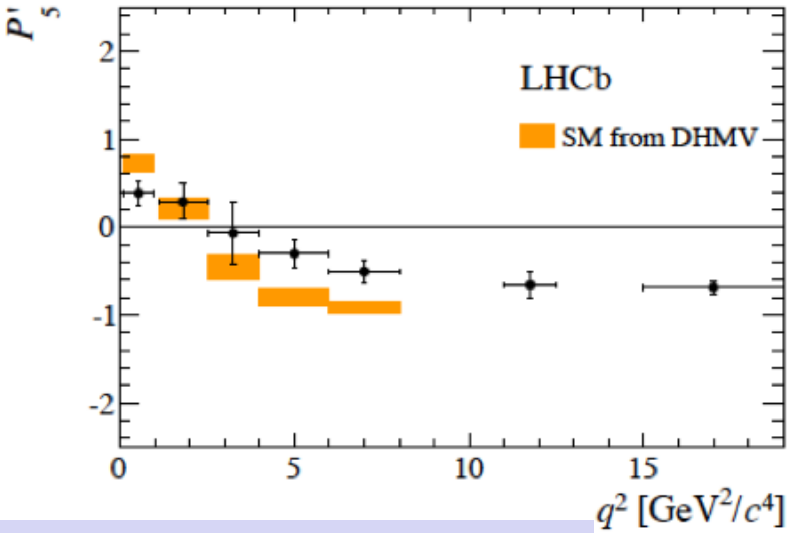
Precise measurements are now possible with large statistics of LHCb-including tests of Lepton Flavor Universality:

First full angular analysis of $B \rightarrow K^{*0}\mu^+\mu^-$ performed with LHCb Run 1 data

Some intriguing results

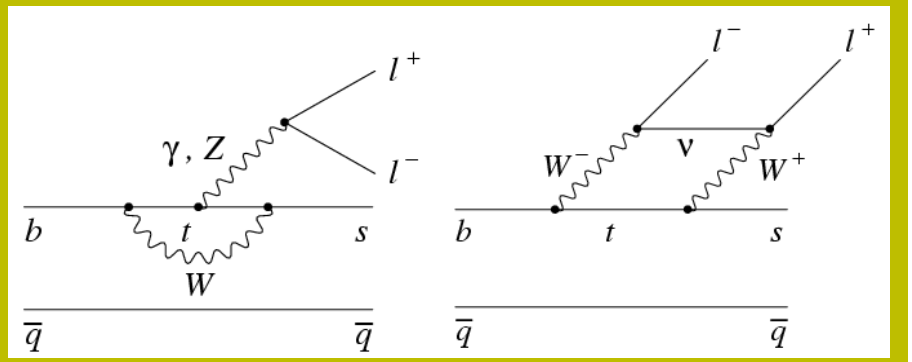
[JHEP 02 (2016) 104]





Overall compatability of LHCb results with SM ~3.4 σ

$B \rightarrow K^{(*)}\mu^+\mu^-$



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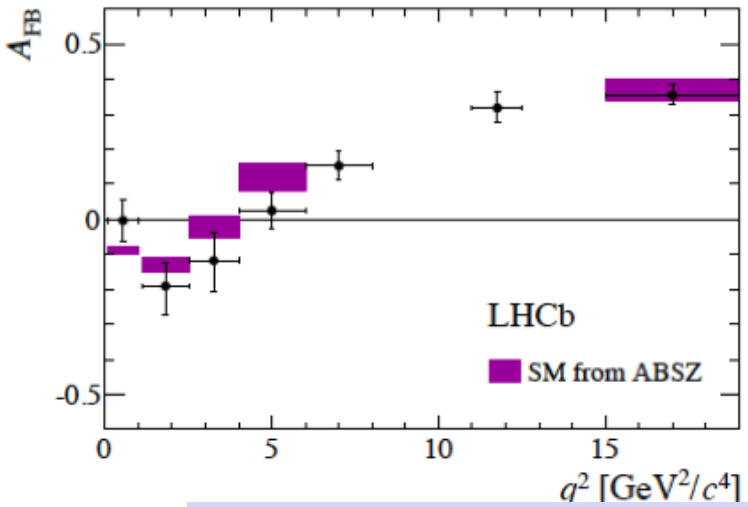

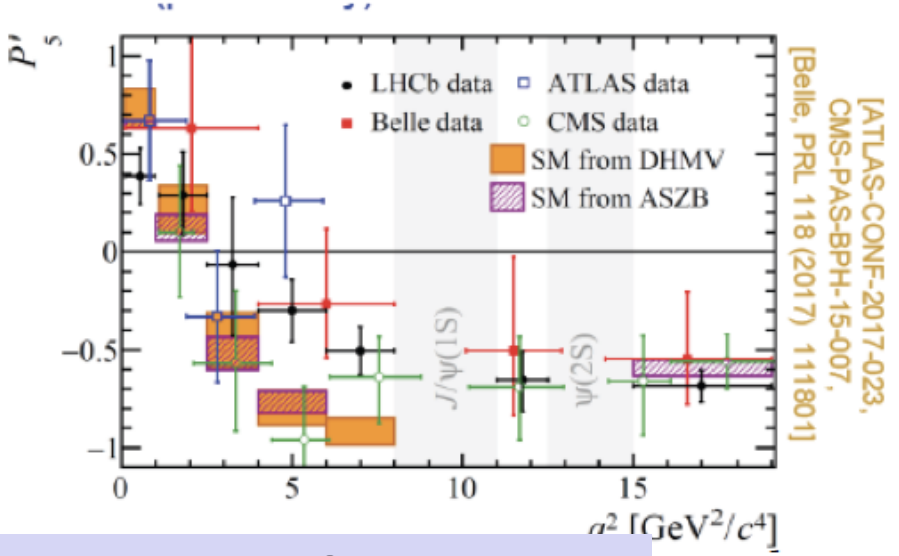

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Tests of Lepton Flavor Universality in $B \to K^{(*)} l^+ l^-$

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

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

Measurement performed as a double ratio:
Significantly reduces the dependence on Lepton Identification efficiencies.

$$\mathcal{R}_{K^{*0}} = \frac{\mathcal{B}(B^0 \to K^{*0} \mu^+ \mu^-)}{\mathcal{B}(B^0 \to K^{*0} J/\psi (\to \mu^+ \mu^-))} \Big/ \frac{\mathcal{B}(B^0 \to K^{*0} e^+ e^-)}{\mathcal{B}(B^0 \to K^{*0} J/\psi (\to e^+ e^-))}$$

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LHCb

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

Within 2.6 σ of SM

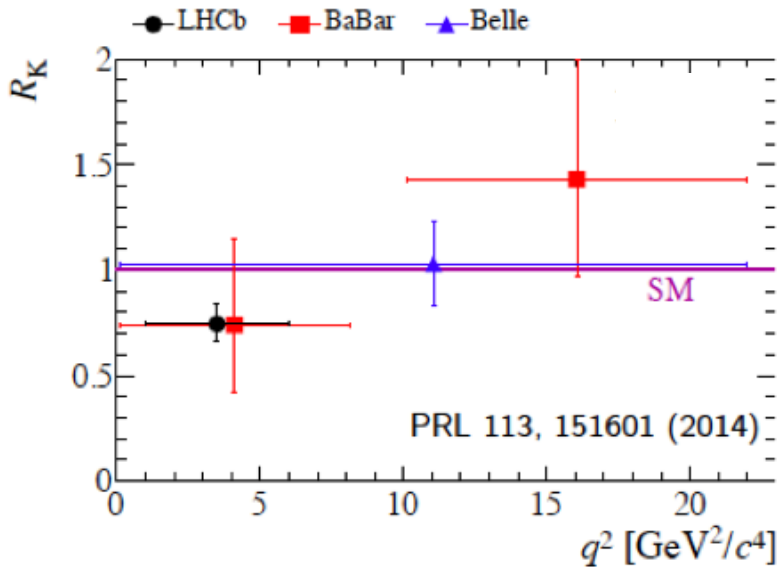
PRL 113, 151601

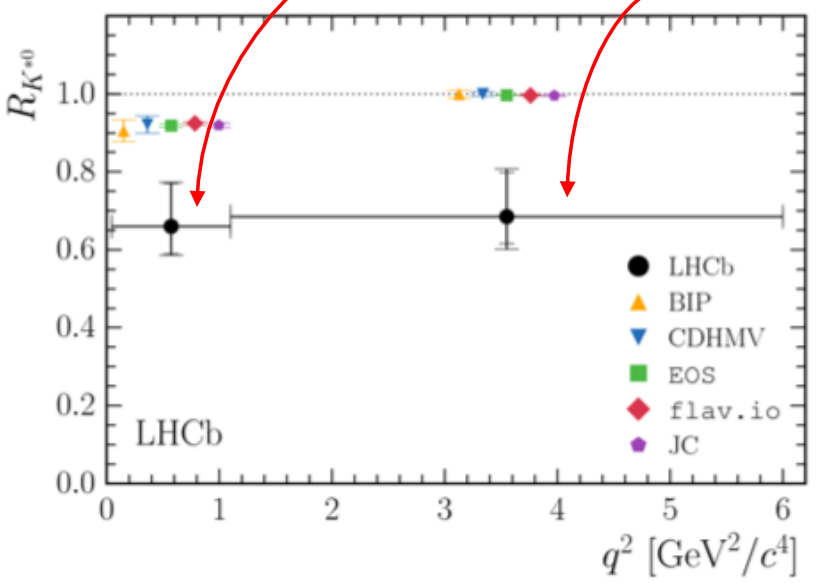
$$R_{K^*} = 0.660^{+0.110}_{-0.070} \pm 0.024 \quad low - q^2$$

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

Within 2.1-2.3 σ & 2.4-2.5 σ of SM

JHEP 08(2017)055





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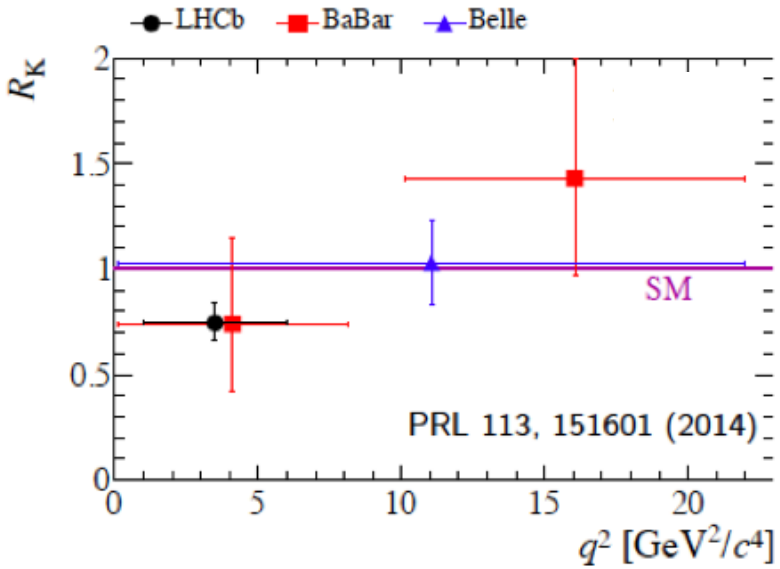
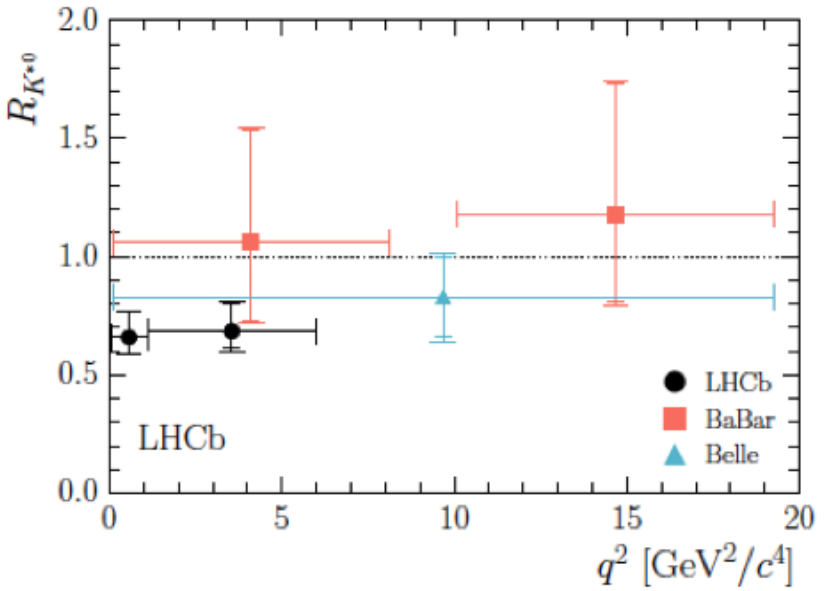
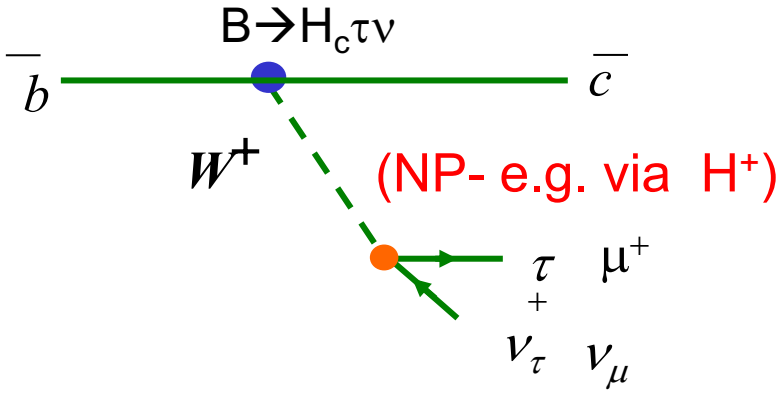
JHEP 08(2017)055





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 scalar form factors- helicity suppressed contributions that are negligible for e & μ channels

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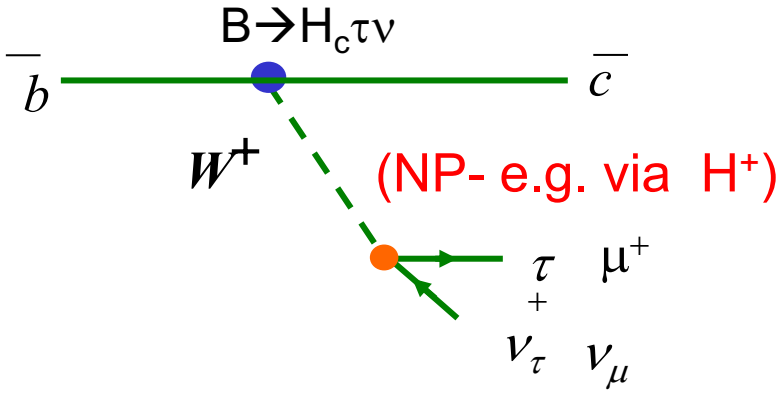

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Hints of deviation from these predictions first seen by BaBar

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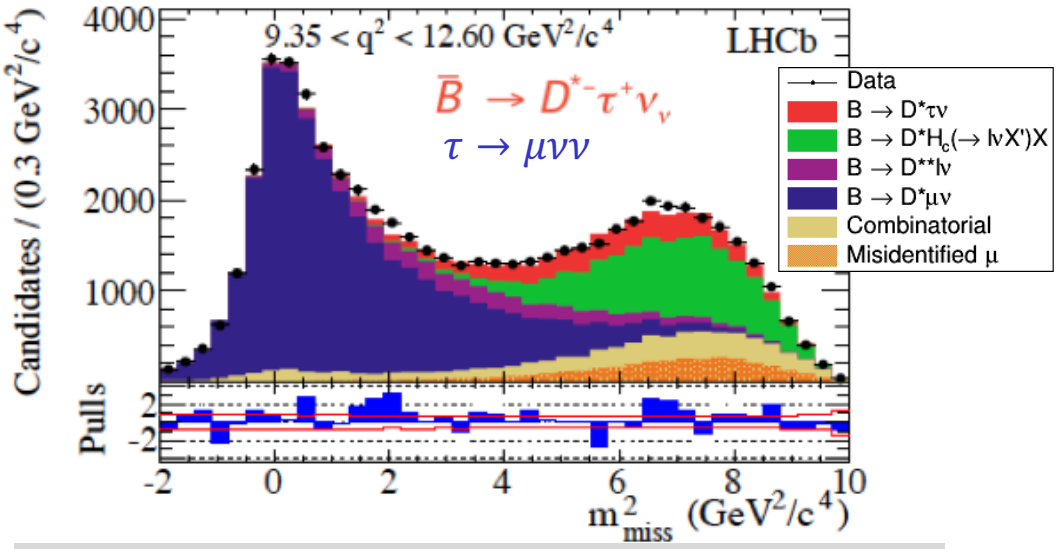
All with Run 1 Data- so far

2015

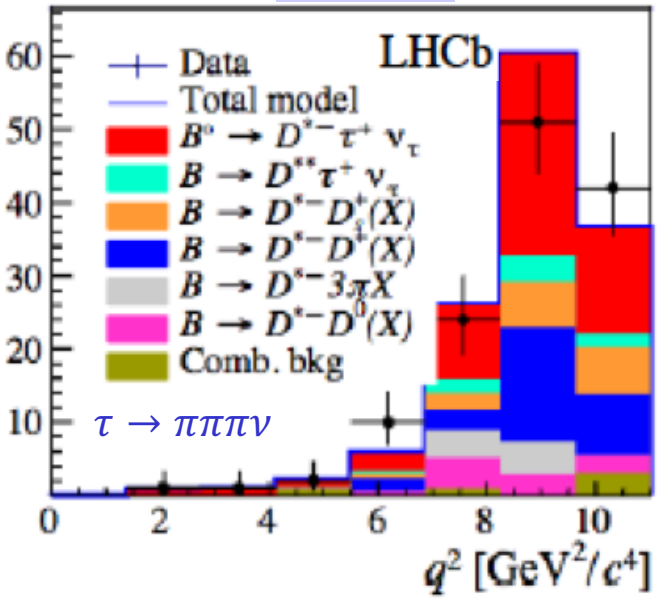


R(D*) = 0.336±0.027 (stat)±0.030 (syst)

Within 2.1 σ of SM

PRL 113, 111803

2017

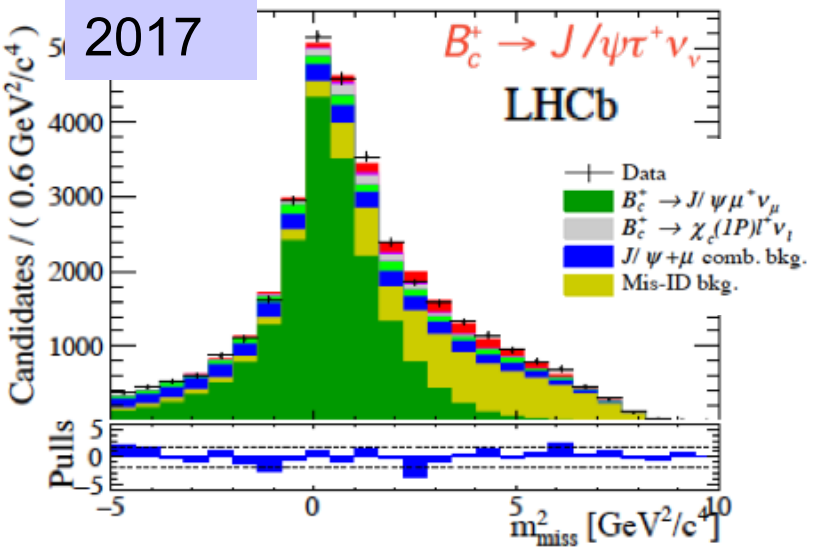


R(D*) = 0.291±0.019±0.026±0.013

Within 1 σ of SM

PRL 120, 171802

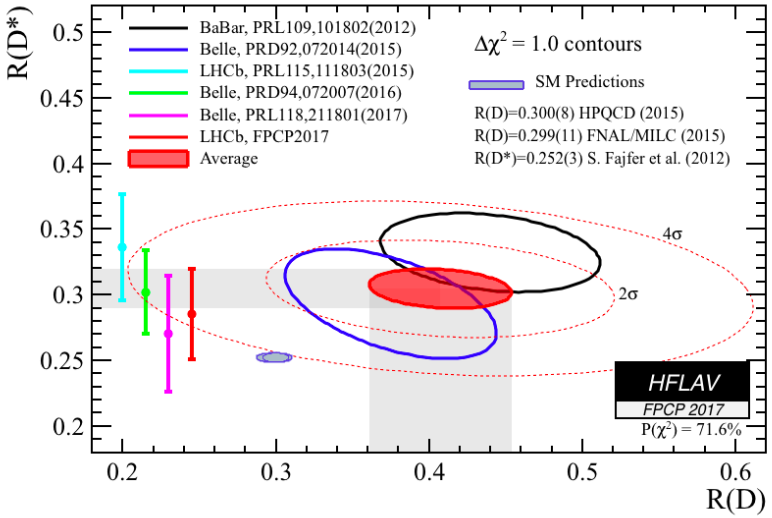
2017



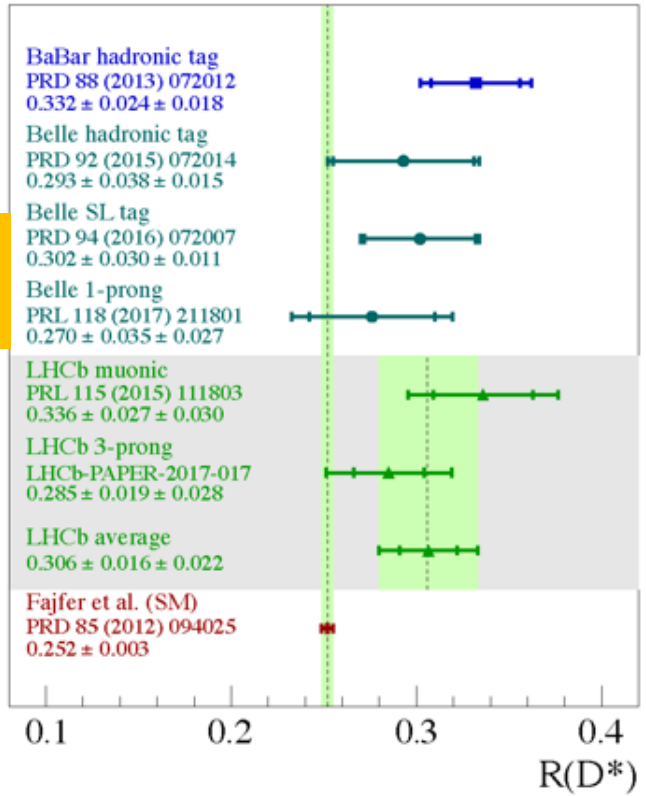
R(J/ψ) = 0.71±0.17 (stat)±0.18 (syst)

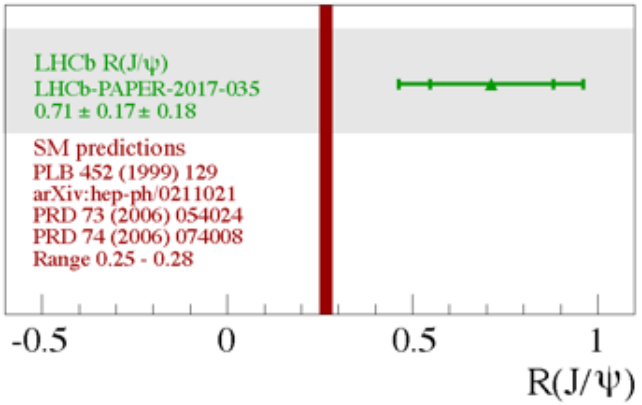
Within 2 σ of SM

PRL 120, 12180



4.1 σ tension with LFU/SM





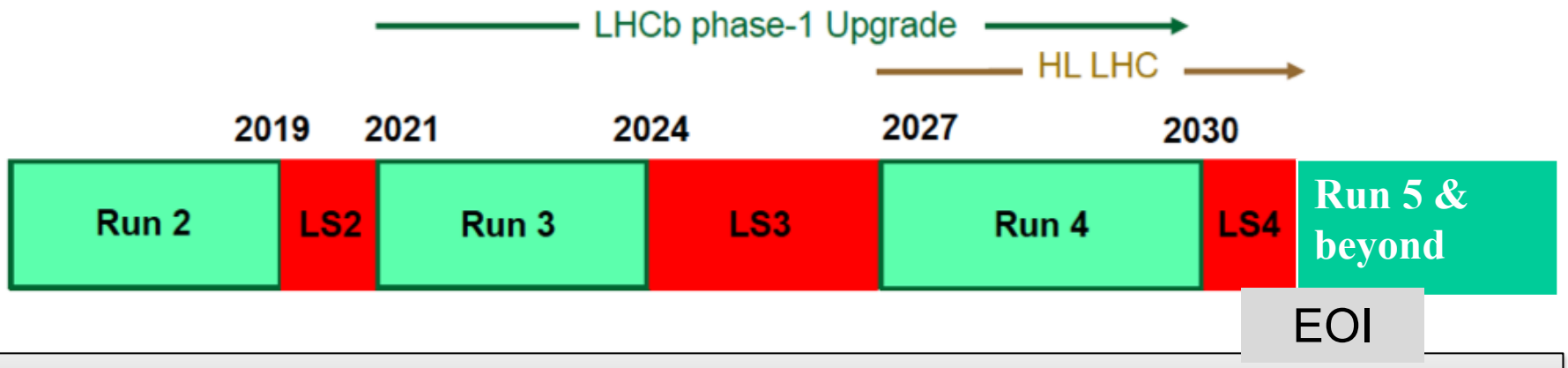
- Several Intriguing results: away from SM in the same direction.
- Several New Physics scenarios are proposed: leptoquarks, right-handed sterile neutrinos, …

Some caution:

- No single measurement is yet at or beyond 3 sigma away from SM -Too early to consider LFU overthrown.
- Theoretical SM predictions are being improved

Future

Experimental Landscape



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

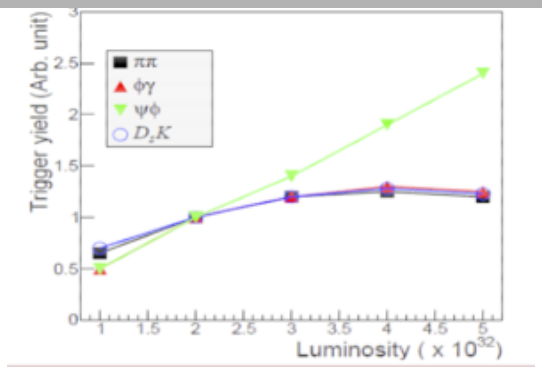
+ Data from ATLAS and CMS for some key channels

	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 →	2031–2033, 2035 →	2×10^{34}	300	50

The LHCb upgrade-I: Trigger

High Luminosity running requires major changes to the LHCb trigger scheme

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



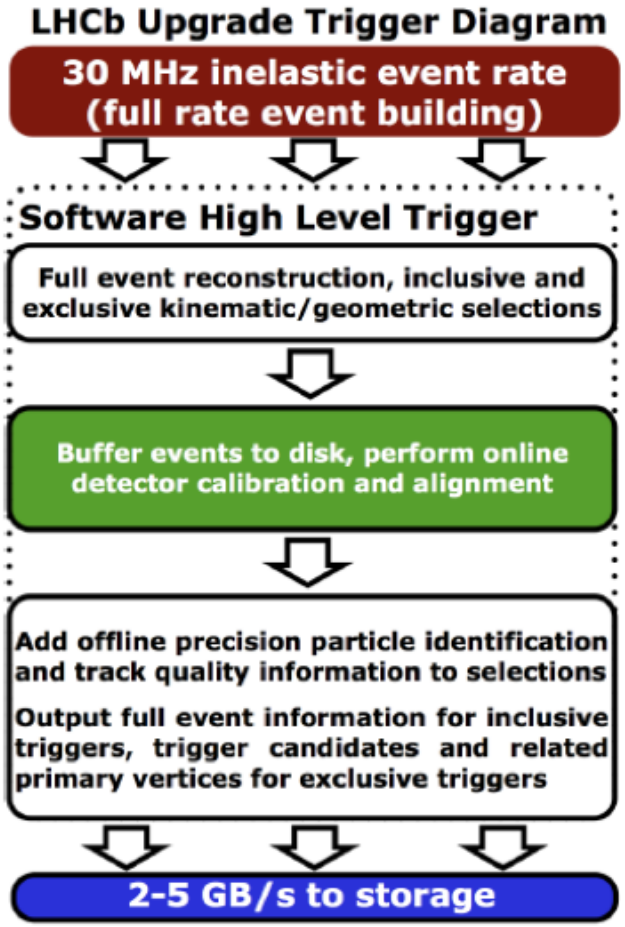
➔ New Trigger Apporach:

- 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 Trigger



Upgrade-I

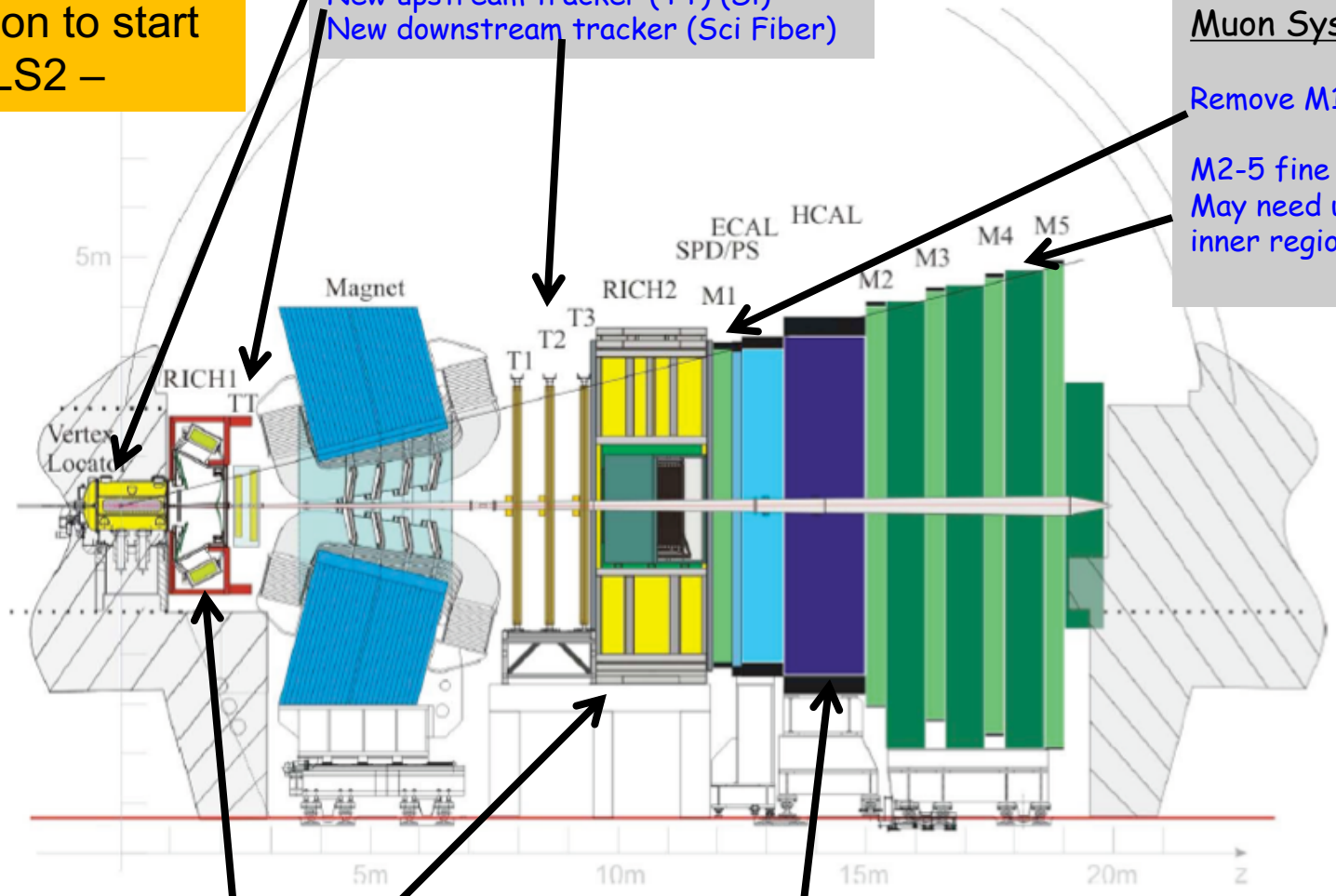
The assembly and installation to start in LHC LS2 –

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

Muon System:

Remove M1

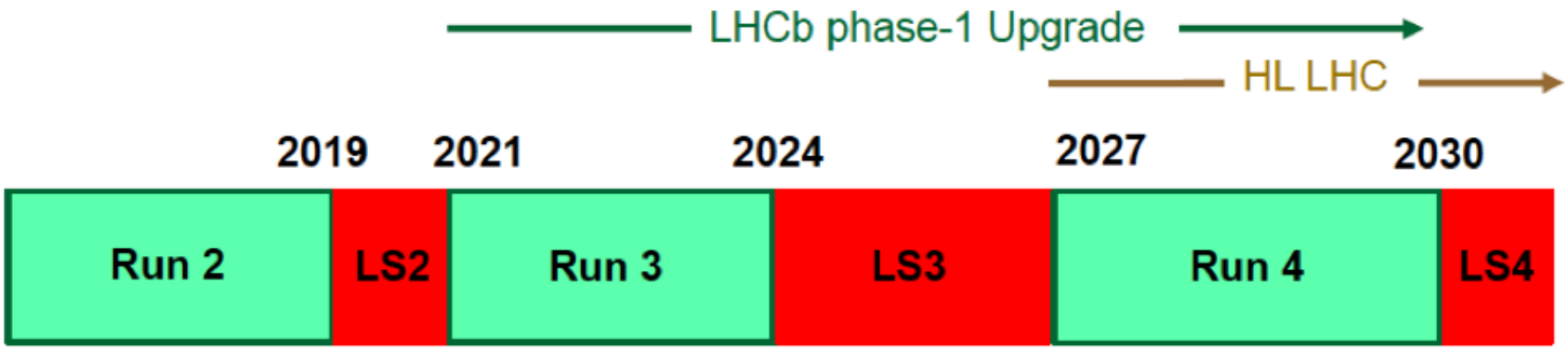
M2-5 fine for 1×10^{33}
May need upgrade of inner region at 2×10^{33}



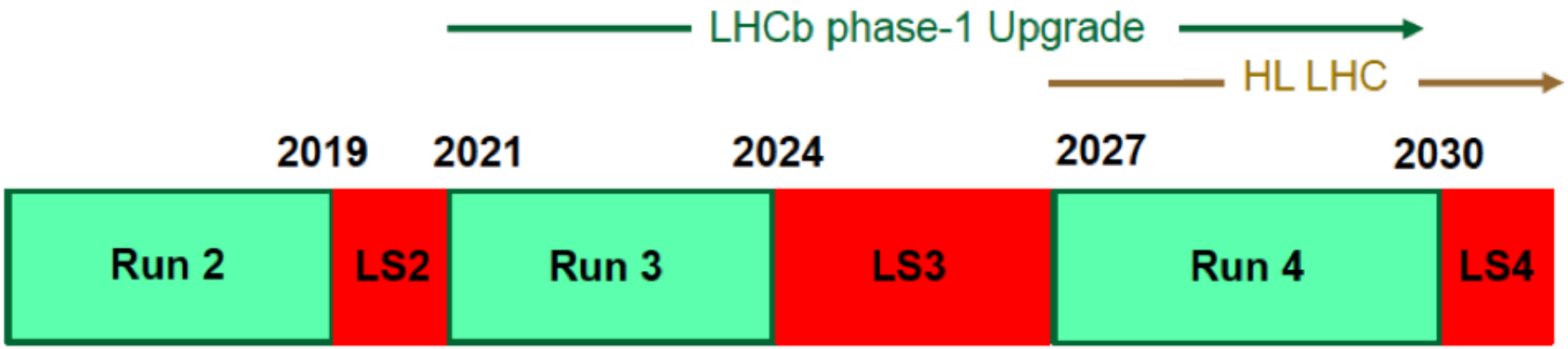
RICH 1 & RICH 2
HPD→ MaPMT
New 40 MHz R/O
RICH1: new optics
remove aerogel

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

Further in Future: Upgrade-II



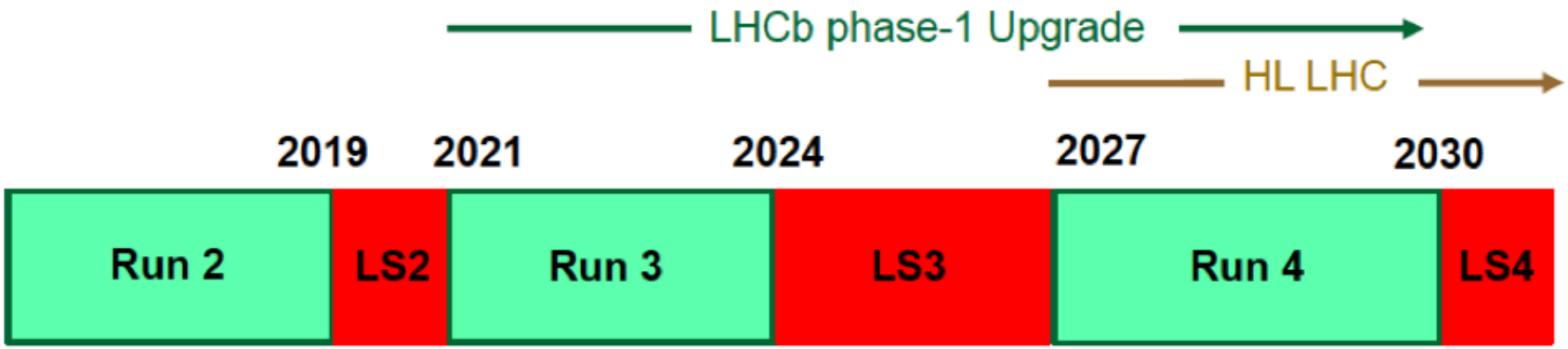
Upgrade-II: Challenges



- Current studies indicate $2x10^{34}$ 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 the enormous increase in data rate (>ATLAS & CMS)
- Next: narrow the space of solutions and develop TDR

Upgrade-II: Physics Goals

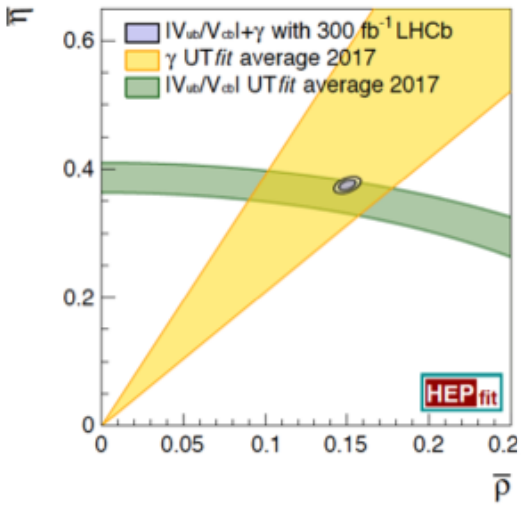


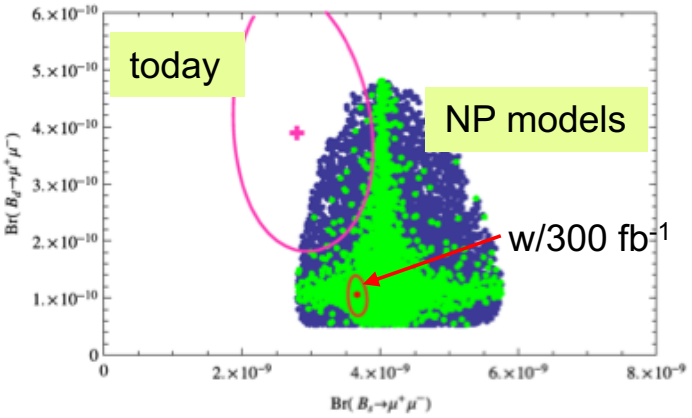
Expression-of-Interest submitted for LHCb Upgrade-II

- A comprehensive measurement programme of observables in a wide range of $b \to sl^+l^-$ and $b \to dl^+l^-$ transitions, many not accessible in the current experiment or Phase-I Upgrade, employing both muon and electron modes;
- Measurements of the CP-violating phases γ and ϕ_s with a precision of 0.4° and 3 mrad, respectively;
- Measurement of $R \equiv \mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ with an uncertainty of 20%, and the first precise measurements of associated $B_s^0 \to \mu^+\mu^-$ observables;
- A wide-ranging set of lepton-universality tests in $b \to cl^-\bar{\nu}_l$ decays, exploiting the full range of b-hadrons;
- CP-violation studies in charm with 10^{-5} precision.

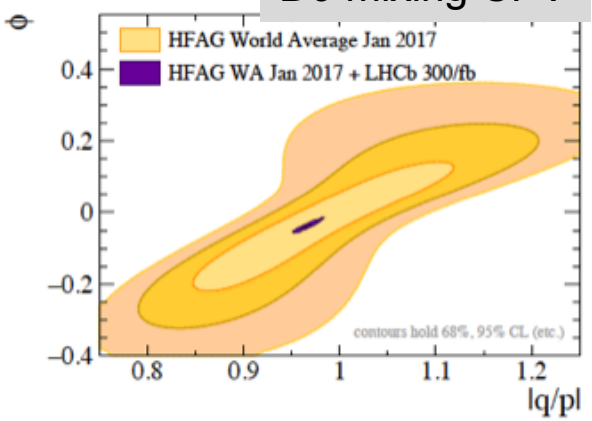
A much sharper picture to emerge

CERN-LHCC-2017-003





D0 mixing CPV



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→μμ/Bs→μμ	90%	~40%	--	~20%
B→K(*)νν		--	~12%	--

Summary comments

- Flavor physics remains one of the primary drivers of the search for the physics beyond SM, as 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, 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 (LHCb upgrades I & II)-together with Belle-II - will result in a much sharper picture of the physics of flavor- will resolve or solidify some of the current anomalies with potential to reveal solid evidence for new physics.