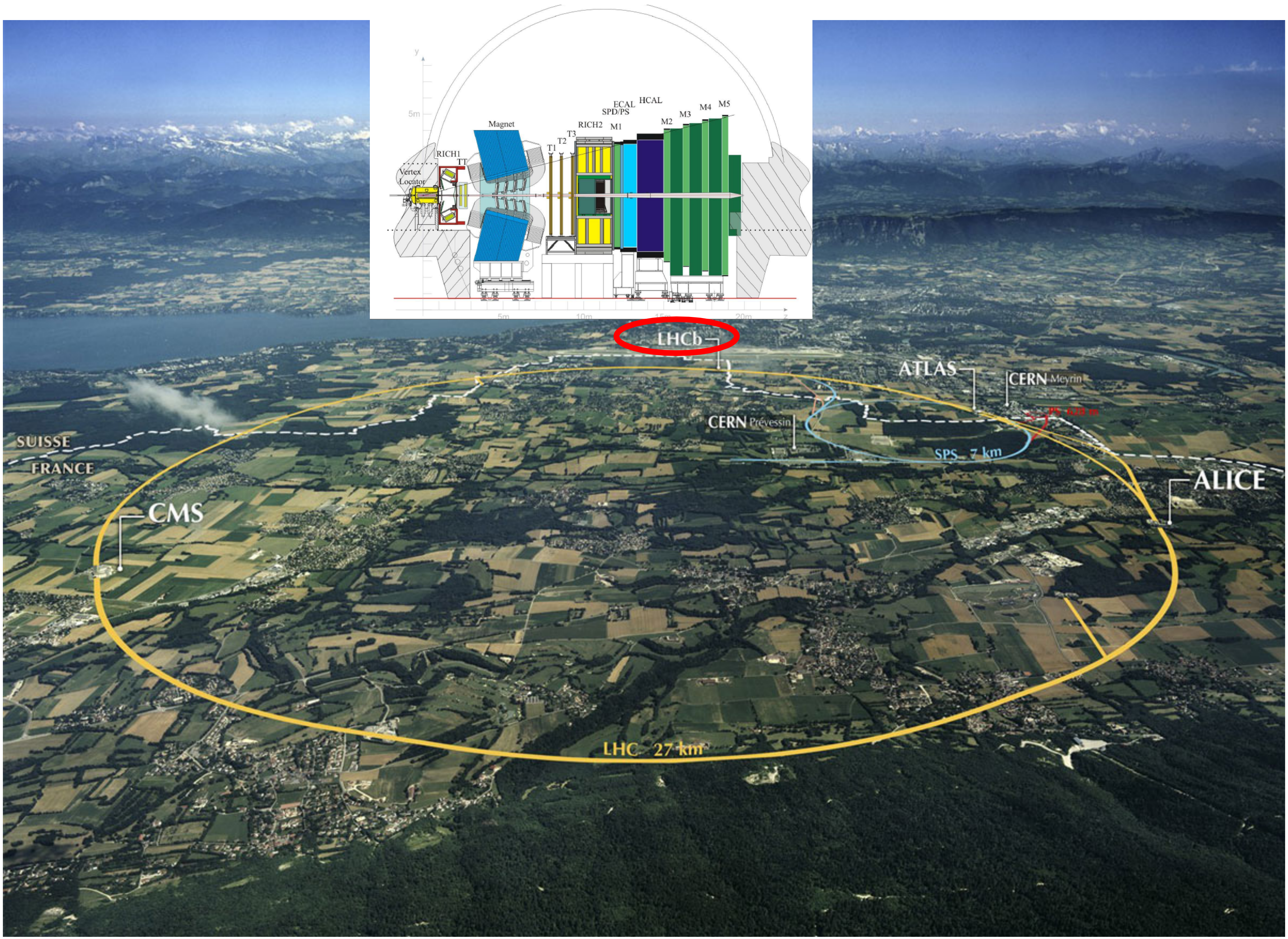
Physics at LHCb

Status of the experiment
Selection of Physics
Future plans

On behalf of the LHCb collaboration

May 8, 2018
Hassan Jawahery
University of Maryland


Magnet
RICH1
TT
Vertex Locator
T1
T2
T3
RICH2
SPD/PS
ECAL
HCAL
M1
M2
M3
M4
M5
LHCb
ATLAS
CERN Meyrin
CERN Prévessin
SPS 7 km
ALICE
CMS
SUISSE
FRANCE
LHC 27 km

The LHCb Detector

A Single Arm Spectrometer at LHC

Acceptance: $2 < \eta < 5$

σ_{inel}~70-80 mb

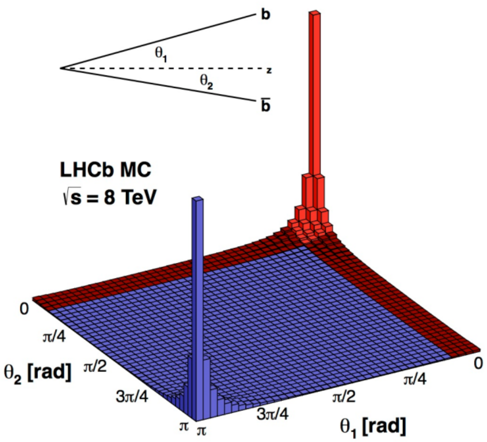
σ_{cc}~6 mb (7 TeV)

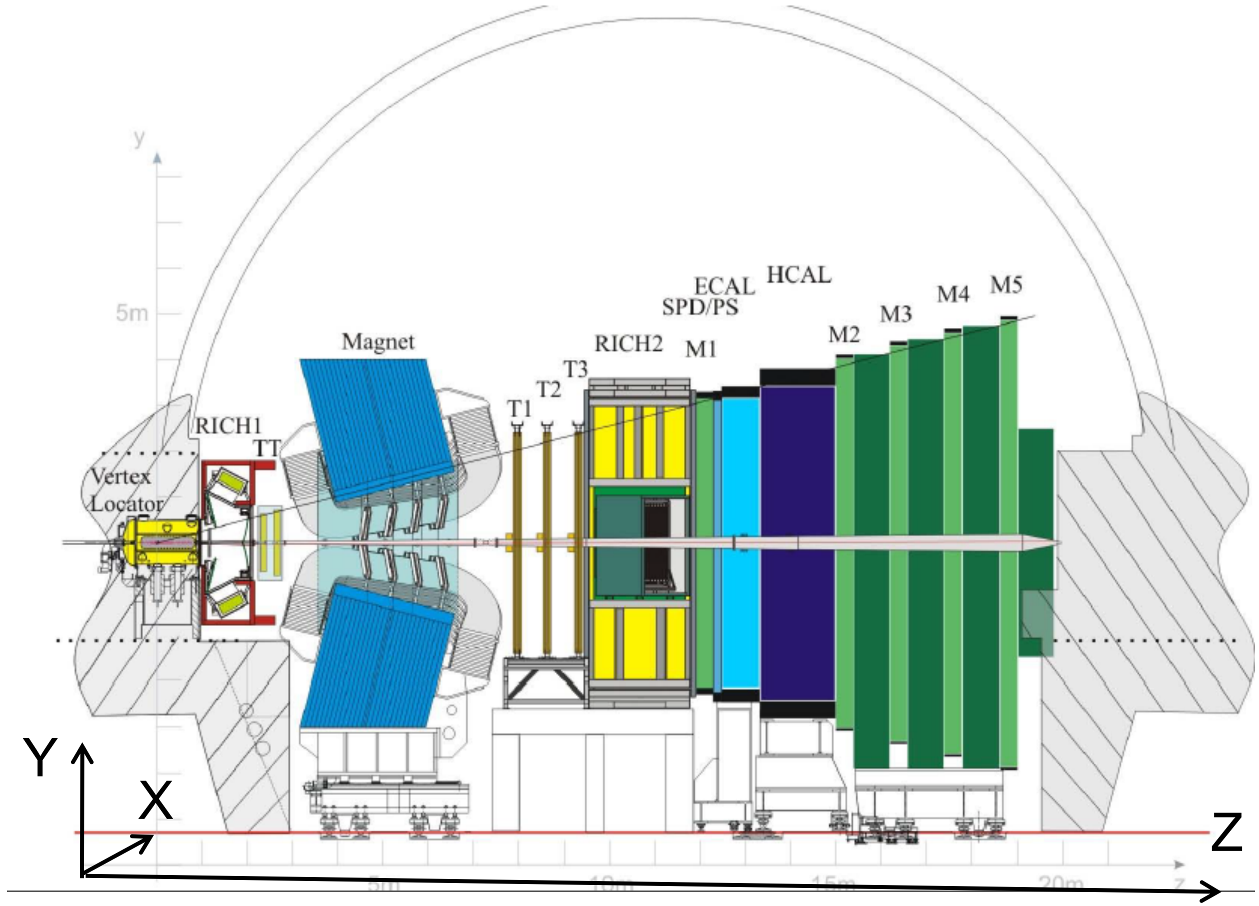
σ_{τ}~80 μb (7 TeV)

σ_{bb}~280 μb (7 TeV)

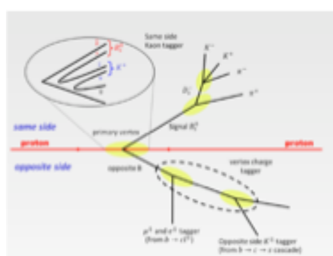
σ_{bb}~500 μb (14 TeV)

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





Access to all species of B hadrons

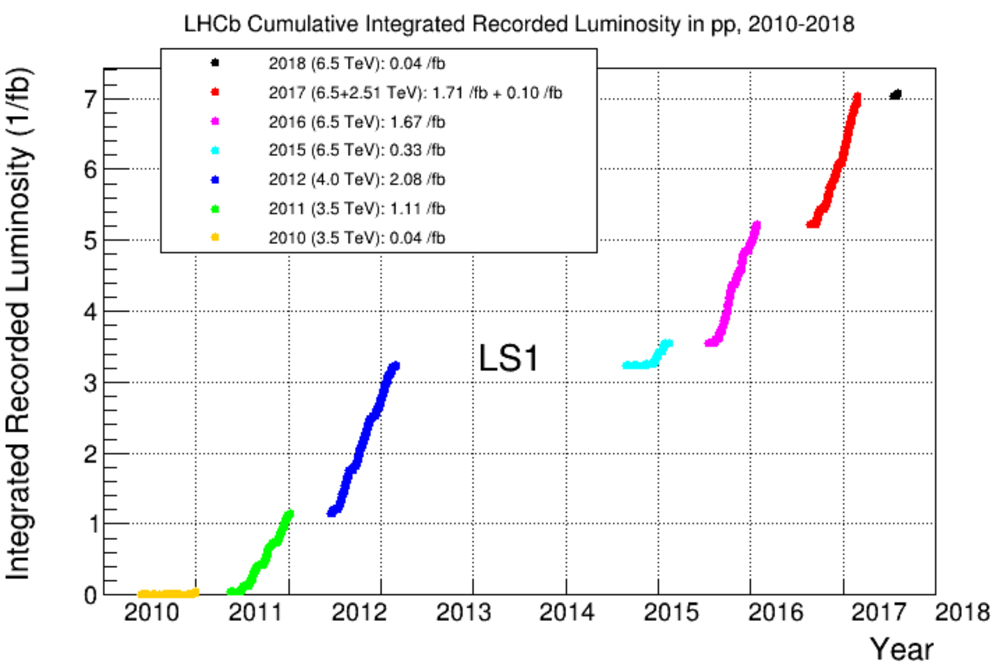


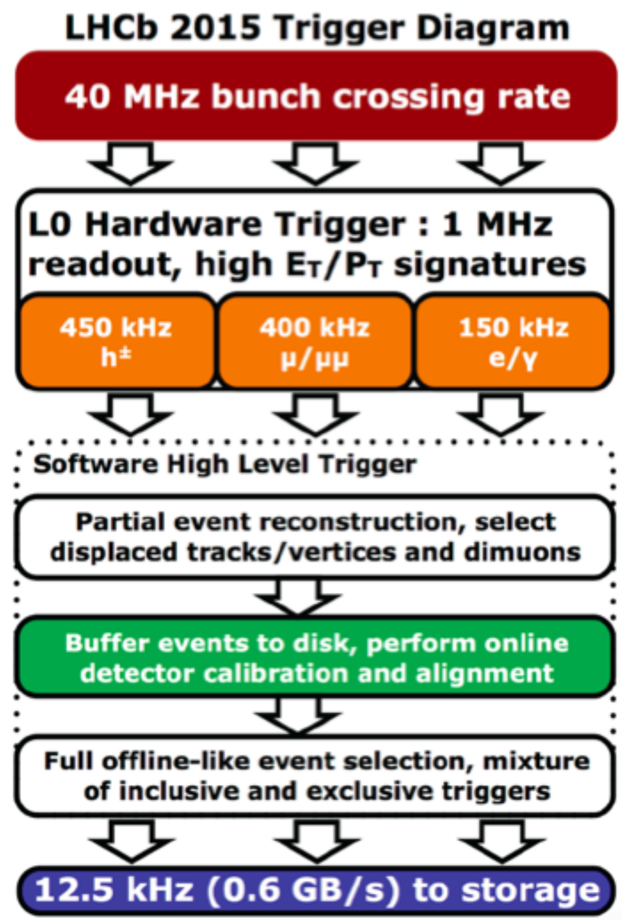
JINST 3 (2008) S08005.

Int. J. Mod. Phys. A30 (2015) 1530022.

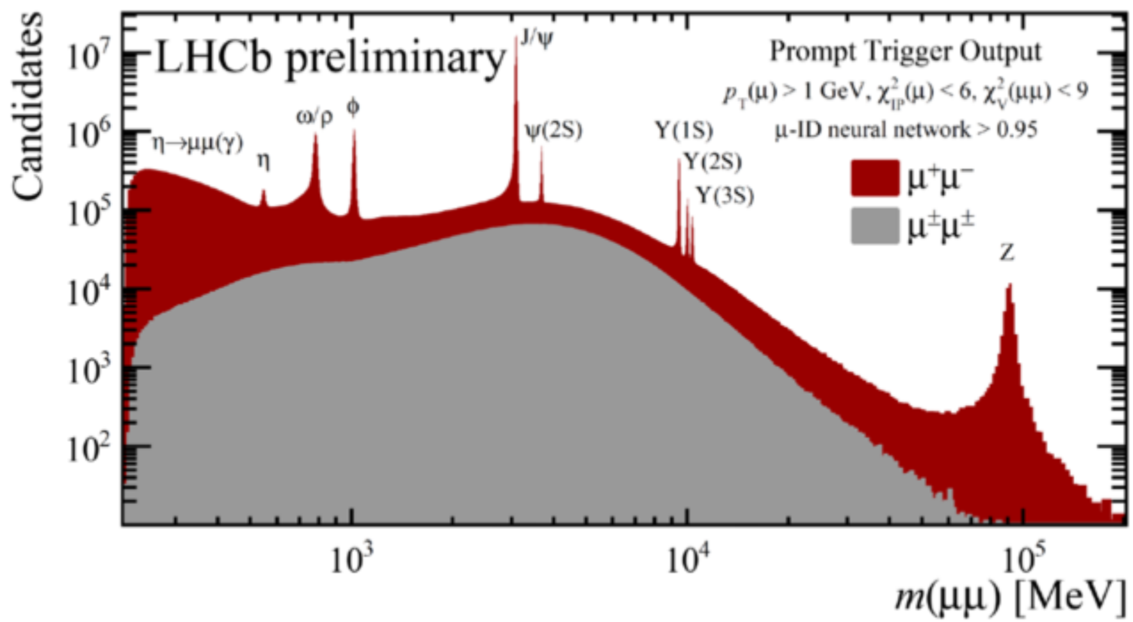
LHCb Status

- 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 ~ 7 fb-1



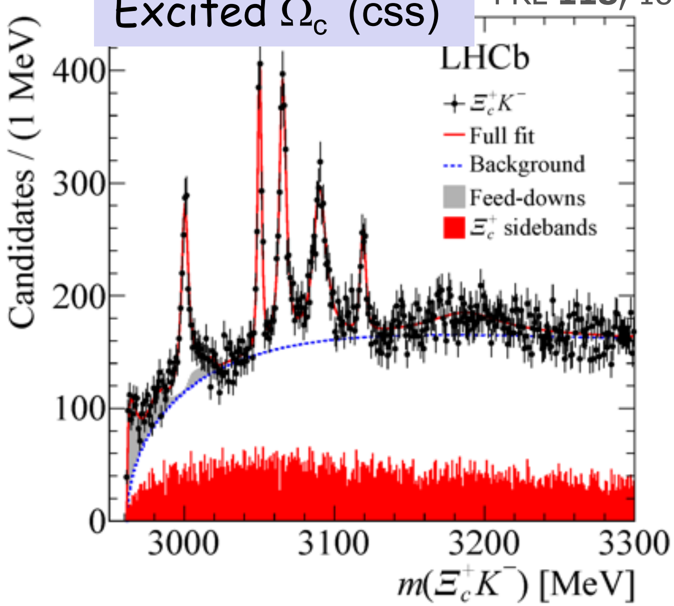


Some measures of the power of the Spectrometer

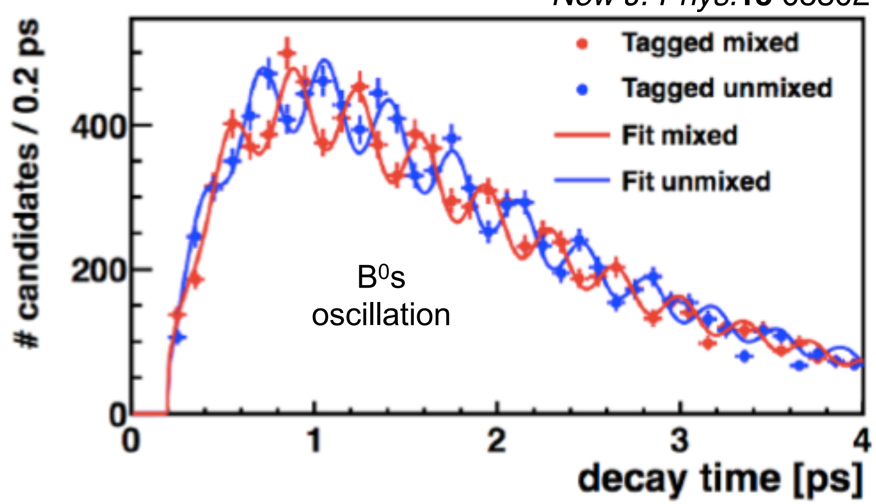


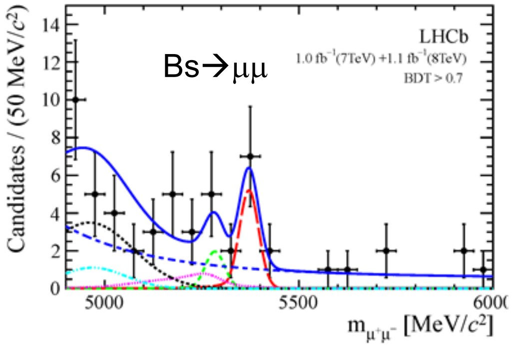
Excited Ω_c (css)

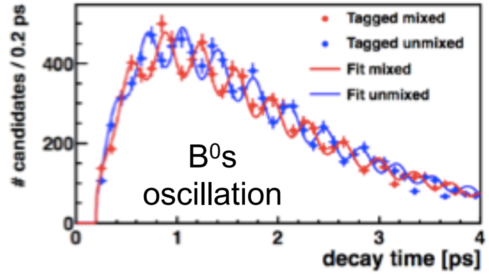
PRL **118**, 182001

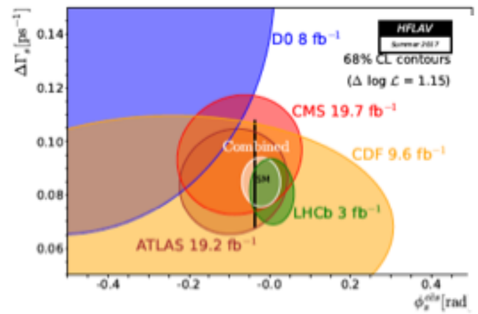


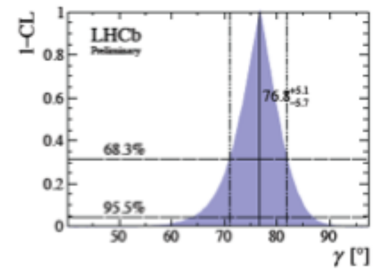
New J. Phys. **15** 053021

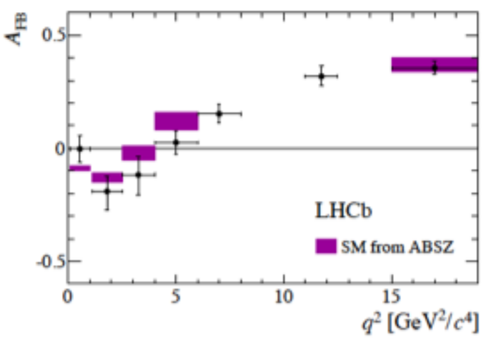


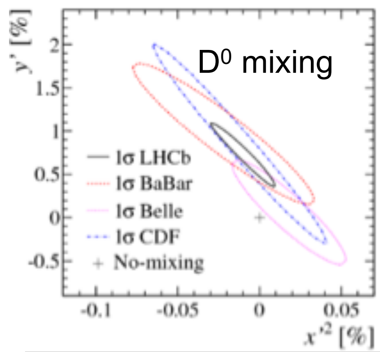


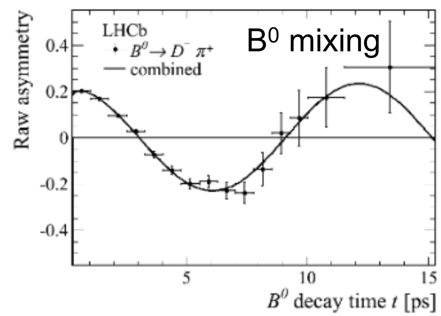


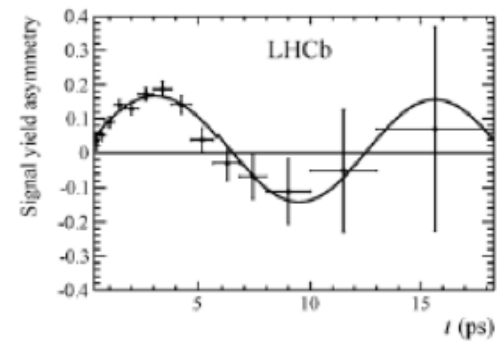


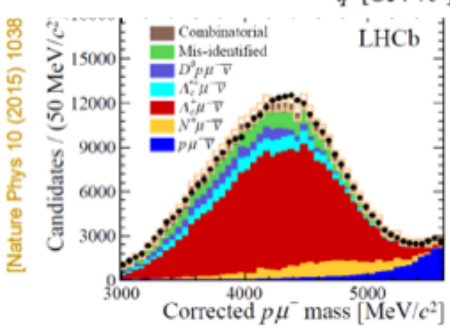




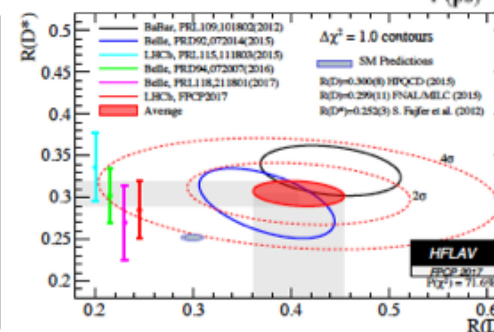


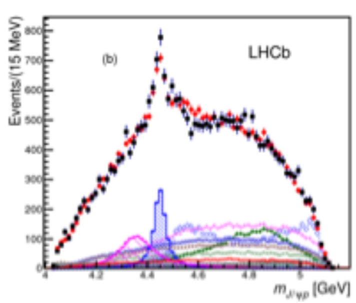


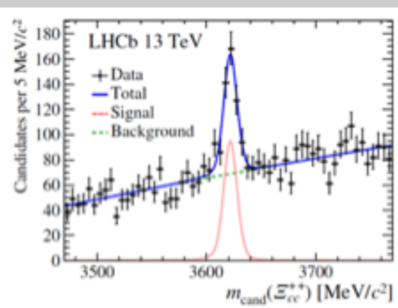


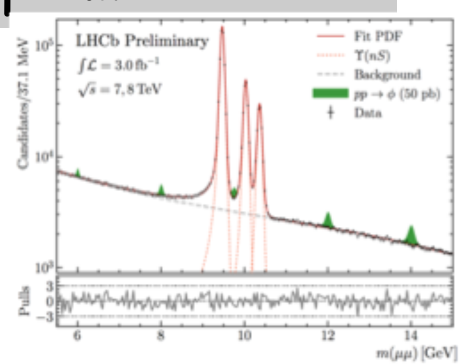


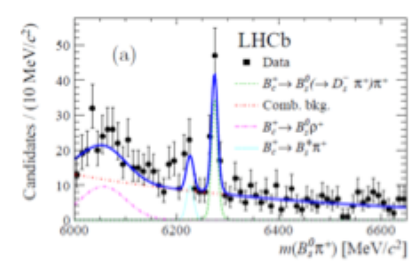
LHCb covers a very broad spectrum of physics, from Flavor to EW, DM search, QCD, pA…

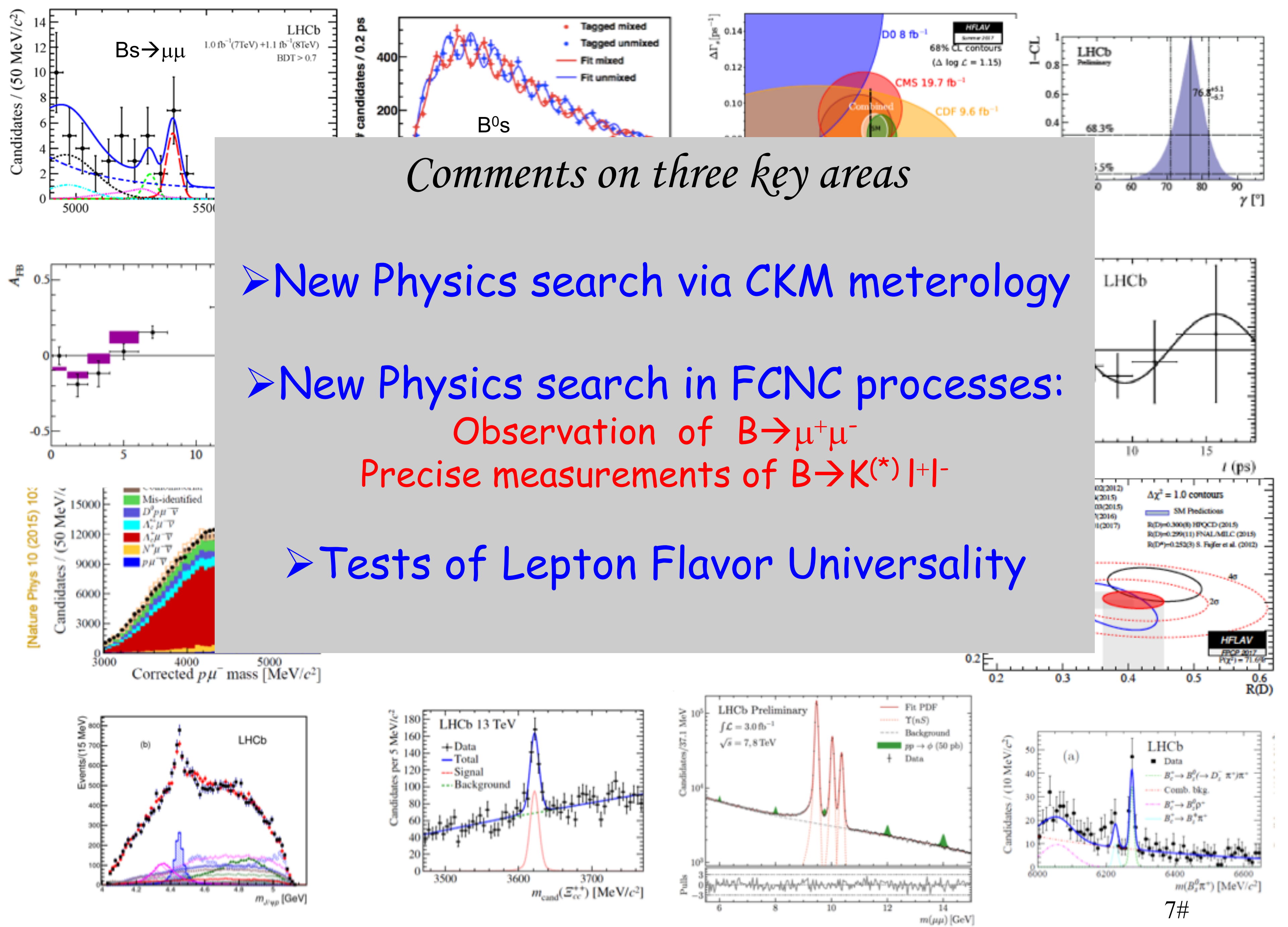










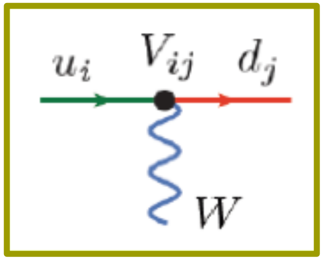


Comments on three key areas

- ➢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

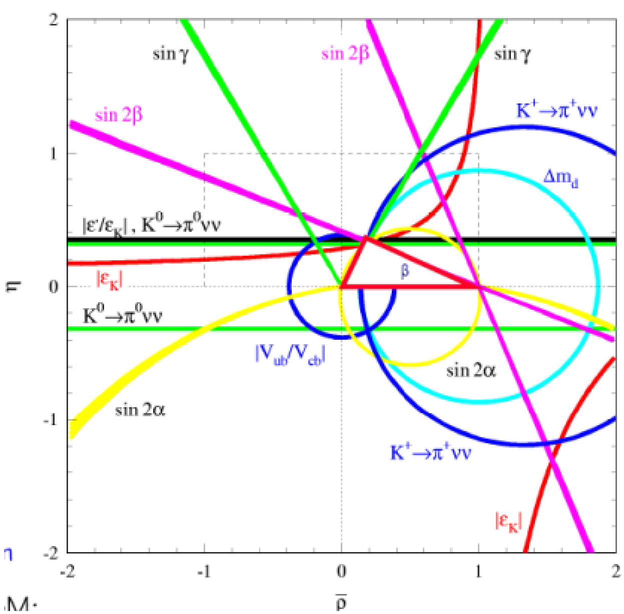
Continue to sharpen the CKM picture

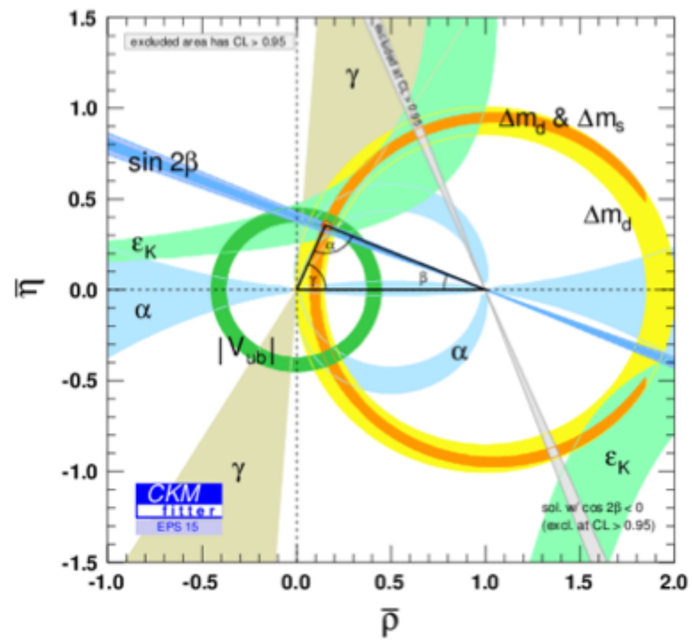
L. Wolfenstein Parameterization of CKM matrix (1983)



$$\begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\,\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\,\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

All CPV effects governed by a single parameter- the complex phase of CKM - η



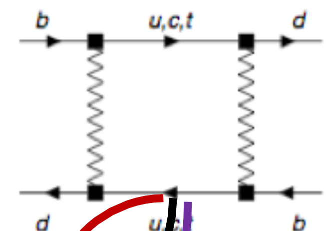


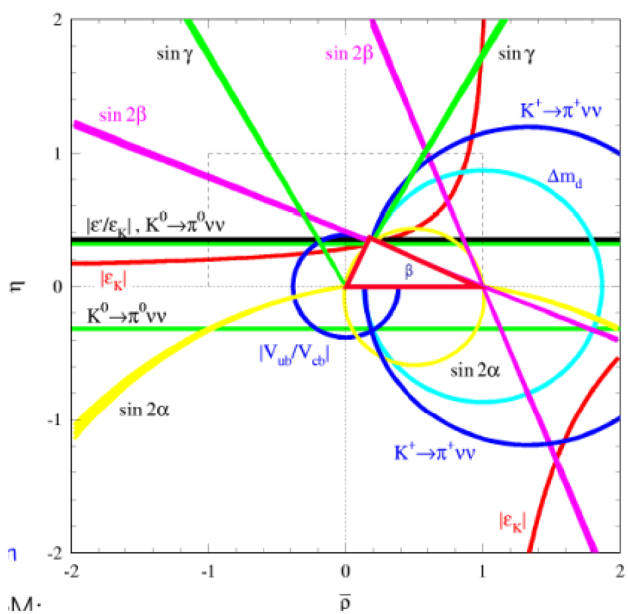
Continue to sharpen the CKM picture

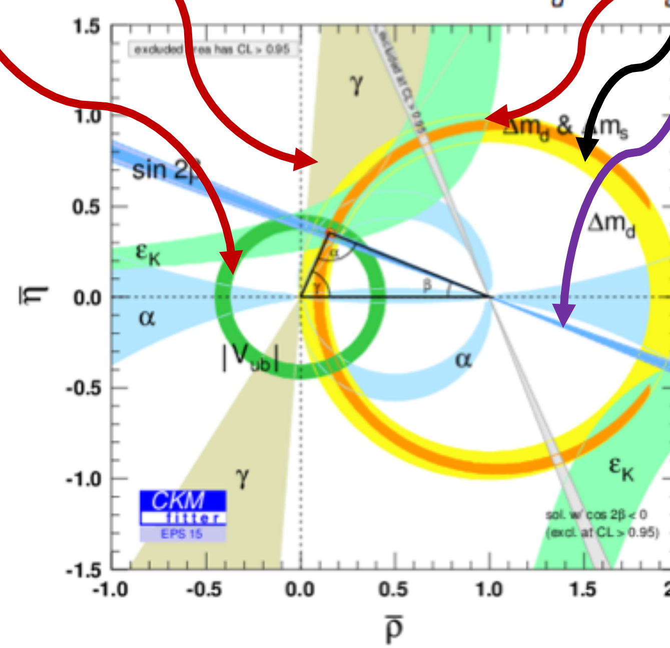
The picture may be modified by the presence of New Physics (NP)

Observables involving
$B^0 \Leftrightarrow \overline{B^0}$ oscillation
Bring in sensitivity to New Physics

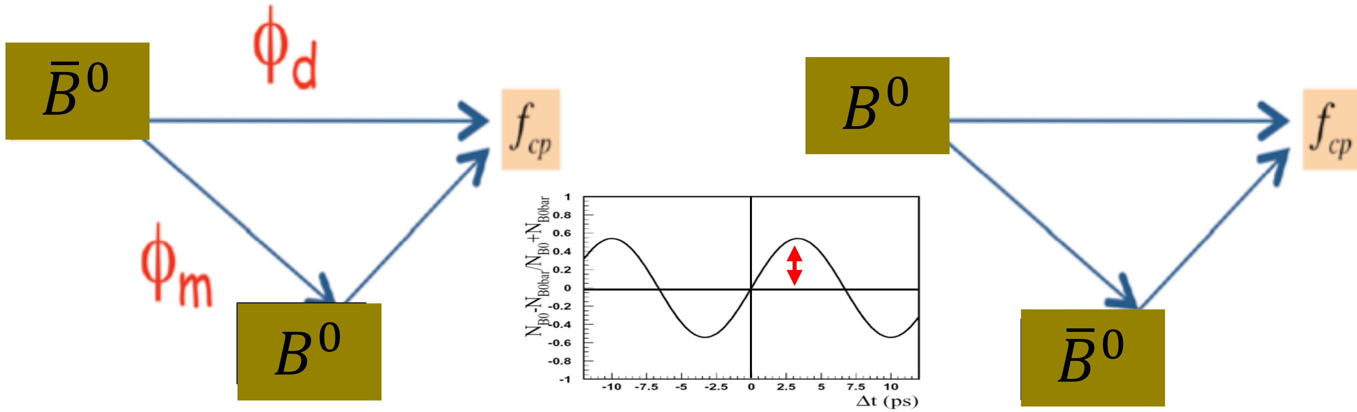
NP free measurements -tree level processes: V_{ub} & γ







"CP" Interferometer to access the phase of CKM



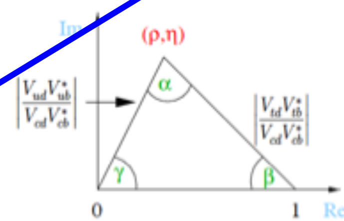
$$A_{cp}(t) = \frac{\Gamma(B^0(t) \to f_{cp}) - \Gamma(\bar{B}^0(t) \to f_{cp})}{\Gamma(B^0(t) \to f_{cp}) + \Gamma(\bar{B}^0(t) \to f_{cp})} = \sin 2(\varphi_m - \varphi_D)\sin \Delta m t$$

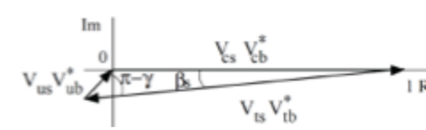
$$\begin{pmatrix} 1 - \frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\,\eta) \\ -\lambda & 1 - \frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1 - \rho - i\,\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

With careful set up of the initial and final states

$B_d \to J/\psi\, K^0_s$ :: $\boldsymbol{\beta \propto \arg(V^*_{td}) \sim 24^o}$

$B_s \to J/\psi\, K^+K^-$ :: $\boldsymbol{\varphi_s \propto \arg(V^*_{ts}) \sim 1^o}$

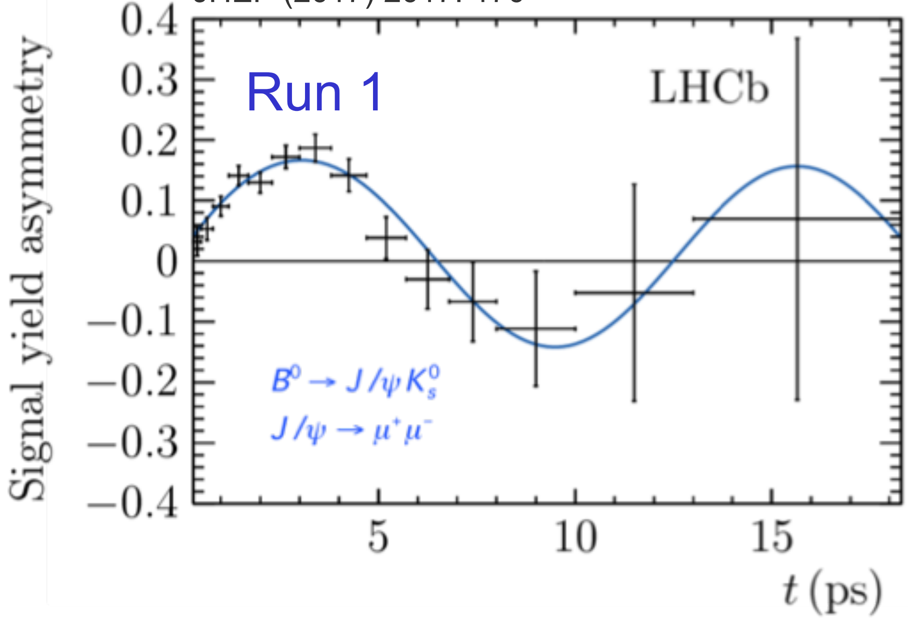


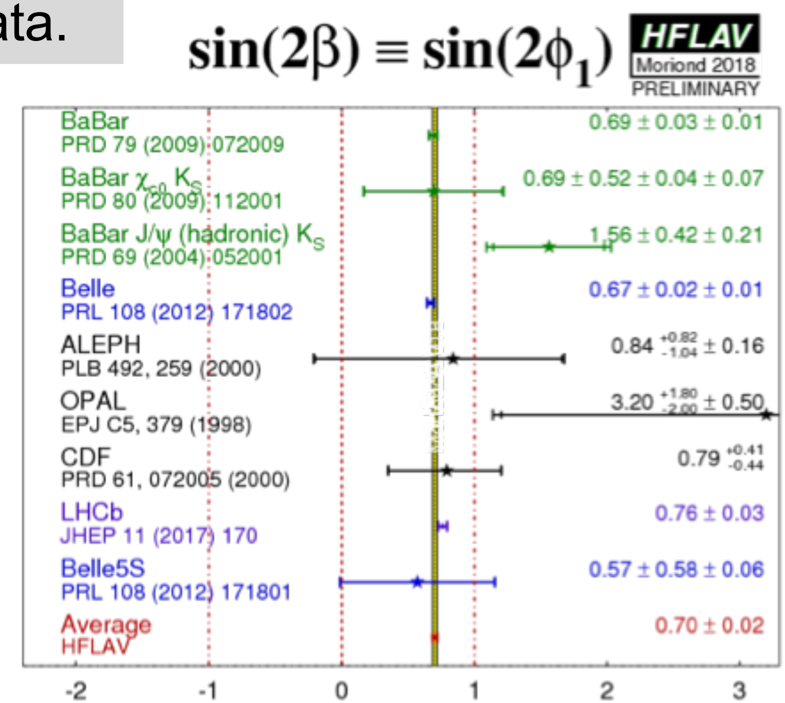


Measurement of $\beta = \arg(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{td}^*})$

Measured to high accuracy at the B factories.
LHCb is already competitive with Run 1 data.

JHEP (2017) 2017: 170

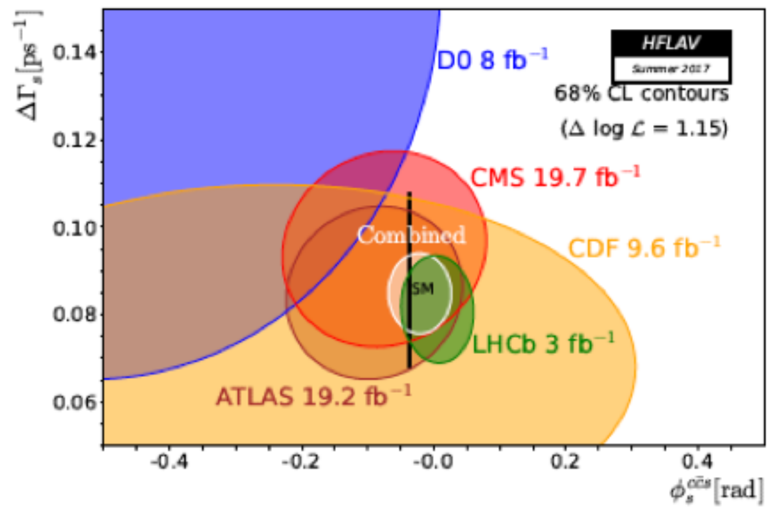




World Average
$\beta = (22.2 \pm 0.7)^\circ$
Most precisely measured element of the CKM Unitarity Triangle.

Measurement of $\phi_s = 2\arg\left(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right)$

LHCb measurements dominate:



$$B_s^0 \to J/\psi K^+K^- \quad \varphi - region$$

$$B_s^0 \to J/\psi K^+K^- \quad High - mass - region$$

$$B_s^0 \to J/\psi \pi^+\pi^-$$

$$B_s^0 \to \psi(2S) K^+K^-$$

Combining LHCb results:

JHEP 08 (2017) 037

$$\phi_s^{J/\psi hh} = 0.001 \pm 0.037$$
$$\Delta\Gamma_s = 0.0813 \pm 0.0081$$
$$\Gamma_s = 0.6588 \pm 0.0026$$

Summer 2017

HFLAV combination

$$\phi_s^{c\bar{c}s} = -0.021 \pm 0.031 \text{ rad}$$
$$\Delta\Gamma_s = 0.085 \pm 0.006 \text{ ps}^{-1}$$
$$\Gamma_s = 0.6640 \pm 0.0020 \text{ ps}^{-1}$$

SM

$$\varphi_s^{c\bar{c}s} = -0.0370 \pm 0.0006 \ rad$$

$$\Delta\Gamma_s = 0.088 \pm 0.020 \ ps^{-1}$$

Measurement of $\gamma = \arg(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*})$

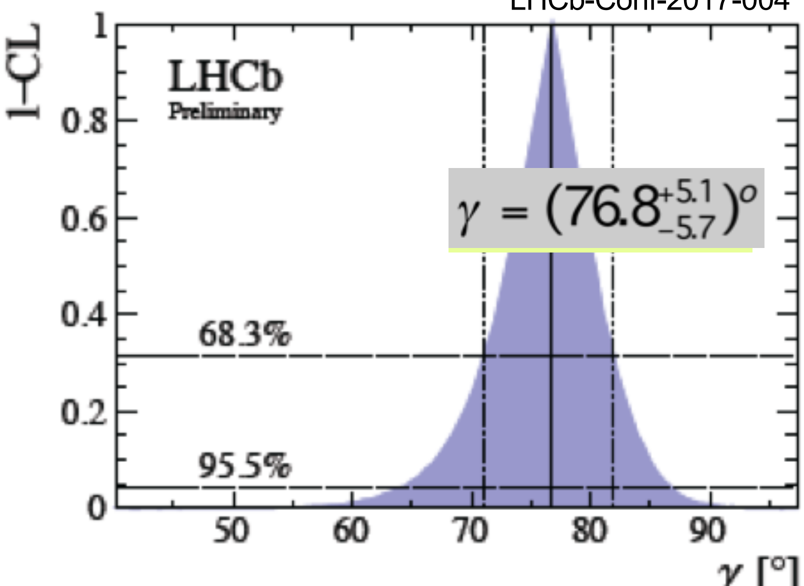
Yet another interferometer: tree level processes b->c & b->u

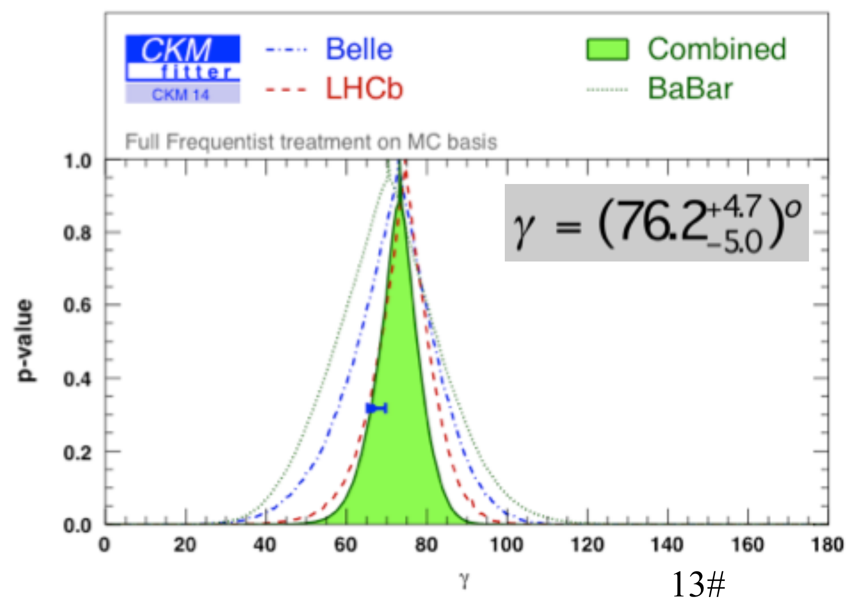
$$\boxed{A[B^- \to (D^{(*)} \to f)h^-] = A_c A_f e^{i(\delta_c+\delta_f)} + A_u A_{\bar{f}} e^{i(\delta_u+\delta_{\bar{f}}-\gamma)}}$$

Final state "f" is common to D & $\bar{D}$

Analysis updates involve several new channels & some includes Run 2 data

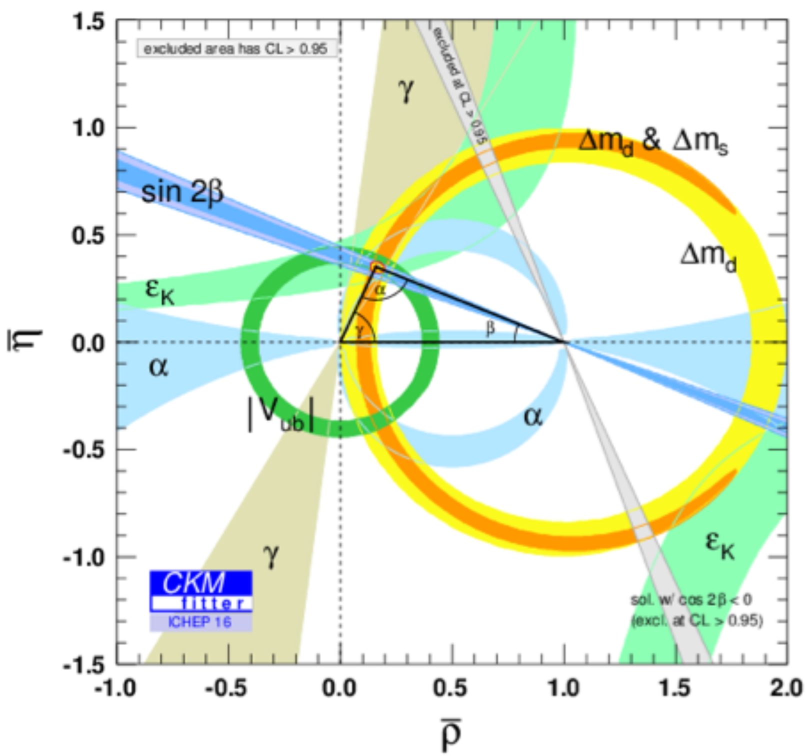
LHCb-Conf-2017-004





Status of CKM (2018)

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



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

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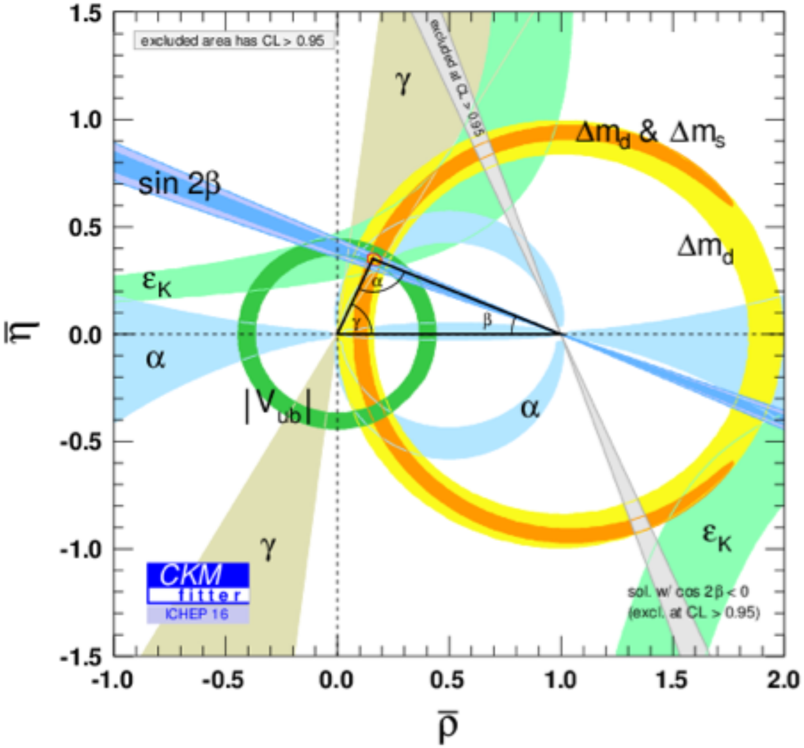

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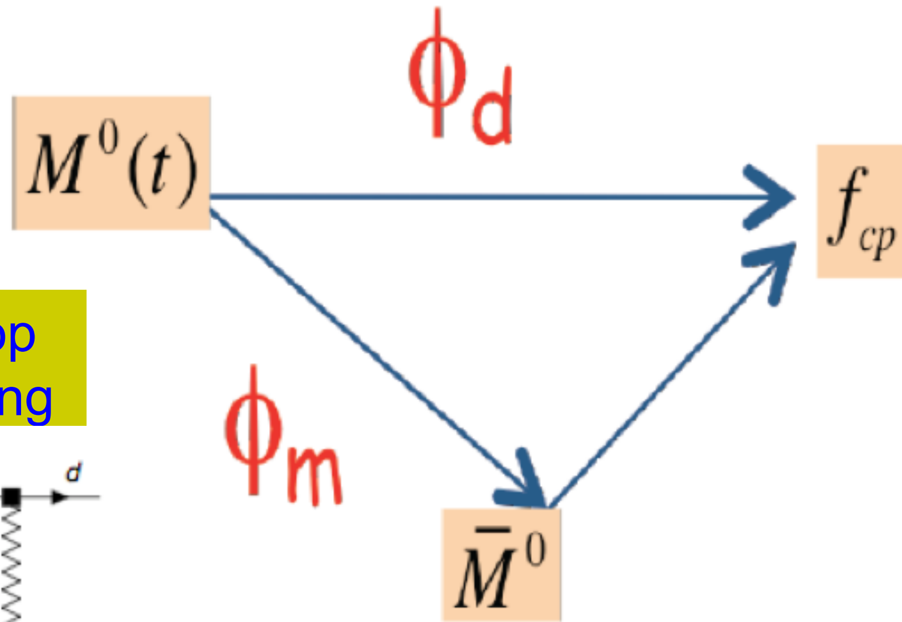
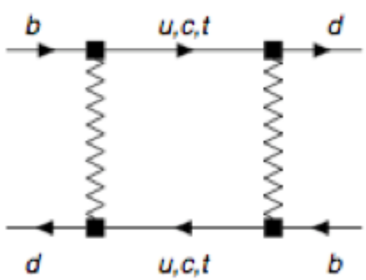
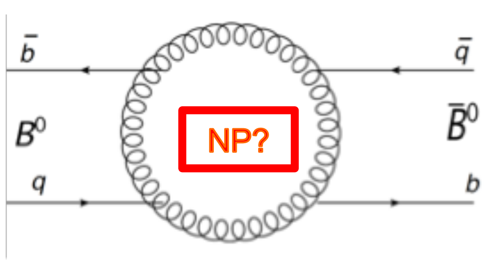
Is there room for New Physics?
CPV sources beyond SM?

New Physics Through Mixing



Through new loop diagrams in mixing

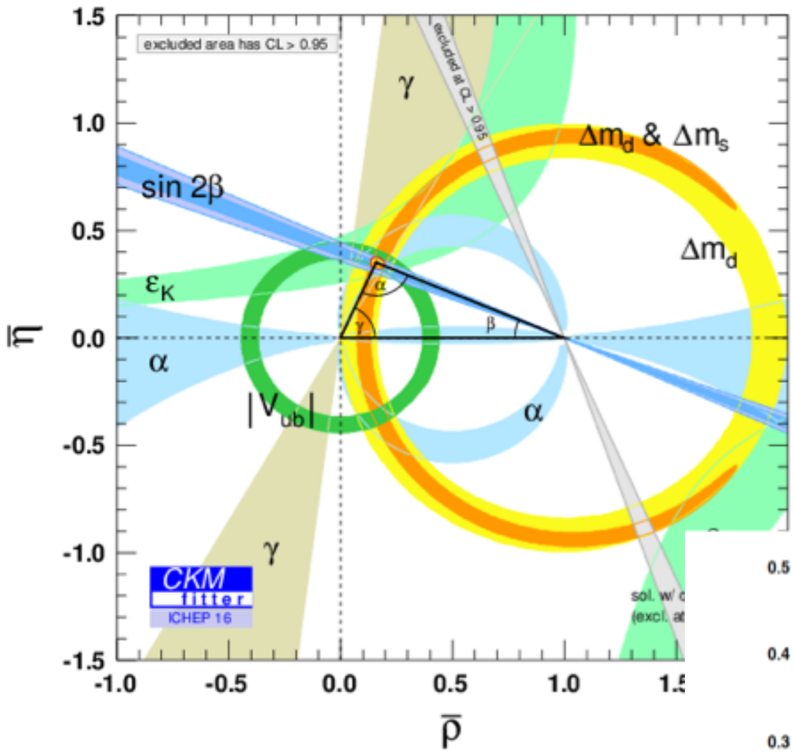


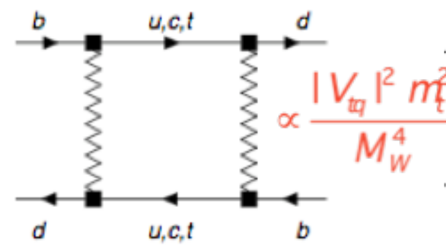


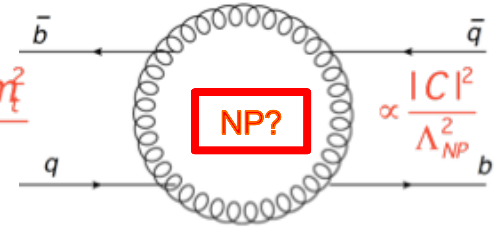
New Physics Through Mixing

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

For New Physics through Mixing

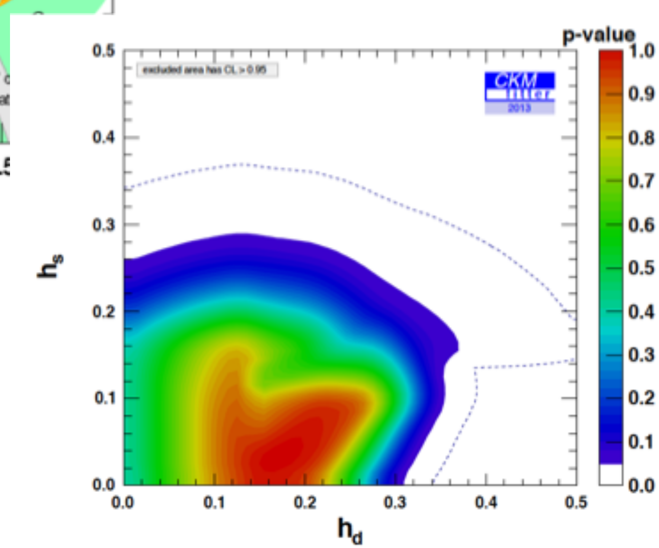






$$M_{12} = M_{12}^{\rm SM} \times \left(1 + h\, e^{2i\sigma}\right)$$

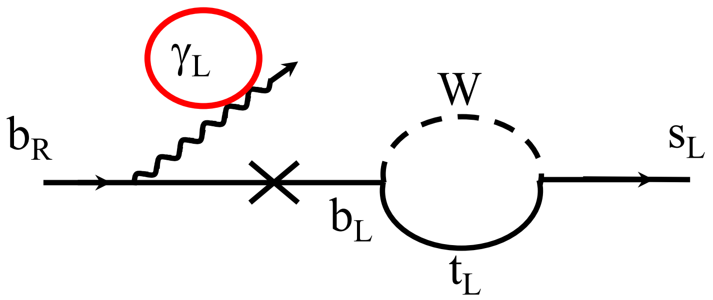
Constraint on NP/SM amplitude
See *(arXiv: 1309.2293)*



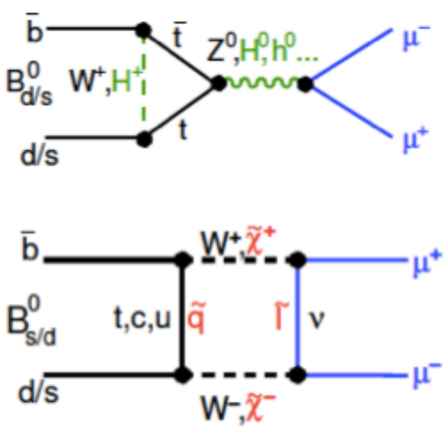
$A_{NP} < 0.3 A_{SM}$

$\Lambda_{NP} > 10^3$ TeV
For c~1

Search for New Physics footprint in other FCNC Processes



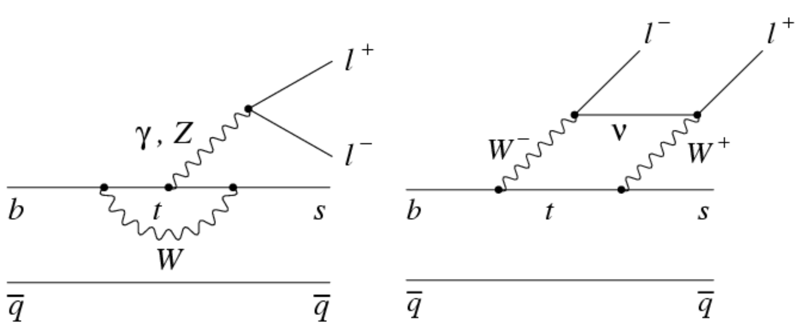
A key probe of NP in B decays
Observables: Rate, CPV, polarization of γ



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

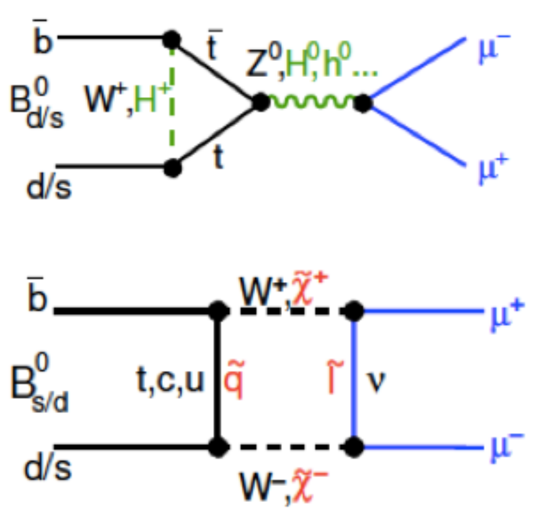
PRL 112, 101801

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

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



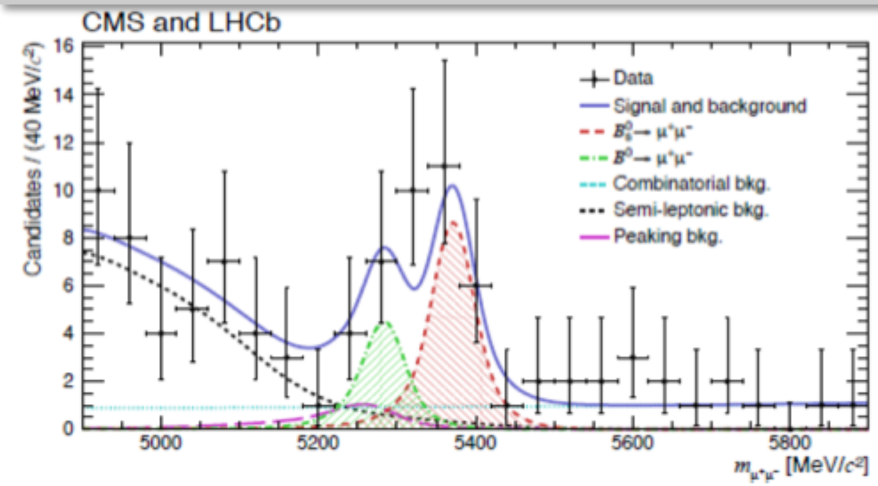
$$SM : Br(B_s^0 \to \mu^+\mu^-) = (3.66 \pm 0.23) \times 10^{-9}$$

PRL 112, 101801

Observation by LHCb & CMS Run -1
consistent with SM

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

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

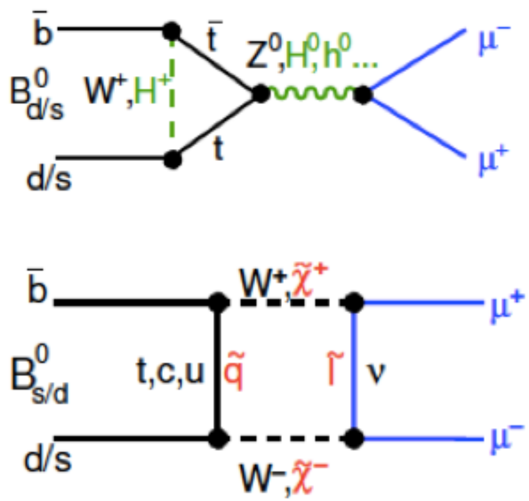


[arXiv:1411.4413,
Nature 522 (2015) 68]

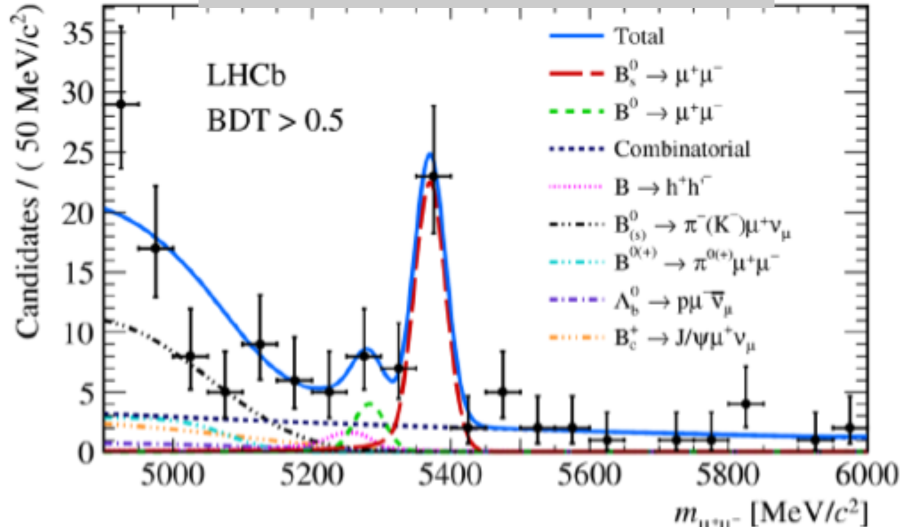
$$ATLAS : Br(B_s^0 \to \mu^+\mu^-) = (0.9^{+1.1}_{-0.8}) \times 10^{-9}$$

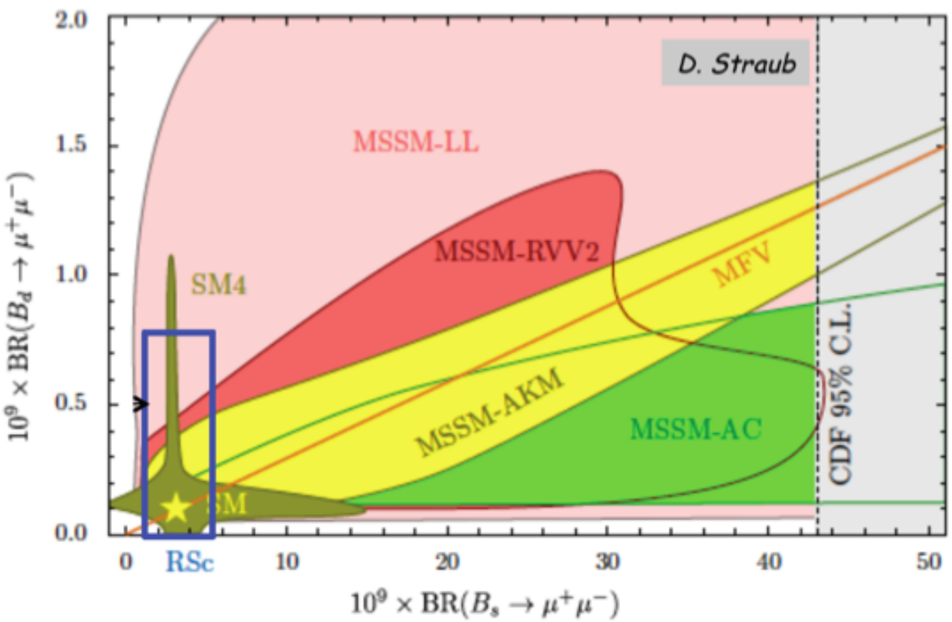
Eur. Phys. J. C76(2016) no. 9, 513

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



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





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

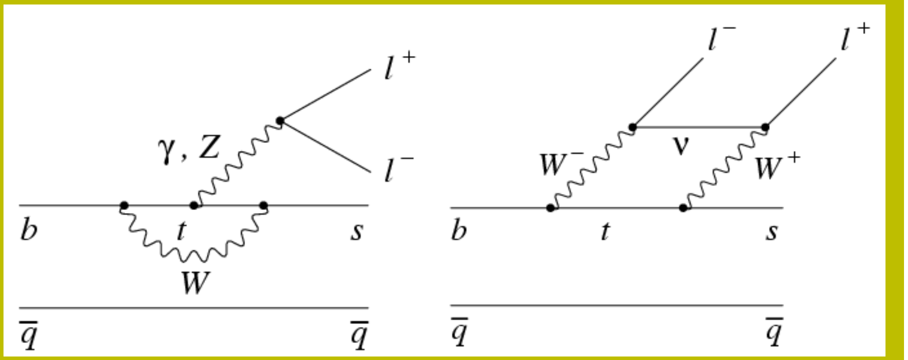
7.8 σ

PRL 118, 191801 (2017)

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

PRL 112, 101801

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

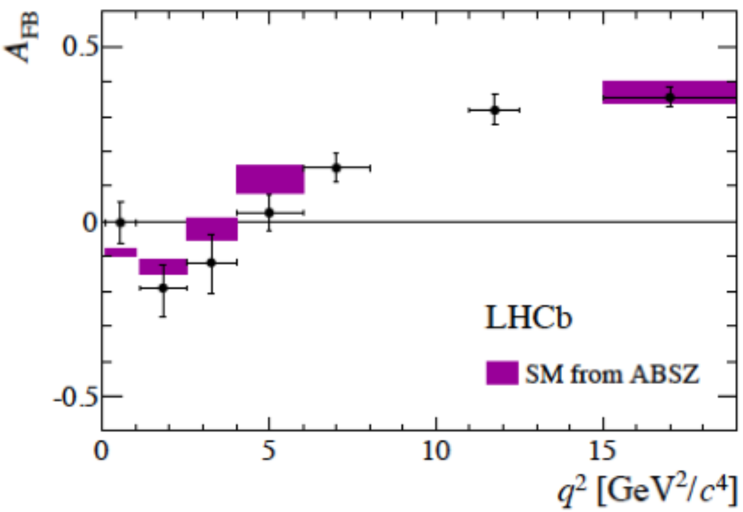


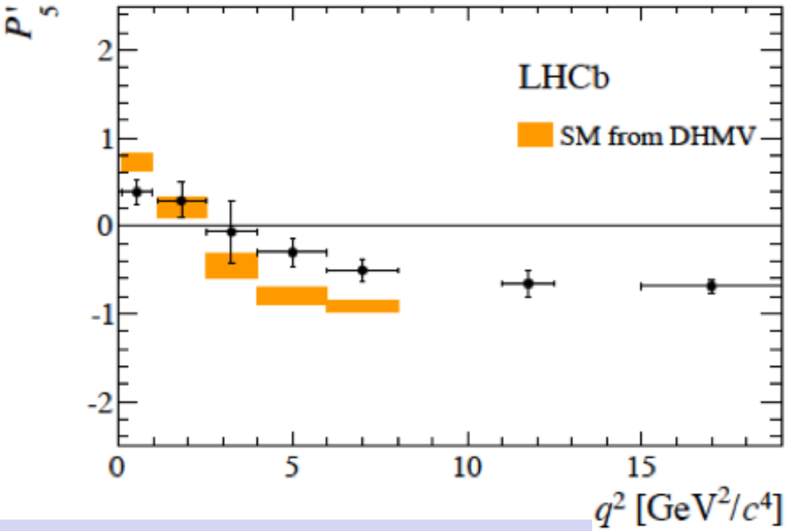
Several observables- sensitive to New Physics- extracted from differential rates.

Precise measurements from LHCb dominate this channel, including tests of Lepton Flavor Universality:
Some intriguing results

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

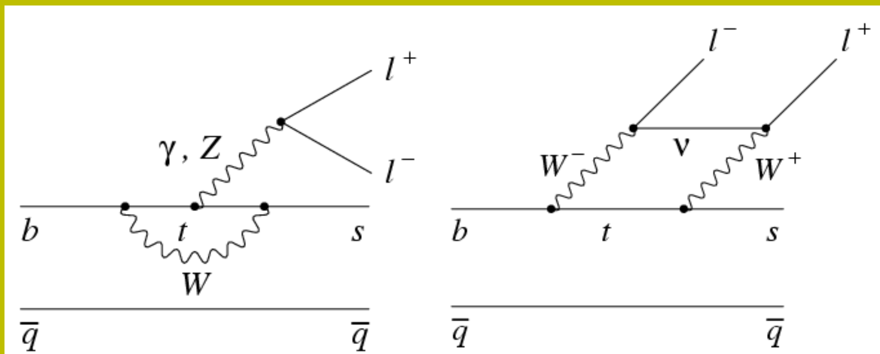
[JHEP 02 (2016) 104]





Overall compatability of LHCb results with SM ~3.4 σ

B→K$^{(*)}\mu^+\mu^-$



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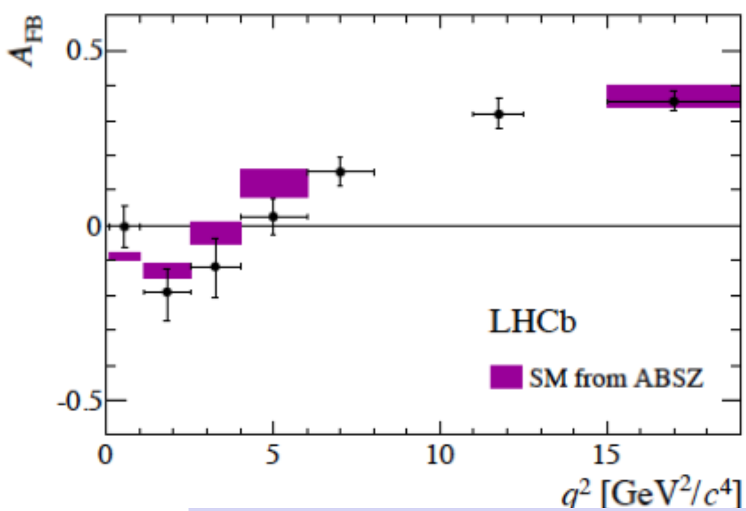

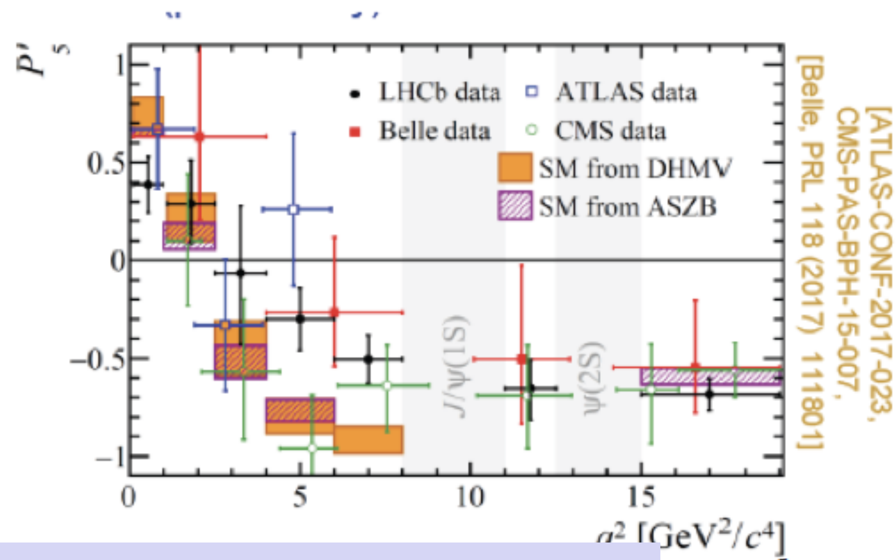

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Tests of Lepton Flavor Universality in $B \to K^{(*)} l^+ l^-$

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

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

LHCb

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

Within 2.6 σ of SM

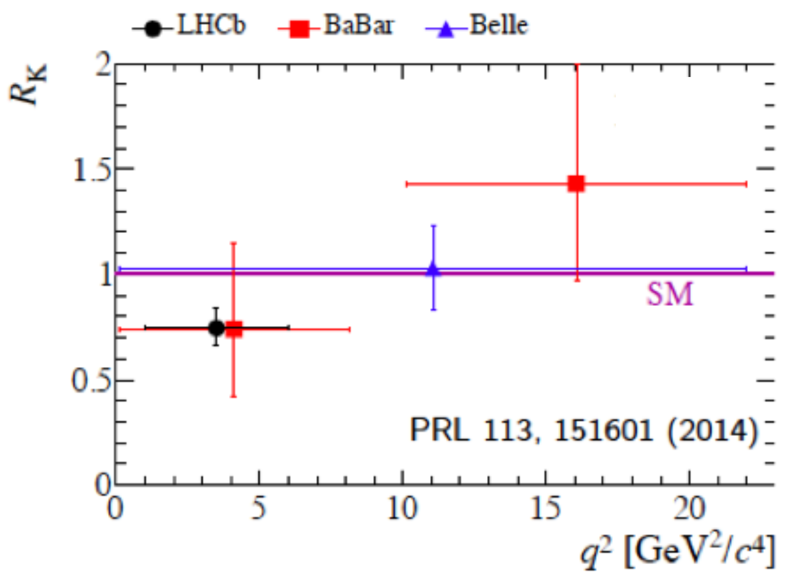
PRL 113, 151601

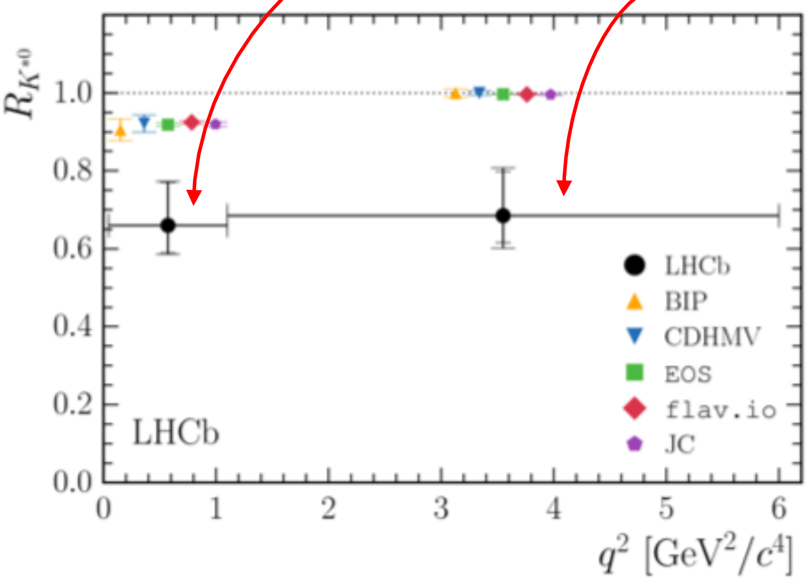
$$R_{K^*} = 0.660^{+0.110}_{-0.070} \pm 0.024 \quad low - q^2$$

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

Within 2.1-2.3 σ & 2.4-2.5 σ of SM

JHEP 08(2017)055





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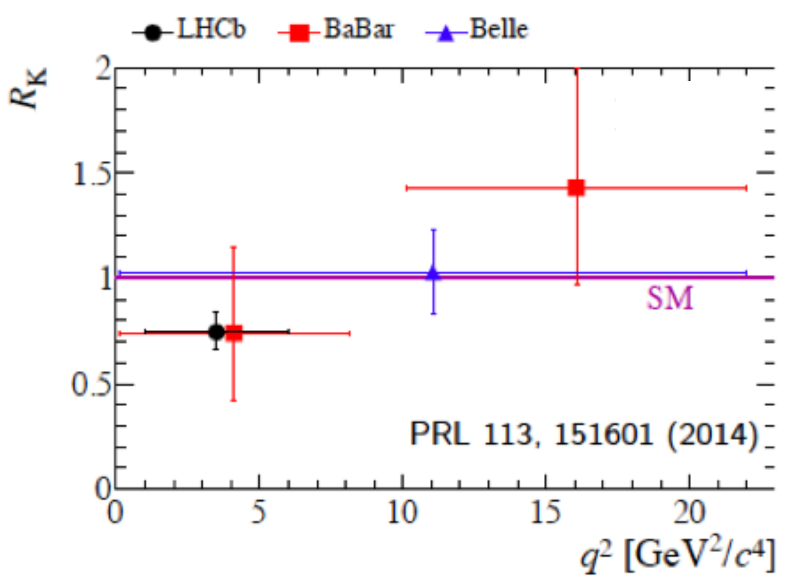
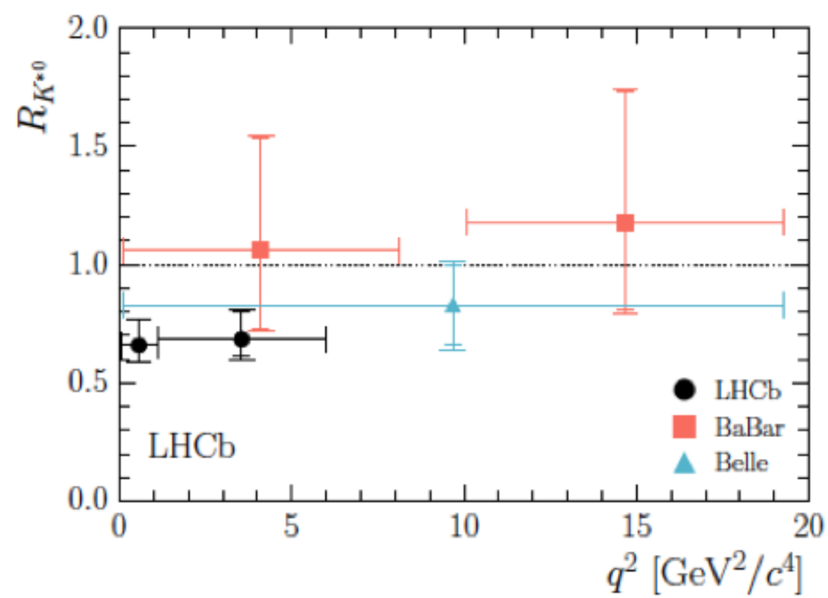
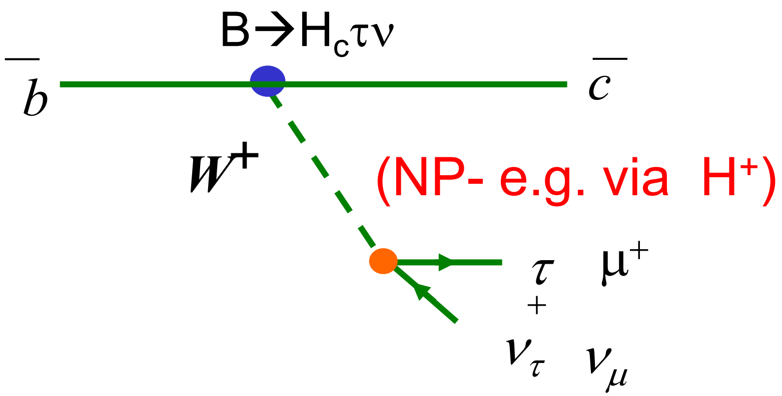




Tests of Lepton Flavor Universality (2)



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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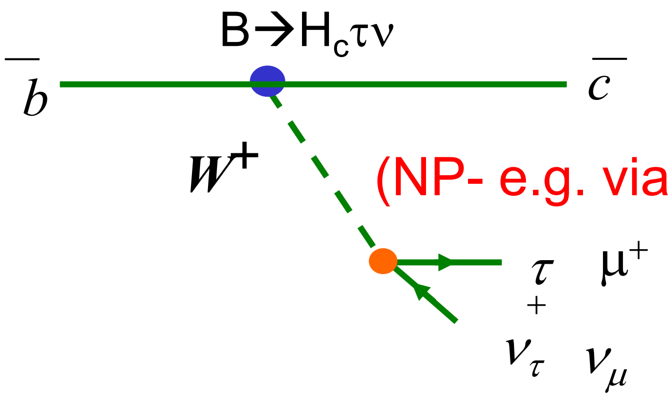

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Hints of deviation from these predictions first seen by BaBar

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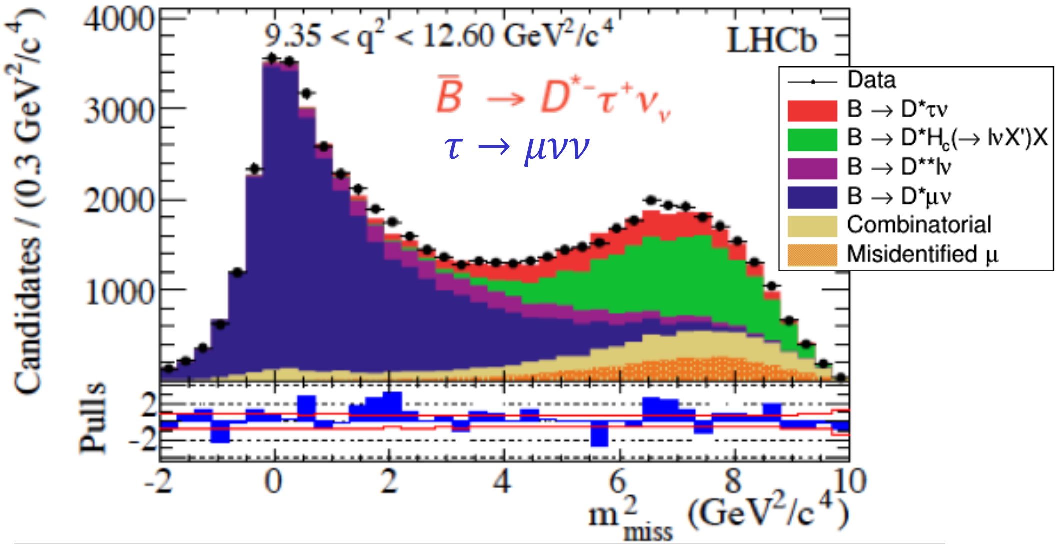
All with Run 1 Data- so far

2015

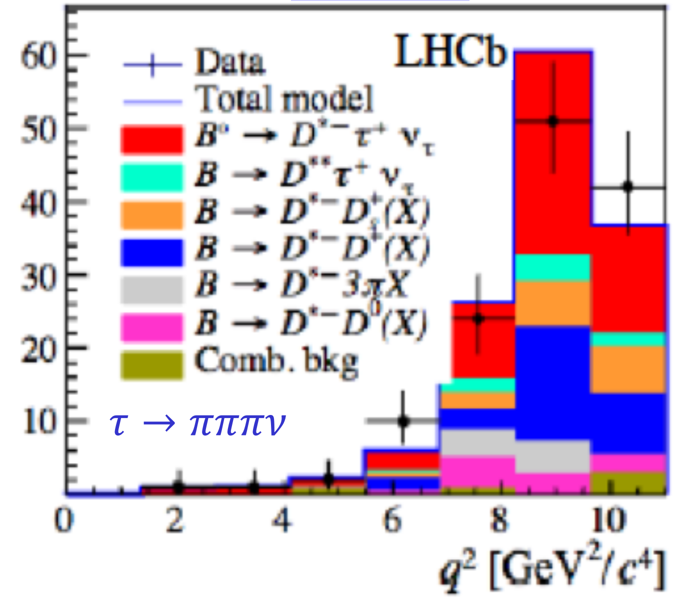


R(D*) = 0.336±0.027 (stat)±0.030 (syst)

Within 2.1 σ of SM

PRL 113, 111803

2017

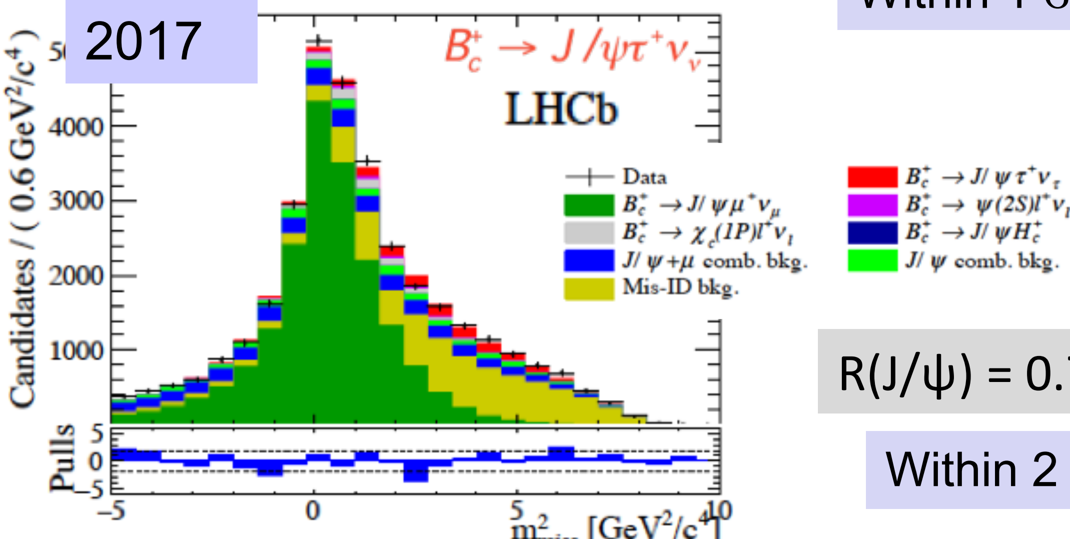


R(D*) = 0.291±0.019±0.026±0.013

Within 1 σ of SM

PRL 120, 171802

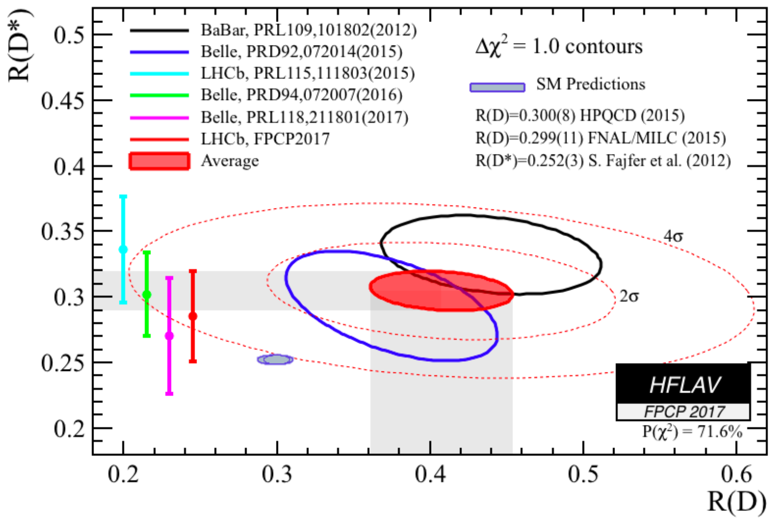
2017



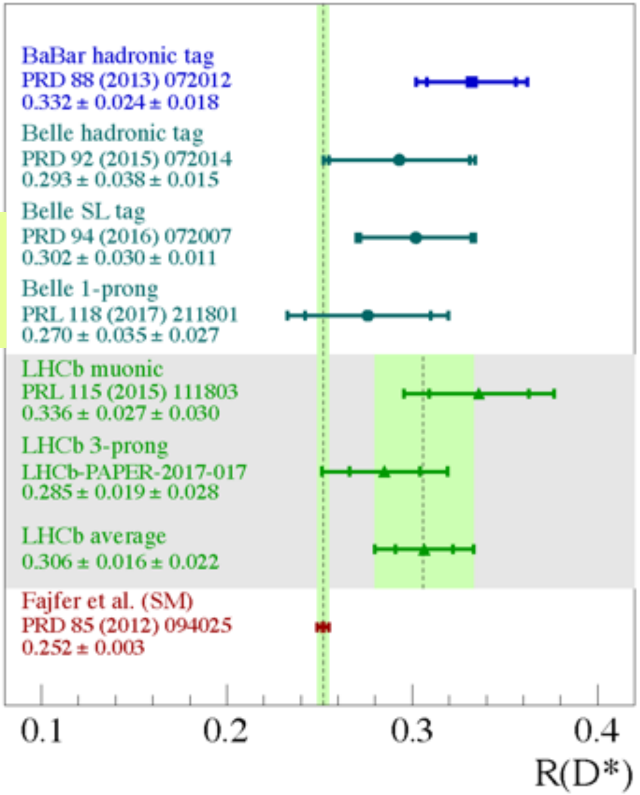
R(J/ψ) = 0.71±0.17 (stat)±0.18 (syst)

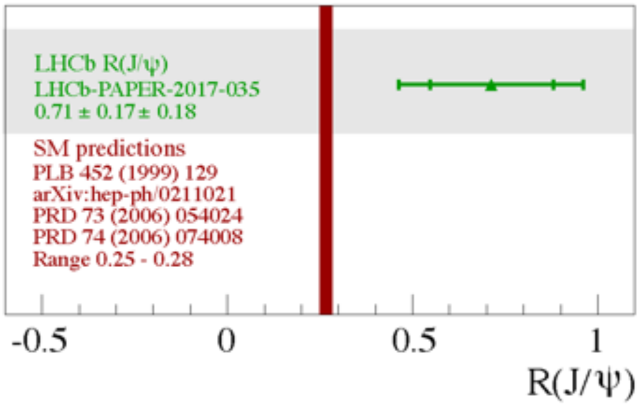
Within 2 σ of SM

PRL 120, 12180



4.1 σ tension with LFU/SM

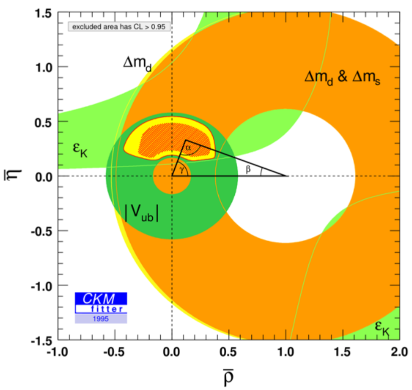
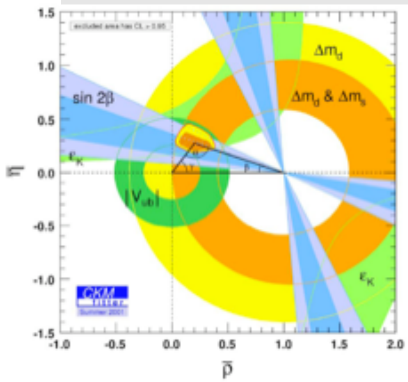
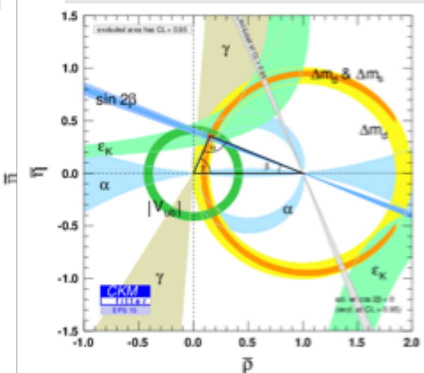
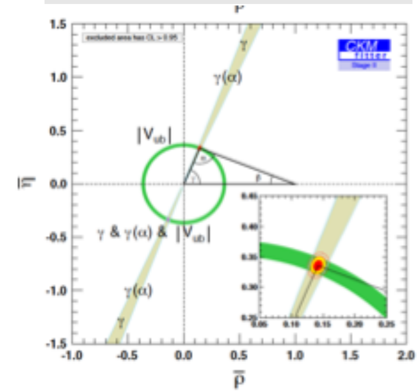




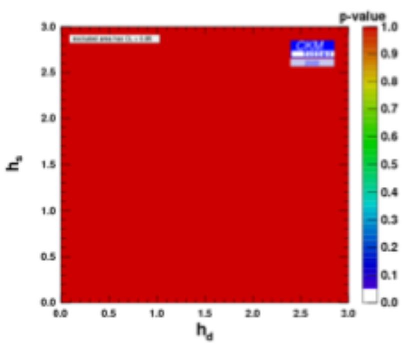
- Several Intriguing results: away from SM in the same direction.
- No single measurement is yet at or beyond 3 sigma away from SM
- Too early to consider LFU in serious trouble
- Several theoretical scenarios- e.g. models with leptoquarks- can accommodate the data.

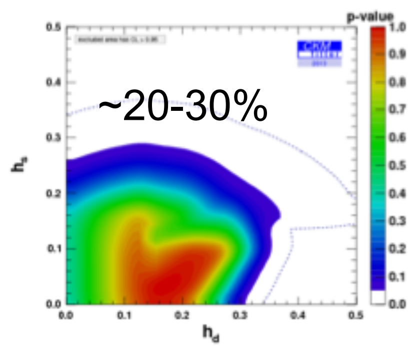
Future

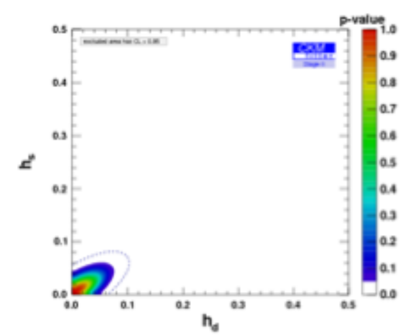
Toward precision Flavor Physics-O(1%): CKM and Rare Decays & much more

Last century	2001	Today	2025+
			

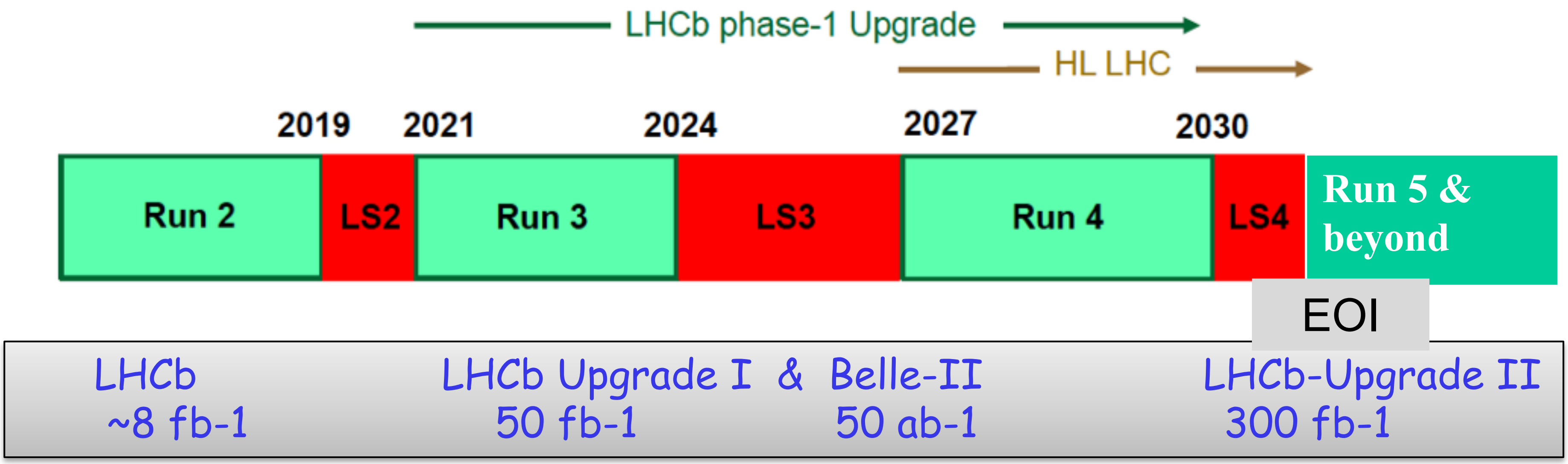
Constraint on NP/SM amplitude
See *(arXiv: 1309.2293)*







Experimental Landscape

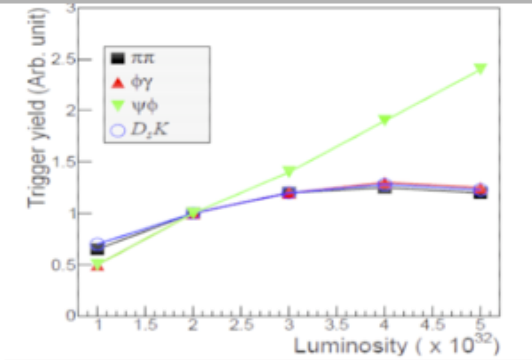


	LHC Run	Period of data taking	Maximum $\mathcal{L}$ $[\mathrm{cm}^{-2}\mathrm{s}^{-1}]$	Cumulative $\int \mathcal{L}\,dt$ $[\mathrm{fb}^{-1}]$	Pile up
Current detector	1 & 2	2010–2012, 2015–2018	4×10^{32}	8	1.1
Phase-1 Upgrade	3 & 4	2021–2023, 2026–2029	2×10^{33}	50	6
Phase-2 Upgrade	5 $\rightarrow$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

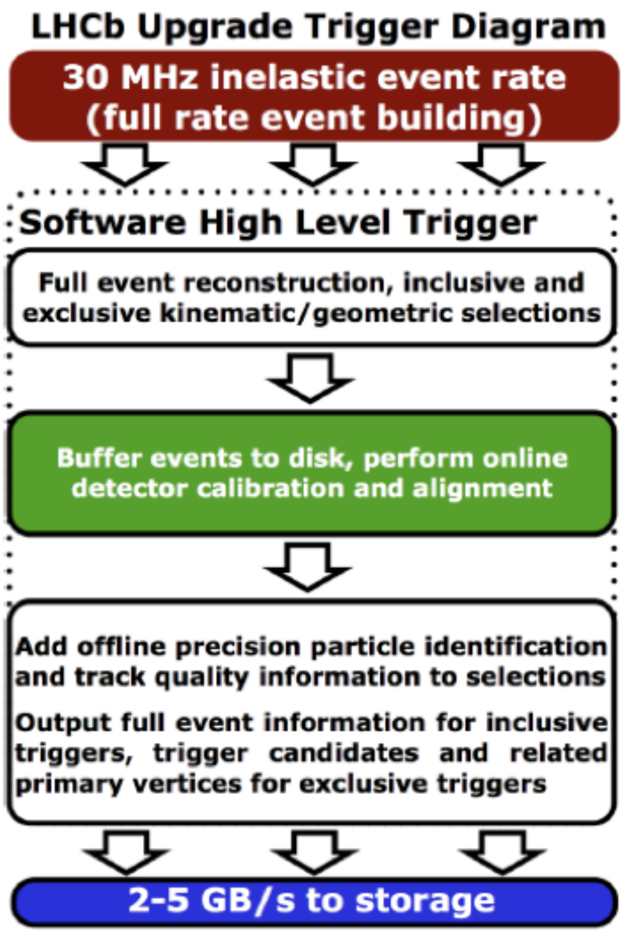
The LHCb upgrade: Trigger

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



Upgrade Trigger



➔ 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-I

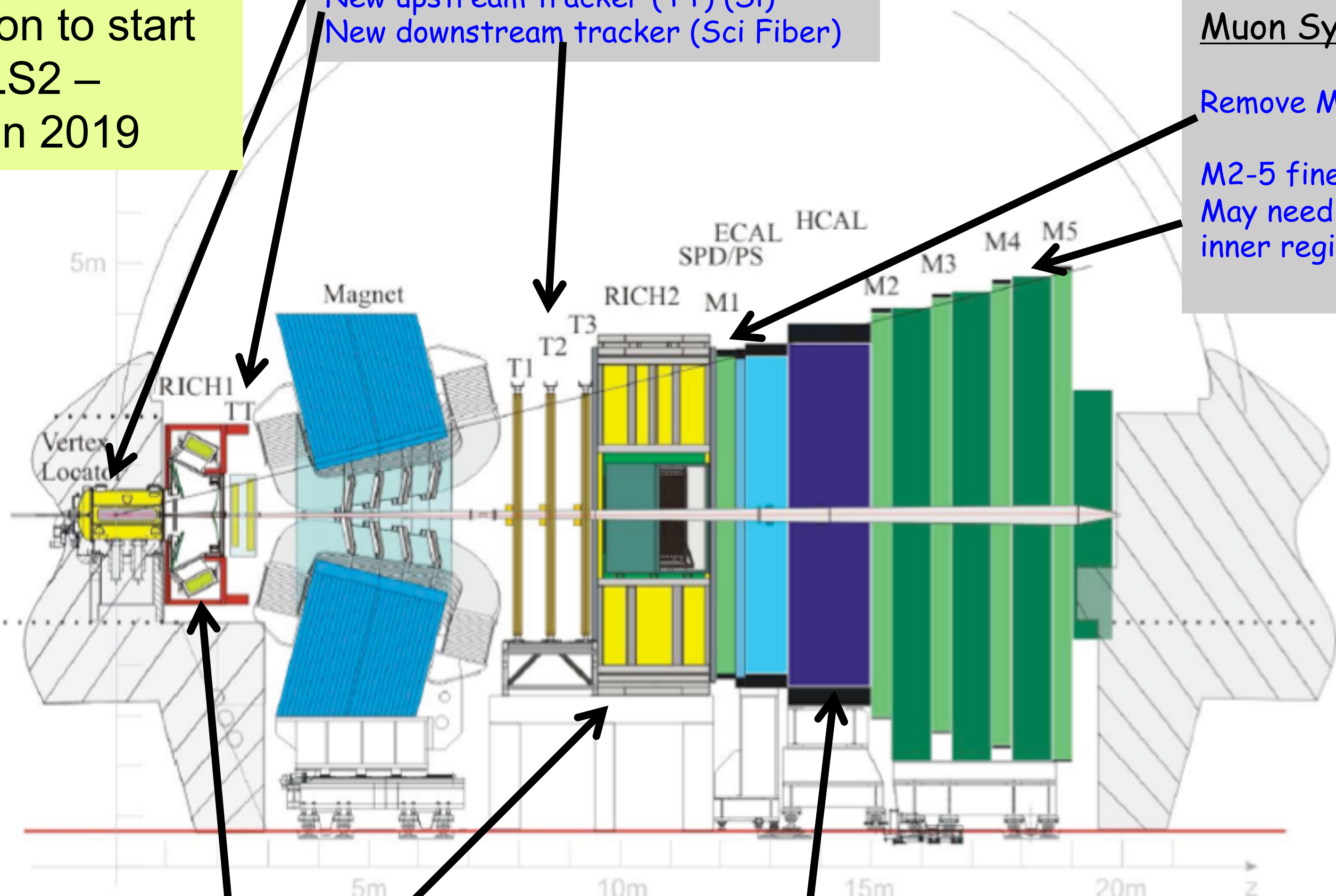
The assembly and installation to start in LHC LS2 – starting in 2019

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

Muon System:

Remove M1

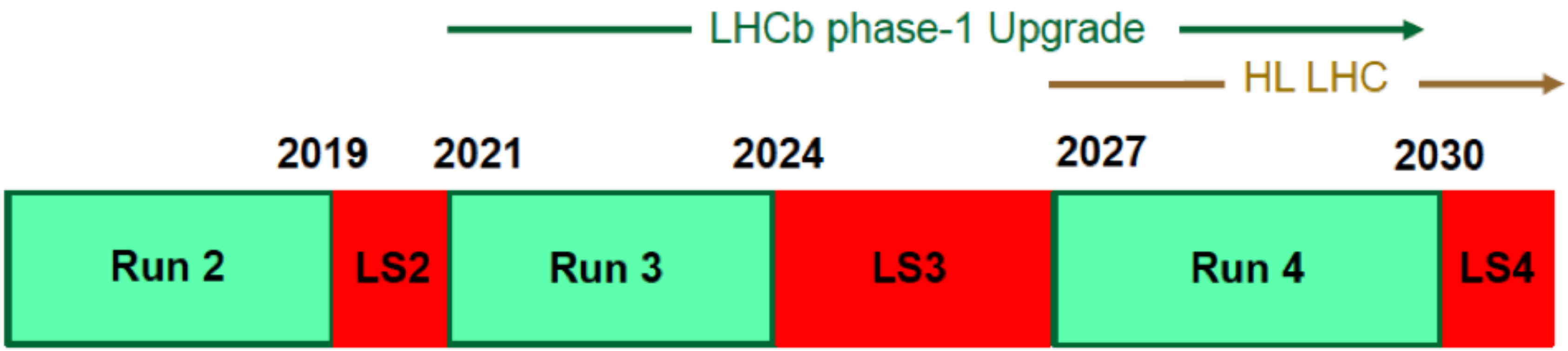
M2-5 fine for 1x10^{33}
May need upgrade of inner region at 2x10^{33}



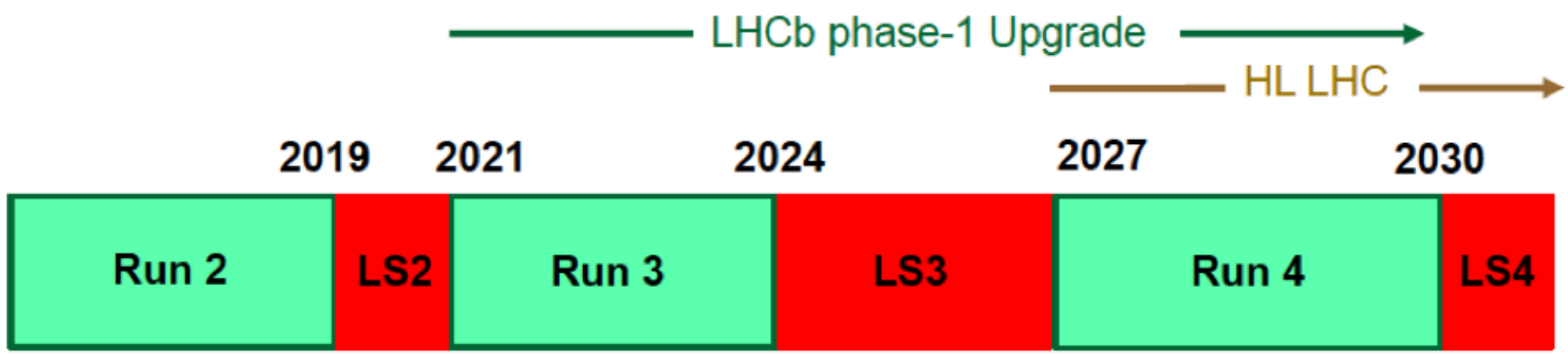
RICH 1 & RICH 2
HPD→ MaPMT
New 40 MHz R/O
RICH1: new optics
remove aerogel

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

Further in Future: Upgrade-II



Upgrade-II: Challenges



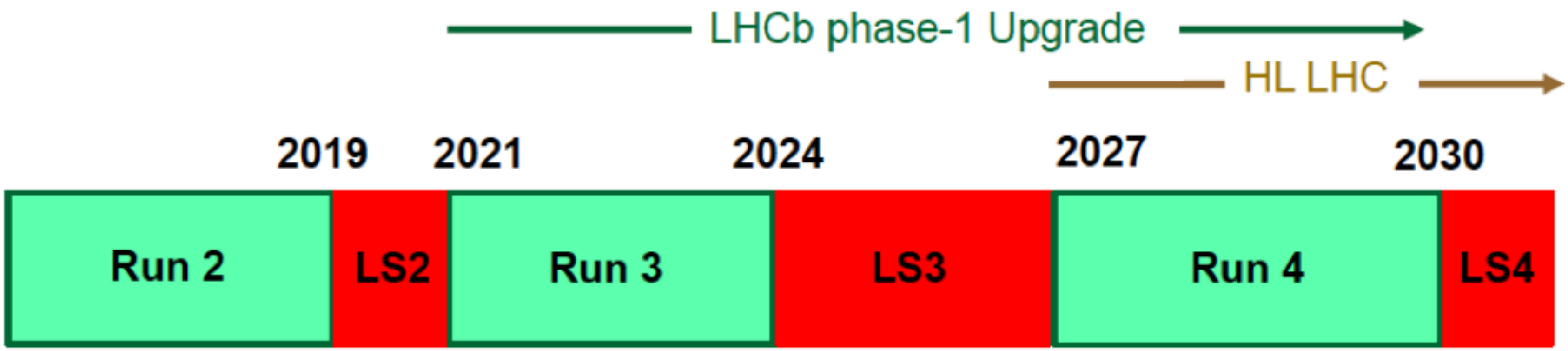
Major challenges for LHC & LHCb at peak Luminosity of 2×10^{34} /cm^2/s:

- 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

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 $3\,\mathrm{mrad}$, 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.

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.