The LHCb Experiment

Status
Physics Highlights &
Future plans

November 2 , 2017

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University of Maryland

The LHCb Detector

A Single Arm Spectrometer at LHC

Acceptance: $2 < \eta < 5$

σ_{inel}~70-80 mb

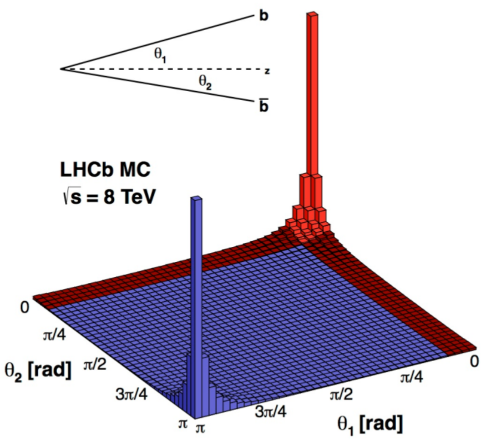
σ_{cc}~6 mb (7 TeV)

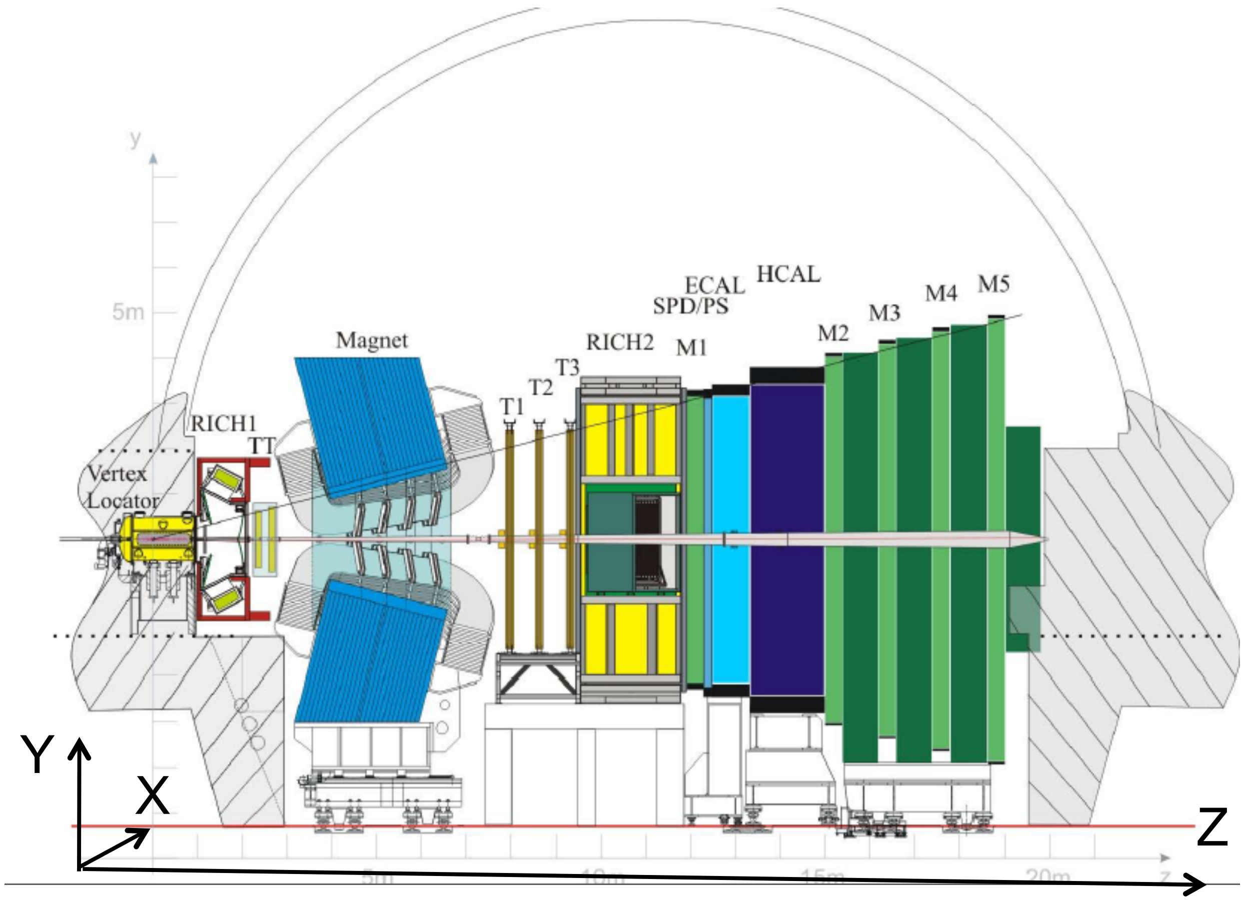
σ_{τ}~80 μb (7 TeV)

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

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US Participation:
Cincinnati, Maryland, MIT & Syracuse (EPP NSF)
LANL, U. Michigan (Nucl.)

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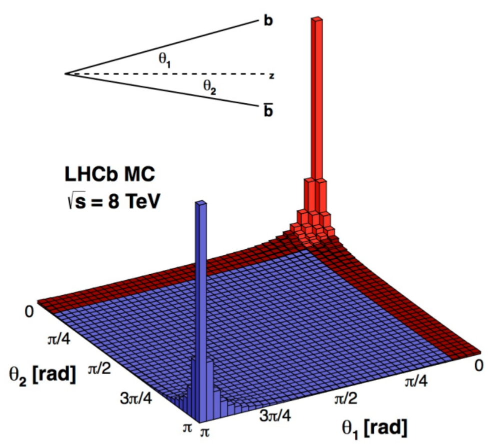
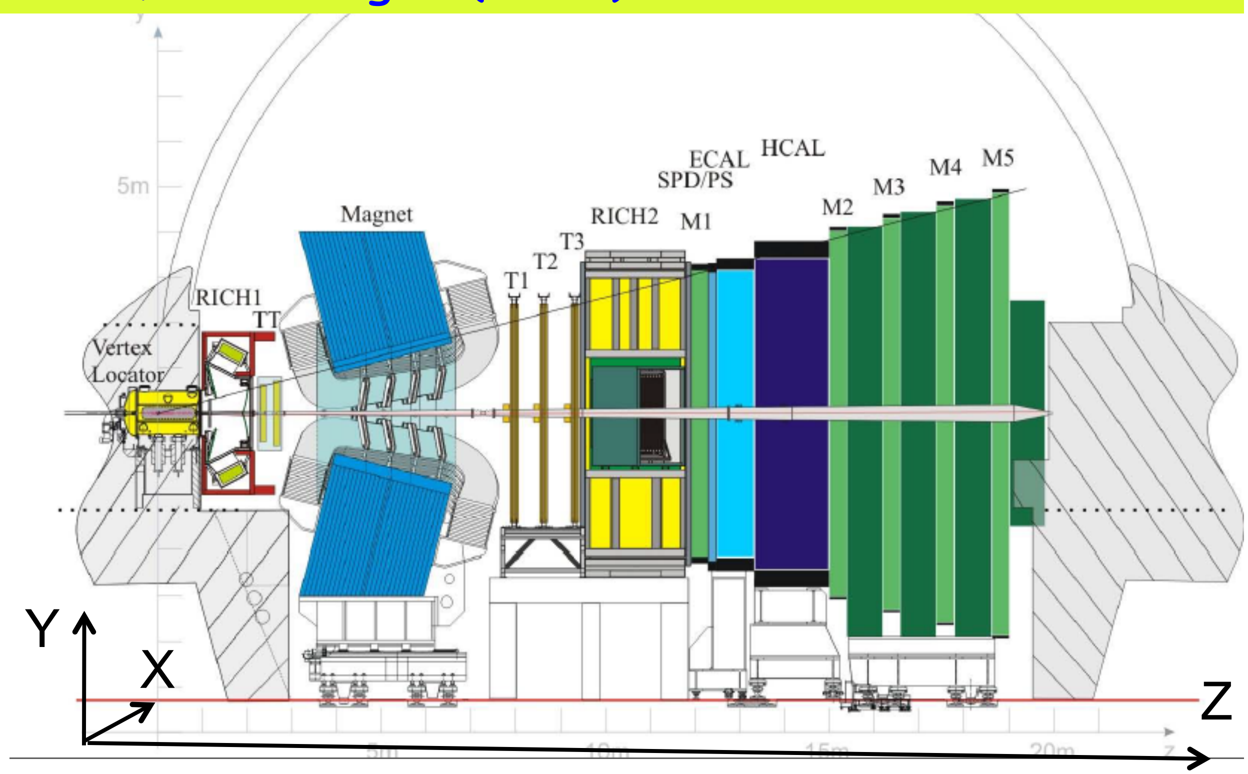
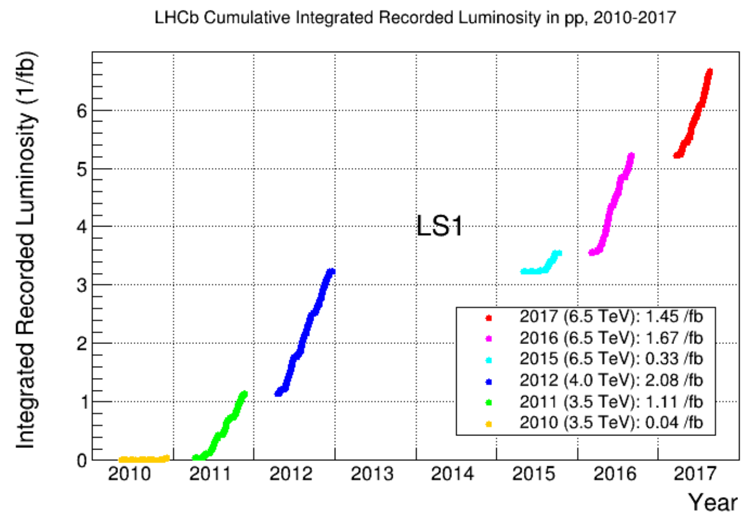


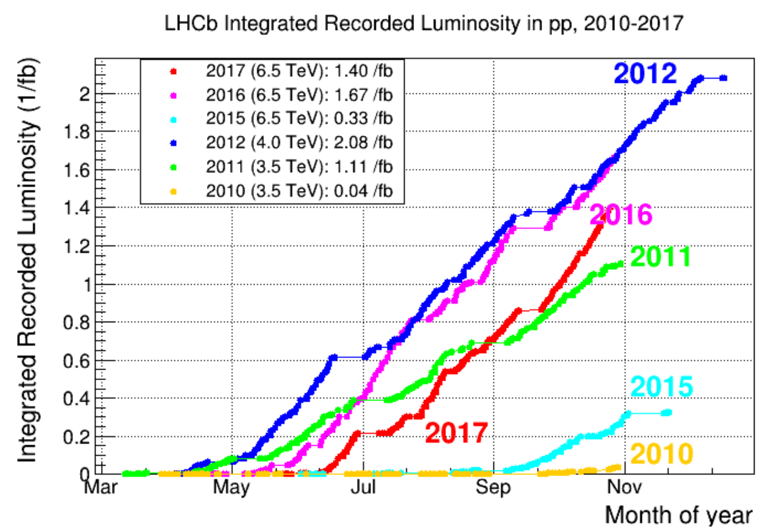


Access to all species of B hadrons

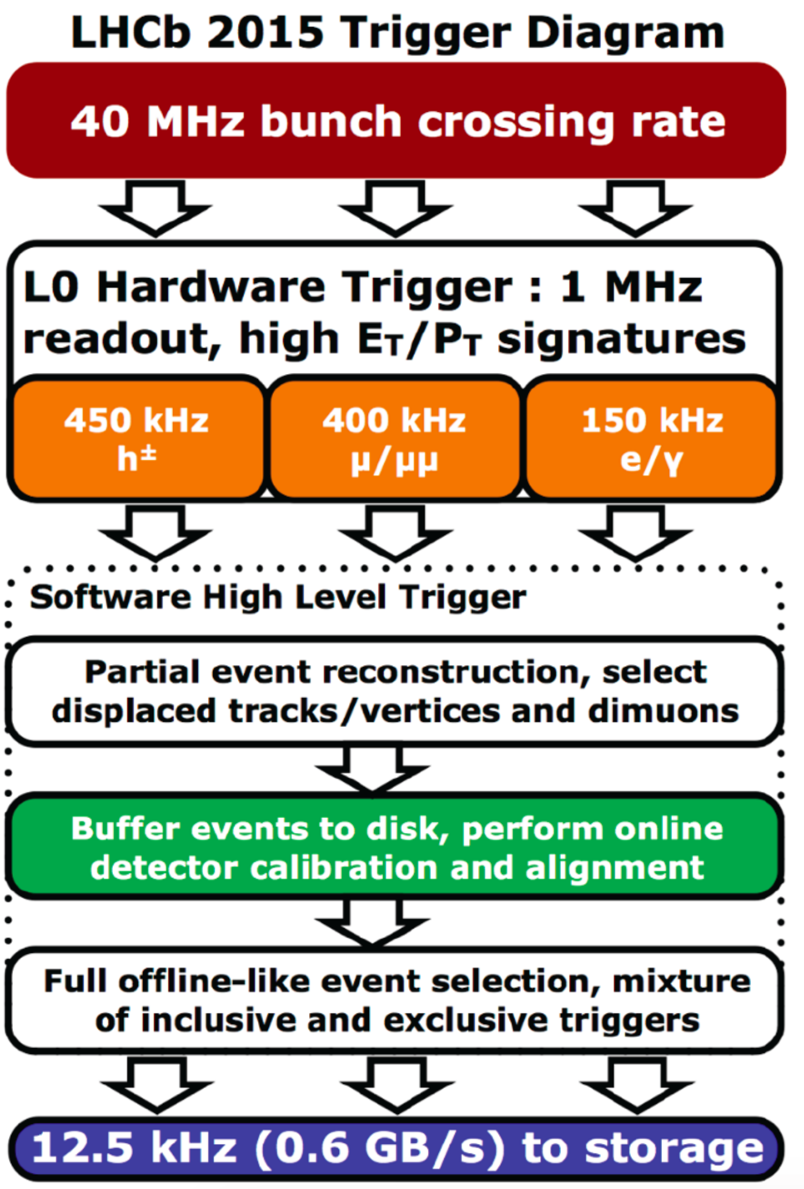
LHCb performance

- LHCb detector working smoothly
- Inst. Luminosity ~4×10^{32} cm^{-2} s^{-1}
- Luminosity levelling: Beam separation is adjusted to keep the luminosity constant.
- Average number of visible collisions per crossing is ~1.1 (Run 2)
- Recorded Luminosity > 6.5 fb-1
- High data-taking efficiency (> 90%) (vs maximum 93%- deadtime limit)

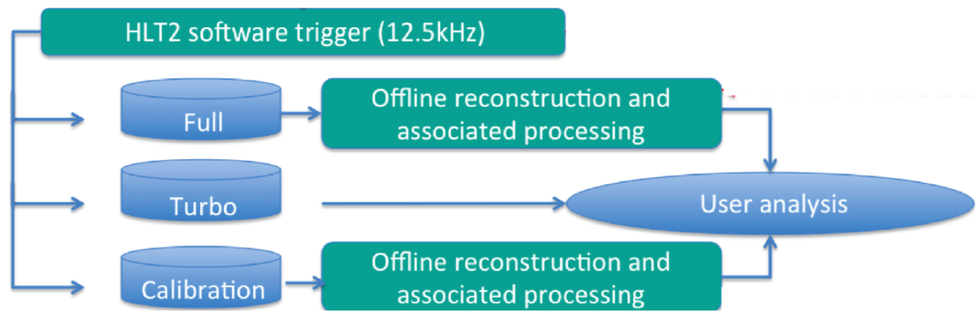


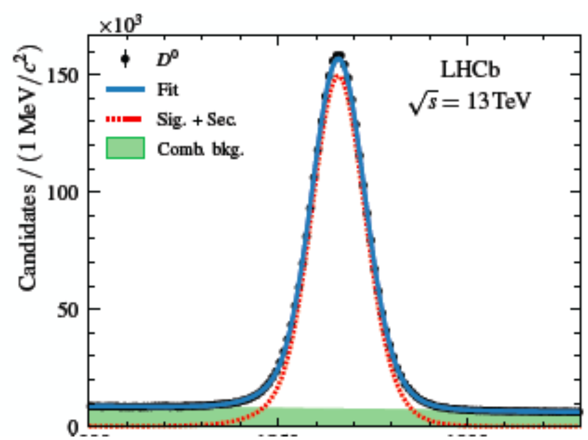


Trigger

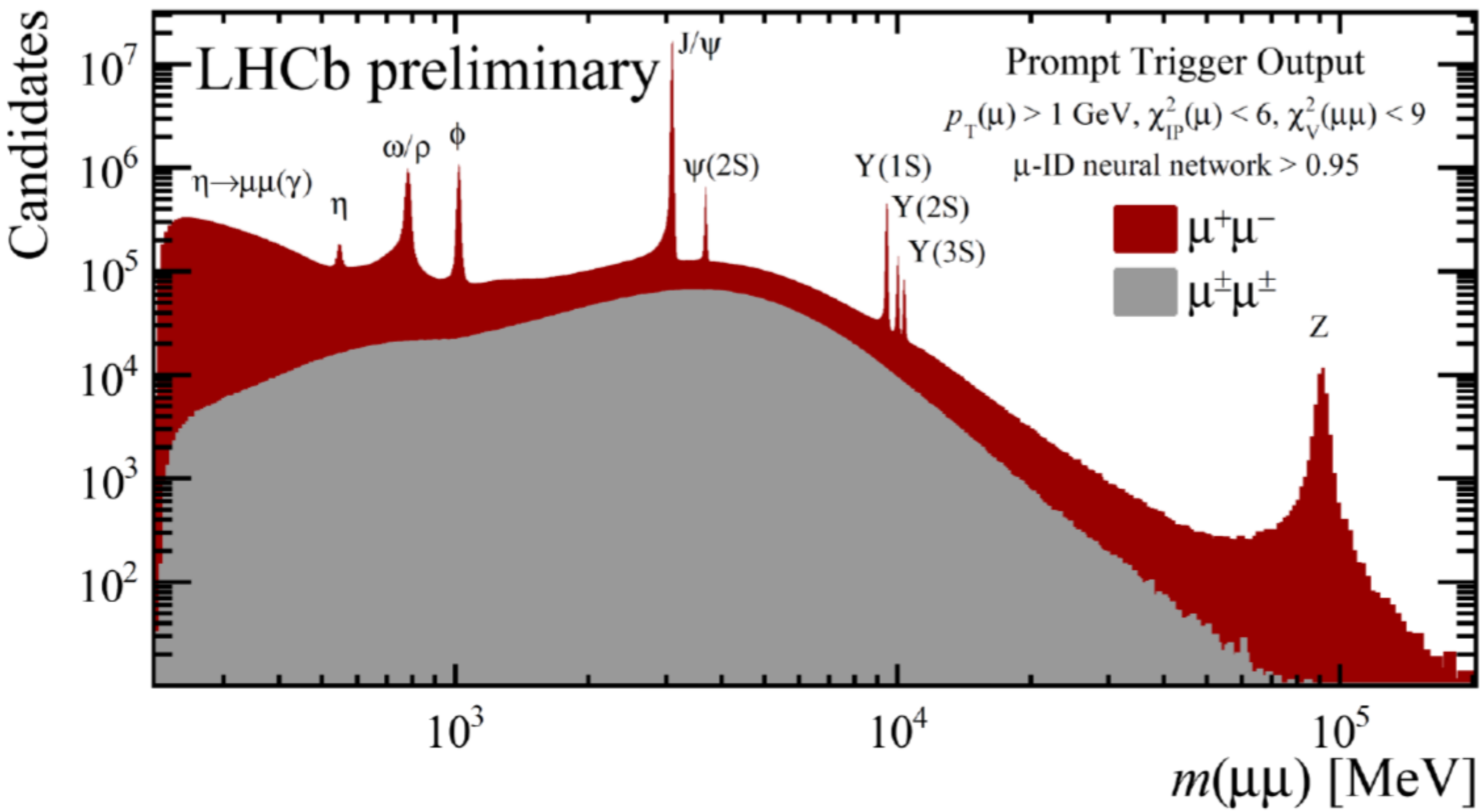


- Detector alignment, calibration and Particle ID at the trigger level
- Same reconstruction in online and offline



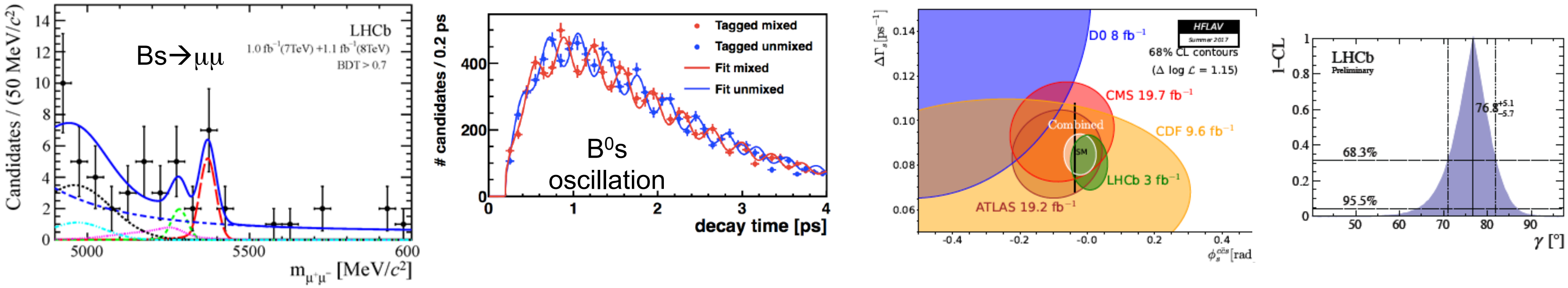


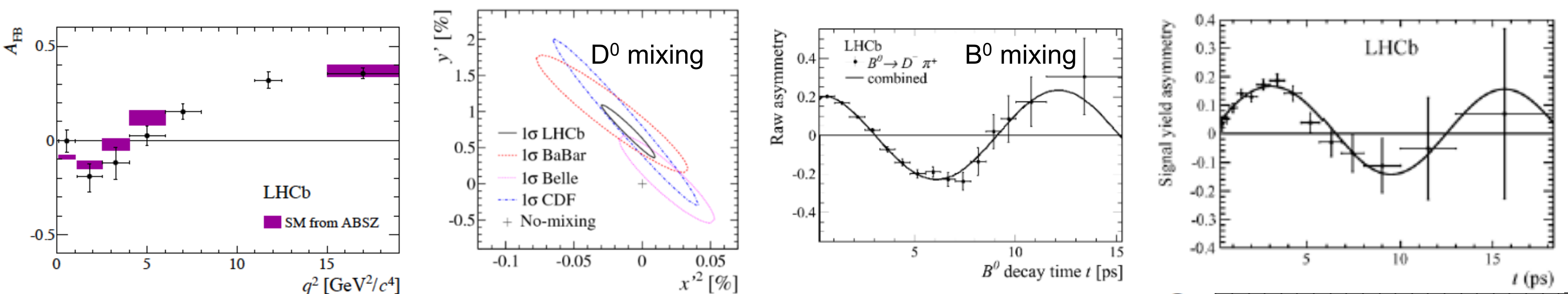
Trigger Level/ Turbo Output

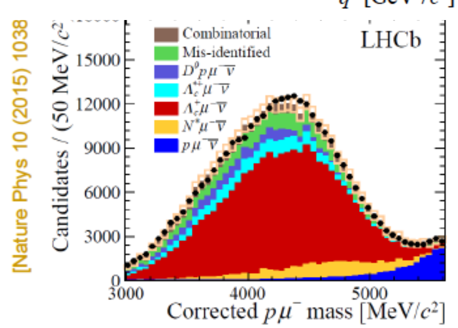


Forms the basis of a search for light dark matter candidates: A'→$\mu^+\mu^-$

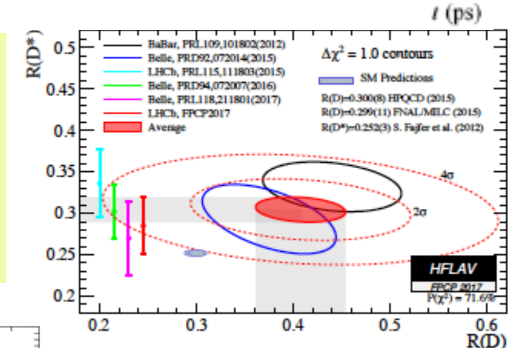
discussed in the talk on "Run 2 results" (S. Stone) talk this afternoon

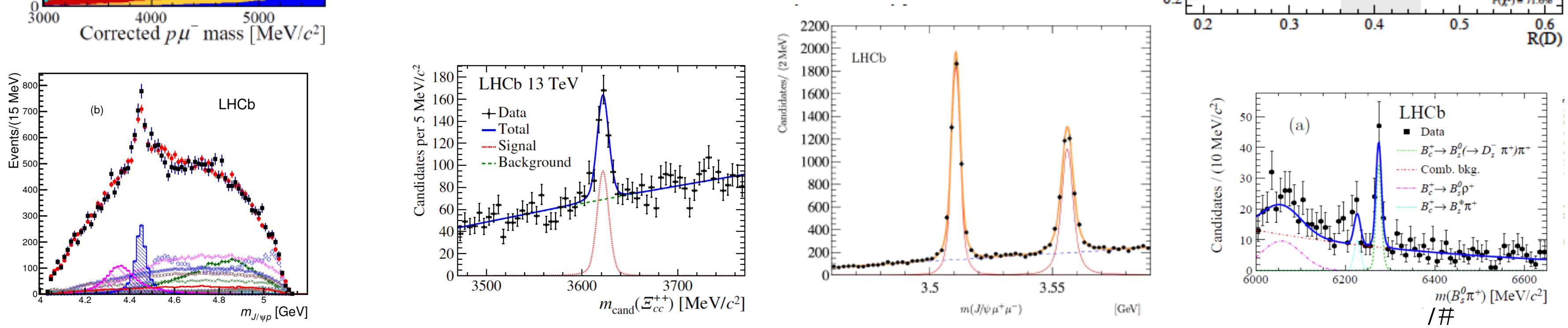


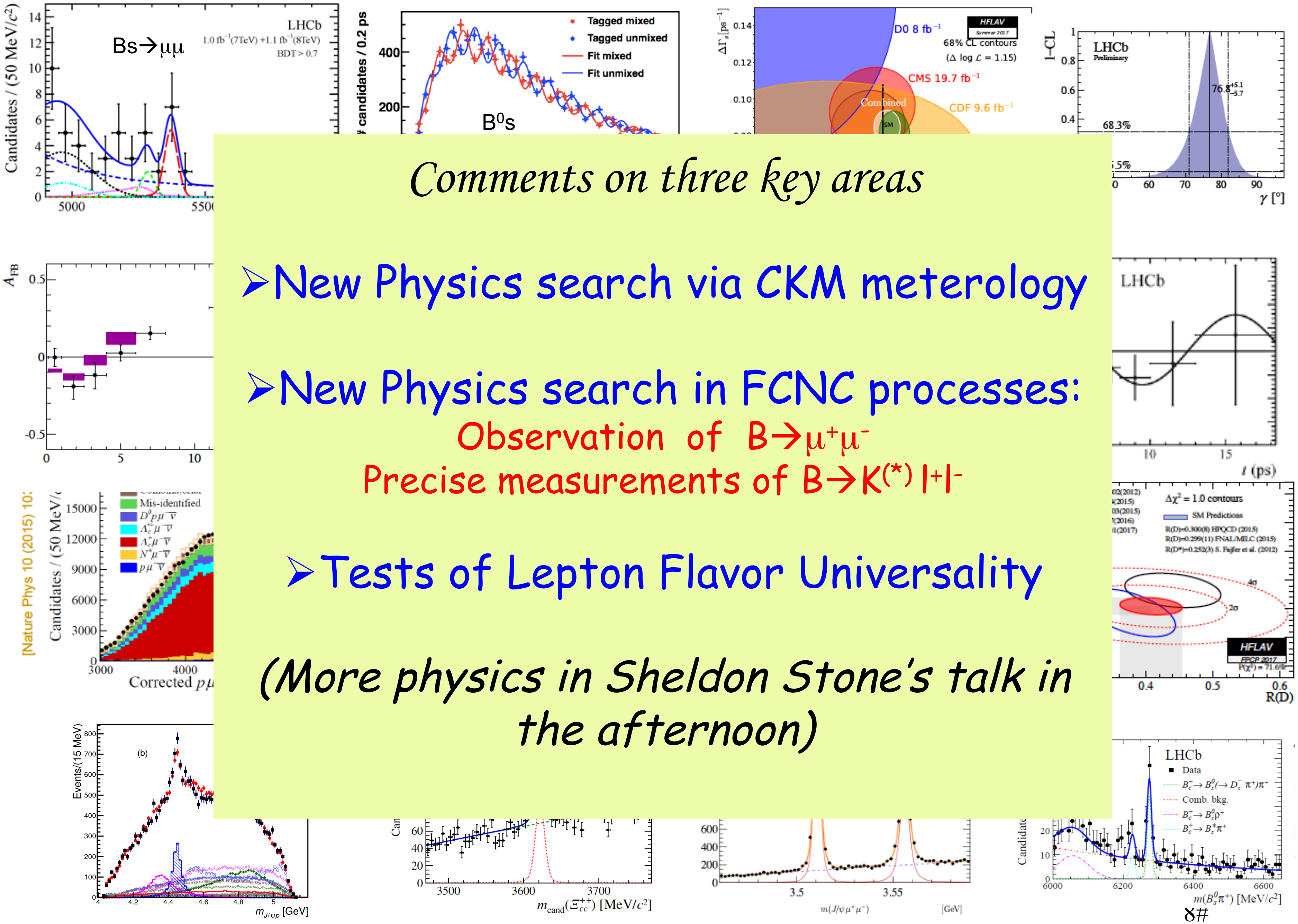




LHCb Physics Covers a very broad spectrum from Flavor to EW, QCD, pA…







Comments on three key areas

- ➢New Physics search via CKM meterology

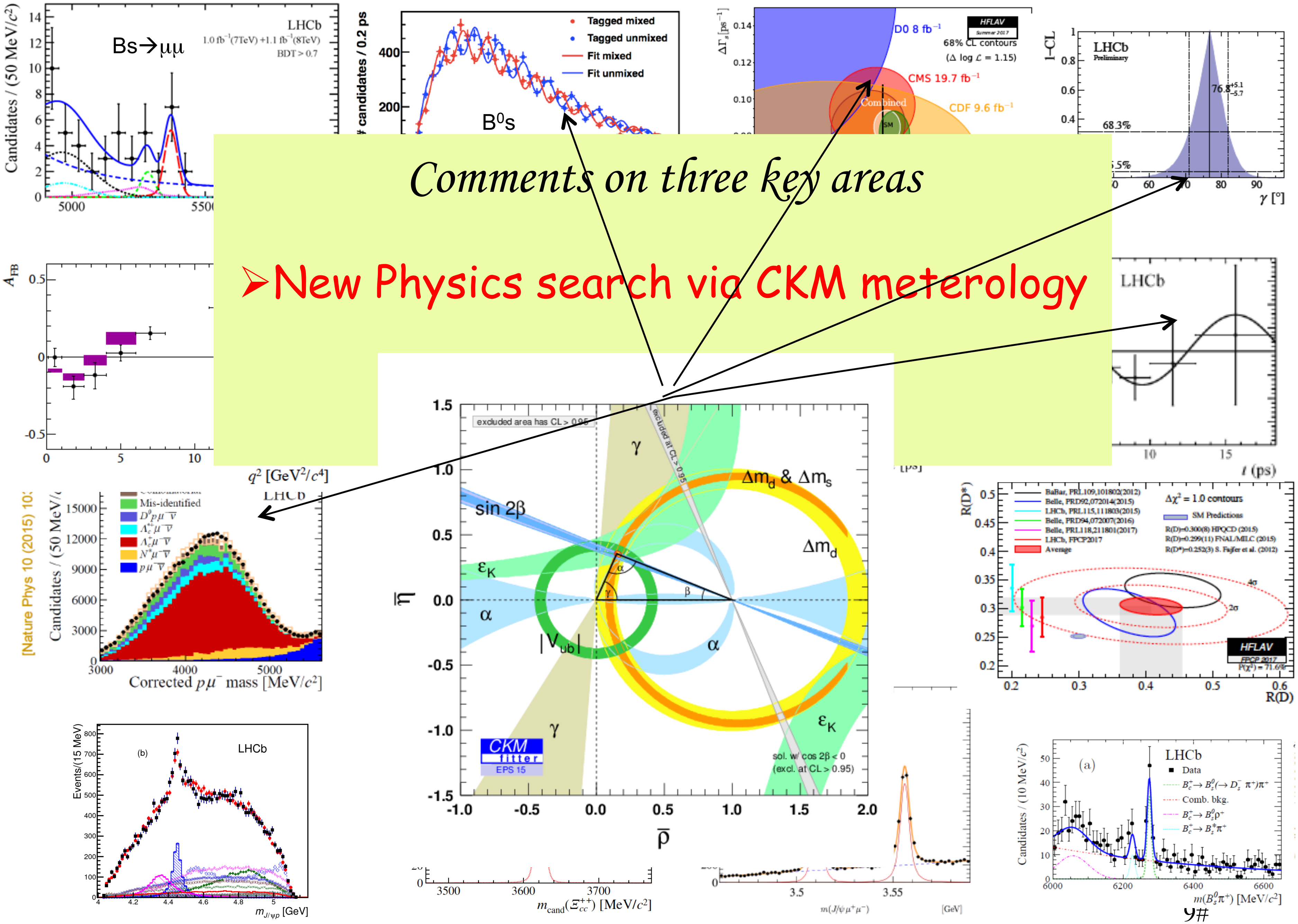
- ➢New Physics search in FCNC processes:
  - Observation of $B\to\mu^+\mu^-$
  - Precise measurements of $B\to K^{(*)} l^+l^-$

- ➢Tests of Lepton Flavor Universality

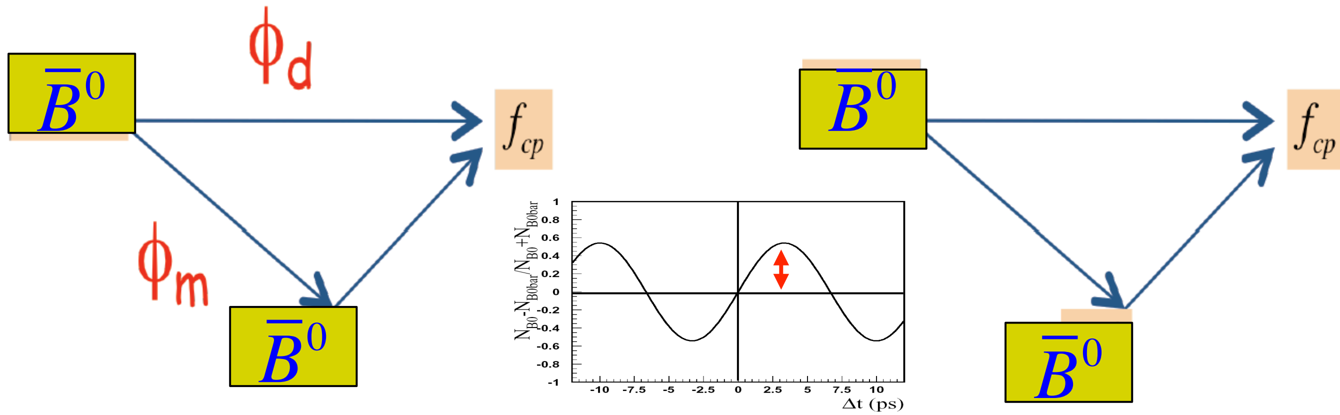
(More physics in Sheldon Stone's talk in the afternoon)

Comments on three key areas

➢New Physics search via CKM meterology



Reminder “CP” interferometer to access the phase of CKM



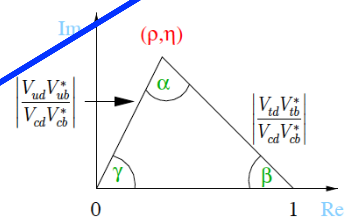
$$A_{cp}(t) = \frac{\Gamma(B^0(t) \to f_{cp}) - \Gamma(\overline{B}^0(t) \to f_{cp})}{\Gamma(B^0(t) \to f_{cp}) + \Gamma(\overline{B}^0(t) \to f_{cp})} = \sin 2(\varphi_m - \varphi_D)\sin \Delta m t$$

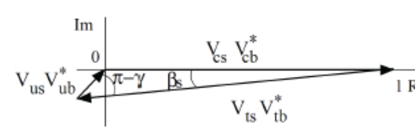
With careful set up of both initial and final states

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

$B_d \to J/\psi\ K^0_s$ :: $\sin 2\beta \sim \arg(V^*_{td}) \sim 25^o$

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





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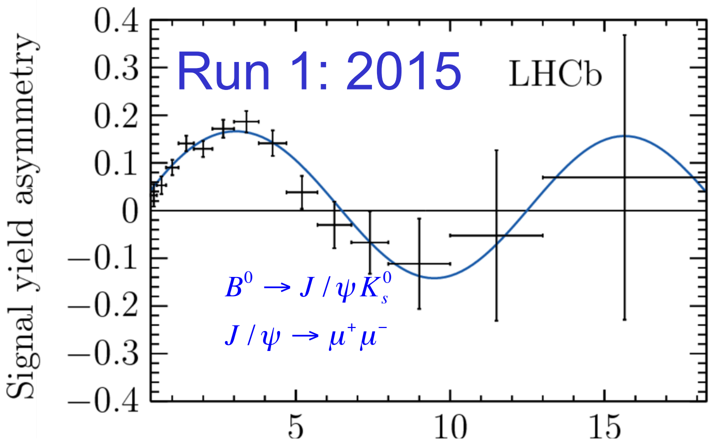
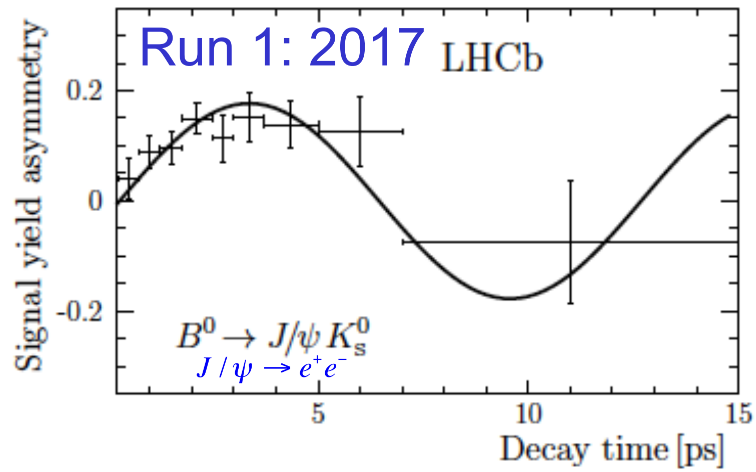
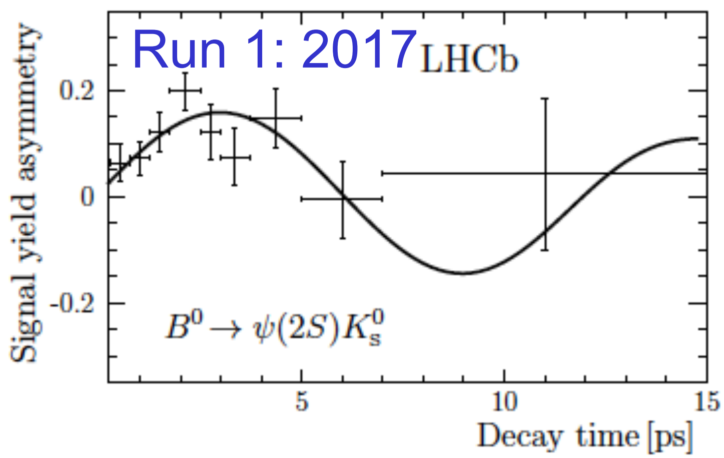






$\sin 2\beta = 0.76 \pm 0.034$ *LHCb*

$\sin 2\beta = 0.69 \pm 0.02$ *World – Average(HFAG)*

Run-1 precision at LHCb already comparable to BaBar and Belle individually

$B_d \to J/\psi\ K^0_s$ :: $\sin 2\beta \sim \arg(V_{td}^*) \sim 25^O$

$B_s \to J/\psi\ K^+K^-$ $\varphi_s \sim \arg(V_{ts}^*) \sim 1^O$

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

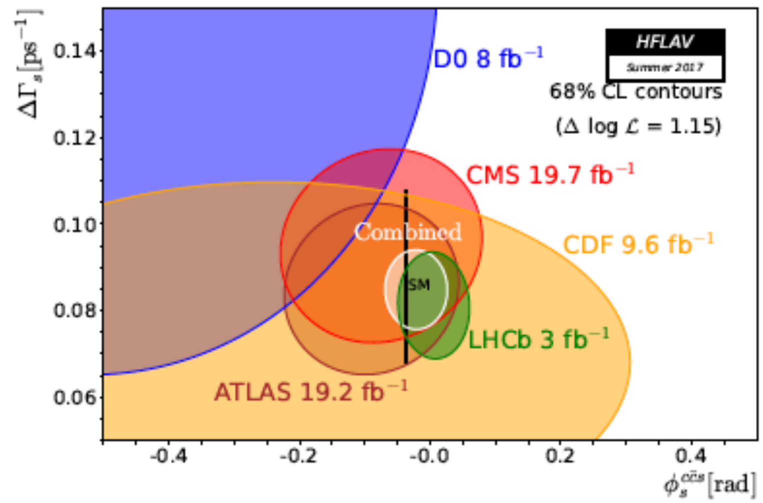
LHCb measurement using:

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

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

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

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



Combining LHCb results:

JHEP 08 (2017) 037

$$\varphi_s^{c\bar{c}s} = 0.001 \pm 0.037$$

$$\Delta\Gamma_s = 0.0813 \pm 0.0081$$

$$\Gamma_s = 0.6588 \pm 0.0026$$

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

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

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

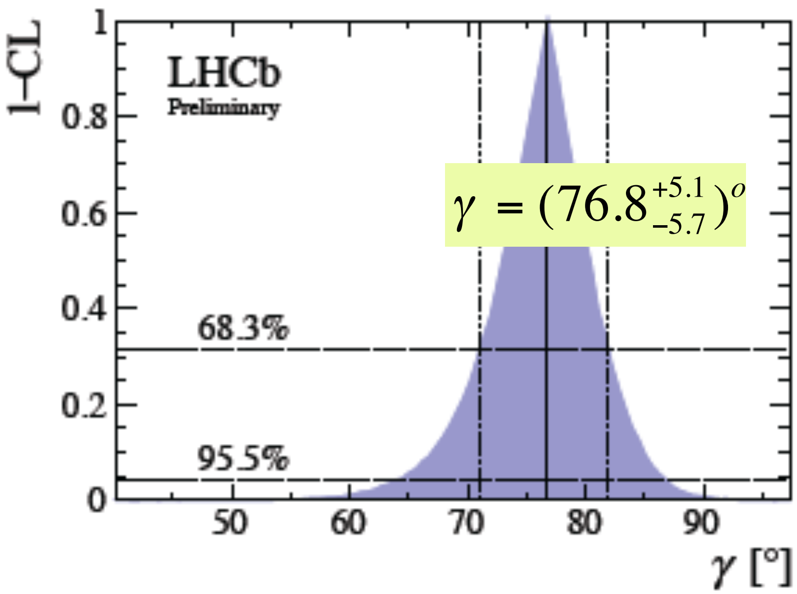
Measurement of $\gamma = \arg\left(\frac{V_{ud}V_{ub}^{*}}{V_{cd}V_{cb}^{*}}\right)$

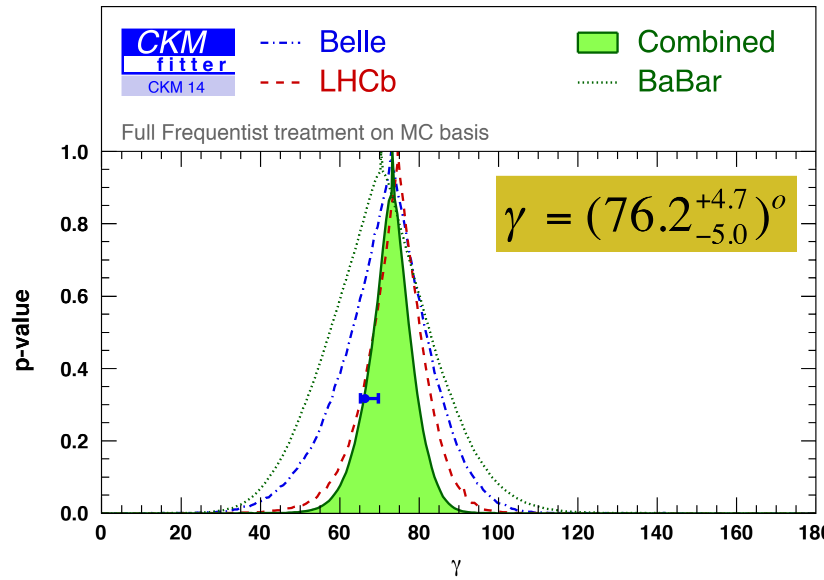
Yet another interferometer: tree level processes b->c & b->u

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

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

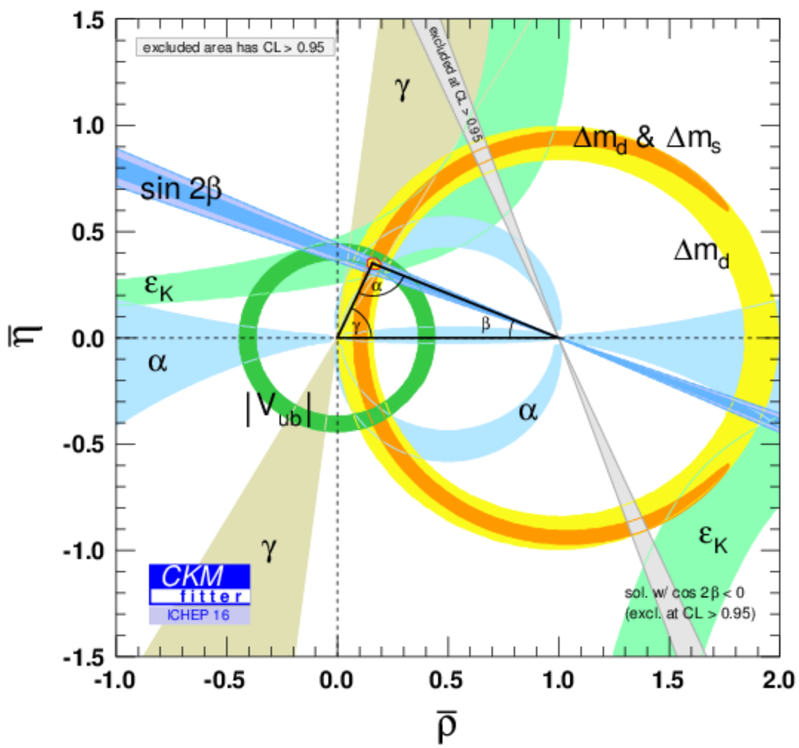
Analysis updates involve several new channels & some includes Run 2 data





Status of CKM (2017)

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

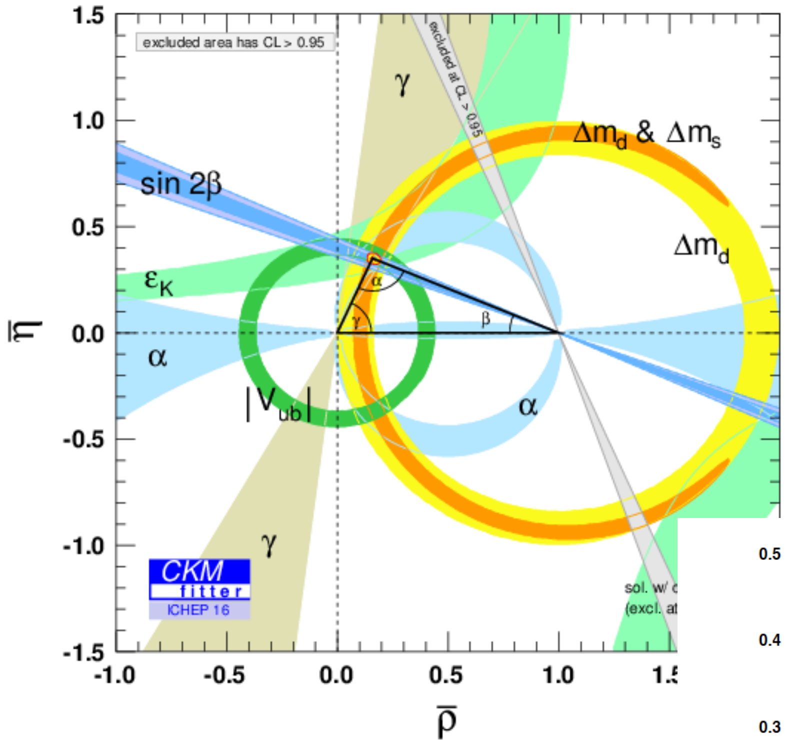


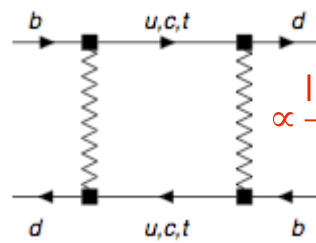
	Direct	CKM fit
α	$\left(87.6^{+3.5}_{-3.3}\right)^o$	$\left(92.1^{+1.5}_{-1.1}\right)^o$
β	$\left(21.85^{+0.68}_{-0.67}\right)^o$	$\left(23.74^{+1.13}_{-0.98}\right)^o$
γ	$\left(76.2^{+4.7}_{-5.0}\right)^o$	$\left(65.9^{+0.96}_{-2.54}\right)^o$
$-2\beta_s$	-0.021 ± 0.031	-0.0370 ± 0.0006

Is there room for New Physics?

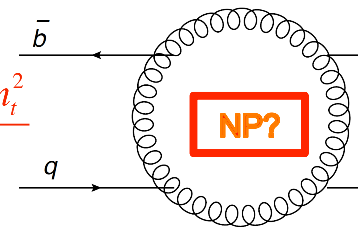
All is well with the CKM picture at O(10%) level:

For New Physics through Mixing





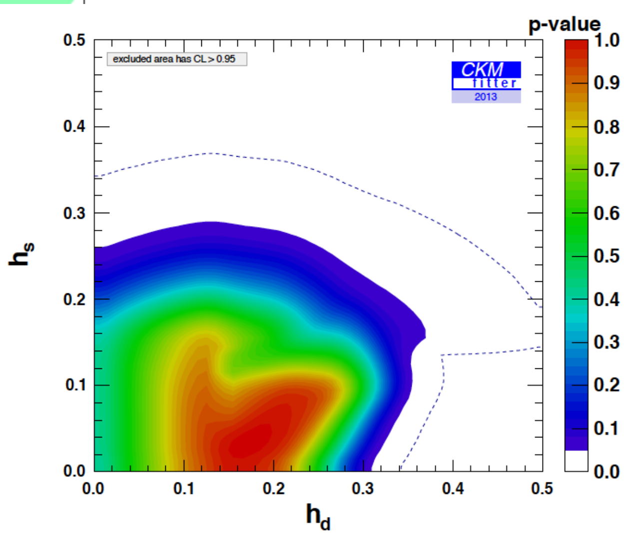
$$\propto \frac{|V_{tq}|^2 m_t^2}{M_W^4}$$



$$\propto \frac{|C|^2}{\Lambda_{NP}^2}$$

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

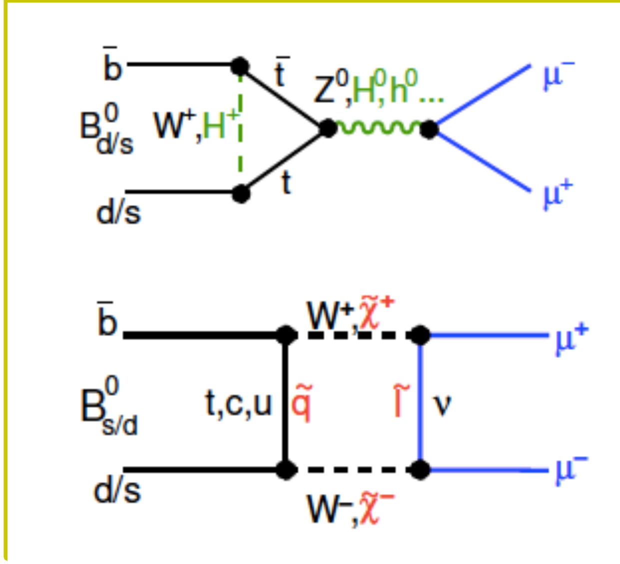
Constraint on NP/SM amplitude See *(arXiv: 1309.2293)*



for $C = 1$

$\Lambda_{NP} \gg 10^3 TeV$

Search for New Physics with very rare processes

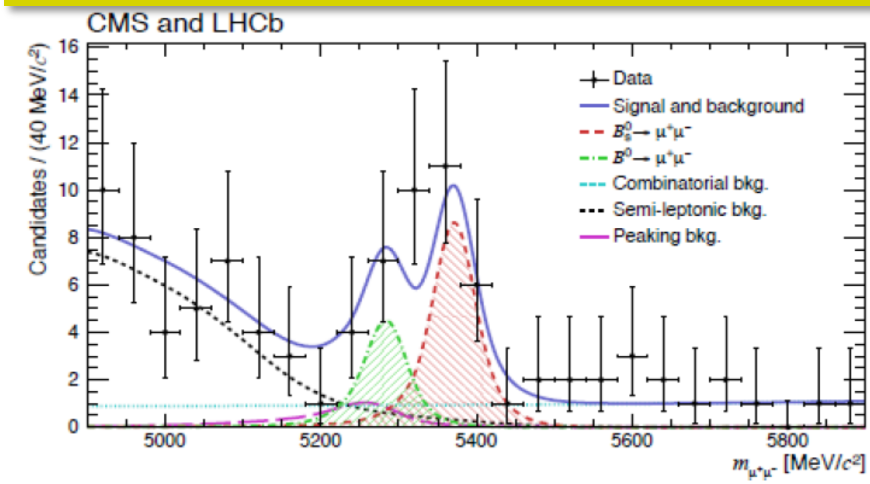


$$SM : Br(B_s^0 \to \mu^+\mu^-) = (3.66 \pm 0.23) \times 10^{-9}$$

Observation by LHCb & CMS Run -1
consistent with SM

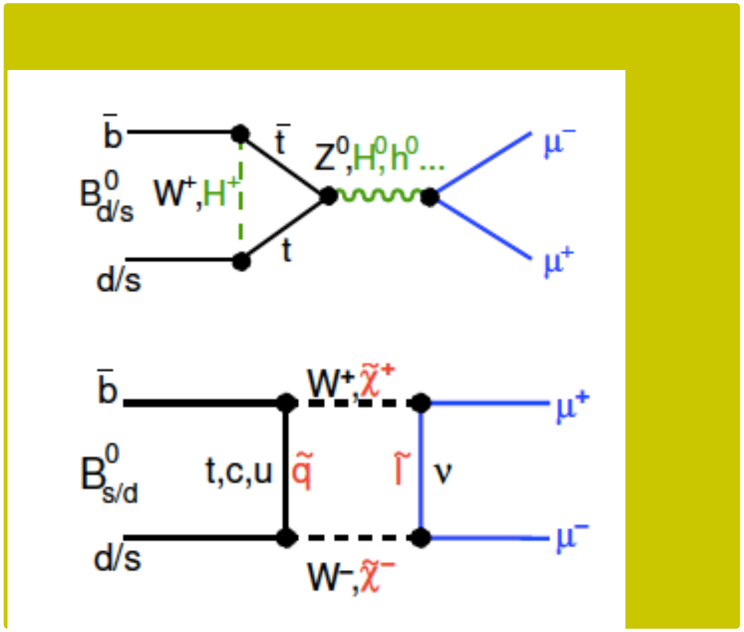
$$Br(B_s^0 \to \mu^+\mu^-) = (2.8^{+0.7}_{-0.6}) \times 10^{-9} \quad 6.2\sigma$$

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

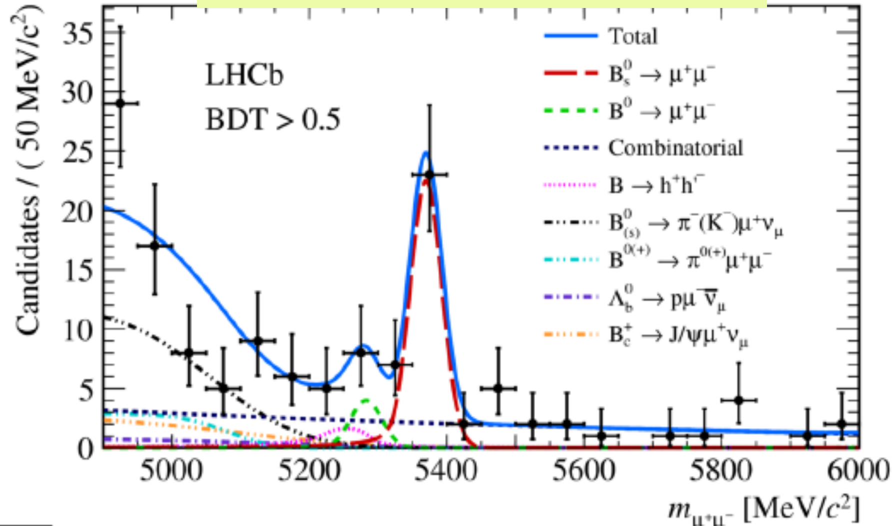


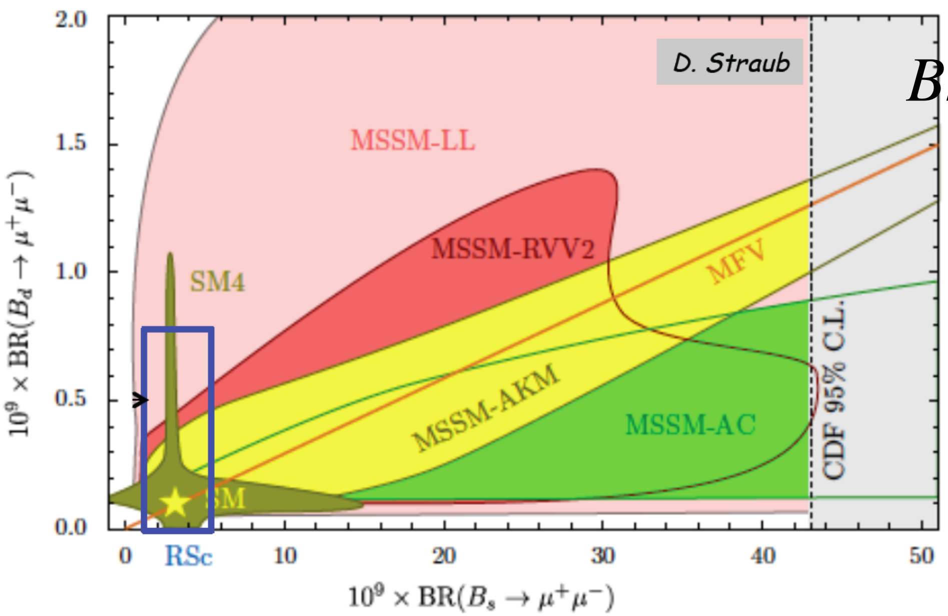
$$ATLAS : Br(B_s^0 \to \mu^+\mu^-) = (0.9^{+1.1}_{-0.8}) \times 10^{-9}$$

Search for New Physics with very rare processes



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



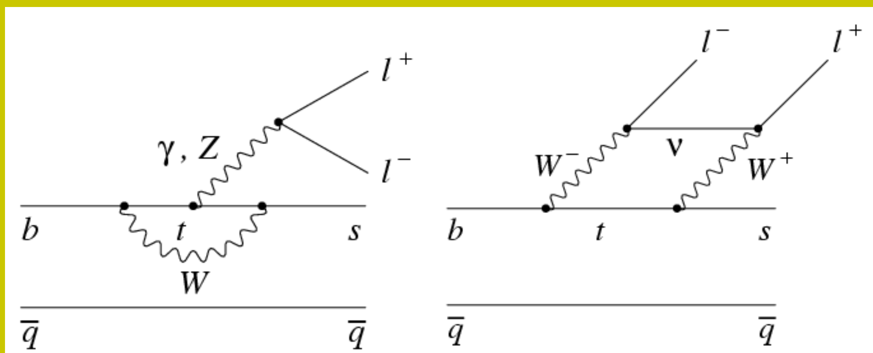


$$Br(B^0_s \to \mu^+\mu^-) = (3.0 \pm 0.6^{+0.3}_{-0.2}) \times 10^{-9}$$

7.8 σ

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

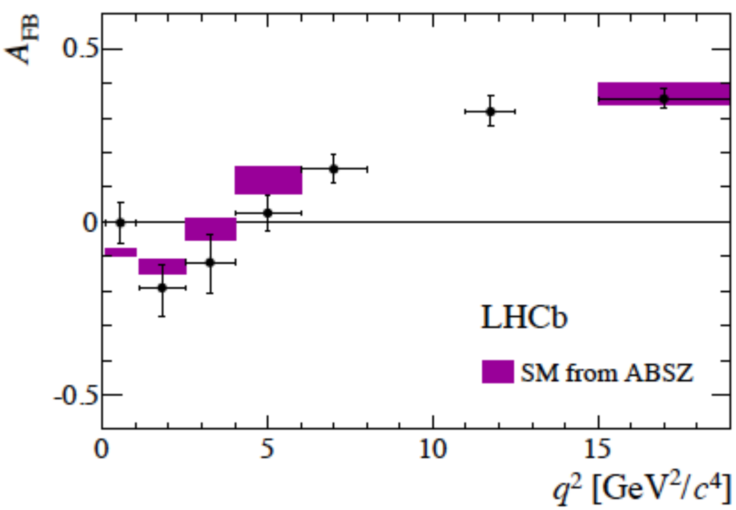
Search for New Physics with very rare processes

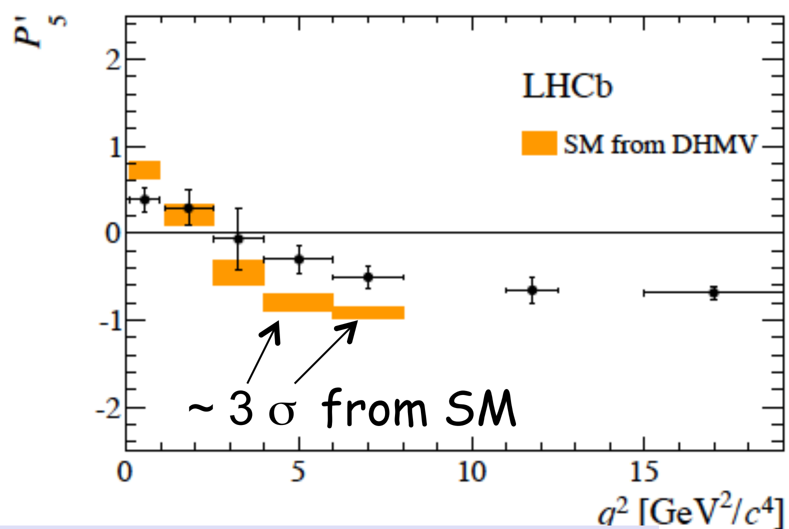


Several observables- sensitive to New Physics- extracted from differential rates.

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

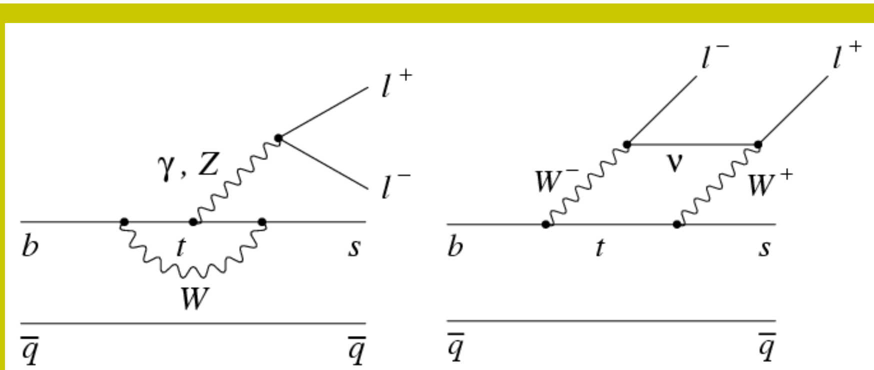
First full angular analysis of $B \rightarrow K^{*0}\mu^+\mu^-$ performed with LHCb Run 1 data:





Overall compatability of LHCb results with SM ~3.4 σ

Search for New Physics with very rare processes



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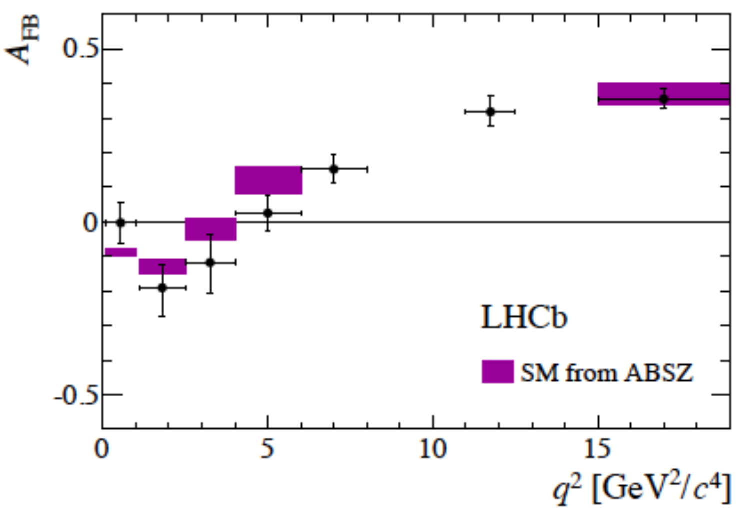
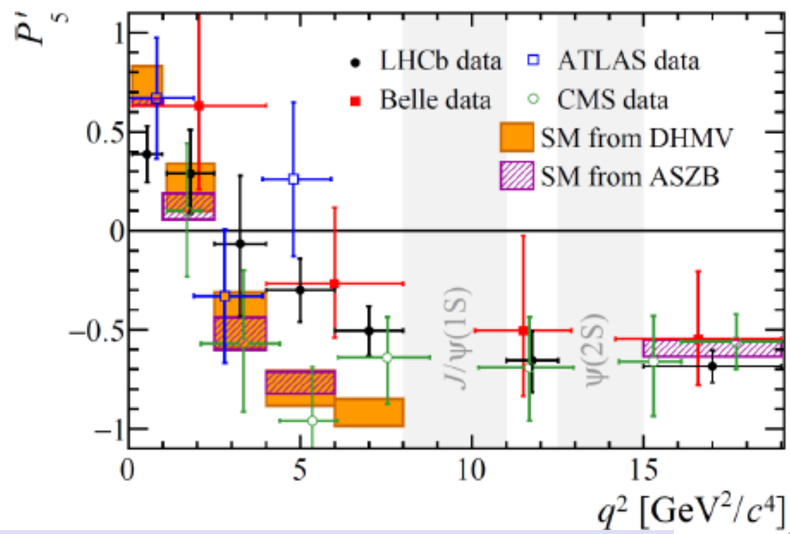




Overall compatability of LHCb results with SM ~3.4 σ

Tests of Lepton Flavor Universality (1)

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

Within SM at high precision $R_{K^{(*)}} = 1.0$

LHCb

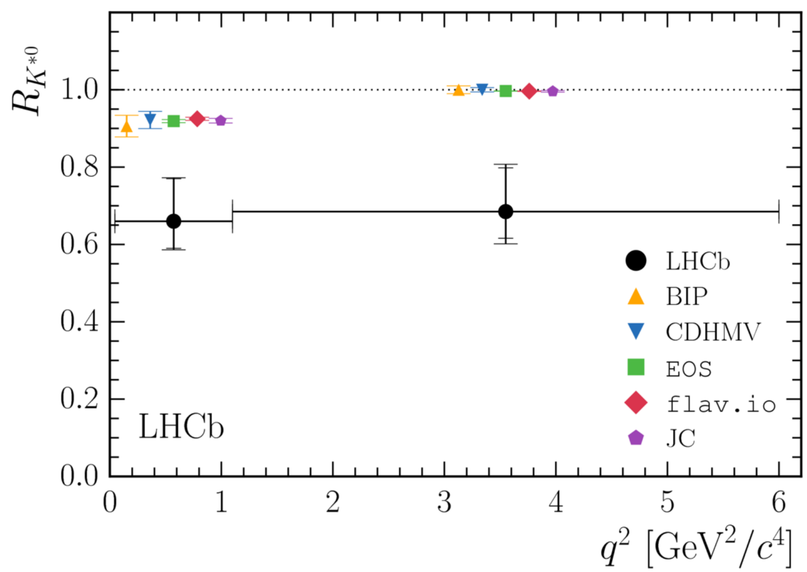
$$R_K = 0.745^{+0.090}_{-0.074} \pm 0.036$$

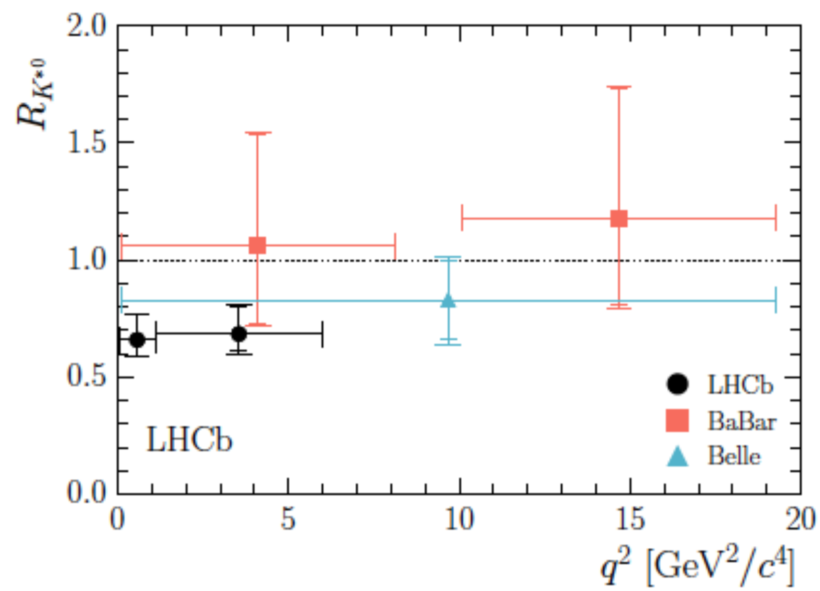
Within 2.6 σ of SM

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

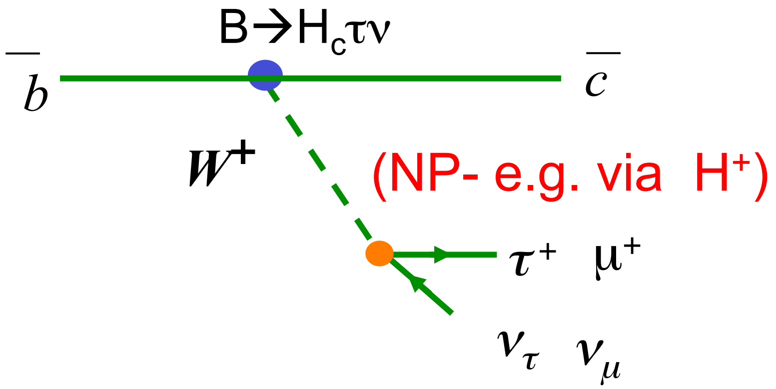
$$R_{K^*} = 0.685^{+0.113}_{-0.069} \pm 0.047 \quad high - q^2$$

Within 2.1-2.3 σ & 2.4-2.5 σ of SM





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

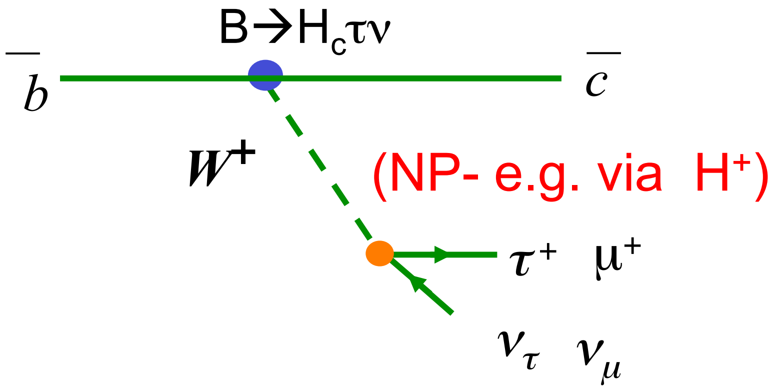
$R(D) = 0.300 \pm 0.008$ H. Na et al., (LQCD)

$R(D^*) = 0.252 \pm 0.003$ 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

Tests of Lepton Flavor Universality (2)



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

Hints of deviation from these predictions first seen by BaBar

- These are theoretically very "clean", computed
- Form-Factor Uncertainties largely cancel

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

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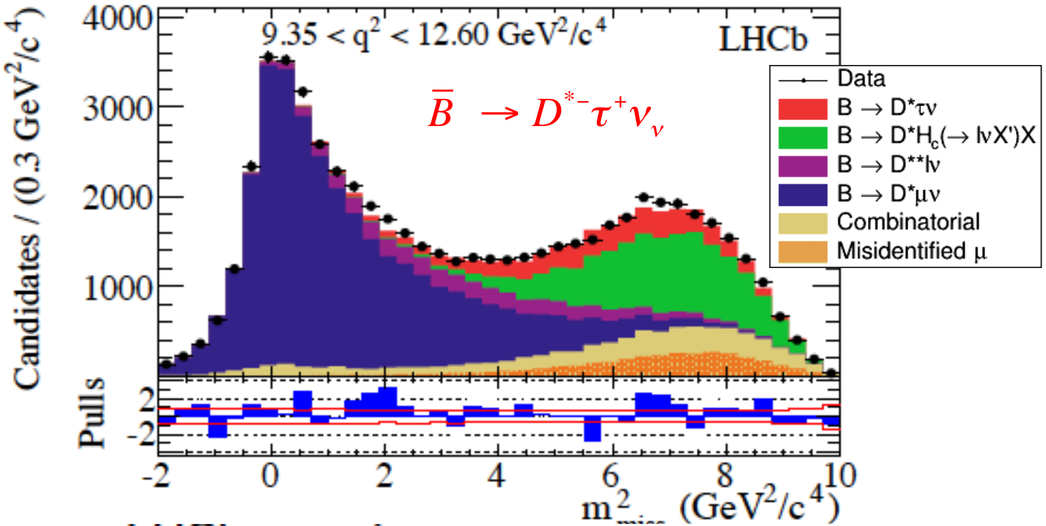
All with Run 1 Data- so far

2015

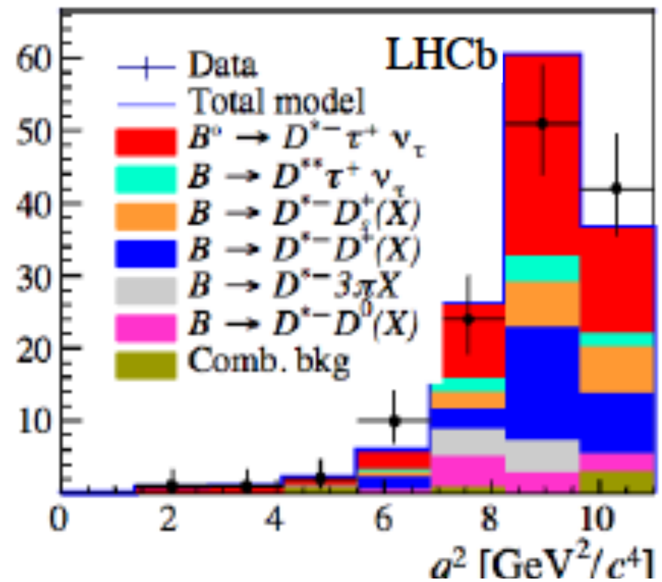


- **LHCb muonic**

$R(D^*) = 0.336 \pm 0.027 \pm 0.030$

Within 2.1 σ of SM

2017

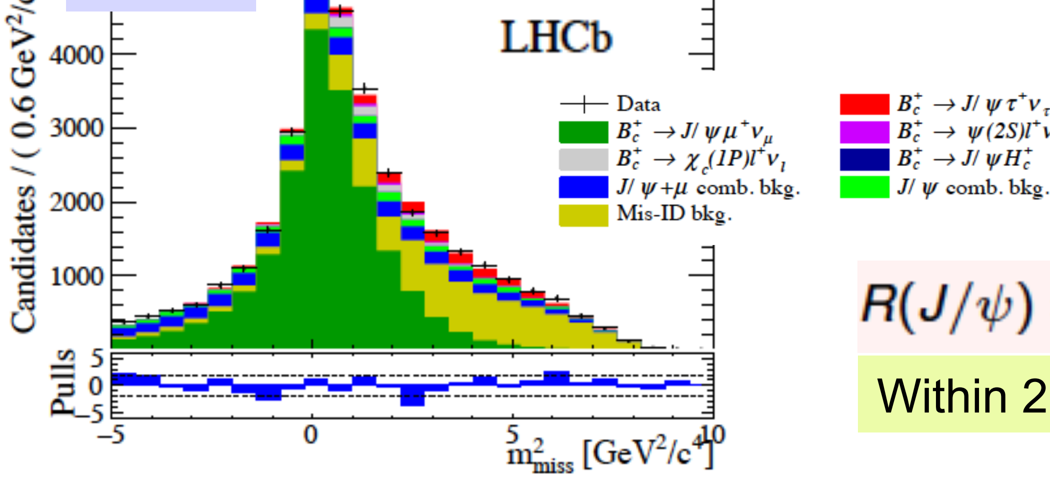


- **LHCb hadronic**

$R(D^*) = 0.285 \pm 0.019 \pm 0.025 \pm 0.013$

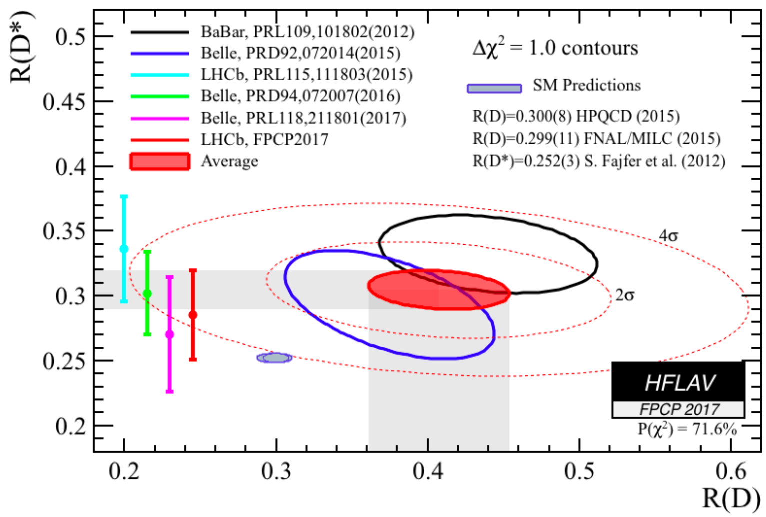
Within 1 σ of SM

2017

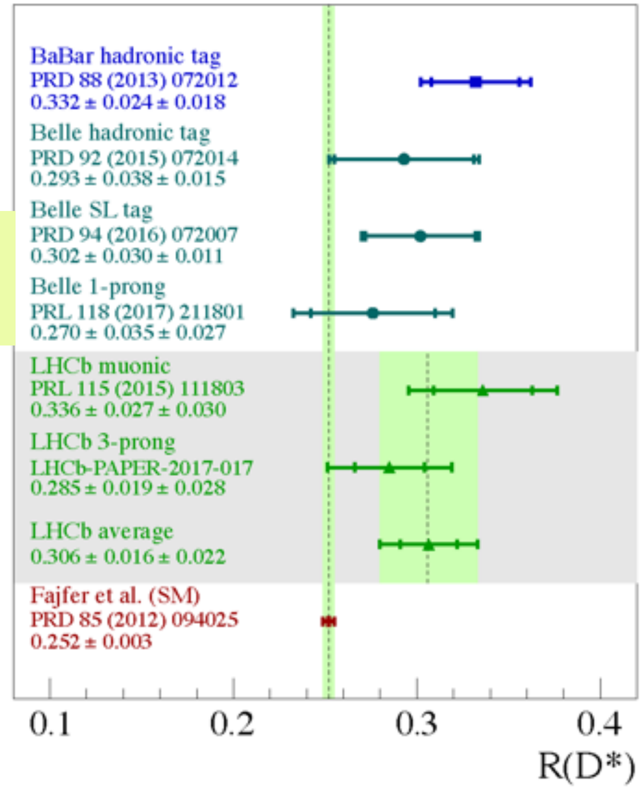


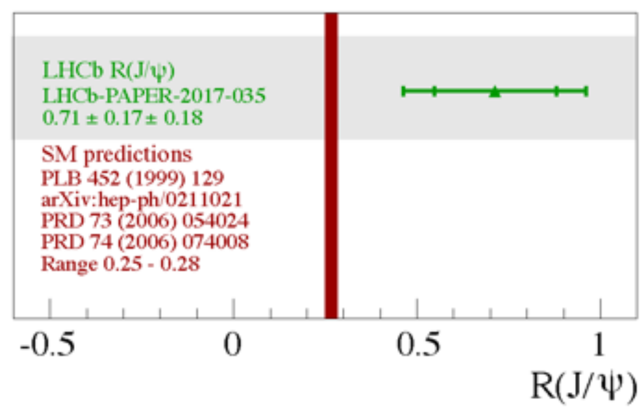
$R(J/\psi) = 0.71 \pm 0.17 \pm 0.18$

Within 2 σ of SM



4.1 σ tension with LFU/SM



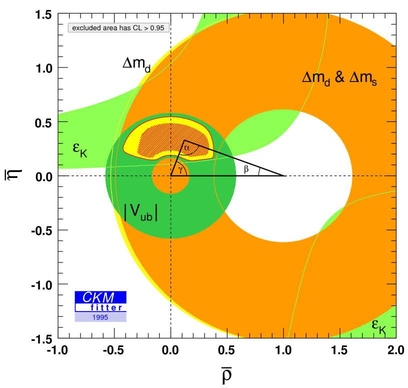


- Several Intriguing results: away from SM in the same direction.
- No single measurement is yet at or beyond 3 sigma away from SM
- Too early to consider LFU in serious trouble
- Several theoretical scenarios- e.g. models with leptoquarks- can accommodate the data.

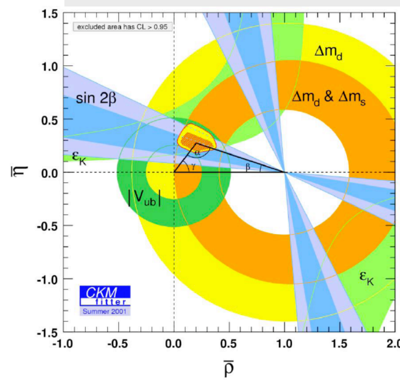
Future

Toward precision Flavor Physics
CKM and Rare Decays & much more

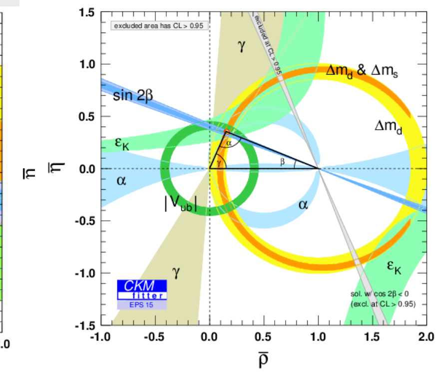
Last century



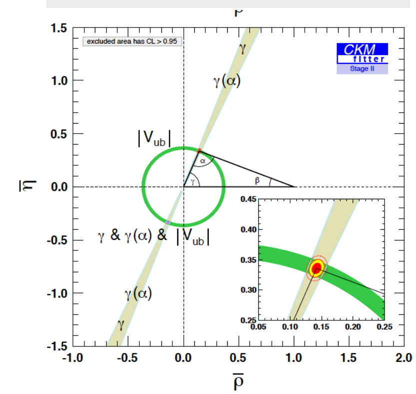
2001



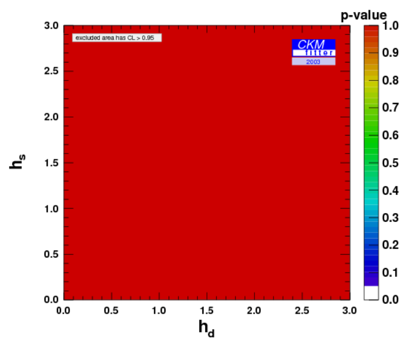
Today

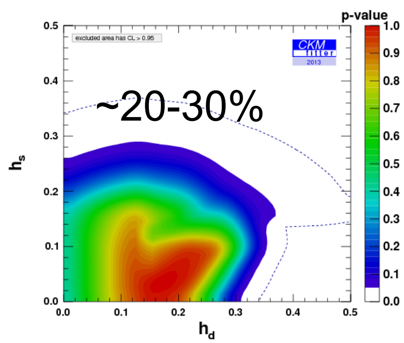


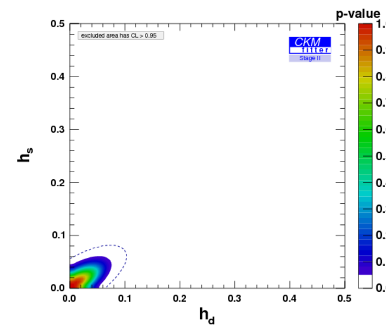
2025+



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







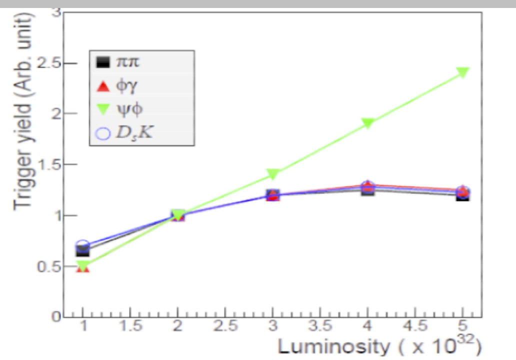
Upgrade-I: LHCb upgrade (Near Future)

- The upgrade is aimed at a data set of 50 fb^{-1}, with sensitivity to set strong constraints on NP & potential to reveal evidence for it.
  - The LHCb program has unique capability in the B^0_s sector, as well as the Bc & B-baryons, and extremely high statistical power in key exclusive & semi-inclusive B decays, and the charm system.
- The upgrade is designed to run at luminosity of (1-2)x10^{33} $cm^{-2}s^{-1}$.
  - $\mathcal{L}$x$t_{LHC\text{-}running}$ ~5fb^{-1}/year
  - All sub-detectors must be compatible with 2x10^{33} $cm^{-2}s^{-1}$.
    Major upgrade of the detector is required.

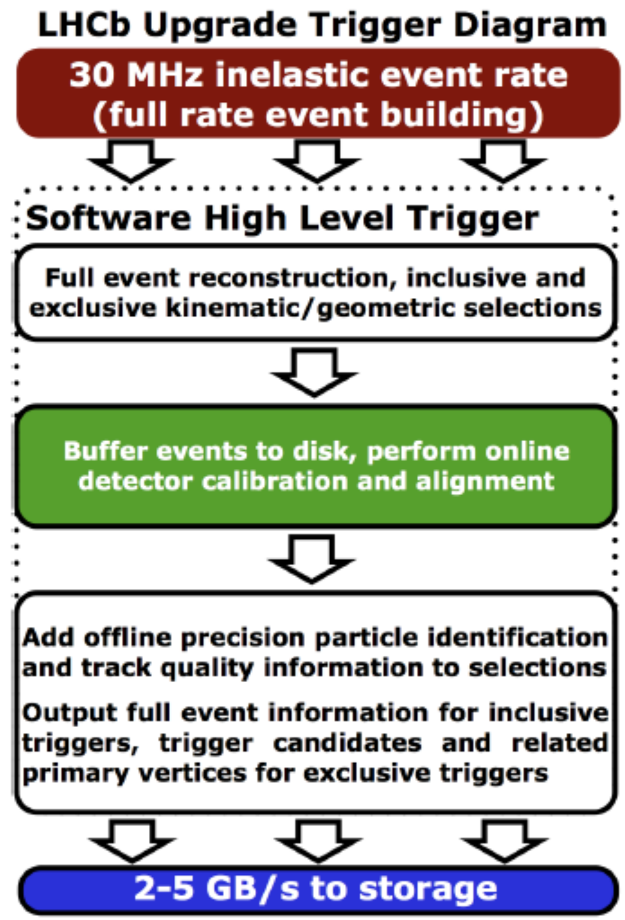
The LHCb upgrade: Trigger

High Luminosity running requires major change 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:

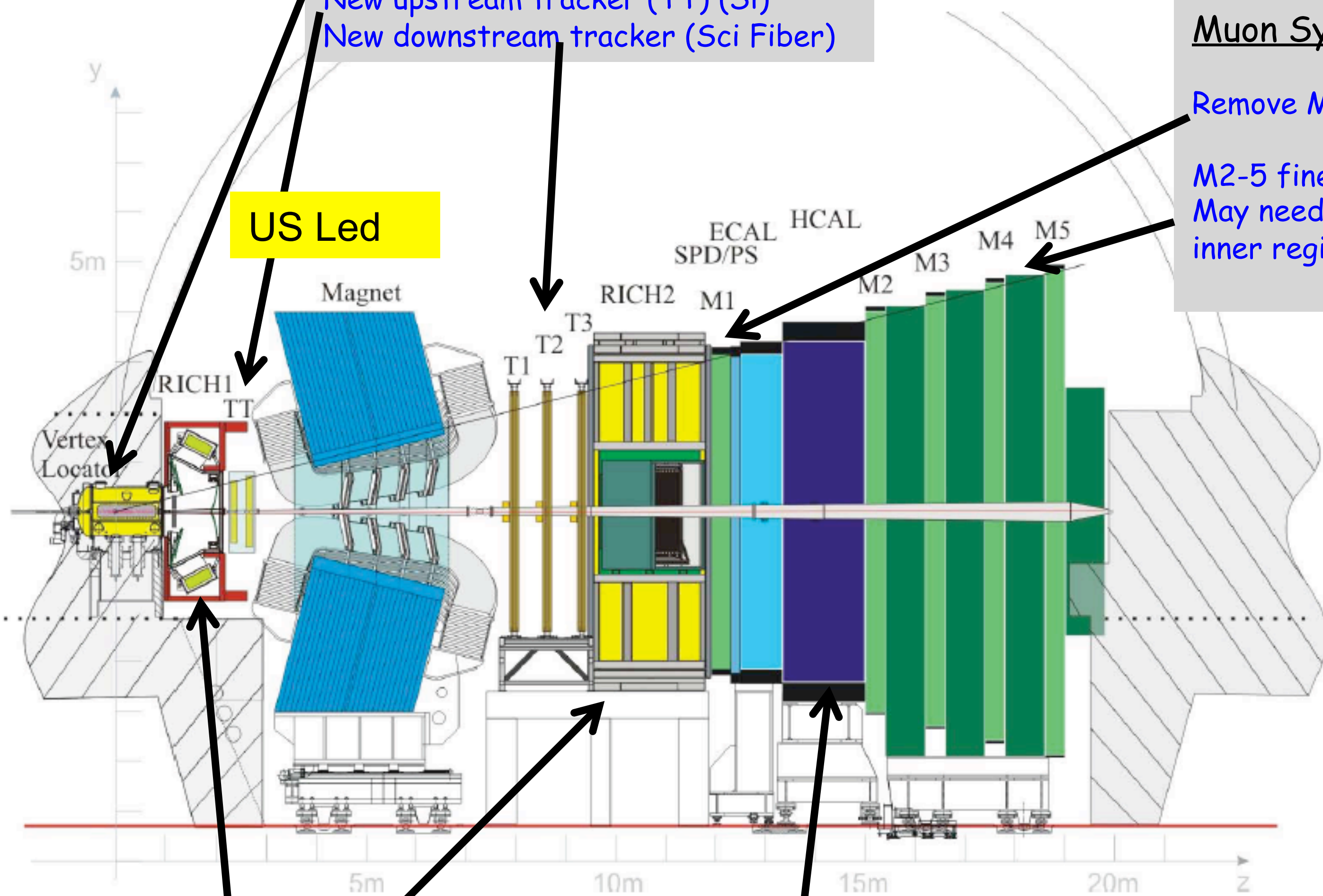
- Remove L0 (hardware) trigger
- Readout the detector at the 40 MHz LHC clock rate
- Move to a fully flexible software trigger

→ 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

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}

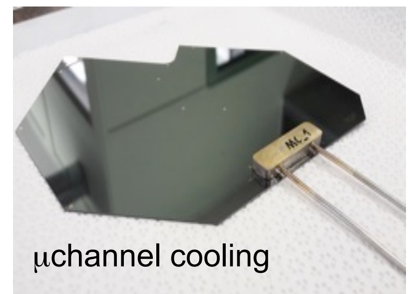
RICH 1 & RICH 2
- HPD→ MaPMT
- New 40 MHz R/O
- RICH1: new optics
  remove aerogel

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

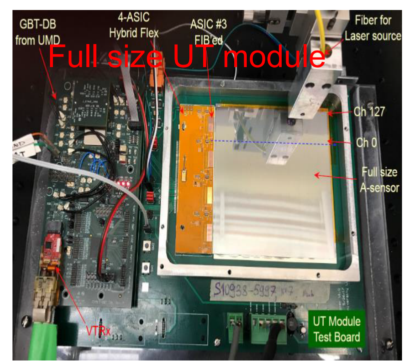
Upgrade Status

- The upgrade program is on track. All sub-detectors are in production phase. But the schedule is tight & some elements on critical path:
  - Downstream tracker: Scintillating Fibers (SciFi) modules in production : 20 modules already at CERN

  - Vertex Locator and Upstream tracks (UT): R&D on sensors, cooling and other elements finalized. Moving to production.

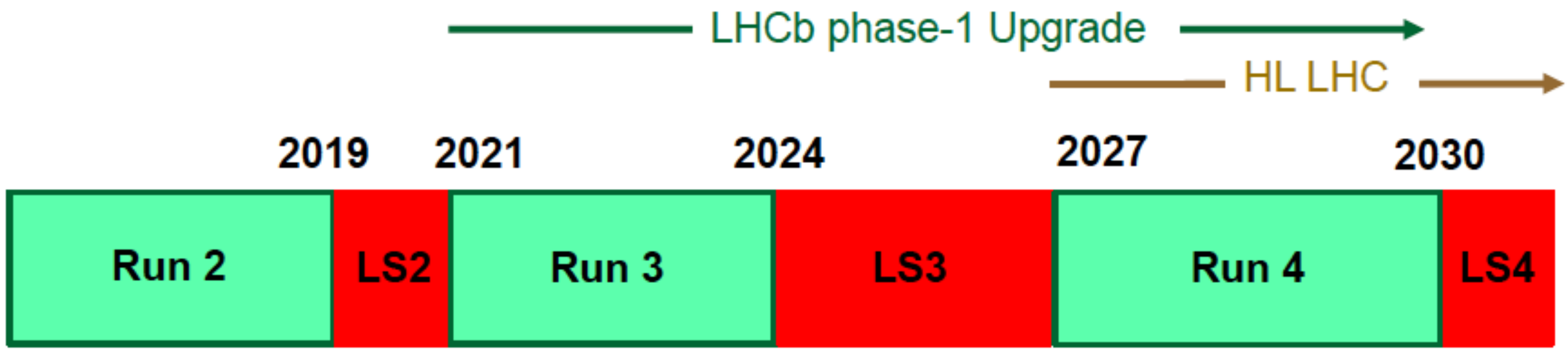


  - Electronics:
    - SciFi front-end, ASIC PACIFICv5, successfully produced and tested
    - FE ASICS for VELO and UT: VELOPIX and SALT are in final stages- latest submissions being evaluated



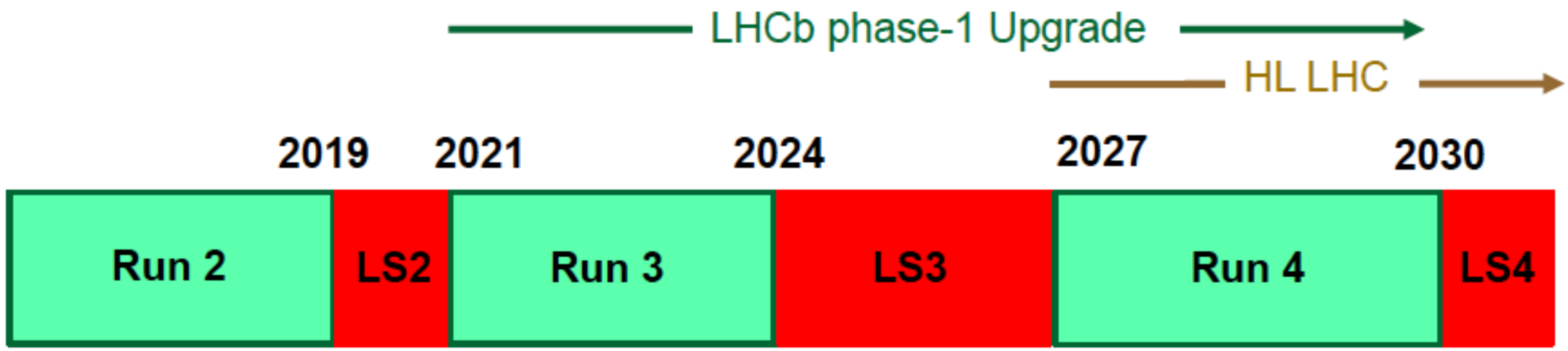
  - RICH Upgrade – HPD→ MaPMT & new optics progressing well and on schedule.

Further in Future: Upgrade-II



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

Further in Future: Upgrade-II



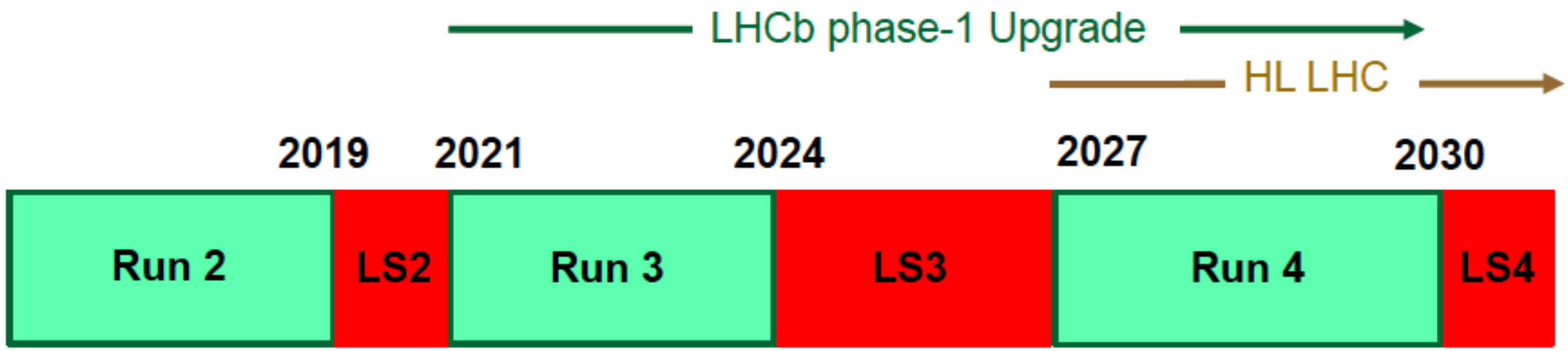
Expression-of-Interest submitted for LHCb Upgrade-II

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

- Current studies indicate $2\text{x}10^{34}$ 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 & Calorimertry (with fine granularity- e.g. SiW)

Further in Future: Upgrade-II



Expression-of-Interest submitted for LHCb Upgrade-II

- A comprehensive measurement programme of observables in a wide range of $b \to s l^+ l^-$ and $b \to d l^+ l^-$ 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 $R \equiv \mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B^0_s \to \mu^+\mu^-)$ with an uncertainty of 20%, and the first precise measurements of associated $B^0_s \to \mu^+\mu^-$ observables;
- A wide-ranging set of lepton-universality tests in $b \to c l^- \bar{\nu}_l$ decays, exploiting the full range of b-hadrons;
- CP-violation studies in charm with 10^{-5} precision.

Summary

- Flavor physics remains one of the primary drivers of the search for New Physics beyond SM, complementing the direct searches.
  - 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 under examination.

- LHCb has been smoothly operating during Run 2- tripled the available statistics of the b-hadron sample & more to come.
  - The current physics output has already left a major mark on the search for New Physics through precise CKM measurements and rare flavor processes. And many new states (in SM) found.
  - Development of the LHCb upgrade-I is progressing well. All elements are in production phase now.
  - EOI submitted for Upgrade-II, aimed at a dataset of ~300 fb^{-1}