MANCHESTER 1824

The University of Manchester

LHCb

LHCb highlights

Silvia Borghi

On behalf of the LHCb Collaboration

ICHEP 2020 | PRAGUE

40th INTERNATIONAL CONFERENCE ON HIGH ENERGY PHYSICS

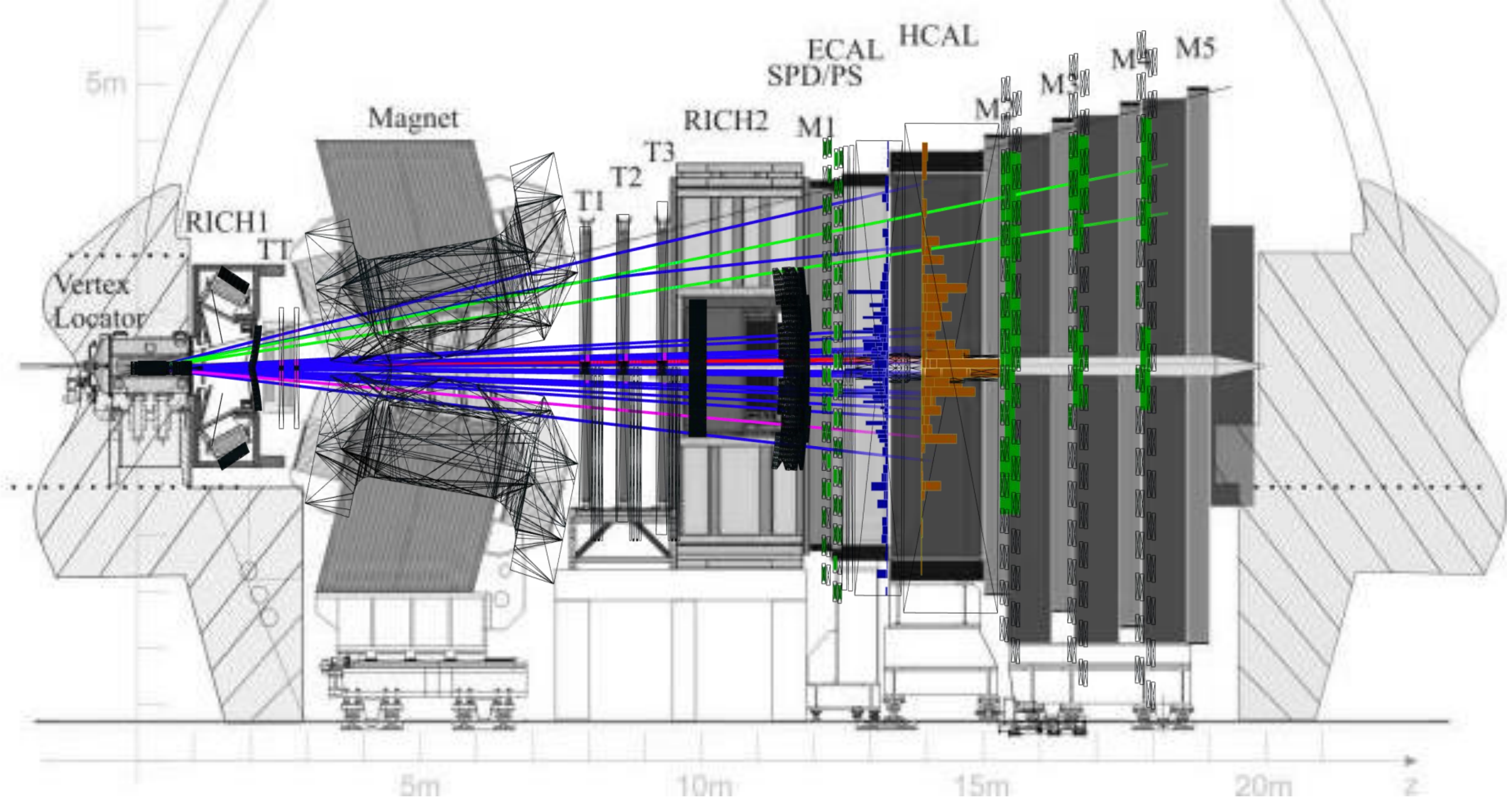
VIRTUAL CONFERENCE

28 JULY - 6 AUGUST 2020

PRAGUE, CZECH REPUBLIC

Detector and performance in Run 1 and Run 2

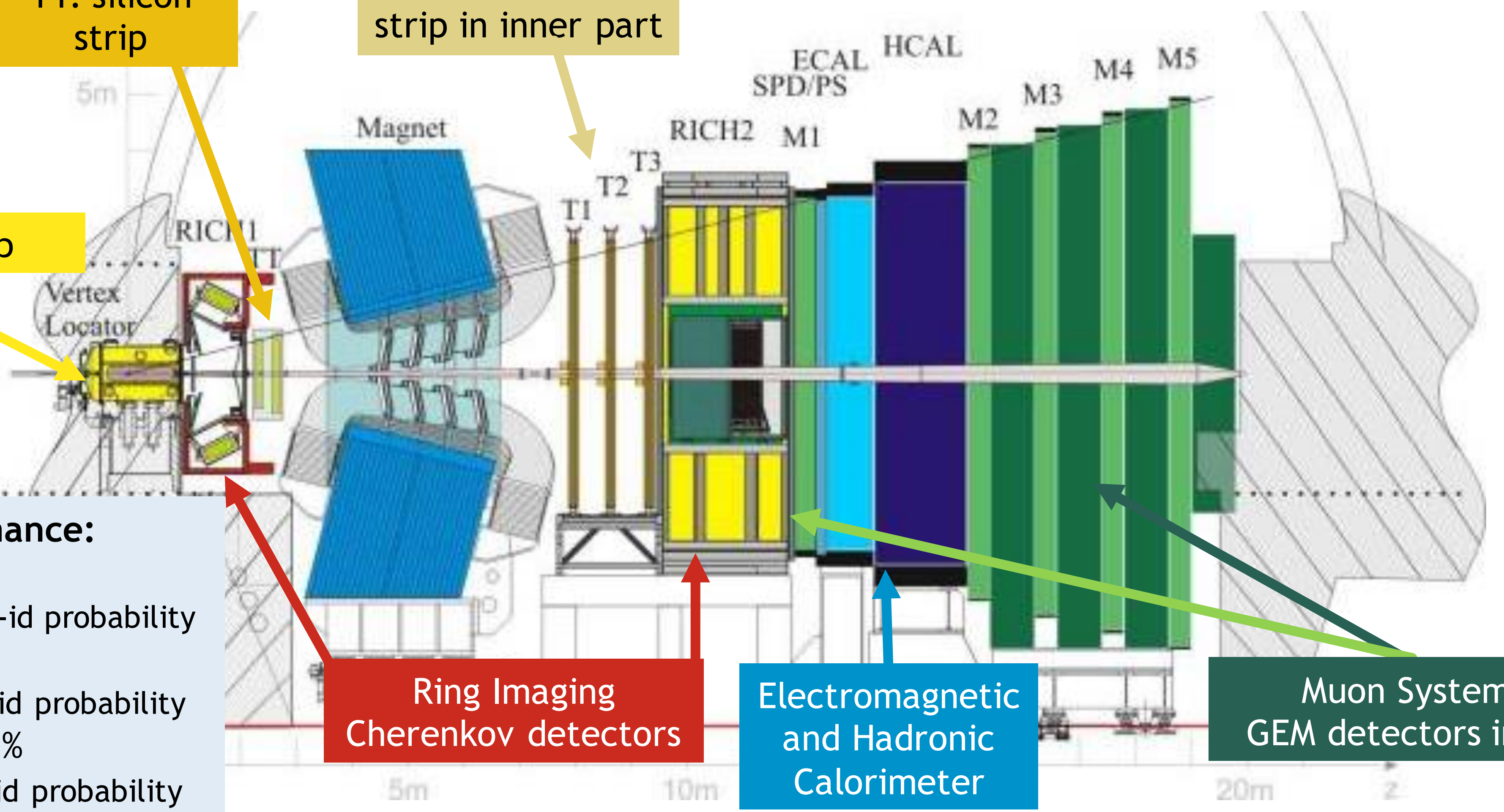
- Forward spectrometer with an acceptance 2<η<5
- Trigger: low level trigger and 2 stages of software trigger



JINST 14 (2019) P11023, JINST 14 (2019) P04013, Int. J. Mod. Phys. A 30 (2015) 1530022, JINST 3 (2008) S08005

Detector and performance in Run 1 and Run 2

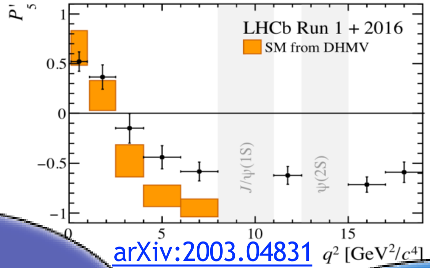
Tracking system performance:
- track reconstruction efficiency: ~ 96 %
- momentum resolution: $\Delta p/p$=0.5 %
- impact parameter resolution: (15 +29/p_T[GeV]) μm
- decay time resolution: ~45 fs for $B_s \rightarrow J/\psi\ \varphi$



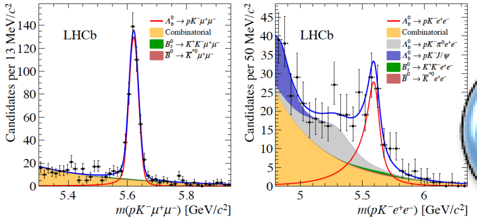
Particle ID performance:
- Muon ID ~ 97 %
  for 1-3 % π→μ mis-id probability
- Kaon ID ~ 95 %
  for ~ 5 % π→K mis-id probability
- Electron ID ~ 90 %
  for ~ 5 % e→h mis-id probability

Physics at LHCb

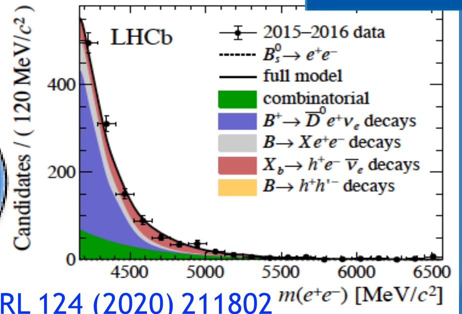
List of publications



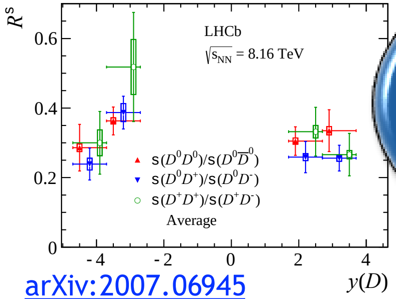
arXiv:2003.04831



JHEP 05 (2020) 040



PRL 124 (2020) 211802



arXiv:2007.06945

Lepton Universality

CPV and CKM

Rare decays

Heavy ions

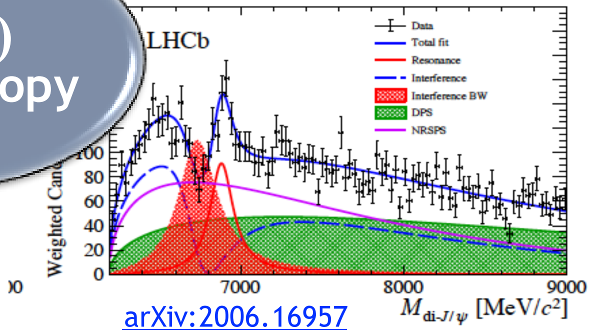
Physics results

(Exotic) Spectroscopy

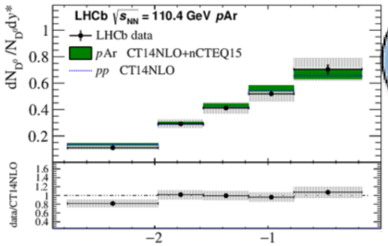
Fixed Target

Exotic searches

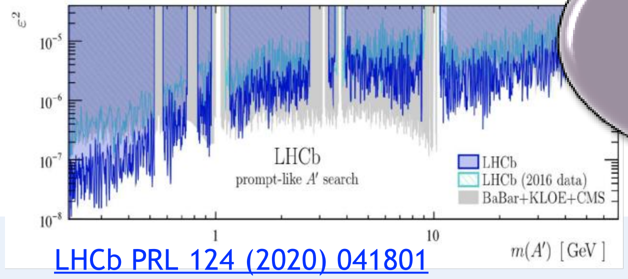
Electroweak and QCD



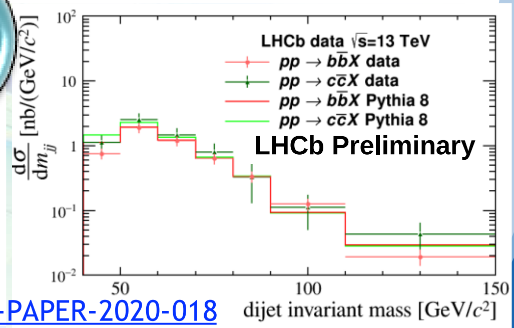
arXiv:2006.16957



PRL 122 (2019) 132002



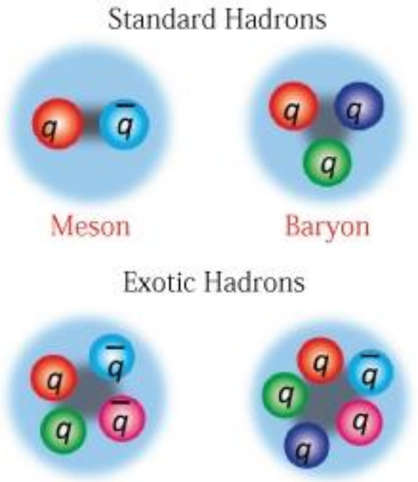
LHCb PRL 124 (2020) 041801



LHCB-PAPER-2020-018

Exotic Spectroscopy

Exotic spectroscopy



- Exotic states: beyond conventional mesons ($q\bar{q}$) and baryons (qqq)
  - Provide new insights into internal structure and dynamics of hadrons
  - A good platform to study non-perturbative behavior of QCD

$\chi_{c1}(3872)$

- the first observed charmonium-like exotic hadron (Belle 2003) with most abundant experimental information
- **Intriguing properties**, e.g. mass extremely close to $D^0\bar{D}^{*0}$ threshold
- **Nature still unclear**: conventional $\chi_{c1}(2^3P_1)$, $D^0\bar{D}^{*0}$ molecular state, tetraquark, $c\bar{c}g$ hybrid, vector glueball, or mixed?

Study of $\chi_{c1}(3872)$

arXiv: 2005.13419 arXiv: 2005.13422

- 2 independent measurements assuming Breit-Wigner lineshape

LHCb average

$m(\chi_{c1}(3872)) = 3871.64 \pm 0.06 \pm 0.01$ MeV/c^2

$\Gamma(\chi_{c1}(3872)) = 1.19 \pm 0.19$ MeV/c^2

$\delta E = m(\chi_{c1}(3872)) - m(D^0\bar{D}^{*0}) = 0.07 \pm 0.12$ MeV/c^2

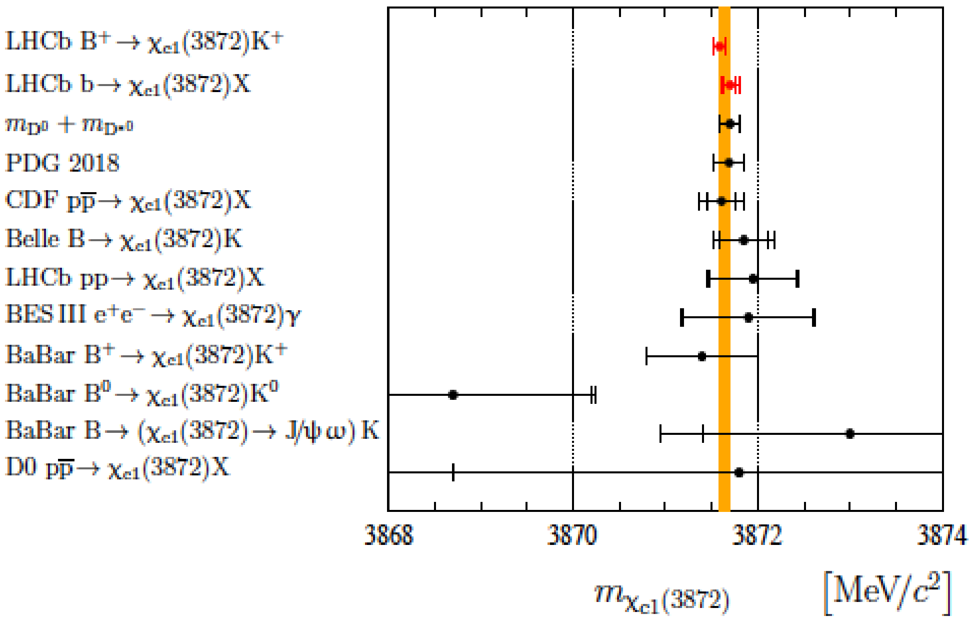
- **First width measurement** and most precise measurement of mass and δE
- Proximity to $D^0\bar{D}^{*0}$ threshold distorts the lineshape from a BW: alternative fit using a Flatté parametrization [PRD 76 (2007) 034007, PRD 80 (2009) 074004]

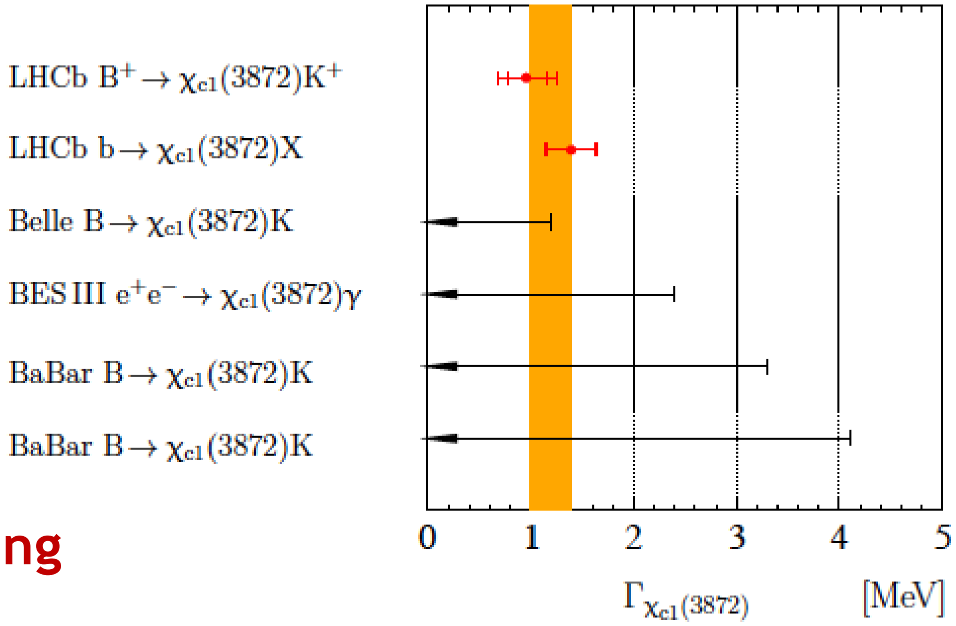
Mean: $3871.69^{+0.00+0.05}_{-0.04-0.13}$ MeV$/c^2$; FWHM: $0.22^{+0.06+0.25}_{-0.08-0.17}$ MeV$/c^2$

$\Rightarrow$ **Need physically well-motivated lineshape parametrization**

- Study about its nature
  - Consistent with **$D^0\bar{D}^{*0}$ quasi-bound state** with E_b<100 keV at 90% C.L.
  - Quasi-virtual state cannot be excluded

Need additional measurements to increase our understanding

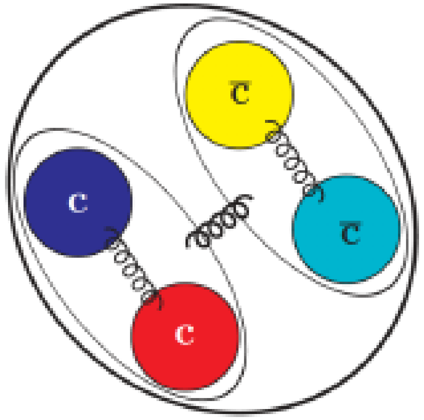




Observation of structure in the J/ψ -pair mass spectrum

- Existence of $T_{QQ\bar{Q}\bar{Q}}$ states (Q= c or b) is expected by many QCD models
  - No observed exotic states with more than 2 heavy quarks

- The four charm-state, $T_{cc\bar{c}\bar{c}}$
  - predicted to have a mass between 5.8 and 7.4 GeV/c^2
  - can decay into a pair of charmonia => search in J/ψ pair mass spectrum



- J/ψ pair production
  - single parton scattering process includes resonant production via intermediate states, e.g. $T_{cc\bar{c}\bar{c}}$
  - Double parton scattering process: two J/ψ produced independently

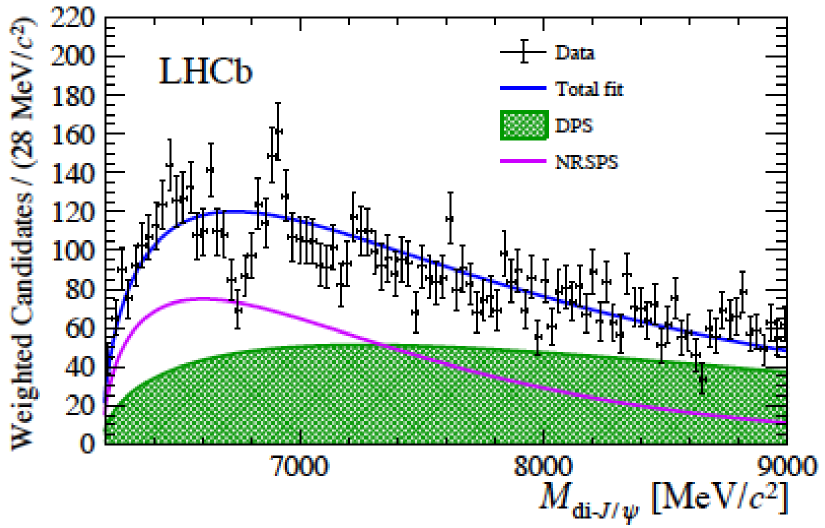
arXiv:2006.16957

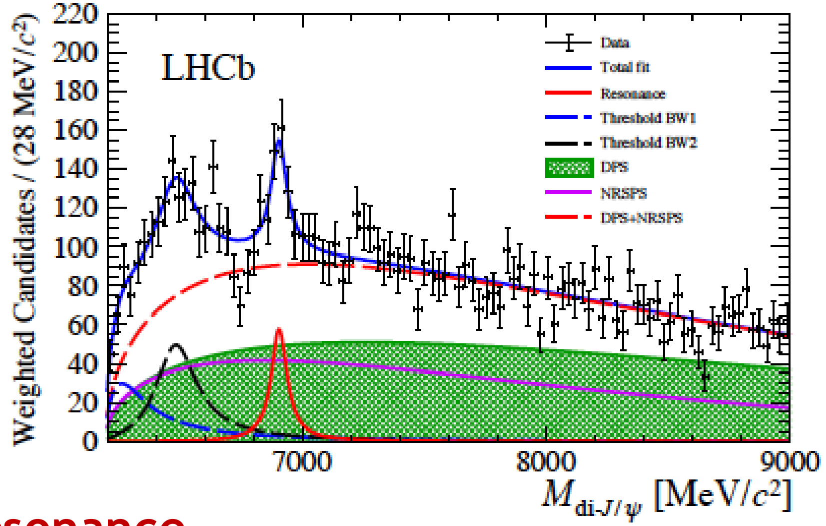
Observation of structure in the J/ψ -pair mass spectrum

- A narrow peaking structure at ~6.9 GeV/c^2 matching the lineshape of a resonance
- A broader structure close to threshold
- **Inconsistent** in the 6.2-7.4 GeV/c^2 mass region with **non-resonant SPS + DPS only** hypothesis **by >5 σ**
- The structure at 6.9 GeV/c^2 **consistent with $T_{cc\bar{c}\bar{c}}$** predicted in various tetraquark models.
- Describing the X(6900) structure with a Breit-Wigner lineshape

$$m[X(6900)] = 6905 \pm 11 \pm 7\,\mathrm{MeV}/c^2$$
$$\Gamma[X(6900)] = 80 \pm 19 \pm 33\,\mathrm{MeV},$$

- Other models considered and confirmed the resonance





More data needed to gain more insight into the observed resonance

Measurement of the CKM angle γ

Measurement of the CKM angle γ

LHCb-CONF-2020-001

NEW

- Sensitivity to γ from b→u and b→c interference

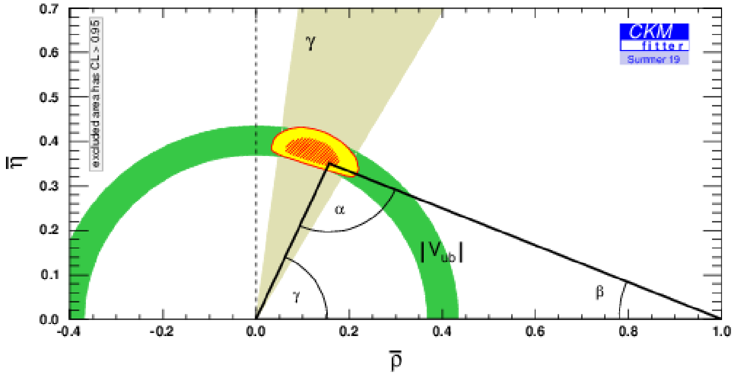
The case of the CKM angle γ (= ϕ_3) [CKMFitter] $\gamma_{\text{direct}} = 72.1^{+5.4°}_{-5.7}$ $\stackrel{?}{=}$ $\gamma_{\text{indirect}} = 65.66^{+0.90°}_{-2.65}$

- Measurement CPV observables in the decays channels $B^\pm \to D^0 K^\pm$ and $B^\pm \to D^0 \pi^\pm$ (with $D^0 \to K^0_s \pi^+ \pi^-$ or $D^0 \to K^0_s K^+ K^-$) using the model-independent approach

$$N^-_{\mp i} \propto F_{\pm i} + (x^2_- + y^2_-) F_{\mp i} + 2\sqrt{F_i F_{-i}}(x_- c_{\pm i} + y_- s_{\pm i})$$

$$r_B \exp[i(\delta_B \pm \gamma)] = x_\pm + i y_\pm$$

Constraints from "tree-level" observables



- Update using the full statistics: $\mathcal{L}$ =9 fb^{-1}
- **Systematic** uncertainties significantly **reduced** due to new control and **updated strong-phase inputs from BESIII** [arXiv:2003.00091]
- This measurements is **consistent with indirect measurements**
- This is the best stand-alone measurement of γ to date

Results in terms of γ and CP conserving phase difference

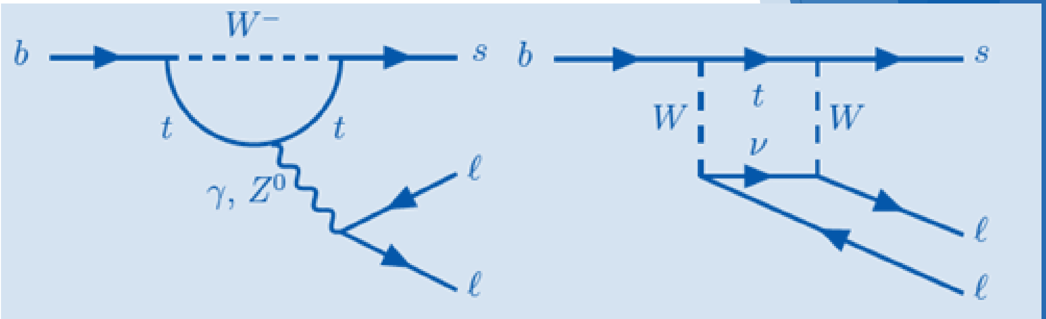
Preliminary

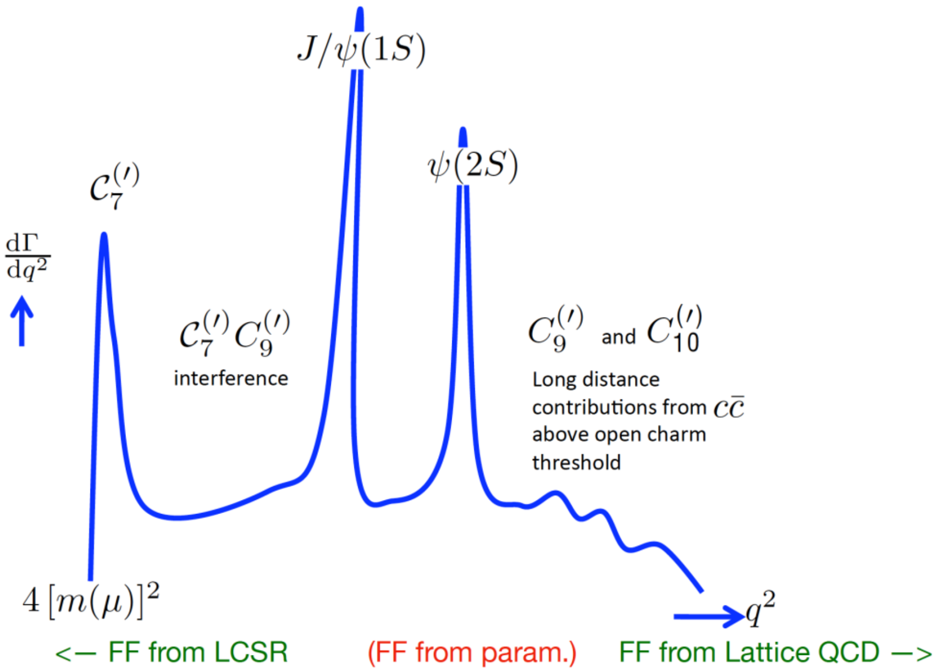
$$\gamma = (69 \pm 5)^\circ$$
$$\delta_B^{DK} = (118 \pm 6)^\circ$$

Anomalies
in Electroweak Penguin Decays

Anomalies in $b \to s\ell^+\ell^-$ transitions

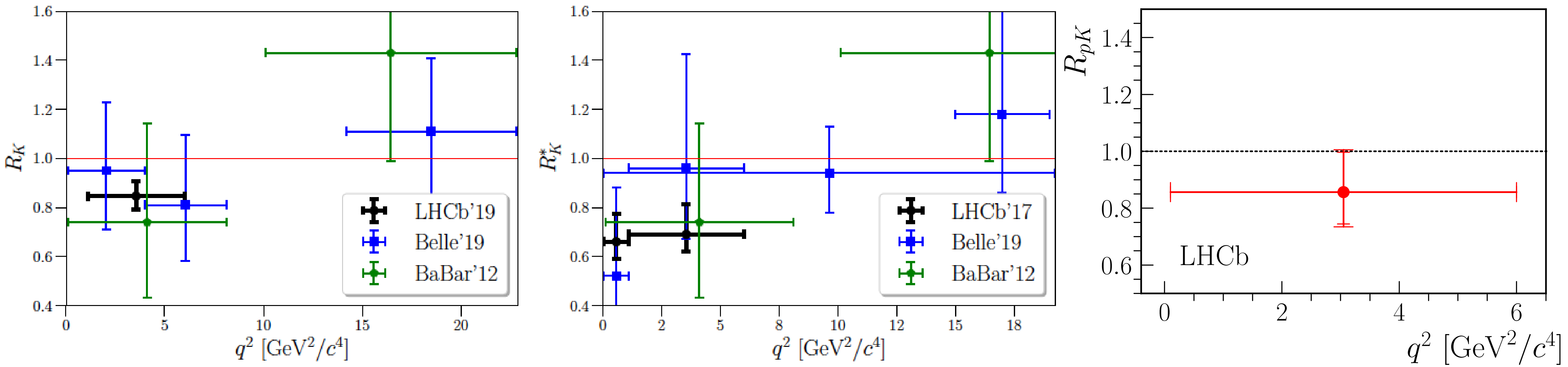
- FCNC forbidden at tree-level in the SM
- Sensitive to NP in loops:
  - modifying the decay rate
  - changes the angular distribution of final state particles
- **Anomalies observed** in different measurements
  - **Decay rates** are consistently **lower than SM** in $b \to s\mu^+\mu^-$ decays:
    - $B^+ \to K^+\mu^+\mu^-$, $B^0 \to K^0\mu^+\mu^-$ and $B^+ \to K^{*+}\mu^+\mu^-$ JHEP 06 (2014) 133
    - $B^0 \to \phi\mu^+\mu^-$: JHEP 09 (2015) 179
    - $\Lambda_b \to \Lambda\mu^+\mu^-$: JHEP 06 (2015) 115
    - $B^0 \to K^{*0}\mu^+\mu^-$: JHEP 11 (2016) 047
  - Ratio of decay rate to different lepton flavours:
    - R_{K^*}: JHEP 1708 (2017) 055 ;
    - R_K: PRL 122 (2019) 191801;
    - R_{pk}: JHEP 05 (2020) 040
  - Angular observables as function of q^2
    - JHEP 02 (2016) 104,
    - PRL125(2020) 011802





Lepton universality

- Measurement of the ratio of the decay rates $R_{H_s} = \frac{\int_{q^2_{min}}^{q^2_{max}} \frac{d\Gamma(H_b \to H_s \mu^+\mu^-)}{dq^2} dq^2}{\int_{q^2_{min}}^{q^2_{max}} \frac{d\Gamma(H_b \to H_s e^+e^-)}{dq^2} dq^2}$
- Evaluation of the double ratio to suppress detector effects
- $R_K(B^+ \to K^- \ell^+ \ell^-)$ and $R_{K^*}(B^0 \to K^* \ell^+ \ell^-)$ compatible at **2-2.5 σ with the SM**
- R_{pK} for $\Lambda^0_b \to pK^- \ell^+ \ell^-$ is the **first test of LU with b baryons**



$$R_K = 0.846 \,^{+0.060}_{-0.054} \,^{+0.016}_{-0.014}$$

$$R_{K^{*0}} = \begin{cases} 0.66 \,^{+\,0.11}_{-\,0.07} \pm 0.03 \text{ for } 0.045 < q^2 < 1.1 \text{ GeV}^2/c^4 \\ 0.69 \,^{+\,0.11}_{-\,0.07} \pm 0.05 \text{ for } 1.1 < q^2 < 6.0 \text{ GeV}^2/c^4 \end{cases}$$

$$R_{pK} = 0.86 \,^{+0.14}_{-0.11} \pm 0.05$$

LHCb [JHEP 08 (2017) 055] [PRL 122 (2019) 191801]; BaBar [PRD86 (2012) 032012]
Belle [arXiv:1904.02440] [arXiv:1908.01848],

JHEP 05 (2020) 040

$B^0 \to K^{*0}\mu^+\mu^-$ angular analysis

Phys. Rev. Lett. 125, 011802 (2020)

- Study the differential decay rate described by q^2 and 3 decay angles to evaluate:
  - S_i are the CP-averaged observables
  - A_{FB} is the forward backward asymmetry of the dimuon system
  - F_L is the fraction of longitudinal polarisation of the K^{*0}
- P_i parameters optimized to reduce the theory uncertainties [JHEP 05 (2013) 137]

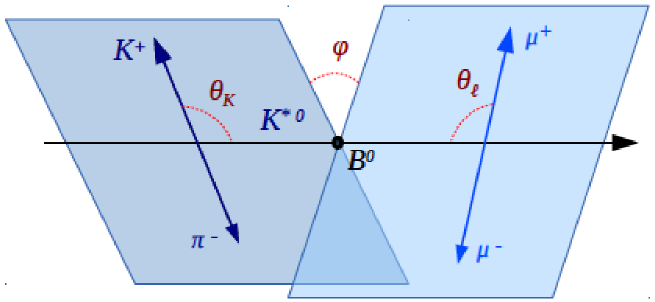
$$\rightarrow P'_5 = \frac{S_5}{\sqrt{F_L(1-F_L)}}$$

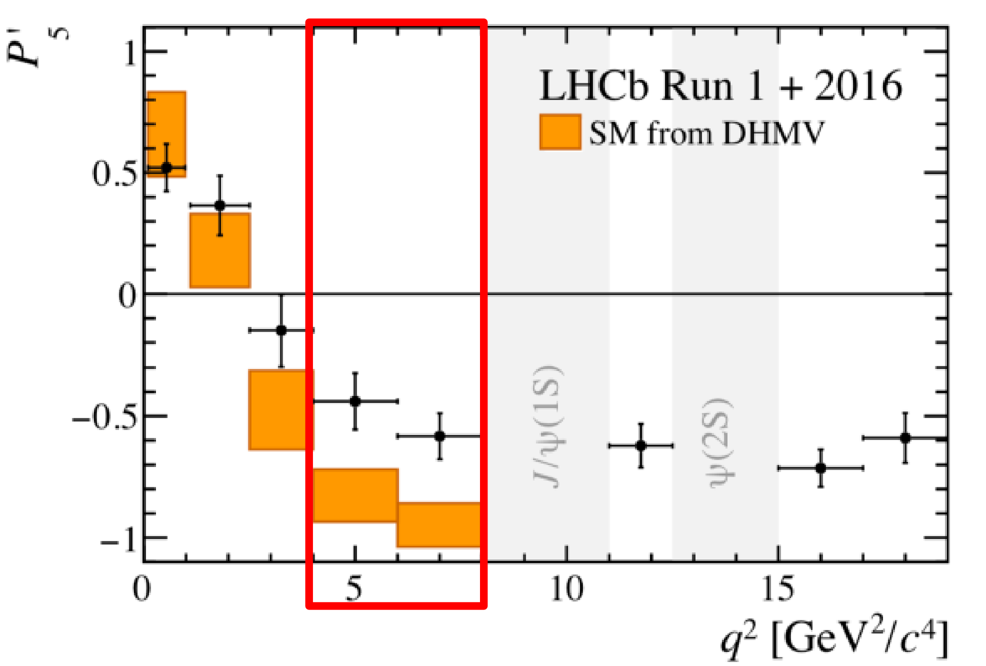
- Update of previous measurement [JHEP 02 (2016) 104]
- Observables consistent with SM, largest tension from S_5
- P'_5 has a local **discrepancy** in two bins

$4.0 < q^2 < 6.0$ GeV^2/c^4 : Run1 + 2016: 2.5 σ

$6.0 < q^2 < 8.0$ GeV^2/c^4: Run1 + 2016: 2.9 σ

→ Local tension in P'_5 still present





DHMV: [JHEP 12 (2014) 125], [JHEP 09 (2010) 089]

$B^0 \to K^{*0}\mu^+\mu^-$ angular analysis

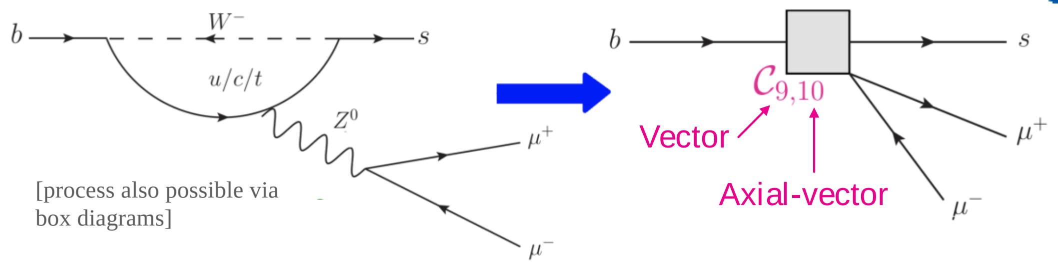
[Phys. Rev. Lett. 125, 011802 (2020)](https://doi.org/10.1103/PhysRevLett.125.011802)

- Effective theory

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* \frac{e^2}{16\pi^2} \sum_i \mathcal{C}_i \mathcal{O}_i$$

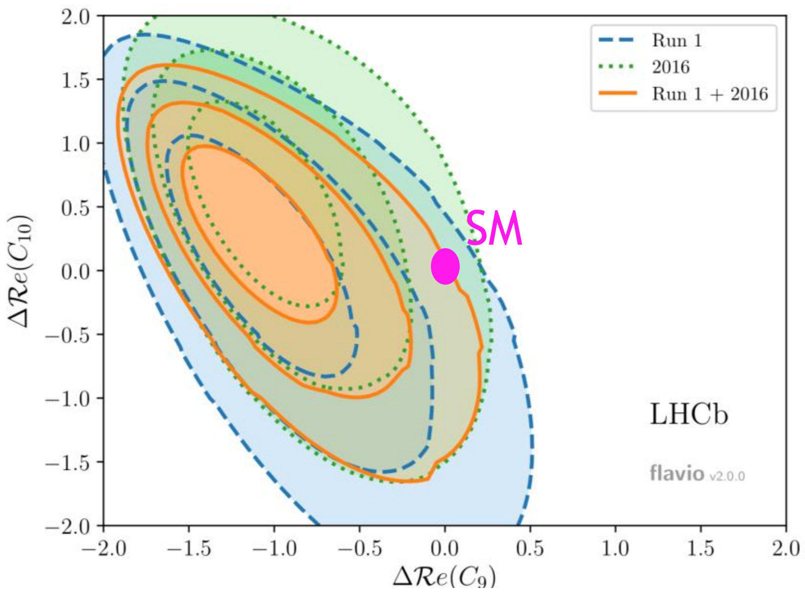
Local operator → $\mathcal{O}_i$

Wilson coefficient ("effective coupling") → $\mathcal{C}_i$

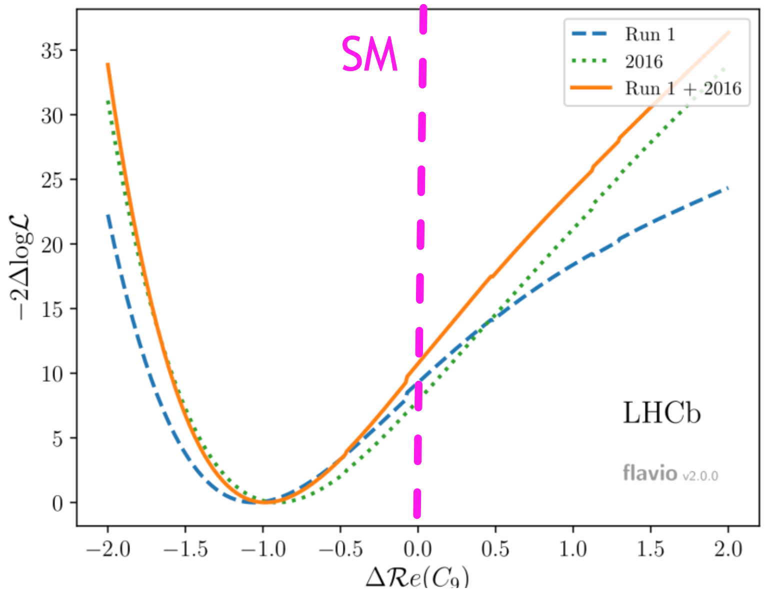


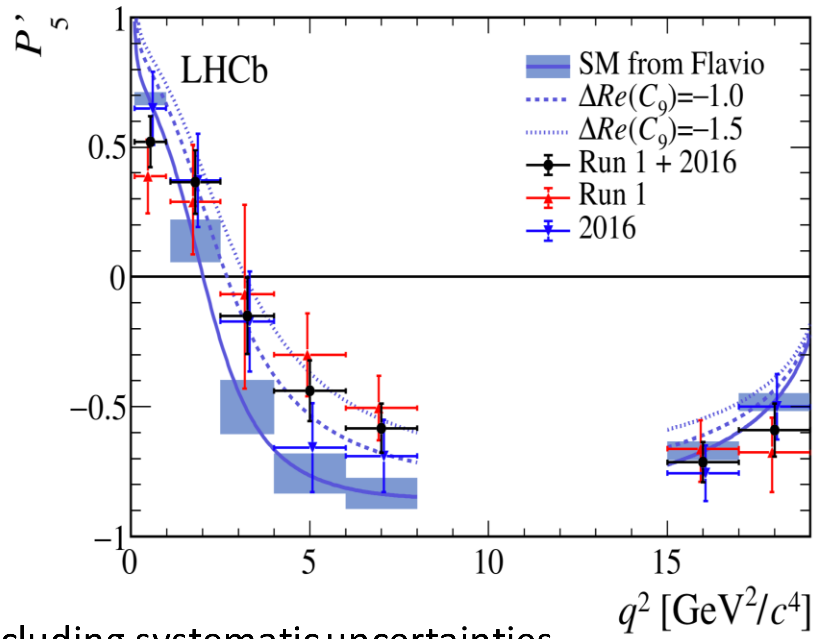
varying only Re(C_9) and Re(C_{10}):
2.8 σ from SM

flavio: [arXiv:1810.08132](https://arxiv.org/abs/1810.08132)



varying only Re(C_9):
3.3 σ from SM

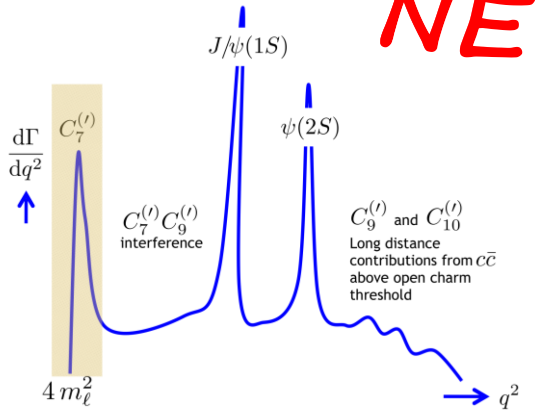




2016 data set is shown for illustrative purposes: not coverage- and bias-corrected, and not including systematic uncertainties.

Rare decays

$B^0 \to K^{*0} e^+ e^-$ angular analysis



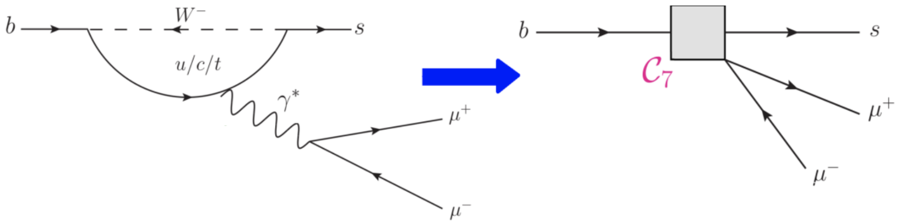
- Photon polarisation predominately left handed in the SM
- BSM in the loop can contribute a right-handed current
- $B^0 \to K^{*0} e^+ e^-$ decay dominated by $b \to s\gamma$ at very-low q^2
- Extract photon polarization by angular analysis at very-low q^2

Sensitivity to γ polarisation:

$$A_T^{(2)}(q^2 \to 0) = \frac{2\mathcal{R}e\left(\mathcal{C}_7 \mathcal{C}_7'^*\right)}{|\mathcal{C}_7|^2 + |\mathcal{C}_7'|^2}$$

$$A_T^{Im}(q^2 \to 0) = \frac{2\mathcal{I}m\left(\mathcal{C}_7 \mathcal{C}_7'^*\right)}{|\mathcal{C}_7|^2 + |\mathcal{C}_7'|^2}$$

They vanish for purely left-handed polarisation

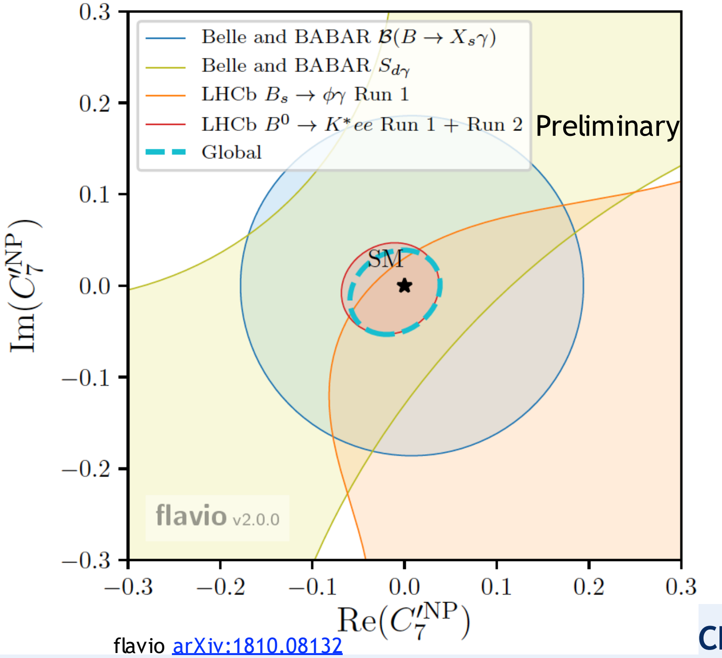


- Update of Run 1 analysis [JHEP 04 (2015) 064]
- Results $(0.0008 < q^2 < 0.257 \text{ GeV}^2/c^4)$

Preliminary

$$A_T^{(2)} = +0.106 \pm 0.103^{+0.016}_{-0.017}$$
$$A_T^{Im} = +0.015 \pm 0.102 \pm 0.012,$$

- **Consistent at 0.3σ with SM predictions**
- Statistically limited measurements



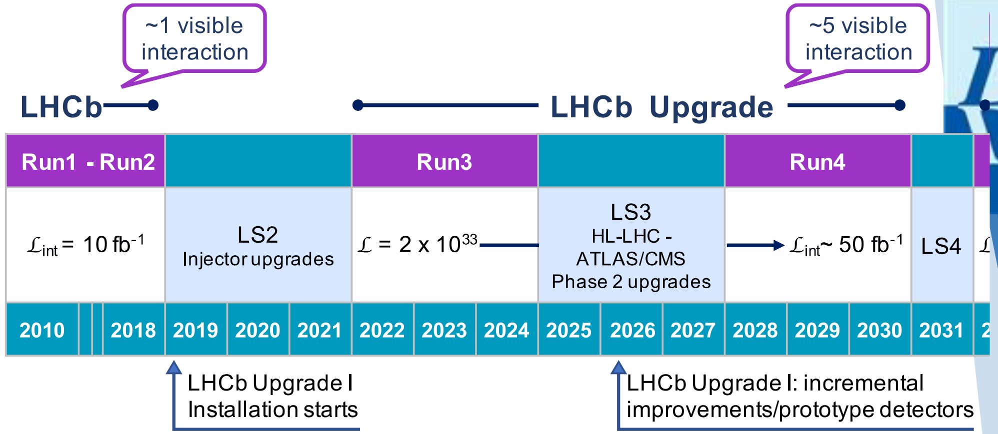
flavio arXiv:1810.08132

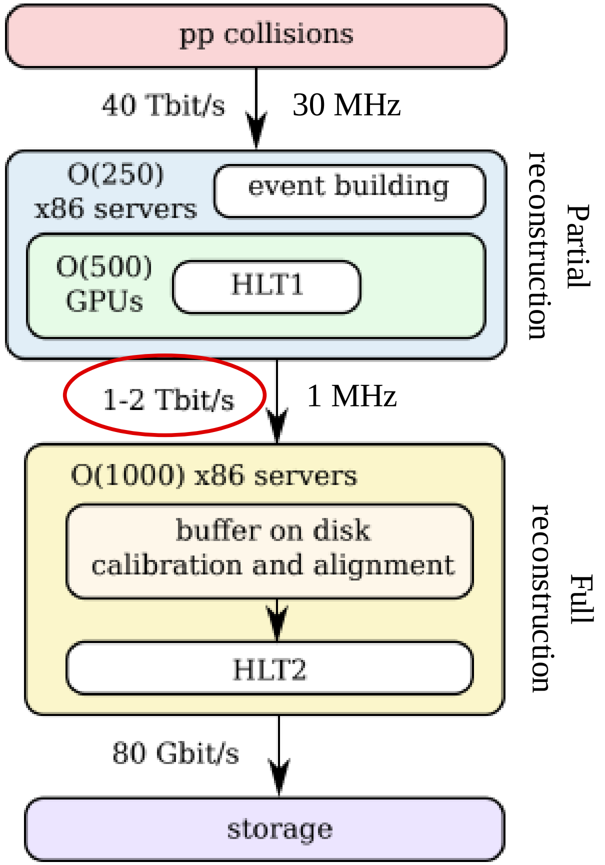
Dominating the sensitivity to right-handed coupling C′$_7$

Upgrade

Upgrade for Run 3 data taking

- Run at 2×10^{33} cm^{-1} s^{-1} with ~5 visible interaction
- Expected to collect about 50 fb^{-1} in Run3 and Run 4
- 40 MHz readout of all sub-detectors
- **Major upgrade of the detector**:
  - New flexible fully-software trigger
    - Hybrid trigger technology: GPU in the first high level trigger stage (HLT1) and CPU in second high level trigger stage (HLT2)
  - Real-time alignment and calibration before HL2
  - Run the full reconstruction in HLT2
  - New tracking system
  - Upgrade of PID subdetectors
  - Significant progress made by all sub-detectors

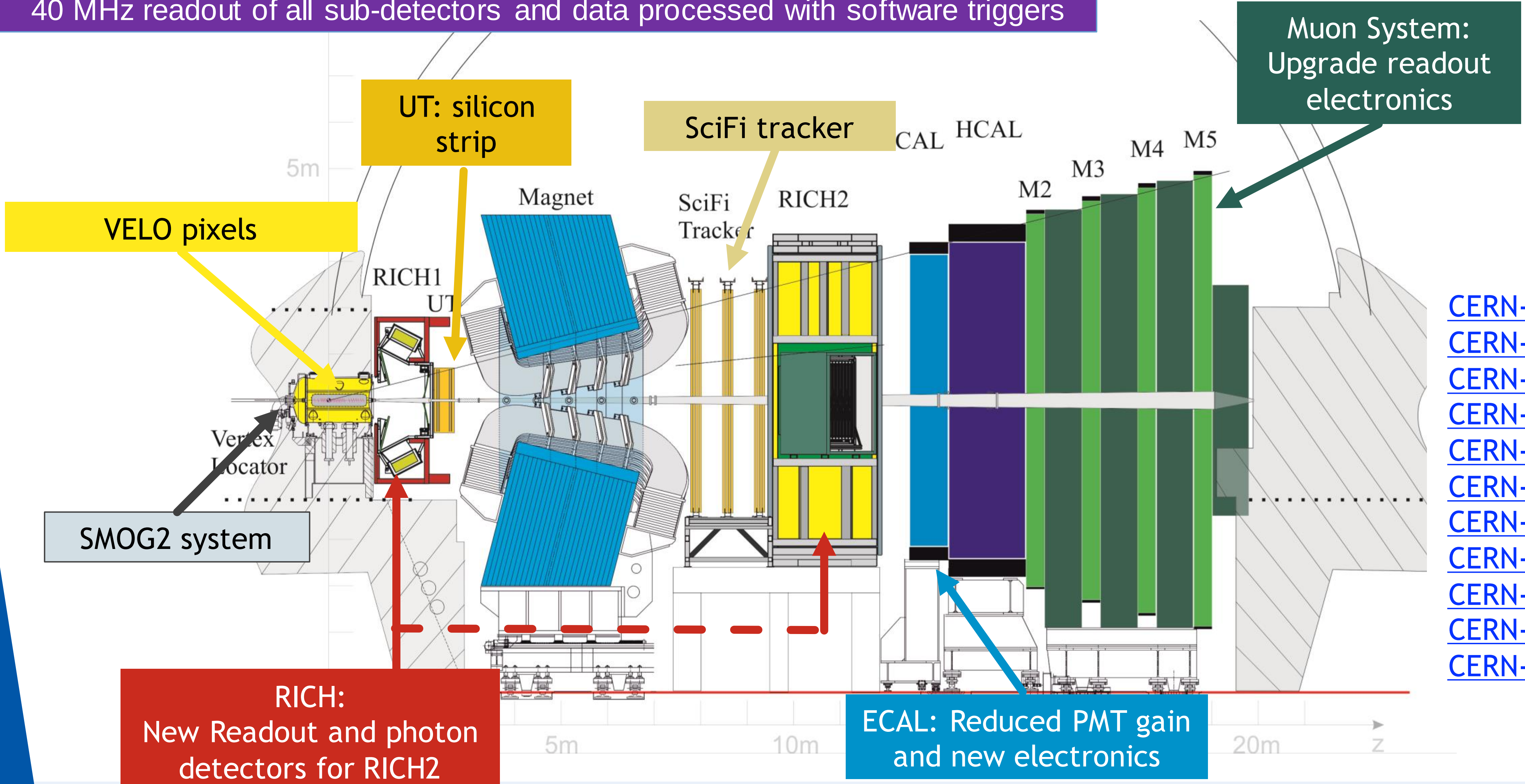




Comput. Softw. Big Sci. (2020) 4, 7
CERN-LHCC-2020-006

Upgrade

40 MHz readout of all sub-detectors and data processed with software triggers



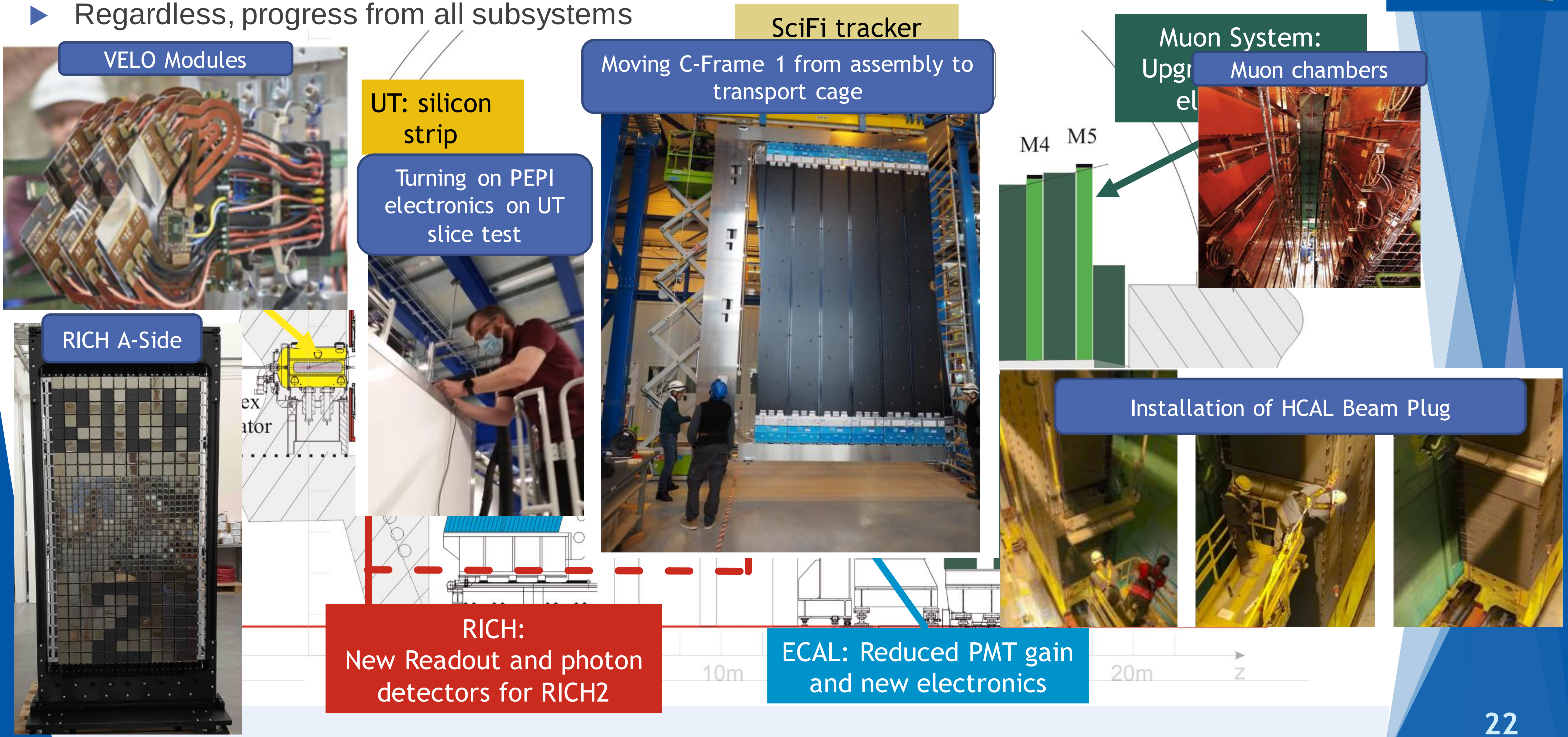
TDR

- [CERN-LHCC-2008-007]()
- [CERN-LHCC-2011-001]()
- [CERN-LHCC-2012-007]()
- [CERN-LHCC-2013-021]()
- [CERN-LHCC-2013-022]()
- [CERN-LHCC-2014-001]()
- [CERN-LHCC-2014-016]()
- [CERN-LHCC-2018-007]()
- [CERN-LHCC-2018-014]()
- [CERN-LHCC-2019-005]()
- [CERN-LHCC-2020-006]()

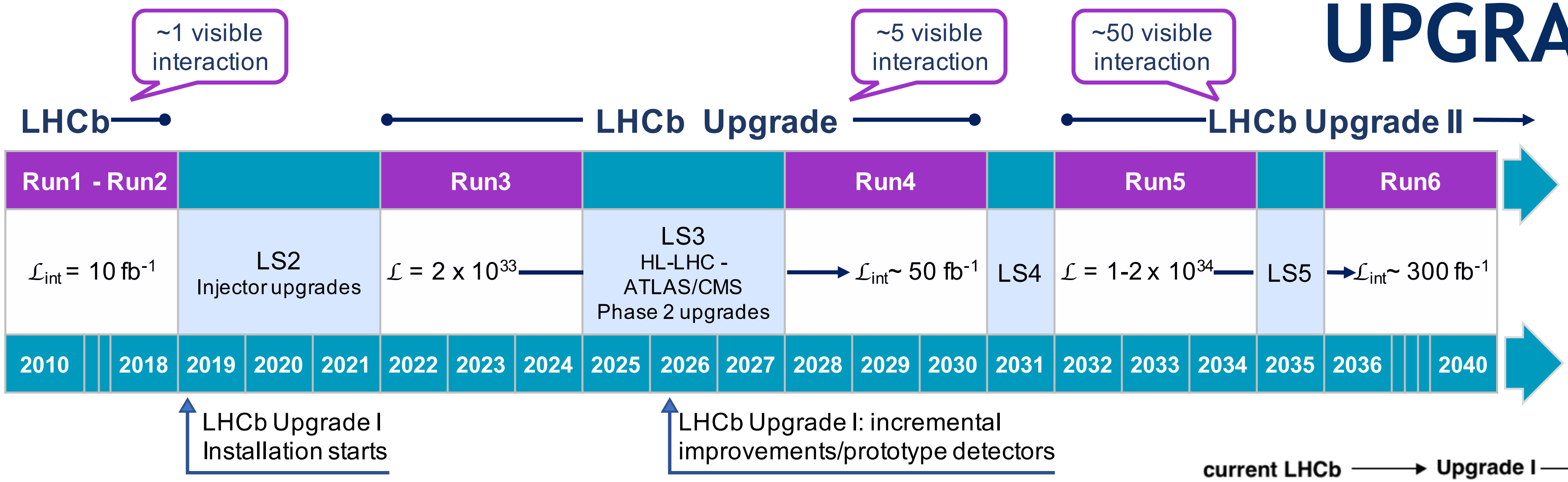
Upgrade

Installation and commissioning impacted by Covid-19

- Regardless, progress from all subsystems

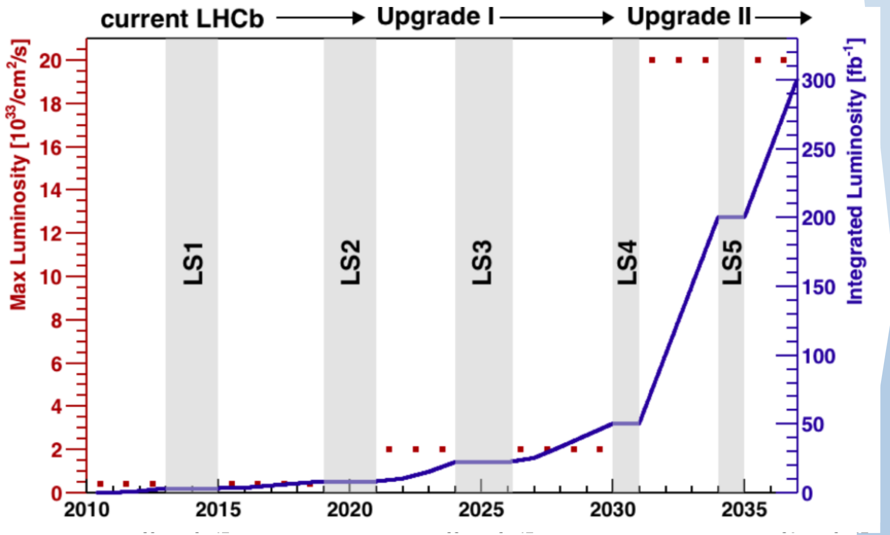


UPGRADE II



- Challenge:
  - Improve even more LHCb precision: measurements statistical limited even after Run 4
  - Fully exploit HL-LHC
- Plan to record more than 300 fb^{-1}
  - L=1.5 $\times 10^{34}$ cm^{-2}s^{-1} and μ~45

    ⇒ Include timing information for tracking and particle ID
- **Many interesting opportunities for detector R&D for LS4**, interested groups welcome to contact us:
  - E.g. precision timing in vertexing, Cherenkov detectors, calorimetry and CMOS for tracking
- **Strong support from European Strategy for Particle Physics**



EoI [CERN-LHCC-2017-003]
Physics case [arXiv:1808.08865]
Framework TDR expected 2021

Conclusion

- New results in several areas:
  - Exotic Spectroscopy: observed resonance at 6.9 Ge/c^2 consistent with $T_{cc\bar{c}\bar{c}}$ prediction
  - Searches for NP: anomalies persist in $B^0 \to K^{*0}\mu^+\mu^-$ decays
  - Precision measurements of CKM: most precise measurement of γ
  - and many others…
- Many results in the pipeline with the full Run 1 and Run 2 data sample
- Upgrade for Run 3 data taking
  - Major upgrade of the detector ongoing
  - flexible fully-software trigger
- Foreseen Upgrade II for Run 5 to fully exploit HL-LHC

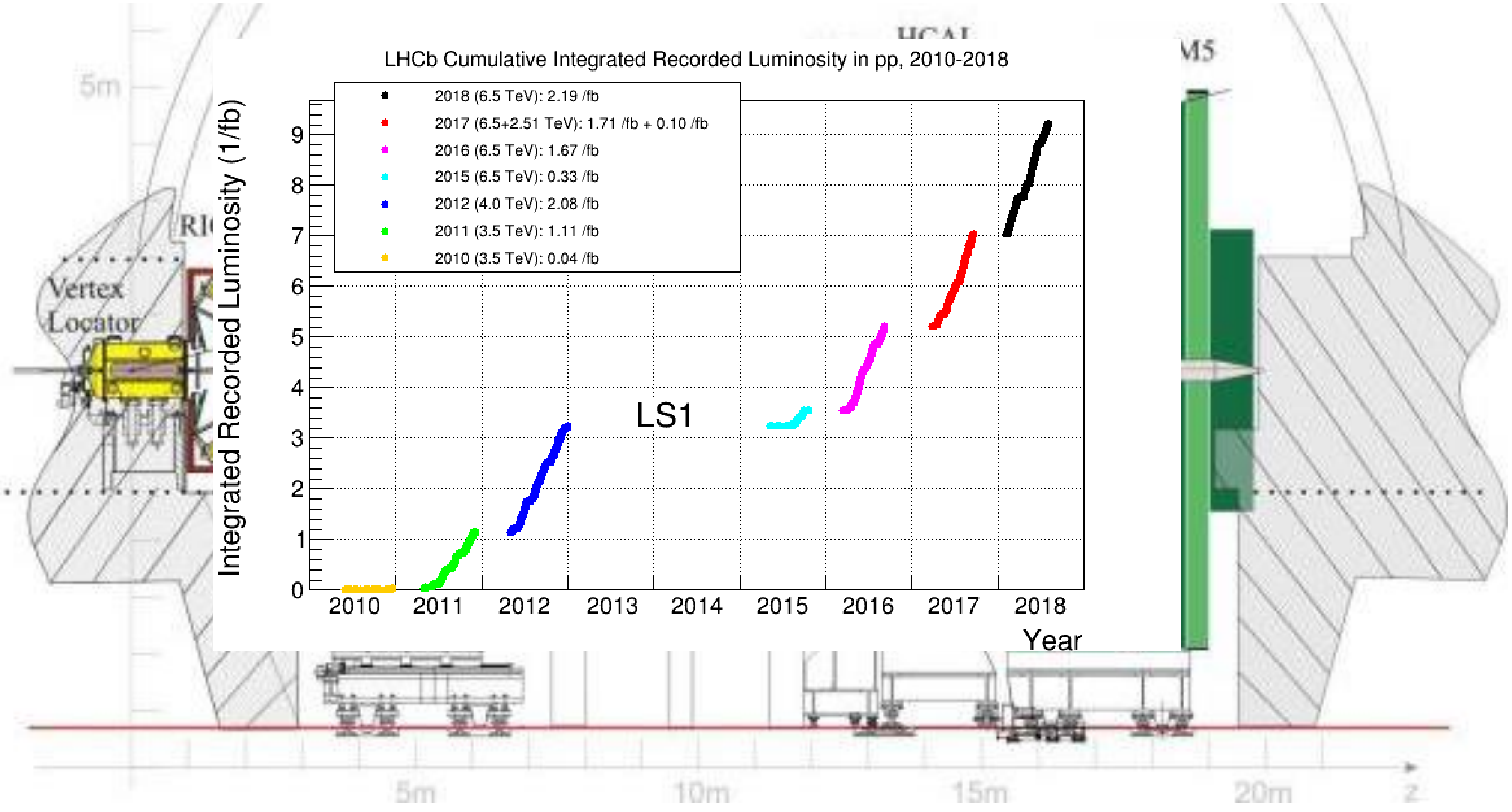
More exciting results are to come!

Discussion panel at 14h on 04/08
with Sneha Malde
Apologize, I cannot make it

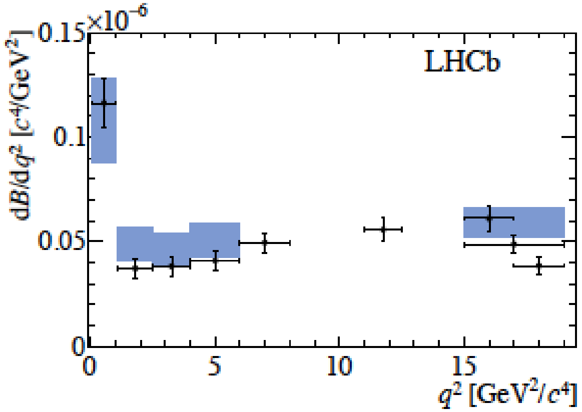
Backup

Detector and performance

- Collected Integrated luminosity in Run1 + Run2: ~9 fb^{-1}

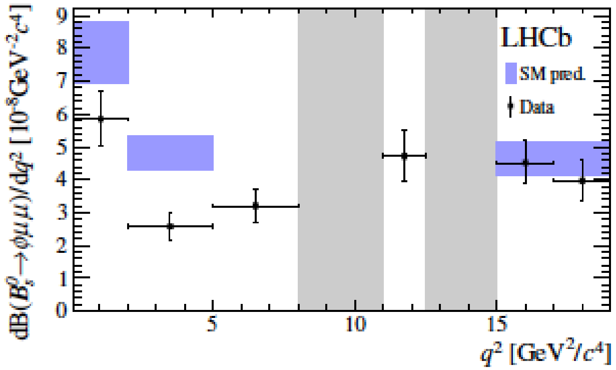


BF of $b \to s\mu^+\mu^-$



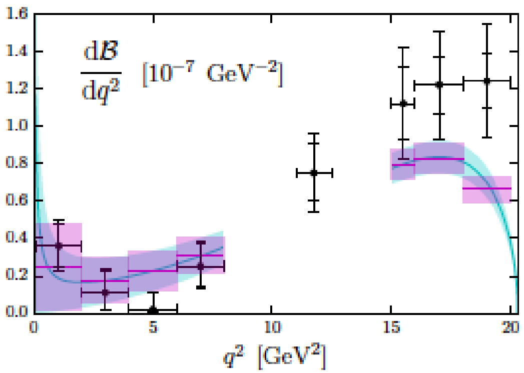
$B^0 \to K^{*0}\mu^+\mu^-$

[JHEP 11 (2016) 047],



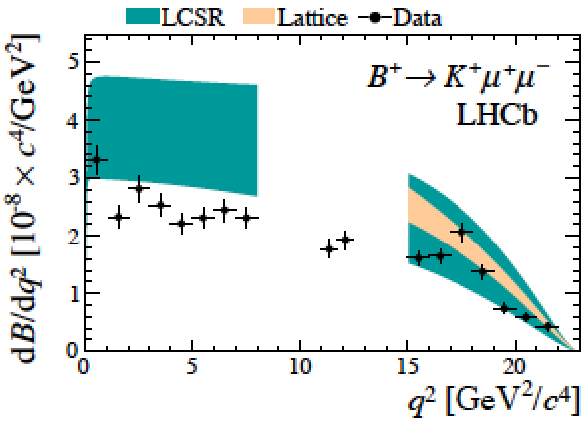
$B^0_s \to \phi\mu^+\mu^-$

[JHEP 09 (2015) 179]



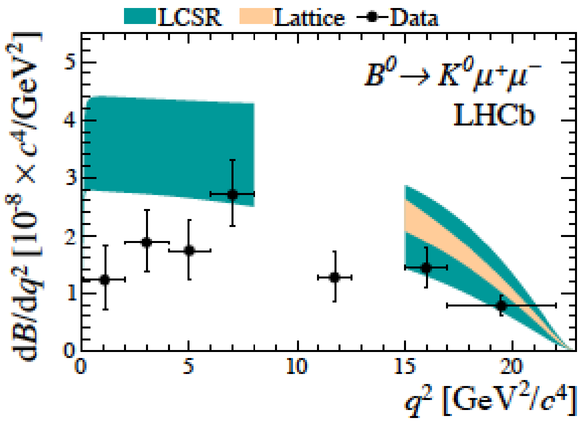
$\Lambda^0_b \to \Lambda\mu^+\mu^-$

- [JHEP 06 (2015)



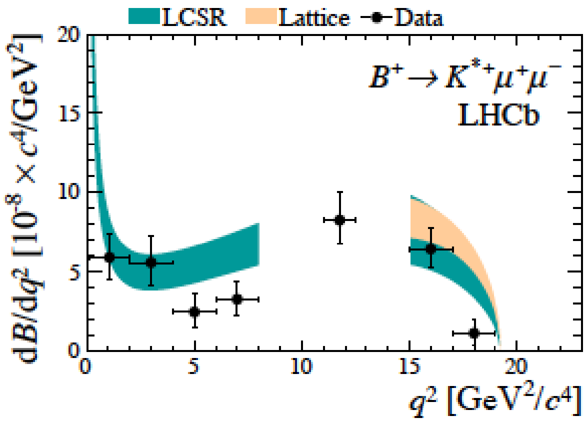
$B^+ \to K^+\mu^+\mu^-$

[JHEP 06 (2014) 133]



$B^0 \to K^0\mu^+\mu^-$

[JHEP 06 (2014) 133]



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

[JHEP 06 (2014) 133]

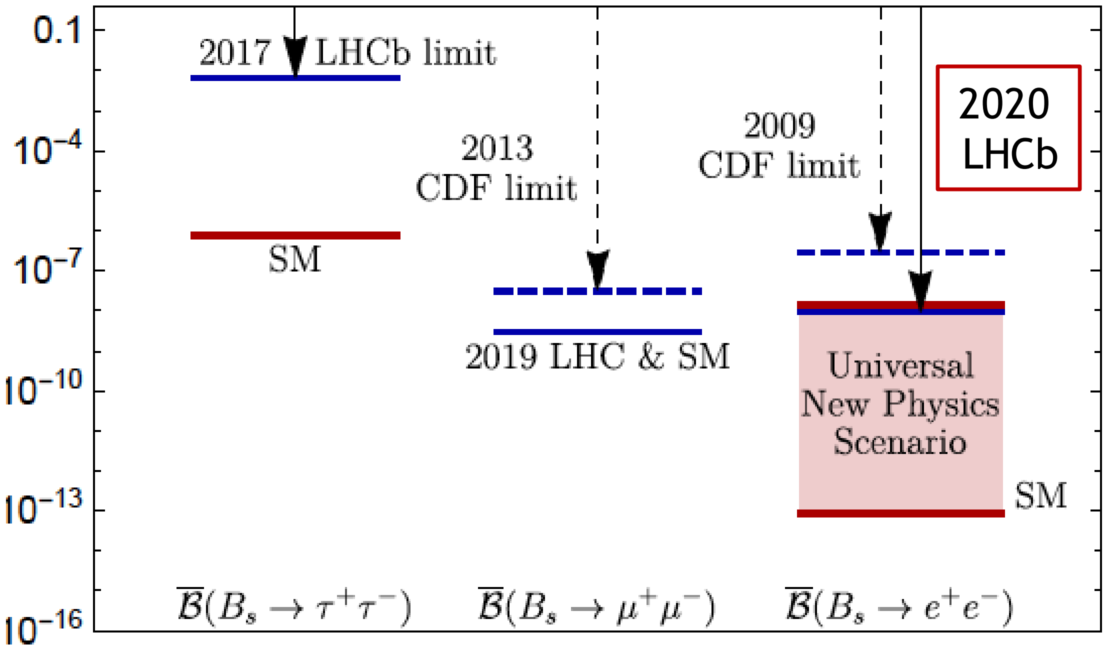
Phys. Rev. Lett. 124 (2020) 211802

Search for $B^0_{(s)} \to e^+ e^-$

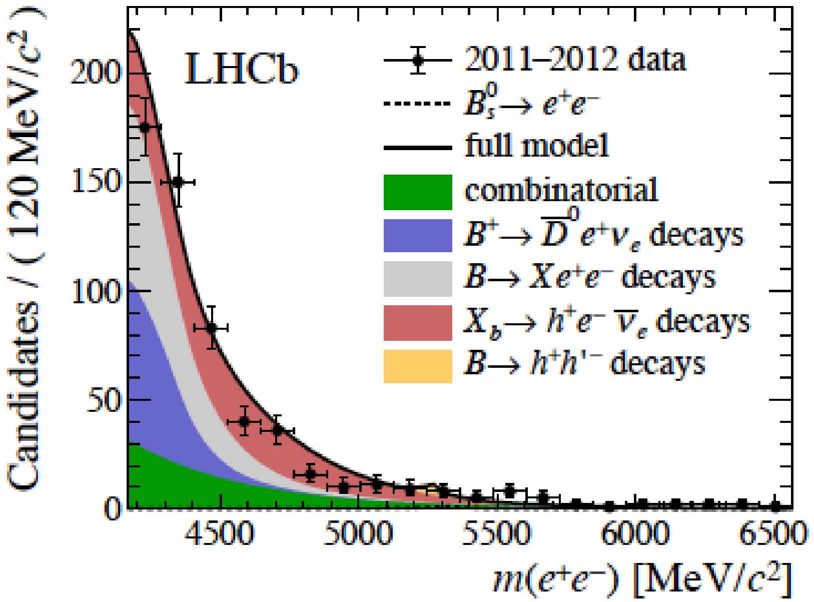
- SM predicts BF is 10^{-14} and 10^{-15}. NP prediction up to 10^{-8} and 10^{-10} [JHEP 05 (2017) 156, JHEP 10 (2019) 232]

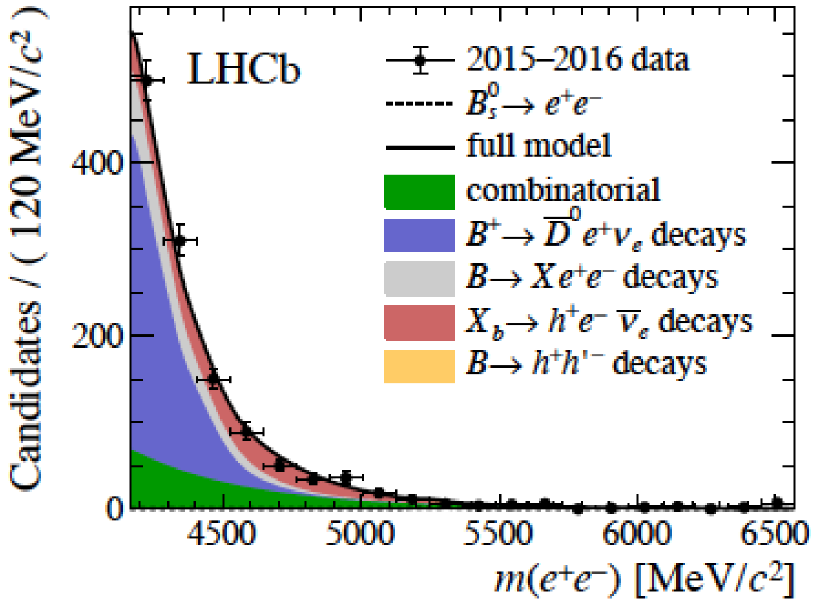
⇒ any signal would be a sign of NP.

- New limits with $\mathcal{O}(10)$ times improvements
  - $\mathcal{B}(B^0_s \to e^+e^-) < 9.4\ (11.2) \times 10^{-9}$ at 90 (95) % CL
  - $\mathcal{B}(B^0 \to e^+e^-) < 2.5\ (3.0) \times 10^{-9}$ at 90 (95) % CL



$\sqrt{s}$ (TeV)	$\mathcal{L}$ (fb^{-1})
7	1
8	2
13	2





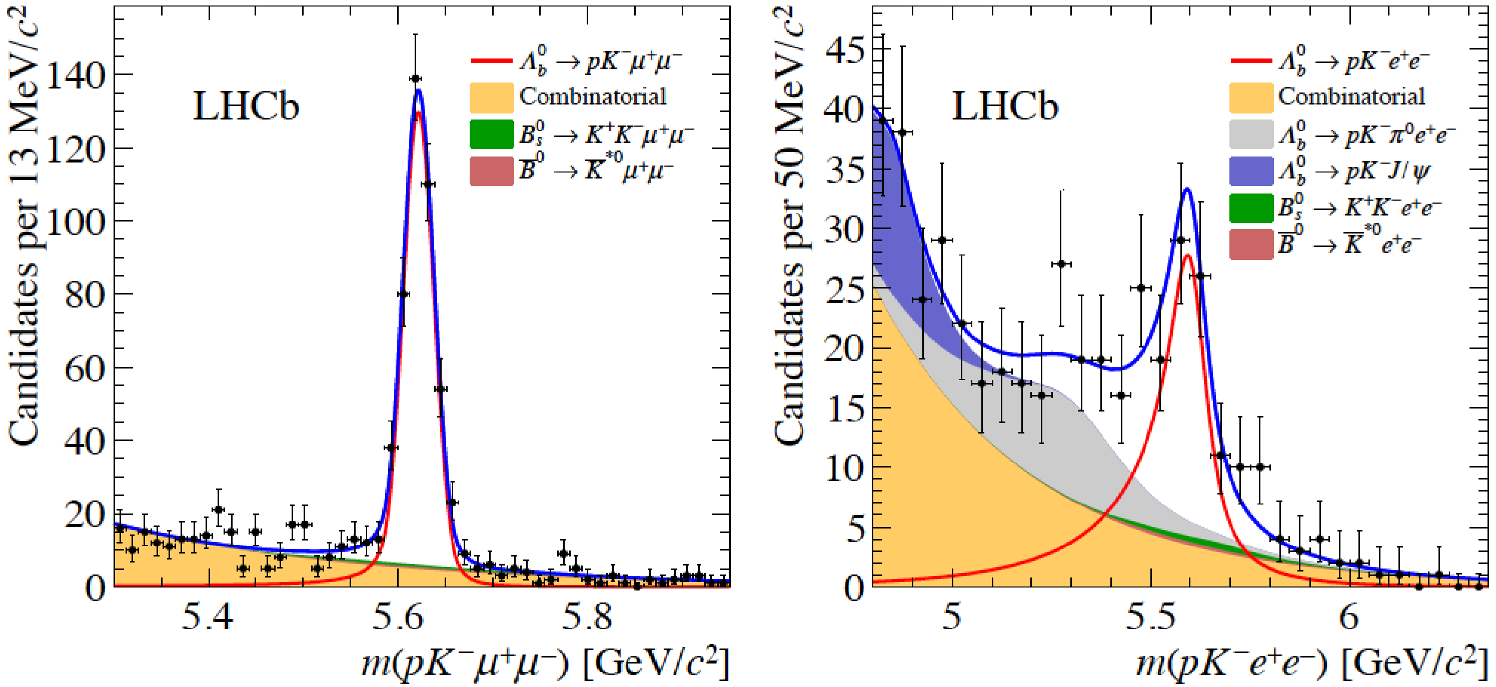
Lepton universality in $\Lambda^0_b \to pK^-\ell^+\ell^-$

JHEP 05 (2020) 040

- Evaluation of the double ratio to suppress detector effects
- Run1 + 2016 data samples: $\mathcal{L}$ =4.7 fb^{-1}

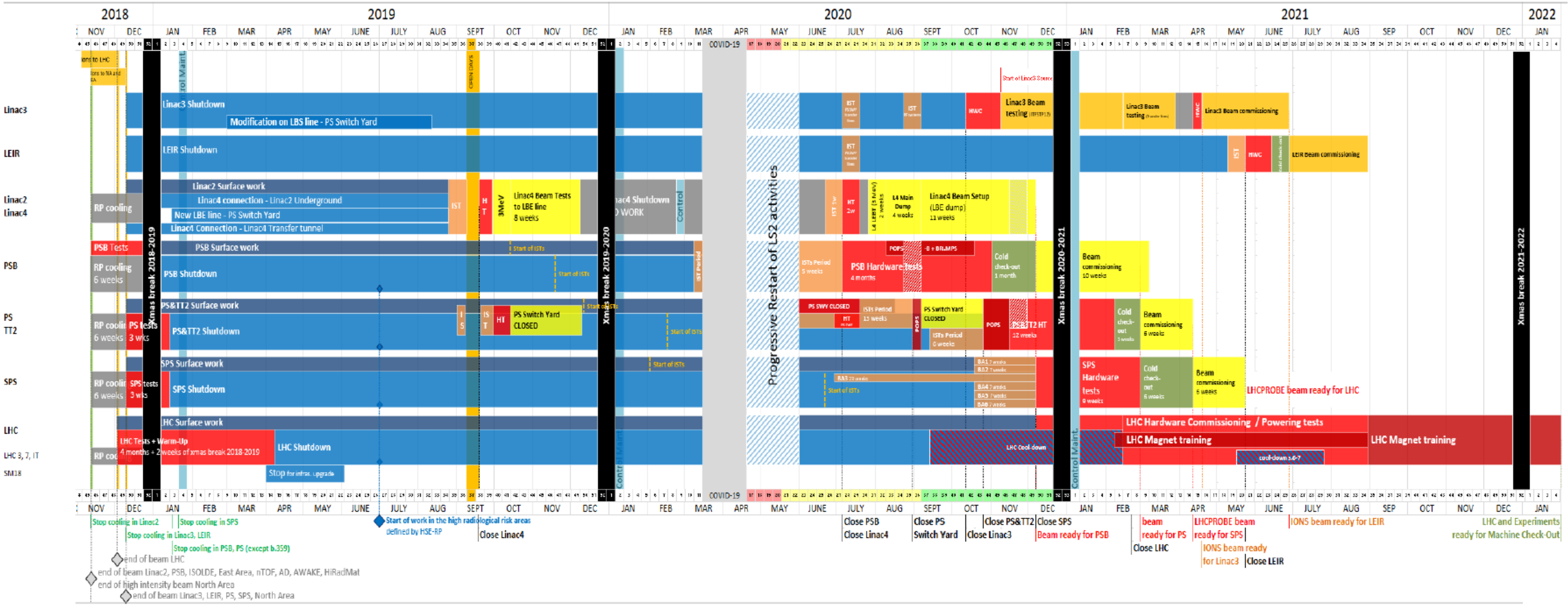
$$R_{pK}^{-1} = \frac{\dfrac{\mathcal{B}(\Lambda_b^0 \to pK^-e^+e^-)}{\mathcal{B}(\Lambda_b^0 \to pK^-J/\psi(\to e^+e^-))}}{\dfrac{\mathcal{B}(\Lambda_b^0 \to pK^-\mu^+\mu^-)}{\mathcal{B}(\Lambda_b^0 \to pK^-J/\psi(\to \mu^+\mu^-))}}$$

$$R_{pK} = 0.86^{+0.14}_{-0.11} \pm 0.05$$



- Compatible with previous R_H measurements and with unity
- This is the first test of lepton universality with b baryons

LS2 Master Schedule V2.7 approved on 12th June 2020



ACC-PM-MS-0002 v.2.7 EDMS: 1687788

Update on the re-start plan
Frédérick Bordry
29th June 2020

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