Recent LHCb results

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on behalf of the LHCb collaboration

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QFTHEP 2019

SOCHI RUSSIA

Plan of the talk

- Introduction
- LHCb: detector, data taking, scientific output
- CP violation
- First observation of CP violation in D^0 meson decays
- Precision measurement of $D^0 - \overline{D}^0$ mixing
- Measurement of phases ϕ_s and $\phi_s^{s\bar{s}s}$
- Rare decays. Exotics. Lepton universality. Summary of $B_s \to \mu\mu$
- Hadron spectroscopy: new states, pentaquarks, lifetimes
- Upgrade I & II
- Conclusions

Dedicated LHCb talks on this conference:

Pavel Krokovny: Lepton flavour universality tests at LHCb
Evgenii Kurbatov: LHCb results on rare leptonic decays of B-mesons
Dmitrii Pereima: Search for new decays of the Λb0-baryon at the LHCb
Slava Matiunin: Recent LHCb results on charm and charmonium spectroscopy

See http://lhcb-public.web.cern.ch/lhcb-public/ for more information

Undisputable triumph of the Standard Model: Higgs boson, EW and QCD physics, decays and mixings…

and still **nothing beyond**

At the same time we are sure that ***there is physics*** beyond the **SM**:

- Neutrino masses and oscillations
- Dark matter
- Baryon asymmetry of the Universe
- …

Besides that, there are many «why» and «how» in the **SM**:

- How is EW scale so smaller than UV scale?
- Why 3 generations (the enigma of flavour)?
- Why are lefts doublets and rights singlets?
- Why is this CKM matrix structure & CP?
- …

Large Hadron Collider beauty (LHCb) experiment addresses many of these deep questions via:

- precision studies of b- and c-hadron decays
- CP violation in decays and mixing
- hadron spectroscopy
- rare and forbidden decays
- indirect searches of New physics
- ...

Complementary to direct searches in ATLAS & CMS

Main requirements to the detector:

- High yield → efficient trigger and selection, large production cross sections (b-production: 110 μb @ 13 TeV in LHCb acceptance, arXiv:1612.05140)
- Low background → mass resolution, particle identification
- Vertexing & Tracking → excellent resolutions
- Particle identification: **π** / **K** / **p** (RICH), **e** / **γ** (E/HCAL), **μ** (MUON)
- Trigger: L0 (high $\mathbf{p_T}$ candidate particles), HLT1 & HLT2 (software)

LHCb: detector, data taking, scientific output:

Operating at inst. luminosity

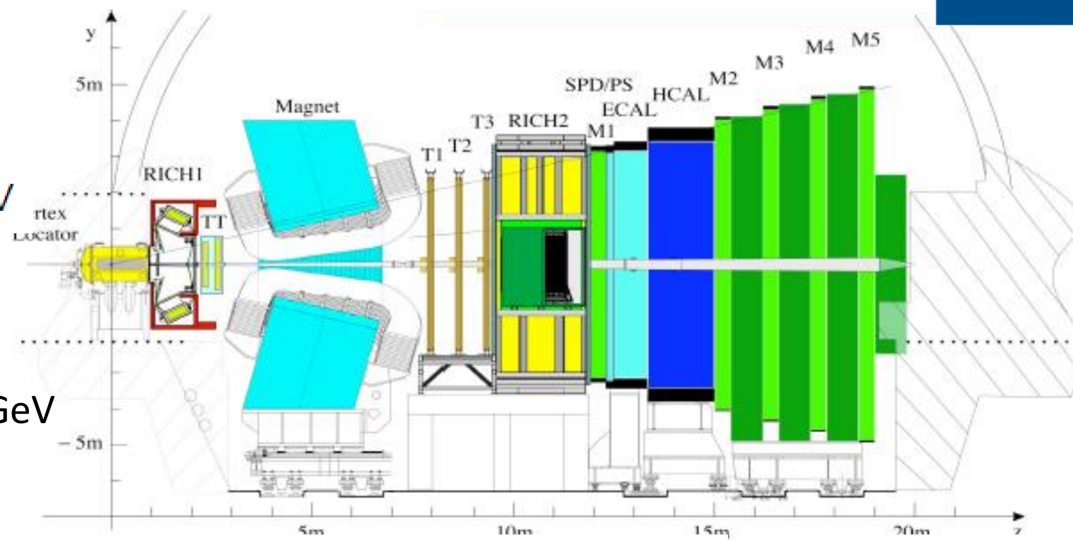
$$\mathcal{L} \sim 4\times10^{32}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$$

Run 1: $\int \mathcal{L} = 3\ \mathrm{fb}^{-1}$ @7 and 8 TeV

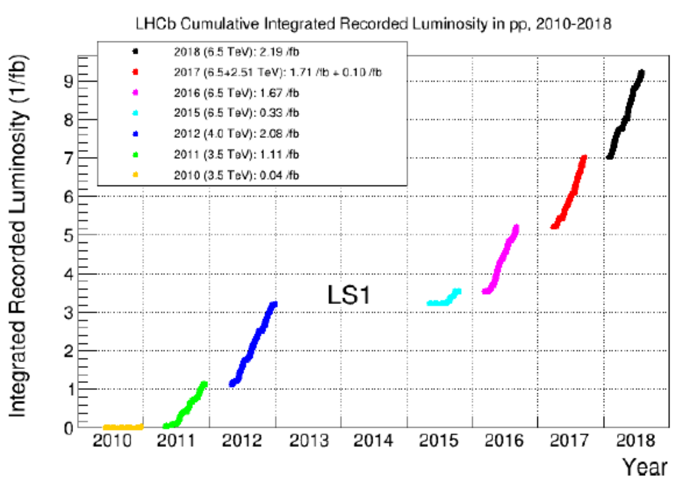
Run 2: $\int \mathcal{L} \simeq 6\ \mathrm{fb}^{-1}$ @13 TeV

Excellent resolution:

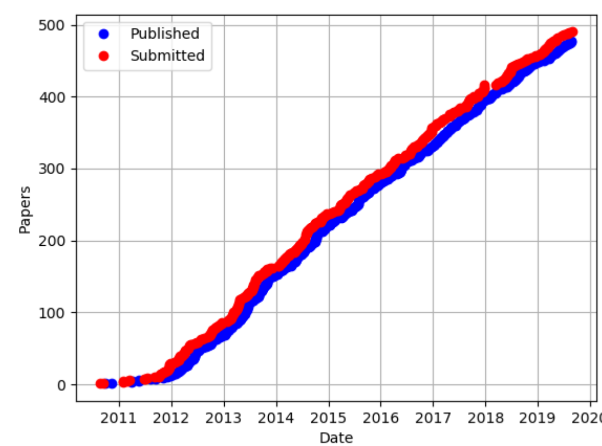
momentum: **0.4 – 0.6 %** at 5–100 GeV
muon ID efficiency: **97 %**
electron ID efficiency: **90%**
kaon ID efficiency: **95%**



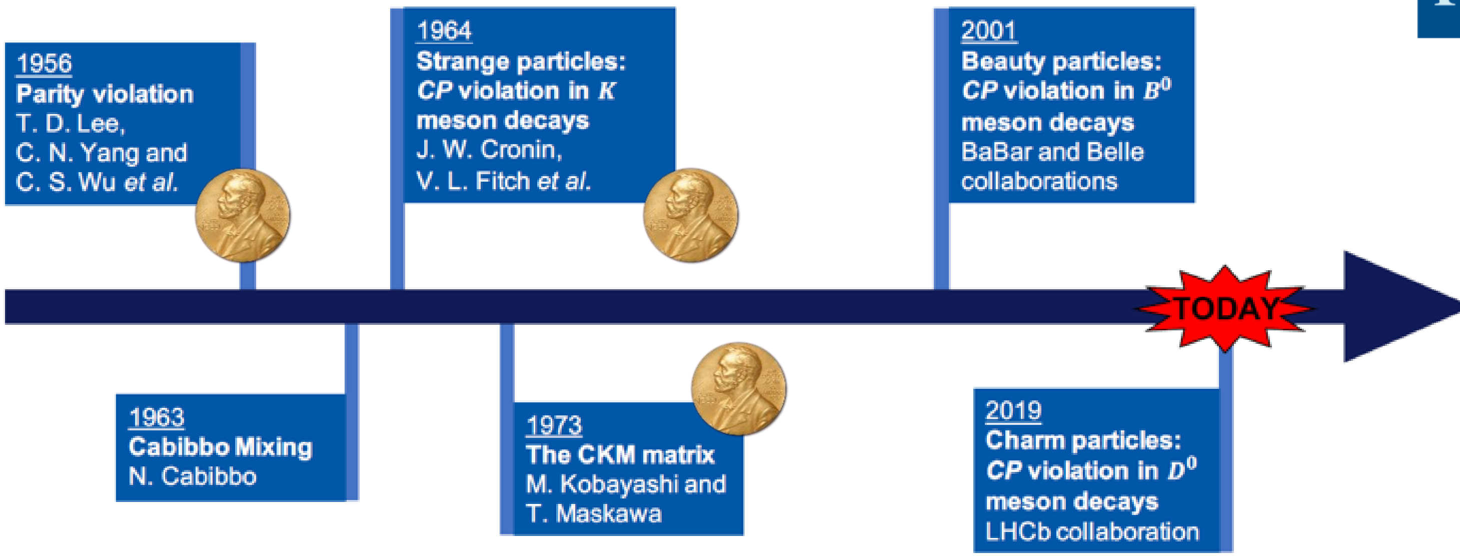
Int. J. Mod. Phys. A30 (2015)1530022 2008 JINST 3 S08005



490+ papers



CP violation

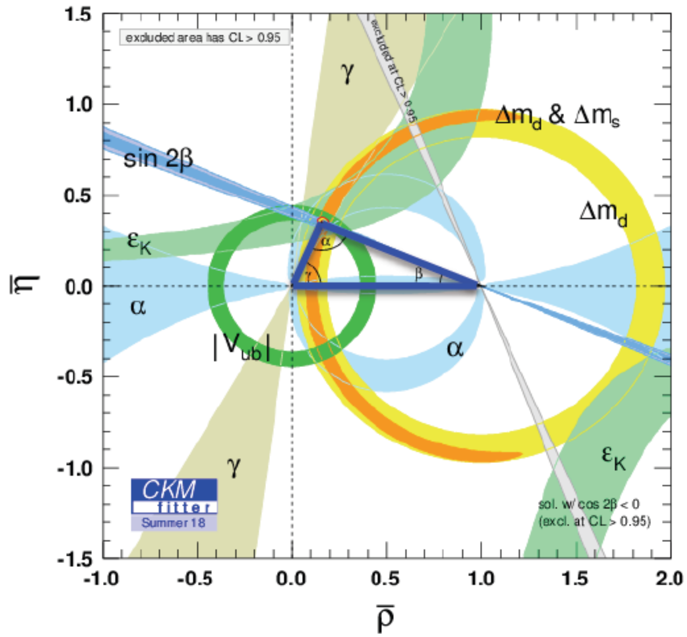


CP violation is described in the SM through one parameter in the CKM matrix – complex phase and it was established experimentally in K and B meson decays since many years.

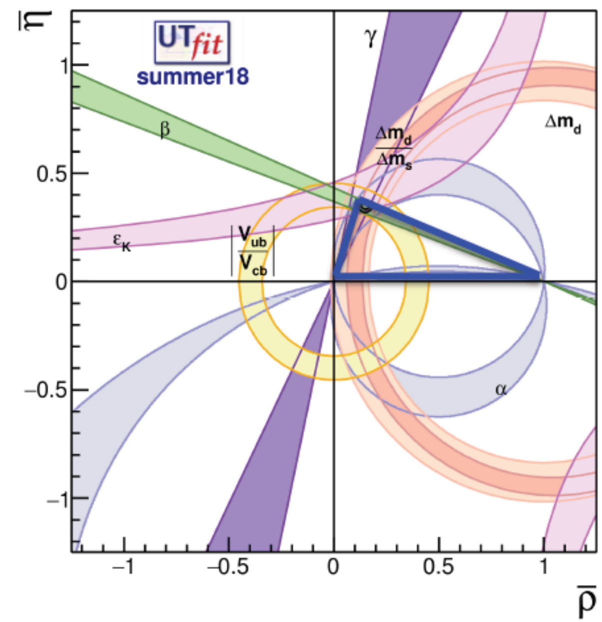
New physics beyond the SM could contribute to CP violation.

The conventional way to parameterize CKM matrix is the Unitarity Triangle. To over-constrain it is a way to search for New physics.

http://ckmfitter.in2p3.fr



http://www.utfit.org



All of the available measurements agree in a highly nontrivial way to the current level of precision – tremendous success of the CKM paradigm!

Mixing and CP violation in the quark flavour sector is generally well described by the CKM mechanism – we must look for small discrepancies.

First observation of CP violation in D^0 meson decays

Phys. Rev. Lett. 122 (2019) 211803

The asymmetry

$$A_{CP}(f;\,t) \equiv \frac{\Gamma(D^0(t) \to f) - \Gamma(\overline{D}^0(t) \to f)}{\Gamma(D^0(t) \to f) + \Gamma(\overline{D}^0(t) \to f)}$$

is sensitive to both direct and indirect CP violation.

Time integrated measurement: huge statistics from

$$\overline{B} \to D^0 \mu^- \bar{\nu}_\mu X \qquad D^{*+} \to D^0(f)\pi^+$$

$$A_{CP}(f) \approx a_{CP}^{\rm dir}(f) - \frac{\langle t(f)\rangle}{\tau(D^0)} A_\Gamma(f)$$

the mean decay time $D^0 \to f$

Strong suppression of the systematic uncertainties by measuring the difference

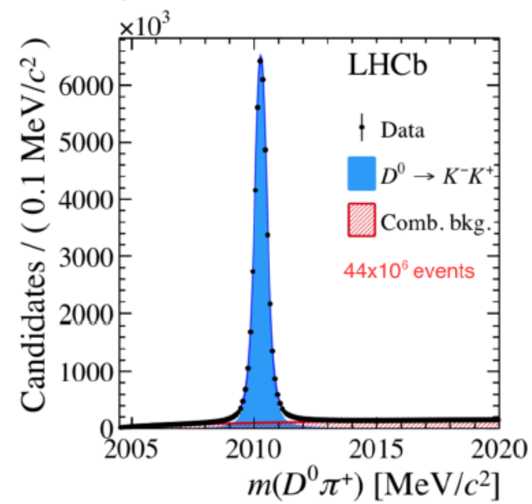
$$\Delta A_{CP} \equiv A_{CP}(K^-K^+) - A_{CP}(\pi^-\pi^+)$$

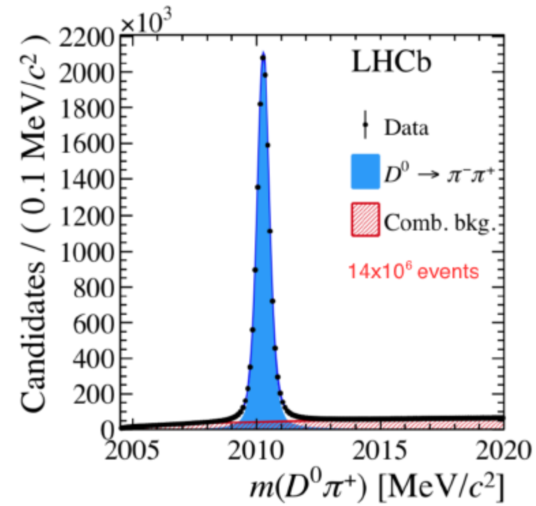
The result (including LHCb Run 1):

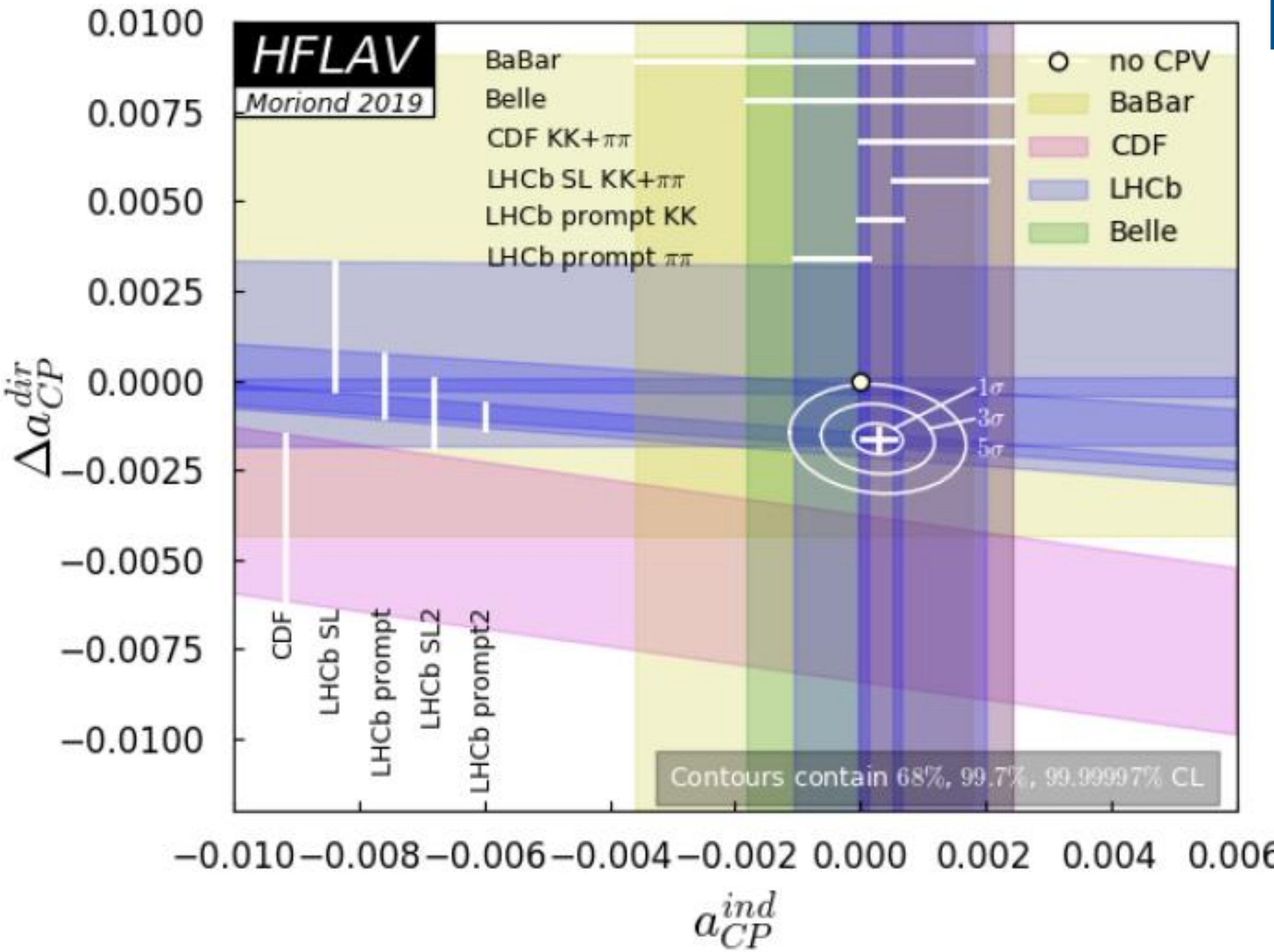
$$\boxed{\Delta A_{CP} = (-15.4 \pm 2.9) \times 10^{-4}}$$

5.3 standard deviations. The first observation of CP violation in the decay of charm hadrons.

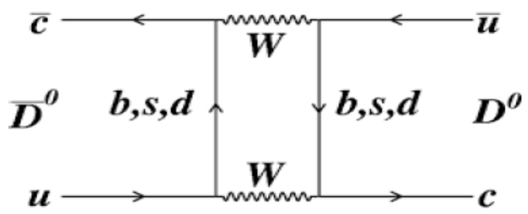
$\int \mathcal{L} = 5.9\ \mathrm{fb}^{-1}$ – Run2






HFLAV
Moriond 2019
BaBar
Belle
CDF KK+ππ
LHCb SL KK+ππ
LHCb prompt KK
LHCb prompt ππ
no CPV
BaBar
CDF
LHCb
Belle
1σ
3σ
5σ
CDF
LHCb SL
LHCb prompt
LHCb SL2
LHCb prompt2
Contours contain 68%, 99.7%, 99.99997% CL
0.0100
0.0075
0.0050
0.0025
0.0000
−0.0025
−0.0050
−0.0075
−0.0100
−0.010 −0.008 −0.006 −0.004 −0.002 0.000 0.002 0.004 0.006
Δa_{CP}^{dir}
a_{CP}^{ind}

Precision measurement of $D^0 - \bar{D}^0$ mixing



Phys. Rev. Lett. 122 (2019) 231802

D-mesons oscillate like their K- and B- counterparts. It is worth reminding however, that despite the corresponding Feynman diagrams look similar, the physical picture of mixing is very different.

For K and B mesons the dominant contribution comes from the heaviest up-type quark propagating in the loop, corresponding to the external down quarks, so the oscillation frequency provides information about “the nearest” heavy degree of freedom.

But for D^0 mesons there is no such thing as “the nearest heaviest” down-type quark, since b-quark belongs to another generation.

In other words D is “inverse analog” of K oscillations: c-quark dominating K oscillations is heavy d.o.f. for K while s-quark dominating D oscillations is light d.o.f. for D.

D oscillations are dominated by long-distance physics.

Physical mass eigenstates are a mixture of flavor eigenstates:

$$|D_{1,2}\rangle \equiv p|D^0\rangle \pm q|\overline{D}^0\rangle$$

$$x \equiv (m_1 - m_2)c^2/\Gamma \qquad y \equiv (\Gamma_1 - \Gamma_2)/(2\Gamma)$$

$$z_{CP} \pm \Delta z \equiv -(q/p)^{\pm 1}(y + ix)$$

$$x_{CP} \equiv -\mathrm{Im}(z_{CP}) \qquad y_{CP} \equiv -\mathrm{Re}(z_{CP})$$

$$\Delta x \equiv -\mathrm{Im}(\Delta z) \qquad \Delta y \equiv -\mathrm{Re}(\Delta z)$$

$\Delta x = \Delta y = 0$
if CP is conserved

Old world average:

$$x = (3.6\,^{+2.1}_{-1.6}) \times 10^{-3}$$

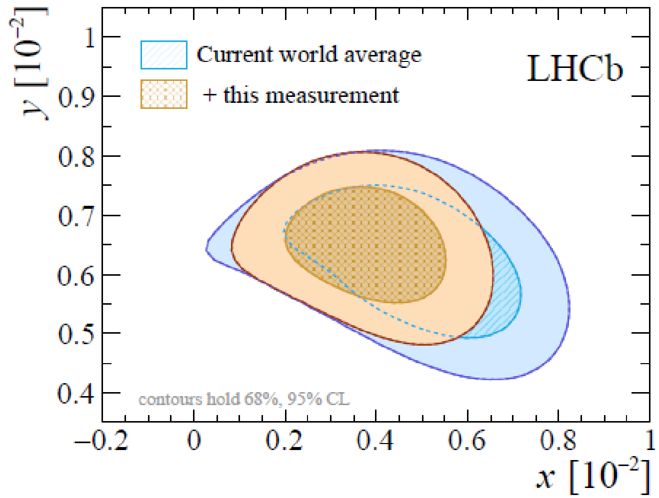
$$y = (6.7\,^{+0.6}_{-1.3}) \times 10^{-3}$$

HFAG, Eur. Phys. J. C77 (2017) 895

Use self-conjugate multibody decays $D^0 \to K^0_S\pi^+\pi^-\pi^0$

The result (CP-averaged) is the most precise single measurement:

Parameter	Value $[10^{-3}]$
x_{CP}	$2.7 \pm 1.6 \pm 0.4$
y_{CP}	$7.4 \pm 3.6 \pm 1.1$
Δx	$-0.53 \pm 0.70 \pm 0.22$
Δy	$0.6 \pm 1.6 \pm 0.3$



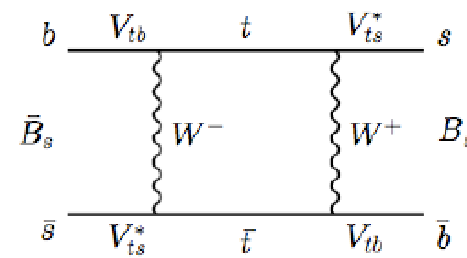
Phys. Rev. Lett. 122 (2019) 231802

New global average: $x = (3.9\,^{+1.1}_{-1.2}) \times 10^{-3}$

Measurement of ϕ_s

Phys. Rev. Lett. 122 (2019) 211803

Neutral B_s mesons can oscillate to its antiparticle via box diagram

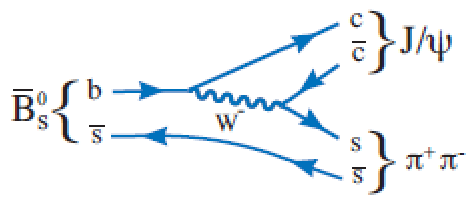


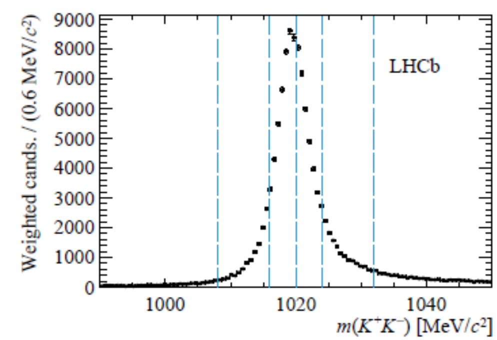
Mixing induced time dependent CP violation:

$$A(f,t) = \frac{\Gamma\left(B_s^0(t) \to f\right) - \Gamma\left(\bar{B}_s^0(t) \to f\right)}{\Gamma\left(B_s^0(t) \to f\right) + \Gamma\left(\bar{B}_s^0(t) \to f\right)}$$

$$A(f,t) \sim \eta_f \sin\phi_s \sin(\Delta m_s t)$$

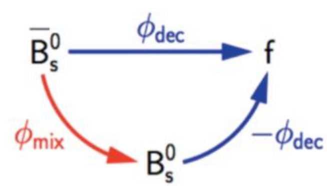
$$\phi_s = -\arg\left(\frac{q}{p}\frac{\bar{A}_f}{A_f}\right)$$

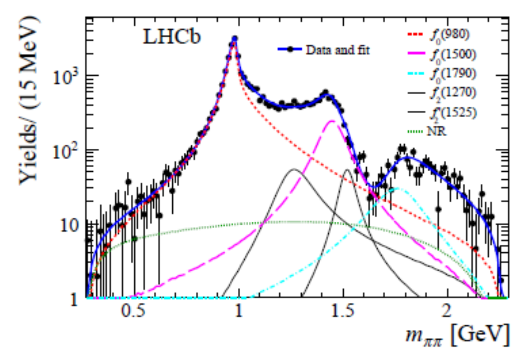


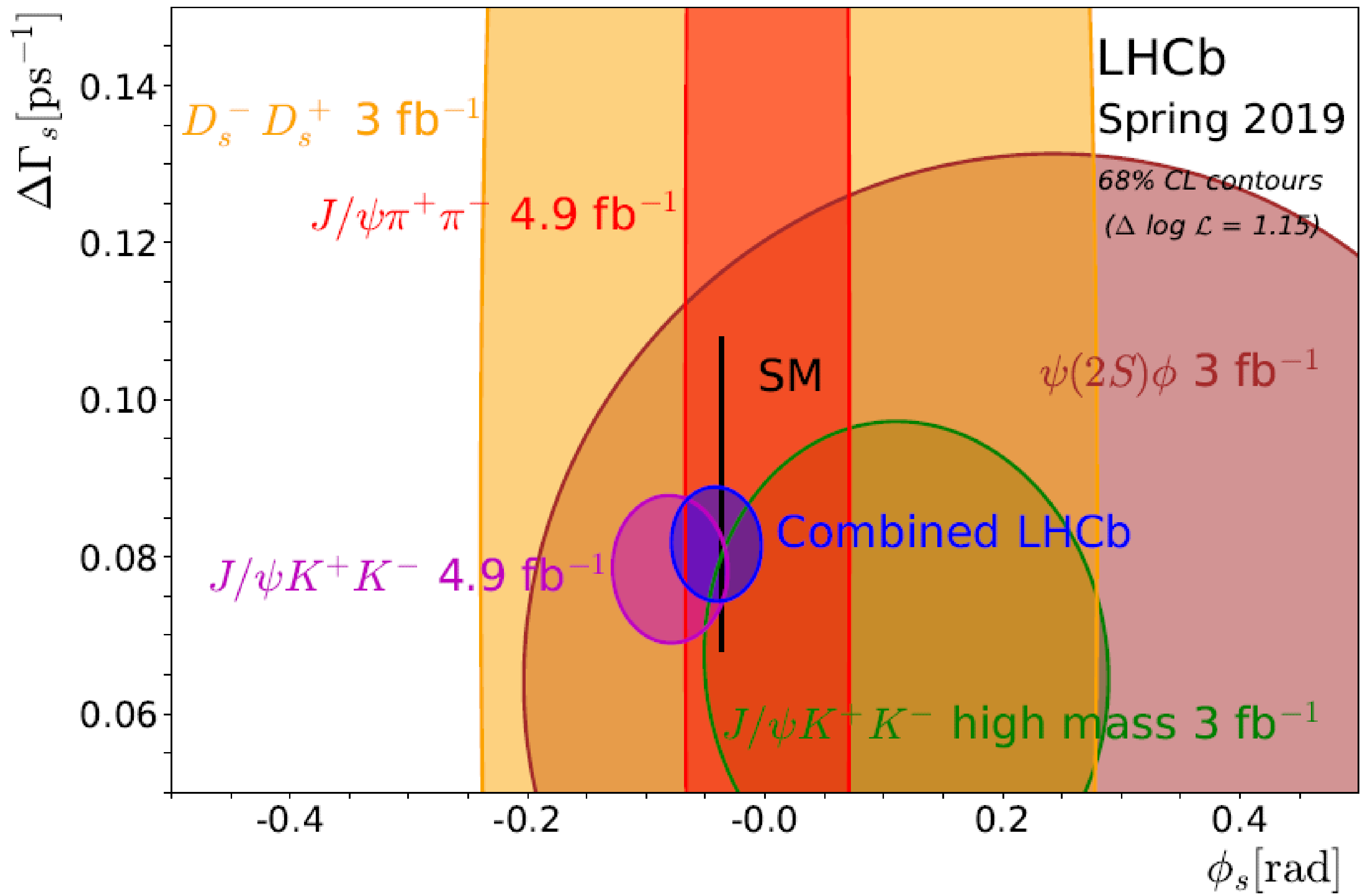


Results use 1.9/fb Run 2 data combined with previous LHCb Run 1 measurements

$$\boxed{\begin{aligned} \phi_s &= -0.041 \pm 0.025\,\text{rad}\,, \\ |\lambda| &= 0.993 \pm 0.010\,, \\ \Gamma_s &= 0.6562 \pm 0.0021\,\text{ps}^{-1}\,, \\ \Delta\Gamma_s &= 0.0816 \pm 0.0048\,\text{ps}^{-1}\,. \end{aligned}}$$







(M.Romero, at KAON 2019)

Measurement of $\phi_s^{s\bar{s}s}$

The decay $B_s^0 \to \phi\phi$ can proceed only via gluonic penguin diagram

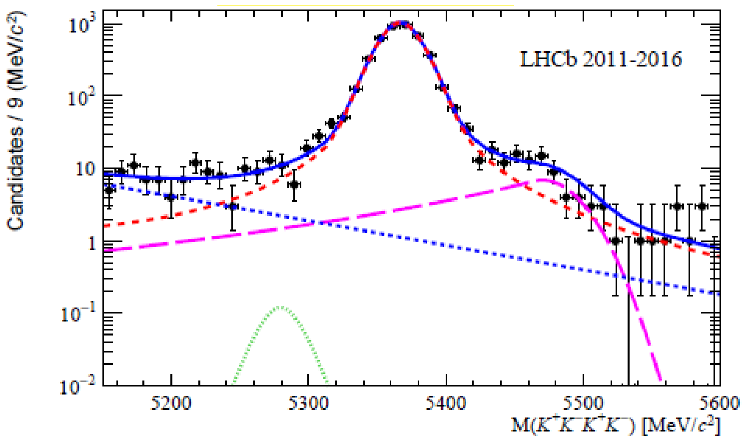
$$A(f,t) \sim \eta_f \sin\phi_s^{s\bar{s}s} \sin(\Delta m_s t)$$

The SM prediction: $|\phi_s^{s\bar{s}s}| < 20\,\mathrm{mrad}$ Phys. Rev. D80 (2009) 114026

Measuring a larger value would be a clear indication of NP

Time-dependent tagged and angular analysis
similar to that for $B_s^0 \to J/\psi K^+ K^-$
Different CP eigenstates contributing
Background contribution suppressed thanks
to excellent PID and mass resolution
Excellent decay-time resolution **σ_t ~ 43 fs**
Efficiency to tag the initial flavour **5.7%**

arXiv: 1907.10003



Results:

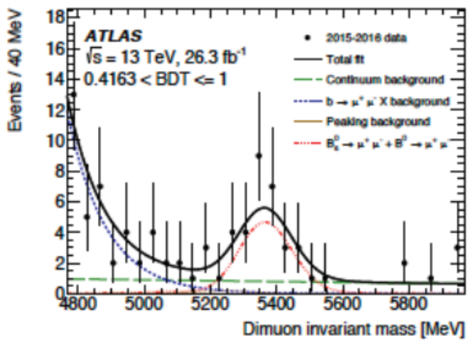
$$\begin{aligned} \phi_s^{s\bar{s}s} &= -0.073 \pm 0.115\,(\mathrm{stat}) \pm 0.027\,(\mathrm{syst})\ \ \mathrm{rad}, \\ |\lambda| &= 0.99 \pm 0.05\,(\mathrm{stat}) \pm 0.01\,(\mathrm{syst}). \end{aligned}$$

Consistent with SM expectations

Rare decays. Summary of $B_s \to \mu\mu$

JHEP 04 (2019) 098

- $25+36 fb^{-1}$ of Run 1 + 2
  - Most stringent limit on $B_d \to \mu^+\mu^-$



B_s Significance: 4.6σ

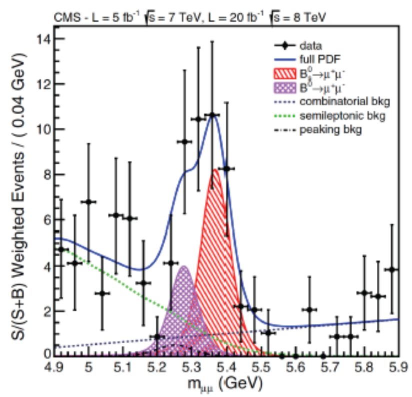
Run 1 + Run 2 combined:

$$BR(B_s \to \mu^+\mu^-) = (2.8^{+0.8}_{-0.7}) \times 10^{-9}$$

$$\boxed{BR(B^0 \to \mu^+\mu^-) < 2.1 \times 10^{-10} @ 95\%CL}$$

PRL 111 (2013) 101804

- $25 fb^{-1}$ of Run 1 data
  - Sensitivity on comparable dataset very similar to LHCb



B_s Significance: 4.3σ

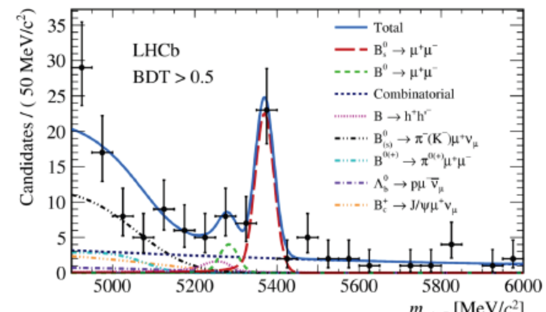
$$BR(B_s \to \mu^+\mu^-) = (3.0^{+1.0}_{-0.9}) \times 10^{-9}$$

$$BR(B^0 \to \mu^+\mu^-) = (3.5^{+2.1}_{-1.8}) \times 10^{-10}$$

$$BR(B^0 \to \mu^+\mu^-) < 11 \times 10^{-10} @ 95\%CL$$

PRL 118 (2017) 191801

- 2012: LHCb found the first evidence for $B_s \to \mu^+\mu^-$
- Update: $3+1.4 fb^{-1}$
  - First single experiment observation



B_s Significance: 7.8σ

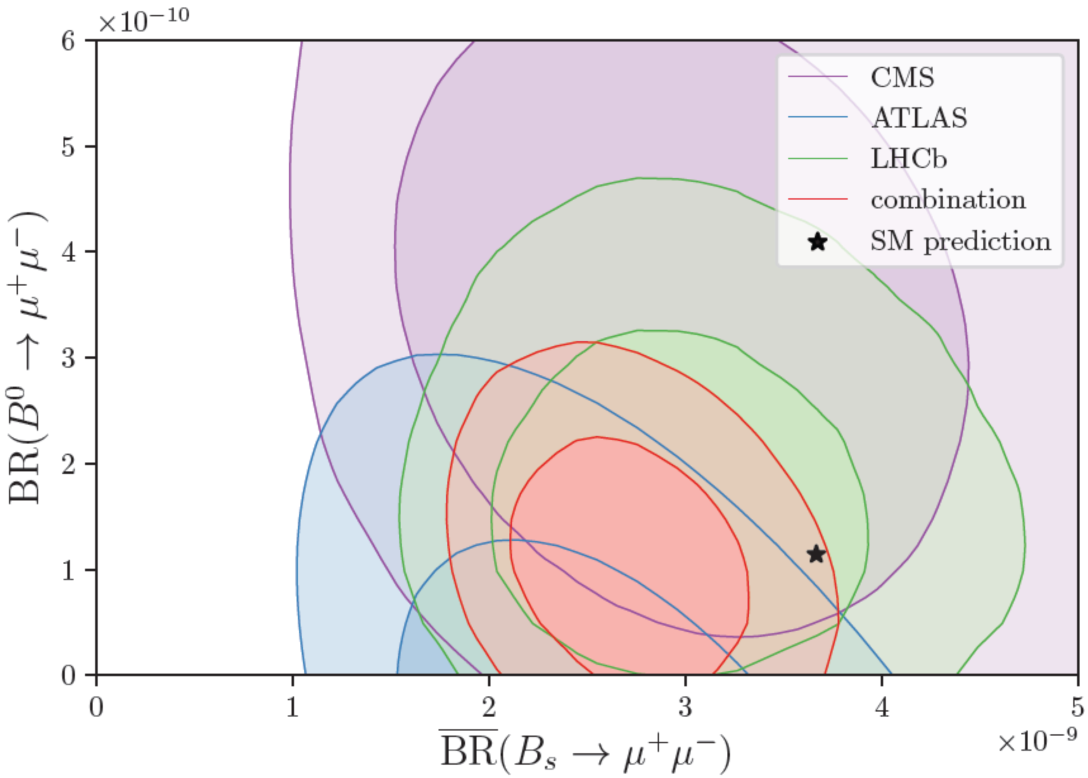
$$\boxed{BR(B_s \to \mu^+\mu^-) = (3.0 \pm 0.7) \times 10^{-9}}$$

$$BR(B^0 \to \mu^+\mu^-) < 3.4 \times 10^{-10} @ 95\%CL$$

- Effective $\mathbf{B_s}$ lifetime also measured

(J.Albrecht, at EPS HEP 2019)

$B_s \to \mu\mu$: combination of ATLAS, CMS & LHCb



ATLAS: JHEP 04 (2019) 098
CMS: PRL111(2013)101804
LHCb: PRL118(2017)191801

Combining all three LHC experiments

$$BR(B_s \to \mu^+\mu^-) = (2.71 \pm 0.4) \times 10^{-9}$$

SM: Buras, Isidori et al
EPJC72(2012) 2172
$BR(B_s \to \mu^+\mu^-) = 3.5 \pm 0.3 \times 10^{-9}$

→ agrees within 2σ

D. Straub, Moriond EW 2019 & 1903.10434

(J.Albrecht, at EPS HEP 2019)

中国科学院高能物理研究所
Institute of High Energy Physics Chinese Academy of Sciences

Search for $K_S^0 \to \mu^+\mu^-$

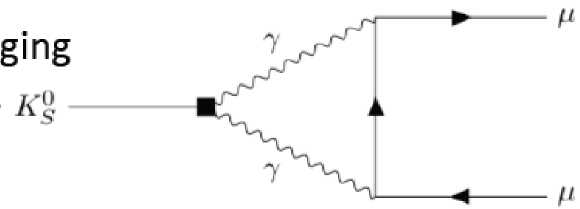
LHCb-CONF-2019-002 (LHCb preliminary, presented at KAON yesterday*)

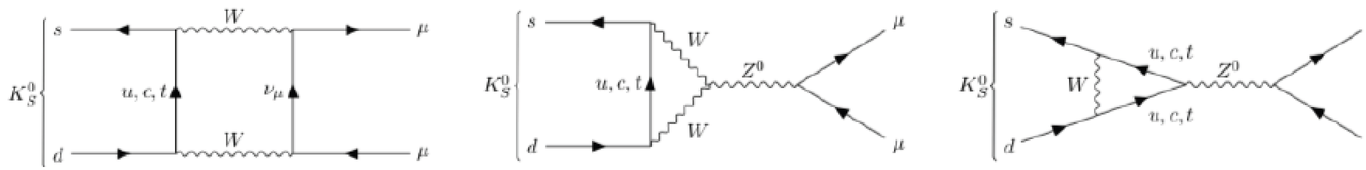
* See https://indico.cern.ch/event/769729/contributions/3510936/ for more details.

Run 2, 5.6 fb^{-1}

SM: BR ~ 5×10^{-12}
[JHEP 05 (2018) 024]
[JHEP 01 (2004) 009]
[NPB 366 (1991) 189]

- Strongly suppressed Flavour-changing Neutral Current (FCNC) transition.
- Dominated by long distance contributions through $K_S^0 \to \gamma\gamma$.





Preliminary result obtained from the posterior probability of the branching fraction in the fit [LHCB-CONF-2019-002].

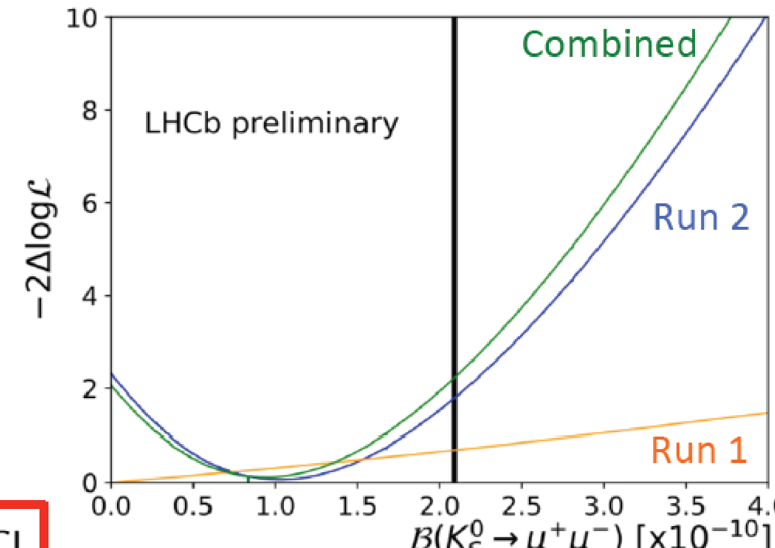
Using Run-II data only:

$$\mathcal{B}\left(K_S^0 \to \mu^+\mu^-\right) < 2.2(2.6)\times10^{-10} \text{ at } 90(95)\% \text{ CL}$$

Minimum: $\mathcal{B}\left(K_S^0 \to \mu^+\mu^-\right) = 1.03^{+0.76}_{-0.68} \times 10^{-10}$

Combine with Run 1 [JHEP 01 (2013) 090]

$$\boxed{\mathcal{B}\left(K_S^0 \to \mu^+\mu^-\right) < 2.1(2.4) \times 10^{-10} \text{ at } 90(95)\% \text{ CL}}$$

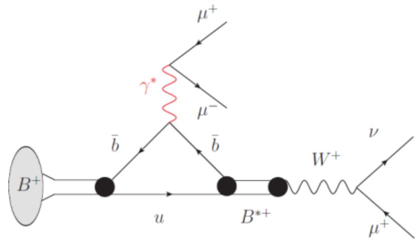


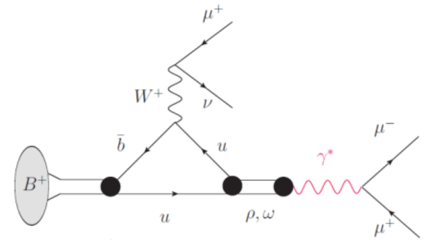
(M.Tobin, at 139th LHCC Meeting)

Search for $B_s \to \mu\mu\mu\nu_\mu$

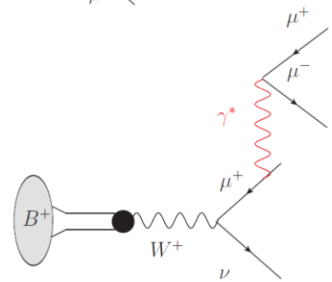
Eur. Phys. J. C 79 (2019) 675

(see talk by E.Kurbatov)





Important background for $B^+ \to \mu^+\nu_\mu$



Easier to reconstruct than $B^+ \to \mu^+\nu_\mu\gamma$

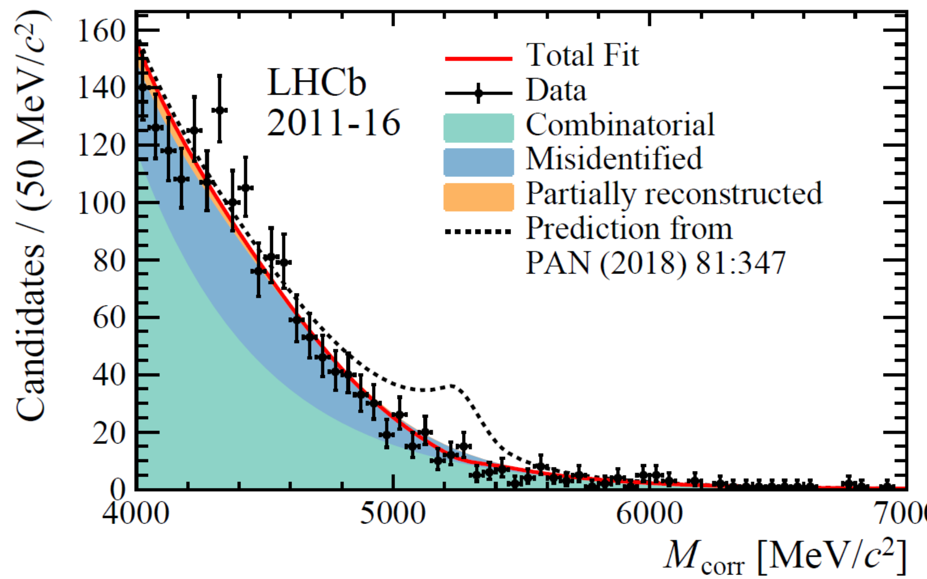
$$M_{\rm corr} = \sqrt{M^2_{\mu\mu\mu} + |p_\perp|^2} + |p_\perp|$$

Theory estimates (A.Danilina, N.Nikitin, ’18)

$$\mathcal{B}(B^+ \to \mu^+\mu^-\mu^+\nu_\mu) \sim 1.3 \times 10^{-7}$$

Results use 4.7/fb Run 1+2 data

$$\boxed{\mathcal{B}(B^+ \to \mu^+\mu^-\mu^+\nu_\mu) < 1.6 \times 10^{-8}}$$



Search for lepton-universality violation in $B^+ \to K^+ l^+ l^-$

Phys. Rev. Lett. 122 (2019) 191801 (dedicated talk by P.Krokovny)

The electroweak couplings of all three charged leptons are identical in the SM and, consequently, the decay properties (and the hadronic effects) are expected to be the same up to corrections related to the lepton mass, regardless of the lepton flavour – lepton universality.

Suppression of systematic uncertainties

$$R_H = \frac{\int_{q^2_{\min}}^{q^2_{\max}} \frac{\mathrm{d}\Gamma[B \to H\mu^+\mu^-]}{\mathrm{d}q^2}\mathrm{d}q^2}{\int_{q^2_{\min}}^{q^2_{\max}} \frac{\mathrm{d}\Gamma[B \to He^+e^-]}{\mathrm{d}q^2}\mathrm{d}q^2}$$

is unity within $\mathcal{O}(1\%)$

$$R_K = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to J/\psi(\to \mu^+\mu^-)K^+)} \Bigg/ \frac{\mathcal{B}(B^+ \to K^+e^+e^-)}{\mathcal{B}(B^+ \to J/\psi(\to e^+e^-)K^+)}$$

Results use 5.0/fb Run 1+2 data

$$1.1 < q^2 < 6.0\,\mathrm{GeV}^2/c^4$$

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

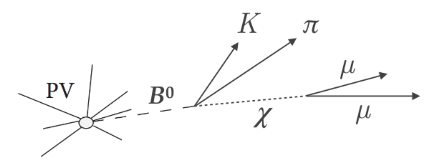
The SM prediction within **2.5** standard deviations.

Search for exotic low mass particles

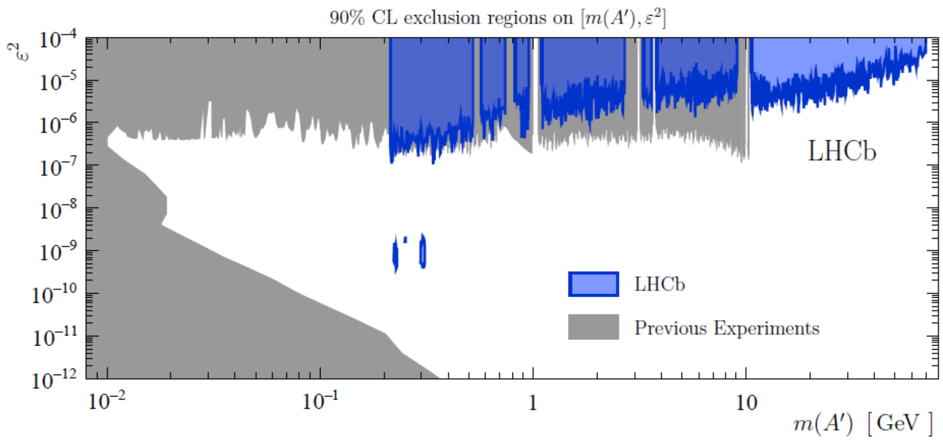
LHCb is capable to exploit low masses and low lifetimes:

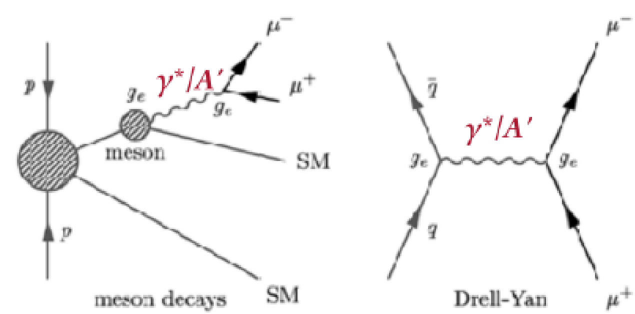
Phys. Rev. Lett. 120 (2018) 221803

- Search for a di-muon resonance in decays $\Sigma^+ \to p\mu^+\mu^-$
- Search for candidates produced in B-hadron decays
- Search for candidates produced in pp-collision, including:
  - ✓ Dark photons decaying into pairs of muons
  - ✓ Dark bosons in the mass region close to Upsilon resonances
  - ✓ Axion-like particles (ALPs) decaying into pairs of photons
  - ✓ Dark pions in SM Higgs decaying into jets



Example of the results: Phys. Rev. Lett. 120 (2018) 061801



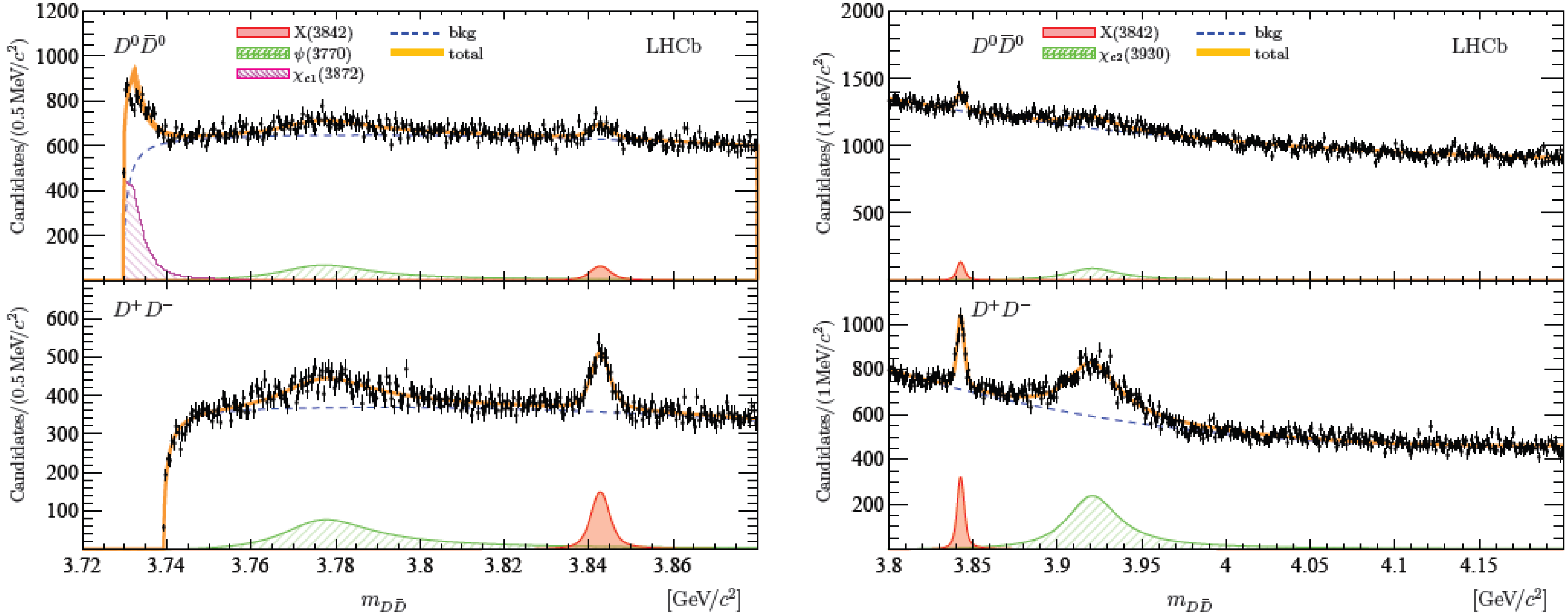


1.6 / fb @ 13 TeV

Hadron spectroscopy: new states

JHEP 07 (2019) 035

(dedicated talks by V.Matyunin and D.Pereima)



New narrow state X(3842) seen in $D^0\bar{D}^0$ and D^+D^-

First **J=3** state observation!

$$m_{X(3842)} = 3842.71 \pm 0.16 \pm 0.12\,\mathrm{MeV}/c^2\,,$$
$$\Gamma_{X(3842)} = 2.79 \pm 0.51 \pm 0.35\,\mathrm{MeV}\,,$$

Mass and width consistent with charmonium state

$\psi_3(1^3D_3)$ $\quad J^{PC} = 3^{--}$

Hadron spectroscopy: pentaquarks

The inventors of the quark model considered multiquark states as equally legitimate with (qqq) and ($\bar{q}$q) back in 1964.

Volume 8, number 3 PHYSICS LETTERS 1 February 1964

A SCHEMATIC MODEL OF BARYONS AND MESONS *

M. GELL-MANN
California Institute of Technology, Pasadena, California

Received 4 January 1964

If we assume that the strong interactions of baryons and mesons are correctly described in terms of the broken "eightfold way" 1-3), we are tempted to look for some fundamental explanation of the situation. A highly promised approach is the purely dynamical "bootstrap" model for all the strongly interacting particles within which one may try to derive isotopic spin and strangeness conservation and broken eightfold symmetry from self-consistency alone 4). Of course, with only strong interactions, the orientation of the asymmetry in the unitary space cannot be specified; one hopes that in some way the selection of specific components of the F-spin by electromagnetism and the weak interactions determines the choice of isotopic spin and hypercharge directions.

Even if we consider the scattering amplitudes of strongly interacting particles on the mass shell only and treat the matrix elements of the weak, electromagnetic, and gravitational interactions by means

ber $n_t - n_{\bar{t}}$ would be zero for all known baryons and mesons. The most interesting example of such a model is one in which the triplet has spin $\frac{1}{2}$ and $z = -1$, so that the four particles d^-, s^-, u^0 and b^0 exhibit a parallel with the leptons.

A simpler and more elegant scheme can be constructed if we allow non-integral values for the charges. We can dispense entirely with the basic baryon b if we assign to the triplet t the following properties: spin $\frac{1}{2}$, $z = -\frac{1}{3}$, and baryon number $\frac{1}{3}$. We then refer to the members $u^{\frac{2}{3}}$, $d^{-\frac{1}{3}}$, and $s^{-\frac{1}{3}}$ of the triplet as "quarks" 6) q and the members of the anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations $(q\,q\,q)$, $(q\,q\,q\,q\,\bar{q})$, etc., while mesons are made out of $(q\,\bar{q})$, $(q\,q\,\bar{q}\,\bar{q})$, etc. It is assuming that the lowest baryon configuration $(q\,q\,q)$ gives just the representations **1**, **8**, and **10** that have been observed, while the lowest meson configuration $(q\,\bar{q})$ similarly gives just **1** and **8**.

AN SU_3 MODEL FOR STRONG INTERACTION SYMMETRY AND ITS BREAKING

G. Zweig *)
CERN - Geneva

8182/TH.401
17 January 1964

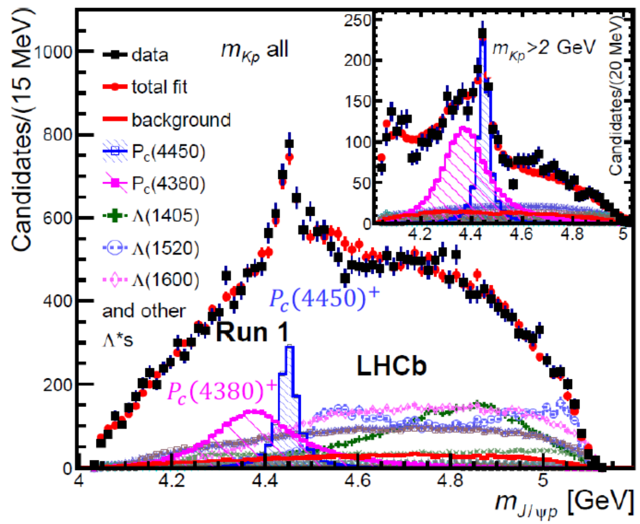
A B S T R A C T

...

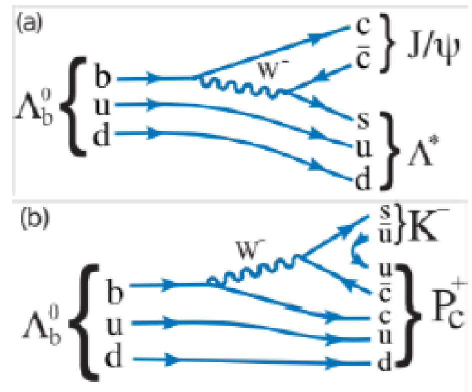
In general, we would expect that baryons are built not only from the product of three aces, AAA, but also from $\bar{A}AAAA$, $\bar{A}\bar{A}AAAAA$, etc., where $\bar{A}$ denotes an anti-ace. Similarly, mesons could be formed from $\bar{A}A$, $\bar{A}\bar{A}AA$ etc. For the low mass mesons and baryons we will assume the simplest possibilities, $\bar{A}A$ and AAA, that is, "deuces and treys".

However only in 2015 LHCb announced the discovery of two pentaquark states: **P_c (4450)$^+$** (narrow) and **P_c (4380)$^+$** (broad).

PRL 115 (2015) 072001



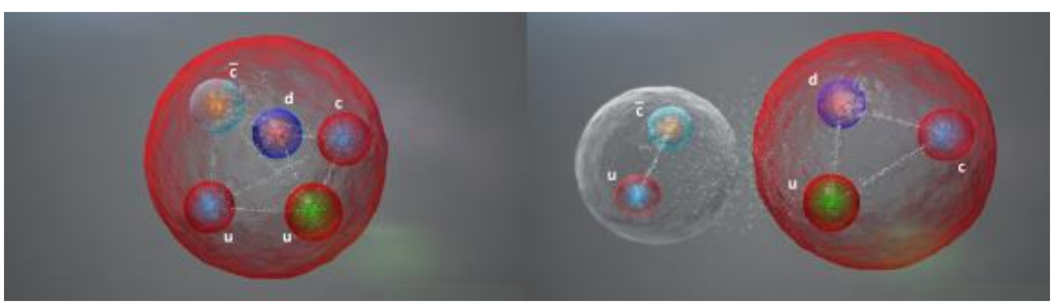
Phys. Rev. Lett. 115 (2015) 072001



Full angular analysis of Run1 data on decays $\Lambda_b^0 \to J/\psi p K^-$

Two states with a clear resonant structure decaying to $J/\psi p$

The results attracted lots of theoretical interest. Models with tightly bound object vs loosely bound (molecular-like) states.

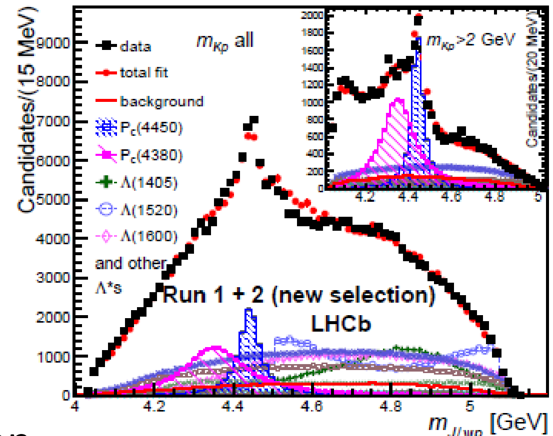


New results from the analysis on the full data sample (Run1+Run2)

Phys. Rev. Lett. 122 (2019) 222001

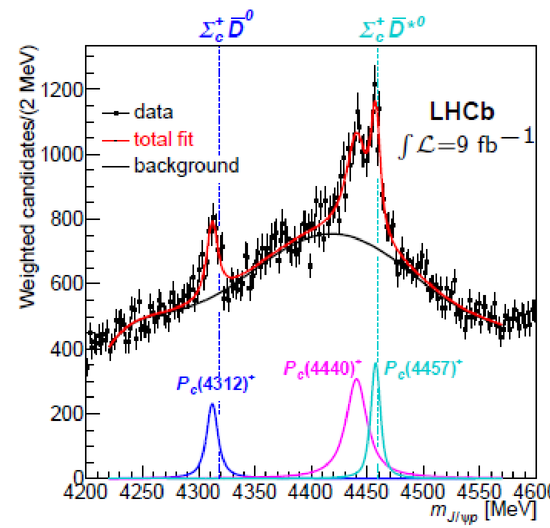
$$\Lambda_b^0 \to J/\psi\, p K^-$$

Larger data set is consistent with the old one, but more accurate – allows finer binning



Results:

- **P$_c$ (4450)$^+$** narrow state is resolved in two states: **P$_c$ (4440)$^+$** and **P$_c$ (4457)$^+$** with widths ~ mass resolution
- Evidence for a 3rd narrow state
- 1D mass fit is inconclusive about the presence of broad state **P$_c$ (4380)$^+$** – need full angular analysis



State	M [MeV]	Γ [MeV]	(95% CL)
$P_c(4312)^+$	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	$9.8 \pm 2.7^{+\ 3.7}_{-\ 4.5}$	(< 27)
$P_c(4440)^+$	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+\ 8.7}_{-10.1}$	(< 49)
$P_c(4457)^+$	$4457.3 \pm 0.6^{+4.1}_{-1.7}$	$6.4 \pm 2.0^{+\ 5.7}_{-\ 1.9}$	(< 20)

Hadron spectroscopy: heavy baryons lifetimes

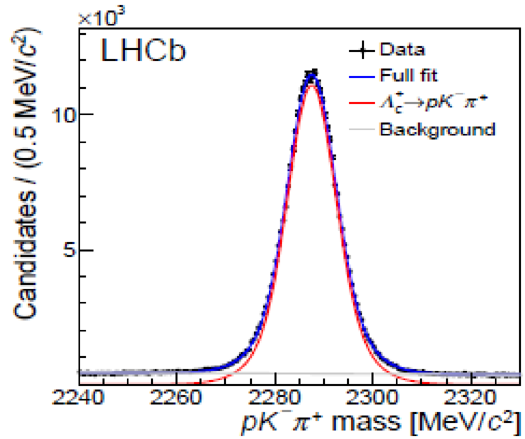
Channels:

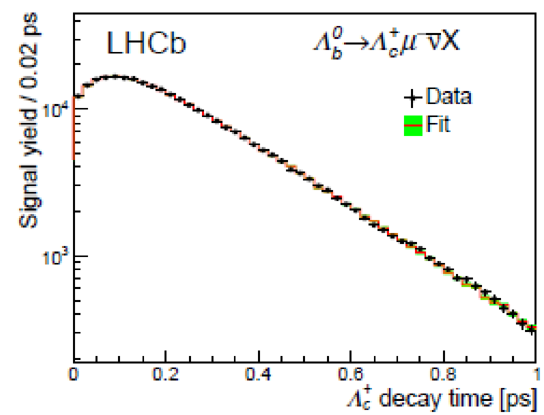
$$\Xi_c^+ \to pK^-\pi^+$$

$$\Lambda_c^+ \to pK^-\pi^+$$

$$\Xi_c^0 \to pK^-K^-\pi^+$$

Larger statistics of signal than any previous measurement



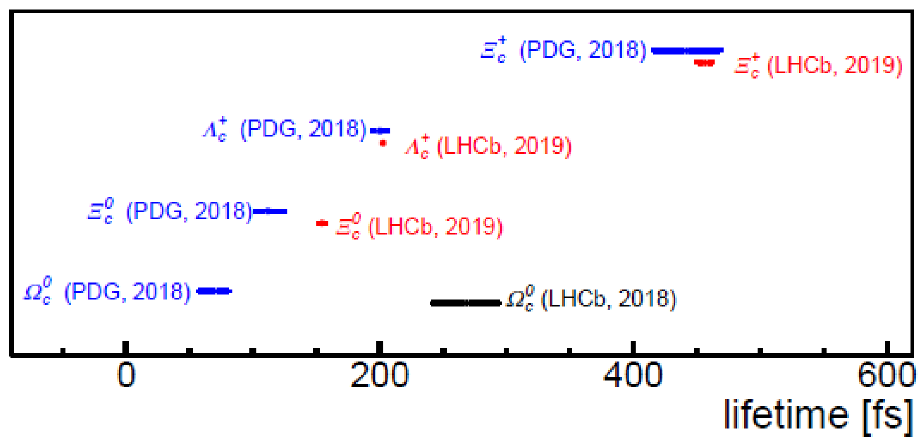


Phys. Rev. D 100 (2019) 032001   Phys. Rev. Lett. 121 (2018) 092003

Results:

$$\boxed{\begin{aligned} \tau_{\Lambda_c^+} &= 203.5 \pm 1.0 \pm 1.3 \pm 1.4 \text{ fs}, \\ \tau_{\Xi_c^+} &= 456.8 \pm 3.5 \pm 2.9 \pm 3.1 \text{ fs}, \\ \tau_{\Xi_c^0} &= 154.5 \pm 1.7 \pm 1.6 \pm 1.0 \text{ fs}, \end{aligned}}$$

$\tau_{\Xi_c^0}$ is 3.3 σ from PDG



uncertainties are statistical, systematic, and due to the uncertainty in the **D⁺** lifetime.

Hadron spectroscopy: new resonances in $\Lambda_b^0\pi^+\pi^-$

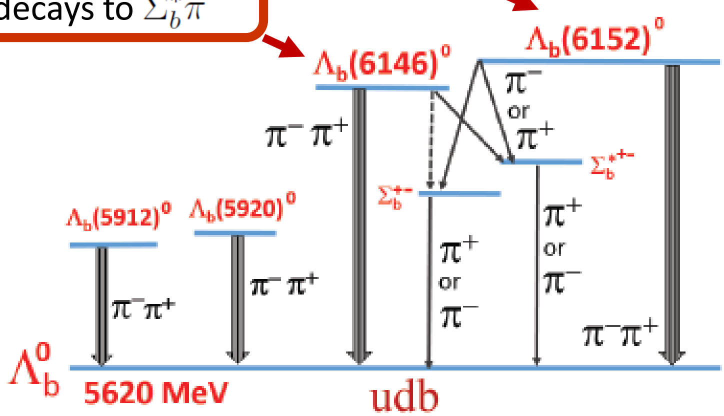
Two close narrow states are found:

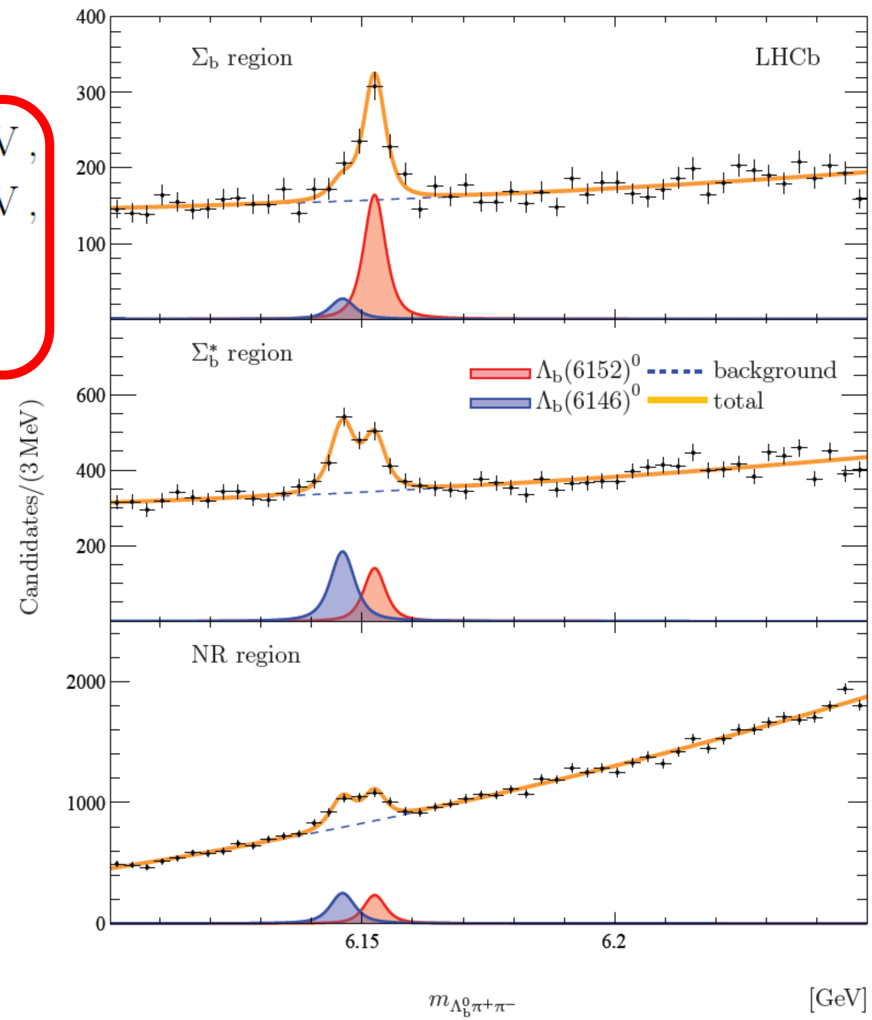
$$\begin{aligned}
m_{\Lambda_b(6146)^0} &= 6146.17 \pm 0.33 \pm 0.22 \pm 0.16\,\text{MeV}\,,\\
m_{\Lambda_b(6152)^0} &= 6152.51 \pm 0.26 \pm 0.22 \pm 0.16\,\text{MeV}\,,\\
\Gamma_{\Lambda_b(6146)^0} &= 2.9 \pm 1.3 \pm 0.3\ \text{MeV}\,,\\
\Gamma_{\Lambda_b(6152)^0} &= 2.1 \pm 0.8 \pm 0.3\ \text{MeV}\,,
\end{aligned}$$

Decays to $\Sigma_b\pi$ and $\Sigma_b^*\pi$

arXiv: 1907.13598

Predominantly decays to $\Sigma_b^*\pi$





Motivation for upgrade

Experimental accuracy of many observables is still statistically limited.

Type	Observable	Current precision	LHCb 2018	**Upgrade** ($50\,\mathrm{fb}^{-1}$)	Theory uncertainty
B_s^0 mixing	$2\beta_s\ (B_s^0 \to J/\psi\ \phi)$	0.10 [9]	0.025	0.008	~ 0.003
	$2\beta_s\ (B_s^0 \to J/\psi\ f_0(980))$	0.17 [10]	0.045	0.014	~ 0.01
	$A_{\mathrm{fs}}(B_s^0)$	6.4×10^{-3} [18]	0.6×10^{-3}	0.2×10^{-3}	0.03×10^{-3}
Gluonic penguin	$2\beta_s^{\mathrm{eff}}(B_s^0 \to \phi\phi)$	–	0.17	0.03	0.02
	$2\beta_s^{\mathrm{eff}}(B_s^0 \to K^{*0}\bar{K}^{*0})$	–	0.13	0.02	< 0.02
	$2\beta^{\mathrm{eff}}(B^0 \to \phi K_S^0)$	0.17 [18]	0.30	0.05	0.02
Right-handed currents	$2\beta_s^{\mathrm{eff}}(B_s^0 \to \phi\gamma)$	–	0.09	0.02	< 0.01
	$\tau^{\mathrm{eff}}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	–	5 %	1 %	0.2 %
Electroweak penguin	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	0.08 [14]	0.025	0.008	0.02
	$s_0\ A_{\mathrm{FB}}(B^0 \to K^{*0}\mu^+\mu^-)$	25 % [14]	6 %	2 %	7 %
	$A_{\mathrm{I}}(K\mu^+\mu^-; 1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	0.25 [15]	0.08	0.025	~ 0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	25 % [16]	8 %	2.5 %	~ 10 %
Higgs penguin	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	1.5×10^{-9} [2]	0.5×10^{-9}	0.15×10^{-9}	0.3×10^{-9}
	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	–	~ 100 %	~ 35 %	~ 5 %
Unitarity triangle angles	$\gamma\ (B \to D^{(*)}K^{(*)})$	~ 10–$12°$ [19, 20]	4°	0.9°	negligible
	$\gamma\ (B_s^0 \to D_s K)$	–	11°	2.0°	negligible
	$\beta\ (B^0 \to J/\psi\ K_S^0)$	0.8° [18]	0.6°	0.2°	negligible
Charm *CP* violation	A_Γ	2.3×10^{-3} [18]	0.40×10^{-3}	0.07×10^{-3}	–
	ΔA_{CP}	2.1×10^{-3} [5]	0.65×10^{-3}	0.12×10^{-3}	–

Table from Framework TDR, many current estimates are better

CERN-LHCC-2012-007

Upgrade I

1. CERN-LHCC-2008-007
2. CERN-LHCC-2011-001
3. CERN-LHCC-2012-007
4. CERN-LHCC-2013-021
5. CERN-LHCC-2013-022
6. CERN-LHCC-2014-001
7. CERN-LHCC-2014-016
8. CERN-LHCC-2018-007
9. CERN-LHCC-2018-014
10. CERN-LHCC-2019-005

Conditions:

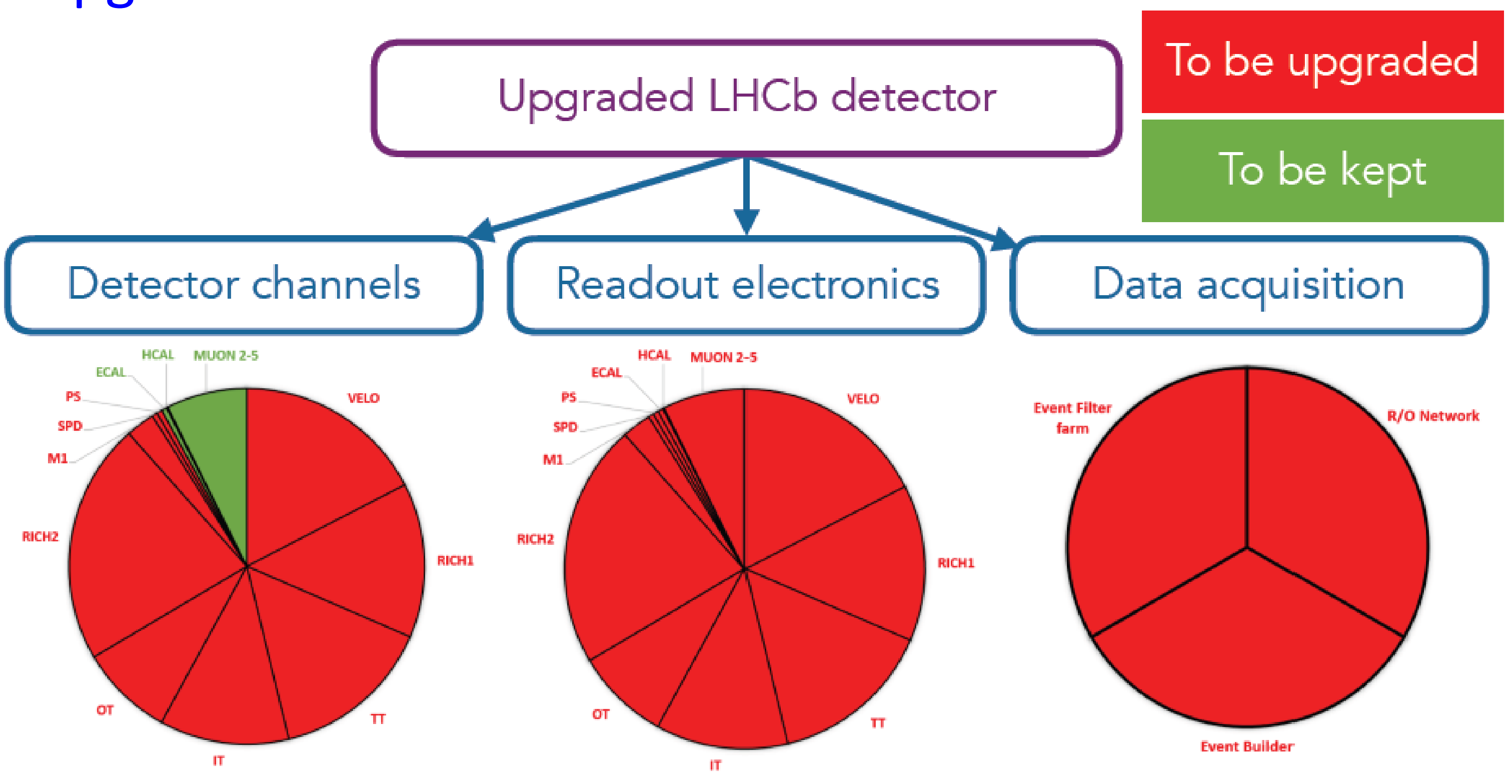
- Luminosity: $\mathbf{2{\times}10^{33}}$ cm^{-2}s^{-1} (instantaneous), **50** fb^{-1}
- **5.2** visible interactions / crossing.

Challenge:

- Maintain current reconstruction performance
- Read out the complete detector at **40** MHz.

CERN-LHCC-2012-007

Upgrade I

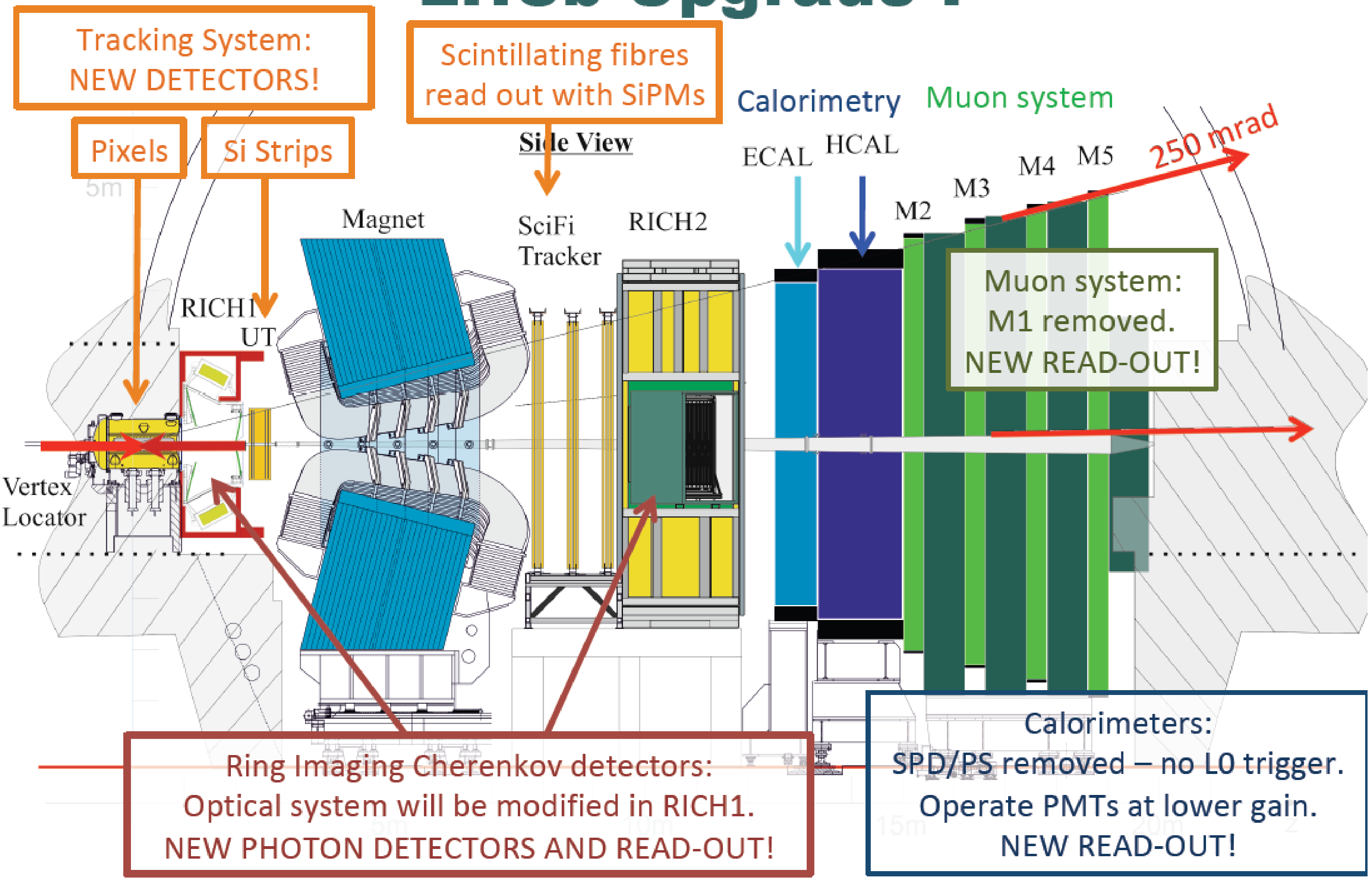


- Less than 10% of the detector will be kept
- 100% of the readout electronics will be replaced
- NEW data acquisition system and data center

The new detector, in fact

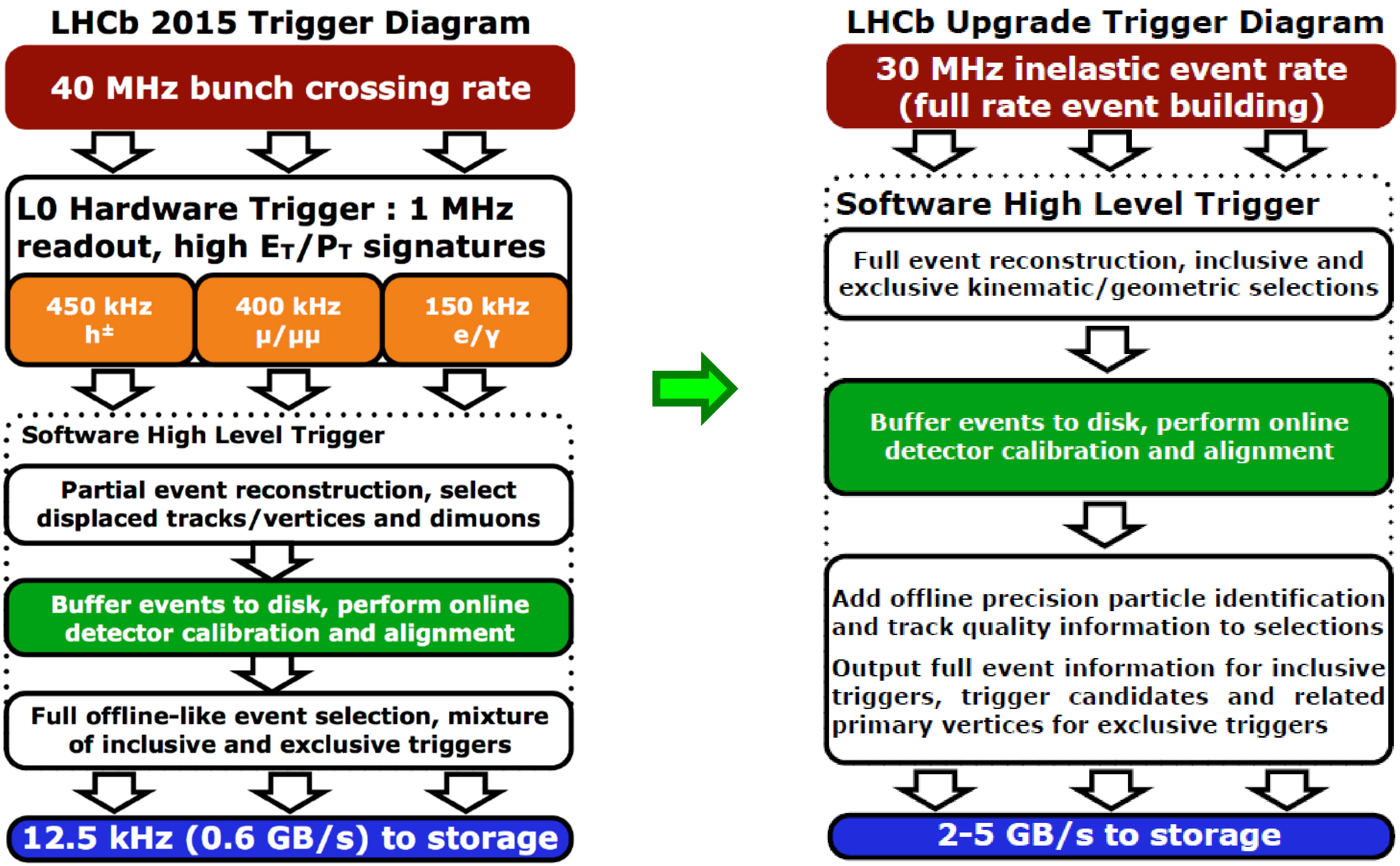
(V.Bellee, at KAON 2019)

LHCb Upgrade I



(M.Tobin, at 139th LHCC Meeting)

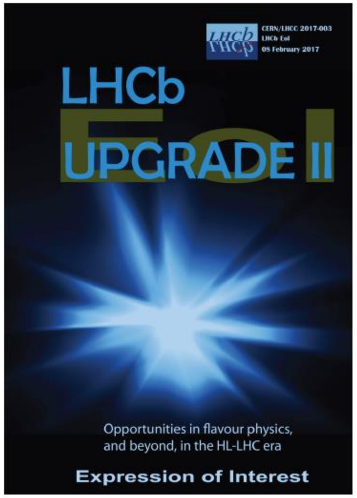
L0 hardware trigger limits the rate to **1** MHz – removing this stage implies data processing at ~ bunch crossing rate

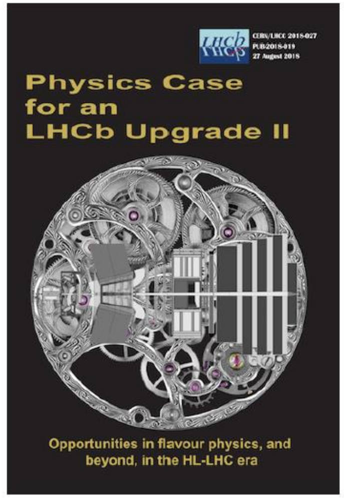


Upgrade I – work is ongoing and will be finished on time

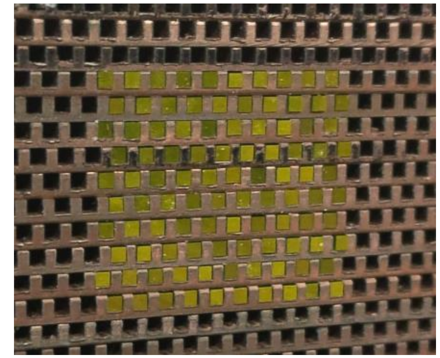
(K.Müller, EPS 2019)

Upgrade II – active R&D across collaboration





1. CERN-LHCC-2017-003
2. CERN-LHCC-2018-027



SPACAL prototype

Conditions:

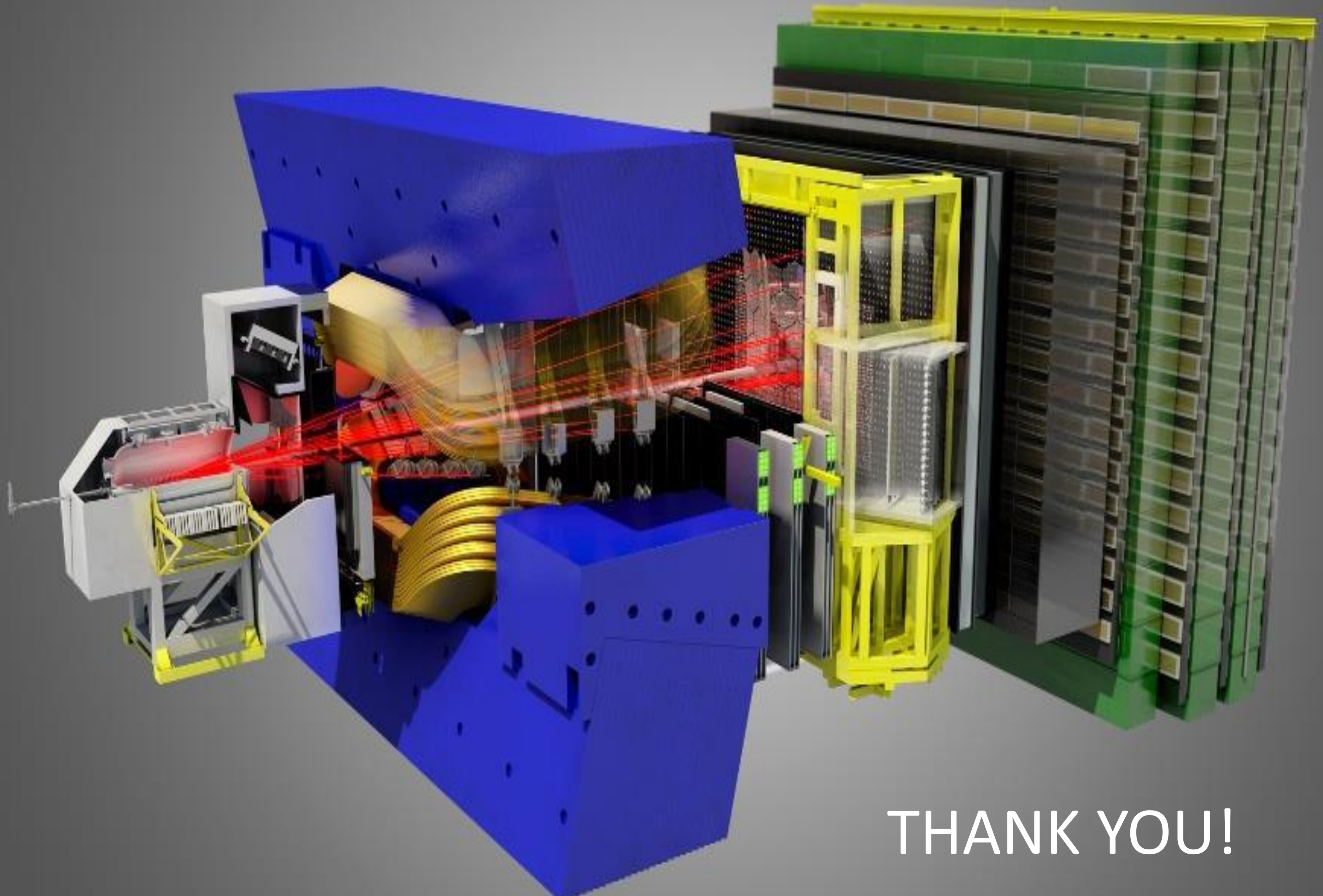
- Luminosity: **1.5×10^{34}** cm^{-2}s^{-1} (instantaneous), **300** fb^{-1}
- **~40** visible interactions / crossing.

Challenge:

- Maintain current reconstruction performance
- Develop detector with timing information for VELO & PID
- …

Conclusion

- 2018 run completed a successful first phase of LHCb
- We were delivered 10/fb which was the goal in our TP in 1998
- A wealth of excellent physics results
  - ✓ Superseded WA precision in several measurements of heavy flavour
  - ✓ Finally established CP violation in charm decays
  - ✓ Lots of interesting results in hadron spectroscopy
- Upgrade I – all subsystems progressing, installation ongoing
- Run 3: 5x the instantaneous luminosity and a completely new readout/trigger, aim to collect 50/fb by end of Run 4
- Upgrade II - green light from LHCC to proceed to TDRs and clear case at ESPP



THANK YOU!