LHCb : recent physics results and upgrades

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On behalf of the LHCb collaboration

Standard Model

accurately describes a very large number of measurements

is unable to answer key-questions:

- dark matter candidate ?
- source of baryon asymmetry generation ?
- origin of flavour (and what underlies the family replication) ?
- source of the hierarchy in the W couplings to the different quarks ?

We are not anymore « theory-guided »
⇒ precise measurements are the clue towards understanding

How to find cracks in the SM fortress ?

Direct evidence for new particles

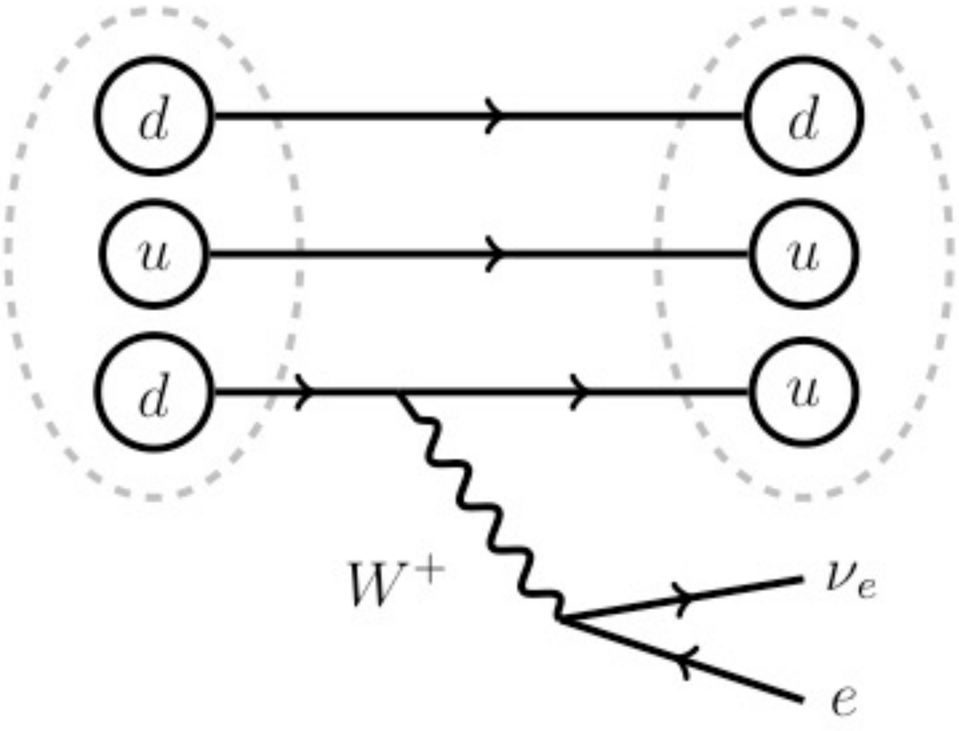
Indirect evidence through precision measurements sensitive to the presence of virtual states present in the decay of SM particles

Indirect searches

β decay of the neutron

Phenomena taking place at ~ 1 GeV reveals physics at the 100 GeV scale

M ~ 1 GeV



M ~ 1 GeV

History is telling us that Flavour physics is a key-tool

Probes scales >> 1 TeV (depending on c_{NP})

CP violation and FCNC : sensitive probes of short distance physics

Many tests limited by statistics not by systematics nor theory

$$A(\psi_i \rightarrow \psi_j + X) = A_0\left(\frac{c_{\mathrm{SM}}}{v^2} + \frac{c_{\mathrm{NP}}}{\Lambda_{\mathrm{NP}}^2}\right)$$

NP scale and coupling

PLB 192 (1987)

OBSERVATION OF B^0–$\bar{B}^0$ MIXING

ARGUS Collaboration

In summary, the combined evidence of the investigation of B^0 meson pairs, lepton pairs and B^0 meson–lepton events on the Υ (4S) leads to the conclusion that B^0–$\bar{B}^0$ mixing has been observed and is substantial.

Parameters	Comments
$r > 0.09$ (90%CL)	this experiment
$x > 0.44$	this experiment
$B^{1/2} f_B \approx f_\pi < 160$ MeV	B meson ($\approx$ pion) decay constant
$m_b < 5$ GeV/c^2	b-quark mass
$\tau < 1.4 \times 10^{-12}$ s	B meson lifetime
$\lvert V_{td} \rvert < 0.018$	Kobayashi–Maskawa matrix element
$\eta_{QCD} < 0.86$	QCD correction factor [a]
$m_t > 50$ GeV/c^2	t quark mass

1987 B_d mixing $\sqrt{s}$=10 GeV (ARGUS)

$$\Delta m_d \sim 0.00002 \times \left(\frac{m_t}{\mathrm{GeV}/c^2}\right)^2 \mathrm{ps}^{-1} \sim 0.5\ \mathrm{ps}^{-1}$$

$\Rightarrow m_t$ >50 GeV

1964 $K_L \rightarrow \pi\pi$: CP violation
3 families

Where to look ?

Two driving ingredients :

1. Precise SM predictions (if beyond-SM predictions are precise it is even better)
2. Excellent experimental precision

What to do ?

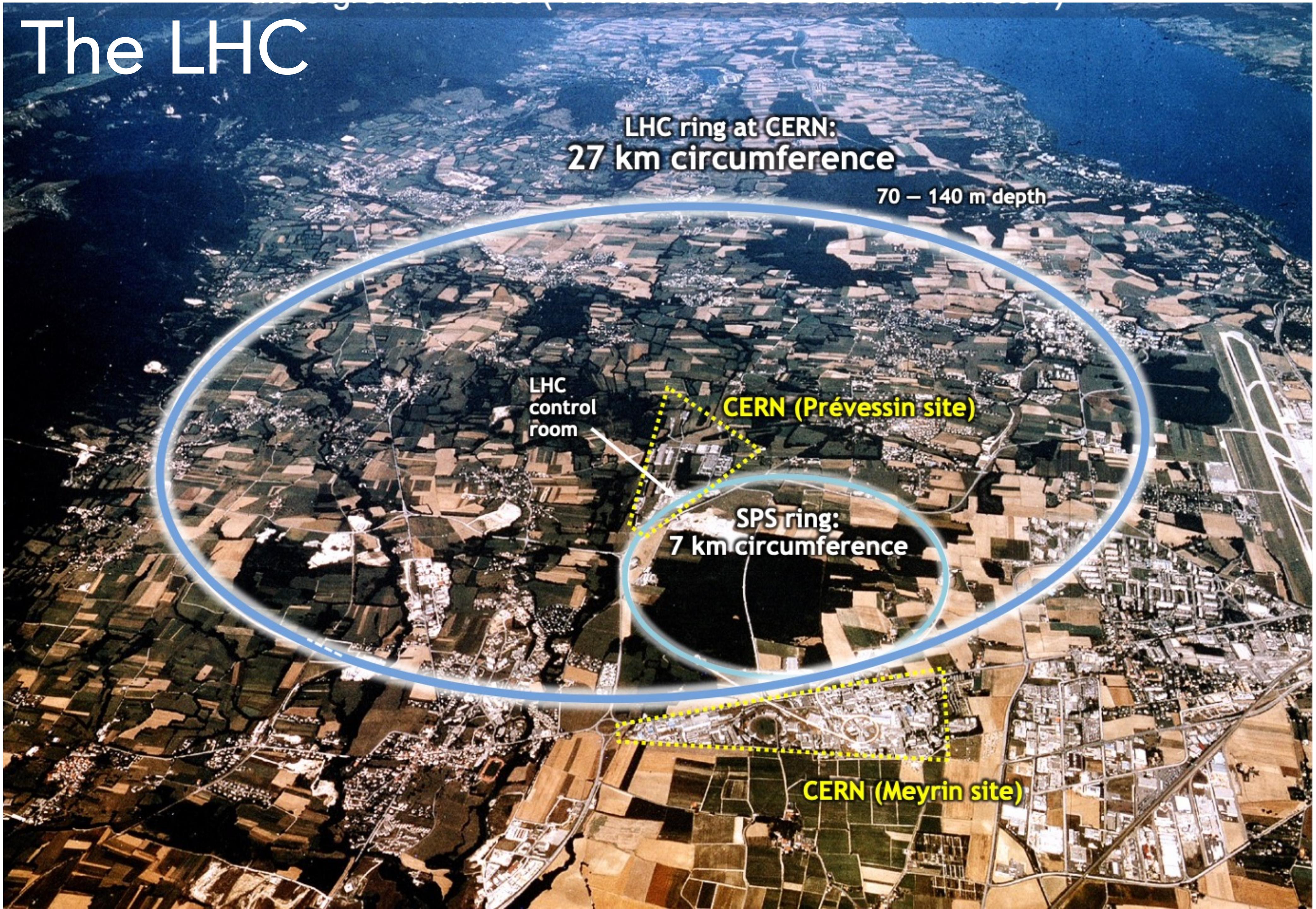
Better understanding of the SM

Challenging the SM

Strong interaction

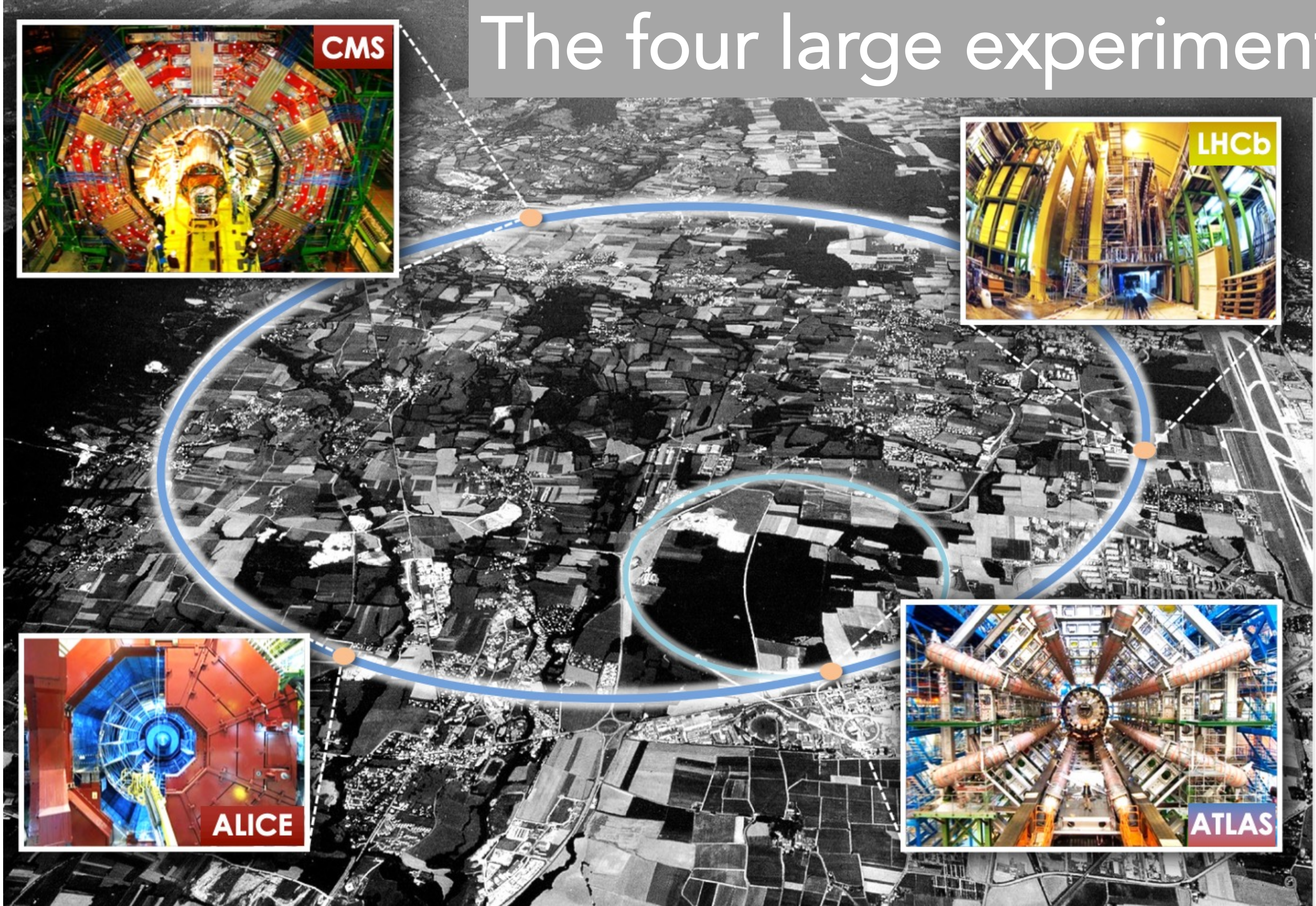
Weak & electromagnetic interactions

The LHC



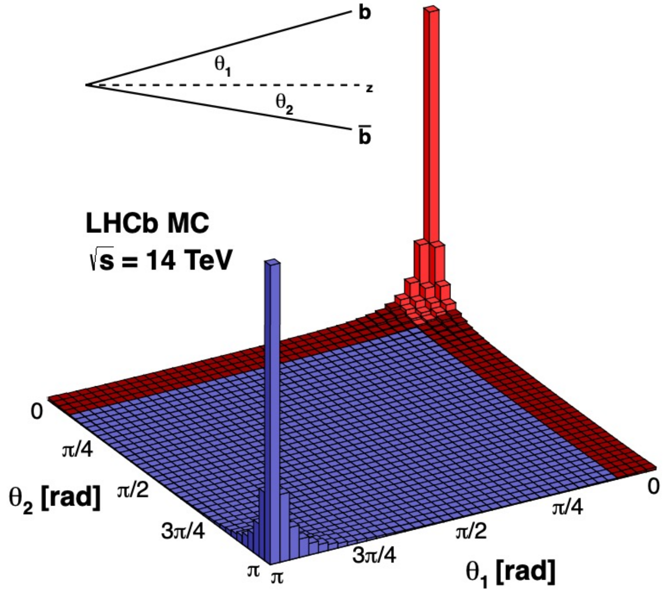
LHC ring at CERN:
27 km circumference
70 – 140 m depth
LHC
control
room
CERN (Prévessin site)
SPS ring:
7 km circumference
CERN (Meyrin site)

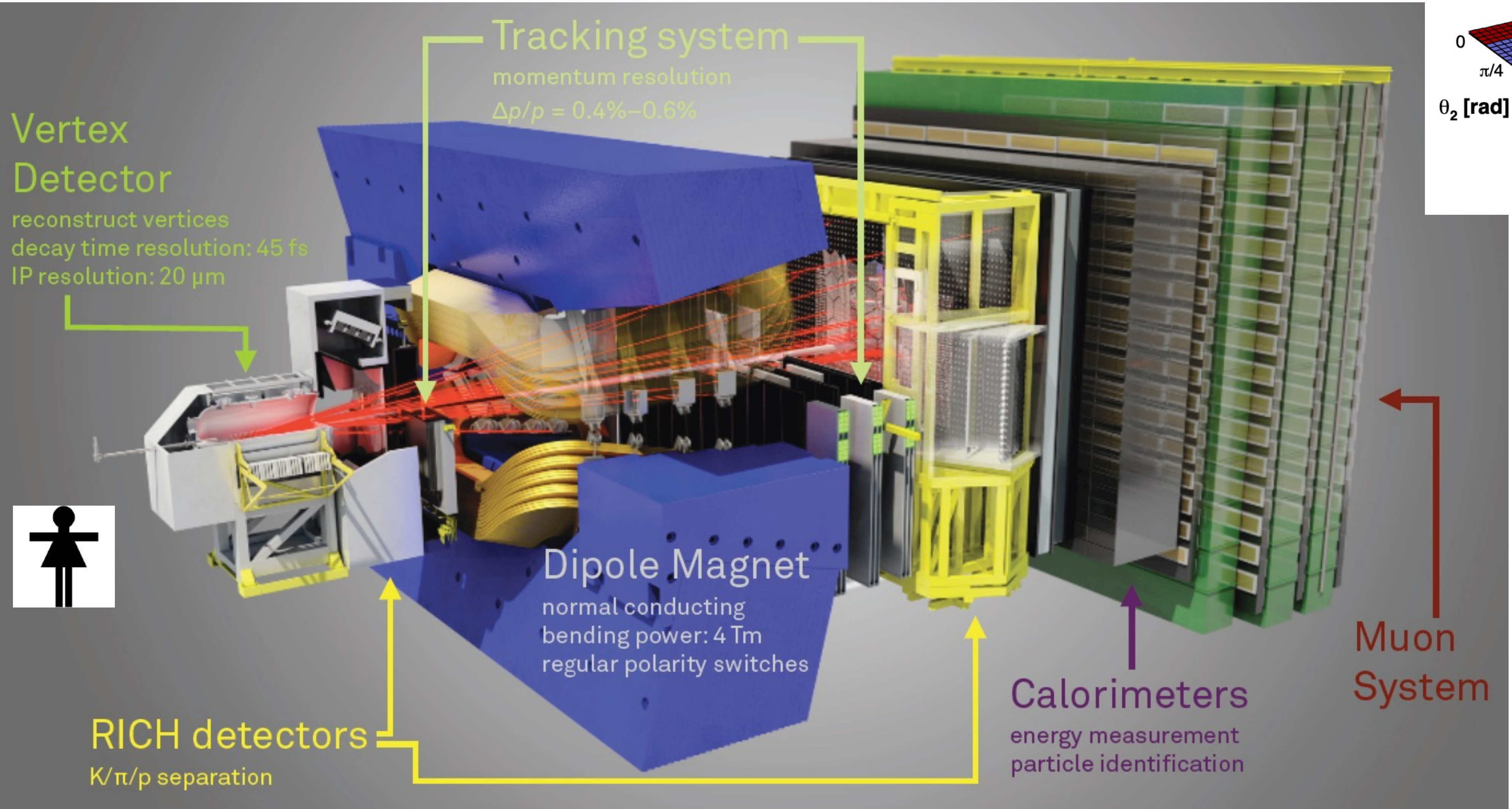
The four large experiments

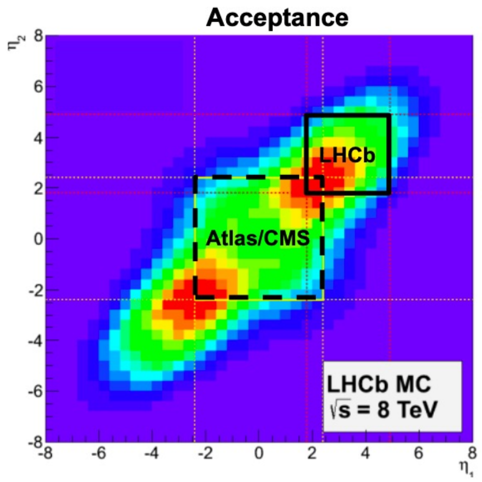


The LHCb detector

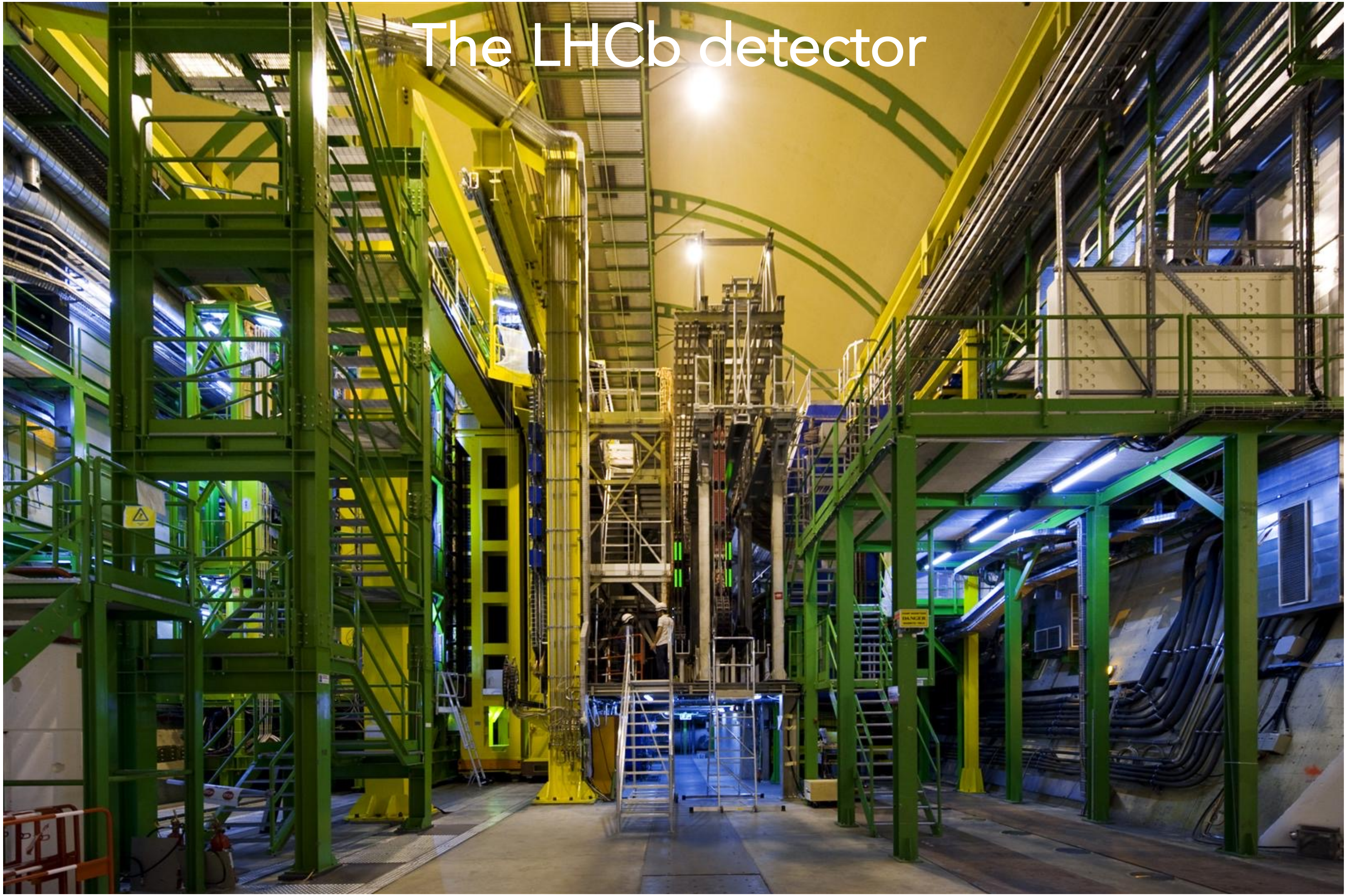
40% of the heavy quark production cross-section in 4% of the solid angle
All type of *b*-hadrons produced



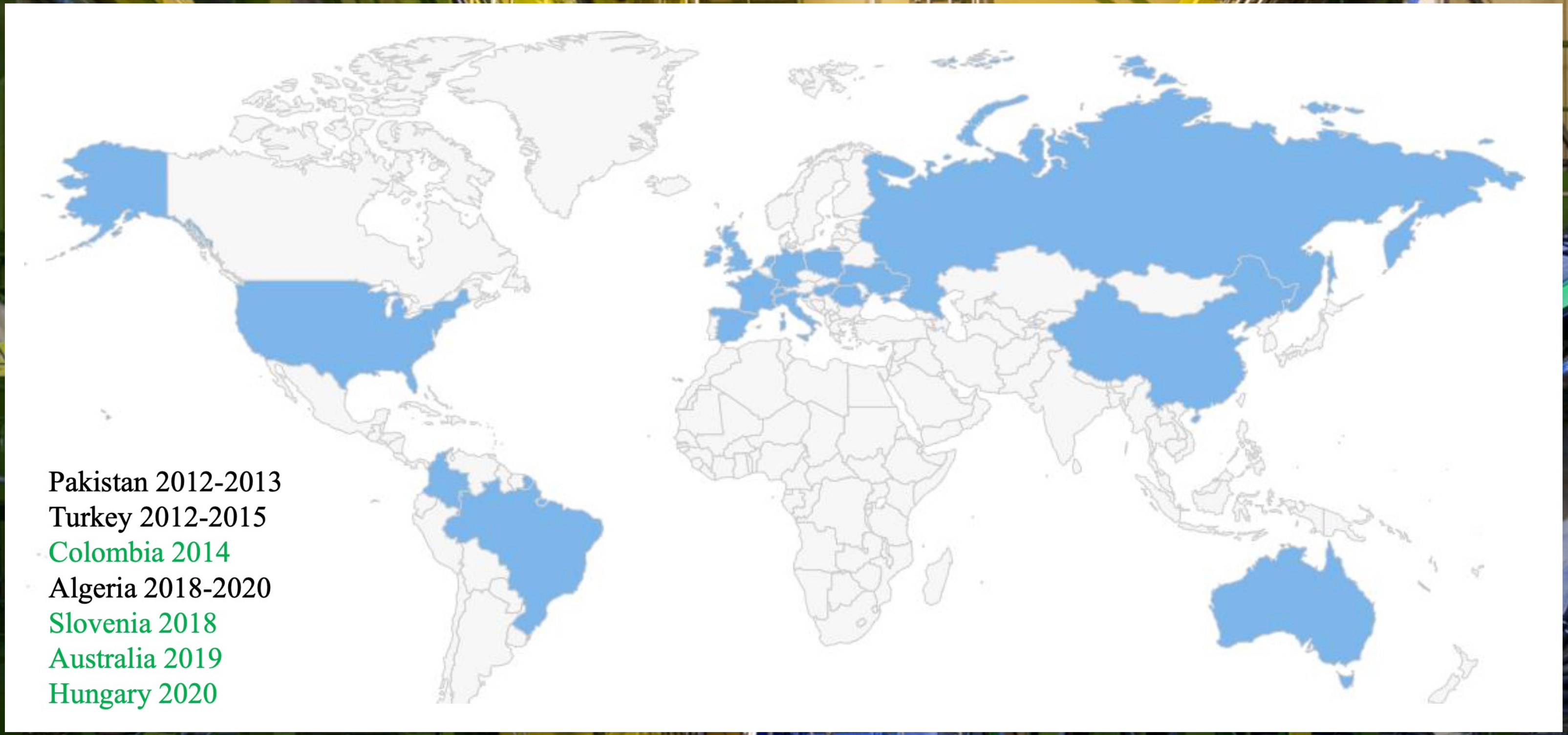




The LHCb detector



in 2021 : 1000 authors from 86 universities or laboratories



LHCb is a multipurpose detector in the forward region

Better understanding of the SM

Challenging the SM

QCD

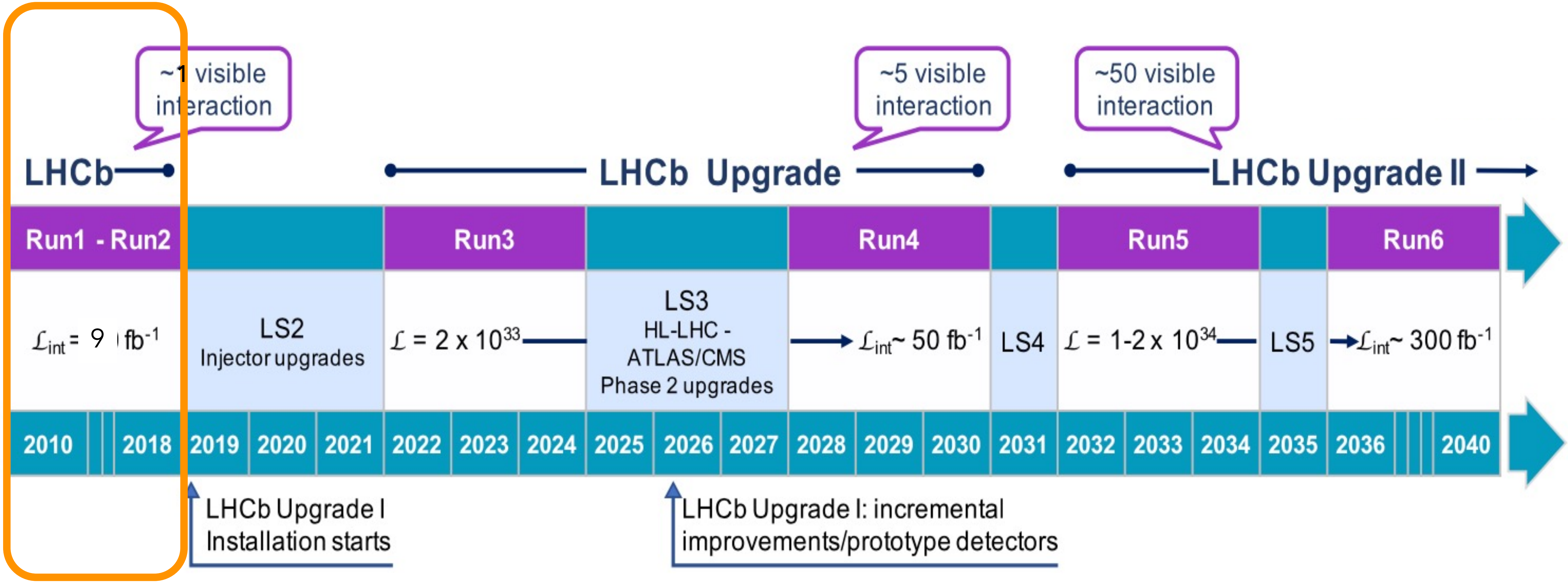
QED & weak int.

Heavy flavour production
Pentaquark and tetraquark states
Cold nuclear effects in heavy ion collisions
Fixed target collisions

Decays of *b*- and *c*- hadrons
CPV in *b*- and *c*- hadrons

Direct searches for beyond-SM particles

LHCb schedule



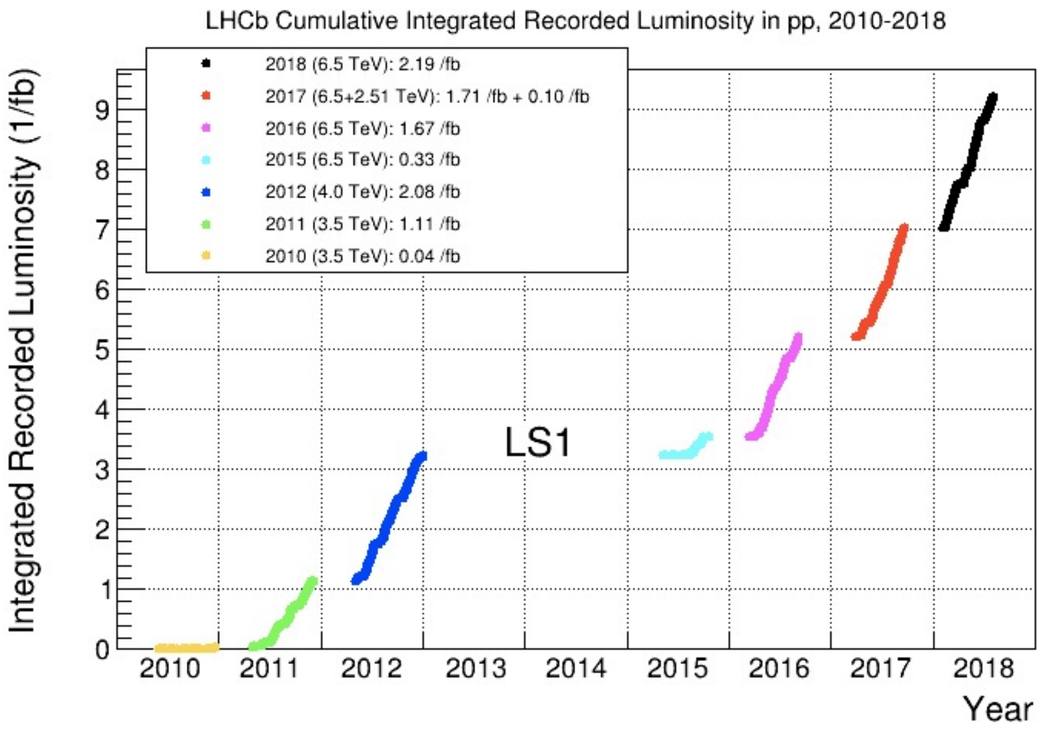
A set of (highly-selected) recent results from Run1 & Run2 data samples

- Rare decays
- CKM matrix : V_{ub} and B_s mixing
- CP violation in charm
- Exotic states

Democritus (460 -370 B.C)

Life with no festivity is a long road without an inn

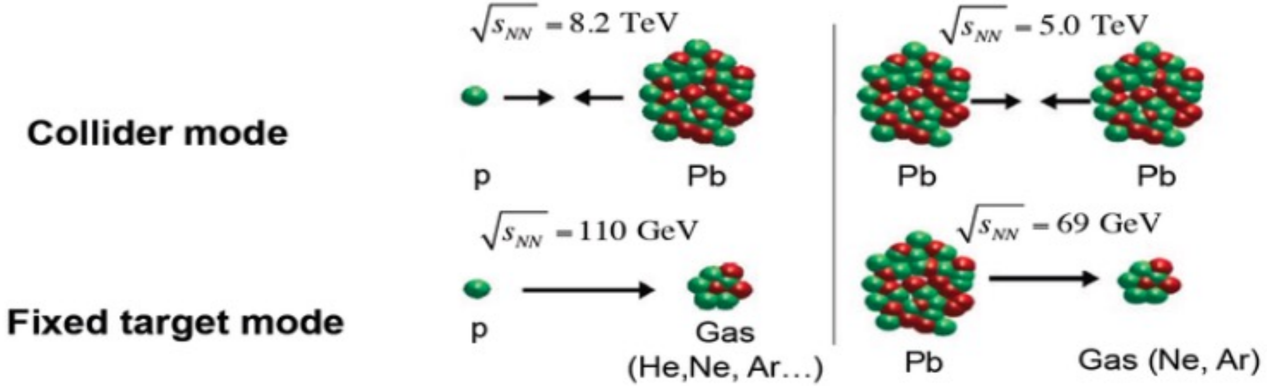
A large sample of pp collisions



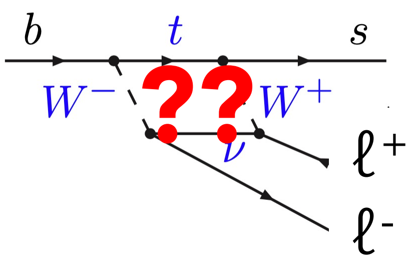
Run 1 (2011 – 2012 at 7 and 8 TeV): ~ 3 fb^{-1}

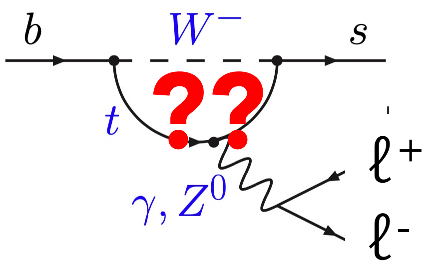
Run 2 (2015 – 2018 at 13 TeV): ~ 6 fb^{-1}

but also :



Rare decays : Flavour-changing $b \rightarrow s$ neutral current





Forbidden at tree-level in SM → BR of $10^{-6} – 10^{-10}$
New physics contribution can be same order as SM

Relative importance of the different diagrams varies with $q^2 = M^2(\ell^+\ell^-)$

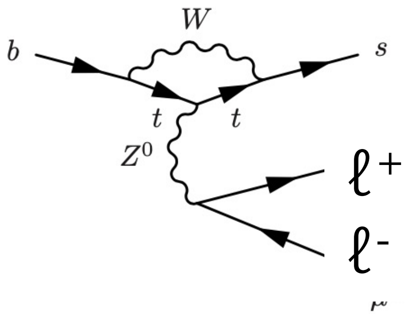
Effective-Hamiltonian approach

$$\mathscr{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}}\frac{e^2}{16\pi^2}V_{tb}V_{ts}^*\sum_i C_i O_i + \text{h.c.}$$

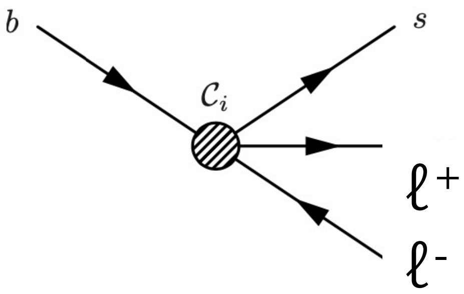
NP enters here $C_i = C_i^{\text{SM}} + C_i^{\text{NP}}$

Operator encoding Lorentz structure

Full theory



Effective description

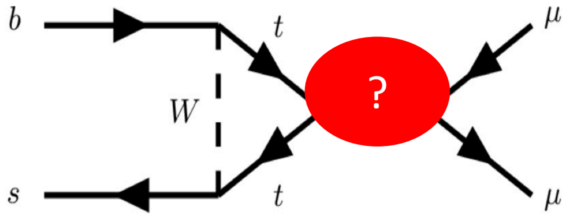


~ Fermi's description of the neutron decay

Decay	$C_7^{(\prime)}$	$C_9^{(\prime)}$	$C_{10}^{(\prime)}$	$C_{S,P}^{(\prime)}$
$B \rightarrow X_s\gamma$	X			
$B \rightarrow K^*\gamma$	X			
$B \rightarrow X_s\ell^+\ell^-$	X	X	X	
$B \rightarrow K^{(*)}\ell^+\ell^-$	X	X	X	
$B_s \rightarrow \mu^+\mu^-$			X	X

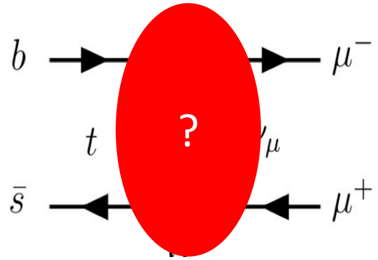
$B_{d,s} \to \mu\mu$

$$\mathcal{B}(B_q^0 \to \mu^+\mu^-)_{SM} = \frac{\tau_{B_q} G_F^4 M_W^4 \sin^4\theta_W}{8\pi^5} |C_{10}^{SM} V_{tb} V_{tq}^*|^2 f_{B_q}^2 m_{B_q} m_\mu^2 \sqrt{1 - \frac{4m_\mu^2}{m_{B_q}^2}} \frac{1}{1-y_q} \qquad q = d, s$$



single Wilson coefficient & single hadronic constant (known at $\simeq 0.5\,\%$!)

[PRD 98 (2019) 074512]

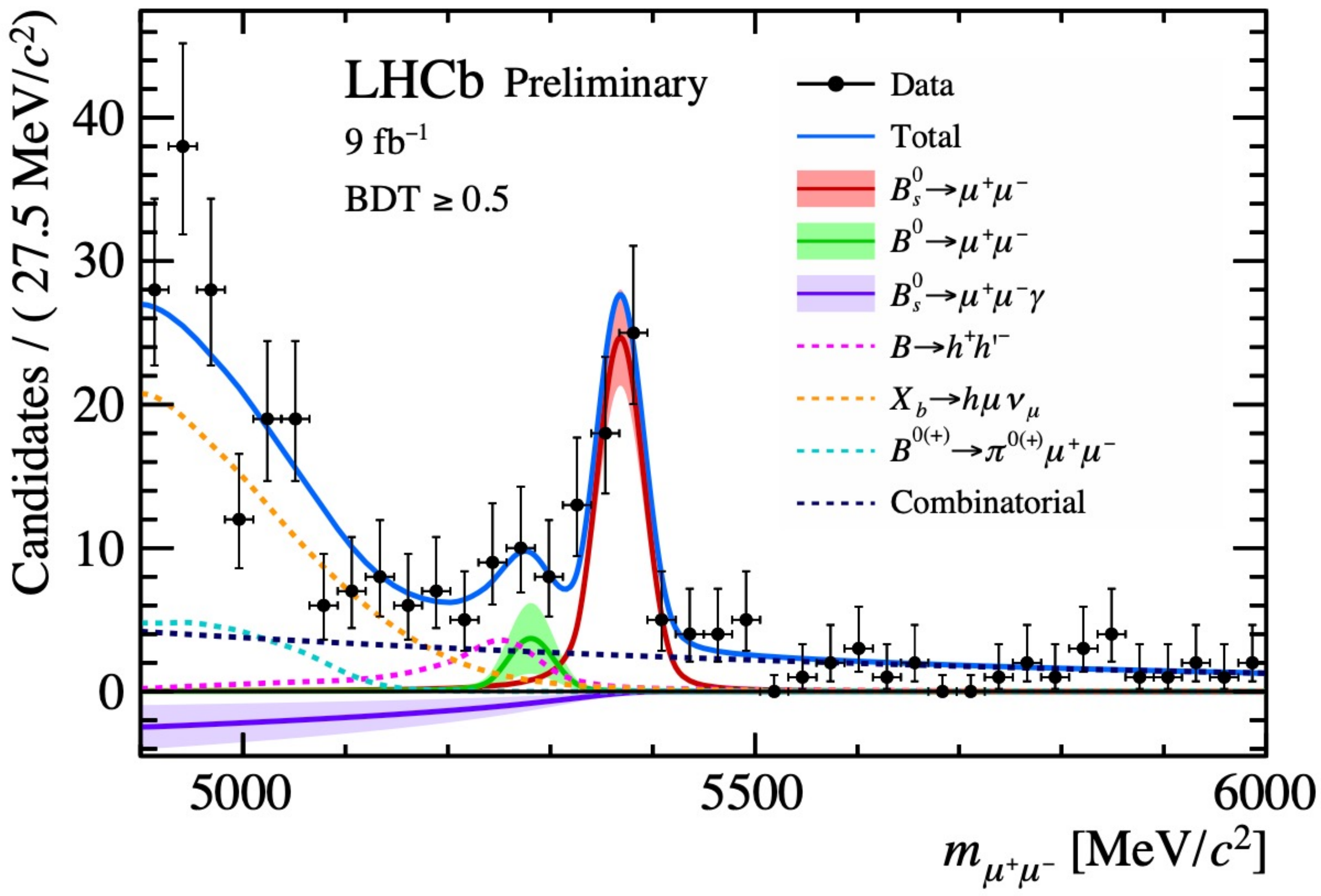


$$\mathcal{B}(B_s^0 \to \mu^+\mu^-)_{SM} = (3.66 \pm 0.14) \times 10^{-9}$$

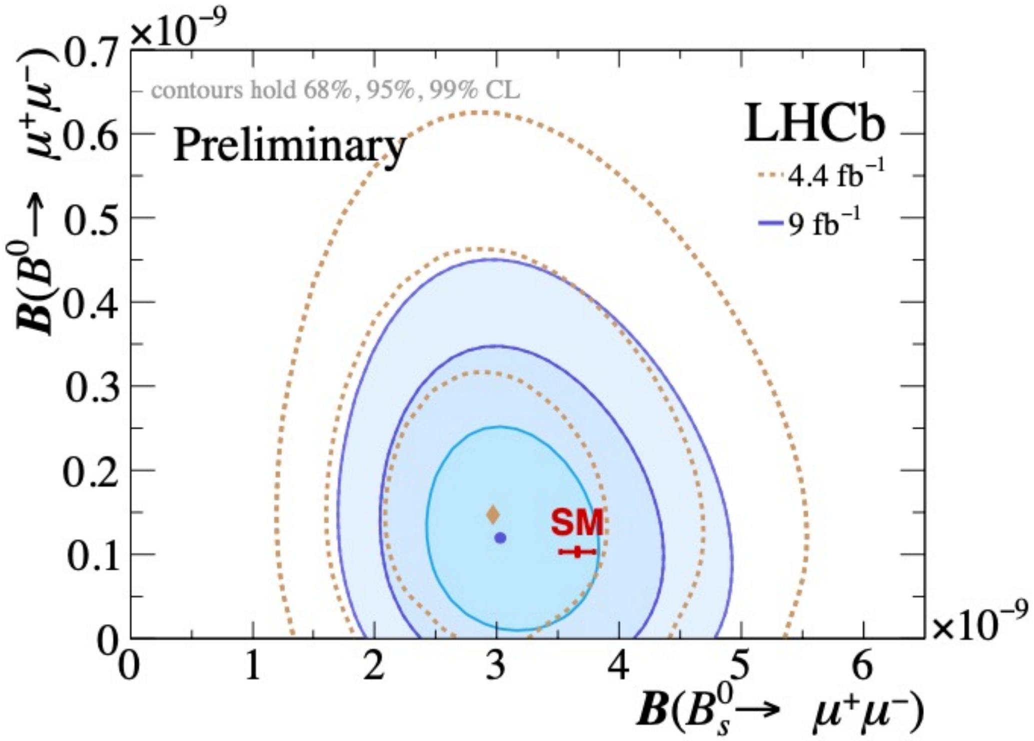
$$\mathcal{B}(B^0 \to \mu^+\mu^-)_{SM} = (1.03 \pm 0.05) \times 10^{-10}$$

[JHEP 10 (2019) 232]

- The rarest modes (helicity suppression)
- Due to the value of the CKM elements , the B_d mode is further suppressed
- Clean experimental signature



LHCB-PAPER-2021-007



- $\mathscr{B}(B_s^0 \to \mu^+\mu^-) = (3.09^{+0.46+0.15}_{-0.43-0.11}) \times 10^{-9}$ (10.8σ)

- $B^0 \to \mu^+\mu^-$ and $B_s^0 \to \mu^+\mu^-\gamma$ compatible with background only at 1.7σ and 1.5σ

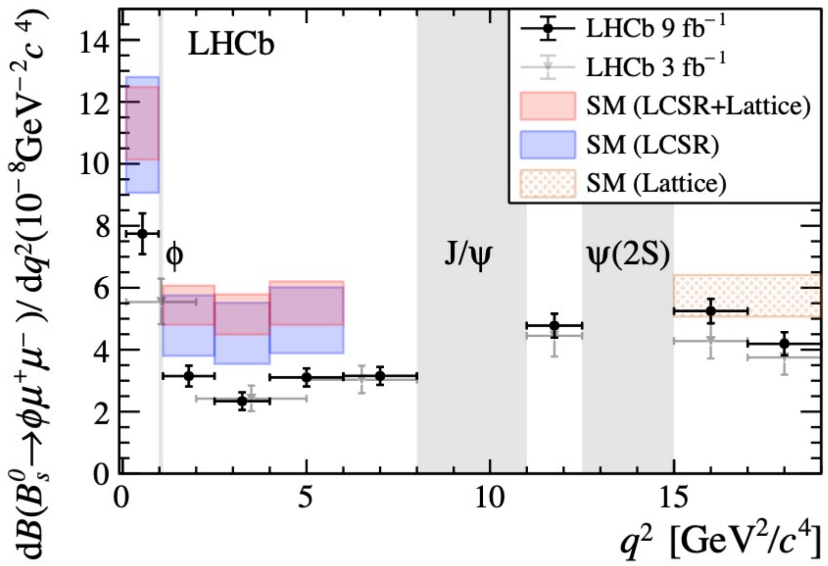
Rare decays : $b \to s\ell\ell$ transitions

$B \to K^{(*)} \ell\ell$, $B_s \to \phi\ell\ell$, $\Lambda_b \to \Lambda^{(*)} \ell\ell$ …

Rich phenomenology:

- Branching Ratios (but large theoretical uncertainties due to non-perturbative QCD)
- Angular observables
- Ratios of BF (test of Lepton Universality)

A recent example : BR ($B_s \to \phi\mu\mu$)



All BR($b \to s\mu\mu$) have a tendency to be low wrt SM prediction

arXiv:2105.14007

b → sℓℓ : the R_{Hs} (R_K , R_{K*} , R_ϕ , R_{pK} …) ratios

$$R_{H_s} = \frac{\mathcal{B}(B \to H_s\mu^+\mu^-)}{\mathcal{B}(B \to H_s e^+e^-)} \overset{SM}{\simeq} 1$$

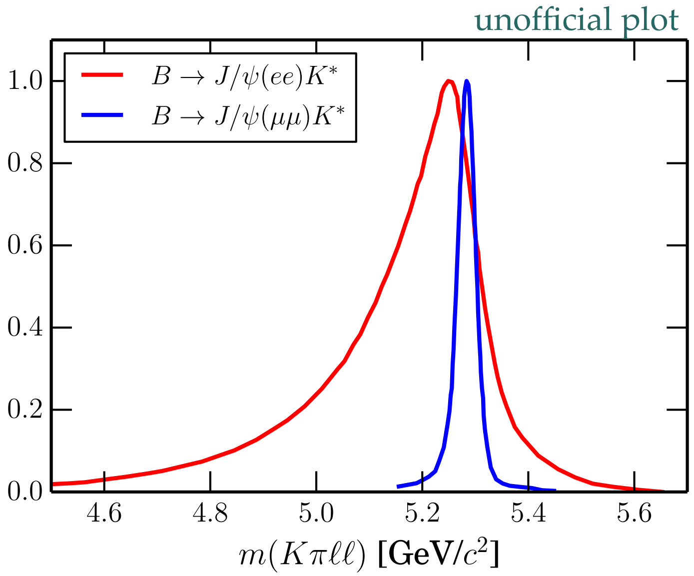
H_s = K, K*, ϕ ….   in a M_{ll}^2 (=q^2) bin

but

Electrons and muons are experimentally very different :

- Bremsstrahlung emission
- Lower efficiency for the electron Trigger (L0)

- Control the Monte Carlo description with unbiased control samples from data



From Martino Borsato

- Check that the determination of the absolute electron/muon scale is under control via the measurement of

$$r_{J/\psi} = \frac{\mathcal{B}(B \to H_s J/\psi(\mu^+\mu^-))}{\mathcal{B}(B \to H_s J/\psi(e^+e^-))}$$

$$\frac{\Gamma(J/\psi \to e^+e^-)}{\Gamma(J/\psi \to \mu^+\mu^-)} = 1.0016 \pm 0.0031$$

PDG

- Use a double ratio

$$R_{H_s} = \frac{\mathcal{B}(B \to H_s\mu^+\mu^-)}{\mathcal{B}(B \to H_s J/\psi(\mu^+\mu^-))} \times \frac{\mathcal{B}(B \to H_s J/\psi(e^+e^-))}{\mathcal{B}(B \to H_s e^+e^-)} =$$

$$\frac{N(B\to H_s\mu^+\mu^-)}{N(B\to H_s J/\psi(\mu^+\mu^-))} \times \frac{N(B\to H_s J/\psi(e^+e^-))}{N(B\to H_s e^+e^-)} \times \frac{\epsilon(B\to H_s J/\psi(\mu^+\mu^-))}{\epsilon(B\to H_s\mu^+\mu^-)} \times \frac{\epsilon(B\to H_s e^+e^-)}{\epsilon(B\to H_s J/\psi(e^+e^-))}$$

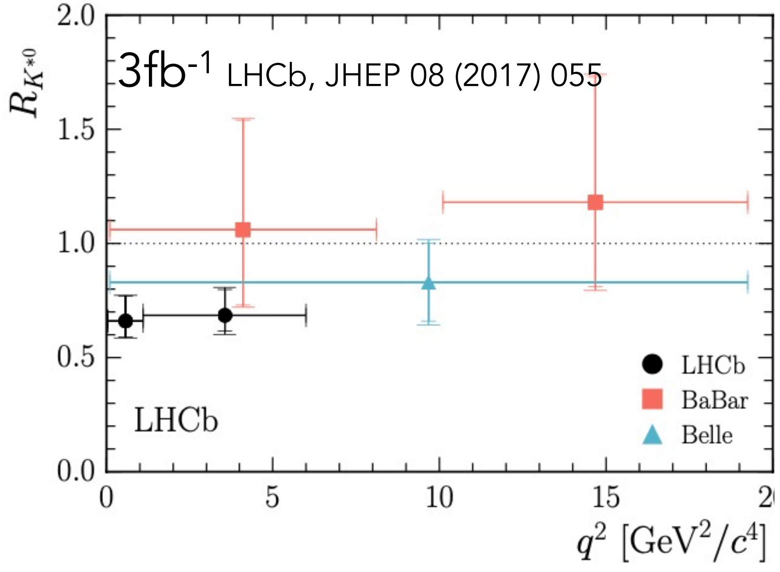
Systematic uncertainties cancel to a large extent

$b \to s\ell\ell$: the R_{Hs} (R_K , R_{K*} , R_ϕ , R_{pK} …) ratios

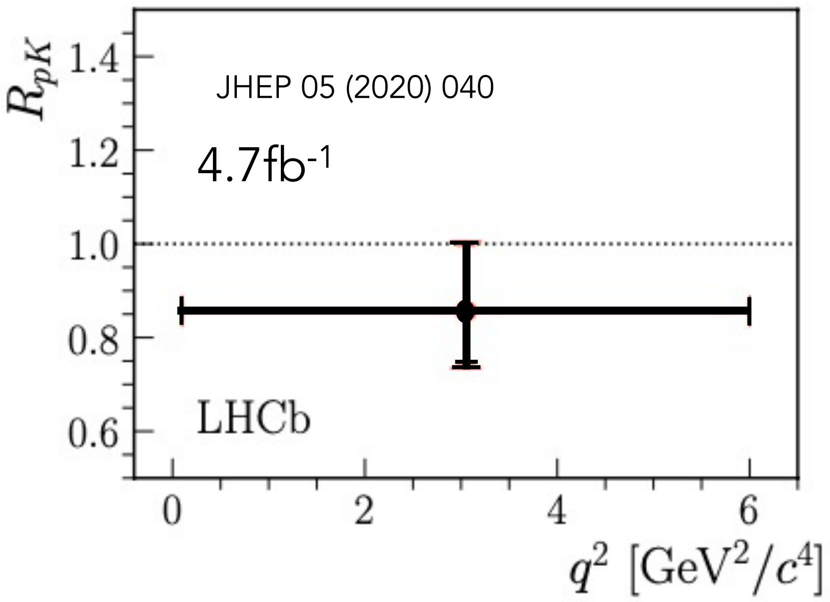
$$R_{H_s} = \frac{\mathcal{B}(B \to H_s \mu^+\mu^-)}{\mathcal{B}(B \to H_s e^+ e^-)}$$

H_s = K, K*, ϕ ….   in a M_{ll}^2 (=q^2) bin

H_s = K*

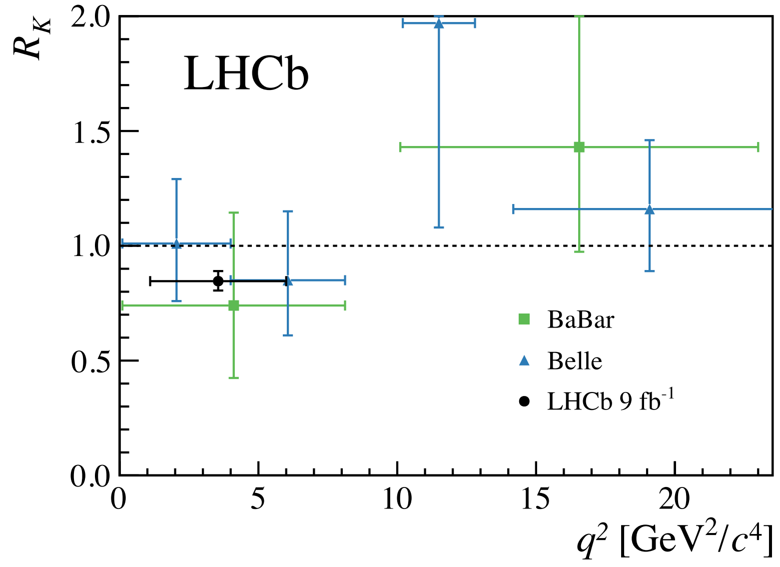


H_s = pK



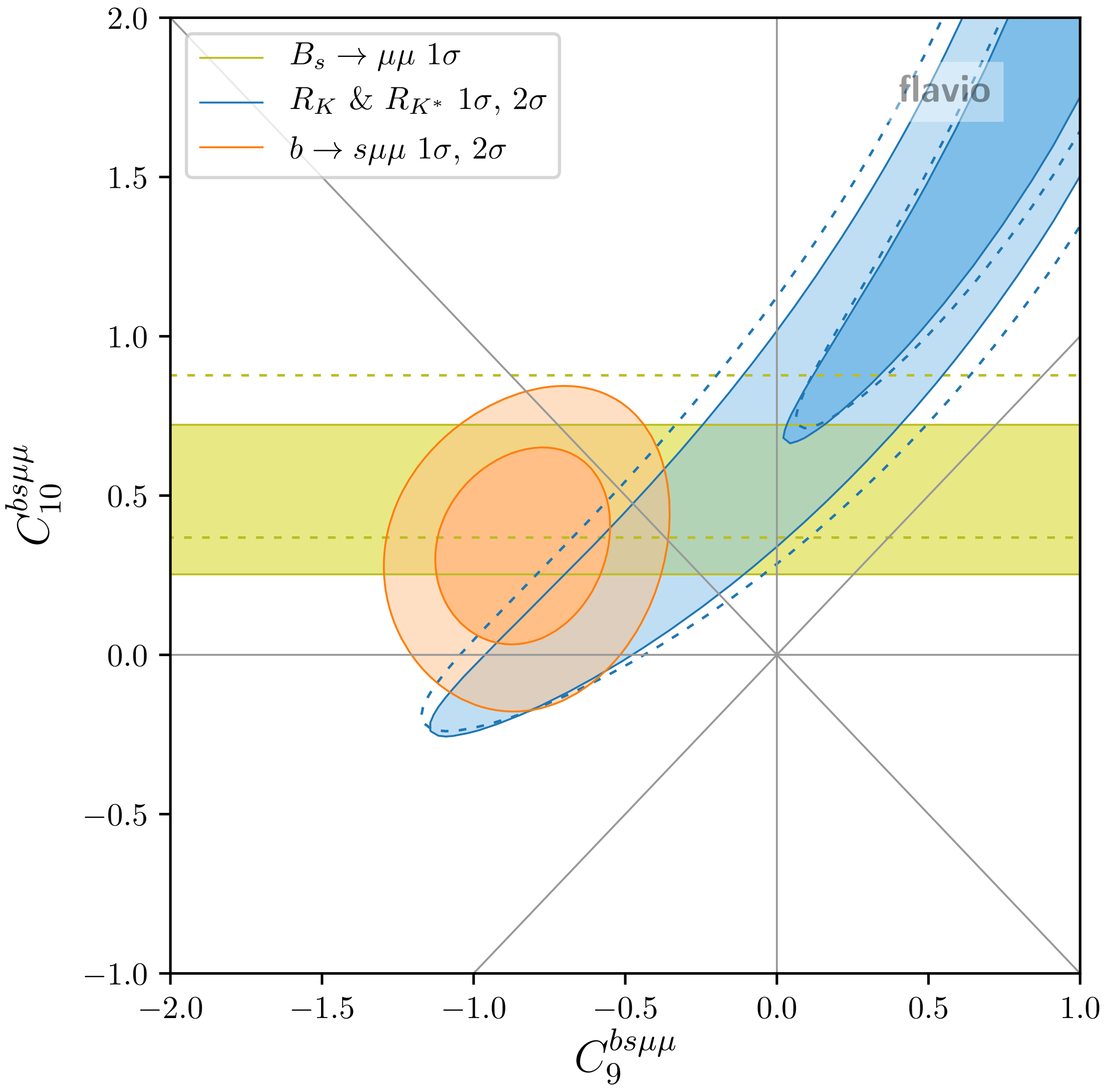
H_s = K

arXiv:2103.11769



3.1σ from SM prediction

arXiv:2103.13370

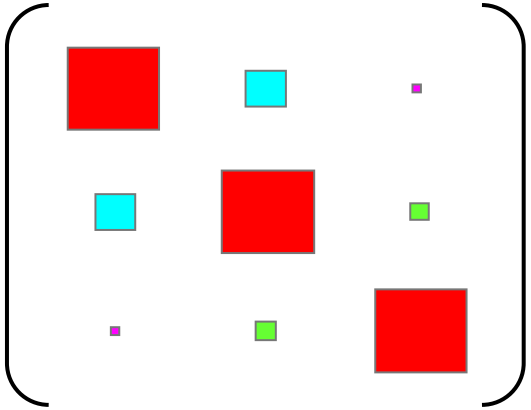


Angular observables and Lepton Universality measurements can be explained together

More data needed

The CKM matrix

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} =$$



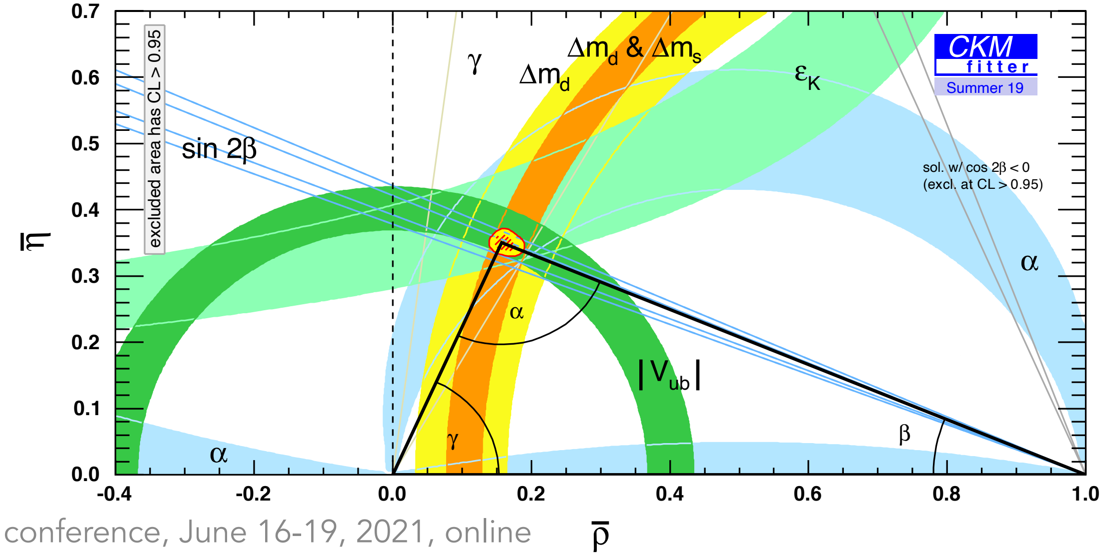
$$\begin{pmatrix} 0.97401 \pm 0.00011 & 0.22650 \pm 0.00048 & 0.00361^{+0.00011}_{-0.00009} \\ 0.22636 \pm 0.00048 & 0.97320 \pm 0.00011 & 0.04053^{+0.00083}_{-0.00061} \\ 0.00854^{+0.00023}_{-0.00016} & 0.03978^{+0.00082}_{-0.00060} & 0.999172^{+0.000024}_{-0.000035} \end{pmatrix}$$

Origin of this structure ?

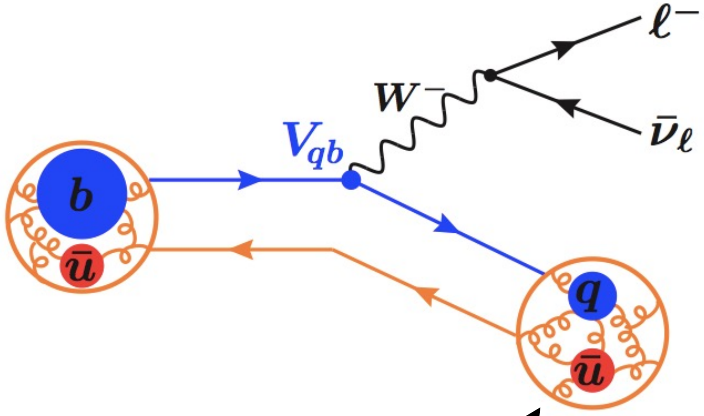
The CKM matrix is unitary ⇒ 4 parameters and several unitary equations

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

Important role played by V_{ub} (and V_{cb})



Semileptonic decays



if a ground state easier theoretical calculation

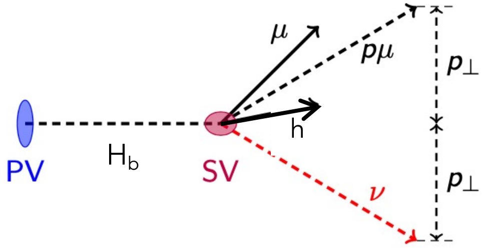
$$\frac{d\Gamma}{dq^2} = \frac{G_F^2 |V_{ub}|^2 p_\pi^3}{24\pi^3} |f^+(q^2)|^2$$

→ measurement of V_{ub} x Form Factor

Challenging modes in the LHC environment (ν)

but precise reconstruction of the vertices :
→ background rejection
→ additional kinematical constraint

$$M_{corr} = \sqrt{p_\perp^2 + M_{h\mu}^2} + p_\perp$$



No access to absolute branching ratios

PID is crucial to reduce the background → focus on decays with clear signatures :

2 fb^{-1} @ 8 TeV
(2012 data)

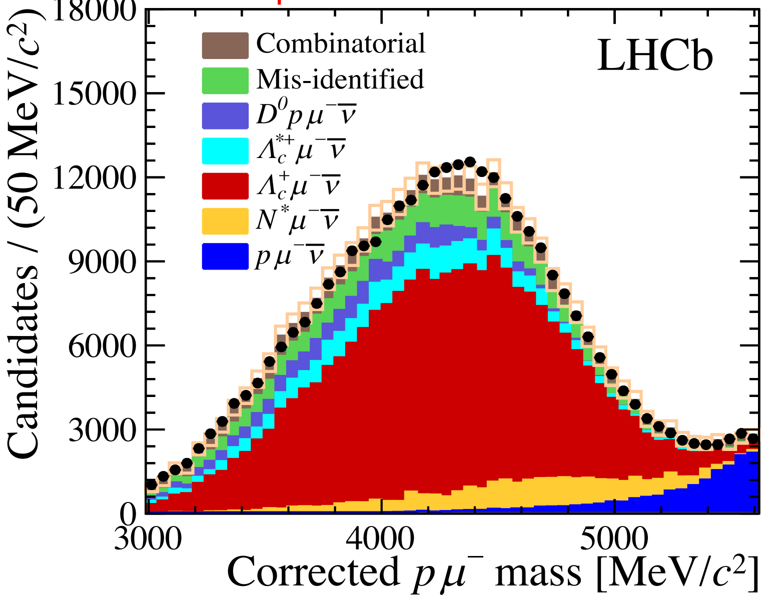
Nature Physics 11 (2015) 743

$$\frac{\mathcal{B}(\Lambda_b \to p\mu^-\overline{\nu}_\mu)_{q^2>15\,\mathrm{GeV}^2/c^4}}{\mathcal{B}(\Lambda_b \to \Lambda_c\mu\nu)_{q^2>7\,\mathrm{GeV}^2/c^4}}$$

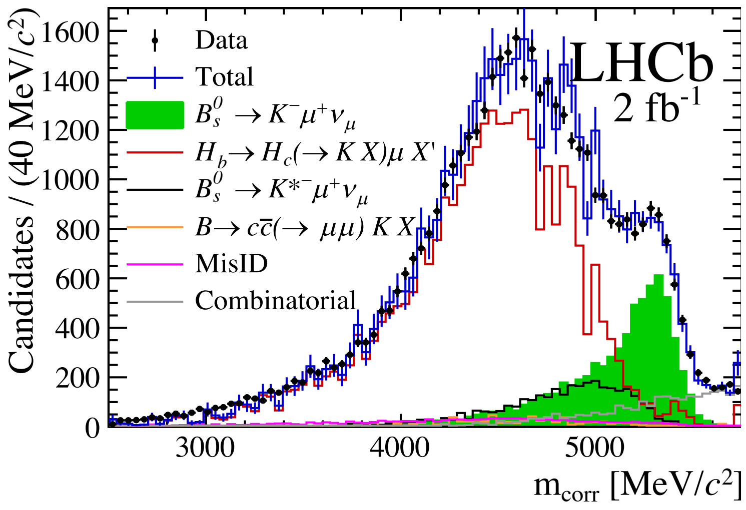
Phys. Rev. Lett. 126 (2021) 081804

$$\frac{\mathcal{B}(\mathrm{B_s^0} \to \mathrm{K}^-\mu^+\nu_\mu)_{q^2<7}}{\mathcal{B}(\mathrm{B_s^0} \to \mathrm{D_s^-}\mu^+\nu_\mu)_{\mathrm{Full}\ q^2}} \qquad \frac{\mathcal{B}(\mathrm{B_s^0} \to \mathrm{K}^-\mu^+\nu_\mu)_{q^2>7}}{\mathcal{B}(\mathrm{B_s^0} \to \mathrm{D_s^-}\mu^+\nu_\mu)_{\mathrm{Full}\ q^2}}$$

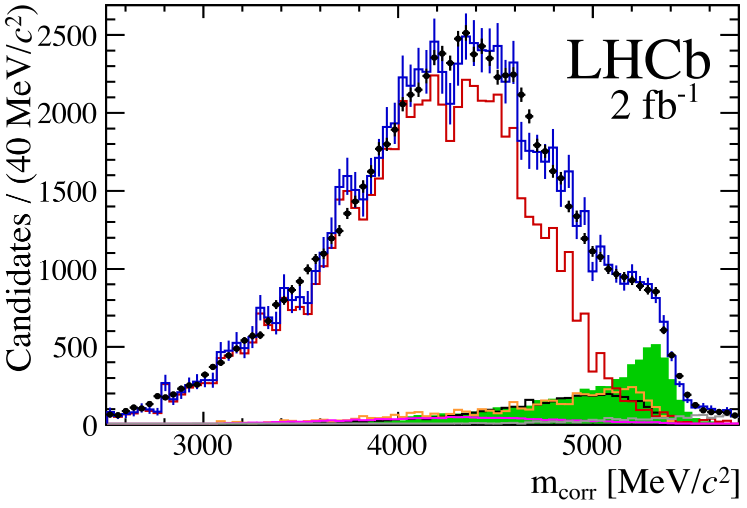
$q^2>15$ GeV^2/c^4



$q^2<7$ GeV^2/c^4



$q^{2}>7$ GeV^2/c^4

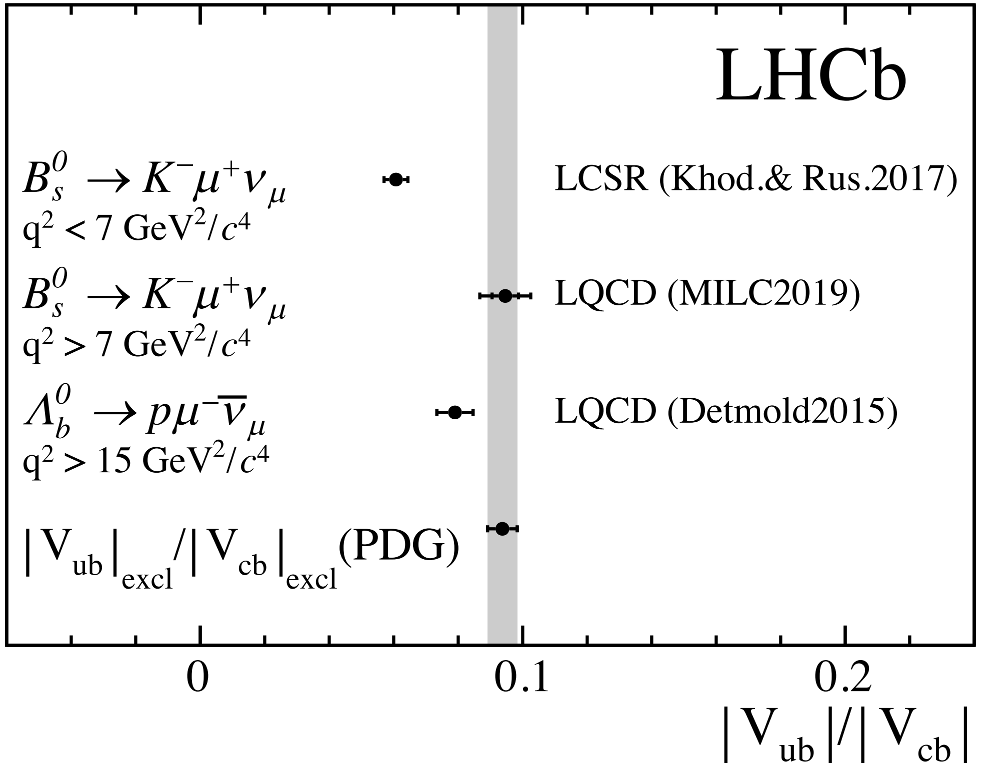


$B_s \rightarrow K\mu\nu$

$$|V_{ub}|/|V_{cb}|(\text{high}) = 0.0946 \pm 0.0030\,(\text{stat})^{+\,0.0024}_{-\,0.0025}\,(\text{syst}) \pm 0.0013\;(D_s) \pm 0.0068\;(\text{FF})$$

$\Lambda_b \rightarrow p\mu\nu$

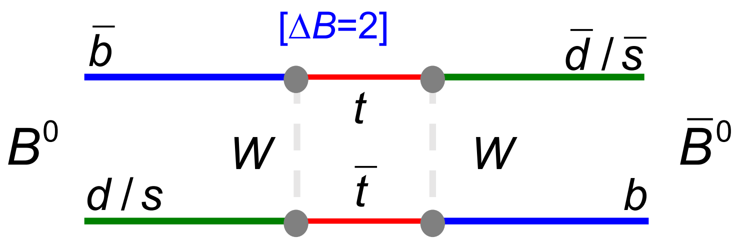
$$\frac{|V_{ub}|}{|V_{cb}|} = 0.083 \pm 0.004 \pm 0.004$$

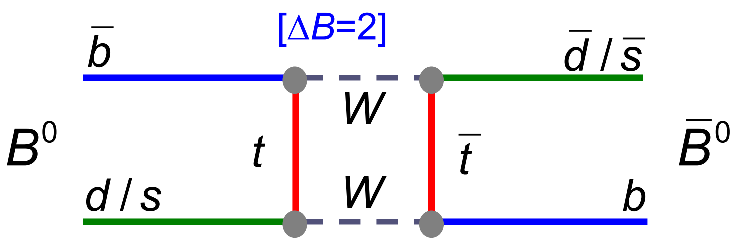


in the high-q2 region where LQCD can be used

- good agreement between both measurements
- in agreement with other exclusive measurements (PDG)

$B_{d/s}\,\bar{B}_{d/s}$ mixing





Perturbative QCD

CKM Matrix Elements

$$\Delta m_q = \frac{G_F^2}{6\pi^2} m_{B_q} m_W^2\, \eta_B\, S(x_t)\, f_{B_q}^2 B_q \left|V_{tq} V_{tb}^*\right|^2 \quad (\text{for } q = d, s)$$

Loop integral (top loop dominates)

Non-perturbative QCD : dominant theoretical uncertainty

$$\frac{\Delta m_d}{\Delta m_s} = \frac{m_{B_d}}{m_{B_s}} \cdot \frac{f_{B_d}^2 B_d}{f_{B_s}^2 B_s} \cdot \lambda^2 \left(\left(1-\bar{\rho}\right)^2 + \bar{\eta}^2\right)$$

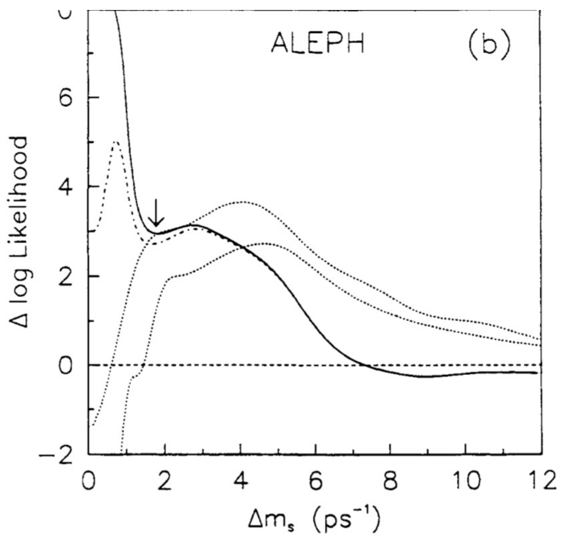
Δm_s measurement is challenging due to the very fast oscillation

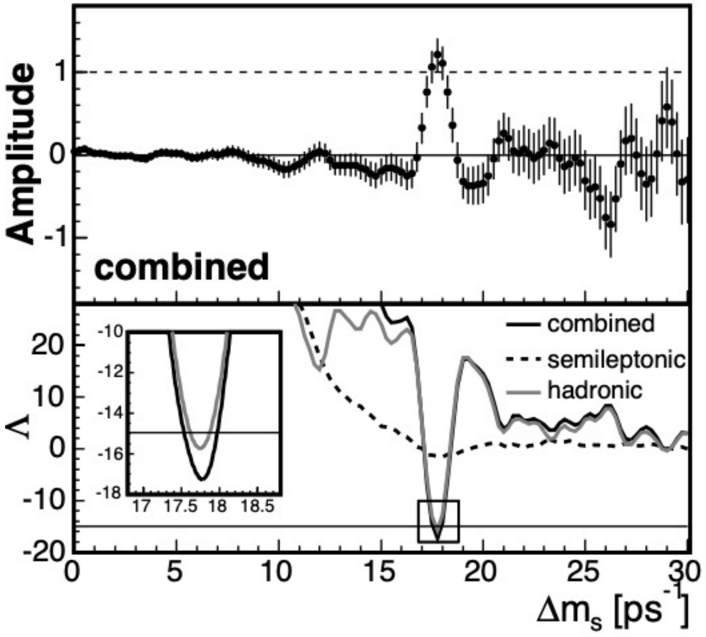
ALEPH - 1993

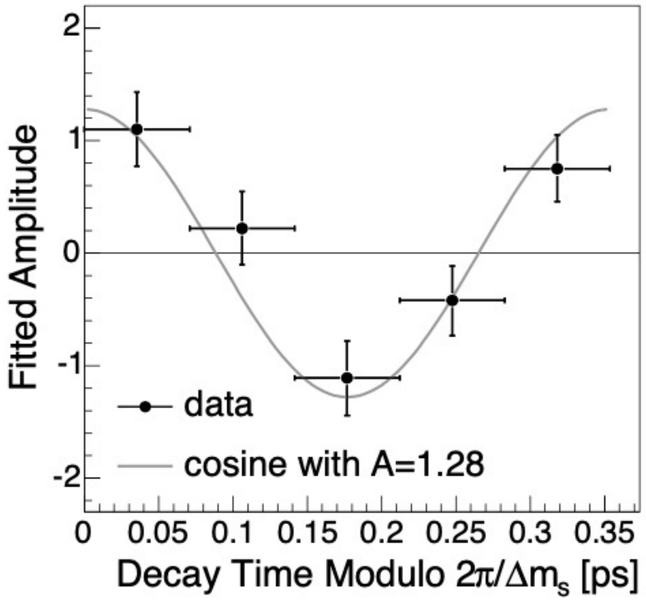
CDF - 2006

First limit $\Delta m_s > 1.8\ ps^{-1}$ at 95%CL !

$\Delta m_s = 17.77 \pm 0.10 \pm 0.07\ ps^{-1}$







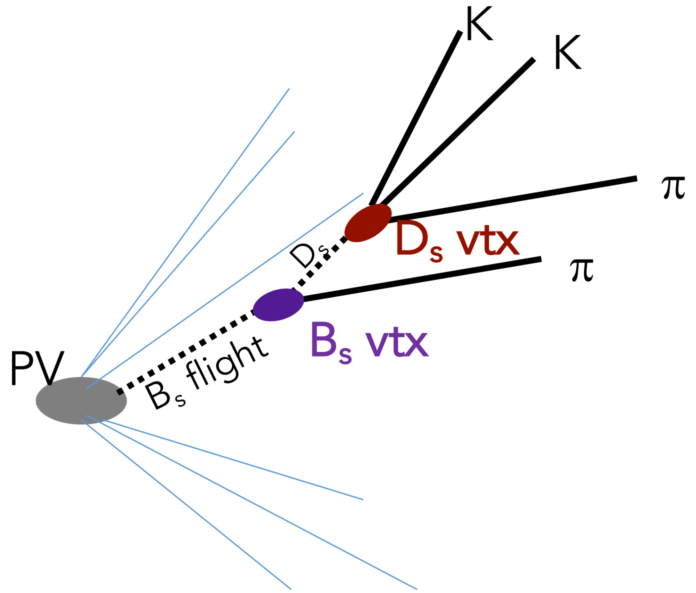
Phys.Lett.B 322 (1994) 441-458

Phys.Rev.Lett. 97 (2006) 242003

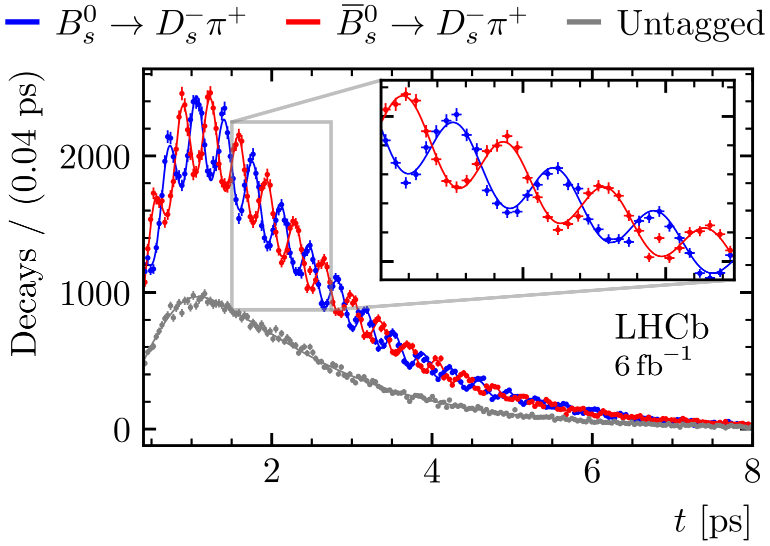
$7\ 10^{-3}$ precision

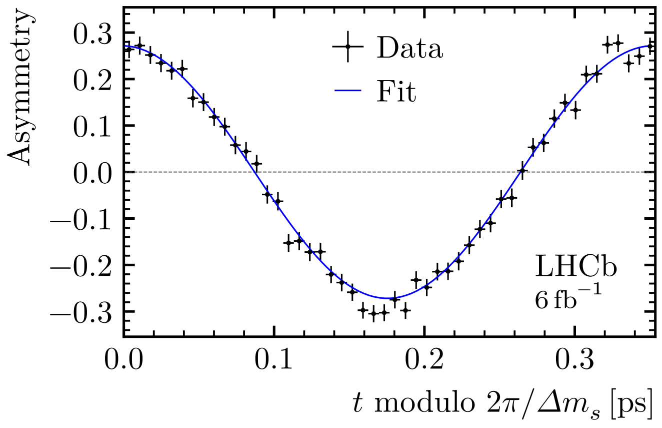
LHCb Δm_s Run1 & Run2 legacy measurement

$B_s \rightarrow D_s \pi$ with Run2 data



arXiv:2104.04421





Decay mode	Data sample	Δm_s ps^{-1}
$B_s^0 \to D_s^- \pi^+$	2011	$17.768 \pm 0.023 \pm 0.006$
$B_s^0 \to D_s^- \pi^- \pi^+ \pi^+$	2011-2018	$17.757 \pm 0.007 \pm 0.008$
$B_s^0 \to D_s^- \pi^+$	2015-2018	$17.7683 \pm 0.0051 \pm 0.0032$
Average		17.7666 ± 0.0057

tagging power ~ 6%

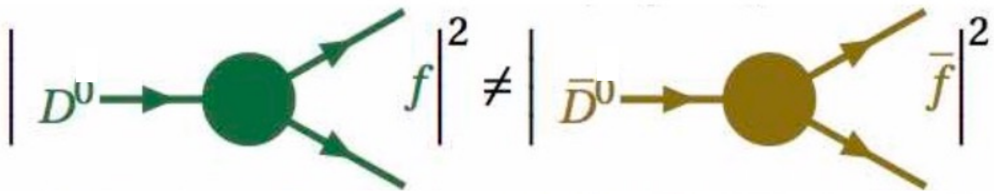
(factor 2 improvement wrt first publication (New J. Phys. 15 (2013) 053021))

3 10^{-4} precision

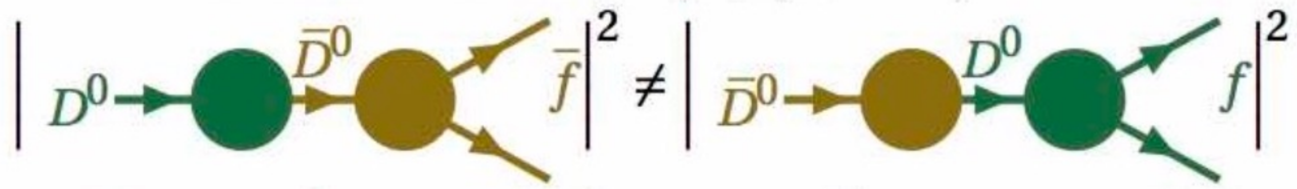
Mixing and CP violation in charm

Three types of CP violation (K, D or B)

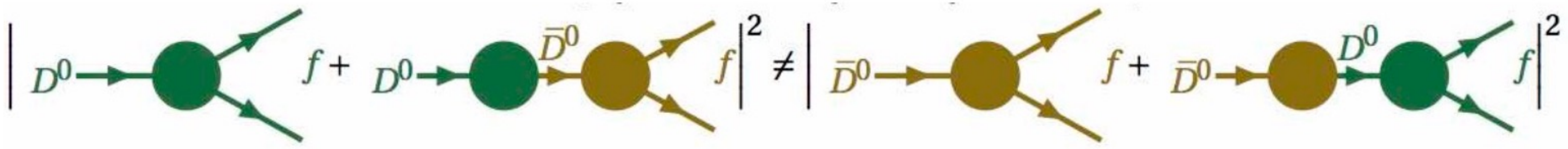
- Direct CP violation



- For neutral mesons:
  - CP violation in the mixing



  - CP violation in the interference between mixing and decay

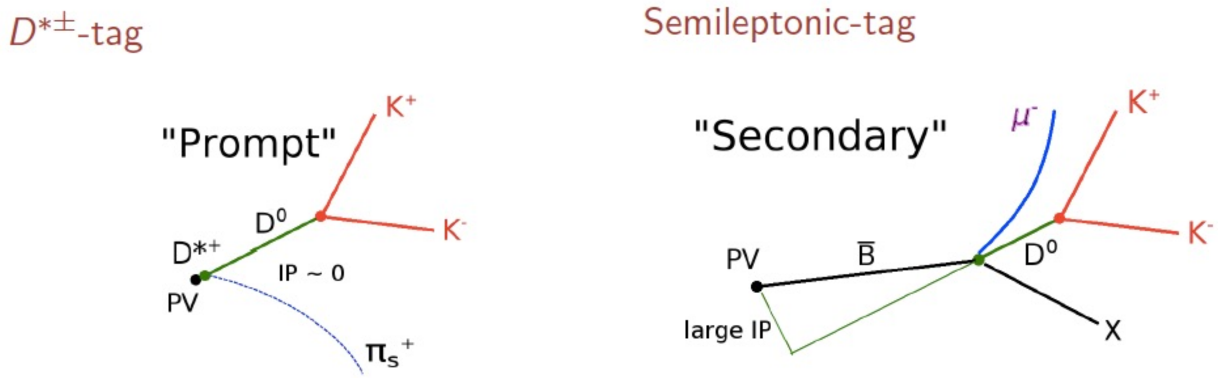


CP violation in up-type sector. SM expectations : 10^{-3} 10^{-4}.

- The only place to study CPV in the up-type quark sector
- Need huge data samples
- At 13 TeV ~ 130 kHz of reconstructible c-hadrons !

First observation of CP violation in charm in 2019

Knowledge of the D^0 flavour at production



Experimentally:

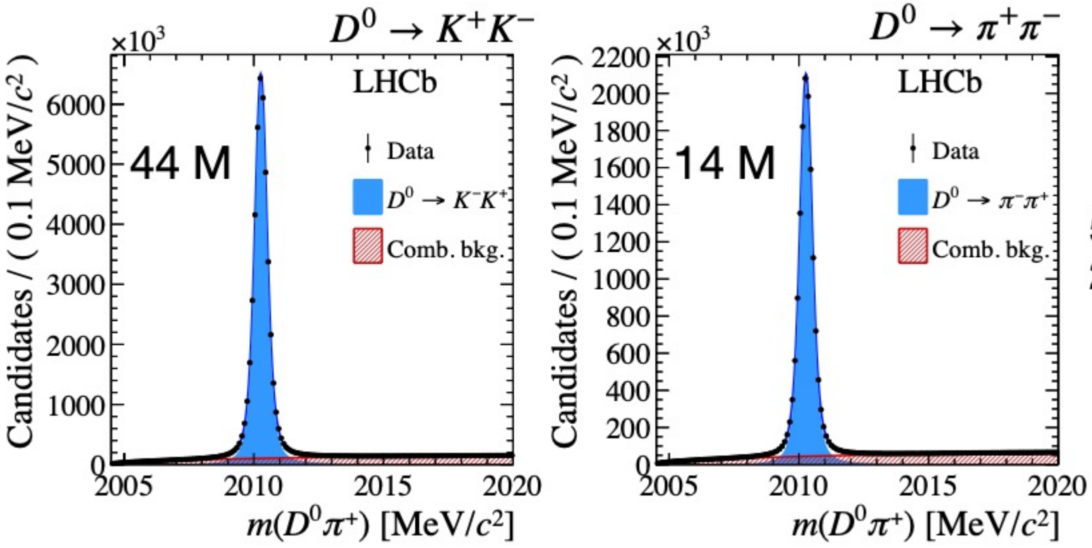
$$A_{raw} = \frac{N(D^0 \to f) - N(\bar{D}^0 \to f)}{N(D^0 \to f) + N(\bar{D}^0 \to f)} = A_{CP} + A_D(\pi_s^+/\mu) + A_P(D^{*+}/D^0_{\text{from } B})$$

$D^0 \to KK$ or $\pi\pi$

charge symmetric

$$\Delta A_{CP} = A_{raw}(KK) - A_{raw}(\pi\pi) \cong A_{CP}(KK) - A_{CP}(\pi\pi)$$

in the limit of U-spin symmetry
$A_{CP}(\pi\pi) = -A_{CP}(KK)$



5.7 fb^{-1}
2015–2018

ΔA_{CP}=(-0.154±0.029)%

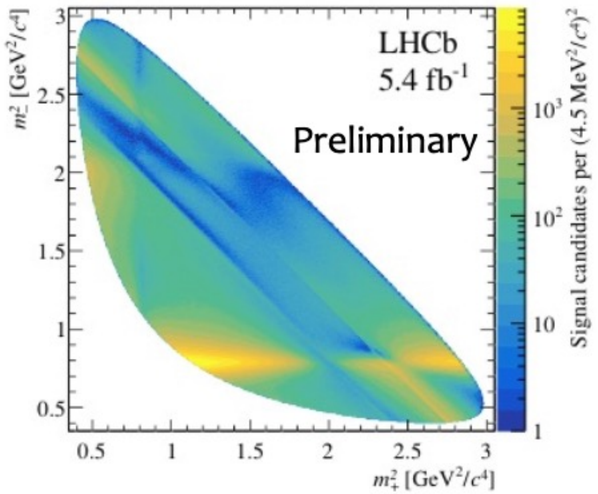
PRL 122 (2019) 211803

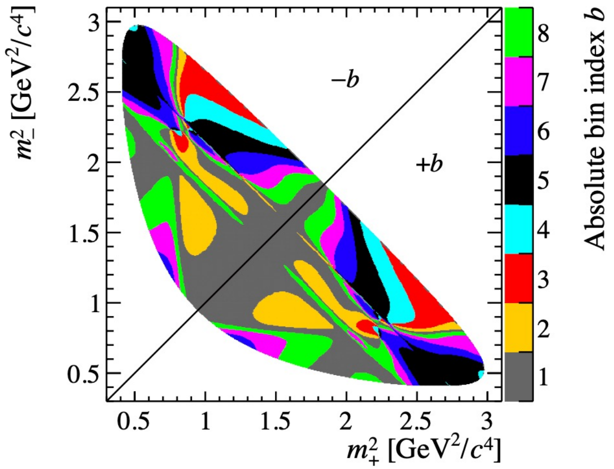
Observation of CP violation in charm at 5.3 σ

Observed value is at the upper end of the SM predictions
→ intense theoretical activity
→ measurements of further decay channels to help unveiling the underlying dynamics

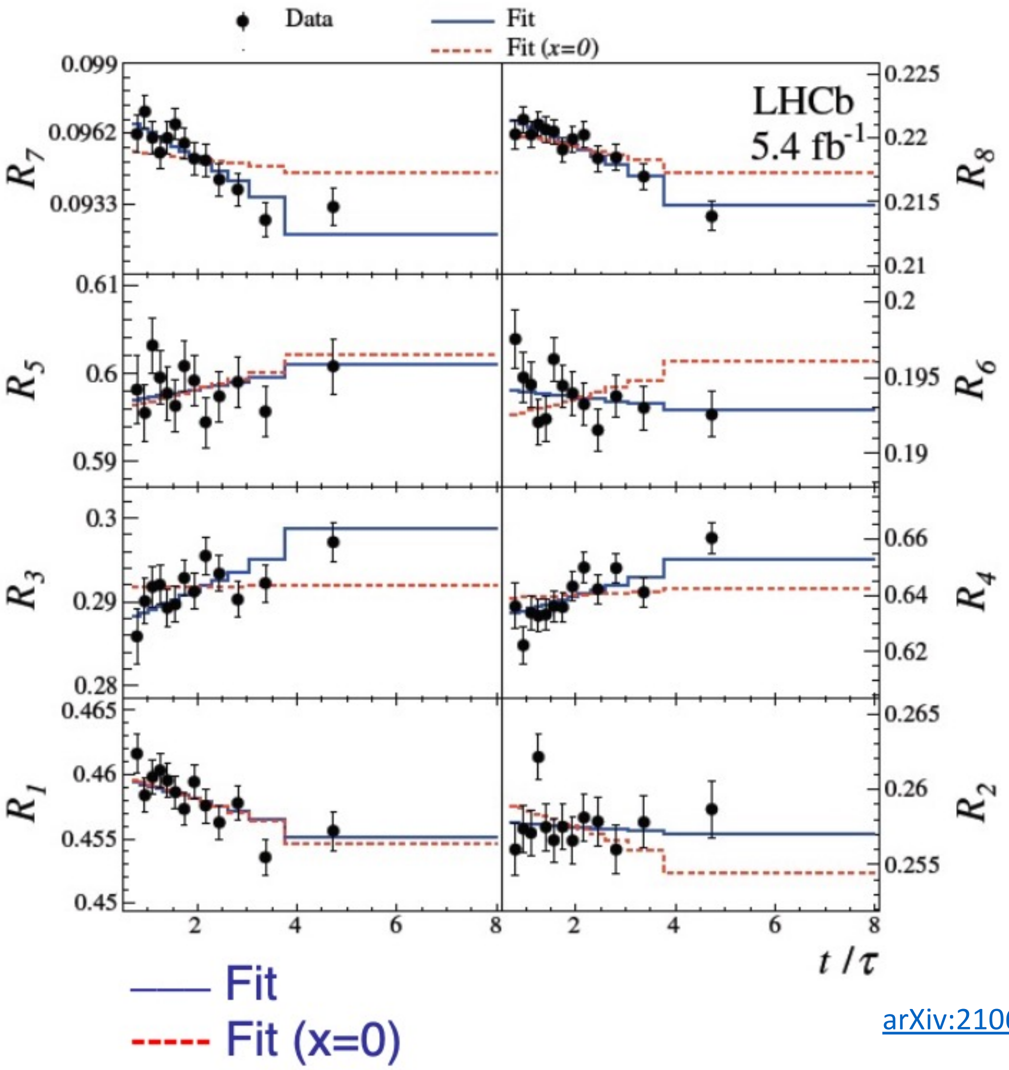
First observation of the mass difference between the two mass eigenstates

- Start with a large sample (30.6 10^6) of tagged $D^0 \rightarrow K_s \pi\pi$ events
- Bin the data according to Dalitz coordinates and decay time (t/τ)
- Form the ratios of yields in opposite Dalitz bins as function of t/τ





inputs from CLEOc and BESIII

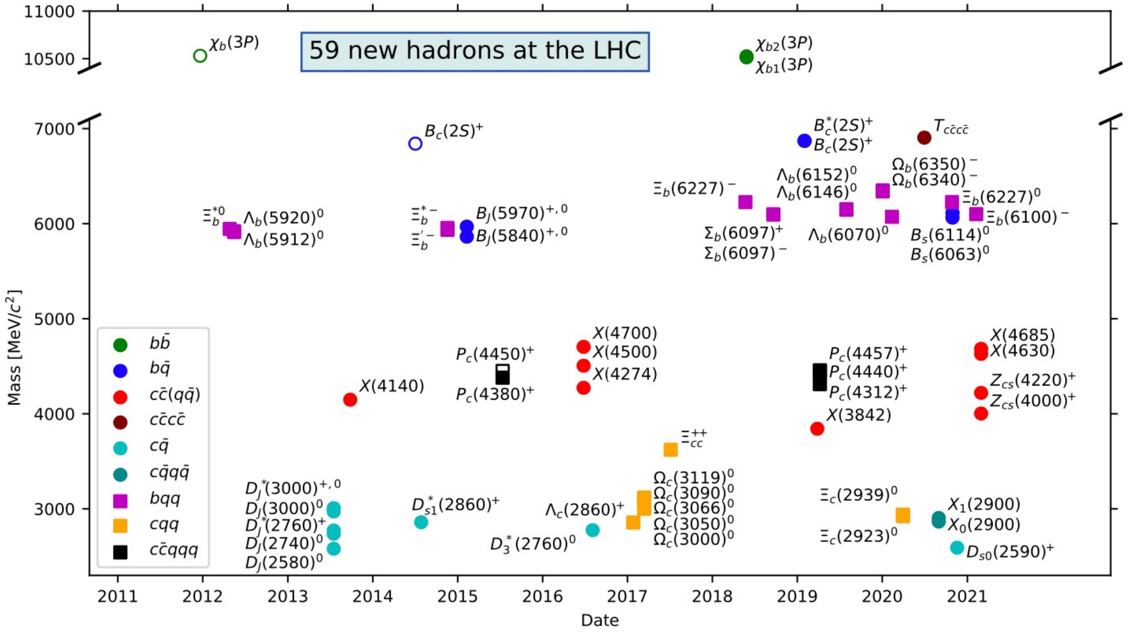


arXiv:2106.03744

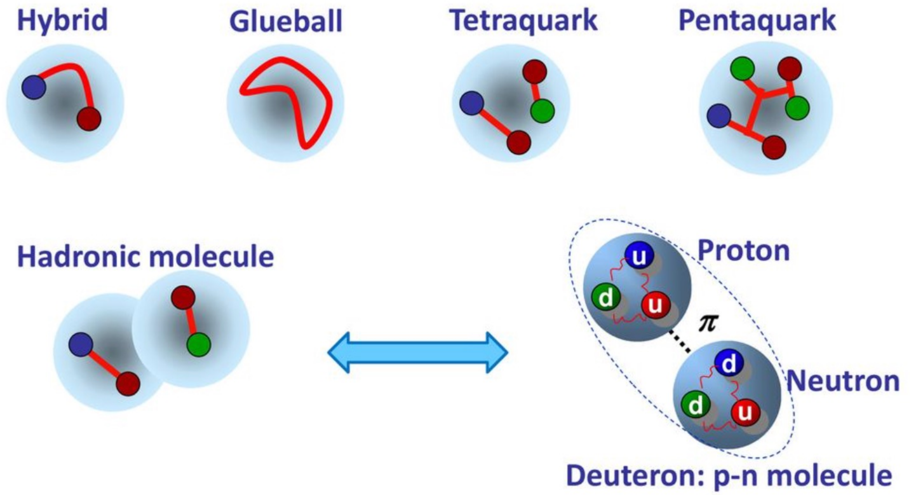
- First observation of a non-zero value of $\Delta m/\Gamma$ (7 σ)
- No mixing-induced CP violation was observed but limits have been significantly improved

Exotic states

A lot of new hadrons discovered at the LHC, mainly by LHCb



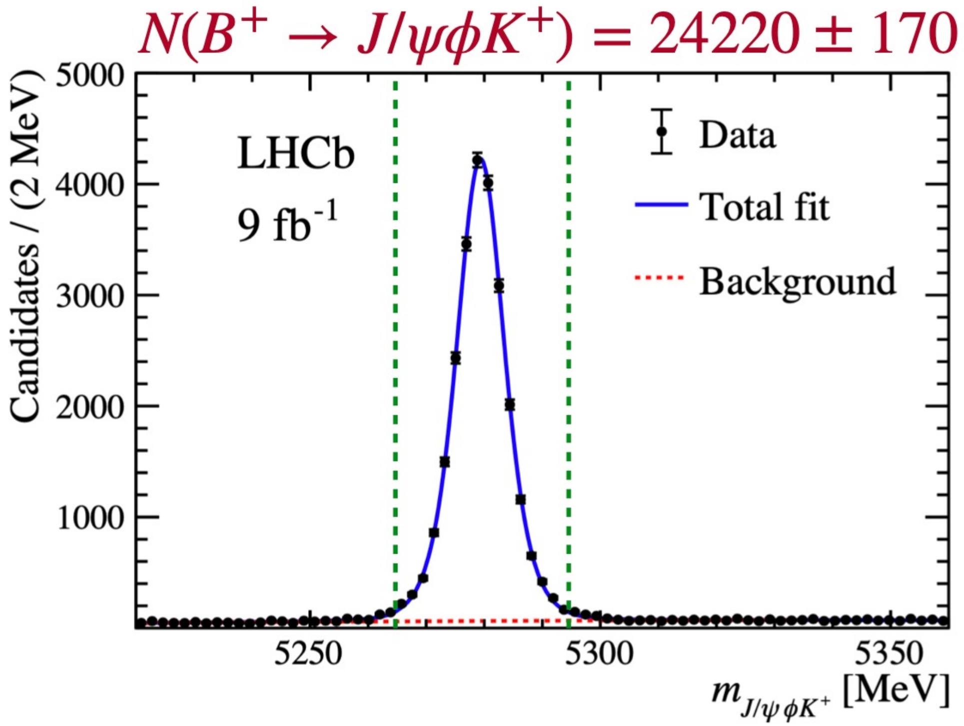
…and more



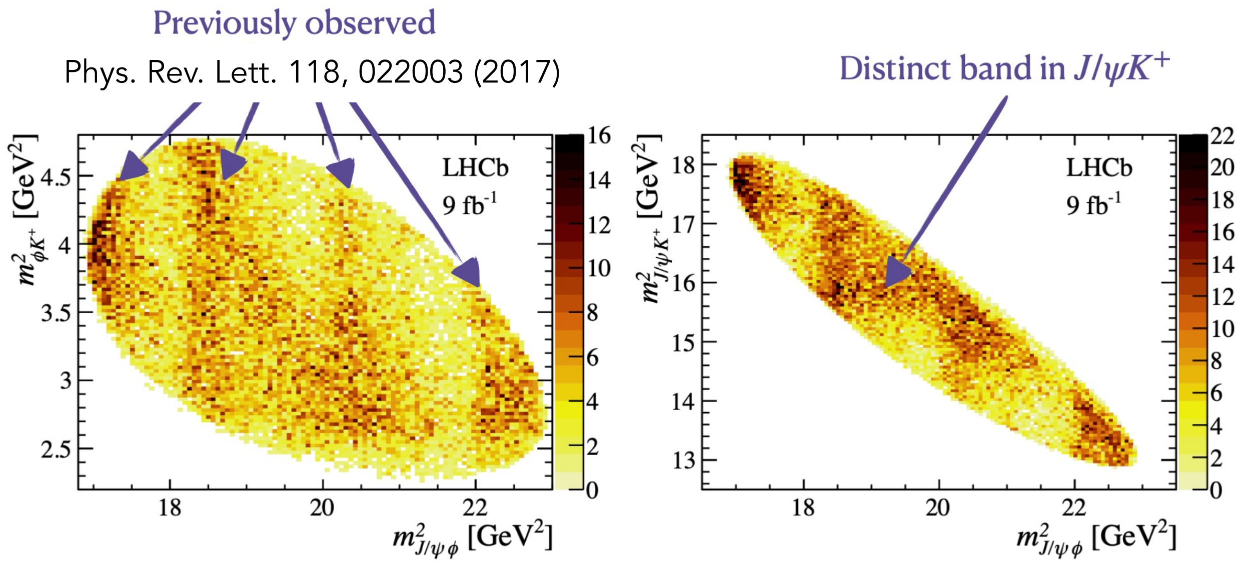
→ internal structure and dynamics of hadrons
→ probe to non-perturbative behaviour of QCD

Exotic states:
- more than 3 valence quarks
- mass/width and/or production and/or decay properties inconsistent with predictions for conventional states

Observation of new resonances decaying to $J/\psi K+$ and $J/\psi\varphi$



arXiv:2103.01803



Amplitude analysis with :

K^{*+}($\rightarrow$ ϕK^+)J/ψ

X($\rightarrow$ J/ψ ϕ)K^+

Z_{cs}^+ ($\rightarrow$ $J/\psi K^+$) ϕ

Spin and parity of each exotic state is probed by testing alternative J^P hypotheses and comparing the fit likelihood values.

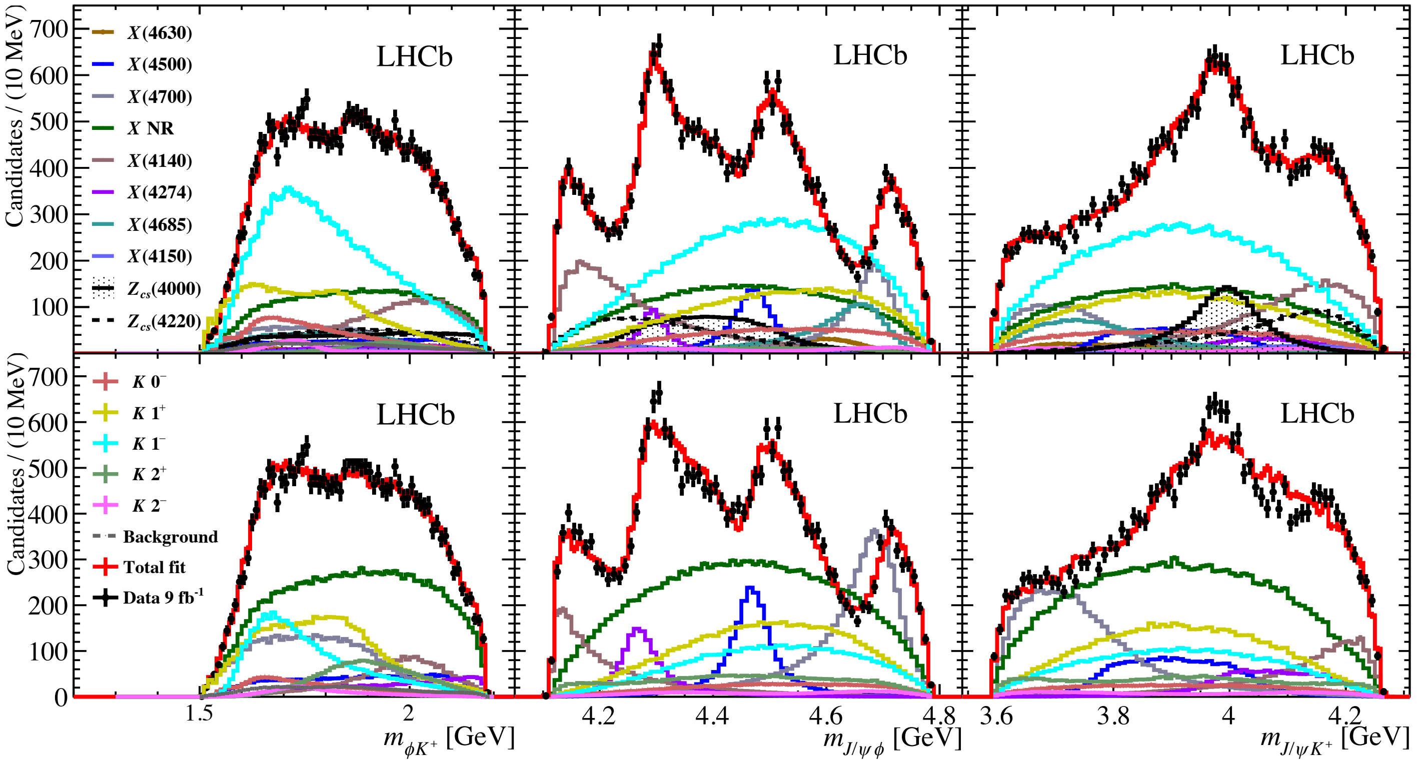
Observation of 2 $c\bar{c}u\bar{s}$ and 2 $c\bar{c}s\bar{s}$ tetraquarks

9 fb^{-1}

$K^{*+}(\rightarrow \phi K^+)$ $X(\rightarrow J/\psi\, \phi)$ $Z_{cs}^+ (\rightarrow J/\psi K^+)$

Improved model

Run1 model



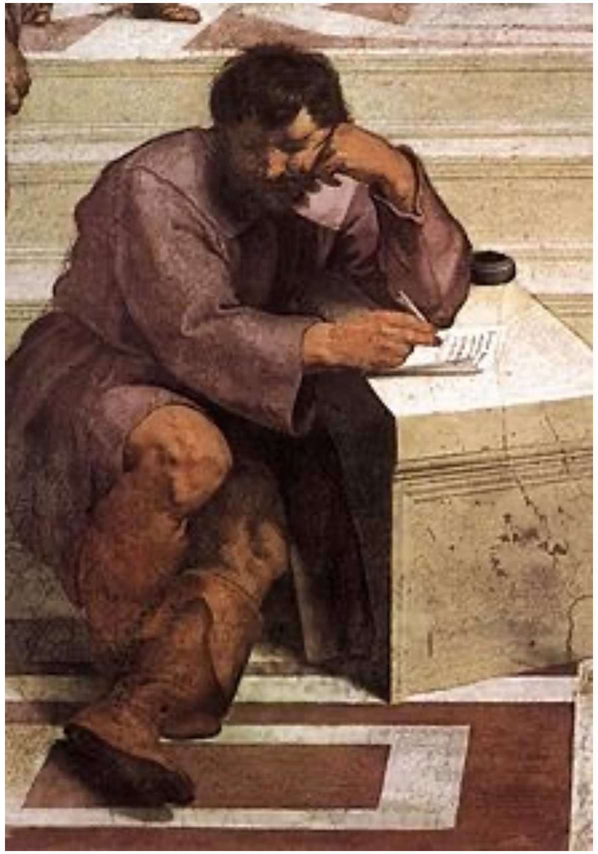
	Contribution	Significance $[\times\sigma]$	M_0 [MeV]	Γ_0 [MeV]	FF [%]
	All $K(1^+)$				$25 \pm 4\,^{+\,6}_{-\,15}$
2^1P_1	$K(1^+)$	4.5 (4.5)	$1861 \pm 10\,^{+\,16}_{-\,46}$	$149 \pm 41\,^{+\,231}_{-\,23}$	
2^3P_1	$K'(1^+)$	4.5 (4.5)	$1911 \pm 37\,^{+\,124}_{-\,48}$	$276 \pm 50\,^{+\,319}_{-\,159}$	
1^3P_1	$K_1(1400)$	9.2 (11)	1403	174	$15 \pm 3\,^{+\,3}_{-\,11}$
	All $K(2^-)$				$2.1 \pm 0.4\,^{+\,2.0}_{-\,1.1}$
1^1D_2	$K_2(1770)$	7.9 (8.0)	1773	186	
1^3D_2	$K_2(1820)$	5.8 (5.8)	1816	276	
	All $K(1^-)$				$50 \pm 4\,^{+\,10}_{-\,19}$
1^3D_1	$K^*(1680)$	4.7 (13)	1717	322	$14 \pm 2\,^{+\,35}_{-\,8}$
2^3S_1	$K^*(1410)$	7.7 (15)	1414	232	$38 \pm 5\,^{+\,11}_{-\,17}$
	$K(2^+)$				
2^3P_2	$K_2^*(1980)$	1.6 (7.4)	$1988 \pm 22\,^{+\,194}_{-\,31}$	$318 \pm 82\,^{+481}_{-\,101}$	$2.3 \pm 0.5 \pm 0.7$
	$K(0^-)$				
2^1S_0	$K(1460)$	12 (13)	1483	336	$10.2 \pm 1.2\,^{+\,1.0}_{-\,3.8}$
	$X(2^-)$				
	$X(4150)$	4.8 (8.7)	$4146 \pm 18 \pm 33$	$135 \pm 28\,^{+\,59}_{-\,30}$	$2.0 \pm 0.5\,^{+\,0.8}_{-\,1.0}$
	$X(1^-)$				
	$X(4630)$	5.5 (5.7)	$4626 \pm 16\,^{+\,18}_{-\,110}$	$174 \pm 27\,^{+\,134}_{-\,73}$	$2.6 \pm 0.5\,^{+\,2.9}_{-\,1.5}$
	All $X(0^+)$				$20 \pm 5\,^{+\,14}_{-\,7}$
	$X(4500)$	20 (20)	$4474 \pm 3 \pm 3$	$77 \pm 6\,^{+\,10}_{-\,8}$	$5.6 \pm 0.7\,^{+\,2.4}_{-\,0.6}$
	$X(4700)$	17 (18)	$4694 \pm 4\,^{+\,16}_{-\,3}$	$87 \pm 8\,^{+\,16}_{-\,6}$	$8.9 \pm 1.2\,^{+\,4.9}_{-\,1.4}$
	$NR_{J/\psi\phi}$	4.8 (5.7)			$28 \pm 8\,^{+\,19}_{-\,11}$
	All $X(1^+)$				$26 \pm 3\,^{+\,8}_{-\,10}$
	$X(4140)$	13 (16)	$4118 \pm 11\,^{+\,19}_{-\,36}$	$162 \pm 21\,^{+\,24}_{-\,49}$	$17 \pm 3\,^{+\,19}_{-\,6}$
	$X(4274)$	18 (18)	$4294 \pm 4\,^{+\,3}_{-\,6}$	$53 \pm 5 \pm 5$	$2.8 \pm 0.5\,^{+\,0.8}_{-\,0.4}$
	$X(4685)$	15 (15)	$4684 \pm 7\,^{+\,13}_{-\,16}$	$126 \pm 15\,^{+\,37}_{-\,41}$	$7.2 \pm 1.0\,^{+\,4.0}_{-\,2.0}$
	All $Z_{cs}(1^+)$				$25 \pm 5\,^{+\,11}_{-\,12}$
	$Z_{cs}(4000)$	15 (16)	$4003 \pm 6\,^{+\,4}_{-\,14}$	$131 \pm 15 \pm 26$	$9.4 \pm 2.1 \pm 3.4$
	$Z_{cs}(4220)$	5.9 (8.4)	$4216 \pm 24\,^{+\,43}_{-\,30}$	$233 \pm 52\,^{+\,97}_{-\,73}$	$10 \pm 4\,^{+\,10}_{-\,7}$

nine K^{*+}, seven X, two Z_+ and one $J/\psi\ \phi$ NR component are taken as the default model, all have a statistical significance of over 5σ.

Previously reported J^P assignments for the four X states are confirmed with high significance. A 1^+ assignment is favoured for the new $X(4685)$ state. Narrow $Z_{cs}(4000)^+$ state is determined to be 1^+, broader $Z_{cs}(4220)$ could be 1^+ or 1^-.

What's next ?

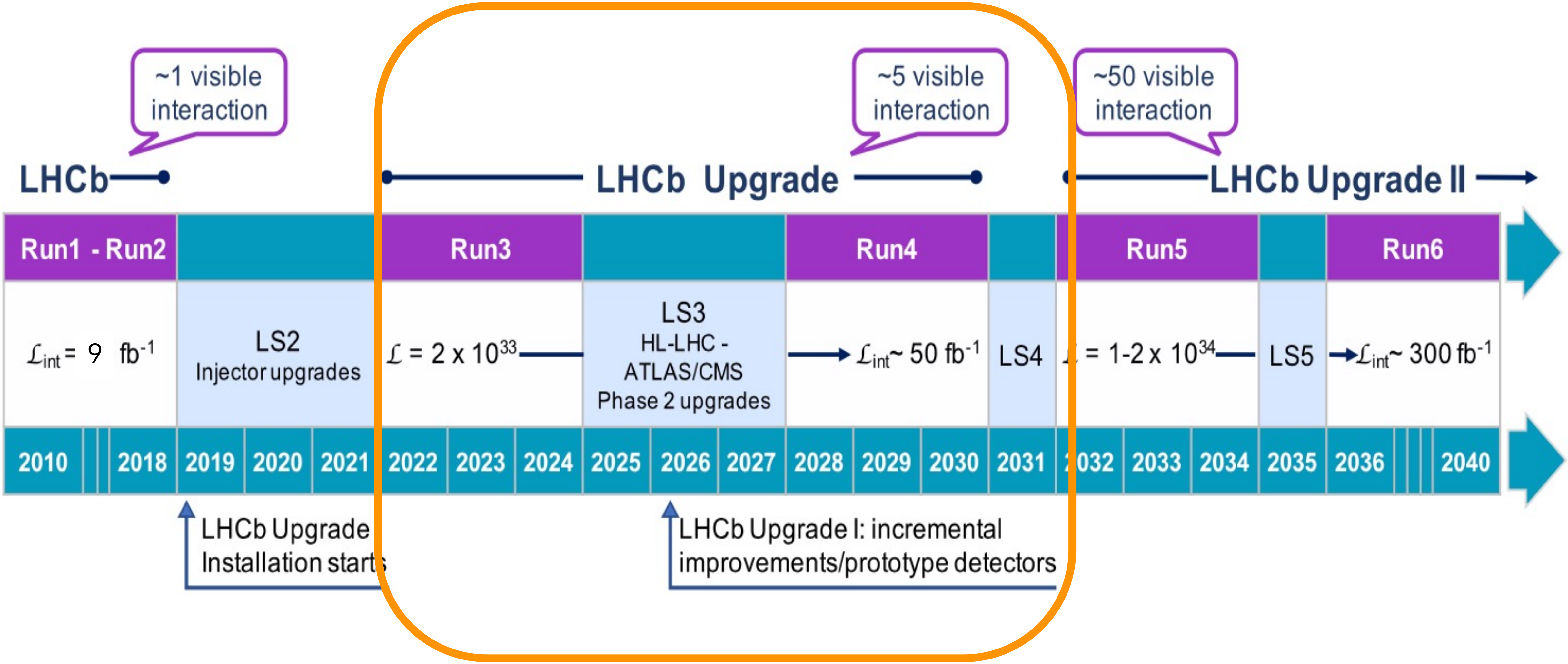
- LHCb-Upgrade I
- LHCb-Upgrade II



Heraclitus (540 – 480 BC)

There is nothing permanent except change

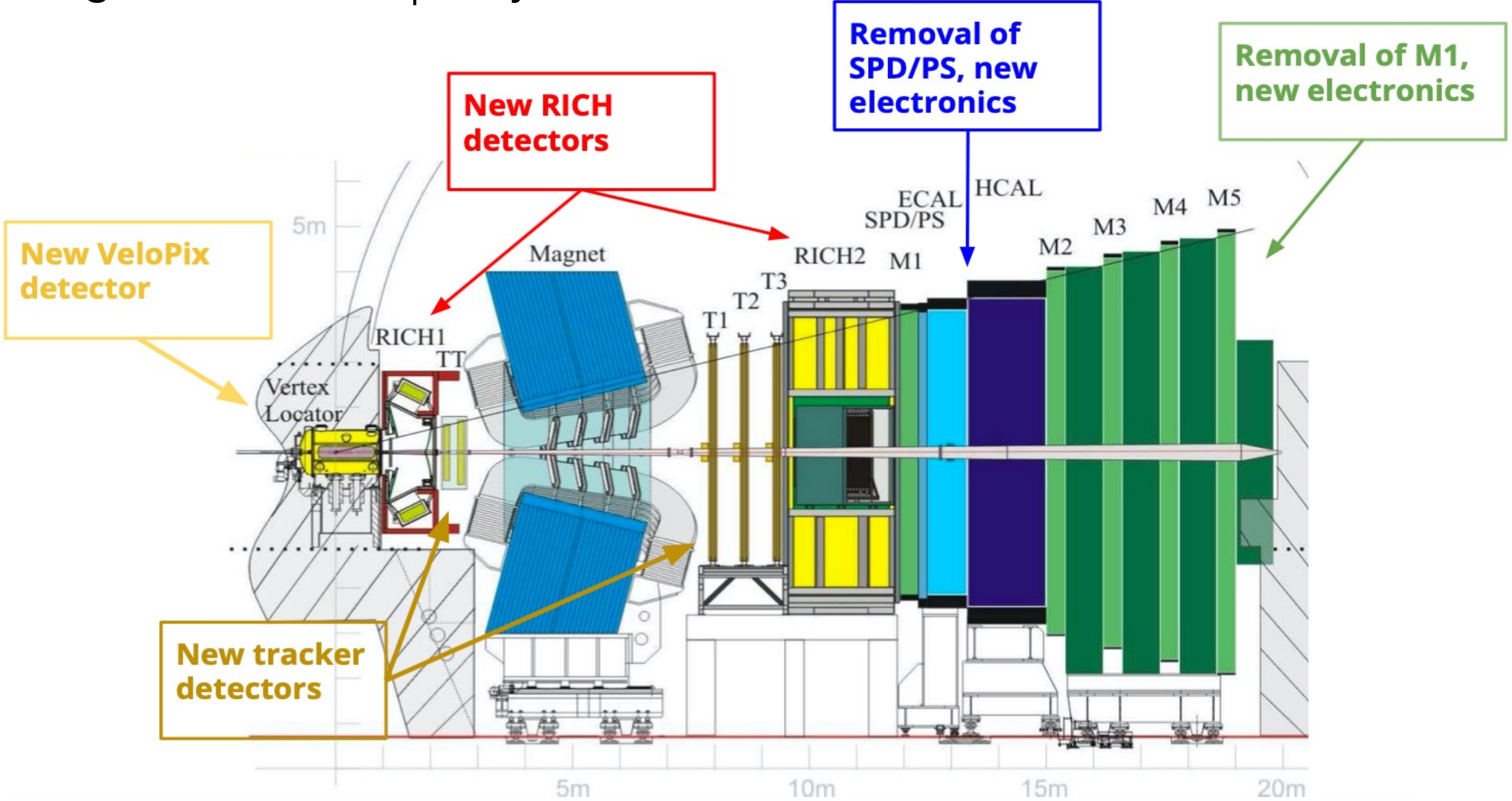
LHCb schedule



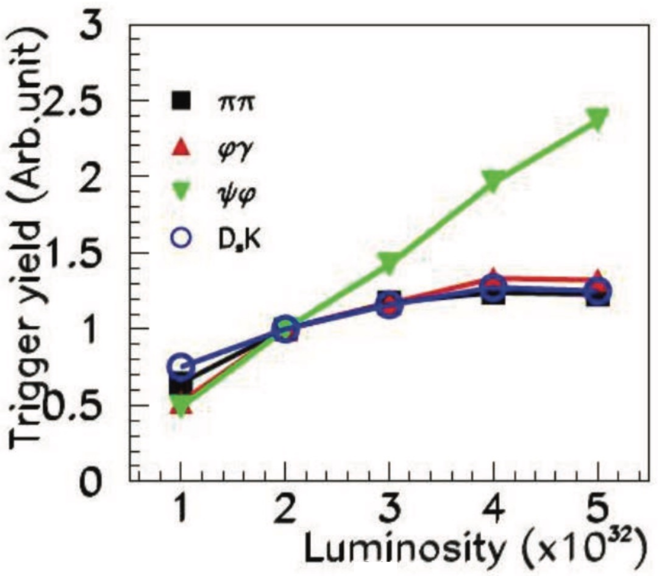
LHCb-Upgrade I : $\mathcal{L} = 2.\ 10^{33}$ cm^{-2} s^{-1} and removal of the L0

→ all detector read-out at 40 MHz (30 MHz collisions to be handled by the event filter farm)

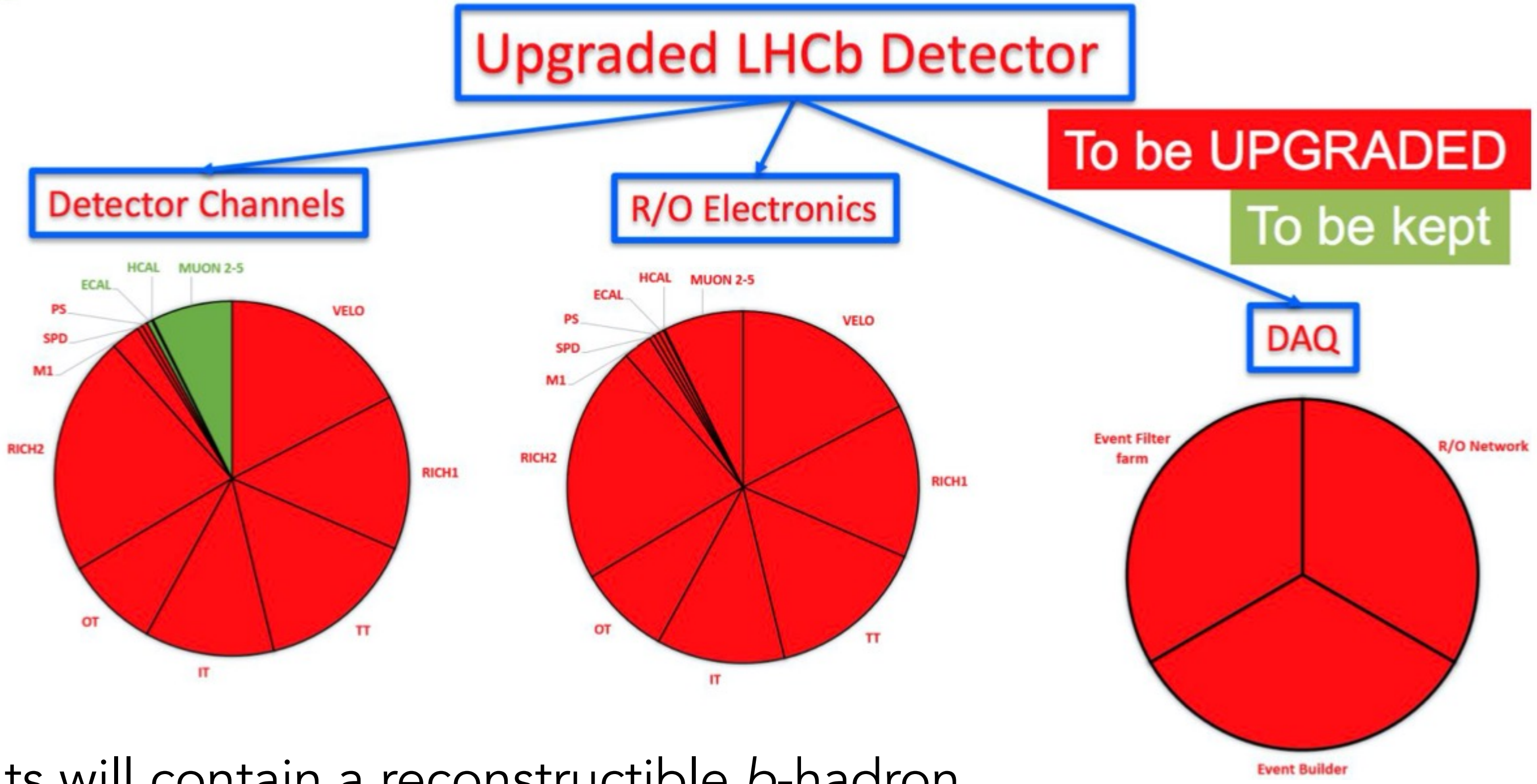
luminosity x5 wrt Run2
5.5 visible interactions/crossing
Higher track multiplicity from ~<70> to ~<180>)



L0 bottleneck



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



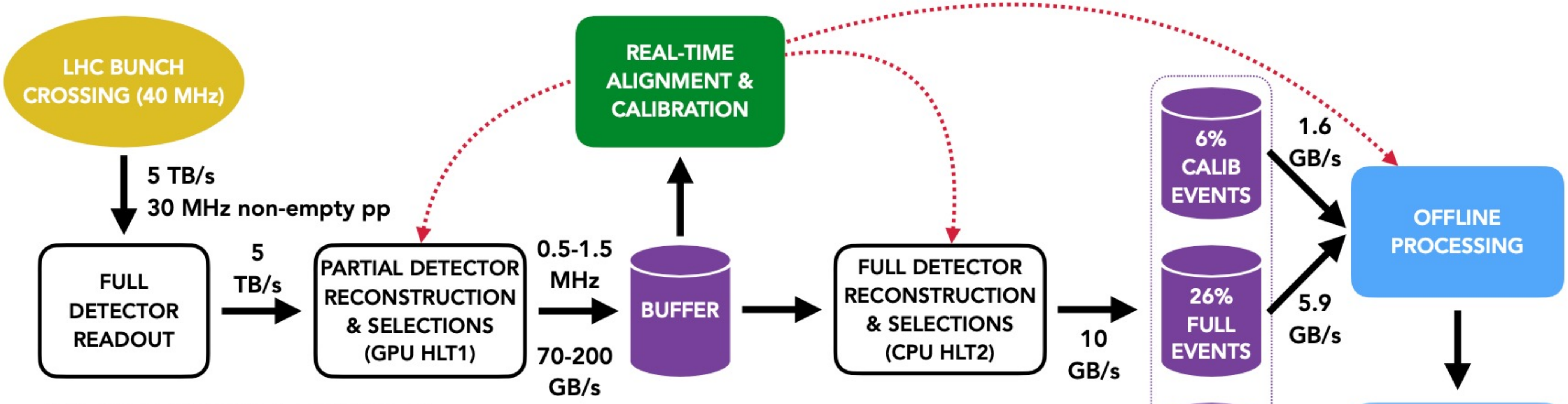
~2% of the events will contain a reconstructible *b*-hadron

Particle type	Run I (kHz)	Upgrade (kHz)
b-hadrons	17.3	270
c-hadrons	66.9	800
Light long-lived hadrons	22.8	264

includes expected trigger and reconstruction efficiencies.

Comput. Phys. Commun. 208 (2016) 35-42

System will mostly categorize signal !



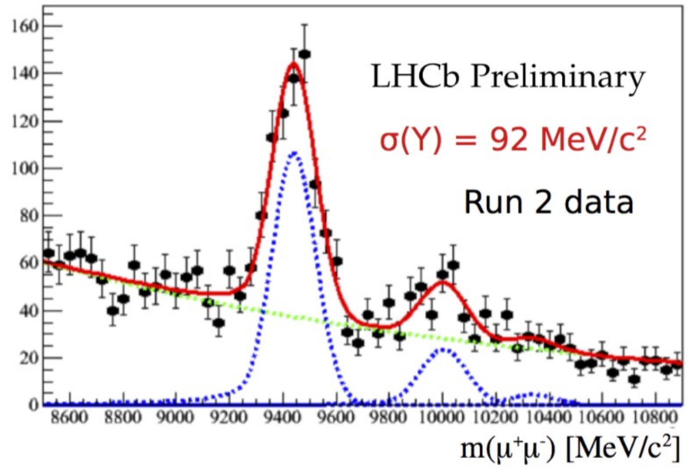
All numbers related to the dataflow are taken from the LHCb

Upgrade Trigger and Online TDR

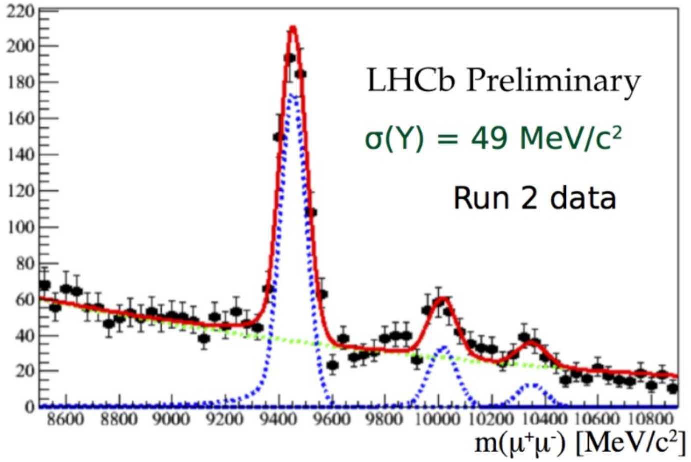
Upgrade Computing Model TDR

M. Alexander, LHCC March 2021

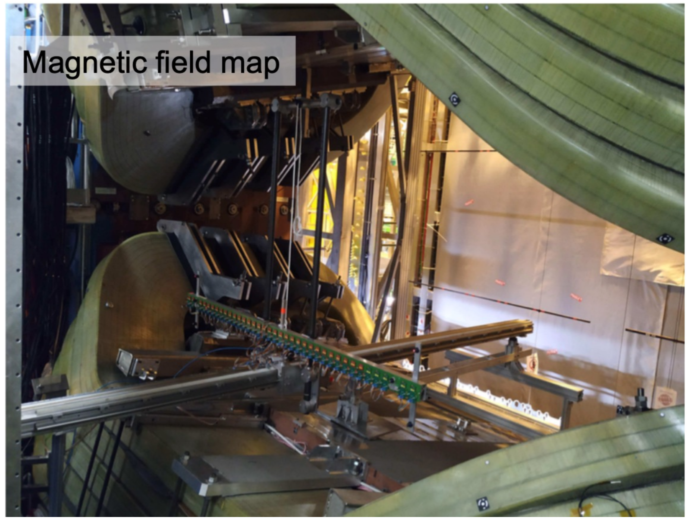
Before alignment



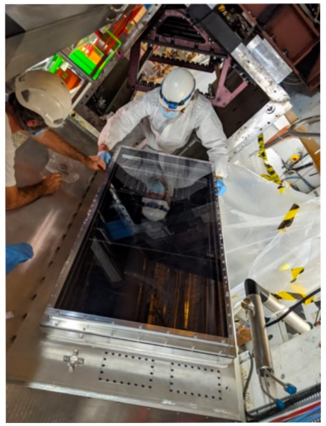
After alignment

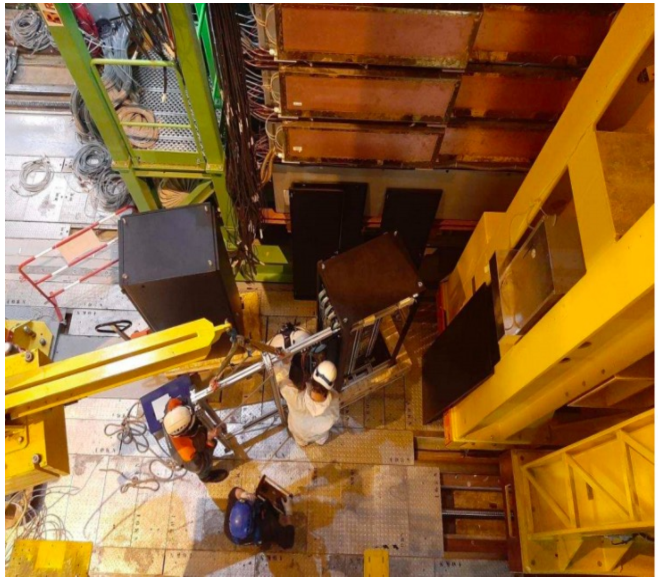


Upgrade I is on-going



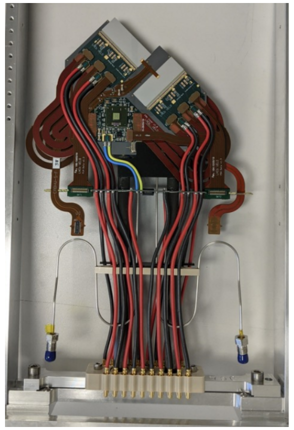
RICH1



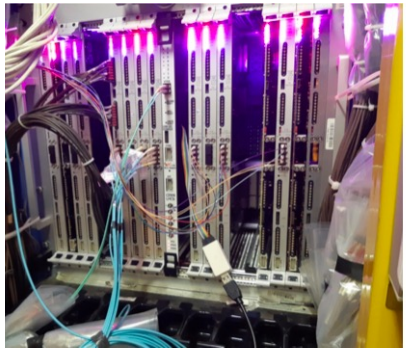


Installation work on the LHCb SciFi Tracker at LHCb

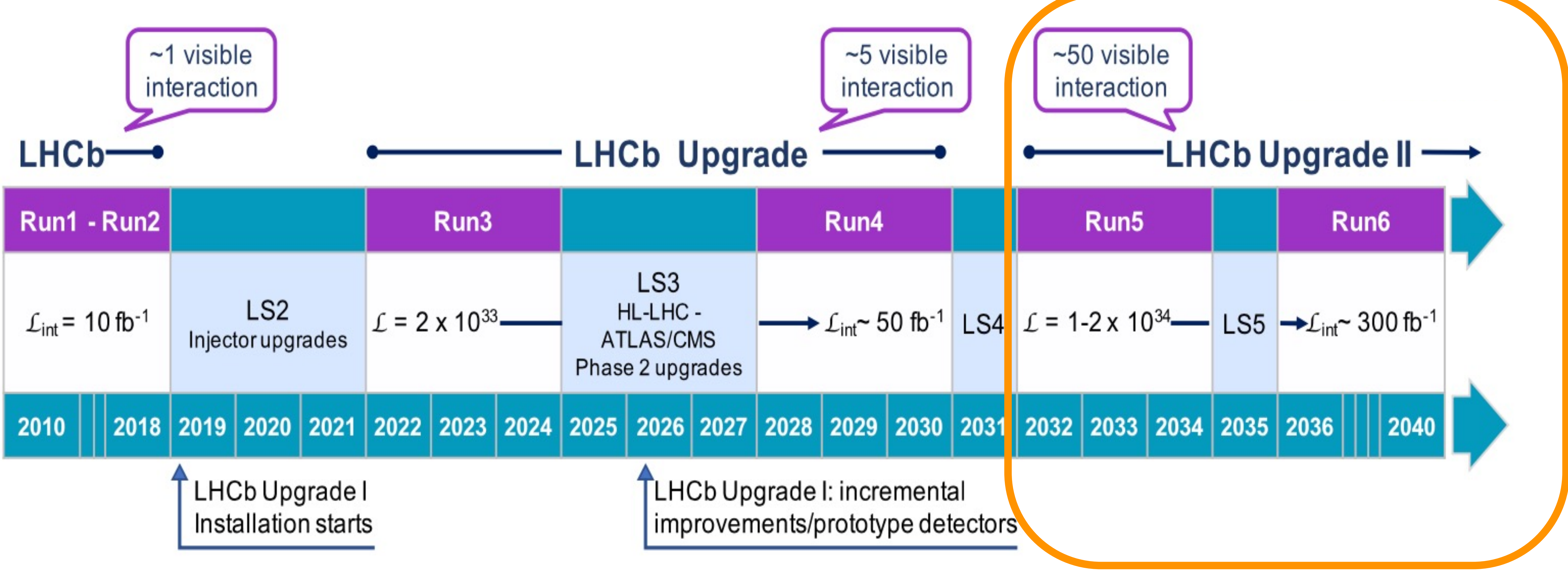
VELO



Calorimeter electronics



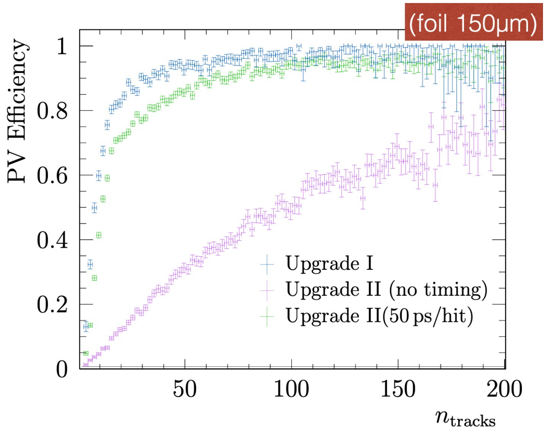
Huge work to keep on schedule despite the impact of the pandemic



Plan: 50 fb^{-1}/ year
→ 300 fb^{-1} by the end of Run6

Pile-up ~40 (~5 for Runs 3 and 4)
→ Use of timing

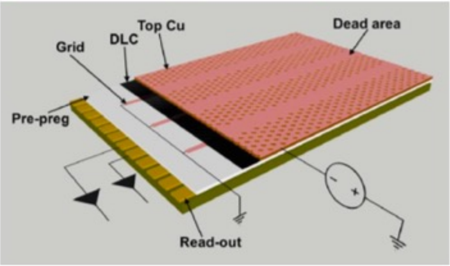
5th Workshop on LHCb Upgrade II

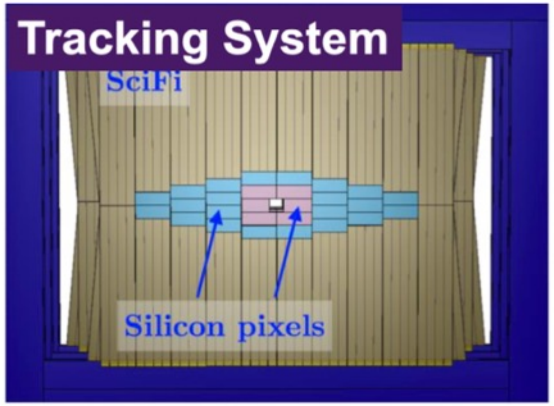


LHCb Upgrade II: R&D Progress

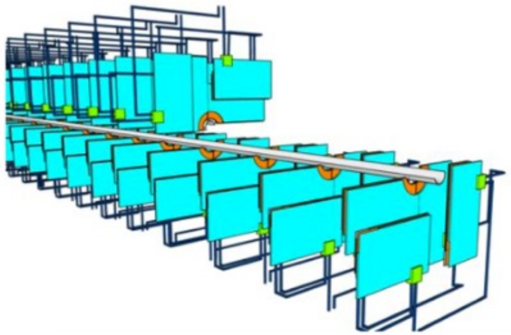
- Future major upgrade of the experiment, mainly for LS4 (~2030)
  - with some preparatory work in LS3 (~2025)
- Innovative Technology: precision timing, novel sensors, heterogeneous computing

Muon system

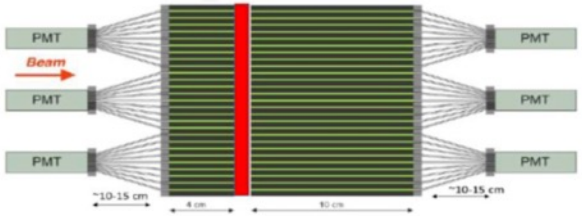




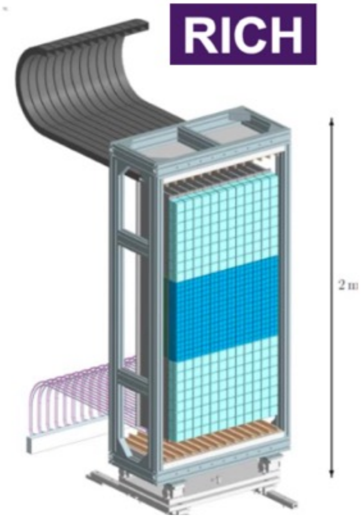
Vertex Detector (VELO)



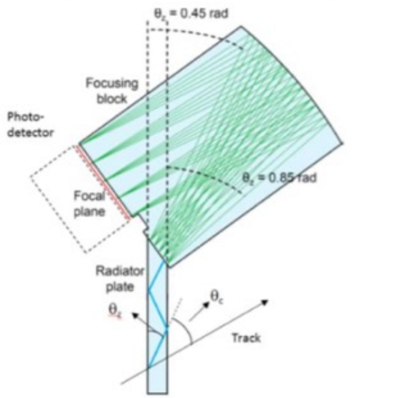
Electromagnetic Calorimetry



RICH



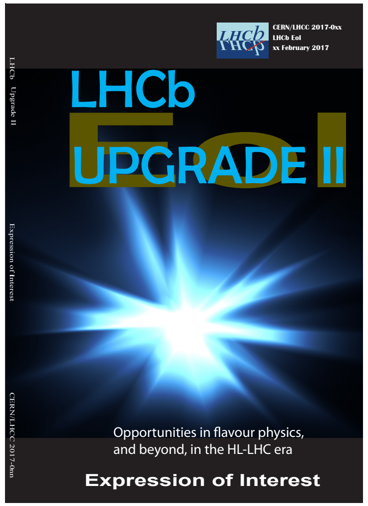
TORCH ToF

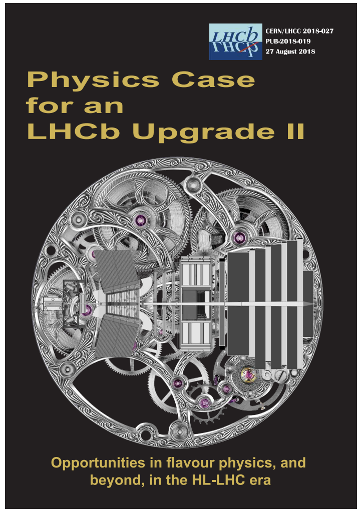


Trigger and DAQ system

LHCb Upgrade II : Opportunities

- Strong Support
  - LHCC - Expression of interest (2017), Physics Case (2018)
  - Strong support in European Strategy (2020)
  - Framework Technical Design Report in preparation
- Applications from new groups actively encouraged
  - Major project after construction timescale of ATLAS/CMS/DUNE/Hyper-K
  - Technical Associate membership: physics on other experiments while pursuing R&D on LHCb
  - Synergy with future projects (EIC, FCC, CEPC…)





Summary

- With 9 fb^{-1} LHCb has demonstrated that it is a multipurpose detector in the forward region :
  - Tensions seen in $b \to s \ell\ell$ transitions (Lepton Universality (e/μ) questioning)
  - CKM matrix tests
  - Exploration of CP violation in the charm sector, first measurement of Δm in the charm sector
  - Discovery of new Tetraquarks
  - ….

- Many more results in the pipeline with the full Run 1 and Run 2 data sample

- Upgrade I (for Run3 data-taking) :
  - Major upgrade of the detector is on-going
  - flexible fully-software trigger
  - expected data sample of ~50 fb^{-1}

- Foreseen Upgrade II for Run5 to fully exploit HL-LHC
  - innovative technologies (timing)
  - aiming at a data sample of ~ 300 fb^{-1}

Exciting times ahead !

Back-up slides

Key-features of the LHCb detector

- All *b*-hadrons species produced
- Low-p_T triggers with calo and muon-chambers
- Good momentum resolution (separate partially reconstructed *b*-hadron decays) and excellent identification of displaced *b*-hadron vertex

  $\Delta p / p = 0.5 - 1.0\%$
  $\Delta IP = (15 + 29/p_T[GeV])\ \mu m$

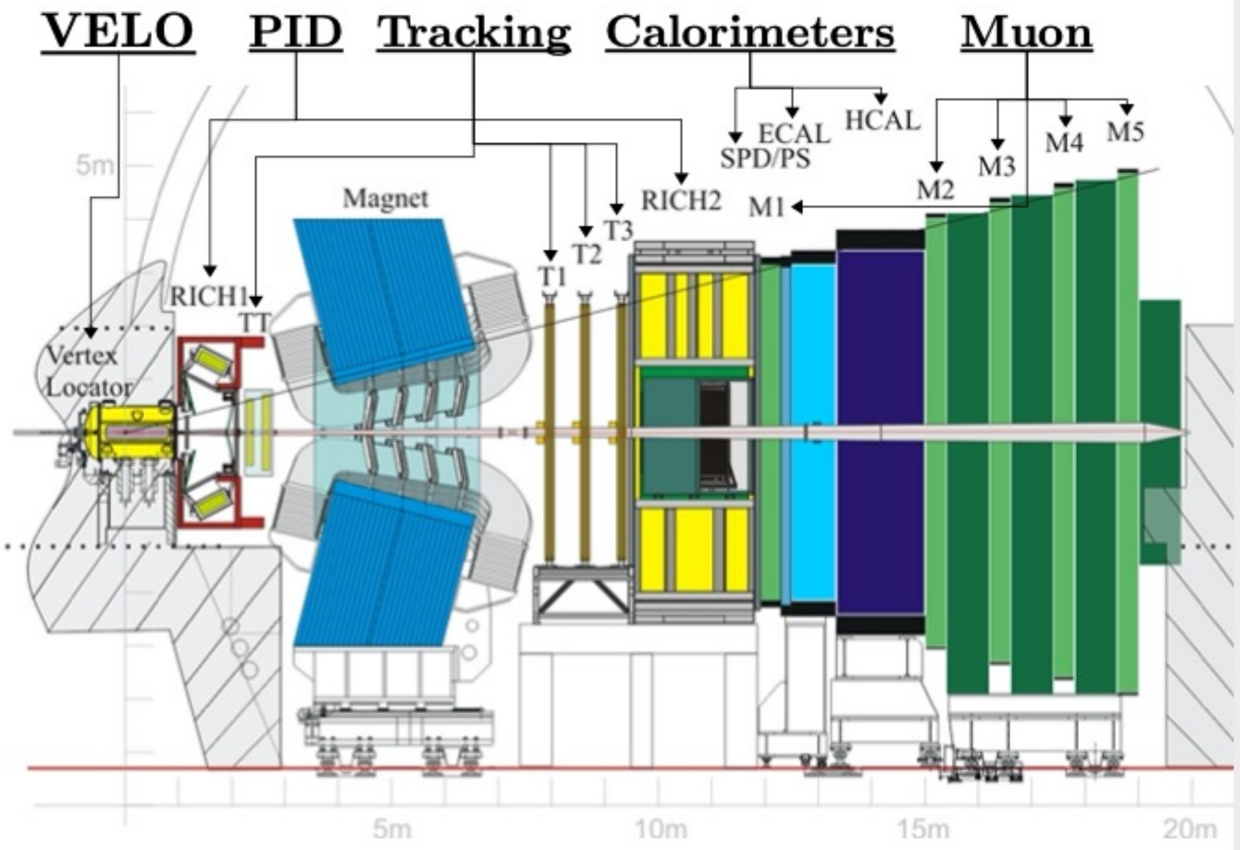
- Excellent PID

  Electron ID ~90% for ~5% e→h mis-id probability

  Kaon ID ~ 95 % for ~ 5 % π→K mis-id probability

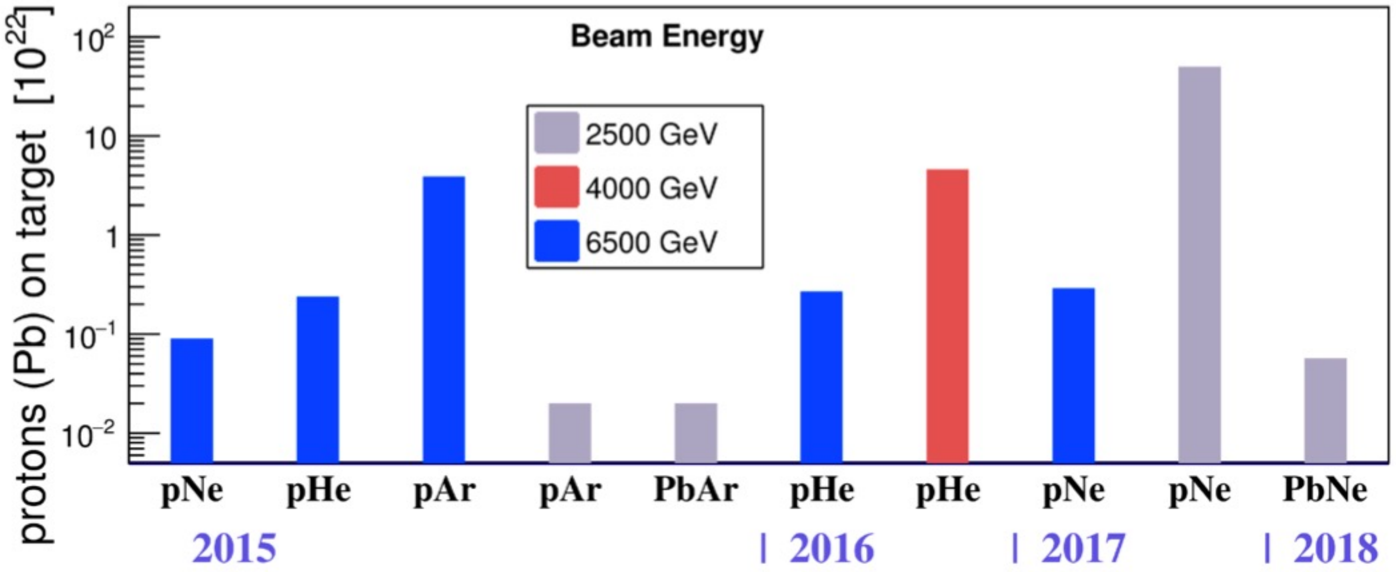
  Muon ID ~ 97% for 1-3% π→μ mis-id probability

- Warm dipole. Polarity can be reversed.

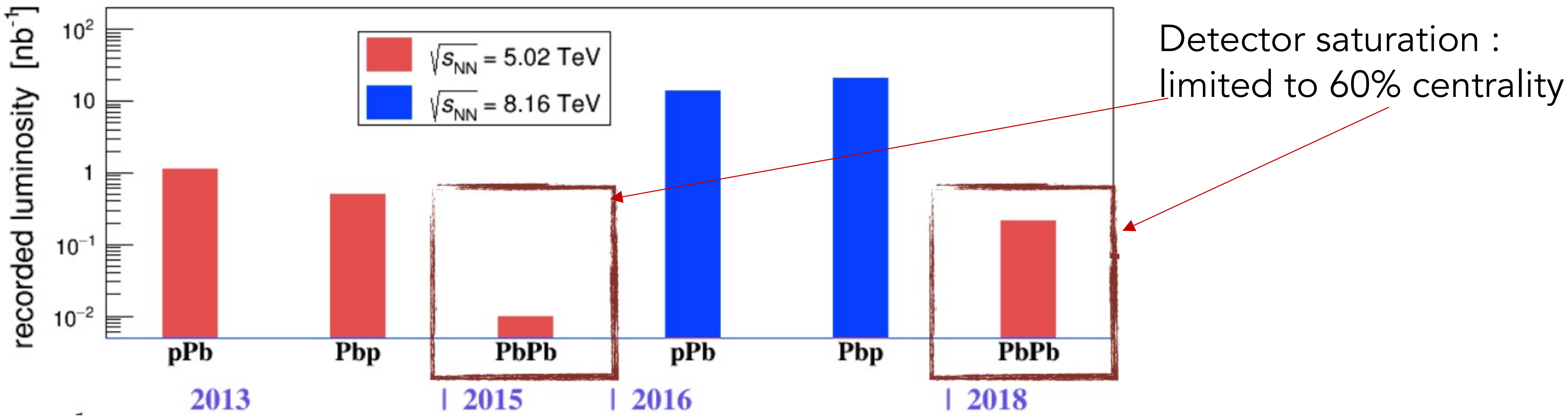


JINST 3 (2008) S08005

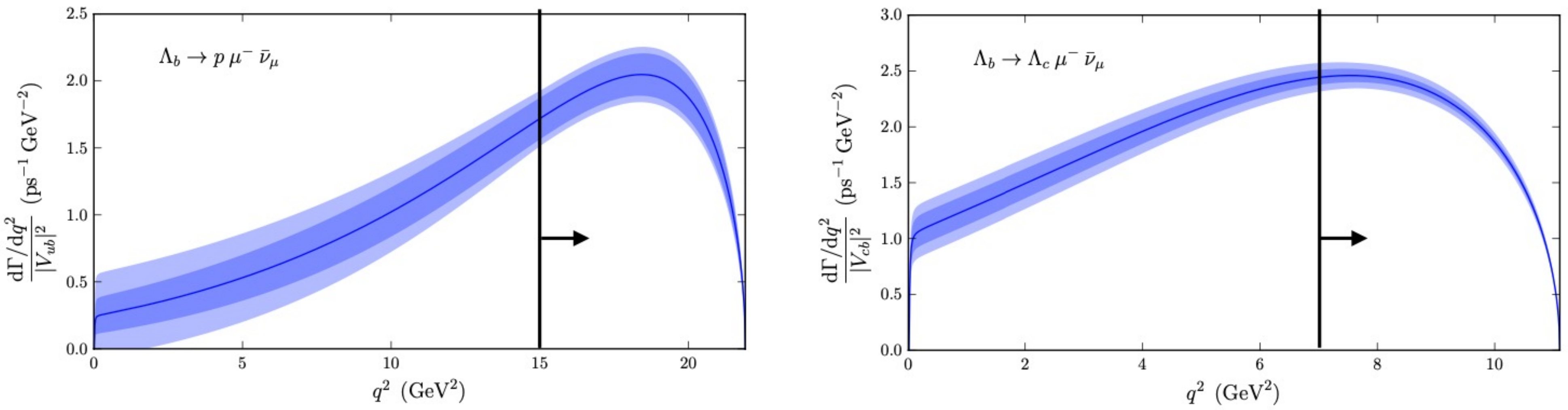
Fixed Target mode samples:



Collider mode samples:



Vub from Lb : q2 cut



Plots from W. Detmold, C. Lehner, S. Meinel, arXiv:1503.01421

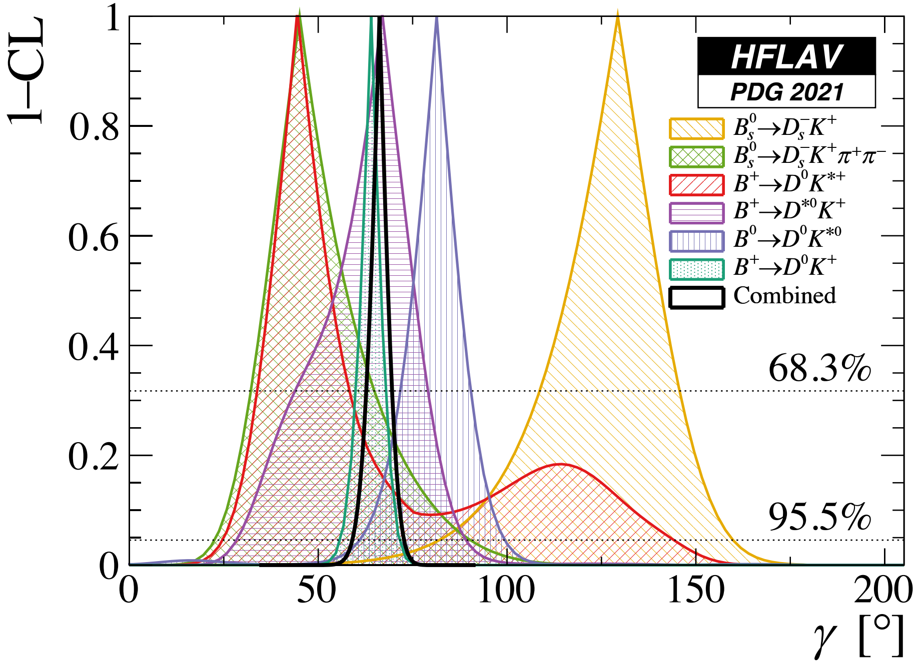
γ angle measurement

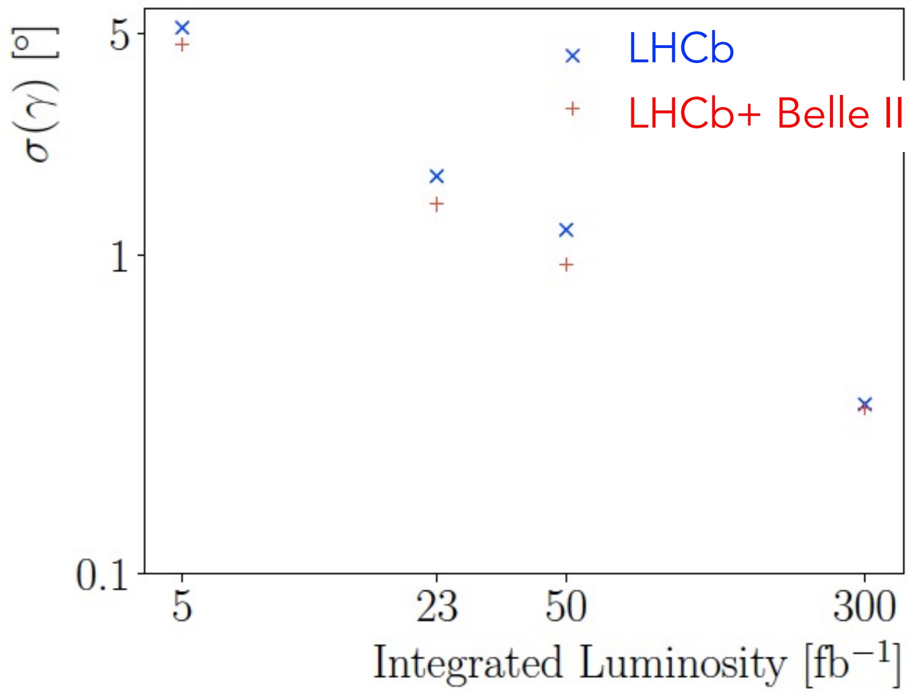
$\gamma = \arg\left(\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$

2021

$\gamma = (66.2^{+3.4}_{-3.6})°$

Fully dominated by LHCb





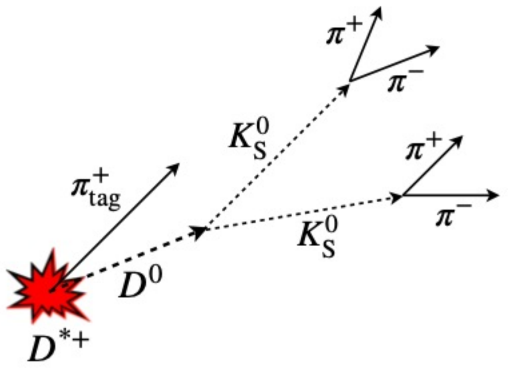
$\sigma_{2021} \sim \sigma_{2012}/3$

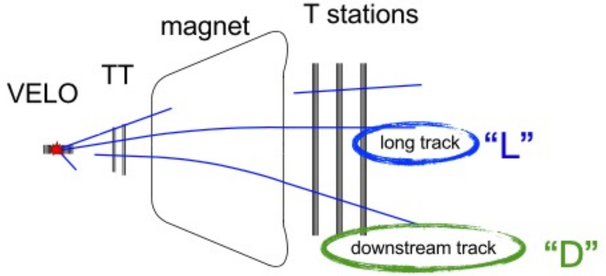
A precise knowledge of the D strong phases is mandatory (BES III, τ-charm)

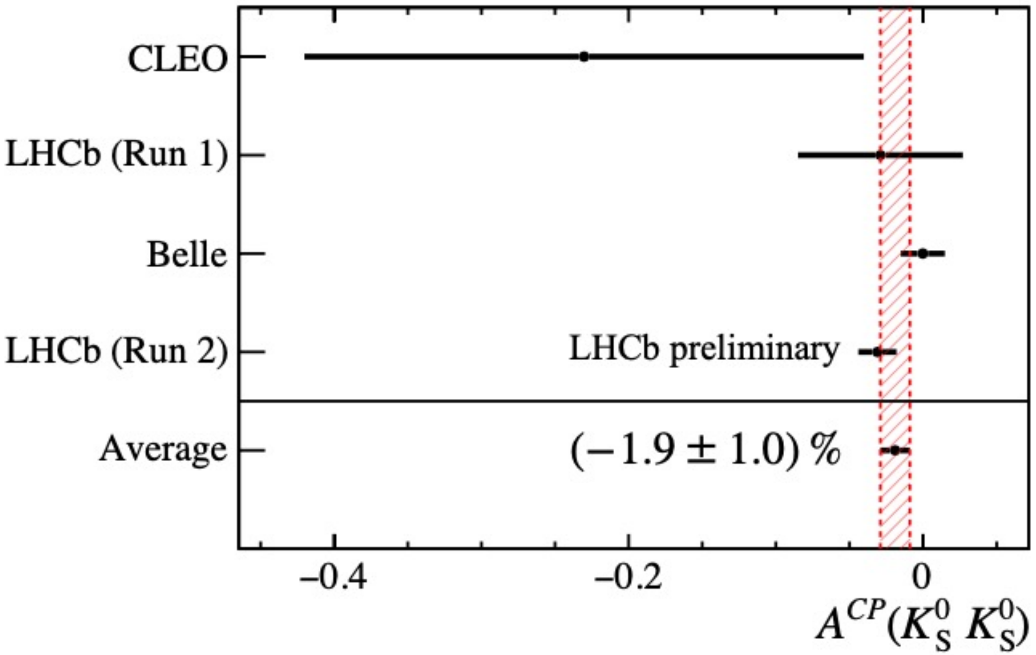
$D^0 \to K_s K_s$

arXiv:2105.01565

CP asymmetry can be large (~ 1%)







Use of $D^0 \to$ KK calibration channel to remove nuisance parameters

$$A^{CP}(D^0 \to K_S^0 K_S^0) = (-3.1 \pm 1.2 \pm 0.4 \pm 0.2)\%$$

compatible with 0 at 2.4 σ

Decay channel challenging
World best measurement

Angular analyses : $B^0 \rightarrow K^{*0} \mu\mu$

Decay described by 3 angles and q^2
Clean (and large) samples

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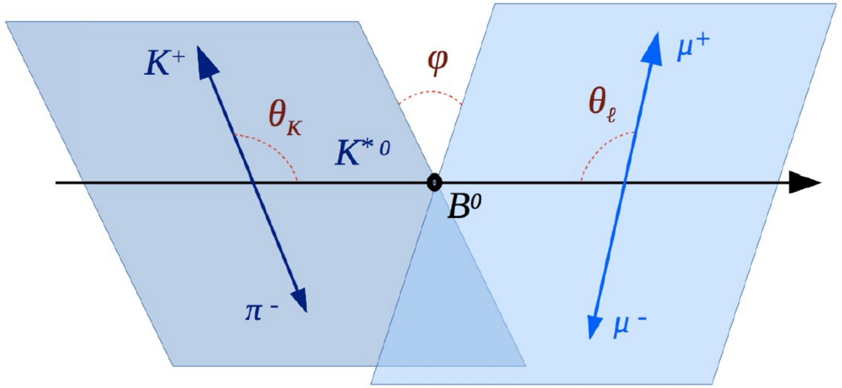

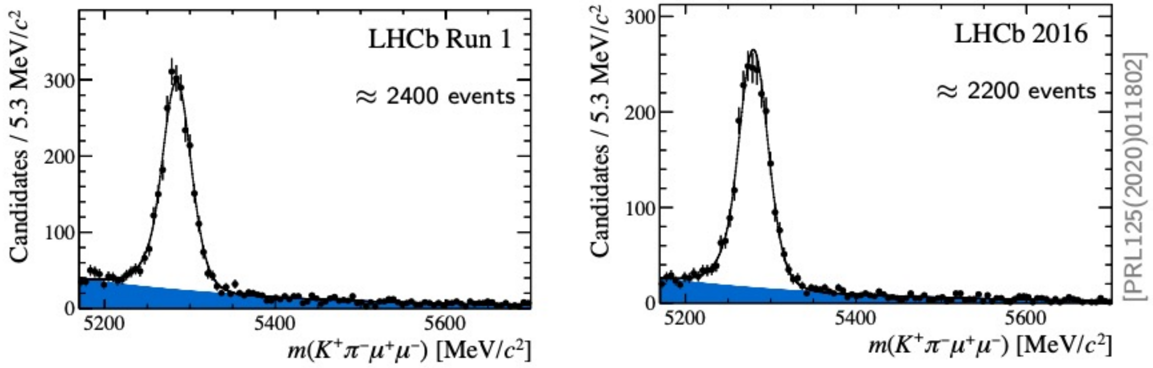

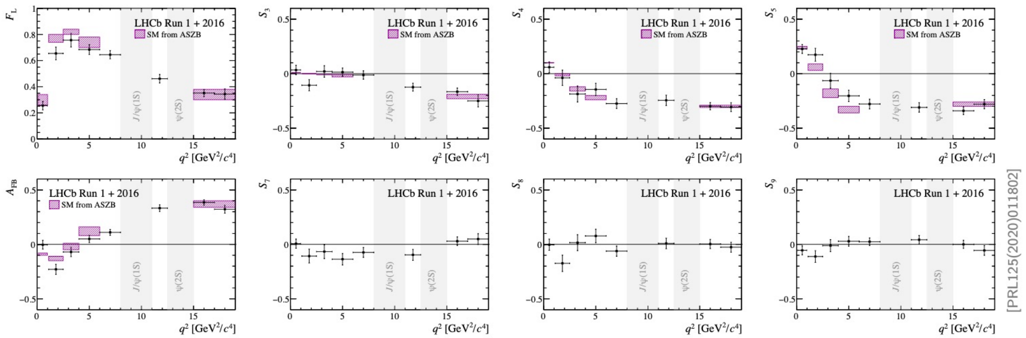

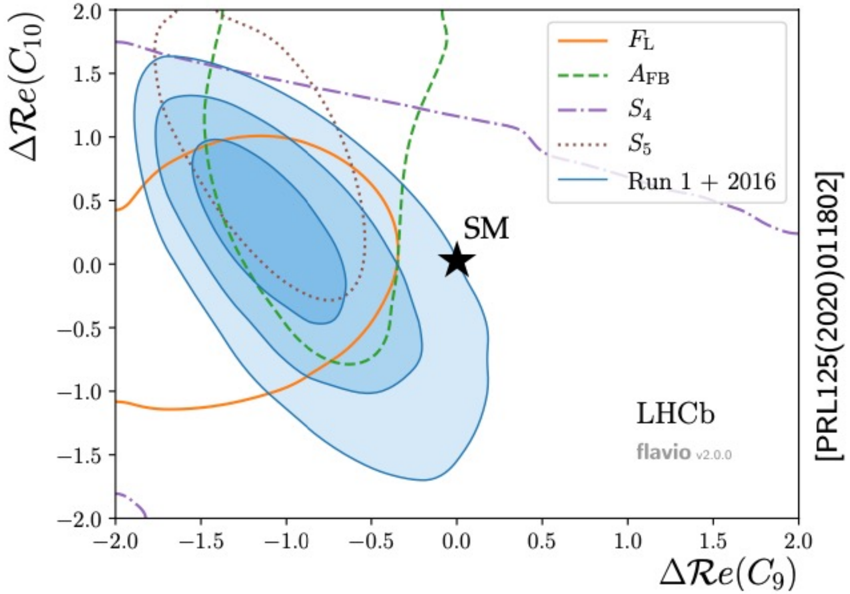

Global Wilson coefficients fit seems to indicate a pattern: different observables give a coherent picture

Similar behaviour in $B^+ \rightarrow K^{*+} \mu\mu$, $B_s \rightarrow \phi\mu\mu$
theoretical debate about $c\bar{c}$ loop impact