Heavy flavour physics at LHCb

- Preamble :
  - Familiar with special relativity and quantum mechanics ?
  - Particle physics background ?

- This lecture :
  - No formal computations
  - Heavy flavour phenomenology and focus on selected LHCb measurements

Outline

Setting the scene

- Flavour physics in the Standard Model
- Heavy flavour phenomenology
- Searching for new physics

The LHCb experiment

- The current detector
- Data taking
- The LHCb upgrade(s)

Highlight of some LHCb results

- The flavour anomalies and CPPM activities

Setting the scene : Flavour physics

- Flavour physics in the Standard Model
- Phenomenology
- Searching for new physics

Reminder : the Standard Model at a glance

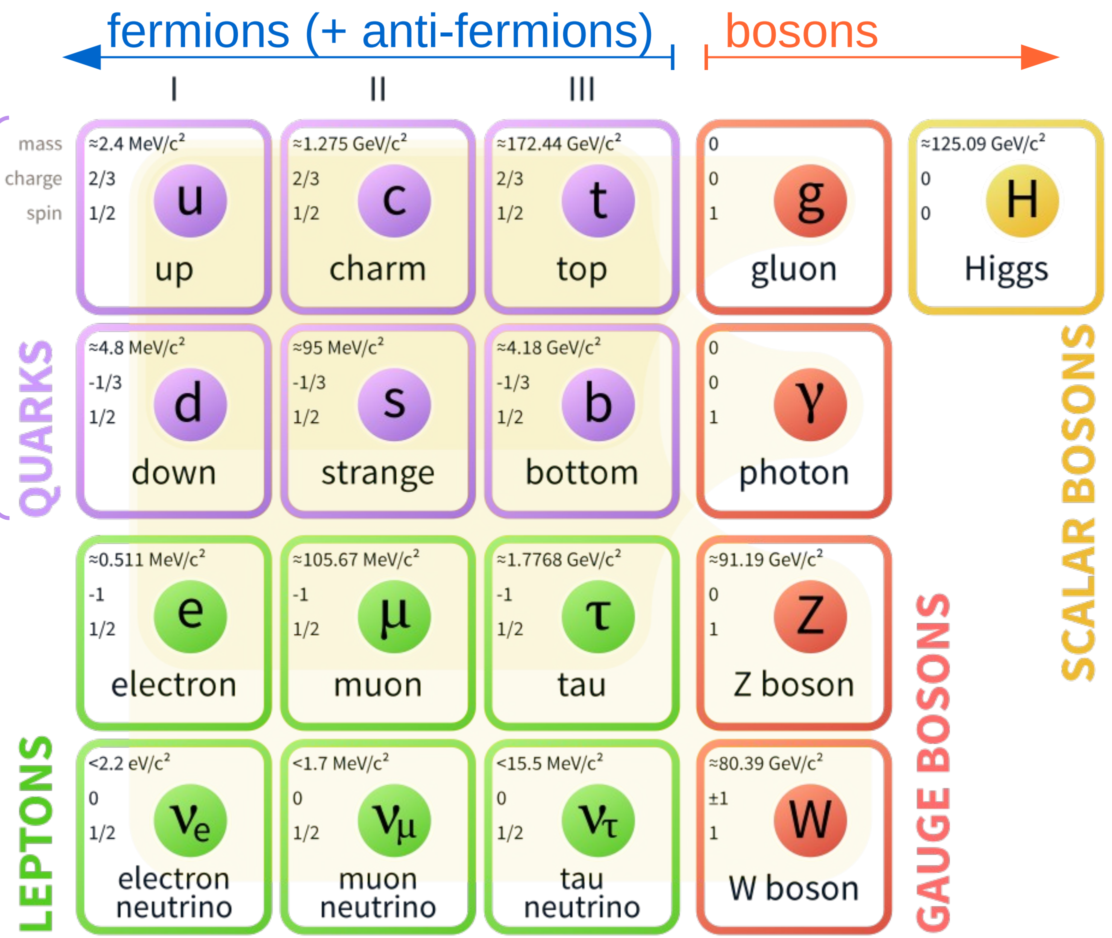
up-type quark : c=2/3

x 3 colours

down-type quark : c=-1/3

charged lepton c=-1

neutral lepton c= 0



Flavour in the SM

- Particle physics can be described to excellent precision by a very simple theory:

$$\mathcal{L}_{\rm SM} = \mathcal{L}_{\rm Gauge}(A_a, \psi_i) + \mathcal{L}_{\rm Higgs}(\phi, A_a, \psi_i)$$

with:

→ Gauge terms that deals with the free fields and their interactions by the strong and electroweak interactions.

→ Higgs terms that gives mass to the SM particles.

Flavour in the SM

- The Lagrangian is invariant under a specific set of symmetry groups:

$$\mathrm{SU}(3)_c \times \mathrm{SU}(2)_\mathrm{L} \times \mathrm{U}(1)_Y$$

- The Gauge part of the Lagrangian is experimentally very well verified,

$$\mathcal{L}_\mathrm{Gauge} = \sum_{j,\psi} i\bar{\psi}_j \not{D} \psi_j - \sum_a \frac{1}{4g_a^2} F^a_{\mu\nu} F^{\mu\nu,a} \ .$$

- The fermion fields are arranged a left-handed doublets and right-handed singlets

$$\psi = Q_\mathrm{L}, u_\mathrm{R}, d_\mathrm{R}, L_\mathrm{L}, e_\mathrm{R}$$

$$Q_\mathrm{L} = \begin{pmatrix} u_L \\ d_L \end{pmatrix} \ , \ L_\mathrm{L} = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$$

There are three replicas of the basic fermion families, which without the Higgs would be identical (huge degeneracy).

Flavour in the SM

- The Higgs part of the Lagrangian, on the other hand, is much more ad-hoc. It is necessary to understand the data but is not stable with respect to quantum corrections (often referred to as the Hierarchy problem).

  It is also the origin of the flavour structure of the SM.

- Masses of the fermions are generated by the Yukawa mechanism:

$$\bar{Q}^{i}_{L} Y^{ij}_{\mathrm{D}} d^{j}_{\mathrm{R}} \phi + \ldots \rightarrow \bar{d}^{i}_{\mathrm{L}} M^{ij}_{\mathrm{D}} d^{j}_{\mathrm{R}} + \ldots$$

$$\bar{Q}^{i}_{L} Y^{ij}_{\mathrm{U}} d^{j}_{\mathrm{R}} \phi_{c} + \ldots \rightarrow \bar{u}^{i}_{\mathrm{L}} M^{ij}_{\mathrm{U}} u^{j}_{\mathrm{R}} + \ldots$$

Flavour in the SM

- Can pick a basis in which one of the Yukawa matrices is diagonal, e.g.

$$Y_{\rm D} = \begin{pmatrix} y_d & 0 & 0 \\ 0 & y_s & 0 \\ 0 & 0 & y_b \end{pmatrix} \;,\; Y_{\rm U} = V^\dagger \begin{pmatrix} y_u & 0 & 0 \\ 0 & y_c & 0 \\ 0 & 0 & y_t \end{pmatrix} \;,\; y_i \approx \frac{m_i}{174 {\rm GeV}}$$

  The matrix V is complex and unitary ($V^\dagger V = 1$)

- To diagonalise both mass matrices it is necessary to rotate $u_{\rm L}$ and $d_{\rm L}$ separately. Consequently, V also appears in charged current interactions,

$$J^\mu_W \rightarrow \bar{u}_{\rm L} V \gamma^\mu d_{\rm L}$$

- V is known as the Cabibbo, Kobayashi, Maskawa matrix ($V_{\rm CKM}$).

  mass eigenstates ≠ weak eigenstates ! $d, s, b \leftrightarrow d', s', b'$

Lepton and baryon number

- SM Lagrangian is invariant under U(3) symmetries of the left-handed doublets and right-handed singlets if fermions are massless.

$$\mathcal{L}_{\text{Gauge}} = \sum_{j,\psi} i\bar{\psi}_j \not{D} \psi_j - \sum_a \frac{1}{4g_a^2} F^a_{\mu\nu} F^{\mu\nu,a} \ .$$

- U(3) symmetries are broken by the Yukawa terms, the only remaining symmetries correspond to lepton and baryon number conservation.

$$U(1)_B \times U(1)_e \times U(1)_\mu \times U(1)_\tau$$

- These are "accidental" symmetries, coming from the particle content rather than being imposed.

Free parameters of the SM

- 3 gauge couplings
- Higgs mass and vacuum expectation value
- 6 quark masses
- 3 quark mixing angles and 1 complex phase (in V_{CKM})
- 3 charged lepton masses
- 3 neutrino masses
- 3 lepton mixing angles and (at least) one complex phase

→ Most of the free parameters of the SM are related to the flavour sector.

Why is flavour important ?

- Most of the free parameters of the SM are related to the flavour sector
- The flavour sector provides the only source of CP violation in the SM
  - → CP : symmetry between particle and anti-particle
  - → key ingredient to understand the lack of anti-matter in the Universe
- Flavour changing neutral current processes can probe mass scales well beyond those accessible at LHC
  - → If there are new particles at the TeV-scale, why don't they manifest themselves in FCNC processes (the so-called New Physics flavour problem)?

Flavour: historical successes (0/2)

Cabibbo angle

- The quark content of the K^+ and K^0 are $(\bar{s}u)$ and $(\bar{s}d)$
- The main decays of the K^+ are

$$K^+ \to \mu^+ \nu_\mu \quad \text{and} \quad K^+ \to \pi^0 e^+ \nu_e$$

  i.e. it decays via the charged current interaction.

- The charged current interaction couples to left-handed doublets, therefore need to construct a doublet that allows $s \to u$ and $d \to u$.
- Cabibbo proposed a solution in terms of quark mixing

$$\begin{pmatrix} u \\ d' \end{pmatrix} = \begin{pmatrix} u \\ d\cos\theta_C + s\sin\theta_C \end{pmatrix}$$

Flavour: historical successes (0/2)

Cabibbo angle

- The quark mixing angle, θC, is determined experimentally to be

$$\sin\theta_C \approx 0.22$$

- Cabibbo's proposed solution also explained a discrepancy between the weak coupling constant between muon decays and nuclear decay.
- However, this opened up a new problem, why is

$$\Gamma[K^+ \to \mu\nu] \gg \Gamma[K_L^0 \to \mu^+\mu^-] \quad ?$$

- If the doublet of the weak interaction is the one Cabibbo suggested, can have neutral currents

$$J_\mu^0 = \bar{d}'\gamma_\mu(1-\gamma_5)d'$$

which introduces tree level FCNCs.

Flavour: historical successes (0/2)

GIM mechanism

- So was Cabibbo wrong? Glashow, Iliopoulos and Maiani provided a solution in 1970 by adding a second doublet

$$\begin{pmatrix} u \\ d' \end{pmatrix} = \begin{pmatrix} u \\ d\cos\theta_C + s\sin\theta_C \end{pmatrix} , \begin{pmatrix} c \\ s' \end{pmatrix} = \begin{pmatrix} c \\ -d\sin\theta_C + s\cos\theta_C \end{pmatrix}$$

- The second doublet exactly cancels the FCNC term.

  Quark mixing led to the prediction of the charm quark.

- For "strange" decays still have an effective GIM suppression.

  2 x 2 unitarity implies

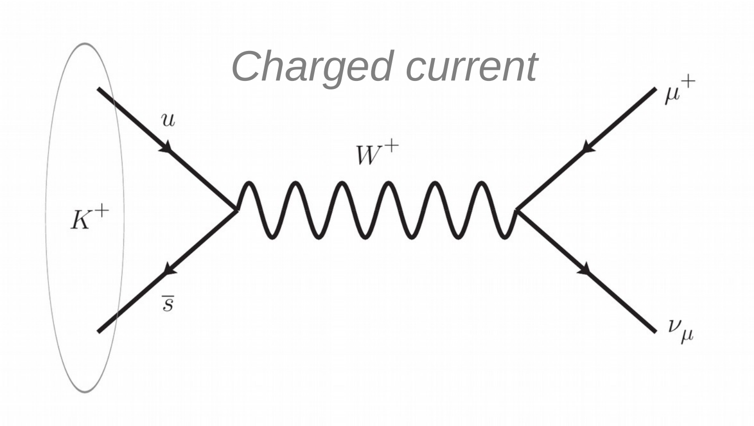
$$V_{us}^* V_{ud} + V_{cs}^* V_{cd} = 0 \qquad \mathcal{A} \approx 0$$

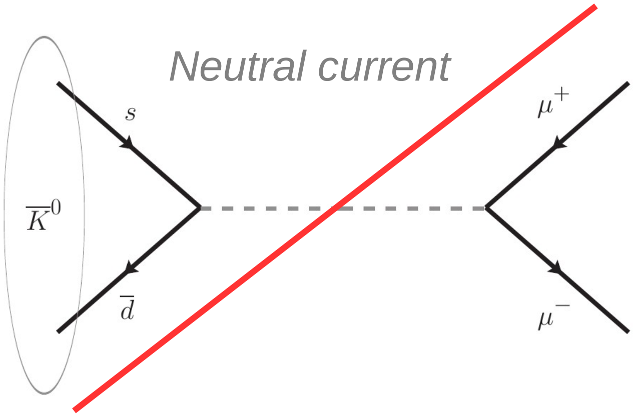
- FCNC decays are very rare,

$$\mathcal{B}(K_L^0 \to \mu^+\mu^-) = (6.8 \pm 0.1) \times 10^{-9}$$

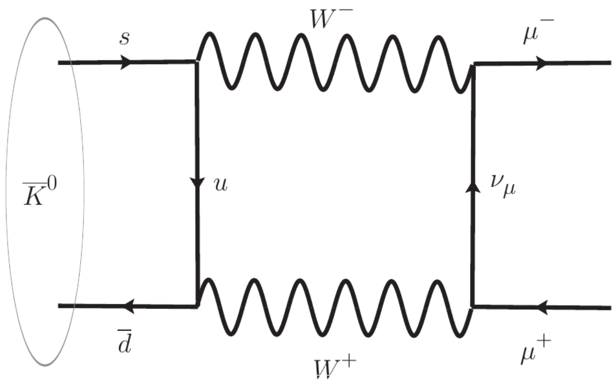
Flavour physics : historical successes (1/2)

No Flavour Changing Neutral Current (FCNC) at tree level



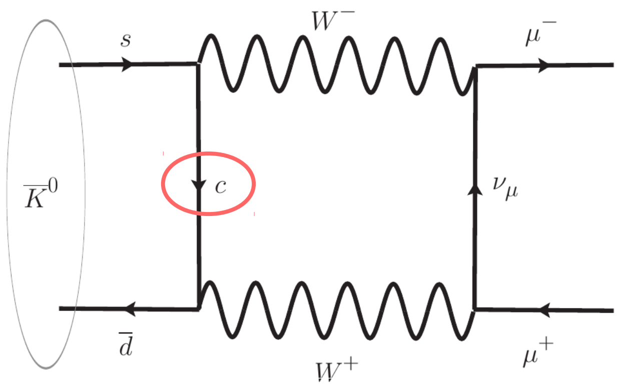


FCNC can occur in loop diagrams



→ But the observed rate of $K \rightarrow \mu\mu$ is very much more suppressed

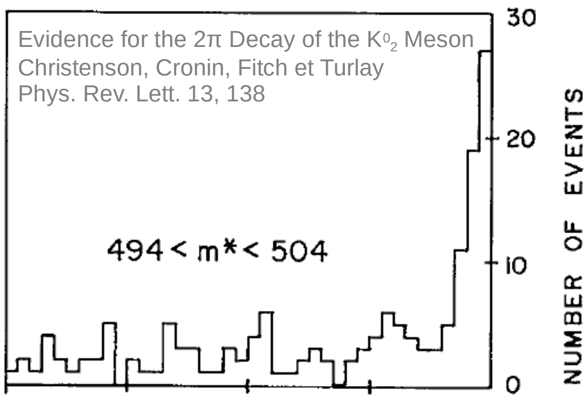
Prediction of the c quark (1970')



→ diagram cancellation ! (GIM mechanism)

Flavour physics : historical successes (2/2)

1964 : first observation of CP violation



1973 : Kobayashi and Maskawa show that this can be explained if there are 3 generations

→ prediction of the third family, directly observed in 1977

1987 : *B* meson mixing

UA1 Collab., Phys. Lett.B186, 247 (1987)
ARGUS Collab, Phys. Lett.B192,245 (1987)(plot)

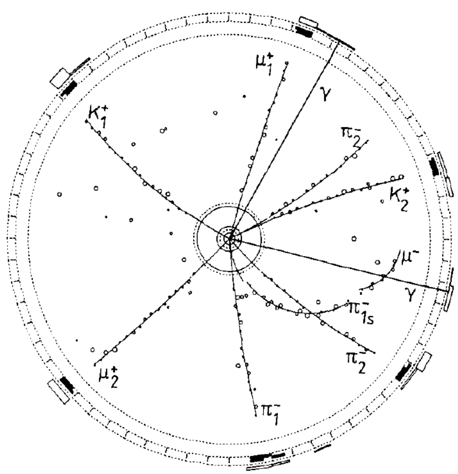
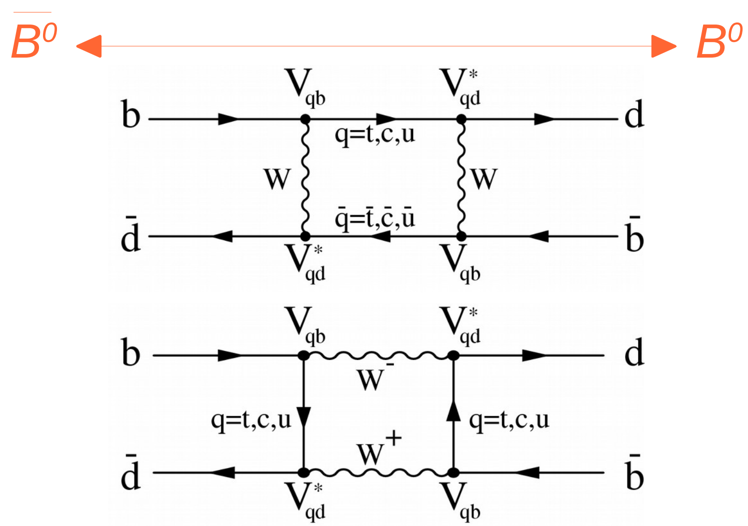
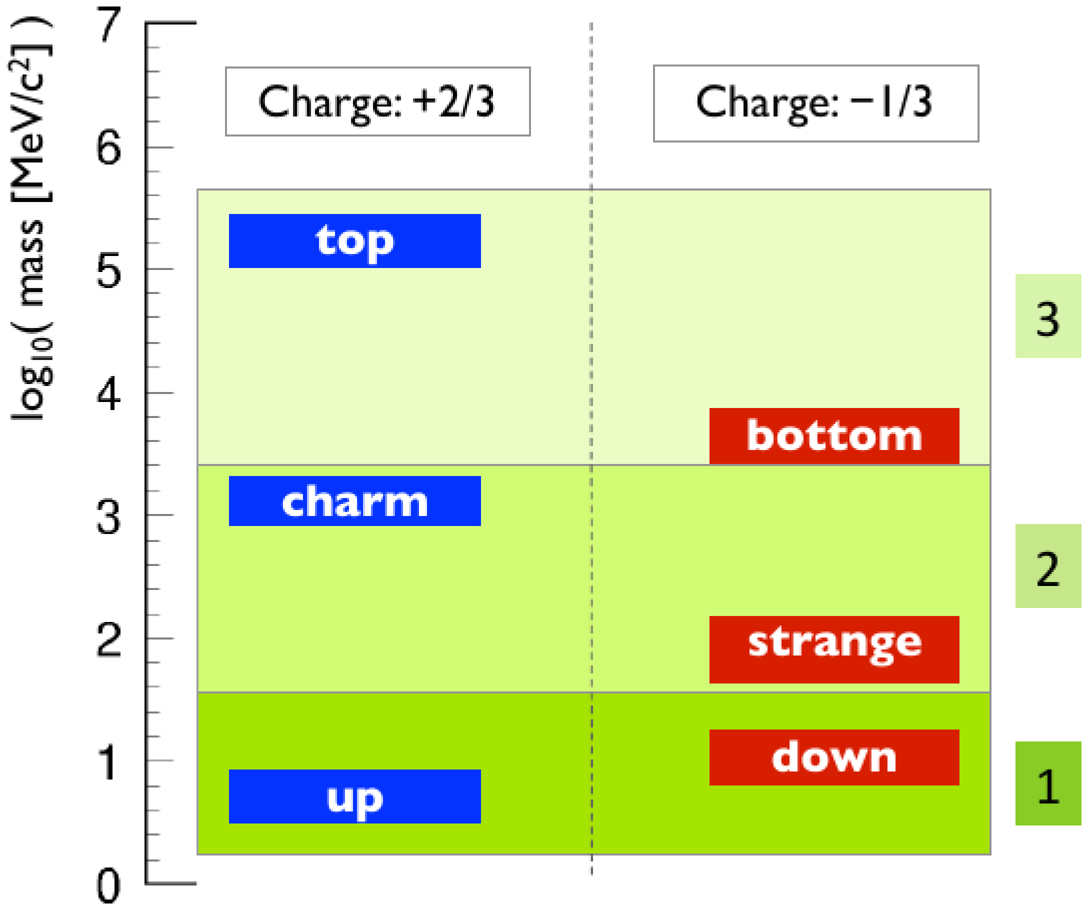


Fig. 2. Completely reconstructed event consisting of the decay Υ (4S)→B^0B^0.



→ First hint of quark top high mass

CKM at play



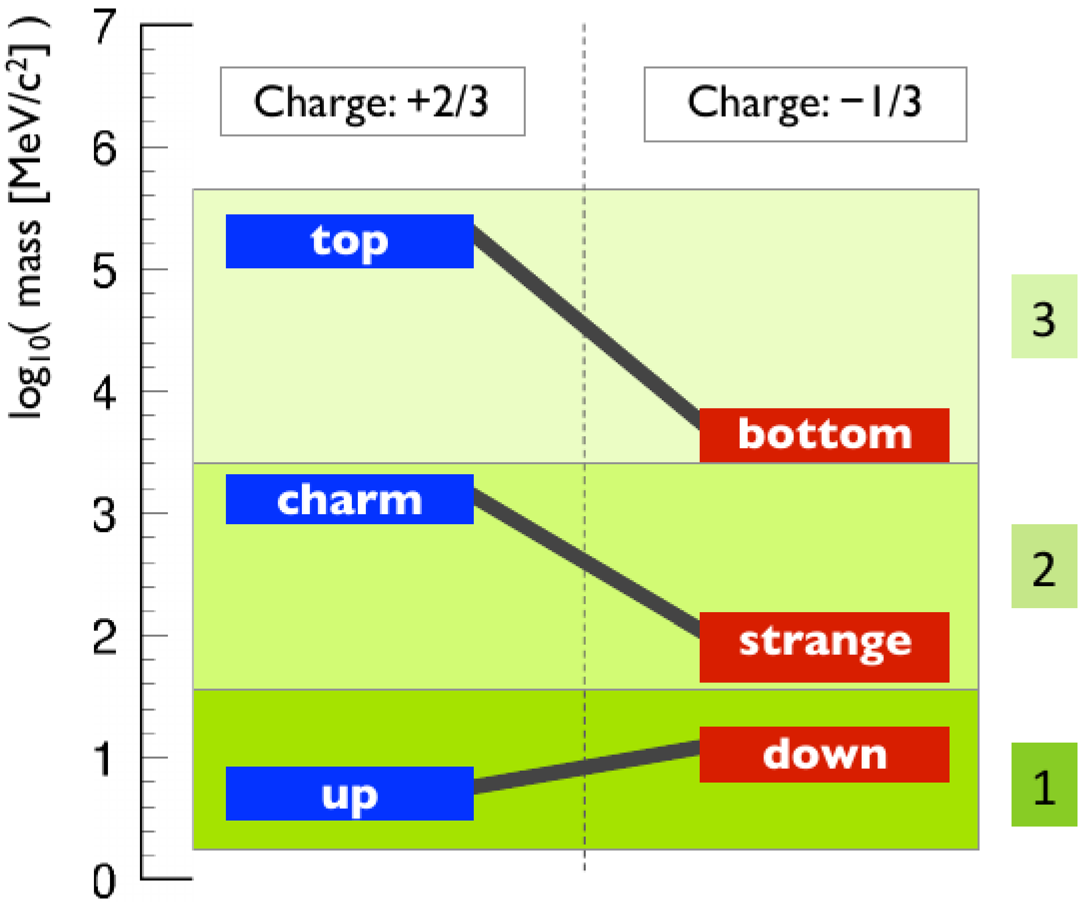
Quark flavour physics :

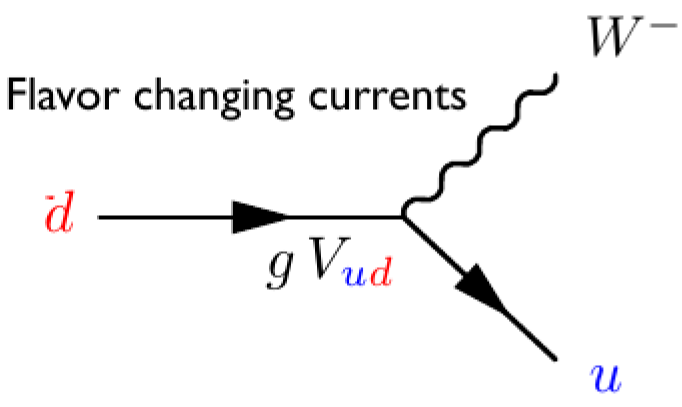
→ flavour changing interaction

The weak interaction is the only one acting on quark flavour

→ flavour changing is due to $W^{\pm}$ exchange

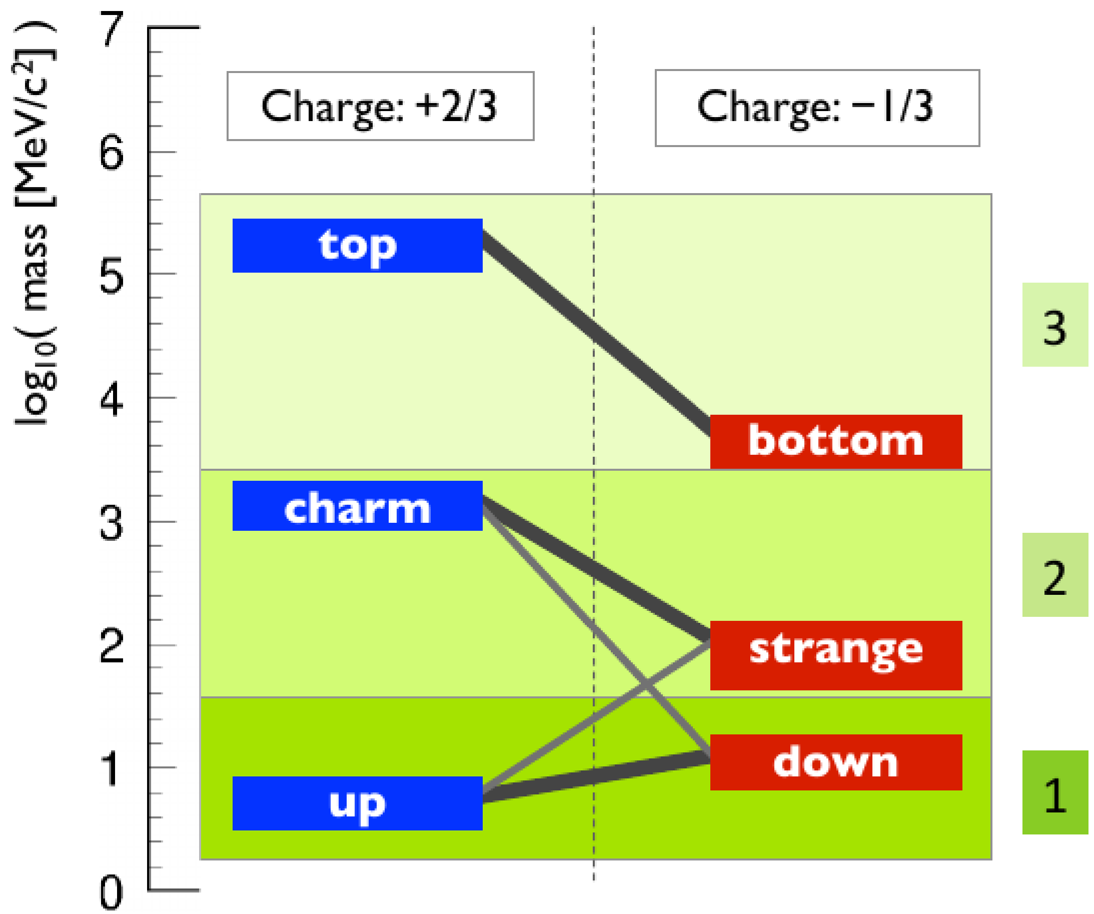
CKM at play

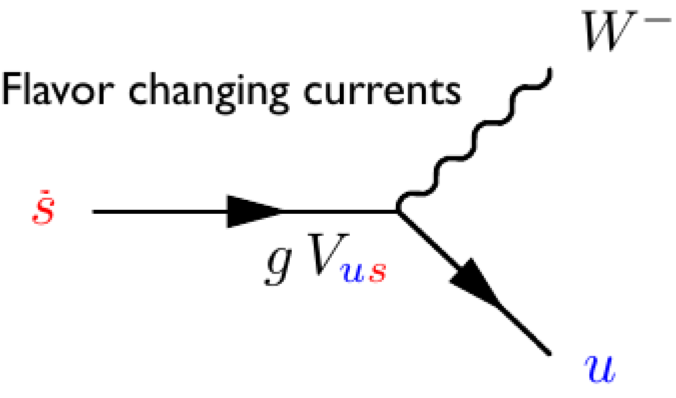




$$V_{\rm CKM} = \begin{pmatrix} V_{ud} & & \\ & V_{cs} & \\ & & V_{tb} \end{pmatrix}$$

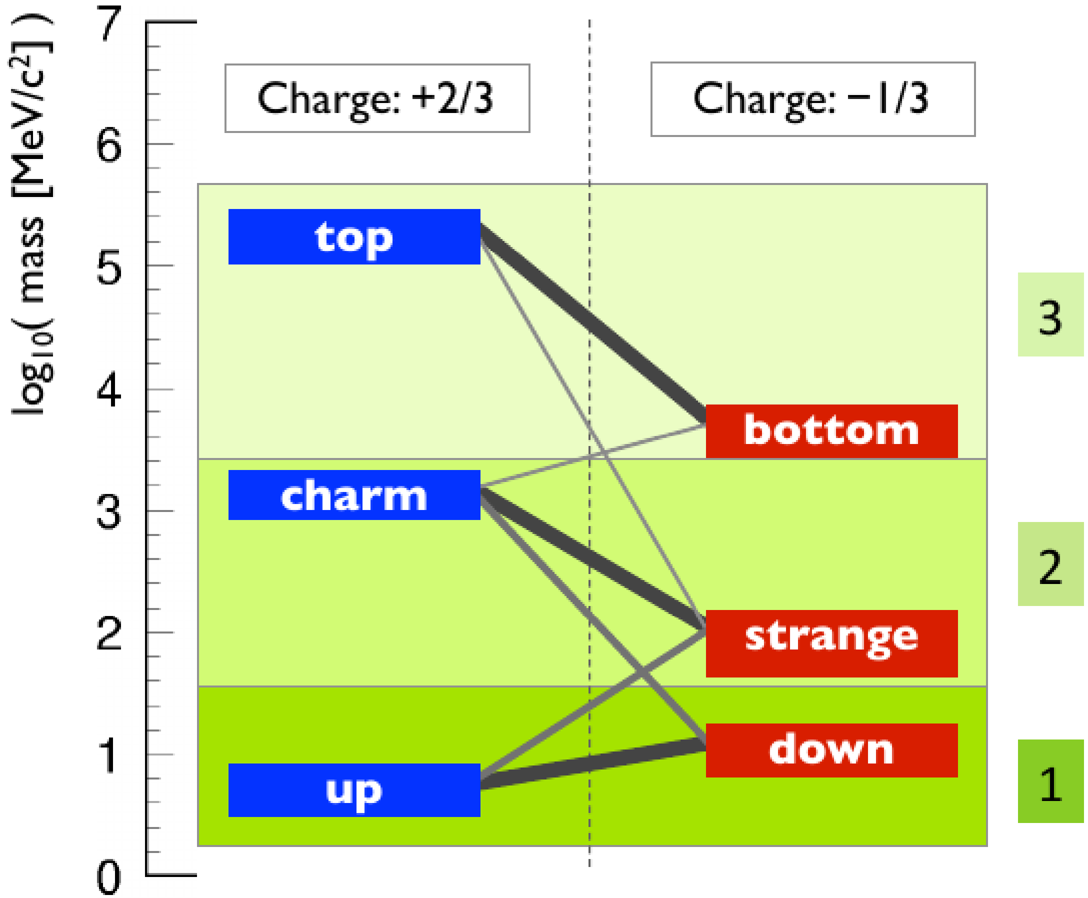
CKM at play

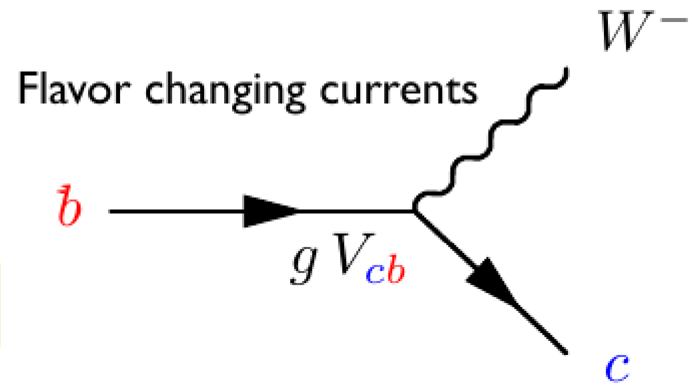




$$V_{\mathrm{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & \\ V_{cd} & V_{cs} & \\ & & V_{tb} \end{pmatrix}$$

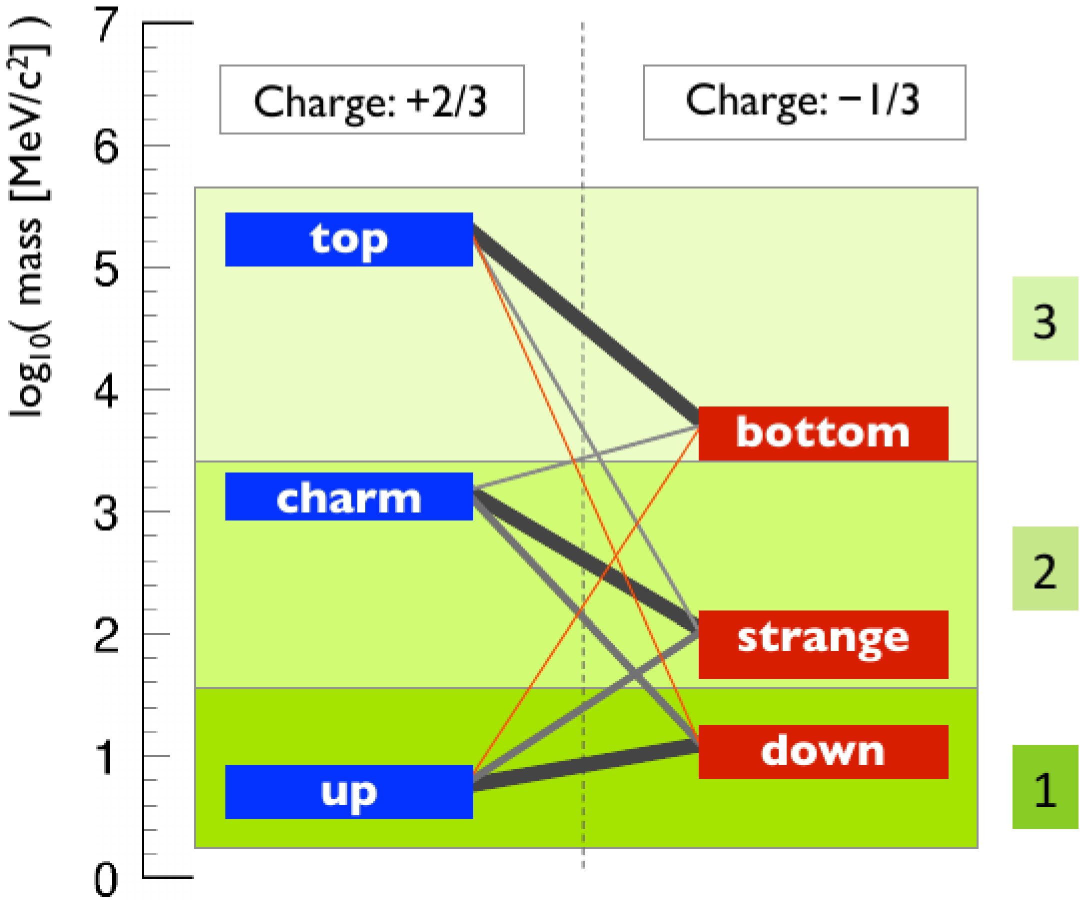
CKM at play

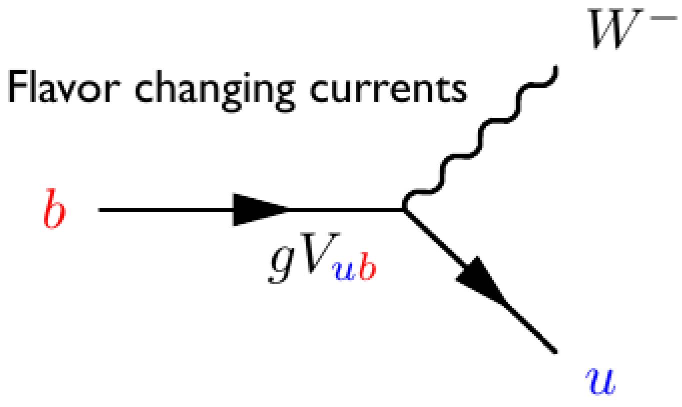




$$V_{\rm CKM} = \begin{pmatrix} V_{ud} & V_{us} & \\ V_{cd} & V_{cs} & V_{cb} \\ & V_{ts} & V_{tb} \end{pmatrix}$$

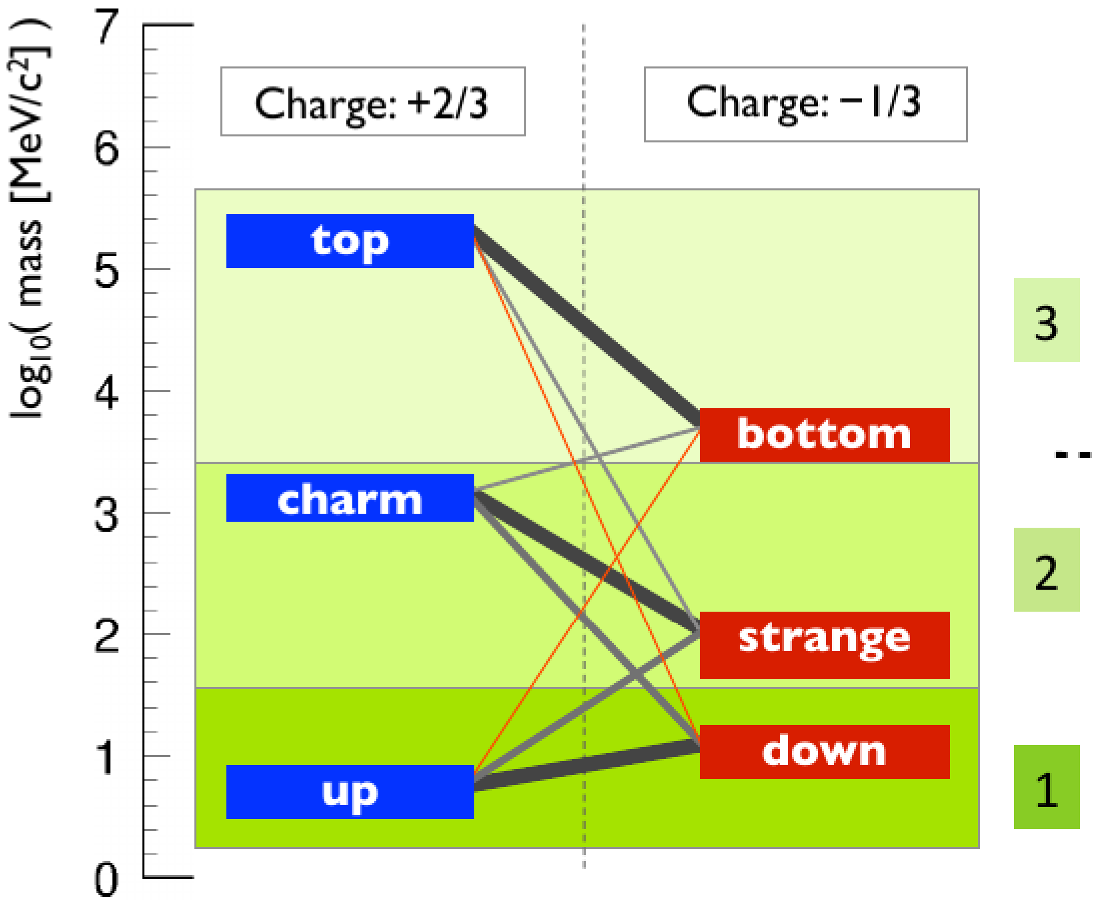
CKM at play

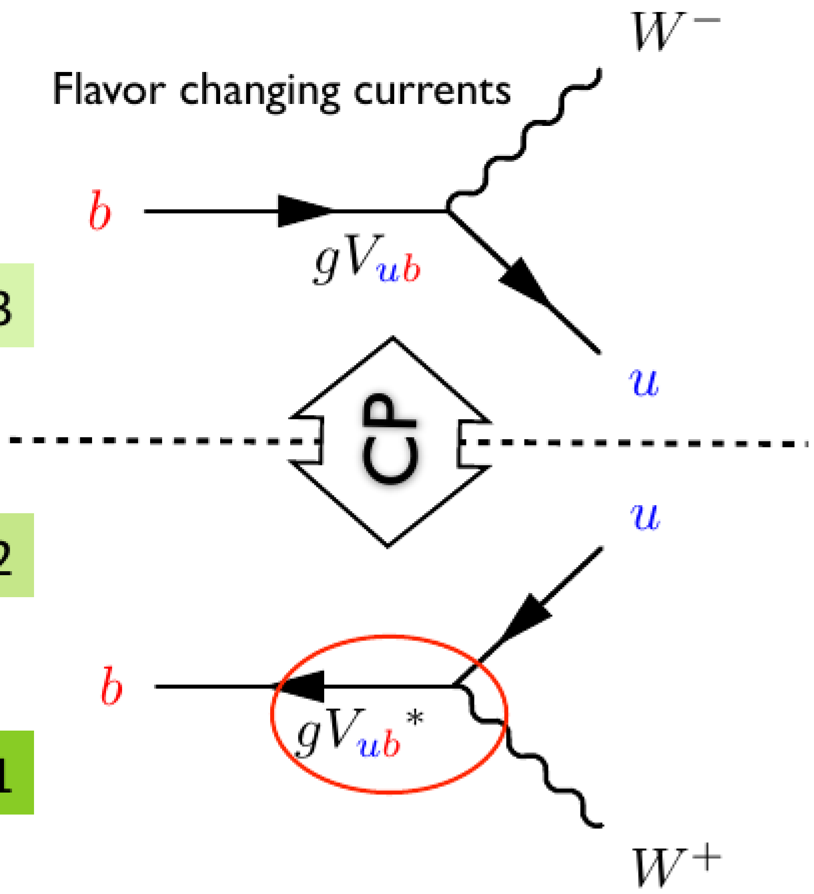




$$V_{\mathrm{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

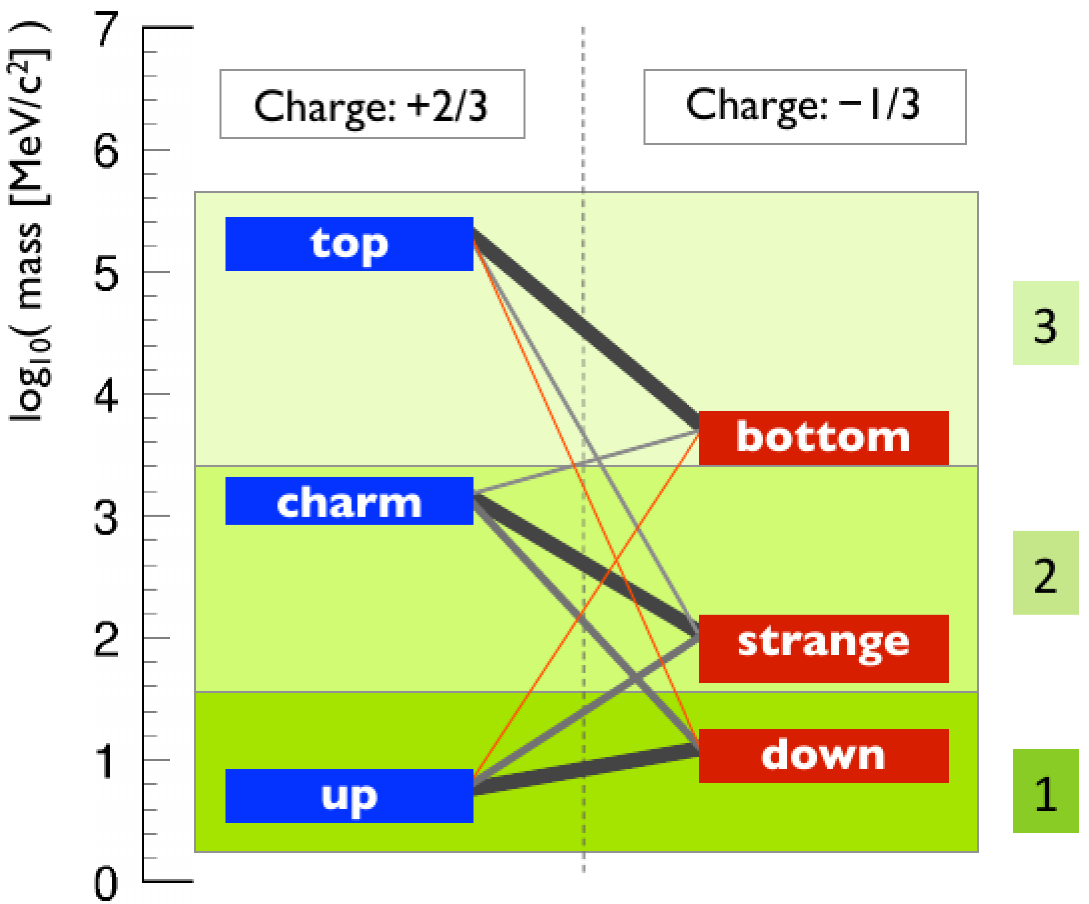
CKM at play



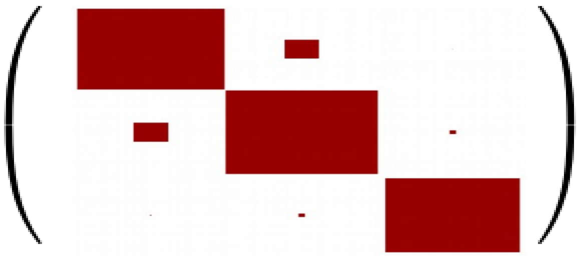


$$V_{\mathrm{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

CKM at play

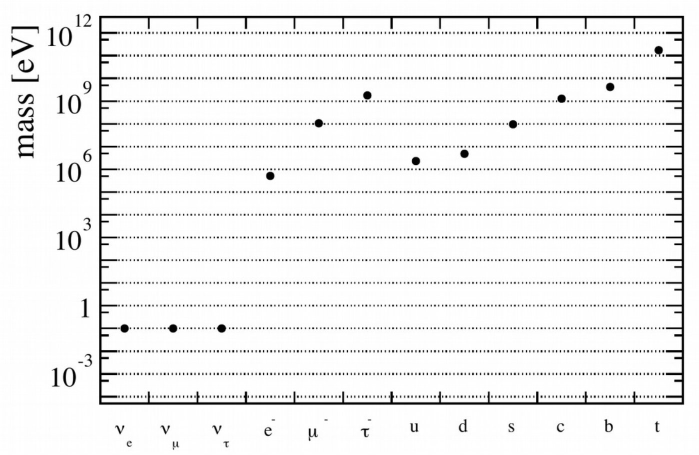


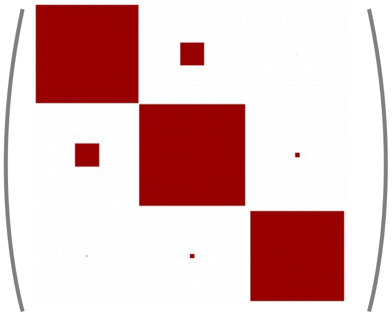
Very strong hierarchy in the CKM elements

$V_{\mathrm{CKM}} =$ 

Remarks (1/2)

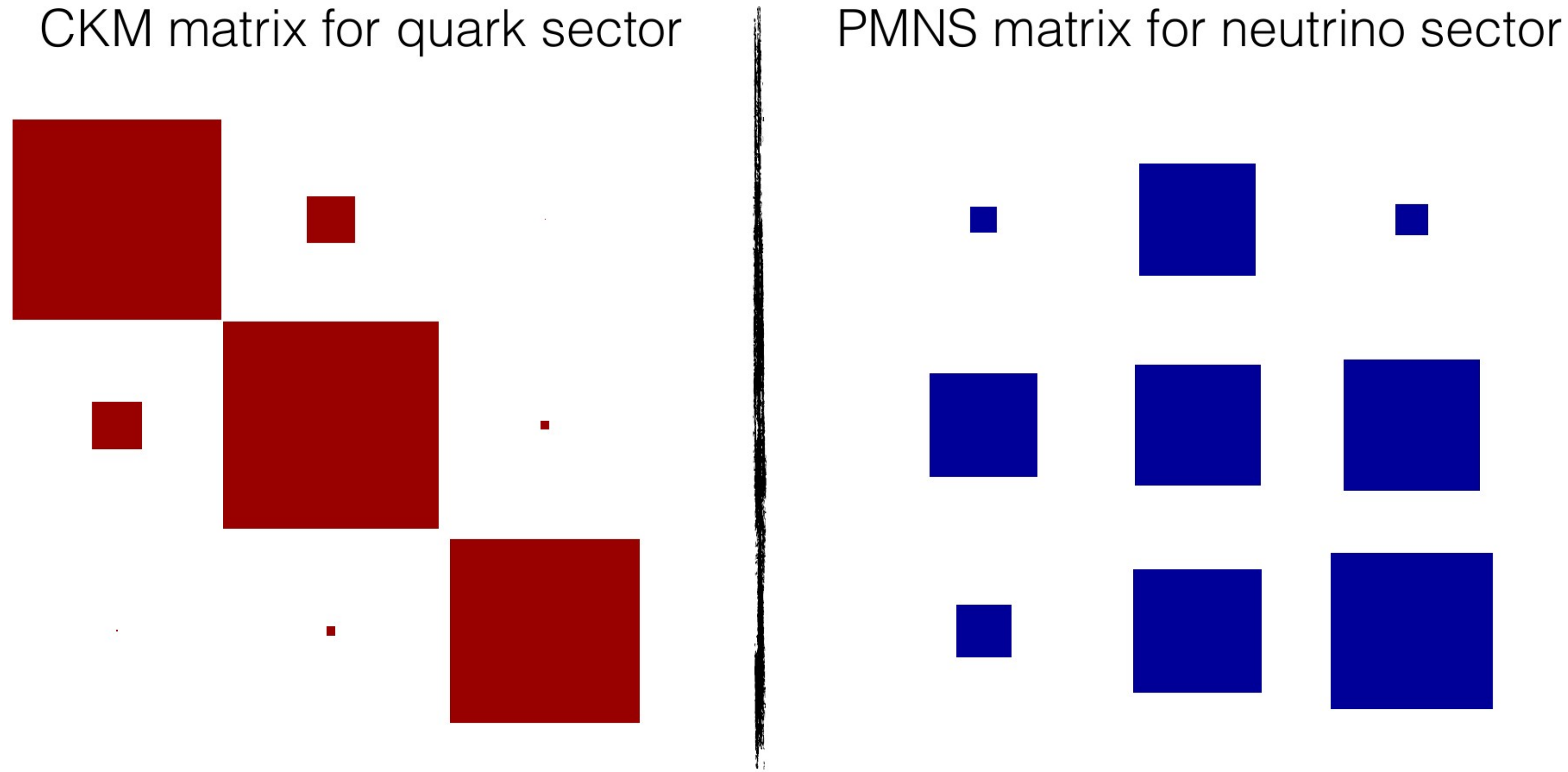
- In the SM, change of quark flavour at tree level always occur via $W^{\pm}$ exchange (charged current interaction)
  - → No flavour changing current at tree level
  - → FCNC (Flavour Changing Neutral Current) always involve loop diagrams
    - – naturally suppressed
    - – suppression can be even stonger due to the GIM mechanism
- CP violation requires a physical phase in the Lagrangian
  - → in the SM, the only place is in Yukawa interactions
  - → CKM quark mixing plays a major role
- The “SM flavour puzzle”:
  - → hierarchy in :
    - – quark masses
    - – mixing angles
  - → not explained within the SM





Remarks (2/2)

Mixing in the lepton sector as well (from neutrino oscillation)



Lepton flavour sector very different

Today : focus on heavy-quark flavour

What is Heavy Flavour physics ?

Flavour changing interactions :
- electroweak processes
- at the quark level

But quarks feel the strong interaction and hadronise
- quark level parameters can not be accessed directly
- hadronic physics effects need to be under control

Heavy quarks ?
- $\Lambda_{QCD} / m_q << 1$ & $\alpha_s(m_q) << 1$
- hadronic physics can be handled perturbatively

Heavy flavor physics :
- study b- (and c-) hadrons decays
  - very rich phenomenology

Main objectives :
- Test the SM / Search for physics beyond the SM (BSM)
- compare precise theoretical prediction with precise experimental measurements

u,d → to light !

m ≈ 2 - 5 MeV

s → maybe

m ≈ 100 MeV

c,b → just right !

m ≈ 1 - 4 GeV

t → too heavy !

m ≈ 170 GeV

Some heavy flavour phenomenology

- Strong interaction and hadronisation
- Neutral Mesons mixing
- CP-violation

Strong interaction

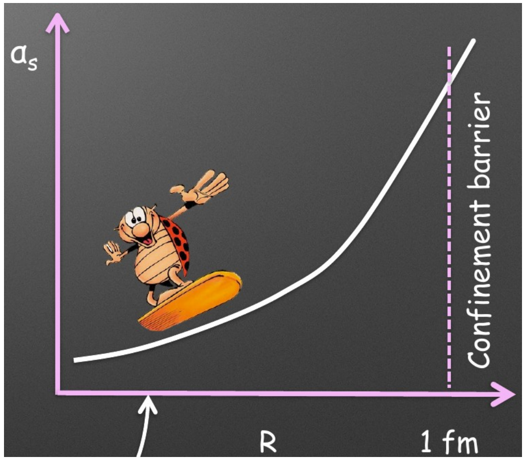
Electromagnetic interaction

- Electric charges (2)
  - +1
  - -1
- Interaction between charges
  - opposite charges are attracted
  - equal charges are repelled
- Neutral object (charge = 0)
  - insensitive to electromagnetic interaction
- Force career
  - photon (neutral)
- Intensity
  - decreases with the distance (1/d)

Strong interaction

- "Color" charges (6)
  - red, green, blue (3 charges "+")
  - $\overline{\text{red}}$, $\overline{\text{green}}$, $\overline{\text{blue}}$ (3 charges "-")
- Interaction between charges
  - all color charges are repelled
- Neutral object (charge = WHITE)
  - rgb = $\overline{\text{rgb}}$ = r$\overline{\text{r}}$ = g$\overline{\text{g}}$ = b$\overline{\text{b}}$ = WHITE
  - insensitive to strong interaction
- Force career
  - gluons (8 – carry colors)
- Intensity
  - grows with the distance !!!

Quark confinement into hadrons



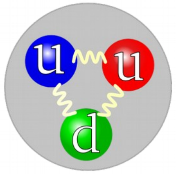
[Y. Schutz; this school 8/7/2017]

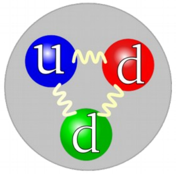
Strong interaction gets stronger with distances

- only WHITE (color neutral) states appear in nature
- quarks are confined into *hadrons*

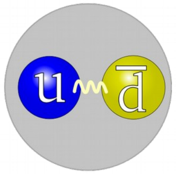
Different types of hadrons

- baryons made of 3 quarks (rgb, $\overline{rgb}$)
  - ex : proton, neutron

p 

n 

- mesons made of a quark and an anti-quark ($r\bar{r}$, $g\bar{g}$, $b\bar{b}$)
  - ex : pions (π), kaons (K)

π^+ 

- also exotic states with 4 or 5 quarks !

Quark confinement into hadrons

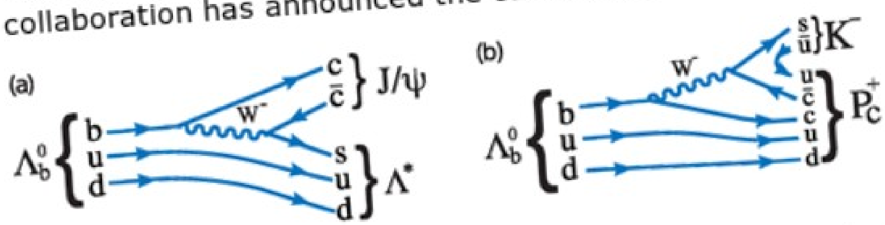
14 July 2015: Observation of particles composed of five quarks,

pentaquark-charmonium states, seen in $\Lambda_b^0 \rightarrow J/\psi p K^-$ decays.

[$m(P_c^+(4450)) = 4449.8 \pm 1.7 \pm 2.5$ MeV, $\Gamma = 39 \pm 5 \pm 19$ MeV]

[$m(P_c^+(4380)) = 4380 \pm 8 \pm 29$ MeV, $\Gamma = 205 \pm 18 \pm 86$ MeV]

The LHCb collaboration submitted today a paper based on run 1 data which reports the observation of pentaquark-charmonium states decaying into a J/ψ meson and a proton p. In the traditional quark model, the strongly interacting particles (hadrons) are formed either from quark-antiquark pairs (mesons) or three quarks (baryons). Particles which cannot be classified within this scheme are called exotic hadrons. In his fundamental 1964 paper, in which he proposed the quark model, Gell-Mann mentioned the possibility of adding a quark-antiquark pair to a minimal meson or baryon quark configuration. It has taken 50 years, however, for measurements to be performed that unambiguously demonstrate the existence of these exotics. In April 2014 the LHCb collaboration published results of measurements which demonstrated that the $Z(4430)^+$ particle, first observed by the Belle collaboration, is composed of four quarks ($c\bar{c}d\bar{u}$). Today, the collaboration has announced the observation of a pentaquark, that is a hadron consisting of five quarks.



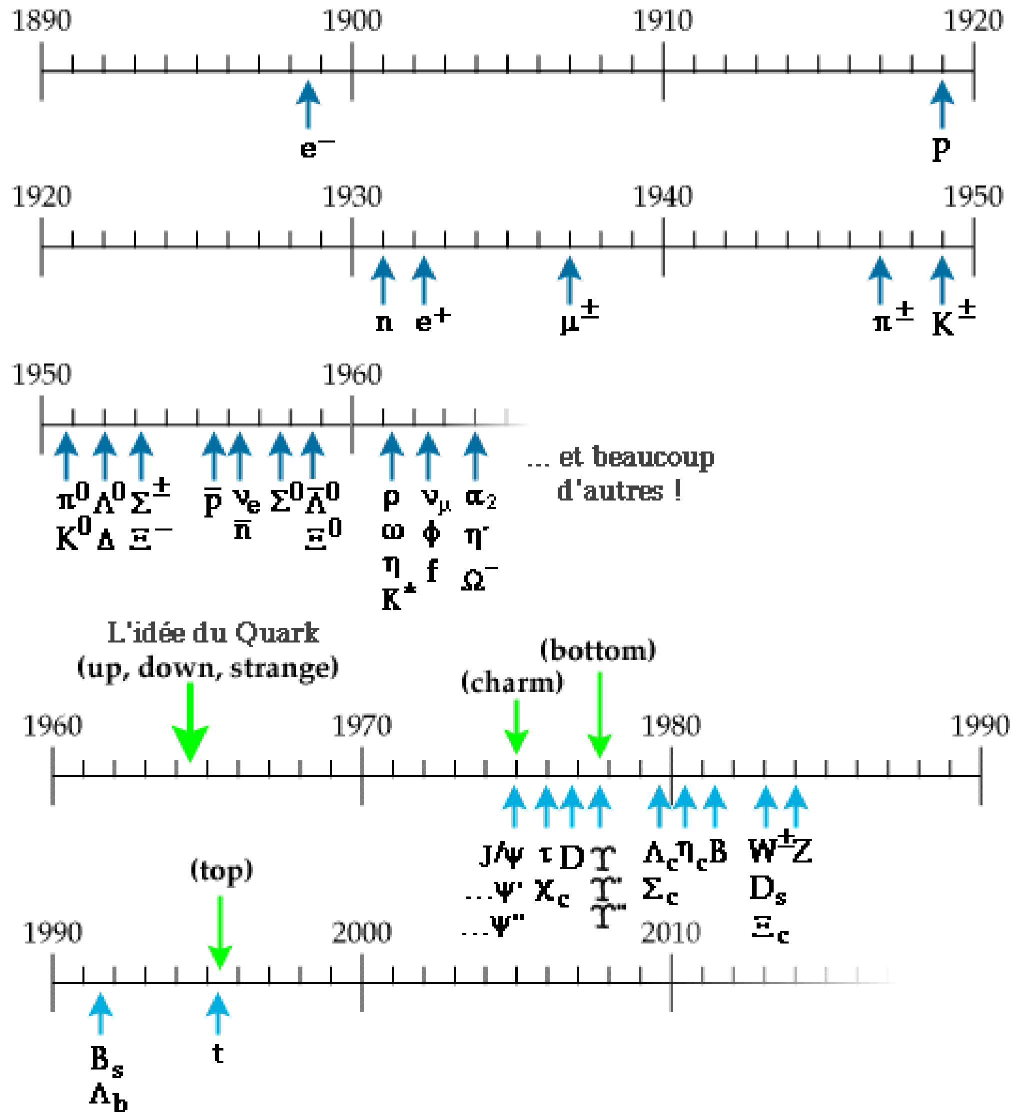
LHCb physicists have analyzed a sample of about 26 000 $\Lambda_b^0 \rightarrow J/\psi p K^-$ decays with only 5% of background contamination. The Λ_b^0 baryon is like a neutron, but containing a beauty quark in place of one of the down quarks. This decay can proceed by the diagram (a), which involves conventional hadrons and is dominated by Λ^* resonances that decay in turn into a proton p and K^- meson. It can also have exotic pentaquark contributions, shown in diagram (b), that result in resonant structures (called P_c^+ in today's paper) at 4380 and 4450 MeV in the J/ψp invariant mass spectrum shown in the left image below. The P_c^+ particles decaying into a J/ψ meson and a proton must have a minimal quark content $c\bar{c}uud$, and are therefore called pentaquark-charmonium.

[Y. Schutz; this school 8/7/2017]

The zoo of hadrons

A few key players :

- baryons (3 quarks)
  - → with u & d quarks (ordinary matter)
    - – proton (uud) / neutron (udd)
  - → …
- mesons (quark+anti-quark)
  - → with u & d quarks (ordinary matter)
    - – $\pi^+(u\bar{d})$ / $\pi^-(\bar{u}d)$ / $\pi^0(u\bar{u}$ ou $d\bar{d})$ → *« pions »*
  - → with a strange quark : s
    - – $K^+(u\bar{s})$ / $K^-(\bar{u}s)$ / $K^0(d\bar{s})$ / $\bar{K}^0(\bar{d}s)$ → *« kaons »*
  - → with a charm quark : c
    - – $D^+(c\bar{d})$ / $D^-(\bar{c}d)$ / $D^0(c\bar{u})$ / $\bar{D}^0(\bar{c}u)$
    - – $D_S^+(c\bar{s})$ / $D_S^-(\bar{c}s)$
  - → with a bottom quark : b
    - – $B^+(u\bar{b})$ / $B^-(\bar{u}b)$ / $B^0(d\bar{b})$ / $\bar{B}^0(\bar{d}b)$
    - – $B_S^0(s\bar{b})$ / $\bar{B}_S^0(\bar{s}b)$
    - – $B_C^+(c\bar{b})$ / $B_C^-(\bar{c}b)$



↘ … and many others with the same quarks and different angular configurations

The zoo of hadrons

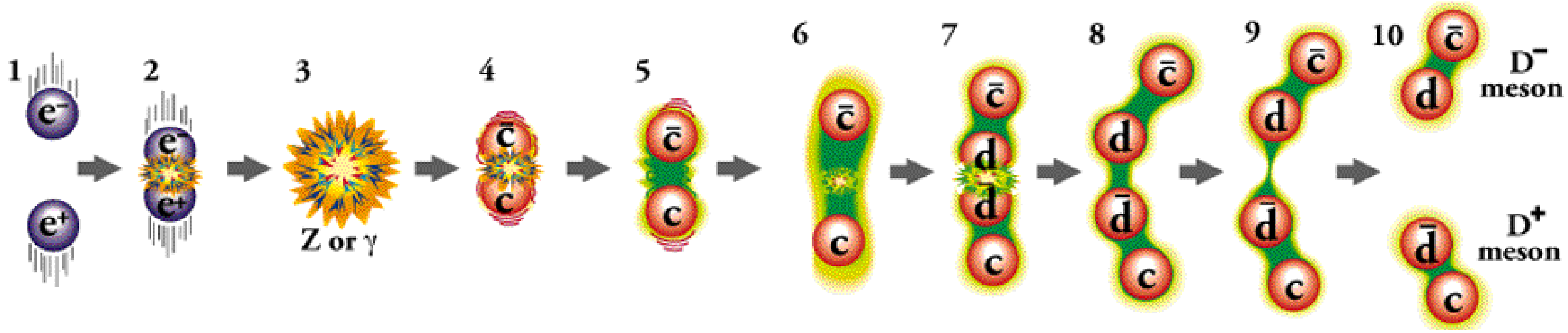
A few key players :

- baryons (3 quarks)
  - → with u & d quarks (ordinary matter)
    - proton (uud) / neutron (udd)
  - → …
- mesons (quark+anti-quark)
  - → with u & d quarks (ordinary matter)
    - $\pi^+(u\bar{d})$ / $\pi^-(\bar{u}d)$ / $\pi^0(u\bar{u}$ ou $d\bar{d})$ → *« pions »*
  - → with a strange quark : s
    - $K^+(u\bar{s})$ / $K^-(\bar{u}s)$ / $K^0(d\bar{s})$ / $\bar{K}^0(\bar{d}s)$ → *« kaons »*
  - → with a charm quark : c
    - $D^+(c\bar{d})$ / $D^-(\bar{c}d)$ / $D^0(c\bar{u})$ / $\bar{D}^0(\bar{c}u)$
    - $D_s^+(c\bar{s})$ / $D_s^-(\bar{c}s)$
  - → with a bottom quark : b
    - $B^+(u\bar{b})$ / $B^-(\bar{u}b)$ / $B^0(d\bar{b})$ / $\bar{B}^0(\bar{d}b)$
    - $B_s^0(s\bar{b})$ / $\bar{B}_s^0(\bar{s}b)$
    - $B_c^+(c\bar{b})$ / $B_c^-(\bar{c}b)$

actively studied in LHCb !

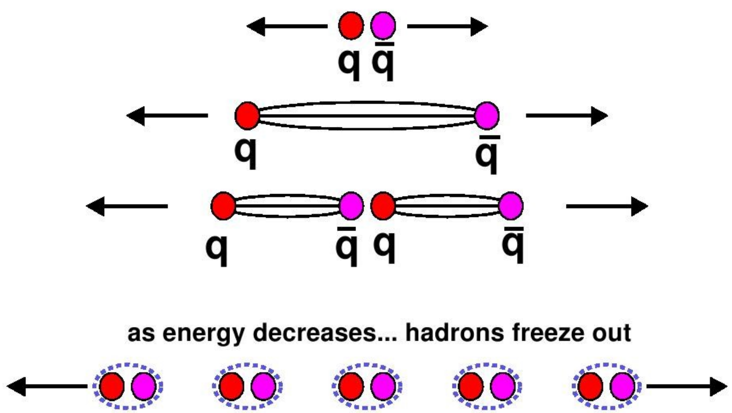
↘ … and many others with the same quarks and different angular configurations

Hadronisation



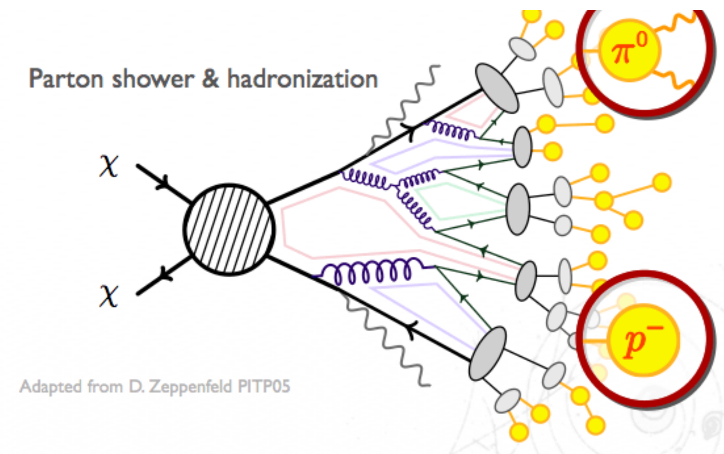
In particle collisions (proton-proton, e+e-, …)

- quarks are produced by pairs ($q\bar{q}$)
- and hadronise



B hadrons hadronisation fractions :

- $f(B^0) \approx f(B^+) \approx 0.37$
- $f(B_s) \approx 0.16$

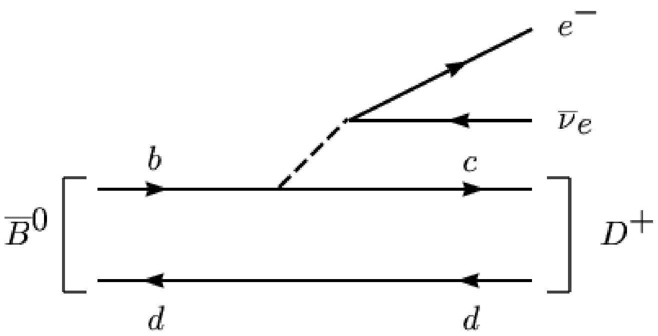


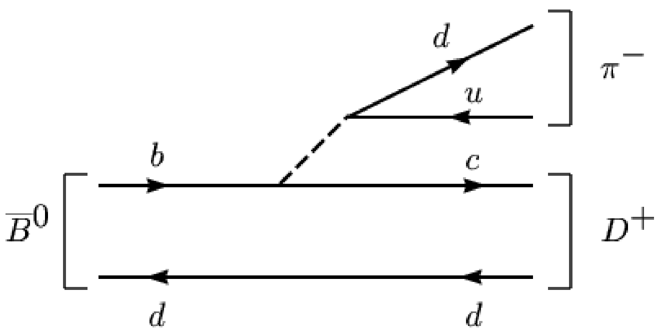
Hadron decays (1/3)

All hadrons (but the proton) are unstable, they decay spontaneously

Most of the hadrons we are interested in are decaying through electroweak transitions :

- ex : tree level processes



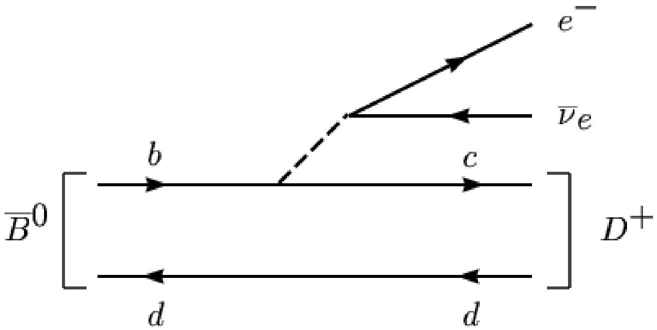


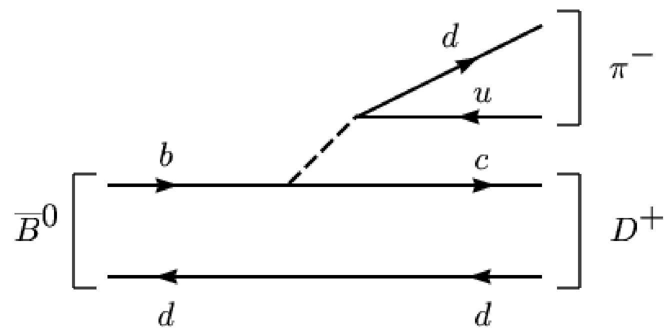
Hadron decays (1/3)

All hadrons (but the proton) are unstable, they decay spontaneously

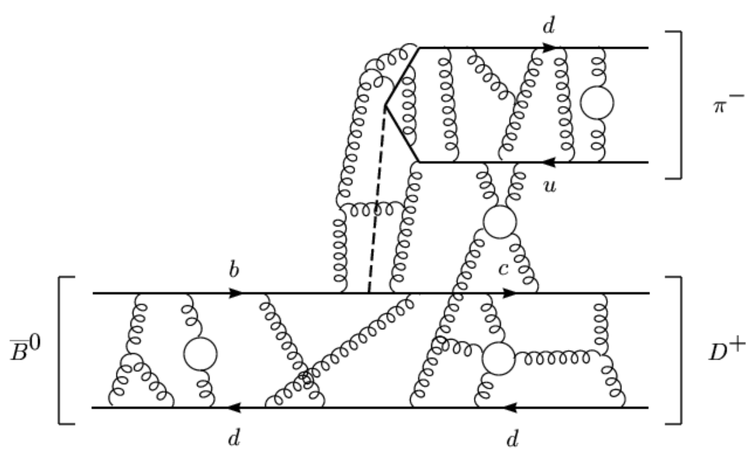
Most of the hadrons we are interested in are decaying through electroweak transitions :

- ex : tree level processes





Note : simplified view, more realistic representation :

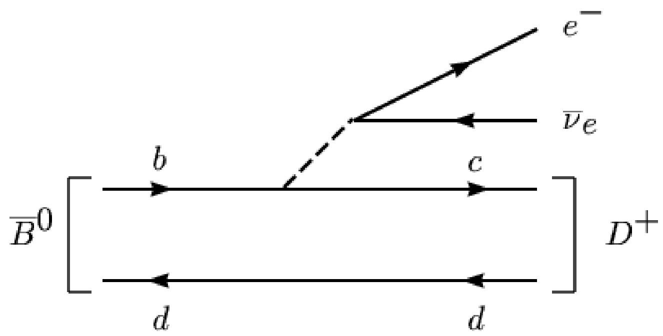


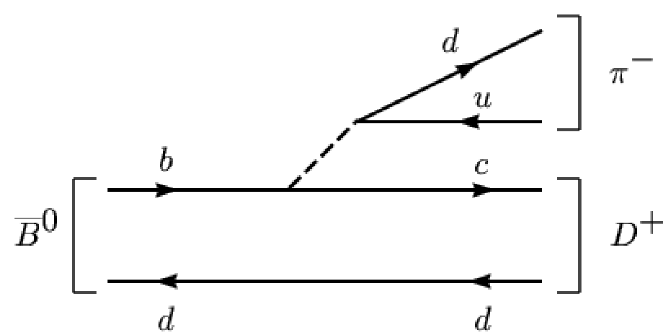
Hadron decays (1/3)

All hadrons (but the proton) are unstable, they decay spontaneously

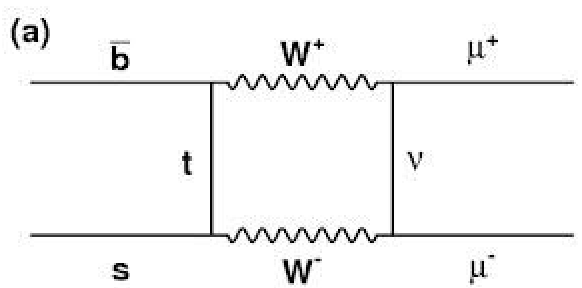
Most of the hadrons we are interested in are decaying through electroweak transitions :

- ex : tree level processes

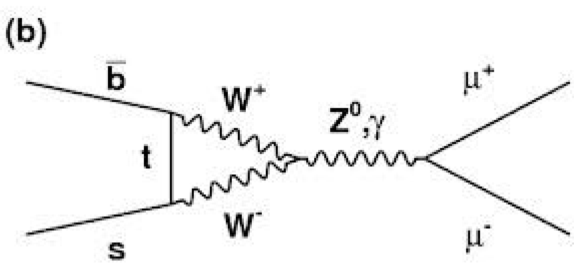


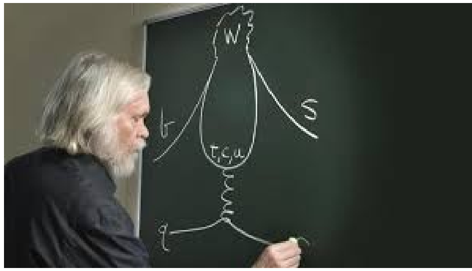


- ex : processes with loops



“Box” diagram





“penguin” diagram

Hadron decays (2/3)

Many possible final states → probabilistic law

Ex : D^0

Citation: J. Beringer et al. (Particle Data Group), PR **D86**, 010001 (2012) and 2013 partial update for the 2014 edition (URL: http://pdg.lbl.gov)

Most decay modes (other than the semileptonic modes) that involve a neutral K meson are now given as K^0_S modes, not as $\overline{K}^0$ modes. Nearly always it is a K^0_S that is measured, and interference between Cabibbo-allowed and doubly Cabibbo-suppressed modes can invalidate the assumption that $2\,\Gamma(K^0_S) = \Gamma(\overline{K}^0)$.

D^0 DECAY MODES		Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
Topological modes				
0-prongs	[j]	$(15 \pm 6)\,\%$		–
2-prongs		$(70 \pm 6)\,\%$		–
4-prongs	[k]	$(14.5 \pm 0.5)\,\%$		–
6-prongs	[l]	$(6.4 \pm 1.3) \times 10^{-4}$		–
Inclusive modes				
e^+ anything	[n]	$(6.49 \pm 0.11)\,\%$		–
μ^+ anything		$(6.7 \pm 0.6)\,\%$		–
K^- anything		$(54.7 \pm 2.8)\,\%$	S=1.3	–
$\overline{K}^0$ anything + K^0 anything		$(47 \pm 4)\,\%$		–
K^+ anything		$(3.4 \pm 0.4)\,\%$		–
$K^*(892)^-$ anything		$(15 \pm 9)\,\%$		–
$\overline{K}^*(892)^0$ anything		$(9 \pm 4)\,\%$		–
$K^*(892)^+$ anything		$< 3.6\,\%$	CL=90%	–
$K^*(892)^0$ anything		$(2.8 \pm 1.3)\,\%$		–
η anything		$(9.5 \pm 0.9)\,\%$		–
η' anything		$(2.48 \pm 0.27)\,\%$		–
ϕ anything		$(1.05 \pm 0.11)\,\%$		–
Semileptonic modes				
$K^- e^+ \nu_e$		$(3.55 \pm 0.05)\,\%$	S=1.2	867
$K^- \mu^+ \nu_\mu$		$(3.31 \pm 0.13)\,\%$		864
$K^*(892)^- e^+ \nu_e$		$(2.16 \pm 0.16)\,\%$		719
$K^*(892)^- \mu^+ \nu_\mu$		$(1.91 \pm 0.24)\,\%$		714
$K^- \pi^0 e^+ \nu_e$		$(1.6\ ^{+1.3}_{-0.5})\,\%$		861
$\overline{K}^0 \pi^- e^+ \nu_e$		$(2.7\ ^{+0.9}_{-0.7})\,\%$		860
$K^- \pi^+ \pi^- e^+ \nu_e$		$(2.8\ ^{+1.4}_{-1.1}) \times 10^{-4}$		843
$K_1(1270)^- e^+ \nu_e$		$(7.6\ ^{+4.0}_{-3.1}) \times 10^{-4}$		498
$K^- \pi^+ \pi^- \mu^+ \nu_\mu$		$< 1.2 \times 10^{-3}$	CL=90%	821
$(\overline{K}^*(892)\pi)^- \mu^+ \nu_\mu$		$< 1.4 \times 10^{-3}$	CL=90%	692
$\pi^- e^+ \nu_e$		$(2.89 \pm 0.08) \times 10^{-3}$	S=1.1	927
$\pi^- \mu^+ \nu_\mu$		$(2.37 \pm 0.24) \times 10^{-3}$		924
$\rho^- e^+ \nu_e$		$(1.9 \pm 0.4) \times 10^{-3}$		771

HTTP://PDG.LBL.GOV   Page 10   Created: 7/12/2013 14:49

Citation: J. Beringer et al. (Particle Data Group), PR **D86**, 010001 (2012) and 2013 partial update for the 2014 edition (URL: http://pdg.lbl.gov)

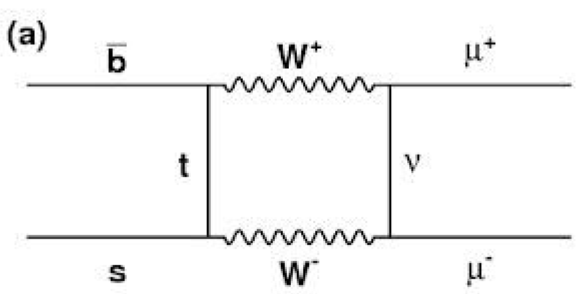
Hadronic modes with one $\overline{K}$				
$K^- \pi^+$		$(3.88 \pm 0.05)\,\%$	S=1.1	861
$K^+ \pi^-$		$(1.37 \pm 0.06) \times 10^{-4}$		861
$K^0_S \pi^0$		$(1.19 \pm 0.04)\,\%$		860
$K^0_L \pi^0$		$(10.0 \pm 0.7) \times 10^{-3}$		860
$K^0_S \pi^+ \pi^-$	[c]	$(2.83 \pm 0.20)\,\%$	S=1.1	842
$K^0_S \rho^0$		$(6.3\ ^{+0.7}_{-0.8}) \times 10^{-3}$		674
$K^0_S \omega$, $\omega \to \pi^+ \pi^-$		$(2.1 \pm 0.6) \times 10^{-4}$		670
$K^0_S (\pi^+ \pi^-)_{S\text{-wave}}$		$(3.4 \pm 0.8) \times 10^{-3}$		842
$K^0_S f_0(980)$, $f_0(980) \to \pi^+ \pi^-$		$(1.22\ ^{+0.40}_{-0.24}) \times 10^{-3}$		549
$K^0_S f_0(1370)$, $f_0(1370) \to \pi^+ \pi^-$		$(2.8\ ^{+0.9}_{-1.3}) \times 10^{-3}$		†
$K^0_S f_2(1270)$, $f_2(1270) \to \pi^+ \pi^-$		$(9\ ^{+10}_{-6}) \times 10^{-5}$		262
$K^*(892)^- \pi^+$, $K^*(892)^- \to K^0_S \pi^-$		$(1.66\ ^{+0.15}_{-0.17})\,\%$		711
$K^*_0(1430)^- \pi^+$, $K^*_0(1430)^- \to K^0_S \pi^-$		$(2.70\ ^{+0.40}_{-0.34}) \times 10^{-3}$		378
$K^*_2(1430)^- \pi^+$, $K^*_2(1430)^- \to K^0_S \pi^-$		$(3.4\ ^{+1.9}_{-1.0}) \times 10^{-4}$		367
$K^*(1680)^- \pi^+$, $K^*(1680)^- \to K^0_S \pi^-$		$(4 \pm 4) \times 10^{-4}$		46
$K^*(892)^+ \pi^-$, $K^*(892)^+ \to K^0_S \pi^+$	[o]	$(1.14\ ^{+0.60}_{-0.34}) \times 10^{-4}$		711
$K^*_0(1430)^+ \pi^-$, $K^*_0(1430)^+ \to K^0_S \pi^+$	[o]	$< 1.4 \times 10^{-5}$	CL=95%	–
$K^*_2(1430)^+ \pi^-$, $K^*_2(1430)^+ \to K^0_S \pi^+$	[o]	$< 3.4 \times 10^{-5}$	CL=95%	–
$K^0_S \pi^+ \pi^-$ nonresonant		$(2.5\ ^{+6.0}_{-1.6}) \times 10^{-4}$		842
$K^- \pi^+ \pi^0$	[c]	$(13.9 \pm 0.5)\,\%$	S=1.7	844
$K^- \rho^+$		$(10.8 \pm 0.7)\,\%$		675
$K^- \rho(1700)^+$, $\rho(1700)^+ \to \pi^+ \pi^0$		$(7.9 \pm 1.7) \times 10^{-3}$		†
$K^*(892)^- \pi^+$, $K^*(892)^- \to K^- \pi^0$		$(2.22\ ^{+0.40}_{-0.19})\,\%$		711
$\overline{K}^*(892)^0 \pi^0$, $\overline{K}^*(892)^0 \to K^- \pi^+$		$(1.88 \pm 0.23)\,\%$		711

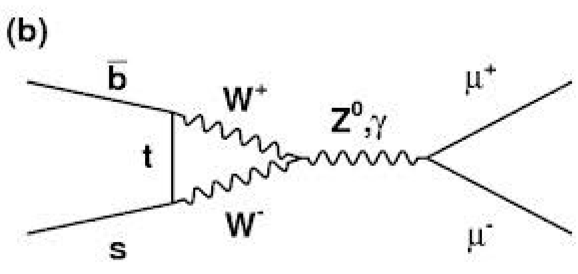
HTTP://PDG.LBL.GOV   Page 11   Created: 7/12/2013 14:49

Hadron decays (3/3)

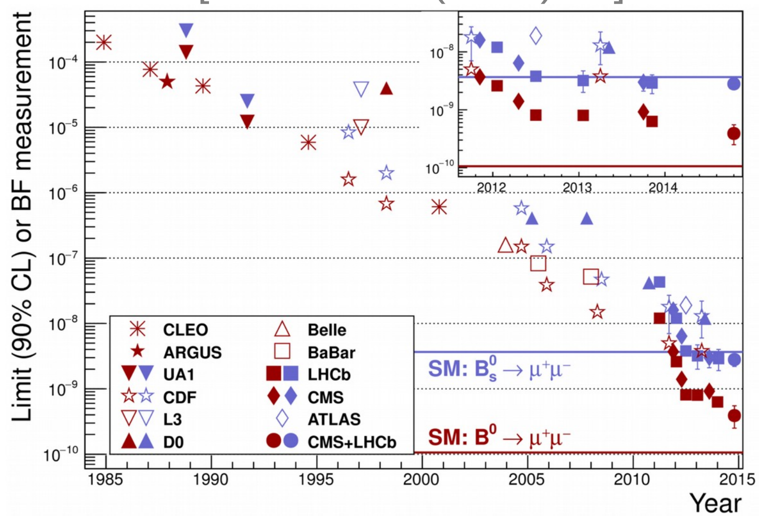
Some decays are very rare :

- ➔ ex : B → μ+ μ-
- doesn't exist at tree level

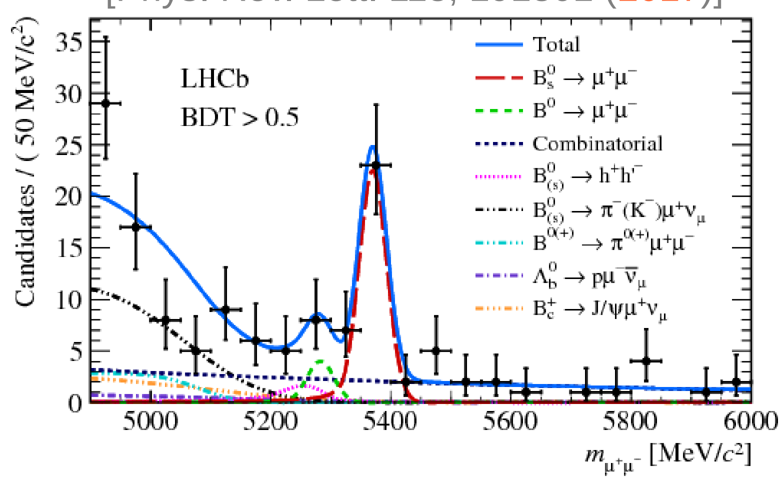




[Nature 522 (2015) 68]



[Phys. Rev. Lett. 118, 191801 (2017)]



CENTRE DE PHYSIQUE DES PARTICULES DE MARSEILLE
CPPM

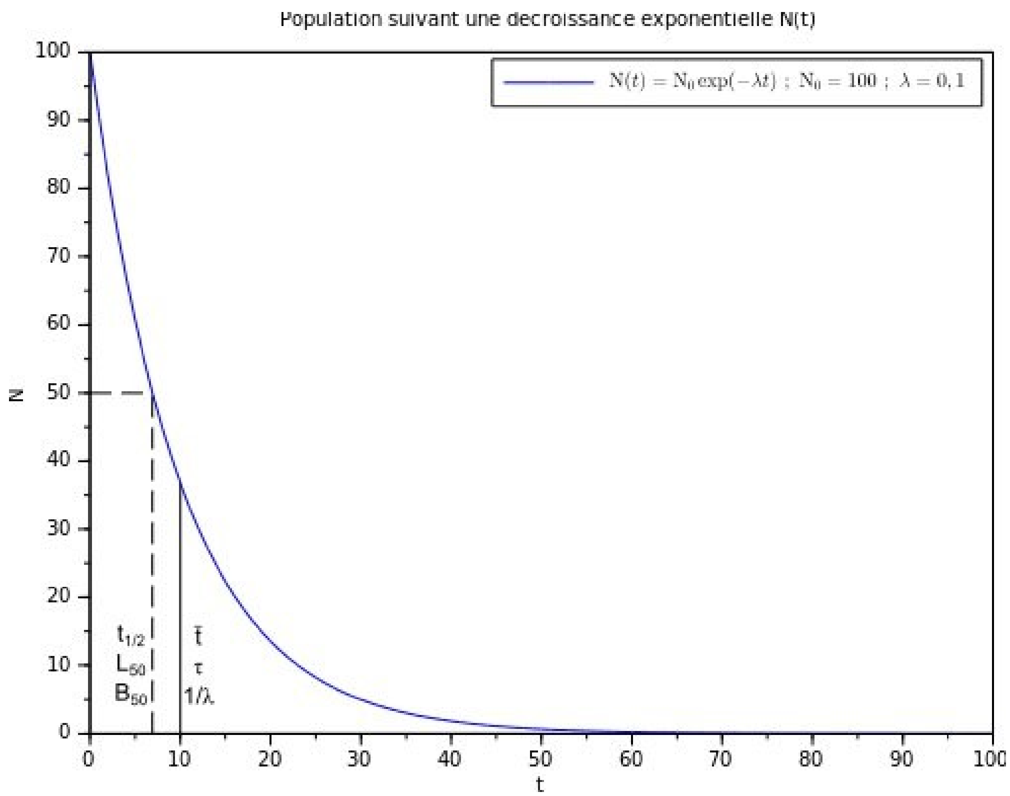
Hadron life time (1/2)

For a particular event, the hadron

- decay mode is not predictable
- neither it's decay time
  - → probabilistic behavior

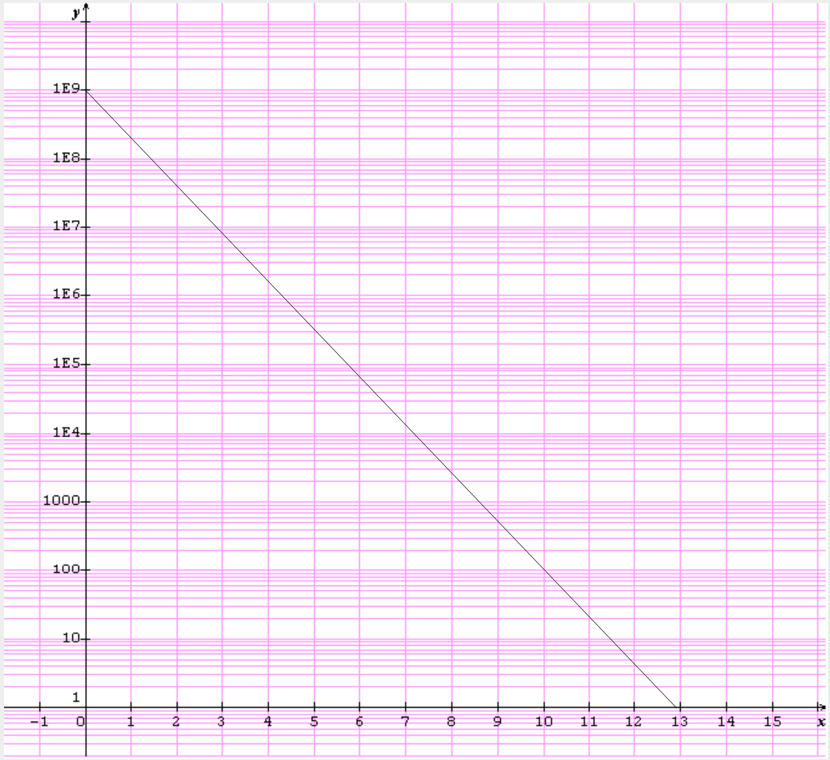
Hadrons do not age

- → same decay time prob. at all times
- → decay time follow an exponential law characterised by the hadron life time



Hadron life time (1/2)

$$y = 10^{9} \exp^{-1{,}6\,x}$$



Reminder : logarithmic scale !

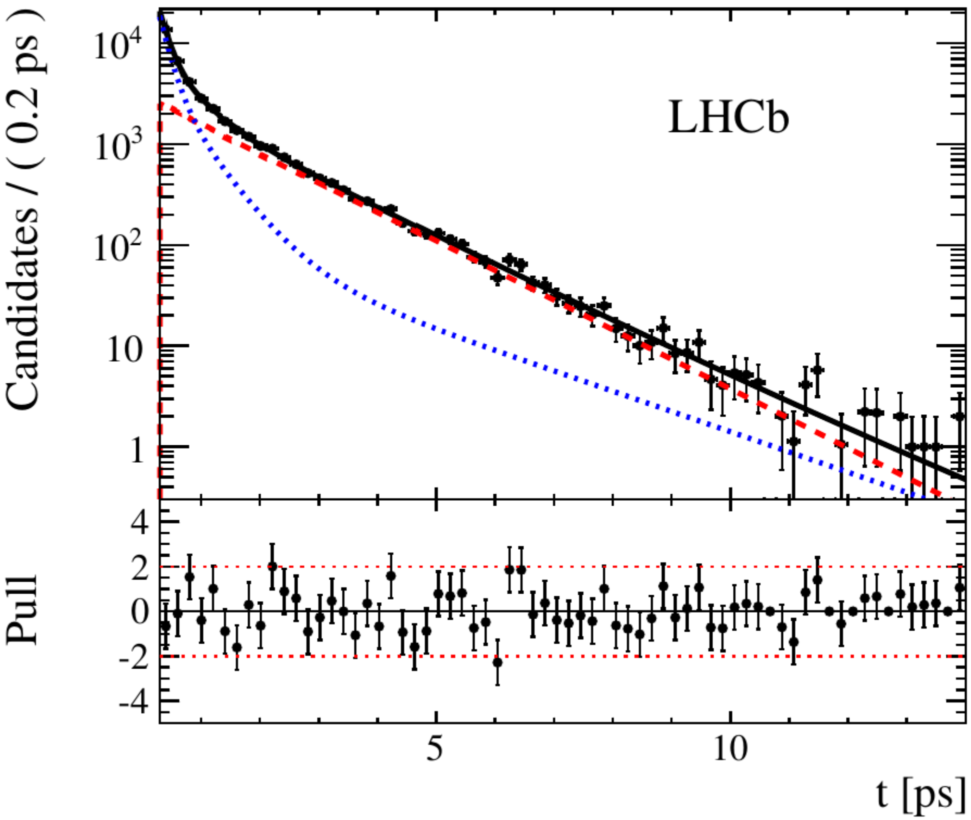
Hadron life time (1/2)

For a particular event, the hadron

- → decay mode is not predictable
- → neither it's decay time
- - probabilistic behavior

Hadrons do not age

- → same decay time prob. at all times
- → decay time follow an exponential law characterised by the hadron life time



[JHEP04(2014)114]

1ps = 10^{-12} s !!!

$\tau(B_s^0 \rightarrow J/\Psi\Phi) = 1.480 \pm 0.011 \pm 0.005$ ps

Hadron life time (2/2)

Charmed and beauty hadrons have large lifetimes :

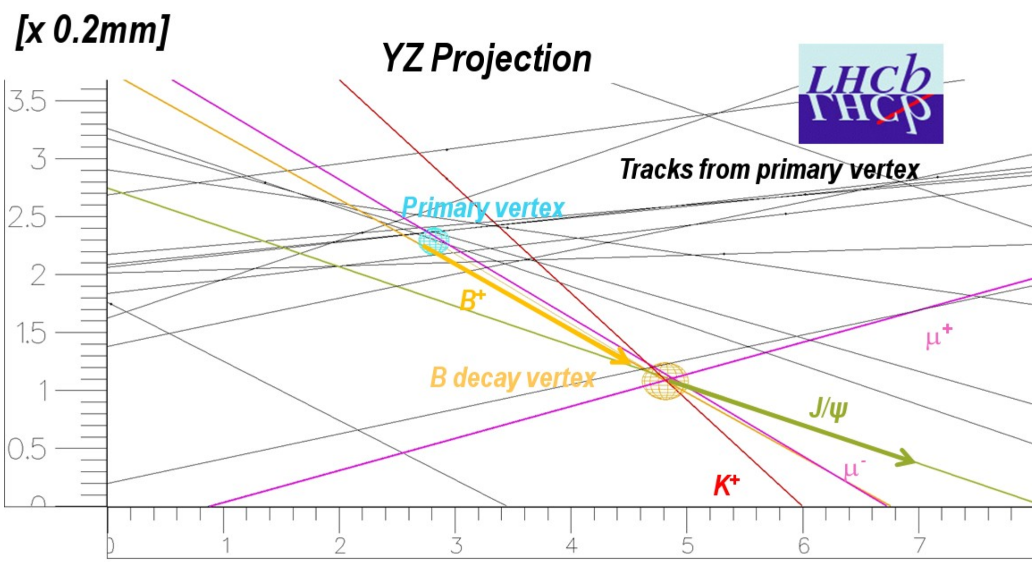
→ cτ (μm)

D^0	123
D^+	312
D_s	150

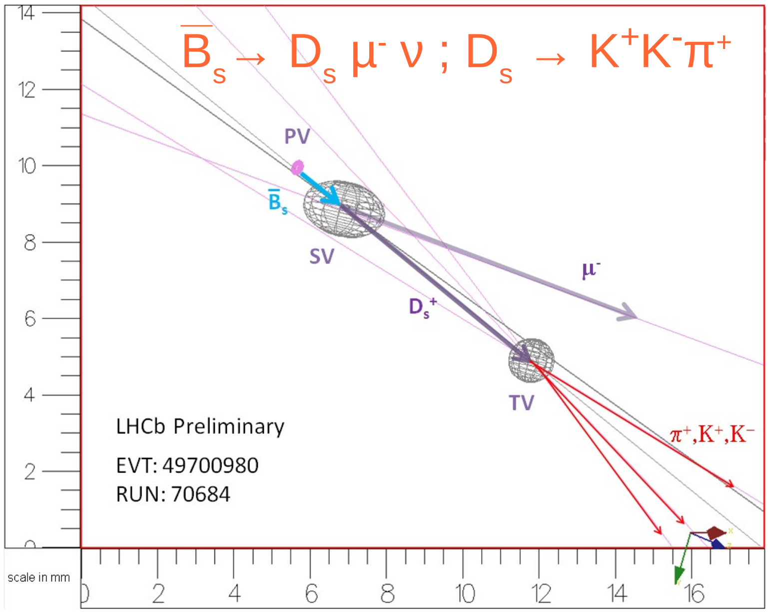
B^0	456
B^+	491
B_s	453

Experimentally :

- → they fly away from the production vertex before decaying
- → flight distance is measurable (allow identification)



$B^+ \to J/\Psi\ K^+$; $J/\Psi \to \mu^+\mu^-$

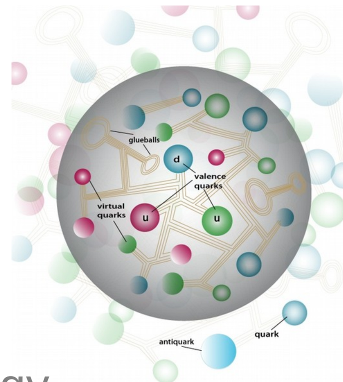


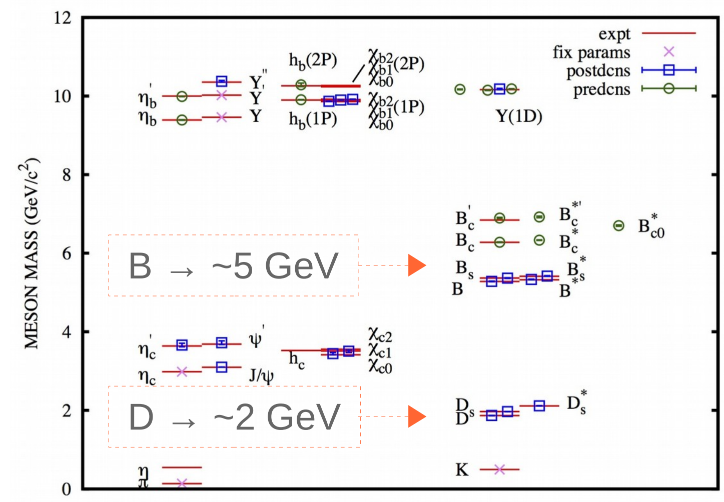
The mass of hadrons

Hadron mass

- → intrinsic property
- → sum of quarks mass

  + their binding energy
- → proton mass :
  - dominated by binding energy
  - ultra-relativistic quarks
- → B hadrons :
  - dominated by m(b) = ~4 GeV



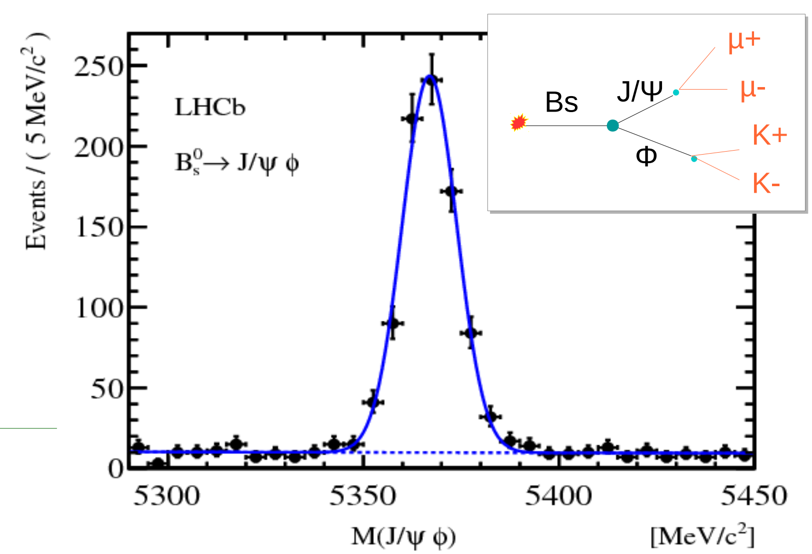


[HPQCD collaboration,]

Experimentally :

- → B hadron mass reconstructed from the measured momenta of the particles in the final state

  $M(B_s) = 5366.90 \pm 0.28\ (\text{stat}) \pm 0.23\ (\text{syst})\ \text{MeV}/c^2$
- → allow identification



[Phys. Lett. B 708 (2012) 241-248]

Energy scale ! ΔE/E < 2.10^{-4}

Hadrons : summary

Hadrons : bound states of quarks

Large variety of hadrons

Each is characterized by :

- → mass
- → life time
- → quantum state (parity, …)

Many decay modes accessible

Heavy hadrons (i.e. with *b* or *c* quarks) have a very rich phenomenology

Some heavy flavour phenomenology

- Strong interaction and hadronisation
- Neutral Mesons mixing
- CP-violation

Neutral meson oscillation (mixing)

Interaction eigenstates : M^0 and $\overline{M}^0$

- M^0 can be $K^0(\bar{s}d)$, $D^0(c\bar{u})$, $B^0(\bar{b}d)$ or $B_s(\bar{b}s)$
- $\overline{M}^0$ is the antiparticle of M^0

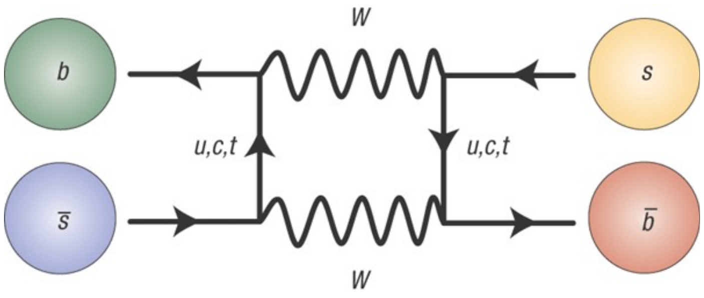
They can mix to each other :

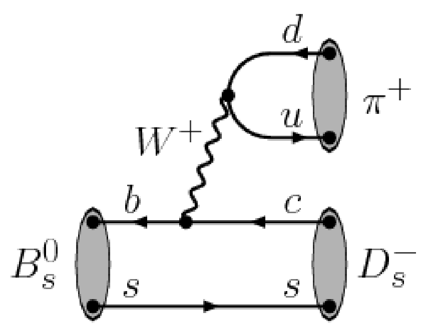
- $M^0 \leftrightarrow \overline{M}^0$

Mass eigenstates : M_1 and M_2

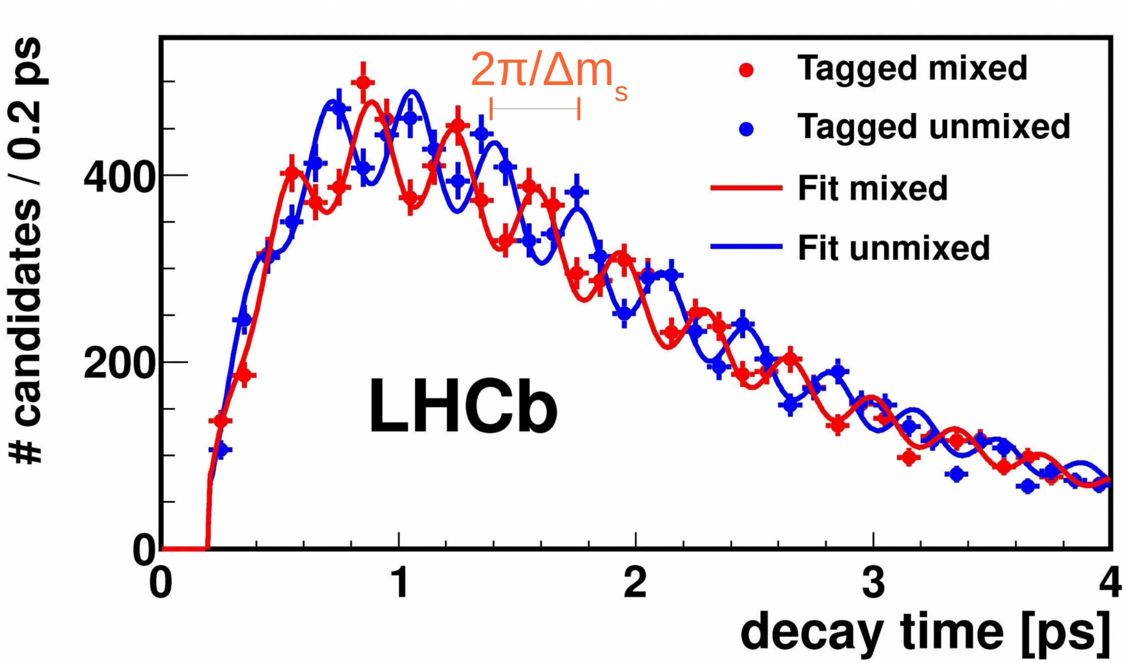
- $M_{1/2} = q\,M^0 \pm p\,\overline{M}^0$ $(\sqrt{(p^2+q^2)} = 1)$

Observation : matter and anti-matter oscillations





[LHCb, New J. Phys. 15 (2013) 053021]



unmixed : $B_s \rightarrow D_s^- \pi^+$ or $\overline{B}_s \rightarrow D_s^+ \pi^-$

mixed : $\overline{B}_s \rightarrow B_s \rightarrow D_s^- \pi^+$ or $B_s \rightarrow \overline{B}_s \rightarrow D_s^+ \pi^-$

Oscillation frequency

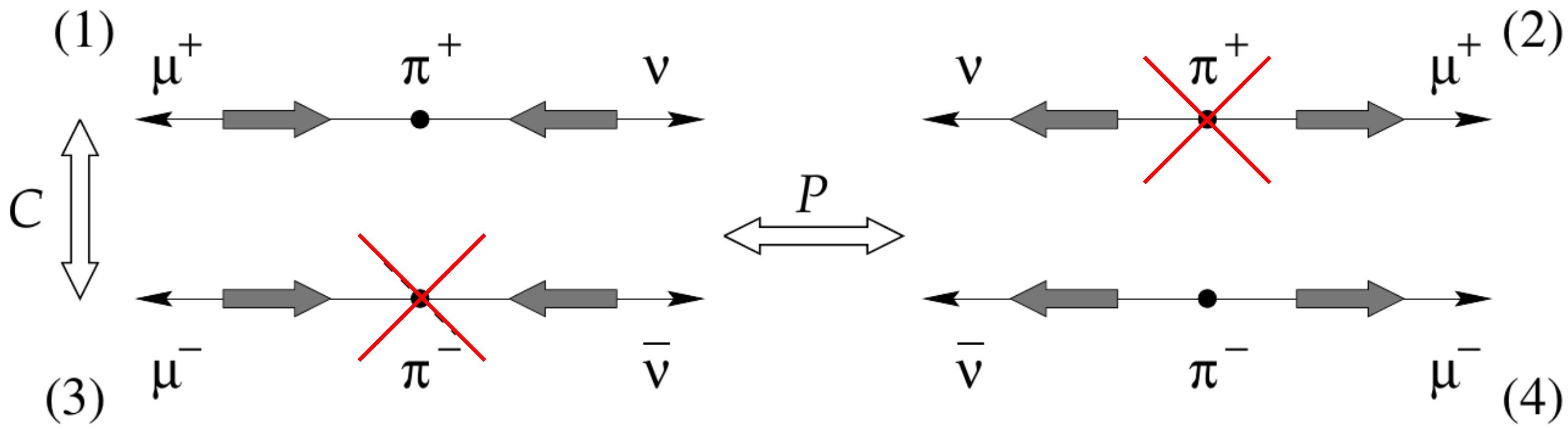
$\Delta m_s = m(M_1) - m(M_2)$

Δm_s α $|V_{ts}|^2$

Some heavy flavour phenomenology

- Strong interaction and hadronisation
- Neutral Mesons mixing
- CP-violation

Discrete symmetries and CP violation (reminder)



C (charge conjugation) :

→ reverse all charges (but mass and spin)
i.e. electric, color, isospin, flavour, ...

P (parity) :

→ reverse spatial coordinates (i.e. momentum)
identical to a mirror transformation

C and *P* are maximally violated by the weak interaction :

→ only left-handed neutrinos and right-handed anti-neutrinos are observed

CP was first thought to be a valid symmetry :

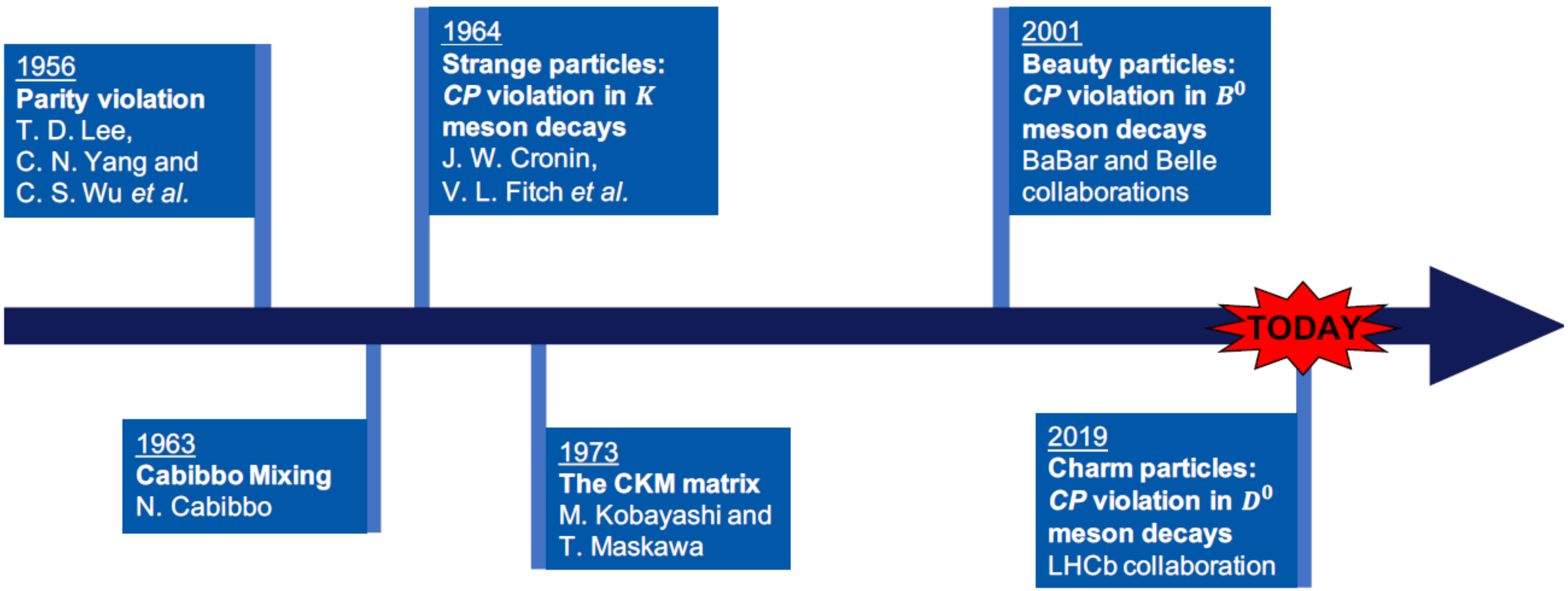
→ a *CP*-mirrored process behave as the original
i.e. anti-matter behaves like matter observed in a mirror

BUT, 1964 : first observation of *CP* violation in the K^0-$\bar{K}^0$ system [Christenson, Cronin, Fitch and Turlay]

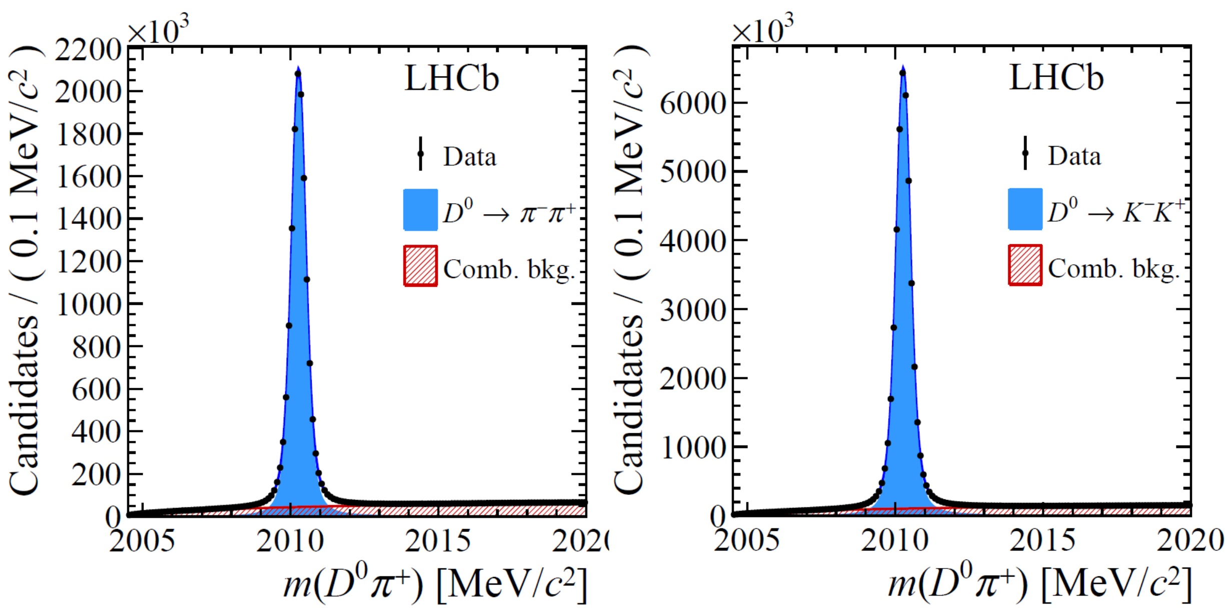
→ very active domain ever since ↘ lead to the prediction to the third family

→ also observed in the B^0-$\bar{B}^0$ system ↘ accounted for in the SM by a phase in the CKM matrix

CP violation history



New: first observation of CP violation in charm decay → ΔA_{CP}= (-0.154±0.029)%



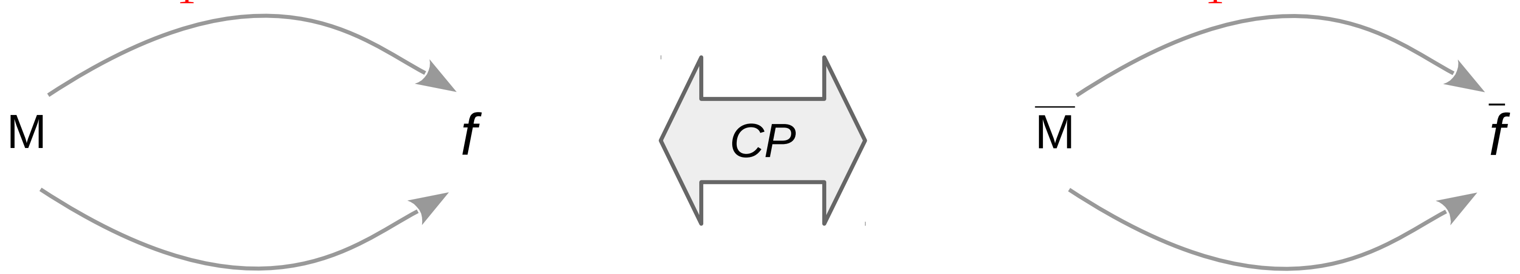
PRL 122 (2019) 211803

Observation of CP violation

CP violation : $|\mathcal{A}(M \to f)|^2 \neq |\mathcal{A}(\overline{M} \to \bar{f})|^2$

CP observation requires 2 interfering amplitudes $\mathcal{A}_1$ and $\mathcal{A}_2$:

$$A_1 e^{i\phi_1} e^{i\delta_1} \qquad\qquad \overline{A}_1 e^{-i\phi_1} e^{i\delta_1}$$



$$A_2 e^{i\phi_2} e^{i\delta_2} \qquad\qquad \overline{A}_2 e^{-i\phi_2} e^{i\delta_2}$$

with $\Delta\phi = \phi_1 - \phi_2$ and $\Delta\delta = \delta_1 - \delta_2$

$$A_1^2 + A_2^2 + 2 A_1 A_2 \cos(\Delta\phi + \Delta\delta) \qquad\qquad A_1^2 + A_2^2 + 2 A_1 A_2 \cos(\Delta\phi - \Delta\delta)$$

Need $\mathcal{A}_1$ and $\mathcal{A}_2$ with :

- different weak phases (~~*CP*~~) : $\phi_1 \neq \phi_2$
- different strong phases (*CP*) : $\delta_1 \neq \delta_2$

CP violation effects classification

3 types :

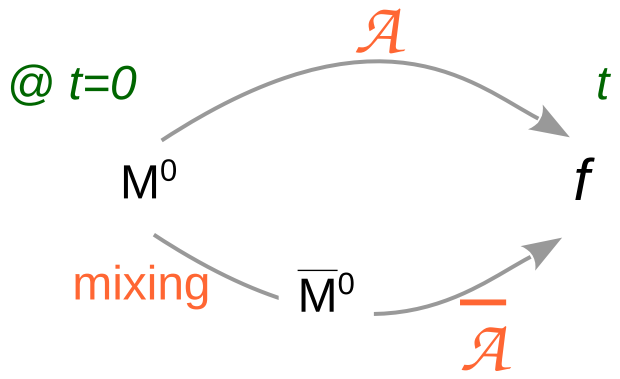
- mixing :

  → $P(M^0 \rightarrow \overline{M}^0) \neq P(\overline{M}^0 \rightarrow M^0)$

- decay

  → $P(M^0 \rightarrow f) \neq P(\overline{M}^0 \rightarrow \bar{f})$

- interference between mixing and decay



CP violation in the mixing

Interaction eigenstates : M^0 and $\overline{M}^0$

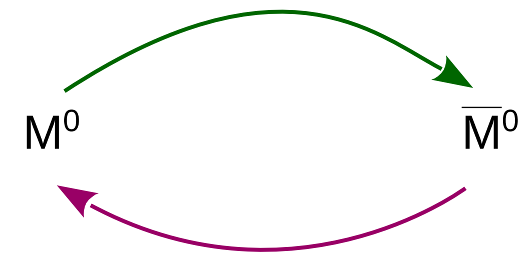
- $CP\, M^0 = \overline{M}^0$

CP eigenstates :

- $M_{even} = (M^0 + \overline{M}^0)\sqrt{2}$
- $M_{odd} = (M^0 - \overline{M}^0) / \sqrt{2}$

Mass eigenstates : M_1 and M_2

- $M_{1/2} = q\, M_0 \pm p\, \overline{M}_0$



$$\mathcal{A}(M^0 \rightarrow \overline{M}^0) \neq \mathcal{A}(\overline{M}^0 \rightarrow M^0)$$

CP violation if mass eigenstates ≠ CP eigenstates

- i.e. if $|p/q| \neq 1$

This is the kind of CP violation observed in 1964 in the Kaon system

- Observation of K_L ($\approx K_{odd}$) $\rightarrow 2\pi$ (a CP even state)
- $K_L = (K_{odd} + \varepsilon_K K_{even}) / \sqrt{(1 + \varepsilon_K^2)}$ with $|\varepsilon_K| \approx 2.10^{-3}$

This type of CP violation is negligible in the B system

CP asymmetry :

$$a_{sl} \equiv \frac{\Gamma(\overline{B} \to f) - \Gamma(B \to \bar{f})}{\Gamma(\overline{B} \to f) + \Gamma(B \to \bar{f})}$$

with $f = (D^- \mu^+ \nu X)$

SM : $a_{sl} = (1.9 \pm 0.3)\, 10^{-5}$

LHCb : $a_{sl} = (0.39 \pm 0.26 \pm 0.20)\%$

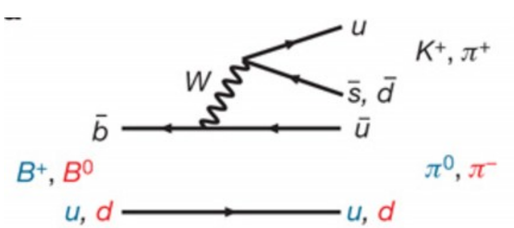
[Phys. Rev. Lett. 117, 061803 (2016)]

CP violation in the decay

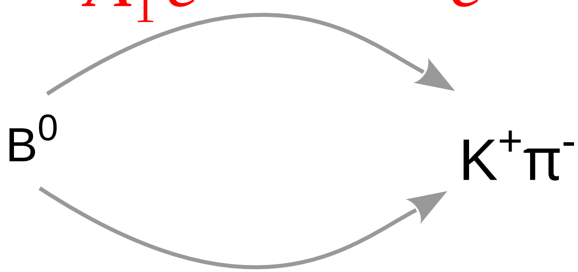
Decays :

- $B^0 \to K^+ \pi^-$ -VS- $\overline{B}^0 \to K^- \pi^+$
- $B_s \to K^- \pi^+$ -VS- $\overline{B}_s \to K^+ \pi^-$

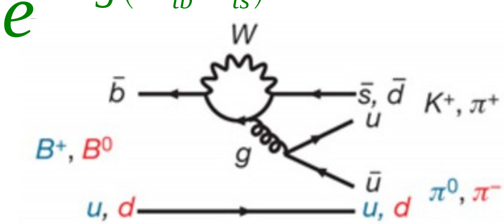
The 2 amplitudes, e.g. for B^0 :



$$A_1 e^{i\,arg(V^*_{ub} V_{us})} e^{i\delta_1}$$

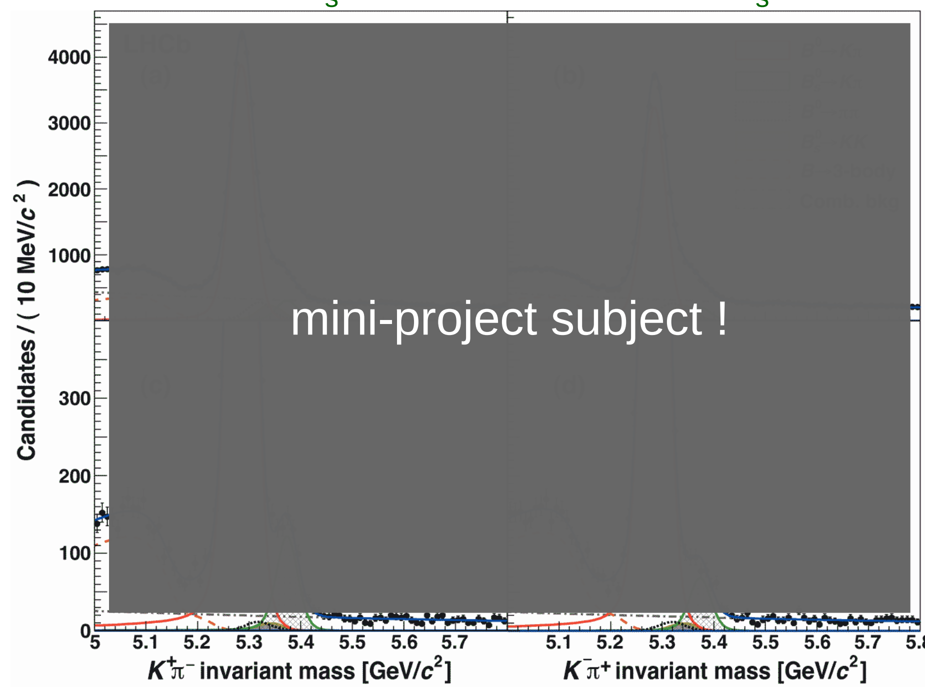


$$A_2 e^{i\,arg(V^*_{tb} V_{ts})} e^{i\delta_2}$$



↘ First observation of CP violation in the decays of B_s mesons

B^0, B_s $\overline{B}^0$, $\overline{B}_s$



[Phys. Rev. Lett. 110 (2013) 221601]

$A_{CP}(B^0 \to K^+\pi^-) =$

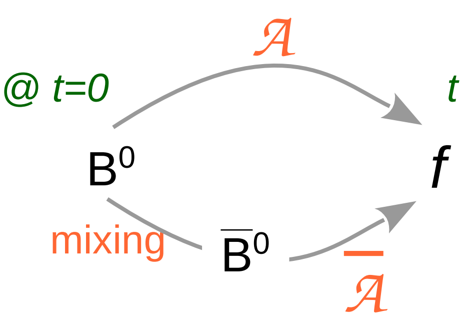
$A_{CP}(B^0_s \to K^-\pi^+) =$

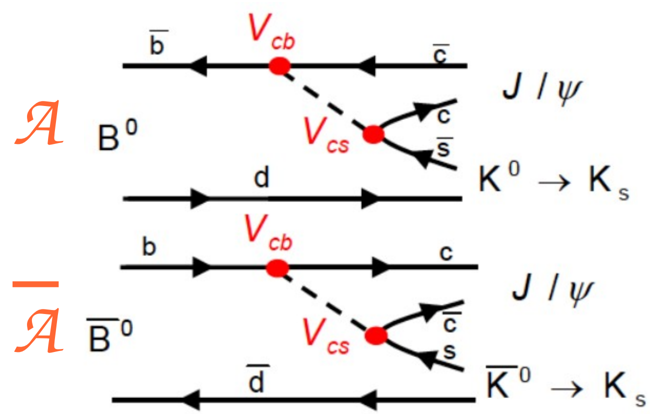
measure it yourself !

CP violation in the interference (1/2)

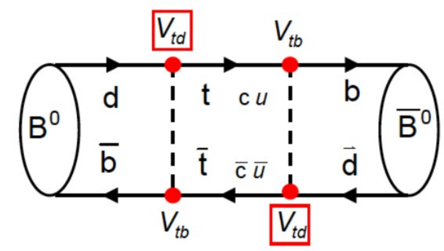
Time dependant CP violation gives access to the mixing phase :

- In the B^0-$\overline{B}^0$ system (mixing phase ϕ_d)
  - → final state accessible by both B^0 and $\overline{B}^0$: $J/\Psi\ K_s$





mixing



Mixing phase in the SM :

$$\phi_d^{SM} = \frac{1}{2} arg\left(\frac{-V_{cb}^{*} V_{cd}}{V_{tb}^{*} V_{td}}\right)$$

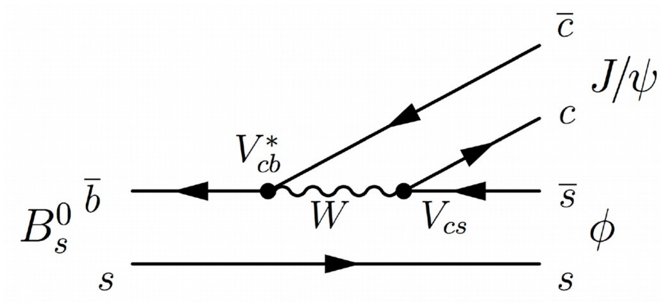
- → Construct the time dependant asymmetry :
  - need to know the production flavour of the B (*tagging*)

$$A_{CP}(t) = \frac{\Gamma(B_{t_0}^0 \rightarrow J/\psi K_s(t)) - \Gamma(\overline{B_{t_0}^0} \rightarrow J/\psi K_s(t))}{\Gamma(B_{t_0}^0 \rightarrow J/\psi K_s(t)) + \Gamma(\overline{B_{t_0}^0} \rightarrow J/\psi K_s(t))} \propto \sin(\phi_d)\sin(\Delta m t)$$

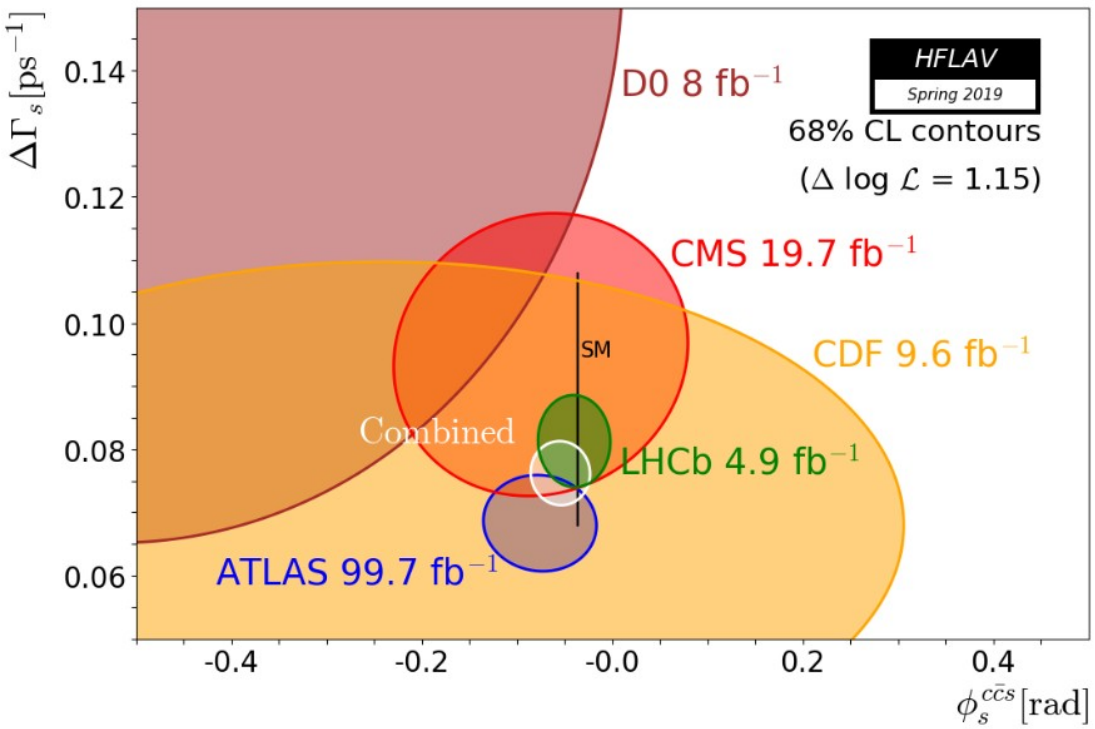
CP violation in the interference (2/2)

Time dependant CP violation gives access to the mixing phase :

- In the B_s-$\overline{B}_s$ system (mixing phase ϕ_s):
  - → Use $J/\Psi\Phi$ final state



  - → Much more complicated analysis
  - \- fit angular distributions



↘ Note : beyond the standard model physics could add an extra contribution to the Standard model mixing phase

CENTRE DE PHYSIQUE DES PARTICULES DE MARSEILLE
CPPM

CP violation in the CKM framework

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

weak mass

CKM :

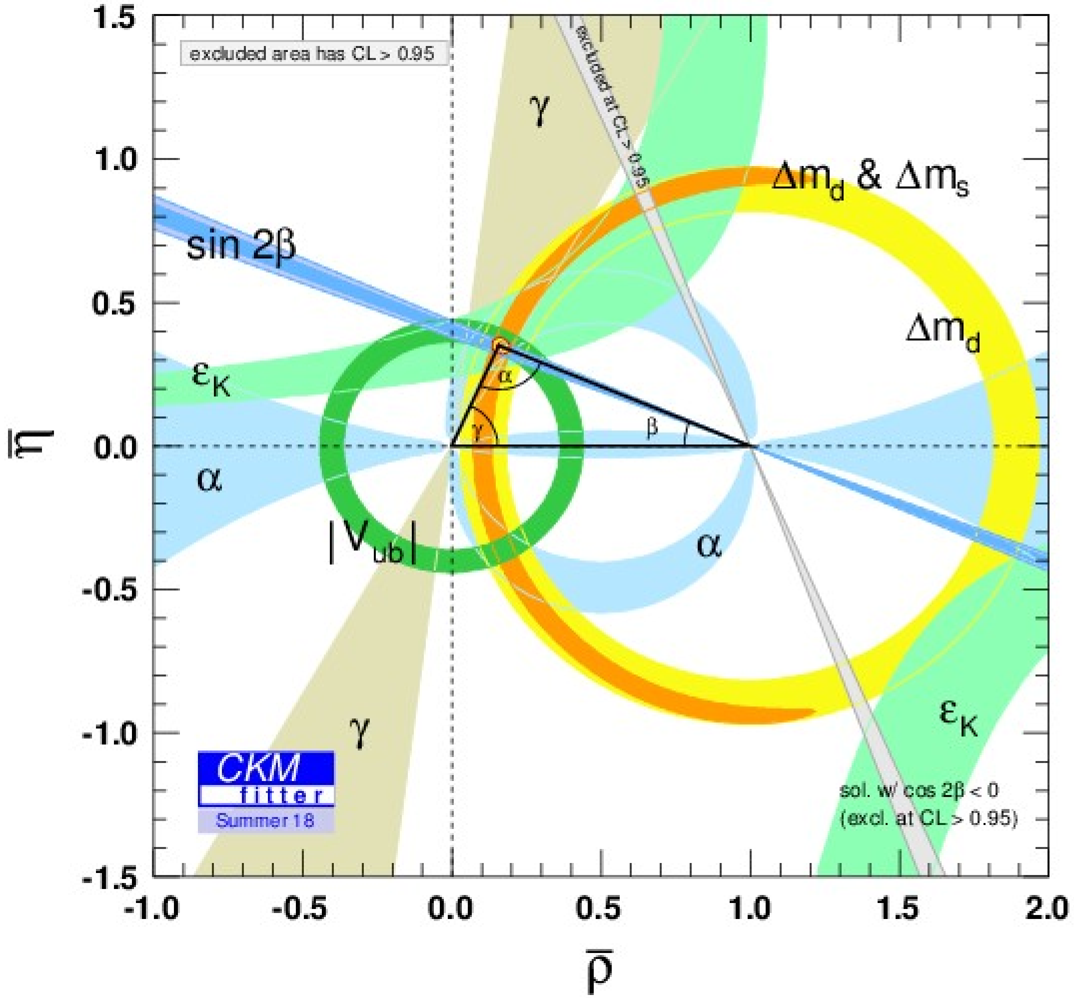
- complex (3x3) unitary matrix → 3 real angles and 6 phases
- freedom to redefine the phase of the quark mass eigenstates
- only 1 physical phase remains

↘ this physical phase is the one responsible for the CP violation in the SM

Wolfenstein parametrisation ($O(\lambda^6)$)

$$\begin{pmatrix} 1-\frac{1}{2}\lambda^2-\frac{1}{8}\lambda^4 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda+\frac{1}{2}A^2\lambda^5[1-2(\rho+i\eta)] & 1-\frac{1}{2}\lambda^2-\frac{1}{8}\lambda^4(1+4A^2) & A\lambda^2 \\ A\lambda^3[1-(1-\frac{1}{2}\lambda^2)(\rho+i\eta)] & -A\lambda^2+\frac{1}{2}A\lambda^4[1-2(\rho+i\eta)] & 1-\frac{1}{2}A^2\lambda^4 \end{pmatrix}$$

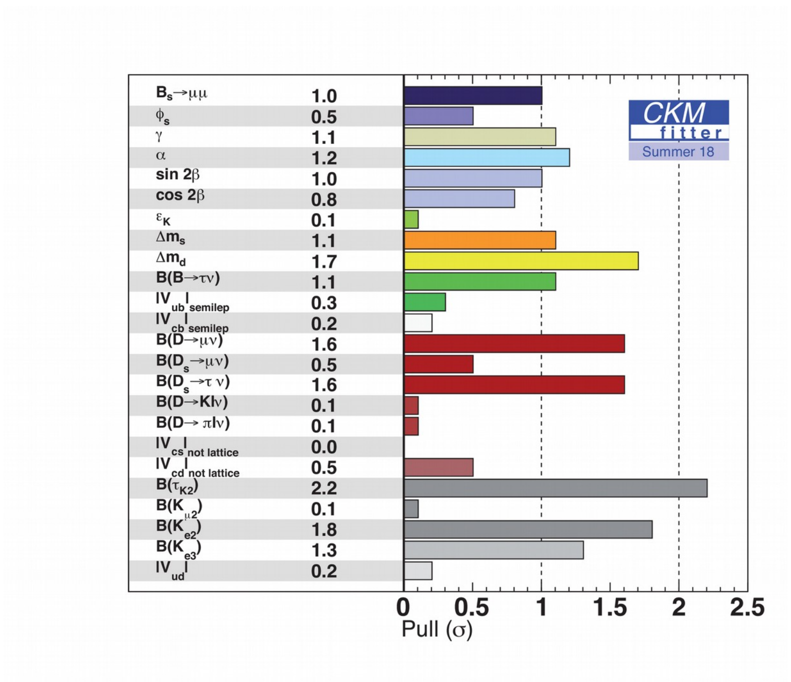
Standard model tests with heavy flavour



Lot's of precision measurements are being compared to the SM prediction

- e.g. lot's of redundant measurements of the parameters of the CKM matrix to check consistency

Remarkable agreement so far … But ?



Standard model tests with heavy flavour

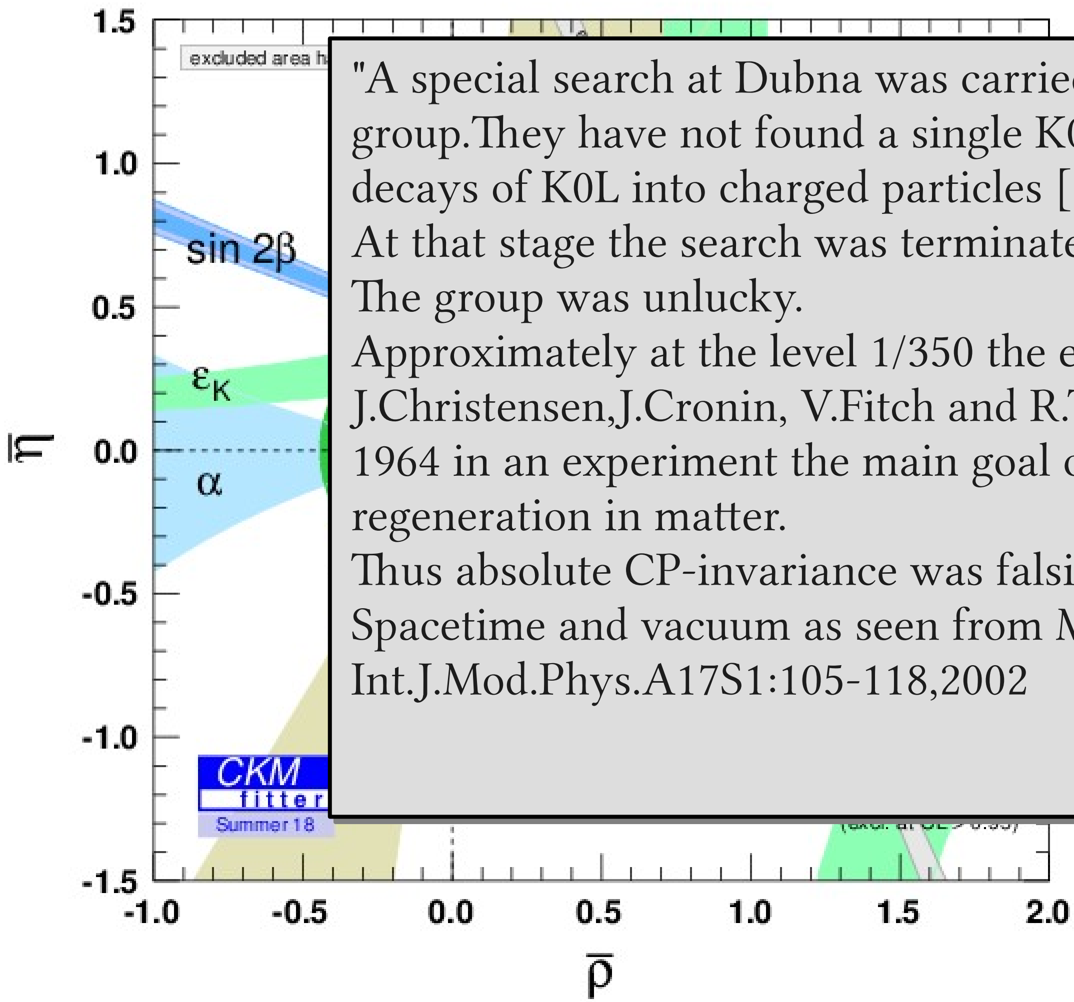
Lot's of precision measurements are

…M prediction

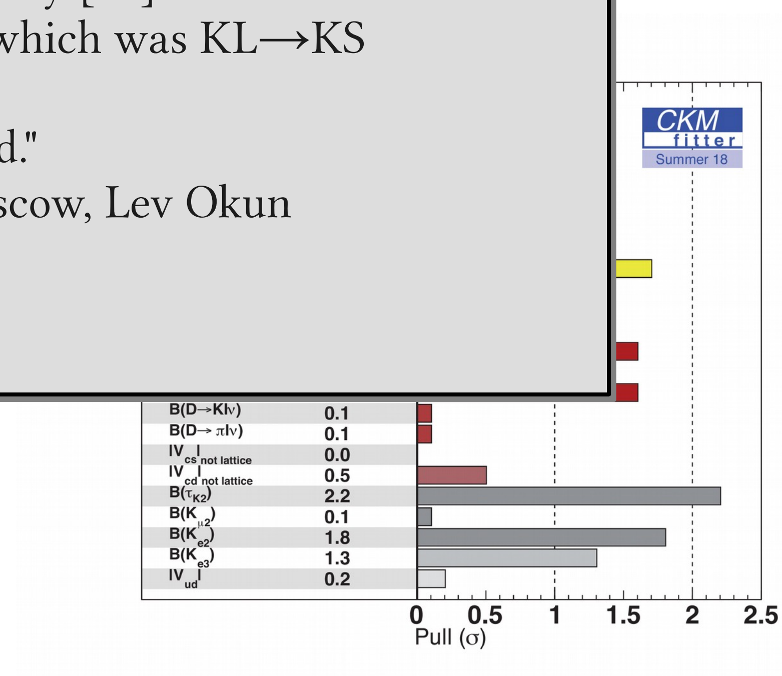
…parameters of

…eck

…o far … But ?

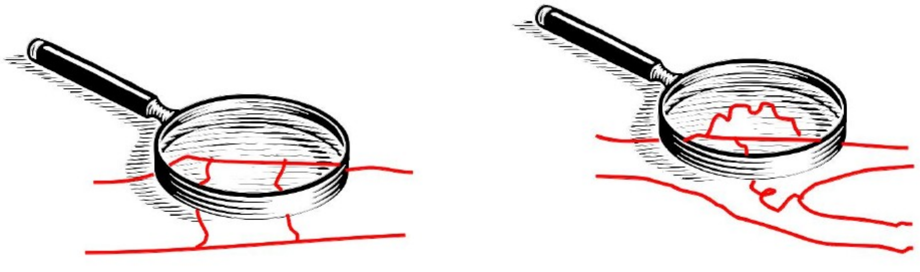


"A special search at Dubna was carried out by E. Okonov and his group.They have not found a single K0L⟶π+π−event among 600 decays of K0L into charged particles [13] (Anikina et al., JETP, 1962). At that stage the search was terminated by administration of the Lab. The group was unlucky.
Approximately at the level 1/350 the effect was discovered by J.Christensen,J.Cronin, V.Fitch and R.Turlay [14] at Brookhaven in 1964 in an experiment the main goal of which was KL⟶KS regeneration in matter.
Thus absolute CP-invariance was falsified."
Spacetime and vacuum as seen from Moscow, Lev Okun
Int.J.Mod.Phys.A17S1:105-118,2002



BSM searches with heavy flavour

- The quantum path



Mysteries of flavour physics

Why are there so many different fermions ?

What is responsible for their organisation into generations / families ?

Why are there 3 generations / families each of quarks and leptons ?

Why are there flavour symmetries ?

What breaks the flavour symmetries ?

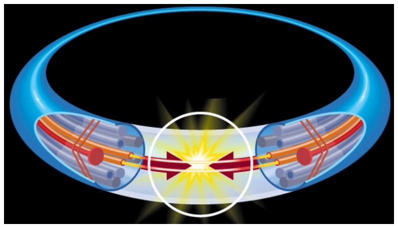
What causes matter–antimatter asymmetry ? (SM CP violation is not enough)

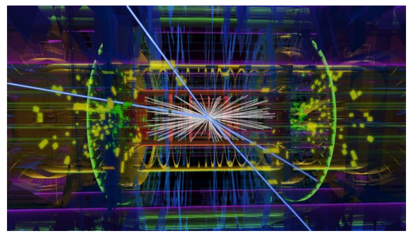
What about Dark matter ?

Search for physics beyond the Standard Model (BSM)

Direct

E=mc²





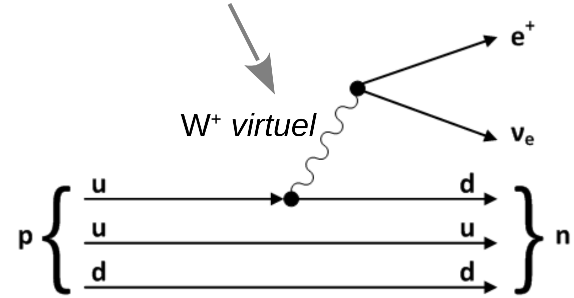
High energy

Direct observation :

- produce “new” particles on shell and detect decay products
- more intuitive, “really” produced
- limited by collision energy

Indirect

$\Delta E . \Delta t < h/2\pi$



High precision

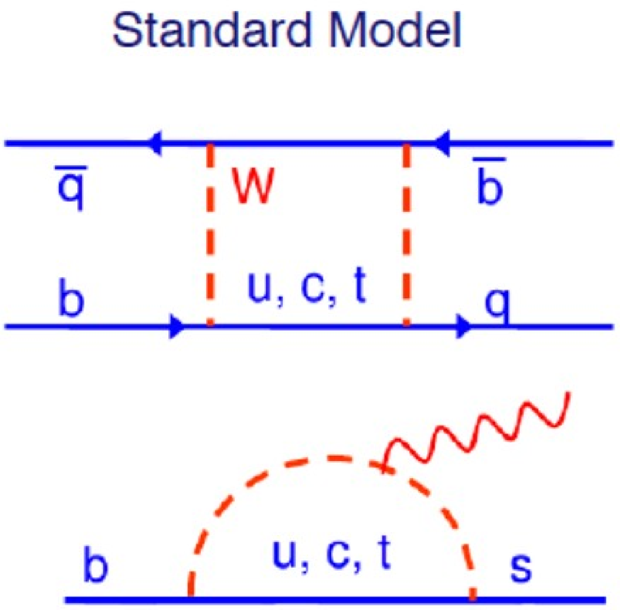
Indirect observation :

- virtual “new” particles can be discovered in loop processes
- less intuitive, “quantum” level
- not limited by collision energy, limited by precision (of measurements and theoretical predictions)

Complementary approaches → both are needed !

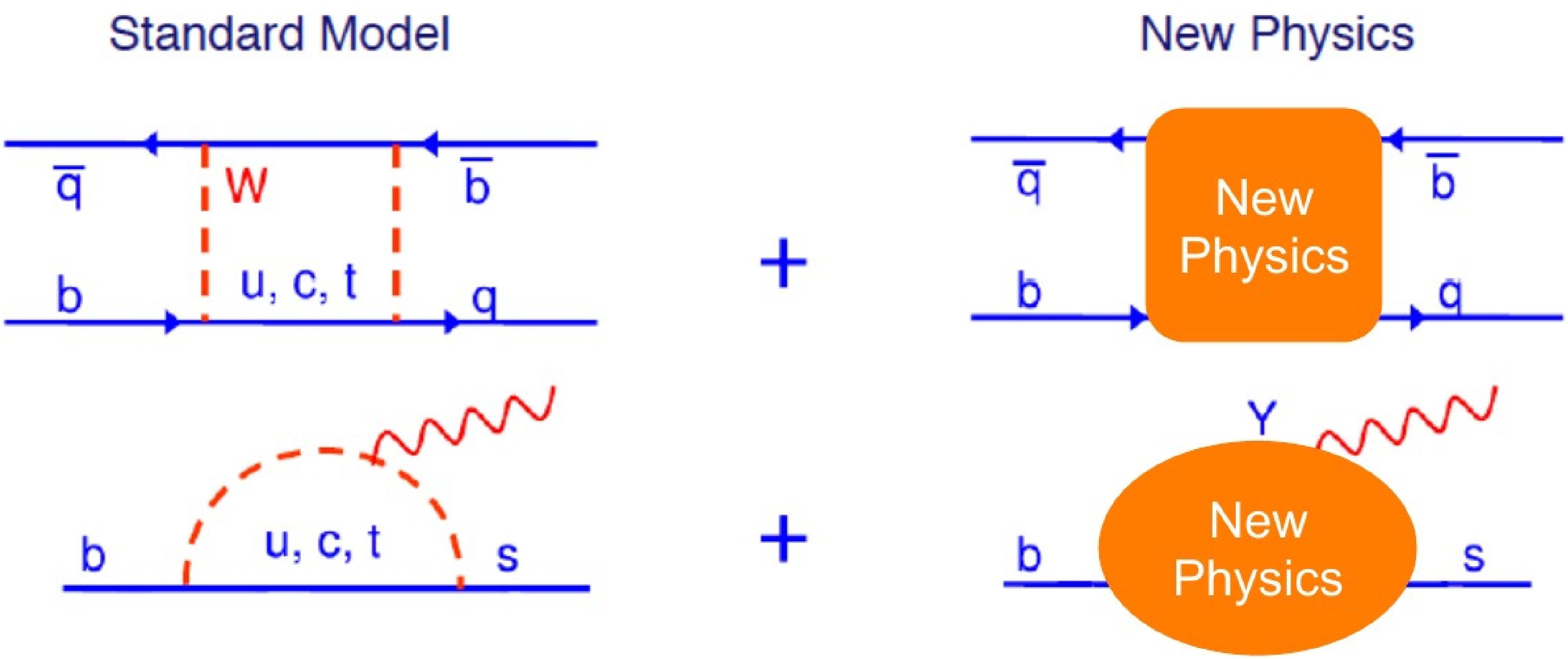
BSM searches with heavy flavour

Contribution to New Physics as a correction to the Standard Model



BSM searches with heavy flavour

Contribution to New Physics as a correction to the Standard Model



$$\mathcal{A}_{BSM} = \mathcal{A}_0 \left(\frac{c_{SM}}{m_W^2} + \boxed{\frac{c_{NP}}{\Lambda^2}} \right)$$

↘ What is the scale of New Physics Λ? What are its coupling C_{NP}?

The New Physics flavour problem

The hierarchy problem (Higgs with a large radiative correction) can be solved with:

$$\Lambda \lesssim 4\pi m_W \sim 1 \text{ TeV}$$

But: current bounds obtained from flavour physics (meson mixing and CP violation) gives:

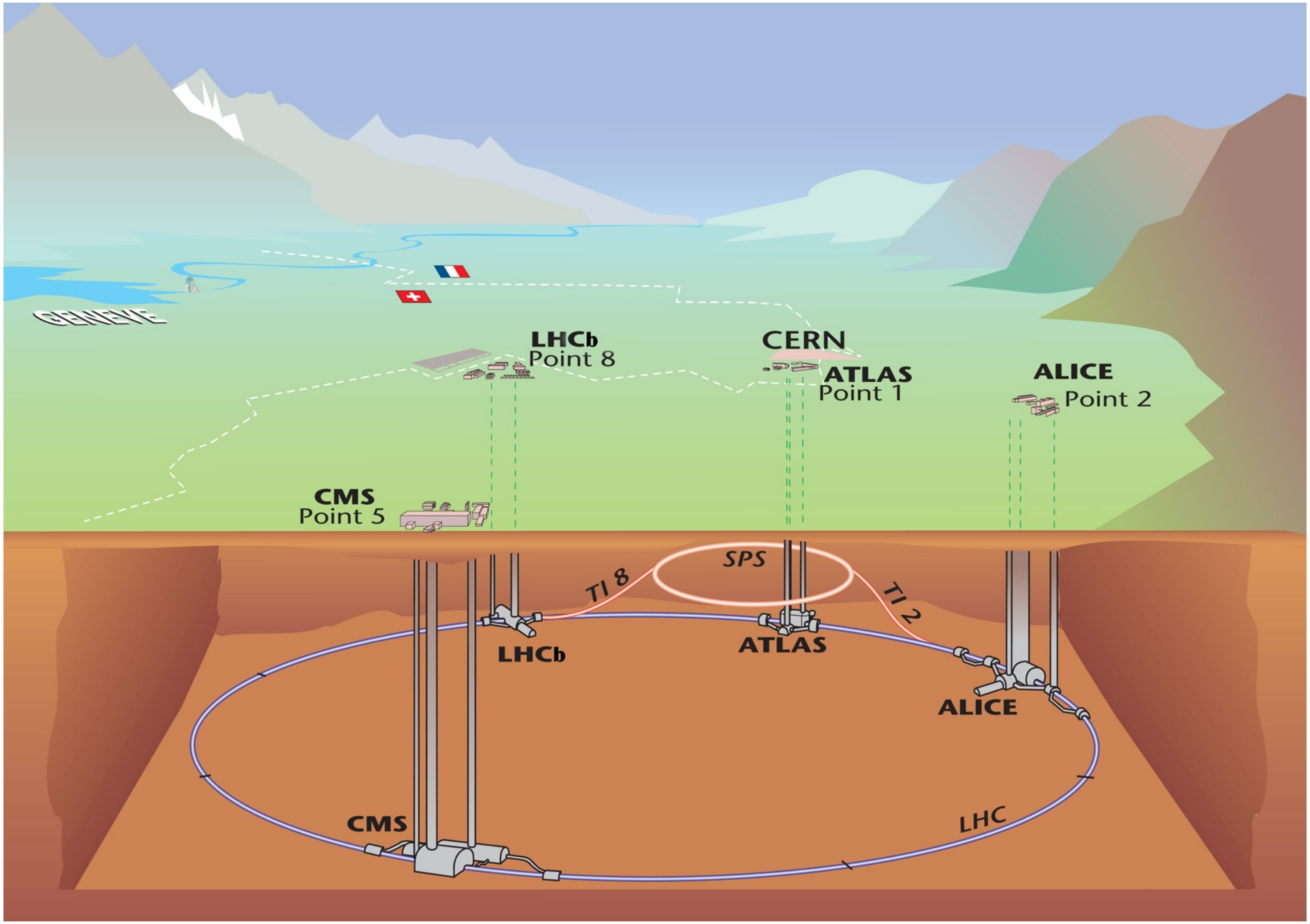
$$\Lambda \gtrsim \text{few } \times 10^4 \text{ TeV}$$

→This tension implies that any TeV-scale New Physics cannot have a generic flavour structure.

The LHCb experiment

- The LHCb detector
  and its upgrades

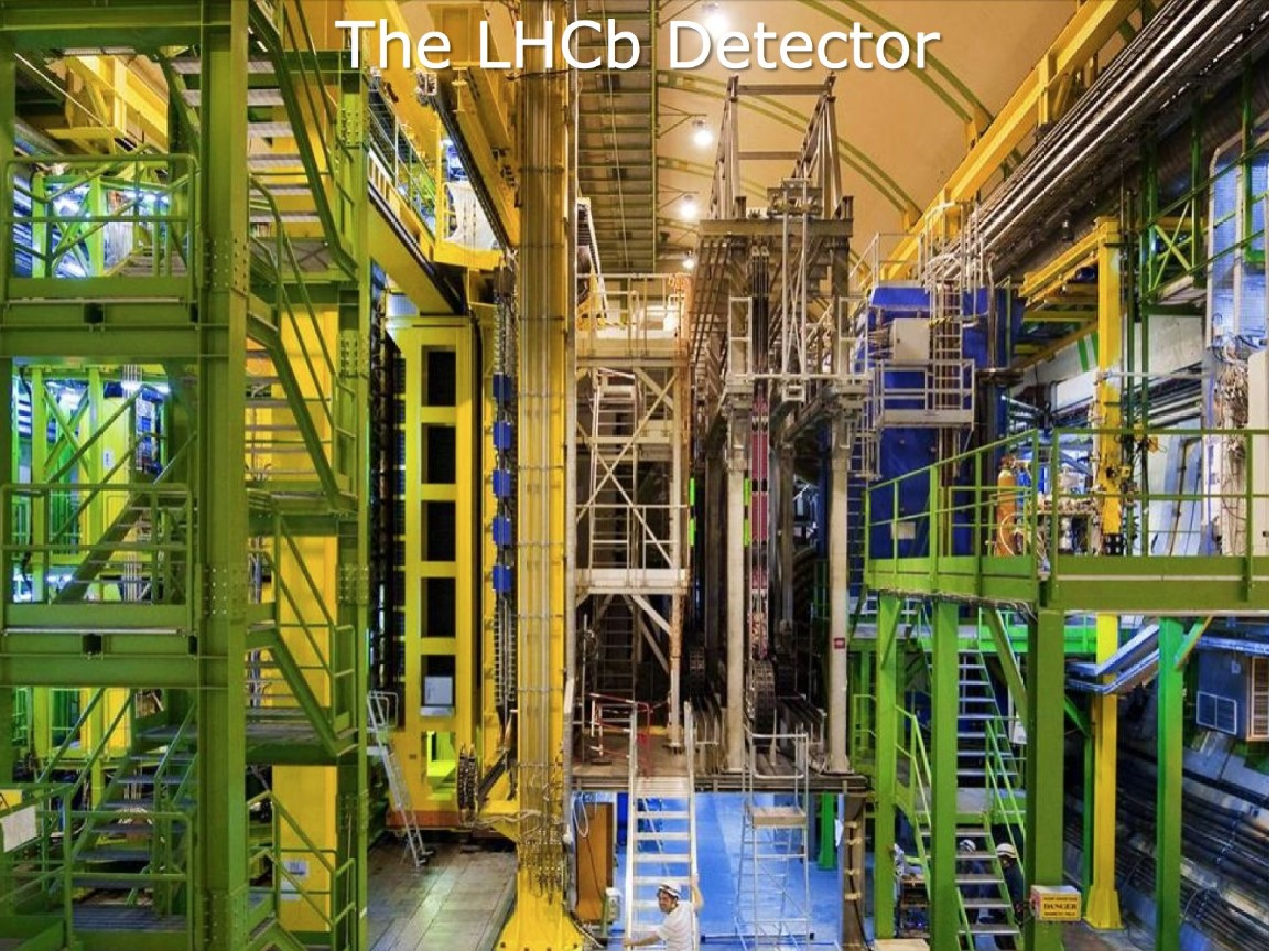
LHCb @ LHC



One of the 4 main LHC experiments

- Designed for heavy flavour physics precision measurements

The LHCb Detector




The LHCb collaboration
934 members
65 institutes
17 countries

Beauty and Charm production at the LHC

LHC is a Flavor Factory, e.g. @ 7 TeV :

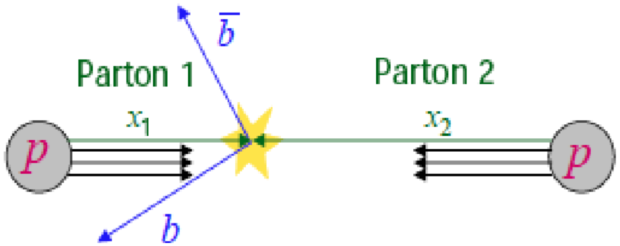
- $\sigma(pp \rightarrow c\bar{c}\,X)$ = ~ 6 mb [LHCb-CONF-2010-013]
- $\sigma(pp \rightarrow b\bar{b}\,X)$ = ~0.3 mb [PLB 694 (2010) 209]
  - note : the cross section grows lineraly with the energy
- B factories : $\sigma(e^+e^- \rightarrow b\bar{b})$@Y(4S) = ~ 1 nb

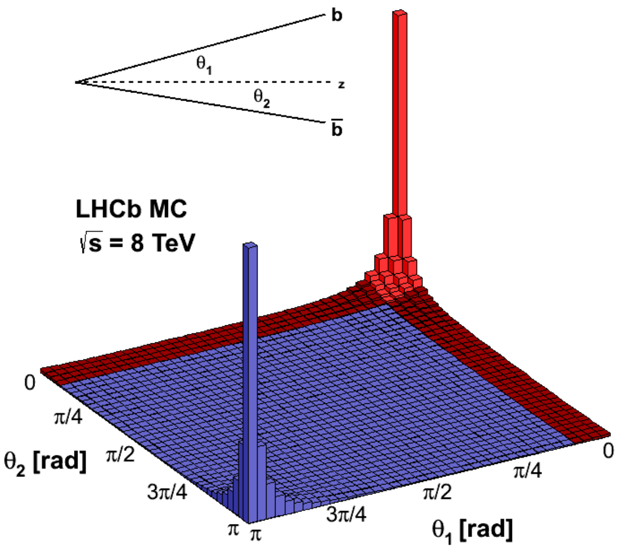
Challenging background condition :

- $\sigma(pp \rightarrow X)_{inel}$ = 60 mb [JINST 7 (2012) P01010]

All B hadron species are produced : B^0, B_s, B_c, ...

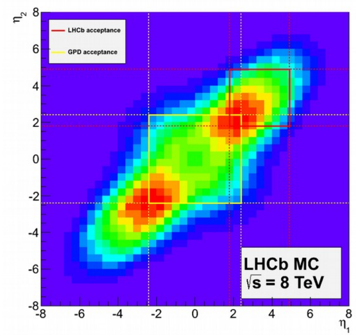
bb/cc pairs are produced predominantly
in the forward or backward directions



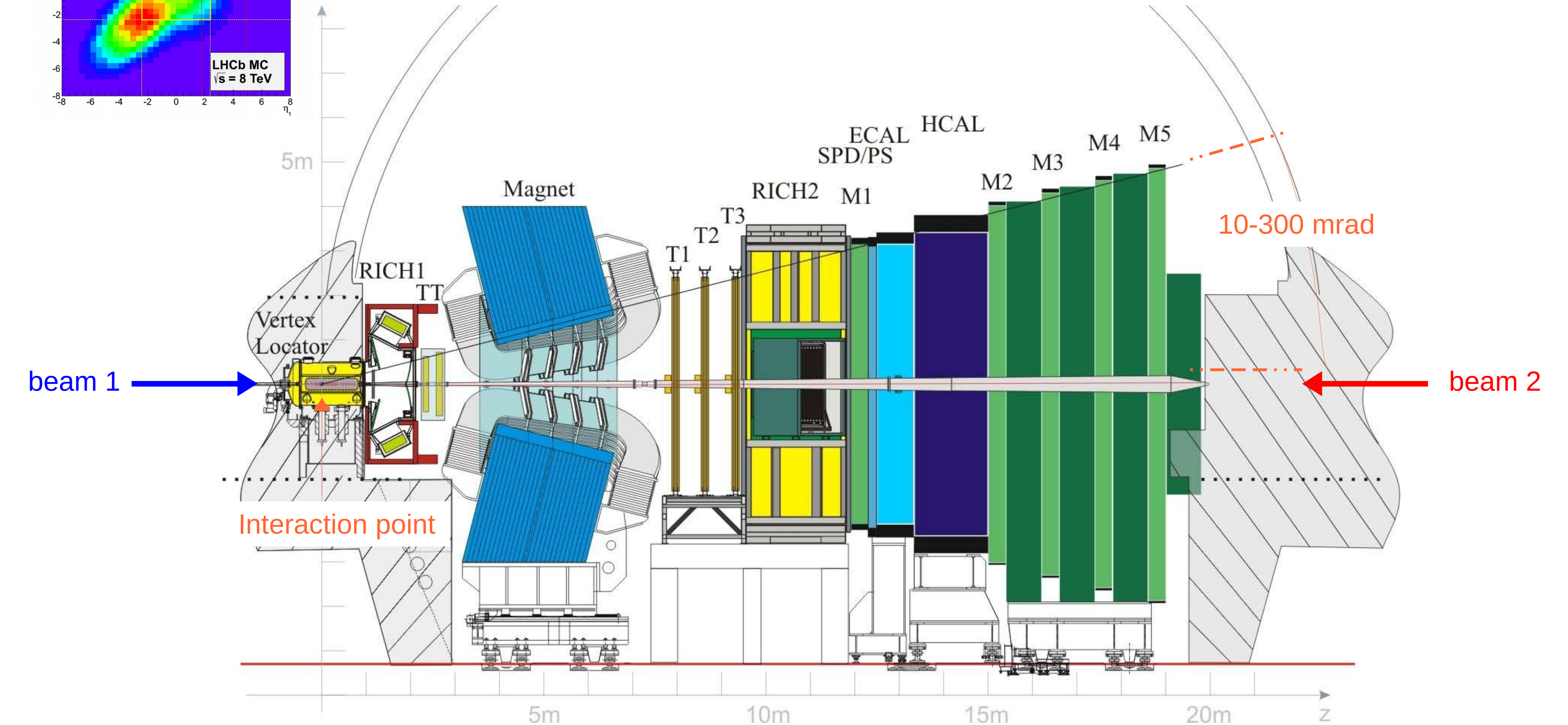


A forward spectrometer (1/2)

B forward-peaked production

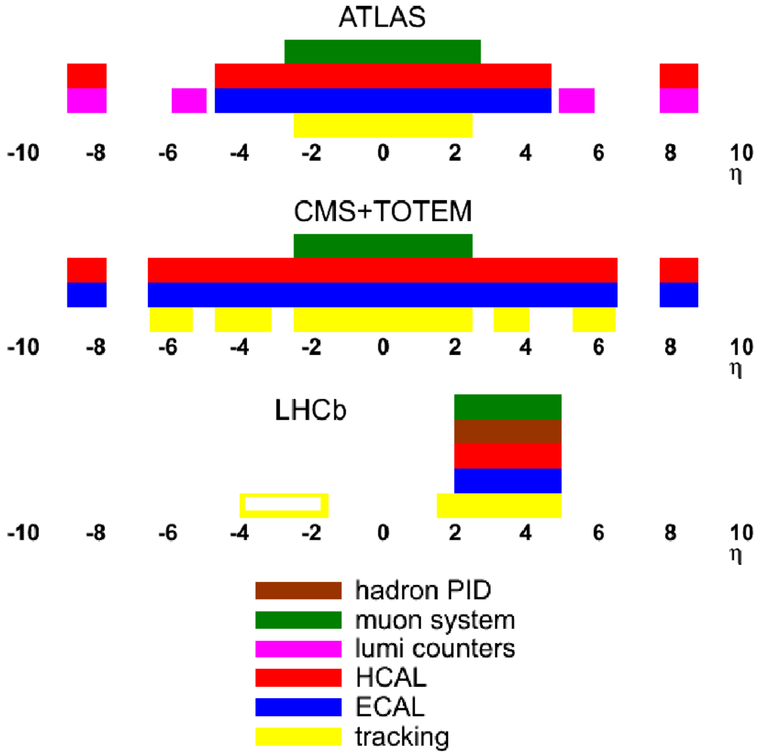


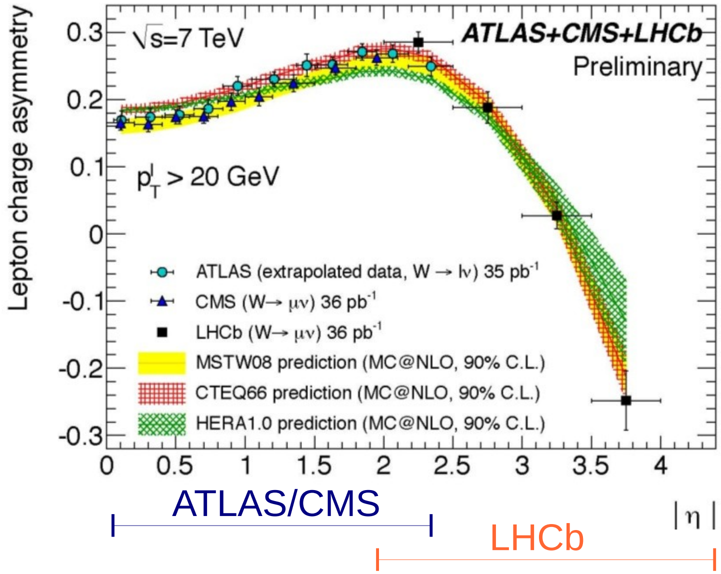
LHCb is a forward spectrometer
(operating in collider mode)



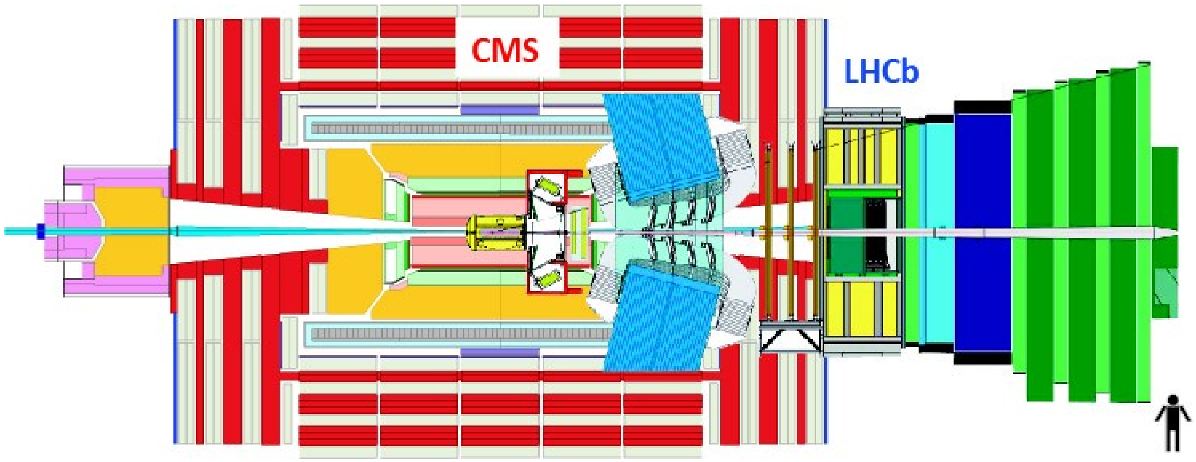
A forward spectrometer (2/2)

With unique rapidity coverage at LHC → complementary measurements

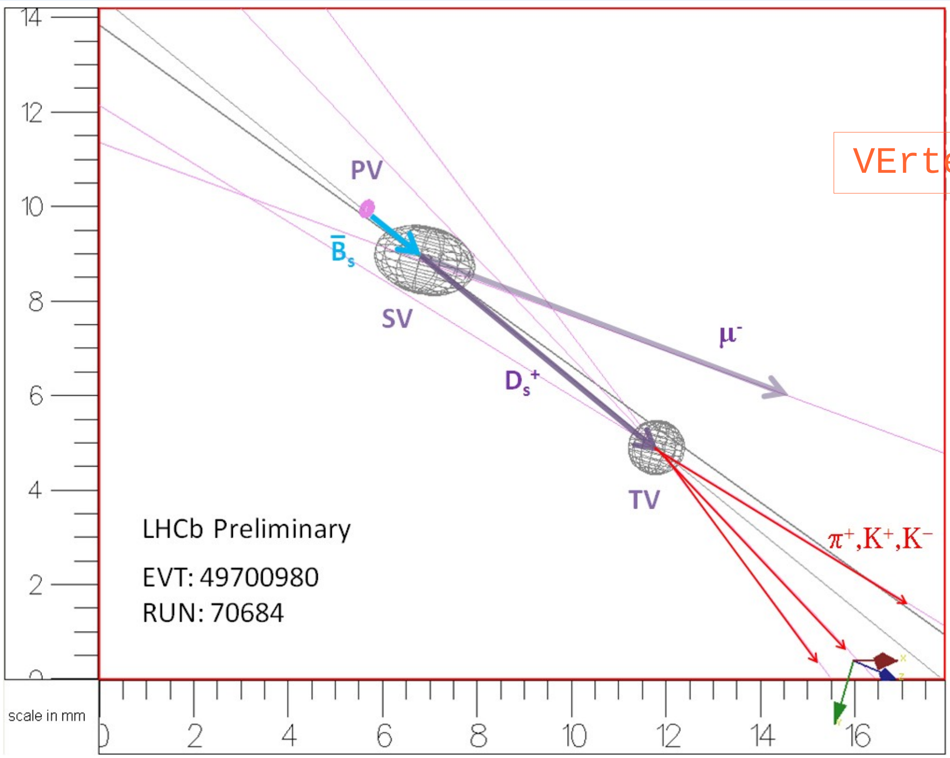


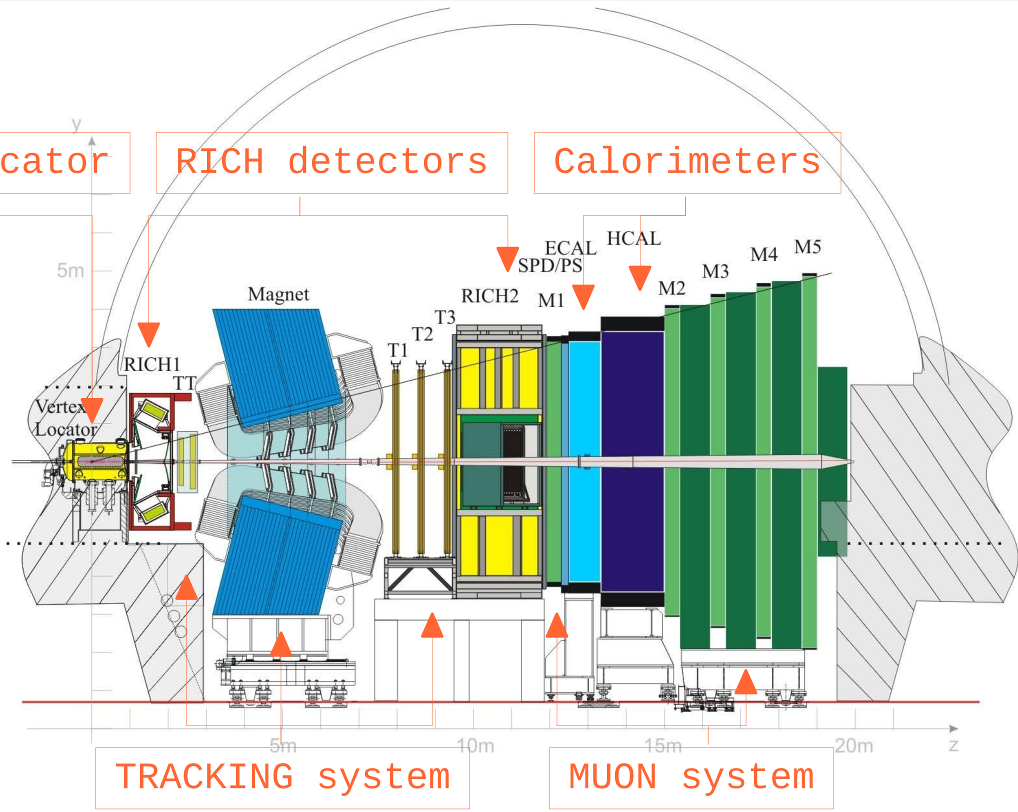


- LHCb acceptance : 2 <η < 5
- fully covered by tracking and particle identification



A forward spectrometer optimised for heavy flavors





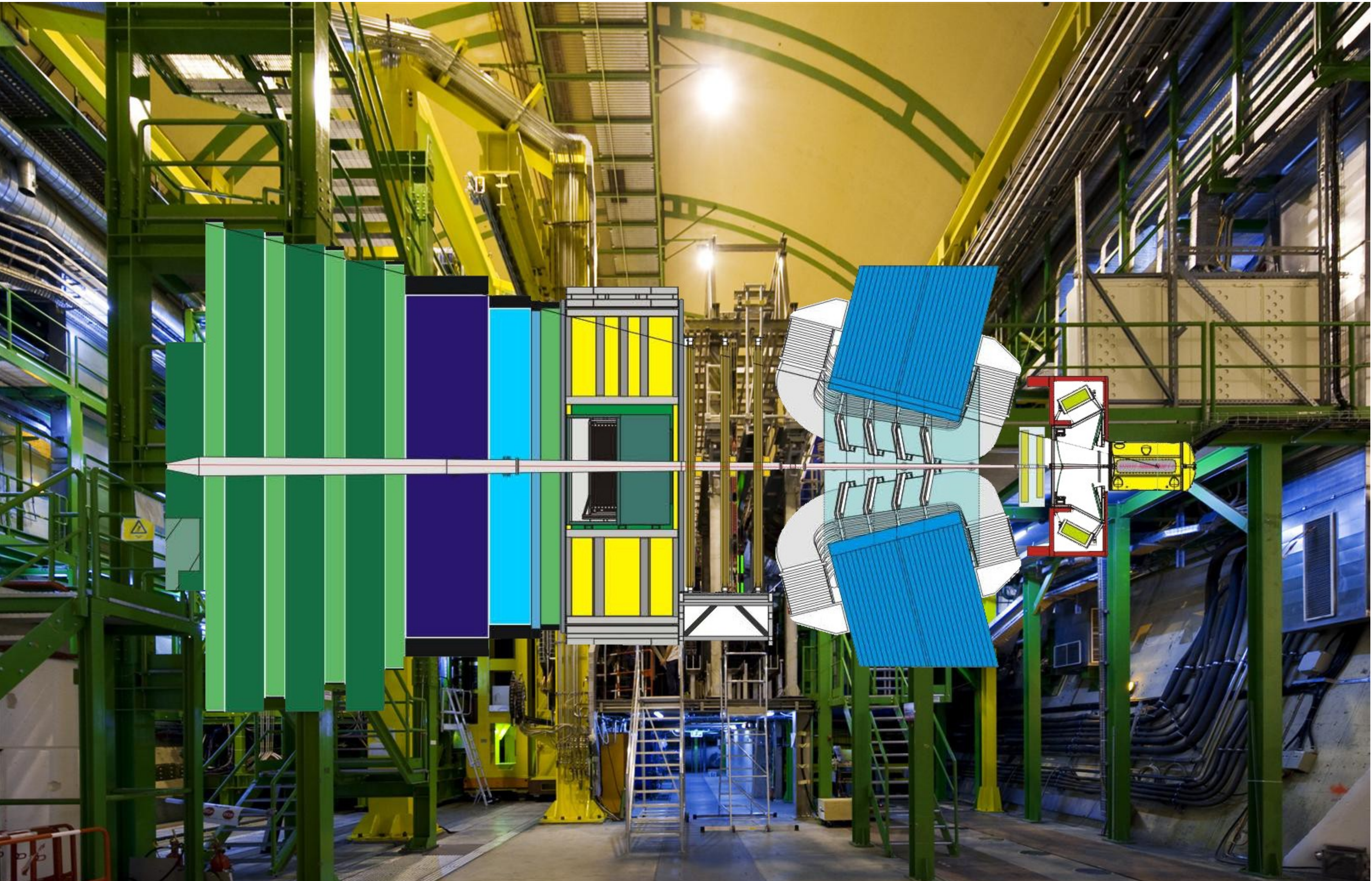
Key requirements

- B and D decay identification and resolve fast B_s oscillation
- Final state reconstruction and background rejection
- collect high statistic

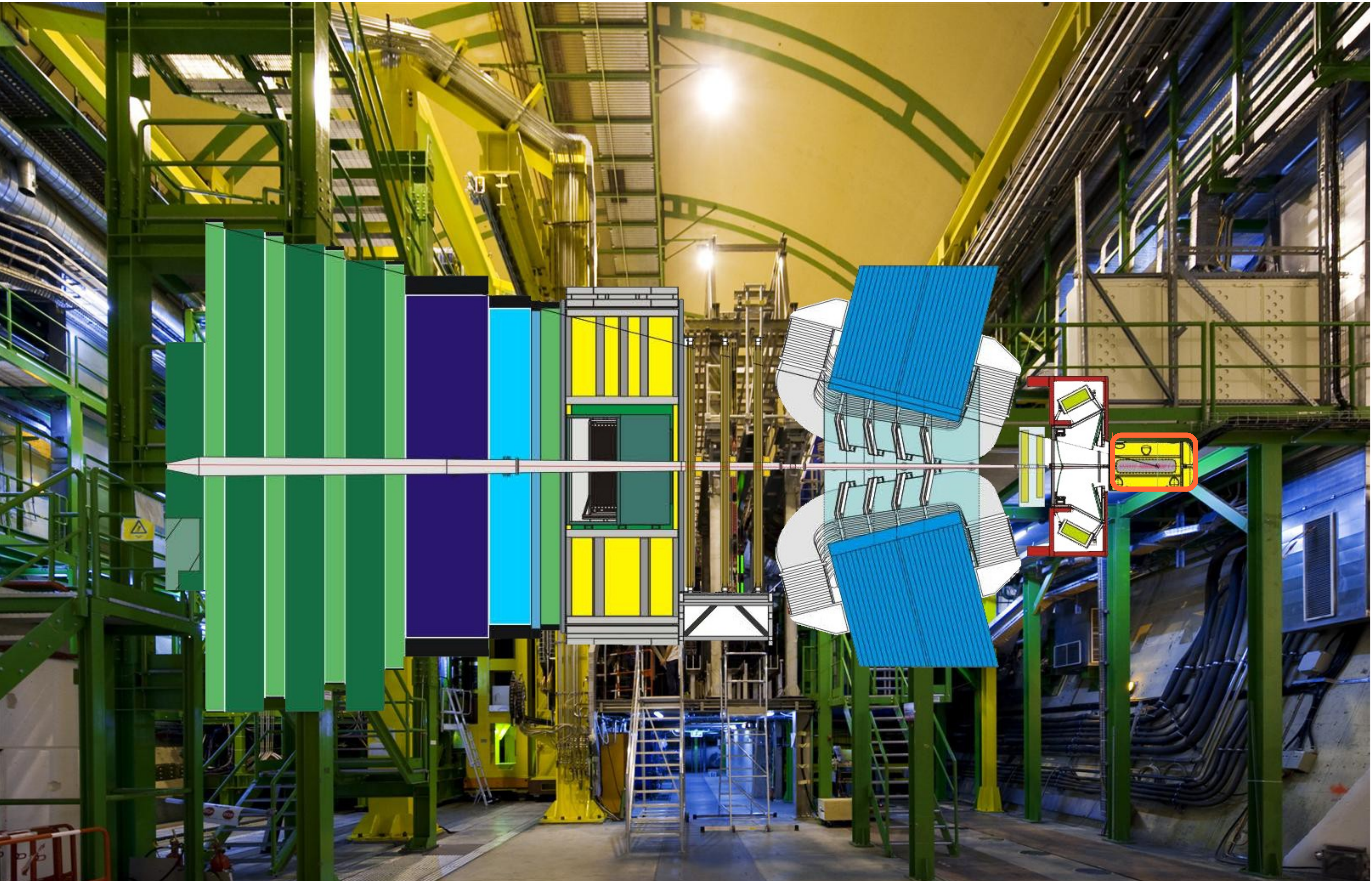
Detector design :

- High precision vertexing and tracking
  - VELO, TRACKING system
- Particle identification
  - RICH, CALO + MUON system
- Trigger
  - L0 (hardware) + HLT (software)

LHCb detector

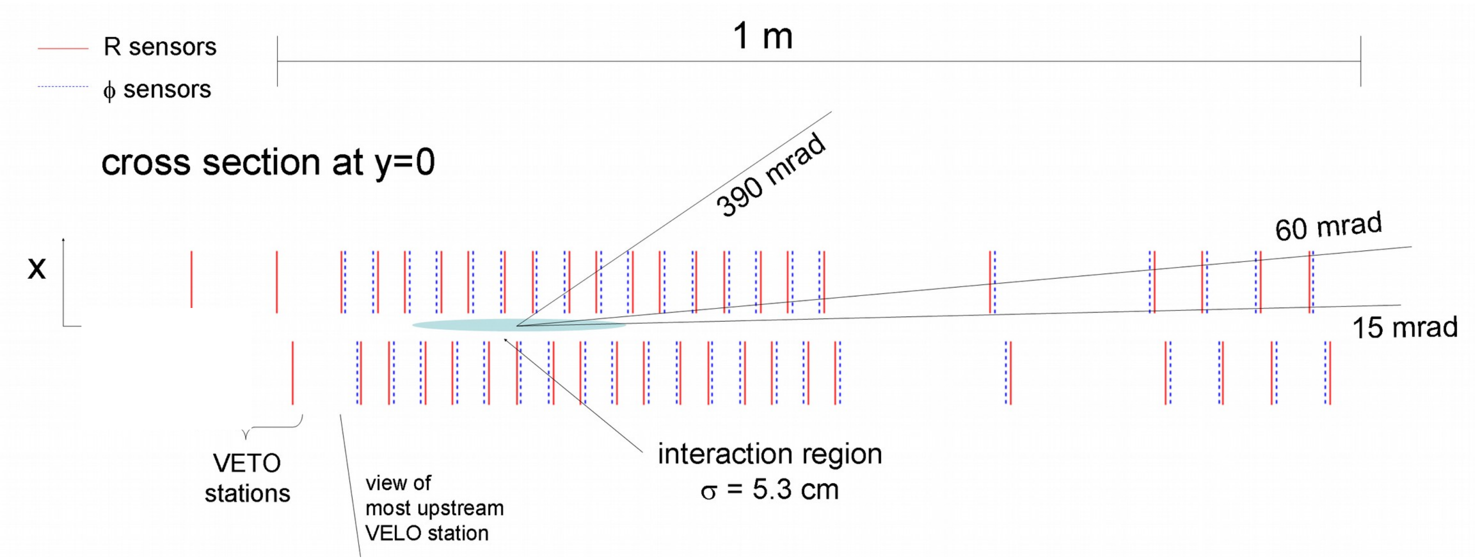


The VErtex LOcator (VELO) (0/3)



The VErtex LOcator (VELO) (1/3)

Reconstruction of primary and decay vertices, track seeds

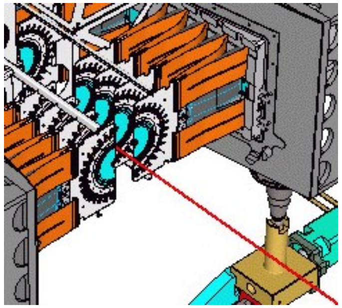


21 modules of R-Φ sensors

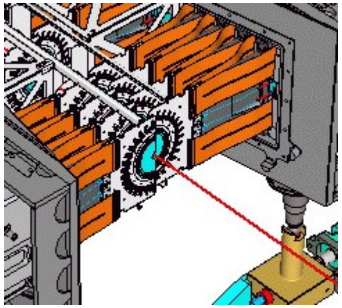
Movable device (retracted for safety during beam injection) :

- 35 mm from beam out of physics
- **8 mm from beam during physics**

Operated in vacuum

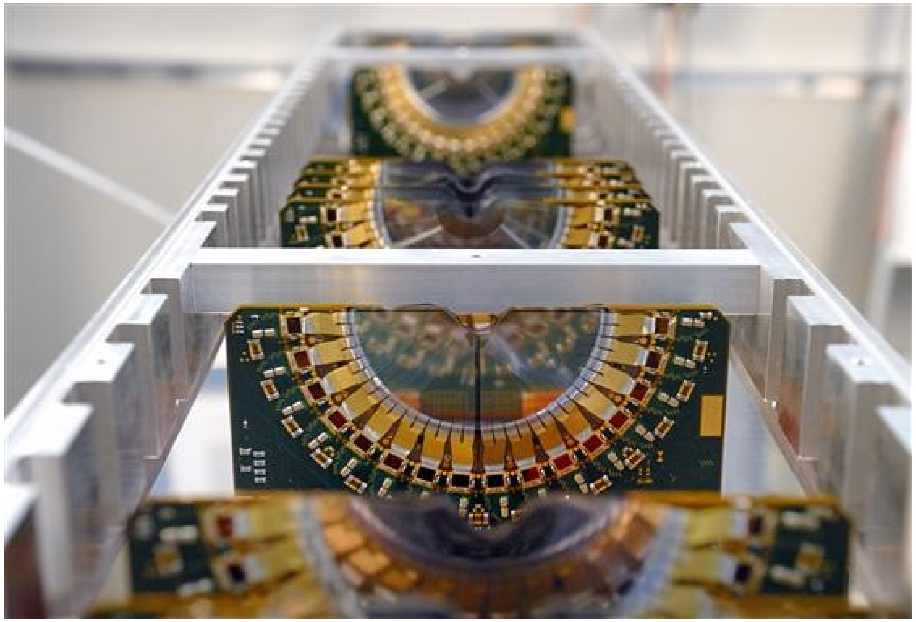


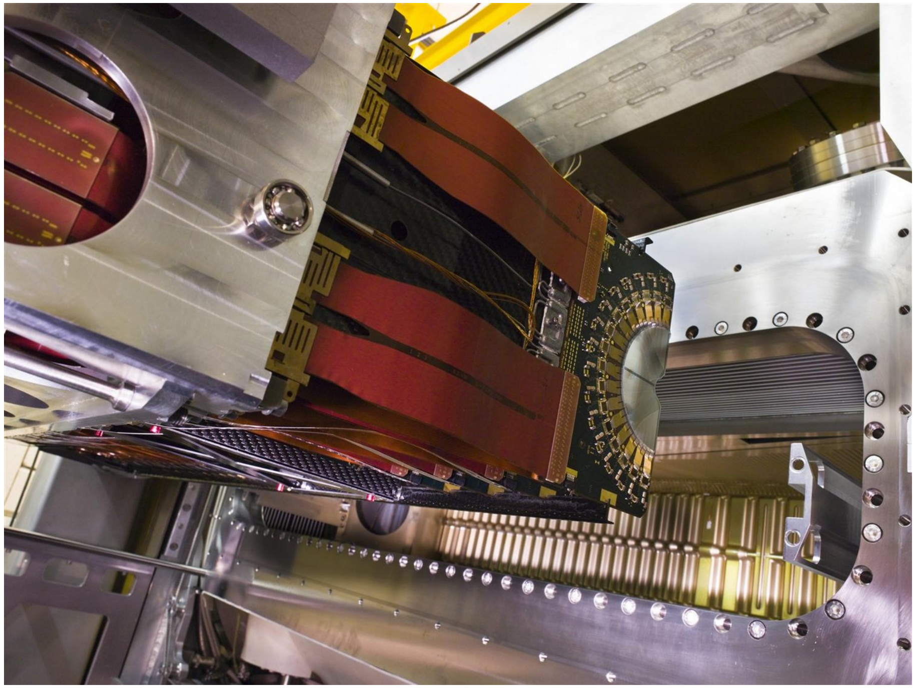
OPEN

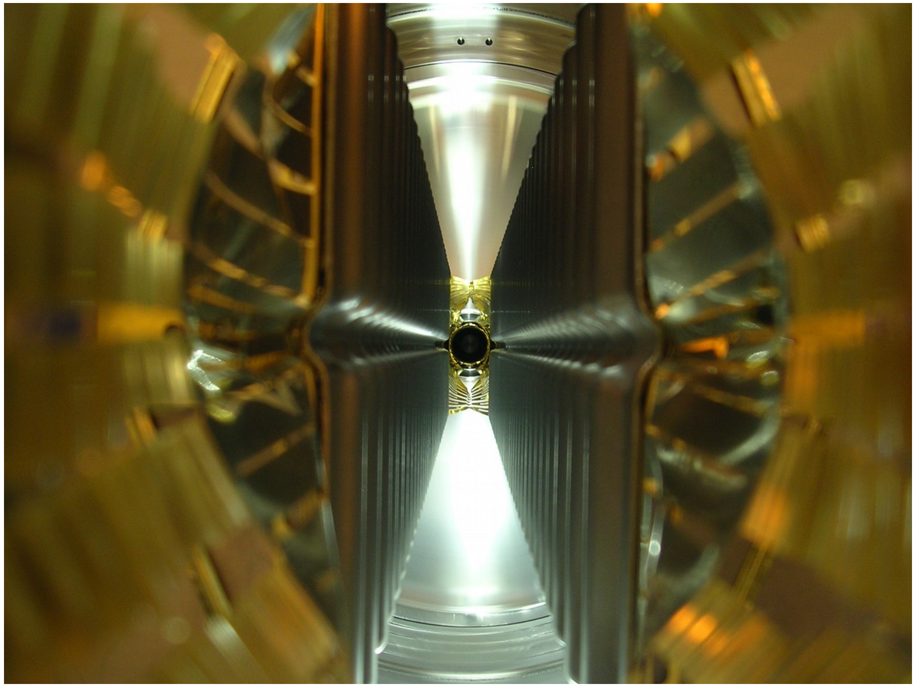


CLOSE

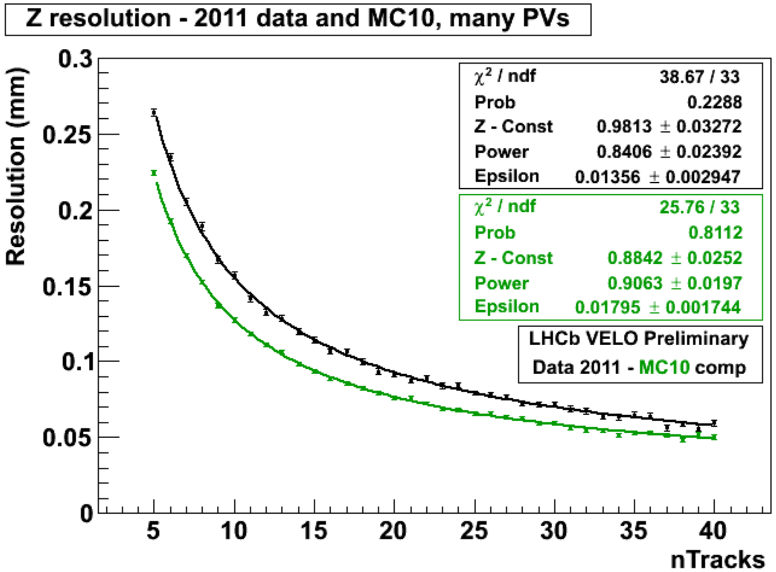
The VErtex LOcator (VELO) (2/3)



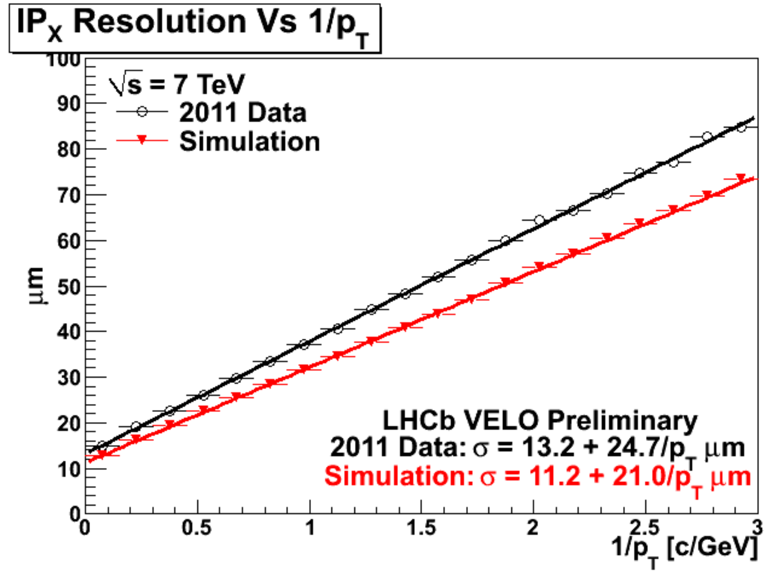




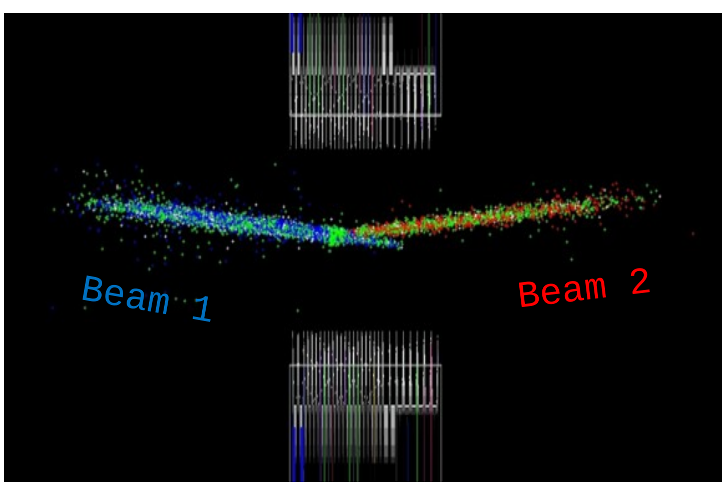
The VErtex LOcator (VELO) (3/3)



For 25 tracks : $\sigma_X \approx \sigma_Y \approx 16\ \mu m$, $\sigma_Z \approx 76\ \mu m$

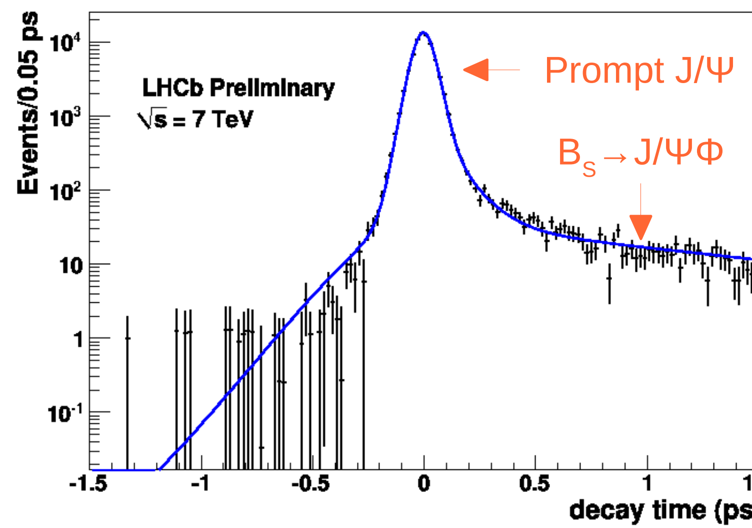


Impact parameter resolution
for high p_T track : ~ 20 µm



[PLB **693** 69]

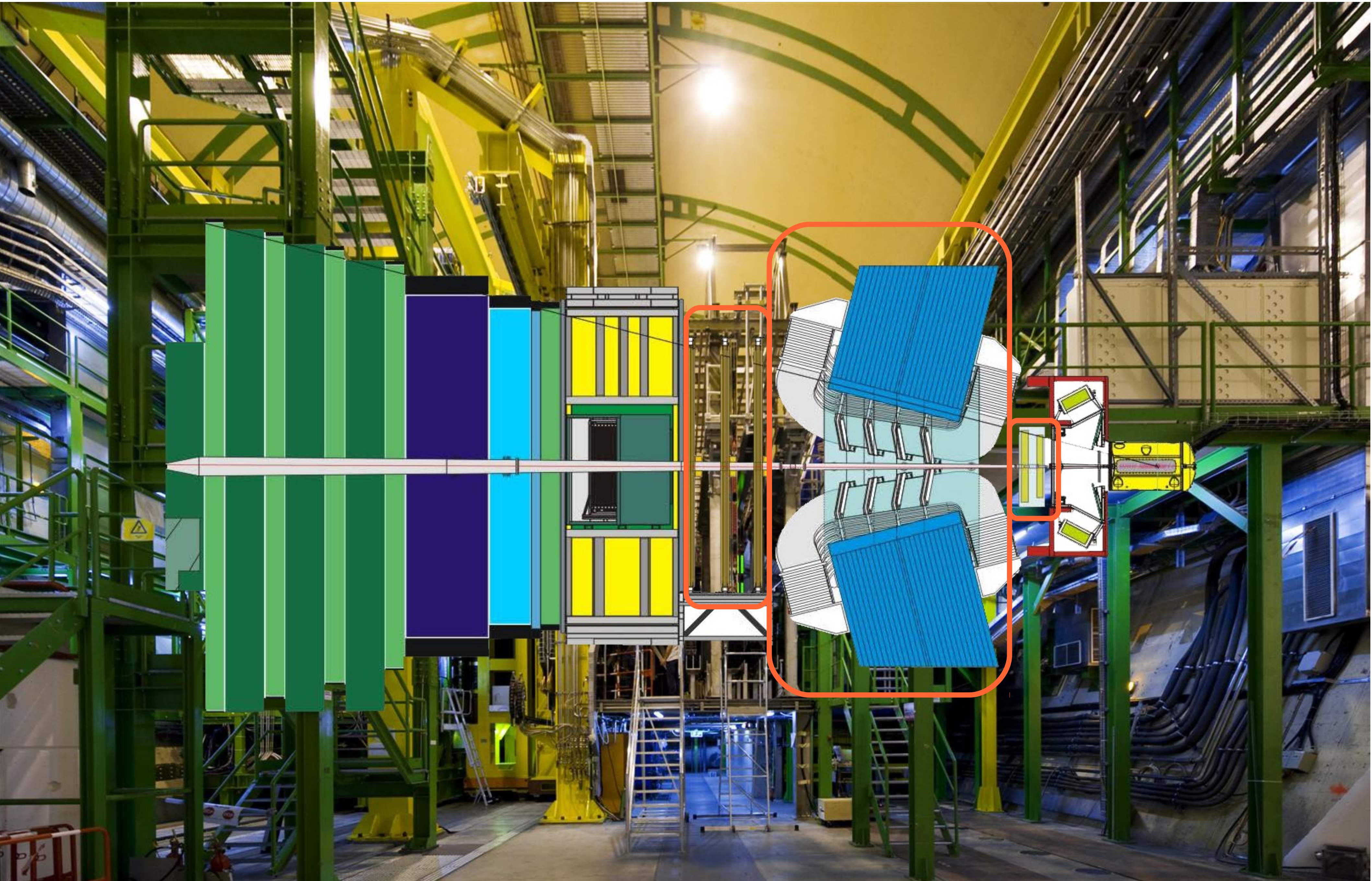
Reconstructed beam-gaz vertices
(used for luminosity measurement)



[CONF-2012-002]

Proper time resolution : σ_t = ~ 45 fs
(cf. $\lambda = 2\pi/\Delta m_s$ ~350 fs)

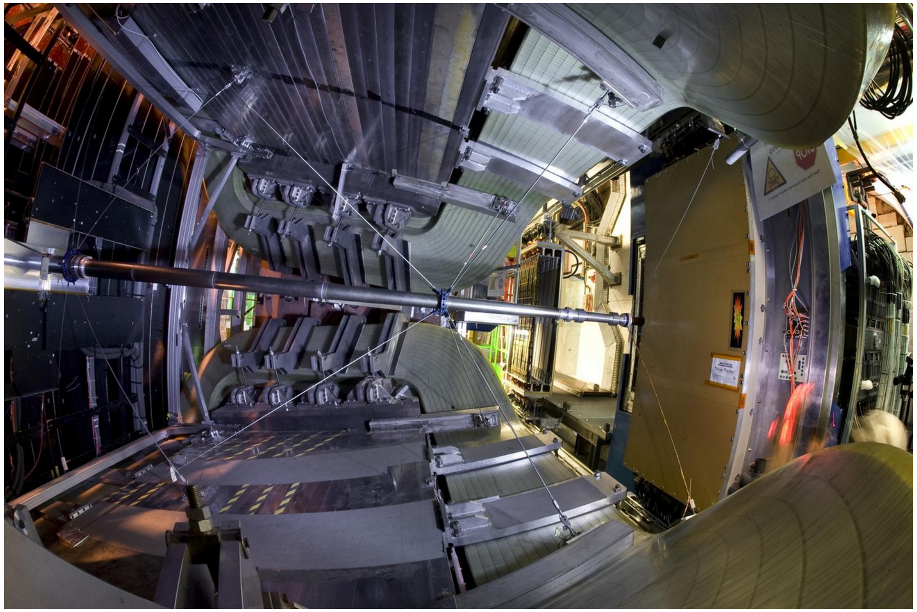
The Tracking System (0/2)



The Tracking System (1/2)

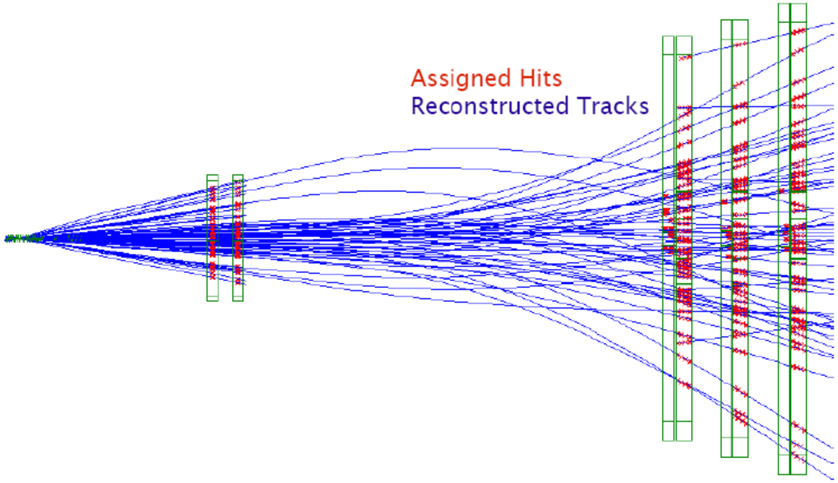
System :

- 1 tracking station before magnet (TT) :
  - → 4 layers of Si-Strips sensors
- Magnet
  - → ∫Bdl = ~ 4 Tm ; polarity switched regularly
- 3 tracking stations after magnet,
  4 layers each split into:
  - → Inner Tracker (Si-sensors)
  - → Outer Tracker (straw tube)



Track finding :

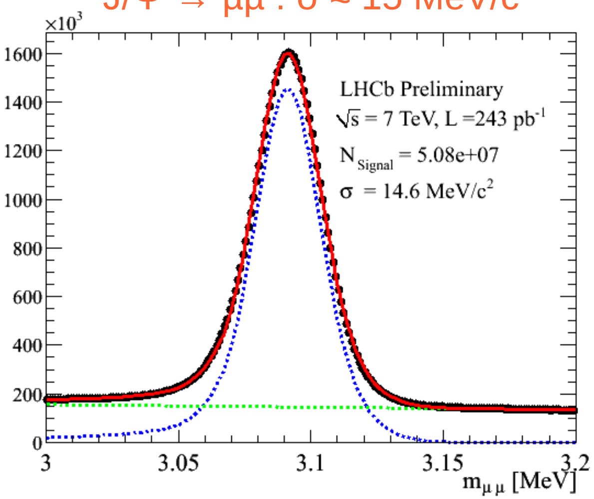
- Long tracks : high-momentum tracks traversing the full LHCb tracking setup
  - → combine track seeds in VELO and T-stations and add TT hits
  - → measured with highest precision
  - → most numerous in the main LHCb acceptance



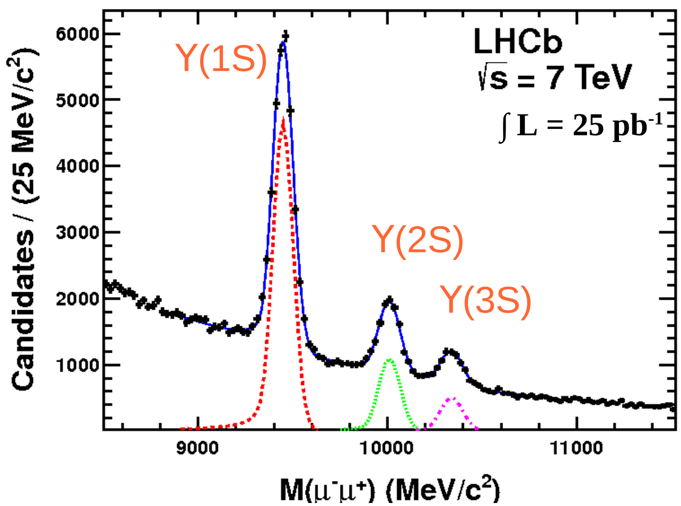
The Tracking System (2/2)

Momentum resolution : σ(p)/p = 0.4-0.6% (5-100 GeV/c)

J/Ψ → μμ : σ ≈ 15 MeV/c²

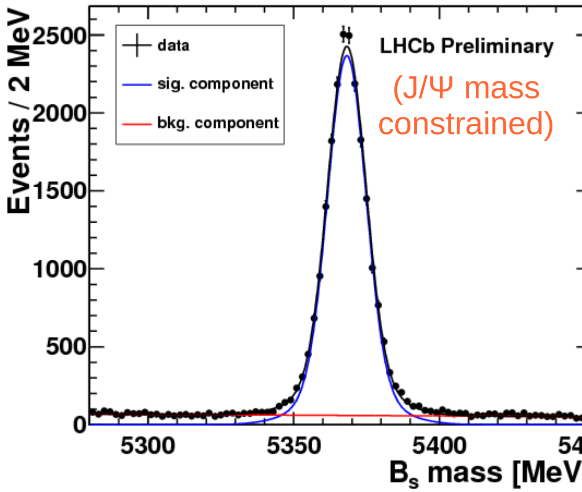


Υ(1S) → μμ : σ ≈ 54 MeV/c²



[Eur.Phys. J. C, (72),6]

$B_s \to J/\Psi\Phi$: σ ≈ 8 MeV/c²



[CONF-2012-002]

cf. [CMS DPS-2010-040] ~ 16 MeV/c²
[ATLAS CONF-2011-050] ~ 22 MeV/c²

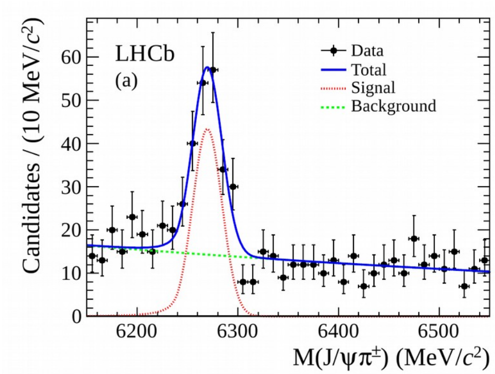
Momentum scale and detector alignment well controlled :

B hadron mass world's best measurements (2010 data only, 37pb⁻¹)

Quantity	LHCb measurement	Best previous measurement	PDG fit
$M(B^+)$	5279.38 ± 0.35	5279.10 ± 0.55	5279.17 ± 0.29
$M(B^0)$	5279.58 ± 0.32	5279.63 ± 0.62	5279.50 ± 0.30
$M(B^0_s)$	5366.90 ± 0.36	5366.01 ± 0.80	5366.3 ± 0.6
$M(\Lambda^0_b)$	5619.19 ± 0.76	5619.7 ± 1.7	–
$M(B^0) - M(B^+)$	0.20 ± 0.20	0.33 ± 0.06	0.33 ± 0.06
$M(B^0_s) - M(B^+)$	87.52 ± 0.32	–	–
$M(\Lambda^0_b) - M(B^+)$	339.81 ± 0.72	–	–

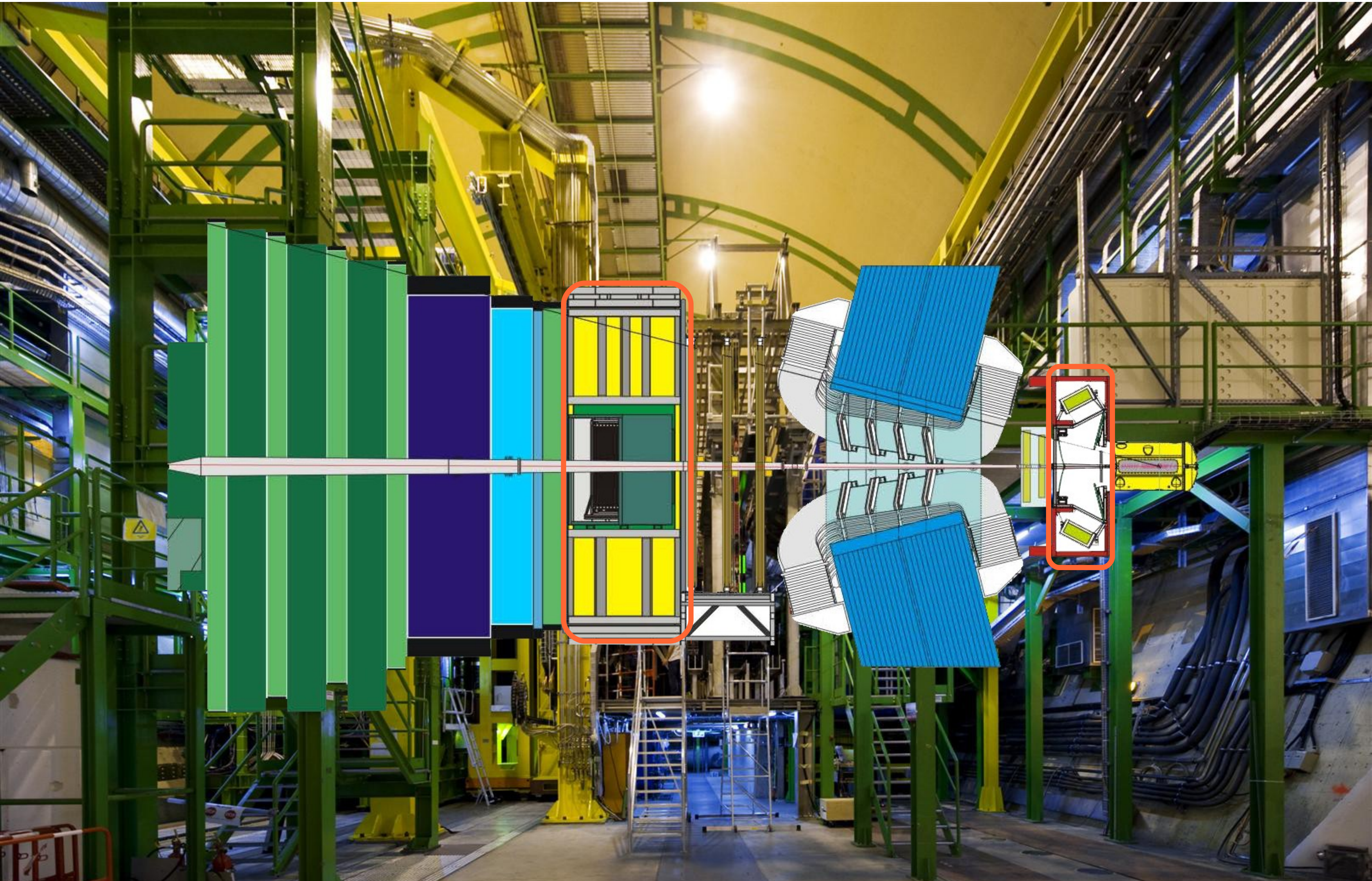
[PLB 708 (2012) 241]

B_c^+ mass also measured



[arXiv:1209.5634]

The RICH detectors (Particle Identification) (0/3)

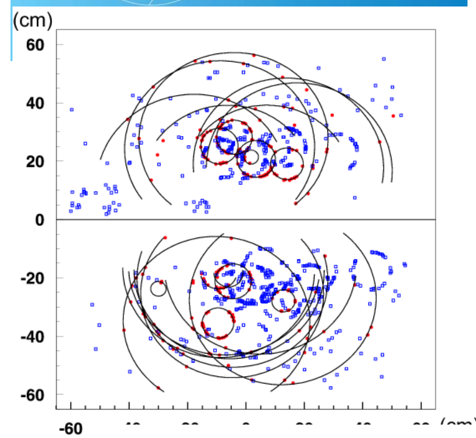


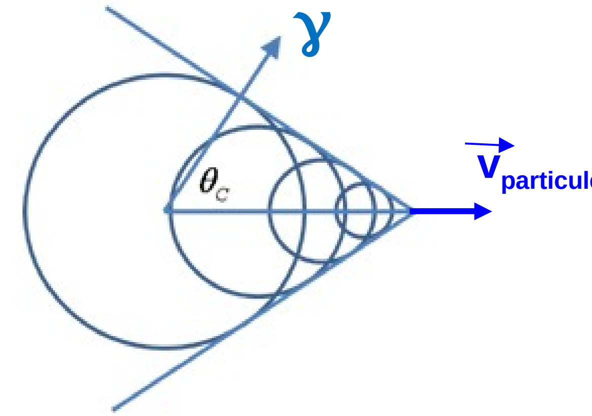
The RICH detectors (PID) (1/3)

Cerenkov effect :

- Cerenfov effect : when a particle travels faster than light in a medium,

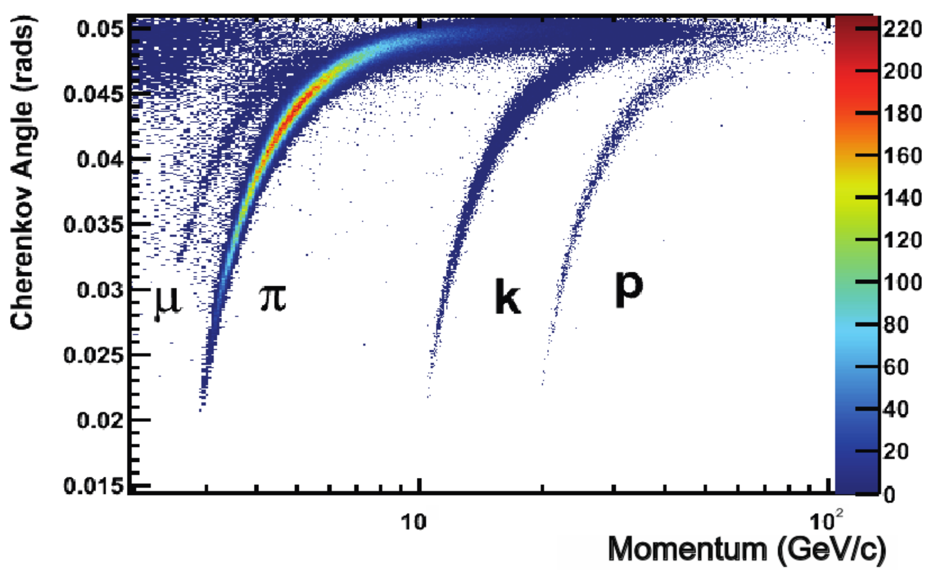
  it emits photons
- the photons are emitted in a cone with a opening angle proportional to the speed of the particle





LHCb's RICHs : Cerenkov imaging detector

- allow to identify charged hadrons



The RICH detectors (PID) (2/3)

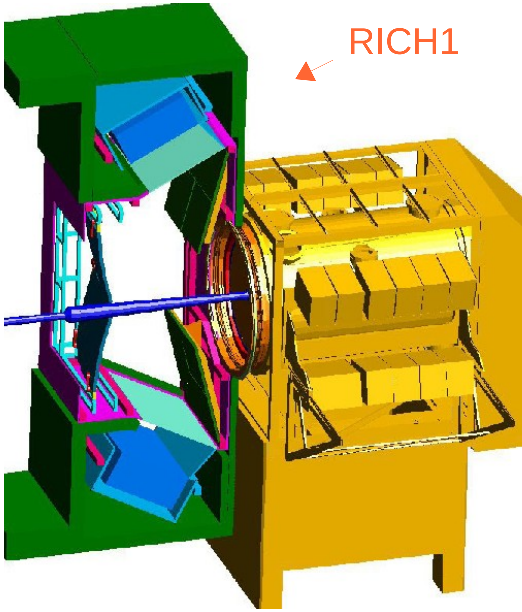
K/π separation over the full 1-100 GeV/c range

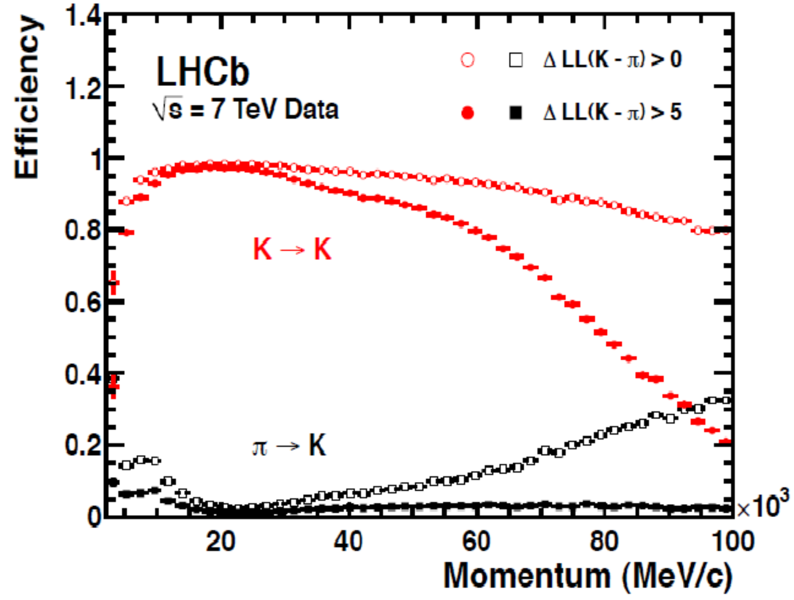
The detectors :

- RICH1 :
  - full angular acceptance
  - covers low momentum range : 1-60 GeV/c
  - aerogel & C_4F_{10} radiators
- RICH2 :
  - limited angular acceptance (~±15 → ~±100 mrad)
  - high momentum range : ~15 GeV/c - > 100 GeV/c
  - CF_4 radiator
- Hybrid Photon Detectors (HPDs)
  - 500 each with 1024 pixels
  - High efficiency, low noise

Performances

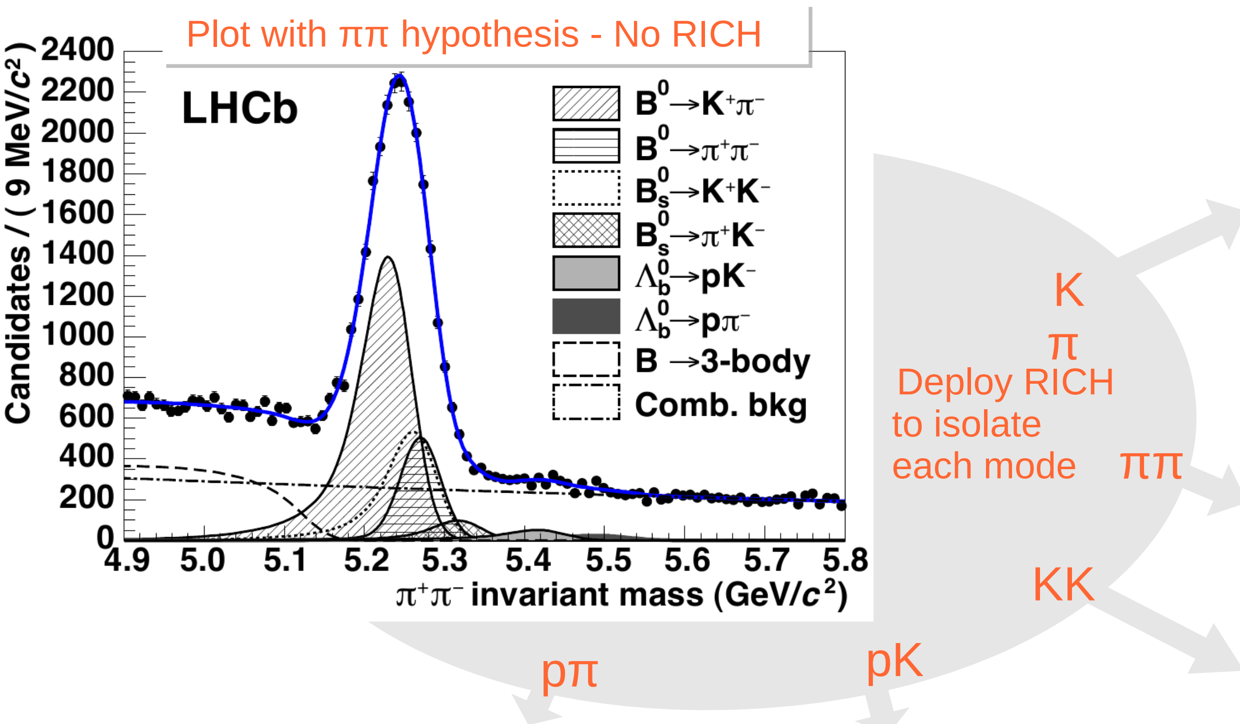
- ε ≈ 95 % for 5% π-K misID probability
- performances well described by simulation

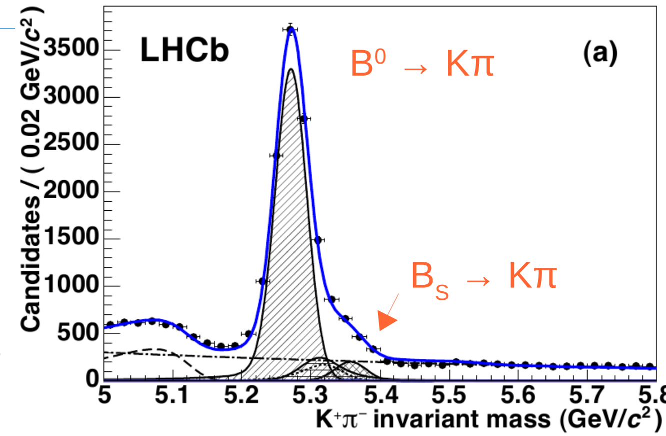


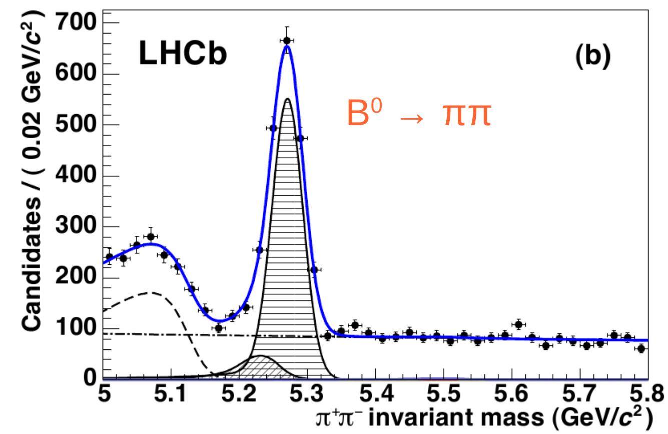


The RICH detectors (PID) (3/3)

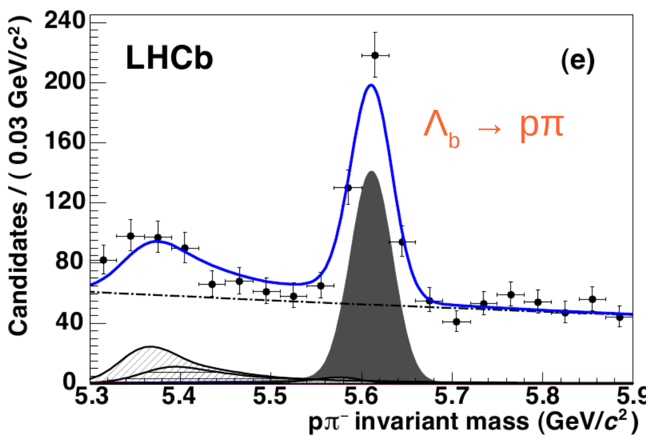
Charmless B decays : sensitive probes of CKM matrix

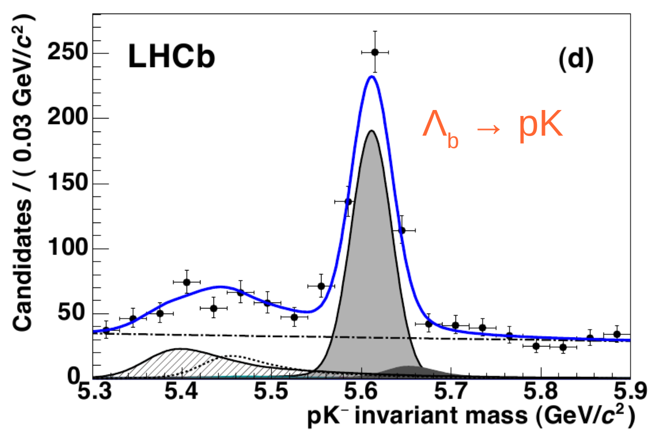


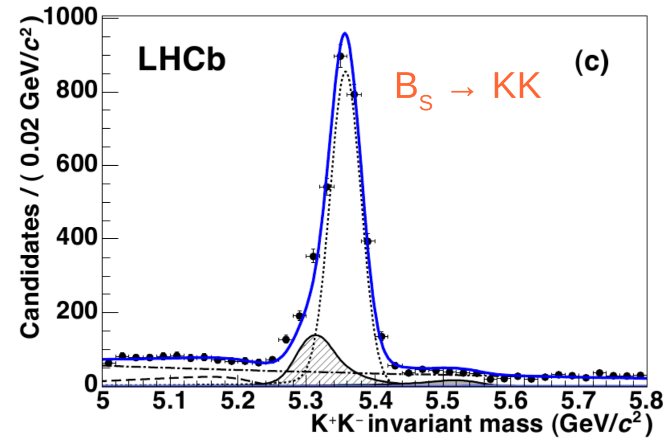




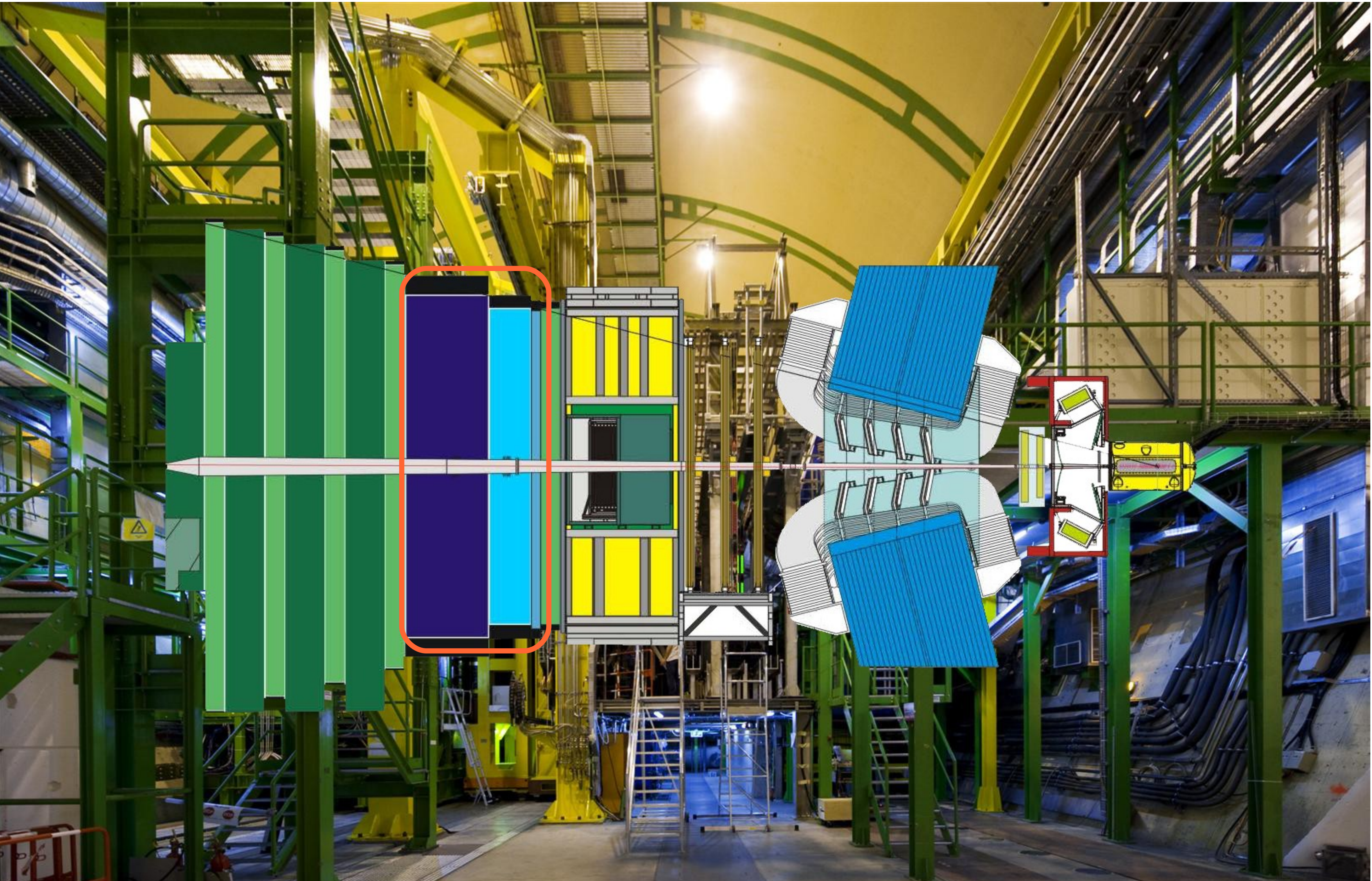
[arXiv:1206.2794]



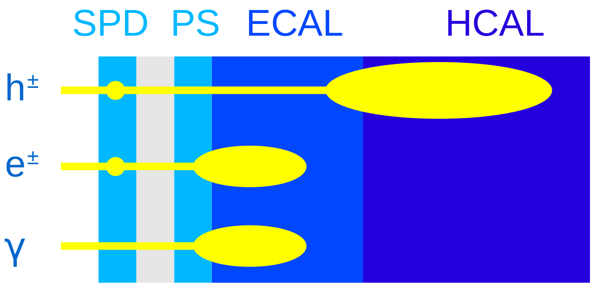


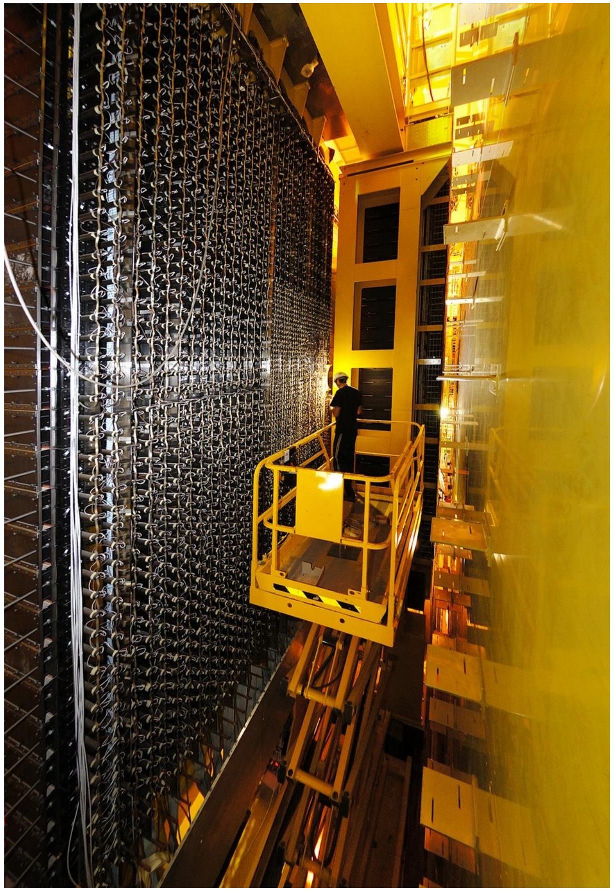


The Calorimeters (Particle Identification) (0/2)



The Calorimeters (Particle Identification) (1/2)




The ECAL detector

Scintillator Pad Detector / PreShower :

- robust e/γ and e/hadron separation
- single layer scintillator tiles separated by Pb sheet (2.5 X_0)
- $\varepsilon(e^{\pm})$ = 90% for 5% e-hadron MisID

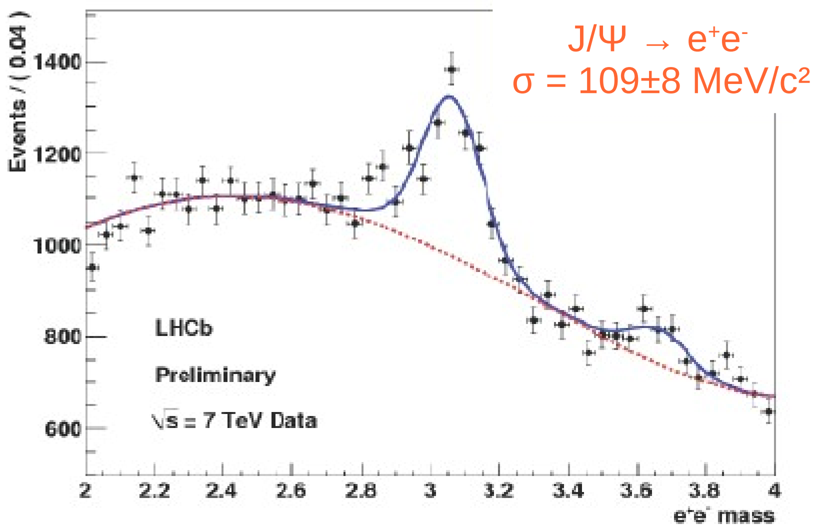
Electromagnetic CALorimeter :

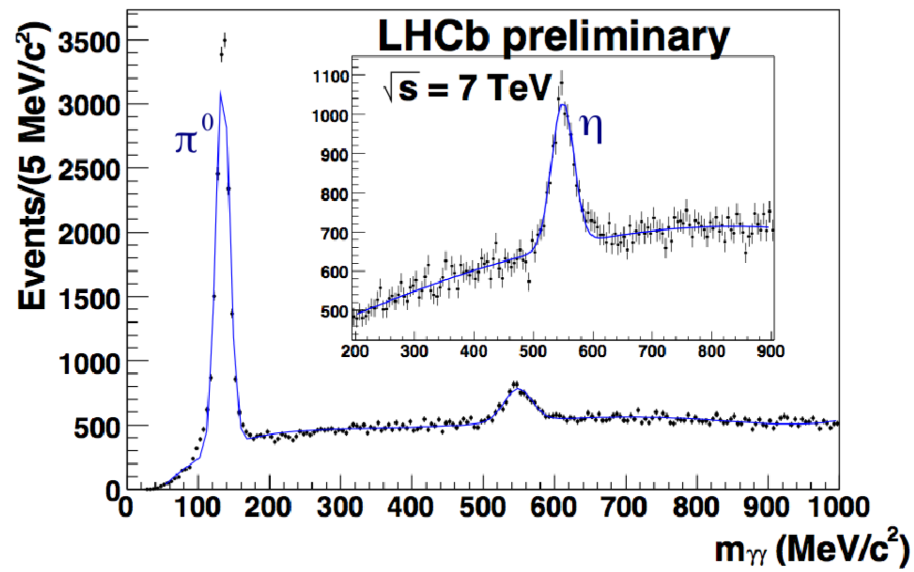
- e and γ energy measurement
- trigger on electromagnetic decay channels
- Pb plates / scintillator tiles (25 X_0)
- $\sigma(E)/E = 10\%/\sqrt{E(GeV)} + 1\%$ (nominal)

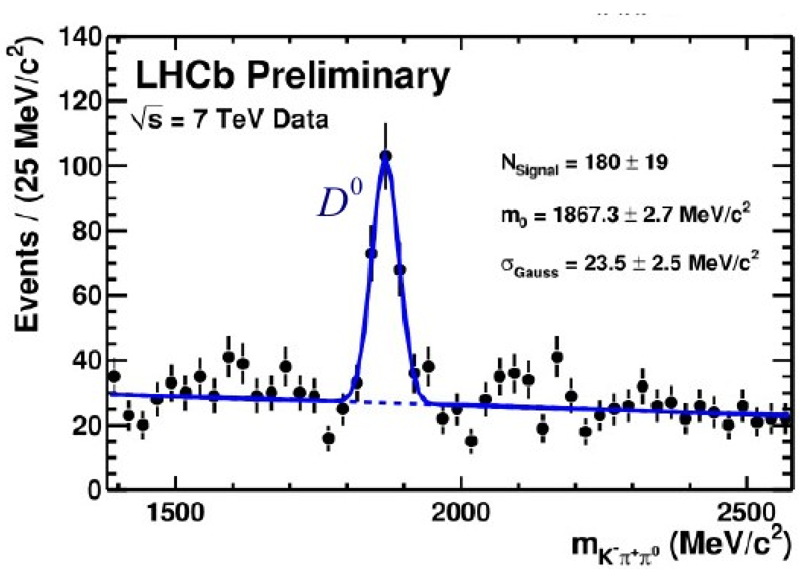
Hadronic CALorimeter :

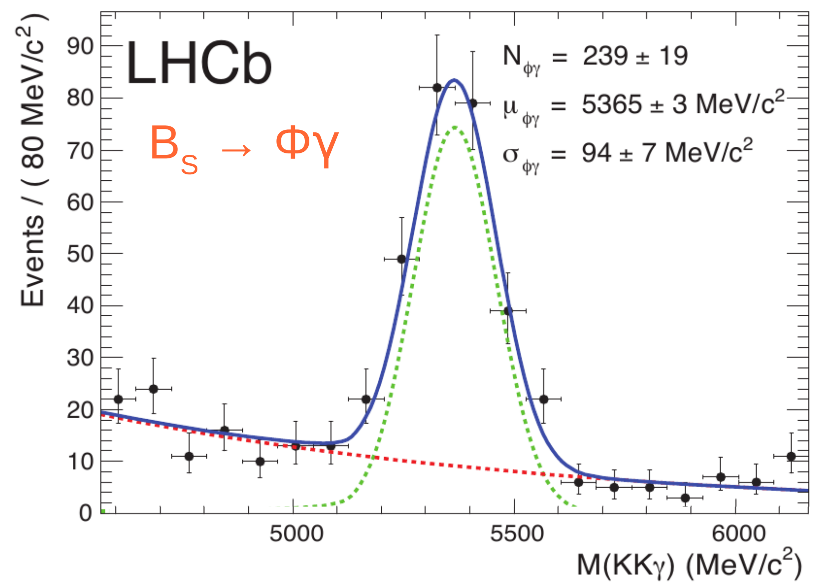
- energy measurement for hadron
- trigger on hadronic decay channels
- Fe plates / scintillator tiles
- $\sigma(E)/E = 69\%/\sqrt{E(GeV)} + 9\%$ (nominal), moderate but enough for triggering

The Calorimeters (Particle Identification) (2/2)



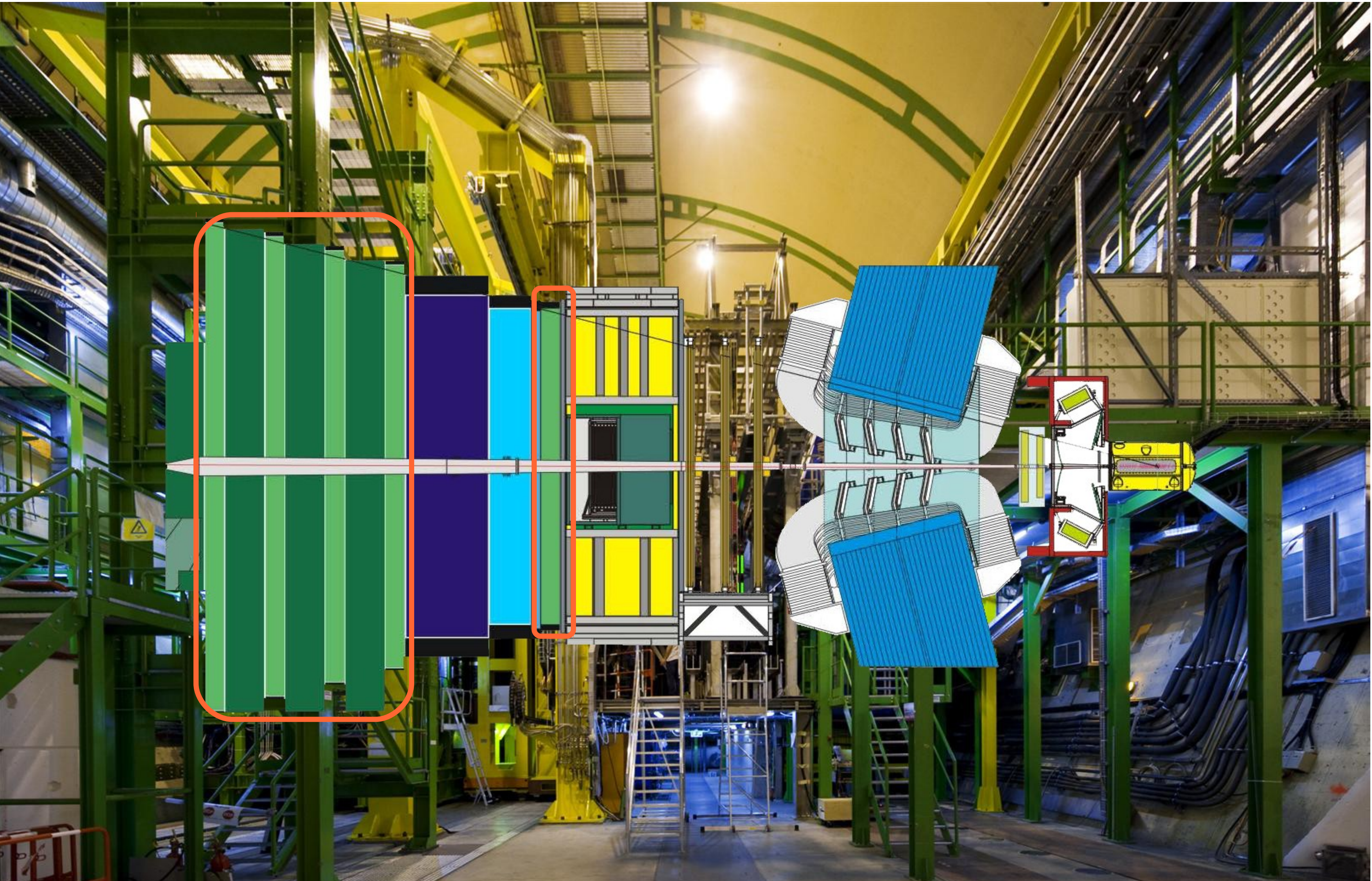






[arXiv:1202.6267]

The Muon system (Particle Identification) (0/1)

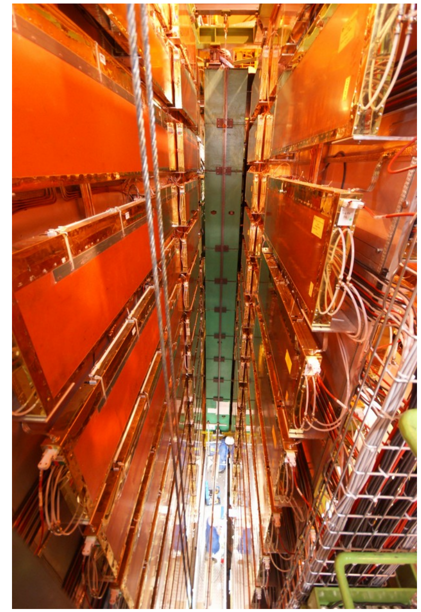


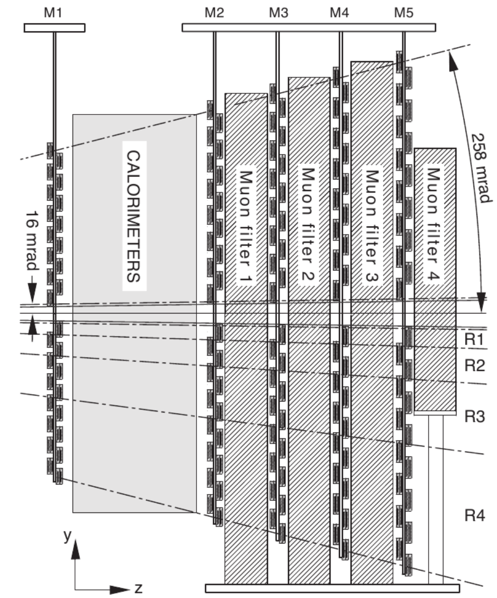
The Muon system (Particle Identification) (1/1)

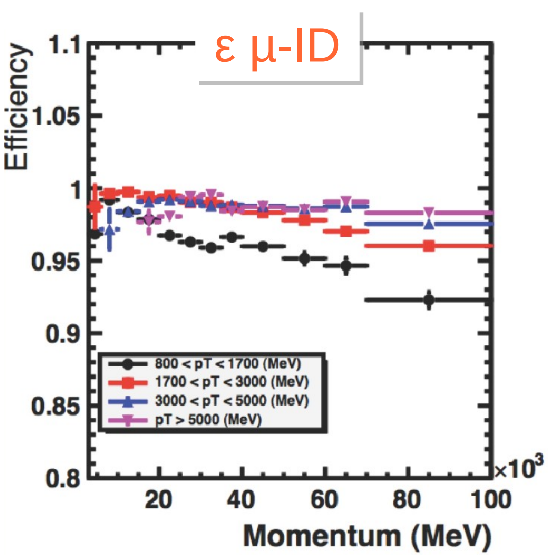
5 stations interleaved with iron absorbers

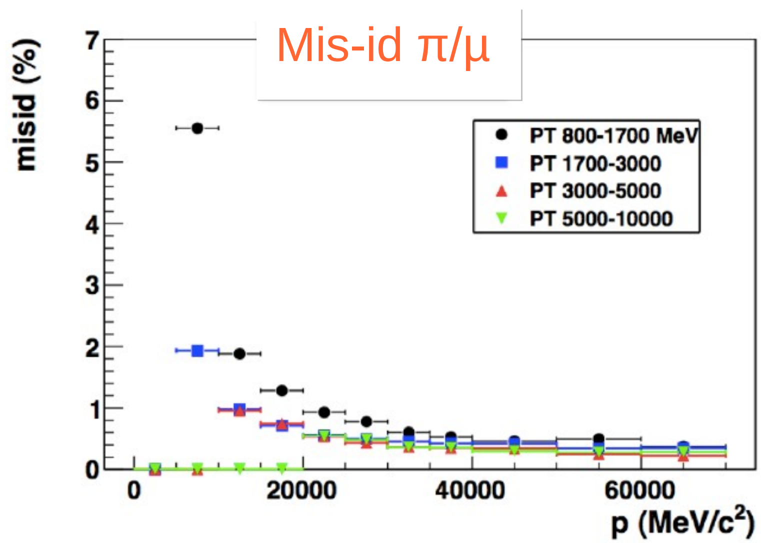
- muon identification
- trigger on muonic decay channels
- Muon ID $\varepsilon(\mu)$ = 97 %

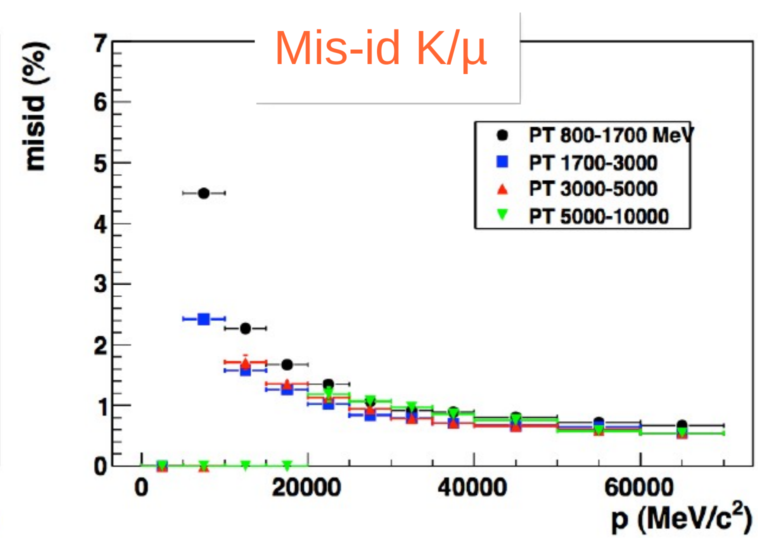
  for 1-3% π-μ MisID



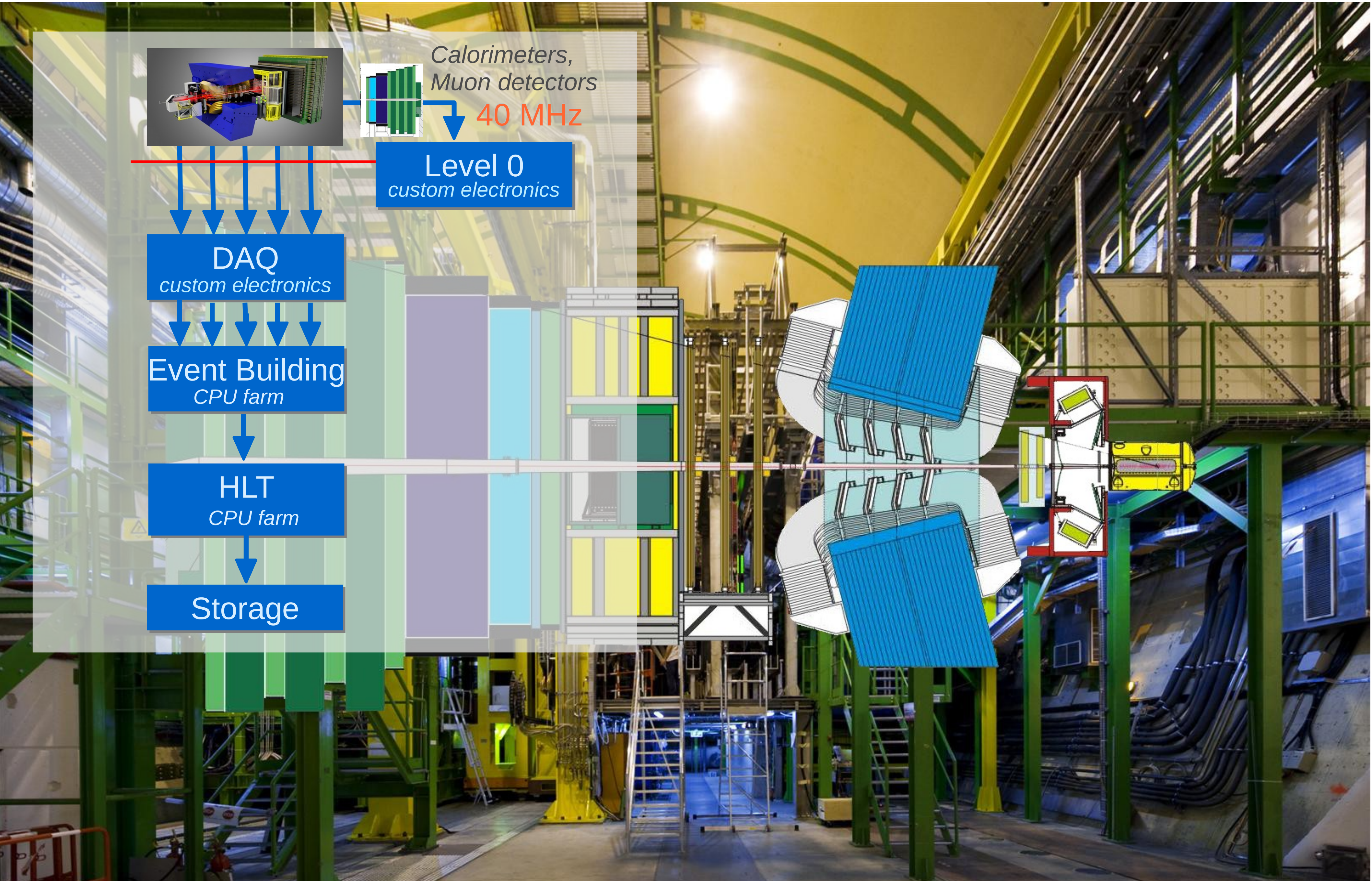




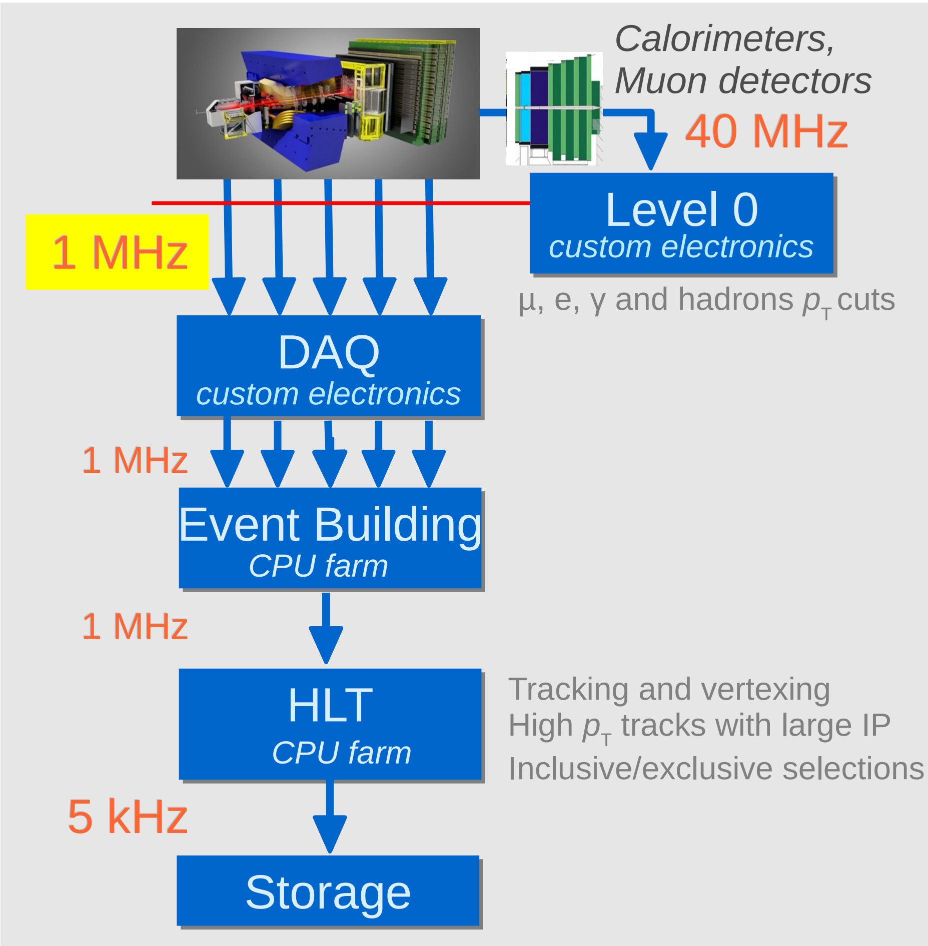




Data acquisition (0/1)



Data acquisition (1/1)



By design :

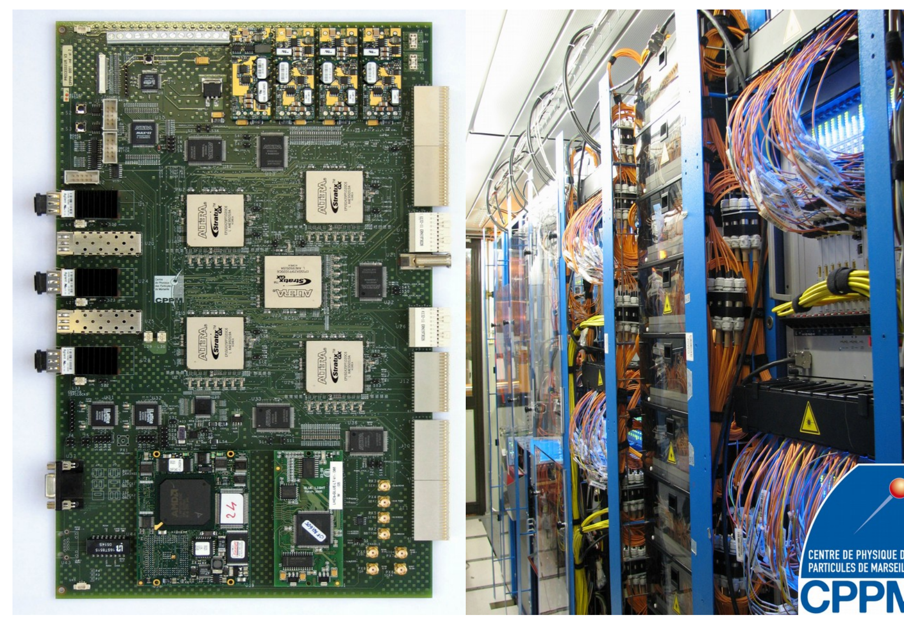
- full detector read-out @ 1MHz
- need to reduce the LHC collision rate from 40 MHz to 1Mhz

L0 : custom electronic @40Mhz, 4 μs latency

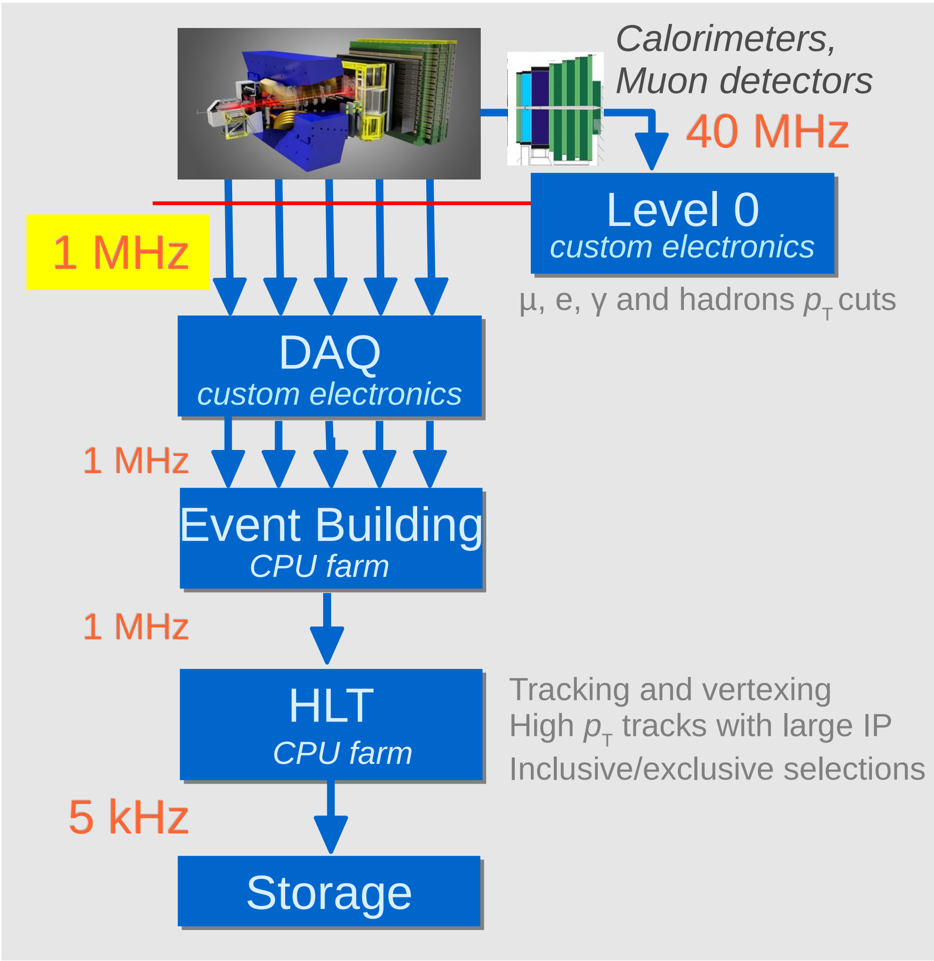
- based on Muon and calorimeters system
- search for high-p_T μ, e, γ, hadron candidates
- $p_T(\mu)>1.4$; $E_T(e/\gamma)>2.7$; $E_T(\text{hadron})>3.6$ [GeV]

L0Muon made in Marseille

- custom electronic boards



Data acquisition (1/1)



L0 : custom hardware trigger

HLT : software trigger

- ~30000 tasks in parallel on over 1500 nodes
- HLT1 : track and vertex reconstruction
  - Impact parameter cuts
- HLT2 : global event reconstruction and PID
  - select exclusive and inclusive modes

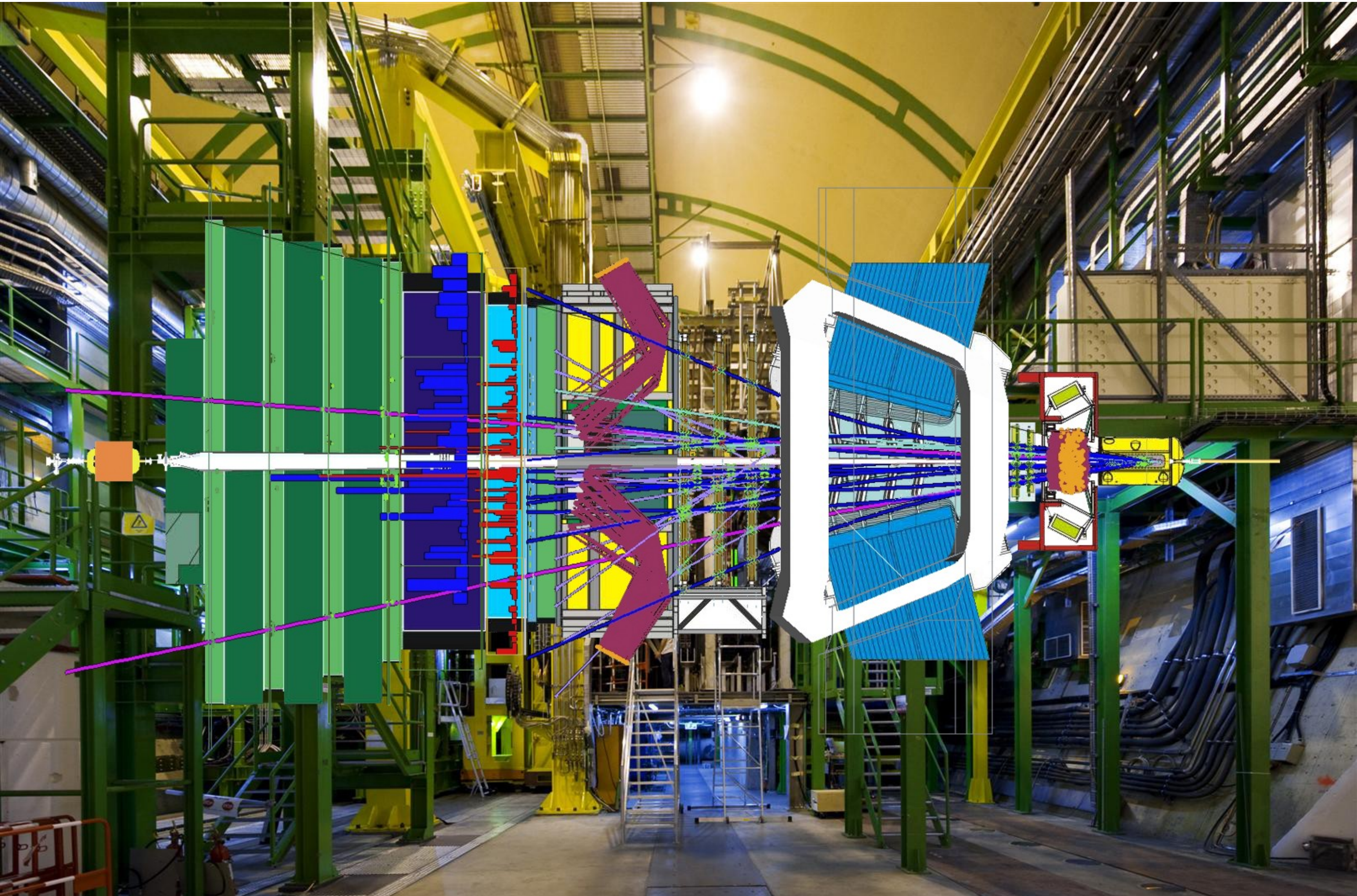
Offline : ~10^{10} events, 700 TB recorded/year

- centralized stripping selections to reduce the sample sizes to 0(10^7) events for physics analysis
- ~800 selections

Performances at 8 TeV in 2012 (L0xHLT)

- B decays with μμ : ε ≈ 90 %
- B decays with hadrons : ε ≈ 30 %
- Charm decays : ε ≈ 10 %

LHCb Operation



Luminosity

LHCb designed luminosity :

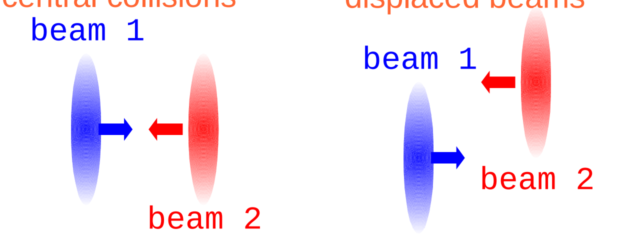
– $\mathcal{L}^{inst}$ = 2x10^{32} cm^{-2}s^{-1} with μ=0.4 (# of visible pp int./crossing)

– Precision physics depending on vertex structure

→ easier in a low-pileup environment

Full luminosity central collisions

Reduced luminosity : displaced beams

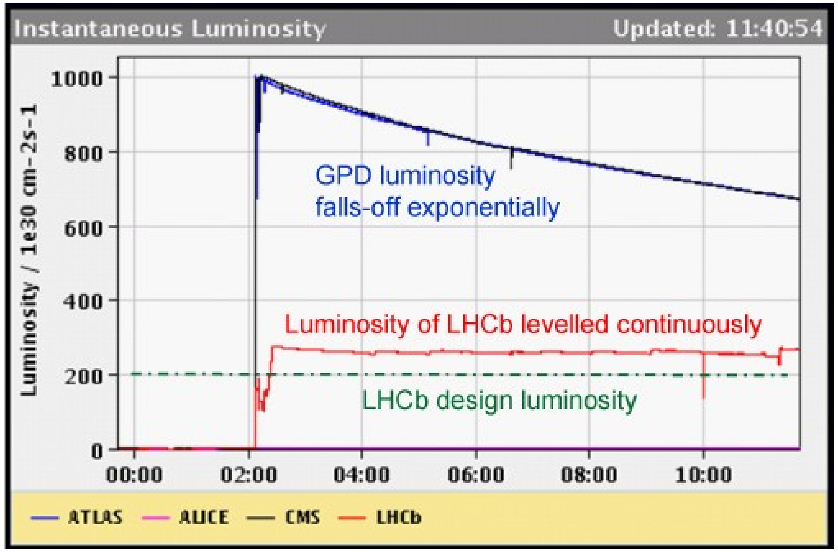


Luminosity levelling at LHCb

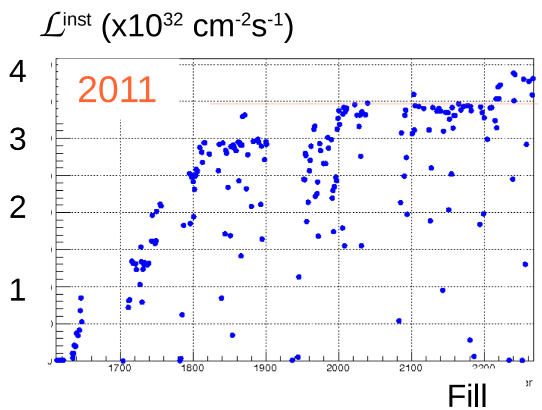
– run with constant luminosity

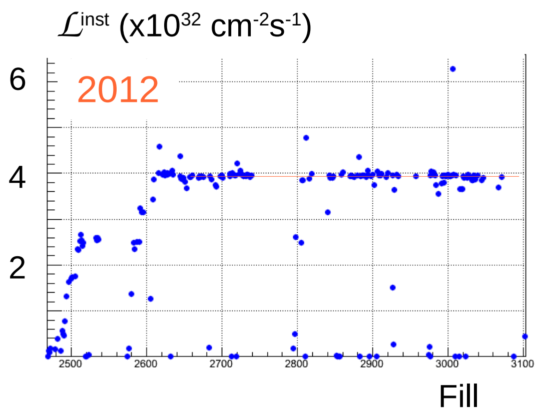
→ beam overlap adjusted regularly

– automatic procedure between LHC&LHCb



2011 & 2012 instantaneous luminosities :

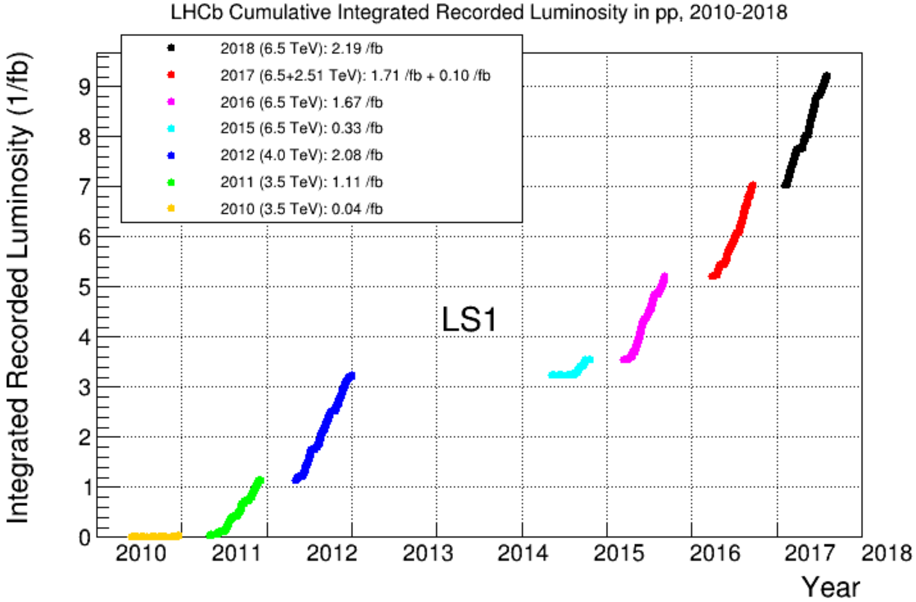




2011 : $\mathcal{L}^{inst}$ = ~ 3.5x10^{32} cm^{-2}s^{-1}, μ = ~1.5

2012 : $\mathcal{L}^{inst}$ = ~ 4.0x10^{32} cm^{-2}s^{-1}, μ = ~1.7

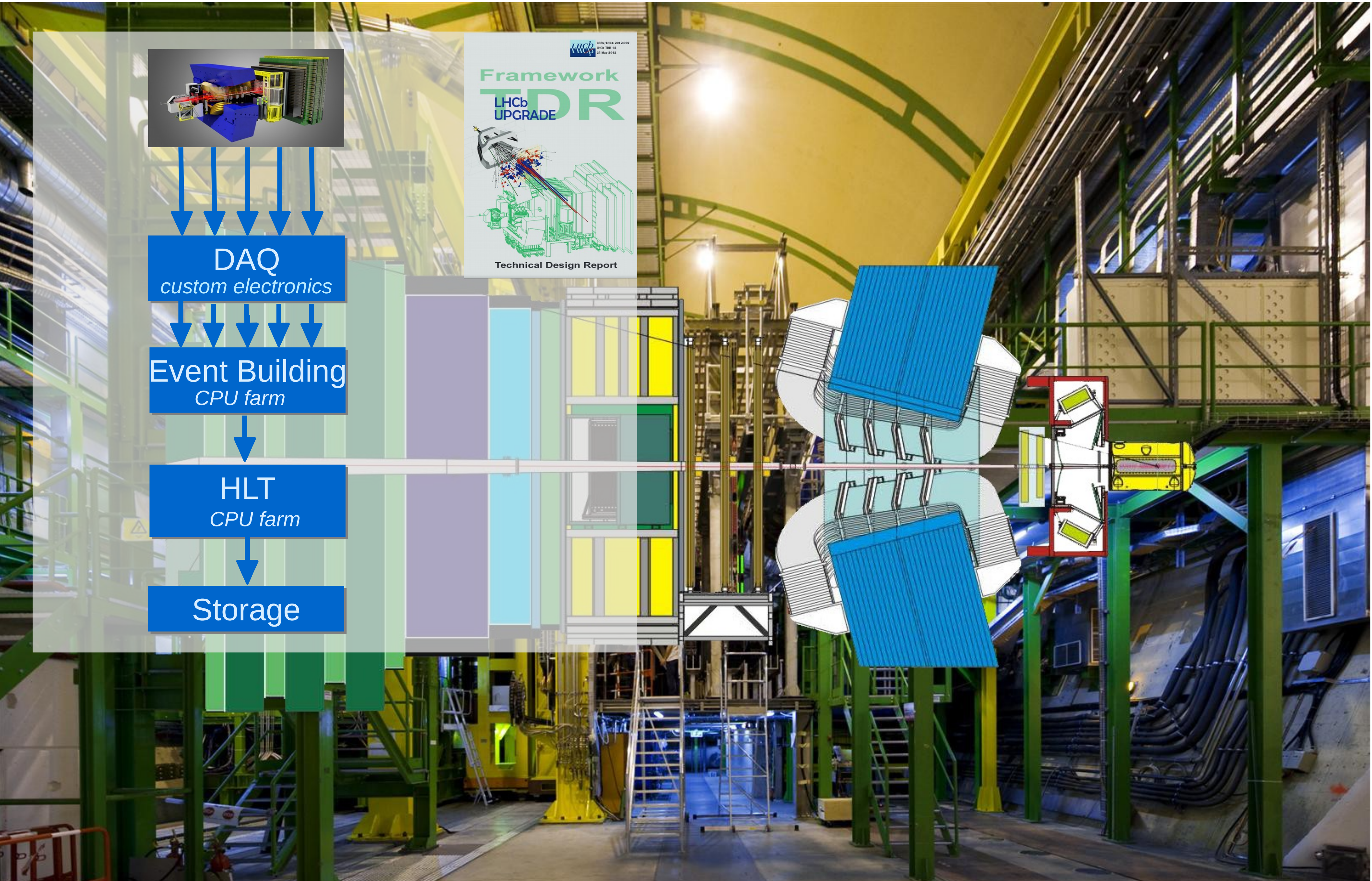
Data Taking



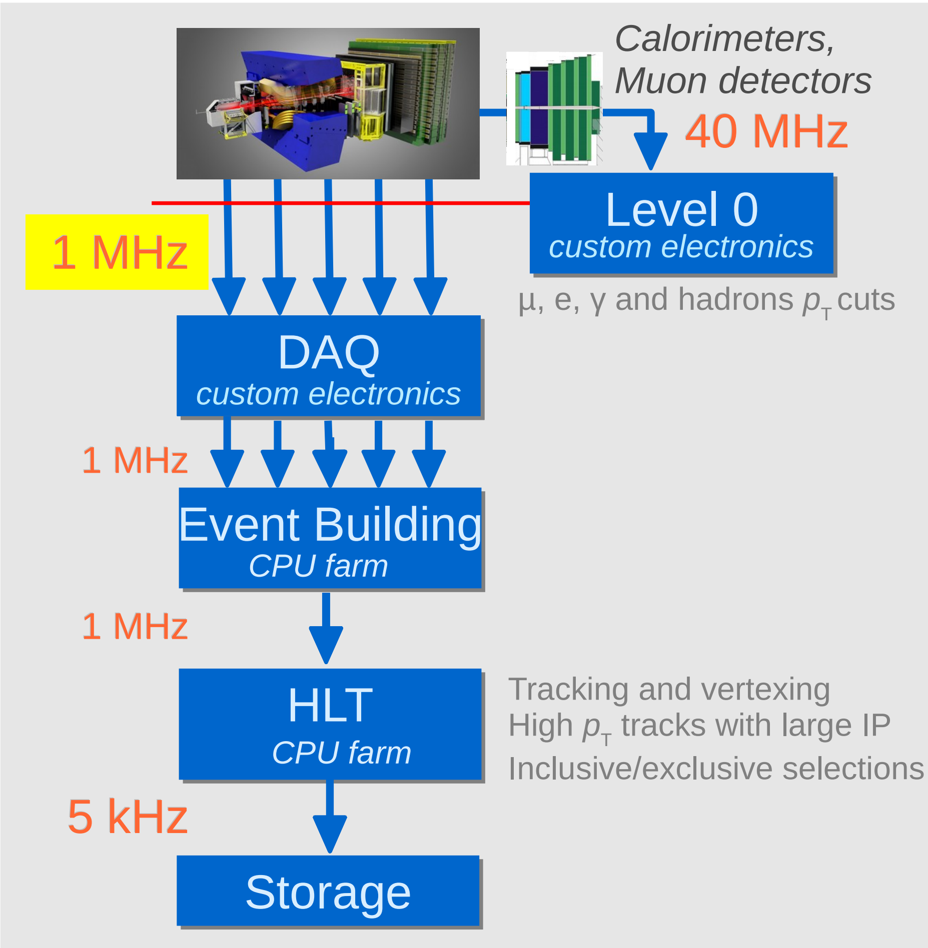
Recorded Luminosity :

- → Run1:
  - 2011: 1 fb^{-1} @ 7 TeV
  - 2012: 2 fb^{-1} @ 8 TeV
- → Run2:
  - 2015-2018: 6 fb^{-1} @ 13 TeV
- → Note : $\sigma(pp \to b\bar{b})_{Run2} \approx 2x\ \ \sigma(pp \to b\bar{b})_{Run1}$

LHCb upgrade (0/3)

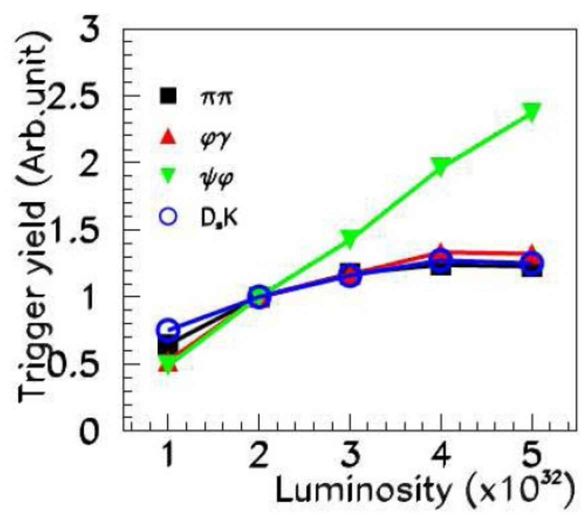


LHCb upgrade (1/3)



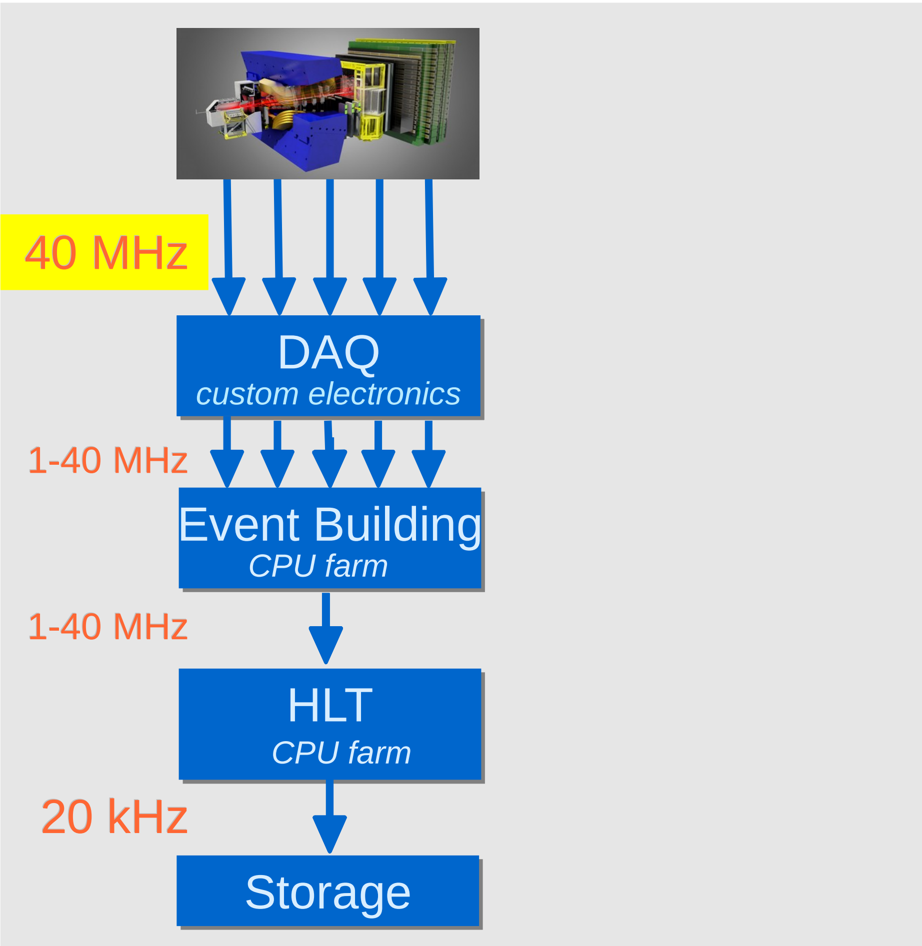
Upgrade goal : increase instantaneous luminosity

With current design : saturation of the yields



- p_T cuts must be raised to cope with the 1 MHz limitation on the read-out rate
- no gain beyond 2-3 1032 cm-2s-1 for hadronic modes

LHCb upgrade (2/3)



- In preparation for Run3 (2020)

To benefit from higher luminosity :

- remove L0 bottleneck
- read full detector at 40 MHz

Full read out at 40 MHz:

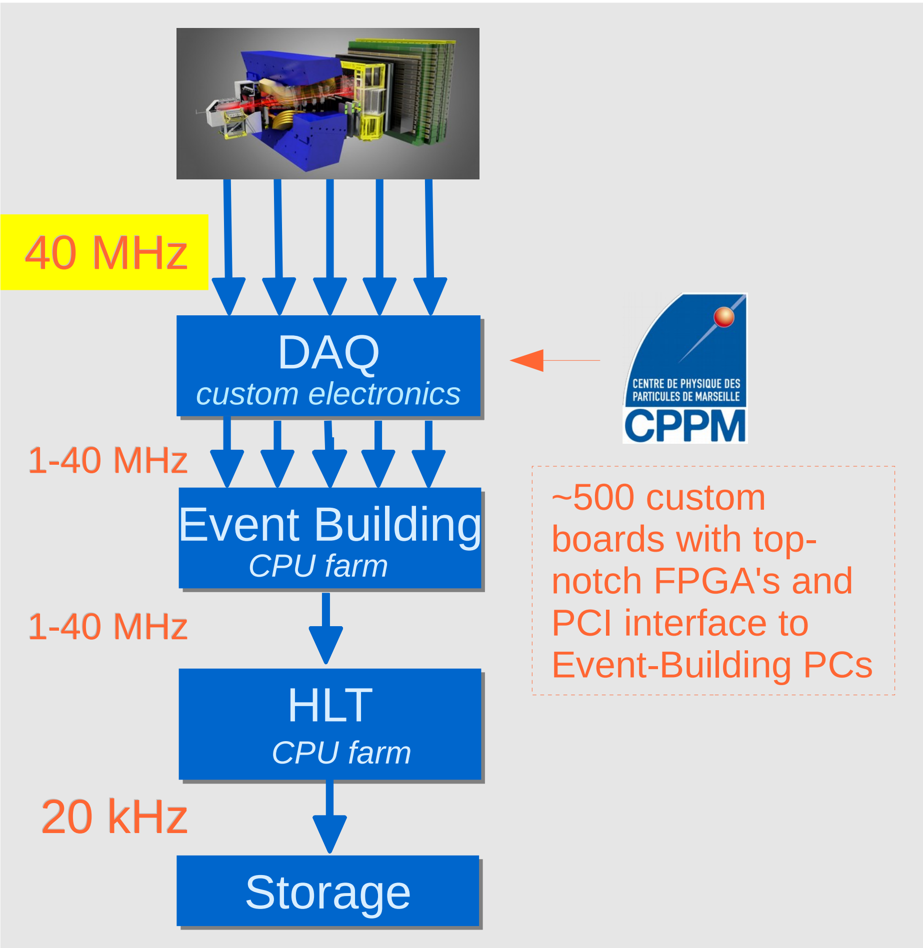
- replacement of all front-end and back-end electronics
- fast high-level software trigger

Replace some detector to cope with higher particle density

- optimize geometry for fast reconstruction
- sustain increased radiation dose

Final output bandwidth : 20 kHz

LHCb upgrade (2/3)



- In preparation for Run3 (2020)

To benefit from higher luminosity :

- remove L0 bottleneck
- read full detector at 40 MHz

Full read out at 40 MHz:

- replacement of all front-end and back-end electronics
- fast high-level software trigger

Replace some detector to cope with higher particle density

- optimize geometry for fast reconstruction
- sustain increased radiation dose

Final output bandwidth : 20 kHz

LHCb upgrade (3/3)

The 40 MHz detector :

VELO

radiation dose and occupancy
→ replace sensors

Si tracker

embedded FE
→ replace sensors

Calorimeters

occupancy
→ remove SPD & PS
→ reduce HV & PM gain

RICHs

embedded FE
→ replace HPDs
occupancy (RICH1)
→ redesign mirrors

Outer tracker

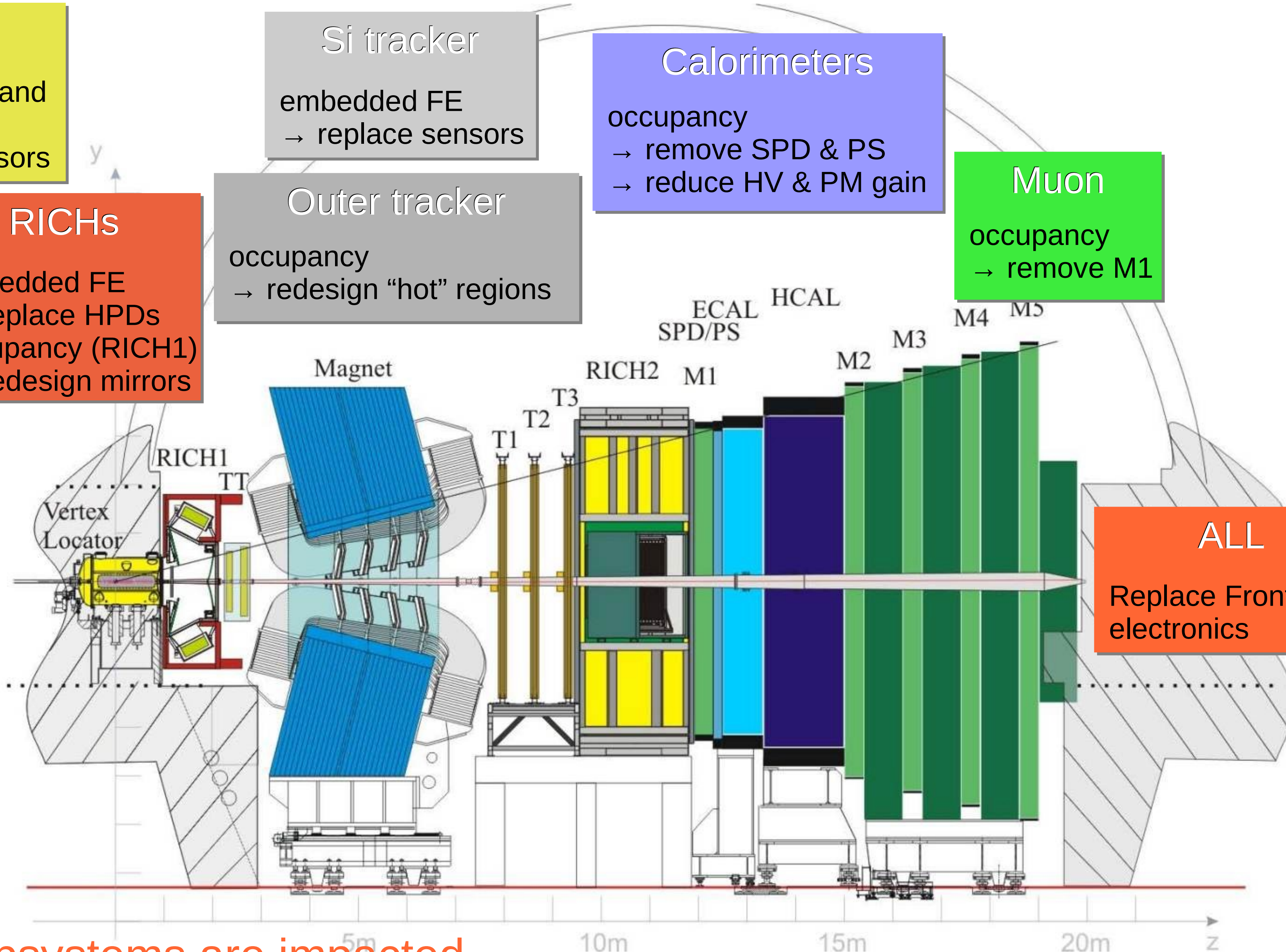
occupancy
→ redesign “hot” regions

Muon

occupancy
→ remove M1

ALL

Replace Front-end electronics



all subsystems are impacted

LHCb future upgrade ...

Highlight on some LHCb results

- biased selection with a focus on CPPM's activities
  - → The flavour anomalies :
    - $b \to s\ell\ell$ transitions
    - $b \to s\ell\nu$ transitions

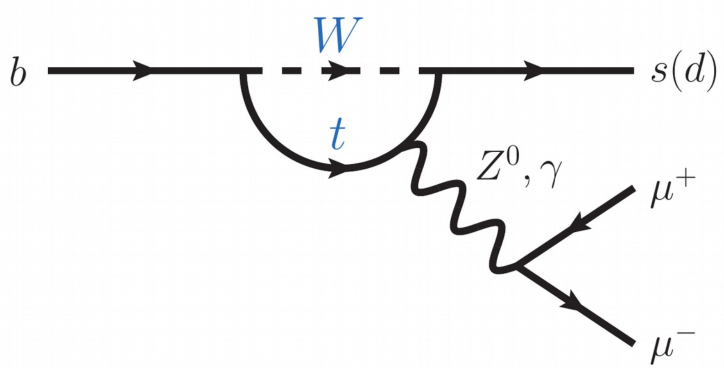
Selected LHCb results

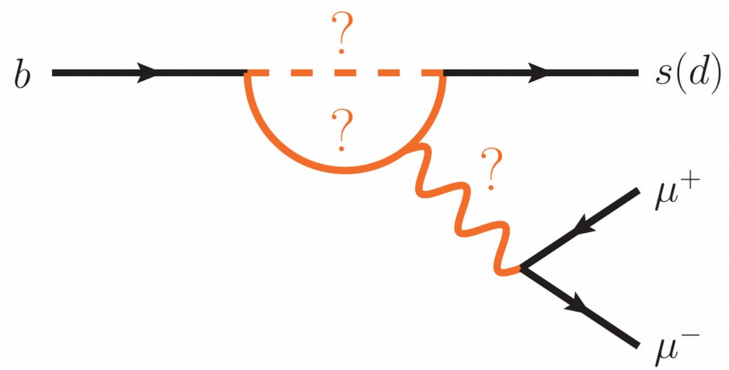
- $b \to s\ell\ell$ transitions
- $b \to c\ell\nu$ transitions

$b \rightarrow s\ell\ell$ transitions

$b \rightarrow s\ell\ell$ transitions are FCNC (flavour changing neutral current)

- forbidden in the SM at the tree level
- only exist at loop level → highly suppressed → rare decay !





Physics beyond the Standard Model (BSM) enter at the same level as the SM

BSM can modify a range of observables

- branching fractions
- angular distributions
- CP/isospin asymmetries

Different type of decays give access to different observables

- sensitive to different BSM contributions

Correlation between the observables allow to identify the type of new physics involved

- important to measure all possible observables

A harvest of results

Branching fractions & isospin asymmetries

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

Branching fractions & angular analysis

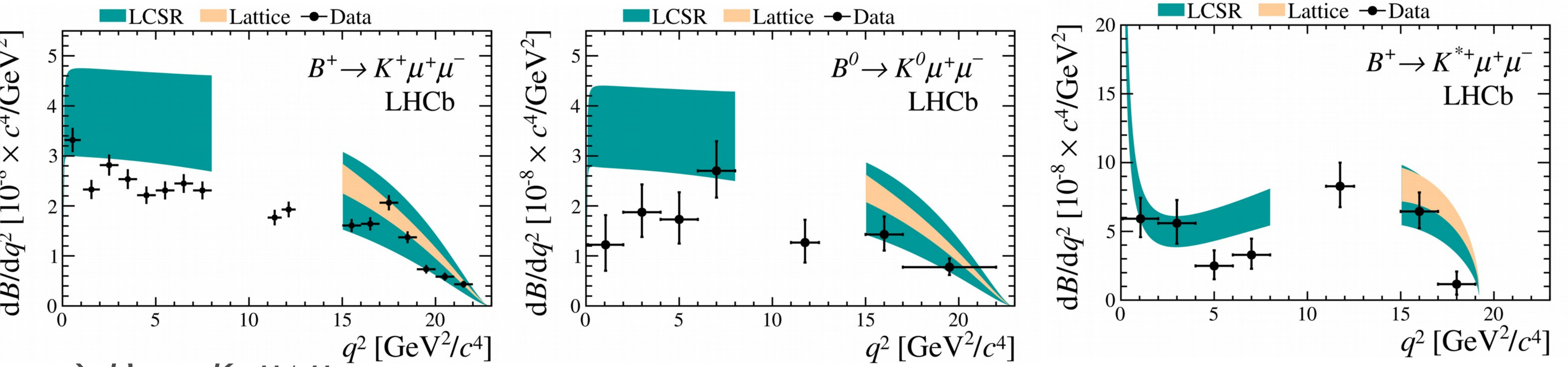
- $B \to K \mu^+\mu^-$
- $B_s \to \Phi \mu^+\mu^-$
- $\Lambda_b \to \Lambda \mu^+\mu^-$
- $B \to K e^+e^-$

Lepton flavour universality tests:

- R(K*)
- R(K)

A harvest of results

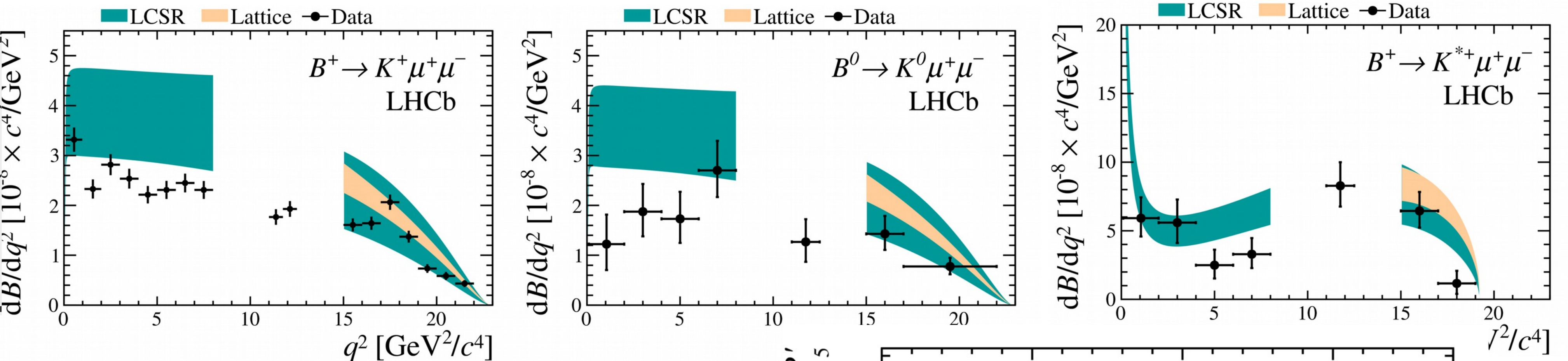
[JHEP 06 (2014) 133]



- $B \to K\ \mu^+\mu^-$
- $B_s \to \Phi\ \mu^+\mu^-$
- $\Lambda_b \to \Lambda\ \mu^+\mu^-$
- $B \to K\ e^+e^-$

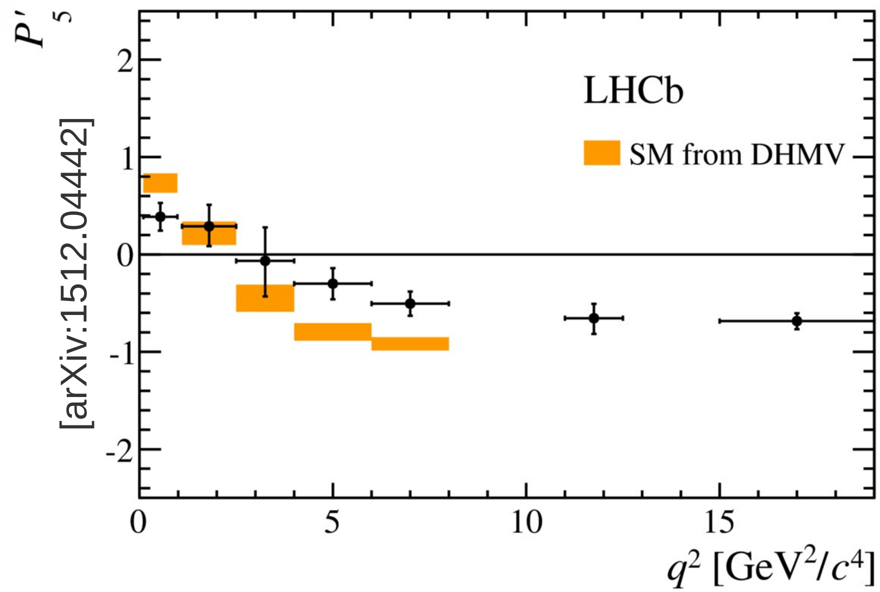
A harvest of results

[JHEP 06 (2014) 133]



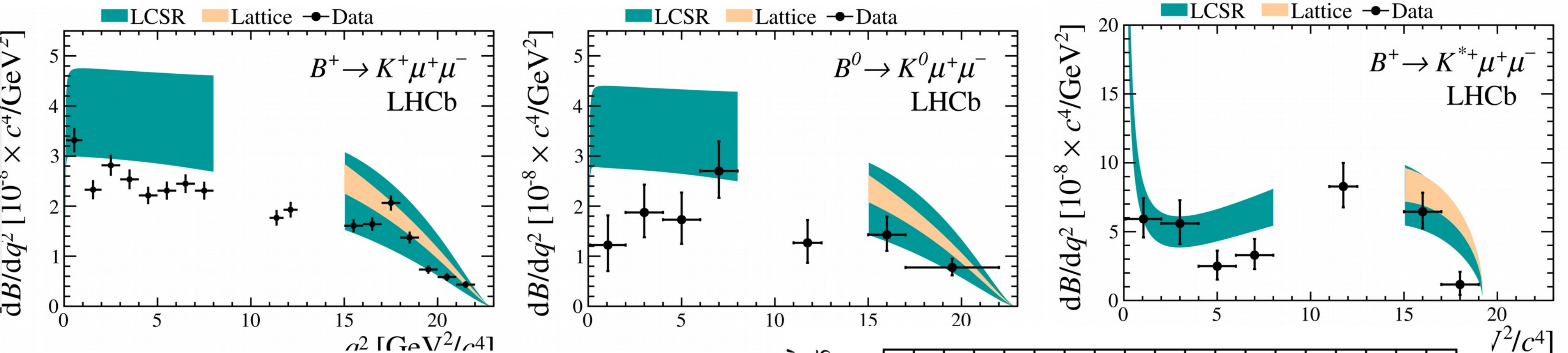
- $B \to K\ \mu^+\mu^-$
- $B_s \to \Phi\ \mu^+\mu^-$
- $\Lambda_b \to \Lambda\ \mu^+\mu^-$
- $B \to K\ e^+e^-$

[arXiv:1512.04442]

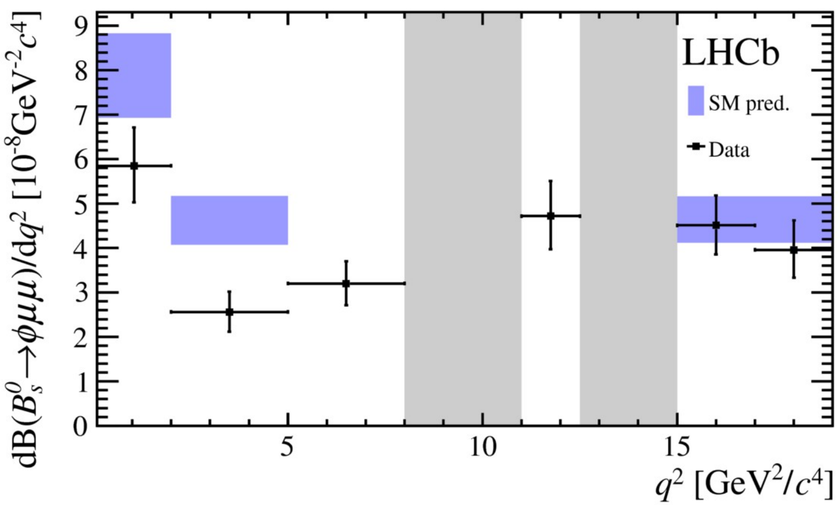


A harvest of results

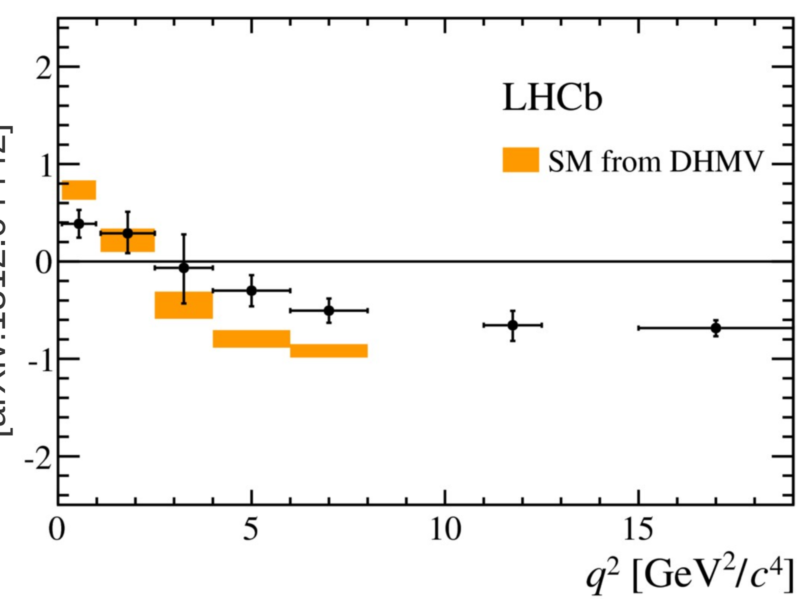
[JHEP 06 (2014) 133]



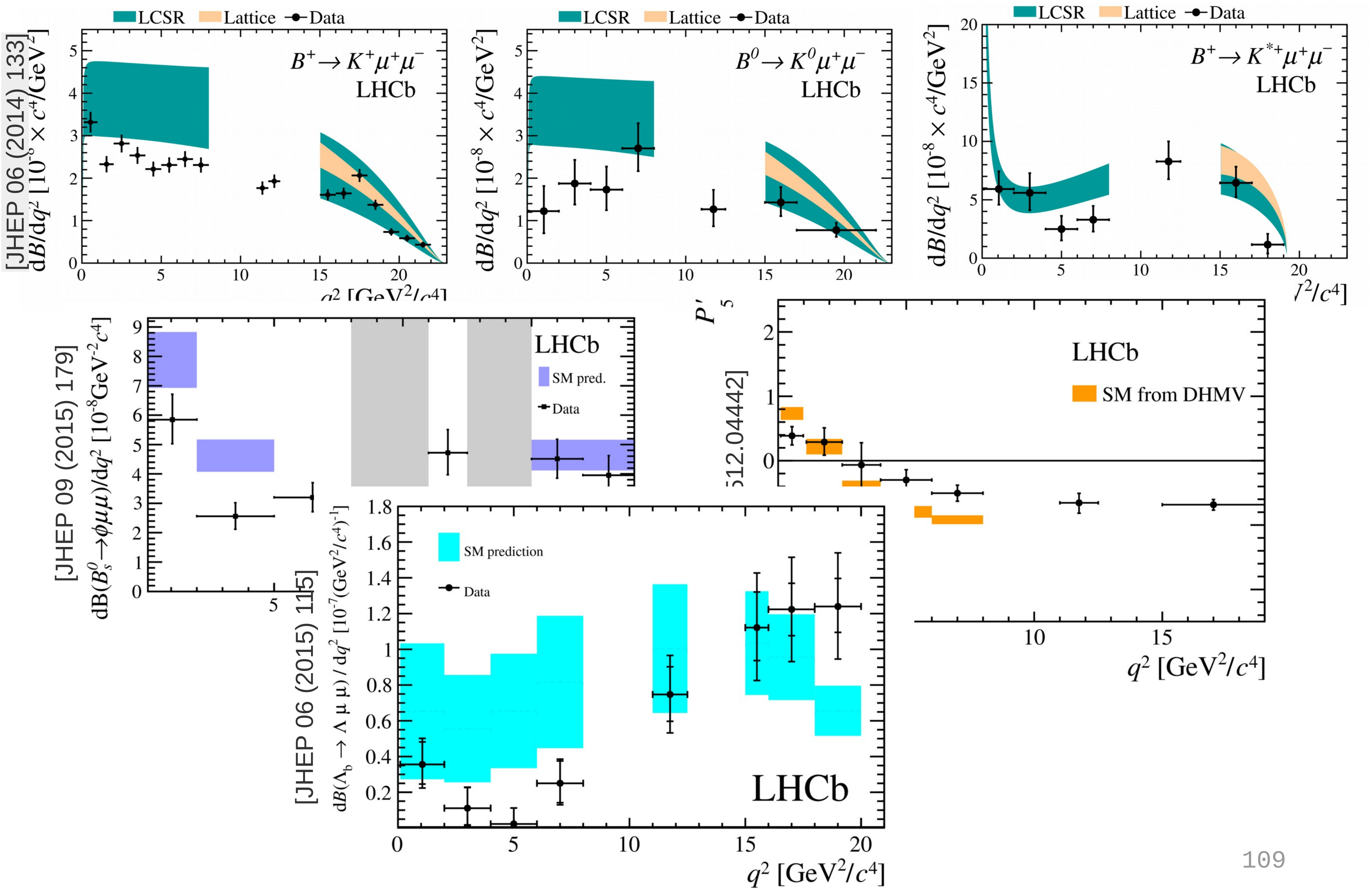
[JHEP 09 (2015) 179]



[arXiv:1512.04442]

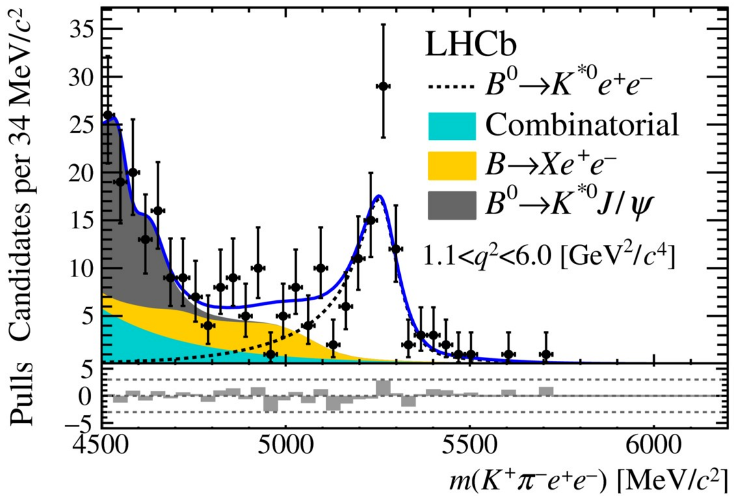


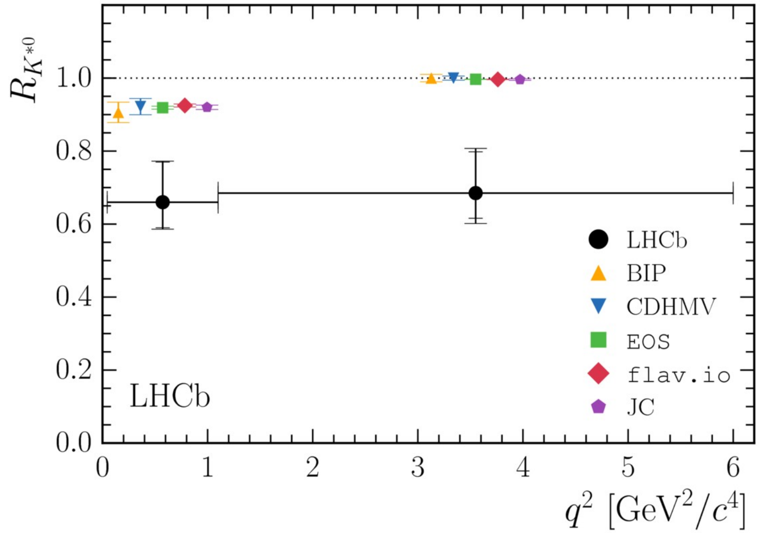
A harvest of results

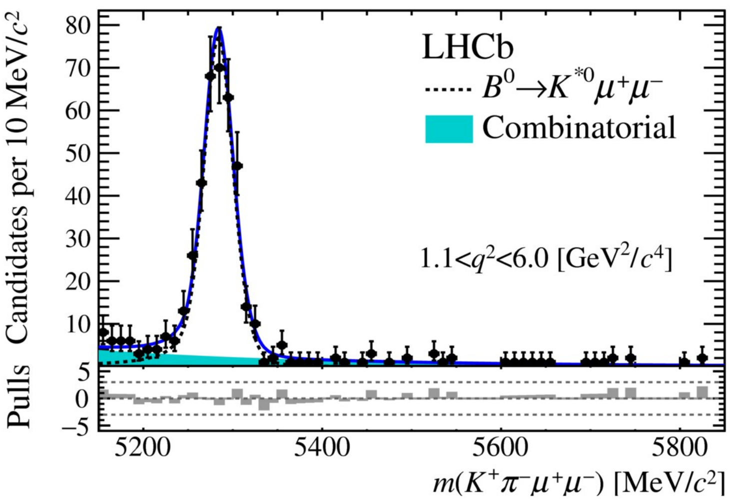


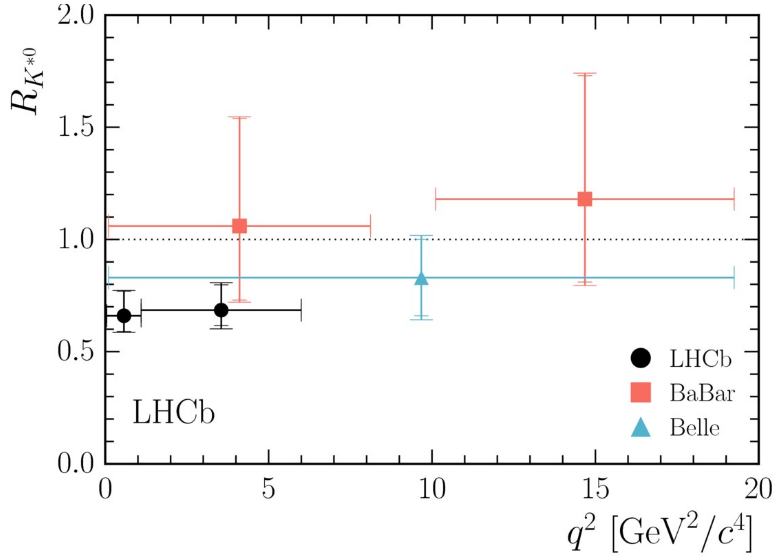
A harvest of results

LFU test : R(K*) = Γ($B^0 \to K^{*0} \mu^+\mu^-$) / Γ($B^0 \to K^{*0} e^+e^-$)



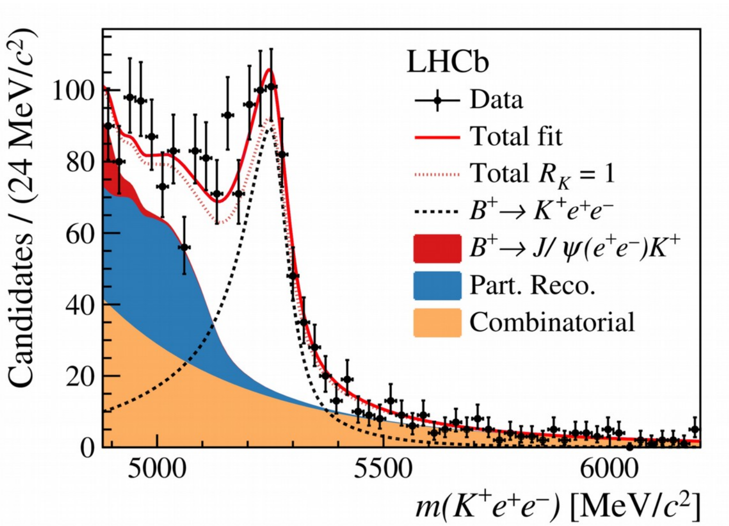


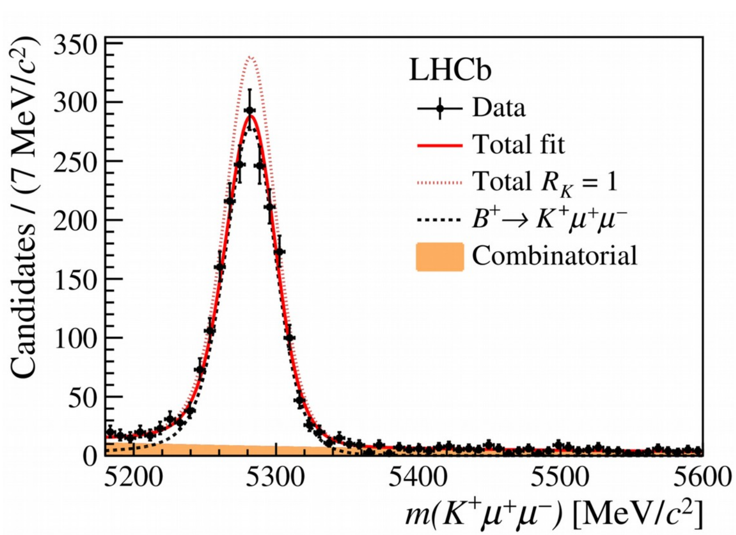




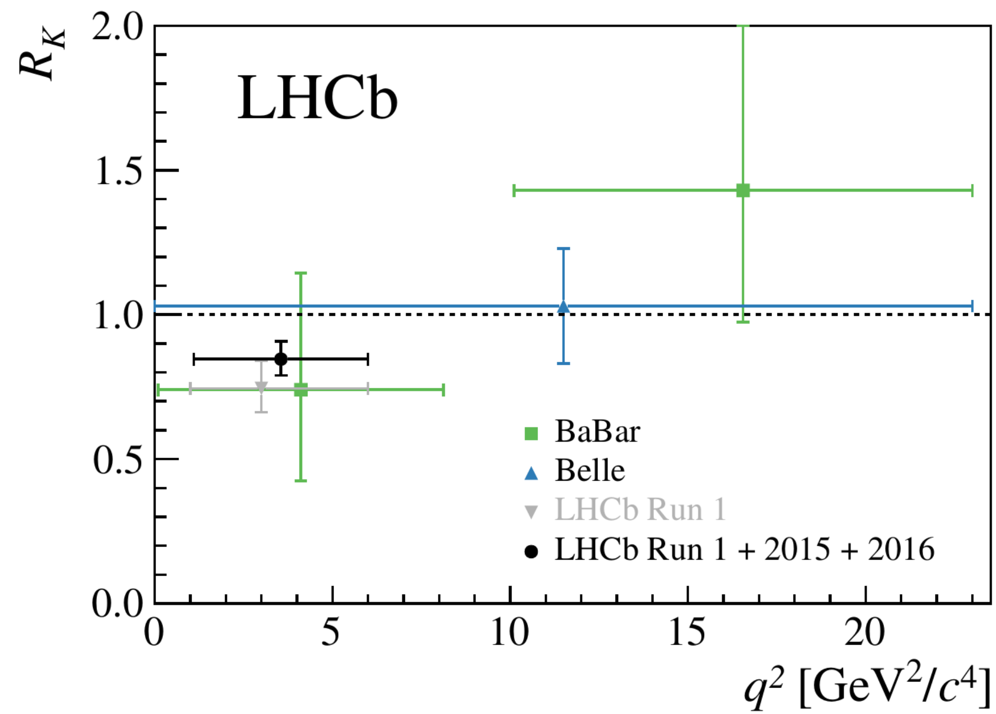
A harvest of results

LFU test : R(K) = $\Gamma(B^+ \to K^+ \mu^+\mu^-) / \Gamma(B^+ \to K^+ e^+e^-)$





PRL 122 (2019) 191801



compatible with SM at 2.5 σ

Model independent analysis of $b \to s$ transitions

$M_{Z,W,t} \gg m_b \to$ low energy effective theory :

$$\mathcal{H}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i (C_i \mathcal{O}_i + C_i' \mathcal{O}_i')$$

left-handed part ($C_i \mathcal{O}_i$)

right-handed part ($C_i' \mathcal{O}_i'$) suppressed in SM

i = 1,2..... tree
i = 3-6,8 . gluon penguin
i = 7 .... photon penguin
i = 9,10 .. electroweak penguin
i = S .... Scalar penguin
i = P .... Pseudo scalar penguin

- Local operators O_i depends on hadronic form factor
  - → (dominant) source of theoretical uncertainties
- Wilson coefficients C_i describe the short distance effect
  - → can be modify by new physics : $C = C^{SM} + C^{NP}$
    (including operators not present or suppressed in the SM)

Results interpretation

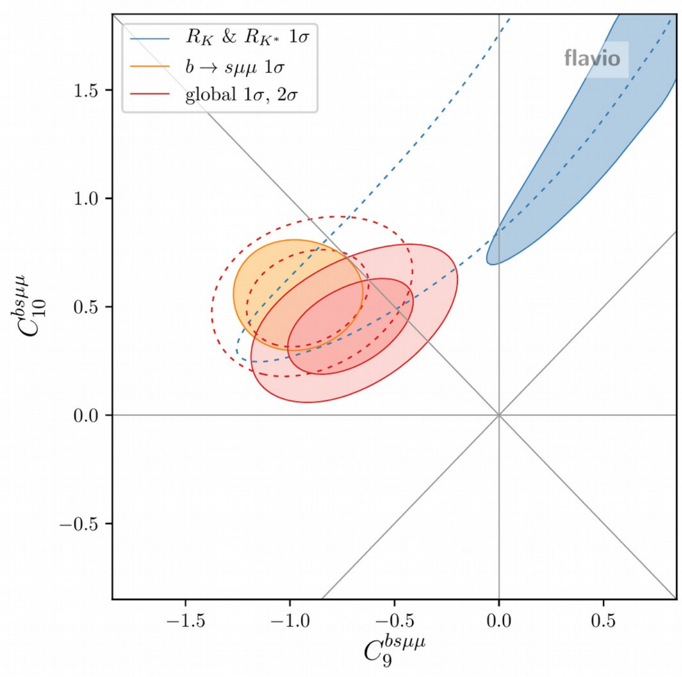
Global fit (with all $b \to s\ell\ell$ observables)

Favours new physics contribution to the coefficient C_9

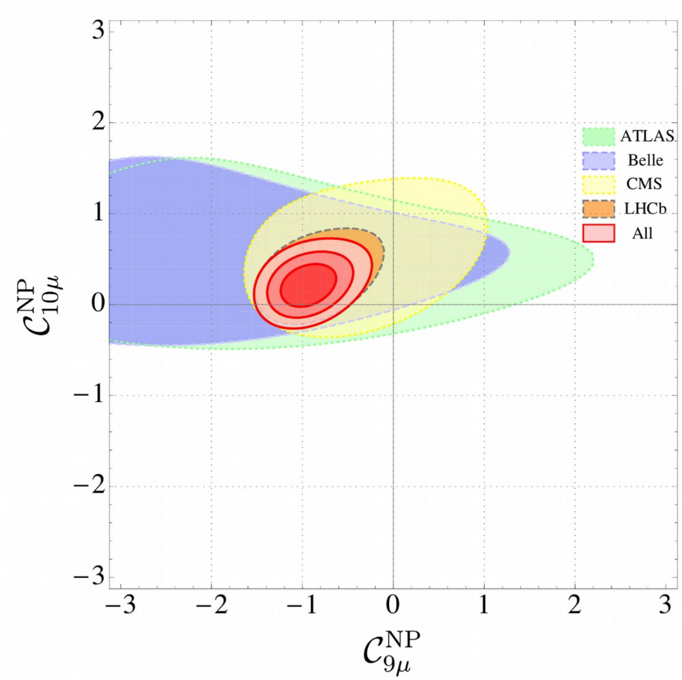
- ➔ significance ~ 5 σ !

Hints of violation of the lepton universality

- ➔ significance > 3 σ



J. Aebischer *et al.*, arxiv-1903.09578



M. Alguero *et al.*, arxiv-1903.09578

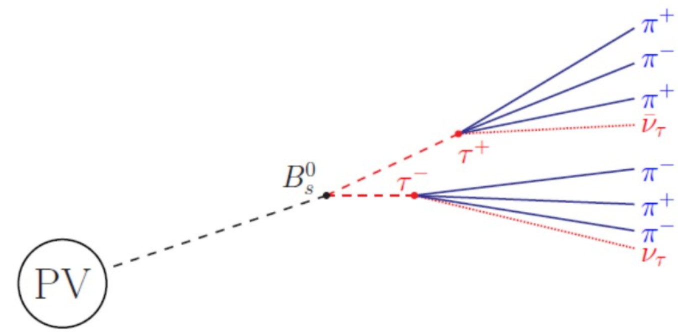
CPPM $b \to s\ell\ell$ activities

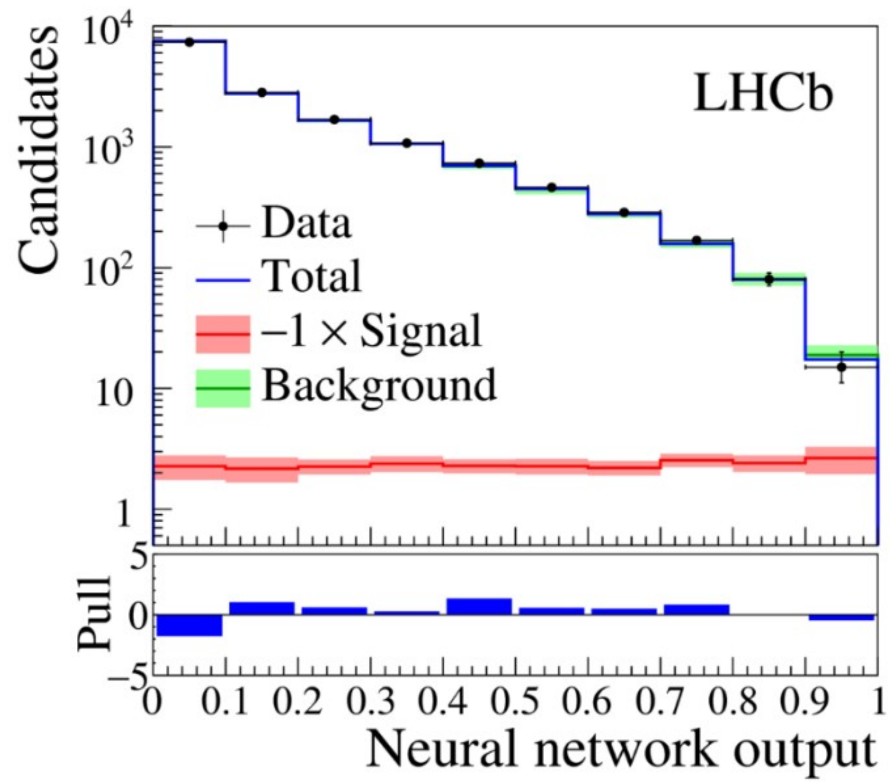
CPPM worked on the B → μμ analysis

Now, focus on decays with τ in the final state

$B_{(s)} \to \tau^+\tau^-$ (published in 2017)

- Analysis
  - → the τ decay in flight and are not reconstructed
  - → use the $\tau \to \pi\pi\pi\nu$ mode
  - neutrino escapes detection
    - missing energy
    - no invariant mass reconstruction
- Results :
  - → upper limits on branching ratio :
  - $BR(B_s \to \tau\tau) < 6.8\ 10^{-3}$ (first limit)
  - $BR(B^0 \to \tau\tau) < 2.1\ 10^{-3}$ (best limit)





[PRL118(2017)251802]

Submitted to publication :

- → $B_{(s)} \to \tau\mu$ (lepton flavour violation !)

Prospects

- → $B_s \to K^*\tau\tau$
- → ...

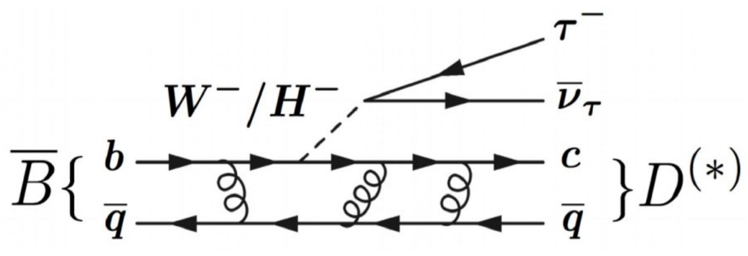
Selected LHCb results

- $b \to s\ell\ell$ transitions
- $b \to c\ell\nu$ transitions

Anomalies in $b \to c\tau\nu$ transition

$$R(D) \equiv \frac{\mathcal{B}(B^0 \to D^- \tau^+ \nu_\tau)}{\mathcal{B}(B^0 \to D^- \ell^+ \nu_\ell)}, \quad \ell \in \{\mu, e\}$$

$$R(D^*) \equiv \frac{\mathcal{B}(B^0 \to D^{*-} \tau^+ \nu_\tau)}{\mathcal{B}(B^0 \to D^{*-} \ell^+ \nu_\ell)}, \quad \ell \in \{\mu, e\}$$



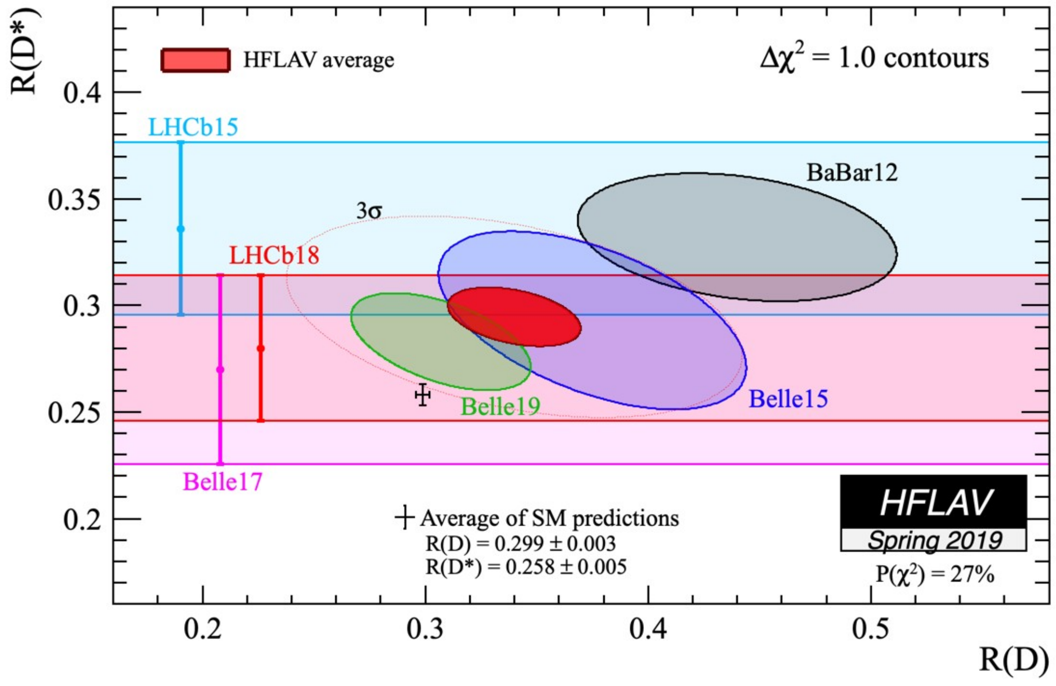
All measurements above the SM

Combining Belle, BaBar and LHCb

- measurements are ~4σ away from SM

At CPPM :

- participate in analysis of R(D^*) with Run2 data
- if central value is unchanged, enough sensitivity to discovered BSM !

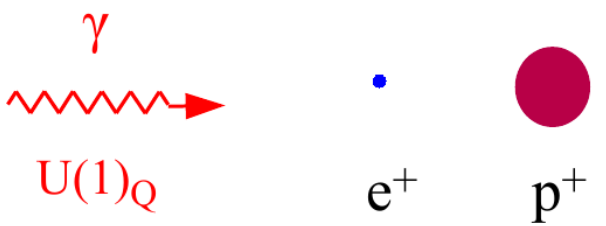


Final focus

- Lepton Flavour (non-) Universality
  - → LFU: equal electroweak coupling to all charged leptons

Introduction [*a digression on LFU*]

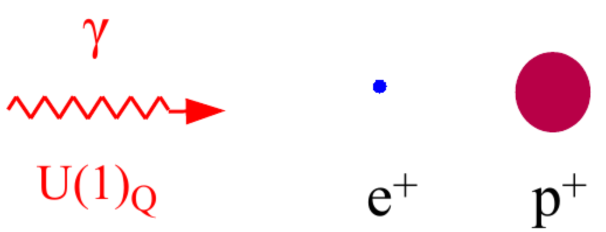
Let's go back ~ 100 years, and suppose we can test matter only with long wave-length photons...



These two particles seems to be "identical copies" but for their mass ...

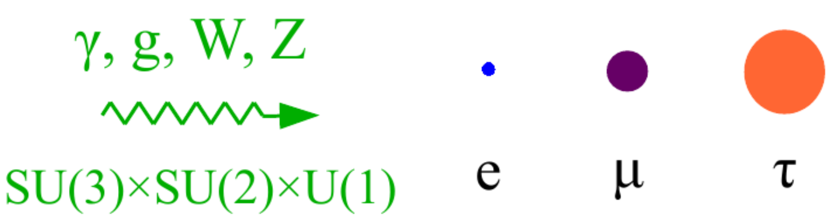
Introduction [*a digression on LFU*]

Let's go back ~ 100 years, and suppose we can test matter only with long wave-length photons...



These two particles seems to be "identical copies" but for their mass ...

That's exactly the same (misleading) argument we use to infer LFU...



These three (families) of particles seems to be "identical copies" but for their mass ...

The SM quantum numbers of the three families could be an "accidental" low-energy property: the different families may well have a very different behavior at high energies, as signaled by their different mass

Conclusion and prospect

Still many open questions in and beyond the Standard Model

Without any sign of new physics in the direct search, the precision era is open !

The heavy flavour sector is still a promising sector for BSM discoveries

More data and measurements are needed to resolve the tensions that are building up in heavy hadrons decays

→ Lepton flavour non-universality ???

Come and join us !