Kraków Applied Physics and Computer Science Summer School'21

2nd of July 2021

Physics at LHCb

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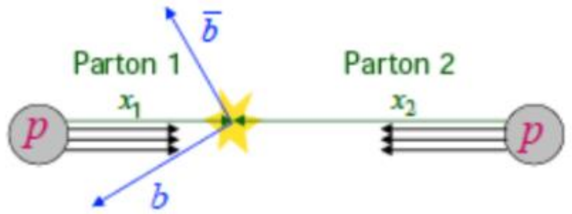
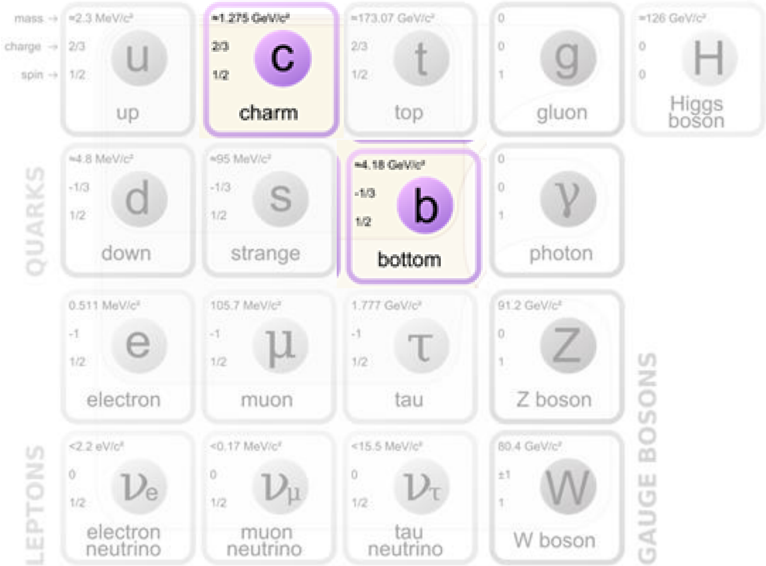
AGH UST Kraków

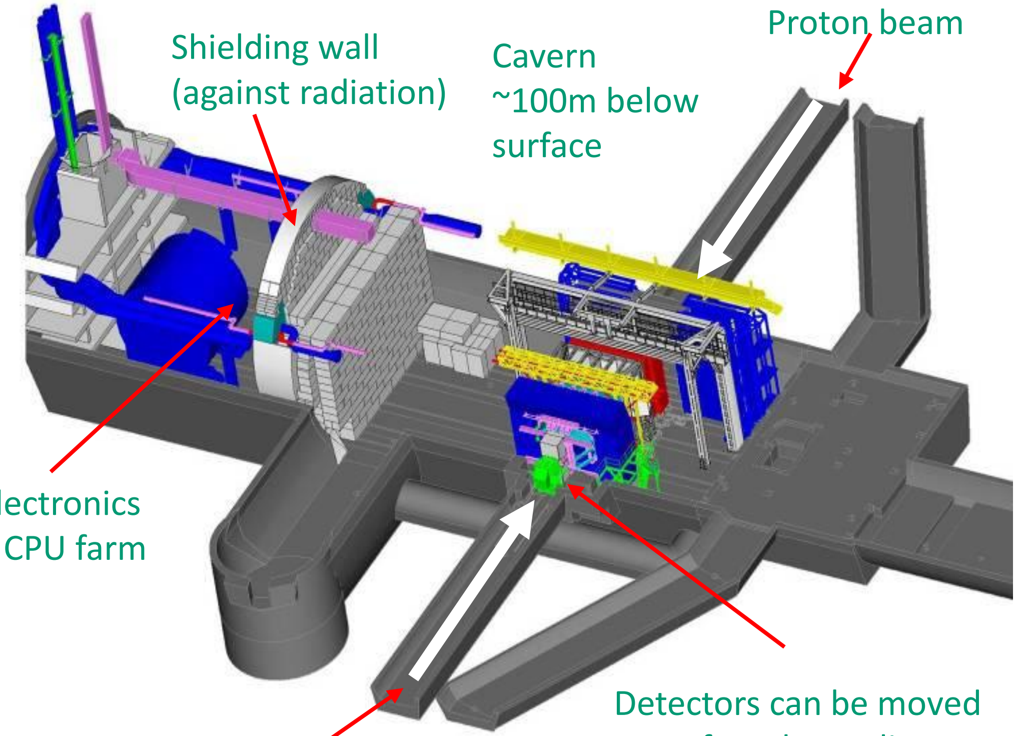
LHCb experiment for heavy flavour physics

LHCb experiment is dedicated for studying flavour physics at LHC.
Especially CP violation and rare decays of beauty and charm mesons.

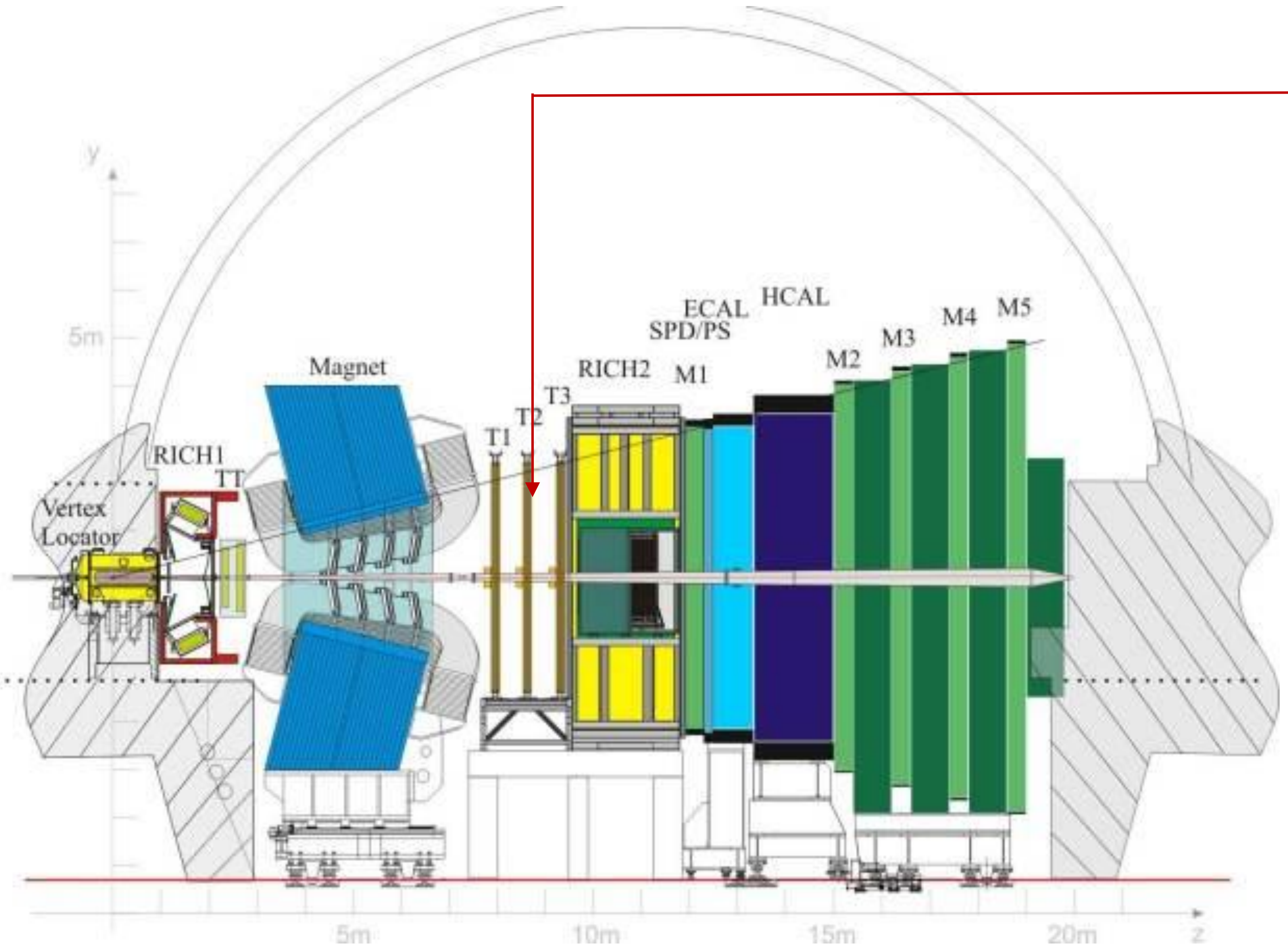


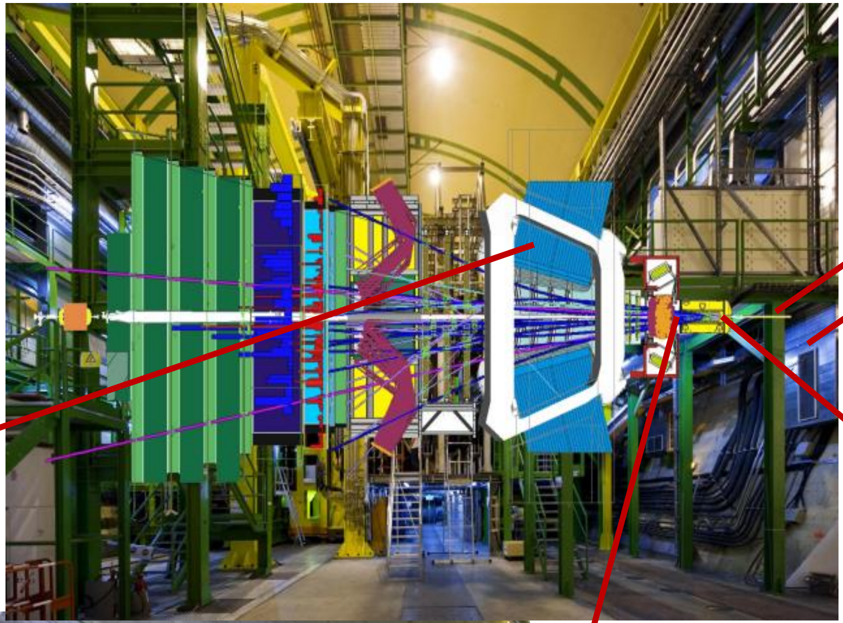
Standard Model





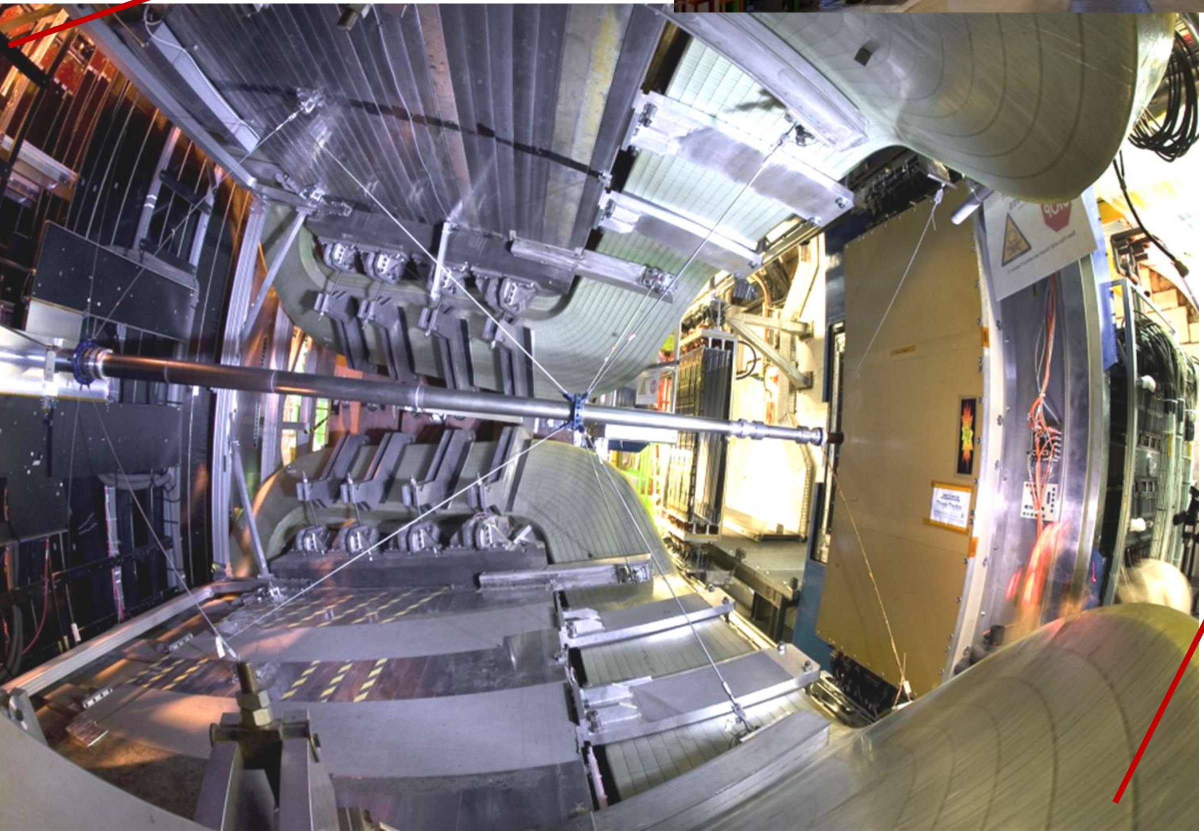
LHCb spectrometer



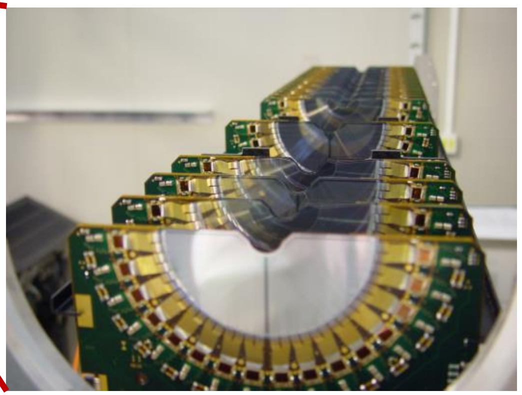


Beam pipe

Inside the magnet



Vertex Locator

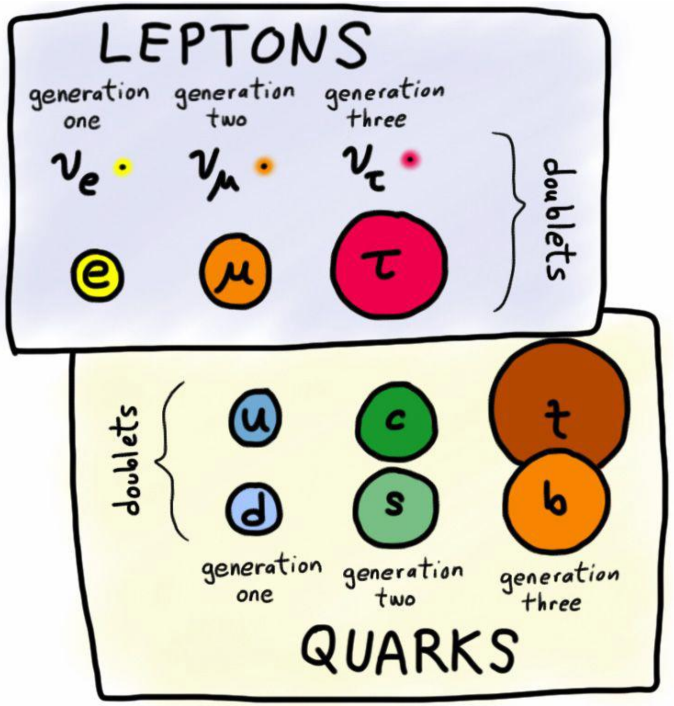


What is Flavour Physics?

CERNCOURIER

In 1971, at a Baskin-Robbins ice-cream store in Pasadena, California, Murray Gell-Mann and his student Harald Fritzsch came up with the term "flavour" to describe the different types of quarks. From the three types known at the time – up, down and strange – the list of quark flavours grew to six. A similar picture evolved for the leptons: the electron and the muon were joined by the unexpected discovery of the tau lepton at SLAC in 1975 and completed with the three corresponding neutrinos. These 12 elementary fermions are grouped into three generations of increasing mass. Camalich & Zupan 2019

Just as ice cream has both color and flavour, so do quarks!

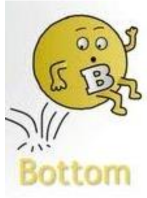


Flavour physics refers to the study of the interactions that distinguish between the fermion generations.

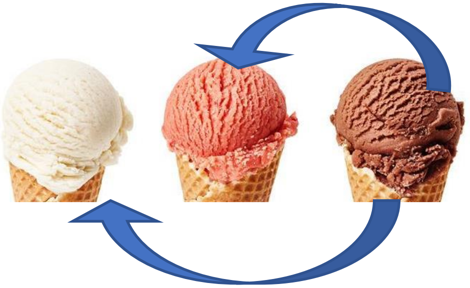
Heavy flavour physics

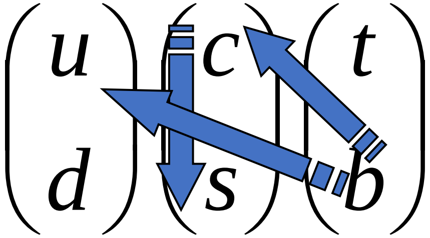
Heavy flavour physics deals with change of quarks' flavour.

Especially heavy quarks: 

and 

because they are heavy!

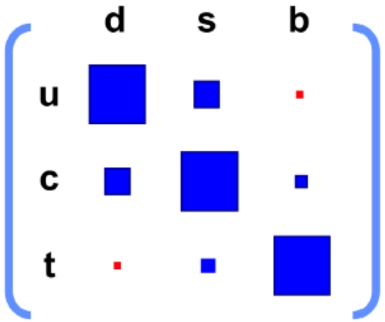


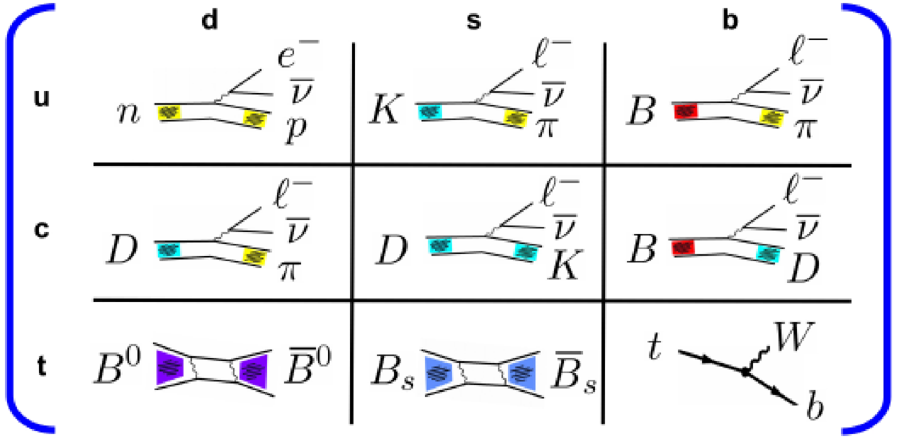


WEAK interactions!

Transitions between quarks are described by a (famous) CKM matrix:

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



V =


V_{CKM} elements:

- are described within the Standard Model,
- are obtained experimentally !

Matter-antimater difference

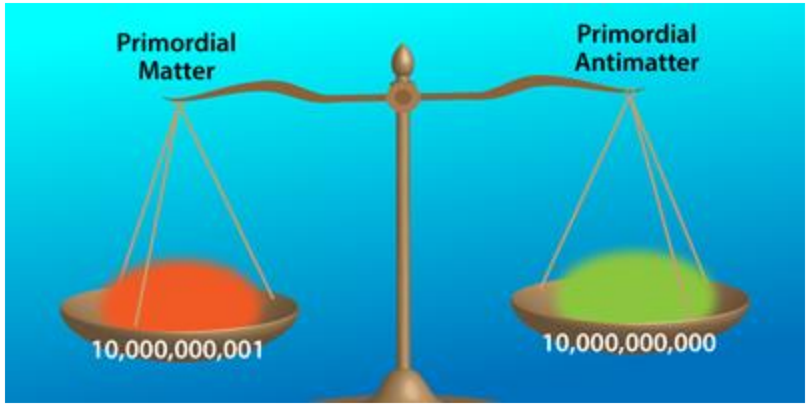
1. A long, long time ago, in the early Universe, there were an equal number of baryons and antibaryons…..

   High energy photons constantly produce protons and antiprotons which later annihilate:

$$\gamma + \gamma \rightleftharpoons p + \overline{p}$$

2. Then comes the time when temperature decreases and photons have not enough energy for particle creation.
3. As the Universe expanded the density of baryons and antibaryons decreased and annihilation was less and less probable.
4. The number of baryons and antibaryons was equal and related to number of photons:

$$n_B = n_{\overline{B}} \sim 10^{-18}\, n_\gamma$$



5. Meanwhile in the experiment…

… we observe that the Universe is dominated by baryons:

$$n_B - n_{\overline{B}} \sim 10^{-9}\, n_\gamma$$

It means that in order to generate this asymmetry we need to have $10^9 + 1$ baryons annihilating with 10^9 antibaryons (one baryon survives)

CPV might help?

Matter-antimater difference

Sakharov conditions for matter-antimatter asymmetry of the universe (1967):

1. **There must be a process that violates baryon number conservation.**

   Proton – the lightest baryon should decay. So far this is unobserved, the lifetimes of proton is greater than 10^{35} years.

2. **Both C and CP symmetries should be violated.**

   $$\boldsymbol{p \neq \overline{p}}$$

   This the subject of the following story.

3. **These two conditions must occur in a phase when there was no thermal equilibrium.**

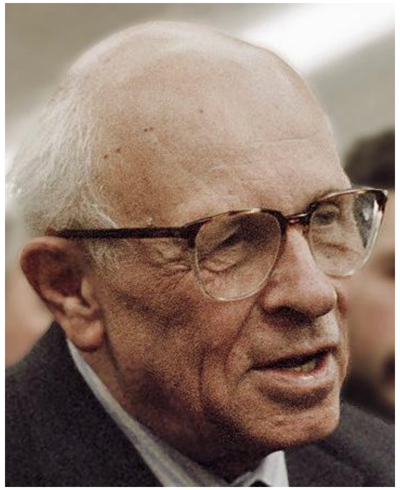
Otherwise $N_{baryons} = N_{\overline{baryons}}$

Из эффекта С. Окубо
при большой температуре
для Вселенной сшита шуба
по ее кривой фигуре

НАРУШЕНИЕ *CP*-ИНВАРИАНТНОСТИ, *C*-АСИММЕТРИЯ
И БАРИОННАЯ АСИММЕТРИЯ ВСЕЛЕННОЙ

А.Д.Сахаров

Теория расширяющейся Вселенной, предполагающая сверхплотное начальное состояние вещества, по-видимому, исключает возможность макроскопического разделения вещества и антивещества; поэтому следует



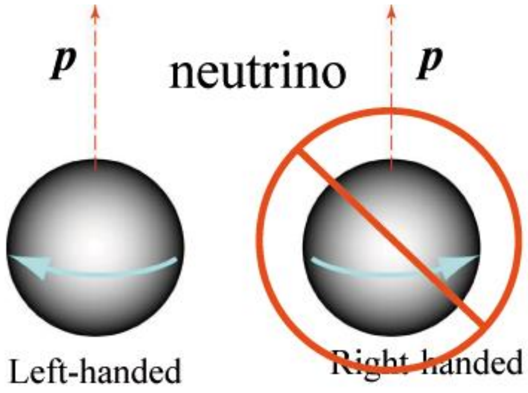
Andrei Sakharov:
- „father" of Soviet hydrogen bomb
- Dissident
- Nobel Peace Prize Winner

Parity Operator P

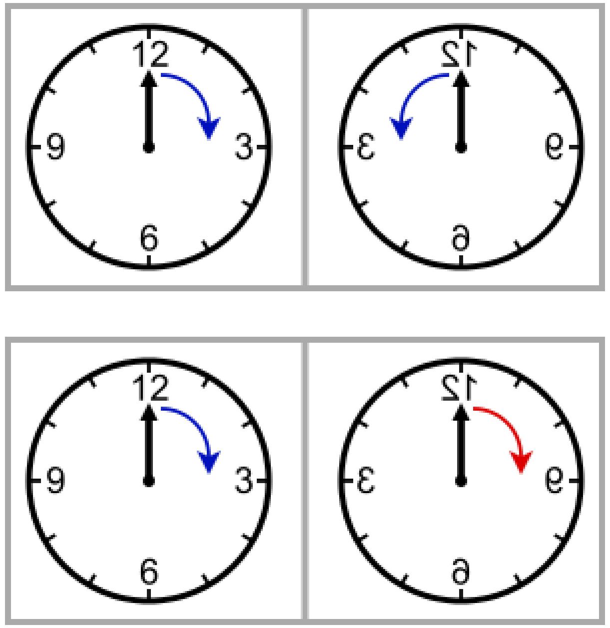
- The parity operator is a unitary operator that reverses the sign of spatial coordinates:

$$\hat{P}\,\Psi(\vec{r}) = \Psi(-\vec{r})$$

- In daily life we see no difference between „our world" and world in the mirror.
- In the world of particles – the difference is HUUGE!



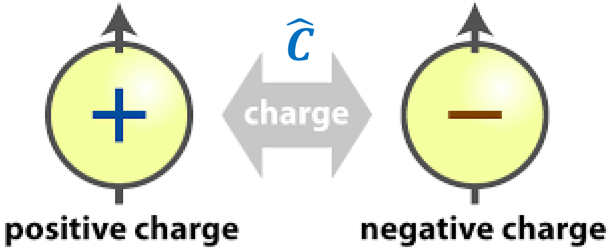
Which clock violates P symmetry?



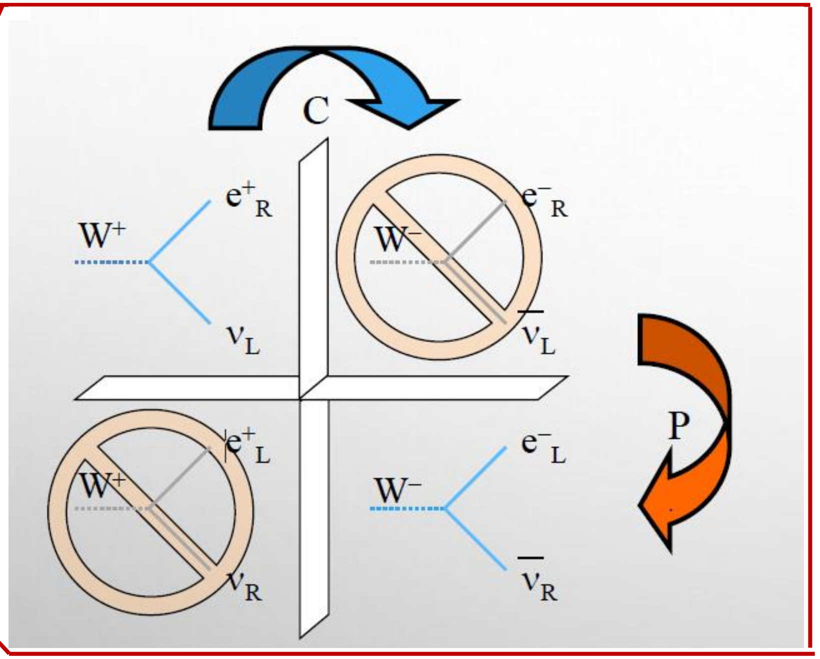
Charge C and combined CP Symmetry

- Charge conjugation $\hat{C}$ is a unitary operator that changes particle to antiparticle:

$$\hat{C}|\pi^0\rangle = +|\pi^0\rangle$$
$$\hat{C}|\gamma\rangle = -|\gamma\rangle$$
$$\hat{C}|e^-\rangle = |e^+\rangle$$



- Before weak interaction were studied, one cannot say in which side of the mirror lived or whether he/she was build of matter or antimatter.
- We call this „Strong and electromagnetic interactions conserve C and P symmetry, but weak interaction does not".
- Let's combine C and P together and see if neutrino is OK now:



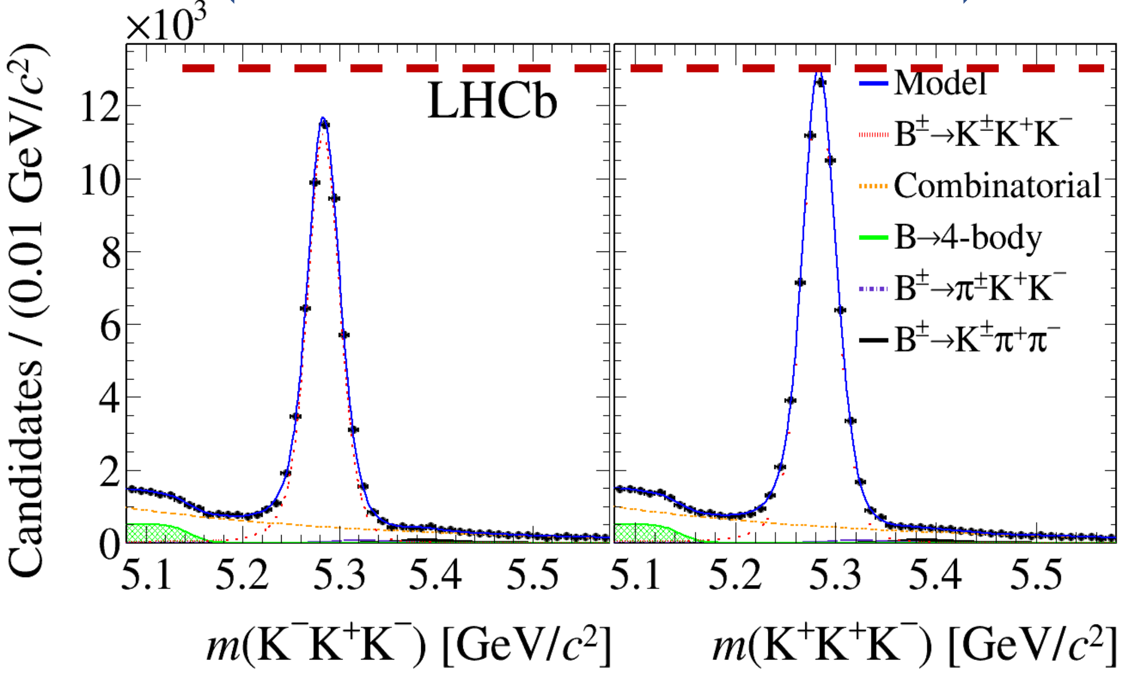
CP Violation (in decay)

1. One of the simplest way to discover $\mathcal{CPV}$ is to compare the decay rates $\Gamma(P \to f)$ with $\Gamma(\bar{P}) \to \bar{f}$
2. If we define the asymmetry between $\mathcal{CP}$ conjugated decays, for charged and neutral mesons:

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

Huge direct **CP** violation in decay amplitudes seen in B⁻/B⁺ decays

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



R. Aaij *et al.* (LHCb Collaboration) Phys. Rev. D **90**, 112004

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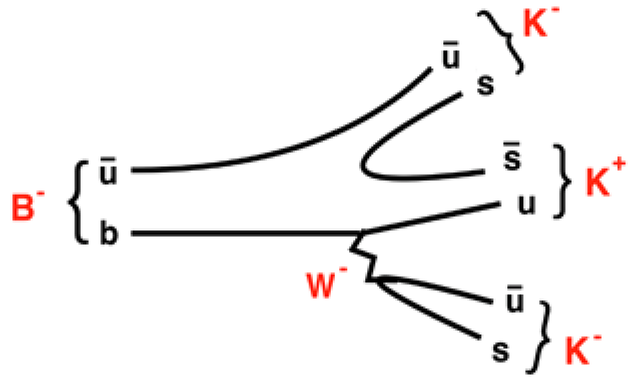
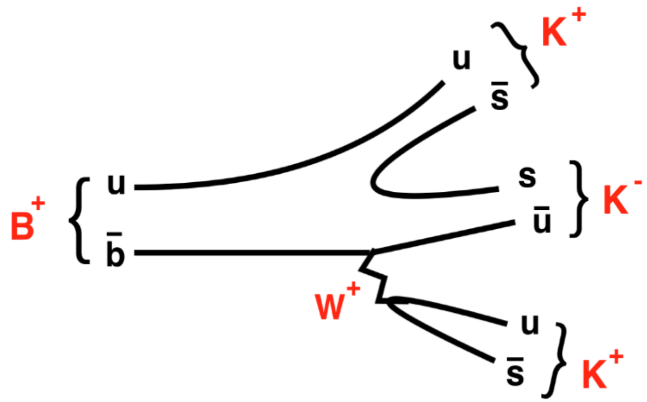


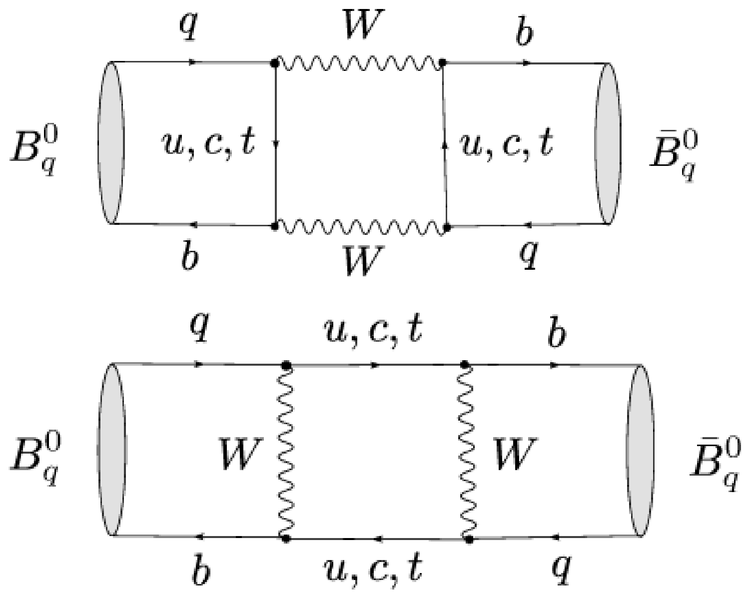
Can you find the quark transitions (change of flavour)?

V_{ub} and V_{us}

This shows the connection between „simple" counting of decays and the Standard Model

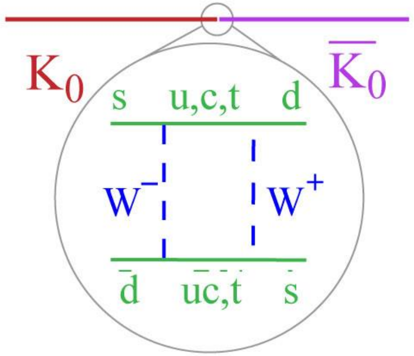


CP violation in mixing

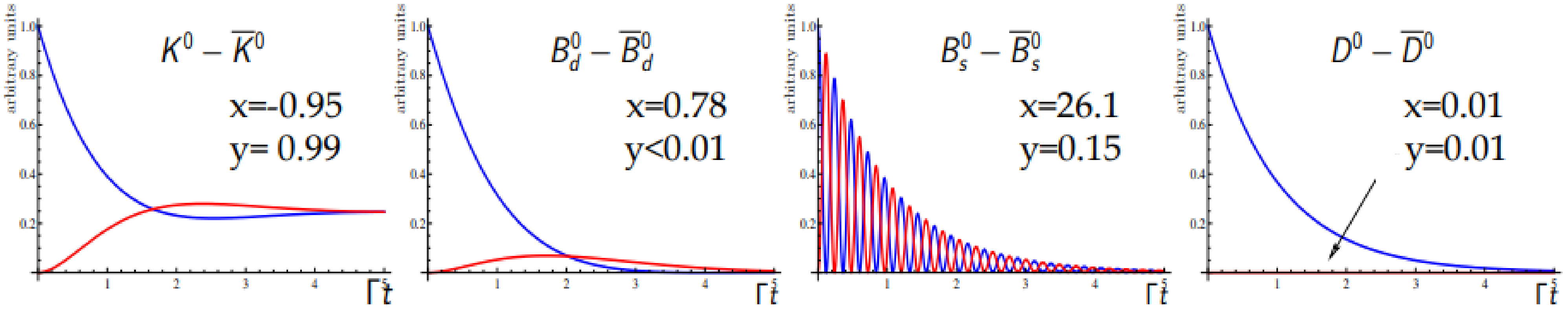


- Weak interactions makes possible the change of quark flavour.

This rule can do some magic transition from matter to antimatter:



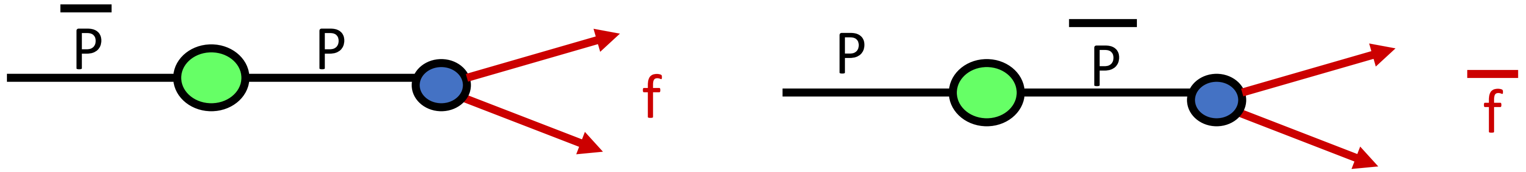
- We found that having started the observation with a P^0 meson, after some time t we can have $\overline{P^0}$ (P^0 has oscillated to $\overline{P^0}$)!
- SM and V_{CKM} provide us with the parameters of oscillations



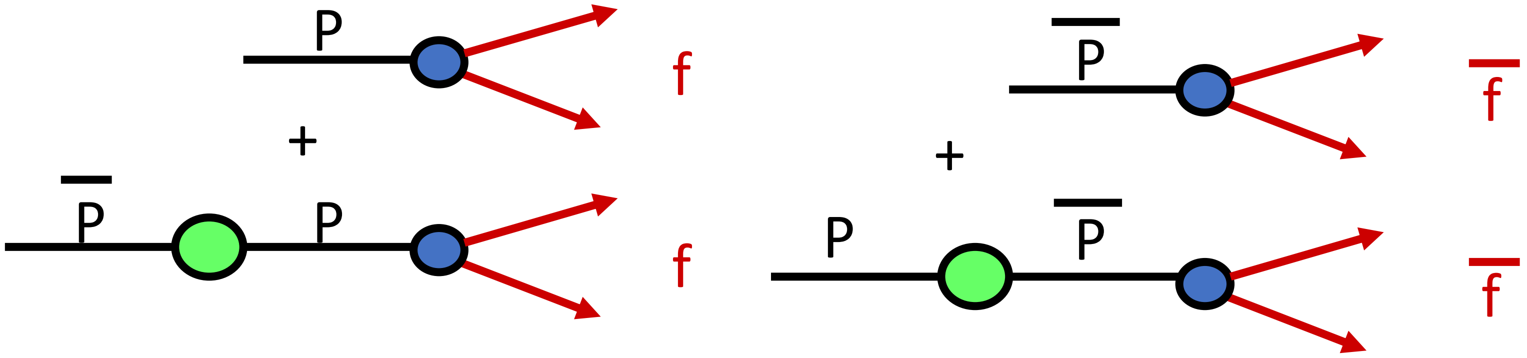
CP violation – all ways

I. CP violation in decay (direct CP Violation)

II. CP violation in mixing (indirect CP Violation)



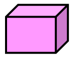
III. CP violation in interference between mixing and decay



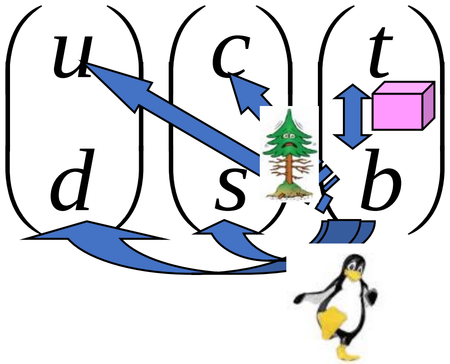
Heavy flavour physics

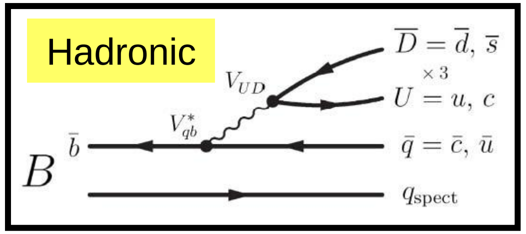
NOW

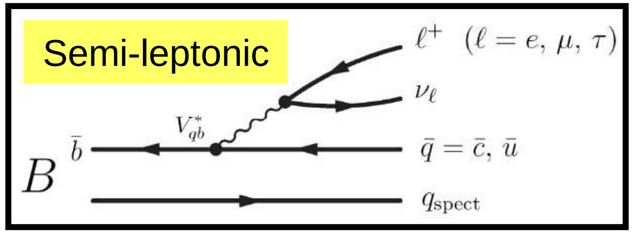
trees 

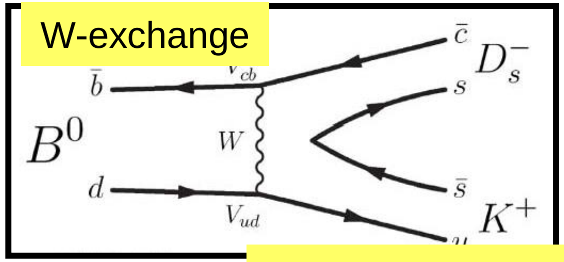
boxes 

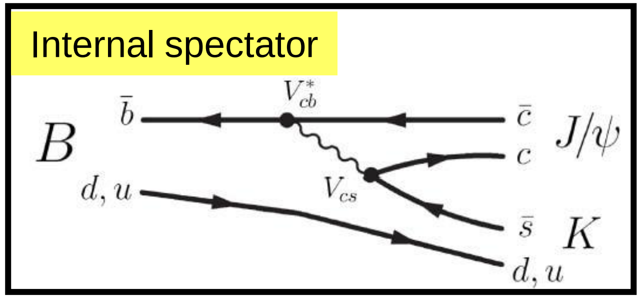
pinguins 

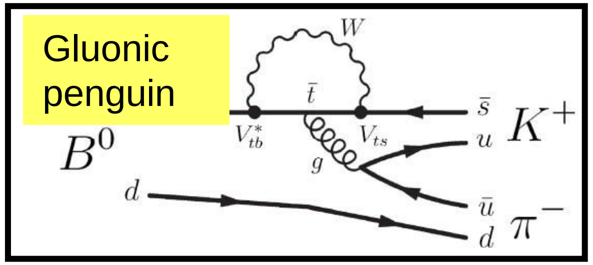


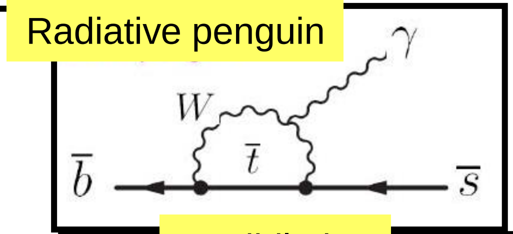


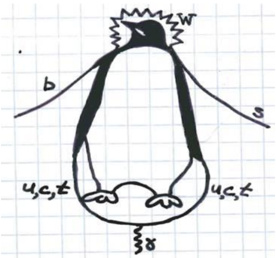




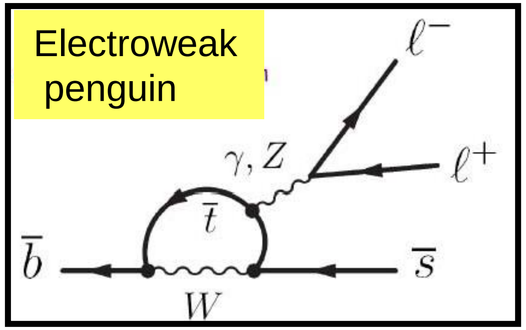


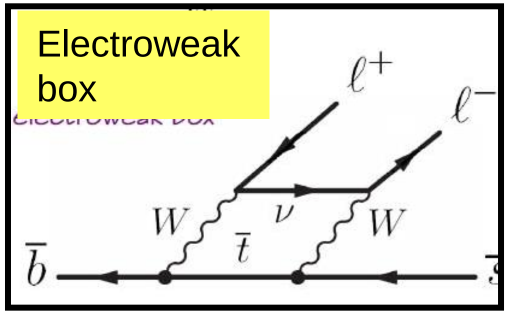


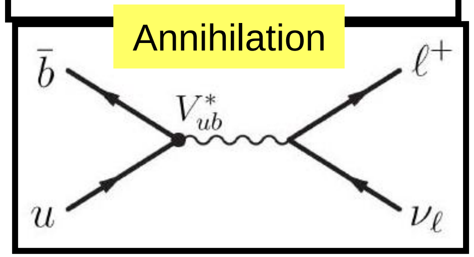


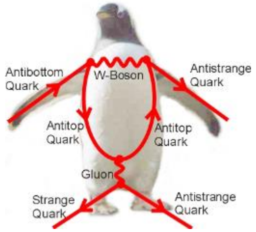


John Ellis 1977
lost darts bet









Heavy flavour physics - parameters

- We have two aims: either confirm Standard Model or/and find evidences of Physics Beyond the SM
- Decay rates are used for absolute BR measurements and observation of CPV in decays
- CKM matrix elements are obtained with:

  decay rates measurement

  angles....

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

$$V_{CKM} = \begin{pmatrix} 1 & \lambda & \boldsymbol{\lambda^3} e^{-\gamma} \\ -\lambda - \boldsymbol{\lambda^5} e^{-\phi} & 1 & \lambda^2 \\ \lambda^3 e^{-i\boldsymbol{\beta}} & -\lambda e^{-i\boldsymbol{\beta_s}} & 1 \end{pmatrix}$$

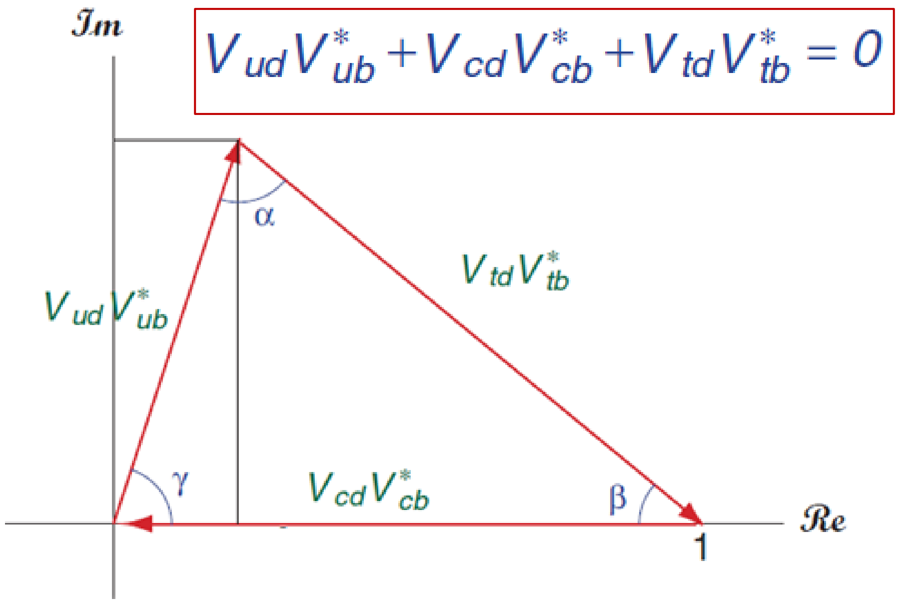
V_{CKM} elements are complex numbers (absolute value and phase) proportional to the transition amplitude between quarks

CKM matrix must be unitary, so we have conditions on its parameters:

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

$$V_{us}V_{ub}^* + V_{cs}V_{cb}^* + V_{ts}V_{tb}^* = 0 \quad \text{(+ 4 more)}$$

and can be represented as triangles:

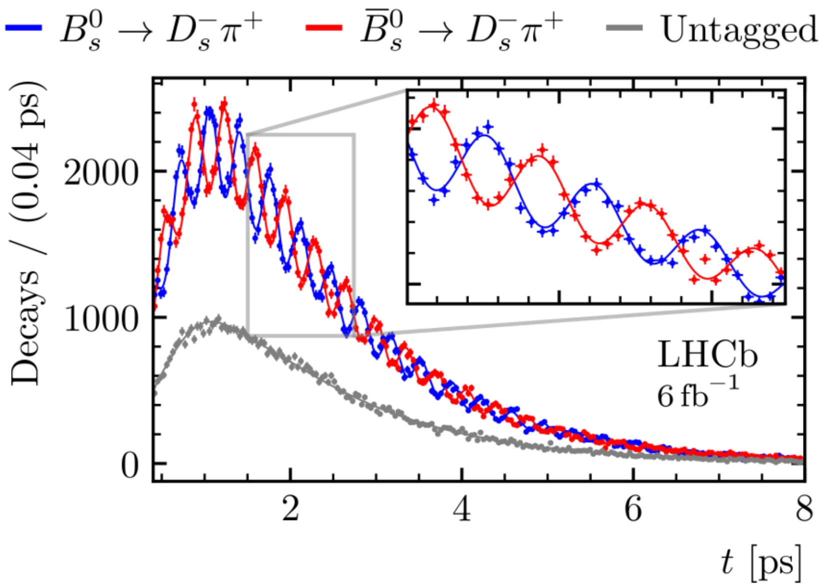


$$V_{ud}^*V_{td} + V_{us}^*V_{ts} + V_{ub}^*V_{tb} = 0$$

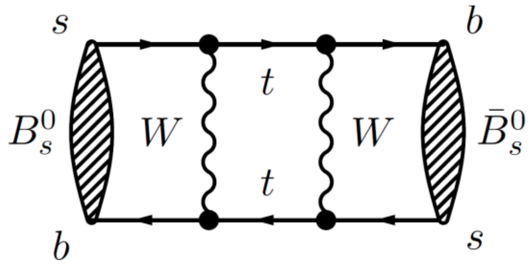
Precise determination of the B_s^0–B_s^0 oscillation frequency

Visual example of the quantum-mechanical nature of our universe

$$P(t) \sim e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) + C\cos(\Delta m_s\, t)\right]$$



$$\Delta m_s = 17.7683 \pm 0.0051(stat) \pm 0.0032(syst)\ ps^{-1}$$



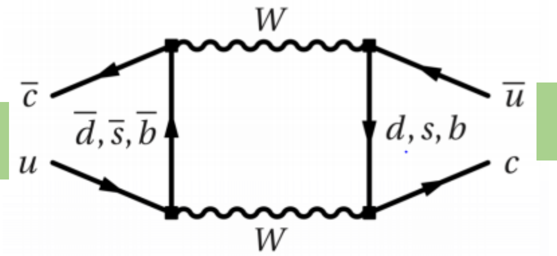
dancer oscillating in front of CP violating mirror. In a given time slot the image in the mirror is different

First observation of the mass difference between neutral charm mesons

8 June 2021

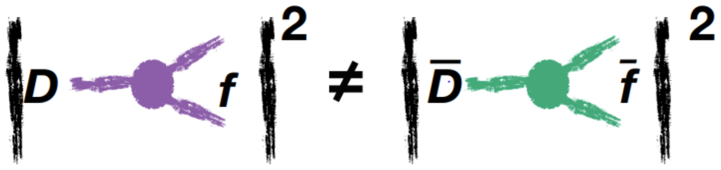
arXiv:2106.03744

The mass difference determines the frequency of $D^0 \leftrightarrow \overline{D}^0$ neutral charm meson oscillations

$\overline{D}^0$  D^0

CPV in the **decay**

Occurs if $|A_f|^2 \neq |\bar{A}_{\bar{f}}|^2$

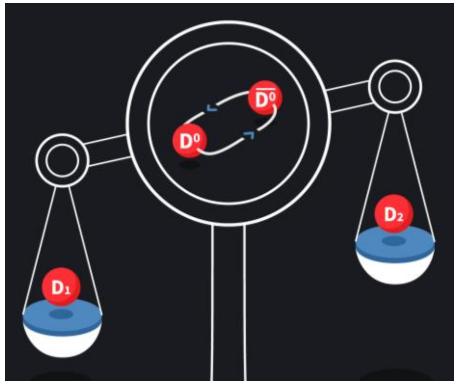


$D^0 \rightarrow K^0\pi^+\pi^-$ — how to distinguish D^0 from $\overline{D}^0$??? — $\overline{D}^0 \rightarrow K^0\pi^+\pi^-$

$D^{*+} \rightarrow D^0\pi^+$

$D^{*-} \rightarrow \overline{D}^0\pi^-$

sign of this pion is a TAG indicating the flavour of D-meson

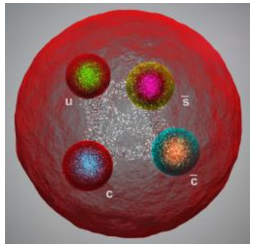


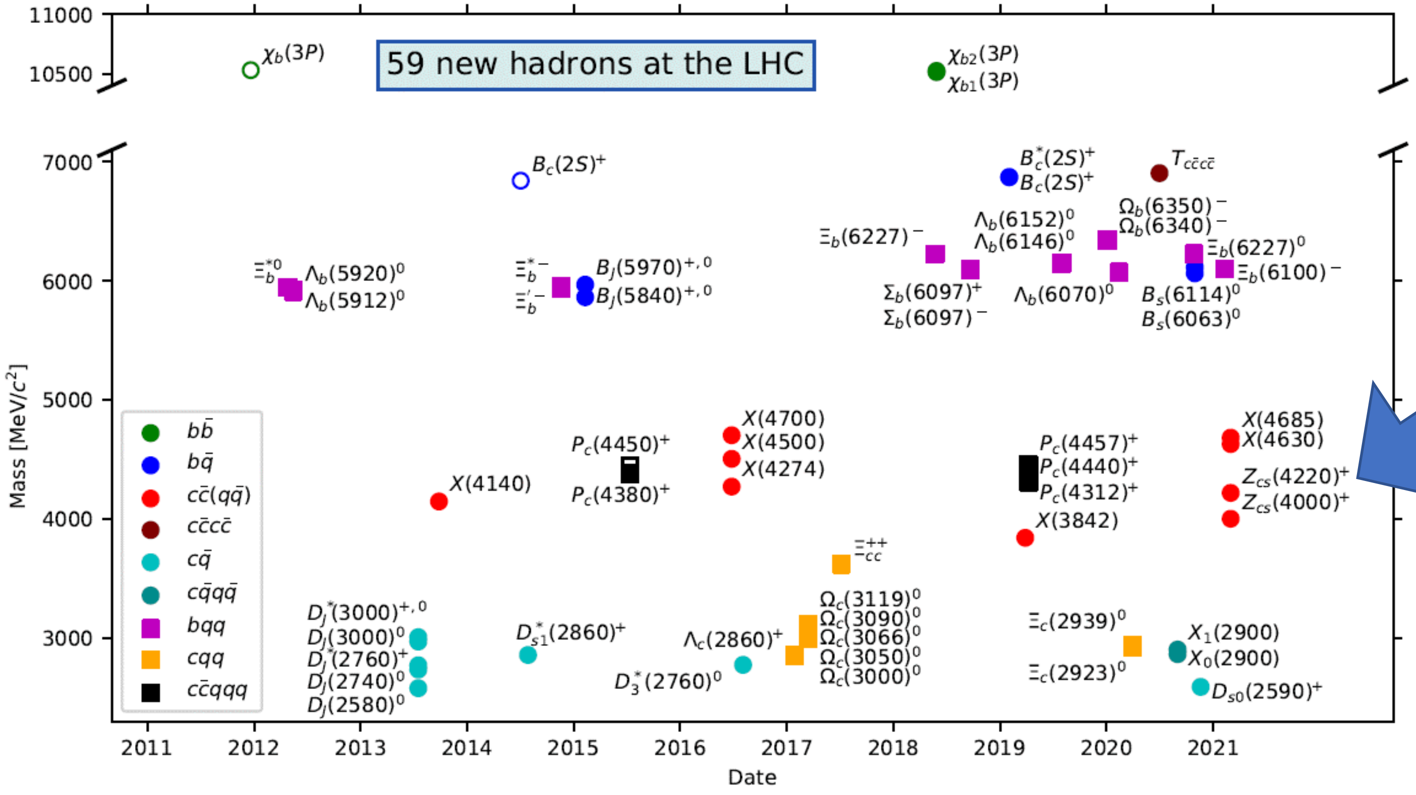
$$m_1 - m_2 = 6.4 \times 10^{-6}\, eV$$

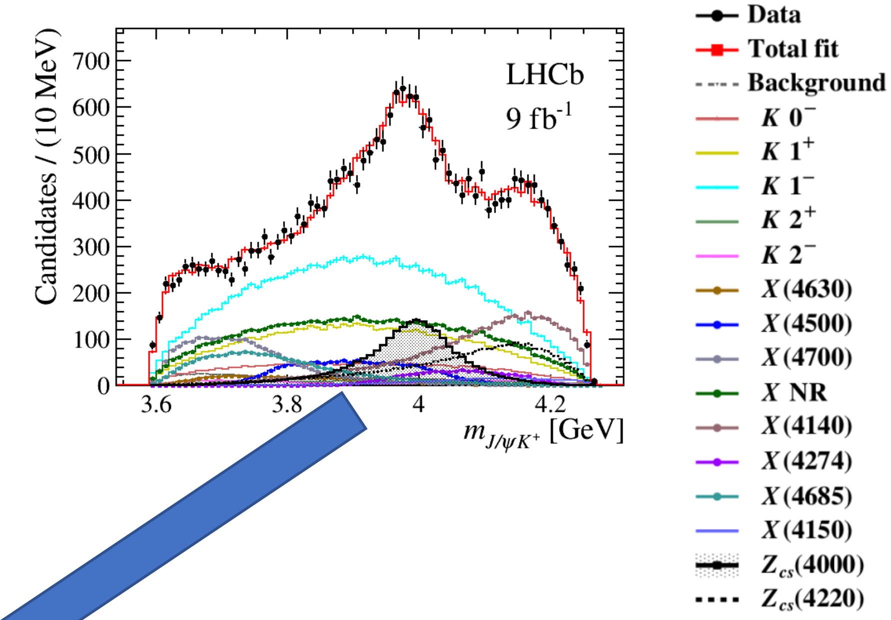
$$\frac{m_1 - m_2}{D^0 mass} = 3 \times 10^{-15}$$

Heavy flavour physics – spectroscopy

Tetraquarks $Z_{cs}(4220)^+$ $(c\bar{c}u\bar{s})$



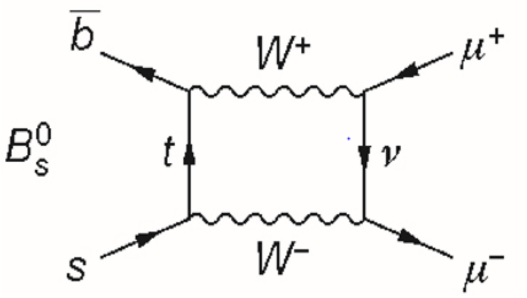


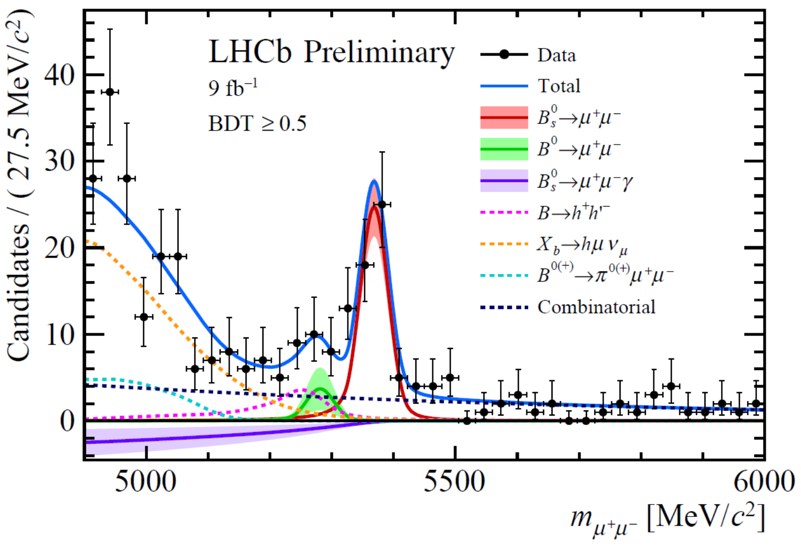


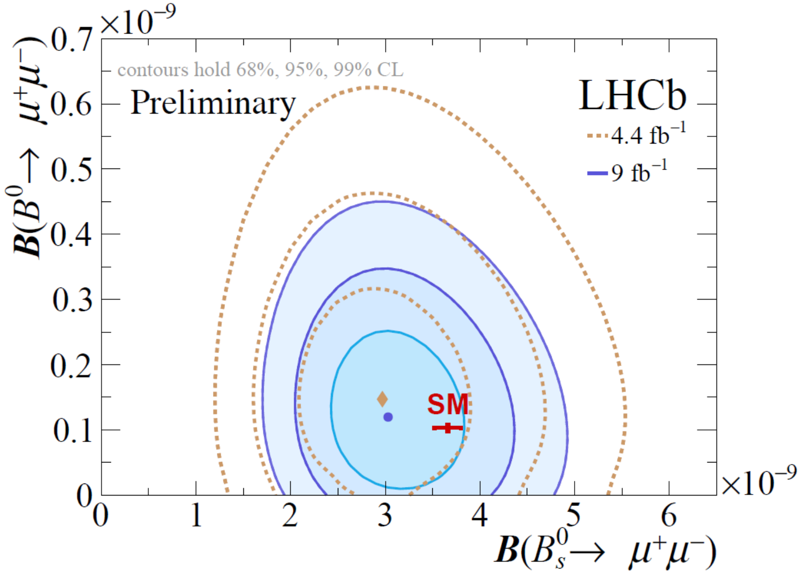
The Ultimate Quest to find New Physics

$B_s^0 \to \mu^+\mu^-$

- Purely leptonic flavour-changing neutral current mediated decay
- In SM tree diagrams are not possible, only pinguins and boxes
- Clean probe of new physics







$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \left(2.69^{+0.37}_{-0.35}\right) \times 10^{-9}$

2.1σ away from SM

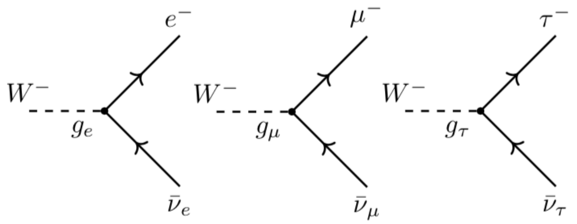
The Ultimate Quest to find New Physics

CERN-EP-2021-042
LHCb-PAPER-2021-004
23 March 2021

arXiv:2103.11769

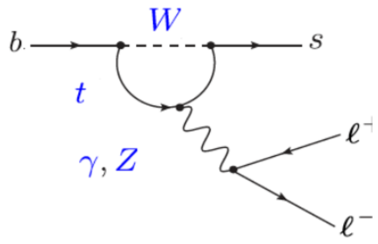
Nature Physics

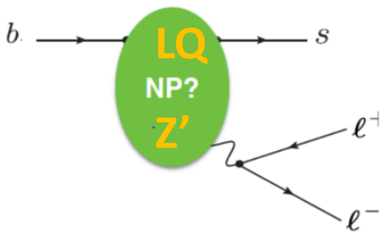
Lepton universality

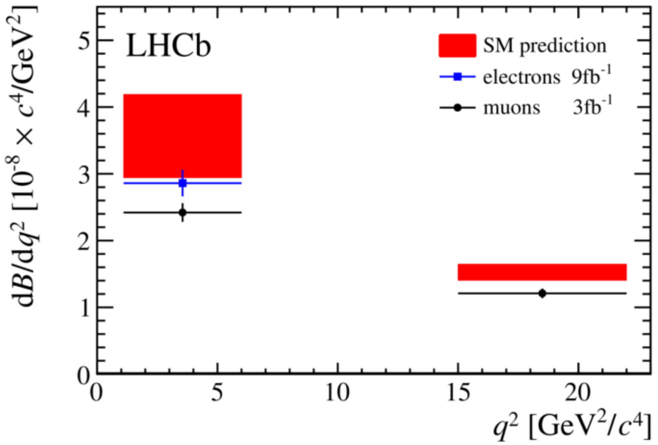


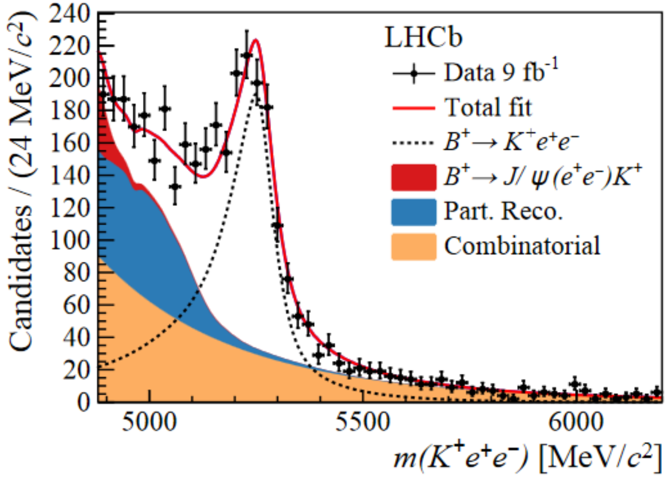
- SM couplings of charged leptons to gauge bosons are identical
- Very clean and precise measurement at electron collider

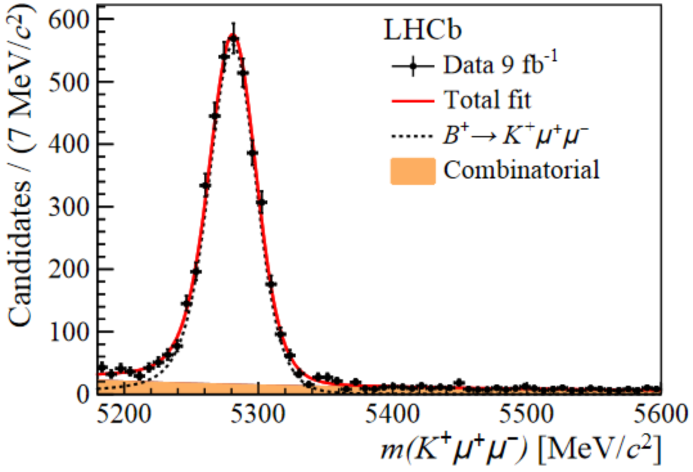
Observables are sensitive **to new (virtual) particles**











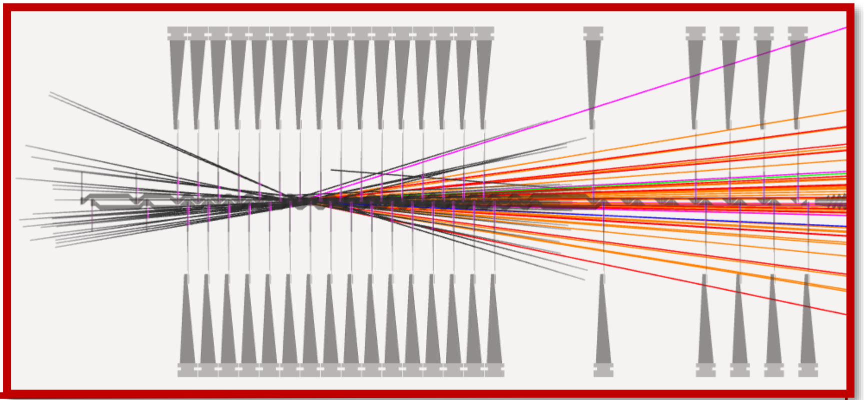
$$R_K = 0.846 \; ^{+0.042}_{-0.039} \, (stat) \; ^{+0.013}_{-0.012} \, (syst)$$

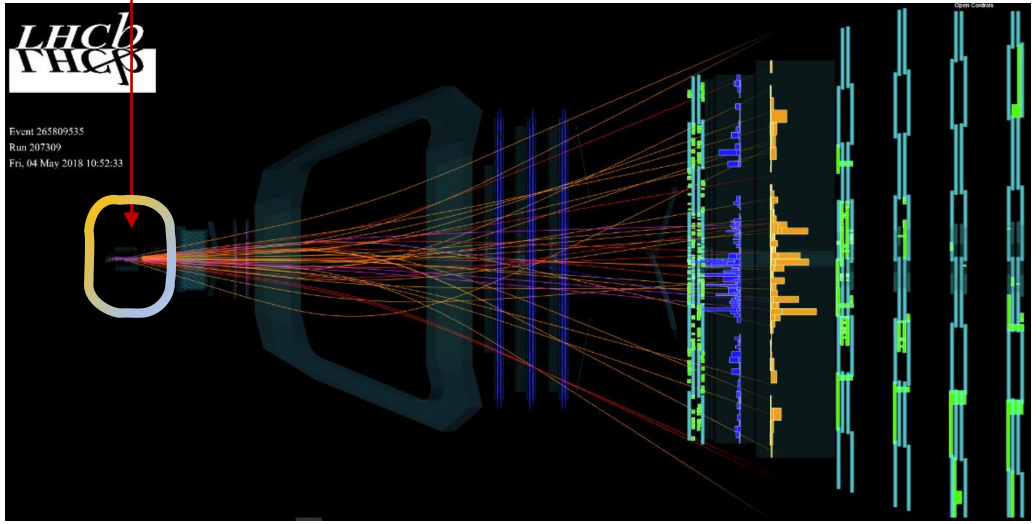
p-value under SM hypothesis: 0.0010

evidence of LFU violation at 3.1σ

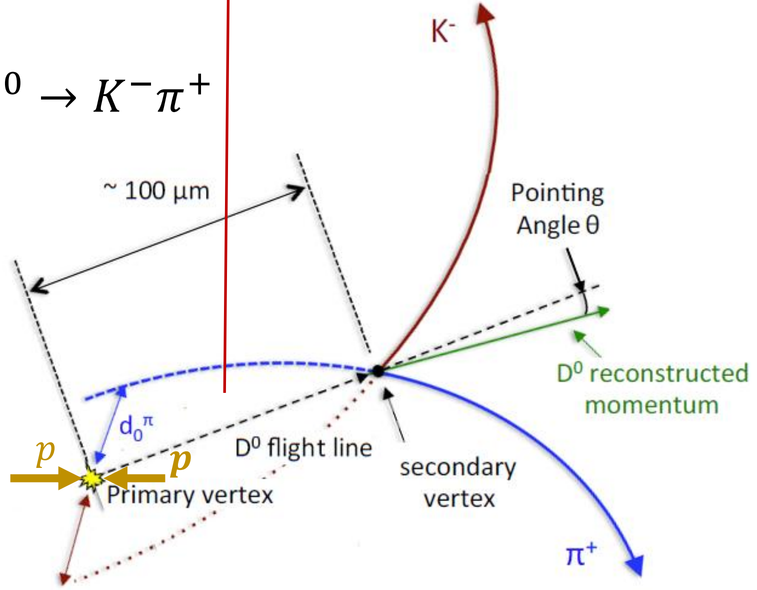
Flavour physics – how we do the measurement?

- Point of creation and decay – primary and secondary vertex.
- Tracing detector with sensors as close as possible to the proton interaction point.
- Distance between PV and SV is converted into time of life.



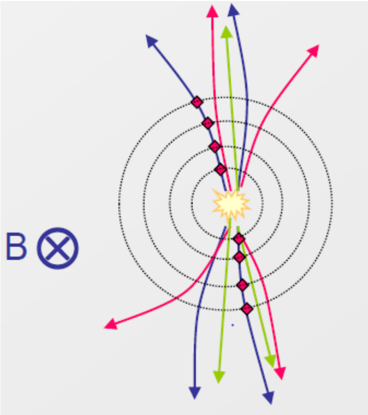


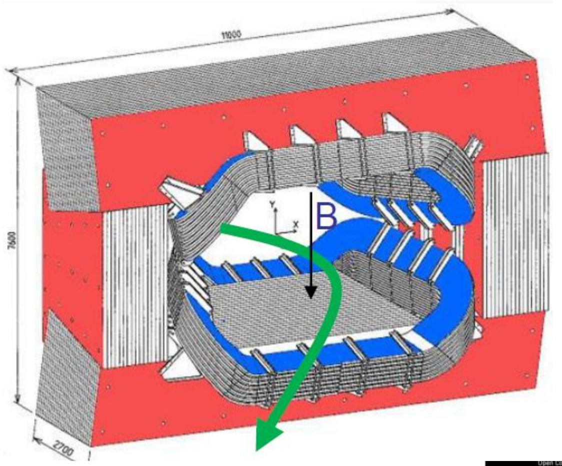
$D^0 \rightarrow K^- \pi^+$



Measurement of the momentum

- **Momentum *p*** measured with the radius of curvature in a magnetic field

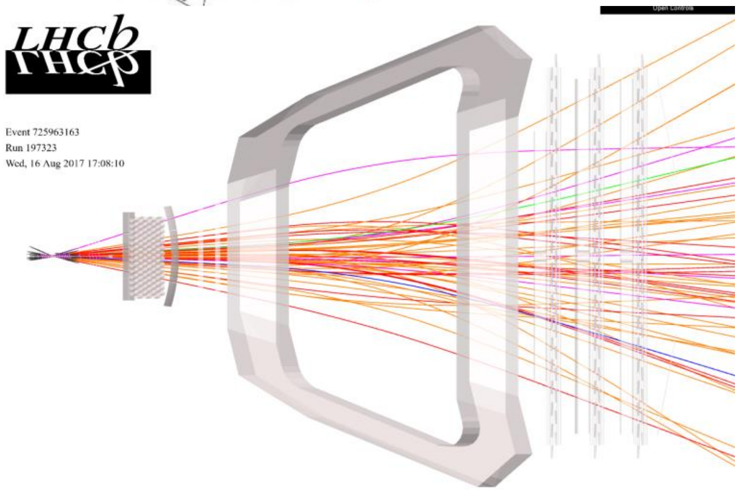


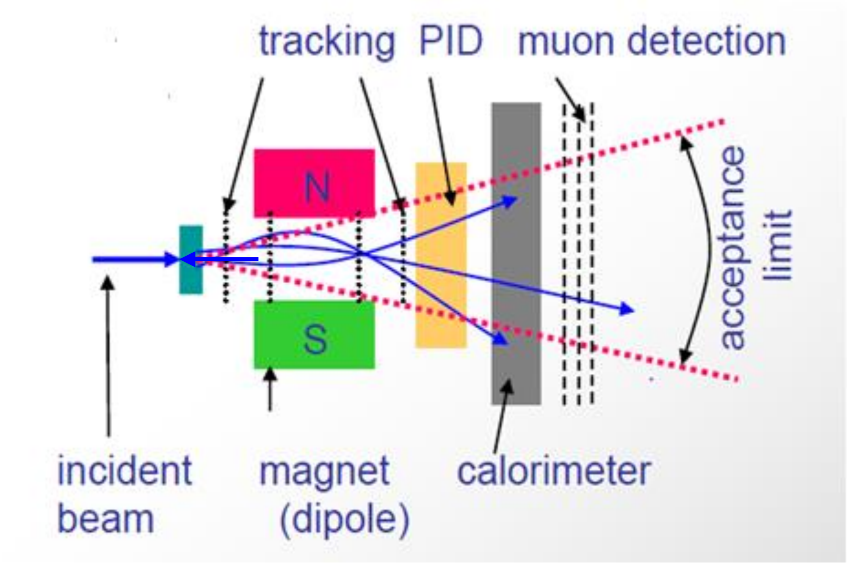


$$\vec{F_L} = q\,\vec{v} \times \vec{B}$$

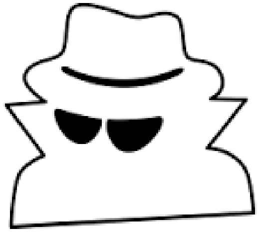
$$F_L = F_d$$

$$qvB = \frac{mv^2}{R}$$



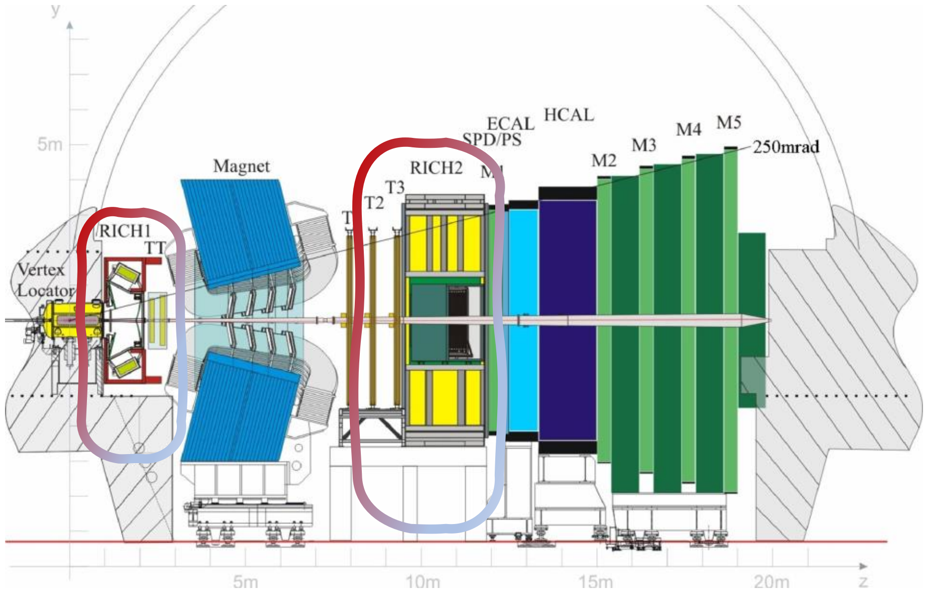


Identification



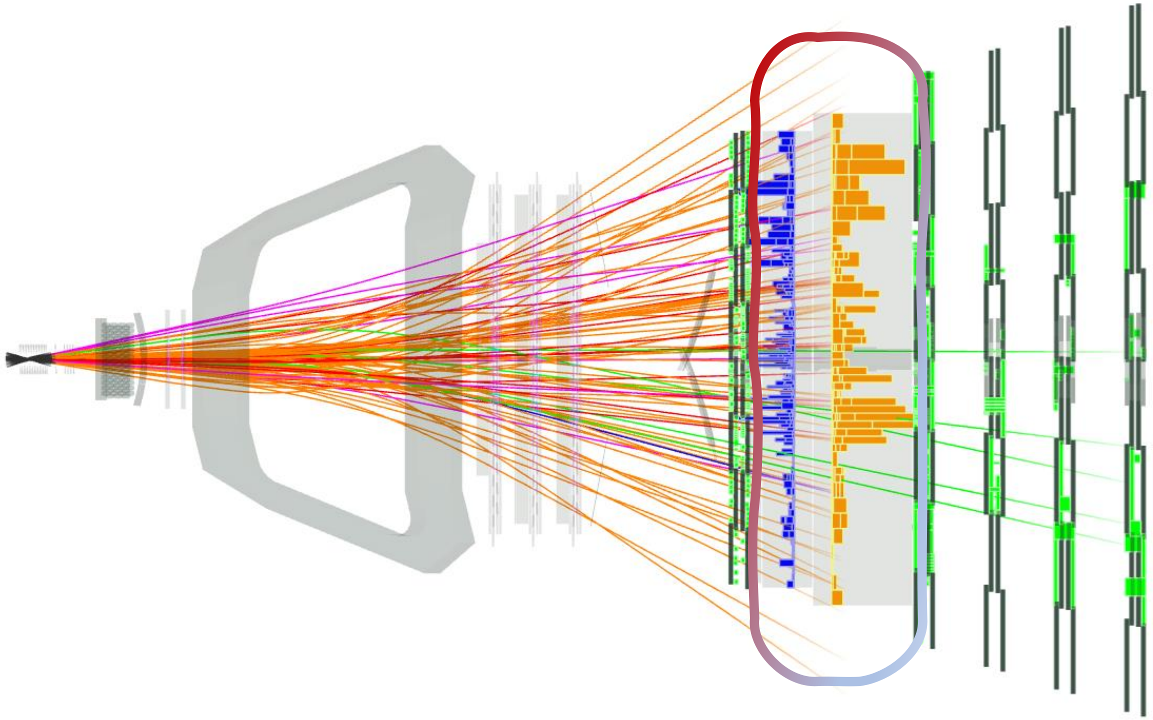
- We can identify stable particle, i.e. particles that do not decay in the detector volume, like π, K, p, e, μ
- Particles can have the same charge, spin and other properties.
- To distinguish them, one can use:
  - ✓ Particle mass – different particles have different mass.
  - ✓ Lifetime - different particles have different lifetimes.
  - ✓ Type of interaction with matter.

RICH – Ring Imaging Cherenkov radiation



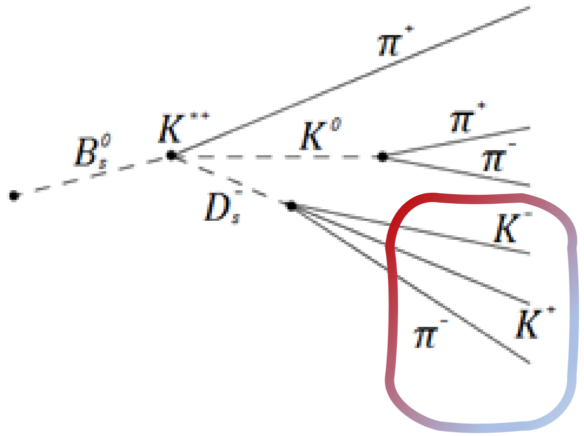
Energy measurement

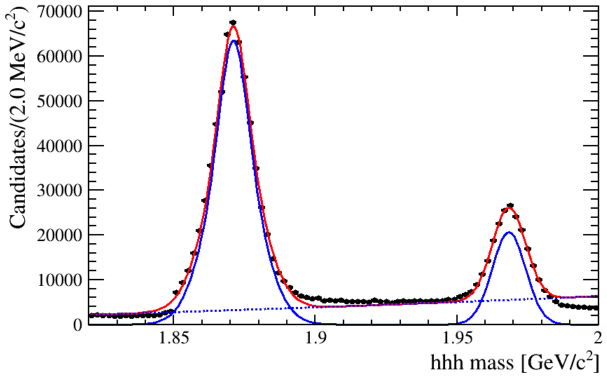
- Electromagnetic calorimeter used for the measurement of electron and photon energy
- Hadron calorimeter – helps to distinguish hadrons



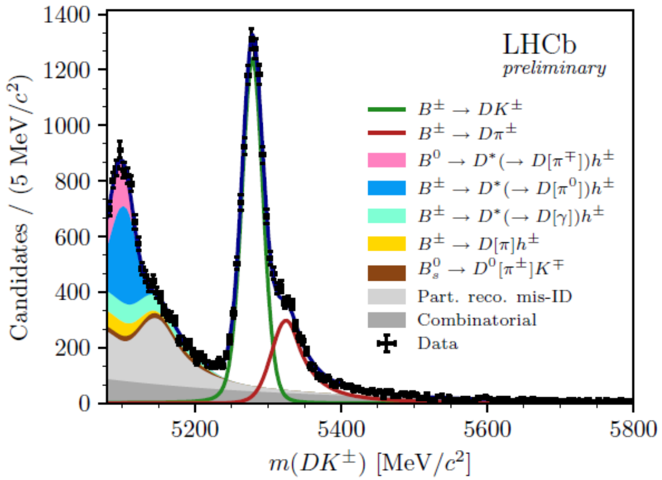
Mass and life-time distribution – selection and fitting

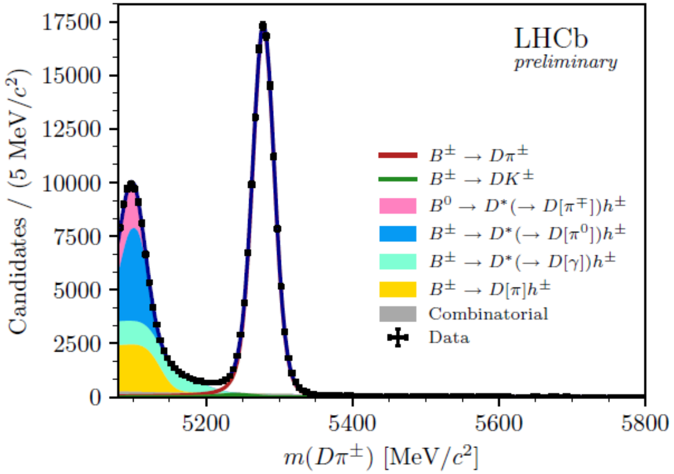
$$m^2 = \left(\sum E\right)^2 - \left(\sum \vec{p}\right)^2$$





1) track reconstruction
2) particle identification
3) pre-selection
4) selection
5) multivariate analysis
6) distribution fitting





Future of Heavy flavour physics – Upgrades

	Run I (2010-12)	Run II (2015-18)	Run III (2022-23)	Run IV-V (2025-28, >30)
Integrated Luminosity	3 fb^{-1}	8 fb^{-1}	23 fb^{-1}	150 fb^{-1}
Energy $\sqrt{s}$	7-8 TeV	13TeV	14 TeV	14 TeV

Upgrade of LHCb during LS2

LHCb up to 2018 ≥ 8 fb^{-1} @ 13 TeV:

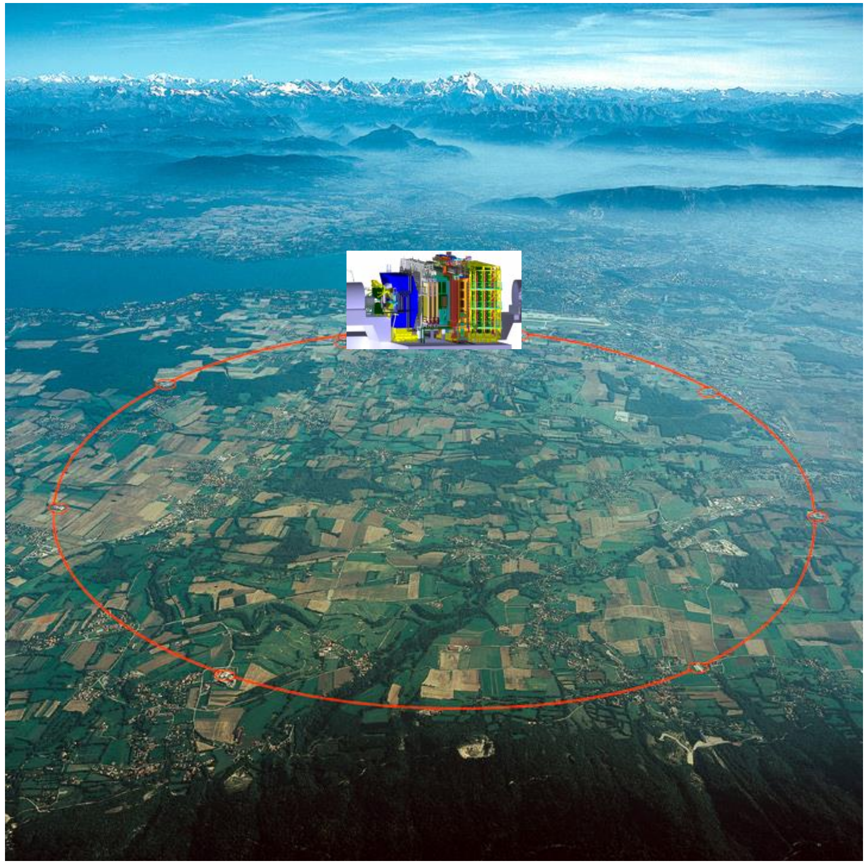
- find or rule out the evidences of New Physics and sources of flavour symmetry breaking
- searches of rare decays and exotic states,
- physics in the forward region.

LHCb Upgrade + HL LHC ≥ 50 fb^{-1} @ 14 TeV:

- increase precision on quark flavour observables,
- aim – experimental sensitivities comparable to theoretical uncertainties,

Summary

- There is the Large Hadron Collider that accelerates and collides high-energy protons.
- LHCb spectrometer is designed to study quark transitions in weak interaction to explain matter-antimatter asymmetry and search for New Physics evidences.
- So – let's do what we came here for!



https://www.facebook.com/fizagh/

Track reconstruction*

* see additional slides!