Physics at LHCb 2

I. The LHCb experiment
II. Heavy flavour physics
III. Measurements @ LHCb
IV. Plans for Upgrade 1 and 2
V. How to do precise measurements:
   - mass and momentum resolution
   - proper time-life

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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….

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

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

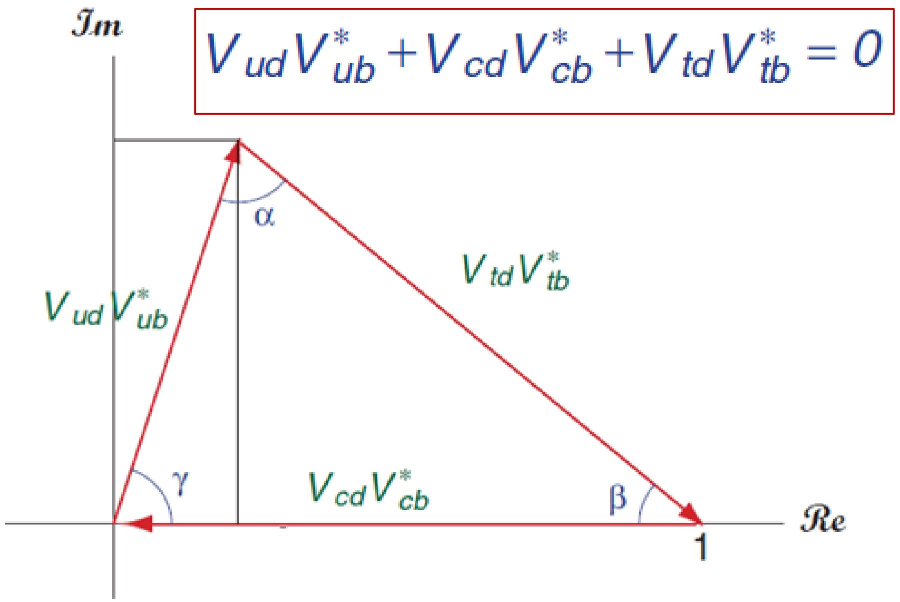
V_{CKM} elements are complex numbers (absolute value and phase) proportional to the transition amplitude between quarks

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:

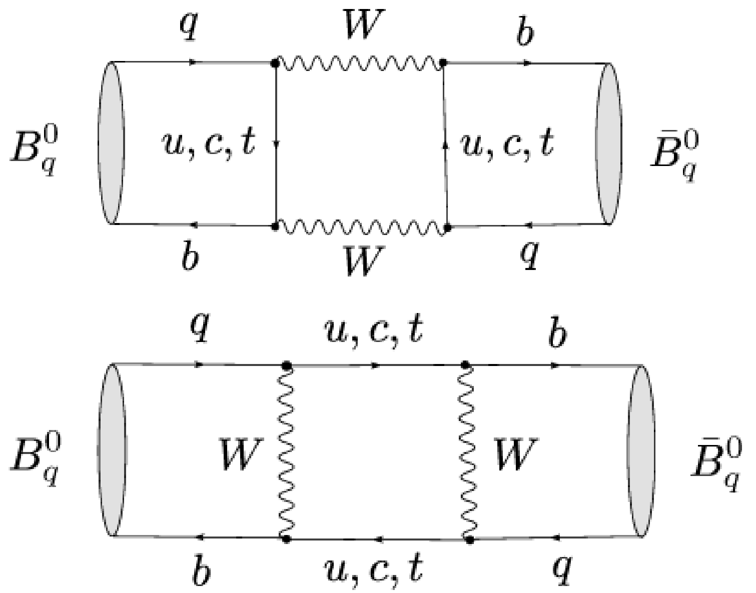


$$V_{ud}^*V_{td} + V_{us}^*V_{ts} + V_{ub}^*V_{tb} = 0$$

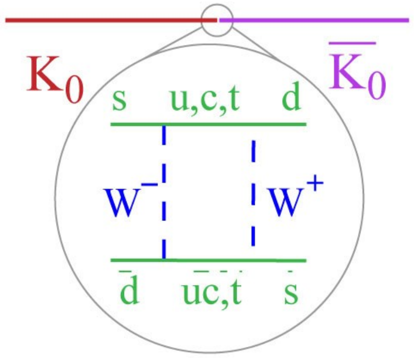
CP violation in mixing

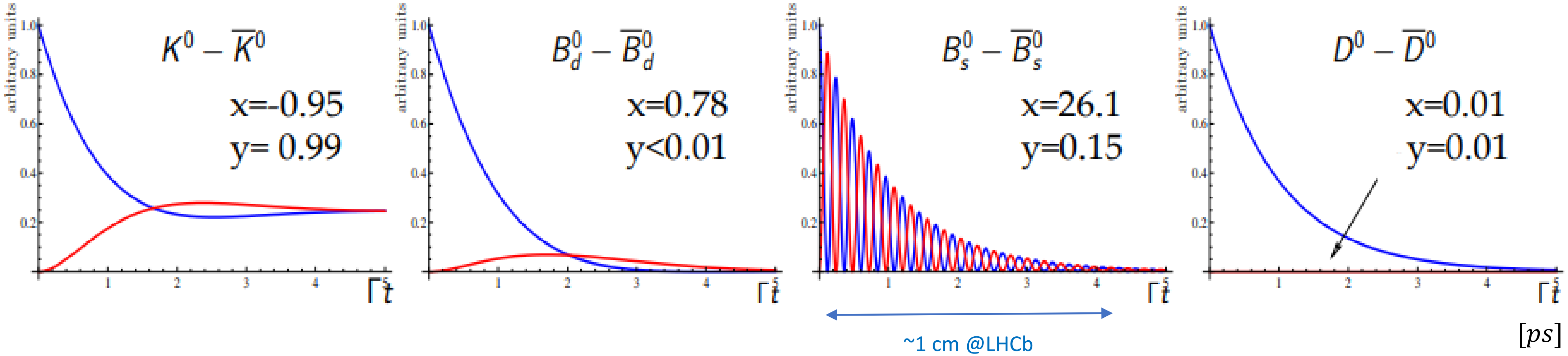
- Weak interactions makes possible the change of quark flavour.

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



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





Time evolution of neutral mesons*

1. The eigenstates of effective Hamiltonian (weak) written in the form:

$$|P_1\rangle = p|P^0\rangle + q|\overline{P^0}\rangle$$

$$|P_2\rangle = p|P^0\rangle - q|\overline{P^0}\rangle$$

p and q are complex numbers satisfying: $|p|^2 + |q|^2 = 1$ (for K_1^0 and K_2^0 : $p = q = \frac{1}{\sqrt{2}}$)

2. Solving Schrödinger equation we see time evolution of the eigenstates:

$$|P_1(t)\rangle = |P_1\rangle \, e^{-i\left(m_1 - \frac{i\Gamma_1}{2}\right)t}$$

$$|P_2(t)\rangle = |P_2\rangle \, e^{-i\left(m_2 - \frac{i\Gamma_2}{2}\right)t}$$

These relations show that the original P^0 meson after some time can either convert to $\overline{P^0}$ or decay.

Time evolution of neutral mesons*

9. Finally the time evolution of weak eigenstates as a combination of flavour eigenstates:

$$|P^0(t)\rangle = f_+(t)|P^0\rangle + \frac{q}{p} f_-(t)|\overline{P^0}\rangle$$

$$|\overline{P^0}(t)\rangle = f_+(t)|\overline{P^0}\rangle + \frac{p}{q} f_-(t)|P^0\rangle$$

$$f_\pm(t) = \frac{1}{2}\left[e^{-i(m_1-\frac{i}{2}\Gamma_1)t} \pm e^{-i(m_2-\frac{i}{2}\Gamma_2)t}\right]$$

solve this!

$$|f_\pm(t)|^2 = \frac{1}{4}\left[e^{-i\Gamma_1 t} + e^{-i\Gamma_2 t} \pm 2e^{-\bar{\Gamma}t}\cos(\Delta m t)\right]$$

$$\bar{\Gamma} = \frac{\Gamma_1 + \Gamma_2}{2}$$

interference term

10. The time evolution of mixing probabilities, i.e. the probability that having started the observation with a P^0 meson, after some time t we still have P^0 (or it has oscillated to $\overline{P^0}$):

$$P(P^0 \to P^0; \mathrm{t}) = |\langle P^0|P^0(t)\rangle|^2 = |f_+(t)|^2$$

$$P(P^0 \to \overline{P^0}; \mathrm{t}) = |\langle \overline{P^0}|P^0(t)\rangle|^2 = \left|\frac{q}{p} f_-(t)\right|^2$$

Let's look closer at the parameters of flavour oscillations:

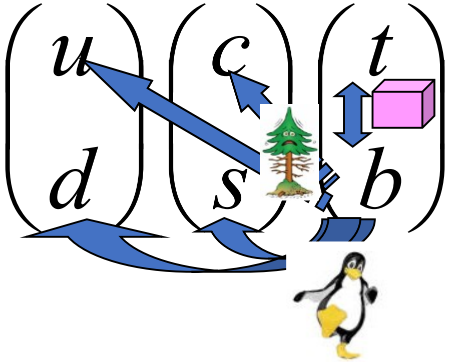
III. Measurements @ LHCb

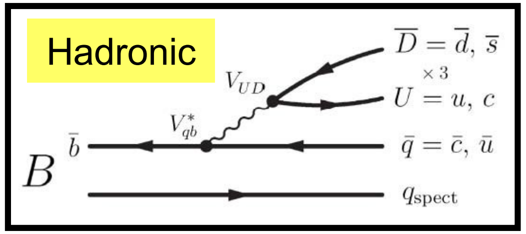
Heavy flavour physics

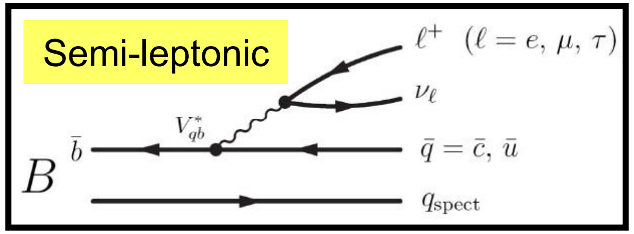
trees

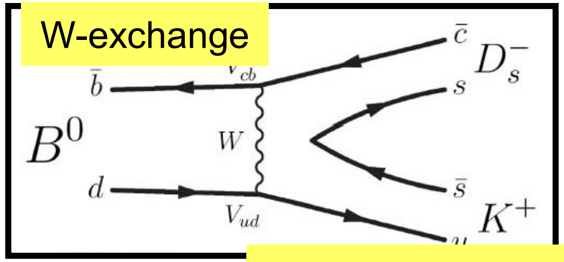
boxes

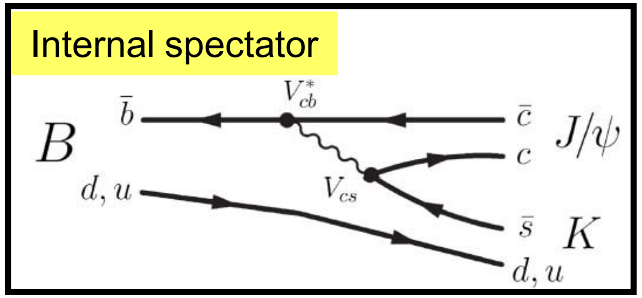
pinguins

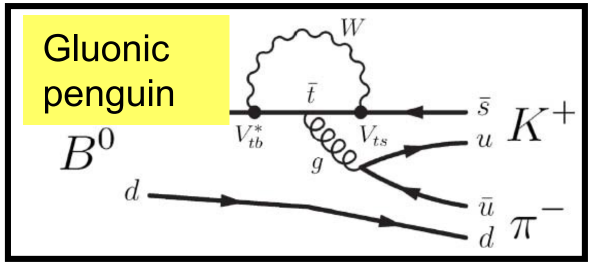


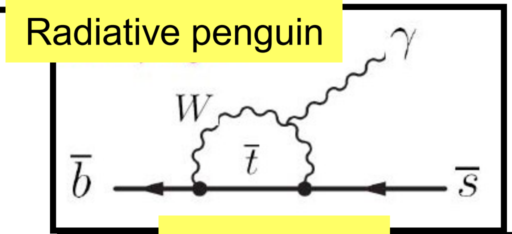


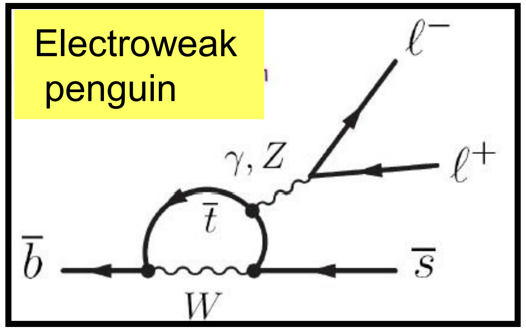


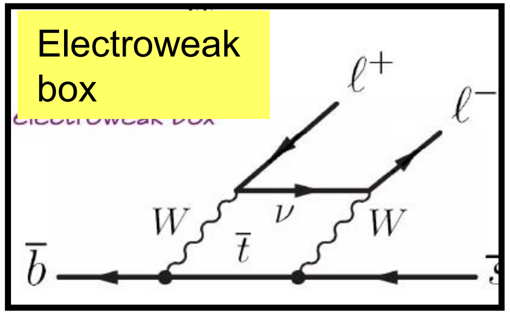


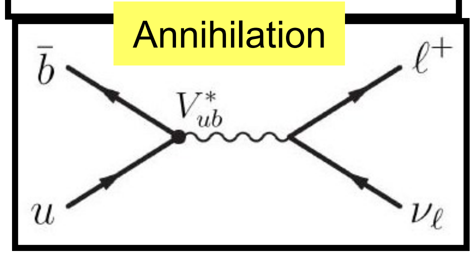


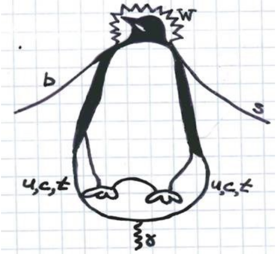




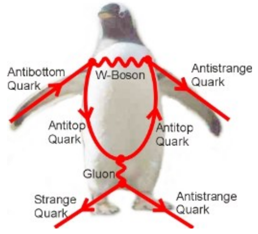








John Ellis 1977
lost darts bet



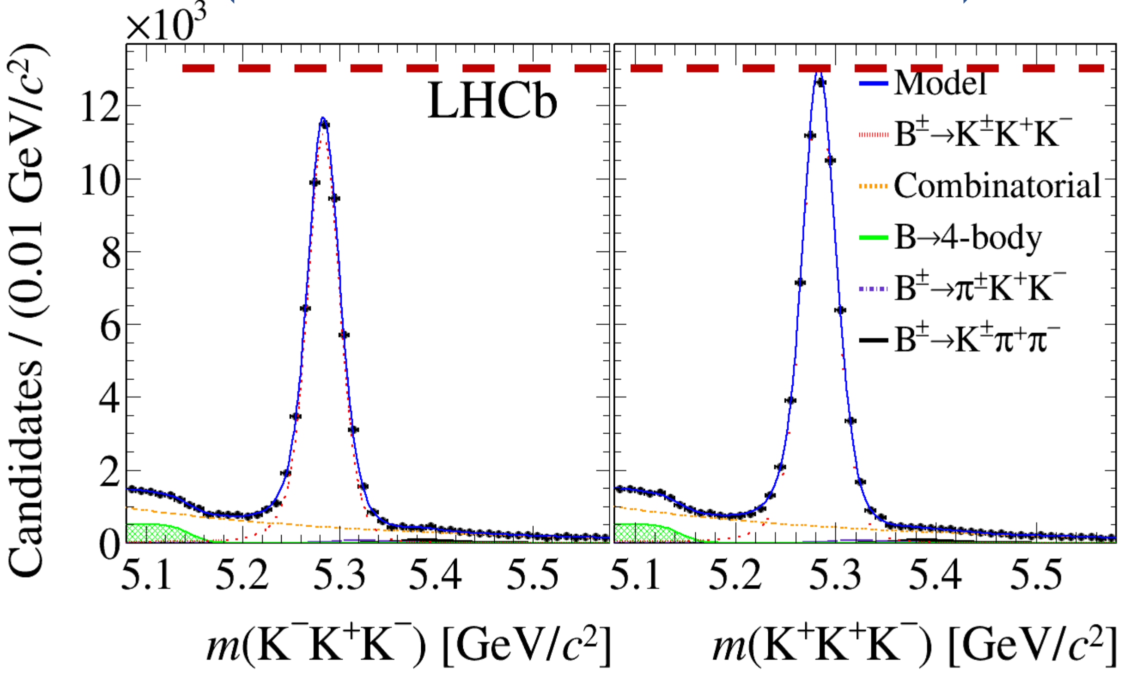
CP Violation (in decay)

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

CP Violation (in decay)

March 2022

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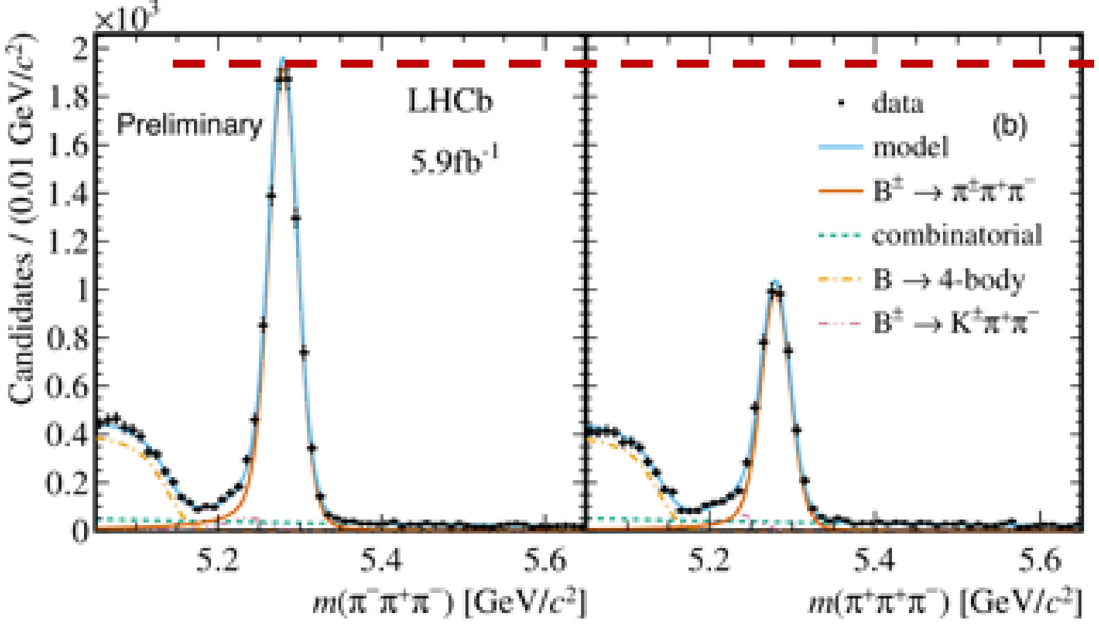

Rencontres de Moriond EW

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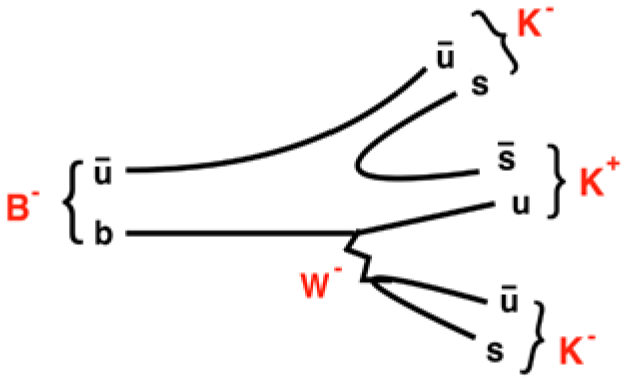
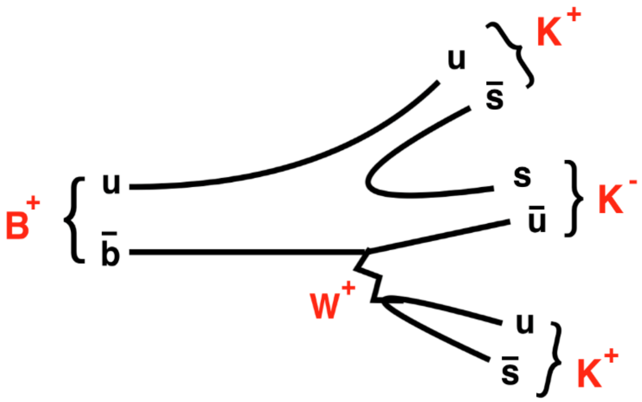


Can you find the quark transitions (change of flavour)?

V_{ub} and V_{us}

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



Sides of the Unitary Triangles

Sides of the UT can be measured with:

V_{ud}	β-decay	Nuclear physics	$\cos\vartheta_i$
V_{us}	K decay	$K^{+0} \to \pi^{0+} l^+ \nu_l$	$\sin\vartheta_i$
V_{cd}	Neutrino scatering	$\nu_\mu d \to \mu^+ c$	$\cos\vartheta_i$
V_{cs}	Charm decay	$D_S^+ \to \mu^+ \nu_\mu$	BR
V_{ub}	B decay	$B^0 \to \pi^- e^+ \nu_e$	BR
V_{cb}	B decay to charm		
V_{td}	B mixing		

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

$b \to u$ transitions

$b \to c$ transitions

B^0 mixing

Angles of the Unitary Triangles

Angles of the UT can be measured with:

$B^0 \to J/\psi K_S$	$\sin 2\beta$
$B^0 \to \pi^+\pi^-$	$\sin 2\alpha$
$B_S^0 \to D_S^+ K^-$	$\sin 2\gamma$
Weak phase	$\boldsymbol{\beta_s}$

Short history of flavour physics:

1. First B physics experiments were build on symmetric electron-positron collider:
   - Petra (DESY) in 80'ties
   - LEP at CERN in 1994-2000
2. Then two asymmetric B-factories (currently not taking data):
   - Belle (Japan)
   - BaBar (SLAC,USA)
3. LHC
   - **LHCb – dedicated B physics experiment**
   - CMS, ATLAS also interested in heavy flavours

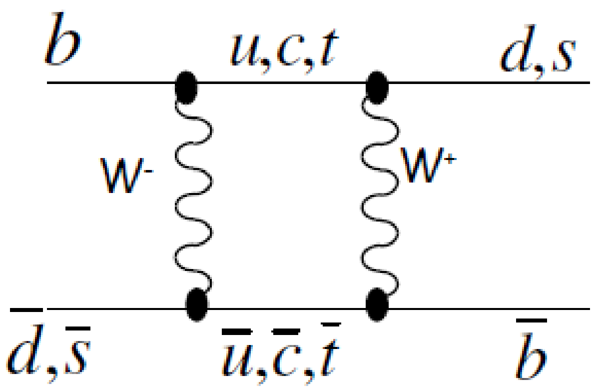
Mixing of B^0 and B_S^0 meson*

1. Like neutral kaon system, neutral B mesons may also oscillate:
2. The top quark transition has the dominant amplitude:

$$A \propto \sum all\ pair\ of\ quarks\ A_{bi}A_{jb}^*$$

$$\begin{pmatrix} B^0 = d\bar{b} \\ \overline{B^0} = \bar{d}b \end{pmatrix}$$

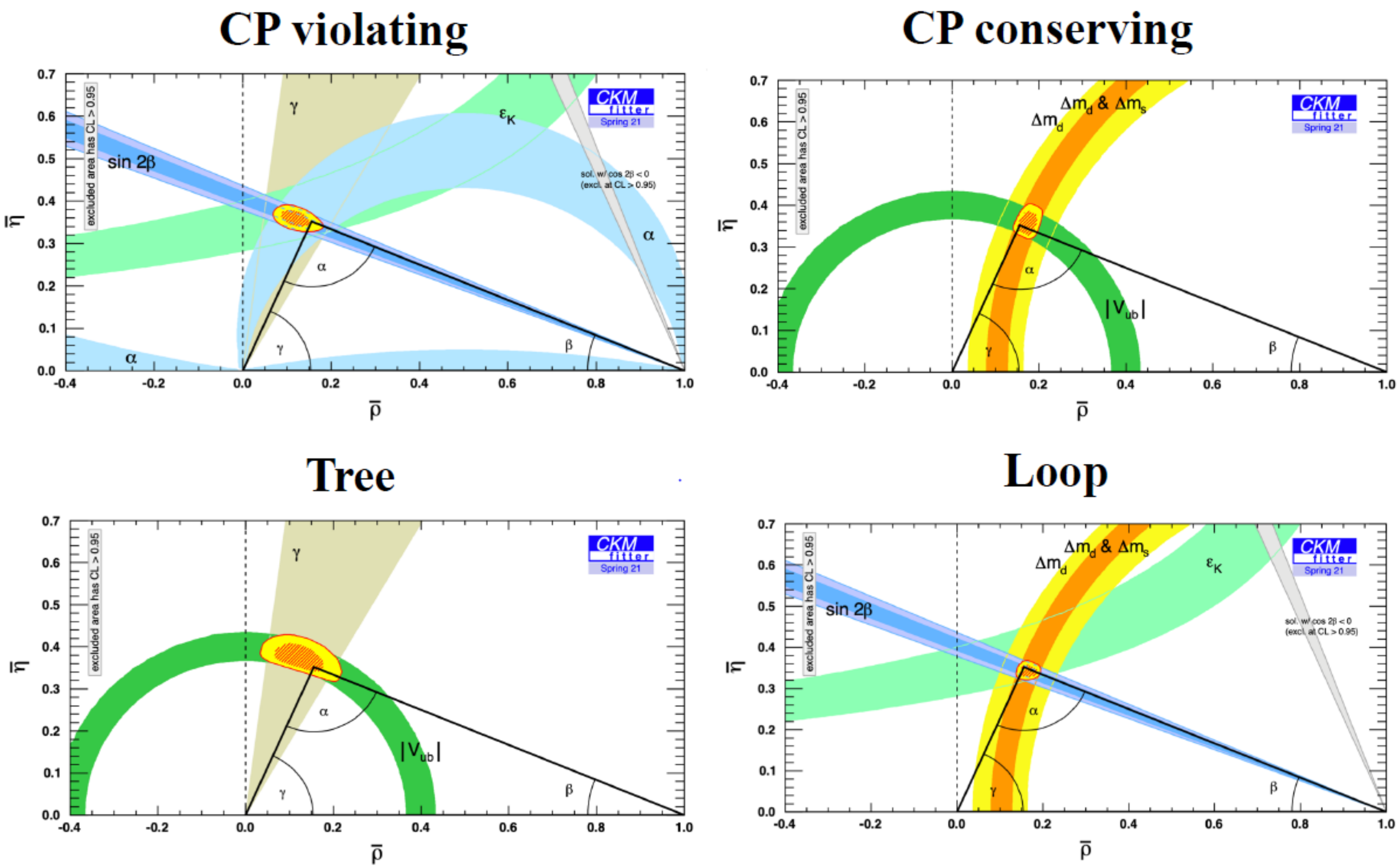
$$\begin{pmatrix} B_S^0 = s\bar{b} \\ \overline{B_S^0} = \bar{d}s \end{pmatrix}$$



	$\boldsymbol{B^0 = d\bar{b}\ \ \overline{B^0} = \bar{d}b}$	$\boldsymbol{B_S^0 = s\bar{b}\ \ \overline{B_S^0} = \bar{d}s}$
Oscillations parameter	$x_d = \frac{\Delta m_d}{\overline{\Gamma_d}} \approx 0.72$	$x_s = \frac{\Delta m_s}{\overline{\Gamma_s}} \approx 24$
Large mass difference	$\Delta m_d \approx 3.3 \cdot 10^{-13}\ GeV \approx 0.5\ ps^{-1}$	$\Delta m_s \approx 17.8\ ps^{-1}$
Small lifetime difference	$x_d = \frac{\Delta\Gamma_d}{\overline{\Gamma_d}} \approx 5 \cdot 10^{-3}$	$x_d = \frac{\Delta\Gamma_s}{\overline{\Gamma_s}} \approx 0.1$
$\frac{q}{p}$ - sensitivity to weak phase	$\frac{q}{p} = \frac{V_{td}V_{tb}^*}{V_{tb}V_{td}^*} \sim \beta$	$\frac{q}{p} = \frac{V_{ts}V_{tb}^*}{V_{tb}V_{ts}^*} \sim \beta_s$

$$\frac{q}{p} = \sqrt{\frac{M_{12}^*}{M_{12}}}$$

Overconstraining CKM matrix



Mixing of B^0 and B^0_S meson*

1. The weak B-meson states are a combination of flavour states:

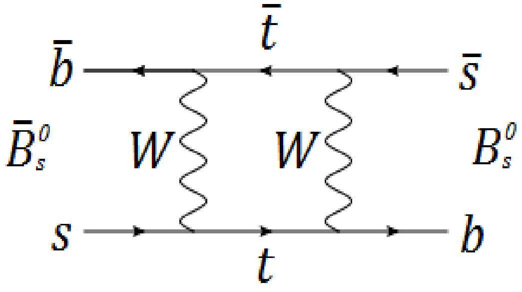
$$|B_L\rangle = p|B^0\rangle + q|\overline{B^0}\rangle \qquad |B_H\rangle = p|B^0\rangle - q|\overline{B^0}\rangle$$

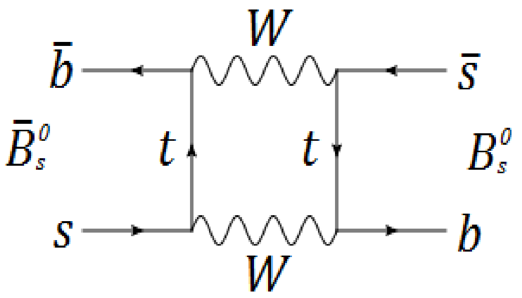
2. In terms of the CKM elements $\boldsymbol{q/p}$ is given by:

$$\frac{q}{p} = \frac{V_{td}V_{tb}^*}{V_{tb}V_{td}^*} = e^{-i2\beta}$$

here d is replaced by s in case of B_S^0

$$\frac{q}{p} = \frac{V_{ts}V_{tb}^*}{V_{tb}V_{ts}^*} = e^{-i2\beta_S}$$





so now the physical states are written as:

$$|B_L\rangle = 1/\sqrt{2}\left[|B^0\rangle + e^{-i2\beta}|\overline{B^0}\rangle\right]$$
$$|B_H\rangle = 1/\sqrt{2}\ \left[|B^0\rangle - e^{-i2\beta}|\overline{B^0}\rangle\right]$$

the eigenstates of the effective Hamiltonian, with definite mass and lifetime, are mixtures of the flavour eigenstates

and β is also called the $\boldsymbol{B^0}$ **mixing phase**

3. The states B_L and B_H are lighter and heavier state, with almost identical lifetimes: $\Gamma_L = \Gamma_H \equiv \Gamma$

4. The mass difference $\boldsymbol{\Delta m}$ between them is greater then in kaons.

Mixing of B^0 and B_S^0 meson*

5. If we write the flavour states as a combination of weak states:

$$|B^0\rangle = 1/\sqrt{2}\,[|B_L\rangle + |B_H\rangle]$$

then the wavefunction evolves according to the time dependence of physical states:

$$\boldsymbol{|B(t)\rangle = 1/\sqrt{2}\{a(t)|B_L\rangle + b(t)|B_H\rangle\}}$$

where time dependence of coefficients is:

$$\boldsymbol{a(t)} = e^{-i(m_L - \frac{i}{2}\Gamma)t} \qquad \boldsymbol{b(t)} = e^{-i(m_H - \frac{i}{2}\Gamma)t}$$

Now substitute $a(t)$ and $b(t)$ and $|B_{L,H}\rangle$ into time-dependent wave function.

Do not forget to express mass states as a combination of flavour states….

$$|B_L\rangle = 1/\sqrt{2}\,[|B^0\rangle + e^{-i2\beta}|\overline{B^0}\rangle]$$
$$|B_H\rangle = 1/\sqrt{2}\,[|B^0\rangle - e^{-i2\beta}|\overline{B^0}\rangle]$$

Mixing of B^0 and B_S^0 meson*

6. Now substitute $a(t)$ and $b(t)$ and $|B_{L,H}\rangle$ into time-dependent wave function:

$$|\boldsymbol{B(t)}\rangle = \mathbf{1}/\sqrt{\mathbf{2}}\{\boldsymbol{a(t)}|\boldsymbol{B_L}\rangle + \boldsymbol{b(t)}|\boldsymbol{B_H}\rangle\}$$

$$|B_L\rangle = 1/\sqrt{2}\left[|B^0\rangle + e^{-i2\beta}|\overline{B^0}\rangle\right]$$

$$|B_H\rangle = 1/\sqrt{2}\left[|B^0\rangle - e^{-i2\beta}|\overline{B^0}\rangle\right]$$

$$\boldsymbol{a(t)} = e^{-i(m_L - \frac{i}{2}\Gamma)t} \qquad \boldsymbol{b(t)} = e^{-i(m_H - \frac{i}{2}\Gamma)t}$$

…. and calculate the probabilities of the state to stay as a $|B^0\rangle$

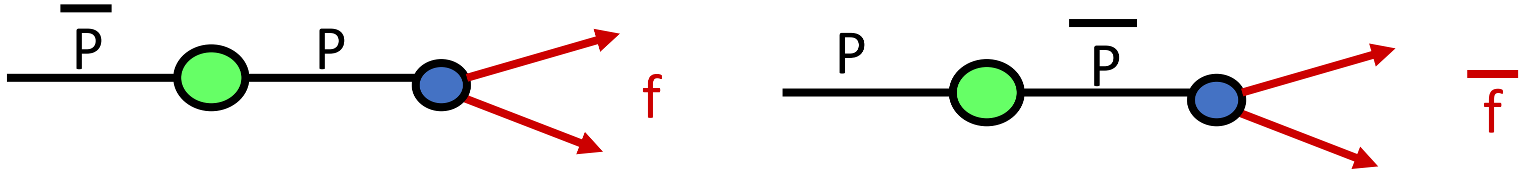
$$P(B^0(t=0) \to B^0;\mathrm{t}) = |\langle B^0(t)|B^0\rangle|^2 =..=..= e^{-\Gamma t}\, cos^2\left(\frac{\Delta m}{2}t\right)$$

7. The same calculation can be done for B_S^0

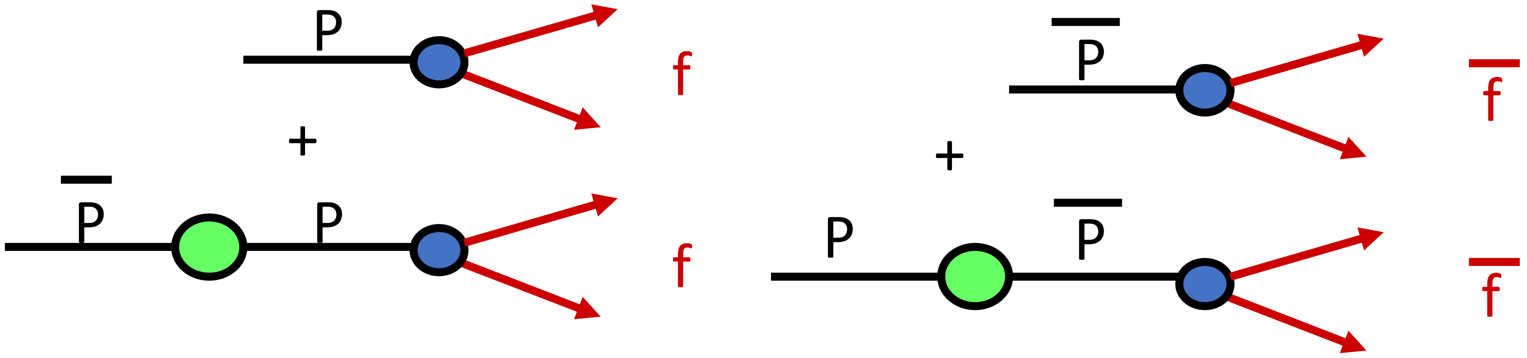
CP violation – three ways

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



CP violation – it's all about amplitudes

- One of the simplest way to discover $\mathcal{CP}V$ is to compare the decay rates $\Gamma(P \to f)$ with $\Gamma(\overline{P}) \to \overline{f}$

$$\Gamma(P \to f) \propto N_{cand}$$

- This is a method for direct $\mathcal{CP}V$ in decay amplitudes, when two amplitudes with different phases interfere.
- If we define the asymmetry between $\mathcal{CP}$ conjugated decays, for charged and neutral mesons:

$$A_{CP,dir} = \frac{\Gamma\{P \to f\} - \Gamma\{\overline{P} \to \overline{f}\}}{\Gamma\{P \to f\} + \Gamma\{\overline{P} \to \overline{f}\}}$$

where:

$$\Gamma(P \to f) \propto \left|A_f\right|^2$$

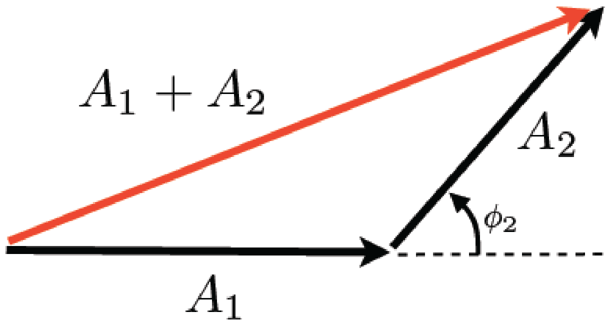
- Amplitude A_f is defined as a matrix element that describes the transition between state P and f, such that $P \to f$ depends on: $A_f = \langle f|H|P\rangle$ and $\overline{P} \to f$ on: $\overline{A_f} = \langle f|H|\overline{P}\rangle$

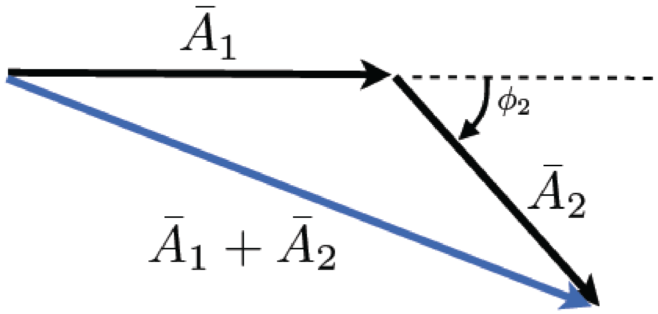
Essence of amplitude interference

$$A_j = \langle \mathrm{final}|H_j|\mathrm{initial}\rangle = |A_j| e^{+i\phi_j^{\mathrm{weak}}}$$

CP

$$\bar{A}_j = A_j^* = |A_j| e^{-i\phi_j^{\mathrm{weak}}}$$





$$P(i \to f) = |A_1 + A_2|^2$$

$$P(\bar{i} \to \bar{f}) = |\bar{A}_1 + \bar{A}_2|^2$$

$$= |A_1|^2 + 2|A_1||A_2|\cos\phi_2 + |A_2|^2$$

In case of only one decay amplitude – the decay rates are equal:

$$\boldsymbol{\Gamma(P \to f) = \Gamma(\bar{P} \to \bar{f})}$$

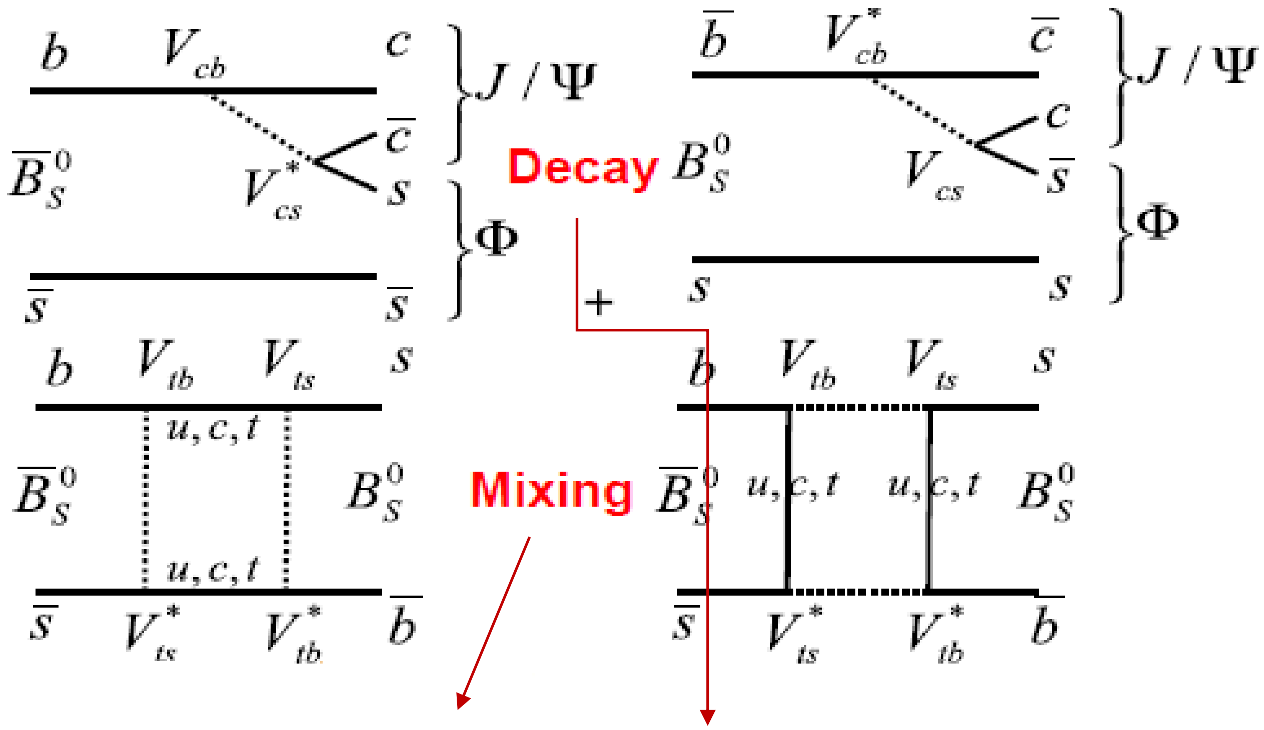
and no CP violation occurs.

For two amplitudes the decay rates may differ and the asymmetry is sensitive to relative phase

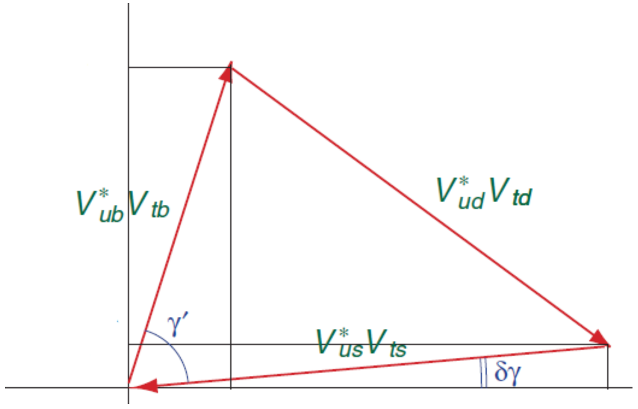
$$A = \frac{|\bar{A}_f|^2 - |A_f|^2}{|\bar{A}_f|^2 + |A_f|^2}$$

The weak phase ϕ_s

The weak phase ϕ_s can be extracted from tagged Bs decays to CP eigenstates: $B_s \to J/\psi\phi$



$\phi_s = -0.036 \pm 0.002$

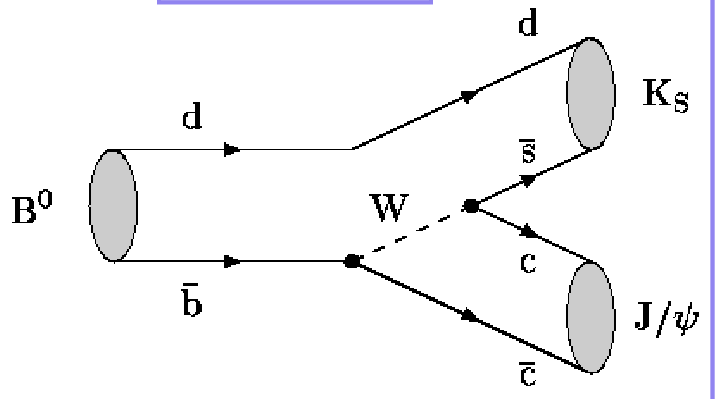


Very small value of ϕ_s is predicted in SM. So any deviation from zero is a sign of new particle exchanged – Physics Beyond the Standard Model

Golden channel for $\sin 2\beta$

1. The process $B^0 \to J/\psi \; K_S$ is called the „golden mode" for measurement of the β angle:
   a) clean theoretical description,
   b) clean experimental signature,
   c) large (for a B meson) branching fraction of order ~10^{-4}.
2. This is a process with interference of amplitudes with and without mixing:

Amplitude 1



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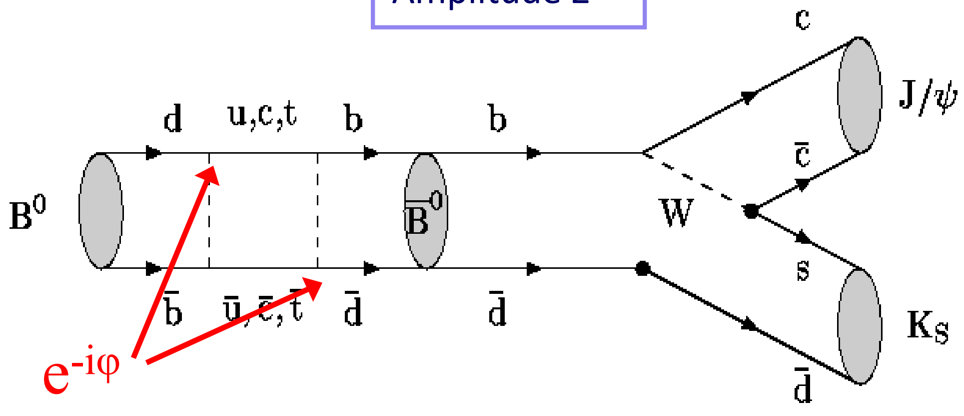
Amplitude 2



(φ=2β)

3. The β angle sensitivity comes from the $B^0 \leftrightarrow \overline{B^0}$ mixing due to the $\bar{t} \to \bar{d}$ and $t \to d$ transitions.

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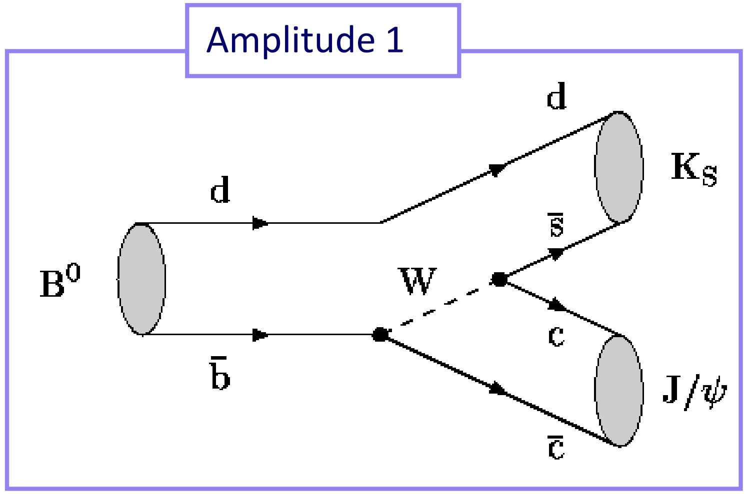
   c) large (for a B meson) branching fraction of order ~10^{-4}.
2. This is a process with interference of amplitudes with and without mixing:



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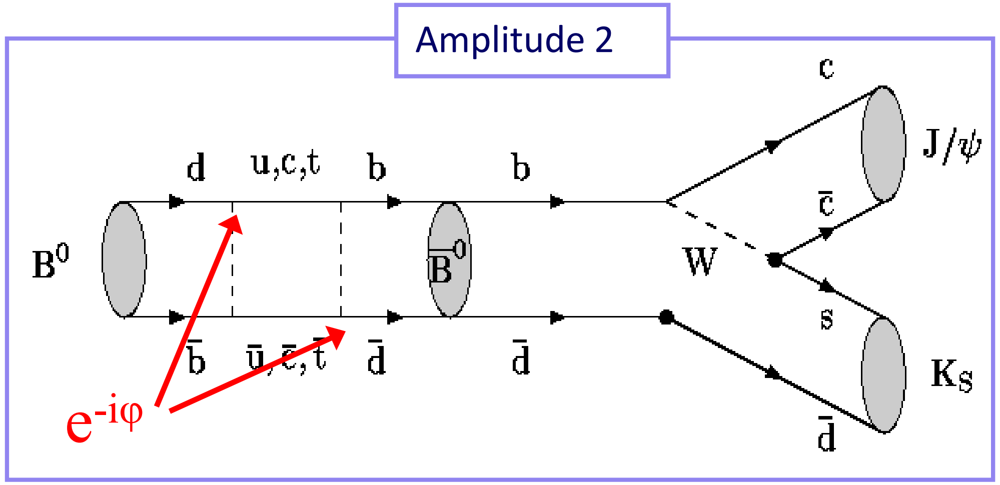


($\varphi=2\beta$)

3. The β angle sensitivity comes from the $B^0 \leftrightarrow \overline{B^0}$ mixing due to the $\bar{t} \rightarrow \bar{d}$ and $t \rightarrow d$ transitions.

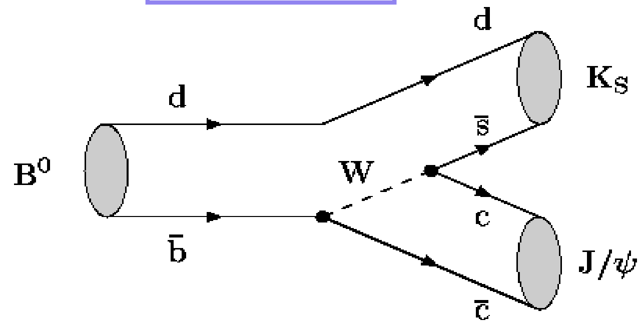
Golden channel for $\sin 2\beta$

4. We need to calculate the asymmetry of the type:

$$A_{CP}(t) = \frac{\Gamma_f - \overline{\Gamma_f}}{\Gamma_f + \overline{\Gamma_f}}$$

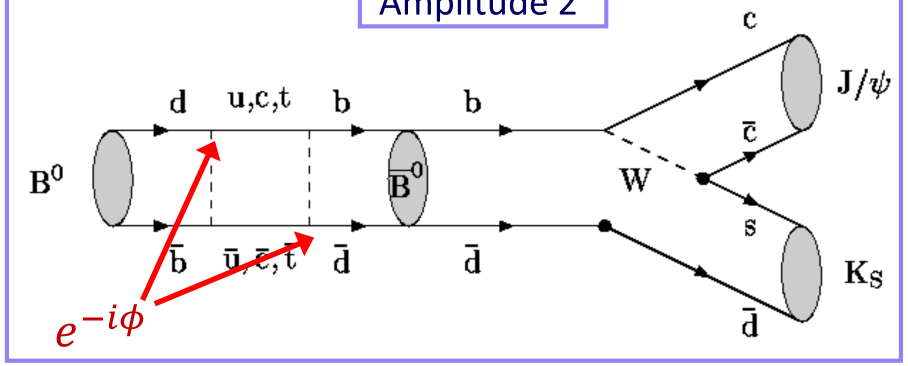
and remember that decay rate depends on (see lect 4): $\Gamma(B \to f) \propto |A_f|^2 = |A_1 + A_2|^2$

Amplitude 1



+

Amplitude 2



$\phi = 2\beta$

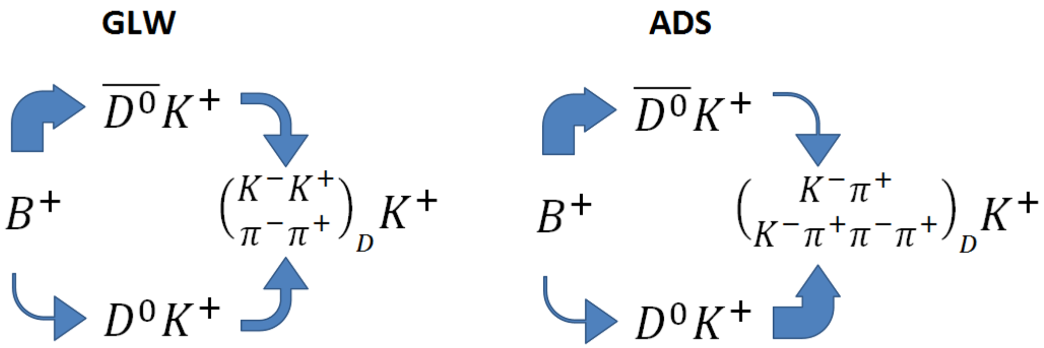
$$\Gamma(B \to J/\psi\ K_S) = \left| A e^{-imt-\Gamma t} \left(\cos\frac{\Delta m t}{2} + e^{-i\phi} \sin\frac{\Delta m t}{2} \right) \right|^2$$

$$A_{CP}(t) = \frac{\Gamma\{B \to J/\psi\ K_S\} - \Gamma\{\bar{B} \to J/\psi\ K_S\}}{\Gamma\{B \to J/\psi\ K_S\} + \Gamma\{\bar{B} \to J/\psi\ K_S\}} =$$

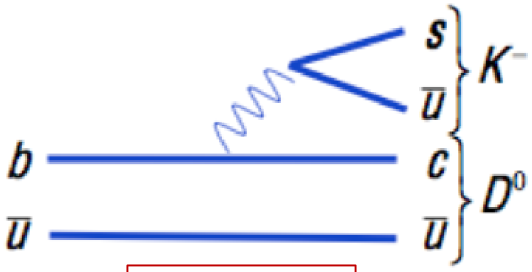
$$-\sin 2\boldsymbol{\beta} \sin \Delta m t$$

Time integrated methods $B_s^0 \rightarrow D_s^- K^+$: CKM γ angle

- This is a measurement of angle γ with the processes $B^{\pm} \rightarrow D^0 K^{\pm}$.
- Plenty of methods which differ by the final states:

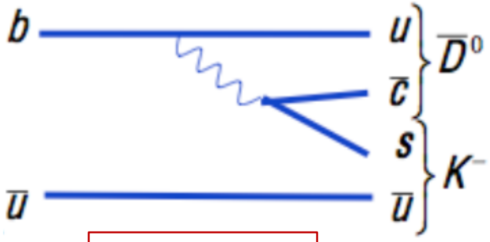


Interference between two diagrams:



$\propto V_{cb} V_{us}^*$

colour allowed



$\propto V_{ub} V_{cs}^*$

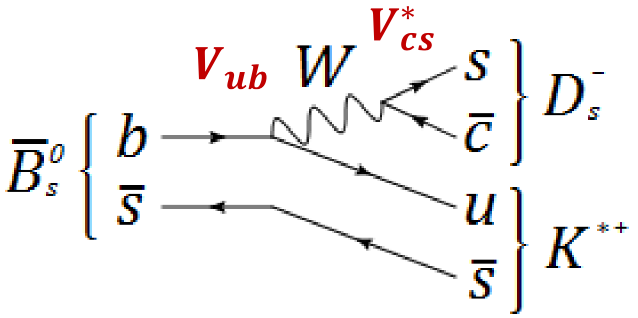
colour suppressed

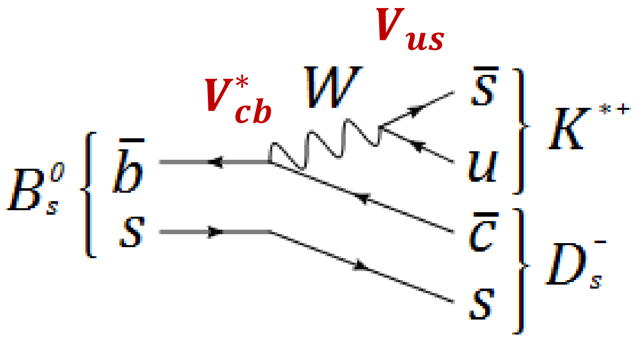
$$A_{CP} = \frac{\Gamma\{B^- \rightarrow D^0 K^-\} - \Gamma\{B^+ \rightarrow D^0 K^+\}}{\Gamma\{B^- \rightarrow D^0 K^-\} + \Gamma\{B^+ \rightarrow D^0 K^+\}} \propto \sin\gamma$$

Time dependent methods $B_s^0 \to D_s^- K^+$: CKM γ angle

$\boldsymbol{B_s^0}$ and $\boldsymbol{\overline{B_s^0}}$ decay to the same final state.

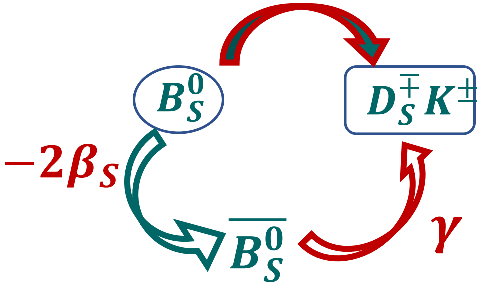
$$V_{CKM} = \begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}|e^{-i\beta} & -|V_{ts}|e^{i\beta_s} & |V_{tb}| \end{pmatrix}$$





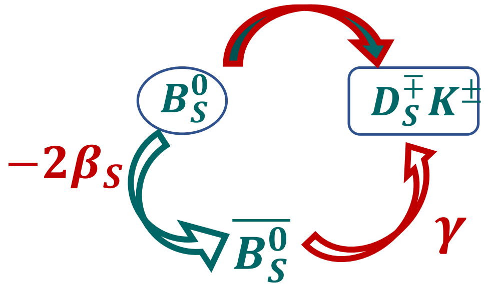
$\boldsymbol{B_s^0}$ and $\boldsymbol{\overline{B_s^0}}$ can oscillate into one another.

So we have interference between two processes:



Time dependent methods $B_s^0 \to D_s^- K^+$: CKM γ angle

We have some experience in decay rate equation…
The probability of B meson decay to final state f is given by the Fermi golden rule:



$$\Gamma_{B_s^0 \to f}(t) \sim |\langle f|T|B_s^0(t)\rangle|^2$$

and we can try to calculate it…

$$\Gamma_{B_s^0 \to f}(t) = |A_f|^2 \left(1 + |\lambda_f|^2\right) \frac{e^{-\Gamma_s t}}{2} \cdot \left(\cosh\frac{\Delta\Gamma_s t}{2} + D_f \sinh\frac{\boldsymbol{\Delta\Gamma_s} t}{2} + C_f \cos \boldsymbol{\Delta m_s} t - S_f \sin \Delta m_s t\right)$$

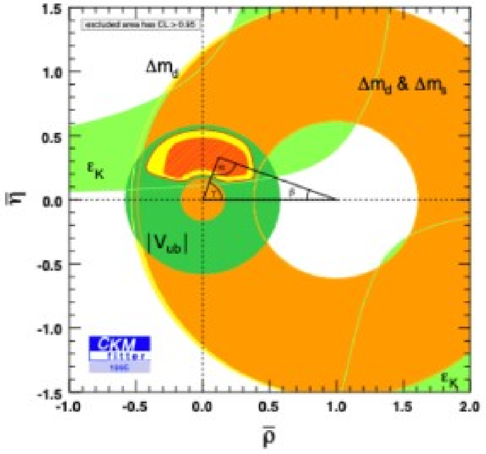
$$\Gamma_{\overline{B}_s^0 \to f}(t) = |A_f|^2 \left|\frac{p}{q}\right|^2 \left(1 + |\lambda_f|^2\right) \frac{e^{-\Gamma_s t}}{2} \cdot \left(\cosh\frac{\Delta\Gamma_s t}{2} + D_f \sinh\frac{\Delta\Gamma_s t}{2} - C_f \cos \Delta m_s t + S_f \sin \Delta m_s t\right)$$

$$D_f = \frac{2Re\lambda_f}{1 + |\lambda_f|^2} \qquad C_f = \frac{1 - |\lambda_f|^2}{1 + |\lambda_f|^2} \qquad S_f = \frac{2Im\lambda_f}{1 + |\lambda_f|^2} \qquad \lambda_f \equiv \frac{1}{\bar{\lambda}_f} = \frac{q}{p}\frac{\bar{A}_f}{A_f}$$

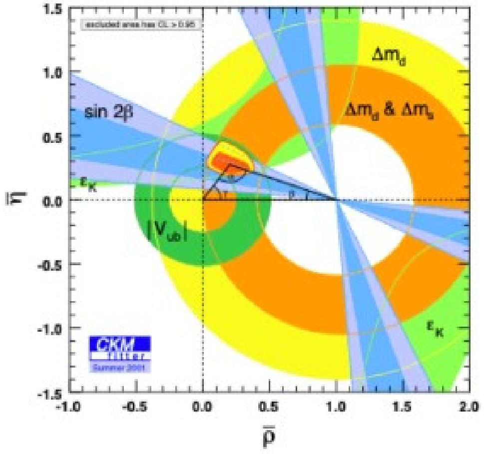
$$A_f = \langle f|T|B_s^0\rangle \qquad \bar{A}_{\bar{f}} = \langle \bar{f}|T|\bar{B}_s^0\rangle$$

$$\boldsymbol{\Gamma(P \to f) \propto N_{cand}}$$

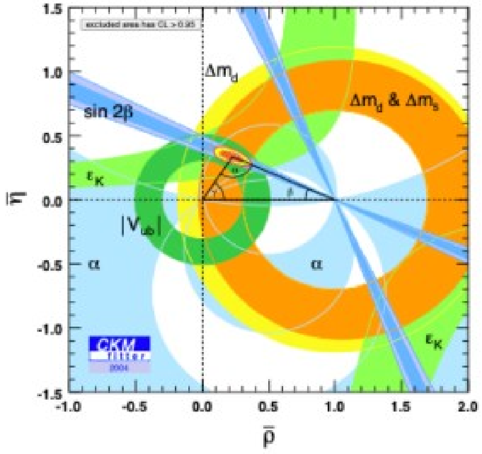
More and more precise



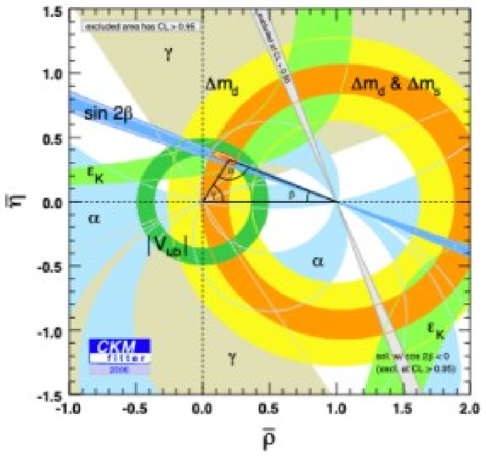
1995



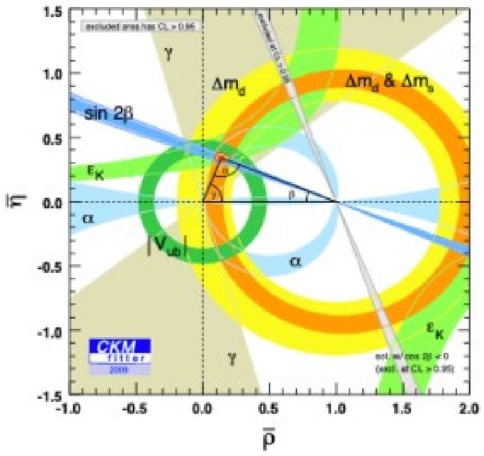
2001



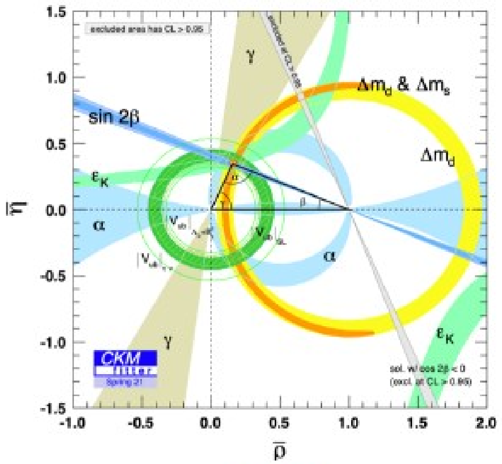
2004



2006



2009

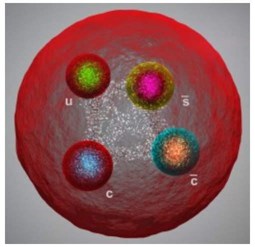


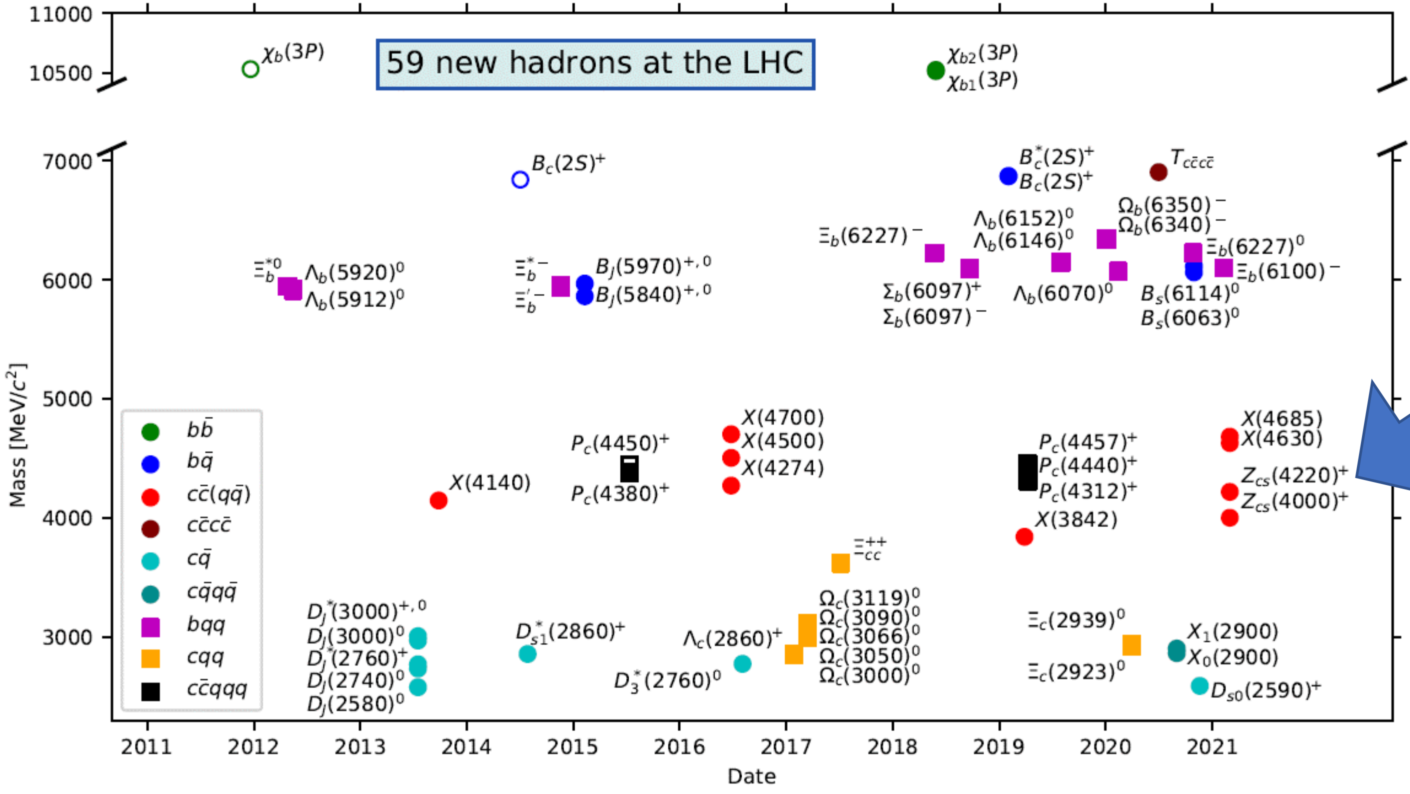
2021

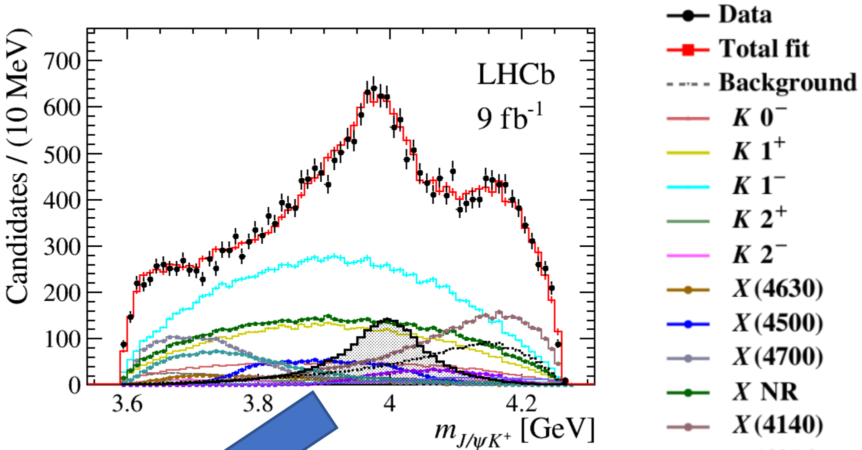
http://ckmlive.in2p3.fr/

Heavy flavour physics – spectroscopy

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



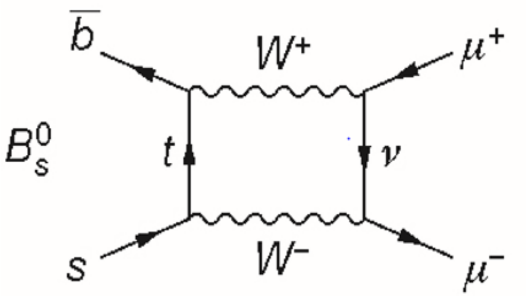


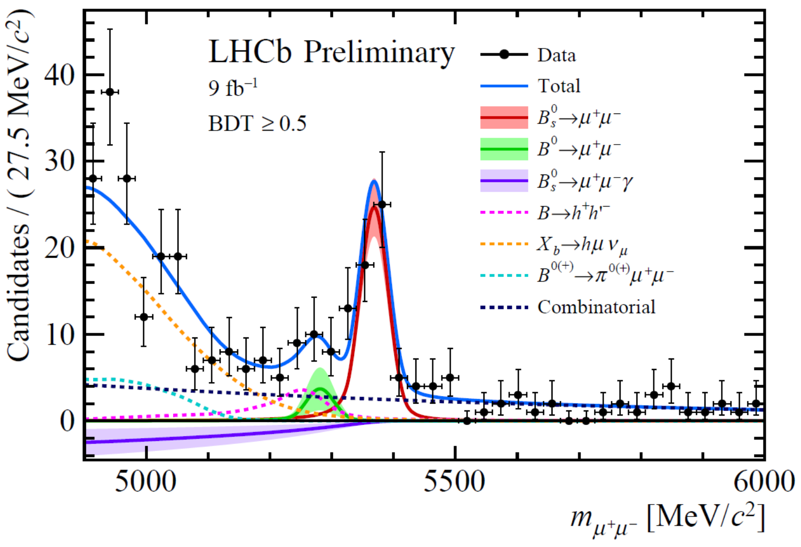


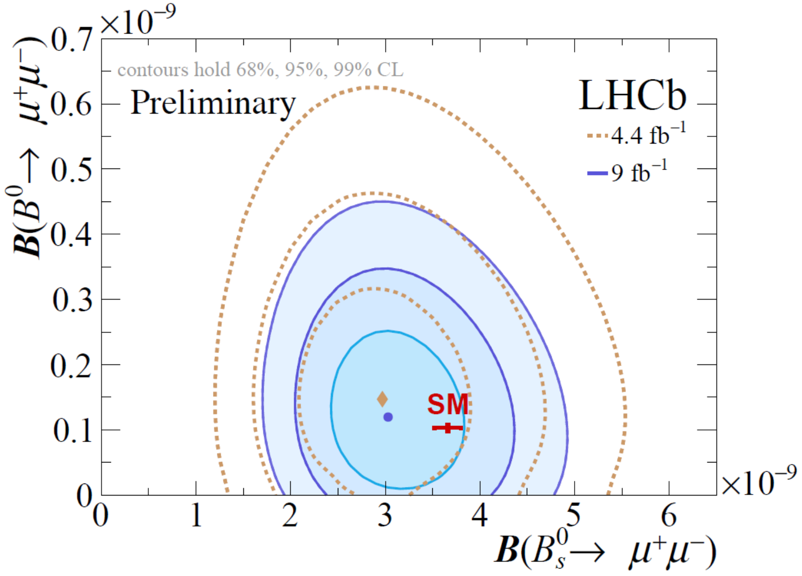
The Ultimate Quest to find New Physics

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

- 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

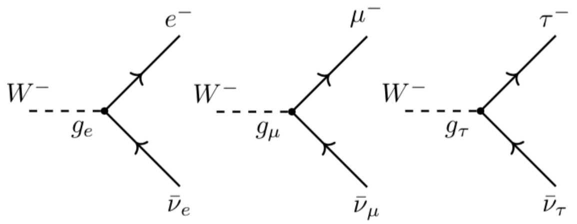
The Ultimate Quest to find New Physics

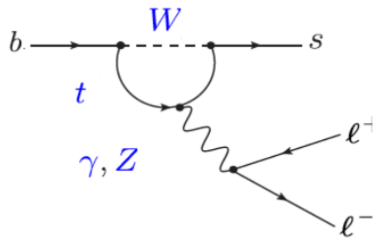
CERN-EP-2021-042
LHCb-PAPER-2021-004
23 March 2021

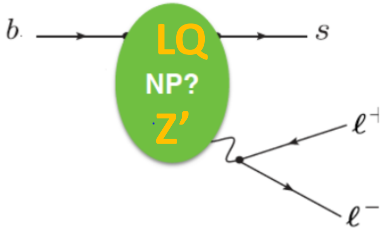
arXiv:2103.11769

Nature Physics

Lepton universality

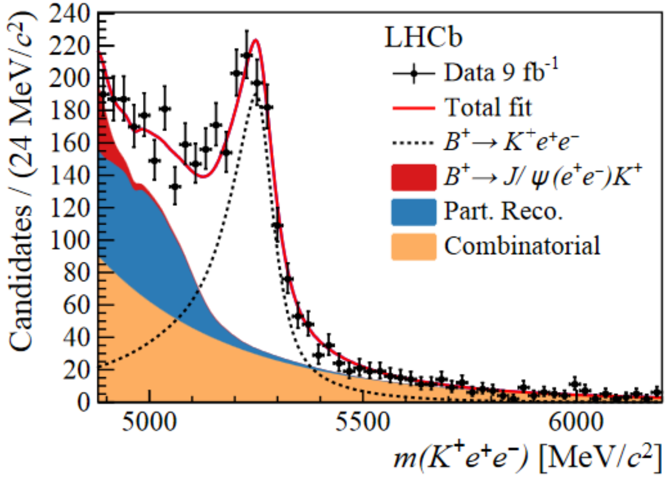


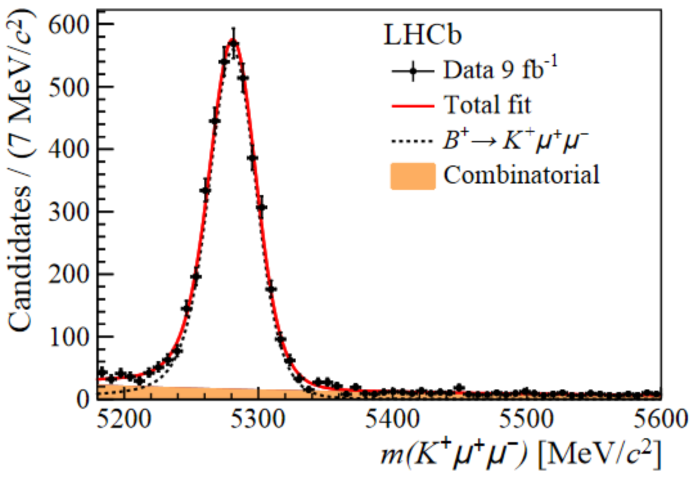


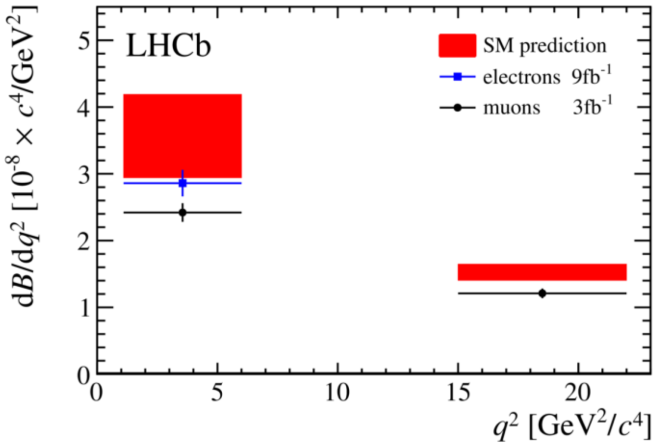


- SM couplings of charged leptons to gauge bosons are identical
- Very clean and precise measurement at electron collider

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





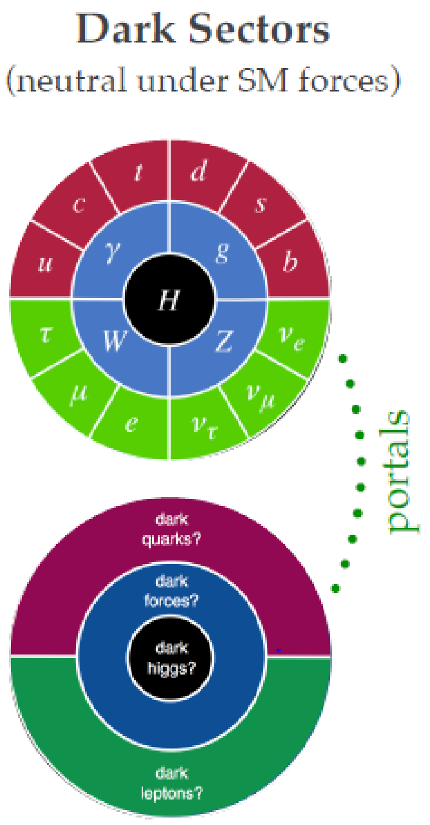


$$R_K = 0.846\ ^{+0.042}_{-0.039}\ (stat)\ ^{+0.013}_{-0.012}\ (syst)$$

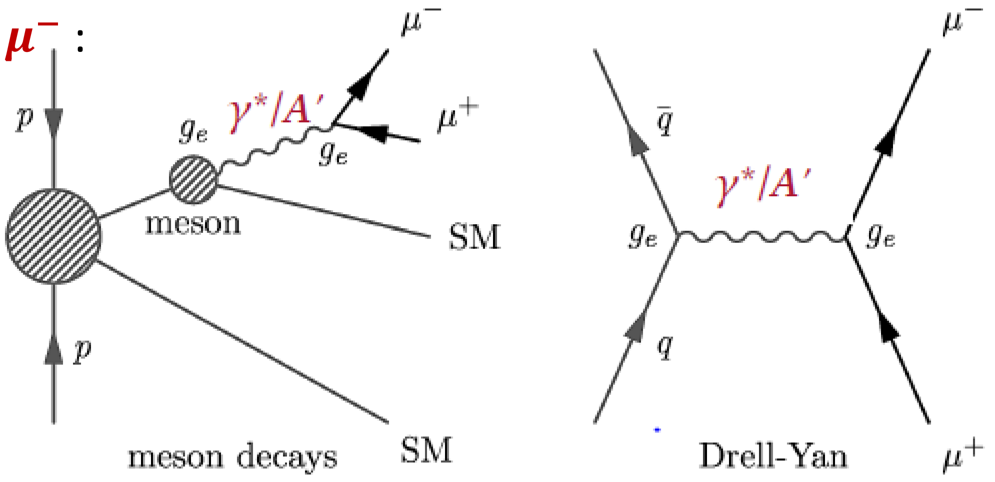
p-value under SM hypothesis: 0.0010

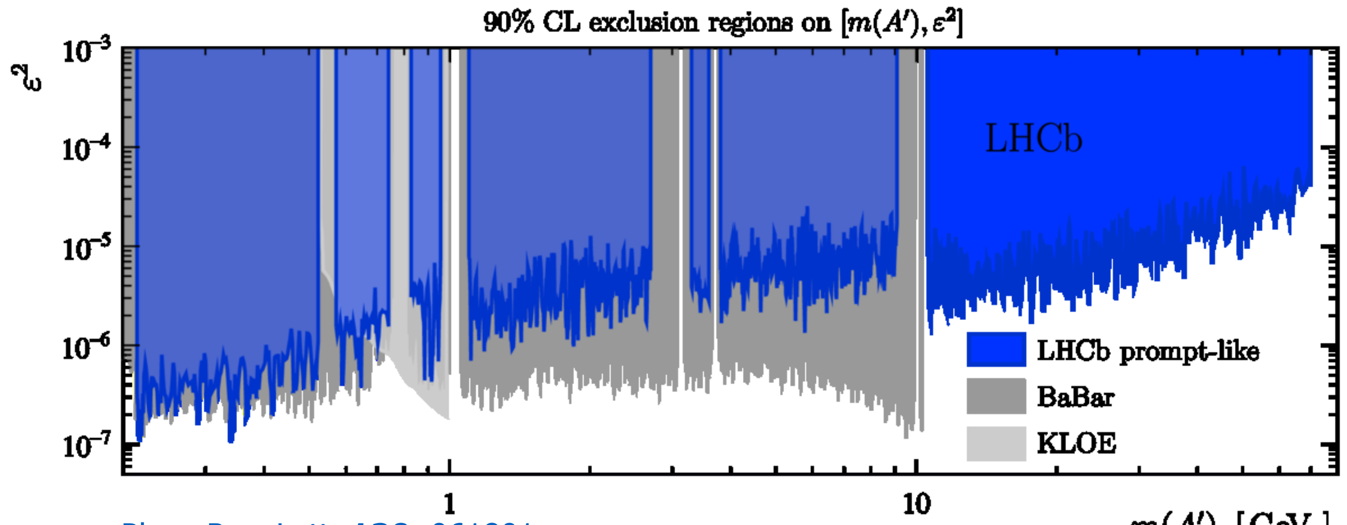
evidence of LFU violation at 3.1σ

The Ultimate Quest to find New Physics – Dark Matter



Dark photons searches $A' \to \mu^+\mu^-$:
- massive
- massles





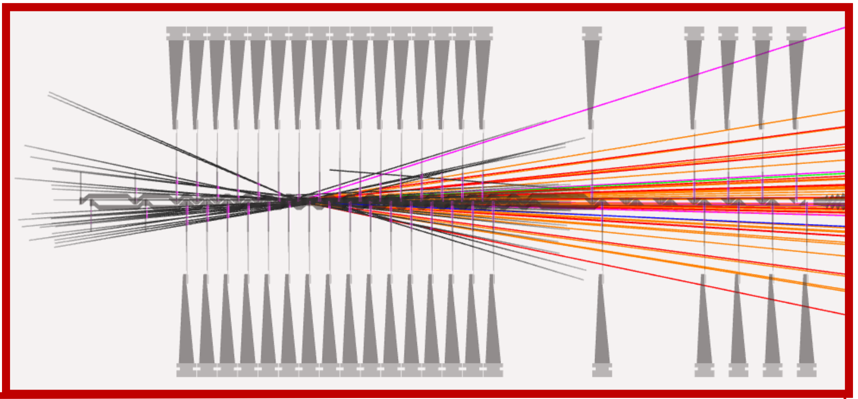
Phys. Rev. Lett. **120**, 061801

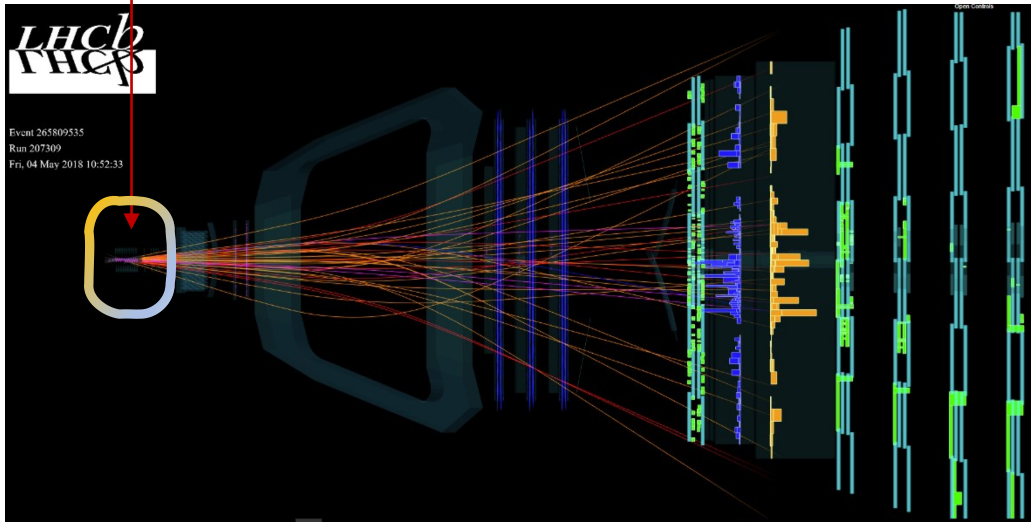
IV. How to do precise measurements

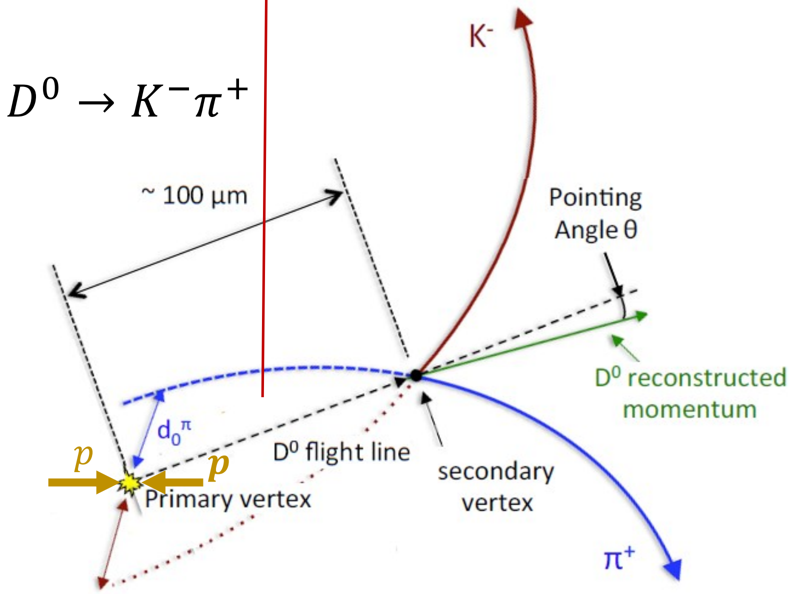
- flavour
- time
- mass

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.

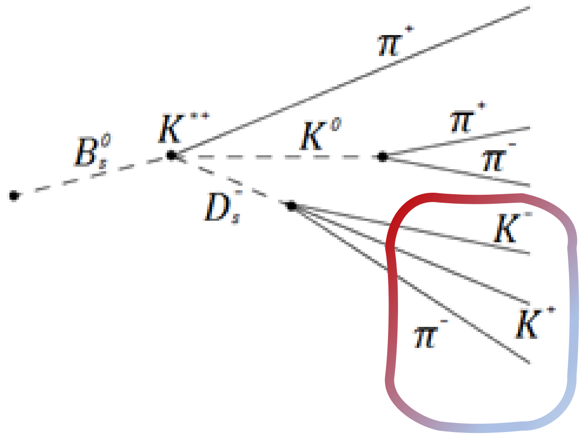


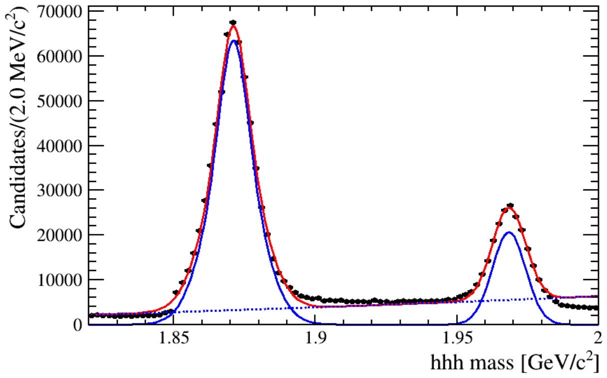




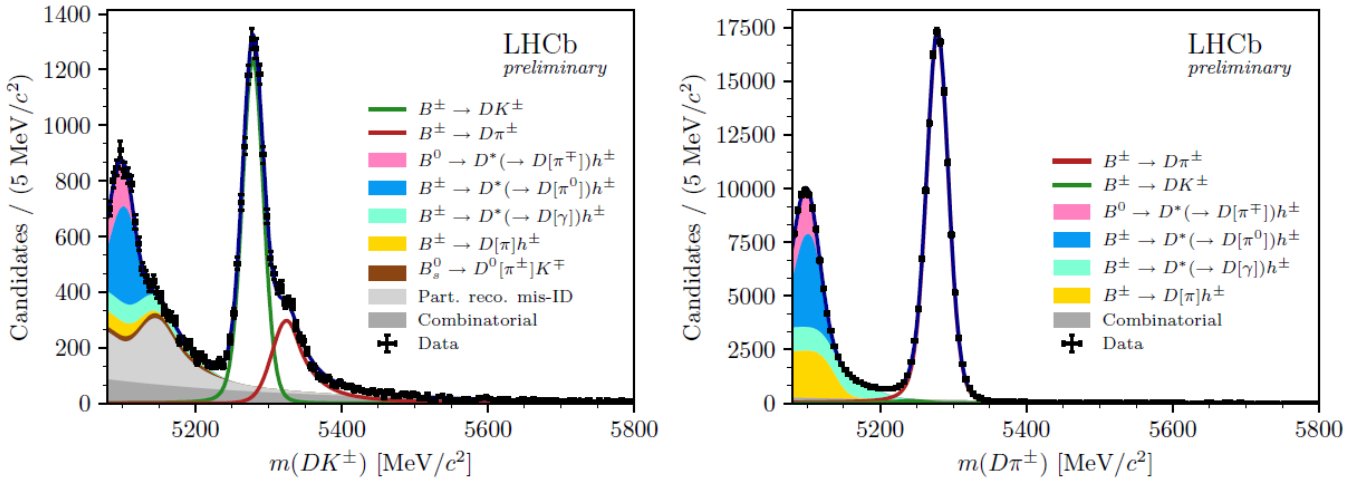
Mass and life-time distribution – selection and fitting

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





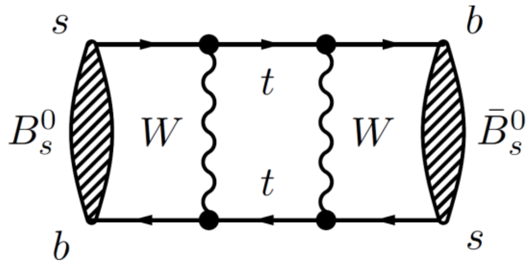
1) track reconstruction
2) particle identification
3) pre-selection
4) selection
5) multivariate analysis
6) distribution fitting

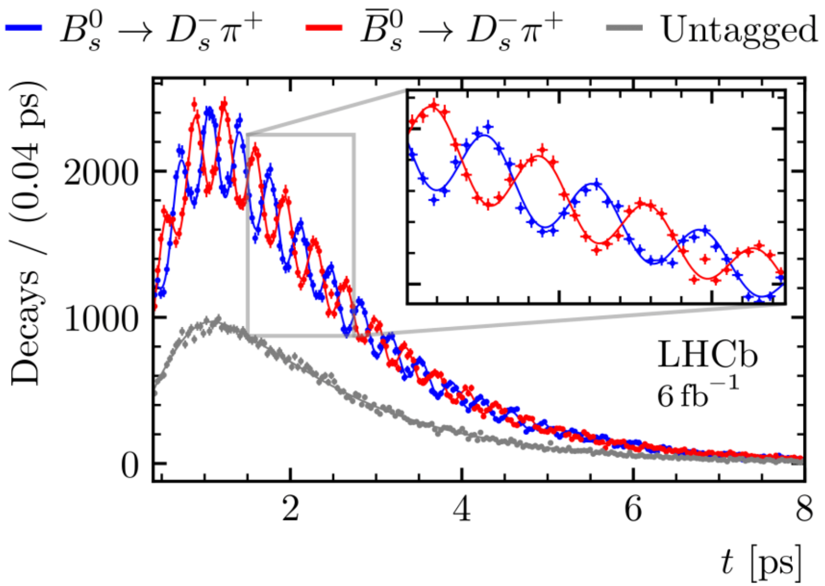


Precise determination of the B_s^0–B_s^0 oscillation frequency

Visual example of the quantum-mechanical nature of our universe

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





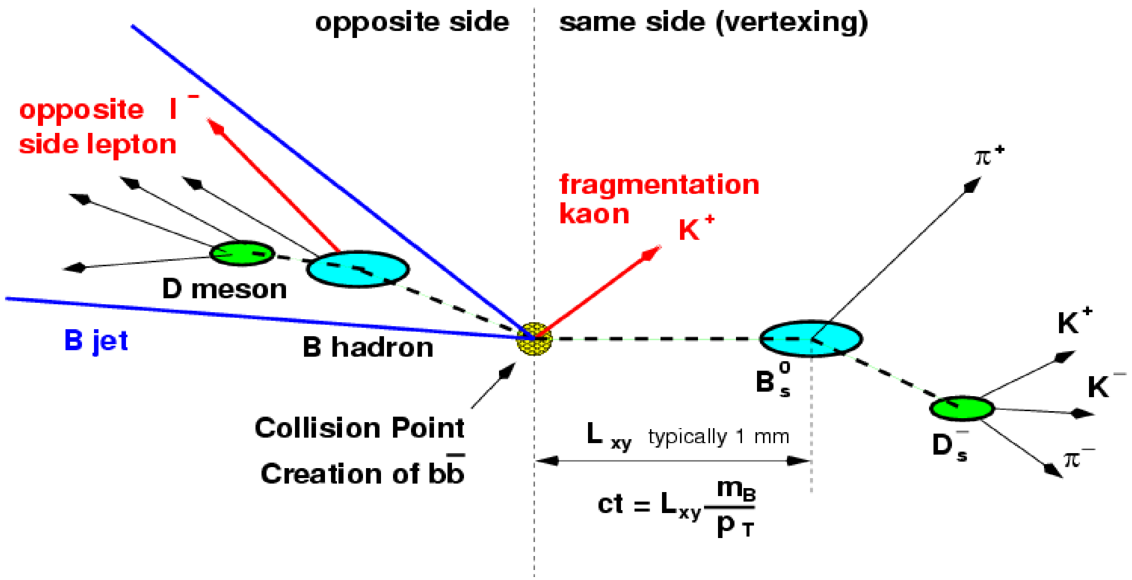
$\Delta m_s = 17.7683 \pm 0.0051(stat) \pm 0.0032(syst)\ ps^{-1}$

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

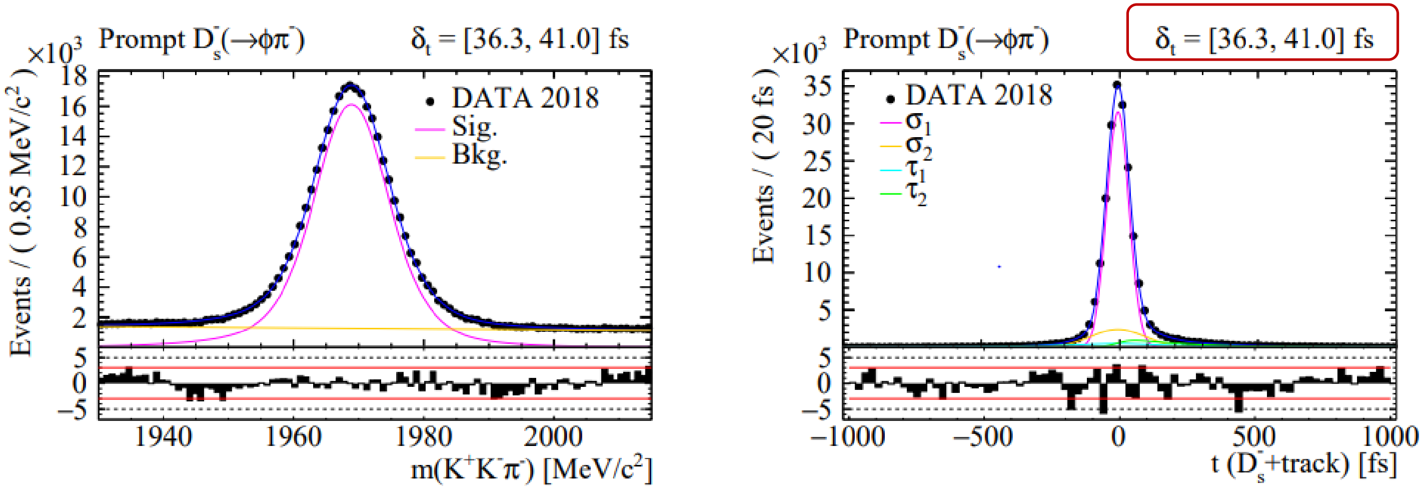
B^0 or $\overline{B}^0$?

1. Need to determine:
   a) Flavour at production ⇔ **tagging**
   b) Flavour at decay, from final state
   c) B decay length

Tagging parameters
- dilution *D = 1 – 2w*
- *w* = mistag probability
- ε = efficiency
- εD^2 = effective tagging power



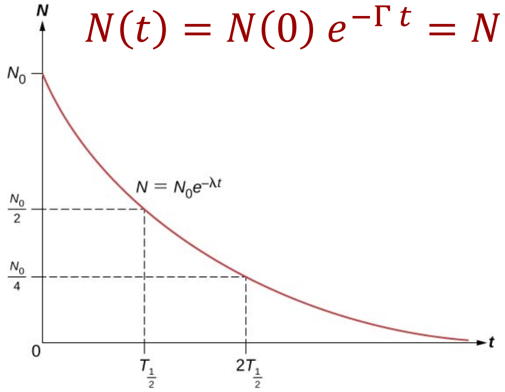
Decay mode tags b flavor at decay



Time measurement

Decay time and oscillations:

$N(t) = N(0)\, e^{-\Gamma t} = N(0) e^{\frac{-t}{\tau}}$



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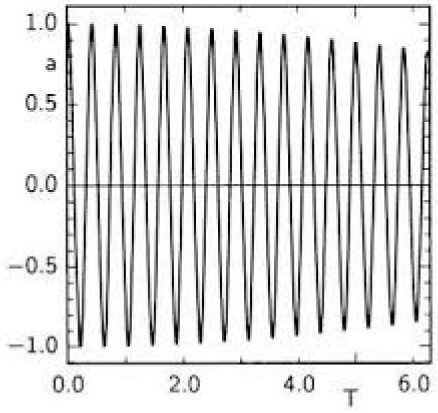

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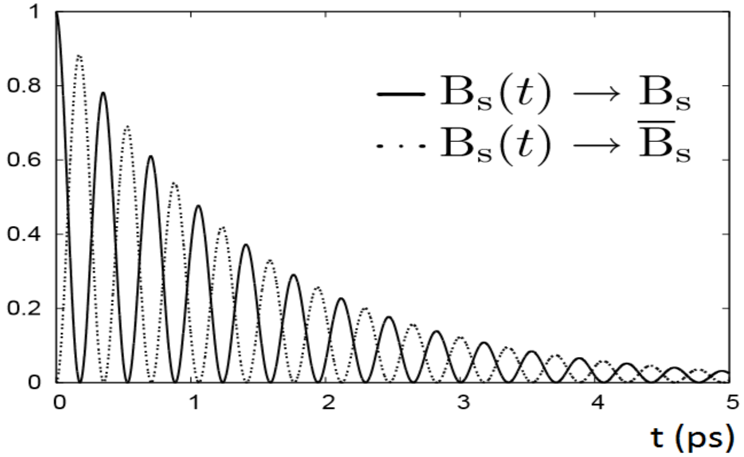
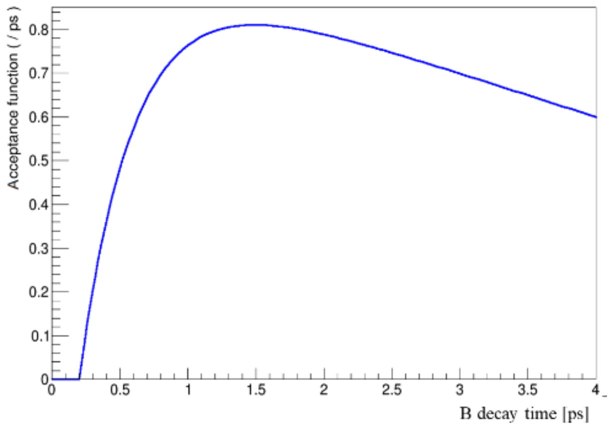


Detector acceptance:



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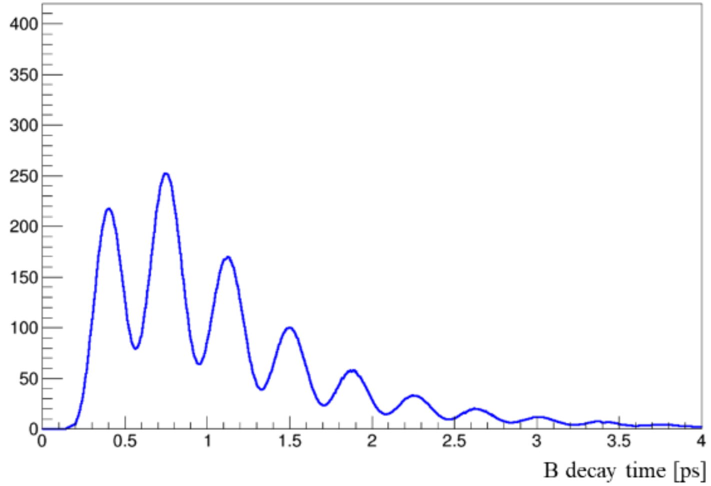
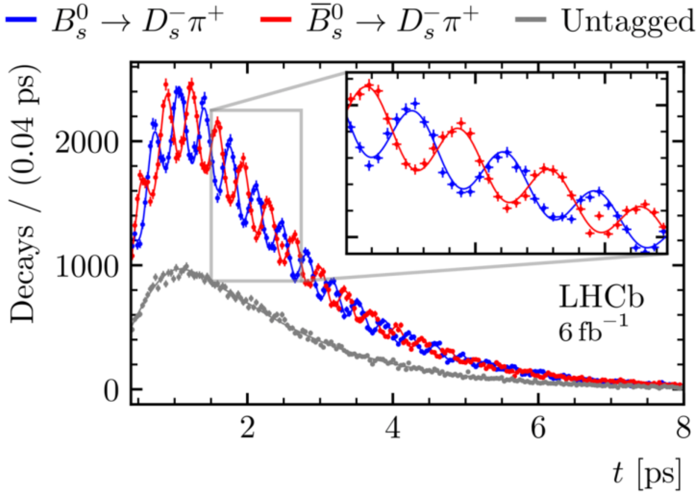




Time dependent $B_s^0 \to D_s^- K^+$ detector effects

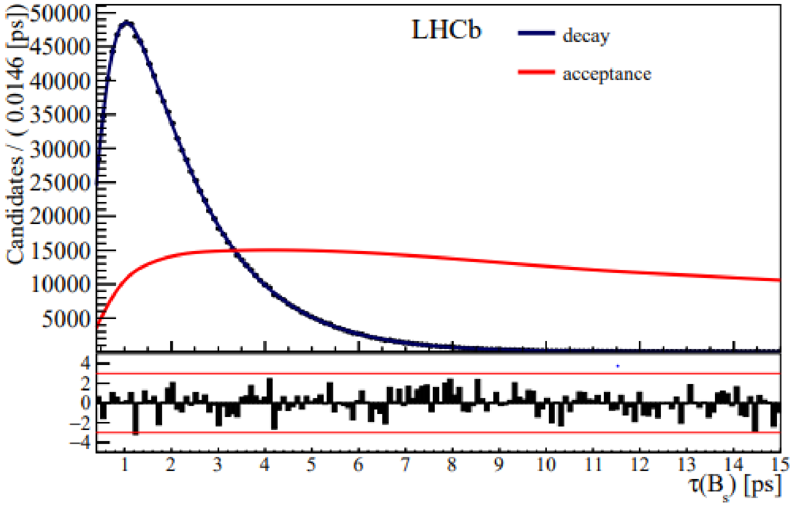
real data

time resolution

The finite decay-time resolution of the detector leads to a dilution of the observable oscillation if the resolution is of similar magnitude compared to the oscillation period

acceptance & cuts

$$\frac{d\Gamma(t)^{acc}}{dt} = \frac{d\Gamma(t)}{dt} \times a(t)$$



tagging

$$\mathcal{P}(t;\delta_t,q,\vec{d},\vec{\eta}) \sim \varepsilon(t)\cdot P(\eta^{OS})\cdot P(\eta^{SS})\cdot P(\delta_t)\int R(t-t'|\delta_t)\cdot P_a(t'|q,\vec{d},\vec{\eta})dt$$

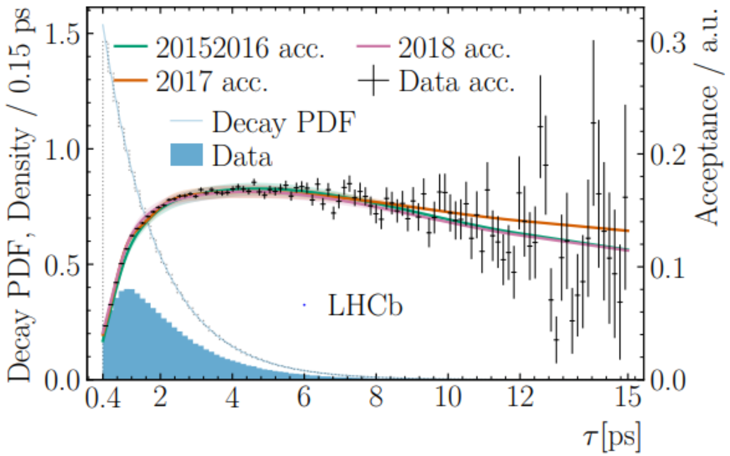
η: mistag estimation

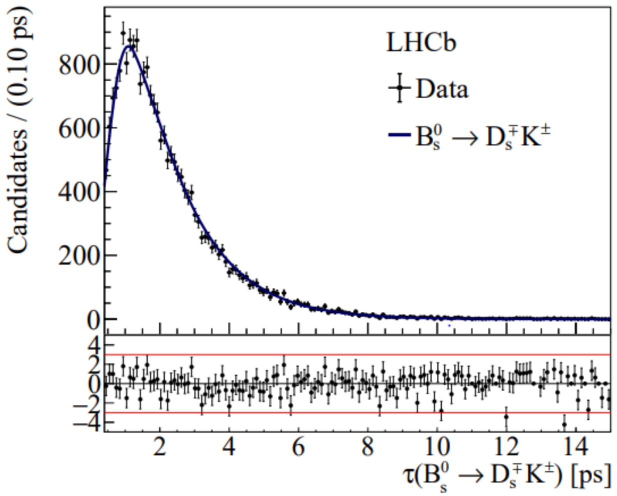
Time dependent $B_s^0 \to D_s^- K^+$ detector effects

real data

time resolution

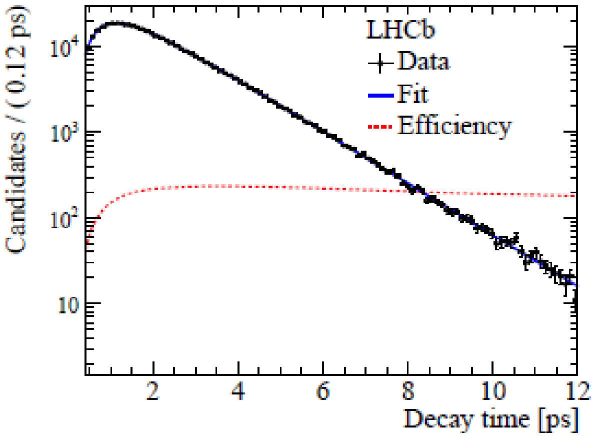
acceptance & cuts





tagging

$B^0 \to D^{\mp}\pi^{\pm}$



$$A_{sig} = \frac{N(B^0 \to D^{\pm}\pi^{\mp}) - N(\bar{B}^0 \to D^{\pm}\pi^{\mp})}{N(B^0 \to D^{\pm}\pi^{\mp}) + N(\bar{B}^0 \to D^{\pm}\pi^{\mp})}$$

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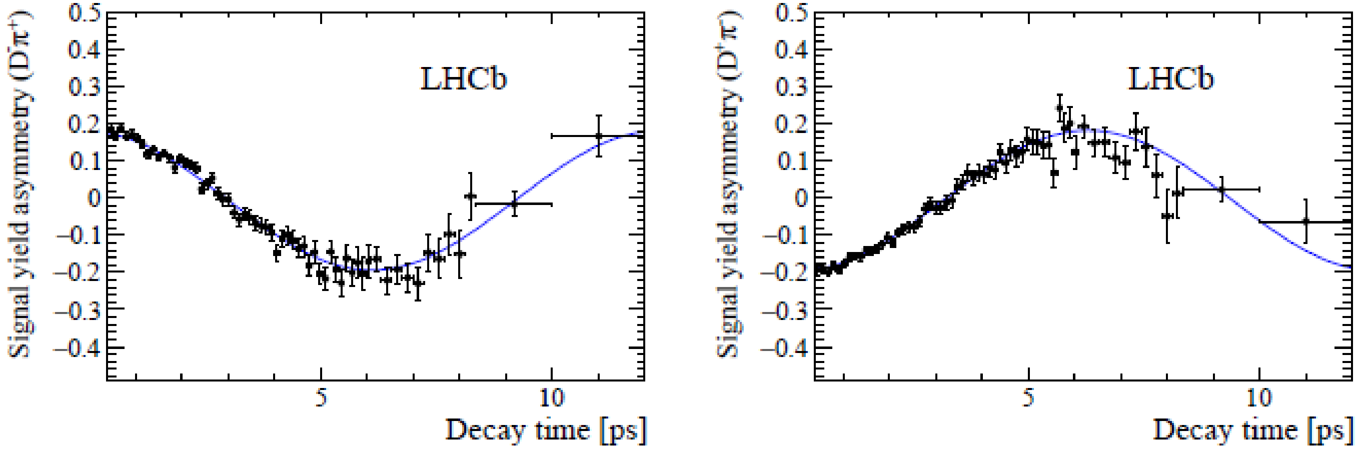
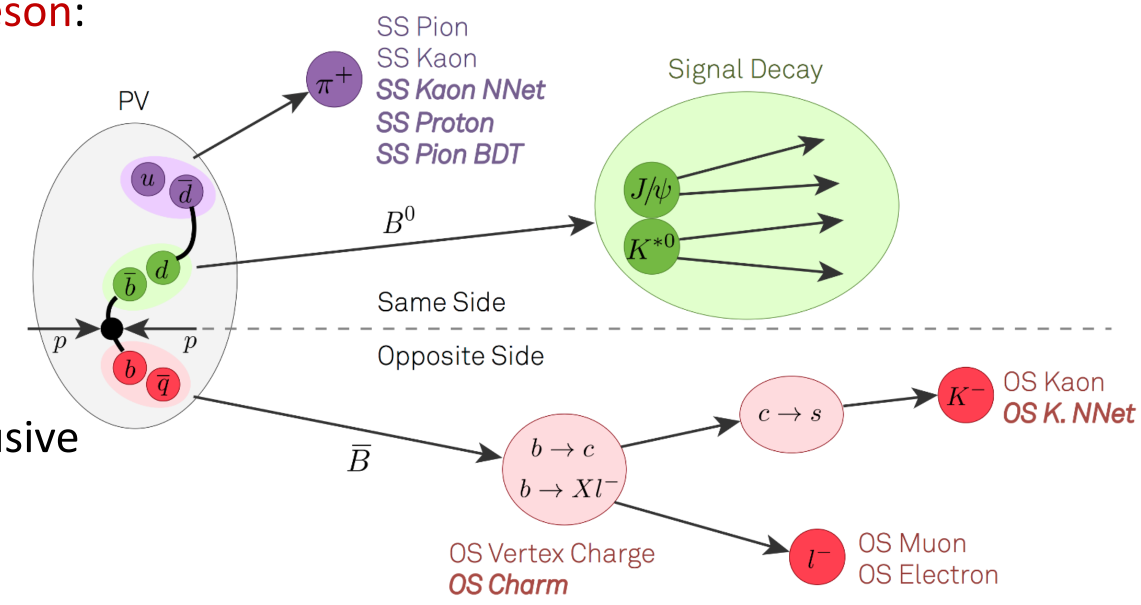


Flavour Tagging

- In LHCb we have two method of tagging the initial flavour of B-meson:
  - same side taggers (SS, about 37% B candidates):
    - search for the additional kaon or pion accompanying the fragmentation of the signal,
  - opposite side taggers (OS, 79%) use:
    - charge of the lepton (e, μ) from semileptonic B decays,
    - charge of kaons from $b \to c \to s$ chain, charge of the inclusive secondary vertex reconstructed from b decay.
  - 31% B mesons are tagged by two taggers.



$$\mathcal{E}_{tag} = \frac{N_{tagged}}{N_{tagged} + N_{untagged}} \approx 75\%$$

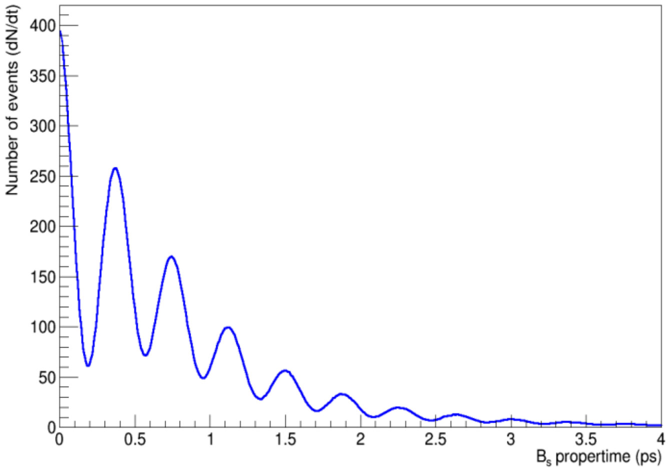
- The fitting parameters are diluted by: $A_{meas} = A_{th}(1 - 2\omega)$,
  - mistag probability $\omega = \frac{N\ wrong\ tagged}{N\ tagged}$, $\omega \in [0; 0.5]$;
  - effective tagging efficiency $\mathcal{E}_{eff} = \mathcal{E}_{tag}(1 - 2\omega)^2$ is above 5%.

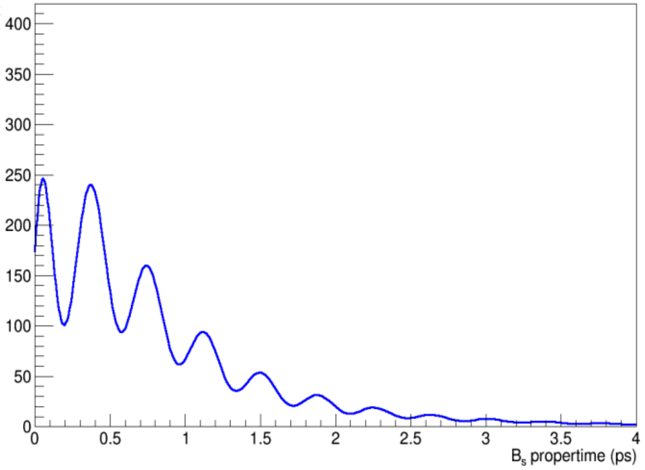
Time dependent $B_s^0 \to D_s^- K^+$ detector effects

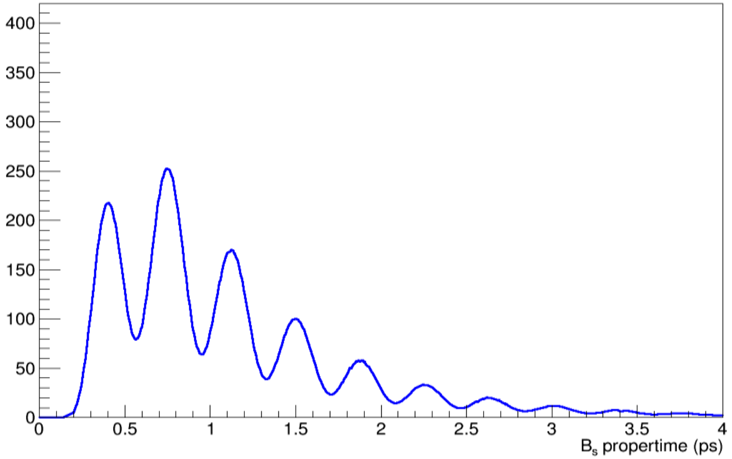
simulation

time resolution

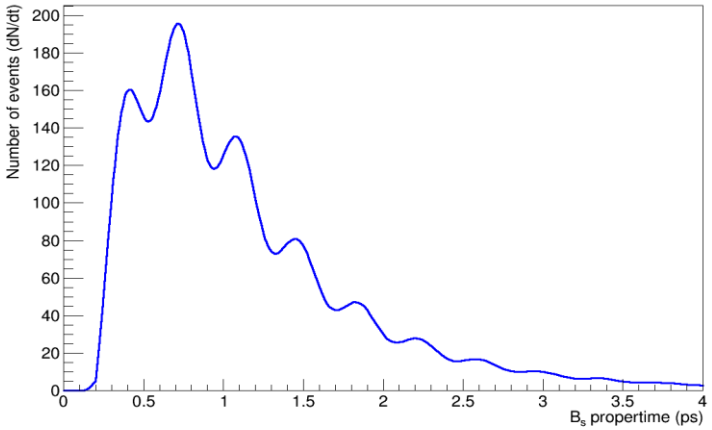
acceptance

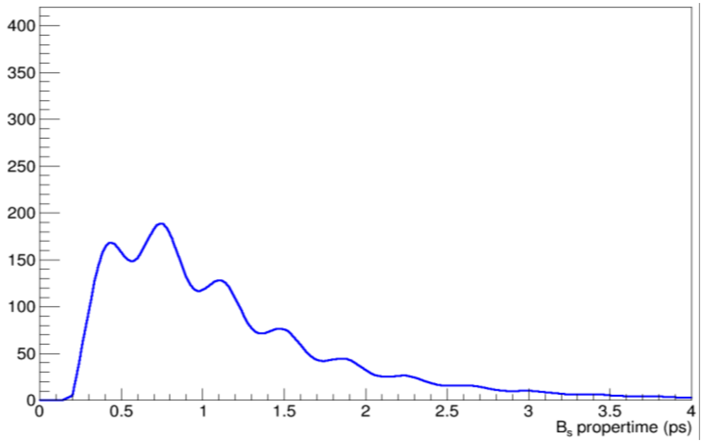




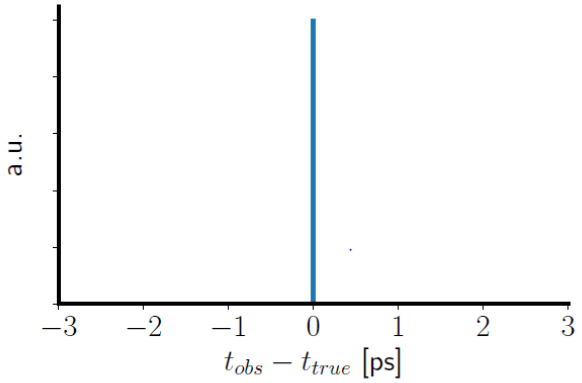


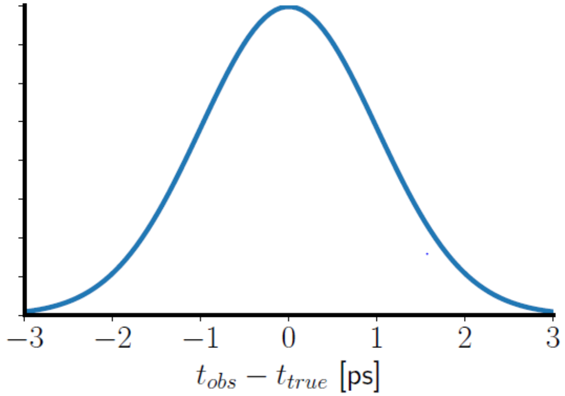
tagging

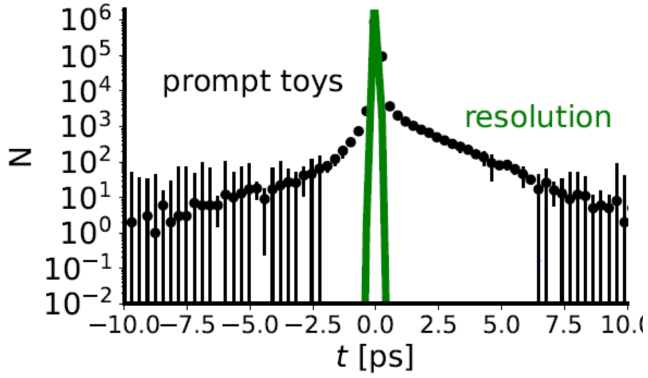


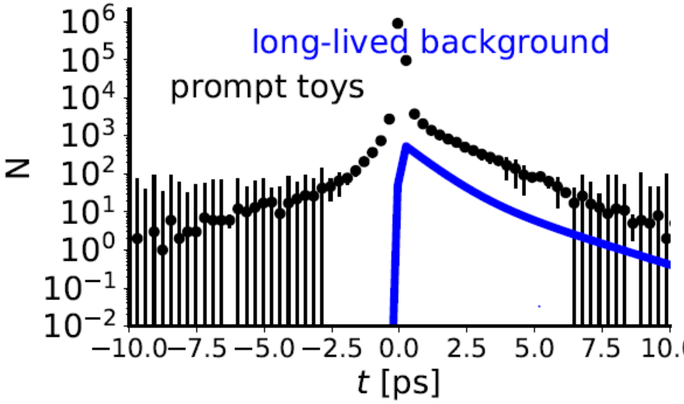


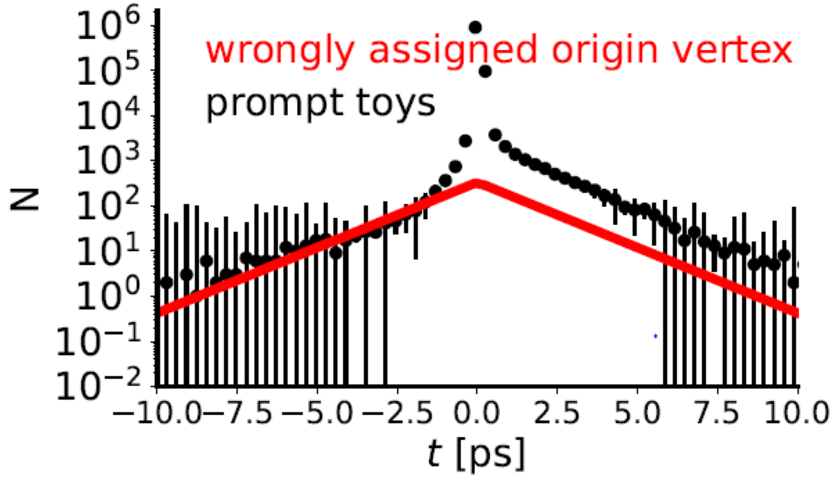
Time measurements - background

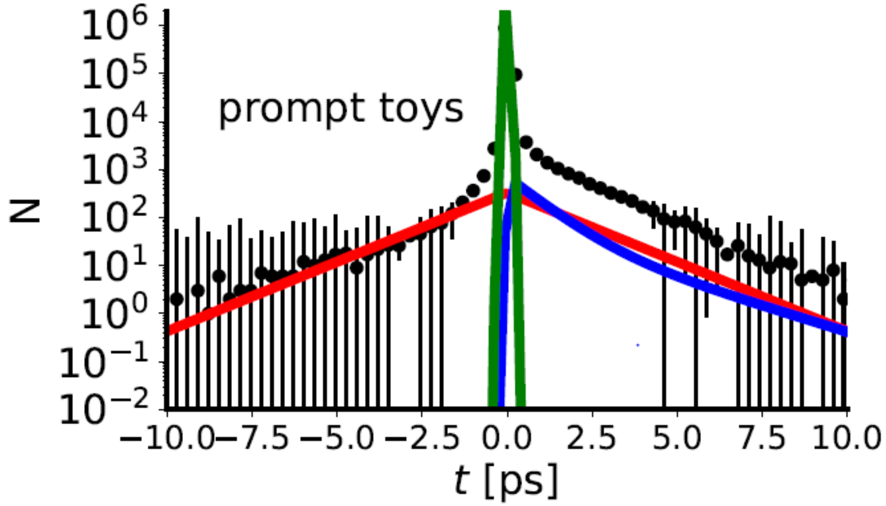






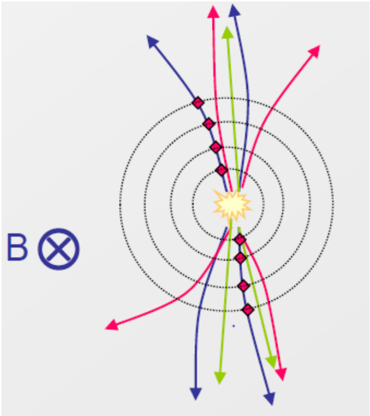


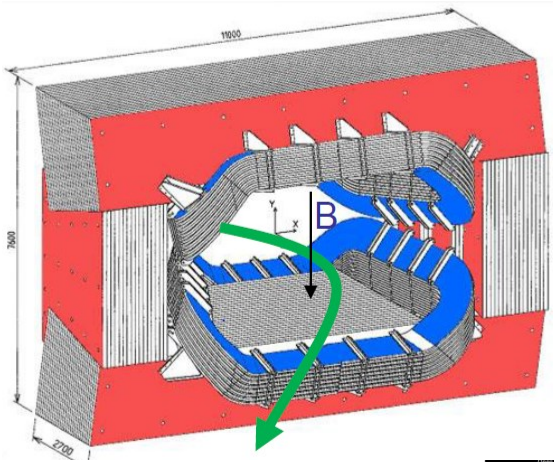


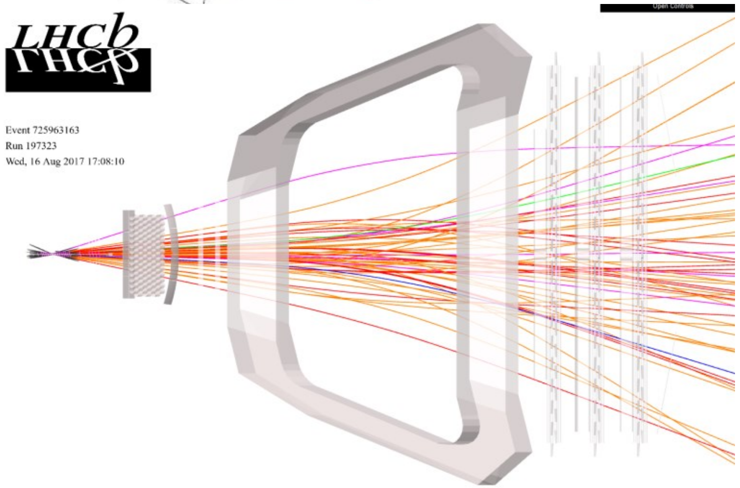


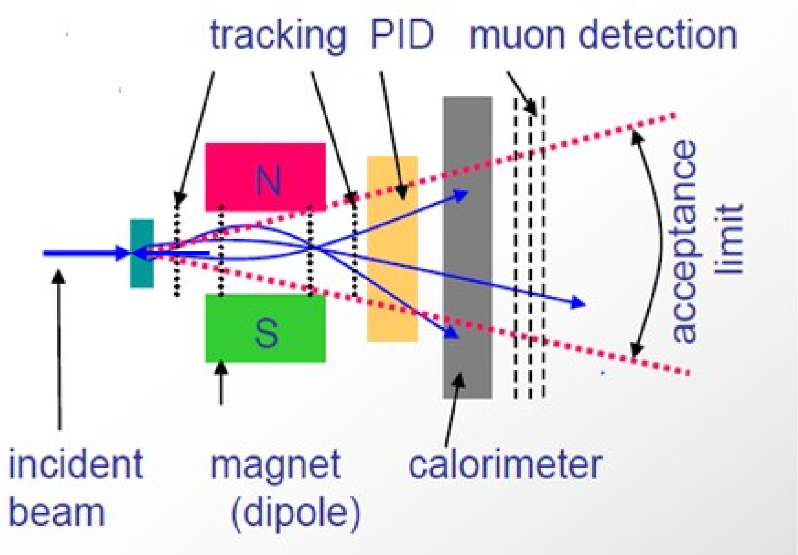
Measurement of the momentum

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







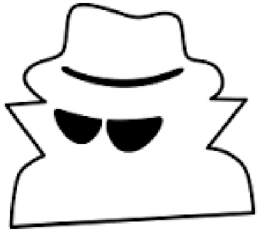


$$\overrightarrow{F_L} = q\,\vec{v} \times \vec{B}$$

$$F_L = F_d$$

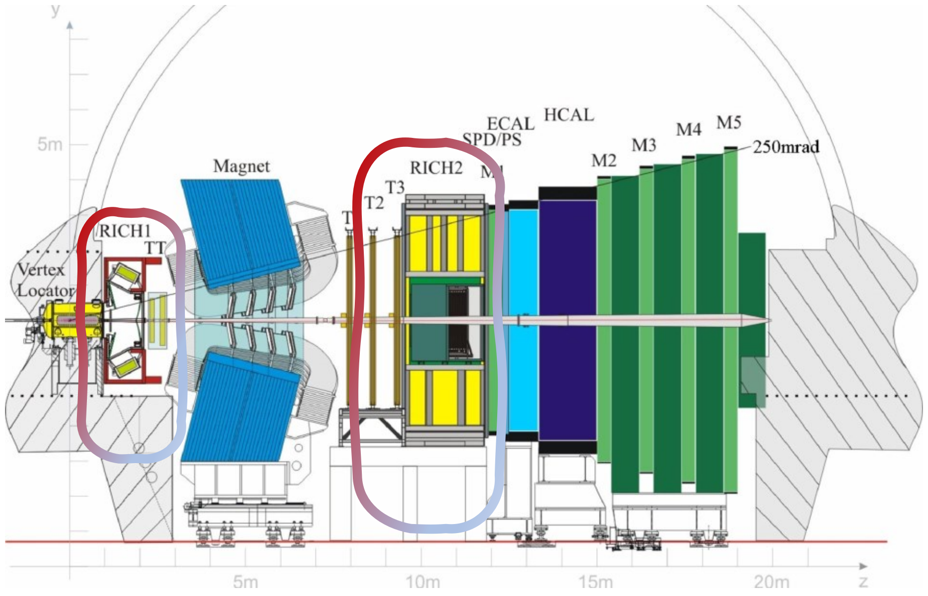
$$qvB = \frac{mv^2}{R}$$

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



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:

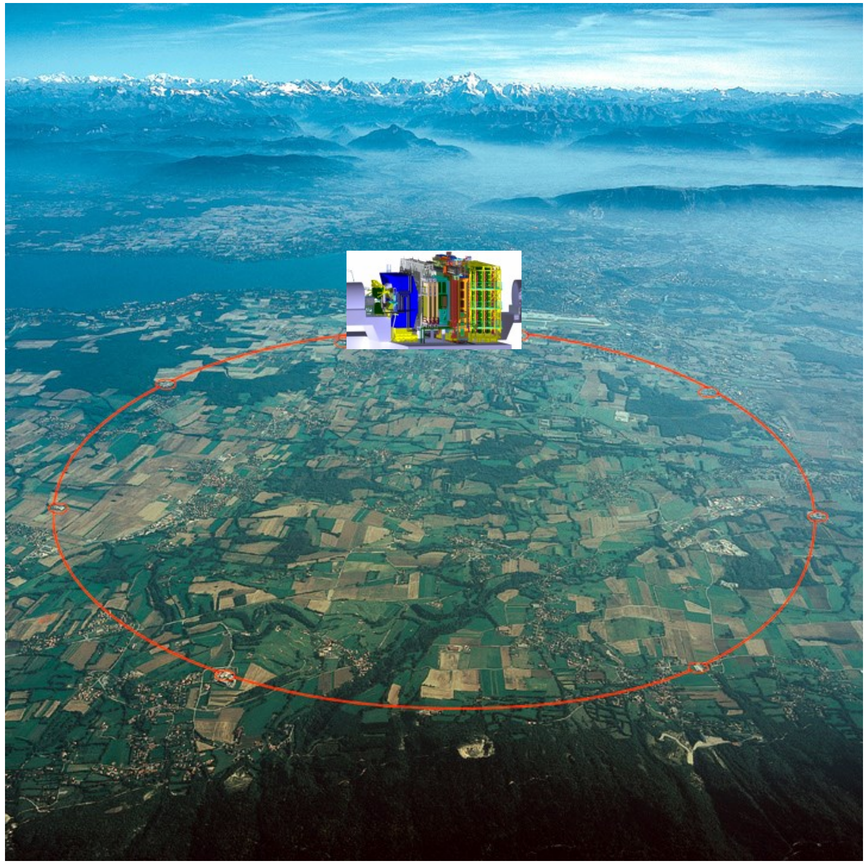
- find or rule out the evidences of New Physics and sources of flavour symmetry breaking
- searches of rare decays and exotic states,
- physics in the forward region.

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.



Physics @ LHCb – zagadnienia

1. LHCb – eksperyment do precyzyjnych pomiarów w sektorze ciężkich kwarków.
2. Macierz CKM – parametryzacja Wolfensteina i trójkąty unitarności.
3. Związek między macierzą CKM a Modelem Standardowym.
4. Trzy sposoby łamania parzystości kombinowanej CP.
5. Metody obserwacji CPV – przykład eksperymentalny.
6. Czynniki wpływające na pomiar czasu życia i masy:
   - precyzja wyznaczenia wierzchołków (pierwotnych i wtórnych),
     - parametr zderzenia
   - możliwość pomiaru niskich pędów 250-500 MeV/c i p_t<500 MeV/c
   - wyznaczenie pędów z precyzją 0.5% -1% (200 GeV)
   - czasowa zdolność rozdzielcza: 45 fs
   - identyfikacja hadronów w szerokim zakresie pędów (do 100 GeV), ok. 95% efektywności
   - znakowanie (tagging) zapachu mezonu, ok 5% efektywności

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….

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

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

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

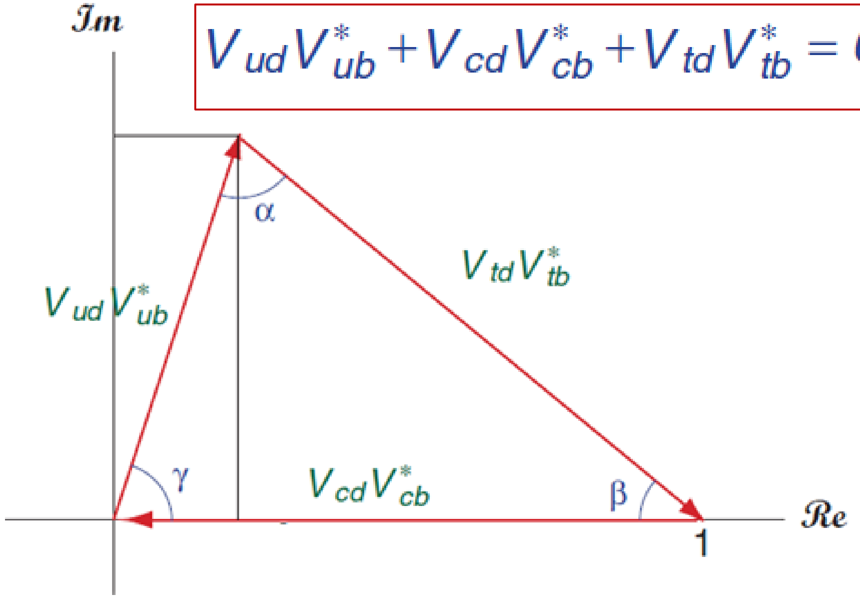
CKM matrix must be unitary, so we have conditions on its parameters:

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

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

and can be represented as triangles:

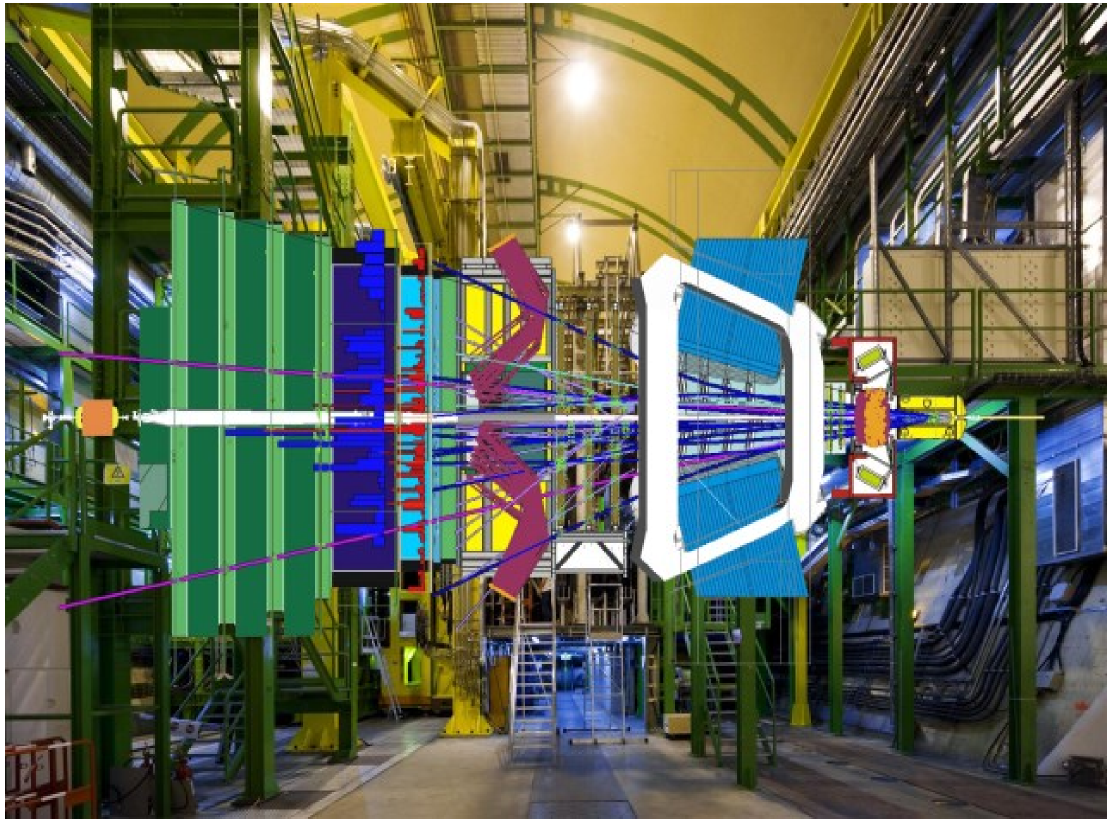
$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$



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

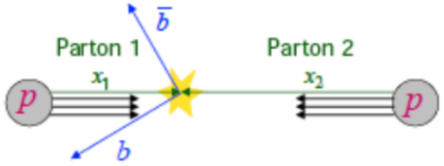
LHCb spectrometer

The detector dedicated for studying flavour physics at LHC.
Especially *CP* violation and rare decays of beauty and charm mesons.



Physics program:

- *CP* Violation ,
- Rare B decays,
- B decays to charmonium and open charm,
- Charmless B decays,
- Semileptonic B decays,
- Charm physics,
- B hadron and quarkonia,
- QCD, electroweak, exotica …



$$\left.\begin{aligned}\sigma_{b\bar{b}} &= (75.3 \pm 14.1)\ \mu b \\ \sigma_{c\bar{c}} &= (1419 \pm 133)\ \mu b\end{aligned}\right\} \sqrt{s}=7\ \text{TeV}$$

Excellent performance:

3 fb^{-1} accumulated in RUN I, 3.26 fb^{-1} in Run II;

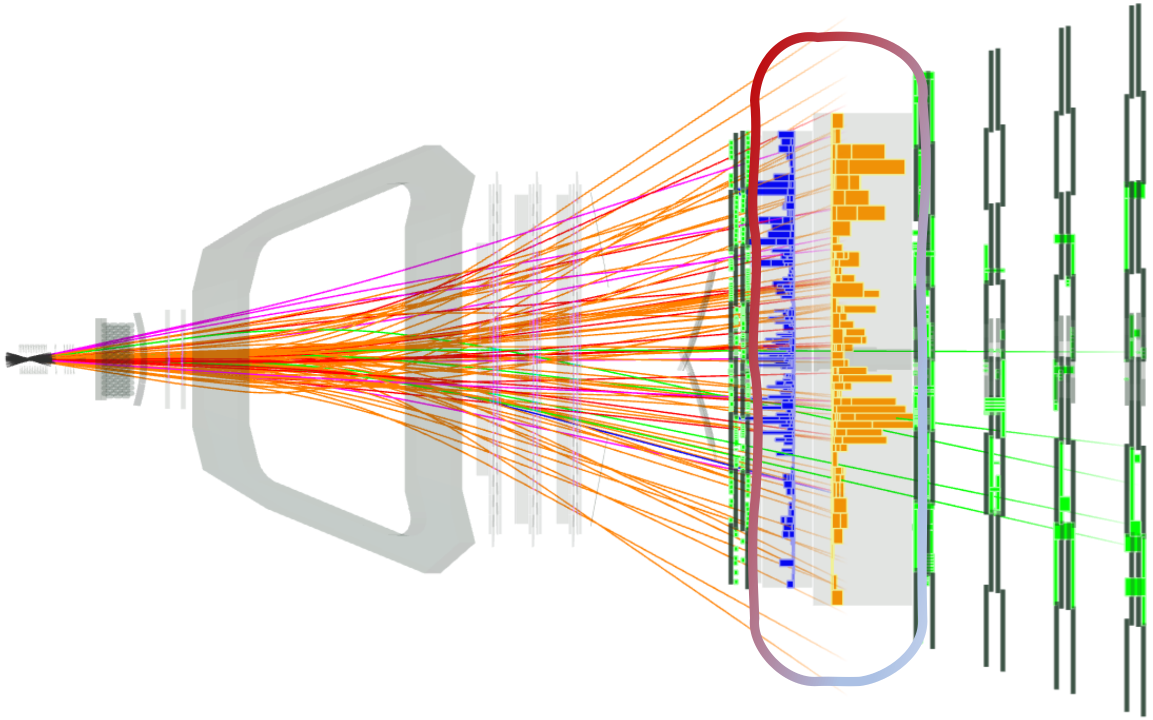
Excellent time (50 fs) and Impact Parameter resolution (20 μm);

Precise tracking: $\delta p/p \sim 0.5 - 1\%$ (up to 200 GeV);

Hadronic identification 2-100 GeV/c

Energy measurement

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



CPV in Standard Model

CPV in Standard Model

Track reconstruction*

* see additional slides!