Flavour Tagging within the LHCb experiment

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Outline

- LHCb Physics & CP Violation
- The LHCb experiment
- Flavour Tagging
- Performances & Physics results

A bit of history ...

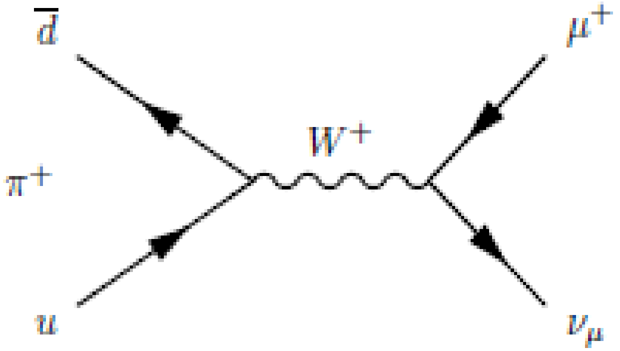
LHCb Physics. CP Violation

- Standard Model is the best model to describe the interactions of fundamental particles. But has still some weak spots (mass hierarchy, neutrino masses are zero, gravity not included, higgs, ...).
- **CP Violation** are mechanisms that break the symmetry between the behavior of matter and anti-matter
- In particular, cosmological observations show an indirect excess of **CP violation** wrt the SM. CP Violation related effects can be very interesting for the discovery of new physics.
- LHCb has been specially designed to study flavour physics (CP violation) and rare decays in the B mesons sector (charm too!).

CP

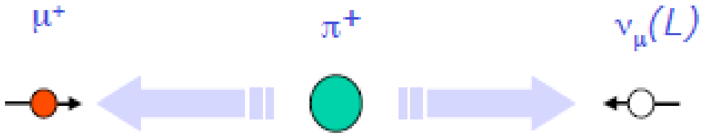
- CP transformation combines charge conjugation (Q --> -Q) with parity (x, y, z --> -x, -y, -z). What is exactly CP Violation? First a bit of history...
- C, P are conserved in strong and EM interactions but they are completly broken by the weak interaction. (P violation firstly observed by Wu in radiative decays)

Look at the pion decay: $\pi^+ \rightarrow \mu^+ \nu_\mu$

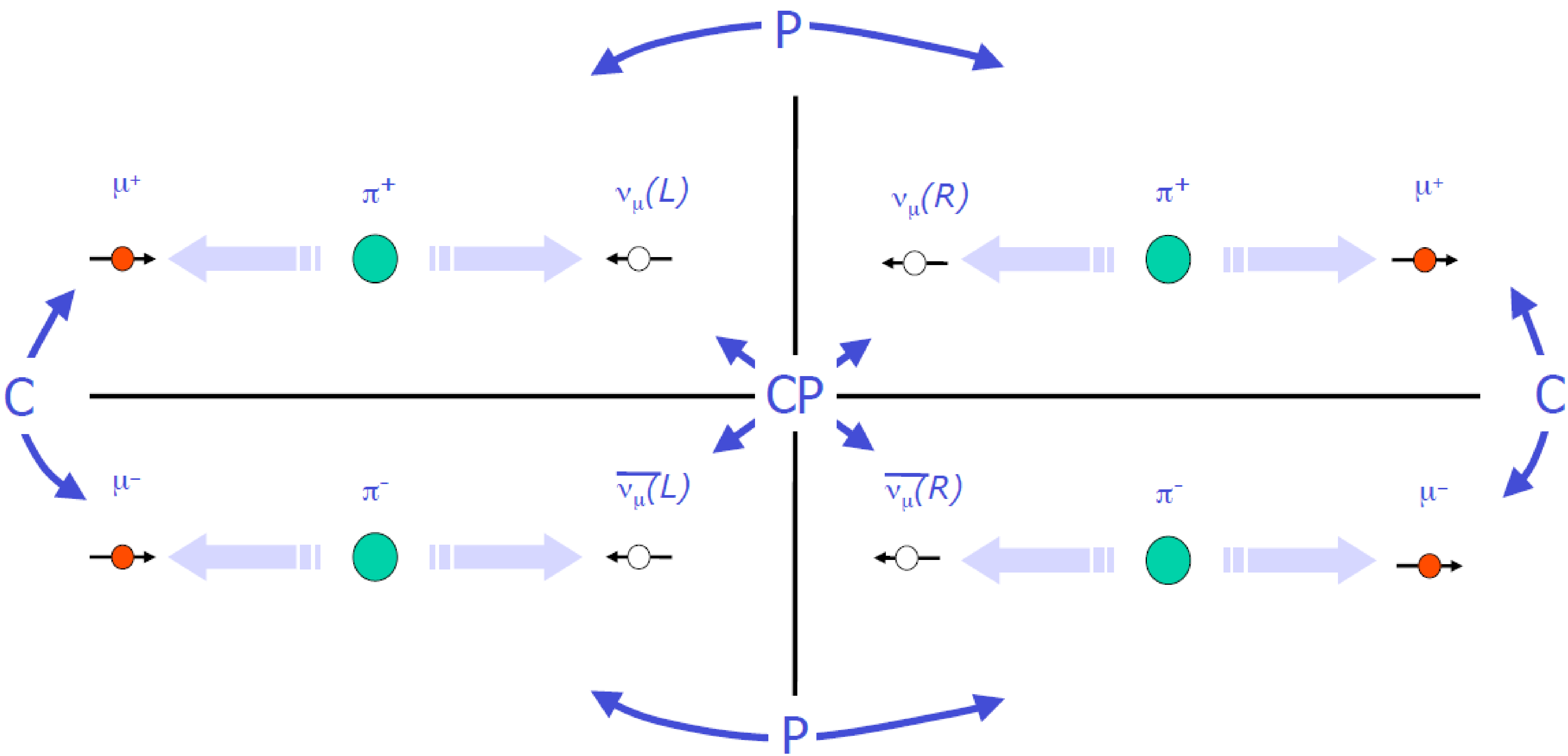


Pion has spin 0; μ ν_μ both have spin 1/2

- Spin of decay products must be oppositely aligned
- Helicity of the muon is the same as that of neutrino

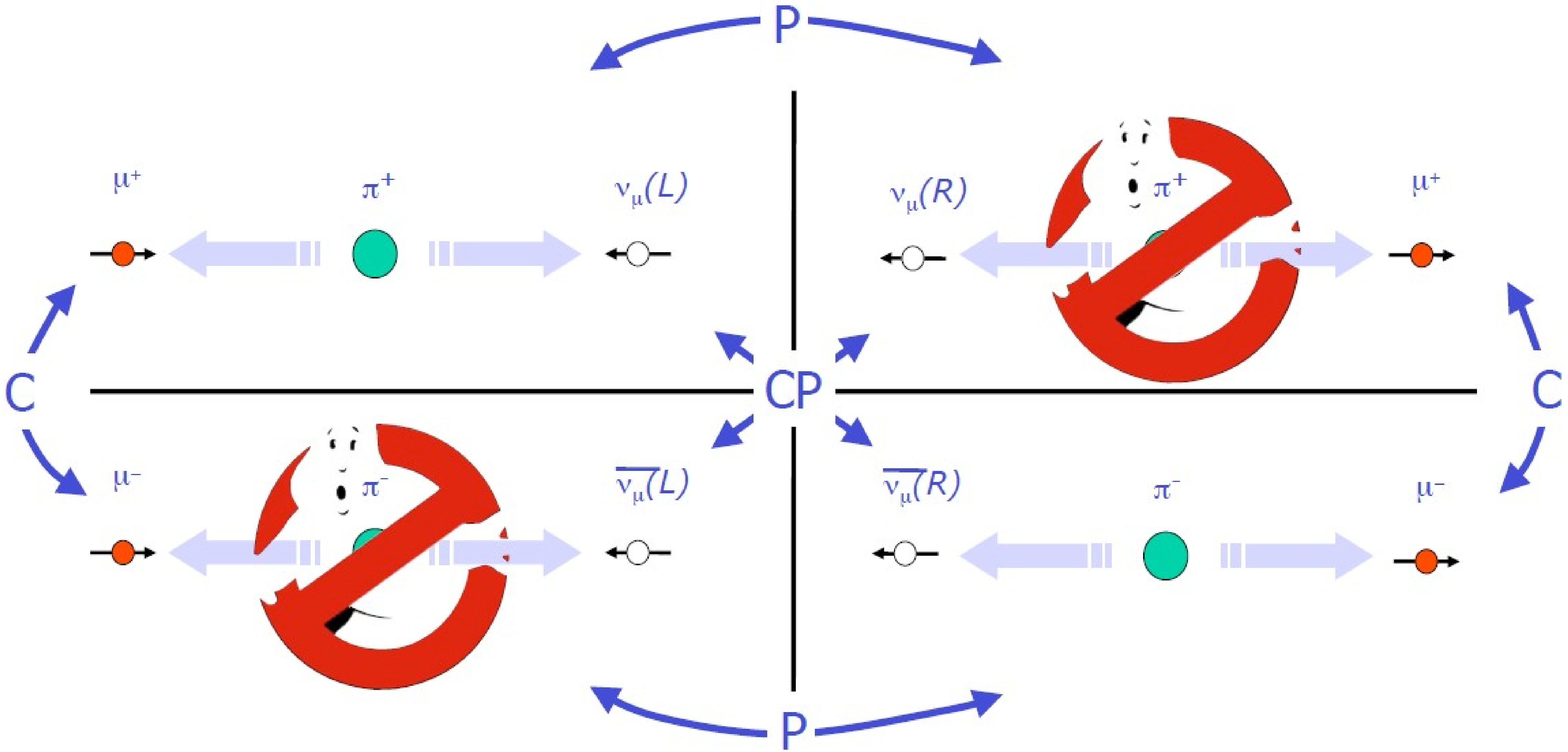


C, P and CP



P
μ^+
π^+
$\nu_\mu(L)$
$\nu_\mu(R)$
π^+
μ^+
C
CP
C
μ^-
π^-
$\overline{\nu_\mu}(L)$
$\overline{\nu_\mu}(R)$
π^-
μ^-
P

C, P and CP



In 1956, C.S Wu observed that the right handed neutrino does not exist.
C, P are broken but CP seems to be preserved in weak interaction.

CP Violation

Discovered in 1964 by James Cronin and Val Fitch in the neutral K-meson system.

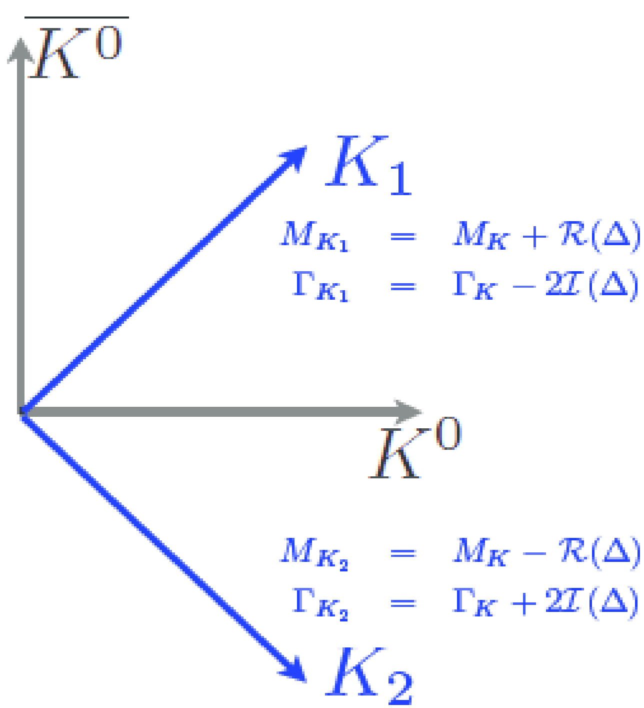
$$\Psi(t) = a(t)\left|K^0\right\rangle + b(t)\left|\overline{K^0}\right\rangle \equiv \begin{pmatrix} a(t) \\ b(t) \end{pmatrix}$$

$$i\frac{\partial}{\partial t}\Psi = \hat{H}\Psi$$

K^0 are mass eigenstates, but the weak eigenstates have a defined mass and lifetime

$$|K_1\rangle = \frac{\left|K^0\right\rangle + \left|\overline{K^0}\right\rangle}{\sqrt{2}}$$

$$|K_2\rangle = \frac{\left|K^0\right\rangle - \left|\overline{K^0}\right\rangle}{\sqrt{2}}$$



Only the CP even state can decay into 2 pions

$|K_1>$ (CP=+1) → ππ (CP = -1 * -1 = +1)

The CP odd state will decay into 3 pions instead

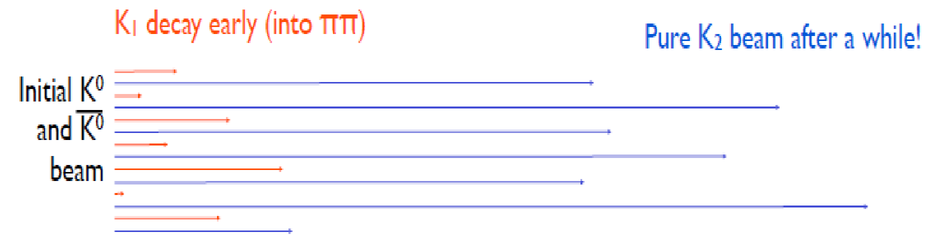
$|K_2>$ (CP=-1) → ππ π (CP = -1*-1*-1 = -1)

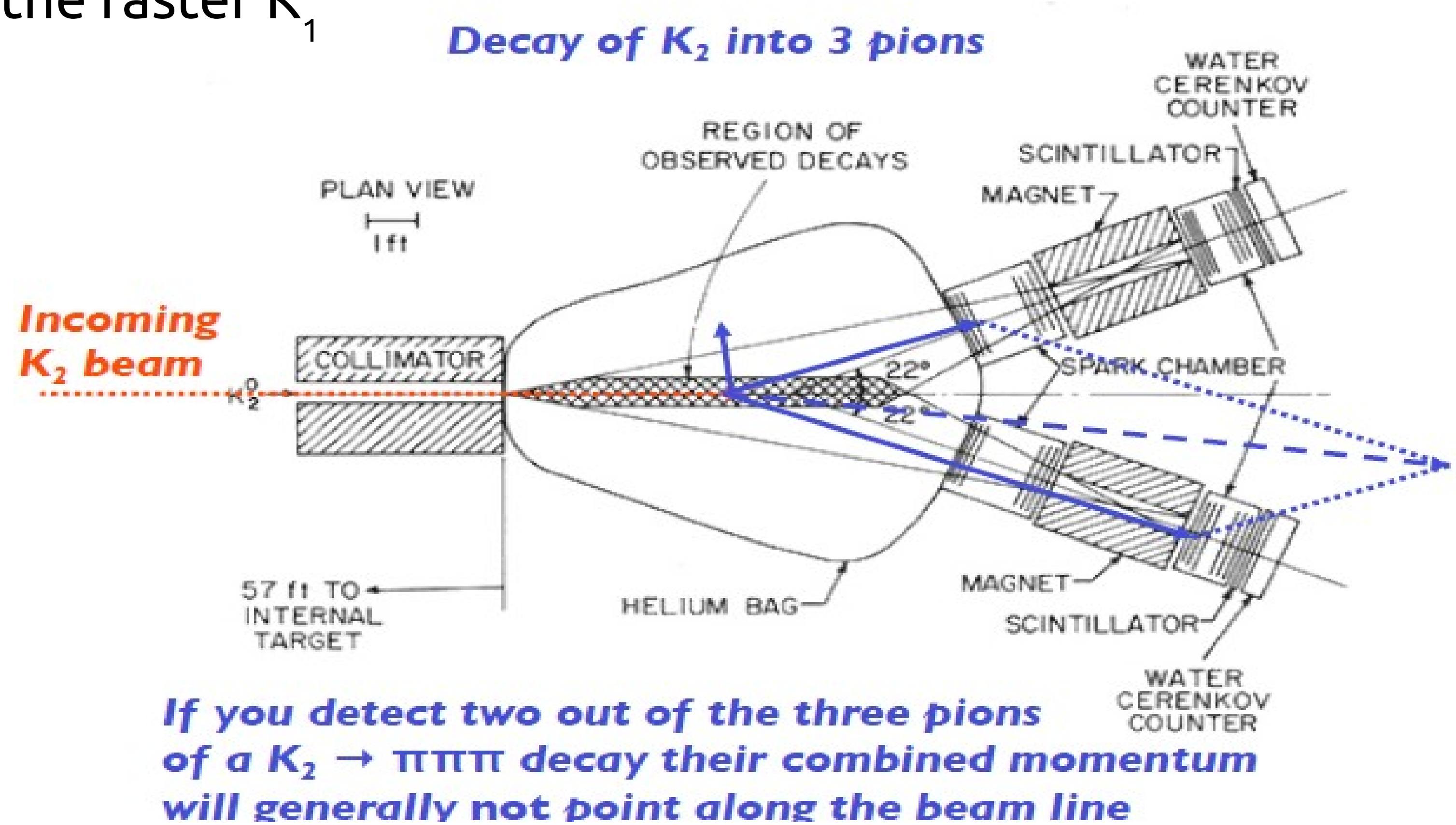
CP Violation

Experiment:

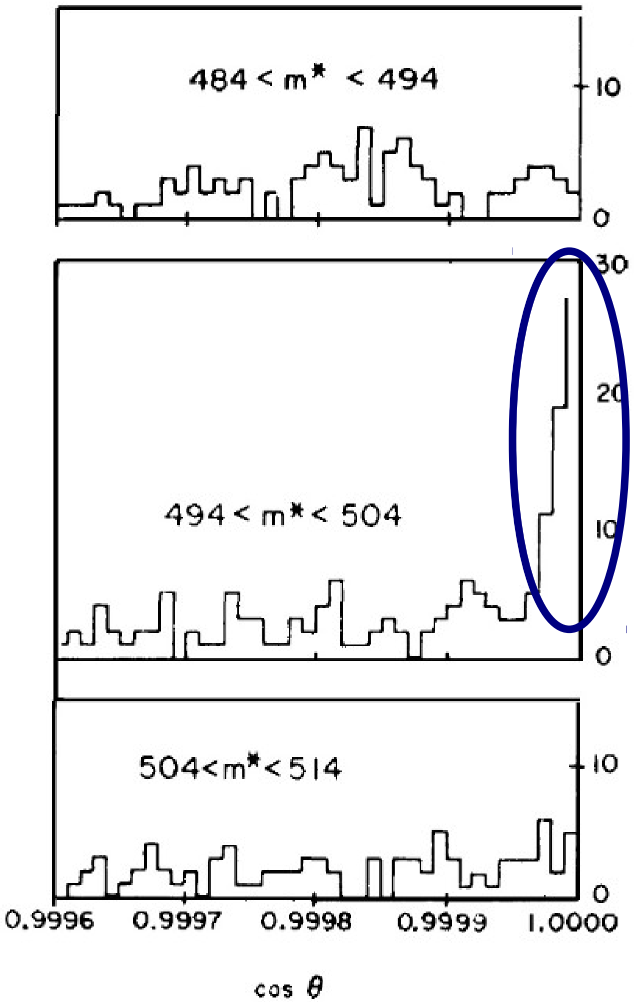
Build a K_2 beam and look for 2 pion decay.

Exploit the faster K_1 decay



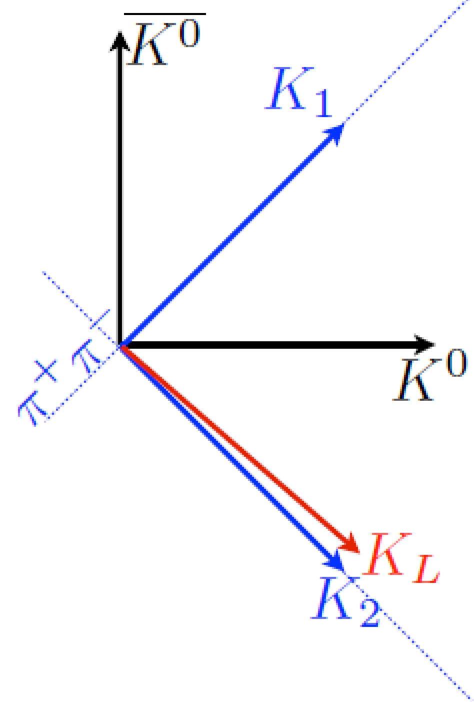


CP Violation



Decay of K_2 into 2 pions

Deacy of K_2 into 2 pions (0.2% violate CP)



The weak and mass eigenstates of quarks are not the same.

$$u_i^{(weak)} = U_{ij}^{(u)} u_j^{(mass)}$$

$$d_i^{(weak)} = U_{ij}^{(d)} d_j^{(mass)}$$

They are related by the V_{CKM} matrix.

Neutral weak interaction ⟶ $(\bar{u}_i^{(weak)} u_i^{(weak)} = \bar{u}_i^{(mass)} u_i^{(mass)})$

Charged weak interaction ⟶ $\bar{u}_i^{(weak)} d_i^{(weak)} \rightarrow \bar{u}_i^{(mass)} (U^{(u)})^\dagger U^{(d)} d_i^{(mass)}$

V_{CKM}

CKM Matrix

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

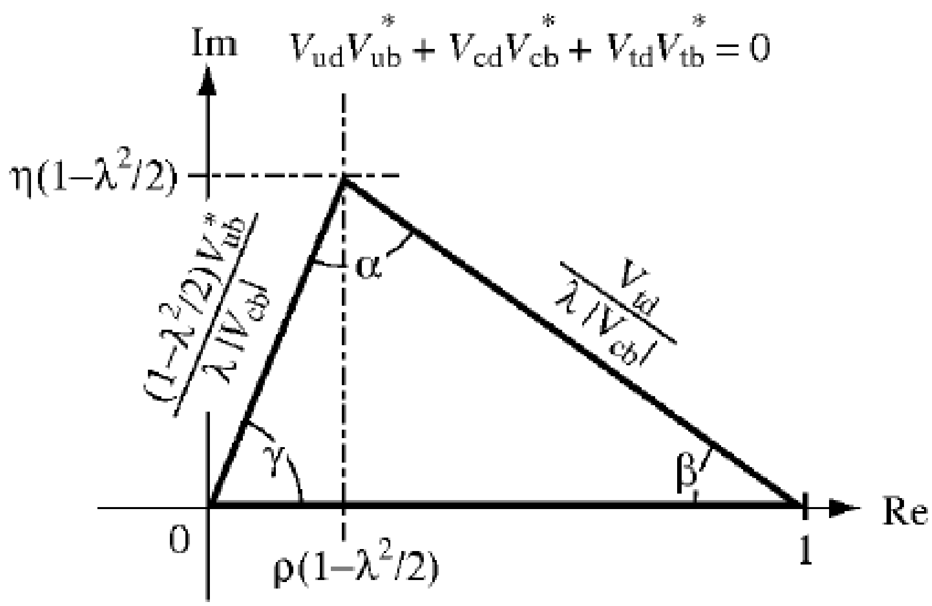
The CKM matrix can be described by four real parameters; three rotation angles and a complex phase.

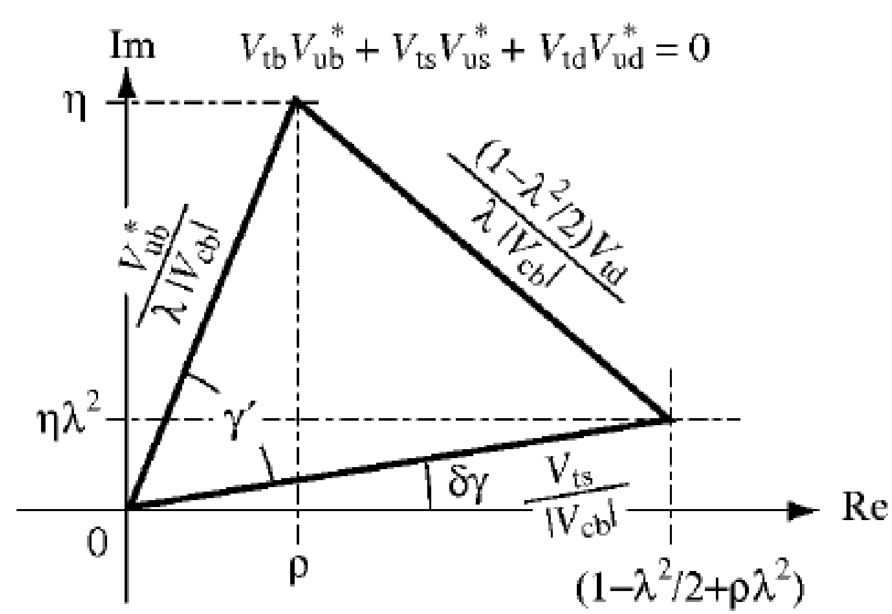
$$V_{CKM} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

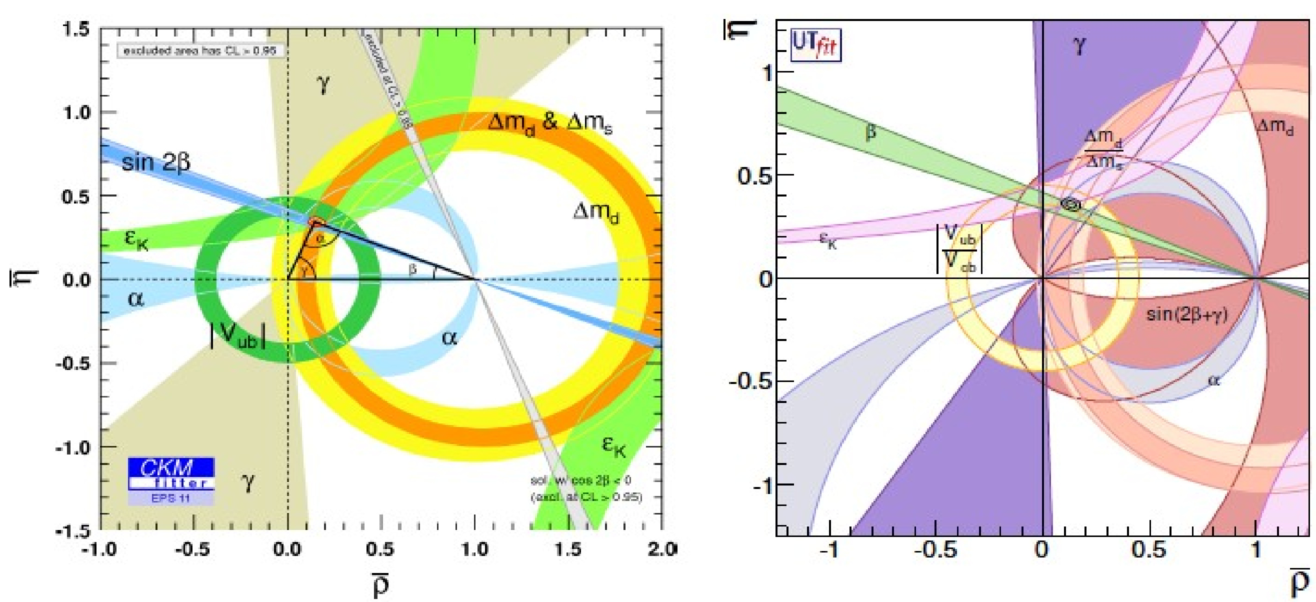
with $s_{ij} = \sin\theta_{ij}, c_{ij} = \cos\theta_{ij}$
so with four parameters $\theta_{12}, \theta_{23}, \theta_{13}, \delta$

The unitarity of the CKM matrix implies various relations among its elements. Each of these relations requires the sum of three complex quantities to vanish and so they can be geometrically represented in a complex plane as triangles

Unitarity triangles







(a) CKM Fitter (b) UT Fit

B mesons system

- The eigenstates of the total hamiltonian, with definite mass and lifetime, are mixtures of the flavour eigenstates.

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

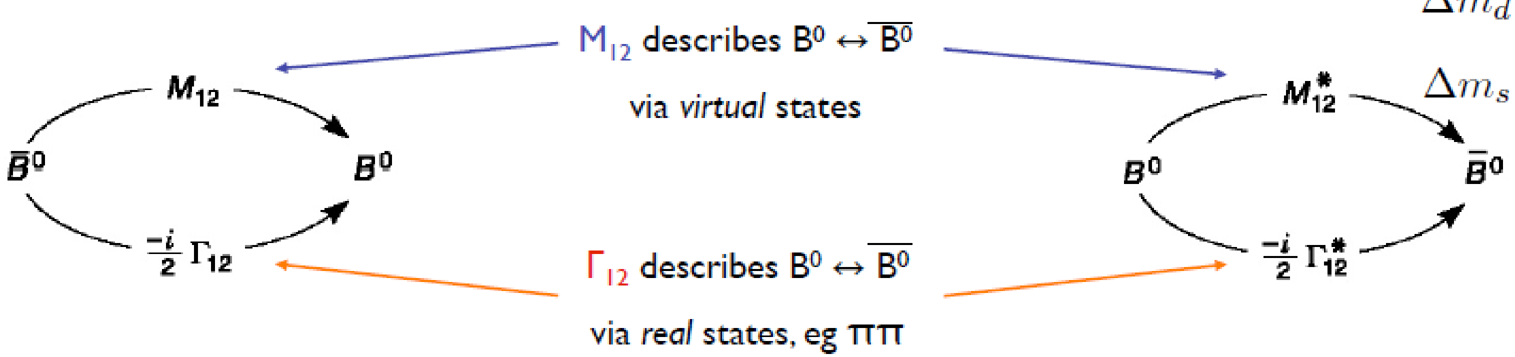
- The evolution of the B meson is given by

$$|B^0(t)\rangle = e^{-imt}e^{\Gamma t/2}\{cos(\Delta m_d t/2)|B^0(t)\rangle + i(q/p)sin(\Delta m_d t/2)|\bar{B}^0(t)\rangle\}$$

$$|\bar{B}^0(t)\rangle = e^{-imt}e^{\Gamma t/2}\{cos(\Delta m_d t/2)|\bar{B}^0(t)\rangle + i(p/q)sin(\Delta m_d t/2)|B^0(t)\rangle\}$$

$$\Delta m_d = 0.507 \pm 0.005 \text{ ps}^{-1}$$

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



CP Violation was observed in neutral B decays in 2001 by Babar and Belle

Types of CP Violation

- **Direct CP Violation (in decay)**. When the decay amplitudes of particles and antiparticles are different.

$$\mathcal{A}_{CP} = \frac{\Gamma(\overline{B} \to \overline{f}) - \Gamma(B \to f)}{\Gamma(\overline{B} \to \overline{f}) + \Gamma(B \to f)} = \frac{1 - |\overline{A}_{\overline{f}}/A_f|^2}{1 + |\overline{A}_{\overline{f}}/A_f|^2}$$

- **Indirect CP Violation (mixing)**. It manifest itself in the neutral meson mixing. If the B meson evolution is described by:

$$|B(t)\rangle = g_+(t)|B\rangle + \frac{q}{p}g_-(t)|\bar{B}\rangle$$

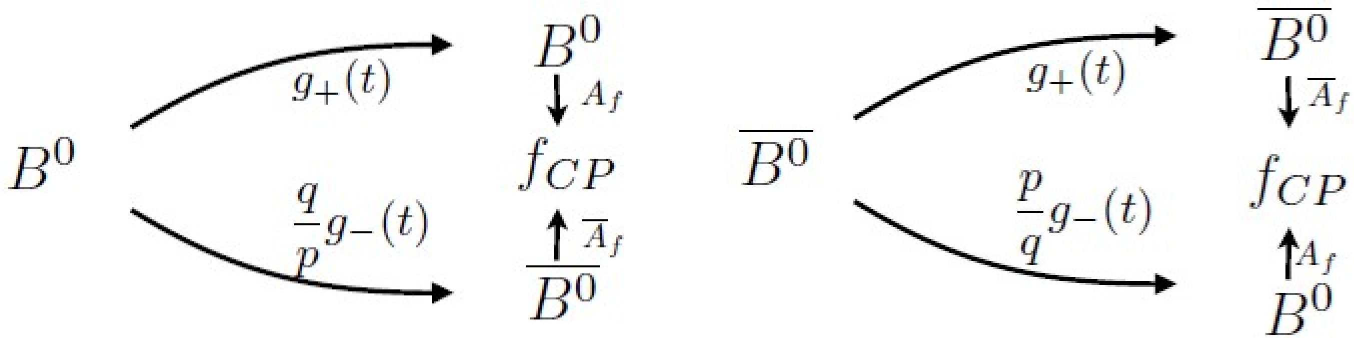
$$|\bar{B}(t)\rangle = g_+(t)|\bar{B}\rangle + \frac{p}{q}g_-(t)|B\rangle$$

CP violation occur when: $|q/p| \neq 1 \Longrightarrow Prob(B^0 \to \bar{B}^0) \neq Prob(\bar{B}^0 \to B^0)$

$$\mathcal{A}_T = \frac{\Gamma(|\bar{B}^0(t)\rangle \to l^+\nu X) - \Gamma(|B^0(t)\rangle \to l^-\overline{\nu} X)}{\Gamma(|\bar{B}^0(t)\rangle \to l^+\nu X) + \Gamma(|B^0(t)\rangle \to l^-\overline{\nu} X)}$$

Types of CP Violation

- CP Violation from Interference (decay and mixing).



$$\mathcal{A}_{f_{CP}}(t) = \frac{\Gamma(|\bar{B}^0(t)\rangle \to f_{CP}) - \Gamma(|B^0(t)\rangle \to f_{CP})}{\Gamma(|\bar{B}^0(t)\rangle \to f_{CP}) + \Gamma(|B^0(t)\rangle \to f_{CP})} = S_{f_{CP}} \sin(\Delta m_d t) - C_{f_{CP}} \cos(\Delta m_d t)$$

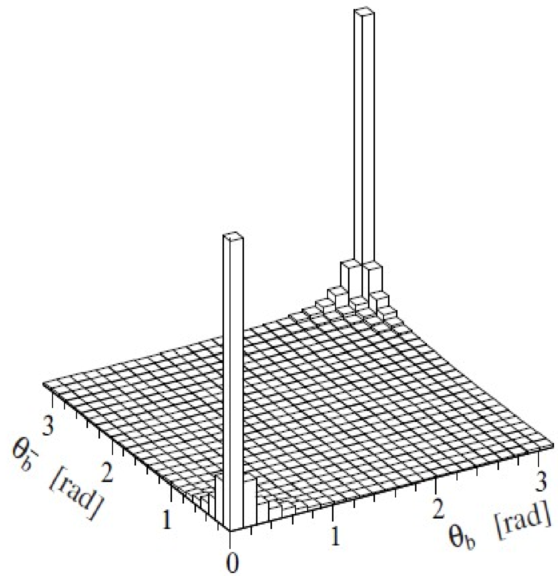
$$S_{f_{CP}} = \frac{2Im(\lambda_{f_{CP}})}{1+|\lambda_{f_{CP}}|^2} \quad and \quad C_{f_{CP}} = \frac{1-|\lambda_{f_{CP}}|^2}{1+|\lambda_{f_{CP}}|^2} \qquad \lambda_f = \frac{q}{p}\frac{\overline{A}_f}{A_f}$$

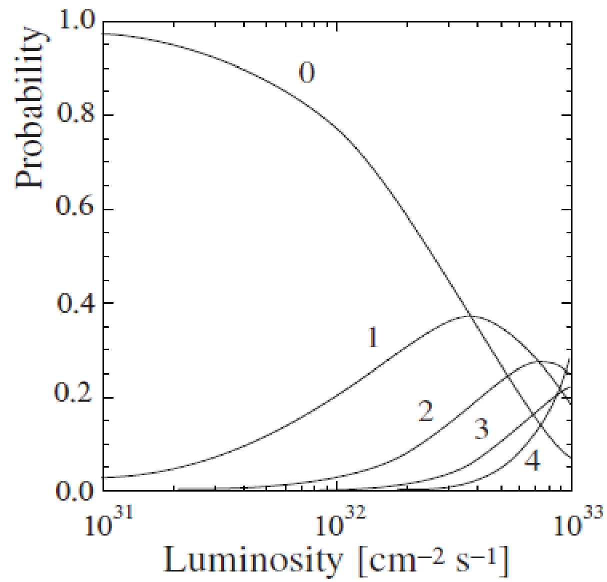
LHCb

The LHCb experiment

It is designed to study CP violation and rare decays in the B meson sector in pp-collision at the LHC machine with a center of mass energy up to 14 TeV and a bunch crossing frequency of 40 Mhz.

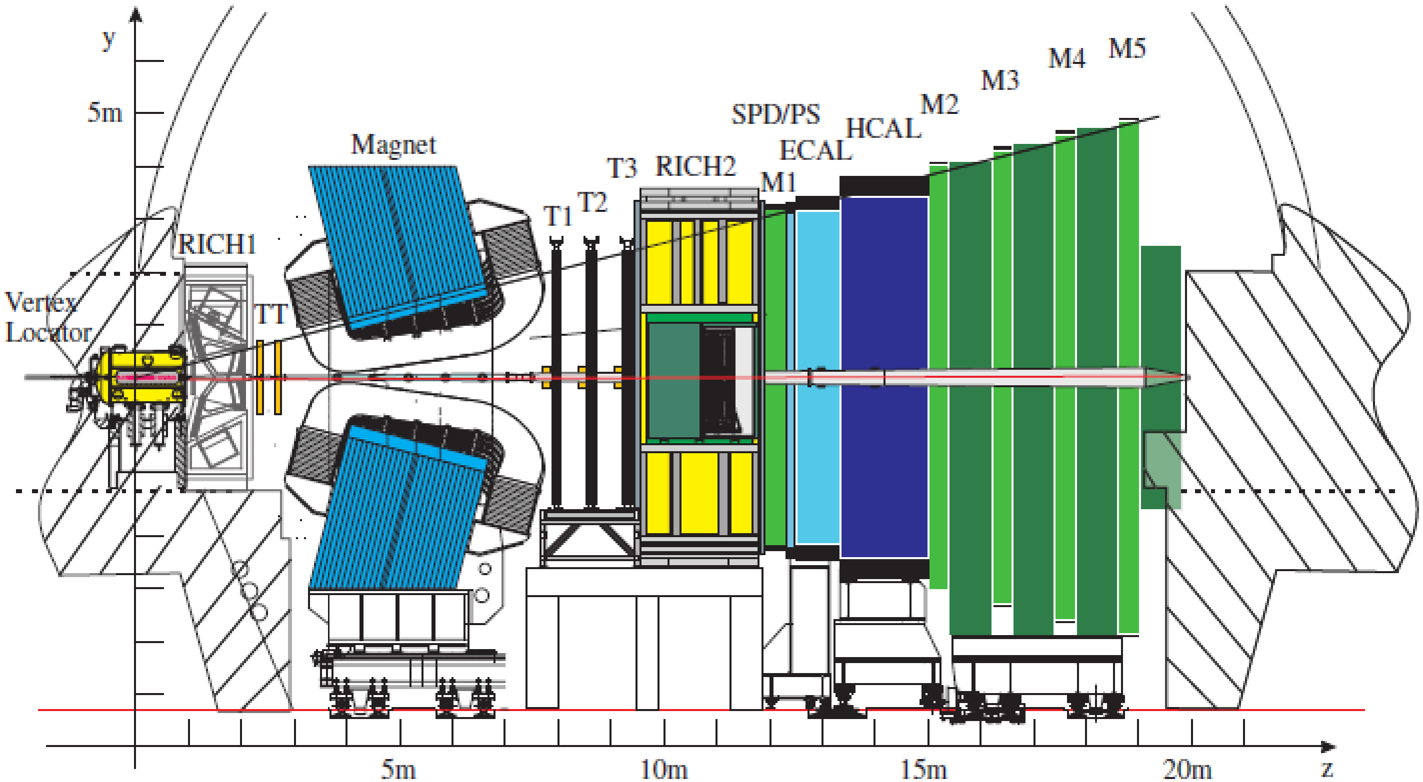
It is a single arm spectrometer in the forward direction, it focuses on the high rapidity region on the majority of the $b\bar{b}$ pairs are produced.





The LHCb operates at a lower luminosity than the LHC design. The beams are defocused to deliver a luminosity of $2x10^{32}cm^{-2}s^{-1}$, reducing the number of pp-interactions.

The LHCb experiment



$2010 : 3.6 pb^{-1}$

$2011 : \sim 1 fb^{-1}$

High trigger efficiency (L0 hardware, HLT software)
Excellent tracking (vertexing) system
    Time, IP resolution, Mass resolution
Excellent particle Identification (PID)

Event reconstruction

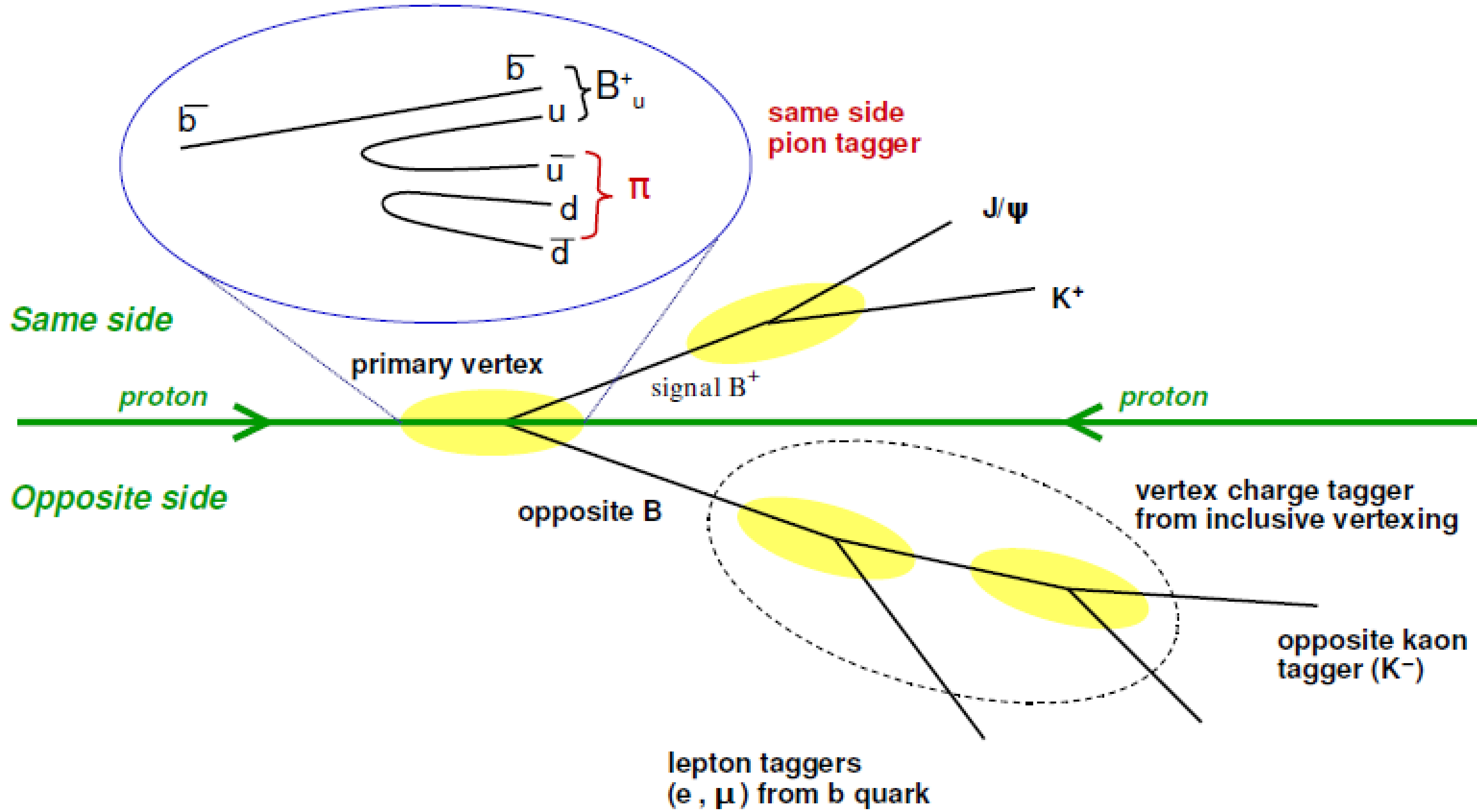
- Tracking system combines the hits in the VELO, the tracking stations and taking into account the deviation due to the magnetic field it estimates the particle trajectory.
- PID system uses the RICH detectors, the calorimeter and the muon detector to associate to each proto-particle a likelihhod for each long-lived mass hypotheses.
- Particle decays chains are reconstructed with “DaVinci”. These particles can be used to create other particles, with associated properties that can be calculated from kinematics. Particles can be filtered by requiring particle properties to lie in certain regions.
- A distributed computing system, called GRID, can be used for physics analysis.

Flavour Tagging

Flavour Tagging

- Flavour Tagging is the procedure to determine the flavour of the reconstructed B meson at production time.
- Tagging is mandatory for B oscillations and for most of the CP violation measurements.
- B meson are produced as $b\overline{b}$ pairs. One meson is completly reconstructed (signal B) and the other (opposite B) is used to tag the initial flavour of the signal B
- Different tagging algorithms, with varying accuracy, are used. They are usually classified as
  - Oppsoite side, when look at the flavour of the opposite b quark (leptons, kaons, vertex charge)
  - Same side, determine directly the flavour of the signal B exploiting the correlation in the decay chain

Flavour Tagging at LHCb



Tagging efficiency $$\varepsilon_{tag} = \frac{N_R + N_W}{N_R + N_W + N_U}$$

Taggers

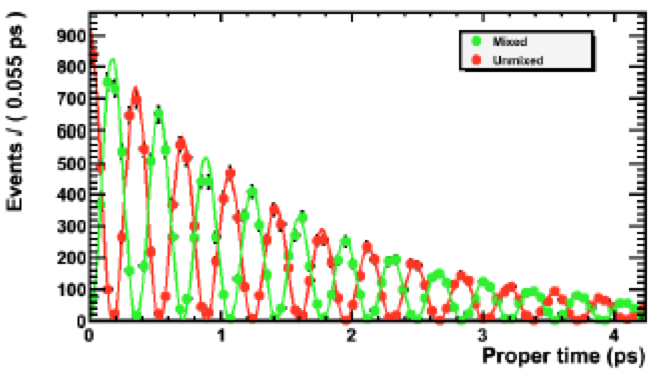
OS: muons, electrons, kaons, vertex charge

SS: kaons (B_s) or pions ($B_{d,u}$)

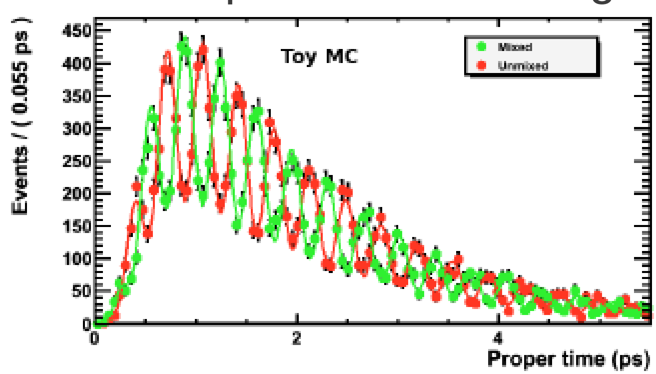
Wrong tag fraction $$\omega = \frac{N_W}{N_R + N_W}$$

Tagging and dilution

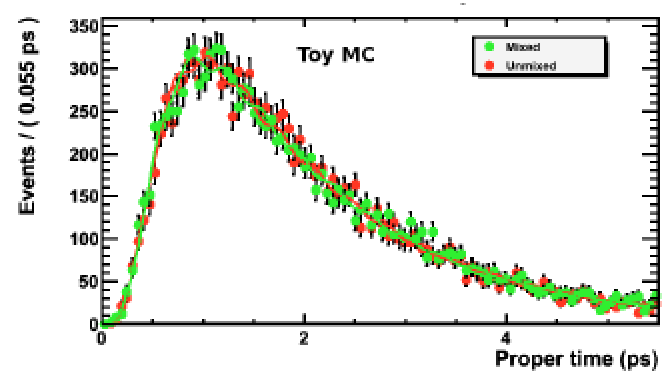
- The tagging algorithm may fail in identifying the flavour so that the observed asymmetry is diluted. (+ acceptance and time resolution effects)



Acceptance and mistag



Time resolution



- The statistical uncertainty on the measured asymmetry is directly related to the effective tagging efficiency

Effective efficiency

$$\varepsilon_{eff} = \varepsilon_{tag}(1-2\omega)^2$$

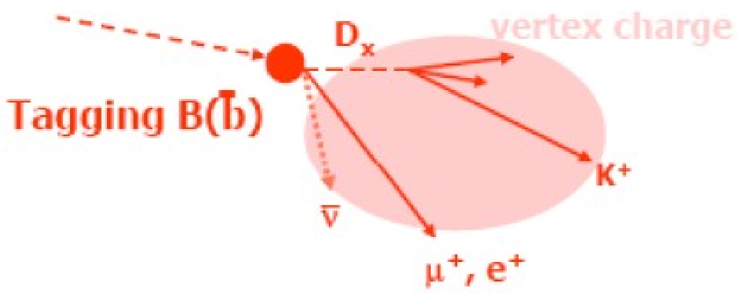
B-factories vs LHCb

B-factories vs. b-factory

	$e^+e^- \to \Upsilon(4S) \to B\bar{B}$ PEPII, KEKB	$pp \to b\bar{b}X$ ($\sqrt{s}$ = 14 TeV, Δt_{bunch}=25 ns) LHC (LHCb–ATLAS/CMS)	
Production σ_{bb}	1 nb	~500 μb	☺
Typical $b\bar{b}$ rate	10 Hz	100–1000 kHz	
$b\bar{b}$ purity	~1/4	$\sigma_{bb}/\sigma_{incl}$ = 0.6% Trigger is a major issue !	☹
Pileup	0	0.5–5	
b-hadron types	B^+B^- (50%) $B^0\bar{B}^0$ (50%)	B^+ (40%), B^0 (40%), B_s (10%) B_c (< 0.1%), b-baryons (10%)	☺
b-hadron boost	Small	Large (decay vertexes well separated)	
Production vertex	Not reconstructed	Reconstructed (many tracks)	
Neutral B mixing	Coherent $B^0\bar{B}^0$ pair mixing	Incoherent B^0 and B_s mixing (extra flavour-tagging dilution)	☹
Event structure	$B\bar{B}$ pair alone	Many particles not associated with the two b hadrons	

Opposite side taggers

- Tagging objects from b $\rightarrow$ l or b $\rightarrow$ c $\rightarrow$ s chain, and vertex charge.



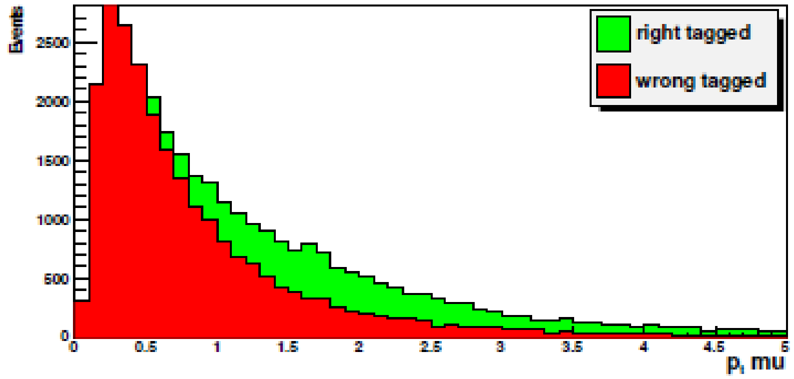
Muon
Electron
Kaon
Vertex Charge

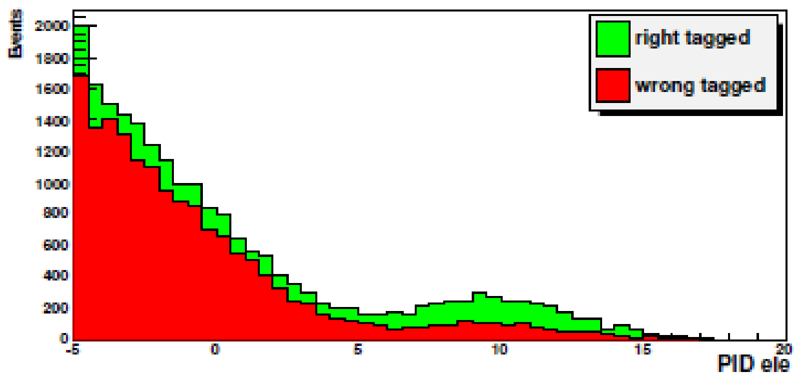
- Only a preselected tagging candidates are used (to discard particles from the primary vertex..)
- The charge of the lepton (Kaon or vertex) determine the quark content
- In case Bopp is a neutral meson an intrisic dilution will occur.

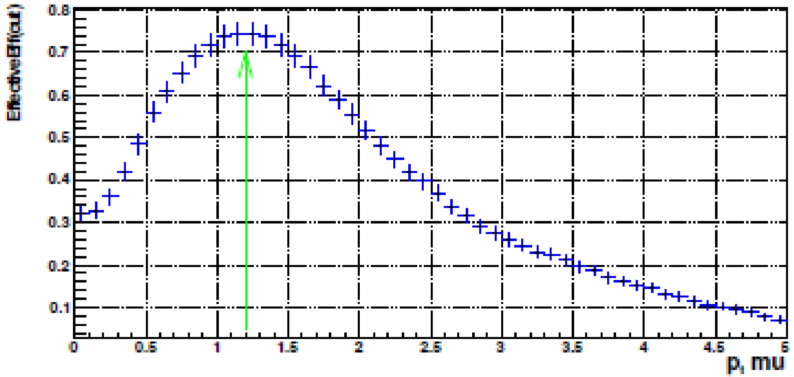
B Opposite side meson composition (%)	
B_d 39.1 $\pm$ 0.7	B^+ 39.1 $\pm$ 0.7
B_s^0 9.58 $\pm$ 0.5	B_c^+ 0.12 $\pm$ 0.06
Barions 12.1 $\pm$ 0.6	

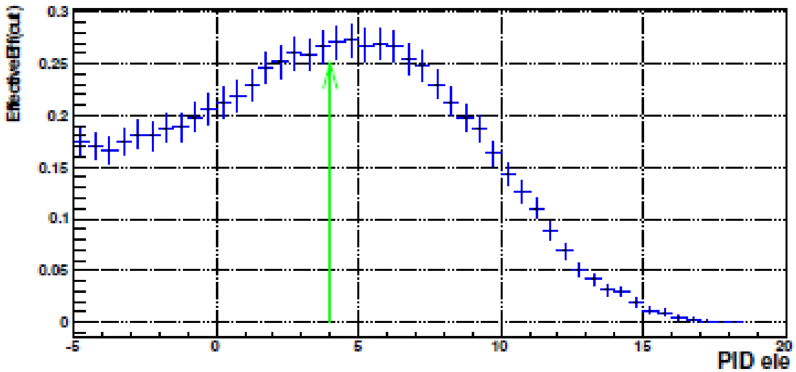
Opposite side taggers

- Kinematic and geometrical properties show a dependence in purity of right vs wrong tagged events. Find the optimal cut which maximize the performances.









Vertex charge tagger

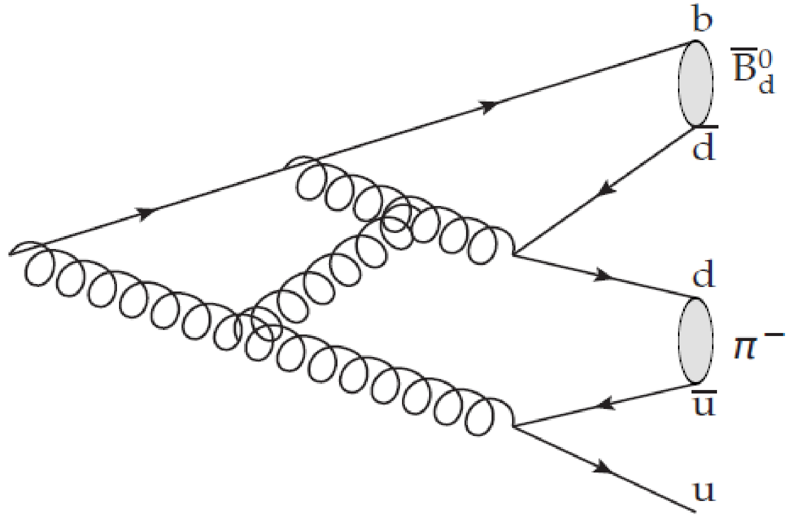
- It is based in the inclusive reconstruction of a secondary vertex corresponding to the opposite B hadron decay. The process goes as follow:
  - A 2-track seed is build to form the secondary vertex (SV) from all possible tagging candidates. A likelihood is used to select the best seed.
  - After some geometric and kinematic cuts, more tracks are added to the seed.
  - The weighted charge of the reconstructed SV is computed to obtain a tagging decision.

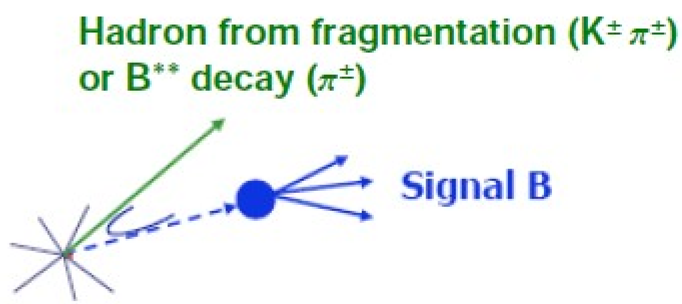
$$Q_{vtx} = \frac{\Sigma_i p_T^k(i) Q_i}{\Sigma_i p_T^k(i)}$$

  - Different set of cuts are applied to the reconstructed SV to improve the effective tagging efficiency.

Same side taggers

- Same side taggers exploits the correlation in the charge of the meson produced in the fragmentation chain of the B signal.





- Pions can be originated when an extra d quark is available, but also from excited states of the B^0.
- In case of B_s mesons, an extra s quark is available to form a charged kaon in about 50% of the cases

Tag decision and mistag probability

- For OS taggers, the charge of the tagger identify the flavour of the Bopp, while for SS taggers it is related with the flavour of the Bsig.

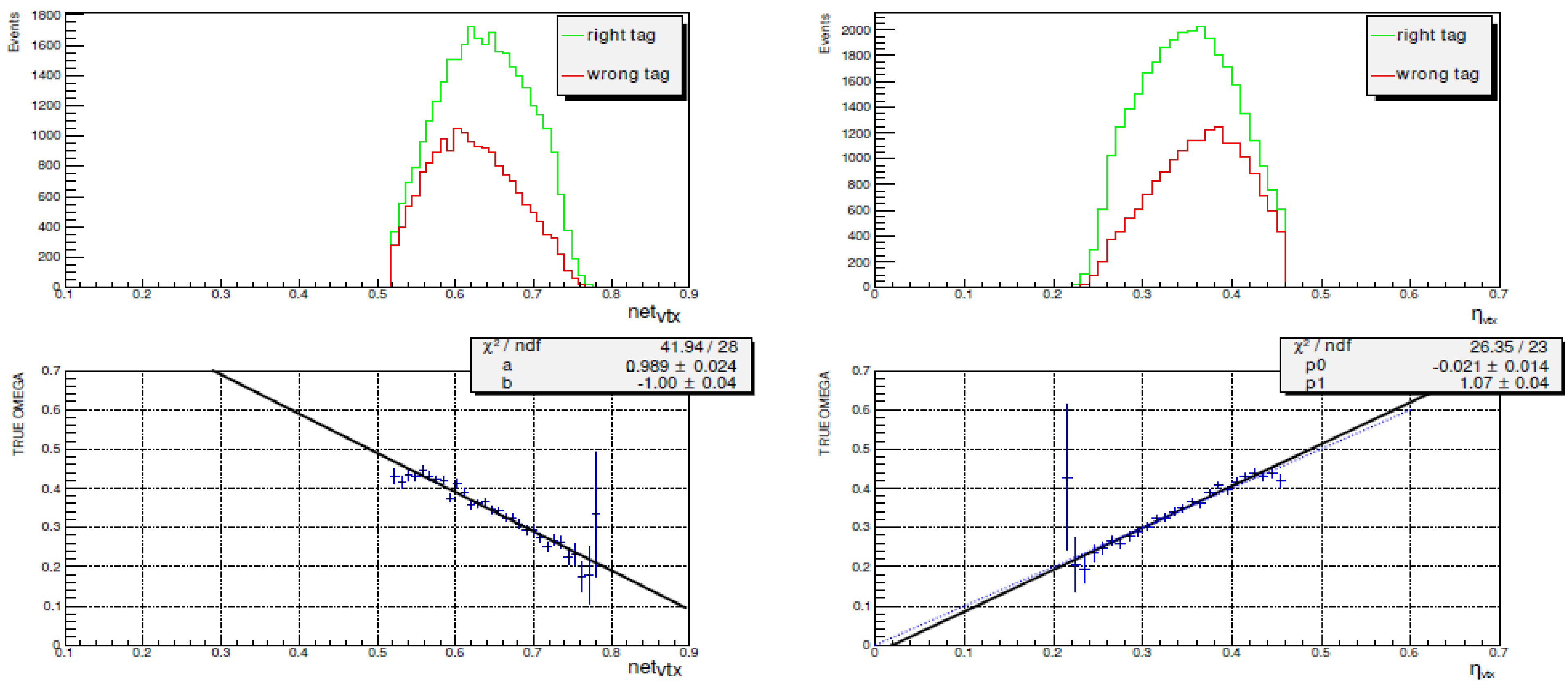
- For each tagger, a probability of the tag decision to be correct is estimated evt-per-evt by means of a NN

$$p_i = 1 - \omega_i$$

  - NN is trained on MC evts to identify the correct flavour of the signal B meson.
  - To correct for differences between data and MC, this probability must be calibrated on data.

Mistag probability

- The dependence of the wrong tag fraction ω on the NN output can be parametrized by a polynomial.
- This will correct for differences between the true ω and the estimated by the NN called η



Optimization and calibration

- FT algorithms were initially developed on MC, however, differences between data and MC could make the tagging performances not optimal.
  - The optimization process is applied on LHCb data with the aim of find the set of cuts which maximize the performances
  - The calibration aims to obtain a reliable mistag estimation which can be used in the CP fits later on.
  - Control channels are decays to flavour-specific final state.

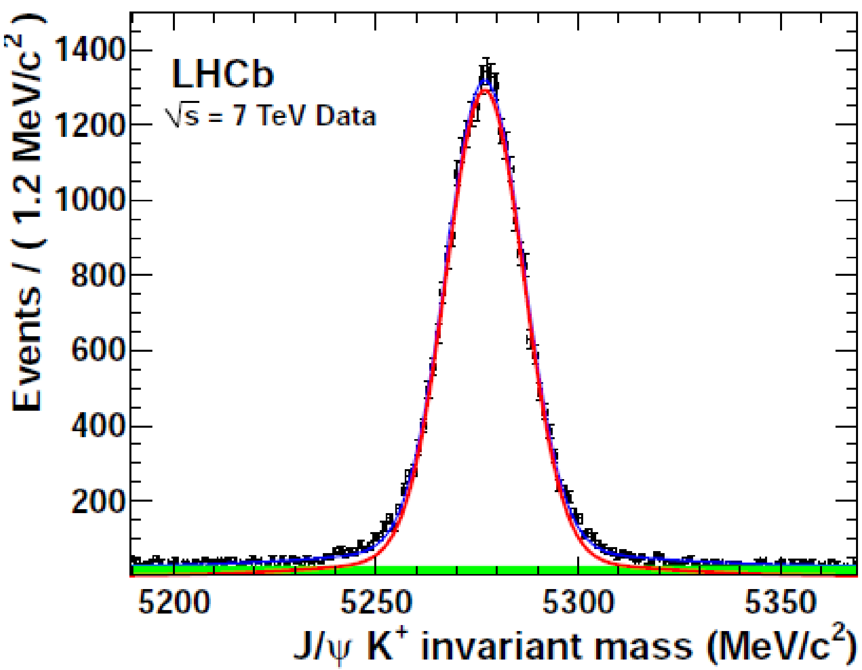
$$B^0 \to D^{*-}\mu^+\nu_\mu, B^+ \to J/\psi K^+, B^0 \to J/\psi K^*, B^0 \to D^-\pi^+$$

- This process was performed with:

  36 pb^{-1}, 337 pb^{-1} and 1 fb^{-1}

Optimization on B^+

- Look at the reconstructed decay products to guess the true flavour of the signal B.
- The tagging parameters can be obtained counting the right and wrong tagged events.
- All events with t > 0.3ps^{-1} and a mass window around the B meson of 25MeV are used as signal justified by the low B/S (0.034)



To avoid over-tuning the sample is split randomly in 2.

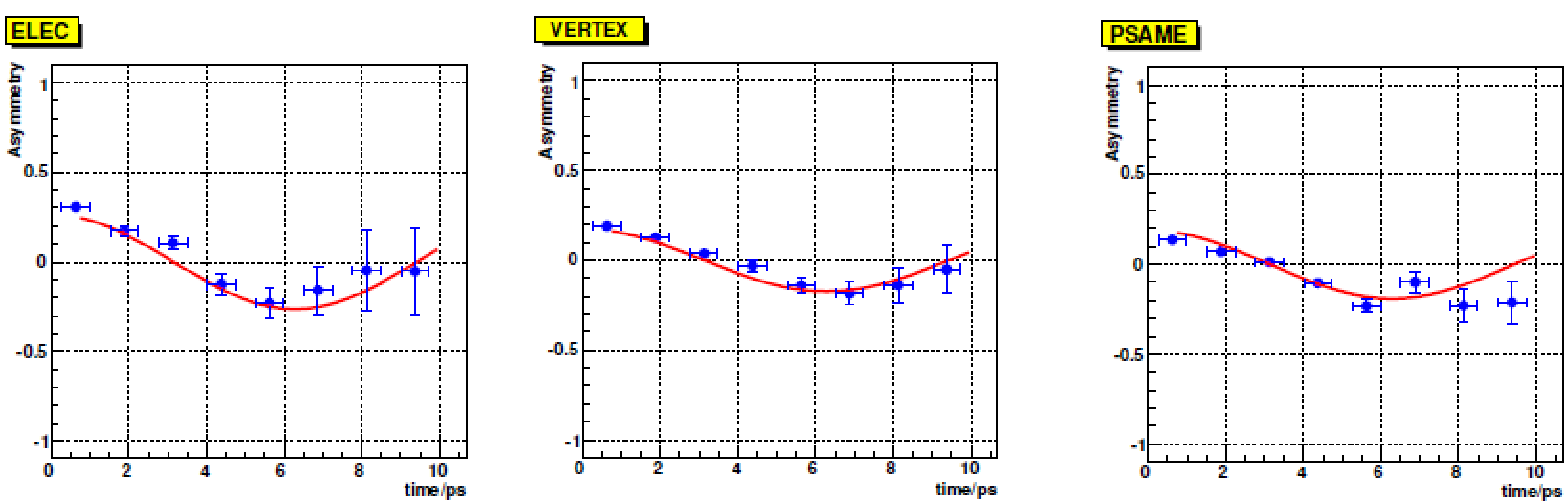
Due to the lack of statistics with 36pb^{-1}, the $B^0 \rightarrow D^{*-} \mu \nu_\mu$ was used for the first optimization of the OS and SS p.

Optimization on B^0 channel

- In a B0 channel the tagging efficiency and ω can be obtained through a fit to the flavour oscillation of the B meson as a function of the decay time.

$$A(t) = \frac{N^{\mathrm{unmix}}(t) - N^{\mathrm{mix}}(t)}{N^{\mathrm{unmix}}(t) + N^{\mathrm{mix}}(t)} \longrightarrow A(t) = (1 - 2\omega)\cos(\Delta m_d t)$$

Bkg sources can be disentagled from signal by using evt within a tight mass window around the D* - D^0, the D* and D^0 mass as well as using evt with large proper time (t>0.3)



Calibration

- For a reliable tagging information, the estimated mistag is calibrated.
  - The measured mistag fraction ω is compared with the estimated mistag η.

$$\omega(\eta) = p_0 + p_1 \cdot (\eta - < \eta >)$$

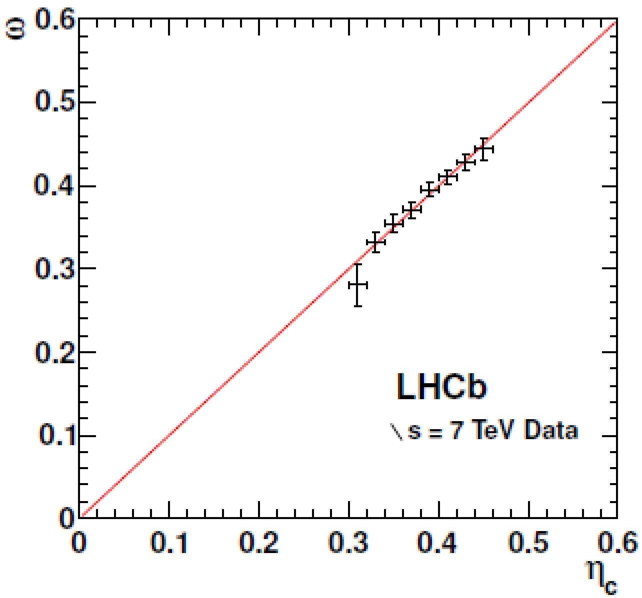
  - P_0 and p_1 are free parameters an <η> is the mean mistag probability.
  - The linearity assumption is motivated by the fact that the calibration should be a minor correction to account for differences between data/MC because η is already precalibrated on MC.

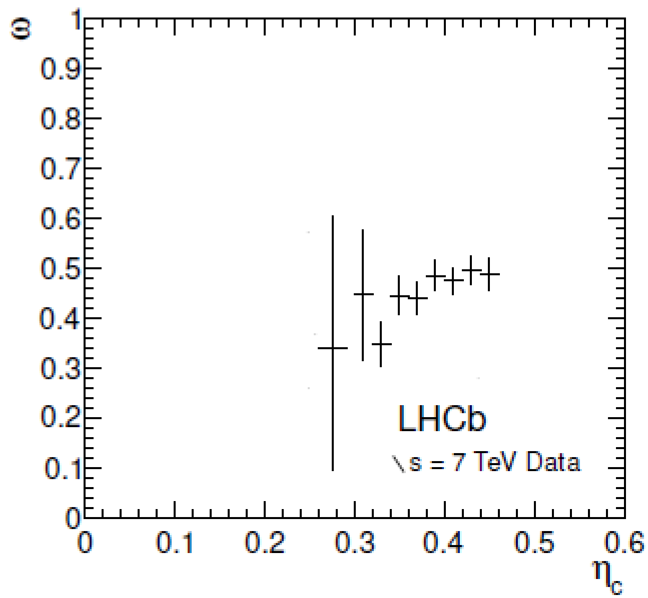
Calibration

- After the calibration the values p_0 p_1 are compatible with <η> and 1.

1 fb^{-1} of $B^+ \to J/\psi K^+$ signal events			
Taggers	p_0	p_1	$< \eta >$
μ	0.309±0.004	1.20±0.06	0.304
e	0.306±0.006	0.974±0.09	0.346
K	0.393±0.002	0.706±0.04	0.354
Q_{vtx}	0.404±0.002	0.84±0.03	0.362

1 fb^{-1} of $B^+ \to J/\psi K^+$ signal events			
Taggers	p_0	p_1	$< \eta_c >$
μ	0.294±0.006	1.044±0.08	0.315
e	0.309±0.009	0.998±0.15	0.307
K	0.394±0.004	0.998±0.10	0.395
Q_{vtx}	0.403±0.004	0.992±0.09	0.398





The calibration parameters were corsschecked on other calibration control channels

Combination of FT algorithms

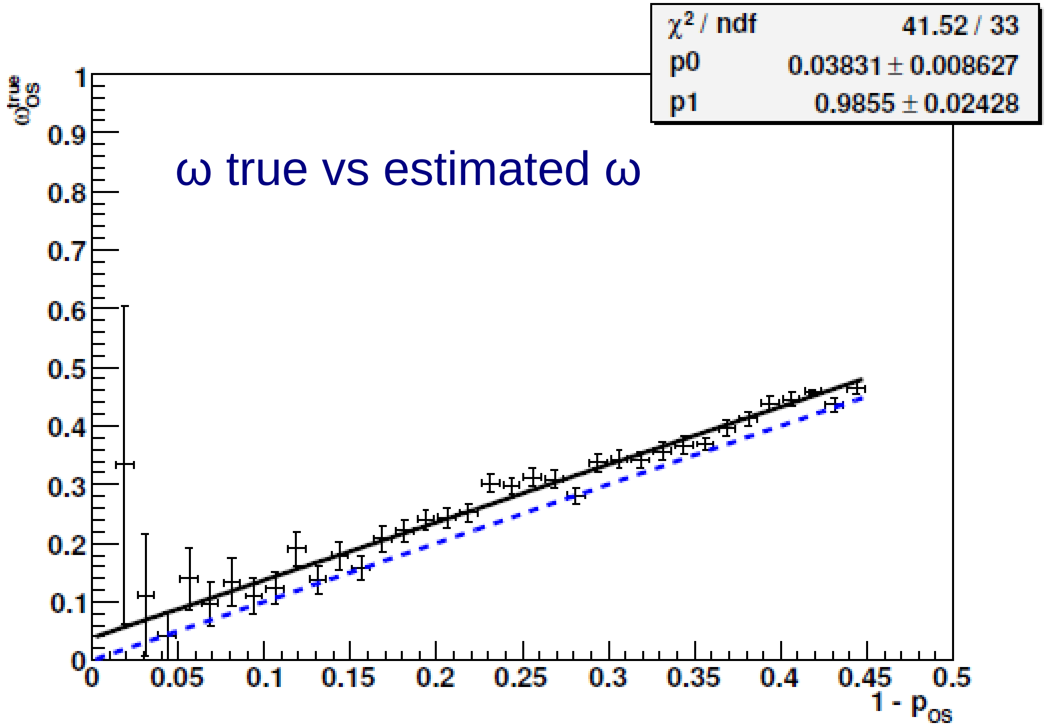
- Combine the taggers to give a single tag decision
- For each tagger, a decision and ω are given
- The final probability evt probability will be a combination of the taggers wrong tag fraction

  - $P^{+1} = (1-\omega_k)\,\omega_e \ldots$ $\quad P(B)= P^{+1}/(P^{+1} + P^{-1})$
  - $P^{-1} = \omega_k\,(1-\omega_e) \ldots$ $\quad P(\overline{B})= 1 - P(B)$

- Other alternative were forseen (PID sorting and NN based combination)

Calibration of the OS combination

- Due to correlations between the OS taggers the combined ω is slightly underestimated



MC

tagger	μ	e	K	Q_{vtx}
μ	18%	0.3%	2.6%	6.3 %
e	–	8.7%	1.6%	3.3 %
K	–	–	44 %	18.3%
Q_{vtx}	–	–	–	59 %

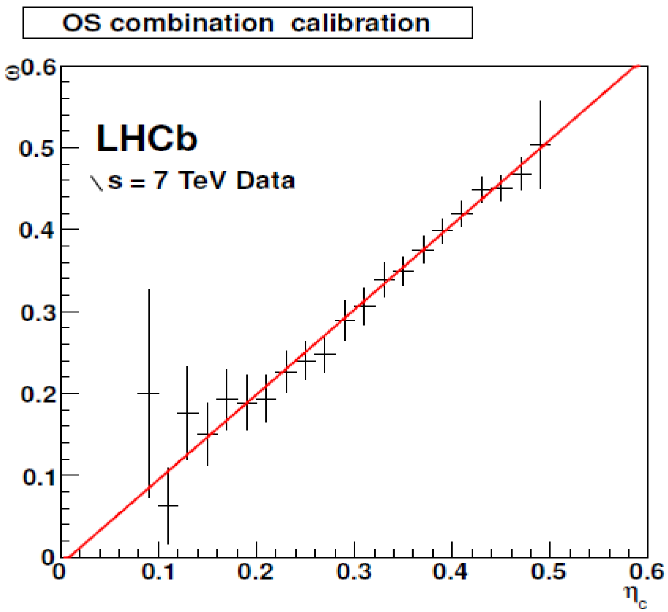
Data

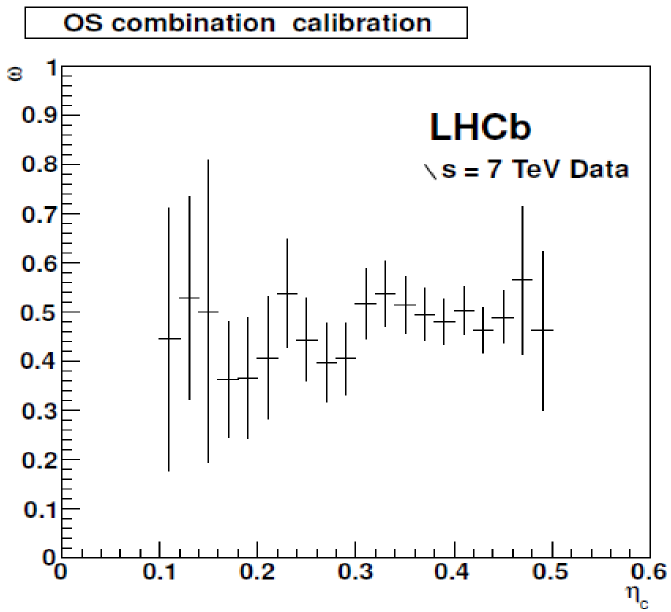
tagger	μ	e	K	Q_{vtx}
μ	19%	0.34%	2.9%	5.1 %
e	–	7.8%	1.6%	2.2 %
K	–	–	42 %	13%
Q_{vtx}	–	–	–	54 %

- A calibration is needed $\omega(\eta) = p_0 + p_1 \cdot (\eta - <\eta>)$

OS combination

- Calibration plots after calibration for signal and bkg



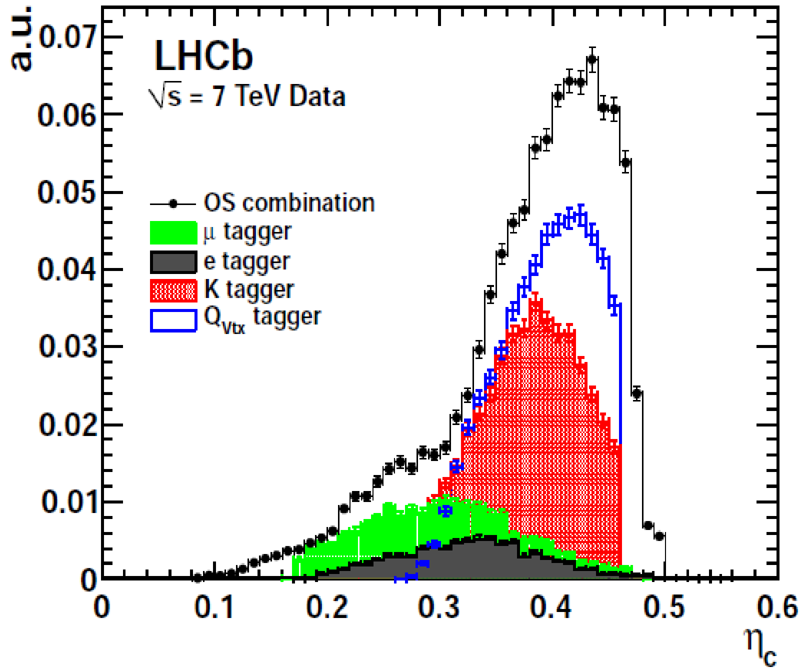


- Fit values of the mistag calibration parameters can be exported to other channels

channel	p_0	p_1	$< \eta_c >$	$\rho(p_0, p_1)$
$B^+ \to J/\psi K^+$	0.392 ± 0.002	1.035 ± 0.021	0.391	0.12
$B^0 \to J/\psi K^*$	0.400 ± 0.004	1.013 ± 0.053	0.390	0.06
$B^0 \to D^- \pi^+$	0.398 ± 0.003	1.010 ± 0.039	0.393	
$B^0 \to K^+ \pi^-$	0.355 ± 0.014	0.99 ± 0.16	0.353	0.14

OS combined decision

- Different ways to compute the tagging performance
  - Average
    (all events with the same weight)
  - In (5) categories
    (distinguish between “bad”/”good” evt)
  - Evt by evt

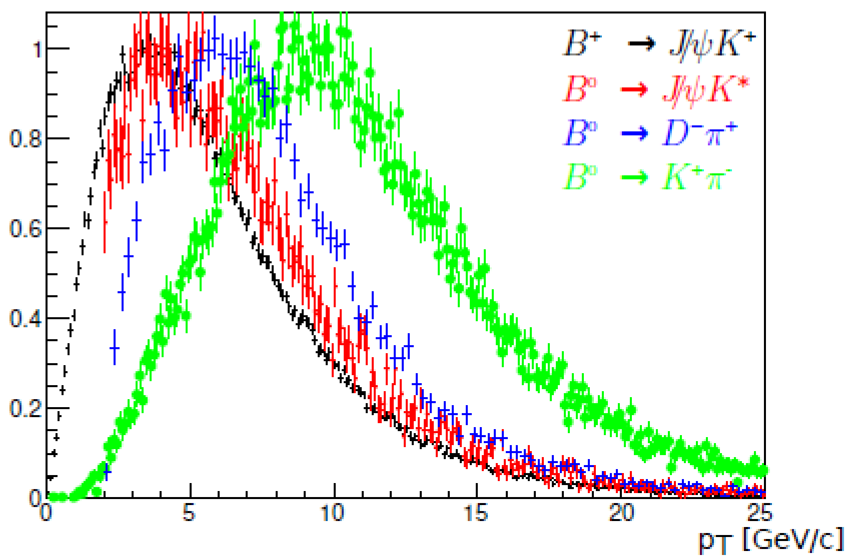


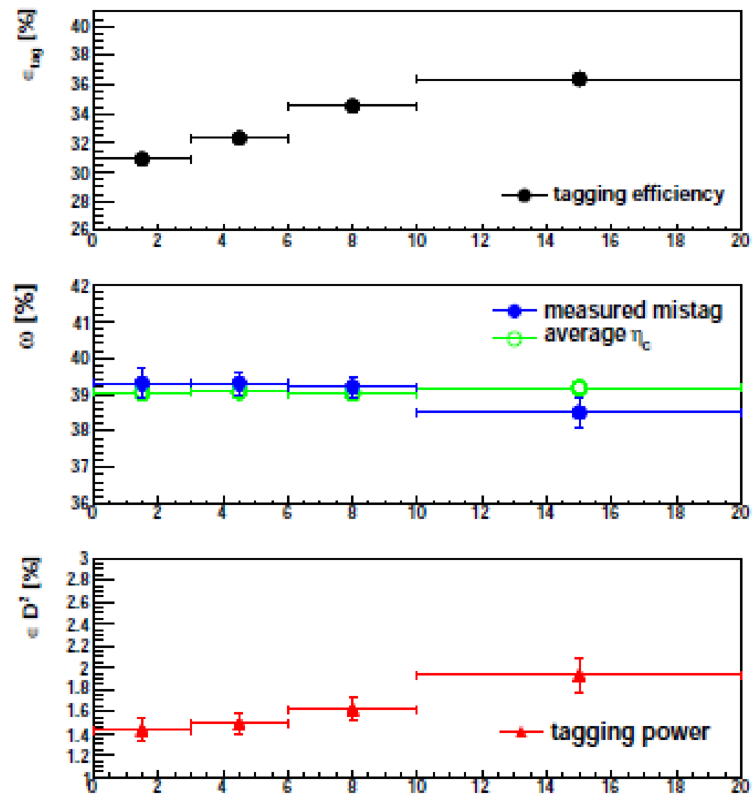
Channel	$\epsilon_{eff}^{average}$ (%)	$\epsilon_{eff}^{combine}$ (%)	$\epsilon_{eff}^{evt-p-evt}$ (%)
$B^+ \to J/\psi K^+$	1.69 ± 0.1	2.07 ± 0.11	2.10 ± 0.08
$B^0 \to J/\psi K^*$	1.24 ± 0.20	1.57 ± 0.22	2.09 ± 0.09
$B^0 \to D^{*-}\mu^+\nu_\mu$	1.58 ± 0.06	2.05 ± 0.06	2.53 ± 0.10

Systematics

- Dependence of the OS tagging on evt properties
  - Flavour of the signal B
  - Tag decision
  - Magnet polairty
  - Pt of the signal B

No significant differences were seen

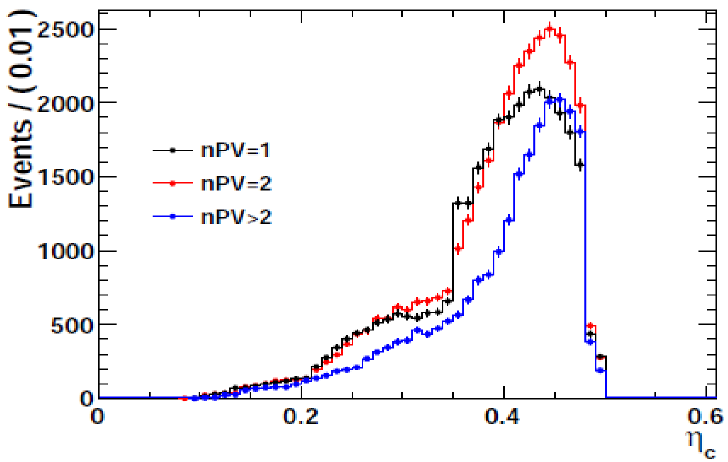


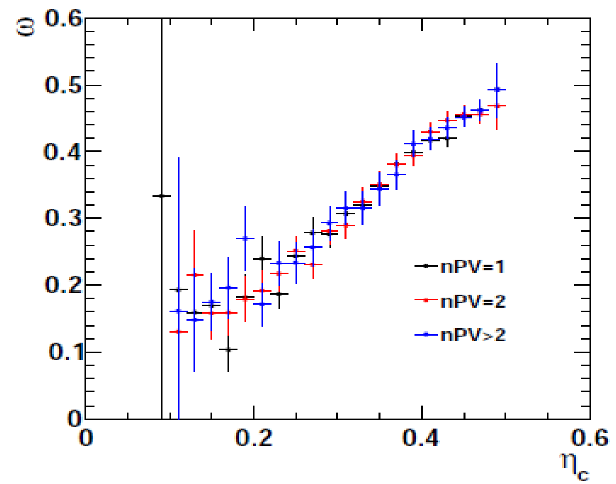


  - NPV, loss of tagging power with increasing number of interactions

Systematics

- Analysis is performed evt-p-evt, where a calibrated evt-p-evt mistag is used
  - ω systematics are evaluated in different conditions
    - Magnet polairty, signal flavour, tag decision, nPV, different fit model,..
    - NPV:





Systematic effect	δp_0	δp_1
Fit model assumptions $\mathcal{P}(\eta)$	$< \pm 0.001$	± 0.012
B-flavour	± 0.005	–
Control channel dependence	± 0.0075	–
Total	± 0.009	± 0.012

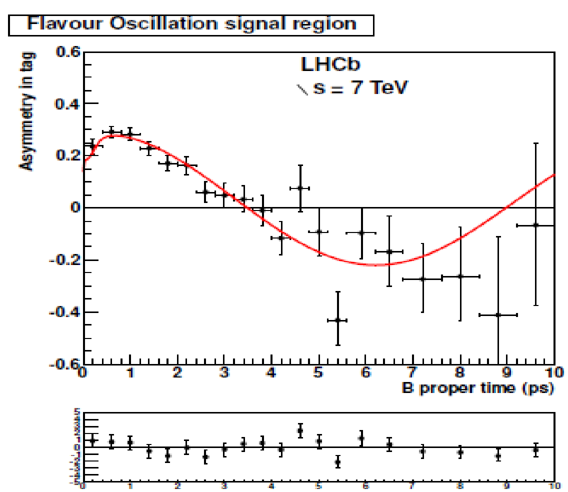
Physics results

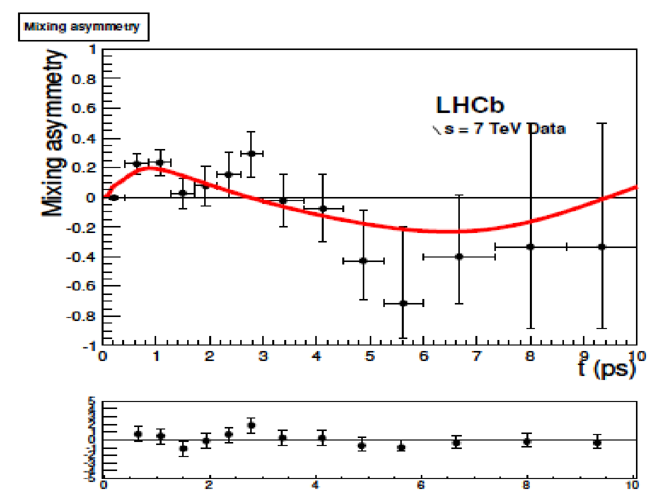
35 pb^{-1}

- First tagging performances and flavour oscillations measured at LHCb.

$B^+ \to J/\psi K^+$	$\epsilon_{tag}(\%)$	ω (%)	$\epsilon_{tag}(1-2\omega)^2$ (%)
OS average (η_c <0.44)	15.4±0.4	33.3±1.2	1.71±0.29
OS combine (η_c <0.44)	15.4±0.3	32.2±1.2	1.97±0.31
OS + SSπ average (η_c <0.44)	22.7±0.4	35.5±1.2	1.92±0.30
OS + SSπ combine (η_c <0.44)	23.0±0.5	33.9±1.2	2.38±0.33

$B^0 \to D^{*-}\mu^+\nu_\mu$ $\quad$ $B^0 \to J/\psi K^*$

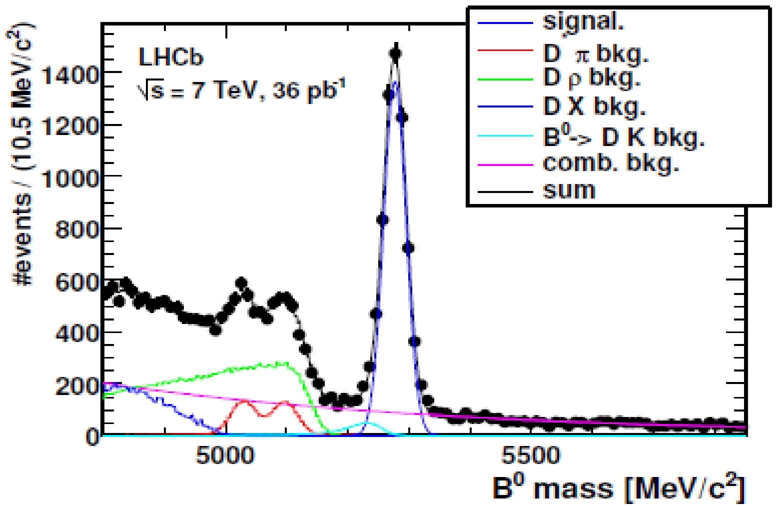


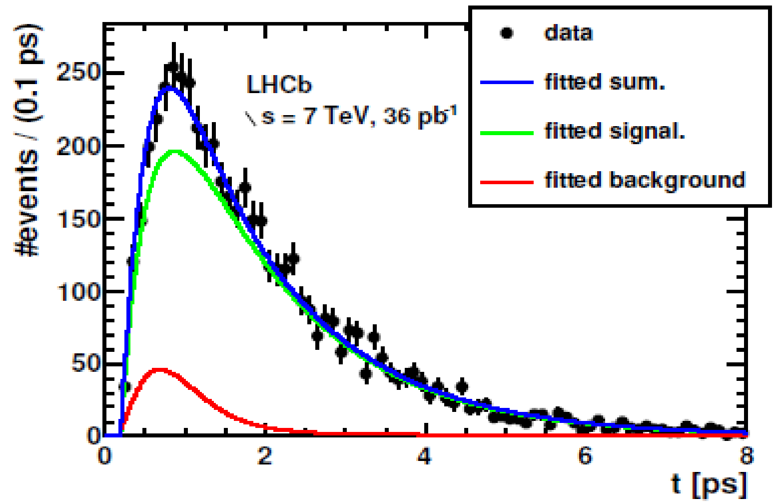


- First physics analyses

$\overline{B}^0 - B^0$ oscillations

- $B^0 \to D^-(K^+\pi^-\pi^-)\,\pi^+$ signal decays

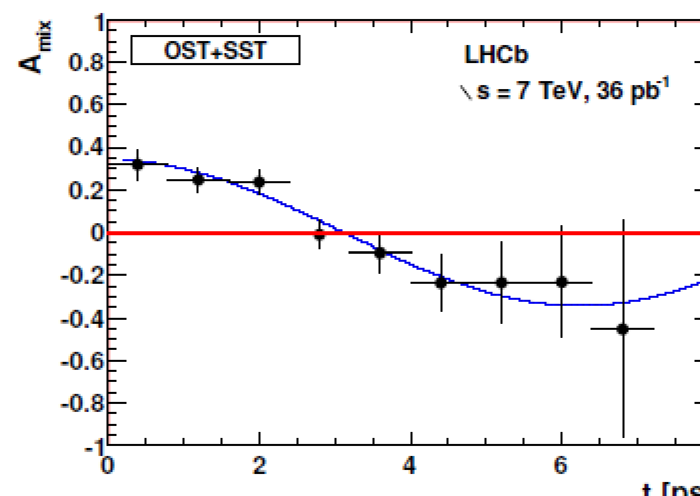




- $\epsilon_{eff}^{OS} = 3.4 \pm 0.9\%$ $\qquad$ $\epsilon_{eff}^{SS+OS} = 4.3 \pm 1.0\%$

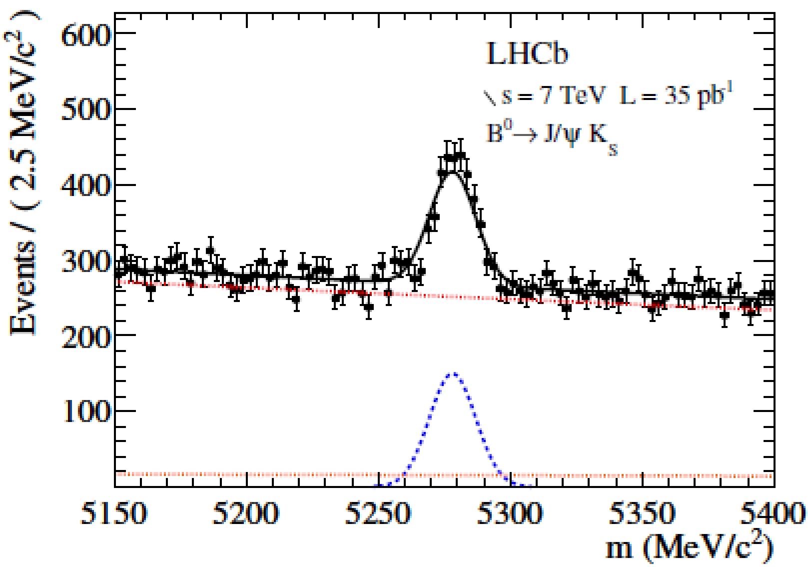
$$A_{mix}(t) = \frac{N(tagged\ as\ unmixed)(t) - N(tagged\ as\ mixed)(t)}{N(tagged\ as\ unmixed)(t) - N(tagged\ as\ mixed)(t)},$$

$$\Delta m_d = 0.499 \pm 0.032(\mathrm{stat}) \pm 0.003(\mathrm{syst})\mathrm{ps}^{-1}$$

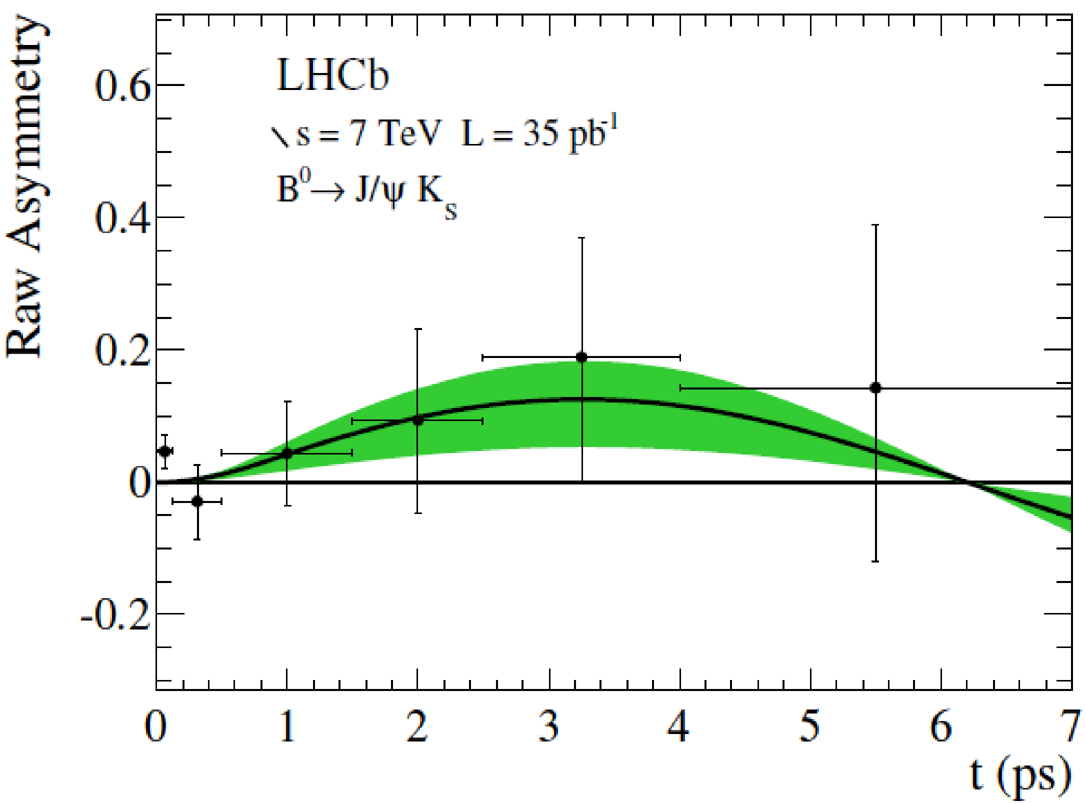


Sin2β in $B^0 \to J/\psi K^0_s$

- $$\mathcal{A}_{J/\psi K_s} \equiv \frac{\Gamma(\bar{B}^0 \to J/\psi K_s) - \Gamma(B^0 \to J/\psi K_s)}{\Gamma(\bar{B}^0 \to J/\psi K_s) + \Gamma(B^0 \to J/\psi K_s)} = S_{J\psi K^0_S} \sin(\Delta m_d t) - C_{J\psi K^0_S} \cos(\Delta m_d t).$$
- Assuming direct CP violation is negligible (C=0)
- Only ~280 signal tagged events were selected

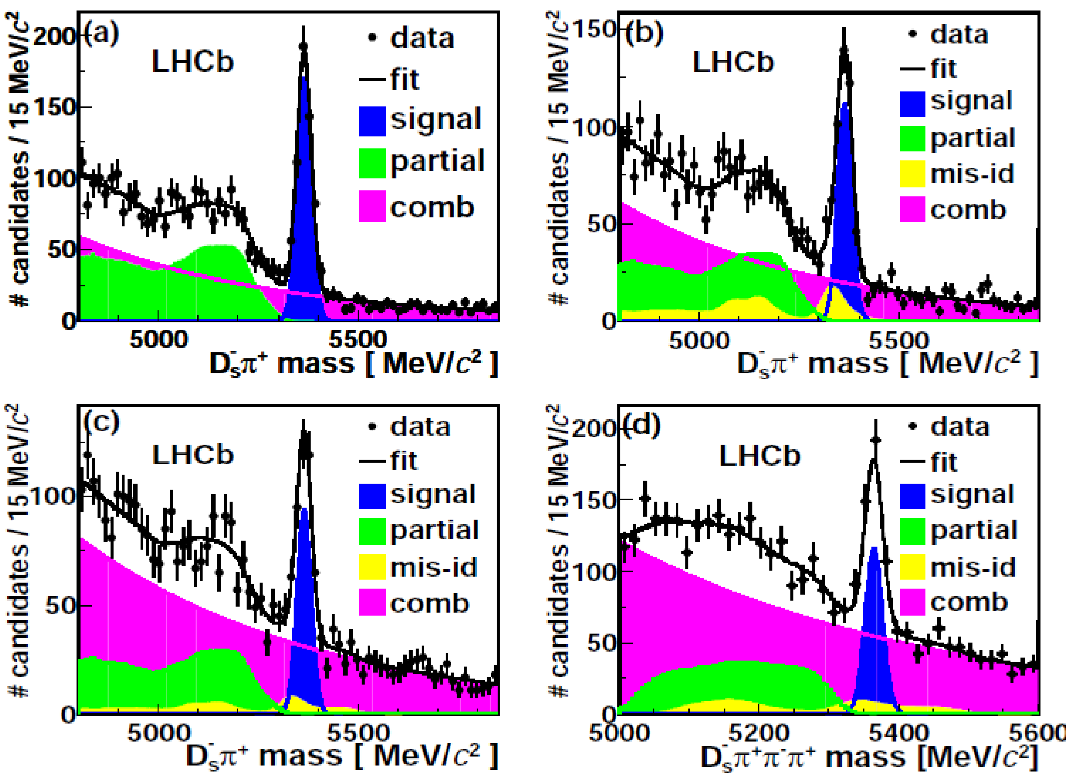


$$S_{J\psi K^0_S} = 0.53^{+0.28}_{-0.29}(\text{stat}) \pm 0.08(\text{syst})$$



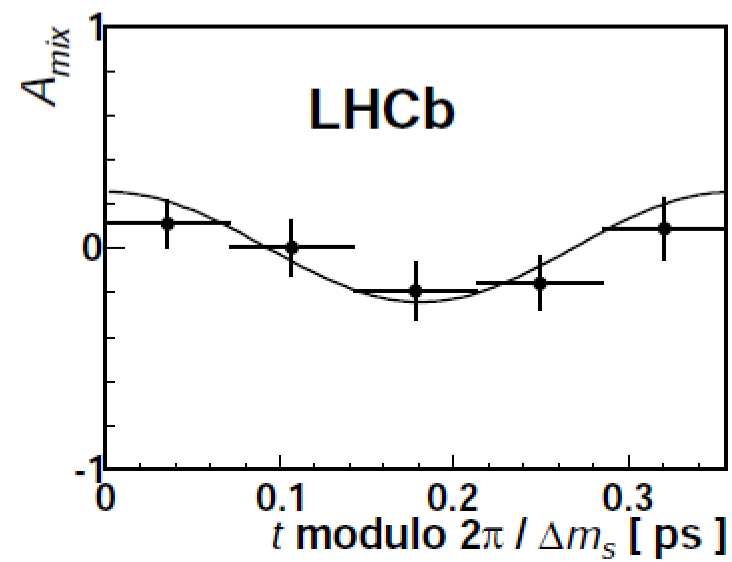
$\overline{B}^0_s - B^0_s$ oscillations

- The fast oscillation is a prerequisite for many physics analysis ($B^0 \to J/\psi\ \phi$)



Bef LHCb

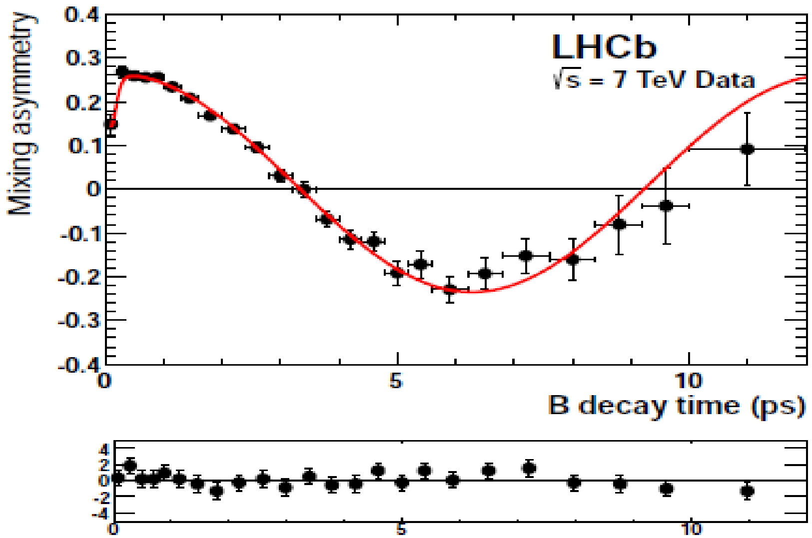
$$\Delta m_s = 17.77 \pm 0.10(\text{stat}) \pm 0.07(\text{syst})\ \text{ps}^{-1}$$



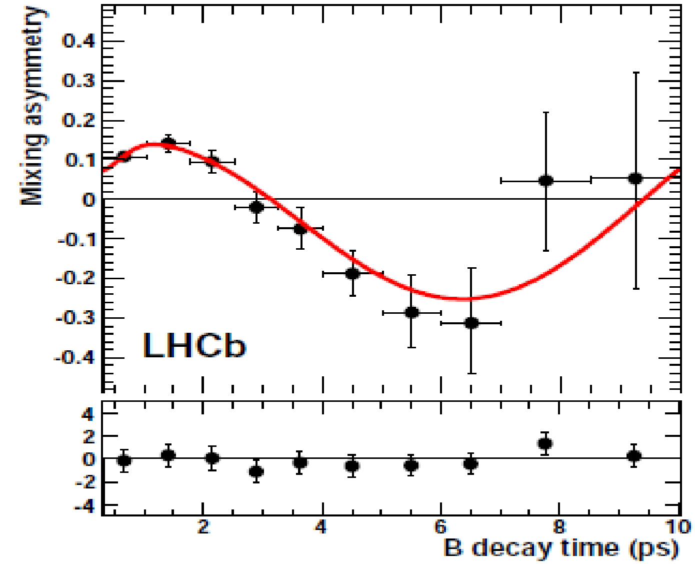
$$\Delta m_s = 17.63 \pm 0.11(\text{stat}) \pm 0.02(\text{syst})\text{ps}^{-1}.$$

337 pb^{-1} & 1 fb^{-1}

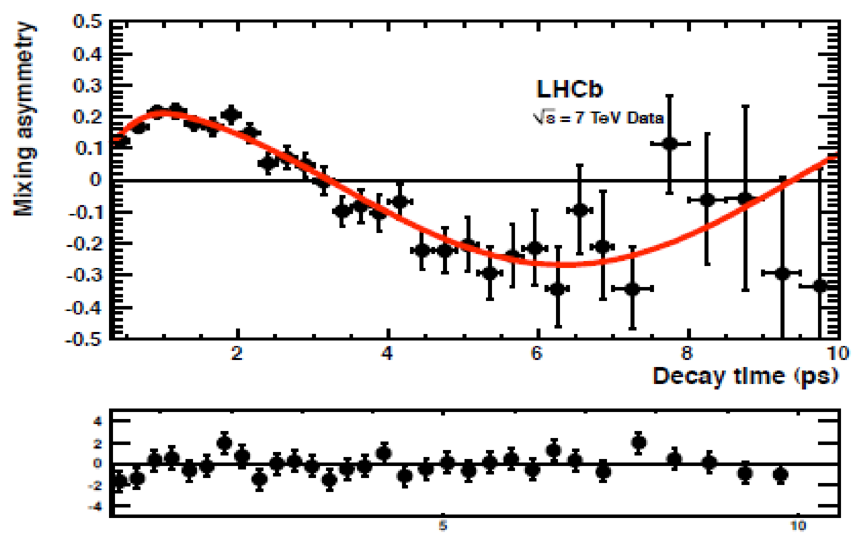
$$B^0 \to D^{*-}\mu^+\nu_\mu$$



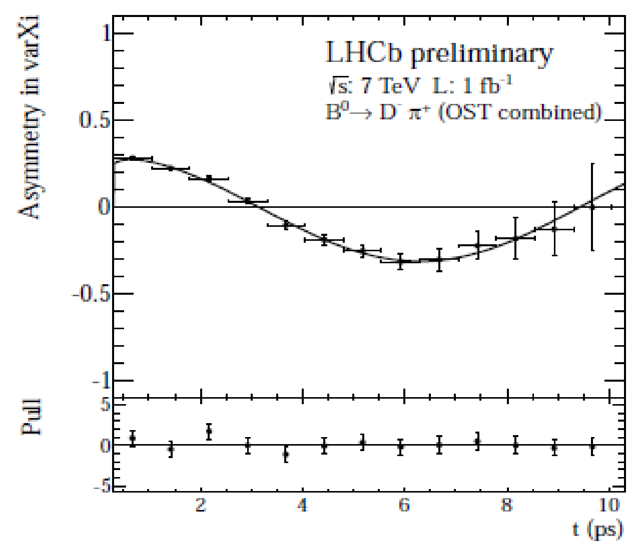
$$B^0 \to J/\psi K^*$$



$$B^0 \to D^{*-}\mu^+\nu_\mu$$



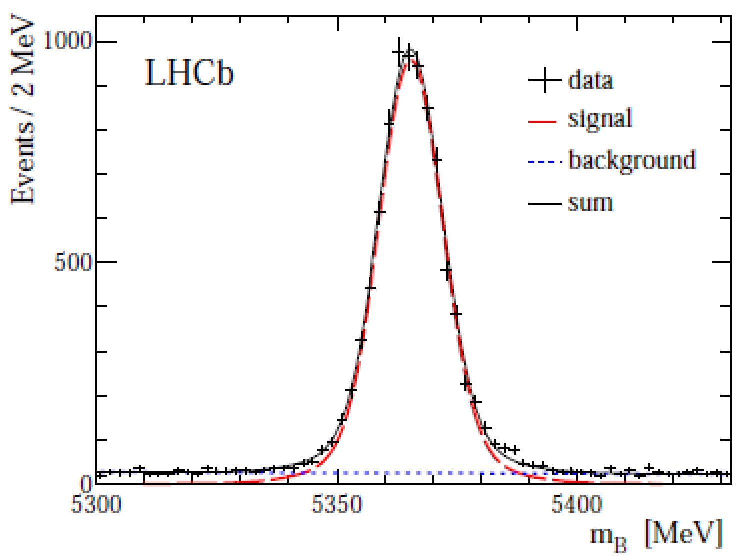
$$B^0 \to D^-\pi^+$$



ϕ_s in the $B^0_s \to J/\psi\, \phi$

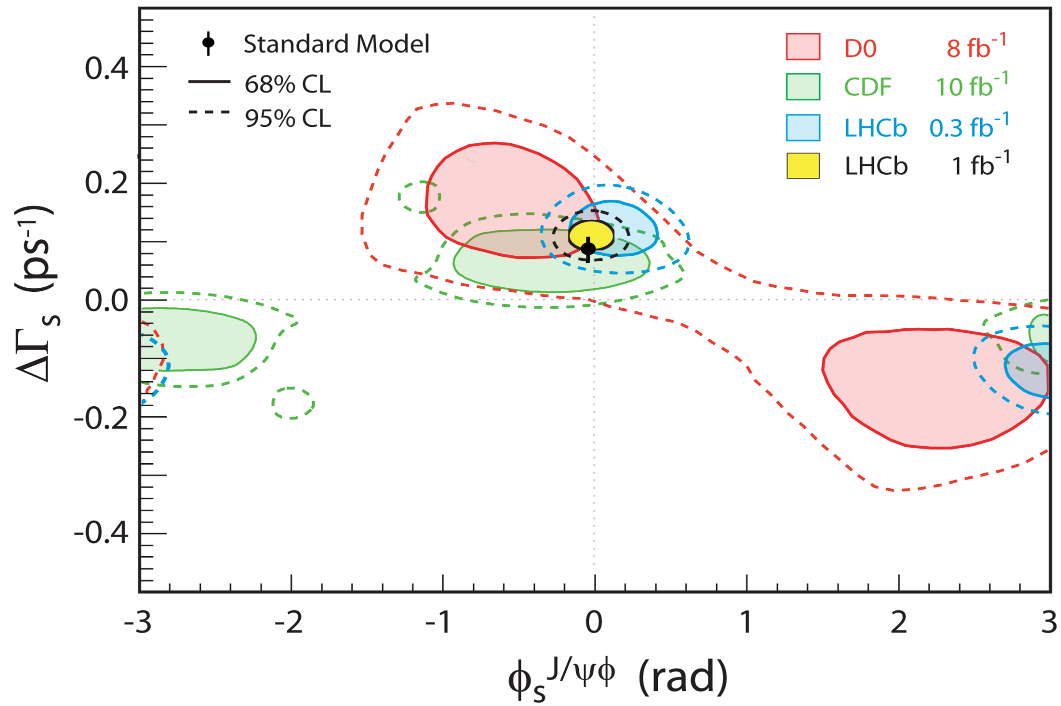
- B meson decays to a final state accessible to both B and $\overline{B}$.
- Interference between the amplitude for the direct decay and the amplitude for decay after oscillation

$$B^0_s \to \mu^+\mu^- K^+ K^-$$



$$\phi_s = -0.001 \pm 0.101 \pm 0.027$$

Combined result with $B^0_s \to J/\psi\, f_0(980)$



$$\phi_s = -0.002 \pm 0.083 \pm 0.027$$

Conclusions

- Flavour tagging is a fundamental ingredient for B physics measurements in LHCb
- LHCb is already tagging the flavour of the reconstructed B

Channel	$\epsilon_{tag}[\%]$	ω [%]	$\epsilon_{tag}\mathcal{D}^2$ [%]
$B^+ \to J/\psi K^+$	27.3 ± 0.1	$36.1 \pm 0.3 \pm 0.8$	$2.10 \pm 0.08 \pm 0.24$
$B^0 \to J/\psi K^*$	26.7 ± 0.2	$36.0 \pm 0.3 \pm 0.8$	$2.09 \pm 0.09 \pm 0.24$
$B^0 \to D^{*-}\mu^+\nu_\mu$	30.5 ± 0.1	$35.6 \pm 0.3 \pm 0.8$	$2.53 \pm 0.10 \pm 0.27$
$B_s^0 \to J/\psi\phi$	24.9 ± 0.5	$36.1 \pm 0.3 \pm 0.8$	$1.91 \pm 0.08 \pm 0.22$

Tagger & Channel	$\epsilon_{tag}[\%]$	ω [%]	$\epsilon_{tag}\mathcal{D}^2$ [%]
SSK $B_s^0 \to D_s^-\pi^+$	16.3 ± 04	35.3 ± 2.1	1.4 ± 0.4
SSπ $B^0 \to J/\psi K^*$	17.6 ± 0.12	39.7 ± 0.5	0.75 ± 0.08
SSπ $B^0 \to D^-\pi^+$	24.08 ± 0.12	39.2 ± 0.4	1.12 ± 0.08

- First physics results already published (some with the best precision ever)
- ToDo: differences between data/MC (mult, PID,..), different performances for different channels (pT, TIS/TOS,...), upgrade (multiple PV,..)
- More data and flavour tagging improvements (inclusion of SSK) will lead to measurements with unprecedented precision, and hopefully evidencies for new physics.

STAY TUNED

Thanks!

Back Up

CP Violation

Discovered in 1964 by James Cronin and Val Fitch in the neutral K-meson system.

$$\Psi(t) = a(t)\left|K^0\right\rangle + b(t)\left|\overline{K^0}\right\rangle \equiv \begin{pmatrix} a(t) \\ b(t) \end{pmatrix}$$

$$i\frac{\partial}{\partial t}\Psi = \hat{H}\Psi$$

K^0 are mass eigenstates, but the weak eigenstates have a defined mass and lifetime

Now consider the effect of CP symmetry:

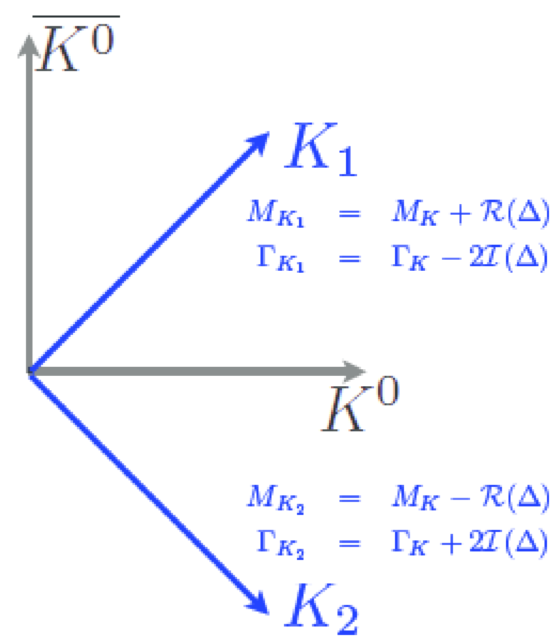
CP

$$K^0 \leftrightarrow \pi^+\pi^-$$

$$\overline{K^0} \leftrightarrow \pi^+\pi^-$$

$$\Longleftrightarrow \quad K^0 \leftrightarrow \overline{K^0}$$

$$\hat{H} = \begin{pmatrix} M_K - \frac{i}{2}\Gamma_K & \Delta \\ \Delta & M_K - \frac{i}{2}\Gamma_K \end{pmatrix}$$



CP Violation

$$|K_1\rangle = \frac{|K^0\rangle + |\overline{K^0}\rangle}{\sqrt{2}}$$

$$|K_2\rangle = \frac{|K^0\rangle - |\overline{K^0}\rangle}{\sqrt{2}}$$

Only the CP even state can decay into 2 pions

$|K_1\rangle$ (CP=+1) → ππ (CP = -1 * -1 = +1)

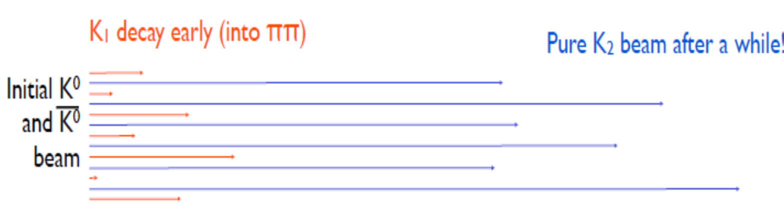
The CP odd state will decay into 3 pions instead

$|K_2\rangle$ (CP=-1) → ππ π (CP = -1*-1*-1 = -1)

<u>Experiment</u>:

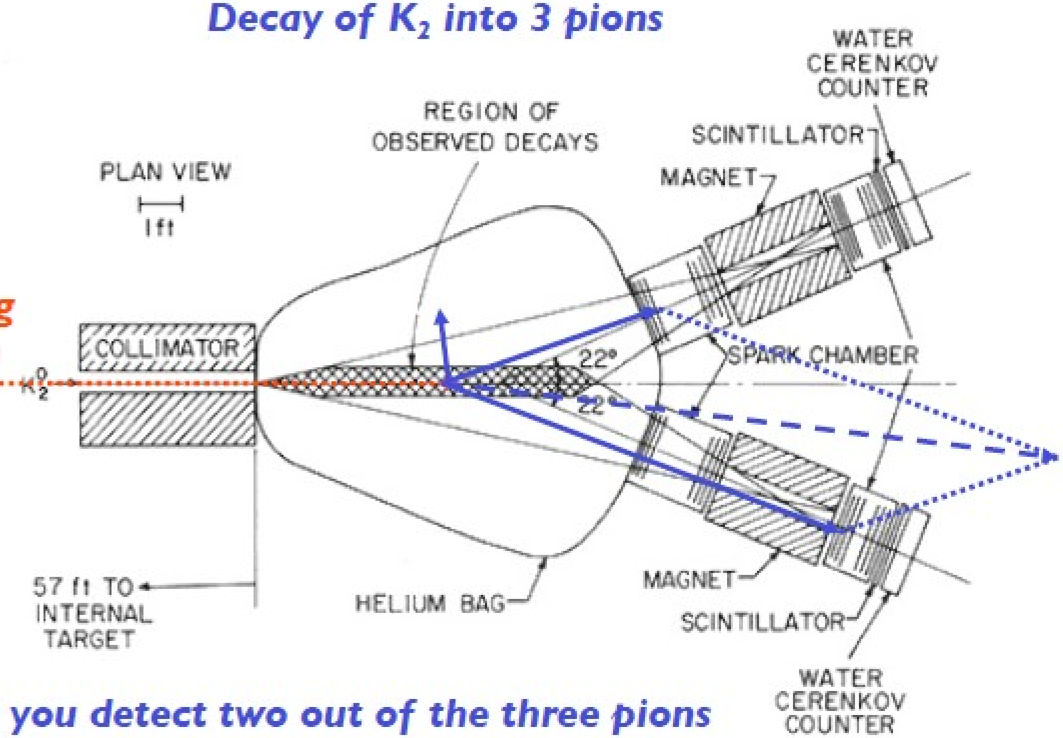
Build a K_2 beam and look for 2 pion decay.

Exploit the faster K_1 decay



Decay of K_2 into 3 pions

Incoming K_2 beam



If you detect two out of the three pions of a $K_2 \to \pi\pi\pi$ decay their combined momentum will generally not point along the beam line

Use of unitarity constrains

The 9 unitarity conditions of the 3×3 generations CKM matrix:

$$|V_{ud}|^2 + |V_{cd}|^2 + |V_{td}|^2 = 1$$
$$|V_{us}|^2 + |V_{cs}|^2 + |V_{ts}|^2 = 1$$
$$|V_{ub}|^2 + |V_{cb}|^2 + |V_{tb}|^2 = 1$$

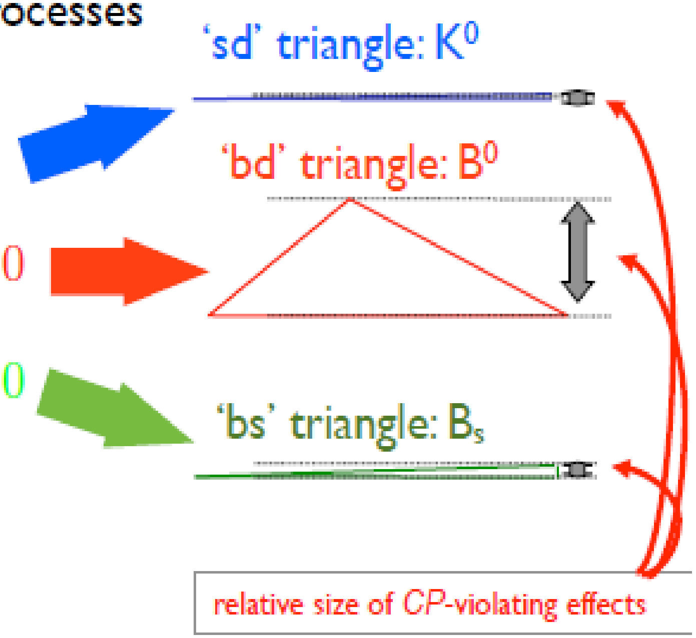
$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

The 6 complex "**Unitarity Triangles**" involve different physics processes

$$V_{us}^* V_{ud} + V_{cs}^* V_{cd} + V_{ts}^* V_{td} = 0 \qquad \mathcal{O}(\lambda) + \mathcal{O}(\lambda) + \mathcal{O}(\lambda^5) = 0$$

$$V_{ub}^* V_{ud} + V_{cb}^* V_{cd} + V_{tb}^* V_{td} = 0 \qquad \mathcal{O}(\lambda^3) + \mathcal{O}(\lambda^3) + \mathcal{O}(\lambda^3) = 0$$

$$V_{ub}^* V_{us} + V_{cb}^* V_{cs} + V_{tb}^* V_{ts} = 0 \qquad \mathcal{O}(\lambda^4) + \mathcal{O}(\lambda^2) + \mathcal{O}(\lambda^2) = 0$$



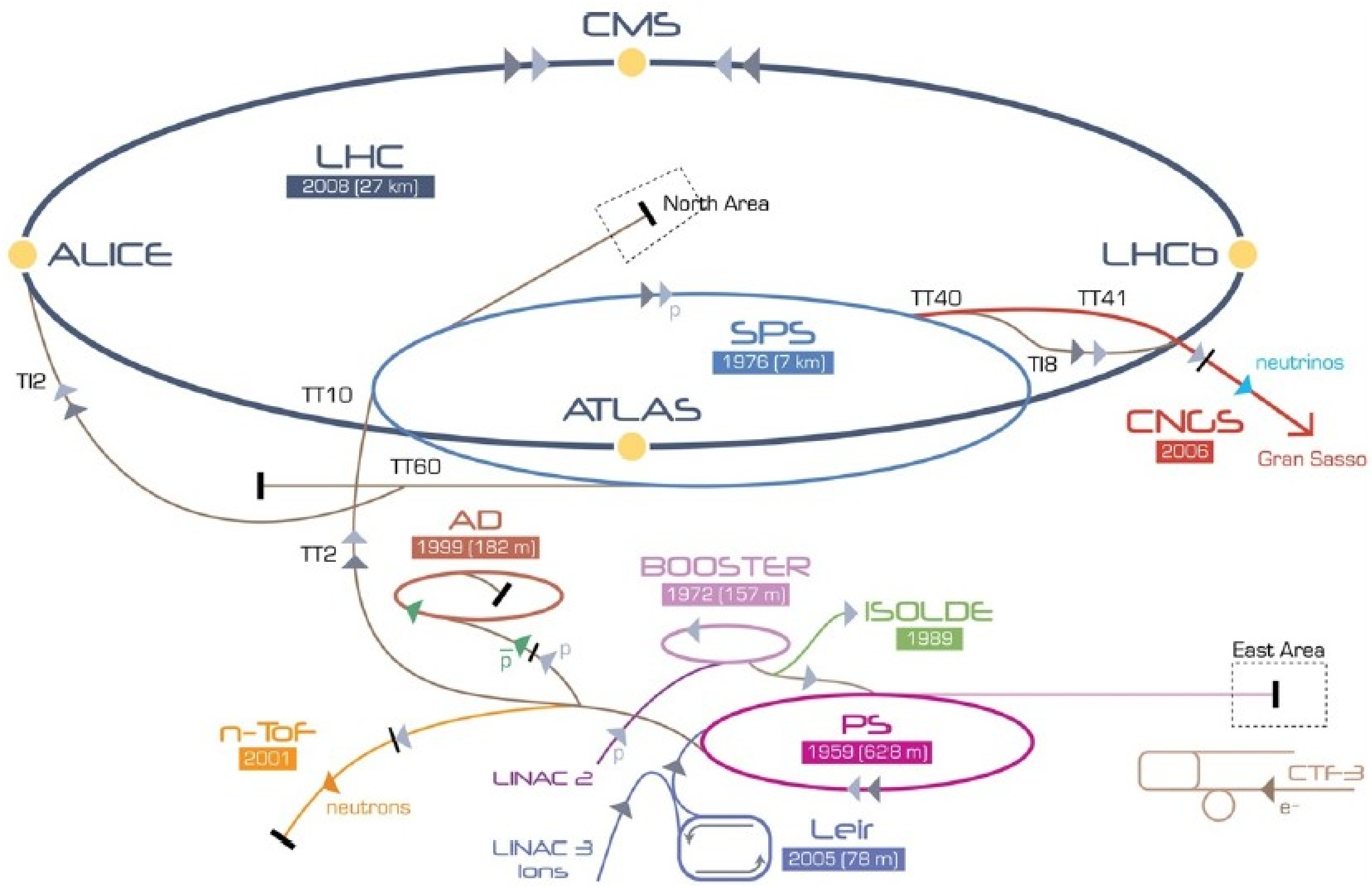
$$V_{ud} V_{cd}^* + V_{us} V_{cs}^* + V_{ub} V_{cb}^* = 0$$

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

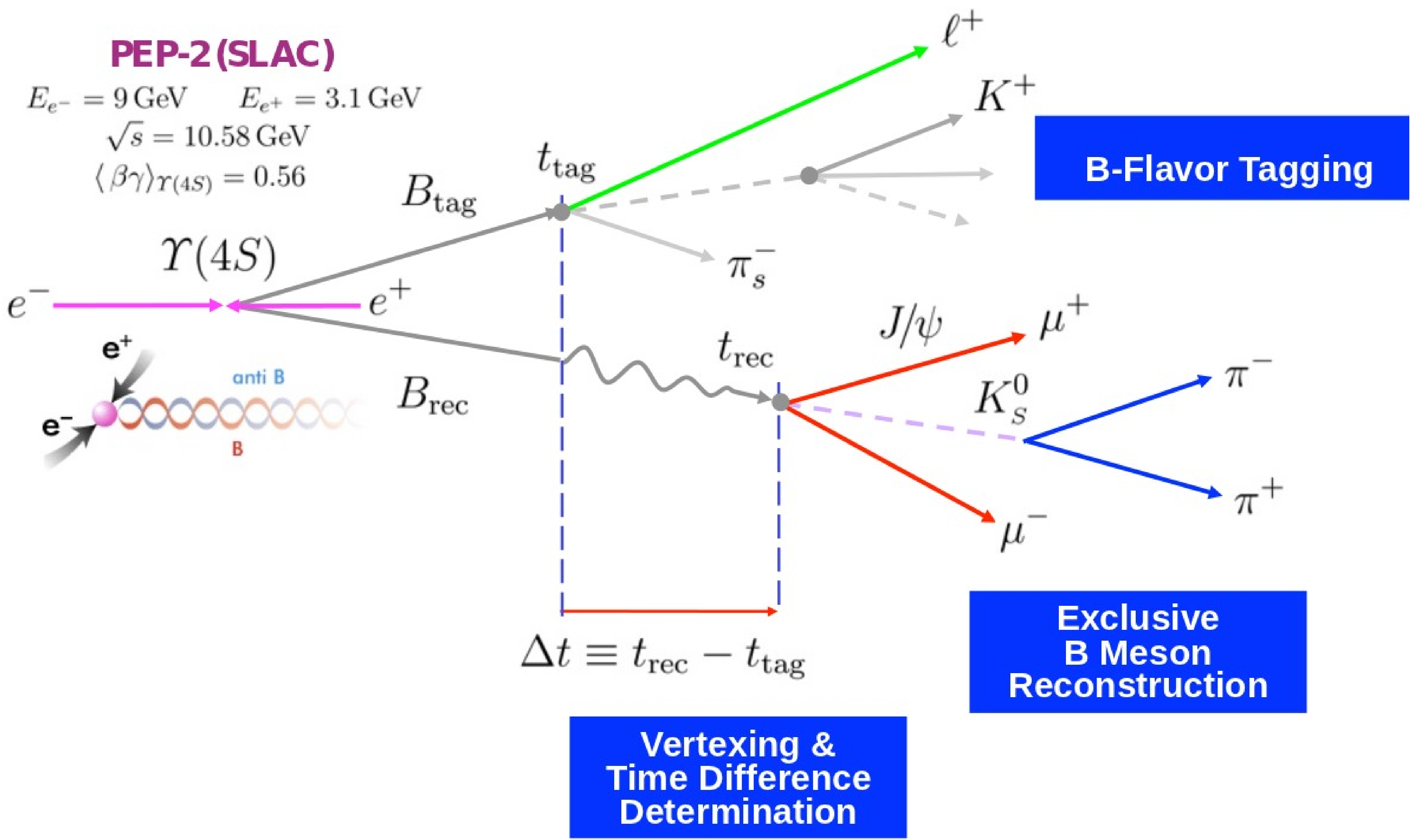
$$V_{cd} V_{td}^* + V_{cs} V_{ts}^* + V_{cb} V_{tb}^* = 0$$

The LHC

- The CERN acceleration complex



Tagging @ B-factory



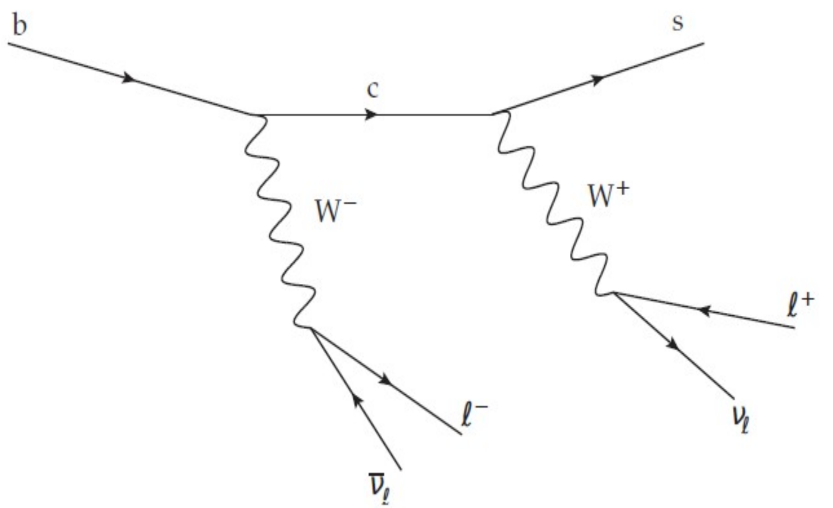
Tag decision and mistag probability

- For OS taggers, the charge of the tagger identify the flavour of the Bopp, while for SS taggers it is related with the flavour of the Bsig.
  - The tag decision is defined as d=-1 for signal B hadrons containing a b quark and d=+1 for signal B hadrons containing a bbar quark.
- For each tagger, a probability of the tag decision to be correct is estimated evt-per-evt as a function of several kinematic and geometrical properties of the tagger and the event itself.
  - This is done by means of a NN trained on MC evt to identify the correct flavour of the signal B meson. To correct for differences between data and MC, this probability must be calibrated on data. When more data will be available, the training will be directly performed on data.

$$p_i = 1 - \omega_i$$

Other Opposite side taggers

- Ideas for b → c → l tagger. Assuming for the same tagging efficiency a reduction of 10%-15% wrong tagged events could be achieved increasing the tagging performances around 20%.



- Opposite D0 tagger. Look for vertex which can be associated to the D0 meson decay. All possible combinations of one kaon and one pion of opposite charge are studied. Some extra cuts can be added to increase the tagging power. A effective efficiency between 0.1% and 0.3% can be achieved with and without mass cuts. Due to high correlations with the Vertex charge and OS K taggers it was finally not used

Optimization cuts

tagger	min p_T [GeV/c]	min p [GeV/c]	min IP/σ_{IP}	max track χ^2/ndf	Particle Identification Cuts	min $IP_{PU}/\sigma_{IP_{PU}}$	min $\|\Delta\phi\|$	extra cuts	$Prob_{min}$ $(1-\omega)$
Cuts optimized on 2010 data - Moriond 2011									
μ	1.1	-	-	2.2	$\Delta LL_{\mu-\pi} > 2$	3	5mrad	NSH CloneDistance	-
e	1	-	2	5	$\Delta LL_{e-\pi} > 4$	3	30mrad	VeloChMax <1.6 $E/p > 0.6$	-
OS K	0.8	4	4	2.7	$\Delta LL_{K-\pi} > 5$ $\Delta LL_{K-\pi} - \Delta LL_{p-\pi} > -4$	6	5mrad	$\|IP\| < 1.5$mm NSH	
OS K(*)	0.8	5.875	4.05	2.125	$\Delta LL_{K-\pi} > 6.5$ $\Delta LL_{K-\pi} - \Delta LL_{p-\pi} > -3.5$	4.72	5mrad	$\|IP\| < 1.25$mm NSH	0.51
Cuts optimized on summer 2011 data - LP 2011									
μ	1.2	-	-	3.2	$\Delta LL_{\mu-\pi} > 2.5$	3	5mrad	NSH CloneDistance	-
e	1	-	2	5	$\Delta LL_{e-\pi} > 4$	3	30mrad	VeloChMax <1.6 $E/p > 0.6$	-
OS K	0.8	5.875	4.05	2.125	$\Delta LL_{K-\pi} > 6.5$ $\Delta LL_{K-\pi} - \Delta LL_{p-\pi} > -3.5$	4.72	5mrad	$\|IP\| < 1.25$mm NSH	0.51
Cuts optimized on 2011 data - Moriond 2012									
μ	1.2	-	-	3.2	$\Delta LL_{\mu-\pi} > 2.5$	3	5mrad	NSH CloneDistance	-
e	1	-	1	3.85	$\Delta LL_{e-\pi} > 4$	5	5mrad	VeloChMax <1.6 $E/p > 0.75$	-
OS K	0.7	5	4.3	2.15	$\Delta LL_{K-\pi} > 0.75$ $\Delta LL_{K-\pi} - \Delta LL_{p-\pi} > -3$	7.5	5mrad	$\|IP\| < 1.45$mm NSH	0.54

OS Vch	Seed Prob	Power K	min abs(Vch)	min $\Sigma_i p_T^i$ [GeV/c^2]	min $\Sigma_i IP^i/\sigma_{IP}^i$	min $\Sigma_i p^i$ [GeV/c^2]	min $\Sigma_{i,j}^{i\neq j} DOCA^{ij}$ [mm]	min $\Sigma_{i,j}^{i\neq j} m^{ij}$ [GeV/c^2]	$Prob_{min}$ $(1-\omega)$
Cuts optimized on 2010 data - Moriond 2011									
	0.4	0.4	0.17	-	-	-	-	-	0.53
Cuts optimized on summer 2011 data - LP 2011									
	0.4	0.4	0.275	1.5	10	10	0.5	0.5	0.54
Cuts optimized on 2011 data - Moriond 2012									
	0.42	0.55	0.2	1.55	10	8	0.5	0.6	0.54

Optimization cuts

SS π	min p_T [GeV/c]	min p [GeV/c]	max IP/σ_{IP} max $IP(mm)$	max track χ^2/ndf	Particle Identification Cuts	$\Delta\eta$, $\Delta\phi$ and ΔR	ΔQ	$Prob_{min}$ $(1-\omega)$
Cuts optimized on 2010 data - Moriond 2011								
	0.75	5	3.5	5	$\Delta LL_{K-\pi} < 3$ $\Delta LL_{p-\pi} < 10$	- -	$\Delta Q < 1.5$GeV/c^2	0.53
Cuts optimized on summer 2011 data - LP 2011								
	0.75	5	3.5	5	$\Delta LL_{K-\pi} < 3$ $\Delta LL_{p-\pi} < 10$	- -	$\Delta Q < 1.5$GeV/c^2	0.54
Cuts optimized on 2011 data - Moriond 2012								
	0.6	4	9	5	$\Delta LL_{K-\pi} < 4.3$ $\Delta LL_{p-\pi} < 14$	-0.5< $\Delta\eta < 0.35$ $\lvert\Delta\phi\rvert < 0.75$ $\lvert\Delta R\rvert < 0.75$	$\Delta Q < 1.2$GeV/c^2	0.56

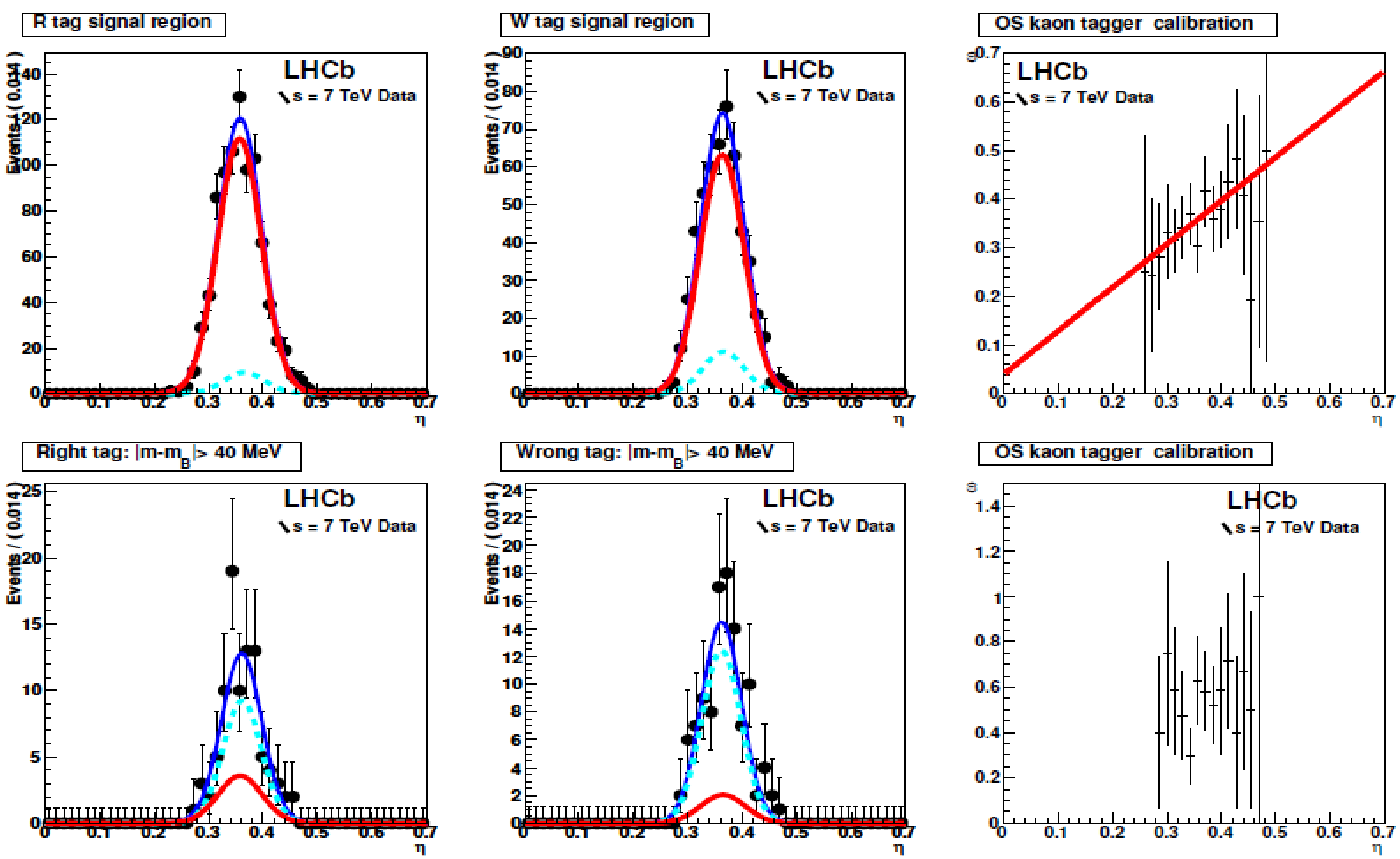
SSK selection cuts (prompt D_s data)
$\Delta LL_{K-\pi} > 4.5$
$\Delta LL_{K-p} >$ -8.5
$p_T > 0.75$ GeV/c
$p > 5.25$ GeV/c
track $\chi^2/d.o.f < 3.75$
$IP/\sigma_{IP} < 4.125$
$\Delta\eta < 0.525$
$\Delta\phi < 0.7$
$dQ < 1.4625$ GeV

SSK selection cuts ($B_s^0 \to D_s^- \pi^+$data)
$\Delta LL_{K-\pi} > 3.5$
$\Delta LL_{K-p} >$ -8.5
$p_T > 0.85$ GeV/c
$p > 5.25$ GeV/c
track $\chi^2/d.o.f < 3.75$
$IP/\sigma_{IP} < 4.125$
$\Delta\eta < 0.6$
$\Delta\phi < 0.825$
$dQ < 1.85$ GeV

Calibration fit

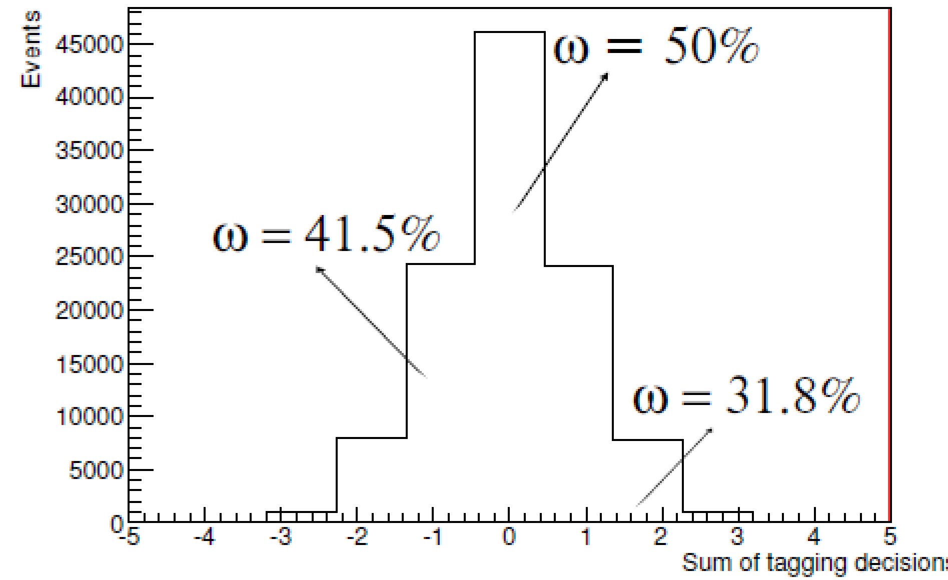
- In case of B^+

$$\mathcal{P}^{\rm tag}(r,\eta) = \begin{cases} \epsilon_{tag}\,(1-\omega(\eta))\,\mathcal{P}(\eta) & \text{if r=1, right tag,} \\ \epsilon_{tag}\,\omega(\eta)\mathcal{P}(\eta) & \text{if r=-1, wrong tag,} \\ 1-\epsilon_{tag} & \text{if r=0, untag.} \end{cases}$$

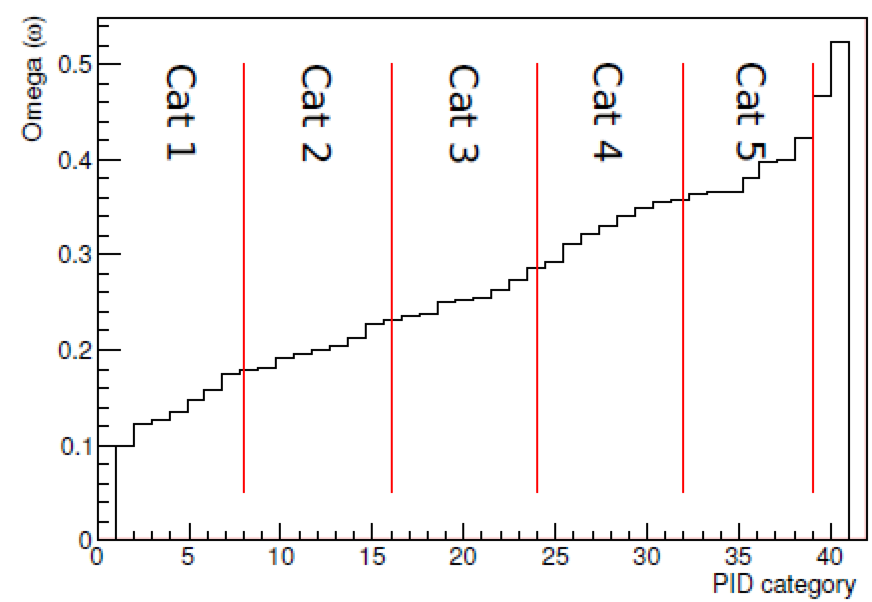


PID based combination

- Form possible combinations according to particle identification (mu, e, k, vtx, SS), and the sum of the individual taggers decision.



- Sort all possible combinations, according to the estimated omega in a control channel, and bin the events in categories



Systematics

- Dependences on tagging performances must be considered when using the average or the sum of categories.
- Only systematics in ω calibration for evt-p-evt analsyes

$$p_0 = 0.392 \pm 0.002(\mathrm{stat}) \pm 0.009(\mathrm{syst})$$

$$p_1 = 1.035 \pm 0.021(\mathrm{stat}) \pm 0.012(\mathrm{syst})$$

$$< \eta_c >= 0.391 \qquad \rho(p_0, p_1) = 0.12$$

OS syst

$$p_0 = 0.350 \pm 0.015(\mathrm{stat}) \pm 0.005(\mathrm{syst})$$

$$p_1 = 0.51 \pm 0.16(\mathrm{stat}) \pm 0.02(\mathrm{syst})$$

$$< \eta_c >= 0.324$$

SSK syst

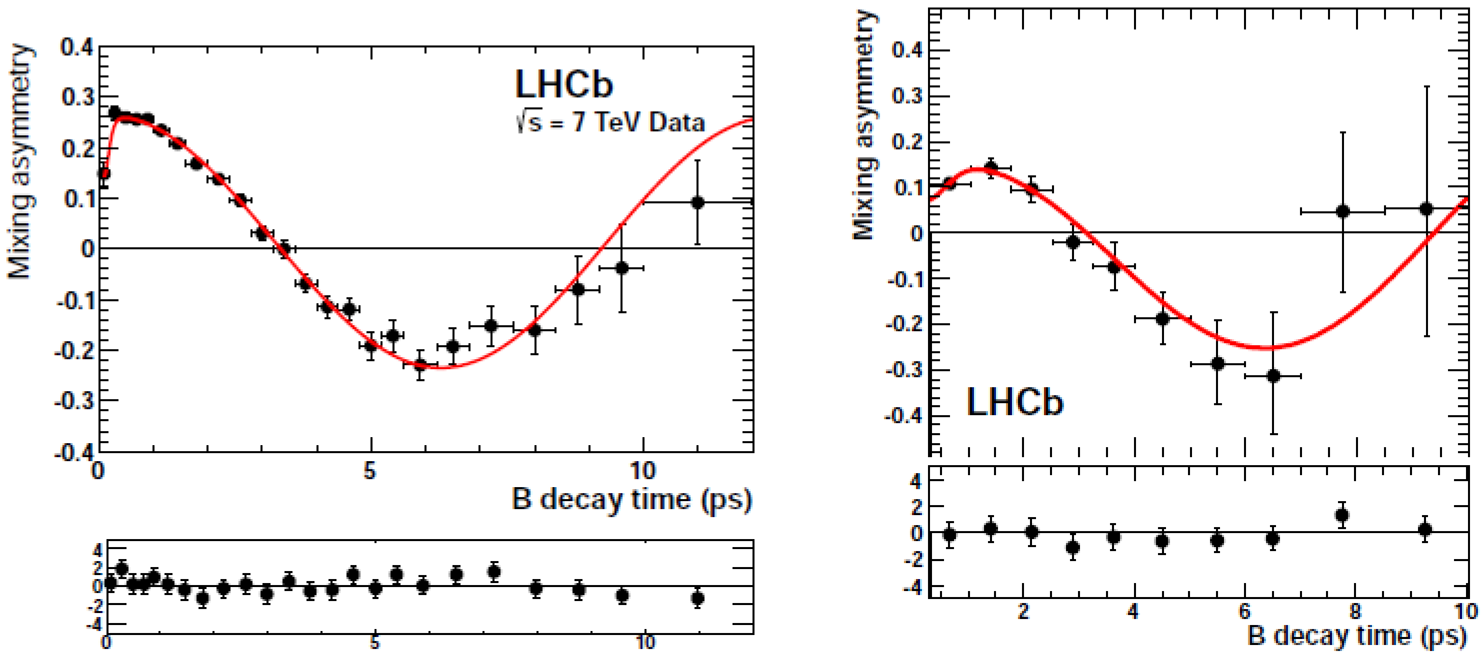
SS Π (being studied)

$337\ pb^{-1}$

Only OS

Channel	$\epsilon_{tag}[\%]$	ω [%]	$\epsilon_{tag}\mathcal{D}^2$ [%]
$B^+ \to J/\psi K^+$	27.3 ± 0.1	$36.1 \pm 0.3 \pm 0.8$	$2.10 \pm 0.08 \pm 0.24$
$B^0 \to J/\psi K^*$	26.7 ± 0.2	$36.0 \pm 0.3 \pm 0.8$	$2.09 \pm 0.09 \pm 0.24$
$B^0 \to D^{*-}\mu^+\nu_\mu$	30.5 ± 0.1	$35.6 \pm 0.3 \pm 0.8$	$2.53 \pm 0.10 \pm 0.27$
$B_s^0 \to J/\psi\phi$	24.9 ± 0.5	$36.1 \pm 0.3 \pm 0.8$	$1.91 \pm 0.08 \pm 0.22$

$B^0 \to D^{*-}\mu^+\nu_\mu$ $\qquad$ $B^0 \to J/\psi K^*$

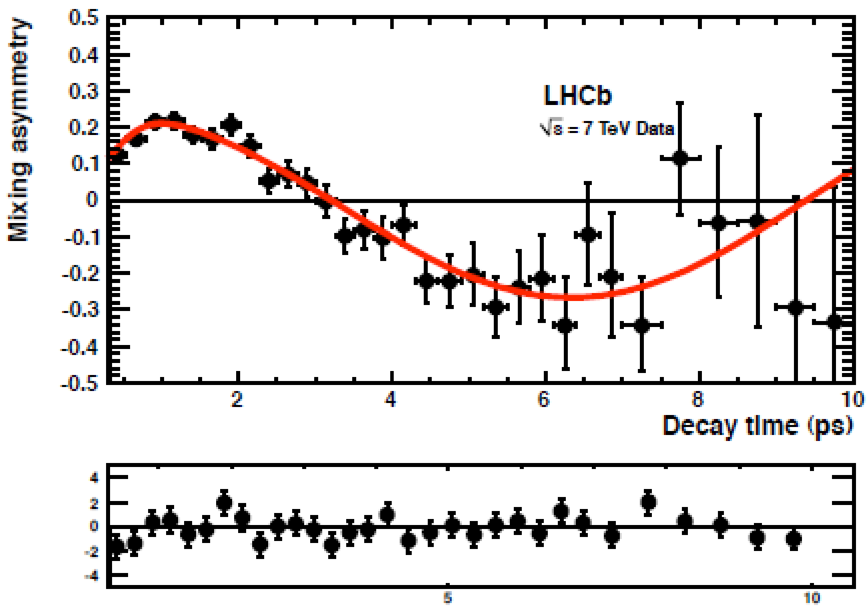


1 fb^{-1}

Tagger & Channel	$\epsilon_{tag}[\%]$	ω [%]	$\epsilon_{tag}\mathcal{D}^2$ [%]
SSK $B_s^0 \to D_s^- \pi^+$	16.3 ± 04	35.3 ± 2.1	1.4 ± 0.4
SSπ $B^0 \to J/\psi K^*$	17.6 ± 0.12	39.7 ± 0.5	0.75 ± 0.08
SSπ $B^0 \to D^- \pi^+$	24.08 ± 0.12	39.2 ± 0.4	1.12 ± 0.08

tagging performances measured with SS taggers

$$B^0 \to D^{*-}\mu^+\nu_\mu$$



$$B^0 \to D^-\pi^+$$