CP Violation in B Decays with LHCb Experiment

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On behalf of LHCb Collaboration

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Outline

- CKM Matrix and CP Violation

- The LHCb Experiment and Performance

- Main LHCb Physics Objectives:

  - B_s oscillation phase φ_s
  - CKM angle γ from Tree and Loops diagrams
  - CP Violation in charm decays

- Covered here:

  - β measurement
  - β_s prospect
  - γ prospect

- Results and Perspectives

CKM Matrix and CP Violation

- CP Violation is introduced in the Standard Model via a complex phase in the CKM matrix

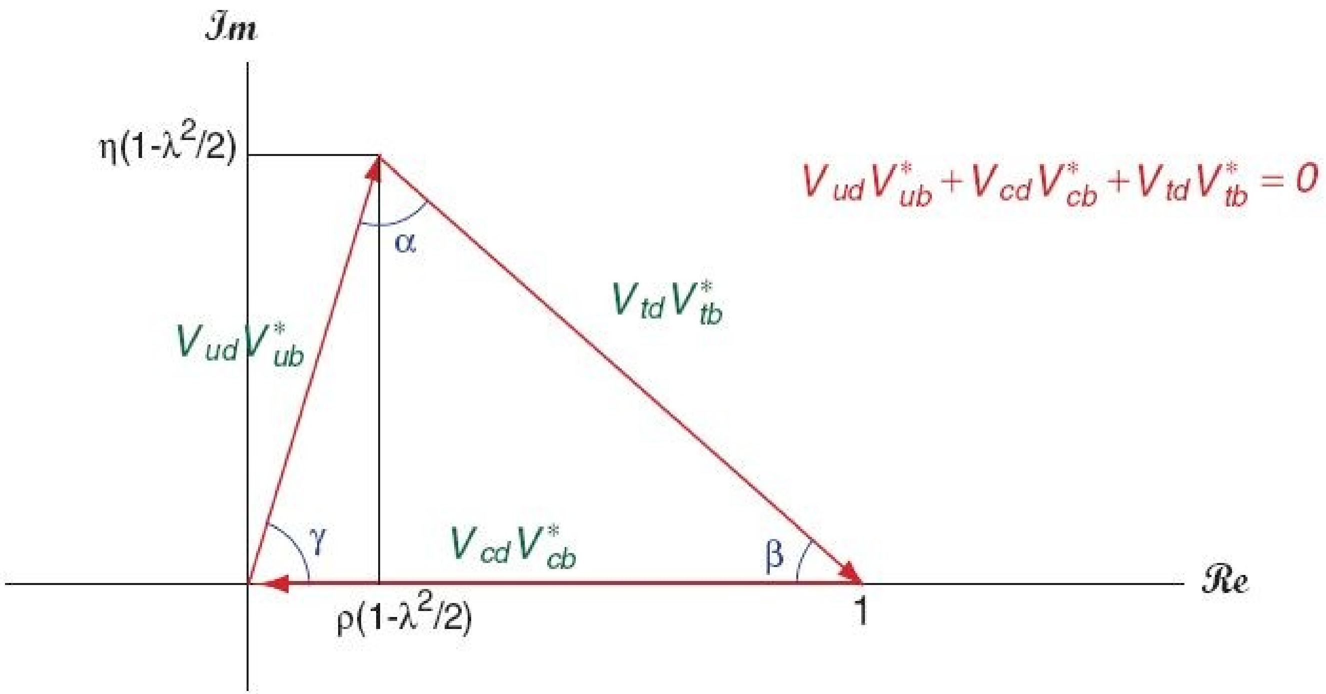
$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \Rightarrow V = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

- From unitary:

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

CKM Matrix and CP Violation

- CKM Matrix unitarity provides the following triangle:



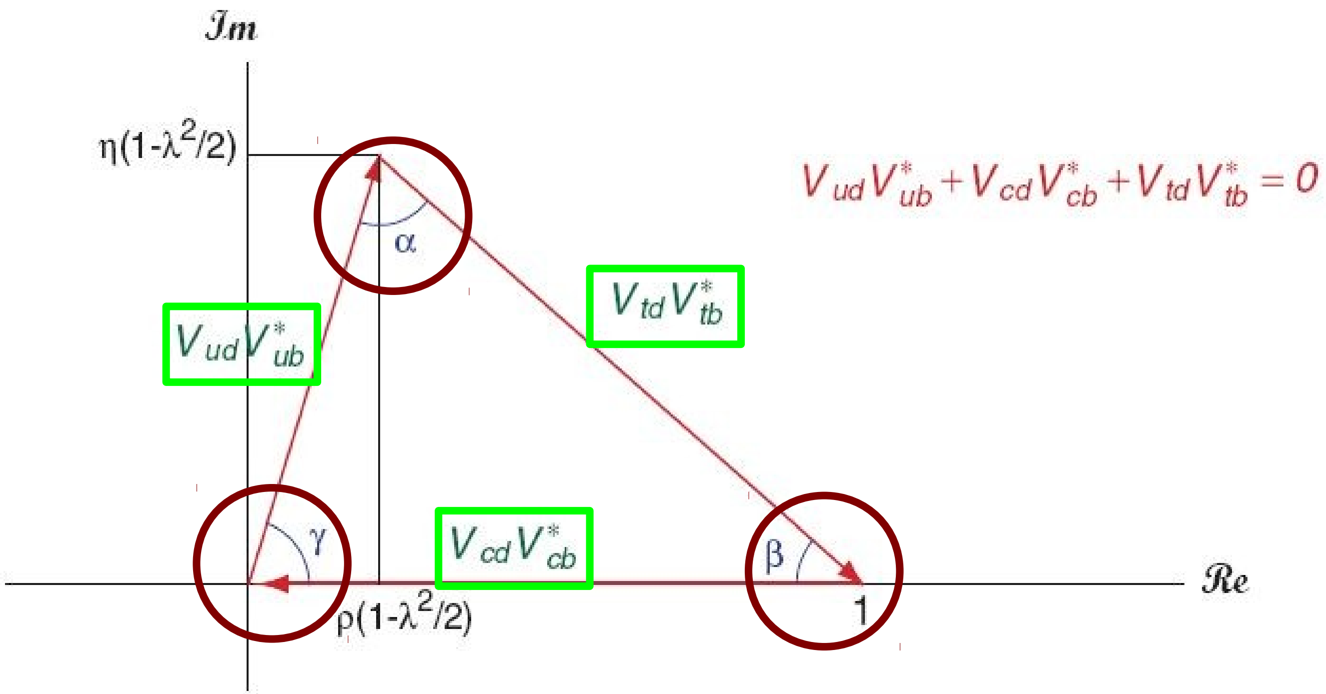
$$\beta = \arg\left\{\frac{-V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right\}$$

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

- β angle is already well measured

CKM Matrix and CP Violation

- Angles and sides measured independently.



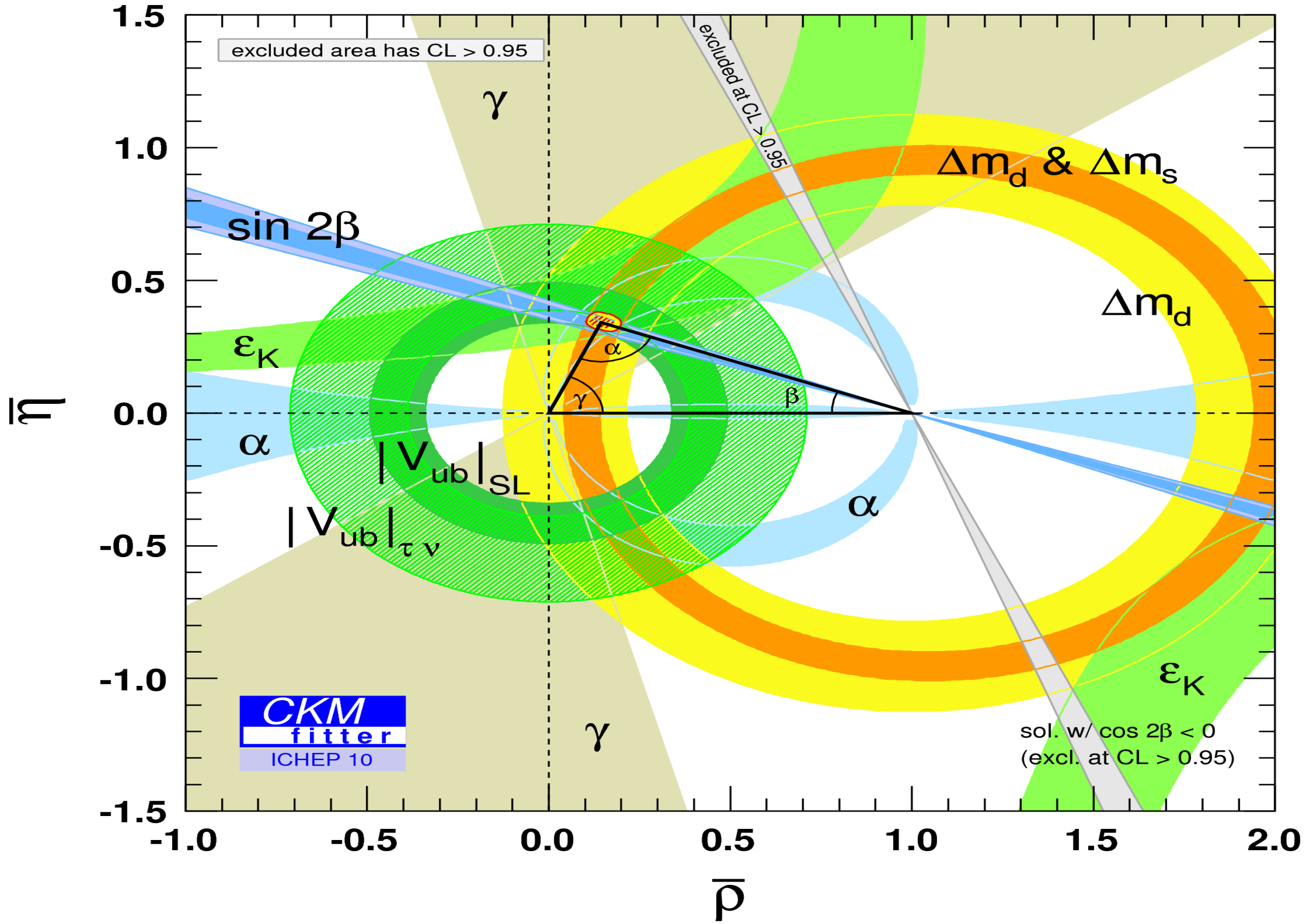
- Any result not compatible with the triangle means new physics!

- If $V_{us}V_{ub}^* + V_{cs}V_{cb}^* + V_{ts}V_{tb}^* = 0$ relation is used:

$$\boxed{\beta_s = \arg\left\{\frac{-V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right\}}$$

CKM Matrix and CP Violation

- γ angle currently with a high uncertanty!



- γ angle measurement is important for the CKM unitarity in order to quantify New Physics (NP) amplitudes and phases!

CP Violation on LHCb

- The LHCb has potential to provide a precise γ measurement which is a missing part for a global Standard Model (SM) consistency;

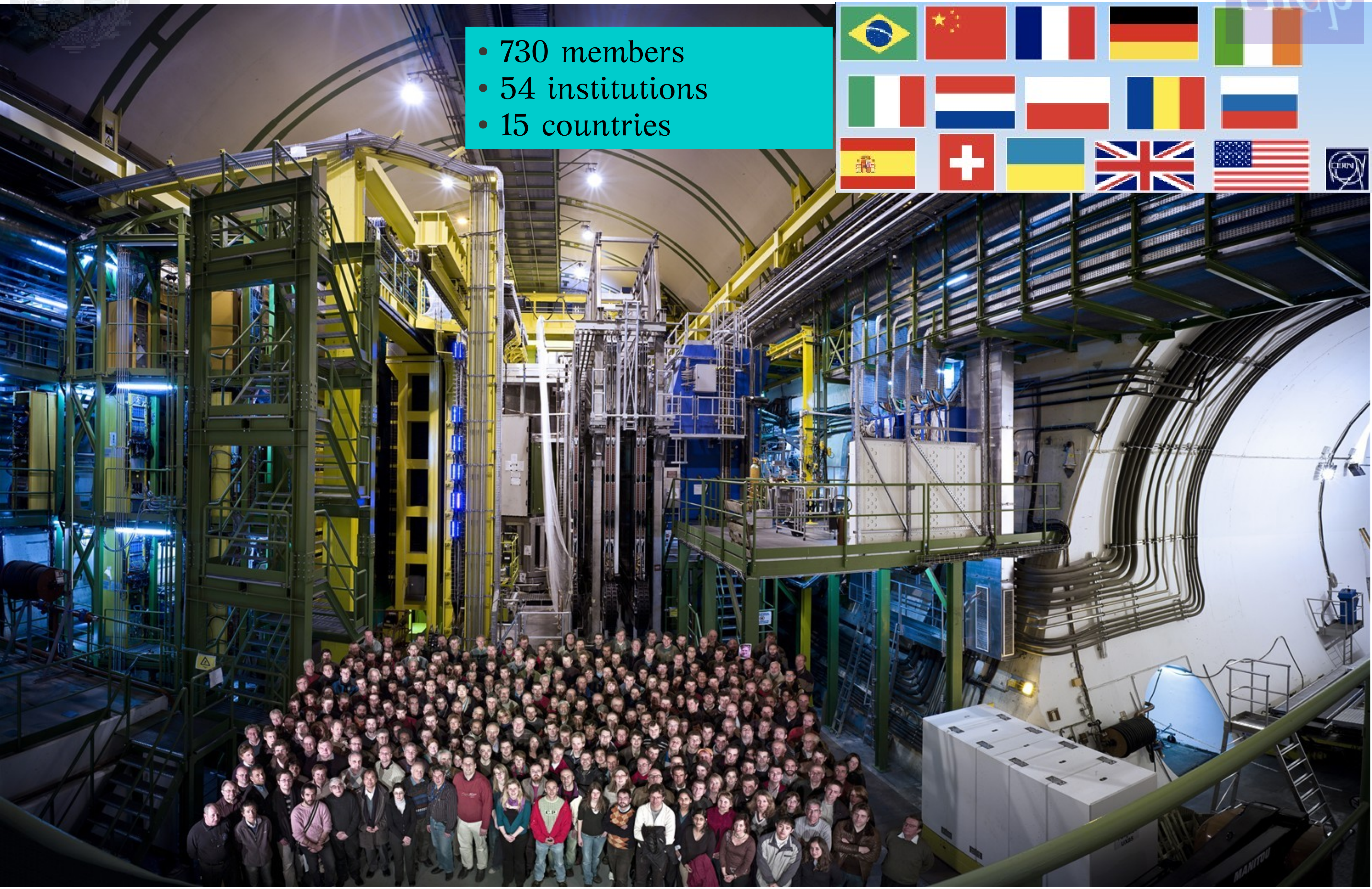
- γ measurements may lead to large NP contribution, especially in B_d and B_s system (more details later);

- The LHCb has also potential for measuring CP violation in D decays (see Carla Gobel's presentation);

- The LHCb experiment combined with LHC machine can provide accurate measurements on rare decays that serves as tests for SM;

The LHCb Experiment

- 730 members
- 54 institutions
- 15 countries

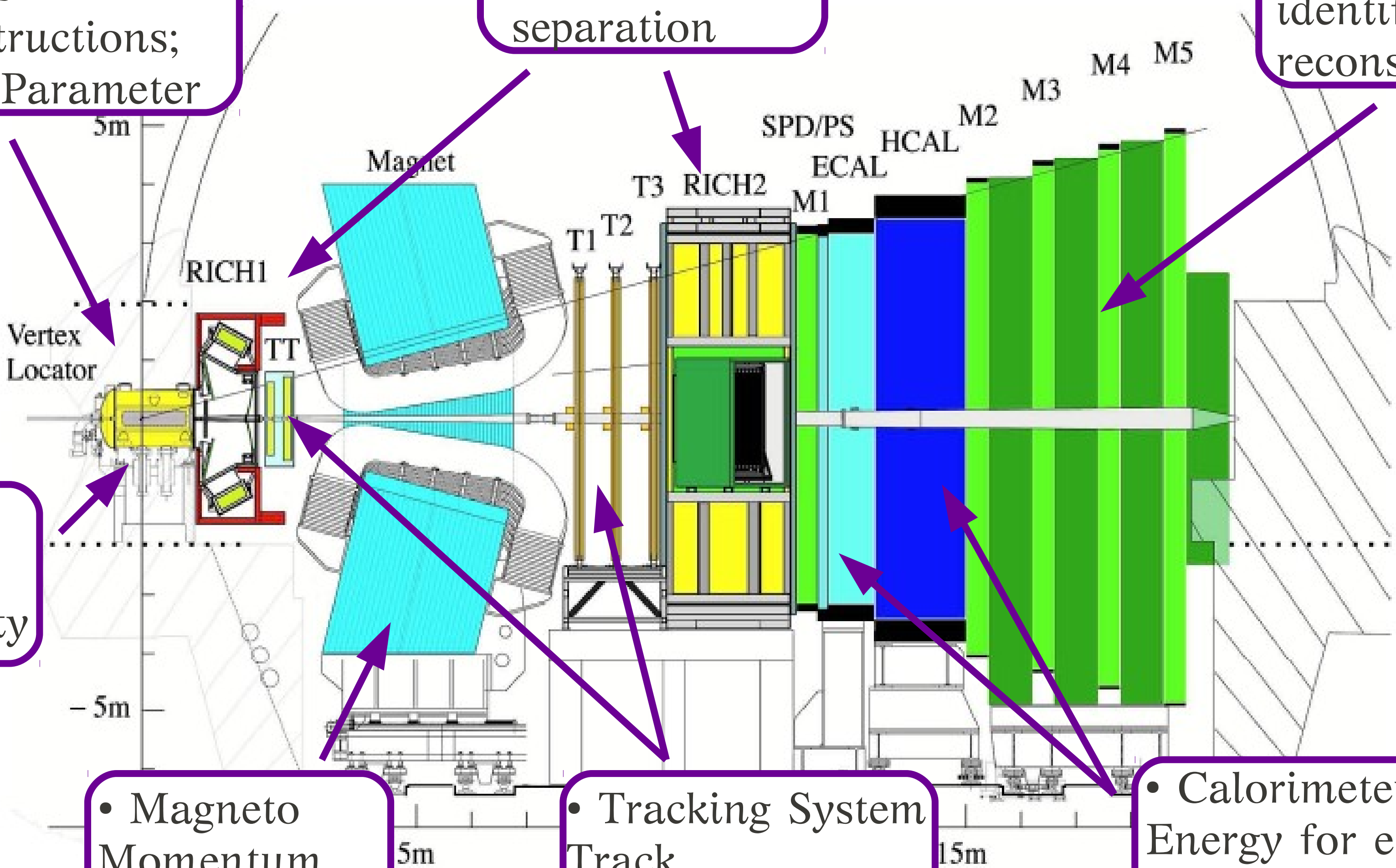


The LHCb Experiment

- Velo
Vertices Reconstructions; Impact Parameter

- Riches
PID: K and Pions separation

- Muon System
Muons identification and reconstruction



- Pile Up
Event Multiplicity

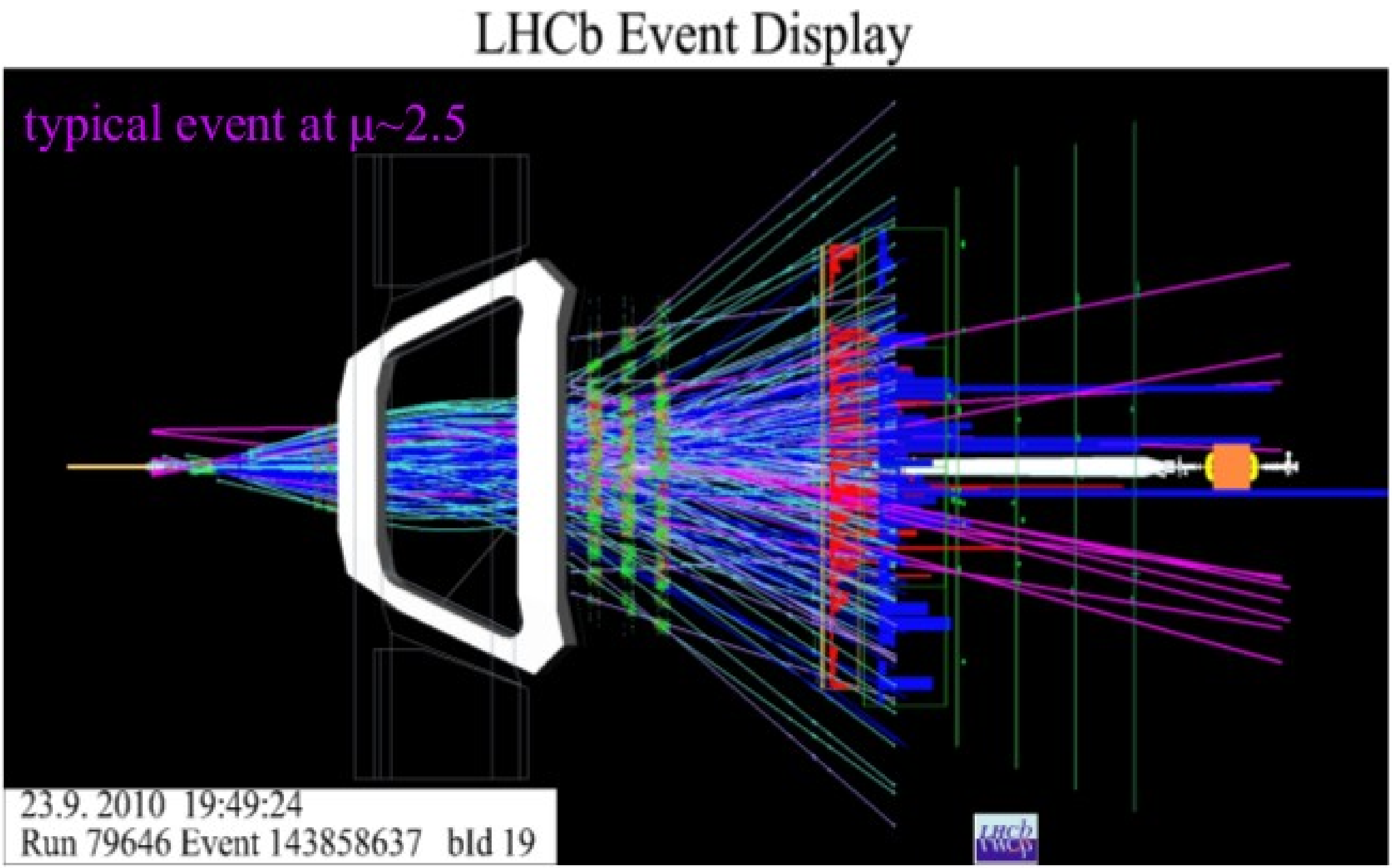
- Magneto
Momentum measurements

- Tracking System
Track reconstruction

- Calorimeters
Energy for e, γ, π^0 and hadrons

The LHCb Experiment

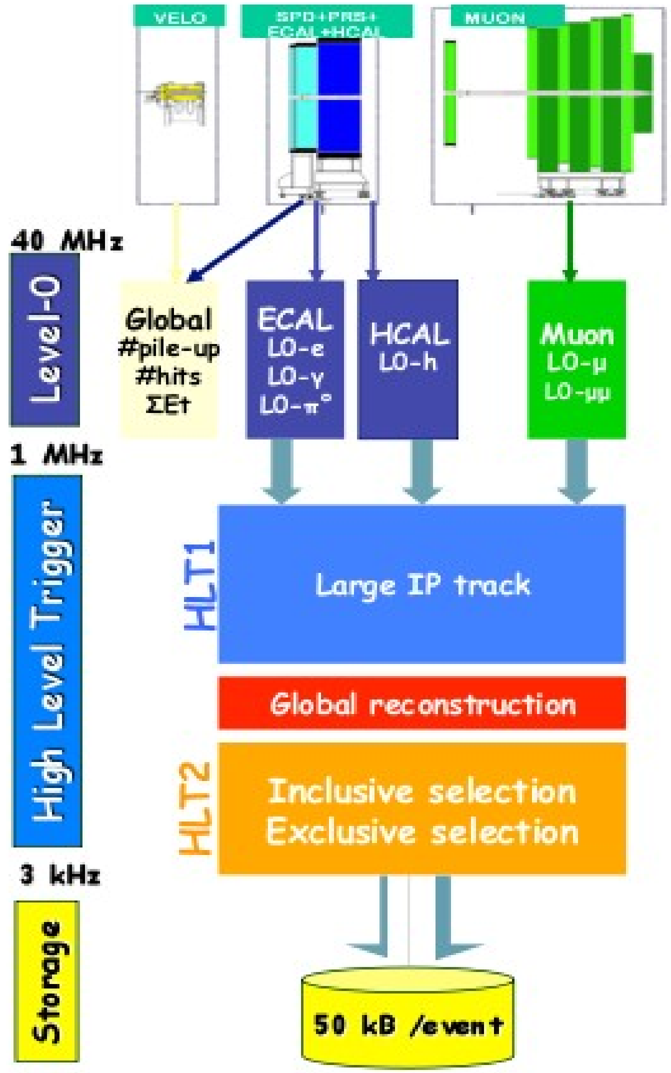
- Putting everything together:



- Challenge for the Trigger System!

The LHCb Trigger

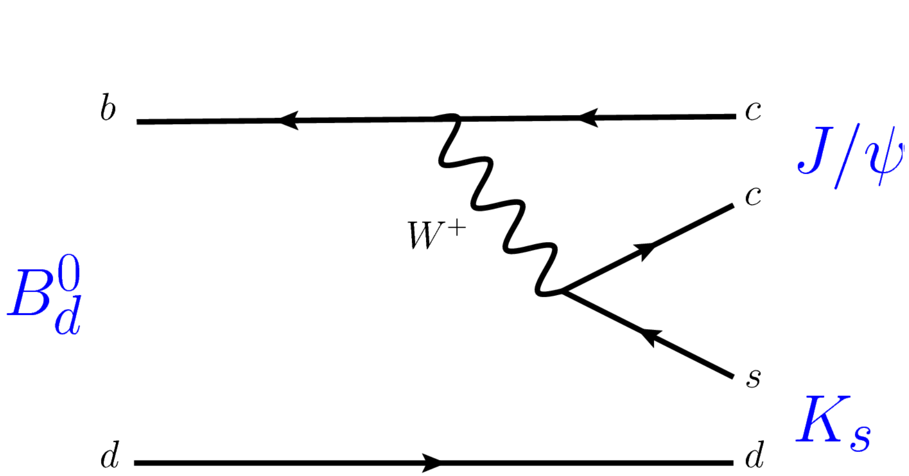
- The trigger is divided in two main levels and optimized for the following channels:
  - $B_u \to K\pi\pi$;
  - $B_s \to D_s K$;
  - $B_u \to D^0 K$;
  - $B_u \to HH$;
  - $B_d \to K^* ee$;
  - $B_s \to J/\psi \Phi$;
  - $B_s \to \mu\mu$;
  - $B_d \to K^* \mu\mu$;
  - $D \to KK\pi$;
  - $D \to \mu\mu\pi$;
  - $B_s \to$ Semileptonic;
  - $B_d \to$ Semileptonic;
  - $B_d \to K^* \gamma$;

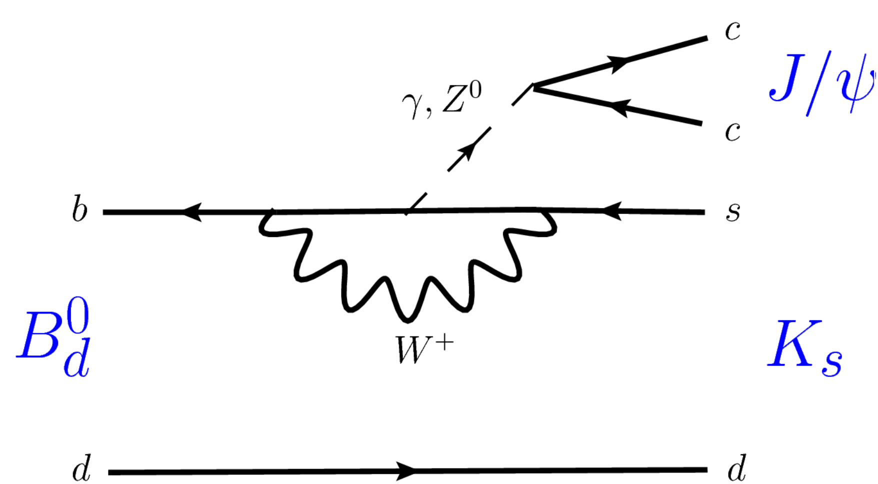


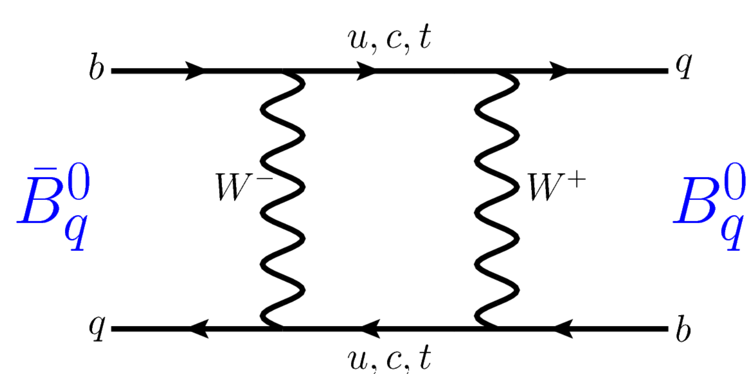
- All channels represent an important physics measurement for LHCb experiment.
- Crucial to provide precise CP Violation results!

$B \to J/\psi\ K_s$

- It's a golden mode for $\sin 2\beta$ measurements;
- Both B^0 and $\overline{B}^0$ decays to the same final state;
- In this case, the CP violation comes from interference between mixing and decay;







$B \to J/\psi\ K_s$

- Asymmetry expected in the time-dependent decay rate:

$$A_{J/\psi K_S}(t) = \frac{\Gamma(\overline{B}^0(t) \to J/\psi K_S) - \Gamma(B^0(t) \to J/\psi K_S)}{\Gamma(\overline{B}^0(t) \to J/\psi K_S) + \Gamma(B^0(t) \to J/\psi K_S)}$$

$$A_{J/\psi K_S}(t) = S_{J/\psi K_S} \sin(\Delta m_d t) - C_{J/\psi K_S} \cos(\Delta m_d t)$$

Direct CP Violation

Interference CP Violation

- In the SM: C = 0; S = sin2β
- sin2β well established by Belle and BaBar collaborations

$$\boxed{\sin 2\beta = 0.673 \pm 0.023}$$

Tagging at LHCb

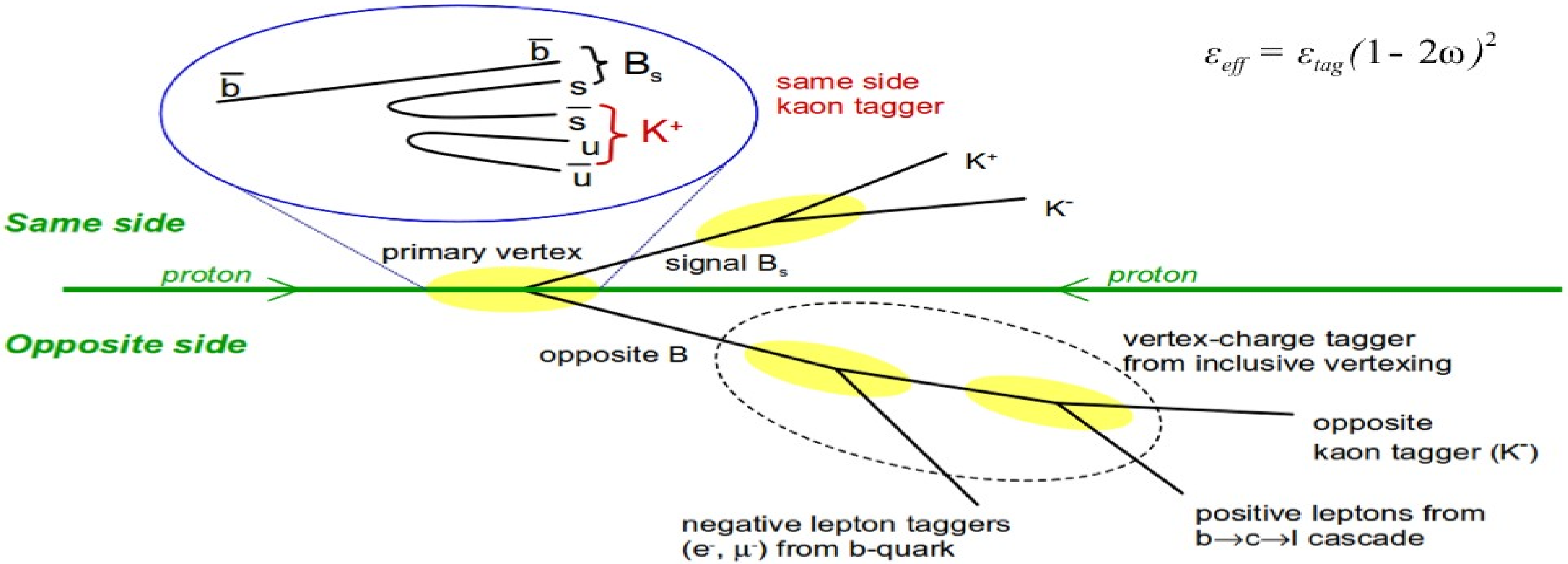
• B^0 and $\overline{B}^0$ have the same final state;

• Flavour tagging → procedure to determine the flavour of the reconstructed B meson at production;

• Taggers per event:

$$\varepsilon_{tag} = \frac{N_R + N_W}{N_R + N_W + N_U} \qquad \omega = \frac{N_W}{N_R + N_W}$$

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



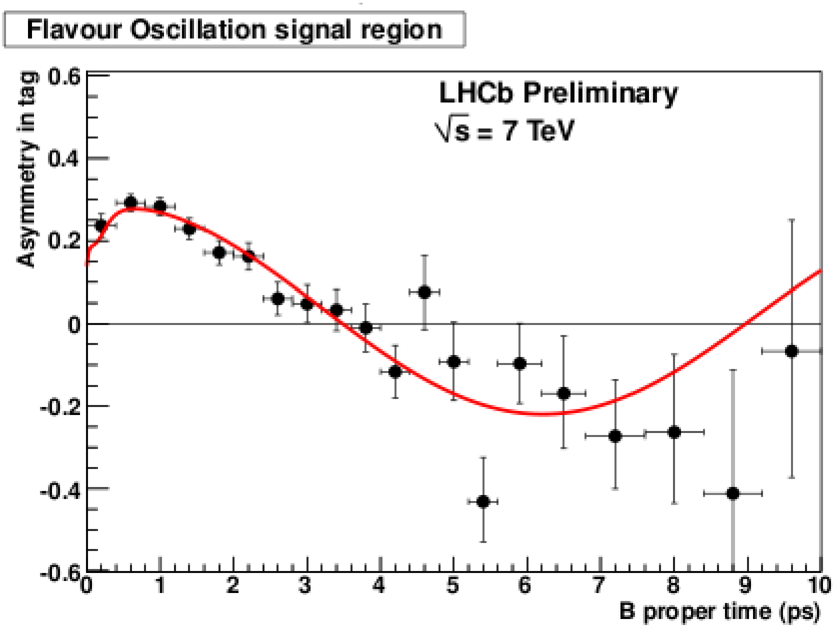
• sin2β depends directly on tagging efficiency!

• Tagging algorithm optimized and calibrated on real data with $B^0 \rightarrow D^* \mu \nu$, $B \rightarrow J/\psi K$ and $B \rightarrow J/\psi K^{0*}$

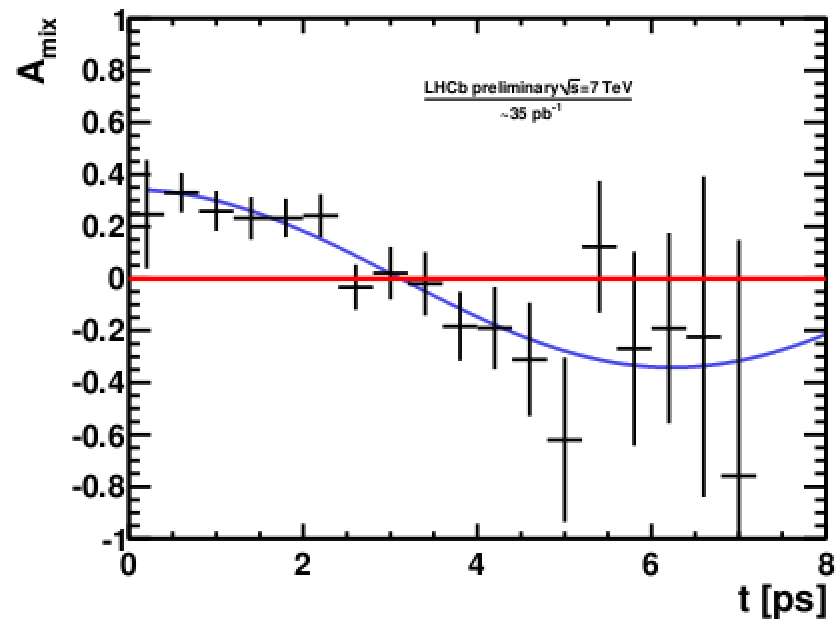
Tagging at LHCb

LHCb–CONF–2011-010

48k $B^0 \rightarrow D^{-*} \mu^+ \nu_\mu$



6k $B^0 \rightarrow D^- \pi^+$



- Tagging working properly:

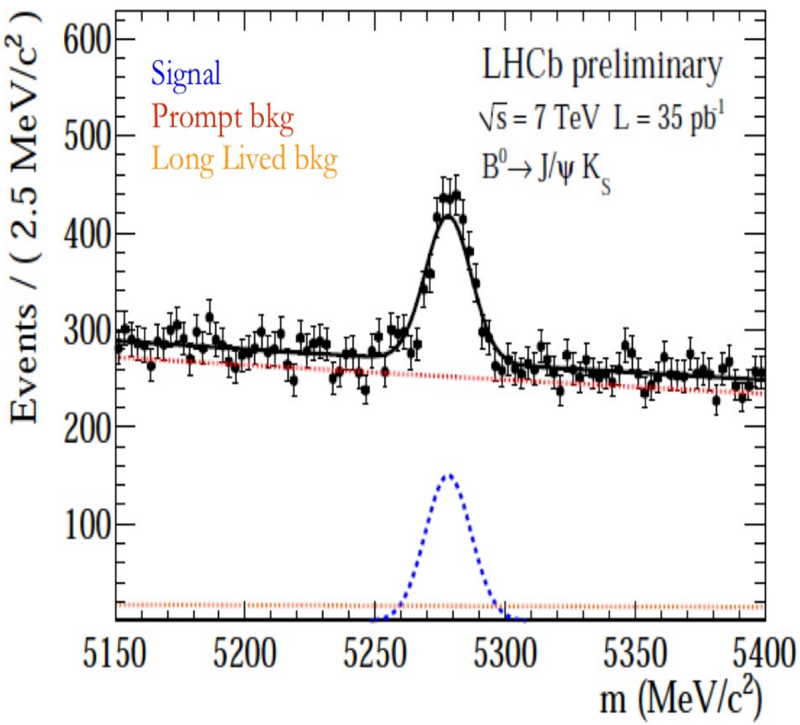
$$\Delta m_d = 0.499 \pm 0.032(\text{stat}) \pm 0.003(\text{sys})\ \text{ps}^{-1}$$

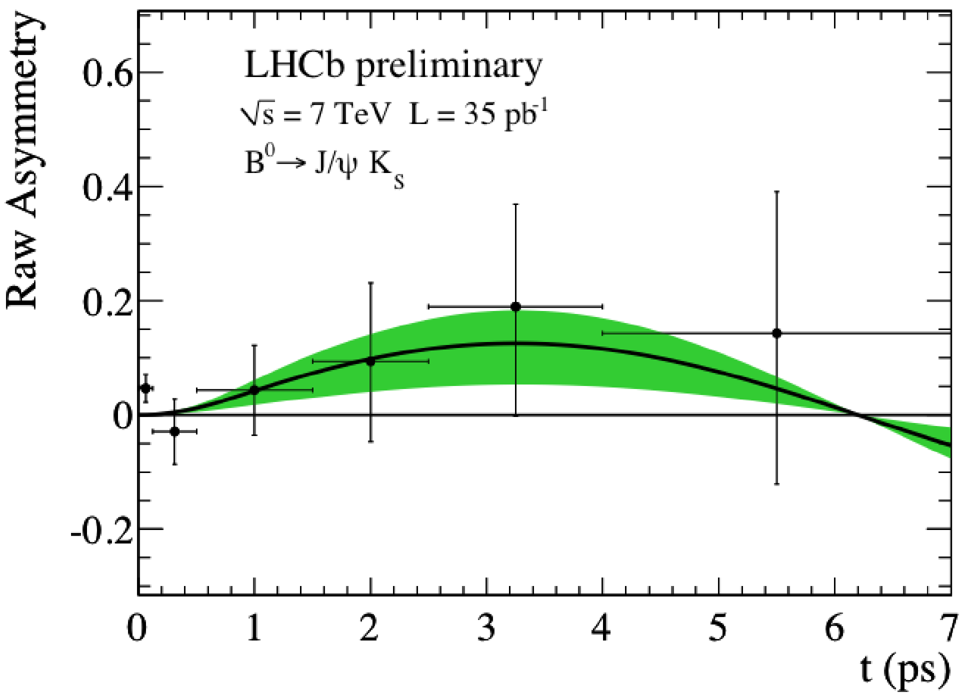
World Average: $0.507 \pm 0.005\ \text{ps}^{-1}$

$B \to J/\psi\ K_s$ in LHCb

LHCb–CONF–2011-004

- Raw asymmetry between $B^0 - \bar{B}^0$ just computed!





$$S_{J/\psi Ks} = 0.53^{+0.28}_{-0.29}\,(\text{stat}) \pm 0.05(\text{syst})$$

$$\sin 2\beta = 0.673 \pm 0.023$$

$B_s \rightarrow J/\psi\ \varphi, f_0$ in LHCb

• For B_s decays also the interference between direct decay amplitude and mixing amplitude allow observation of a CP violation phase → $2\boldsymbol{\beta}_s$!

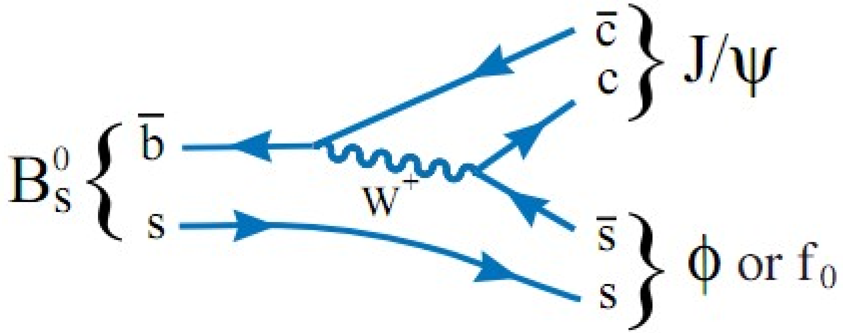
• β_s in SM is 20 times smaller than 2β phase just measured.

$$\boxed{2\beta_s = -\ 0.0363 \pm 0.0017}$$

• β_s phase can be drastically increased by the presence of NP and it is accessible via $B_s \rightarrow J/\psi\ \varphi$ decays.

• However, the final state consists of spin-1 particle hence an angular analisys is needed → More statistics is needed to gain sensibility in β_s.

• f_0 is scalar and J/ψ is a vector particle. A final state $B_s \rightarrow J/\psi\ f_0$ is CP eingestate. If this decays is abundant enough, it simplifies the study!

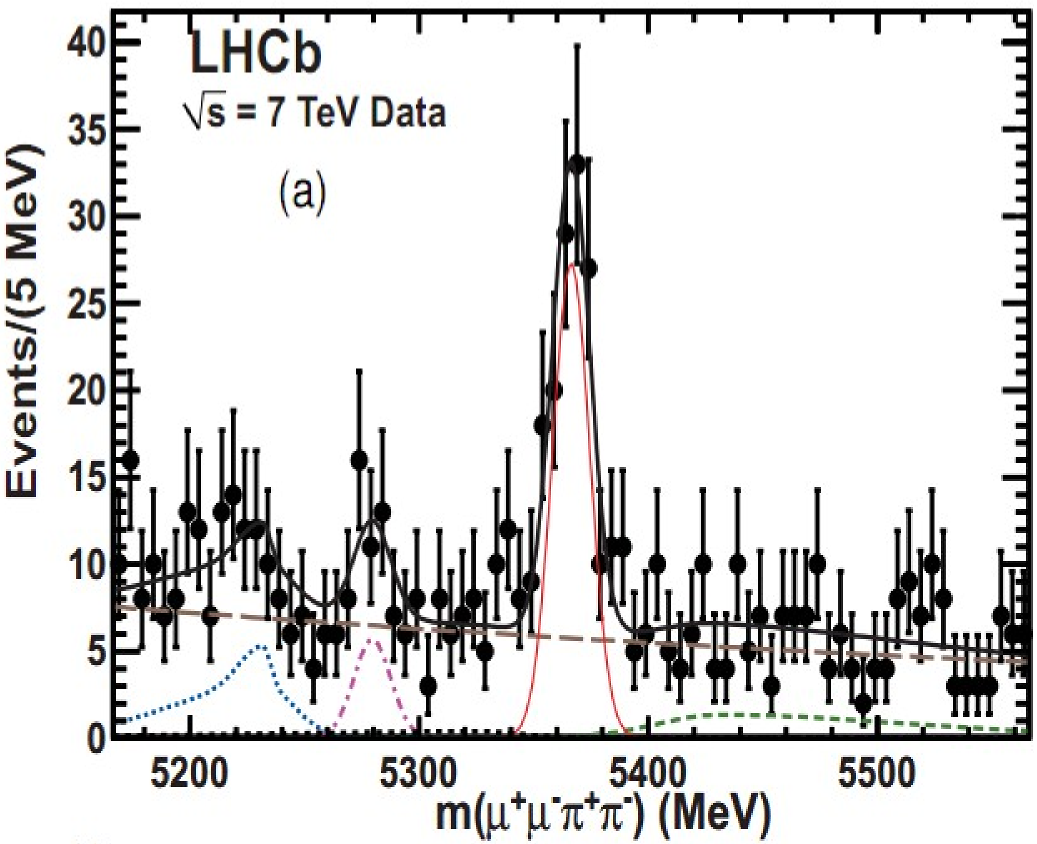


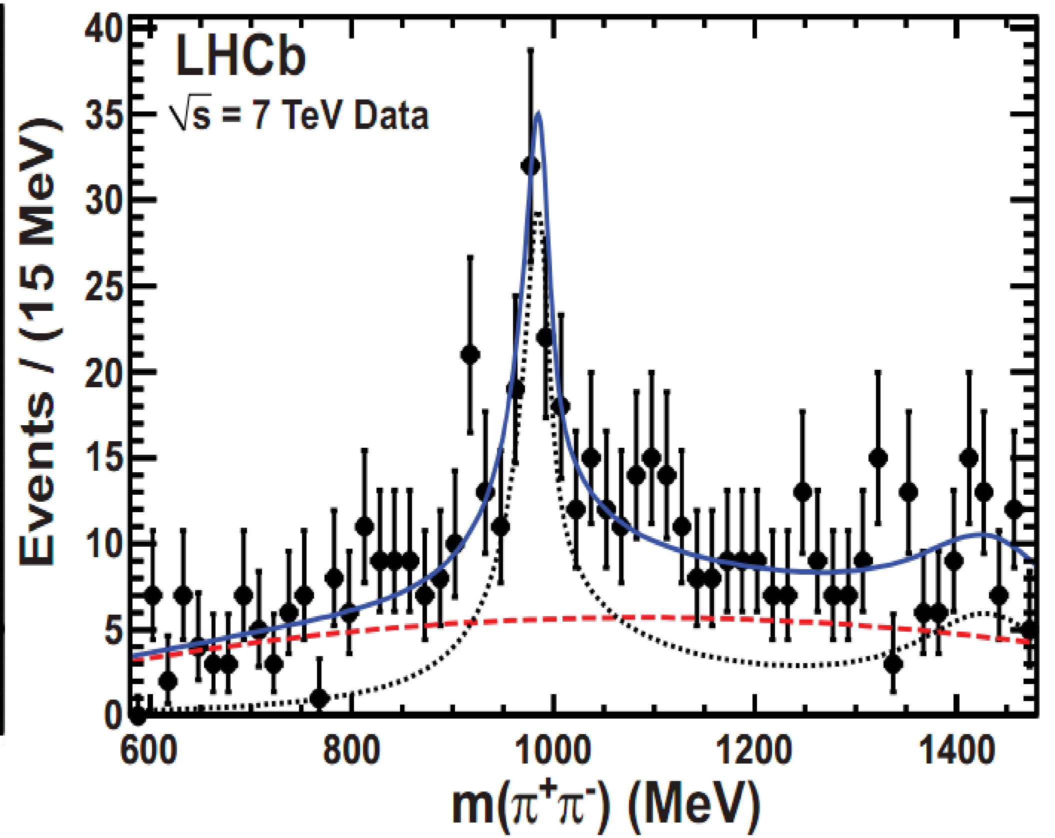
First Observation of Bs → J/ψ f_0

Phys.Lett.B698:115-122,2011

- The $B_s \rightarrow J/\psi\ f_0$ mode has been observed for the first time at LHCb!
- Its rate is considerably large:

$$\frac{\Gamma(B_s \rightarrow J/\psi\ f_0,\ f_0 \rightarrow \pi\pi)}{\Gamma(B_s \rightarrow J/\psi\ \varphi,\ \varphi \rightarrow KK)} = 0.0252^{+0.046+0.027}_{-0.032-0.033}$$





CP Violation from Tree-Level Decays

*Phys.Lett.B253:483,1991;Phys.Lett.B265:172,1991
**Phys.Rev.Lett.78:3257,1997

- The main goal to study CP Violation in Tree-Level decays is to measure the angle γ.

- The current γ values is:

BaBar: $\gamma = (68 \pm 14 \pm 4 \pm 3)^\circ$
Belle: $\gamma = (78 \pm 12 \pm 4 \pm 9)^\circ$

CKMFit: $\gamma = (69 \pm 20)^\circ$
UTFit: $\gamma = (72 \pm 11)^\circ$

- Many decays modes allow γ measurements through interferences between $b \to c$ and $b \to u$ transitions:

  - $B_s \to Ds^* K$;
  - $B \to D^* \pi$;

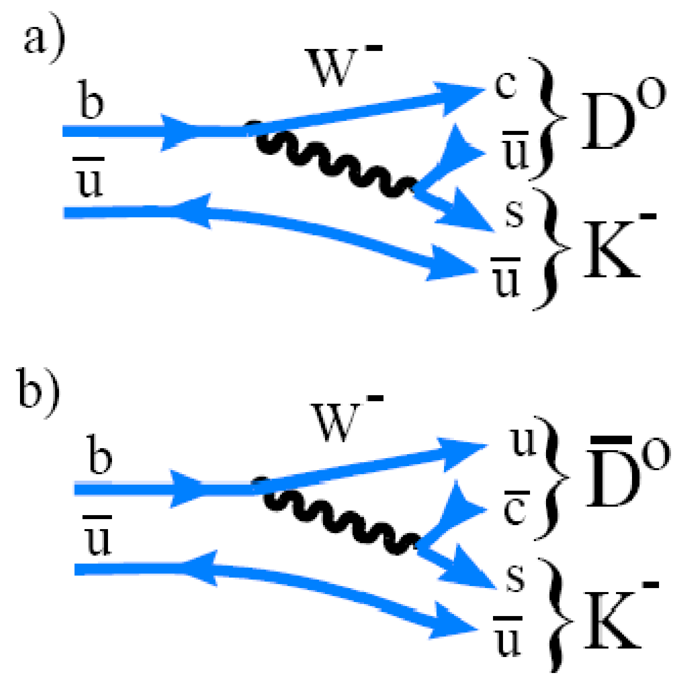
  } Time-dependent CP Violation

  - $B_u \to D^0(KK, \pi\pi)\ K,\pi$ (**GLW**)*
  - $B_u \to D^0(K\pi)\ K,\pi$ (**ADS**)**

  } Direct CP Violation

  - $B \to D^0$(single final state) K,π
  - $B \to DK\pi$

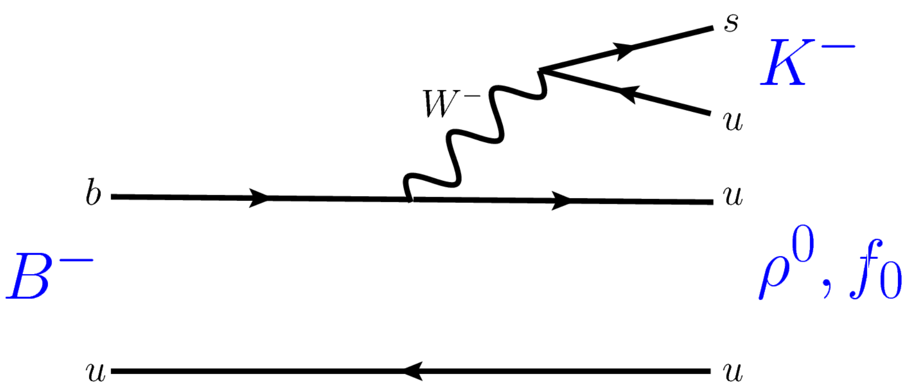
  } Dalitz Plot analysis

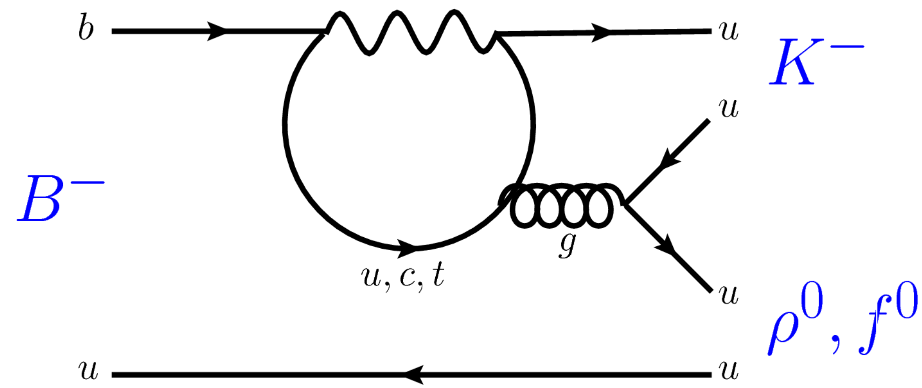


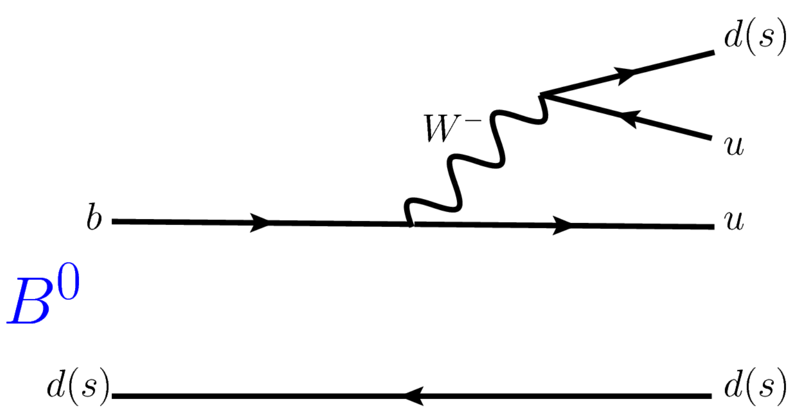
- **The γ precision expected is around 7° for 1 fb^{-1}!**

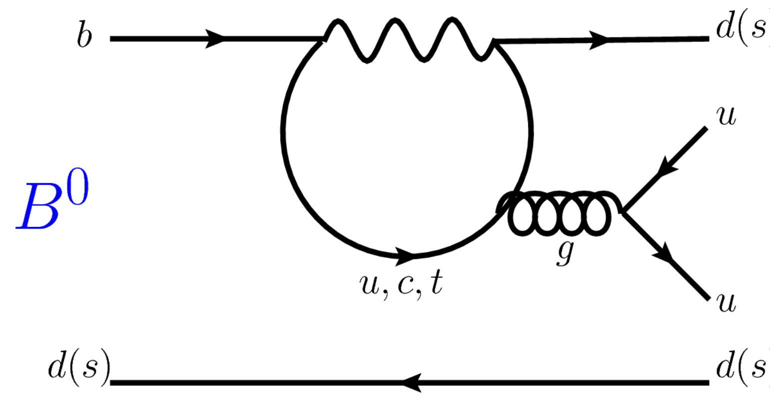
CP Violation from Loop-Level Decays

- CP Violation also appears from interferences between Tree and Loop diagrams





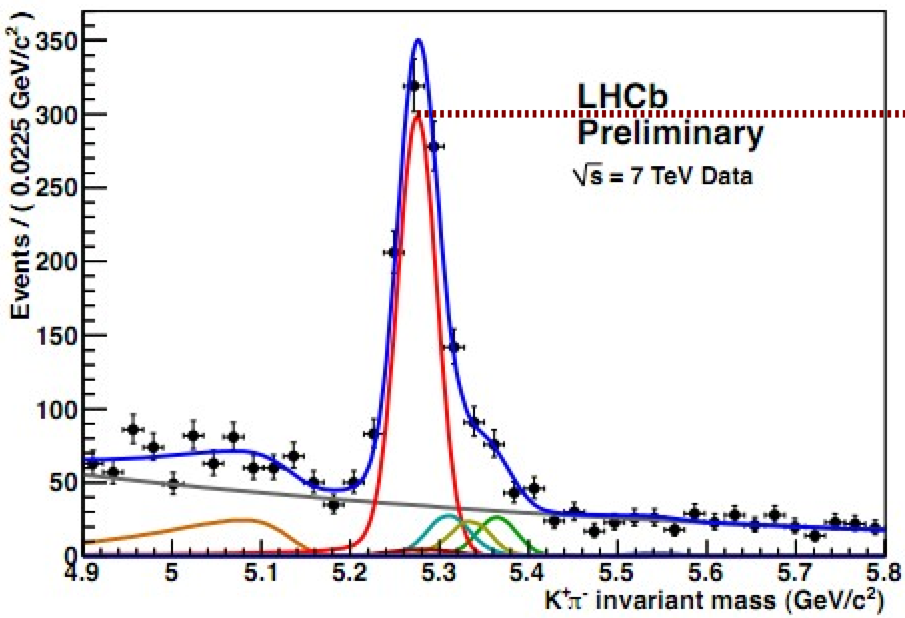


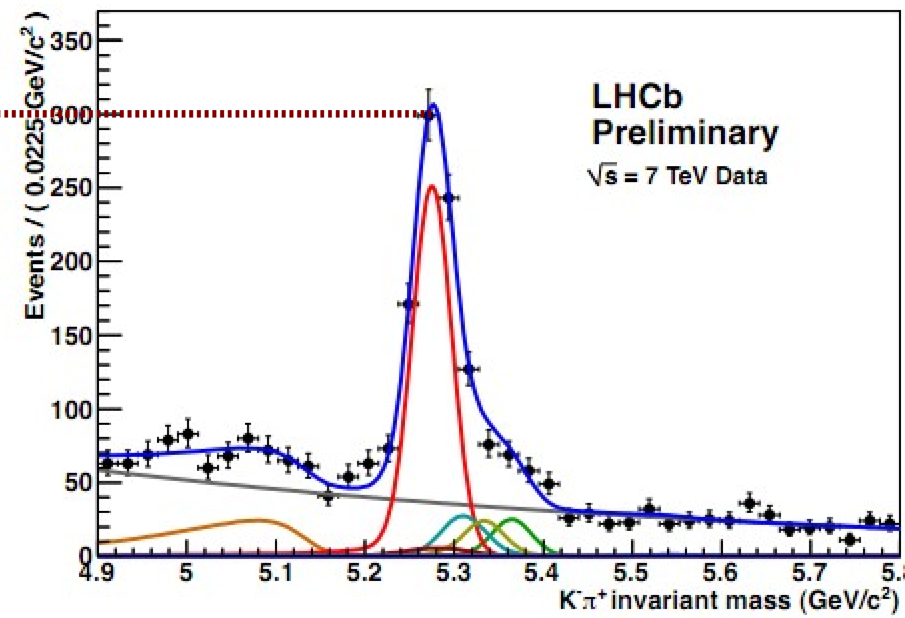


Direct CP Violation in $B \to hh$

LHCb–CONF–2011-011

- The direct CP asymmetry is well established for $B^0 \to K\pi$.
- Asymmetry production is controlled from $B_u \to J/\psi\ K$ (pp collisions!)
- Detector asymmetry controlled with magnet up/down data with D* and $D^0 \to K\pi$





$A_{cp}(B^0 \to K^+\pi^-) = -0.074 \pm 0.033 \pm 0.008$

$A_{cp}(B_s^0 \to \pi^+K^-) = 0.15 \pm 0.19 \pm 0.02$

$$A_{CP}(B^0 \to K^+\pi^-) = -0.098^{+0.012}_{-0.011}$$

$$A_{CP}(B_s^0 \to \pi^+K^-) = 0.39 \pm 0.15 \pm 0.08$$

HFAG and CDF Respectivelly

CP Violation in B → hhh

- Charmless charged B decays where h stands for protons, kaons and pions.
- Exploit the interferences between Tree and Loops diagrams to extract γ.
- Dalitz plot (DP) fit using a modeled amplitude → model dependent and long term task!
- Before DP fit one can evaluate the anisotropy in each bin of the Dalitz Plot defined as:

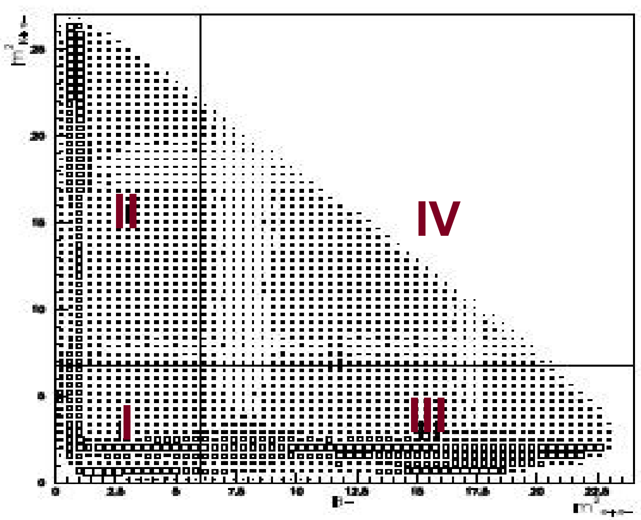
$$\boxed{{}^{DP}\mathcal{S}_{CP} = \frac{N_+(i) - N_-(i)}{\sqrt{N_+(i) + N_-(i)}}.}$$

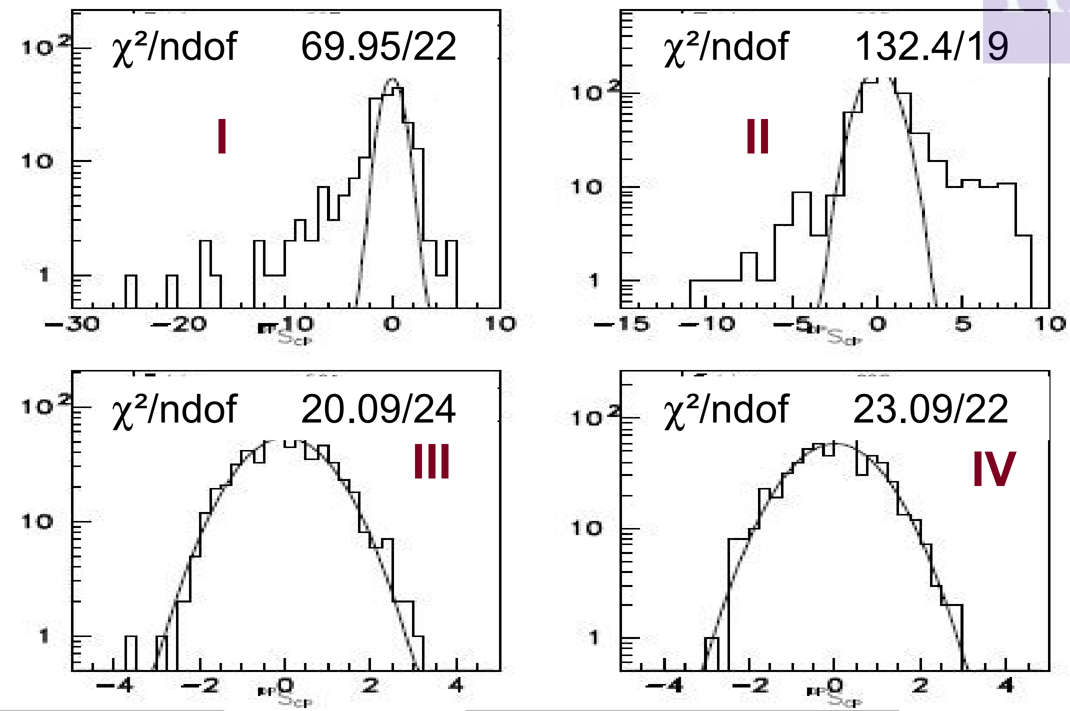
Phys.Rev.D80:096006,2009

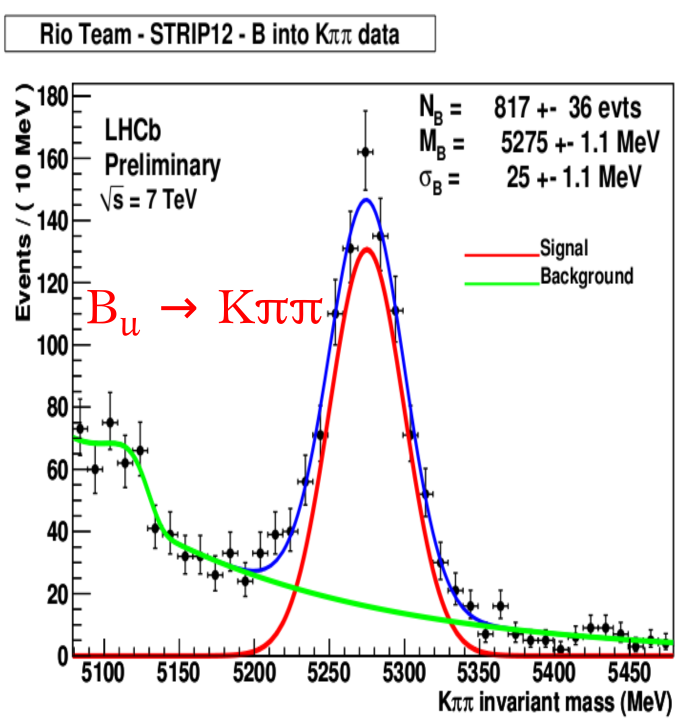
- In the case of CP symmetry conserved, the S_{cp} distribution is a gaussian centered at 0 and with unit width!
- Strong CP violation signature especially in the interference regions of the DP.
- Also useful for neutral B decays!

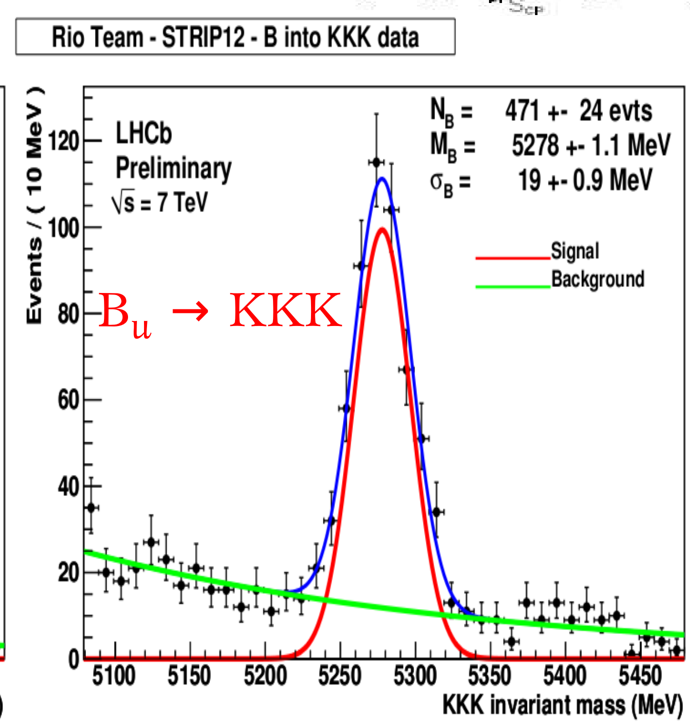
CP Violation in B → hhh

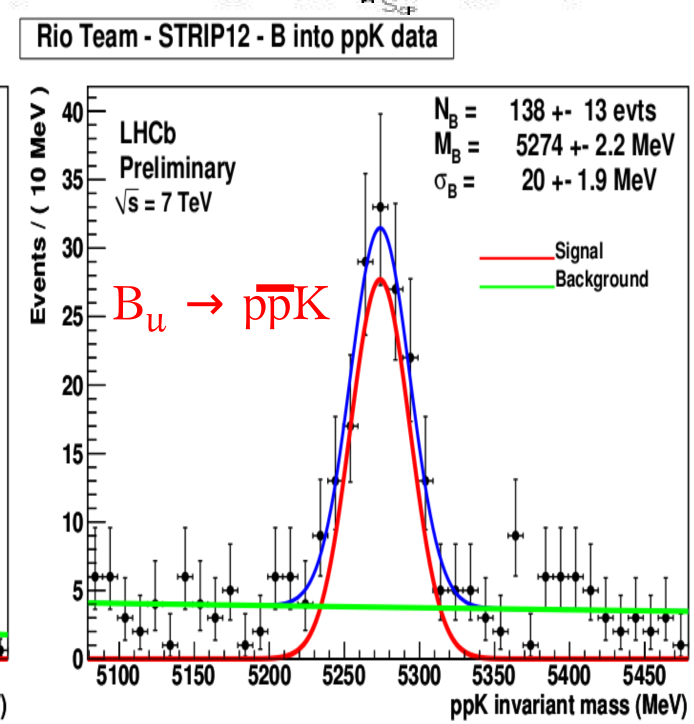
Toy MC: $B_u \rightarrow \varrho(K\pi)\ \pi$











Conclusions and Perspectives

• The LHCb Experiment has shown a great potential to measure different paramaters related to CP violation.

• The $B \to J/\psi\ K_s$ analysis already measured a sin2β measurement compatible with world average:

$$S_{J/\psi Ks} = 0.53\ ^{+0.28}_{-0.29}\ (\text{stat}) \pm 0.05(\text{syst})$$

• The $B \to J/\psi\ f_0$ mode have been first observed and it is abundant enough to allow a β_s measurement without an angular analysis

$$\frac{\Gamma(B_s \to J/\psi\ f_0,\ f_0 \to \pi\pi)}{\Gamma(B_s \to J/\psi\ \varphi,\ \varphi \to KK)} = 0.0252\ ^{+0.046+0.027}_{-0.032-0.033}$$

• The LHCb experiment already have a direct CP violation measurement from $B^0 \to K\pi$ mode

$$A_{cp}(B^0 \to K^+\pi^-) = -0.074 \pm 0.033 \pm 0.008$$
$$A_{cp}(B_s^0 \to \pi^+K^-) = 0.15 \pm 0.19 \pm 0.02$$

• Prospects with Tree and Loop level: Anisotropy in the Dalitz Plot to identify CP violation and γ measurement using ADS, GWL and Dalitz Plot analysis.

Stay tuned for Summer conferences:
first results from 2011 data!