Selected CPV results from LHCb Run I and prospects for CKM γ measurements in Run II

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XXII Krakow Epiphany Conference
7-9.01.2016

Outline

I. Three ways of CPV
II. Selected CPV results from LHCb:
   - $\boldsymbol{sin\,2\beta}$ in $\boldsymbol{B^0 \to J/\psi\ K_S^0}$
   - CPV in decays (direct) via $\boldsymbol{B \to hh, hhh}$
   - CKM $\boldsymbol{\gamma}$ angle with $\boldsymbol{B \to DK}$
   - search for CPV in charm
III. Prospects for measurements in Run II
IV. Summary

See also other talks @ this conference:

- Past present and future of the LHCb detector
- LHCb measurements at 13 TeV
- Highlights of LHCb measurement in rare decays with Run1 data
- Determination of CP-violating phase ϕ_S in $B_S^0 \to J/\psi\ \phi$ decay

CP Violation in SM

- Within the framework of the Standard Model **CP Violation effects** arise from the **CKM matrix** parameters.
- The **predicted CP** asymmetry in the SM is not sufficient to explain the baryon dominance in the Universe.
- **New Physics CPV** effects would be warmly welcomed.

weak eigenstates

mass eigenstates

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

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

- Four free parameters to (over-)constrain
- So let's **measure (very precisely)** CPV in the SM and try to see if any differerences emerge.

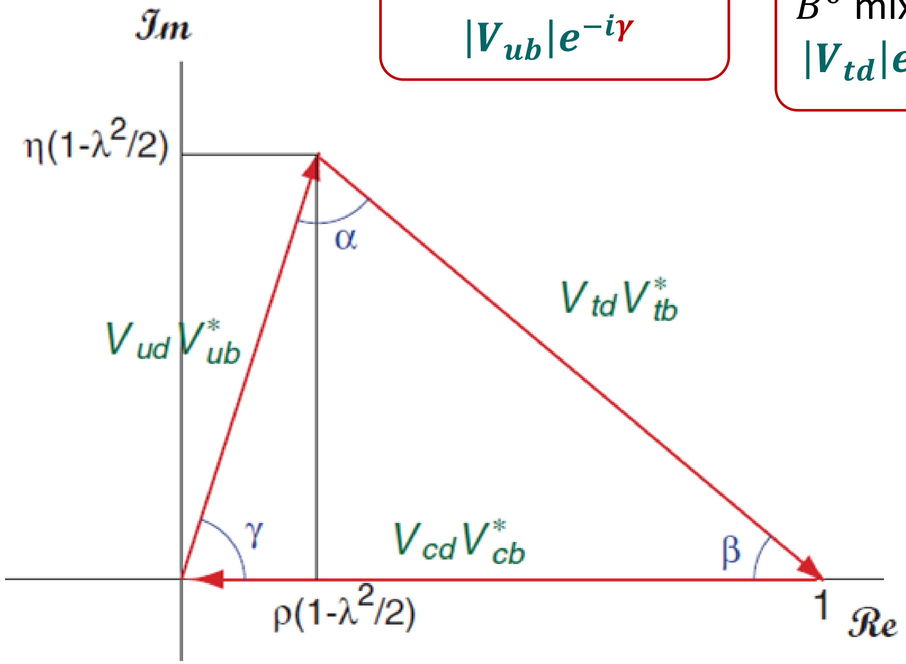
The unitary triangle

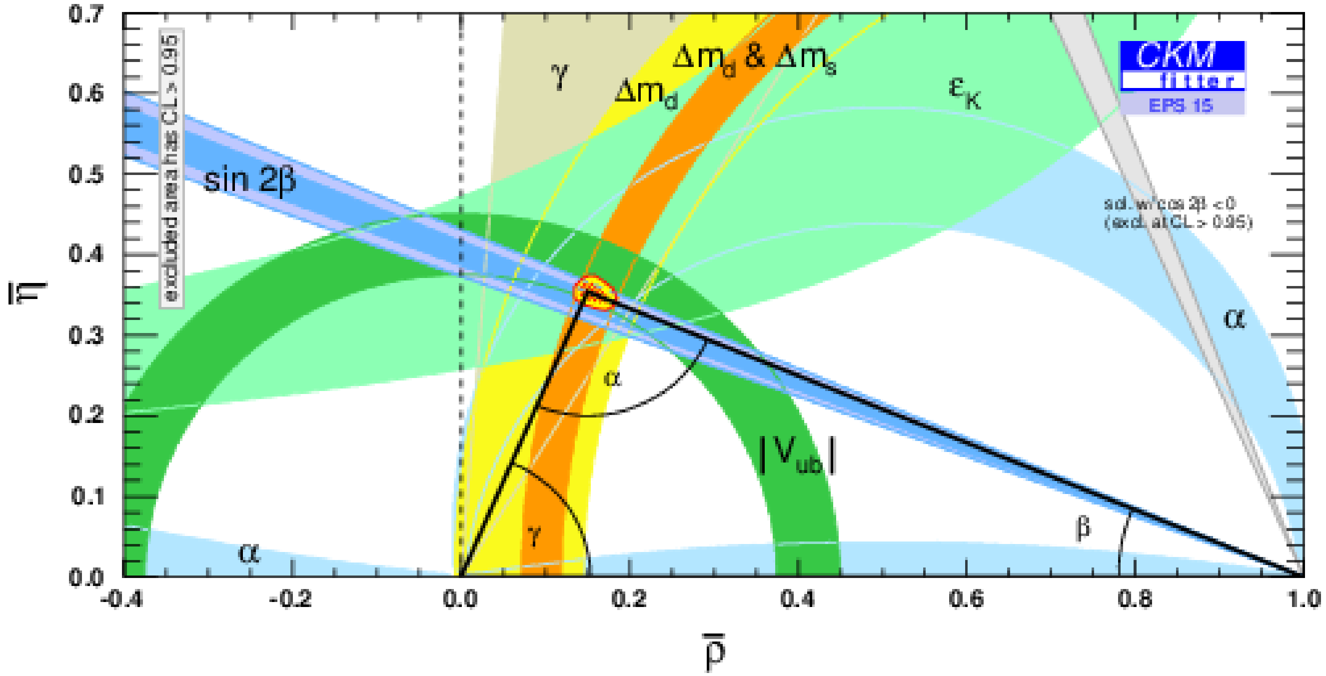
- We assume the CKM matrix is **unitary.**
- The unitary condition can be represented in a complex plane as unitary triangles.
- Among them there is one of a special meaning:

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

$b \to u$ transitions $|V_{ub}|e^{-i\gamma}$

B^0 mixing $|V_{td}|e^{-i\beta}$





- Experimentally the observation of CPV effects involve measuring the sides and angles of the UT

Three types of CP Violation

Where do we hope to find CP Violation effects?

In decays

two amplitudes
with different
phases interfere

$B^0 \rightleftarrows f \rightleftarrows \overline{B^0}$

In mixing

$P(B^0 \to \bar{B}^0)$
$\neq P(\bar{B}^0 \to B^0)$

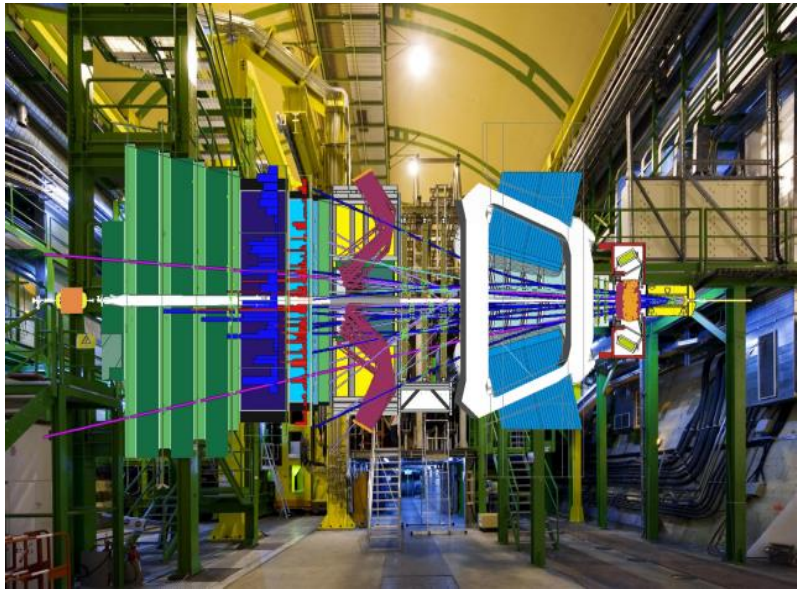
$B^0 \longleftrightarrow \overline{B^0}$

In the interference between mixing and decay

$B^0 \to f$, $B^0 \to \overline{B^0} \to f$

Whenever a quark's flavour change occurs!

LHCb @



Excellent performance:

3 fb^{-1} accumulated in RUN I
Excellent Decay time resolution $\sim 50 fs$
Precise tracking: $\delta p/p \sim 0.4 - 0.6\%$
Particle identification $2 - 100\ GeV/c$

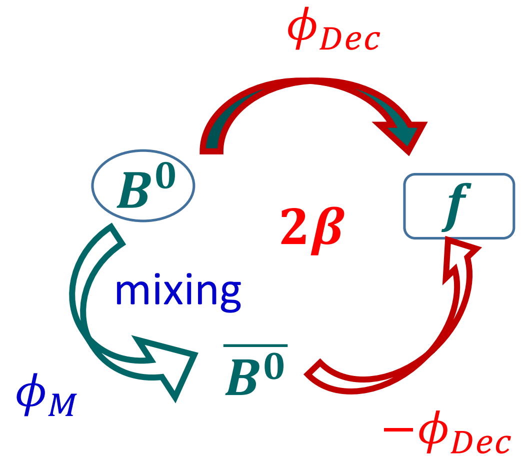
Let's see how it's going…

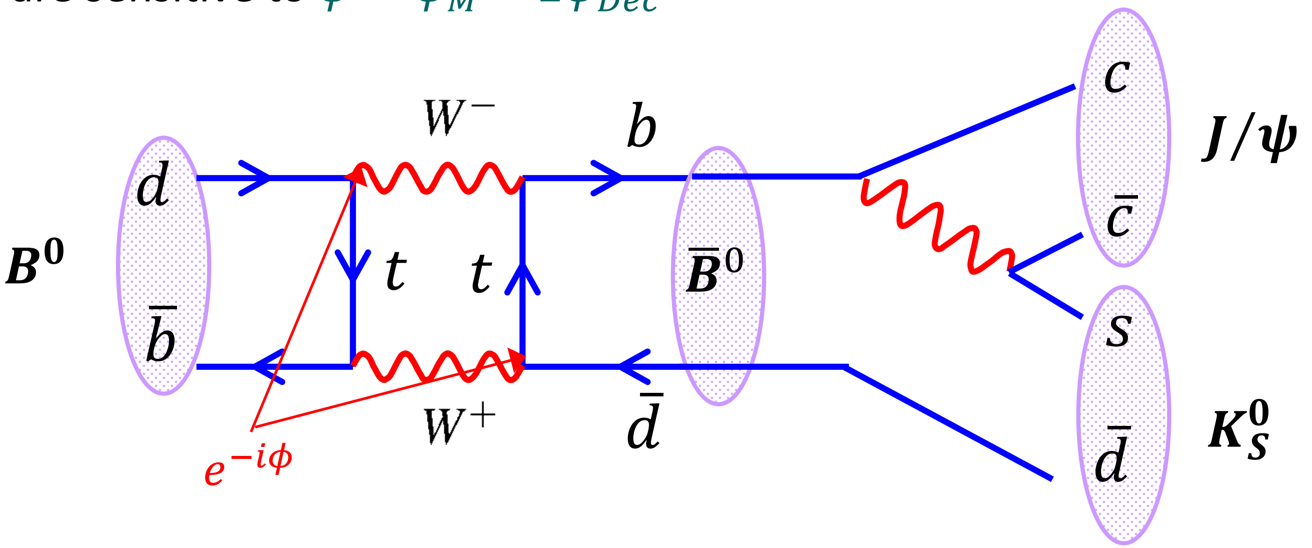
sin 2β measurement strategy

$B^0 \to J/\psi\ K_S^0$

- The first observation made by BaBar and Belle in 2001.

- The sensitivity to angle β comes from the $B^0 \leftrightarrow \overline{B}^0$ mixing: $\beta = \arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right)$
- CPV in interference between direct decays $B^0 \to f$ and decays after mixing, $B^0 \to \overline{B}^0 \to f$
- The decay width are sensitive to $\phi = \phi_M - 2\phi_{Dec}$





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

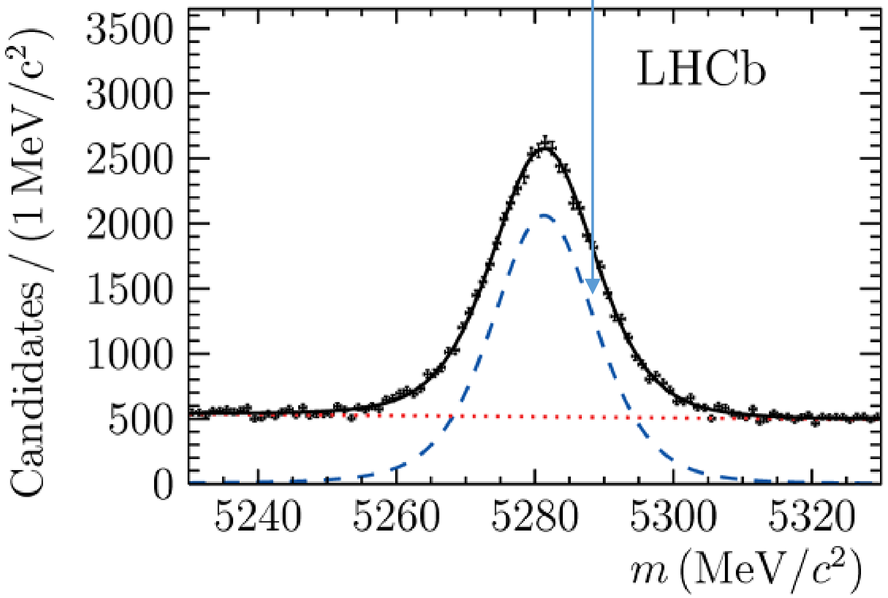
sin 2β - the results

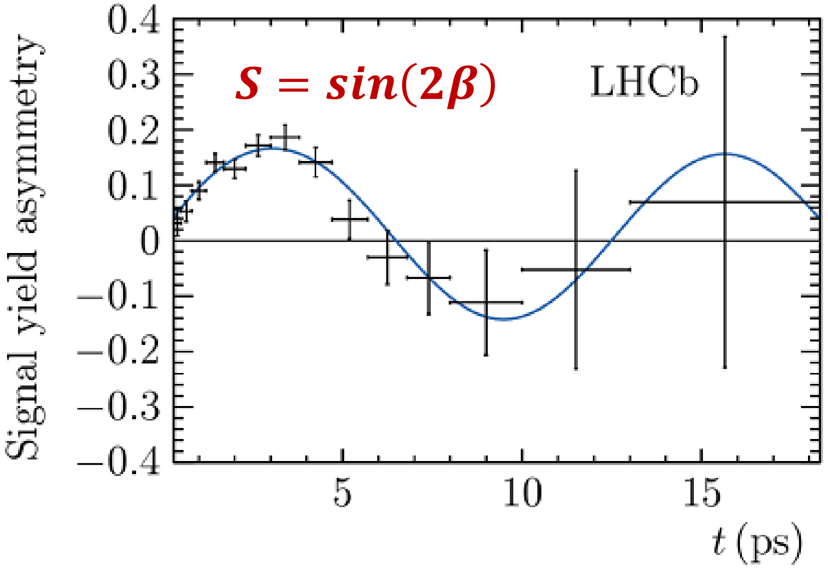
Phys.Rev.Lett. 115 (2015) 031601

- Time dependent assymmetry (relies strongly on flavour tagging)
- 114 000 signal candidates (41 000 tagged)
- need a handle on penguin pollution $sin\,2\beta \rightarrow sin(2\beta + \phi_{NP})$

$$A_{CP}(t) = \frac{\Gamma\{B \rightarrow J/\psi\ K_S\} - \Gamma\{\bar{B} \rightarrow J/\psi\ K_S\}}{\Gamma\{B \rightarrow J/\psi\ K_S\} + \Gamma\{\bar{B} \rightarrow J/\psi\ K_S\}} = -\sin 2\boldsymbol{\beta} \sin \Delta mt$$

$$\boldsymbol{A_{CP}(t) = S\, sin(\Delta mt)}$$





$$\boldsymbol{S = 0.731 \pm 0.035(stat) \pm 0.020(syst)}$$

new result from $\mathcal{L} = 3fb^{-1}$

sin 2β summary of the results

Phys.Rev.Lett. 115 (2015) 031601

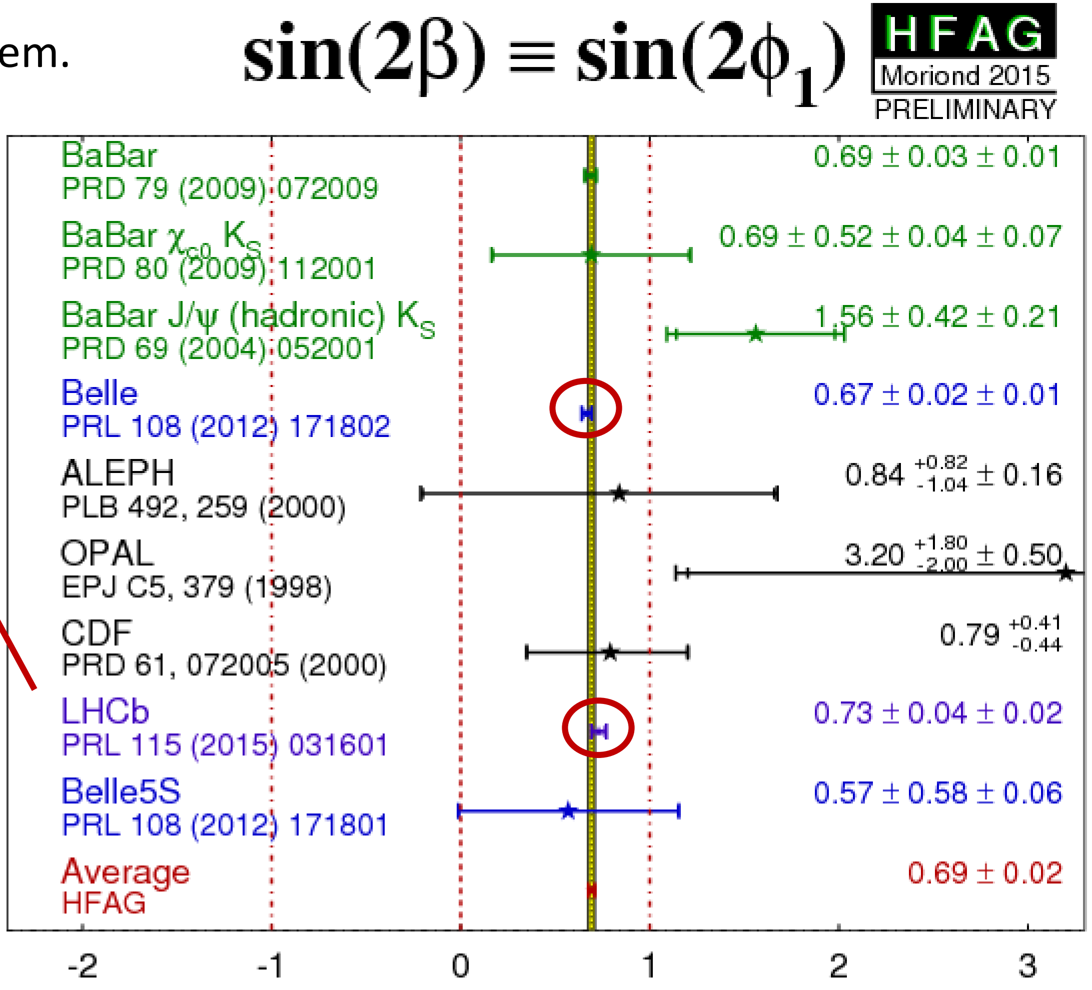
$B^0 \to J/\psi\ K_S^0$ is a „golden mode" for CP violation in B^0 meson system.

The world average is:

$$\sin 2\beta = 0.682 \pm 0.019$$

The SM expectation:

$$\sin 2\beta(SM) = 0.771\ ^{+0.017}_{-0.041}$$



The values are consistent with the current world averages and with the Standard Model expectations.
The most precise time-dependent CP violation measurement at hadron colliders.
The precision is competitive with B-factories

$$S = 0.731 \pm 0.035(stat) \pm 0.020(syst)$$

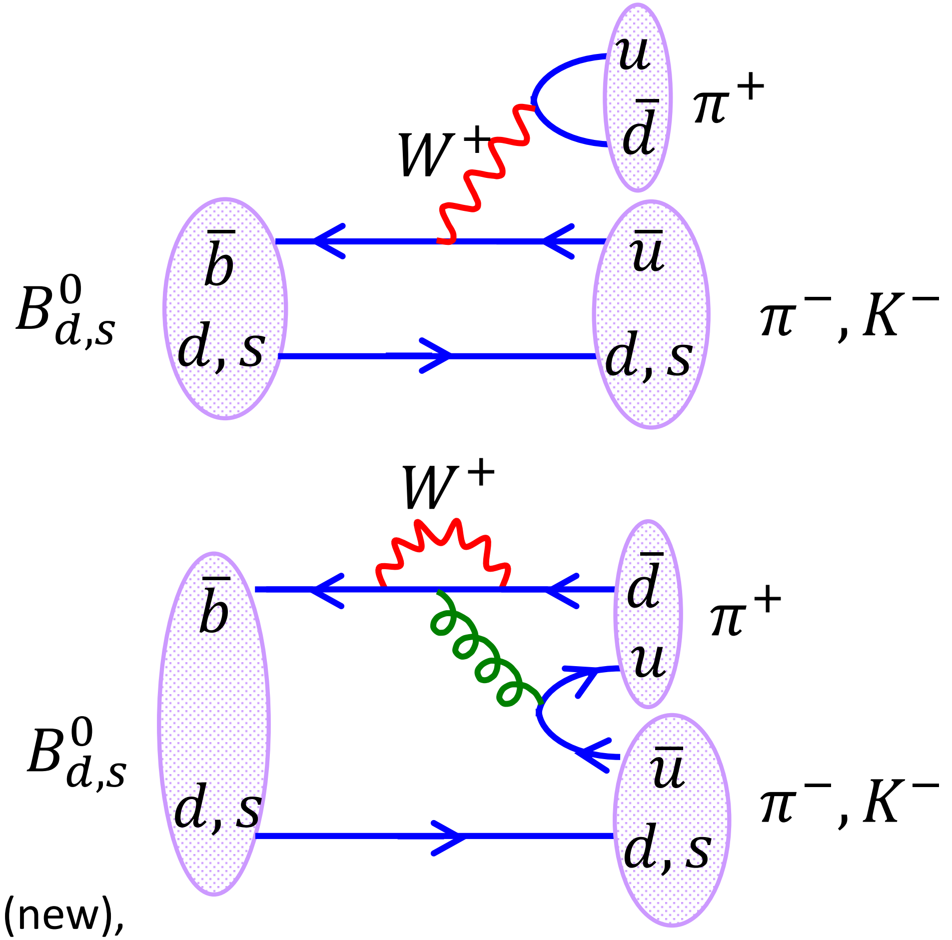
Direct CPV in $B_s \to K\pi$

PRL 110 (2013) 221601

- Direct CPV requires the existence of (at least two) amplitudes with different both weak and strong phases.
- Large asymmetries are expected in the interferences between trees and penguin diagrams.
- First direct CPV in beauty sector:

2004 $B^0 \to K^+\pi^-$ Belle & BaBar — Phys.Rev.Lett. 87 (2001) 0091801; Phys.Rev.Lett. 87 (2001) 0091802

2013 $B_S^0 \to K^-\pi^+$ LHCb



Direct (time integrated) CP asymmetry:

$$A_{CP} = \frac{\Gamma\{\bar{B} \to K^+\pi^-\} - \Gamma\{B \to K^-\pi^+\}}{\Gamma\{\bar{B} \to K^+\pi^-\} + \Gamma\{B \to K^-\pi^+\}}$$

- available with flavour tagging – opposide side, same-side pion (new),
- with the determination of production and detection asymmetry

Direct CPV in $B_S \to K\pi$ – the results

PRL 110 (2013) 221601

- This is the most precise measurement to date:

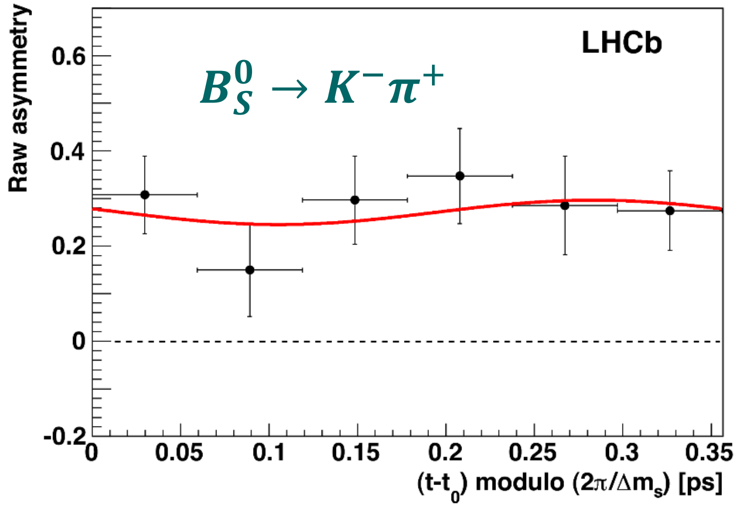
$$A(B^0 \to K^+\pi^-) = -8.0 \pm 0.7 \pm 0.3\ \%$$

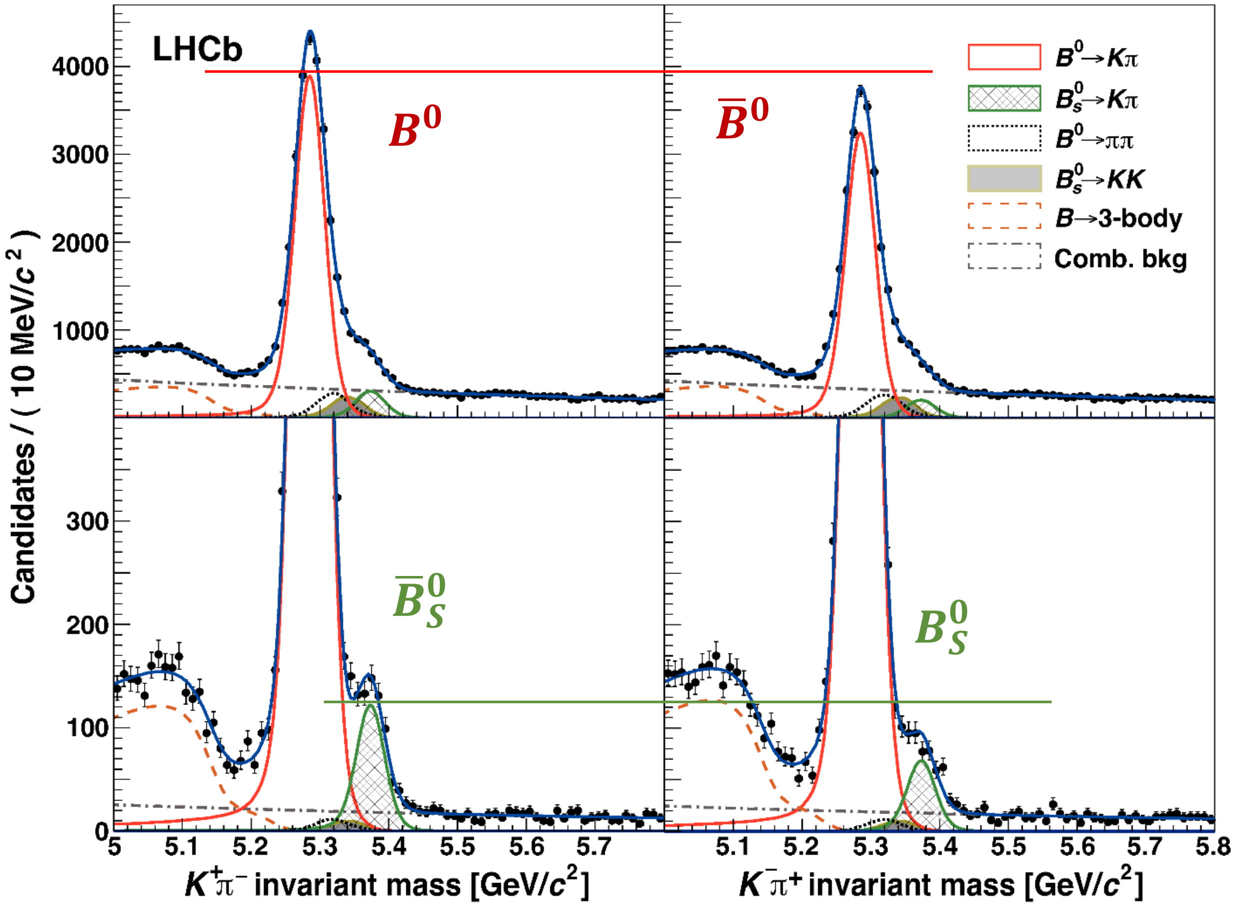
significance $10.5\ \sigma$.

- First observation of direct CPV in B_S^0 meson:

$$A(B_S^0 \to K^-\pi^+) = 27 \pm 4 \pm 1\ \%$$

with significance $6.5\ \sigma$



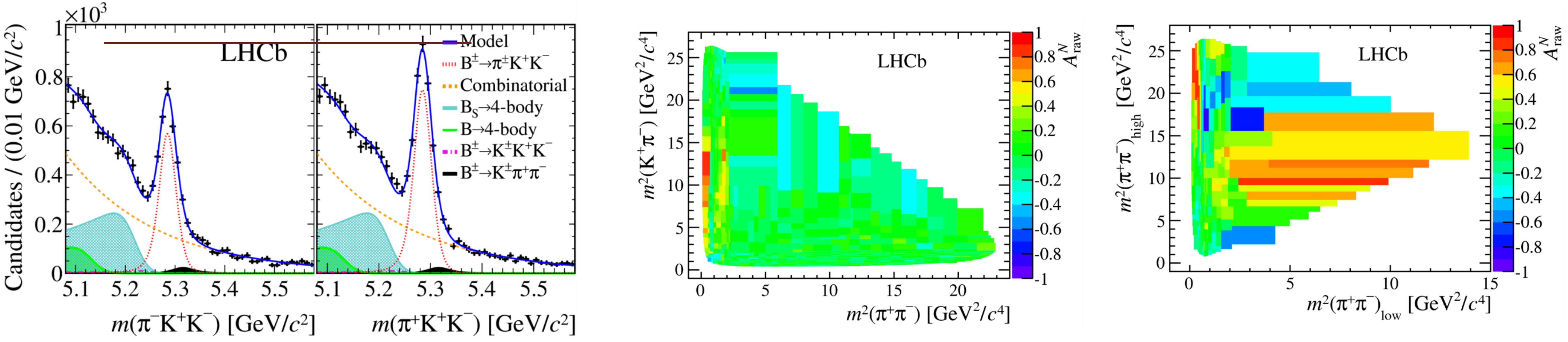


Consistent with SM

Direct CP violation in $B^{\pm} \to h^{\pm}h^{+}h^{-}$

Phys.Rev.D90(2014)112004

$B^{-} \to h^{-}h^{+}h^{-}$ ⟷ CP ⟷ $B^{+} \to h^{-}h^{+}h^{+}$



- Inclusive charge asymmetries and CP asymm. in the regions of phase space
- Rich resonance structure, variety of strong phases,
- CP asymmetries ∝ weak and strong phase differences (Dalitz plots)
- Large asymmetries in low mass (KK) and $(\pi\pi)$ region (final state rescattering?) , the CP asymmetries are positive for pions, negative for kaons

$A_{CP}(B^{\pm} \to \pi^{\pm}K^{+}K^{-}) = -0.123 \pm 0.017 \pm 0.012 \pm 0.007$ 5.6 σ

$A_{CP}(B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}) = +0.058 \pm 0.008 \pm 0.009 \pm 0.007$ 4.2 σ

$A_{CP}(B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}) = +0.025 \pm 0.004 \pm 0.004 \pm 0.007$ 2.8 σ

$A_{CP}(B^{\pm} \to K^{\pm}K^{+}K^{-}) = -0.036 \pm 0.004 \pm 0.002 \pm 0.007$ 4.3 σ

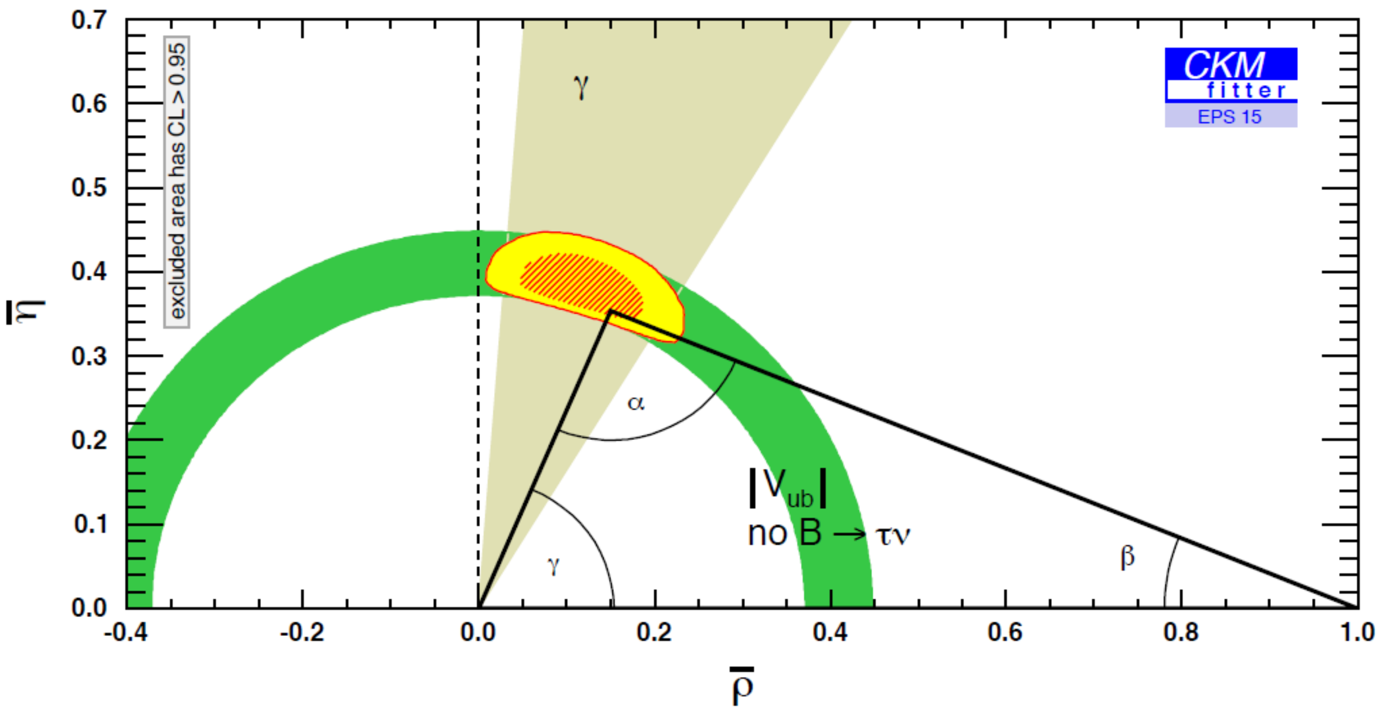
CKM γ angle

1. The $\boldsymbol{\gamma}$ angle is the only one that can be determined from tree only processes, no loop diagrams, no New Physics
2. The weak phase $\boldsymbol{\gamma}$ can be measured in the interference of $b \to c$ and $b \to u$ decays.
3. Theoretically clean: $\delta\gamma/\gamma \leq \mathcal{O}(10^{-7})$

$$\boldsymbol{\gamma \equiv \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)}$$

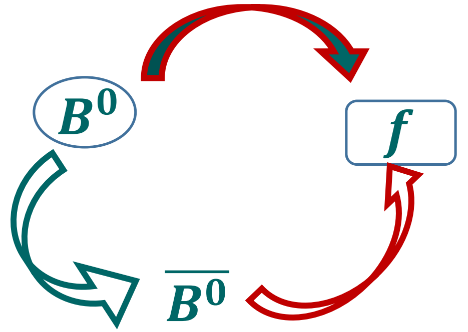
4. So far has the worst precision:
   a) direct measurements:
      - BaBar: $\gamma = (69 \pm 17)^\circ$,
      - Belle: $\gamma = (68 \pm 15)^\circ$
   b) indirect measurements (dominated by loops): $(66.9^{+1.0}_{-3.7})^\circ$
5. CKM fitter 2015: $\gamma = (73.2^{+6.3}_{-7.0})^\circ$

trees - direct



γ combination in LHCb

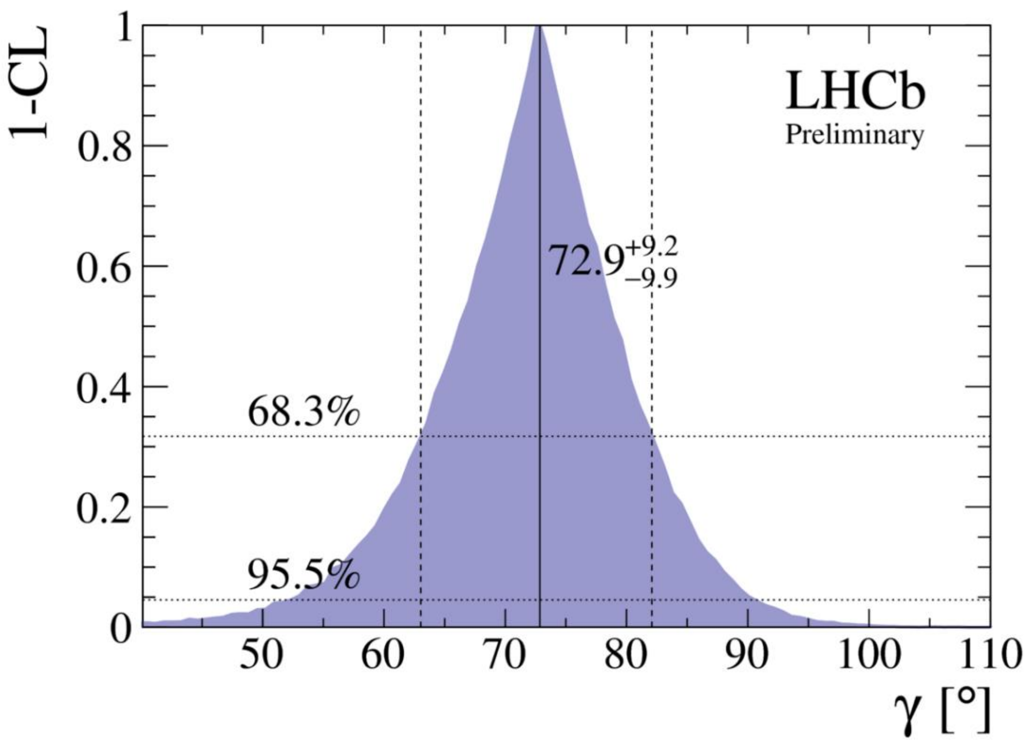
6. Direct, time integrated measurements: $B^{\pm 0} \rightarrow D^0 K^{\pm *0}$
7. Mixing induced, time dependent analysis: $B_S^0 \rightarrow D_S^{\mp} K^{\pm}$



The 2014 combination for γ measurement (LHCb-CONF-2014-004)

$$\gamma = \left(72.9^{+9.2}_{-9.9}\right)^{\circ}$$

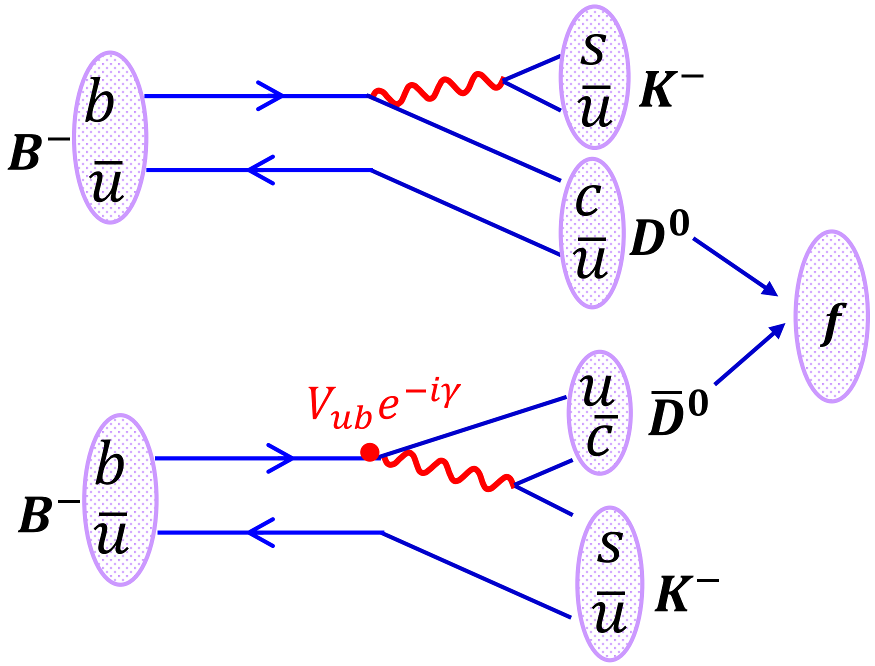
mixture of $\mathcal{L} = 3fb^{-1}$ and $\mathcal{L} = 1fb^{-1}$ measurements



LHCb Analysis
$B^+ \to DK^+$, $D \to hh$, GLW/ADS
$B^+ \to DK^+$, $D \to K\pi\pi\pi$, ADS
$B^+ \to DK^+$, $D \to K_S^0 hh$, model-independent GGSZ
$B^+ \to DK^+$, $D \to K_S^0 K\pi$, GLS
$B^0 \to DK^{*0}$ GLW/ADS
$B_s^0 \to D_s^{\mp} K^{\pm}$

CKM γ angle from $B^{\pm} \to DK^{\pm}$

$B^{\pm 0} \to D^0 K^{\pm * 0}$



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

1. Sensitive to the γ when D^0 and $\overline{D^0}$ decay to the same final state.
2. The interference of these two amplitudes depends on their relative magnitudes - one of them is usually suppressed.

$$A(B^- \to K^- f) \sim A(D \to f) + r_B e^{i(\delta_B - \gamma)} A(\bar{D} \to f)$$

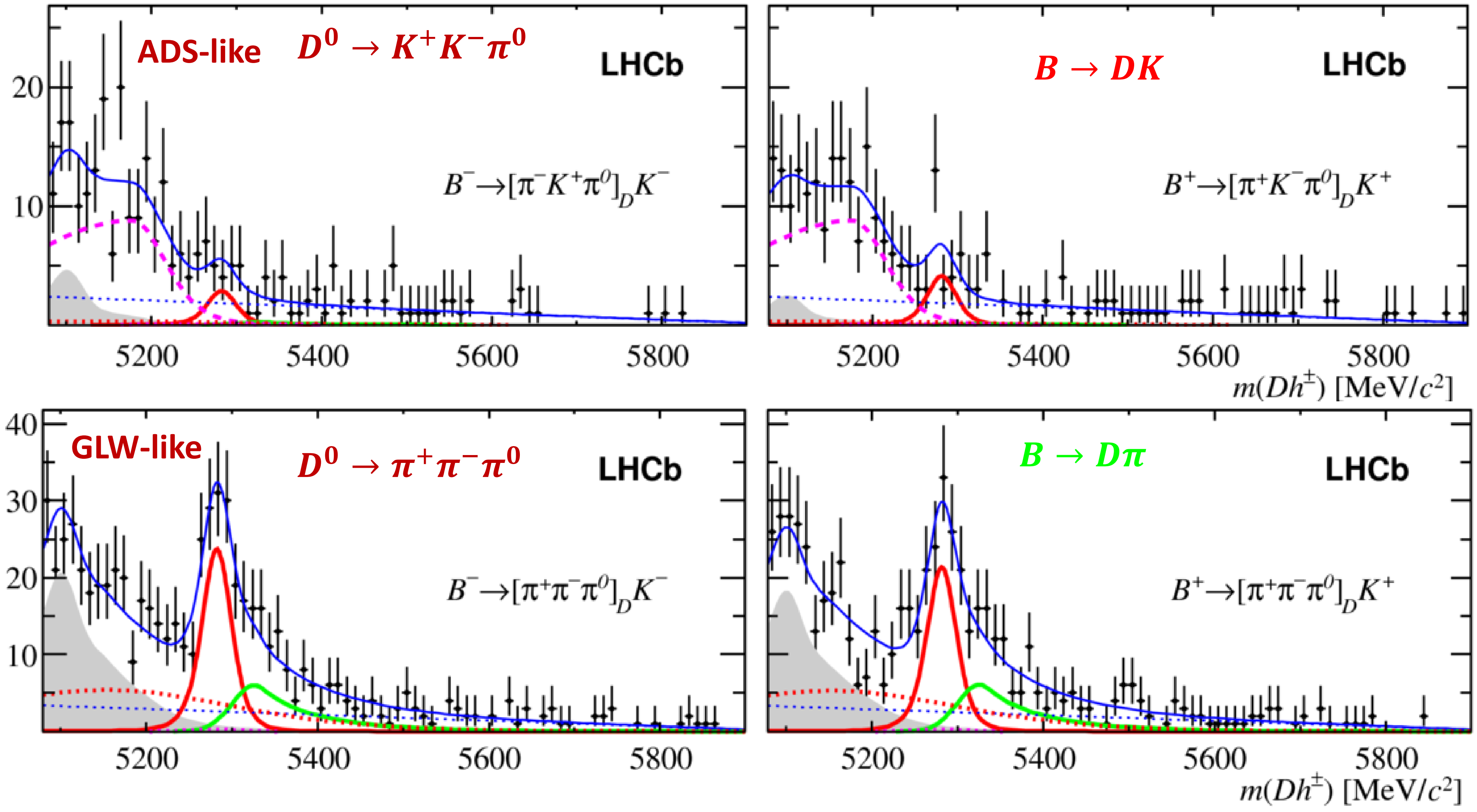
$$r_B e^{i\delta_B} = \frac{A(B^- \to \bar{D}K^-)}{A(B^- \to DK^-)}$$

3. Hadronic unknows: r_B and δ_B
4. Different experimental techniques (GLW, ADS, GGSZ).
5. Plenty (>16) of final states : new!
   - $D \to CP$ eigenstates: $K^+K^-, \pi^+\pi^-, K^+K^-\pi^0, \pi^+\pi^-\pi^0$
   - $D \to CP$ flavour specific: $K^+\pi^-, K^+\pi^-\pi^+\pi^-, K_S K^+\pi^-$
   - $D \to$3 body self-conjugated: $K_S\pi^+\pi^-, K_S K^+K^-$

CKM γ angle from multibody final states

NEW!

Phys.Rev. D91 (2015) 112014

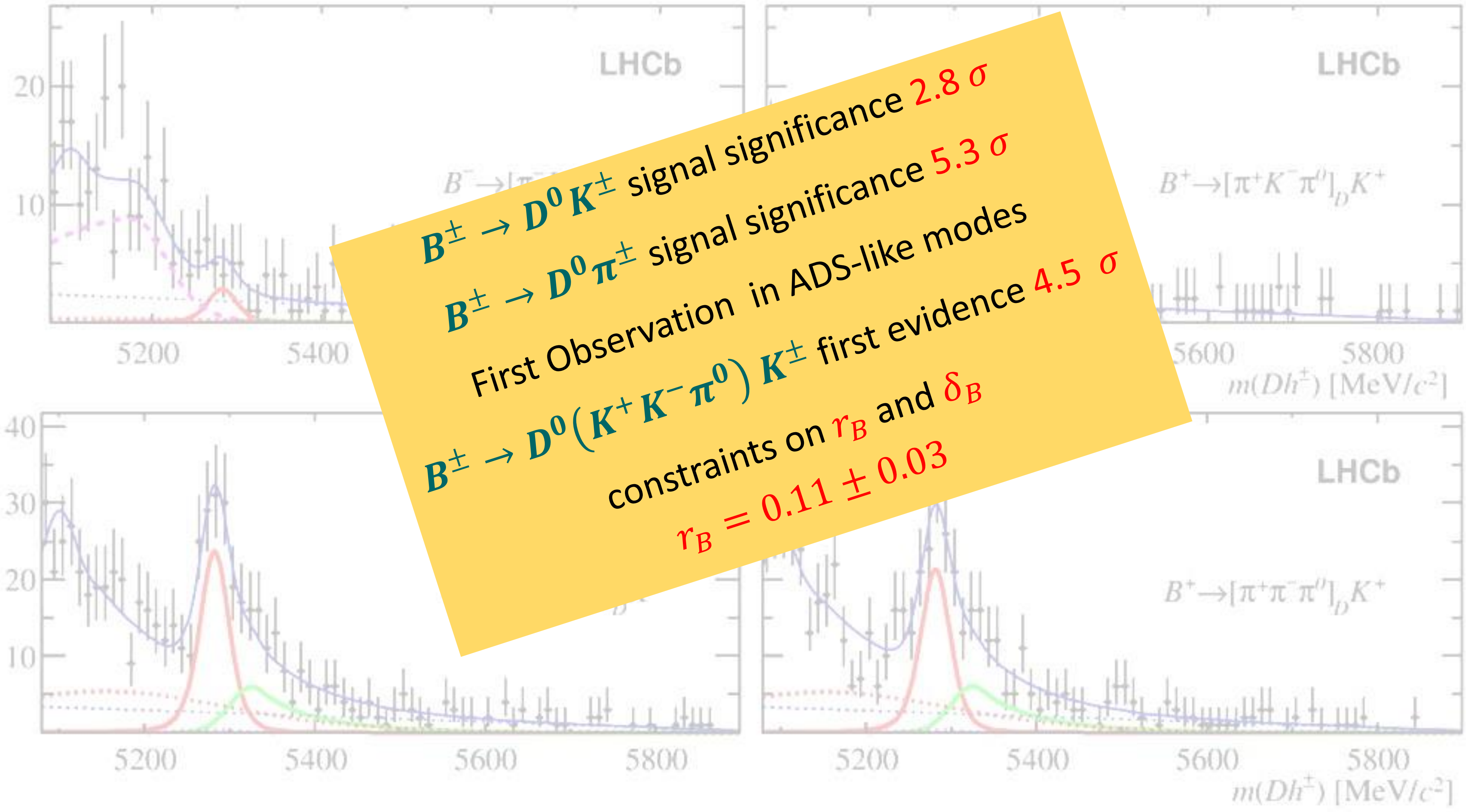


CKM γ angle from $B^{\pm} \to DK^{\pm}$

NEW!

Phys.Rev. D91 (2015) 112014

AGH



$B^{\pm} \to D^{0} K^{\pm}$ signal significance 2.8 σ

$B^{\pm} \to D^{0} \pi^{\pm}$ signal significance 5.3 σ

First Observation in ADS-like modes

$B^{\pm} \to D^{0}(K^{+}K^{-}\pi^{0})\, K^{\pm}$ first evidence 4.5 σ

constraints on r_B and δ_B

$r_B = 0.11 \pm 0.03$

CKM γ angle from $B^{\pm} \to Dh^{\pm}\pi\pi$

NEW! HOT

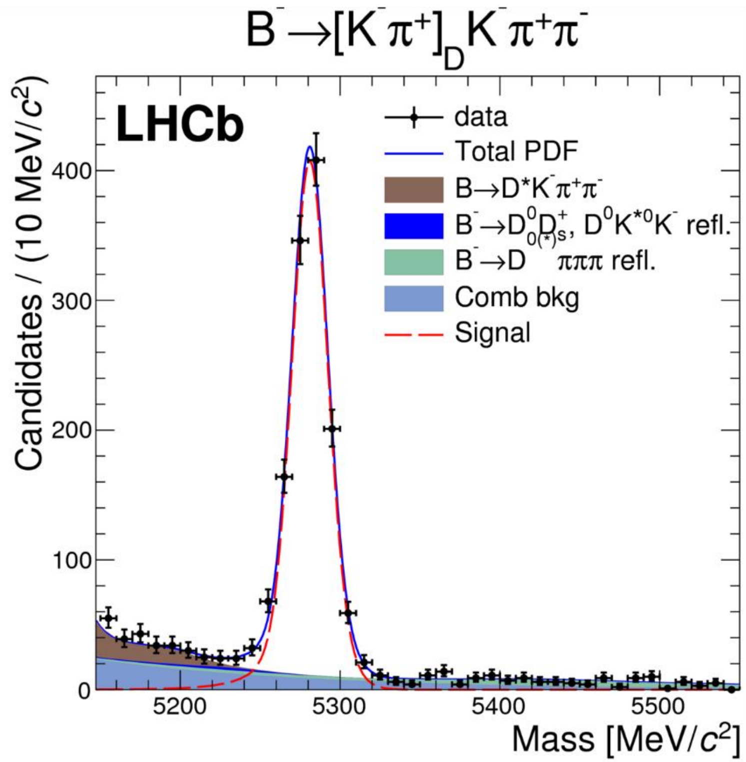
Phys. Rev. D 92, 112005 (2015)

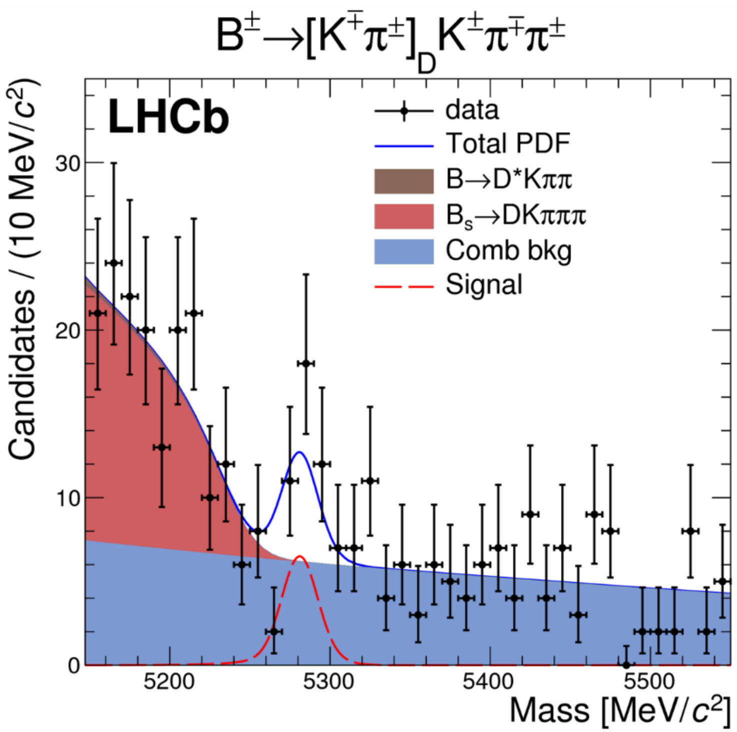
- Inclusive analysis of the process: $B^{\pm} \to DX_S^{-}$, where $X_S^{-} = K^{-}\pi^{+}\pi^{-}$ and $D \to K^{+}K^{-}, \pi^{+}\pi^{-}, K^{\pm}\pi^{\mp}$

suppressed: $B^{-} \to DK^{-}\pi^{+}\pi^{-}$

favoured: $B^{-} \to D\pi^{-}\pi^{+}\pi^{-}$

$D \to K^{+}\pi^{-}$ is doubly suppressed





Decay mode	B^- yield	B^+ yield
	(N^f_{fit,X_d^-})	(N^f_{fit,X_d^+})
$B^{\pm} \to DX_d^{\pm}$, $D \to K^-\pi^+$	$36\,956 \pm 214$	$37\,843 \pm 219$
$B^{\pm} \to DX_d^{\pm}$, $D \to K^+\pi^-$	161 ± 20	162 ± 20
	(N^f_{fit,X_s^-})	(N^f_{fit,X_s^+})
$B^{\pm} \to DX_s^{\pm}$, $D \to K^-\pi^+$	1234 ± 37	1226 ± 37
$B^{\pm} \to DX_s^{\pm}$, $D \to K^+\pi^-$	13.0 ± 5.3	6.6 ± 4.0

γ is mainly constrained by the suppressed modes

first measurement with these modes

$$\gamma = \left(74^{+20}_{-19}\right)^{\circ}$$

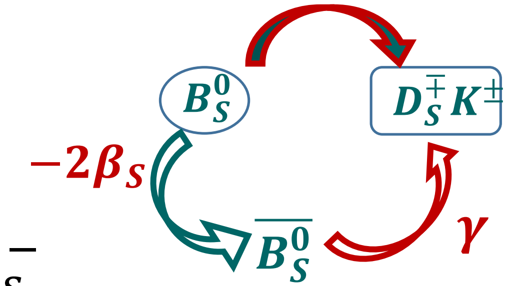
CKM γ angle from $B_S^0 \to D_S^{\mp} K^{\pm}$

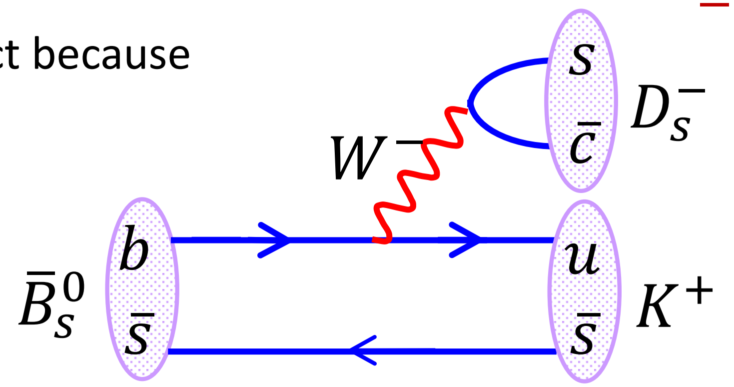
JHEP 11 (2014) 060

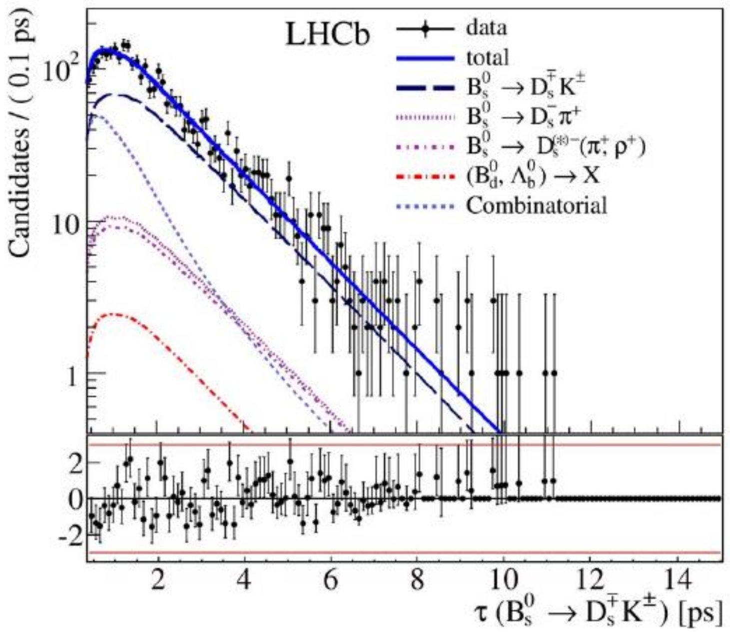
$B_S^0 \to D_S^{\mp} K^{\pm}$

Time dependent

1. The interference between mixing and direct decay, large effect because decays are not colour suppressed,
2. Sensitive to $(\gamma + \phi_s)$, strong phase δ,
3. Need to measure 4 time dependent decay rates







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

$D_f \propto cos(\delta - (\gamma - 2\beta_S))$

$S_f \propto sin(\delta - (\gamma - 2\beta_S))$

First measurement with this technique, $1 fb^{-1}$

$$\gamma = \left(115^{+28}_{-43}\right)^{\circ}$$

Search for CPV in charm

In the Standard Model:

- expected CPV in charm sector is small $\leq \mathbf{10^{-3}}$
- New Physics contributions enhance CPV up to $\mathbf{10^{-2}}$

LHCb measurement of the A_Γ asymmetry from $D^0 \to K^+K^-, D^0 \to \pi^+\pi^-$:

The asymmetry of the decay frequencies of D^0 and $\bar{D}^0$ to CP- eigenstates $D^0 \to K^+K^-, D^0 \to \pi^+\pi^-$

$$A_\Gamma \equiv \frac{\Gamma(D^0 \to K^+K^-) - \Gamma(\bar{D}^0 \to K^+K^-)}{\Gamma(D^0 \to K^+K^-) + \Gamma(\bar{D}^0 \to K^+K^-)} \approx (\tfrac{1}{2}A_m + A_d) y \cos\phi - x \sin\phi$$

$$A_m \equiv \frac{|q/p|^2 - |p/q|^2}{|q/p|^2 + |p/q|^2}$$

in the mixing

in the decay amplitudes

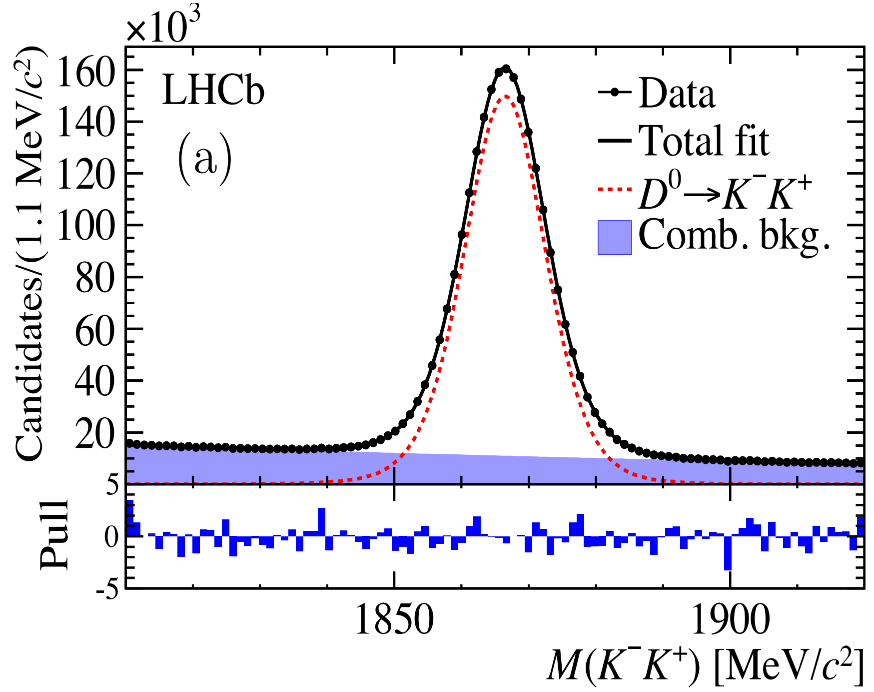
$$A_d \equiv \frac{|A_f|^2 - |\bar{A}_f|^2}{|A_f|^2 + |\bar{A}_f|^2}$$

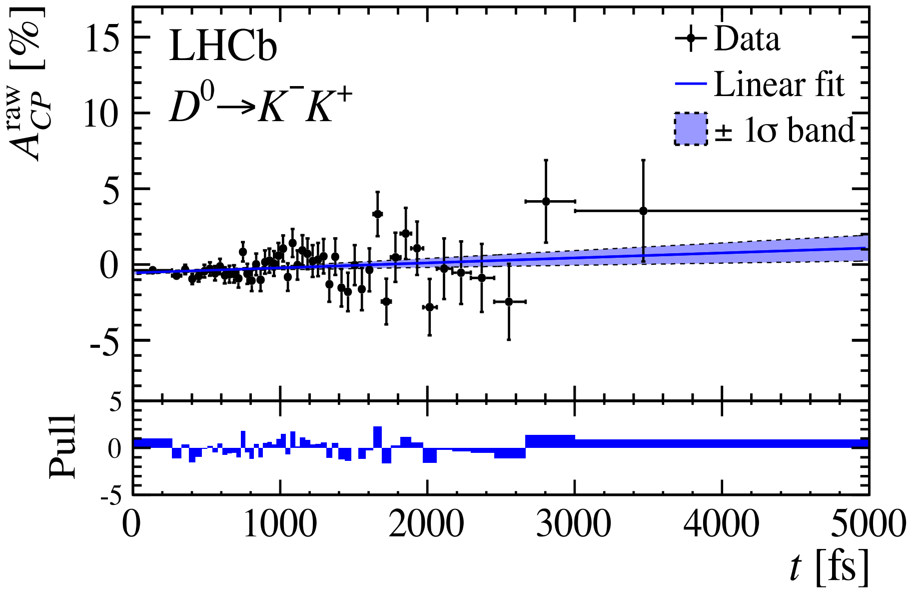
A_Γ asymmetry

$B^0 \to D^0\mu^- X$ and $B^0 \to \bar{D}^0\mu^- X$

A_Γ is a measure of indirect CPV, since the contribution from direct CPV is considered as very small.

2.3 M events of K^+K^-





$$A_\Gamma(K^+K^-) = \left(-0.134 \pm 0.077^{+0.026}_{-0.034}\right)\%$$

$$A_\Gamma(\pi^+\pi^-) = \left(-0.092 \pm 0.145^{+0.025}_{-0.033}\right)\%$$

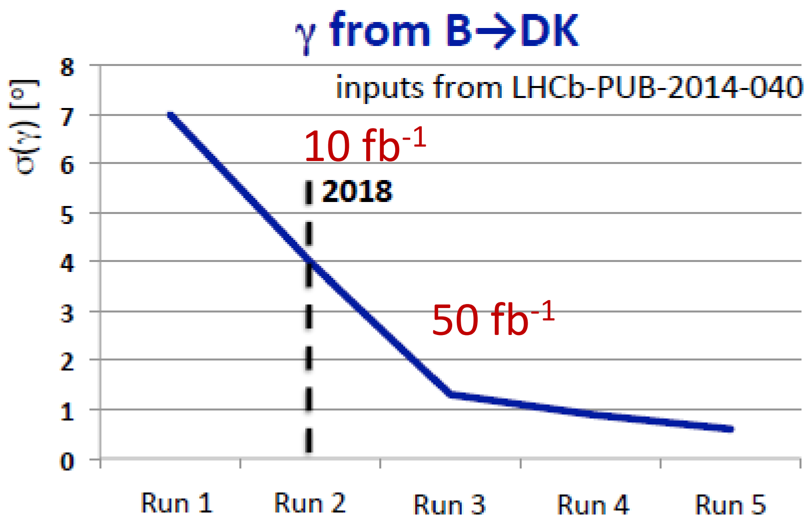
No evidence for indirect CPV in charm within 1 per mil.

Prospects for γ in Run II

1. What are the requirements for better precision for the $\boldsymbol{\gamma}$ angle?
   the theoretical predictions are of order of 10^{-7} (no penguins), so the only quest is to obtain:
   - more data,
   - more signal events to perform time dependent analysis of more challenging channels as $\boldsymbol{B_S^0 \to D_S^{\mp *} K^{\pm *}}$
   - more signal in suppressed modes,
   - less background,
   - no loss in tracking performance & vertex resolution.

2. The higher energy @ Run II means 2x higher bb cross-section
3. During Run II LHCb detector will benefit from novel approach to trigger performance.
4. The trigger is optimized to reconstruct charm events with greater efficiency .

We expect close to 10 fb^{-1} of data Run II (2016-18)
The precision for $\boldsymbol{\gamma}$ of the order of $\sigma(\boldsymbol{\gamma})\sim 4°$



The TURBO stream power

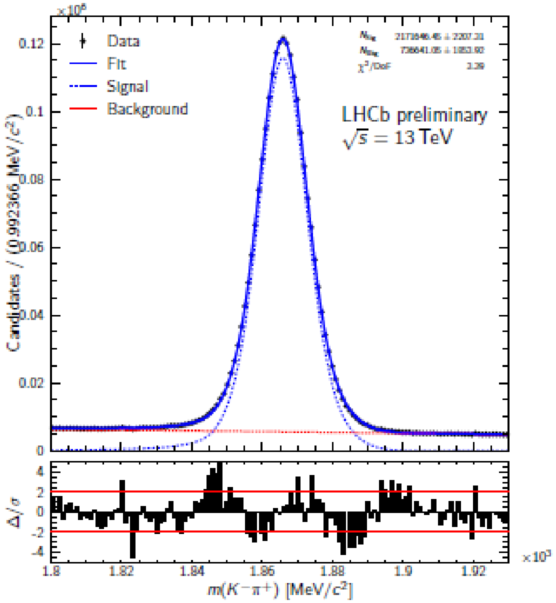
This idea is quite amazing!

1. Let’s save only the trigger level objects that caused it to „fire”
   - Tracks and vertices
   - No raw data is stored for the TURBO

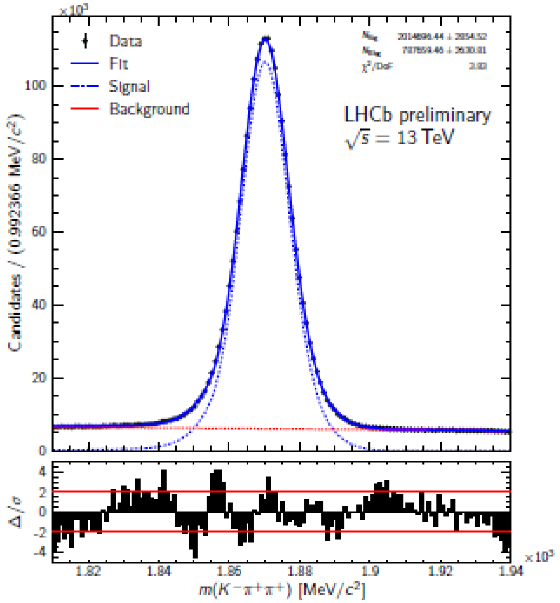
2. Huge gain
   - The event size is much smaller
   - No reprocessing
   - Analysis much faster

Used for high yield exclusive modes (charm)

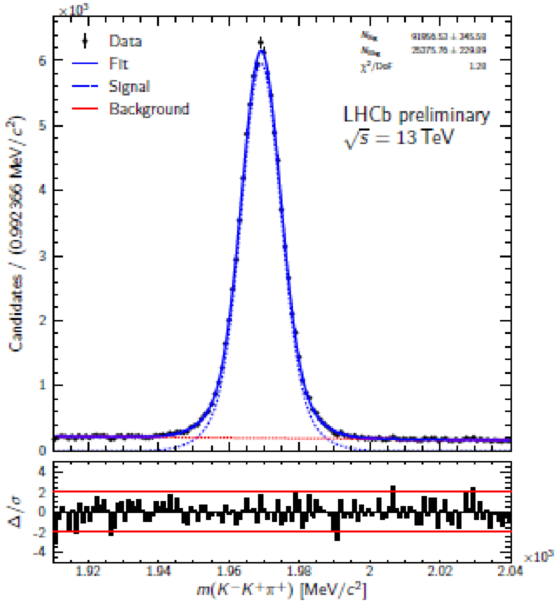
Plots obtained directly after the HLT



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



$D^+ \to K^-\pi^+\pi^+$



$D_s^+ \to K^-K^+\pi^+$

Background almost non existent

The number of events much higher that in RUN I

Summary

1. LHCb is the experiment to study CP Violation.
2. After three years of data taking in data with B decays:
   a) weak phases:

      $\sin 2\beta = 0.731 \pm 0.035(stat) \pm 0.020(syst)$

      γ obtained with variety of methods in $B \to DK$ decays,

   b) Direct CP Violation observed in $B \to h^+h^-(h^-)$ -
3. LHCb managed to achieve precision comparable with or better than B factories in β and made a great progress in the γ angle measurement

ALL within the Standard Model limits