Measuring the Unitarity Triangle with LHCb

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On behalf of the LHCb Collaboration

September 3rd 2016

Corfu Summer Institute

16th Hellenic School and Workshops on Elementary Particle Physics and Gravity

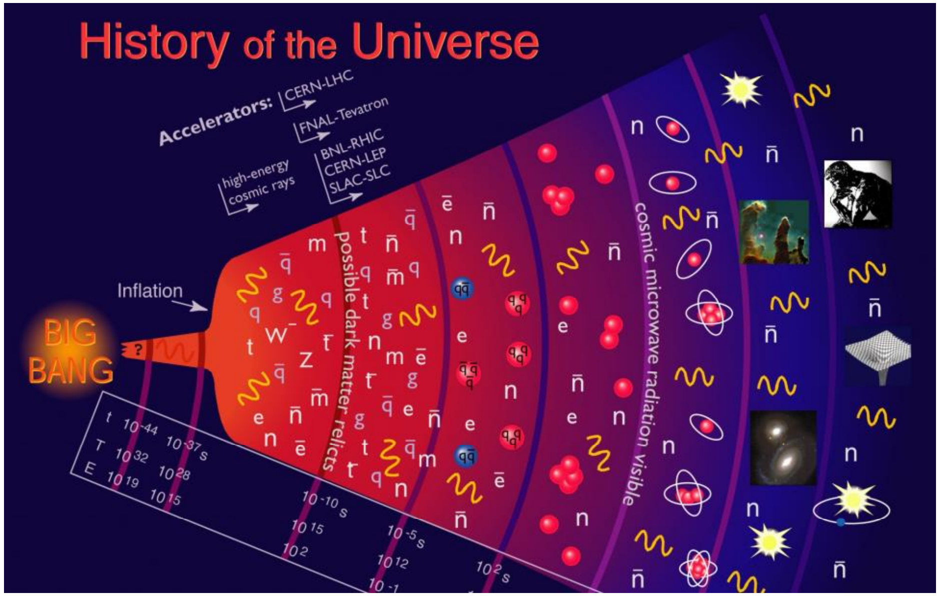
Corfu, Greece 2016

Outline

- General introduction
- The LHCb detector and running conditions
- Measurement of the Unitarity Triangle parameters
  - The angle β
  - The triangle sides
  - The angle α
  - The focus of this talk : measurement of the angle γ
- Summary and outlook

Analyses presented here come largely from the full 2011 and 2012 datasets (7 and 8 TeV)

The puzzle of the matter abundance

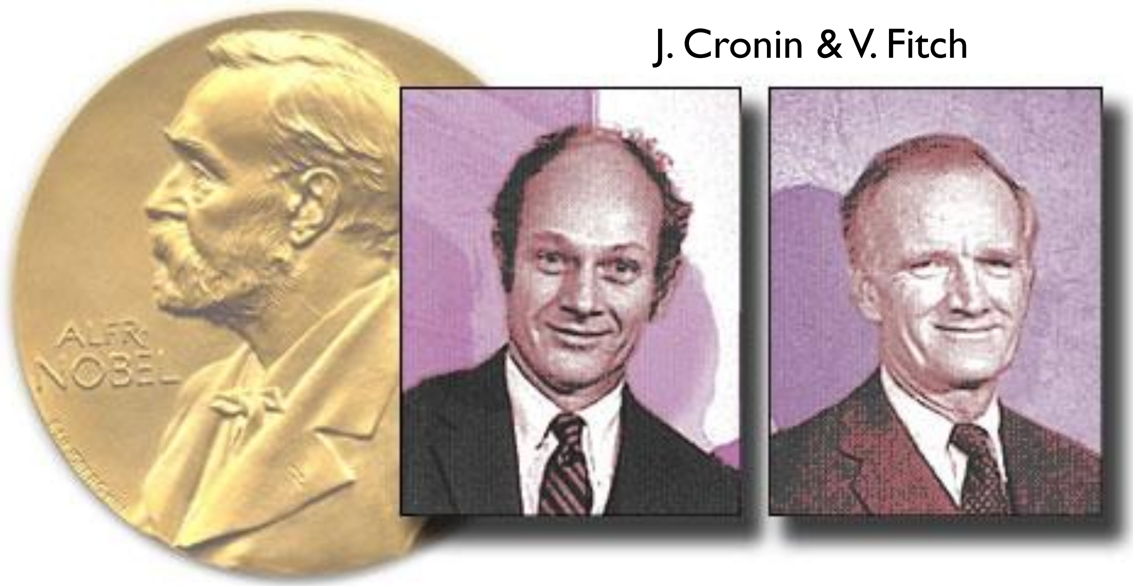


- Matter and antimatter were produced in equal abundance after the Big Bang
- However matter is now manifest in our Universe
- After the first few microseconds, there must have been (10^{10}-1) antiquarks for every 10^{10} quarks, the Universe is left with the remaining 1.

CP Violation and New Physics

- First Observation of CPV was in the Kaon system in 1964
- Nobel prize awarded in1980
- First observation in B decays in 2001

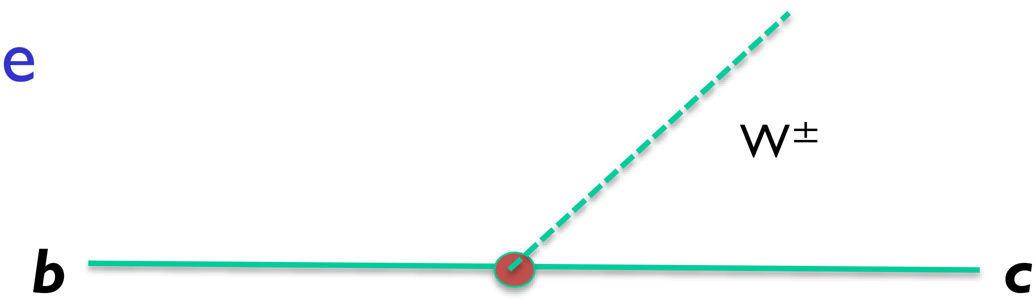
J. Cronin & V. Fitch



- To date CP-violation only observed in the quark sector, but at levels far below that required to explain the asymmetry in the Universe
- There must be a mechanism(s) beyond the Standard Model by which differences between matter and anti-matter are generated.

The CKM Matrix

- In the SM, quarks change flavour by the emission or absorption of a $W^{\pm}$ boson



  - Charge $-1/3$ quarks (d, s, b) are "mixed"
  - The mixing is described by the CKM matrix

$$\begin{pmatrix} u \\ c \\ t \end{pmatrix} \leftarrow W^{\pm} \rightarrow \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

The CKM matrix

- The CKM matrix is unitary, and reduces to three rotation angles and one phase.
- The Wolfenstein parameterisation is commonly used to expand in orders of λ, the sine of the Cabibbo angle: $\lambda \sim 0.22$
- The phase gives rise to CP violation in the SM

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(1-\rho-i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

- Measured magnitudes:

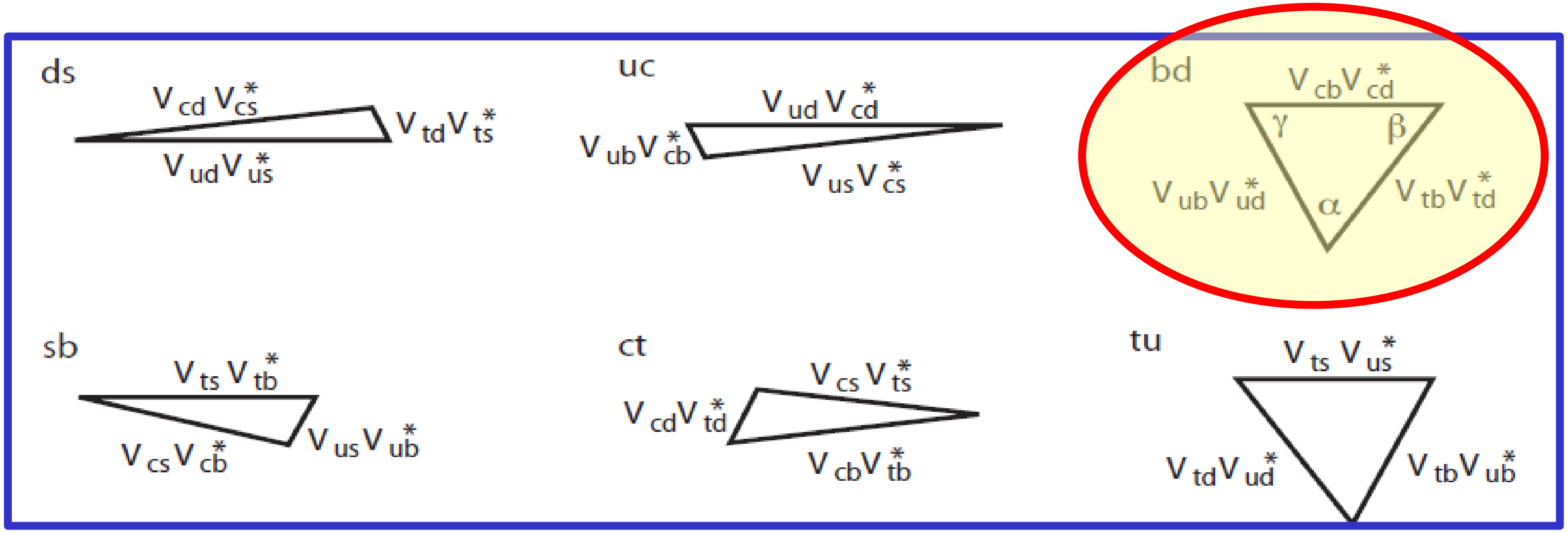
$$V_{\mathrm{CKM}} = \begin{pmatrix} 0.97427 \pm 0.00014 & 0.22536 \pm 0.00061 & 0.00355 \pm 0.00015 \\ 0.22522 \pm 0.00061 & 0.97343 \pm 0.00015 & 0.0414 \pm 0.0012 \\ 0.00886^{+0.00033}_{-0.00032} & 0.0405^{+0.0011}_{-0.0012} & 0.99914 \pm 0.00005 \end{pmatrix}$$

PDG group: pdg.lbl.gov/2015/reviews/rpp2015-rev-ckm-matrix.pdf

The Unitarity Triangle

- 6 unitarity conditions of the CKM matrix
- Gives 6 triangles in the complex plane
- 2 of these triangles do not have a side much shorter than the other two:

$(V^*_{ub}V_{ud}+V^*_{cb}V_{cd}+V^*_{tb}V_{td}) = 0$ $(V^*_{ud}V_{td}+V^*_{us}V_{ts}+V^*_{ub}V_{tb}) = 0$

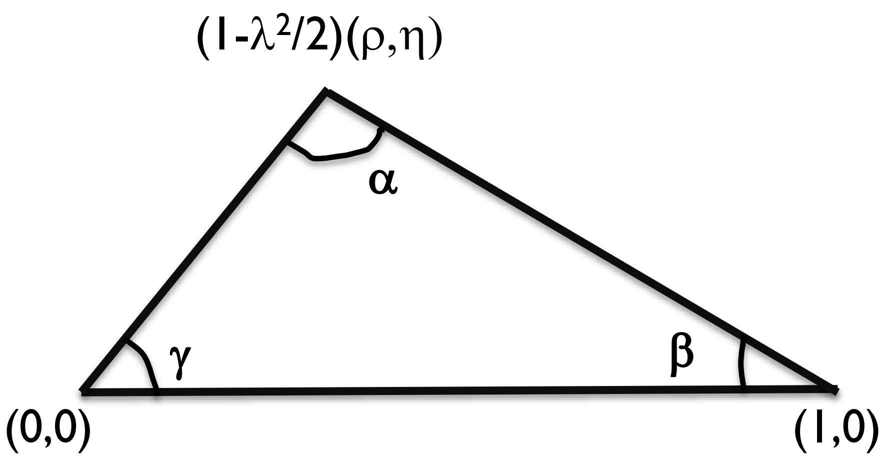


THE unitarity triangle

The Unitarity Triangle

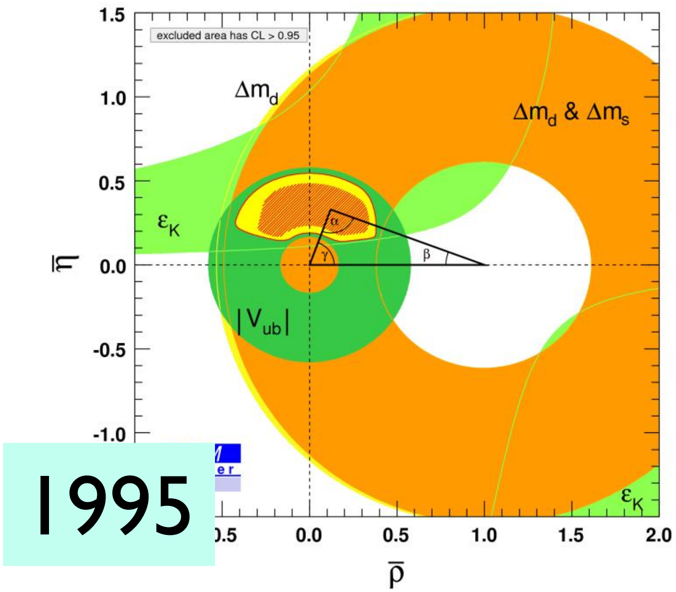
$$(V^*_{ub}V_{ud}+V^*_{cb}V_{cd}+V^*_{tb}V_{td}) = 0$$

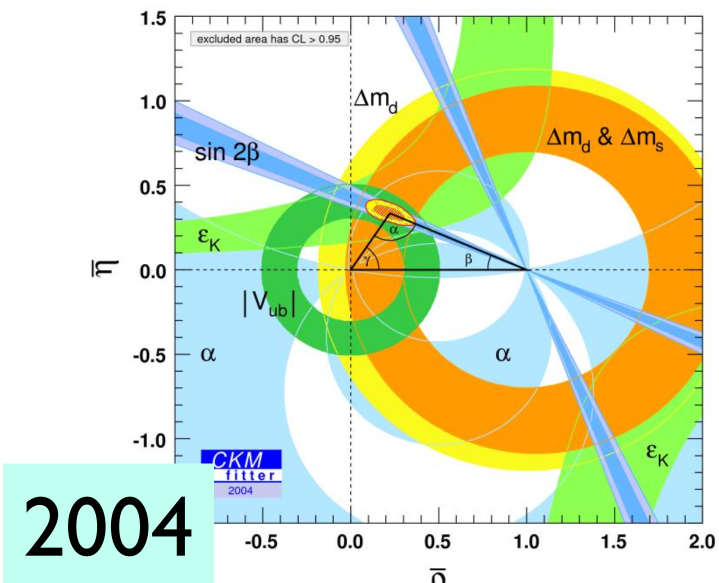
- Unitarity condition → triangle in the complex plane
- Divide through by $V^*_{cb}V_{cd}$
- Results in base of unit length



$$0 = 1 + \frac{V^*_{tb}V_{td}}{V^*_{cb}V_{cd}} + \frac{V^*_{ub}V_{ud}}{V^*_{cb}V_{cd}}$$

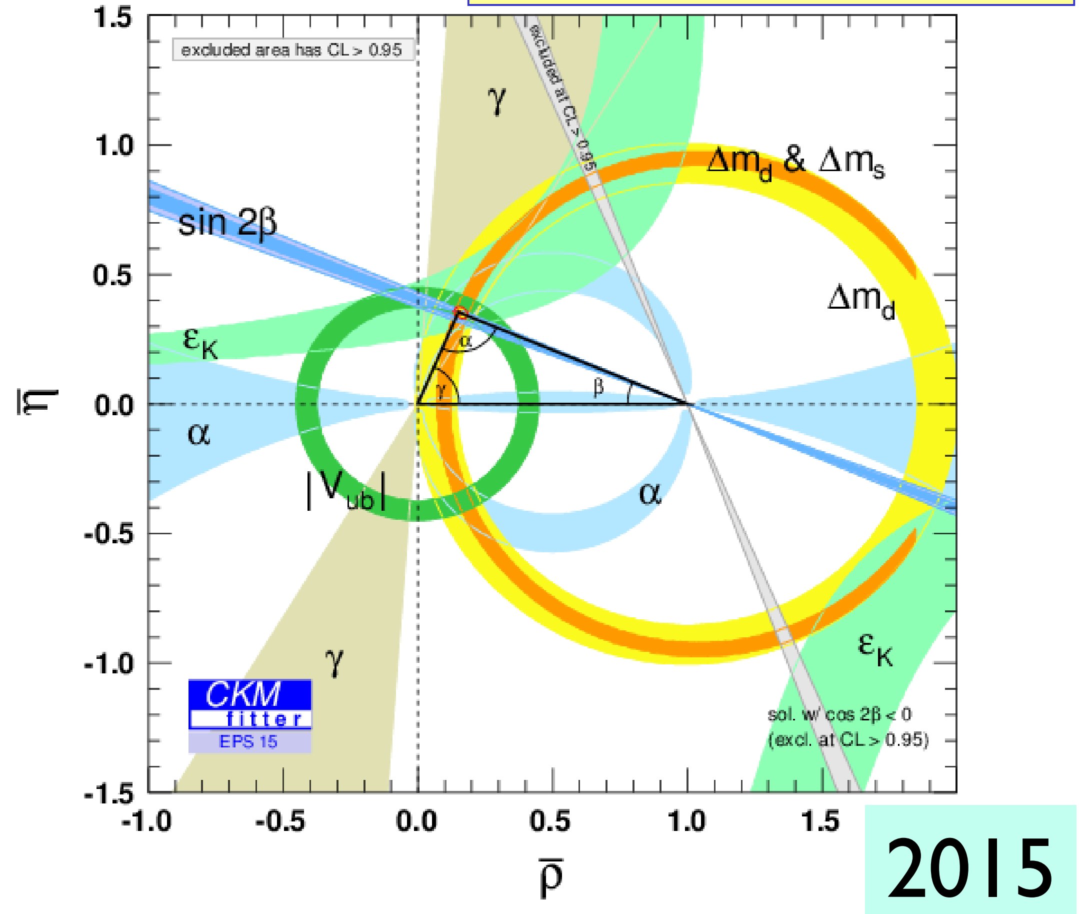
Unitarity triangle measurements





- Amazing progress in the last 20 years; the SM remains intact, but still a whole lot still to learn

http://ckmfitter.in2p3.fr



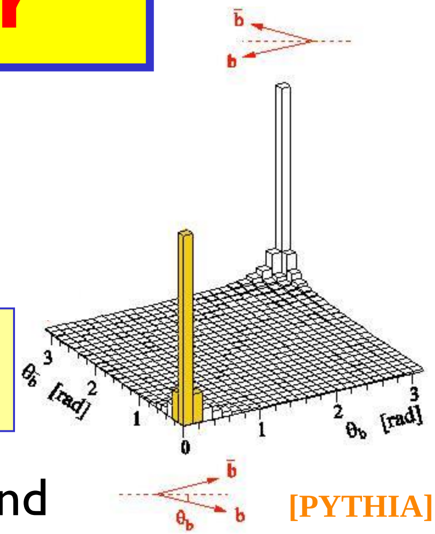
LHCb forward spectrometer

- Forward-peaked production → LHCb is a forward spectrometer (operating in LHC collider mode)
- $b\bar{b}$ cross-section = 71.5 ± 0.5 ± 6.5 μb at $\sqrt{s}$ = 7 TeV

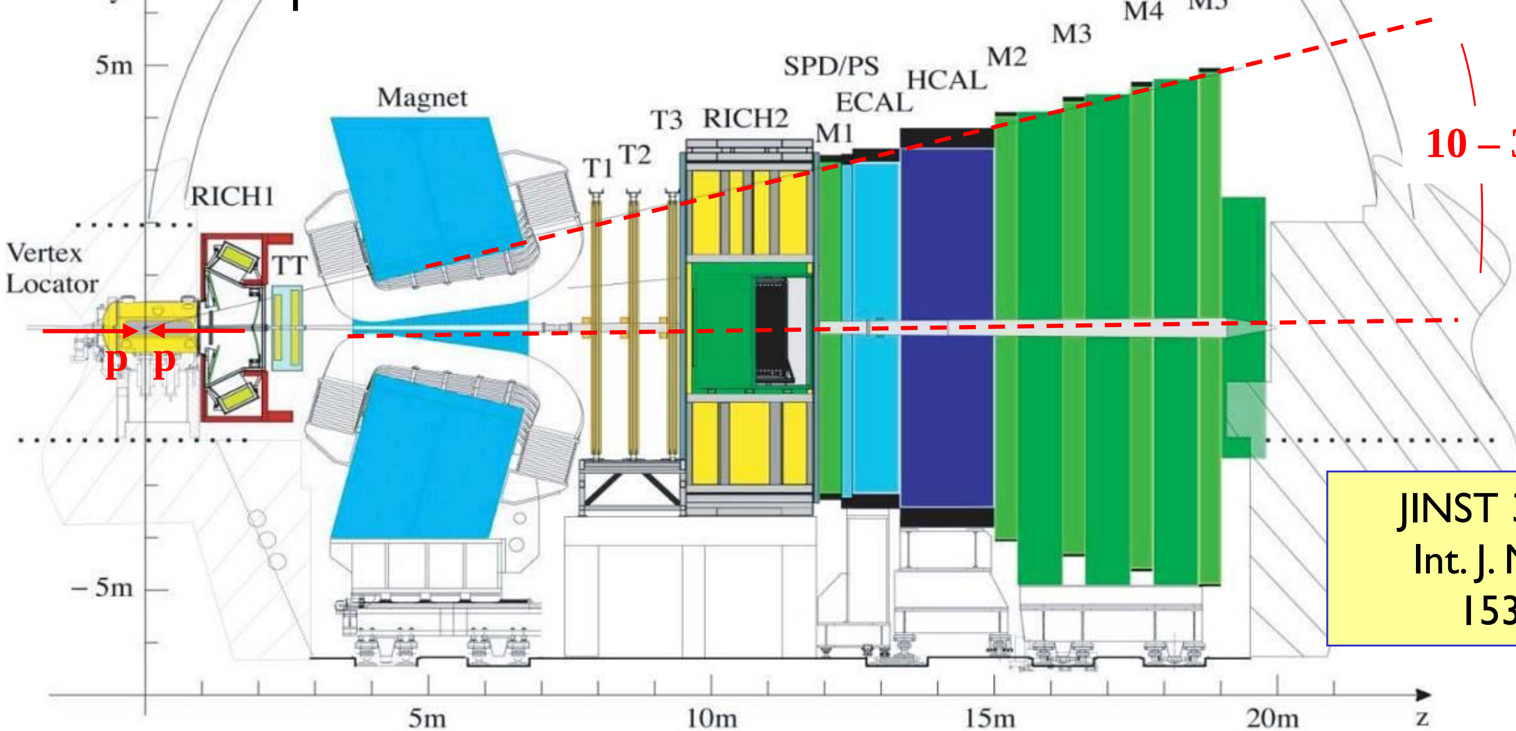
  in the LHCb acceptance 2< η < 5

  At $\sqrt{s}$ = 13 TeV : 164.6 ± 2.3 ± 14.6 μb

LHCB-PAPER-2016-031-002



→ ~ 100,000 $b\bar{b}$ pairs produced/second (10^4 × B factories) and all species of B hadron

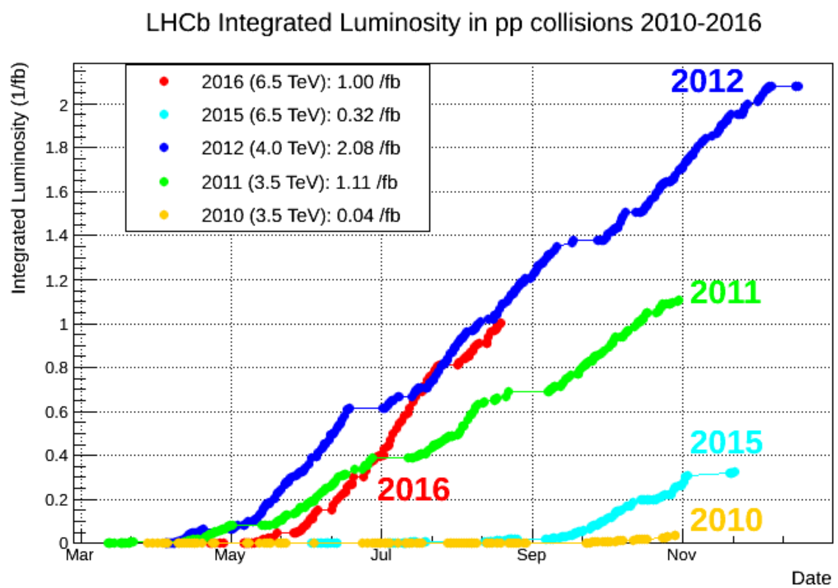


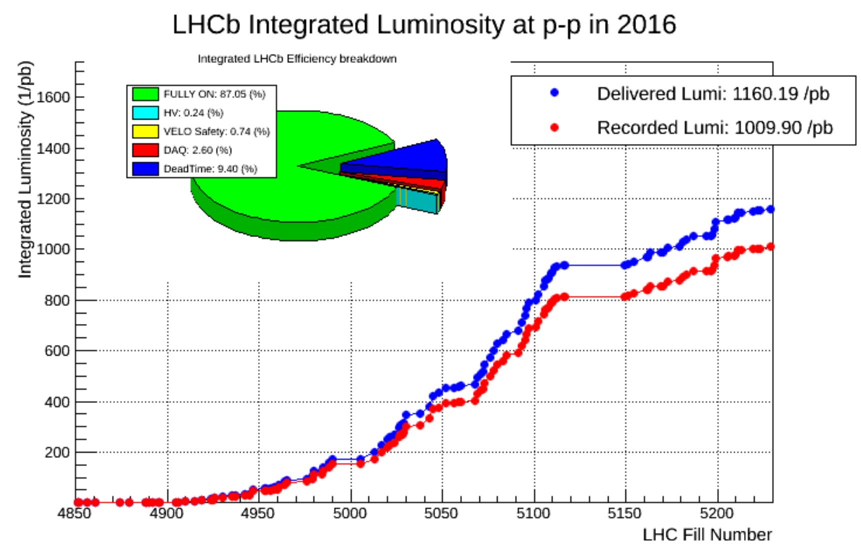
JINST 3:S08005 (2008), Int. J. Mod. Phys. A 30, 1530022 (2015)

LHCb data taking

- Nominal luminosity = 2×10^{32} $cm^{-2} s^{-1}$ (50 times less than ATLAS/CMS) : however, LHCb has learned to run at >2 times this
  - 37 pb^{-1} @ 7 TeV collected in 2010
  - 1 fb^{-1} @ 7 TeV in 2011
  - 2 fb^{-1} @ 8 TeV in 2012
  - 324 pb^{-1} @ 13 TeV in 2015

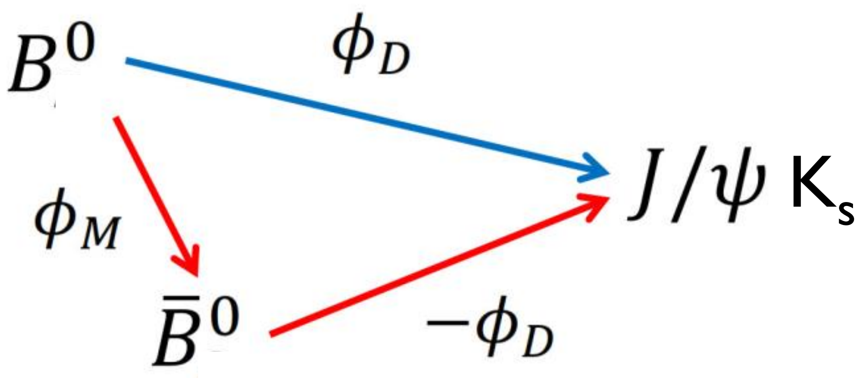
1 fb^{-1} @ 13 TeV in 2016 !!



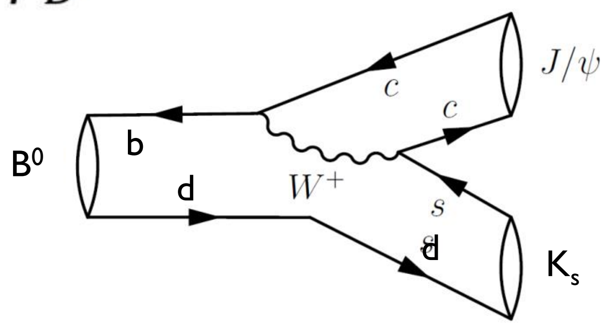


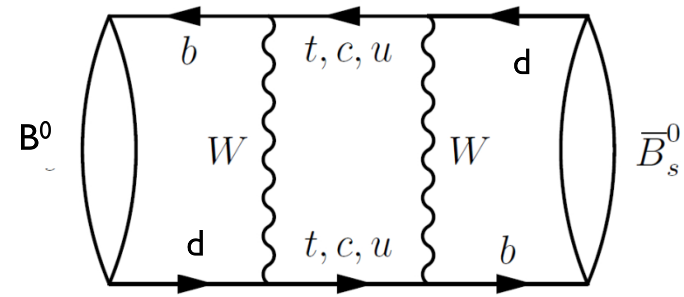
The angle β

Measurement of angle β



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





- *Interference* between B^0 decay to $J/\psi K^0_S$ directly and via B^0 $\overline{B^0}$ oscillation gives rise to a CP violating phase

  $\phi = \phi_{Mixing} - 2\,\phi_{Decay} = 2\beta$

LHCb measurement of sin(2β)

Phys. Rev. Lett 115,031601 (2015)

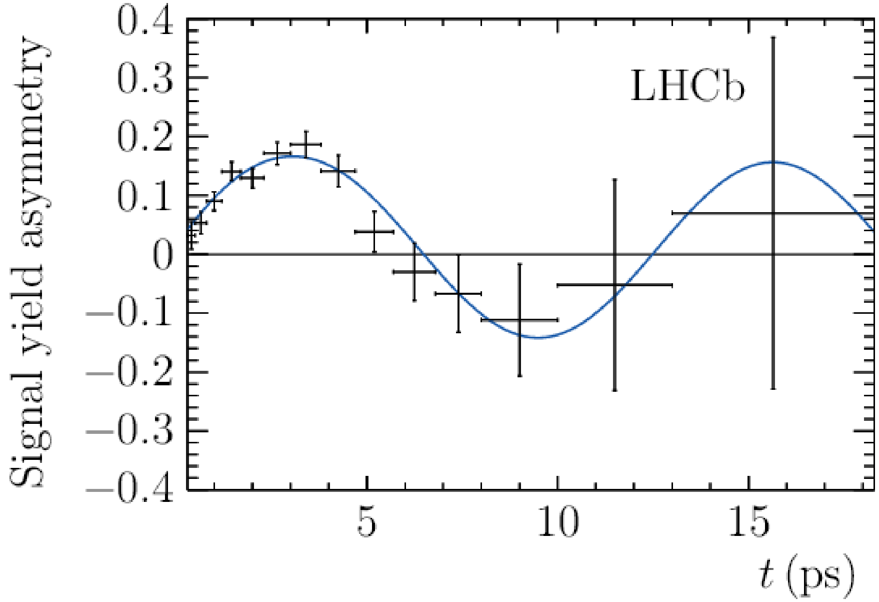
sin(2β) from $B^0 \to J/\psi K^0_S$

$$\mathcal{A}_{J/\psi K^0_S}(t) \equiv \frac{\Gamma(\overline{B}^0(t) \to J/\psi K^0_S) - \Gamma(B^0(t) \to J/\psi K^0_S)}{\Gamma(\overline{B}^0(t) \to J/\psi K^0_S) + \Gamma(B^0(t) \to J/\psi K^0_S)}$$
$$= S_{J/\psi K^0_S} \sin(\Delta m_d t) - C_{J/\psi K^0_S} \cos(\Delta m_d t).$$

where $S_{J/\psi KS}$ = sin(2β) assuming $C_{J/\psi KS}$ (≡ penguin contribution) = 0

$S_{J/\psi Ks}$ = 0.731 ± 0.035 (stat) ± 0.020 (syst)

$C_{J/\psi Ks}$ = 0.0308 ± 0.032 (stat) ± 0.005 (syst)

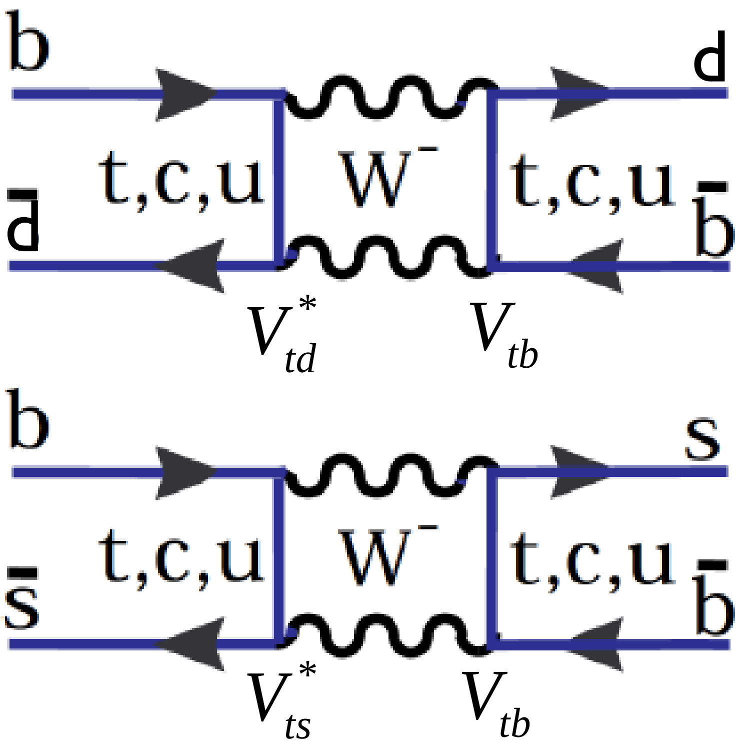


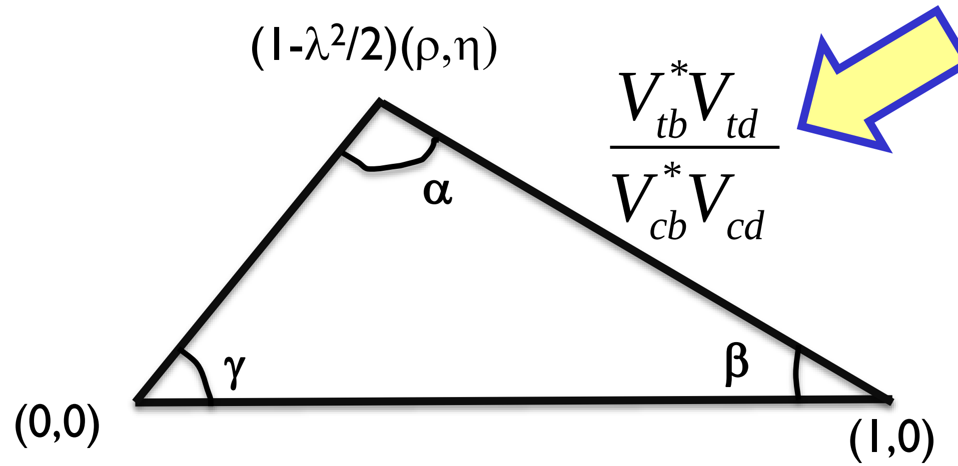
World average from (HFAG) all modes :
sin(2β) = 0.691 ± 0.0170

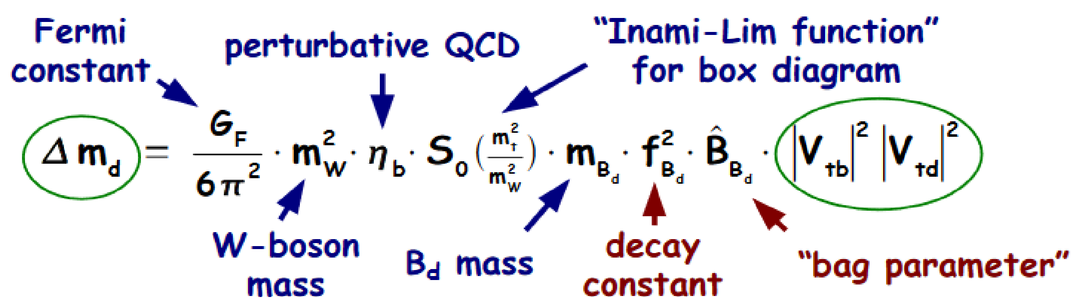
World average from $B^0 \to J/\psi K^0_S$ (EPS 2015) : sin(2β) = $0.748^{+0.030}_{-0.032}$

The sides of the triangle

$B_{(s)}$ mixing for side opposite to γ



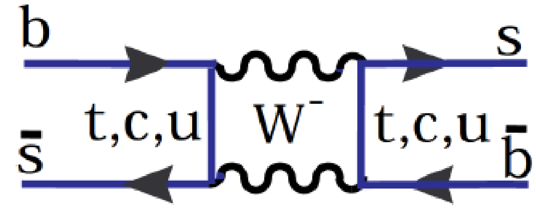


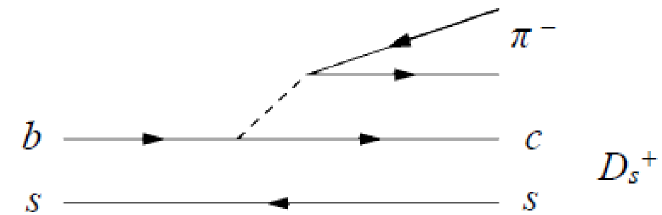


- Mixing loop dominated by the top
- Length of side from ratio of B_d and B_s : mixing frequencies extracted with input from lattice QCD (systematics cancel)

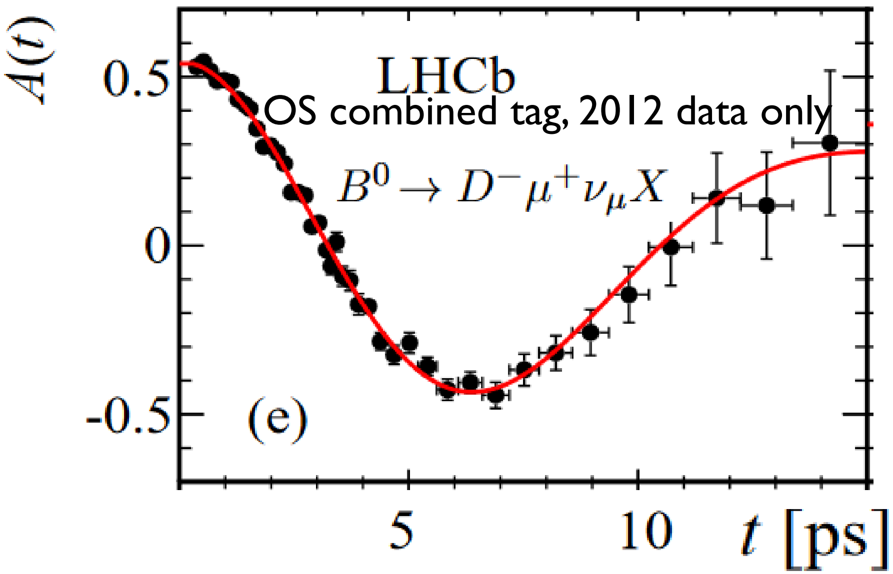
$$\left|\frac{V_{tb}^* V_{td}}{V_{cb}^* V_{cd}}\right| \approx \frac{|V_{td}|}{|V_{ts}|} \times \frac{1}{|V_{cd}|}, \qquad \frac{|V_{td}|}{|V_{ts}|} \sim \sqrt{\frac{\Delta m_d}{\Delta m_s}}$$

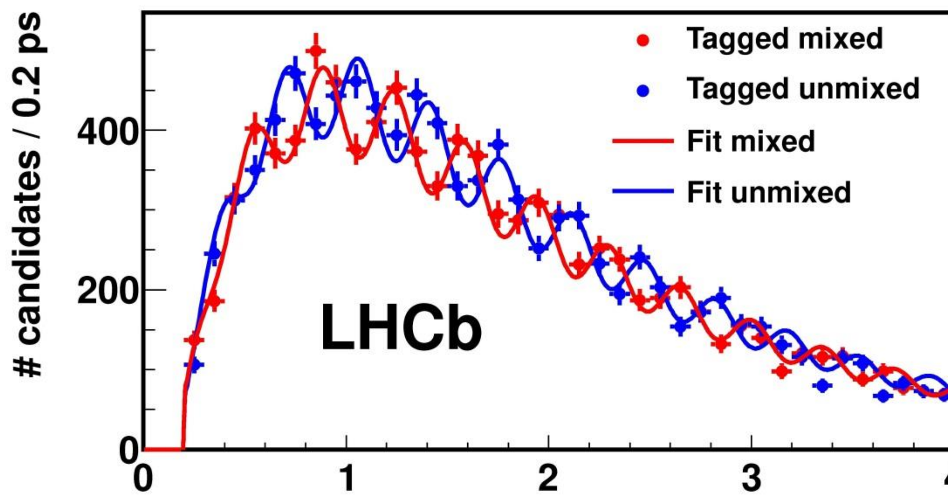
$B_{(s)}$ mixing at LHCb





$$\frac{N(B^0 \to B^0) - N(B^0 \to \bar{B}^0)}{N(B^0 \to B^0) + N(B^0 \to \bar{B}^0)}$$





$$\Delta m_d = (505.0 \pm 2.1 \pm 1.0)\ \mathrm{ns}^{-1}$$

Eur. Phys. J. C76 (2016) 412

J. Phys. 15 (2013) 053021

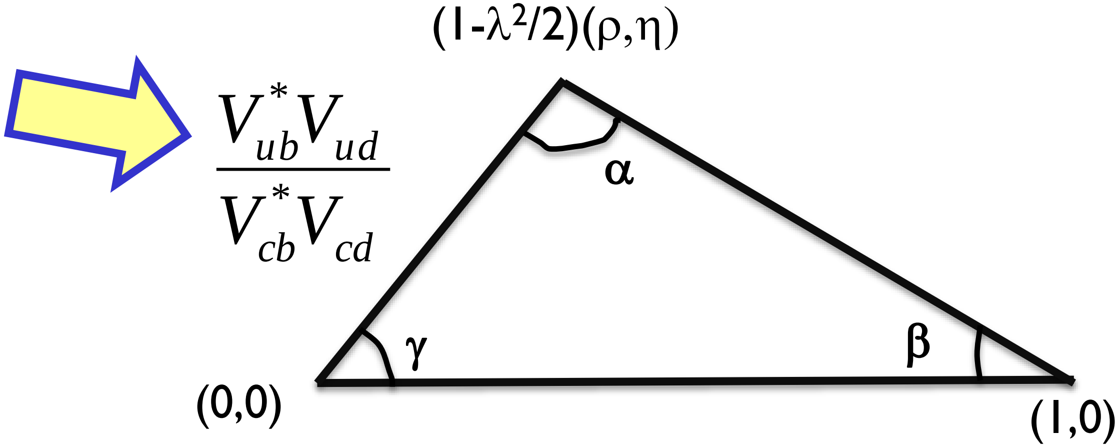
$\Delta m_s = 17.768 \pm 0.023 \pm 0.006\ \mathrm{ps}^{-1}$

$$|V_{td}/V_{ts}| = 0.216 \pm 0.001 \pm 0.011$$

PDG group: pdg.lbl.gov/2015/reviews/rpp2015-rev-ckm-matrix.pdf

Mixing measurements dominated by LHCb (L-QCD systematics to be improved)

$|V_{ub}|$ measurement for side opposite to β

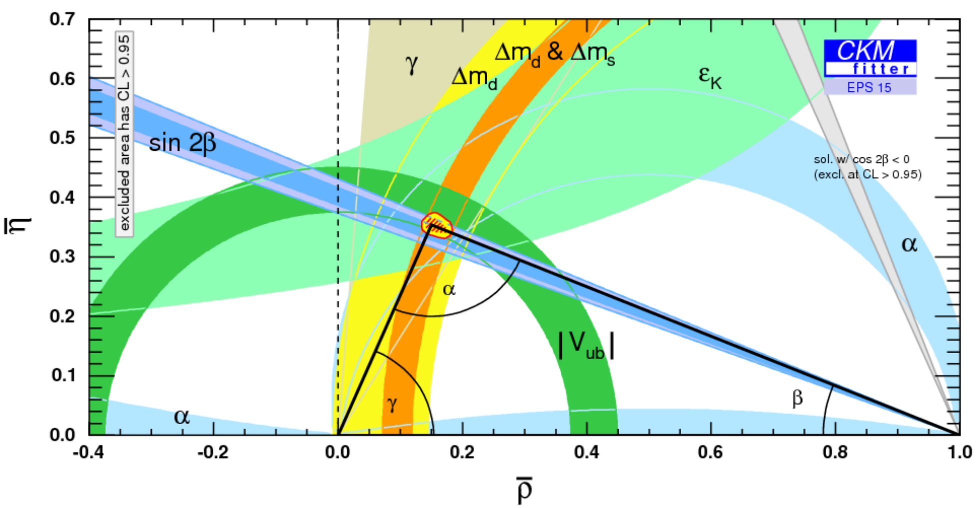


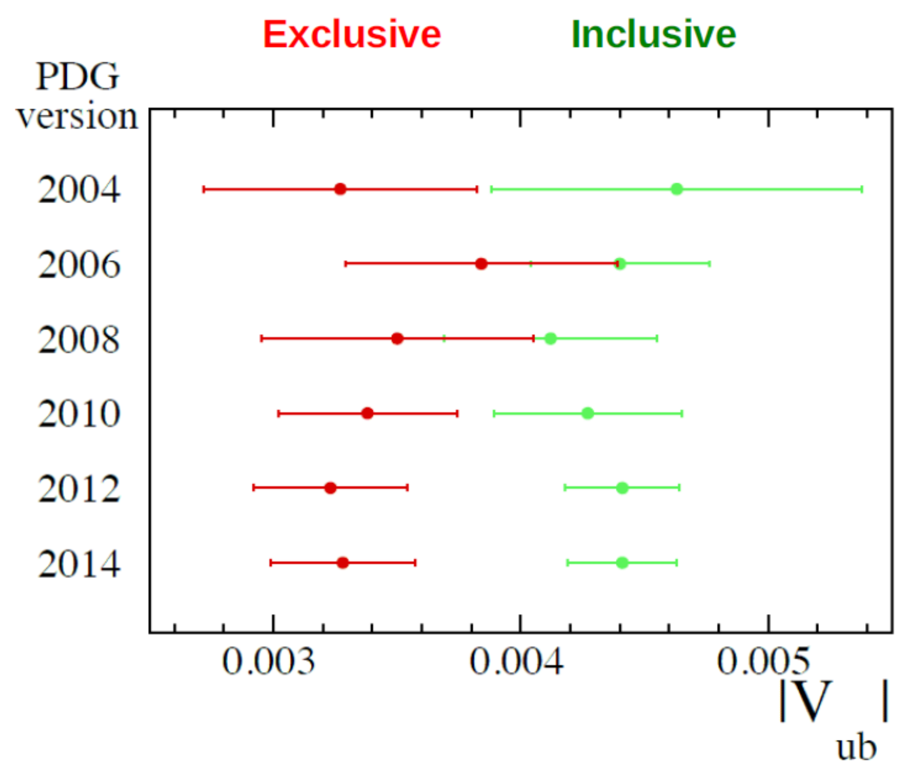
$$\frac{V_{ub}^{*}V_{ud}}{V_{cb}^{*}V_{cd}}$$

- Closure test of UT mainly limited by $|V_{ub}|$
- Side opposite to β proportional to $|V_{ub}|$ / $|V_{cb}|$
- V_{ud} and V_{cd} very well known. $|V_{cb}|$ known to better than 3%
- The decay rate $B \rightarrow X_u l\nu$ is directly proportional to $|V_{ub}|^2$ and which can be calculated using HQET

LHCb measurement of $|V_{ub}|$

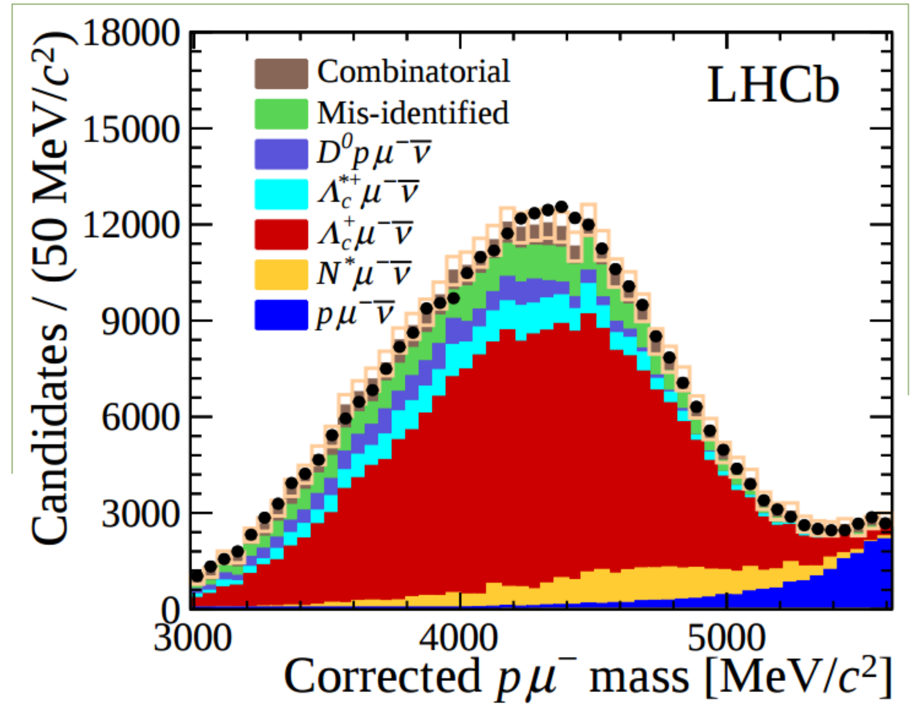
- Current measurements of $|V_{ub}|$ have an internal inconsistency between
  - Exclusive measurement: $B^0 \rightarrow \pi^- \mu^+ \nu$
  - Inclusive measurement : $B^0/B^+ \rightarrow X_u \mu^+ \nu$
- LHCb recently in the game





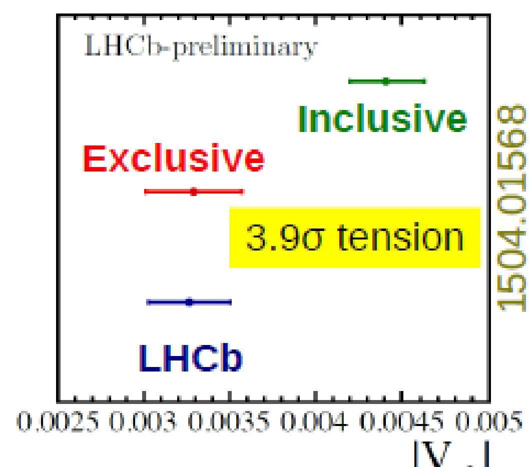
- $|V_{ub}|/|V_{cb}|$ difficult at hadron colliders due to presence of neutrino
- LHCb measures $\Lambda_b \rightarrow p\, \mu^- \nu$
- Measurement relies on recent $\Lambda_b \rightarrow p$ form factors from the lattice)

(Nature Physics 10 (2015) 1038)



$$|V_{ub}| = (3.27 \pm 0.15(\text{exp}) \pm 0.17(\text{theory}) \pm 0.06\ (|V_{cb}|) \times 10^{-3}$$

Tension between inclusive and exclusive $|V_{ub}|$ persists : limits the precision on UT side



The angle α

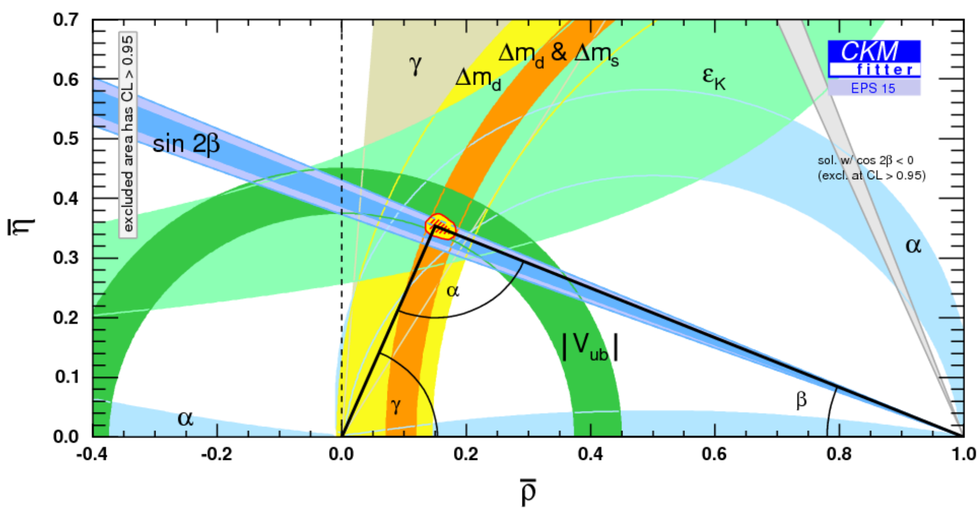
Measurement of α

- Constraints on α from $B\rightarrow\pi\pi$, $\rho\pi$ and $\rho\rho$ (Babar and Belle)
- $\alpha = (87.6\ ^{+3.5}_{-3.3})^{\circ}$ world average measurement
- Compared to the prediction from the global CKM fit (not including the α -related measurements)
  $\alpha = (90.6\ ^{+3.9}_{-1.1})^{\circ}$

http://ckmfitter.in2p3.fr

$$\alpha \equiv \arg\left[-\frac{V_{td}V_{tb}^{*}}{V_{ud}V_{ub}^{*}}\right]$$

- As yet there has been no LHCb 'standalone' measurement of α
- LHCb can provide useful input to B-factories measurements to constrain alpha.

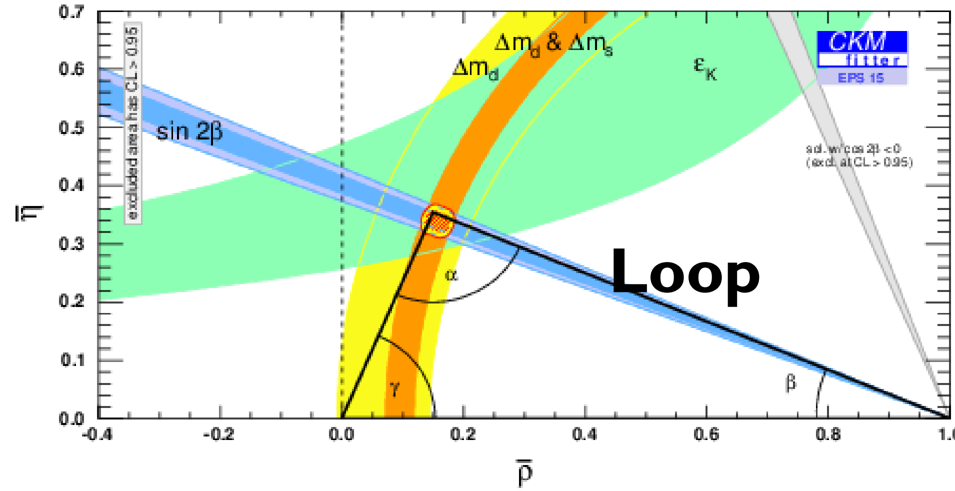


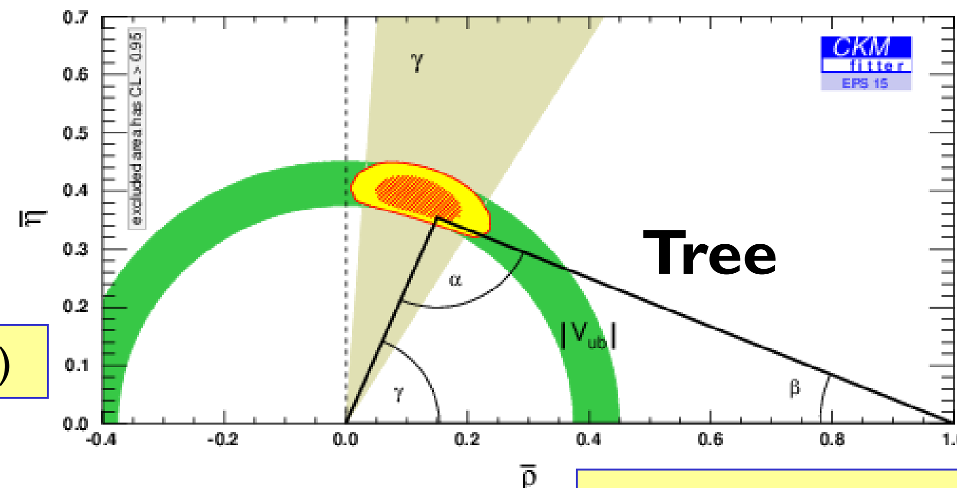
The angle γ

γ – why is this a key goal ?

- Loop processes are very sensitive to the presence of New Physics
- Constraints on the triangle apex largely come from loop decay measurements
- Large uncertainty on γ, the only angle accessible at tree level : forms a SM benchmark*
- γ measurement theoretically

JHEP 01 (2014) 051, PRD 92(3):033002 (2015)



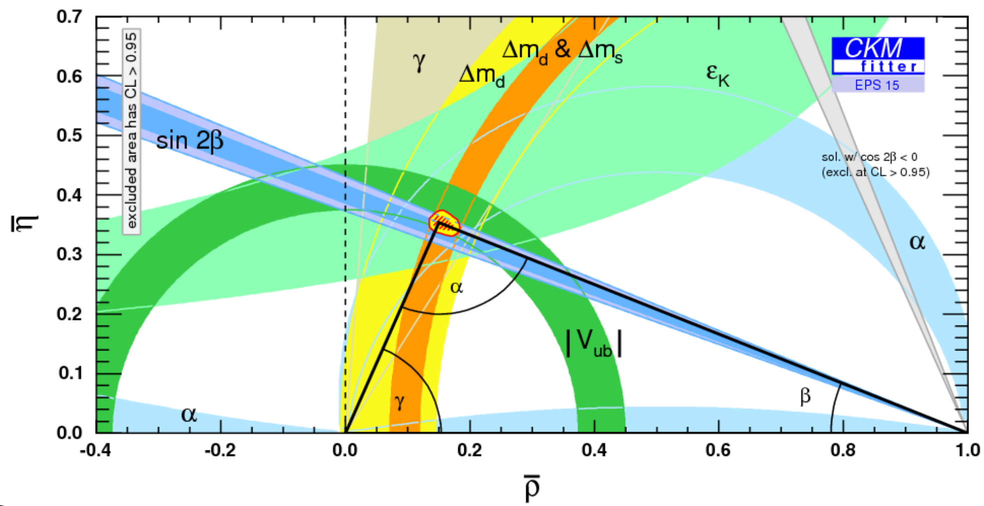


* assuming no New Physics in tree decays

http://ckmfitter.in2p3.fr

γ : indirect & direct determinations

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



Combination of all direct measurements (summer 2015)

$$\gamma = (73.2^{+6.3}_{-7.0})^{\circ}$$

http://ckmfitter.in2p3.fr

Approach from CKM fit excluding all direct measurements of γ

$$\gamma = (66.9^{+0.94}_{-3.44})^{\circ}$$

EPJC (2016) 76 197

Reaching degree level precision from direct measurements is crucial

Uncertainties from LQCD, expect to reduce over the next decade

Several methods to measure γ

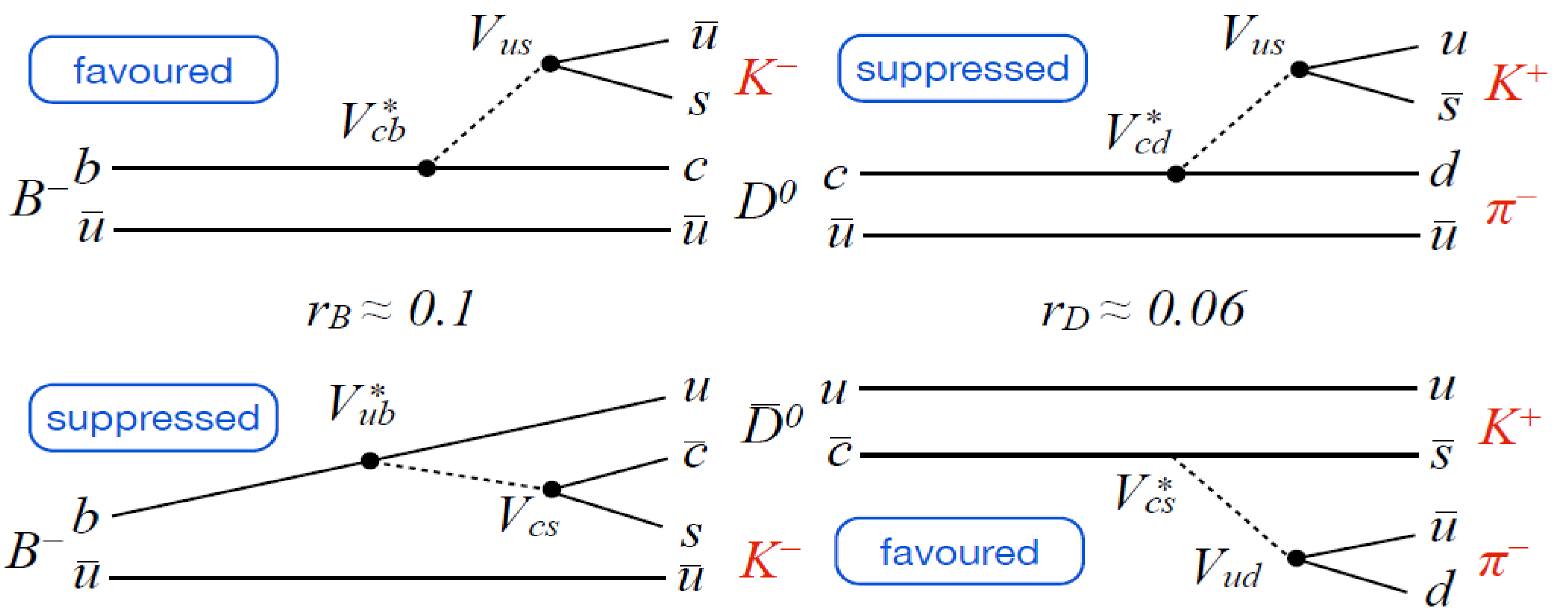
- $B^{\pm}$ (and $\overset{(-)}{B}{}^0$) decays : the "time-integrated", direct CP-violation modes $B^{\pm} \rightarrow \overset{(-)}{D}{}^0 K^{\pm}$
  - GLW — Gronau & London, PLB 253 (1991) 483, Gronau & Wyler PLB 265 (1991) 172
  - ADS — Atwood, Dunietz & Soni PRL 78 (1997) 3257, Atwood, Dunietz & Soni PRD 63 (2001) 036005
  - GGSZ — Giri, Gronau, Soffer & Zupan, PRD 68 (2003) 054018
- $B_s^0 \rightarrow D_s K$ time dependent analysis

Dunietz & Sachs Phys. Rev. D37(1988) 3186,
R. Aleksan, I. Dunietz & B. Kayser, Z. Phys. C54 (1992) 653

The time-integrated mode: $B^- \rightarrow D^0K^-$

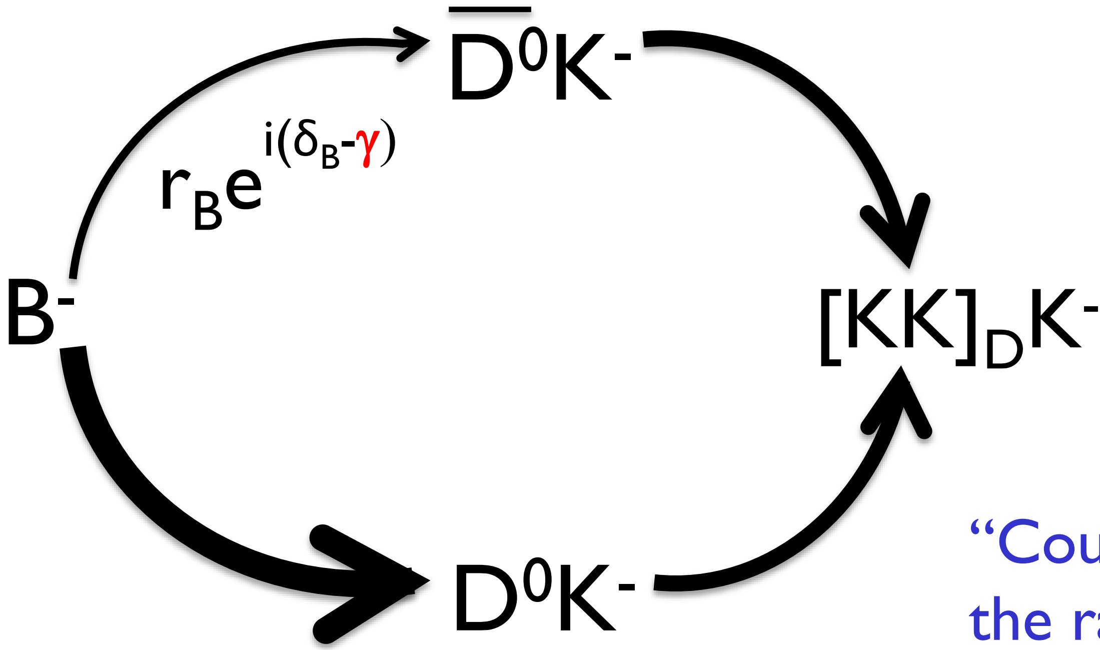
$$\gamma \equiv \arg\left[-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right]$$

(and charge conjugate mode $B^+ \rightarrow \overline{D}^0K^+$)



- Interference possible if $\overline{D}^0$ and D^0 decay to same final state
- Branching fraction for favoured B decay ~10^{-4}
  - Measurements require high statistics

"GLW" method



- Method where D^0 and $\overline{D}^0$ decay to CP eigenstates
- Eigenstates are equally accessible to D^0 and $\overline{D}^0$
- r_B, δ_B hadronic parameters to be determined alongside γ (r_B ~0.1)

"Counting experiment" : observe the rate of B^- vs. B^+ decays

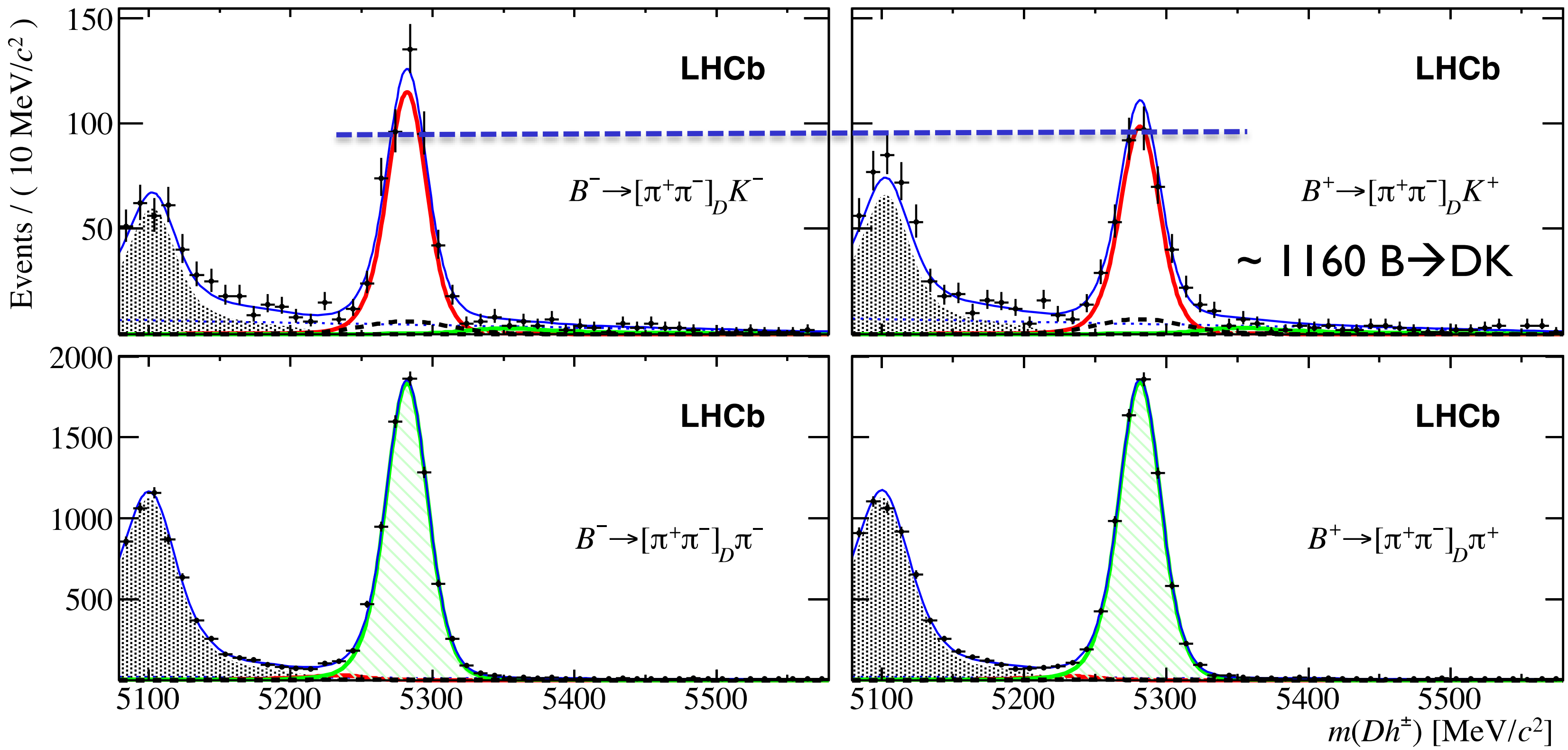
Weak phase changes sign for equiv B^+ diagram, thickness of arrows indicate relative strengths

$$\frac{N(B^-)-N(B^+)}{N(B^-)+N(B^+)} = A_{CP+} = \frac{1}{R_{CP+}} 2r_B(2F_+-1)\sin(\delta_B)\sin(\gamma)$$

$$\frac{N(B\to[KK]_D K)\times\Gamma(D\to K\pi)}{N(B\to[K\pi]_D K)\times\Gamma(D\to KK)} = R_{CP+} = 1+r_B^2+2r_B(2F_+-1)\cos(\delta_B)\cos(\gamma)$$

For CP+ eigenstates e.g KK, π π , $F_+ = 1$; For non CP eigenstates, F_+ measured at CLEO

B→D(π π)h (where h = K, π)



$$A_K^{\pi\pi} = 0.128 \pm 0.037 \pm 0.012$$

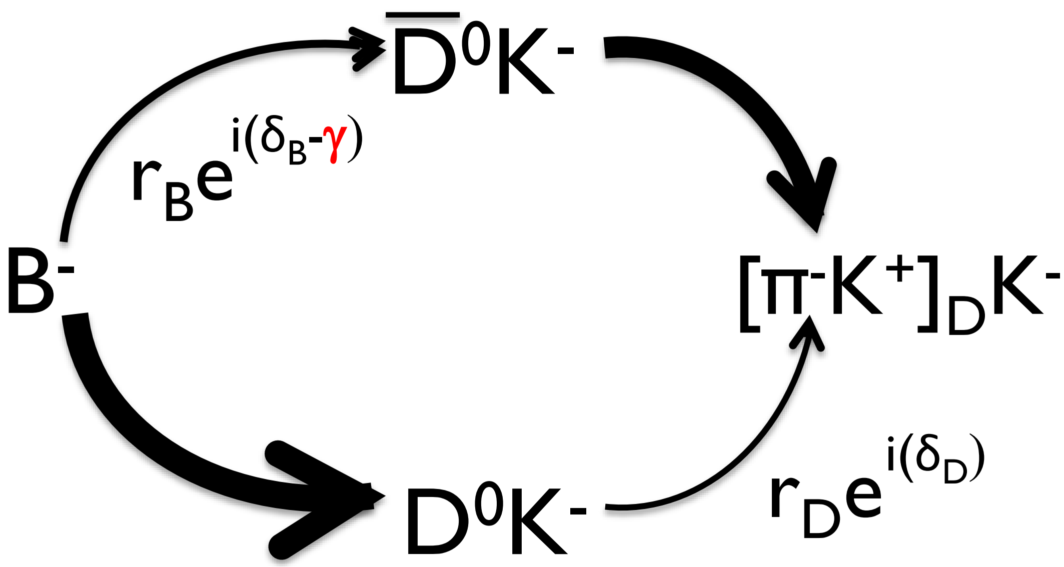
PLB 760 (2016) 117

Combined observation of CP violation

COMBINED (KK, ππ)

5σ

"ADS" method



Weak phase changes sign for equivalent B^+ diagram

- Decay into flavour-specific final states
- Larger interference effects than for GLW as both amplitudes of similar sizes.
- r_B, δ_B hadronic parameters again to be determined alongside γ ($r_B \sim 0.1$)
- Additional two parameters r_D, δ_D. External inputs from charm mixing ($r_D \sim 0.06$)

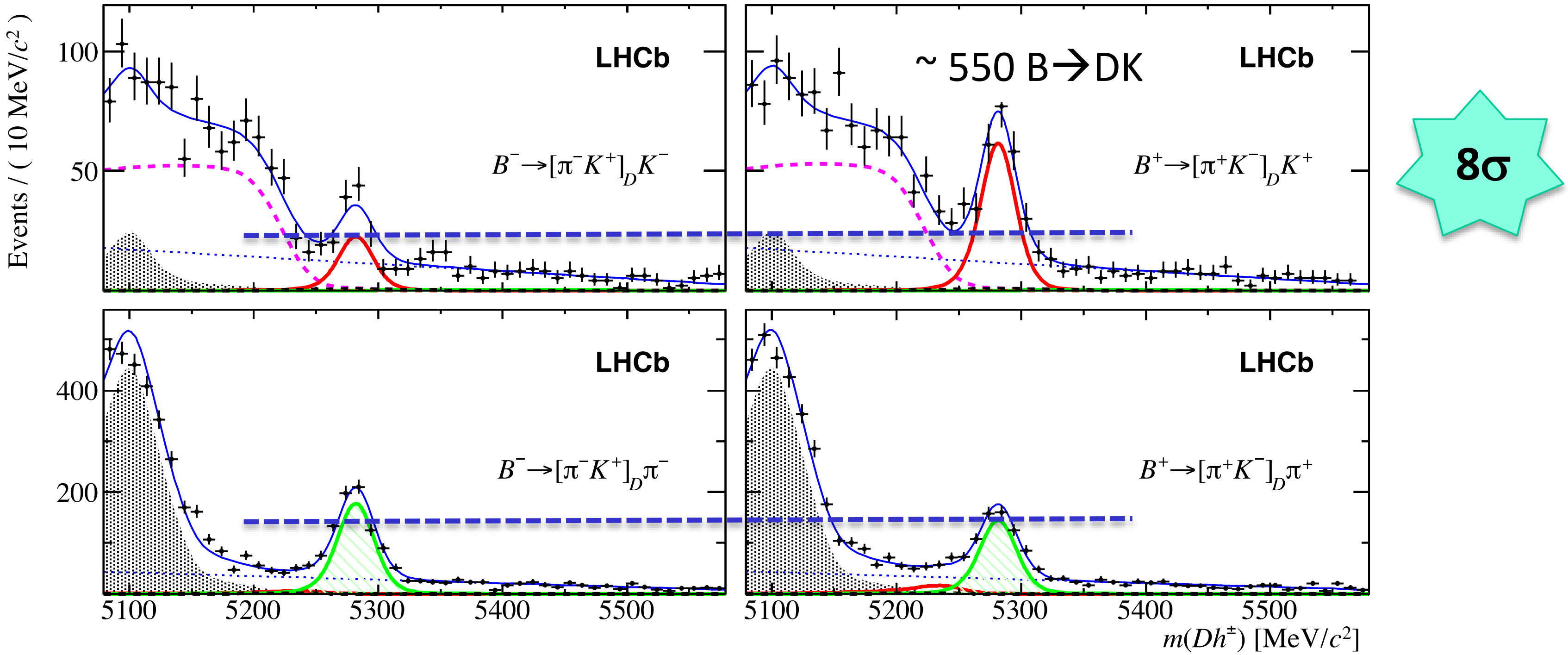
$$\frac{N(B^-)-N(B^+)}{N(B^-)+N(B^+)} = A_{ADS} = \frac{1}{R_{ADS}} 2r_Br_D\sin(\delta_B+\delta_D)\sin(\gamma)$$

$$\frac{N(B^\pm \to [\pi^\pm K^\mp]_D K^\pm)}{N(B^\pm \to [K^\pm \pi^\mp]_D K^\pm)} = R_{ADS} = r_B^2 + r_D^2 + 2r_Br_D\cos(\delta_B+\delta_D)\cos(\gamma)$$

Again, a counting experiment : observing the rate of B^- vs. B^+ decays

B→D(K π)h (where h = K, π)

ADS: Observation of CP violation in B→DK, BF ~10^{-7}



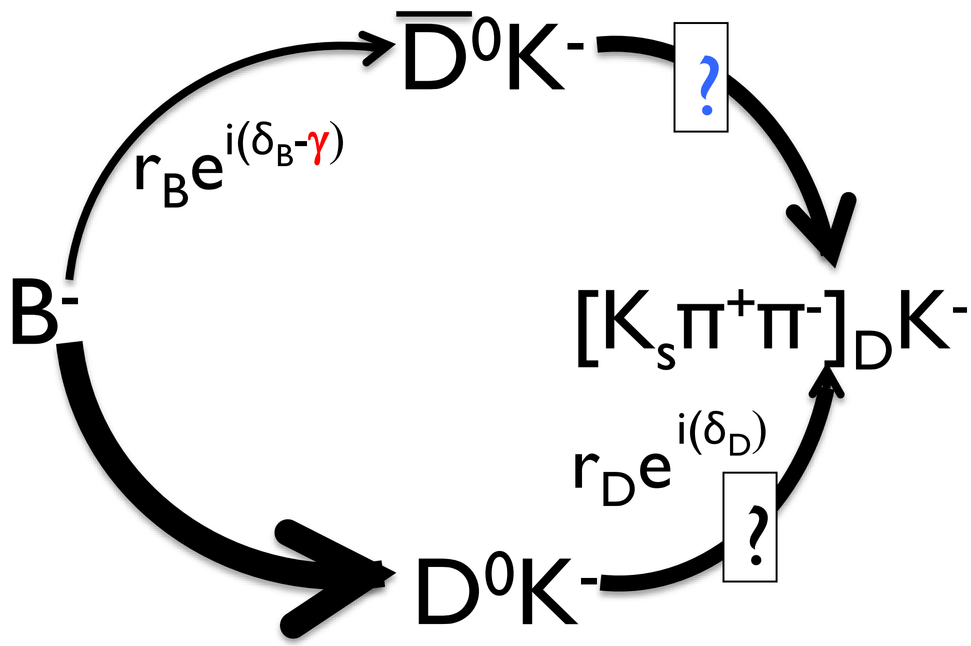
arXiv:1603.08993

$$A_K^{\pi K} = -0.403 \pm 0.056 \pm 0.011$$

$$A_\pi^{\pi K} = 0.100 \pm 0.031 \pm 0.009$$

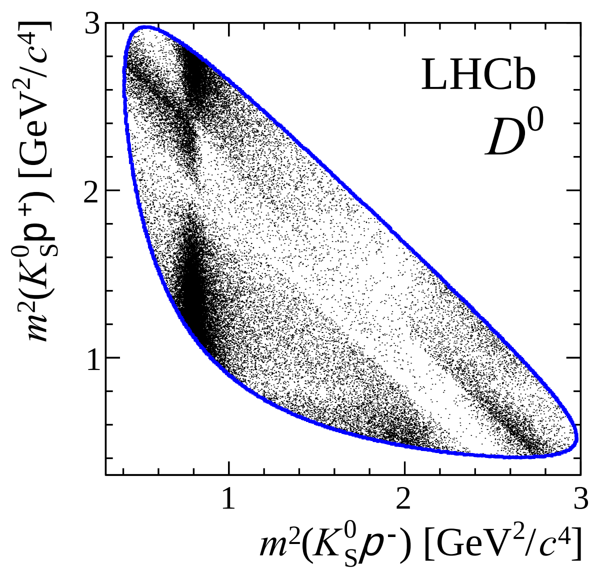
CPV also starts to become visible in B→Dπ : Combined with D→KK D→ππ significance **3.9σ**

"GGSZ" method: Dalitz plot analysis

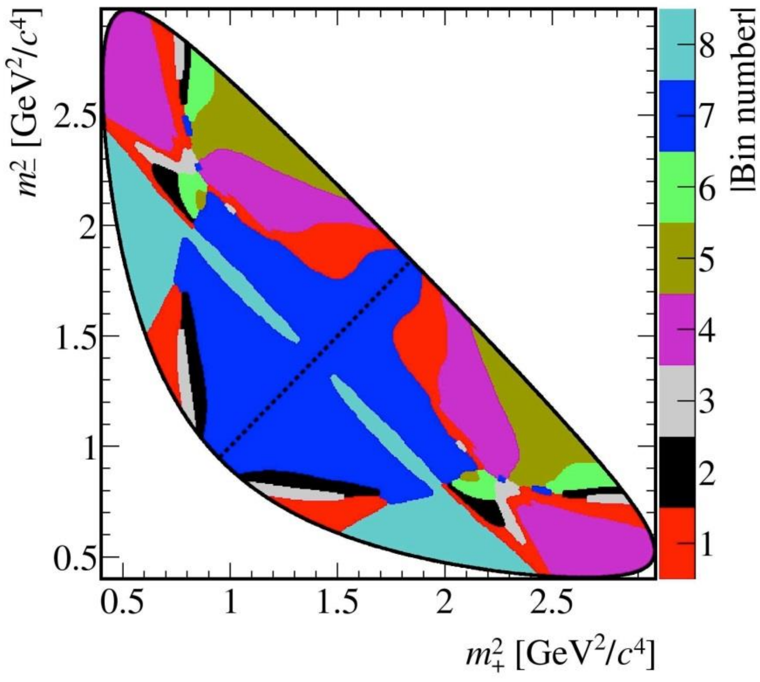


- D decays to multibody final state (>2 particles)
- Value of F_+ for certain self conjugate decays could be ~0.5
- Hence inclusive treatment can lose most of the sensitivity to γ → analyse the Dalitz plot

- Each point on the Dalitz plot represents a different value of r_D and δ_D (and differs between B^+ and B^-)



Model-independent GGSZ analysis



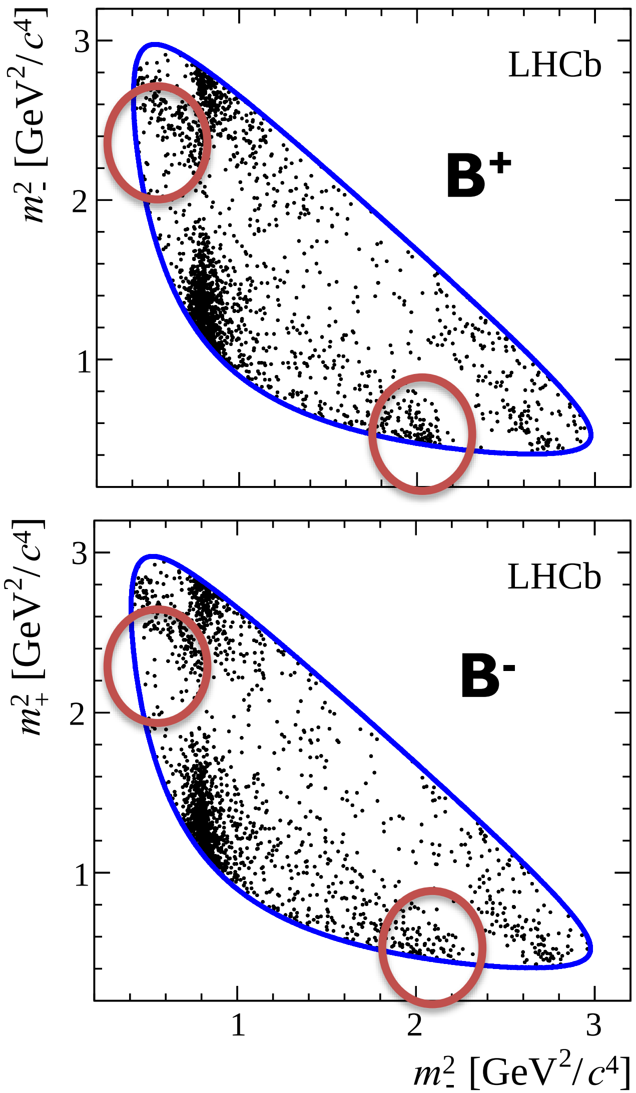
$$x_\pm \equiv r_B \cos(\delta_B \pm \gamma)$$

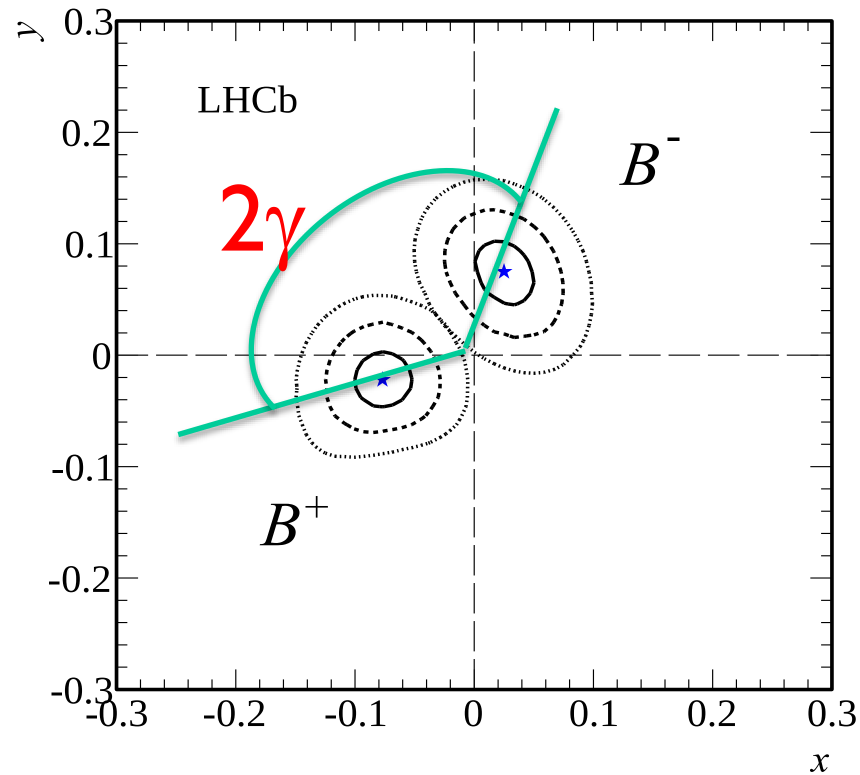
$$y_\pm \equiv r_B \sin(\delta_B \pm \gamma)$$

- Reduces to a counting experiment in bins of Dalitz Plot
- Use CLEO data to measure average values of r_D and δ_D in pre-defined bins PRD 82 (2010) 112006
- Bin definition designed to minimise statistical loss
- Bin yields + strong phase information → measurement of x and y

B→D[$K_s$hh]K via GGSZ

JHEP 10 (2014) 097



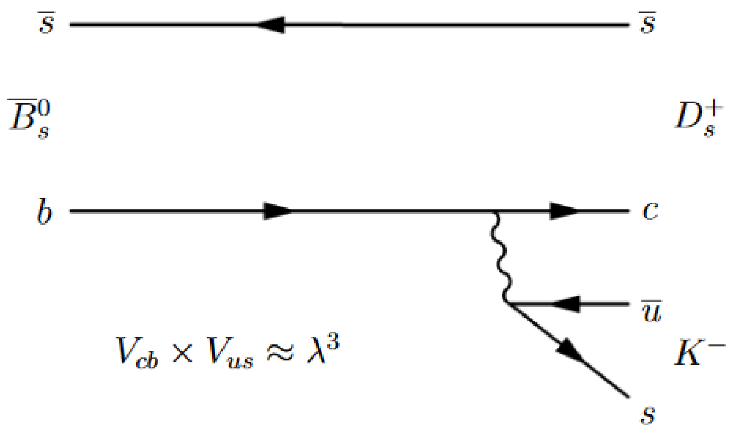


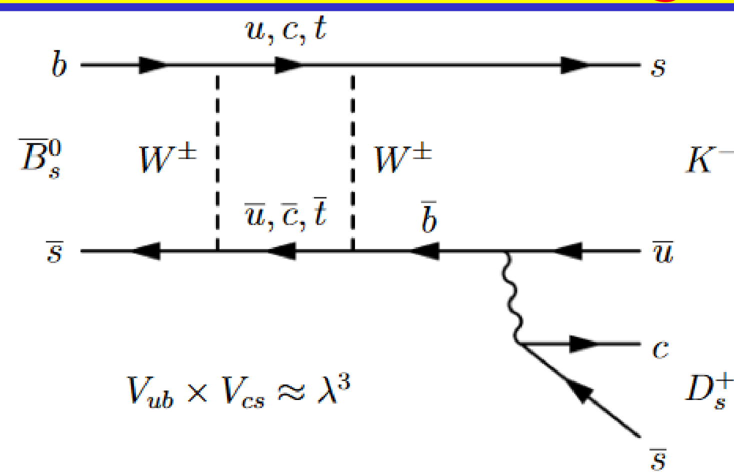
Separation (x_+, y_+) , (x_-, y_-) shows CPV

$K_s\pi\pi$ and K_sKK decay modes used.
Signal yield ~2400

$$\gamma = (62^{+15}_{-14})^\circ$$

Time dependent analysis : $\overline{B}^0 \to D_s^+K^-$





- *Interference* between $\overline{B}^0$ decay to $D_s^+K^-$ directly and via $B^0\,\overline{B}^0$ oscillation gives a CP violating phase

  $\phi = \phi_{Decay} - \phi_{Mixing} = \ (\gamma - 2\beta_S)$

β_S is (small) mixing phase, $\phi_s = -2\beta_S = 0.01 \pm 0.07 \pm 0.01$ (syst) rad.

Phys. Rev. (2013) 112010

$$\frac{d\Gamma_{B_s^0 \to f}(t)}{dt} = \frac{1}{2}|A_f|^2(1+|\lambda_f|^2)e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) + A_f^{\Delta\Gamma}\sinh\left(\frac{\Delta\Gamma_s t}{2}\right) + C_f\cos(\Delta m_s t) - S_f\sin(\Delta m_s t)\right],$$

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

JHEP 11 (2014) 060, Phys. Rev. (2013) 112010

$B^0 \to \bar{D}_s^+ K^-$ continued

JHEP 11 (2014) 060

- Only 1 fb^{-1} of data published so far. The full Run-I 3 fb^{-1} measurement is expected towards the end of this year.

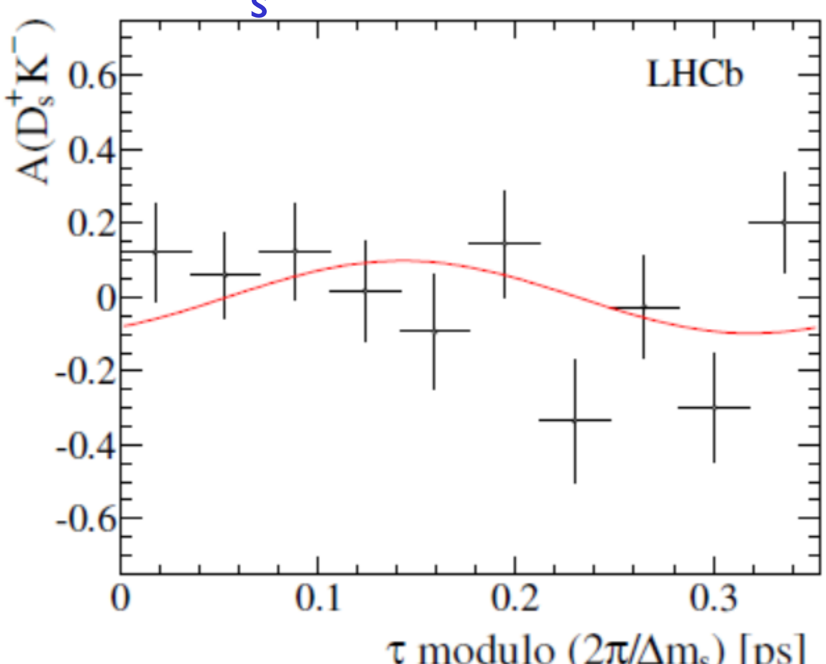
$$A_f^{\Delta\Gamma} = \frac{-2r_{D_sK}\cos(\delta-(\gamma-2\beta_s))}{1+r_{D_sK}^2}, \quad A_{\bar{f}}^{\Delta\Gamma} = \frac{-2r_{D_sK}\cos(\delta+(\gamma-2\beta_s))}{1+r_{D_sK}^2}, \quad C_f = \frac{1-r_{D_sK}^2}{1+r_{D_sK}^2}$$

$$S_f = \frac{2r_{D_sK}\sin(\delta-(\gamma-2\beta_s))}{1+r_{D_sK}^2}, \quad S_{\bar{f}} = \frac{-2r_{D_sK}\sin(\delta+(\gamma-2\beta_s))}{1+r_{D_sK}^2}.$$

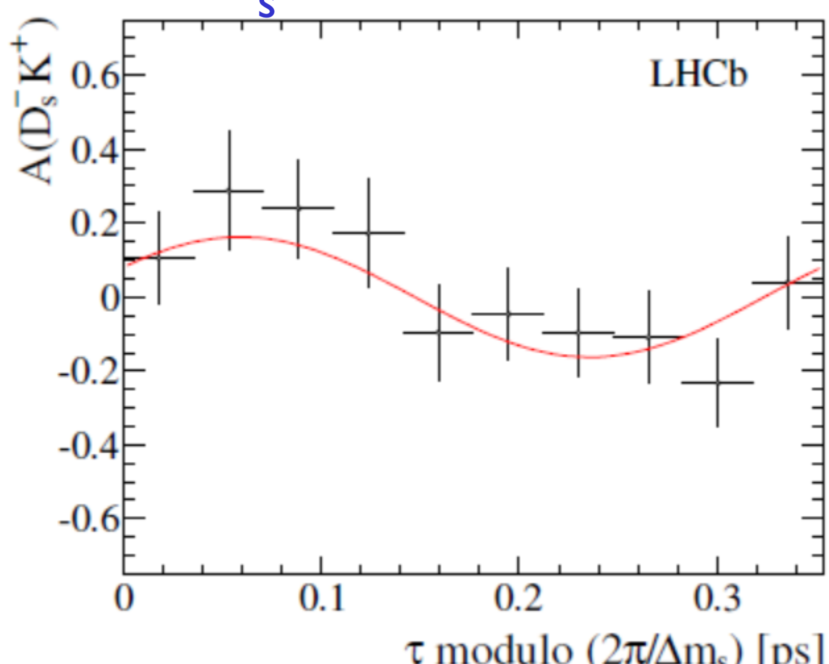
- Measure folded asymmetry distributions:

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

$D^+_s K^-$

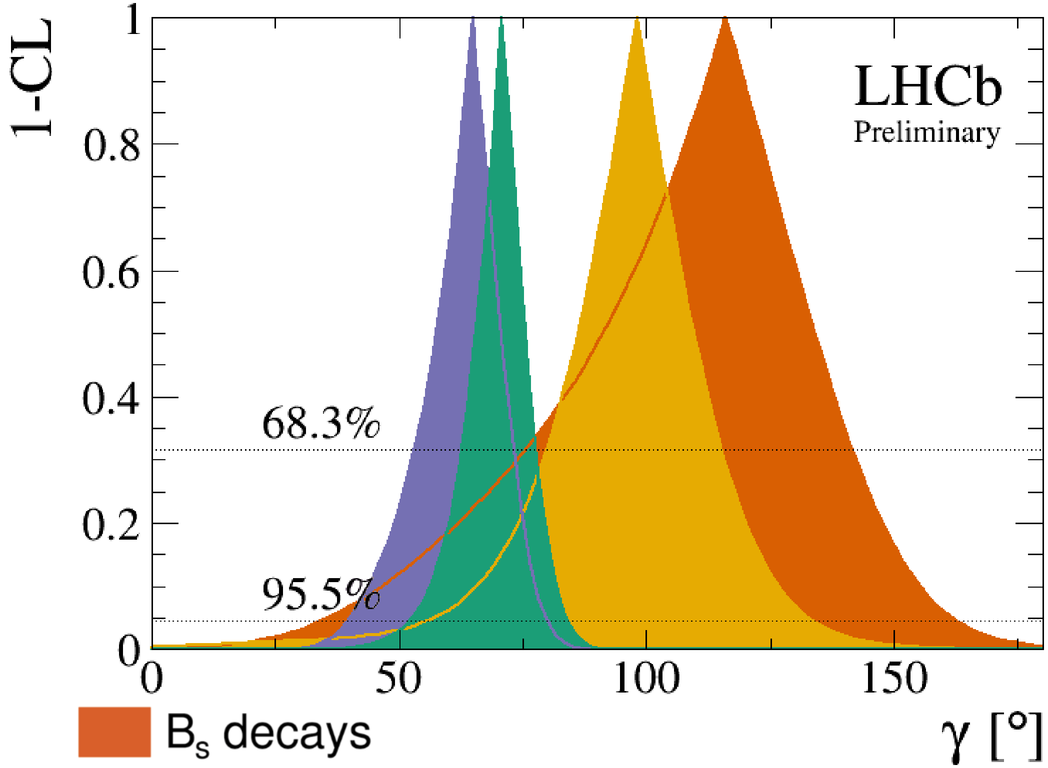


$D^-_s K^+$



Contribution from different modes

LHCb-PAPER-2016-032



$$\gamma = (70.9^{+7.1}_{-8.5})^\circ$$

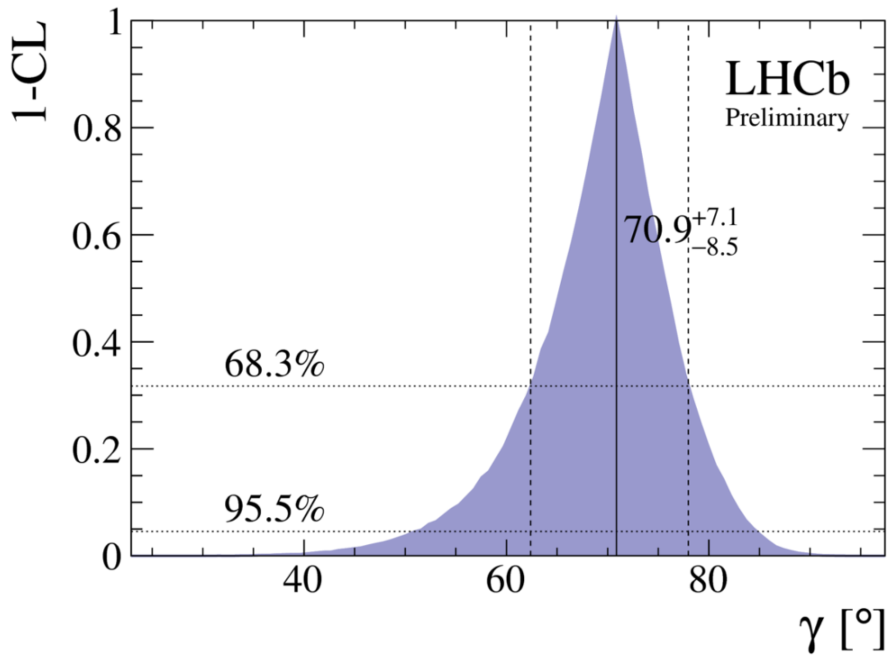
- It is necessary to pursue different B decays to provide crosschecks
- Current measurements are dominated by statistical uncertainties
- Improved precision compared to previous combination by ~20%
- Good agreement with B factory results

BaBar : $\gamma = (69^{+17}_{-16})^\circ$ PRD 87 (2013) 052015

Belle: $\gamma = (73^{+15}_{-14})^\circ$ arXiv:1301.2033

γ prospects : Run 1 → Run 2 → upgrade

- Run 1 target of 8° attained : analyses now mostly complete)
- 2016 data incoming
- Run 2 : target 4° (7-8 fb^{-1})
- LHCb Upgrade : target 0.9° (~50 fb^{-1})



EPJC (2013) 73:2373

Summary and Outlook

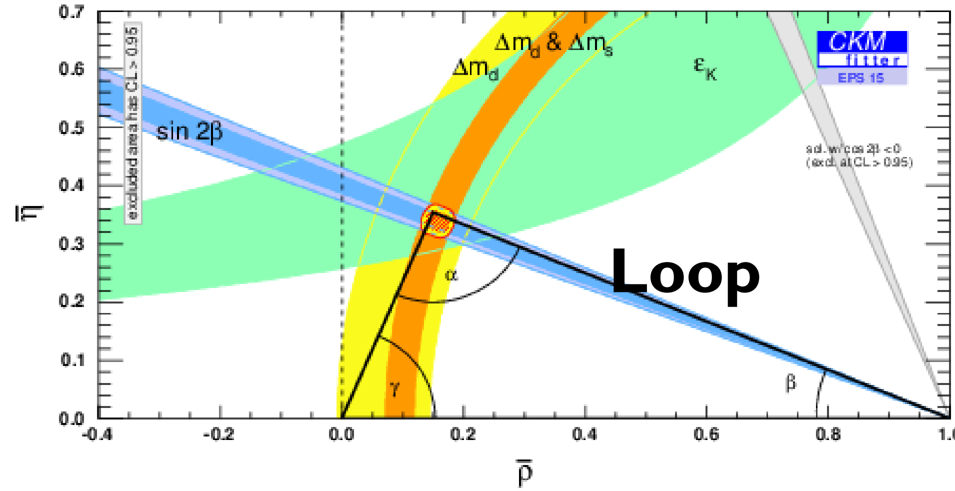
- The LHCb experiment is performing spectacularly well
- So far all UT measurements are in good agreement with the Standard Model
  $\rightarrow$ New physics is becoming constrained in the flavour sector
- Up to 2018 we expect 7-8 fb^{-1} of data, much of this at $\sqrt{s}$ =13 TeV) at ~twice the 8 TeV heavy-flavour production cross-section
- Still much room for new physics, but higher precision required
  $\rightarrow$ preparing for LHCb Upgrade beyond 2020 !

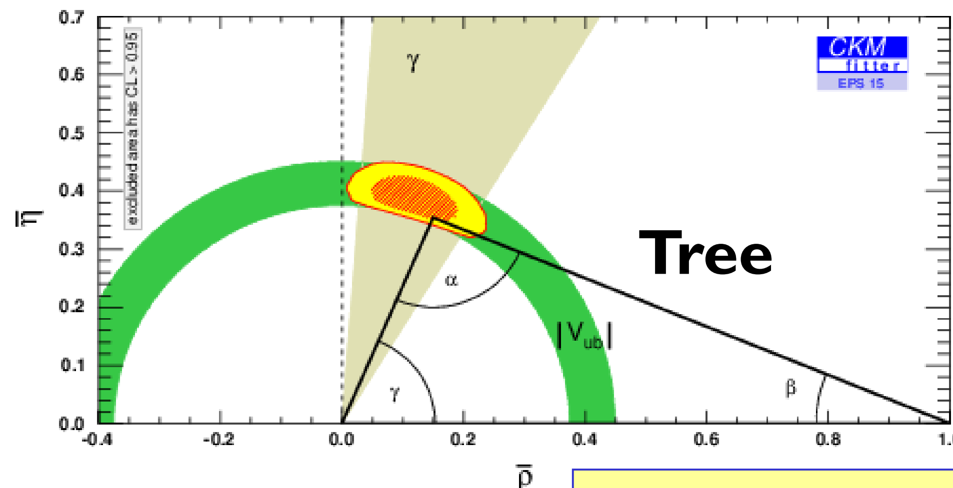
I would like to extend my thanks to Sneha Malde (University of Oxford) in preparing this talk

Spare Slides

Loop vs tree measurements

- Loop processes are sensitive to the presence of New Physics
- Constraints on the triangle apex largely come from loop decay measurements
- Largest uncertainty is on γ, a process accessible at tree level which forms a SM benchmark*





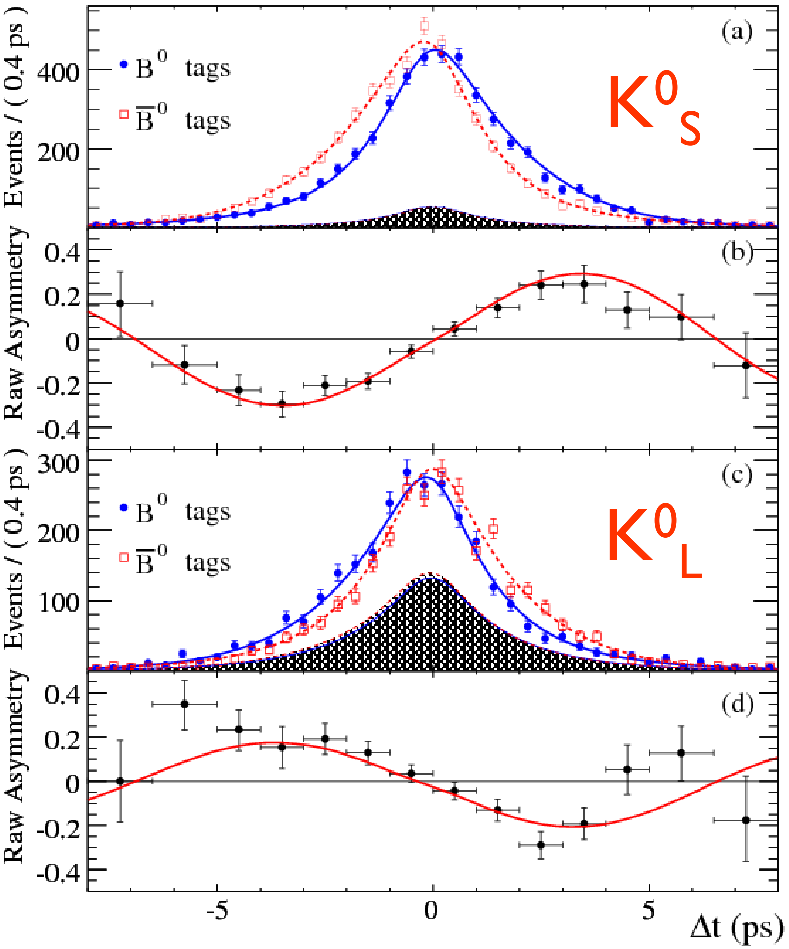
* assuming no New Physics in tree decays

http://ckmfitter.in2p3.fr

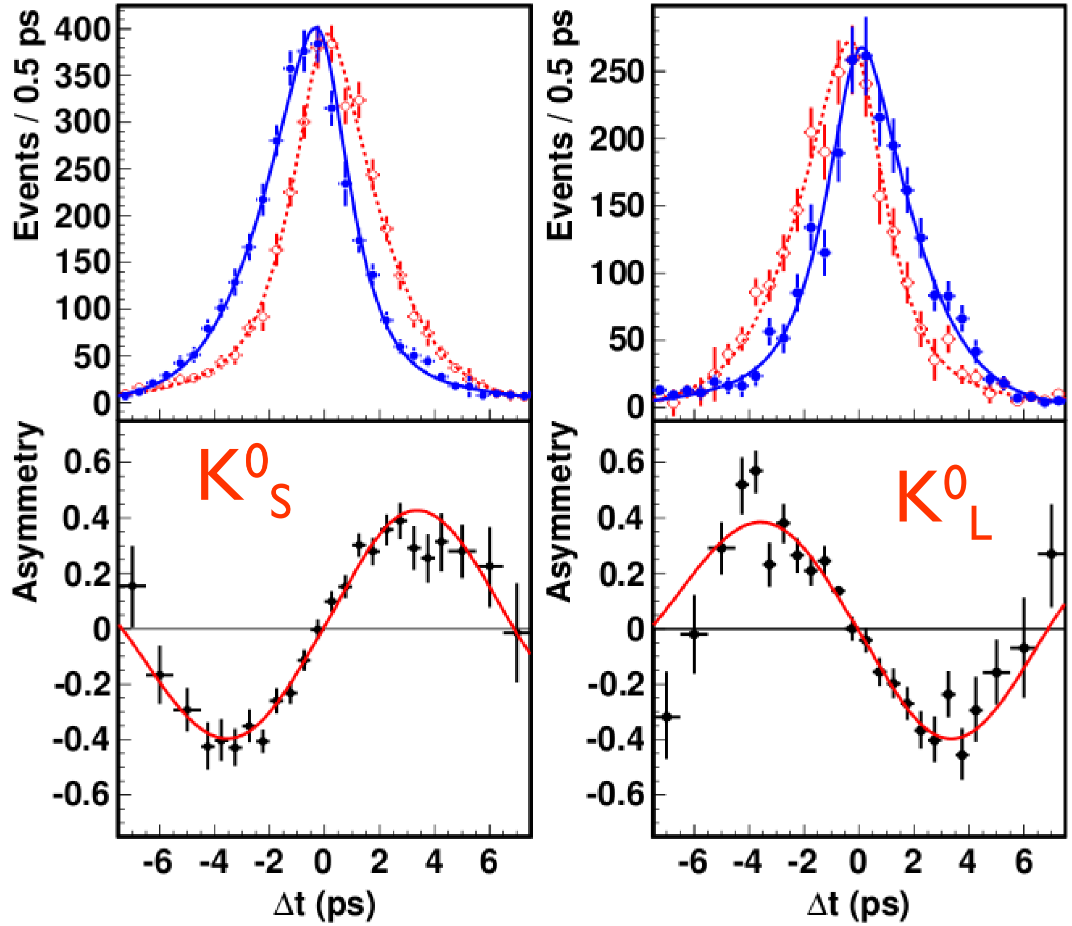
Spectacular results from e^+e^- B factories on CP violation

Large CP violation effects : sin(2β) from $B^0 \rightarrow J/\psi K^0_{S/L}$

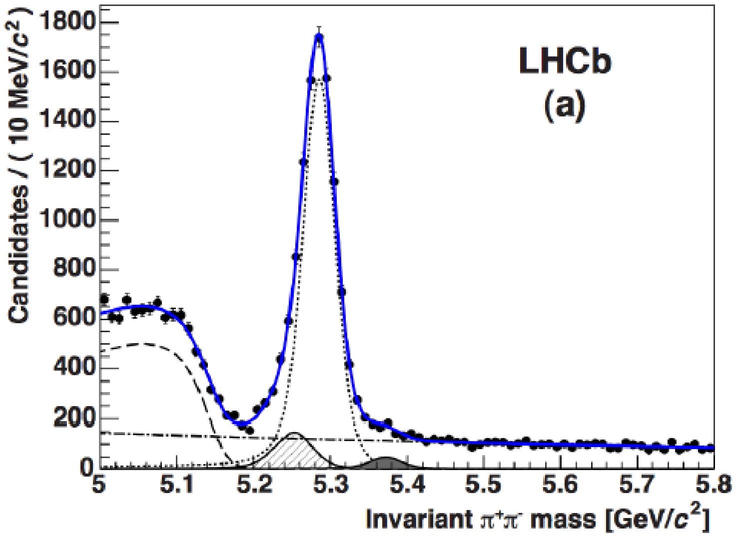
Babar PRD 79 (2009) 072009



Belle PRL 108 (2012) 171802



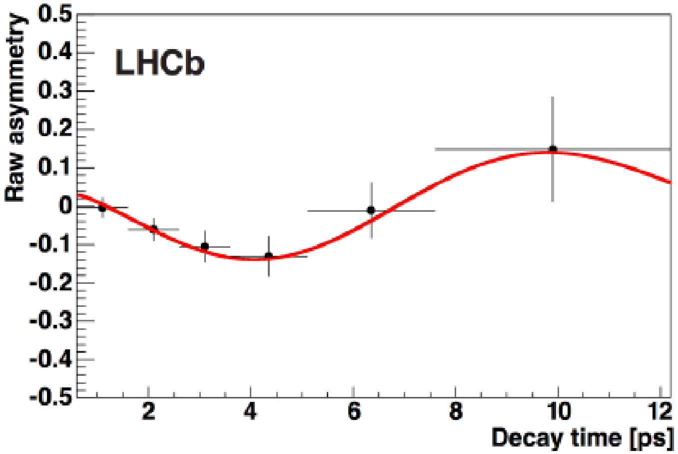
LHCb: CP violation in $B \to \pi^+\pi^-$ & $B_s \to K^+K^-$ (angle α/γ)



- 1 fb^{-1} : ~9000 $B^0 \to \pi^+\pi^-$ events
- First time-dependent CP asymmetry plot of $B^0 \to \pi^+\pi^-$ at a hadron collider

$$C_{\pi\pi} = -0.38 \pm 0.15 \pm 0.02$$ cos term (direct)

$$S_{\pi\pi} = -0.71 \pm 0.13 \pm 0.02$$ sine term (indirect)

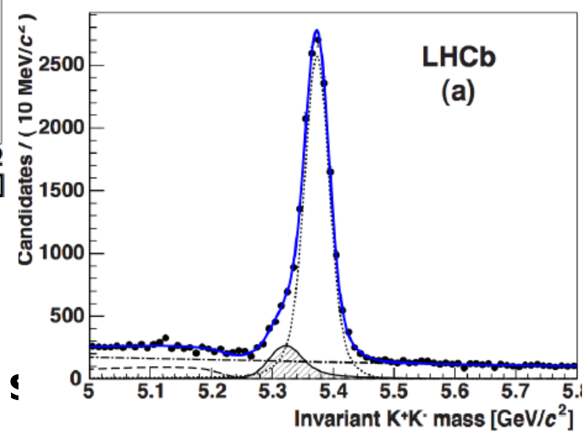


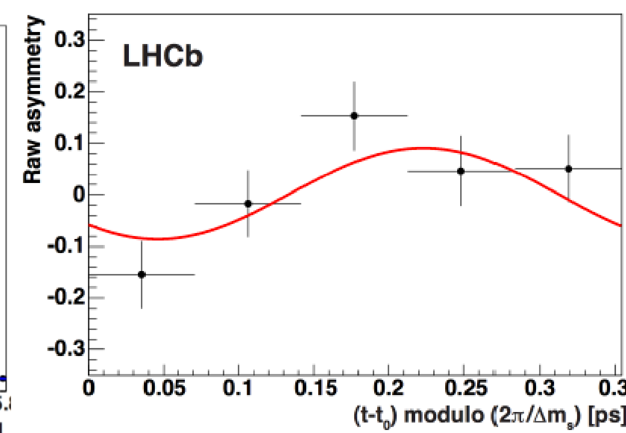
- Also first time-dependent asymmetry seen in $B_s \to K^+K^-$

$$C_{KK} = 0.14 \pm 0.11 \pm 0.03$$

$$S_{KK} = 0.30 \pm 0.12 \pm 0.04$$

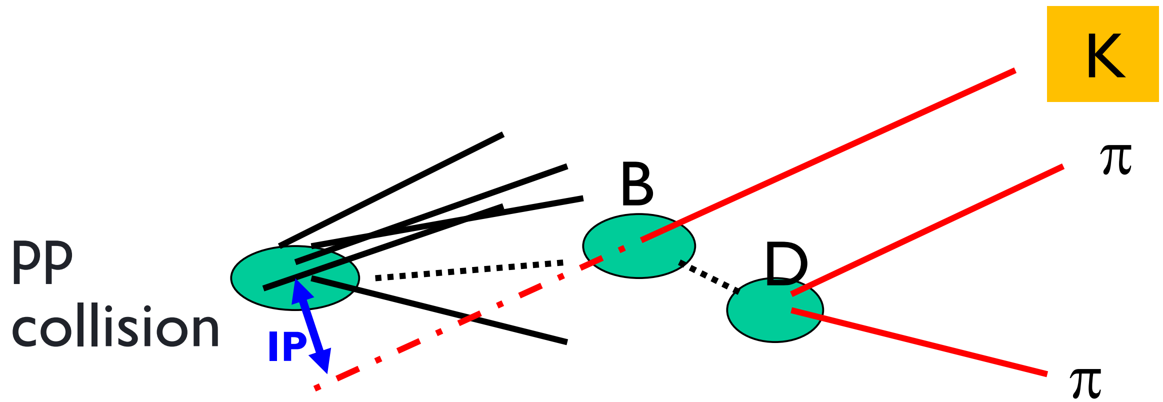
JHEP 10 (2013) 183





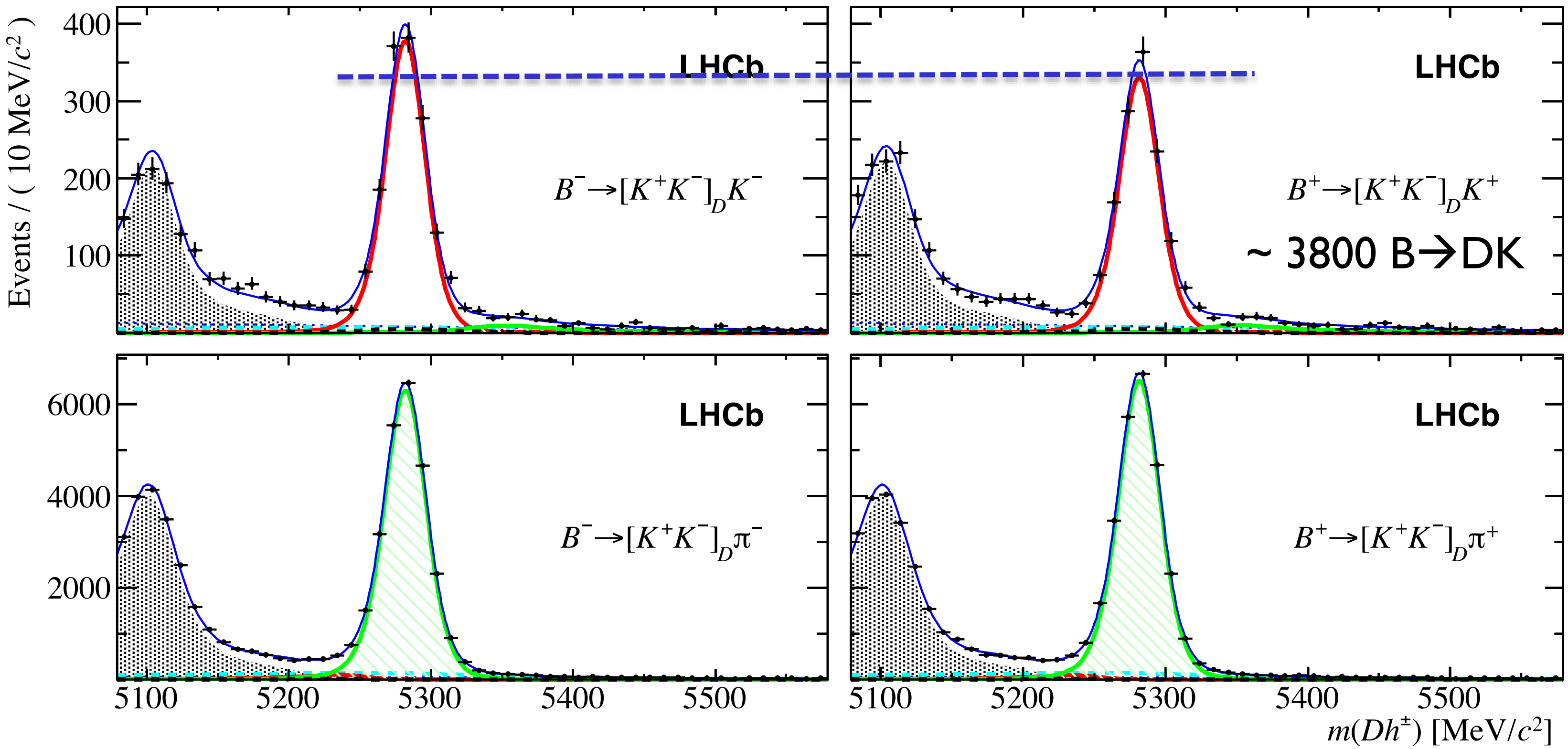
B→ DK event selection

All analyses shown below employ similar strategies



- Need to separate the topology of interest from random combinations
- Use of multi-variate analysis techniques. Useful variables include:
  - Impact parameters
  - Flight distances from primary vertex (B travels ~ a cm)
  - Flight distances from B – removes e.g B→Kππ backgrounds
  - Vertex quality
  - Particle ID
- Specific vetos against particular backgrounds

GLW: $B^- \to D^0 (KK) h^-$ (where h = K, π)



PLB 760 (2016) 117

$$A_K^{KK} = 0.087 \pm 0.020 \pm 0.008$$

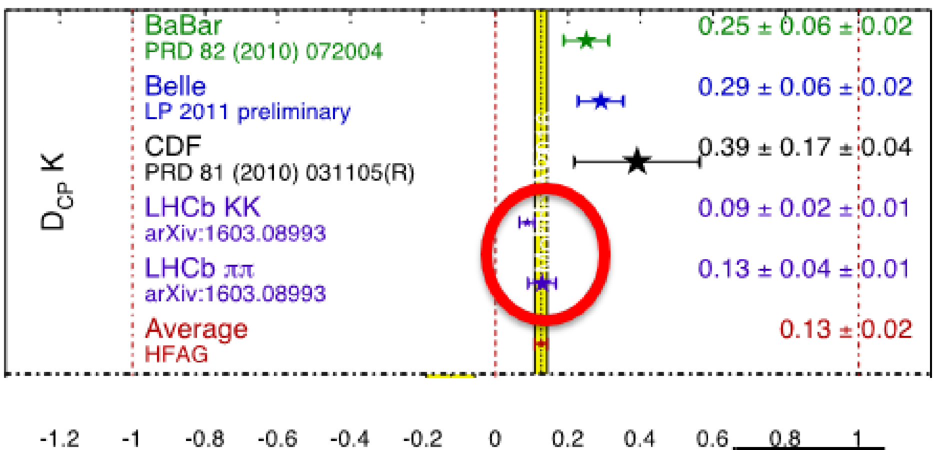
Statistical uncertainty dominant

Description of background is the leading systematic uncertainty

ADS & GLW: comparison of results

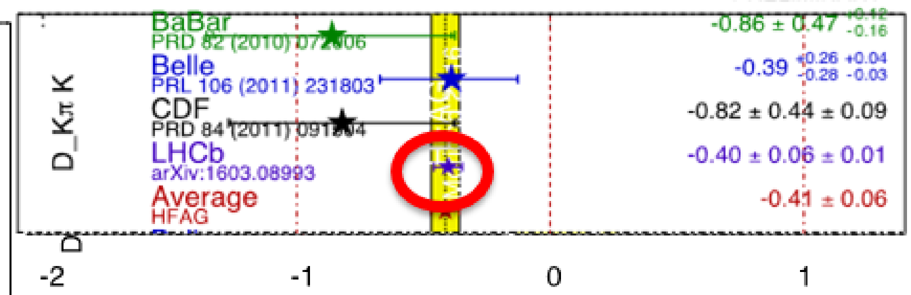
A_{CP+} Averages

HFAG
Moriond 2016
PRELIMINARY



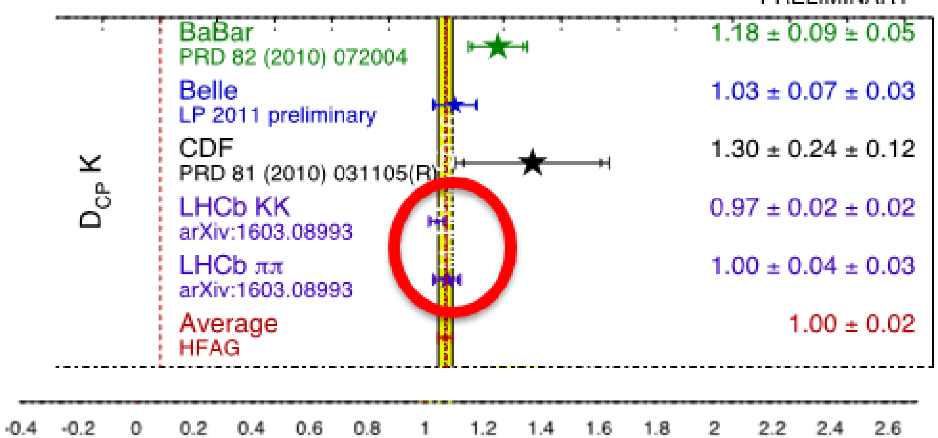
A_{ADS} Averages

HFAG
Moriond 2016
PRELIMINARY



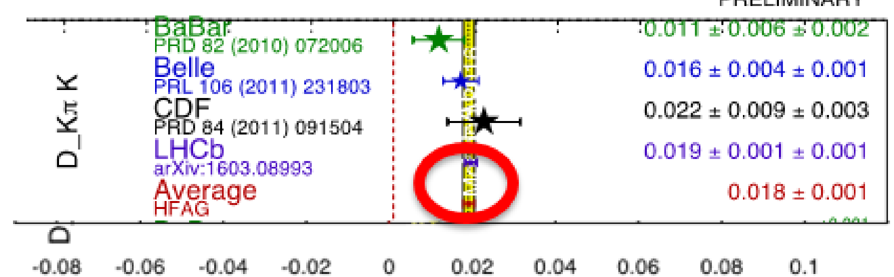
R_{CP+} Averages

HFAG
Moriond 2016
PRELIMINARY



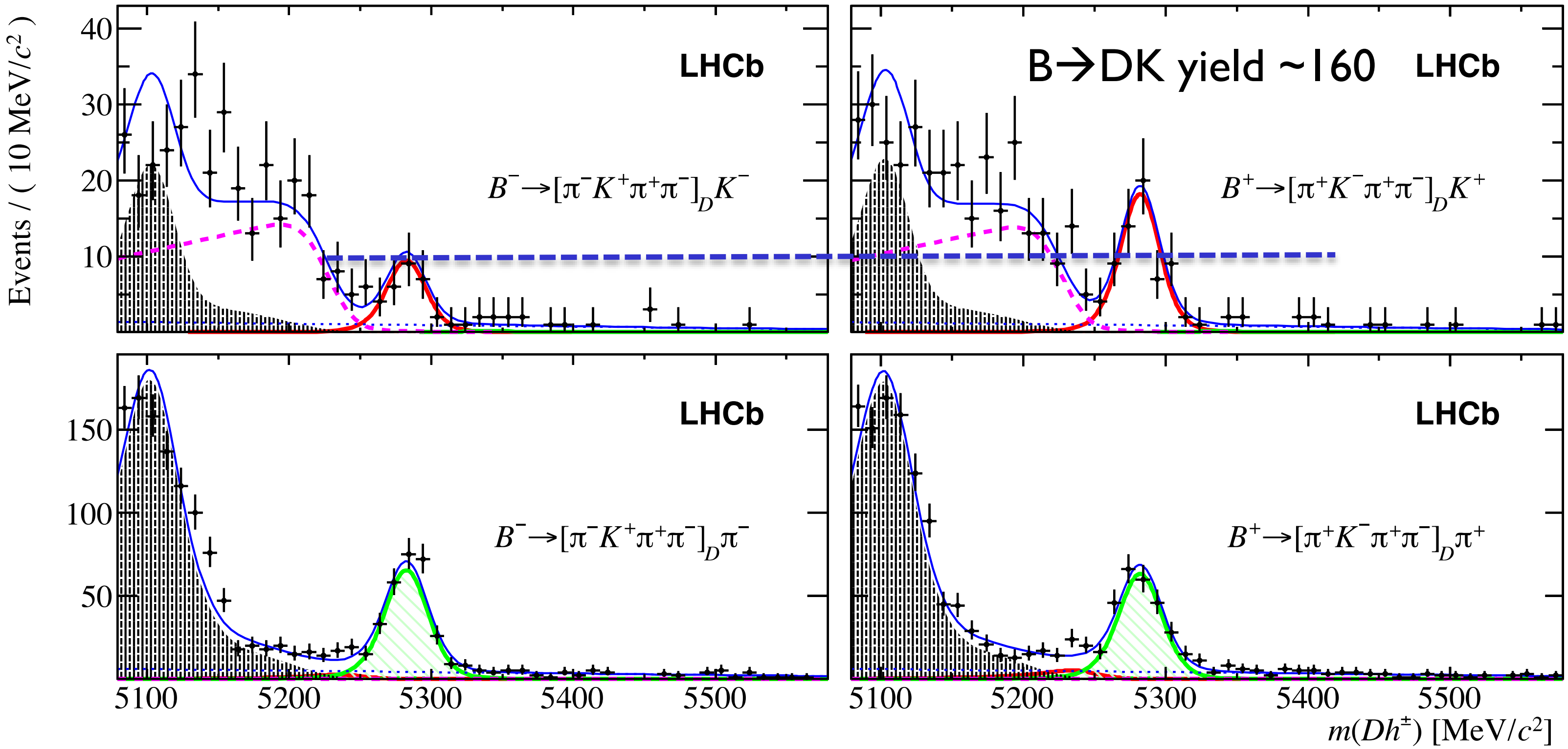
R_{ADS} Averages

HFAG
Moriond 2016
PRELIMINARY



LHCb results dominate world averages

ADS complementary decay : D→K3π



PLB 760 (2016) 117

$$A_K^{\pi K \pi\pi} = -0.313 \pm 0.102 \pm 0.038$$ Relies on CLEO-c input.

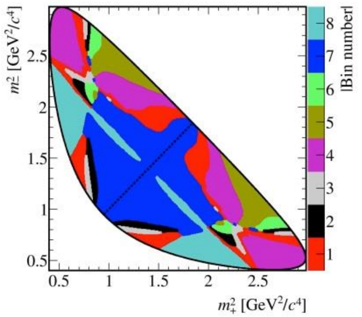
Two methods for accessing D decay information

Two ways to deal with the varying r_D , δ_D

Model dependent

- r_D and δ_D determined from flavour tagged decays (eg Babar/Belle) via amplitude model
- Systematic uncertainties due to model hard to quantify

Model independent

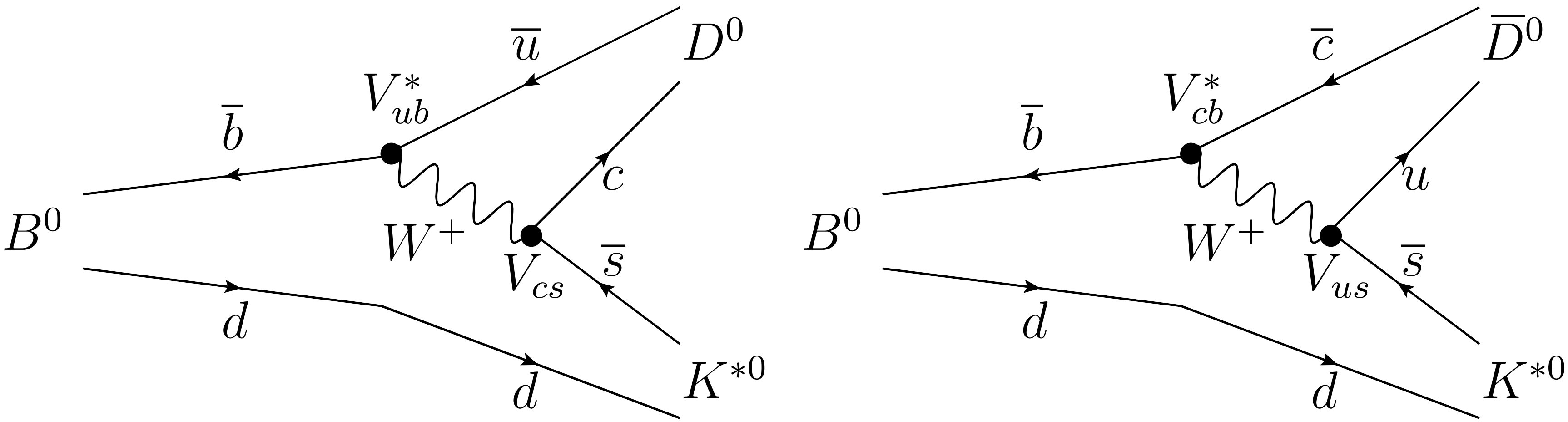


- Use CLEO data to measure average values of r_D and δ_D in pre-defined bins

PRD 82 (2010) 112006

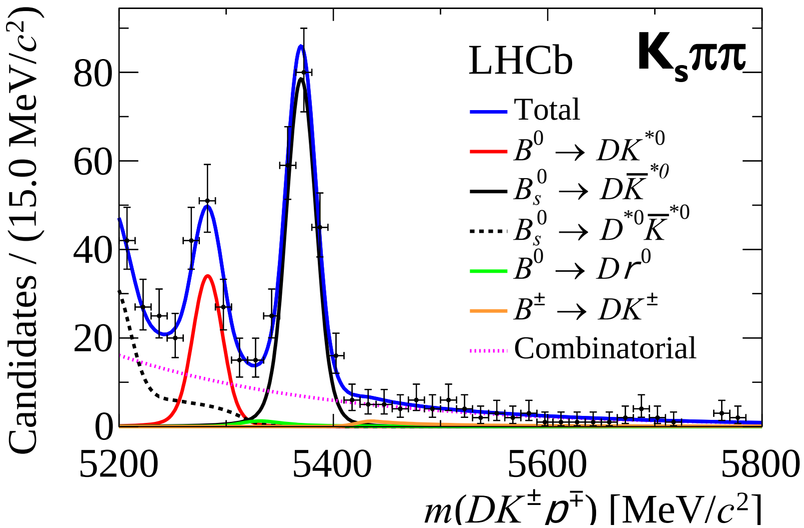
- Direct phase information, uncertainties on which can be propagated

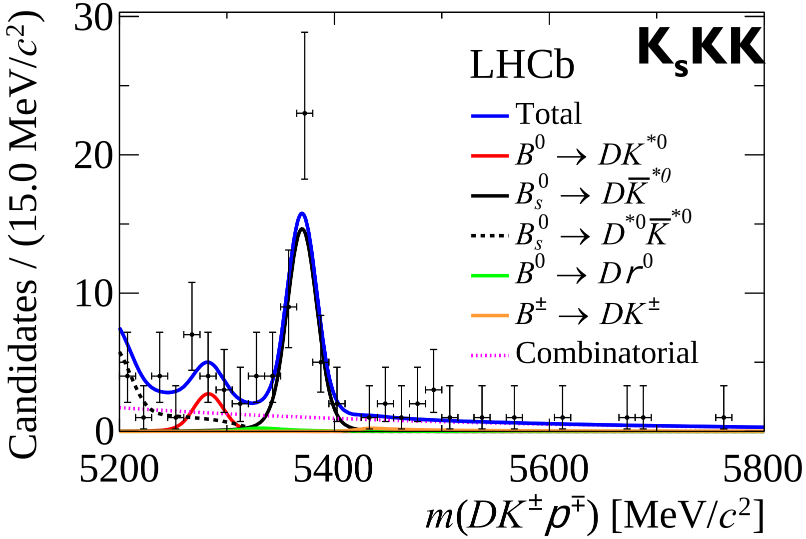
Example of B^0 mode: $B^0 \to DK^*$



- Favoured and suppressed decay both colour suppressed
- $r_B \sim 0.3 \to$ larger interference
- $K^* \to K^+\pi^-$, charge of kaon tags flavour of B at decay
- Yields at LHCb now becoming viable for analysis

Selection of $B^0 \to DK^*$

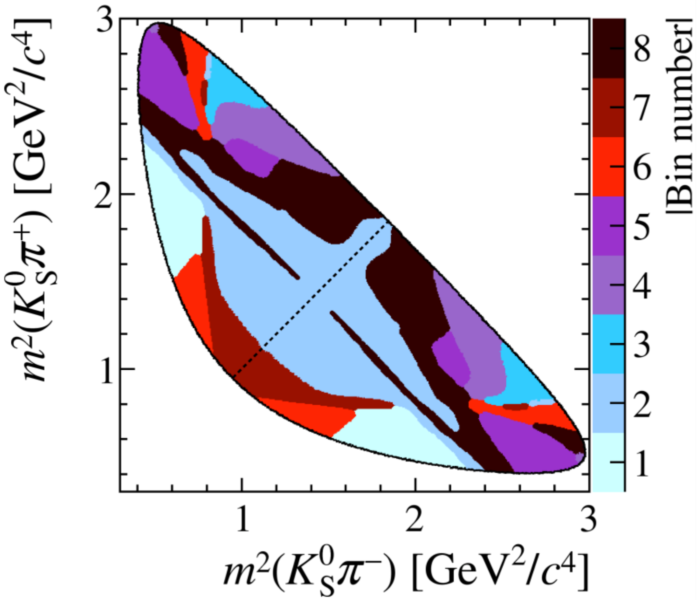


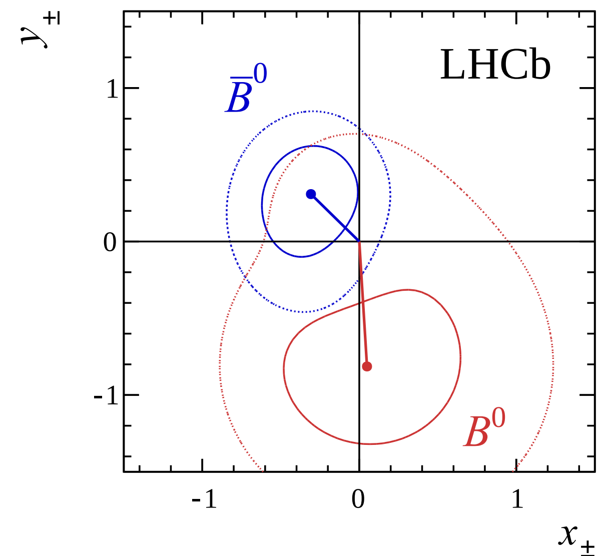


- Yields ~ 90 in $K_s\pi\pi$, (10 in ~K_sKK). Twice yield of B factories.
- Irreducible B_s backgrounds
- Look for differences in the Dalitz plot distributions

JHEP 1606 (2016) 131

GGSZ analysis $B^0 \to DK^*$, $D \to K_S\pi\pi$





JHEP 06 (2016) 131

- Divide Dalitz plot into bins and look at asymmetries in yields
- Measured parameters are again x, y (dependent on γ)
- Input on average strong phases from CLEO used in model independent method (MD gives similar results).

$$x_\pm \equiv r_B \cos(\delta_B \pm \gamma)$$

$$y_\pm \equiv r_B \sin(\delta_B \pm \gamma)$$

$$\gamma = (71 \pm 20)^\circ$$

Combining results from LHCb

LHCb measurement	Type/ Dataset	Reference
$B^+ \to DK^+$ $D \to 2h,4h$	ADS/(q-)GLW ($3fb^{-1}$)	PLB 760 (2016) 117
$B^0 \to DK\pi$	Dalitz ($3fb^{-1}$)	arXiv: 1602.03455
$B^0 \to DK^*$ $D \to Ks\pi\pi$	GGSZ MD ($3fb^{-1}$)	JHEP 1606 (2016) 131
$B^+ \to DK^+$ $D \to hh\pi^0$	ADS/q-GLW ($3fb^{-1}$)	PRD 91(2015) 112014
$B^+ \to DK\pi\pi$, $D \to 2h$	ADS/GLW ($3fb^{-1}$)	PRD 92 (2015) 112005
$B^0 \to DK^*$ $D \to 2h$	ADS ($3fb^{-1}$)	PRD 90 (2014) 112002
$B^+ \to DK$ $D \to K_s hh$	GGSZ MI ($3fb^{-1}$)	JHEP 10 (2014) 097
$B^+ \to DK$, $D \to KsK\pi$	ADS ($3fb^{-1}$)	PLB 733 (2014) 36
$B_s \to D_s K$, $D_s \to hhh$	Time dep ($1fb^{-1}$)	JHEP 11 (2014) 060

Results new or updated since last combination (2014)

New results from 2015

Other $B \to DK$ 'like' results completed in 2014

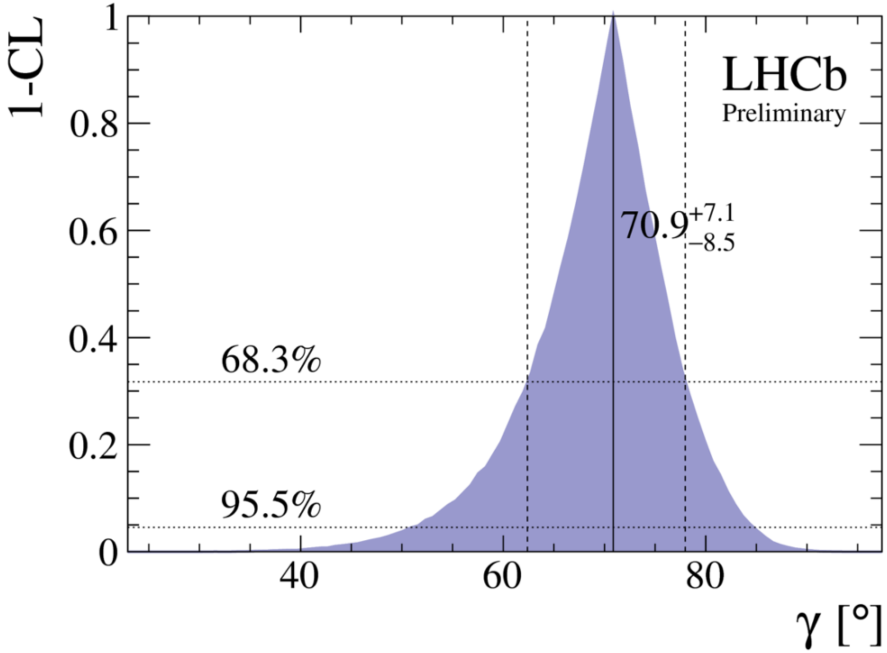
LHCb-PAPER-2016-032

Combining results : other inputs

Parameters	Source	Reference
Charm mixing and CPV in $D \rightarrow hh$	HFAG	www.slac.stanford.edu/xorg/hfag/charm/index.html
κ, δ_D: $D \rightarrow K3\pi$, $D \rightarrow K\pi\pi^0$	LHCb & CLEO data	PLB 757 (2016) 520
κ, δ_D : $D \rightarrow K_s K\pi$	CLEO data	PRD 85 (2012) 092016
CP fraction $D \rightarrow 4\pi$, $D \rightarrow hh\pi^0$	CLEO data	PLB 747 (2015) 9
Strong phase information for $D \rightarrow K_s hh$	CLEO data	PRD 82 (2010) 112006
Constraint on ϕ_s	LHCb data	PRL 114 (2015) 041801

LHCb combination results

LHCb-PAPER-2016-032



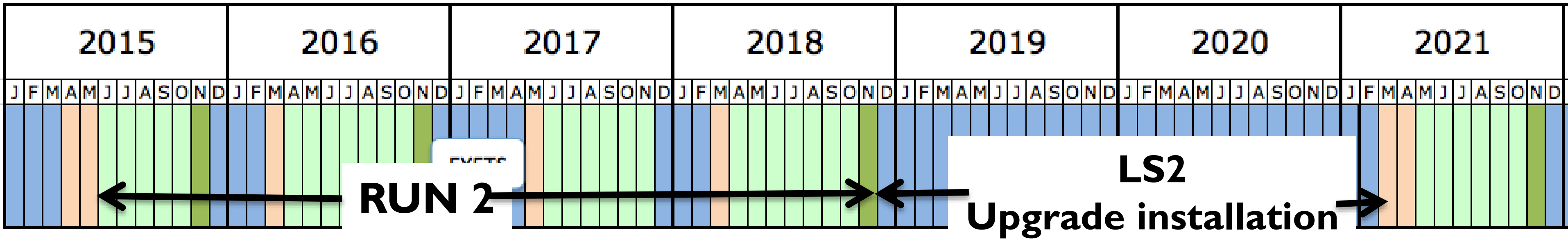
$$\gamma = (70.9^{+7.1}_{-8.5})^{\circ}$$

- Frequentist combination : 71 observables and 32 parameters (Bayesian interpretation is consistent)
- Improved precision compared to previous combination by ~20%
- Good agreement with B factory results

BaBar : $\gamma = (69^{+17}_{-16})^{\circ}$ PRD 87 (2013) 052015

Belle: $\gamma = (73^{+15}_{-14})^{\circ}$ arXiv:1301.2033

γ and the LHCb upgrade



- Full upgrade in LS2
- Run at higher luminosity from 2021 onwards
  (~4 x 10^{32} $cm^{-2}s^{-1}$ → 2 x 10^{33} $cm^{-2}s^{-1}$)
- L0 hardware trigger → software trigger
  - Increase efficiency for hadronic modes
- External inputs will benefit from BES-III data

LHCb upgrade projection (50 fb^{-1}) for γ is 0.9°

EPJC (2013) 73:2373

This precision will pin down all UT parameters : and hopefully New Physics