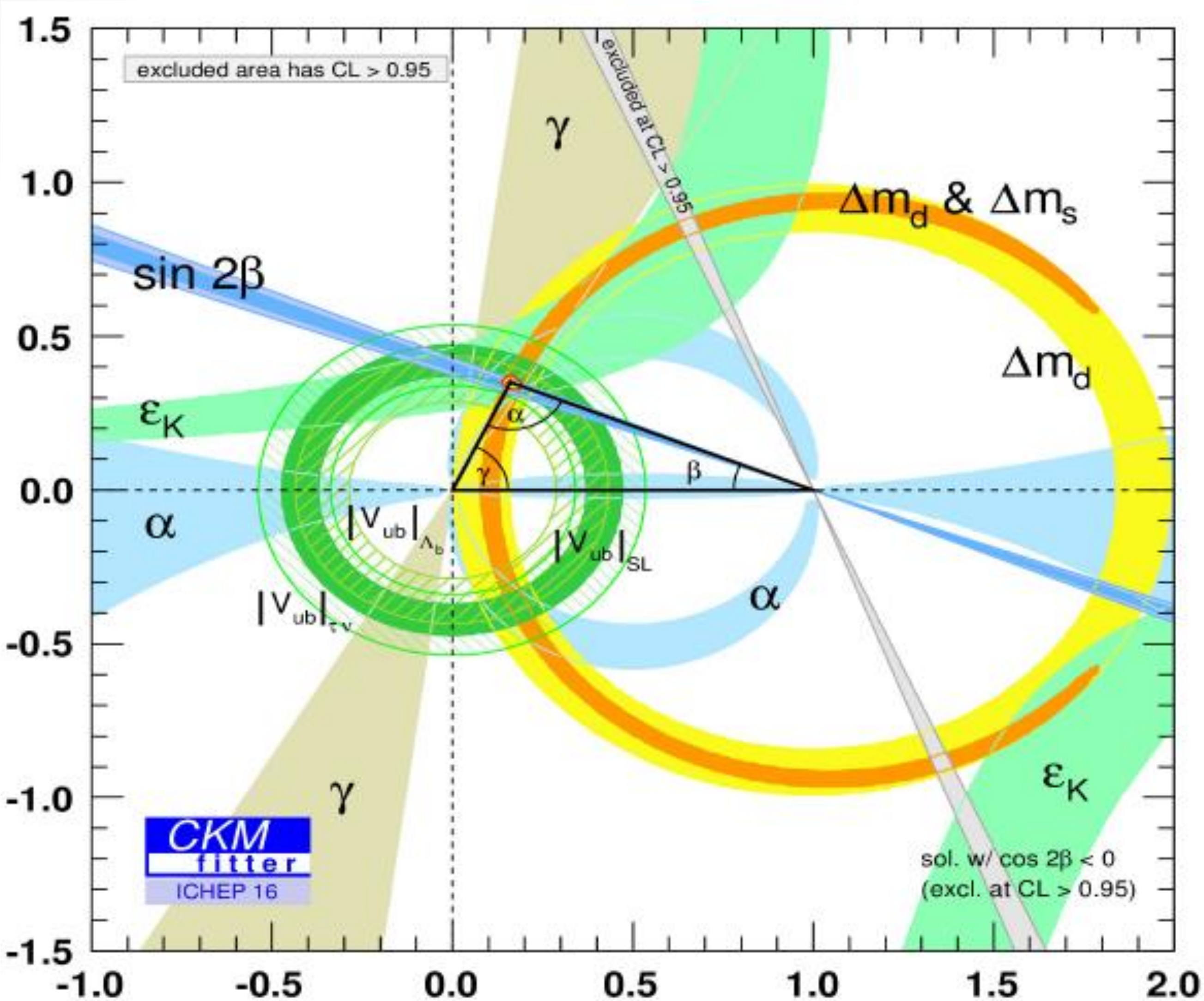
Measurements of the CKM Unitarity Triangle Angles

Jim Libby (Indian Institute of Technology, Madras)

Overview

- Introducing the triangle
- The experiments and datasets
  - BABAR/Belle
  - LHCb
- The measurements
  - Angles
  - Sides
    - Of interest but improvements largely theoretical rather than experimental
    - Omit in the interests of time
  - Other triangles
- Outlook



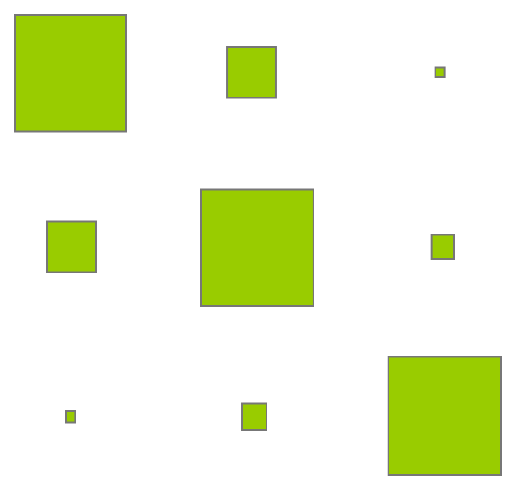
CPV IN THE STANDARD MODEL

CKM matrix

$$(u \quad c \quad t)\begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix}\begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

- Extension of Cabibbo's two by two mixing matrix
  - Kobayashi and Maskawa proposed third generation to explain observed CP violation in kaon decays
- 3 × 3 unitary complex matrix
  - 4 parameters
  - 3 mixing angle and 1 phase
- Intergenerational coupling disfavoured

Relative magnitude of elements



Responsible for CP violation

Wolfenstein parametrisation – the path to the triangle

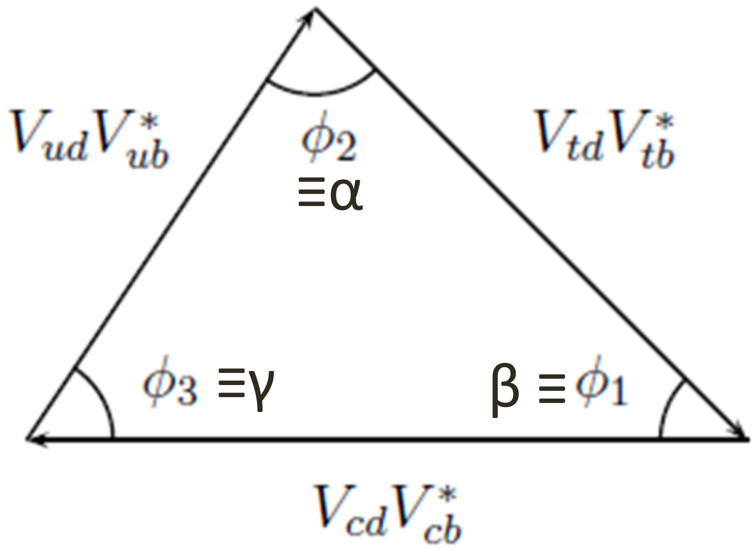
1)
$$\begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3\left[1-(\rho+i\eta)\right] & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

$$\lambda = \sin\theta_C$$

2) Exploit unitarity (1st and 3rd col.)

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

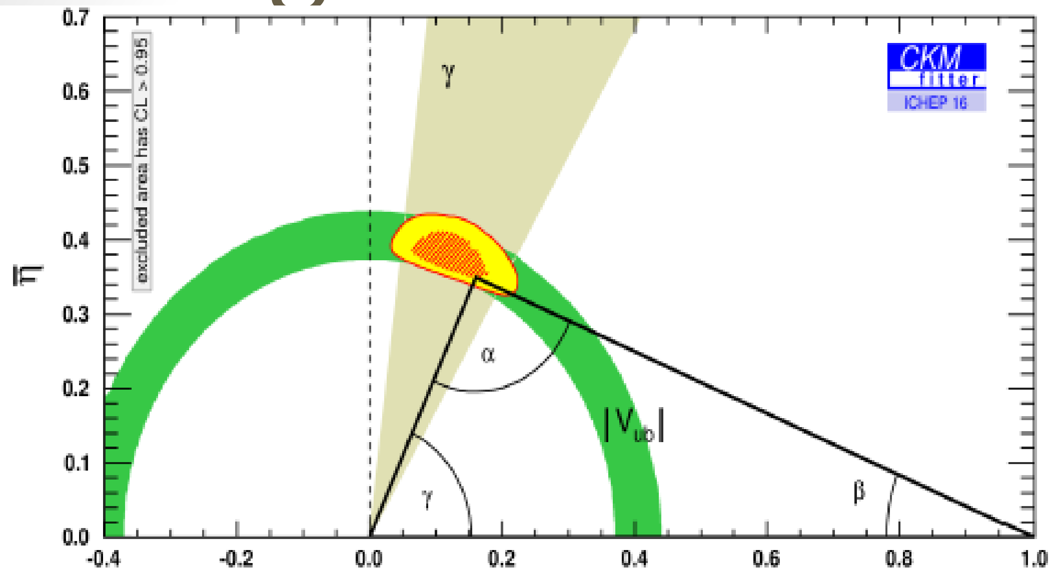
3)



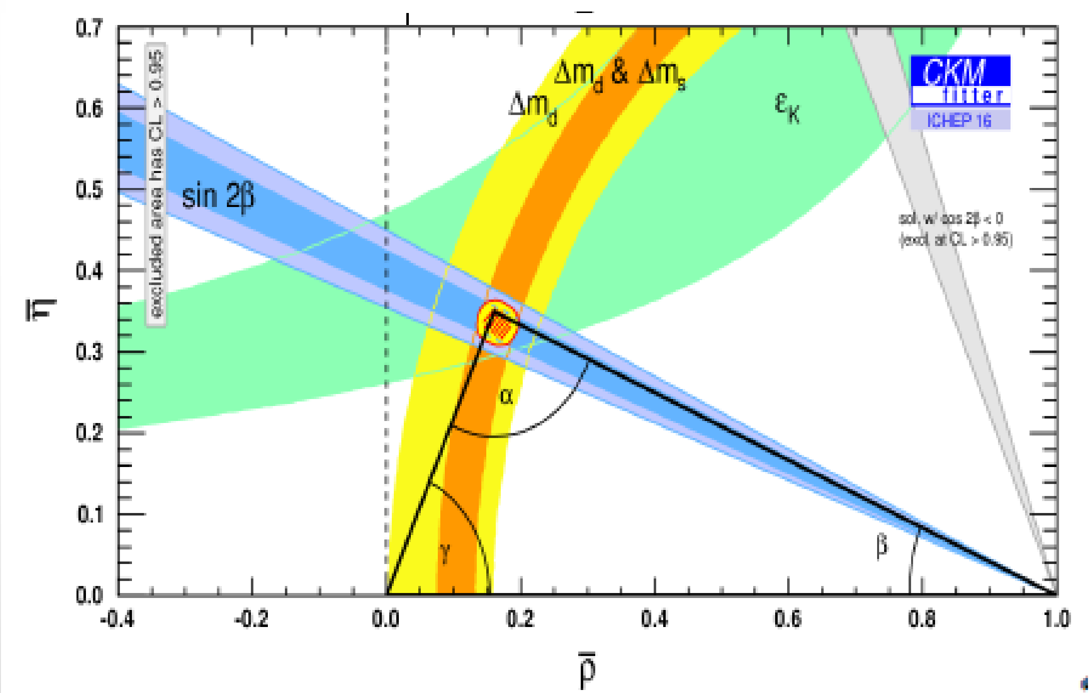
$$\phi_1 = \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right)$$

$$\simeq \arg\left(\frac{1}{1-\rho-i\eta}\right)$$

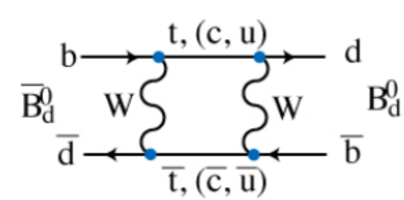
The goal: over constraint



Tree level only



Loop-level only

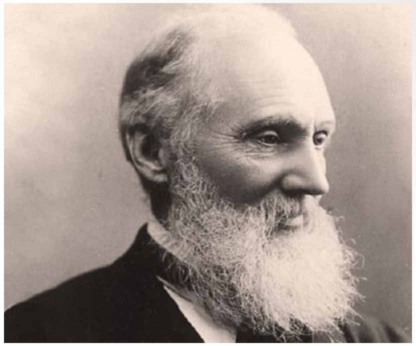


NP at O(>TeV)?

The context of flavour

- Overconstraint of Unitarity Triangle is an important **indirect** test of the SM
- This is an intensity frontier pursuits
- Complements searches at the energy frontier……

The context of flavour



- Overconstraint of Unitarity Triangle is an important test of the SM
- This is an intensity frontier pursuits
- Complements searches at the energy frontier……

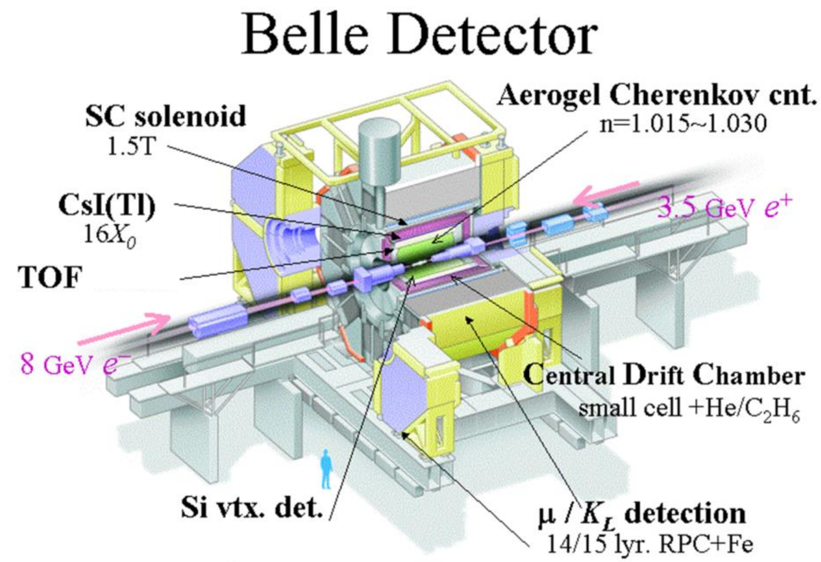
- "Accurate and minute measurement seems to the non-scientific imagination, a less lofty and dignified work than looking for something new. But [many of] the grandest discoveries of science have been but the rewards of accurate measurement and patient long-continued labour in the minute sifting of numerical results", Lord Kelvin, 1872

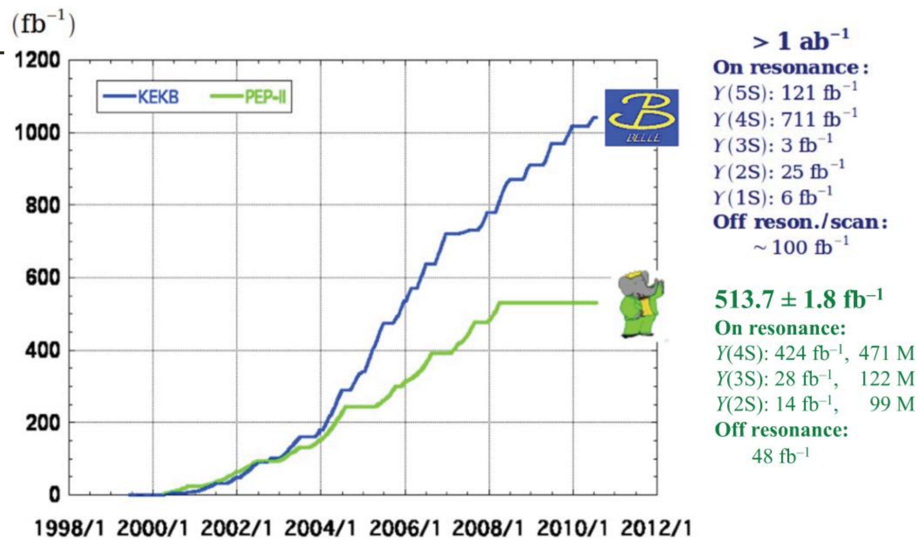
  Reminded of this recently in A. Hoecker arXiv:1611.07864 [hep-ex]

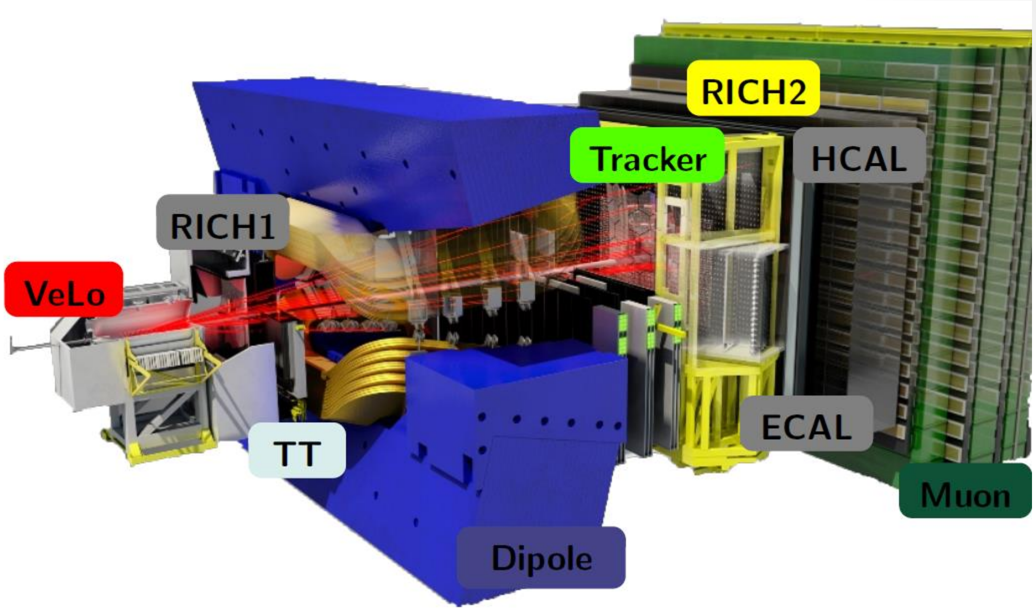
EXPERIMENTS AND DATASETS

e⁺e⁻ B-factories

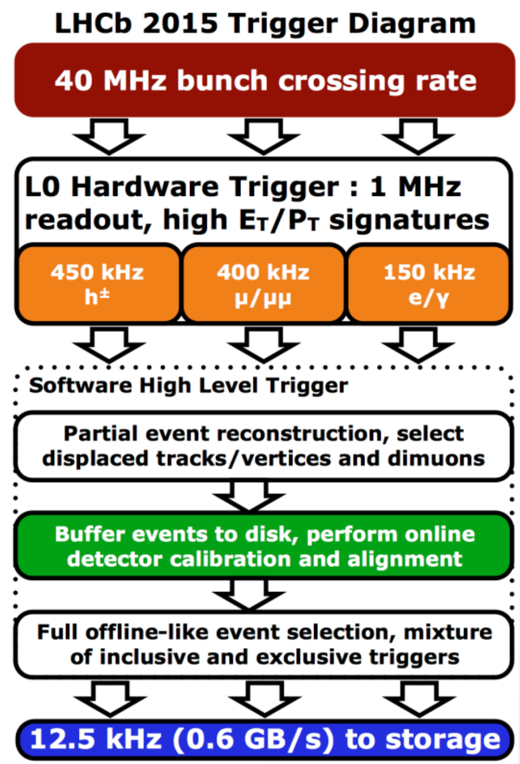
- Operation from 1999 to 2009 (BABAR)/2010 (Belle)
- $e^+e^- \to \Upsilon(4S) \to B\bar{B}$ for CKM measurements
- Asymmetric energy to allow time-dependent measurements
- Coherent production of $B^0\overline{B^0}$
- Low multiplicity
- Detectors with good tracking, PID and calorimetry
  - plus hermeticity for full event reconstruction/tagging







- Exploits large cross section for $b\bar{b}$ production in the forward region of *pp* collisions
- All b-hadrons produces with large boost i.e. B_s and Λ_b
- Warm dipole which can be reversed in polarity
  - Excellent tracking and **vertexing**
- PID over a large range of momenta
- Two stage trigger: 12.5 kHz rate to tape
- Run 1 and 2 data sets
  - 1 fb^{-1} @ 7 TeV
  - 2 fb^{-1} @ 8 TeV
  - 2 fb^{-1} so far @ 13 TeV

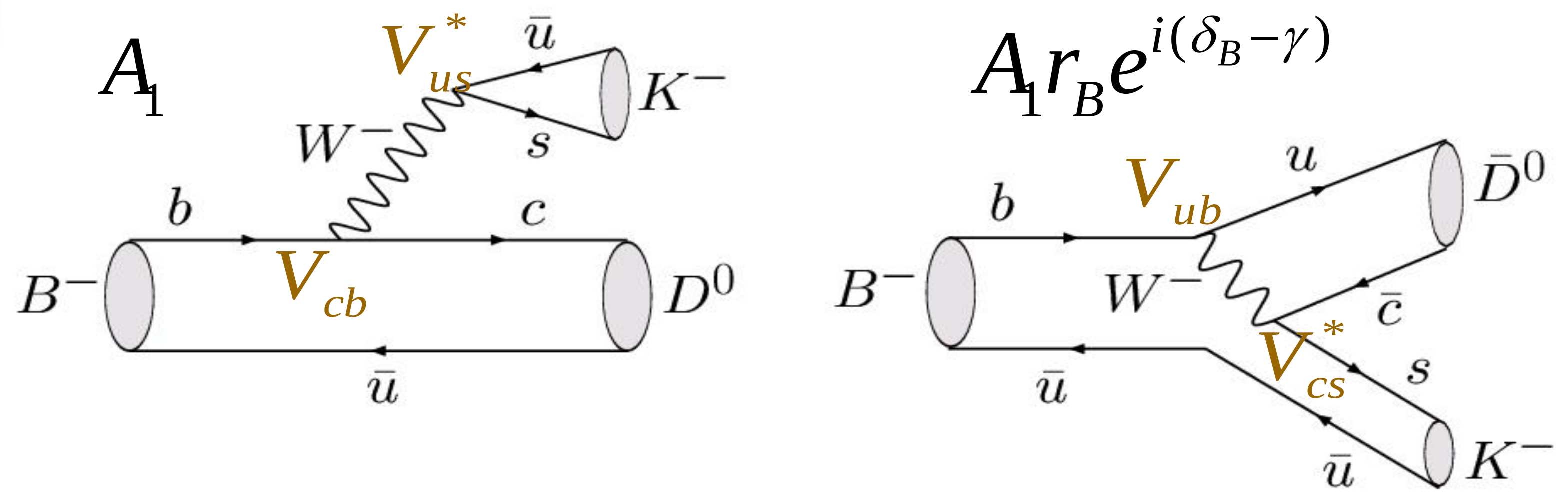


~~Roman~~ Candle

$\gamma \equiv \phi_3$

$B \to DK$

- Tree-level determination γ



- Same final state for D and $\overline{D}$ $\Rightarrow$ interference $\Rightarrow$ **the possibility of DCPV**
- Four types of D final states generally used
  - **CP-eigenstates [GLW]**
    - Gronau & London, PLB **253**, 483 (1991), Gronau, & Wyler, PLB **265**, 172 (1991)
  - **K^+X^- ($X^-=\pi^-, \pi^- \pi^0, \pi^-\pi^- \pi^+$) - CF and DCS [ADS]**
    - Atwood, Dunietz & Soni, PRD **63**, 036005 (2001)
  - **Self-conjugate multibody states: $K_S h^+h^-$ [Dalitz/GGSZ]**
    - Giri, Grossman, Soffer and Zupan, PRD **68**, 054018 (2003); Bondar (unpublished)
  - **None of the above (SCS): $K_S K^+\pi^-$ [GLS]**
    - Grossman, Ligeti and Soffer, Phys. Rev. D67 071301 (2003)

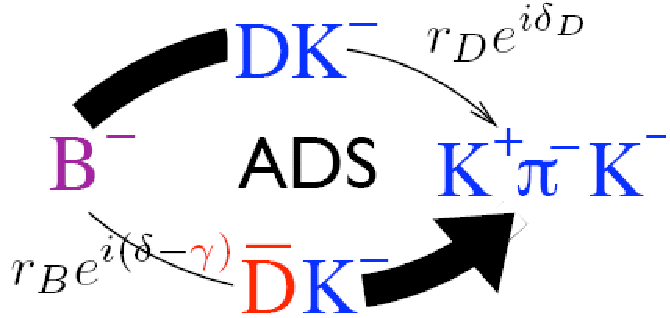
Atwood-Dunietz-Soni (ADS) Method

PRL 78, 3257 (1997)

f(D) = non-CP Eigenstate (e.g. $K^+\pi^-$)

$$\frac{< D^0 \longrightarrow K^+\pi^- >}{< \overline{D}^0 \longrightarrow K^+\pi^- >} = r_D e^{i\delta_D}$$

~0.06



$$\Gamma(B^- \rightarrow (K^-\pi^+)_D K^-) \propto 1 + (r_B r_D^{K\pi})^2 + 2 r_B r_D^{K\pi} \cdot \cos(\delta_B - \delta_D^{K\pi} - \gamma) \quad (1)$$

$$\Gamma(B^- \rightarrow (K^+\pi^-)_D K^-) \propto r_B^2 + (r_D^{K\pi})^2 + 2 r_B r_D^{K\pi} \cdot \cos(\delta_B + \delta_D^{K\pi} - \gamma) \quad (2)$$

$$\Gamma(B^+ \rightarrow (K^+\pi^-)_D K^+) \propto 1 + (r_B r_D^{K\pi})^2 + 2 r_B r_D^{K\pi} \cdot \cos(\delta_B - \delta_D^{K\pi} + \gamma) \quad (3)$$

$$\Gamma(B^+ \rightarrow (K^-\pi^+)_D K^+) \propto r_B^2 + (r_D^{K\pi})^2 + 2 r_B r_D^{K\pi} \cdot \cos(\delta_B + \delta_D^{K\pi} + \gamma) \quad (4)$$

- From counting these 4 rates, together with those from CP eigenstates (KK,$\pi\pi$), a determination of γ can be made
- Can determine δ_D from rates but **external constraints improve precision considerably**

LHCb γ combination

arXiV: 1611.03076 [hep-ex]
accepted by JHEP

- $B^+ \to DK^+$, $D \to h^+h^-$, GLW/ADS, $3\,\text{fb}^{-1}$
- $B^+ \to DK^+$, $D \to h^+\pi^-\pi^+\pi^-$, quasi-GLW/ADS, $3\,\text{fb}^{-1}$
- $B^+ \to DK^+$, $D \to h^+h^-\pi^0$, quasi-GLW/ADS, $3\,\text{fb}^{-1}$
- $B^+ \to DK^+$, $D \to K^0_S h^+h^-$, model-independent GGSZ, $3\,\text{fb}^{-1}$
- $B^+ \to DK^+$, $D \to K^0_S K^+\pi^-$, GLS, $3\,\text{fb}^{-1}$
- $B^0 \to DK^+\pi^-$, $D \to h^+h^-$, GLW-Dalitz, $3\,\text{fb}^{-1}$
- $B^0 \to DK^{*0}$, $D \to K^+\pi^-$, ADS, $3\,\text{fb}^{-1}$
- $B^0 \to DK^{*0}$, $D \to K^0_S\pi^+\pi^-$, model-dependent GGSZ, $3\,\text{fb}^{-1}$
- $B^+ \to DK^+\pi^+\pi^-$, $D \to h^+h^-$, GLW/ADS, $3\,\text{fb}^{-1}$
- $B^0_s \to D^\mp_s K^\pm$, time-dependent, $1\,\text{fb}^{-1}$

LHCb γ combination

arXiV: 1611.03076 [hep-ex]
accepted by JHEP

- $B^+ \to DK^+$, $D \to h^+h^-$, GLW/ADS, $3\,\text{fb}^{-1}$
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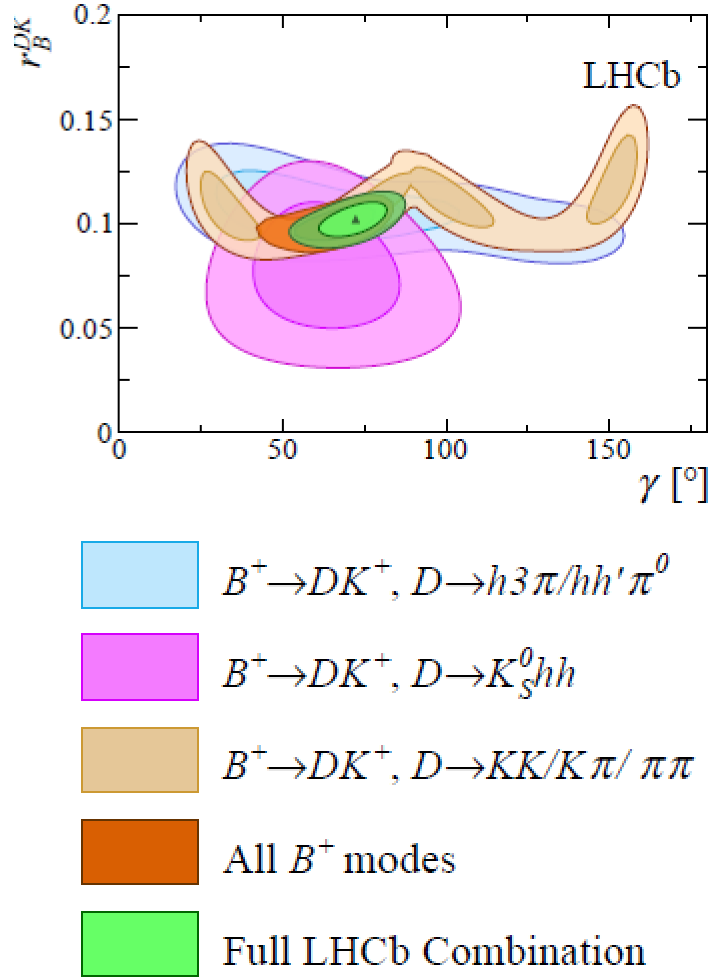
- $B^0_s \to D_s^{\mp}K^{\pm}$, time-dependent, $1\,\text{fb}^{-1}$

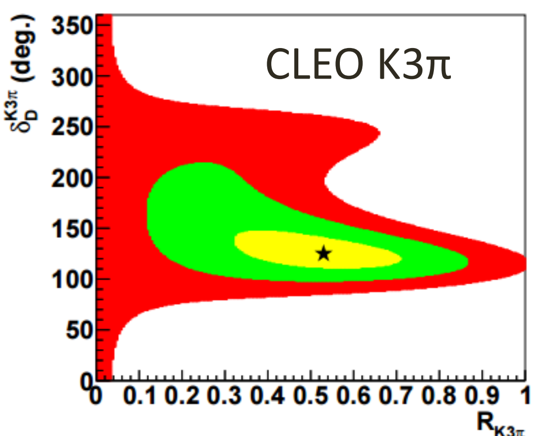


$$\gamma = (72.2^{+6.8}_{-7.3})^\circ$$

Most precise single experiment determination
…but still a long way to go
Other loop based measures predict to 1 deg.

Charm inputs to determine γ

Decay	Parameters	Source
D^0–$\overline{D}^0$-mixing	x_D, y_D	HFAG
$D \to K^+\pi^-$	$r_D^{K\pi}$, $\delta_D^{K\pi}$	HFAG
$D \to h^+h^-$	$A_{KK}^{\rm dir}$, $A_{\pi\pi}^{\rm dir}$	HFAG
$D \to K^\pm\pi^\mp\pi^+\pi^-$	$\delta_D^{K3\pi}$, $\kappa_D^{K3\pi}$, $r_D^{K3\pi}$	CLEO+LHCb
$D \to \pi^+\pi^-\pi^+\pi^-$	$F_{\pi\pi\pi\pi}$	CLEO
$D \to K^\pm\pi^\mp\pi^0$	$\delta_D^{K2\pi}$, $\kappa_D^{K2\pi}$, $r_D^{K2\pi}$	CLEO+LHCb
$D \to h^+h^-\pi^0$	$F_{\pi\pi\pi^0}$, $F_{KK\pi^0}$	CLEO
$D \to K_S^0K^-\pi^+$	$\delta_D^{K_SK\pi}$, $\kappa_D^{K_SK\pi}$, $r_D^{K_SK\pi}$	CLEO
$D \to K_S^0K^-\pi^+$	$r_D^{K_SK\pi}$	LHCb



Evans et al
Phys.Lett. **B757** (2016) 520

Without these measurements LHCb combination has double the uncertainty!

Strong phase differences between $\overline{D}$ and D vary over phase space but can be determined in quantum correlated ψ(3770) decay

Measurements made with 0.8 fb^{-1} CLEO-c data

BES III already has 2.9 fb^{-1} and will collect 10-20 fb^{-1}

Key ingredient of a future 1 deg. measurement of γ

Kowolski: Physics Coordinator

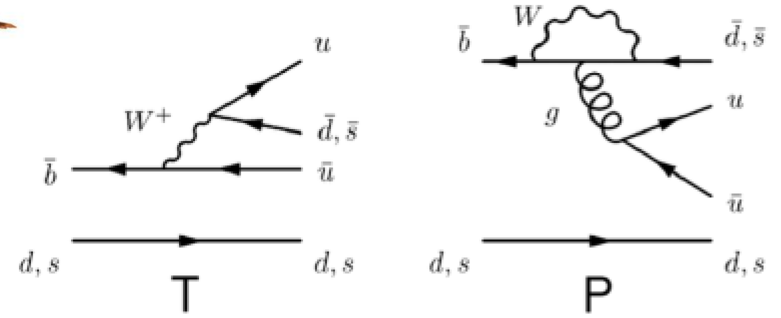
Rico: loose cannon!
(every exp. has one)

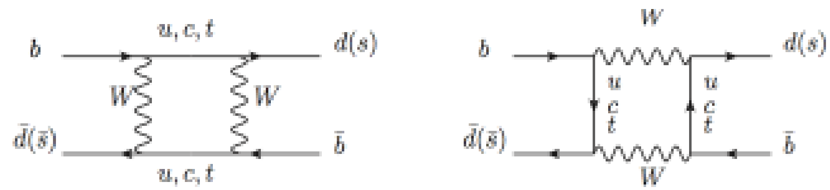
Private:
Graduate student

Skipper: Spokesman

$B_{(s)} \rightarrow hh$

LHCb-CONF-2016-018 (Run 1 3 fb^{-1})

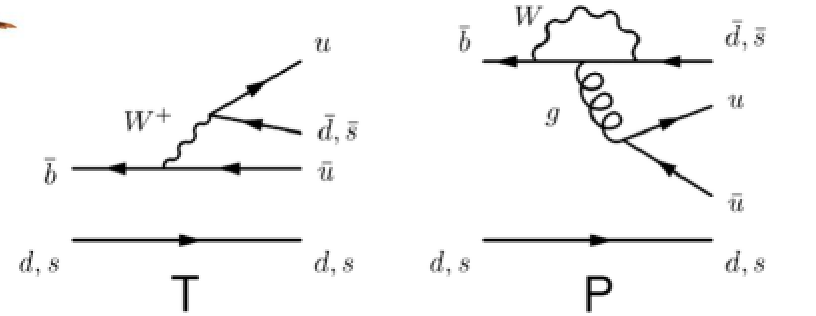


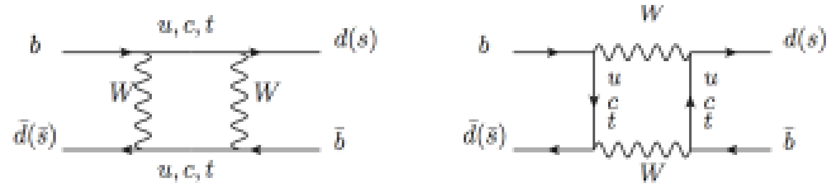


- Sensitivity to γ but potential for new physics contributions with presence of the penguin (P) diagram

$B_{(s)} \to hh$

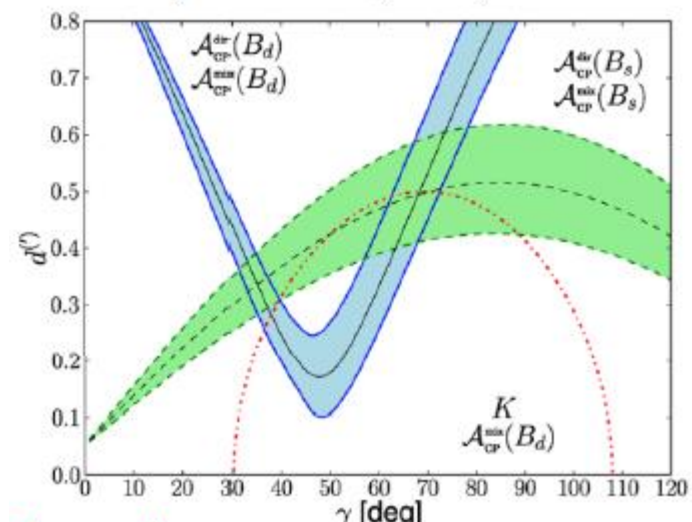
LHCb-CONF-2016-018 (Run 1 3 fb^{-1})





- Sensitivity to γ but potential for new physics contributions with presence of the penguin (P) diagram
- Combine $B_d \to \pi\pi$ and $B_s \to KK$ measurements to reduce QCD uncertainties – U-spin
- CP violation comes directly but also from the interference between mixing and decay – time-dependent measurement

Phys. J. C71 (2011) 1532



Observables

Observables are the time-dependent asymmetries of the $B^0 \to \pi^+\pi^-$ and $B_s \to K^+K^-$

$$\mathcal{A}(t) = \frac{\Gamma_{\bar{B}^0_{(s)}\to f}(t) - \Gamma_{B^0_{(s)}\to f}(t)}{\Gamma_{\bar{B}^0_{(s)}\to f}(t) + \Gamma_{B^0_{(s)}\to f}(t)} = \frac{-C_f \cos\left(\Delta m_{d(s)} t\right) + S_f \sin\left(\Delta m_{d(s)} t\right)}{\cosh\left(\frac{\Delta\Gamma_{d(s)}}{2} t\right) + A_f^{\Delta\Gamma} \sinh\left(\frac{\Delta\Gamma_{d(s)}}{2} t\right)}$$

CPV from mixing/decay interference

$$S_f = \frac{2\mathrm{Im}\lambda_f}{|\lambda_f|^2 + 1}$$

CPV in the decay

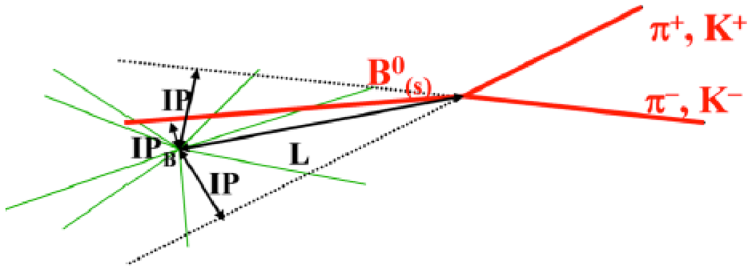
$$C_f = \frac{1 - |\lambda_f|^2}{1 + |\lambda_f|^2}$$

$$|C_f|^2 + |S_f|^2 + |A_f^{\Delta\Gamma}|^2 = 1$$

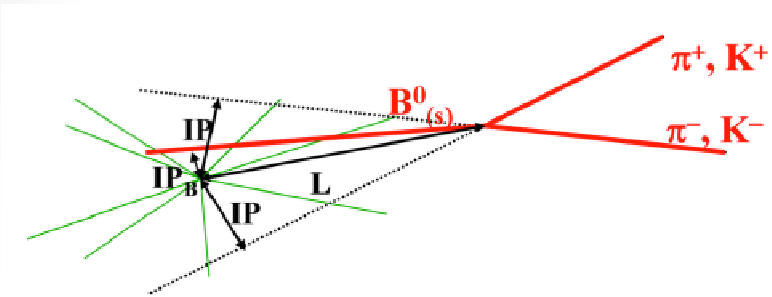
$$\lambda_f = \frac{q}{p}\frac{\bar{A}_f}{A_f}$$

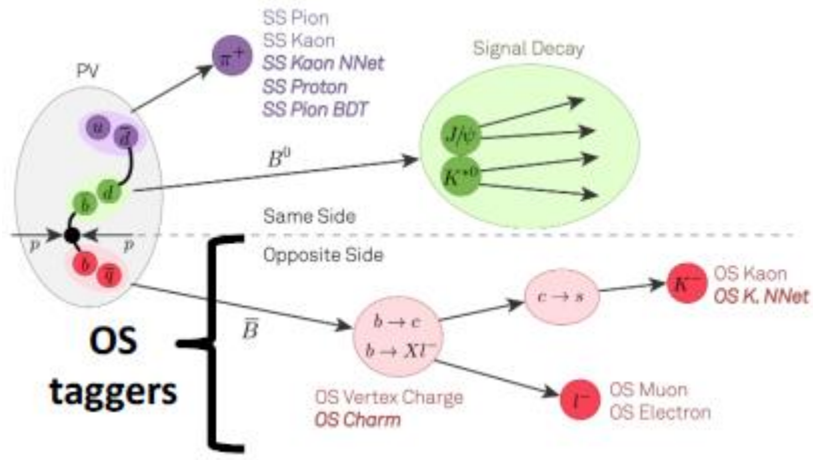
- q/p is related to the neutral B mixing
- $A_f/\bar{A}_f$ is the ratio between the CP conjugate decay amplitudes

Measurements



Measurements





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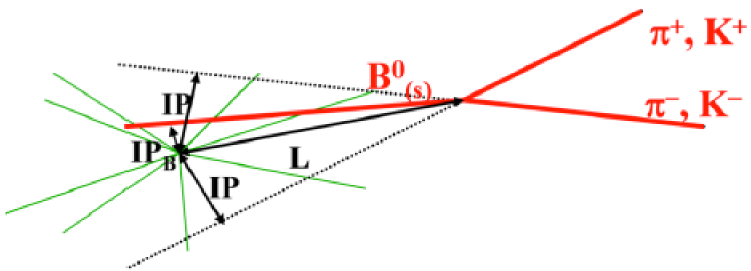
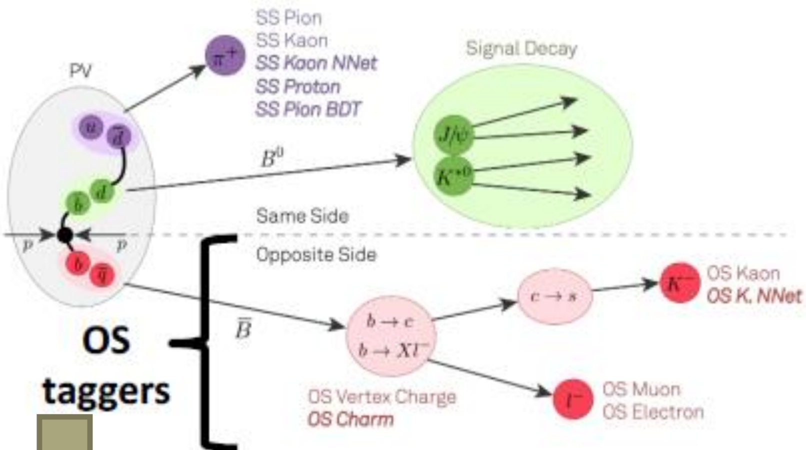
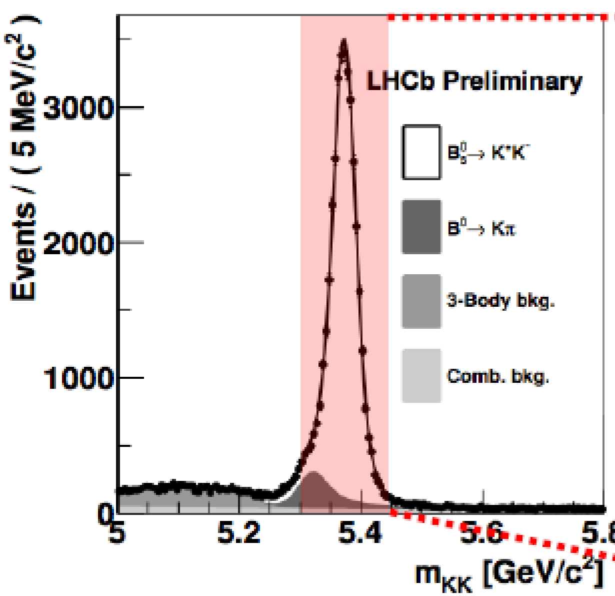
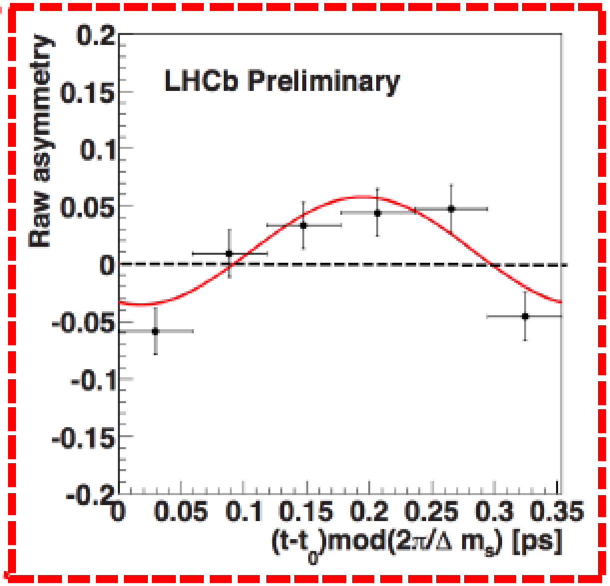




OS taggers





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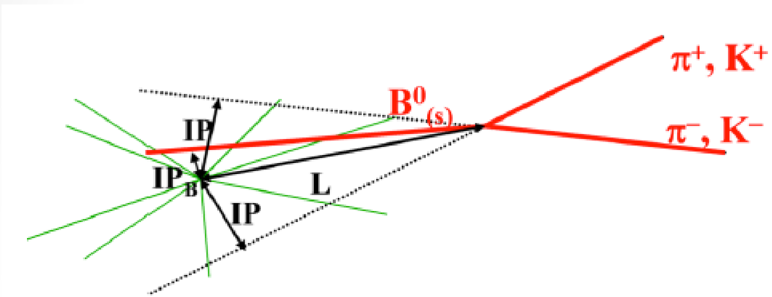
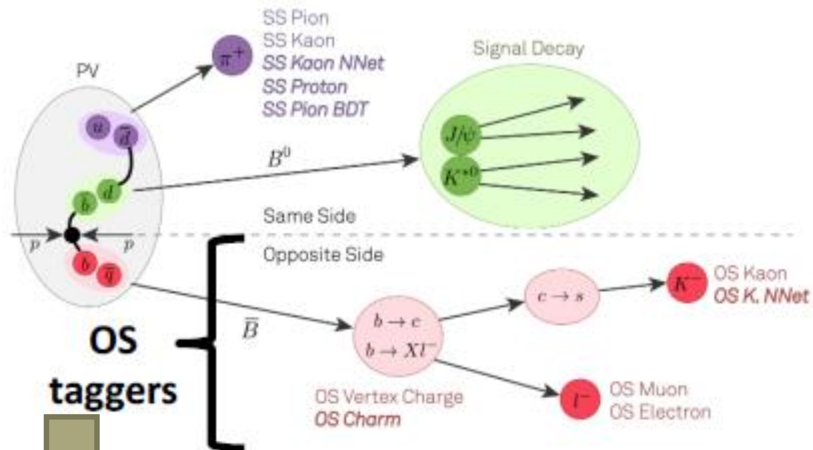
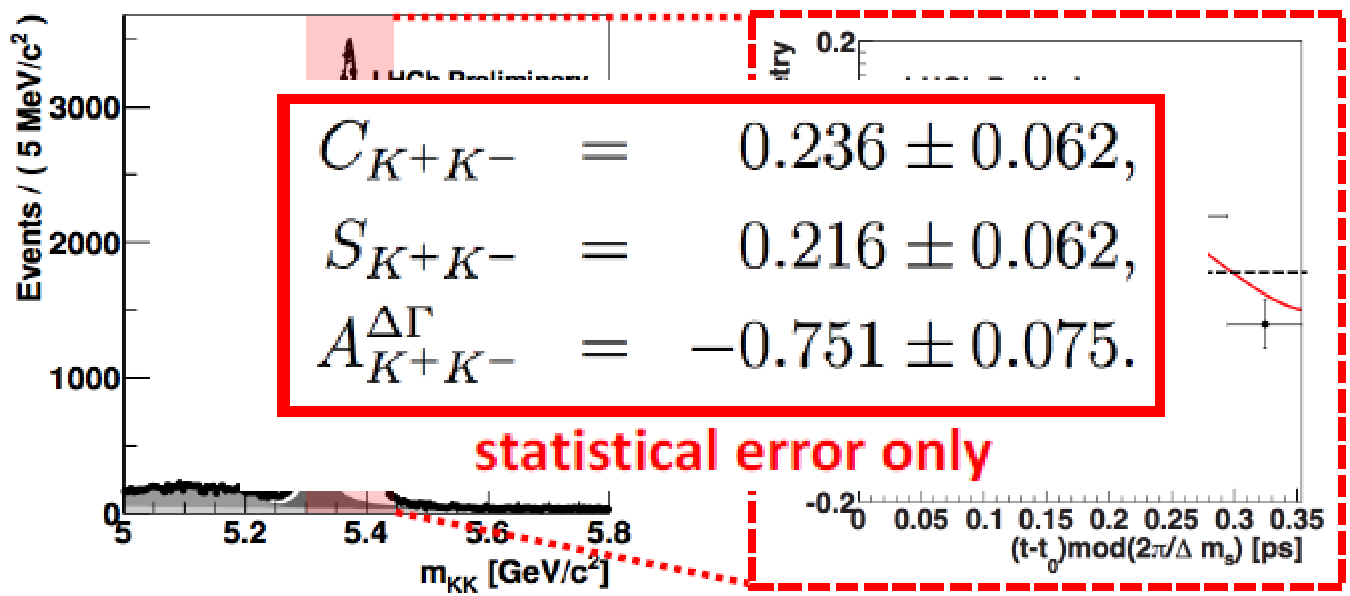






$$C_{K^+K^-} = 0.236 \pm 0.062,$$
$$S_{K^+K^-} = 0.216 \pm 0.062,$$
$$A^{\Delta\Gamma}_{K^+K^-} = -0.751 \pm 0.075.$$

statistical error only

5.3σ significance for time-dependent CP violation in B_s

First observation!

Interpretation for γ to follow

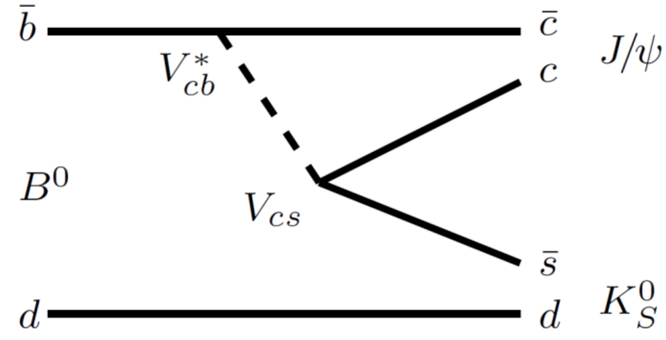
β – the golden mode

The Golden Mode

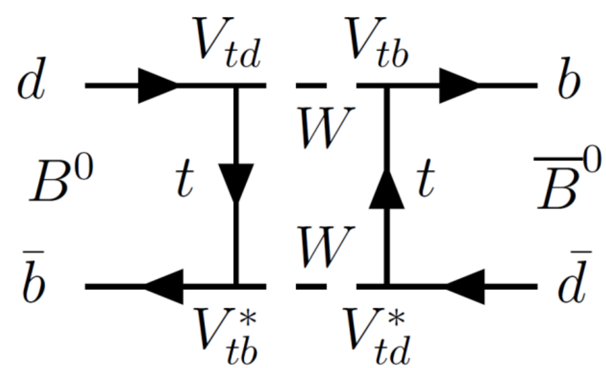
$B^0 \to J/\psi K_S^0$ sensitive to

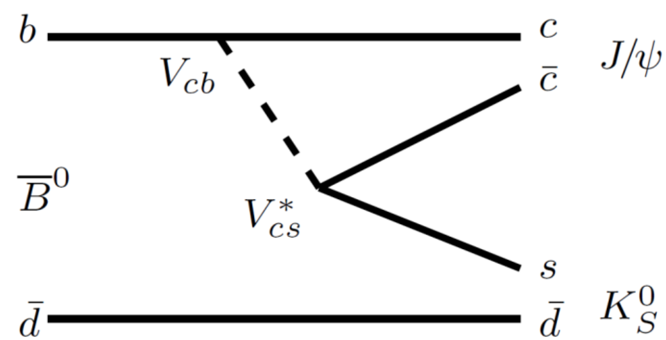
$$\beta = \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right)$$

CP violation in the 'interference of mixing and decay amplitudes'



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



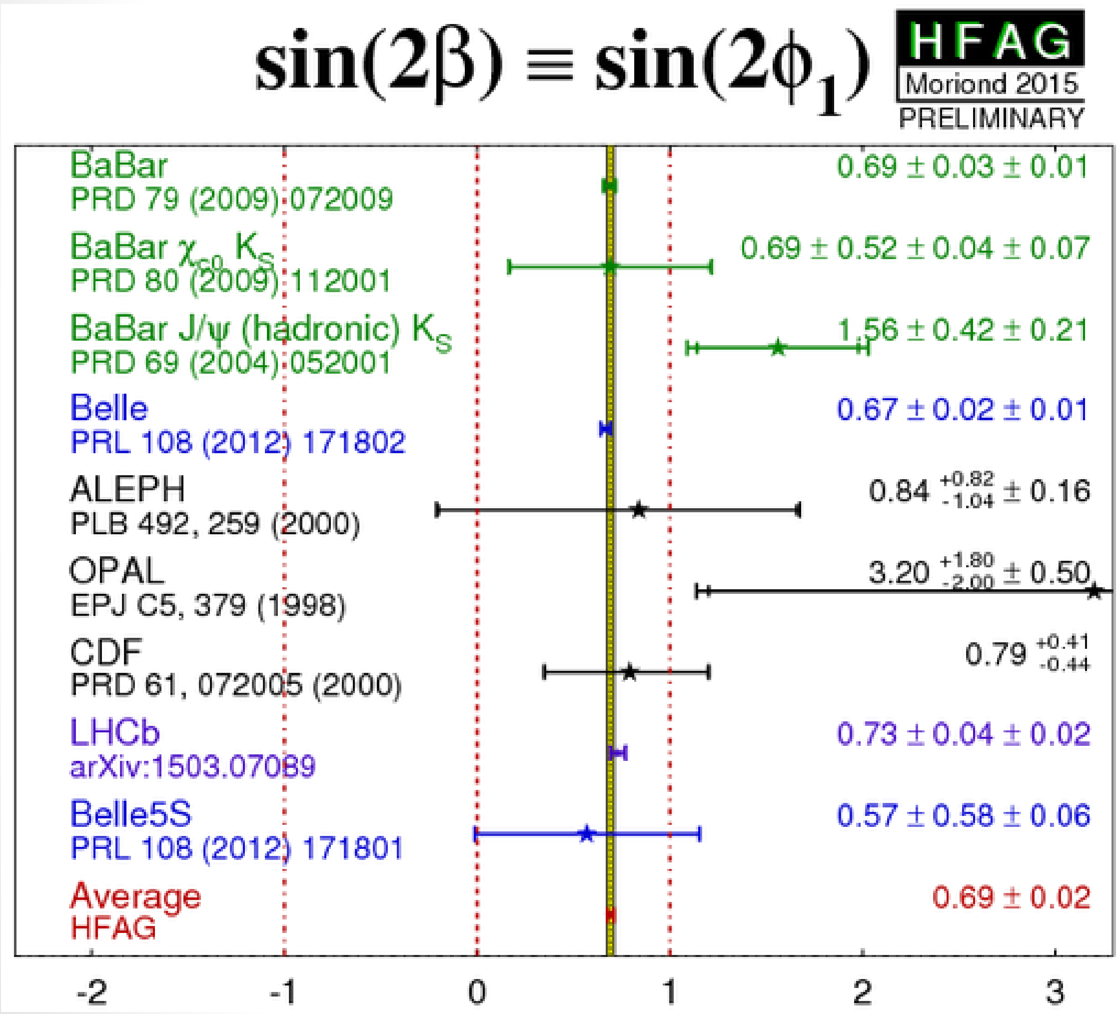


$$A_{CP}(\Delta t) = \frac{\Gamma\left[\overline{B}^0(\Delta t) \to f\right] - \Gamma\left[B^0(\Delta t) \to f\right]}{\Gamma\left[\overline{B}^0(\Delta t) \to f\right] + \Gamma\left[B^0(\Delta t) \to f\right]} = S_f \sin(\Delta m_d \Delta t) - C_f \cos(\Delta m_d \Delta t)$$

In SM $S_f = \eta_f \sin 2\beta$ and $C_f = 0$ when no CPV in f

$\eta_f = CP$ eigenvalue of f

Comparison of measurements



Consistency amongst the measurements

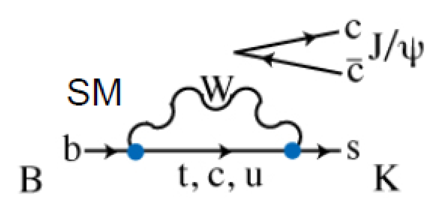
Systematics largely derived from data control samples

The SM prediction excluding this measurements is

$$\sin 2\beta = 0.771^{+0.034}_{-0.032}$$

[CKMFitter]

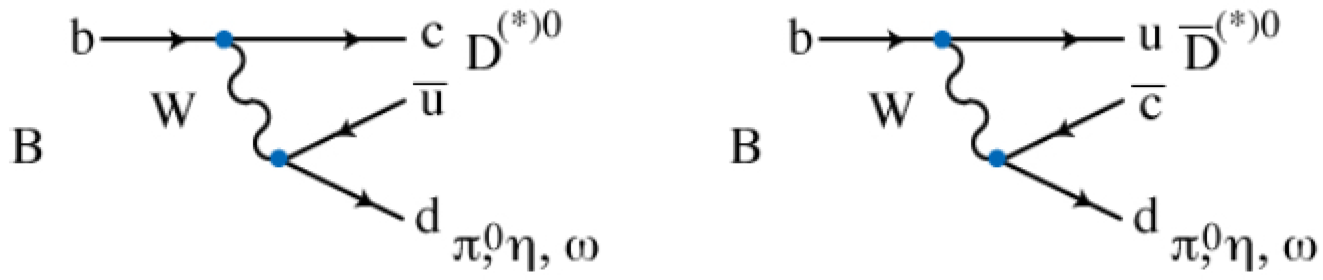
Control of loop/penguin contribution important



Tree level measurement

- Another avenue is to measure sin2β with a tree-level only final state

$B^0 \to D^{(*)0} h^0$, $h^0 = \pi^0, \eta, \omega$



Leading : Tree
No complex phase
in decay amplitude

Sub-Leading : also Tree
V_{ub} has complex phase,
but it is within the SM, to be
under control.

- $D^0/\overline{D^0}$ to a CP eigenstate i.e. K^+K^- or self-conjugate final state such as $K^0_S\pi^+\pi^-$
- Branching fraction is limiting factor

PRL **115**, 121604 (2015)

Combined B factory analysis

- First analysis of combined Babar and Belle data sets corresponding to 1.2 billion $e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B}$
- Reconstruct:

$$B^0 \rightarrow D^{(*)}h^0, h^0 = \pi^0, \eta, \omega$$

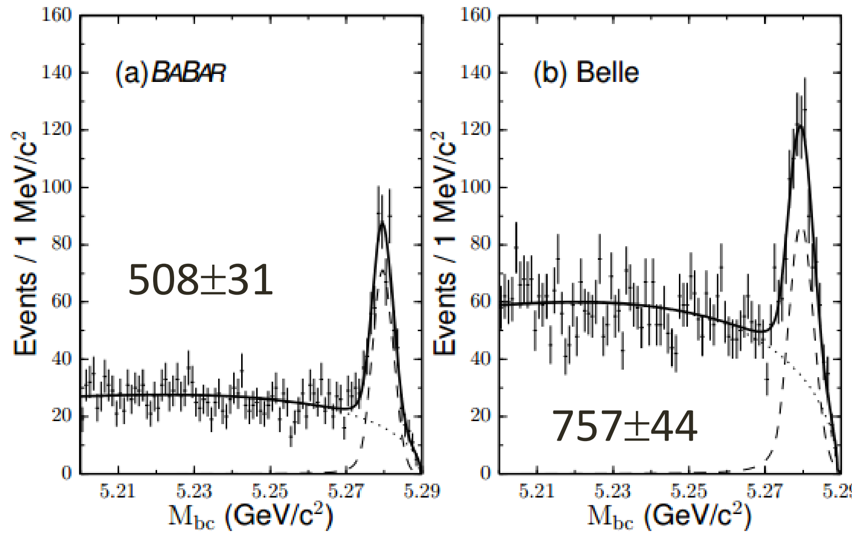
$$D \rightarrow K_S^0\pi^0, K_S^0\omega, K^+K^-$$

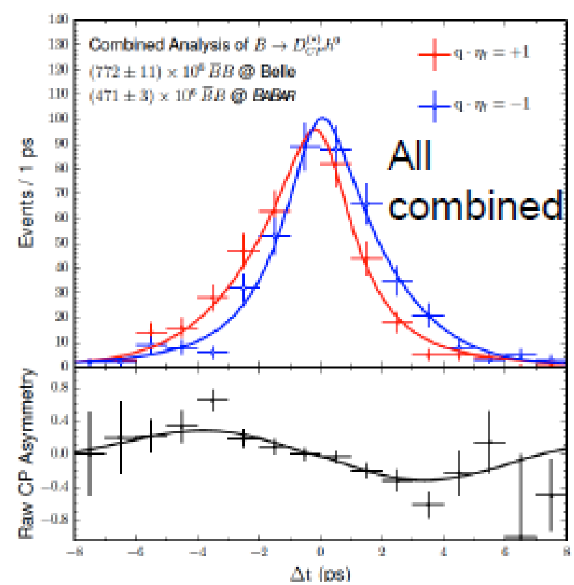
$$D^* \rightarrow D\left(K_S^0\pi^0\right)\pi^0$$

- > 5σ significance of CP violation

$$\sin 2\beta = 0.66 \pm 0.10 \pm 0.06$$

- Very interesting measurement for Belle II σ≈0.02

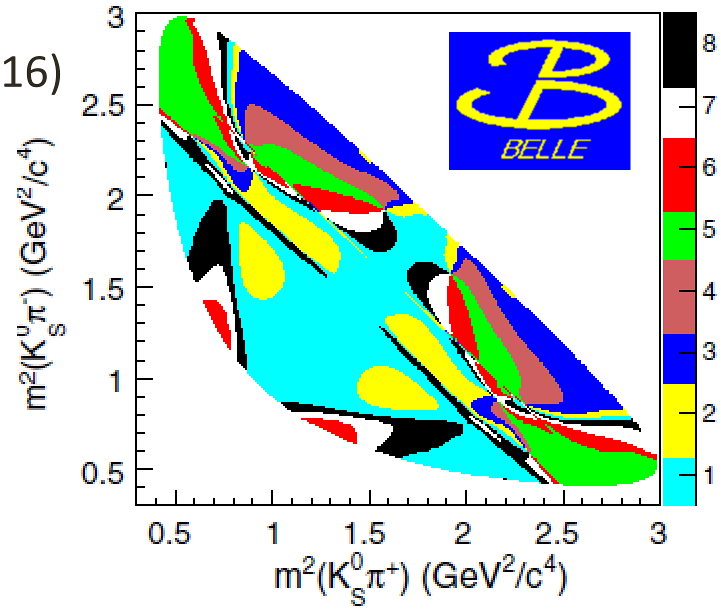


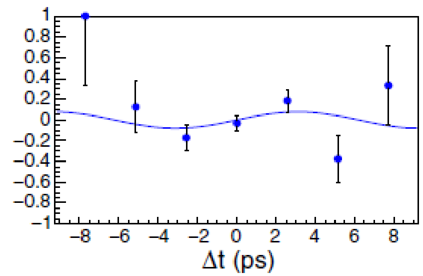


$B^0 \to D(K_S\pi\pi)h^0$

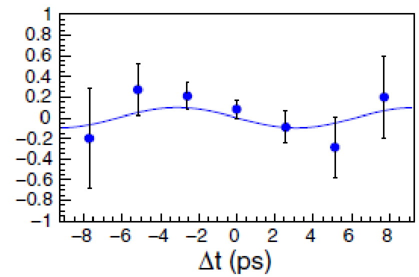
PRD 94, 052004 (2016)

- Knowledge of average strong phase difference D to $\overline{D}$ in bins of the Dalitz space allows a time-dependent fit to extract both cos 2β and sin 2β
  - Measurements from CLEO-c to be improved by BES III
- ~1000 events from the full Belle sample
- Not as precise as CP states but unambiguous determination of $\beta \equiv \phi_1$



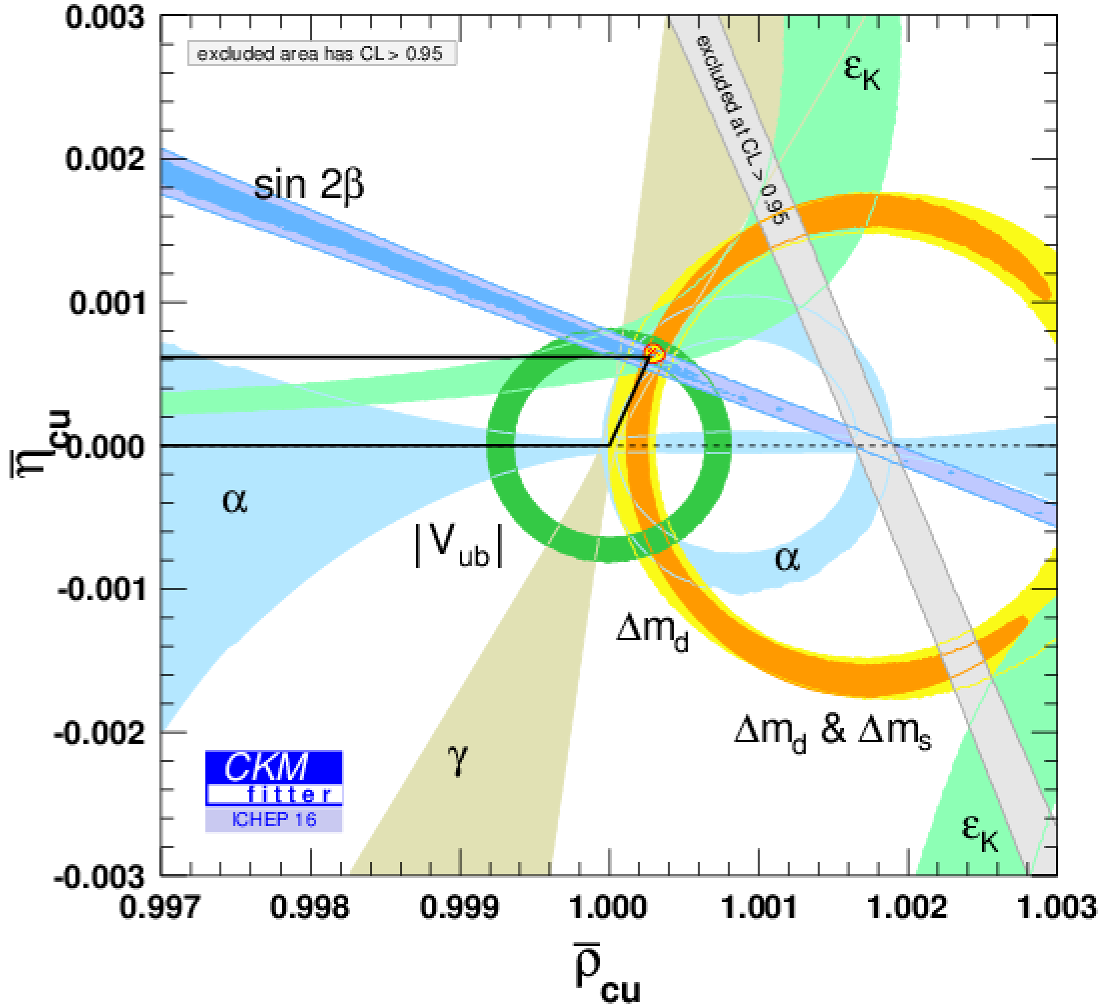


Bin 1



Bin 5

$$\sin 2\varphi_1 = 0.43 \pm 0.27(\mathrm{stat}) \pm 0.08(\mathrm{syst})$$
$$\cos 2\varphi_1 = 1.06 \pm 0.33(\mathrm{stat})^{+0.21}_{-0.15}(\mathrm{syst}),$$
$$\varphi_1 = 11.7^\circ \pm 7.8^\circ(\mathrm{stat}) \pm 2.1^\circ(\mathrm{syst})$$



OTHER TRIANGLES: CHARM DECAYS

Charm physics

- Unique arena to study up type dynamics
- Tiny expectations for CP violation and FCNC

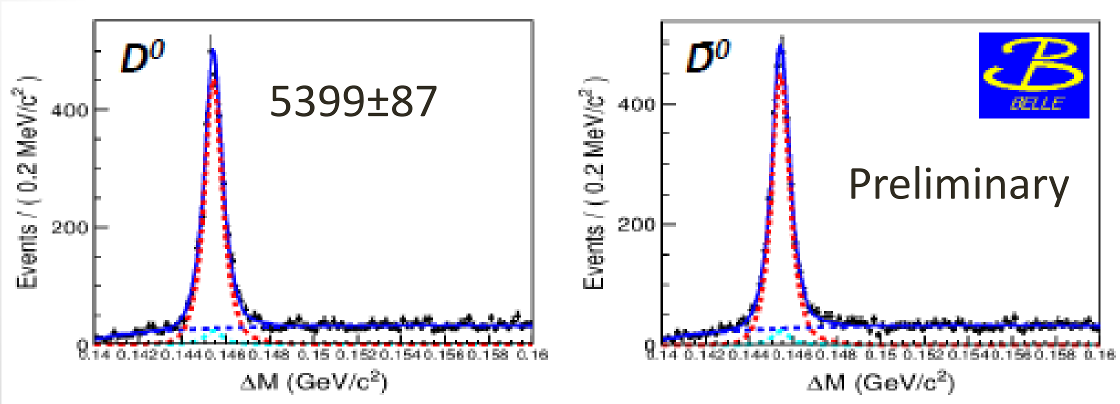
$$\begin{pmatrix} 1-\frac{1}{2}\lambda^2-\frac{1}{8}\lambda^4 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda+A^2\lambda^5(\frac{1}{2}-\rho-i\eta) & 1-\frac{1}{2}\lambda^2-\frac{1}{8}\lambda^4(1+4A^2) & A\lambda^2 \\ A\lambda^3\left[1-\left(1-\frac{1}{2}\lambda^2\right)(\rho+i\eta)\right] & -A\lambda^2+\frac{1}{2}A\lambda^4\left[1-2(\rho+i\eta)\right] & 1-1/2A^2\lambda^4 \end{pmatrix}+O(\lambda^6)$$

- Expected to appear in Cabibbo suppressed decays or via mixing O(10^{-3})
- But general idea is to look everywhere as any anomaly a signature of new physics
- B factories and LHCb are also D factories
- Will focus on a couple of examples of direct CP violation searches at Belle and LHCb
  - For mixing and mixing-induced CP violation
    - see Gobel, Bhardwaj, Maguire and Martinelli at CKM 2016

arXiv:1609.06393 [hep-ex]

$D^0 \to K_s^0 K_s^0$

- Due to cancellations among the diagrams involved
  - Standard model prediction $A_{CP} \leq 1.1\%$
    - Nierste & Schach Phys. Rev. D92, 054036 (2015)
- No vertex – ideal for the B factories
- Select $D^{*+} \to D^0(K_s^0 K_s^0)\pi^+$ events so that charge of pion tags the flavour of the *D*
- Also ΔM = M(D*) − M(D) excellent signal and background discrimination



A_{CP}=(−0.02±1.53±0.17)%

Three times more precise than previous

Excellent Belle 2 prospects

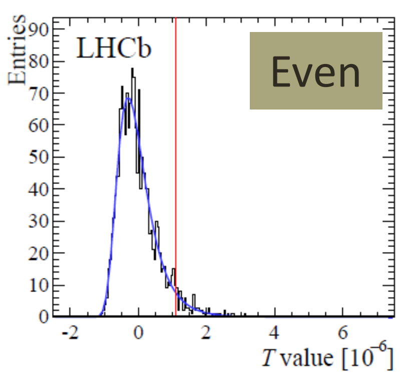
arXiv:1612.03207v1 [hep-ex]

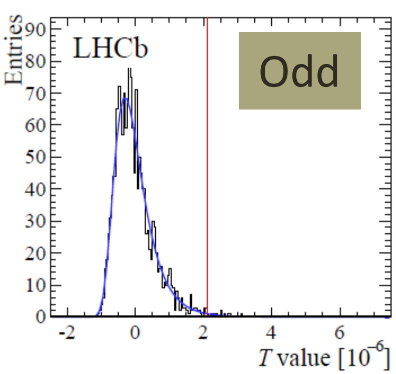
$D^0 \to \pi^+\pi^-\pi^+\pi^-$

- Huge sample $0(10^6)$ collected by LHCb
- Look for variations over the 5D phase space using an energy test for n D events and $\bar{n}$ $\bar{D}$ events with a test metric of phase space separation ψ_{ij}

$$T = \underbrace{\sum_{i,j>i}^{n} \frac{\psi_{ij}}{n(n-1)}}_{D \leftrightarrow D} + \underbrace{\sum_{i,j>i}^{\bar{n}} \frac{\psi_{ij}}{\bar{n}(\bar{n}-1)}}_{\bar{D} \leftrightarrow \bar{D}} - \underbrace{\sum_{i,j}^{n,\bar{n}} \frac{\psi_{ij}}{n\bar{n}}}_{\bar{D} \leftrightarrow D}$$

- T=0 in the absence of CPV – two tests that probe CP even and CP odd part of the amplitude



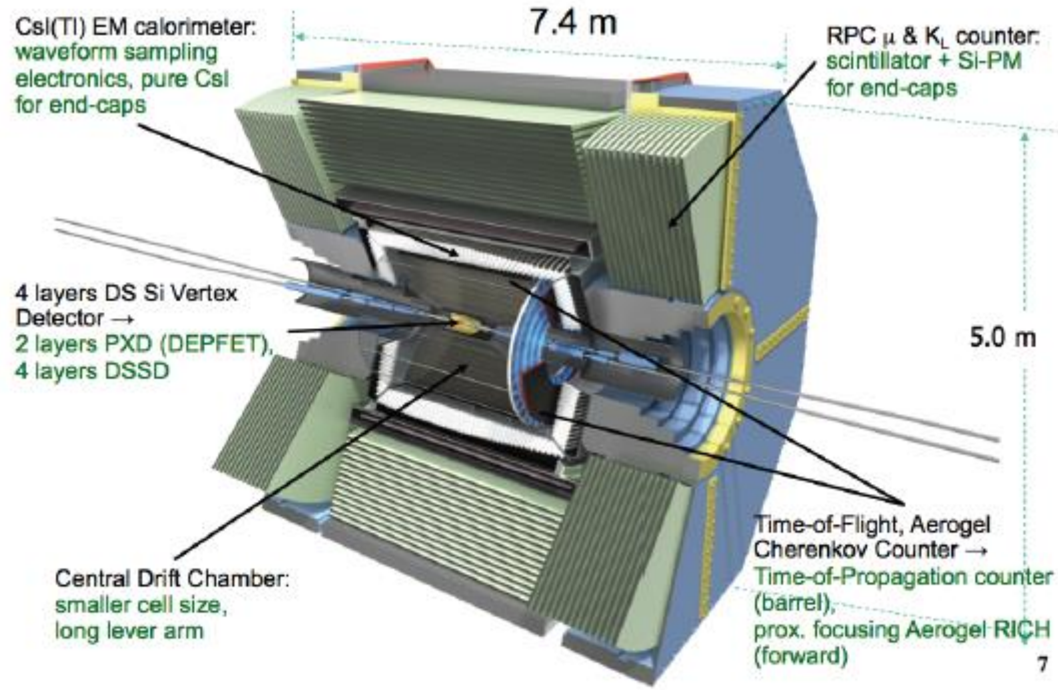


- p-value from comparing to no CPV pseudo experiments
- Even: p-value = 4.3%
- **Odd: p-value = 0.6%**

FUTURE PROSPECTS

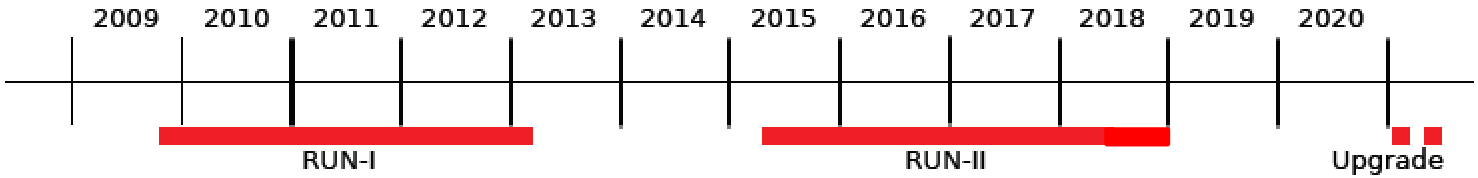
Belle II

- Goal to produce a 50 ab^{-1} dataset
- KEKB and Belle detector significant upgrades
- Time of Propagation PID
- Pixel vertexing
- Waveform sampling electromagnetic calorimetry
- Better precision on all measurements discussed and many more

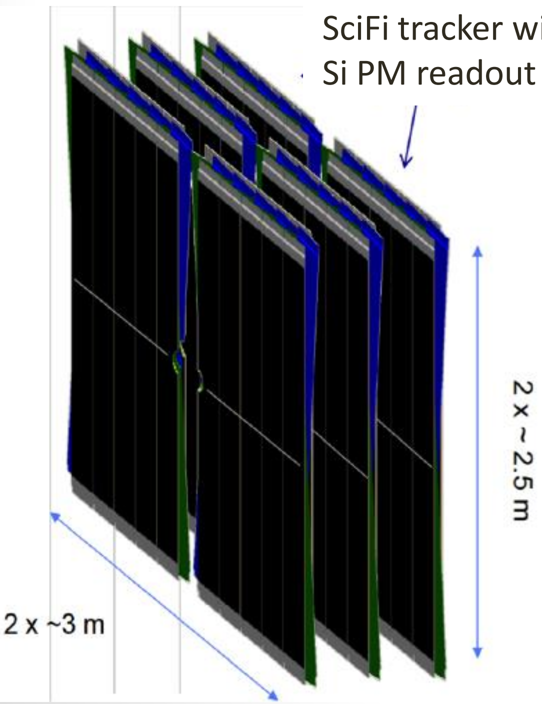


- 2016 first turns
- 2018 first collisions
- 2024 end 50 ab^{-1}

LHCb run 2 and upgrade



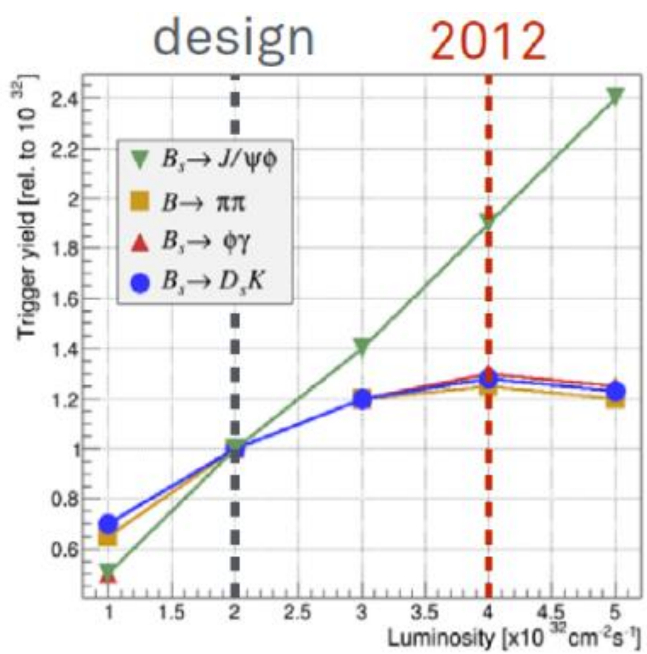
Run I: 3 fb^{-1} at 7 and 8 TeV – 5 kHz to tape
Run II: 5 fb^{-1} at 13 TeV – 1.6 x the cross section – 12.5 kHz to tape
Upgrade: 50 fb^{-1} - 5 x instantaneous luminosity – no 1 MHz hardware trigger
New tracker, new vertex, ECAL, and all new frontend electronics



Upgrade II: 300 fb^{-1}

"New experiment" to exploit – LHC hi-lumi running to 2035

Expression of Interest CERN-LHCC-2017-003

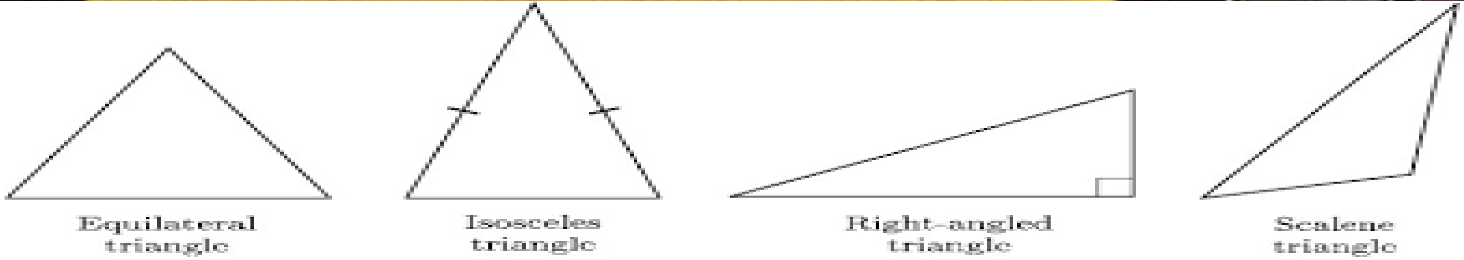


Summary

- Flavour physics is probing the SM indirectly in complementary way to other approaches: energy, ν, cosmological
- Many measurements not discussed – apologies
- Indicates the rich range of observables available – strong interplay between experiment and theory in their interpretation
- More data required to go to the next level of precision
  - Belle II to start in 2018
  - LHCb Run II until then
  - LHCb upgrades from 2020

BACKUP

Terry Gilliam, Monty Python credits



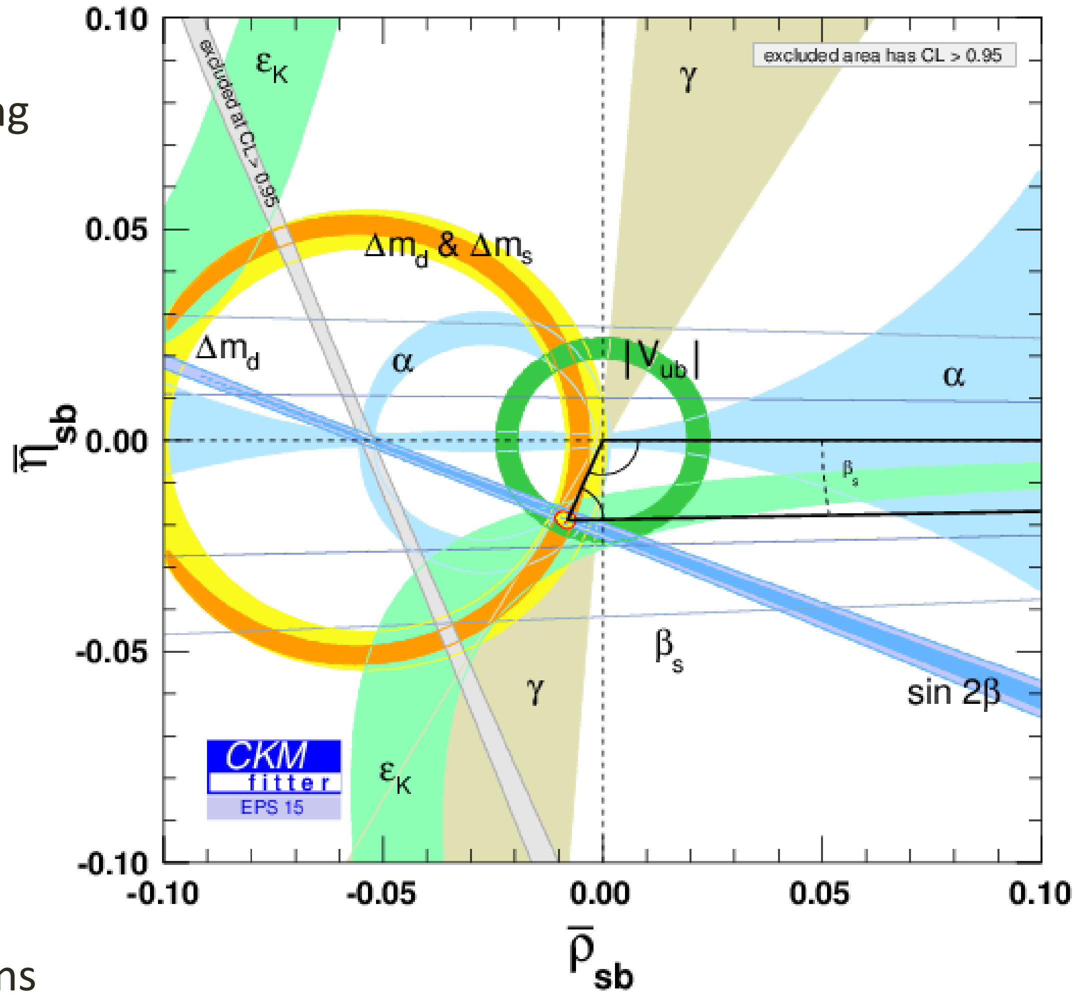
ϕ_S: A SQUASHED TRIANGLE

ϕ_s introduction

- This is the phase of B_s mixing
- It is related to the small opening angle of another squashed unitarity triangle
- Predicted from other CKM measurements

$$\phi_s \equiv -2\beta_s$$
$$= -2\arg\left(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right)$$
$$= -\left(36.3^{+1.4}_{-1.2}\right)\text{mrad}$$

- Preserve of the LHC:
  - B_s production with large boost to resolve oscillations



Different loops potential new physics contribution

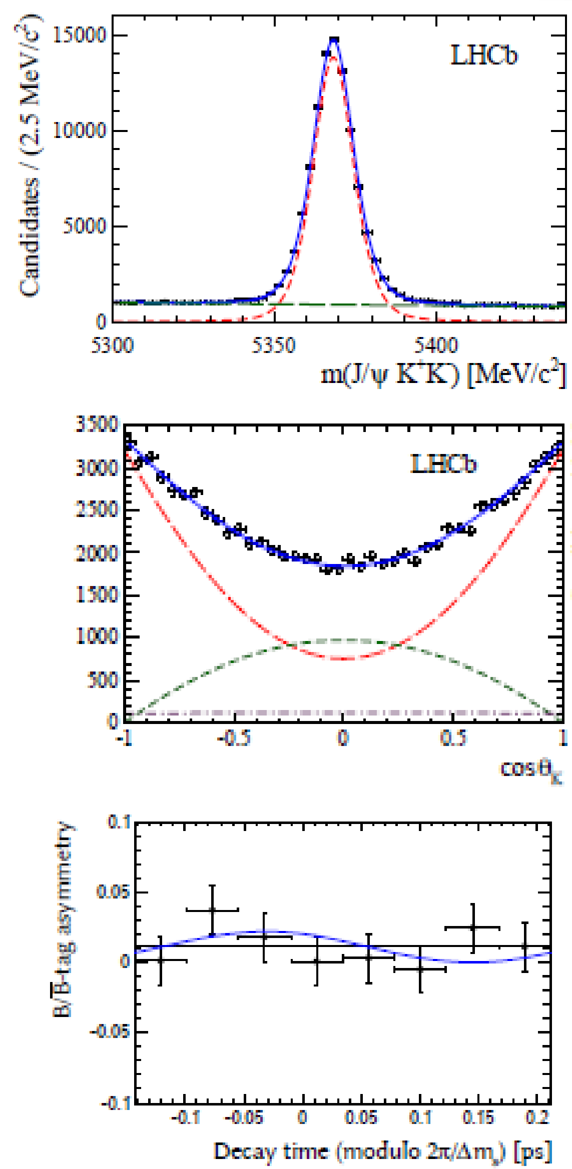
LHCb: $B_s \to J/\psi K^+K^-$

- Full angular analysis of KK invariant mass spectra required to resolve different helicity components and non-VV component
- Tagging power of 3.7%
  - Same side kaon better than pion

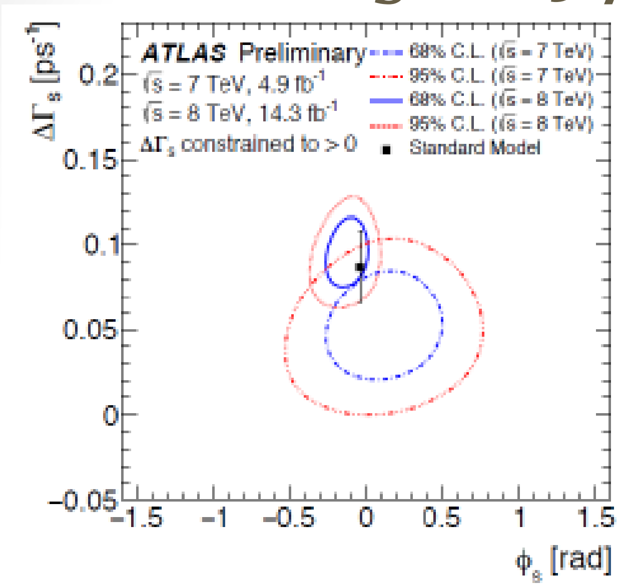
$$\varphi_s = -0.058 \pm 0.049 \pm 0.006\,\mathrm{rad},$$

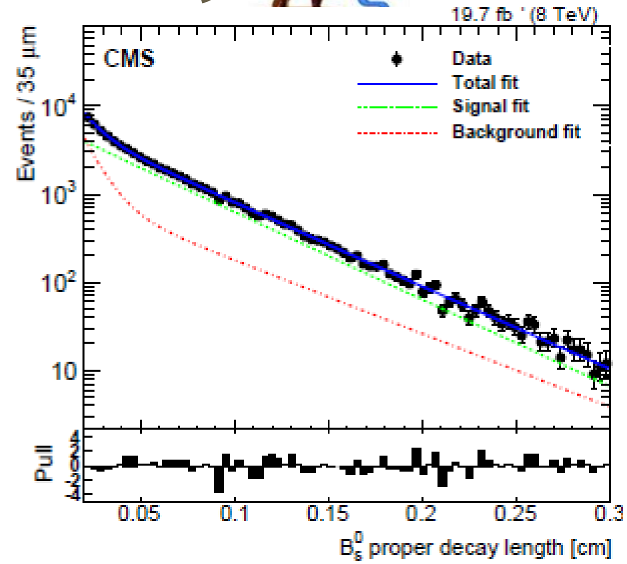
- Also determine the lifetime difference between the different mass eigenstates of the Bs

$$\Delta\Gamma_s = \quad 0.0805 \pm 0.0091 \pm 0.0033\,\mathrm{ps}^{-1}$$



GPDs: $B_s \to J/\psi\phi(K^+K^-)$

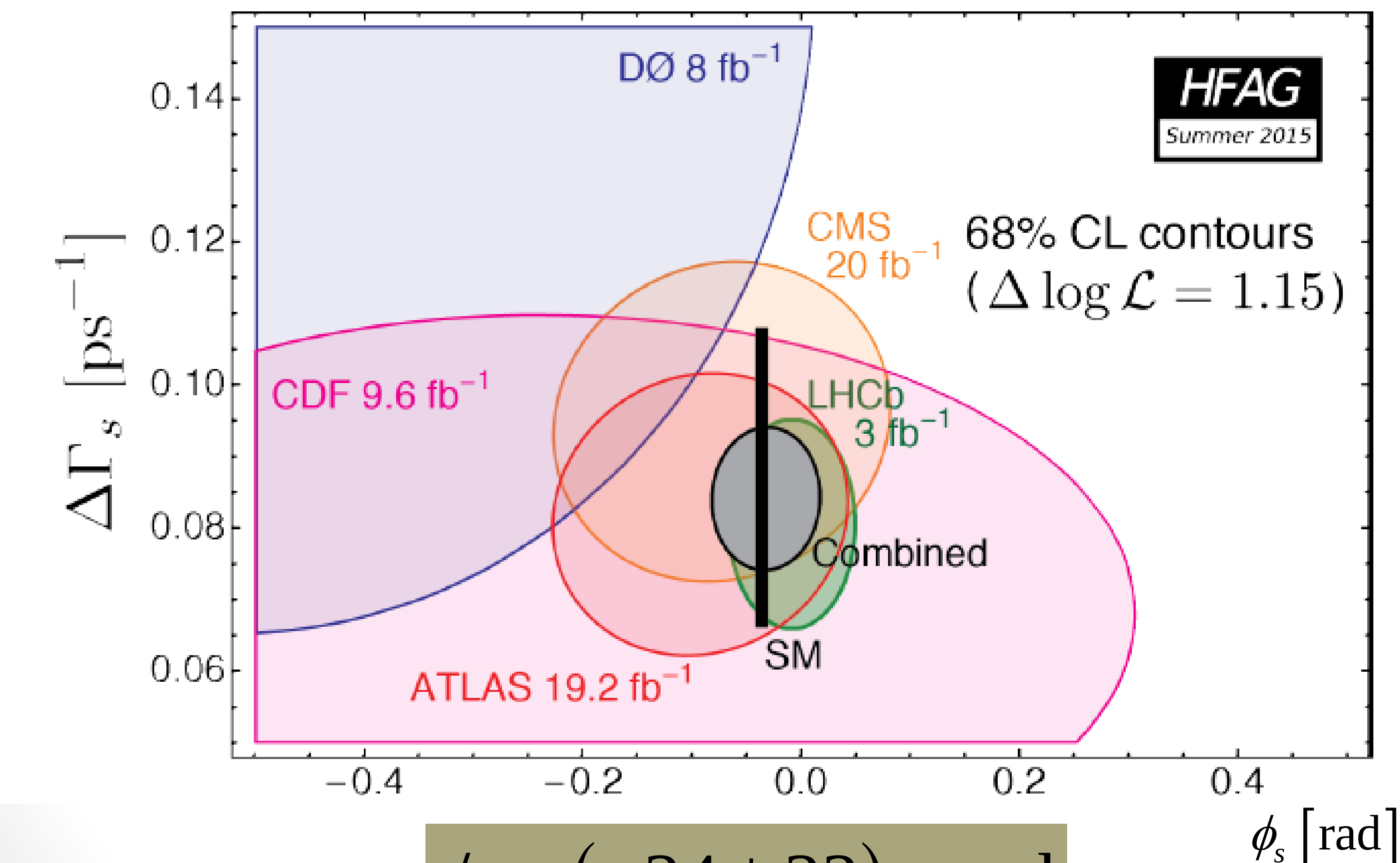




	ATLAS	CMS
Luminosity (fb^{-1})	19.2	19.7
Tagging power (%)	1.49	1.31
ϕ_s (mrad)	$-94\pm63\pm33$	$-75\pm97\pm31$
$\Delta\Gamma_s$ (ps^{-1})	$0.082\pm0.011\pm0.007$	$0.095\pm0.013\pm0.007$

Combination

Additional modes from LHCb: $J/\psi\pi\pi$ and D_sD_s



$$\phi_s = (-34 \pm 33)\ \text{mrad}$$