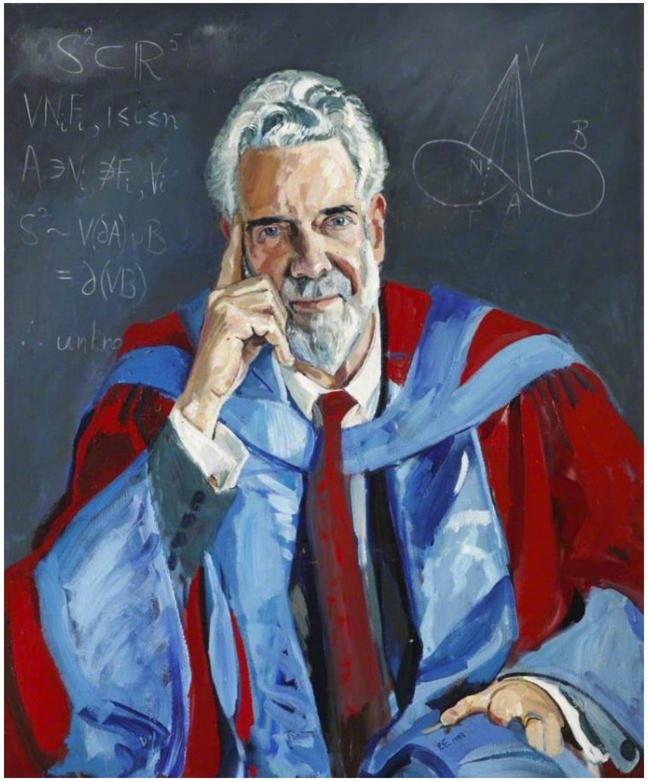
CKM angles and CP violation

Jim Libby (Indian Institute of Technology, Madras)

Overview

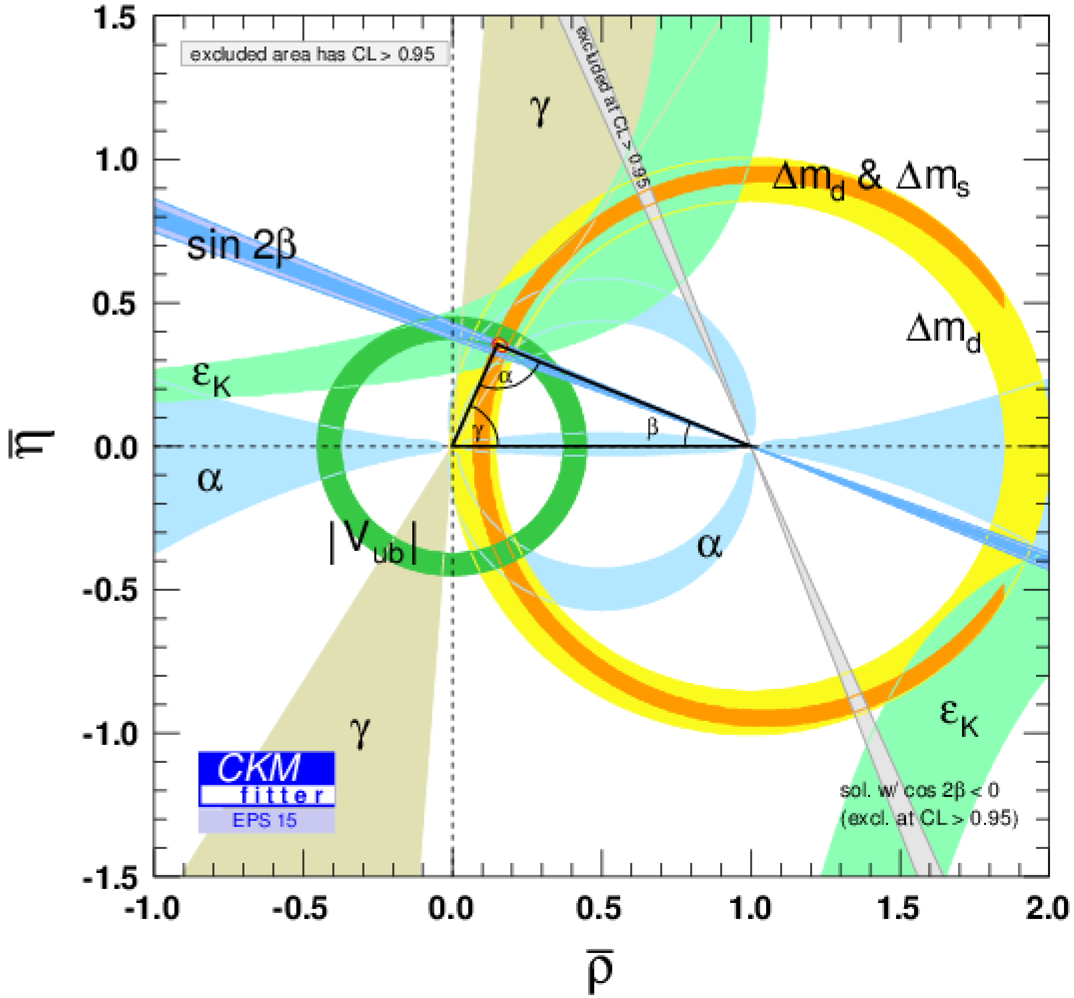
- CP violation in the SM
  - Unitarity triangle(s)
- The experiments and datasets
  - Belle and Babar
  - LHCb (+Atlas/CMS)
- The measurements
  - $\beta \equiv \phi_1$
  - $\gamma \equiv \phi_3$
  - $\alpha \equiv \phi_2$
  - ϕ_s
- Outlook



Prof Sir Cristopher Zeeman FRS
by Peter Douglas Edwards
(Collection: Hertford College, Oxford)

"Imitation is the sincerest form of flattery" – Caleb Charles Colton

- Excellent recent reviews by:
  - Patrick Koppenberg – EPS, Vienna
  - Kenkichi Miyabayashi – LP, Ljubljana
- Invaluable resources
  - Heavy Flavour Averaging Group – Unitarity Triangle
    - http://www.slac.stanford.edu/xorg/hfag/triangle/index.html
    - Primary contact: T. Gershon, Warwick
  - CKMfitter (2015 update)
    - http://ckmfitter.in2p3.fr/
    - **Disclaimer: there are other fitters available**
- This talk in the context of other speakers:
  - Val Gibson – related measurements
  - Peng Haiping - CP violation in Charm
  - Gagan Mohanty – sides of the triangle
  - Cristina Lazzeroni – kaon physics….where it all began



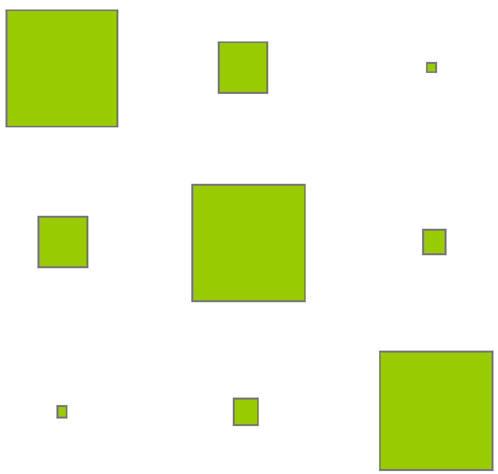
CPV IN THE STANDARD MODEL

CKM matrix

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

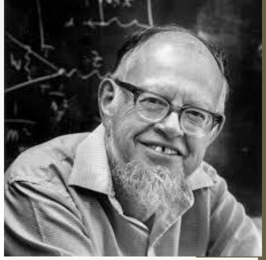
- Extension of Cabibbo's two by two mixing matrix
  - Kobayashi-Maskawa proposed third generation to explain observed CP violation in kaon decays
- 3×3 unitary complex matrix
  - 4 parameters
  - 3 mixing angle and 1 phase
- Intergenerational coupling disfavoured

Relative magnitude of elements



Responsible for CP violation

Wolfenstein parametrisation – the path to the triangle



1923-2015

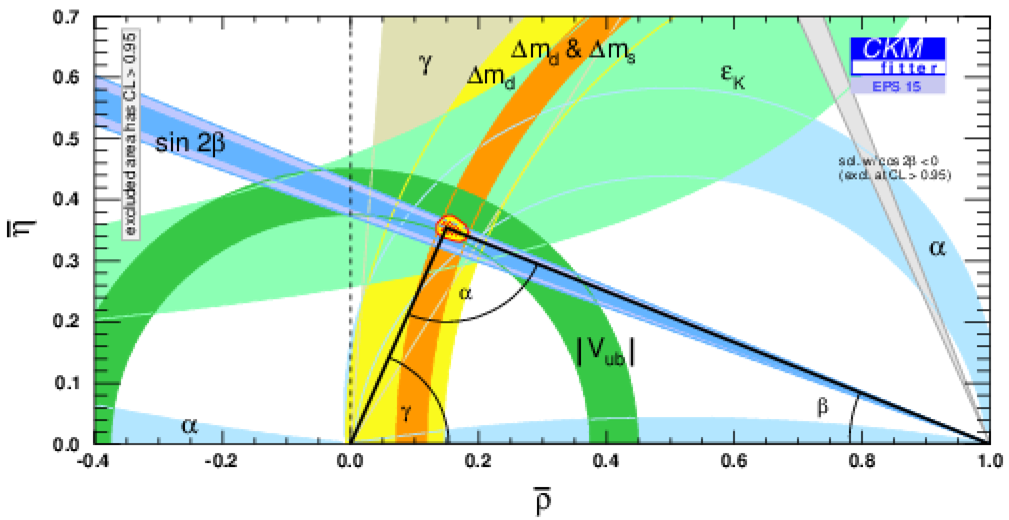
1) $$\begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3\left[1-(\rho-i\eta)\right] & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

$$\lambda = \sin\theta_C$$

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

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

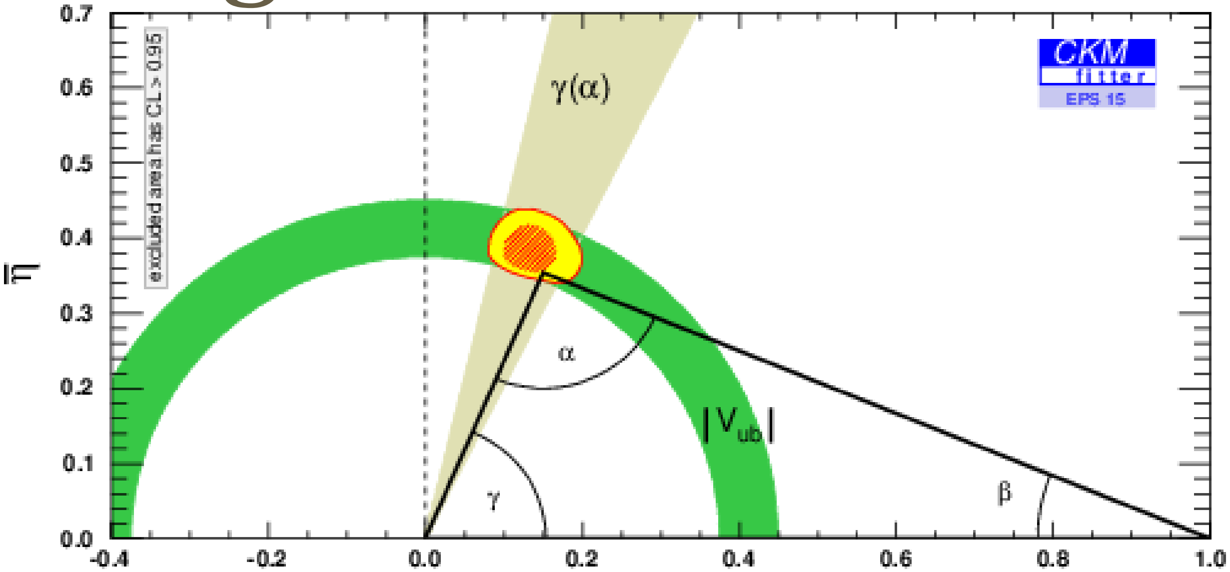
3)



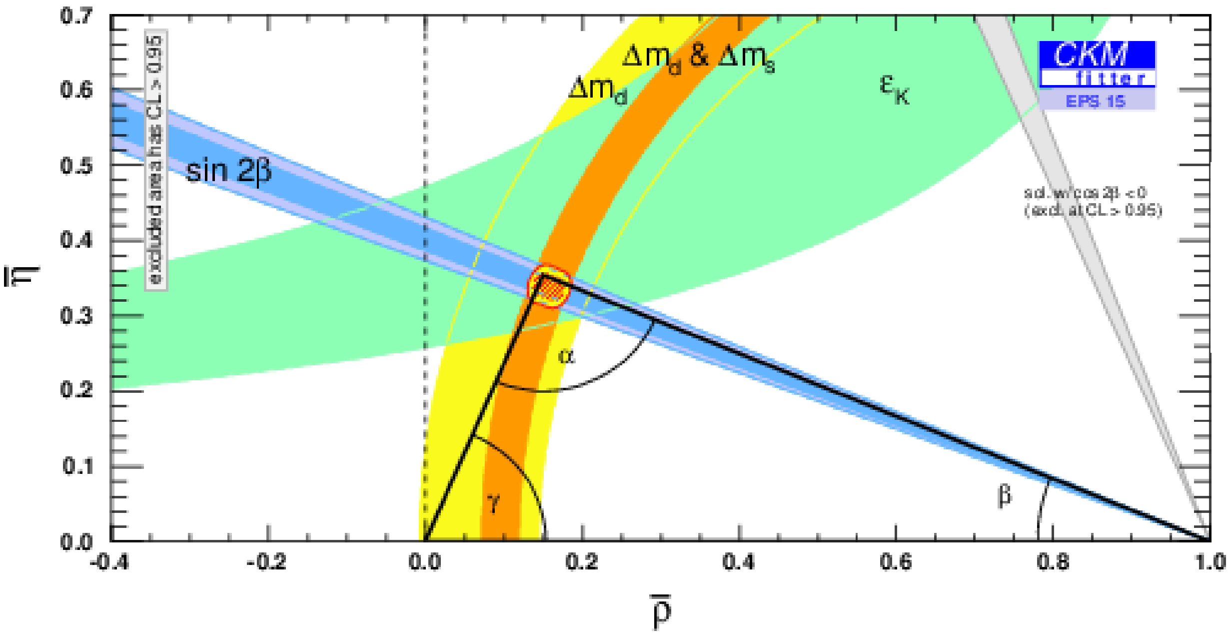
$$\beta = \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right)$$

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

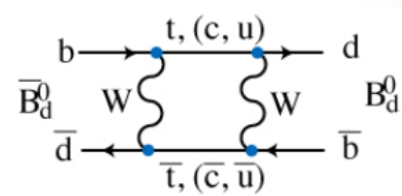
The goal: over constraint



Tree level only



Loop-level only

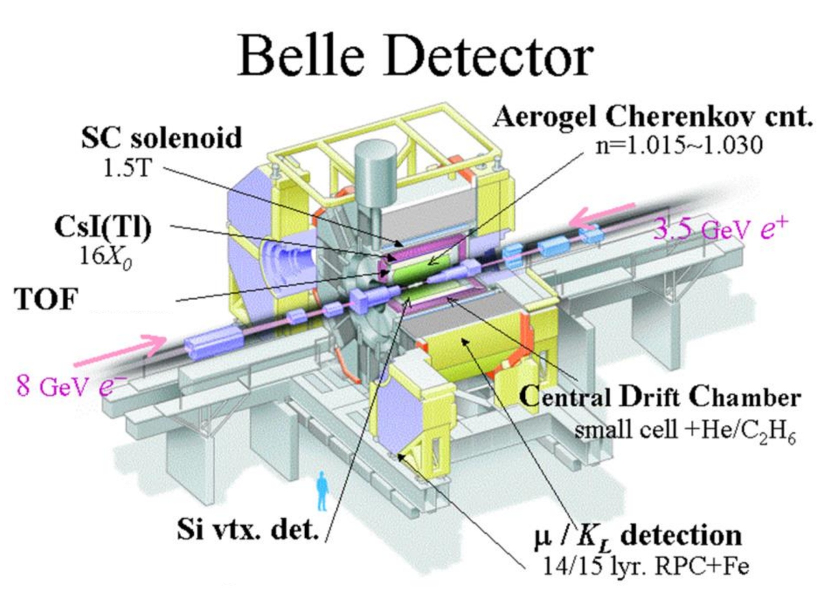


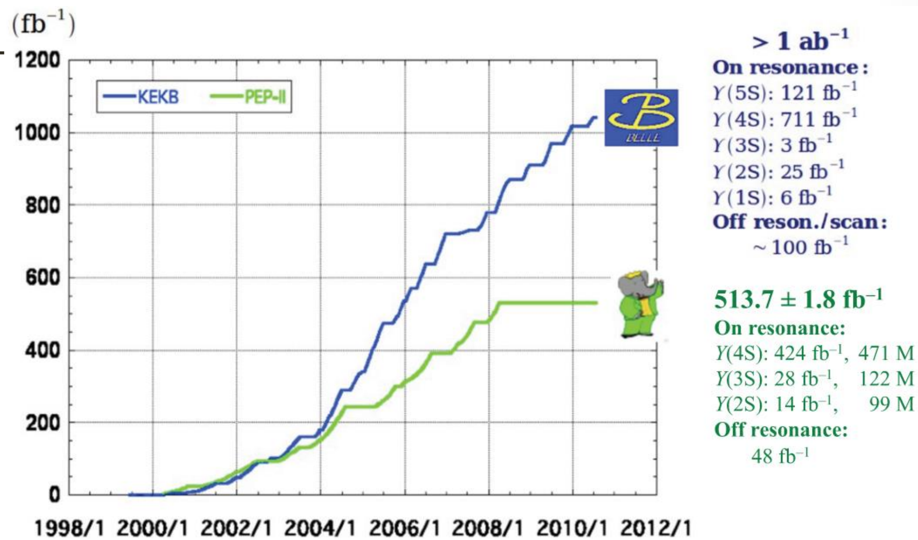
NP at O(>TeV)?

EXPERIMENTS AND DATASETS

e^+e^- B-factories

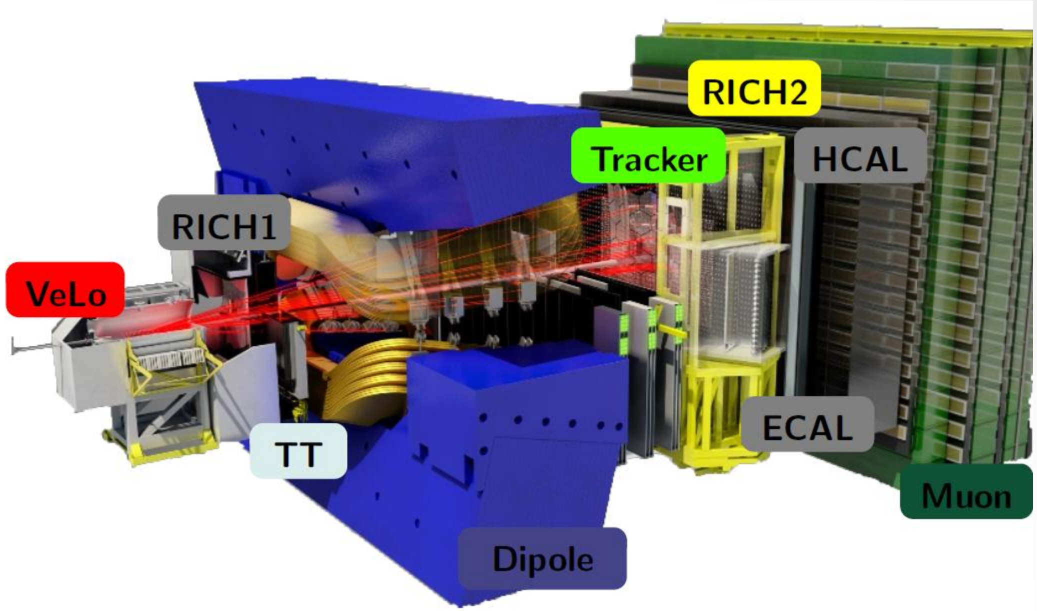
- Operation from 1999 to 2009 (BABAR)/2010 (Belle)
- $e^+e^- \to \Upsilon(4S) \to B\bar{B}$ for CKM measurements
- Asymmetric energy to allow time-dependent measurements
- Coherent production of $B^0\overline{B^0}$
- Low multiplicity
- Detectors with good tracking, PID and calorimetry
  - plus hermeticity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



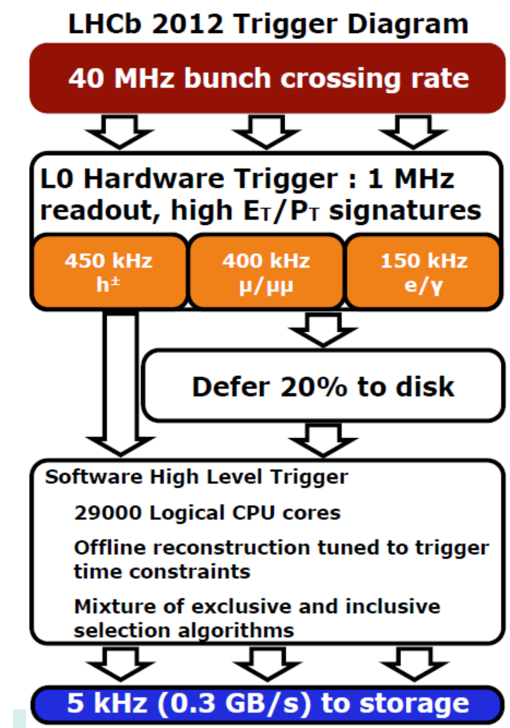


LHCb

- 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: 5kHz rate to tape
- Data set
  - 1 fb^{-1} @ 7 TeV
  - 2 fb^{-1} @ 8 TeV



PHYSICAL REVIEW D VOLUME 23, NUMBER 7 1 APRIL 1981

CP violation in *B*-meson decays

Ashton B. Carter and A. I. Sanda
The Rockefeller University, New York, New York 10021
(Received 27 June 1980)

+ **Notes on the observability of CP violations in B decays**
I Bigi and A. I. Sanda, Nucl. Phys. **B193** (1981)

Physics in Collisions I – Blacksburg, VA - 1981

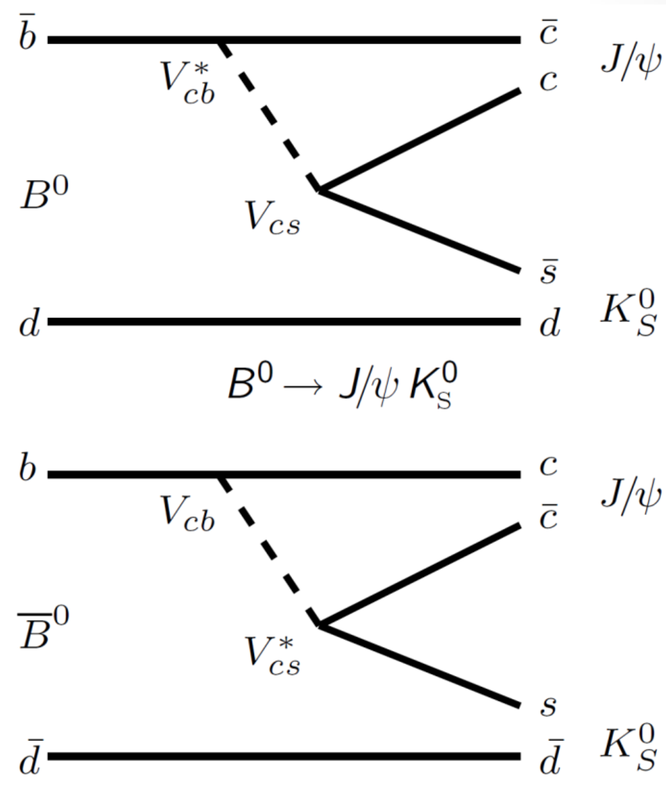
$\beta \equiv \phi_1$

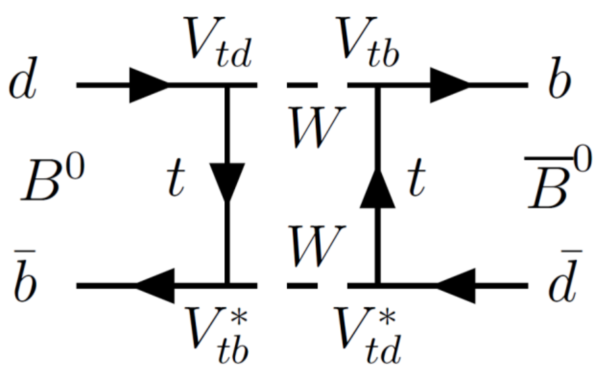
The Golden Mode

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





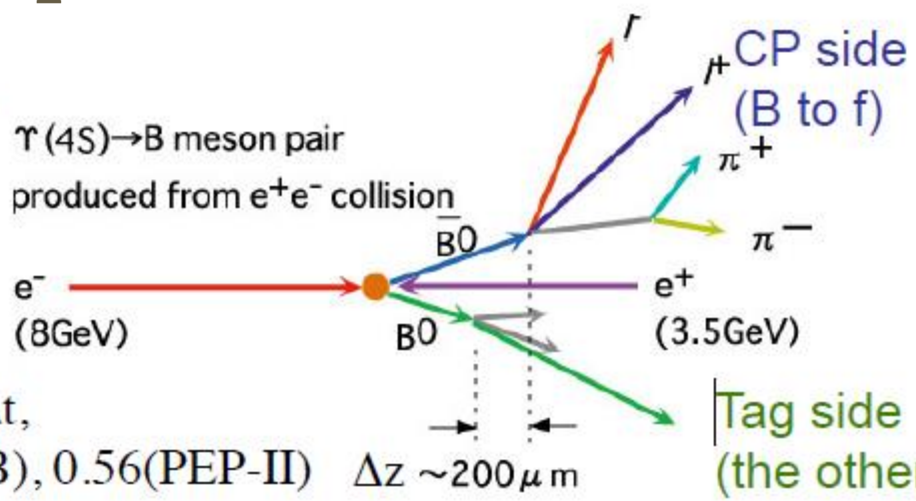
$$A_{CP}(\Delta t) = \frac{\Gamma\left[\overline{B}^0(\Delta t) \to f\right] - \Gamma\left[B^0(\Delta t) \to f\right]}{\Gamma\left[\overline{B}^0(\Delta t) \to f\right] + \Gamma\left[B^0(\Delta t) \to f\right]} = S_f \sin(\Delta m_d \Delta t) - C_f \cos(\Delta m_d \Delta t)$$

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

$\eta_f = CP$ eigenvalue of f

Time-dependent CPV violation

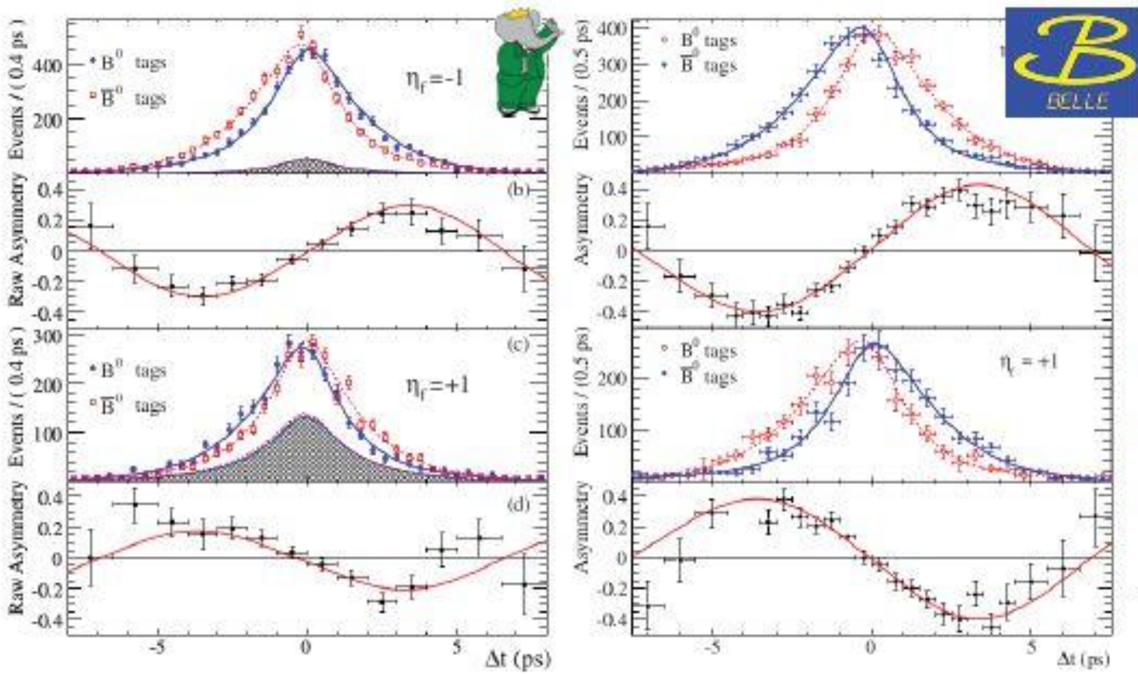
In order to see CPV by interference between decay and mixing.

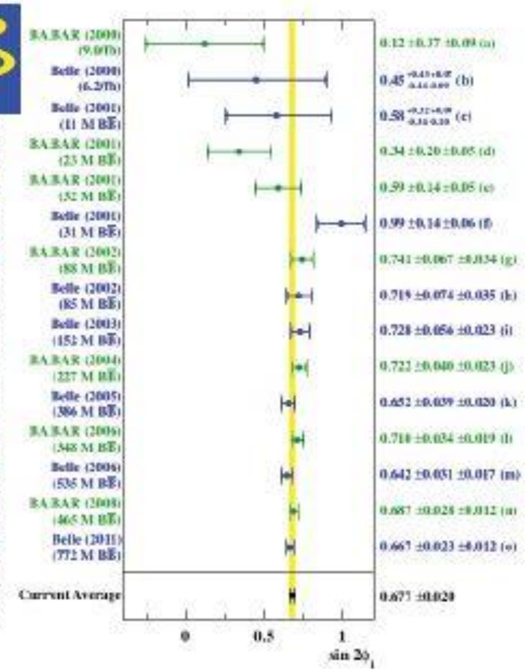


Tagging power $= \varepsilon(1-2\omega)^2 \approx 30\%$

$\Delta z = \beta\gamma c \Delta t$,

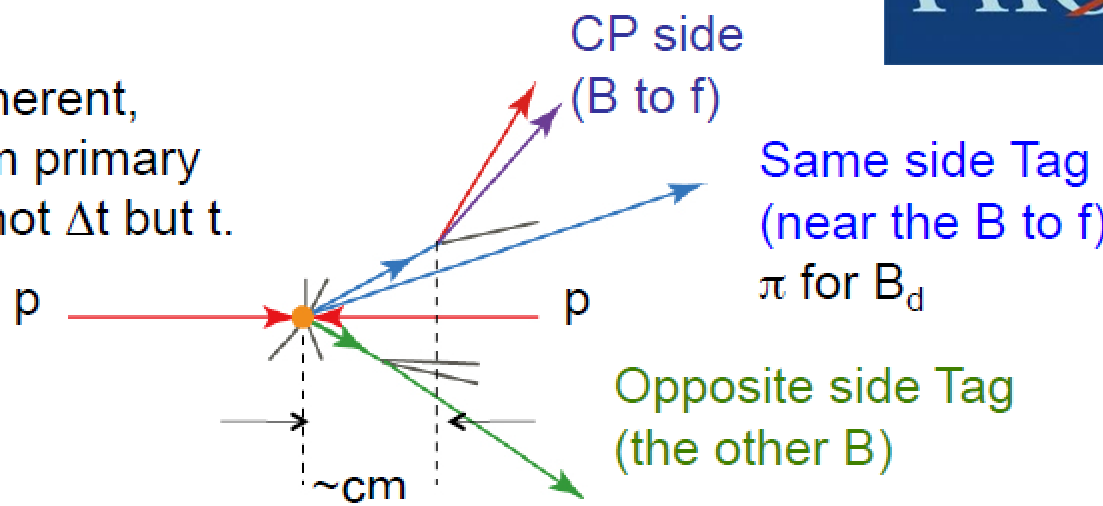
$\beta\gamma = 0.425$(KEKB), 0.56(PEP-II)

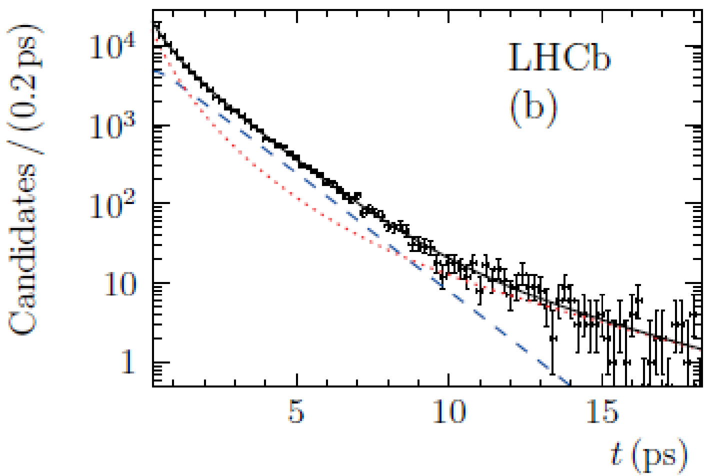




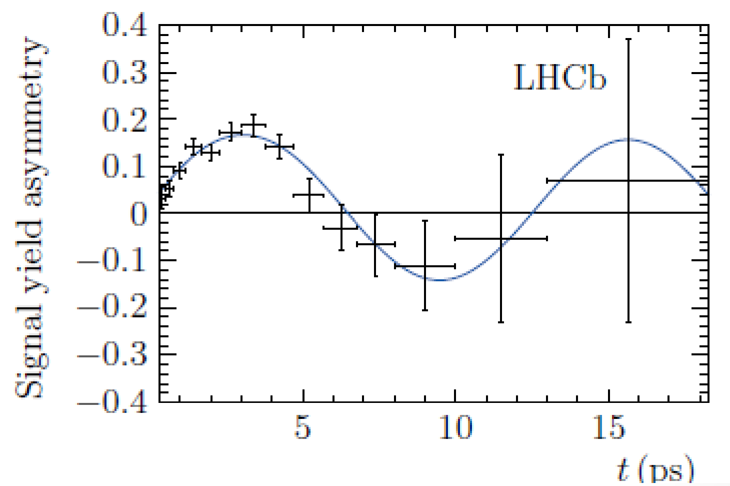
LHCb result

Oscillation is incoherent, time evolution from primary production point, not Δt but t.



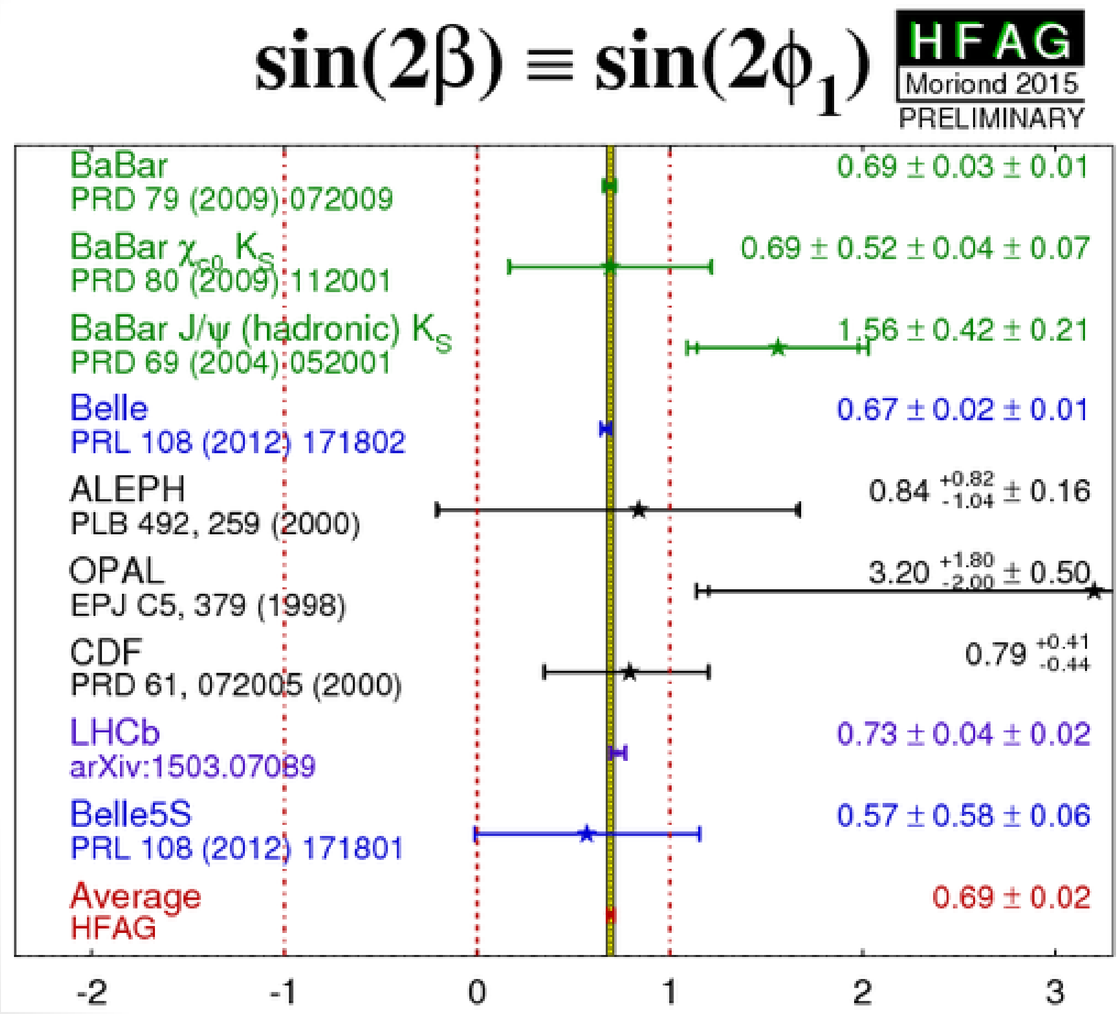


Tagging power = (2.99±0.03)%



$$S = 0.731 \pm 0.035 \pm 0.020$$
$$C = -0.038 \pm 0.032 \pm 0.005$$

Comparison of measurements



Consistency amongst the measurements

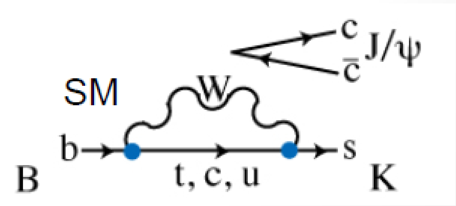
Systematics largely derived from data control samples

The SM prediction excluding this measurements is

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

[CKMFitter]

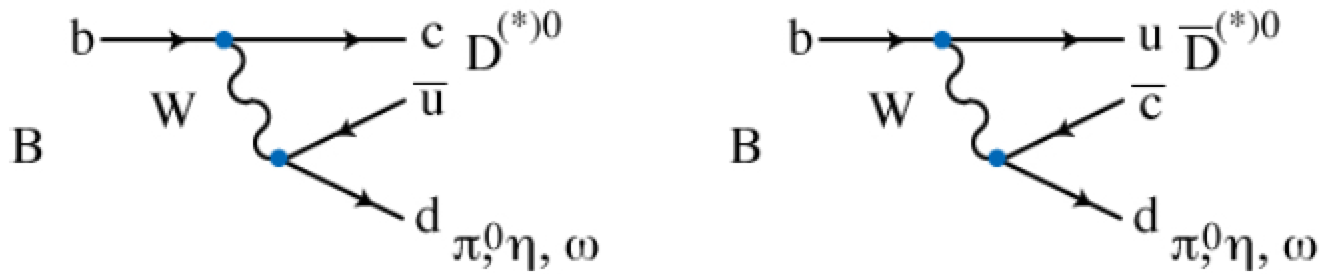
Control of loop/penguin contribution important – See V. Gibson's talk



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^-
- Branching fraction is limiting factor

Accepted by PRL
arXiv: 1505.04147

Combined 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:

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

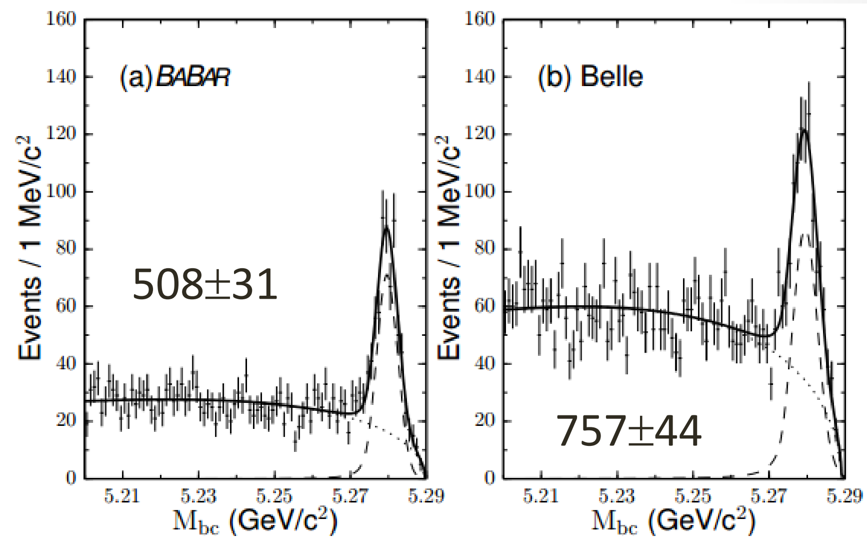
$$D \rightarrow K_S^0\pi^0, K_S^0\omega, K^+K^-$$

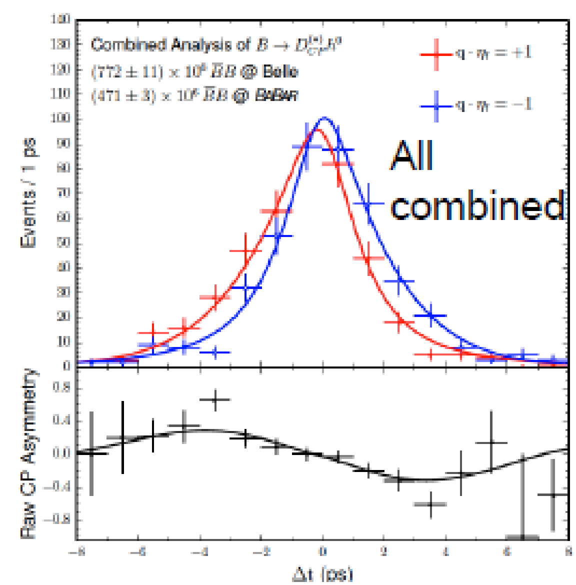
$$D^* \rightarrow D\left(K_S^0\pi^0\right)\pi^0$$

- > 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





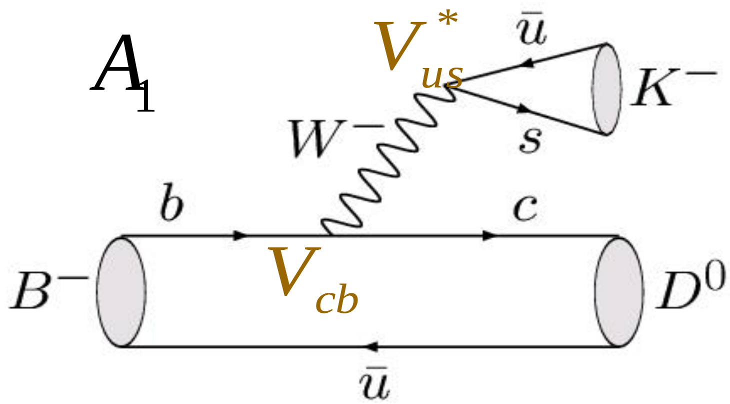
~~Roman~~ Candle

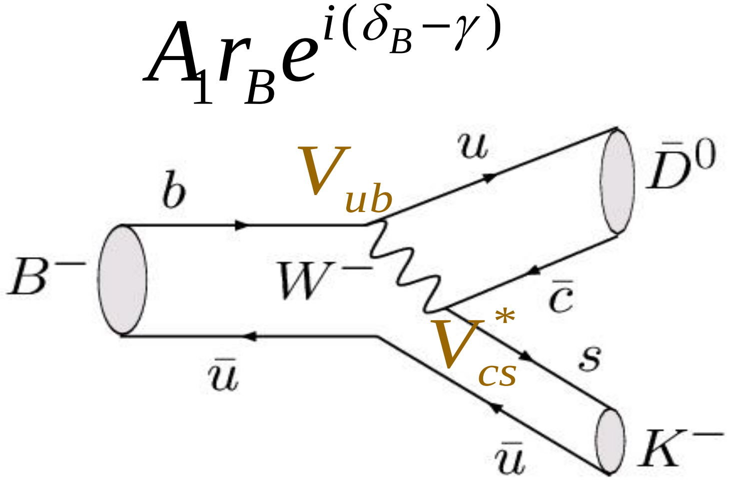
* Factory in same state as Madras (but not too near)

$\gamma \equiv \phi_3$

$B \rightarrow DK$

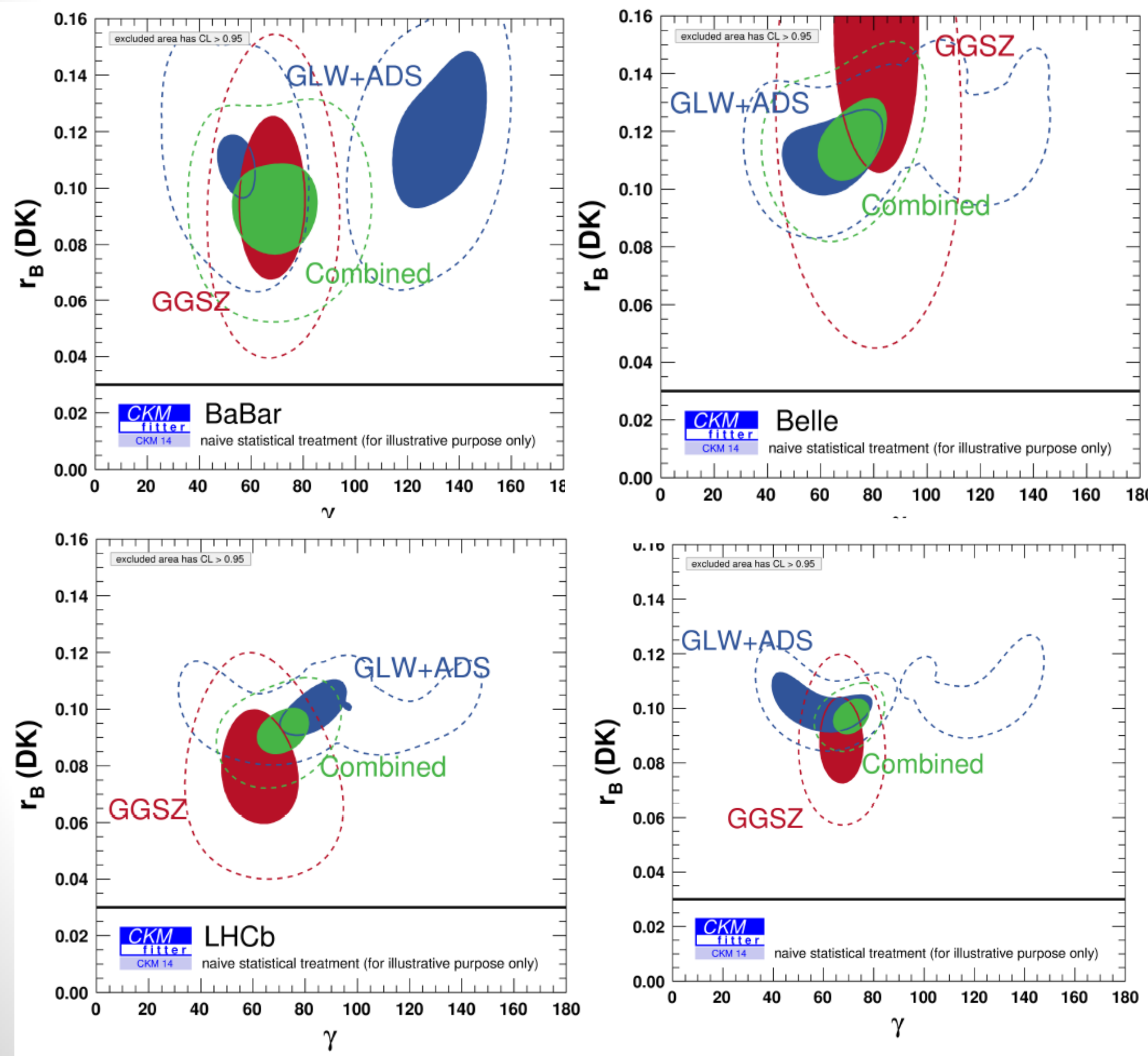
- Tree-level determination γ





- 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)

World average – no change



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

$$r_B = (0.097 \pm 0.006)$$

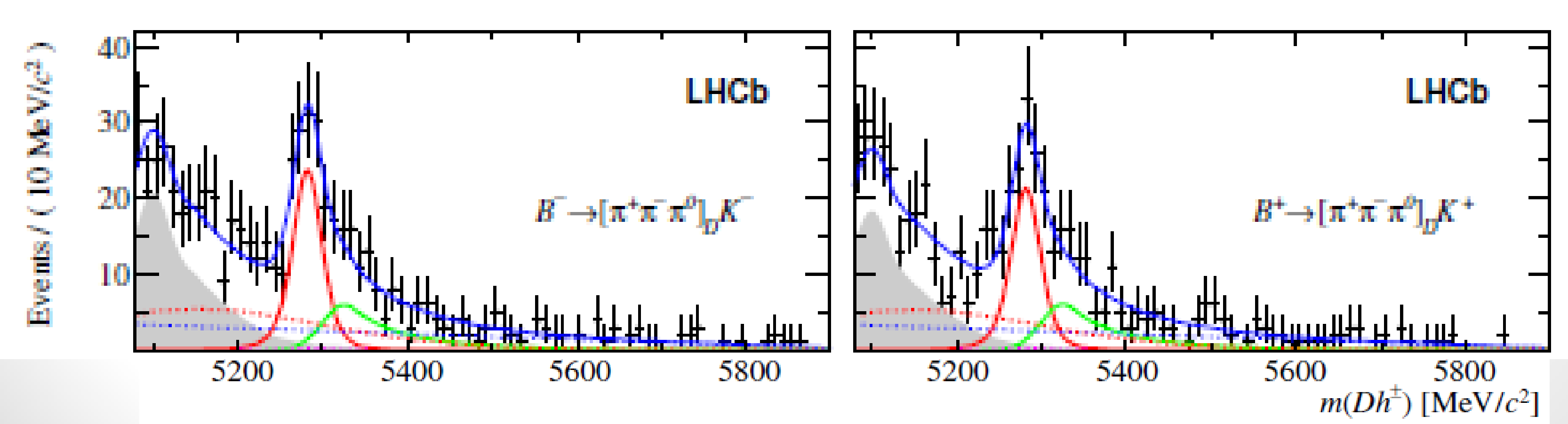
$$\delta_B = (125.4^{+7.0}_{-7.8})^\circ$$

Mixing and DCPV corrected

No $B_s \to D_s K$ or $B \to D\pi$

ADS/GLW with $D \to hh\pi^0$

- Any $D \to K^+X^-$ ($X^- = \pi^-$, $\pi^-\pi^0$, $\pi^-\pi^-\pi^+$) can exhibit significant DCPV
- - Atwood & Soni: PRD 68 033003 (2003)
- However, the D strong phase difference varies over phase space for three or more body final states – can dilute DCPV effects
- Correlated $D\overline{D}$ production is used to quantified this dilution – so called **coherence factor**
  - **CLEO-c data**: PLB, **731C** (2014), 197
  - $K^+\pi^-\pi^0$ coherent – can observe DCPV
- Also from CLEO-c data show $D \to \pi\pi\pi^0$ is an almost pure CP even eigenstate – additional GLW mode: PLB **740B** 1 (2015)



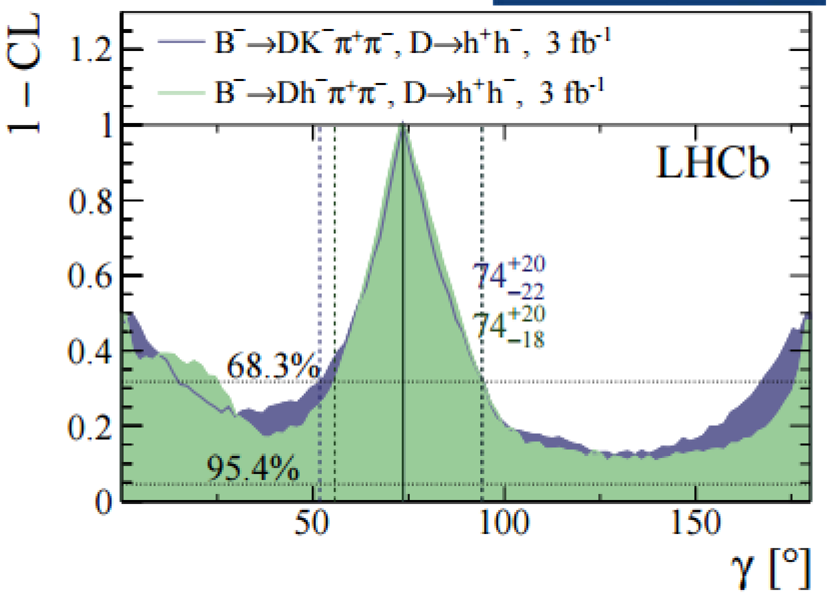
arXiv:1505.07044

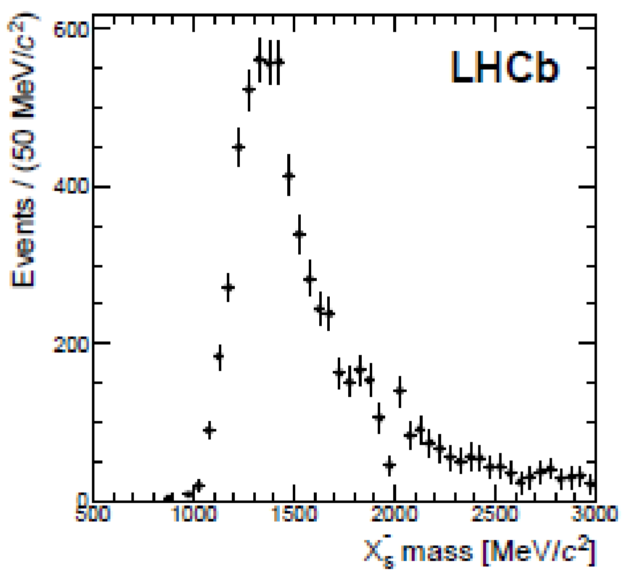
B→DKππ

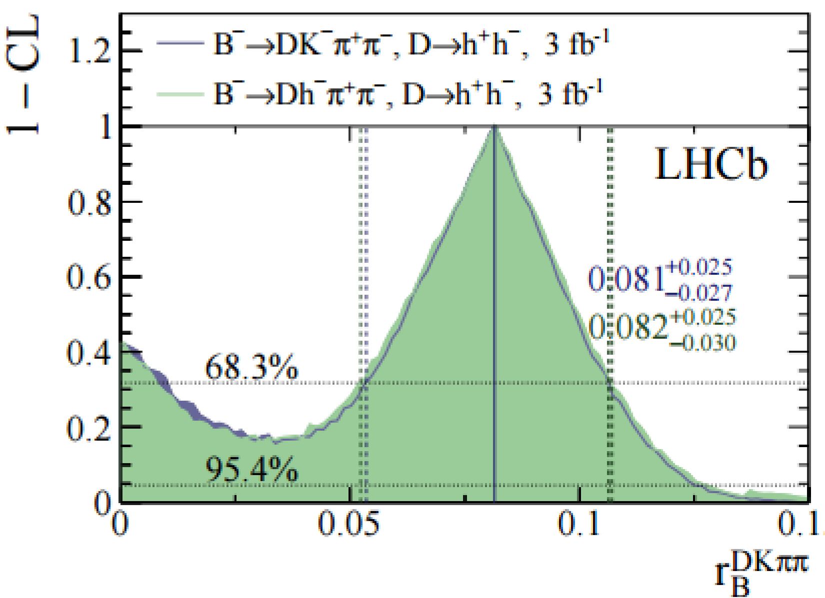
Same underlying tree decays but with X_s=Kππ instead of a K

Non-trivial constraint on γ combining all $D \to h^+h^-$ ADS/GLW modes

All such extensions add useful information to the global determination







Kowolski: Physics Coordinator

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

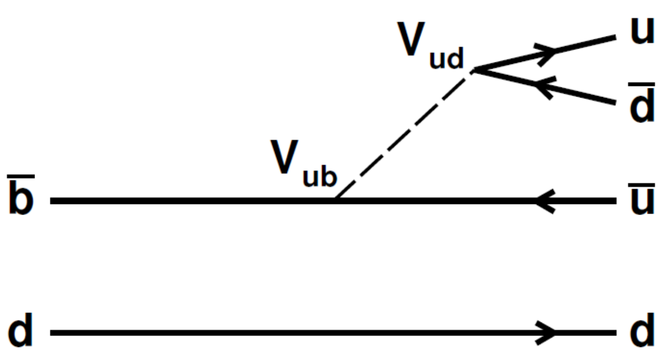
Private:
Graduate student

Skipper: Spokesman

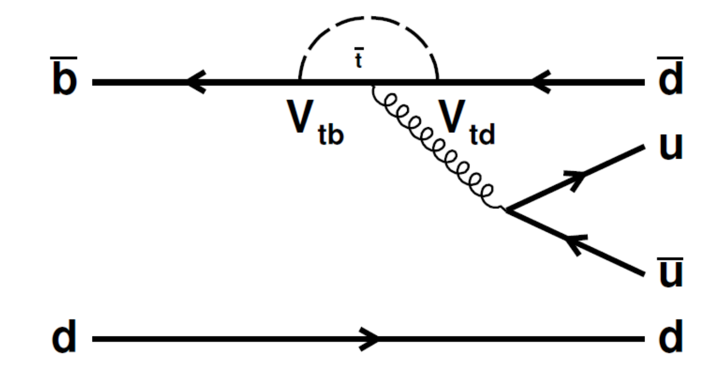
$\alpha \equiv \phi_2$

Sensitivity to α

- If there was only a tree level contribution, time-dependent CP violation in the interference between mixing and decay in $B^0 \to \pi^+\pi^-$ and $B^0 \to \rho^+\rho^-$ then s_f = sin2α
- But interference with $b \to d$ penguin amplitude destroys this simple relation



Tree

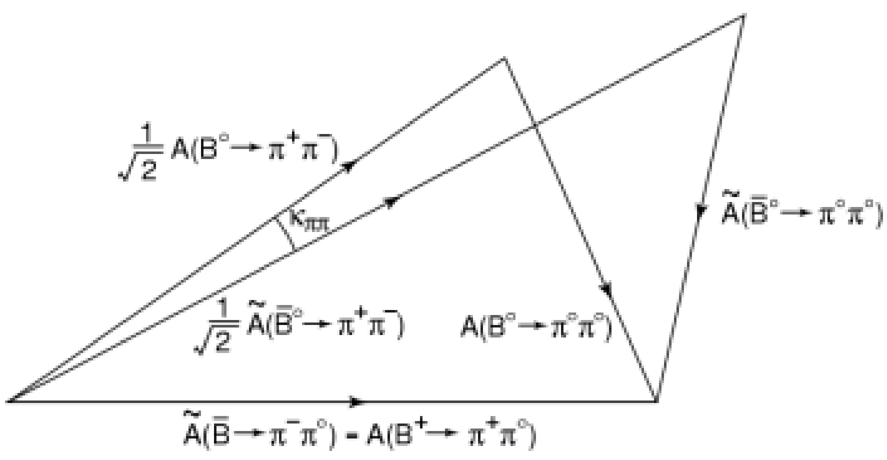


Penguin

Isospin analysis

Gronau-London
Phys. Rev. Lett. **65**, 3381

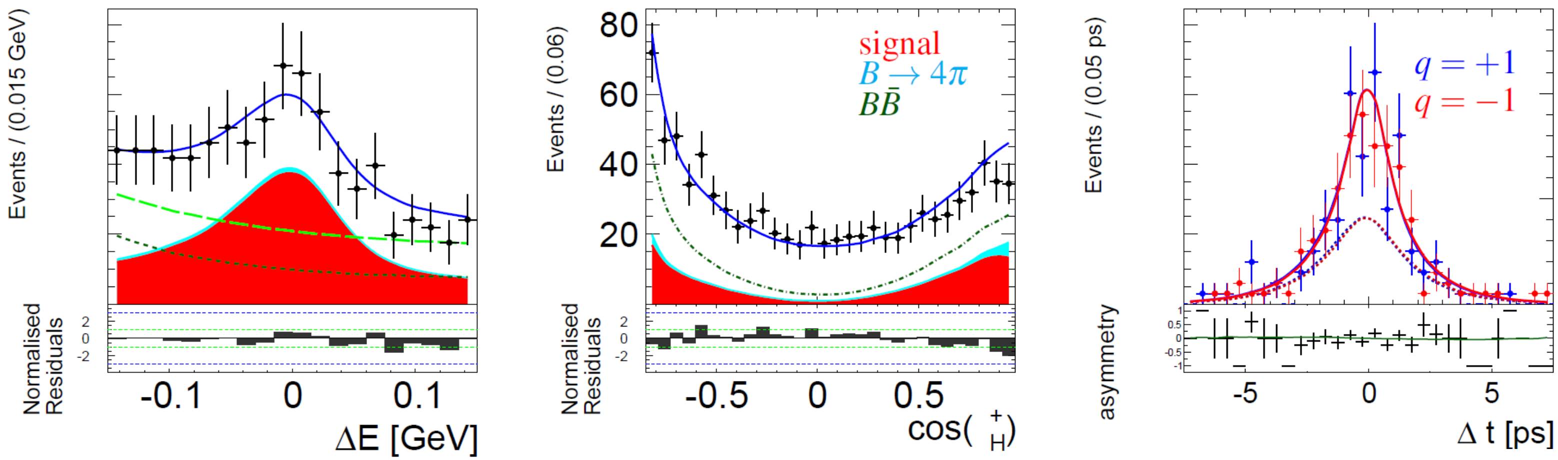
- An isospin analysis allows a constraint on α to be extracted from the ππ/ρρ system even in the presence of non-negligible penguin contributions.
- The isospin analysis uses as input the branching fractions and CP-violating asymmetries of all three ππ or longitudinal components of ρρ decay modes i.e $\rho^+\rho^-$, $\rho^-\rho^0$, $\rho^0\rho^0$
  - A similar analysis could be done for each polarisation amplitude, but the others are found to not be statistically significant.



$B^0 \to \rho^+\rho^-$

Preliminary

- Time-dependent angular analysis of full $\Upsilon(4S)$
  - Two-fold improvement in precision over previous result



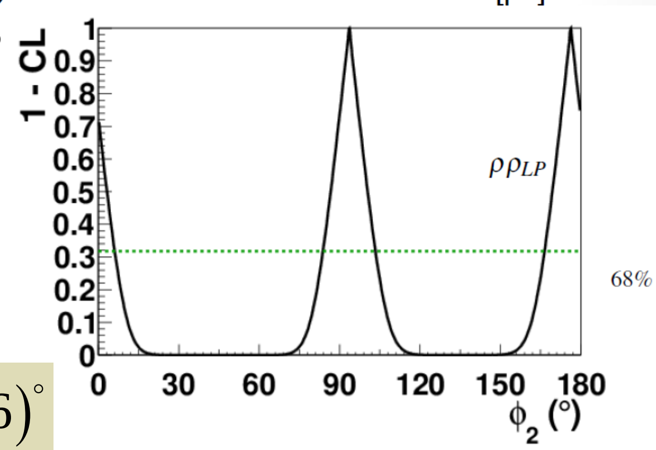
$$B(B^0 \to \rho^+\rho^-) = (28.3 \pm 1.5 \pm 1.4) \times 10^{-6}$$

$$f_L = 0.988 \pm 0.012 \pm 0.23$$

$$S = -0.13 \pm 0.15 \pm 0.05$$

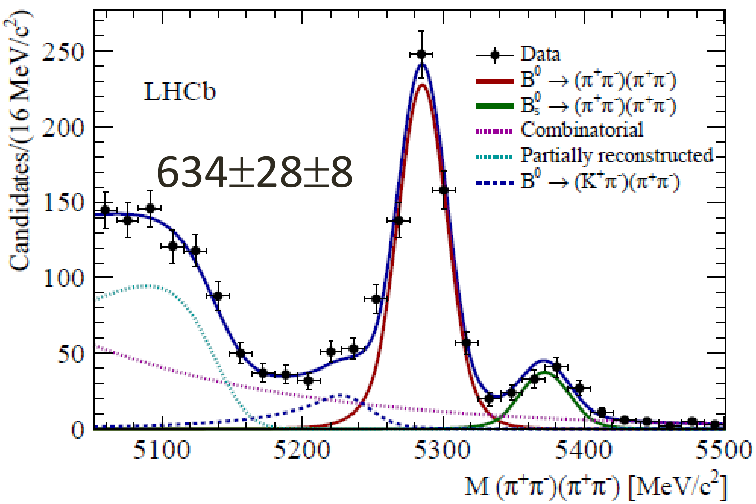
$$C = \quad 0.00 \pm 0.10 \pm 0.06$$

$$\alpha_{\text{Belle}} = (93.7 \pm 10.6)^\circ$$



PLB **747** (2015) 468

$B^0 \to \rho^0 \rho^0$



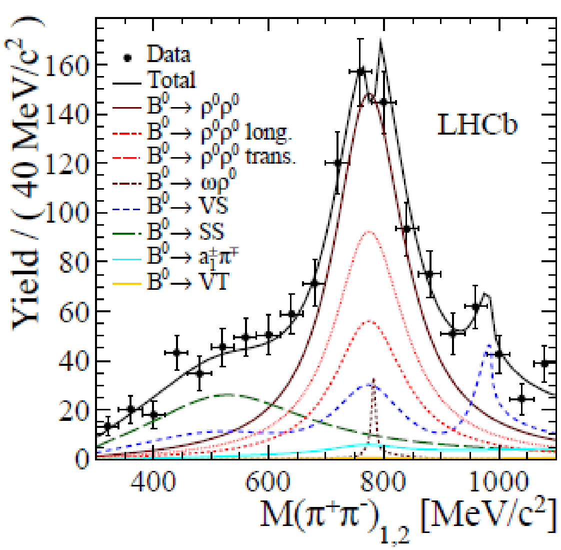
Normalisation to ϕK^*

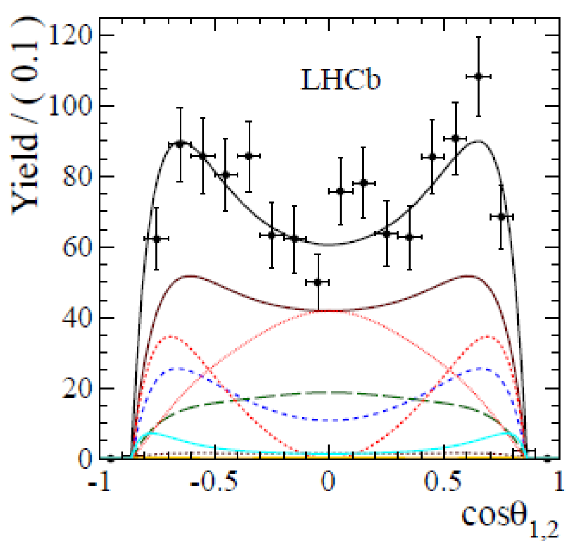
$$f_L = 0.745^{+0.48}_{-0.58} \pm 0.034$$

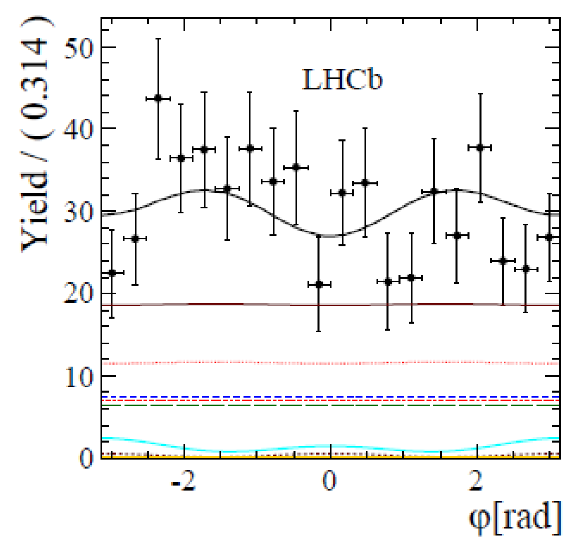
$$B\left(B^0 \to \rho^0 \rho^0\right) = (0.94 \pm 0.17 \pm 0.09 \pm 0.06) \times 10^{-6}$$

Polarization: consistent with BABAR/2.3σ tension with Belle

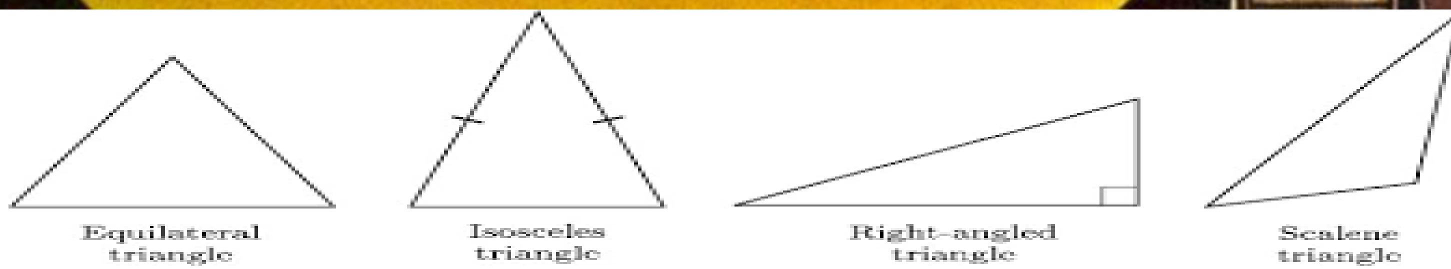
Most precise BF measurement to date will improve α







Terry Gilliam, Monty Python credits



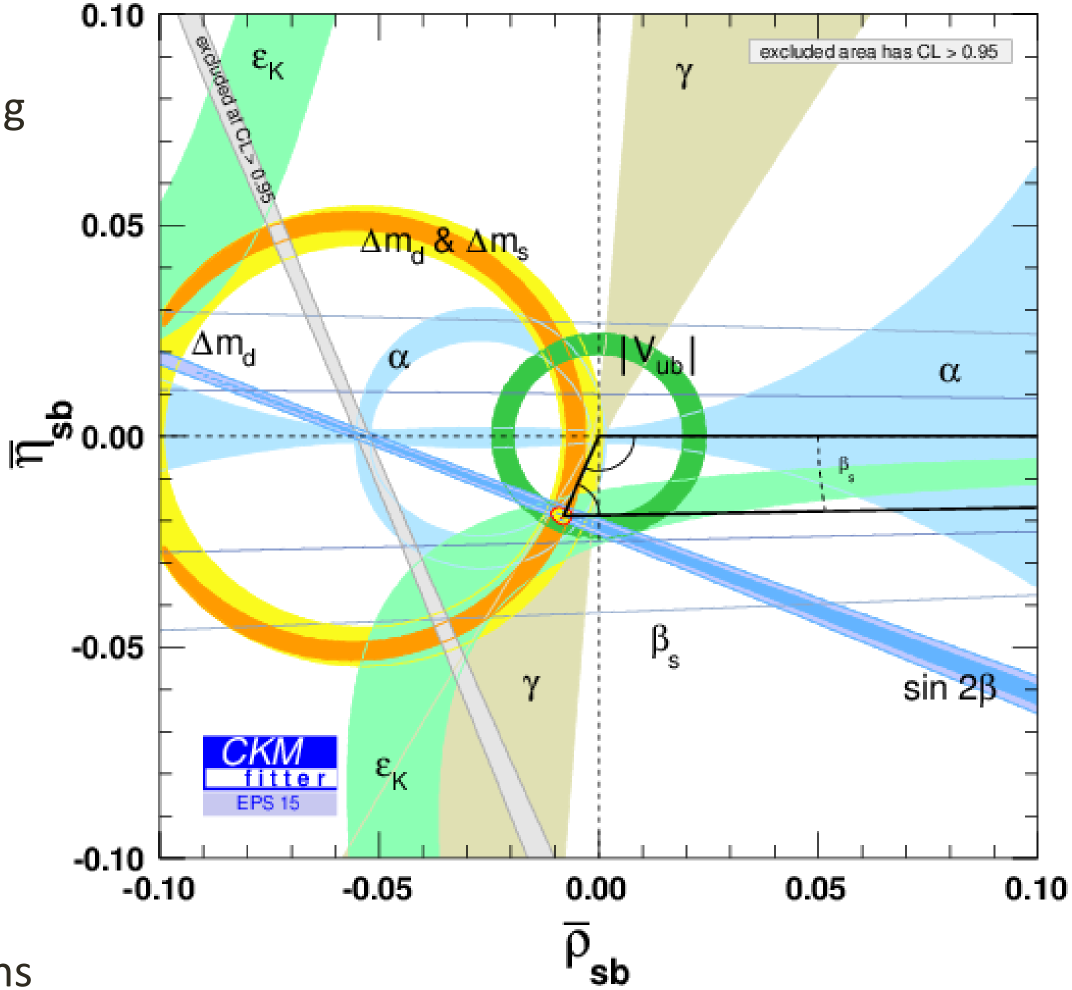
ϕ_S: A SQUASHED TRIANGLE

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

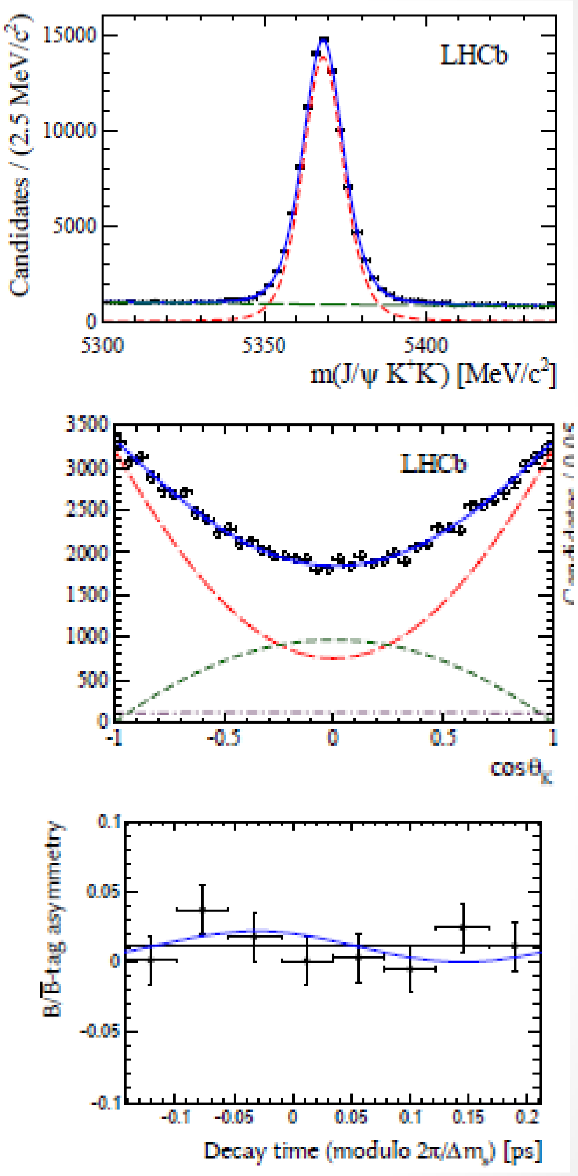
- Full angular analysis of KK invariant mass spectra required to resolve different helicity components and non-VV component

- Tagging power of 3.7%
  - Same side kaon better than pion

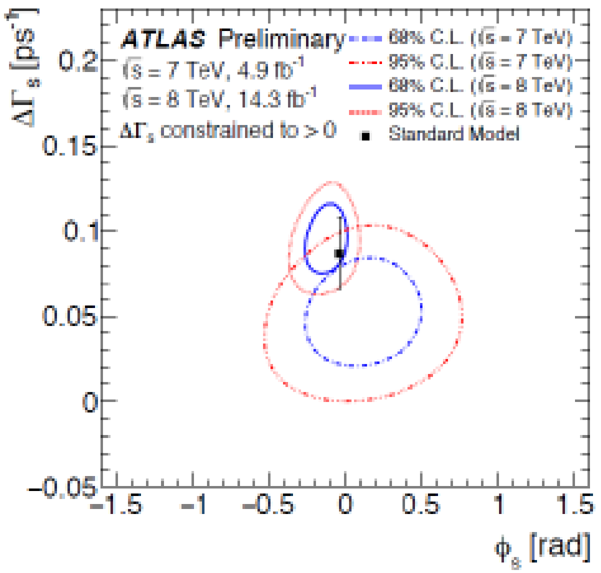
$$\varphi_s = -0.058 \pm 0.049 \pm 0.006\,\text{rad},$$

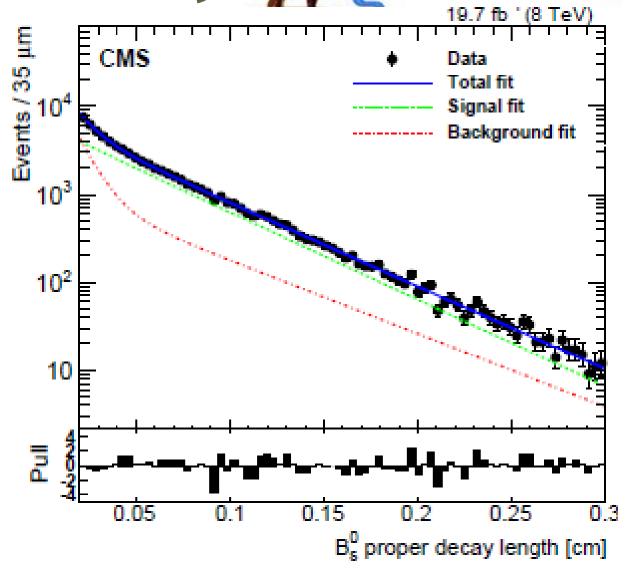
- Also determine the lifetime difference between the different mass eigenstates of the Bs

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



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

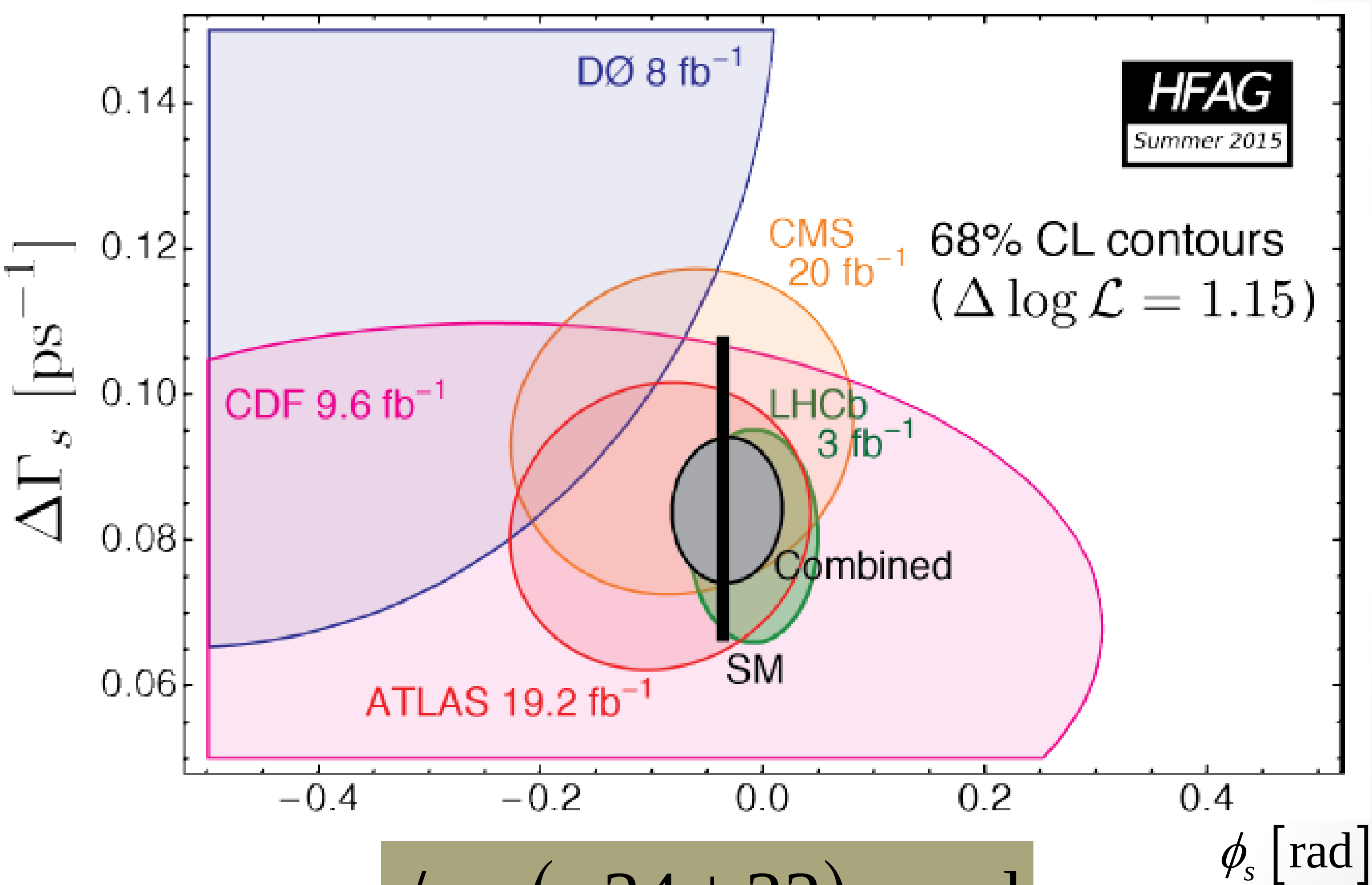




	ATLAS	CMS
Luminosity (fb^{-1})	19.2	19.7
Tagging power (%)	1.49	1.31
ϕ_s (mrad)	$-94\pm63\pm33$	$-75\pm97\pm31$
$\Delta\Gamma_s$ (ps^{-1})	$0.082\pm0.011\pm0.007$	$0.095\pm0.013\pm0.007$

Combination

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



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

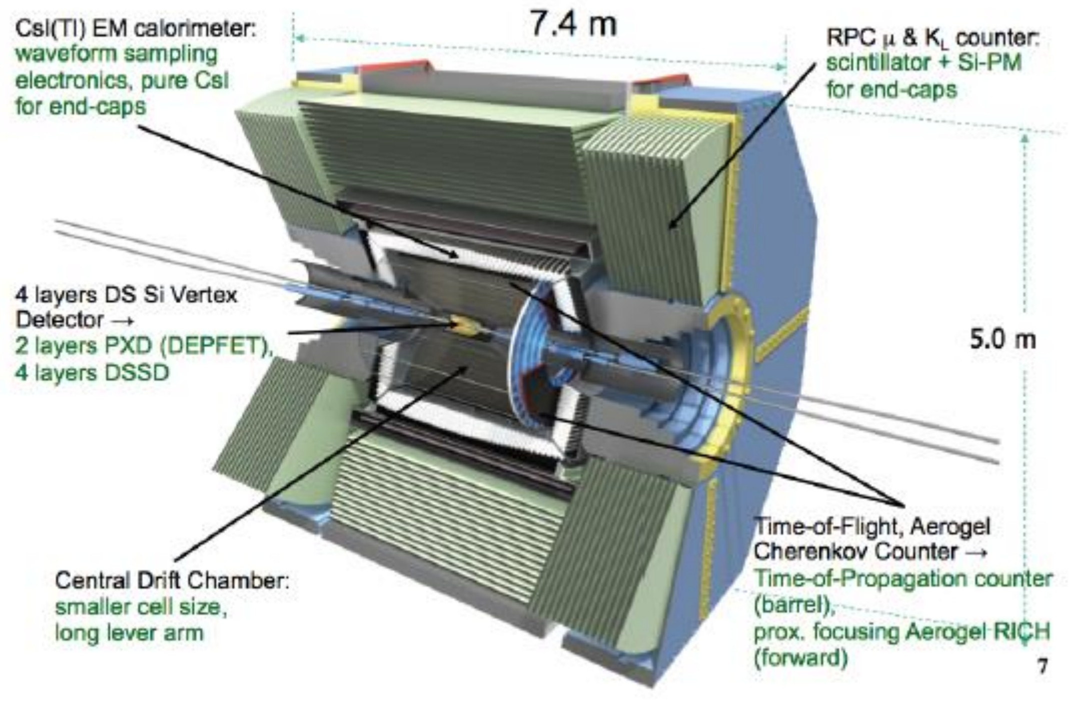
"If you can look into the seeds of time,
And say which grain will grow and which will not,
Speak then to me, who neither beg nor fear
Your favours nor your hate."
(Macbeth act 1, scene 3)

Chandos Portrait, National Portrait Gallery, London

FUTURE PROSPECTS

Belle II

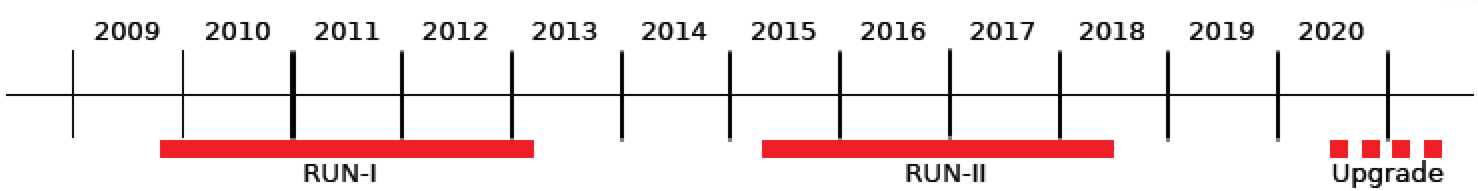
- Goal to produce a 50 ab^{-1} dataset by mid 2020s
- KEKB and Belle detector significant upgrades
- Time of Propagation PID
- Pixel vertexing
- Waveform sampling electromagnetic calorimetry



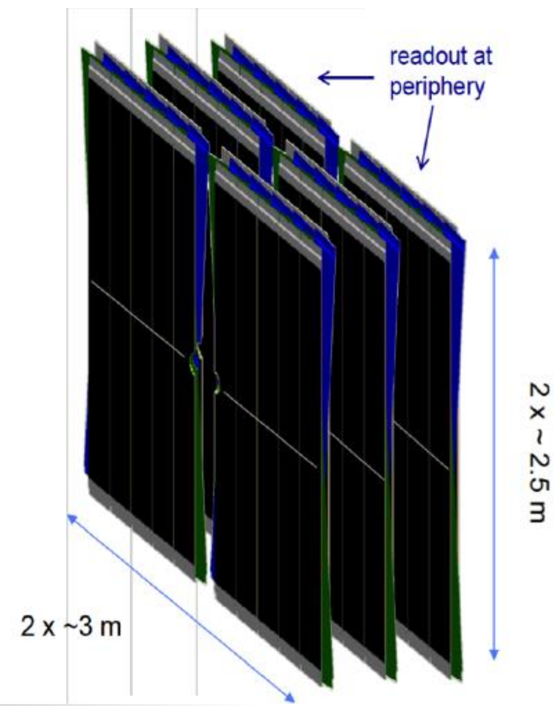
CPV highlights

- Degree level precision for γ and α
- Sub-degree β
- Penguin modes i.e. $K\pi$

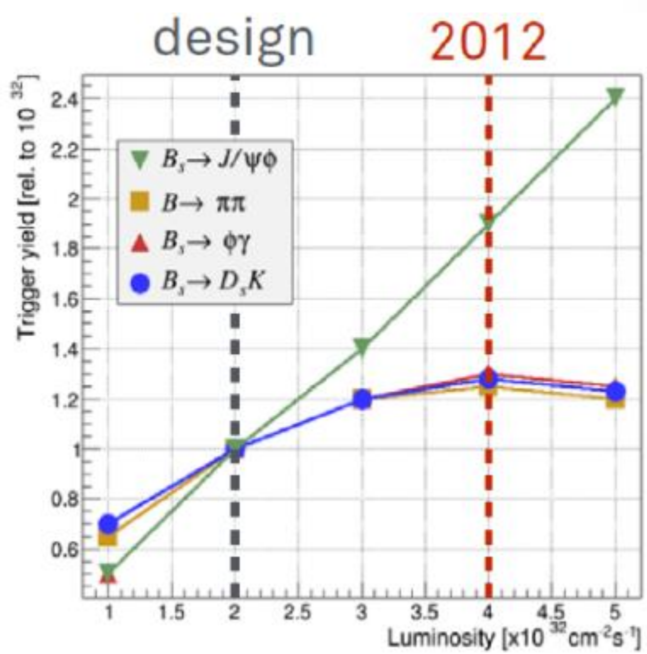
LHCb run 2 and upgrade



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 and all new frontend electronics



SciFi tracker with
Si PM readout



Precisions - just of measurements in this talk

Parameter	PIC XXXV	Belle II	LHCb Upgrade
ϕ_s (mrad)	-34 ± 33	N/A	9
sin2β	0.69 ± 0.02	0.007	0.016
sin2β - tree	0.66 ± 0.12	0.02	N/A
γ (°)	73.2 ± 6.6	1.5	1.1
α (°)	87.6 ± 3.4	1	N/A

More on the physics potential at
https://belle2.cc.kek.jp/~twiki/bin/view/B2TiP (Belle II Theory Interface Platform)

https://twiki.cern.ch/twiki/bin/view/LHCb/LHCbUpgrade

Conclusion

- New results
  - β
    - LHCb $B \rightarrow J/\psi K_s$
    - Belle + BABAR penguin free
  - γ
    - More modes being explored by LHCb
  - α
    - Additional $\rho\rho$ from Belle and LHCb
  - ϕ_s
    - New measurements from LHC experiments
- Future of CPV measurements in the B-system in safe hands
  - Belle II, LHCb run II and upgrade

Concise conclusion

Kobayashi-Maskawa mechanism reigns supreme……for now