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The Mysteries of Flavour

Fergus Wilson

Rutherford Appleton Laboratory/STFC

RAL Academic Lectures

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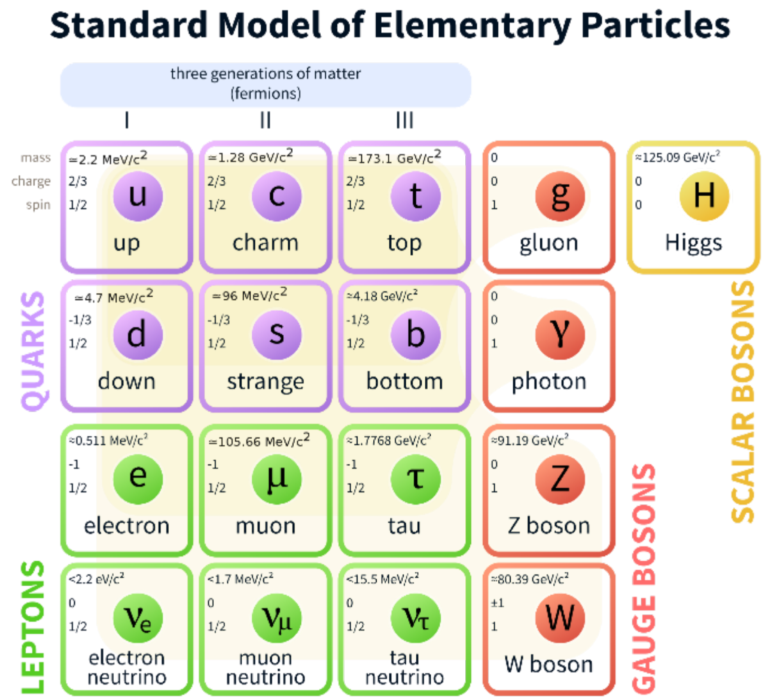
INTRODUCTION

Mysteries of Flavour

- Mystery #1: Why do so many Flavour measurements agree with the Standard Model?
- Mystery #2: Why do some flavour measurements "disagree" with the Standard Model?
- Mystery #3: How can Mysteries 1 and 2 both be true?

Flavour Physics in a nut shell



Precision measurements of the properties of quarks and charged leptons.

Multiple measurements of the same property using different methods.

Comparison between Standard Model predictions and measurements.

Search for New Physics.

Outline – What's in this talk

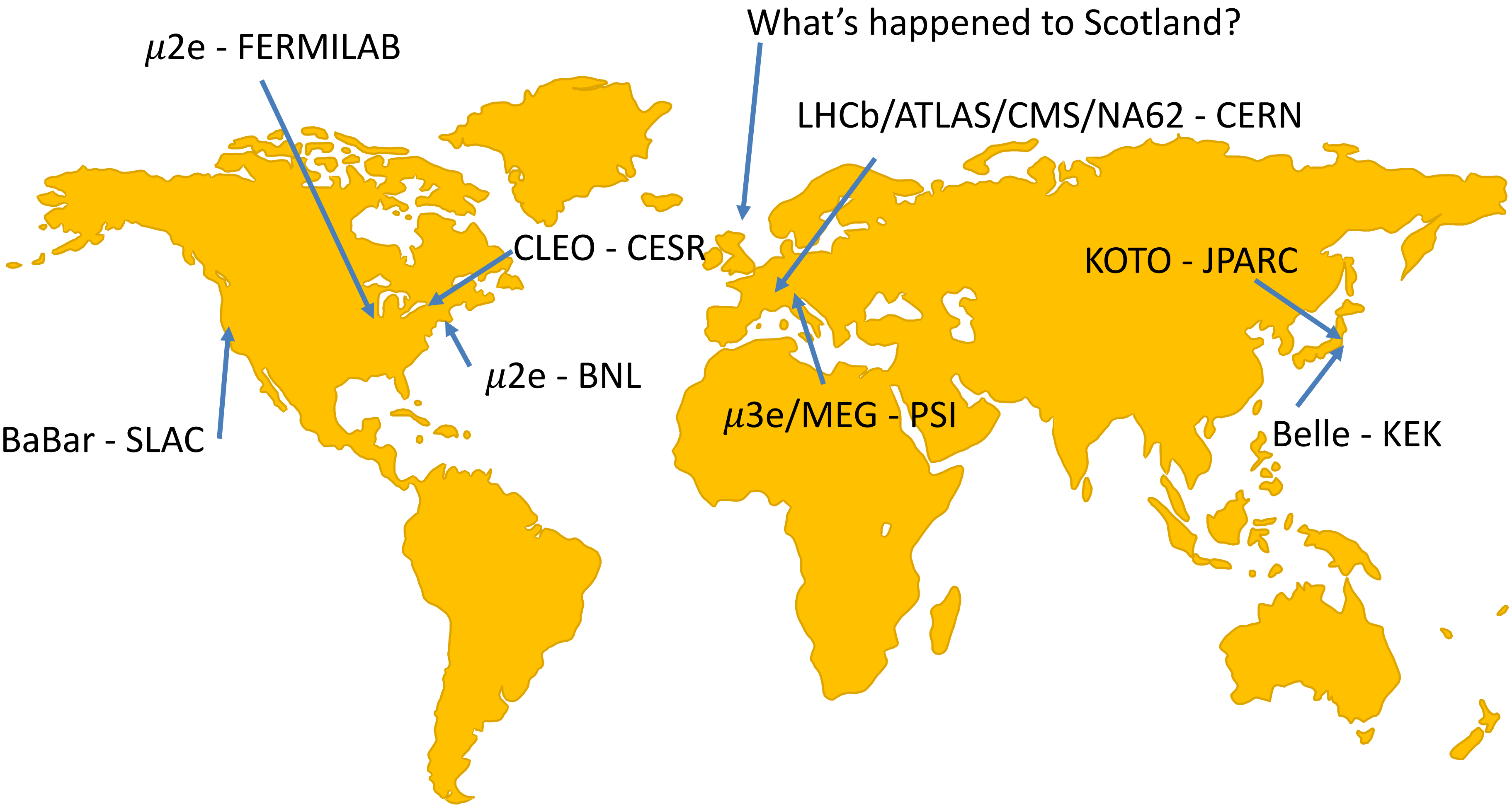
1. Detectors (old and new)
2. CKM matrix
3. Heavy Flavour and rare decays
4. R(X) anomalies
5. Lepton Flavour and Lepton Number Violations
6. Dedicated Charged Lepton Flavour Violation experiments
7. Look to the Future

Outline – What's not in this talk

1. Neutrinos (Dirac and Majorana)
2. Dark Sector searches
3. Long-lived particles
4. Higgs
5. Top quark
6. Tetraquarks/Pentaquarks
7. g-2/EDM

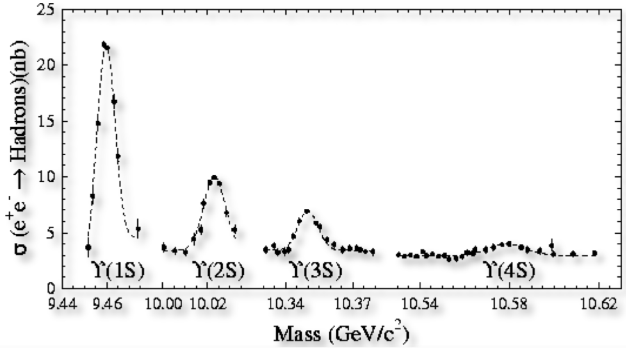
(Flavour) Detectors

Detectors worldmap

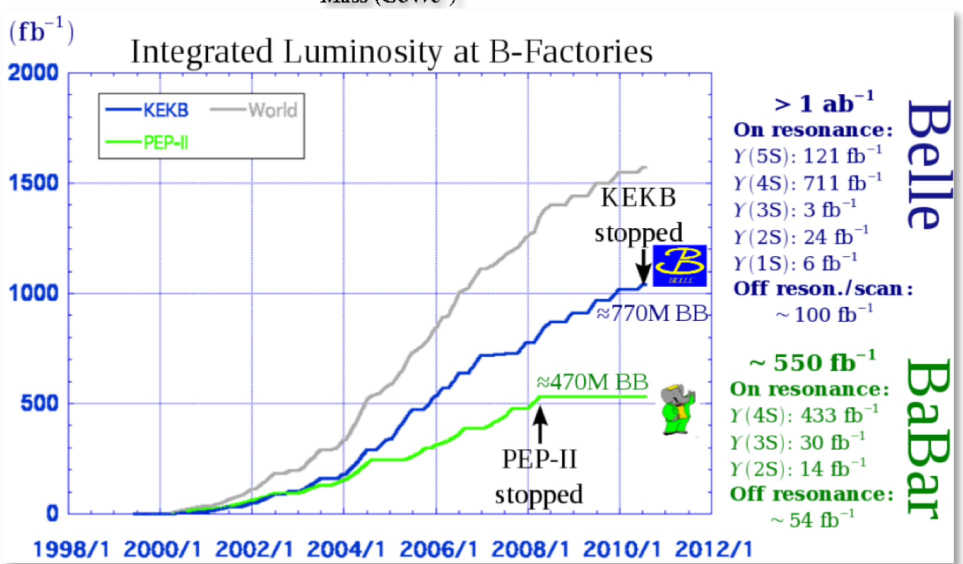


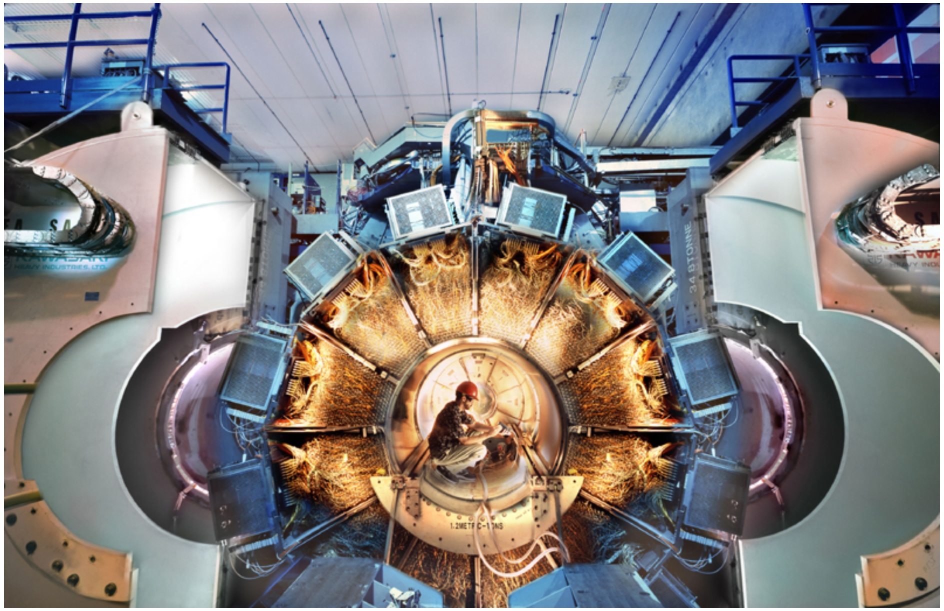
BaBar (US) and Belle (Japan): 1999 - 2010

- Asymmetric beam energies colliding e^+ and e^- at the $\Upsilon(4S)$ resonance
  - $\Upsilon(4S) \rightarrow B^0/\bar{B}^0, B^+/B^-$
  - BaBar+Belle collected 1.1 ab^{-1} (1.24 billion B pairs) at $\Upsilon(4S)$.

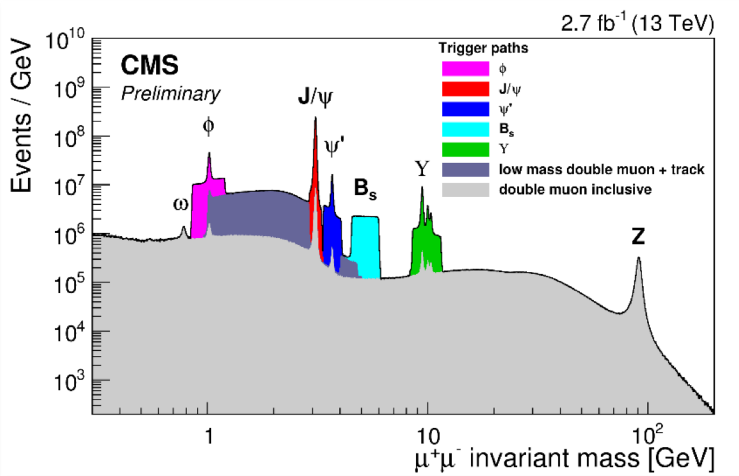


Advantages	**Known initial state, low backgrounds, good tagging efficiency (30%), good neutral detection, quantum correlated B production, almost hermetic detectors**
Disadvantages	Production x-section ~1 nb, limited B_s production, no B_c, no high mass baryons, limited Υ(1,2,3,5S).

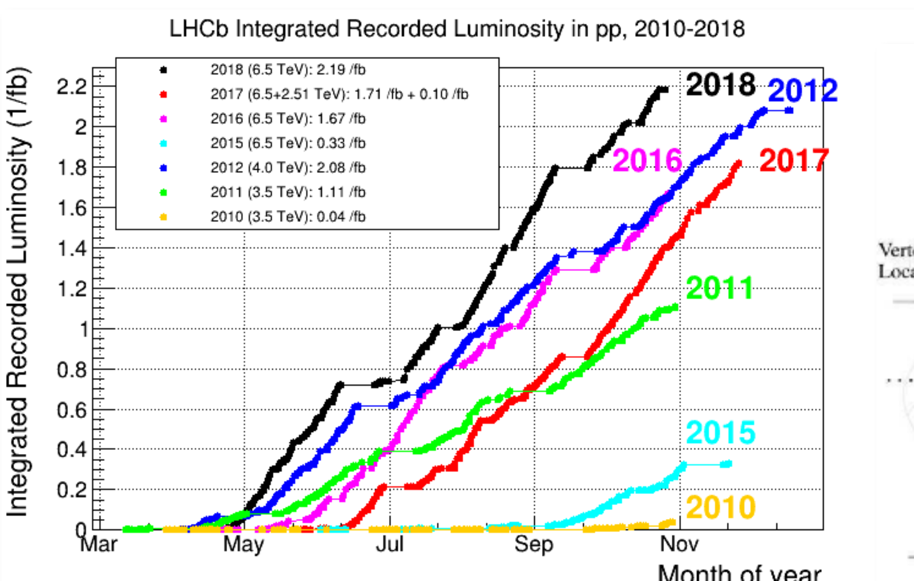


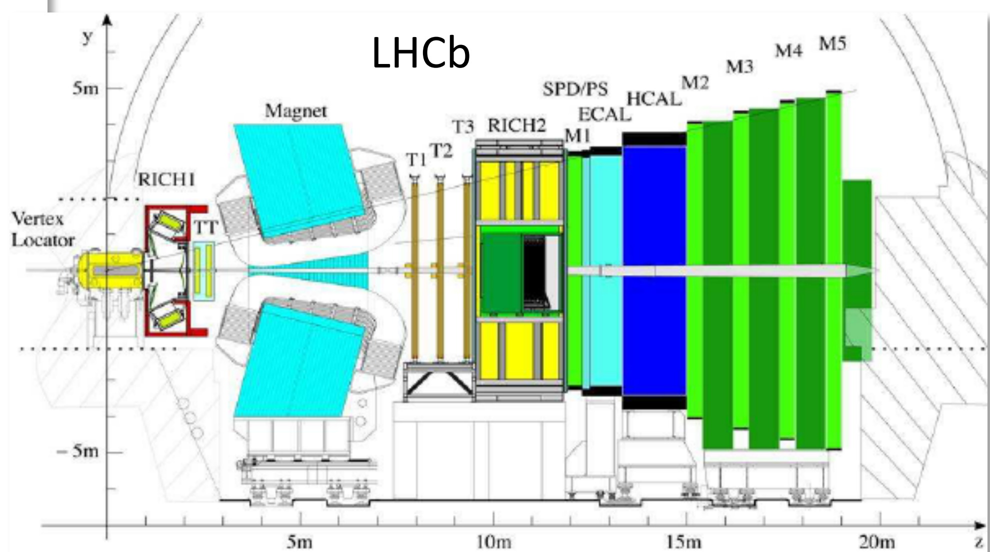


LHC Hadron collider: 2008 – ∞…



Advantages	Huge production x-section (100s ub), Produce all particles at the same time
Disadvantages	Unknown initial energies of quarks and gluons, multiple collisions per event, Potentially high backgrounds, Harder to deal with neutrinos, Harder to deal with neutrals, "Low" tagging efficiency (~3%)

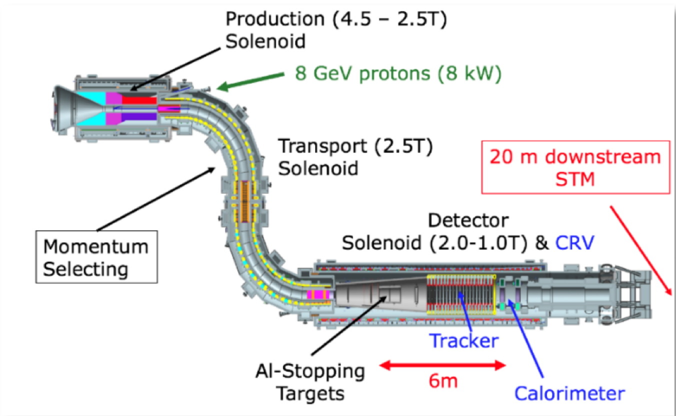


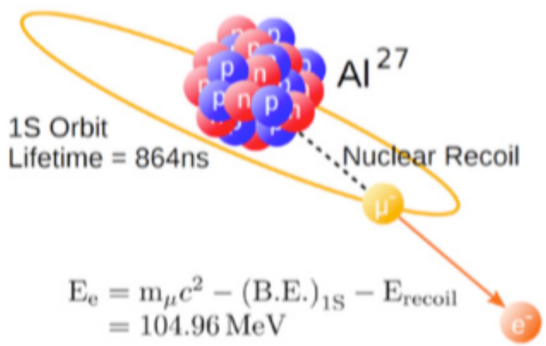


Dedicated Lepton Flavour Violation experiments

mu2e at Fermilab (data-taking 2023)

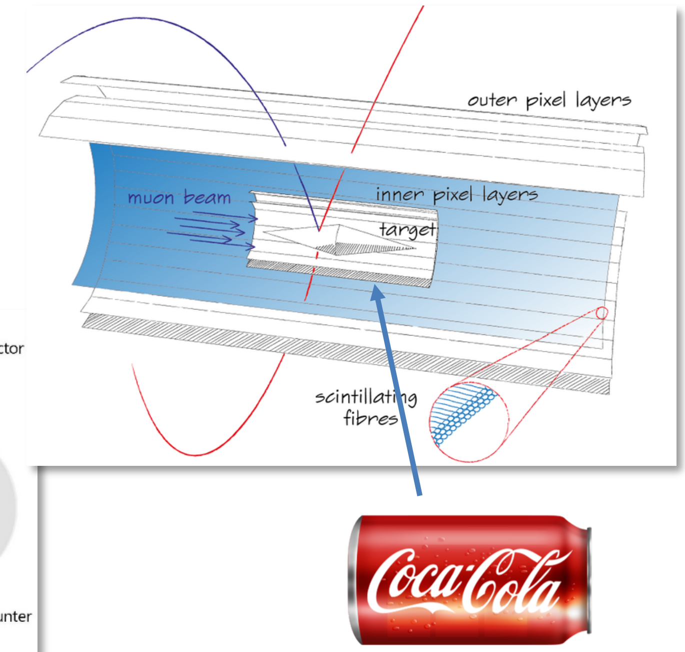
$\mu^- N \rightarrow e^- N$ conversion

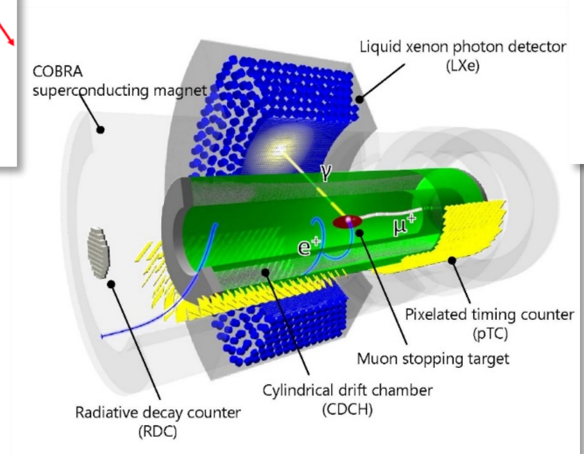




mu3e at PSI (commissioning 2021)

$\mu^+ \rightarrow e^+ e^- e^+$





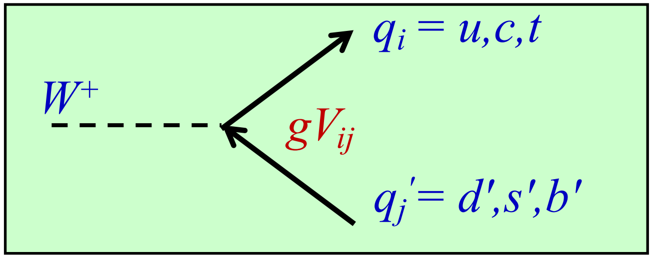
MEG at PSI (being upgraded)

$\mu^+ \rightarrow e^+ \gamma$

THE CKM MATRIX - INTRODUCTION

CKM Matrix and Unitarity Triangle

"CKM" matrix



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

"Euler" representation: 3 angles, 1 phase e.g. $c_{12} = \cos(\theta_{12}) = \cos(\theta_C)$

$$V_{CKM} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

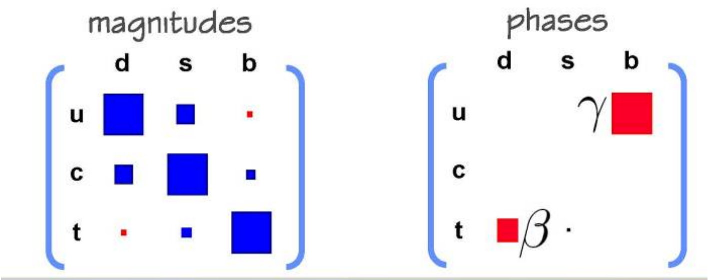
"Wolfenstein" parametrization: expansion in $\lambda = \sin(\theta_{12}) = 0.225$

$$V_{\mathrm{CKM}} \approx \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

$$A \approx 0.8, \quad \lambda \approx 0.23, \quad \rho \approx 0.2, \quad \eta \approx 0.4$$

CKM Matrix and Unitarity Triangle

$$V_{\text{CKM}} \approx \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$



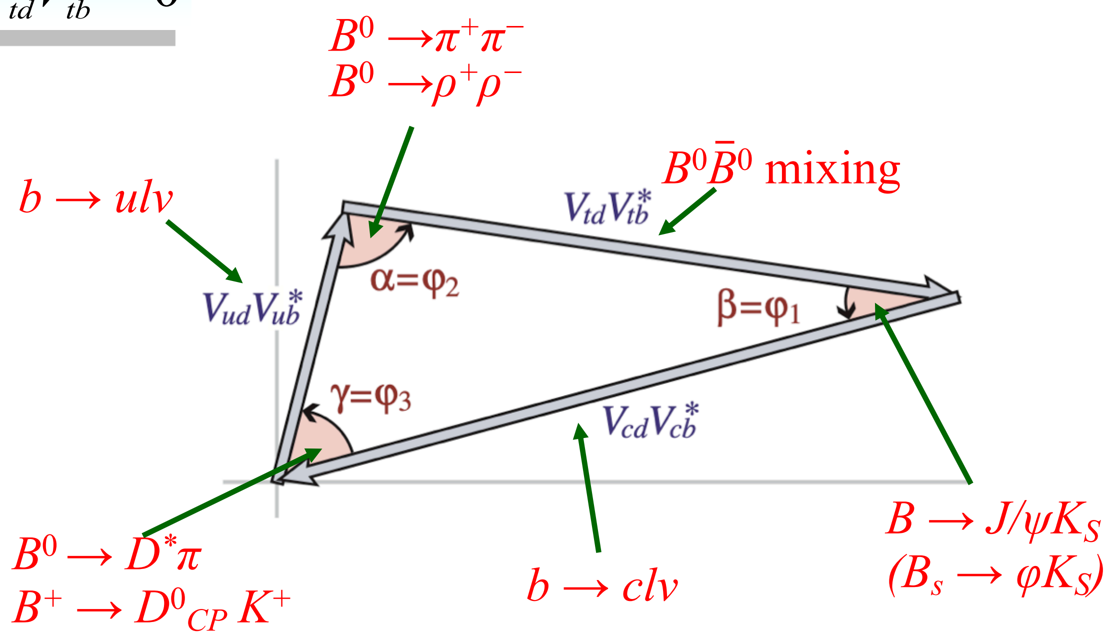
$$\sum_{i=1}^{3} V_{ji} V_{ki}^* = 0 \qquad j,k = 1,\ldots,3, \quad j \neq k.$$

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

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

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

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



CKM Matrix and Unitarity Triangle

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

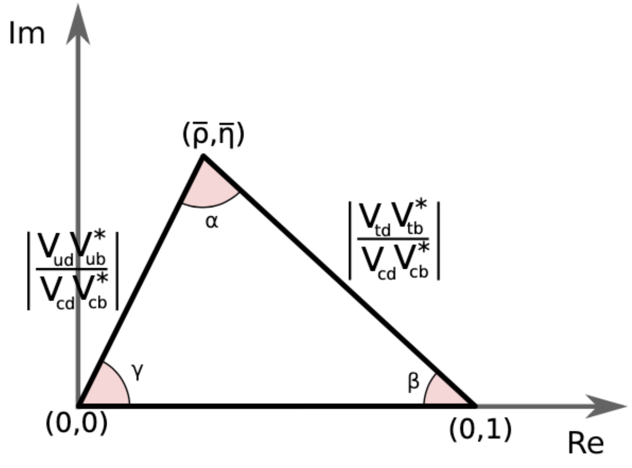


Figure 2.2: Unitarity triangle corresponding to the B_d system

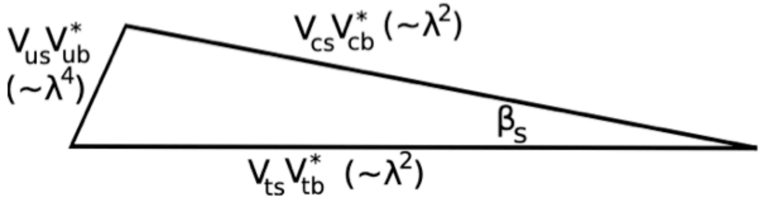
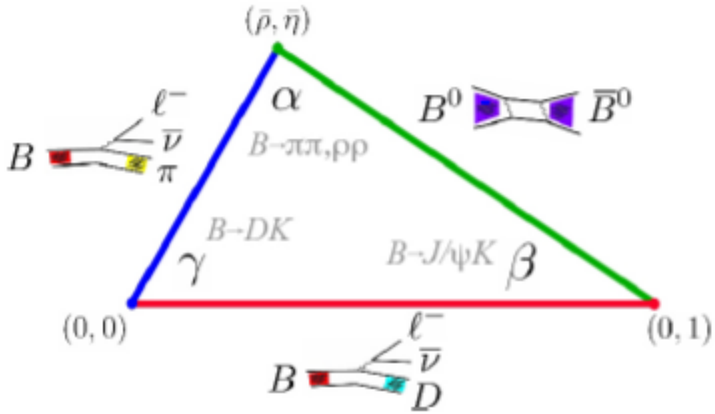
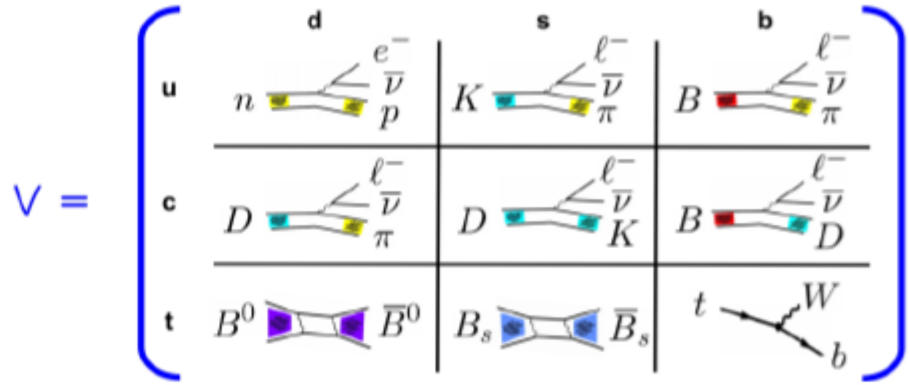


Figure 2.3: Unitarity triangle corresponding to the unitarity relation of the B_s^0 system (equation 2.15). λ is the sine of the Cabibbo angle.

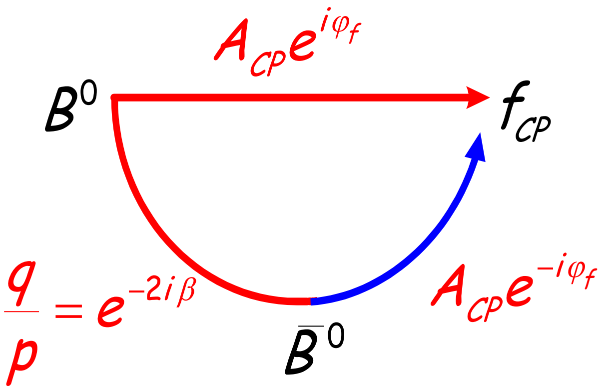
What should we measure?





Decay		Decay/Process	
$B \to \pi\pi, \rho\rho$	α	$B \to D^* l\nu$, $b \to cl\nu$	$\lvert V_{cb} \rvert$
$B \to D^{(*)}K^{(*)}$	γ	$B \to \pi l\nu$, $b \to ul\nu$	$\lvert V_{ub} \rvert$
$B \to J/\psi\ K^0_s$	β	$M \to l\nu(\gamma)$	$\lvert V_{ud} \rvert$
$B_s \to J/\psi\ \phi$	β_s	$B_{(d,s)} \to \mu^+\mu^-$	$\lvert V_{t(d,s)} \rvert$
$K \to \pi\bar{\nu}\nu$	ρ,η	Δm_d, Δm_s	$\lvert V_{tb} \rvert$

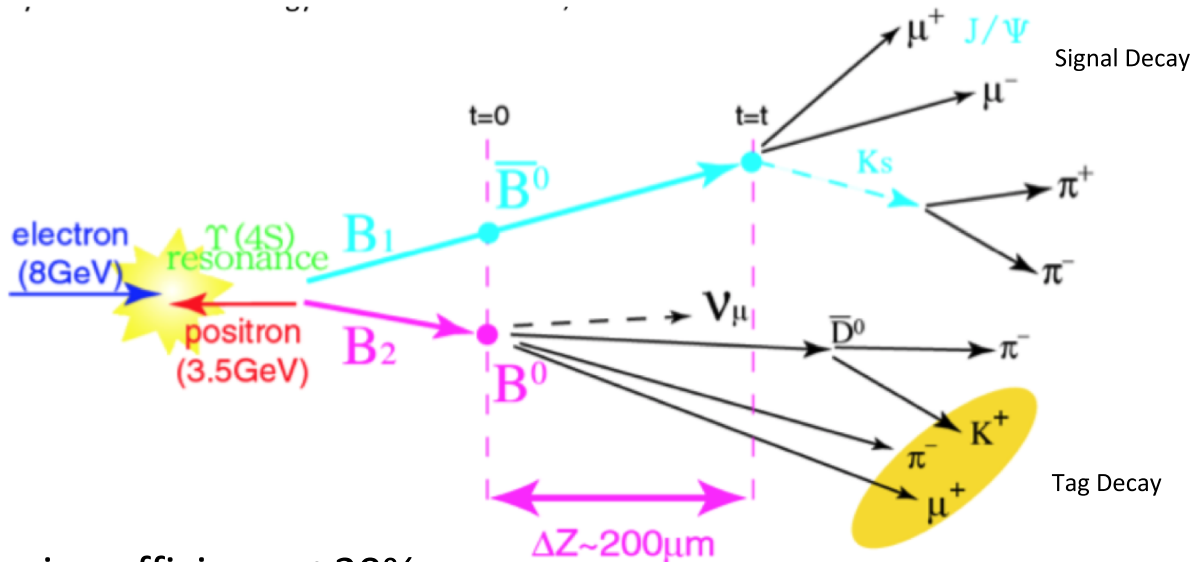
Time Dependent CP Violation



$$A_{f_{CP}}(\Delta t) = \frac{\Gamma(\bar{B}^0 \rightarrow f_{CP}) - \Gamma(B^0 \rightarrow f_{CP})}{\Gamma(\bar{B}^0 \rightarrow f_{CP}) + \Gamma(B^0 \rightarrow f_{CP})}$$
$$= -\eta_{CP}[S_{f_{CP}} \sin(\Delta m_d \Delta t) + C_{f_{CP}} \cos(\Delta m_d \Delta t)]$$

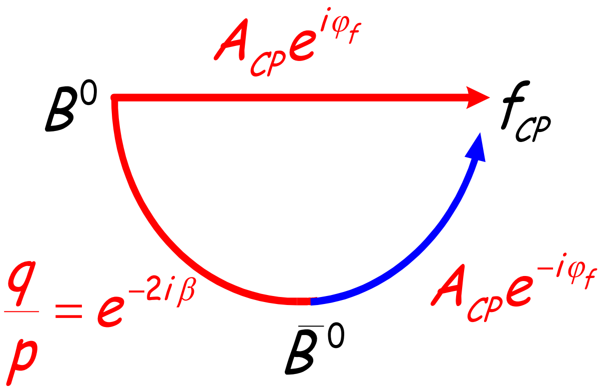
$\Delta m_d = 0.5065 \pm 0.0019\ ps^{-1}$
$\Delta m_s = 17.757 \pm 0.007\ ps^{-1}$

BaBar/Belle/Belle II



Tagging efficiency ~30%

Time Dependent CP Violation



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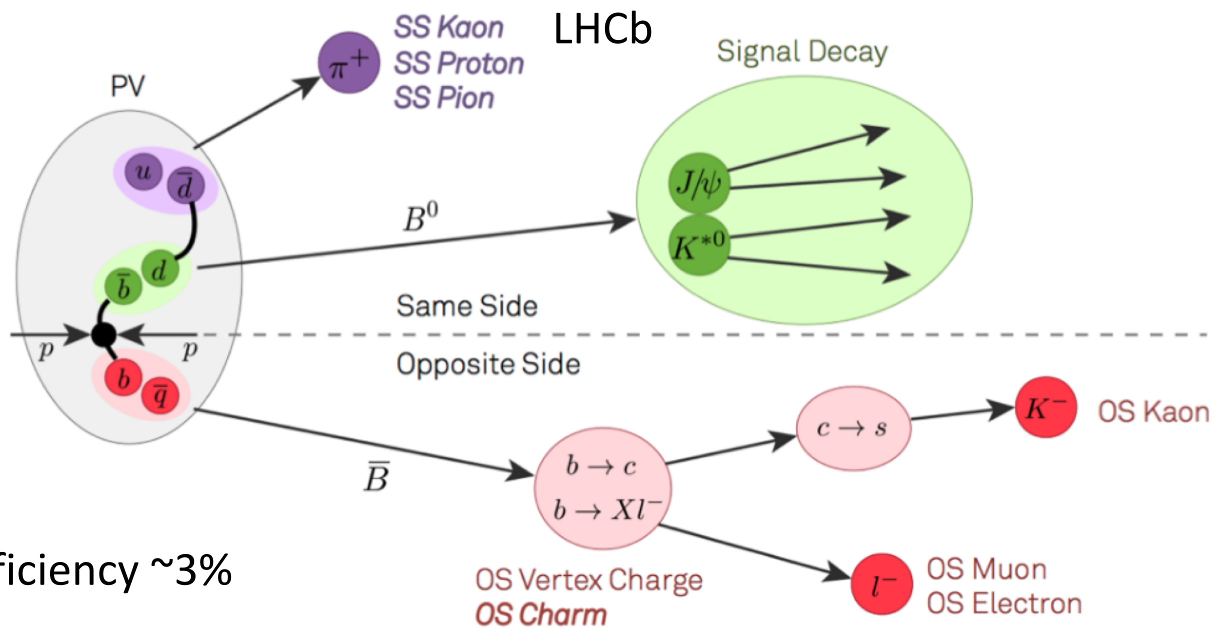


Tagging efficiency ~3%

CKM MATRIX - SIDES

Measuring the CKM sides $|V_{CKM}|$

1. Leptonic decays, with f_B from Lattice QCD:

$$\Gamma(B \to l_1 l_2) = \frac{G_F^2 f_B^2 \zeta_{12} \lambda_{12}^{1/2}}{8\pi M_B^2} |V_{ub}|^2$$

2. Exclusive semi-leptonic decays, with form factor F(w) from theory extrapolations (e.g. "CLN" and "BGL"):

$$\frac{d\Gamma}{d\omega}(B \to D^* l \nu_l) = |V_{cb}|^2 \frac{G_F^2 m_B^5}{48\pi^3} (w^2 - 1)^{1/2} P(w) (\eta_{ew} F(w))^2$$

3. Inclusive semi-leptonic decays, with decay rate described by Heavy Quark Expansion (HQE):

$$\Gamma(B \to X_c l \nu) = |V_{cb}|^2 \frac{G_F^2 m_b^5(\mu)}{192\pi^3} (1 + A_{ew}) \times HQE(\mu)$$

$$\lambda_{12} = (M_B^2 - m_1^2 - m_2^2)^2 - 4m_1^2 m_2^2$$

$$\zeta_{12} = m_1^2 + m_2^2 - \frac{(m_1^2 - m_2^2)^2}{M_B^2}$$

$$\beta_{12} = 1 - \frac{m_1^2 + m_2^2}{q^2} - \frac{\lambda_{12}}{q^4}$$

$$P(w) = \text{phase space factor}$$

$$w = v_i . v_f$$

$|V_{cb}|$ and $|V_{ub}|$

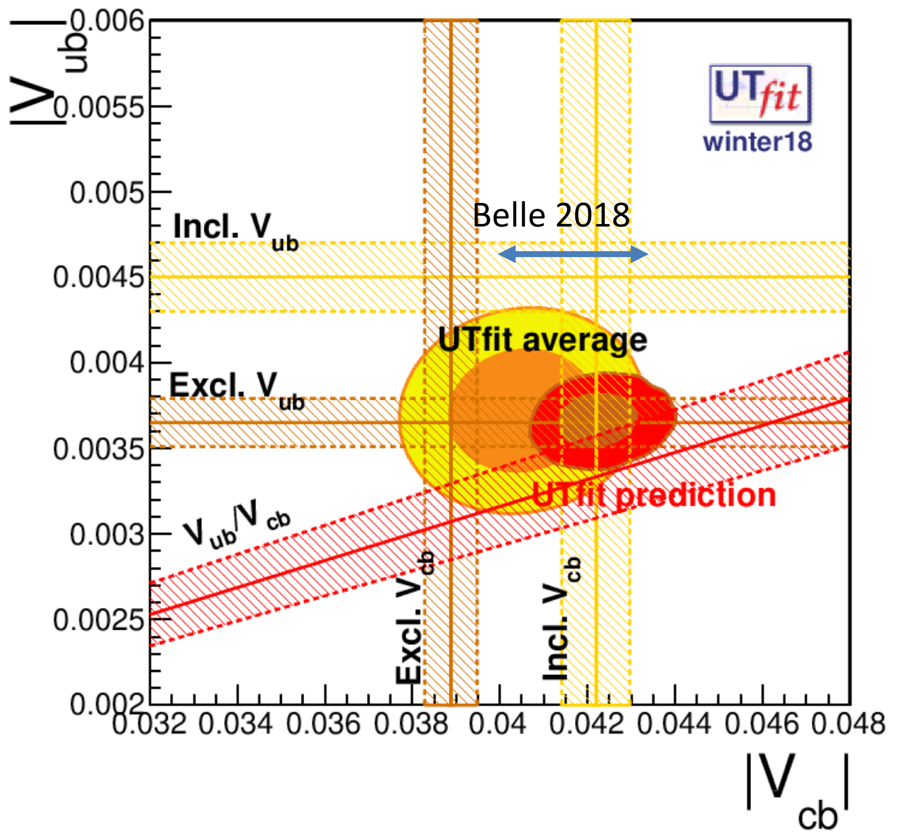
There is a long-standing difference in Inclusive (e.g. $B \to X_q l \nu$) and Exclusive (e.g. $B \to \pi l \nu$/$B \to D^* l \nu$) measurements:

- Inclusive: $|V_{cb}| = (42.2 \pm 0.8) \times 10^{-3}$
- Exclusive: $|V_{cb}| = (39.5 \pm 0.9) \times 10^{-3}$ (2018)
  - 3.3σ difference
- Inclusive: $|V_{ub}| = (4.25 \pm 0.12 \pm 0.15 \pm 0.23) \times 10^{-3}$
- Exclusive: $|V_{ub}| = (3.70 \pm 0.10 \pm 0.12) \times 10^{-3}$
  - 3.4σ difference

Belle showed at ICHEP 2018

- Exclusive $|V_{cb}| = (42.5 \pm 0.3 \pm 0.7 \pm 0.6) \times 10^{-3}$
- Does this mean inclusive and exclusive $|V_{cb}|$ agree?

Caution: Input to $|V_{cb}|$ exclusive comes from $B^0 \to D^{*+} l^- \nu$, the same decay that shows deviations in Lepton Universality (see later).

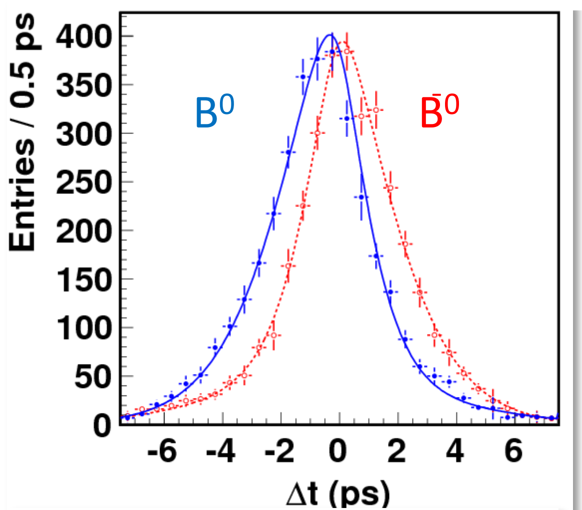


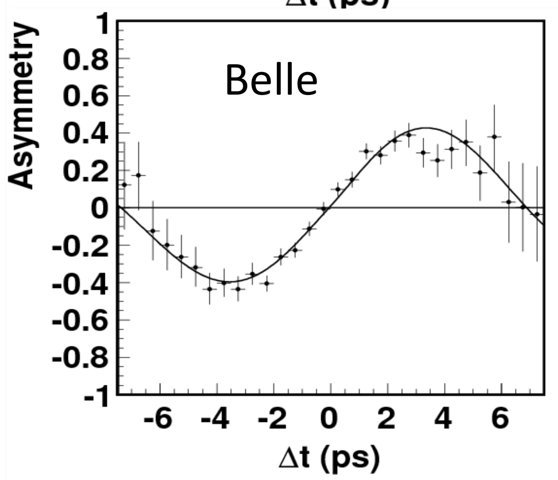
CKM MATRIX - ANGLES

CKM MATRIX ANGLE - β AND ϕ_s

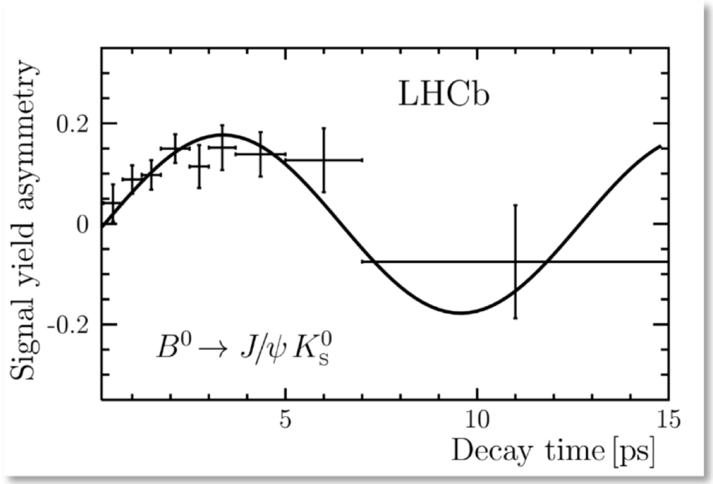
Sin(2β) – "Golden Mode" $B^0 \to J/\psi K^0_s$

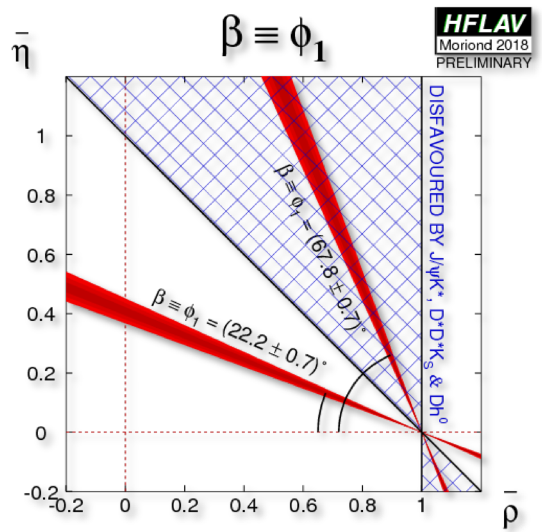
$$\mathcal{A}_{[c\bar{c}]K^0_S}(t) \equiv \frac{\Gamma(\overline{B}^0(t)\to[c\bar{c}]K^0_S) - \Gamma(B^0(t)\to[c\bar{c}]K^0_S)}{\Gamma(\overline{B}^0(t)\to[c\bar{c}]K^0_S) + \Gamma(B^0(t)\to[c\bar{c}]K^0_S)}$$
$$= \frac{S\sin(\Delta m\, t) - C\cos(\Delta m\, t)}{\cosh(\Delta\Gamma\, t/2) + A_{\Delta\Gamma}\sinh(\Delta\Gamma\, t/2)} \approx S\sin(\Delta m\, t) - C\cos(\Delta m\, t)\,,$$





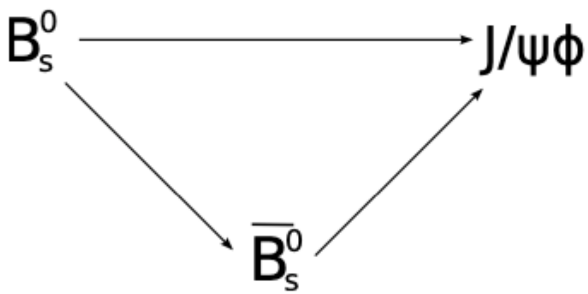
C = 0, S = sin2β

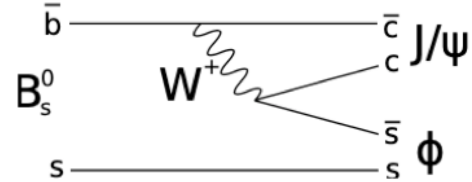


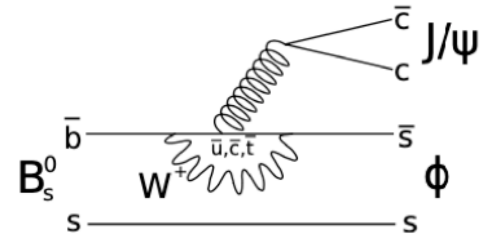


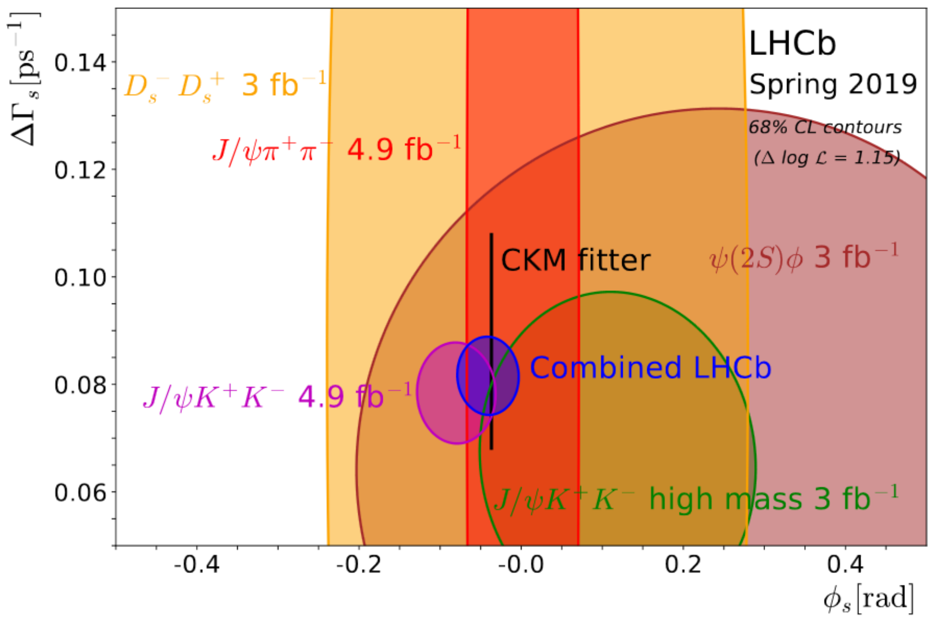
HFLAV average = $(22.2 \pm 0.7)^o$

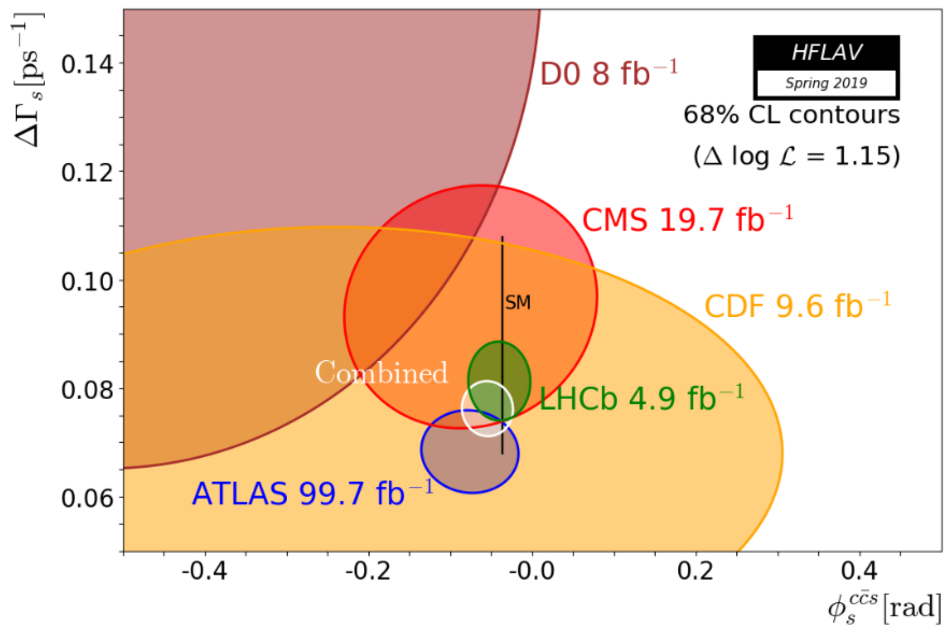
CP phase $\phi_s = 2\beta_s$ in B^0_s -> J/ψ K^+K^-







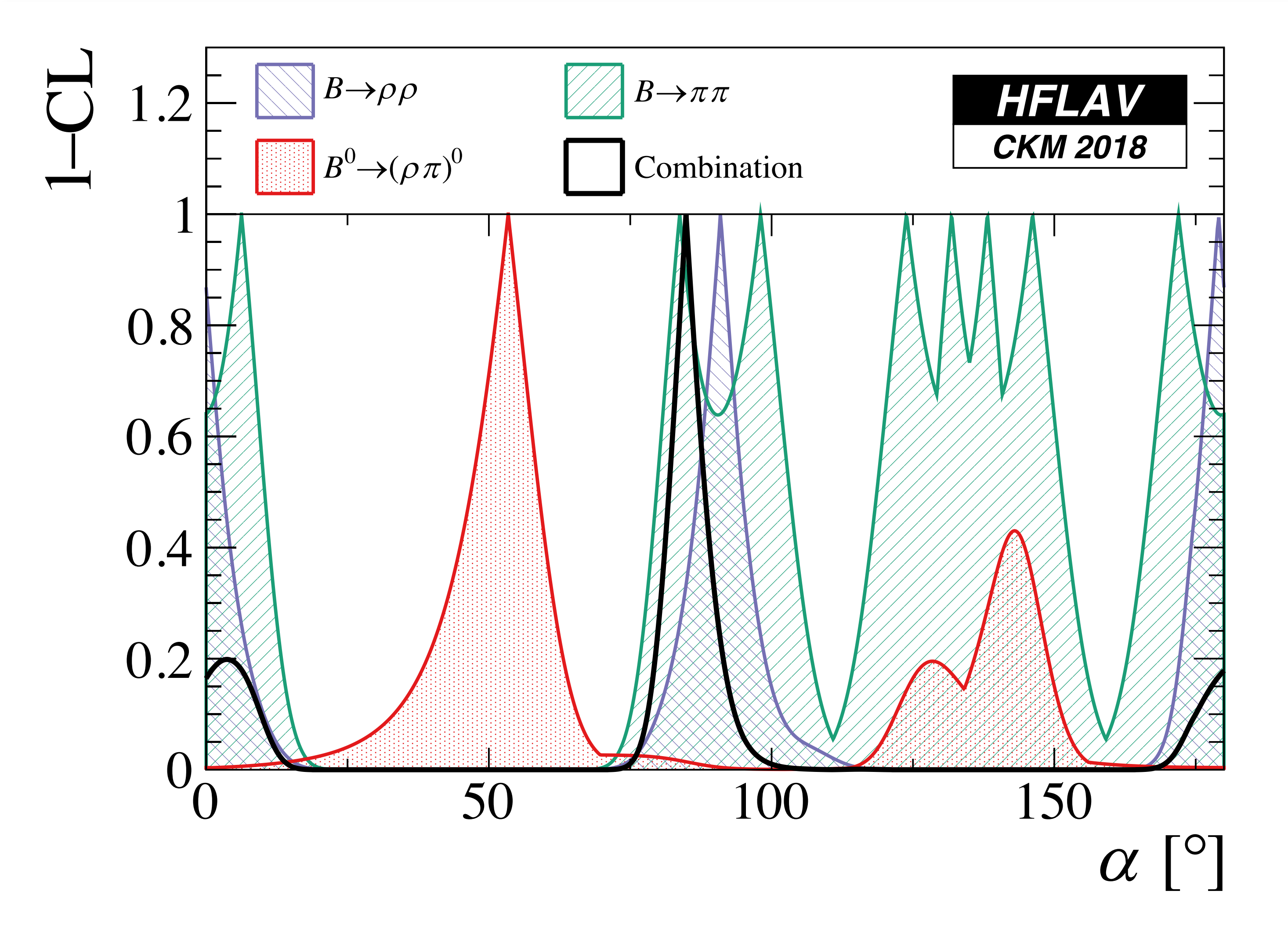




ϕ_s (theory) = -0.037±0.002 rad $\quad$ ϕ_s (PDG) = -0.021±0.031 rad

CKM MATRIX ANGLE - α

Angle α

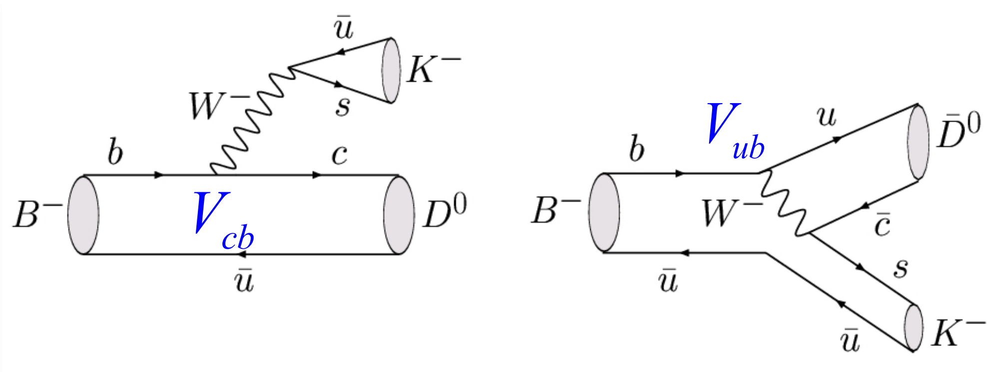


HFLAV average = $\left(84.9^{+5.1}_{-4.5}\right)^{o}$

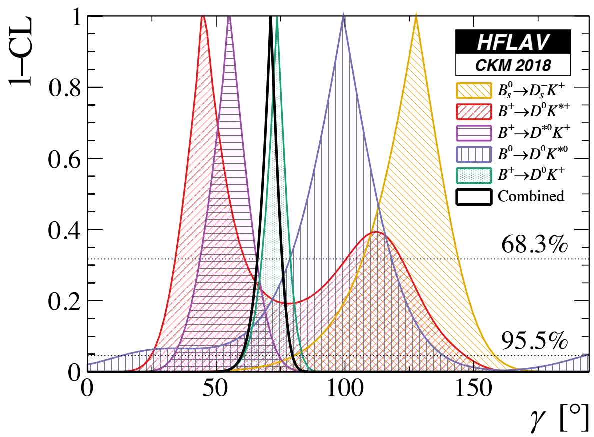
CKM MATRIX ANGLE – γ

Angle γ

Use interference between tree decays of: Cabibbo-suppressed ($b \to c$) $B^- \to$ anti-D^0K^- and CKM- and colour-suppressed ($b \to u$) $B^- \to D^0K^-$ where D^0 and anti-D^0 decay to same final state.



	Method	Modes	Final State	Advantage	Disadvantage
1	GLW	$D^0(CP_\pm)$	CP Eigenstate	Constraints	Low stats, small interf.
2	ADS	$D^0(K\pi)$	Flavour Eigenstate	Large interf.	Low stats
3	GGSW	$D^0(K_shh)$ Dalitz	Three-body	Large stats, Dalitz info	Dalitz model



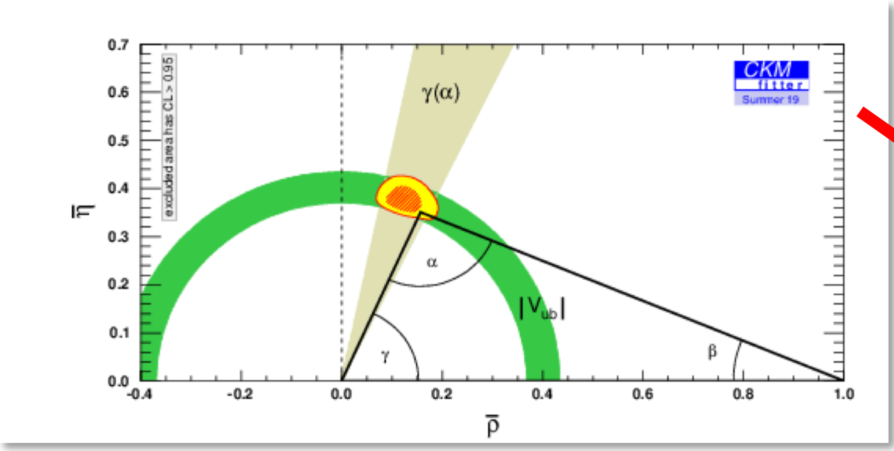
LHCb average = $\left(74.0^{+5.0}_{-5.8}\right)^{\rm o}$

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

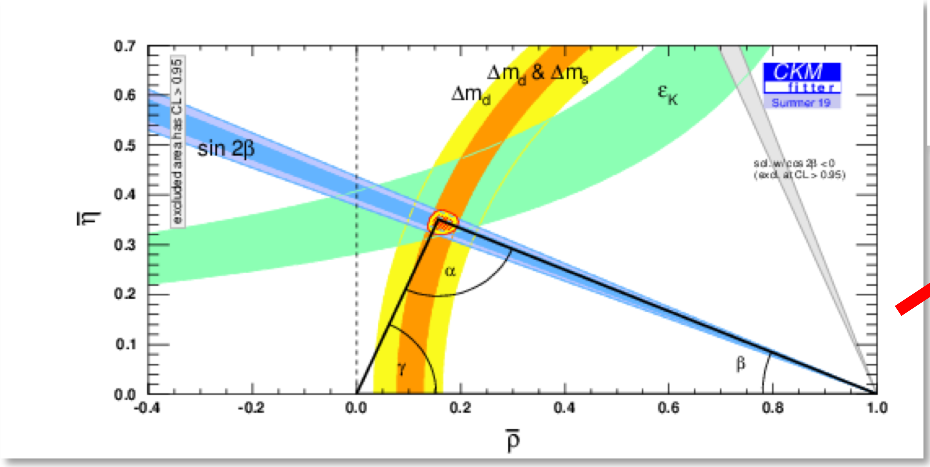
LHCb-CONF-2018-002

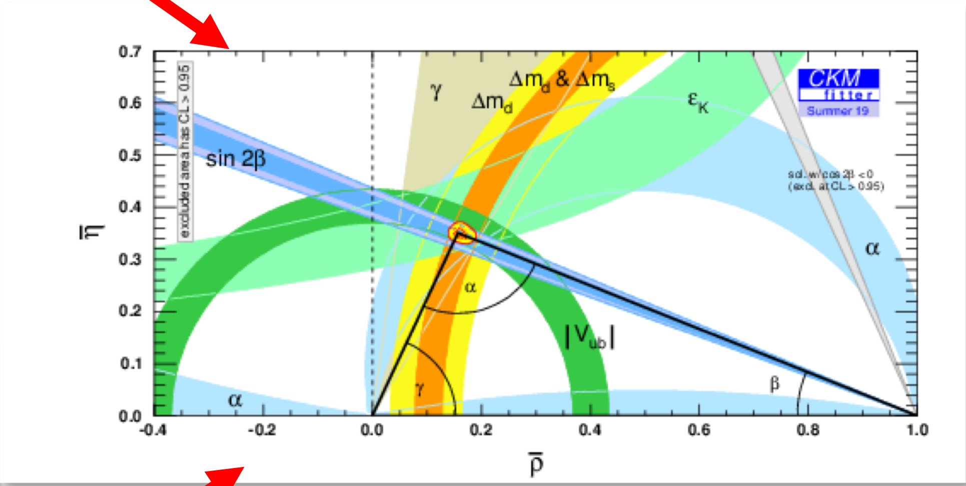
CKM Summary

CKM measured with "Tree" processes (not expected to be affected by New Physics)



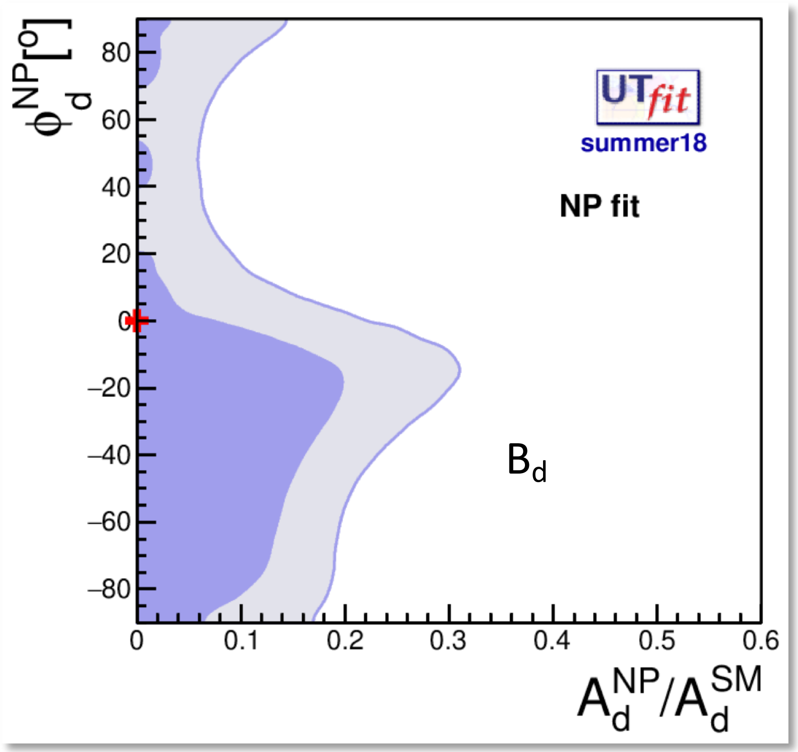
CKM measured with processes sensitive to New Physics

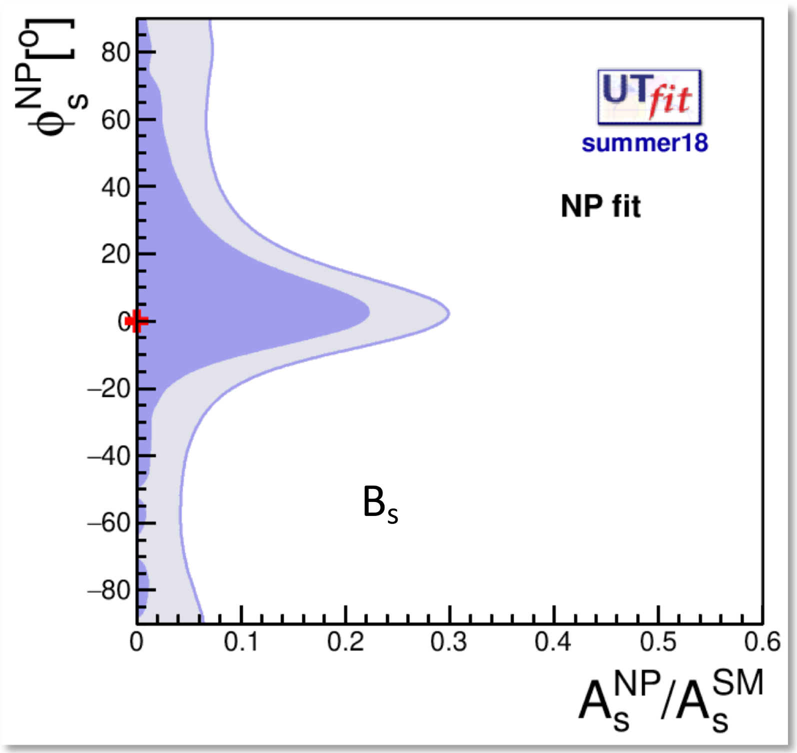




Is there room for New Physics in the CKM?

$$A_q = \left(1 + \frac{A_q^{NP}}{A_q^{SM}} e^{2i(\phi_q^{NP} - \phi_q^{SM})}\right) A_q^{SM}\, e^{2i\phi_q^{SM}}$$





The ratio of New Physics / Standard Model amplitudes is

< 18% @68% probability in B_d mixing

< 20% @68% probability in B_s mixing