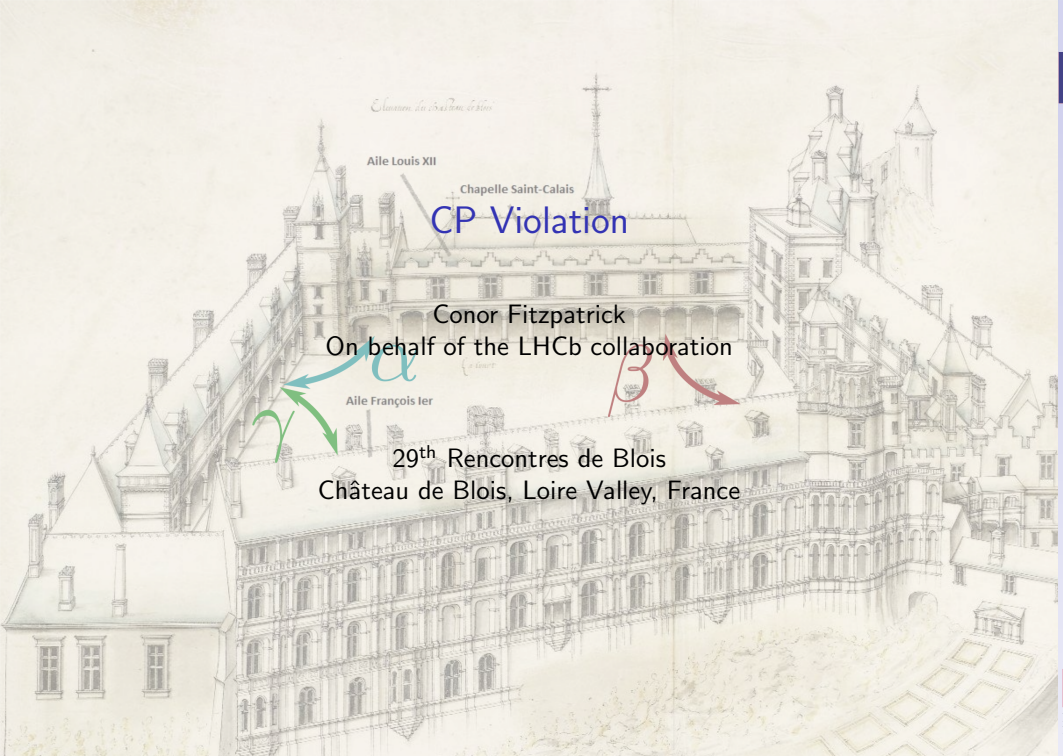


CP Violation

Conor Fitzpatrick
On behalf of the LHCb collaboration

29th Rencontres de Blois
Château de Blois, Loire Valley, France

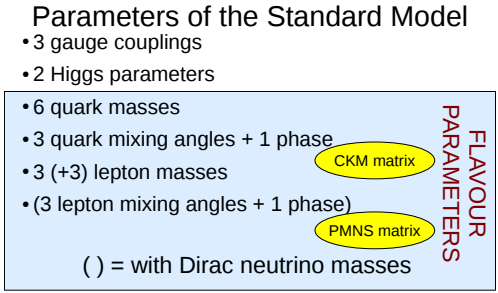
CP Violation
Introduction
Selected results
~~$\mathcal{CP}$~~ in charm
CKM angle γ
~~$\mathcal{CP}$~~ in B mixing
~~$\mathcal{CP}$~~ in $B \to KK, \pi\pi$
β in $J/\psi K^0_S$
ϕ_s in $J/\psi\phi$
~~$\mathcal{CP}$~~ in Baryons
Conclusions

C. Fitzpatrick

May 30, 2017

Introduction

- $\mathcal{CP}$ violation: Matter and Antimatter are not symmetric in their behavior



- $\mathcal{CP}$ (and the physics of flavour in general) covers a significant fraction of the parameters of the SM

- Measurements of $\mathcal{CP}$ violating parameters are of particular interest because the SM is not consistent with cosmology:
- Matter-antimatter asymmetry of the universe $>>$ than that measured within the SM

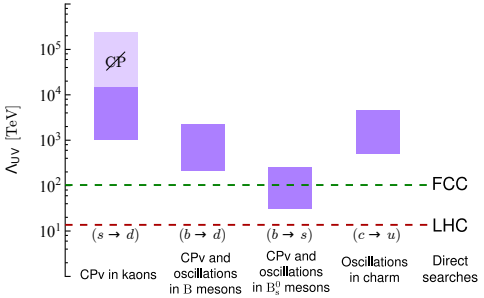
CP Violation
Introduction
Selected results
$\not{\mathcal{CP}}$ in charm
CKM angle γ
$\not{\mathcal{CP}}$ in B mixing
$\not{\mathcal{CP}}$ in $B \to KK, \pi\pi$
β in $J/\psi K^0_S$
ϕ_s in $J/\psi\phi$
$\not{\mathcal{CP}}$ in Baryons
Conclusions

C. Fitzpatrick

May 30, 2017

Measuring CP violation

- Measurements of the decay of heavy (beauty, charm hadrons) and not-so heavy (Kaons) particles provide insight into the CKM mechanism and $\not{CP}$
- Indirect measurements in mixing and $\not{CP}$ are complimentary to direct searches[1]:



- I will focus in this talk on beauty and charm
- Similar structure in the neutrino sector: PMNS matrix also permits $\not{CP}$
  - Several current and planned experiments aim to measure it
  - See talks in the parallel session today and plenary on Wednesday

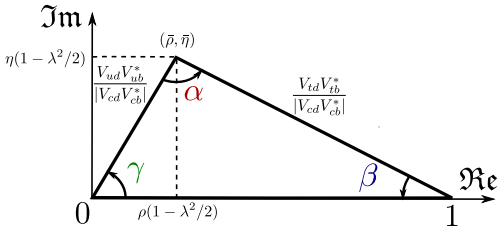
[1] M. Neubert, EPS-HEP, 2011

C. Fitzpatrick

May 30, 2017

Measuring the CKM matrix

- Unitarity condition: $VV^\dagger = 1$: $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$
- Can be represented as a triangle in the complex plane:



$$\alpha = \arg\left[-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right] \qquad \beta = \arg\left[-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right] \qquad \gamma = \arg\left[-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right]$$

- b − d condition forms 'the' unitary triangle. Other triangles exist, eg: b − s
- Measurements of the CKM angles overconstrain the triangles: A powerful test of the SM

C. Fitzpatrick

May 30, 2017

$\mathcal{CP}$ phenomenology

- Accessed through measurements of decays of particles and antiparticles: interfering amplitudes with different CKM phases

$\mathcal{CP}$ in decay:
$\mathcal{A}(X \to f) \neq \mathcal{A}(\bar{X} \to \bar{f})$

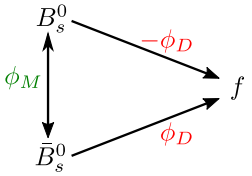
- Amplitudes for $\mathcal{CP}$ conjugates differ
- Eg: $B \to K^+\pi^-$ / $\overline{B} \to K^-\pi^+$
- Particularly interesting in charm sector: $\mathcal{A}_{\mathcal{CP}}(K^+K^-), \mathcal{A}_{\mathcal{CP}}(\pi^+\pi^-)$

$\mathcal{CP}$ in mixing: $|X_{L,H}> \propto q|X^0> \pm p|\bar{X}^0>$

- $|q/p| \neq 1$
- Neutral meson mixing: Mass eigenstates $\neq$ flavor eigenstates
- Difference in decay rates of wrong-sign semileptonic decays:

$$\mathcal{A}_{sl}^{s,d} = \frac{R(\overline{B}^0 \to \bar{\ell}X) - R(B^0 \to \ell X)}{R(\overline{B}^0 \to \bar{\ell}X) + R(B^0 \to \ell X)}$$

$\mathcal{CP}$ in interference between mixing and decay:



$\phi_s = \phi_M - 2\phi_D$

- Final state accessible to $X^0, \bar{X}^0$:

$$\frac{\mathcal{A}(\bar{X}^0 \to f) - \mathcal{A}(\bar{X}^0 \to f)}{\mathcal{A}(\bar{X}^0 \to f) + \mathcal{A}(\bar{X}^0 \to f)} = \frac{C_f \cos(\Delta m t) - S_f \sin(\Delta m t)}{\cosh(\Delta\Gamma t/2) + A_f^{\Delta\Gamma} \sinh(\Delta\Gamma t/2)}$$

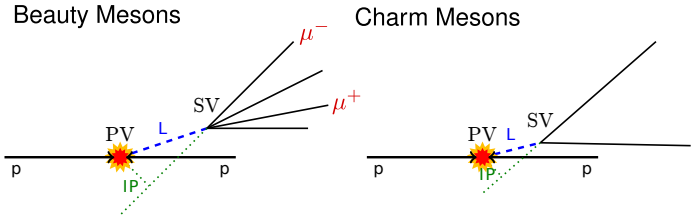
- S_f: interference between mixing & decay. C_f: direct $\mathcal{CP}$
- Important measurements: $\sin(2\beta)$ (b-factories, LHCb), ϕ_s (Tevatron + LHC)

C. Fitzpatrick

Measuring $\mathcal{CP}$

Common signatures:

- Decays of b-hadrons:
- Heavy ($M \sim 5.3$ GeV), long-lived particles ($\tau \sim 1.6$ps)
- Decay products have high $p_T \sim 1$ GeV
- Important signatures:
  - $B \to J/\psi X$ with $J/\psi \to \mu^- \mu^+$
  - Suppressed $B \to DX$ decays with small branching ratios
- Decays of charm mesons: also heavy ($M \sim 1.8$ GeV), long-lived particles ($\tau \sim 0.4$ps)



- Beauty and charm mesons are produced in abundance in pp collisions
- e^+e^- collisions at $\Upsilon(4S)$ are a clean source of $B^{\pm}$,B^0 and charm mesons

C. Fitzpatrick

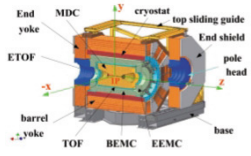
Experimental concerns:

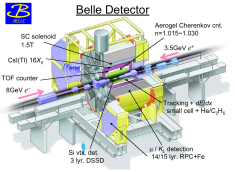
To measure $\not{CP}$ then, experiments need:

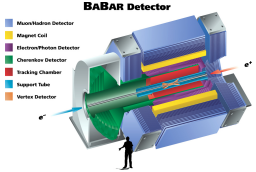
- Excellent vertexing
  - to cleanly separate primary and secondary vertices
  - to resolve fast oscillations
- Particle ID:
  - to distinguish between topologically identical final states
  - to tag the initial flavour content
- Enormous datasets to measure small deviations

C. Fitzpatrick

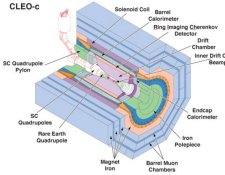
Dramatis personæ

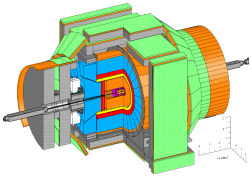


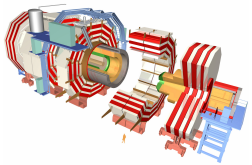




- e^+e^- experiments: BESIII, CLEO-c, ARGUS, LEP
  - CLEO-c,BESIII dedicated to charm
  - Clean environments and tunable collision energies
- b-factories: *BABAR* (SLAC) & Belle (KEK)
  - Ran throughout the 2000s
  - Asymmetric e^+e^- beams at $\Upsilon(4S)$
  - Very clean B^+ and B^0 samples
  - Excellent flavor tagging
- hadron collider experiments: CDF, DØ, ATLAS, CMS
  - General purpose detectors
  - Good vertex resolution (LHC) with tracker upgrades
  - Great sensitivity to final states with dileptons





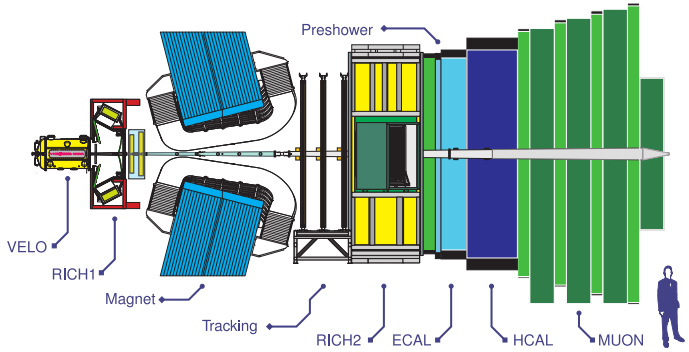


C. Fitzpatrick

May 30, 2017

LHCb: The precision flavour experiment

- The Tevatron experiments showed it was possible (and interesting!) to study B meson properties at a hadron collider
- LHCb is a hadron collider experiment built explicitly for beauty and charm physics

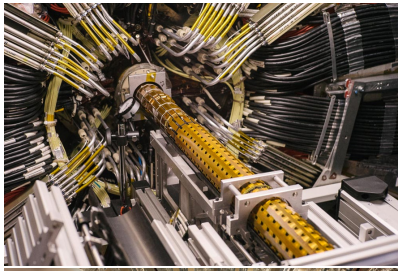


- Enormous signal rates: 10^5 $b\bar{b}$ pairs per second, 10^6 charm!
- Precise particle identification (RICH)
- Decay time resolution: $\sim$45fs (VELO)
- Efficient signal categorisation using real time alignment and calibration

C. Fitzpatrick

But LHCb faces stiff competition...

- ATLAS and CMS:
  - Excellent mass resolution
  - Very high rates
  - Good (di)lepton identification
- Substantial upgrades to inner trackers in Run 2
  - ATLAS Insertable B Layer[2]
  - CMS Pixel detector upgrade[3]
- Dramatically improved vertexing $\rightarrow$ improved time resolution for B decays



[2] ATL-PHYS-PUB-2013-010
[3] CMS-TDR-11

C. Fitzpatrick

May 30, 2017

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE
10 / 24

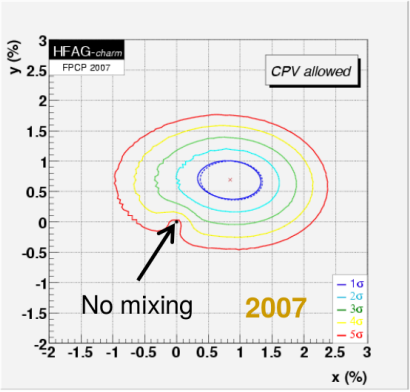
The state of the art

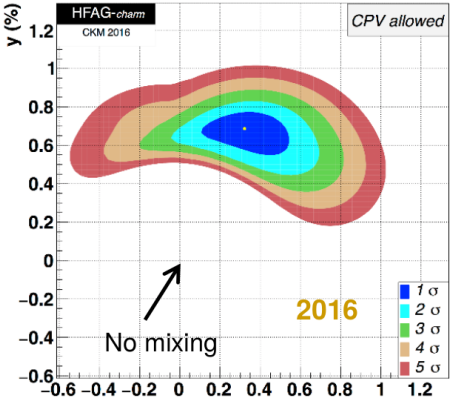
- I will present a selection of recent $\not{CP}$ measurements
  - I have tried to cover most of the available phase space
  - Many excellent results and little time: Apologies to those I will miss
  - See in particular the summaries of Tevatron and b-factory results in the HF & QCD sessions

C. Fitzpatrick

$\mathcal{CP}$ in charm

- $\mathcal{CP}$ in the charm sector expected to be small ($< 10^{-3}$)
- Mixing first confirmed by the b-factories in combination
- Current status: No $\mathcal{CP}$ observed yet, but prospects are excellent



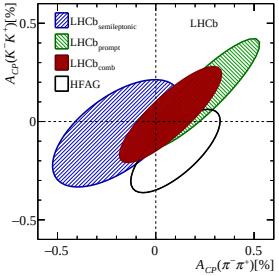


C. Fitzpatrick

May 30, 2017

Direct $\mathcal{CP}$ in charm

$A_{\text{raw}}(D \to X) = \frac{N(D \to X) - N(\bar{D} \to \bar{X})}{N(D \to X) + N(\bar{D} \to \bar{X})}$ where $A_{\text{raw}} \approx A_{\text{CP}} + A_{\text{P}} + A_{\text{D}}$



- Initial D flavour obtained using $D^* \to D\pi^+$ decays
- LHCb combination[4] using $D \to K^+K^-, \pi^+\pi^-$

$A_{CP(K^+K^-)} = (0.04 \pm 0.12(\text{stat}) \pm 0.10(\text{syst}))\%$
$A_{CP(\pi^+\pi^-)} = (0.07 \pm 0.14(\text{stat}) \pm 0.11(\text{syst}))\%$

- Recent results in additional direct $\mathcal{CP}$ measurements:
  - $D^+_{(s)} \to \eta'\{\pi^+\pi^-\gamma\}\pi^+$: [arXiv:1701.01871]
    First measurement at a hadron collider, most precise measurement to date
  - $D^0 \to \pi^+\pi^-\pi^+\pi^-$: [PLB 03 (2017) 062]
    World best measurement in a 4-body decay

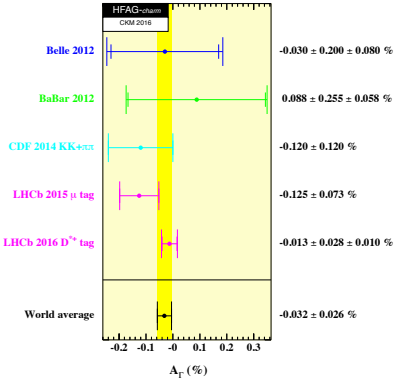
[4] Phys. Lett. B 767 177-187

C. Fitzpatrick

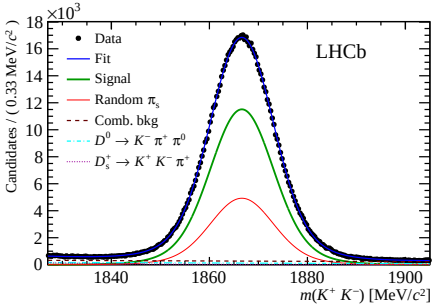
Indirect $\mathcal{CP}$ in charm

$$A_{CP}(t) = \frac{\Gamma(D^0 \to f) - \Gamma(\overline{D}^0 \to f)}{\Gamma(D^0 \to f) + \Gamma(\overline{D}^0 \to f)} \simeq a^f_{dir} - A_\Gamma \frac{t}{\tau_D}$$

- A_Γ is the effective decay width asymmetry, sensitive to indirect $\mathcal{CP}$: $A_\Gamma^{SM} < \mathcal{O}(10^{-3})$ [HFLAV 2016]



- Charm yields at the LHC are enormous[5]: 10 million D^* tagged $D^0 \to K^+K^-$ in 3fb^{-1}



- No evidence yet for $\mathcal{CP}$ in charm, but at the limit of SM sensitivity

[5] LHCb PAPER-2016-063 submitted to PRL

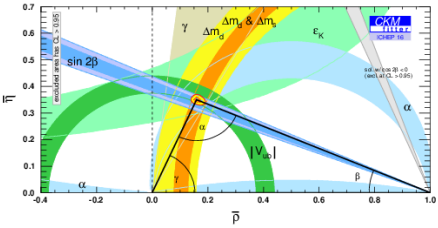
CP Violation
Introduction
Selected results
$\mathcal{CP}$ in charm
CKM angle γ
$\mathcal{CP}$ in B mixing
$\mathcal{CP}$ in $B \to KK, \pi\pi$
β in $J/\psi K^0_S$
ϕ_s in $J/\psi\phi$
$\mathcal{CP}$ in Baryons
Conclusions

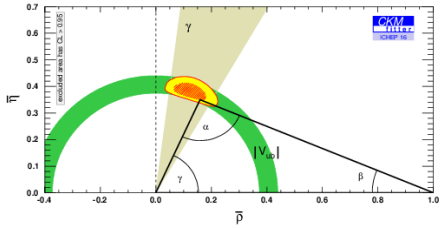
C. Fitzpatrick

May 30, 2017

γ in the UT

- The UT is well constrained but not immune to hadronic effects:





- Global fits to CKM constraining measurements[6]
- Using all available measurements, angles are determined to sub-2 deg precision

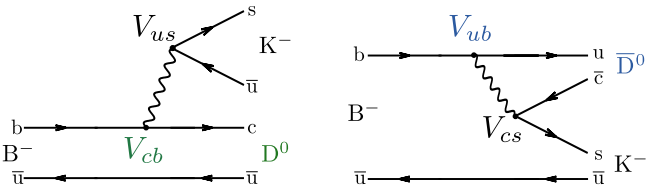
- Decays involving mixing and loops can be influenced by hadronic effects
- The only tree-level constraints in the Unitary triangle are from V_{ub} and γ

[6] UTFit, CKMFitter (shown)

CP Violation
Introduction
Selected results
~~$\mathcal{CP}$~~ in charm
CKM angle γ
~~$\mathcal{CP}$~~ in B mixing
~~$\mathcal{CP}$~~ in $B \to KK, \pi\pi$
β in $J/\psi K^0_S$
ϕ_s in $J/\psi\phi$
~~$\mathcal{CP}$~~ in Baryons
Conclusions

Measuring γ is crucial

- γ is unique among the CKM angles: Can be measured in the interference between $b \to c$ and $b \to u$ transitions, eg:



- Both decays are tree level: No room for hadronic pollution
- Negligible irreducible theory uncertainties[7]
- Second-order EW corrections at most contribute $[\delta\gamma/\gamma] \lesssim \mathcal{O}\left(10^{-7}\right)$

[7] JHEP 1401(2014)051

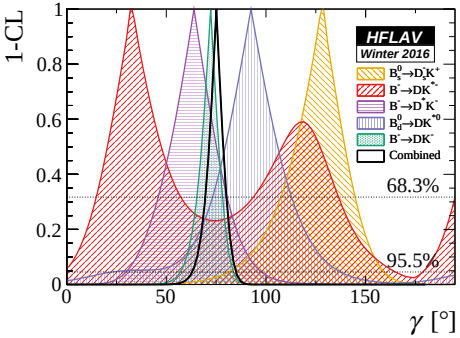
CP Violation
Introduction
Selected results
~~$\mathcal{CP}$~~ in charm
CKM angle γ
~~$\mathcal{CP}$~~ in B mixing
~~$\mathcal{CP}$~~ in $B \to KK, \pi\pi$
β in $J/\psi K^0_S$
ϕ_s in $J/\psi\phi$
~~$\mathcal{CP}$~~ in Baryons
Conclusions

C. Fitzpatrick

May 30, 2017

Measuring γ is hard

- Nothing worth doing is easy:
  - Signal yields are small: BR for suppressed $B^- \to DK^-$ modes $\approx 10^{-7}$
  - Interference between favored and suppressed decay modes at the 10% level for DK, 0.5% for Dπ
  - Hadronic final states are hard to distinguish
- No single measurement so far is sensitive to γ at better than $\pm 15°$:
  Need to make many measurements and combine!



- hflav[a] combination (tree only):
  $\gamma = (71.3^{5.7}_{-6.1})°$
  - incorporates results from *BABAR*, Belle, CDF & LHCb
- compare to CKMFitter[b] indirect constraint: $\gamma = (65.33^{+0.96}_{-2.54})°$

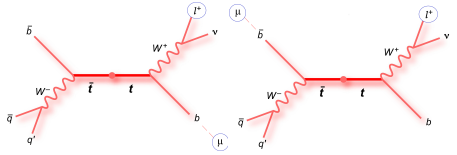
[a] hflav, winter 2016, arxiv:1612.07233
[b] CKMFitter, Summer 2016

CP Violation
Introduction
Selected results
~~CP~~ in charm
CKM angle γ
~~CP~~ in B mixing
~~CP~~ in $B \to KK, \pi\pi$
β in $J/\psi K^0_S$
ϕ_s in $J/\psi\phi$
~~CP~~ in Baryons
Conclusions

$\mathcal{CP}$ in B mixing

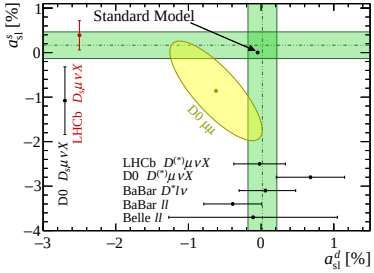
DØ measurement of anomalous like-sign dimuon asymmetry[8] caused a stir:

- Asymmetry can be measured in flavor-specific final state:
  $a_{SL} = \frac{\Gamma_{\bar{B}_{(s)} \to f}(t) - \Gamma_{B_{(s)} \to \bar{f}}(t)}{\Gamma_{\bar{B}_{(s)} \to f}(t) + \Gamma_{B_{(s)} \to \bar{f}}(t)}$
- Recent ATLAS measurement using charge asymmetries in muons from top and b-hadron in $t\bar{t}$ events [JHEP 02 (2017) 071]



- Four CP asymmetries measured: 3 direct and one mixing
- Consistent with zero asymmetry and compatible with the SM

- $\mathcal{CP}$ in mixing is small in the SM [arXiv:1102.4274]:
  $a^d_{sl}(SM) = (-4.1 \pm 0.6) \times 10^{-4}$
  $a^s_{sl}(SM) = (+1.9 \pm 0.3) \times 10^{-5}$
- Results from LHCb, *BABAR*, Belle and DØ in inclusive analyses PRL 117, 061803 (2016):



[8] PRD 89 012002 (2014)

C. Fitzpatrick

May 30, 2017

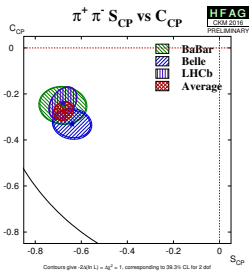
$\mathcal{CP}$ in $B \to KK, \pi\pi$

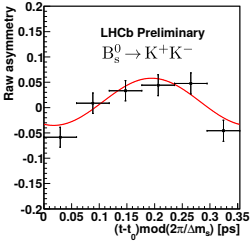
Time-dependent CP asymmetries can constrain γ and ϕ_s assuming U-spin symmetry[9]

$$A_f^{CP} = \frac{\Gamma_{B_{(s)} \to f}(t) - \Gamma_{\overline{B}_{(s)} \to f}(t)}{\Gamma_{B_{(s)} \to f}(t) + \Gamma_{\overline{B}_{(s)} \to f}(t)} = \frac{-C_f \cos(\delta m\ t) + S_f \sin(\delta m\ t)}{\cosh(\Delta\Gamma t/2) - A_f^{\Delta\Gamma} \sinh(\Delta\Gamma t/2)}$$

C_f measures direct $\mathcal{CP}$, S_f measures $\mathcal{CP}$ in interference.
$B^0 \to \pi^+\pi^-$ constrains CKM angle α.

- *BABAR*, Belle and LHCb have measured $\mathcal{CP}$ in $B^0 \to \pi^+\pi^-$
- Only LHCb measures[10] $B_s^0 \to K^+K^-$
  $C_{KK} = 0.24 \pm 0.06(\text{stat}) \pm 0.02(\text{syst})$
  $S_{KK} = 0.22 \pm 0.06(\text{stat}) \pm 0.02(\text{syst})$
- LHCb result uses Run 1 dataset
- Result is preliminary: Sensitivity will improve with more powerful tagging





[9] PLB 741 (2015) 1
[10] LHCb-CONF-2016-018

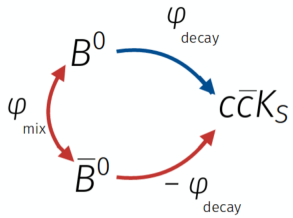
CP Violation
Introduction
Selected results
$\mathcal{CP}$ in charm
CKM angle γ
$\mathcal{CP}$ in B mixing
$\mathcal{CP}$ in $B \to KK, \pi\pi$
β in $J/\psi K_S^0$
ϕ_s in $J/\psi\phi$
$\mathcal{CP}$ in Baryons
Conclusions

C. Fitzpatrick

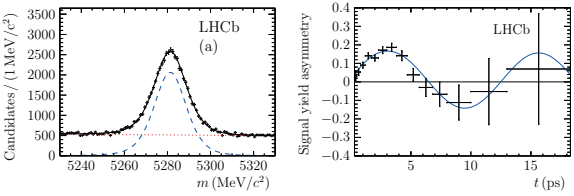
May 30, 2017

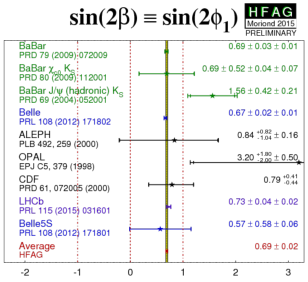
$\mathcal{CP}$ in interference: β

- Interference between mixing and decay of B^0 mesons
  $\sin 2\beta^{SM} = \sin 2\arg\left[-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right] = 0.711^{+0.017}_{-0.041}$ [CKMFitter]
- 'Golden mode' $B^0 \to J/\psi K^0_S$
- Time dependent measurement with flavour tagging:
  Challenging in a pp environment



$2\beta \sim \phi_{\text{mix}} - 2\phi_{\text{decay}}$





- b-factories still dominate the combination
- LHCb result with Run1[11]:
  $\sin 2\beta = 0.731 \pm 0.035(\text{stat}) \pm 0.020(\text{syst})$

[11] PRL 115 (2015) 031601

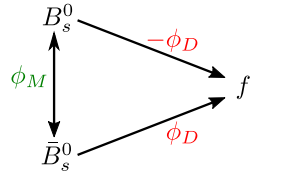
C. Fitzpatrick

May 30, 2017

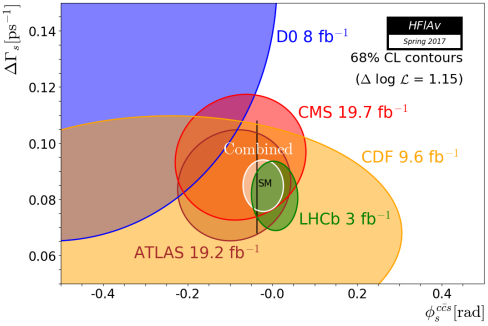
$\mathcal{CP}$ in interference: ϕ_s

- Interference between mixing and decay of B_s^0 mesons

  $\phi_s^{SM} = -2\arg\left[-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right] = -36.5^{+1.3}_{-1.2}$ mrad
- LHCb, ATLAS, CMS + Tevatron experiments
- Needs angular analysis to disentangle contributions



$\phi_s = \phi_M - 2\phi_D$



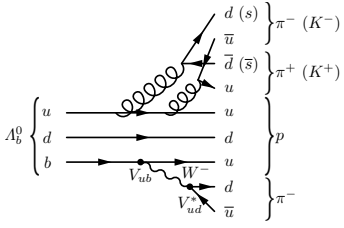
- Combination: $\phi_s = -21 \pm 31$mrad [HFLAV preliminary]
- LHCb results for $B_s^0 \to J/\psi\{\phi, K^+K^-, \pi^+\pi^-\}$, $B_s^0 \to \psi(2S)\phi$ and $B_s^0 \to D_s^+D_s^-$
- CMS + ATLAS results for $B_s^0 \to J/\psi\phi$
- Significant improvements in sensitivity expected with new CMS + ATLAS pixel detectors

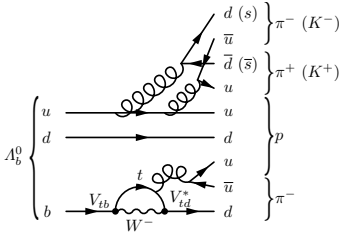
CP Violation
Introduction
Selected results
~~$\mathcal{CP}$~~ in charm
CKM angle γ
~~$\mathcal{CP}$~~ in B mixing
~~$\mathcal{CP}$~~ in $B \to KK, \pi\pi$
β in $J/\psi K_S^0$
ϕ_s in $J/\psi\phi$
~~$\mathcal{CP}$~~ in Baryons
Conclusions

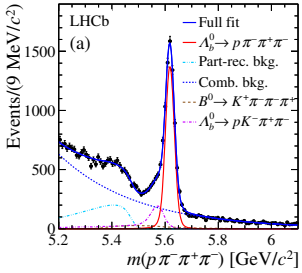
C. Fitzpatrick

May 30, 2017

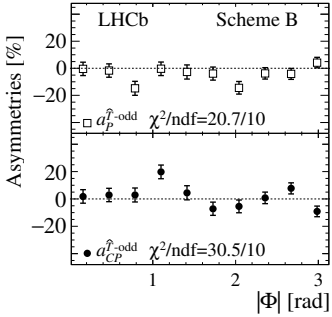
$\mathcal{CP}$ in Baryons







- A world first[12]: $\Lambda_b \to p\pi^-\pi^+\pi^-(K^+K^-)$
- $\mathcal{CP}$ in interference using P- and T-odd asymmetry observables
  $C = p_p \cdot (p_{h_1^-} \times p_{h_2^+})$, $\bar{C} = p_{\bar{p}} \cdot (p_{h_1^+} \times p_{h_2^-})$
  $(h_1, h_2 = \pi\pi, \pi K)$
- Asymmetries:
  $A = \frac{N(C>0)-N(C<0)}{N(C>0)+N(C<0)}$, $\bar{A} = \frac{\bar{N}(-\bar{C}>0)-\bar{N}(\bar{C}<0)}{\bar{N}(-\bar{C}>0)+\bar{N}(\bar{C}<0)}$
- CP- and P- violating observables:
  $a_{CP} = \frac{1}{2}(A - \bar{A})$, $a_P = \frac{1}{2}(A + \bar{A})$
- LHCb finds: $a_{CP} \neq 0$ in $\Lambda_b \to p\pi^-\pi^+\pi^-$ at 3.3σ global



[12] [Nature Physics 13, 391396 (2017)]

CP Violation
Introduction
Selected results
$\mathcal{CP}$ in charm
CKM angle γ
$\mathcal{CP}$ in B mixing
$\mathcal{CP}$ in $B \to KK, \pi\pi$
β in $J/\psi K_S^0$
ϕ_s in $J/\psi\phi$
$\mathcal{CP}$ in Baryons
Conclusions

C. Fitzpatrick

May 30, 2017

Conclusions

- Recent measurements of $\not{CP}$ observables in charm and beauty are remarkably consistent with the SM
- Many new measurements have exceeded those from the b-factories and the Tevatron
- Uncertainties are still very large in many places however:
- Charm $\not{CP}$ could be just around the corner...
- $\gamma \to 1^\circ$ is a major goal of the LHCb Upgrade for Run 3 & 4
  - Belle II will soon be taking data: Potential to greatly enhance the combination
  - BES III inputs to γ measurements will further reduce systematic uncertainties
- ATLAS, CMS + LHCb can strongly constrain NP in mixing with $B_s^0 \to J/\psi\phi$
  - ϕ_s sensitivity will require careful control of hadronic effects
- Significant quantities of data at the LHC are still to be analysed

CP Violation
Introduction
Selected results
$\not{CP}$ in charm
CKM angle γ
$\not{CP}$ in B mixing
$\not{CP}$ in $B \to KK, \pi\pi$
β in $J/\psi K_S^0$
ϕ_s in $J/\psi\phi$
$\not{CP}$ in Baryons
Conclusions

C. Fitzpatrick

May 30, 2017

Thanks for listening

α β γ

C. Fitzpatrick

May 30, 2017

LHCb phase 1 upgrade sensitivity

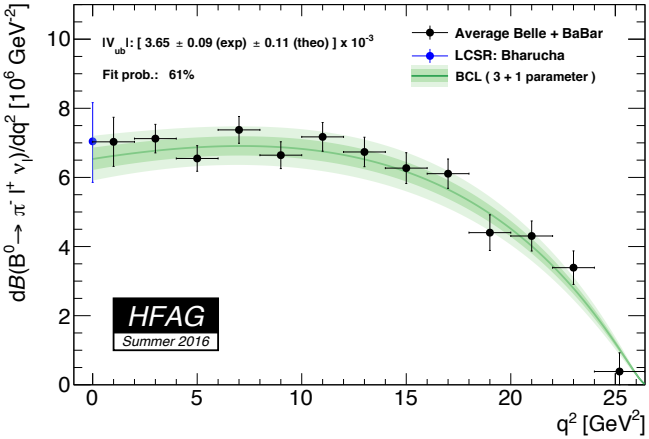
Type	Observable	LHC Run 1	LHCb 2018	**LHCb upgrade**	Theory
B_s^0 mixing	$\phi_s(B_s^0 \to J/\psi\,\phi)$ (rad)	0.049	0.025	**0.009**	~ 0.003
	$\phi_s(B_s^0 \to J/\psi\; f_0(980))$ (rad)	0.068	0.035	**0.012**	~ 0.01
	$A_{\rm sl}(B_s^0)$ (10^{-3})	2.8	1.4	**0.5**	0.03
Gluonic	$\phi_s^{\rm eff}(B_s^0 \to \phi\phi)$ (rad)	0.15	0.10	**0.018**	0.02
penguin	$\phi_s^{\rm eff}(B_s^0 \to K^{*0}\bar{K}^{*0})$ (rad)	0.19	0.13	**0.023**	< 0.02
	$2\beta^{\rm eff}(B^0 \to \phi K_{\rm S}^0)$ (rad)	0.30	0.20	**0.036**	0.02
Right-handed	$\phi_s^{\rm eff}(B_s^0 \to \phi\gamma)$ (rad)	0.20	0.13	**0.025**	< 0.01
currents	$\tau^{\rm eff}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	5%	3.2%	**0.6%**	0.2 %
Electroweak	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,{\rm GeV}^2/c^4)$	0.04	0.020	**0.007**	0.02
penguin	$q_0^2\, A_{\rm FB}(B^0 \to K^{*0}\mu^+\mu^-)$	10%	5%	**1.9%**	$\sim 7\%$
	$A_{\rm I}(K\mu^+\mu^-; 1 < q^2 < 6\,{\rm GeV}^2/c^4)$	0.09	0.05	**0.017**	~ 0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	14%	7%	**2.4%**	$\sim 10\%$
Higgs	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ (10^{-9})	1.0	0.5	**0.19**	0.3
penguin	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	220%	110%	**40%**	$\sim 5\,\%$
Unitarity	$\gamma(B \to D^{(*)}K^{(*)})$	7°	4°	**0.9°**	negligible
triangle	$\gamma(B_s^0 \to D_s^\mp K^\pm)$	17°	11°	**2.0°**	negligible
angles	$\beta(B^0 \to J/\psi\, K_{\rm S}^0)$	1.7°	0.8°	**0.31°**	negligible
Charm	$A_\Gamma(D^0 \to K^+K^-)$ (10^{-4})	3.4	2.2	**0.4**	–
CP violation	ΔA_{CP} (10^{-3})	0.8	0.5	**0.1**	–

LHCb-PUB-2014-040

C. Fitzpatrick

May 30, 2017

$|V_{ub}|$, the other tree-level measurement



- Measured using semileptonic decays $B \to \pi \ell \nu$[13], $\Lambda_b \to p \mu \nu$[14]
- Fit of form factor to theory predictions and q^2 spectrum in data

[13] Heavy Flavour Averaging Group 2016
[14] Nature Physics 11, 743747 (2015)