Measuring the CKM angle γ

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Neckarzimmern B Physics Workshop

March 22, 2017

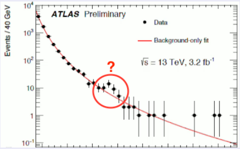
γ as a preamble to this evenings entertainment...?

1. Introduction

Summary of 2016

March 2016 - Started with such promise

50th anniversary celebration and 750 GeV structure mini-session, *chairperson Boaz Klima*		
08:30 - 08:35	Etienne Auge (Orsay)	Welcome
08:40 - 09:05	Etienne Auge (Orsay) Bolek Pietrzyk (Annecy) Eckhard Elsen (CERN)	50th anniversary celebration
	750 GeV structure mini-session	
09:05 - 09:25	Frederick Bordry (CERN)	LHC status
09:30 - 09:45	Jan Stark (Grenoble)	New physics in high p_T dijet, dilepton and di-photon final states at ATLAS
09:50 - 10:05	John Paul Chou (Rutgers)	New physics in final states with light SM particles at CMS



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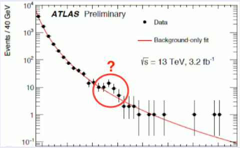
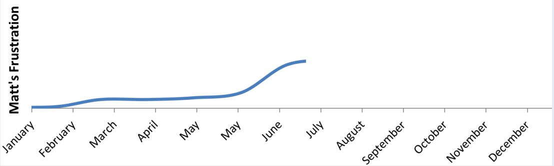


June 2016 - Brexit

My levels of despair



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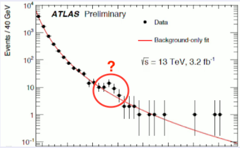

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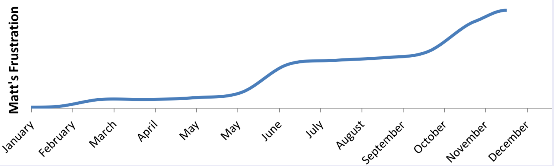

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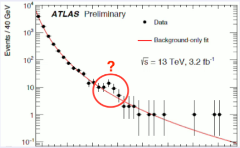

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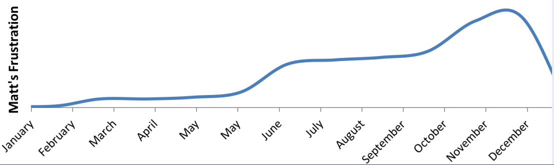
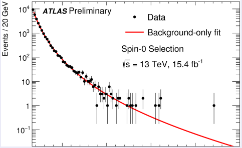
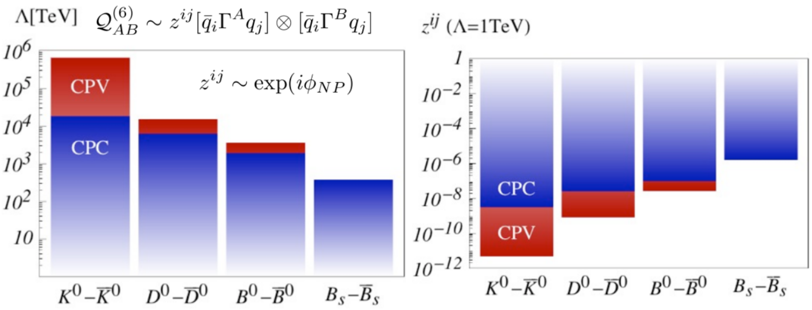
End of 2016 - Still no New Physics (NP)





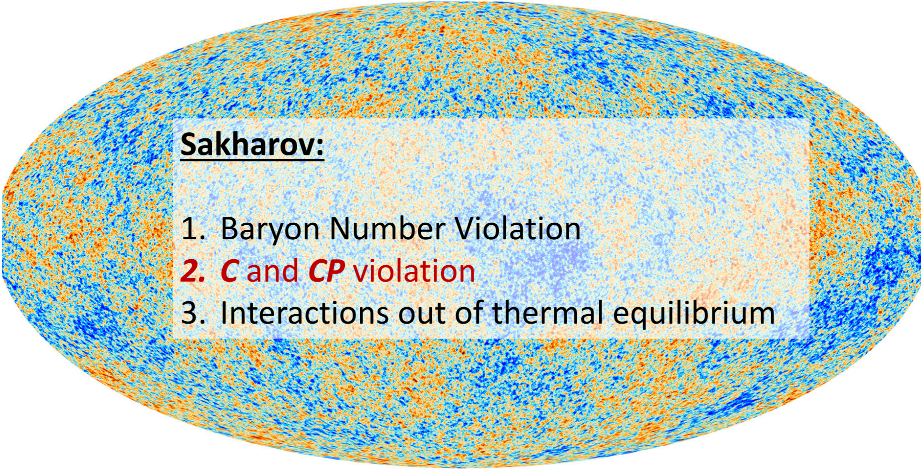
Don't despair!

- Direct NP discovery by ATLAS/CMS is still possible
- **Flavour sector provides another window of opportunity**



- Today I will discuss looking for new sources of CPV by constraining CKM angle γ
  - Mainly focused towards LHCb's searches
  - Also include information from Belle and BaBar for HFAG / CKM / PDG world average
  - With some future prospects from Belle II and LHCb

How does a matter dominated universe arise?



- We live in a matter (and photon) dominated universe
- CP violation is a crucial ingredient to this problem
- CPV in the SM ($\sim 10^{-20}$) does not nearly account for the observed baryon-photon ratio ($\sim 10^{-10}$)

2. CP violation and the CKM matrix

CKM matrix

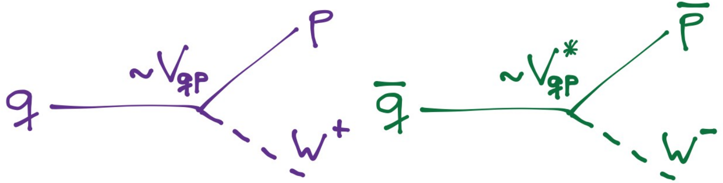
- In the SM quarks can change flavour by emission of a $W^{\pm}$ boson
- Quark mixing in the SM is described by the 3×3 unitary CKM matrix

CKM matrix

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

flavour eigenstates — mass eigenstates

- The matrix elements determine the transition probability



- Parameterised by three mixing angles (θ_{12}, θ_{13}, θ_{23}) and a CP violating phase (δ)

CKM matrix

- The CKM matrix exhibits a clear hierachy, $\sin(\theta_{13}) << \sin(\theta_{23}) << \sin(\theta_{12}) << 1$, so often expressed in Wolfenstein parameterisation (A, λ, ρ, η)

Wolfenstein parametrisation

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

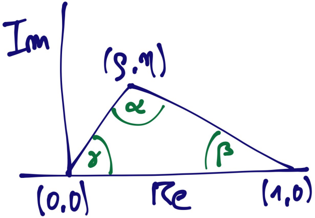
- **Hierachy gives very distinctive behaviour to the flavour sector** of the SM which gives strong constraints on NP
- CKM matrix gives the only source of CP violation in the SM ($m_\nu = \theta_{QCD} = 0$)

Unitarity gives a triangle in the complex plane

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

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

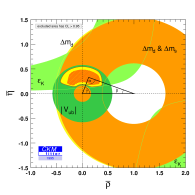
- **Area** corresponds to **total CPV** in SM
- SM implies that $\alpha + \beta + \gamma = 180^\circ$



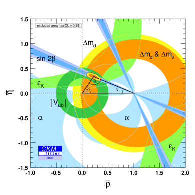
CKM picture is now well verified

- Any discrepancies would be of great importance
- CKM angle γ is the *least well known* constraint

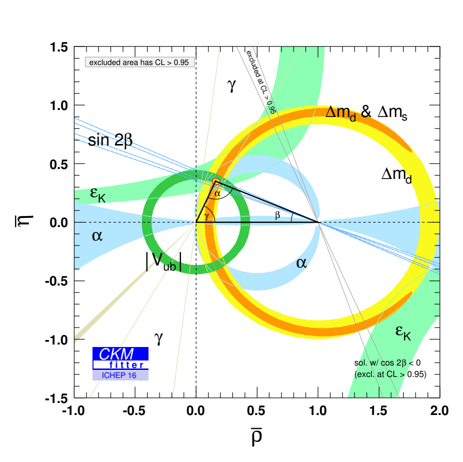
1995



2004



2016



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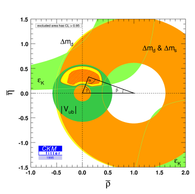

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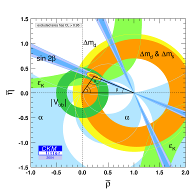
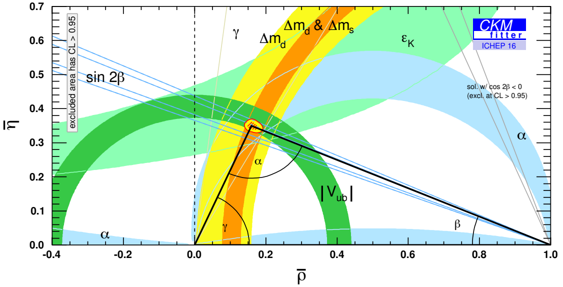


2016 - zoom



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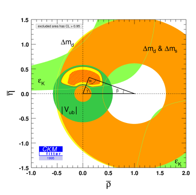

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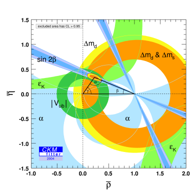


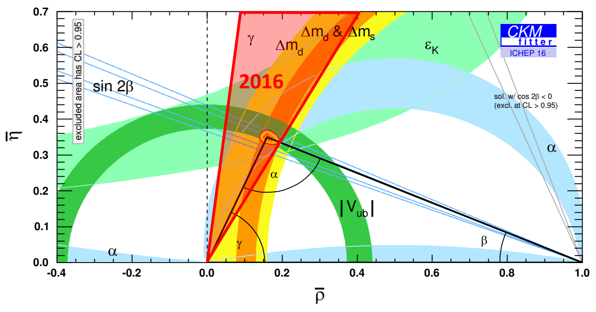
Direct γ measurements

$$\gamma = (72.1^{+5.4}_{-5.8})^{\circ}$$

Indirect γ extrapolation

$$\gamma = (65.3^{+1.0}_{-2.5})^{\circ}$$

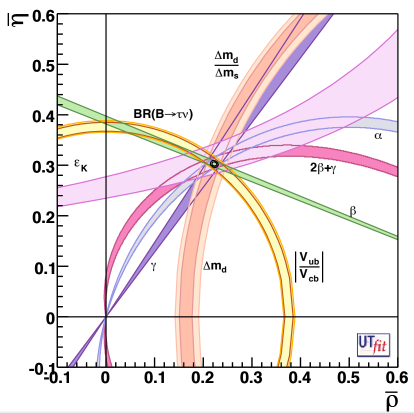
2015 - zoom



The Ultimate Test

- γ is an excellent probe of new physics
- Not just via direct / indirect disagreement but many constraints from new physics in neutral mixing require input of γ

"The nightmare" - [arXiv:0710.3799]



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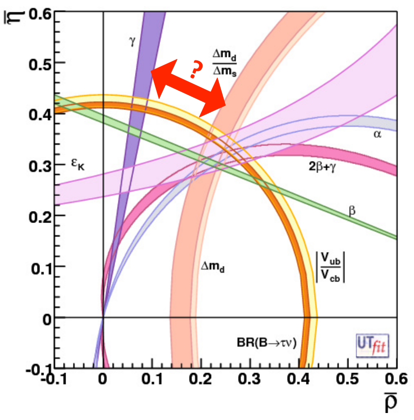
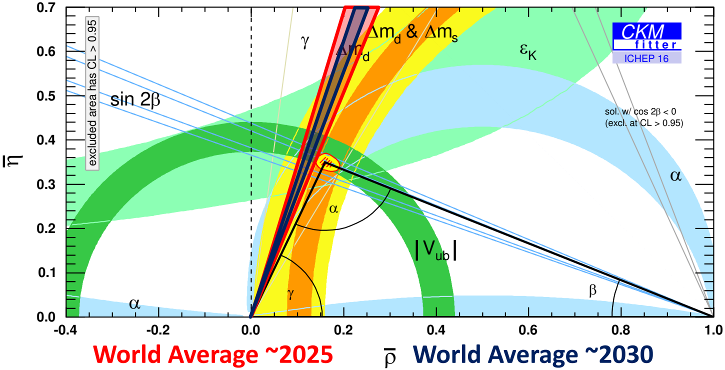


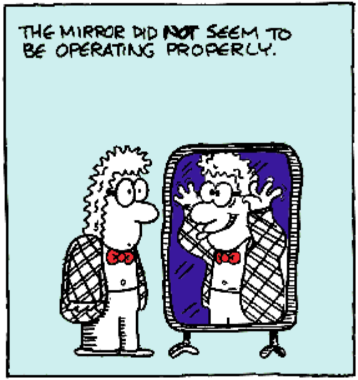
The Ultimate Test

- LHCb expected precision in 2019 (end of Run 2) $\sim \pm 3\text{-}4^\circ$
- LHCb expected precision in 2024 (end of Run 3) $\sim \pm 1.5^\circ$
- Belle II expected precision in 2023 (end of Run) $\sim \pm 1.5^\circ$
- LHCb expected precision in 2029 (end of Run 4) $< 1^\circ$

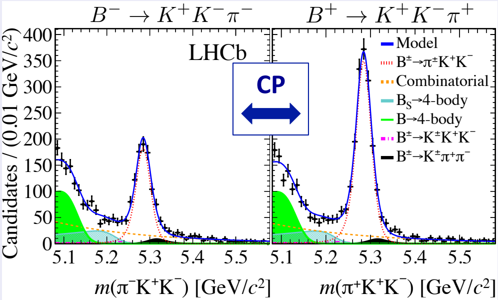


CP violation

- **CKM matrix is the only place in the SM with CP violation** $(m_\nu = \theta_{QCD} = 0)$
- Given CPV in SM is ten orders of magnitude to small to explain baryon-photon ratio
- New sources of CP violation would be a clear indiction of NP



LHCb - [PRD 90 (2014) 112004]



CPV recap

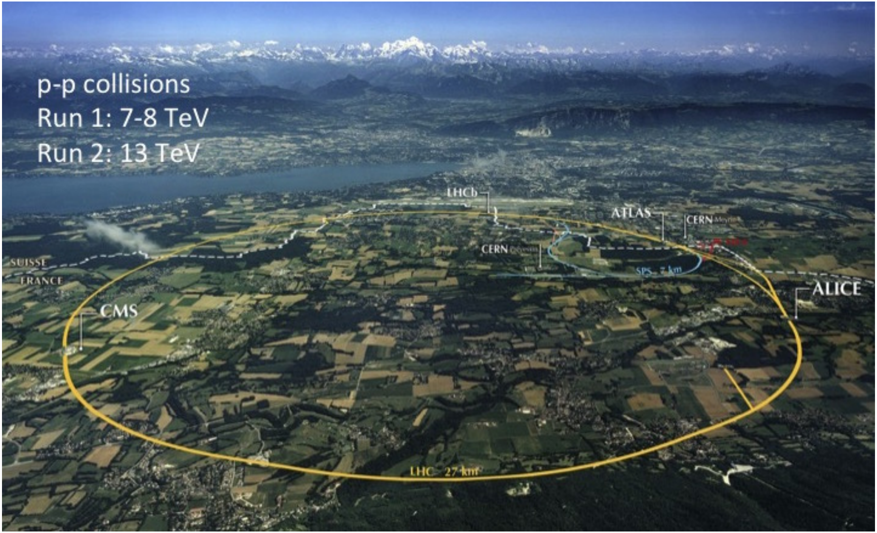
- Phenomenology of quark mixing → neutral meson osciallation
$$B^0_H = qB^0 + q\bar{B}^0 \quad \text{and} \quad B^0_L = pB^0 - q\bar{B}^0 \quad \text{where} \quad p^2 + q^2 = 1 \tag{1}$$
- Define decay amplitudes to final state f as
$$A_f = \Gamma(B \to f)\ , \quad \bar{A}_f = \Gamma(\bar{B} \to f)\ , \quad A_{\bar{f}} = \Gamma(B \to \bar{f})\ , \quad \bar{A}_{\bar{f}} = \Gamma(\bar{B} \to \bar{f}) \tag{2}$$
- For any hadron carrying conserved quantum numbers (any charged meson and all baryons) then B and $\bar{B}$ cannot decay to same final state
  - Only possible manifestiation of CPV is:
  - **CPV in decay:** $|A_f| \neq |\bar{A}_{\bar{f}}|$
- For neutral mesons (consider f as a CP eigenstate) define $\lambda_f = \frac{q}{p}\frac{\bar{A}_f}{A_f}$
  - **CPV in decay:** $|\bar{A}_f/A_f| \neq 1$ (as for charged mesons)
  - **CPV in mixing:** $|q/p| \neq 1$
  - **CPV in mixing/decay interference:** $\arg(\lambda_f) \neq 0$

Summary of observed CPV effects - [arXiv:1607.06746]

	K^0	K^+	Λ	D^0	D^+	D_s^+	Λ_c^+	B^0	B^+	B_s^0	Λ_b^0
Mixing	✓	-	-	✗	-	-	-	✗	-	✗	-
Mixing/Decay Int.	✓	-	-	✗	-	-	-	✓	-	✗	-
Decay	✓	✗	✗	✗	✗	✗	✗	✓	✓	✓	✗

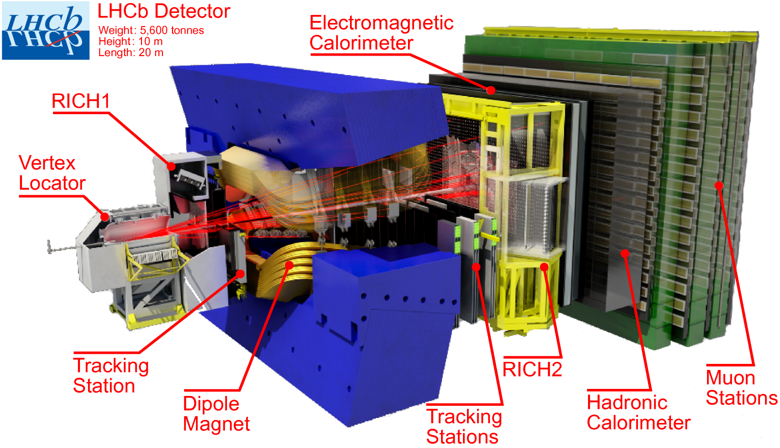
3. The LHCb Experiment

LHC, CERN, Geneva



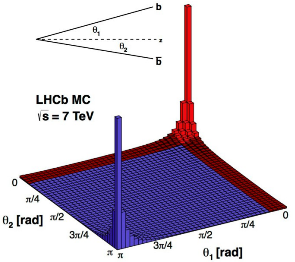
LHCb Detector

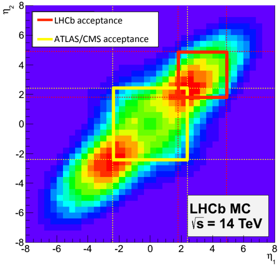
- A single arm forward spectrometer



LHCb Detector

- A single arm forward spectrometer
- A factory for beauty and charm decays
- Acceptance range $2 < \eta < 5$
- 100K $b\bar{b}$ pairs produced per second ($10^4 \times$ B factories)
- $\sigma(b\bar{b}) = 284 \pm 54\mu\text{b}$
- $\sigma(c\bar{c}) \approx 20 \times \sigma(b\bar{b})$





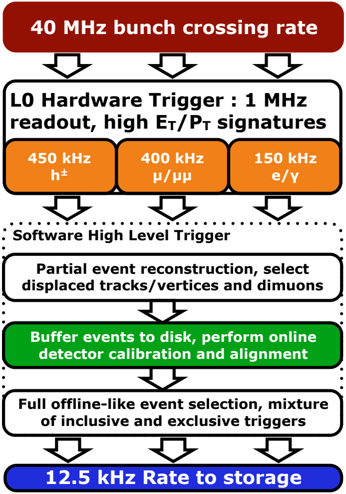
LHCb performance paper - [arXiv:1412.6352]

- IP resolution $\approx 20\mu\text{m}$
- p resolution $\approx 0.5\%$
- τ resolution ≈ 45 fs
- Calorimeter ID for γ, e, π^0
- Particle ID $\epsilon(K) \sim 95\%$ with 5% $\pi \to K$ mis-id
- Muons $\epsilon(\mu) \sim 97\%$ with $(1-3)\%\pi \to \mu$ mis-id

LHCb Trigger

- The detector is complimented with an incredibly sophisticated and versatile trigger system
- Allow detector alignment and calibration in real time!
- In turn means online and offline reconstruction are identical
- Allows performing of many analyses online
- Allows high readout rate
- High efficiency for a broad range of topics
- Larger gains expected in the future (full software readout)

LHCb 2015 Trigger Diagram



4. CKM angle γ

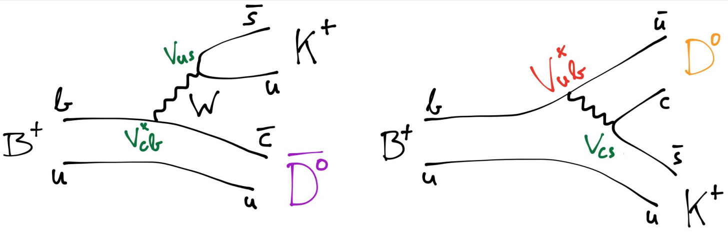
Measuring γ

- γ is the phase between $V_{ub}^* V_{ud}$ and $V_{cb}^* V_{cd}$
  - Require interference between $b \to cW$ and $b \to uW$ to access it
  - No dependence on CKM elements involving the top
  - **Can be measured using tree level B decays**
  - Makes it a benchmark of the SM (no loops)

$$\gamma = \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$

- The "textbook" case is $B^\pm \to \overset{(-)}{D}{}^0 K^\pm$:
  - Transitions themselves have different final states (D^0 and $\bar{D}^0$)
  - Interference occurs when D^0 and $\bar{D}^0$ decay to the same final state f

Reconstruct the $D^0/\bar{D}^0$ in a final state accesible to both to acheieve interference



- **The crucial feature of these (and similar) decays is that the D^0 can be reconstructed in several different final states**

γ from theory

$$\gamma = \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$

- γ is known very well
- Can be determined entirely from tree decays
  - Unique property among all *CP* violation parameters
  - Hadronic parameters can be determined from data
- Neglible theoretical uncertainty (Zupan and Brod 2013)

Theory uncertainty on γ

$\delta\gamma/\gamma \approx \mathcal{O}(10^{-7})$ - [arXiv:1308.5663]

- γ can probe for new physics at extrememly high energy scales (Zupan)
  - (N)MFV new physics scenarios: $\sim \mathcal{O}(10^2)$ TeV
  - gen. FV new physics scenarios: $\sim \mathcal{O}(10^3)$ TeV
- NP contributions to $C_{1,2}$ can cause sizeable shifts ($\mathcal{O}(4^\circ)$) in γ (Brod, Lenz et. al 2014) - [arXiv:1412.1446]

γ from experiment

- γ is NOT known very well
- It is quite challenging to measure
- The decay rates are small

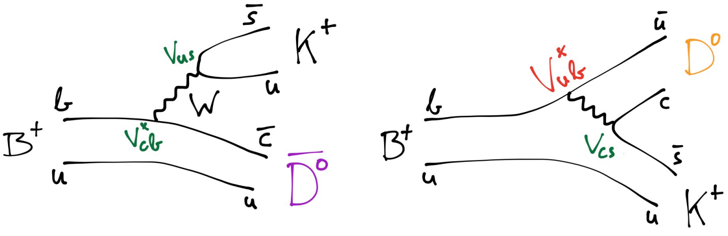
Branching ratio for suppressed γ mode

$$BR(B^- \to DK^-, D \to \pi K) \approx 2 \times 10^{-7}$$

- Small interference effect typically $\sim 10\%$
- Fully hadronic decays - hard to trigger on
- Many channels have a K^0_S in the final state - low efficiency
- Many channels have a π^0 in the final state - very hard at LHCb
- Many different decay channels, many observables and many hadronic unknowns make it statistically challenging

Methods to measure γ

Reconstruct the $D^0/\bar{D}^0$ in a final state accesible to both to acheive interference



- GLW method
  - CP eigenstates e.g. $D \to KK$
  - Gronau, London, Wyler (1991)
- ADS method
  - CF or DCS decays e.g. $D \to K\pi$
  - Atwood, Dunietz, Soni (1997,2001)
- GGSZ method
  - 3-body final states e.g. $D \to K_S^0\pi\pi$
  - Giri, Grossman, Soffer, Zupan (2003)

- [Phys. Lett. B253 (1991) 483]
- [Phys. Lett. B265 (1991) 172]
- [Phys. Rev. D63 (2001) 036005]
- [Phys. Rev. Lett. 78 (1997) 3257]
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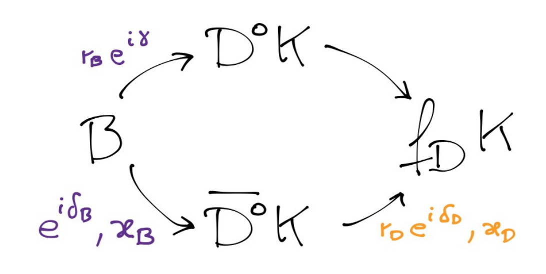

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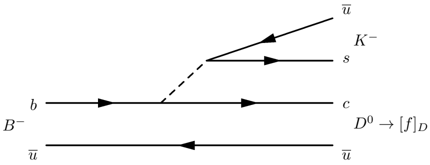
γ with *CP* eigenstates (GLW)

- Use the $B^{\pm} \to \overset{(-)}{D}{}^0 K^{\pm}$ case as an example:
  - **Consider only *D* decays to *CP* eigenstates, f_{CP}**
  - Favoured: $b \to c$ with strong phase δ_F and weak phase ϕ_F
  - Supressed: $b \to u$ with strong phase δ_S and weak phase ϕ_S

Favoured:



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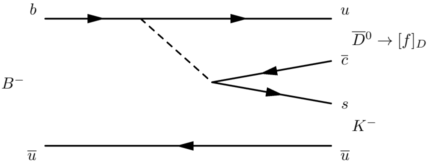


Subsequent amplitude to final state f_{CP} is:

$$A_f = |F|e^{i(\delta_F - \phi_F)} + |S|e^{i(\delta_S - \phi_S)} \quad (3)$$

$$\bar{A}_f = |F|e^{i(\delta_F + \phi_F)} + |S|e^{i(\delta_S + \phi_S)} \quad (4)$$

because strong phases (δ) don't change sign under CP while weak phases (ϕ) do

γ with *CP* eigenstates (GLW)

- Define the *CP* asymmetry as the rate difference between meson with b ($\overline{B}$) and $\overline{b}$ (B)

$$\mathcal{A}_{CP} = \frac{|\bar{A}_{\bar{f}}|^2 - |A_f|^2}{|\bar{A}_{\bar{f}}|^2 + |A_f|^2} \quad \textbf{(experimental observable)}$$
$$= \frac{2|F||S|\sin(\delta_F - \delta_S)\sin(\phi_F - \phi_S)}{|F|^2 + |S|^2 + 2|F||S|\cos(\delta_F - \delta_S)\cos(\phi_F - \phi_S)}$$

- Choose $r_B = \frac{|S|}{|F|}$ (so that $r < 1$) and use strong phase difference $\delta_B = \delta_F - \delta_S$
- γ is the weak phase difference $\phi_F - \phi_S$
- Subsequently the *CP* asymmetry becomes

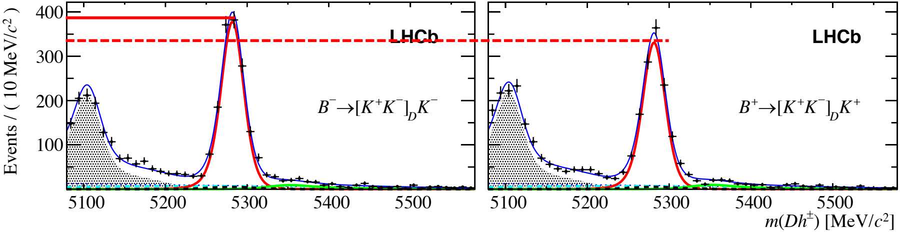
GLW *CP* asymmetry

$$\mathcal{A}_{CP} = \frac{\pm 2 r_B \sin(\delta_B)\sin(\gamma)}{1 + r_B^2 \pm 2 r_B \cos(\delta_B)\cos(\gamma)}$$

- The $+(-)$ sign corresponds to *CP*-even (-odd) final states
- Note that r_B and δ_B (ratio and strong phase difference of favoured and supressed modes) are different for each B decay
- **The value of γ is shared by all such decays**

An example GLW analysis

- GLW analysis of $B^{\pm} \to DK^{\pm}$ with $D \to K^{+}K^{-}$ - [arXiv:1603.08993]
- CP asymmetry can be seen by eye



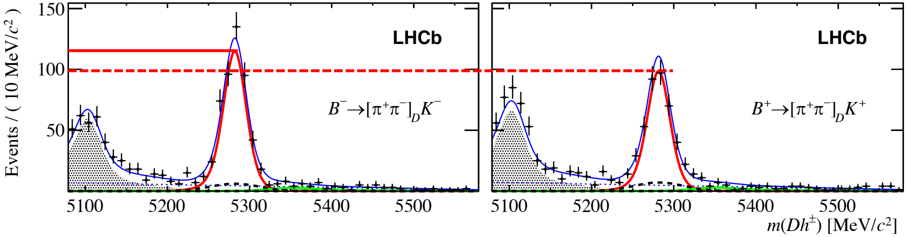
GLW asymmetry for $B^{\pm} \to DK^{\pm}$ and $D \to K^{+}K^{-}$

$$\mathcal{A}_{CP}^{DK,KK} = \frac{\Gamma(B^{-} \to [K^{+}K^{-}]_{D}K^{-}) - \Gamma(B^{+} \to [K^{+}K^{-}]_{D}K^{+})}{\Gamma(B^{-} \to [K^{+}K^{-}]_{D}K^{-}) + \Gamma(B^{+} \to [K^{+}K^{-}]_{D}K^{+})}$$
$$= 0.087 \pm 0.020 \pm 0.008$$

$\sim 4\sigma$ from zero

An example GLW analysis

- Same story with the $B^{\pm} \to DK^{\pm}$ and $D \to \pi^+\pi^-$
- CP asymmetry can be seen by eye



GLW asymmetry for $B^{\pm} \to DK^{\pm}$ and $D \to K^+K^-$

$$\mathcal{A}_{CP}^{DK,\pi\pi} = \frac{\Gamma(B^- \to [\pi^+\pi^-]_D K^-) - \Gamma(B^+ \to [\pi^+\pi^-]_D K^+)}{\Gamma(B^- \to [\pi^+\pi^-]_D K^-) + \Gamma(B^+ \to [\pi^+\pi^-]_D K^+)}$$

$$= 0.128 \pm 0.037 \pm 0.012$$

$\sim 3\sigma$ from zero

γ with CF and DCS decays (ADS)

- A 2-body D decay to final state f accesible to both D^0 and $\bar{D}^0$ can be
  - Cabibbo-favoured (CF) - $D^0 \to \pi^- K^+$
  - Doubly-Cabibbo-supressed (DCS) - $\bar{D}^0 \to \pi^- K^+$
- Introduces 2 new hadronic parameters:
  - r_D - ratio of magnitudes for D^0 and $\bar{D}^0$ decay to f
  - δ_D - relative phase for D^0 and $\bar{D}^0$ decay to f
- Leads to an additional (modified) asymmetry defintion and an additional ratio observable

ADS asymmetry

$$\mathcal{A}_{ADS} = \frac{2 r_D r_B \sin(\delta_B + \delta_D) \sin(\gamma)}{r_D^2 + r_B^2 + 2 r_B r_D \cos(\delta_B + \delta_D) \cos(\gamma)}$$

ADS ratio

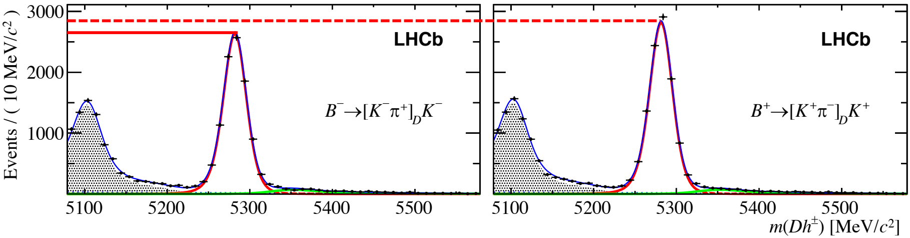
$$\mathcal{R}_{ADS} = \frac{|\bar{A}_{\bar{f}}|^2 + |A_f|^2}{|\bar{A}_f|^2 + |A_{\bar{f}}|^2} = r_B^2 + r_D^2 + 2 r_B r_D \cos(\delta_B + \delta_D) \cos(\gamma)$$

- Hadronic parameters r_D and δ_D can be de independently determined (using CLEO data and HFAG averages)
- **Combining all information for various decays allows determination of γ, r_B and δ**

An example ADS analysis

- ADS analysis of $B^{\pm} \to DK^{\pm}$ with $D \to K^{\pm}\pi^{\mp}$ which has **two asymmetries**
  1. "Favoured:"
     - $B^{-} \to [D^0 \to K^-\pi^+]K^-$ **AND** $B^{-} \to [\bar{D}^0 \to K^-\pi^+]K^-$
     - (fav. B with fav. D) **AND** (sup. B with sup. D)

Dominated by doubly favoured



Favoured ADS asymmetry for $B^{\pm} \to DK^{\pm}$ and $D \to K^{\pm}\pi^{\mp}$

$$\mathcal{A}_{CP}^{DK,K\pi} = \frac{\Gamma(B^- \to [K^-\pi^+]_D K^-) - \Gamma(B^+ \to [K^+\pi^-]_D K^+)}{\Gamma(B^- \to [K^-\pi^+]_D K^-) + \Gamma(B^+ \to [K^+\pi^-]_D K^+)}$$

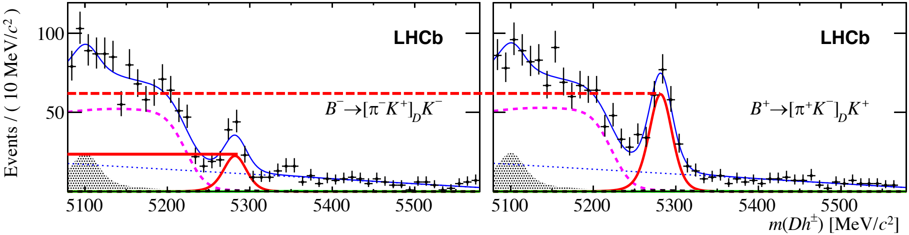
$$= -0.0194 \pm 0.0072 \pm 0.0060$$

$\sim 2\sigma$ from zero

An example ADS analysis

- ADS analysis of $B^\pm \to DK^\pm$ with $D \to K^\pm\pi^\mp$ which has **two asymmetries**
  2. Supressed:
     - $B^- \to [D^0 \to K^+\pi^-]K^-$ **AND** $B^- \to [\bar{D}^0 \to K^+\pi^-]K^-$
     - (fav. B with sup. D) **AND** (sup. B with fav. D)

Both of similar size so large CP effect



Favoured ADS asymmetry for $B^\pm \to DK^\pm$ and $D \to K^\mp\pi^\pm$

$$\mathcal{A}_{\rm ADS}^{DK,\pi K} = \frac{\Gamma(B^- \to [K^+\pi^-]_D K^-) - \Gamma(B^+ \to [K^-\pi^+]_D K^+)}{\Gamma(B^- \to [K^+\pi^-]_D K^-) + \Gamma(B^+ \to [K^-\pi^+]_D K^+)}$$

$$= -0.403 \pm 0.056 \pm 0.011$$

$\sim 7\sigma$ from zero

Aside: Multibody final states

- **The GLW/ADS formalisms are fairly trivally extended to multibody final states**

GLW

- Multibody quasi-CP states
- $D \to K^+K^-\pi^0$
- $D \to \pi^+\pi^-\pi^0$
- $D \to \pi^+\pi^-\pi^+\pi^-$
- Account for the fraction, F^+ of CP-even content

ADS

- Multibody DCS decys
- $D \to K^+\pi^-\pi^0$
- $D \to K^+\pi^-\pi^+\pi^-$
- Account for the dilution, κ, from interference between resonances

quasi-GLW asymmetry

$$\mathcal{A}_{CP} = \frac{\pm 2(2F^+ + 1) r_B \sin(\delta_B)\sin(\gamma)}{1 + r_B^2 \pm 2(2F^+ + 1) r_B \cos(\delta_B)\cos(\gamma)}$$

quasi-ADS asymmetry

$$\mathcal{A}_{CP} = \frac{2\kappa r_D r_B \sin(\delta_B + \delta_D)\sin(\gamma)}{r_D^2 + r_B^2 + 2\kappa r_B r_D \cos(\delta_B + \delta_D)\cos(\gamma)}$$

- We can also construct partial rate ratios as additional observables

γ with 3-body self-conjugate states (GGSZ)

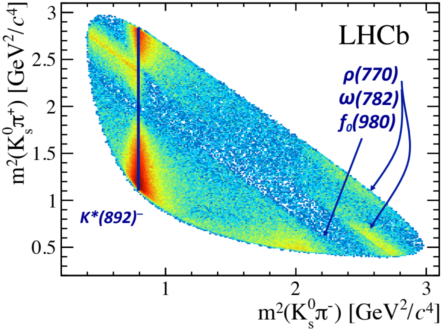
- Now get additional sensitivity over the 3-body phase space
- Idea is to perform a GLW/ADS type analysis across the D decay phase space
- For example $D^0 \to K^0_S \pi^+\pi^-$ has contributions from
  - Singly-Cabibbo-suppressed decay $D^0 \to K^0_S \rho^0$
  - Doubly-Cabibbo-suppressed decay $D^0 \to K^{*+}\pi^-$
  - Interference between them enhances sensitivity and resolves amigiuities in γ determination

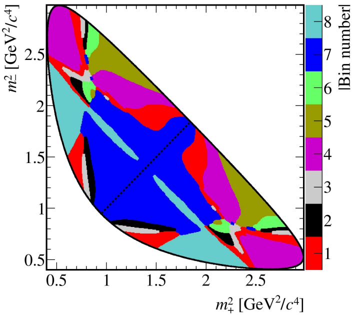
Partial B rate as function of Dalitz position $(+,-) = (m_{K^0_S\pi^+}, m_{K^0_S\pi^-})$

$$d\Gamma_{B^\pm}(\mathbf{x}) = A^2_{(\pm,\mp)} + r_B^2 A^2_{(\mp,\pm)} + 2A_{(\pm,\mp)}A_{(\mp,\pm)}\left[\underbrace{r_B\cos(\delta_B \pm \gamma)}_{x_\pm}\cos(\delta_{D(\pm,\mp)}) + \underbrace{r_B\sin(\delta_B \pm \gamma)}_{y_\pm}\sin(\delta_{D(\pm,\mp)})\right]$$

- Model-dependent - Fit Dalitz plot with full amplitude model for $(x_\pm, y_\pm)$
- Model-independent - Choose binning scheme in Dalitz plane to minimize δ_D variation across bin and fit simultaneously in each bin for $(x_\pm, y_\pm)$

Examples of the $D^0 \to K^0_S \pi^+ \pi^-$ Dalitz distribution





- Model-dependent - Fit Dalitz plot with full amplitude model for $(x_\pm, y_\pm)$
- Model-independent - Choose binning scheme in Dalitz plane to minimize δ_D variation across bin and fit simultaneously in each bin for $(x_\pm, y_\pm)$
- **Sensitivity to γ by comparing D Dalitz distributions for B^+ and B^-**
- In other words *CP* asymmetry in bins of Dalitz space

The cartesian coordinates

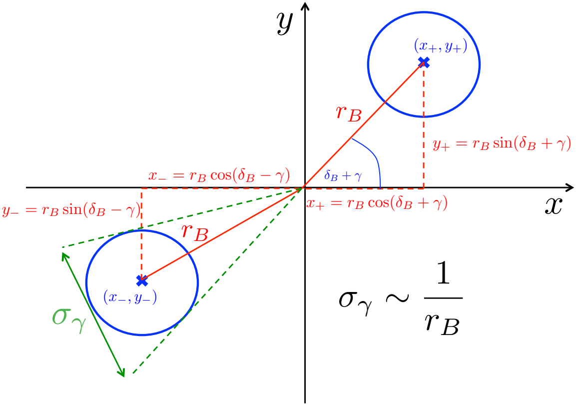
Cartesian definition

$$x_\pm + iy_\pm = r_B e^{i(\delta_B \pm \gamma)}$$

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

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

- Use these for fit stability
- Ease of combianation
- Good statistical behaviour

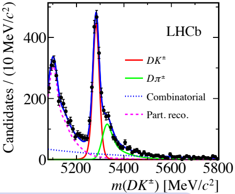


Uncertainty on γ is inversely proportional to central value of hadronic unknown!!

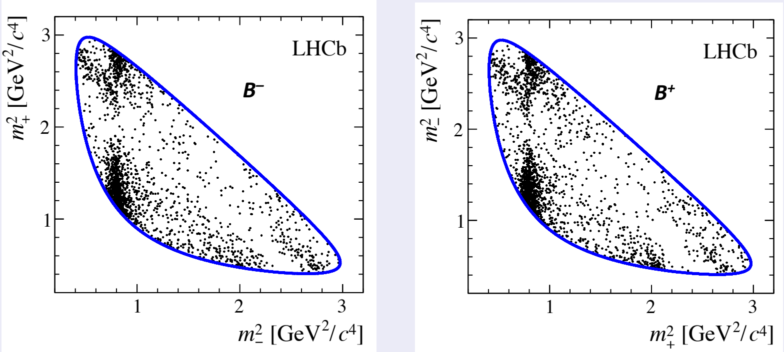
- Fluctuation in nuisance parameter = fluctuation in error on parameter of interest!

An example GGSZ analysis - $B^{\pm} \to DK^{\pm}$, $D \to K^0_S \pi^+ \pi^-$

- First fit invariant B mass distrbution
- Project (cut) signal candidates into Dalitz plane
- Requires experimental efficiency and background distributions in DP
- Control channels used are $B^{\pm} \to D\pi^{\pm}$ and $B^- \to D\mu^-\nu$



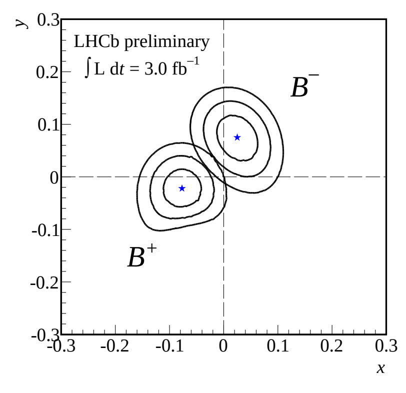
Compare bin by bin differences for signal candidates in the Dalitz plane



An example GGSZ analysis

- GGSZ analyses have excellent standalone sensitivity with a single solution

$B^{\pm} \to D^0(\to K^0_S hh)K^{\pm}$



"Third" uncertainty arises from:

- MD: - amplitude model uncertainty
- MI: - knowledge of strong phase in DP bins

$$x_+ = -0.077 \pm 0.024 \pm 0.010 \pm 0.004$$
$$y_+ = -0.022 \pm 0.025 \pm 0.004 \pm 0.010$$
$$x_- = 0.025 \pm 0.025 \pm 0.010 \pm 0.005$$
$$y_- = 0.075 \pm 0.029 \pm 0.005 \pm 0.014$$

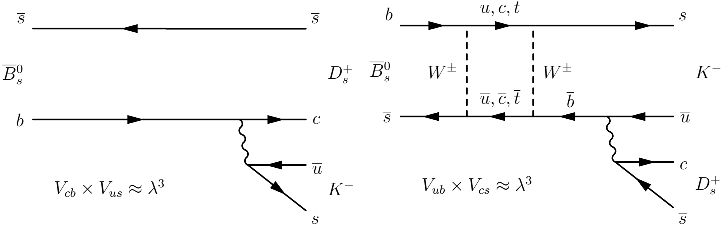
Extensions to other decays

Extension for many other decays with inclusion of relevant coherence factors, κ

1. Obvious extensions to higher resonant final states
    - $B^{\pm} \to D^0 K^{*\pm}$ ($K^{*\pm} \to K^0_S \pi^{\pm}$)
    - $B^{\pm} \to D^{*0} K^{\pm}$ ($D^{*0} \to D^0 \gamma$ or $D^{*0} \to D^0 \pi^0$)
    - mainly just the B factories so far - LHCb starting for Run 2
    - Similar hadronic parameters as $B^{\pm} \to D^0 K^{\pm}$ but lower yields
2. Extensions to other B decays (swapping spectator quark)
    - $B^0 \to D^0 K^{*0}$ ($K^{*0} \to K^+ \pi^-$ tags initial B flavour)
    - $B^0 \to D^0 K^0_S$ (not self tagging)
    - $B^0_s \to D^0 \phi$ (not self tagging and low rate)
    - $B^{\pm}_c \to D^0 D^{\pm}$ (very low rate - favoured mode not yet seen)
    - under exploration at LHCb with some $B^0 \to D^0 K^{*0}$ published
    - Typically enhanced r_B because favoured diagram is colour supressed
3. Extension into baryon sector (add/swap spectators)
    - $\Lambda^0_b \to D^0 \Lambda$ ($\Lambda \to p\pi^-$)
    - Difficult - either long lived final state or dominated by strong interaction
4. Swap final state $K^{\pm}$ for $\pi^{\pm}$
    - $B^{\pm} \to D^0 \pi^{\pm}$
    - Tried at LHCb - problematic as r_B is very small - statistical difficulties
5. Other methods
    - Time-dependent method ($B^0_s \to D^{\mp}_s K^{\pm}$ etc.)
    - Dalitz method (multibody B decays e.g. $B^0 \to D^0 K^{\pm} \pi^{\mp}$)
    - Both tried at LHCb

The time-dependent method with $B_s^0 \to D_s^{\mp} K^{\pm}$

- B_s^0 and $\overline{B}_s^0$ can both decay to same final state $D_s^{\mp} K^{\pm}$ (one via $b \to cW$, the other via $b \to uW$)
- Intereference acheived by neutral B_s^0 mixing (requires knowledge of $-2\beta_s \equiv \phi_s$)
  - Weak phase difference is $(\gamma - 2\beta_s)$



- Requires tagging the initial B_s^0 flavour
- Requires a time-dependent analysis to observe the meson oscillations
- Fit the decay-time-dependent decay rates
- Also requires knowledge of Γ_s, $\Delta\Gamma_s$, Δm_s

The time-dependent method with $B_s^0 \to D_s^\mp K^\pm$

Time-dependent decay rate for initial B_s^0 or $\bar{B}_s^0$ at $t = 0$

$$\frac{\mathrm{d}\Gamma_{B_s^0\to f}(t)}{\mathrm{d}t} \propto e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) + A_f^{\Delta\Gamma_s}\sinh\left(\frac{\Delta\Gamma_s t}{2}\right) + C_f\cos\left(\Delta m_s t\right) - S_f\sin\left(\Delta m_s t\right)\right]$$

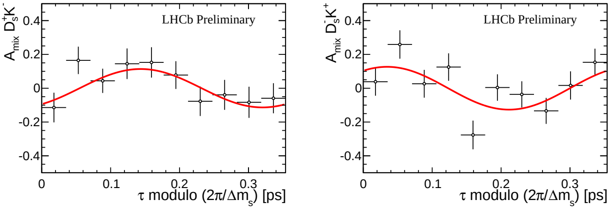
$$\frac{\mathrm{d}\Gamma_{\bar{B}_s^0\to f}(t)}{\mathrm{d}t} \propto e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) + A_f^{\Delta\Gamma_s}\sinh\left(\frac{\Delta\Gamma_s t}{2}\right) - C_f\cos\left(\Delta m_s t\right) + S_f\sin\left(\Delta m_s t\right)\right]$$

Time-dependent rate asymmetry

$$\mathcal{A}_{CP}(t) = \frac{\Gamma_{\bar{B}_s^0\to f}(t) - \Gamma_{B_s^0\to f}(t)}{\Gamma_{\bar{B}_s^0\to f}(t) + \Gamma_{B_s^0\to f}(t)} = \frac{S_f\sin(\Delta m_s t) - C_f\cos(\Delta m_s t)}{\cosh(\frac{\Delta\Gamma_s t}{2}) + A_f^{\Delta\Gamma_s}\sinh(\frac{\Delta\Gamma_s t}{2})}$$

The time-dependent method with $B_s^0 \to D_s^{\mp} K^{\pm}$

- Fit for decay-time-dependent asymmetry

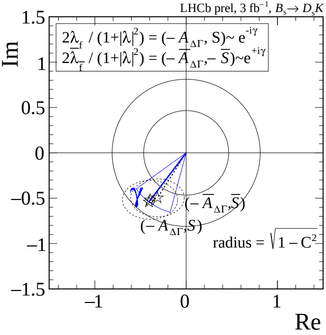


Variable definitions

$$C_f = -C_{\bar{f}} = \frac{1 - r_B^2}{1 + r_B^2}$$

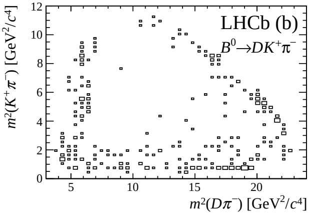
$$A_{f(\bar{f})}^{\Delta\Gamma_s} = \frac{-2 r_B \cos(\gamma - 2\beta_s \mp \delta_B)}{1 + r_B^2}$$

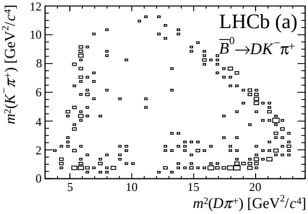
$$S_{f(\bar{f})} = \frac{\pm 2 r_B \sin(\gamma - 2\beta_s \mp \delta_B)}{1 + r_B^2}$$

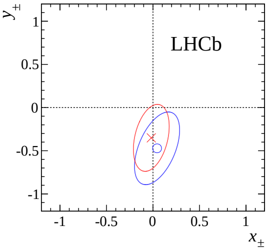


Dalitz methods

- Study Dalitz structure of 3-body *B* **decays** with $B^0 \to DK^+\pi^-$
  - In principle has excellent sensitivity to γ
  - "GW method"? (Gershon-Williams - [arXiv:0909.1495])
- Get multiple interfering resonances which increase sensitivity to γ
  - $D^*{}_0(2400)^-$, $D^*{}_2(2460)^-$, $K^*(892)^0$, $K^*(1410)^0$, $K^*{}_2(1430)^0$
- Fit *B* decay Dalitz Plot for cartesian parameters (similar to GGSZ except for the *B* not the *D*)
  - $D \to K^+K^-$, $D \to \pi^+\pi^-$ - GLW-Dalitz (done by LHCb - [arXiv:1602.03455])
  - $D \to K^\pm\pi^\mp$ - ADS-Dalitz (problematic backgrounds from $B_s^0 \to DK^\pm\pi^\mp$)
  - $D \to K_S^0\pi^+\pi^-$ - GGSZ-Dalitz (double Dalitz!)



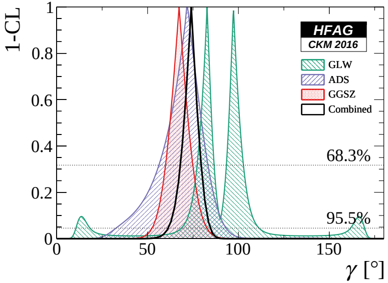


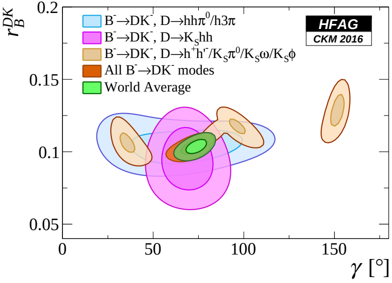


5. Combination of Measurements

Combining measurements to determine γ

- The different methods mentioned previously are complimentary in determining γ
  - GLW - excellent sensitivty but multiple solutions
  - ADS - poorer sensitivty but fewer solutions
  - GGSZ - a single unambigous solution
- Best precision can only be obtained by combining several measurements together
- Requires knowledge of external parameters
  - Particularly in the D system (e.g. r_D, δ_D, κ_D)
  - Extracted from charm data obtained elsewhere (HFAG, CLEO, LHCb)
- Should also account for D^0-$\bar{D}^0$ mixing (*and* K^0 *mixing*)
  - Although impact is small for most $B \to DK$-like systems (as $r_D << r_B$)
- Will discuss here the LHCb combination and world average for HFAG/CKMfitter/PDG

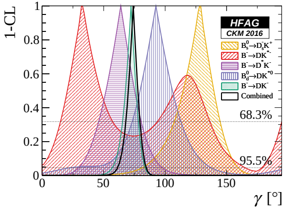


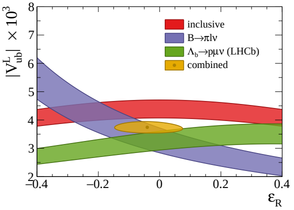


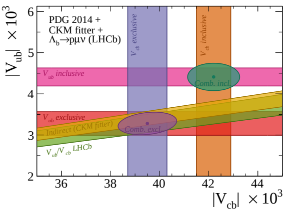
ASIDE: GammaCombo

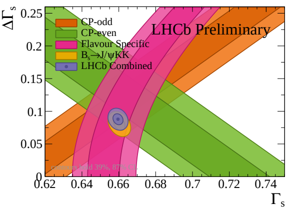
- Software plug!
- GammaCombo is a statistical software originally designed for averaging
  - https://github.com/gammacombo/gammacombo
  - http://gammacombo.hepforge.org
- Also in development (*almost finished*) as limit setting software

- Most common statistical methods available
  - Profile Likelihood
  - Feldman-Cousins (Plugin, Highland-Cousins)
  - CLs (Asymptotic, Hybrid)
  - *Bayesian MC (on the wish-list)*
- **Contributors and users are welcome!**









LHCb γ combination inputs

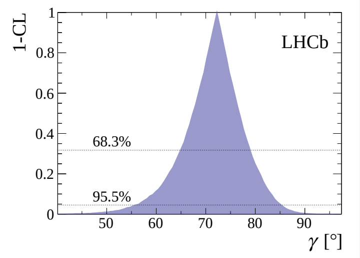
	B decay	D decay	Type	$\int \mathcal{L}$	Ref.
LHCb Inputs	$B^+ \to DK^+$	$D \to hh$	GLW/ADS	$3\,\text{fb}^{-1}$	[arXiv:1603.08993]
	$B^+ \to DK^+$	$D \to h\pi\pi\pi$	GLW/ADS	$3\,\text{fb}^{-1}$	[arXiv:1603.08993]
	$B^+ \to DK^+$	$D \to hh\pi^0$	GLW/ADS	$3\,\text{fb}^{-1}$	[arXiv:1504.05442]
	$B^+ \to DK^+$	$D \to K^0_S hh$	GGSZ	$3\,\text{fb}^{-1}$	[arXiv:1405.2797]
	$B^+ \to DK^+$	$D \to K^0_S K\pi$	GLS	$3\,\text{fb}^{-1}$	[arXiv:1402.2982]
	$B^0 \to D^0 K^{*0}$	$D \to K\pi$	ADS	$3\,\text{fb}^{-1}$	[arXiv:1407.3186]
	$B^+ \to DK^+\pi\pi$	$D \to hh$	GLW/ADS	$3\,\text{fb}^{-1}$	[arXiv:1505.07044]
	$B^0_s \to D^\mp_s K^\pm$	$D^+_s \to hhh$	TD	$1\,\text{fb}^{-1}$	[arXiv:1407.6127] *
	$B^0 \to D^0 K^+\pi^-$	$D \to hh$	GLW-Dalitz	$3\,\text{fb}^{-1}$	[arXiv:1602.03455]
	$B^0 \to D^0 K^{*0}$	$D \to K^0_S \pi\pi$	GGSZ	$3\,\text{fb}^{-1}$	[arXiv:1604.01525]
	Decay	**Parameters**	**Source**		**Ref.**
Auxiliary Inputs	D^0–$\bar{D}^0$ mixing		HFAG	-	[arXiv:1412.7515]
	$D \to K\pi\pi\pi$	$(\delta_D,\, \kappa_D,\, r_D)$	CLEO+LHCb	-	[arXiv:1602.07430] *
	$D \to \pi\pi\pi\pi$	(F^+)	CLEO	-	[arXiv:1504.05878]
	$D \to K\pi\pi^0$	$(\delta_D,\, \kappa_D,\, r_D)$	CLEO+LHCb	-	[arXiv:1602.07430]
	$D \to hh\pi^0$	(F^+)	CLEO	-	[arXiv:1504.05878]
	$D \to K^0_S K\pi$	$(\delta_D,\, \kappa_D)$	CLEO	-	[arXiv:1203.3804] *
	$D \to K^0_S K\pi$	(r_D)	CLEO	-	[arXiv:1203.3804]
	$D \to K^0_S K\pi$	(r_D)	LHCb	-	[arXiv:1509.06628]
	$B^0 \to D^0 K^{*0}$	$(\kappa_B,\, \bar{R}_B,\, \bar{\Delta}_B)$	LHCb	-	[arXiv:1602.03455]
	$B^0_s \to D^+_s K^-$	(ϕ_s)	LHCb	-	[arXiv:1411.3104]
Combination:					[arXiv:1611.03076]

New or updated since last combination

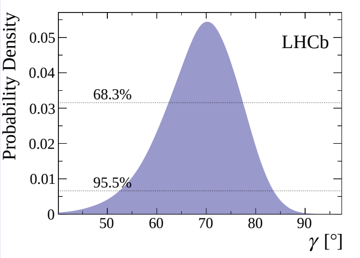
LHCb γ Combination

- Combination of all $B \to DK$-**like** modes
  - 71 observables and 32 free parameters
- Frequentist Feldman-Cousins "plugin" procedure
  - $p(\chi^2, N_{\mathrm{dof}}) = 91.5\%$
  - $p(\mathrm{toys}) = (90.5 \pm 0.2)\%$
- Also perform a Bayesian implementation
- Uncertainty $< 10^\circ$ is better than combined B factories
- The most precise single experiment measurement of γ

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



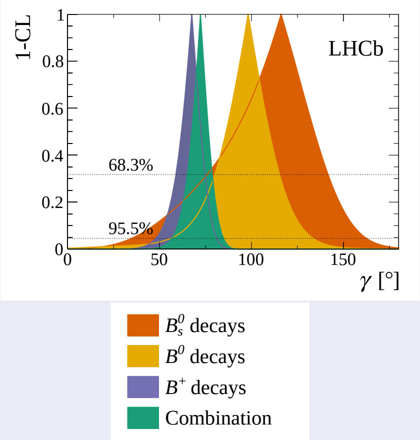
Bayesian - $\gamma = (70.3^{+7.1}_{-7.9})^\circ$



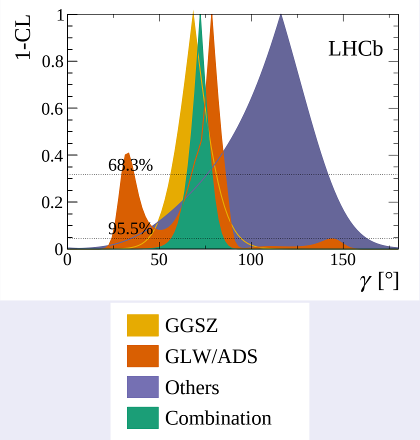
LHCb γ Combination

Naive statistical treatement (profile likelihood method) - plots for demonstrative purposes only

Comparison split by initial B flavour



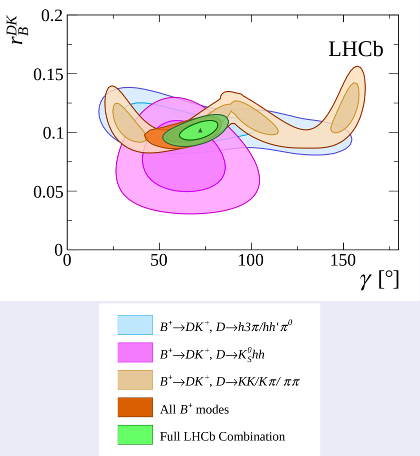
Comparison split by analysis method



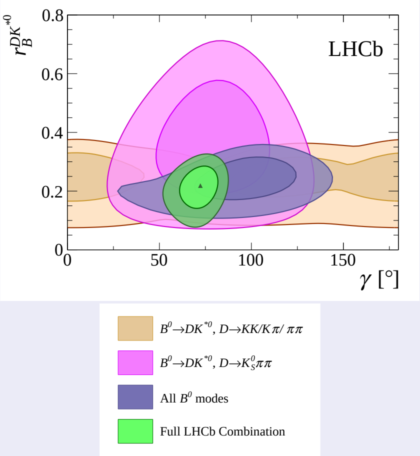
LHCb γ Combination

Naive statistical treatement (profile likelihood method) - plots for demonstrative purposes only

$B^+ \to D^0 K^+$ system



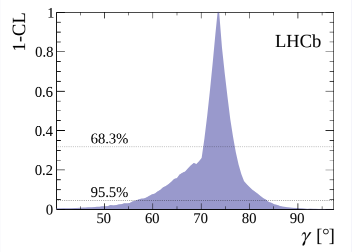
$B^0 \to D^0 K^{*0}$ system

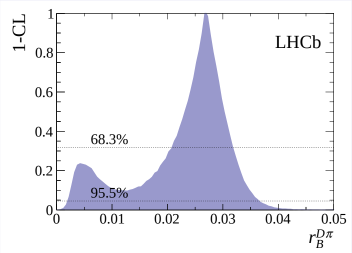


On inclusion of $B \to D\pi$-like modes

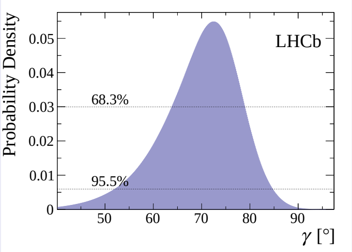
- $r_B^{D\pi}$ expectation ~ 0.005 (favoured enhanced by V_{ud}/V_{us}, suppressed reduced by V_{cd}/V_{cs})

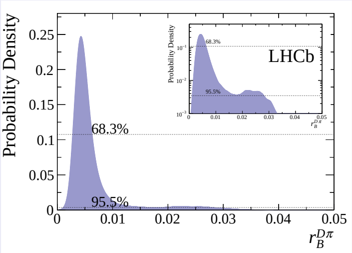
Frequentist





Bayesian

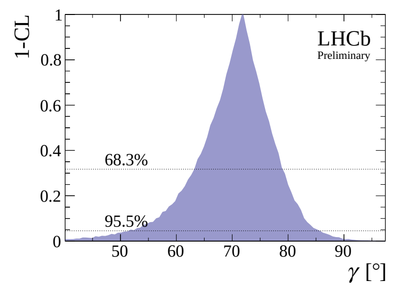




On inclusion of $B \to D\pi$-like modes

- The *a priori* sensitivity gain is rather minimal
- Enforcing a constraint on $r_B^{D\pi}$ using a theory prediction $r_B^{D\pi} = 0.0053 \pm 0.0007$ ([arXiv:1606.09129] - Kenzie, Martinelli, Tuning)
- Recovers similar results to DK-mode combination

Using external constraint on $r_B^{D\pi}$:
$\gamma = (71.8^{+7.2}_{-8.6})^\circ$



HFAG γ combination inputs (1/4)

B decay	D decay	Method	Experiment
$B^- \to DK^-$	$D \to K^+K^-$, $D \to \pi^+\pi^-$, $D \to K^0_S\pi^0$, $D \to K^0_S\omega$, $D \to K^0_S\phi$	GLW	BABAR
$B^- \to DK^-$	$D \to K^+K^-$, $D \to \pi^+\pi^-$, $D \to K^0_S\pi^0$, $D \to K^0_S\omega$, $D \to K^0_S\phi$	GLW	Belle
$B^- \to DK^-$	$D \to K^+K^-$, $D \to \pi^+\pi^-$	GLW	CDF
$B^- \to DK^-$	$D \to K^+K^-$, $D \to \pi^+\pi^-$	GLW	LHCb
$B^- \to D^*K^-$ $D^* \to D\gamma\ (\pi^0)$	$D \to K^+K^-$, $D \to \pi^+\pi^-$, $D \to K^0_S\pi^0$, $D \to K^0_S\omega$, $D \to K^0_S\phi$	GLW	BABAR
$B^- \to D^*K^-$ $D^* \to D\gamma\ (\pi^0)$	$D \to K^+K^-$, $D \to \pi^+\pi^-$, $D \to K^0_S\pi^0$, $D \to K^0_S\omega$, $D \to K^0_S\phi$	GLW	Belle
$B^- \to DK^{*-}$	$D \to K^+K^-$, $D \to \pi^+\pi^-$, $D \to K^0_S\pi^0$, $D \to K^0_S\omega$, $D \to K^0_S\phi$	GLW	BABAR
$B^- \to DK^{*-}$	$D \to K^+K^-$, $D \to \pi^+\pi^-$,	GLW	LHCb
$B^- \to DK^-\pi^+\pi^-$	$D \to K^+K^-$, $D \to \pi^+\pi^-$	GLW	LHCb

HFAG γ combination inputs (2/4)

$B^- \to DK^-\pi^+\pi^-$	$D \to K^+K^-$, $D \to \pi^+\pi^-$	GLW	LHCb
$B^- \to DK^-$	$D \to \pi^+\pi^-\pi^0$	GLW-like	*BABAR*
$B^- \to DK^-$	$D \to h^+h^-\pi^0$	GLW-like	LHCb
$B^- \to DK^-$	$D \to \pi^+\pi^-\pi^+\pi^-$	GLW-like	LHCb
$B^- \to DK^-$	$D \to K^\pm\pi^\mp$	ADS	*BABAR*
$B^- \to DK^-$	$D \to K^\pm\pi^\mp$	ADS	Belle
$B^- \to DK^-$	$D \to K^\pm\pi^\mp$	ADS	CDF
$B^- \to DK^-$	$D \to K^\pm\pi^\mp$	ADS	LHCb
$B^- \to DK^-$	$D \to K^\pm\pi^\mp\pi^0$	ADS	*BABAR*
$B^- \to DK^-$	$D \to K^\pm\pi^\mp\pi^0$	ADS	Belle
$B^- \to DK^-$	$D \to K^\pm\pi^\mp\pi^0$	ADS	LHCb
$B^- \to DK^-$	$D \to K^\pm\pi^\mp\pi^+\pi^-$	ADS	LHCb
$B^- \to D^*K^-$ $D^* \to D\gamma$	$D \to K^\pm\pi^\mp$	ADS	*BABAR*
$B^- \to D^*K^-$ $D^* \to D\pi^0$	$D \to K^\pm\pi^\mp$	ADS	*BABAR*

HFAG γ combination inputs (3/4)

$B^- \to DK^{*-}$	$D \to K^\pm\pi^\mp$	ADS	*BABAR*
$B^- \to DK^{*-}$	$D \to K^\pm\pi^\mp$	ADS	LHCb
$B^- \to DK^-\pi^+\pi^-$	$D \to K^\pm\pi^\mp$	ADS	LHCb
$B^- \to DK^-$	$D \to K^0_s\pi^+\pi^-$	GGSZ MD	*BABAR*
$B^- \to DK^-$	$D \to K^0_s\pi^+\pi^-$	GGSZ MD	Belle
$B^- \to D^*K^-$	$D \to K^0_s\pi^+\pi^-$	GGSZ MD	*BABAR*
$D^* \to D\gamma\ (\pi^0)$			
$B^- \to D^*K^-$	$D \to K^0_s\pi^+\pi^-$	GGSZ MD	Belle
$D^* \to D\gamma\ (\pi^0)$			
$B^- \to DK^{*-}$	$D \to K^0_s\pi^+\pi^-$	GGSZ MD	*BABAR*
$B^- \to DK^{*-}$	$D \to K^0_s\pi^+\pi^-$	GGSZ MD	Belle
$B^- \to DK^-$	$D \to K^0_s\pi^+\pi^-$	GGSZ MI	LHCb
$B^- \to DK^-$	$D \to K^0_sK^+\pi^-$	GLS	LHCb
$B^0 \to DK^{*0}$	$D \to K^\pm\pi^\mp$	ADS	LHCb
$B^0 \to DK^+\pi^-$	$D \to h^+h^-$	GLW-Dalitz	LHCb
$B^0 \to DK^+\pi^-$	$D \to K^0_sh^+h^-$	GGSZ MI	LHCb
$B^0_s \to D_s^\mp K^\pm$	$D_s^+ \to h^+h^-\pi^+$	TD	LHCb

HFAG γ combination inputs (4/4)

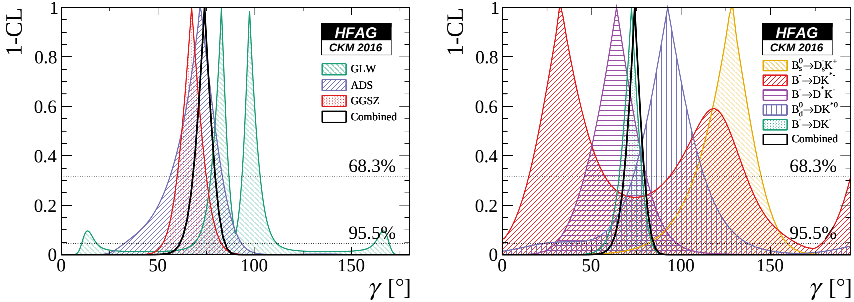
Decay	Parameters	Source
$D \to K^\pm\pi^\mp$	$r_D^{K\pi}$, $\delta_D^{K\pi}$	HFAG
$D \to K^\pm\pi^\mp\pi^+\pi^-$	$\delta_D^{K3\pi}$, $\kappa_D^{K3\pi}$, $r_D^{K3\pi}$	CLEO+LHCb
$D \to \pi^+\pi^-\pi^+\pi^-$	$F_{\pi\pi\pi\pi}$	CLEO
$D \to K^\pm\pi^\mp\pi^0$	$\delta_D^{K2\pi}$, $\kappa_D^{K2\pi}$, $r_D^{K2\pi}$	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
	$r_D^{K_SK\pi}$	LHCb
$B^0 \to DK^{*0}$	$\kappa_B(DK^{*0})$, $\overline{R}_B^{DK^{*0}}$, $\overline{\Delta}_B^{DK^{*0}}$	LHCb
$B_s^0 \to D_s^\mp K^\pm$	ϕ_s	HFAG

The World Average

- World average performed for HFAG ([arXiv:1612.07233]) - soon also to be CKMfitter and PDG
- Add to LHCb results from Belle, BaBar and CDF
  - Plus a few of the latest additions
  - **Always the most up to date result**
- A few minor differences (simplifications)
- **116 observables and 33 free parameters - global fit p-value=**16.4%

World Average

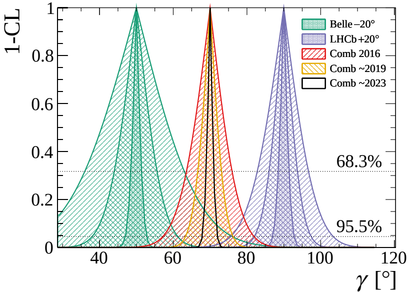
$$\gamma = (74.0^{+5.8}_{-6.4})^\circ$$



6. Conclusion and Prospects

Prospects

- With Run II of the LHC underway and Belle II starting soon the prospects look good
  - **LHCb and Belle II compliment each other for many measurements**
- We can reasonably expect to half the experimental uncertainty on γ in the next 3 years
- We can reasonably expect to have $\sim 1^\circ$ precision in the next 5-8 years
- In 10-12 years we should be $< 1^\circ$
- Current systematic effects are relatively small:
  - GLW/ADS
    - instrumental charge asymmetries
    - PID calibration
  - GGSZ
    - efficiency correction over the Dalitz plane
    - amplitude model uncertainties
  - Time-dependent
    - Decay time resolution
    - Decay time acceptance
    - Knowledge of Δm_s, $\Delta\Gamma_s$, Γ_s



- Tree measurements of γ will not be systematically limited for a little while yet

This does not include smart new ideas which people often have

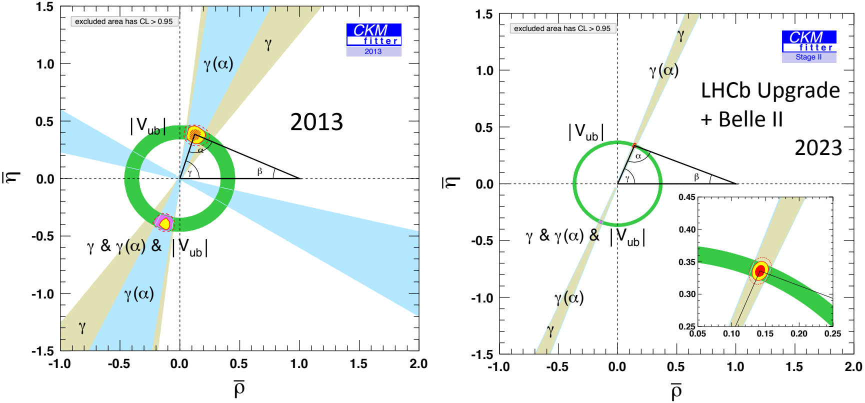
Prospects

- There are several established methods / channels that LHCb haven't exploited yet
  - $B^{\pm} \to D^{*0} K^{\pm}$ - work is underway on both GGSZ and GLW/ADS methods
  - $B^{\pm} \to D^{0} K^{*\pm}$ - first GLW/ADS results shown at CKM (other methods expect inclusion for Moriond or Summer)
  - Any CP-odd GLW decays ($D^0 \to K^0_S \pi^0$, $D^0 \to K^0_S \omega$) - neutrals are **very hard** for LHCb
- There are also ideas for new methods / channels
  - ADS-Dalitz and GGSZ-Dalitz (double Dalitz)
  - Simultaneous GGSZ analysis (reduce systematic uncertainties)
  - TD analyses with $B^0_s \to D_s^{+\star+} K^-$
  - Use decays from B^0, B^0_s, B^+_c (low branching fractions and production rates but topology means larger values of r_B)
  - Use decays from Λ^0_b (difficult final state Λ)
- We anyway struggle to keep up with our data
  - The TD $B^0_s \to D_s^- K^+$ analysis was only just updated to full $3\,\text{fb}^{-1}$ (still only a CONF and not yet a PAPER)
  - This wasn't included for the last LHCb combination but now we already have at least an equivalent size dataset for 2015+2016 and will soon have a much bigger dataset with 2017

Prospects

- We are approaching the first tree-level precision measurement of the CKM triangle
- Direct measurements of V_{ub} play a crucial role in this as well

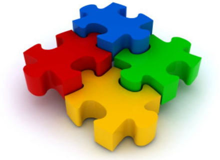
[arXiv:1309.2293]



Conclusions

- CKM matrix is incredibly successful description of the quark sector in the SM
- Measurements of CKM elements are becoming increasingly precise
- Finding new sources of CP violation can lead us to New Physics
- CKM angle γ is one of the only CP measurements accesible with tree-level decays
  - Theoretically very clean
  - Experimentally challenging
- LHCb has the worlds most precise single experiment measurement and dominates the world average
  - $\gamma = (72.2^{+6.8}_{-7.3})^\circ$ (LHCb), $\gamma = (74.0^{+5.8}_{-6.4})^\circ$ (HFAG WA)
- The future looks incredibly bright with the prospect of reducing the direct measurement uncertainty by a factor of ~ 8
  - This will compete with the indirect precision (which assumes the SM)

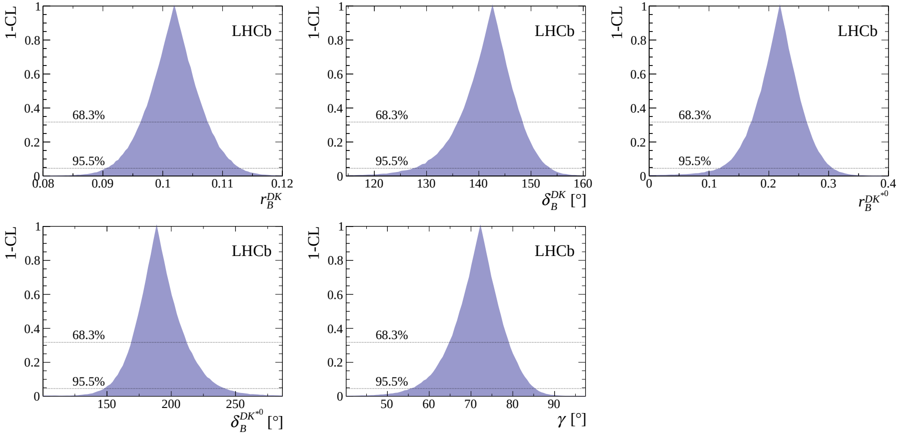
Thank You



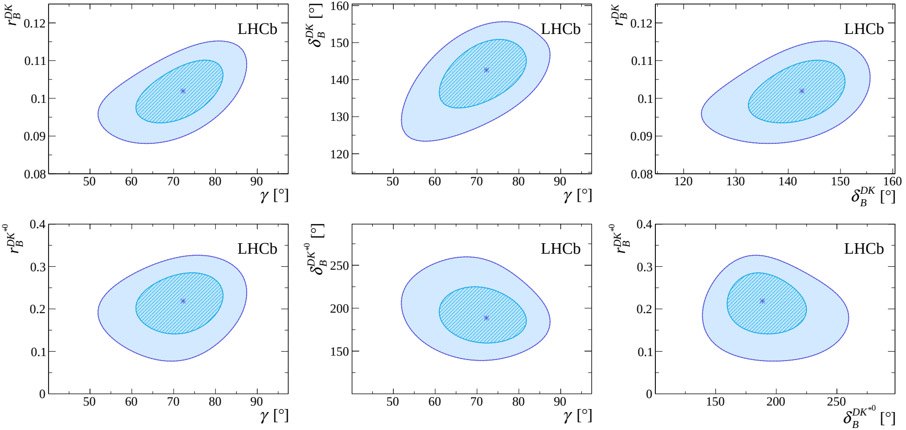
Back Up

BACK UP

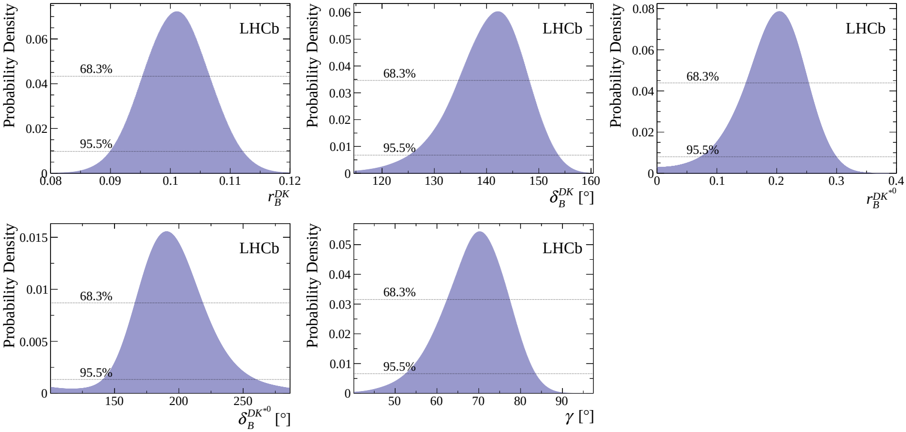
DK frequentist 1D



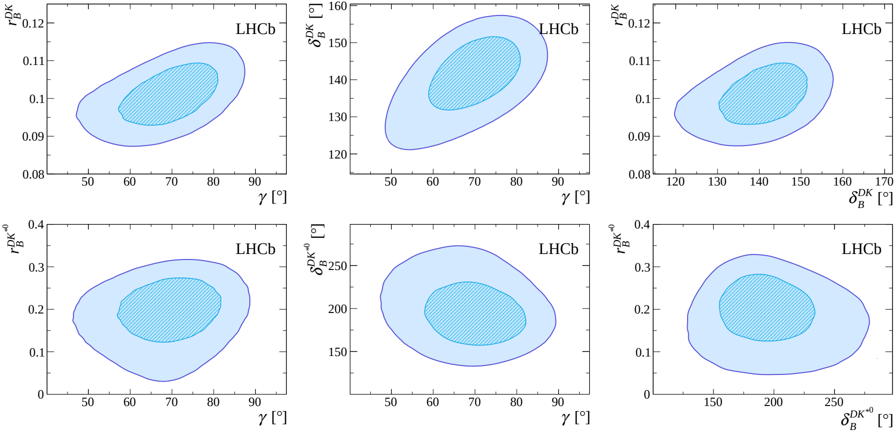
DK frequentist 2D



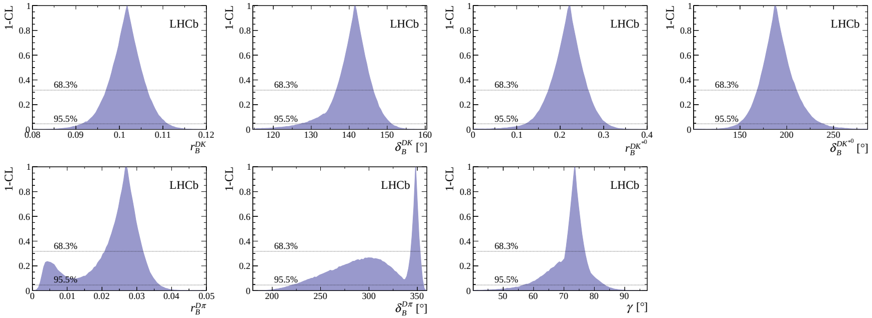
DK Bayesian 1D



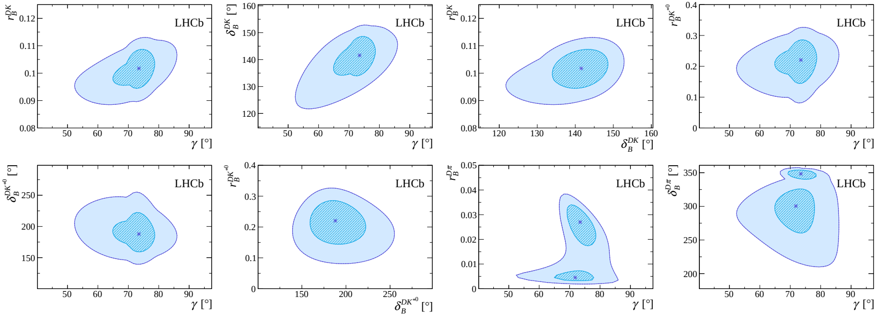
DK Bayesian 2D



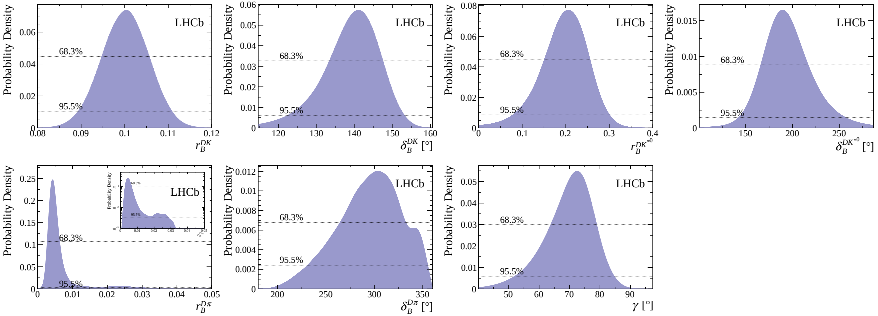
Dh frequentist 1D



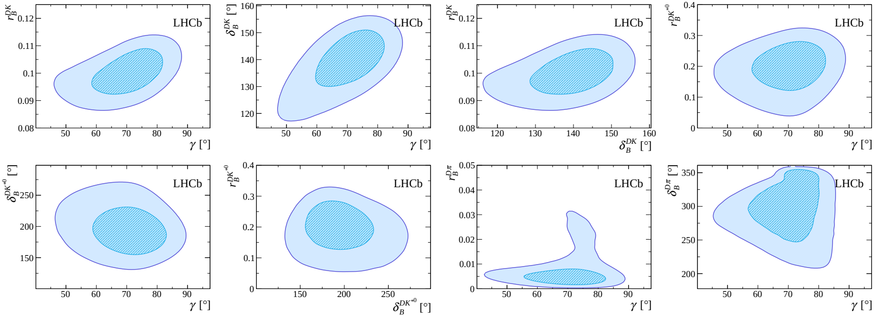
Dh frequentist 2D



Dh Bayesian 1D



Dh Bayesian 2D



Coverage studies