LHCb Combination of the CKM angle γ

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LAL Seminar

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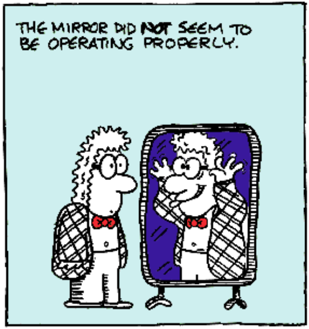
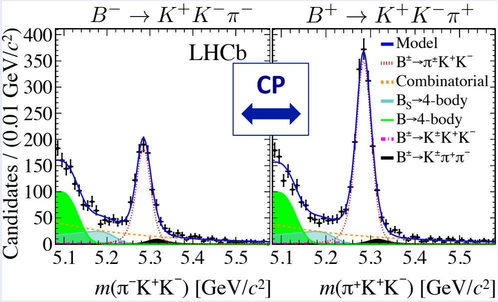
1. CP violation and the CKM matrix

CP violation

- We live in a matter (and photon) dominated universe
- How does baryogenesis lead to a matter / antimatter asymmetry?
- CP violation is a crucial ingredient to this problem (Sacharov)
- CKM matrix is the one place in the SM with CP violation
- CPV in the SM ($\sim 10^{-20}$) does not nearly account for the observed baryon-photon ratio($\sim 10^{-10}$)
- New sources of CP violation would be a clear indiction of New Physics (NP)



LHCb - [PRD 90 (2014) 112004]



CKM matrix

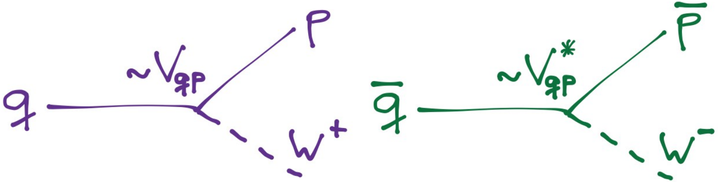
- In the SM quarks can change flavour by emission of a $W^{\pm}$ boson
- Quark mixing in the SM is described by the 3×3 unitary CKM matrix

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

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

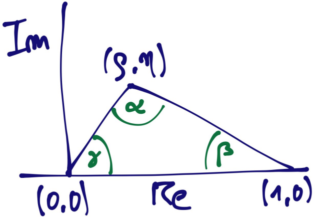
- Hierachy gives very distinctive behaviour to the flavour sector of the SM which gives strong constraints on NP
- CKM matrix gives the only source of CP violation in the SM ($m_\nu = \theta_{QCD} = 0$)

Unitarity gives a triangle in the complex plan

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

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

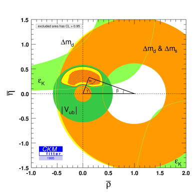
- **Area** corresponds to **total CPV** in SM
- SM implies that $\alpha + \beta + \gamma = 180°$



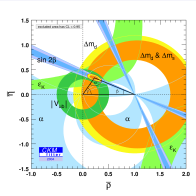
CKM picture is now well verified

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

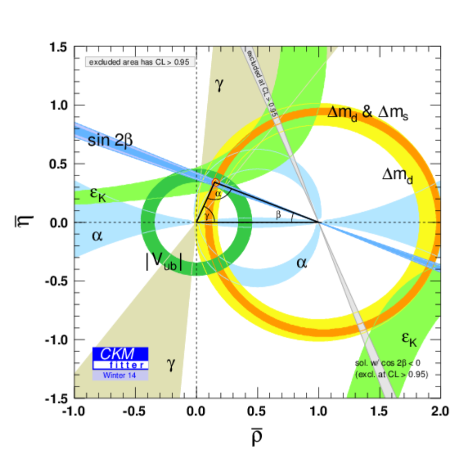
1995



2004



2015



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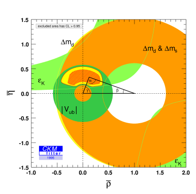
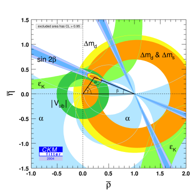
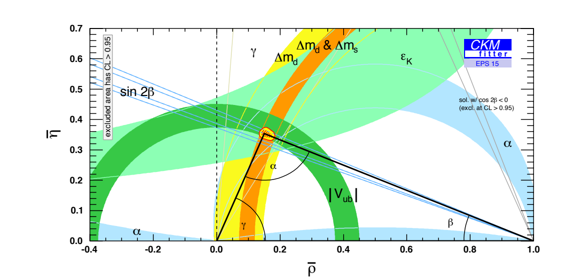


2004



2015 - zoom



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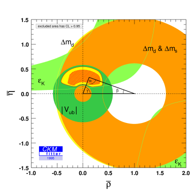
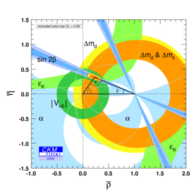


2004



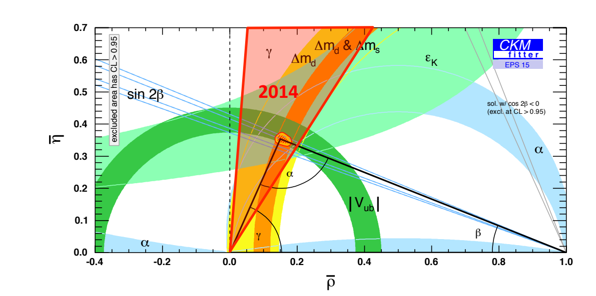
Direct γ measurements

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

Indirect γ extrapolation

$$\gamma = (66.4^{+1.3}_{-3.3})^\circ$$

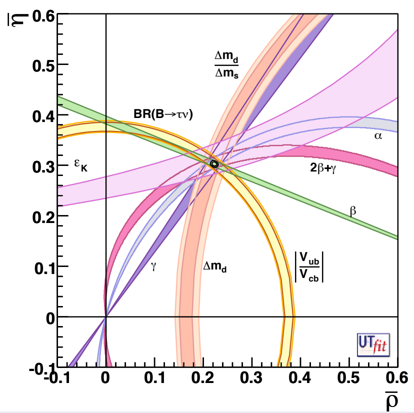
2015 - zoom



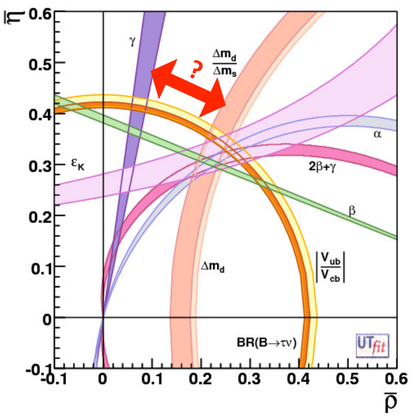
The Ultimate Test

- 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]

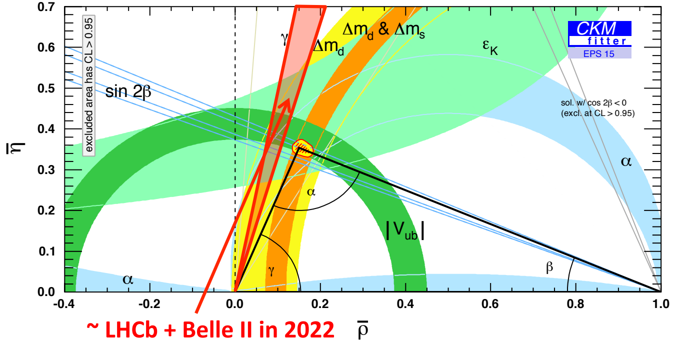


"The dream" - [arXiv:1110.3920]



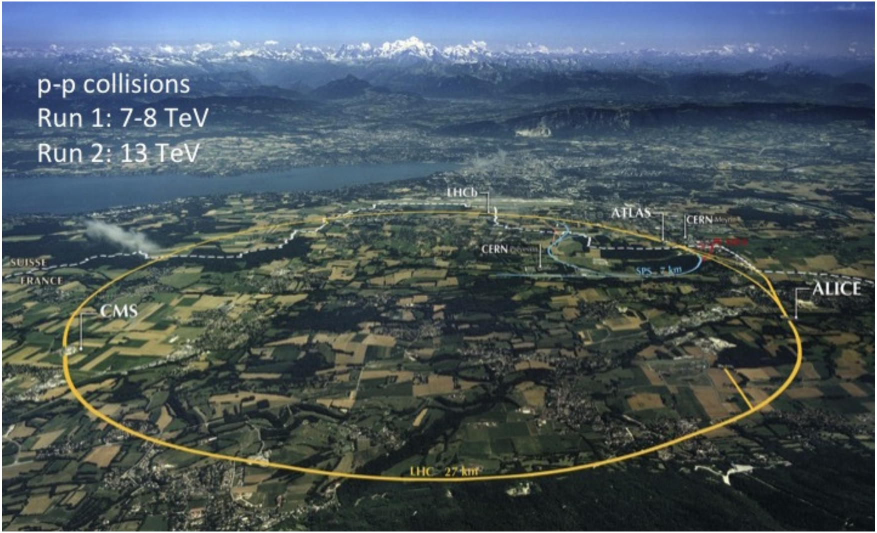
The Ultimate Test

- LHCb expected precision in 2018 $\sim \pm 2\text{-}3^\circ$
- LHCb expected precision in 2029 $\sim \pm 1^\circ$
- Belle II expected precision in 2023 $\sim \pm 2^\circ$



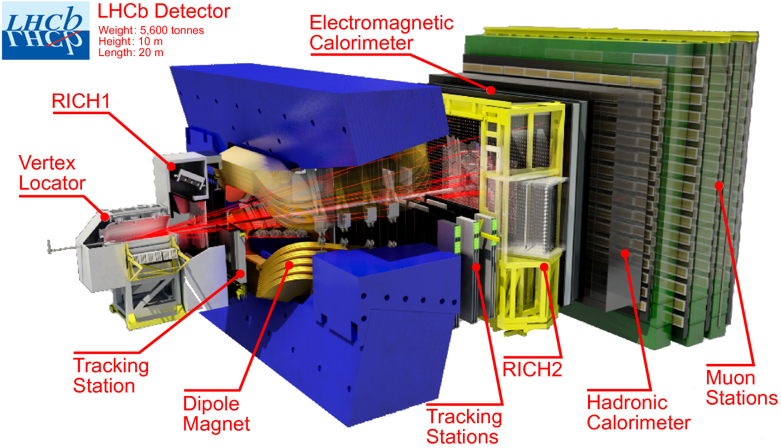
2. The LHCb Experiment

LHC, CERN, Geneva



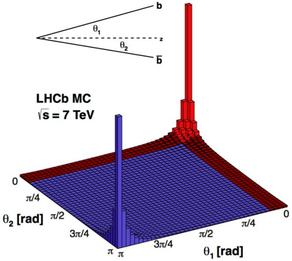
LHCb Detector

- A single arm forward spectrometer



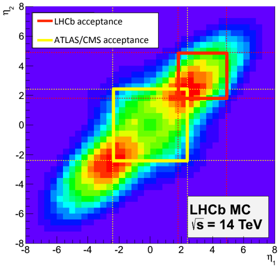
LHCb Detector

- 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]

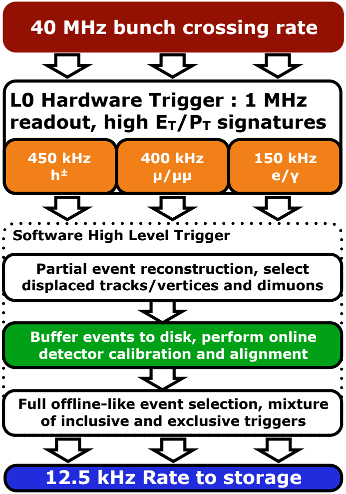
- IP resolution $\approx 20\mu\text{m}$
- p resolution $\approx 0.5\%$
- τ resolution ≈ 45 fs
- Calorimeter ID for γ, e, π^0
- Particle ID $\epsilon(K) \sim 95\%$ with 5% $\pi \to K$ mis-id
- Muons $\epsilon(\mu) \sim 97\%$ with $(1-3)\%\pi \to \mu$ mis-id



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

LHCb 2015 Trigger Diagram



3. CKM angle γ

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

γ from experiment

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

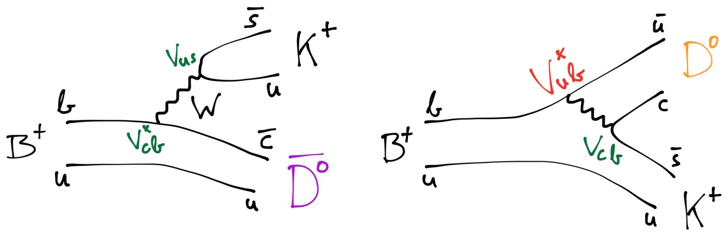
Branching ratio for suppressed γ mode

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

- 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 acheieve 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. $D \to K^0_{\rm S}\pi\pi$
  - 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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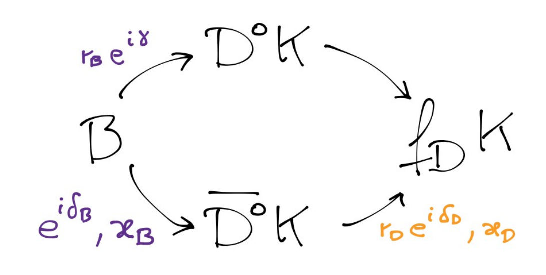

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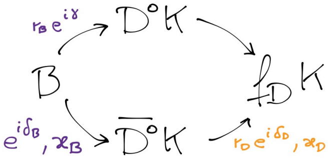
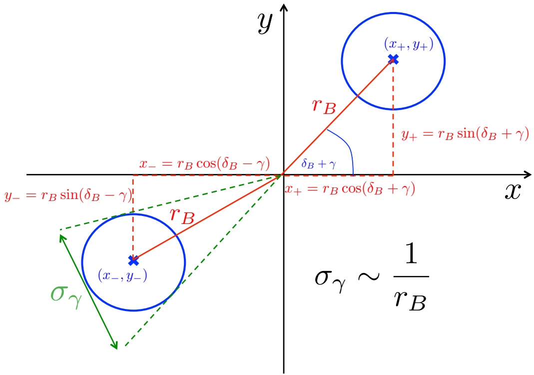
The cartesian coordinates



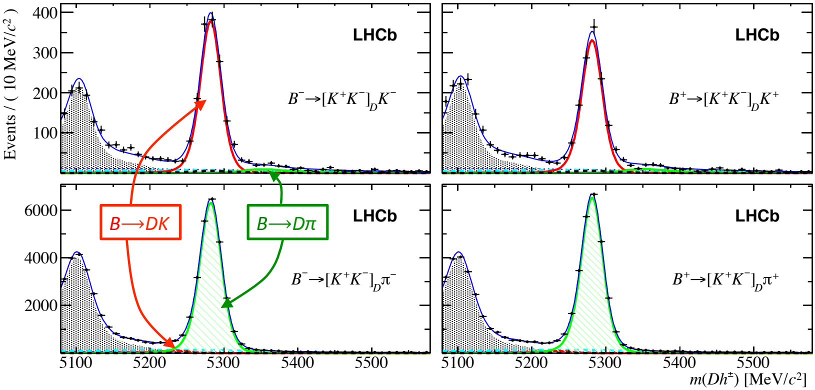


In the cartesian definition

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

An example GLW analysis - $B^{\pm} \to D^0 K^{\pm}$, $D^0 \to K^+ K^-$

[arXiv:1603.08993]



Charge asymmetries

$$A_h^f = \frac{\Gamma(B^- \to [f]_D h^-) - \Gamma(B^+ \to [f]_D h^+)}{\Gamma(B^- \to [f]_D h^-) + \Gamma(B^+ \to [f]_D h^+)}$$

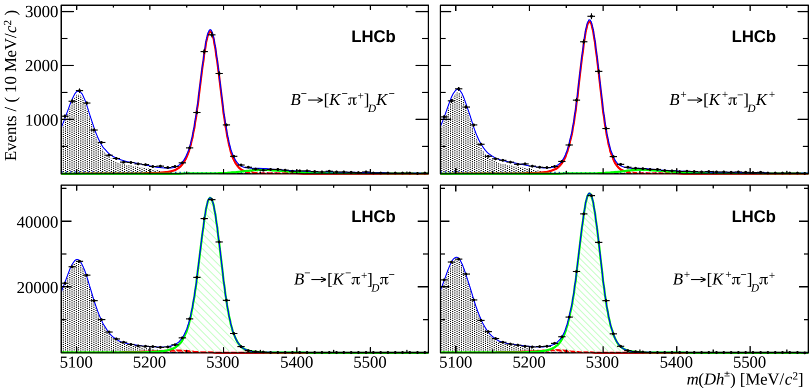
Kaon/pion ratio

$$R_{K/\pi}^f = \frac{\Gamma(B^{\pm} \to [f]_D K^{\pm})}{\Gamma(B^{\pm} \to [f]_D \pi^{\pm})}$$

An example ADS analysis - $B^{\pm} \to D^0 K^{\pm}$, $D^0 \to K^{\pm}\pi^{\pm}$

- Favoured mode

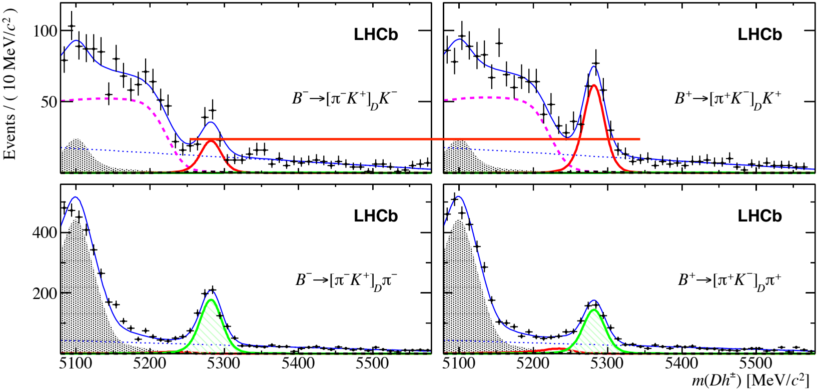
[arXiv:1603.08993]



An example ADS analysis - $B^{\pm} \to D^0 K^{\pm}$, $D^0 \to K^{\pm} \pi^{\pm}$

- Suppressed mode

[arXiv:1603.08993]



An example ADS analysis - $B^{\pm} \to D^0 K^{\pm}$, $D^0 \to K^{\pm} \pi^{\pm}$

- Define observables as yield ratios (many systematics cancel)
- Along with the GLW observables build a system of equations to overconstrain the parameters

ADS ratios of favoured to suppressed

$$R^{\bar{f}}_{\mathrm{ADS}} = \frac{\Gamma(B^- \to [\bar{f}]_D h^-) + \Gamma(B^+ \to [f]_D h^+)}{\Gamma(B^- \to [f]_D h^-) + \Gamma(B^+ \to [\bar{f}]_D h^+)}$$

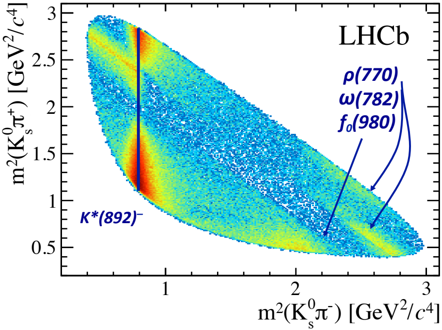
Corresponding charge asymmetries

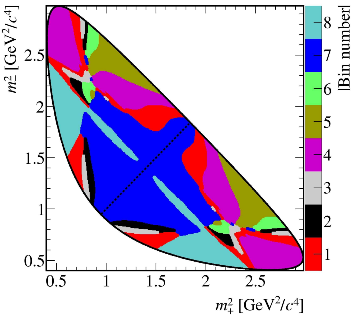
$$A^{\bar{f}}_{\mathrm{ADS}} = \frac{\Gamma(B^- \to [\bar{f}]_D h^-) - \Gamma(B^+ \to [f]_D h^+)}{\Gamma(B^- \to [\bar{f}]_D h^-) + \Gamma(B^+ \to [f]_D h^+)}$$

- Relatively trivial extension to multibody D decays ($D \to 4\pi$, $D \to K3\pi$, $D \to KK\pi^0$, $D \to \pi\pi\pi^0$, $D \to K\pi\pi^0$), multibody B decays ($B^{\pm} \to DK^{\pm}\pi^+\pi^-$) and other initial B states ($B^0 \to DK^{*0}$)

An example GGSZ analysis

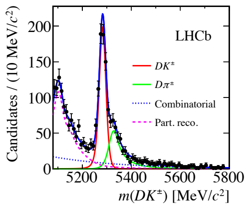
- Requires a self-conjugate 3-body final state ($D^0 \to K^0_S \pi^- \pi^+$, $D^0 \to K^0_S K^- K^+$)
- The basic idea is to perform a GLW/ADS type analysis in each bin of the D decay phase space
- Compare Dalitz distribution for B^+ and B^-
  - Model dependent: use a Dalitz model describing all the intermediate resonances and fit for $x_\pm$, $y_\pm$
  - Model independent: define bins which maximise sensitivity to $x_\pm$, $y_\pm$

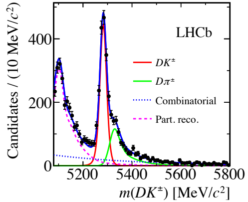




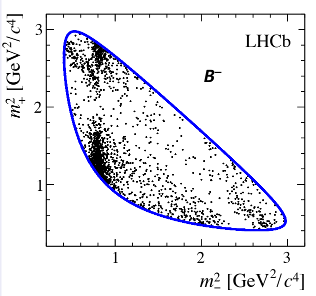
An example GGSZ analysis

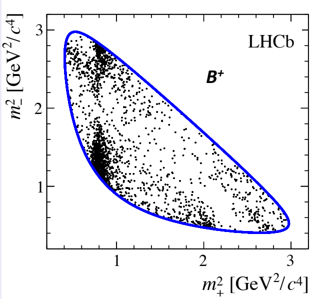
Reconstruct the B invariant mass [arXiv:1408.2748]





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

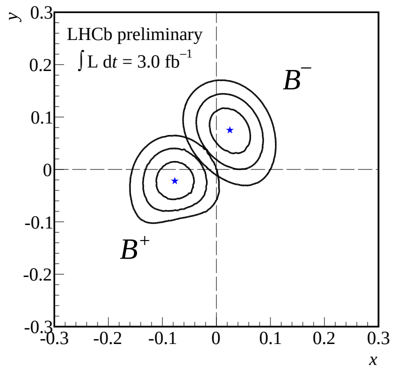




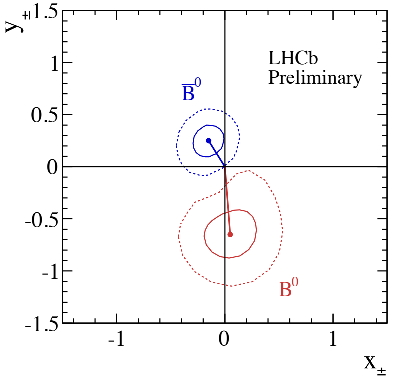
An example GGSZ analysis

- GGSZ analyses have excellent standalone sensitivity with a single solution
- Can trivially extend the methodology for neutral $B^0 \to D^0 K^{*0}$ decays

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

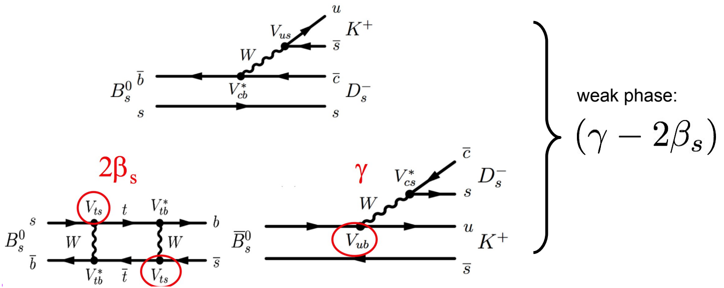


$B^0 \to D^0(\to K^0_S \pi\pi)K^{*0}$



There are also other methods

- Time-dependent method using $B_s^0 \to D_s^- K^+$
  - Large interference occurs via B_s^0 mixing (requires knowledge of $2\beta_s$)
  - Time dependent, flavour tagged analysis - unique to LHCb - [arXiv:1407.6127]



- GLS method
  - Grossman, Ligeti, Soffer (2003) - [Phys. Rev. D67 (2003) 071301]
  - Uses ADS-like method with singly Cabibbo suppressed D decays (e.g. $D^0 \to K_S^0 K\pi$)
  - Poor sensitivity with current statistics

4. LHCb Combination

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]
	$B^0_s \to D_s^\mp K^\pm$	$D_s^+ \to hhh$	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.
Auxilliary 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: [LHCb-CONF-2016-001]

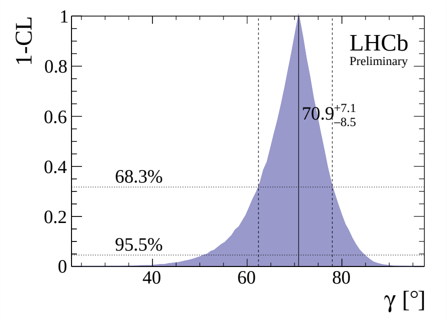
New or updated since last combination

LHCb γ Combination

- Combination of all $B \to DK$-like modes
  - [LHCb-CONF-2016-001]
- Paper to follow soon with information on $B \to D\pi$ modes also
- Nominal results with a frequentist Feldman-Cousins "plugin" procedure
- 71 observables and 32 free parameters
  - $p(\chi^2, N_{\mathrm{dof}}) = 87.6\%$
  - $p(\mathrm{toys}) = (87.0 \pm 0.2)\%$

LHCb γ Combination

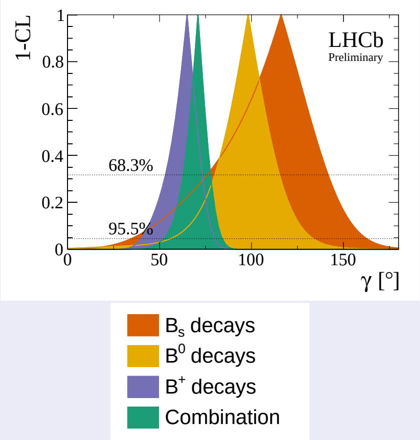
- Nominal result: $\gamma = (70.9^{+7.1}_{-8.5})^\circ$
- Uncertainty $< 10^\circ$ is better than combined B factories
- The most precise single experiment measurement of γ
- LHCb combination paper expected later this year



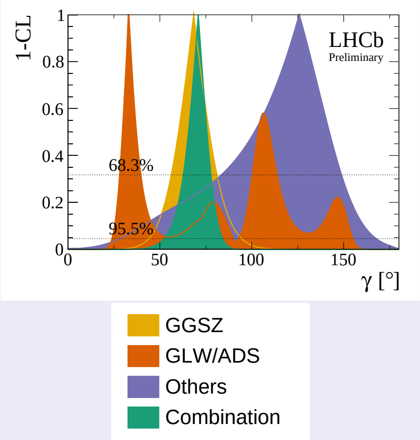
LHCb γ Combination

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

Comparison split by initial B flavour



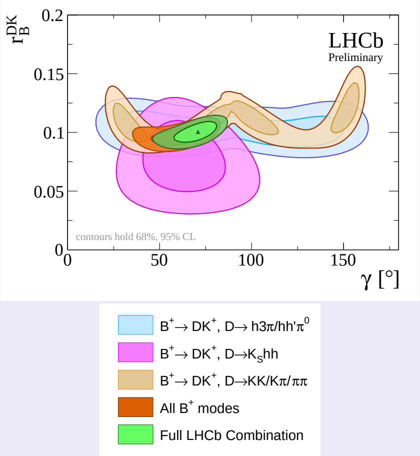
Comparison split by analysis method



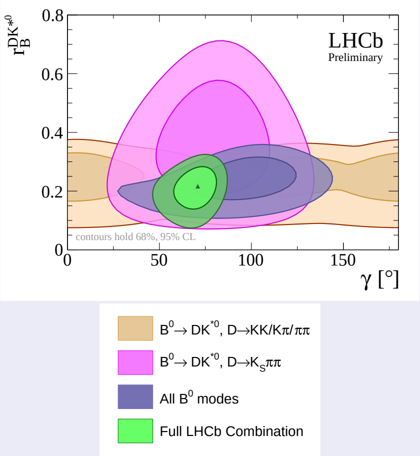
LHCb γ Combination

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



5. Conclusion and Prospects

Prospects

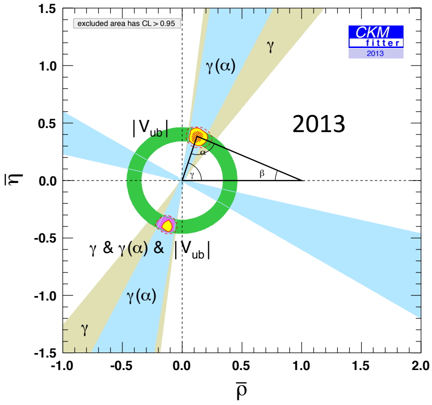
- With Run II of the LHC underway and Belle II starting soon the prospects look good
- We can reasonably expect to half the experimental uncertainty on γ in the next 3 years
- We can reasonably expect to have $\sim 1^\circ$ precision in the next 5-7 years
- Current systematic effects are relatively small
  - GLW/ADS
    - instrumental charge asymmetries
    - PID calibration
  - GGSZ
    - efficiency correction over the Dalitz plane
  - 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 long time (not at 100 times the current dataset)

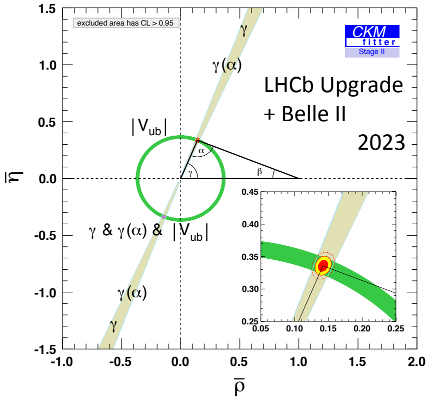
This does not include smart new ideas which people often have

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
  - $\gamma = (70.9^{+7.1}_{-8.5})^{\circ}$
- The future looks incredibly bright with the prospect of reducing the direct measurement uncertainty by a factor of 10
  - This will compete with the indirect precision (which assumes the SM)

Thank You