Measurements of the CKM angle γ at LHCb

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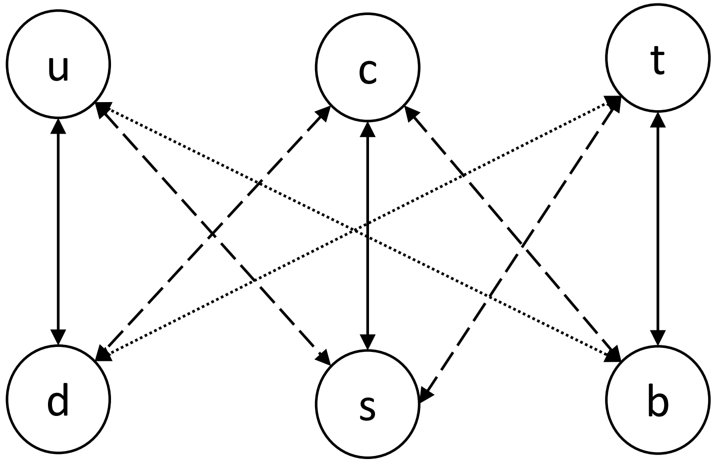
Introduction – CKM matrix

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$



Cabibbo-Kobayashi-Maskawa (CKM) **matrix** – information on the strength of flavour – changing charged weak decays

Quark mixing matrix

CKM matrix is **NOT** diagonal. Weak interaction may change quarks flavour between generation.

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

$$\begin{pmatrix} 0.974 & 0.22 & 0.003 \\ 0.22 & 0.973 & 0.04 \\ 0.008 & 0.04 & 0.999 \end{pmatrix}$$

Cabibbo-Kobayashi-Maskawa (CKM) **matrix**

– information on the strength of flavour – changing charged weak decays

Quark mixing matrix

CKM matrix is **NOT** diagonal. Weak interaction may change quarks flavour between generation.

Introduction – CKM matrix

It's unitarity matrix : $\sum_k V_{ik}V_{jk}^* = 0$

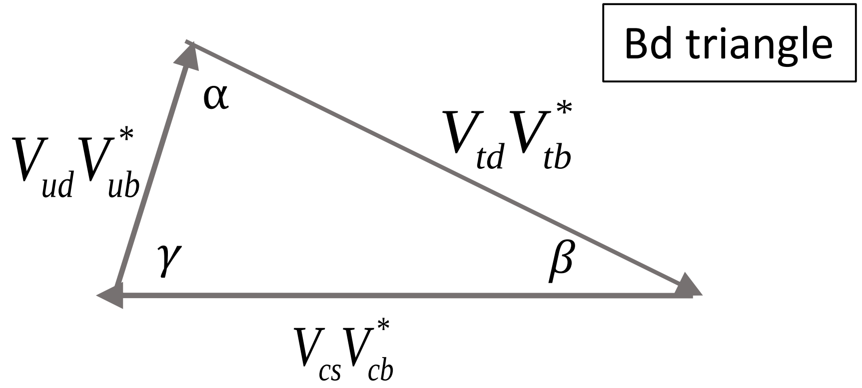
$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$

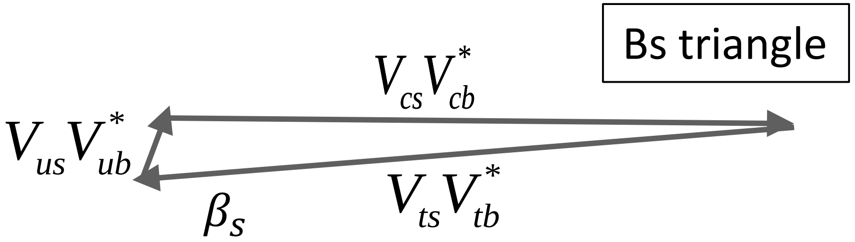
most interesting ones

$V_{us}V_{ub}^* + V_{cs}V_{cb}^* + V_{ts}V_{tb}^* = 0$

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

$$\begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\gamma} \\ -\ |V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}|e^{-i\beta} & -|V_{ts}|e^{-i\beta_s} & |V_{tb}| \end{pmatrix}$$



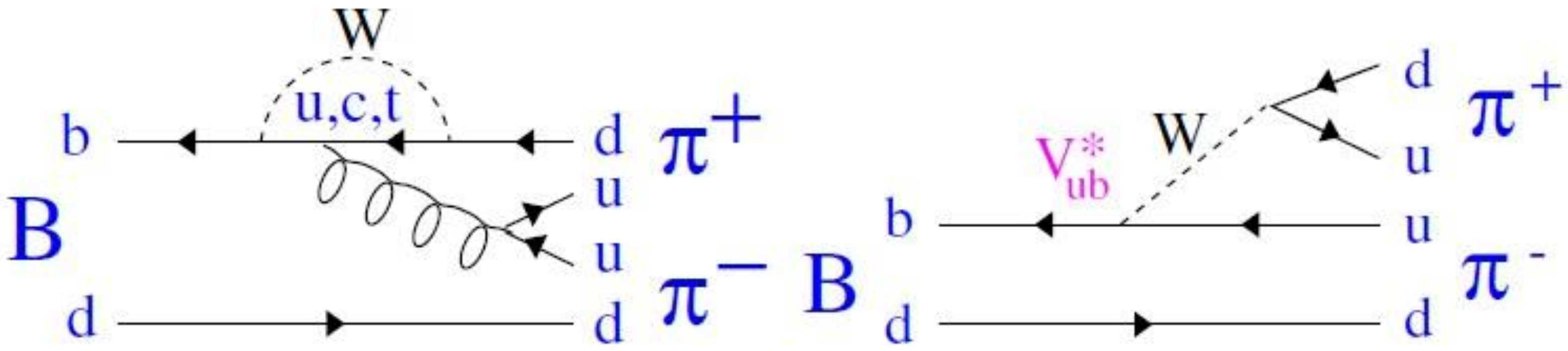


Wolfenstein parametrization

$$\begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\,\lambda^3\,(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\,\lambda^2 \\ A\,\lambda^3(1-\rho-i\eta) & -A\,\lambda^2 & 1 \end{pmatrix}$$

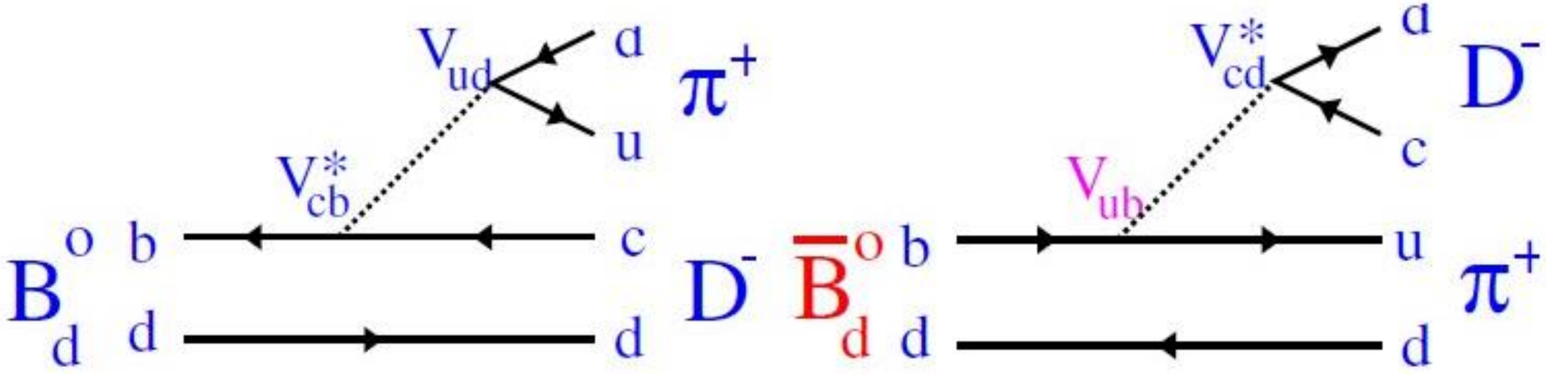
All decays (loop dominated):

- Big yield
- Big theoretical uncertainty

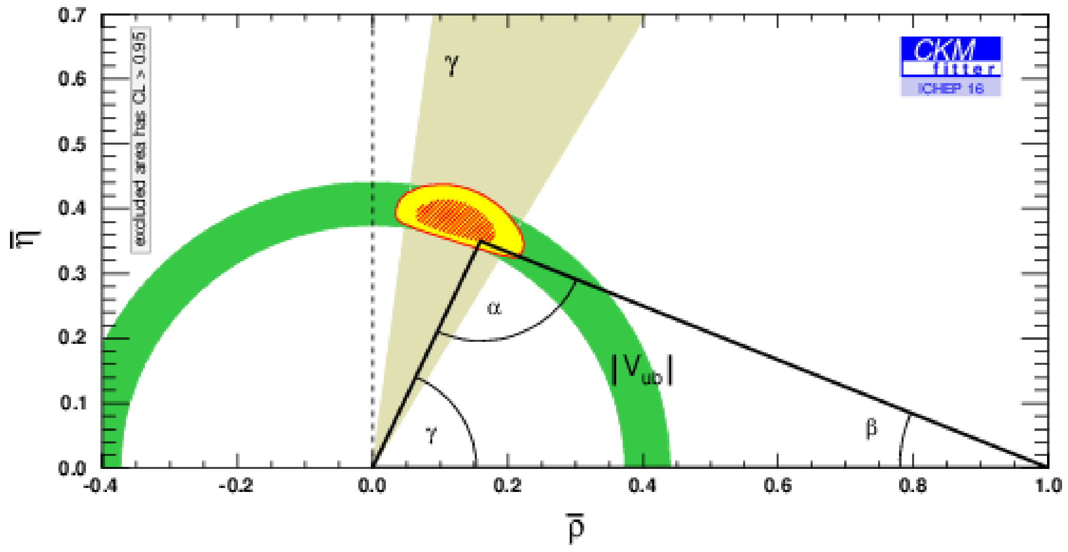


Tree decays:

- Small yield
- Small theoretical uncertainty



Introduction – CKM matrix

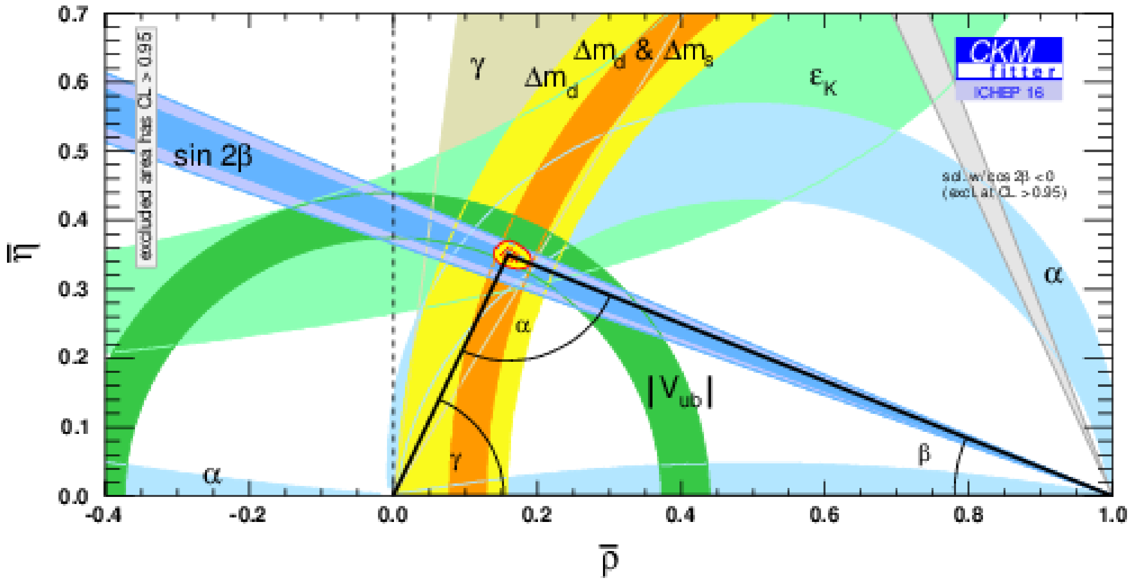


Trees : $\gamma = 72.1^{+5.4\circ}_{-5.8}$

All : $\gamma = 65.3^{+1.0^\circ}_{-2.5}$

All

Trees



Introduction – CKM matrix

Tree-level measurements:

- No loops!
- No theoretical uncertainty

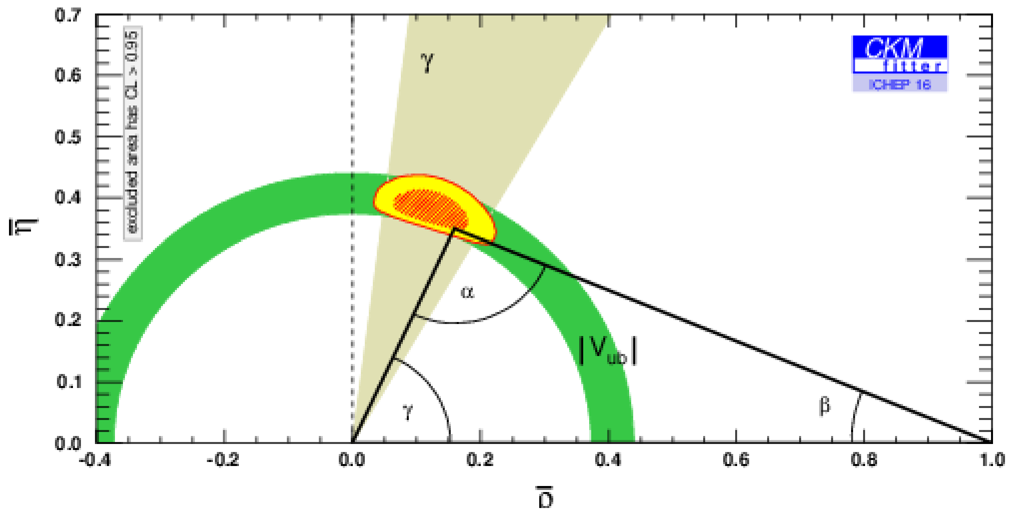
$\delta\gamma/\gamma < 10^{-7}$

- No New Physics contribution!

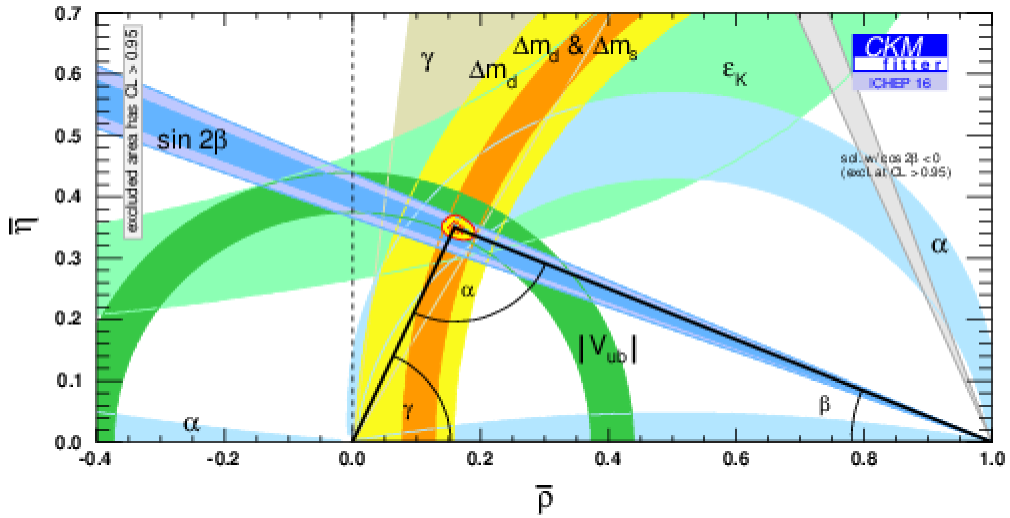
Trees : $\gamma = 72.1^{+5.4\circ}_{-5.8}$

All : $\gamma = 65.3^{+1.0\circ}_{-2.5}$

Trees



All



Introduction – CKM matrix

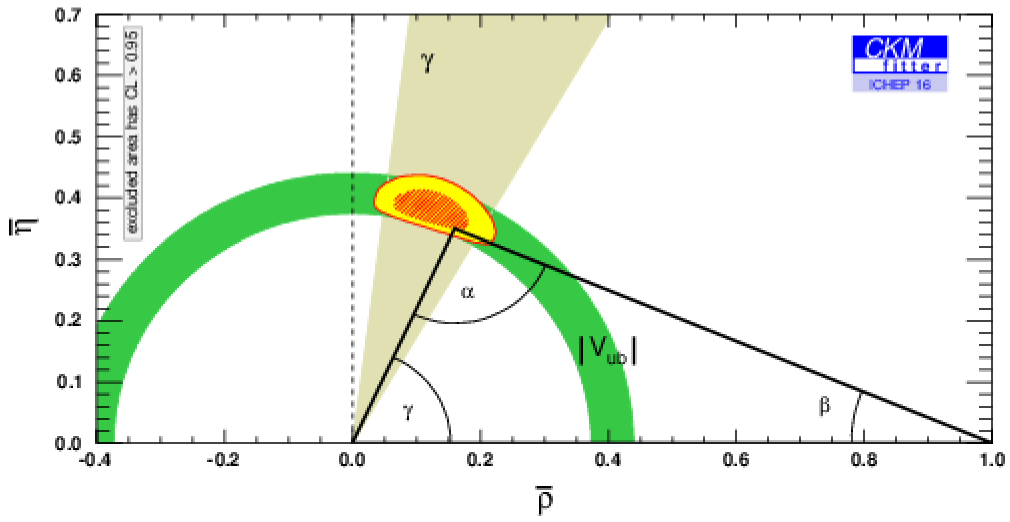
Tree-level measurements:

- Small decay rate $(\sim 10^{-7})$
- Many final states
- Neutral particles (K_S^0, γ)
- Many decay channels, many observables

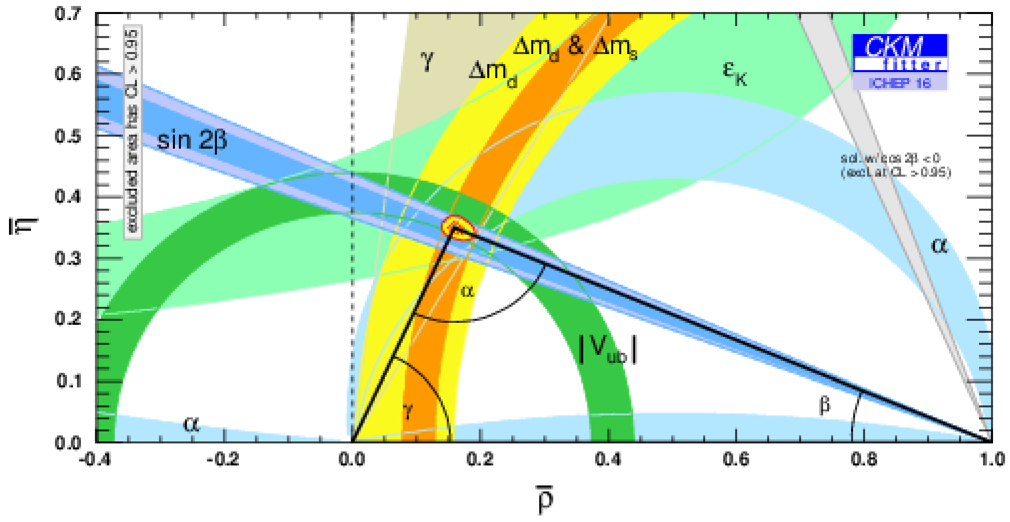
$$\text{Trees}: \gamma = 72.1^{+5.4}_{-5.8}{}^{\circ}$$

$$\text{All}: \gamma = 65.3^{+1.0}_{-2.5}{}^{\circ}$$

Trees



All

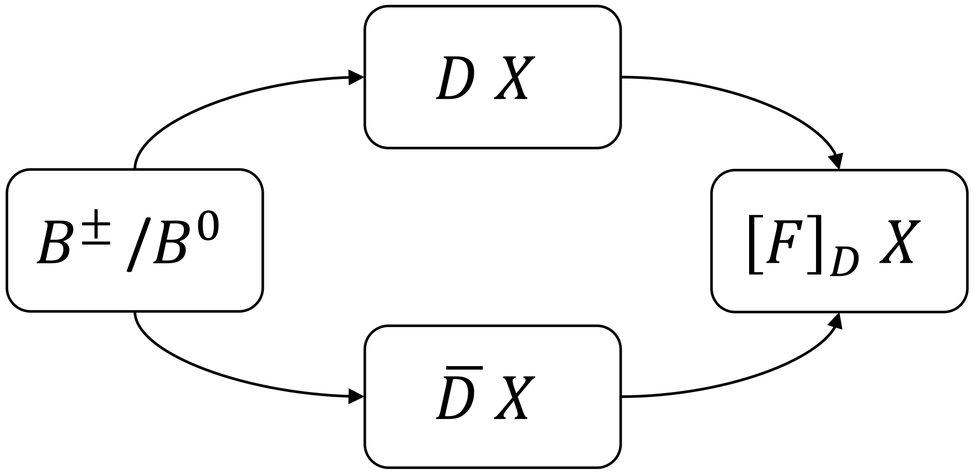


Introduction – $B \to DK$ decay

Motivation

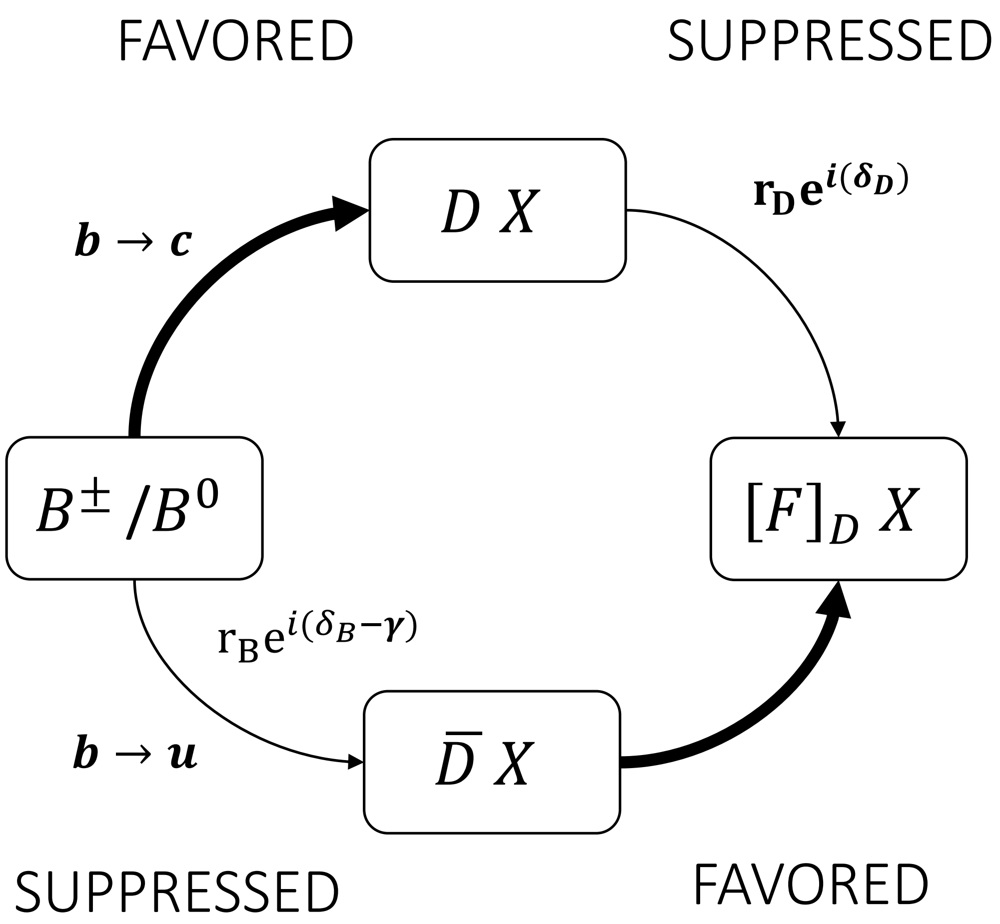
Discrepancies between indirect and direct measurements may indicate new physics

$B \to DK$ measurements



The value of γ can be determined by exploiting the interference between favoured $b \to c$ (Vcb) and suppressed $b \to u$ (Vub) transition amplitudes

Introduction – $B \to DK$ decay



	Method	$\boldsymbol{X}$	$[\boldsymbol{F}]_{\boldsymbol{D}}$
$B^0/B^{\pm}$	**ADS** (mixed state)	K, π	$[K\pi,\ K\pi\pi\pi]$
$B^0/B^{\pm}$	**GLW** (CP eigenstate)	K, π	$[KK,\ \pi\pi,\ \pi\pi\pi\pi]$
B^0	**Dalitz** analysis	K, π	$[KK,\ \pi\pi]$
B^0	**GGSZ**	K^{*0}	$[K_s^0\ hh]$
B^0/B_s^0	**TD**	$K^{*\pm}, K^{*0},$	$[hhh, hh]$

Introduction – LHCb experiment

Int. J. Mod. Phys. A 30, 1530022 (2015)

LHCb Spectrometer designed to study heavy flavour physics

- Covering the pseudorapidity range (2<η<5).
- Identification : $\varepsilon(h-h)\sim 90\%$ $\varepsilon_{\mu}\sim 97\%$

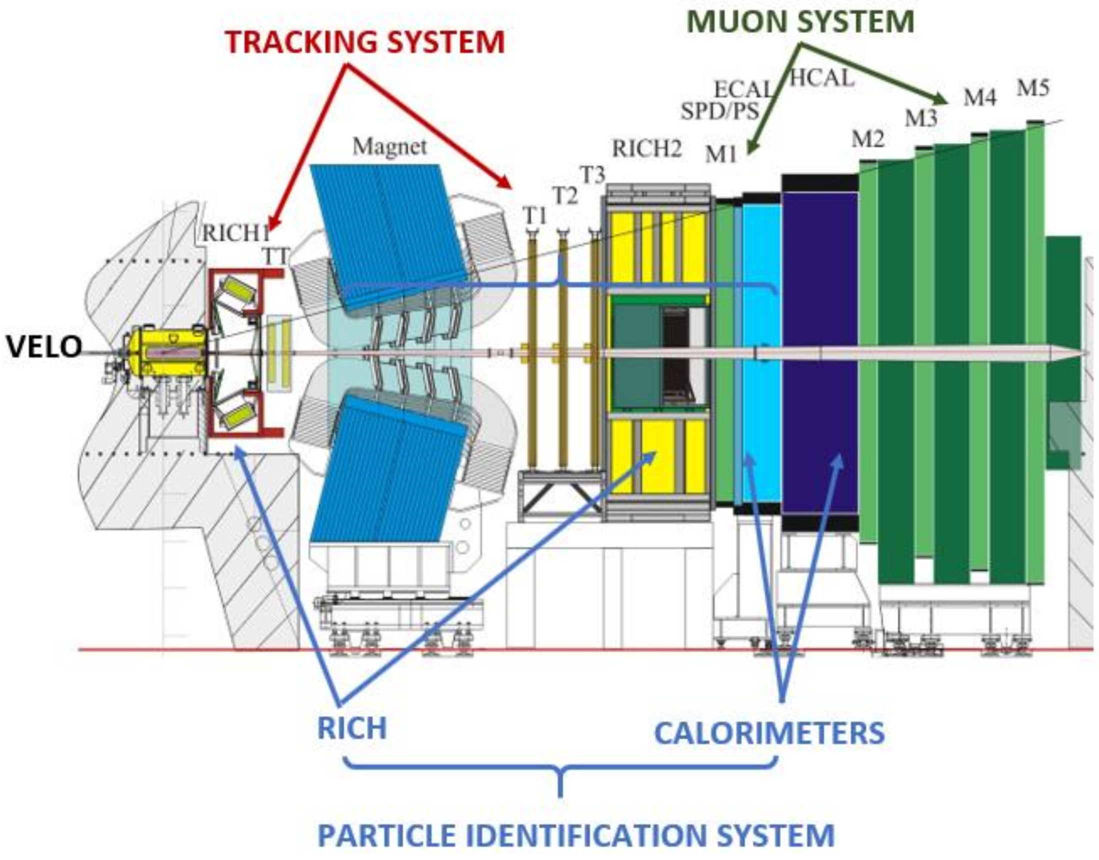
  (low momentum)
- IP resolution : $\sigma_{IP} = 20\ \mu$m

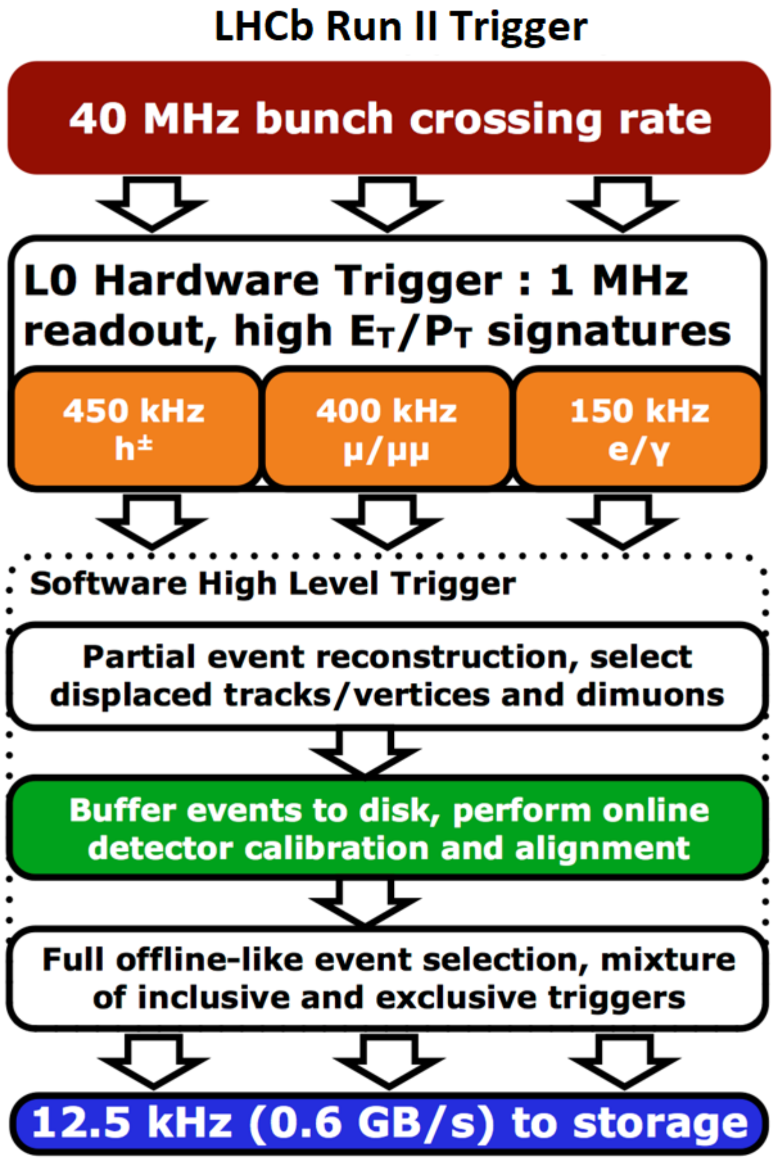
  momentum resolution: $\frac{\Delta p}{p} = 0.5 - 0.8\ \%$

  (for low momenta)

  mass resolution : $\sigma(m_{B\rightarrow hh}) \approx 22$ MeV

  time resolution $45 - 55\ fs$





Some details: Trigger

4 μs to make a decision

collision every 25ns - pipe line

miuon detector & ECAL

VELO & T1-T3

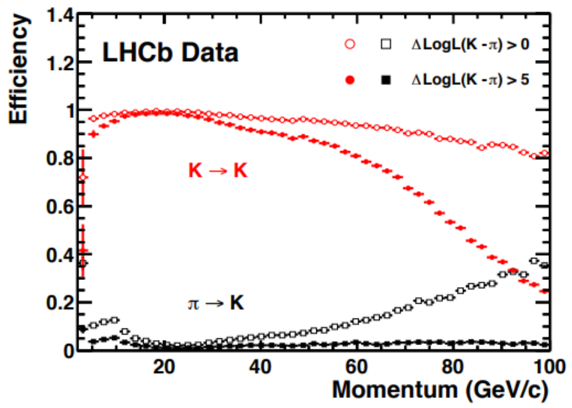
Full information & final decision

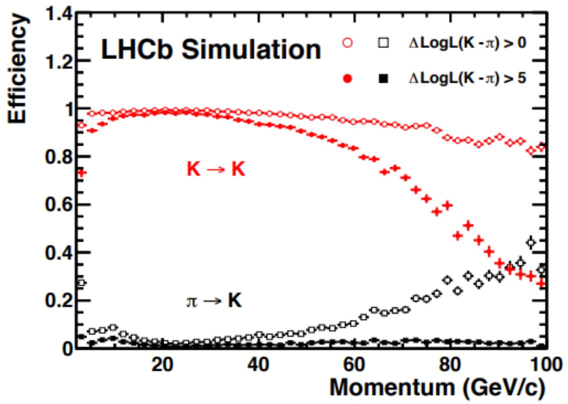
Introduction – LHCb experiment

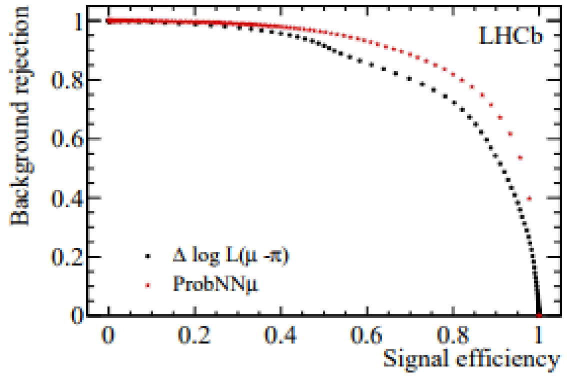
Int. J. Mod. Phys. A 30, 1530022 (2015)

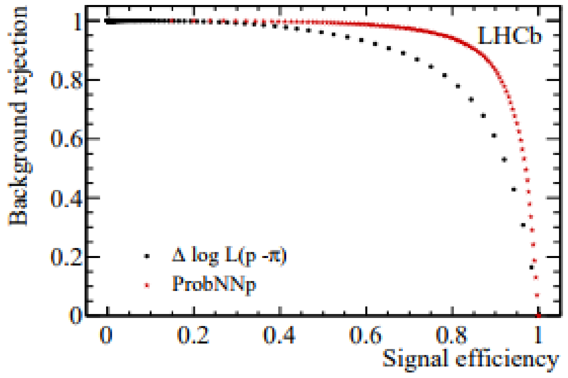
Some details: Identyfication

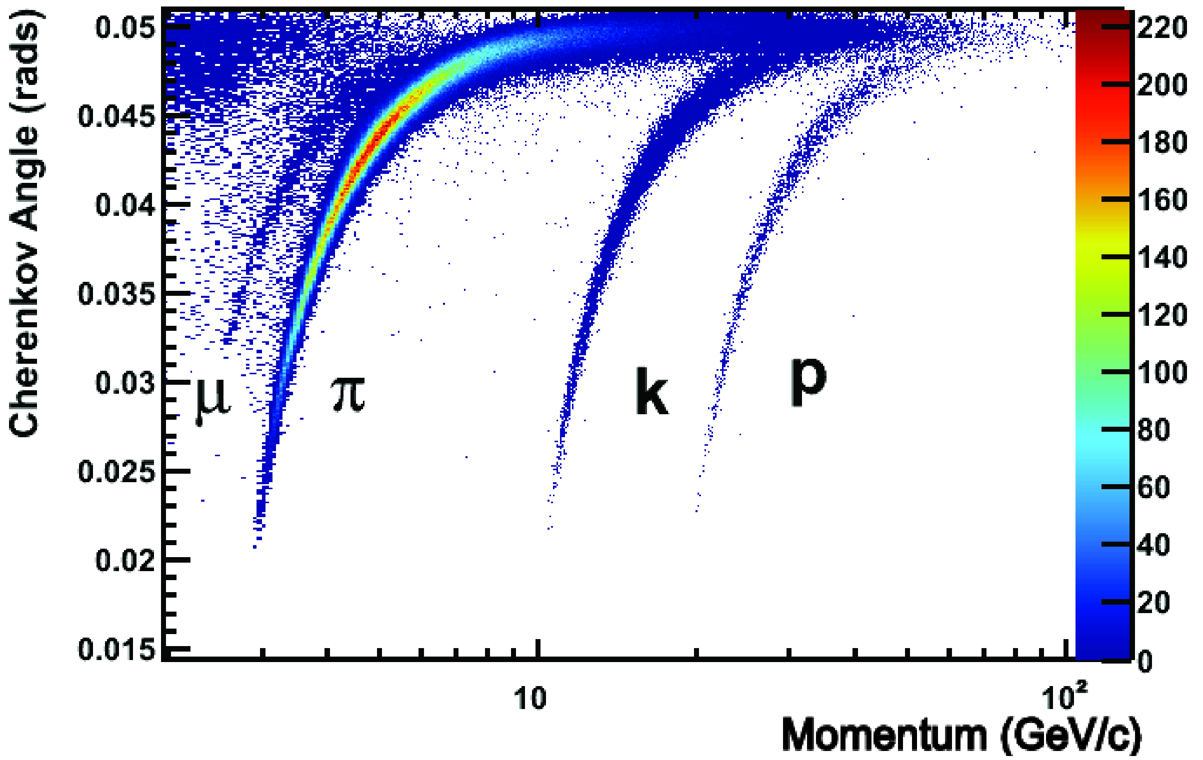
RICH Detector - C_4F_{10} & CF_4











Good agreement between MC & Data

Results of Neural Network usage

Introduction – LHCb experiment

Data:

Run 1:

2011-2013

Luminosity: 3 fb^{-1}

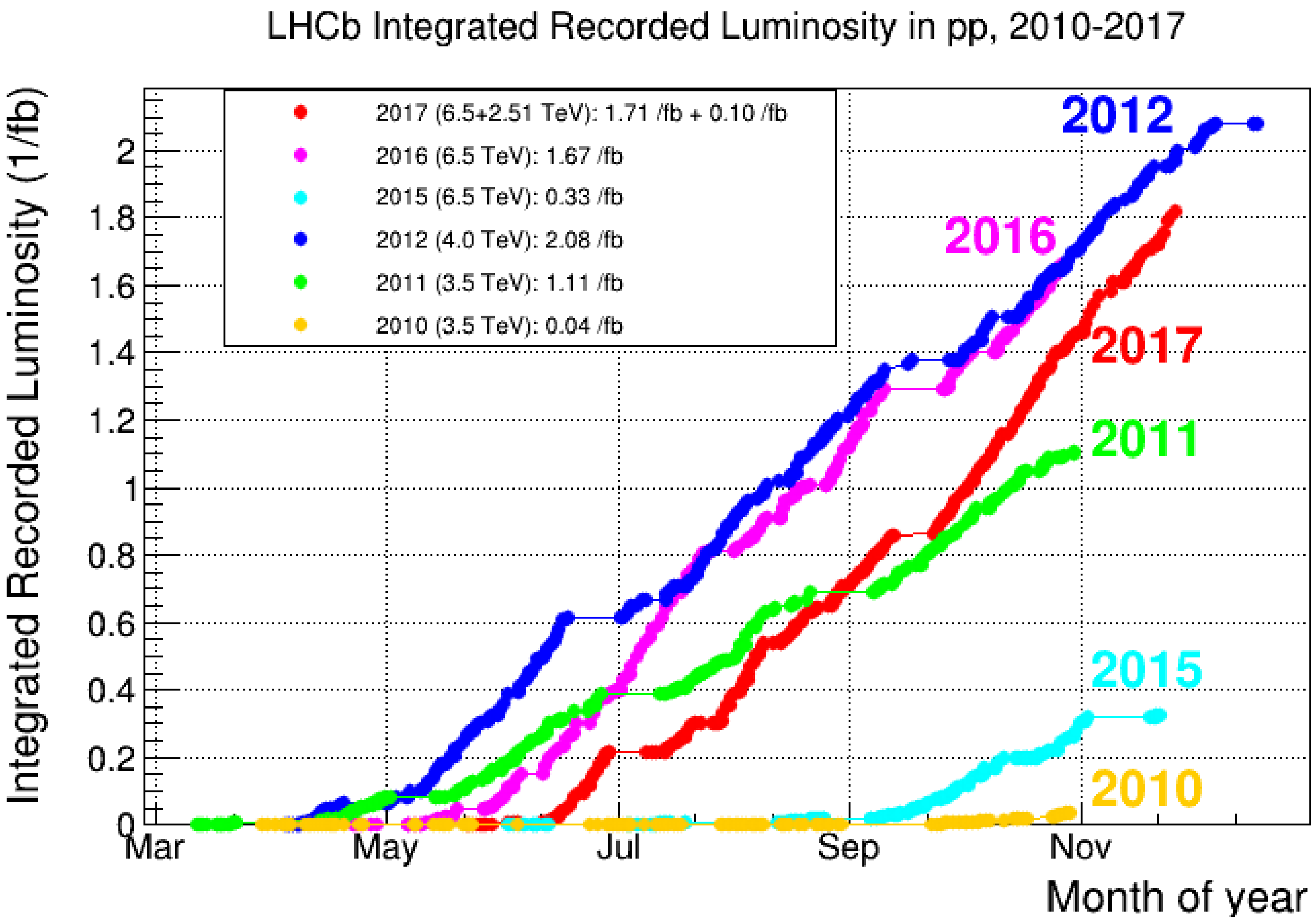
$\sqrt{s} = 7 - 8$ TeV

Run 2:

2015-2018

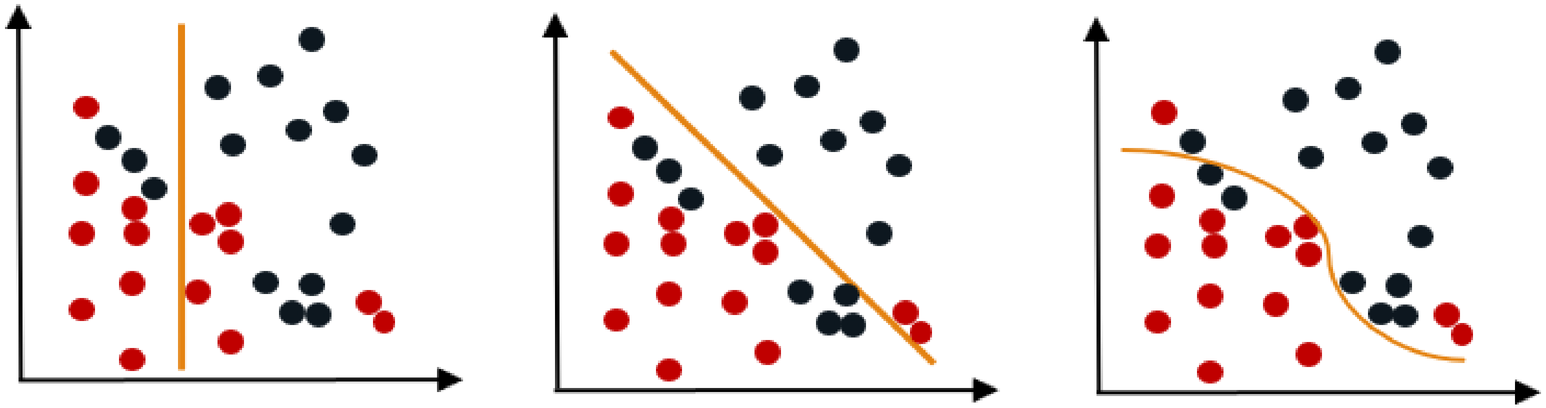
Luminosity: ~ 5 fb^{-1}

$\sqrt{s} = 13$ TeV



2011-2017 : 7 fb^{-1} !

Introduction – Multibody decay analysis method



1D   2D   3D

MVA methods

One dimension selection might be ineffective.

Why not try multivariate approach?

Function (**classifier**) will divide object to class

In HEP: **Signal and Background**

Proper **training**: Representative sample

- **Boosted Decision Trees**
- **Neural Networks**
- Fischer Discriminants
- Rectangular cut
- Likelihood Estimator
- Support Vector Machines

MVA METHODS

Introduction – Multibody decay analysis method

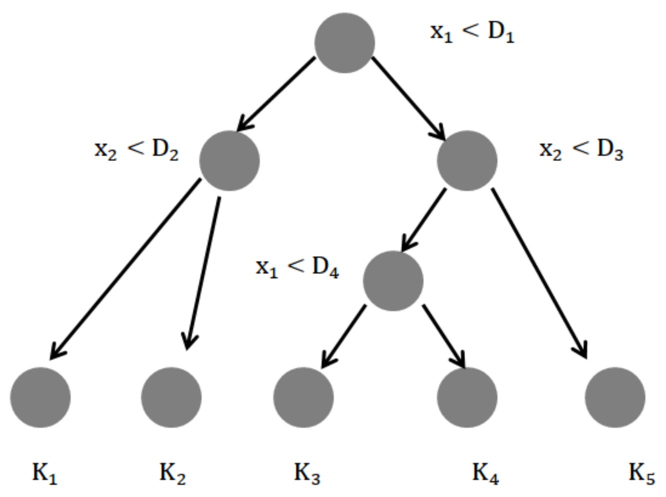
Boosted Decision Tree

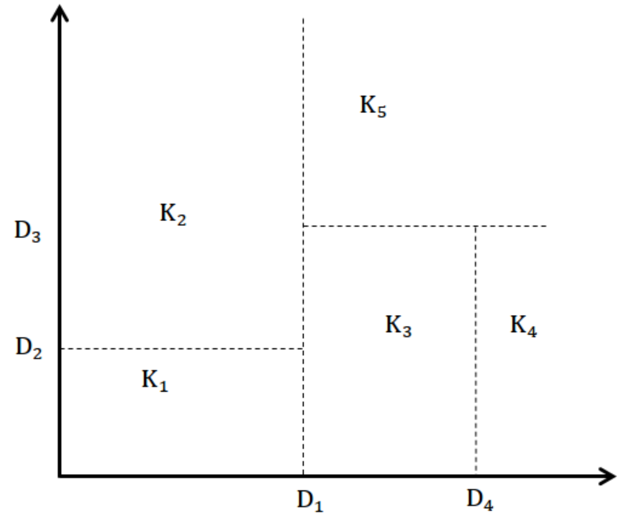
Tree-level structer of classifier

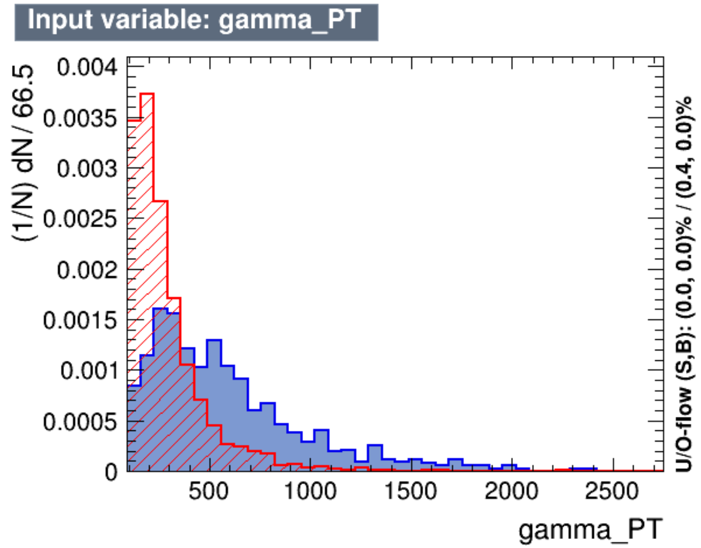
Leaves (at the bottom) – class

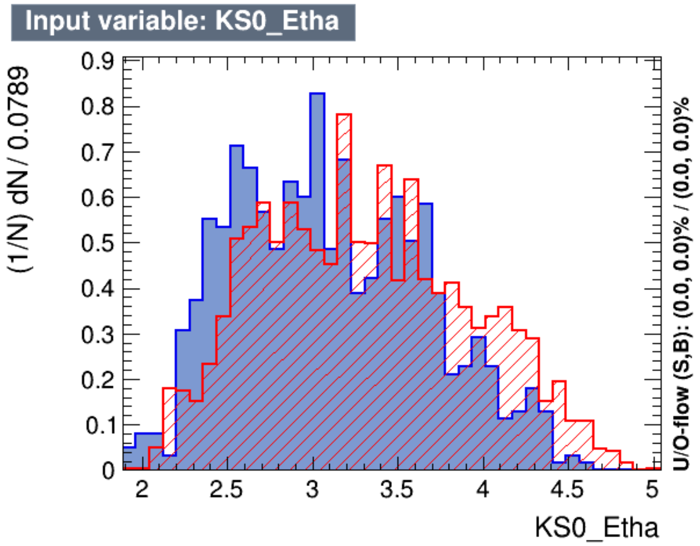
Values – regression tree

Boosting: training of trees on misclassified events by enhancing their importance









Introduction – Multibody decay analysis method

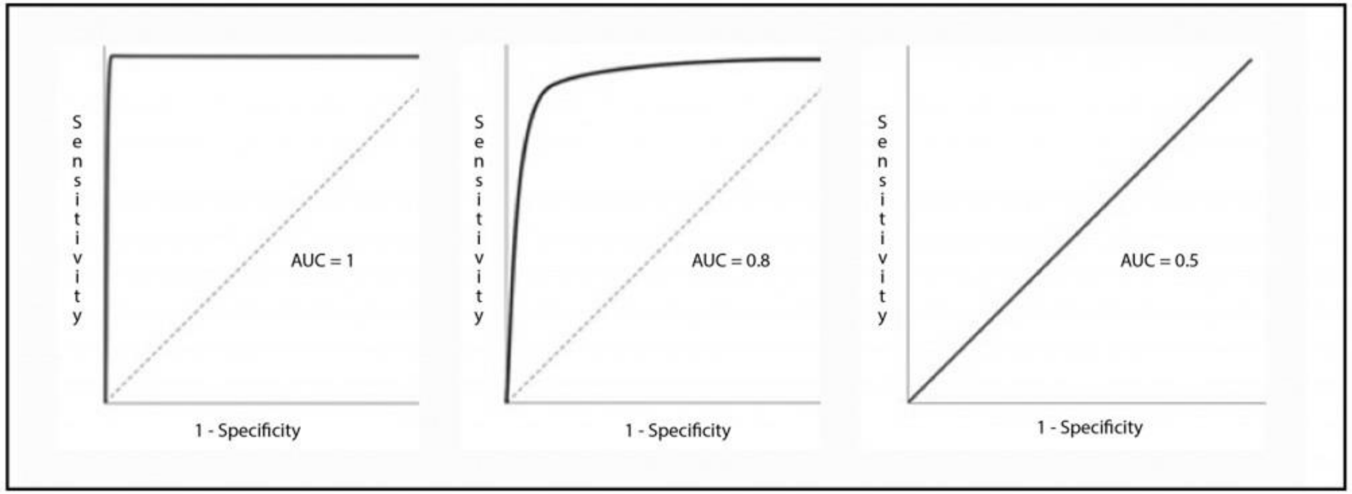
Verification – Confusion Matrix & ROC curve

True Positives (**TP**) vs True Negatives (**TN**)

False Positives (**FP**) vs False Negatives (**FN**)

N	Predicted: NO	Predicted: YES
Actual: NO	TN	FP
Actual: YES	FN	TP

Metrics



Accuracy $\boldsymbol{acc} = \frac{\boldsymbol{TP+TN}}{\boldsymbol{N}}$

Misclassification rate $\boldsymbol{mcl} = \frac{\boldsymbol{FP+FN}}{\boldsymbol{N}}$

Specificity $\boldsymbol{sp} = \frac{\boldsymbol{TN}}{\boldsymbol{m_B}}$

Precision $\boldsymbol{p} = \frac{\boldsymbol{TP}}{\boldsymbol{n_S}}$

AUC = 1 → perfect classification

AUC = 1-0.5 → effective classification

AUC = 0.5 → random classification

RESULTS

$B \to DK$ decay

GLW Method

Phys. Lett. B265 (1991) 172

$B^{\pm} \to D^0 K^{\pm}$

Gronau-London-Wyler method - D^0 decays to CP-eigenstates

$D^0 \to KK/\pi\pi$, $D^0 \to K_s\pi^0, K_s\omega$ ...

Observables:

- CP asymmetries:

$$A_{CP} = \frac{N(B^- \to D^0_{CP}K^-) - N(B^+ \to D^0_{CP}K^+)}{N(B^- \to D^0K^-) + N(B^+ \to D^0K^+)}$$

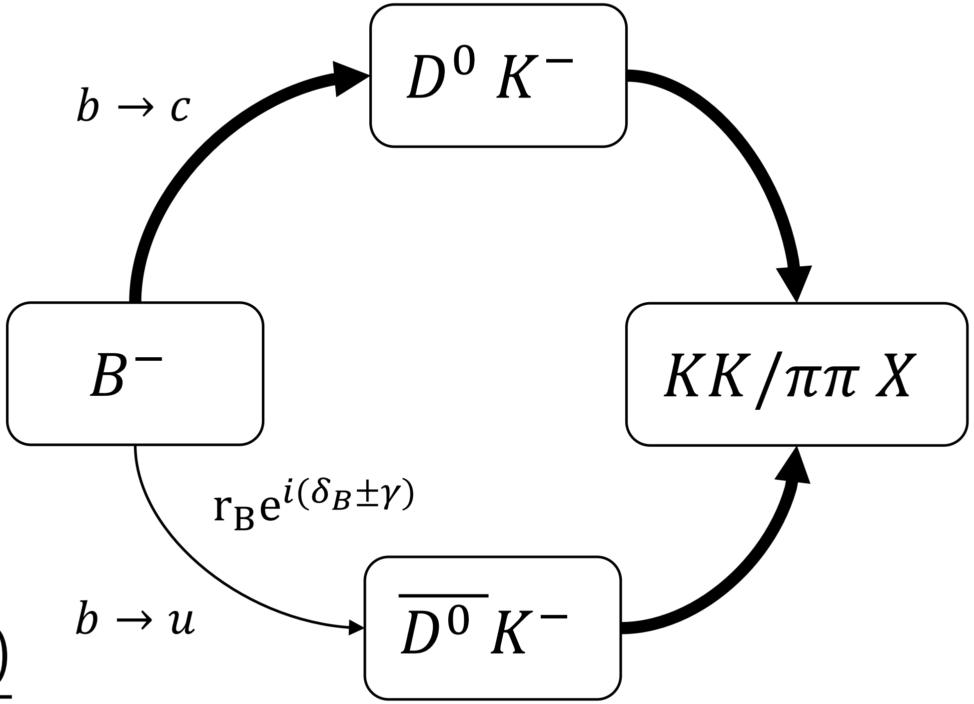
$$A_{CP} = \frac{2r_B \sin(\delta_B)\sin(\gamma)}{1 + r_B^2 \pm 2r_B\cos(\delta_B)\cos(\gamma)}$$

- Partial widths:

$$R_{GLW} = \frac{N(B^- \to D^0_{CP}K^-) + N(B^+ \to D^0_{CP}K^+)}{N(B^- \to D^0K^-) + N(B^+ \to D^0K^+)}$$

$$R_{GLW} = 1 + r_B^2 \pm 2r_B\cos(\delta_B)\cos(\gamma)$$

$\mathcal{CP}|hh\rangle = \pm|hh\rangle$

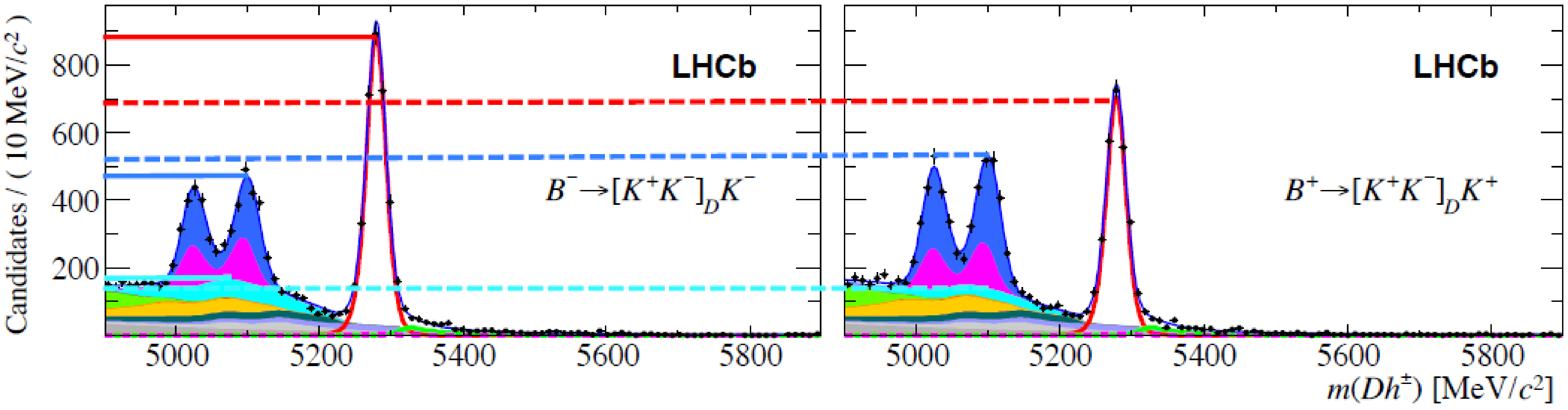


$B^+ \to DK^+$

Phys. Lett. B760 (2016)

The GLW measurement using Run 1 & Run 2 data.

$B^\pm \to D^0(KK)K^\pm$

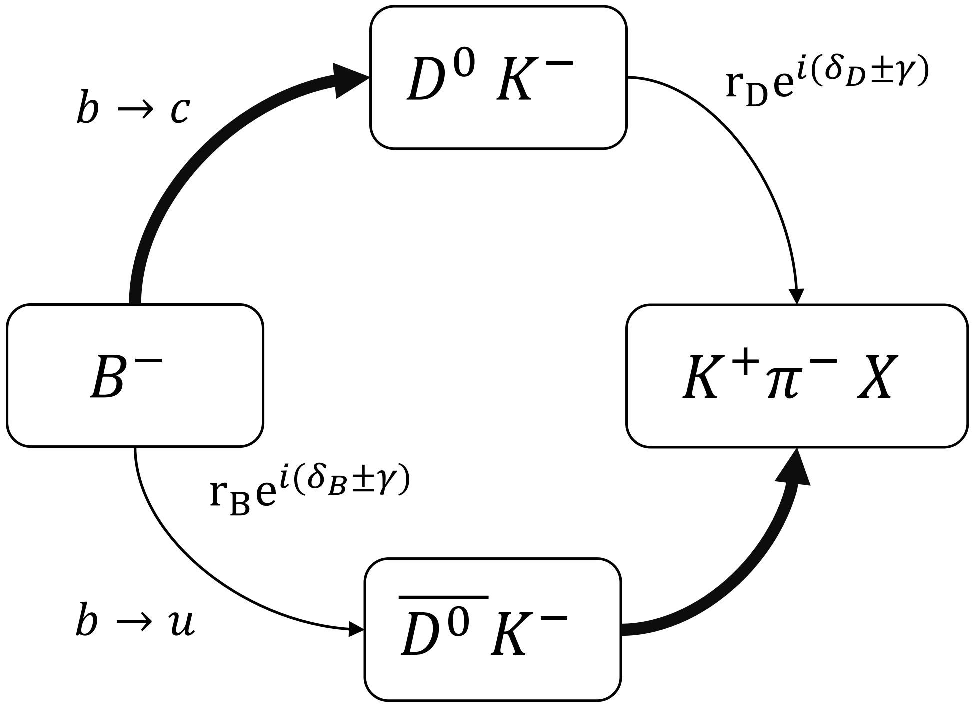


ADS Method

$B^{\pm} \to D^0 K^{\pm}$

Atwood, Dunietz, Soni method: $\boldsymbol{D^0 \to K\pi}$

- B favoured decay and D suppressed Decay
- B suppressed decay and D favoured decay



> Larger interference effects as both amplitudes are of similar sizes.

$$A_{CP} = \frac{N(B^- \to [K^+\pi^-]_{D^0}K^-) - N(B^+ \to [K^-\pi^+]_{D^0}K^+)}{N(B^- \to [K^+\pi^-]_{D^0}K^-) + N(B^+ \to [K^-\pi^+]_{D^0}K^+)}$$

$[K \quad \pi \quad]_{D^0}$

$$A_{CP} = \frac{2 r_B \boldsymbol{r_D} \sin(\delta_B + \delta_d) \sin(\gamma)}{1 + r_B^2 + \boldsymbol{r_D^2} + 2 r_B \boldsymbol{r_D} \cos(\delta_B + \boldsymbol{\delta_d}) \cos(\gamma)}$$

$$R_{ADS} = \frac{N\left(B^- \to [K^+\pi^-]_{D^0}K^-\right) + N\left(B^+ \to [K^-\pi^+]_{D^0}K^+\right)}{N\left(B^- \to [K^-\pi^+]_{D^0}K^-\right) + N\left(B^+ \to [K^+\pi^-]_{D^0}K^+\right)}$$

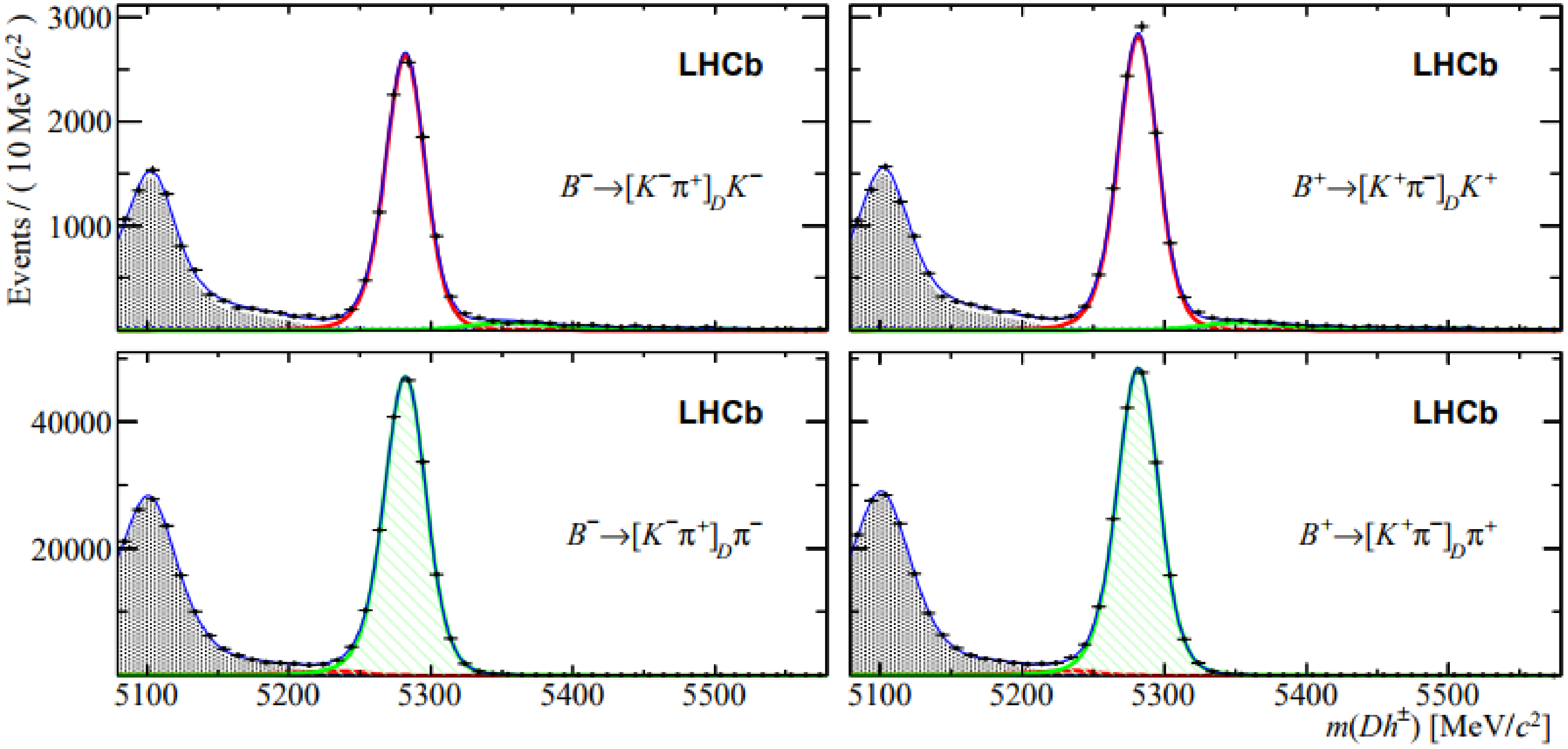
$$R_{ADS} = 1 + r_B^2 + \boldsymbol{r_D^2} + 2 r_B \boldsymbol{r_D} \cos(\delta_B + \boldsymbol{\delta_d}) \cos(\gamma)$$

$B^+ \to DK^+$

The ADS measurement using an Run 1 & Run 2 data.

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

B favoured $\times$ D favoured amplitudes

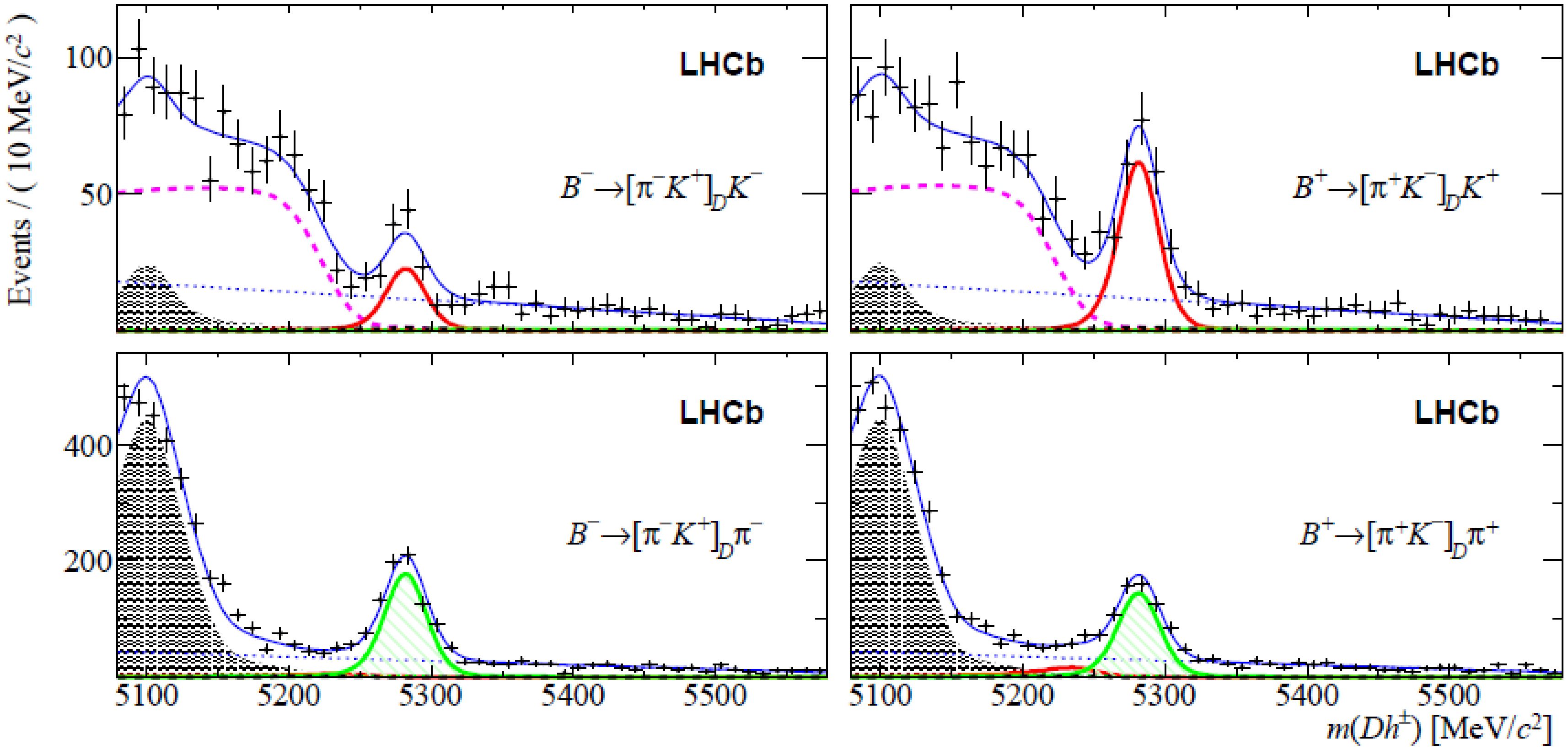


$B^+ \to DK^+$

The ADS measurement using an Run 1 & Run 2 data.

$B^\pm \to D^0(K\pi)K^\pm$

favoured × suppressed amplitudes

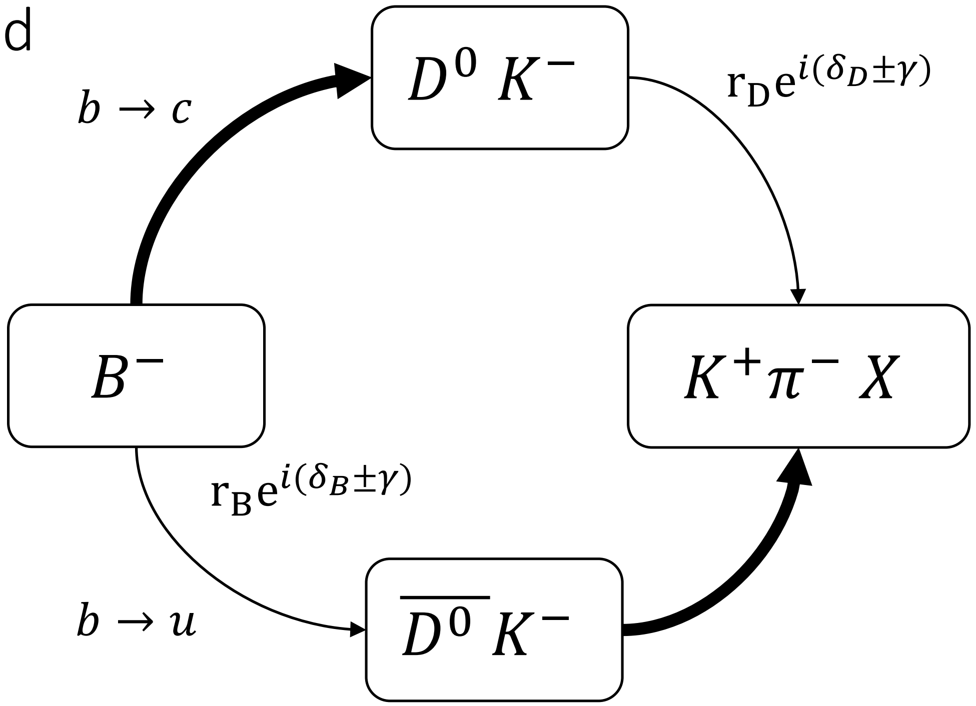


GGSZ Method

$B^{\pm} \to D^0 K^{\pm}$ Giri, Grossman, Soffer, Zupan Method

D decays to 3 body final states $D^0 \to K_s^0 \pi\, \pi$

$D^0 \to K_s^0 K K$



Dalitz Plot encodes all the kinematic information of the decay

Each point on the Dalitz plot represents a different value of r_D and δ_D

D Dalitz plot from B decay will be a superposition of $D^0\ \overline{D^0}$

- Differences between B^+ and B^- are related to $r_B\ \delta_B$ and γ

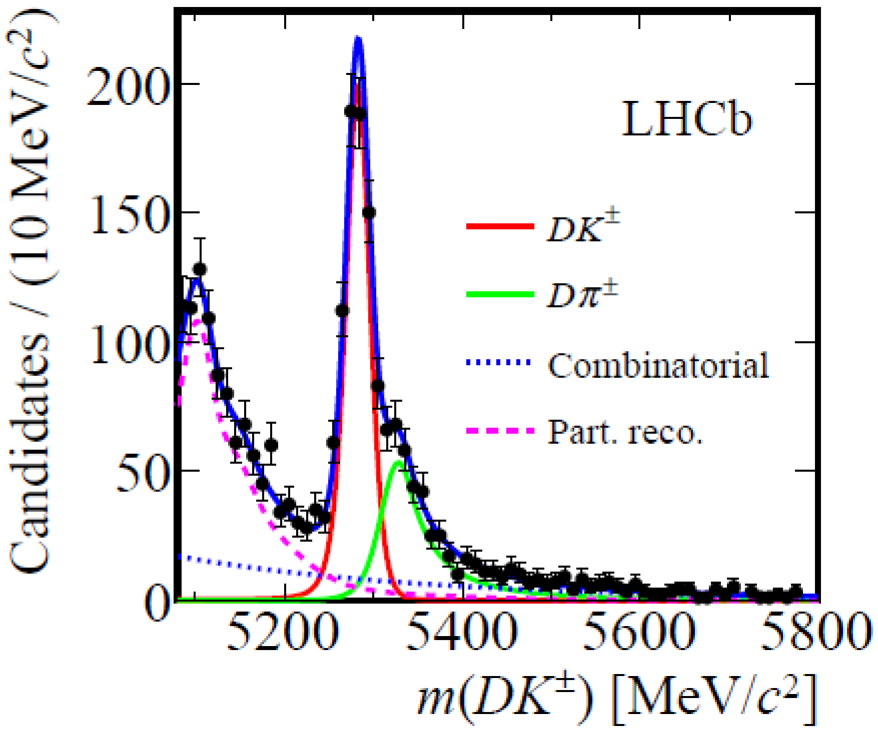
this method requires a good understanding of strong phases in the Dalitz plane (from CLEO)

A model dependent scenario with r_D and δ_D

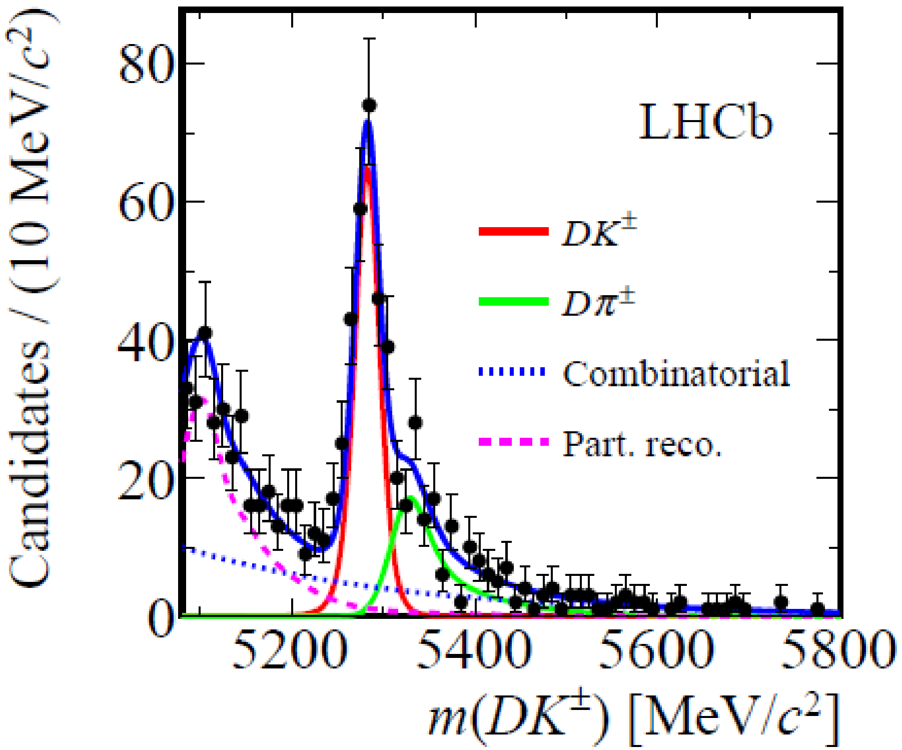
GGSZ Method

$B^{\pm} \to D^0 K^{\pm}$

$D^0 \to K_s^0 \pi\, \pi$



$D^0 \to K_s^0 KK$



$$r_B = 0.080^{+0.019}_{-0.021} \quad \gamma = \left(62^{+15}_{-14}\right)^{\circ} \quad \delta_B = \left(134^{+14}_{-15}\right)^{\circ}$$

$B^0 \rightarrow D\,K^{*0}$

$B^0 \rightarrow D^0 K^{*0}$ $\quad D^0 \rightarrow K_s^0 \pi\,\pi$

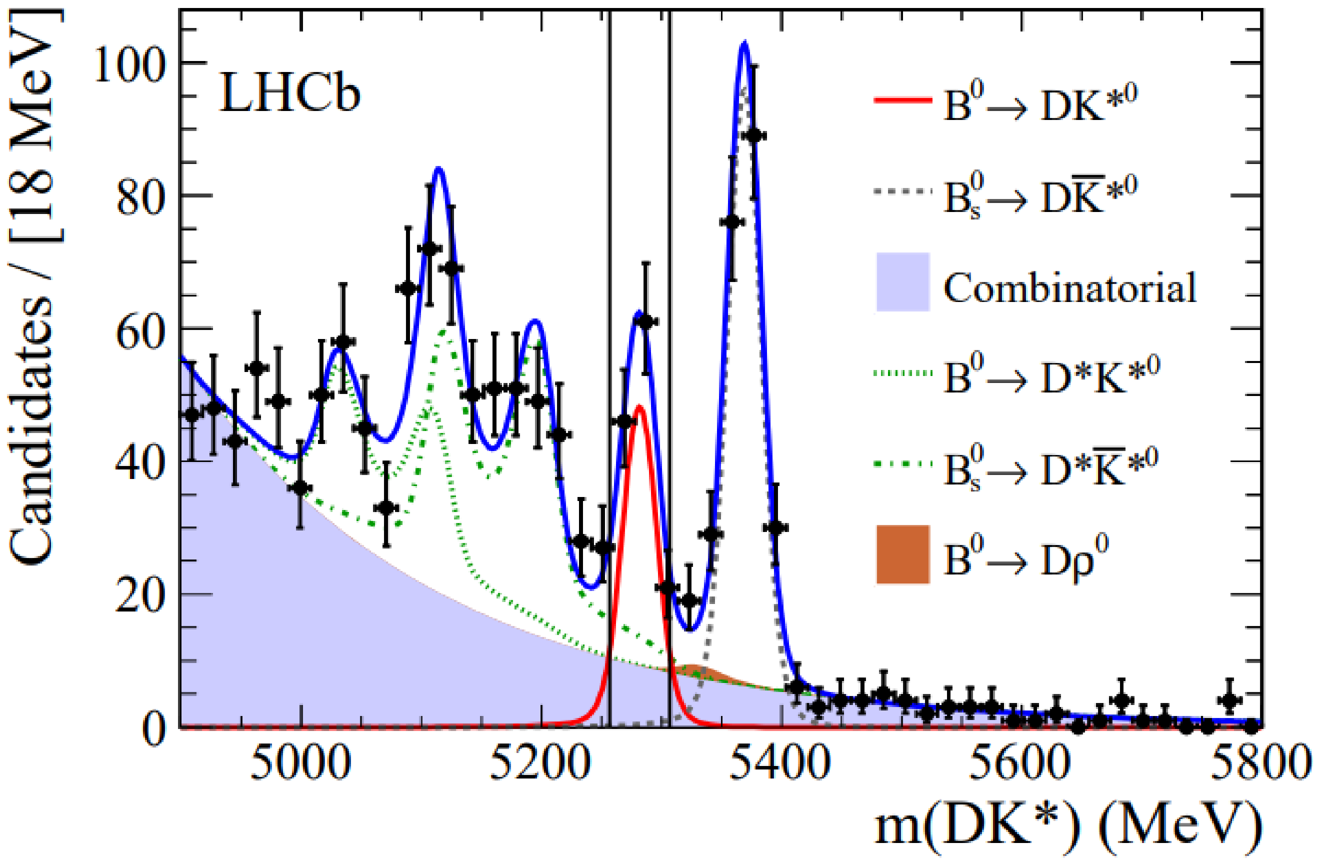
Model - dependent observation

GGSZ analysis measurement using

Run 1 & Run 2 data.

$$\gamma = (80^{+21}_{-22})^{\circ}$$

$$r_B = 0.39 \pm 0.13$$

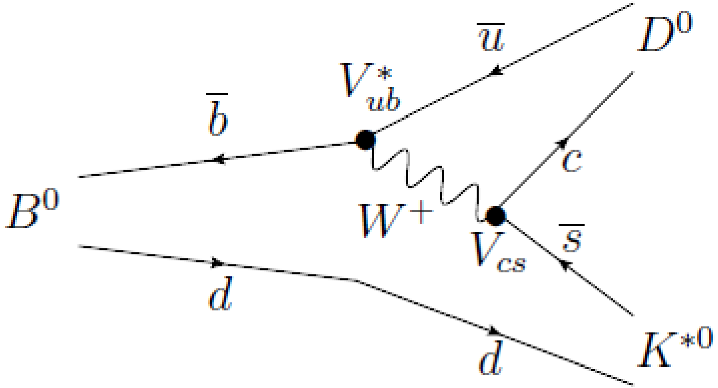


$B^0 \to D\, K^{*0}$

JHEP 06 (2016) 131

$B^0 \to D^0 K^{*0}$ $D^0 \to K_s^0 \pi\, \pi,$ $D^0 \to K_s^0 K K$

Interference of two suppressed amplitudes (comparable in magnitudes)

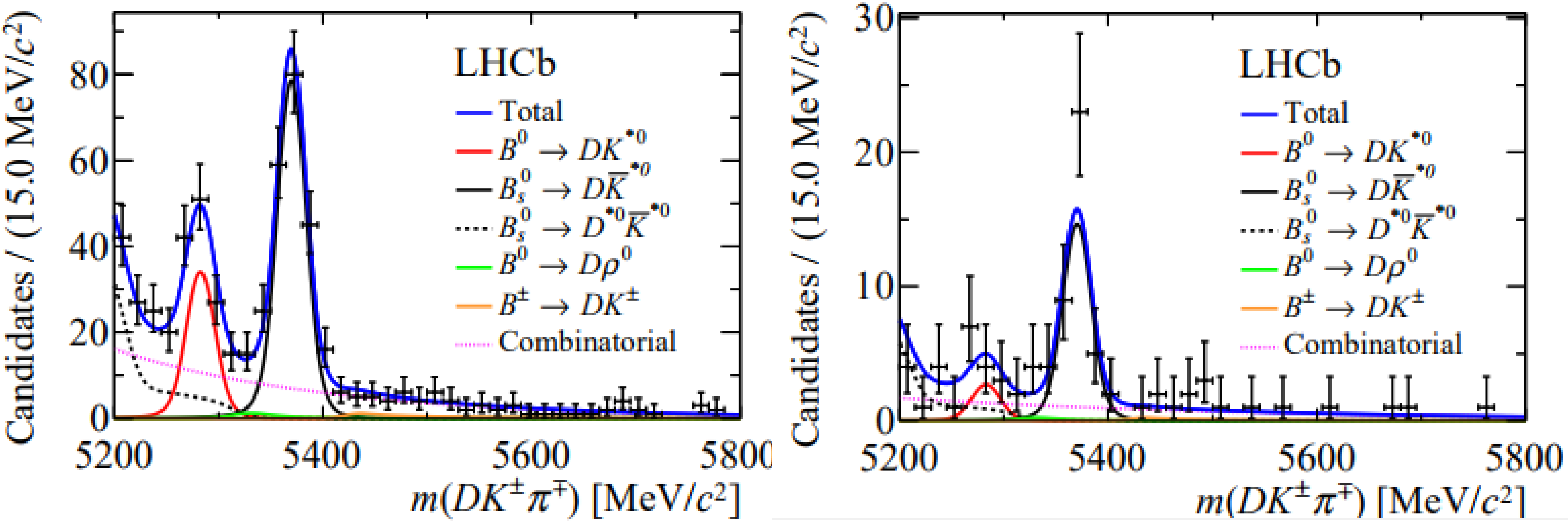


Model - independent observation

- Uses measured δ_D from CLEO – experiment
- Independent of the D decay model.
- Sensitivity to γ obtained by comparing the distribution of events in D^0 and $\overline{D}^0$ Dalitz plots reconstructed in each flavour (K^{*0} decay is self-tagging)

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

JHEP 06 (2016) 131



The three-body self-conjugate decays $D \to KS0\pi^+\pi^-$ and $D \to K_S^0 K^+ K^-$ designated collectively as $D \to K_S^0 h^+ h^-$are accessible to both D0 and D0.

Model - independent observation

$$\gamma = (71 \pm 20)^\circ$$

$$r_{B^0} = 0.56 \pm 0.17$$

$$\delta_{B^0} = (204^{+21}_{-20})^\circ$$

Model - dependent observation with the SAME data

$$\gamma = (80^{+21}_{-22})^\circ$$

Results are consistent within the limits

$B^- \to Dh^-\pi^-\pi^+$

Phys. Rev. D 92, 112005 (2015)

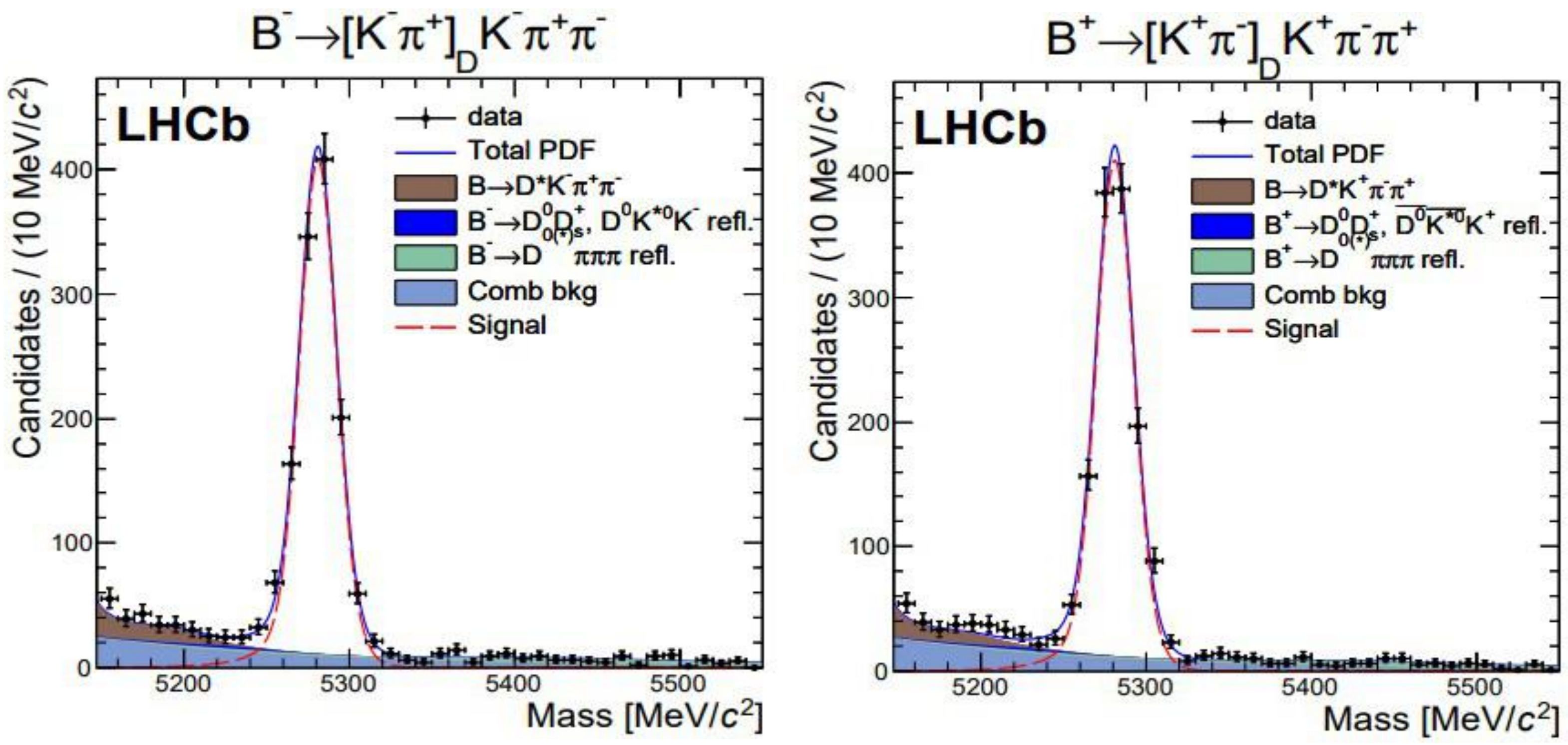
$B^- \to D\, X_S^-$ $X_S^- \equiv K^-\pi^-\pi^+$ $D^0 \to KK,\ K\pi,\ \pi\pi$

- First ADS and GLW analyses

  Run 1 & Run 2 data (3 fb^{-1})

- γ sensitivity similar to the $B^\pm \to D^0 K^\pm$ decays.

- Dilution of interference due to the variation of the strong phase calculated in a model-dependent way by a full amplitude analysis.

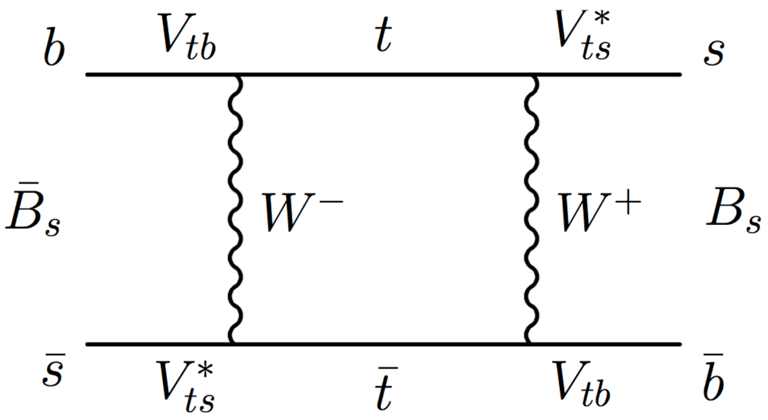


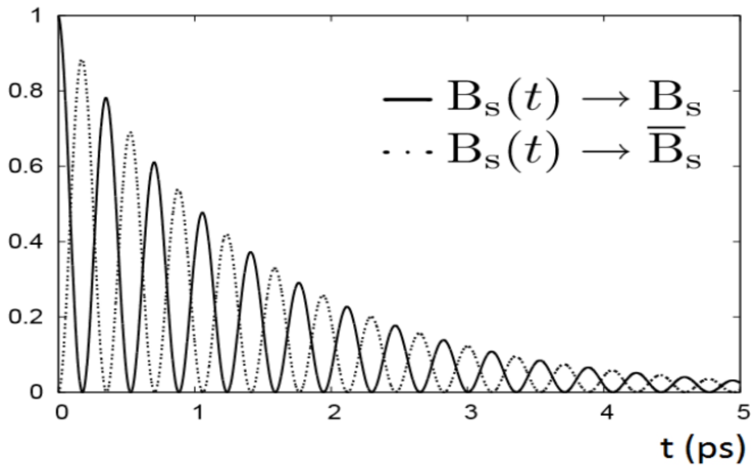
$$\gamma = (74^{+19}_{-20})^\circ \text{ at } 68.3\% \text{ CL}$$

Time – dependent observation

γ angle extraction from

$B^0 - \overline{B^0}$ meson oscillation





Requires tagging the initial B_s^0 flavour

Requires a time-dependent analysis to observe the meson oscillations

The time-dependent decay rates :

$$\Gamma_{B_s^0 \to f}(t) = |A_f|^2 \left(1 + |\lambda_f|^2\right) \frac{e^{-\Gamma_s t}}{2} \left(cosh\frac{\Delta\Gamma_s t}{2} + D_f \, sinh\frac{\Delta\Gamma_s t}{2} + C_f \cos \Delta m_s t - S_f \sin \Delta m_s t\right)$$

$$S_f = \frac{2r_{D_s}Ksin\left(\delta - (\gamma - 2\beta_s)\right)}{1 + r_{D_sK}^2} \qquad C_f = \frac{1 - r_{D_sK}^2}{1 + r_{D_s}^2 K}$$

Time – dependent observation

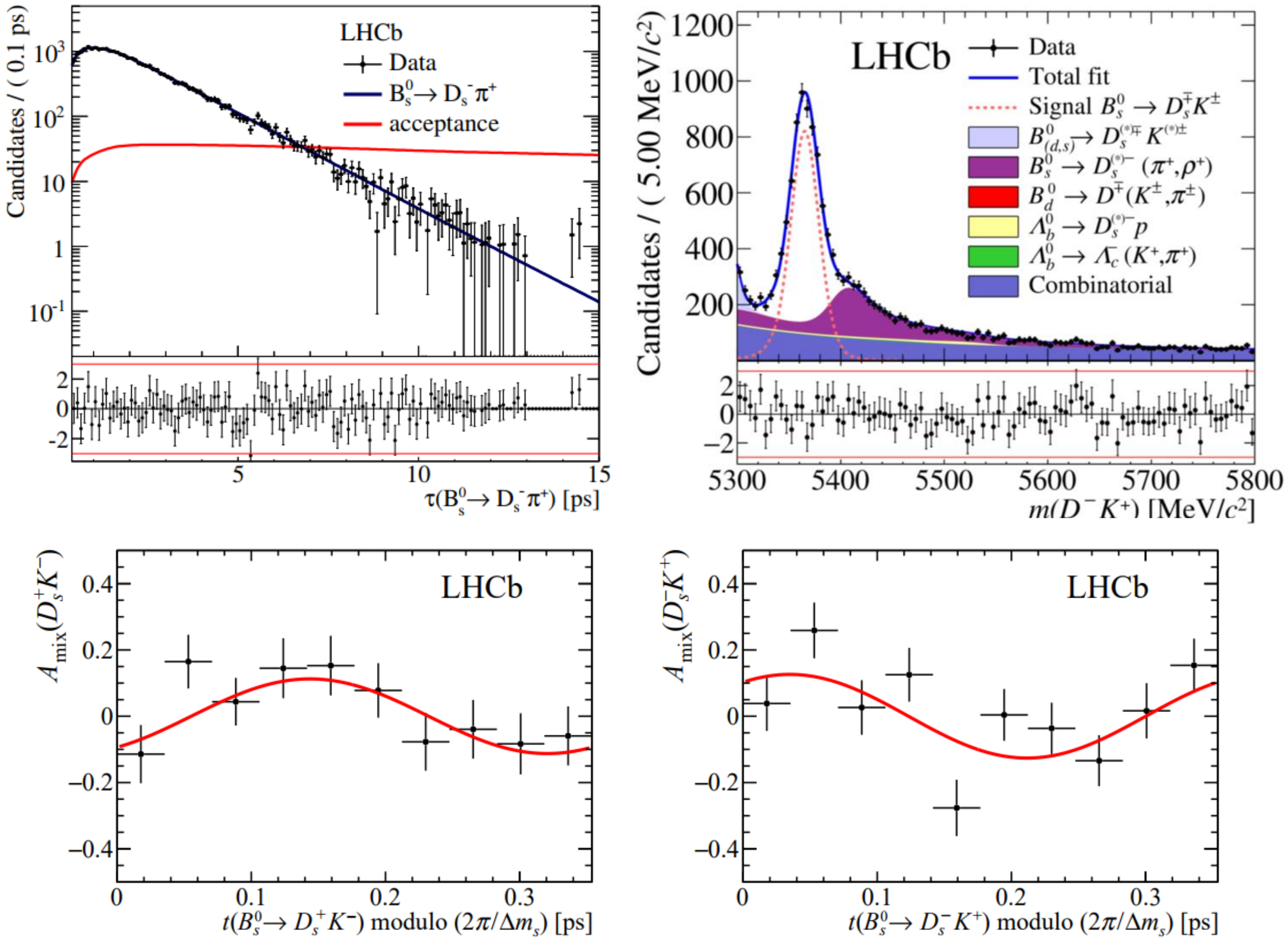
$D_s^{\pm} \to h\,h\,h$

Several experimental aspects

need to be taken into account :

- Finite decay-time resolution
- Decay-time acceptance
- Background
- Tagging efficiency

$$\gamma = (128^{+17}_{-22})^{\circ}$$



One fit with plenty of parameters

Combining γ at LHCb

Only $B \to DK$ decays :

$B^{\pm} \to D^0(KK)K^{\pm}$ - GLW

$B^{\pm} \to D^0(K\pi)K^{\pm}$ - ADS

$B^0 \to DK^{*0}$ GGSZ

$B^0 \to DK^{*0}$ MD

$B_s^0 \to D_s^{\pm} K^{\pm}$ TD

$B^- \to Dh^-\pi^-\pi^+$ GLW/ADS

and more..

$$\boldsymbol{\gamma = \left(76.8^{+5.1}_{-5.7}\right)^{\circ}}$$

Summary

	B decay	D decay	Type	$\int \mathcal{L}$	Ref.
LHCb Inputs	$B^+ \to DK^+$	$D \to hh$	GLW/ADS	$3\,fb^{-1}$	[arXiv:1603.08993]
	$B^+ \to DK^+$	$D \to h\pi\pi\pi$	GLW/ADS	$3\,fb^{-1}$	[arXiv:1603.08993]
	$B^+ \to DK^+$	$D \to hh\pi^0$	GLW/ADS	$3\,fb^{-1}$	[arXiv:1504.05442]
	$B^+ \to DK^+$	$D \to K^0_S hh$	GGSZ	$3\,fb^{-1}$	[arXiv:1405.2797]
	$B^+ \to DK^+$	$D \to K^0_S K\pi$	GLS	$3\,fb^{-1}$	[arXiv:1402.2982]
	$B^0 \to D^0 K^{*0}$	$D \to K\pi$	ADS	$3\,fb^{-1}$	[arXiv:1407.3186]
	$B^+ \to DK^+\pi\pi$	$D \to hh$	GLW/ADS	$3\,fb^{-1}$	[arXiv:1505.07044]
	$B^0_s \to D_s^\mp K^\pm$	$D_s^+ \to hhh$	TD	$1\,fb^{-1}$	[arXiv:1407.6127] *
	$B^0 \to D^0 K^+\pi^-$	$D \to hh$	GLW-Dalitz	$3\,fb^{-1}$	[arXiv:1602.03455]
	$B^0 \to D^0 K^{*0}$	$D \to K^0_S \pi\pi$	GGSZ	$3\,fb^{-1}$	[arXiv:1604.01525]
	Decay	**Parameters**	**Source**		**Ref.**
Auxiliary Inputs	D^0–$\bar{D}^0$ mixing		HFIAv	-	[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]
	$D \to K^0_S K\pi$	(δ_D, κ_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]

Future

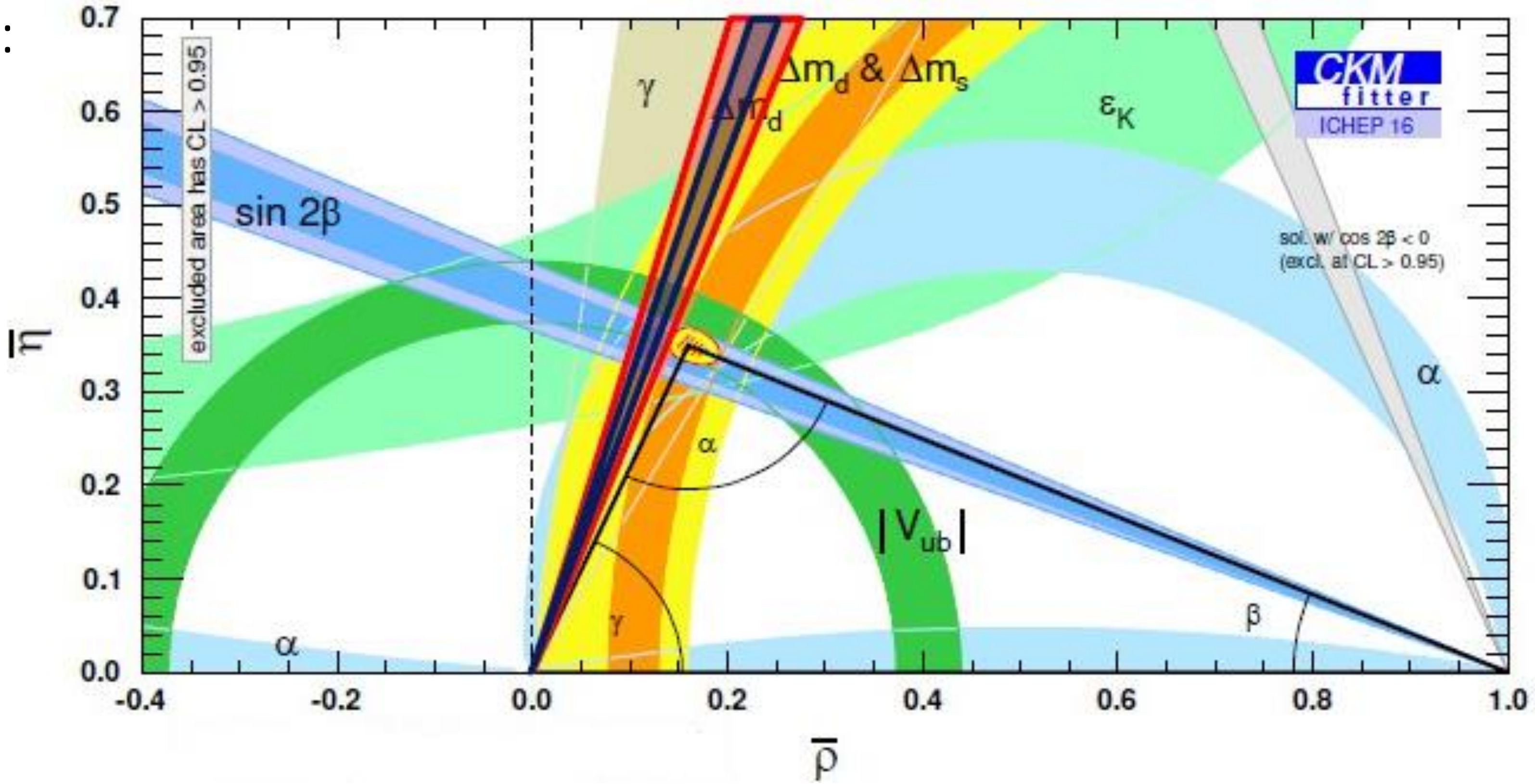
γ angle measurements precision:

2017 (now): ~ 5 °

2018 (expected): ~ $3 - 4°$

2023 (expected): ~ $1.5°$

2029 (expected): ~ $< 1°$

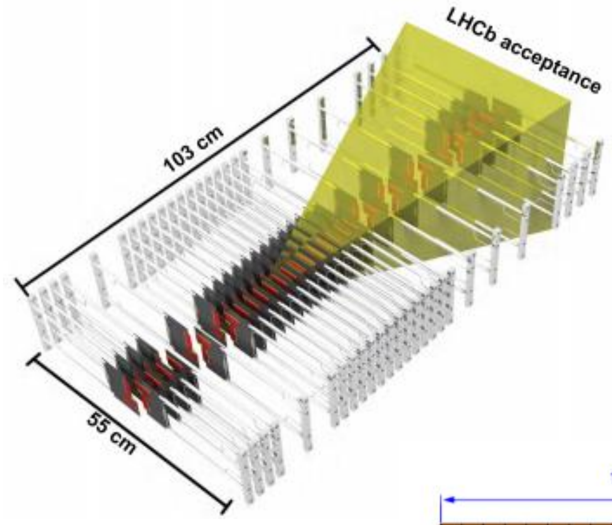


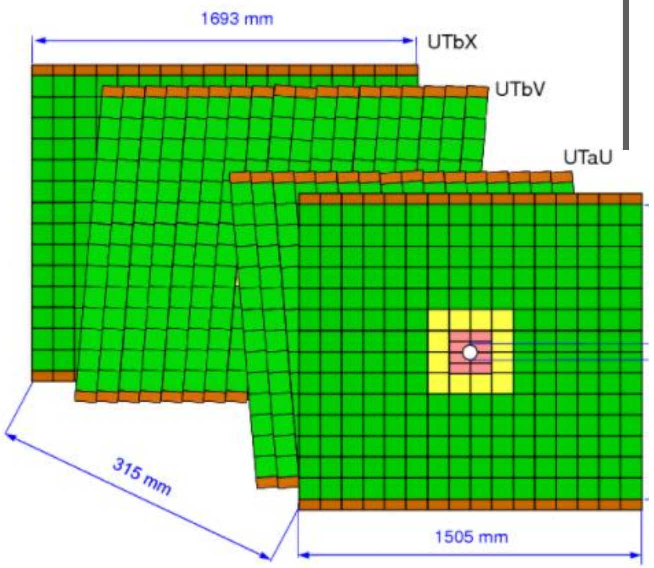
QUESTIONS?

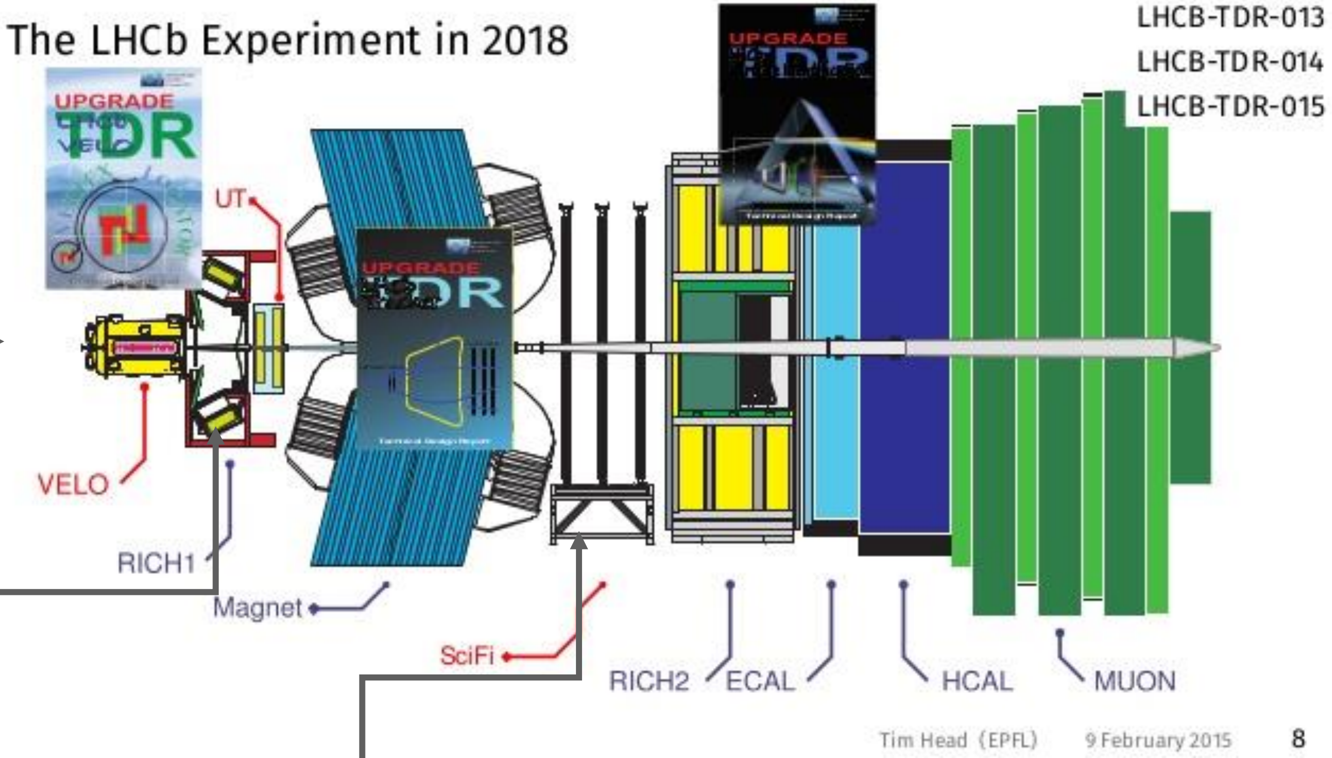
BACKUP

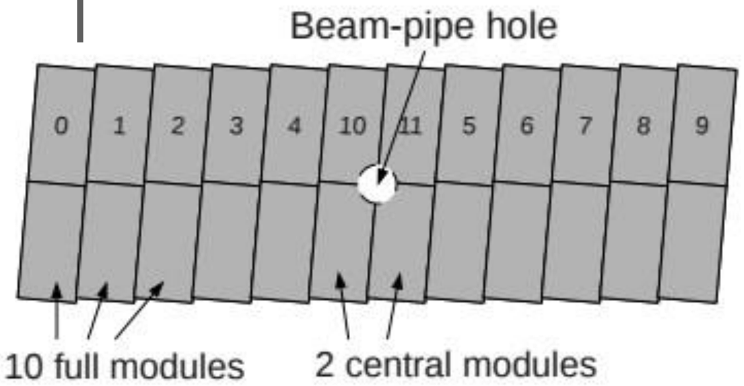
LHCb – Upgrade

LHC – LS2 2018-2019 -> 50 fb-1!

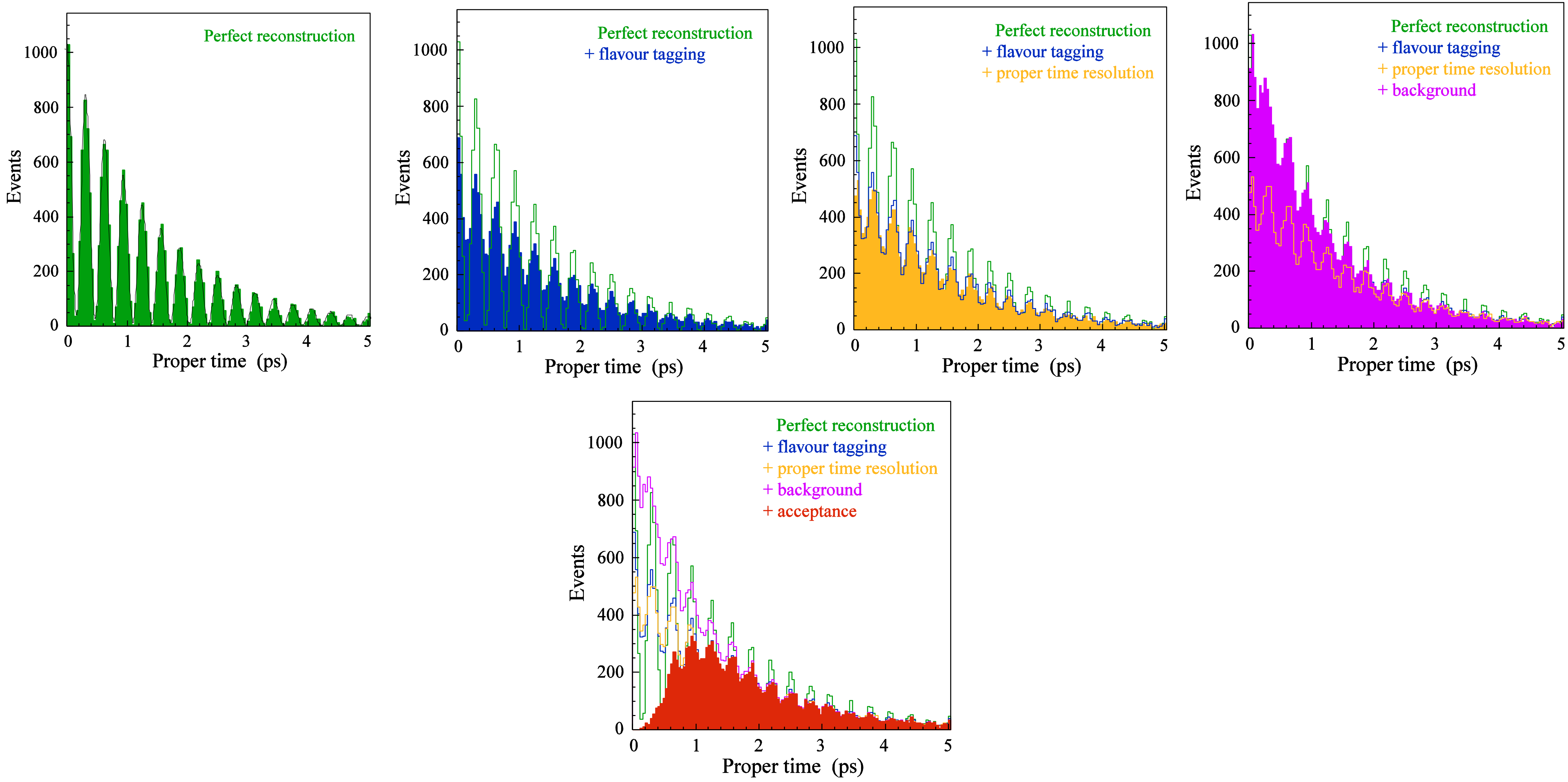




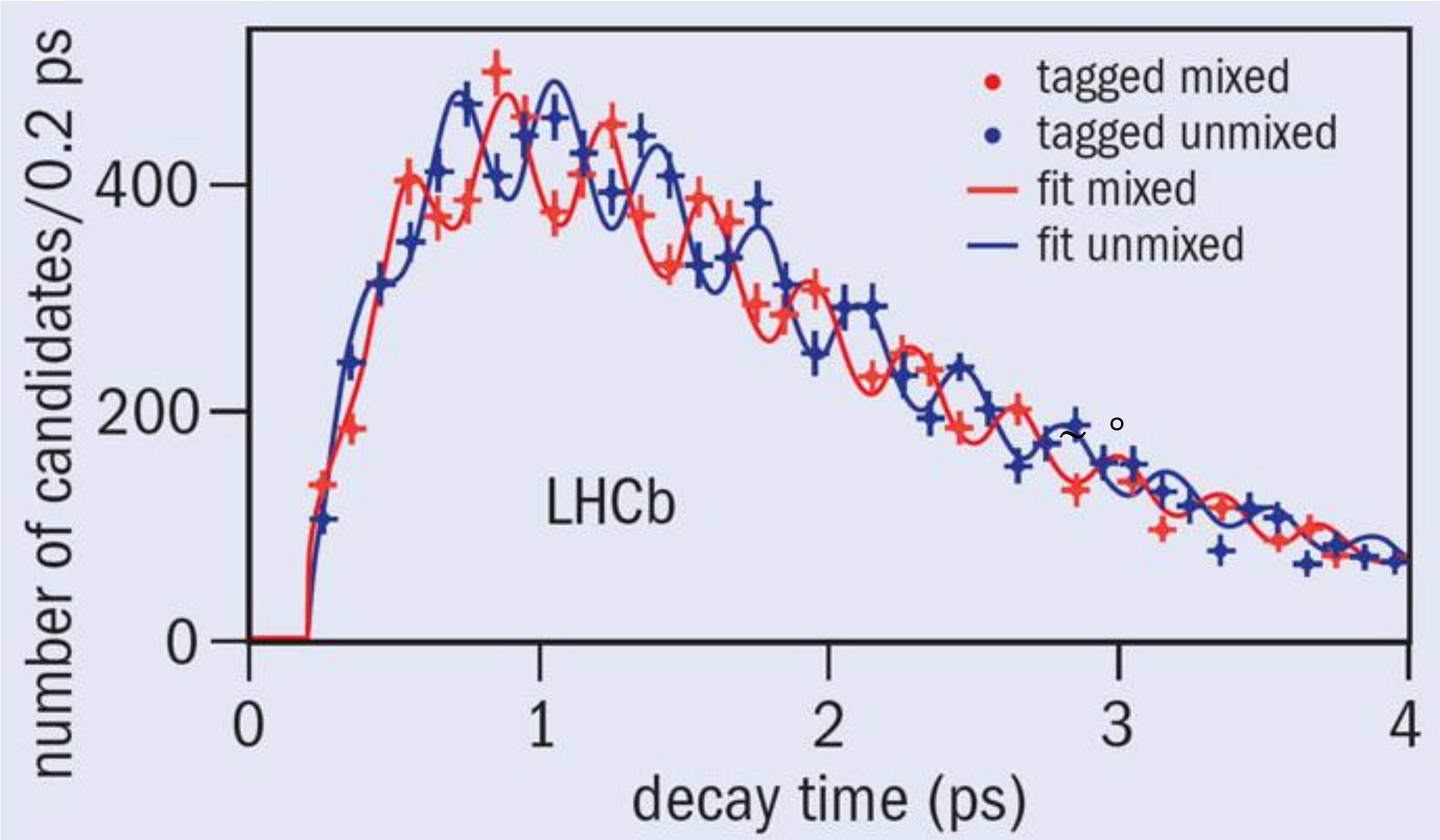




B_s^0 meson oscillation



B_s^0 meson oscillation



Opis parametrów

$$A_f = \langle f|T|B_s^0\rangle \quad , \bar{A}_{\bar{f}} = \langle \bar{f}|T|\bar{B}_s^0\rangle$$

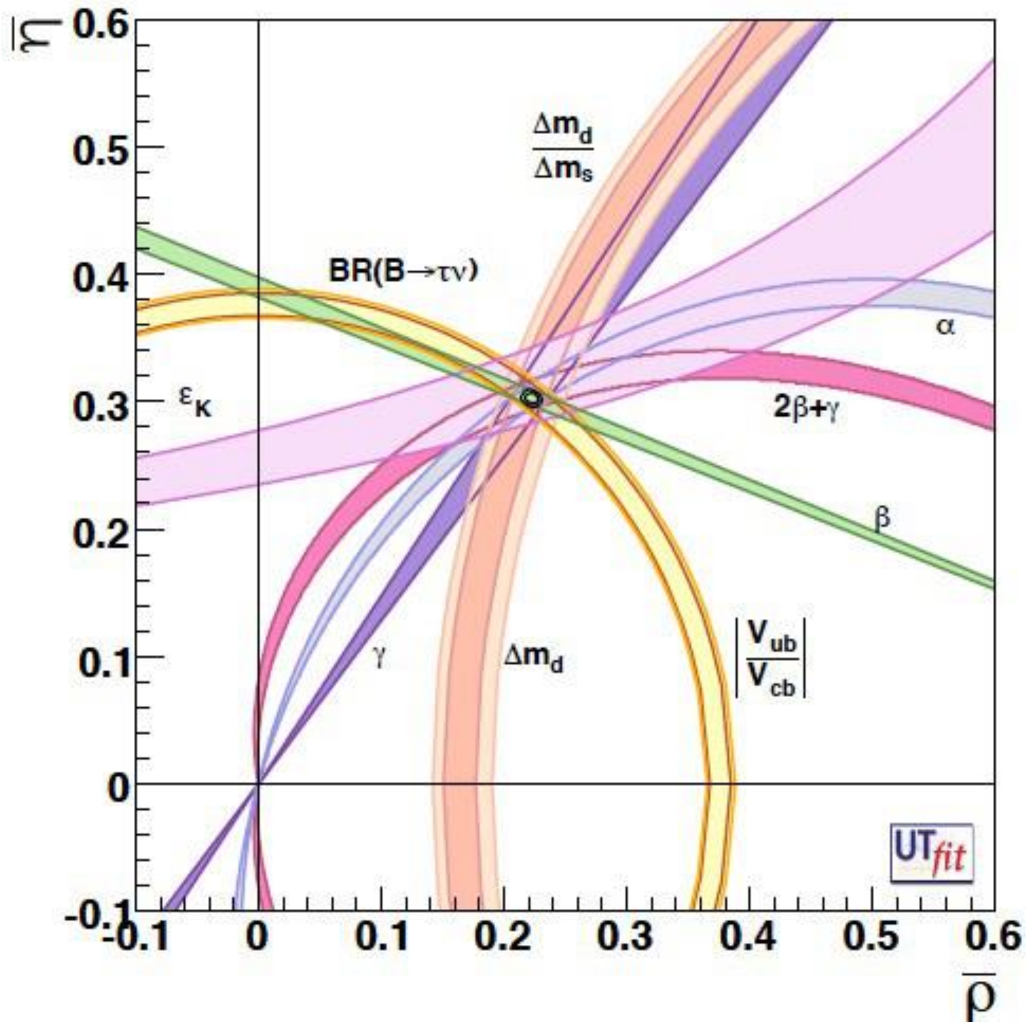
$$\bar{A}_f = \langle f|T|\bar{B}_s^0\rangle \quad A_{\bar{f}} = \langle \bar{f}|T|B_s^0\rangle$$

$$D_f = \frac{2Re\lambda_f}{1+|\lambda_f|^2} \quad , D_{\bar{f}} = \frac{2Re\bar{\lambda}_{\bar{f}}}{1+|\bar{\lambda}_{\bar{f}}|^2}$$

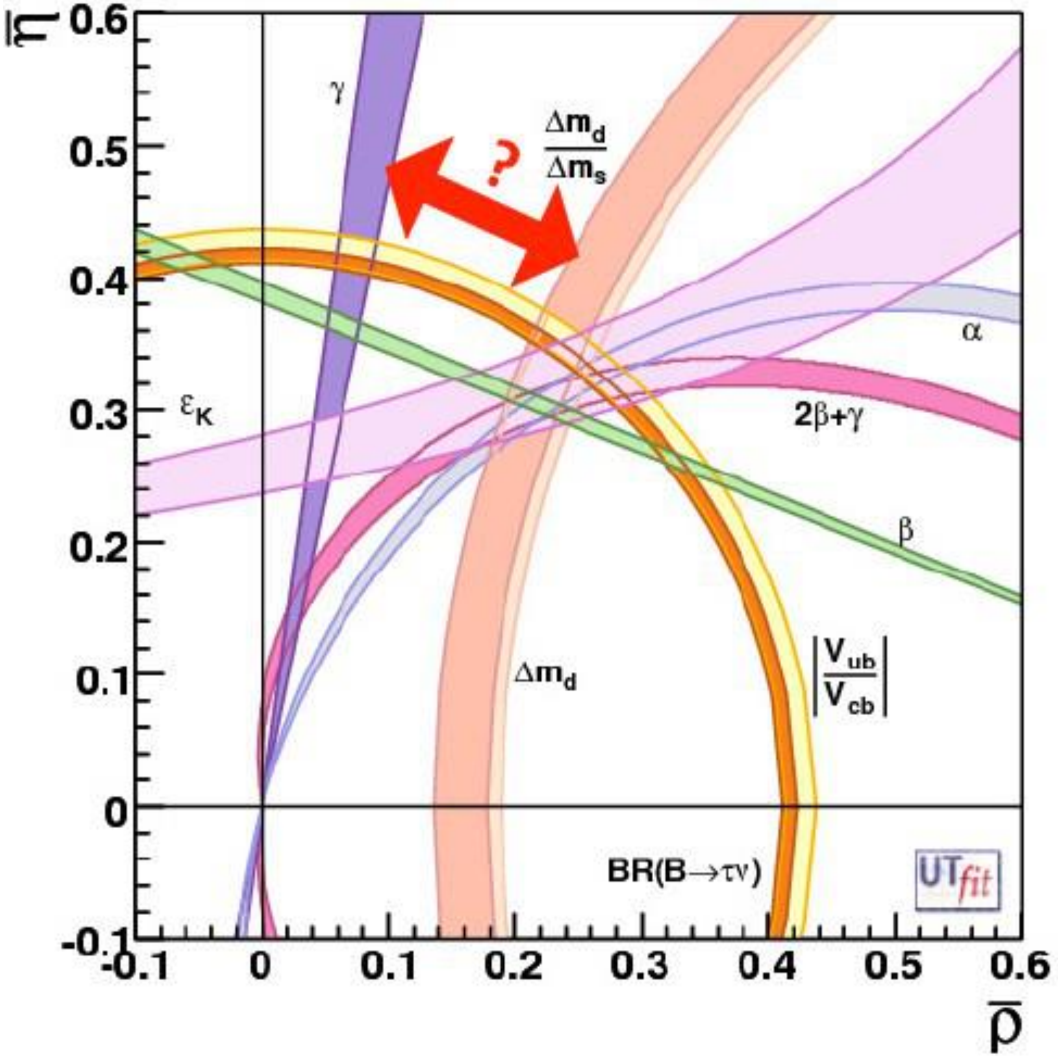
$$C_f = \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2} \quad C_{\bar{f}} = \frac{1-|\bar{\lambda}_{\bar{f}}|^2}{1+|\bar{\lambda}_{\bar{f}}|^2}$$

$$S_f = \frac{2Im\lambda_f}{1+|\lambda_f|^2} \quad S_{\bar{f}} = \frac{2Im\bar{\lambda}_{\bar{f}}}{1+|\bar{\lambda}_{\bar{f}}|^2}$$

Future



$\bar{\eta}$
$\frac{\Delta m_d}{\Delta m_s}$
BR(B→τν)
α
ε_K
2β+γ
β
γ
Δm_d
$\left|\frac{V_{ub}}{V_{cb}}\right|$
UTfit
$\bar{\rho}$



$\bar{\eta}$
γ
?
$\frac{\Delta m_d}{\Delta m_s}$
α
ε_K
2β+γ
β
Δm_d
$\left|\frac{V_{ub}}{V_{cb}}\right|$
BR(B→τν)
UTfit
$\bar{\rho}$