Recent results on the CKM angle γ with open charm B decays at LHCb

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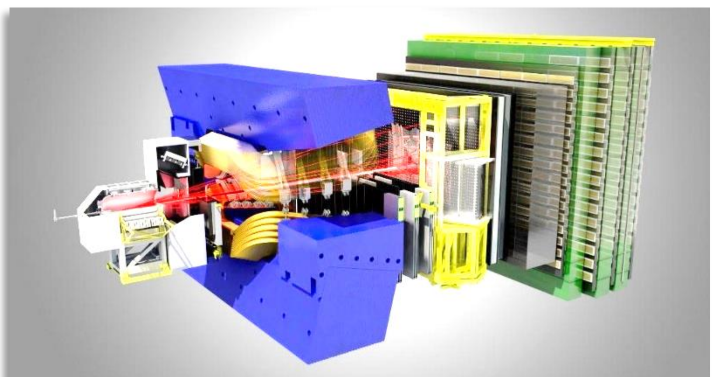
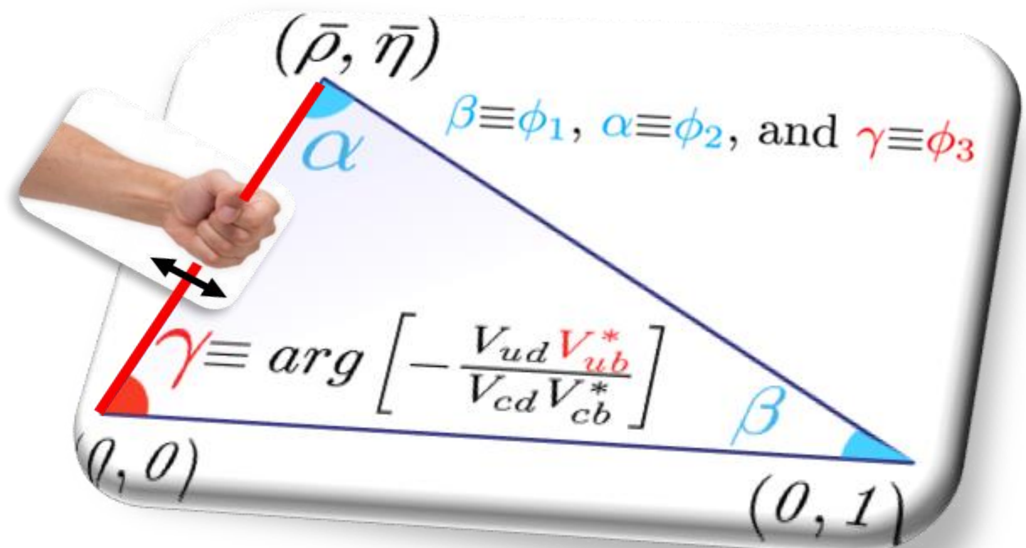
LLR Palaiseau le 28 janvier 2019

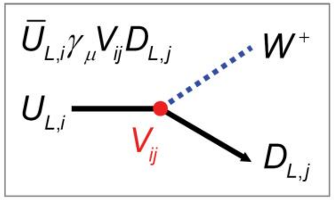




The Standard Model (SM) & the Unitary CKM Matrix
➔ mixing of the 3 quarks families & CP violation

• the Higgs boson gives mass to elementary bosons & fermions (quarks, leptons) through Yukawa couplings, but there is not only that ! :

$$\mathcal{L}_{cc}^{\text{quarks}} = \frac{g}{2\sqrt{2}} W_\mu^\dagger \left[\sum_{ij} \bar{u}_i(q_2)\gamma^\mu(1-\gamma^5) V_{ij} d_j\right] + \text{h.c}$$



charged currents (EW) imply transitions between quark families : quarks decays **[there are no neutral current changing flavour (FCNC) at tree level (i.e. GIM mechanism)].**

$$V_{CKM} = \begin{array}{c|ccc} & d & s & b \\ \hline u & 1-\lambda^2/2 & \lambda & A\lambda^3(\rho-i\eta) \\ c & -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ t & A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{array} + \mathcal{O}(\lambda^4) \qquad (VV^\dagger=1)$$

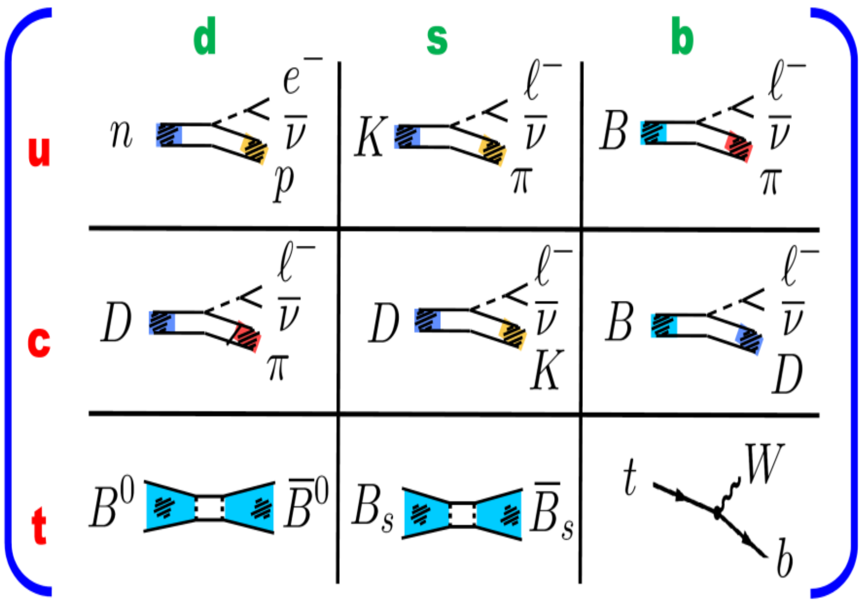
• **strong hierarchy in EW V_{ij} couplings for the 3 families (wrt diagonal couplings $\propto\lambda^N \approx (0.225)^N$: ➔ Cabibbo angle).**

• **KM (Kobayashi-Maskawa) mechanism :**

3 generations ➔ 4 parameters: A, λ, ρ & 1 complex part η which phase is the unique source of CPV in SM.

The CKM Matrix : the unitary triangle & the very rich phenomenolgy of quark flavors

V_{CKM} =



➔4 paramters (A, λ, ρ & η) to be obtained/tested wrt data: nucleons, K, D, $B_{(s)}$ & top quark physics.

➔ unitarity relation in B_d system (1rst line/3rd column):

$$\boxed{\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} + 1 + \frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*} = 0 \\ O(1) + O(1) + O(1)}$$

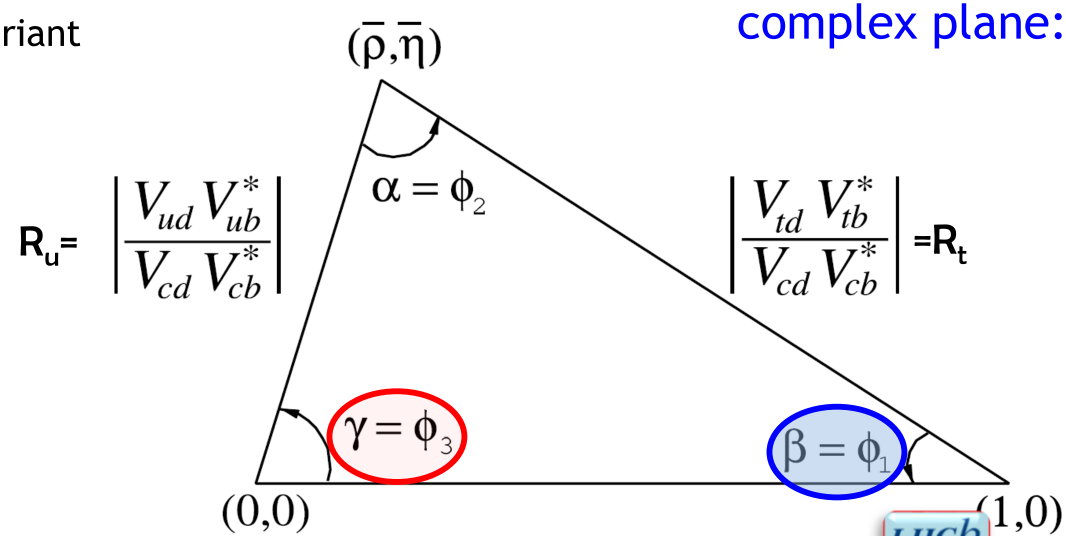
Parametrisation « à la Wolfenstein » phase invariant & valid at any orders in λ @ CKMfitter

(EPJ C41, 1-131, 2005) :

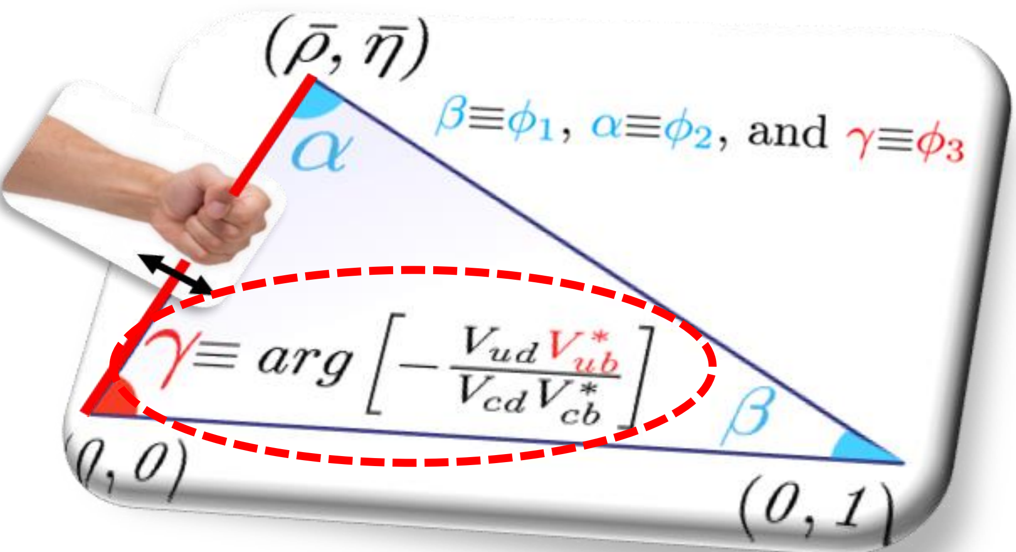
$$\bar\rho + i\bar\eta = -\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}$$

$$\lambda^2 = \frac{|V_{us}|^2}{|V_{ud}|^2 + |V_{us}|^2} \qquad A^2\lambda^4 = \frac{|V_{cb}|^2}{|V_{ud}|^2 + |V_{us}|^2}$$

Unitarity triangle in the ($\bar\rho$,$\bar\eta$) complex plane:



➔ The CKM angle γ is a fundamental parameter of the SM related to the complex phase in the KM mechanism responsible for CP violation in quark sector



Already 10 years ago after the B factories BaBar@SLAC and Belle@KEK we knew that

Kobayashi et Masakwa, Nobel prize of physics 2008

The KM mechanism is the main source of CPV at EW scale (i.e. @ $m_{W/Z)}$

➔ **So why do we still care about the CKM angle γ ?**

γ[combined@2008] = $(70^{+27}_{-29})^\circ$

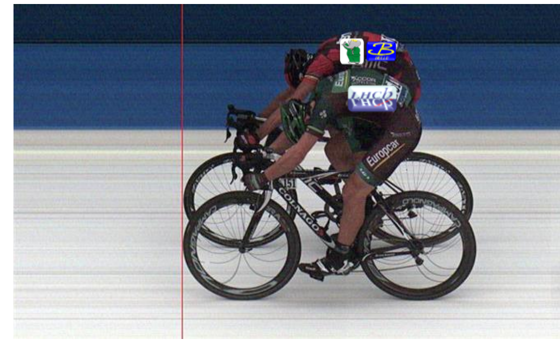
5 years after: the CKM angle γ after LHC run1 in 2013

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

➔ Astonishing/impressive overall consistency:

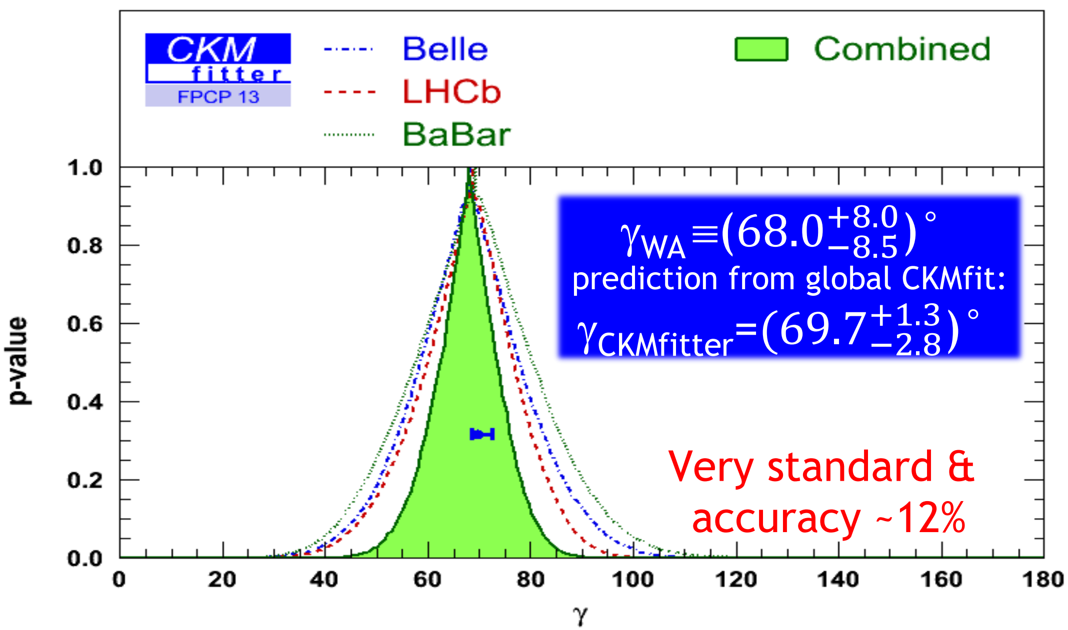
- $(69^{+17}_{-16})^\circ$ PRD 87(2013)052015
- $(68^{+15}_{-14})^\circ$ BELLE arXiv:1301.2033
- $(67 \pm 12)^\circ$ LHCb PLB 726(2013)151 LHCb-CONF-2013-006

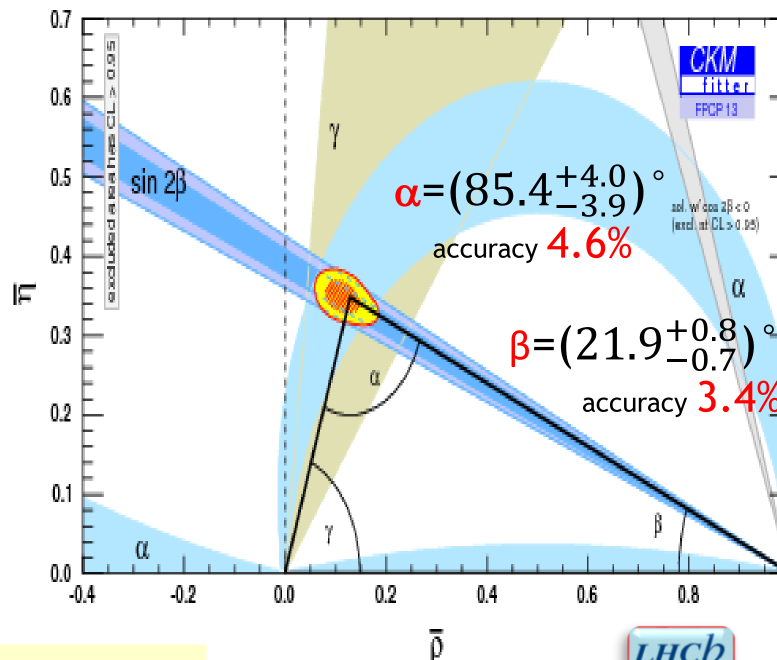
B-factories: $(67 \pm 11)^\circ$ PBF book



➔ Many DK like modes combined, observables are predictable!

➔ M. Karbach (RIP) : “We understand what we're doing!”





LHCb was already competitive with only 2 years of data taking !

The theoretical usefulness of measuring accurately the CKM angle γ in 2018 and beyond

Angle γ is the least well known CKM constraint (although now only just (i.e. similar to α)) and remains a unique CPV parameter:

- **SM benchmark or standard candle - only CKM angle accessible at tree level**

- **Determination form tree $B \to DK$ decay theoretically extremely clean :**

  [arXiv:1308.5663]

$$\boxed{\delta\gamma/\gamma \sim \mathcal{O}\left(10^{-7}\right)}$$

Only one caveat: New physics at tree level in Wilson coeff of interfering amplitudes C_1 and C_2 can cause sizeable (up to 5°) shifts in γ, however quite academic speculation, type of possible NP model very unclear and yet unmotivated [arXiv:1412.1446]

- **Probes NP scales extremely far beyond direct searches in ((N)M)FV NP scenarios:**

  [arXiv:1101.0134]

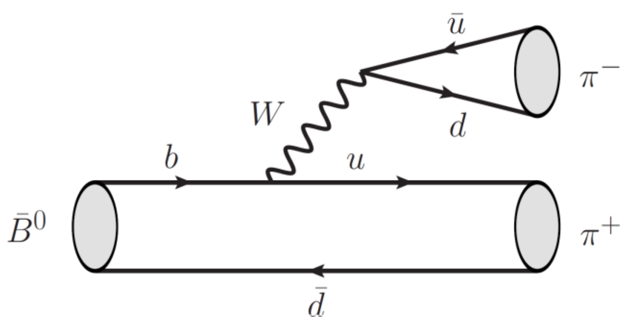
$$\boxed{\Lambda_{NP}^{\gamma} \sim \mathcal{O}\left(10^{3}\ \mathrm{TeV}\right)}$$

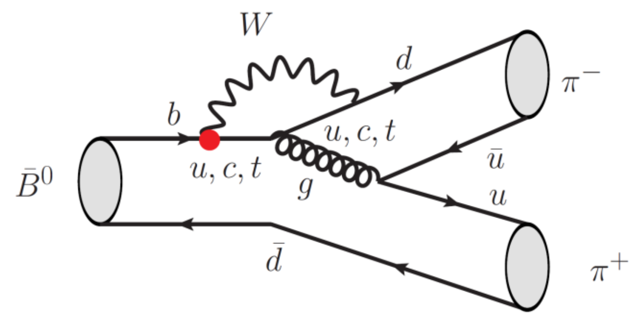
➔ **Use for "direct" vs "indirect" (i.e. "tree" vs "loop" processes) disagreement in global CKM fit consistency test :**

- Tree level decays test the SM and are robust to New Physics ("standard candle for the SM KM coherence tests"): ⊥ constraint to sin(2β), need ideally precision of about ~1° and below
- Loops (B to charmless decays) test for physics beyond the SM but require a clean measurement as input & precise understanding of theory assumptions (SU(3) breaking, U-spin…).

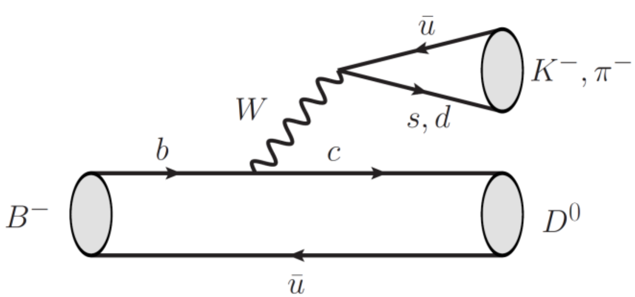
CKM angle γ in loops and trees

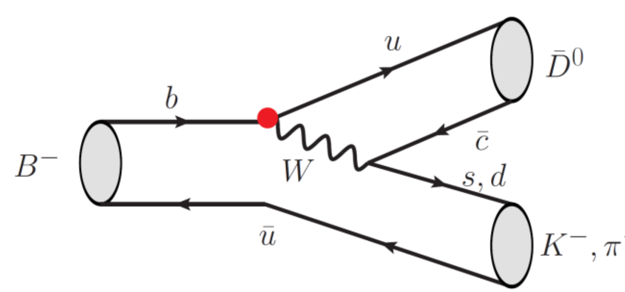
- From $B \to \pi\pi$ determine $\alpha = \pi - \beta - \gamma$ [Gronau, London 1990]
- Use $B \to \pi\pi$ and $B_s \to KK$ to extract γ [Fleischer 1999]





- Compare to γ from tree-level $B \to DK$ [Bigi, Sanda 1981]

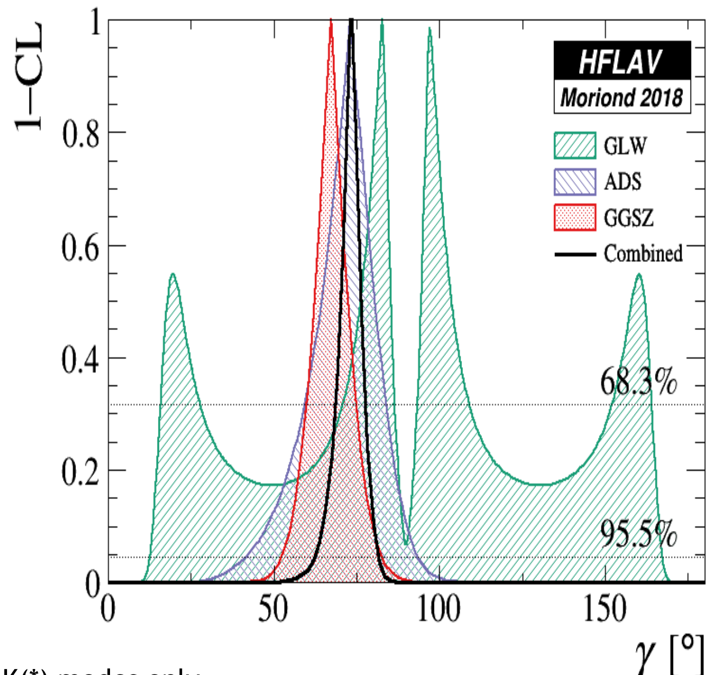


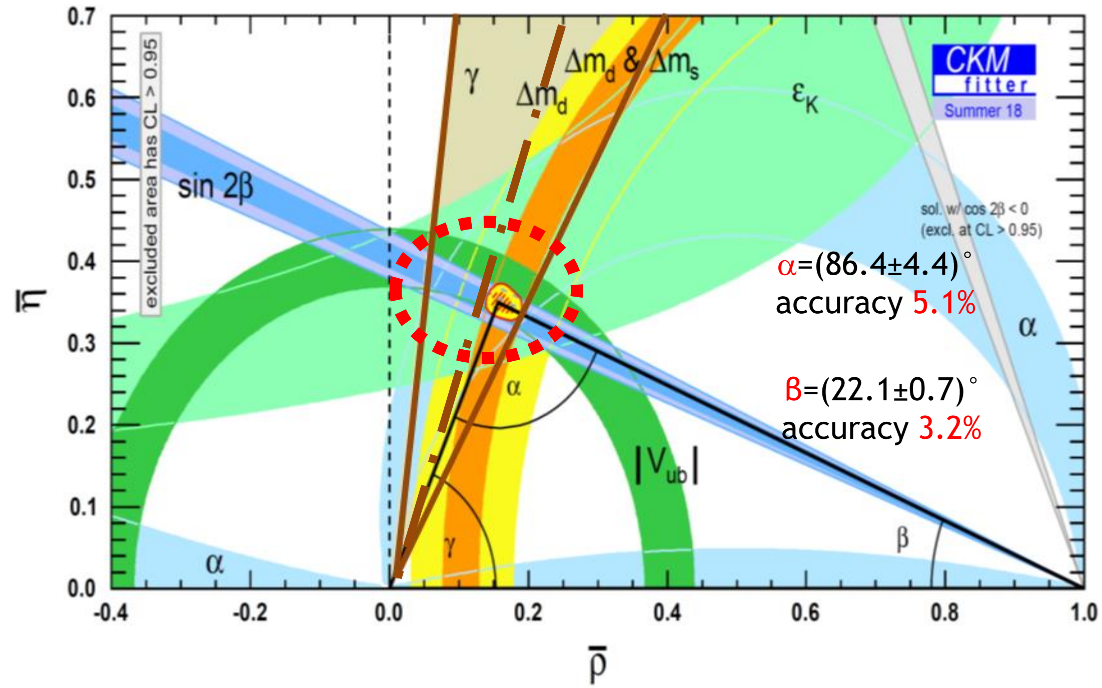


I will come back later on it…

The early 2018 state of play

The current world average (HFLAV), LHCb combination and indirect determination (CKMfitter) on γ





D(*)K(*) modes only

$\gamma_{WA}=(73.5^{+4.2}_{-5.1})°$ $\gamma_{LHCb}=(75.8^{+5.1}_{-5.7})°$ $\gamma_{CKMfitter}=(65.6^{+1.0}_{-3.4})°$

LHCb dominates WA

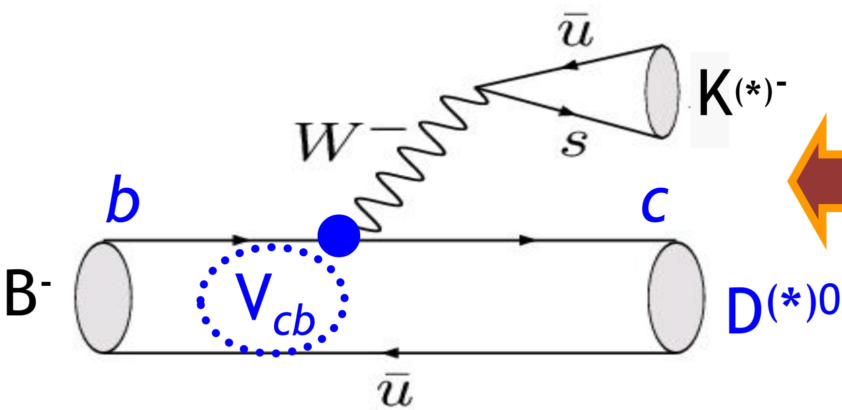
We entered yet the sub 5° (6%) precision era ➔ but still not enough!

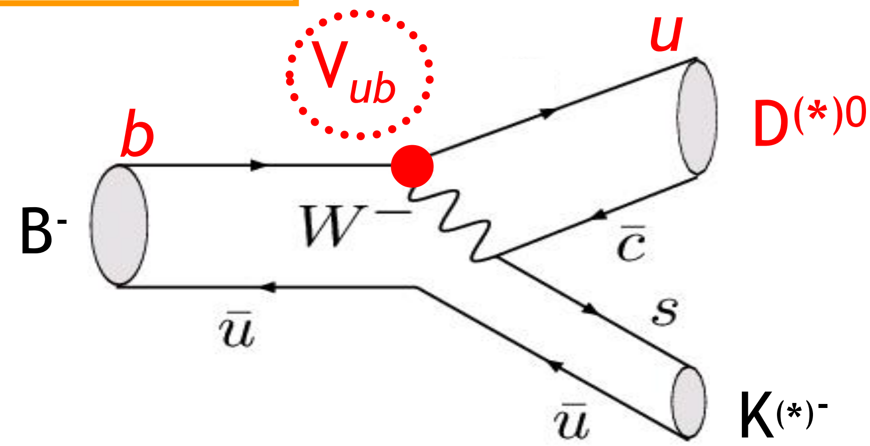
1.5σ shift / WA
Need to measure at < 1° accuracy
➔ test Λ_{NP}>17 TeV (model indep.)

[arXiv:1309.2293]

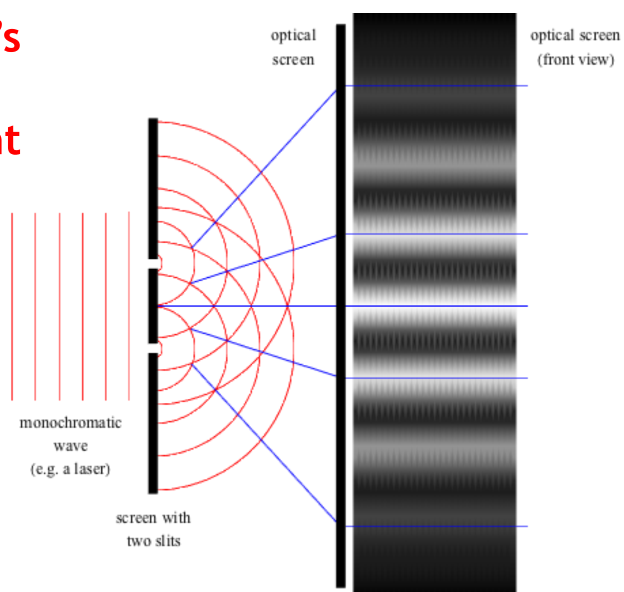
γ in $B^- \to \tilde{D}^{(*)0} K^{(*)-}$

Same final state $\tilde{D}^0 \equiv [D^0 / \bar{D}^0]$





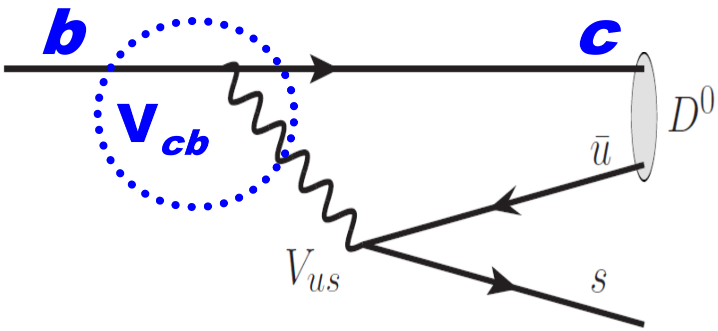
See Young's double slit experiment

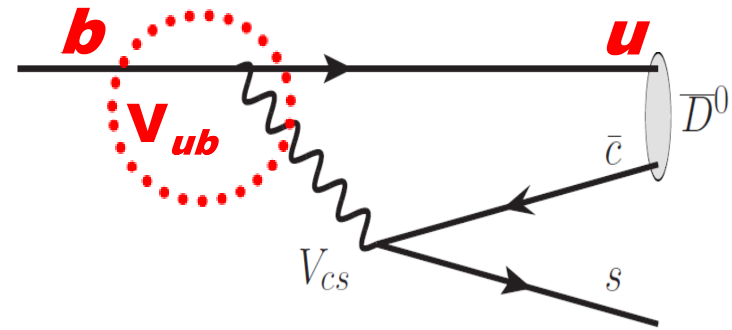


$$\gamma \equiv arg\left[-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right]$$

Obtaining γ : use interference between $b \to c\bar{u}s$ and $b \to u\bar{c}s$

Gronau, Wyler (91); Gronau, London (90)





$\boxed{A_{cb} \propto \lambda^3}$

$\boxed{A_{ub} \propto \lambda^3 \sqrt{\bar{\eta}^2 + \bar{\rho}^2}\, e^{i(\delta_B - \gamma)}}$

relative strong & weak phases

➔ Take any spectator(s) you like. Color-allowed diagrams are also possible for certain spectators. For color-suppressed V_{ub} decays:

$\boxed{A_{tot} = A + A}$

CPV asymmetry size depends upon the critical parameter :

$r_B \equiv |A/A| \sim 5\text{-}30\%$ color/Cabibbo suppression

PLB 557(2003)198

if r_B small ⇒ small experim. sensitivity to γ (precision as $1/r_B$)

same $D \equiv [\, D^0/\overline{D}^0 \,]$ final state

➔ Experimentally unfold γ, δ_B, and r_B from ratios of BFs and B vs $\overline{B}$ asymmetries observables

➔ Hadronic nuisance parameters can be determined from data directly of from external inputs

Experimental aspects of γ measurements

➔ **measuring γ at tree level is difficult** (typical BFs $<10^{-6}$ and less, reconst. & selection efficiencies below %):

- <u>STATISTICS is THE NAME OF THE GAME</u> $\Rightarrow$ **efficient detection/selection/ PID/ tracking/vertexing and even neutrals**

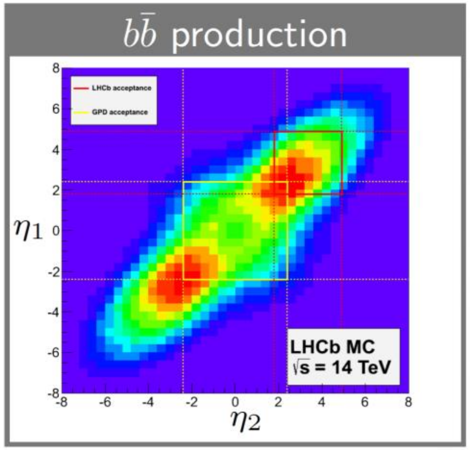
- **combining many measurements/methods + inputs** from charm factories (D parameters + mixing & CPV)

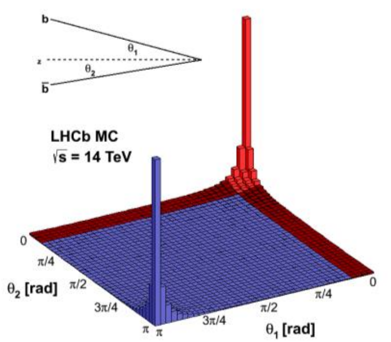
➔ **Many methods/modes to combine for optimal & redundant determination of γ** (and rigorous statistical treatment possibly matters !)

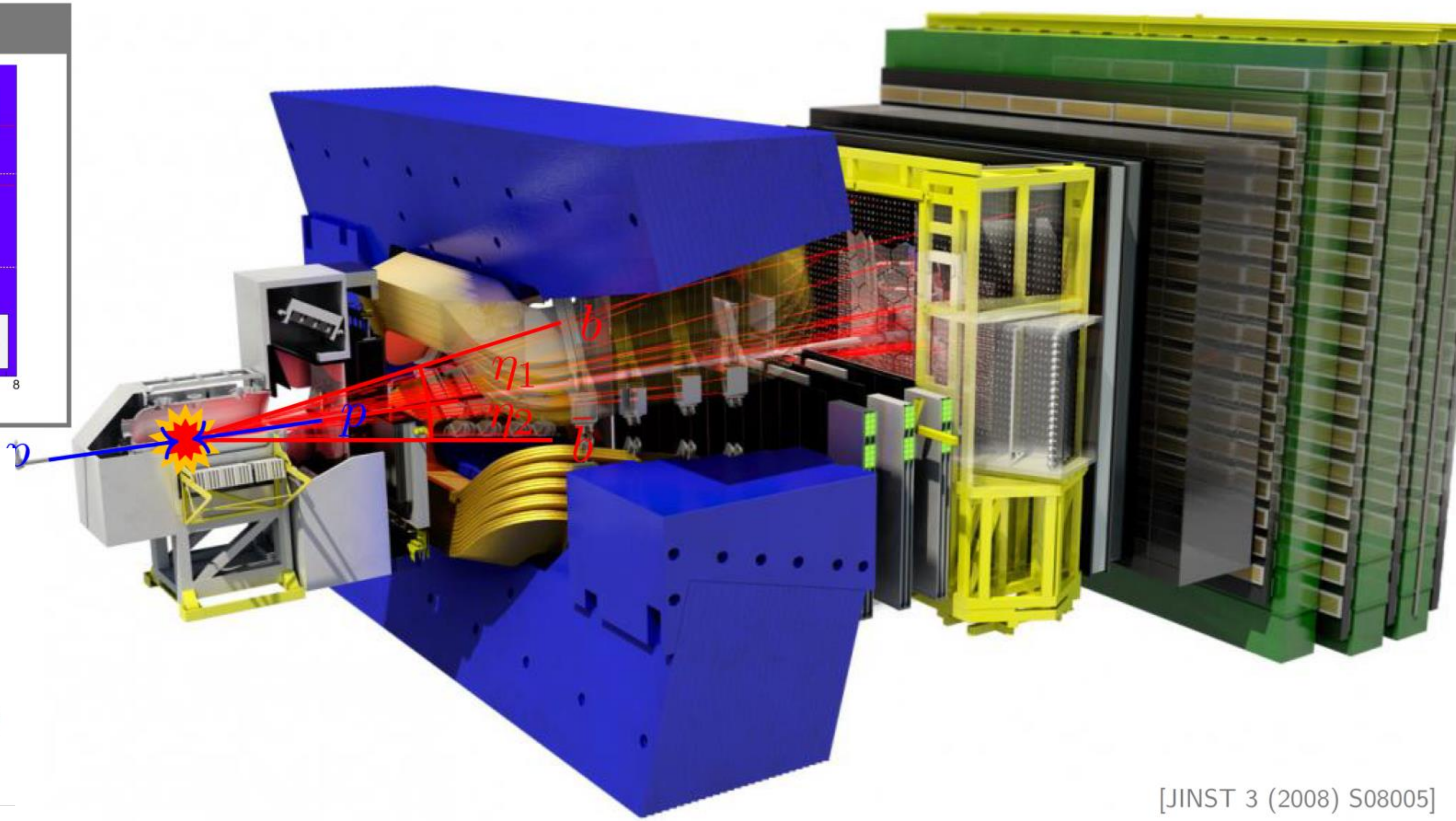
➔ **various charmed modes in B^0, B^+, B^0_s, Λ^0_b, B^+_c decays are useful to understand/confirm possible sensitivity to BSM physics and its nature**

The LHCb experiment at LHC is designed to accomplish all of the above !

LHCb: Optimized for precision flavour measurements







[JINST 3 (2008) S08005]
[IJMPA 30 (2015) 1530022]

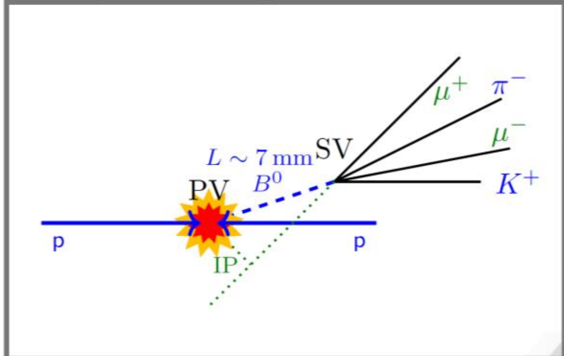
- $b\bar{b}$ produced in forward/backward direction → Optimized acceptance $2 < \eta < 5$
- Huge production cross-sections in LHCb acceptance
  1.4×10^{11} $b\bar{b}$-pairs per fb^{-1} (Run 2)
- All beauty, charm and strange hadrons produced

  B^0_s, Λ^0_b, B_c^+, D_s^+, Λ_c^+, Σ, Ξ, ...

	$\sqrt{s} = 7$ TeV	$\sqrt{s} = 13$ TeV
$\sigma^{\text{acc.}}_{b\bar{b}}$ [μb]	75.3 ± 14.1	$144 \pm 1 \pm 21$
$\sigma^{\text{acc.}}_{c\bar{c}}$ [μb]	1419 ± 134	2940 ± 241
Refs.	[PLB 694:209 (2010)] [NPB 871 (2013) 1-20]	[PRL 118 (2017) 052002] [JHEP 03 (2016) 159]

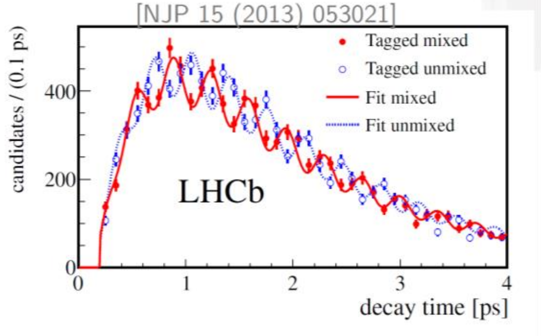
LHCb: Optimized for precision flavour measurements

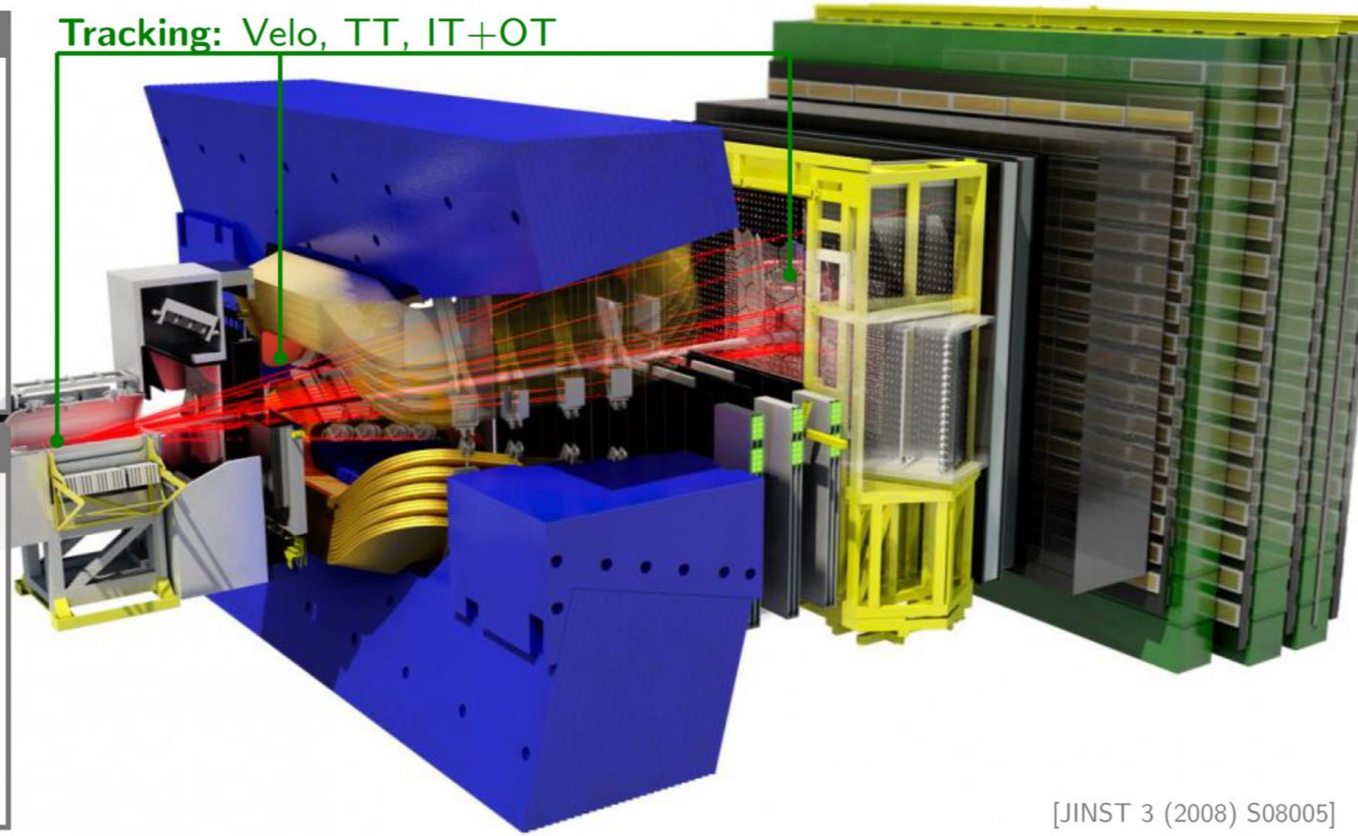
Heavy flavour signature



B_s^0 mixing

[NJP 15 (2013) 053021]



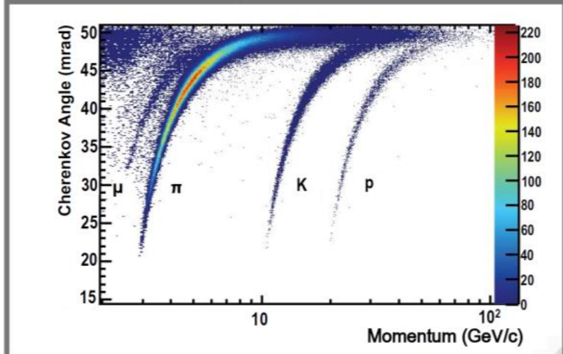


[JINST 3 (2008) S08005]
[IJMPA 30 (2015) 1530022]

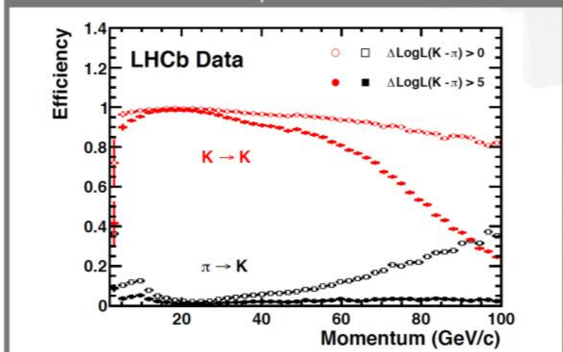
- Excellent IP resolution $\sim 20\,\mu\mathrm{m}$ to identify B decay vertices
- Decay time resolution $\sim 45\,\mathrm{fs}$
- Resolutions $\sigma(p)/p = 0.5 - 1\%$, $\sigma(m) \sim 22\,\mathrm{MeV}$ for two-body B-decays
  $\rightarrow$ Low combinatorial backgrounds

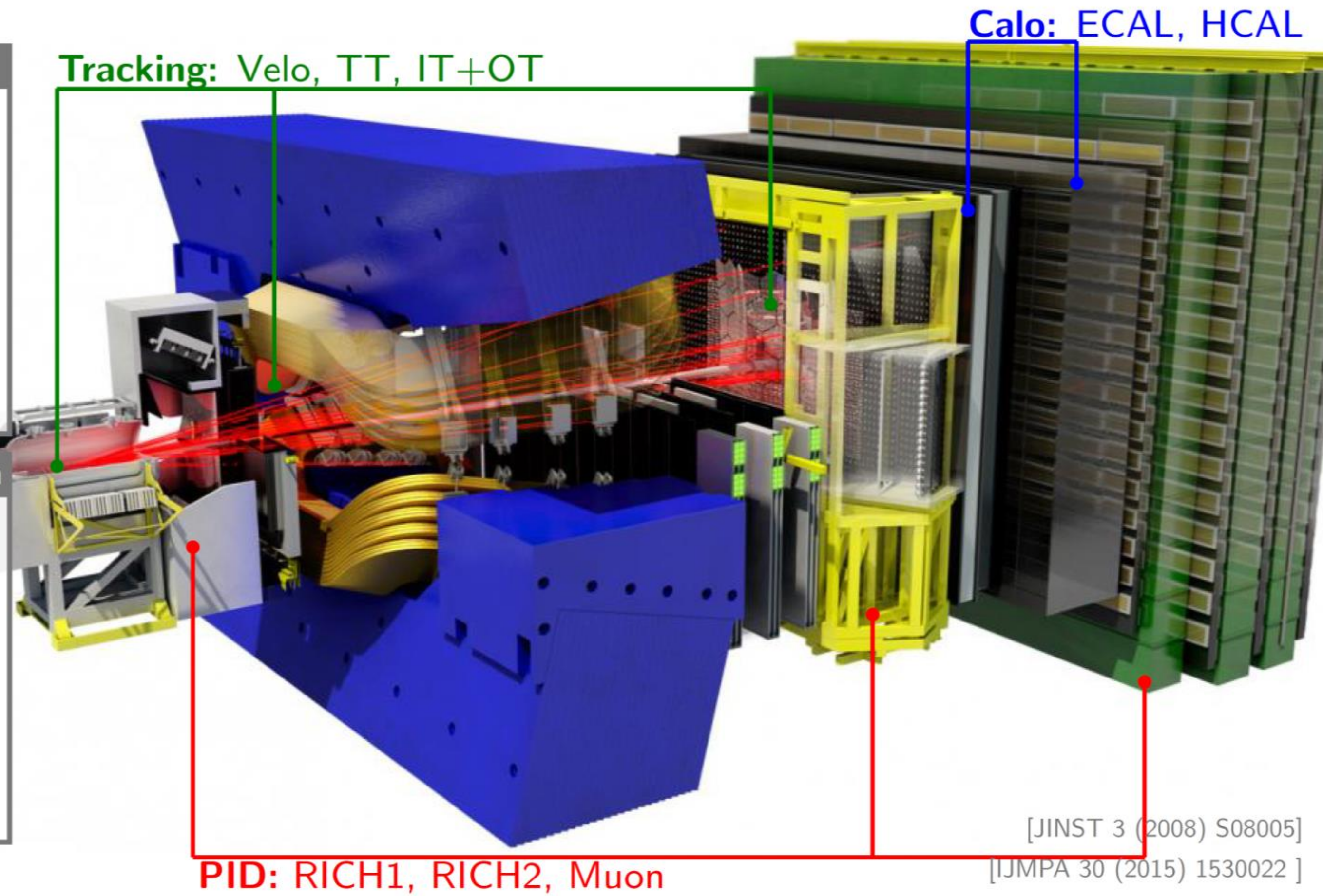
LHCb: Optimized for precision flavour measurements

Cherenkov angle *vs.* momentum



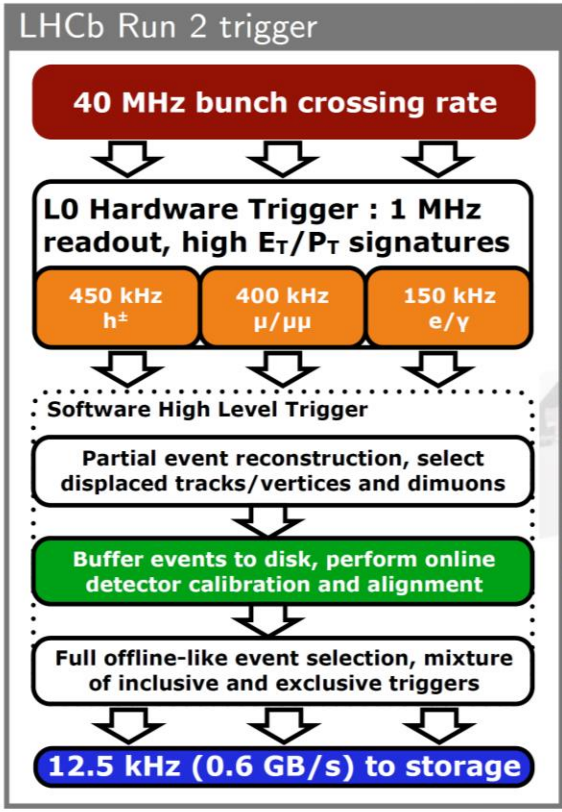
K identification/π misidentification

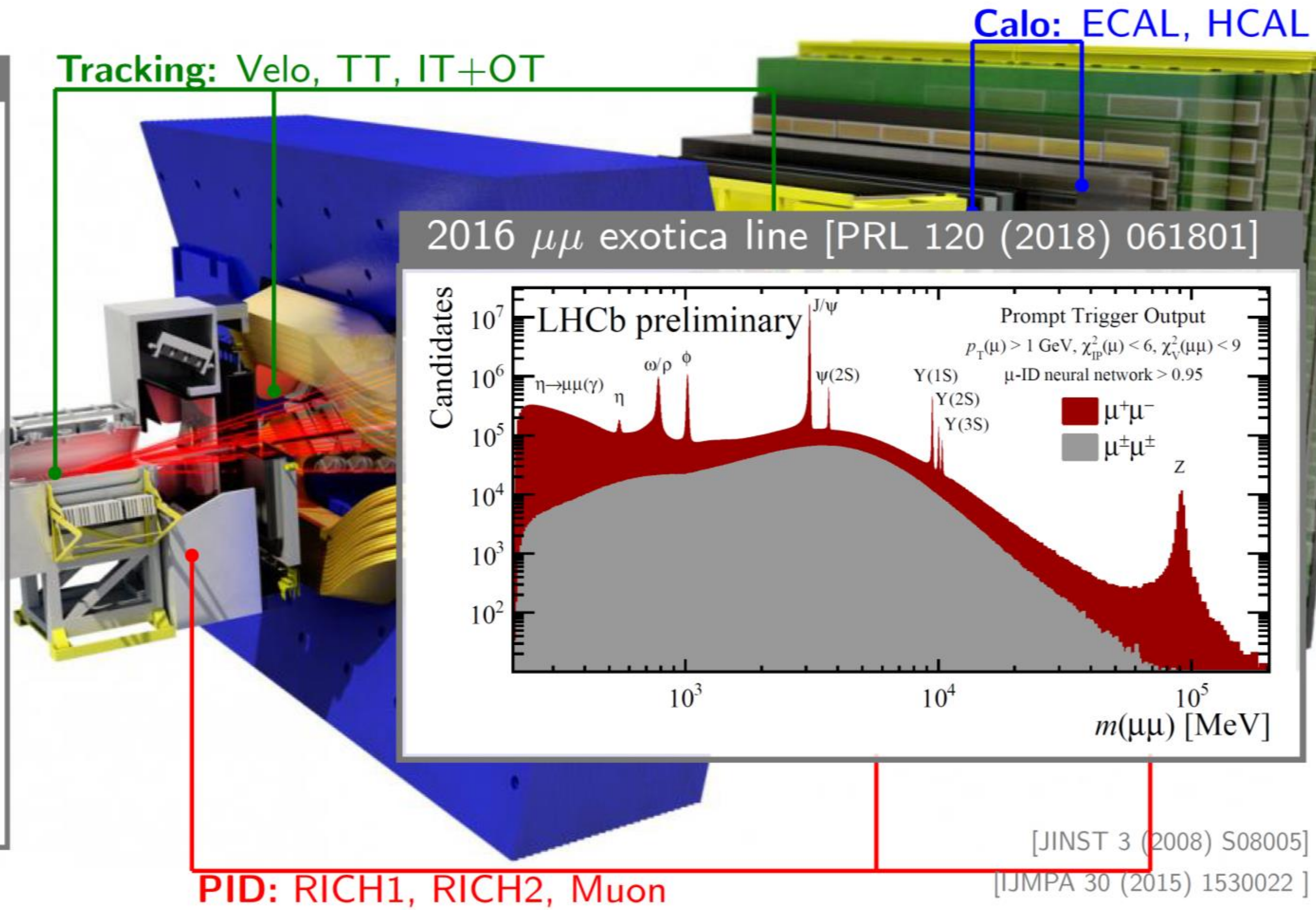




- Excellent particle identification through RICH detectors and muon system
- High identification efficiencies $\epsilon_{K\to K} \sim 95\%$, $\epsilon_{\mu\to\mu} \sim 97\%$
- Low misidentification probabilities $\epsilon_{\pi\to K} \sim 5\%$, $\epsilon_{\pi\to\mu} \sim 1-3\%$
  $\to$ Low backgrounds from misidentification

LHCb: Optimized for precision flavour measurements

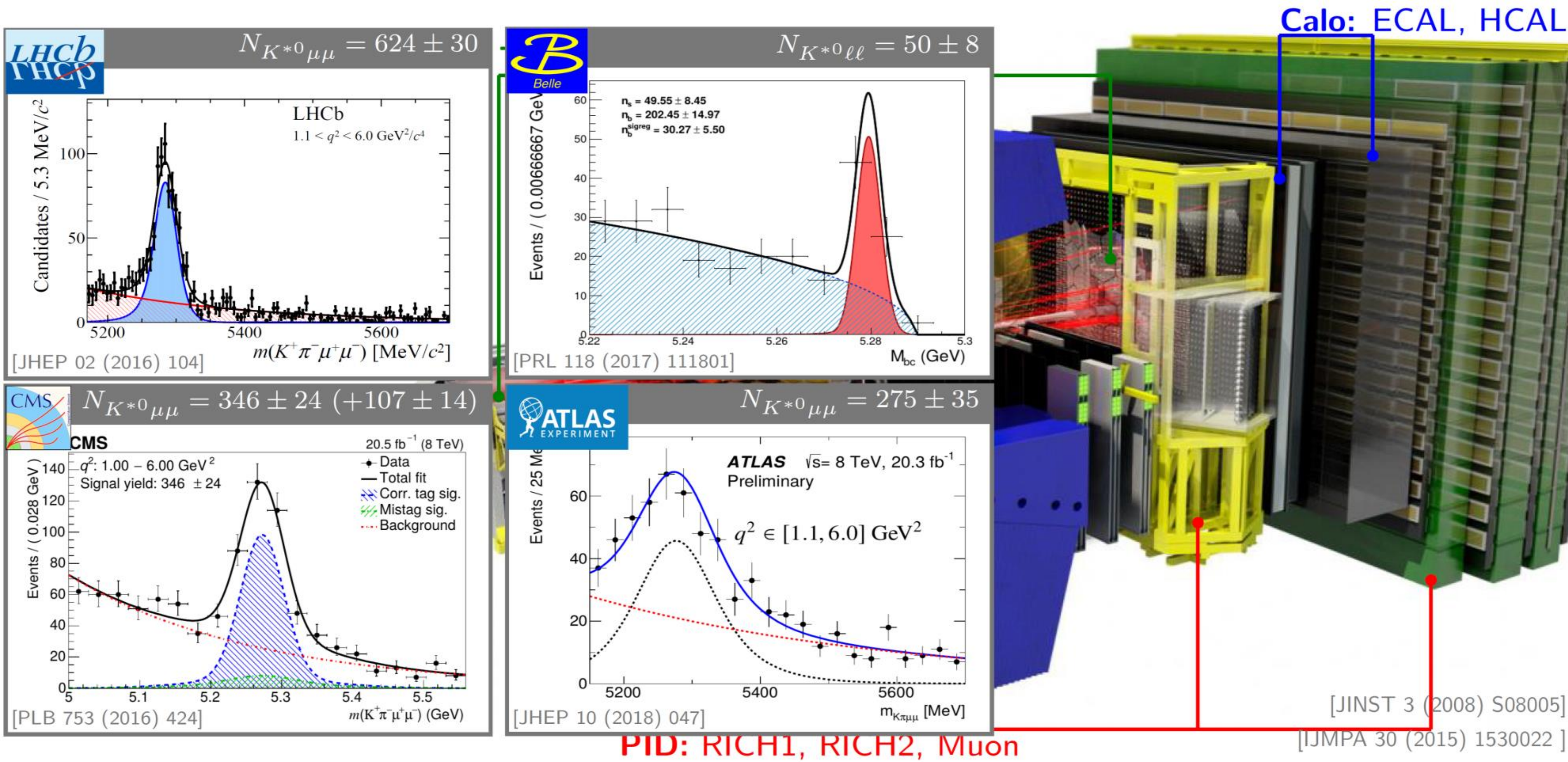




- Flexible trigger system with low thresholds: $p_T(\mu) > 1.8\,\text{GeV}$, $E_T(e) > 3.0\,\text{GeV}$
- High efficiencies, *e.g.* $\epsilon_{\text{trigger}}(B \to J/\psi\, X) \sim 90\%$
- Since Run 2: Online calibration and alignment, allows use of PID in trigger
- Allows low p_T physics: charm, strange, exotica, . . .

➔ L0 HW trigger to be removed during LHC LS2

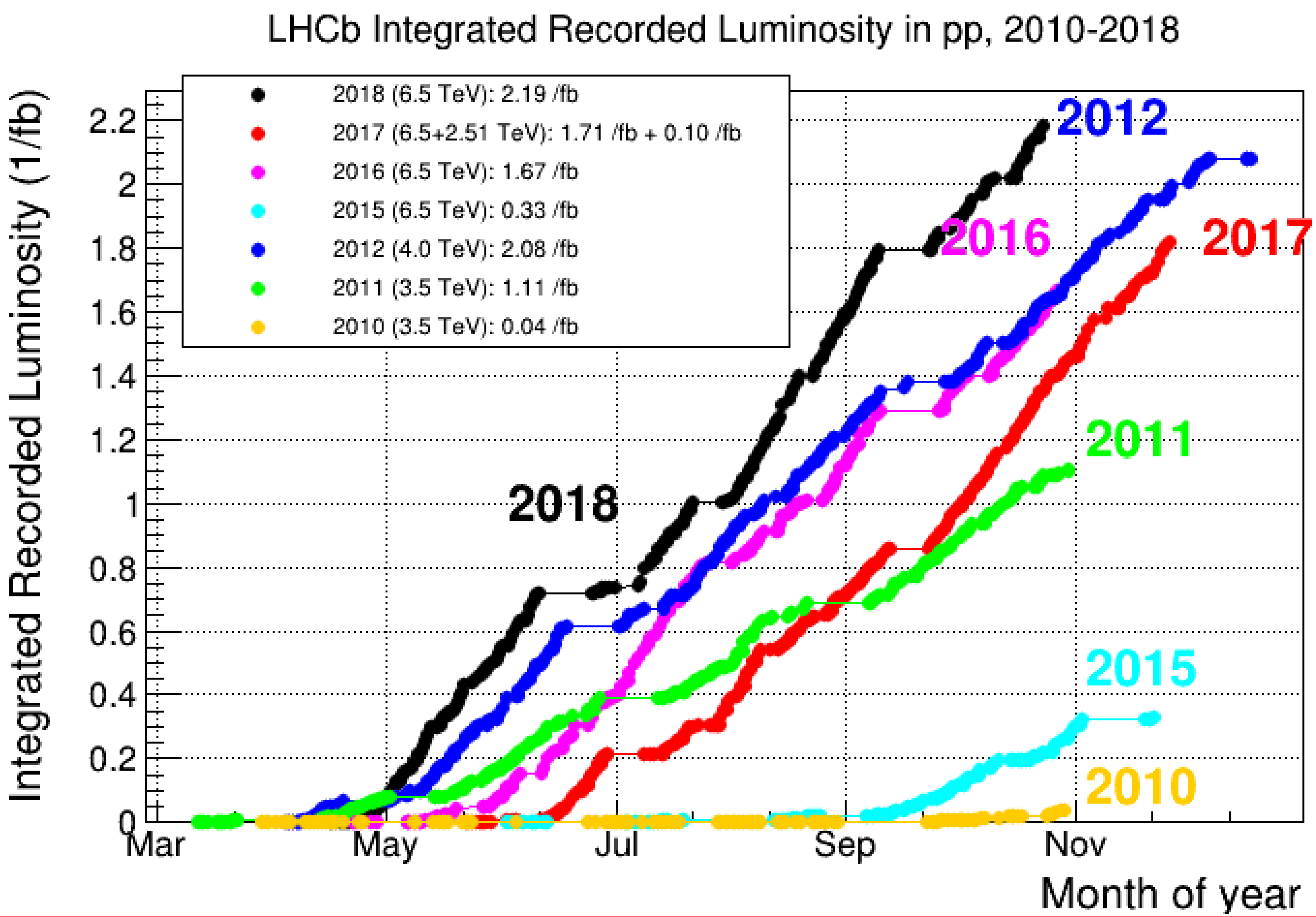
LHCb: Optimized for precision flavour measurements



- Performance comparison using $B^0 \to K^{*0}\mu^+\mu^-$ Run 1 results as example
- LHCb compares very favourably
  - Largest yields ($b\bar{b}$ cross-section, large acceptance and high trigger efficiencies)
  - Excellent mass resolution and low combinatorial backgrounds
  - Negligible peaking backgrounds due to powerful particle identification

LHCb: so far accumulated statistics in LHC Run 1&2

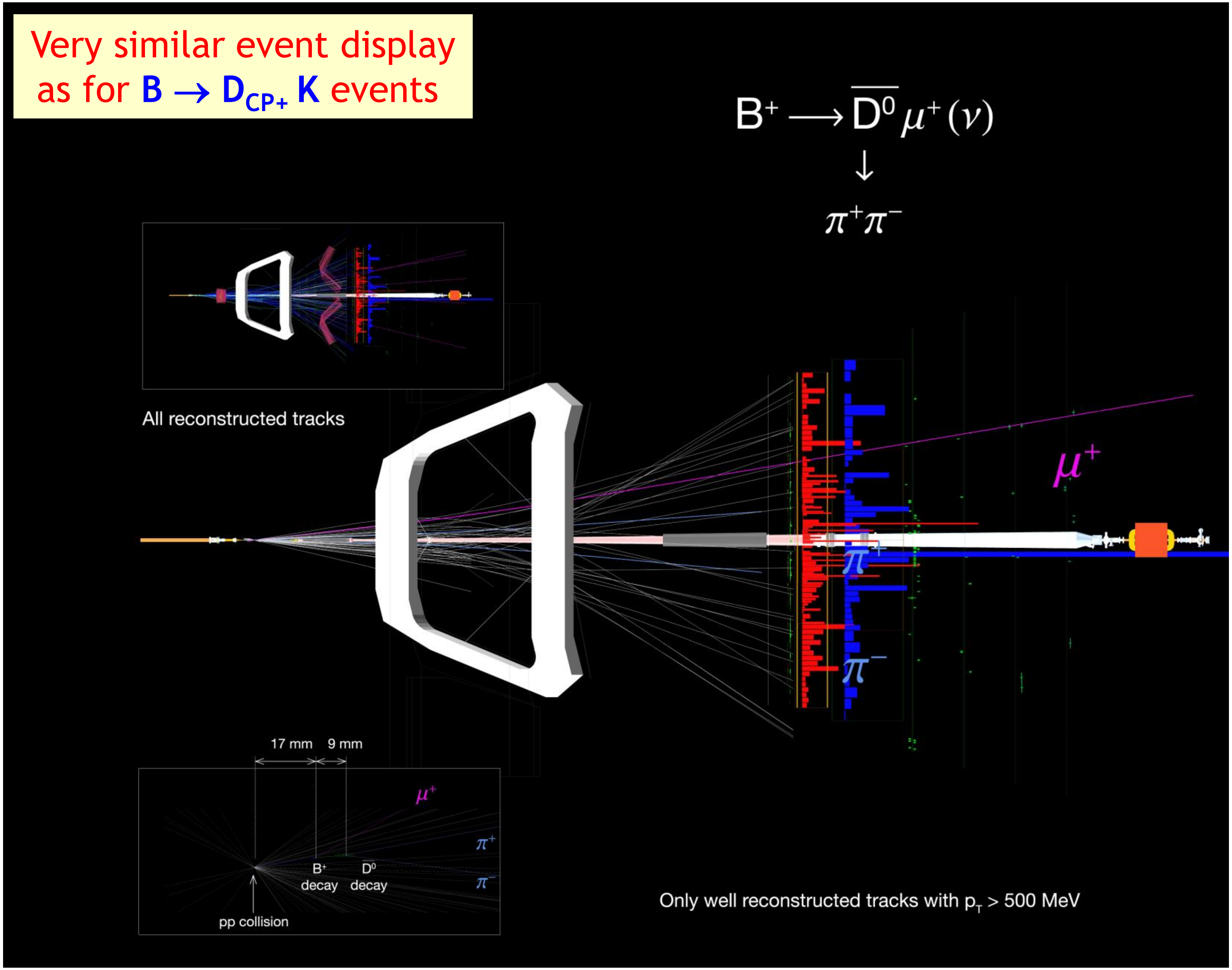
- Instantaneous luminosity was from 3.3 to 4.4 x 10^{32} $cm^{-2}.s^{-1}$
- the heavy-flavour cross-section is ~twice at 13 TeV compared to 7 TeV



- Most published results use part of LHC Run 1 (<2013) + Run 2 (>2014) data
- Total number of b-hadrons is Run 1+Run 2 is about 5 times that of Run 1

LHCb: Optimized for precision flavour measurements

Very similar event display as for $B \rightarrow D_{CP+} K$ events

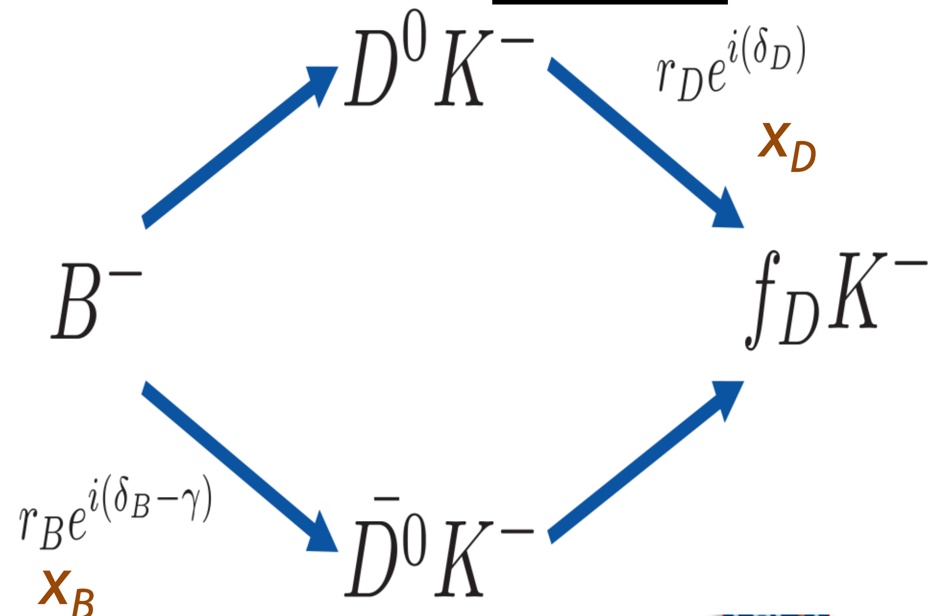


Experimental aspects of γ measurements

- Theoretically straightforward, experimentally more challenging
  - Branching fractions (~10^{-7}) and interference effects tend to be small (~10%)
  - Triggering on fully hadronic final states is not trivial (LHCb Trigger upgrade after LHCb LS2)
  - Many decay modes feature K_S^0 or π^0 mesons - lower efficiencies at LHCb
  - Statistically challenging - many decay modes, observables and hadronic parameters
  - External inputs required for several beauty and charm parameters

CLEO-c HFLAV BESIII

- The golden mode $B^- \to DK^-$
  - Sensitivity from interference of $b \to c$ and $b \to u$ amplitudes
  - Weak phase difference γ the same for all D meson decay final states



Measuring γ : several methods and approaches depending on the D meson decays

➔ Time-integrated "well known" methods that need a lot of B mesons

➔ counting direct CPV, N(B) vs N($\bar{B}$):

- **GLW:** D≡CP-eigenstate: many modes, but small asymmetry. PLB253(1991)483; PLB265(1991)172
- **ADS:** D≡Doubly-Cabibbo suppressed decays (DCS) $D^0 \to K^+\pi^-$ OS to B^- decays: large asymmetry, but very few events. PRL78(1997)3257; PRD63(2001)036005
- **GGSZ:** D≡Dalitz: better than a mixture of ADS+GLW ⇒ large asymmetry in some regions, but strong phases varying other the Dalitz plane (model dep. vs indep.) PRL78(1997)3257; PRD68(2003)054018
- **GLS** (Grossman-Ligeti-Soffer): "Less well known" ADS variant D≡Singly-Cabibbo suppressed decays (SCSD) both OS and SS decays comparable in size ⇒ 4 amplitudes: 3-body $KK^0_S\pi$ dominated by coherent KK* PRD-RC 67(2003)071301 GLS

➔ Largest effects due to:

- Charm mixing
- Charm CPV

Can't be ignored/neglected any more with improved sensitivity (especially for Dπ). Ways exist to account for it, when unfolding γ from modified observables (was PRD-RC72(2005)031501; PRD 67(2003)071301; PLB 649(2007)61; PRD82(2010)034033). A lot of papers + HFAG: PRD89(2014)014021; PRD 87 (2013)074002; EPJC73(2013)2476; PRD87(2013)034005; PRL 110(2013)061802 …

➔ Different B-decays (DK, D*K, DK*…) ⇒different hadronic nuisance factors (r_B, δ_B) for each

➔ Many more modes explored at LHCb and B-factories (see next slide)

Measuring γ : some other methods/examples (non-exhaustive list)

- **Many-body B final states:**
  - $B^+ \to DK^+\pi^0$, $B^+ \to DK^+\pi^+\pi^-$, $B^0 \to D\pi^- K^+$, $DK_s\pi$
  - $B_s \to DK^+K^-$

Aleksan, Petersen, Soffer (02), Gershon (08), Gershon, Williams (09), Gershon, Poluektov (09, 10), Gronau, London (91), Gronau et al. (04, 07), London, Nandi (12)

- **Use D^{*0} in addition to D^0** Bondar, Gershon (04)
- Use self tagging D^{0**}, D^{2*-} Sinha (04), Gershon (08)
- **Use DK^*& also $DK^*_{0,2}$** Wang (11)

- **Other neutral B decays:**
  - **time dependent CPV (i.e. tagging & vertexing) :** B_s $(\bar{B}_s) \to D_s^{\mp} K^{\pm}$ or $D_s^{\mp} K^{\pm}\pi\pi$ $(\sin(2\beta_s+\gamma))$ or B_d $(\bar{B}_d) \to D^{(*)\mp}\rho^{\pm}/\pi^{\pm}$ $(\sin(2\beta+\gamma))$
  - **time-integrated, self-tag:** $B_d \to DK^{*0}$

Aleksan, Dunietz, Kayser(92), Kayser, London (00), Atwood, Soni (03), Fleischer(03), Gronau et al. (04)

- **Use beauty baryons:** $\Lambda^0_b \to DpK^-$

- **Use other b-hadrons:** $B^+_c \to D^+_s D$ & $B_s \to D^{(*)0}\phi$

Measuring γ : what LHCb actually has published

Latest update is LHCb-CONF-2018-002 (ICHEP18) last was for EPS 2017

In Feb 2018 Joint BESIII-LHCb workshop in IHEP

B decay	D decay	Method	Ref.	Dataset†	Status since last combination [3]
$B^+ \to DK^+$	$D \to h^+h^-$	GLW	[14]	Run 1 & 2	Minor update
$B^+ \to DK^+$	$D \to h^+h^-$	ADS	[15]	Run 1	As before
$B^+ \to DK^+$	$D \to h^+\pi^-\pi^+\pi^-$	GLW/ADS	[15]	Run 1	As before
$B^+ \to DK^+$	$D \to h^+h^-\pi^0$	GLW/ADS	[16]	Run 1	As before
$B^+ \to DK^+$	$D \to K^0_S h^+h^-$	GGSZ	[17]	Run 1	As before
$B^+ \to DK^+$	$D \to K^0_S h^+h^-$	GGSZ	[18]	Run 2	New
$B^+ \to DK^+$	$D \to K^0_S K^+\pi^-$	GLS	[19]	Run 1	As before
$B^+ \to D^*K^+$	$D \to h^+h^-$	GLW	[14]	Run 1 & 2	Minor update
$B^+ \to DK^{*+}$	$D \to h^+h^-$	GLW/ADS	[20]	Run 1 & 2	Updated results
$B^+ \to DK^{*+}$	$D \to h^+\pi^-\pi^+\pi^-$	GLW/ADS	[20]	Run 1 & 2	New
$B^+ \to DK^+\pi^+\pi^-$	$D \to h^+h^-$	GLW/ADS	[21]	Run 1	As before
$B^0 \to DK^{*0}$	$D \to K^+\pi^-$	ADS	[22]	Run 1	As before
$B^0 \to DK^+\pi^-$	$D \to h^+h^-$	GLW-Dalitz	[23]	Run 1	As before
$B^0 \to DK^{*0}$	$D \to K^0_S\pi^+\pi^-$	GGSZ	[24]	Run 1	As before
$B^0_s \to D_s^{\mp}K^{\pm}$	$D_s^+ \to h^+h^-\pi^+$	TD	[25]	Run 1	Updated results
$B^0 \to D^{\mp}\pi^{\pm}$	$D^+ \to K^+\pi^-\pi^+$	TD	[26]	Run 1	New

† Run 1 corresponds to an integrated luminosity of 3 fb^{-1} taken at centre-of-mass energies of 7 and 8 TeV. Run 2 corresponds to an integrated luminosity of 2 fb^{-1} taken at a centre-of-mass energy of 13 TeV.

98 observables, 40 free params.

[15] PLB **760** (2016) 117

[16] PRD **91** (2016) 112014

[17] JHEP **10** (2014) 097

[19] PLB **773** (2014) 36

[20] JHEP **11** (2017) 156

[21] PRD **92** (2015) 112005

[22] PRD **90** (2014) 112002

[23] PRD **93** (2016) 112018

[24] JHEP **08** (2016) 137

[25] JHEP **03** (2018) 059

[26] LHCb-PAPER-2018-009

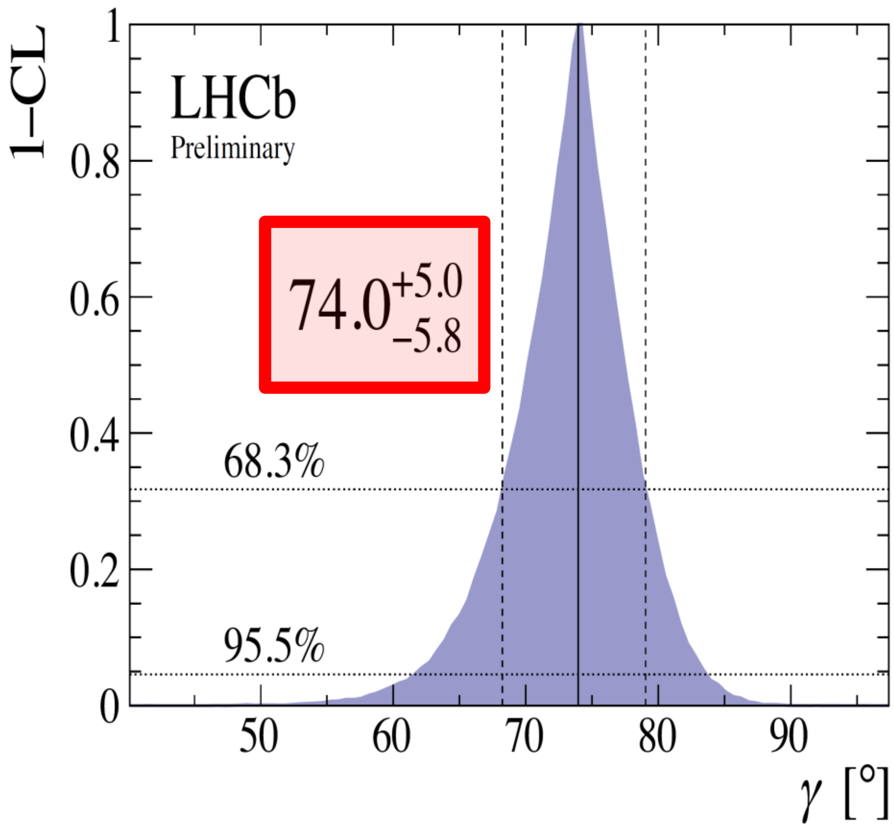
Most are Run1 based or partial Run2, many more to come soon.

Measuring γ : the latest LHCb average

Latest update is LHCb-CONF-2018-002 (ICHEP18) last was for EPS 2018
In Feb 2018 Joint BESIII-LHCb workshop in IHEP

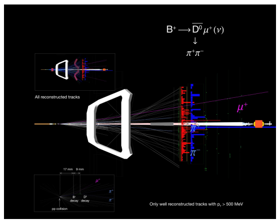
- We now have 98 observables and 40 free parameters

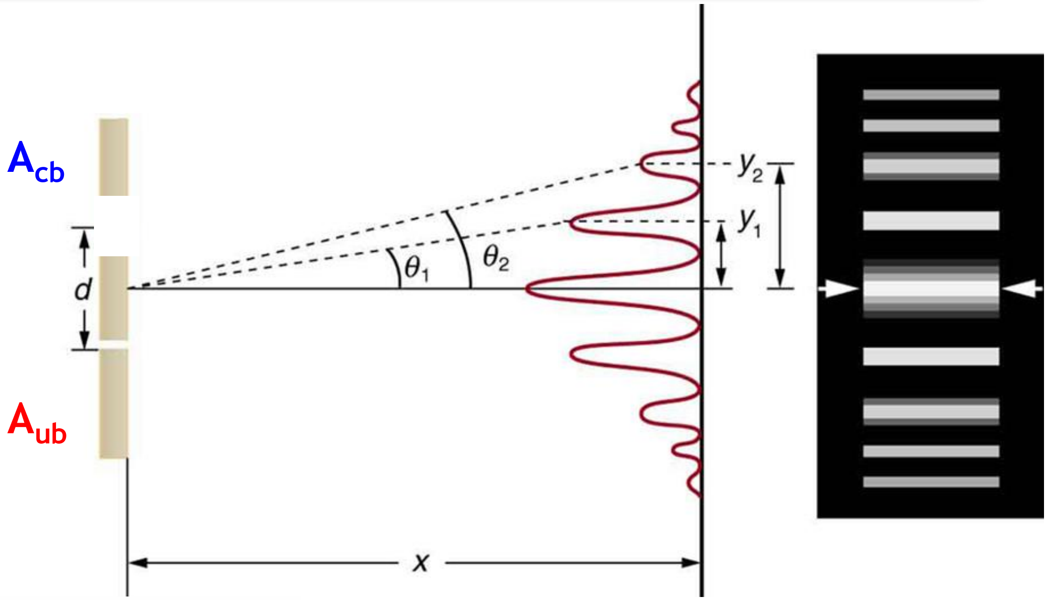
[LHCb-CONF-2018-002]

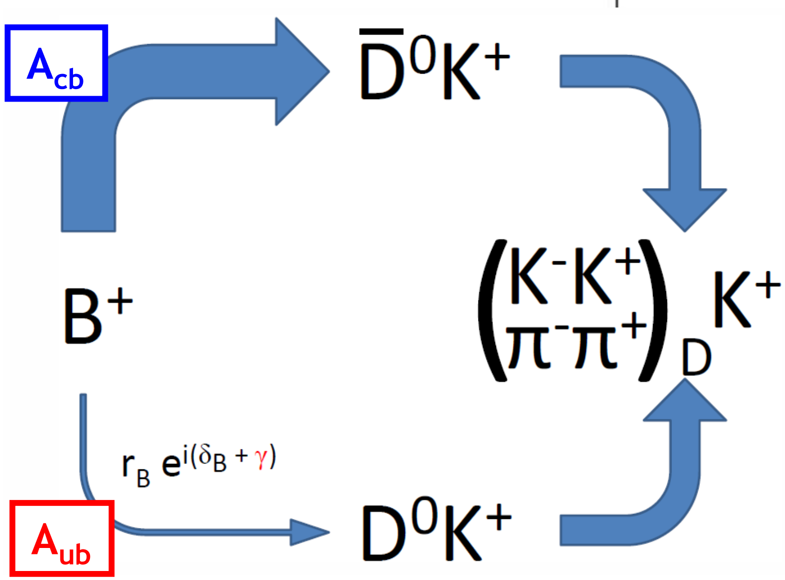


Quantity	Value	68.3% CL	95.5% CL
γ [°]	74.0	[68.2, 79.0]	[61.6, 83.7]
r_B^{DK}	0.0989	[0.0939, 0.1040]	[0.0891, 0.1087]
δ_B^{DK} [°]	131.2	[125.3, 136.3]	[118.3, 140.9]
$r_B^{D^*K^+}$	0.191	[0.153, 0.236]	[0.121, 0.287]
$\delta_B^{D^*K^+}$ [°]	331.6	[321.4, 339.8]	[309, 346]
$r_B^{DK^{*+}}$	0.092	[0.059, 0.110]	[0.034, 0.126]
$\delta_B^{DK^{*+}}$ [°]	40	[20, 132]	[5, 155]
$r_B^{DK^{*0}}$	0.221	[0.174, 0.265]	[0.123, 0.309]
$\delta_B^{DK^{*0}}$ [°]	187	[167, 210]	[148, 239]
$r_B^{DK\pi\pi}$	0.081	[0.054, 0.106]	[0.000, 0.125]
$\delta_B^{DK\pi\pi}$ [°]	351.4	[314.0, 359.8]	[180, 360]
$r_B^{D_s^{\mp}K^{\pm}}$	0.301	[0.215, 0.391]	[0.14, 0.49]
$\delta_B^{D_s^{\mp}K^{\pm}}$ [°]	355	[339, 372]	[321, 390]
$\delta_B^{D^{\mp}\pi^{\pm}}$ [°]	17	[0, 46]	[0, 76]

Measuring γ : GLW D(*)K

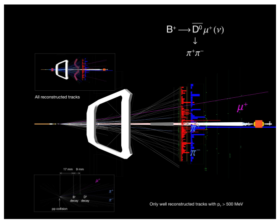


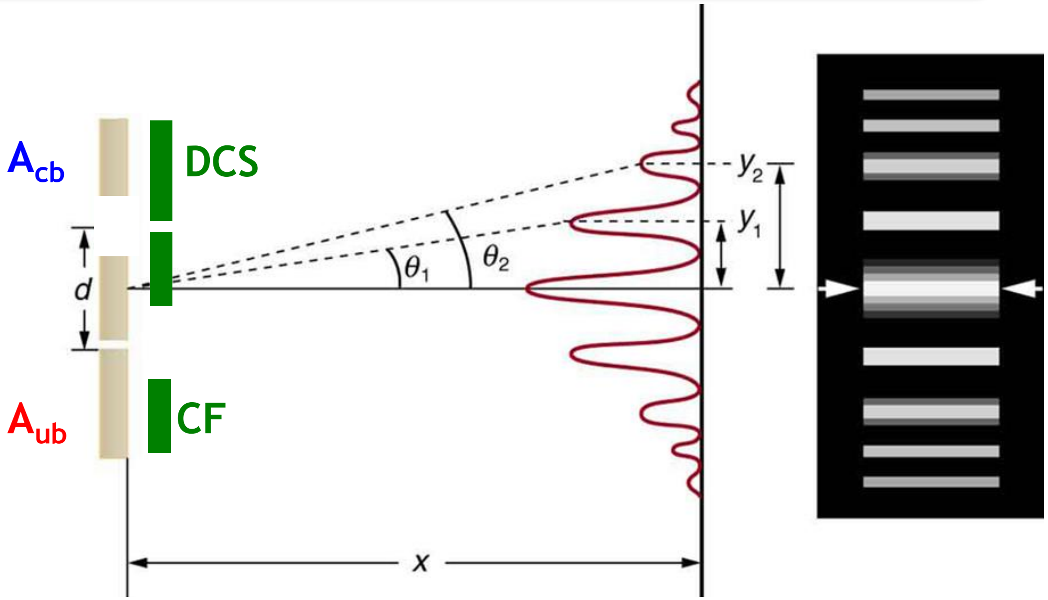


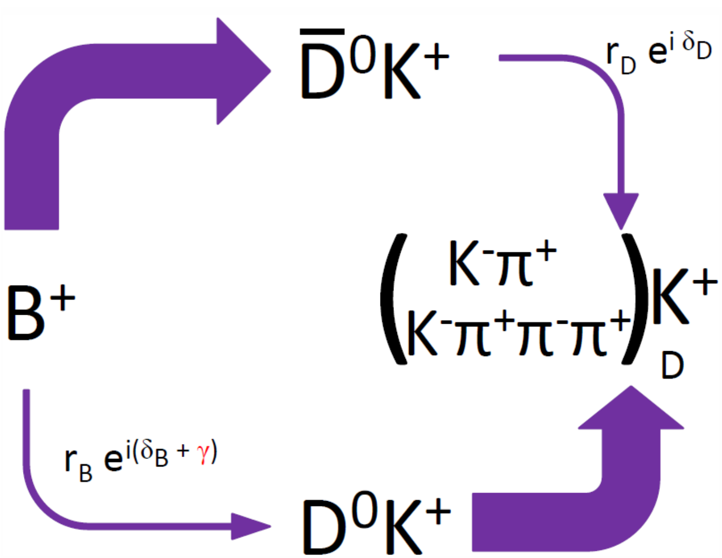


One of the 2 Young's slit (i.e. the b to c) is 10 times larger than the other slit (i.e. the b to u)

Measuring γ : ADS DK



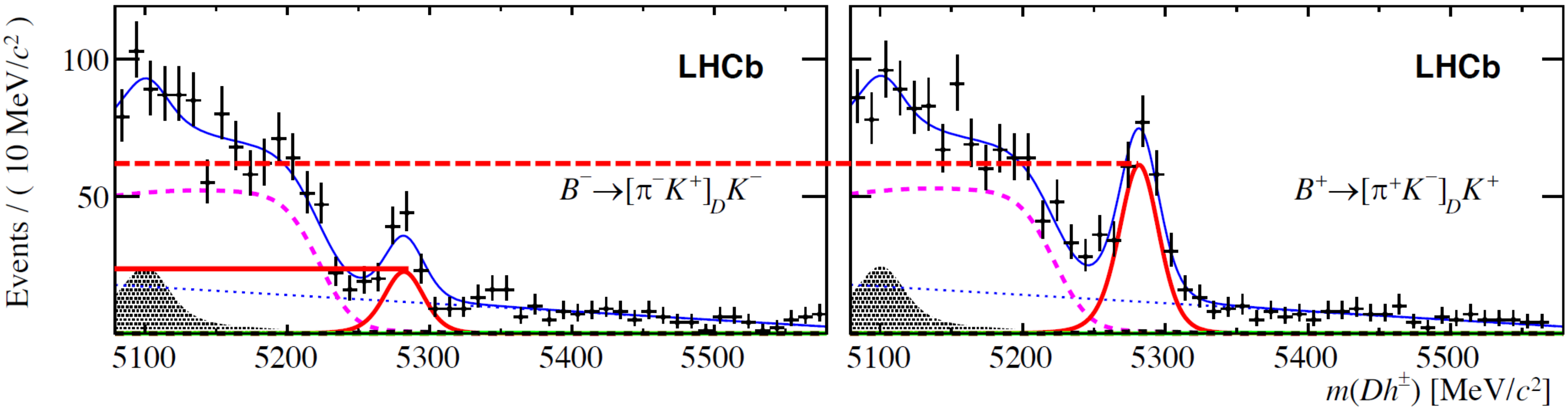




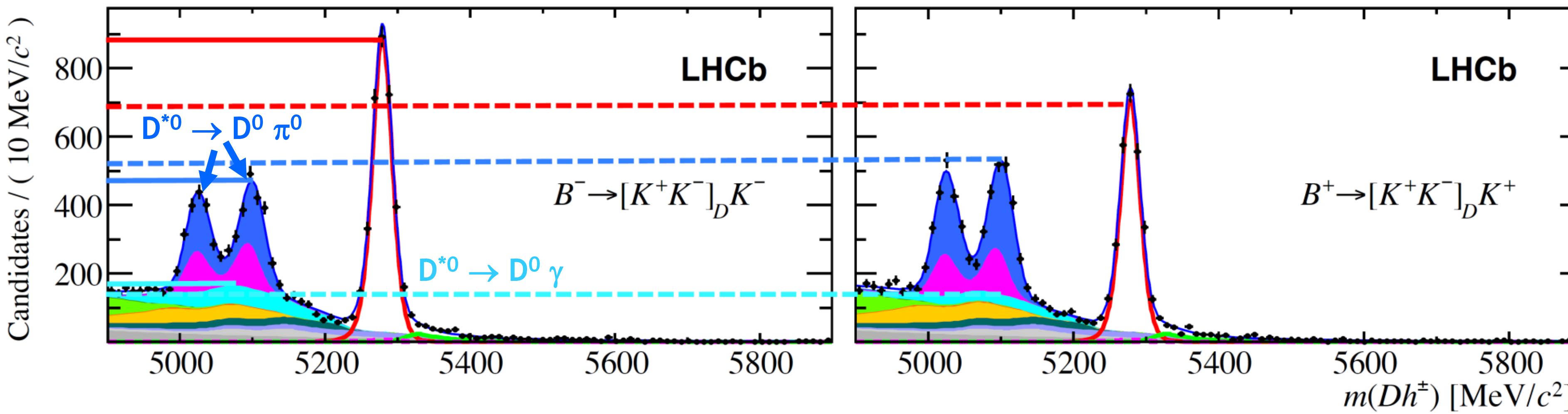
One of the 2 Young's slit (i.e. the b to c)
is 10 times larger than the
other slit (i.e. the b to u)
But there is an other screen with a smaller
slit behind the large in the first screen to compensate
Doubly Cabibbo suppressed D decay (DCS)

Measuring γ : ADS DK & GLW D(*)K

ADS textbook like [arXiv:1603.08993] -40% asymmetry! (only Run1)

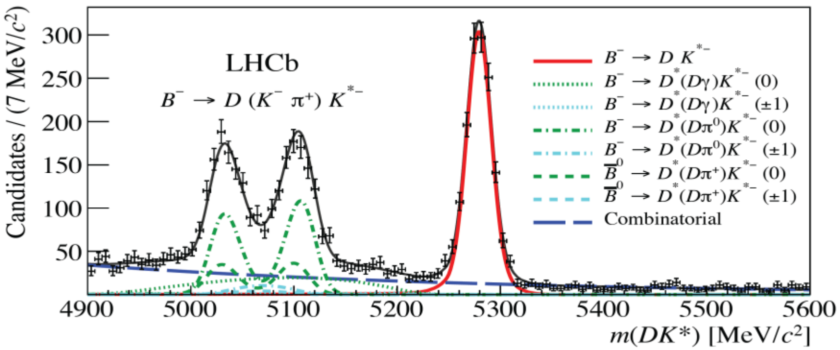


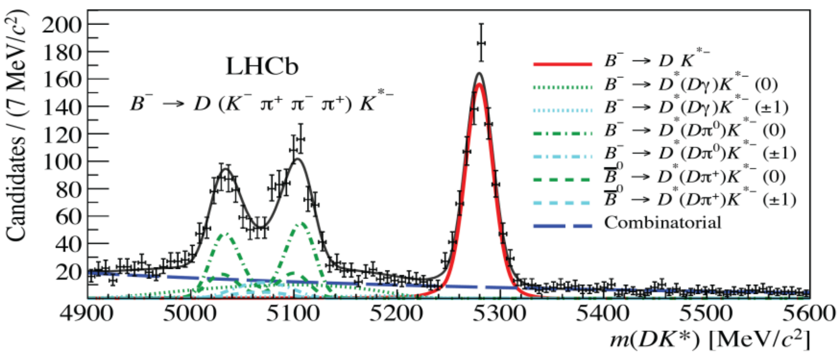
GLW DK and partial D*K [arXiv:1708.06370] (Run1& "Run2")

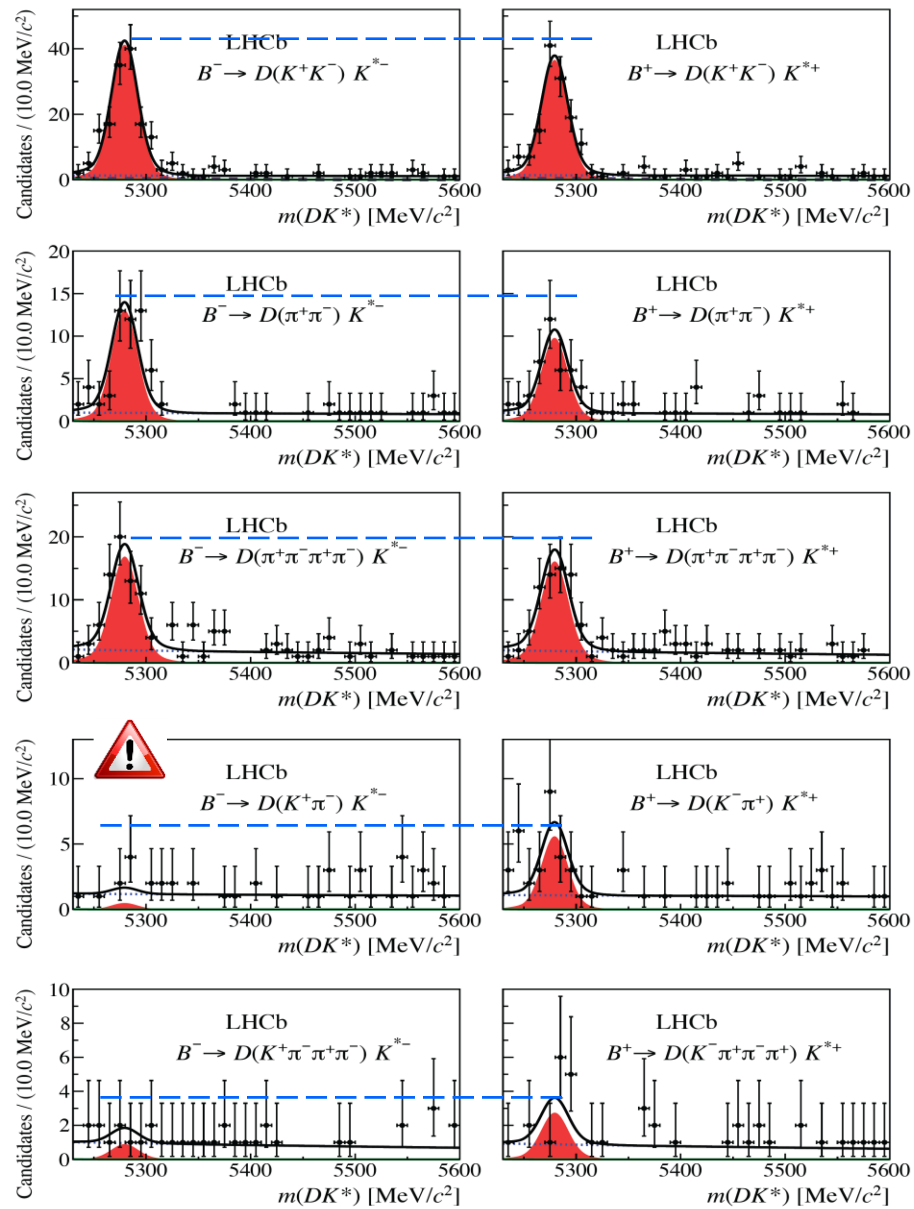


Measuring γ : ADS/GLW DK*-

A fit to the favoured decays in an extended range fixes signal and background models.







Simultaneous fit to 56 subsamples: yields of favoured modes and CP observables.

JHEP **11** (2017) 156

(Run1& “Run2”)

K^{*-} in $K_s\pi^-$ and $K\pi^0$ is underway

Measuring γ : ADS/GLW DK*-

$$A_{CP+} = 0.08 \pm 0.06 \pm 0.01$$

$$R_{CP+} = 1.18 \pm 0.08 \pm 0.01$$

$$R_{ADS}^{K\pi} = \quad 0.011 \pm 0.004 \pm 0.001$$

$$A_{ADS}^{K\pi} = -0.81 \quad \pm 0.17 \quad \pm 0.04$$

Huge asymmetry in ADS

$$A_{ADS}^{K\pi\pi\pi} = -0.45 \quad \pm 0.21 \quad \pm 0.14$$

$$R_{ADS}^{K\pi\pi\pi} = \quad 0.011 \pm 0.005 \pm 0.003$$

Values are inputs to the γ combination

(Run1& "Run2")

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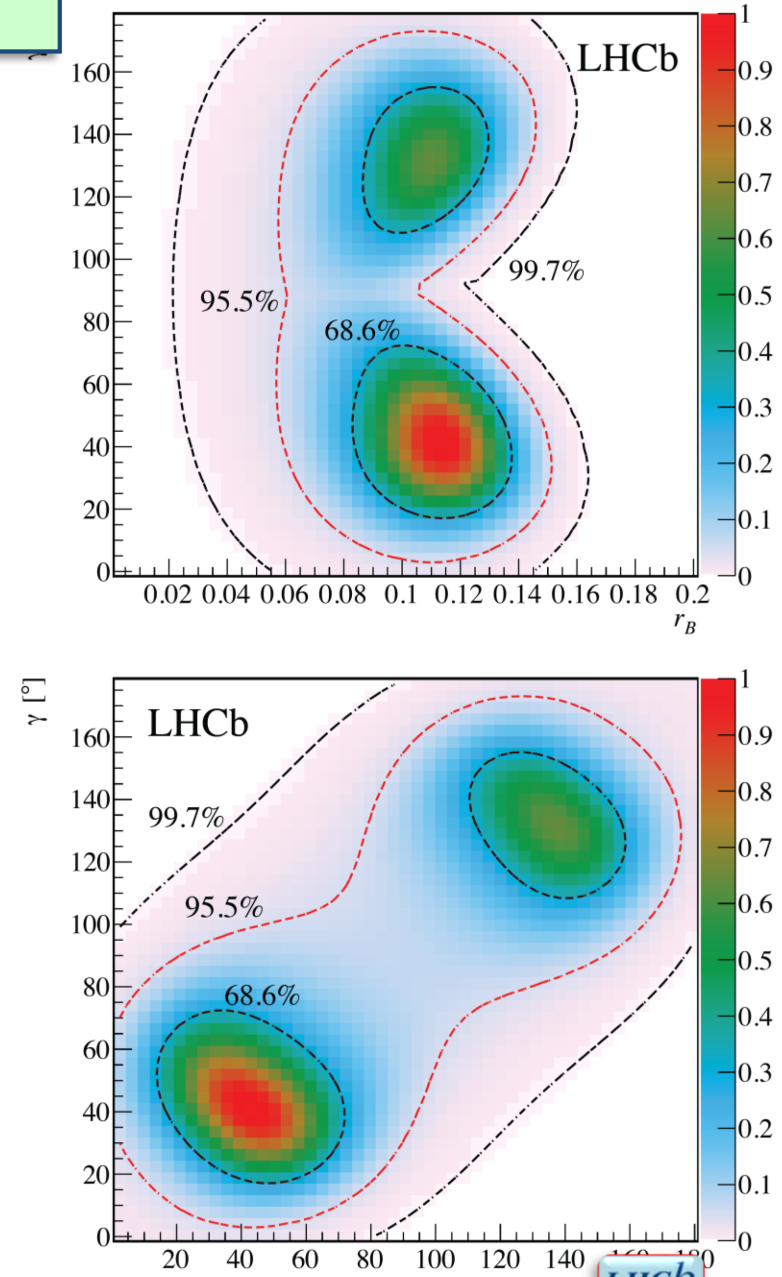
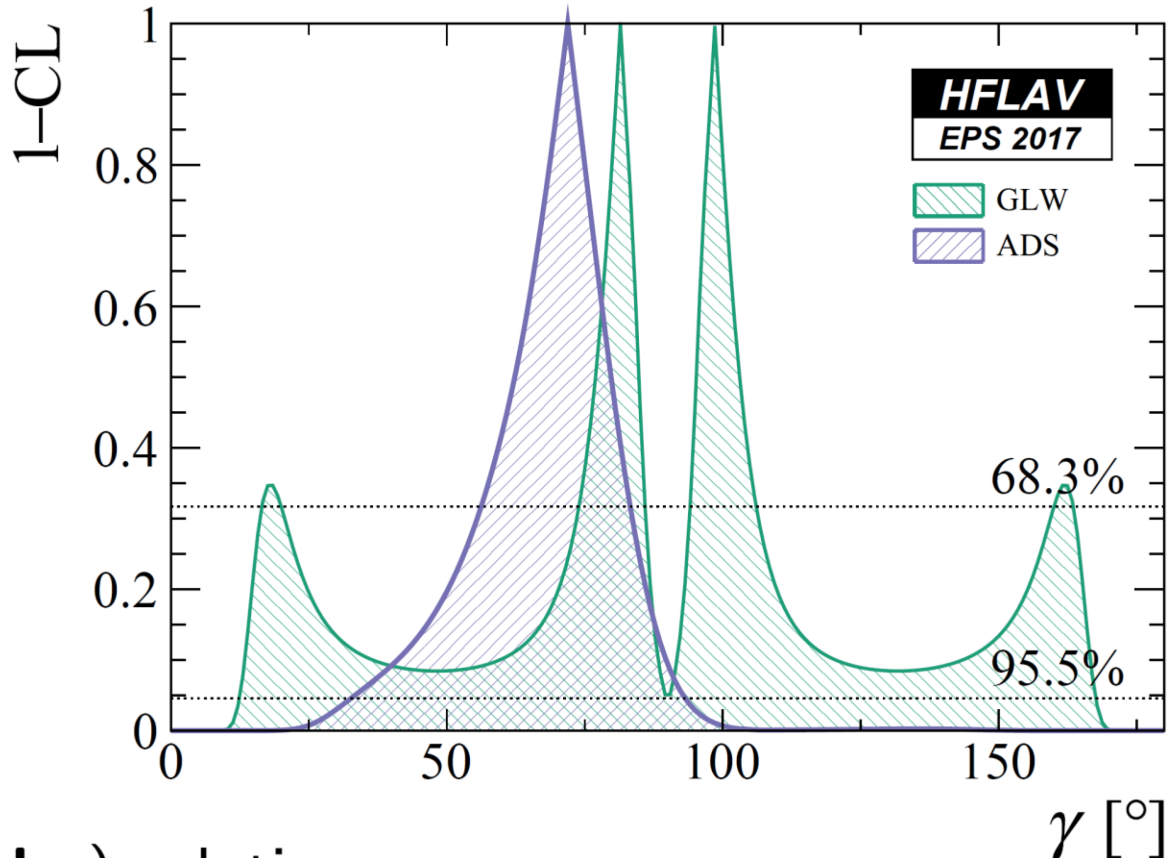


Measuring γ : ADS DK and GLW D(*)K



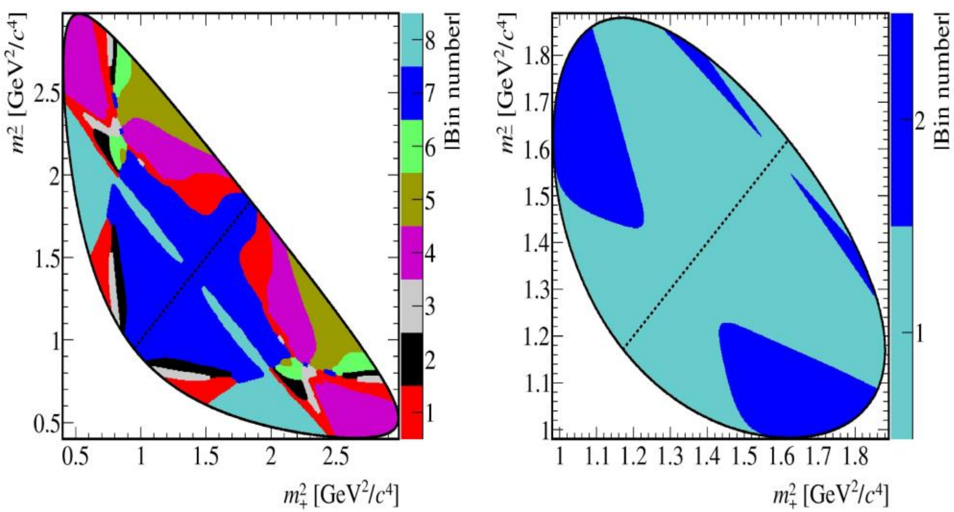
- A single (**yet broader**) solution (ADS & GLW is 4-folds ambiguous)
- Require knowledge of r_D, δ_D, κ_D from charm friends

CLEO-c HFLAV BESIII

The most precise measurement of γ : GGSZ DK and D→Ks$\pi\pi$ & KsKK Model Independent Method (MIM)

- GGSZ method for 3 body decays like $D \to K^0_S \pi^+ \pi^-$ [Phys. Rev. D68 (2003) 054018]
  - Strong phase variation across the D Dalitz plot required as an input
  - Model independent - take inputs from quantum correlated $D^0 \bar{D}^0$ decays (CLEO-c)
  - Model dependent - perform an amplitude analysis to the D Dalitz plot
- LHCb Run II analysis with $B^- \to D(K^0_S \pi^+ \pi^-, K^0_S K^+ K^-) K^-$
  - New analysis with Run II data
  - Take strong phase information from CLEO-c in bins of the D Dalitz plot
  - Bins optimised for best sensitivity to γ, strong phase is ~constant across each bin

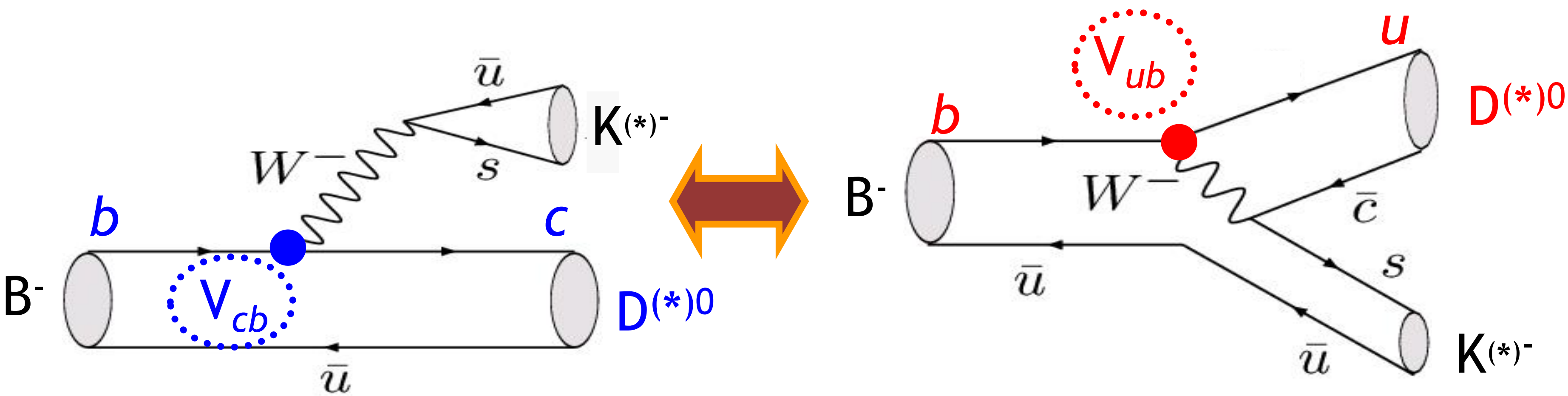
[LHCb-PAPER-2018-017]



- $B \to D^{*\pm} \mu^\mp \nu_\mu X$, $B^\pm \to D\pi^\pm$: control channels

γ in $B^- \to \tilde{D}^{(*)0} K^{(*)-}$

Same final state $\tilde{D}^0 \equiv [D^0 / \bar{D}^0]$



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

How does this GGSZ MIM work ?

- The amplitude for $B^- \to [K^0_S h^+ h^-]_D K^-$:

$$A_{B^-} \propto A_D(m_-^2, m_+^2) + r_B e^{i(\delta_B - \gamma)} A_{\bar{D}}(m_-^2, m_+^2)$$

- The Dalitz plot density :

$$\frac{d\Gamma}{dm_-^2\ dm_+^2} = A_D^2(m_-^2, m_+^2) + r_B^2 A_D^2(m_+^2, m_-^2) + \boxed{2r_B\ \mathrm{Re}[A_D(m_-^2, m_+^2) A_D^*(m_+^2, m_-^2)\ e^{-i(\delta_B - \gamma)}]}$$

symmetric w.r.t $m_+ = m_-$, $m_\pm \equiv m(K^0_S h^\pm)$

- Measure the yields in each of the bins of the Dalitz plot

[LHCb-PAPER-2018-017]

$$N^+_{\pm i} = h_{B^+}(F_{\mp i} + (x_+^2 + y_+^2) F_{\pm i} + 2\sqrt{F_i F_{-i}}(x_+ c_{\pm i} + y_+ s_{\pm i}))$$

$$N^-_{\pm i} = h_{B^-}(F_{\pm i} + (x_-^2 + y_-^2) F_{\mp i} + 2\sqrt{F_i F_{-i}}(x_- c_{\pm i} + y_- s_{\pm i}))$$

- Fraction of D^0 and $\bar{D}^0$ in each bin (from semileptonic control sample)
- Strong phase measurements from CLEO-c measurements of QC $D^0 \bar{D}^0$ decays
- The parameters of interest!

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

Ratio of B decay amplitudes

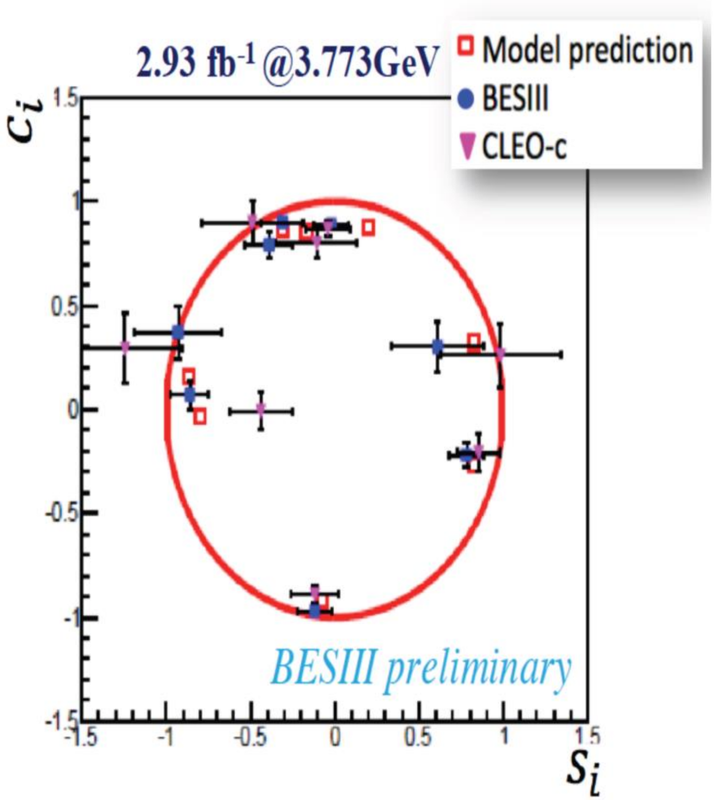
Strong phase difference of B decay amplitudes

Eagerly waiting for this to be combined/deployed !
We need BESIII for this and other D decays strong inputs

- $D^0 \to K_S\pi^-\pi^+$ strong phase differences c_i and s_i

	c_i		s_i	
Bins	BES-III	CLEO-c	BES-III	CLEO-c
1	0.066 ± 0.066	-0.009 ± 0.088	-0.843 ± 0.119	-0.438 ± 0.184
2	0.796 ± 0.061	0.900 ± 0.106	-0.357 ± 0.148	-0.490 ± 0.295
3	0.361 ± 0.125	0.292 ± 0.168	-0.962 ± 0.258	-1.243 ± 0.341
4	-0.985 ± 0.017	-0.890 ± 0.041	-0.090 ± 0.093	-0.119 ± 0.141
5	-0.278 ± 0.056	-0.208 ± 0.085	0.778 ± 0.092	0.853 ± 0.123
6	0.267 ± 0.119	0.258 ± 0.155	0.635 ± 0.293	0.984 ± 0.357
7	0.902 ± 0.017	0.869 ± 0.034	-0.018 ± 0.103	-0.041 ± 0.132
8	0.888 ± 0.036	0.798 ± 0.070	-0.301 ± 0.140	-0.107 ± 0.240

CLEO-c results can be found in Phys.Rev. D82 (2010) 112006



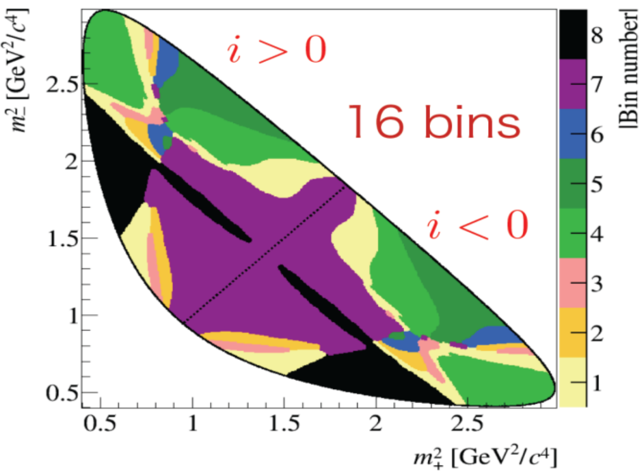
Dan Ambrose, APS 2014

This (CLEO-c) limits the systematics on γ GGSZ:
4° (strong phase map) wrt to 2° (LHCb exp.)

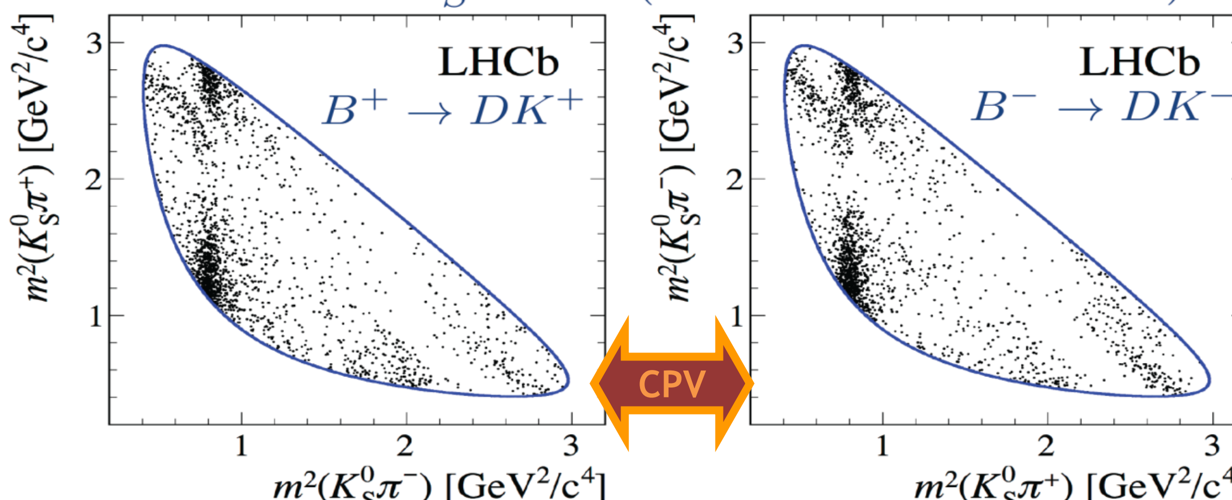
2° achievable, see arXiv:1712.07853
(Craik, Gershon, Poluektov: $B0\to DK+\pi-$, $D\to K0S\pi+\pi-$ double Dalitz plot analysis)

Following the B-mass fits perform the CP fit for Extract yields in each bin of the Dalitz plot

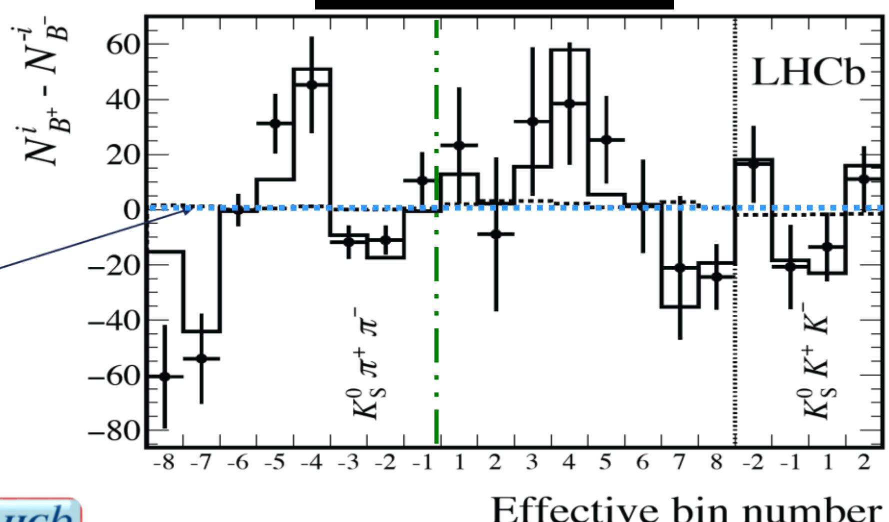
("Run2")



$D \to K_S^0\pi^+\pi^-$ ($\sim 3.8K$ $B^\pm$ candidates)



Asymmetry in bins

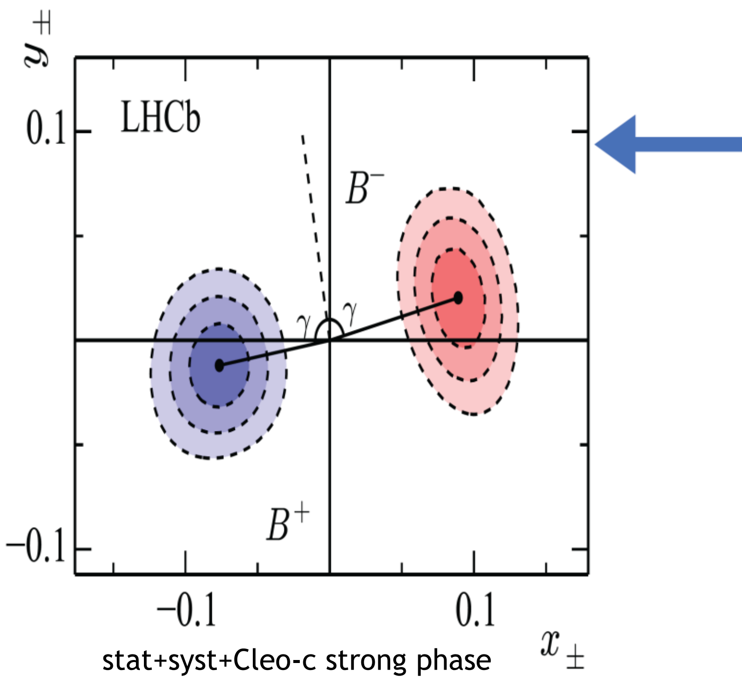


- $B^\pm \to DK^\pm$ yields determined independently as a cross-check, and compared to the nominal fit
- data fitted assuming no CPV
  $x_+ = x_- \equiv x_0, \quad y_+ = y_- \equiv y_0$
- p-value of 2×10^{-6} disfavours CP-conserving hypothesis

GGSZ MIM Run2 &1+2

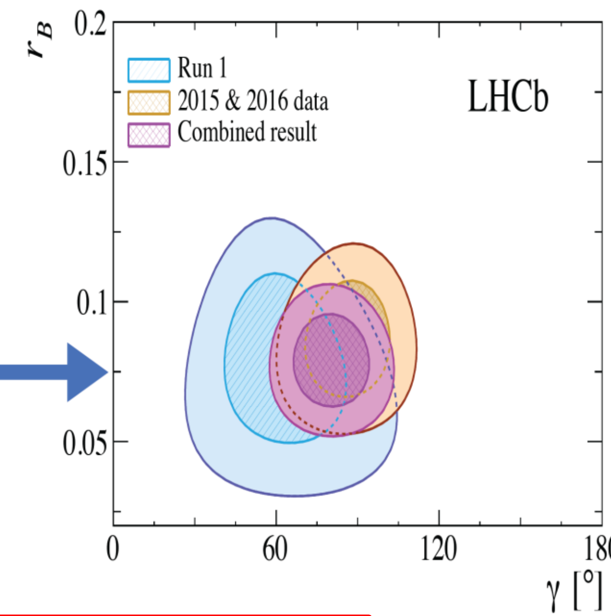
- Following the mass fits perform the CP fit for $x_\pm, y_\pm$

[LHCb-PAPER-2018-017]



Run II results

Run I + II combination



stat+syst+Cleo-c strong phase

$$x_- = (\ \ 9.0 \pm 1.7 \pm 0.7 \pm 0.4) \times 10^{-2}$$
$$y_- = (\ \ 2.1 \pm 2.2 \pm 0.5 \pm 1.1) \times 10^{-2}$$
$$x_+ = (-7.7 \pm 1.9 \pm 0.7 \pm 0.4) \times 10^{-2}$$
$$y_+ = (-1.0 \pm 1.9 \pm 0.4 \pm 0.9) \times 10^{-2}$$

$$|(x_+, y_+) - (x_- y_-)| = (17.0 \pm 2.7) \times 10^{-2}$$

6.4σ : first observation of CPV in $B^\pm \to DK^\pm$ with $D^0 \to K^0_S h^+ h^-$

Run1+2

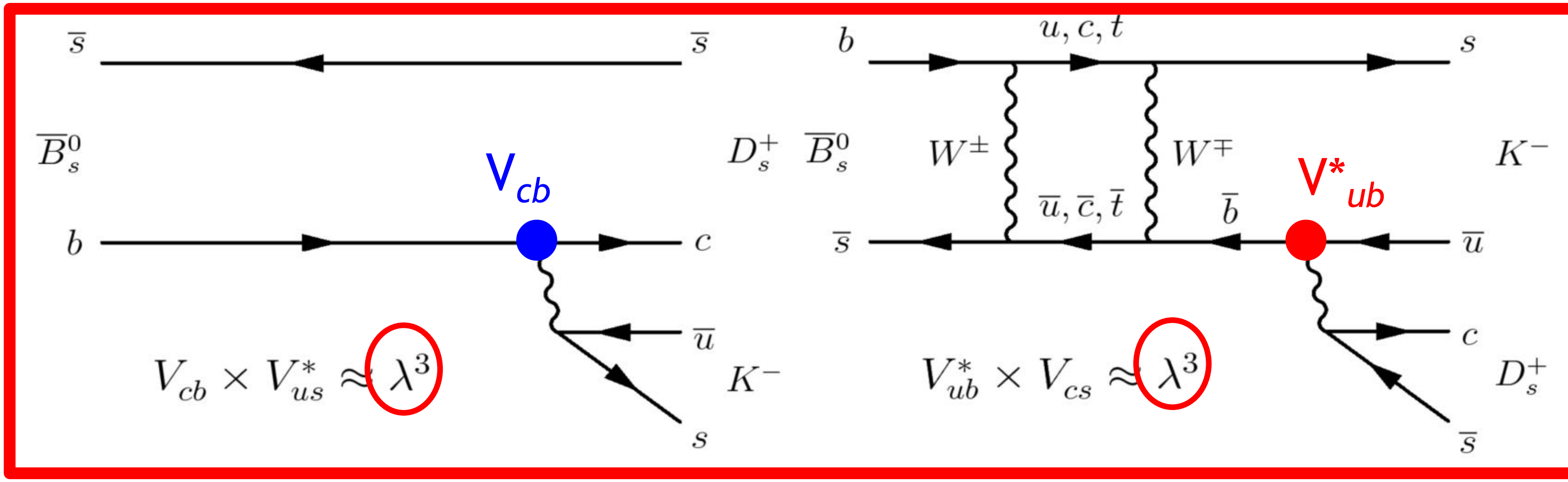
$$\gamma = 80^\circ\, ^{+10^\circ}_{-9^\circ} \left(^{+19^\circ}_{-18^\circ} \right)$$

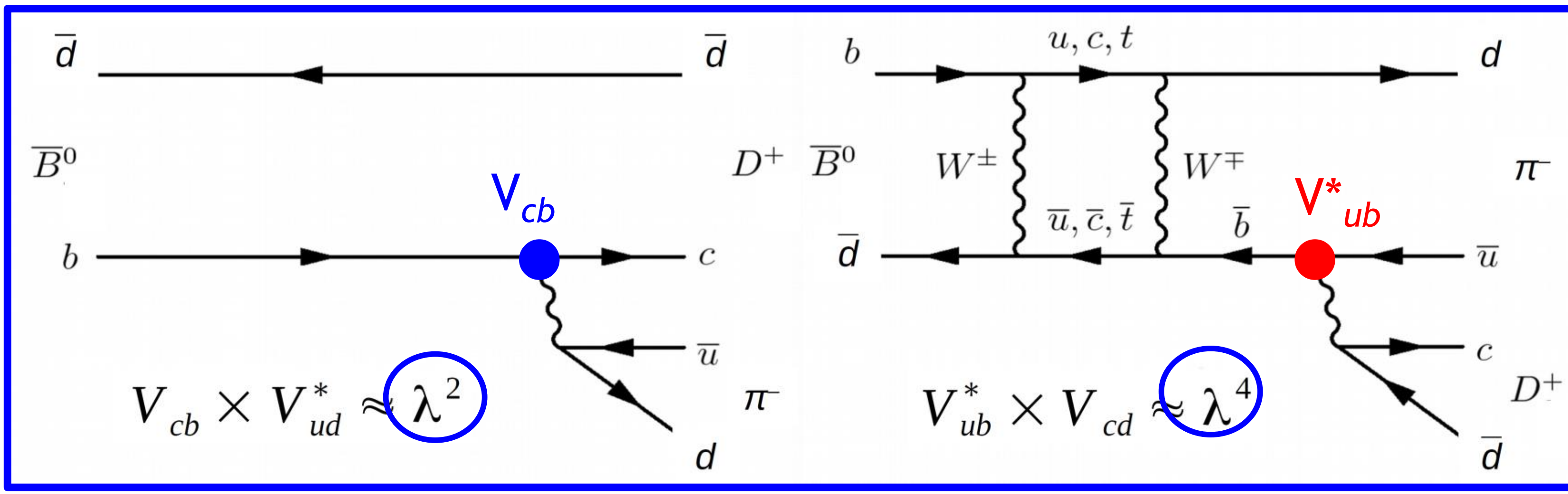
$$r_B = 0.080\, ^{+0.011}_{-0.011} \left(^{+0.022}_{-0.023} \right)$$

$$\delta_B = 110^\circ\, ^{+10^\circ}_{-10^\circ} \left(^{+19^\circ}_{-20^\circ} \right)$$

68, 95% CL

Time dependent CPV measurements
$B_s \to D_s^{\mp} K^{\pm}$ & $B_d \to D^{\mp}\pi^{\pm}$





➔ Sensitive to $\gamma - 2\beta_s$ ($B_s \to D_s K$) or $\gamma + 2\beta$ ($B^0 \to D\pi$), i.e. not Trees !!!!
Know $\beta_{(s)}$ independently → sensitivity to γ [or vice versa]

Time dependent CPV measurements $B_s \to D_s^{\mp} K^{\pm}$ & $B_d \to D^{\mp}\pi^{\pm}$ PROS & CONS

$B_s \to D_s K$ (LHCb golden mode: vertexing/PID/trigger)

- Smaller yields
  - background challenges
  - control samples available
- Fast oscillations
- Non-zero $\Delta\Gamma s$
  extra observables
- Large interference effects

$B^0 \to D\pi$ (challenging but excellent LHCb sensitivity)

- Huge yields
  - little background
  - control sample challenges
- Slow oscillations
- Negligible $\Delta\Gamma d$
  fewer observables
- Small interference effects

[arXiv:1712.07428]
(Run1)

TD CPV $B_s \to D_s^{\mp} K^{\pm}$

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

$$\frac{d\Gamma_{\bar{B}_s^0\to f}(t)}{dt} = \frac{1}{2}|A_f|^2\left|\frac{p}{q}\right|^2(1+|\lambda_f|^2)e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) + \underline{A_f^{\Delta\Gamma}}\sinh\left(\frac{\Delta\Gamma_s t}{2}\right) - \underline{C_f}\cos(\Delta m_s t) + \underline{S_f}\sin(\Delta m_s t)\right],$$

Five observables for three unknowns → measure $\gamma - 2\beta_s$ (up to ambiguity)

… and similar equations for $\bar{f}$ (e.g. $f = D_s^- K^+$, $\bar{f} = D_s^+ K^-$)

$$C_f = \frac{1 - r_{D_sK}^2}{1 + r_{D_sK}^2},$$

Also determine strong phase difference δ

$$A_f^{\Delta\Gamma} = \frac{-2r_{D_sK}\cos(\delta - (\gamma - 2\beta_s))}{1 + r_{D_sK}^2}, \quad A_{\bar{f}}^{\Delta\Gamma} = \frac{-2r_{D_sK}\cos(\delta + (\gamma - 2\beta_s))}{1 + r_{D_sK}^2},$$

$$S_f = \frac{2r_{D_sK}\sin(\delta - (\gamma - 2\beta_s))}{1 + r_{D_sK}^2}, \quad S_{\bar{f}} = \frac{-2r_{D_sK}\sin(\delta + (\gamma - 2\beta_s))}{1 + r_{D_sK}^2}.$$

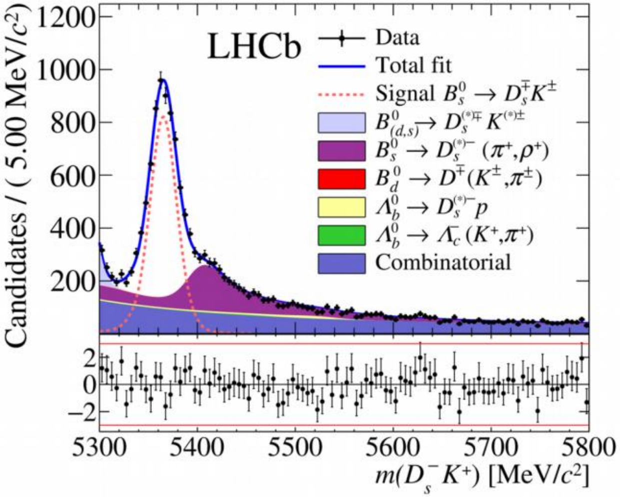
[arXiv:1712.07428] (Run1)

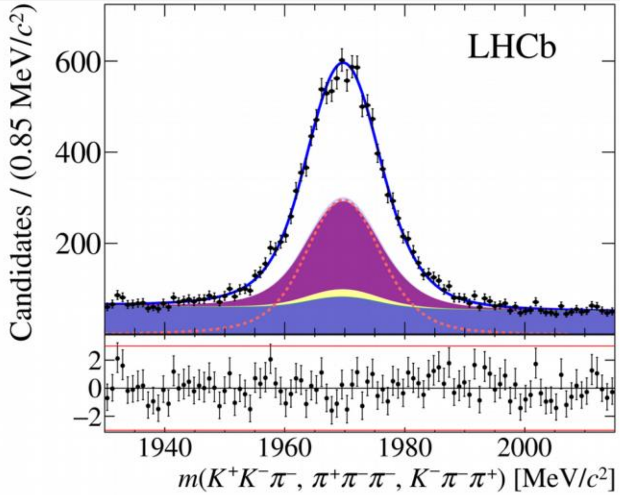
5955±90 signal events

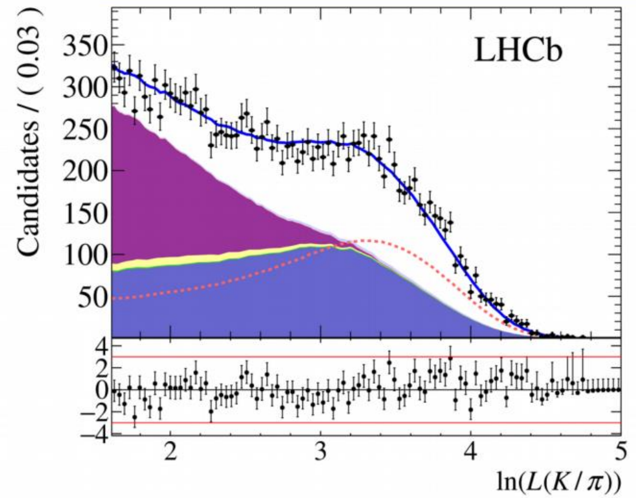
TD CPV $B_s \to D_s^{\mp} K^{\pm}$

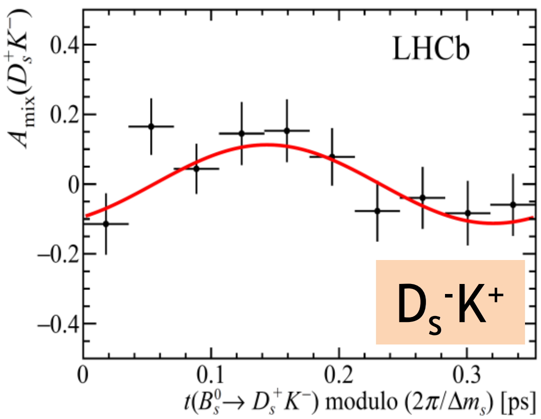
efficient flavour tagging

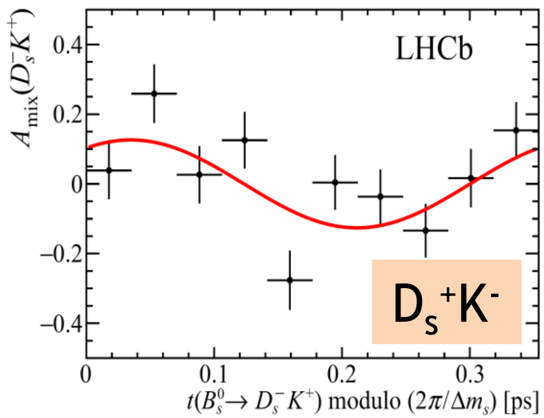
$\varepsilon_{eff}=(5.80\pm0.25)\%$











Parameter	Value
C_f	$0.730 \pm 0.142 \pm 0.045$
$A_f^{\Delta\Gamma}$	$0.387 \pm 0.277 \pm 0.153$
$A_{\overline{f}}^{\Delta\Gamma}$	$0.308 \pm 0.275 \pm 0.152$
S_f	$-0.519 \pm 0.202 \pm 0.070$
$S_{\overline{f}}$	$-0.489 \pm 0.196 \pm 0.068$

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

$$\delta = (358\,^{+13}_{-14})^{\circ}$$

$$r_{D_sK} = 0.37\,^{+0.10}_{-0.09}\,,$$

3.8σ evidence for CP violation

2.3σ compatibility wrt LHCb@2016 average

[arXiv:1805.03448]
(Run1)

TD CPV $B_d \to D^{\mp}\pi^{\pm}$

$$\Gamma_{B^0\to f}(t) \propto e^{-\Gamma t}\left[1 + \underline{C_f}\cos(\Delta m\, t) - \underline{S_f}\sin(\Delta m\, t)\right]$$
$$\Gamma_{B^0\to \bar{f}}(t) \propto e^{-\Gamma t}\left[1 + \underline{C_{\bar{f}}}\cos(\Delta m\, t) - \underline{S_{\bar{f}}}\sin(\Delta m\, t)\right]$$

…and similar Eqs. for $\overline{B^0}$ (e.g. $f = D^-\pi^+$, $\bar{f} = D^+\pi^-$)

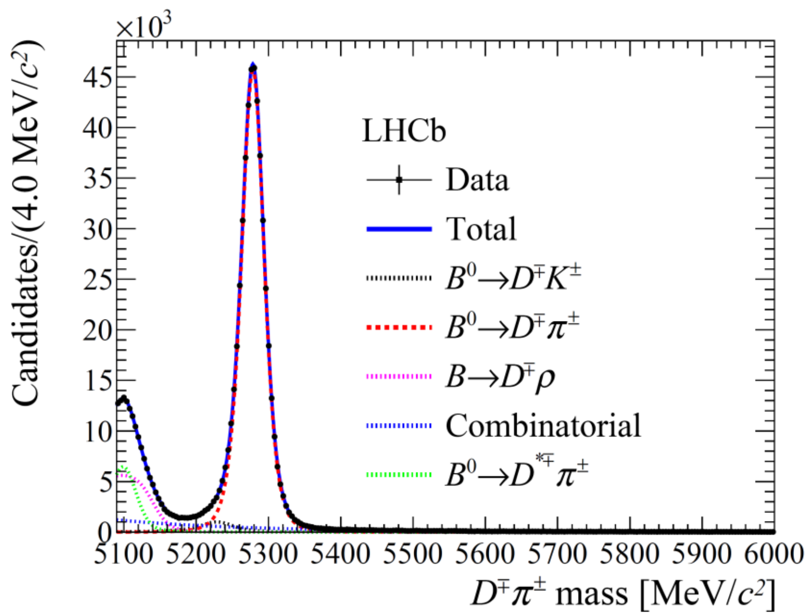
$$C_f = \frac{1 - r_{D\pi}^2}{1 + r_{D\pi}^2} = -C_{\bar{f}}\,,$$
$$S_f = -\frac{2r_{D\pi}\sin\left[\delta - (2\beta+\gamma)\right]}{1 + r_{D\pi}^2}\,,$$
$$S_{\bar{f}} = \frac{2r_{D\pi}\sin\left[\delta + (2\beta+\gamma)\right]}{1 + r_{D\pi}^2}\,,$$

But $r_{D\pi}$ is about 2% so C is very close to 1 !

So we have only 2 observables
for three unknowns
➔ need external input to measure γ+2β

Signal yield of 479 000 ± 700 !!!
Against 34 400 ± 300 bkgd

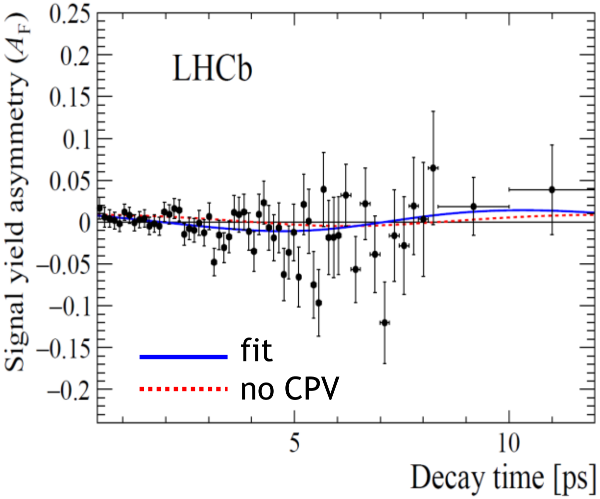
Flavour Tagging ε_{eff} = (5.59 ± 0.01)%



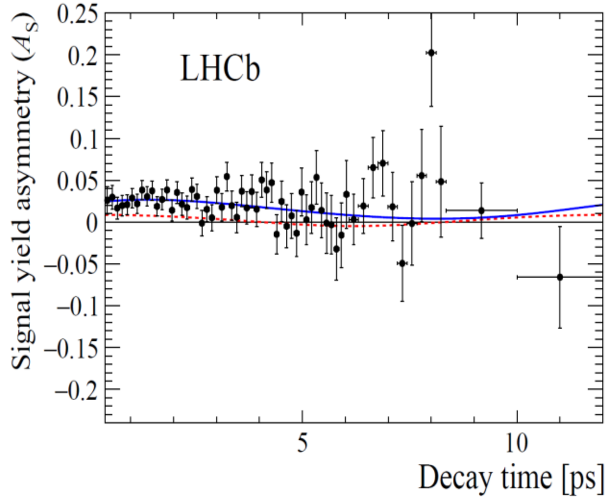
[arXiv:1805.03448]
(Run1)

TD CPV $B_d \to D^{\mp}\pi^{\pm}$

favoured (F) $\bar{b} \to \bar{c}u\bar{d}$



suppressed (S) $\bar{b} \to \bar{u}c\bar{d}$



$$A_F = \frac{\Gamma_{B^0\to f}(t) - \Gamma_{\bar{B}^0\to \bar{f}}(t)}{\Gamma_{B^0\to f}(t) + \Gamma_{\bar{B}^0\to \bar{f}}(t)}$$

$$A_S = \frac{\Gamma_{\bar{B}^0\to f}(t) - \Gamma_{B^0\to \bar{f}}(t)}{\Gamma_{\bar{B}^0\to f}(t) + \Gamma_{B^0\to \bar{f}}(t)}$$

$$S_f = 0.058 \pm 0.020\,(\text{stat}) \pm 0.011\,(\text{syst})$$
$$S_{\bar{f}} = 0.038 \pm 0.020\,(\text{stat}) \pm 0.007\,(\text{syst})$$

correlations of 60% (−41%) for statistical (systematic) uncertainties

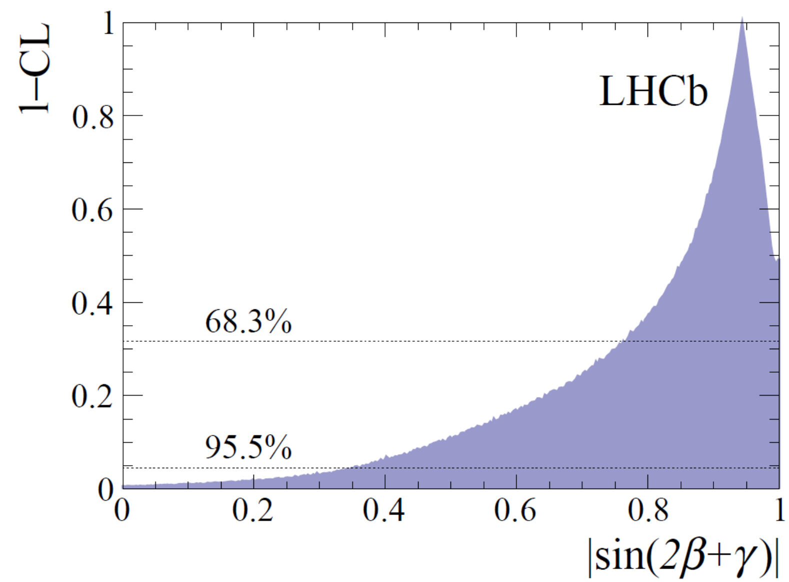
➔ $r_{D\pi}$ from external inputs (PDG, LQCD, CKMfitter):

$$r_{D\pi} = \tan\theta_c \frac{f_{D^+}}{f_{D_s}} \sqrt{\frac{\mathcal{B}(B^0 \to D_s^+\pi^-)}{\mathcal{B}(B^0 \to D^-\pi^+)}}$$

= (1.82 ± 0.12 ± 0.36)% (includes 20% SU(2) breaking)

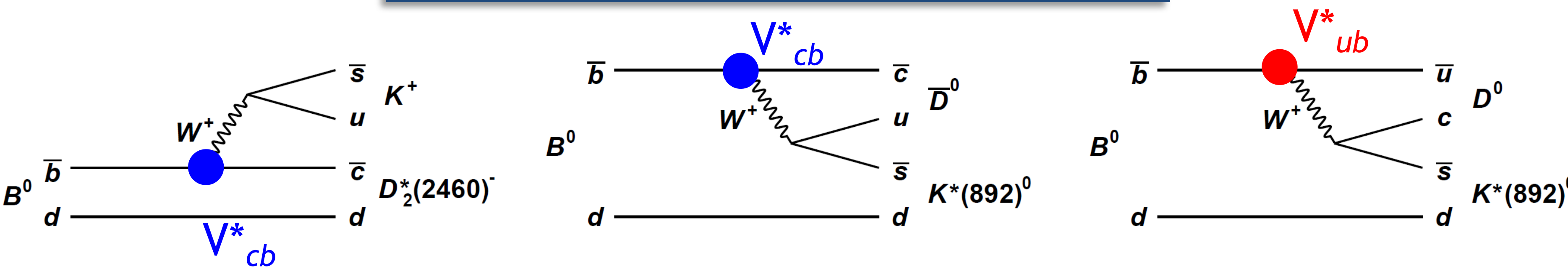
➔ HFLAV β=(22.2±0.7)%, bings to CPV@2.7 σ:

$$\boxed{\gamma \in [5, 86]^\circ \cup [185, 266]^\circ \text{ @68\% CL}}$$

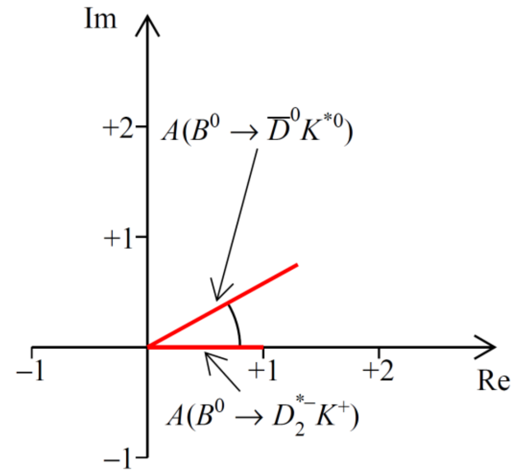


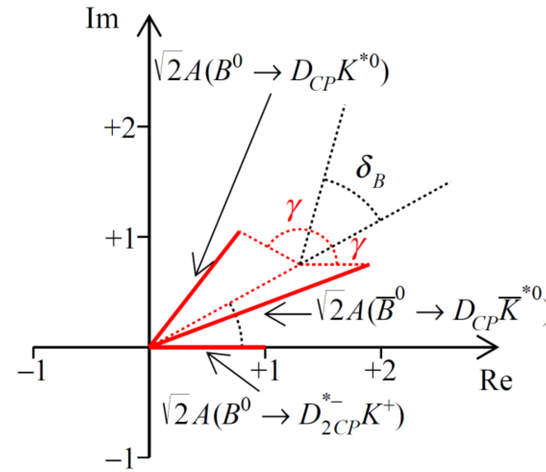
[arXiv:1602.03445]
(Run1)

3-body decay $B^0 \to D\pi^- K^+$



➔ 1rst idea Gershon, Williams (2009):
use Dalitz structure of B decays





$B^0 \to D\pi^- K^+$ [Phys. Rev. D80 (2009) 092002]

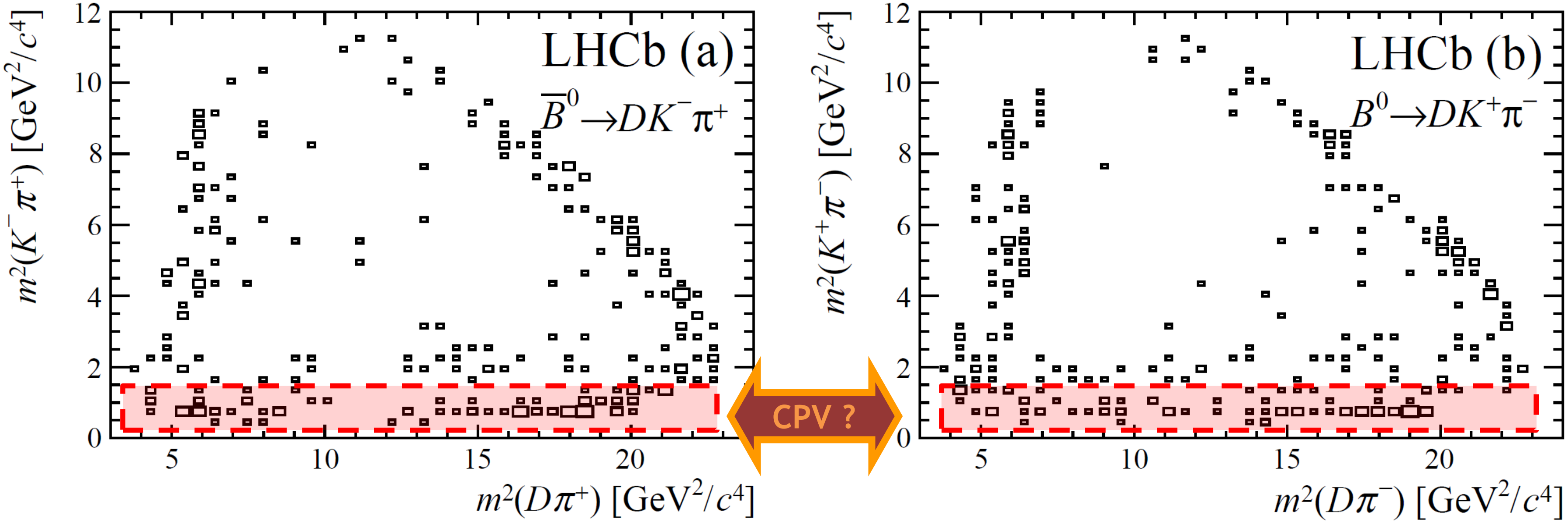
➔ Get multiple interfering resonances which increase sensitivity to
$D^*_0(2400)^-$, $D^*_2(2460)^-$, $K^*(892)^0$, $K^*(1410)^0$, $K^*_2(1430)^0$

➔ Fit B decay Dalitz Plot for cartesian parameters
(similar to GGSZ except for the B not the D)

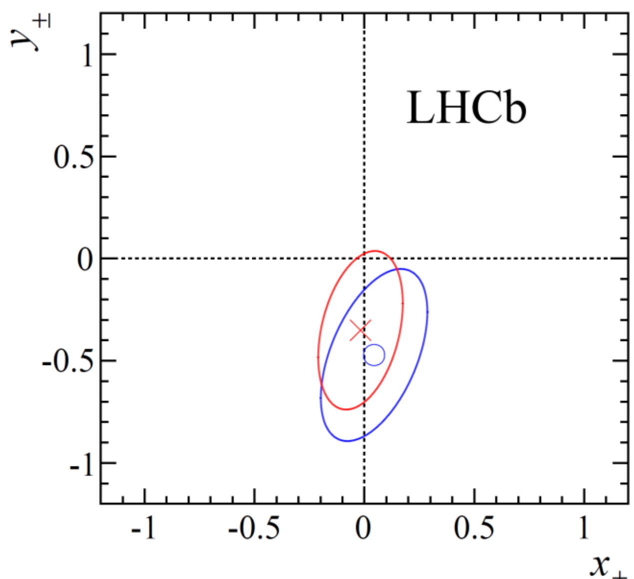
- $D_{CP+} \to K^+K^-$, $\pi^+\pi^-$ - GLW-Dalitz (done by LHCb - [arXiv:1602.03455]) HERE !
- $D \to K\pi$ - ADS-Dalitz (difficult due to backgrounds from $B^0_s \to D^{(*)0}K^+\pi^-$)
- $D \to K^0_S \pi^+\pi^-$ - GGSZ-Dalitz (double Dalitz!)

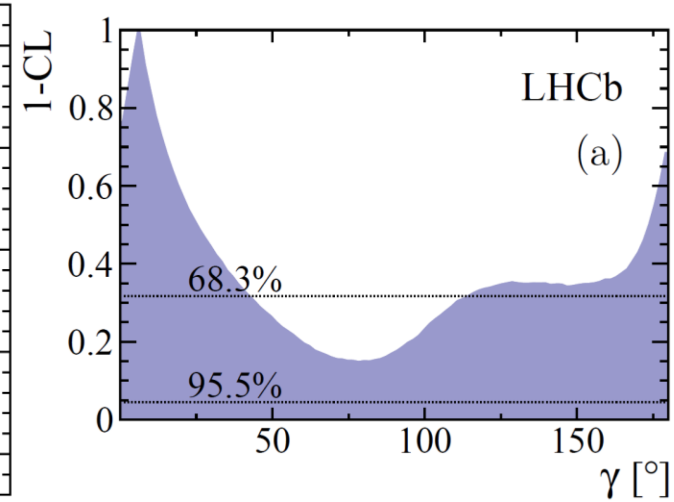
[arXiv:1602.03445]
(Run1)

3-body decay $B^0 \to D\pi^- K^+$



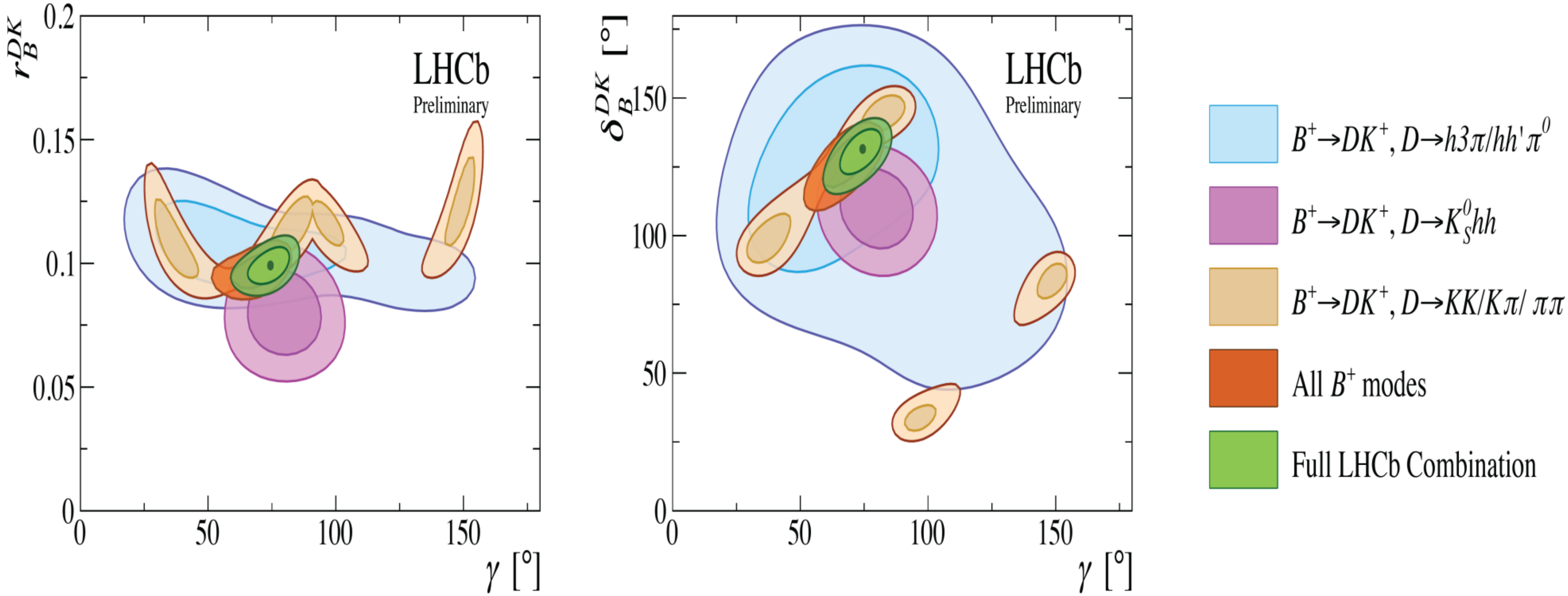
For the first time in the
$B^0 \to DK^*(892)^0$ decay
- @68% CL
- no CPV ≡ (0,0)
- yet weak constraint
- proof of feasibility





The new LHCb combination

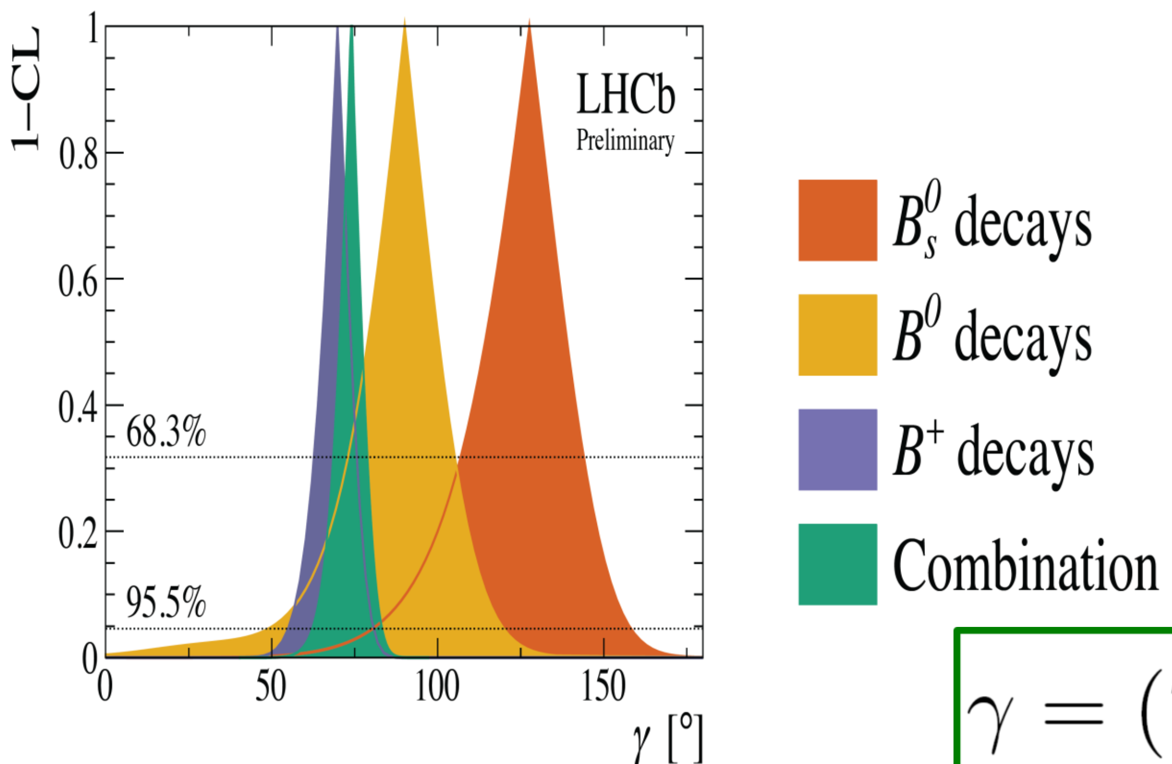
- Breakdown the results by methods - the power of the combination
  - For example look at inputs from B^+ decays
  - Methods vary in precision and number of solutions



[LHCb-CONF-2018-002]

The new LHCb combination

- Breakdown the results by B meson type
  - Everything consistent at the 2 sigma level currently
  - In the SM they should be the same - if NP appears it could affect the different species differently due to differing decay topologies



$$\gamma = (74.0\,^{+5.0}_{-5.8})^\circ$$

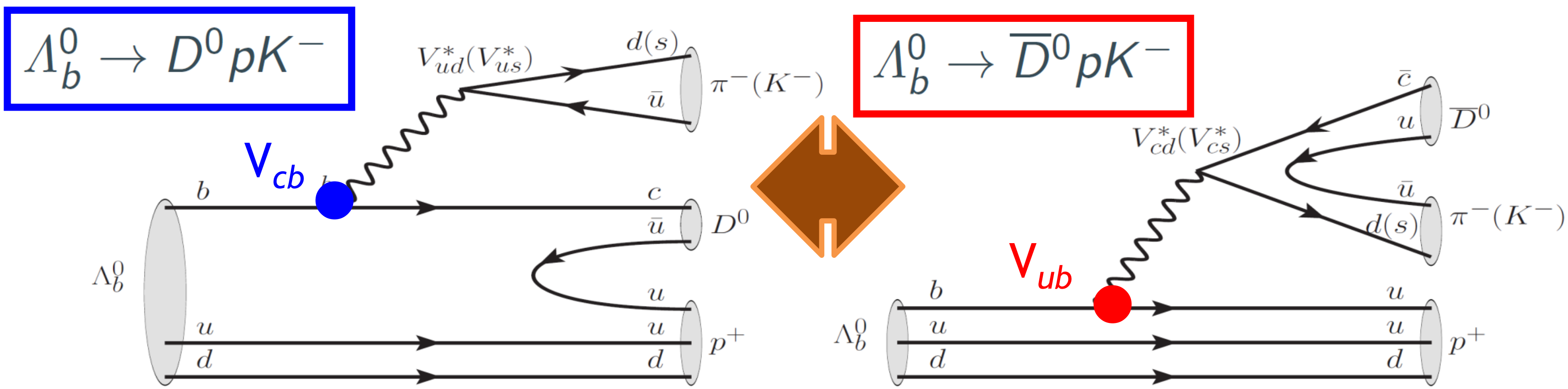
Beauty baryon Λ^0_b/Ξ^0_b decays to D^0ph^- final states

1 fb^{-1}
(2011)

PRD 89(2014)03 (arXiv:1311.4823)

- Beauty baryon sector remains largely unexplored ⇒ this is LHCb game field
- Decays such as $\Lambda_b \to D^0\Lambda$ and $\Lambda_b \to D^0pK^-$ can be used to measure γ

Z. Phys.C56(1992)129; Mod. Phys. Lett. A 14(1999)63; PRD 65(2002)073029



- LHCb has studied beauty baryon decays to D^0ph^- and $\Lambda_c^+h^-$ final states, using 1 fb^{-1} of data:
  - The Cabibbo favored final states $D^0 \to K^-\pi^+$ and $\Lambda_c^+ \to pK^-\pi^+$ are used. The Common $pK^-\pi^+h$ final states is used to reduce systematic uncertainties.
  - $\Lambda_b \to D^0p\pi^-$ seen with 3 383 ± 94 ! See also Amp. Analysis: [arXiv:1701.07873]

Beauty baryon Λ^0_b/Ξ^0_b decays to D^0ph^- final states

1 fb^{-1} (2011)

PRD 89(2014)03 (arXiv:1311.4823)

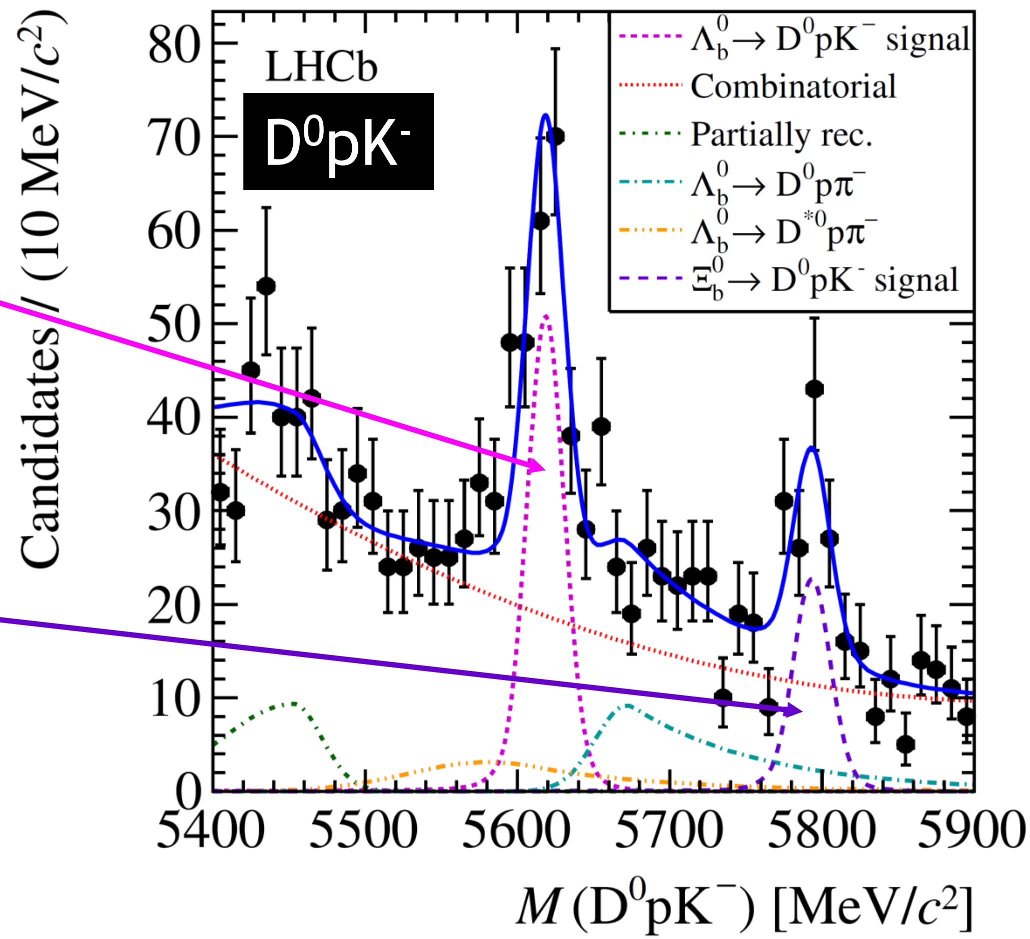
➔ Observation of (signif incl. syst.):

$\Lambda^0_b \to D^0pK^-$ @ 9.0σ : $R_{\Lambda^0_b \to D^0pK^-}$

$$\frac{\mathcal{B}(\Lambda^0_b \to D^0pK^-)}{\mathcal{B}(\Lambda^0_b \to D^0p\pi^-)} = (7.3 \pm 0.8^{+0.5}_{-0.6})\%$$

$\Xi^0_b \to D^0pK^-$ @ 5.9σ : $R_{\Xi^0_b \to D^0pK^-}$

$$\frac{f_{\Xi^0_b} \times \mathcal{B}(\Xi^0_b \to D^0pK^-)}{f_{\Lambda^0_b} \times \mathcal{B}(\Lambda^0_b \to D^0pK^-)} = (44 \pm 9 \pm 6)\%$$



A lot of events already ⇒ high time to move to CP analyses
LHCb has almost 15 times this is hands (ADS underway)

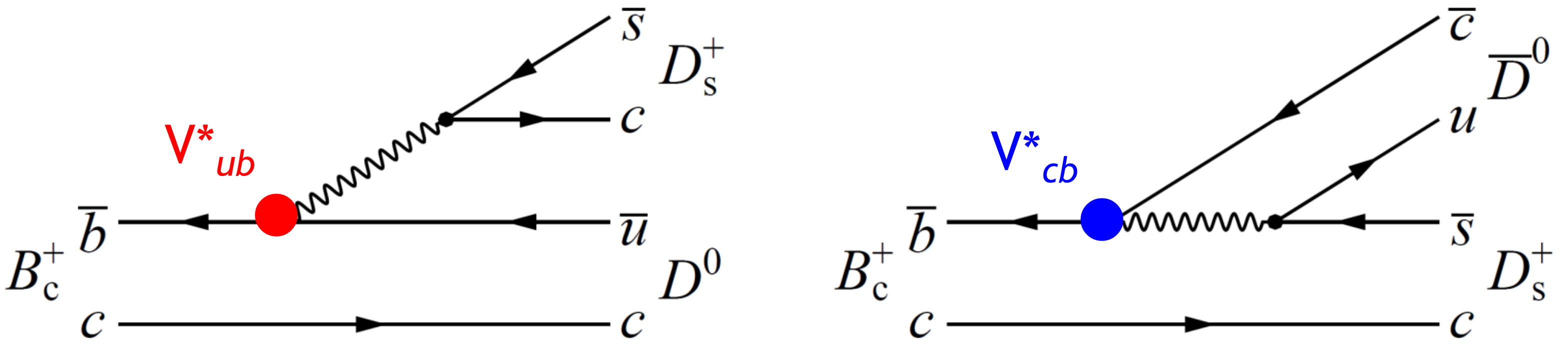
γ measurements in B^+_c decays ?

[arXiv:1712.04702] (Run1)

- Massive sample of B^+_c produced in LHCb: ~30K $B^+_c \to J/\psi\pi^+$ with Run1+Run2
- Branching fraction of $B^+_c \to J/\psi\pi+$: $(0.6-2.9)\times10^{-3}$

PRD 49 (1994) 3399, PRD 68 (2003) 094020, PRD 89 (2014) 034008

- Able to access B^+_c decays with Branching Fractions of 10^{-5}–10^{-6}
- $B^+_c \to D^+_{(s)} D^0$ decays sensitive to γ with r_{Ds}~1 and r_D~0.1



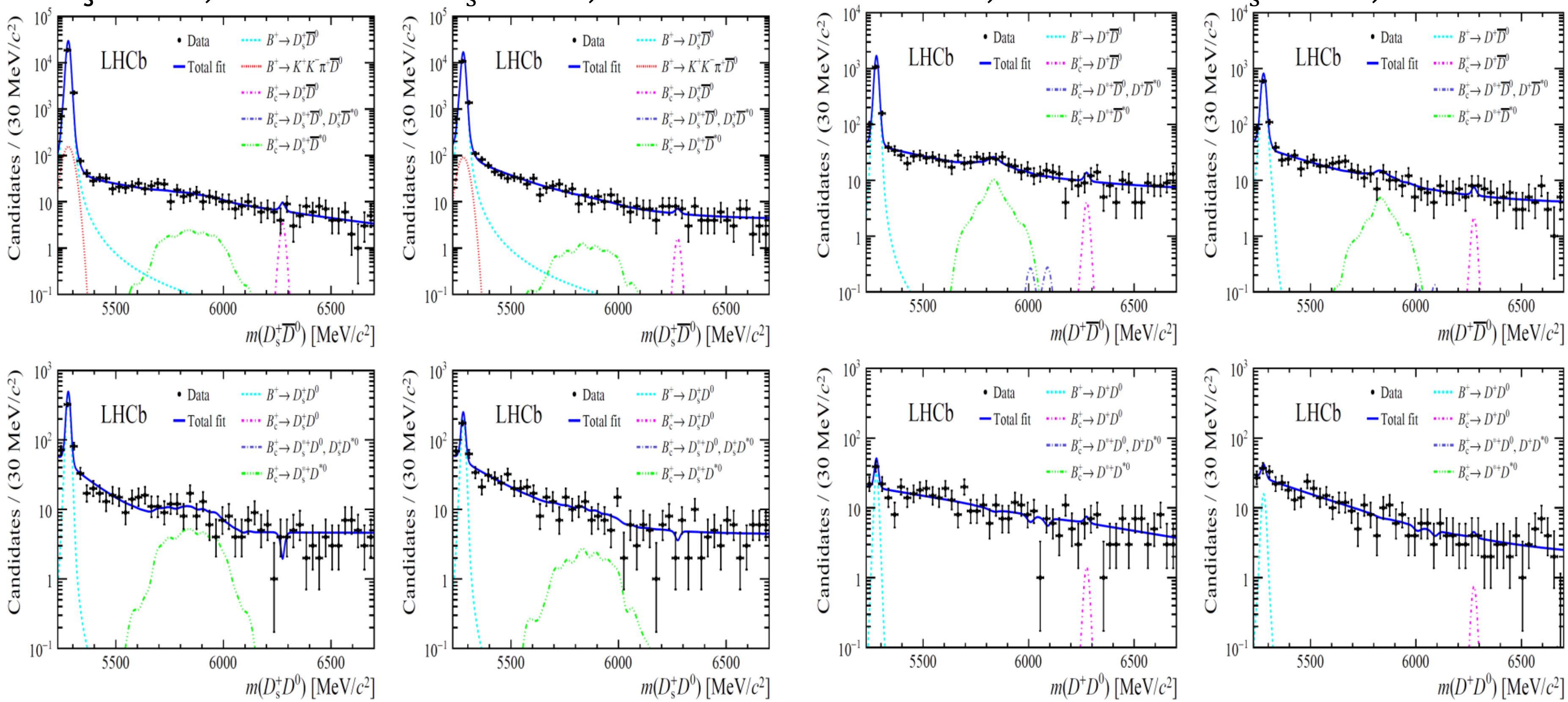
- The branching fractions are predicted to be:

	Prediction for the branching fraction $[10^{-6}]$			
Channel	Ref. [9]	Ref. [10]	Ref. [11]	Ref. [12]
$B_c^+ \to D_s^+ \overline{D}^0$	2.3 ± 0.5	4.8	1.7	2.1
$B_c^+ \to D_s^+ D^0$	3.0 ± 0.5	6.6	2.5	7.4
$B_c^+ \to D^+ \overline{D}^0$	32 ± 7	53	32	33
$B_c^+ \to D^+ D^0$	0.10 ± 0.02	0.32	0.11	0.32

Results of $B^+_c \to D_{(s)}^{(*)+} D^{(*)0}$ searches

[arXiv:1712.04702]
(Run1)

$D_s^{(*)+}D^{(*)}$, $D\to K\pi$ | $D_s^{(*)+}D^{(*)}$, $D\to K3\pi$ | $D^{(*)+}D^{(*)}$, $D\to K\pi$ | $D_s^{(*)+}D^{(*)}$, $D\to K3\pi$



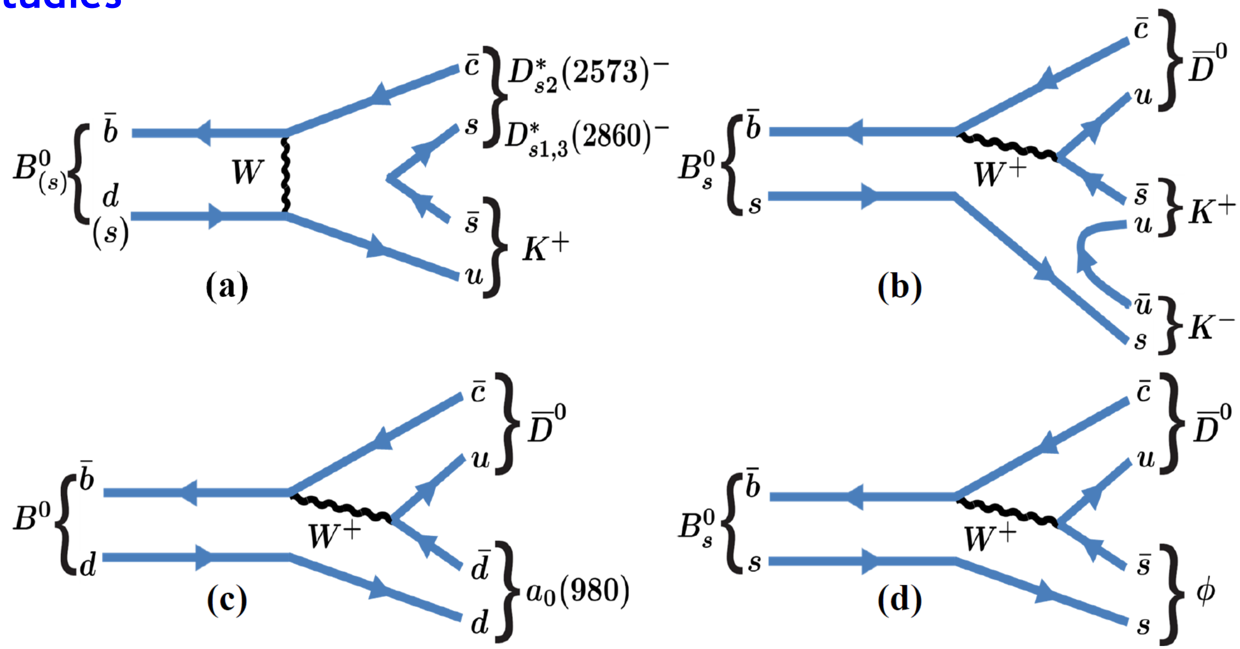
- **Nothing observed and upper limits set on these decays**
- **Absolute Branching fraction upper limits at level of 10^{-4}–10^{-3}, consistent with expectations in previous slide**
- **Decays with D(s)* and D* are searched without reconstructing γ/π^0**

arXiv:1807.01891

Physics with/of $B^0_{(s)} \to \bar{D}^0 K^+ K^-$ decays

✓ **Time-Dependent Dalitz analyses** can be used to access CKM angles γ and to obtain clean (i.e. tree decays) determination of $\beta_{(s)}$ in $B_{(s)}$-$\bar{B}_{(s)}$ mixing (Phys. Rev D85 (2012) 114015)

✓ **Rich phenomenology of Dalitz structures** are interesting for exited D_s^{**} charmed B-decays spectroscopy studies



First steps:

✓ Analysis already performed with early LHCb dataset (0.6/fb) : observation of B^0 channel and only evidence for B^0_s mode (Phys. Rev. Lett. 109 (2012) 131801)

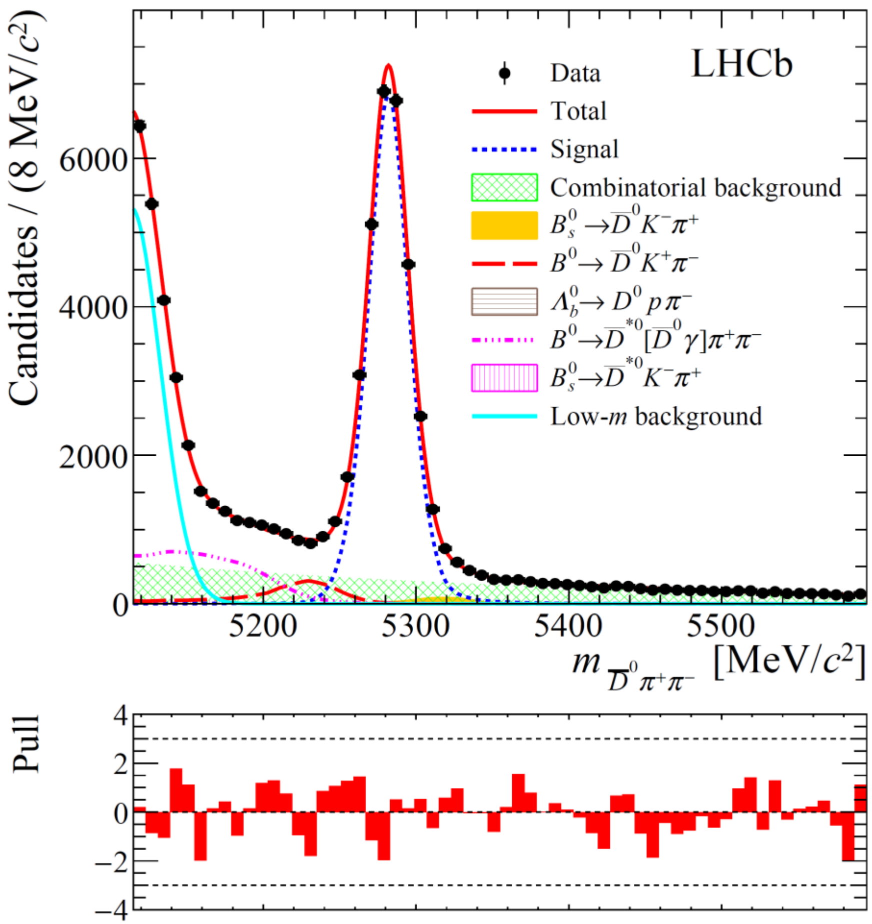
✓ Updated measurements performed with 3/fb (Run1: 2011+2012) ➔ new analysis
- Improved background treatment (e.g. : $B^0_{(s)} \to \bar{D}^0 K^- \pi^+$ and $\Lambda_b \to D^0 p K^-$)
- control/norm. mode: $\bar{B}^0 \to D^0 \pi^+ \pi^-$

Future developments in collaboration with UCAS/Tsinghua colleagues

arXiv:1807.01891

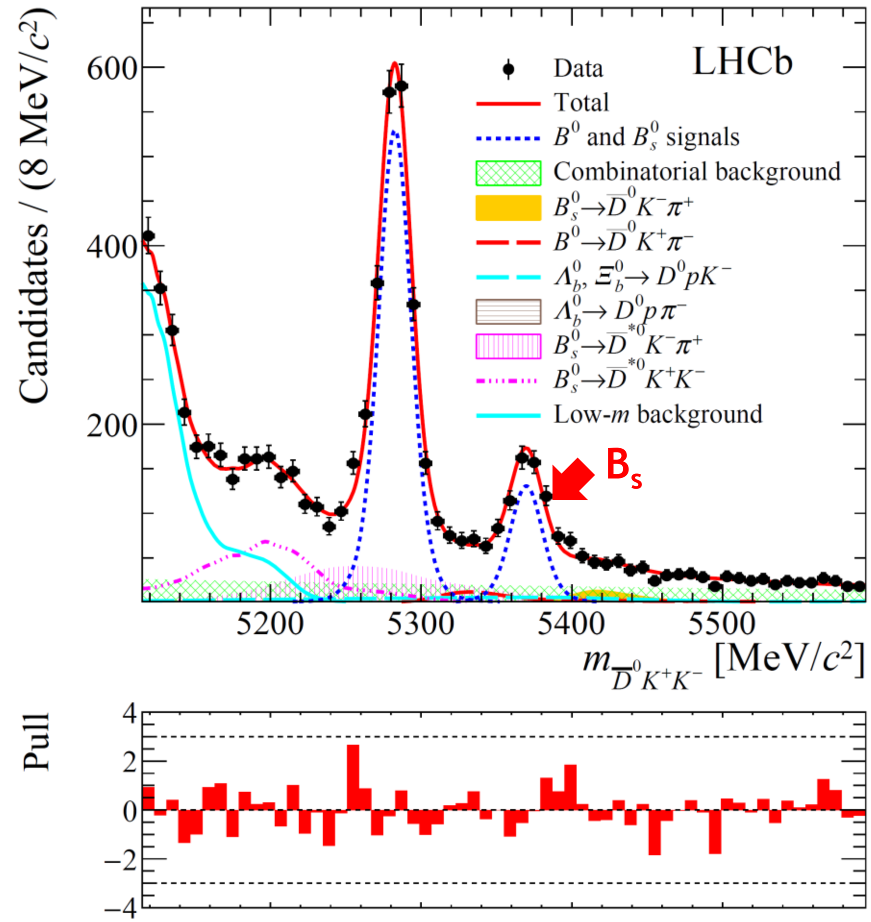
invariant mass fit of $B^0_{(s)} \to \bar{D}^0 h^+ h^-$ decays

$B^0 \to \bar{D}^0 \pi^+ \pi^-$



29 943 ± 243

$B^0_{(s)} \to \bar{D}^0 K^+ K^-$



1918 ± 74 B^0 & NEW → 473 ± 33 B^0_s
Observed for the 1st time!

ratio of yields $r_{B^0_s/B^0}$=(24.7±1.7)%

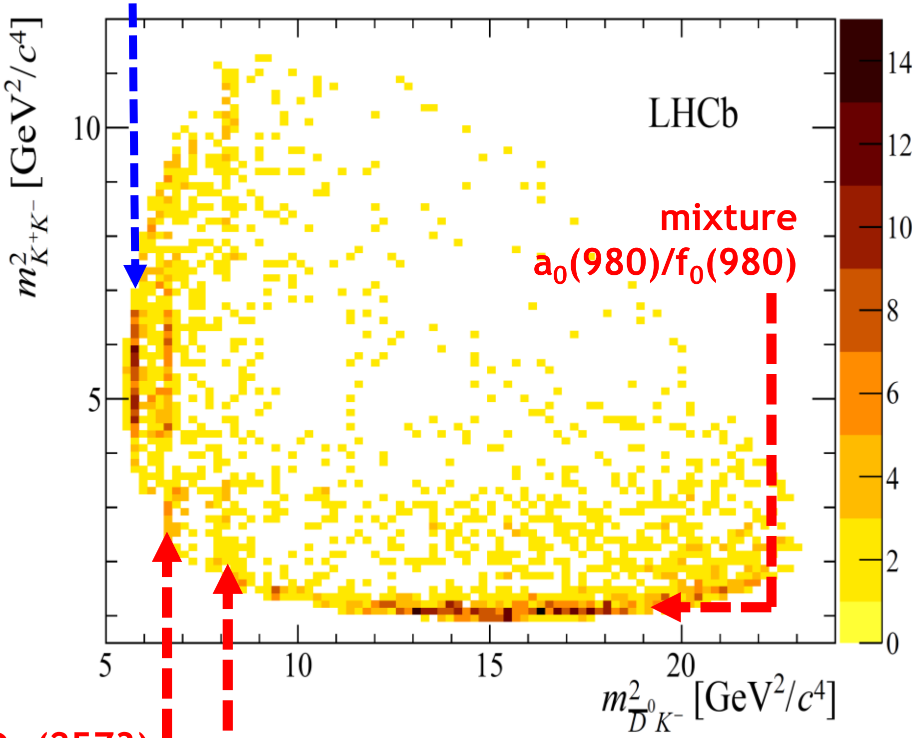
arXiv:1807.01891

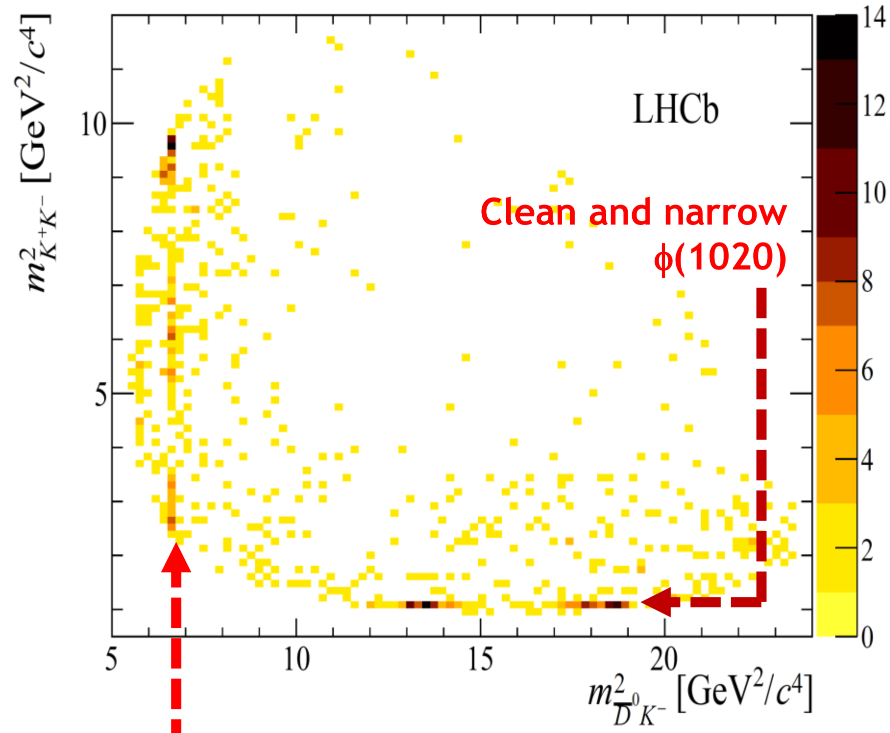
Inspection of Dalitz plot

$B^0 \to \bar{D}^0 K^+ K^-$ (in [5240,5320] MeV/c²)

$B^0_s \to \bar{D}^0 K^+ K^-$ (in [5340,5400] MeV/c²)

non subtracted background $D_{s1}(2536)$





➔ **Performed only with LHC Run1 : motivates amplitude analysis with additional LHCb data**

Future developments in collaboration with UCAS/Tsinghua colleagues

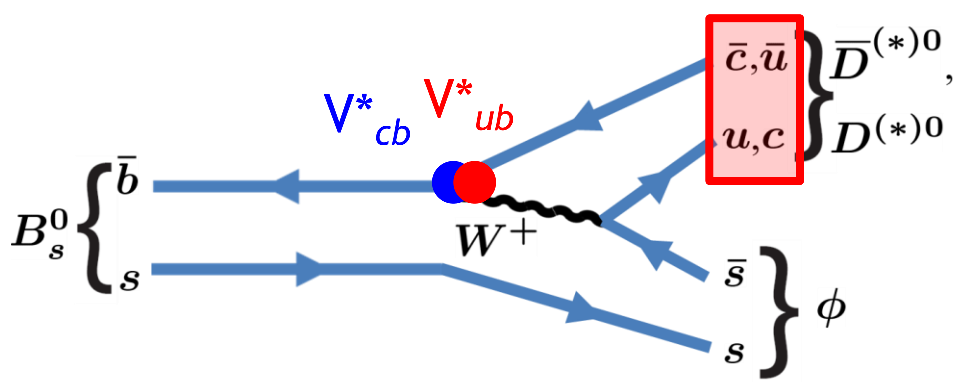
arXiv:1807.01892
Phys. Rev. D98 071103(R) (2018)

Studies of $B^0_{(s)} \to \bar{D}^{(*)0}\phi$

✓ The $\phi(1020)$ is a narrow resonance and using the selected candidates in $B^0_{(s)} \to \bar{D}^0 K^+ K^-$ of 1807.01891 (Phys. Rev. D98 072006 (2018)) permits studies on $B^0_{(s)} \to \bar{D}^{(*)0}\phi$

✓ Significant sensitivity to the CKM angle γ for $B^0_s \to \bar{D}^{(*)0}\phi$ decays:
(Phys. Lett. B253 (1991) 483 & LHCb-PUB-2010-005)

- Precision on CKM angle γ still limited (i.e. around 5°) to indirectly constraint BSM physics
  ➔ alternate methods are very welcome
- $b \to c$ and $b \to u$ interfering transition of about same size: $r_B \approx 30$-50% ($B^0_s \to D^+_s K^-$ JHEP 03 (2018) 059)
- For the D^{*0} decay (VV) the reconstruction can be partial, if f_L known, to almost double the B^0_s dataset (i.e. omit γ/π^0 (Phys. Lett. B777 (2017) 16))



Before summer 2018:

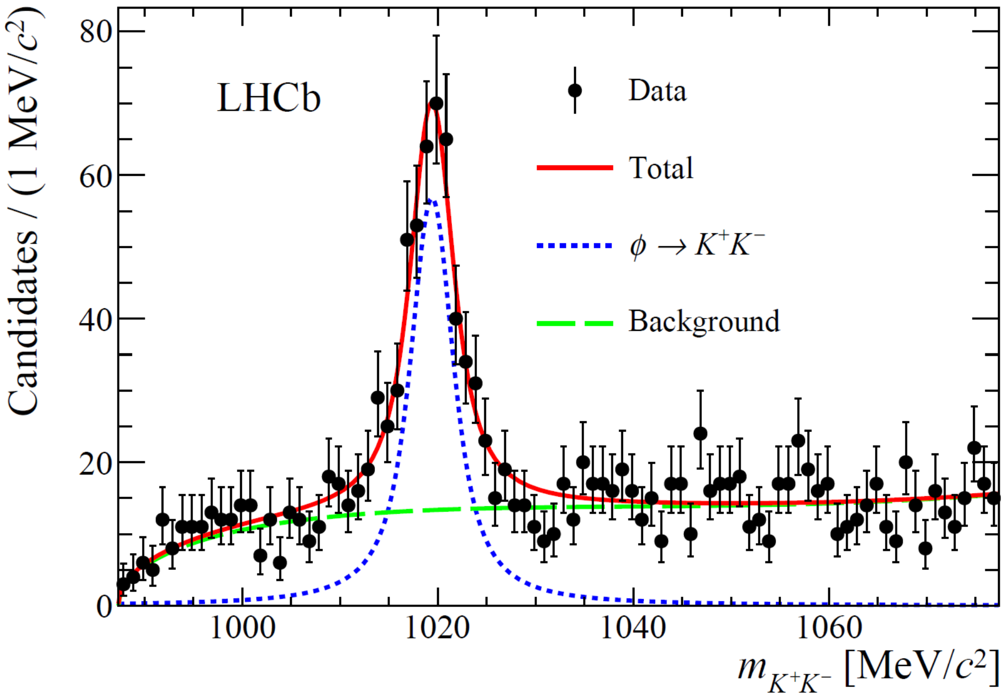
✓ $\mathcal{B}(B^0_s \to \bar{D}^0\phi)$ is $(3.0 \pm 0.8) \times 10^{-5}$ as measured with LHCb 1/fb with a specific selection normalised to $\mathcal{B}(B^0_s \to \bar{D}^0 \bar{K}^{*0})$ (Phys. Lett. B727 (2013) 403)

✓ $B^0_s \to \bar{D}^{*0}\phi$ was still unobserved

arXiv:1807.01892
Phys. Rev. D98 071103(R) (2018)

The $\phi \to K^+K^-$ spectrum of $B^0_{(s)} \to \bar{D}^{(*)0}K^+K^-$

✓ Using selected $B^0_{(s)}$ candidates (see slide on invariant mass fit) in the window $m_{DKK} \in [5000, 6000]$ GeV/c² obtain the following m_{KK} spectrum:



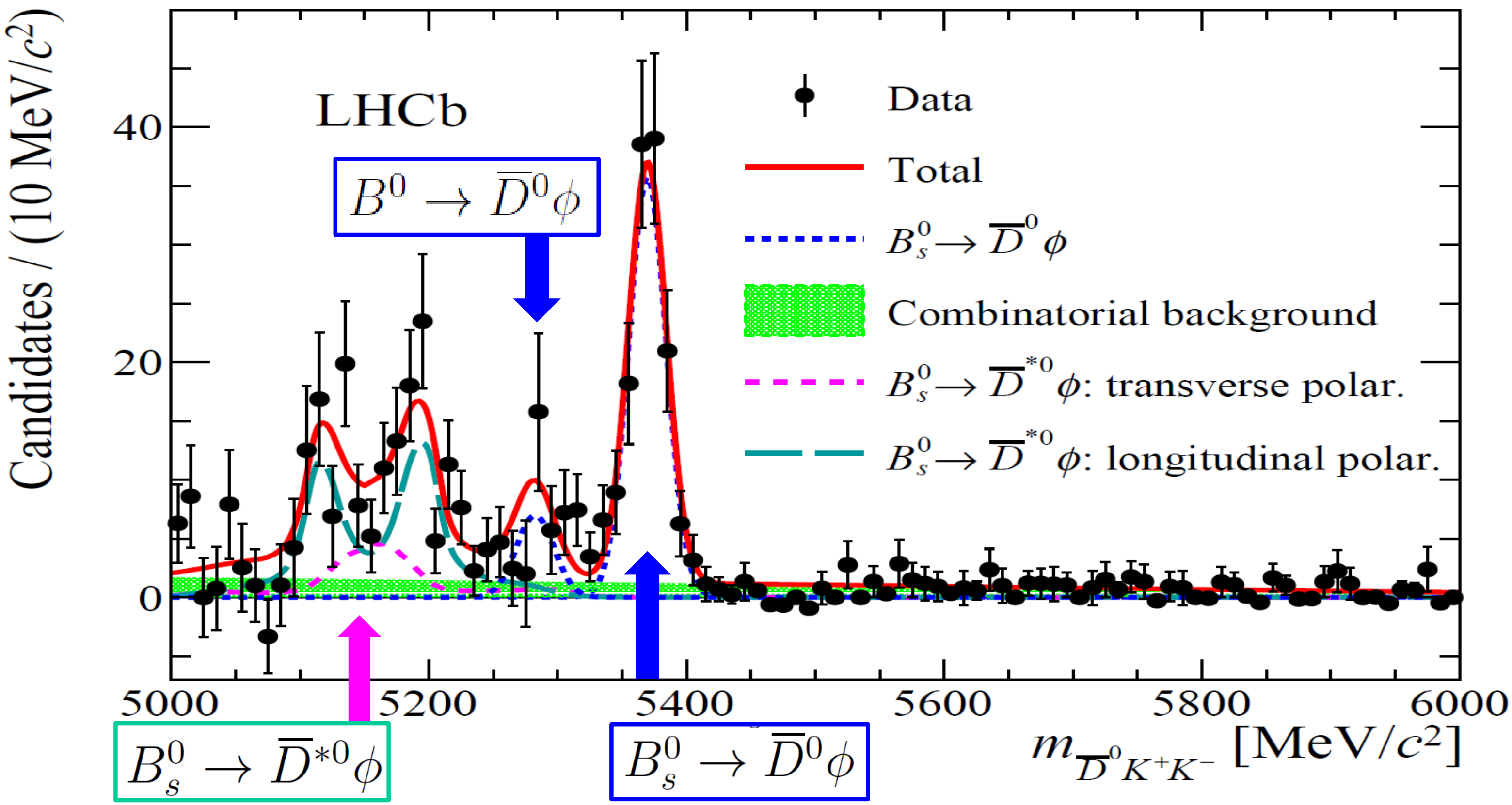
427 ± 30 ϕ signal candidates
1152 ± 41 K^+K^- background

✓ Fit signal with relativistic Breit-Wigner PDF and background with threshold PDF proportional to $(p \times q).(1 + ax + b(2x^2 - 1))$, where p & q are the momentum of the K in the KK rest frame and D in DKK rest frame and $x = 2(m_{K+K-} - 2m_K)/90\ \mathrm{MeV}/c^2 - 1$

✓ Fit used to obtain sPlot-projected mass spectrum $m_{\bar{D}^0 K^+ K^-}$ (correlations with m_{KK} less than 6%)

arXiv:1807.01892
Phys. Rev. D98
071103(R) (2018)

The projected mass spectrum of $B^0_{(s)} \to \bar{D}^{(*)0}\phi$

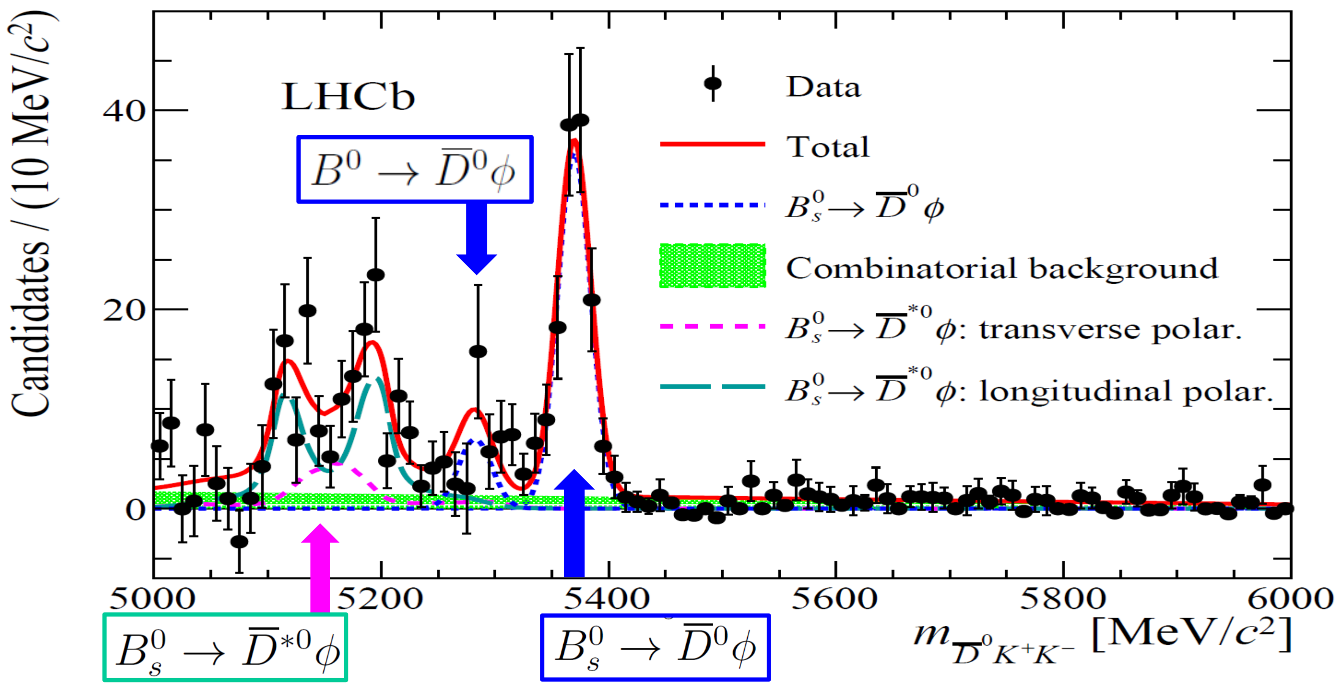


Invariant mass fit:

- ✓ Shape of B^0 and B^0_s decaying to $\bar{D}^0\phi$ modelled by Gaussian functions (mass difference fixed to PDG2018).
- ✓ Shape of B^0_s decaying to $\bar{D}^{*0}\phi$ determined from simulation : sum of 2 PDFs with fully longitudinal/transverse polarisation (f_L=1 or 0) and relative branching fraction D^{*0} to $D^0\gamma/D^0\pi^0$ fixed to PDG2018 value.
- ✓ Remaining combinatorial background modelled by straight line.

arXiv:1807.01892
Phys. Rev. D98
071103(R) (2018)

Fit results for $B^0_{(s)} \to \bar{D}^{(*)0}\phi$



$$N_{B^0_s\to\bar{D}^0\phi} = 132\pm13,\ N_{B^0\to\bar{D}^0\phi} = 26\pm11, \text{ and } \boxed{N_{B^0_s\to\bar{D}^{*0}\phi} = 163\pm19}, \text{ with } f_L = (73\pm15)\%.$$

Observation of $B^0_s \to \bar{D}^{*0}\phi$ with more than 7 standard deviations !

The whole procedure was repeated with various m_{KK} background fit parameters obtained from various regions to evaluate possible biases due to K^+K^- S-Waves under the ϕ resonance.

Future developments in collaboration with UCAS/Tsinghua colleagues

Measuring γ in $B^0_s \to \bar{D}^{(*)0}\phi$ decays

Based on Phys. Lett. B253 (1991) 483 & LHCb-PUB-2010-005 one can define in a **time integrated manner** with D Cabibbo-favoured (CF) or doubly-Cabibbo suppressed decays (DCS) decays merged the observables (normalised rates):

$D \to K\pi$, $K3\pi$, $K\pi\pi^0$ flavour specific

$$R^-_{K\pi} = \frac{\Gamma(D(K^-\pi^+)\phi)}{\Gamma(D(K^-\pi^+)\phi)+\Gamma(D(K^+\pi^-)\phi)}$$

$$R^+_{K\pi} = \frac{\Gamma(D(K^+\pi^-)\phi)}{\Gamma(D(K^-\pi^+)\phi)+\Gamma(D(K^+\pi^-)\phi)}$$

$$R^-_{K3\pi} = \frac{\Gamma(D(K^-3\pi)\phi)}{\Gamma(D(K^-\pi^+)\phi)+\Gamma(D(K^+\pi^-)\phi)}$$

$$R^+_{K3\pi} = \frac{\Gamma(D(K^+3\pi)\phi)}{\Gamma(D(K^-\pi^+)\phi)+\Gamma(D(K^+\pi^-)\phi)}$$

$$R^-_{K\pi\pi^0} = \frac{\Gamma(D(K^-\pi^+\pi^0)\phi)}{\Gamma(D(K^-\pi^+)\phi)+\Gamma(D(K^+\pi^-)\phi)}$$

$$R^+_{K\pi\pi^0} = \frac{\Gamma(D(K^+\pi^-\pi^0)\phi)}{\Gamma(D(K^-\pi^+)\phi)+\Gamma(D(K^+\pi^-)\phi)}$$

$D \to KK$ & $\pi\pi$ CP+ eigenstates

$$R_{KK} = \frac{\Gamma(D(K^+K^-)\phi)}{\Gamma(D(K^-\pi^+)\phi)+\Gamma(D(K^+\pi^-)\phi)}$$

$$R_{\pi\pi} = \frac{\Gamma(D(\pi^+\pi^-)\phi)}{\Gamma(D(K^-\pi^+)\phi)+\Gamma(D(K^+\pi^-)\phi)}$$

or D $\to$Ks**ππ** KsKK with lower rates and more challenging

- ➔ **Precision Counting $B_s \to D^{(*)0}\phi$ signal rates in those modes allows to access to γ and $(r^{(*)}_{Bs}, \delta^{(*)}_{Bs})$ parameters : 8x3 observables and 3 unknowns**
- ➔ **with external inputs on strong D decays + Bs decay time & mixing parameters $y=\Delta\Gamma s/2\Gamma s$ & βs**

HFLAV CLEO-c BESIII

Future developments in collaboration with UCAS/Tsinghua colleagues

Measuring γ in $B^0_s \to \bar{D}^{(*)0}\phi$ decays

Based on Phys. Lett. B253 (1991) 483 & LHCb-PUB-2010-005 one can define in a **time integrated manner** with D Cabibbo-favoured (CF) or doubly-Cabibbo suppressed decays (DCS) decays merged the observables (normalised rates):

$$R^-_{K\pi} = \frac{\left(1+r_B^2\right)\left(1+\left(r_D^{K\pi}\right)^2\right)+4r_B r_D^{K\pi}\cos\delta_B\cos\left(\delta_{K\pi}+\gamma\right)-2yr_B\cos\left(2\beta_s+\delta_B-\gamma\right)}{2\left[\left(1+r_B^2\right)\left(1+\left(r_D^{K\pi}\right)^2\right)+4r_B r_D^{K\pi}\cos\delta_B\cos\delta_{K\pi}\cos\gamma-2yr_B\cos\left(2\beta_s-\gamma\right)\cos\delta_B\right]}$$

$$R^+_{K\pi} = \frac{\left(1+r_B^2\right)\left(1+\left(r_D^{K\pi}\right)^2\right)+4r_B r_D^{K\pi}\cos\delta_B\cos\left(\delta_{K\pi}-\gamma\right)-2yr_B\cos\left(2\beta_s-\delta_B-\gamma\right)}{2\left[\left(1+r_B^2\right)\left(1+\left(r_D^{K\pi}\right)^2\right)+4r_B r_D^{K\pi}\cos\delta_B\cos\delta_{K\pi}\cos\gamma-2yr_B\cos\left(2\beta_s-\gamma\right)\cos\delta_B\right]}$$

$$R_{KK} = F_{KK}\frac{4\left[1+r_B^2+2r_B\cos\delta_B\cos\gamma-2y\sqrt{1+2r_B^2+4r_B\cos\delta_B\cos\gamma}\cos\left(2\beta_s+\tan^{-1}\left(\frac{r_B\sin\left(\delta_B-\gamma\right)}{1+r_B\cos\left(\delta_B-\gamma\right)}\right)-\tan^{-1}\left(\frac{r_B\sin\left(\delta_B+\gamma\right)}{1+r_B\cos\left(\delta_B+\gamma\right)}\right)\right)\right]}{2\left[\left(1+r_B^2\right)\left(1+\left(r_D^{K\pi}\right)^2\right)+4r_B r_D^{K\pi}\cos\delta_B\cos\delta_{K\pi}\cos\gamma-2yr_B\cos\left(2\beta_s-\gamma\right)\cos\delta_B\right]}$$

$$avec \quad F_{KK} = \frac{\varepsilon\left(D\to KK\right)Br\left(D^0\to KK\right)}{\varepsilon\left(D\to K\pi\right)\left[Br\left(D^0\to K^-\pi^+\right)+Br\left(D^0\to K^+\pi^-\right)\right]}$$

$$R_{\pi\pi} = F_{\pi\pi}\frac{4\left[1+r_B^2+2r_B\cos\delta_B\cos\gamma-2y\sqrt{1+2r_B^2+4r_B\cos\delta_B\cos\gamma}\cos\left(2\beta_s+\tan^{-1}\left(\frac{r_B\sin\left(\delta_B-\gamma\right)}{1+r_B\cos\left(\delta_B-\gamma\right)}\right)-\tan^{-1}\left(\frac{r_B\sin\left(\delta_B+\gamma\right)}{1+r_B\cos\left(\delta_B+\gamma\right)}\right)\right)\right]}{2\left[\left(1+r_B^2\right)\left(1+\left(r_D^{K\pi}\right)^2\right)+4r_B r_D^{K\pi}\cos\delta_B\cos\delta_{K\pi}\cos\gamma-2yr_B\cos\left(2\beta_s-\gamma\right)\cos\delta_B\right]}$$

$$avec \quad F_{\pi\pi} = \frac{\varepsilon\left(D\to\pi\pi\right)Br\left(D^0\to\pi\pi\right)}{\varepsilon\left(D\to K\pi\right)\left[Br\left(D^0\to K^-\pi^+\right)+Br\left(D^0\to K^+\pi^-\right)\right]}$$

➔ Efficiencies must accounts decay time acceptance

$$R^-_{K3\pi} = F^-_{K3\pi}\frac{\left[\left(1+r_B^2\right)\left(1+\left(r_D^{K3\pi}\right)^2\right)+4r_B R_{K3\pi}r_D^{K3\pi}\cos\delta_B\cos\left(\delta_{K3\pi}+\gamma\right)-2yr_B\cos\left(2\beta_s+\delta_B-\gamma\right)\right]}{2\left[\left(1+r_B^2\right)\left(1+\left(r_D^{K\pi}\right)^2\right)+4r_B r_D^{K\pi}\cos\delta_B\cos\delta_{K\pi}\cos\gamma-2yr_B\cos\left(2\beta_s-\gamma\right)\cos\delta_B\right]}$$

$$avec \quad F^-_{K3\pi} = \frac{\varepsilon\left(D\to K3\pi\right)\left[Br\left(D^0\to K^-3\pi\right)+Br\left(\bar{D}^0\to K^-3\pi\right)\right]}{\varepsilon\left(D\to K\pi\right)\left[Br\left(D^0\to K^-\pi^+\right)+Br\left(D^0\to K^+\pi^-\right)\right]}$$

$$R^+_{K3\pi} = F^+_{K3\pi}\frac{\left[\left(1+r_B^2\right)\left(1+\left(r_D^{K3\pi}\right)^2\right)+4r_B R_{K3\pi}r_D^{K3\pi}\cos\delta_B\cos\left(\delta_{K3\pi}-\gamma\right)-2yr_B\cos\left(2\beta_s-\delta_B-\gamma\right)\right]}{2\left[\left(1+r_B^2\right)\left(1+\left(r_D^{K\pi}\right)^2\right)+4r_B r_D^{K\pi}\cos\delta_B\cos\delta_{K\pi}\cos\gamma-2yr_B\cos\left(2\beta_s-\gamma\right)\cos\delta_B\right]}$$

$$avec \quad F^+_{K3\pi} = \frac{\varepsilon\left(D\to K3\pi\right)\left[Br\left(D^0\to K^+3\pi\right)+Br\left(\bar{D}^0\to K^+3\pi\right)\right]}{\varepsilon\left(D\to K\pi\right)\left[Br\left(D^0\to K^-\pi^+\right)+Br\left(D^0\to K^+\pi^-\right)\right]}$$

$$R^-_{K\pi\pi^0} = F^-_{K\pi\pi^0}\frac{\left[\left(1+r_B^2\right)\left(1+\left(r_D^{K\pi\pi^0}\right)^2\right)+4r_B R_{K\pi\pi^0}r_D^{K\pi\pi^0}\cos\delta_B\cos\left(\delta_{K\pi\pi^0}+\gamma\right)-2yr_B\cos\left(2\beta_s+\delta_B-\gamma\right)\right]}{2\left[\left(1+r_B^2\right)\left(1+\left(r_D^{K\pi}\right)^2\right)+4r_B r_D^{K\pi}\cos\delta_B\cos\delta_{K\pi}\cos\gamma-2yr_B\cos\left(2\beta_s-\gamma\right)\cos\delta_B\right]}$$

$$avec \quad F^-_{K\pi\pi^0} = \frac{\varepsilon\left(D\to K\pi\pi^0\right)\left[Br\left(D^0\to K^-\pi\pi^0\right)+Br\left(\bar{D}^0\to K^-\pi\pi^0\right)\right]}{\varepsilon\left(D\to K\pi\right)\left[Br\left(D^0\to K^-\pi^+\right)+Br\left(D^0\to K^+\pi^-\right)\right]}$$

$$R^+_{K\pi\pi^0} = F^+_{K\pi\pi^0}\frac{\left[\left(1+r_B^2\right)\left(1+\left(r_D^{K\pi\pi^0}\right)^2\right)+4r_B R_{K\pi\pi^0}r_D^{K\pi\pi^0}\cos\delta_B\cos\left(\delta_{K\pi\pi^0}-\gamma\right)-2yr_B\cos\left(2\beta_s-\delta_B-\gamma\right)\right]}{2\left[\left(1+r_B^2\right)\left(1+\left(r_D^{K\pi}\right)^2\right)+4r_B r_D^{K\pi}\cos\delta_B\cos\delta_{K\pi}\cos\gamma-2yr_B\cos\left(2\beta_s-\gamma\right)\cos\delta_B\right]}$$

$$avec \quad F^+_{K\pi\pi^0} = \frac{\varepsilon\left(D\to K\pi\pi^0\right)\left[Br\left(D^0\to K^+\pi\pi^0\right)+Br\left(\bar{D}^0\to K^+\pi\pi^0\right)\right]}{\varepsilon\left(D\to K\pi\right)\left[Br\left(D^0\to K^-\pi^+\right)+Br\left(D^0\to K^+\pi^-\right)\right]}$$

Future developments in collaboration with UCAS/Tsinghua colleagues

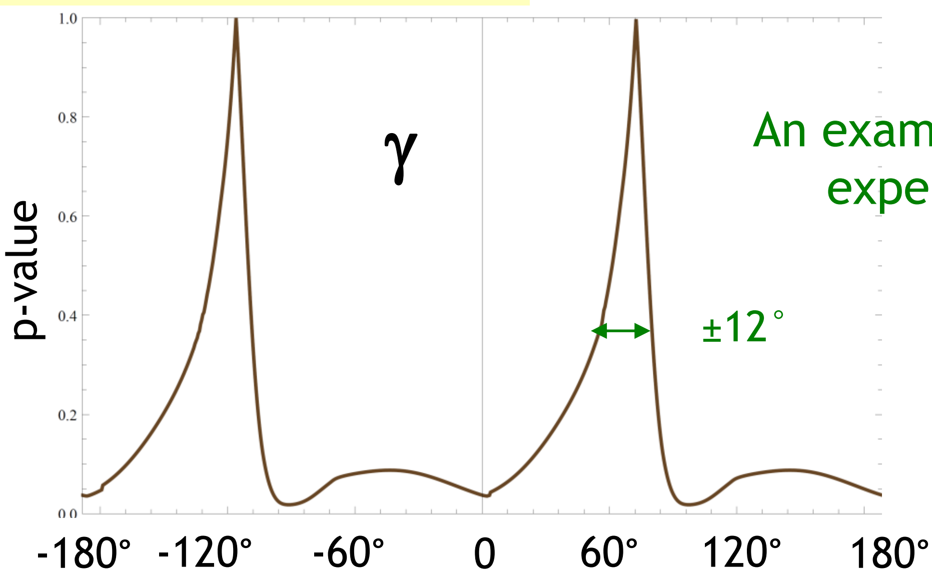
Sensitivity to γ in $B^0_s \to \bar{D}^{(*)0}\phi$ decays

An educated but rough estimate of LHCb Run1+Run2 data number of quasi pure $B_s \to D^{(*)0}\phi$ candidates (with only B to $D^*\phi$ events with f_L=1, for a defined CP eigen-state):

decay	$K\pi$	$K3\pi$	K^+K^-	$\pi^+\pi^-$	$K\pi\pi^0$	$K^0_s\pi^+\pi^-$	$K^0_sK^+K^-$
$D\phi$	604	228	80	23	60	52	7-8
$D^*(D\pi^0)\phi$	350	132	46	14	35	-	-
$D^*(D\gamma)\phi$	191	72	25	7	19	-	-

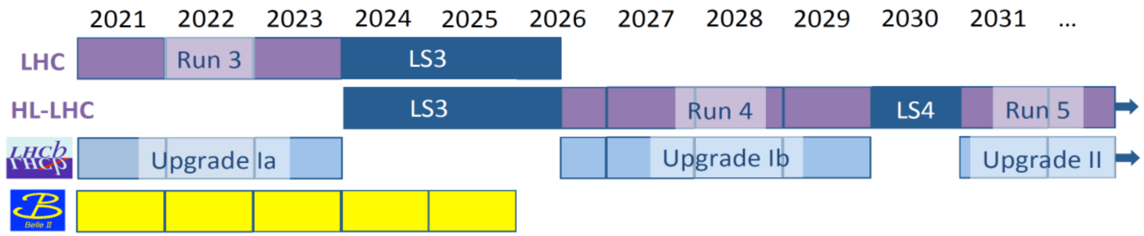
VERY PRELIMINARY:
Expect a statistical sensitivity to the angle γ at the level of <10-15°

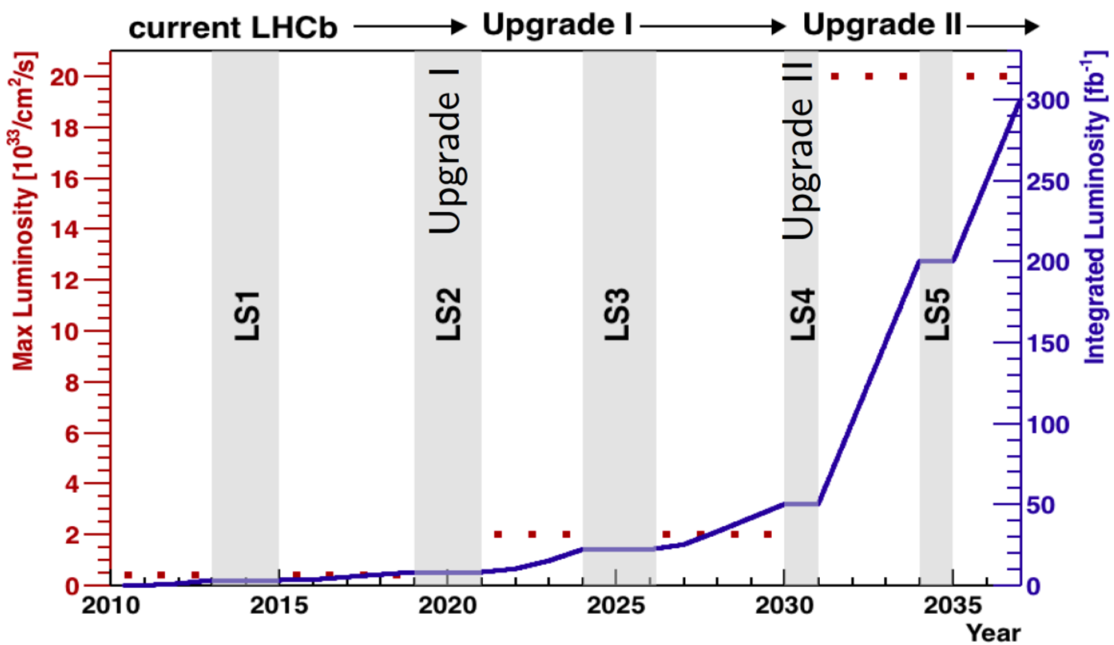
Detailled sensitivity study underway with UCAS/Tsinghua LHCb colleagues, using CKMfitter package



An example of Toy experiment

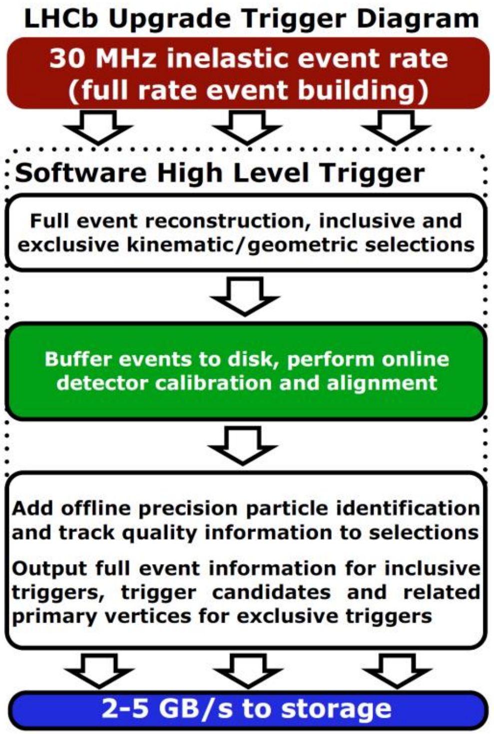
LHCb upgrade schedule towards 50/fb and 300/fb in 12 and 20 years !





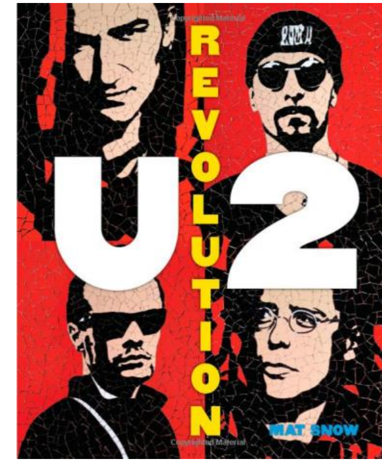
- Upgrade I a+b: $50\,\mathrm{fb}^{-1}$ after Run 3+4 at $\mathcal{L} = 2 \times 10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$
- Upgrade II: $300\,\mathrm{fb}^{-1}$ after Run 5+6 at $\mathcal{L} = 2 \times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$
- Full Belle 2 detector data taking starting 2019, $50\,\mathrm{ab}^{-1}$ sample 2025

LHCb: Trigger/detector upgrade phase 1 for Run 3 starting in 2021



- Removal of L0 bottleneck and move to full software trigger will increase efficiencies, by a factor of ~ 2 for hadronic modes
- Upgrade I replaces frontend electronics: readout at inelastic $30\,\mathrm{MHz}$ rate
- Far reaching detector upgrades to improve occupancy, radiation hardness
  Vertex Locator $\rightarrow$ Pixel; Main trackers $\rightarrow$ SciFi Tracker, UT; RICH photodetectors

LHCb: upgrade Phase 2 (U2)



Physics case for an LHCb Upgrade II

Opportunities in flavour physics, and beyond, in the HL-LHC era

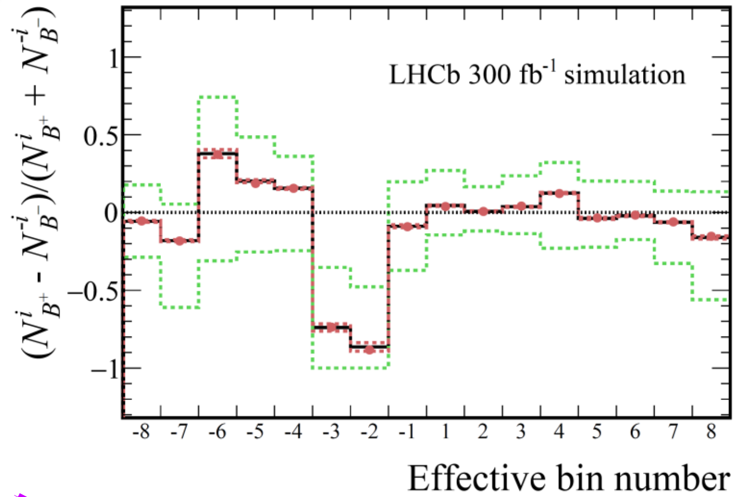
The LHCb collaboration

Abstract

The LHCb Upgrade II will fully exploit the flavour-physics opportunities of the HL-LHC, and study additional physics topics that take advantage of the forward acceptance of the LHCb spectrometer. The LHCb Upgrade I will begin operation in 2020. Consolidation will occur, and modest enhancements of the Upgrade I detector will be installed, in Long Shutdown 3 of the LHC (2025) and these are discussed here. The main Upgrade II detector will be installed in long shutdown 4 of the LHC (2030) and will build on the strengths of the current LHCb experiment and the Upgrade I. It will operate at a luminosity up to $2 \times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$, ten times that of the Upgrade I detector. New detector components will improve the intrinsic performance of the experiment in certain key areas. An Expression Of Interest proposing Upgrade II was submitted in February 2017. The physics case for the Upgrade II is presented here in more depth. *CP*-violating phases will be measured with precisions unattainable at any other envisaged facility. The experiment will probe $b \to s\ell^+\ell^-$ and $b \to d\ell^+\ell^-$ transitions in both muon and electron decays in modes not accessible at Upgrade I. Minimal flavour violation will be tested with a precision measurement of the ratio of $\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B^0_s \to \mu^+\mu^-)$. Probing charm *CP* violation at the 10^{-5} level may result in its long sought discovery. Major advances in hadron spectroscopy will be possible, which will be powerful probes of low energy QCD. Upgrade II potentially will have the highest sensitivity of all the LHC experiments on the Higgs to charm-quark couplings. Generically, the new physics mass scale probed, for fixed couplings, will almost double compared with the pre-HL-LHC era; this extended reach for flavour physics is similar to that which would be achieved by the HE-LHC proposal for the energy frontier.

Looking forwards : LHCb upgrade & gains on γ precision

Physics case for an LHCb Upgrade II
arXiv:1808.08865

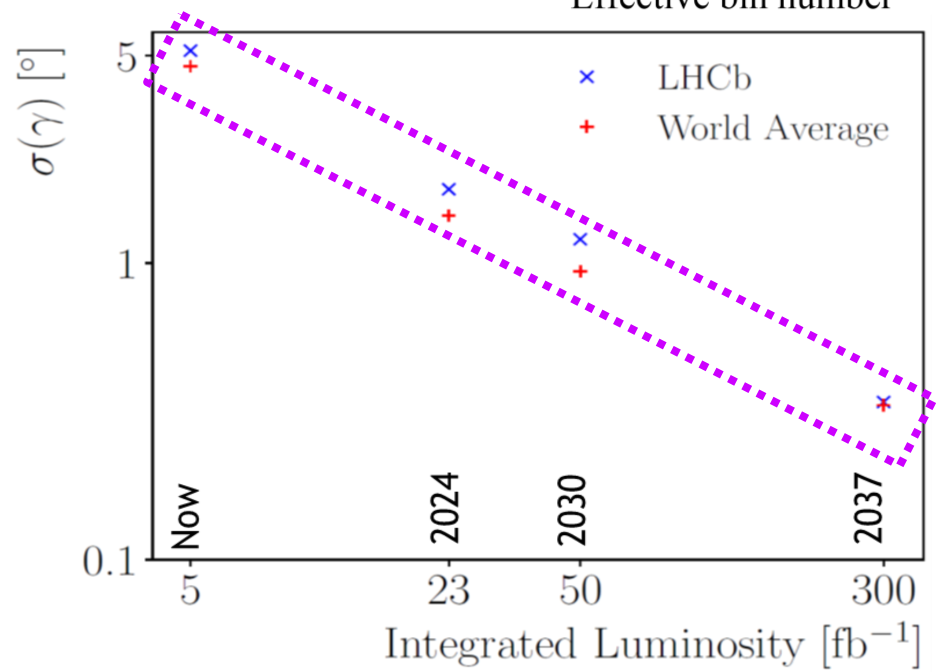


Exciting times - measurements of γ are reaching a high precision era:

- We look forward to collaboration and competition from Belle-II

- With 50 ab^{-1} at Belle-II and a possible 300 fb^{-1} sample at LHCb: $\sigma(\gamma)<0.35°$ to tackle BSM physics in CKM global fit well above a few 10 TeVs

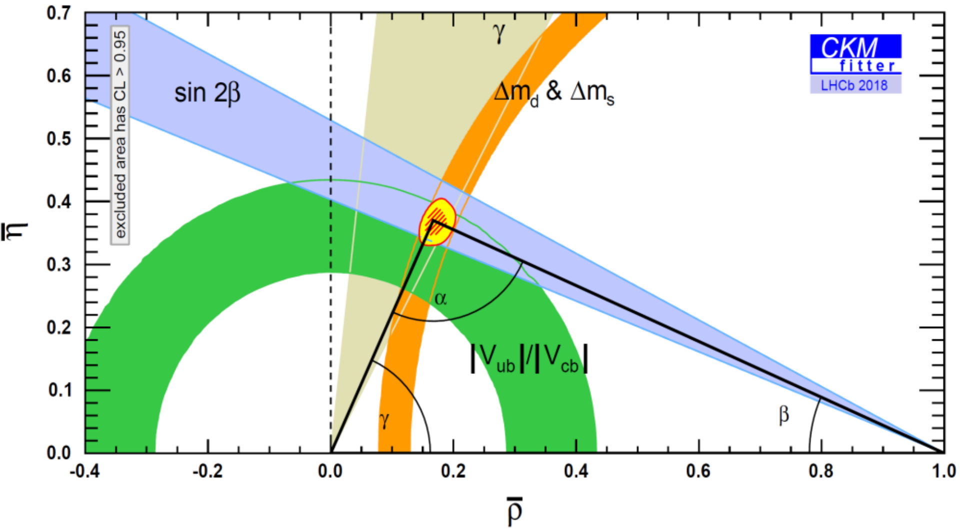
- New ideas can help us go even further (some of them shown in this seminar)
- Will require new charm inputs from BES-III, LHCb and Belle-II



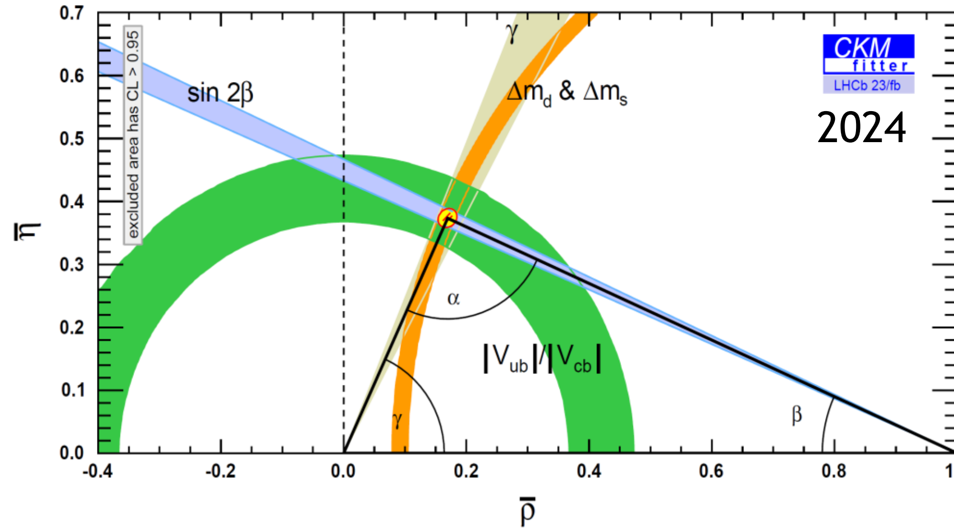
Prospects for CKM fit : LHCb upgrade

Physics case for an LHCb Upgrade II
arXiv:1808.08865

LHCb now



LHCb Upgrade Ia 23 fb^{-1}

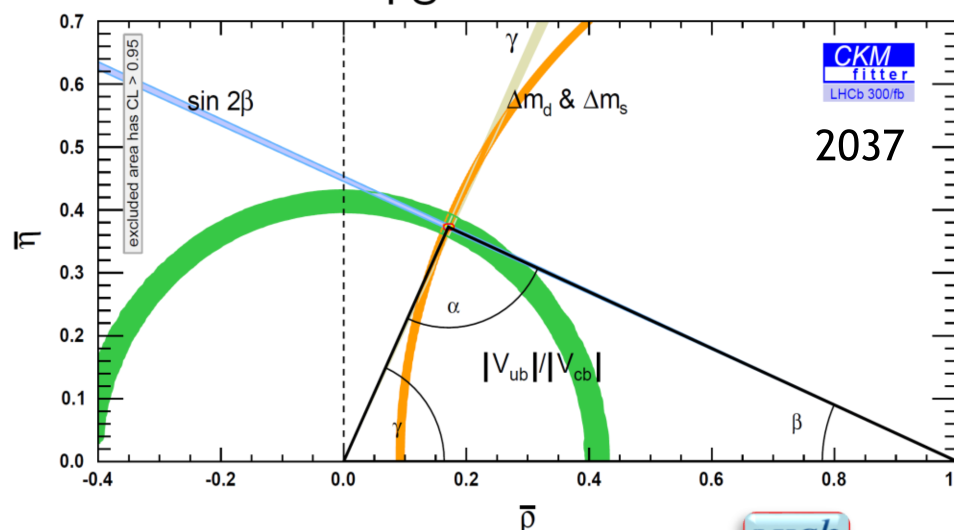


Inputs

	LHCb (now)	LHCb 23 fb^{-1}	LHCb 300 fb^{-1}
CKM inputs (LHCb)			
$\sin 2\beta$	0.760 ± 0.034	0.7480 ± 0.0095	0.7480 ± 0.0024
γ rad	$1.296^{+0.087}_{-0.101}$	1.136 ± 0.025	1.136 ± 0.005
$\lvert V_{\mathrm{ub}}\rvert / \lvert V_{\mathrm{cb}}\rvert$	15%	6%	1%
$\Delta m_d (\mathrm{ps}^{-1})$	0.5065 ± 0.0020	same or better	same
$\Delta m_s (\mathrm{ps}^{-1})$	17.757 ± 0.021	same	same
Hadronic input (LQCD)			
$\xi = \frac{f_{B_d}\sqrt{B_{B_d}}}{f_{B_s}\sqrt{B_{B_s}}}$	2.0%	0.6%	0.2%

LHCb "alone"

LHCb Upgrade II 300 fb^{-1}



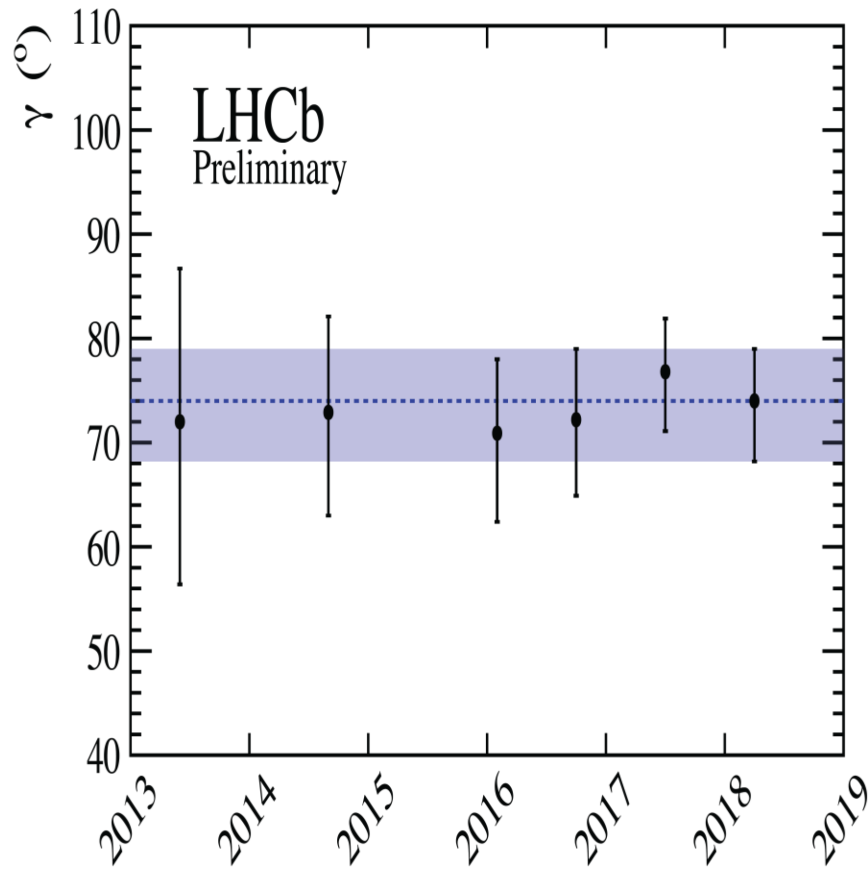
Facing other experiments

Physics case for an LHCb Upgrade II
arXiv:1808.08865

Observable	Current LHCb	LHCb 2025	Belle II	Upgrade II	ATLAS & CMS
EW Penguins					
R_K $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1 [274]	0.025	0.036	0.007	–
R_{K^*} $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1 [275]	0.031	0.032	0.008	–
R_ϕ, R_{pK}, R_π	–	0.08, 0.06, 0.18	–	0.02, 0.02, 0.05	–
CKM tests					
γ, with $B_s^0 \to D_s^+ K^-$	$(^{+17}_{-22})^\circ$ [136]	4°	–	1°	–
γ, all modes	$(^{+5.0}_{-5.8})^\circ$ [167]	1.5°	1.5°	0.35°	–
$\sin 2\beta$, with $B^0 \to J/\psi K_S^0$	0.04 [609]	0.011	0.005	0.003	–
ϕ_s, with $B_s^0 \to J/\psi\phi$	49 mrad [44]	14 mrad	–	4 mrad	22 mrad [610]
ϕ_s, with $B_s^0 \to D_s^+ D_s^-$	170 mrad [49]	35 mrad	–	9 mrad	–
$\phi_s^{s\bar{s}s}$, with $B_s^0 \to \phi\phi$	154 mrad [94]	39 mrad	–	11 mrad	Under study [611]
a_{sl}^s	33×10^{-4} [211]	10×10^{-4}	–	3×10^{-4}	–
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$	6% [201]	3%	1%	1%	–
$\boldsymbol{B_s^0, B^0 \to \mu^+\mu^-}$					
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	90% [264]	34%	–	10%	21% [612]
$\tau_{B_s^0 \to \mu^+\mu^-}$	22% [264]	8%	–	2%	–
$S_{\mu\mu}$	–	–	–	0.2	–
$\boldsymbol{b \to c\ell^-\bar{\nu}_l}$ **LUV studies**					
$R(D^*)$	0.026 [215, 217]	0.0072	0.005	0.002	–
$R(J/\psi)$	0.24 [220]	0.071	–	0.02	–
Charm					
$\Delta A_{CP}(KK - \pi\pi)$	8.5×10^{-4} [613]	1.7×10^{-4}	5.4×10^{-4}	3.0×10^{-5}	–
A_Γ $(\approx x \sin\phi)$	2.8×10^{-4} [240]	4.3×10^{-5}	3.5×10^{-4}	1.0×10^{-5}	–
$x \sin\phi$ from $D^0 \to K^+\pi^-$	13×10^{-4} [228]	3.2×10^{-4}	4.6×10^{-4}	8.0×10^{-5}	–
$x \sin\phi$ from multibody decays	–	$(K3\pi)$ 4.0×10^{-5}	$(K_S^0\pi\pi)$ 1.2×10^{-4}	$(K3\pi)$ 8.0×10^{-6}	–

Conclusions

- Excellent progress from LHCb over the last few years
  - As shown today we are currently exploiting our beautiful Run-II data sample
  - The Run-II precision will be around 3 or 4 degrees



- Latest combination gives

$$\gamma_{\mathrm{LHCb}}=(74.0^{+5.0}_{-5.8})^{\circ}$$

- Indirect measurements

$$\gamma_{\mathrm{CKMfitter}}=(65.6^{+1.0}_{-3.4})^{\circ}$$

1.7σ shift

- Watch this space…
  - Lots more to come from LHCb, LHCb upgrade(s) and Belle-II!

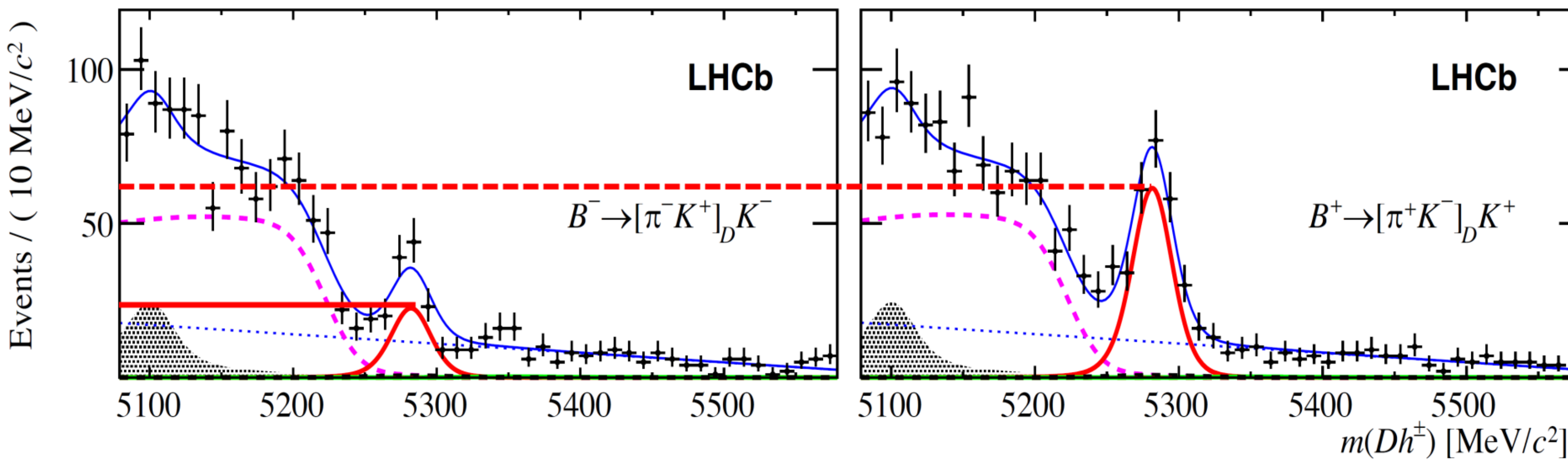
BACKUP
Slides

Measuring γ : ADS DK

ADS observables

$$A_{ADS} = \frac{\Gamma(B^- \to [K^+\pi^-]_D K^-) - \Gamma(B^+ \to [K^-\pi^+]_D K^+)}{\Gamma(B^- \to [K^+\pi^-]_D K^-) + \Gamma(B^+ \to [K^-\pi^+]_D K^+)} = \frac{2 r_B r_D \kappa_D \sin(\delta_B + \delta_D)\sin(\gamma)}{r_B^2 + r_D^2 + 2 r_B r_D \kappa_D \cos(\delta_B + \delta_D)\cos(\gamma)} \quad (3)$$

$$R_{ADS} = \frac{\Gamma(B^- \to [K^+\pi^-]_D K^-) + \Gamma(B^+ \to [K^-\pi^+]_D K^+)}{\Gamma(B^- \to [K^-\pi^+]_D K^-) + \Gamma(B^+ \to [K^+\pi^-]_D K^+)} = r_B^2 + r_D^2 + 2 r_B r_D \kappa_D \cos(\delta_B + \delta_D)\cos(\gamma) \quad (4)$$



- Much harder to extract partially reconstructed observables because of $B_s^0 \to D^{(*)0} K^+ \pi^-$ backgrounds.

Measuring γ : GLW D(*)K

- a positive CP asymmetry observed in $B^{\pm} \to D_{CP} K^{\pm}$
- $B^- \to D^* K^-, \;\; D^* \to D\pi^0$:

$$D = D^0 + r_B e^{i(\delta_B - \gamma)} \overline{D}^0$$

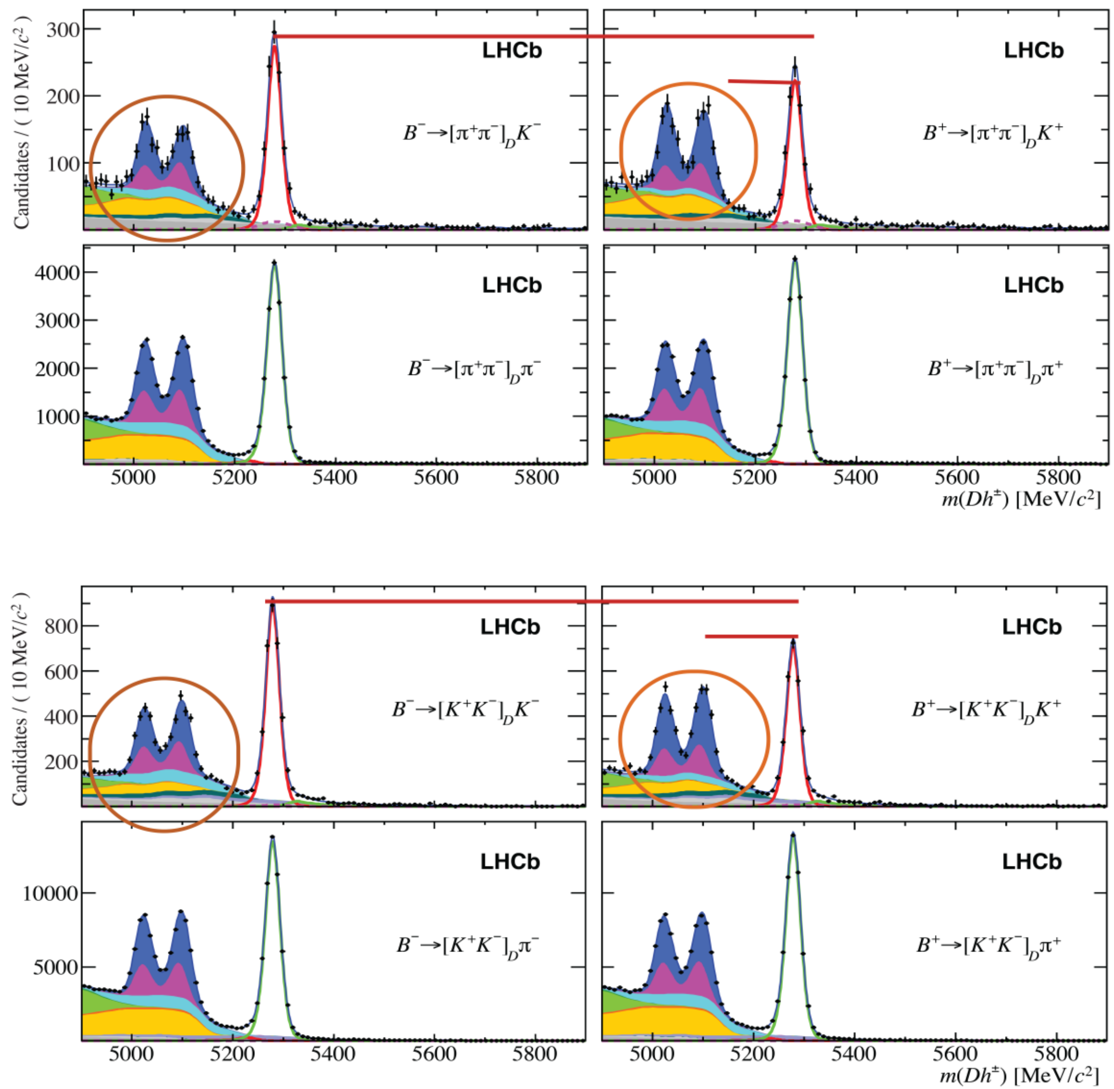
- $B^- \to D^* K^-, \;\; D^* \to D\gamma$:

$$D = D^0 + r_B e^{i(\delta_B + \pi - \gamma)} \overline{D}^0$$

PRD **70**, 091503

CP asymmetries from $D^* \to D\pi^0$ and $D^* \to D\gamma$ have opposite signs

The $B^{\mp} \to D^{(*)} h^{\mp}$ signals



PLB **777** (1028) 16

Measuring γ : GLW D(*)K

Defining

$$R^{K\pi}_{K/\pi} \equiv \frac{\Gamma(B^- \to [K^-\pi^+]_D K^-) + \Gamma(B^+ \to [K^+\pi^-]_D K^+)}{\Gamma(B^- \to [K^-\pi^+]_D \pi^-) + \Gamma(B^+ \to [K^+\pi^-]_D \pi^+)} \approx \frac{\mathcal{B}(B^- \to D^0 K^-)}{\mathcal{B}(B^- \to D^0 \pi^-)}$$

and averaging R_{KK}, $R_{\pi\pi}$ and A^{KK}_{CP}, $A^{\pi\pi}_{CP}$:

$$R_{CP+} = \frac{\Gamma(B^- \to D_{CP} K^-) + \Gamma(B^+ \to D_{CP} K^+)}{\Gamma(B^- \to D_{CP} \pi^-) + \Gamma(B^+ \to D_{CP} \pi^+)} \times \frac{1}{R^{K\pi}_{K/\pi}}$$

$$= 1 + (r_B^{DK})^2 + 2 r_B^{DK} \cos \delta_B^{DK} \cos \gamma$$

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

$$\boxed{\begin{aligned} R_{CP+} &= 0.989 \pm 0.013 \pm 0.010 \\ A_{CP+} &= 0.124 \pm 0.012 \pm 0.002 \end{aligned}}$$

PLB **777** (1028) 16

Values of these and the other observables to be used in the γ combination

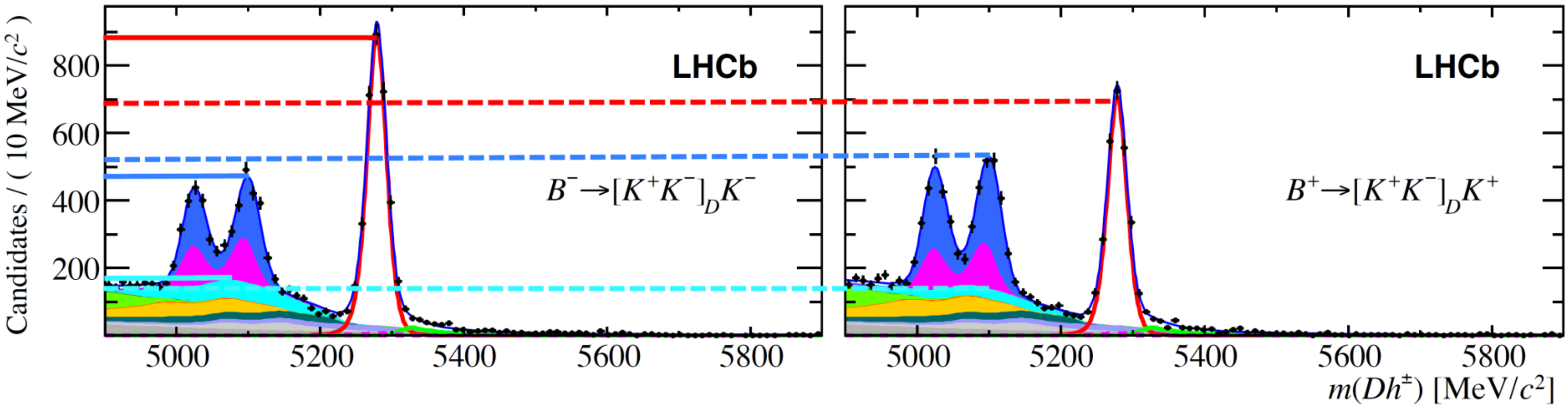
Measuring γ : GLW D(*)K

- CP eigenstates e.g. $D \to KK$, $D \to K^0_S\pi^0$
- Gronau, London, Wyler (1991)
- [Phys. Lett. B253 (1991) 483]
- [Phys. Lett. B265 (1991) 172]

GLW observables

$$A_{CP} = \frac{\Gamma(B^- \to D^0_{CP}K^-) - \Gamma(B^+ \to D^0_{CP}K^+)}{\Gamma(B^- \to D^0_{CP}K^-) + \Gamma(B^+ \to D^0_{CP}K^+)} = \frac{\pm 2r_B(2F^+ + 1)\sin(\delta_B)\sin(\gamma)}{1 + r_B^2 \pm 2r_B(2F^+ + 1)\cos(\delta_B)\cos(\gamma)} \quad (1)$$

$$R_{CP} = \frac{\Gamma(B^- \to D^0_{CP}K^-) + \Gamma(B^+ \to D^0_{CP}K^+)}{\Gamma(B^- \to D^0K^-) + \Gamma(B^+ \to D^0K^+)} = 1 + r_B^2 \pm 2r_B(2F^+ + 1)\cos(\delta_B)\cos(\gamma) \quad (2)$$



- **LHCb has recently extracted GLW observables from partially reconstructed $B^- \to D^{*0}K^-$ in the same fit** - [Phys. Lett. B777 (2018) 16]
- Can extend to quasi-CP-eigenstates ($D^0 \to KK\pi^0$) if fraction of CP content, F^+, is known

F^+=0 in Eq (1) & (2) for KK and $\pi\pi$

Measurement of CP observables in $B^{\pm} \to DK^{*\pm}$ decays using two- and four-body D final states JHEP 11(2017) 156

12 CP observables from $B^- \to D(\to f)K^*(892)^-$, $K^*(892)^- \to K_S^0\pi^-$

$$f = K^-K^+,\ \pi^-\pi^+,\ K^{\mp}\pi^{\pm},\ \pi^+\pi^-\pi^+\pi^-,\ K^{\mp}\pi^{\pm}\pi^+\pi^-$$

$$A_{CP}^f = \frac{\Gamma(B^- \to D(\to f)K^{*-}) - \Gamma(B^+ \to D(\to \bar{f})K^{*+})}{\Gamma(B^- \to D(\to f)K^{*-}) + \Gamma(B^+ \to D(\to \bar{f})K^{*+})} \quad (A_{CP} = A_{\text{raw}} - A_{\text{prod}} - A_{\text{det}})$$

$$R_f = \frac{\Gamma(B^- \to D(\to f)K^{*-}) + \Gamma(B^+ \to D(\to \bar{f})K^{*+})}{\Gamma(B^- \to D_{\text{fav}}K^{*-}) + \Gamma(B^+ \to D_{\text{fav}}K^{*+})} \times \frac{\mathcal{B}(D^0_{\text{fav}})}{\mathcal{B}(D^0 \to f)}$$

Neglecting CPV and mixing in D decays:

$$A_{CP}^{KK} = A_{CP}^{\pi\pi} = A_{CP+}$$
$$R_{KK} = R_{\pi\pi} = R_{CP+}$$

The ADS modes:

$$B^- \to [K^+\pi^-]_D K^{*-}$$
$$B^- \to [K^+\pi^-\pi^+\pi^-]_D K^{*-}$$

No CPV expected in favoured decays D_{fav}

$$B^- \to [K^-\pi^+]_D K^{*-}$$
$$B^- \to [K^-\pi^+\pi^+\pi^-]_D K^{*-}$$

The relation between CP observables and physics parameters:

$$A_{CP+} = \frac{2\kappa r_B \sin\delta_B \sin\gamma}{1 + r_B^2 + 2\kappa r_B \cos\delta_B \cos\gamma} , \qquad R_{CP+} = 1 + r_B^2 + 2\kappa r_B \cos\delta_B \cos\gamma ,$$

κ accounts for $K_S^0\pi$ not from K^* ($\kappa = 1$: pure K^*)

$\kappa = 0.95 \pm 0.06$, from simulations

$$A_{\pi\pi\pi\pi} = \frac{2\kappa\,(2F_{4\pi} - 1)\, r_B \sin\delta_B \sin\gamma}{1 + r_B^2 + 2\kappa\,(2F_{4\pi} - 1)\, r_B \cos\delta_B \cos\gamma} ,$$

$$R_{\pi\pi\pi\pi} = 1 + r_B^2 + 2\kappa\,(2F_{4\pi} - 1)\, r_B \cos\delta_B \cos\gamma ,$$

$F_{4\pi}(\sim 0.75)$: $\pi^-\pi^+\pi^-\pi^+$ is not a pure CP eigenstate

PLB **747** (2015) 9

ADS decays need additional external inputs

$$R^{\pm}_{K\pi} = \frac{r_B^2 + \left(r_D^{K\pi}\right)^2 + 2\kappa r_B r_D^{K\pi} \cos(\delta_B + \delta_D^{K\pi} \pm \gamma)}{1 + r_B^2 \left(r_D^{K\pi}\right)^2 + 2\kappa r_B r_D^{K\pi} \cos(\delta_B - \delta_D^{K\pi} \pm \gamma)} ,$$

$r_D^{K\pi}$, $\delta_D^{K\pi}$

HFLAV, arXiv:1612.07233

$$R^{\pm}_{K\pi\pi\pi} = \frac{r_B^2 + \left(r_D^{K3\pi}\right)^2 + 2\kappa r_B \kappa_{K3\pi} r_D^{K3\pi} \cos(\delta_B + \delta_D^{K3\pi} \pm \gamma)}{1 + \left(r_B r_D^{K3\pi}\right)^2 + 2\kappa r_B \kappa_{K3\pi} r_D^{K3\pi} \cos(\delta_B - \delta_D^{K3\pi} \pm \gamma)} .$$

$r_D^{K3\pi}$, $\delta_D^{K3\pi}$, $\kappa_{K3\pi}$

PRL **116** (2016) 241801

PLB **757** (2016) 520

Measure strong phases

e.g. probe strong-phase distribution of multibody decays…

$D^{*+} \rightarrow D^0 \pi^+$ or $D^0 \rightarrow Kl\nu$

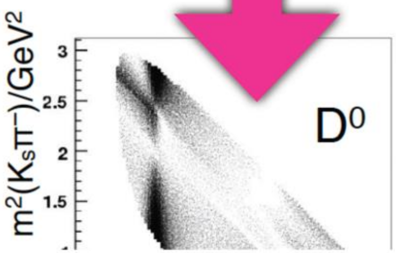
$\rightarrow D^0 \rightarrow K_S \pi^+ \pi^-$

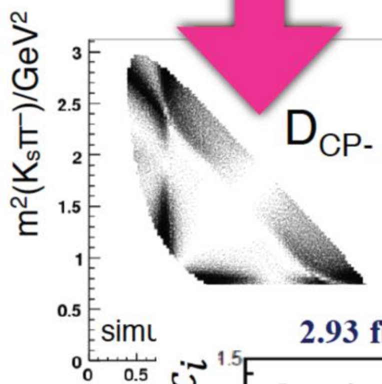
$\psi'' \rightarrow D_a D_b$

$\rightarrow D_a \rightarrow KK$ eg. CP+

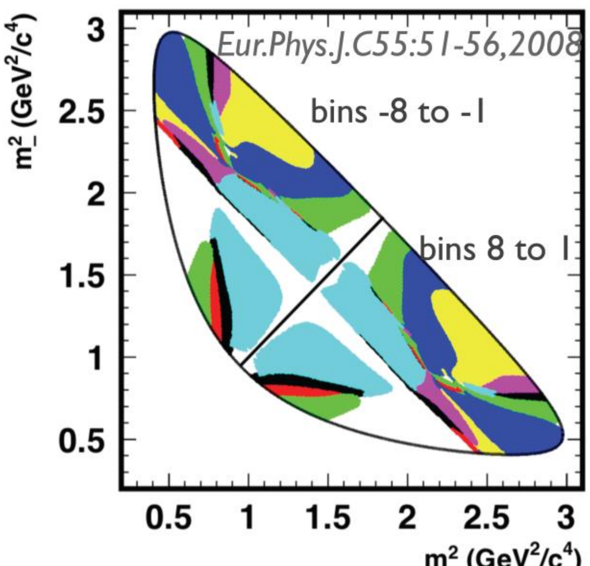
$\rightarrow D_b \rightarrow K_S \pi^+ \pi^-$

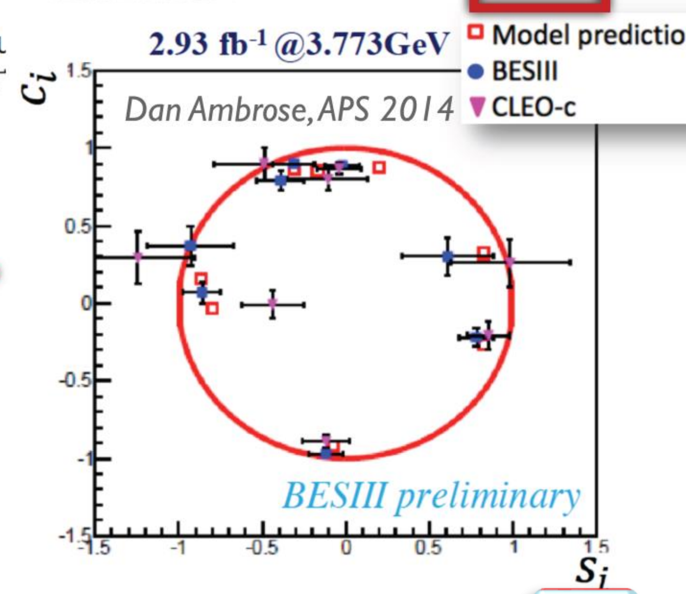
Flavour tagged Distribution ~ $|D^0|^2$ or $|\bar{D}^0|^2$





CP-tagged ~ $|D^0|^2 + |\bar{D}^0|^2 \pm 2 D^0\bar{D}^0 \boxed{\cos\delta}$

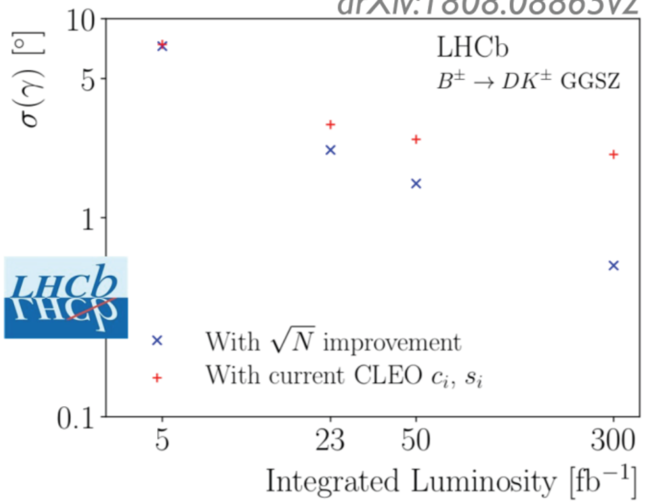




Importance of this measurement

- Most precise determination of γ from a single channel from B→DK with D→$K_S$hh $\gamma = \left(80.0^{+10.0}_{-9.0}\right)^\circ$ *JHEP 08 176*
- Uncertainty due to strong-phase inputs (CLEO-c) 4° > uncertainty due to experimental systematic effects 2°

arXiv:1808.08865v2



3° with 50 ab^{-1} at BELLEII

P. Krishnan, FPCP2018

- Input important for B→DKπ with D→$K_S$hh, precision of 2° achievable after the upgrade *Craik et al.,arXiv:1712.0853*

How does this GGSZ Model Indep. Method works ?

- The Dalitz plot is divided into 2n bins, from $i=-n$ to $i=+n$. The populations of bins $\pm i$ are

$$N^{+}_{\pm i} = \boxed{h_{B^+}} \left[\boxed{F_{\mp i}} + (x_+^2 + y_+^2) F_{\pm i} + 2\sqrt{F_i F_{-i}} (x_+ \boxed{c_{\pm i}} - y_+ \boxed{s_{\pm i}}) \right]$$

$$N^{-}_{\pm i} = \boxed{h_{B^-}} \left[\boxed{F_{\pm i}} + (x_-^2 + y_-^2) F_{\mp i} + 2\sqrt{F_i F_{-i}} (x_- \boxed{c_{\pm i}} + y_- \boxed{s_{\pm i}}) \right]$$

normalization factors

fraction of decays in bins $\pm i$

strong phases from CLEO-c

$$F_i = \frac{\int_i dm_-^2 dm_+^2 |A_D(m_-^2, m_+^2)|^2 \, \eta(m_-^2, m_+^2)}{\sum_j \int_j dm_-^2 dm_+^2 |A_D(m_-^2, m_+^2)|^2 \, \eta(m_-^2, m_+^2)}$$

from $B \to D^{*\pm} \mu^{\mp} \nu_\mu X$ with $D^{*+} \to D^0 \pi^+, \ D^0 \to K_S^0 \pi^+ \pi^+$

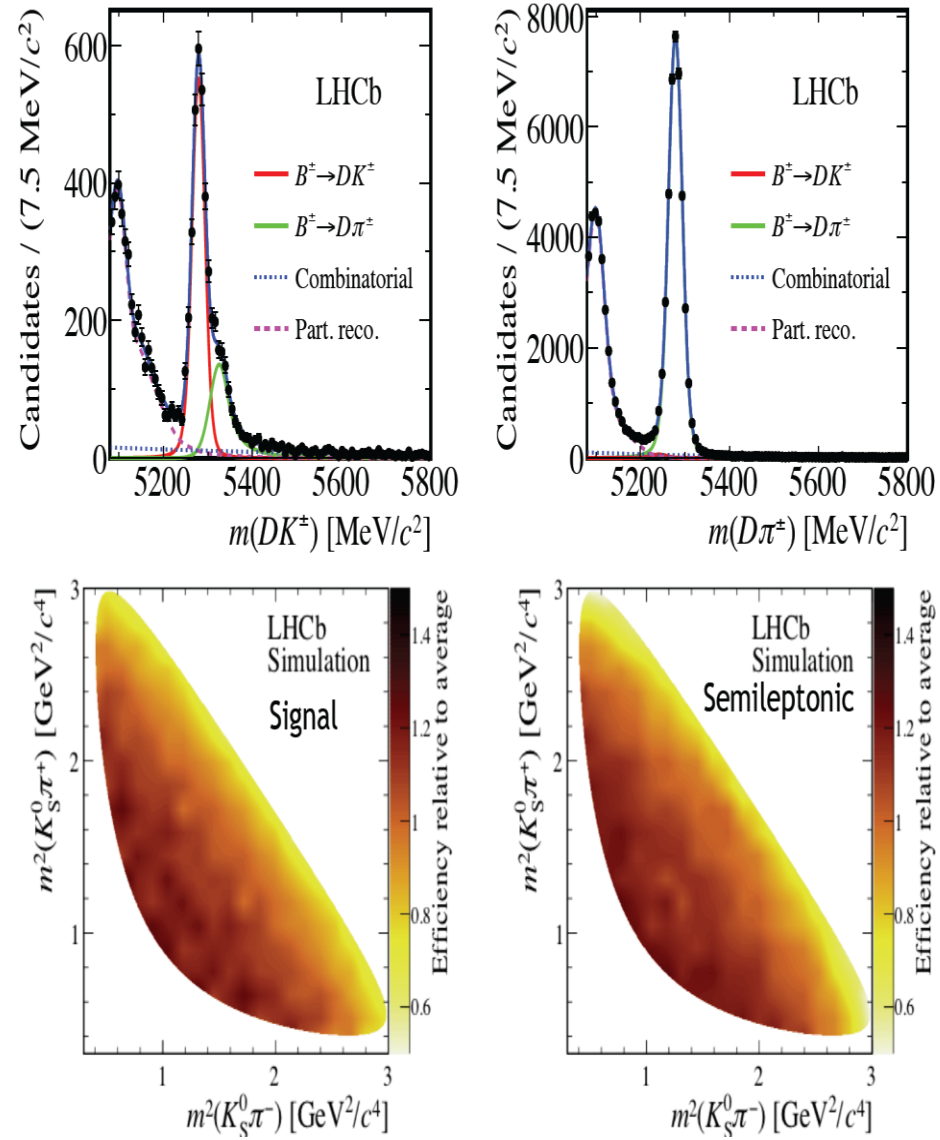
$$c_i \equiv \frac{\int_i dm_-^2\, dm_+^2\, |A_D(m_-^2, m_+^2)||A_D(m_+^2, m_-^2)| \cos[\delta_D(m_-^2, m_+^2) - \delta_D(m_+^2, m_-^2)]}{\sqrt{\int_i dm_-^2\, dm_+^2\, |A_D(m_-^2, m_+^2)|^2 \int_i dm_-^2\, dm_+^2\, |A_D(m_+^2, m_-^2)|^2}}$$

$\gamma,\ r_B,\ \delta_B$ translated into $x_\pm \equiv r_B \cos(\delta_B \pm \gamma), \quad y_\pm \equiv r_B \sin(\delta_B \pm \gamma)$

How does this GGSZ Model Indep. Method works ?

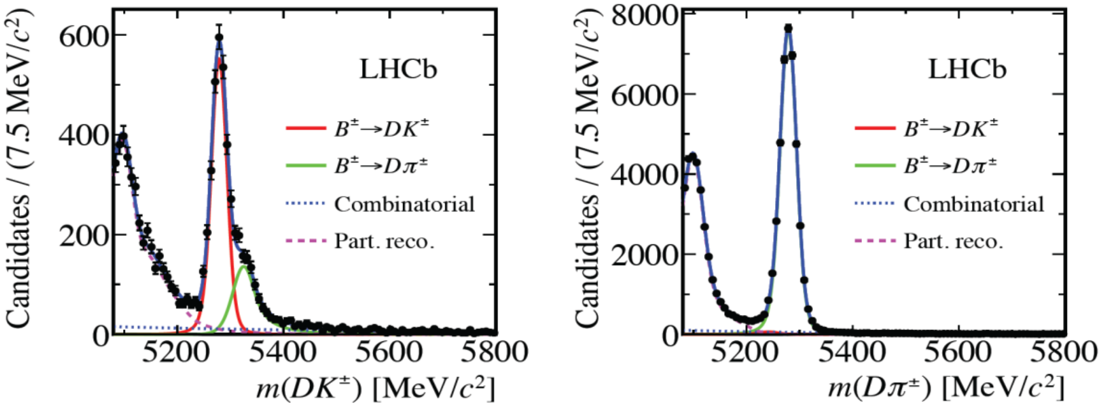
- Fitting the invariant mass distribution
  - Cross-feeds from $\pi \to K$ misid taken from control mode $B^- \to D\pi^-$
- Efficiencies over the D Dalitz plot
  - Taken from simulation with data driven corrections
  - Smoothly varying
  - Account for differences between the signal decays and semileptonic control sample used to described the fraction of $D^0\bar{D}^0$ in each bin

[LHCb-PAPER-2018-017]

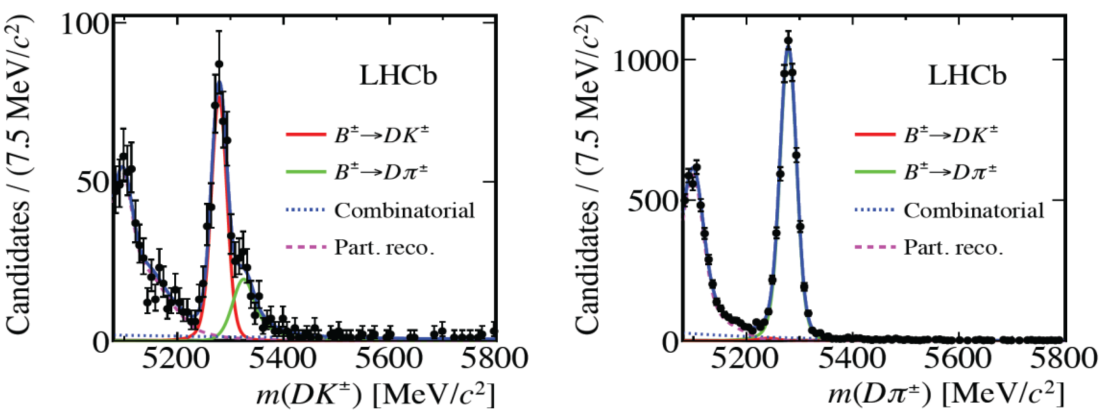


How does this GGSZ Model Indep. Method works ?

$D^0 \to K^0_S \pi^+ \pi^-$ JHEP **08**, 176



$D^0 \to K^0_S K^+ K^+$



$B^- \to D\pi^-$ used to estimate contamination in $B^- \to DK^-$ sample due to $\pi - K$ misID

A fit to the 8 $B^\pm \to Dh^\pm$ subsamples, integrated over the DP, fix the shapes of signal and bkg.

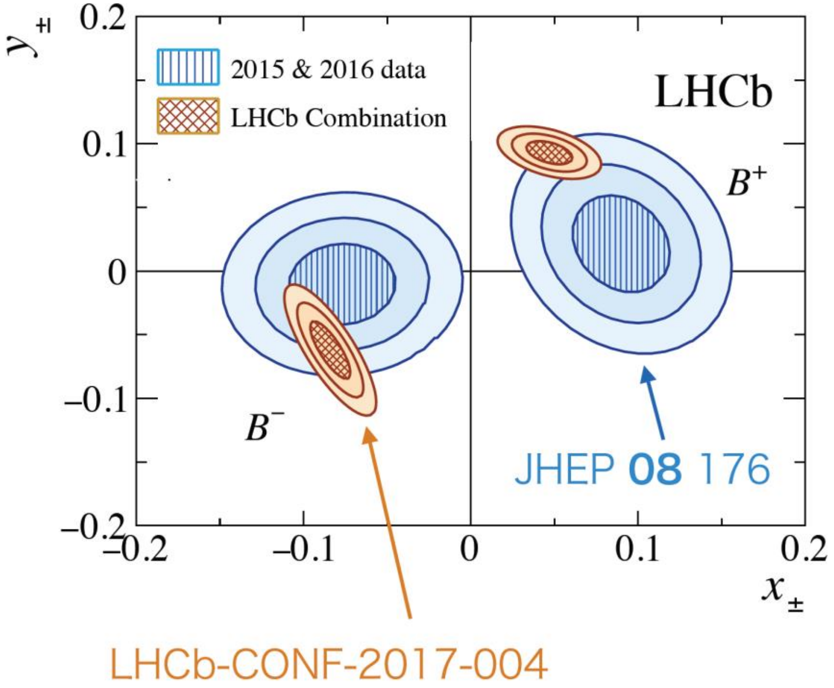
yields/bin of $B^\pm \to D\pi^\pm$: direct $B^\pm$ mass fit

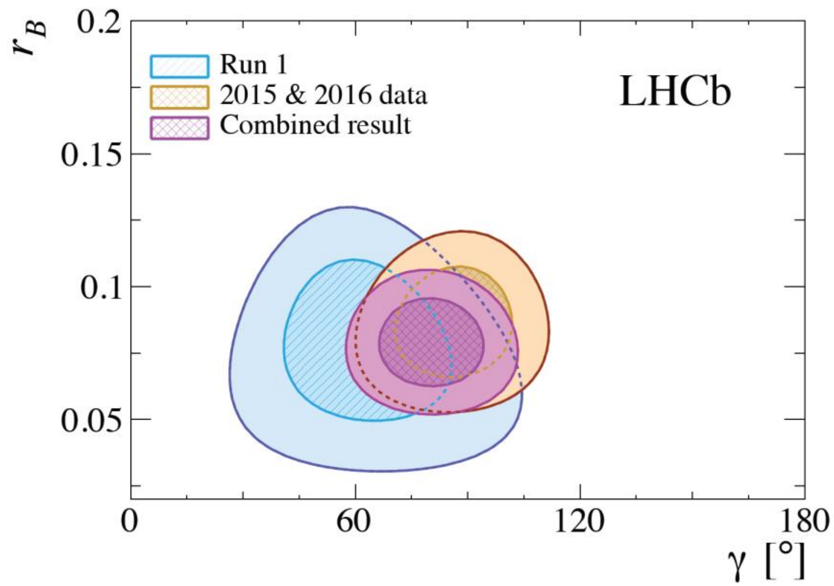
yields/bin of $B^\pm \to DK^\pm$:

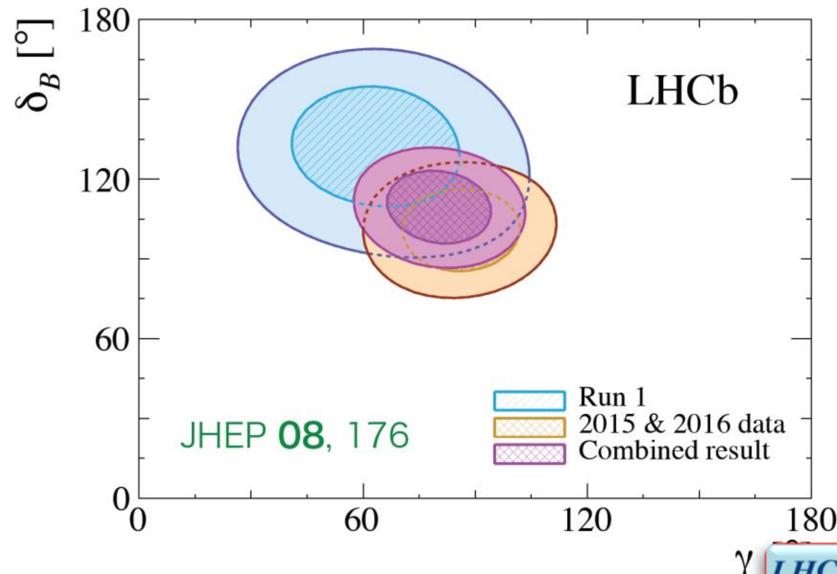
$$S_i^\pm = N_{\mathrm{tot}}(DK) \times \frac{N_i^\pm}{\sum_{-n}^{+n} N_i^\pm}$$

$$N^+_{\pm i} = h_{B^+} \left[F_{\mp i} + (x_+^2 + y_+^2) F_\pm + 2\sqrt{F_i F_{-i}} (x_+ c_{\pm i} - y_+ s_{\pm i}) \right]$$

GGSZ Model Indep. Method Run1/2







Dalitz structure of other multibody D modes

- We have a good model for the GGSZ modes ($D \to K^0_S\pi\pi$ and $D \to K^0_S KK$) but development of others (e.g. the 4-body charm decays) could prove very useful.
- Recent measurements of $D^0 \to K^+\pi^-\pi^+\pi^-$ amplitude model at LHCb - [arXiv:1712.08609]
  - Indeed equivalent knowledge of c_i and s_i for this and related modes allows for binned Dalitz analyses in γ (see Tim Evans talk later)
- For some modes (e.g. $D \to KK\pi^0$ and $D^0 \to 4\pi$) there is a low F^+ value suggesting a Dalitz analysis could offer considerable improvement
- Many recent developments in $D^0 \to \pi^+\pi^-\pi^+\pi^-$ and $D^0 \to K^+K^-\pi^+\pi^-$ Dalitz models with CLEO data - [JHEP 05 (2017) 143]
- Can one define optimal binning schemes for various $D^0 \to 4h$ and $D^0 \to hh\pi^0$ from which c_i and s_i equivalents can be extracted?

TDCPV $B_s \to D_s^{\mp} K^{\pm}$

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

$$\frac{d\Gamma_{\bar{B}_s^0\to f}(t)}{dt} = \frac{1}{2}|A_f|^2\left|\frac{p}{q}\right|^2(1+|\lambda_f|^2)e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) + \underline{A_f^{\Delta\Gamma}}\sinh\left(\frac{\Delta\Gamma_s t}{2}\right) - \underline{C_f}\cos(\Delta m_s t) + \underline{S_f}\sin(\Delta m_s t)\right],$$

… and similar equations for $\bar{f}$ (e.g. $f = D_s^- K^+$, $\bar{f} = D_s^+ K^-$)

Five independent observables assuming no CP violation in mixing or in decay

$$C_f = \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2} = -C_{\bar{f}} = -\frac{1-|\lambda_{\bar{f}}|^2}{1+|\lambda_{\bar{f}}|^2},$$

$$S_f = \frac{2\mathcal{I}m(\lambda_f)}{1+|\lambda_f|^2}, \quad A_f^{\Delta\Gamma} = \frac{-2\mathcal{R}e(\lambda_f)}{1+|\lambda_f|^2},$$

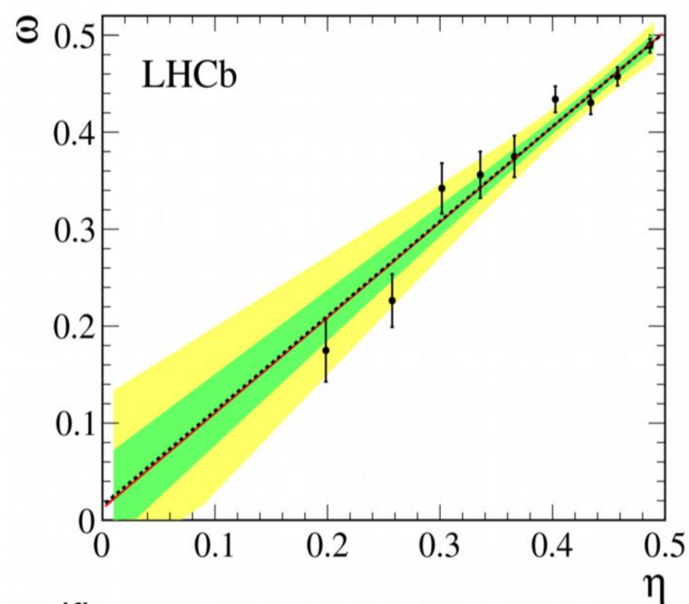
$$S_{\bar{f}} = \frac{2\mathcal{I}m(\lambda_{\bar{f}})}{1+|\lambda_{\bar{f}}|^2}, \quad A_{\bar{f}}^{\Delta\Gamma} = \frac{-2\mathcal{R}e(\lambda_{\bar{f}})}{1+|\lambda_{\bar{f}}|^2}.$$

$$\boxed{\lambda_f = \frac{q}{p}\frac{\bar{A}_f}{A_f}}$$

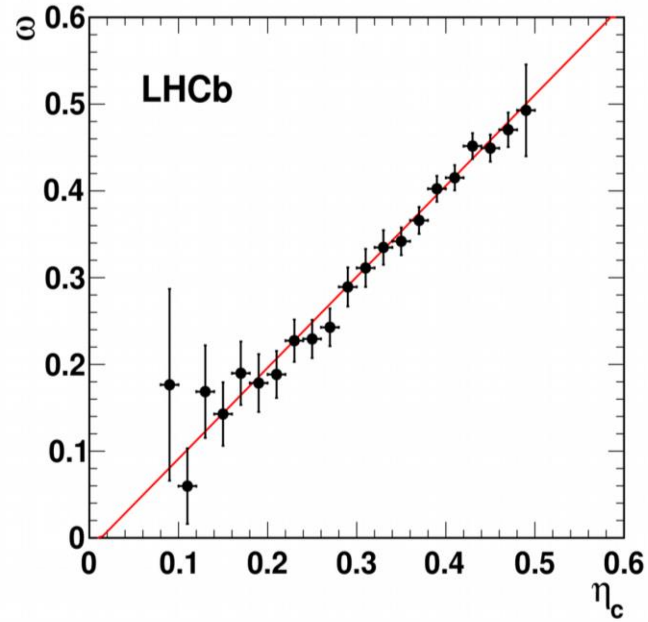
$$\boxed{|\lambda_f| = |\lambda_{\bar{f}}| \equiv r_{D_s K} \sim 0.4}$$

Tagging $B_s \to D_s^{\mp} K^{\pm}$

Same side kaon
LHCb-PAPER-2015-056
JINST 11 (2016) P05010



Opposite side taggers
LHCb-PAPER-2011-027
EPJ C72 (2012) 2022



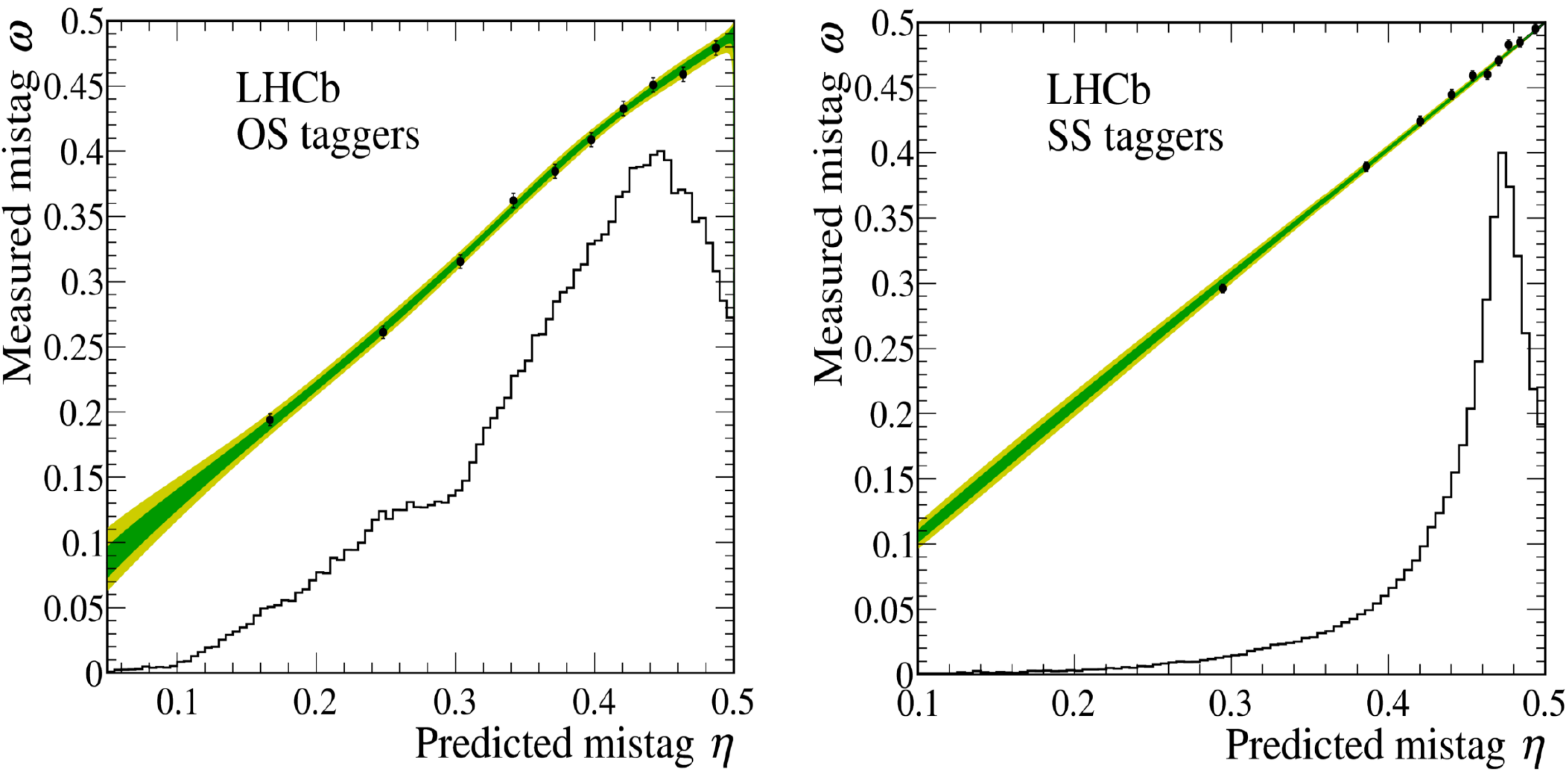
Analysis-specific calibration:

$B_s^0 \to D_s^- \pi^+$	$\varepsilon_{\rm tag}$ [%]	$\varepsilon_{\rm eff}$ [%]
OS only	12.94 ± 0.11	1.41 ± 0.11
SS only	39.70 ± 0.16	1.29 ± 0.13
Both OS and SS	24.21 ± 0.14	3.10 ± 0.18
Total	76.85 ± 0.24	5.80 ± 0.25

LHCb-PAPER-2017-047, 3 fb^{-1}
JHEP 03 (2018) 059

$$\epsilon_{eff} = \epsilon_{tag} (1 - 2\langle \omega \rangle)^2$$

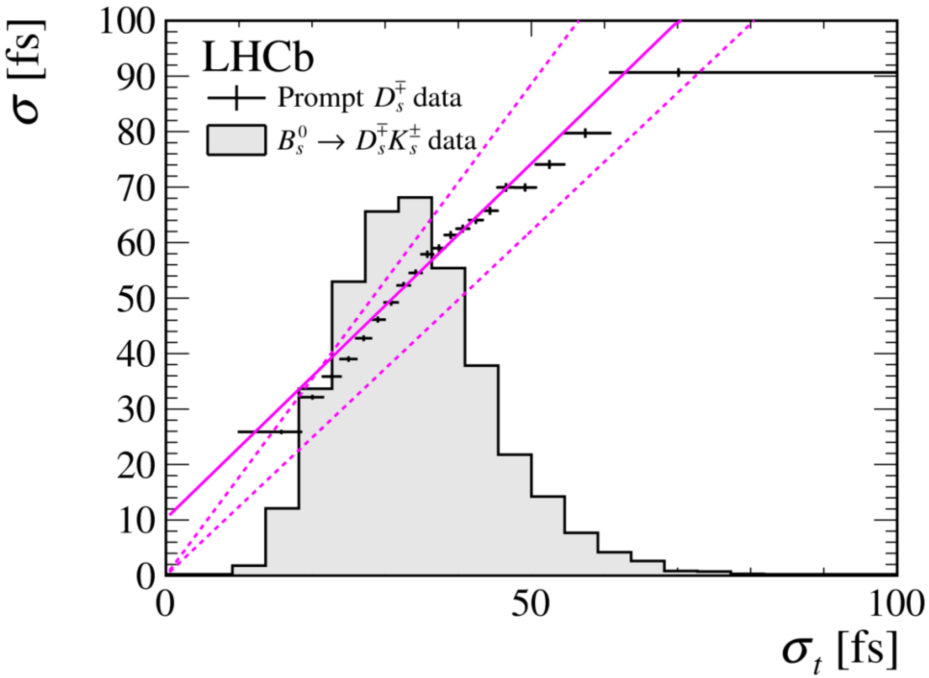
Tagging $B_d \to D^{\mp}\pi^{\pm}$

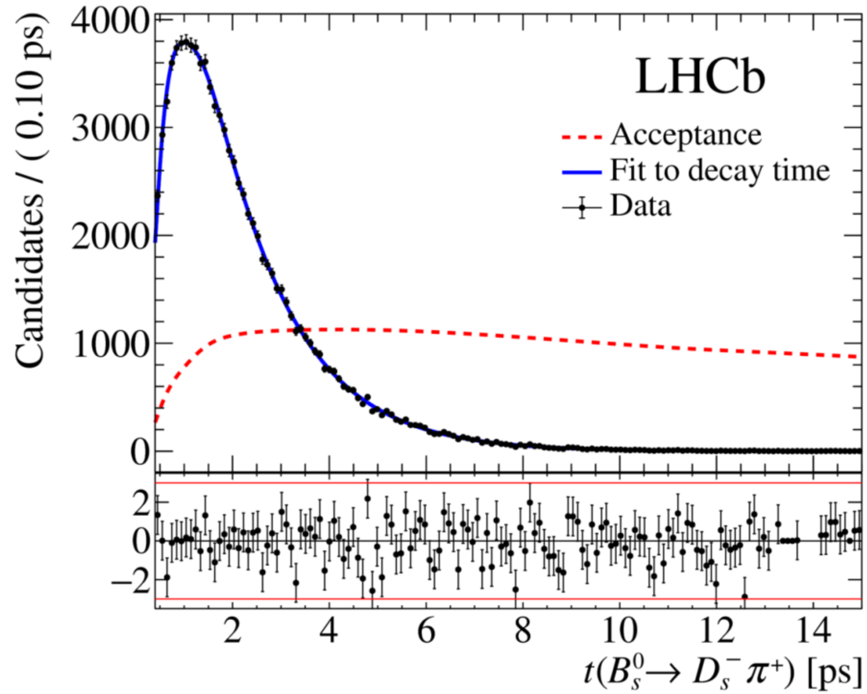


Exploit fact that |C|=1 to calibrate tagging with signal channel

ε_{eff} = (5.59 ± 0.01)%

Decay time resolution and acceptance $B_s \to D_s^{\mp} K^{\pm}$





- Candidate-by-candidate resolution used to improve sensitivity
  - Vertex fit gives good estimate (σ_t); calibrated with prompt D_s mesons
- Known lifetime of $B_s \to D_s \pi$ used to obtain acceptance function
  - Corrections for $B_s \to D_s K / B_s \to D_s \pi$ differences obtained from MC
  - Important source of systematic uncertainty on $A^{\Delta\Gamma}$ observables

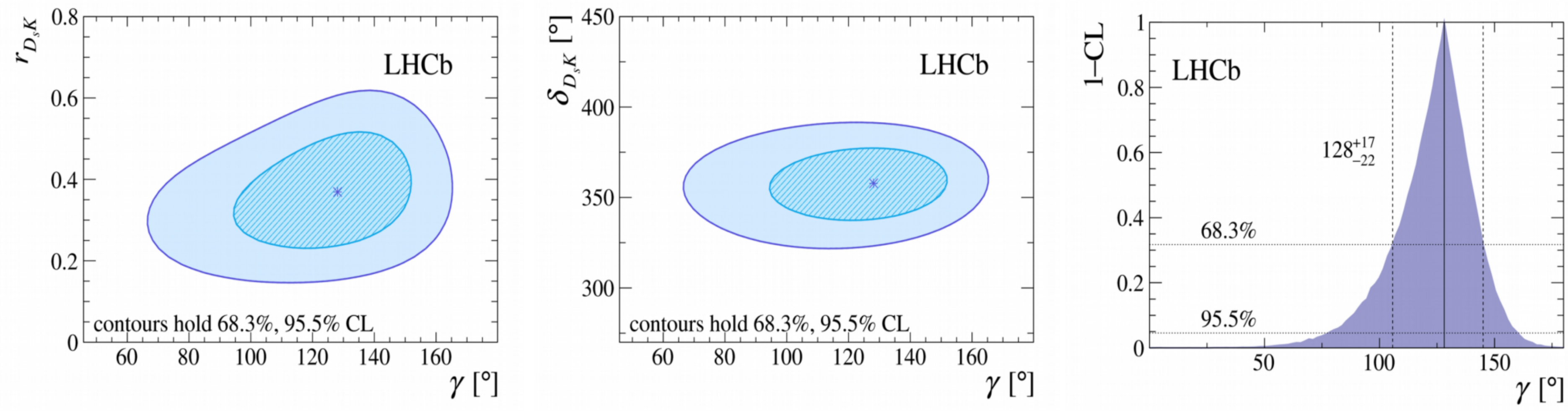
Systematics $B_s \to D_s^{\mp} K^{\pm}$

Quoted relative to the statistical uncertainty

Source	C_f	$A_f^{\Delta\Gamma}$	$A_{\bar{f}}^{\Delta\Gamma}$	S_f	$S_{\bar{f}}$
Detection asymmetry	0.02	0.28	0.29	0.02	0.02
Δm_s	0.11	0.02	0.02	0.20	0.20
Tagging and scale factor	0.18	0.02	0.02	0.16	0.18
Tagging asymmetry	0.02	0.00	0.00	0.02	0.02
Correlation among observables	0.20	0.38	0.38	0.20	0.18
Closure test	0.13	0.19	0.19	0.12	0.12
Acceptance, simulation ratio	0.01	0.10	0.10	0.01	0.01
Acceptance data fit, Γ_s, $\Delta\Gamma_s$	0.01	0.18	0.17	0.00	0.00
Total	0.32	0.55	0.55	0.35	0.35

Mainly from control samples – will scale with statistics
Others also appear reducible

Constraint on γ: $B_s \to D_s^{\mp} K^{\pm}$



Measurements of five observables converted to constraints on three parameters using *GammaCombo* (LHCb-PAPER-2016-032, LHCb-CONF-2018-002)

$\gamma-2\beta_s$ converted to γ using $-2\beta_s$ from $B_s \to J/\psi\varphi$

$$\gamma = (128\,^{+17}_{-22})^\circ\,,$$
$$\delta = (358\,^{+13}_{-14})^\circ\,,$$
$$r_{D_sK} = 0.37\,^{+0.10}_{-0.09}\,,$$

3.8σ evidence for CP violation

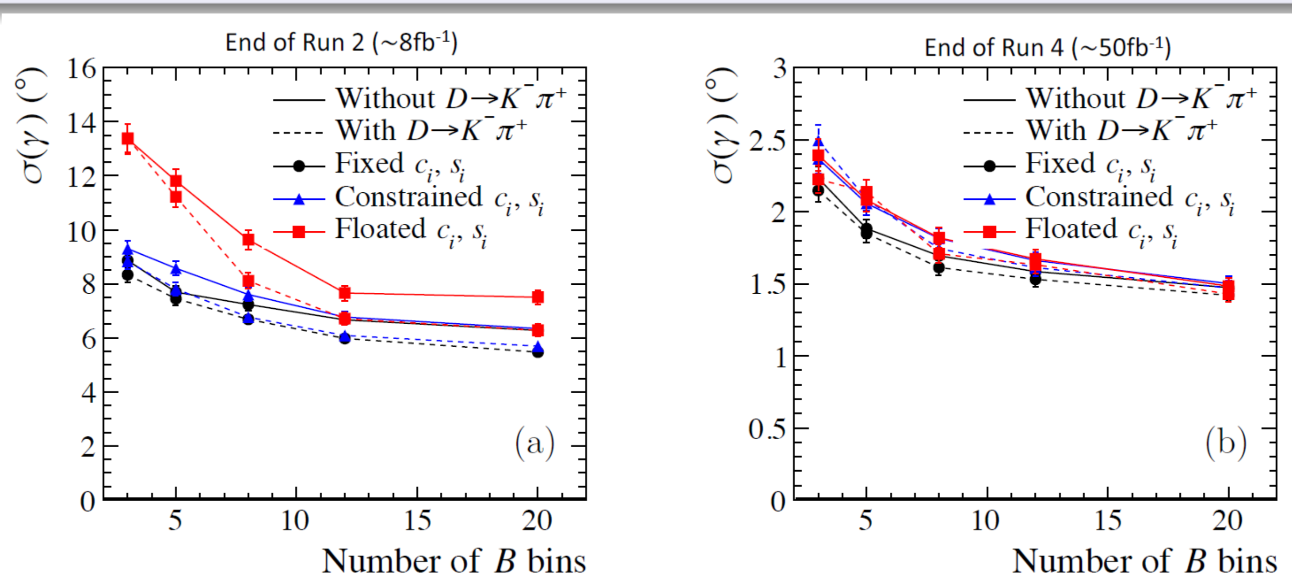
[arXiv:1602.03445]
(Run1)

3-body decay $B^0 \to D\pi^- K^+$

- Some studies of future prospects of the B Dalitz method with GGSZ modes in [arXiv:1712.07853]
- Can include GLW, ADS and GGSZ modes in single framework to improve constraints on B Dalitz bins, $\varkappa_j$ and σ_j
- The double Dalitz method has sufficient information (large number of bins) to extract c_i and s_i

Double Dalitz observables (partial rate as function of both Dalitz positions)

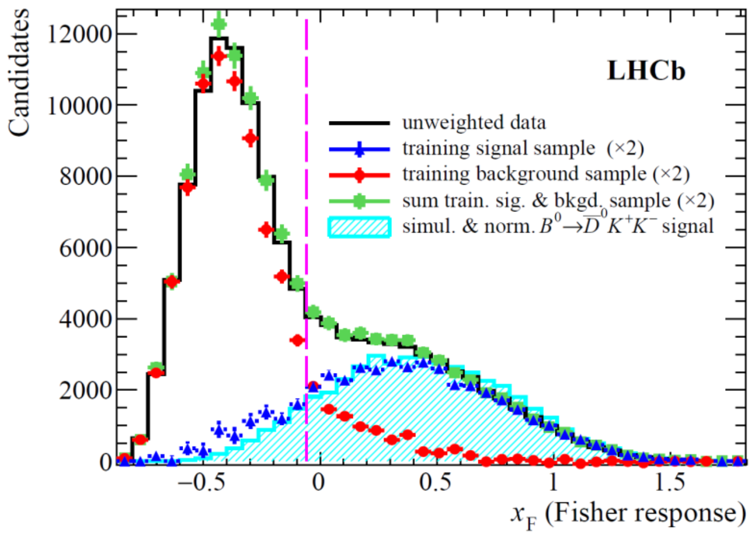
$$|A|^2 = |A_B|^2|A_D|^2 + |\bar{A}_B|^2|\bar{A}_D|^2 + 2|A_B||A_D||\bar{A}_B||\bar{A}_D|[(\varkappa c - \sigma s)\cos(\gamma) - (\varkappa s + \sigma c)\sin(\gamma)]$$



arXiv:1807.01891

Selection of $B^0_{(s)} \to \bar{D}^0 K^+ K^-$ decays

- ✓ $\bar{D}^0$ reconstructed in $K^+\pi^-$ decay
- ✓ Kinematic and topological discriminating variables
- ✓ Charmless B decays rejected by requiring the D meson vertex to be downstream of the B meson vertex
- ✓ Veto of $B^0 \to D^*(2010)^-\pi^+$, $D^*(2010)^- \to \bar{D}^0\pi^-$
- ✓ Combinatorial background rejected with robust MVA Fisher discriminant optimised on data with $B^0 \to \bar{D}^0\pi^+\pi^-$ using sPlot technique



- ✓ Selections for $B^0_{(s)} \to \bar{D}^0 K^+ K^-$ signal and $B^0 \to \bar{D}^0\pi^+\pi^-$ normalisation modes differ only on the PID of the h^+h^- pair (use of RICHs)
- ✓ One candidate/event only

invariant mass fit of $B^0_{(s)} \to \bar{D}^0 h^+ h^-$ decays

- ✓ **Signals modelled with 2 Crystal Ball functions** (tails params. fixed from simulation) **and mass difference between B^0 and B^0_s for DK^+K^- fixed to PDG2018 value** (87.35 MeV/c²)
- ✓ **Surviving combinatorial background modelled with exponential function**
- ✓ **Mis-identified and partially reconstructed b-hadron decays modelled from simulation with corrections to match data**
- ✓ **Specific treatment of $\Lambda_b \to D^0 p\pi^-$, $\Lambda_b \to D^0 pK^-$ and $\Xi_b \to D^0 pK^-$ backgrounds constrained from data**

Likelihood function:

$$\mathcal{L}_{\bar{D}^0 h^+ h^-} = \frac{v^n}{n!} e^{-v} \prod_{i=1}^{n} \mathcal{P}_\theta^{\text{tot}}(m_{i,\bar{D}^0 h^+ h^-})$$

v is the sum of the yields and n the number of observed candidates

- **$B^0 \to \bar{D}^0 \pi^+\pi^-$ (7 background components):**

$$\mathcal{P}_\theta^{\text{tot}}(m_{\bar{D}^0\pi^+\pi^-}) = N_{\bar{D}^0\pi^+\pi^-} \times \mathcal{P}_{\text{sig}}^{B^0}(m_{\bar{D}^0\pi^+\pi^-}) + \sum_{j=1}^{7} N_{j,\text{bkg}} \times \mathcal{P}_{j,\text{bkg}}(m_{\bar{D}^0\pi^+\pi^-})$$

- **$B^0_{(s)} \to \bar{D}^0 K^+K^-$ (2 signal + 9 background components):**

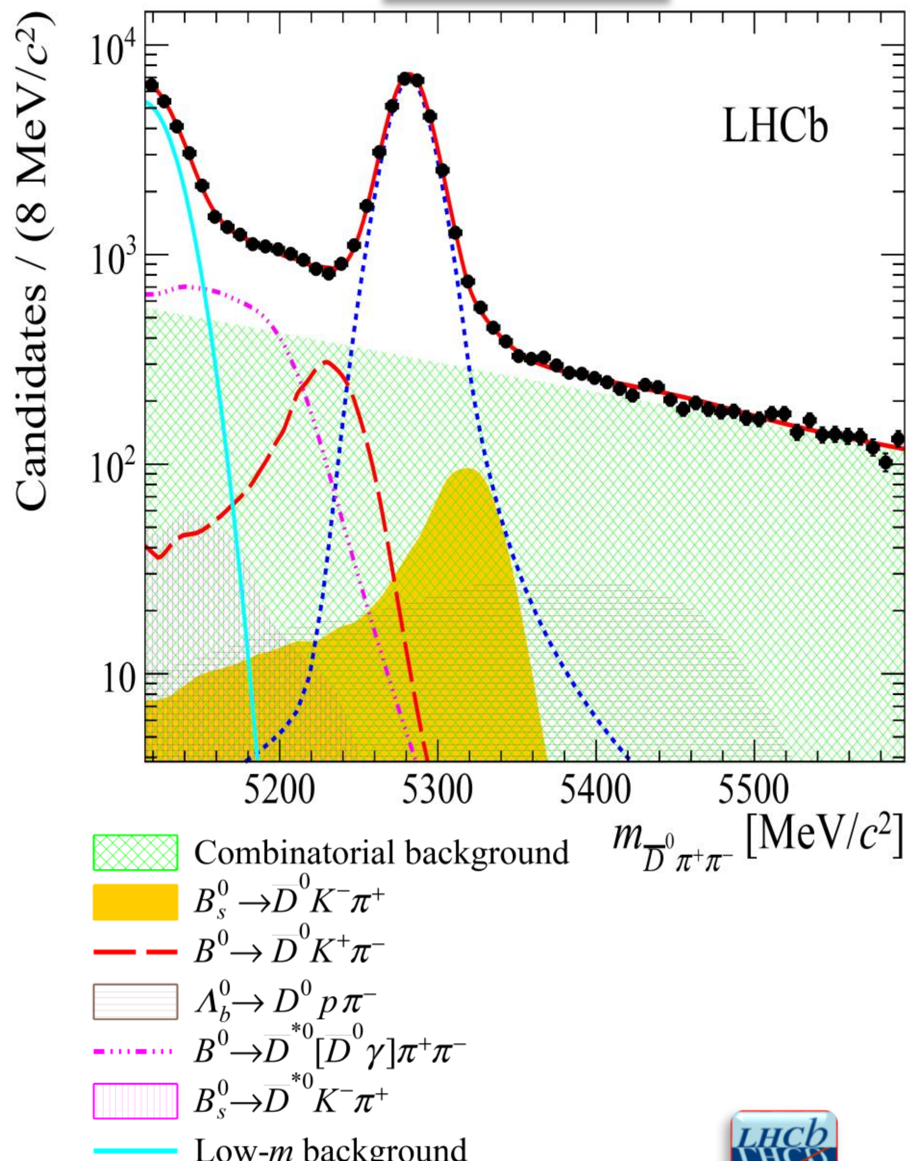
$$\begin{aligned}\mathcal{P}_\theta^{\text{tot}}(m_{\bar{D}^0K^+K^-}) &= N_{B^0\to\bar{D}^0K^+K^-} \times \mathcal{P}_{\text{sig}}^{B^0}(m_{\bar{D}^0K^+K^-}) \\ &+ N_{B^0_s\to\bar{D}^0K^+K^-} \times \mathcal{P}_{\text{sig}}^{B^0_s}(m_{\bar{D}^0K^+K^-}) \\ &+ \sum_{j=1}^{9} N_{j,\text{bkg}} \times \mathcal{P}_{j,\text{bkg}}(m_{\bar{D}^0K^+K^-}).\end{aligned}$$

invariant mass fit of $B^0_{(s)} \to \bar{D}^0 h^+ h^-$ decays

Fit output details

Parameter	$B^0 \to \bar{D}^0\pi^+\pi^-$	$B^0_{(s)} \to \bar{D}^0 K^+K^-$
m_0 [MeV/c^2]	5282.0 ± 0.1	5282.6 ± 0.3
σ_1 [MeV/c^2]	9.7 ± 1.0	fixed at 9.7
σ_2 [MeV/c^2]	16.2 ± 0.8	fixed at 16.2
$f_{\rm CB}$	0.3 ± 0.1	0.6 ± 0.1
$a_{\rm comb.}$ $[10^{-3} \times ({\rm MeV}/c^2)^{-1}]$	-3.2 ± 0.1	-1.3 ± 0.4
$N_{B^0\to\bar{D}^0h^+h^-}$	$29\,943 \pm 243$	1918 ± 74
$N_{B^0_s\to\bar{D}^0h^+h^-}$	–	473 ± 33
$N_{\rm comb.}$	$20\,266 \pm 463$	1720 ± 231
$N_{B^0_s\to\bar{D}^0K^-\pi^+}$	923 ± 191	151 ± 47
$N_{B^0\to\bar{D}^0K^+\pi^-}$	2450 ± 211	131 ± 65
$N_{\Lambda^0_b\to D^0pK^-}$ (constrained)	–	197 ± 44
$N_{\Xi^0_b\to D^0pK^-}$ (constrained)	–	57 ± 20
$N_{\Lambda^0_b\to D^0p\pi^-}$ (constrained)	1016 ± 136	74 ± 32
$N_{B^0_s\to\bar{D}^{*0}K^-\pi^+}$	540 (fixed)	833 ± 185
$N_{B^0_s\to\bar{D}^{*0}K^+K^-}$	–	775 ± 100
$N_{B^0\to\bar{D}^{*0}[\bar{D}^0\gamma]\pi^+\pi^-}$	7697 ± 325	–
$N_{\rm Low-m}$	$14\,914 \pm 222$	1632 ± 68
χ^2/ndf (p-value)	52/46 (25%)	43/46 (60%)

$B^0 \to \bar{D}^0\pi^+\pi^-$

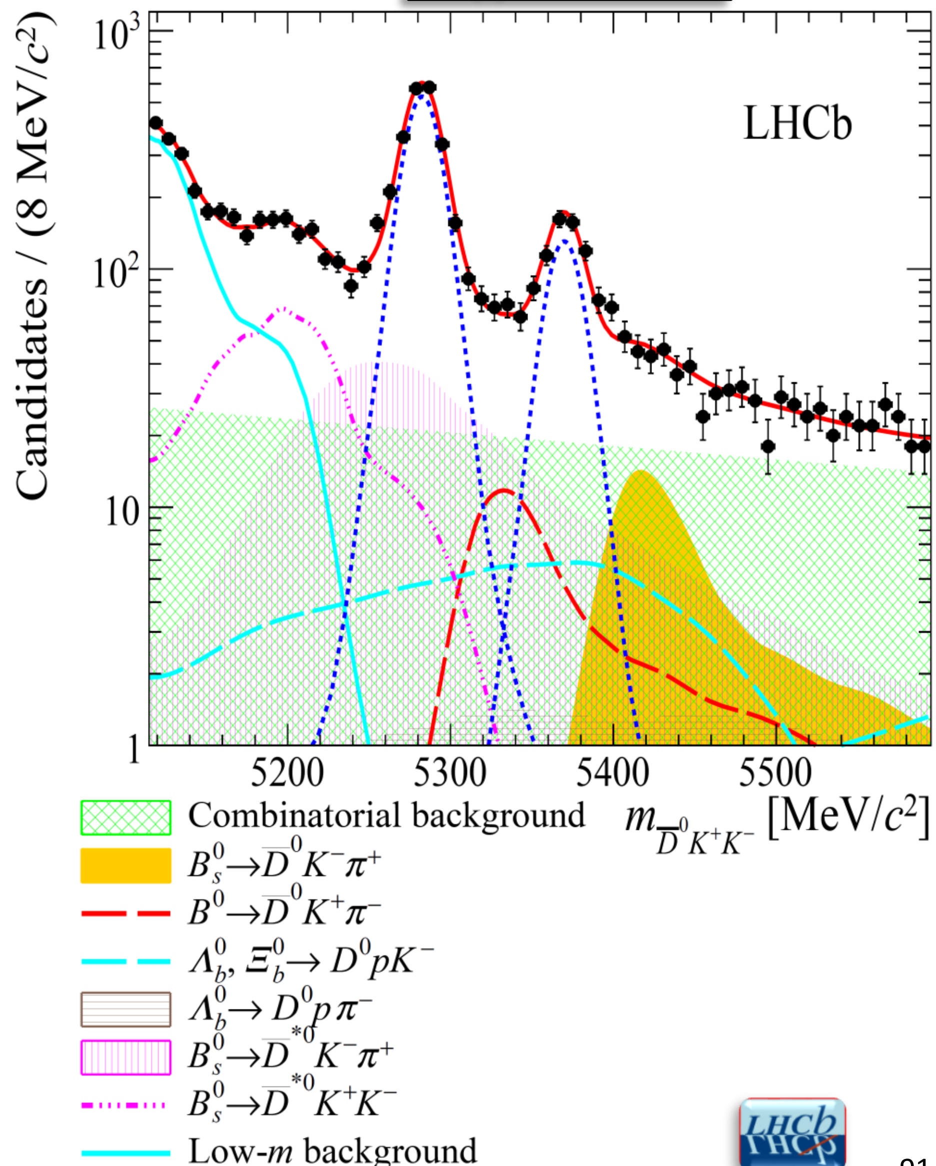


invariant mass fit of $B^0_{(s)} \to \bar{D}^0 h^+ h^-$ decays

Fit output details

Parameter	$B^0 \to \bar{D}^0\pi^+\pi^-$	$B^0_{(s)} \to \bar{D}^0 K^+ K^-$
m_0 [MeV/c^2]	5282.0 ± 0.1	5282.6 ± 0.3
σ_1 [MeV/c^2]	9.7 ± 1.0	fixed at 9.7
σ_2 [MeV/c^2]	16.2 ± 0.8	fixed at 16.2
$f_{\rm CB}$	0.3 ± 0.1	0.6 ± 0.1
$a_{\rm comb.}$ $[10^{-3} \times (\mathrm{MeV}/c^2)^{-1}]$	-3.2 ± 0.1	-1.3 ± 0.4
$N_{B^0\to\bar{D}^0 h^+h^-}$	$29\,943 \pm 243$	1918 ± 74
$N_{B^0_s\to\bar{D}^0 h^+h^-}$	–	473 ± 33
$N_{\rm comb.}$	$20\,266 \pm 463$	1720 ± 231
$N_{B^0_s\to\bar{D}^0 K^-\pi^+}$	923 ± 191	151 ± 47
$N_{B^0\to\bar{D}^0 K^+\pi^-}$	2450 ± 211	131 ± 65
$N_{\Lambda^0_b\to D^0 pK^-}$ (constrained)	–	197 ± 44
$N_{\Xi^0_b\to D^0 pK^-}$ (constrained)	–	57 ± 20
$N_{\Lambda^0_b\to D^0 p\pi^-}$ (constrained)	1016 ± 136	74 ± 32
$N_{B^0_s\to\bar{D}^{*0} K^-\pi^+}$	540 (fixed)	833 ± 185
$N_{B^0_s\to\bar{D}^{*0} K^+K^-}$	–	775 ± 100
$N_{B^0\to\bar{D}^{*0}[\bar{D}^0\gamma]\pi^+\pi^-}$	7697 ± 325	–
$N_{\rm Low-m}$	$14\,914 \pm 222$	1632 ± 68
χ^2/ndf (p-value)	52/46 (25%)	43/46 (60%)

$B^0_{(s)} \to \bar{D}^0 K^+ K^-$



arXiv:1807.01891

Ratios of branching fractions & efficiencies

✓ Compute ratios of branching fractions:

$$\frac{\mathcal{B}\left(B^0 \to \overline{D}^0 K^+ K^-\right)}{\mathcal{B}\left(B^0 \to \overline{D}^0 \pi^+ \pi^-\right)} = \frac{N_{B^0 \to \overline{D}^0 K^+ K^-}}{N_{B^0 \to \overline{D}^0 \pi^+ \pi^-}} \times \frac{\varepsilon_{B^0 \to \overline{D}^0 \pi^+ \pi^-}}{\varepsilon_{B^0 \to \overline{D}^0 K^+ K^-}}$$

$$\frac{\mathcal{B}\left(B^0_s \to \overline{D}^0 K^+ K^-\right)}{\mathcal{B}\left(B^0 \to \overline{D}^0 K^+ K^-\right)} = r_{B^0_s/B^0} \times \frac{\varepsilon_{B^0 \to \overline{D}^0 K^+ K^-}}{\varepsilon_{B^0_s \to \overline{D}^0 K^+ K^-}} \times \frac{1}{f_s/f_d}$$

✓ $\mathcal{B}\left(B^0 \to \overline{D}^0 \pi^+ \pi^-\right)$ **from PDG2018** (including Phys. Rev. D 92 (2015) 032002)

✓ f_s/f_d **from LHCb** (JHEP 04 (2003) 001 & LHCb-CONF-2013-011)

✓ Efficiencies account for acceptance/reconstruction, hardware L0 /software HLT1/2 triggering, PID and selections (including Fisher discriminant).

- Mostly computed with simulation, but PID/tracking simulation corrected with data control samples.
- Hardware L0 trigger part determined from calibration data samples.
- Global efficiency corrected for phase-space effects in $B^0_{(s)} \to \overline{D}^0 h^+ h^-$ multi-body decays on event-by-event basis using sPlot technique (i.e. sWeights).

Systematic uncertainties

- ✓ Many sources of systematic uncertainty cancel in the ratios of branching fractions
- ✓ Other non-vanishing sources:
  - Hardware L0 trigger (signal specific part).
  - PID difference in the h^+h^- selection for $B^0_{(s)} \to \bar{D}^0 K^+ K^-$ signal and $B^0 \to \bar{D}^0 \pi^+ \pi^-$ normalisation mode.
  - Signal and background modelling in the invariant mass fit.

Source [%]	$\mathcal{R}_{\bar{D}^0 K^+ K^- / \bar{D}^0 \pi^+ \pi^-}$	$\mathcal{R}_{B^0_s / B^0}$
HW trigger efficiency	2.0	–
PID efficiency	2.0	–
PDF modelling	3.2	4.5
f_s/f_d	–	5.8
Total [%]	4.3	7.3

Where:

$$\mathcal{R}_{\bar{D}^0 K^+ K^- / \bar{D}^0 \pi^+ \pi^-} \equiv \mathcal{B}(B^0 \to \bar{D}^0 K^+ K^-) / \mathcal{B}(B^0 \to \bar{D}^0 \pi^+ \pi^-)$$

$$\mathcal{R}_{B^0_s / B^0} \equiv \mathcal{B}(B^0_s \to \bar{D}^0 K^+ K^-) / \mathcal{B}(B^0 \to \bar{D}^0 K^+ K^-)$$

arXiv:1807.01891

Results 3/fb

$$\frac{\mathcal{B}(B^0 \to \overline{D}{}^0 K^+ K^-)}{\mathcal{B}(B^0 \to \overline{D}{}^0 \pi^+ \pi^-)} = (6.9 \pm 0.4 \pm 0.3)\%$$

stat. syst.

$$\mathcal{B}(B^0 \to \overline{D}{}^0 K^+ K^-) = (6.1 \pm 0.4 \pm 0.3 \pm 0.3) \times 10^{-5}$$

stat. syst. normalis.

(was $(4.7 \pm 0.9 \pm 0.6 \pm 0.5) \times 10^{-5}$ with 0.6/fb *)

$$\frac{\mathcal{B}(B_s^0 \to \overline{D}{}^0 K^+ K^-)}{\mathcal{B}(B^0 \to \overline{D}{}^0 K^+ K^-)} = (93.0 \pm 8.9 \pm 6.9)\%$$

stat. syst.

$$\mathcal{B}(B_s^0 \to \overline{D}{}^0 K^+ K^-) = (5.7 \pm 0.5 \pm 0.4 \pm 0.5) \times 10^{-5}$$

stat. syst. normalis.

Observed !

(was $(4.2 \pm 1.3 \pm 0.9 \pm 1.1) \times 10^{-5}$ with 0.6/fb *)

* Phys. Rev. Lett. 109 (2012) 131801

arXiv:1807.01892

Branching fractions of $B^0_{(s)} \to \bar{D}^{(*)0}\phi$

$$\frac{\mathcal{B}(B^0_{(s)} \to \overline{D}^{(*)0}\phi)}{\mathcal{B}(B^0 \to \overline{D}^0\pi^+\pi^-)} = \frac{N_{B^0_{(s)}\to\overline{D}^{(*)0}\phi} \times \varepsilon(B^0 \to \overline{D}^0\pi^+\pi^-)}{N_{B^0\to\overline{D}^0\pi^+\pi^-} \times \varepsilon(B^0_{(s)} \to \overline{D}^{(*)0}\phi)} \times \frac{\mathcal{F}}{\mathcal{B}(\phi \to K^+K^-)},$$

where $\mathcal{F}$ is 1 for B^0 decays and f_d/f_s for B^0_s decays.

- ✓ **Efficiencies computed as for 1807.01891.**
- ✓ **Various sources of systematic uncertainties considered [%]:**

Source	$\frac{\mathcal{B}(B^0_s\to\overline{D}^0\phi)}{\mathcal{B}(B^0\to\overline{D}^0\pi^+\pi^-)}$	$\frac{\mathcal{B}(B^0\to\overline{D}^0\phi)}{\mathcal{B}(B^0\to\overline{D}^0\pi^+\pi^-)}$	$\frac{\mathcal{B}(B^0_s\to\overline{D}^{*0}\phi)}{\mathcal{B}(B^0\to\overline{D}^0\pi^+\pi^-)}$	$\frac{\mathcal{B}(B^0_s\to\overline{D}^{*0}\phi)}{\mathcal{B}(B^0_s\to\overline{D}^0\phi)}$	f_L
$N_{B^0_{(s)}\to\overline{D}^{(*)0}\phi}$	1.5	27.0	4.8	4.9	4.1
$N_{B^0\to\overline{D}^0\pi^+\pi^-}$	2.0	2.0	2.0	–	–
ϵ_{PID}	2.0	2.0	2.0	–	–
$\epsilon_{\text{trigger}}$	2.0	2.0	2.0	–	–
$\mathcal{B}(\phi \to K^+K^-)^*$	1.0	1.0	1.0	–	–
f_s/f_d**	5.8	–	5.8	–	–
Lifetime***	0.8	–	0.8	1.6	1.6
Total	7.0	27.1	8.4	5.2	4.4

* PDG2018 ** JHEP 04 (2003) 001 & LHCb-CONF-2013-011 *** See: Phys. Rev. D 86 (2012) 014027

arXiv:1807.01892

Results for Branching fractions of $B^0_s \to \bar{D}^{(*)0}\phi$

$$\frac{\mathcal{B}(B^0_s \to \bar{D}^0 \phi)}{\mathcal{B}(B^0 \to \bar{D}^0 \pi^+ \pi^-)} = (3.4 \pm \underbrace{0.4}_{\text{stat.}} \pm \underbrace{0.2}_{\text{syst.}})\%$$

$$\mathcal{B}(B^0_s \to \bar{D}^0 \phi) = (3.0 \pm \underbrace{0.3}_{\text{stat.}} \pm \underbrace{0.2}_{\text{syst.}} \pm \underbrace{0.2}_{\text{normalis.}}) \times 10^{-5}$$

Compatible and twice as accurate as Phys. Lett. B727 (2013) 403

$$\frac{\mathcal{B}(B^0_s \to \bar{D}^{*0} \phi)}{\mathcal{B}(B^0 \to \bar{D}^0 \pi^+ \pi^-)} = (4.2 \pm \underbrace{0.5}_{\text{stat.}} \pm \underbrace{0.4}_{\text{syst.}})\%$$

Observation with more than 7 standard deviations !

$$\mathcal{B}(B^0_s \to \bar{D}^{*0} \phi) = (3.7 \pm \underbrace{0.5}_{\text{stat.}} \pm \underbrace{0.3}_{\text{syst.}} \pm \underbrace{0.2}_{\text{normalis.}}) \times 10^{-5}$$

$$\frac{\mathcal{B}(B^0_s \to \bar{D}^{*0} \phi)}{\mathcal{B}(B^0_s \to \bar{D}^0 \phi)} = 1.23 \pm \underbrace{0.20}_{\text{stat.}} \pm \underbrace{0.06}_{\text{syst.}}$$

Fraction of longitudinal polarisation:

$$f_L = (73 \pm \underbrace{15}_{\text{stat.}} \pm \underbrace{3}_{\text{syst.}})\%$$

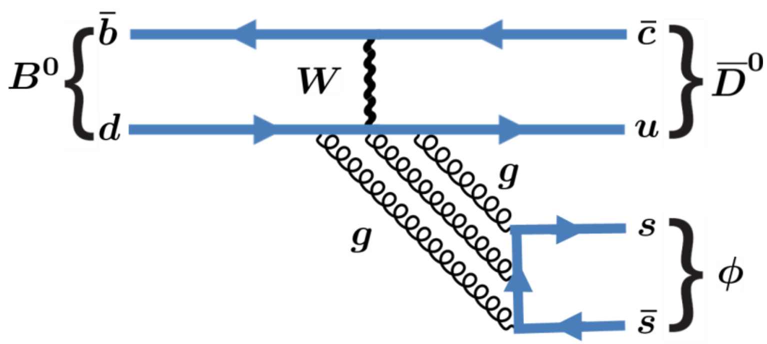
- ✓ **f_L<90%, compatible with colour-suppressed VV open charm B^0-decays** (e.g. BaBar: Phys. Rev D 84 (2011) 112007 or Belle: Phys. Rev. D 92 (2015) 012013)
- ✓ **About the same number of fully longitudinally polarised $B_s \to D^*\phi$ wrt $B_s \to D\phi$:** 1.23x0.73=0.9

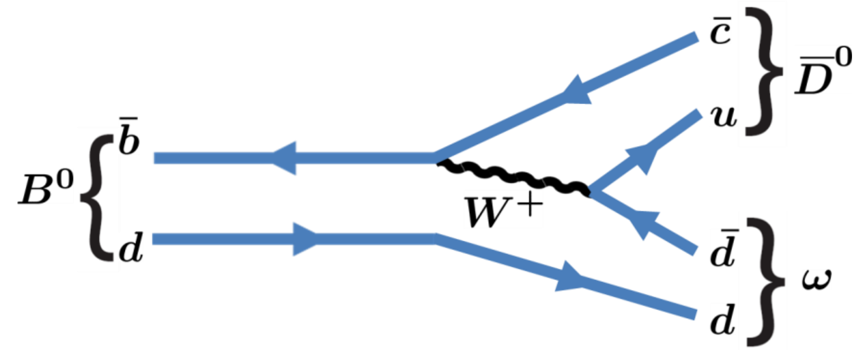
➔ Yet another mode for CKM angle γ !

arXiv:1807.01892

Search for the $B^0 \to \bar{D}^0 \phi$ decay

➔ Occurs through W-exchange diagram + Okubo-Zweig-Iizuka (OZI) suppression or through ω-ϕ mixing





➔ Yet non-significant $B^0 \to \bar{D}^0 \phi$ signal (~2σ), interpreted as:

$$\frac{\mathcal{B}(B^0 \to \bar{D}^0 \phi)}{\mathcal{B}(B^0 \to \bar{D}^0 \pi^+ \pi^-)} = (1.2 \pm \underset{\text{stat.}}{0.7} \pm \underset{\text{syst.}}{0.3}) \times 10^{-3}$$

$$\Rightarrow \mathcal{B}(B^0 \to \bar{D}^0 \phi) = (1.1 \pm \underset{\text{stat.}}{0.6} \pm \underset{\text{syst.}}{0.3} \pm \underset{\text{normalis.}}{0.1}) \times 10^{-6}$$

Adapted prediction from Phys. Lett. B 666 (2008) 185 + BaBar Phys. Rev. D 84 (2011) 112007: $(1.6 \pm 0.1) \times 10^{-6}$

➔ Upper limits set on both branching fraction and mixing angle (i.e. ideally mixed states*) assuming that the contribution from ω-ϕ mixing dominates (@ 90% (95%) of CL):

$$\mathcal{B}(B^0 \to \bar{D}^0 \phi) < 2.0\ (2.2) \times 10^{-6} \quad \Rightarrow \quad |\delta| < 5.2^\circ\ (5.5^\circ)$$

Factor 6 better improvement wrt BaBar (Phys. Rev. D76 (2007) 051103)

* $\omega^I \equiv (u\bar{u} + d\bar{d})/\sqrt{2}$ and $\phi^I \equiv s\bar{s}$ $\quad \begin{pmatrix} \omega \\ \phi \end{pmatrix} = \begin{pmatrix} \cos\delta & \sin\delta \\ -\sin\delta & \cos\delta \end{pmatrix} \begin{pmatrix} \omega^I \\ \phi^I \end{pmatrix}$