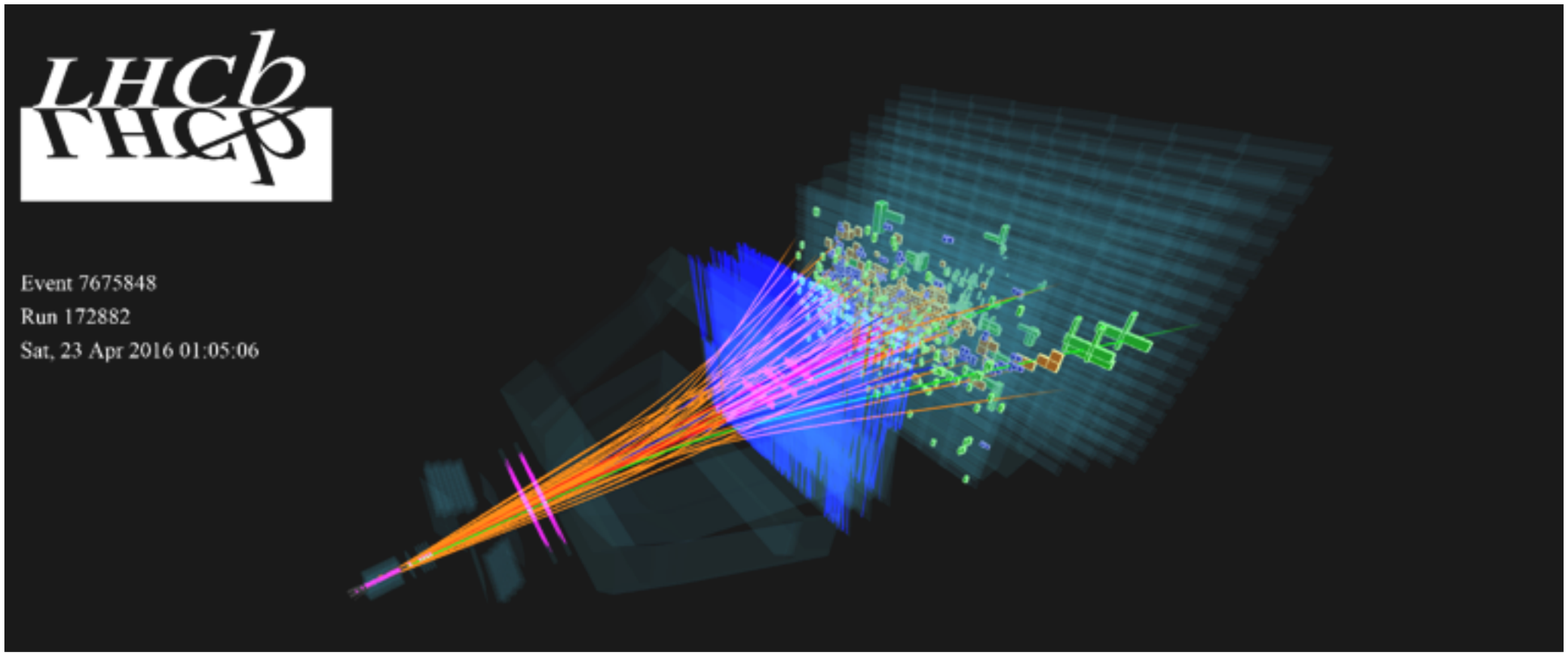
CP violation in *B* and charm decays



Simon Akar[1]

on behalf of the LHCb Collaboration

[1]*CPPM, Aix-Marseille Université CNRS/IN2P3, Marseille, France*

28th Rencontres de Blois

Blois, France, 29/05-03/06 2016

Outline

- Physics motivations
- Mixing and *CP* violation in charm
- Constraints on the CKM angle γ
- *CP* asymmetry in $B_s^0 - \overline{B}_s^0$ mixing
- Summary & conclusions

1

Physics motivations

CKM phenomenology

Quark mixing in the Standard Model (SM) described by the CKM matrix:

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

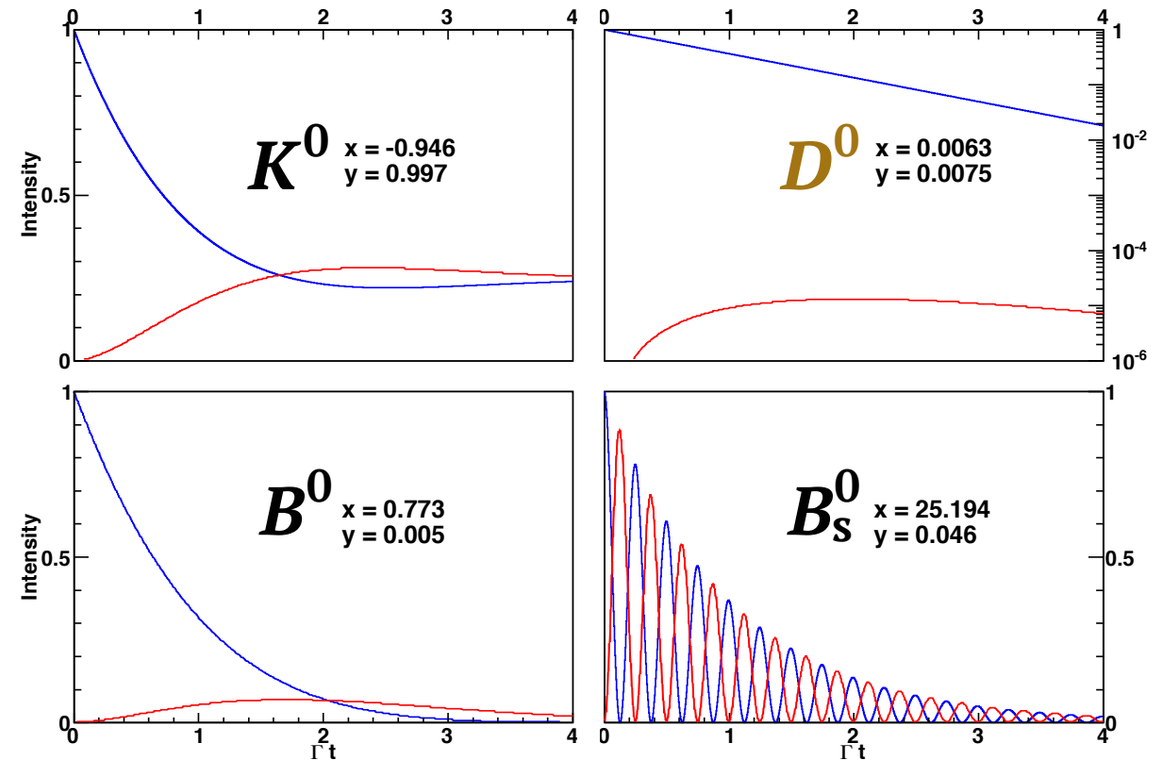
- **CKM theory is highly predictive**
  - **huge range of phenomena over a large energy interval predicted using only 4 parameters (+ G_F, m_q and QCD)**
- **CKM matrix is hierarchical**
  - **CKM structure not necessarily replicated in extended theories $\rightarrow$ strong constraints on New Physics (NP) models**
- **CKM mechanism introduces *CP* violation and neutral meson mixing phenomena**
  - **The presence of new heavy particles exchanged in virtual loops could introduce additional phases altering the corresponding measurements** (NP contributions to tree-level processes also possible in some models)

2

Mixing and CP violation in charm

Motivations and ingredients

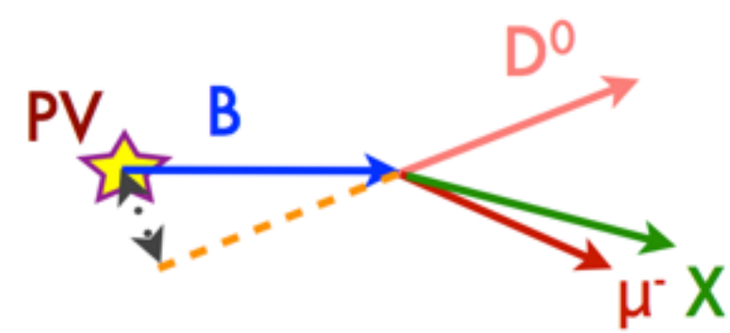
- **Charm mixing, although expected to be very small in the SM compared to other neutral mesons, is established**
- **Any significant enhancement of mixing or *CP* violation in charm would be an indication of NP**



- **Here the knowledge of the initial flavour is needed**
  Two methods used:

Pion tag: (prompt $D^{*+} \to D^0 \pi^+$)

Muon tag: ($B^- \to D^0 \mu^- X$)



2

Mixing and *CP* violation in charm

- **First observation of D^0–$\overline{D}^0$ oscillations in $D^0 \to K^+\pi^-\pi^+\pi^-$**

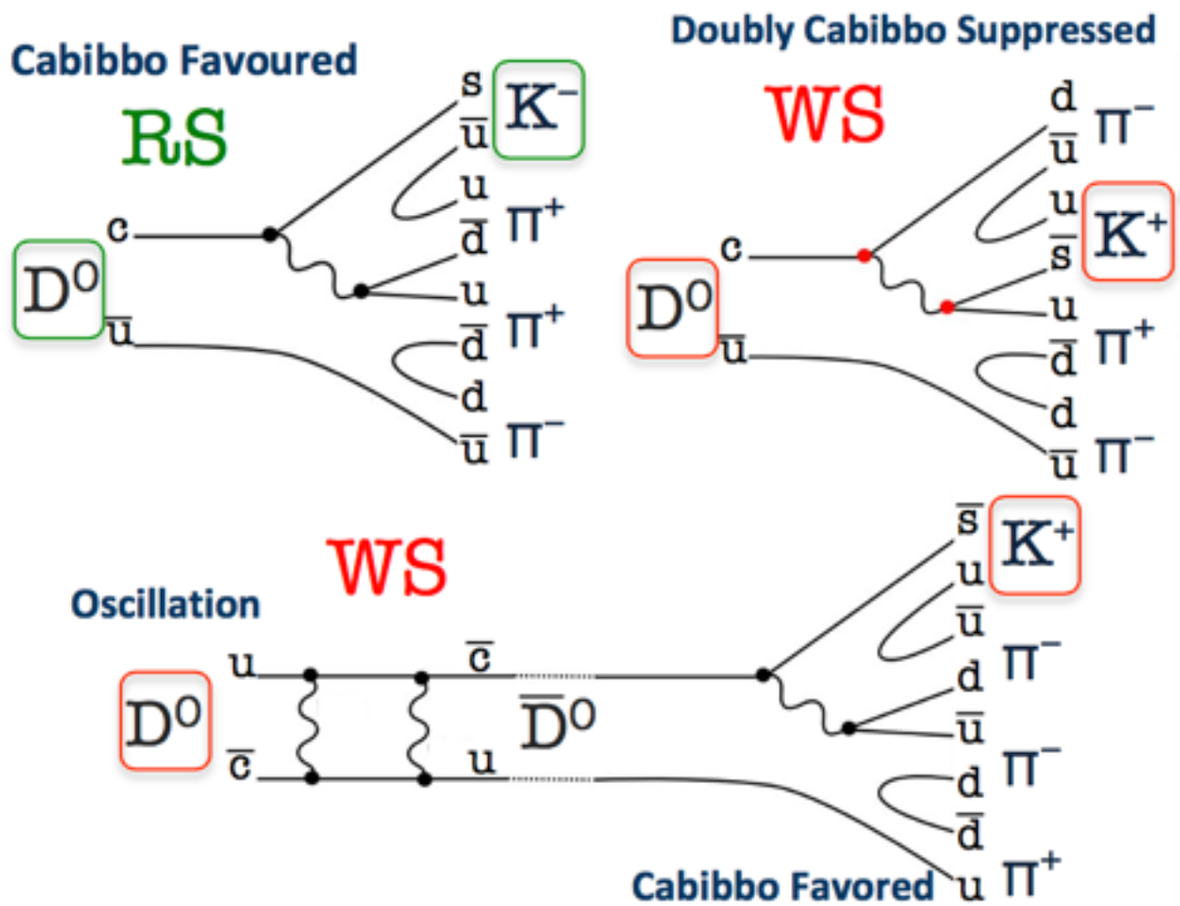
  arXiv:1602.07224 [hep-ex]

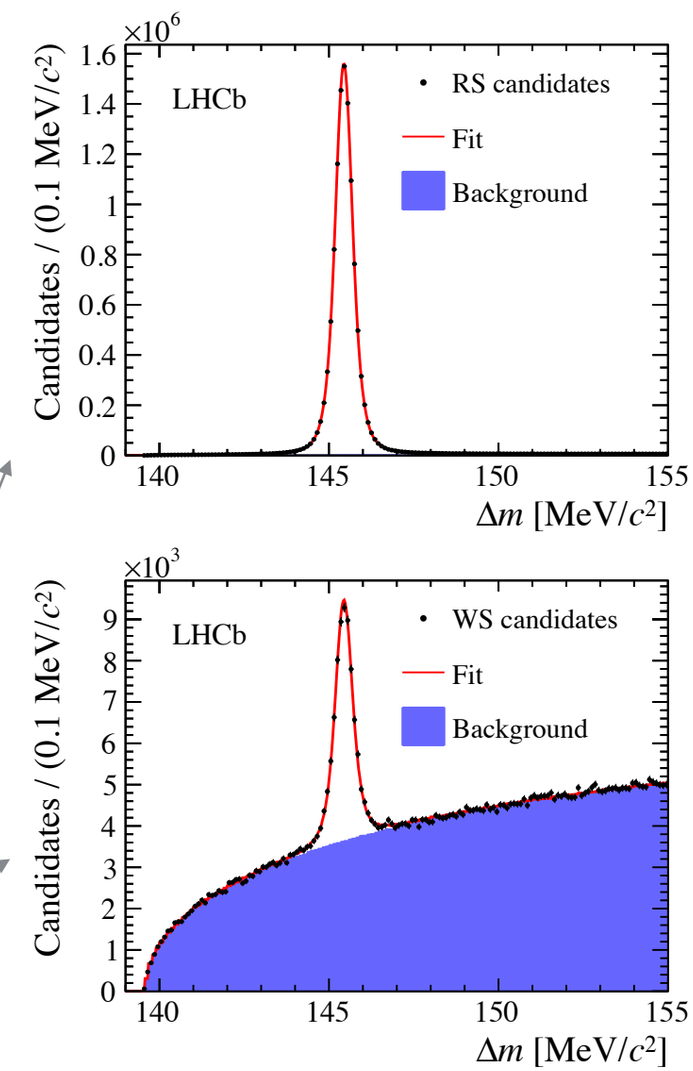
  Full Run1 data: 3 fb^{-1}

First observation of $D^0 - \bar{D}^0$ oscillations in $D^0 \to K^+\pi^-\pi^+\pi^-$

arXiv:1602.07224 [hep-ex]

- Tagging D^0 with pion tag method using prompt $D^{*+} \to D^0\pi^+$ decays
- **Interference between right sign (RS) Cabibbo favored ($D^0 \to K^-\pi^+\pi^-\pi^+$) and wrong sign (WS) doubly Cabibbo suppressed ($D^0 \to K^+\pi^-\pi^+\pi^-$) amplitudes**





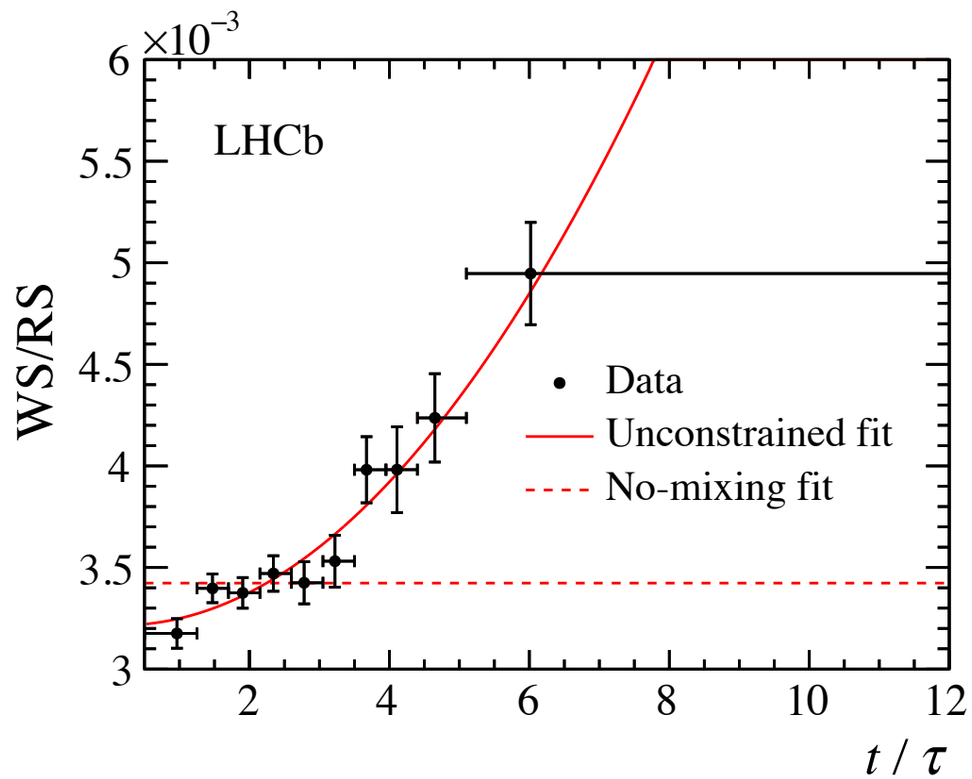
- **Fit for $\Delta m = m(K^+\pi^-\pi^+\pi^-\pi_s^\pm) - m(K^+\pi^-\pi^+\pi^-)$**

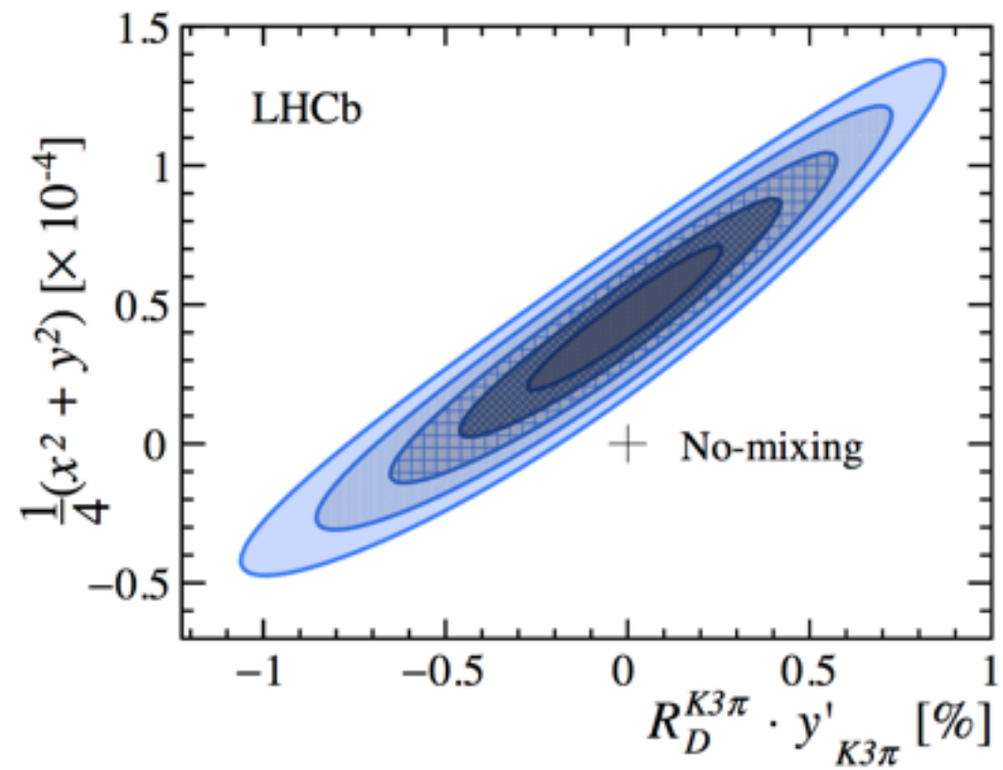
First observation of $D^0 - \bar{D}^0$ oscillations in $D^0 \to K^+\pi^-\pi^+\pi^-$

arXiv:1602.07224 [hep-ex]

- **Time dependent ratio of WS over RS amplitudes, $R(t)$:**

$$R(t) \approx \left(r_D^{K3\pi}\right)^2 - r_D^{K3\pi} R_D^{K3\pi} \cdot y'_{K3\pi} \frac{t}{\tau} + \frac{x^2+y^2}{4}\left(\frac{t}{\tau}\right)^2$$





- **First observation of $D^0 - \bar{D}^0$ mixing in a decay other than $D \to K\pi$**
- Using (x,y) as input from HFAG, can obtain the amplitude ratio and phase: $r_D^{K3\pi}$, $\delta_D^{K3\pi}$
  - **Important input to γ combination**

2

Mixing and *CP* violation in charm

- First observation of $D^0 - \bar{D}^0$ oscillations in $D^0 \to K^+\pi^-\pi^+\pi^-$
  arXiv:1602.07224 [hep-ex]
  Full Run1 data: 3 fb^{-1}
- **Search for *CP* violation in $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$**
  arXiv: 1602.03160 [hep-ex]
  Full Run1 data: 3 fb^{-1}

NEW!

Search for *CP* violation in $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$

arXiv:1602.03160 [hep-ex]

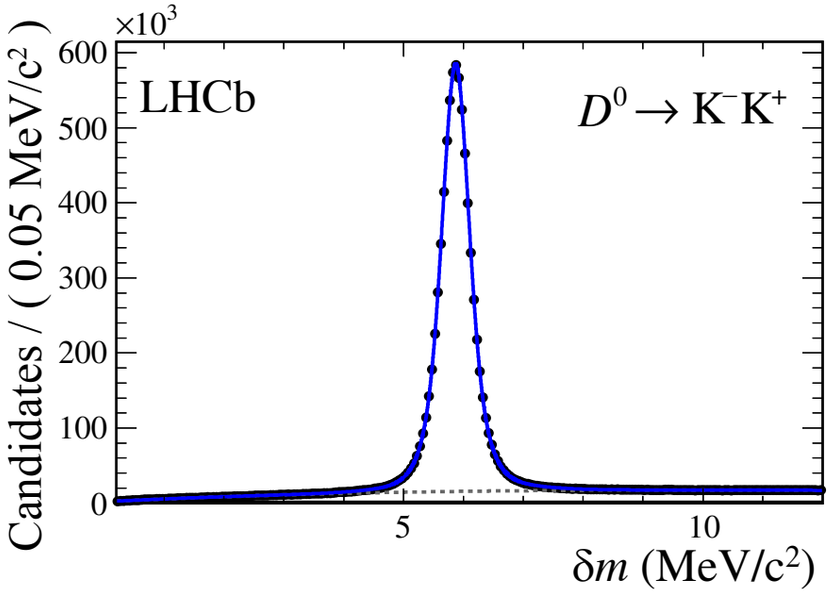
- Tagging D^0 with pion tag method using prompt $D^{*+} \to D^0\pi^+$ decays
- **Fit for $\delta m = m(D^{*+}) - m(D^0 \to f)$ with $f = K^+K^-$ or $f = \pi^+\pi^-$ and compute the asymmetry:**

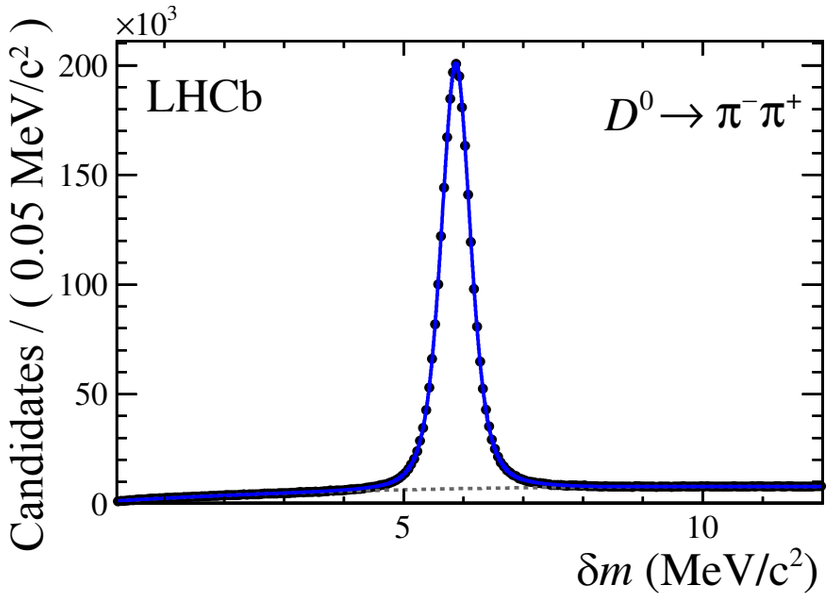
$$A_{CP}(f) = \frac{N\left(D^{*+} \to D^0(f)\pi_s^+\right) - N\left(D^{*-} \to \overline{D}^0(f)\pi_s^-\right)}{N\left(D^{*+} \to D^0(f)\pi_s^+\right) + N\left(D^{*-} \to \overline{D}^0(f)\pi_s^-\right)}$$

- **After correcting for detection and production asymmetries** (details in back-up ⇨)**:**

$$\begin{aligned} \Delta A_{CP} &\equiv A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-) \\ &= (-0.10 \pm 0.08\ (\text{stat}) \pm 0.03\ (\text{syst}))\,\% \end{aligned}$$

- **World's most precise measurement of *CP* asymmetry in $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ decays!**
- **Consistent with no *CP* violation**



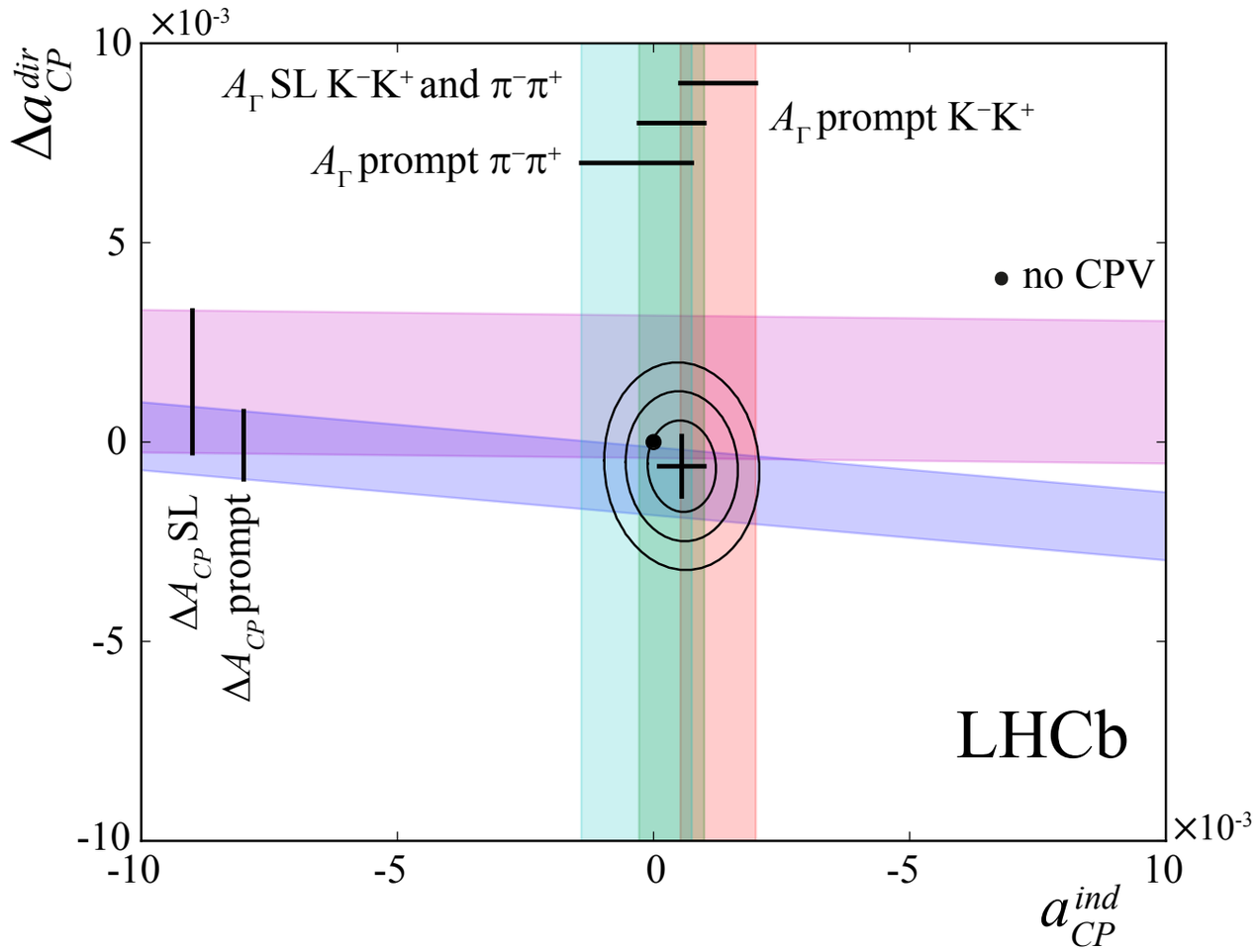


Search for *CP* violation in $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$

arXiv:1602.03160 [hep-ex]

Combination with previous *CP* violation measurements in charm:

- Indirect *CP* asymmetries with prompt $D^{*+} \to D^0\pi^+$: $A_\Gamma(K^+K^-)$ and $A_\Gamma(\pi^+\pi^-)$ [PRL 112, 041801 (2014)]
- Indirect *CP* asymmetries with semileptonic (SL) $B^- \to D^0\mu^-\nu$ [JHEP 04 (2015) 043]
- Direct *CP* asymmetries with semileptonic (SL) $B^- \to D^0\mu^-\nu$ [JHEP 07 (2014) 041]



Consistent with no *CP* violation in the charm sector!

3

Constraints on the CKM angle γ

Motivations

- **The CKM angle γ can be directly measured at tree level, without pollution from penguin amplitudes**

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

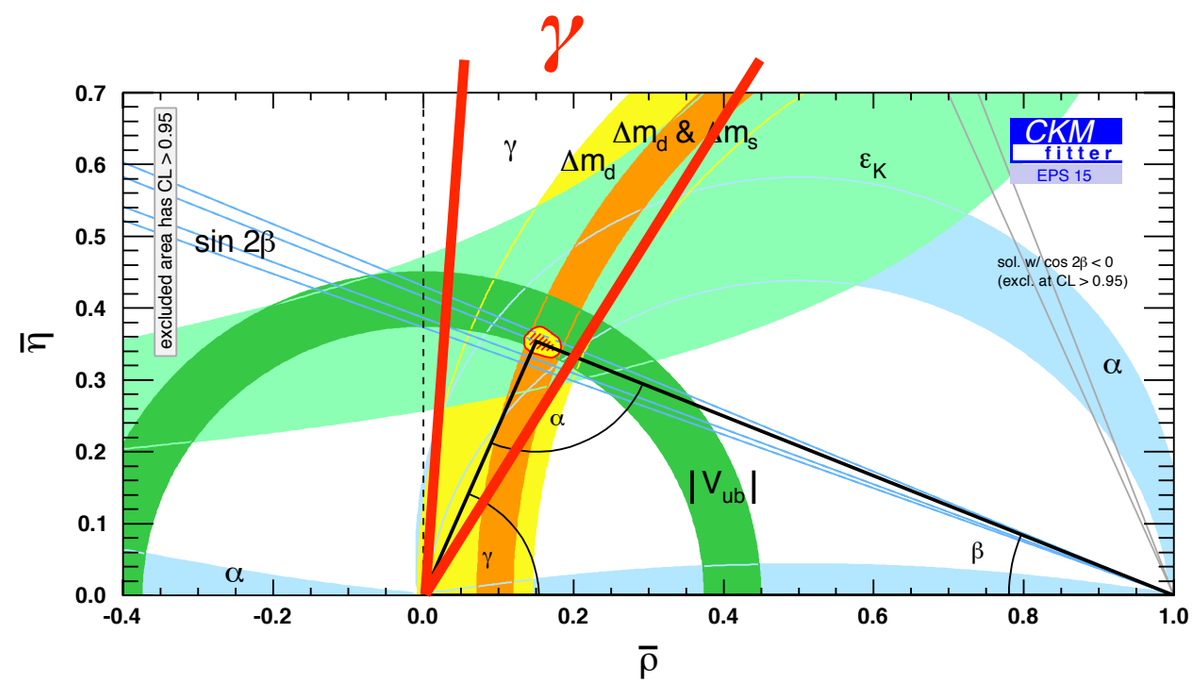
- **To probe NP, one can compare direct and indirect measurements of γ:**

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

Combination of direct measurement from BaBar, Belle and LHCb (CKM2014)

$$\gamma = (66.85^{+0.94}_{-3.44})^\circ$$

Indirect determination from global fit to CKM parameters (excluding γ)

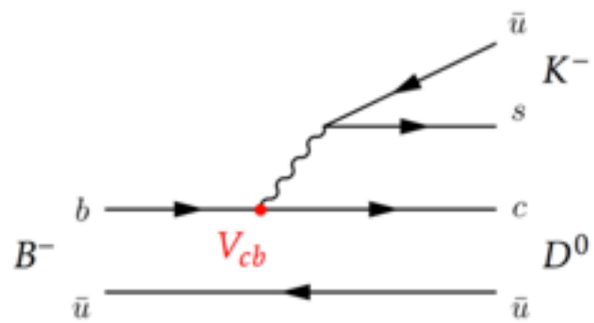


- **The "ultimate" γ-from tree-decays precision will be reached through many individual measurements, with very different sensitivities (due to different $b \to u$ to $b \to c$ amplitudes ratio)**

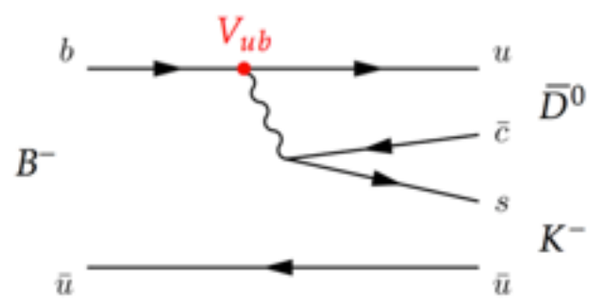
Ingredients for γ measurements

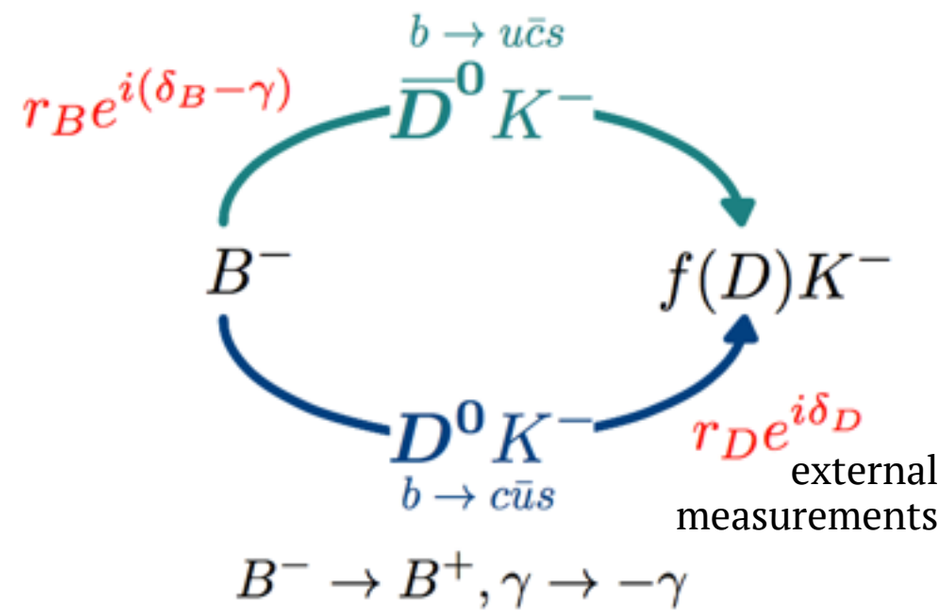
- **Use tree decays of $B^{\pm} \to DK^{\pm}$ which lead to the same final state with interference between $D^0 - \overline{D}^0$ decays to the same final state**

Cabibbo favored (CF)

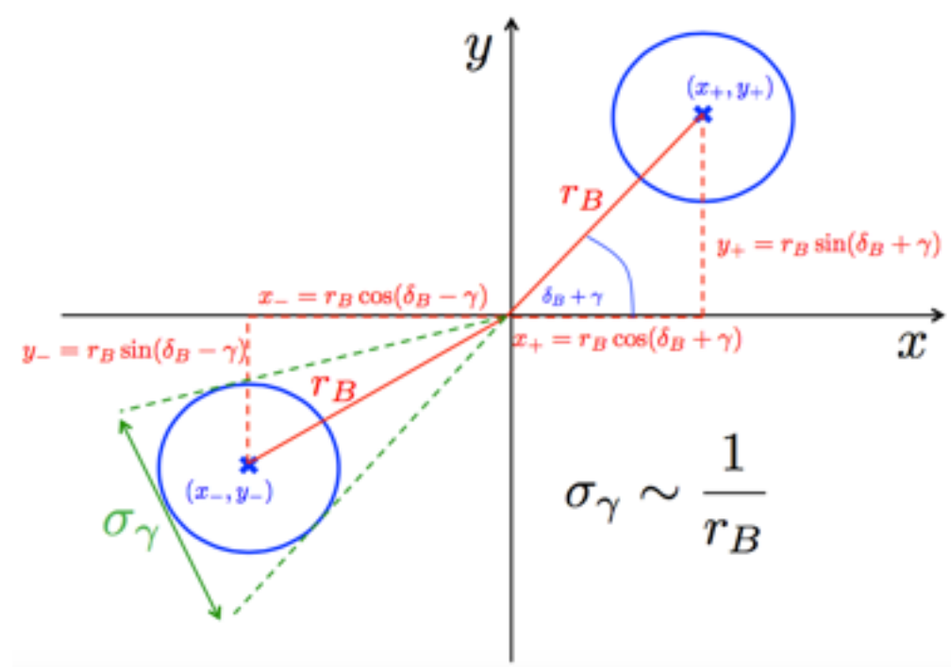


Doubly Cabibbo suppressed (DCS)





- **Combination of results from several modes using different experimental methods ⇨:**
  - **GLW: CP-even final states**
    [PLB 265 (1991) 172]
    [PLB 253 (1991) 483]
  - **ADS: CF or DCS final states**
    [PRL 78, 3257 (1997)]
    [PRD 63 (2001) 036005]
  - **GGSZ: 3 body final states**
    [PRD 68 (2003) 054018]



Inputs for γ combination

	B decay	D decay	Type	$\int \mathcal{L}$	Ref.
LHCb Inputs	$B^+ \to DK^+$	$D \to hh$	GLW/ADS	3fb^{-1}	[arXiv:1603.08993] ⋆
	$B^+ \to DK^+$	$D \to h\pi\pi\pi$	GLW/ADS	3fb^{-1}	[arXiv:1603.08993] ⋆
	$B^+ \to DK^+$	$D \to hh\pi^0$	GLW/ADS	3fb^{-1}	[arXiv:1504.05442] ⋆
	$B^+ \to DK^+$	$D \to K^0_S hh$	GGSZ	3fb^{-1}	[arXiv:1405.2797]
	$B^+ \to DK^+$	$D \to K^0_S K\pi$	GLS	3fb^{-1}	[arXiv:1402.2982]
	$B^0 \to D^0 K^{\star 0}$	$D \to K\pi$	ADS	3fb^{-1}	[arXiv:1407.3186]
	$B^+ \to DK^+\pi\pi$	$D \to hh$	GLW/ADS	3fb^{-1}	[arXiv:1505.07044] ⋆
	$B^0_s \to D^\mp_s K^\pm$	$D^+_s \to hhh$	TD	1fb^{-1}	[arXiv:1407.6127]
	$B^0 \to D^0 K^+\pi^-$	$D \to hh$	Dalitz	3fb^{-1}	[arXiv:1602.03455] ⋆
	$B^0 \to D^0 K^{\star 0}$	$D \to K^0_S\pi\pi$	GGSZ	3fb^{-1}	[arXiv:1605.01082] ⋆

	Decay	Parameters	Source		Ref.
Auxilliary Inputs	Charm mixing		HFAG	-	[arXiv:1412.7515]
	$D \to K\pi\pi\pi$	$(\delta_D, \kappa_D, r_D)$	CLEO+LHCb	-	[arXiv:1602.07430] ⋆
	$D \to \pi\pi\pi\pi$	(F^+)	CLEO	-	[arXiv:1504.05878] ⋆
	$D \to K\pi\pi^0$	$(\delta_D, \kappa_D, r_D)$	CLEO+LHCb	-	[arXiv:1602.07430] ⋆
	$D \to hh\pi^0$	(F^+)	CLEO	-	[arXiv:1504.05878] ⋆
	$D \to K^0_S K\pi$	(δ_D, κ_D)	CLEO	-	[arXiv:1203.3804]
	$D \to K^0_S K\pi$	(r_D)	CLEO	-	[arXiv:1203.3804]
	$D \to K^0_S K\pi$	(r_D)	LHCb	-	[arXiv:1509.06628]
	$B^0 \to D^0 K^{\star 0}$	$(\kappa_B, \overline{R}_B, \overline{\Delta}_B)$	LHCb	-	[arXiv:1602.03455] ⋆
	$B^0_s \to J/\psi h^+h^-$	(ϕ_s)	LHCb	-	[arXiv:1411.3104]
Combination:					**[LHCb-CONF-2016-001]**

⋆ new or updated since last combination

Inputs for γ combination

	B decay	D decay	Type	$\int \mathcal{L}$	Ref.
LHCb Inputs	$B^+ \to DK^+$	$D \to hh$	GLW/ADS	3fb^{-1}	[arXiv:1603.08993] ⋆
	$B^+ \to DK^+$	$D \to h\pi\pi\pi$	GLW/ADS	3fb^{-1}	[arXiv:1603.08993] ⋆
	$B^+ \to DK^+$	$D \to hh\pi^0$	GLW/ADS	3fb^{-1}	[arXiv:1504.05442] ⋆
	$B^+ \to DK^+$	$D \to K^0_S hh$	GGSZ	3fb^{-1}	[arXiv:1405.2797]
	$B^+ \to DK^+$	$D \to K^0_S K\pi$	GLS	3fb^{-1}	[arXiv:1402.2982]
	$B^0 \to D^0 K^{\star 0}$	$D \to K\pi$	ADS	3fb^{-1}	[arXiv:1407.3186]
	$B^+ \to DK^+\pi\pi$	$D \to hh$	GLW/ADS	3fb^{-1}	[arXiv:1505.07044] ⋆
	$B^0_s \to D^\mp_s K^\pm$	$D^+_s \to hhh$	TD	1fb^{-1}	[arXiv:1407.6127]
	$B^0 \to D^0 K^+\pi^-$	$D \to hh$	Dalitz	3fb^{-1}	[arXiv:1602.03455] ⋆
	$B^0 \to D^0 K^{\star 0}$	$D \to K^0_S\pi\pi$	GGSZ	3fb^{-1}	[arXiv:1605.01082] ⋆

	Decay	Parameters	Source		Ref.
Auxilliary Inputs	Charm mixing		HFAG	-	[arXiv:1412.7515]
	$D \to K\pi\pi\pi$	$(\delta_D, \kappa_D, r_D)$	CLEO+LHCb	-	[arXiv:1602.07430] ⋆
	$D \to \pi\pi\pi\pi$	(F^+)	CLEO	-	[arXiv:1504.05878] ⋆
	$D \to K\pi\pi^0$	$(\delta_D, \kappa_D, r_D)$	CLEO+LHCb	-	[arXiv:1602.07430] ⋆
	$D \to hh\pi^0$	(F^+)	CLEO	-	[arXiv:1504.05878] ⋆
	$D \to K^0_S K\pi$	(δ_D, κ_D)	CLEO	-	[arXiv:1203.3804]
	$D \to K^0_S K\pi$	(r_D)	CLEO	-	[arXiv:1203.3804]
	$D \to K^0_S K\pi$	(r_D)	LHCb	-	[arXiv:1509.06628]
	$B^0 \to D^0 K^{\star 0}$	$(\kappa_B, \overline{R}_B, \overline{\Delta}_B)$	LHCb	-	[arXiv:1602.03455] ⋆
	$B^0_s \to J/\psi h^+h^-$	(ϕ_s)	LHCb	-	[arXiv:1411.3104]
Combination:					**[LHCb-CONF-2016-001]**

⋆ new or updated since last combination

3

Constraints on the CKM angle γ

GLW / ADS

$B^{\pm} \to Dh^{\pm}$ (2-4 body)

arXiv:1603.08993 [hep-ex]

Full Run1 data: 3 fb^{-1}

GLW / ADS $B^{\pm} \to Dh^{\pm}$ (2-4 body)

arXiv:1603.08993 [hep-ex]

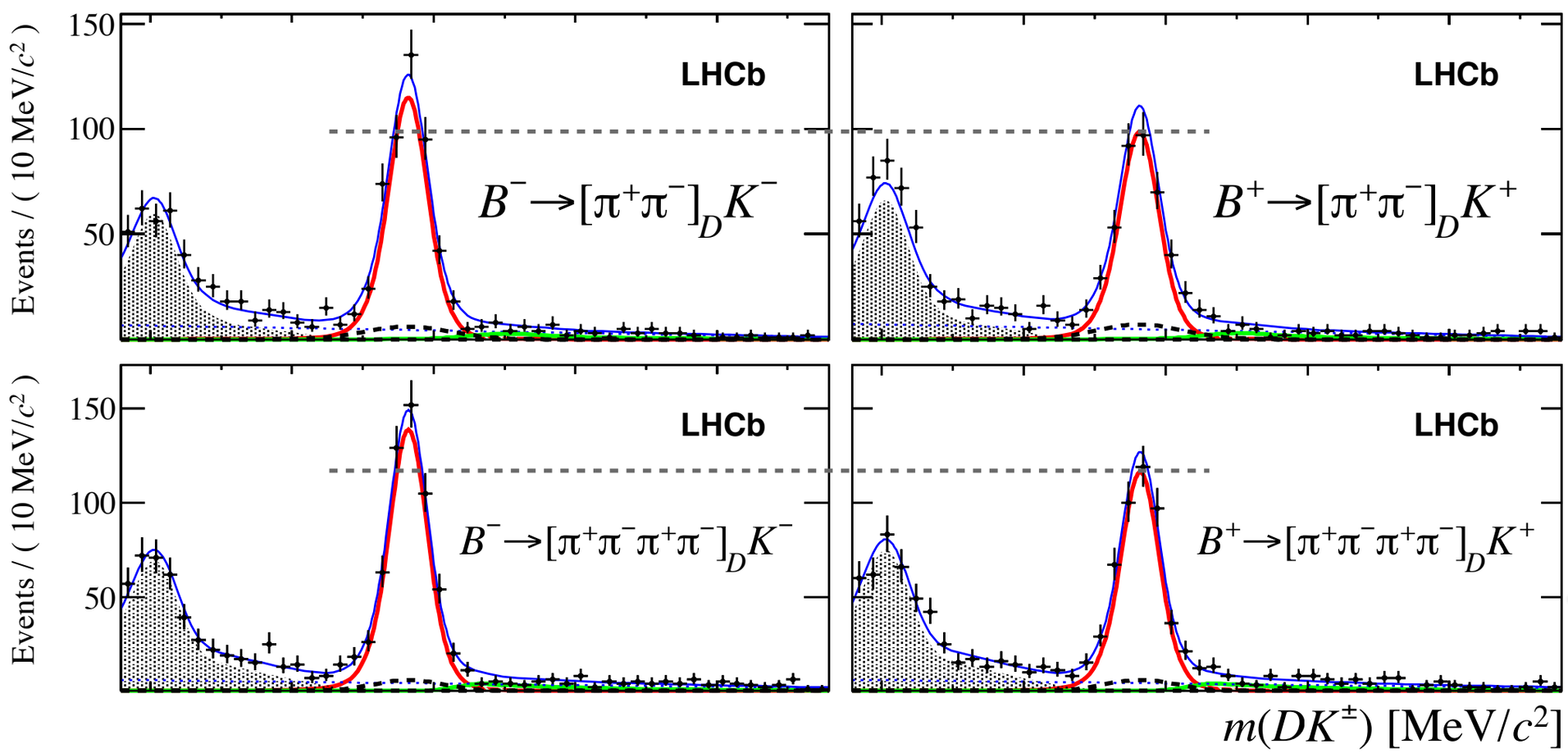
- **Measure charge asymmetries (A) and partial width ratios (R)**

$$A = \frac{\Gamma\left(B^- \to f_D h^-\right) - \Gamma\left(B^+ \to \bar{f}_D h^+\right)}{\Gamma\left(B^- \to f_D h^-\right) + \Gamma\left(B^+ \to \bar{f}_D h^+\right)} \qquad R = \frac{\Gamma\left(B^- \to f_D h^-\right) + \Gamma\left(B^+ \to \bar{f}_D h^+\right)}{\Gamma\left(B^- \to f'_D h^-\right) + \Gamma\left(B^+ \to \bar{f}'_D h^+\right)}$$

with $h = (K,\pi)$

- **GLW: $D^0 \to K^+K^-$ / $\pi^+\pi^-$ / $\pi^+\pi^-\pi^+\pi^-$**

Examples



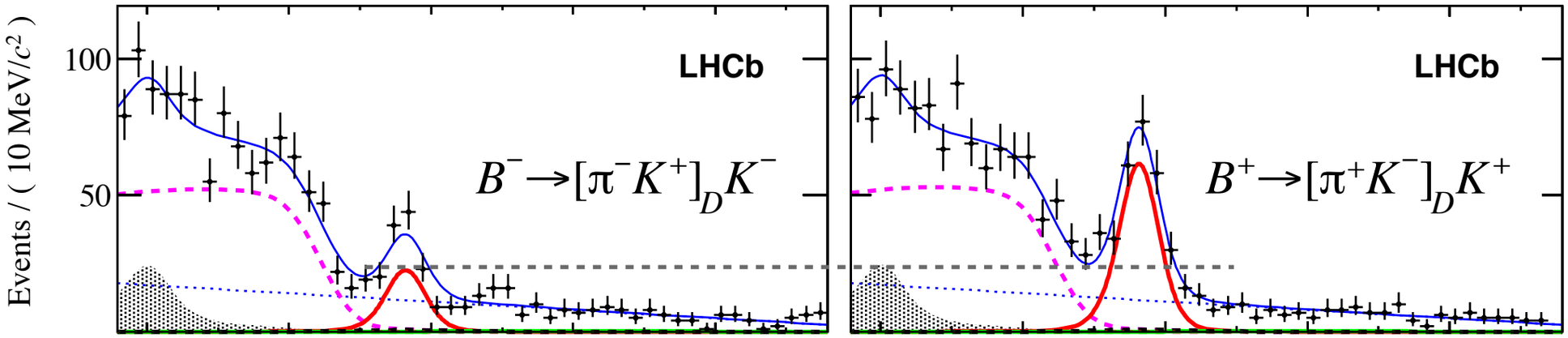
First time

GLW / ADS $B^{\pm} \to Dh^{\pm}$ (2-4 body)

arXiv:1603.08993 [hep-ex]

- **ADS:** $D^0 \to K^{\pm}\pi^{\mp}$ / $K^{\pm}\pi^{\mp}\pi^{+}\pi^{-}$

Example

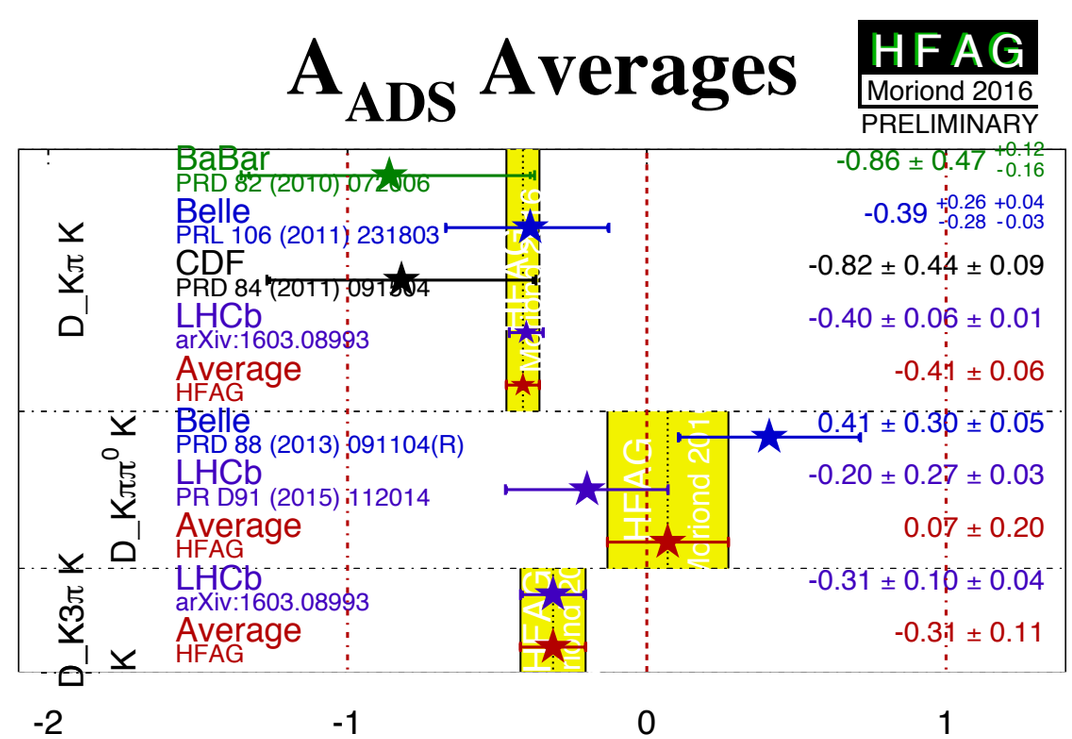


$m(DK^{\pm})$ [MeV/c^2]

$A \neq 0$ @ 8σ

First observation of *CP* violation in single $B \to Dh$ decay mode

- **GLW/ADS:**
  - In total 21 *CP* observables entering in the γ combination
  - Good sensitivity to the ADS modes compared to other experiments



3

Constraints on the CKM angle γ

- GLW / ADS
  $B^{\pm} \to Dh^{\pm}$ (2-4 body)
  arXiv:1603.08993 [hep-ex]
  Full Run1 data: 3 fb^{-1}

- **GGSZ analysis of $B^0 \to DK^{*0}$ decays**
  arXiv:1605.01082 [hep-ex]
  Full Run1 data: 3 fb^{-1}

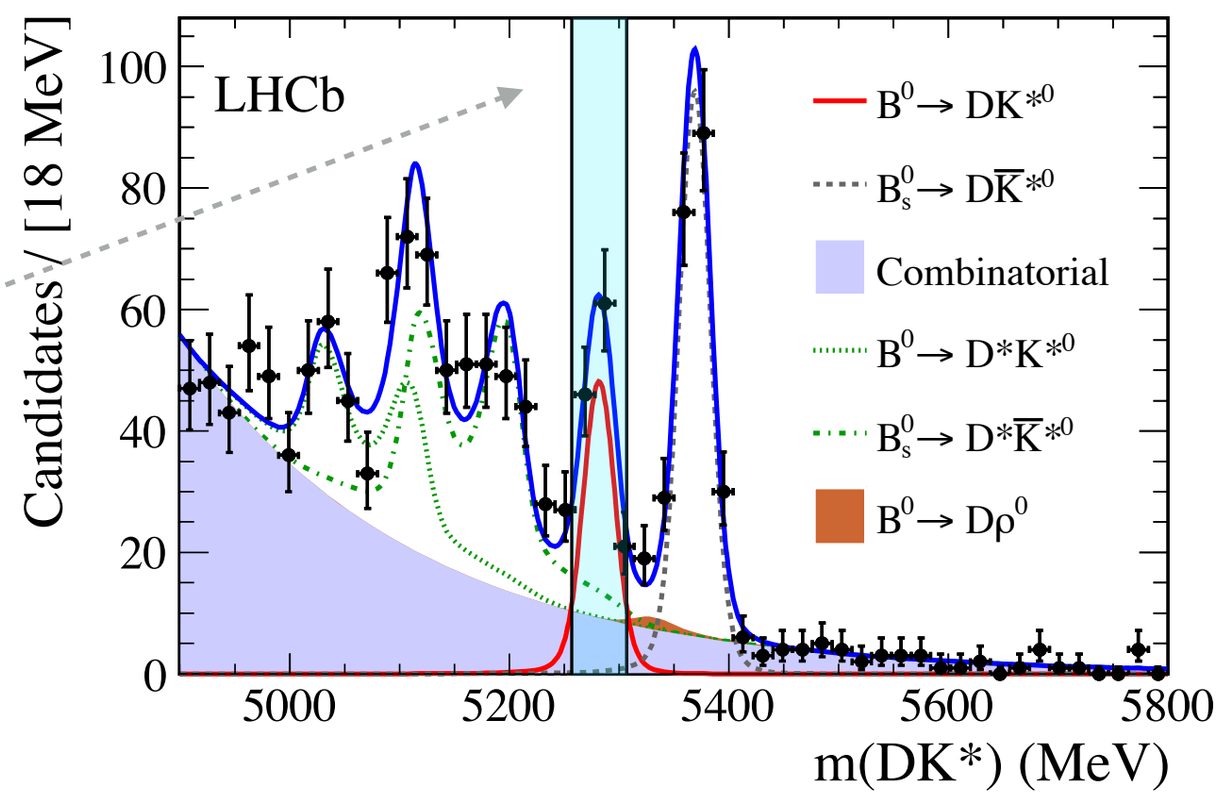
NEW!

GGSZ analysis of $B^0 \to DK^{*0}$ decays

arXiv:1605.01082 [hep-ex]

- **Lower rate than $B^\pm \to DK^\pm$, but larger interference effects ($r_{B^0} \sim 3\, r_{B^+}$)**
- **GGSZ: $D^0 \to K_S^0 \pi^+ \pi^-$**
  - Multi-body D decays $\Rightarrow$ charge asymmetry varies accros Dalitz plane
  - Two experimental methods:
    model dependent (**MD**) [arXiv:1605.01082] ; model independent (**MI**) [arXiv:1604.01525]
    (only **MD** γ in combination)

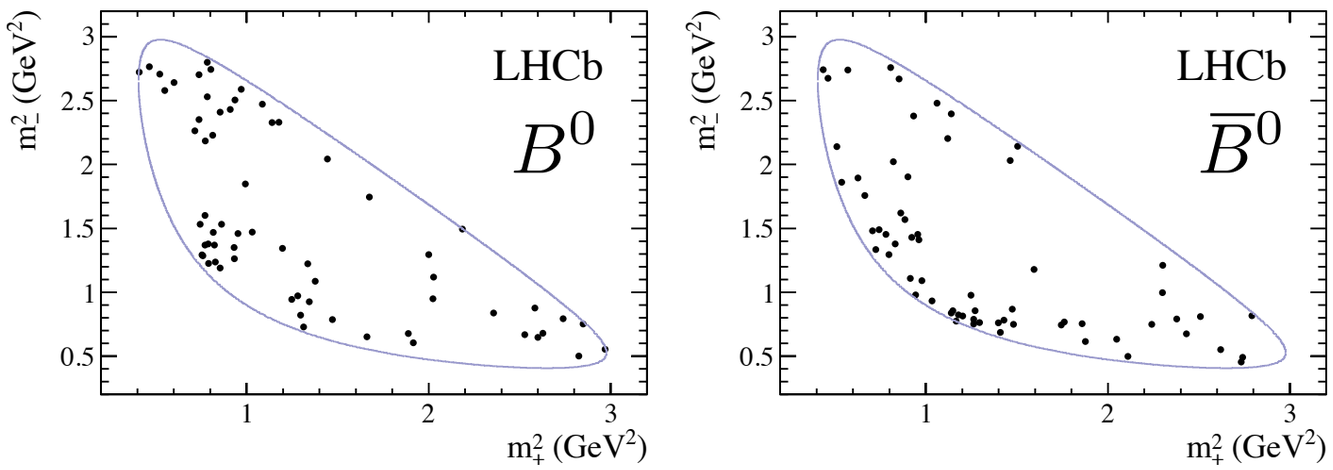
- **Model-dependent analysis:**
  - First perform a fit to the B^0 mass
  - Making use of BaBar's amplitude model [arXiv:1005.1096] to fit Dalitz plane for events within signal region
  - Signal yield (89 ± 11)
    Twice more events than previous B-factory measurement



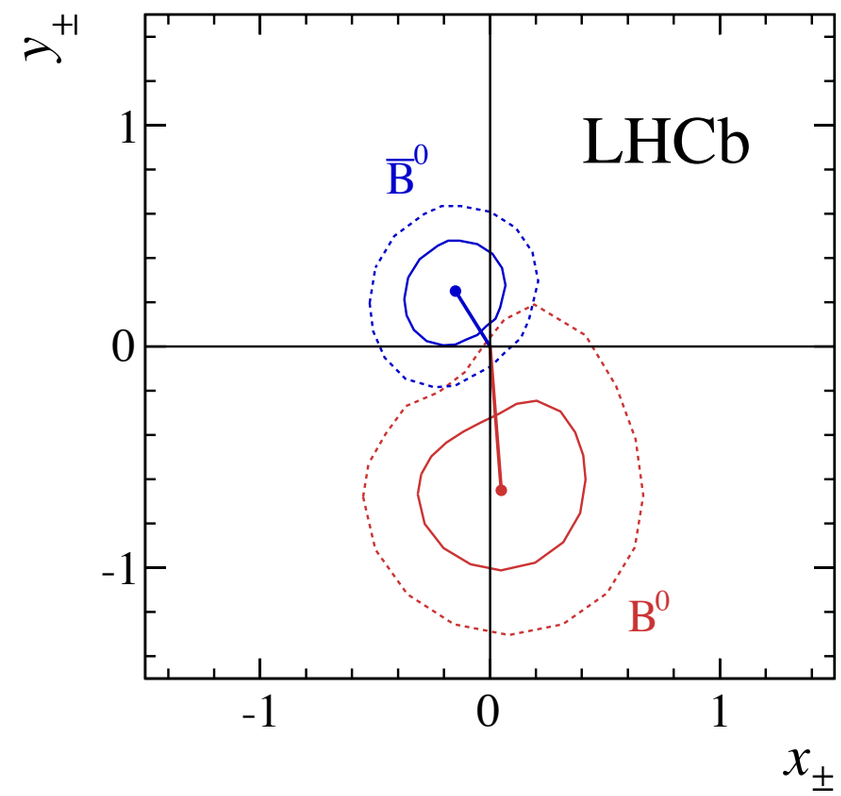
GGSZ analysis of $B^0 \to DK^{*0}$ decays

arXiv:1605.01082 [hep-ex]

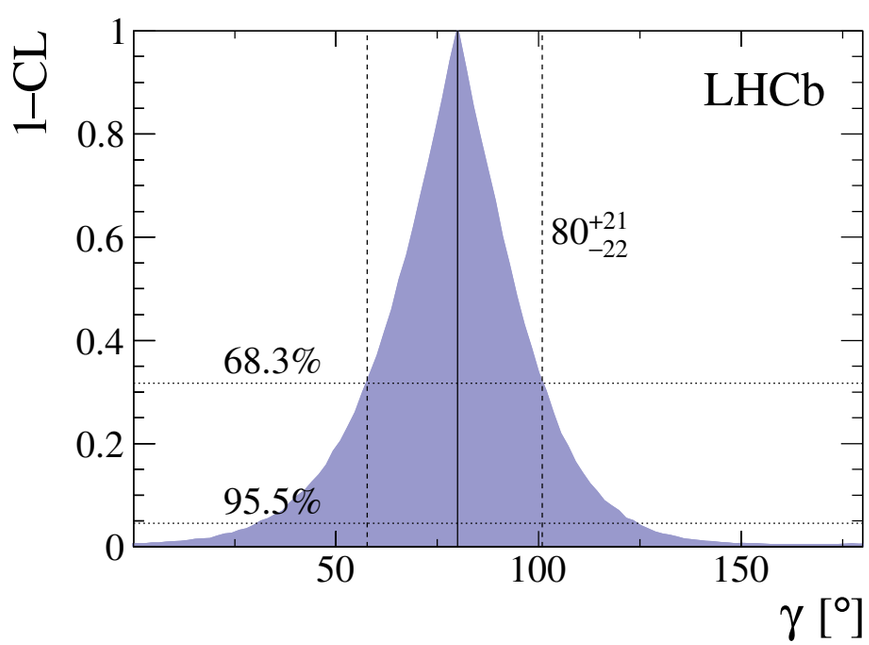
- **Fit Dalitz plane to extract *CP* observables ($x_\pm$,$y_\pm$)**



$$x_\pm = r_{B^0}\cos(\delta_{B^0} \pm \gamma)$$
$$y_\pm = r_{B^0}\sin(\delta_{B^0} \pm \gamma)$$



- **Results (MD):**
  - *CP* observables compatible with MI results
  - **Leads to a unique solution for γ:**



3

Constraints on the CKM angle γ

- **LHCb γ combination**
  LHCb-CONF-2016-001

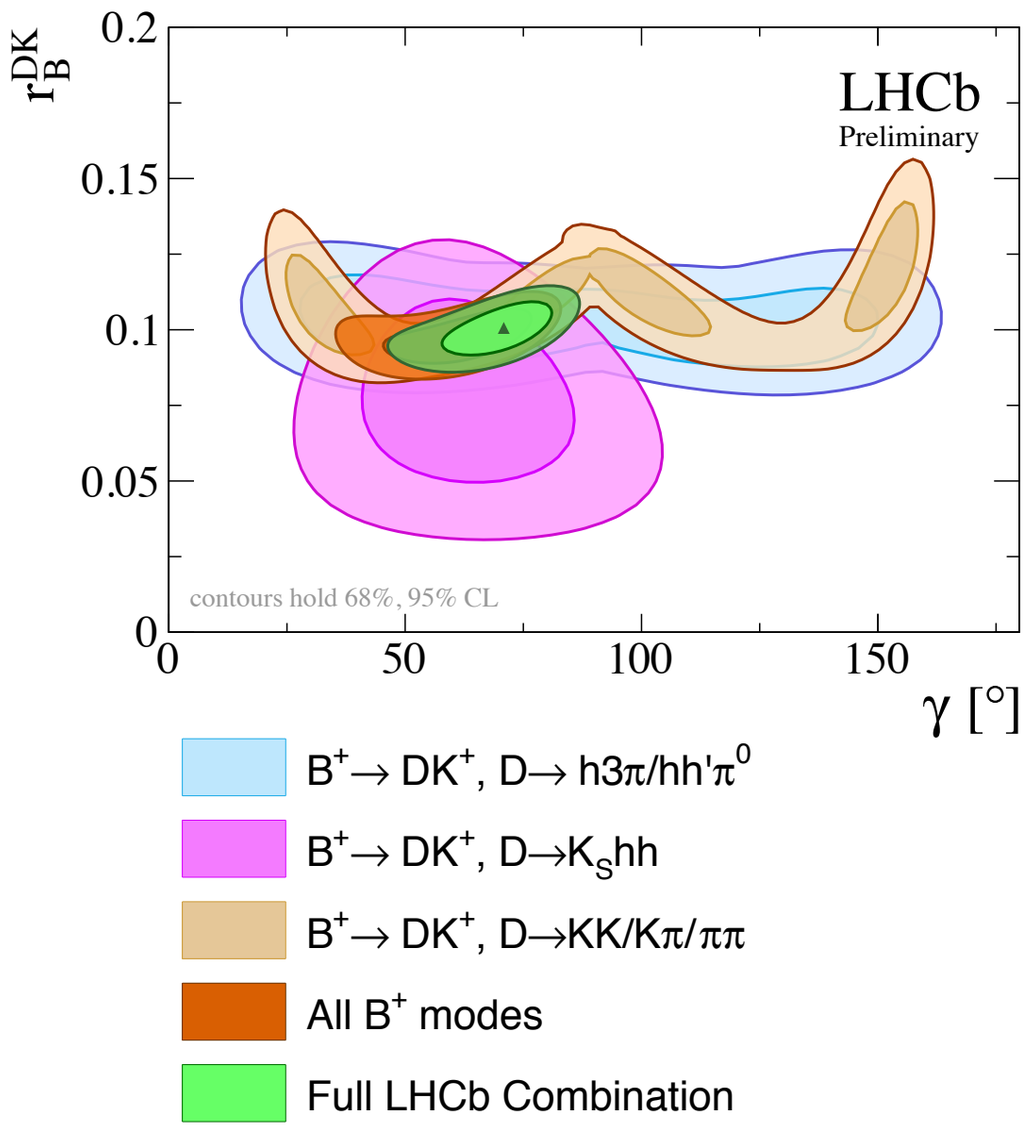
NEW!

LHCb γ combination

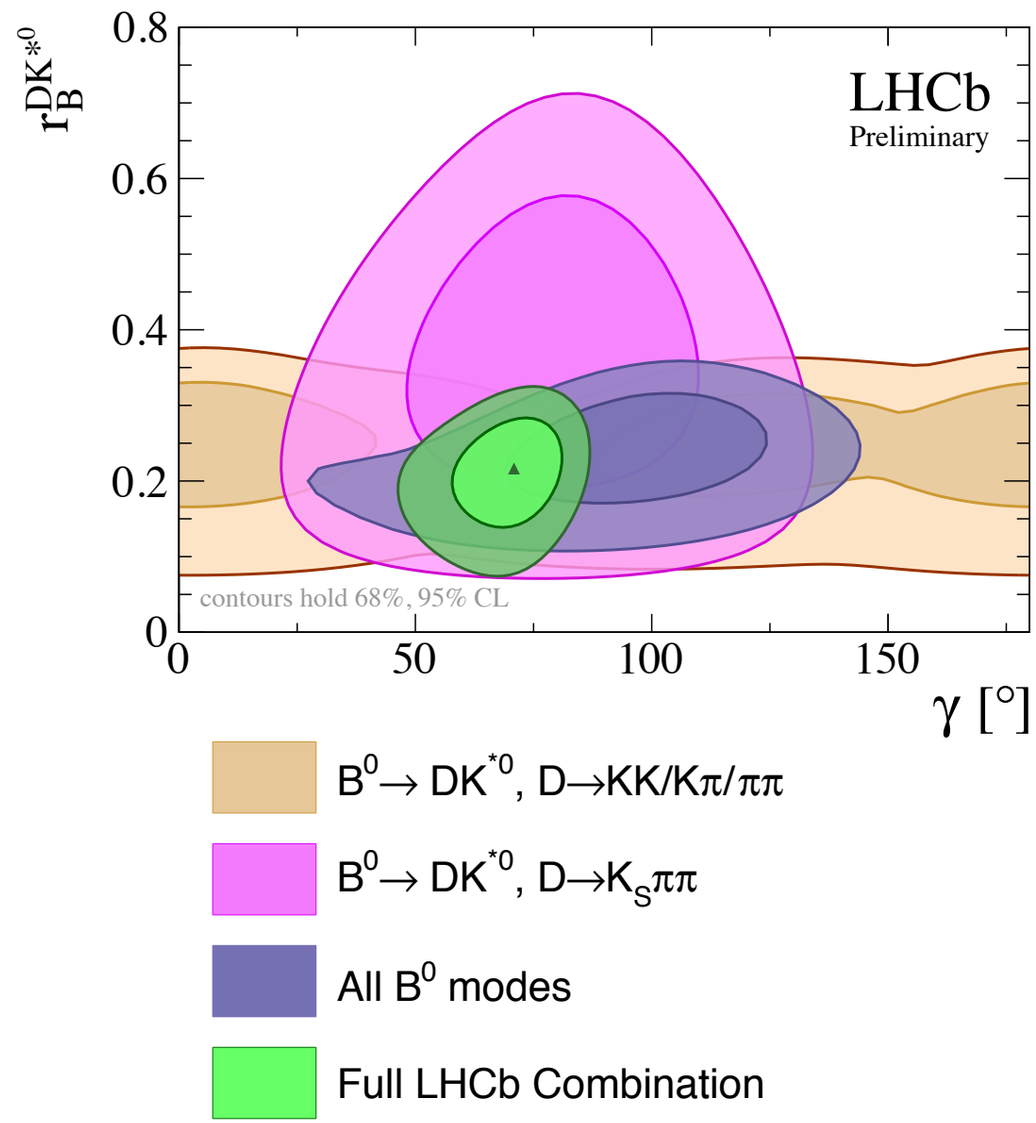
LHCb-CONF-2016-001

- **Complementarity of different methods:** ADS/GLW, quasi-ADS/GLW, GGSZ

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



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



LHCb γ combination

LHCb-CONF-2016-001

- **Most precise measurement from a single experiment:**

$$\gamma = (70.9^{+7.1}_{-8.5})^\circ$$

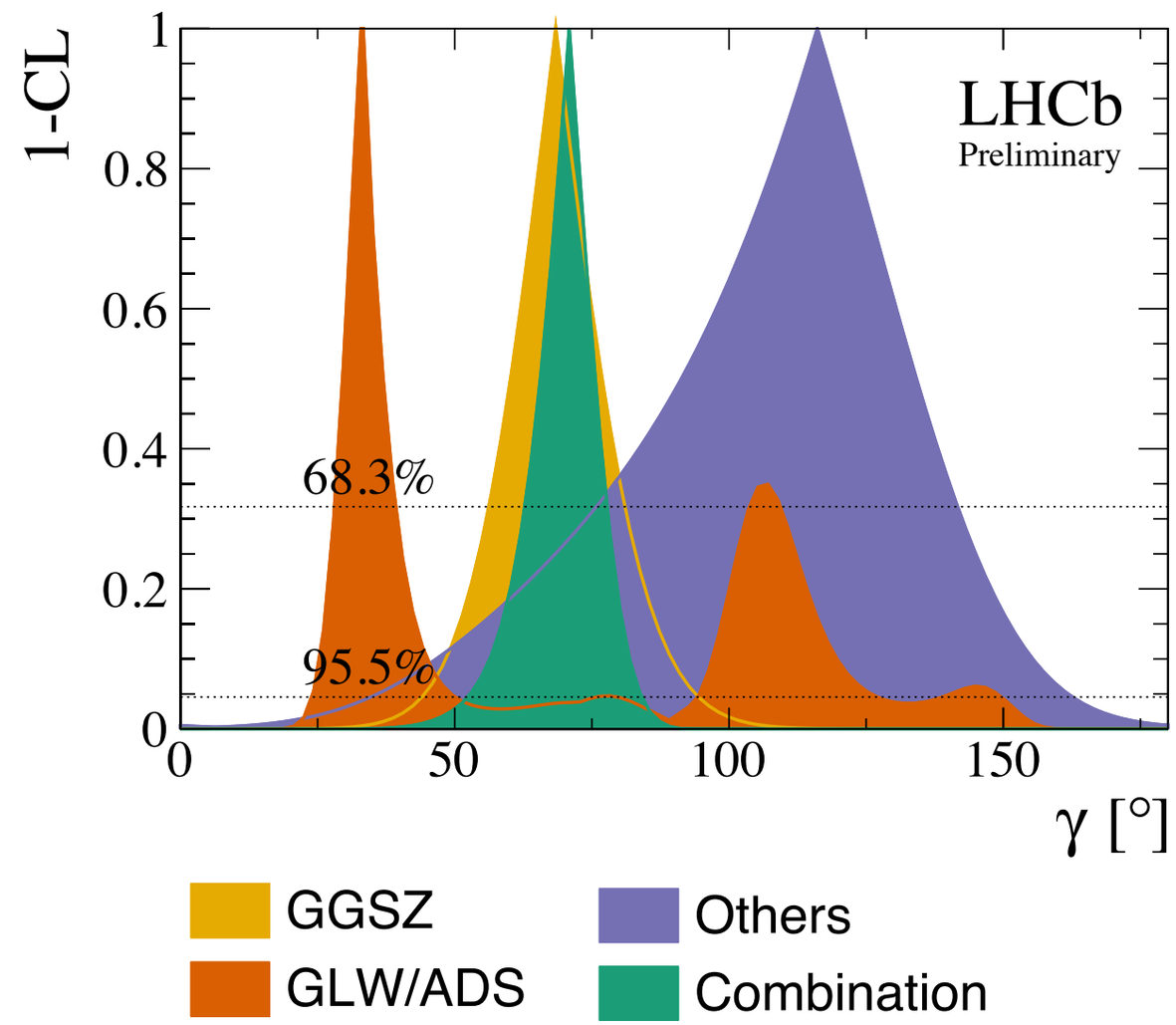
- **Consistent with *B*-factories:**

BaBar: $(70 \pm 18)^\circ$

Belle: $(73\,^{+13}_{-15})^\circ$

and indirect determination:

$$\gamma = (66.85^{+0.94}_{-3.44})^\circ$$



4

CP asymmetry in $B_s^0 - \bar{B}_s^0$ mixing

Preliminary results

Full Run1 data: 3 fb^{-1}

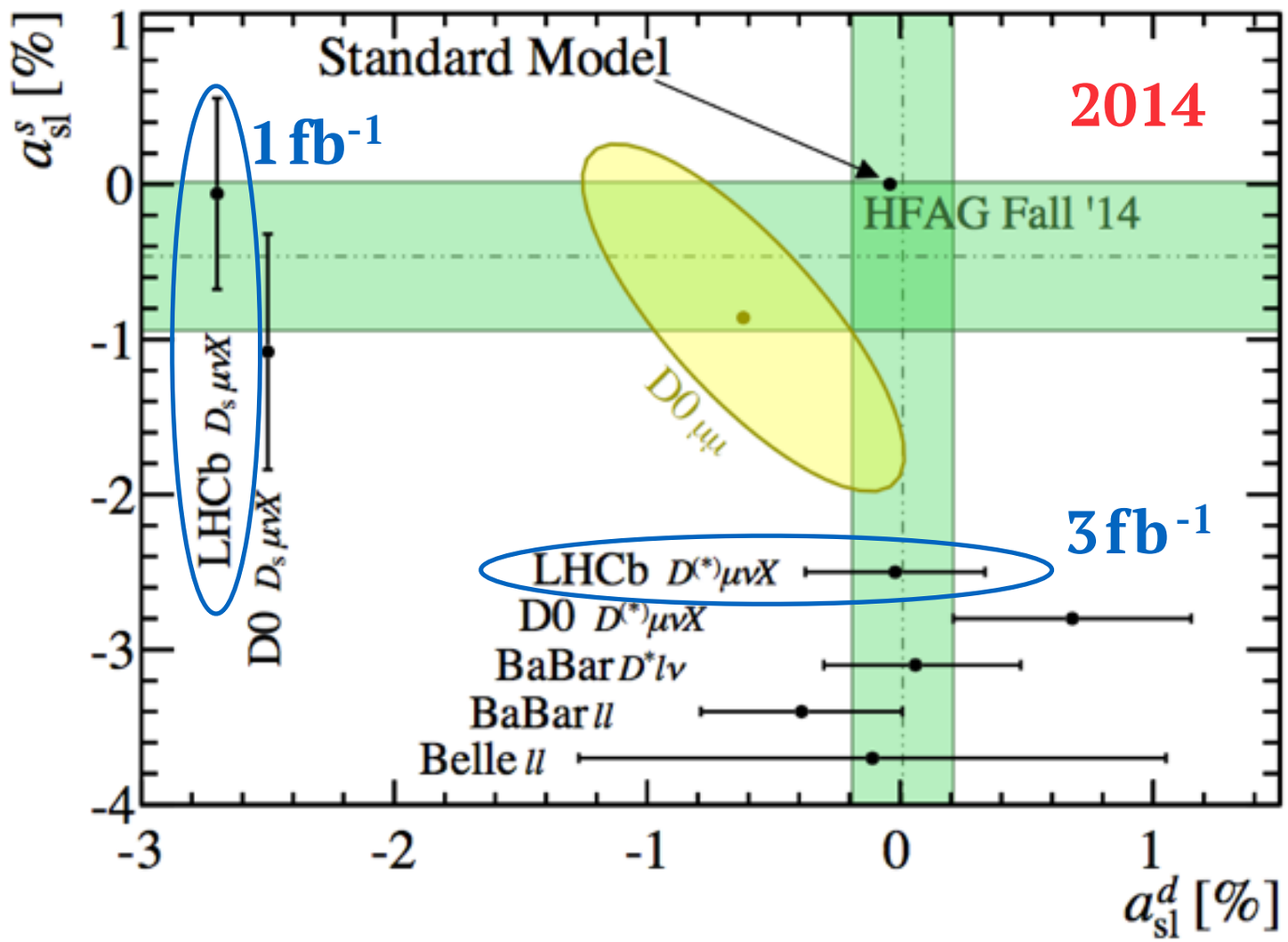
CP asymmetry in $B_s^0 - \overline{B}_s^0$ mixing

preliminary results

- **As in charm sector, any significant *CP* violation in $B_s^0 - \overline{B}_s^0$ mixing would be an indication of NP:**

$$a_{sl}^s = \frac{\mathcal{P}(\overline{B}_s^0 \to B_s^0) - \mathcal{P}(B_s^0 \to \overline{B}_s^0)}{\mathcal{P}(\overline{B}_s^0 \to B_s^0) + \mathcal{P}(B_s^0 \to \overline{B}_s^0)} \overset{\text{SM}}{\sim} \mathcal{O}(10^{-5})$$

[arXiv:1511.09466]

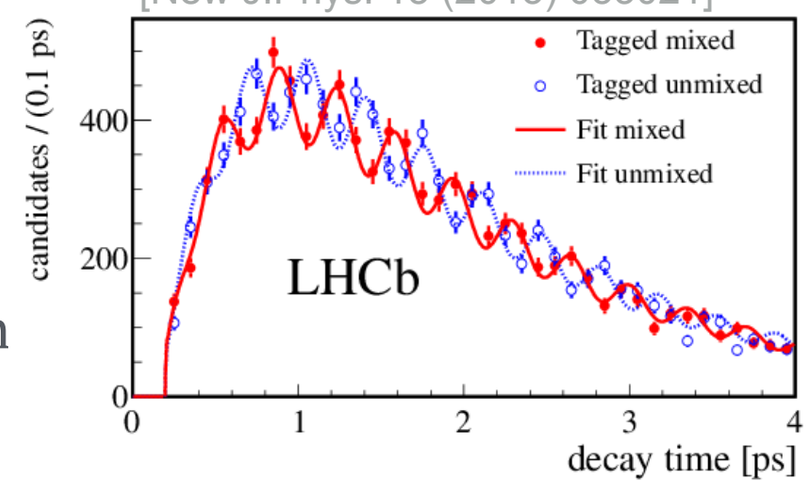


CP asymmetry in $B_s^0 - \bar{B}_s^0$ mixing

preliminary results

- **Update of a_{ls}^s with 3 fb^{-1}:**
  - **Inclusive $B_s^0 \to D_s^- \mu^+ \nu_\mu X$ decays**
  - **Time integrated analysis:**
    production asymmetry cancels thanks to fast B_s^0 oscillation

[New J.Phys. 15 (2013) 053021]



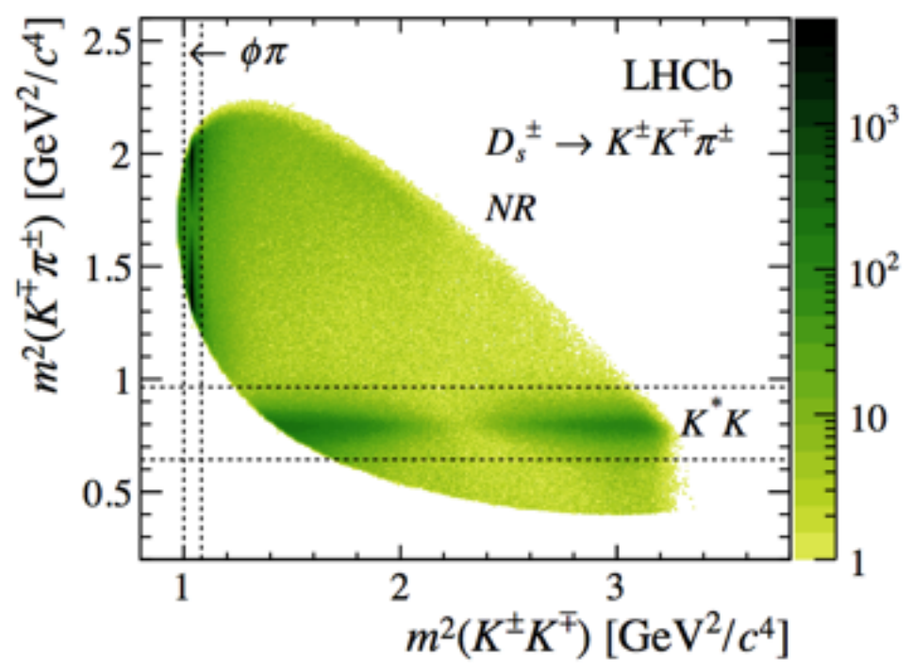
$$a_{\rm sl}^s = \frac{2}{1 - f_{\rm bkg}} (A_{\rm raw} - A_{\rm det} - f_{\rm bkg} A_{\rm bkg})$$

$$A_{\rm raw} = \frac{N(D_s^- \mu^+) - N(D_s^+ \mu^-)}{N(D_s^- \mu^+) + N(D_s^+ \mu^-)}$$

$$A_{\rm det} \approx A_{\rm track} + A_{\rm PID} + A_{\rm trig}$$

(details in back-up ⇨)

- **Measurement performed separately in 3 regions of Dalitz** ($f_{\rm bkg}$ dependent)



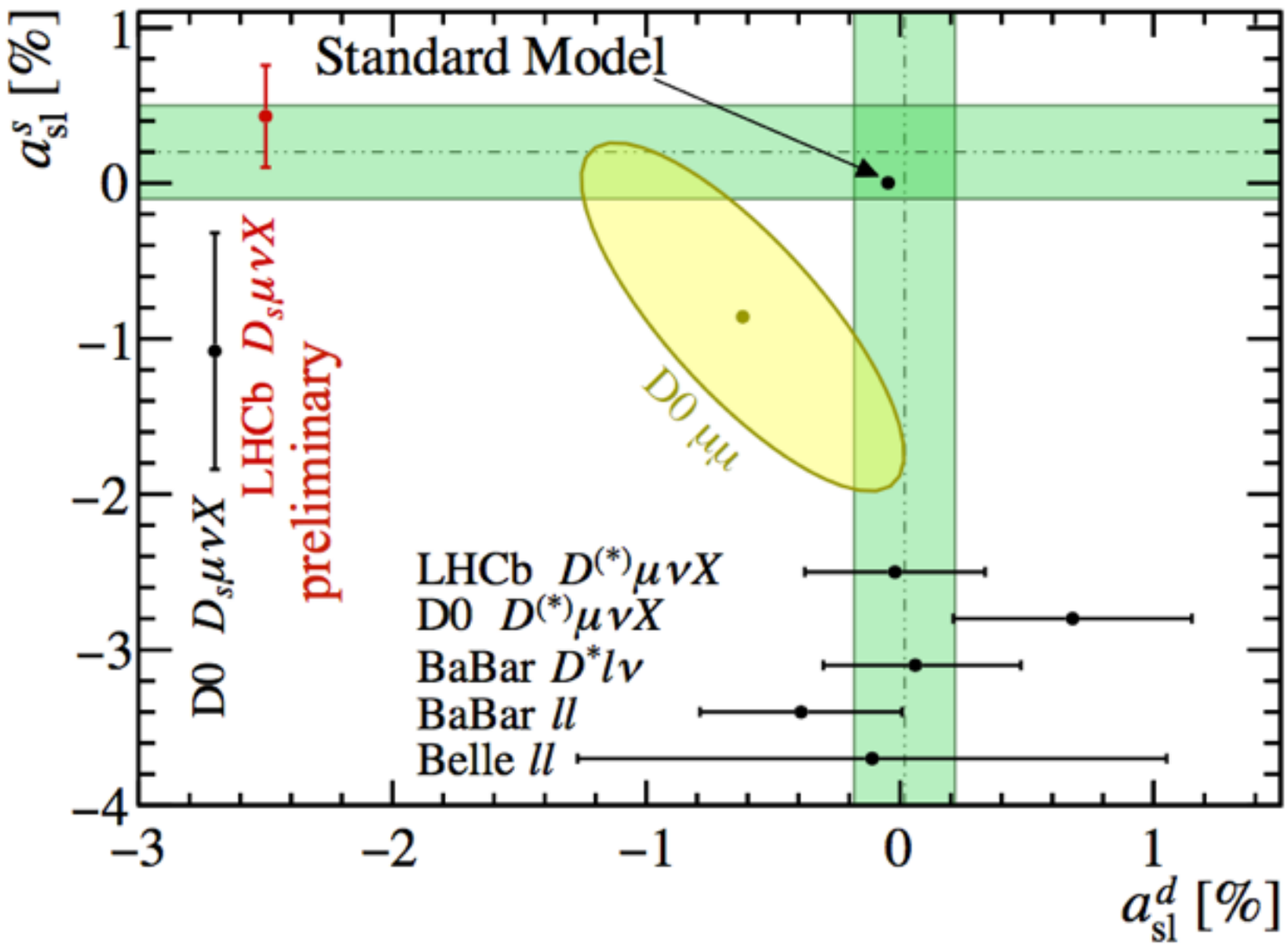
- $A_{\rm bkg}$ mainly from production asymmetries

CP asymmetry in $B_s^0 - \bar{B}_s^0$ mixing

preliminary results

- **Results:** (preliminary)

$$a_{sl}^s = (0.45 \pm 0.26(\text{stat}) \pm 0.20(\text{syst}))\,\%$$



5

Summary and Conclusions

Summary and conclusion

- **CKM matrix is incredibly successful description of the quark sector in the SM, and the measurements of CKM elements are becoming increasingly precise**
  - **Most precise measurement of γ from a single experiment:**

$$\gamma = (70.9^{+7.1}_{-8.5})^{\circ}$$

  - **No evidence for *CP* violation in charm**
  - ***CP* violation in $B_s^0 - \overline{B}_s^0$ mixing consistent with SM prediction**

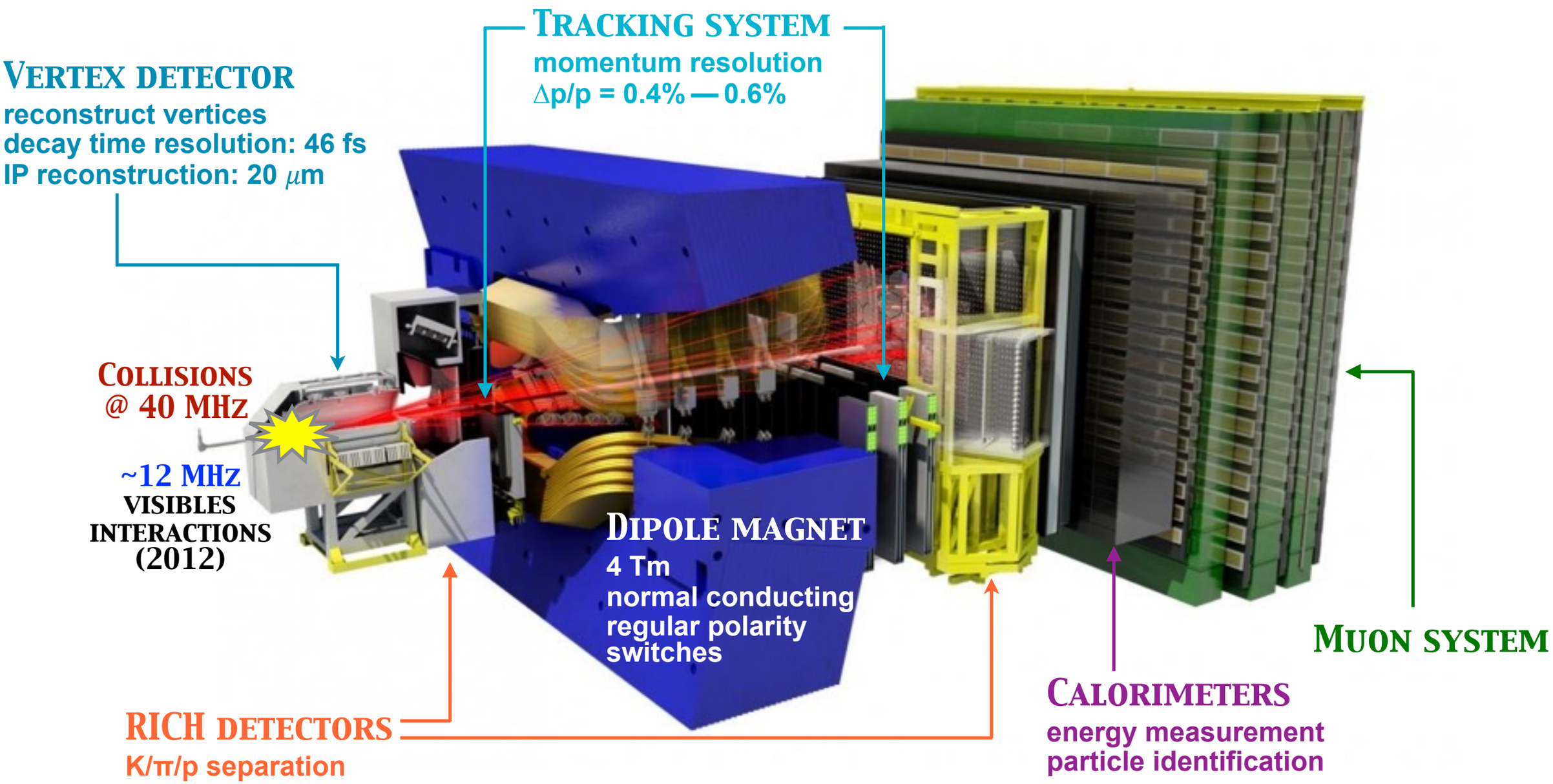
- **Expect several new results with improved sensitivity in the future**
  - **Current results mostly statistically dominated**
  - **Improved trigger scheme for Run2 and LHCb Upgrade leads to billion of charm events and significant increase of hadronic B decays efficiencies!**

Additional material

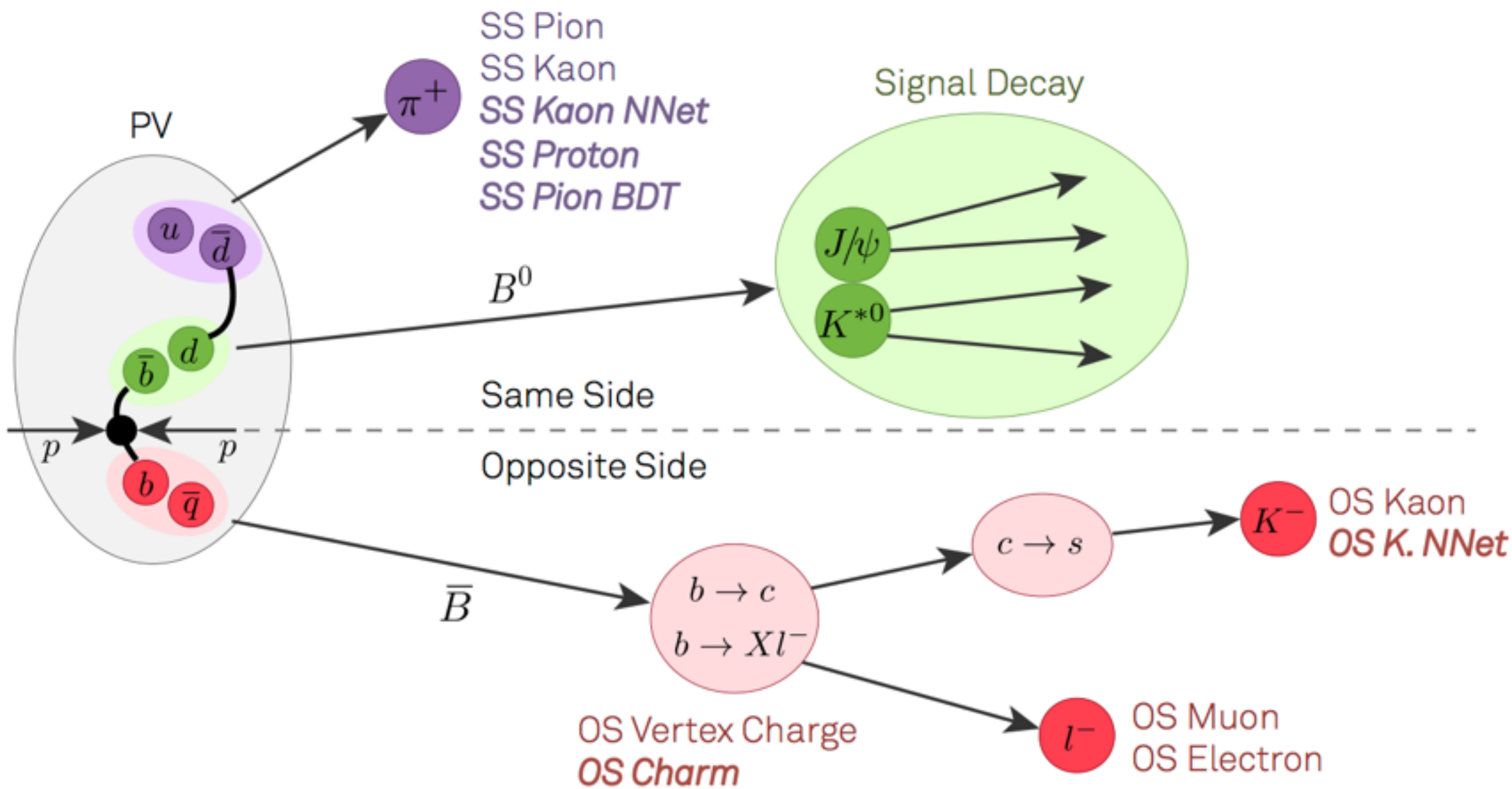
- **Experiment apparatus and analysis techniques** ⇨
- **Mixing and *CP* violation in charm:**
  - **First observation of $D^0 - \overline{D}^0$ oscillations in $D^0 \to K^+\pi^-\pi^+\pi^-$** ⇨
  - **Search for *CP* violation in $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$** ⇨
- **Constraints on the CKM angle γ:**
  - **GLW / ADS $B^\pm \to Dh^\pm$ (2-4 body)** ⇨
  - **GGSZ analysis of $B^0 \to DK^{*0}$ decays** ⇨
  - **LHCb γ combination** ⇨
- ***CP* asymmetry in $B_s^0 - \overline{B}_s^0$ mixing** ⇨

The LHCb experiment

- **Forward General-Purpose Detector at the LHC**
- **~30 % of heavy quark production cross-section with just 4% of solid angle**



Flavor tagging



First observation of $D^0 - \bar{D}^0$ oscillations in $D^0 \to K^+\pi^-\pi^+\pi^-$

arXiv:1602.07224 [hep-ex]

- Fitted parameters (uncertainties include all systematics)

Fit Type χ^2/ndf (p-value)	Parameter	Fit result	Correlation coefficient $r_D^{K3\pi}$	$R_D^{K3\pi} \cdot y'_{K3\pi}$	$\frac{1}{4}(x^2+y^2)$
Unconstrained	$r_D^{K3\pi}$	$(5.67 \pm 0.12) \times 10^{-2}$	1	0.91	0.80
7.8/7 (0.35)	$R_D^{K3\pi} \cdot y'_{K3\pi}$	$(0.3 \pm 1.8) \times 10^{-3}$		1	0.94
	$\frac{1}{4}(x^2+y^2)$	$(4.8 \pm 1.8) \times 10^{-5}$			1
			$r_D^{K3\pi}$	$R_D^{K3\pi} \cdot y'_{K3\pi}$	x	y
Mixing-constrained	$r_D^{K3\pi}$	$(5.50 \pm 0.07) \times 10^{-2}$	1	0.83	0.17	0.10
11.2/8 (0.19)	$R_D^{K3\pi} \cdot y'_{K3\pi}$	$(-3.0 \pm 0.7) \times 10^{-3}$		1	0.34	0.20
	x	$(4.1 \pm 1.7) \times 10^{-3}$			1	-0.40
	y	$(6.7 \pm 0.8) \times 10^{-3}$				1

Search for *CP* violation in $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$

arXiv:1602.03160 [hep-ex]

Measured asymmetry:

$$A_{\text{raw}}(f) = \frac{N\left(D^{*+} \to D^0(f)\pi_s^+\right) - N\left(D^{*-} \to \overline{D}^0(f)\pi_s^-\right)}{N\left(D^{*+} \to D^0(f)\pi_s^+\right) + N\left(D^{*-} \to \overline{D}^0(f)\pi_s^-\right)}$$

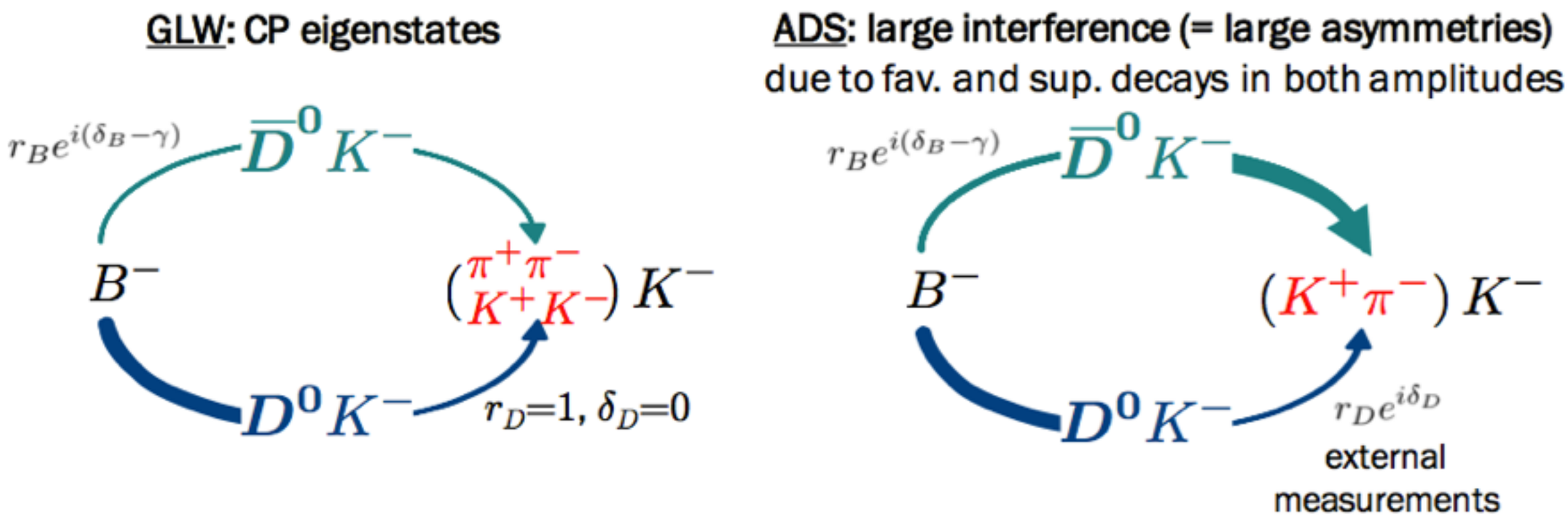
$$A_{\text{raw}}(f) = \left(A_{CP}(f) + A_D(f) + A_D(\pi_s^+) + A_P(D^{*+})\right) + \mathcal{O}(10^{-6})$$

$$\Delta A_{CP} = A_{\text{raw}}(K^+K^-) - A_{\text{raw}}(\pi^+\pi^-)$$

- $A_D(K^+K^-)$ and $A_D(\pi^+\pi^-)$ cancels due to self-conjugated final states.
- $A_D(\pi_s^+)$ and $A_P(D^{*+})$ independent of the final state *f* in any given kinematic region, and thus cancel in the difference:
  - Residual differences due to different kinematics between K^+K^- and $\pi^+\pi^-$ cancelled thanks to reweighing K^+K^- kinematic to match those of $\pi^+\pi^-$

$$\Delta A_{CP} = A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-)$$

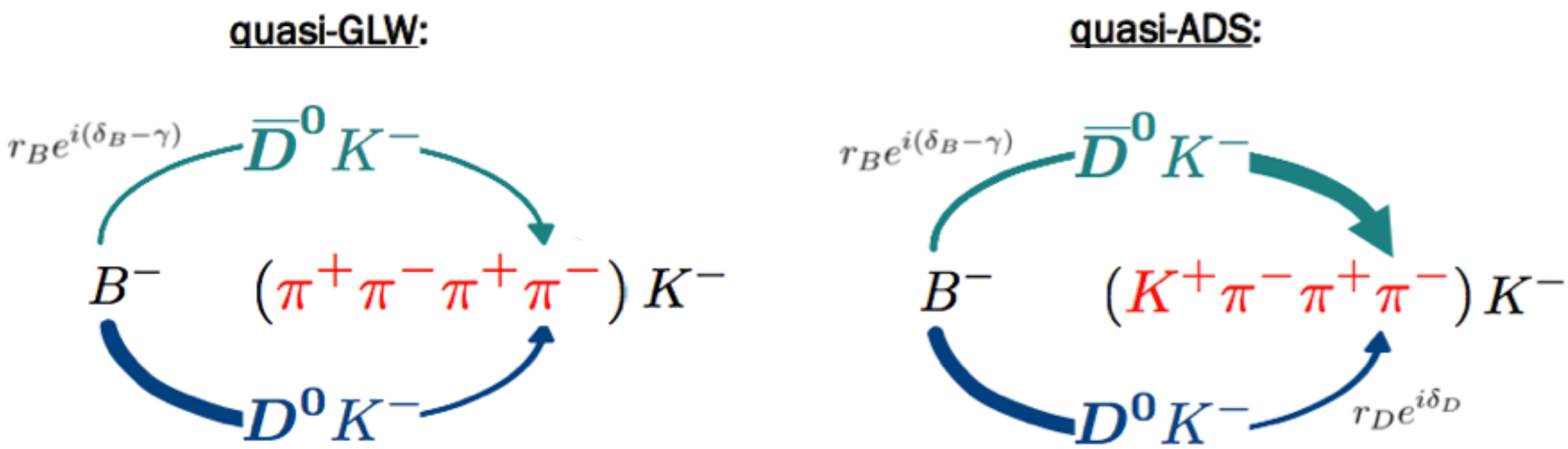
Principles of the methods: 2 body final states



GLW: $\Gamma(B^{\mp} \to f_D K^{\mp}) \propto 1 + r_B^2 + 2 r_B \cos(\delta_B \mp \gamma)$

ADS: $\Gamma(B^{\mp} \to f_D K^{\mp}) \propto (r_D^f)^2 + r_B^2 + 2 r_B r_D^f \cos(\delta_B + \delta_D^f \mp \gamma)$

Principles of the methods: 4 body final states



GLW: $\Gamma(B^{\mp} \to f_D K^{\mp}) \propto 1 + r_B^2 + (2F_+ - 1)2r_B \cos(\delta_B \mp \gamma)$

ADS: $\Gamma(B^{\mp} \to f_D K^{\mp}) \propto r_B^2 + (r_D^f)^2 + 2r_B r_D^f \kappa_D^f \cos(\delta_B + \delta_D^f \mp \gamma)$

fractional CP-even content
$F_+ = 0.737 \pm 0.028$
$2F_+ - 1 \approx 0.5$

Malde et al., PLB 747 (2015) 9

coherence factor
$\kappa_D^{K3\pi} = 0.32 \pm 0.10$

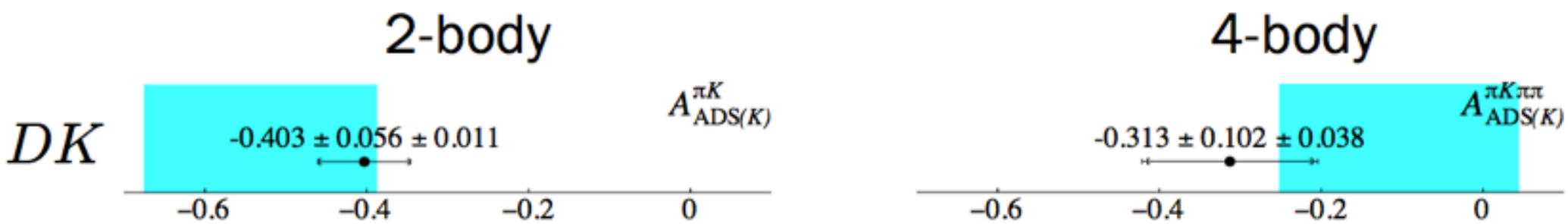
Atwood and Soni, PRD 68 (2003) 033003
LHCb collaboration, arXiv:1602.07430

GLW / ADS $B^{\pm} \to Dh^{\pm}$ (2-4 body)

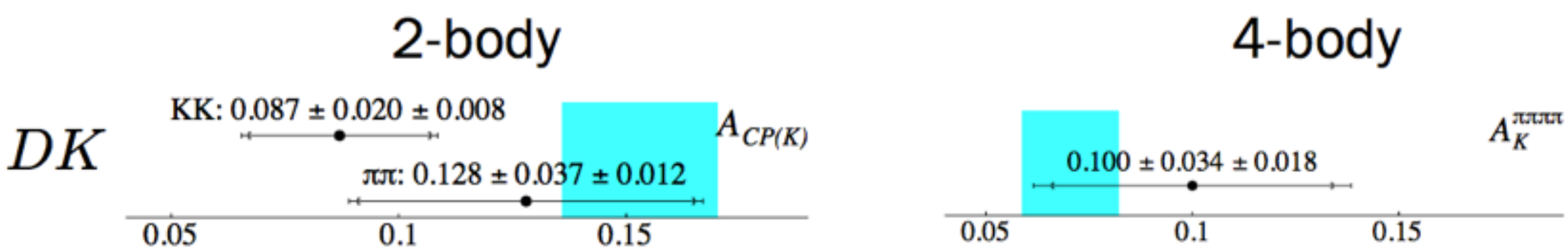
arXiv:1603.08993 [hep-ex]

Results summary:

- **ADS:** $D^0 \to K^{\pm}\pi^{\mp}$ / $K^{\pm}\pi^{\mp}\pi^{+}\pi^{-}$



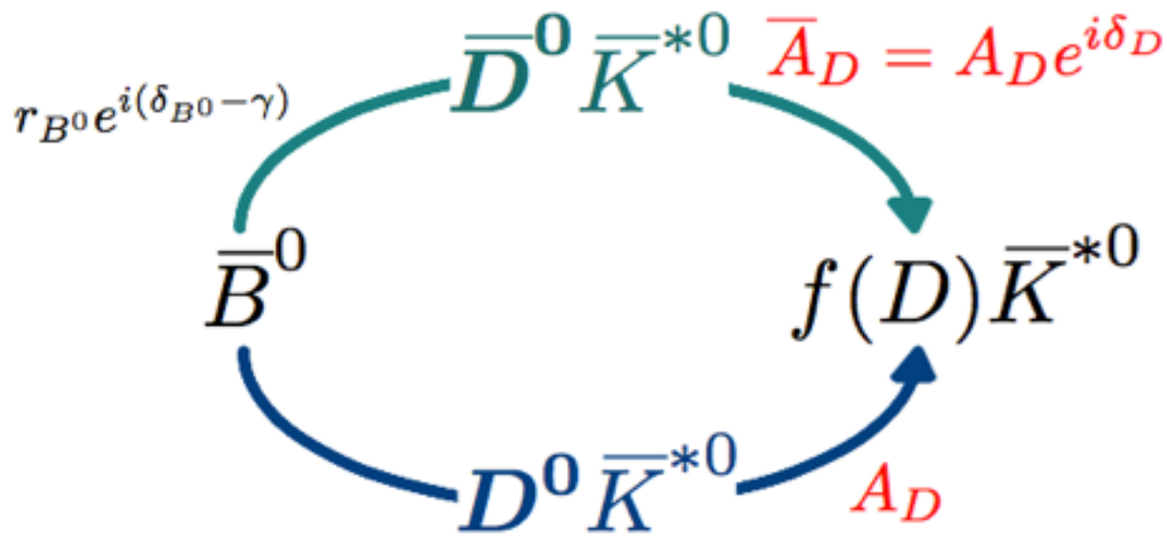
- **GLW:** $D^0 \to K^{+}K^{-}$ / $\pi^{+}\pi^{-}$ / $\pi^{+}\pi^{-}\pi^{+}\pi^{-}$



= 1σ expectation from current knowledge of r_B, δ_B, γ

GGSZ analysis of $B^0 \to DK^{*0}$ decays

Principle of the methods:



- **Model-dependent method:** [arXiv:1605.01082]
  - Making use of an amplitude model providing the strong phase δ_D
- **Model-independent method:** [arXiv:1604.01525]
  - Direct access to δ_D from a binned Dalitz plot analysis simultaneously with $D^0 \to K_S^0 K^+ K^-$

GGSZ analysis of $B^0 \to DK^{*0}$ decays

arXiv:1605.01082 [hep-ex]

Model-dependent method:

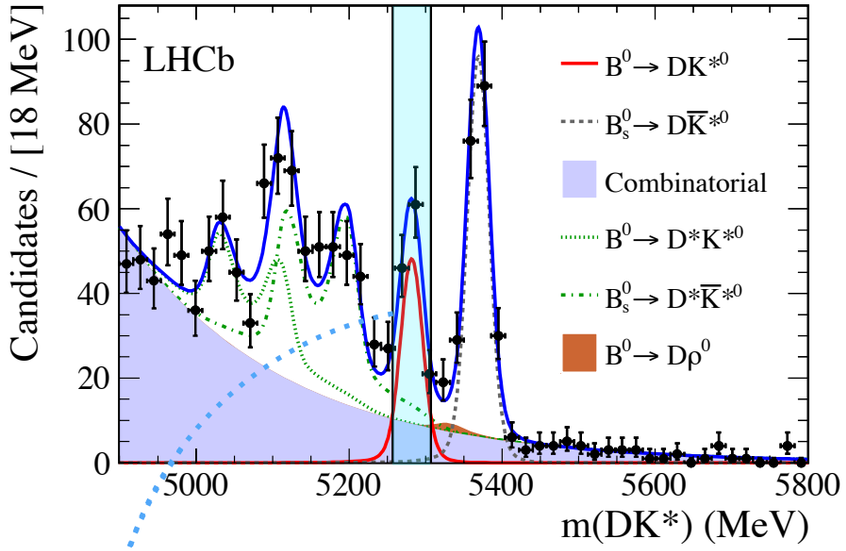
- Decay rate at a **point** of the Dalitz plane:

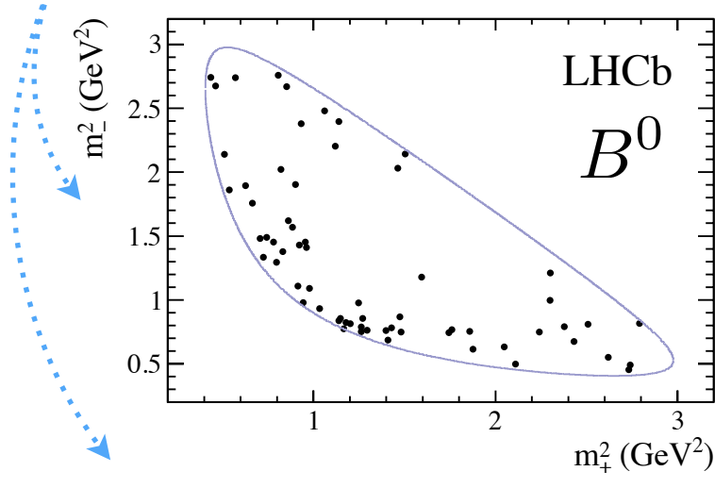
$$d\Gamma(B^0 \to DK^{*0}) \propto |A_D|^2 + r_{B^0}^2|\bar{A}_D|^2 + 2\kappa \mathrm{Re}\left(\bar{A}_D A_D^* \, r_{B^0} e^{i(\delta_{B^0}+\gamma)}\right)$$

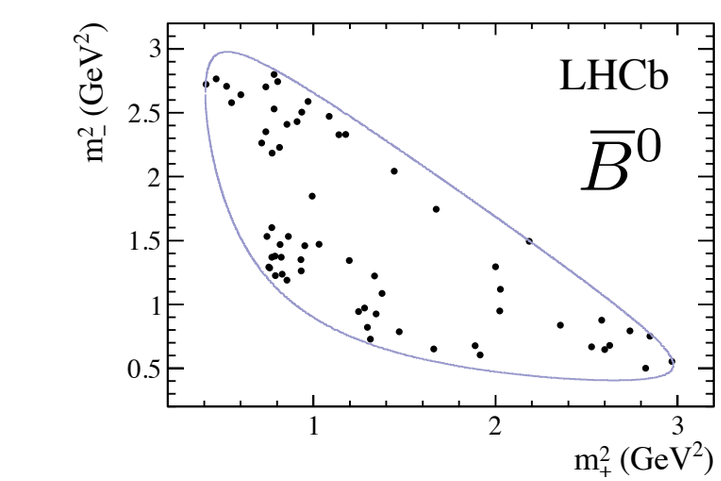
$$d\Gamma(\overline{B}^0 \to D\overline{K}^{*0}) \propto |A_D|^2 + r_{B^0}^2|\bar{A}_D|^2 + 2\kappa \mathrm{Re}\left(\bar{A}_D A_D^* \, r_{B^0} e^{i(\delta_{B^0}-\gamma)}\right)$$

  - the coherence factor κ is obtained from an amplitude analysis of $B^0 \to DK^+\pi^-$ [arXiv:1602.03455]

$$\kappa = 0.958\,^{+0.005}_{-0.010}\,^{+0.002}_{-0.045}$$





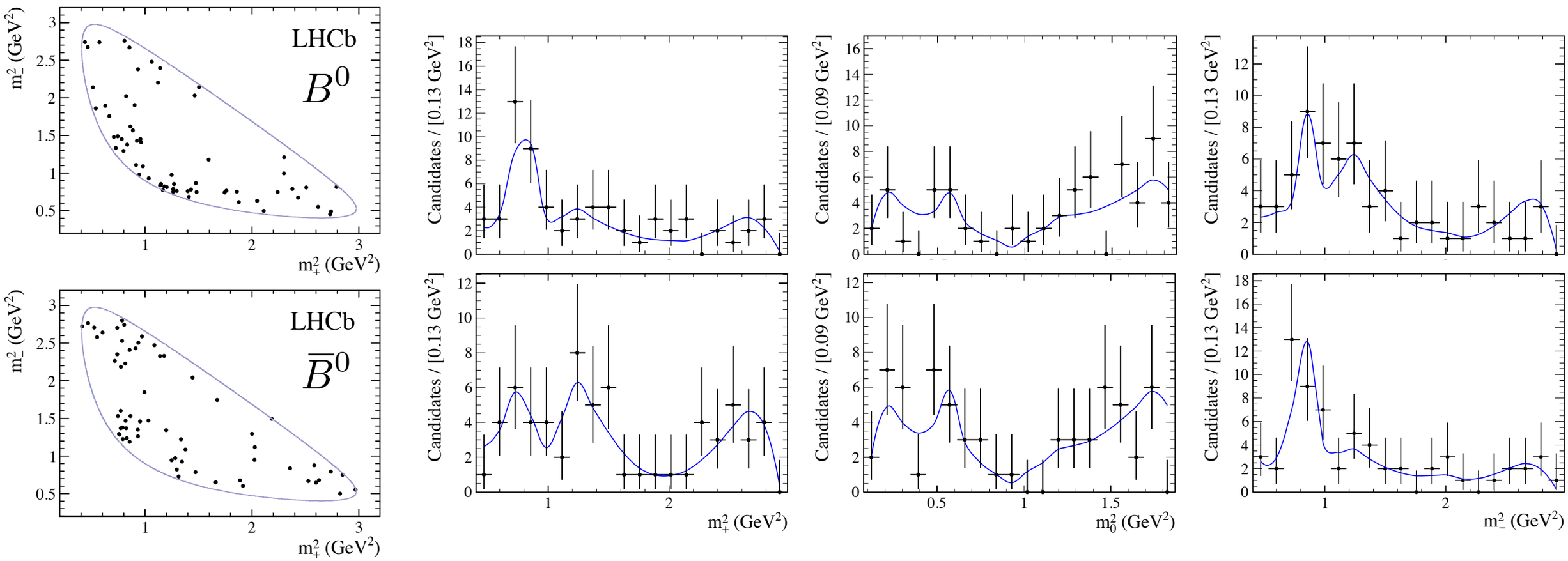


GGSZ analysis of $B^0 \to DK^{*0}$ decays

arXiv:1605.01082 [hep-ex]

Model-dependent method:

- Decay rate at a **point** of the Dalitz plane:
  - *CP* observables: $x_\pm = r_{B^0}\cos(\delta_{B^0} \pm \gamma)$ $\quad y_\pm = r_{B^0}\sin(\delta_{B^0} \pm \gamma)$



GGSZ analysis of $B^0 \to DK^{*0}$ decays

arXiv:1604.01525 [hep-ex]

Model-independent method:

- Decay rate in a **bin** of the Dalitz plane:

$$N_i(B^0) \propto F_{\mp i} + (x_+^2 + y_+^2)F_{\pm i} + 2\kappa\sqrt{F_{+i}F_{-i}}(x_+ c_{\pm i} - y_+ s_{\pm i})$$

$$N_i(\overline{B}^0) \propto F_{\pm i} + (x_-^2 + y_-^2)F_{\mp i} + 2\kappa\sqrt{F_{+i}F_{-i}}(x_- c_{\pm i} + y_- s_{\pm i})$$

  - the parameters c_i and s_i taken from CLEO measurements using quantum-correlated $\psi(3770) \to D\overline{D}$ decays [PRD 82 (2010) 112006]

$$c_i = \frac{\int_i |A_D||\bar{A}_D^*| \cos\delta_D}{\sqrt{\int_i |A_D|^2 \int_i |\bar{A}_D^*|^2}}$$

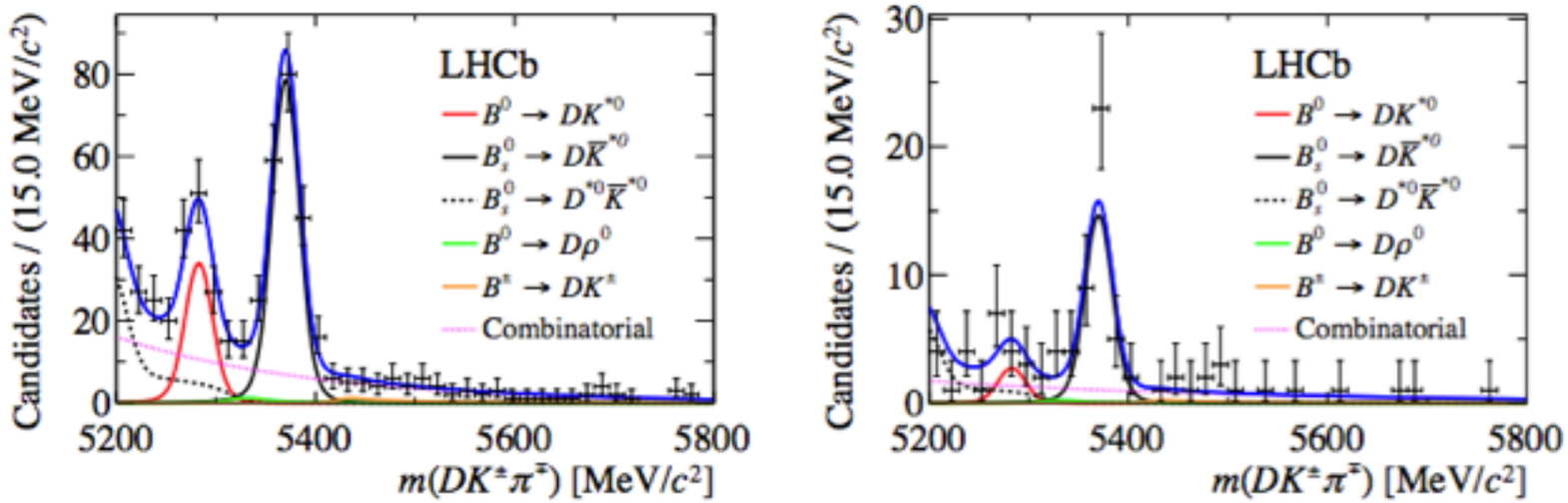
$$s_i = \frac{\int_i |A_D||\bar{A}_D^*| \sin\delta_D}{\sqrt{\int_i |A_D|^2 \int_i |\bar{A}_D^*|^2}}$$

GGSZ analysis of $B^0 \to DK^{*0}$ decays

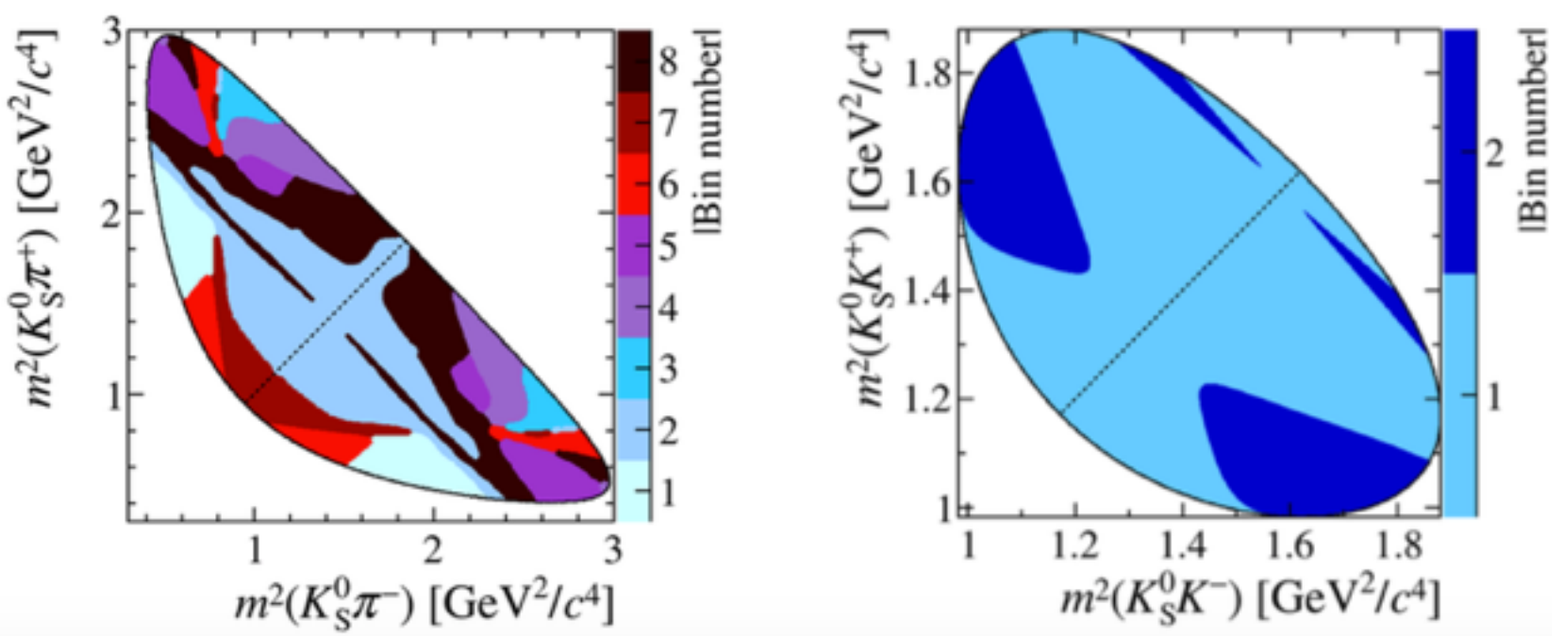
arXiv:1604.01525 [hep-ex]

Model-independent method:

- Fit simultaneously $D^0 \to K_S^0\pi^+\pi^-$ and $D^0 \to K_S^0K^+K^-$

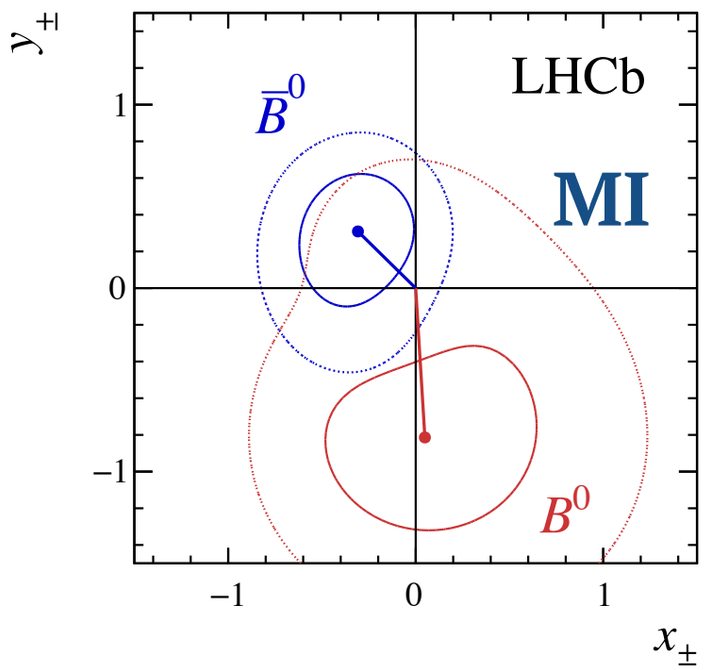


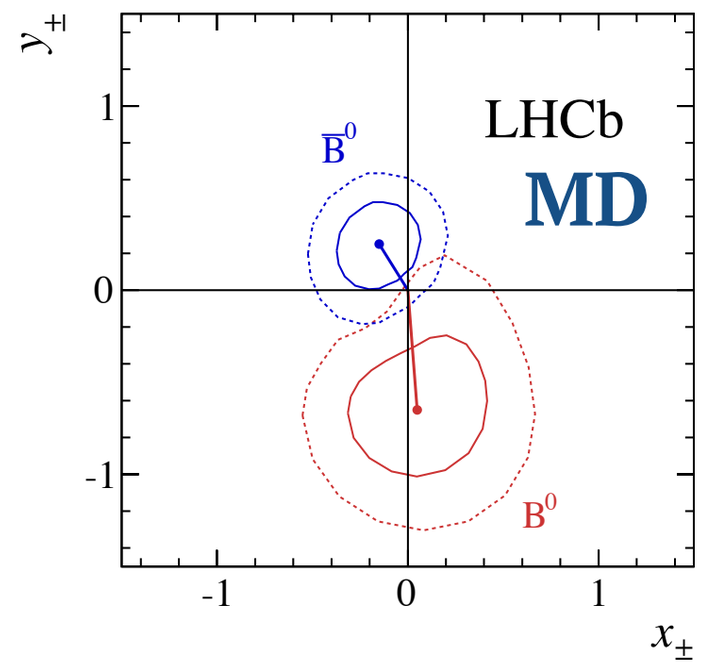
$N(K_S^0\pi^+\pi^-) = 84^{+15}_{-14}$ $\qquad$ $N(K_S^0K^+K^-) = 7^{+5}_{-3}$



GGSZ analysis of $B^0 \to DK^{*0}$ decays

MI and MD results:





$$x_+ = 0.05 \pm 0.35 \pm 0.02,$$
$$x_- = -0.31 \pm 0.20 \pm 0.04,$$
$$y_+ = -0.81 \pm 0.28 \pm 0.06,$$
$$y_- = 0.31 \pm 0.21 \pm 0.05,$$

$$r_{B^0} = 0.56 \pm 0.17,$$
$$\delta_{B^0} = (204\,^{+21}_{-20})^\circ,$$
$$\gamma = (71 \pm 20)^\circ.$$

$$x_- = -0.15 \pm 0.14 \pm 0.03 \pm 0.01,$$
$$y_- = 0.25 \pm 0.15 \pm 0.06 \pm 0.01,$$
$$x_+ = 0.05 \pm 0.24 \pm 0.04 \pm 0.01,$$
$$y_+ = -0.65\,^{+0.24}_{-0.23} \pm 0.08 \pm 0.01,$$

$$r_{B^0} = 0.39 \pm 0.13,$$
$$\delta_{B^0} = \left(197^{+24}_{-20}\right)^\circ,$$
$$\gamma = \left(80^{+21}_{-22}\right)^\circ.$$

LHCb γ combination

LHCb-CONF-2016-001

- **Auxiliary inputs:**

$D^0 \to K^\pm\pi^\mp$	$A(D^0 \to \pi^- K^+)/A(D^0 \to K^-\pi^+) = r_D^{K\pi} e^{-i\delta_D^{K\pi}}$	$r_D^{K\pi}$, $\delta_D^{K\pi}$
$D^0 \to K^+\pi^-\pi^0$	amplitude ratio, effective strong phase difference, and coherence factor	$r_D^{K2\pi}$, $\delta_D^{K2\pi}$, $\kappa_D^{K2\pi}$
$D^0 \to K^\pm\pi^\mp\pi^+\pi^-$	amplitude ratio, effective strong phase difference, and coherence factor	$r_D^{K3\pi}$, $\delta_D^{K3\pi}$, $\kappa_D^{K3\pi}$
$D^0 \to K_S^0 K^\pm\pi^\mp$	amplitude ratio, effective strong phase difference, and coherence factor	$r_D^{K_S K\pi}$, $\delta_D^{K_S K\pi}$, $\kappa_D^{K_S K\pi}$
$D^0 \to h^+h^-\pi^0$	fraction of CP even content	$F_{KK\pi^0}$, $F_{\pi\pi\pi^0}$
$D^0 \to \pi^+\pi^-\pi^+\pi^-$	fraction of CP even content	$F_{\pi\pi\pi\pi}$
$D^0 \to K^+K^-$	direct CP asymmetry	$A_{CP}^{\rm dir}(KK)$
$D^0 \to \pi^+\pi^-$	direct CP asymmetry	$A_{CP}^{\rm dir}(\pi\pi)$
$B^0 \to D^0 K^{*0}$	relative amplitude ratio and phase shift between pure K^{*0} resonance ($B^0 \to DK^+\pi^-$ analysis) and K^{*0} window ($B^0 \to D^0K^{*0}$ analyses)	$\bar{R}_B^{DK^{*0}}$, $\bar{\Delta}_B^{DK^{*0}}$
D^0–$\bar{D}^0$	mixing parameters	x_D, y_D
B_s^0–$\bar{B}_s^0$	mixing phase	$2\beta_s$

LHCb γ combination

LHCb-CONF-2016-001

- **Auxiliary input values:**

$$
\begin{aligned}
x_D &= 0.0037 \pm 0.0016\,, & \kappa_D^{K3\pi} &= 0.32 \pm 0.10\,,\\
y_D &= 0.0066 \pm 0.0009\,, & \delta_D^{K3\pi} &= 2.97 \pm 0.66\,,\\
\delta_D^{K\pi} &= 3.35 \pm 0.21\,, & \kappa_D^{K2\pi} &= 0.81 \pm 0.07\,,\\
R_D^{K\pi} &= 0.00349 \pm 0.00004\,, & \delta_D^{K2\pi} &= 3.14 \pm 0.30\,,\\
A_{CP}^{\rm dir}(\pi\pi) &= 0.0010 \pm 0.0015\,, & r_D^{K3\pi} &= 0.0552 \pm 0.0007\,,\\
A_{CP}^{\rm dir}(KK) &= -0.0015 \pm 0.0014\,. & r_D^{K2\pi} &= 0.0440 \pm 0.0012\,.
\end{aligned}
$$

$$
\begin{aligned}
F_{\pi\pi\pi^0} &= 0.973 \pm 0.017\,,\\
F_{KK\pi^0} &= 0.732 \pm 0.055\,,\\
F_{\pi\pi\pi\pi} &= 0.737 \pm 0.032\,.
\end{aligned}
$$

$$
\begin{aligned}
\delta_D^{K_SK\pi} &= 0.46 \pm 0.28\,,\\
\kappa_D^{K_SK\pi} &= 1.00 \pm 0.16\,.\\
R_D^{K_SK\pi} &= 0.370 \pm 0.003 \pm 0.012\,.
\end{aligned}
$$

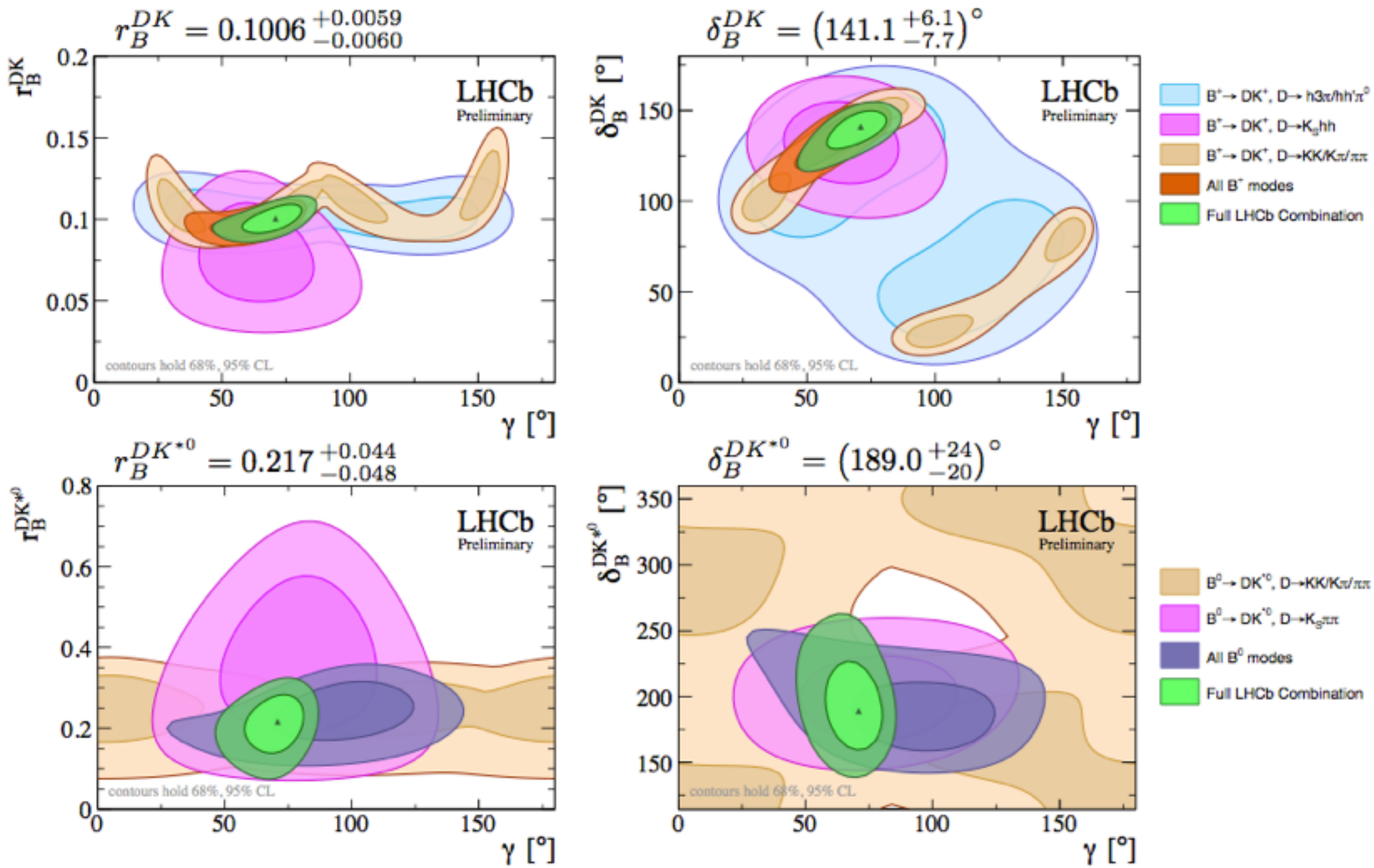
$$
\begin{aligned}
\kappa_B^{DK^{*0}} &= 0.958 \pm 0.008 \pm 0.024,\\
\bar{R}_B^{DK^{*0}} &= 1.020 \pm 0.020 \pm 0.060,\\
\bar{\Delta}_B^{DK^{*0}} &= 0.020 \pm 0.025 \pm 0.110.
\end{aligned}
$$

$$
\phi_s = -0.010 \pm 0.039\,\mathrm{rad}\,.
$$

LHCb γ combination

LHCb-CONF-2016-001

- **Complementarity of different methods:** ADS/GLW, quasi-ADS/GLW, GGSZ

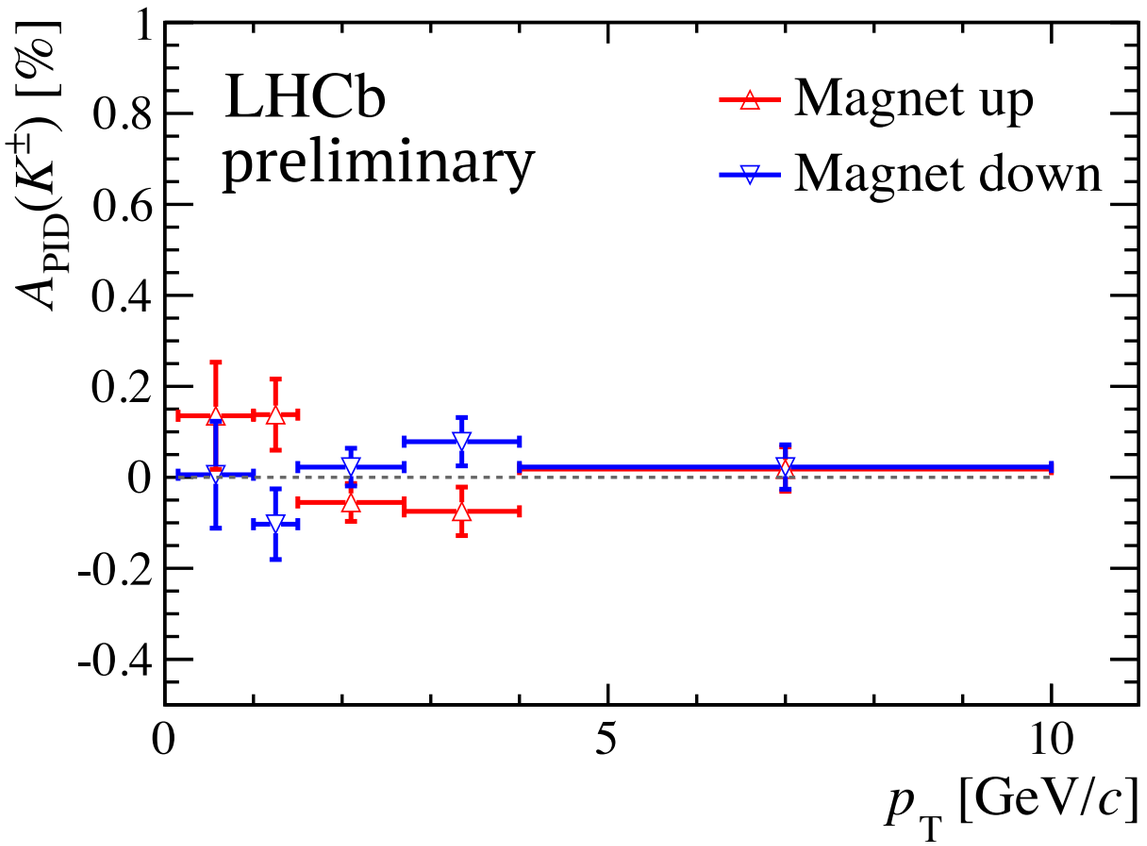


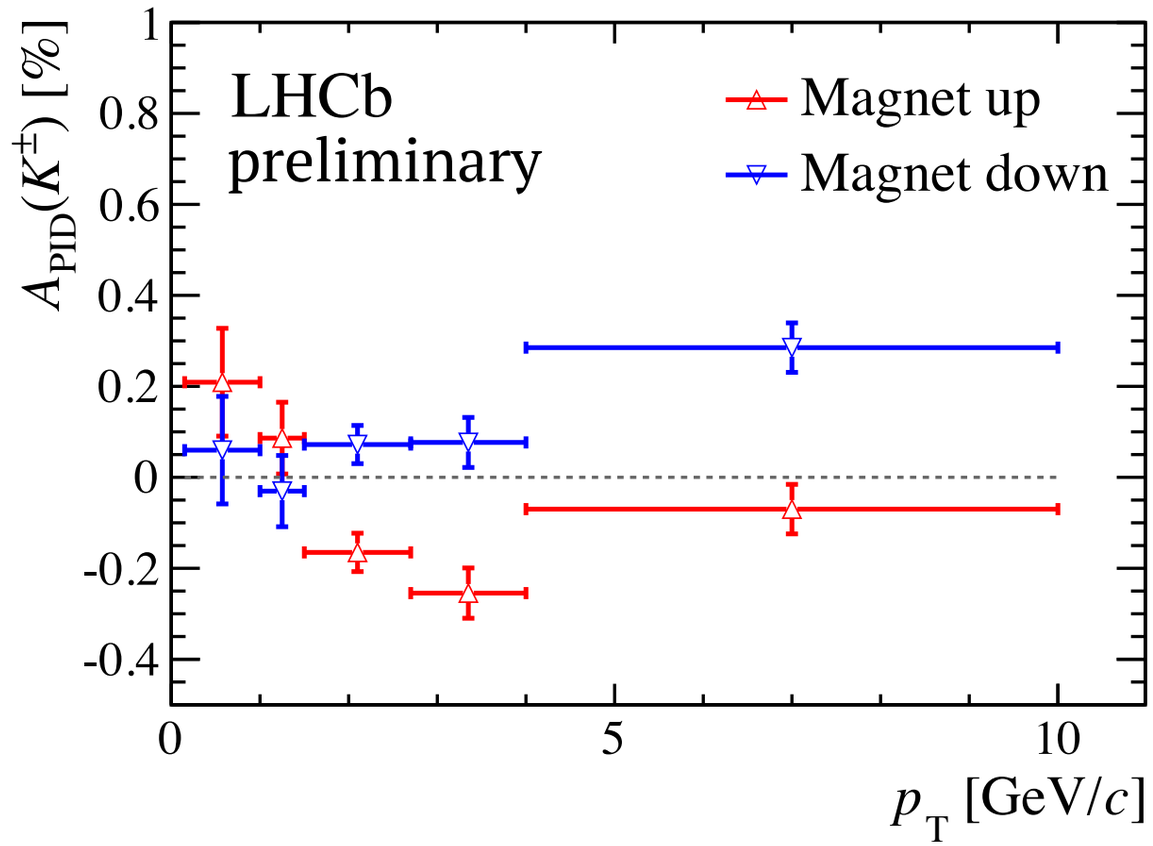
CP asymmetry in $B_s^0 - \bar{B}_s^0$ mixing

preliminary results

Detection asymmetries:

- PID



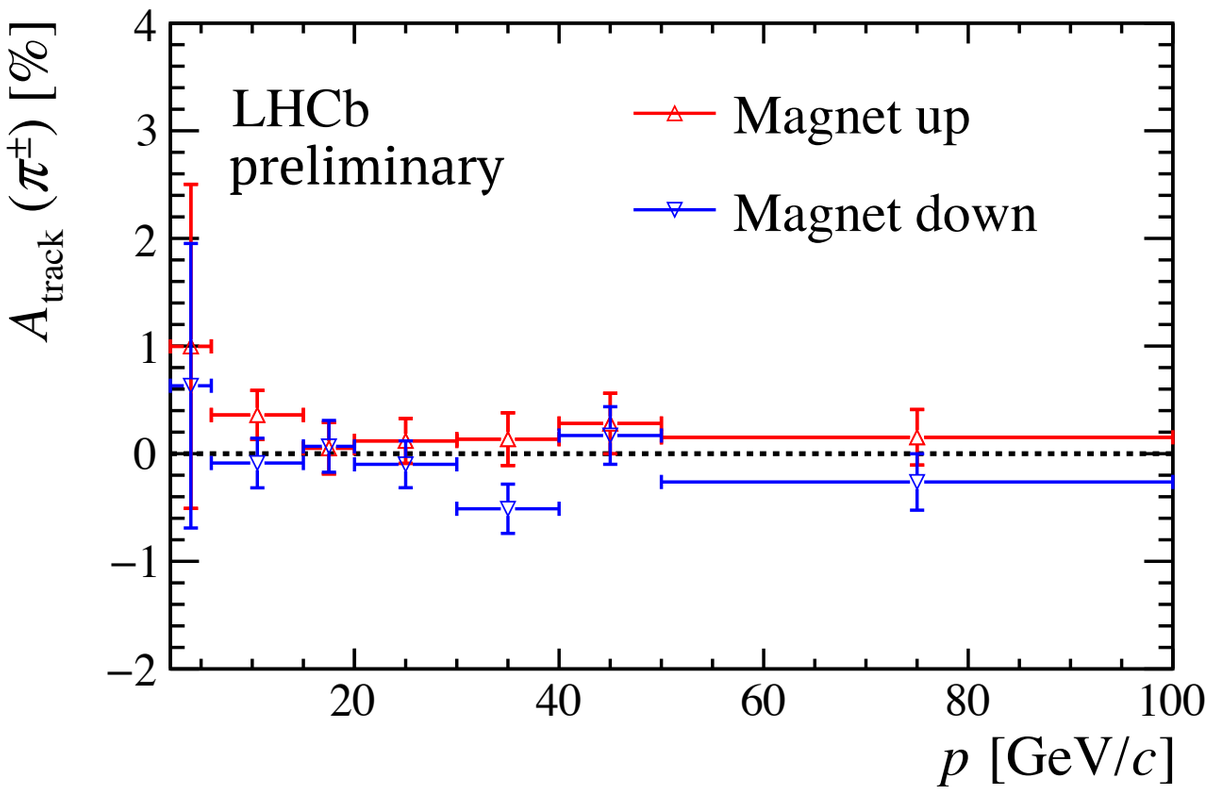


CP asymmetry in $B_s^0 - \bar{B}_s^0$ mixing

preliminary results

Detection asymmetries:

- Tracking

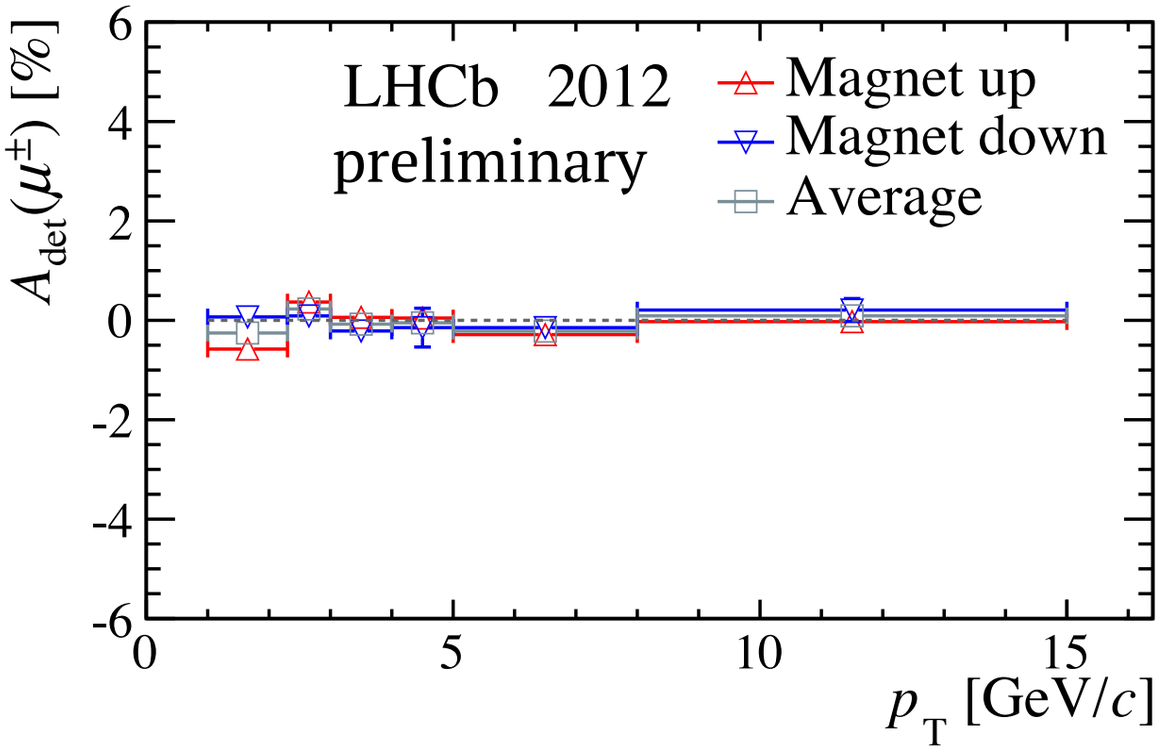


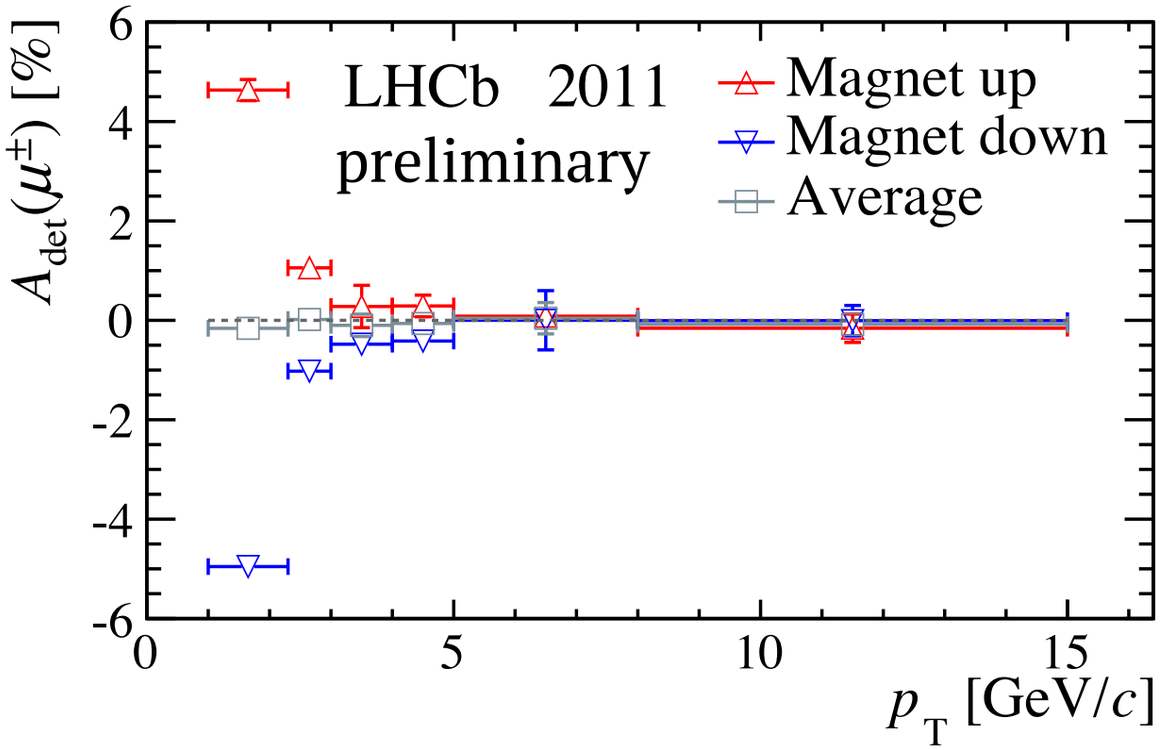
CP asymmetry in $B_s^0 - \bar{B}_s^0$ mixing

preliminary results

Detection asymmetries:

- Trigger

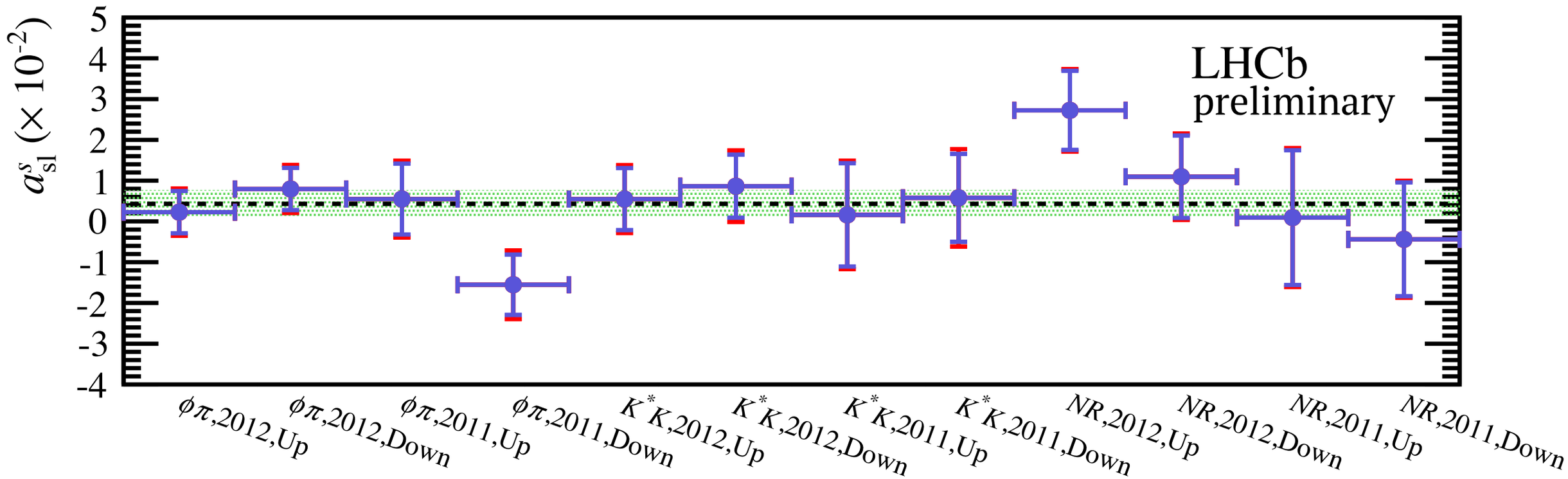




CP asymmetry in $B_s^0 - \bar{B}_s^0$ mixing

preliminary results

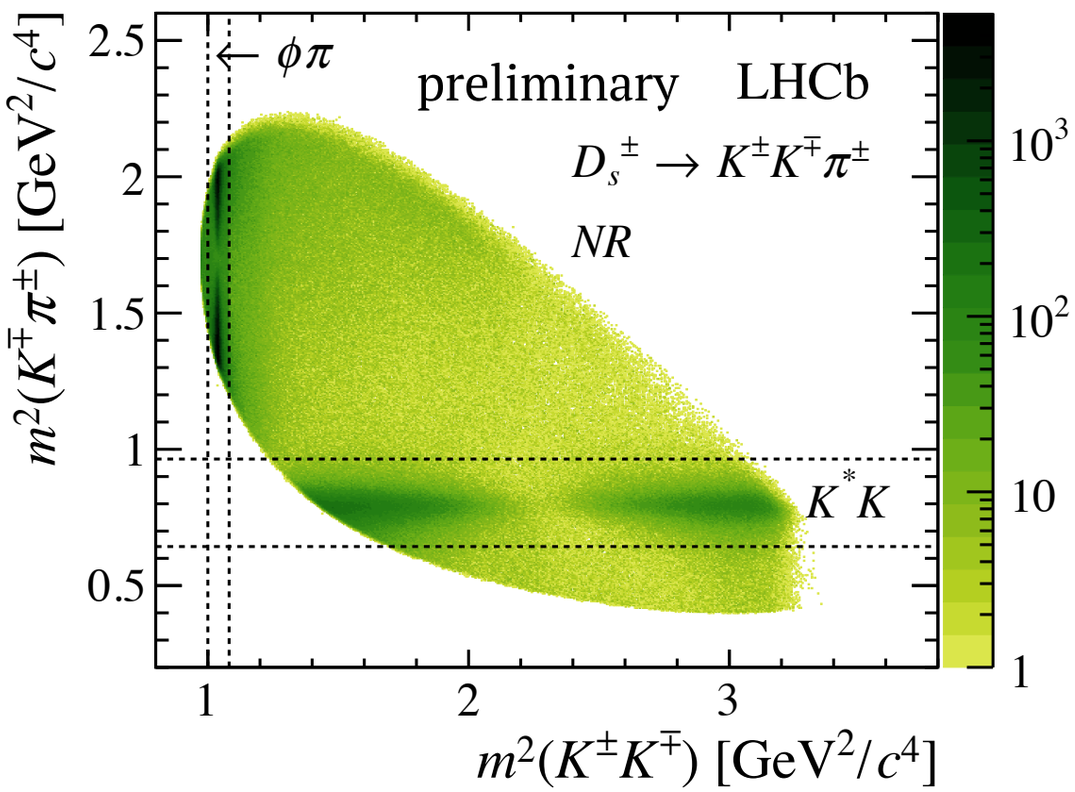
Results in categories:

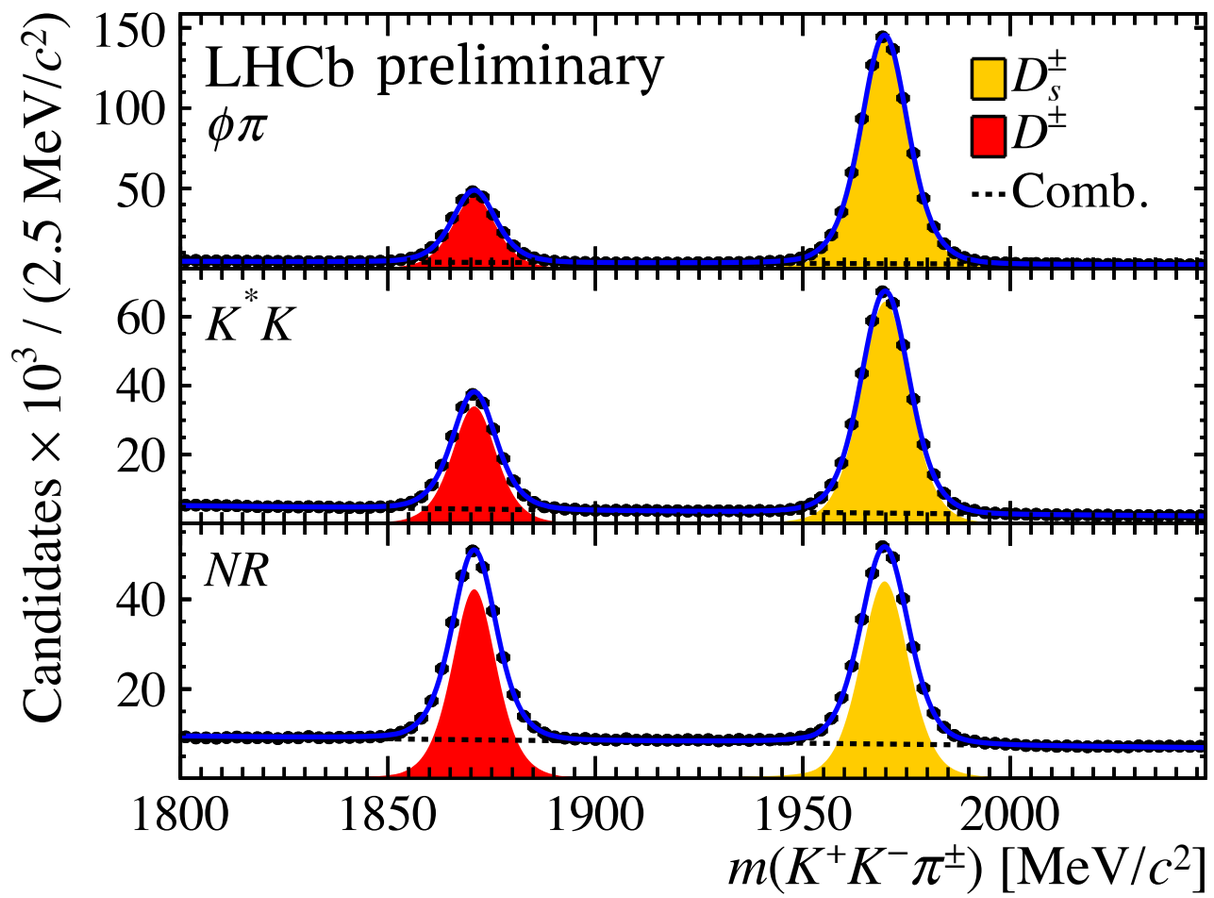


CP asymmetry in $B_s^0 - \bar{B}_s^0$ mixing

preliminary results

Mass fit projections:





CP asymmetry in $B_s^0 - \bar{B}_s^0$ mixing

preliminary results

Peaking backgrounds:

Mode	$\mathcal{B}$ [%]	$\mathcal{B}(c \to \mu)$ [%]	$\varepsilon_{\rm sig}/\varepsilon_{\rm bkg}$	$f_{\rm bkg}/f_{\rm sig}$ [%]	$A_{\rm bkg}$ [%]
$B^+ \to D^{(*)0} D_s^{(*)+} X$	7.9 ± 1.4	6.5 ± 0.1	4.34	5.8 ± 1.1	-0.6 ± 0.6
$B^0 \to D^0 D_s^{(*)+} X$	5.7 ± 1.2	6.5 ± 0.1	4.08	4.4 ± 1.0	-0.18 ± 0.13
$B^0 \to D^- D_s^{(*)+} X$	4.6 ± 1.2	16.1 ± 0.3	6.41	5.6 ± 1.5	-0.18 ± 0.13
$B_s^0 \to D_s^{(*)-} D_s^{(*)+}$	4.5 ± 1.4	8.1 ± 0.4	3.68	1.0 ± 0.3	–
$\Lambda_b^0 \to \Lambda_c^+ D_s^{(*)+} X$	$10.3^{+2.1}_{-1.8}$	4.5 ± 1.7	4.51	3.0 ± 1.4	-0.4 ± 0.9
$B^- \to D_s^+ K^- \mu^- \nu X$	0.061 ± 0.010	–	2.43	1.3 ± 0.2	0.6 ± 0.6
$\bar{B}^0 \to D_s^+ K_S^0 \mu^- \nu X$	0.061 ± 0.010	–	2.89	1.1 ± 0.2	0.18 ± 0.13

CP asymmetry in $B_s^0 - \bar{B}_s^0$ mixing

preliminary results

Systematics:

Source	Value	Stat. uncert.	Syst. uncert.
A_{raw}	0.11	0.09	0.02
$A_{\text{track}}(K^+K^-)$	−0.01	0.00	0.03
$A_{\text{track}}(\pi^-\mu^+)$	−0.01	0.05	0.04
A_{PID}	0.01	0.02	0.03
$A_{\text{trig}}(\text{hardware})$	−0.03	0.02	0.02
$A_{\text{trig}}(\text{software})$	0.00	0.01	0.02
$f_{\text{bkg}}\ A_{\text{bkg}}$	−0.05	-	0.03
f_{bkg}	-	-	0.06
Total a_{sl}^s	0.45	0.26	0.20

$$2/(1 - f_{\text{bkg}}) = 2.45$$