WG5 summary
Direct CP violation

2 December 2016

Malcolm John – Tom Latham – Rukmani Mohanta

15 speakers

12 new results

97,000 air miles

180,000 calories of curry

γ/φ_3 from $B \to D^0X$

Direct CPV in $H_b \to$ charmless

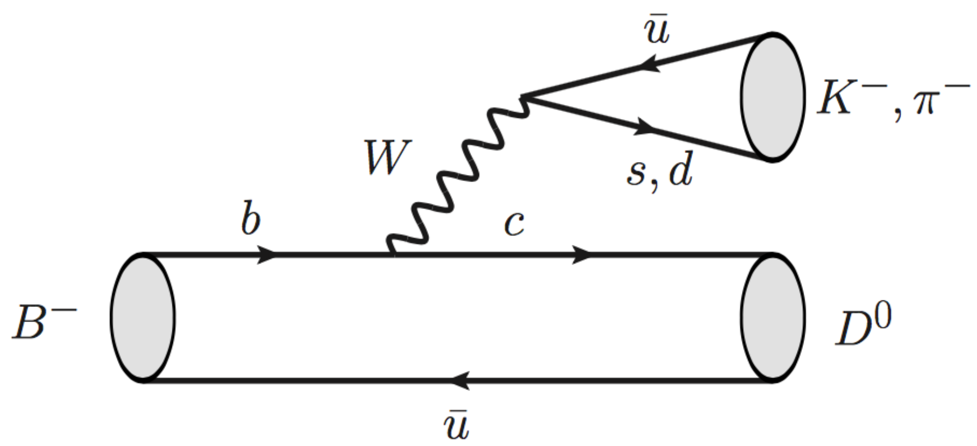
New modes and searches (no *CP* study)

Prospects for 2020s

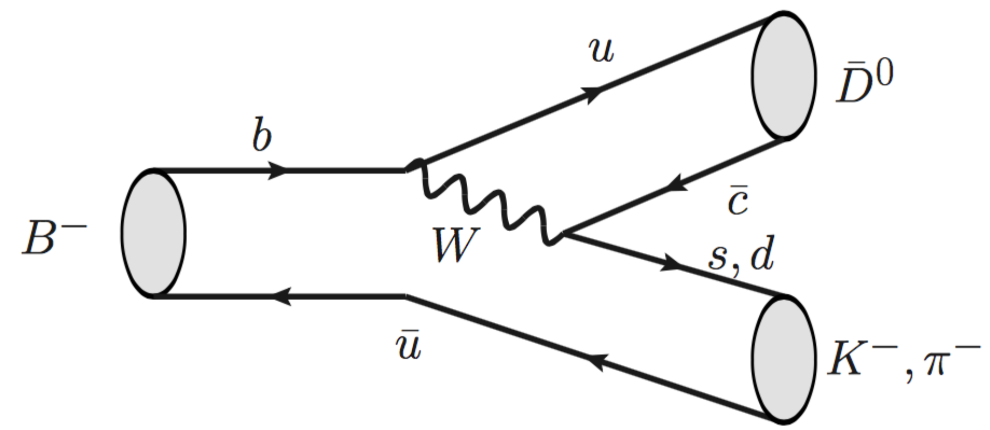
γ/φ_3 from $B \rightarrow D^0 X$

Including the development of new D decays

γ from tree decays



$\propto V_{cb} V^*_{us(d)}$



$\propto V_{ub} V^*_{cs(d)}$

- $b \to c\bar{u}s(d)$, $b \to u\bar{c}s(d)$
- no penguin contribution
- interference from common D^0, $\bar{D}^0$ final states

$$r_B^{Dh} e^{i(\delta_B - \gamma)} = \frac{A(B^- \to \bar{D}^0 h^-)}{A(B^- \to D^0 h^-)}$$

Joachim Brod

γ from tree decays

- CP eigenstates (e.g. $D \to K^+K^-, \pi^+\pi^-; K_S\pi^0$)

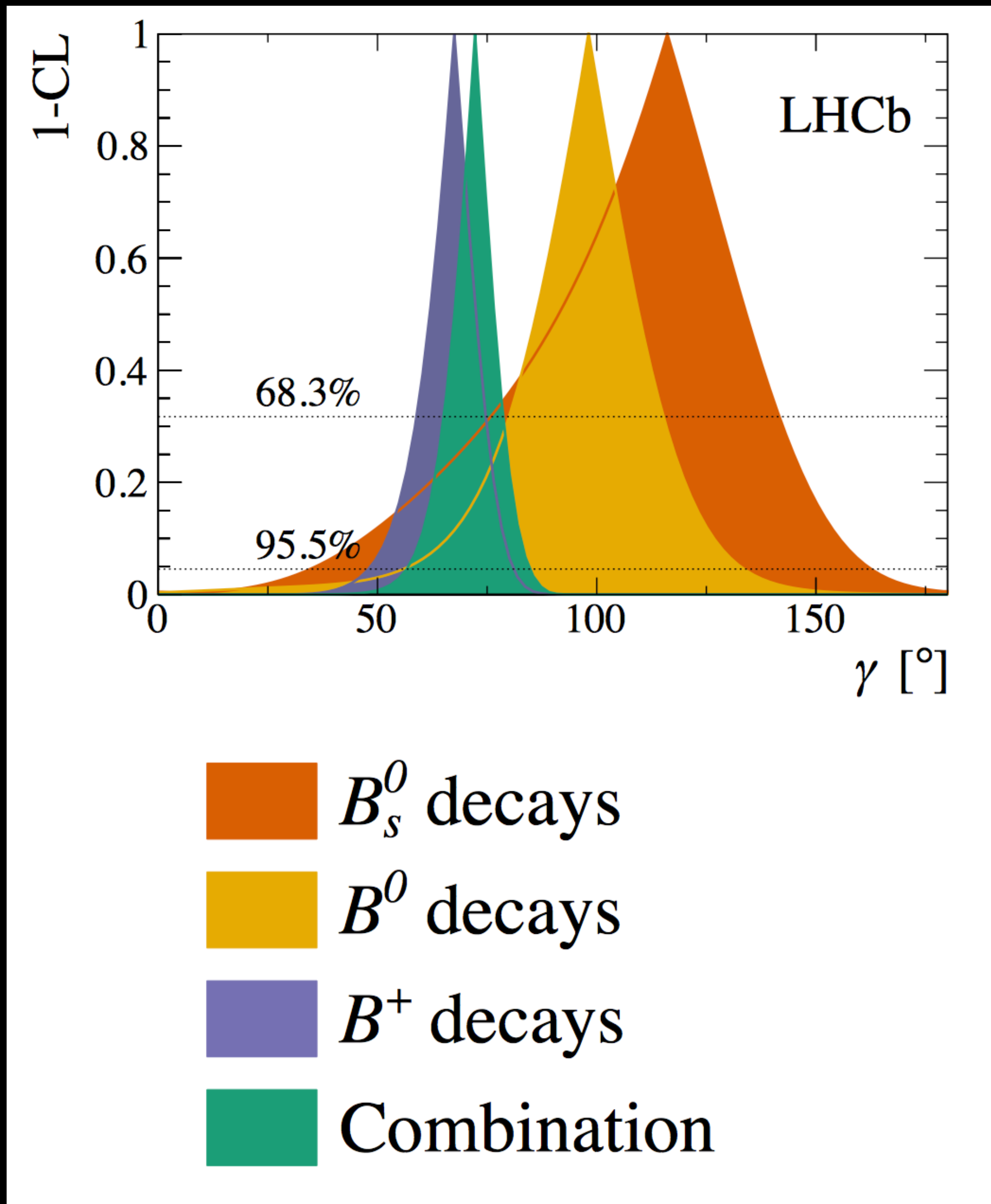
  [Gronau, London 1990, Gronau, Wyler 1991]
- Flavor states (e.g. $D \to \pi^-K^+, \pi^+K^-$) [Atwood, Dunietz, Soni 1997]
- Many-body final states (e.g. $D \to K_S K^+K^-, K_S\pi^+\pi^-$)

  [Giri, Grossman, Soffer, Zupan 2003; Poluektov 2004]
- Many variants:
  - Use $D^* \to D\pi^0, D\gamma$ [Bondar, Gershon 2004]
  - Many-body B final states

    [Aleksan, Petersen, Soffer 2002; Gershon 2008; Gershon, Poluektov 2009]
  - Neutral B_d, B_s [Aleksan, Dunietz, Kayser 1992; Kayser, London 2000; Atwood, Soni 2003; Fleischer 2003; Gronau et al. 2004]
  - ...
- Have $\sim n_D n_B$ measurements, $\sim n_D + n_B$ unknowns

Joachim Brod

γ from 2011+2012 data



B decay	D decay	Method
$B^+ \to Dh^+$	$D \to h^+h^-$	GLW/ADS
$B^+ \to Dh^+$	$D \to h^+\pi^-\pi^+\pi^-$	GLW/ADS
$B^+ \to Dh^+$	$D \to h^+h^-\pi^0$	GLW/ADS
$B^+ \to DK^+$	$D \to K_S^0 h^+h^-$	GGSZ
$B^+ \to DK^+$	$D \to K_S^0 K^-\pi^+$	GLS
$B^+ \to Dh^+\pi^-\pi^+$	$D \to h^+h^-$	GLW/ADS
$B^0 \to DK^{*0}$	$D \to K^+\pi^-$	ADS
$B^0 \to DK^+\pi^-$	$D \to h^+h^-$	GLW-Dalitz
$B^0 \to DK^{*0}$	$D \to K_S^0\pi^+\pi^-$	GGSZ
$B_s^0 \to D_s^\mp K^\pm$	$D_s^+ \to h^+h^-\pi^+$	TD

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

Conor Fitzpatrick

arxiv:1611.03076

γ from tree decays

- γ from $B \to DK$ is theoretically extremely clean,
  - $\delta\gamma^{DK}/\gamma \lesssim \mathcal{O}(10^{-7})$
- γ from $B \to D\pi$ is most likely theoretically extremely clean,
  - $\delta\gamma^{D\pi}/\gamma \lesssim \mathcal{O}(10^{-4})$

- γ from $B \to DK$ has built-in test for NP in decay amplitude

  [J. Zupan, talk at LHCb Implications 2012]

$$r_{B^+} \to \left| r_B e^{i(\delta_B+\gamma)} + r'_B e^{i(\delta'_B+\gamma)} \right|, \quad r_{B^-} \to \left| r_B e^{i(\delta_B-\gamma)} + r'_B e^{i(\delta'_B-\gamma)} \right|$$

Joachim Brod

JHEP 1401 (2014) 051
B743 (2015) 56-60
PRD92 (2015) 033002

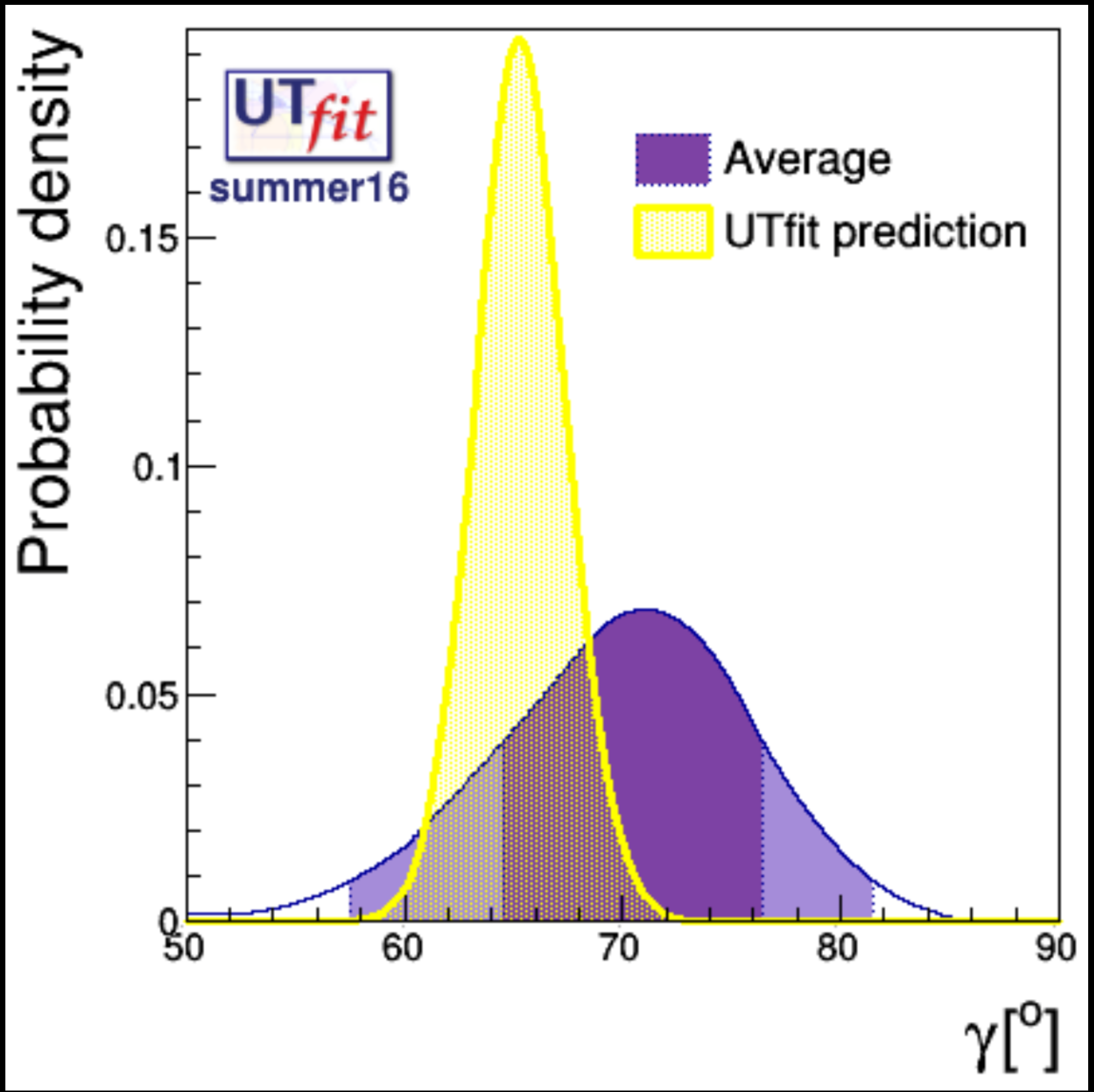
γ from 2011+2012 data

Observable	Central value	68.3% Interval
$\gamma\,(^\circ)$	72.2	[64.9, 79.0]
r_B^{DK}	0.1019	[0.0963, 0.1075]
$\delta_B^{DK}\,(^\circ)$	142.6	[136.0, 148.3]
$r_B^{DK^{*0}}$	0.218	[0.171, 0.263]

LHCb Frequentist

Observable	Central value	68.3% Interval
$\gamma\,(^\circ)$	70.3	[62.4, 77.4]
r_B^{DK}	0.1012	[0.0954, 0.1064]
$\delta_B^{DK}\,(^\circ)$	142.2	[134.7, 148.1]
$r_B^{DK^{*0}}$	0.204	[0.149, 0.253]

LHCb Bayesian

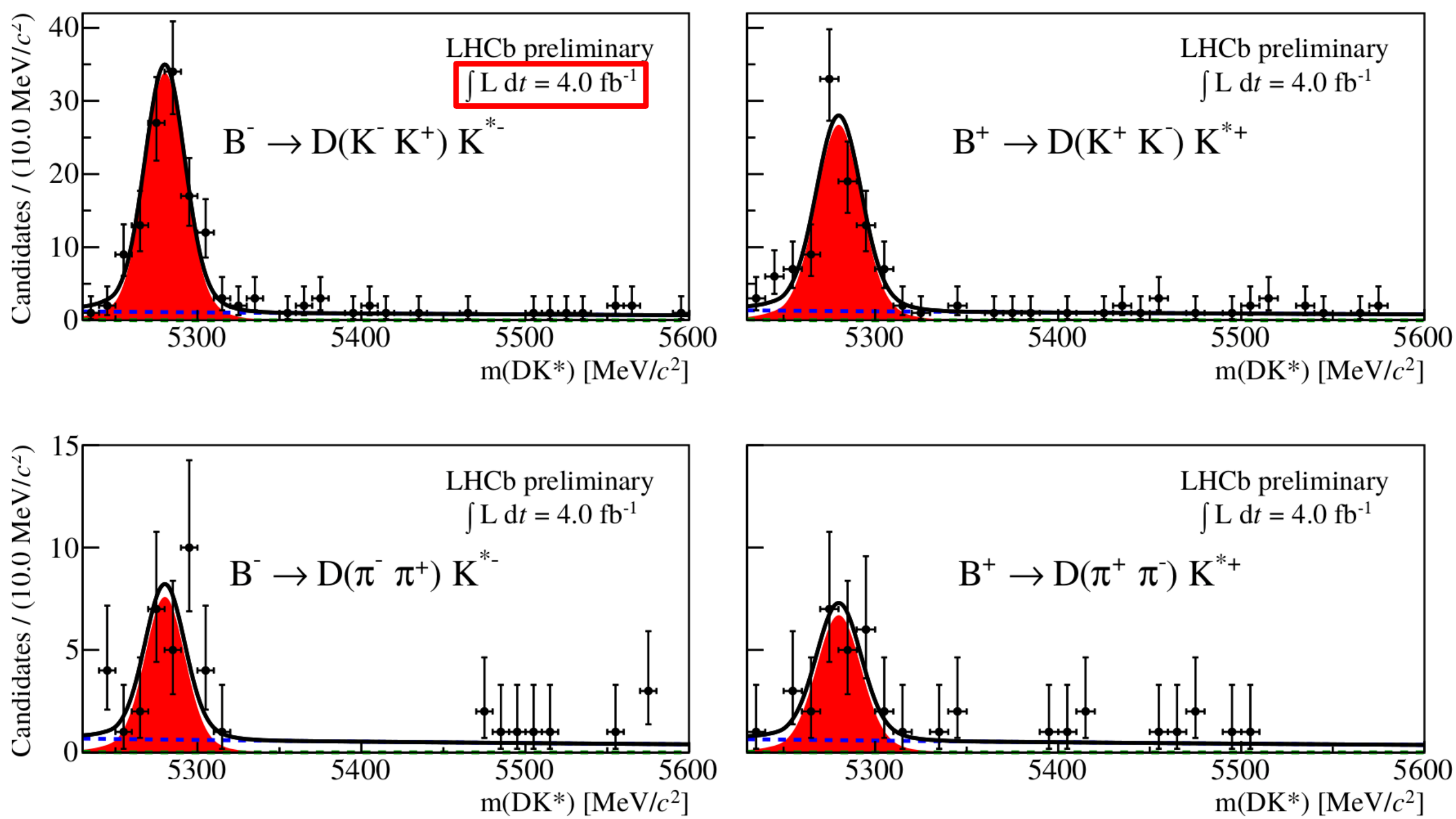


combined: (70.5 ± 5.7)°

UTfit prediction: (65.4 ± 2.1)°

Marcella Bona

$B^- \to DK^{*-}$ ADS/GLW

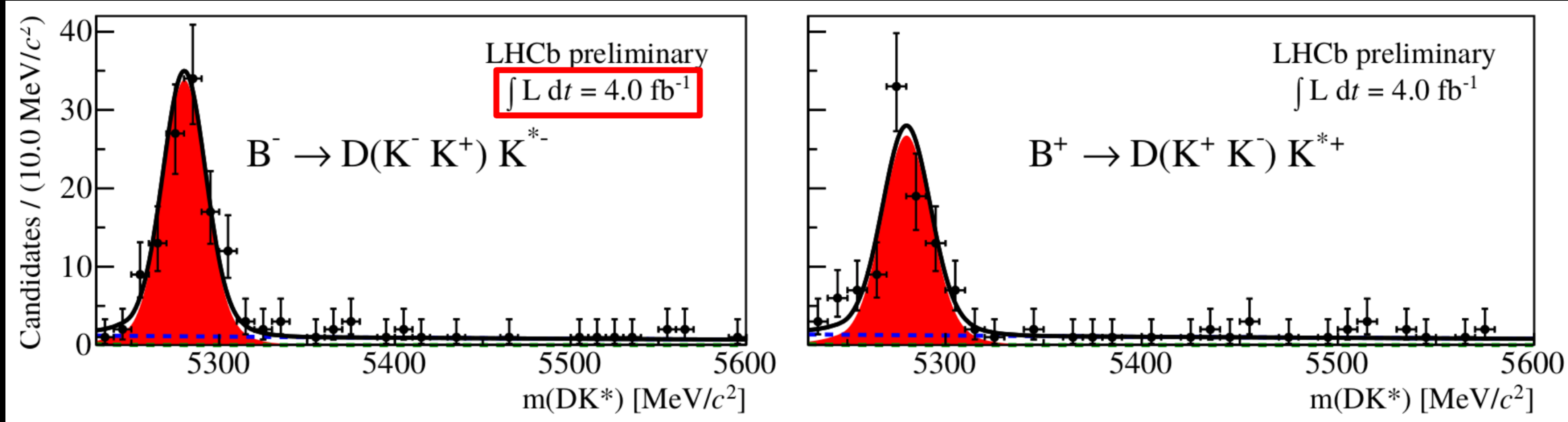


- $A_{KK} = 0.12 \pm 0.08 \pm 0.01$
- $R_{KK} = 1.31 \pm 0.11 \pm 0.05$
- $A_{\pi\pi} = 0.08 \pm 0.16 \pm 0.02$
- $R_{\pi\pi} = 0.98 \pm 0.17 \pm 0.04$

LHCb-CONF-2016-014

Frédéric Machefert

$B^- \rightarrow DK^{*-}$ ADS/GLW



2009 Babar result

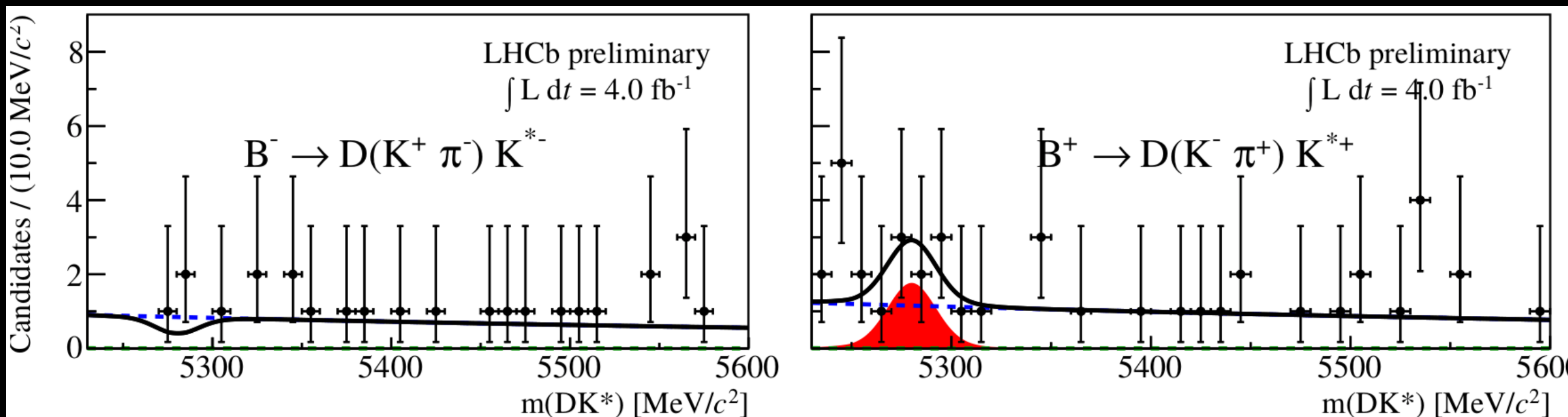
$$\mathcal{A}_{CP+} = 0.09 \pm 0.13(\text{stat.}) \pm 0.06(\text{syst.})$$

$$\mathcal{R}_{CP+} = 2.17 \pm 0.35(\text{stat.}) \pm 0.09(\text{syst.})$$

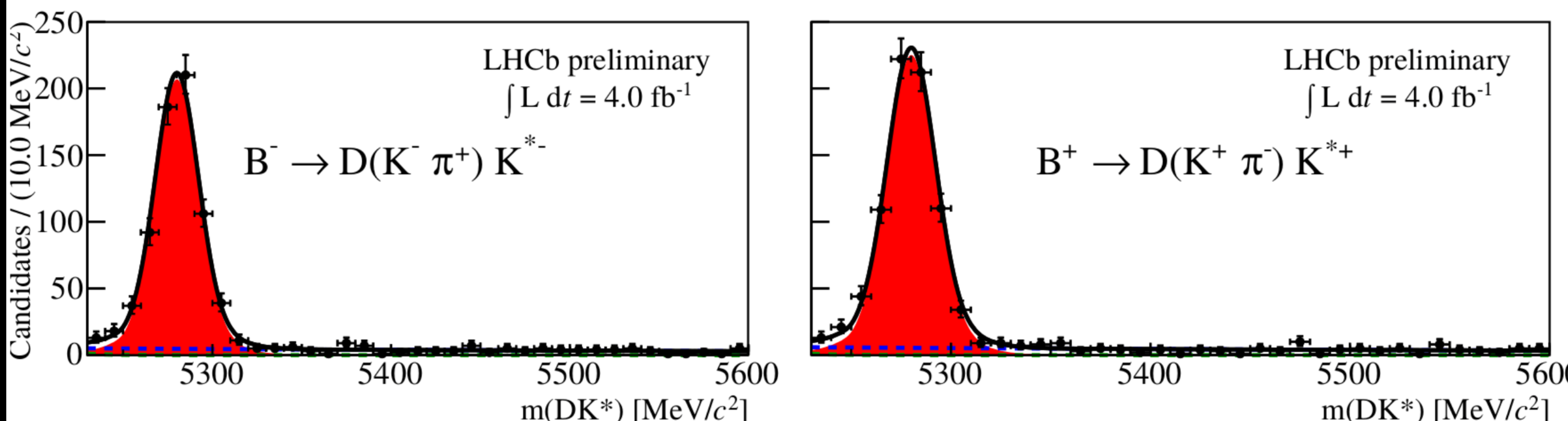
- $A_{KK} = 0.12 \pm 0.08 \pm 0.01$
- $R_{KK} = 1.31 \pm 0.11 \pm 0.05$
- $A_{\pi\pi} = 0.08 \pm 0.16 \pm 0.02$
- $R_{\pi\pi} = 0.98 \pm 0.17 \pm 0.04$

LHCb-CONF-2016-014

$B^- \to DK^{*-}$ ADS/GLW



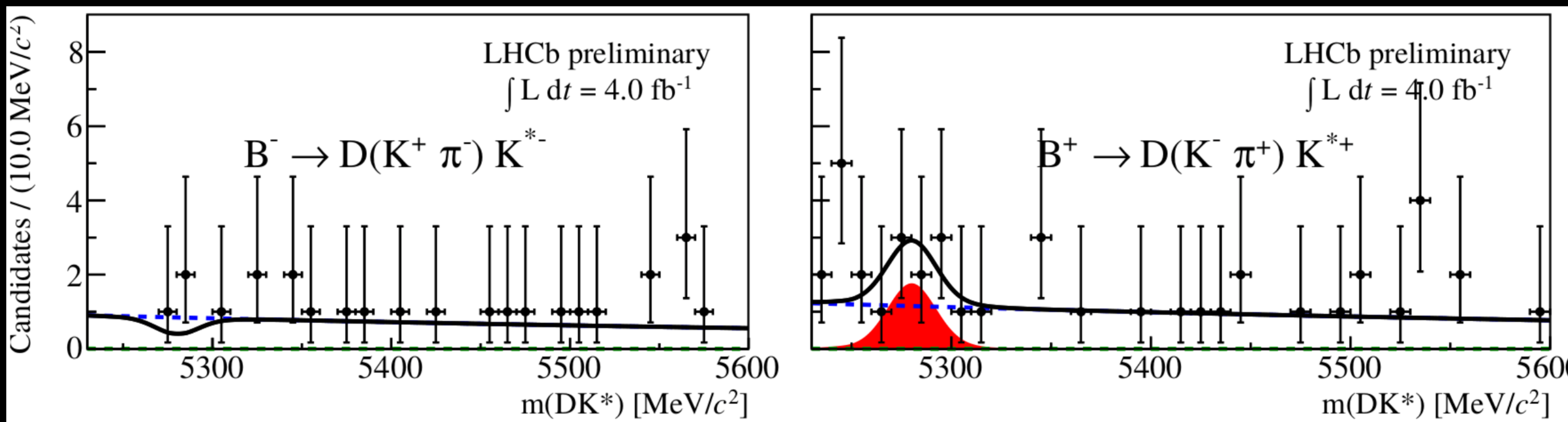
- $R^+ = 0.009 \pm 0.007 \pm 0.002$
- $R^- = -0.003 \pm 0.004 \pm 0.002$



Frédéric Machefert

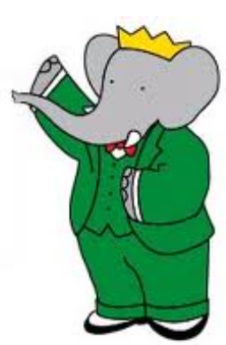
LHCb-CONF-2016-014

$B^- \to DK^{*-}$ ADS/GLW



- $R^+ = 0.009 \pm 0.007 \pm 0.002$
- $R^- = -0.003 \pm 0.004 \pm 0.002$

2009 Babar result



$$\mathcal{A}_{ADS} = -0.34 \pm 0.43(\text{stat.}) \pm 0.16(\text{syst.})$$
$$\mathcal{R}_{ADS} = \ 0.066 \pm 0.031(\text{stat.}) \pm 0.010(\text{syst.}).$$

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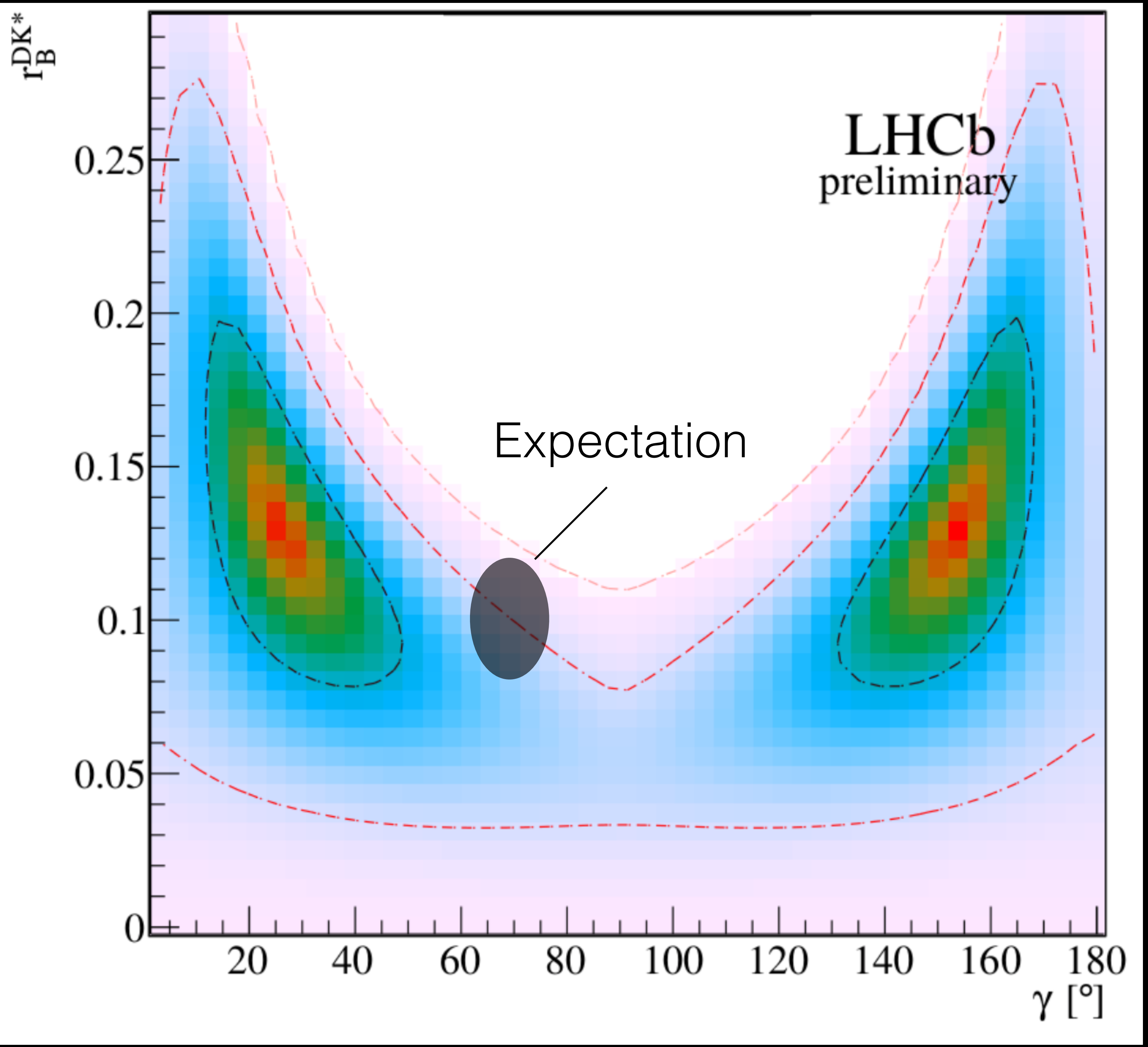
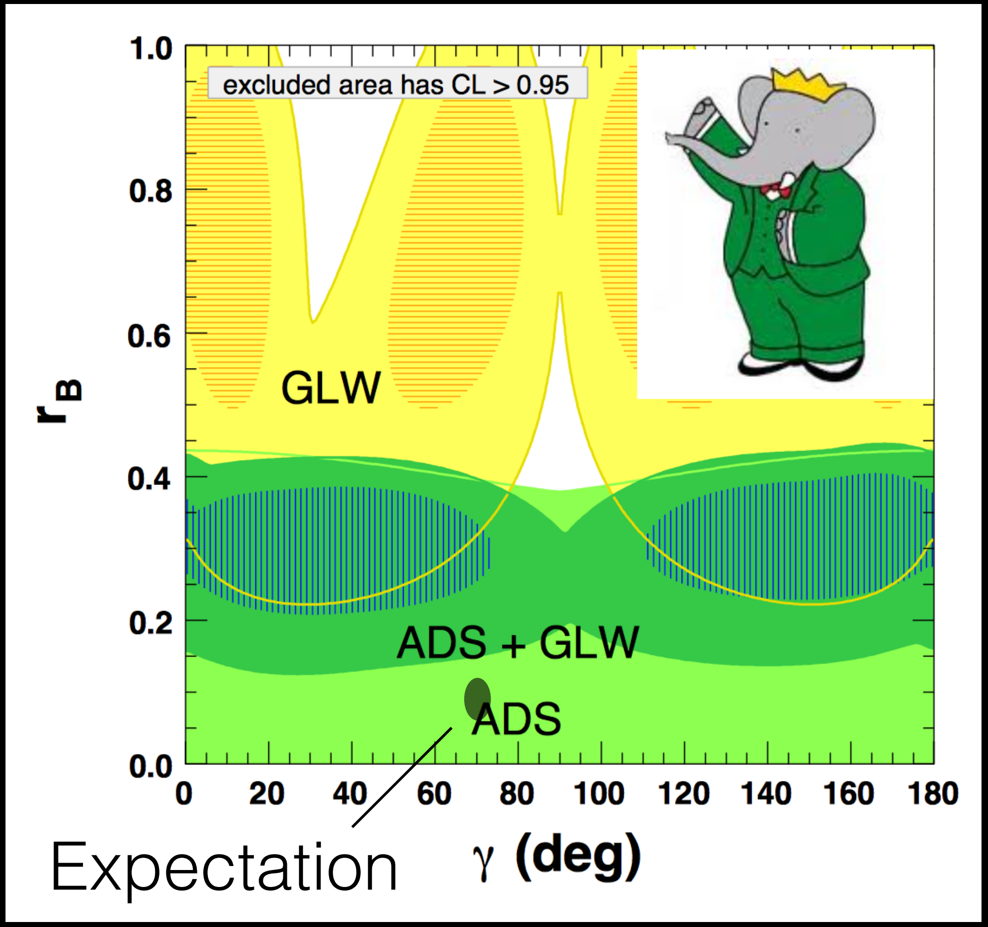
$B^- \to DK^{*-}$ ADS/GLW

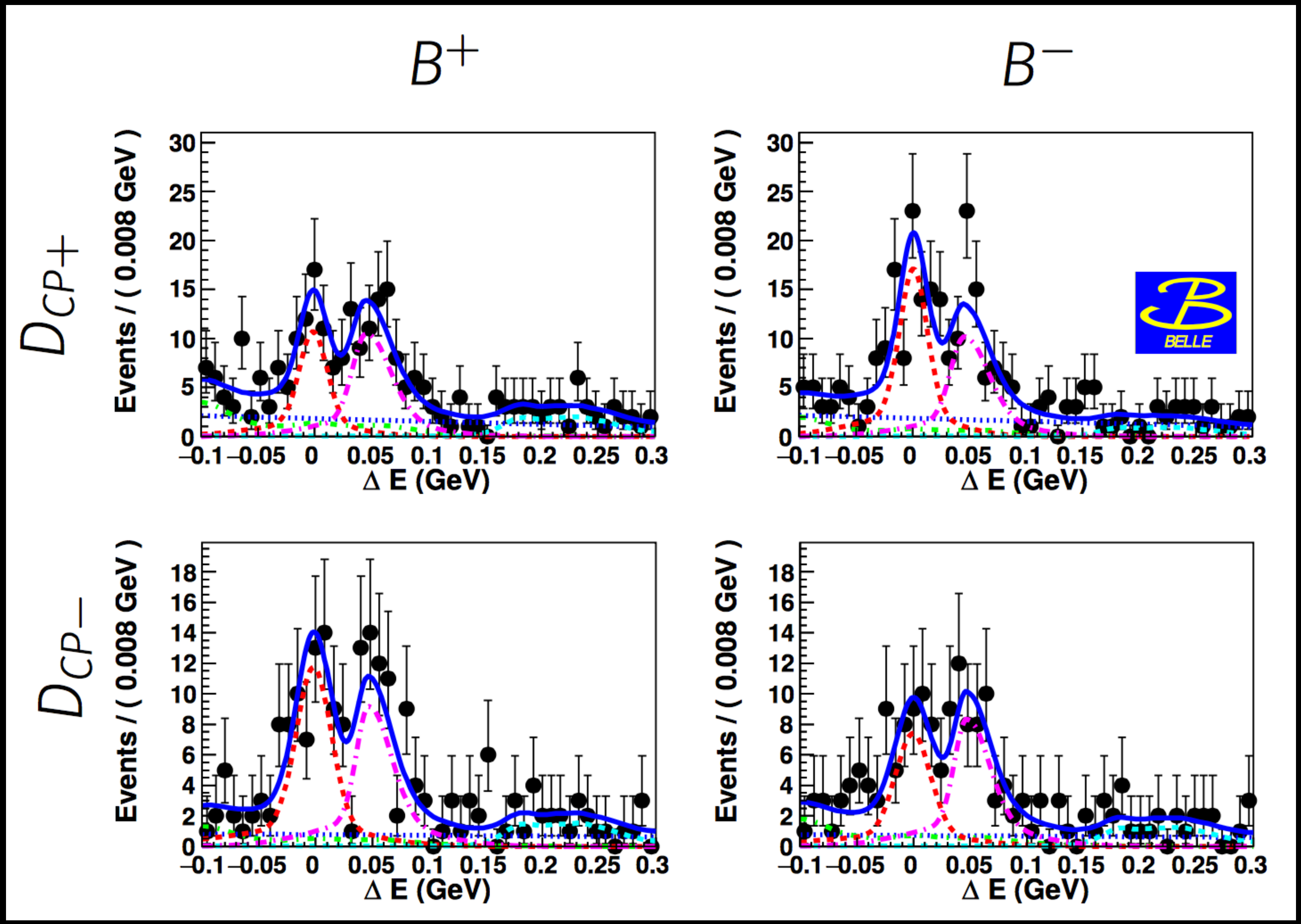




LHCb-CONF-2016-014

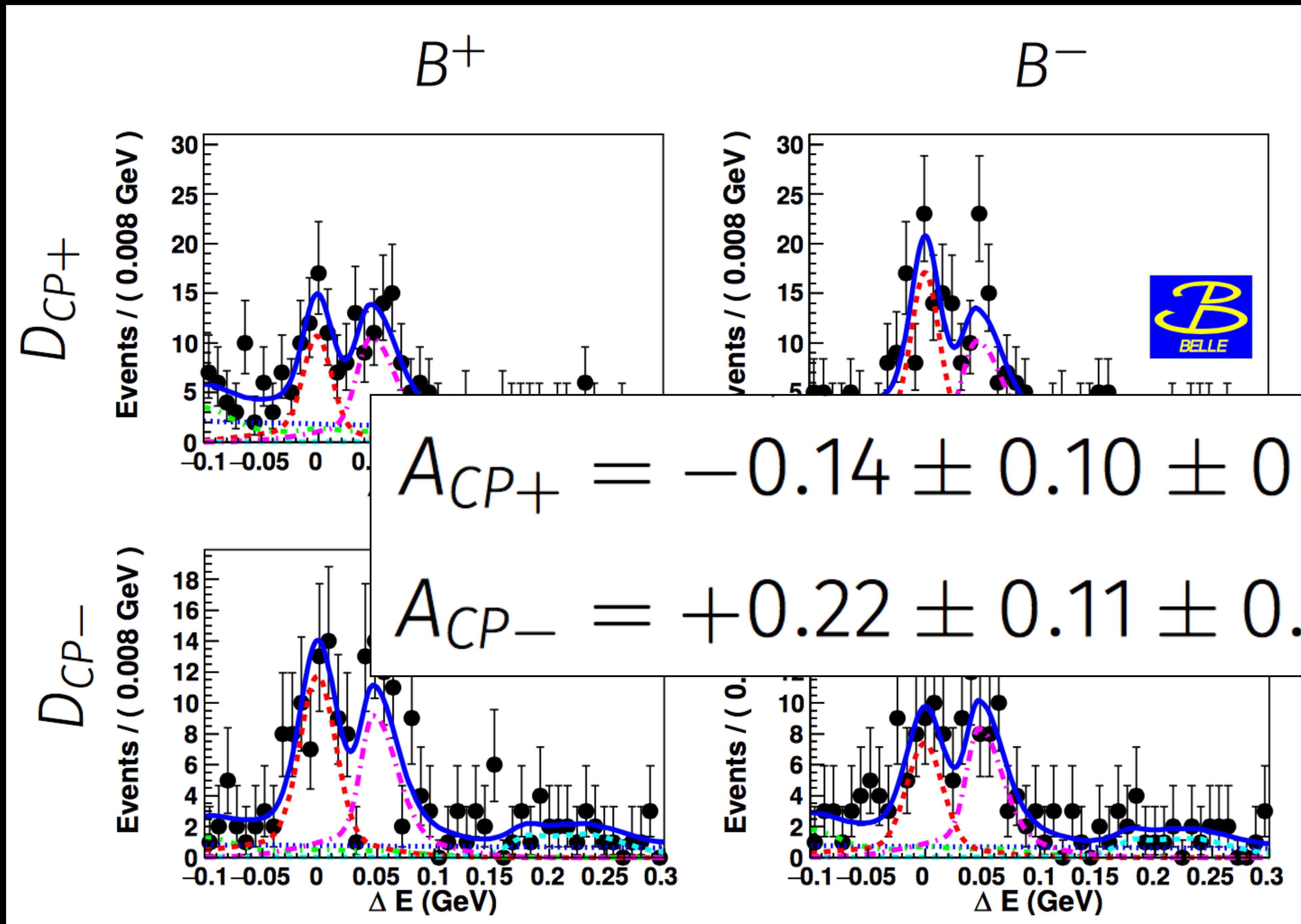
Facts are facts and will not disappear on account of your likes.

$B^- \to [D^0\gamma/\pi]^* K^-$ ADS/GLW



to be published soon

$B^{-} \to [D^{0}\gamma/\pi]^{*} K^{-}$ ADS/GLW



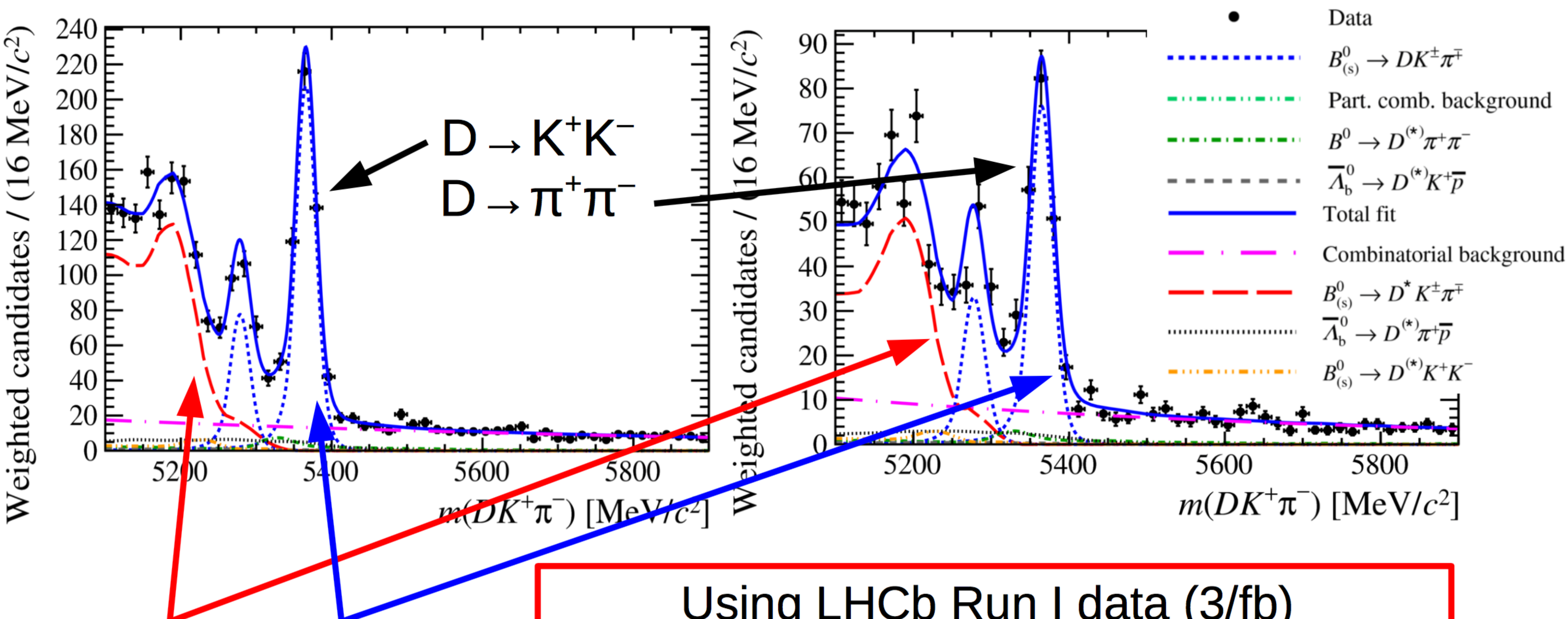
$$A_{CP+} = -0.14 \pm 0.10 \pm 0.01$$

$$A_{CP-} = +0.22 \pm 0.11 \pm 0.01$$

to be published

Dalitz analysis of $B^0 \to DK^+\pi^-$

- Simultaneous DP fit to $D \to K^+\pi^-$, K^+K^-, $\pi^+\pi^-$

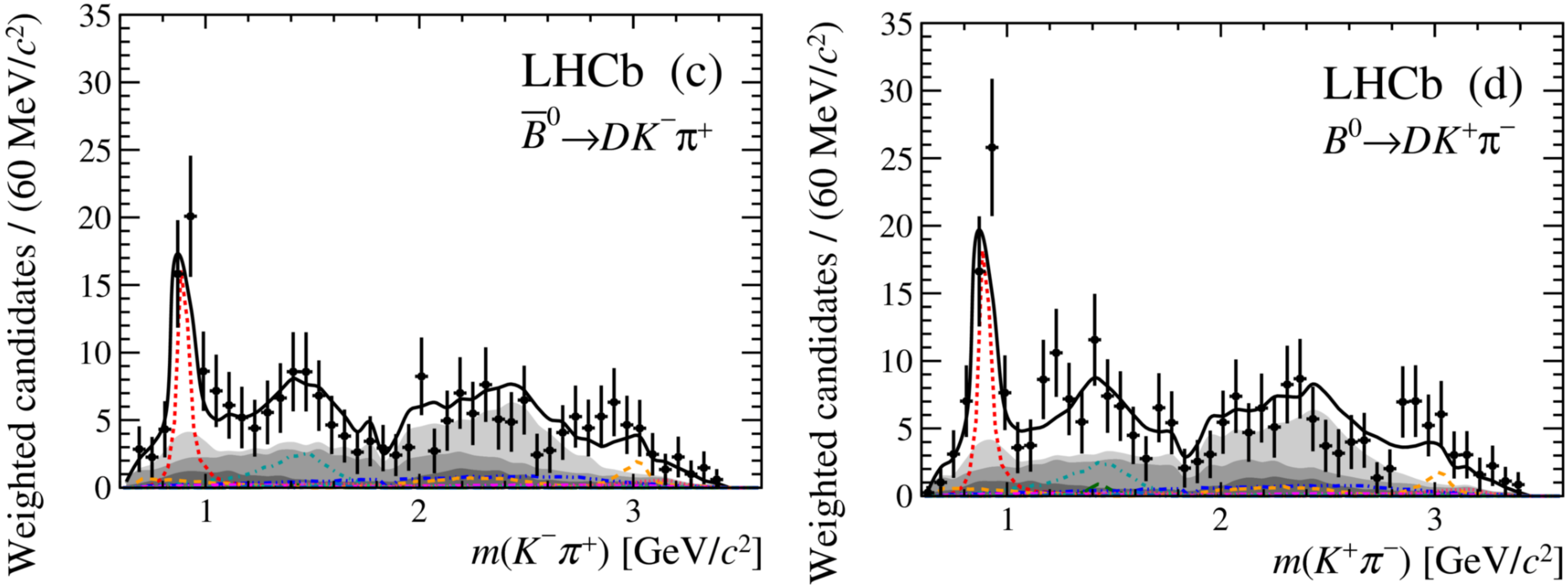


$B_s^0 \to D^*K\pi$ / $DK\pi$ backgrounds

Using LHCb Run I data (3/fb)
339 ± 22 / 168 ± 19 K^+K^- / $\pi^+\pi^-$ decays
in B^0 signal region

PR D93 (2016) 112018

Dalitz analysis of $B^0 \to DK^+\pi^-$



no clear asymmetry in B0→DK*(892)0

analysis to be revisited with new data

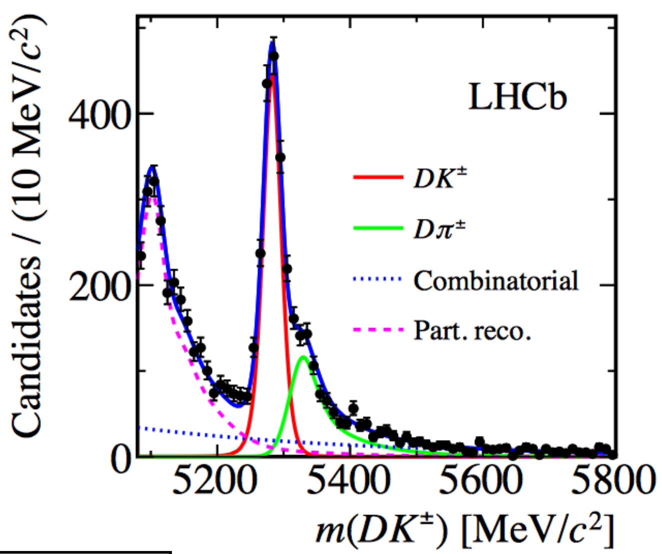
PR D93 (2016) 112018

Binned $B^- \to [\pi\pi\pi\pi]_D K^-$

- Similar numbers of $K_S\pi^+\pi^-$ and 4π reconstructed at LHCb with 3.0 fb^{-1}

$K^0_S\pi^+\pi^-$

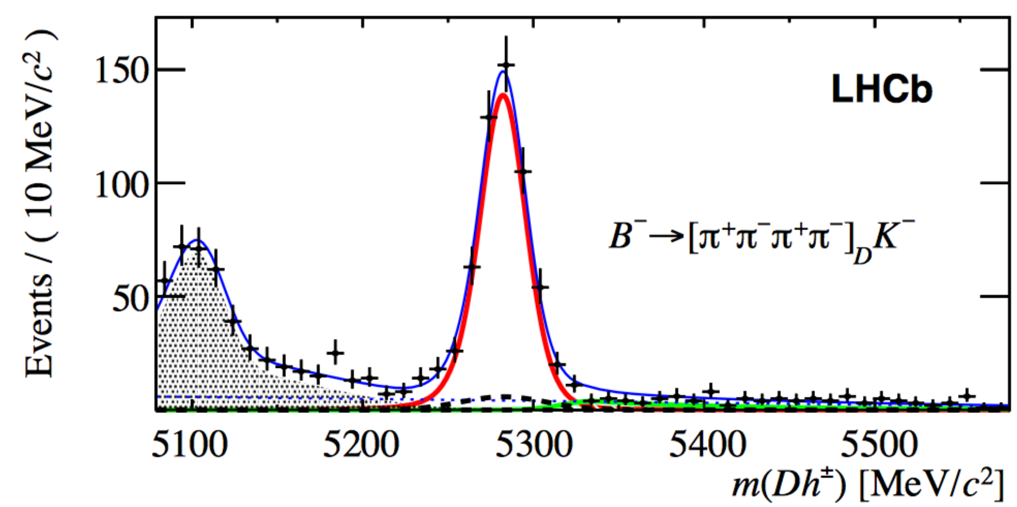
JHEP 10 (2014) 097 (https://arxiv.org/abs/1408.2748)



2257 ± 43

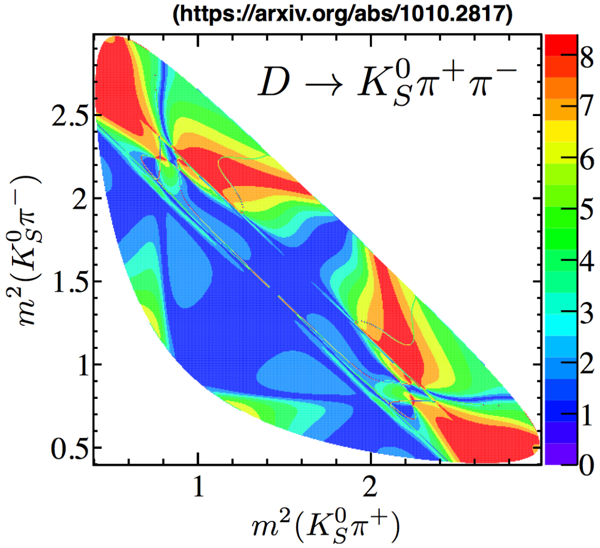
$\pi^+\pi^-\pi^+\pi^-$

Phys. Let. B 760 (2016)117-131 (https://arxiv.org/abs/1603.08993)



1497 ± 60

Phys. Rev. D 82 (2010) 112006 (https://arxiv.org/abs/1010.2817)



would expect to obtain a similar sensitivity to γ

to be published

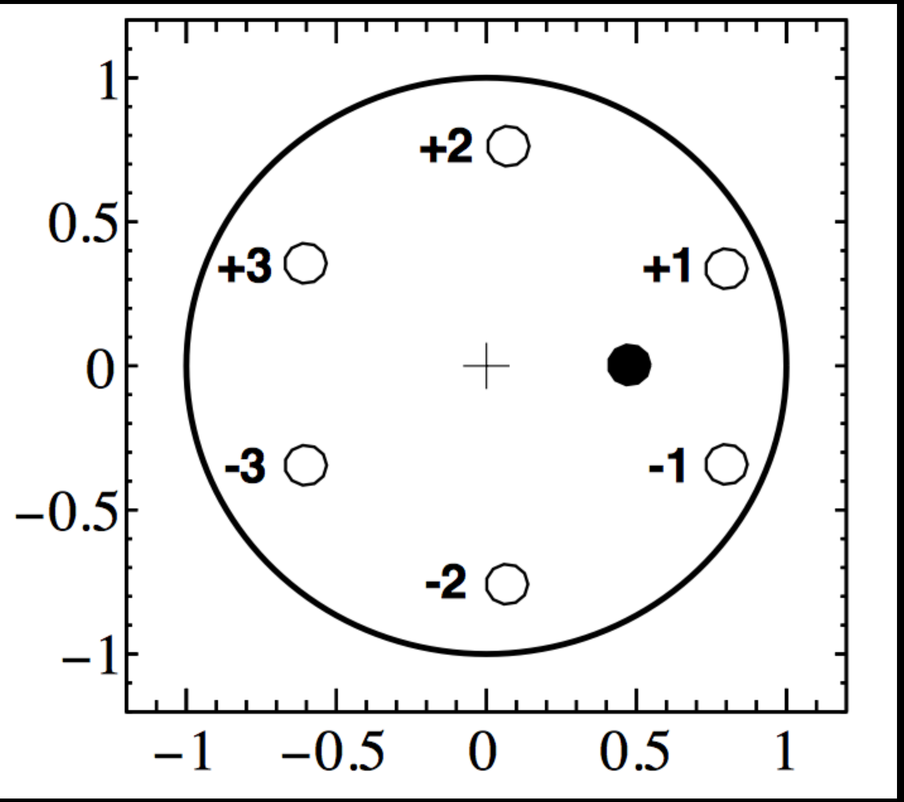
Sam Harnew

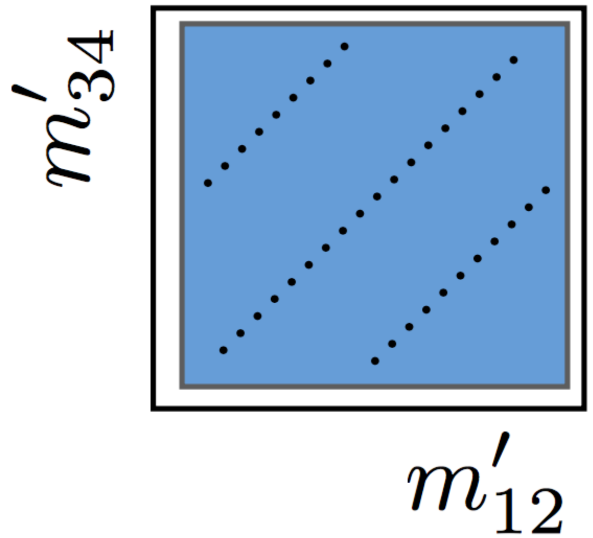
$D^0 \rightarrow \pi\pi\pi\pi$

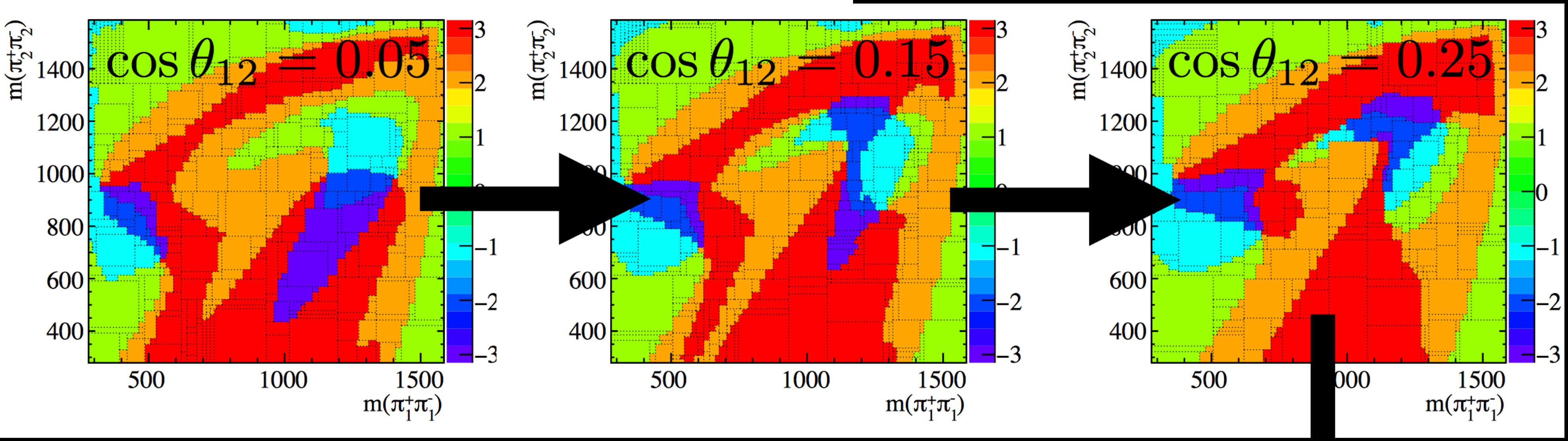
$$\mathbf{p} = (m'_{12}, m'_{34}, \cos\theta_{12}, \cos\theta_{34}, \phi)$$

Helicity angle of the ij pair

Angle between the decay planes of 12 and 34







to be published

Sam Harnew

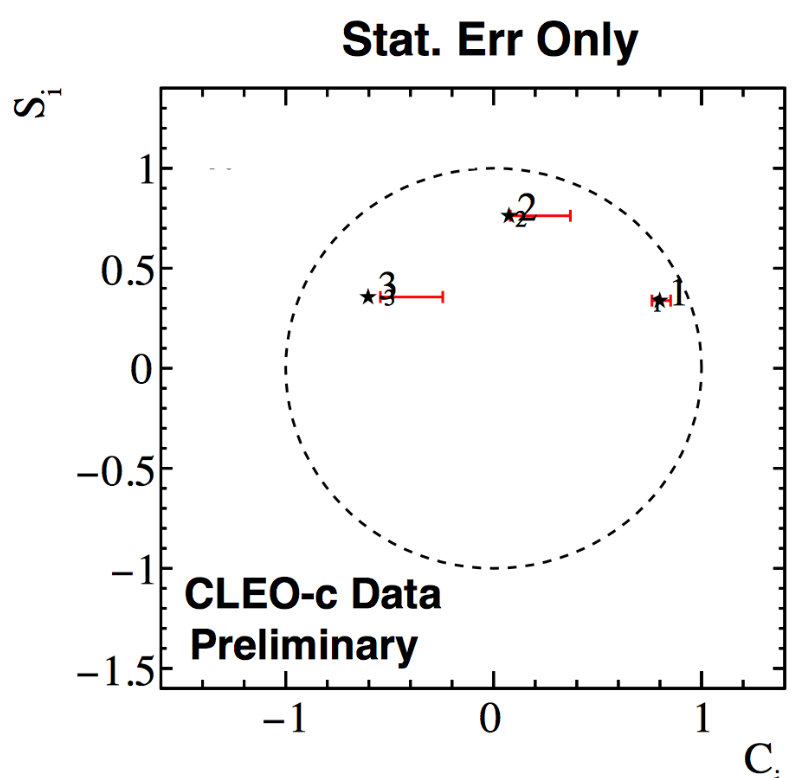
Quantum correlated data of CLEO-c

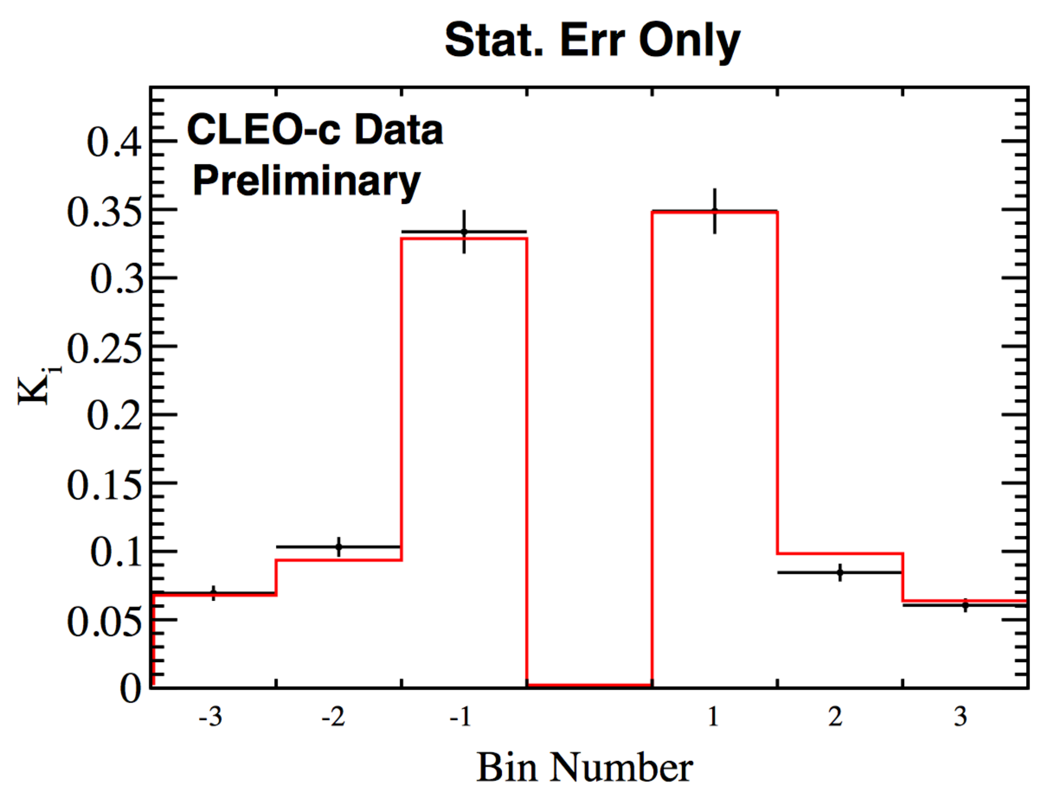
$$J^{PC} = 1^{--}$$

$$K_S^0\pi^0 \longleftarrow D_1 \longleftarrow \psi(3770) \longrightarrow D_2$$

$$D_1 = |D^0\rangle - |\overline{D^0}\rangle \qquad D_2 = |D^0\rangle + |\overline{D^0}\rangle$$

$$\left|\langle \pi^+\pi^-\pi^+\pi^- | \mathcal{H} | D_2 \rangle\right|^2 \propto K_i + \overline{K}_i + 2c_i\sqrt{K_i\overline{K}_i}$$





to be published

Sam Harnew

$D^0 \to K_S^0 \pi\pi\pi^0$ with CLEO-c data

- The decay $D^0 \to K_S^0\pi^+\pi^-\pi^0$ has a relatively large branching fraction of 5.2% which is almost twice that of $K_S^0\pi^+\pi^-$ [6].

Bin	c_i	s_i
1	-1.12 ± 0.12	0.12 ± 0.17
2	-0.29 ± 0.07	0.11 ± 0.13
3	-0.41 ± 0.09	-0.08 ± 0.18
4	-0.84 ± 0.12	-0.73 ± 0.34
5	-0.54 ± 0.13	0.65 ± 0.13
6	-0.22 ± 0.12	1.37 ± 0.22
7	-0.90 ± 0.16	-0.12 ± 0.40
8	-0.70 ± 0.14	-0.03 ± 0.44

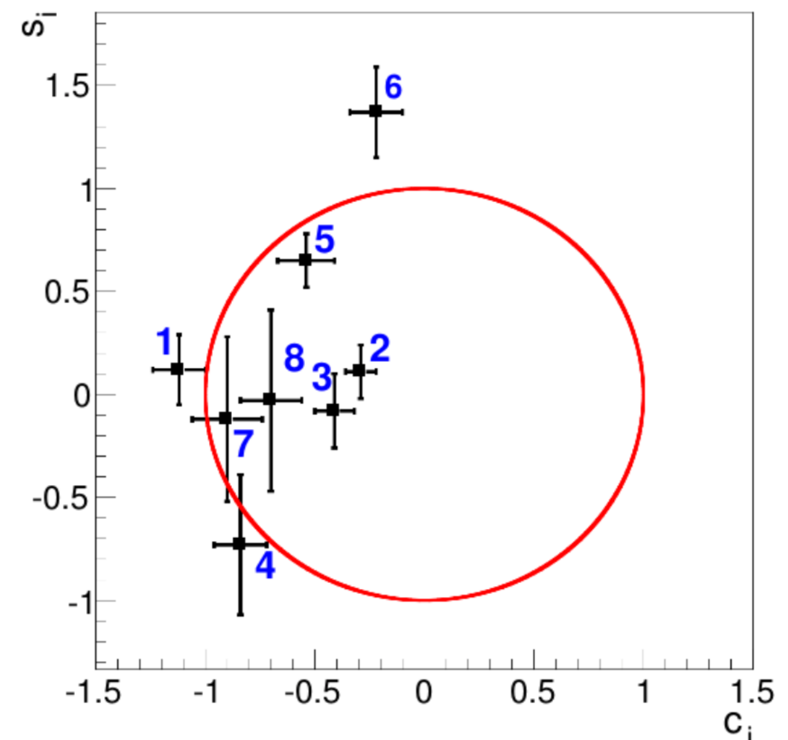


Figure : c_i and s_i values in each bin.

- The uncertainties shown are statistical only.
- $c_i < 0 \Rightarrow$ **CP oddness** of $K_S^0\pi^+\pi^-\pi^0$.

to be published

Resmi P.K.

Binned $B^{-} \to [K_S{}^0 \pi\pi\pi^0]_D K^{-}$ study for Belle II

- Assumed increase in BF compensated by loss of efficiency due to π^0 in final state.
- With 1200 events (Belle sample of $B^{\pm} \to D(K_S^0\pi^+\pi^-)K^{\pm}$) $\sigma_{\phi_3} = 25°$ - 1000 pseudo experiments using c_i, s_i, K_i and $\bar{K}_i$ measurements reported.
- Project to a 50 ab^{-1} sample $\sigma_{\phi_3} = 3.5°$.
- Compare to $B^{\pm} \to D(K_S^0\pi^+\pi^-)K^{\pm}$ $\sigma_{\phi_3} \sim 2°$.

to be published

Resmi P.K.

Direct CPV in $H_b \rightarrow$ charmless

B-factory Dalitz plot analyses

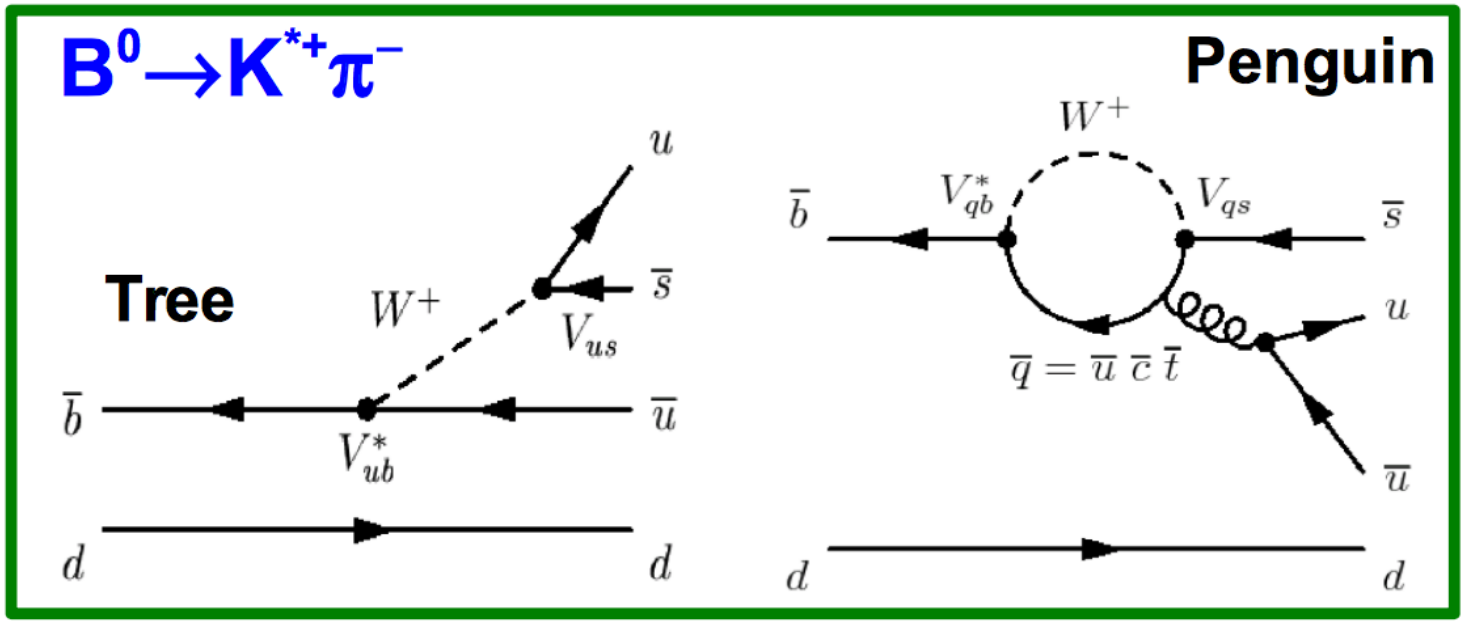
$K^+K^+K^-$	PR D85 (2012) 112010	PR D71 (2005) 092003
$K^+K^+K_S$	PR D85 (2012) 112010	PR D82 (2010) 073011
$K^+K_SK_S$	PR D85 (2012) 112010	No amplitude analysis
$K_SK_SK_S$	PR D85 (2012) 054023	No amplitude analysis
$K^+\pi^+\pi^-$	PR D78 (2008) 012004	PRL 96 (2006) 251803
$K_S\pi^+\pi^-$	PR D80 (2009) 112001	PR D79 (2009) 072004
$K^+\pi^-\pi^0$	PR D83 (2011) 112010	No amplitude analysis
$K_S\pi^+\pi^0$	arXiv:1501.00705	No amplitude analysis
$\pi^+\pi^+\pi^-$	PR D79 (2009) 072006	No amplitude analysis
$\pi^+\pi^+\pi^0$	PR D88 (2013) 012003	PR D77 (2008) 072001

Phenomenology of B→Kππ modes

SU(2) Isospin relations:

$$A^{0+} + \sqrt{2}A^{+0} = \sqrt{2}A^{00} + A^{+-}$$

$$\overline{A}^{0+} + \sqrt{2}\overline{A}^{+0} = \sqrt{2}\overline{A}^{00} + \overline{A}^{+-}$$



(S)

$$A(B^0\to K^{*+}\pi^-) = V_{us}V^*_{ub}T^{+-} + V_{ts}V^*_{tb}P^{+-}$$

$$A(B^+\to K^{*0}\pi^+) = V_{us}V^*_{ub}N^{0+} + V_{ts}V^*_{tb}(-P^{+-}+P^{C}_{EW})$$

$$\sqrt{2}A(B^+\to K^{*+}\pi^0) = V_{us}V^*_{ub}(T^{+-}+T^{00}_{C}-N^{0+}) + V_{ts}V^*_{tb}(P^{+-}-P^{C}_{EW}+P_{EW})$$

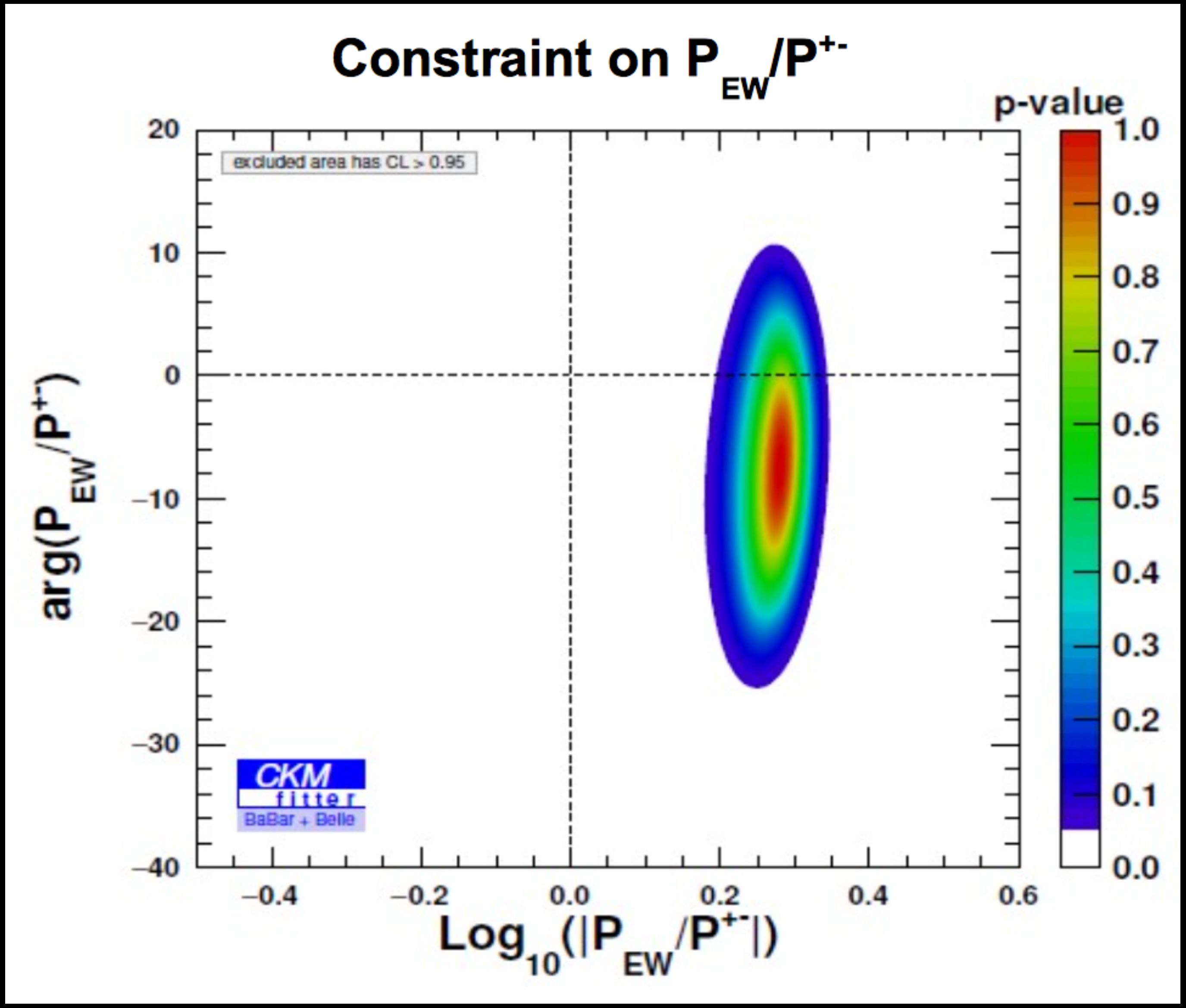
$$\sqrt{2}A(B^0\to K^{*0}\pi^0) = V_{us}V^*_{ub}T^{00}_{C} + V_{ts}V^*_{tb}(-P^{+-}+P_{EW})$$

Take CKM from global fit and constrain hadronic parameters

in preparation

Alejandro Pérez Pérez

$B \to K^* \pi$



Current data favours a relatively high P_{EW}

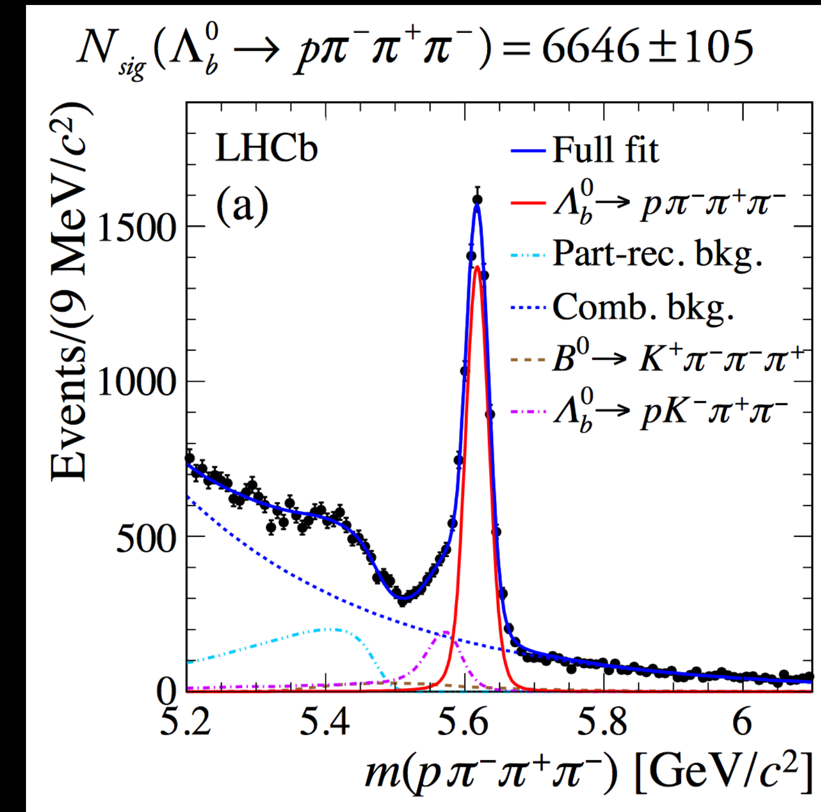
$B^0 \to K\pi\pi^0$ analysis performed only by BABAR

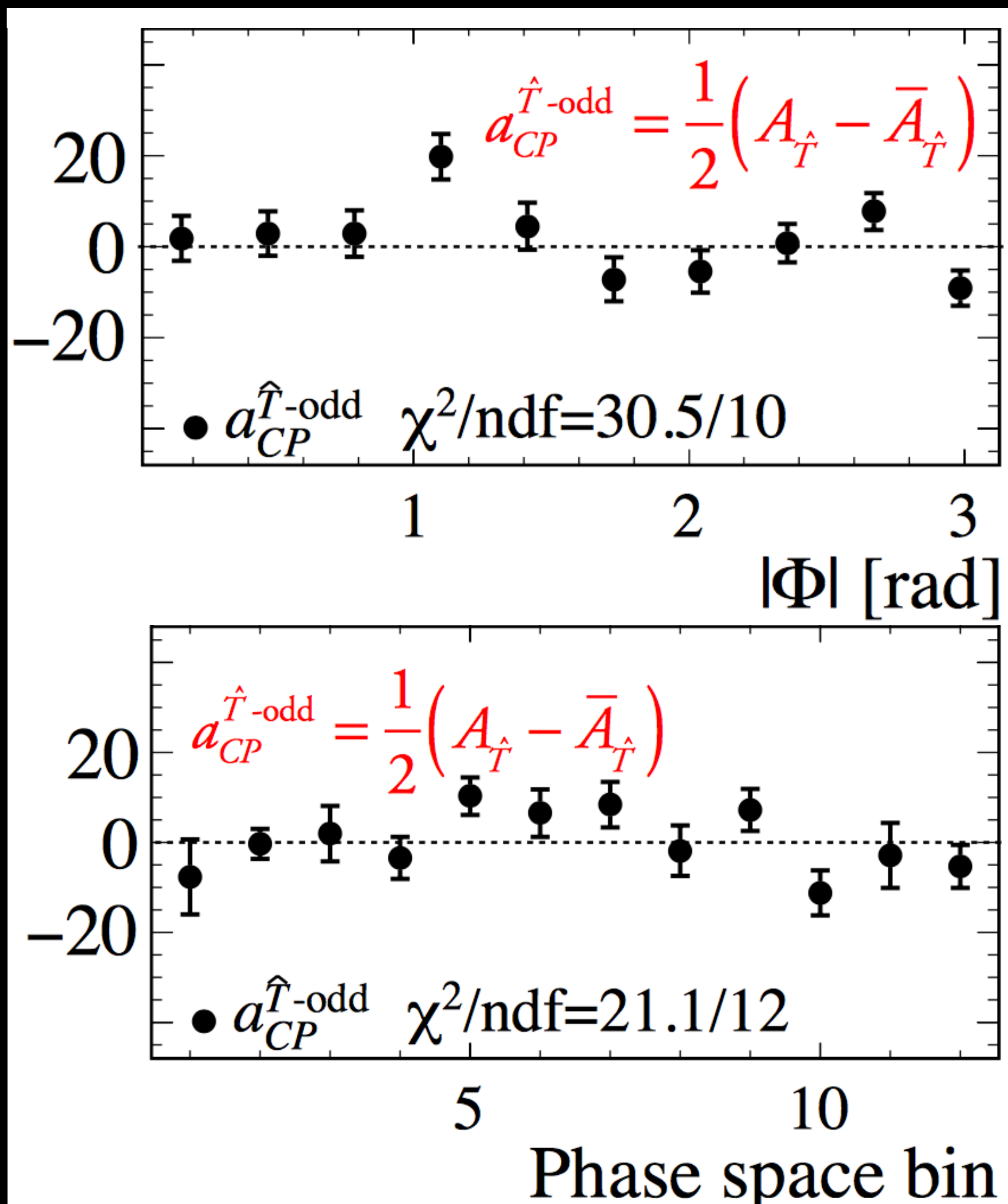
Independent confirmation needed to claim non-zero (and large!) P_{EW} value

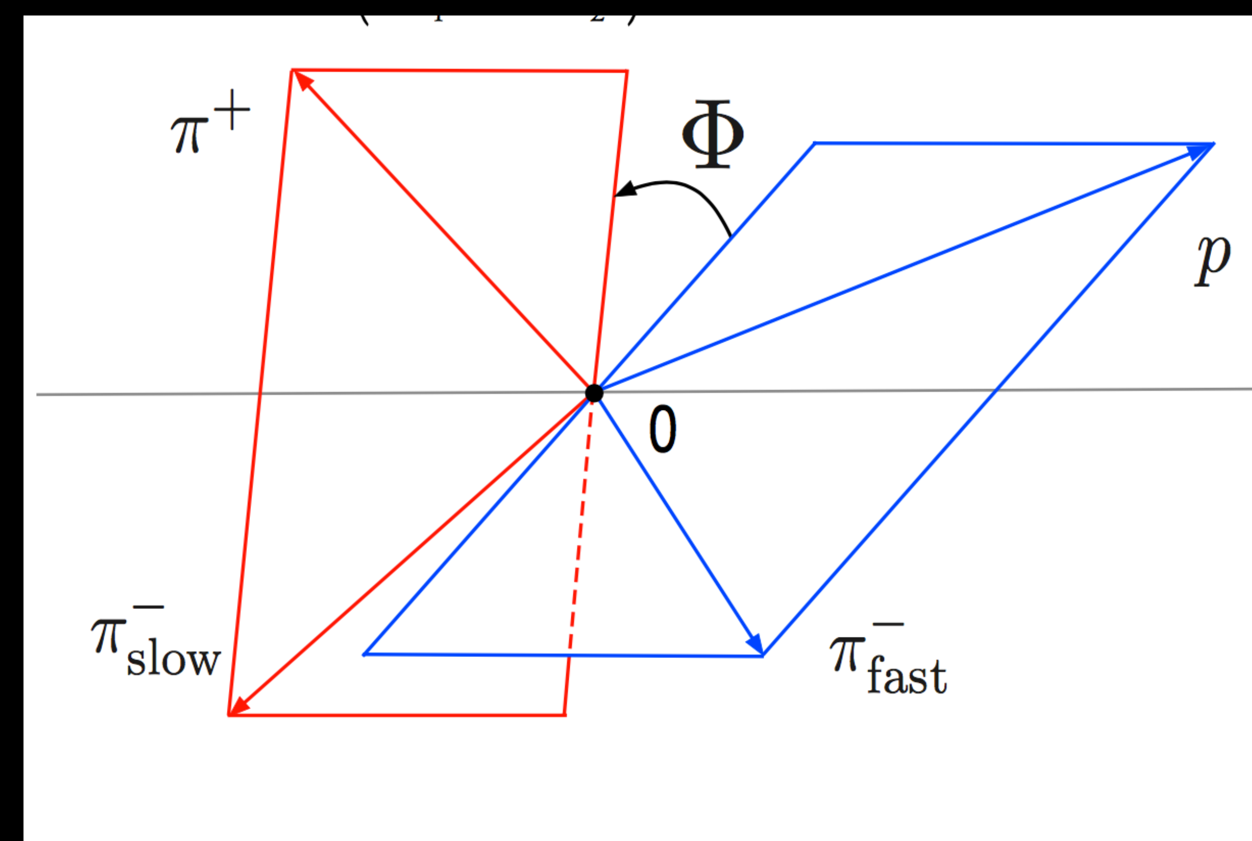
in preparation

Alejandro Pérez Pérez

CPV in $\Lambda_b \to p\pi\pi\pi$



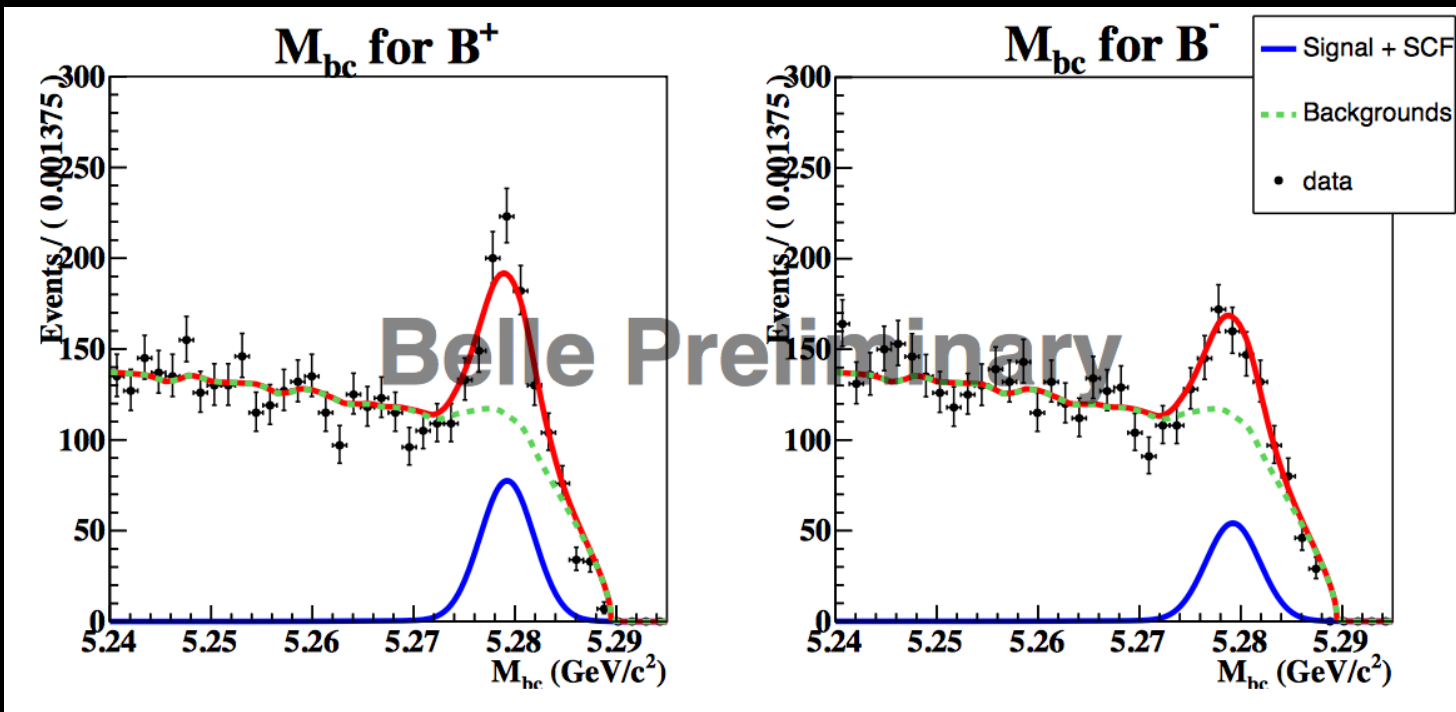




3.3σ CPV effect

arXiv: 1609.05216

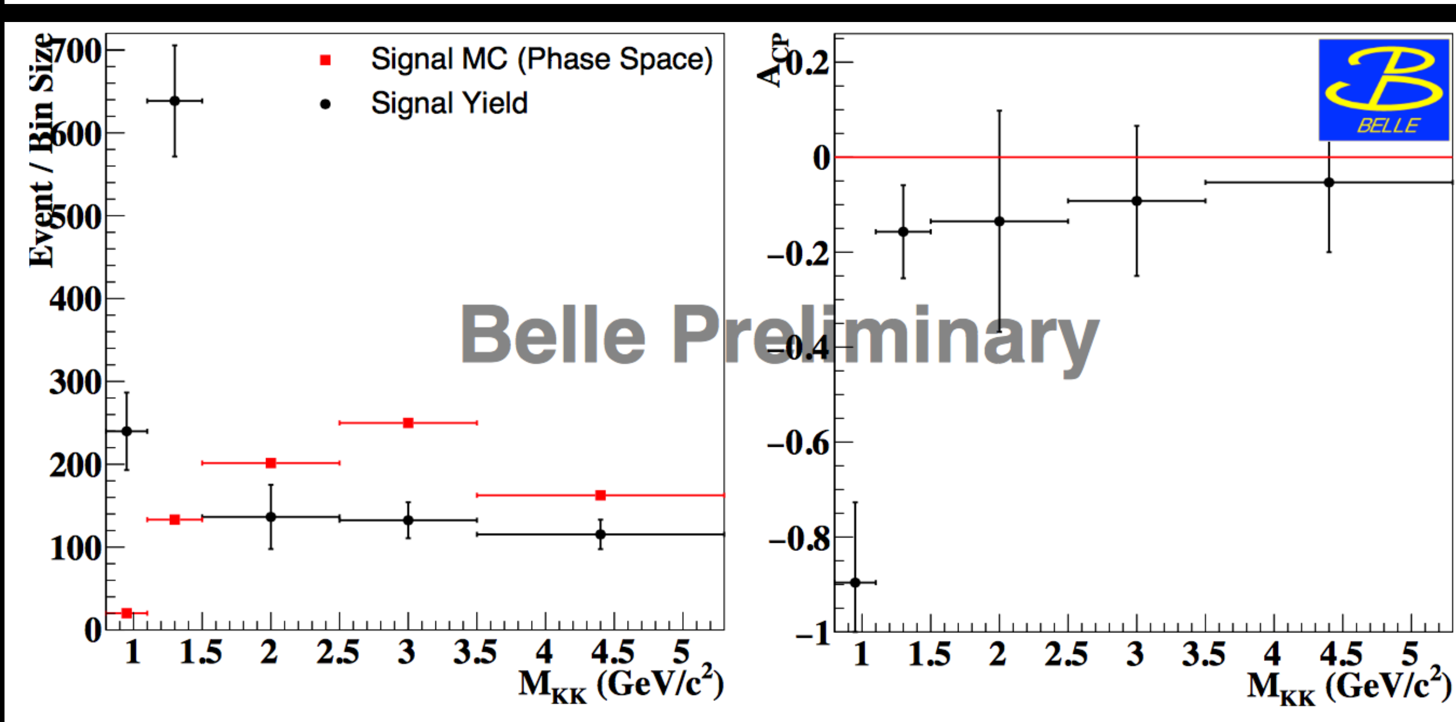
CP violation in $B^+ \to K^+ K^- \pi^+$



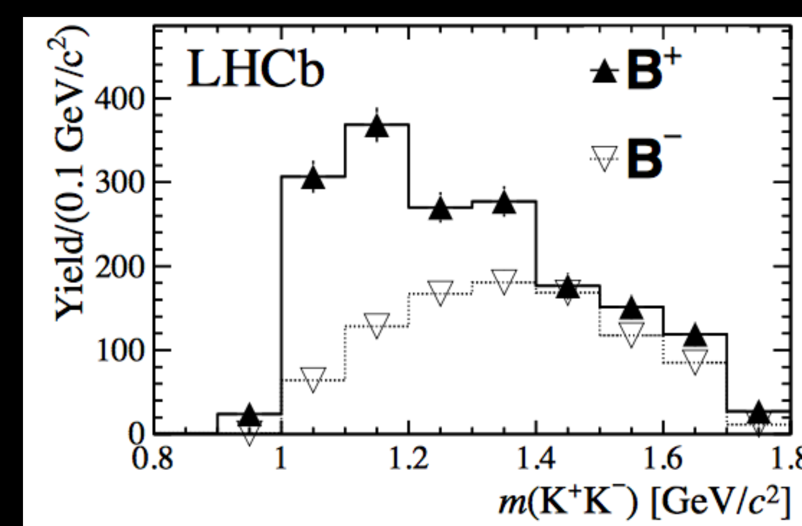
$$\mathcal{B}(K^+K^-\pi^\pm) = (5.68 \pm 0.38 \pm 0.25) \times 10^{-6}$$
$$\mathcal{A}_{CP} = -0.177 \pm 0.067 \pm 0.006$$

ACP in $M_{KK} < 1.1$ GeV/c^2

$$\mathcal{A}_{CP} = -0.896 \pm 0.166 \pm 0.030$$



Confirms LHCb result



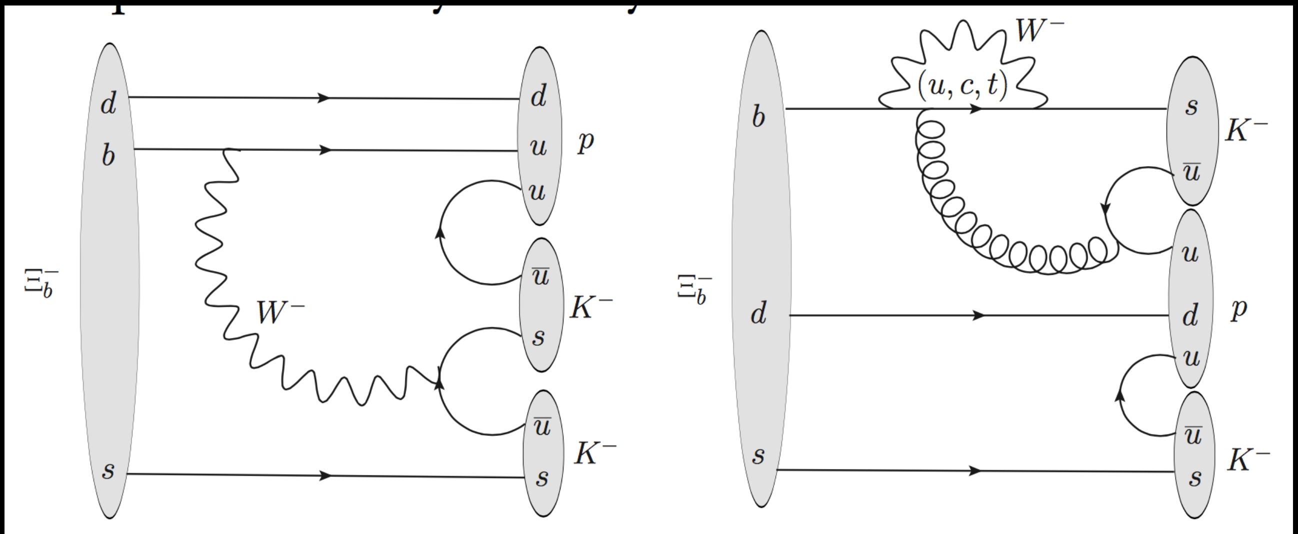
to be published

Chia-Ling Hsu

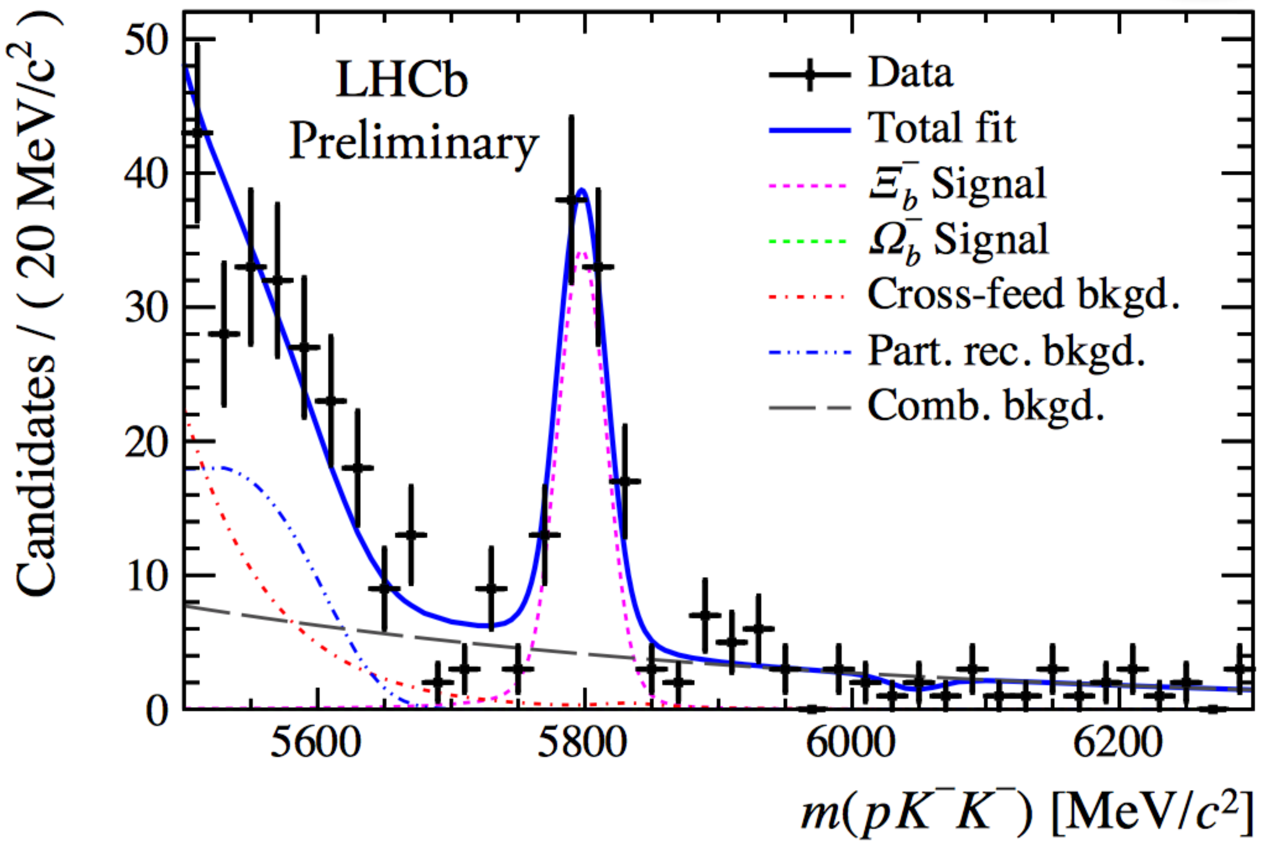
I keep six honest serving men (they taught me all I knew);
Theirs names are What and Why and When And How And
Where and Who.

New modes and searches

$\Xi_b^- \to pK^-h^-$

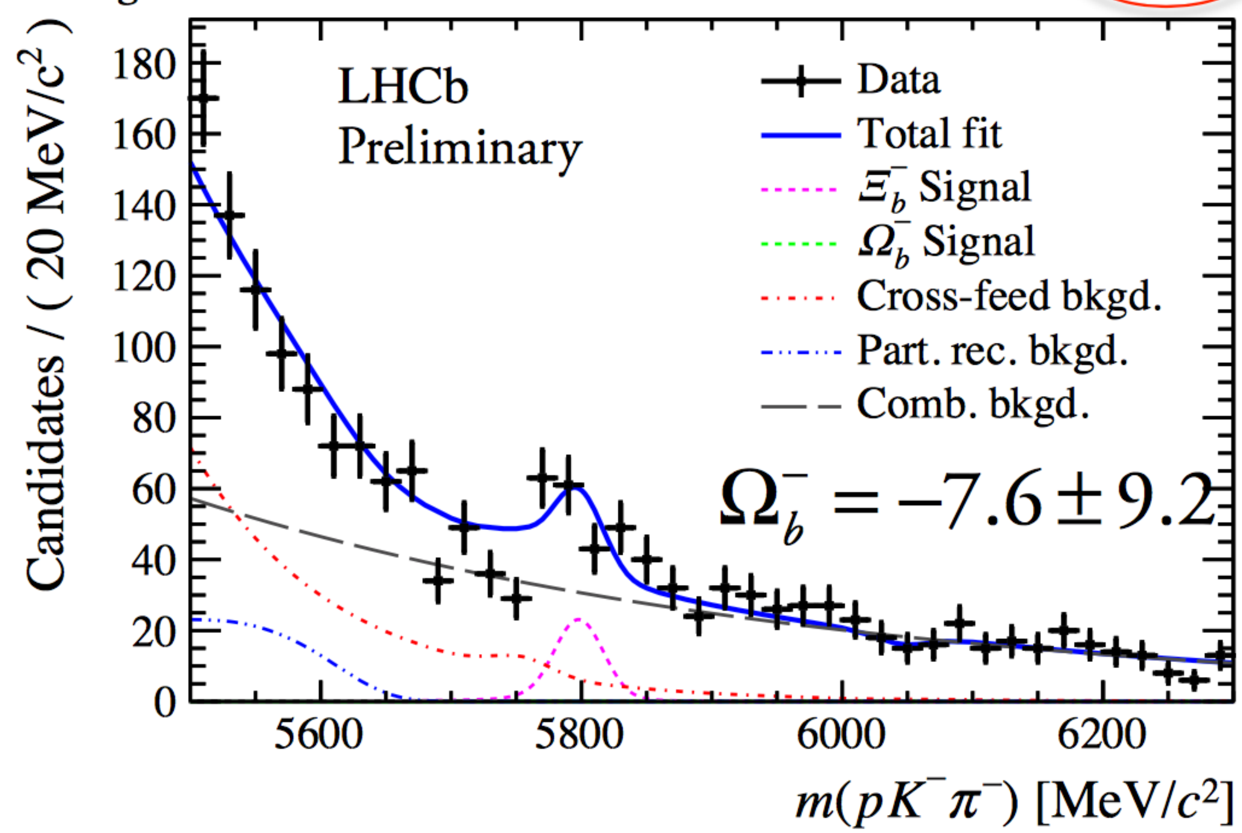


$$N_{sig}(\Xi_b^- \to pK^-K^-) = 82.9 \pm 10.4, 8.7\sigma$$



$$\frac{f_{\Xi_b^-}}{f_u}\frac{\mathcal{B}(\Xi_b^- \to pK^-K^-)}{\mathcal{B}(B^- \to K^+K^-K^-)} = (265 \pm 35 \pm 47) \times 10^{-5}$$

$$N_{sig}(\Xi_b^- \to pK^-\pi^-) = 59.6 \pm 16.0, 3.4\sigma$$



$$\frac{\mathcal{B}(\Xi_b^- \to pK^-\pi^-)}{\mathcal{B}(\Xi_b^- \to pK^-K^-)} = 0.98 \pm 0.27 \pm 0.09$$

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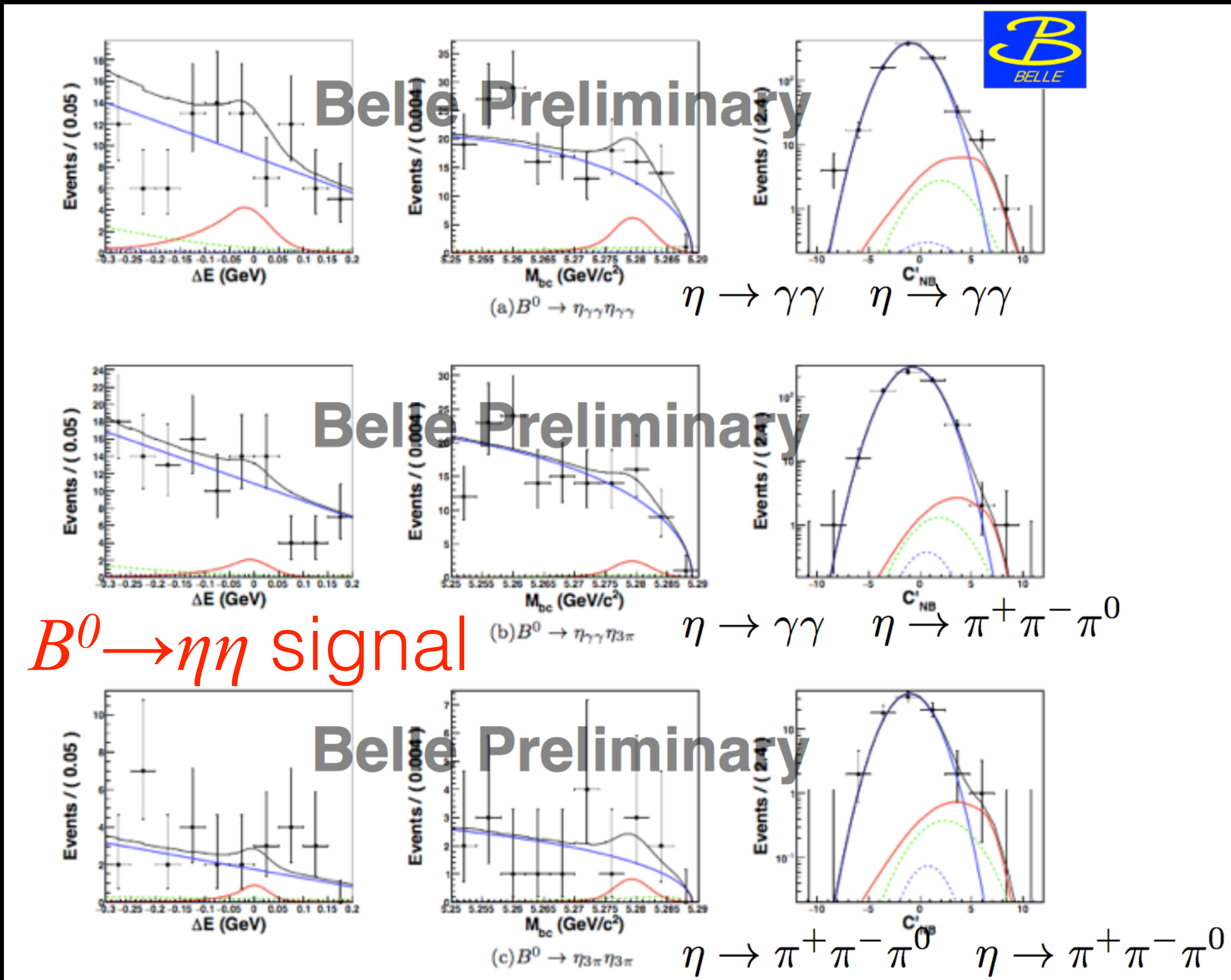
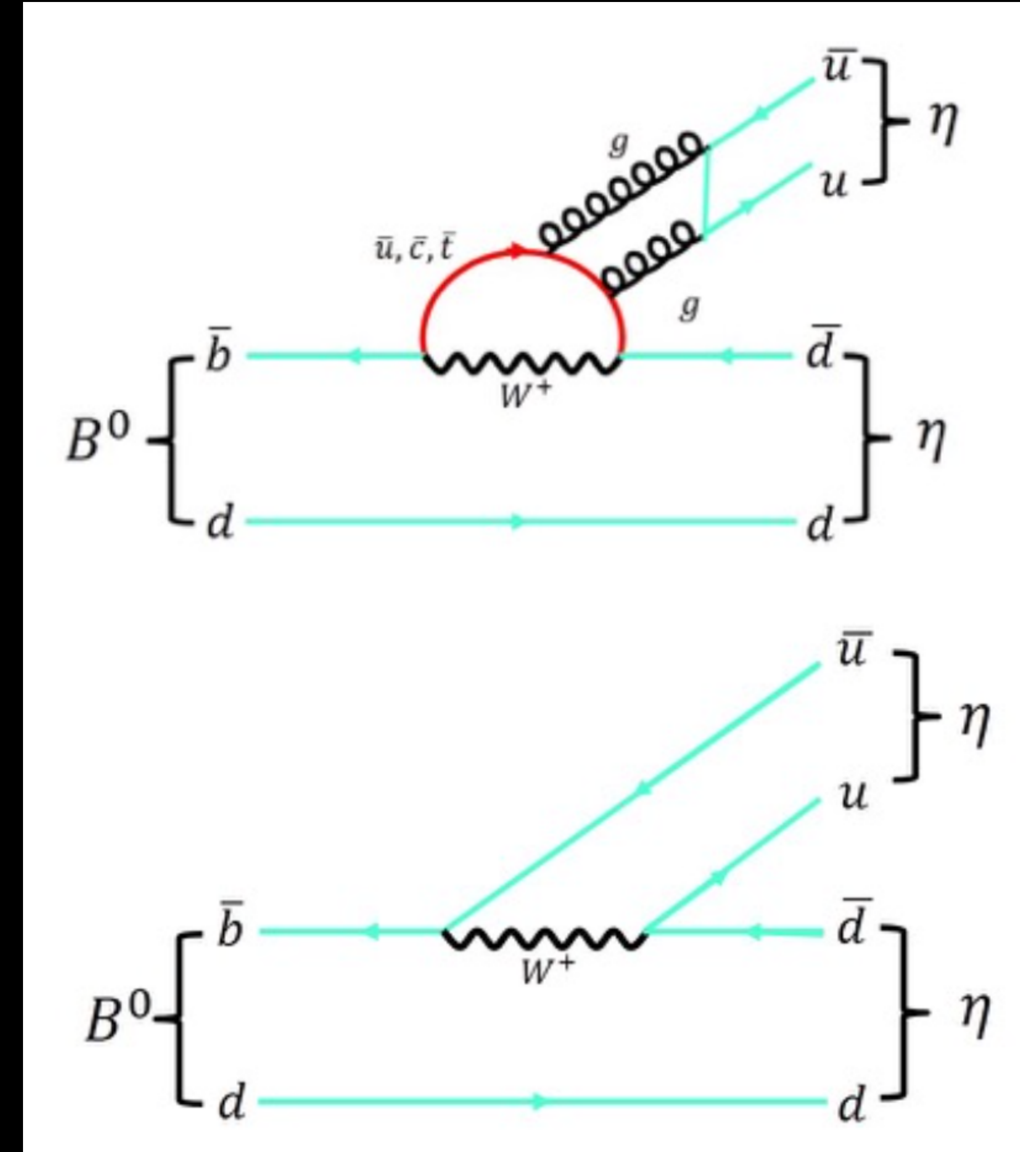
$B^0 \to \eta\eta$





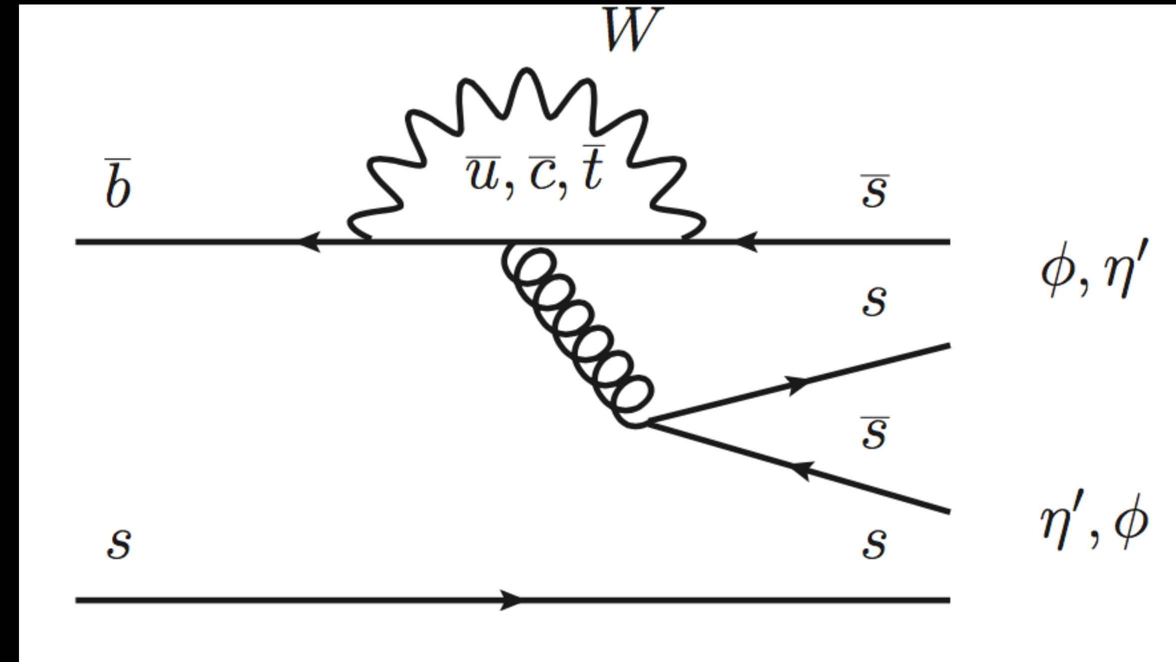
Sub-decay model	Yield
$\eta_{\gamma\gamma}\eta_{\gamma\gamma}$	$23.6^{+8.1}_{-6.9}$
$\eta_{\gamma\gamma}\eta_{3\pi}$	$9.2^{+3.2}_{-2.7}$
$\eta_{3\pi}\eta_{3\pi}$	$2.7^{+0.9}_{-0.8}$

$$\mathcal{B}(B^0 \to \eta\eta) = (7.6^{+2.7+1.4}_{-2.3-1.5}) \times 10^{-7} \text{ at } 3.3\sigma$$

arXiv:1609.03267

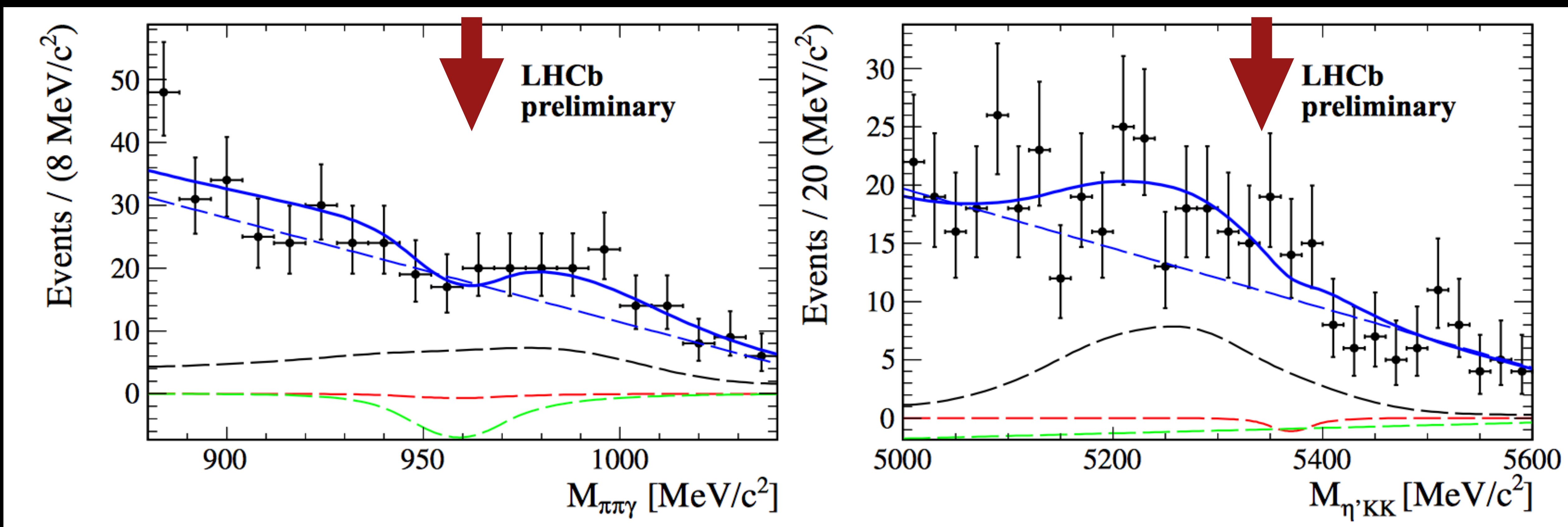
Chia-Ling Hsu

$B_s^0 \to \varphi\eta'$



$B_s \to \varphi\varphi$
"Golden mode": large yield, but needs angular analysis
$\varphi_s = -0.17 \pm 0.15 \pm 0.03$
[PRD 90 (2014) 052011]

$B_s \to \eta'\eta'$
Pure CP eigenstate, large BF, but modest yield
$N_{B_s \to \eta'\eta'}$ (Run1) = $36.4 \pm 7.8 \pm 1.6$
$B(B_s \to \eta'\eta') = (33.1 \pm 6.4 \pm 2.8 \pm 1.2) \times 10^{-6}$
[PRL 115 (2015) 051801]

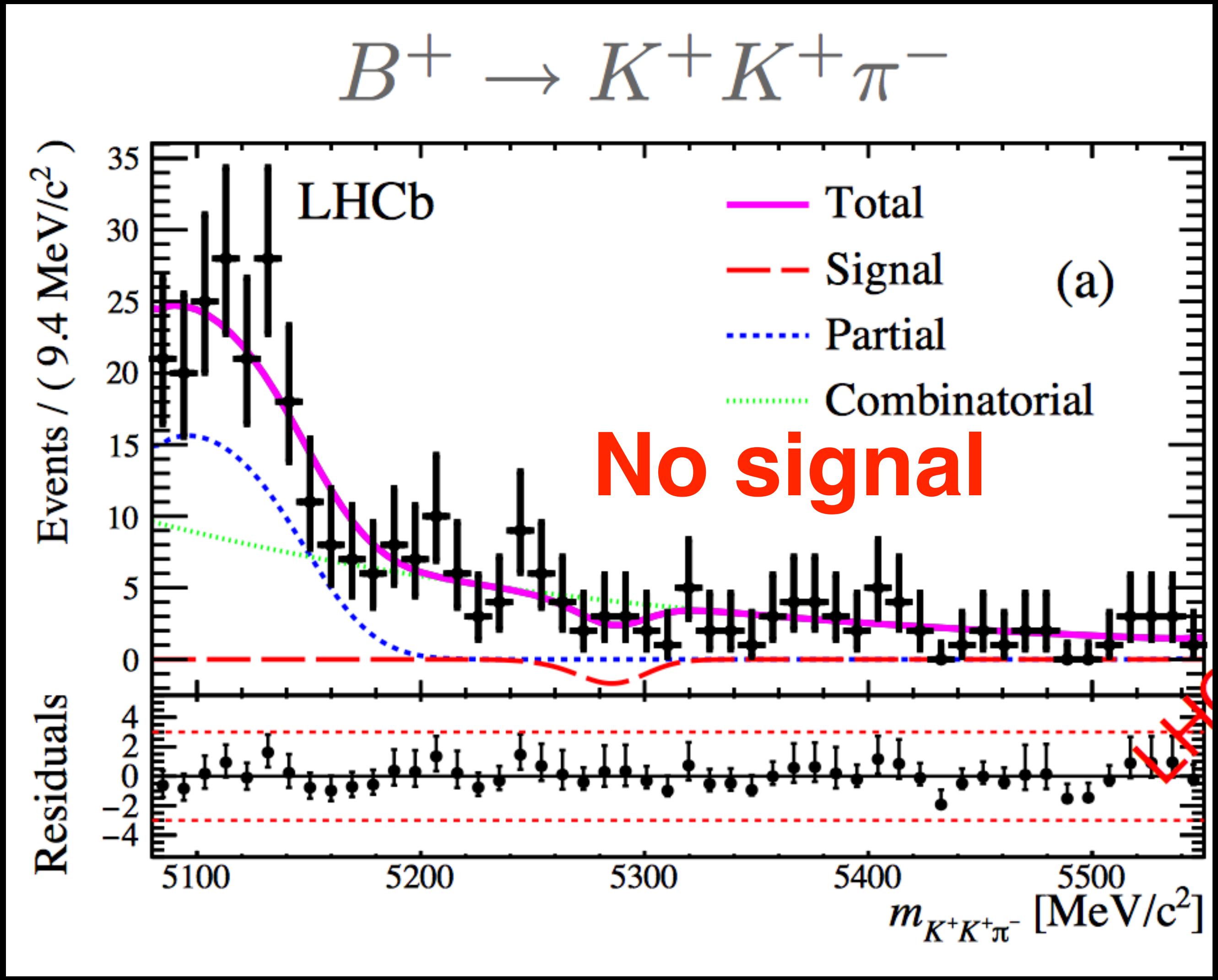


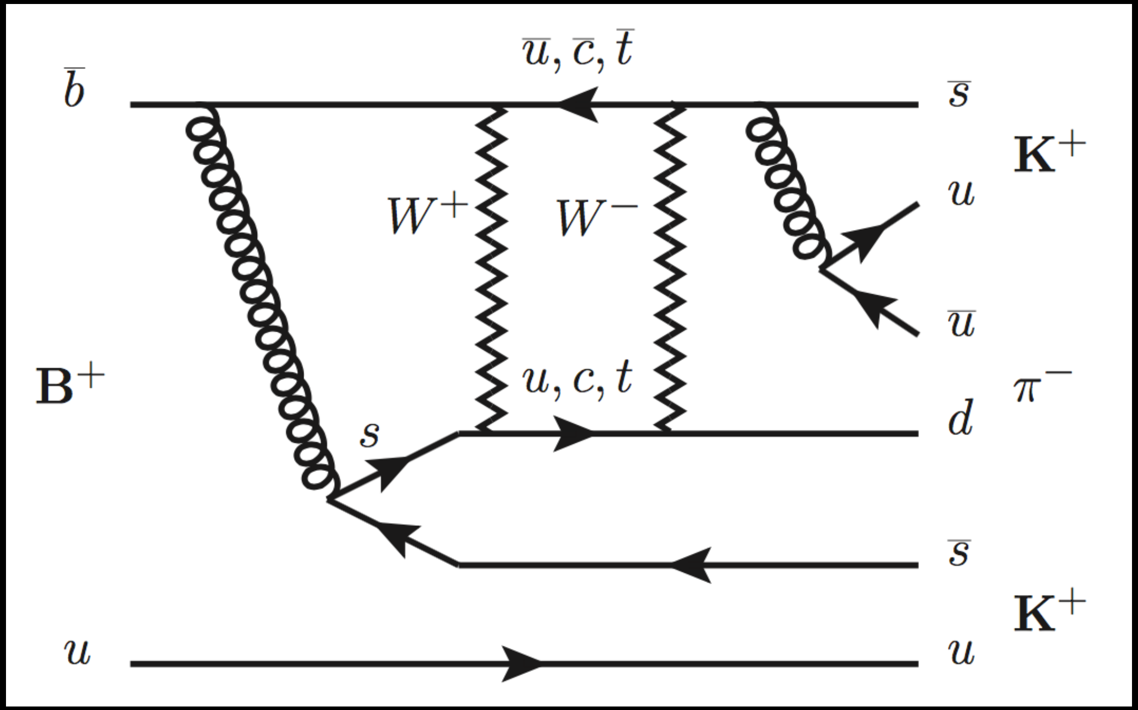
$BR(B_s \to \eta'\phi) < 0.82\ (1.01) \times 10^{-6}$ at 90% (95%) CL

LHCb-PAPER—2016-060

Sebastiana Gianì

Search for $B^+ \to K^+ K^+ \pi^-$





Branching fractions $\mathcal{O}(10^{-11})$ in the SM

$$\mathcal{B}(B^+ \to K^+ K^+ \pi^-) < 1.1 \times 10^{-8} (1.8 \times 10^{-8}) \text{ at } 90\% (95\%) \text{ CL}$$

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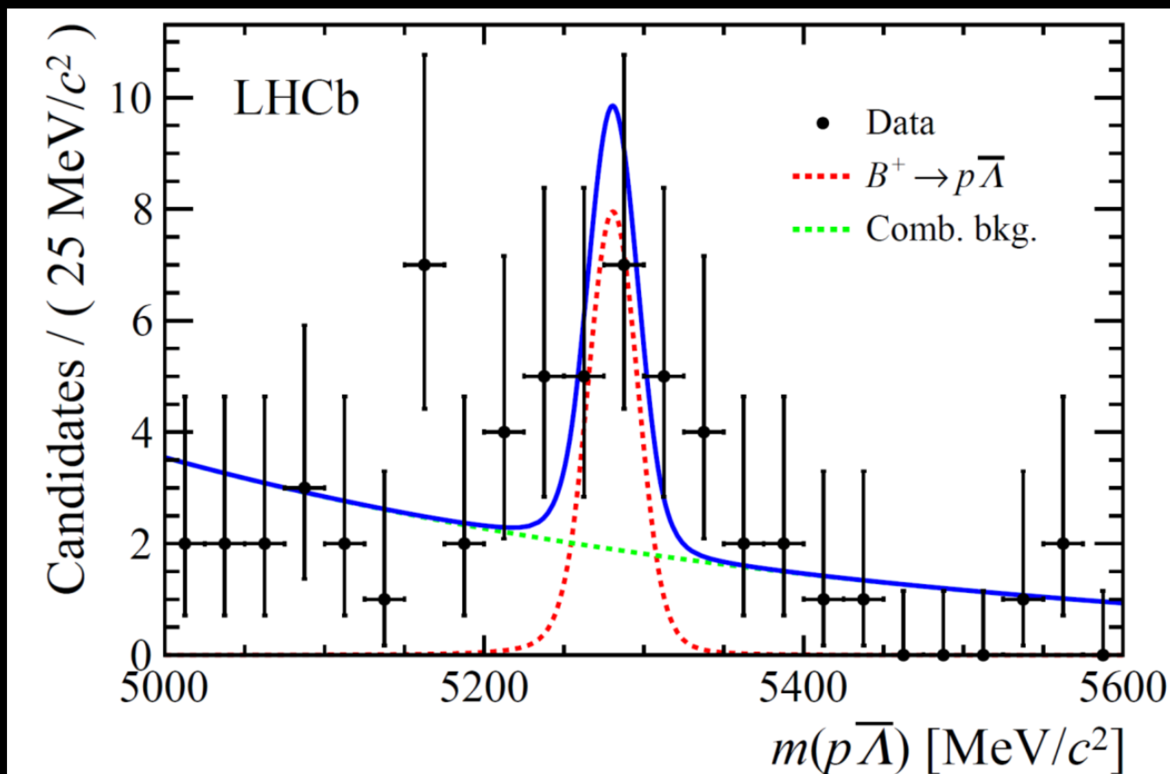
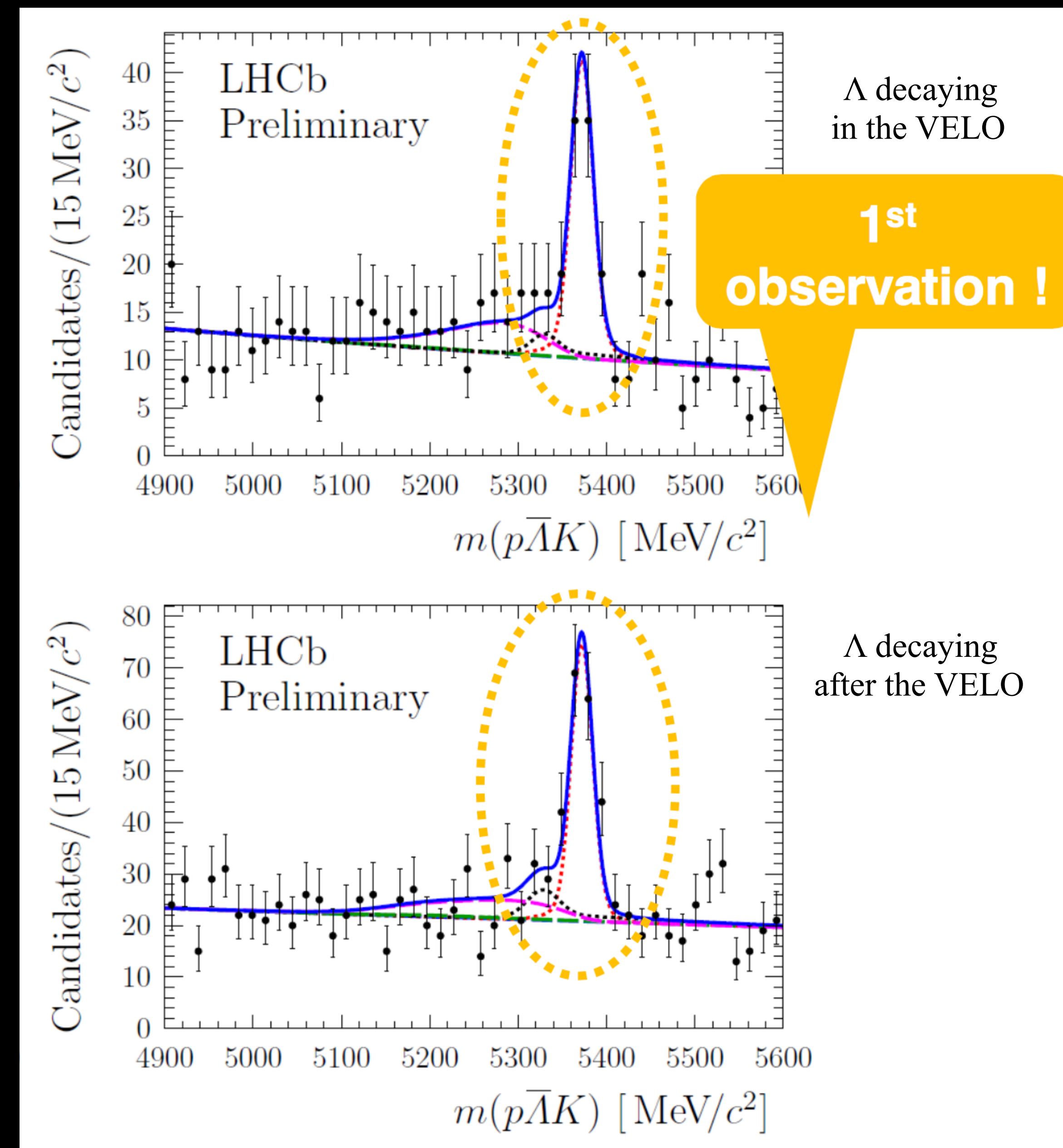
$B^+ \to p\bar{\Lambda}$, $B_s^0 \to p\bar{\Lambda}K^-$



4.1σ signal

$$\mathcal{B}(B^+ \to p\bar{\Lambda}) = (2.4\,^{+1.0}_{-0.8} \pm 0.3) \times 10^{-7}$$

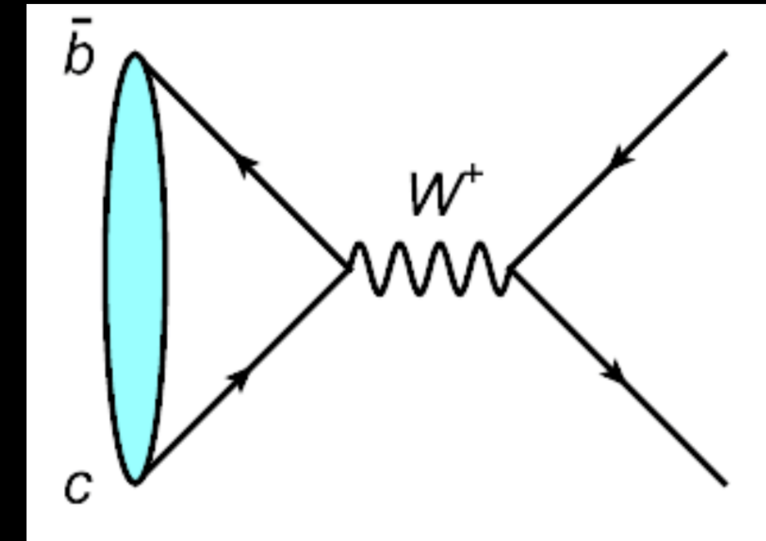


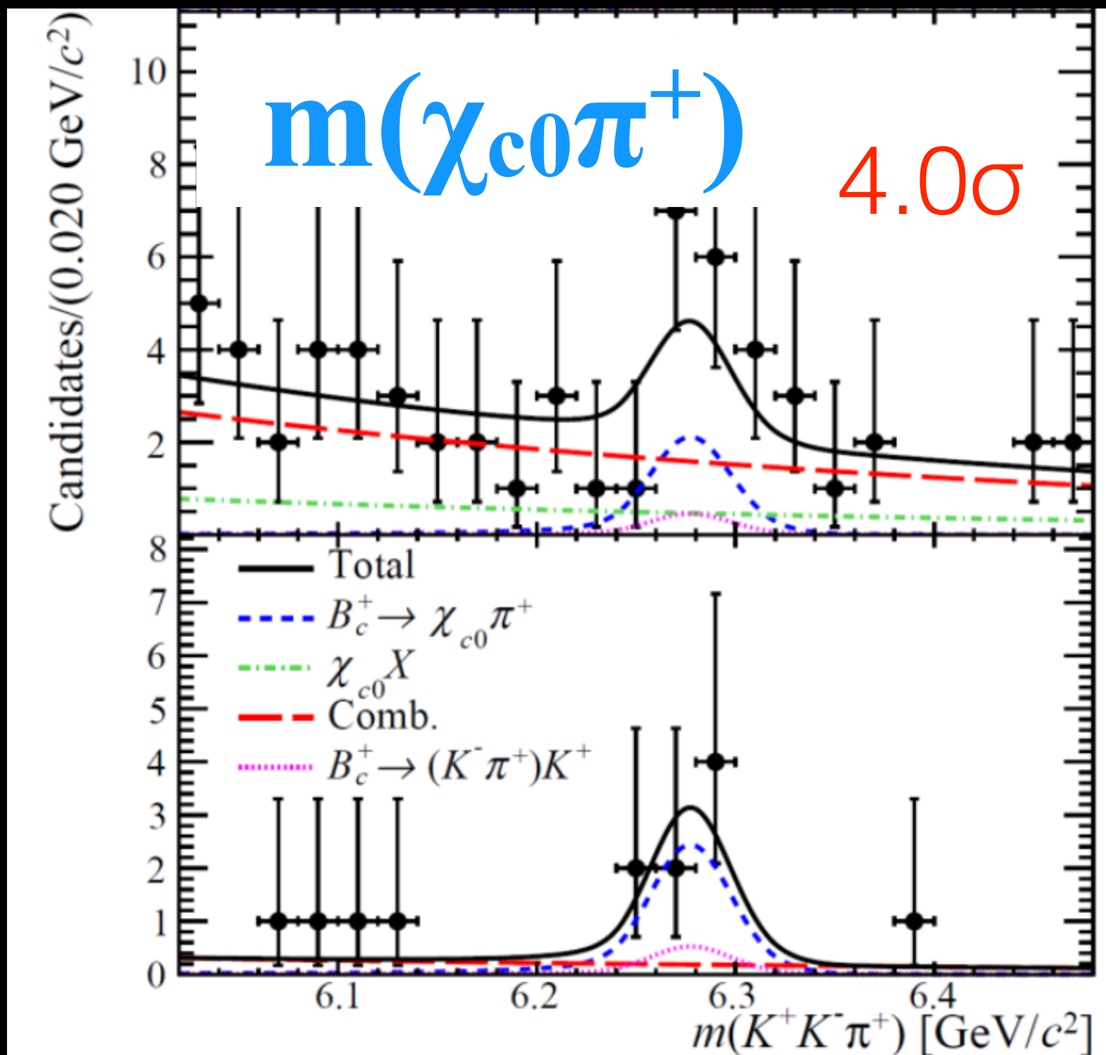
$$\mathcal{B}(B_s^0 \to p\bar{\Lambda}K^-) = \left[5.48^{+0.82}_{-0.80}\,(\text{stat}) \pm 0.60\,(\text{syst}) \pm 0.51(\mathcal{B}) \pm 0.32(f_s/f_d)\right] \times 10^{-6}$$

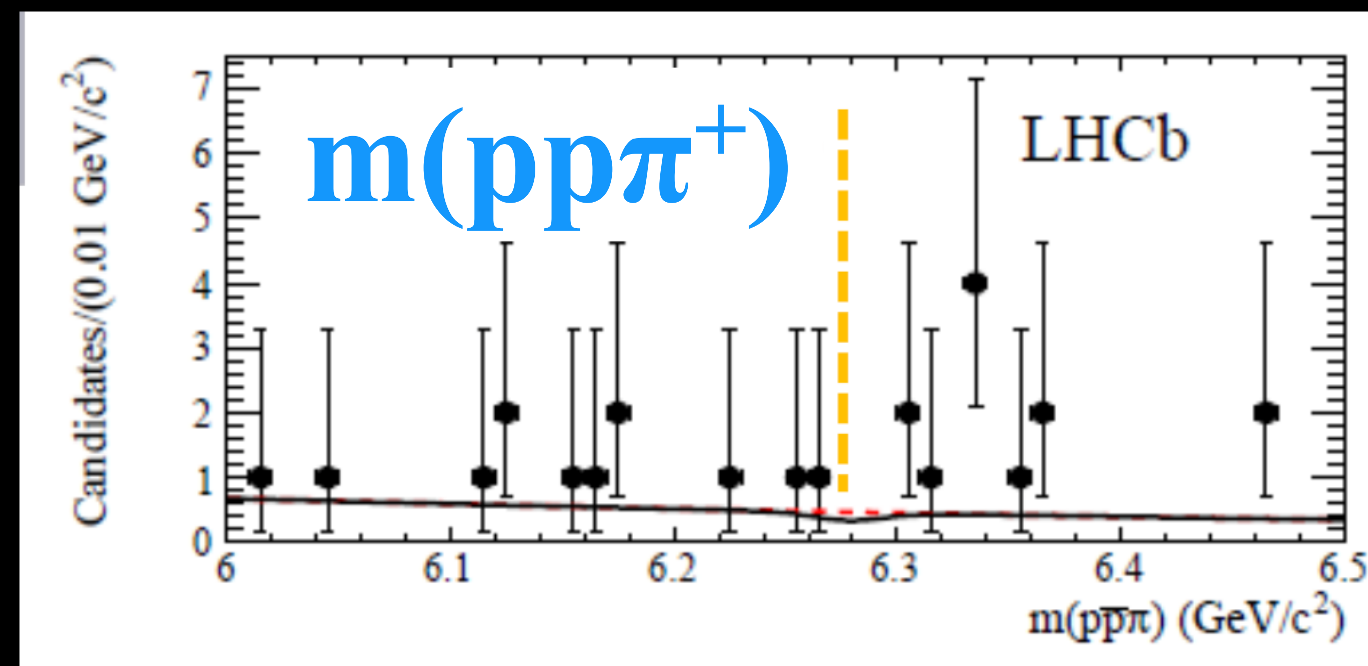
LHCb-PAPER-2016-048

Eduardo Rodrigues

$B_c^+ \to$charmless







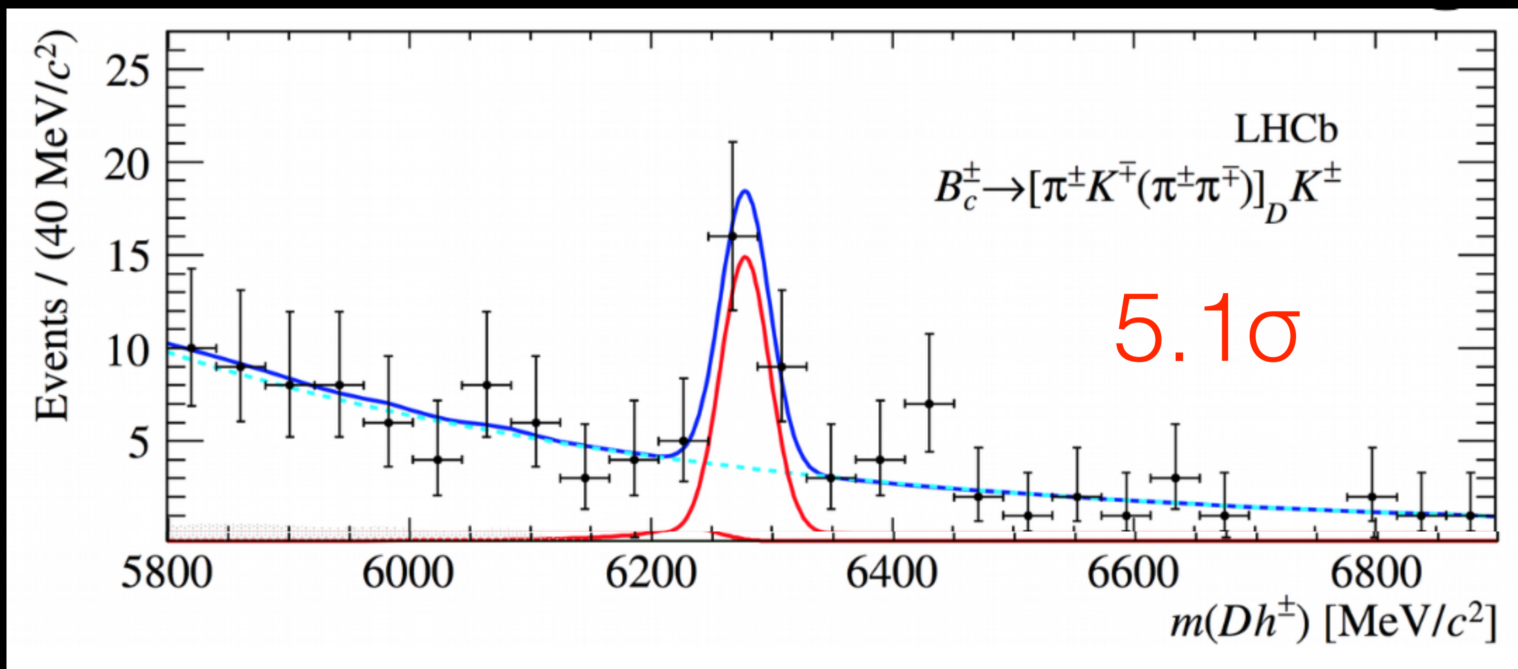
$$\frac{\sigma(B_c^+)}{\sigma(B^+)} \times \mathcal{B}(B_c^+ \to \chi_{c0}\pi^+) = (9.8^{+3.4}_{-3.0}(\text{stat}) \pm 0.8(\text{syst})) \times 10^{-6}$$

$$\frac{f_c}{f_u} \times \mathcal{B}(B_c^+ \to p\bar{p}\pi^+) < 3.6 \times 10^{-8}$$

arXiv:1607.06134

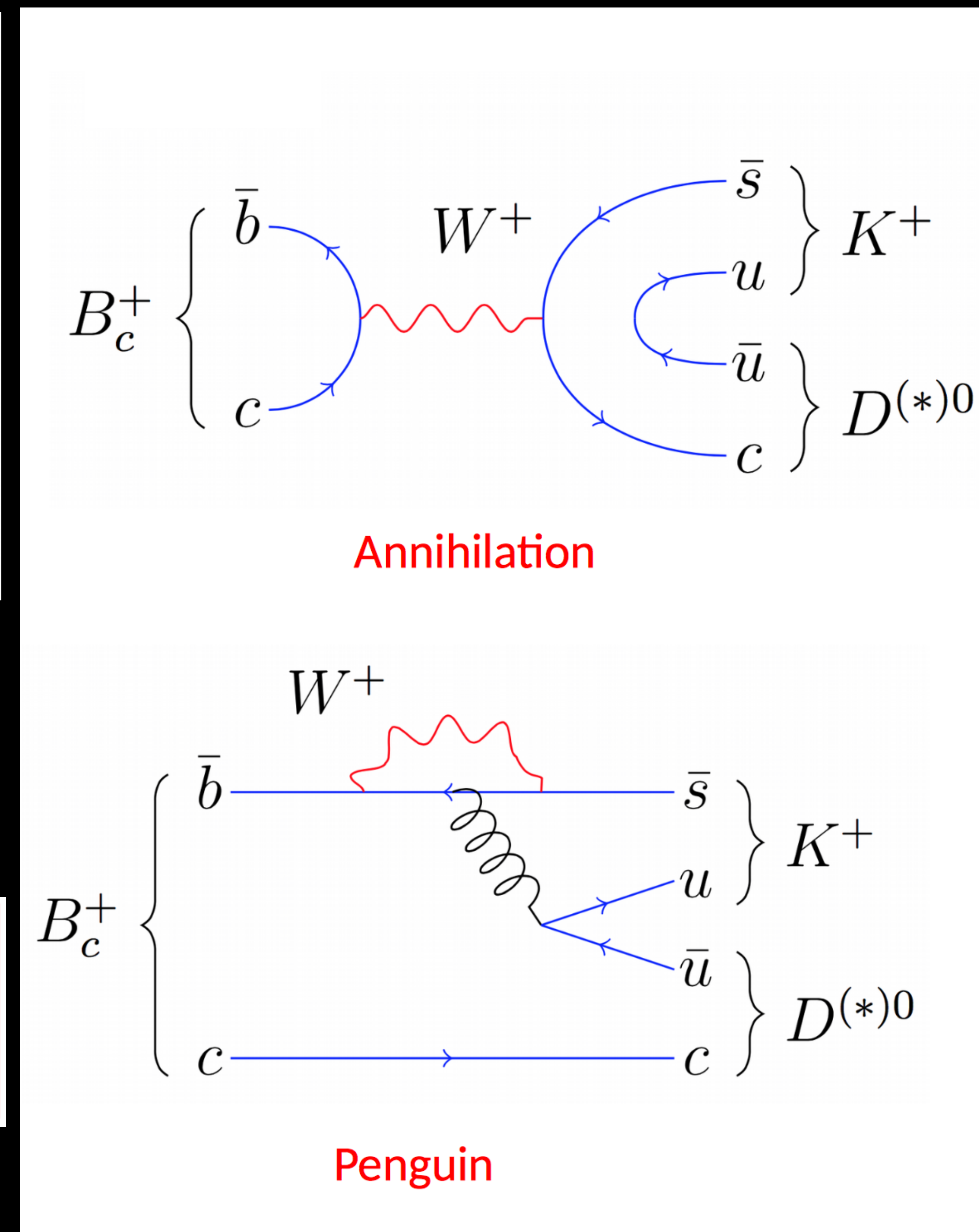
PLB 759 (2016) 313-321

Observation of $B_c^+ \to D^0 K^+$



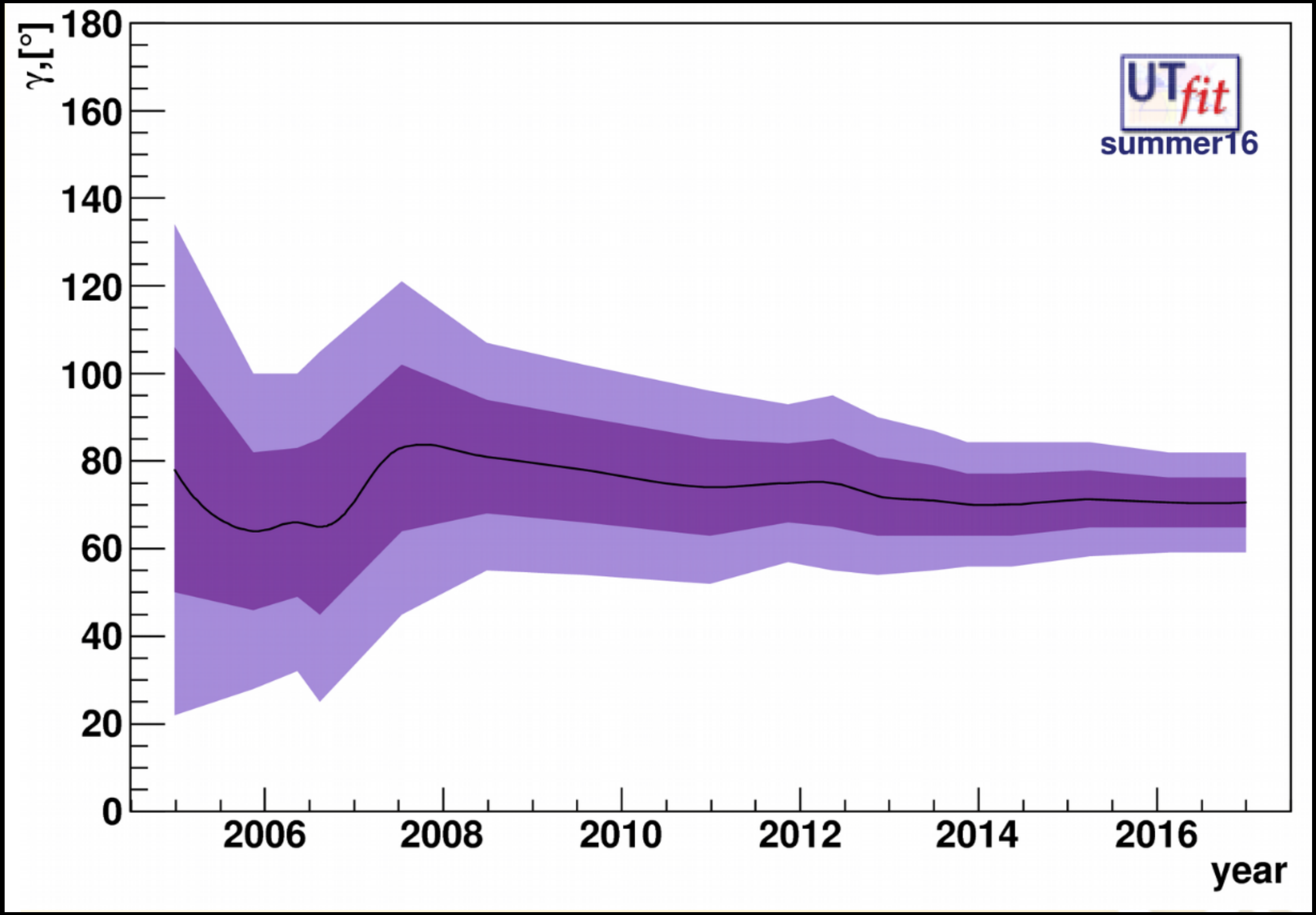
$$r_{B_c}^{DK} = \left(9.3^{+2.8}_{-2.5} \pm 0.6\right) \times 10^{-7} = \frac{f_c}{f_u} \times BR\left(B_c^+ \to D^{(*)0} h^+\right)$$

$$\frac{BR\left(B_c^+ \to D^0 K^+\right)}{BR\left(B_c^+ \to J/\psi \pi^+\right)} = 0.13 \pm 0.04 \pm 0.01 \pm 0.01$$



LHCb-PAPER-2016-058

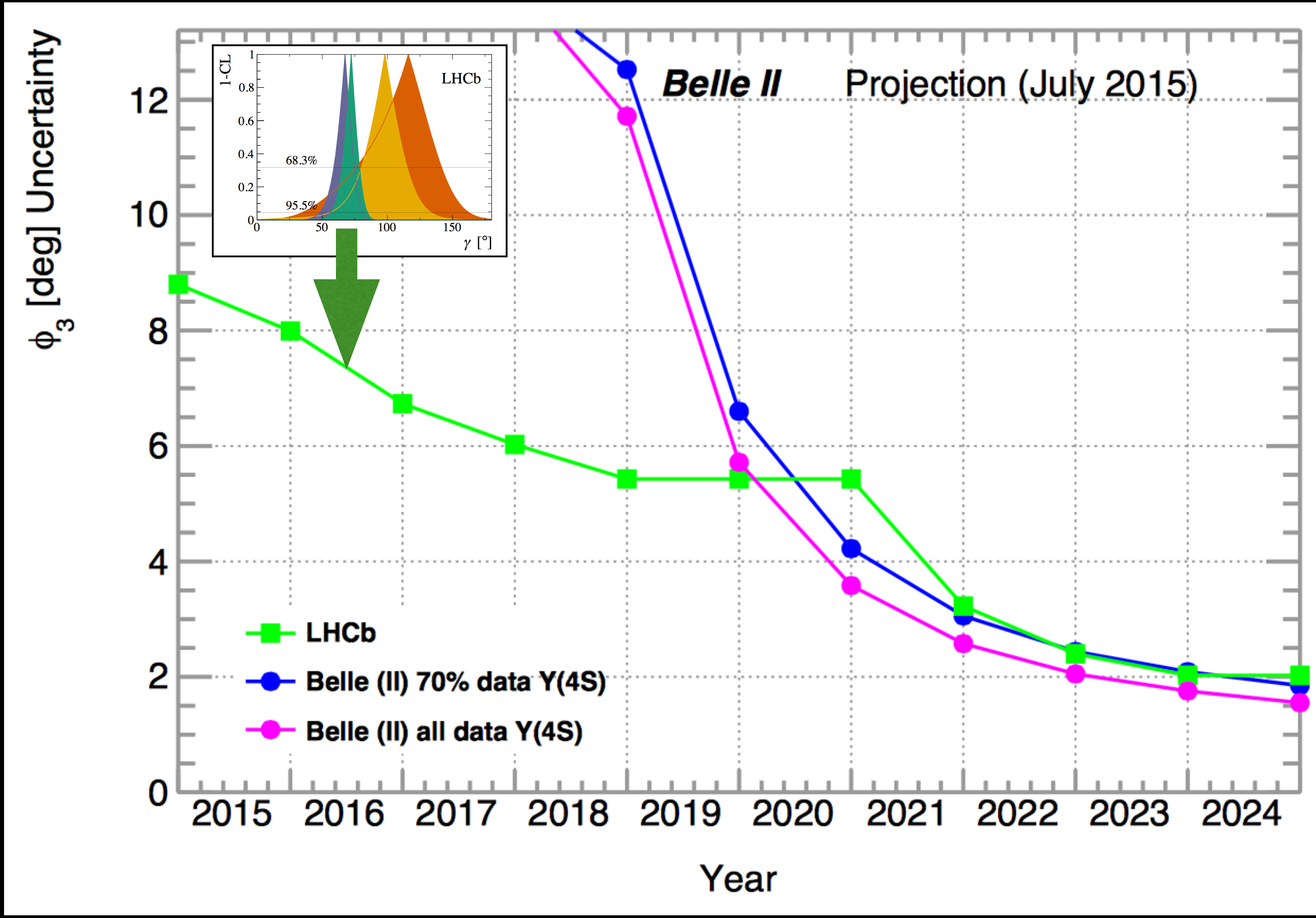
Prospects for 2020s



"After a decade of analyses and almost 50 papers published, the world average uncertainty has decreased by a factor 3"

Marcella Bona

γ/φ_3 projection



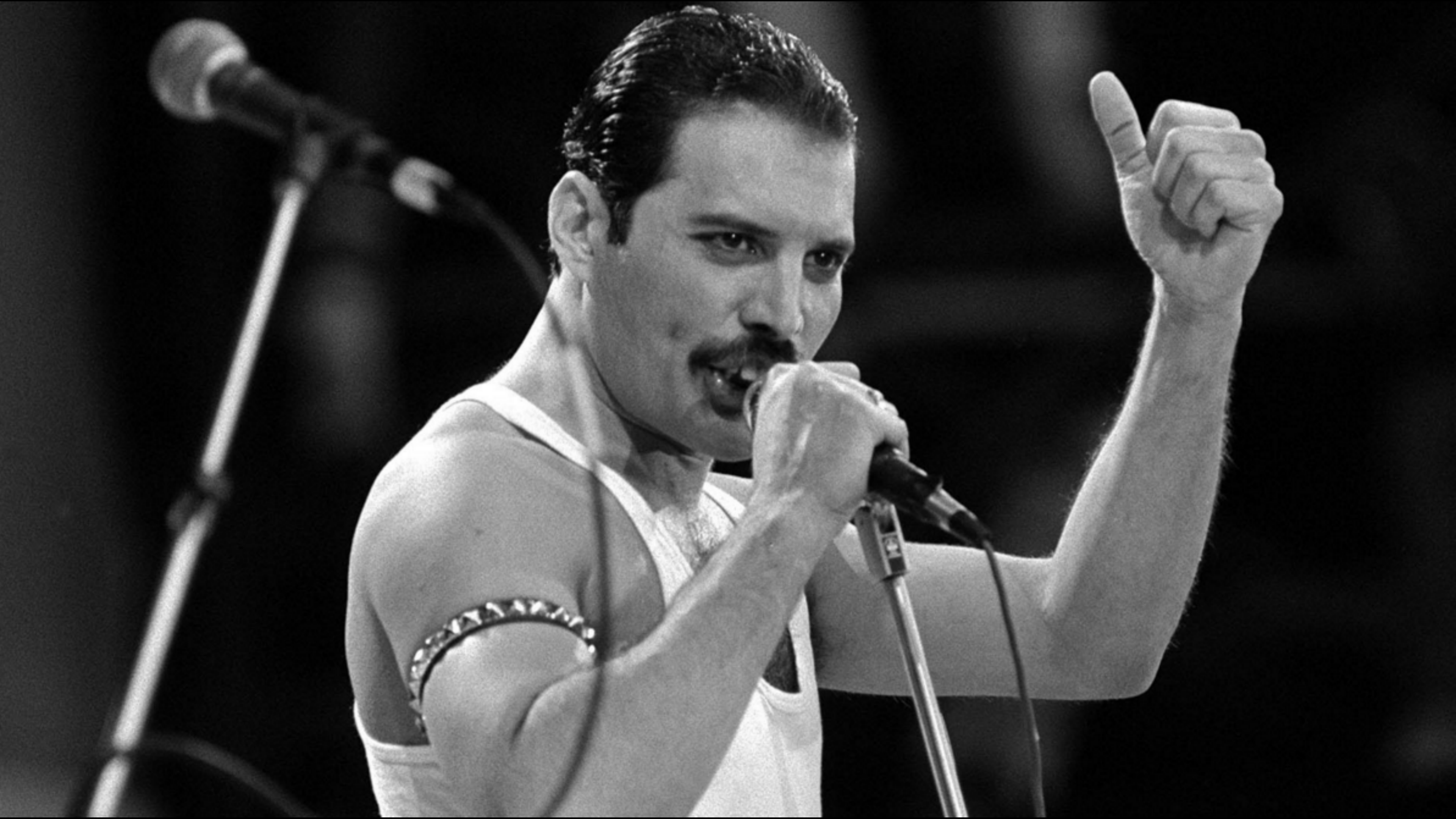
Daniel Červenkov

Towards a precise determination of $\gamma(\phi_3)$
[unfortunately painfully slow]

Amarjit Soni
HET, BNL
CKM -2014 (WG5); Vienna

Thanks : Tim Gershon, Matteo Rama

Soni (CKM2014)



I consider it a challenge before the whole human race
And I need to go on, and on, and on, and on
We are the champions, my friends

End