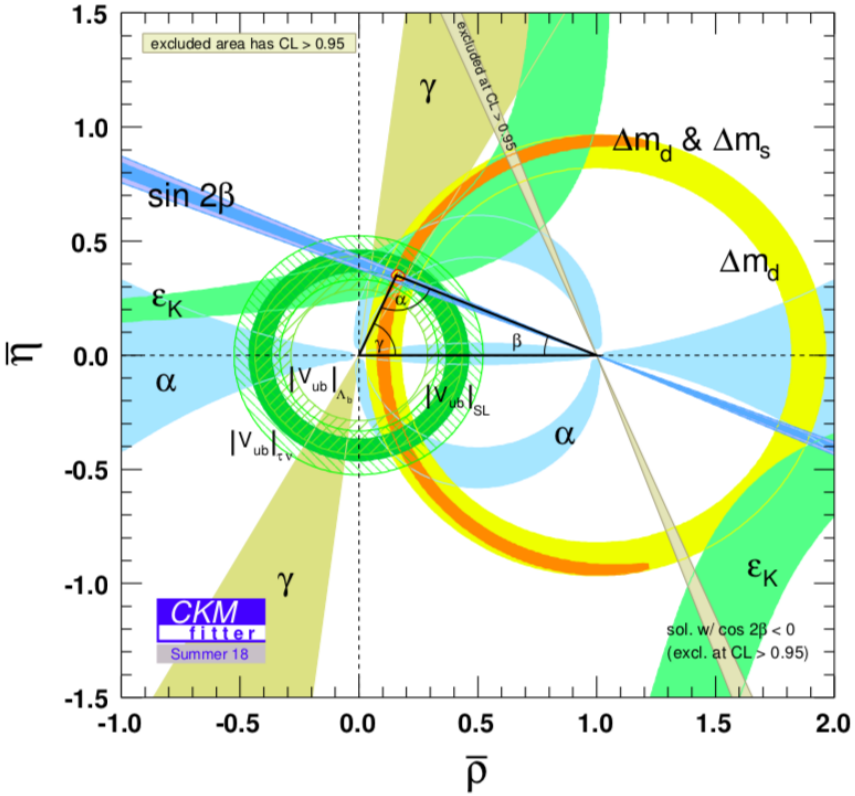
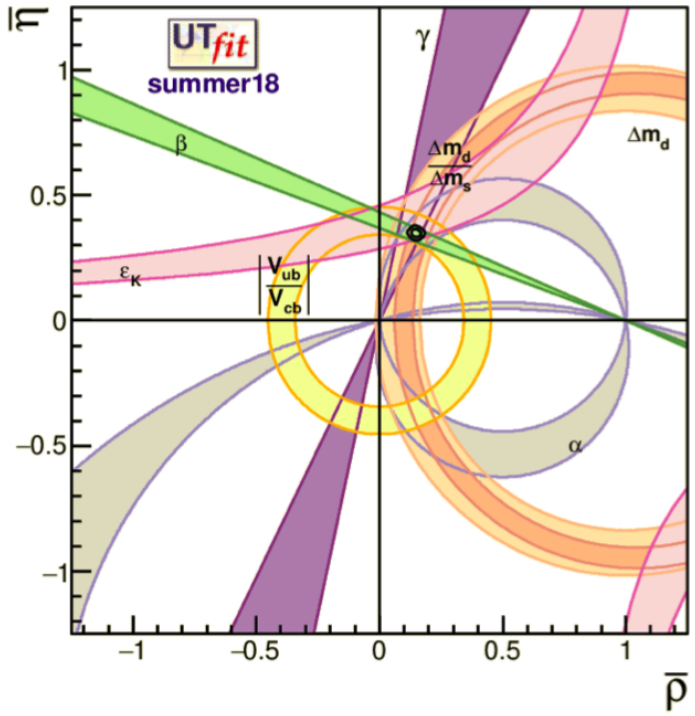
Summary of WG5

Keri Vos, Stefano Perazini and Marco Sevoir

J. Brod, A. Reis, Resmi PK, E. Gersabeck, V. Tisserand, B. Bhattacharya, E. Bertholet, P. Lu, P. Magalhaes, E. Ben-Haim, T. Huber, G. Sarpis, R. Jaarsma, B. Pal, T. Gershon, D. Fazzini, L. Vale Silva and M. Bona

Determination of γ from $B \to DK/D\pi$





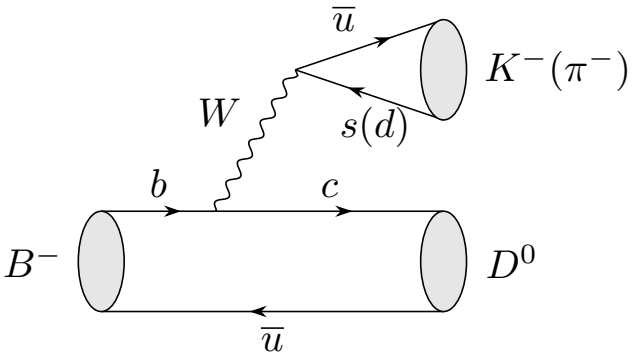
Talks by Marcella Bona and Luiz Vale Silva

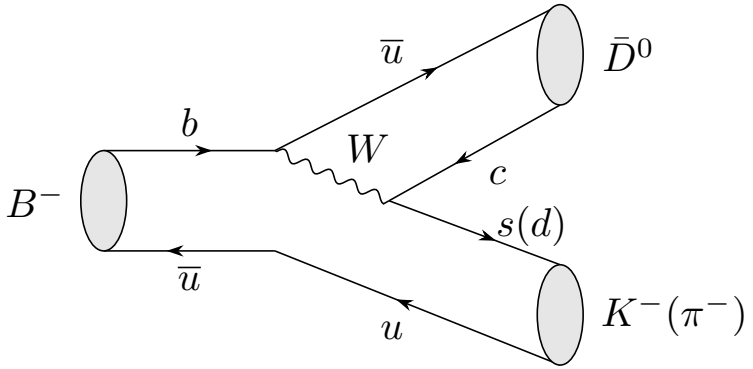
Determination of γ from $B \to DK, B \to D\pi$

Gronau, Wyler [1991]; Gronau, London [1991]; Atwood, Dunietz, Soni [1997] Giri, Grossman, Soffer, Zupan [2003]

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

Talk by Joachim Brod





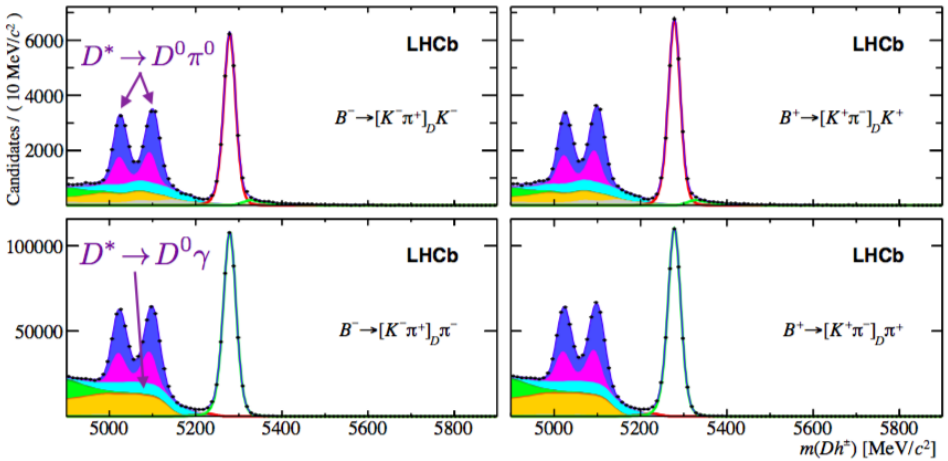
$\propto V_{cb}V_{us(d)}^*$ $\propto V_{ub}V_{cs(d)}^*$

- Important parameter: key input of the CKM
- Theoretically extremely clean (no penguin contributions)
  - Electroweak box corrections tiny Brod, Zupan [2013]; Brod [2014]

$$\delta\gamma^{DK}/\gamma \simeq \mathcal{O}(10^{-7}) \quad \delta\gamma^{D\pi}/\gamma \simeq \mathcal{O}(10^{-4})$$

A few highlights from $B \to Dh$ analyses [LHCb]

PLB 777 (2018) 16 Talk by Alberto Reis



Very nice analysis:

- Signals are the partially reconstructed $B \to D^* h$ decays
- Small mass difference between D^0 and D^* allows description of the mass shape

$$R_{CP} = 0.989 \pm 0.013 \pm 0.01$$

$$A_{CP} = 0.124 \pm 0.012 \pm 0.002$$

To be used in the combination of $\gamma \to$ relevant contribution!

A few highlights from $B \to Dh$ analyses [Belle(II)]

Talk by Resmi P K

- Full Belle data set of 711 fb^{-1}.
- GLW modes : $KK, \pi\pi, K^0_S\pi^0, K^0_S\eta$
- ADS mode : $K\pi$

GLW

- With the CP modes for $D^* \to D\pi^0, D\gamma$ decays combined,
  - $A_{CP+} = -0.14 \pm 0.10 \pm 0.01$
  - $A_{CP-} = +0.22 \pm 0.11 \pm 0.01$

ADS

- $R_{D^*K,D\pi^0} = [1.0^{+0.8}_{-0.7}(\text{stat})^{+0.1}_{-0.2}(\text{syst})]\times10^{-2}$
- $R_{D^*K,D\gamma} = [3.6^{+1.4}_{-1.2}(\text{stat}) \pm 0.2(\text{syst})]\times10^{-2}$
- To be published...

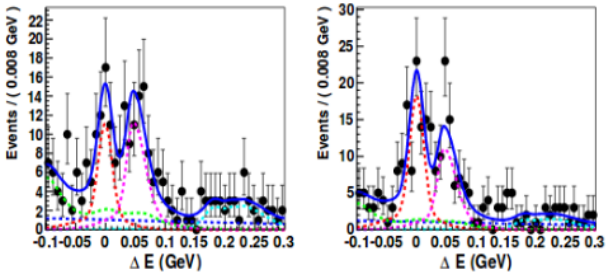
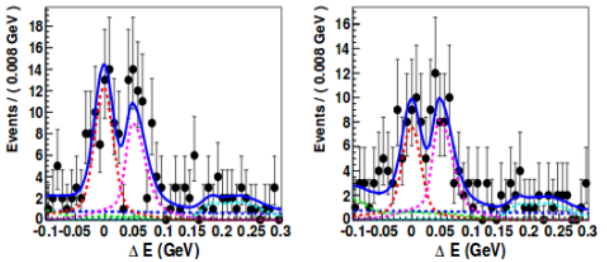


Figure : B^- and B^+ for D_{CP+}



- $D^{0*} \to D^0\gamma$ and $D^{0*} \to D^0\pi^0$
- also looking for unconventional modes in the future

Unconventional modes to measure γ [Belle(II)]

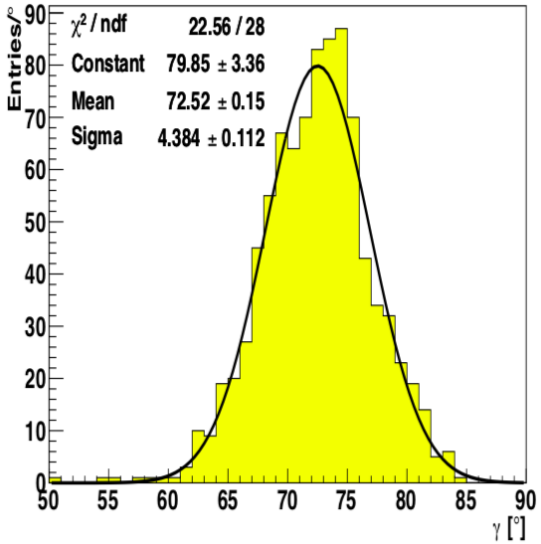
Talk by Resmi P K

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

- Relatively large branching fraction of 5.2%
- Interesting resonance substructures: $K_S\omega$ and $K^*\pi^+\pi^0$
- Binning around resonances in absence of amplitude model

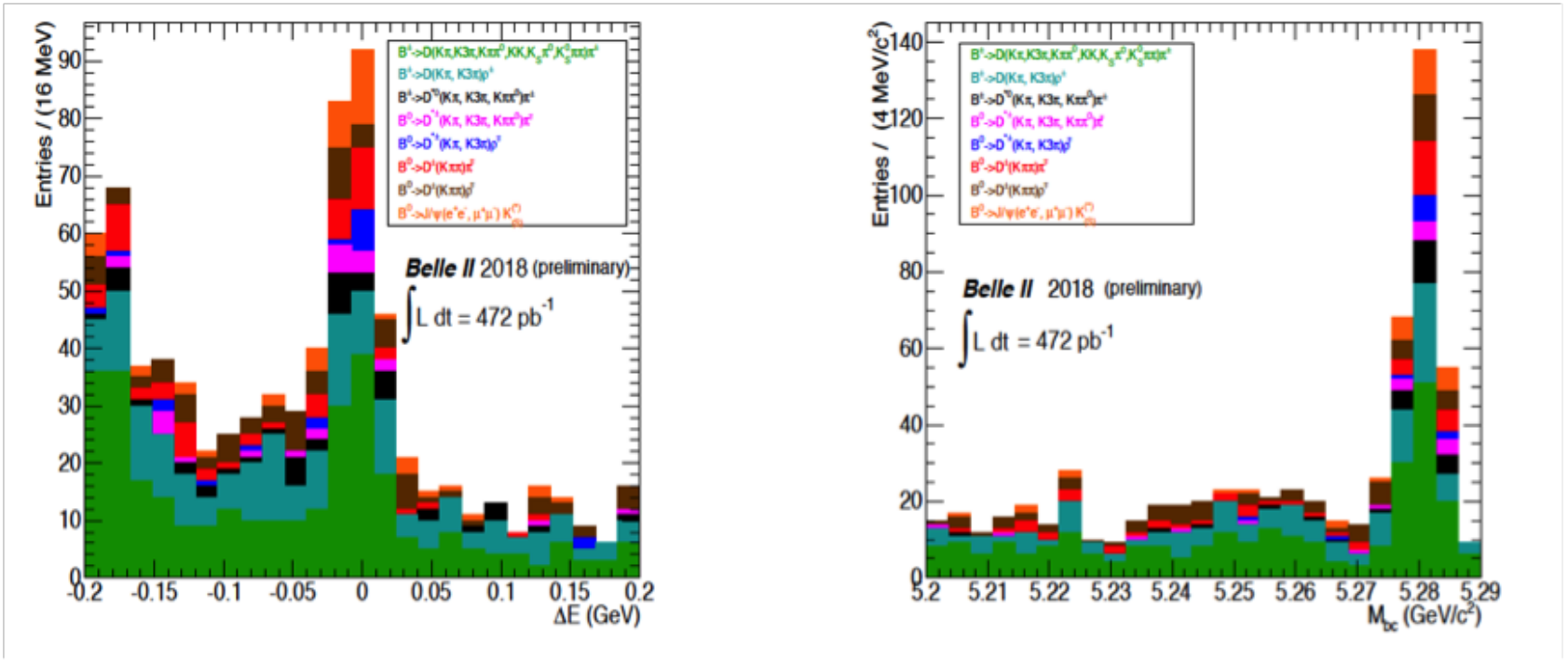
Estimated sensitivities

- $\gamma \sim 25^\circ$ with full Belle dataset
- $\gamma \sim 4.4^\circ$ with 50 ab^{-1} at Belle II



Rediscovering the B meson at Belle II

Talk by Resmi P K



- Total 245 B candidates were found

Unconventional modes to measure γ

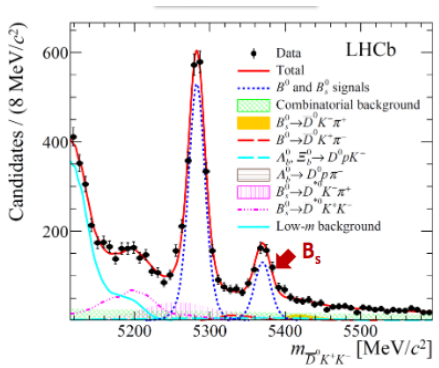
Talk by Vincent Tisserand

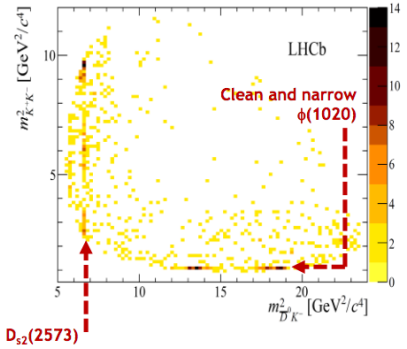
Very nice peak of $B_s \to D^0 K^+ K^-$

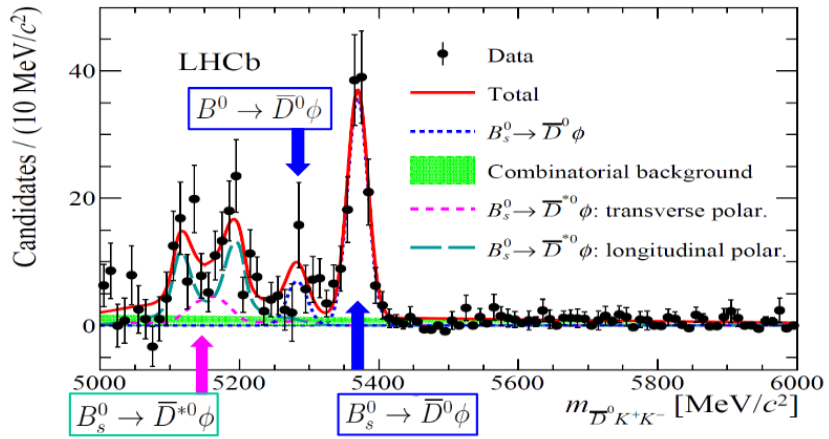
- First step to exploit $B_s \to D^0 \phi$ to measure γ
- Very promising PL253 (1991) 463, LHCb-PUB-2010-005

First observation of $B_s \to D^{(*)} \phi (> 7\sigma)$

- Exploitable to determine γ



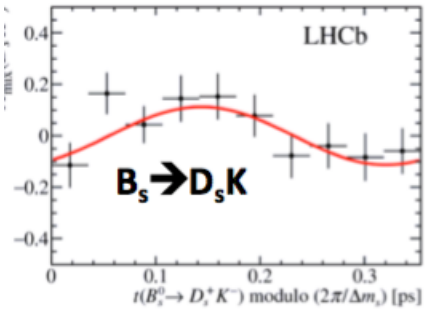




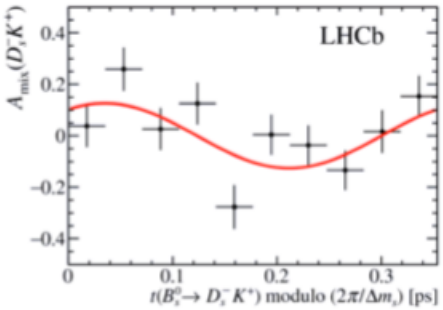
Other $B_{(s)} \to D_{(s)}h$ modes to measure γ

Talk by Tim Gershon

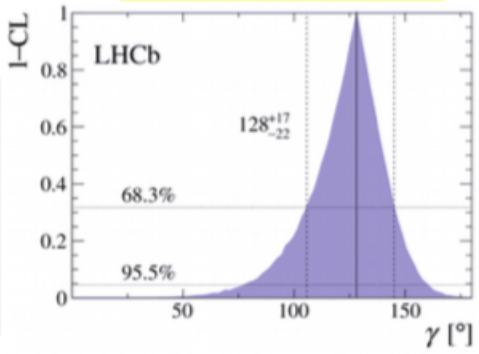
Tagged time-dependent analysis allows a very clean determination of $\gamma \pm 2\beta_{(s)}$



3.8σ CPV



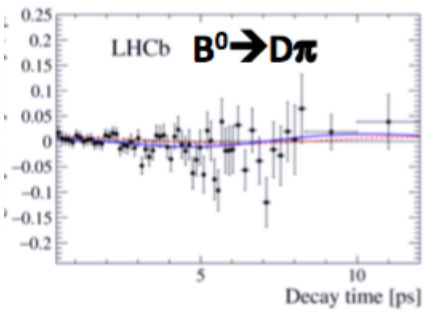
LHCb-PAPER-2017-047, 3 fb^{-1}
JHEP 03 (2018) 059

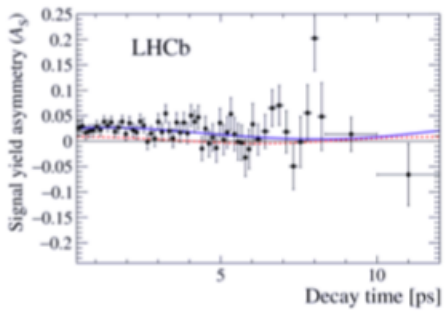


Only Run1 data (3/fb)

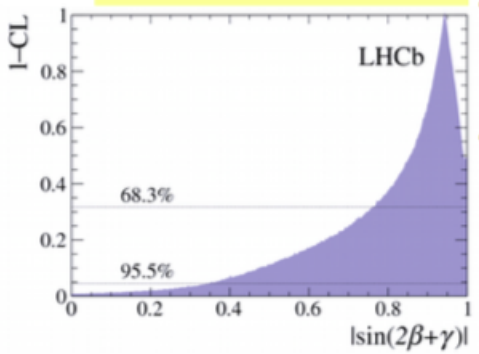
$$\gamma = (128\,^{+17}_{-22})^\circ$$

Using -2β_s measured from $B_s \to J/\psi\phi$





LHCb-PAPER-2018-009, 3 fb^{-1}
JHEP 06 (2018) 084



Only Run1 data (3/fb)

- Needed to assume U-spin:
  - Assumed up to 20% U-spin breaking
- Might become limiting syst. in the future

se:

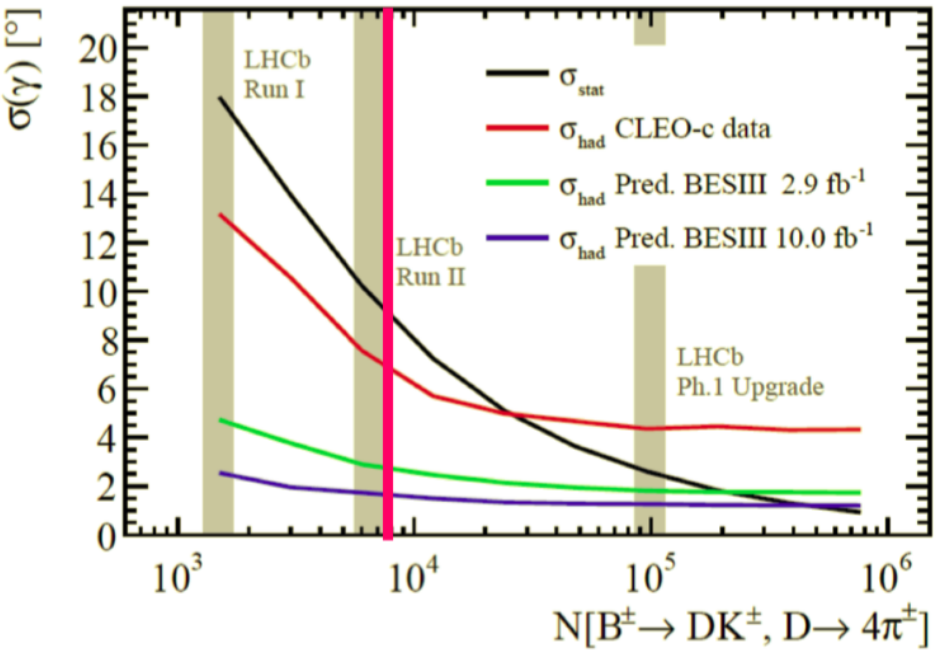
$$r_{D\pi} = \tan\theta_c \frac{f_{D^+}}{f_{D_s}} \sqrt{\frac{\mathcal{B}(B^0 \to D_s^+\pi^-)}{\mathcal{B}(B^0 \to D^-\pi^+)}},$$
$$= 0.0182 \pm 0.0012 \pm 0.0036$$

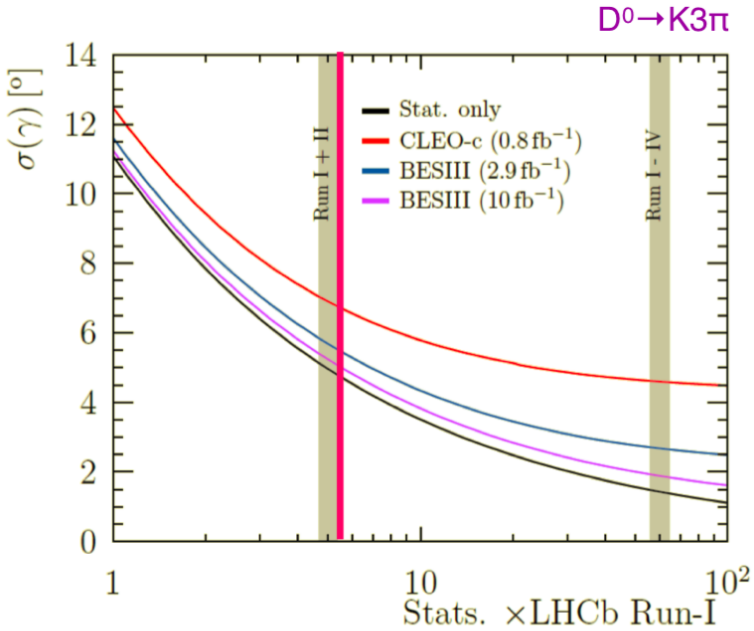
20% SU(3)-breaking uncertainty

Importance of BES III input

Talk by Eva Gersabeck

- Crucial inputs from charm factories for the hadronic parameters
- Most precise determination of γ from $B \to D(K_S hh)K$ is $\mathcal{O}(10^\circ)$
- Uncertainty 4° (strong-phase inputs) versus 2° (exp)



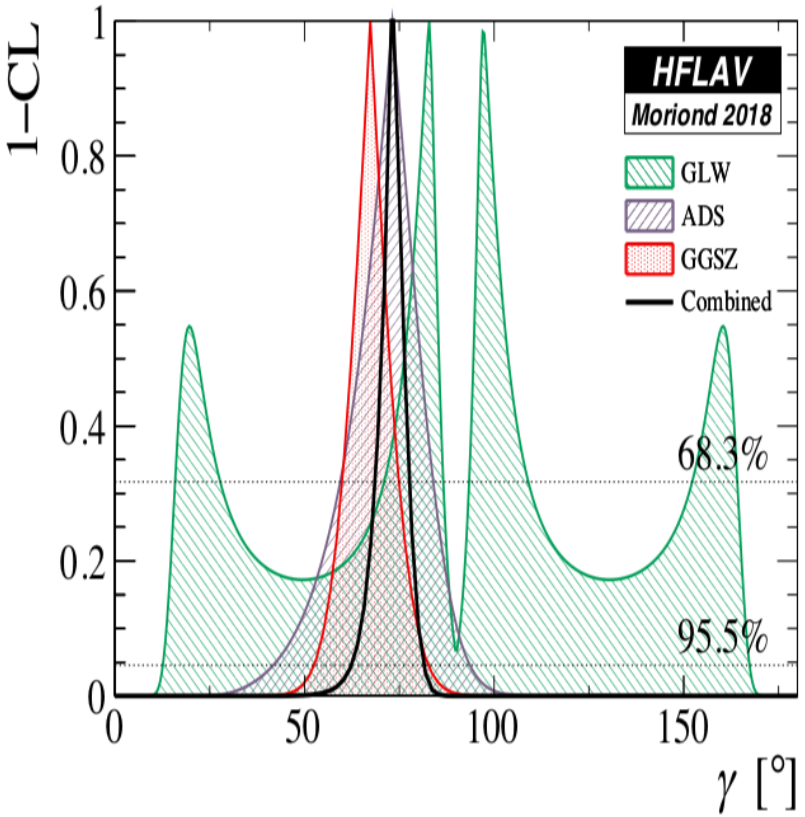


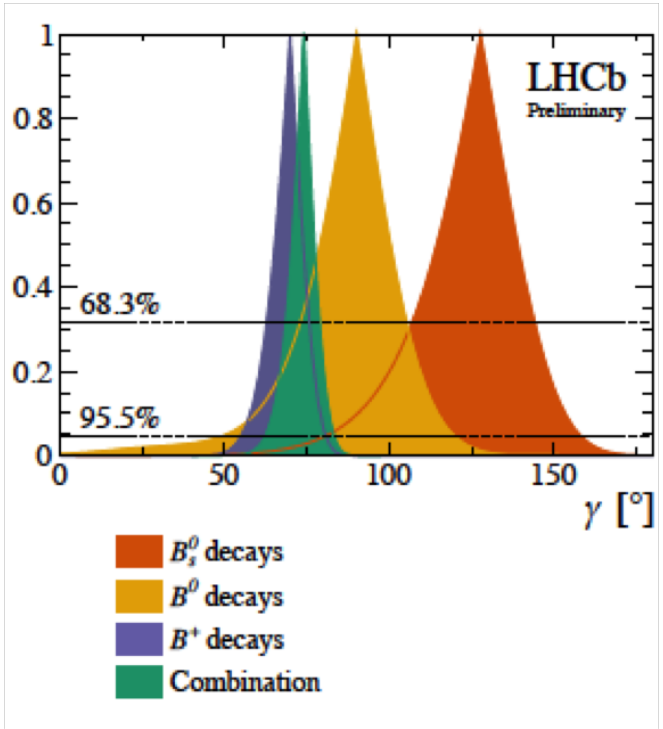
G.Wilkinson BESIII-LHCb joint workshop 2018

γ entering in the precision era

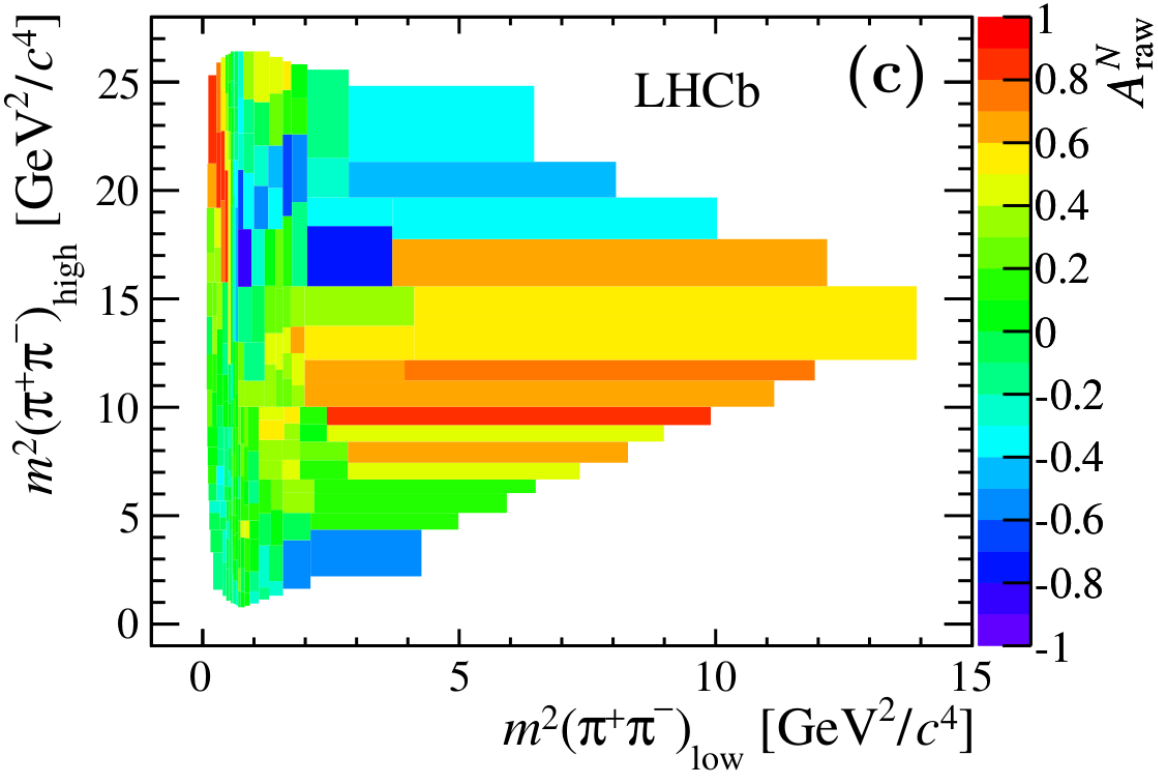
Talk by Alberto Reis

$$\gamma = (74^{+5.0}_{-5.8})^\circ$$





γ from loops



Tree versus loop determination of γ

Talk by Bhubanjyoti Bhattacharya

Two-body (tree-level)

- $B \to DK, B \to D\pi$
- Interference between $D^0, \bar{D}^0, D_{\mathrm{CP}}$
- Methods: GLW, ADS, GSZ
- n parameters, m observables
- Theoretically very clean!

Three-body (loop-level)

- Charmless $B \to hhh$ $(h = \pi, K)$
- Find scenarios with more observables than parameters
- Use $SU(3)$ symmetry
  - Diagrammatic approach
  - Dynamical assumptions
  - How clean is it?

Extracting γ using U-spin symmetry

Bhattacharya, Imbeault, London [2013]; Bhattacharya, London [2015]

Talk by Bhubanjyoti Bhattacharya

a, b, c, d hadronic parameters

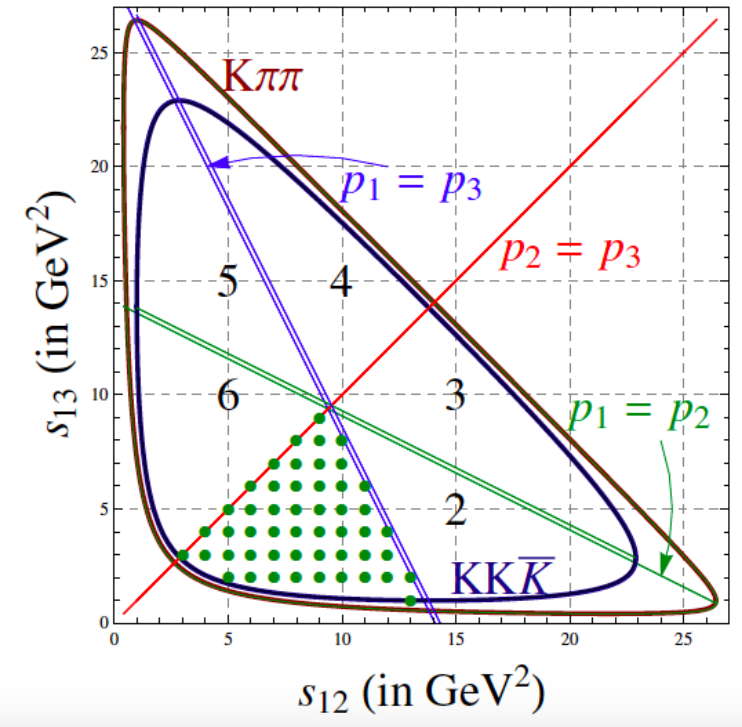
$$A(B^0 \to K^0 K^0 \bar{K}^0)_{\text{FS}} = f_{SU(3)}\, a$$
$$\sqrt{2}A(B^0 \to K^+ K^0 K^-)_{\text{FS}} = f_{SU(3)}(-ce^{i\gamma} - a + \kappa b)$$
$$2A(B^0 \to K^+ \pi^0 \pi^-)_{\text{FS}} = be^{i\gamma} - \kappa c$$
$$\sqrt{2}A(B^0 \to K^0 \pi^+ \pi^-)_{\text{FS}} = -de^{i\gamma} - a + \kappa d$$
$$\sqrt{2}A(B^+ \to K^+ \pi^+ \pi^-)_{\text{FS}} = -ce^{i\gamma} - a + \kappa b$$

- Treat hadronic parameters as observables (related by $SU(3)$)
- Single parameter to account for $SU(3)$-breaking
- Construct observables braching ratio, direct ACP and indirect ACP

11 parameters and 13 observables $\to$ extract γ

Extracting γ using U-spin symmetry

Talk by Bhubanjyoti Bhattacharya & Emilie Bertholet



- Fully symmetric DP
- 6 regions containing the same information
- Kinematic boundaries of the modes different $\rightarrow$ limited by the smallest DP

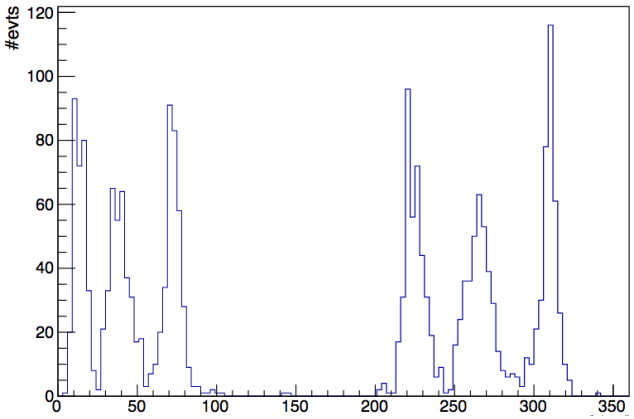
Several points in the DP

- Improve the validity of $SU(3)$ assumption
- Improve statistical uncertainty

Flavour $SU(3)$ symmetry is on average conserved

γ from charmless three-body decays

Talk by Emilie Bertholet



$$\gamma_1 = 12.9^\circ {}^{+8.4^\circ}_{-4.3^\circ} (\text{stat.}) \pm 1.3^\circ (\text{syst.})$$

$$\gamma_2 = 36.6^\circ {}^{+6.6^\circ}_{-6.1^\circ} (\text{stat.}) \pm 2.6^\circ (\text{syst.})$$

$$\gamma_3 = 68.9^\circ {}^{+8.6^\circ}_{-8.6^\circ} (\text{stat.}) \pm 2.4^\circ (\text{syst.})$$

$$\gamma_4 = 223.2^\circ {}^{+10.9^\circ}_{-7.5^\circ} (\text{stat.}) \pm 1.0^\circ (\text{syst.})$$

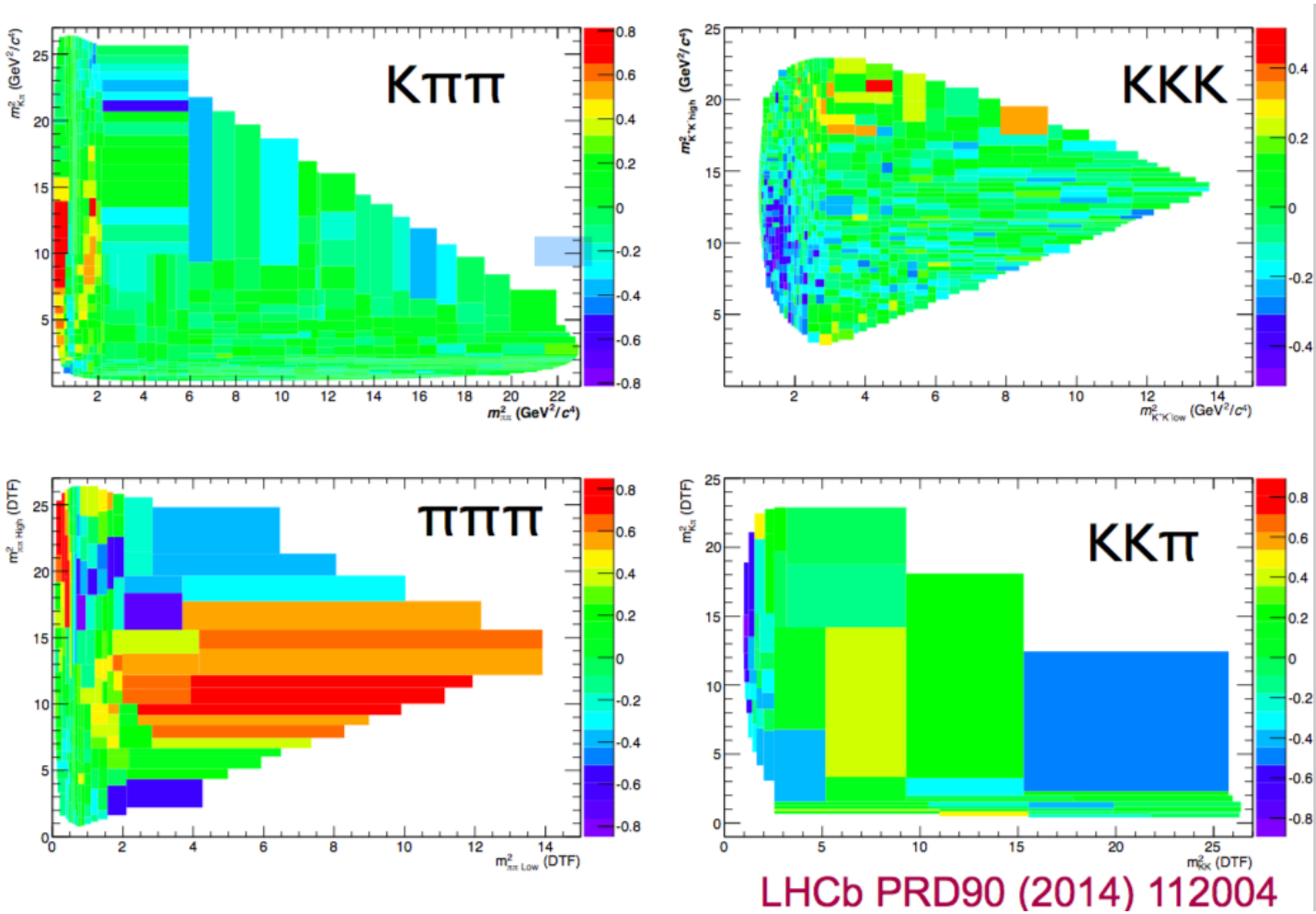
$$\gamma_5 = 226.4^\circ {}^{+9.2^\circ}_{-10.8^\circ} (\text{stat.}) \pm 1.9^\circ (\text{syst.})$$

$$\gamma_6 = 307.5^\circ {}^{+6.9^\circ}_{-8.1^\circ} (\text{stat.}) \pm 1.1^\circ (\text{syst.})$$

- Using Babar results $\rightarrow$ statistical error dominates

Paper in preparation!

CP violation in multibody decays

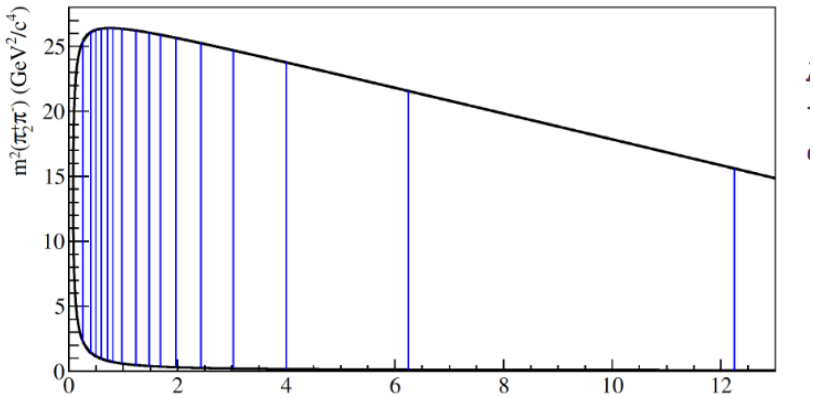


Multibody decays at LHCb

Talk by Alberto Reis

Full exploitation requires amplitude analysis

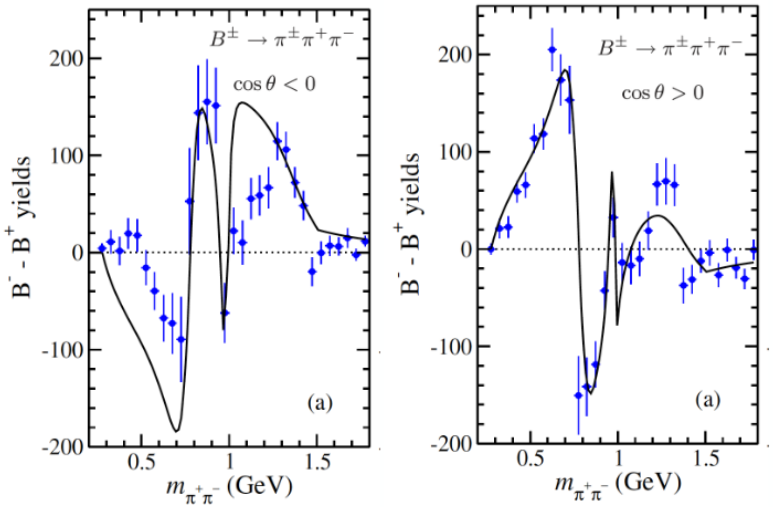
- Modelling of non-resonant part challenging
- Three different approaches



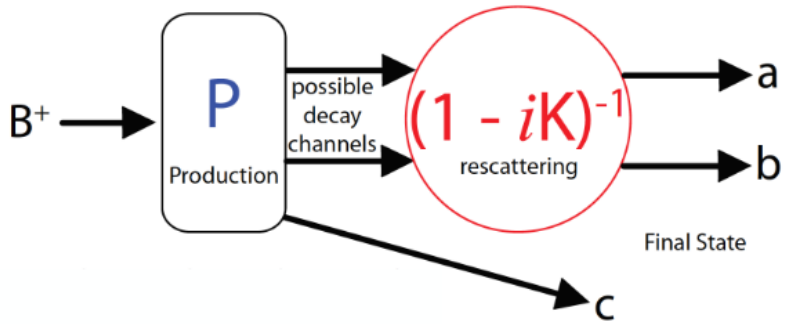
Quasi Model Independent

Isobar + NR rescattering

Formalism tested with LHCb data on $B^{\pm} \to \pi^-\pi^+\pi^{\pm}$ using a simple model: $\rho(770)^0 + f_0(980) + NR$



K-matrix



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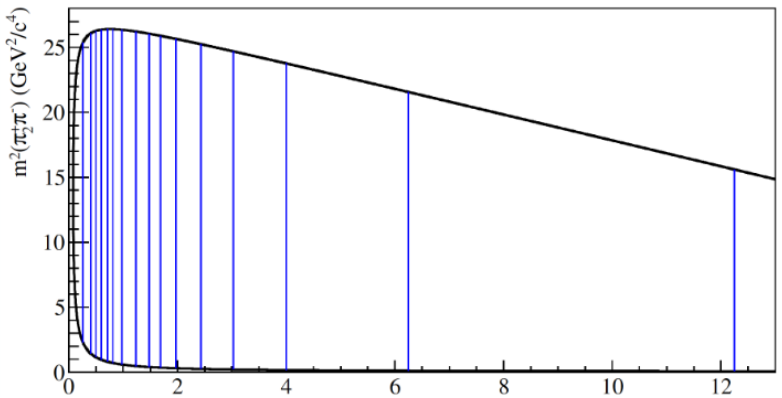

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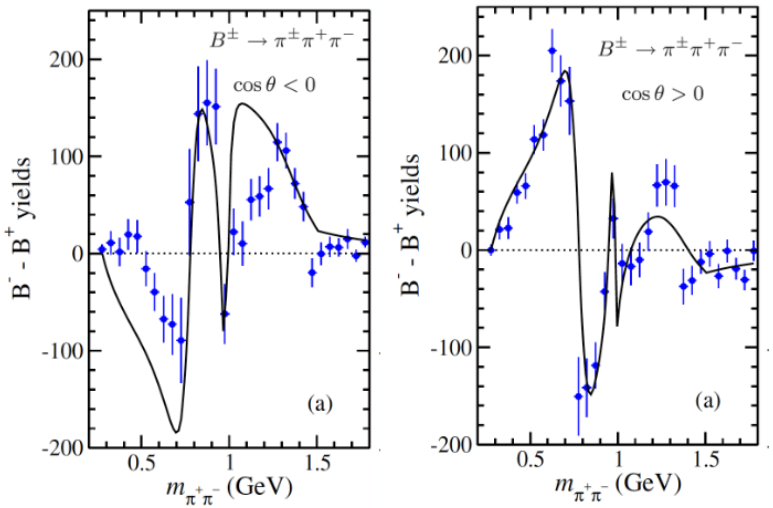
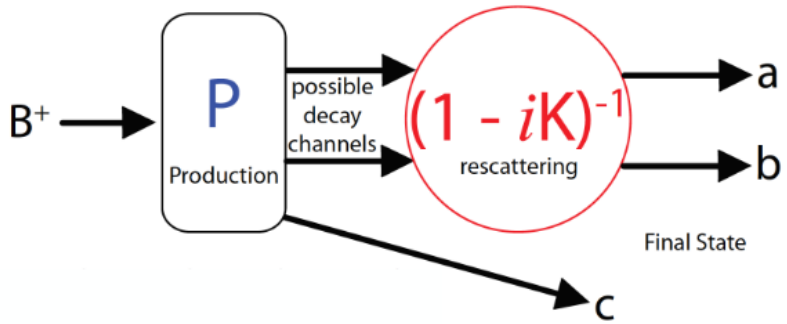


K-matrix

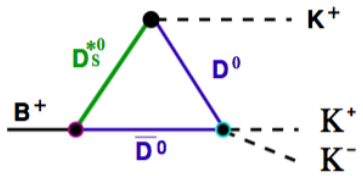


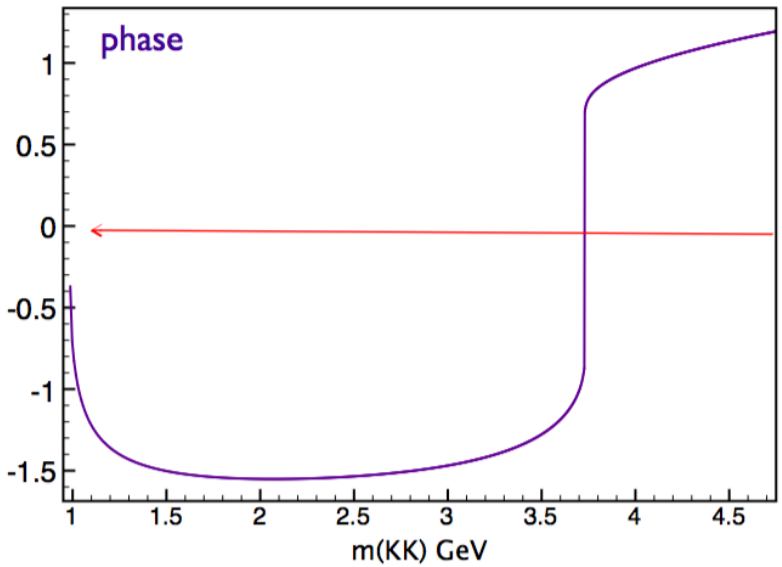
Stay Tuned!!

Hadronic Triangle Final-State-Interactions

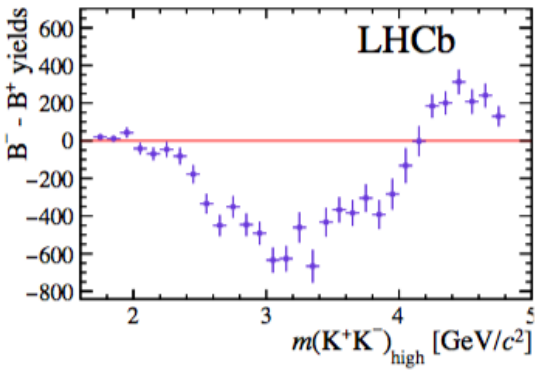
PLB 789 (2018) 357, arXiv:1808.02945 Talk by Patricia Magalhaes

- Rescattering $D^0\bar{D}^0 \to K^+K^-$ plays a major role
  - charm intermediate processes give strong phase
- Final-state-interactions provide an additional strong phase





Interesting applications for B_c

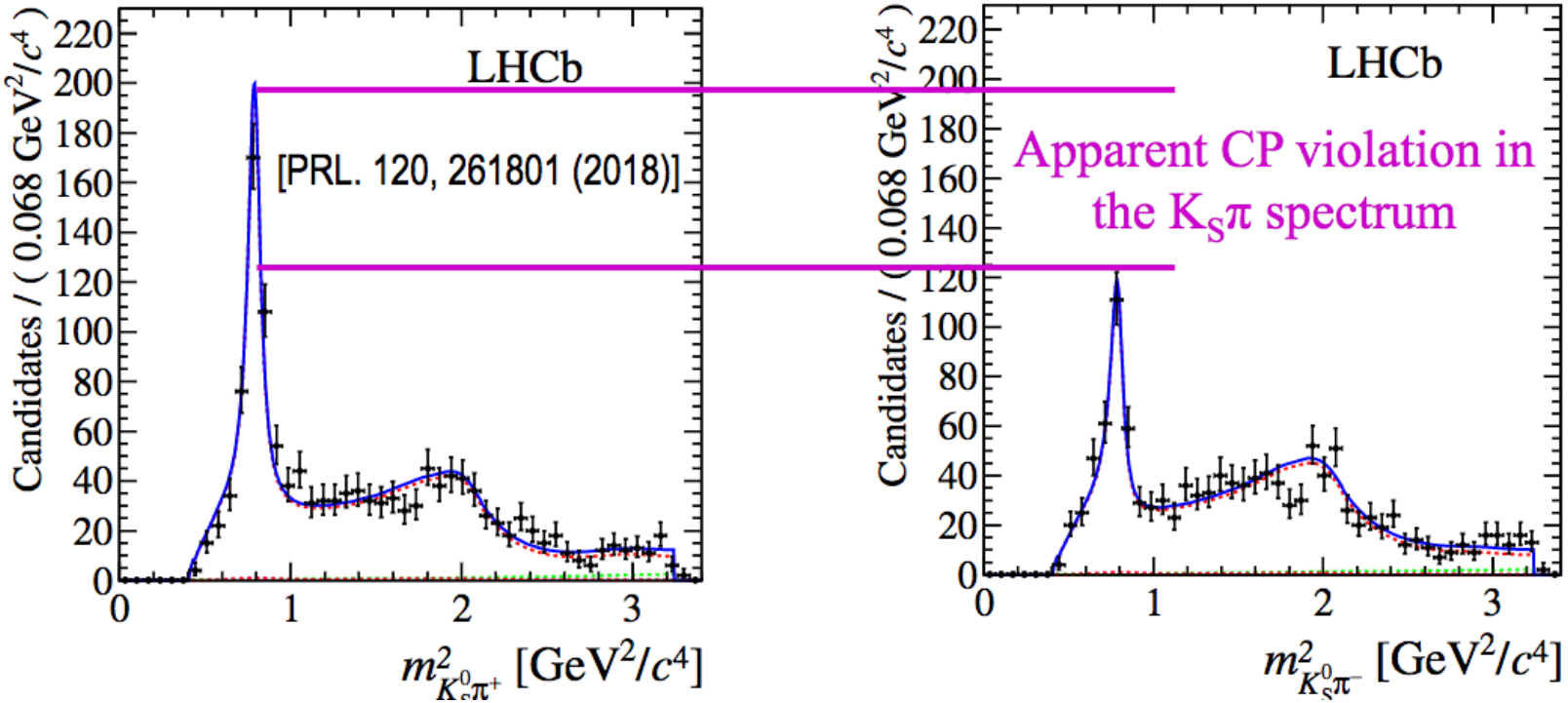


Strong phase shift can change CP signal!

Charmless multibody decays at LHCb

Talk by Eli Ben-Haim

Amplitude analysis of $B_s^0 \to K_S\pi^+\pi^-$ PRL 120 (2018) 261801



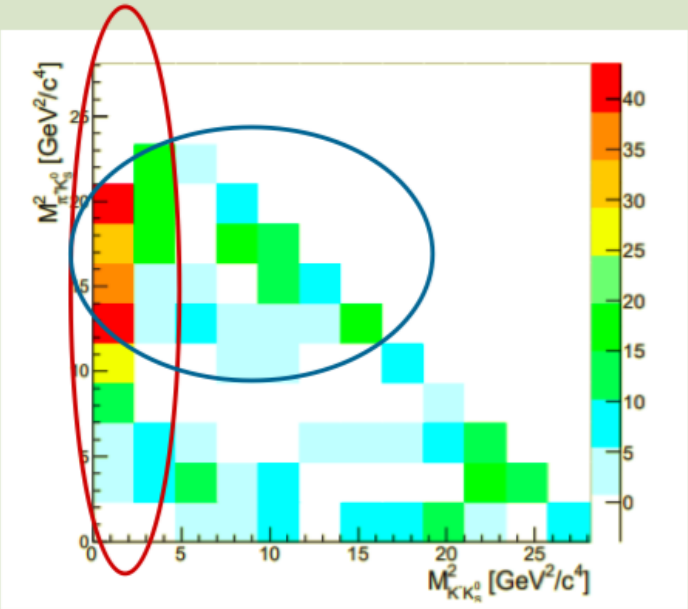
First observation of CP violation in $B^0 \to K^*(892)\pi$ with 6σ

$$A_{CP}(K^*(892)^-\pi^+) = -0.308 \pm 0.060(\text{stat.}) \pm 0.001(\text{syst.}) \pm 0.012(\text{model})$$

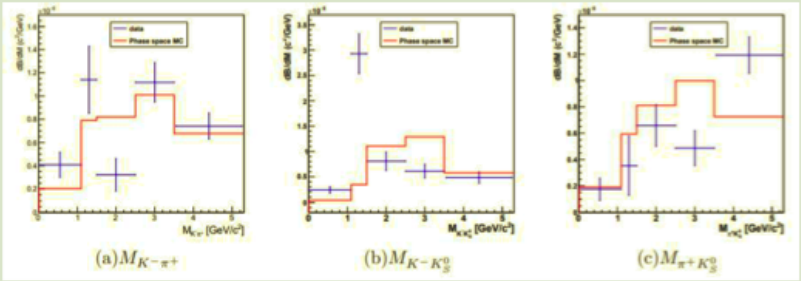
Charmless multibody decays at Belle

Talk by Peicheng Lu

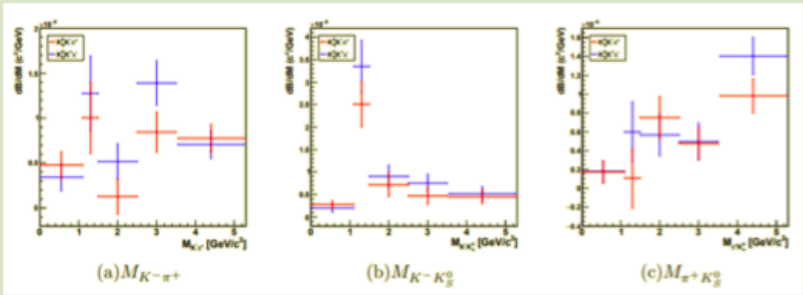
$\bar{B}^0(B^0) \to K^0_S K^{\mp} \pi^{\pm}$



Background-subtracted Dalitz plot



Differential branching fraction as a function
Histogram: 3-body phase space MC
Cross: data point



Differential branching fraction as functions
$K^0_S K^- \pi^+$
$K^0_S K^+ \pi^-$

Exciting prospects for Belle II

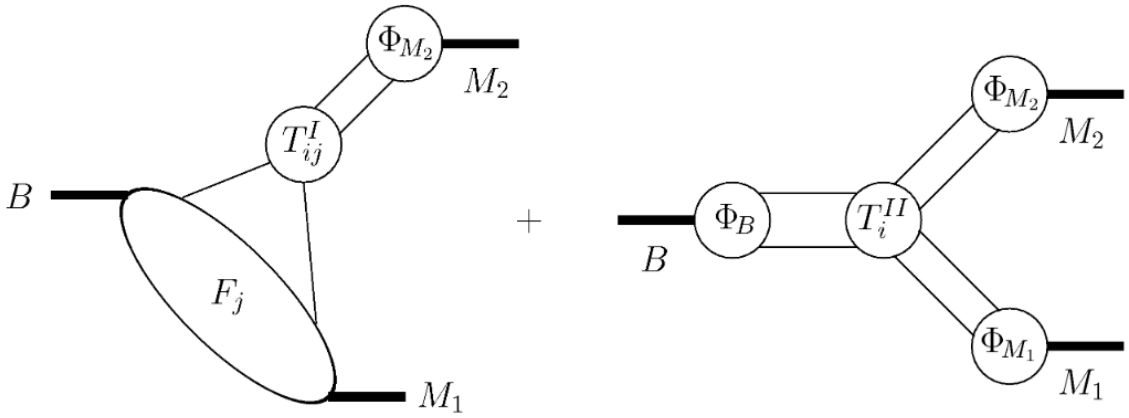
CP violation in charmless two-body B decays

QCD Factorization in two-body decays

Talk by Tobias Huber

Beneke, Buchalla, Neubert, Sachrajda [1999]; Beneke, Neubert [2003]

At leading order in the heavy-quark expansion (Λ/m_b)



Hard scattering kernels $T^{I,II}$ perturbatively calculable

$$\langle M_1 M_2|\mathcal{O}_i|\bar{B}\rangle = F^{B\to M_1}\int du\, T_i^I(u)\Phi_{M_2}(u) + \int d\omega\, du\, dv\, T_i^{II}\phi_B(\omega)\Phi_{M_1}(u)\Phi_{M_2}(v)$$

Form factors and LCDAs universal non-perturbative objects

- Vertex corrections $T^I = 1 + \mathcal{O}(\alpha_s/\pi)$
- Spectator scattering $T^{II} = \mathcal{O}(\alpha_s)$ and real

NNLO penguin contractions of current-current operators computed Beneke, Bell, Huber, Li $\to$ In progress

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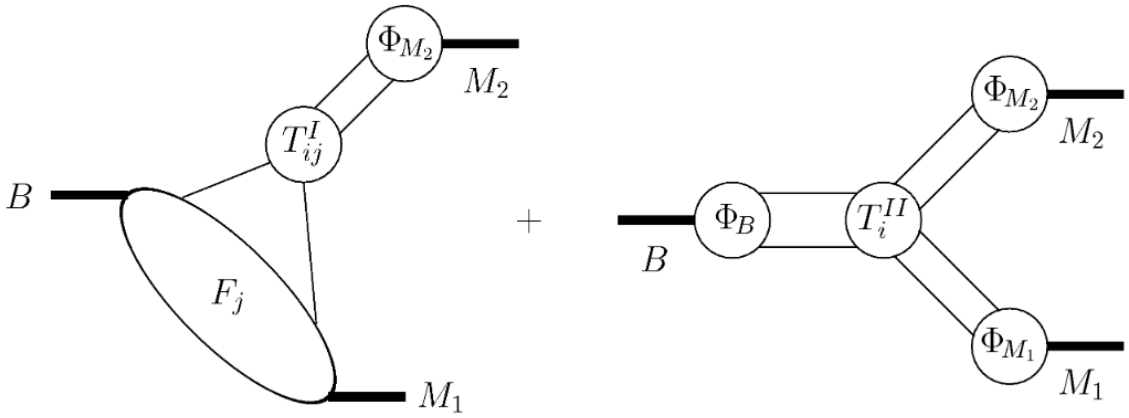

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Form factors and LCDAs universal non-perturbative objects

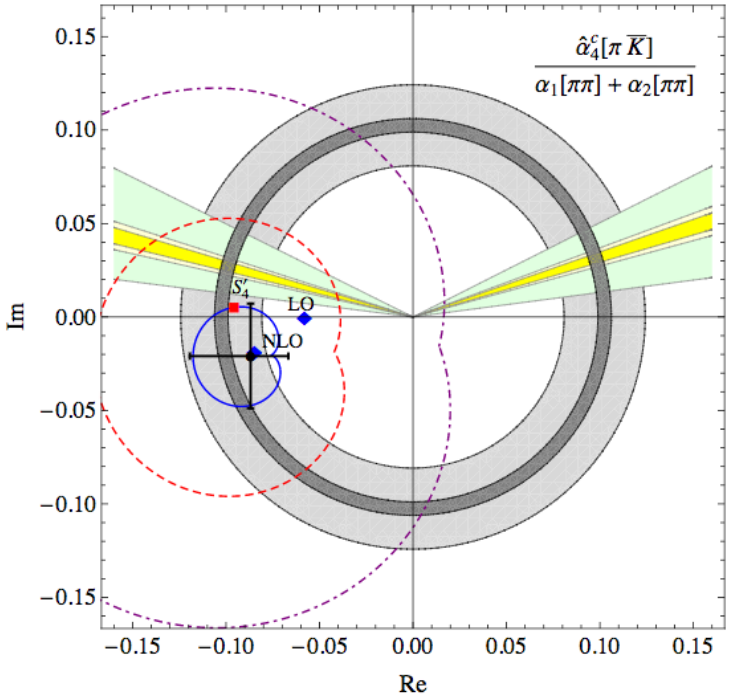
$$A_{CP} = \mathcal{O}(\alpha_s/\pi) + \mathcal{O}(\Lambda/m_b)$$

NNLO is NLO for CP asymmetries!

QCD Factorization in two-body decays

Beneke, Bell, Huber [2015]

Talk by Tobias Huber



- Extension to three-body decays recently discussed Mannel, Virto, Vos
- Experimental studie of $\bar{B}^0 \to D^+(\pi\pi)^-$ crucial
- Handle on power corrections obtained through $\bar{B}^0 \to D^+\pi^-$

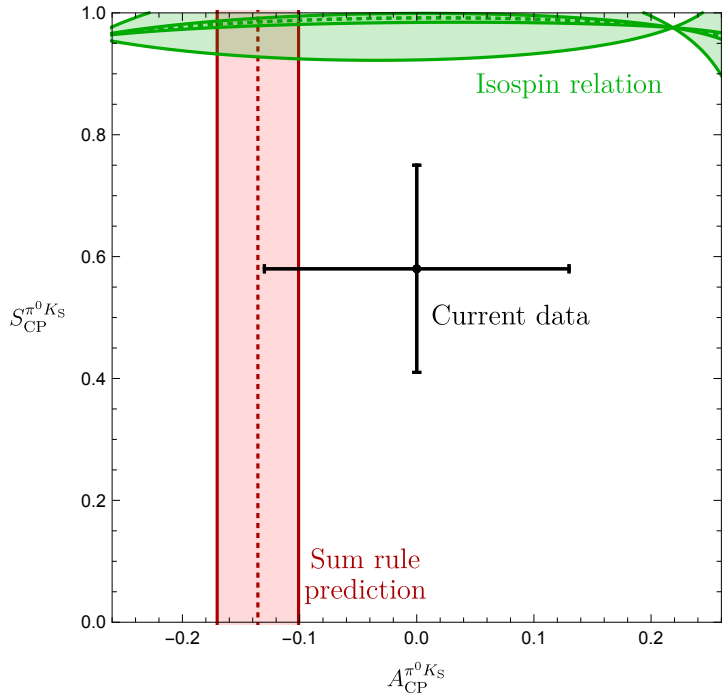
The $B \to \pi K$ puzzle using flavour symmetry

Nir, Quin [1991]; Gronau, Hernandez, London, Rosner [1995]

Fleischer, Jaeger, Pirjol, Zupan [2008]; Fleischer, Jaarsma, KKV [2018]

Talk by Ruben Jaarsma

- Theoretically clean isospin relation and γ as an input parameter



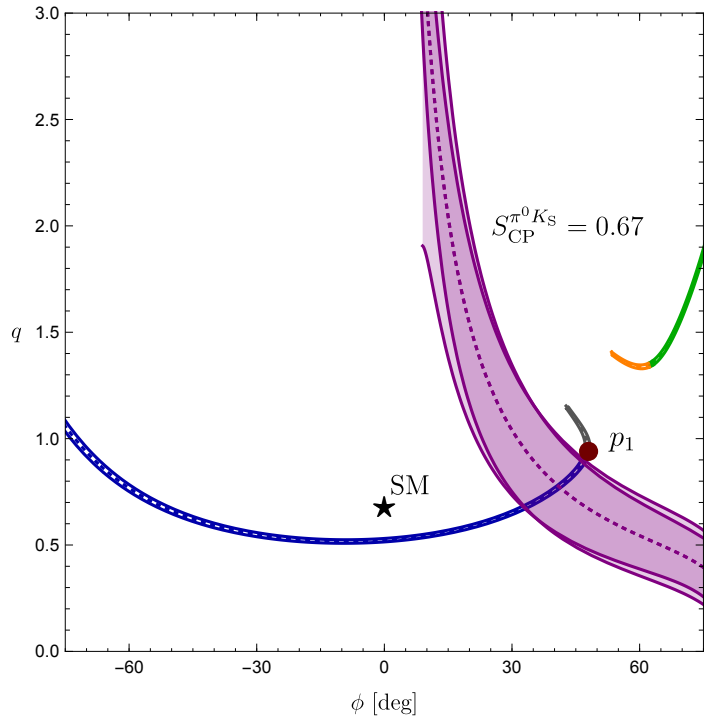
Hints at New Physics in the EWP sector?

Pinning down New Physics in EWP sector

Fleischer, Jaarsma, KKV [2018]; Fleischer, Jaarsma, Malami, KKV [2018]

Talk by Ruben Jaarsma

Mixing-induced CP asymmetry in $B_d^0 \to \pi^0 K^0$ provides additional tests



Exciting prospects for Belle-II and LHCb

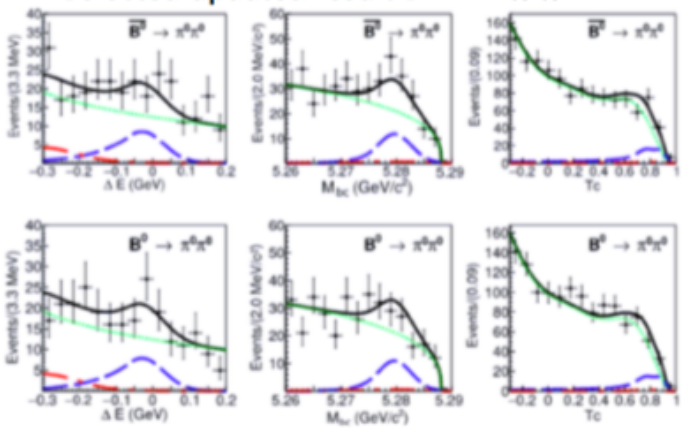
Charmless two-body decays at Belle(II)

Talk by Bilas Pal

- $B^0 \to \eta\pi^0$
- $B^0 \to \eta\eta$
- $B^0 \to \pi^0\pi^0$
- $B_s \to K_S K_S$

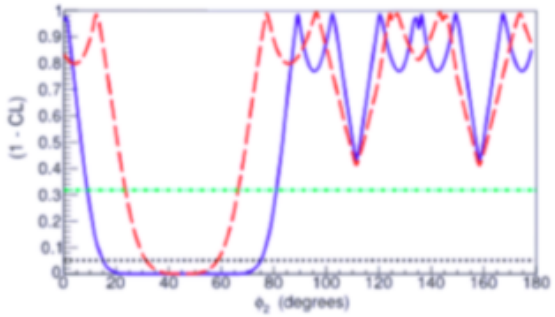
All measurements shown here are based on the final set of Belle data set [711/fb for Y(4S) and 121/fb for Y(5S)]

Selected updated result on $B^0 \to \pi^0\pi^0$

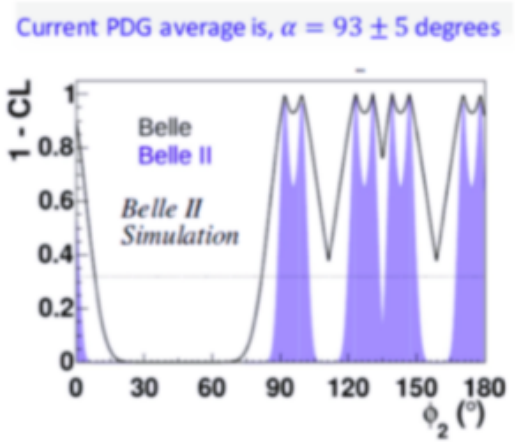


$$\mathcal{B}(B^0 \to \pi^0\pi^0) = (1.31 \pm 0.19 \pm 0.19) \times 10^{-6}$$
$$A_{CP} = +0.14 \pm 0.36 \pm 0.10$$

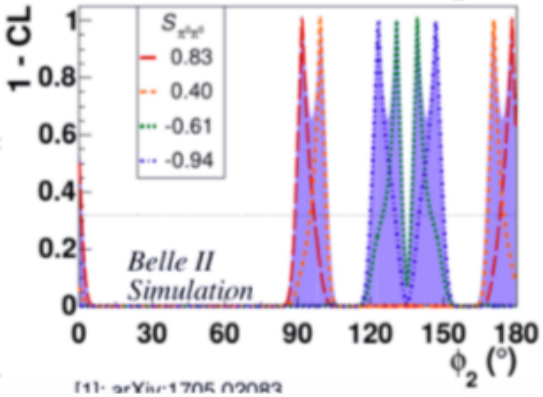
PRD 96, 032007 (2017)



Red represents the previous Belle constraint
Blue includes the newly measured Br and A_{CP}



- Updated result on $B^0 \to \pi^0\pi^0$ has a relevant impact on α/ϕ_2
- Prospects for Belle II are very promising
  - Measuring S_{00}



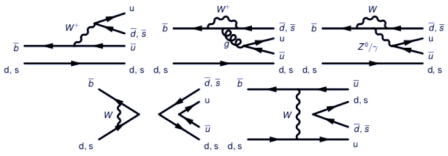
[1] arXiv:1705.02083

Charmless two-body decays at LHCb

Talk by Davide Fazzini

Sensible probe of CKM phases
but also of NP in penguin diagrams

Decay diagrams



Mixing diagrams

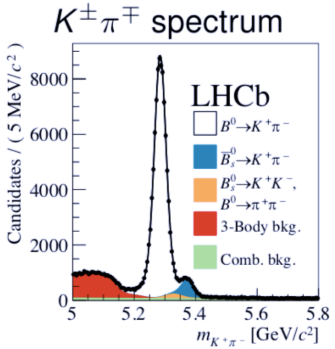
$C_{\pi^+\pi^-}$	=	$-0.34 \pm 0.06 \pm 0.01$
$S_{\pi^+\pi^-}$	=	$-0.63 \pm 0.05 \pm 0.01$
$C_{K^+K^-}$	=	$0.20 \pm 0.06 \pm 0.02$
$S_{K^+K^-}$	=	$0.18 \pm 0.06 \pm 0.02$
$A^{\Delta\Gamma}_{K^+K^-}$	=	$-0.79 \pm 0.07 \pm 0.10$
$A^{B^0}_{CP}$	=	$(-8.4 \pm 0.4 \pm 0.3)\%$
$A^{B^0_s}_{CP}$	=	$(21.3 \pm 1.5 \pm 0.3)\%$

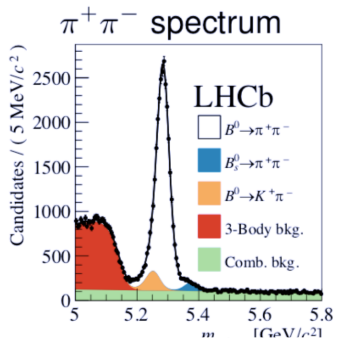
Only Run1 data (3/fb)

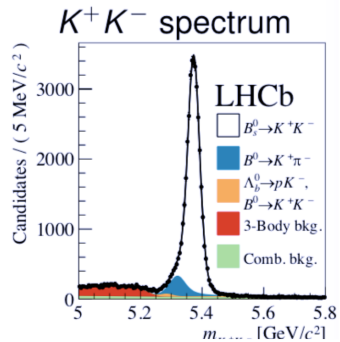
[Phys. Rev. D 98 (2018) 032004]

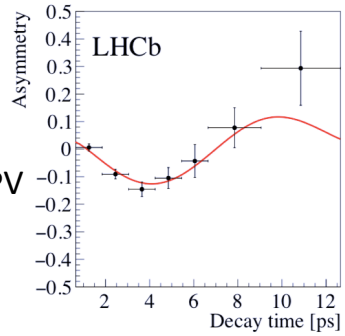
Most precise from single experiment

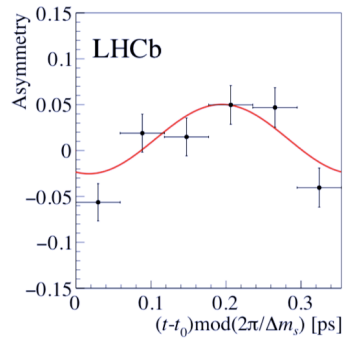
Strong evidence of time-dependent CPV in B_s ➔ 4σ











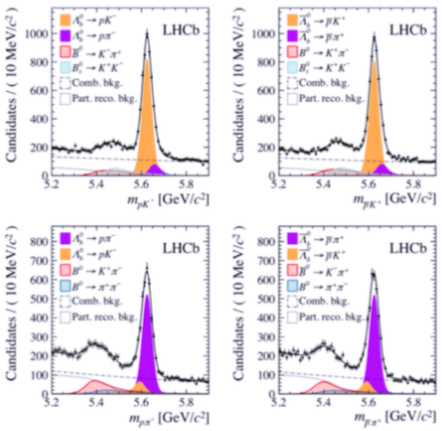
- SM test assuming U-spin validity [PLB 621 (2005) 126]

$$\Delta = \frac{A^{B^0}_{CP}}{A^{B^0_s}_{CP}} + \frac{\mathcal{B}(B^0_s\to\pi^+K^-)}{\mathcal{B}(B^0\to K^+\pi^-)}\frac{\tau_d}{\tau_s} = -0.11 \pm 0.03 \pm 0.04 \text{ (from } A_{CP})$$

Not only mesons but also B-baryons

Talk by Gediminas Sarpis

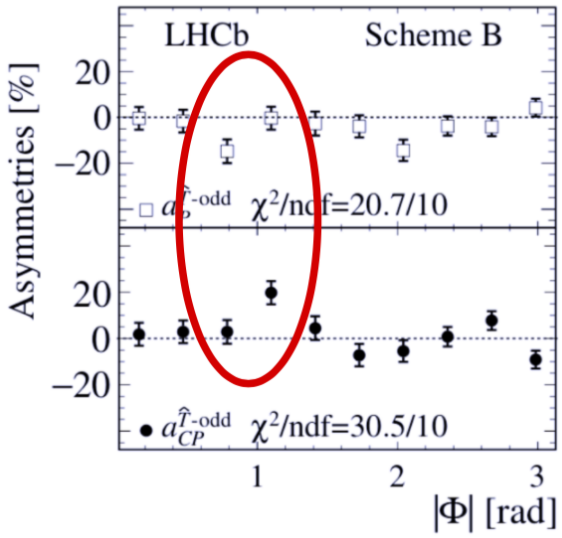
LHCb-PAPER-2018-025



$A_{CP}^{pK^-} = -0.020 \pm 0.013 \pm 0.019$

$A_{CP}^{p\pi^-} = -0.035 \pm 0.017 \pm 0.020$

Nature Phys. 13 (2017) 391-396



JHEP 1802(2018) 098

- $\mathcal{B}(\Lambda_b^0 \to p\pi^-\pi^+\pi^-) = (1.90 \pm 0.06 \pm 0.10 \pm 0.16 \pm 0.07) \cdot 10^5$
- $\mathcal{B}(\Lambda_b^0 \to pK^-\pi^+\pi^-) = (4.55 \pm 0.08 \pm 0.20 \pm 0.39 \pm 0.17) \cdot 10^5$
- $\mathcal{B}(\Lambda_b^0 \to pK^-K^+\pi^-) = (0.37 \pm 0.03 \pm 0.04 \pm 0.03 \pm 0.01) \cdot 10^5$
- $\mathcal{B}(\Lambda_b^0 \to pK^-K^+K^-) = (1.14 \pm 0.03 \pm 0.07 \pm 0.10 \pm 0.05) \cdot 10^5$
- $\mathcal{B}(\Xi_b^0 \to pK^-\pi^+\pi^-) \cdot f_{\Xi_b^0}/f_{\Lambda_b^0} = (1.72 \pm 0.21 \pm 0.25 \pm 0.15 \pm 0.07) \cdot 10^6$
- $\mathcal{B}(\Xi_b^0 \to pK^-\pi^+K^-) \cdot f_{\Xi_b^0}/f_{\Lambda_b^0} = (1.56 \pm 0.16 \pm 0.19 \pm 0.13 \pm 0.06) \cdot 10^6$
- $\mathcal{B}(\Xi_b^0 \to pK^-K^+K^-) \cdot f_{\Xi_b^0}/f_{\Lambda_b^0} \in [0.11 - 0.25] \cdot 10^{-6}$ *at 90% C.L.*

$\Delta\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\pi^-) \pm \Delta\mathcal{B}(\Lambda_c^+ \to p\pi^+K^-)$

A lot of measurements with B-baryons going on

- First evidence of CP violation in $\Lambda_b \to p3\pi$ with 3.3σ significance
- Analyses with additional Run2 data are ongoing
- Theoretical study???

Summary of the Summary

- Extraction of γ from $B \to DK$ is theoretically clean
  - Impressive 1° precision in the upgrade era expected
  - Collaboration with BESIII required!
- Challenging to improve QCDF CP asymmetry predicitions
  - Crucial to have data on $B \to D\pi$ and $\bar{B}^0 \to D^+(\pi\pi)^-$
- $B \to \pi K$ decays remain puzzling $\to$ good prospects
  - Improved CP asymmetries in $B_d \to \pi^0 K_S$ needed
- Three-body decays still offer many interesting avenues to explore
  - New results for $B \to hhh$ coming (soon)!

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Thanks to all speakers and for your attention