CP violation in B hadron decays

Science and Technology Facilities Council

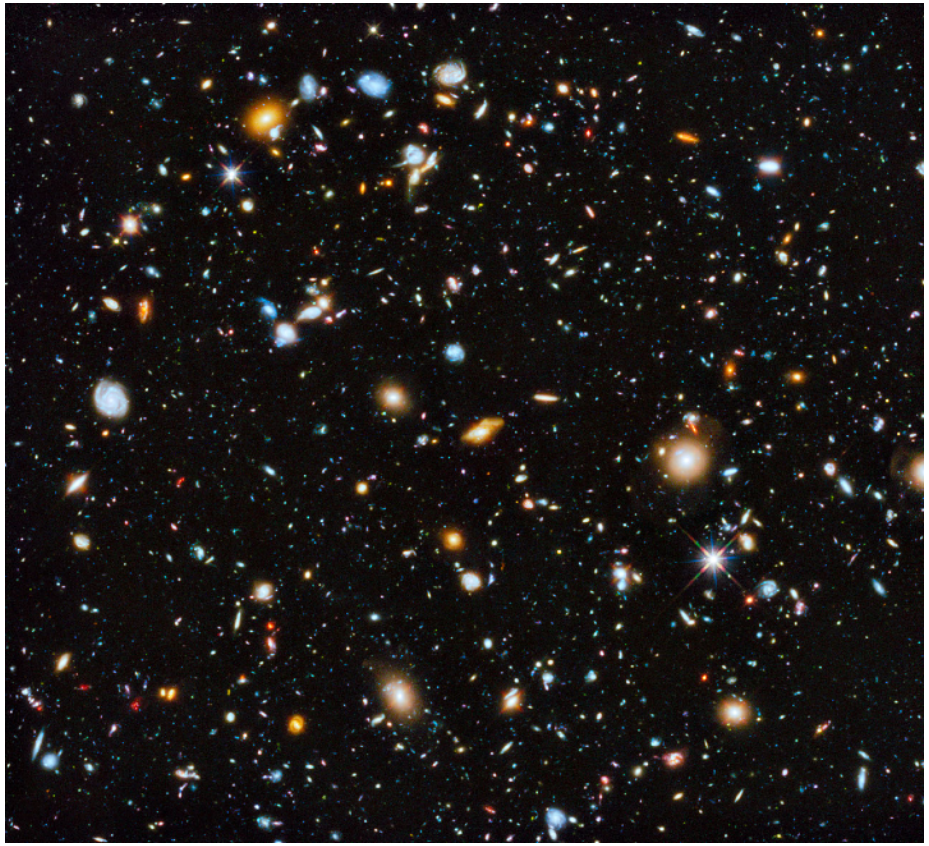
Mark Whitehead

University of BRISTOL

on behalf of the ATLAS, CMS and LHCb collaborations

Setting the scene

- The Universe is dominated by matter and not antimatter
  - Charge-parity (CP) violation allows decays of particles and antiparticles to be different
- In the Standard Model, CP violation is encoded in the quark mixing (CKM) matrix
- CP violation in the Standard Model only explains a tiny fraction of this difference
  - There must be new sources of CP violation
  - From new particles or interactions - “New physics”



NASA, ESA, H. Teplitz and M. Rafelski (IPAC/Caltech), A. Koekemoer (STScI), R. Windhorst (Arizona State University), and Z. Levay (STScI)

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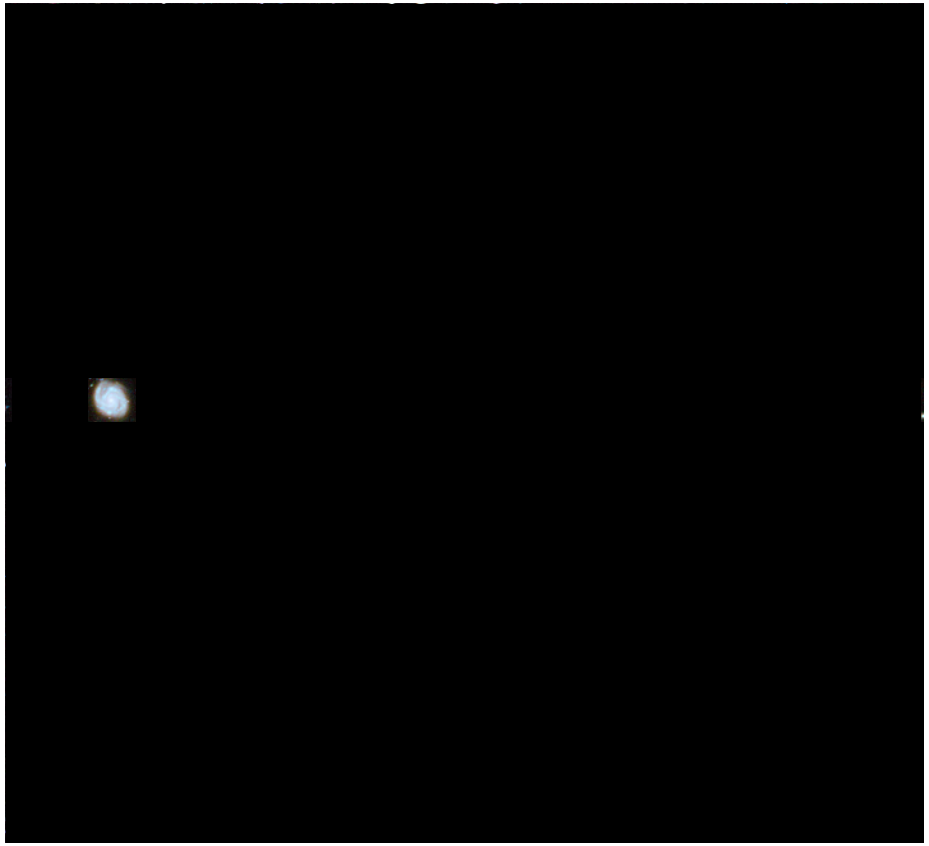

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Contents

- I can't cover everything - so try to focus on results since LHCP 2019

- Unitary triangle(s)
  - γ, β, ϕ_s

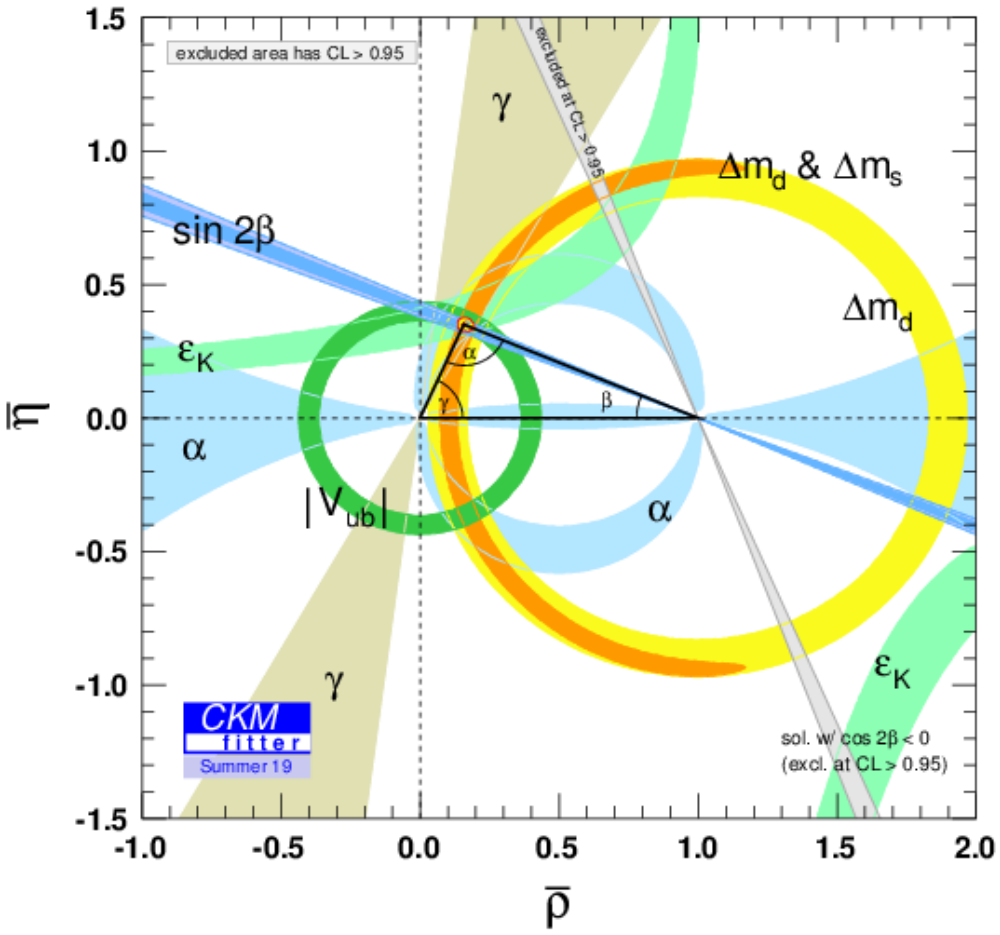
- Baryon CPV searches
  - $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$

- Charmless B meson decays
  - $B^+ \to \pi^+\pi^+\pi^-$

If you missed them, please see parallel talks from:
- Jinlin Fu - LHCb
- Alberto Bragagnolo -CMS
- Maria Smizanska - ATLAS
- Christoph Bobeth - Theory

The unitarity triangle

- Unitarity triangle(s) from CKM matrix unitarity
  - The most famous of these has the angles α, β, γ
  - Precision test of the SM, if measurements are not consistent with a triangle - sign of NP
  - Area of the triangle proportional to CPV in the quark sector of the SM
- Current status
  - Consistent with the SM
  - Both γ and α are the least precise measurements
  - Excellent progress from LHCb in the last decade, looking forward to Belle II and LHCb upgrades!
  - No updates on α today

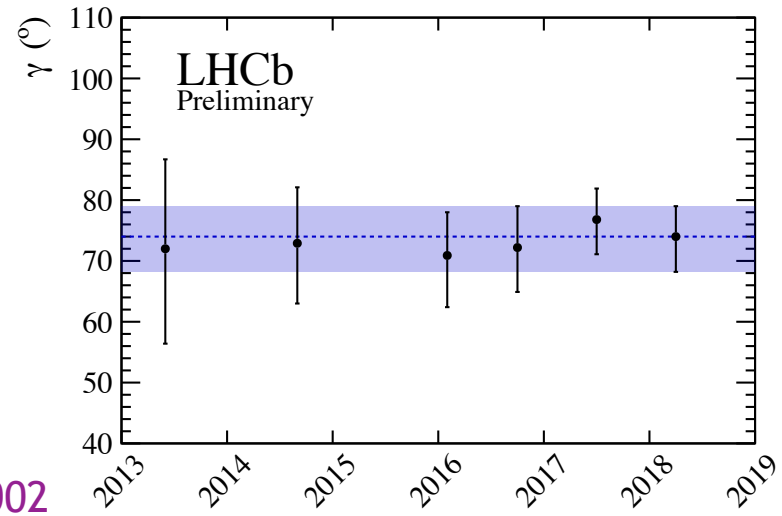


The latest on the angle γ

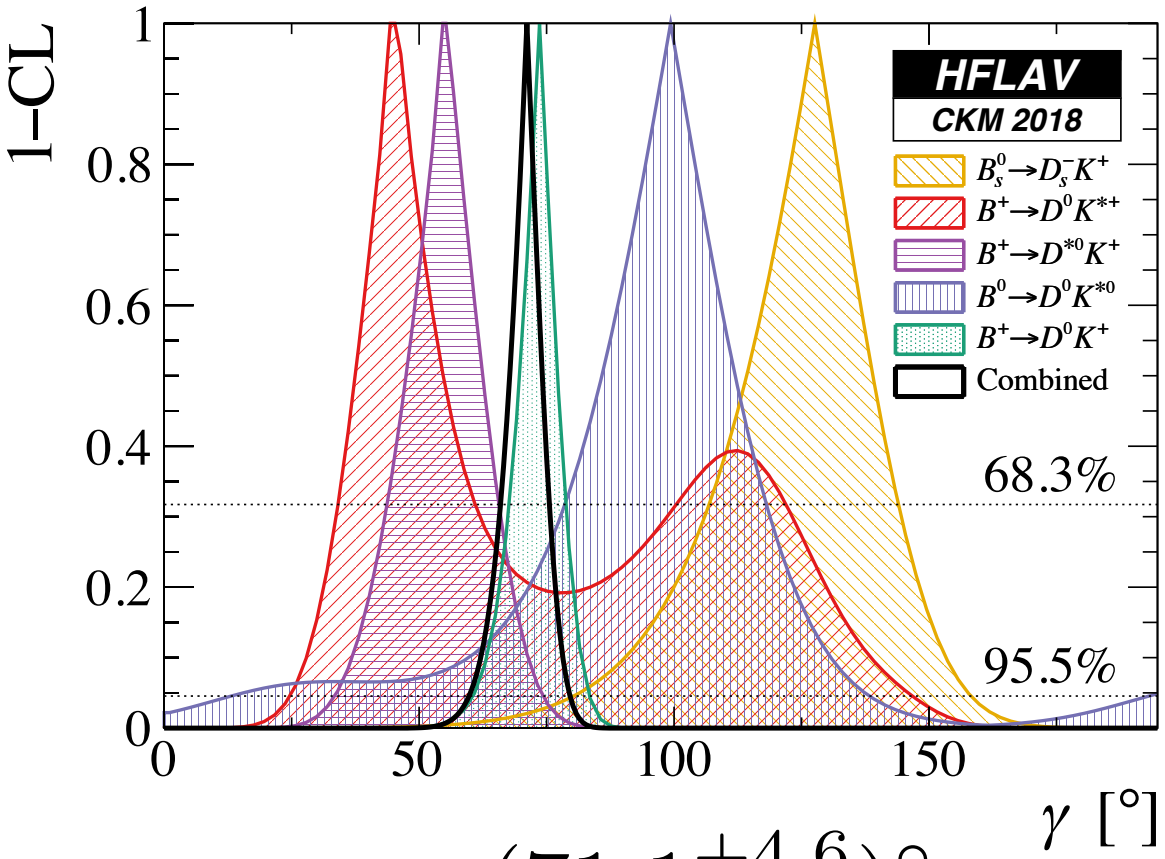
- World average (currently) dominated by LHCb's gamma combination
  - Defined as:

$$\gamma = \phi_3 = \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$

  - Measurements with B^+, B^0, B_s^0 decays
- Great progress in the last decade



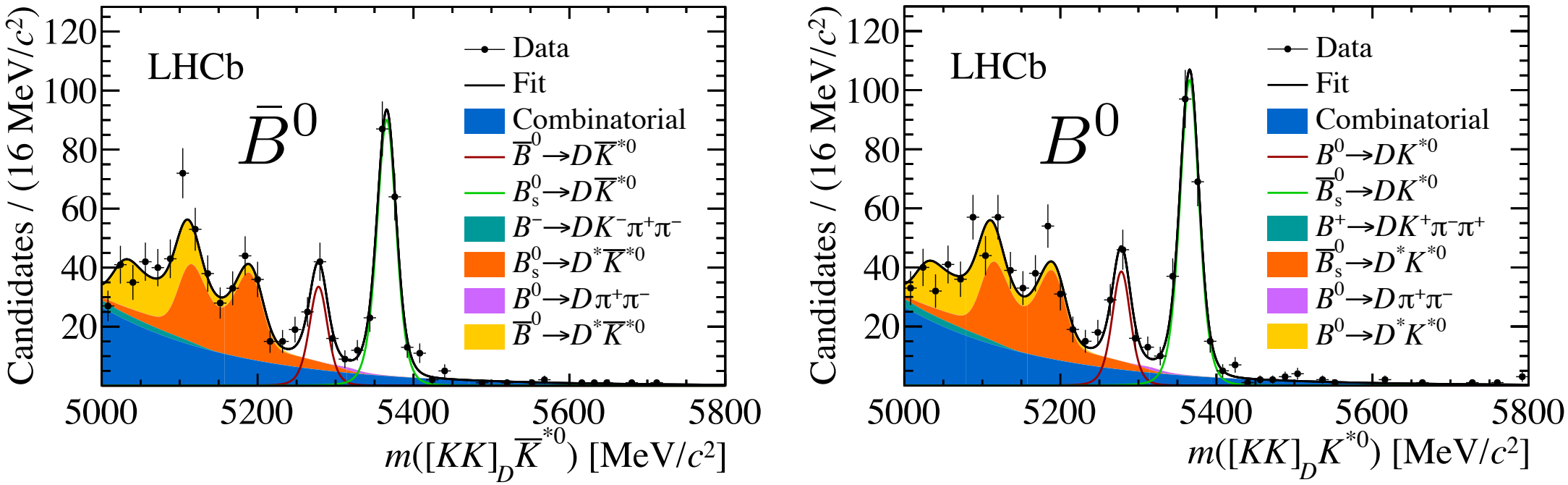
LHCb-CONF-2018-002



$$\gamma = (71.1^{+4.6}_{-5.3})^\circ$$

GLW/ADS analysis with $B^0 \to DK^{*0}$ decays

- Improving measurements of γ from B^0 decays
  - GLW/ADS approach with $D \to K^{\pm}\pi^{\mp}$, K^+K^-, $\pi^+\pi^-$, $K^{\pm}\pi^{\mp}\pi^{\pm}\pi^{\mp}$, $\pi^+\pi^-\pi^+\pi^-$
  - Data from 2011-2016: $4.8\ \mathrm{fb}^{-1}$
  - Measure CP asymmetries and yield ratios which can be interpreted in term of γ



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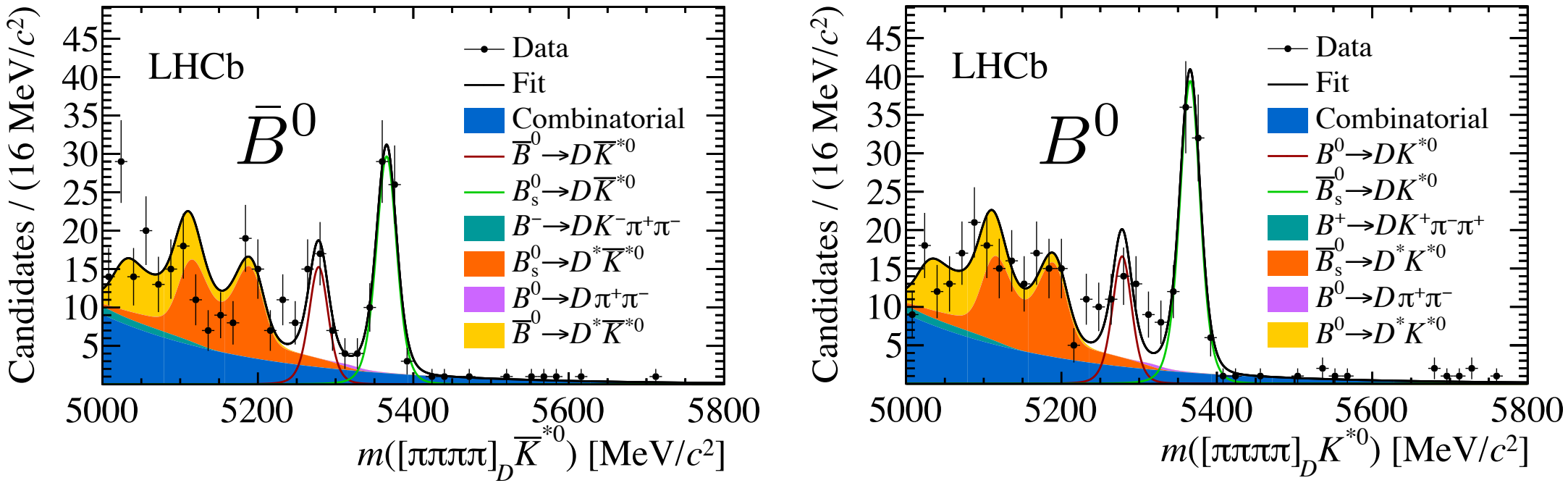
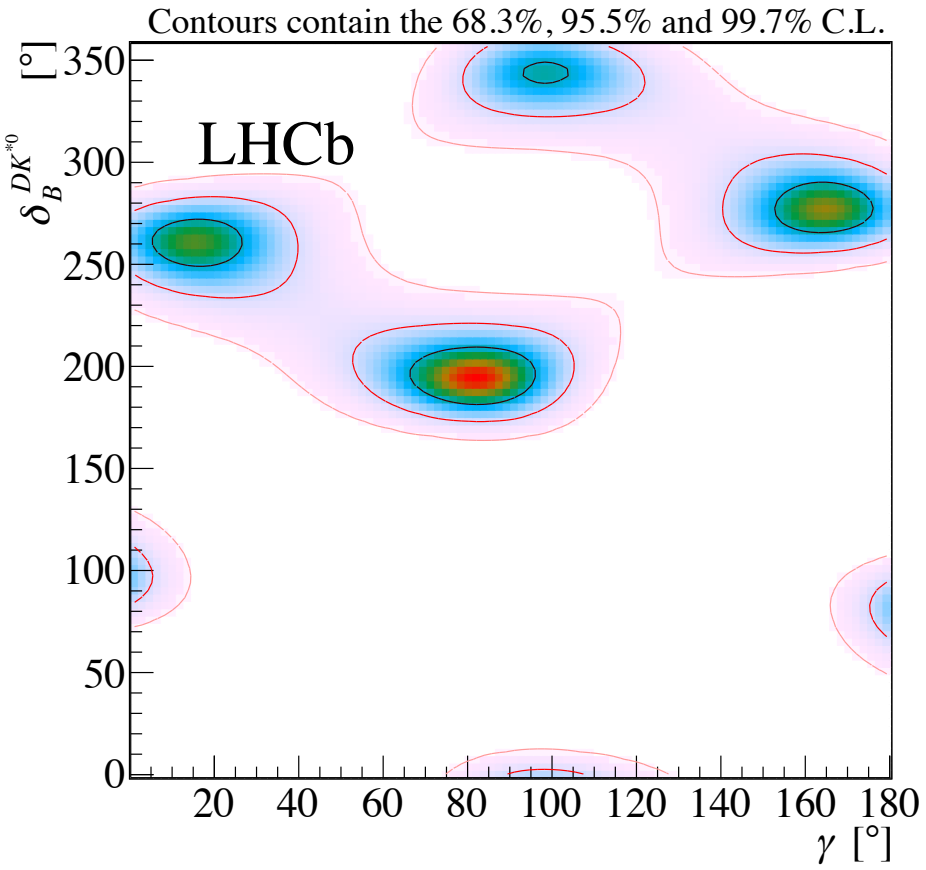


GLW/ADS analysis with $B^0 \to DK^{*0}$ decays

- Lots of results
  - First observation of πK, $\pi^+\pi^-\pi^+\pi^-$ modes
  - CP asymmetries consistent with 0 at 2σ level
  - Combination of observables can constrain γ

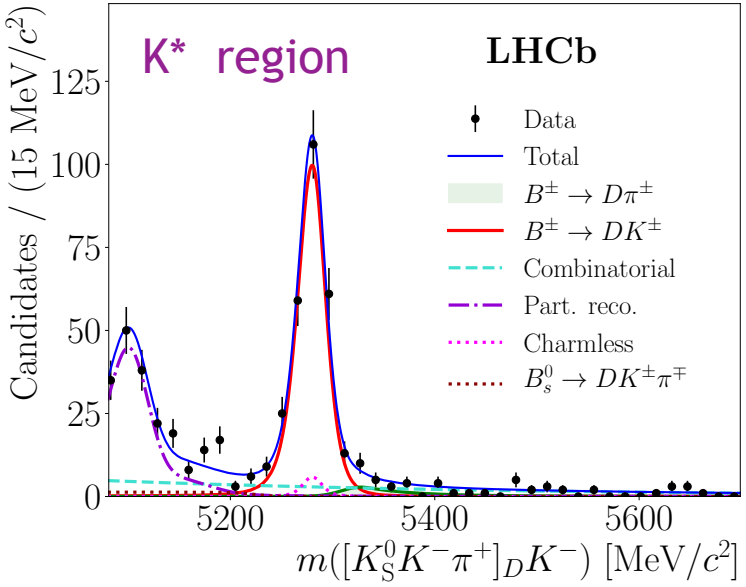
$$
\begin{aligned}
\mathcal{A}_{CP}^{KK} &= -0.05 \pm 0.10 \pm 0.01, \\
\mathcal{A}_{CP}^{\pi\pi} &= -0.18 \pm 0.14 \pm 0.01, \\
\mathcal{R}_{CP}^{KK} &= 0.92 \pm 0.10 \pm 0.02, \\
\mathcal{R}_{CP}^{\pi\pi} &= 1.32 \pm 0.19 \pm 0.03, \\
\mathcal{A}_{CP}^{4\pi} &= -0.03 \pm 0.15 \pm 0.01, \\
\mathcal{R}_{CP}^{4\pi} &= 1.01 \pm 0.16 \pm 0.04, \\
\mathcal{R}_{+}^{\pi K} &= 0.064 \pm 0.021 \pm 0.002, \\
\mathcal{R}_{-}^{\pi K} &= 0.095 \pm 0.021 \pm 0.003,
\end{aligned}
$$

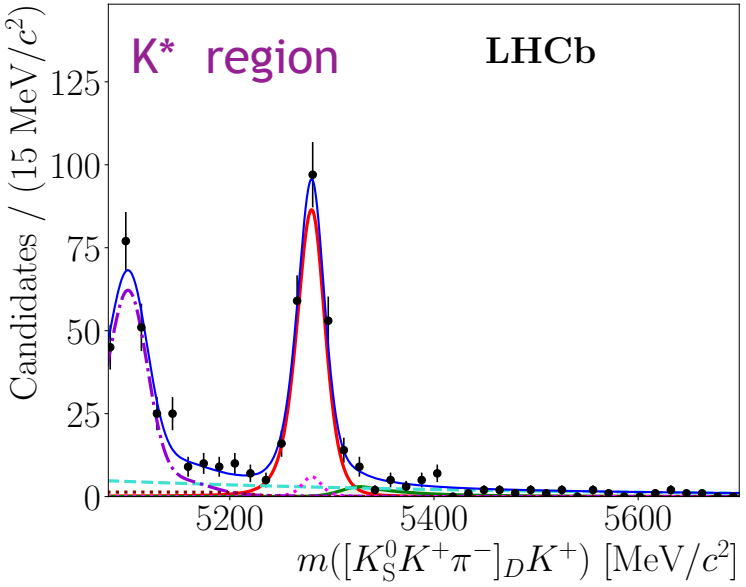
$$
\begin{aligned}
\mathcal{R}_{+}^{\pi K\pi\pi} &= 0.074 \pm 0.026 \pm 0.002, \\
\mathcal{R}_{-}^{\pi K\pi\pi} &= 0.072 \pm 0.025 \pm 0.003, \\
\mathcal{A}_{\mathrm{ADS}}^{K\pi} &= 0.047 \pm 0.027 \pm 0.010, \\
\mathcal{A}_{\mathrm{ADS}}^{K\pi\pi\pi} &= 0.037 \pm 0.032 \pm 0.010, \\
\mathcal{A}_{\mathrm{ADS}}^{\pi K} &= 0.19 \pm 0.19 \pm 0.01, \\
\mathcal{R}_{\mathrm{ADS}}^{\pi K} &= 0.080 \pm 0.015 \pm 0.002, \\
\mathcal{A}_{\mathrm{ADS}}^{\pi K\pi\pi} &= -0.01 \pm 0.24 \pm 0.01, \\
\mathcal{R}_{\mathrm{ADS}}^{\pi K\pi\pi} &= 0.073 \pm 0.018 \pm 0.002.
\end{aligned}
$$



GLS analysis with $B^+ \to DK^+$ decays

- Measure CP violation with $D \to K_S^0 K^\pm \pi^\mp$ decays
  - Full Run 1 and 2 data sample
  - Measure asymmetries and yield ratios in the $K^*(892)$ and non $K^*(892)$ regions
  - Results to be added to the LHCb γ combination





K* region

$$A_{SS}^{D\pi} = -0.020 \pm 0.011 \pm 0.003\,,$$
$$A_{OS}^{D\pi} = 0.007 \pm 0.017 \pm 0.003\,,$$
$$A_{SS}^{DK} = 0.084 \pm 0.049 \pm 0.008\,,$$
$$A_{OS}^{DK} = 0.021 \pm 0.094 \pm 0.017\,,$$
$$R_{SS/OS} = 2.585 \pm 0.057 \pm 0.019\,,$$
$$R_{SS}^{DK/D\pi} = 0.079 \pm 0.004 \pm 0.002\,,$$
$$R_{OS}^{DK/D\pi} = 0.062 \pm 0.006 \pm 0.003\,,$$

non - K* region

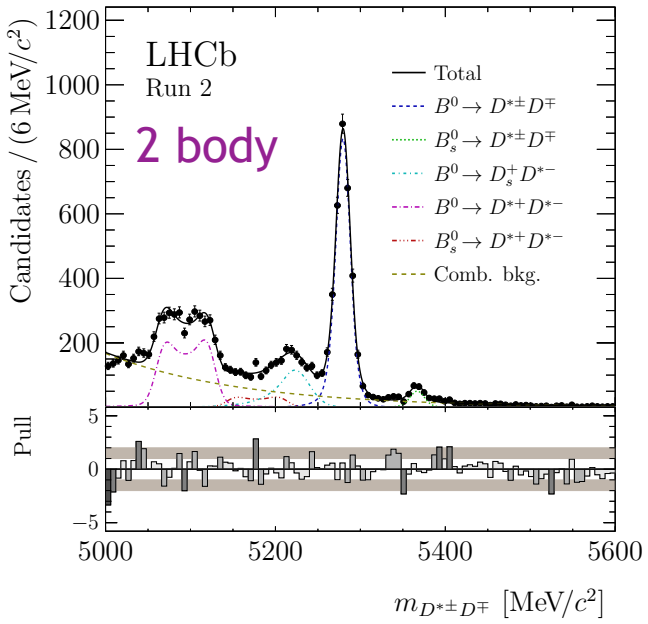
$$A_{SS}^{D\pi} = -0.034 \pm 0.020 \pm 0.003\,,$$
$$A_{OS}^{D\pi} = 0.003 \pm 0.015 \pm 0.003\,,$$
$$A_{SS}^{DK} = 0.095 \pm 0.089 \pm 0.018\,,$$
$$A_{OS}^{DK} = -0.038 \pm 0.075 \pm 0.011\,,$$
$$R_{SS/OS} = 0.706 \pm 0.019 \pm 0.009\,,$$
$$R_{SS}^{DK/D\pi} = 0.081 \pm 0.008 \pm 0.004\,,$$
$$R_{OS}^{DK/D\pi} = 0.073 \pm 0.006 \pm 0.002\,.$$

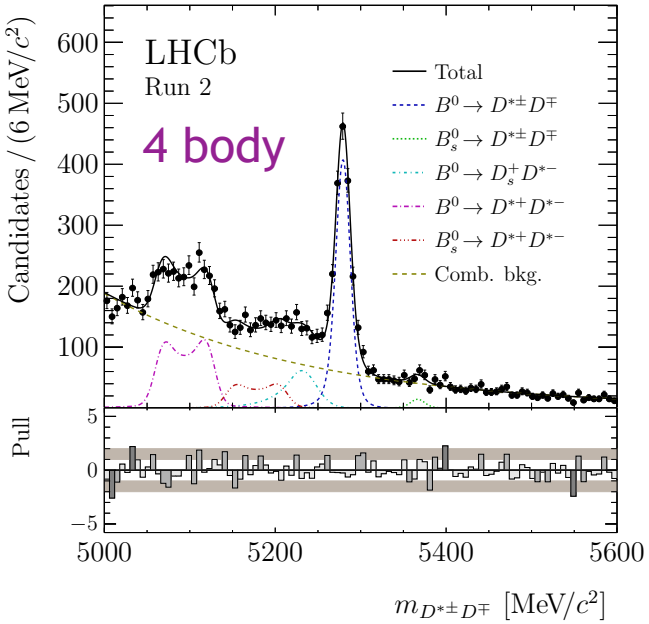
arXiv:2002.08858 [hep-ex]

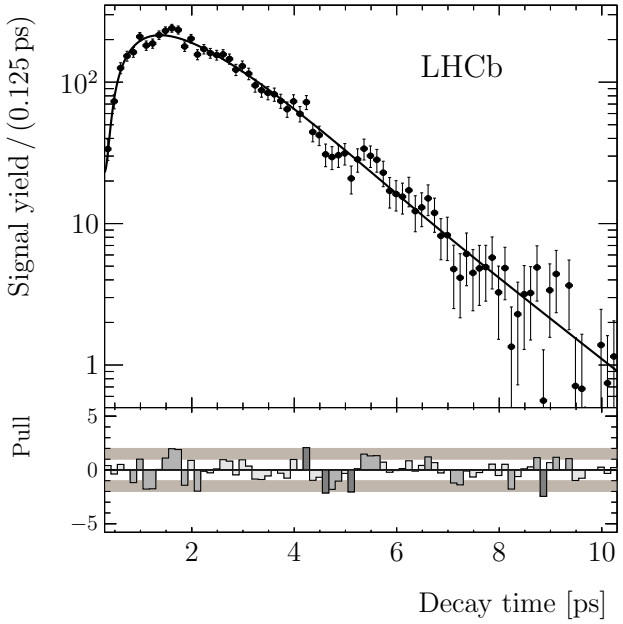
Measuring CPV with $B^0 \to D^{*\pm} D^{\mp}$ decays

- Measurement of time-dependent CP violation at LHCb
  - Full Run 1 + Run 2 data sample of $9\ \mathrm{fb}^{-1}$ with $D^{*+} \to D^0\pi^+$, $D^0 \to K^-\pi^+$, $K^-\pi^+\pi^-\pi^+$ and $D^- \to K^+\pi^-\pi^-$
  - Measure five CP observables from the time-dependent decay rates

$$\frac{\mathrm{d}\Gamma_{\bar{B}^0,f}(t)}{\mathrm{d}t} = \frac{e^{-t/\tau_d}}{8\tau_d}(1+\mathcal{A}_{f\bar{f}})\left[1 + S_f \sin(\Delta m_d t) - C_f \cos(\Delta m_d t)\right]$$







$$S_f = \frac{2\mathcal{I}m\lambda_f}{1+|\lambda_f|^2},$$

$$C_f = \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2},$$

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

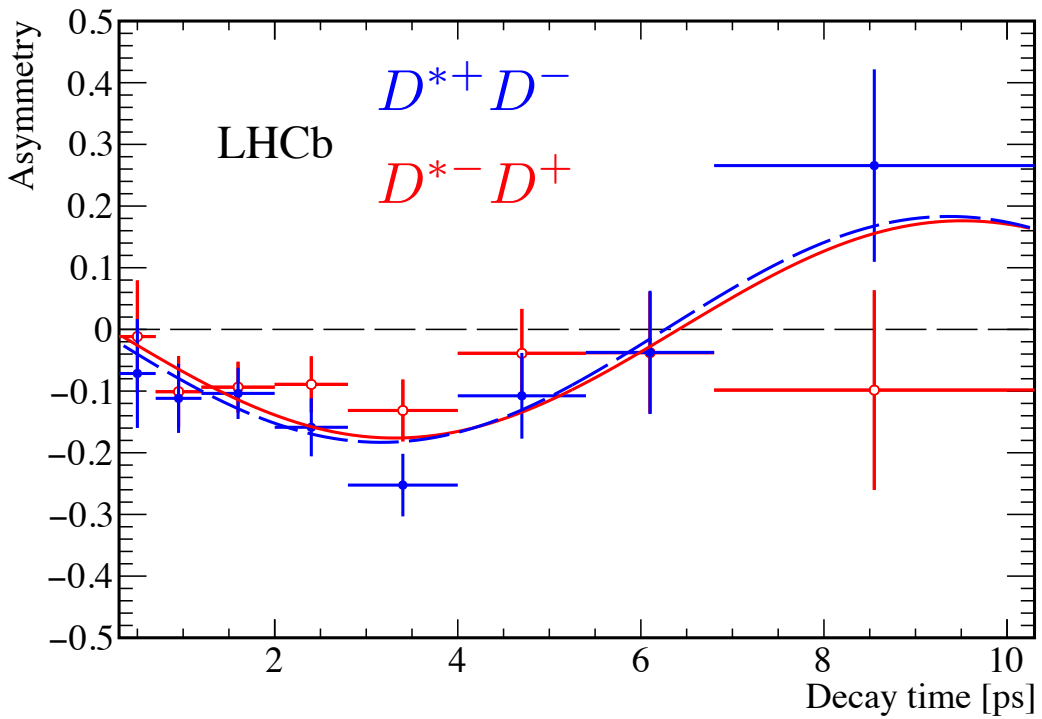
$\mathcal{A}_{f\bar{f}}$ final state production asymmetry

Measuring CPV with $B^0 \to D^{*\pm} D^{\mp}$ decays

- Measure the coefficients and combine them into the CPV observables

$$S_{D^*D} = \frac{1}{2}(S_f + S_{\bar{f}}), \qquad C_{D^*D} = \frac{1}{2}(C_f + C_{\bar{f}}),$$
$$\Delta S_{D^*D} = \frac{1}{2}(S_f - S_{\bar{f}}), \quad \Delta C_{D^*D} = \frac{1}{2}(C_f - C_{\bar{f}}),$$
$$\mathcal{A}_{D^*D} = \mathcal{A}_{f\bar{f}}.$$

$$S_{D^*D} = -0.861 \pm 0.077\,(\text{stat}) \pm 0.019\,(\text{syst})$$
$$\Delta S_{D^*D} = 0.019 \pm 0.075\,(\text{stat}) \pm 0.012\,(\text{syst})$$
$$C_{D^*D} = -0.059 \pm 0.092\,(\text{stat}) \pm 0.020\,(\text{syst})$$
$$\Delta C_{D^*D} = -0.031 \pm 0.092\,(\text{stat}) \pm 0.016\,(\text{syst})$$
$$\mathcal{A}_{D^*D} = 0.008 \pm 0.014\,(\text{stat}) \pm 0.006\,(\text{syst})$$



- Most precise measurement of this channel, excluding CP conservation at 10σ

LHC Run 1 status of ϕ_s

- The mixing phase of $B_s^0 - \bar{B}_s^0$ meson oscillations

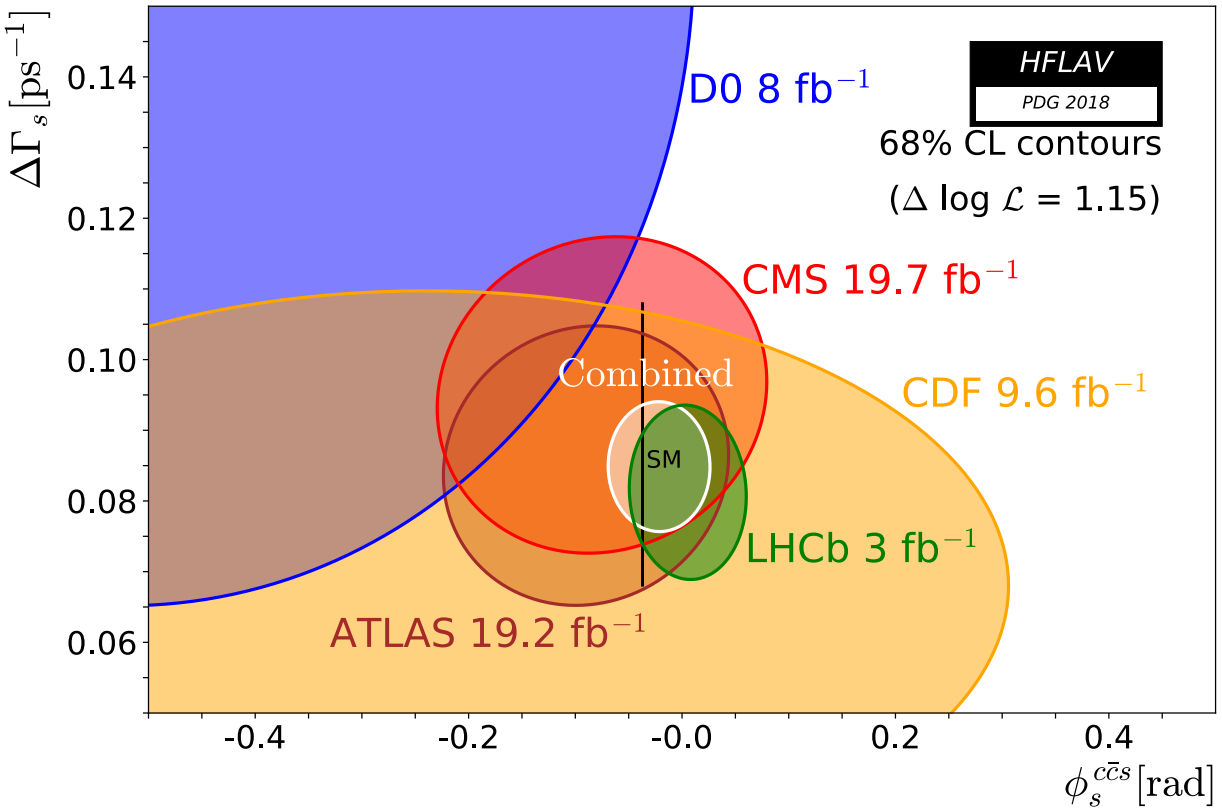
$$\phi_s \approx -2\beta_s = -2\arg[-(V_{\rm ts}V_{\rm tb}^*)/(V_{\rm cs}V_{\rm cb}^*)]$$

  - Using CKM unitarity it is expected to be

$$-2\beta_s = -0.0369^{+0.0010}_{-0.0007}\,\text{rad}$$ CKM Fitter

$$-2\beta_s = -0.0370 \pm 0.0010\,\text{rad}$$ UT Fit

  - Value can be significantly modified by contributions from new physics
  - Work to do to reduce the uncertainty on the direct experimental measurements to have a meaningful comparison

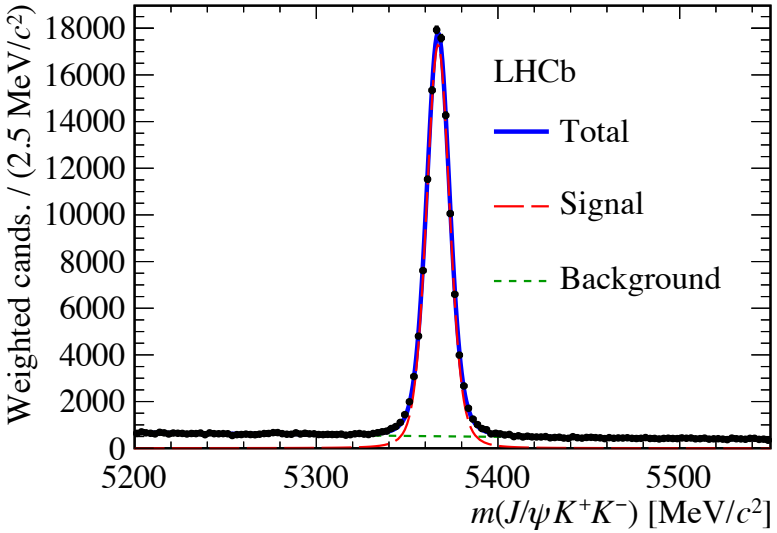


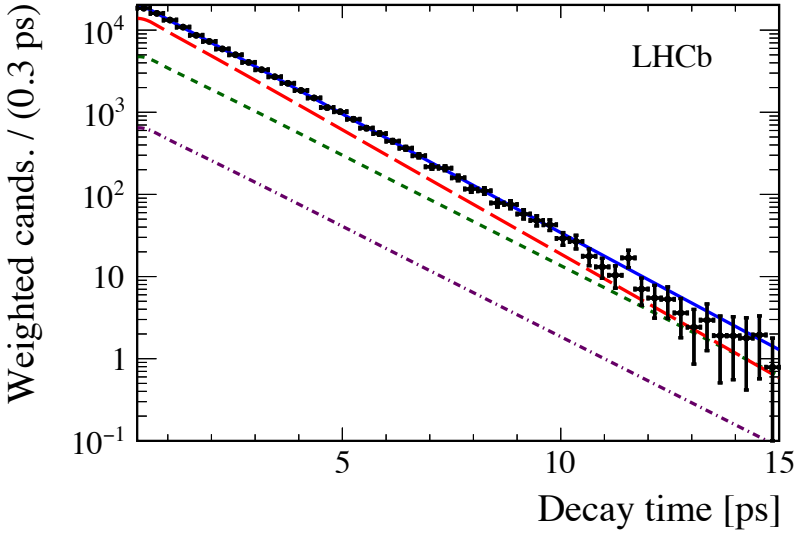
$$\phi_s = -0.021 \pm 0.031\,\text{rad}$$

ϕ_s at LHCb

- Run 2 (2015 + 2016) update
  - Measurement with $B_s^0 \to J/\psi K^+ K^-$ decays in a 60 MeV window around the ϕ meson
  - Yield ~120k candidates
  - Flavour tagging performance

Category	$\epsilon_{\text{tag}}(\%)$	D^2	$\epsilon_{\text{tag}} D^2 (\%)$
OS only	11.4	0.078	0.88 ± 0.04
SSK only	42.6	0.032	1.38 ± 0.30
OS & SSK	23.8	0.104	2.47 ± 0.15
Total	77.8	0.061	4.73 ± 0.34





  - Split into six bins of m(KK) with limits $990,\ 1008,\ 1016,\ 1020,\ 1024,\ 1032,\ 1050\,\text{MeV}/c^2$
  - Full angular analysis including the B mass, decay time, decay time error and decay angles
  - Fit to all data samples simultaneously

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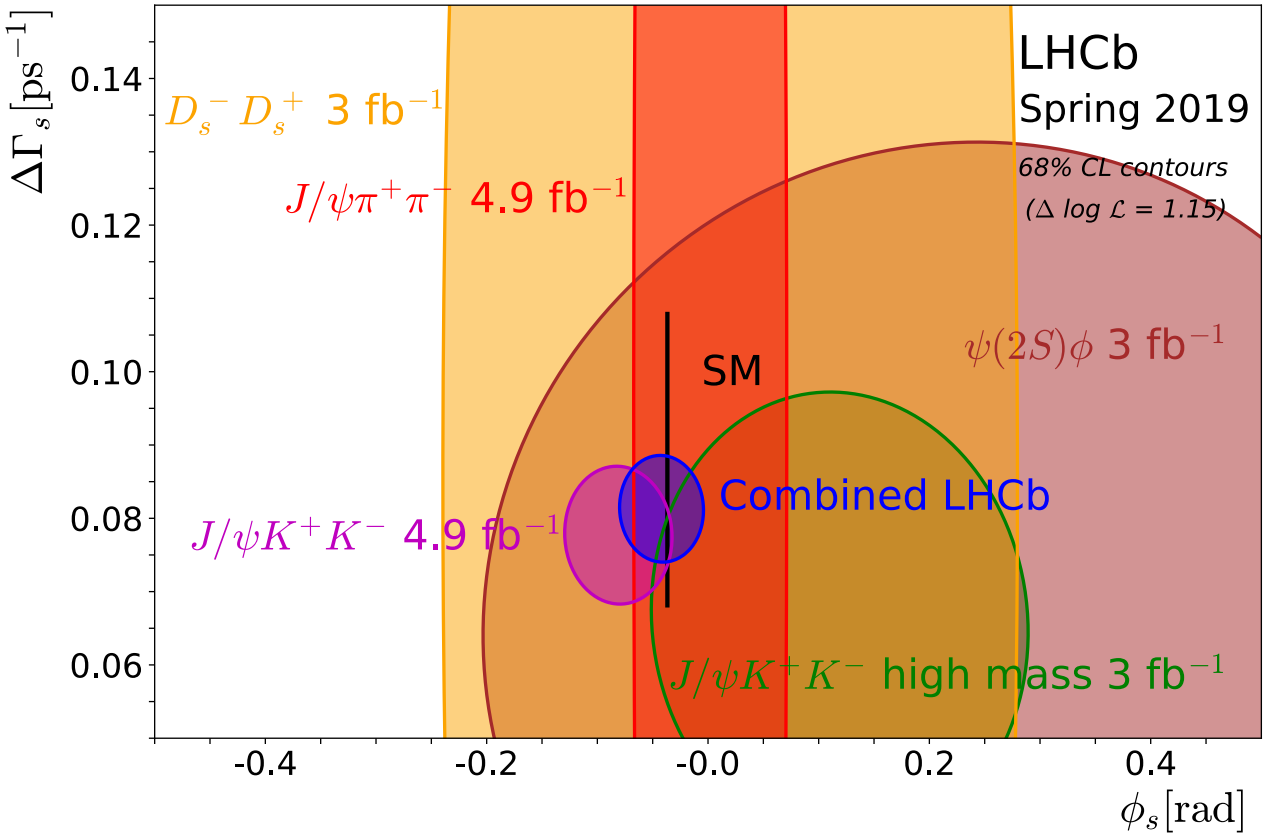
ϕ_s at LHCb

- Results
  - Run 2 only

$$\phi_s = -0.083 \pm 0.041 \pm 0.006\,\mathrm{rad}$$

  - Run 1 + 2

$$\begin{aligned}\phi_s &= -0.081 \pm 0.032\,\mathrm{rad}\,,\\ |\lambda| &= 0.994 \pm 0.013\,,\\ \Gamma_s &= 0.6572 \pm 0.0023\,\mathrm{ps}^{-1}\,,\\ \Delta\Gamma_s &= 0.0777 \pm 0.0062\,\mathrm{ps}^{-1}\,,\\ \Delta m_s &= 17.694 \pm 0.042\,\mathrm{ps}^{-1}\,,\end{aligned}$$



$$\phi_s = -0.042 \pm 0.025\,\mathrm{rad}$$

- LHCb combination
  - Includes this analysis and several others as indicated on the figure

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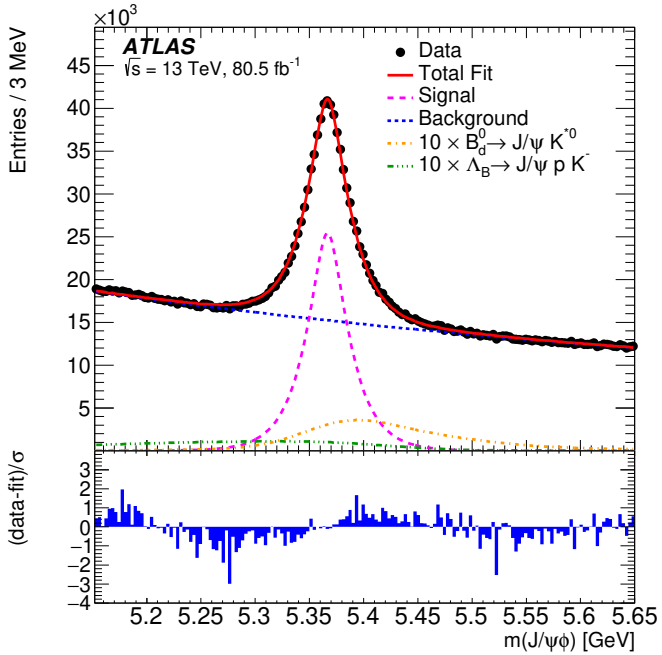
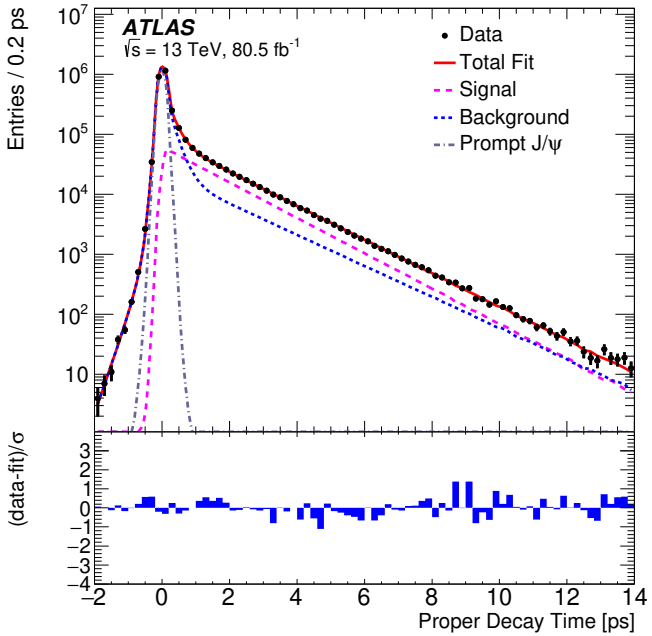
ϕ_s at ATLAS with $B_s^0 \to J/\psi\phi$

- Recent Run 2 update from ATLAS
  - Closely follows the Run 1 analysis
  - Huge signal yield: $> 450\,\mathrm{k}$
  - Flavour tagging power 1.75%

Tag method	ϵ_x [%]	D_x [%]	T_x [%]
Tight muon	4.50 ± 0.01	43.8 ± 0.2	0.862 ± 0.009
Electron	1.57 ± 0.01	41.8 ± 0.2	0.274 ± 0.004
Low-p_T muon	3.12 ± 0.01	29.9 ± 0.2	0.278 ± 0.006
Jet	12.04 ± 0.02	16.6 ± 0.1	0.334 ± 0.006
Total	21.23 ± 0.03	28.7 ± 0.1	1.75 ± 0.01

  - Measured value of ϕ_s compatible with previous measurements
  - Some tension for the value of Γ_s





Parameter	Value	Statistical uncertainty	Systematic uncertainty
ϕ_s [rad]	-0.081	0.041	0.020
$\Delta\Gamma_s$ [ps^{-1}]	0.0607	0.0046	0.0025
Γ_s [ps^{-1}]	0.6687	0.0015	0.0017

For more details see talk by Maria Smizanska

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  - Combine with the Run 1 analysis

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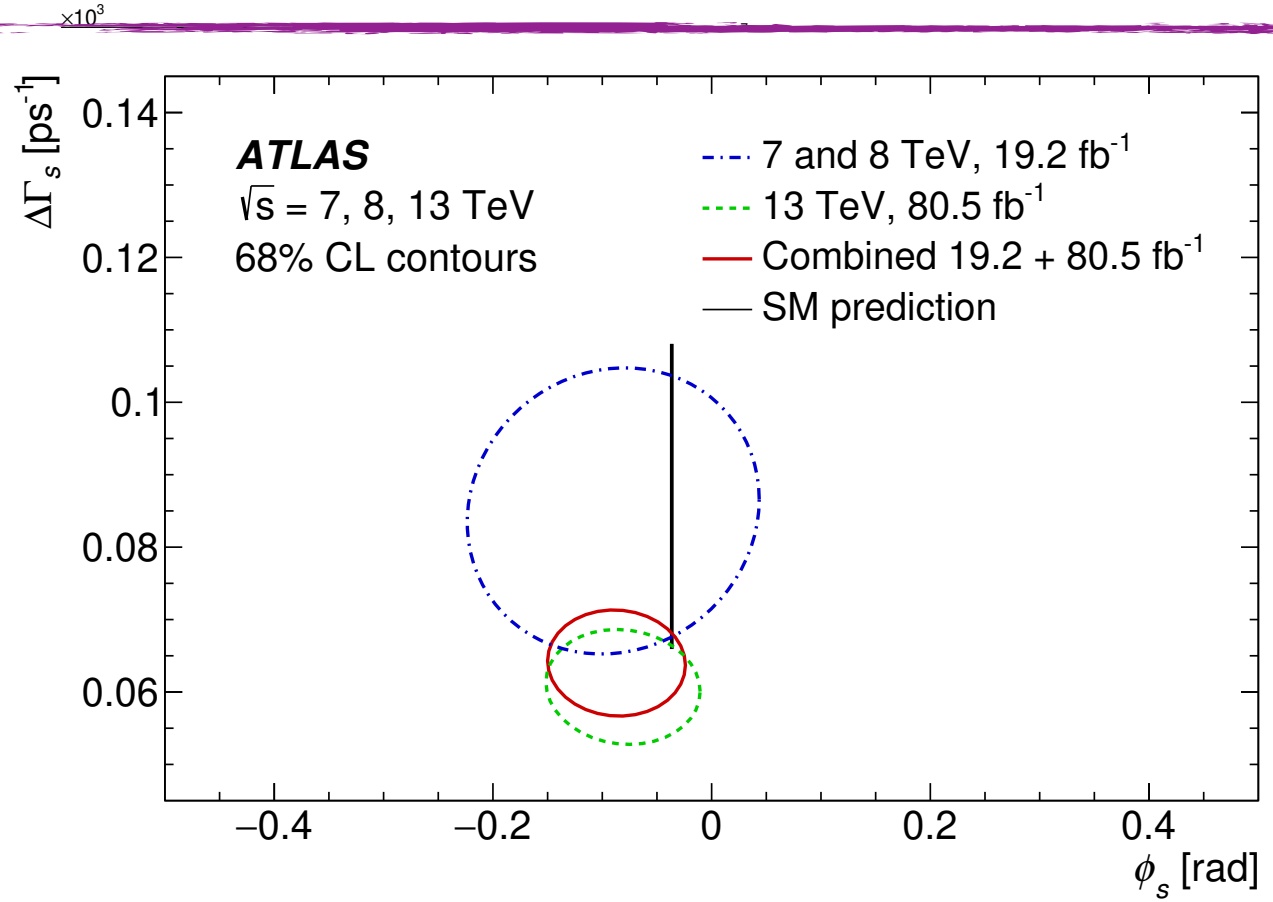
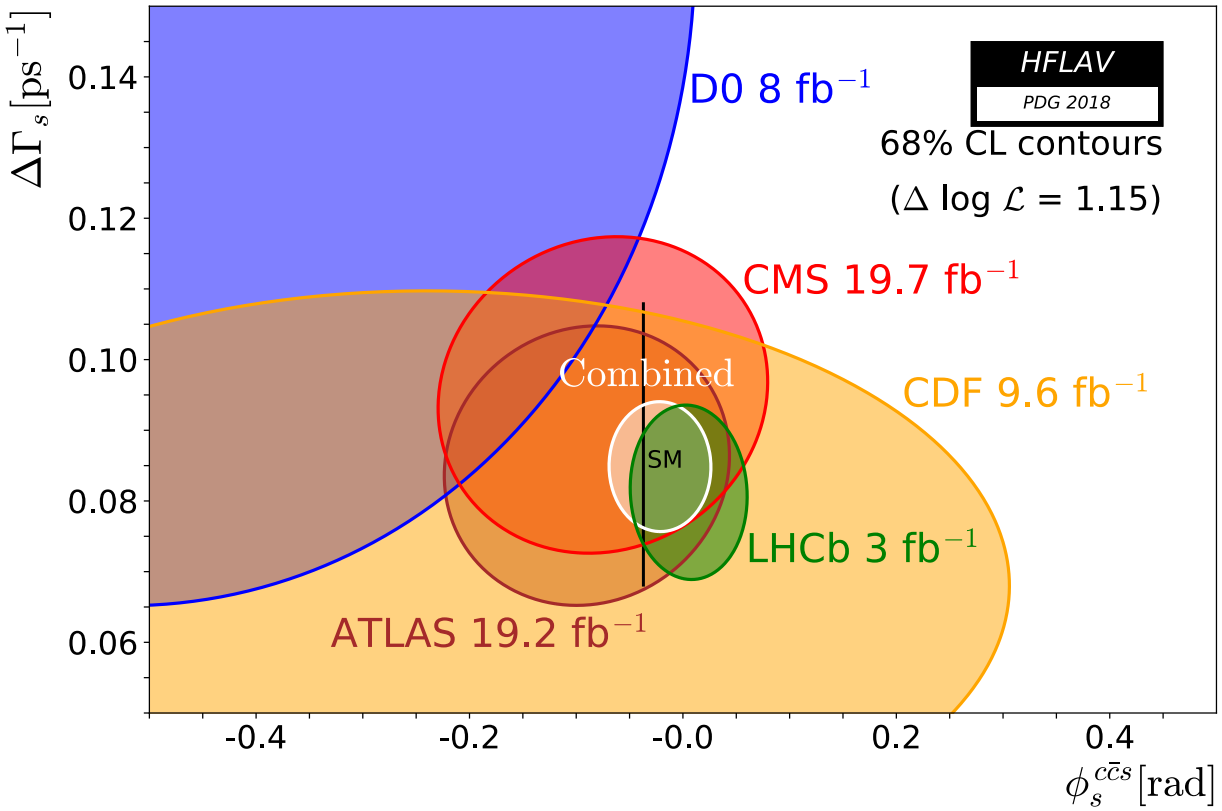


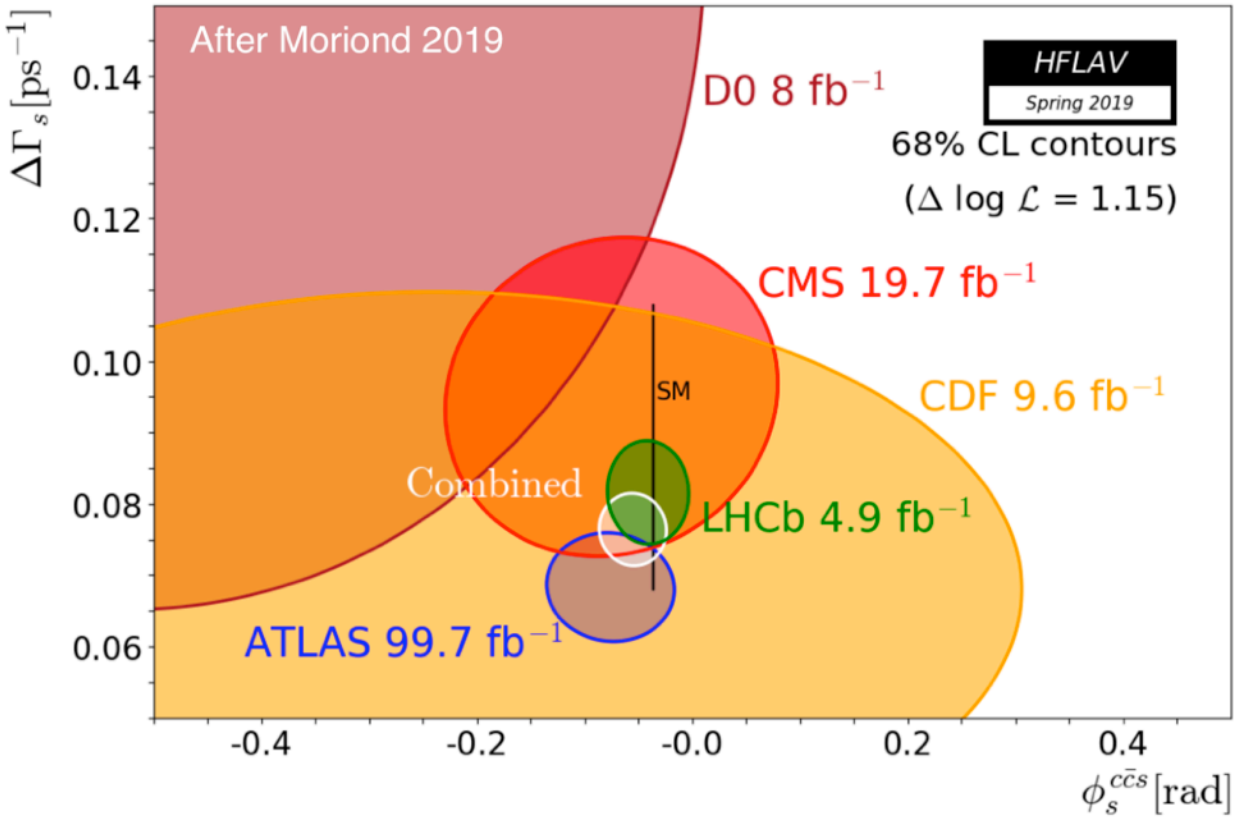
$$\phi_s = -0.087 \pm 0.037 \pm 0.019\,\mathrm{rad}$$

LHC Run 2 status of ϕ_s

- Including the LHCb and ATLAS results



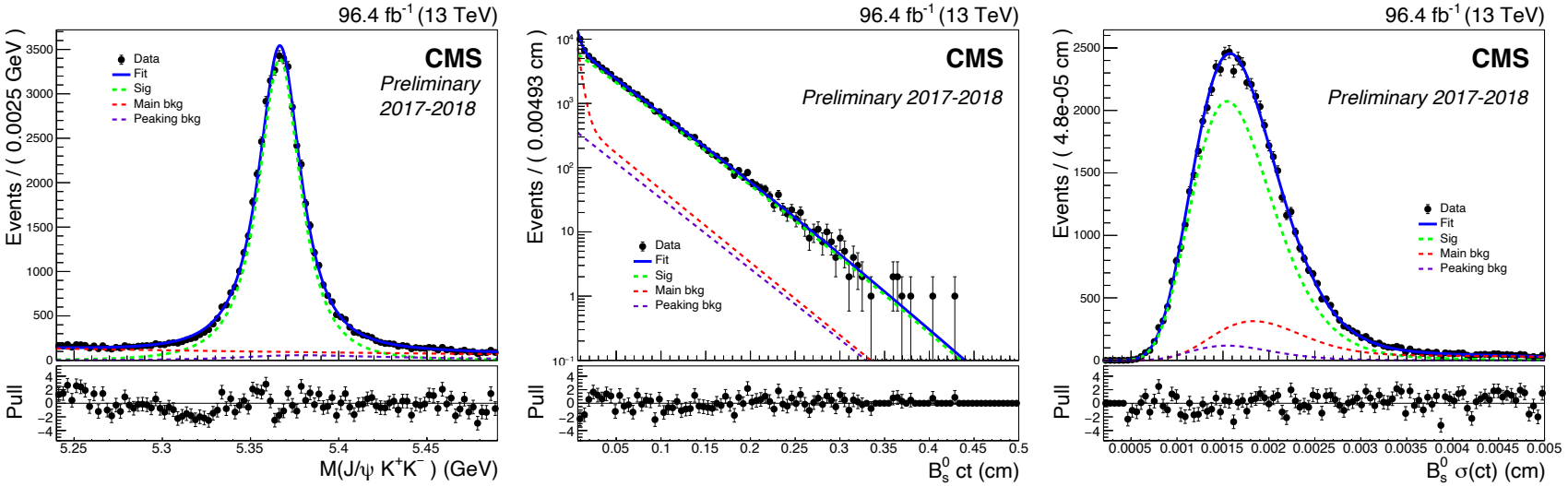
$$\phi_s = -0.021 \pm 0.031\,\mathrm{rad}$$



$$\phi_s = -0.055 \pm 0.021\,\mathrm{rad}$$

ϕ_s at CMS $B_s^0 \to J/\psi\phi$

- Update from Spring 2020
  - Analysis of the 2017-2018 Run 2 data sample
  - Multidimensional fit to B mass, decay time (error), decay angles etc
  - Tagging power increased from ~1% (Run 1) to ~10% for 2017/2018
  - Measurements in good agreement with previous results



Parameter	Fit result	Stat. uncer.	Syst. uncer.
ϕ_s [rad]	-0.011	± 0.050	± 0.010
$\Delta\Gamma_s$ [ps^{-1}]	0.114	± 0.014	± 0.007
Δm_s [$\hbar$ ps^{-1}]	17.51	$^{+0.10}_{-0.09}$	± 0.02
$\lvert\lambda\rvert$	0.972	± 0.026	± 0.008
Γ_s [ps^{-1}]	0.6531	± 0.0042	± 0.0024

For more details see talk by Alberto Bragagnolo

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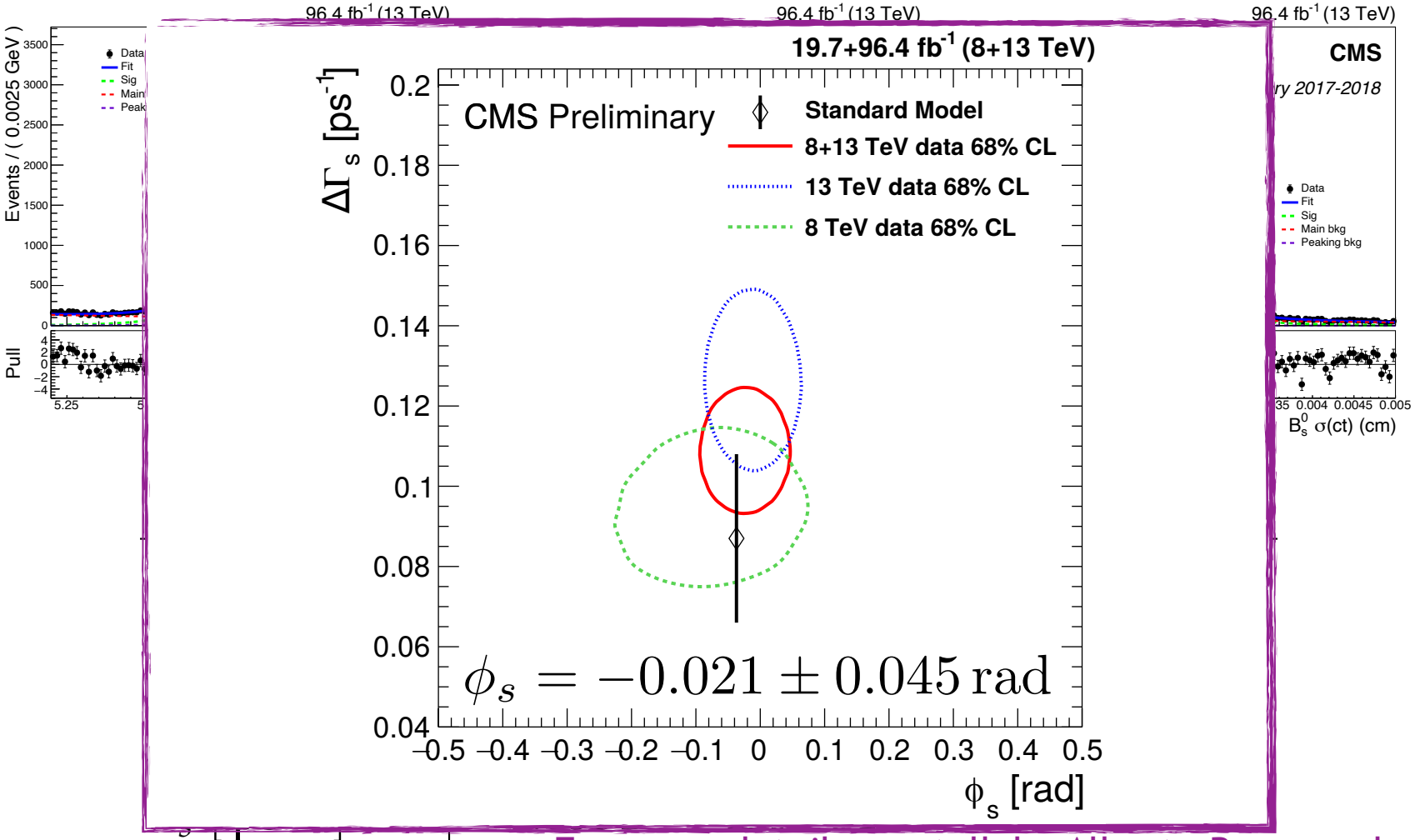
  - Combine with Run 1 results



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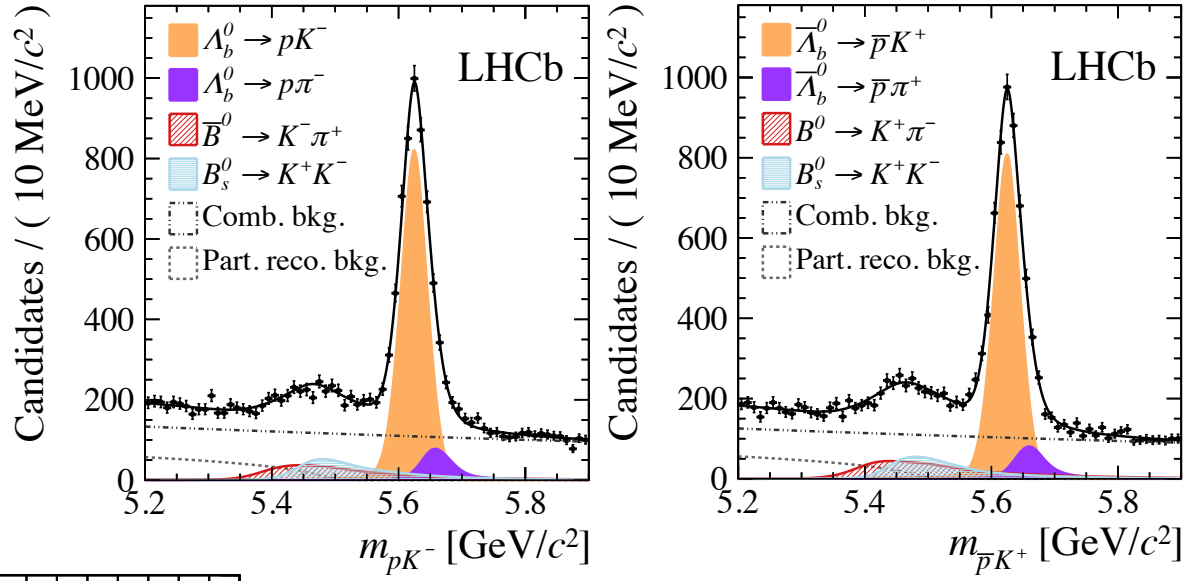
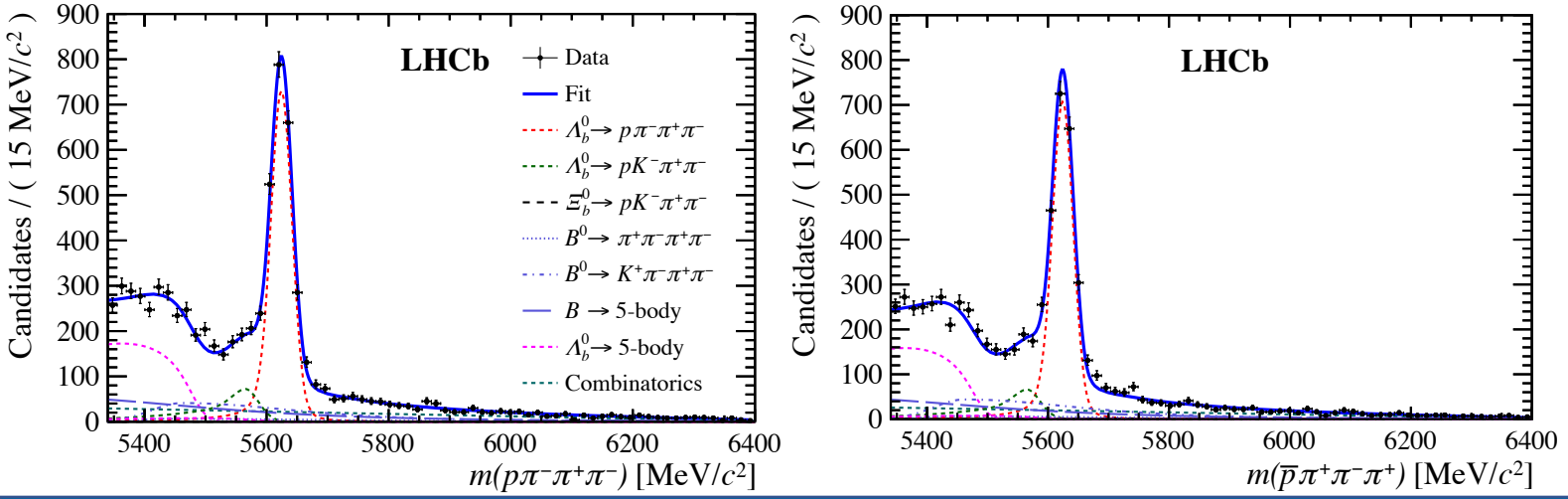
  - $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$

- Charmless B meson decays
  - $B^+ \to \pi^+\pi^+\pi^-$

CPV in B baryons

- Baryon CPV expected but, as yet, unobserved
- Several searches in the last years
  - $\Lambda_b^0 \to pK^-, p\pi^-$
  - No evidence of CP violation observed with Run 1 data





$\Lambda_b^0, \Xi_b^0 \to phhh$

- Evidence for CPV seen at 3.3σ
- Run 1 data
- Update needed!

Phys. Lett. B784 (2018) 124, Nature Phys. 13 (2017) 391–396(2017), Eur. Phys. J. C79 (2019) 745

CPV search in $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$ decays

- LHCb analysis with $6.6\ \mathrm{fb}^{-1}$ of data from Run 1 and 2 (2011-2017)
  - Four times more signal decays than previous analysis
  - Signal yield around 27600 candidates
  - Triple product asymmetries and unbinned energy test methods used

Scalar triple products

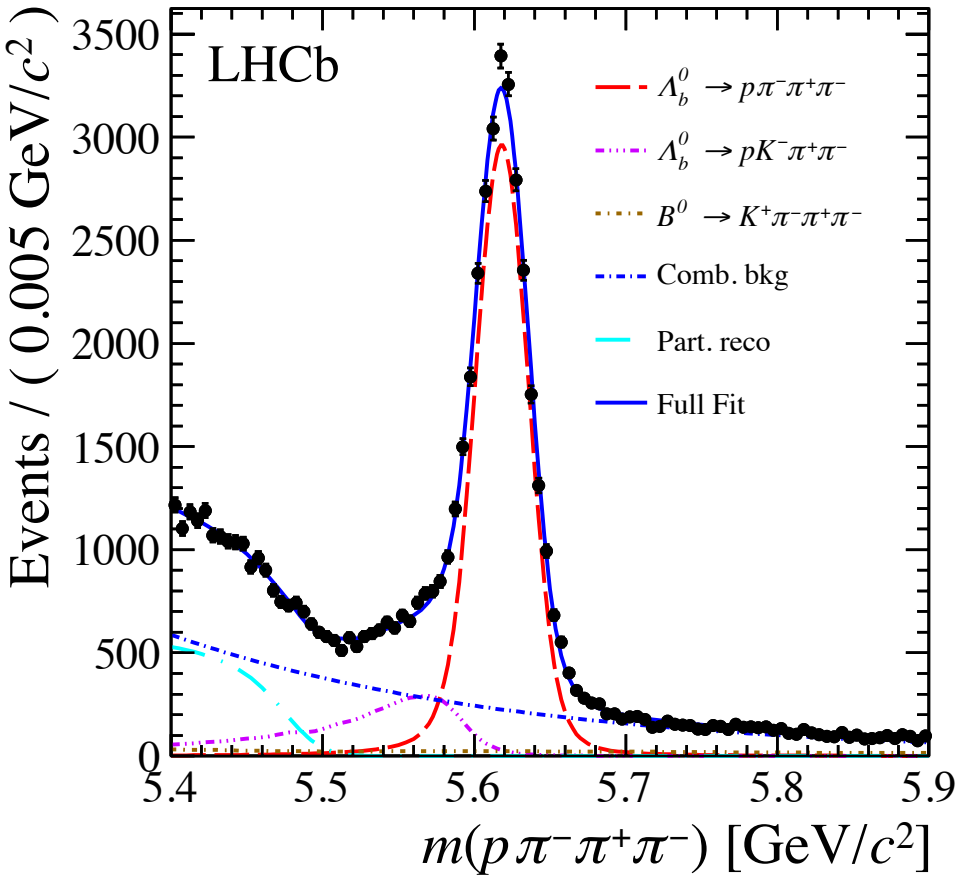
$$C_{\hat{T}} = \vec{p}_p \cdot \left(\vec{p}_{\pi^-_{\mathrm{fast}}} \times \vec{p}_{\pi^+}\right) \quad \overline{C}_{\hat{T}} = \vec{p}_{\overline{p}} \cdot \left(\vec{p}_{\pi^+_{\mathrm{fast}}} \times \vec{p}_{\pi^-}\right)$$

Triple product asymmetries

$$A_{\hat{T}} = \frac{N(C_{\hat{T}} > 0) - N(C_{\hat{T}} < 0)}{N(C_{\hat{T}} > 0) + N(C_{\hat{T}} < 0)}, \overline{A}_{\hat{T}} = \frac{\overline{N}(-\overline{C}_{\hat{T}} > 0) - \overline{N}(-\overline{C}_{\hat{T}} < 0)}{\overline{N}(-\overline{C}_{\hat{T}} > 0) + \overline{N}(-\overline{C}_{\hat{T}} < 0)}$$

CP and P violating asymmetries

$$a_{CP}^{\hat{T}\text{-odd}} = \frac{1}{2}\left(A_{\hat{T}} - \overline{A}_{\hat{T}}\right), \; a_P^{\hat{T}\text{-odd}} = \frac{1}{2}\left(A_{\hat{T}} + \overline{A}_{\hat{T}}\right)$$

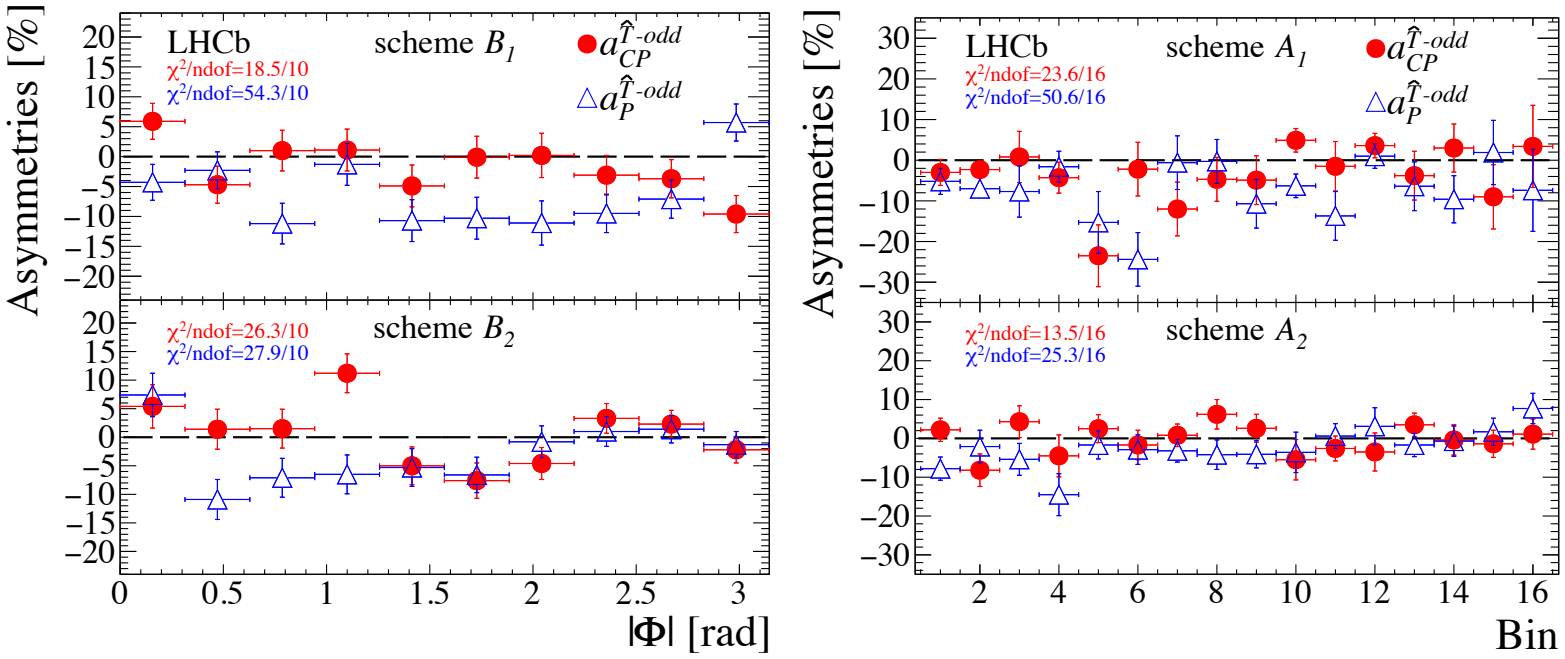


For more details see talk by Jinlin Fu

CPV search in $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$ decays

- Triple product results
  - CP conserved at ($> 2.9\sigma$)
  - P violation observed (5.5σ)

$$a_{CP}^{\widehat{T}\text{-odd}} = (-0.7 \pm 0.7 \pm 0.2)\%$$
$$a_{P}^{\widehat{T}\text{-odd}} = (-4.0 \pm 0.7 \pm 0.2)\%$$



- Energy test results
  - Compares two samples
  - P violation observed (5.3σ)
  - CP conserved at ($> 3.0\sigma$)

Distance scale δ	1.6 GeV$^2/c^4$	2.7 GeV$^2/c^4$	13 GeV$^2/c^4$
p-value (CP conservation, P even)	3.1×10^{-2}	2.7×10^{-3}	1.3×10^{-2}
p-value (CP conservation, P odd)	1.5×10^{-1}	6.9×10^{-2}	6.5×10^{-2}
p-value (P conservation)	1.3×10^{-7}	4.0×10^{-7}	1.6×10^{-1}

$$T \equiv \frac{1}{2n(n-1)} \sum_{i \neq j}^{n} \psi_{ij} + \frac{1}{2\overline{n}(\overline{n}-1)} \sum_{i \neq j}^{\overline{n}} \psi_{ij} - \frac{1}{n\overline{n}} \sum_{i=1}^{n} \sum_{j=1}^{\overline{n}} \psi_{ij}$$

For more details see talk by Jinlin Fu

Contents

- I can't cover everything - so try to focus on results since LHCP 2019

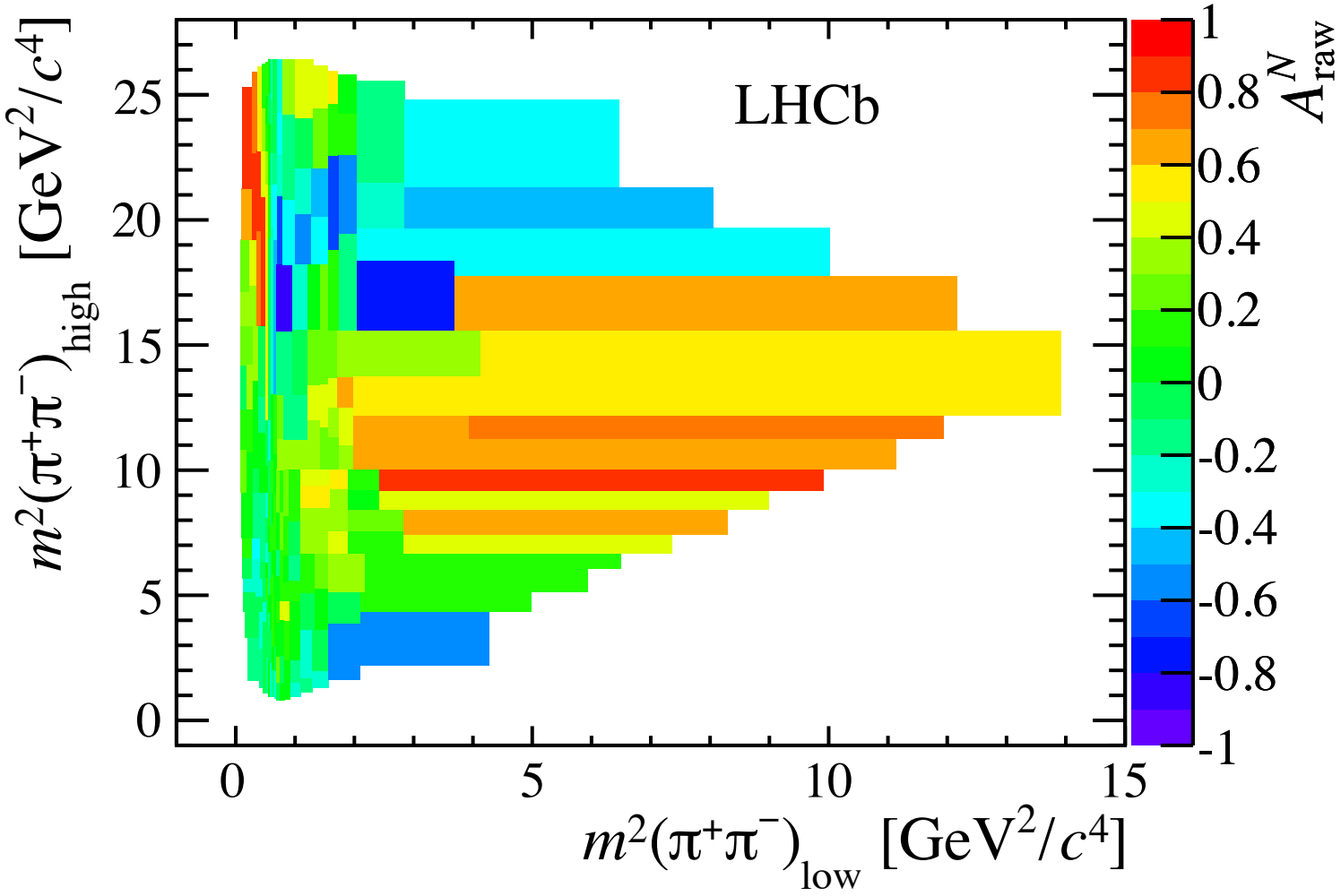
- Unitary triangle(s)
  - γ, β, ϕ_s

- Baryon CPV searches
  - $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$

- Charmless B meson decays
  - $B^+ \to \pi^+\pi^+\pi^-$

CPV in $B^+ \to \pi^+\pi^+\pi^-$

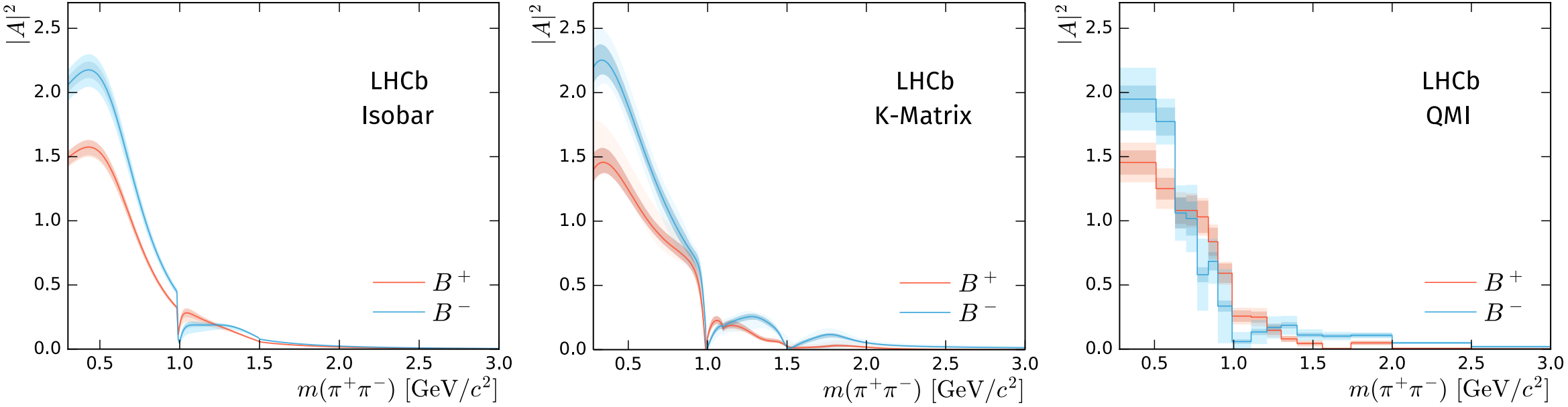
- Exciting results back in 2014
  - Large localised CPV seen
  - Quite a lot of interest and ideas
  - Rescattering effects?
- Amplitude analysis required to shed light on things
  - Arrived last year
  - Run 1 data sample
  - Around 20k signal candidates



Phys. Rev. D90 (2014) 112004

CPV in $B^+ \to \pi^+\pi^+\pi^-$

- Amplitude model implemented using the isobar model (except S-wave)
- Notoriously tricky S-wave models in 3 ways
  - Isobar with $KK \to \pi\pi$ rescattering
  - K-matrix, includes 5 rescattering couplings to intermediate states $\pi\pi, KK, \eta\eta, \eta\eta', 4\pi$
  - Quasi model independent, fit magnitude and phase in bins of the Dalitz plot



Phys. Rev. Lett. 124 (2020) 031801, Phys. Rev. D101 (2020) 012006

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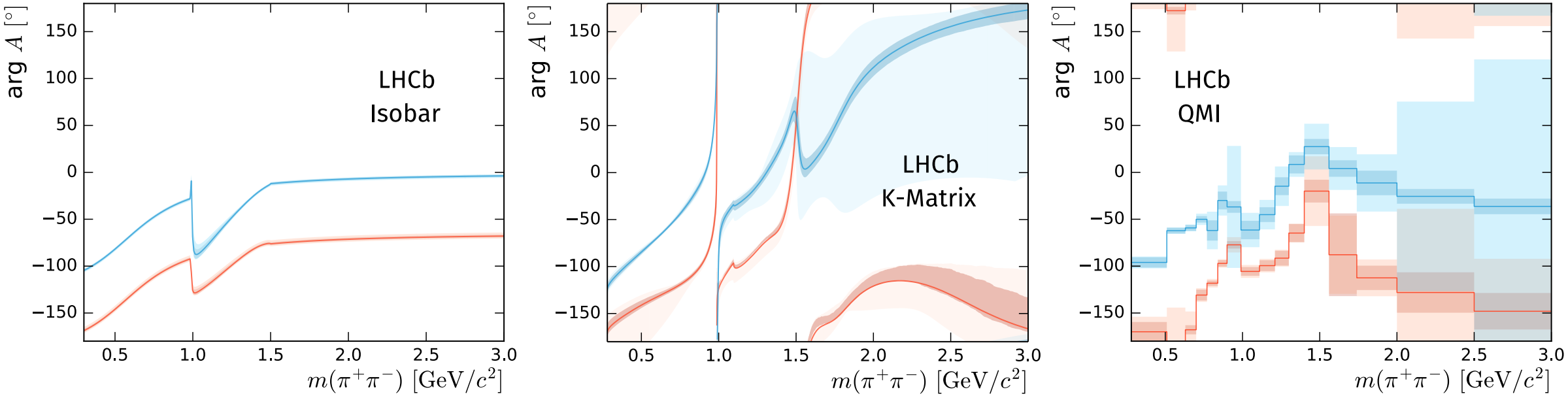


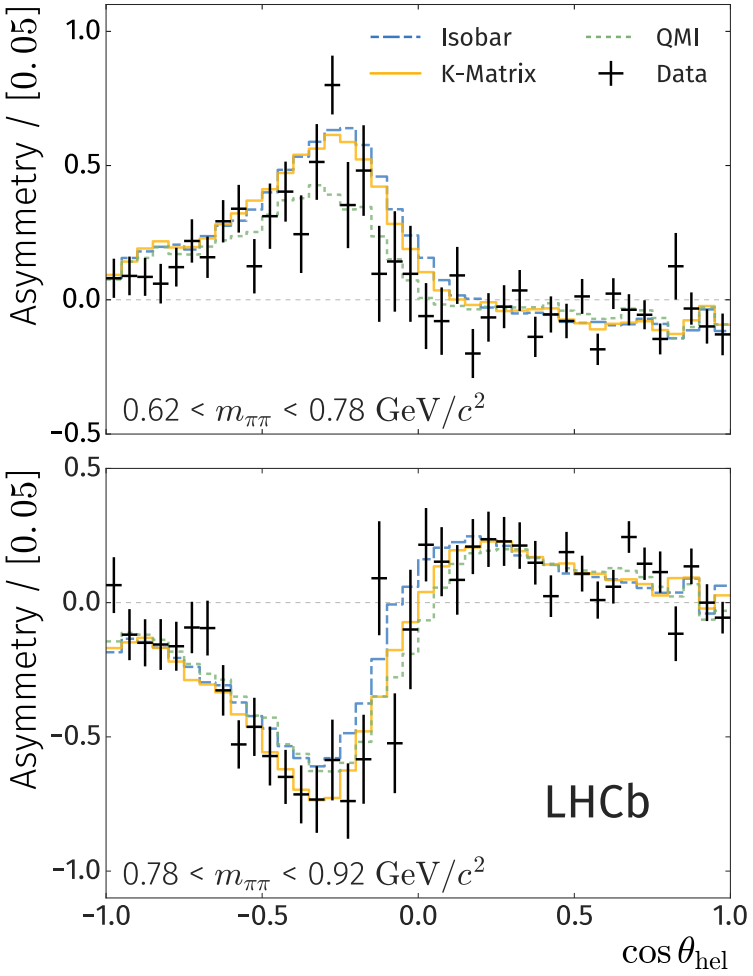
Phys. Rev. Lett. 124 (2020) 031801, Phys. Rev. D101 (2020) 012006

CPV in $B^+ \to \pi^+\pi^+\pi^-$

- Plethora of results in the papers to digest, focus only on CPV here
  - Large CP asymmetries seen in several regions of the Dalitz plot
  - Integrated CPV in the $\rho(770)^0$ resonance cancels but large effects seen above and below the pole

Component	Quasi-two-body CP asymmetries (10^{-2})
$\rho(770)^0$	$+0.7 \pm 1.1 \pm 0.6 \pm 4.0$
$\omega(782)$	$-4.8 \pm 6.5 \pm 1.3 \pm 4.7$
$f_2(1270)$	$+46.8 \pm 6.1 \pm 1.5 \pm 10.2$
$\rho(1450)^0$	$-12.9 \pm 3.3 \pm 3.6 \pm 41.9$
$\rho_3(1690)^0$	$-80.1 \pm 11.4 \pm 7.8 \pm 50.5$
S-wave	$+14.4 \pm 1.8 \pm 1.0 \pm 2.4$

Third uncertainty from the S-wave models



For more details see talk by Jinlin Fu

Phys. Rev. Lett. 124 (2020) 031801, Phys. Rev. D101 (2020) 012006

CPV in $B^+ \to \pi^+\pi^+\pi^-$

- Plethora of results in the papers to digest, focus only on CPV here
  - Large CP asymmetries seen in several regions of the Dalitz plot
  - Significant CPV in the $f_2(1270)$ resonance

Component	Quasi-two-body CP asymmetries (10^{-2})
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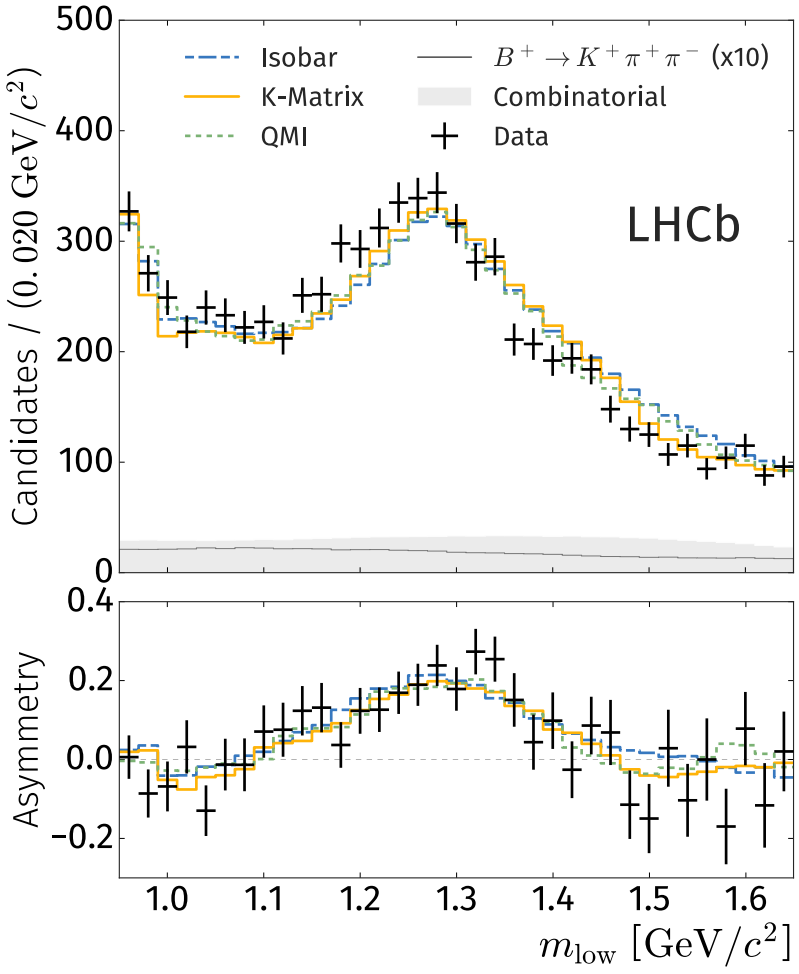

For more details see talk by Jinlin Fu

Phys. Rev. Lett. 124 (2020) 031801, Phys. Rev. D101 (2020) 012006

Summary

- Lots of work going on in CPV searches
  - Regardless of the final flavour anomaly explanations CPV is an excellent test of the SM
  - Expect to reach very interesting sensitivity in the coming years

- Lots to look forward to
  - Full LHCb Run 2 data sample results
  - Belle-II and LHCb Upgrade(s) entering the game

- Plenty of other CPV topics out there
  - Charm discovered recently, whole programme to follow
  - Semi-leptonic asymmetries $a_{\rm sl}^d, a_{\rm sl}^s$
  - Kaons…

Want to ask something else after the session?
https://cern.zoom.us/j/92275377556?pwd=NnRNaHV4dmdwM3VSRFE1QXN5TGVnUT09

Looking forward

Table 10.1: Summary of prospects for future measurements of selected flavour observables for LHCb, Belle II and Phase-II ATLAS and CMS. The projected LHCb sensitivities take no account of potential detector improvements, apart from in the trigger. The Belle-II sensitivities are taken from Ref. [608].

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}	–

arXiv:1808.08865 [hep-ex]

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$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$	6% [201]	3%	1%	1%	–

arXiv:1808.08865 [hep-ex]

Back ups

GLW/ADS analysis with $B^0 \to DK^{*0}$ decays

$$\mathcal{A}_{CP} \equiv \frac{\Gamma(\overline{B}^0 \to D_{CP}\overline{K}^{*0}) - \Gamma(B^0 \to D_{CP}K^{*0})}{\Gamma(\overline{B}^0 \to D_{CP}\overline{K}^{*0}) + \Gamma(B^0 \to D_{CP}K^{*0})},$$

$$\mathcal{A}_{CP} = \frac{2\kappa r_B^{DK^{*0}} \sin\delta_B^{DK^{*0}} \sin\gamma}{\mathcal{R}_{CP}},$$

$$\mathcal{R}_{CP} \equiv 2\frac{\Gamma(\overline{B}^0 \to D_{CP}\overline{K}^{*0}) + \Gamma(B^0 \to D_{CP}K^{*0})}{\Gamma(\overline{B}^0 \to D^0\overline{K}^{*0}) + \Gamma(B^0 \to \overline{D}^0K^{*0})}.$$

$$\mathcal{R}_{CP} = 1 + \left(r_B^{DK^{*0}}\right)^2 + 2\kappa r_B^{DK^{*0}} \cos\delta_B^{DK^{*0}} \cos\gamma.$$

$$\mathcal{A}_{\rm ADS}^{\pi K} \equiv \frac{\Gamma(\overline{B}^0 \to D(\pi^-K^+)\overline{K}^{*0}) - \Gamma(B^0 \to D(\pi^+K^-)K^{*0})}{\Gamma(\overline{B}^0 \to D(\pi^-K^+)\overline{K}^{*0}) + \Gamma(B^0 \to D(\pi^+K^-)K^{*0})},$$

$$\mathcal{A}_{\rm ADS}^{\pi K} = \frac{2\kappa r_B^{DK^{*0}} r_D^{K\pi} \sin(\delta_B^{DK^{*0}} + \delta_D^{K\pi}) \sin\gamma}{(r_B^{DK^{*0}})^2 + (r_D^{K\pi})^2 + 2\kappa r_B^{DK^{*0}} r_D^{K\pi} \cos(\delta_B^{DK^{*0}} + \delta_D^{K\pi}) \cos\gamma},$$

$$\mathcal{R}_{\rm ADS}^{\pi K} \equiv \frac{\Gamma(\overline{B}^0 \to D(\pi^-K^+)\overline{K}^{*0}) + \Gamma(B^0 \to D(\pi^+K^-)K^{*0})}{\Gamma(\overline{B}^0 \to D(K^-\pi^+)\overline{K}^{*0}) + \Gamma(B^0 \to D(K^+\pi^-)K^{*0})},$$

$$\mathcal{R}_{\rm ADS}^{\pi K} = \frac{(r_B^{DK^{*0}})^2 + (r_D^{K\pi})^2 + 2\kappa r_B^{DK^{*0}} r_D^{K\pi} \cos(\delta_B^{DK^{*0}} + \delta_D^{K\pi}) \cos\gamma}{1 + (r_B^{DK^{*0}} r_D^{K\pi})^2 + 2\kappa r_B^{DK^{*0}} r_D^{K\pi} \cos(\delta_B^{DK^{*0}} + \delta_D^{K\pi}) \cos\gamma}.$$

GLS analysis with $B^+ \to DK^+$ decays

$$
\begin{aligned}
N_{\mathrm{SS}}^{DK^\pm} &\propto 1 + r_B^2 r_D^2 + 2 r_B r_D \kappa_D \cos(\delta_B \pm \gamma - \delta_D)\,, \\
N_{\mathrm{OS}}^{DK^\pm} &\propto r_B^2 + r_D^2 + 2 r_B r_D \kappa_D \cos(\delta_B \pm \gamma + \delta_D)\,, \\
N_{\mathrm{SS}}^{D\pi^\pm} &\propto 1 + (r_B^\pi)^2 r_D^2 + 2 r_B^\pi r_D \kappa_D \cos(\delta_B^\pi \pm \gamma - \delta_D)\,, \\
N_{\mathrm{OS}}^{D\pi^\pm} &\propto (r_B^\pi)^2 + r_D^2 + 2 r_B^\pi r_D \kappa_D \cos(\delta_B^\pi \pm \gamma + \delta_D)\,.
\end{aligned}
$$

$$
A_m^{Dh} = \frac{N_m^{Dh^-} - N_m^{Dh^+}}{N_m^{Dh^-} + N_m^{Dh^+}}
$$

where $m \in \{\mathrm{SS}, \mathrm{OS}\}$ and $h \in \{\pi, K\}$.

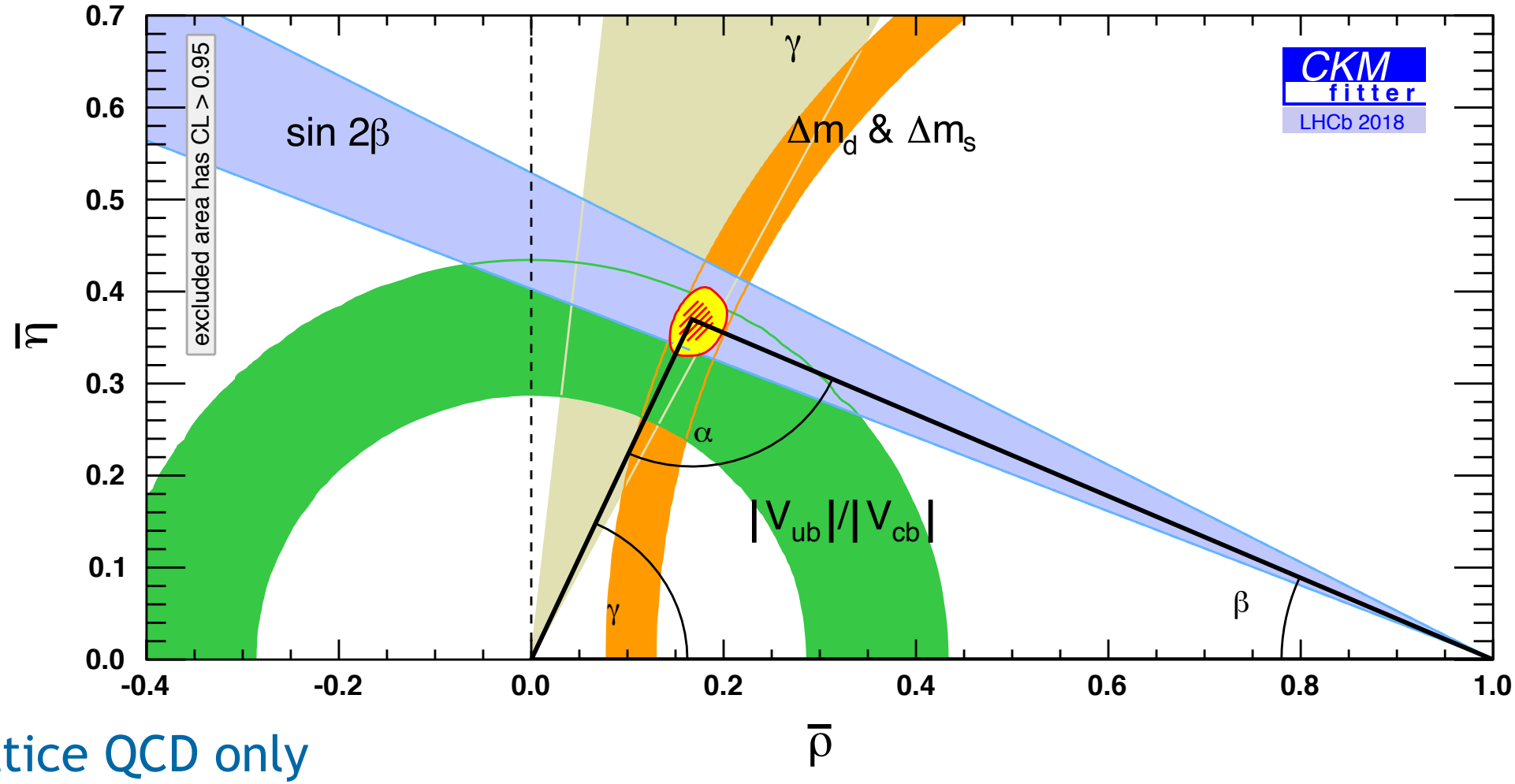
Measuring CPV with $B^0 \to D^{*\pm} D^{\mp}$ decays

$$S_{D^*D} = \frac{1}{2}(S_f + S_{\bar{f}}),$$
$$\Delta S_{D^*D} = \frac{1}{2}(S_f - S_{\bar{f}}),$$

$$S_f = \frac{2R\sin(2\beta+\delta)}{1+R^2},\ S_{\bar{f}} = \frac{2R\sin(2\beta-\delta)}{1+R^2}$$

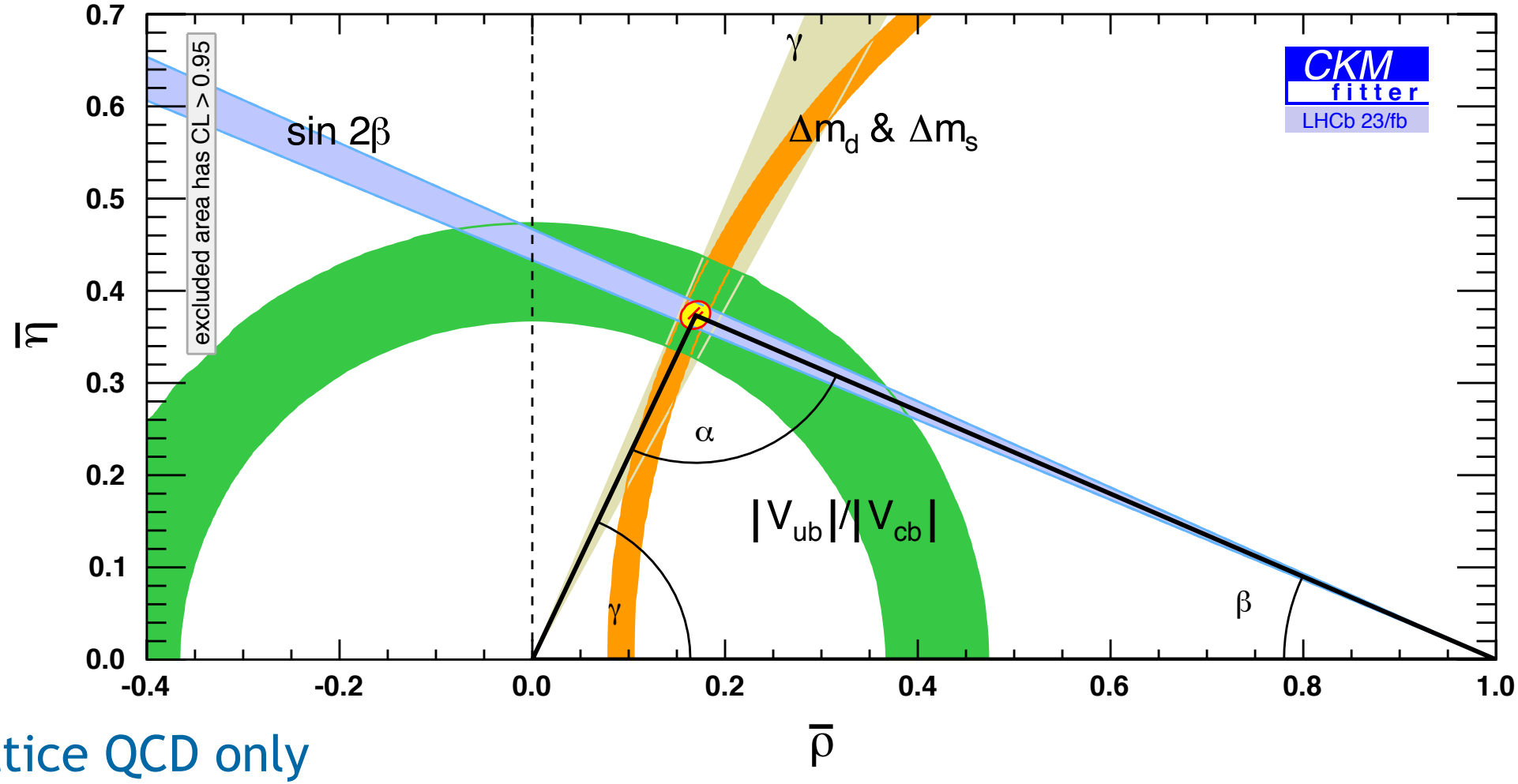
$$S_{D^*D} = \frac{2R\sin(2\beta)\cos(\delta)}{1+R^2},\ \Delta S_{D^*D} = \frac{2R\sin(\delta)\cos(2\beta)}{1+R^2}$$

Today



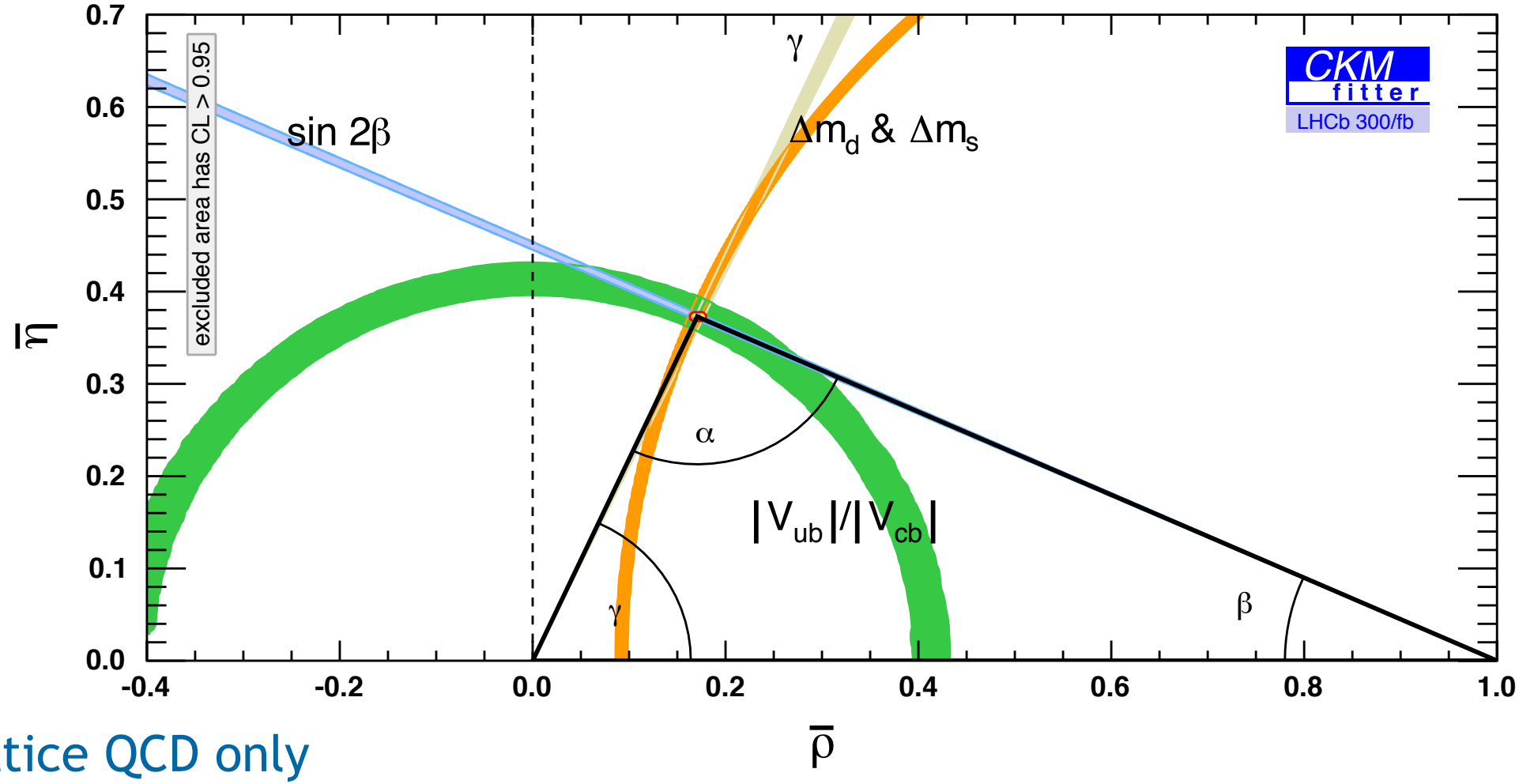
LHCb + lattice QCD only

Pre HL-LHC



LHCb + lattice QCD only

After HL-LHC



LHCb + lattice QCD only