CP violation in beauty and charm: current status and future prospects

Presenting results mostly from LHCb, but also some from ATLAS & CMS, Babar & Belle, and CDF & D0.

Guy Wilkinson
University of Oxford
Blois 2018, 5/6/18

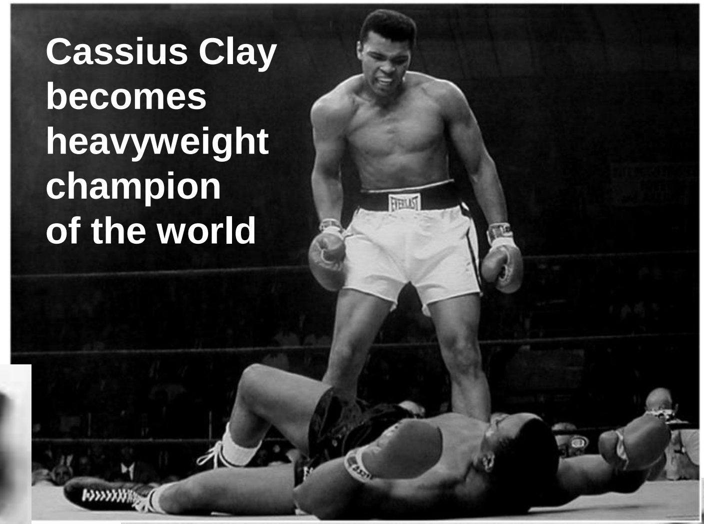
Contents

- Introduction
- The Unitarity Triangle: γ and β
- Hunting for CPV in the B_s system
- The quest for the vanishingly small: CPV in charm
- Prospects
- Conclusions

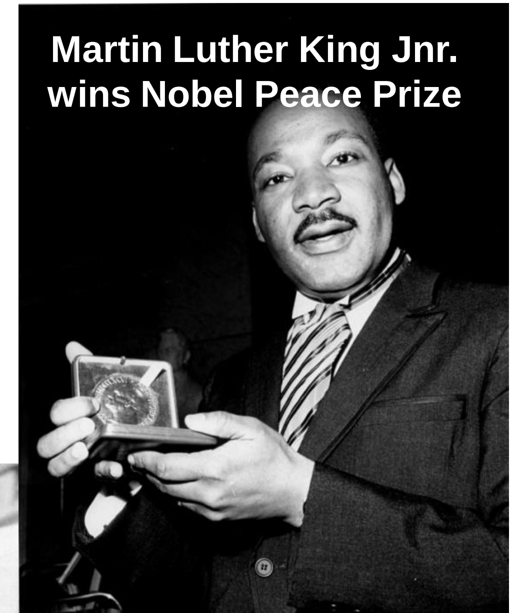
Purposefully a selective review talk, concentrating on the general state of play (and with an emphasis on LHCb). For hot-off-the-press results, please attend the parallel session !

Events of 1964

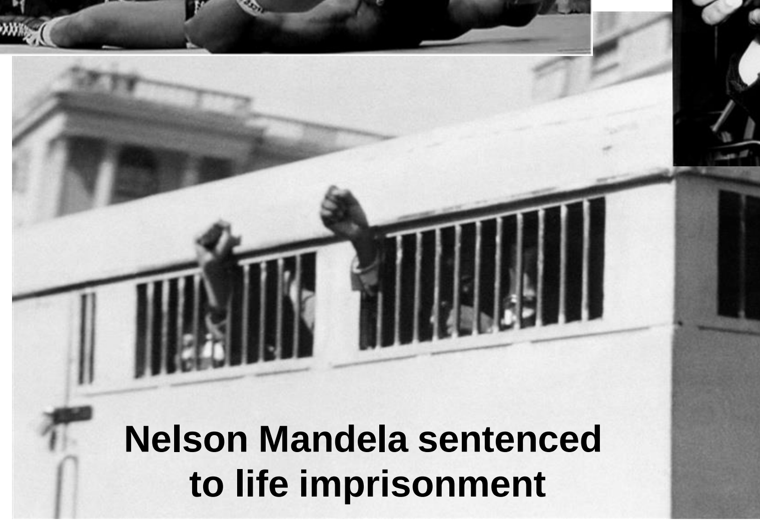
Change of face in the Kremlin



Cassius Clay becomes heavyweight champion of the world

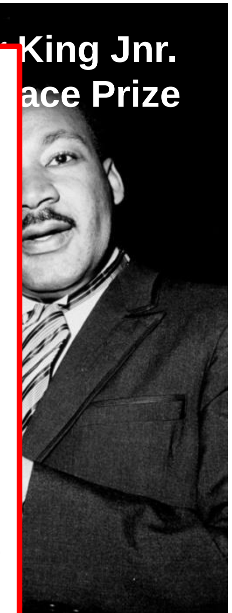


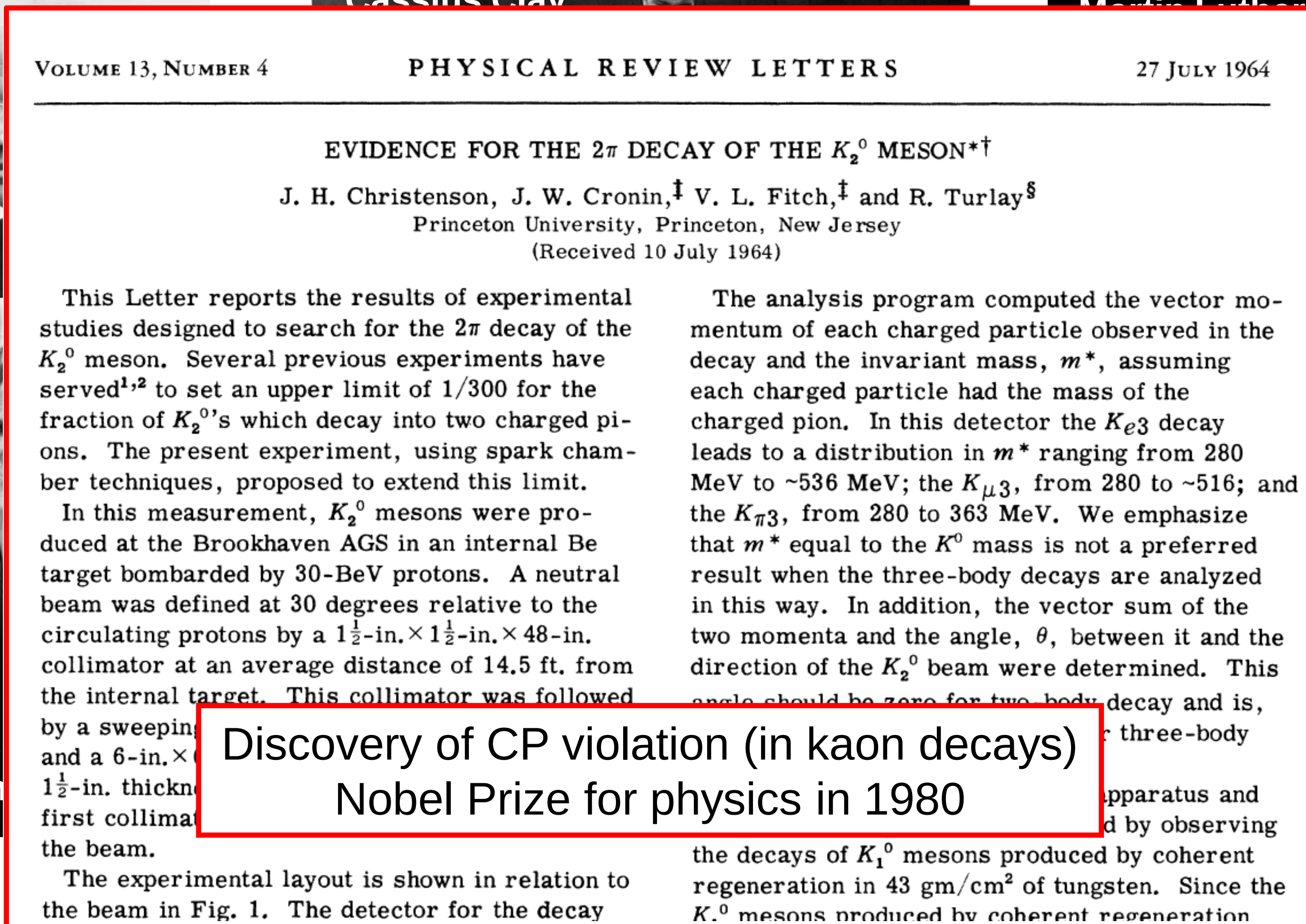
Martin Luther King Jnr. wins Nobel Peace Prize



Nelson Mandela sentenced to life imprisonment

Events of 1964





VOLUME 13, NUMBER 4 PHYSICAL REVIEW LETTERS 27 JULY 1964

EVIDENCE FOR THE 2π DECAY OF THE K_2^0 MESON*†

J. H. Christenson, J. W. Cronin,‡ V. L. Fitch,‡ and R. Turlay§
Princeton University, Princeton, New Jersey

(Received 10 July 1964)

This Letter reports the results of experimental studies designed to search for the 2π decay of the K_2^0 meson. Several previous experiments have served[1,2] to set an upper limit of 1/300 for the fraction of K_2^0's which decay into two charged pions. The present experiment, using spark chamber techniques, proposed to extend this limit.

In this measurement, K_2^0 mesons were produced at the Brookhaven AGS in an internal Be target bombarded by 30-BeV protons. A neutral beam was defined at 30 degrees relative to the circulating protons by a $1\frac{1}{2}$-in.$\times 1\frac{1}{2}$-in.$\times$48-in. collimator at an average distance of 14.5 ft. from the internal target. This collimator was followed by a sweepin[...] and a 6-in.$\times$[...] $1\frac{1}{2}$-in. thickn[...] first collima[...] the beam.

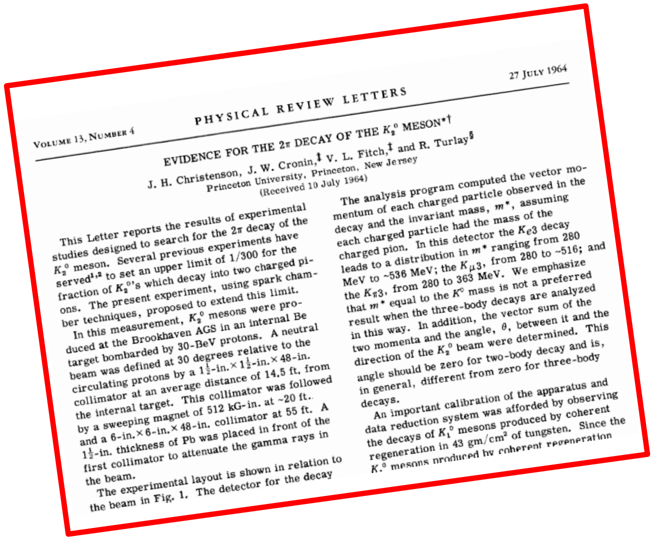
The experimental layout is shown in relation to the beam in Fig. 1. The detector for the decay

The analysis program computed the vector momentum of each charged particle observed in the decay and the invariant mass, m^*, assuming each charged particle had the mass of the charged pion. In this detector the K_{e3} decay leads to a distribution in m^* ranging from 280 MeV to ~536 MeV; the $K_{\mu3}$, from 280 to ~516; and the $K_{\pi3}$, from 280 to 363 MeV. We emphasize that m^* equal to the K^0 mass is not a preferred result when the three-body decays are analyzed in this way. In addition, the vector sum of the two momenta and the angle, θ, between it and the direction of the K_2^0 beam were determined. This angle should be zero for two-body decay and is, [...] three-body [...]

[...]pparatus and [...]d by observing the decays of K_1^0 mesons produced by coherent regeneration in 43 gm/cm² of tungsten. Since the K_1^0 mesons produced by coherent regeneration

Discovery of CP violation (in kaon decays)
Nobel Prize for physics in 1980

2000+: the beautiful millennium



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An important calibration of the apparatus and data reduction system was afforded by observing the decays of K_1^0 mesons produced by coherent regeneration in 43 gm/cm² of tungsten. Since the regeneration by coherent regeneration K_1^0 mesons produced by coherent regeneration

Observation of CP violation (CPV)
was a major discovery in physics...

…and one with clear cosmological connections (*i.e.* Sakharov conditions).

Accommodated, but not explained, in
the SM, through imaginary phase in CKM matrix.

After initial discovery, further experimental progress slow, due to small size of effect, and hadronic uncertainties, in the kaon system. These problems are largely absent in beauty, & since the early years of this century we have been living in a new era of CPV exploration, thanks to the B-factories, the Tevatron & now the LHC.

CPV in the Standard Model

In the Standard Model CP violation only appears through the weak interaction, entering as a single complex phase in the Cabibbo-Kobayashi-Maskawa matrix.

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

This 3x3 matrix contains only 4 independent parameters.

A popular representation is the Wolfenstein parameterisation, in which the matrix is expanded in orders of λ ~ 0.23.

$$V_{CKM} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

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Note that at this order only two elements are complex: V_{ub} and V_{td}.

Unitary nature of the matrix results in relations that can be expressed geometrically.

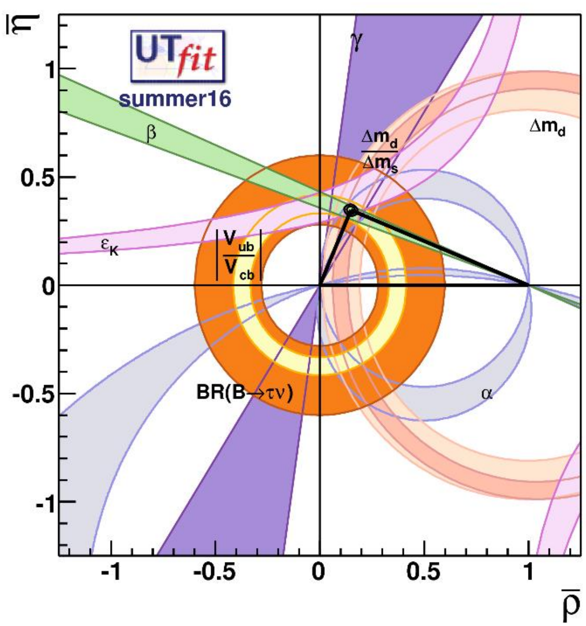
The Unitarity Triangle

The Unitarity Triangle is a geometrical description of *CP*-violation within the context of the Standard Model, which in the flavour sector is the CKM mechanism.

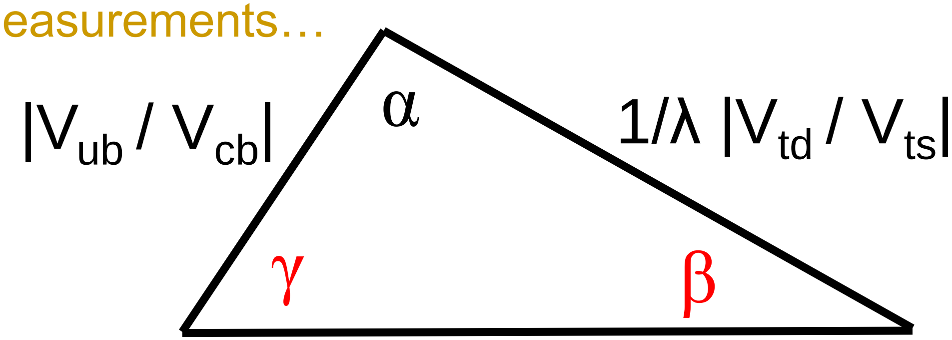
(In fact there are several Unitarity Triangles, but here we refer to the one whose angles are accessible in B^0 and $B^{+/-}$ decays.)

We must check its consistency through *precise* measurements.

The *B* factories did a fantastic job and showed that the CKM paradigm dominates the picture, but New Physics contributions can still be lurking at ~20% level.



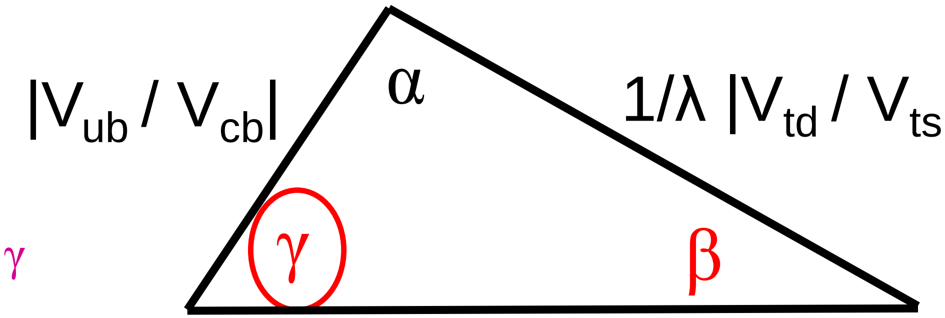
Let's review recent progress in CP-violation measurements…



…for the two key angles γ and β.

(*Loosely* speaking we can regard γ as the phase of V_{ub}, and β as that of V_{td}, but of course they are really phase *differences* w.r.t. other collections of elements.)

The Unitarity Triangle: γ



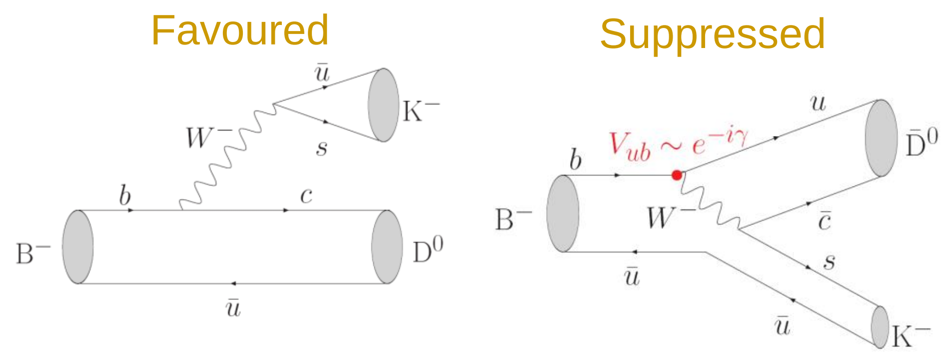
A precise measurement of the angle γ is a raison d'être of LHCb.

Look in $B^{\pm} \rightarrow DK^{\pm}$ decays using common mode for D^0 & $\bar{D}^0$

→ γ sensitive interference

→ different rates for B^+ & B^- (CPV!)

Many possibilities: *Kπ*, *KK*, *Kπππ*...

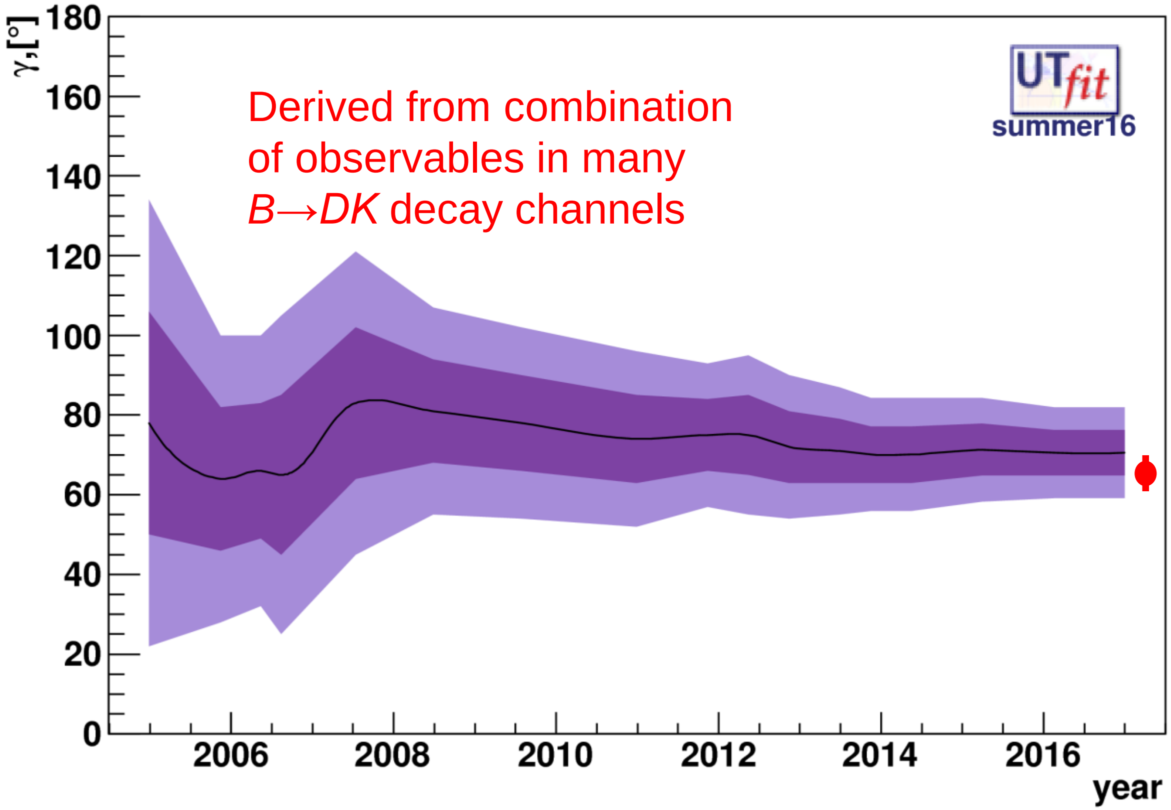


Tree-level decays: strategy very clean & yields result unpolluted by New Physics

This is a good thing! Provides SM benchmark against which other loop-driven NP sensitive observables can be compared (*e.g.* $\Delta m_d/\Delta m_s$, sin2*β*, γ measured in $B \rightarrow hh$)

γ measurement – the last ~10 years

The story so far...



Consistent with the indirect prediction...

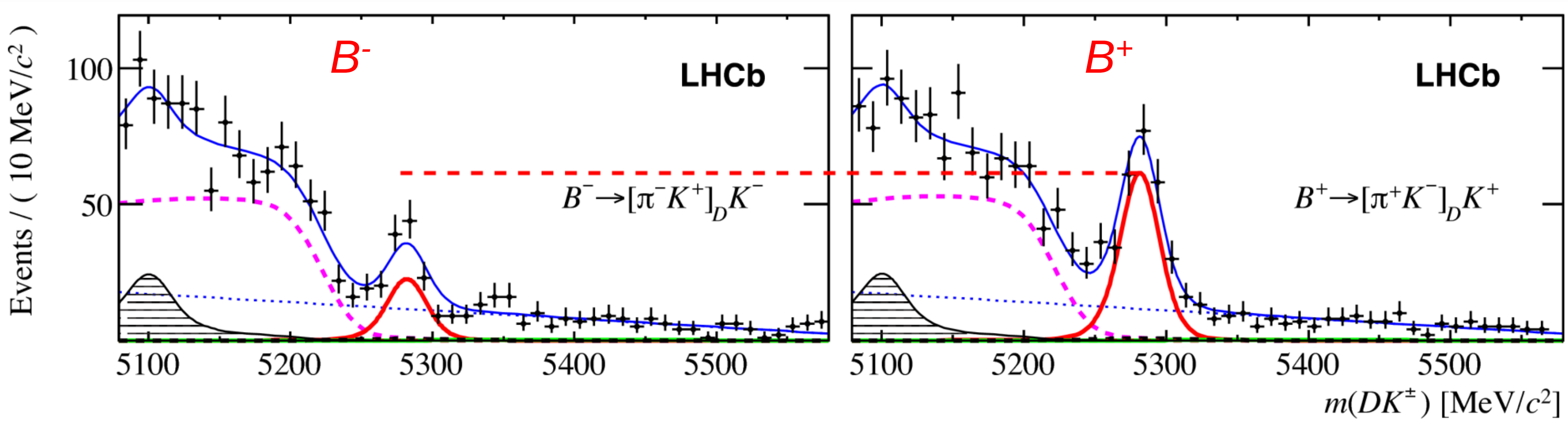
...but not nearly as precise

Indirect prediction from rest of triangle

...factor ~4 improvement in ~10 years.

γ measurement: true precision needs statistical muscle of LHCb

Rare, important decays just beyond the reach of the B-factories (*e.g.* the suppressed 'ADS' $B^\pm \rightarrow (K^\mp \pi^\pm)_D K^\pm$ mode (BR ~ 10^{-7}) was soon seen at LHCb and is now being exploited for high-precision CP-violation measurements.



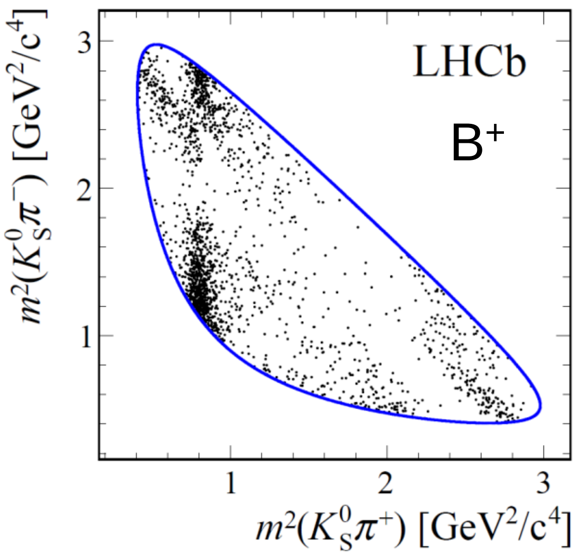
[PLB 760 (2016) 117]

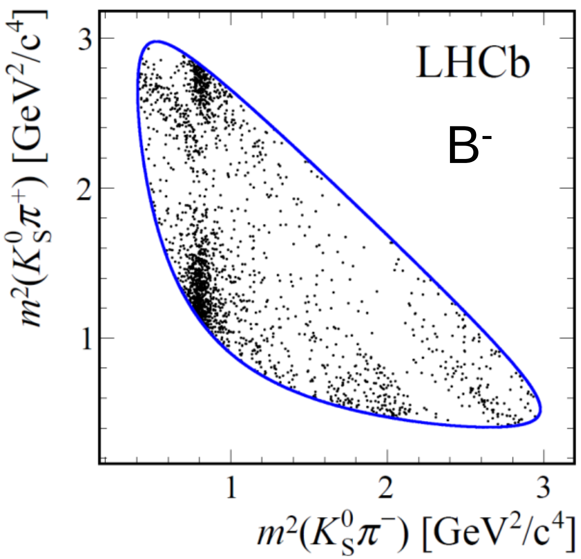
This CP asymmetry carries ultra-clean, easy to interpret, information on γ !

γ measurement at LHCb with $B\to DK$ decays: $D\to K_S\pi\pi$ (and K_SKK) with run-2 data [arXiv:1806.01202]

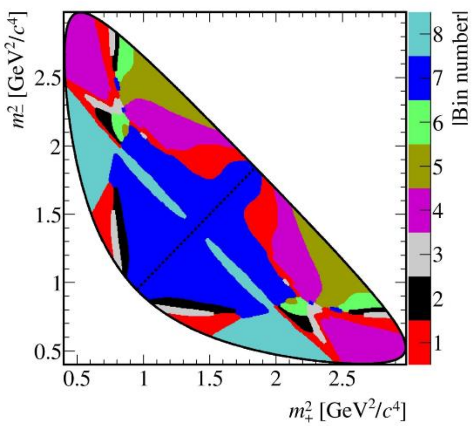
A powerful sub-set of $B\to DK$ analyses is when the D decays into a multibody final state, of which $K_S\pi\pi$ is the most prominent example. Variation of D strong phase over Dalitz space leads to corresponding variation in interference and CP violation.

Analysis of ~3000 decays from 2 fb^{-1} of early run-2 data





Study yields in bins of Dalitz space, chosen for optimal sensitivity.



Info. on D strong phases comes from charm threshold [CLEO, PRD 82 (2010) 112006]
Nice synergy between facilities, which gives measurement model independence.

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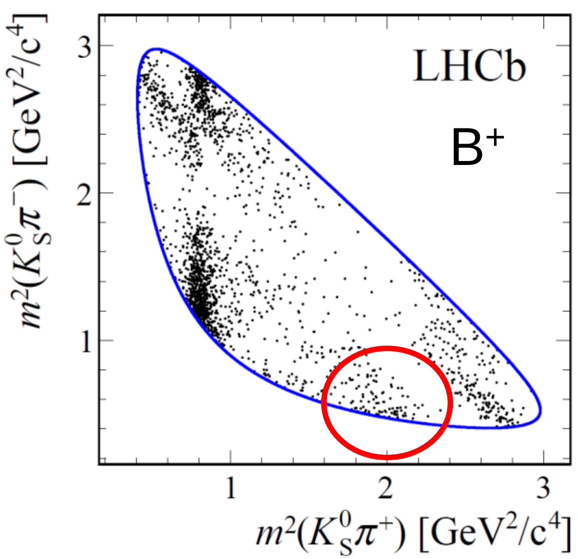

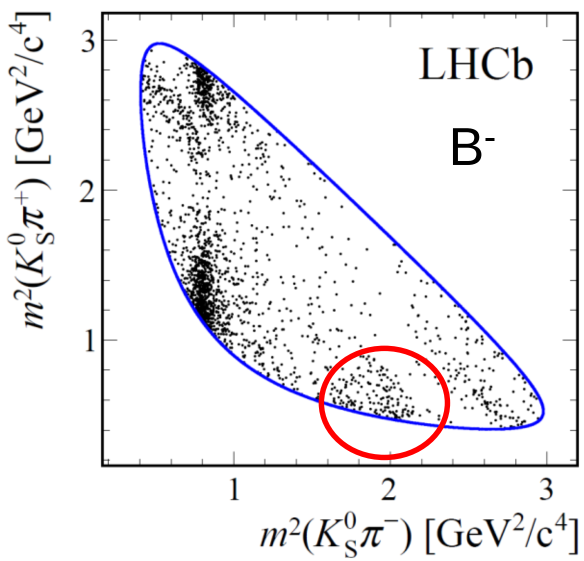

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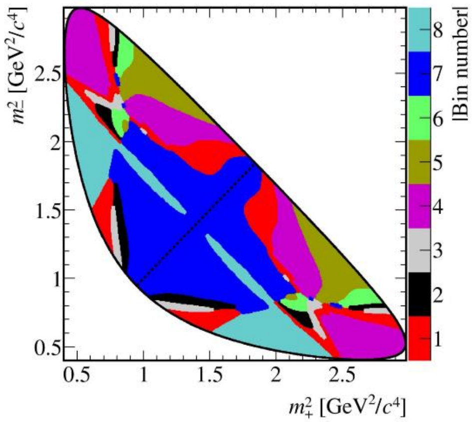

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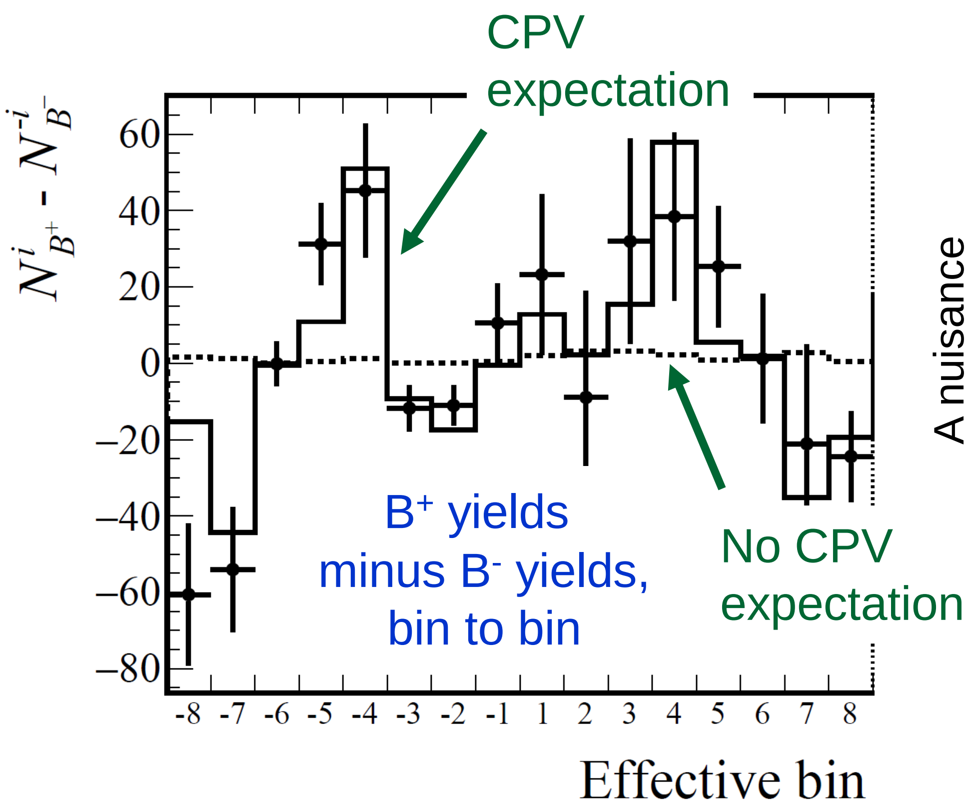
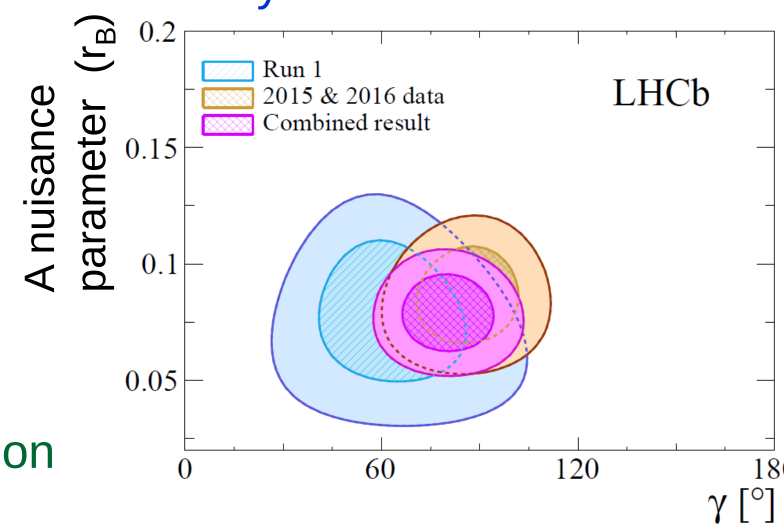


Compatible with run-1 analysis of same channel

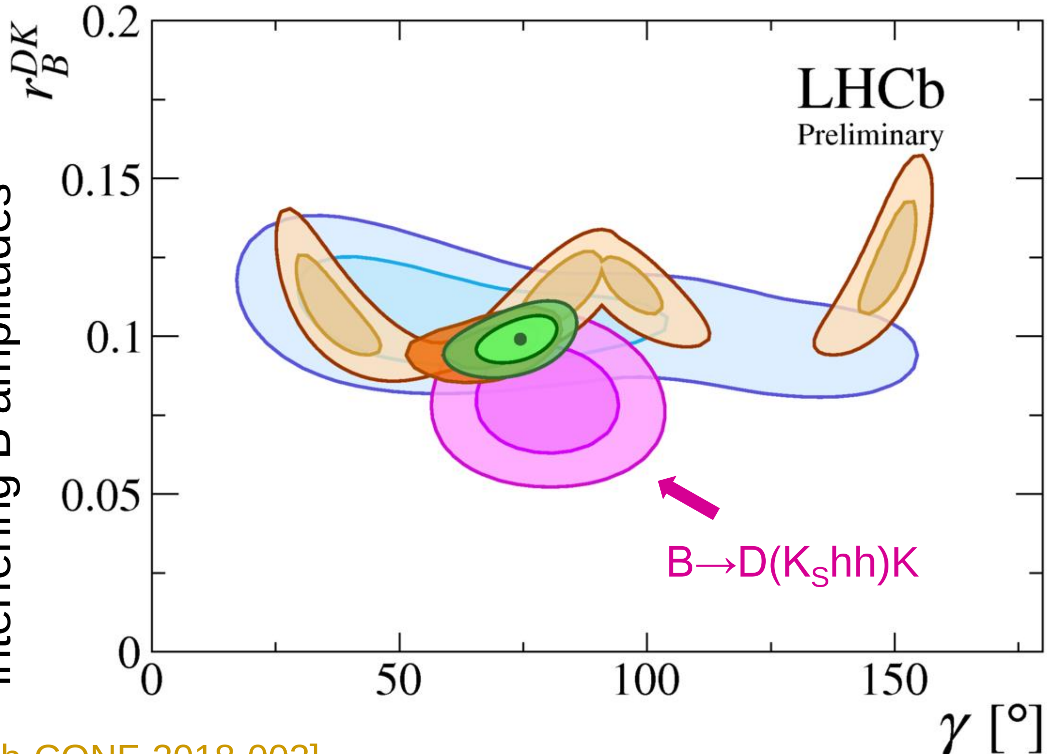


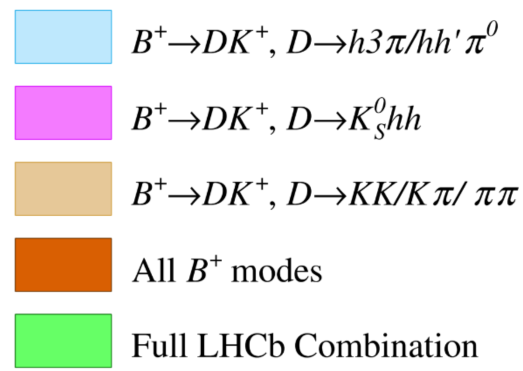
Together gives: $$\gamma = 80^\circ \,{}^{+10^\circ}_{-9^\circ}$$

LHCb: combining B→DK modes for γ

The B→D($K_S\pi\pi$,K_SKK)K result may be combined together with those of other B→DK analyses. They depend on common nuisance parameters, but have difference degeneracies → whole is greater than the sum of the parts !

Relative magnitude of interfering B amplitudes





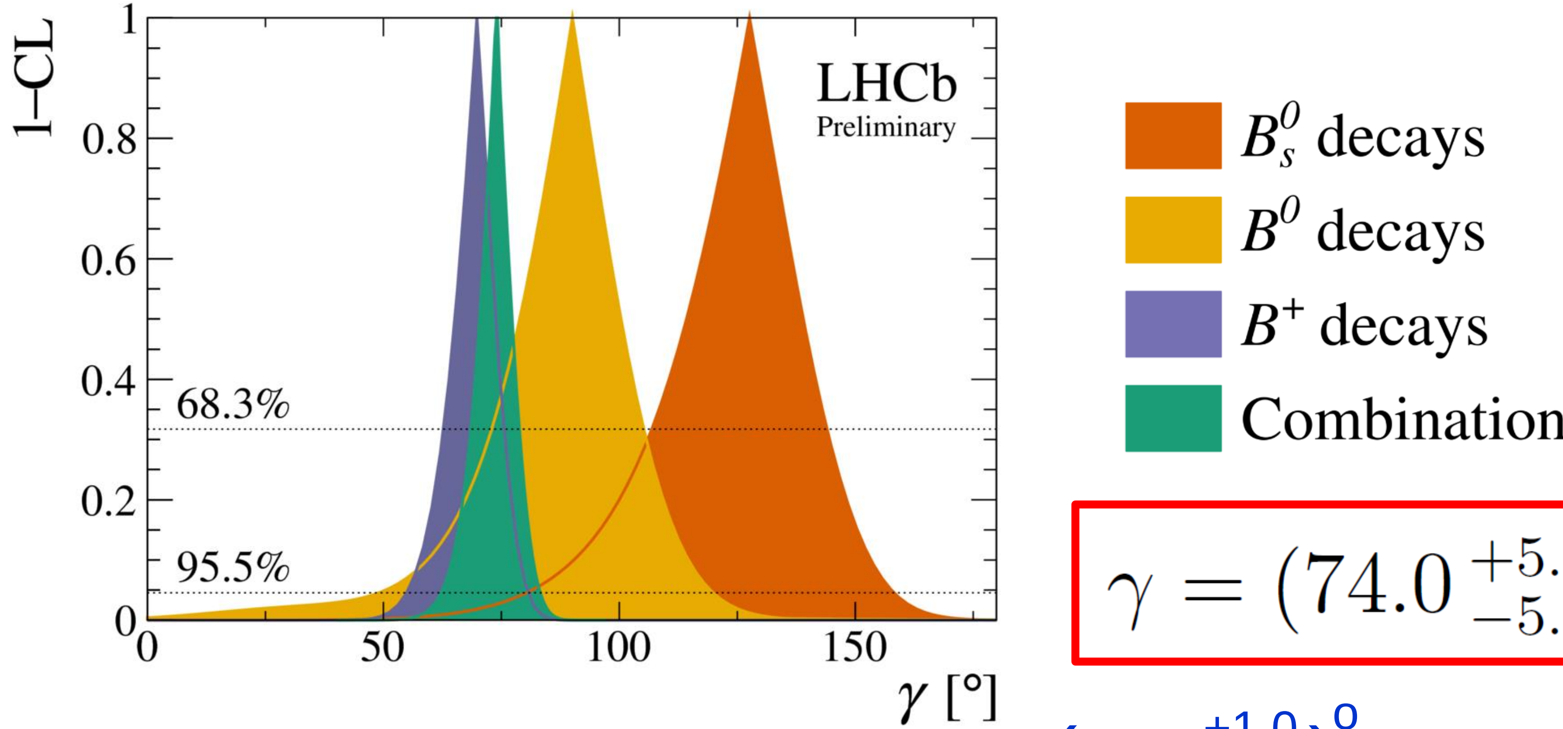
Nicely compatible and pick out a unique solution.

[LHCb-CONF-2018-002]

LHCb: current precision on γ

Global LHCb average, now including information from time-dependent analyses of run-1 data with B_s [JHEP 03 (2018) 059] and B^0 decays [arXiv:1805.03449].

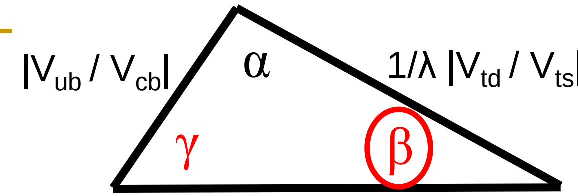
[LHCb-CONF-2018-002]



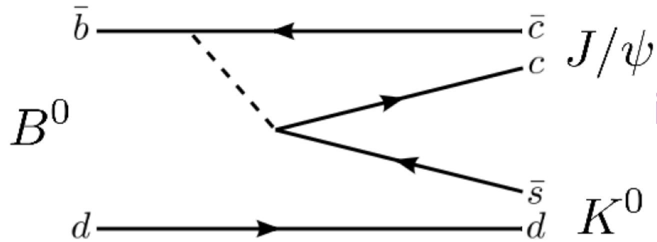
$$\gamma = (74.0^{+5.0}_{-5.8})^\circ$$

Result is to be compared with indirect prediction of $(65.1^{+1.0}_{-2.5})^\circ$ [CKMfitter, 2016].
Compatible, albeit with a little tension (~2σ).
Big improvements expected in near future, as little run-2 data in average.

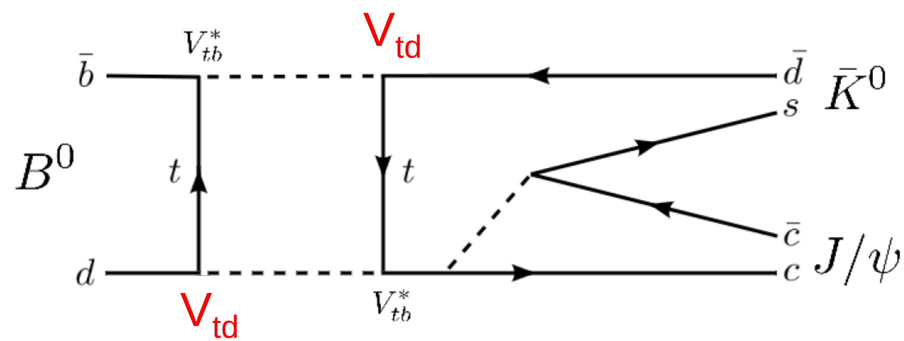
The Unitarily Triangle: sin2β



Study of time-dependent asymmetry of B^0/B^0bar decays to a CP-eigenstate, *e.g.* J/ψK_S , accesses phase of V_{td} and provides a measurement of sin2β.



interferes with



$$\mathcal{A}(t) \equiv \frac{\Gamma(\overline{B}^0(t) \to J/\psi\, K^0_S) - \Gamma(B^0(t) \to J/\psi\, K^0_S)}{\Gamma(\overline{B}^0(t) \to J/\psi\, K^0_S) + \Gamma(B^0(t) \to J/\psi\, K^0_S)}$$

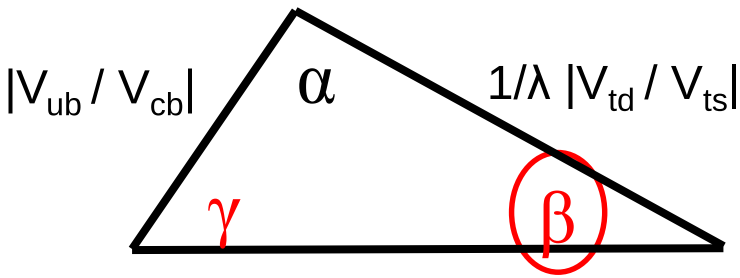
$$= S \sin(\Delta m\, t) - C \cos(\Delta m\, t)$$

sin2β (if no direct CPV)

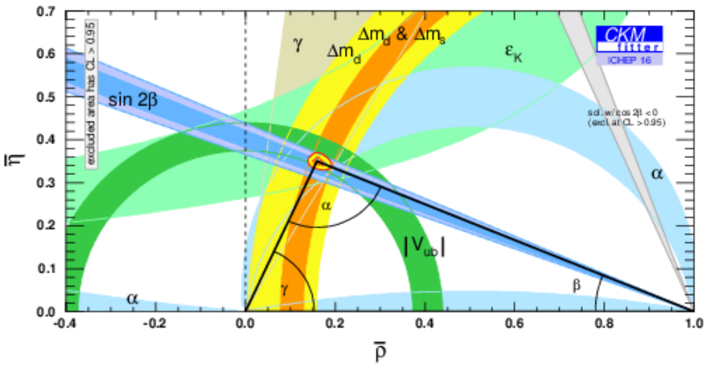
zero if no direct CPV (applies at current experimental precision)

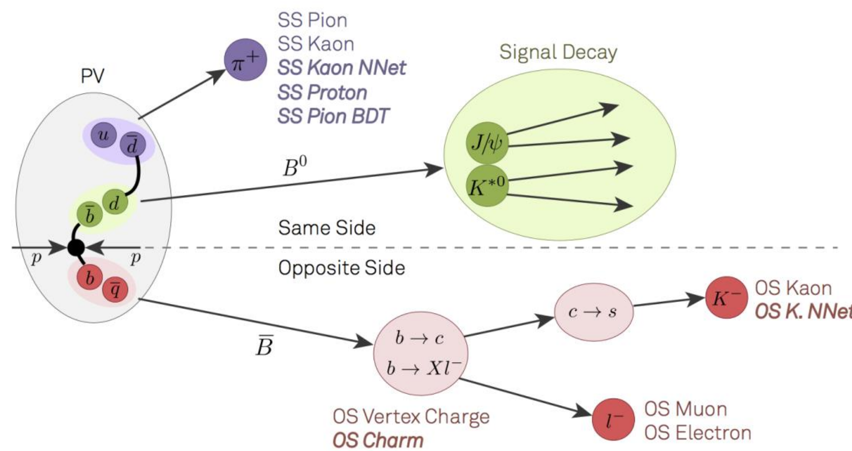
The Unitarily Triangle: sin2β

Measurement on β was the legacy of the B-factories, and helped pave way for 2008 Nobel Prize for Kobyashi and Maskawa. Now LHCb has entered the game !



This measurement requires time-dependent measurement & flavour tagging, which is trickier at a hadron collider than at an e^+e^- machine.





At LHCb a wide range of tagging signatures are exploited, but ‘effective efficiency’ is still ~x10 higher at B-factories, as latter benefits from quantum correlations due to threshold production at ϒ(4S).

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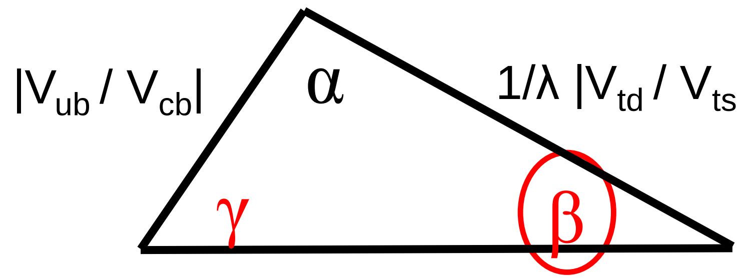

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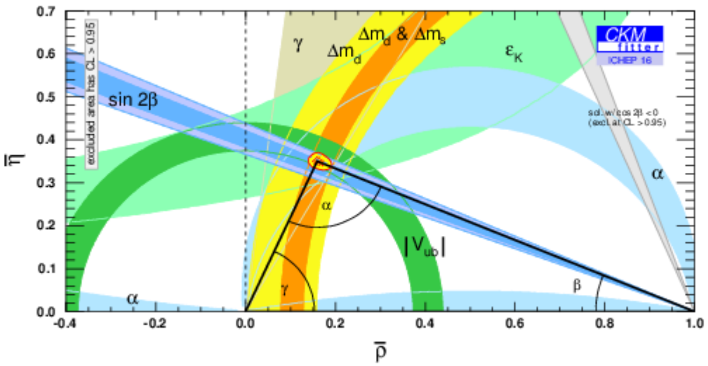
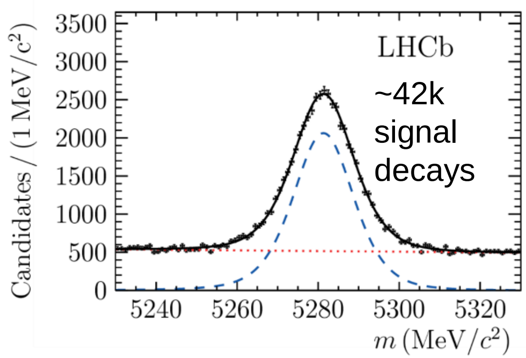
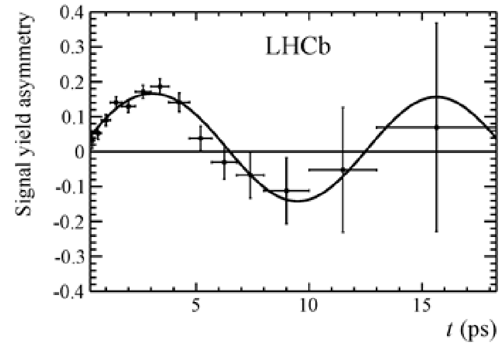






[PRL 115 (2015) 031601]

$\sin 2\beta_{\rm eff} = 0.731 \pm 0.035\,({\rm stat}) \pm 0.020\,({\rm syst})$

(BaBar stat error = 0.036, Belle stat error = 0.029)

Precision obtained by LHCb with $B^0 \to J/\Psi K_S$ is very similar to that of the *B*-factories.

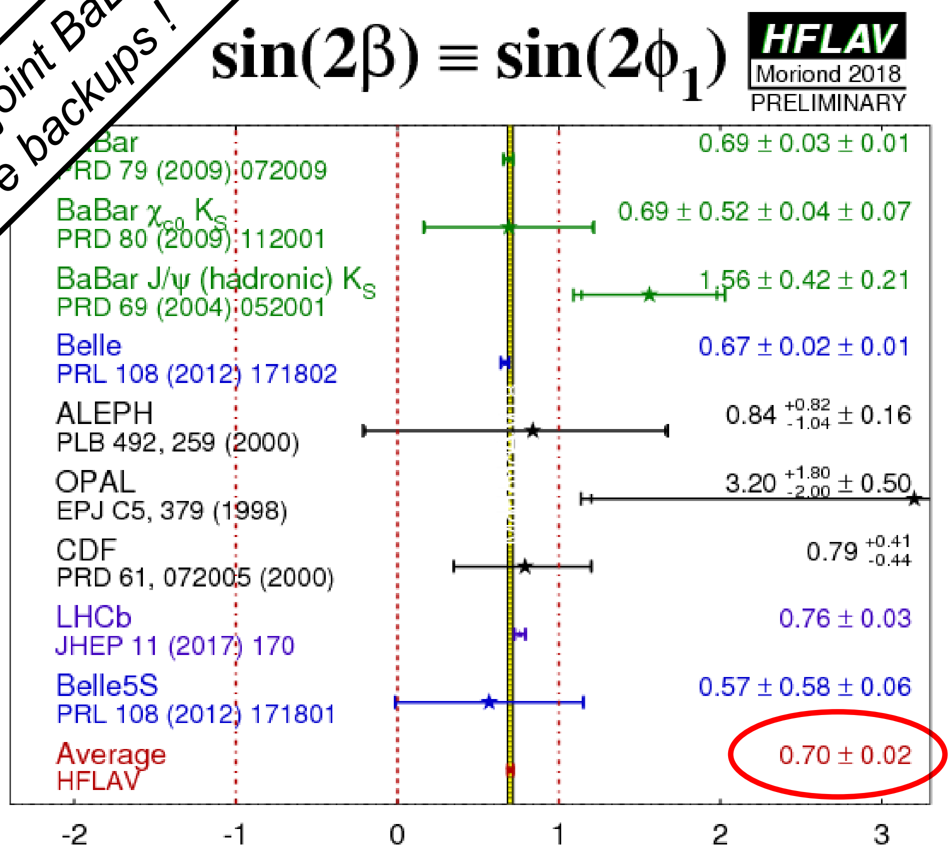
The U... Triangle: sin2β

Measurem... way for
2008 Nobe... the game !

...ependent
...hich is trickier
... machine.

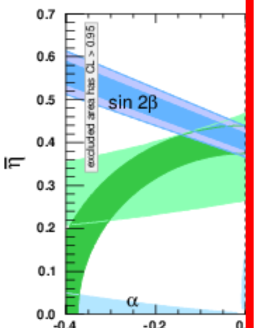
$|V_{ub} / V$...

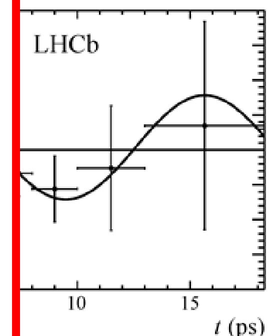
NB: very nice new joint BaBar -Belle result – see backups !



To be compared to prediction of 0.740 $^{+0.020}_{-0.025}$ CKMfitter summer'16

Some tension. Vital to keep improving the precision of this very important parameter. A long-term goal !





[PRL 115 (2015) 031601]

0.020 (syst)

...error = 0.029)

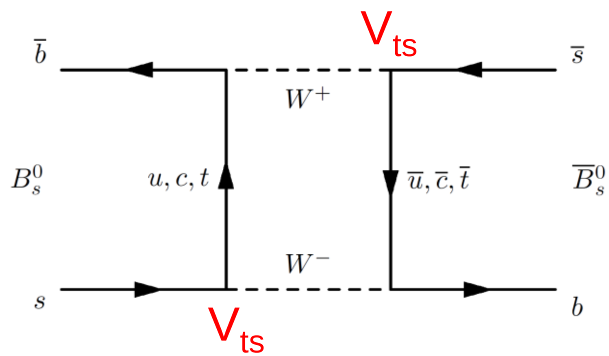
Precision ... e *B*-factories.

Hunting for mixing-induced CPV in the B_s system: φ_s

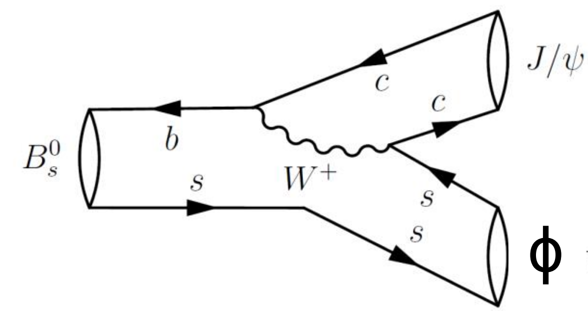
Mixing induced CPV in B_s system: φ_s

Measuring the CPV phase, φ_s, in B_s mixing-decay interference, *e.g.* with $B_s \to J/\Psi\Phi$, is the B_s analogue of the sin2β measurement. In the SM this phase is very small & precisely predicted. Box diagram offers tempting entry point for NP !

Once more interference between mixing…



…and decay



Now we probe CKM elements that are complex only at higher order

$$V_{CKM} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

$$\begin{pmatrix} -\frac{1}{8}\lambda^4 + \mathcal{O}(\lambda^6) & \mathcal{O}(\lambda^7) & 0 \\ \frac{1}{2}A^2\lambda^5[1-2(\rho+i\eta)] + \mathcal{O}(\lambda^7) & -\frac{1}{8}\lambda^4(1+4A^2) + \mathcal{O}(\lambda^6) & \mathcal{O}(\lambda^8) \\ \frac{1}{2}A\lambda^5(\rho+i\eta) + \mathcal{O}(\lambda^7) & \boxed{\frac{1}{2}A\lambda^4(1-2(\rho+i\eta)) + \mathcal{O}(\lambda^6)} & -\frac{1}{2}A^2\lambda^4 + \mathcal{O}(\lambda^6) \end{pmatrix}$$

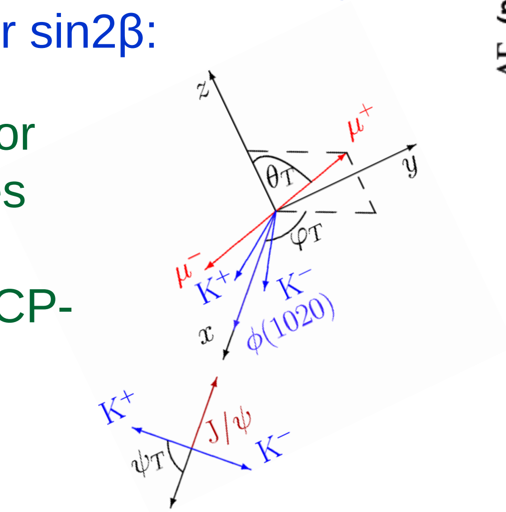
$$\phi_s^{\mathrm{SM}} \equiv -2\arg\left(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right) = -36.3^{+1.6}_{-1.5}\,\mathrm{mrad}$$

Mixing induced CPV in B_s system: φ_s

Measuring the CPV phase, φ_s, in B_s mixing-decay interference, *e.g.* with $B_s \to J/\Psi\Phi$, is the B_s analogue of the sin2β measurement. In the SM this phase is very small & precisely predicted. Box diagram offers tempting entry point for NP !

However the measurement is considerably trickier than is the case for sin2β:

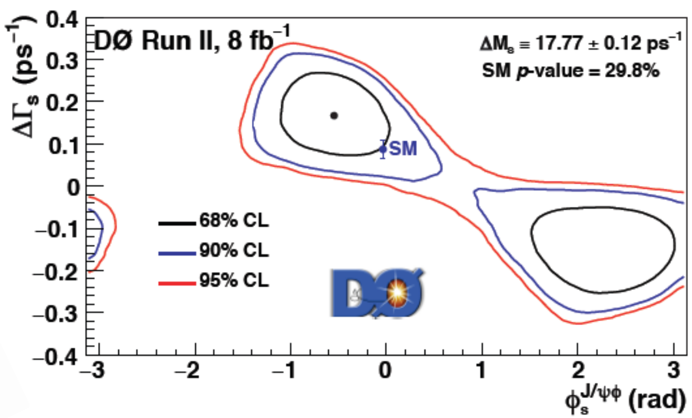
- J/Ψφ is a vector-vector final state, so requires angular analysis to separate out CP+ & CP-



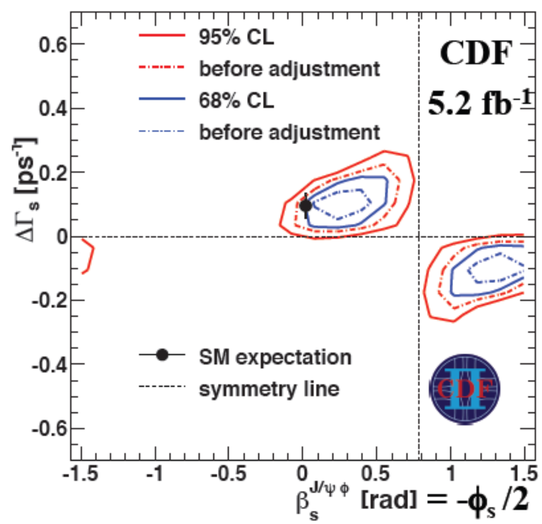
- Very fast oscillations ($\Delta m_s >> \Delta m_d$)

- Possibility of KK S-wave under φ

Heroic early analyses performed by Tevatron. Consistent results and mild (~1σ) tension with SM.



[PRD 85 (2012) 032006]



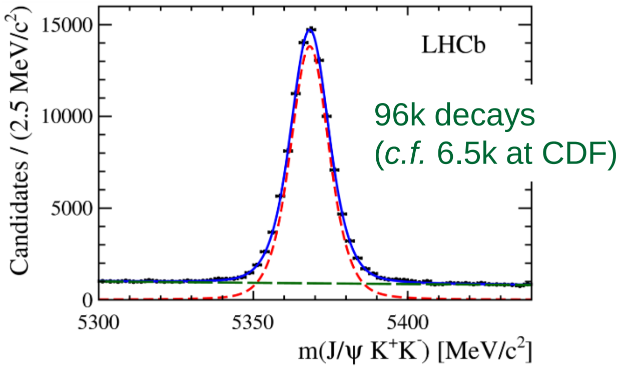
[PRD 85 (2012) 072002]

φ_s – LHCb enters the game

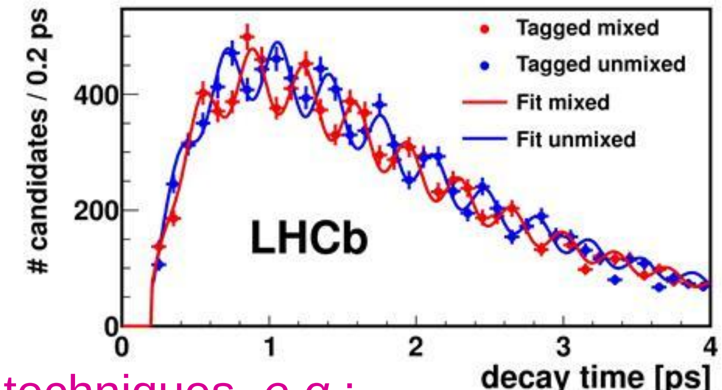
LHCb optimised with φs a key goal. In particular it brings to the game:

- Enormous signal yields

[PRL 114 (2015) 041801]



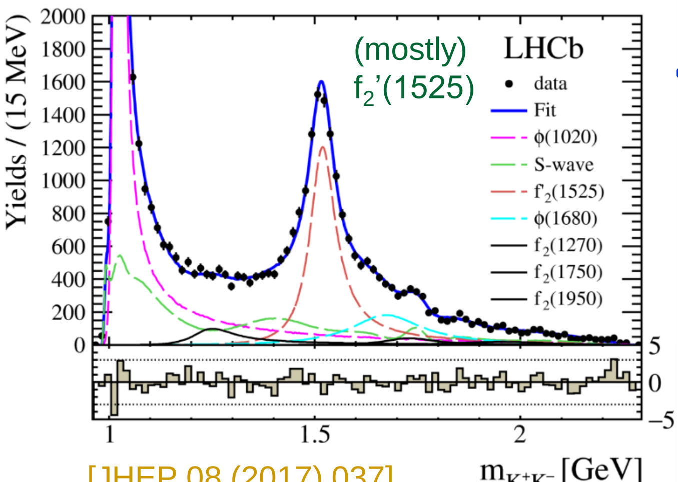
- Excellent proper time resolution



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

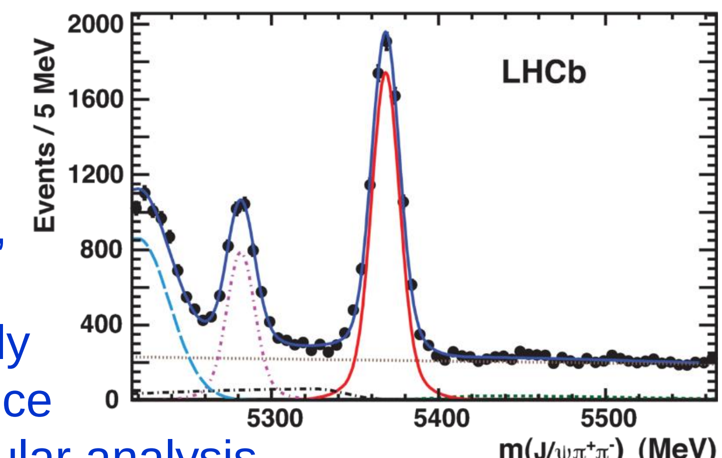
But, in addition, new modes and analysis techniques, *e.g.*:

- Inclusion of JΨKK decays above the φ



[JHEP 08 (2017) 037]

- Inclusion of JΨππ mode (mostly J/Ψf_0), which is overwhelmingly CP-odd & hence needs no angular analysis



[PLB 713 (2012) 378]

φ_s – LHCb enters the game

LHCb optimised with φs a key goal. In particular it brings to the game:

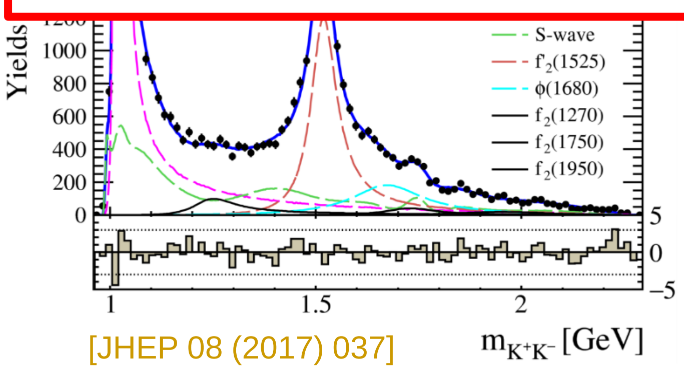
- Enormous signal yields
- Excellent proper time resolution

Final LHCb run-1 results:

$J/\psi K^+K^-$ in ϕ region	-58 $\pm$ 59 $\pm$ 6 mrad	[PRL 114 (2015) 041801]
$J/\psi K^+K^-$ in high mass K^+K^- region	119 $\pm$ 107 $\pm$ 34 mrad	[JHEP 08 (2017) 037]
$J/\psi\pi^+\pi^-$	70 $\pm$ 68 $\pm$ 8 mrad	[PLB 713 (2012) 378]
Overall	1 $\pm$ 37 mrad	

Other measurements:

$\psi(2S)\phi$	$230^{+290}_{-280} \pm 20$ mrad	[PRL B762 (2016) 253]
$D_s^+D_s^-$	20 $\pm$ 170 $\pm$ 20 mrad	[PRL 113 (2014) 211801]



[JHEP 08 (2017) 037]

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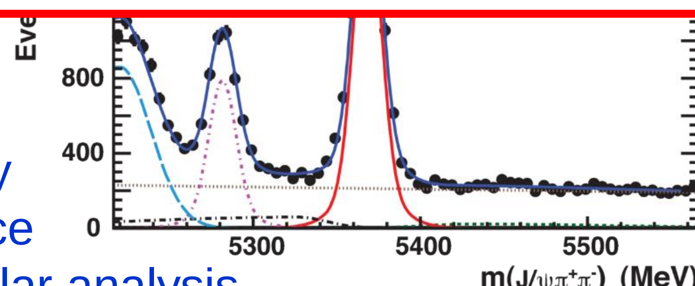


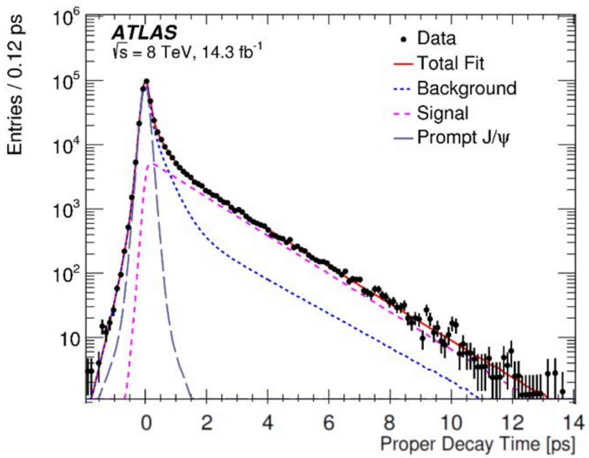
(2012) 378]

Measurement of φ_s at ATLAS and CMS

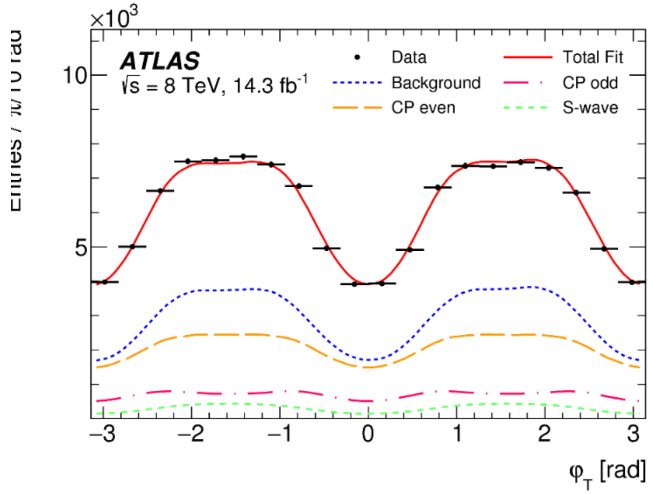
Measurement of φ_s is an key goal of the ATLAS and CMS flavour physics programme, enabled by excellent detector performance and $J/\Psi \rightarrow \mu\mu$ trigger.

e.g. ATLAS $B_s \rightarrow J/\Psi\varphi$ 8 TeV analysis [JHEP 08 (2016) 147]

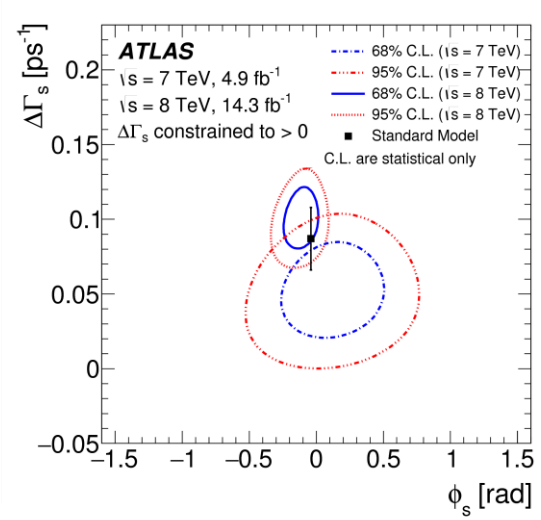
Proper decay time



Transversity angle φ_T



Results, inclduding those of 7 TeV [PRD 90 (2014) 052007]



Combined 7 and 8 TeV results ➡

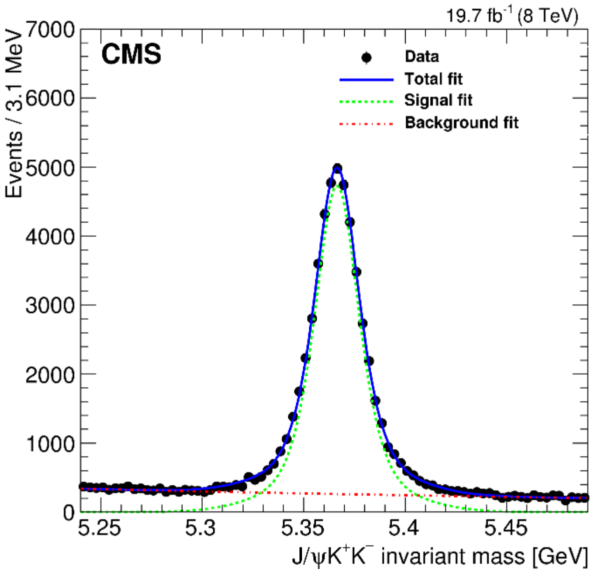
$$
\begin{aligned}
\phi_s &= -0.090 \pm 0.078 \text{ (stat.)} \pm 0.041 \text{ (syst.) rad} \\
\Delta\Gamma_s &= 0.085 \pm 0.011 \text{ (stat.)} \pm 0.007 \text{ (syst.) ps}^{-1} \\
\Gamma_s &= 0.675 \pm 0.003 \text{ (stat.)} \pm 0.003 \text{ (syst.) ps}^{-1}.
\end{aligned}
$$

Measurement of φ_s at ATLAS and CMS

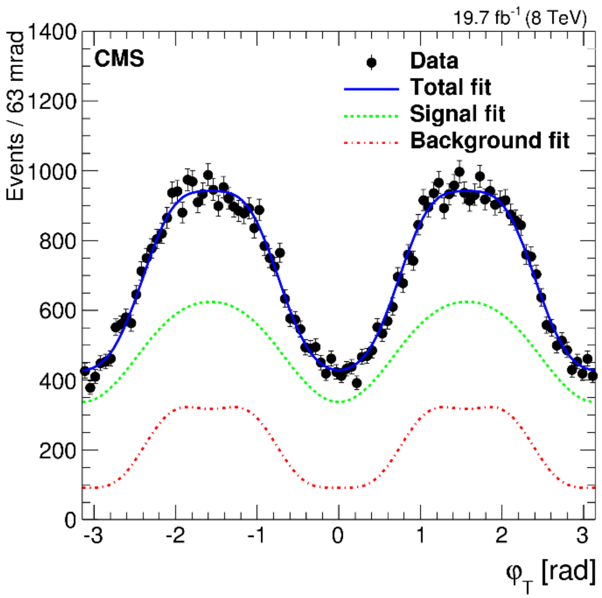
Measurement of φ_s is an key goal of the ATLAS and CMS flavour physics programme, enabled by excellent detector performance and $J/\Psi \to \mu\mu$ trigger.

e.g. CMS $B_s \to J/\Psi\varphi$ 8 TeV analysis [PLB 757 (2016) 97]

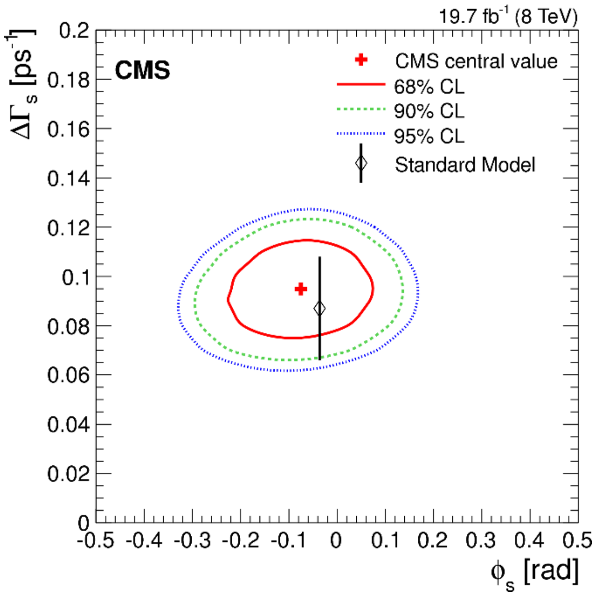
Invariant mass



Transversity angle φ_T

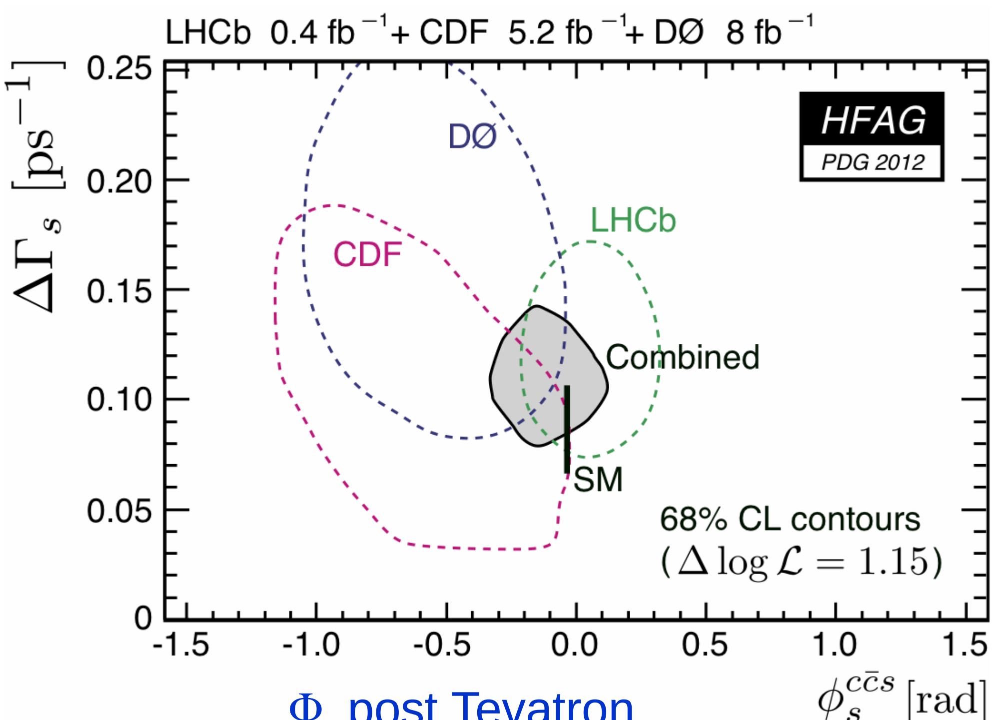


Result contours



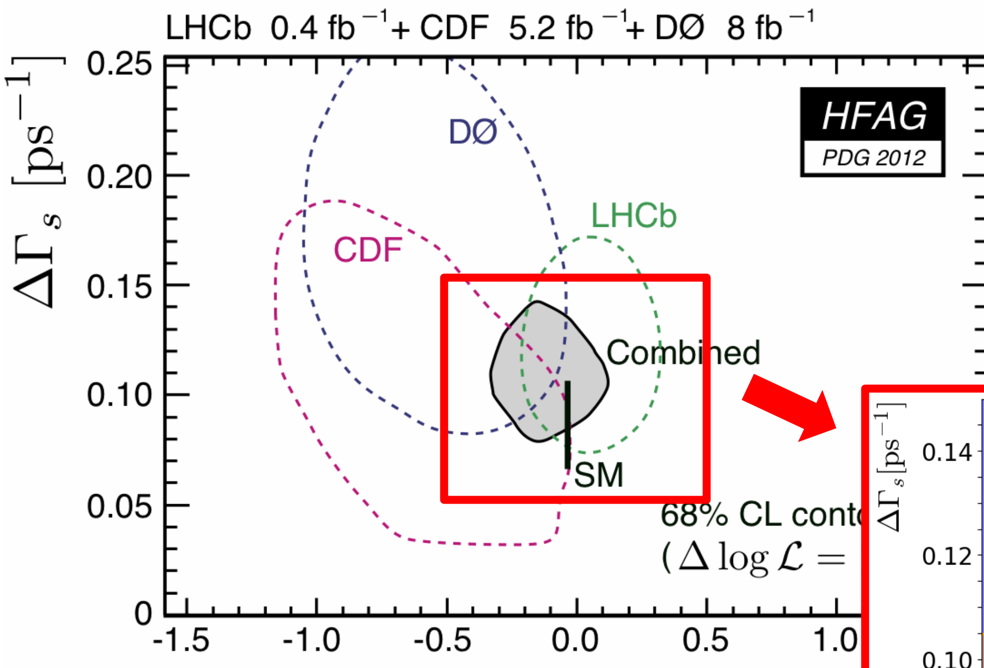
$$\boxed{\begin{aligned} \phi_s &= -0.075 \pm 0.097\,(\text{stat}) \pm 0.031\,(\text{syst})\,\text{rad}, \\ \Delta\Gamma_s &= 0.095 \pm 0.013\,(\text{stat}) \pm 0.007\,(\text{syst})\,\text{ps}^{-1}. \end{aligned}}$$

φ_s : the impact of the LHC



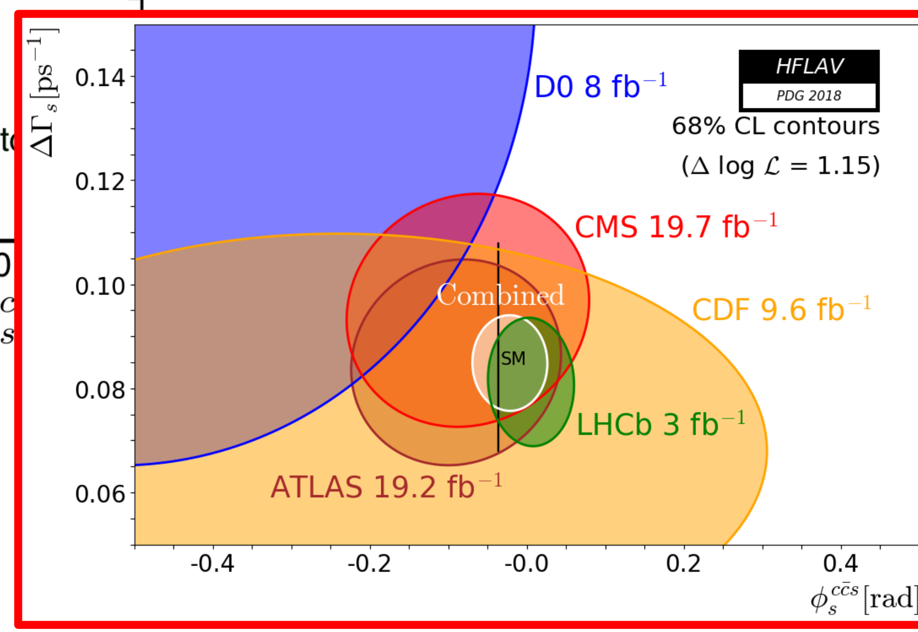
Φ_s post Tevatron
and early LHC data

φ_s : the impact of the LHC

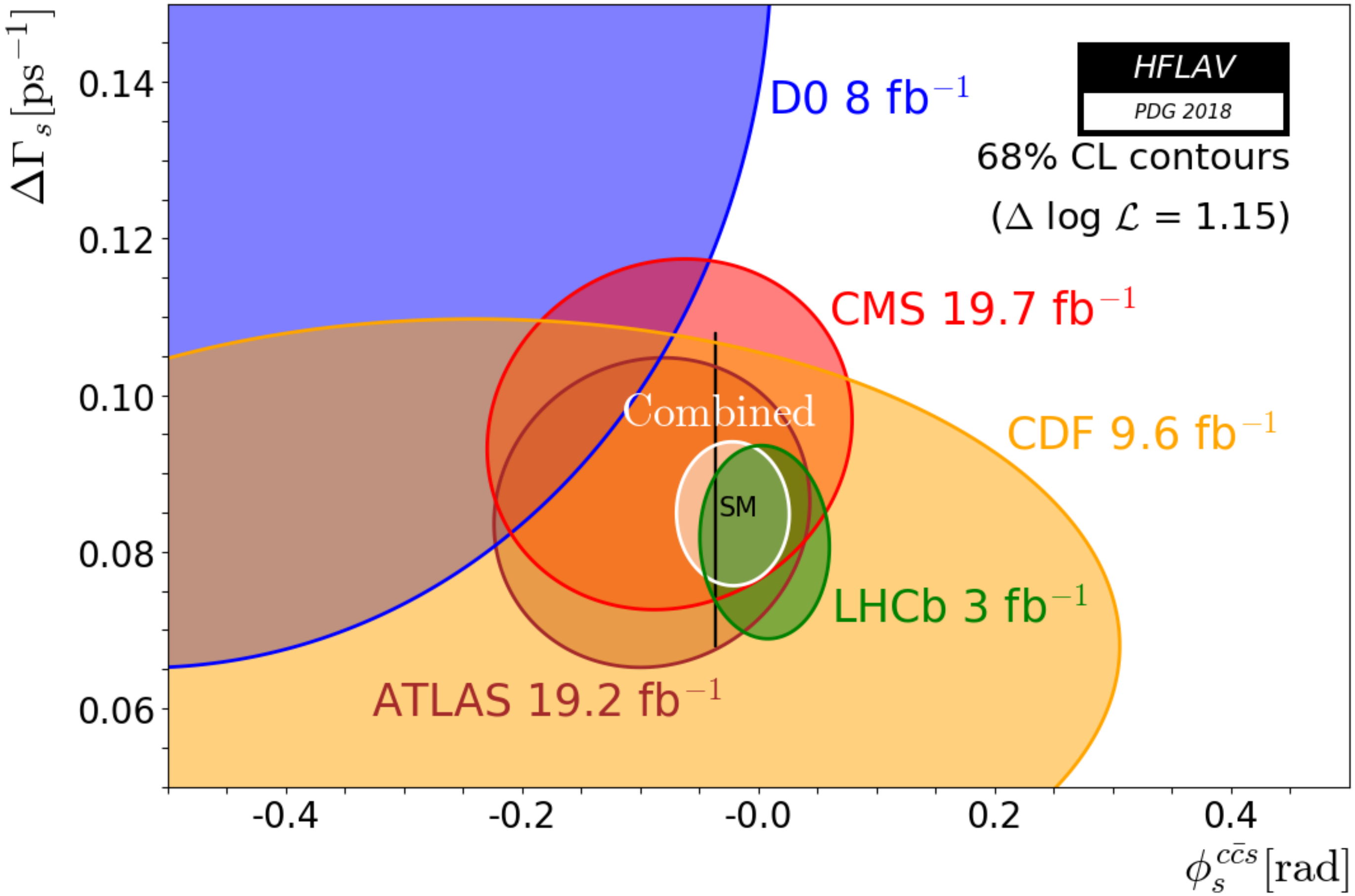


Φ_s post Tevatron
and early LHC data

Φ_s post run-1 LHC



φ_s : the current state of play



φ_s now measured with ~30 mrad precision. So far all is compatible with SM, but first run-2 results to be released very soon. Watch this space !

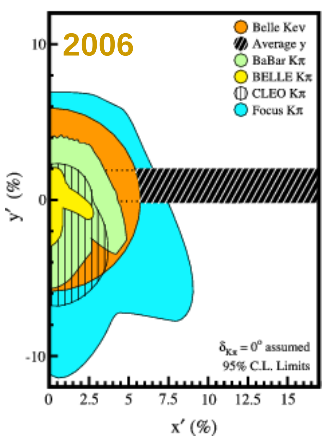
The charm renaissance and the quest for the vanishingly small: CPV in charm

The charm renaissance

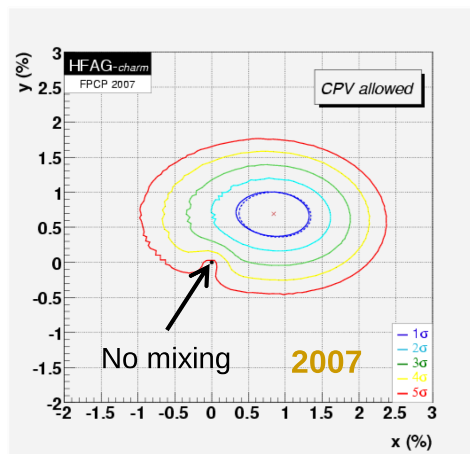
For many years charm was the ‘Cinderella’ of flavour physics studies

- tiny CPV and mixing effects expected in the SM…
- …and no evidence of either despite intensive searches
- long-distance effects complicate predictions

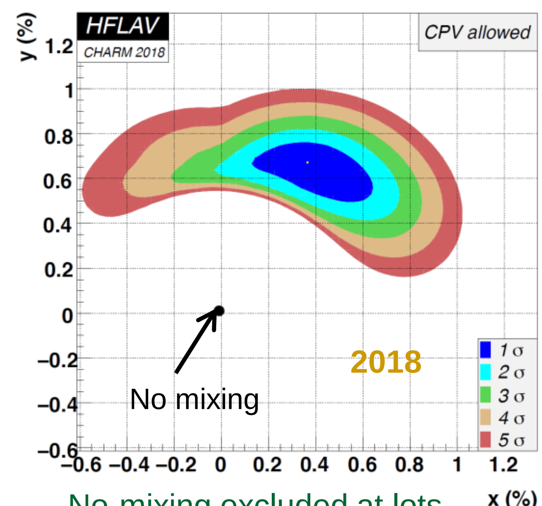
Excluded regions



“All results are null.”
Ian Shipsey, Charm 2006.



Measurement contours;
no-mixing excluded at 5σ



No-mixing excluded at lots
and lots (but x=0 still possible…)

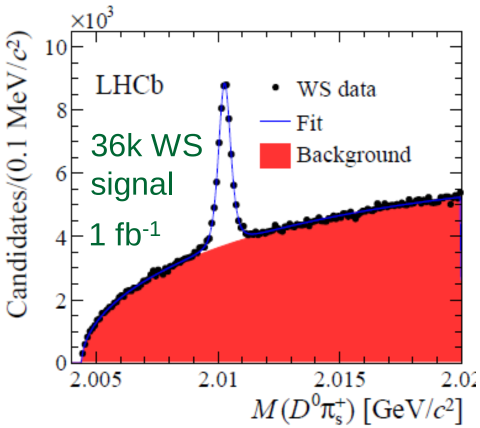
Then combination of B-factory analyses finally saw mixing. New outlook !

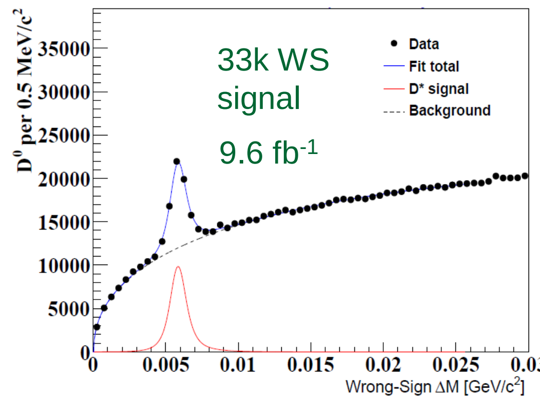
→ mixing parameters not tiny (~1%); good news for (indirect) CPV observables
→ smallness of SM ‘pollution’ not a bad thing in looking for New Physics signal
→ internal down-type quarks in loops – complementary to *b*-physics
→ huge potential of LHC for improving sensitivity

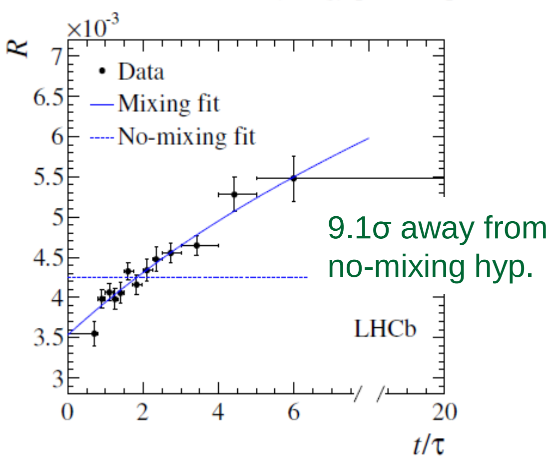
Rise of the hadron machines

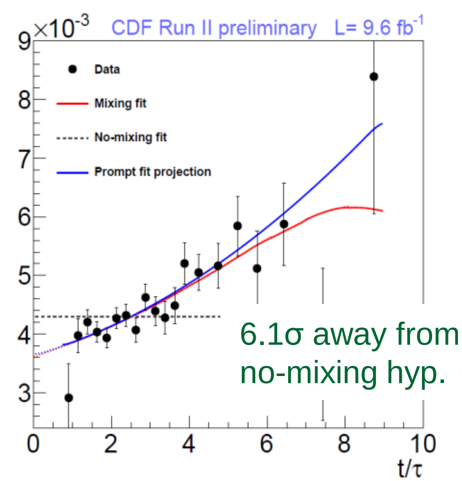
Power of hadron colliders is now clear. In 2013 LHCb and CDF published first individual (>)>5σ measurements, in \`wrong sign' (WS) $K\pi$ analyses.

LHCb, PRL 110 (2013) 101802









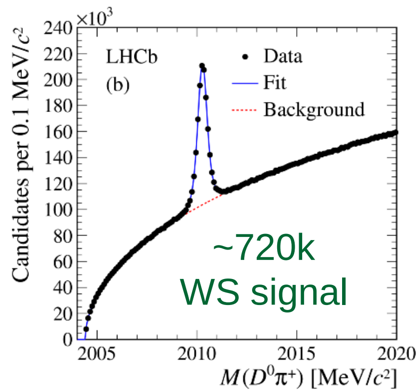
CDF, PRL 111 (2013) 231802

Although e^+e^- machines retain advantages for modes with neutrals, LHC has huge advantages for charged modes (*e.g.* # WS $K\pi$ in above plot, which is a small fraction of Run 1, is 3x whole Belle sample) and also time resolution.

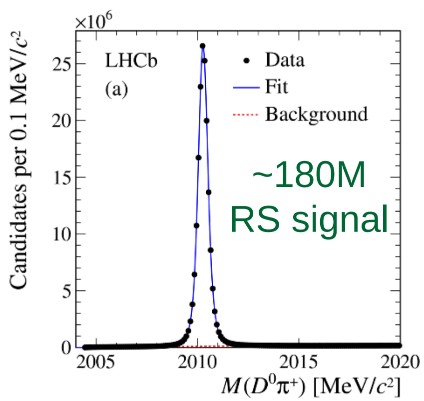
Search for indirect CPV in charm with run 2 data

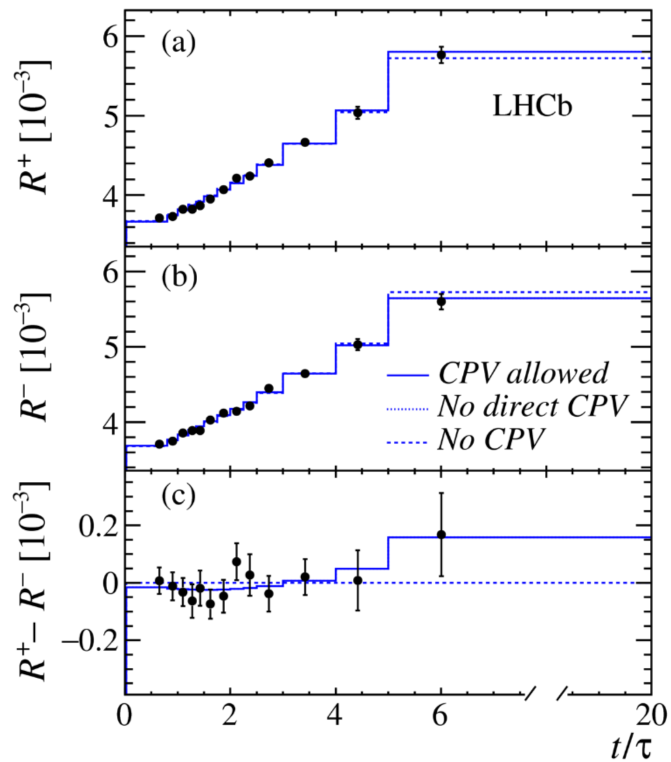
LHCb samples have grown rapidly, and now allow for high sensitivity searches for mixing-induced CPV, *e.g.* take WS Kπ analysis used for mixing discovery, now updated with full run-1 data & 2 fb^{-1} from run 2, and study D^0 & D^0bar separately.

Study ratio of WS (*i.e.* $D^0 \to K^+\pi^-$)…



…to RS (*i.e.* $D^0 \to K^-\pi^+$), vs. proper decay time





For D^0…

…and D^0bar…

…and difference of both.

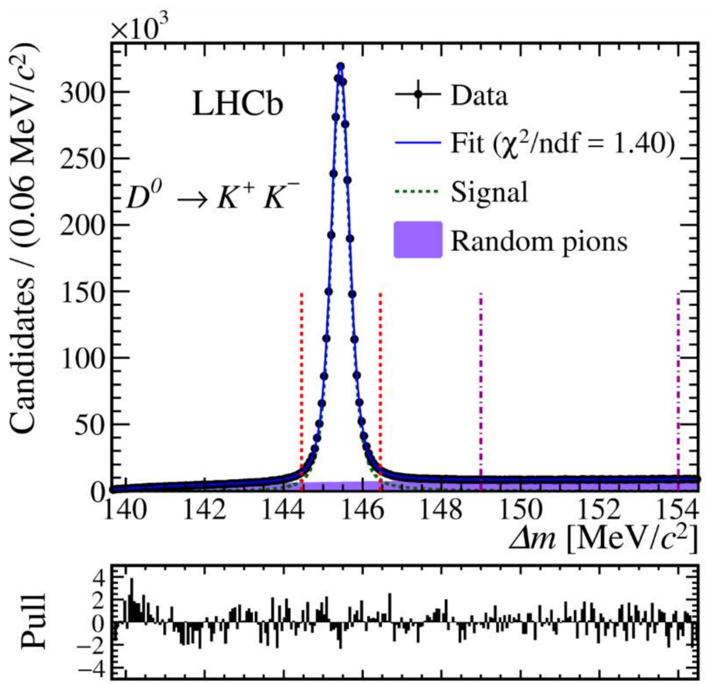
[PRD 97 (2018) 031101]

Difference flat → no evidence of CPV (yet).

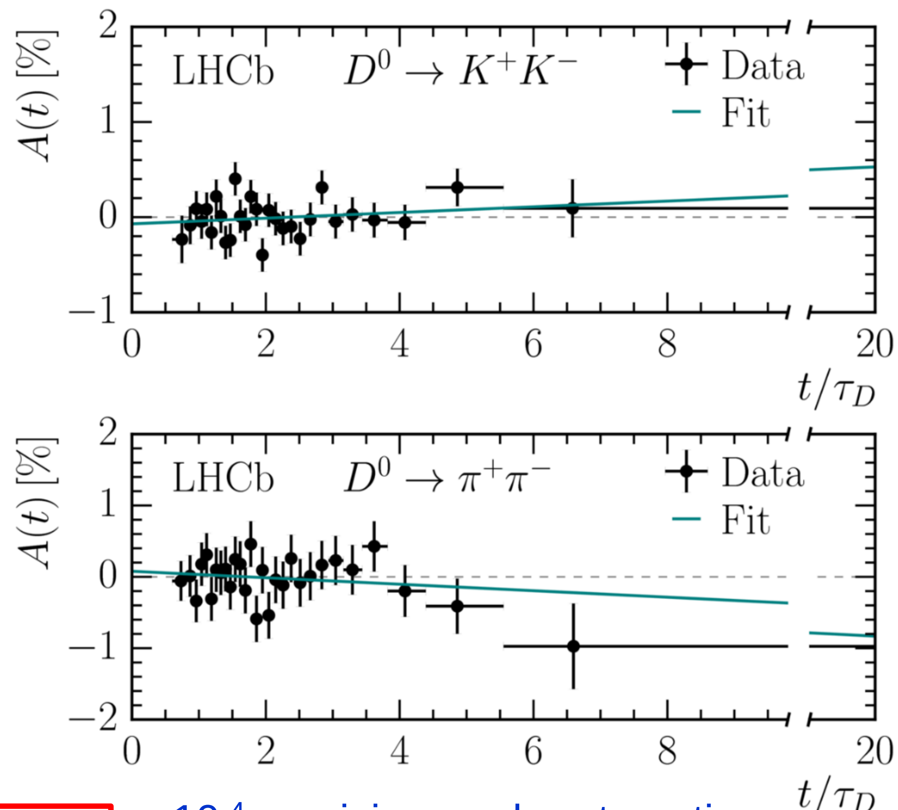
Other CPV searches in mixing (*i.e.* indirect CPV)

Many other observables to probe. *e.g.* look for time-dependent CP asymmetry, expressed in A_Γ parameter, in decay to *CP* eigenstate, such as $D^0 \to KK$ or $\pi\pi$.

Massive, clean & well-understood data sets.



No slope, so no CP violation (yet)



[PRL 118 (2017) 182001]

$$\boxed{\begin{aligned} A_\Gamma(D^0 \to K^+K^-) &= (-0.30 \pm 0.32 \pm 0.14) \times 10^{-3} \\ A_\Gamma(D^0 \to \pi^+\pi^-) &= (0.46 \pm 0.58 \pm 0.16) \times 10^{-3} \end{aligned}}$$

10^{-4} precision, and systematics under good control. This a run-1 study. Excellent prospects for run 2 and beyond !

Future prospects in CPV studies

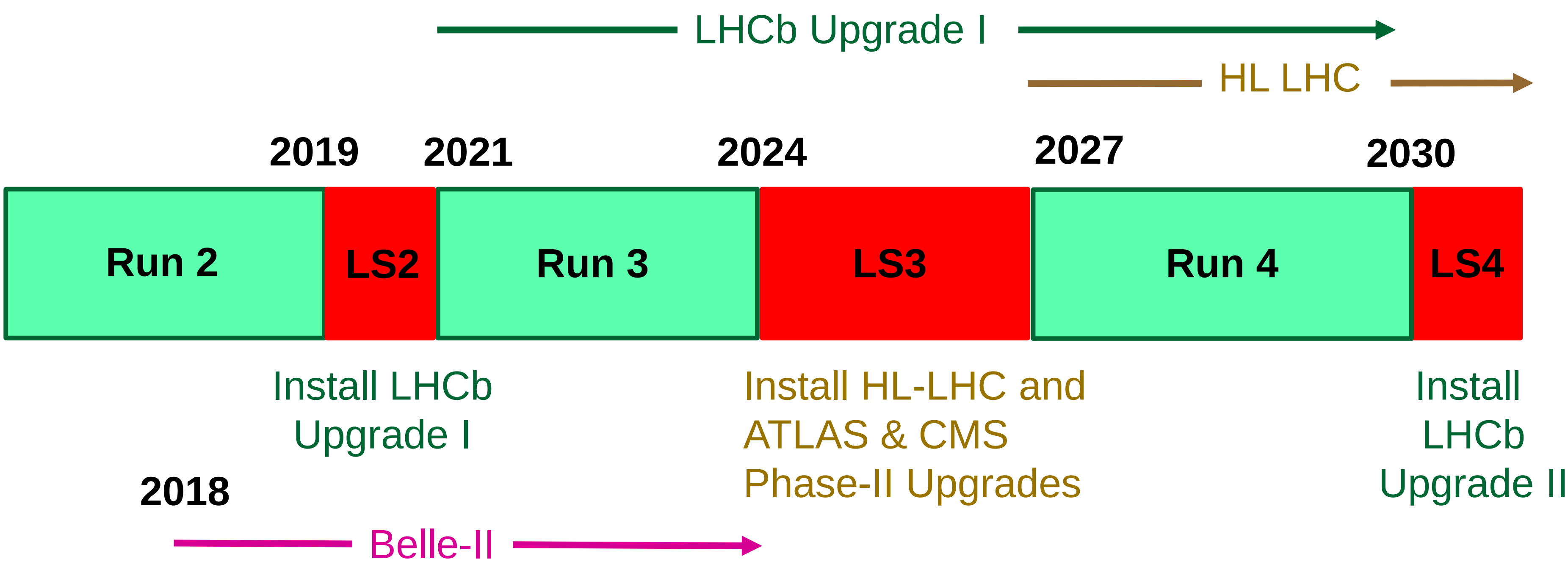
In the b-system all CPV measurements discussed (γ, β and φ_s) are statistically limited and theoretically very clean:

- For γ this is true to 10^{-7} level
- For β and φ_s effects related to direct CPV and 'Penguin pollution' could lurk around the corner, but many strategies exist to control these issues.

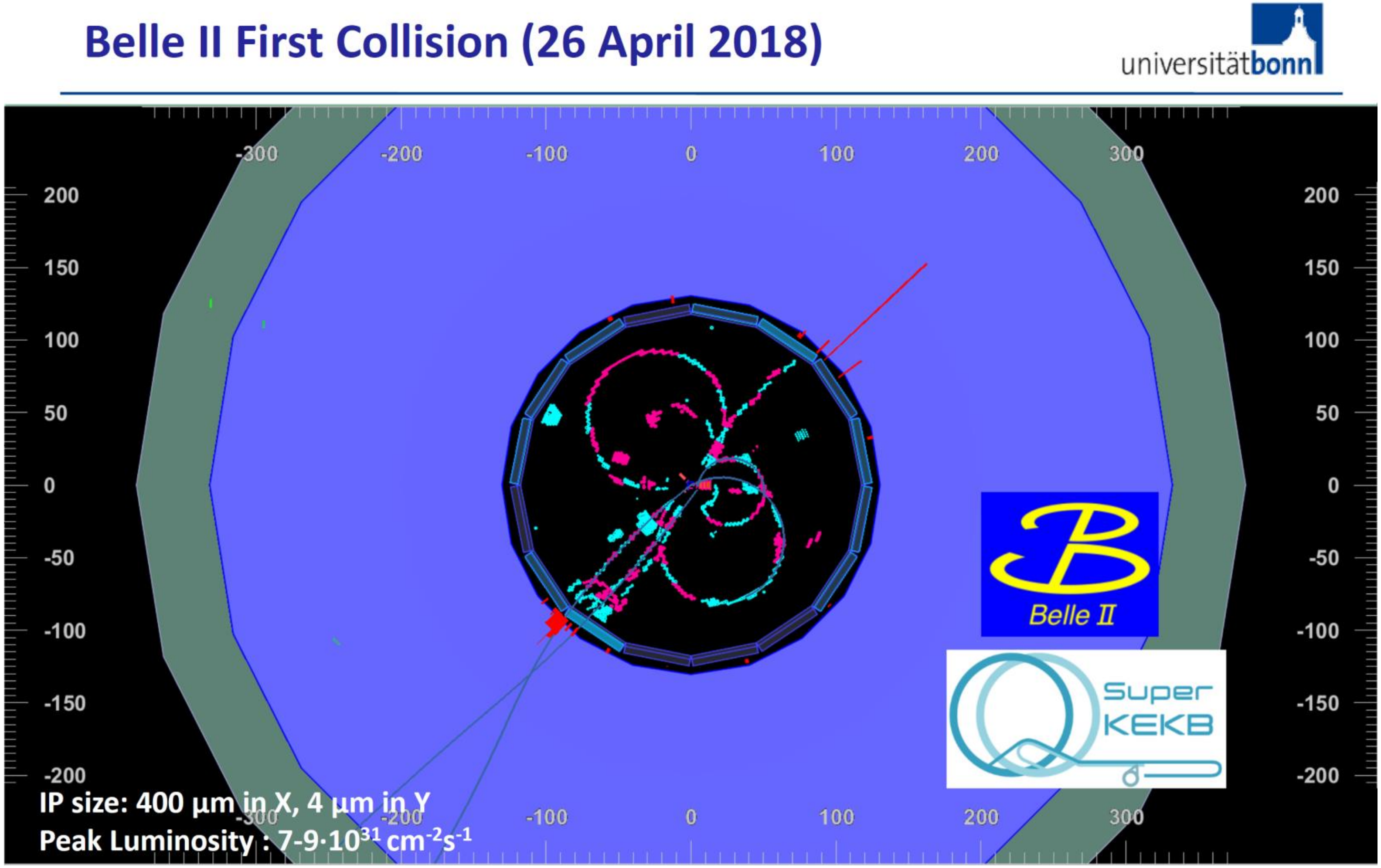
The discovery of CPV in charm would (depending on its size) challenge the SM, and at the very least open up a new sector of flavour studies.

$\rightarrow$ strong motivation to improve sensitivity !

The future of CPV studies & flavour, in the context of the LHC timeline

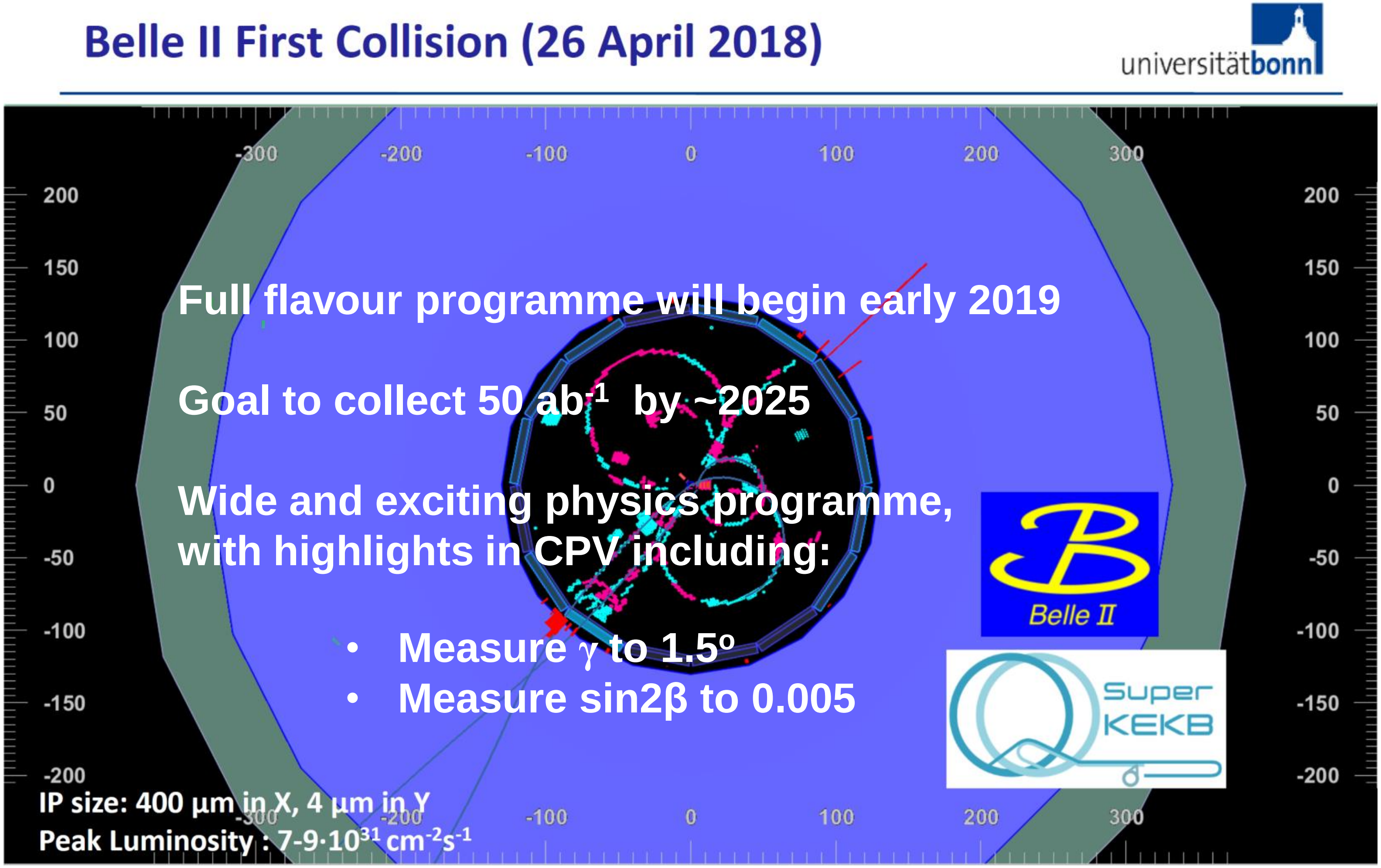


e^+e^- rebooted: Belle II begins operation



[C. Marinas, Beauty 2019, La Biodola, Elba]

e^+e^- rebooted: Belle II begins operation



Full flavour programme will begin early 2019

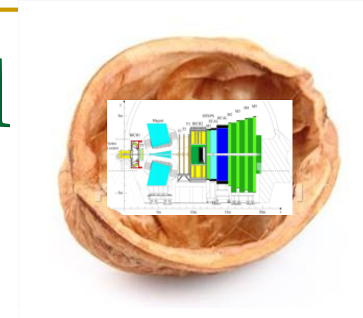
Goal to collect 50 ab^{-1} by ~2025

Wide and exciting physics programme, with highlights in CPV including:

- **Measure γ to 1.5°**
- **Measure $\sin 2\beta$ to 0.005**

[C. Marinas, Beauty 2019, La Biodola, Elba]

LHCb Upgrade I in a nutshell



An LHCb Upgrade is scheduled, with installation in LS2 and first data-taking in run 3. The motivation is to take increased advantage of the huge rate of heavy-flavour production at the LHC.

The LHCb Upgrade

1) *Full* software trigger
- Allows effective operation at higher luminosity
- Improved efficiency in hadronic modes

2) Raise operational luminosity by factor five to $2 \times 10^{33}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$

Necessitates redesign of several sub-detectors & overhaul of readout

Huge increase in precision, *e.g.* measure γ to ~1^{o}, φ_s to <10 mrad, and the ability to perform studies beyond the reach of the current detector.

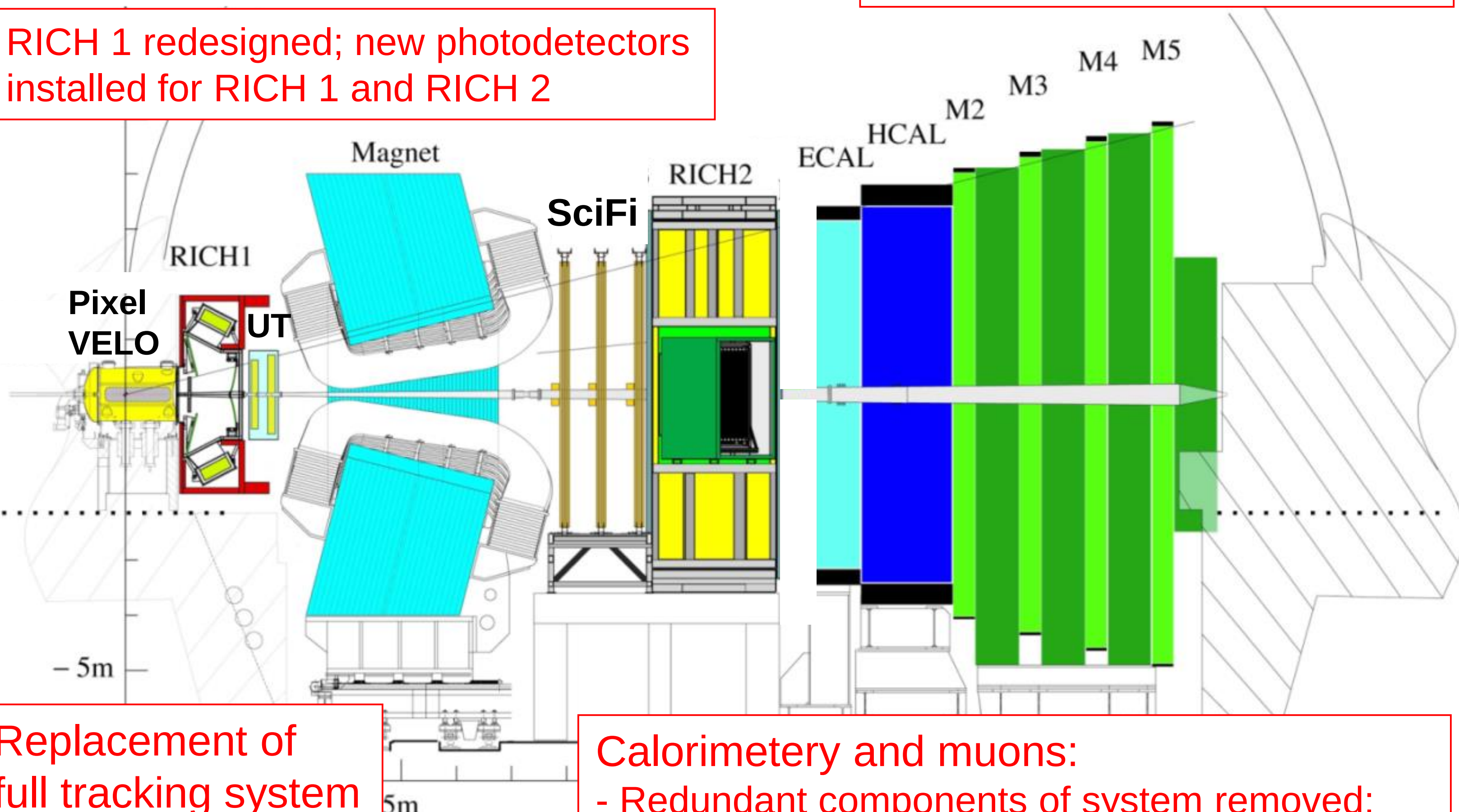
Flexible trigger and unique acceptance also opens up opportunities in other topics apart from flavour ('a general purpose detector in the forward region')

LHCb Upgrade I (LS2)

Current detector → upgraded detector

All sub-detectors read out at 40 MHz for software trigger

RICH 1 redesigned; new photodetectors installed for RICH 1 and RICH 2



Replacement of full tracking system

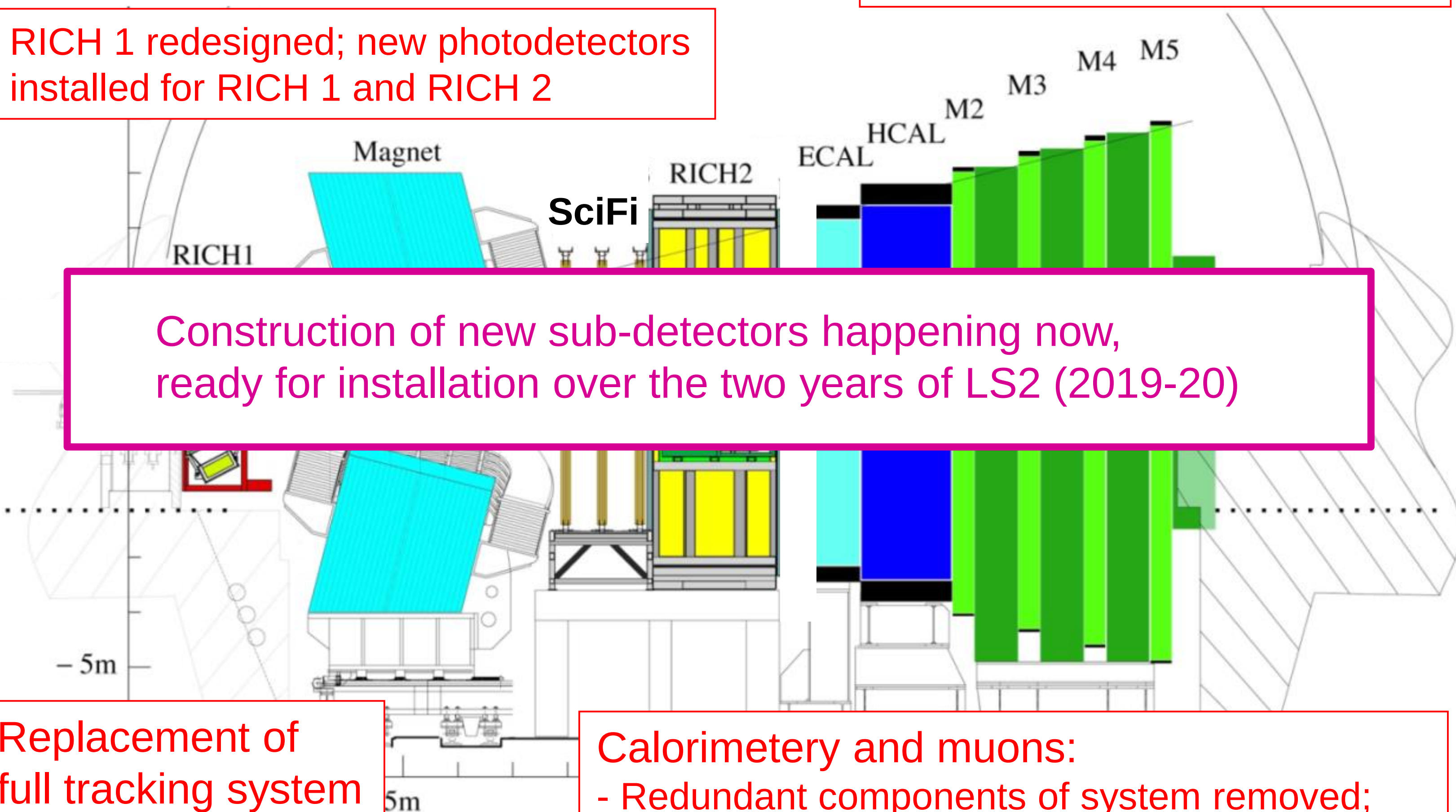
Calorimetery and muons:
- Redundant components of system removed; new electronics added; more shielding included

LHCb Upgrade I (LS2)

Current detector → upgraded detector

All sub-detectors read out at 40 MHz for software trigger

RICH 1 redesigned; new photodetectors installed for RICH 1 and RICH 2



Construction of new sub-detectors happening now, ready for installation over the two years of LS2 (2019-20)

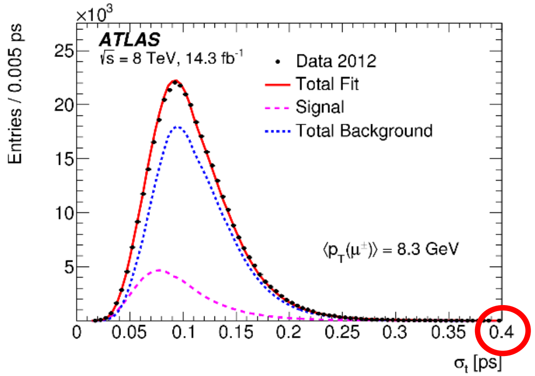
Replacement of full tracking system

Calorimetery and muons:
- Redundant components of system removed; new electronics added; more shielding included

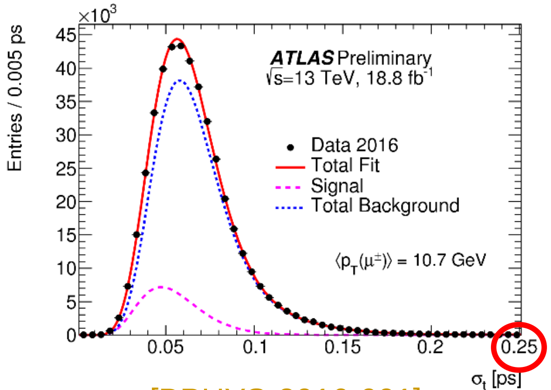
Future riches – evolving CPV prospects at the GPDs

Significant strides forward In precision from ATLAS already expected from run 2.

e.g. IBL of ATLAS improves proper time resolution.



[JHEP 08 (2016) 147]



[BPHYS-2016-001]

Impressive projections from studies for Phase-II Upgrade, *e.g.* for $B_s \to J/\Psi\varphi$

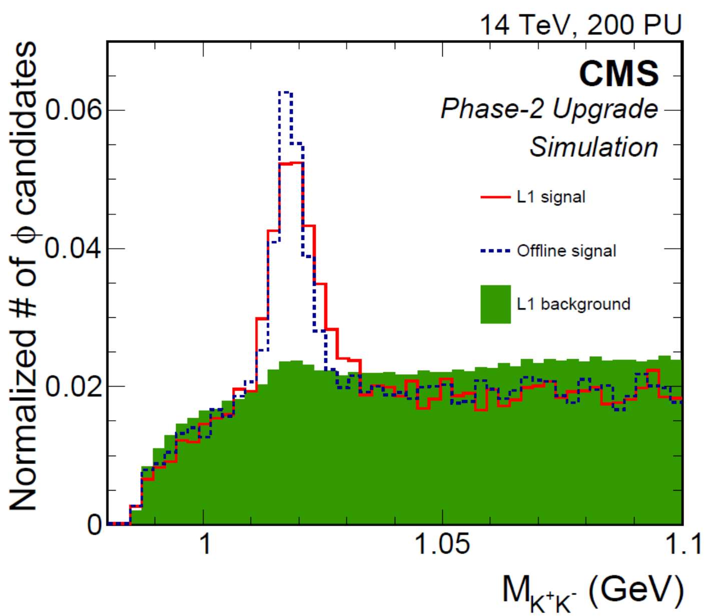
	2011	2012	2015-17		2019-21	2023-30+
Detector	current	current	IBL		IBL	ITK
Average interactions per BX $<\mu>$	6-12	21	60		60	200
Luminosity, fb^{-1}	4.9	20	100		250	3 000
Di-μ trigger p_T thresholds, GeV	4 - 4(6)	4 - 6	6 - 6	11 - 11	11 - 11	11 - 11
Signal events per fb^{-1}	4 400	4 320	3 280	460	460	330
Signal events	22 000	86 400	327 900	45 500	114 000	810 000
Total events in analysis	130 000	550 000	1 874 000	284 000	758 000	6 461 000
MC $\sigma(\phi_s)$ (stat.), rad	0.25	0.12	0.054	0.10	0.064	0.022

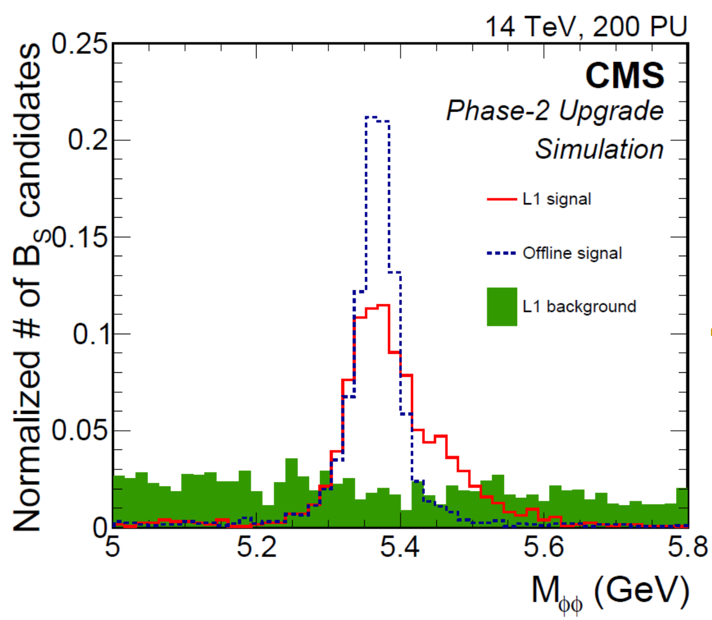
These are probably conservative, given (i) 2011-2012 precision better than foreseen, (ii) later trigger studies [ATL-PHYS-PUB-2016-026] indicate higher yields.

Future riches – evolving CPV prospects at the GPDs

New sub-detectors and associated improvements of Phase-II Upgrade will bring great benefits for B-physics, *e.g.* new tracker which will have improved momentum and impact parameter resolution.

Inclusion of track information in level-1 trigger will make hadronic modes accessible *e.g.* $B_s \rightarrow \varphi(K^+K^-)\varphi(K^+K^-)$



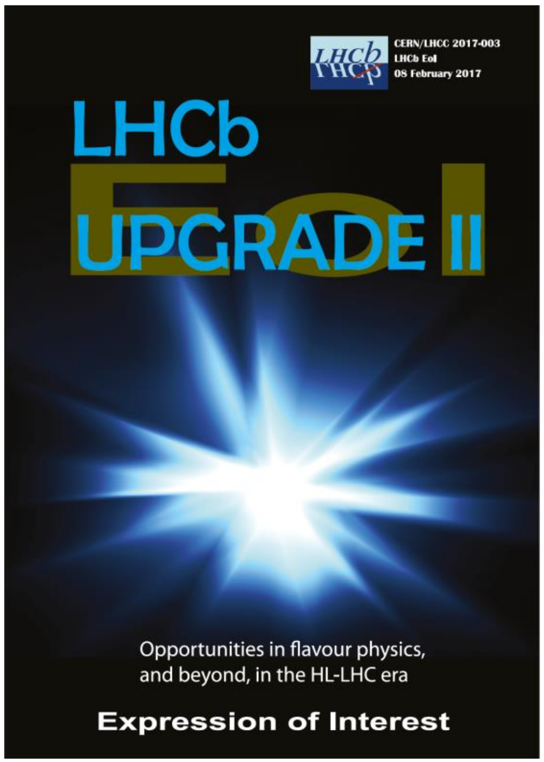


[CERN-LHCC-2017-009; CMS-TDR-014]

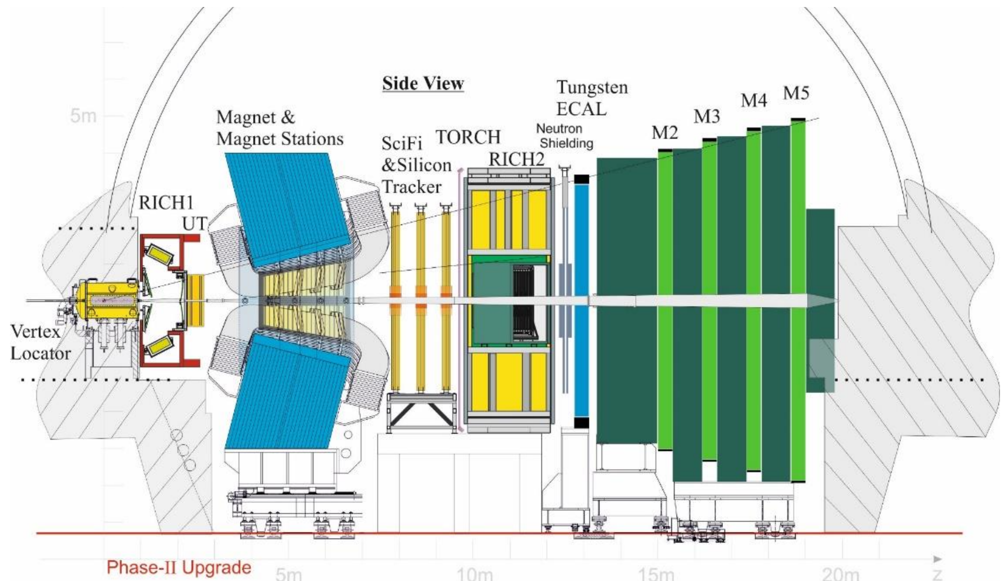
Experiment will continue to deliver strongly in di-muon final states, *e.g.* $B_s \rightarrow J/\Psi\varphi$.

LHCb Upgrade II (LS4)

Plans under development to perform a second upgrade to LHCb, around 2030, which would allow the experiment to operate at ~10^{34} cm^{-2}s^{-1}, collect ~300 fb^{-1}, and bring additional detector enhancements, *e.g* improved ECAL, low p PID *etc.*



[CERN-LHCC-2017-003]



Common themes: improved granularity, fast timing, and radiation hardness.

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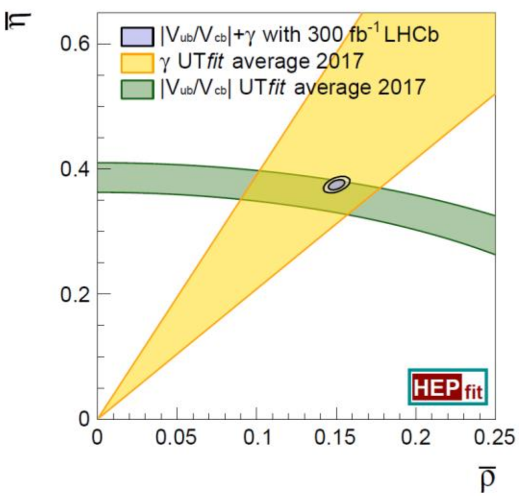
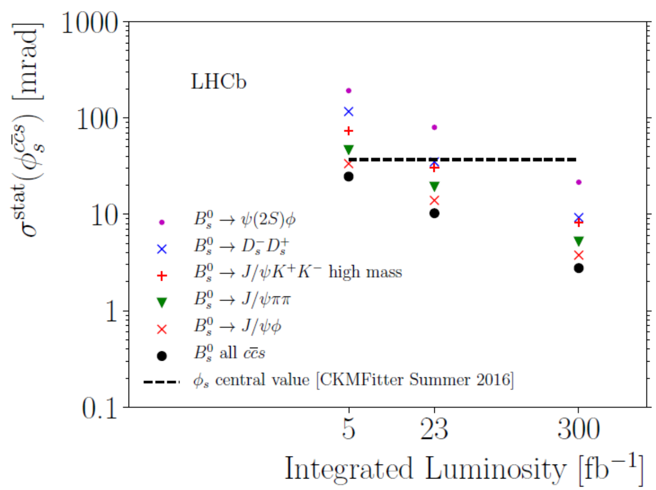
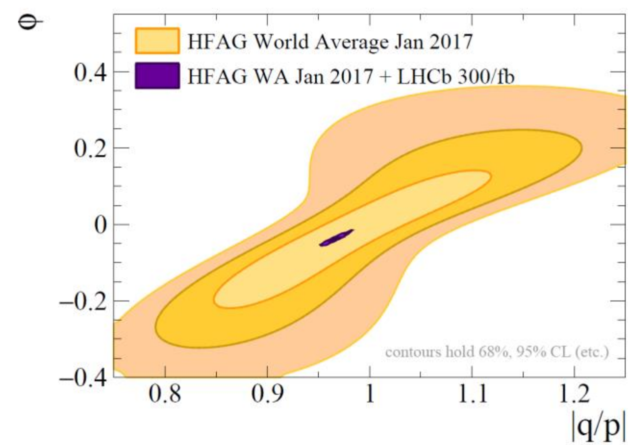
γ measured to a few 0.1 of a degree
sin2β $B^0 \to J/\psi K_S$ measured to 0.003



Φ_s probed below SM central value



Charm observables determined with sensitivity of 10^{-5}



Upgrade II would allow for exquisite precision to be attained in these and many other flavour observables, with exciting capabilities in many studies beyond flavour !

Conclusions

CPV studies probe one of the least understood sectors of the SM and have high discovery potential for New Physics.

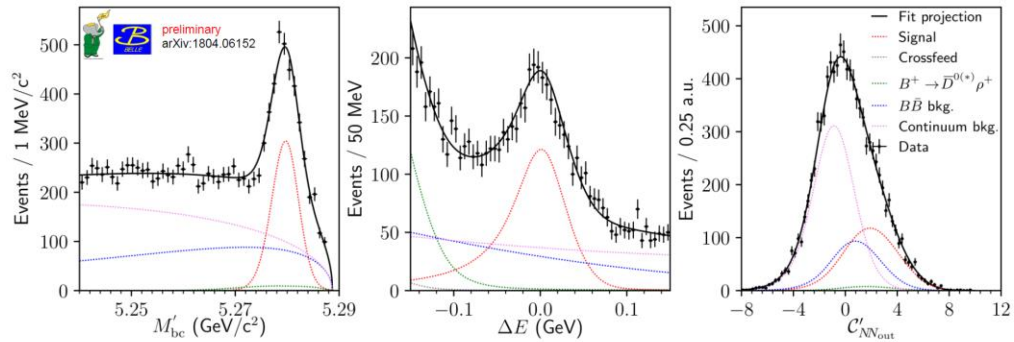
The measurement campaign for the ‘holy trinity’ of γ, β and φ_s has made enormous progress during the LHC Years and is one of the most important sets of ‘precision measurements’ in HEP.

Exciting times are ahead with Belle II, LHCb Upgrade I, the GPD Phase II Upgrades and the ‘ultimate flavour experiment’ of LHCb Upgrade II.

Backups

BaBar and Belle – more gold from the mine: cos2β

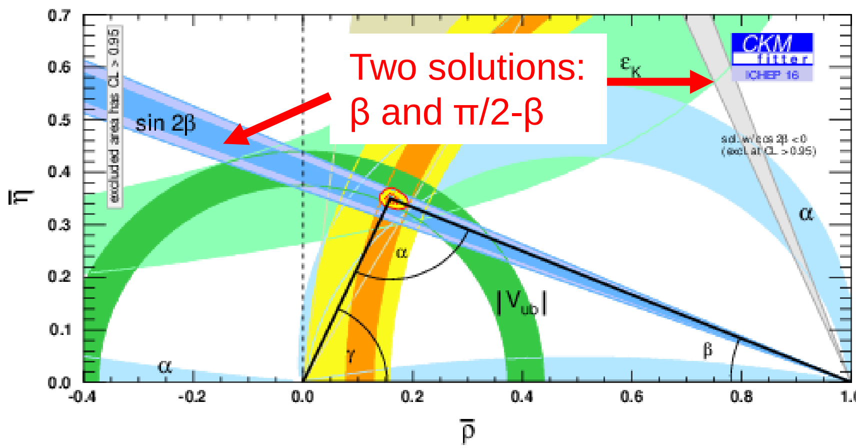
Recently a *joint* analysis of BaBar & Belle data has been released.
[arXiv:1804.06152, arXiv:1804.06153]



A time-dependent analysis is performed of the modes:

$B^0 \to D^{(*)}(K_S\pi\pi)h^0$, with $h^0=\pi,\eta,\omega$

that exploits the strong-phase variation over the D-Dalitz plot to eliminate a trigonometrical ambiguity in the standard analysis → measure cos2β !



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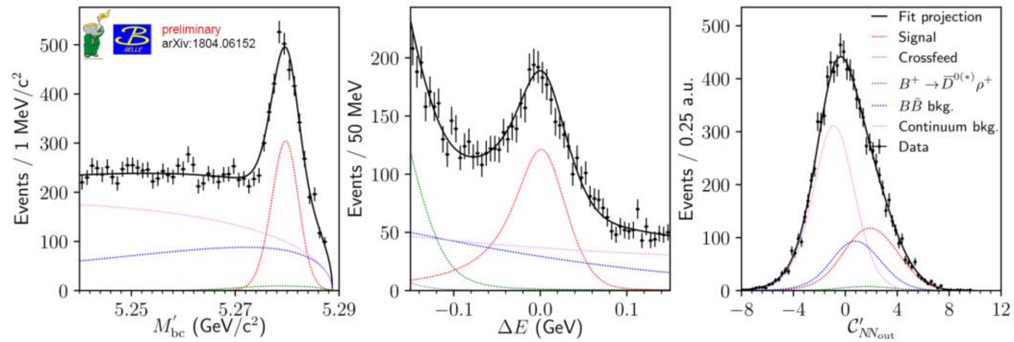

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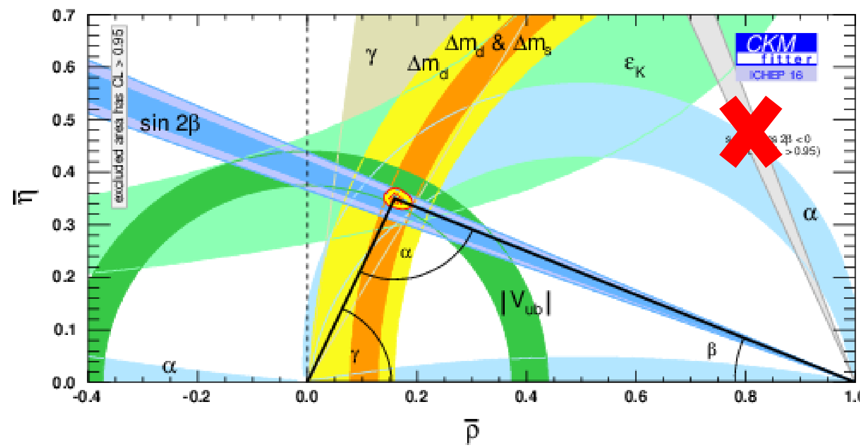
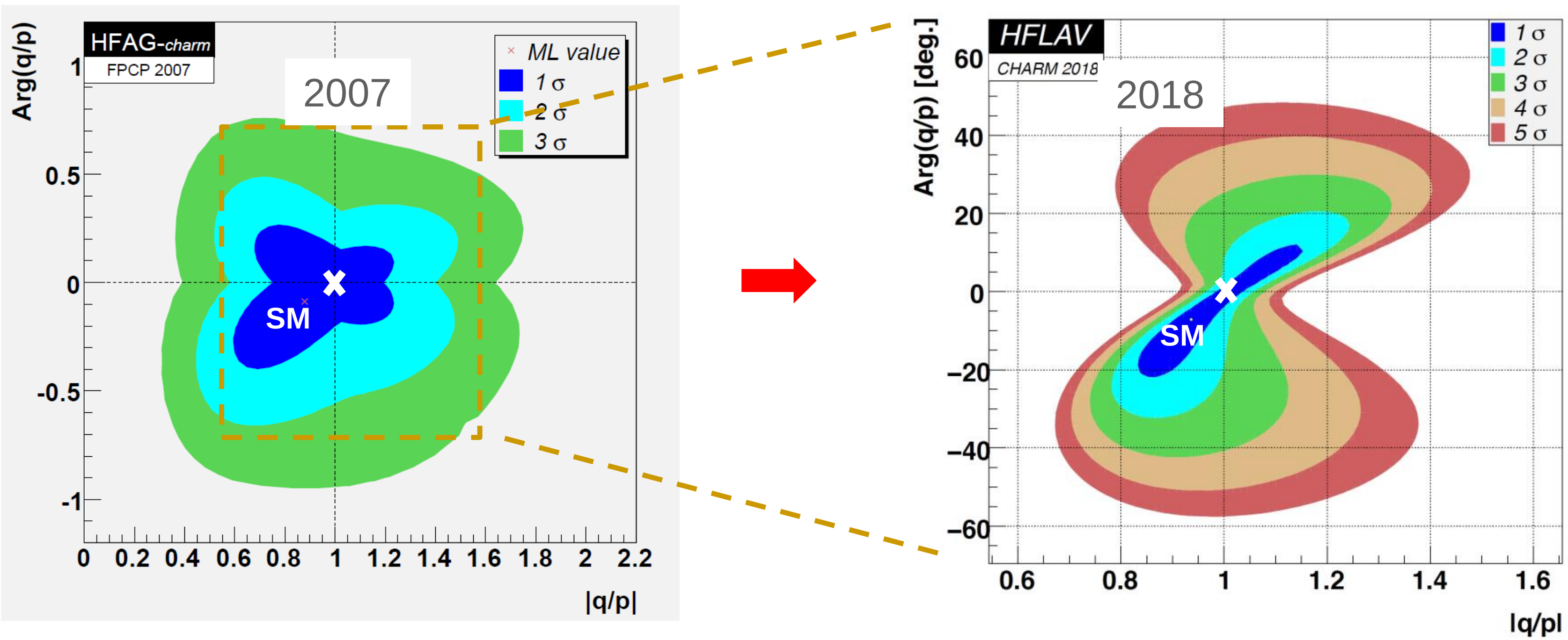
- Demonstrates cos2β>0 (3.7σ)
- Excludes ambiguous solution at 7.3σ



CPV searches in mixing (*i.e.* indirect CPV)

The hunt is now on to find CPV in mixing-related phenomena. Observables are pre-multiplied by x,y, so 'large' (~1%) value of mixing is encouraging in this quest.

Already plenty of progress in last few years…



…any non-zero signal with current and near-future precision would indicate NP.

Searching for direct CPV in SCS charm decays

Also possible to search for direct CPV in charm, which is also expected to be very small (but on how small, opinions vary – under less theoretical control than the indirect case). Can be done with charged mesons or time-integrated D^0 studies.

Best hope of seeing direct CPV is with singly Cabibbo suppressed decays, as here there is hope of interference between diagrams.

Precision that is being attained at LHCb with run-1 data is now at 10^{-3} level:

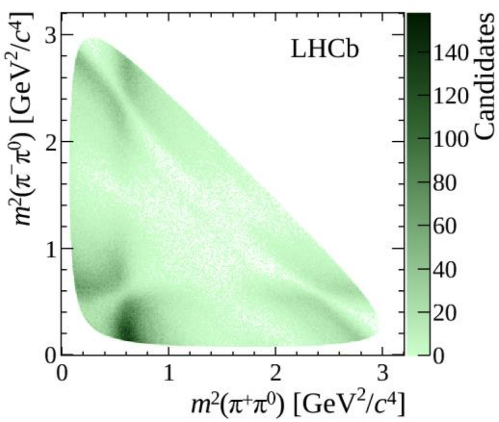
$$\Delta A_{CP} = A_{CP}(K^-K^+) - A_{CP}(\pi^-\pi^+) = (+0.14 \pm 0.16\,(\mathrm{stat}) \pm 0.08\,(\mathrm{syst}))\%$$

[JHEP 07 (2014) 041]

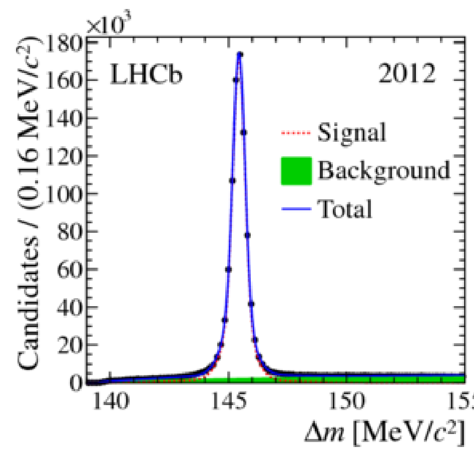
We are entering the regime where there is a real hope to see effect !

Even more interesting is to probe the phase space of multibody modes *e.g.* $D^0 \to \pi\pi\pi^0$ with 'energy test' technique [PLB 740 (2015) 158].

In some such studies interesting hints are emerging *e.g.* 2.7σ tension with SM in $D^0 \to \pi\pi\pi\pi$ [PLB 769 (2017) 345].



$D^0 \to \pi\pi\pi^0$
Dalitz space



$D^0 \to \pi\pi\pi\pi$
signal