Measurements of CP violation at the LHC

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on behalf of the LHCb collaboration with material from ATLAS, CMS and LHCb

Rencontres de Physique de la Vallee D'Aoste,

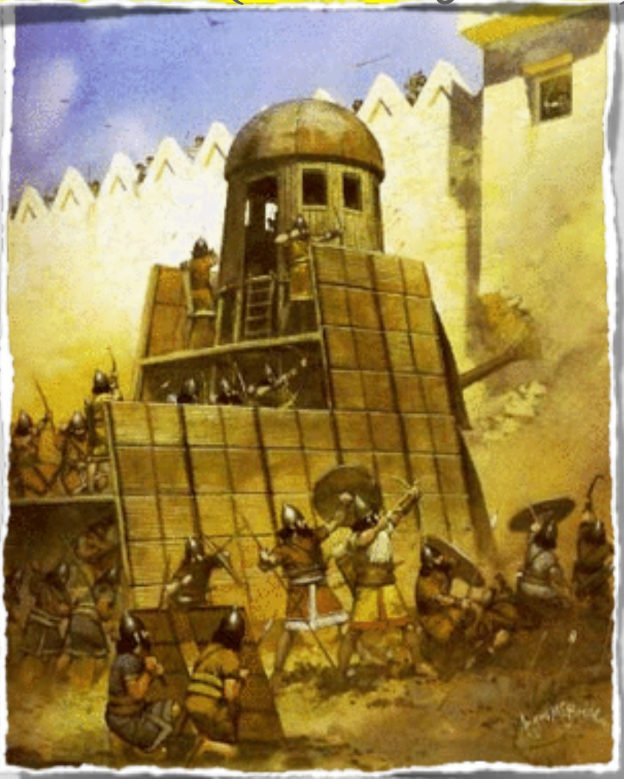
Feb 28, 2018


No.
This ain't stamp
collecting

Everybody says the SM is incomplete

Two ways out (hopefully)

A more powerful machine (unlikely soon)



HE production of new particles. Probe directly structure of matter and its interactions

Get smarter

LE precision measurements access effects of exchange of virtual new particles. Quantum-probe of higher energies than directly accessible

Some say here is where brute force led us so far

Trying to get smarter

Dynamics not invariant for mirror-reversal of the spatial arrangement and replacement of particles with antiparticles.

The SM has enough structure to accommodate CPV without falling apart, but still no clue of where this comes from.

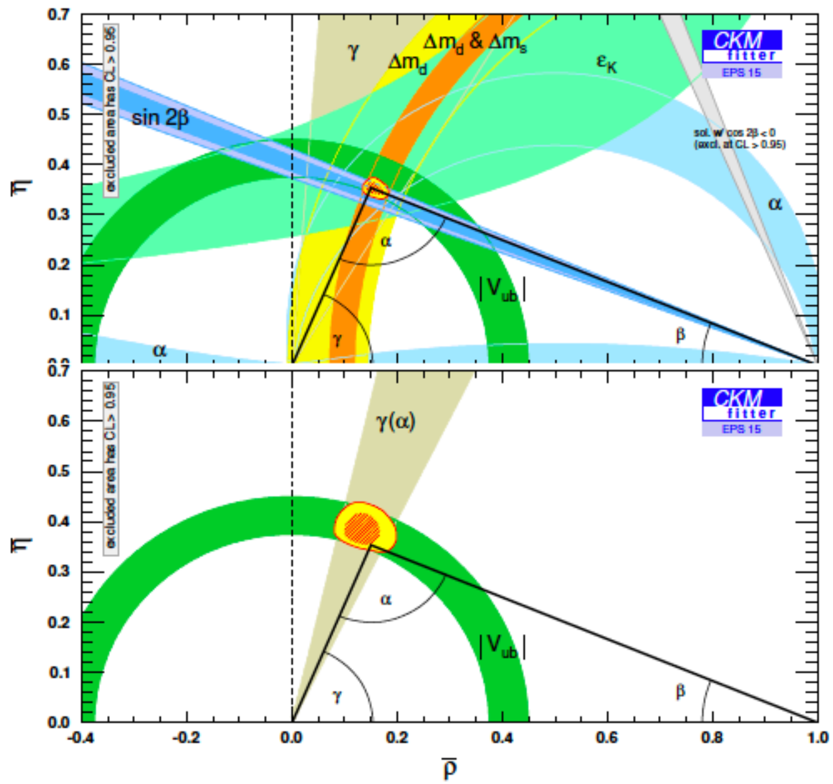
The richness of the phenomenology offers multiple, far-reaching ways to probe non-SM physics.

(The hope is that) By exploring CPV one can gain insight on some of the deepest questions at the intersection of particle physics and cosmology

Status

Z. Ligeti

- SM dominates CP viol. $\Rightarrow$ KM Nobel
- The implications of the consistency often overstated
- Larger allowed region if the SM is not assumed
- Tree-level (mainly V_{ub} & γ) vs. loop-dominated measurements crucial



- $\mathcal{O}(20\%)$ NP contributions to most loop-level processes (FCNC) are still allowed

Plus, there's more to CPV than the Unitarity Triangle: charm physics, baryons, etc...

Shown today

Recent results on CP violation from ATLAS,CMS, and LHCb.

Emphasis on

- LHCb — obviously the most prolific of the bunch in the CPV business.
- *new* results. To keep the talk less boring and the organizers happier. (New means new — no LHCb result shown here dates back more than 3 months ago.)

I'll try to convey a bit of the big-picture. See the nice talks from L. Henry and M. Lucio Martinez for the technicalities

Lots of Heavy ~~Q~~Cuarks

O(100k) b-hadrons and O(1M) c-hadrons per second.

Try to select them online through

- reduced collision pile-up (LHCb)
- dimuons (ATLAS, CMS, LHCb)
- energetic charged particles (LHCb level-0) displaced from the primary vertex (LHC level-1)

Emphasis on final states with (di)muons and charged particles only reduces above numbers to 1-10% of reconstructable candidates interesting for physics.

Still, signal yields in final plots approach 1M for bottom decays and 1 billion for charm decays.

Performance drivers

Goals: Separate from background. Measure the time evolution. Infer flavor at production and orbital angular momentum

Handles: 0.5-1.5 ps lifetimes + O(10 GeV/c) momenta results in O(mm) flight before decay — key to separate signal from prompt particles.

(1) Tracking: O(10) um vertexing resolution and 0.5-1.5% pT resolution

(2) Large acceptance for charged particles and low-momentum muons

(3) Charged-hadron identification — LHCb only

(4) Control over acceptances and instrumental asymmetries (material, ecc)

(5) Integrate all of the above to infer production flavor — effective sample-size reduction of 20x—60x

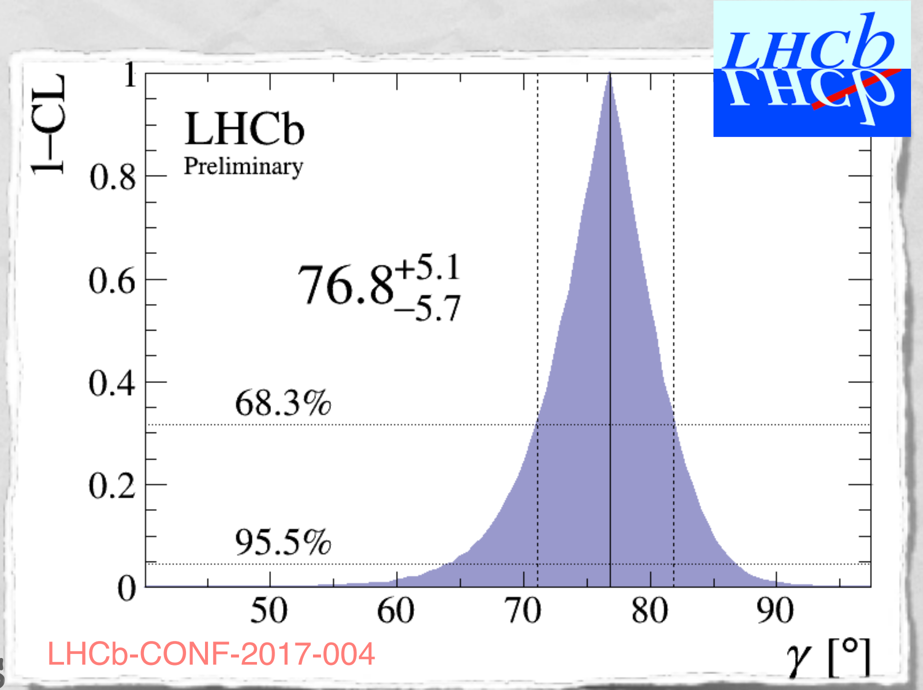
(6) Control samples to check/calibrate instrumental aspects — mainly LHCb

Gamma

The less well known of the Unitarity Triangle parameters.

Determination offers a solid SM reference to compare all other measurements against.

Experimental precision is a challenge due to small sample sizes, which call for combinations of many measurements.



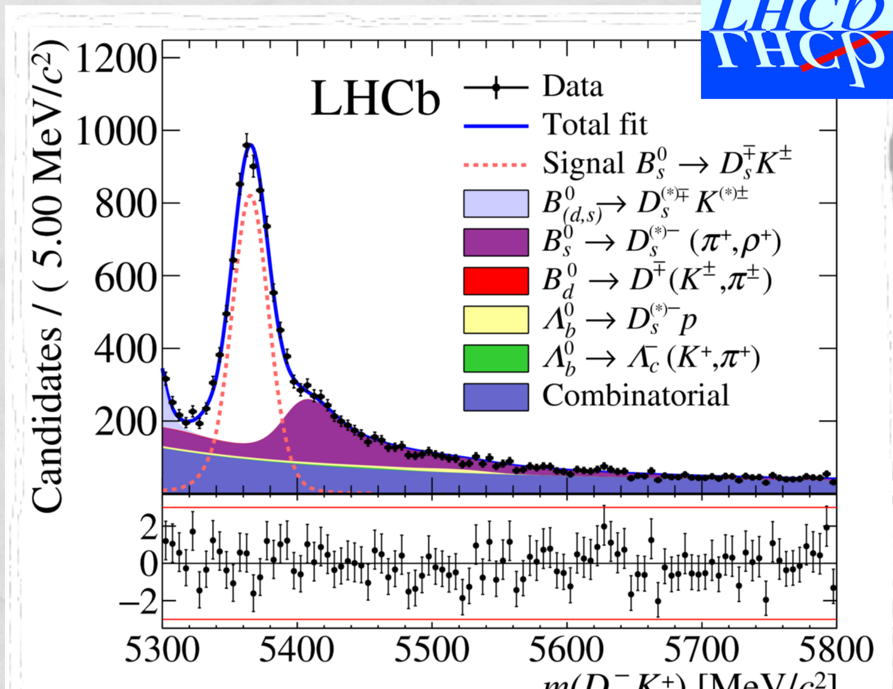
With precisions that outclass Babar and Belle by 3x, LHCb has brought the global gamma knowledge in the 5° ballpark

New!

No stone unturned

$B^0_s \to D^-_s K^+$: similar-size interfering amplitudes and nonzero $\Delta\Gamma_s$. suited for γ. LHCb update to 3/fb.

- Mass (D, B)-PID fit of sample composition
- Flavor tag mesons (5.7% power)
- Fit of time evolution (resolution from prompt D^-_s + rnm trck, extrapolate acceptance from $B^0_s \to D^-_s \pi^+$)



arxiv:1712.07428

$\gamma = 128^{+17}_{-22}$ [°]

3.8σ CPV in $B^0_s \to D^-_s K^+$

CPV in B^0_s mixing

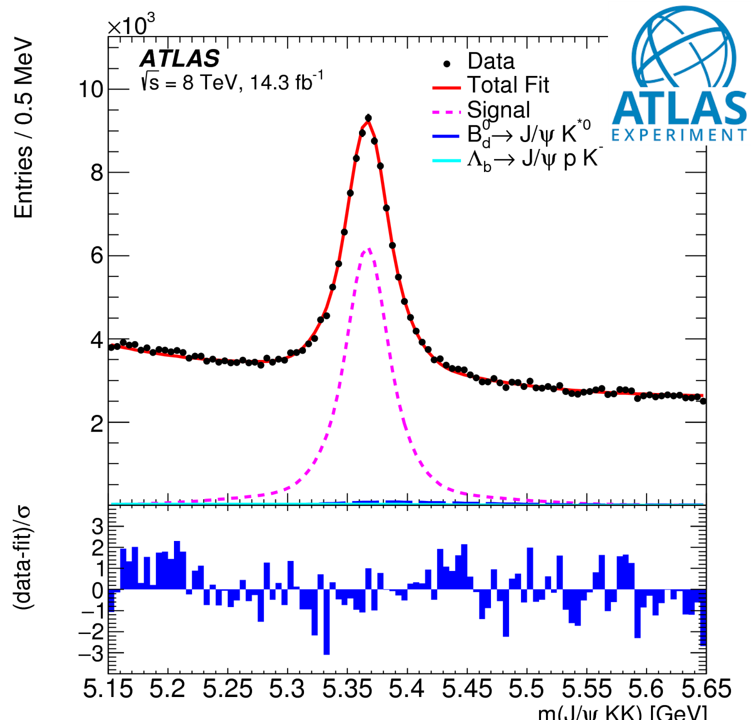
The CP-violating mixing phase Φs is among the deadliest BSM killers of the past decade, thanks to theoretically robust sensitivity to a broad class of generic BSM models and (relative) experimental accessibility.

Impact dominated by angular analysis of the time evolution of flavor tagged $B^0_s \to J/\psi(\to\mu\mu)KK$ decays ("golden-channel")

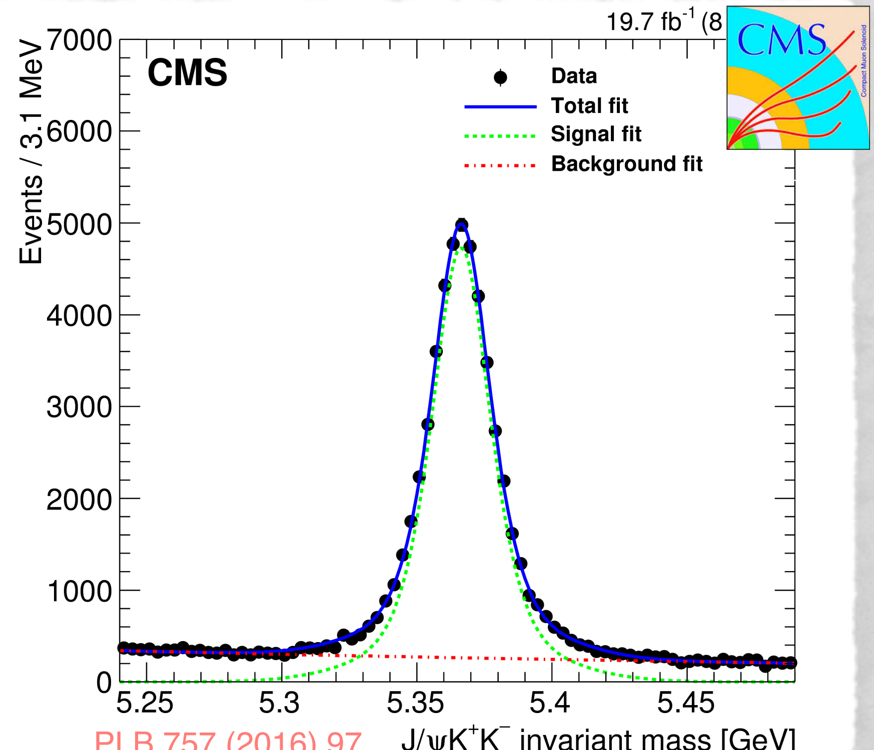
First Tevatron constraints from 2008 improved by >10x by a systematic program carried out at the LHC

- **LHCb:**
  - $J/\psi\phi$: PRL 114, 041801 (2015)
  - $J/\psi KK$: JHEP 08 (2017) 037
  - $J/\psi\pi\pi$: PLB 736 (2014) 186
  - $\psi(2S)\phi$: PLB 762 (2016) 253-262
  - $D_S^+ D_S^-$: PRL 113, 211801 (2014)
- **CMS:** $J/\psi\phi$ PLB 757 (2016) 97
- **ATLAS:** $J/\psi\phi$: JHEP 08 (2016) 147

ATLAS and CMS



JHEP 08 (2016) 147



PLB 757 (2016) 97

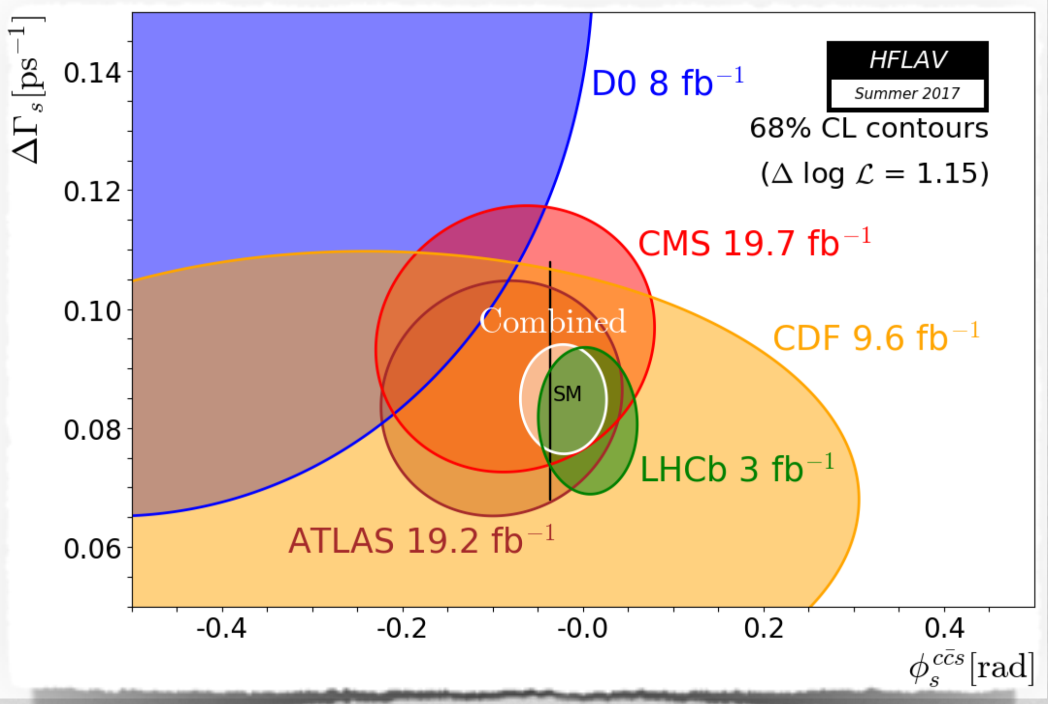
75k signal decays
97 fs decay-time resolution
1.5% tagging power

49k signal decays
75 fs decay-time resolution
1.3% tagging power

$\Phi s = -0.090 \pm 0.078 \pm 0.041$ rad

$\Phi s = -0.075 \pm 0.097 \pm 0.031$ rad

Status



Much sharper picture than a decade ago.
Large BSM ruled out, but allowed range still 10x wider than SM prediction.

LHC experiments are (i) perfecting analyses of golden channel and (ii) exploring novel channels that enhance sensitivity

Penguin-dominated B^0_s mixing phase

New!

First measurement of the CP-violating phase $\phi_s^{d\bar{d}}$ in $B_s^0 \to (K^+\pi^-)(K^-\pi^+)$ decays

The LHCb collaboration†

Abstract

A flavour-tagged decay-time-dependent amplitude analysis of $B_s^0 \to (K^+\pi^-)(K^-\pi^+)$ decays is presented in the $K^\pm\pi^\mp$ mass range from 750 to 1600 MeV/c^2. The analysis uses pp collision data collected with the LHCb detector at centre-of-mass energies of 7 and 8 TeV, corresponding to an integrated luminosity of 3.0 fb^{-1}. Several quasi-two-body decay modes are considered, corresponding to $K^\pm\pi^\mp$ combinations with spin 0, 1 and 2, which are dominated by the $K_0^*(800)^0$ and $K_0^*(1430)^0$, the $K^*(892)^0$ and the $K_2^*(1430)^0$ resonances, respectively. The longitudinal polarisation fraction for the $B_s^0 \to K^*(892)^0\overline{K}^*(892)^0$ decay is measured as $f_L = 0.208 \pm 0.032 \pm 0.046$,

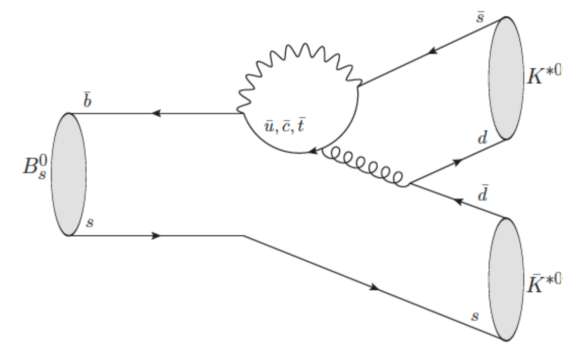
New!

Overview

Decay-time evolution of flavor-tagged $B^0_s \to (K^+\pi^-)(K^-\pi^+)$ decays can reveal presence of non-SM particles contributing to the penguin amplitude.

Boost the signal yield (to 6k in 3/fb) by widening the Kπ ranges to 0.75–1.6 GeV/c²

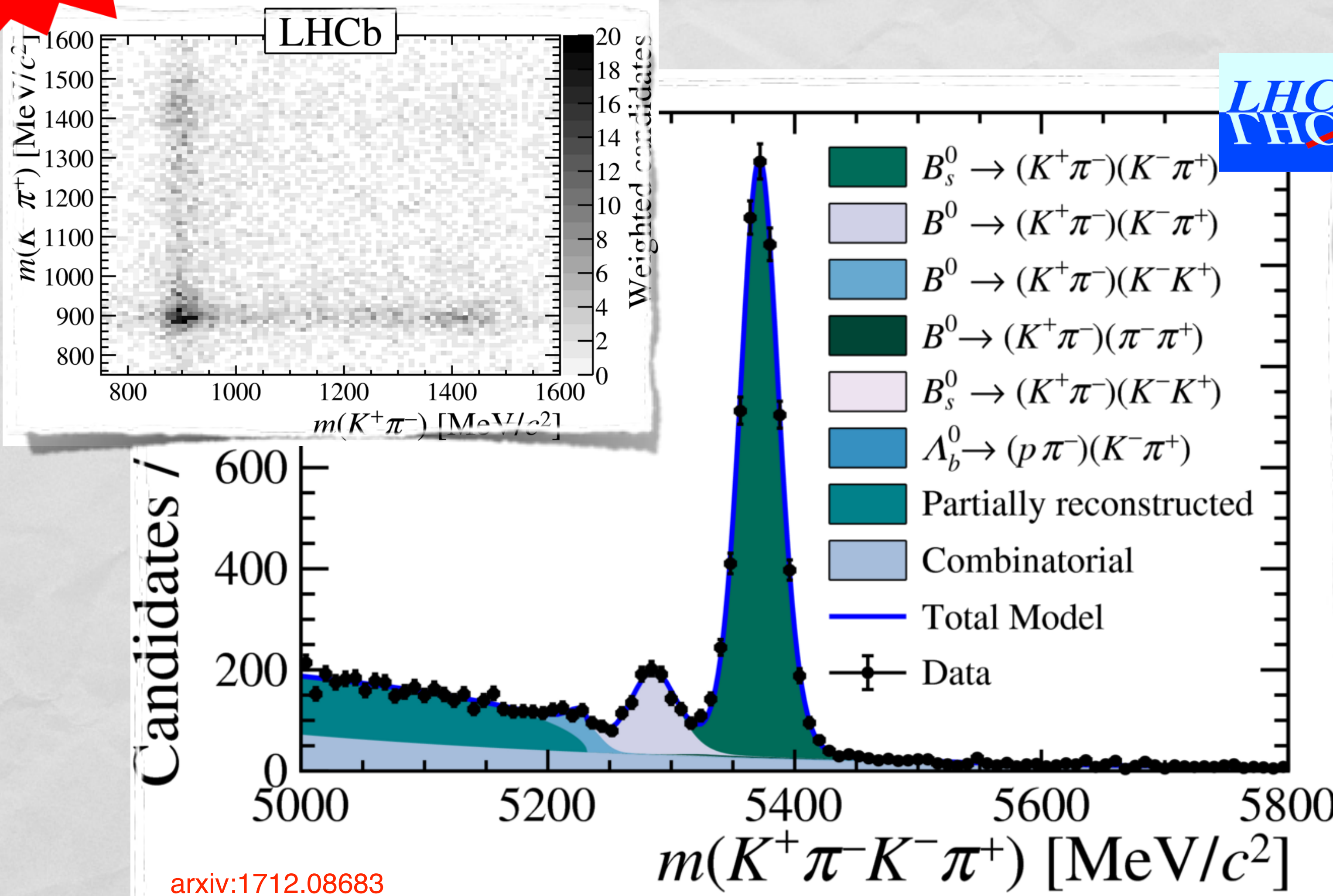
Angular analysis takes into account the strong-dynamics differences between the 9 contributing processes.



$$B^0_s \to (K^+\pi^-)^*_0 (K^-\pi^+)^*_0$$
$$B^0_s \to (K^+\pi^-)^*_0 \overline{K}^*(892)^0$$
$$B^0_s \to K^*(892)^0 (K^-\pi^+)^*_0$$
$$B^0_s \to (K^+\pi^-)^*_0 \overline{K}^*_2(1430)^0$$
$$B^0_s \to K^*_2(1430)^0 (K^-\pi^+)^*_0$$
$$B^0_s \to K^*(892)^0 \overline{K}^*(892)^0$$
$$B^0_s \to K^*(892)^0 \overline{K}^*_2(1430)^0$$
$$B^0_s \to K^*_2(1430)^0 \overline{K}^*(892)^0$$
$$B^0_s \to K^*_2(1430)^0 \overline{K}^*_2(1430)^0$$

New!

Result



arxiv:1712.08683

First determination of mixing phase in this channel

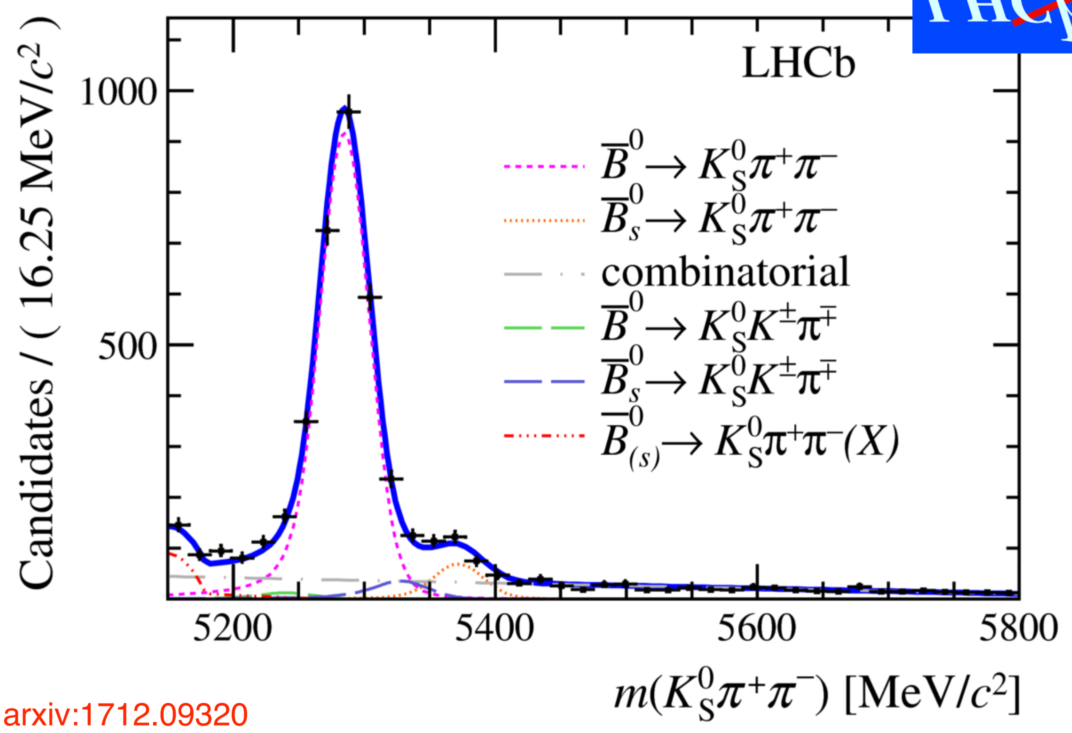
$\Phi = -0.10 \pm 0.13 \pm 0.14$ rad

New! Analysis of $B^0 \to K^0_S \pi^+ \pi^-$

Charmless 3-body decays add valuable info in fits of CPV phenomenology

Dalitz-plot fit (isobar model) of 3k decays from 3/fb.

Correct for production and π +/π- asymmetry

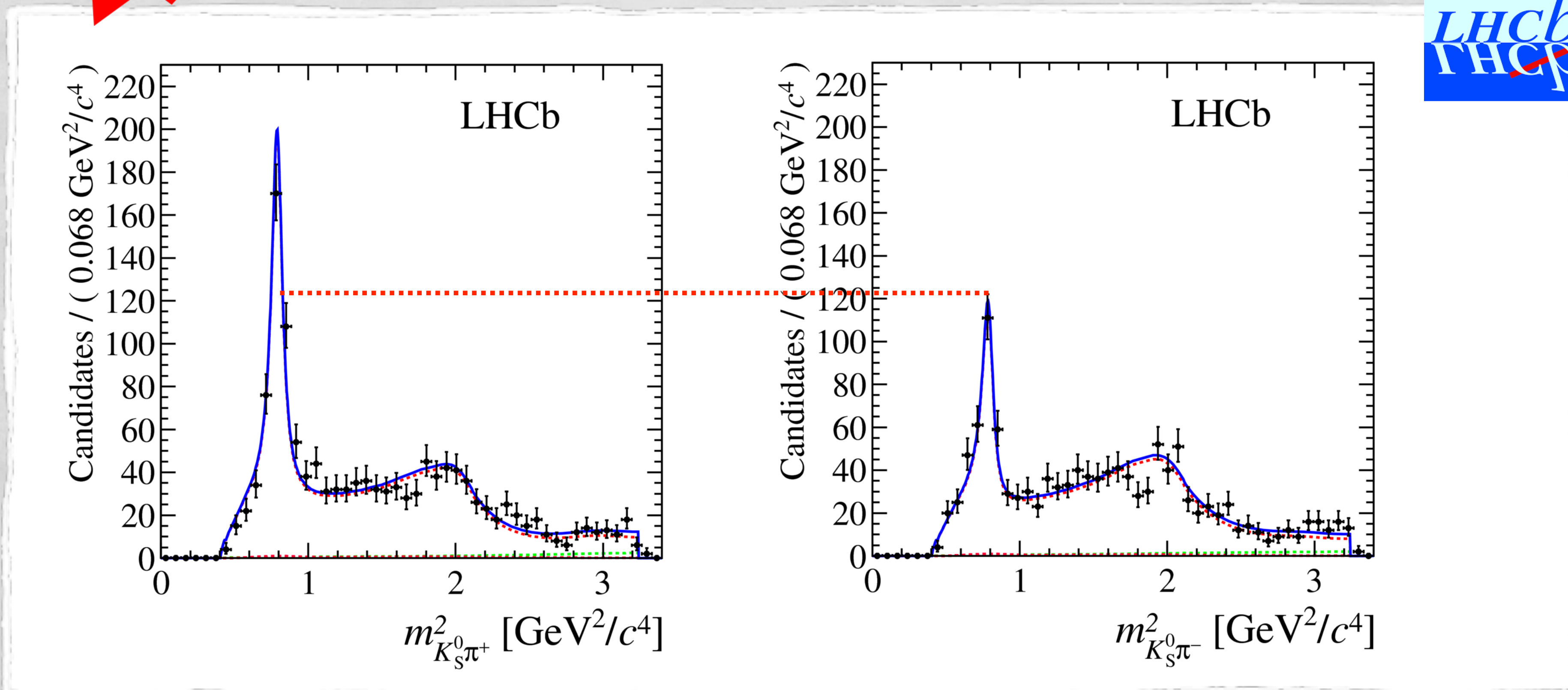


arxiv:1712.09320

Sample composition consistent with Babar/Belle.

New!

This is CP violation



First observation of CPV in $B^0 \rightarrow K^*\pi$ decays

$A_{CP} = -0.308 \pm 0.060 \pm 0.016$

CHARM QUARK

c

Heavier than a strange quark, but not as heavy as a bottom quark, the **CHARM QUARK** was discovered in 1974. Particles that contain charm and anticharm quarks are called "charmed matter."

Acrylic felt/fleece with a mix of poly beads and gravel for medium-heavy mass.

$10.49 PLUS SHIPPING

●●●●●●●●●●○○○

LIGHT HEAVY

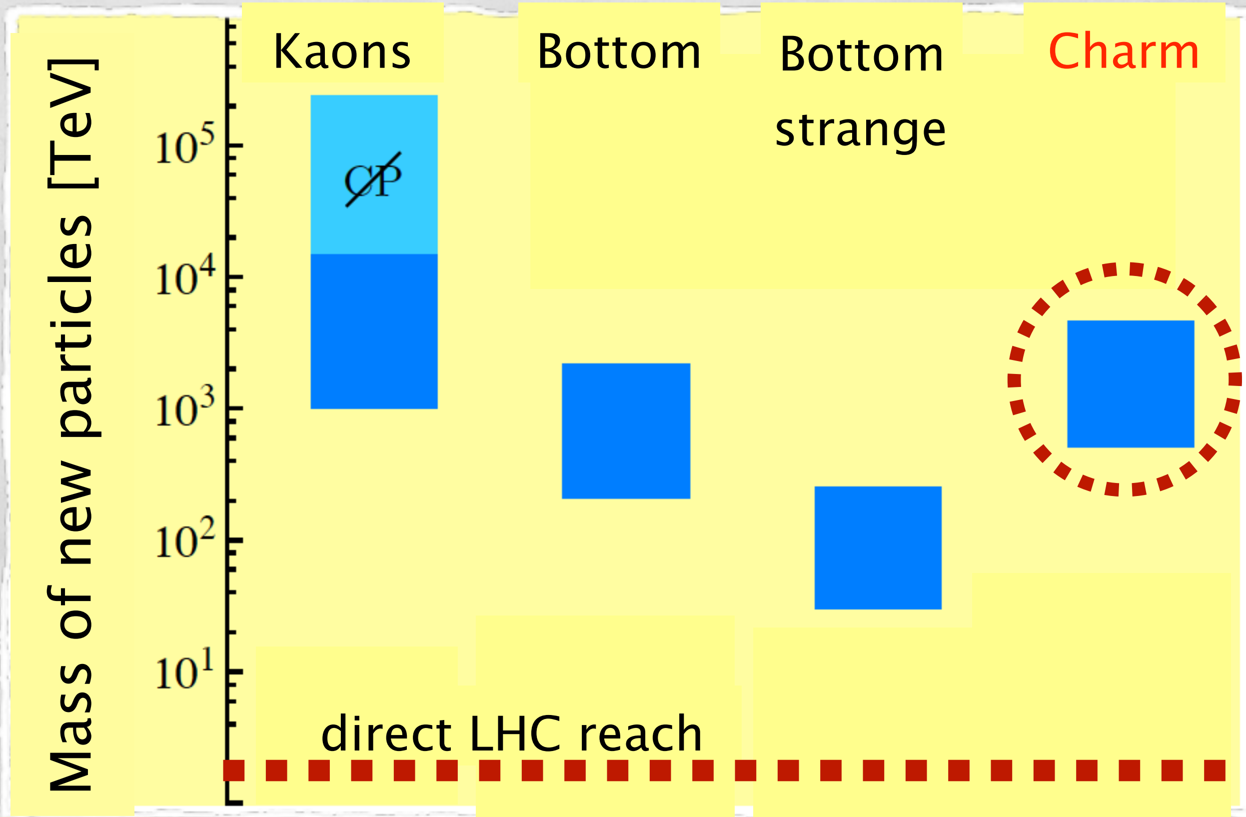
LUON PHOTON NEUTRINO TACHYON ELECTRON UP QUARK DOWN QUARK TAU NEUTRINO MUON UP
EUTRON DOWN QUARK TAU GLUON **CHARM QUARK** TACHYON ELECTRON UP QUARK DOWN QUARK
EUTRINO MUON UP QUARK PROTON NEUTRON DOWN QUARK TAU GLUON PHOTON NEUTRINO TACHY

The PARTICLE ZOO

Unique. Hard.

Unique — c quark is up-type: D sensitive to BSM complementary to that probed by B and K.

Hard — predictions are hard. D isn't a precision probe. Effects are <10^{-3} effects due to dynamic suppression. Call for O(>1M) yields and tight control of systematics.



Charm is second only to kaons in probing the highest scales and it does probe complementary dynamics

New!

CP-violating charge asymmetry in Λ_c decays

A measurement of the CP asymmetry difference in $\Lambda_c^+ \to pK^-K^+$ and $p\pi^-\pi^+$ decays

LHCb collaboration†

Abstract

The difference between the CP asymmetries in the decays $\Lambda_c^+ \to pK^-K^+$ and $\Lambda_c^+ \to p\pi^-\pi^+$ is presented. Proton-proton collision data taken at centre-of-mass energies of 7 and 8 TeV collected by the LHCb detector in 2011 and 2012 are used, corresponding to an integrated luminosity of 3 fb^{-1}. The Λ_c^+ candidates are reconstructed as part of the $\Lambda_b^0 \to \Lambda_c^+\mu^-X$ decay chain. In order to maximize the cancellation of production and detection asymmetries in the difference, the final-state kinematic distributions of the two samples are aligned by applying phase-space-dependent weights to the $\Lambda_c^+ \to p\pi^-\pi^+$ sample. This alters the definition of the integrated CP asymmetry to $A_{CP}^{\rm wgt}(p\pi^-\pi^+)$. Both samples are corrected for reconstruction and selection efficiencies across the five-dimensional Λ_c^+ decay phase space. The difference in CP asymmetries is found to be

$$\Delta A_{CP}^{\rm wgt} = A_{CP}(pK^-K^+) - A_{CP}^{\rm wgt}(p\pi^-\pi^+)$$

At a glance

New!

A charge asymmetry of the $\Lambda_c^+ \rightarrow p\, h^+h^-$ decay rate indicates direct CP violation in Λ_c^+ decays

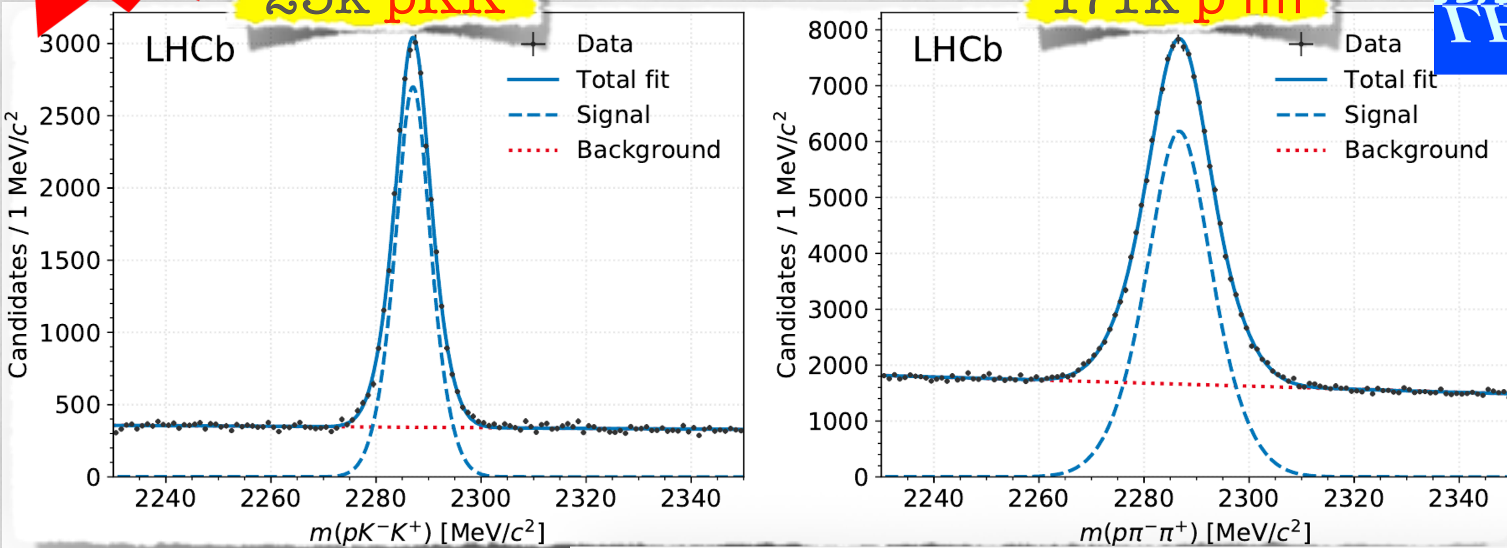
- 3/fb from 2011-2012.
- Restrict to Λ_c^+ from semimuonic Λ_b^0 decays so that Λ_b^0 displacement reduces bckd
- Measure baryon/antibaryon charge asymmetry in 25k $\Lambda_c^+ \rightarrow pK^+K^-$ and 171k $\Lambda_c^+ \rightarrow p\,\pi^+\pi^-$ decays
- Differences between pK^+K^- and $p\,\pi^+\pi^-$ asymmetries to cancel asymmetries in Λ_b^0 and μ/p interactions, yielding a difference in CP-violating asymmetries

New!

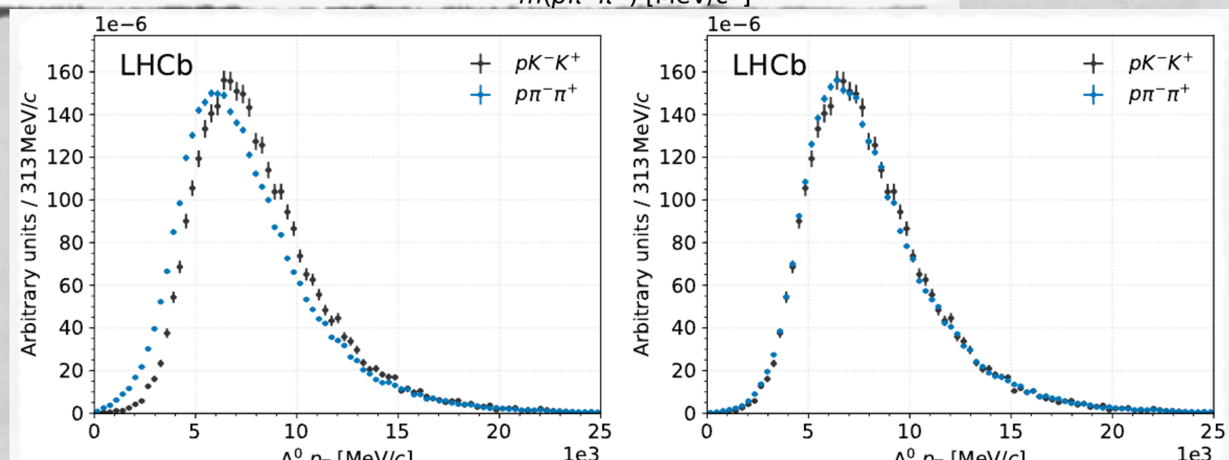
Results

25k pKK

171k p ππ



BDT for a 4-dim kinematic weighting across the two decays



arxiv:1712.07051

$\Delta A_{CP} = (0.30 \pm 0.91 \pm 0.61)\%$

Systematics: mass mismodelings, weight precision, simulation size.

PHYSICAL REVIEW D **VOL..XX,** 000000 (XXXX)

Communications

CP violation in D mixing

New!

Updated determination of D^0–$\bar{D}^0$ mixing and *CP* violation parameters with $D^0 \to K^+\pi^-$ decays

R. Aaij *et al.*[*]
(LHCb Collaboration)

(Received 8 December 2017)

We report measurements of charm-mixing parameters based on the decay-time-depend
$D^0 \to K^+\pi^-$ to $D^0 \to K^-\pi^+$ rates. The analysis uses a data sample of proton-proton collisions co
to an integrated luminosity of 5.0 fb^{-1} recorded by the LHCb experiment from 2011 through 201
charge-parity (*CP*) symmetry, the mixing parameters are determined to be $x'^2 = (3.9 \pm$
$y' = (5.28 \pm 0.52) \times 10^{-3}$, and $R_D = (3.454 \pm 0.031) \times 10^{-3}$. Without this assumption, the m
is performed separately for D^0 and $\bar{D}^0$ mesons, yielding a direct *CP*-violating asymm
$(-0.1 \pm 9.1) \times 10^{-3}$, and magnitude of the ratio of mixing parameters $1.00 < |q/p| <$
68.3% confidence level. All results include statistical and systematic uncertainties and improve
upon previous single-measurement determinations. No evidence for *CP* violation in charm
observed.

New!

Overview

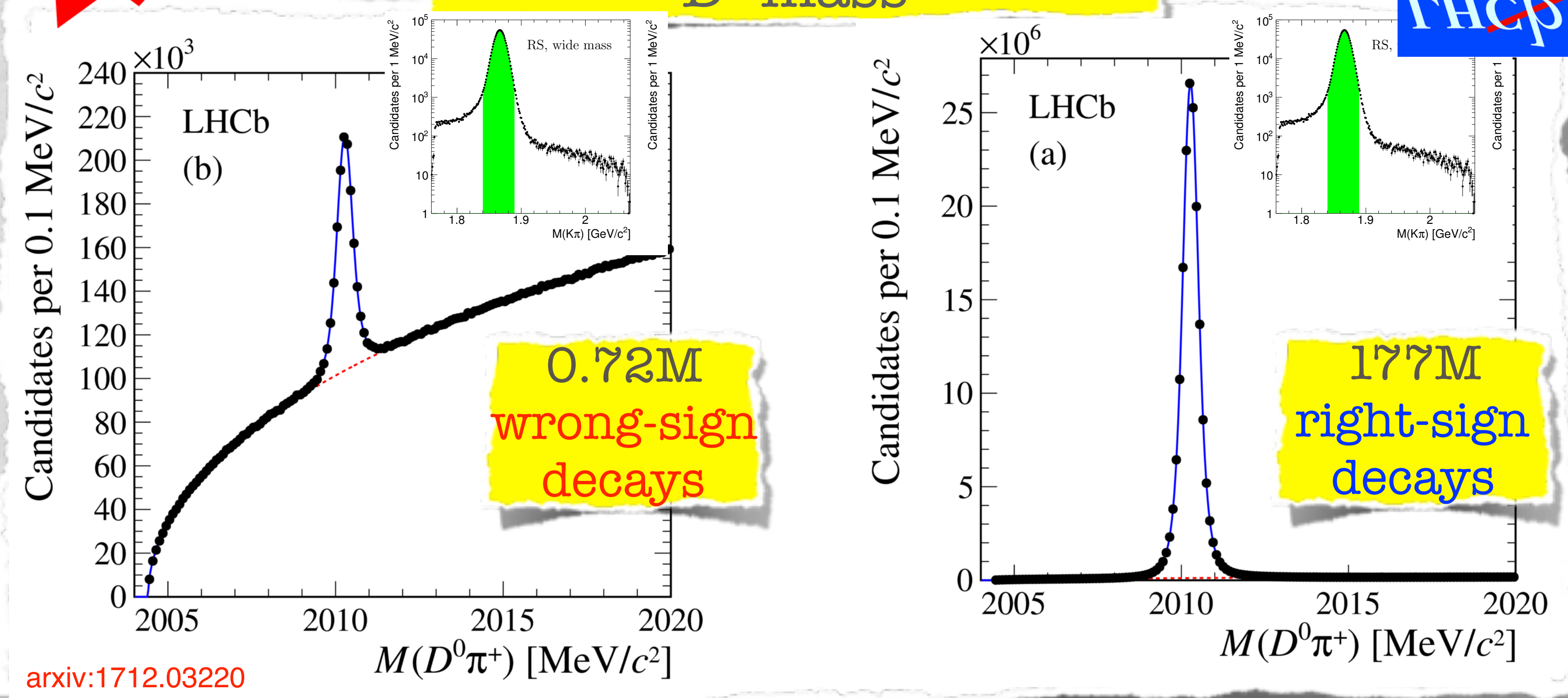
A modulation of the $D^0 \rightarrow K^+\pi^-$ rate versus decay time indicates oscillation. Different oscillation patterns between D^0 and anti-D^0 indicate CPV in oscillations.

- Get as much $D^0 \rightarrow K^+\pi^-$ decays as possible (pT, displacement) using 2011–2016 data (5/fb)
- Identify if were produced as D^0 or anti-D^0 (restrict them to originate from D^{*+} decays)
- Look for differences between the $D^0 \rightarrow K^+\pi^-$ and anti-$D^0 \rightarrow K^-\pi^+$ rate versus decay time

The signal

New!

D* mass



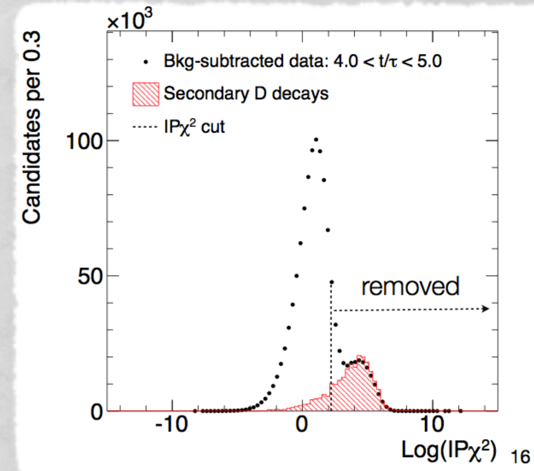
arxiv:1712.03220

Cut tight on M(D) and PID. Fit the yield using M(Dπ) mass.

Fit yields in bins over the 0-20τ range. WS and RS signal shapes constrained to be the same. All the rest independent.

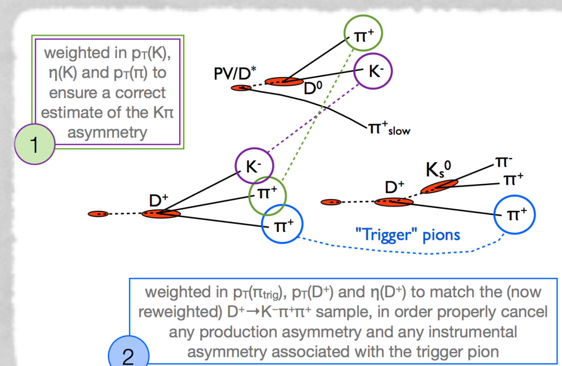
New!

Challenges



B->D decays If undetected, B lifetime mimicks a larger D decay time than it is, diluting oscillations. Require D to point to the primary vertex and include maximum bias from the extrapolated 3% remainder in the systematics.

Peaking bckg: bias the result. Dominated by RS decays with K-π swapping. Extrapolate the fraction using mass sidebands and include maximum bias in the systematics.



Instrumental asymmetries dominated by K+/K- x-sec in matter. Measured to be (1.0 +-0.1)% from control modes in data

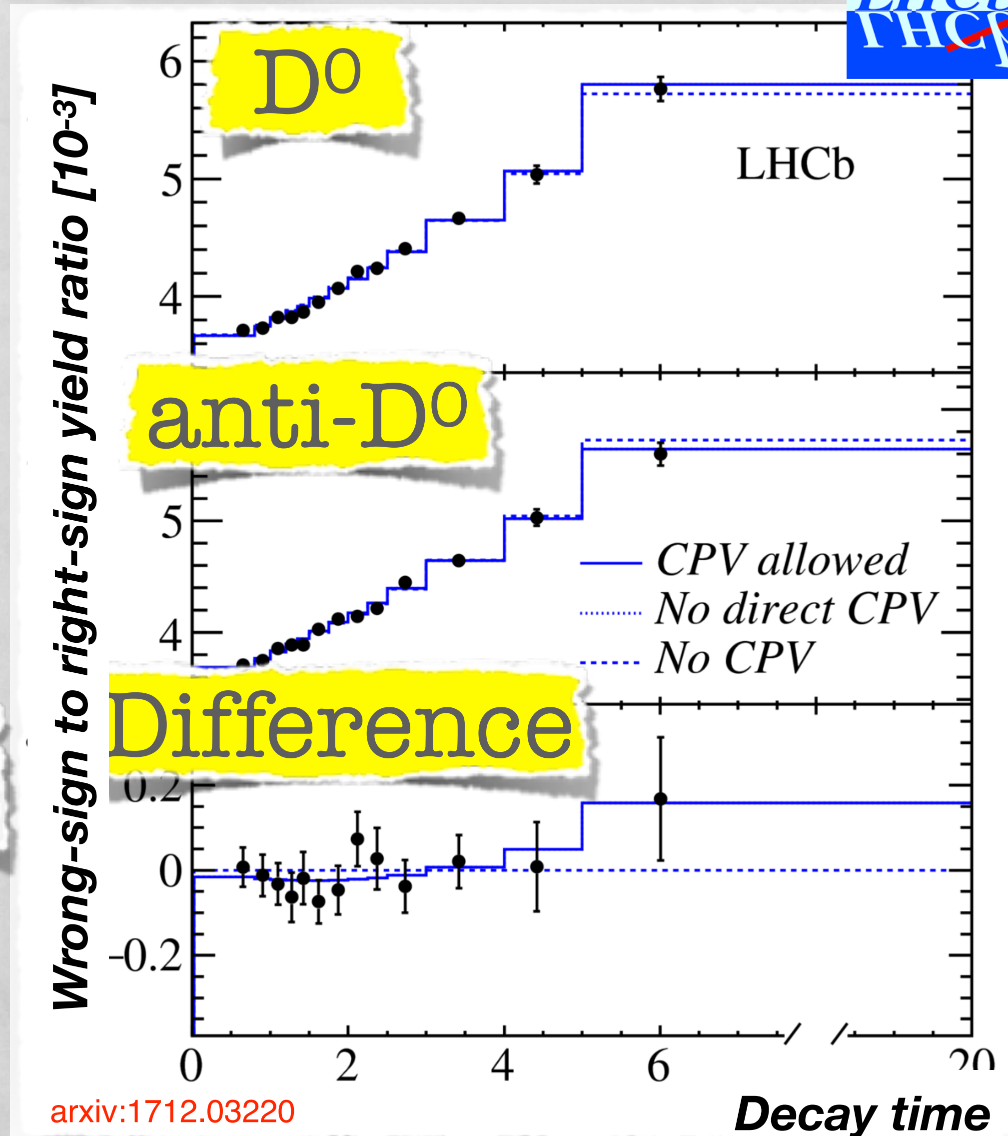
New!

Results

..but no measurable difference observed in oscillation probability between D^0 and anti-D^0.

Fit these to extract the mixing parameters x', y'

$$R(t) \approx R_D + \sqrt{R_D} y' \frac{t}{\tau} + \frac{x'^2 + y'^2}{4} \left(\frac{t}{\tau}\right)^2,$$



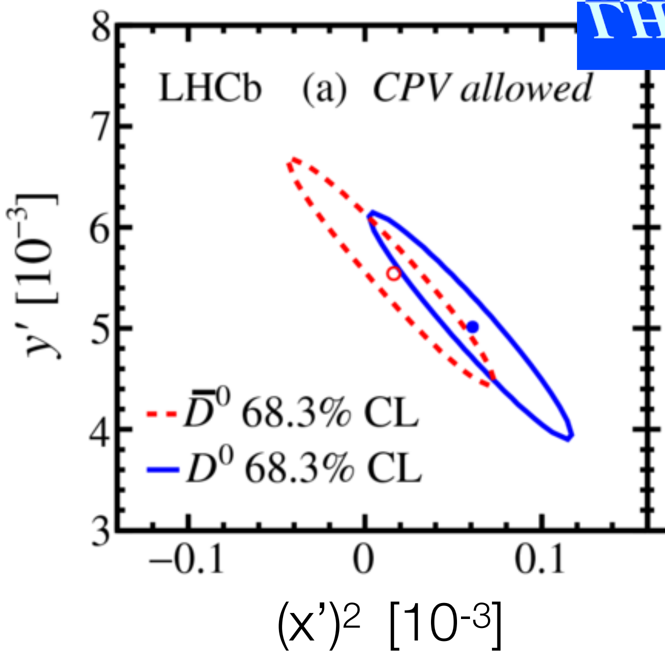
New!

Results

Parameter	Value
R_D^+	$3.454 \pm 0.040 \pm 0.020$
y'^+	$5.01 \pm 0.64 \pm 0.38$
$(x'^+)^2$	$0.061 \pm 0.032 \pm 0.019$
R_D^-	$3.454 \pm 0.040 \pm 0.020$
y'^-	$5.54 \pm 0.64 \pm 0.38$
$(x'^-)^2$	$0.016 \pm 0.033 \pm 0.020$

Results $[10^{-3}]$

arxiv:1712.03220



$1.00 < |q/p| < 1.35$ at the 68% CL

No evidence for CP violation.

World's best (by large) determination of mixing parameters and constraints on CPV in mixing.

Summary

CPV offers insight on some of the deepest questions at the intersection of particle physics and cosmology

Ginormous yields and a dedicated detector make LHC the best game in town.

LHCb leads the exploration. Today shown just a sampler of recent results.

Times seem particularly compelling for CPV studies: LHC expected exciting high-pT physics and boring flavor physics.

Looks like it's getting the other way around.

(Hopefully not) The end