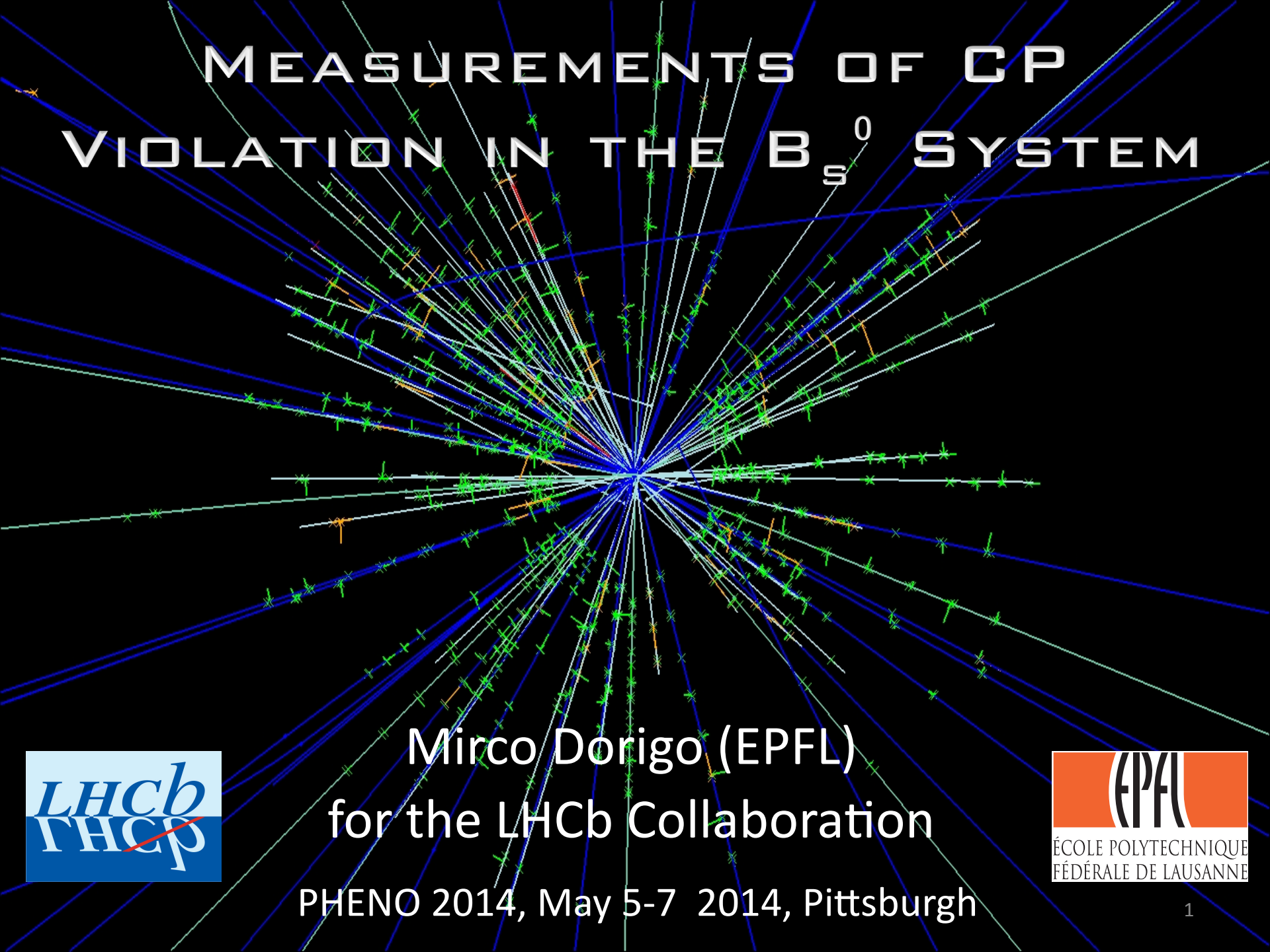
Measurements of CP Violation in the B_s^0 System



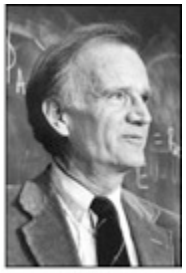
Mirco Dorigo (EPFL)
for the LHCb Collaboration

PHENO 2014, May 5-7 2014, Pittsburgh

50 years of CP Violation

Physics laws are not invariant for mirror-reversal of the spatial arrangement and replacement of all particles with antiparticles


James Cronin


Val Fitch

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)

Who ordered this?

Not the SM – but has sufficient complexity to accommodate it, by a single complex phase in the CKM mechanism.

NP can generate additional source of CP (and flavour) violation.
Multiple, precise experimental tests of the CKM paradigm can reveal early signs of new particles/couplings.

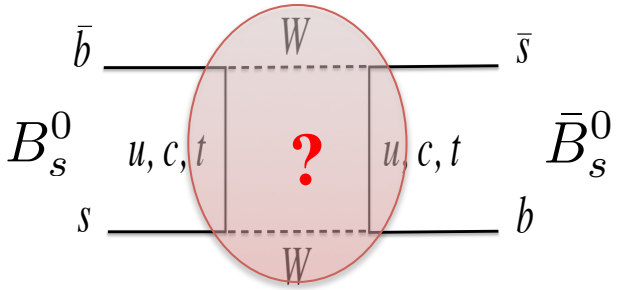
B_s^0 Handles on NP

Broad class of SM extensions can easily alter B_s^0 mixing dynamics.

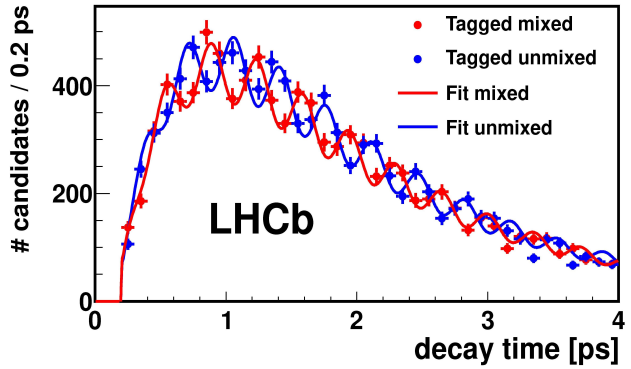
- Mass difference Δm_s sensitive to NP, but requires input from lattice.
- Decay with difference $\Delta\Gamma_s$ less sensitive to NP, but nice byproduct.

Best NP probes, accurate SM predictions

- CP-violating mixing phase ϕ_s very sensitive to NP.
- Flavour specific CP asymmetry a^s_{sl} very sensitive to NP ($a^s_{sl} \approx \Delta\Gamma_s/\Delta m_s \tan\phi_s$)



$$|B_{L,H}\rangle = p|B_s^0\rangle \pm q|\bar{B}_s^0\rangle$$



$\Delta m_s = 17.768 \pm 0.024\ \text{ps}^{-1}$

NJP 15 (2013) 053021

Topics for Today

LHCb has a broad program to measure CP violation in the B_s^0 system.
In this talk, CP asymmetries

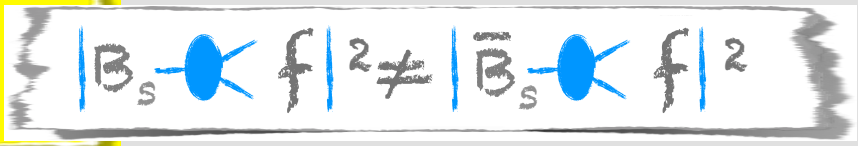
decay-time integrated:

$B_s^0 \to D_s^+ X\mu^-\nu$
measurement of a^s_{sl}
probe CP violation on mixing.

decay-time dependent:

$B_s^0 \to J/\psi\, h^+h^-$ ($h = K,\pi$)
$B_s^0 \to \phi\phi$
direct probe of mixing phase.

$B_s^0 \to K^+K^-$
probe also CP violation in decay.



Large Hadron Collider beauty

More than 2 years of 7-8 TeV proton-proton collisions:

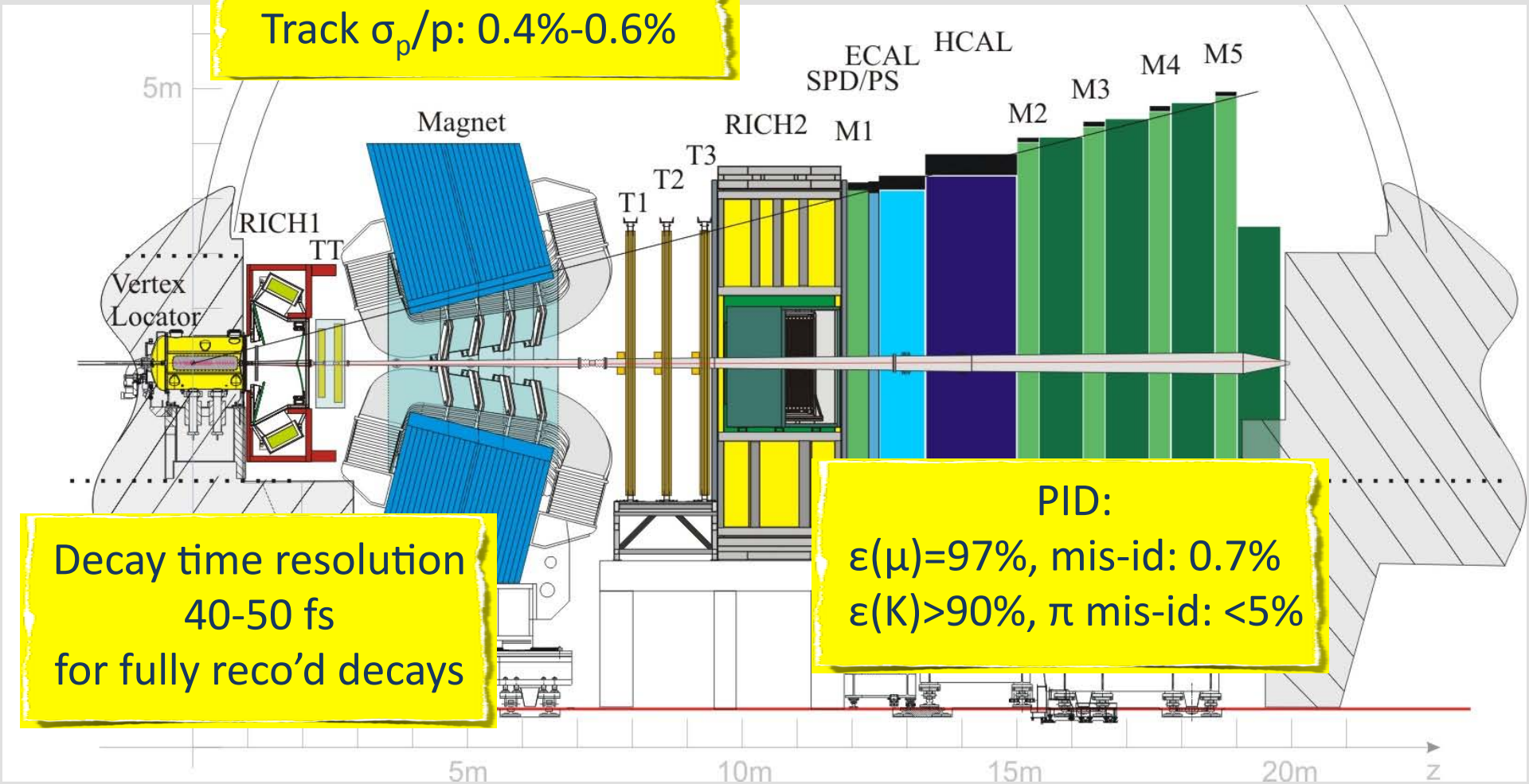
180×10^{12} collisions visible at LHCb,

1.4% yields a $b\bar{b}$ pair in LHCb acceptance,

allows to store the world's largest sample of B_s^0 mesons

Large Hadron Collider beauty

Track σ_p/p: 0.4%-0.6%



Decay time resolution
40-50 fs
for fully reco'd decays

PID:
ε(μ)=97%, mis-id: 0.7%
ε(K)>90%, π mis-id: <5%

CPV in Mixing: a^s_{sl}

PLB 728 (2014), 607-615

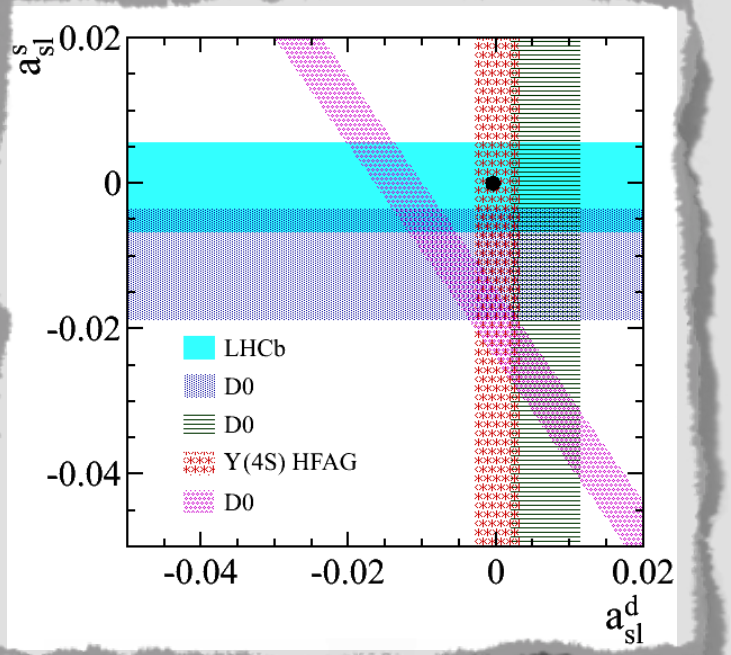
Analyse $B_s^0 \to D_s X \mu \nu$ decays (2011 data).

$$A_{\text{meas}} \equiv \frac{\Gamma[D_s^- \mu^+] - \Gamma[D_s^+ \mu^-]}{\Gamma[D_s^- \mu^+] + \Gamma[D_s^+ \mu^-]} = \frac{a^s_{\text{sl}}}{2} + \left[a_{\text{P}} - \frac{a^s_{\text{sl}}}{2} \right] \frac{\int_{t=0}^{\infty} e^{-\Gamma_s t} \cos(\Delta M_s t) \epsilon(t)\, dt}{\int_{t=0}^{\infty} e^{-\Gamma_s t} \cosh(\frac{\Delta\Gamma_s t}{2}) \epsilon(t)\, dt}$$

B_s^0 production asymmetry negligible: highly suppressed (10^{-4}) due to fast oscillations.

Opposite magnet polarities: cancel most of detection asymmetries of charged particles.

Using large control samples: correct for tracking (0.13%) and background asymmetries (0.05%); account for difference in trigger and PID efficiencies for μ^+ and μ^-.



$a^s_{sl} = (-0.06 \pm 0.50 \pm 0.36)\%$

World's best measurement, consistent with SM expectation

D0 3σ deviation from SM neither ruled out nor confirmed

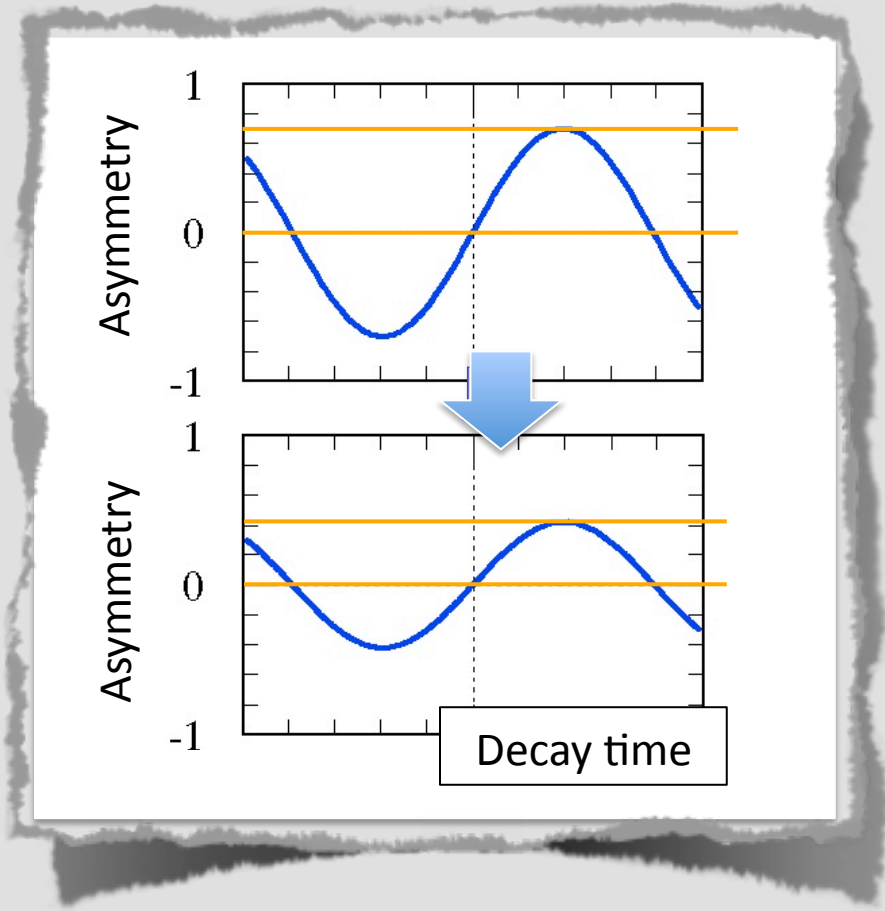
Going Time Dependent

Flavour tagging

Need knowledge of the production flavour: B_s^0 or $\overline{B}_s^0$?
Use flavour tagging algorithms.

Tagging power: $\varepsilon\,(1 - 2\omega)^2$
ε = N(tagged)/N(total)
ω = N(wrong tag)/N(tagged)

Mistag probability ω dilutes the asymmetry. Calibrated in large samples of flavour specific decays.



Decay time resolution

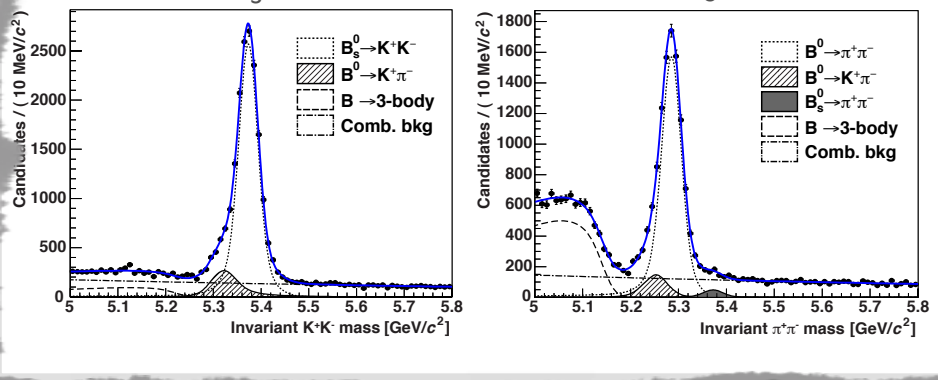
Measured in control sample of prompt decays: 40-50 fs.
Reduce the asymmetry by O(30%).

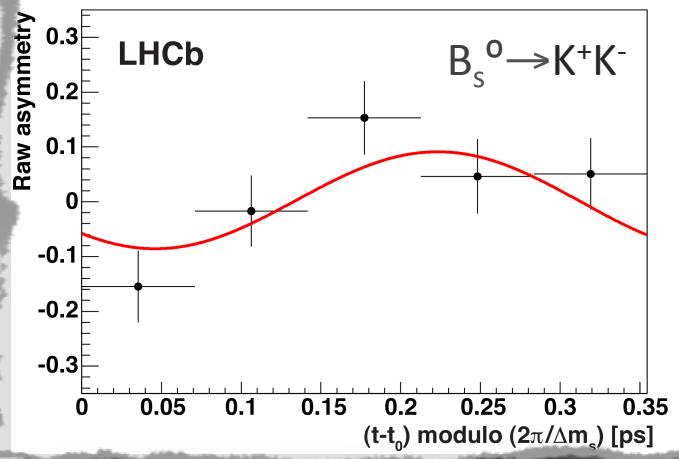
$B_s^0 \to K^+K^-$ CP asymmetries

2011 data, simultaneous analysis of

JHEP 10 (2013), 183

14600 $B_s^0 \to K^+K^-$ 9200 $B_s^0 \to \pi^+\pi^-$





ML fit to B mass and decay time.
Tagging power: (2.45 ± 0.25)%
Mistag calibrated in a sample of $B_{(s)}^0 \to K^+\pi^-$ decays.

Decay time resolution from large samples of
$\psi(1S,2S) \to \mu^+\mu^-$
$\Upsilon(1S,2S,3S) \to \mu^+\mu^-$

CP asymmetries in $B_s^0 \to K^+K^-$:

mix-induced $S_{KK} = 0.14 \pm 0.11 \pm 003$

direct $C_{KK} = 0.30 \pm 0.12 \pm 004$

World's first. Consistent with SM.

CP asymmetries in $B^0 \to \pi^+\pi^-$:

mix-induced $S_{\pi\pi} = -0.38 \pm 0.15 \pm 002$

direct $C_{\pi\pi} = -0.71 \pm 0.13 \pm 002$

confirms Babar's result [PRD 87 (2013) 052009]

$J/\psi h^+h^-$ and $\phi\phi$ Angular Analyses

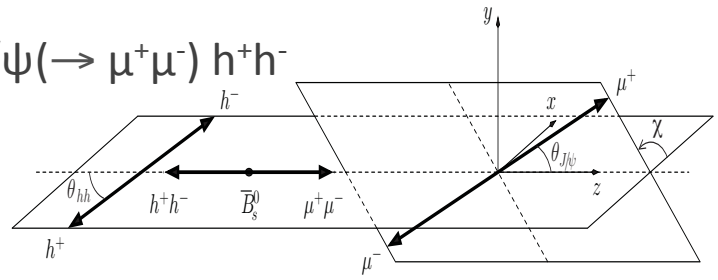
Need to disentangle amplitudes with different CP parity (have different time dependence)

- In case of K^+K^- around the ϕ mass: P-wave (3 polarization amplitudes) and S-wave ($f_0(980)$ and NR)
- For $J/\psi\pi^+\pi^-$: resonances in wide $\pi^+\pi^-$ spectrum (almost pure CP-odd).

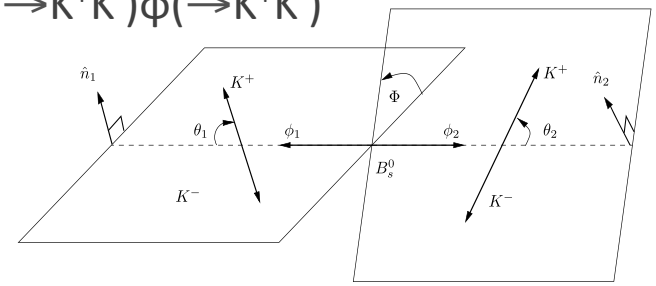
Disentangle the amplitudes by fitting helicity angles of final state particles (muons, kaons/pions).

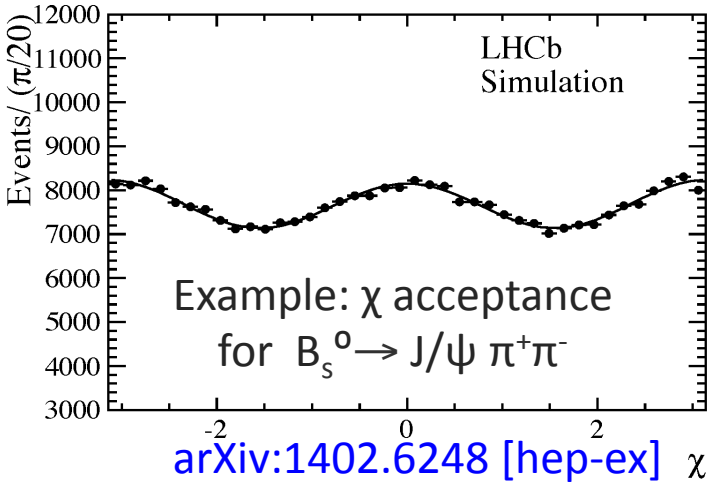
Properly describe angular acceptance with MC simulation. Deviation from uniformity within 10-20%.

$J/\psi(\rightarrow \mu^+\mu^-)\ h^+h^-$



$\phi(\rightarrow K^+K^-)\phi(\rightarrow K^+K^-)$





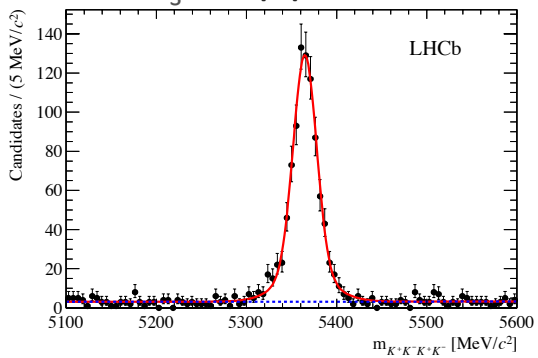
arXiv:1402.6248 [hep-ex]

$\phi\phi$ RESULTS

PRL 110, 241802 (2013)

Analysis of 2011 data set

880 $B_s^0 \to \phi\phi$ candidates



Tagging power (3.29 ± 0.48)%, time resolution 40 fs.
Time biasing selection, acceptance from simulations.

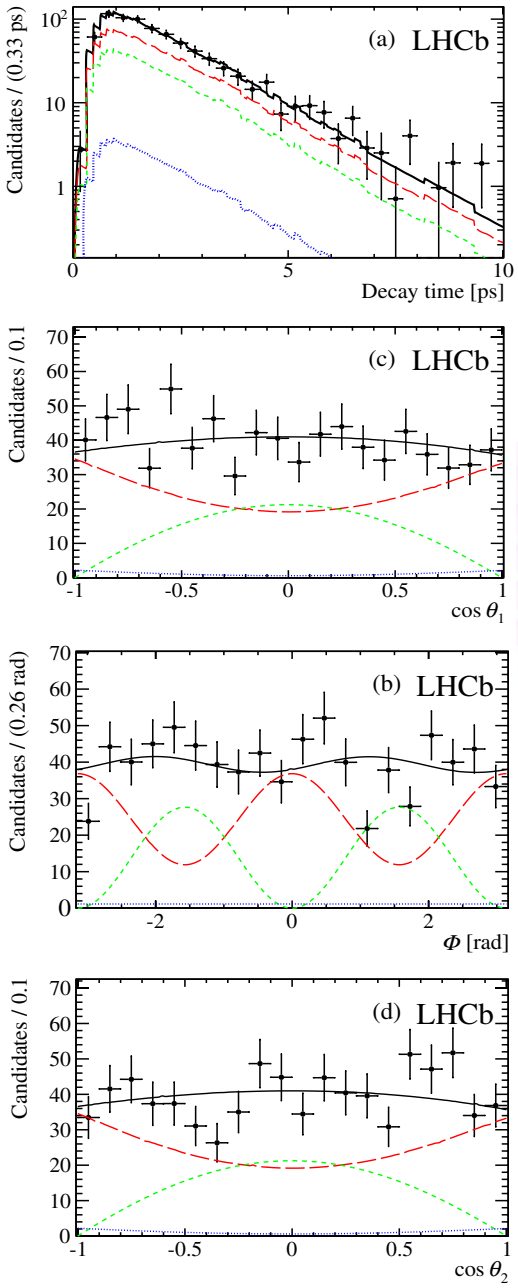
CP-violating phase:

$\phi_s^{(\phi\phi)}$ in [-2.37,-0.92]

@ 68% C.L.

Consistent with the SM (p-value 16%).

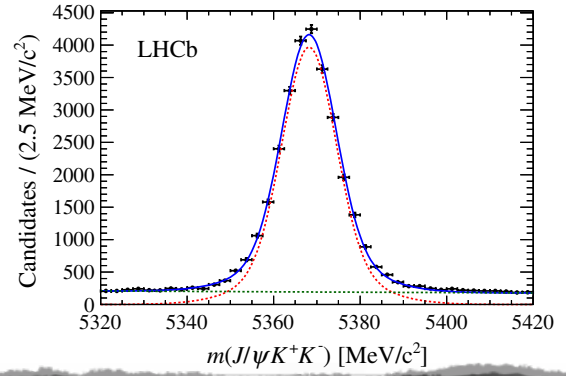
World's first constraint.



ϕ_s with $J/\psi K^+K^-$

Analysis of 2011 data set.

27600 $B_s^0 \to J/\psi K^+K^-$ candidates



Tagging power (3.13 ± 0.23)%, time resolution 45 fs.

By a simultaneous fit with 7500 $B_s^0 \to J/\psi\pi^+\pi^-$ candidates of 2011 data.

$\Gamma_s = 0.661 \pm 0.004 \pm 0.006$ ps^{-1}

$\Delta\Gamma_s = 0.106 \pm 0.011 \pm 0.007$ ps^{-1}

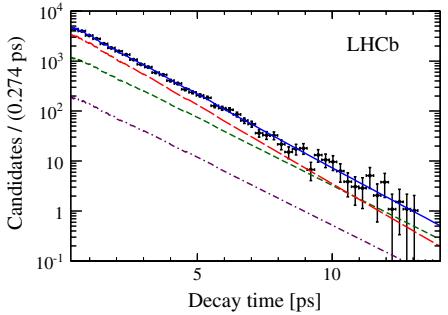
CP-violating phase:

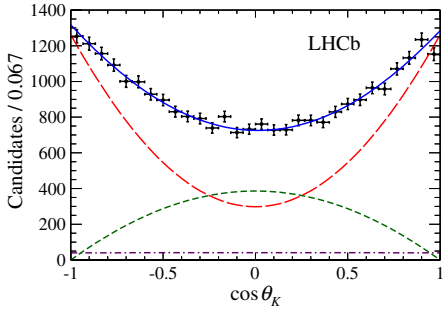
$\phi_s = 0.01 \pm 0.07 \pm 0.01$

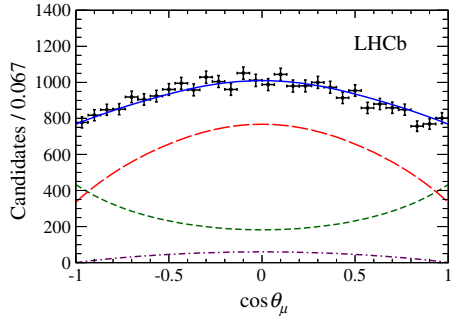
Consistent with the SM.

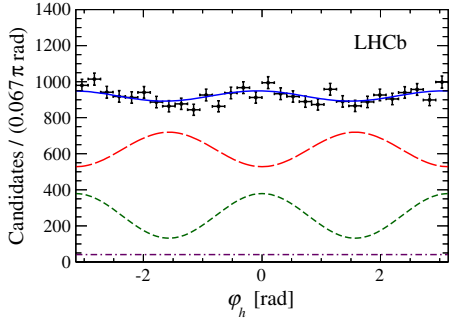
World's best measurements.

PRD 87, 112010 (2013)









Total

CP-even

CP-odd

S-wave

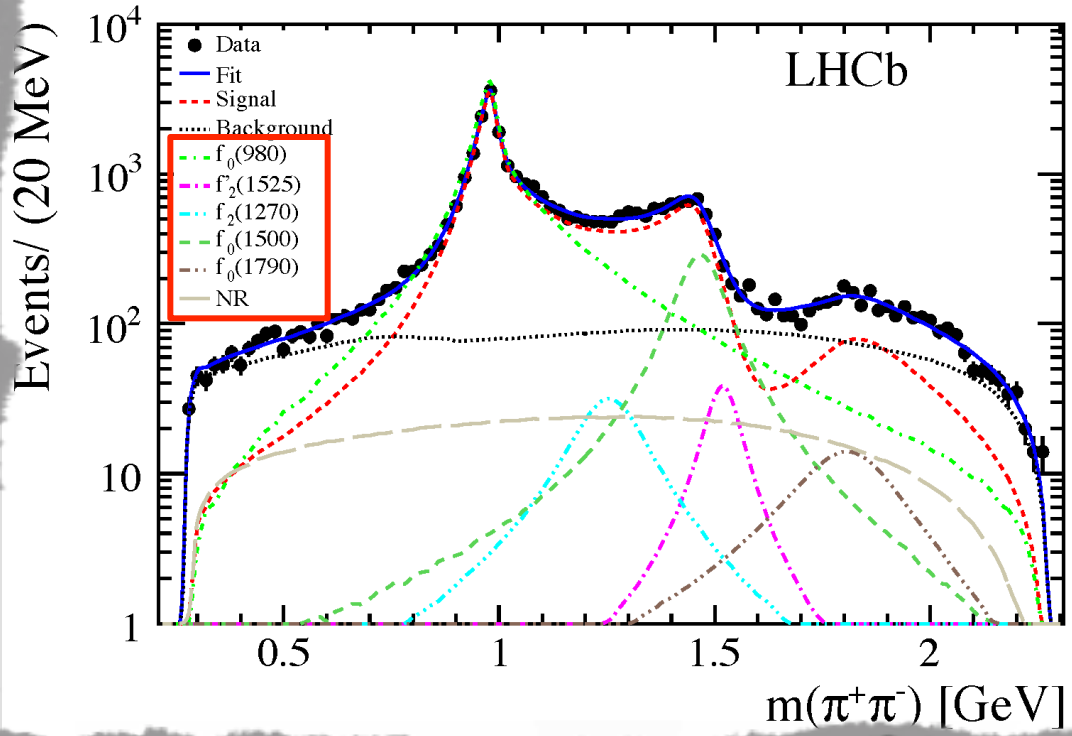
$J/\psi\pi^+\pi^-$ amplitudes Analysis

Full 2011+2012 data set.

Fit simultaneously the $m_{\pi+\pi-}$ spectrum and helicity angles

Five interfering states.
Adding also non-resonant $J/\psi\pi^+\pi^-$ describes well the data.
Given the resonances composition:

arXiv:1402.6248 [hep-ex]



CP-odd >97.7% confirmed @ 95% C.L.

$f_0(500)$ not observed. Stringent limit on the mixing angle between $f_0(500)$ and $f_0(980)$: $|\varphi_m| < 7.7°$ @ 90% C.L.

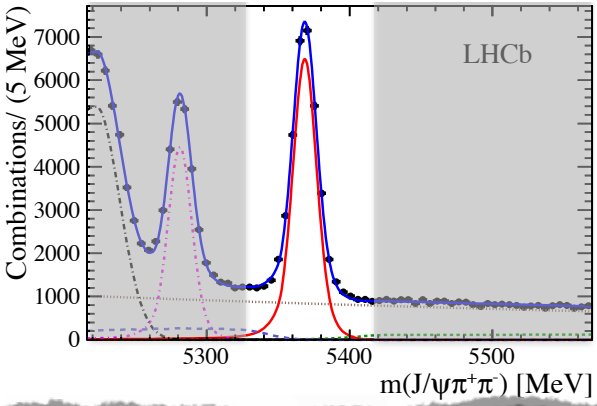
ϕ_s with $J/\psi\pi^+\pi^-$

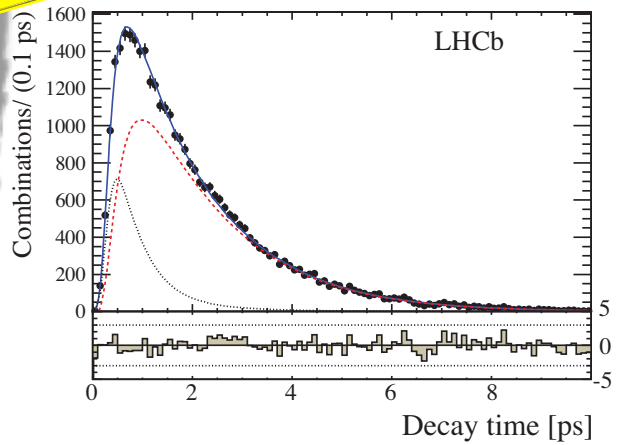
BRAND NEW!

PRELIMINARY

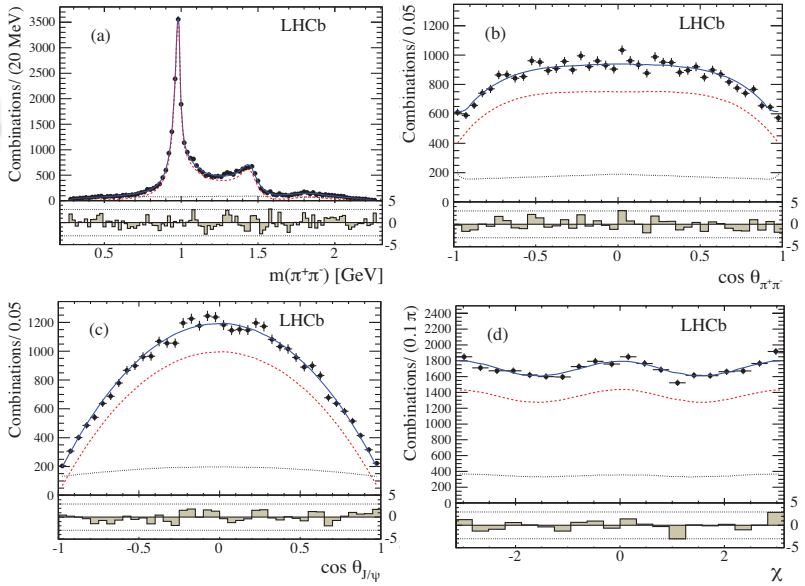
Full 2011+2012 data set,
×3 more data than PLB 713 (2012) 378

27100 $B_s^0 \to J/\psi\pi^+\pi^-$ candidates





Total
Signal
Backg



Improved tagging power, 2.43% → 3.89%.
40 fs time resolution from prompt $J/\psi\pi^+\pi^-$ combinations.

Include the full amplitude analysis, and fit B mass, decay time, $m_{\pi\pi}$, and helicity angles.

Time acceptance from control sample of $B^0 \to J/\psi K^*$ decay.

$\phi_s = 0.075 \pm 0.067 \pm 0.008$
Consistent with the SM.
60% more precise than PLB 713 (2012) 378

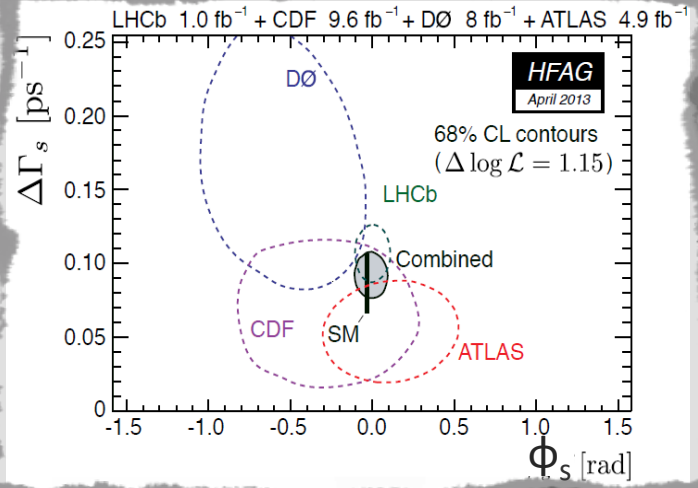
Conclusions

CP violation in the B_s^0 system: rich opportunity to probe non-SM physics.

LHCb leads the effort.

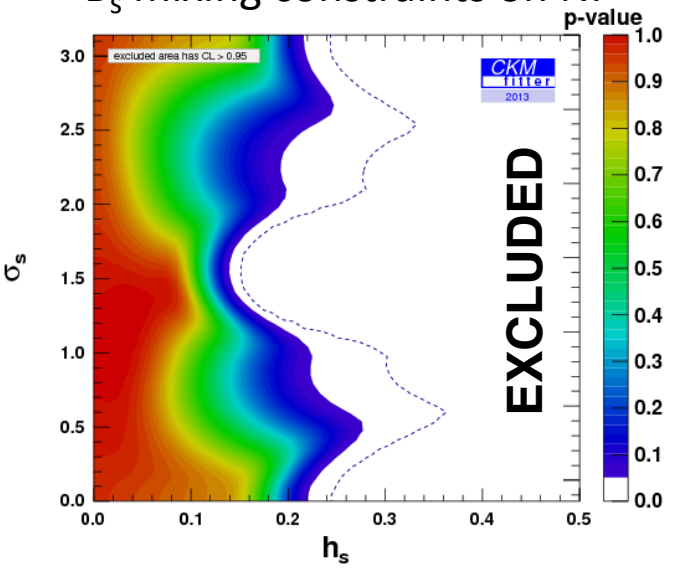
Improved constraints: no anomalies but still room for NP. Measurements statistically dominated.

New updates and more with 2011+2012 data, coming soon!



PRD 89 (2013), 033016

B_s mixing constraints on NP



O(20%) NP contributions still feasible