LHCb latest results, an overview

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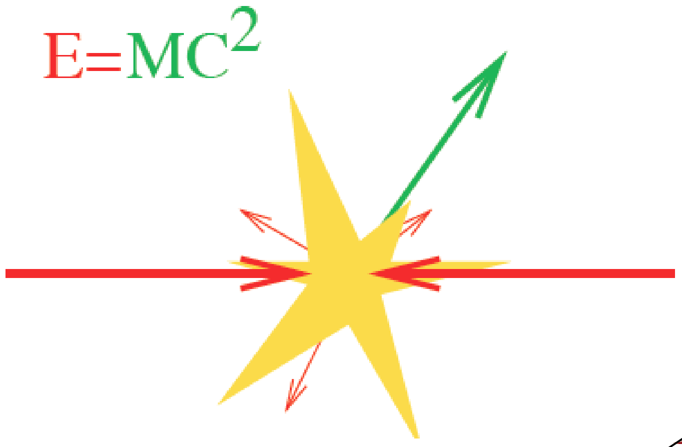
on behalf of the LHCb collaboration

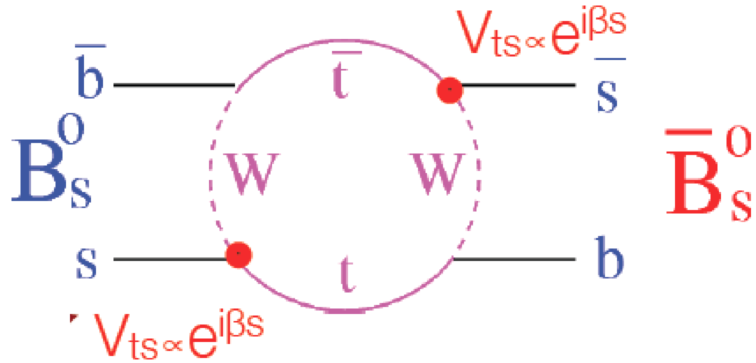
Triggering Discoveries in High Energy Physics
University of Jammu, India - 9-14 September 2013

Two ways to New Physics

Direct observation



Loop-effects



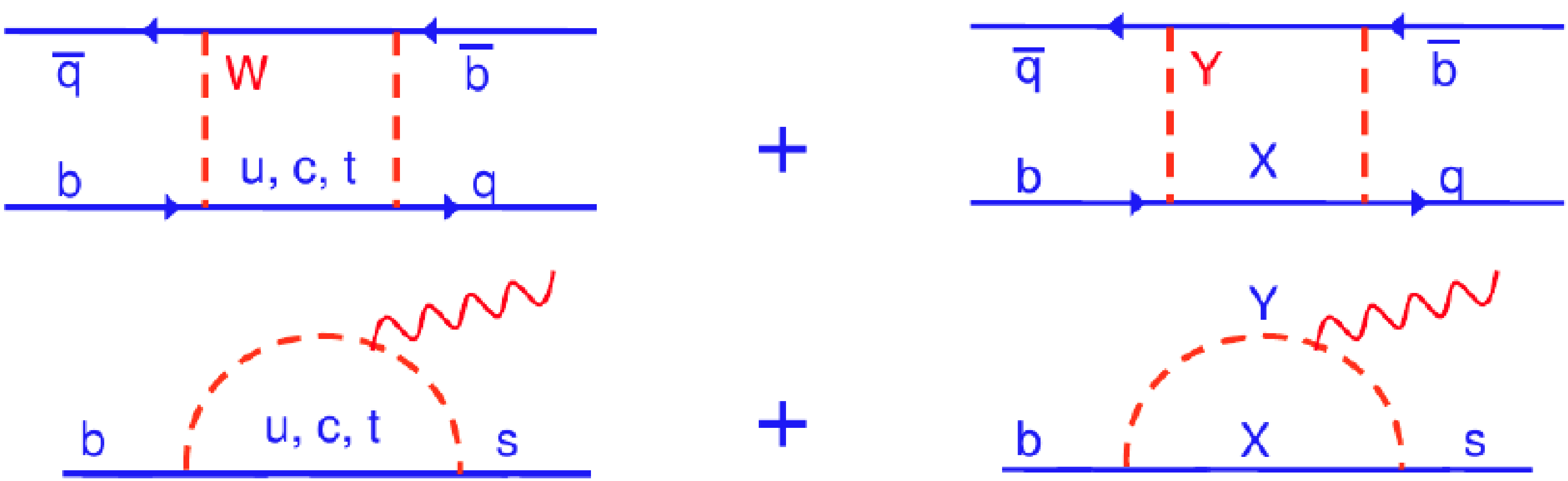
This approach is sensitive to particles far heavier than those produced directly at colliders.
This is what Flavour Physics is about: it lets us see beyond the Energy Frontier.
The key: precision

Search for New Physics in Flavour Sector

Look for new physics in quantum loops as corrections to Standard Model processes:

Standard Model

New Physics



$$\mathcal{A}_{BSM} = \mathcal{A}_0 \left(\frac{C_{SM}}{m_W^2} + \frac{C_{NP}}{\lambda_{NP}^2} \right)$$

Quark Flavour Physics: CP violation, rare processes

Quark Flavour Physics: precision study of quark transitions - the only known source of CP violation

- Test CKM mechanism and SM to ultimate precision
- Tool for searching for new physics in quantum processes

Beauty and Charm systems are excellent laboratories
A few prominent examples:

CKM mechanism: CP violation angle γ (with $B \to Dh$),

CPV in B^0_s (with $B^0 \to K^+\pi^-$, $B^0_s \to \pi^+K^-$)

Processes very sensitive to quantum loops:

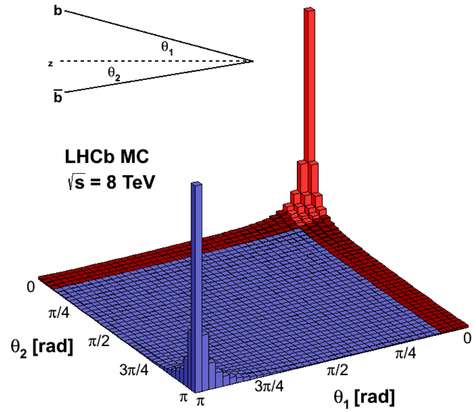
Mixing frequency and phase of B^0_s oscillations

($B^0_s \to D^-_s\pi^+$, $B^0_s \to J/\psi\ K^+K^-$, $J/\psi\ \pi^+\pi^-$)

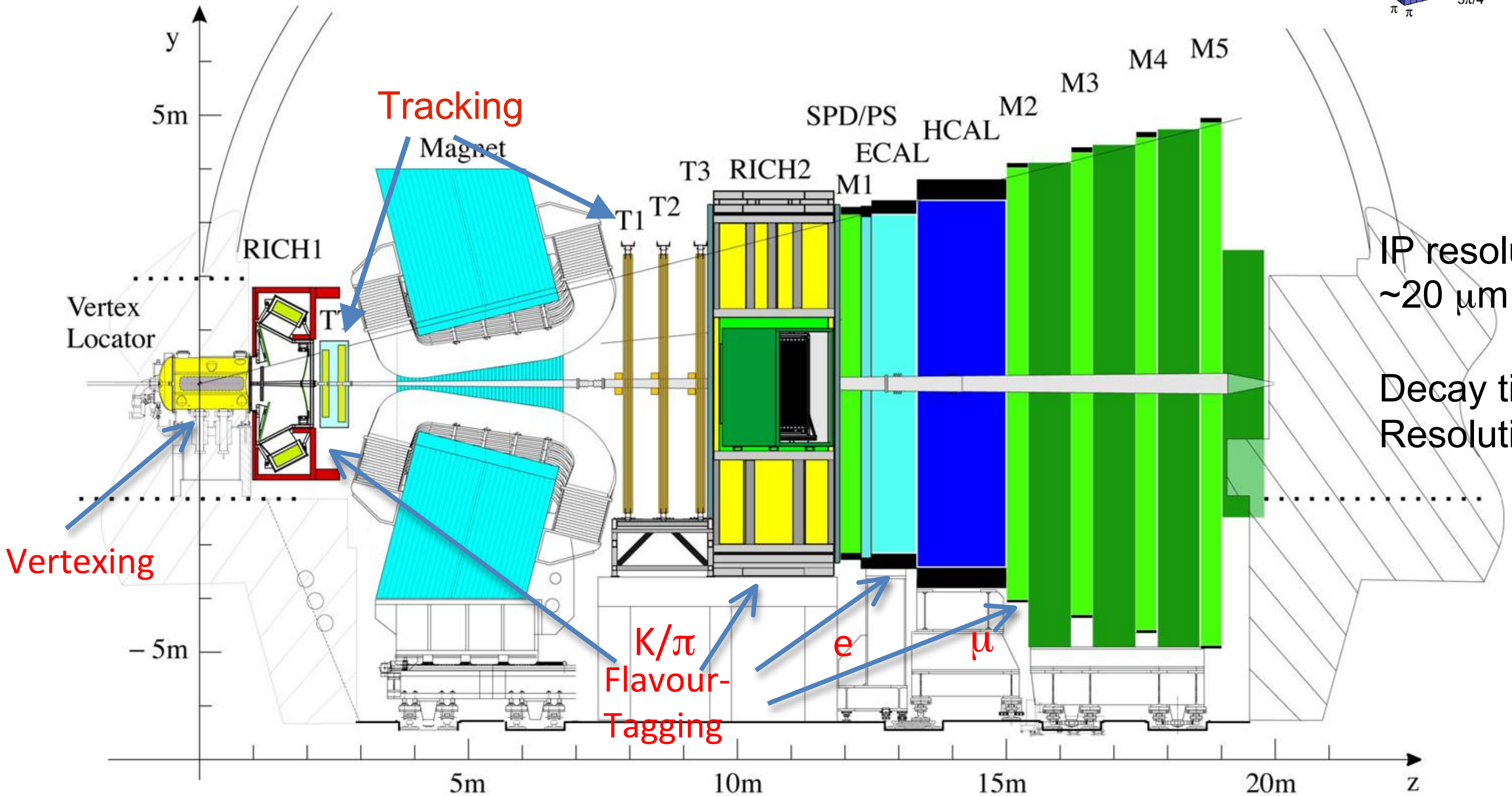
Flavour Changing Neutral Current processes

($B^0_{(s)} \to \mu^+\mu^-$, Angular observables in $B^0 \to K^{*0}\mu^+\mu^-$)

The LHCb Detector



Forward detector (2<η<5), b hadrons produced at low angle
Large bb cross section (~250 μb – 500 μb @ $\sqrt{s}$ =7 – 14 TeV)
>70% K_s decay after the Vertex Locator (VELO)
Harsh hadronic environment :
(1/200 event contains a b quark, typical interesting BR < 10^{-3})

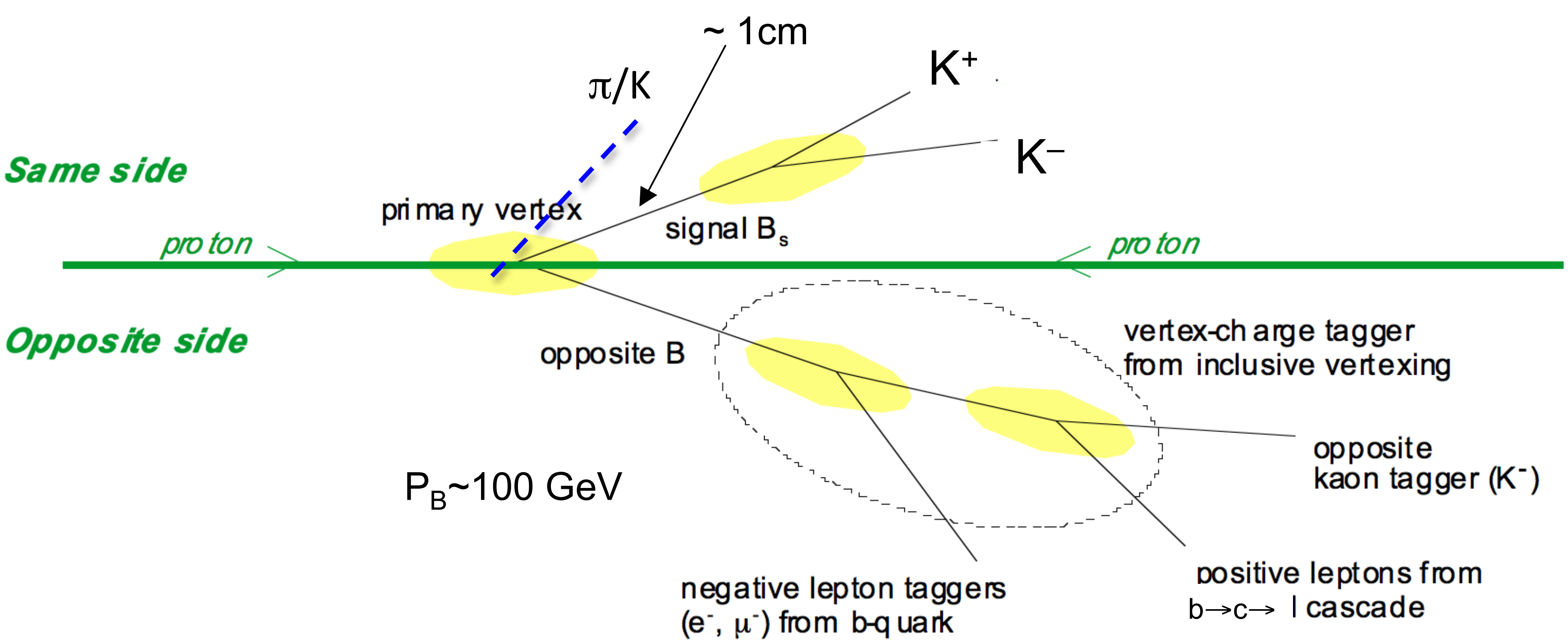


IP resolution ~20 μm

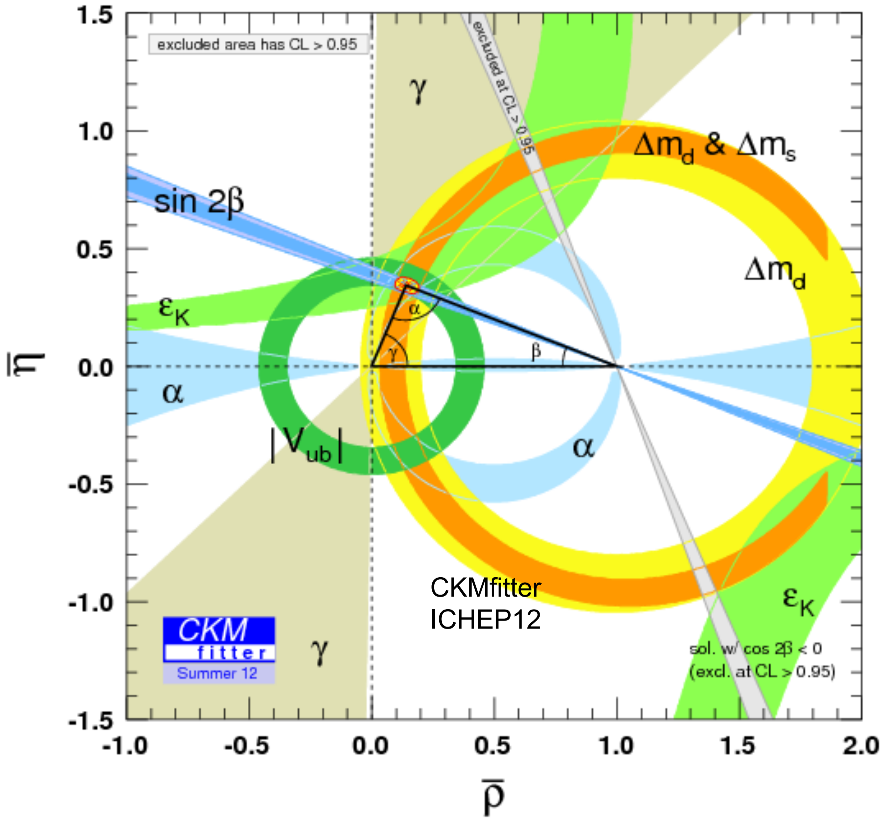
Decay time Resolution ~45 fs

B events at LHCb

K, π, μ final states



CP Violation



Current average from direct measurements:

$\gamma = (69^{+17}_{-16})^o$ (Babar)
[arXiv:1301.3283v1]

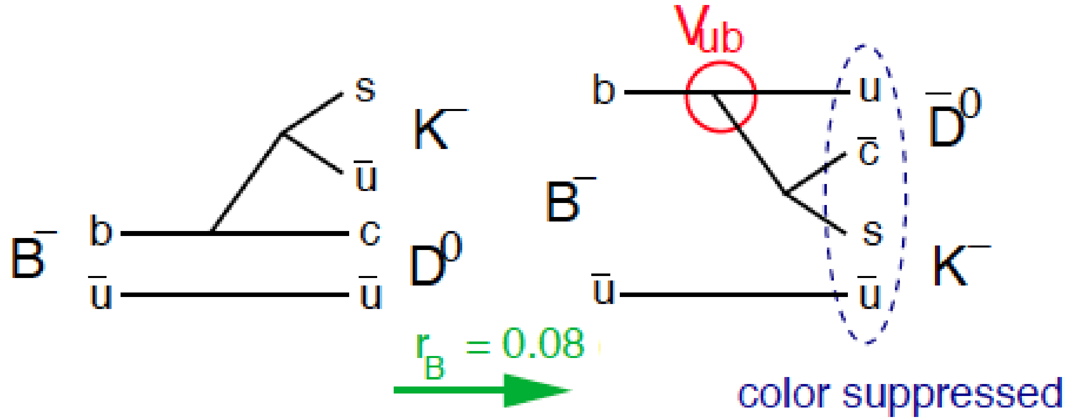
$\gamma = (68^{+15}_{-14})^o$ (Belle)
[CKM2012]

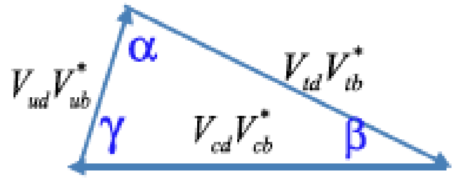
Triangle shown is b-d; LHCb is sensitive also to b-s triangle:
Shown today γ (b-d triangle) and first observation > 5σ of CPV in B_s (b-s triangle)

γ is the only angle that can be measured entirely with tree decays. Tighter experimental constraints on γ come from loops, which are sensitive to new physics.

γ : test CKM to ultimate precision, and compare tree and loop processes

γ Measurement with tree decays: B→Dh





γ = arg[-Vud Vub* / Vcd Vcb*]

Unknowns: r_B, δ_B, γ, r_D, δ_D (r =ratio, δ = strong phase)

B→DK: final state accessible to both D^0 and $\overline{D^0}$ mesons, exploiting interference of b→u$\bar{c}$s and b→c$\bar{u}$s

amplitude ratio between Cabibbo-favoured and suppressed= r_B^K
strong phase difference = δ_B
Uncertainty on γ scales as 1/ r_B^K

B→Dπ: analogous framework but r_B^π expected to be 1 order of magnitude smaller

γ Measurement with tree decays: $B \to Dh$

Measurements are classified by their D final state:

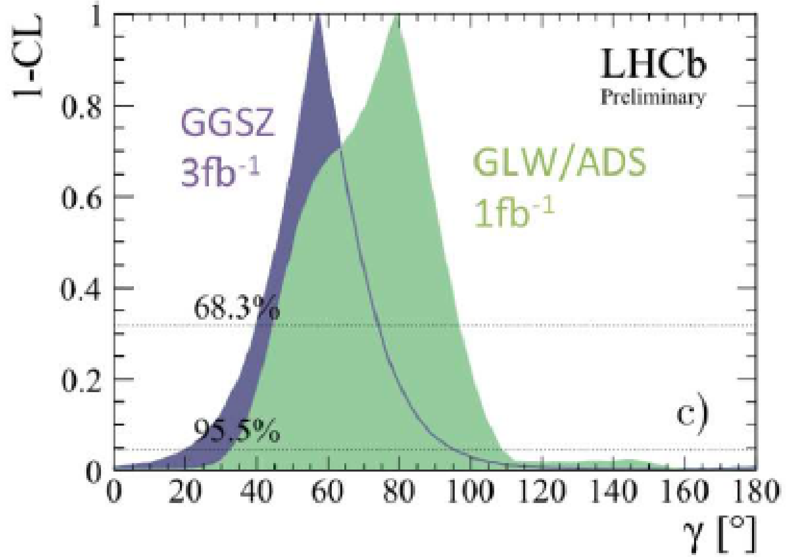
- CP eigenstates (GLW) : e.g. $D \to K^+K^-$, $D \to \pi^+\pi^-$
  1/fb (2011)
  [Phys Lett B 712 (2012) 203][arXiv:1203.3662]

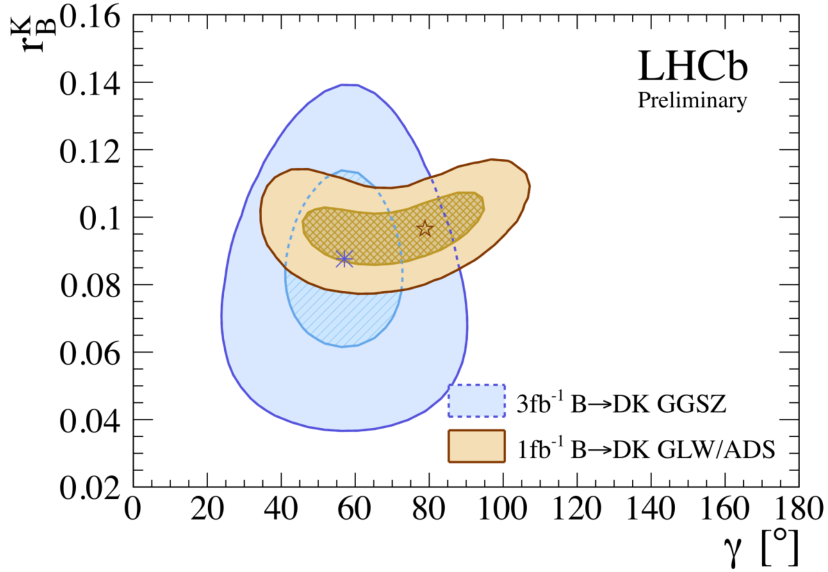
- Flavour eigenstates (ADS) : e.g. $D \to K^\pm \pi^\pm \pi+ \pi-$, $D \to K^+\pi^-$, …
  1/fb (2011)
  [LHCb-Conf-2012-30]

- Self-conjugate three-body final states (GGSZ) : e.g. $D \to K^0_S h+h-$
  1/fb (2011) + 2/fb (2012)
  [arXiv:1209.5869] [arXiv:0903.1681]
  [LHCb-Conf-2013-06]

[Gronau & London, PLB 253 (1991) 483;
Gronau & Wyler, PLB 265 (1991) 172;
Atwood, Dunietz & Soni, PRL 78 (1997) 3257;
Atwood, Dunietz & Soni, PRD 63 (2001) 036005]
Giri, Grossman, Soffer & Zupan, PRD 68 (2003) 054018;
Bondar, Proceedings of BINP Special Analysis Meeting on Dalitz Analysis, 24-26 Sep. 2002, unpublished

Results





quantity	$DK^{\pm}$ combination
γ	67.2°
68% CL	[55.7, 79.6]°
95% CL	[44.6, 90.0]°
r_B	0.0924
68% CL	[0.0847, 0.1004]
95% CL	[0.0766, 0.1077]
δ_B	114.3°
68% CL	[101.7, 126.6]°
95% CL	[89.1, 136.5]°

LHCb result (LHCb-CONF-2013-006)

$$\gamma = (67 \pm 12)^\circ$$

Belle: $\gamma = (68^{+15}_{-14})^\circ$ BaBar: $\gamma = (69^{+17}_{-16})^\circ$

Direct CPV in $B^0 \to K^+\pi^-$ and $B^0_s \to \pi^+K^-$

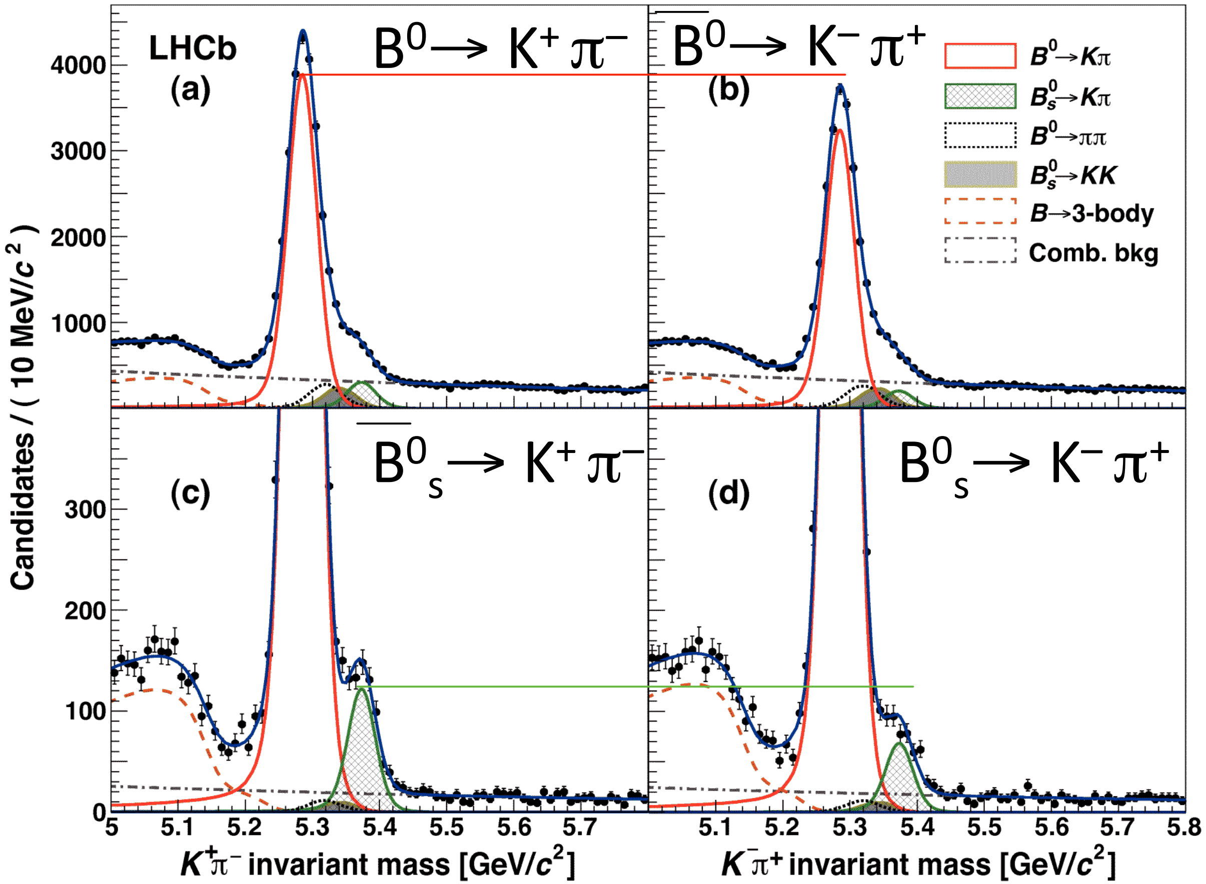
1.0/fb used (2011 data)

Asymmetry:

where $f = K^+\pi^-$ (B^0), π^+K^- (B^0_s)

$$A_{raw} = \frac{N_{\bar{f}} - N_f}{N_{\bar{f}} + N_f}$$

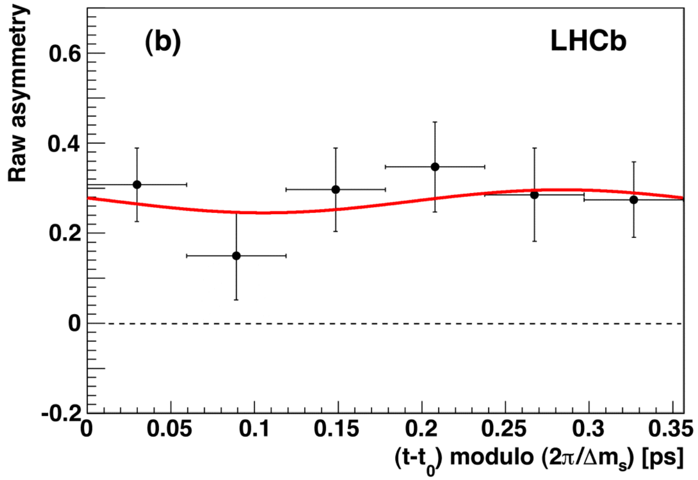
Different heights: CPV



PRL 110 (2013) 221601

Direct CPV in $B^0 \to K^+\pi^-$ and $B^0_s \to \pi^+K^-$

$$A_{raw}(t) \sim A_{\rm CP} + A_{\rm D} + A_{\rm P}\cos(\Delta t)$$



Detection asymmetry corrected using D^{*+}
Production asymmetry corrected using time dependence

$$A_{\rm CP}(B^0 \to K^+\pi^-) = -0.080 \pm 0.007(stat) \pm 0.003(syst)$$

$$A_{\rm CP}(B^0_{\rm s} \to K^-\pi^+) = 0.27 \pm 0.04(stat) \pm 0.01(syst)$$

PRL 110 (2013) 221601

First observation (6.5σ) of CPV in B^0_s decays

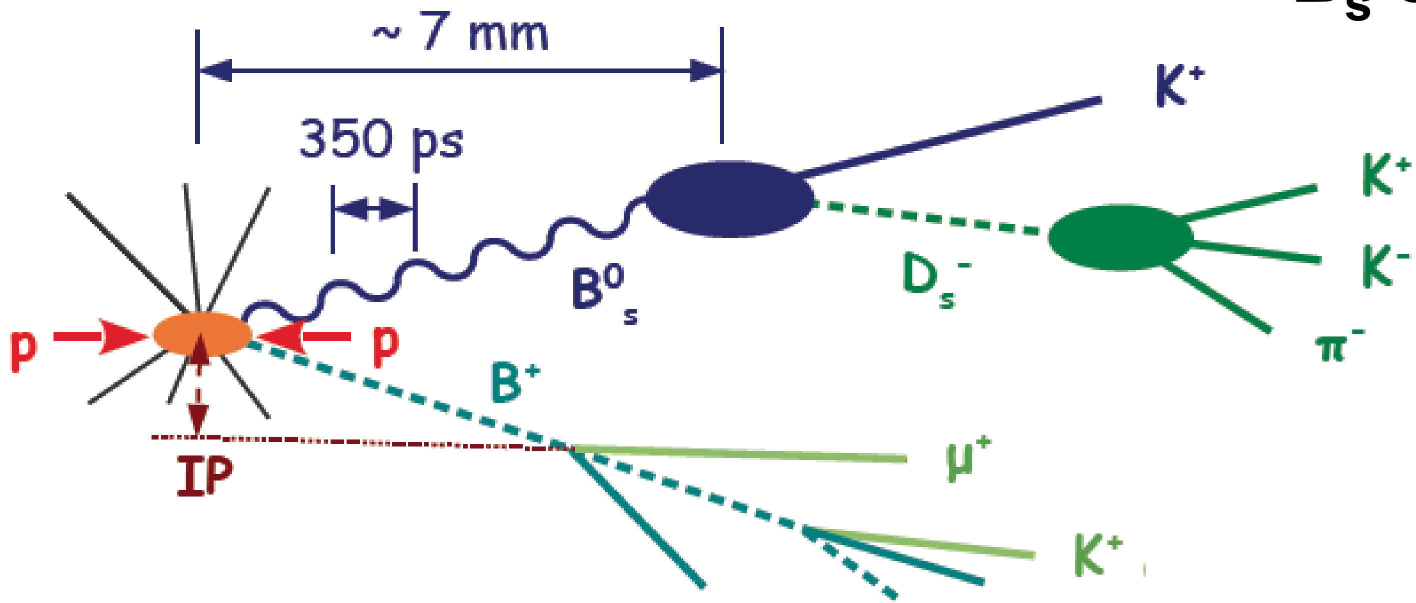
Test SM prediction:

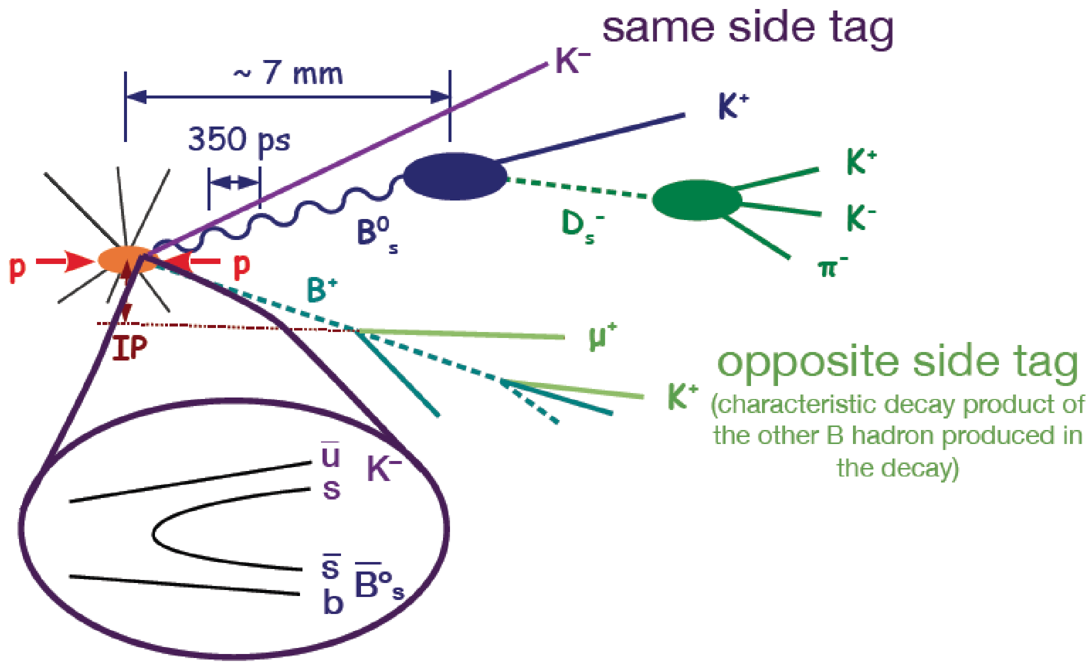
$$\Delta = \frac{A_{CP}(B^0 \to K^+\pi^-)}{A_{CP}(B^0_s \to K^-\pi^+)} + \frac{B(B^0_s \to K^-\pi^+)}{B(B^0 \to K^+\pi^-)}\frac{\tau_d}{\tau_s} = 0$$

From measurements:

$$\Delta = -0.02 \pm 0.05 \pm 0.04$$

B_s events

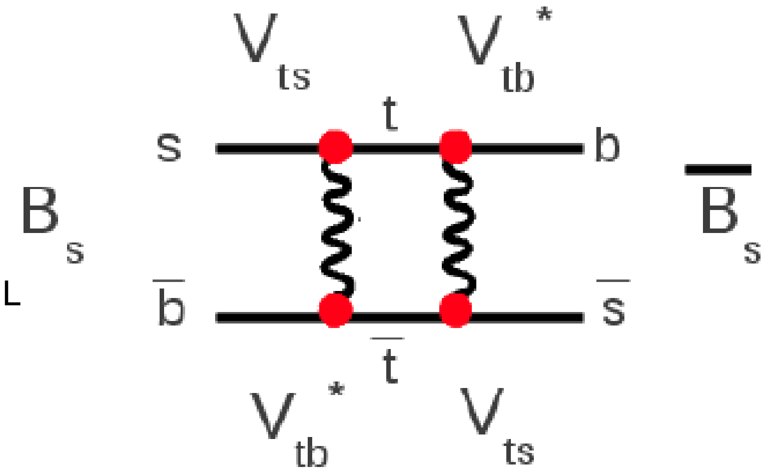

~ 7 mm
350 ps
K+
K+
K-
π-
B0s
Ds-
p
p
B+
IP
μ+
K+


same side tag
K−
~ 7 mm
350 ps
K+
K+
K-
π-
B0s
Ds-
p
p
B+
IP
μ+
K+
opposite side tag
(characteristic decay product of the other B hadron produced in the decay)
u̅
s
K−
s̅
b
B̅0s

B_s - $\overline{B}_s$ oscillations

Weak eigenstate ≠ mass eigenstate

Weak eigenstates B_s , $\overline{B}_s$
Two mass eigenstates with mass m_H and m_L
and width Γ_H and Γ_L

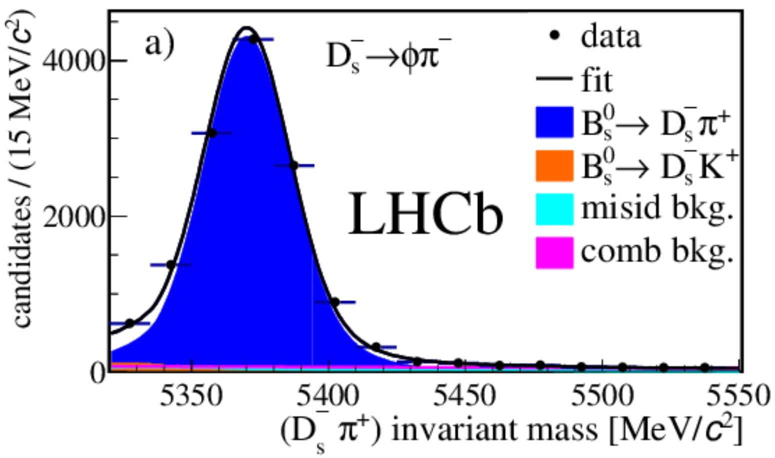


5 parameters: m, Γ, $\Delta\Gamma$, Δm_s, ϕ_s

Oscillation frequency $\Delta m_s = m_H - m_L$
Phase ϕ_s = CP violating phase of the above diagram relative to decay diagram

Reconstructed ~34,000 tagged
$B^0_s \to D^-_s \pi^+$ candidates in 1.0/fb (2011 data)

D^-_s reconstructed in 5 decay modes: $D^-_s \to \phi \pi^-$,
$D^-_s \to K^{0*} K^-$, $D^-_s \to K^+ K^- \pi^-$, $D^-_s \to K^- \pi^+ \pi^-$,
$D^-_s \to \pi^+ \pi^- \pi^-$



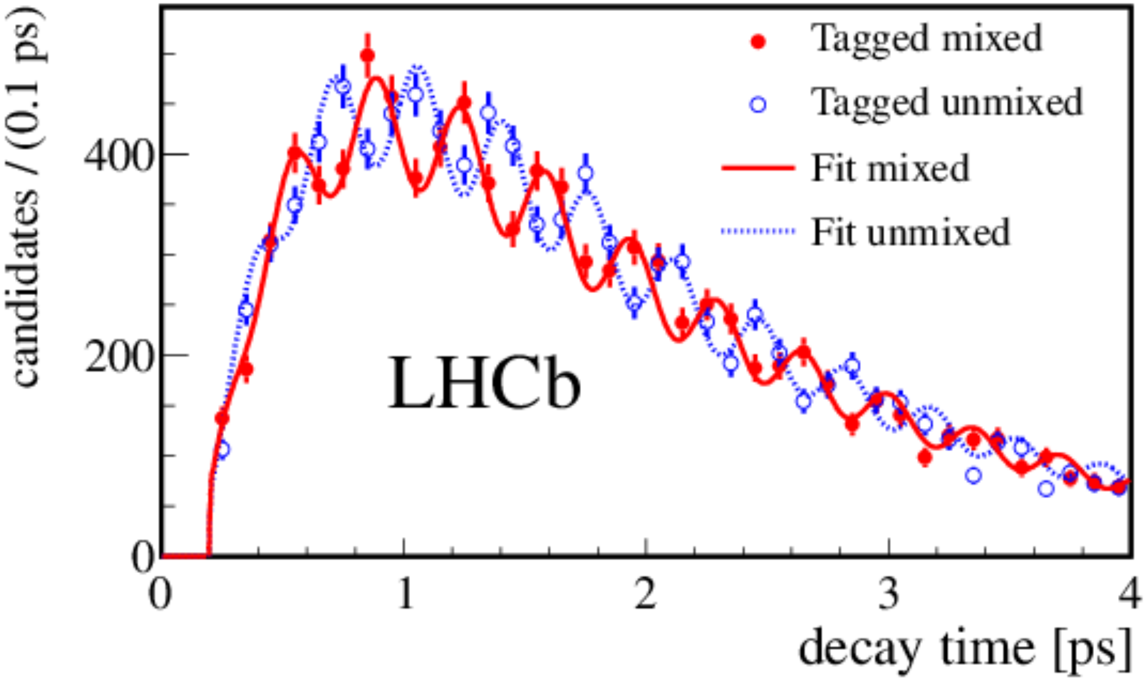
New J. Phys. 15 (2013) 053021

Measurement of Δm_s

Measurement of modulation in decay time distribution

Observable:

$$\sin\phi_s \times \sin\Delta m_s t$$



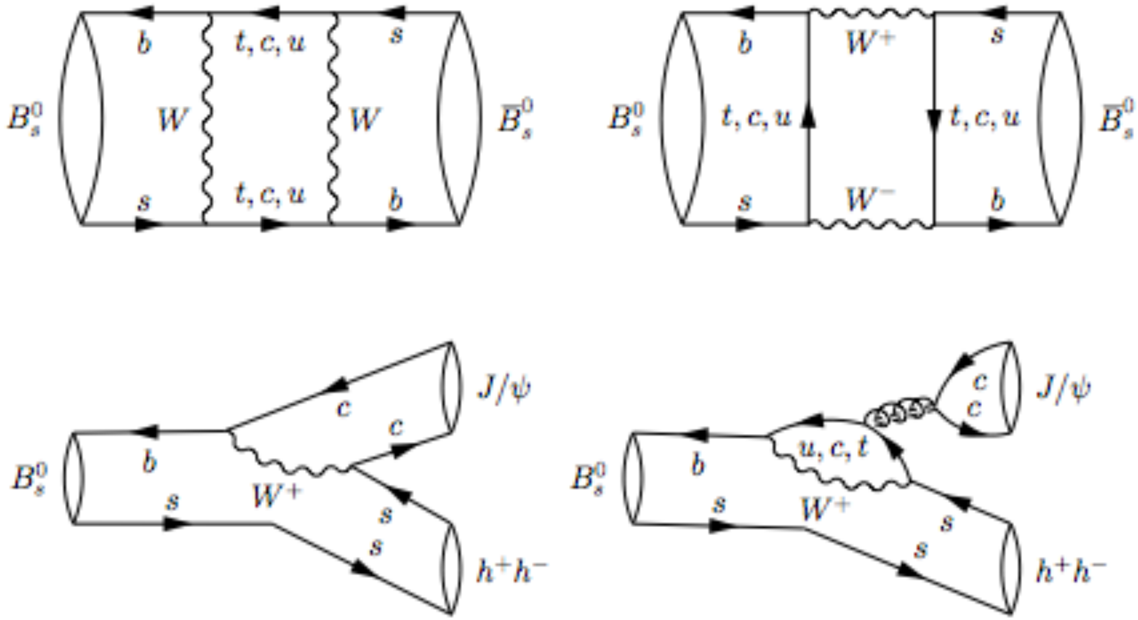
Δm_s = 17.768 ± 0.023(stat.) ± 0.006(syst.)/ps

World's best measurement

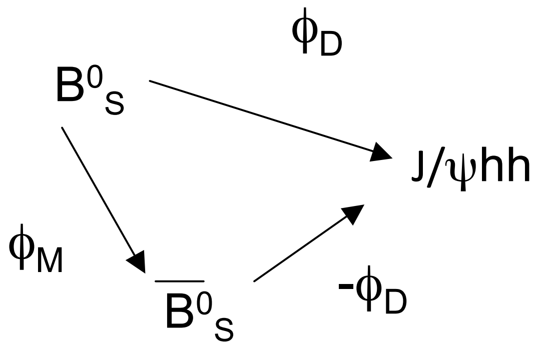
New J. Phys. 15 (2013) 053021

Main syst. uncertainties from distance and momentum scale

ϕ_s from $B^0_s \rightarrow J/\psi\, h^+h^-$ decays ($h=\pi,K$)



Access to phase ϕ_s via interference between mixing+direct decay and direct decay into CP eigenstate



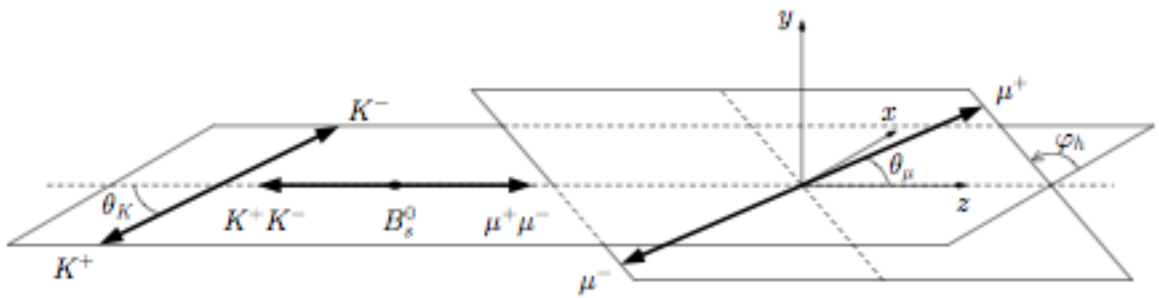
In SM $\phi_s \approx -2\arg(-V_{ts}V^*_{tb} / V_{cs}V^*_{cb})$ phase of V_{ts}

$\phi_s = -0.0364 \pm 0.0016$ rad

New physics in box and/or penguin diagrams

CP states in $B^0_s \rightarrow J/\psi\, h^+h^-$

- $B^0_s \rightarrow J/\psi\, \phi(1020)$: P→VV, CP admixture
  Angular analysis required with 3 amplitudes:
  A_0, $A_{||}$(CP-even), $A_\perp$(CP-odd)



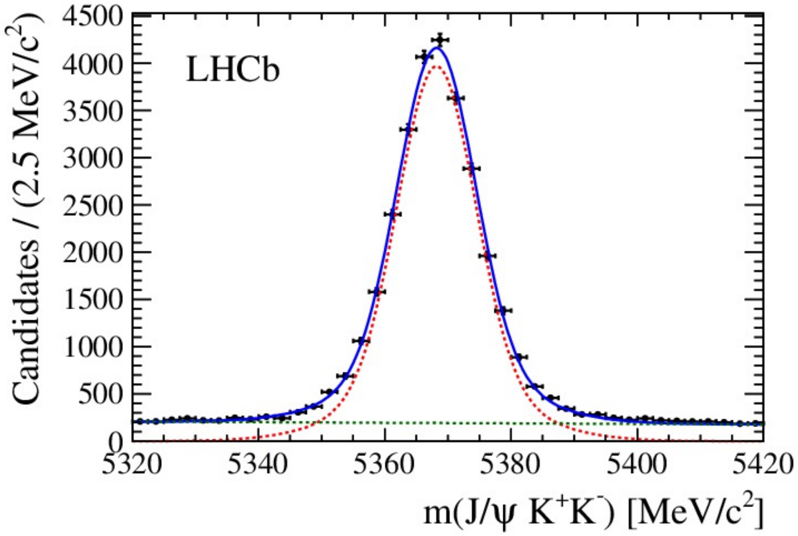
- $B^0_s \rightarrow J/\psi\, K^+K^-$ non resonant: S-wave →CP-odd
  One amplitude A_S

$B^0_s \rightarrow J/\psi\, \pi^+\pi^-$ is pure CP-odd (>97.7% @ 95% CL)
No angular analysis needed [Phys.Rev D86 (2012) 052006]

$B^0_s \to J/\psi\, h^+h^-$ signals

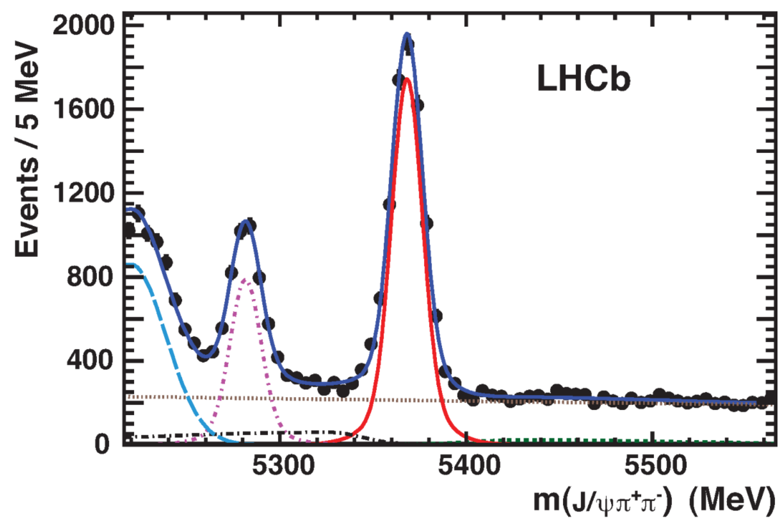
Phys.Rev.D87(2013)112010

27,600 $B^0_s \to J/\psi\, K^+K^-$ in 1.0/fb (2011 data)



7,400 $B^0_s \to J/\psi\, \pi^+\pi^-$ in 1.0/fb (2011 data)

[Phys. Lett. B713 (2012) 378–386]

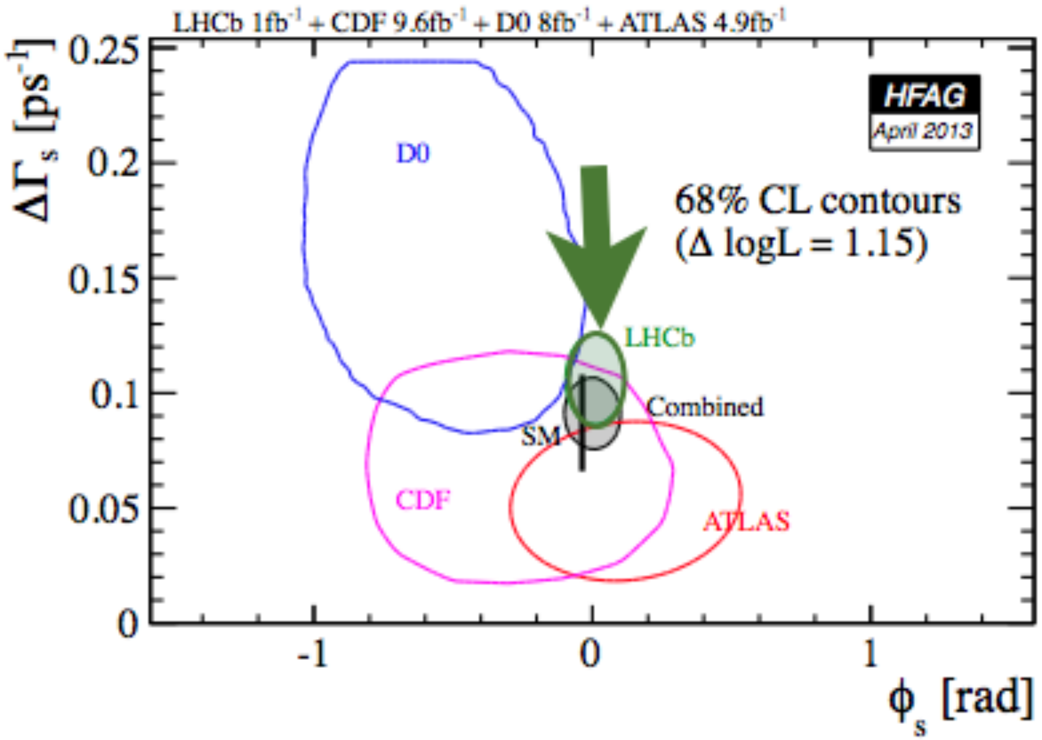


$B^0_s \rightarrow J/\psi\ h^+h^-$ results combined

Combined fit of $B^0_s \rightarrow J/\psi\ K^+K^-$ and $B^0_s \rightarrow J/\psi\ \pi^+\pi^-$

ϕ_s = 0.01 ± 0.07 (stat) ± 0.01 (syst) rad
Γ_s = 0.661 ± 0.004 (stat) ± 0.006 (syst) ps^{-1}
$\Delta\Gamma_s$ = 0.106 ± 0.011 (stat) ± 0.007 (syst) ps^{-1}

World's best measurement



Phys.Rev.D87(2013)112010
Supersedes previous results:
Phys Rev Lett 108 (2012) 101803
Physics Letters B 713 (2012) 378

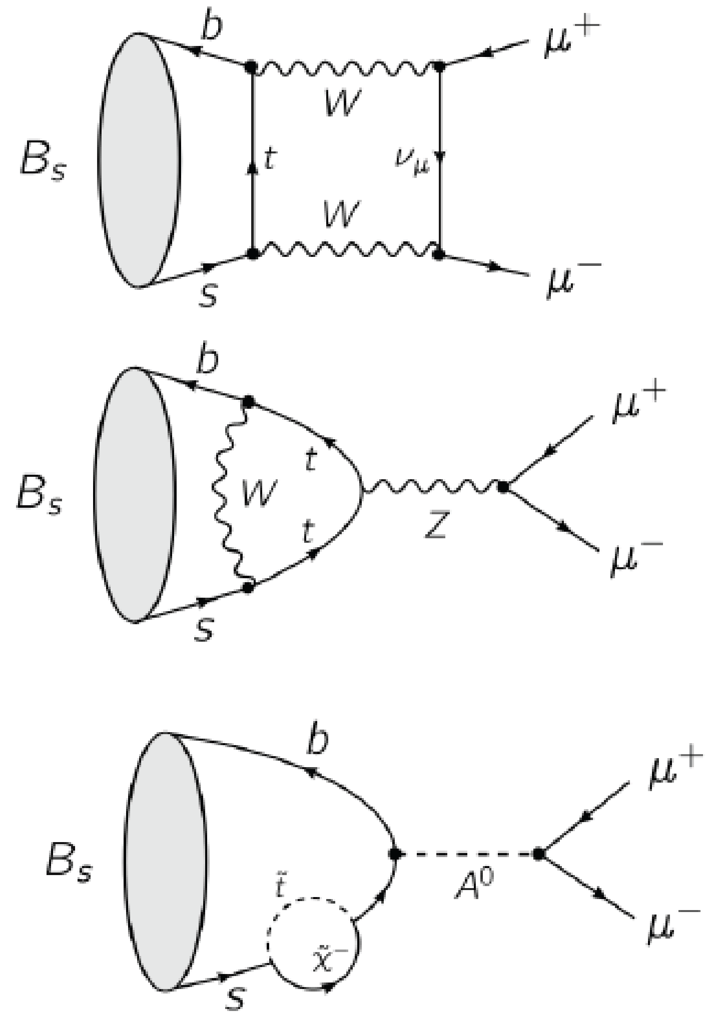
$B^0_s \rightarrow \mu^+\mu^-$

- Suppressed by FCNC and helicity

- Precise SM branching fraction expectations [arXiv:1208.0934] :

$$B(B^0_s \to \mu^+\mu^-) = (3.35 \pm 0.28) \times 10^{-9}$$
$$B(B^0 \to \mu^+\mu^-) = (1.07 \pm 0.10) \times 10^{-10}$$

- Calculable at 10% level
- Possible modified Branching ratio due to range of NP models: extended Higgs models; new scalar, pseudoscalar and axial-vectors; SUSY



$B^0_{(s)} \rightarrow \mu^+\mu^-$ results

- Blind analysis on 3/fb of data recorded in 2011 and 2012
- Large background: excellent PID
- Selection based on mass and Boosted Decision Tree (BDT)
- BDT: kinematic and geometrical variables, trained with MC calibrated on data

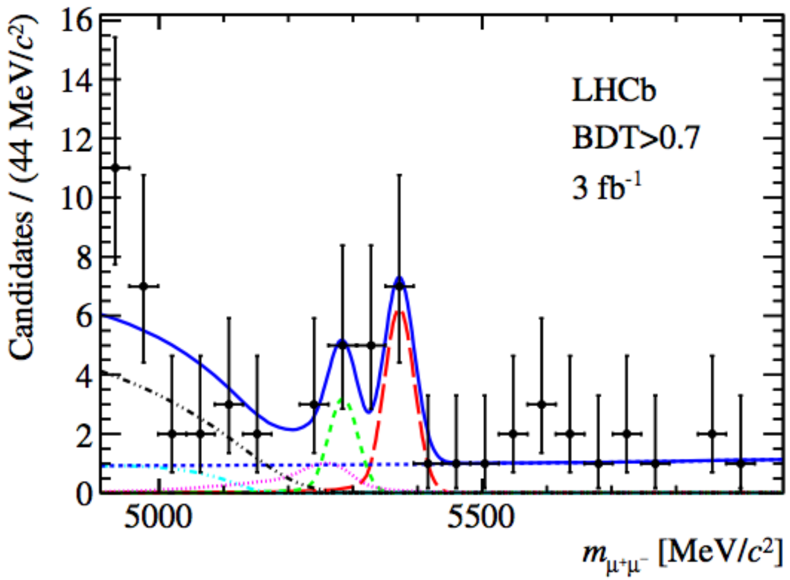
For BDT > 0.7

$$B(B_s^0 \rightarrow \mu^+\mu^-) = (2.9^{+1.1}_{-1.0}(stat)^{+0.3}_{-0.1}(syst)) \times 10^{-9}$$

Significance: 4.0σ

$$B(B^0 \rightarrow \mu^+\mu^-) = (3.7^{+2.4}_{-2.1}(stat)^{+0.6}_{-0.4}(syst)) \times 10^{-10}$$

Significance: 2.0σ



arXiv:1307.5024

Implications of $B^0_{(s)} \to \mu^+\mu^-$ results

LHCb:

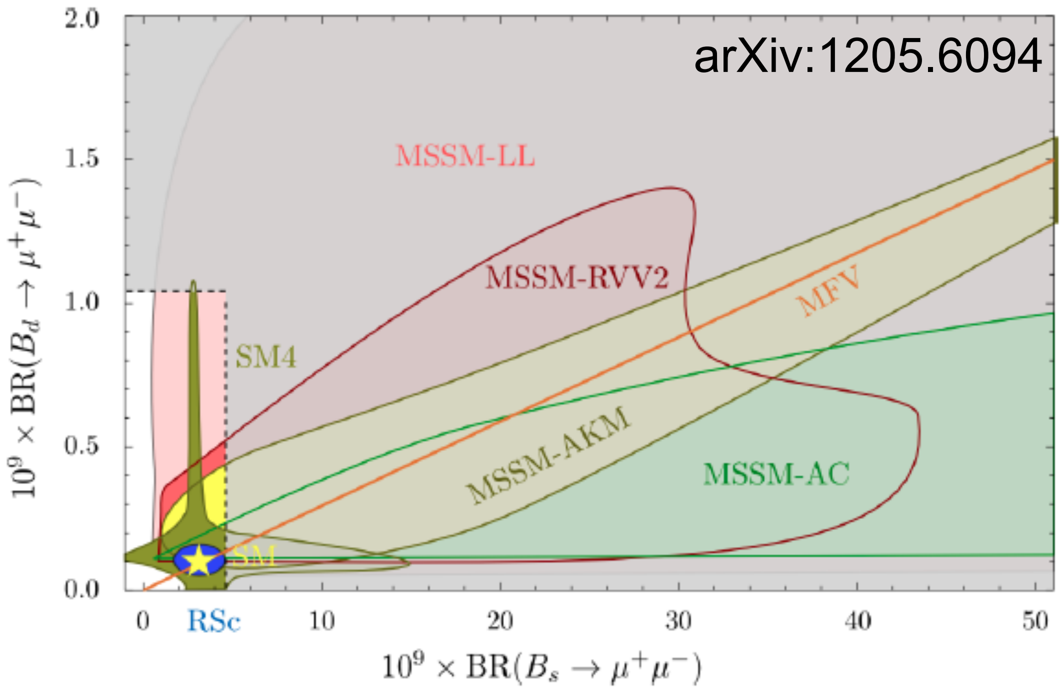
$$B(B_s^0 \to \mu^+\mu^-) = (2.9^{+1.1}_{-1.0}(stat)^{+0.3}_{-0.1}(syst)) \times 10^{-9}$$

$$B(B^0 \to \mu^+\mu^-) = (3.7^{+2.4}_{-2.1}(stat)^{+0.6}_{-0.4}(syst)) \times 10^{-10}$$

SM:

$$B(B_s^0 \to \mu^+\mu^-) = (3.35 \pm 0.28) \times 10^{-9}$$

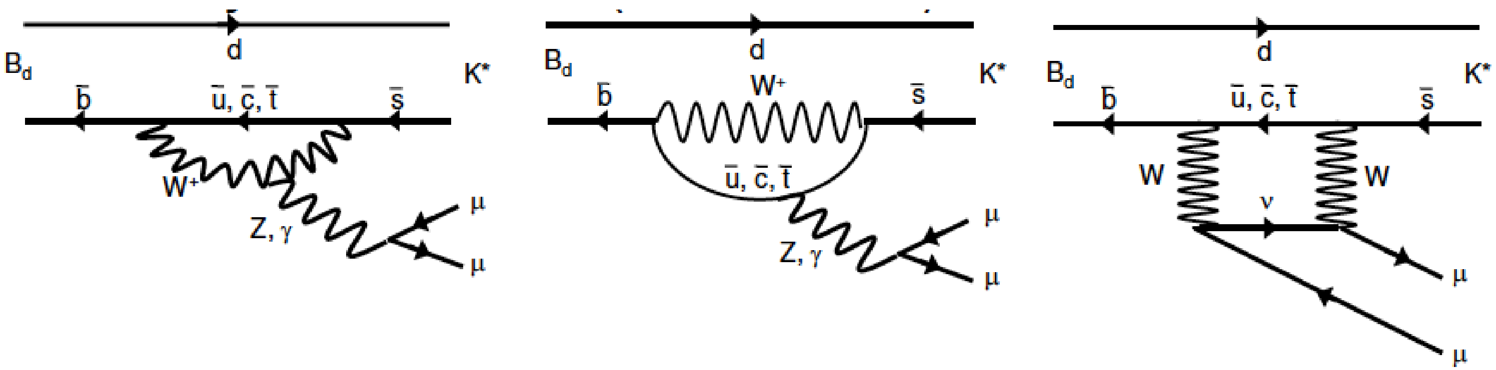
$$B(B^0 \to \mu^+\mu^-) = (1.07 \pm 0.10) \times 10^{-10}$$



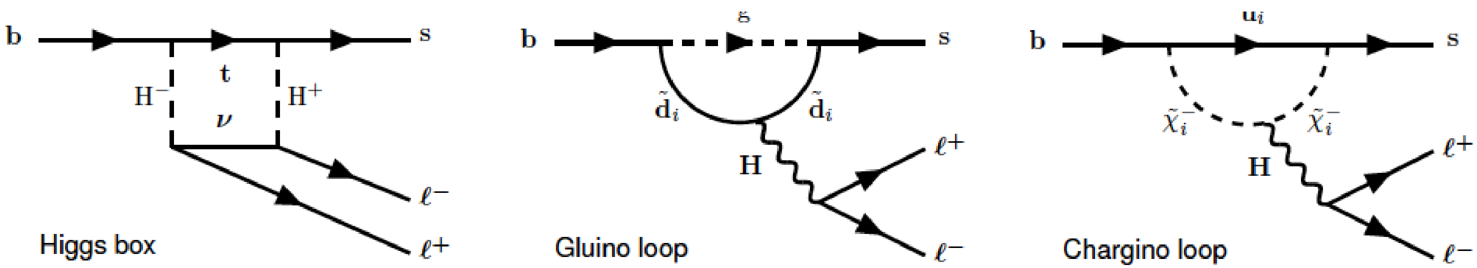
The grey area is ruled out experimentally

$B^0 \rightarrow K^{*0}(K^+\pi^-)\mu^+\mu^-$

Rare decay in SM ($BR \sim 10^{-6}$)

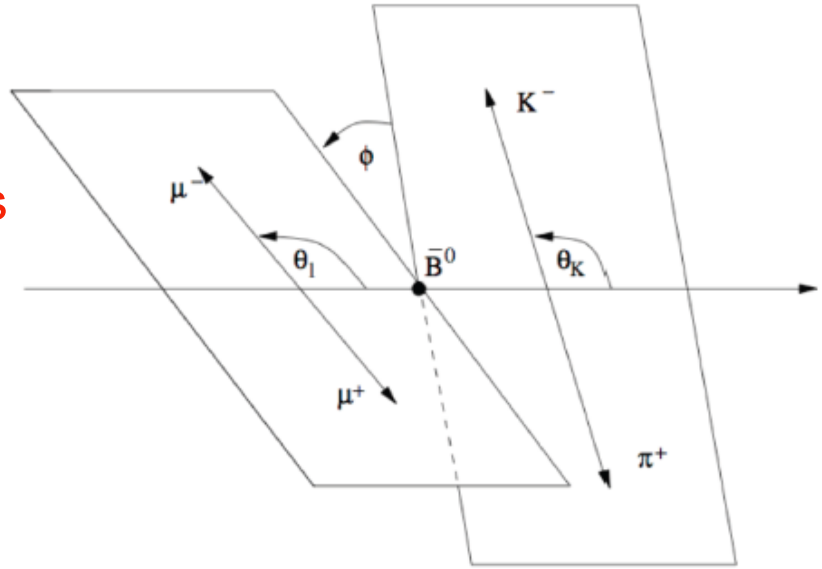


Sensitive to New Physics in loops, e.g.



Observables in $B^0 \to K^{*0}(K^+\pi^-)\mu^+\mu^-$

Angular observables, rates and asymmetries



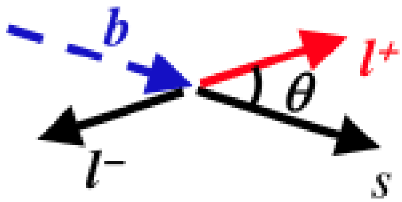
Decay rate described by equations below

Large number of NP-sensitive parameters, accessible through careful analysis of decay kinematics

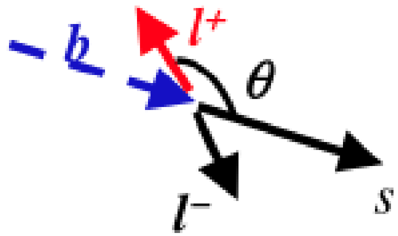
$$\frac{1}{\Gamma}\frac{d^3(\Gamma+\bar{\Gamma})}{d\cos\theta_\ell\, d\cos\theta_K\, d\phi} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_\ell$$
$$- F_L\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi$$
$$+ S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi + S_5\sin 2\theta_K\sin\theta_\ell\cos\phi$$
$$+ S_6\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\phi$$
$$+ S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big]$$

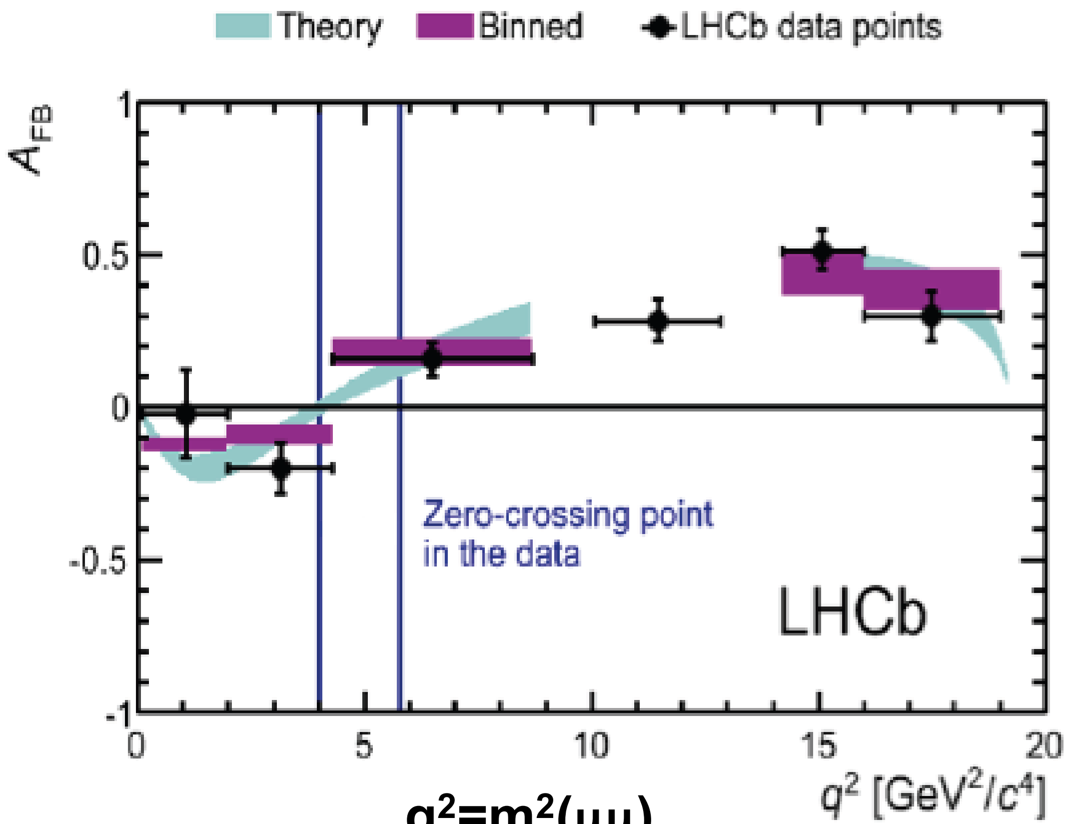
Forward-backward asymmetry in $B^0 \to K^{*0}(K^+\pi^-)\mu^+\mu^-$

Forward:



Backward:





$q^2 = m^2(\mu\mu)$

Good agreement with SM

First measurement of zero-crossing point: $q_0^2 = 4.9 \pm 0.9$ GeV^2/c^4

arXiv:1308.1707(2013)

New observables in $B^0 \to K^{*0}(K^+\pi^-)\mu^+\mu^-$

Observables with decreased dependence on form factor uncertainty:

$$A_T^{(2)} = \frac{2S_3}{(1-F_L)} \quad A_T^{Re} = \frac{S_6}{(1-F_L)}$$

$$P'_4 = \frac{S_4}{\sqrt{(1-F_L)F_L}} \quad P'_5 = \frac{S_5}{\sqrt{(1-F_L)F_L}}$$

$$P'_6 = \frac{S_7}{\sqrt{(1-F_L)F_L}} \quad P'_8 = \frac{S_8}{\sqrt{(1-F_L)F_L}}$$

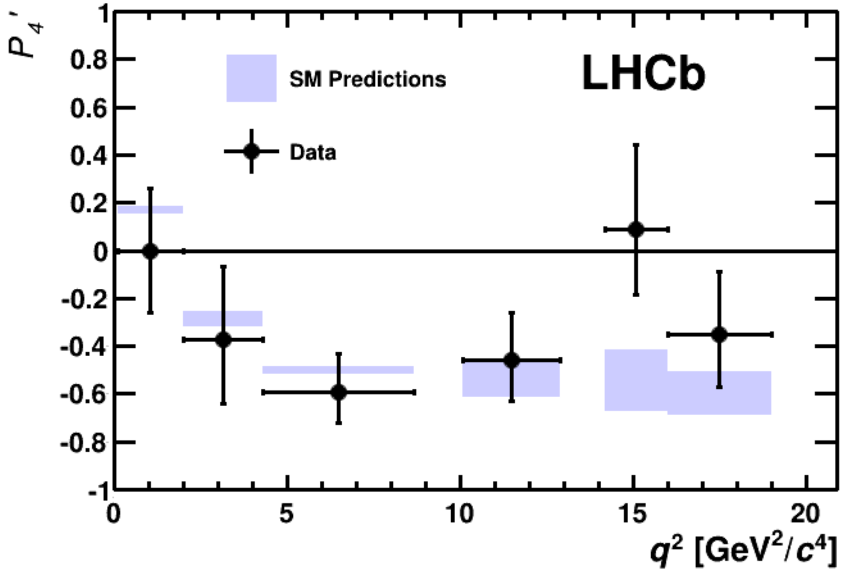
arXiv:1106.3283, arXiv:1202.4266
arXiv:hep-ph/0502060, arXiv:0807.2589,
arXiv.1105.0376, arXiv:1303.5794

Use following folding $\phi \to -\phi$ (if $\phi<0$) and $\theta_l \to \pi-\theta_l$ (if $\theta_l<\pi/2$) to measure P'_5:

$$\frac{1}{\Gamma}\frac{d^3(\Gamma+\bar{\Gamma})}{d\cos\theta_\ell\, d\cos\theta_K\, d\phi} = \frac{9}{8\pi}\Big[\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_\ell - F_L\cos^2\theta_K\cos 2\theta_\ell + \frac{1}{2}(1-F_L)A_T^{(2)}\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi + \sqrt{F_L(1-F_L)}P'_5\sin 2\theta_K\sin\theta_\ell\cos\phi\Big]$$

Transformations for $P'_{4,6,8}$ are similar

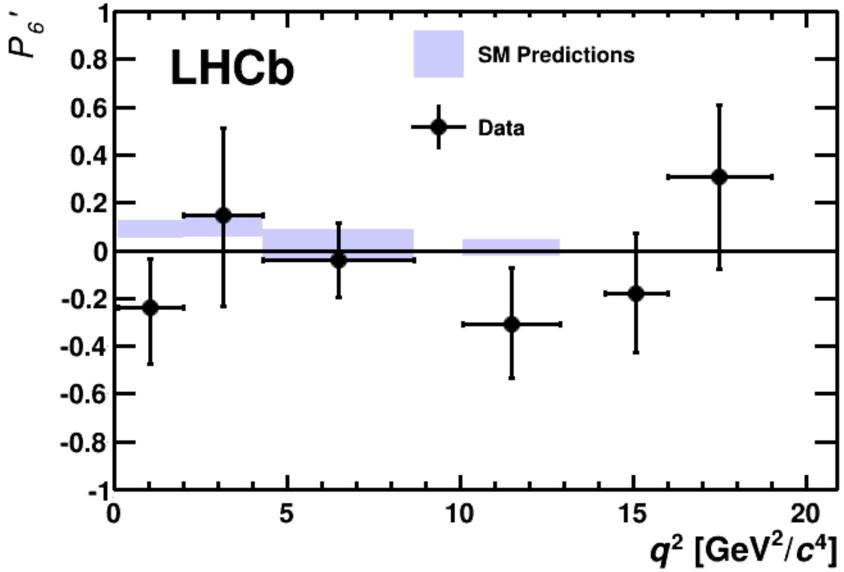
Results: P'_4, P'_6, P'_8

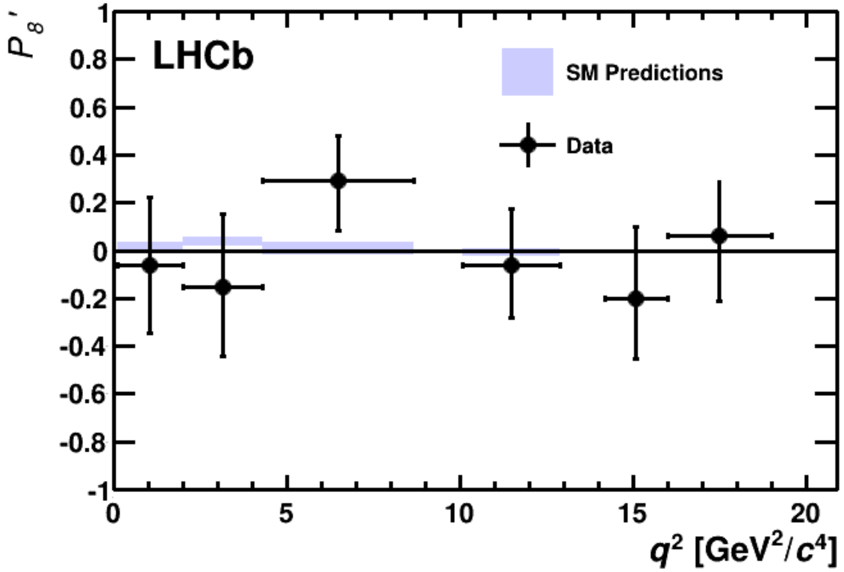


Analysis using 1/fb of data recorded in 2011

Results in good agreement with SM

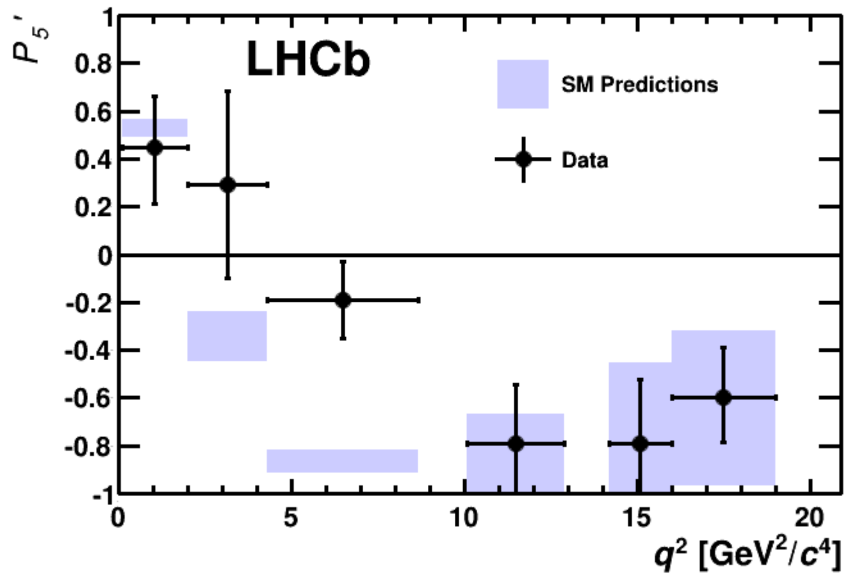
LHCb-PAPER-2013-037, arXiv:1308.1707





Results: P'_5

3.7σ local discrepancy in the region $4.3 < q^2 < 8.68$ GeV^2/c^4



0.5% probability to observe such a deviation considering the 24 independent measurements
(several other variables probed, each In several bins of q^2)

Recently S.Descotes-Genon, J.Matias, J.Virto suggested that combining this with other flavour observables, the observed discrepancy in P'_5 could be caused by a smaller value of the Wilson coefficient C_9 w.r.t SM [arXiv:1308.5683]
Other theorists suggest a flavour changing Z' gauge boson as a possible explanation

Summary

Flavour physics is sensitive to new physics at very high mass scales, looking at quantum loops

LHCb is the most sensitive heavy flavour experiment
So far, constraints on many NP models

Results confirm the SM….
Only discrepancy seen with P'_5 in $B^0 \to K^{*0}\mu^+\mu^-$

This is just the beginning - most of data already taken have still to be analyzed, and most of data have yet to be taken, after LHC shutdown and in LHCb-upgrade