The Abdus Salam International Centre for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization
IAEA International Atomic Energy Agency

2263-13

Beyond the Standard Model: Results with the 7 TeV LHC Collision Data

19 - 23 September 2011

Recent results from the LHCb experiment

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Search for New Physics at LHCb

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(On behalf of the LHCb Collaboration)

Beyond the Standard Model Physics,
ICTP, 19-23 September 2011

Outline

- LHCb and indirect search for new physics
- Search for new physics in B_s mixing
- Search for new physics in $b \to s$ loop decays
- Conclusions

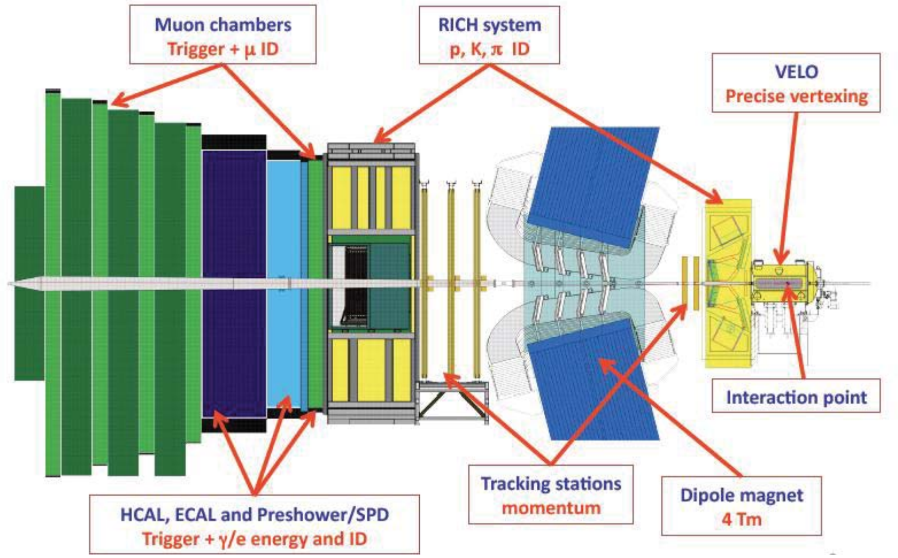
The LHCb Detector

Single arm forward spectrometer optimized for flavour physics

Precise tracking

Good mass and IP resolution to suppress background

Good vertex resolution for time dependent analysis



Excellent particle identification

π/K separation over 2-100 GeV

Powerful muon identification

All B species produced

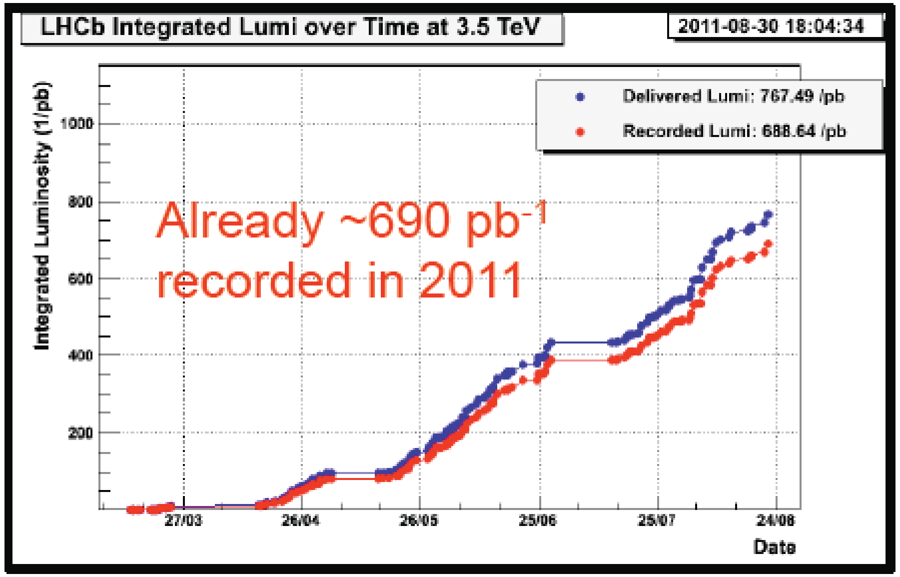
B^-, B_s, B^0, B_c, Λ_b, …, +c.c.

Efficient trigger

Low P_T thresholds for lepton, γ/π^0 and hadron

Luminosity

LHCb collected 37 pb^{-1} of data in 2010



Data taking since 2011

Luminosity increasing rapidly

Data taking efficiency >90%

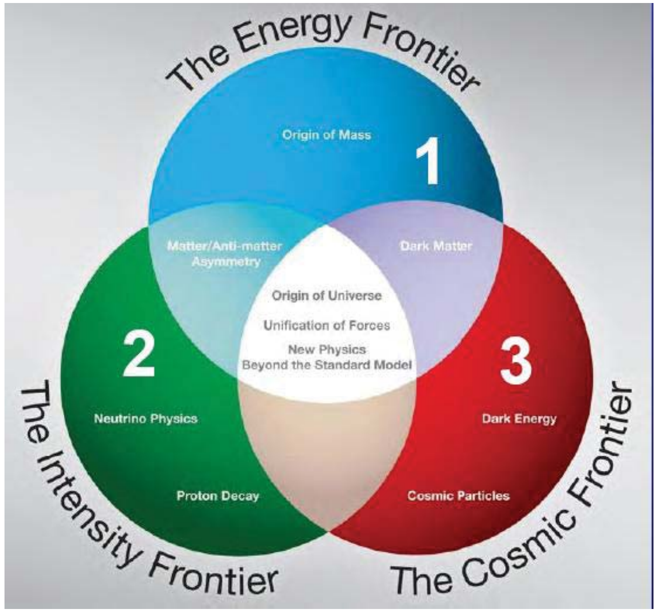
Aim to collect 1 fb^{-1} in 2011, at least the same number in 2012, and ~5 fb^{-1} at 7 TeV before the 2nd LHC shutdown 2017

Data analyses presented today used 37 pb^{-1} collected in 2010 or up to 340 pb^{-1} collected in 2011

New physics search at LHCb

- Physics objective: indirect search for New Physics (NP) effects (mostly) in loop-mediated processes at high intensity frontier
  - New physics in B_s mixing: $B_s \to J/\psi\phi$, $J/\psi f_0$
  - New physics in $b \to s$ loop decays: $B_s \to \mu^+\mu^-$, $B^0 \to K^*\mu^+\mu^-$, $B_s \to \phi\gamma$, $B_s \to \phi\phi$ ...
  - Lepton flavour violation
  - Precision test of CKM mechanism
  - New physics in D^0 mixing or decays
  - …

Today: highlights from 7 TeV data and prospects



Why indirect search

- Sensitive (but not limited) to new physics particles in loop-mediated processes
  - can probe much higher mass scale than $\sqrt{s}$
- Many observables together provide a model-independent search and useful information to discriminate models
  - SUSY, technicolor, extra dimensions, 4^{th} generation…
- Providing information about magnitudes and phases of NP couplings needed for full understanding
- Interesting in its own right: need new source of CP violation to explain matter-antimatter asymmetry

An example of “DNA test”

LHCb		AC	RVV2	AKM	δLL	FBMSSM	LHT	RS
⇢	$D^0-\bar{D}^0$	★★★	★	★	★	★	★★★	?
	ϵ_K	★	★★★	★★★	★	★	★★	★★★
→	$S_{\psi\phi}$	★★★	★★★	★★★	★	★	★★★	★★★
	$S_{\phi K_S}$	★★★	★★	★	★★★	★★★	★	?
→	$A_{\rm CP}(B\to X_s\gamma)$	★	★	★	★★★	★★★	★	?
→	$A_{7,8}(B\to K^*\mu^+\mu^-)$	★	★	★	★★★	★★★	★★	?
→	$A_9(B\to K^*\mu^+\mu^-)$	★	★	★	★	★	★	?
	$B\to K^{(*)}\nu\bar{\nu}$	★	★	★	★	★	★	★
→	$B_s\to\mu^+\mu^-$	★★★	★★★	★★★	★★★	★★★	★	★
	$K^+\to\pi^+\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
	$K_L\to\pi^0\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
	$\mu\to e\gamma$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
	d_n	★★★	★★★	★★★	★★	★★★	★	★★★
	d_e	★★★	★★★	★★	★	★★★	★	★★★
	$(g-2)_\mu$	★★★	★★★	★★	★★★	★★★	★	★★

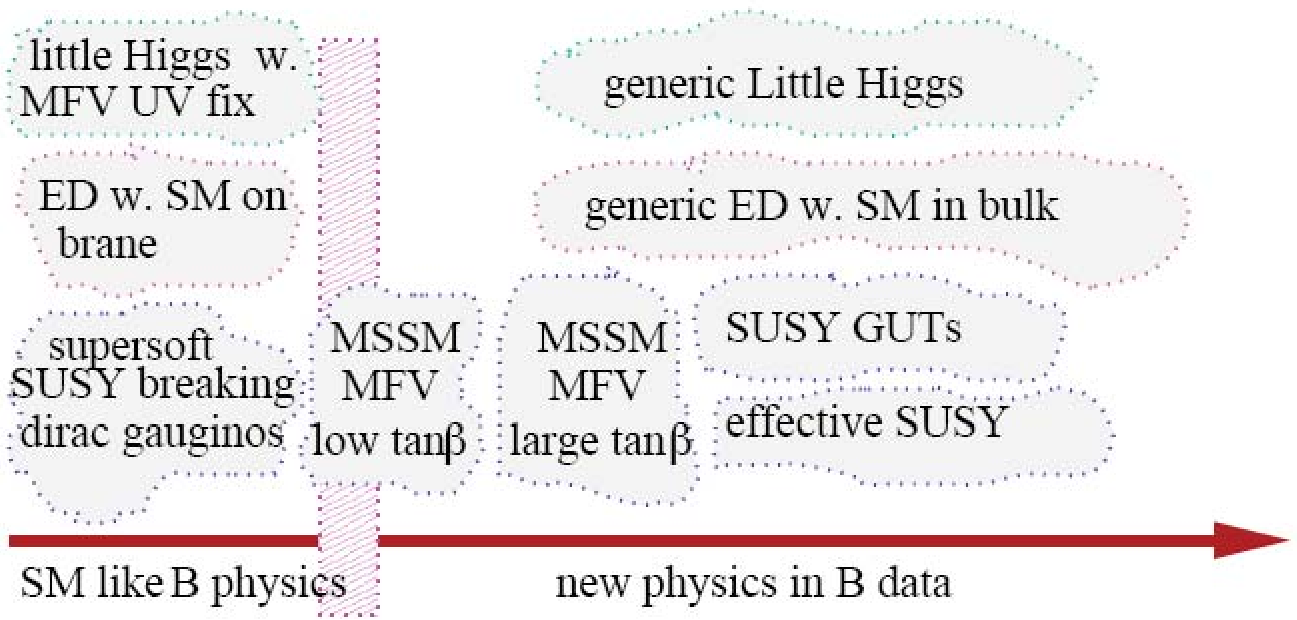
Table 2: “DNA” of flavour physics effects [55] for the most interesting observables in a selection of SUSY and non-SUSY models. ★★★ signals large effects, ★★ visible but small effects and ★ implies that the given model does not predict sizable effects in that observable.

Buras, arXiv:0910.1032v1

Bear in mind the limit

models of EWKSB with NP @ TeV

Fig from hep-ph/0207121



reach in indirect signals depends on beyond the SM flavor/CP violation (minimal=CKM), large parameters such as $\tan\beta$ and theoretical and experimental uncertainties

(Courtesy of G. Hiller)

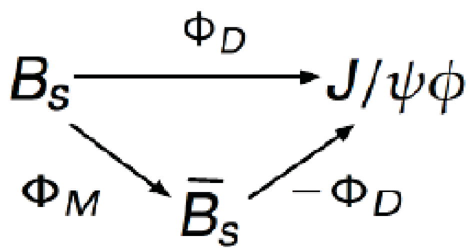
Search for new physics in B_s mixing

$$B_s \longrightarrow J/\psi\phi$$

$$B_s \longrightarrow J/\psi f_0$$

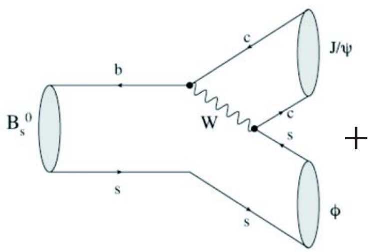
New physics in B_s mixing

- Measure CP violation through interference of decays with and without mixing: $\phi_s = \phi_M - 2\phi_D$

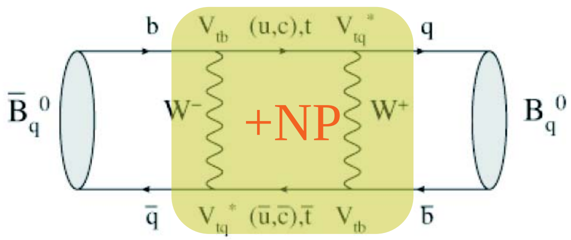


- Precise SM prediction [A. Lenz, arXiv: 1102.4274]

$$\phi_s \overset{\text{SM}}{=} -2\beta_s \equiv -2\arg\left(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right) = -0.036 \pm 0.002 \text{ rad}$$



+ penguin diagrams



Tree decay diagram immune to NP

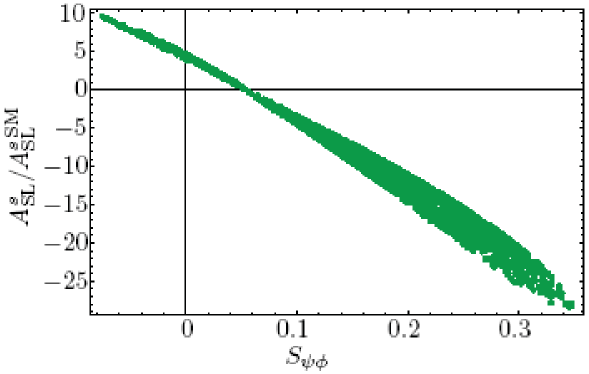
Mixing affected by NP

- New physics can significantly enhance ϕ_s: SUSY, Little Higgs, extra dimension, 4th generation, extra Z', …

Examples of NP effects

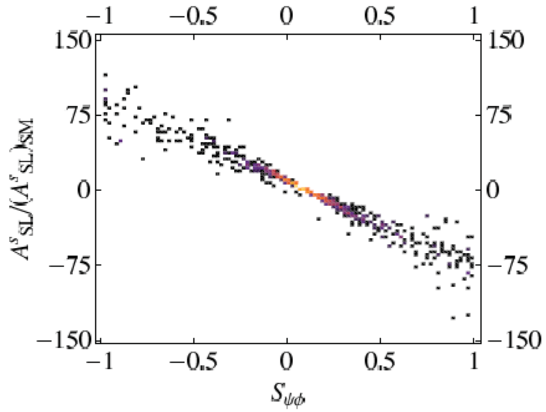
Little Higgs Model with T-Parity

[M. Blanke *et al.*, Acta Phys.Polon.B41:657, 2 010]

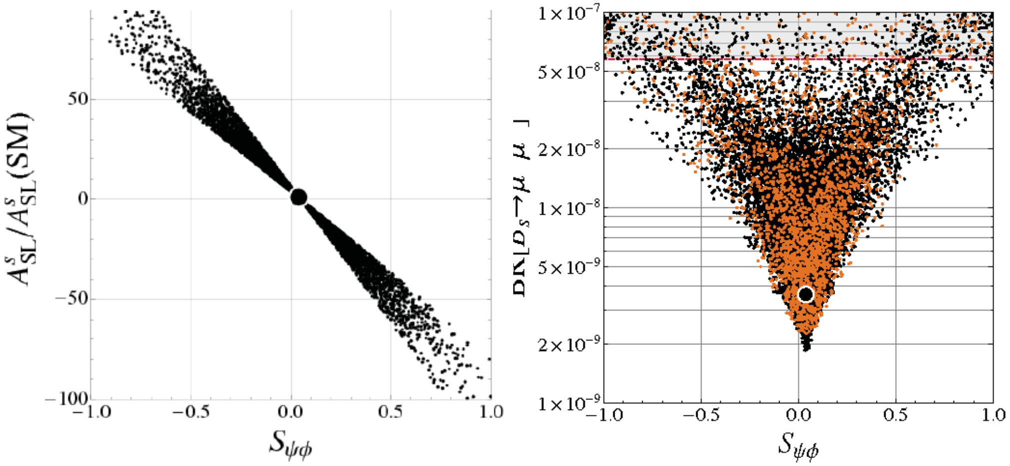


Warped Extra Dimension Model

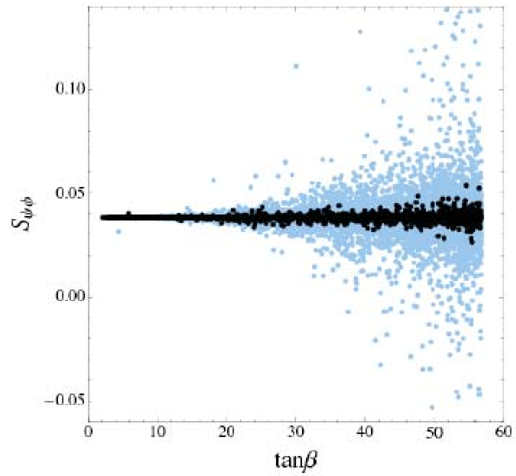
[M. Blanke *et al.*, JHEP 0903:001,2009]



SUSY "AC" Model



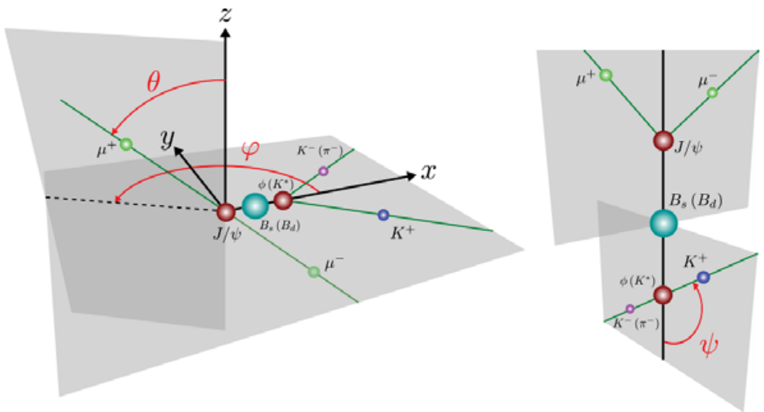
MFV SUSY Model



[W. Altmannshofer *et al.*, arXiv:0909.1333]

Describing $B_s \rightarrow J/\psi K^+K^-$

- $B_s \rightarrow J/\psi K^+K^-$ is mixture of 4 CP eigenstates
  - 3 K^+K^- P-waves and 1 S-wave
- Described in 4D space
  - 3 angles (θ, ϕ, ψ) and proper time t
- 10 physics parameters
  - 6 amplitudes and strong phases
  - ϕ_s, $\Delta\Gamma_s$, Δm_s, Γ_s



$$\frac{d^4\Gamma(B_s^0 \rightarrow J/\psi\phi)}{dt\, d\cos\theta\, d\varphi\, d\cos\psi} \equiv \frac{d^4\Gamma}{dt\, d\Omega} \propto \sum_{k=1}^{10} h_k(t)\, f_k(\Omega)$$

(+ descriptions of background, efficiency, resolution, mistag rate.)

Need flavour-tagged, time-dependent angular analysis.

Extracting ϕ_s in $B_s \to J/\psi K^+ K^-$

ϕ_s is obtained from time evolution of B_s ($\overline{B}_s$) to CP eigenstates

e.g., B_s ($\overline{B}_s$) to longitudinal final state

$$|A_0|^2(t) = |A_0|^2 e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma}{2}t\right) - \cos\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) \pm \sin\phi_s \sin(\Delta m t)\right]$$

+ for B_s
- for $\overline{B}_s$

- Analysis requirements
  - Separate signal and background
  - Separate different CP eigenstates
  - Identify the initial B flavour and know mistag probability
  - Resolve the fast B_s oscillation and know time resolution

Time evolution for refernece

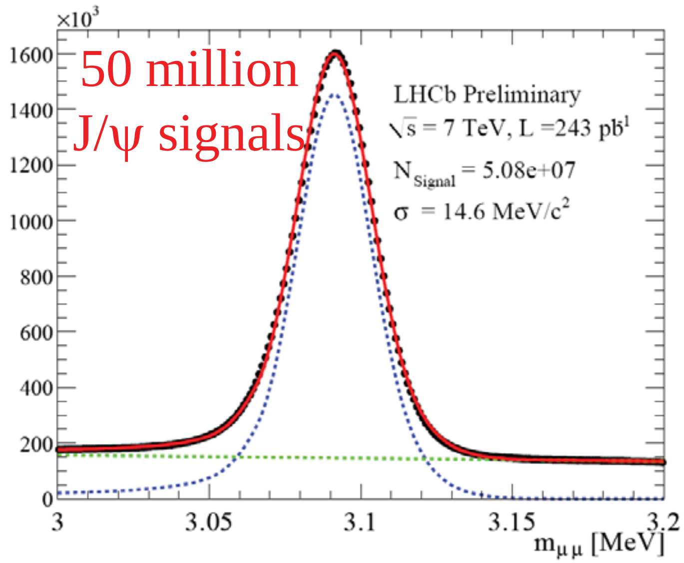
$$
\begin{aligned}
|A_0|^2(t) &= |A_0|^2 e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma}{2}t\right) - \cos\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) + \sin\phi_s \sin(\Delta m t)\right], \\
|A_\parallel(t)|^2 &= |A_\parallel|^2 e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma}{2}t\right) - \cos\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) + \sin\phi_s \sin(\Delta m t)\right], \\
|A_\perp(t)|^2 &= |A_\perp|^2 e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma}{2}t\right) + \cos\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) - \sin\phi_s \sin(\Delta m t)\right], \\
\Im(A_\parallel(t)\,A_\perp(t)) &= |A_\parallel||A_\perp| e^{-\Gamma_s t}\left[-\cos(\delta_\perp - \delta_\parallel)\sin\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right)\right. \\
&\quad \left. - \cos(\delta_\perp - \delta\_\|)\cos\phi_s \sin(\Delta m t) + \sin(\delta_\perp - \delta_\parallel)\cos(\Delta m t)\right], \\
\Re(A_0(t)\,A_\parallel(t)) &= |A_0||A_\parallel| e^{-\Gamma_s t}\cos(\delta_\parallel - \delta_0)\left[\cosh\left(\frac{\Delta\Gamma}{2}t\right) - \cos\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right)\right. \\
&\quad \left. + \sin\phi_s \sin(\Delta m t)\right], \\
\Im(A_0(t)\,A_\perp(t)) &= |A_0||A_\perp| e^{-\Gamma_s t}\left[-\cos(\delta_\perp - \delta_0)\sin\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right)\right. \\
&\quad \left. - \cos(\delta_\perp - \delta_0)\cos\phi_s \sin(\Delta m t) + \sin(\delta_\perp - \delta_0)\cos(\Delta m t)\right], \\
|A_s(t)|^2 &= |A_s|^2 e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma}{2}t\right) + \cos\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) - \sin\phi_s \sin(\Delta m t\right], \\
\Re(A_s^*(t) A_\parallel(t)) &= |A_s||A_\parallel| e^{-\Gamma_s t}\left[-\sin(\delta_\parallel - \delta_s)\sin\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) - \sin(\delta_\parallel - \delta_s)\ \cos\phi_s \sin(\Delta m t)\right. \\
&\quad \left. + \cos(\delta_\parallel - \delta_s)\cos(\Delta m t)\right], \\
\Im(A_s^*(t) A_\perp(t)) &= |A_s||A_\perp| e^{-\Gamma_s t}\sin(\delta_\perp - \delta_s)\left[\cosh\left(\frac{\Delta\Gamma}{2}t\right) + \cos\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right)\right. \\
&\quad \left. - \sin\phi_s \sin(\Delta m t)\right], \\
\Re(A_s^*(t) A_0(t)) &= |A_s||A_0| e^{-\Gamma_s t}\left[-\sin(\delta_0 - \delta_s)\sin\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right)\right. \\
&\quad \left. - \sin(\delta_0 - \delta_s)\cos\phi_s \sin(\Delta m t) + \cos(\delta_0 - \delta_s)\cos(\Delta m t)\right].
\end{aligned}
$$

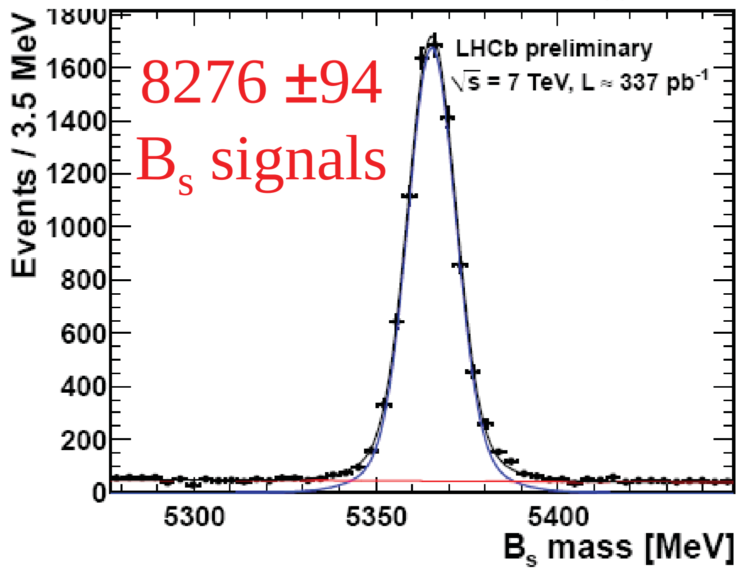
Major source of sensitivity to ϕ_s

Separating signal and background

- Very clean $B_s \rightarrow J/\psi\phi$ signal
  - powerful muon trigger
  - excellent kaon identification
  - require $t(B_s)>0.3$ ps to remove dominant background from prompt J/ψ

- Use B_s candidate mass variable to statistically separate signal and background in fit





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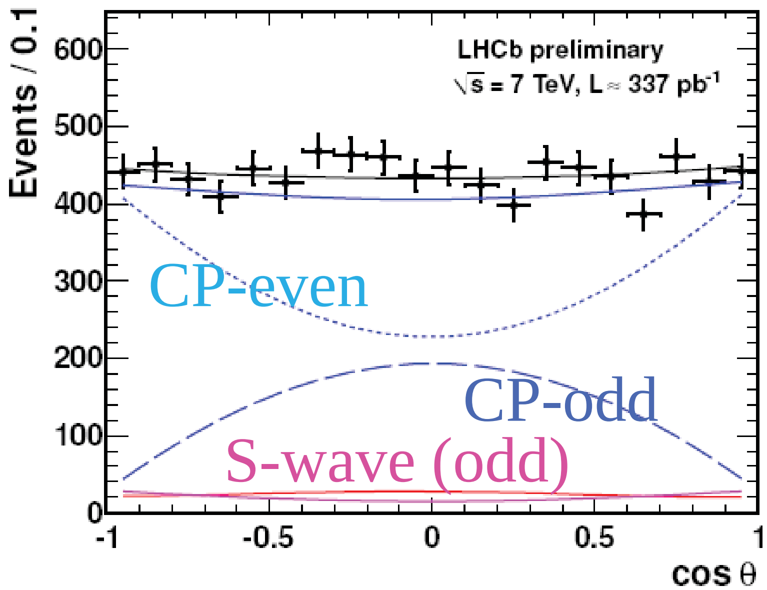
Separating CP eigenstates

Different CP eigenstates are statistically separated in maximum likelihood fit using angular information



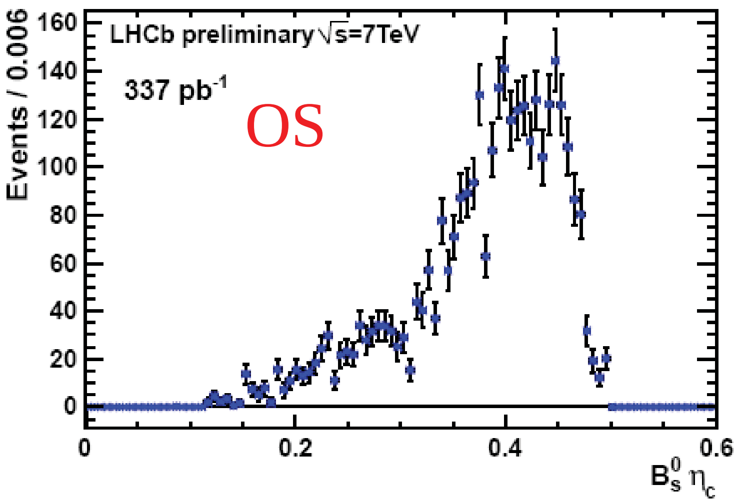
k	$h_k(t)$	$f_k(\theta,\psi,\varphi)$
1	$\lvert A_0\rvert^2(t)$	$2\cos^2\psi\left(1-\sin^2\theta\cos^2\phi\right)$
2	$\lvert A_\parallel(t)\rvert^2$	$\sin^2\psi\left(1-\sin^2\theta\sin^2\phi\right)$
3	$\lvert A_\perp(t)\rvert^2$	$\sin^2\psi\sin^2\theta$
4	$\Im(A_\parallel(t)\,A_\perp(t))$	$-\sin^2\psi\sin 2\theta\sin\phi$
5	$\Re(A_0(t)\,A_\parallel(t))$	$\frac{1}{2}\sqrt{2}\,\sin 2\psi\sin^2\theta\sin 2\phi$
6	$\Im(A_0(t)\,A_\perp(t))$	$\frac{1}{2}\sqrt{2}\,\sin 2\psi\sin 2\theta\cos\phi$
7	$\lvert A_s(t)\rvert^2$	$\frac{2}{3}(1-\sin^2\theta\cos^2\phi)$
8	$\Re(A_s^*(t)A_\parallel(t))$	$\frac{1}{3}\sqrt{6}\sin\psi\sin^2\theta\sin 2\phi$
9	$\Im(A_s^*(t)A_\perp(t))$	$\frac{1}{3}\sqrt{6}\sin\psi\sin 2\theta\cos\phi$
10	$\Re(A_s^*(t)A_0(t))$	$\frac{4}{3}\sqrt{3}\cos\psi(1-\sin^2\theta\cos^2\phi)$

Relative variation of angular efficiency <5% and accounted for according to full MC simulation

Identifying initial B flavour

- Initial flavour of B inferred from
  - Opposite Side: products of the other B meson
  - Same Side: fragmentation particles associated to signal B
- Currently use OS, fully optimized and calibrated on data

  (SS tagging will be used in next round of analysis)



Effective tagging efficiency
(2.08 ±0.41)%

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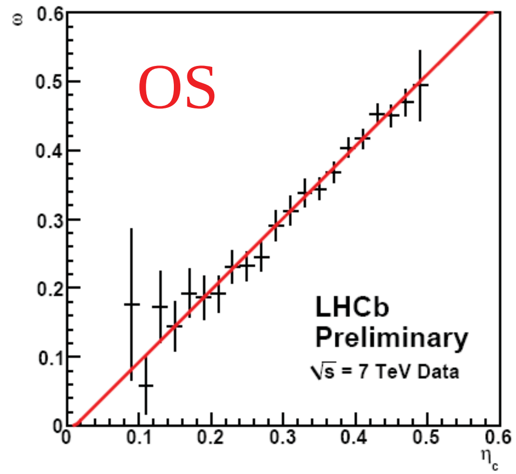
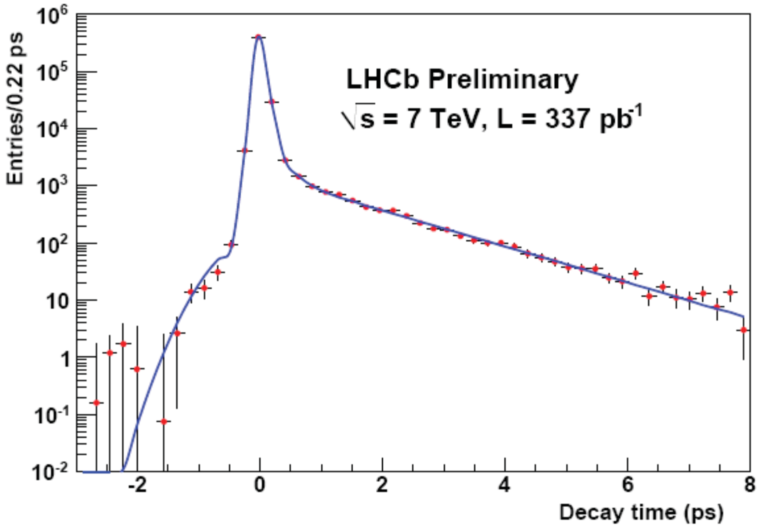


Wrong tagging probability very well calibrated with $B^+ \to J/\psi K^+$

Time resolution and acceptance

- Time resolution model obtained from prompt events



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- Effective proper time resolution 50 fs

- Compared with B_s oscillation period of about 350 fs

$$\Delta m_s = 17.725 \pm 0.041 \pm 0.026\ \text{ps}^{-1}$$ LHCb-CONF-2011-050

- Efficiency as a function of proper time obtained from data

$B_s \rightarrow J/\psi K^+K^-$ fit projections

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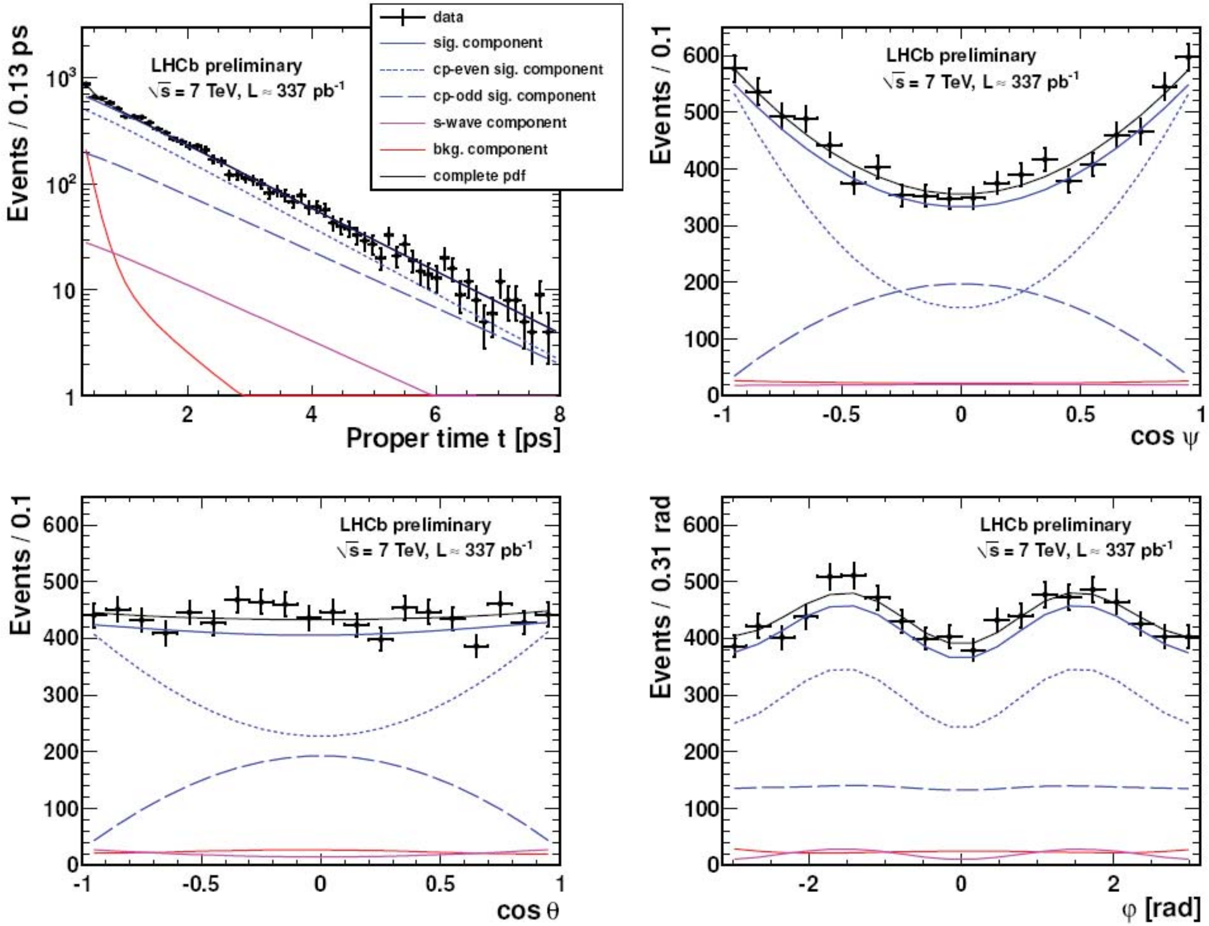

Goodness-of-fit: p-value 0.44 based on point-to-point dissimilarity test [M. Williams, JINST 5 (2010) P09004]

ϕ_s results from $B_s \rightarrow J/\psi K^+K^-$

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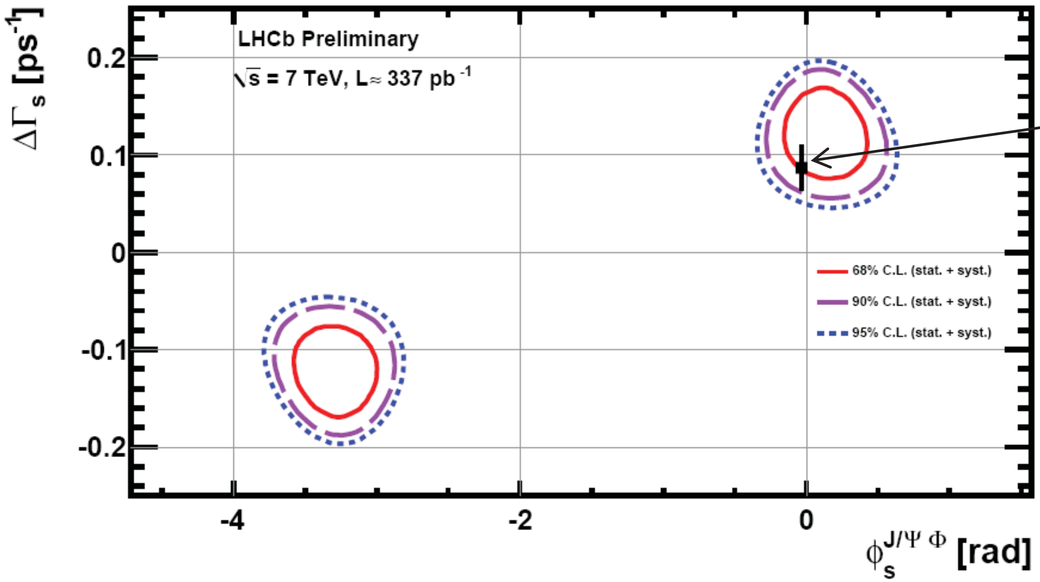


SM prediction [arXiv:1102.4274]

- Two ambiguous solutions $\phi_s \leftrightarrow \pi\text{-}\phi_s$; $\Delta\Gamma_s \leftrightarrow -\Delta\Gamma_s$
- World's most precise measurement of ϕ_s

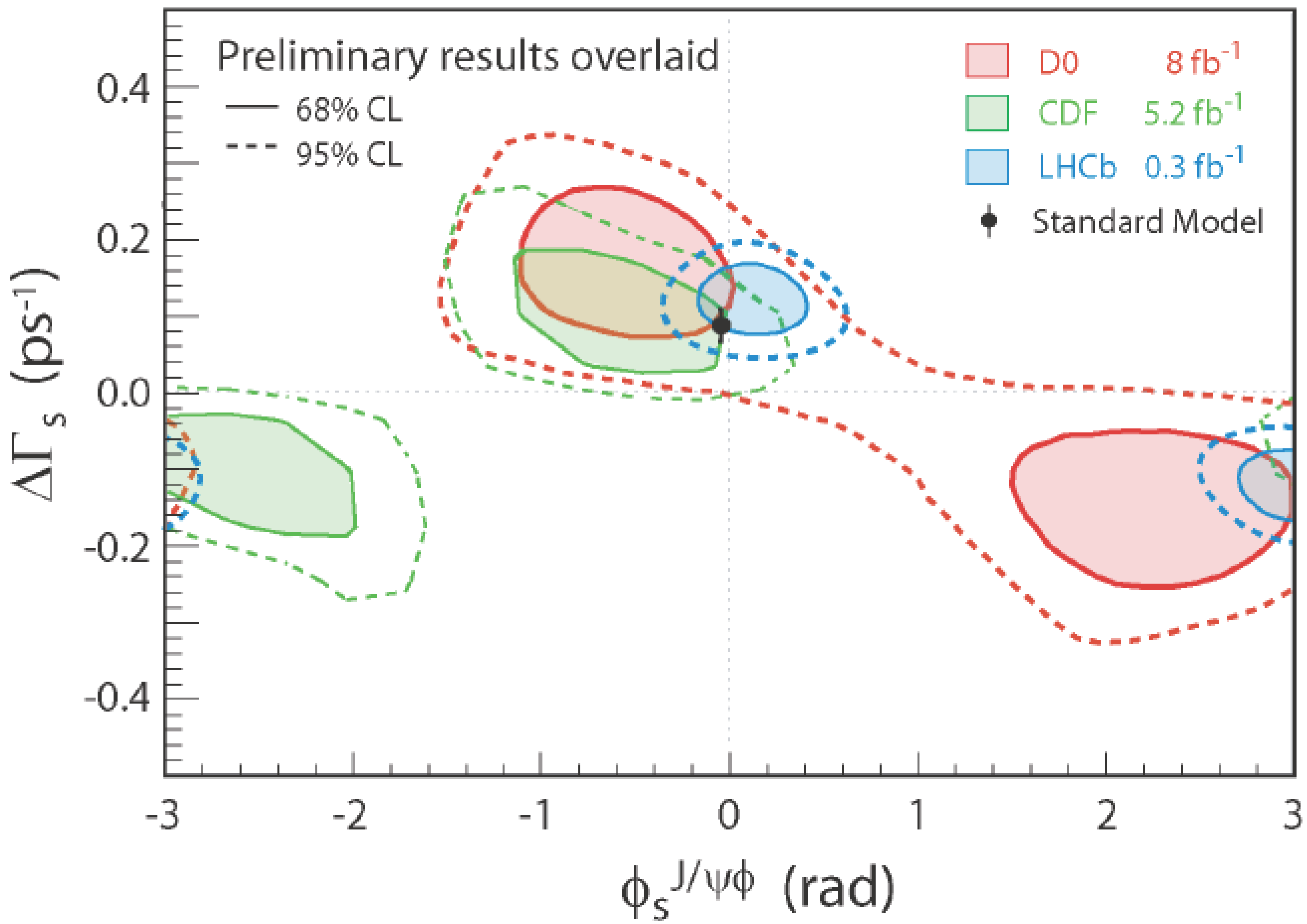
$$\phi_s = 0.13 \pm 0.18\ (\text{stat}) \pm 0.07\ (\text{sys})\ \text{rad}$$

consistent with SM prediction $\phi_s^{SM} = -0.036 \pm 0.002$ rad

- 4σ evidence for $\Delta\Gamma_s \neq 0$

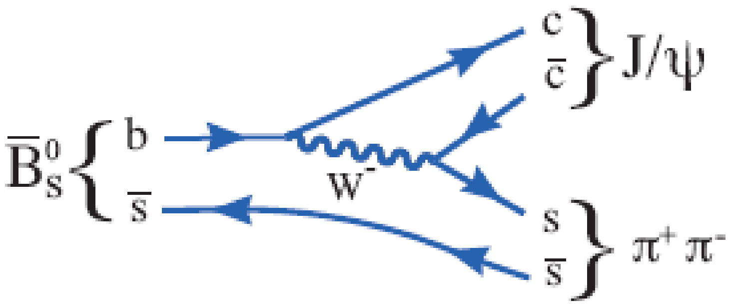
$$\Delta\Gamma_s = 0.123 \pm 0.029\ (\text{stat}) \pm 0.008\ (\text{sys})\ \text{ps}^{-1}$$

“artist’s view”



http://lhcb-public.web.cern.ch/lhcb-public/

$B_s \rightarrow J/\psi f_0$



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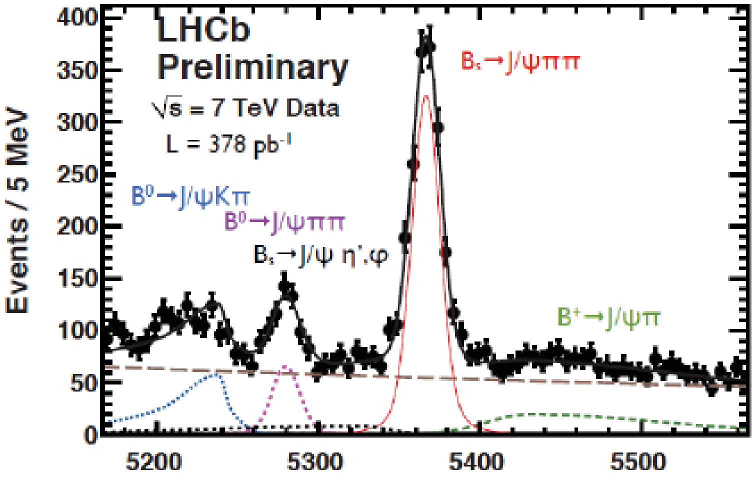
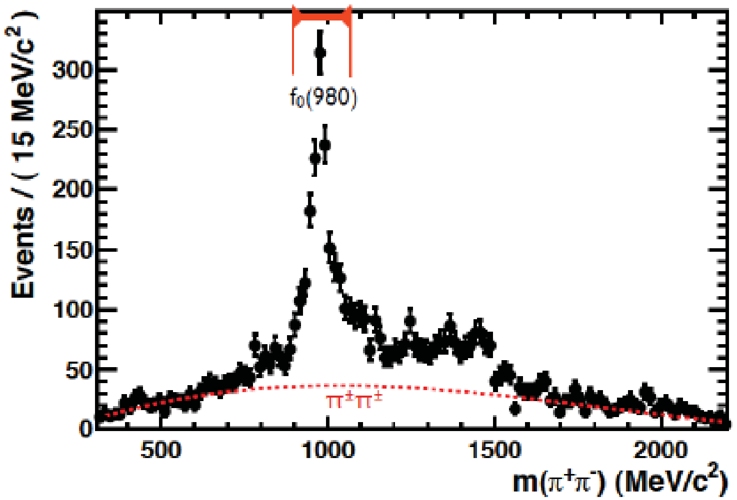
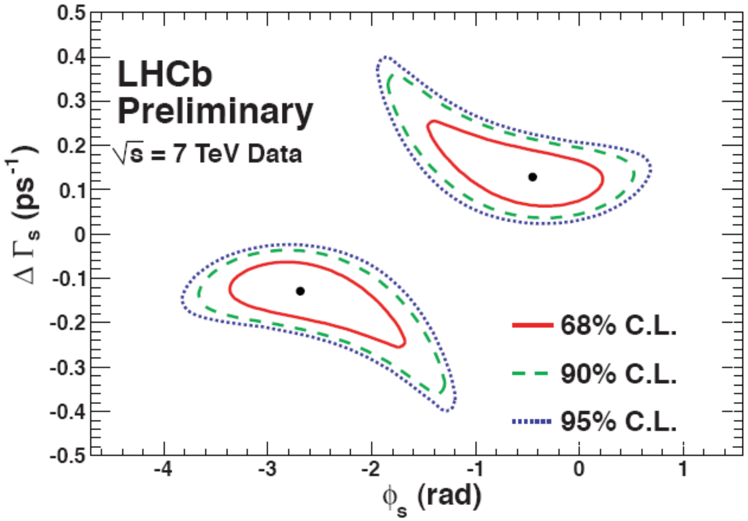




CP odd final state alone cannot determine Γ_s and $\Delta\Gamma_s$

Using Γ_s from $B_s \rightarrow J/\psi\phi$



Using $\Delta\Gamma_s$ and Γ_s from $B_s \rightarrow J/\psi\phi$

$\phi_s = -0.44 \pm 0.44 \pm 0.02$ rad

(+ ambiguous solution)

$B_s \to J/\psi\phi$ and $B_s \to J/\psi f_0$ Combination

- Simultaneous fit of $B_s \to J/\psi\phi$ and $B_s \to J/\psi f_0$ data

  $\phi_s = 0.03 \pm 0.16\ (stat) \pm 0.07\ (sys)$ rad

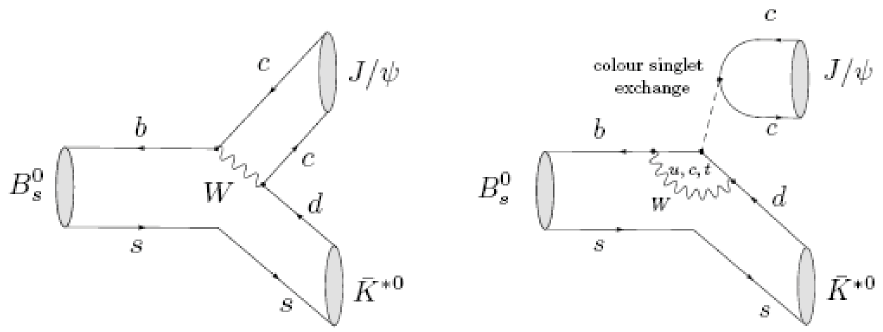
  (+ ambiguous solution) LHCb-CONF-2011-056

- Be careful with combination
  - Hadronic nature of f_0 not clear
  - Different hadronic effects in $B_s \to J/\psi f_0$ and $B_s \to J/\psi\phi$

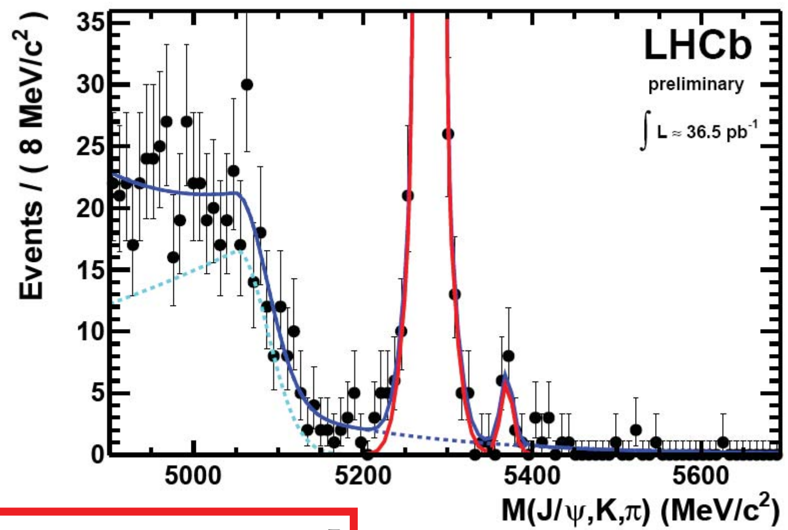
  [R. Fleischer *et al*., arXiv:1109.1112)]

$B_s \to J/\psi K^*$

[S. Faller *et al.*, PRD 79:014005, 2009]



- $b \to c\bar{c}d$ decay
- Can be used to control penguin contribution in $B_s \to J/\psi\phi$
- Need measure:
  - $Br(B_s \to J/\psi K^*)/Br(B_s \to J/\psi\phi)$
  - $A_{CP}(B_s \to J/\psi K^*)$



LHCb measured BR with 37 pb $^{-1}$

LHCb-CONF-2011-048

$$\mathcal{B}(B_s^0 \to J/\psi \overline{K}^{*0}) = (3.5^{+1.1}_{-1.0}(stat.) \pm 0.9(syst.)) \times 10^{-5}$$

CDF, PRD 83:052012, 2011 $\mathcal{B}(B_s^0 \to J/\psi \overline{K}^{*0}) = (8.3 \pm 3.8) \times 10^{-5}.$

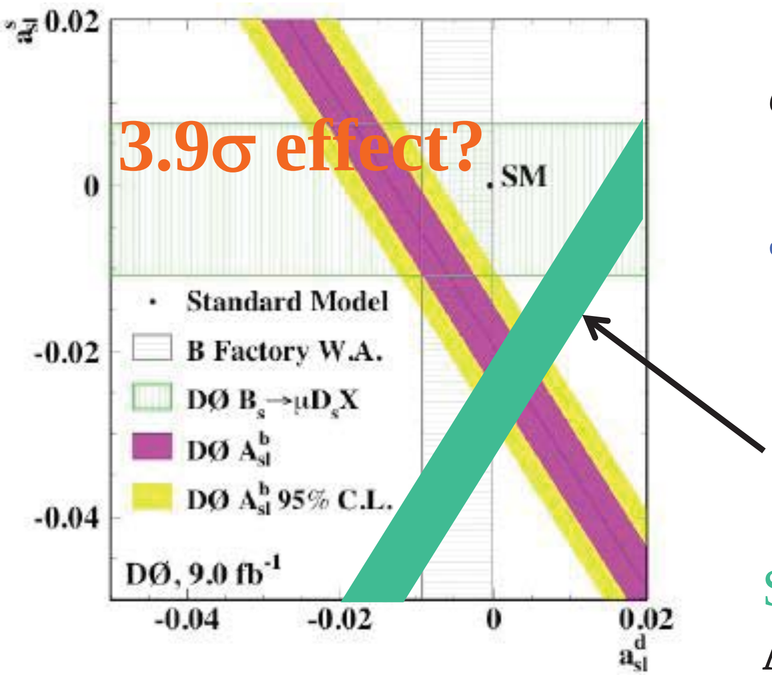
Prospects

- Improve statistical error $\sigma(\phi_s)$ from $B_s \rightarrow J/\psi\phi$
  - Expect 2 fb^{-1} by end of 2012 → $\sigma(\phi_s) \sim 0.07$ from simple scaling
  - Using same side kaon tagging will give further improvement
- Reduce systematic error significantly
  - Use better method to treat background and angular acceptance
- Resolve 2-fold ambiguity of ϕ_s [Y. Xie *et al.*, JHEP 0909:074,2009]
  - Work in progress
- Control theoretical uncertainties
  - Main issue: effect of penguin contribution on ϕ_s needs to be controlled to match the experimental accuracy of ϕ_s with 2 fb^{-1} or more
  - Expect using 2011+2012 data sample to measure $A_{CP}(B_s \rightarrow J/\psi K^*)$ and exploit the U-spin relation between $B_s \rightarrow J/\psi K^*$ and $B_s \rightarrow J/\psi\phi$
    [S. Faller *et al.*, PRD 79:014005, 2009]

Looking forward to ΔA_{fs}

D0 : evidence for an anomalous like-sign dimuon charge asymmetry

D0 Collaboration, arXiv:1106.6308



$$a_{fs}^{s} = \mathrm{Im}\frac{\Gamma_{12}^{s}}{M_{12}^{s}} \approx \frac{\Delta\Gamma_{s}}{\Delta M_{s}}\tan\phi_{s}$$

another sensitive probe of NP in B_s mixing

$$\Delta A_{fs} = \frac{a_{fs}^{s} - a_{fs}^{d}}{2}$$

Supposed LHCb measurement

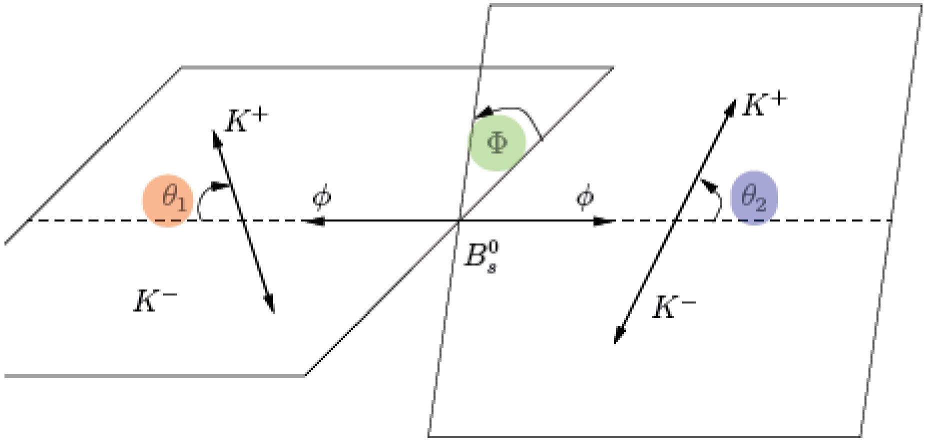
Analysis in progress

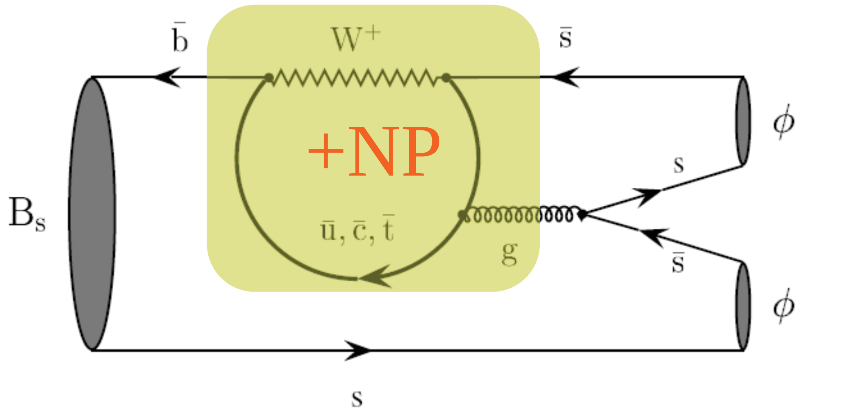
- Use $B_s^0 \to D_s^- \mu^+ \nu$ and $B^0 \to D^- \mu^+ \nu$ with the same final state $K^+ K^- \pi^- \mu^+$ $\to$ same detector asymmetry δ_c^q for these modes.
- Measure the difference between B_s^0 and B^0: $\Delta A_{fs}^{s,d} \simeq \frac{a_{fs}^s - a_{fs}^d}{2}$ $\to$ most of background and production asymmetries also cancel

Search for new physics in $b \to s$ loop decay processes

$B_s \to \phi\phi$	hadronic penguin
$B_s \to \phi\gamma$	radiative penguin
$B_s \to \mu^+\mu^-$	EW or Higgs penguin
$B^0 \to K^*\mu^+\mu^-$	EW penguin

NP in $B_s \to \phi\phi$





Time-integrated
Triple product asymmetry

$$A_U = \frac{N(U>0)-N(U<0)}{N(U>0)-N(U<0)}, A_V = \frac{N(V>0)-N(V<0)}{N(V>0)-N(V<0)}$$

$$\frac{d^4\Gamma}{dt d\Omega} \propto |A_0(t)|^2 \cdot f_1(\Omega) + |A_{\parallel}(t)|^2 \cdot f_2(\Omega) + |A_{\perp}(t)|^2 \cdot f_3(\Omega) + \boxed{\Im(A_{\parallel}^*(t) A_{\perp}(t))} \cdot f_4(\Omega) + \Re(A_0^*(t) A_{\parallel}(t)) \cdot f_5(\Omega) + \boxed{\Im(A_0^*(t) A_{\perp}(t))} \cdot f_6(\Omega),$$

$U = \sin 2\Phi$

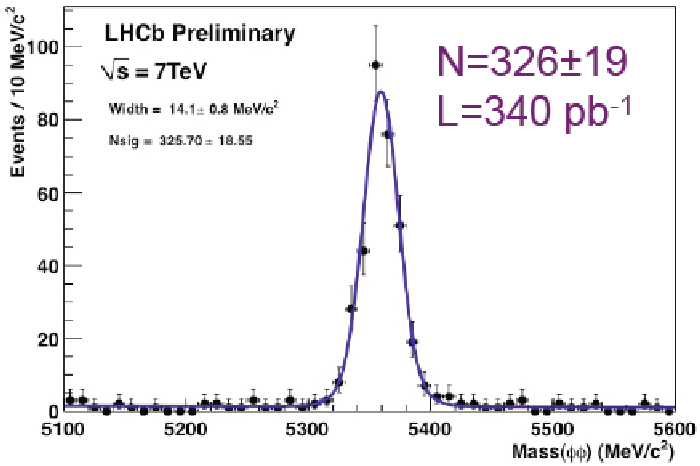
$V = \sin(\pm\Phi)$ sign from $f_6(\Omega)$

SM prediction $A_{U/V} = 0$. Non-zero measurement means weak phase difference between CP even and odd eigenstates, clear sign of NP

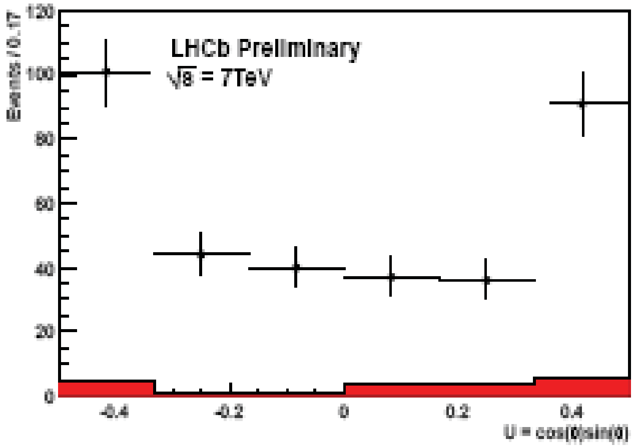
[M. Gronau and J. L. Rosner, arXiv:1107.1232]

$B_s \rightarrow \phi\phi$

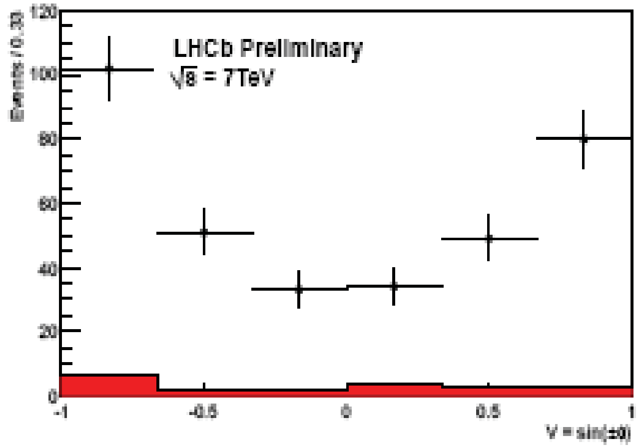
LHCb-CONF-2011-052



Very clean mass peak.
No flavour tagging needed for triple product asymmetry



$$A_U = -0.064 \pm 0.057 \pm 0.014$$

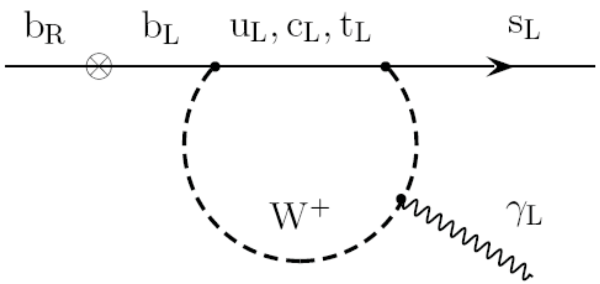


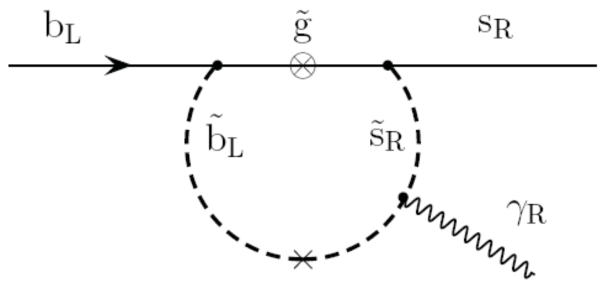
$$A_V = -0.070 \pm 0.057 \pm 0.014$$

CDF (arXiv: 1107.4999):
A_U = -0.007 ± 0.064 (stat) ± 0.018 (syst)
A_V = -0.120 ± 0.064 (stat) ± 0.016 (syst)

- Consistent with zero
- Next step : measure CP asymmetry

NP in $B_s \rightarrow \phi\gamma$





Dominating SM quark level diagram has left handed photons

An example MSSM diagram with right-handed photons

Experimental probe: A_Δ (or effective lifetime)
[F. Muheim, Y. Xie, R. Zwicky, PLB 664:174, 2008]

$$R(t) \propto e^{-\Gamma_s t}\left[\cosh\left(\Delta\Gamma_s t/2\right) + A_\Delta \sinh\left(\Delta\Gamma_s t/2\right)\right]$$

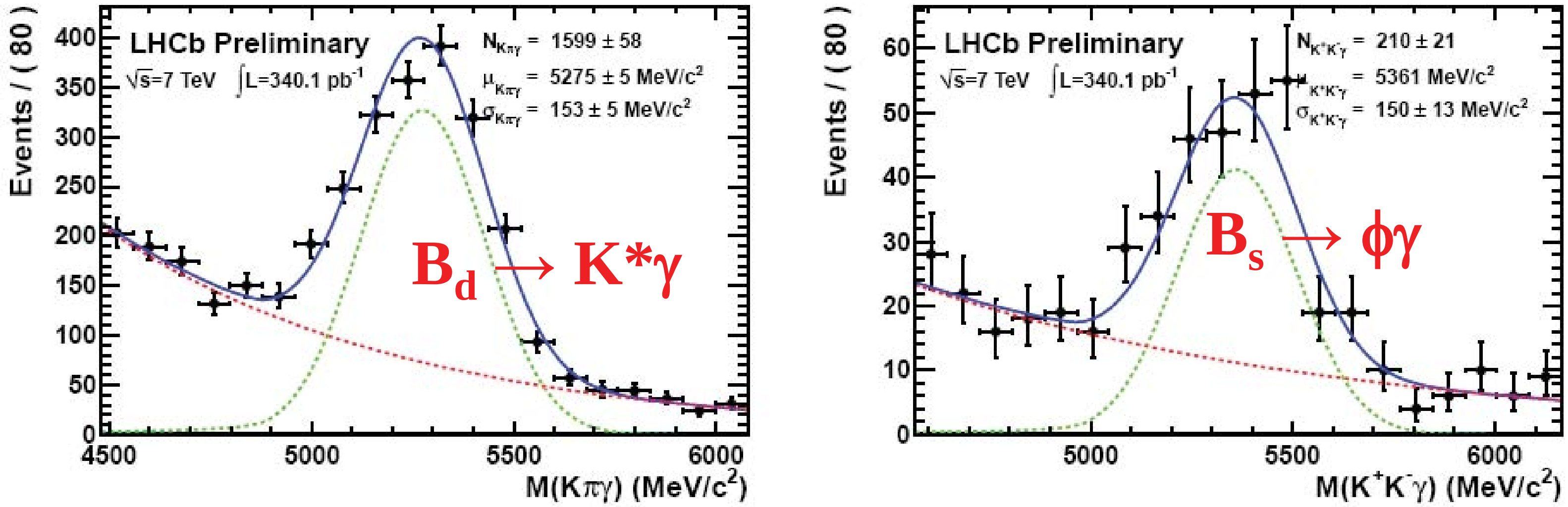
A_Δ sensitive to fraction of right-handed photons (even for small ϕ_s)

$A_\Delta \sim 0$ in SM, can be enhanced by NP with large RH currents.

$B_s \to \phi\gamma$

First step: measure BR. LHCb-CONF-2011-055

$$\frac{\mathcal{B}(B^0 \to K^{*0}\gamma)}{\mathcal{B}(B_s^0 \to \phi\gamma)} = 1.52 \pm 0.14(\text{stat}) \pm 0.10(\text{syst}) \pm 0.12(f_s/f_d)$$



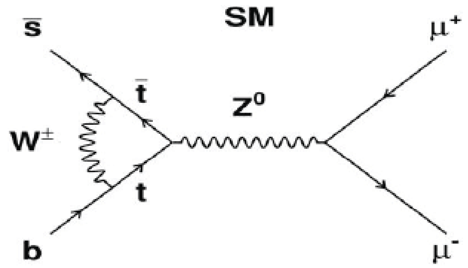
Next step: measure A_Δ (or effective lifetime)

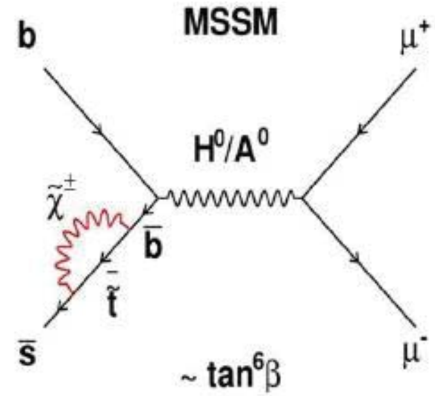
$B_s \to \mu^+\mu^-$

- $B_s \to \mu^+\mu^-$ is very rare but well predicted in the SM
  - FCNC loop suppression
  - Helicity suppression

  $BR_{SM}(B_s \to \mu^+\mu^-) = (3.2 \pm 0.2)\times 10^{-9}$

  [E. Gamiz *et al*., PRD 80:014503, 2009]

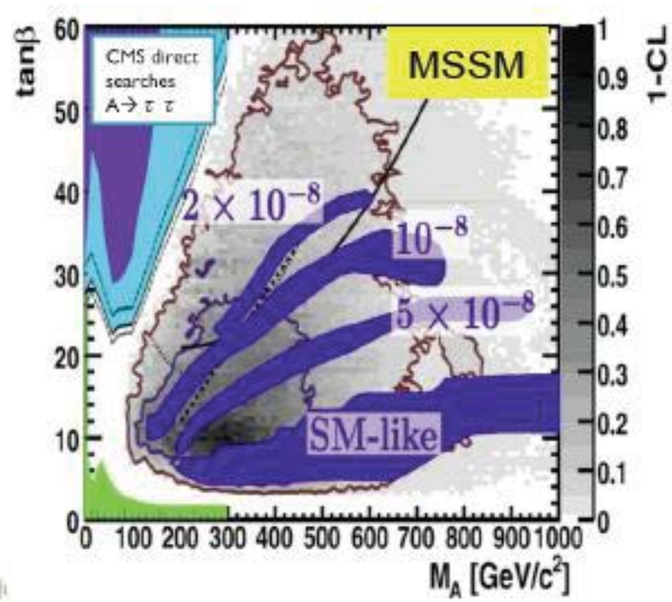




- Sensitive to new physics in scalar/pseudo-scalar sector

  e.g. MSSM with high tanβ

$$BR(B_s \to \mu^+\mu^-) \propto \frac{\tan^6\beta}{M_A^4}$$



- Measurement or limit will become strong constraint on NP, e.g. on (tanβ, M_A) plane

  [O. Buchmueller *et al*., Eur.Phys.J.C64:391, 2009]

$B_s \to \mu^+\mu^-$ status 2011 spring

$B_s \to \mu^+\mu^-$

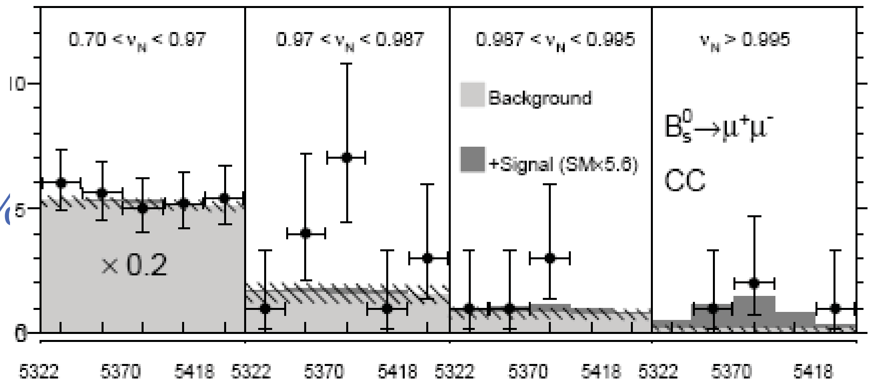
Spring 2011

Experiment	Data	Upper Limit (95% C.L.)
CDF	3.7 fb^{-1}	$< 4.3 \times 10^{-8}$
D0	6.1 fb^{-1}	$< 5.1 \times 10^{-8}$
LHCb	36 pb^{-1}	$< 5.6 \times 10^{-8}$

- CDF recently reported a hint of signal with 7 fb^{-1}
  - p-value background only: 0.3%
  - p-value background + SM BR: 1.9%
  - p-value background + 5.6×SM BR: 50%

$$B\left(B_s \to \mu^+\mu^-\right) = 1.8^{+1.0}_{-0.9} \times 10^{-8}$$

CDF, arXiv:1107.2304



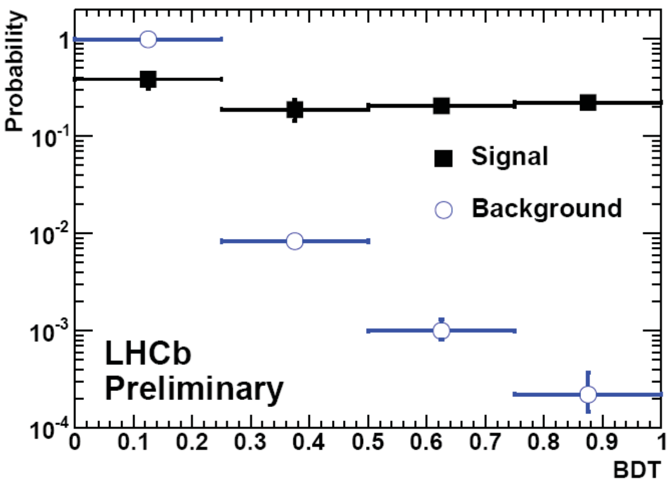
LHCb analysis strategy

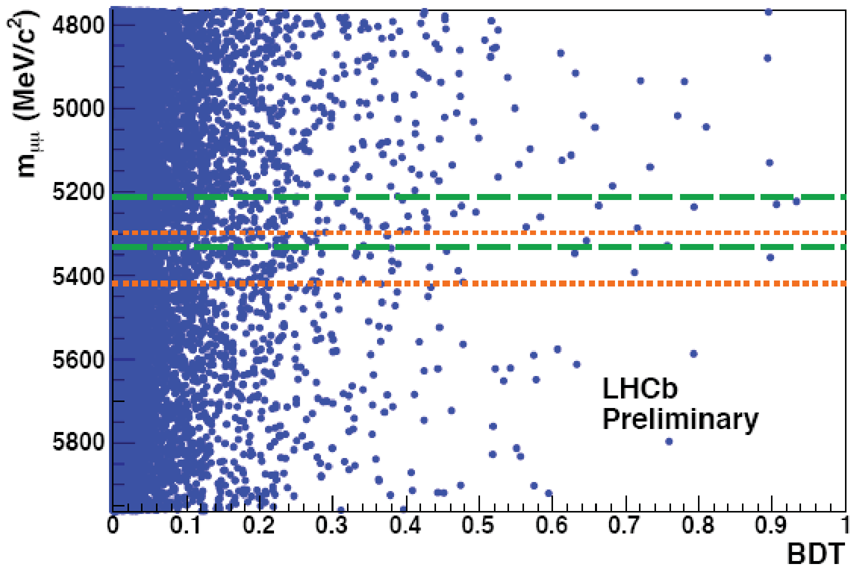
- Discriminating signal and background using 2 variables
  - invariant mass of $\mu^+\mu^-$: parameterization from data
  - output of a Boosted Decision Tree (BDT): built on 9 kinematical and topological variables, trained on MC, shape of BDT output obtained on $B \to hh$ (signal) and B mass sideband (background)
- Normalization
  - using $B^+ \to J/\psi K^+$, $B_s \to J/\psi \phi$ and $B_d \to K\pi$
  - LHCb $f_s/f_d = 0.267^{+0.021}{}_{-0.20}$ [LHCb-CONF-2011-028, arXiv: 1106.4435]
- Assessing BR and setting limit
  - For a given BR, compare observed and expected numbers of events in 6×4 bins of $m(\mu^+\mu^-)$ and BDT output for signal+bkg and bkg hypotheses
  - Calculate CLs [A. Read, J. Phys. G 28 (2002) 2693]
  - Exclude the BR at 1-α C.L. if CLs < α
  - The highest BR which is not excluded is the CLs limit at 1-α C.L.

BDT and mass distributions

4 bins in BDT output
120 MeV B mass search window divided into 6 bins

LHCb-CONF-2011-037



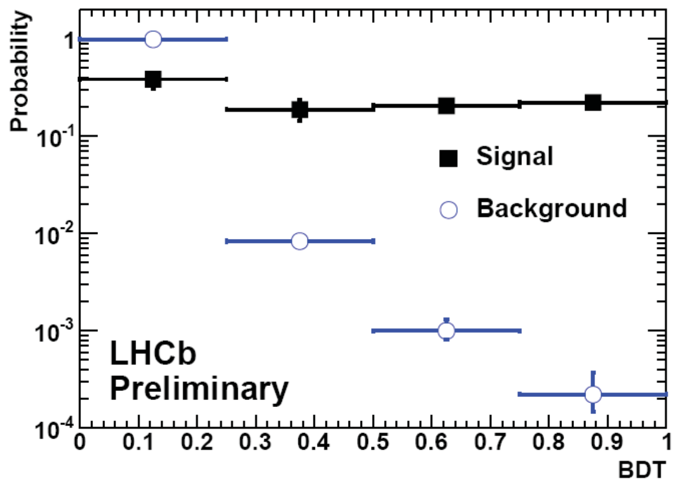


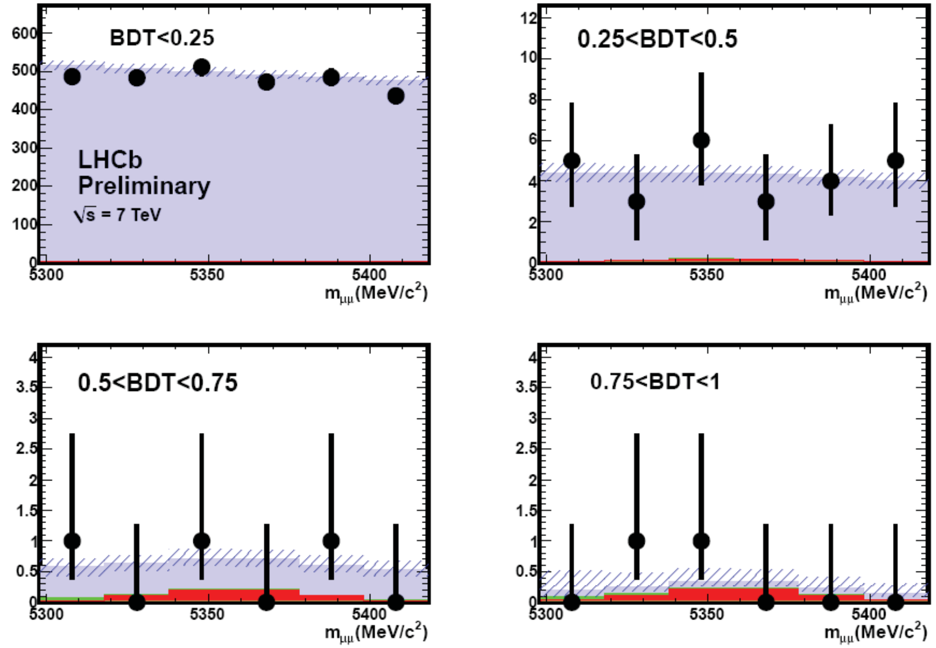
	BDT<0.25	0.25<BDT<0.5	0.5<BDT<0.75	0.75<BDT
Exp.combinatorial	3175 ± 72	26.6 ± 2.5	3.1 ± 0.8	0.7 ± 0.4
Exp. MisID	0.6± 0.1	0.6± 0.1	0.6± 0.1	0.6± 0.1
Observed	3025	31	5	4

BDT and mass distributions

4 bins in BDT output
120 MeV B mass search window divided into 6 bins

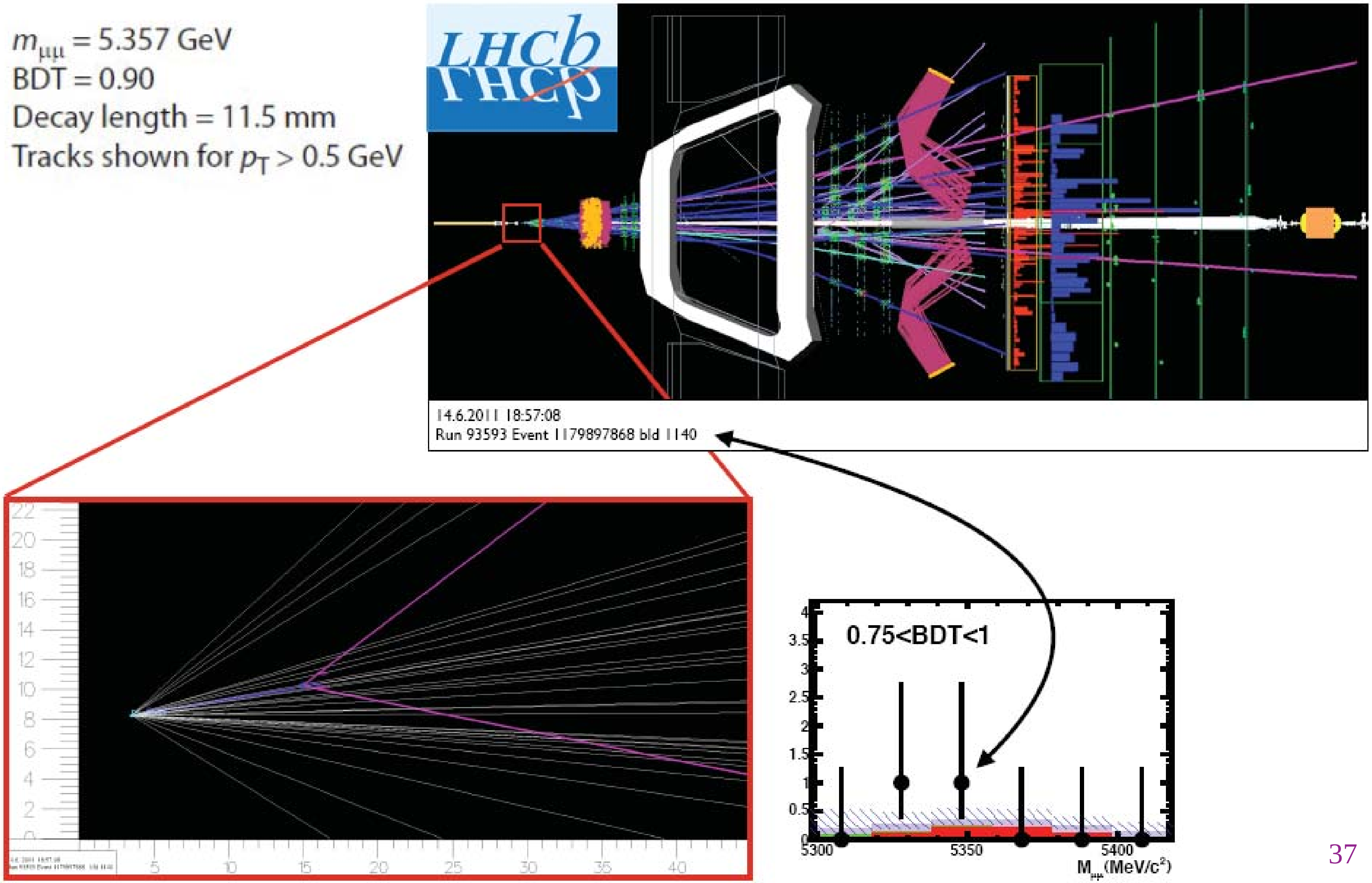
LHCb-CONF-2011-037





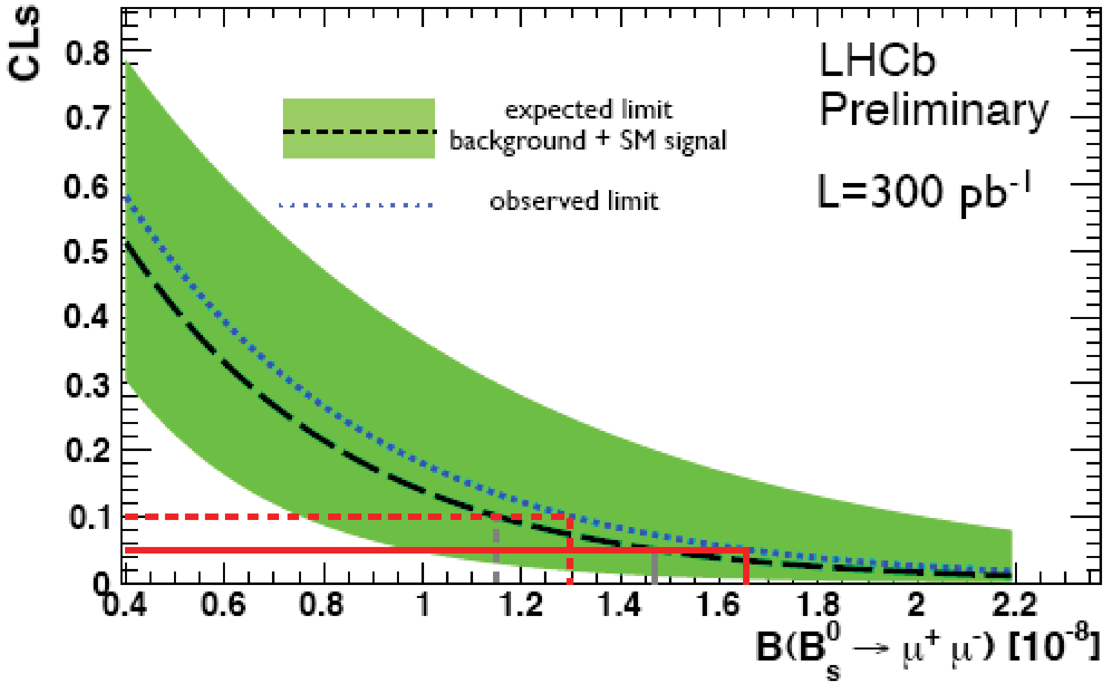
	BDT<0.25	0.25<BDT<0.5	0.5<BDT<0.75	0.75<BDT
Exp.combinatorial	3175 ± 72	26.6 ± 2.5	3.1 ± 0.8	0.7 ± 0.4
Exp. MisID	0.6± 0.1	0.6± 0.1	0.6± 0.1	0.6± 0.1
Observed	3025	31	5	4

LHCb: $B_s \rightarrow \mu^+\mu^-$?



LHCb limit of BR($B_s \to \mu^+\mu$)

LHCb-CONF-2011-037



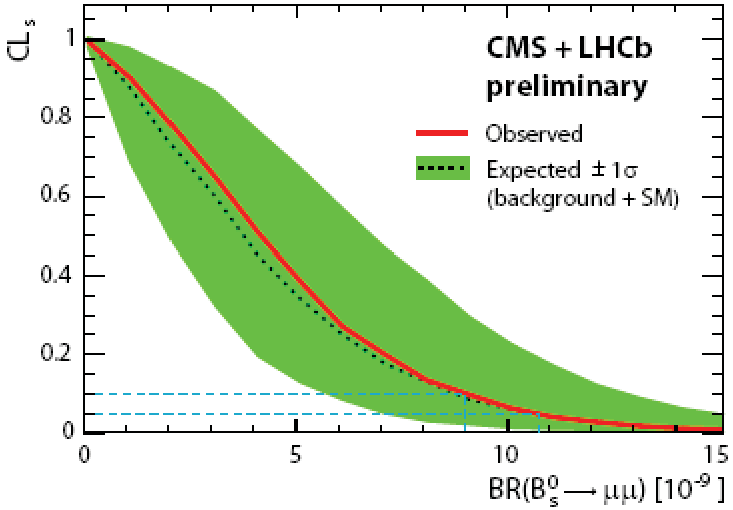
- **Expected limit: BR($B_s \to \mu^+\mu^-$) < 1.5 $\times 10^{-8}$ @ 95% C.L.**
- **Observed limit: BR($B_s \to \mu^+\mu^-$) < 1.6 $\times 10^{-8}$ @ 95% C.L.**
  - **Combined with 2010: < 1.5 $\times 10^{-8}$ @ 95% C.L.**

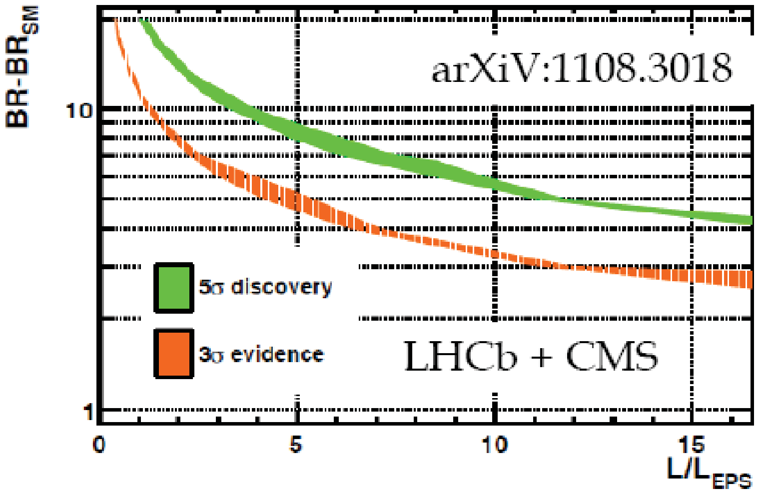
cf. CMS result using 1.14 fb^{-1} CMS -BPH-11-002

Expected limit < 1.8 $\times 10^{-8}$ @ 95% C.L.

Observed limit < 1.9 $\times 10^{-8}$ @ 95% C.L.

LHCb+CMS: combined limit





(L_{EPS} = 1.14 fb^{-1} CMS, 0.34 fb^{-1} LHCb)

LHCb-CONF-2011-047
CMS-PAS-BPH-11-019

Use $(f_s/f_d)_{LHCb} = 0.267^{+0.021}_{-0.020}$

$B(B_s \to \mu^+\mu^-) < 1.08 \times 10^{-8}$ 95% C.L.

p-value background only: 8%

p-value background + SM BR: 55%

95% C.L. limit is 3.4 times SM expected value.
There is plenty of room for new physics.

3σ NP signal can be observed by end of 7 TeV run if $BR(B_s \to \mu^+\mu^-) > 2\, BR(B_s \to \mu^+\mu^-)_{SM}$

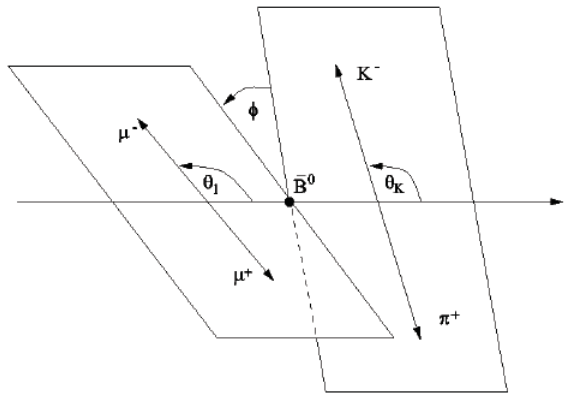
$B^0 \to K^*\mu^+\mu^-$

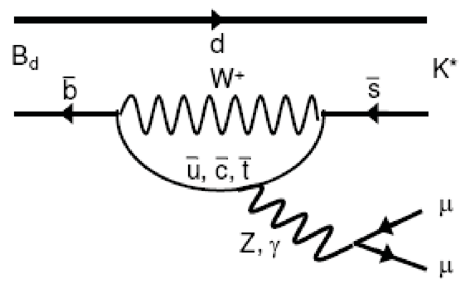
- FCNC $b \to s$ decays
- Sensitive to NP in loops: MSSM, LHT, …
- Described by three angles (θ_l, θ_K, ϕ) and $\mu^+\mu$ invariant mass q^2
- Many observables, particularly lepton forward-backward asymmetry A_{FB} vs q^2

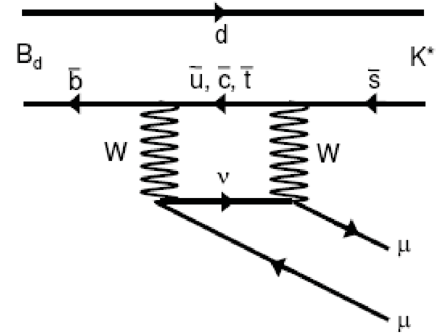
$$A_{\rm FB} = \left[\int_0^1 - \int_{-1}^0\right] d\cos\theta_l \frac{d^2(\Gamma - \bar{\Gamma})}{dq^2\, d\cos\theta_l} \Big/ \frac{d(\Gamma + \bar{\Gamma})}{dq^2} = \frac{3}{8}(2\, S_6^s + S_6^c)$$

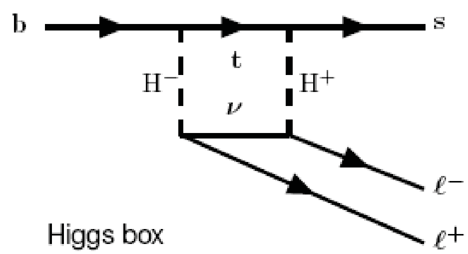
JHEP 0901:019,2009

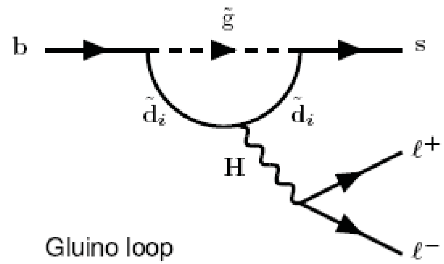
Observable	mostly affected by
S_1^s, S_1^c, S_2^s, S_2^c	C_7, C_7', C_9, C_9', C_{10}, C_{10}'
S_3	C_7', C_9', C_{10}'
S_4	C_7, C_7', C_{10}, C_{10}'
S_5	C_7, C_7', C_9, C_{10}'
S_6^s	C_7, C_9
A_7	C_7, C_7', C_{10}, C_{10}'
A_8	C_7, C_7', C_9, C_9', C_{10}'
A_9	C_7', C_9', C_{10}'
S_6^c	$C_S - C_S'$





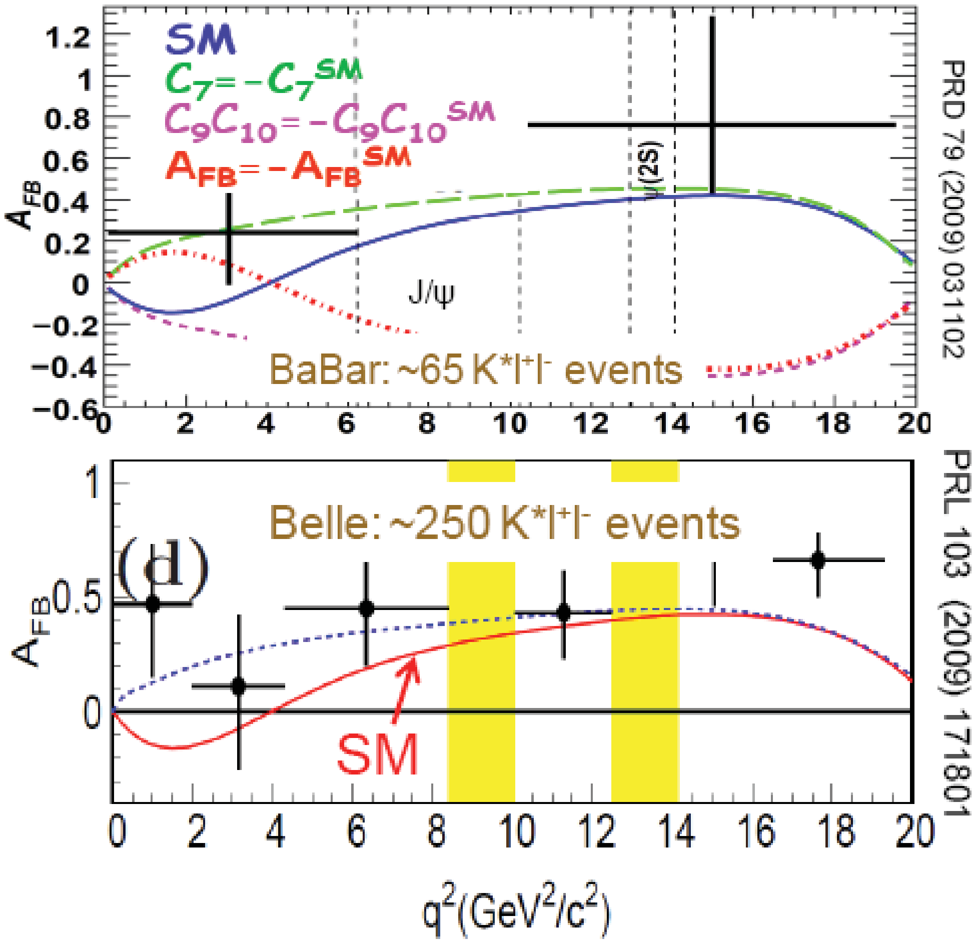


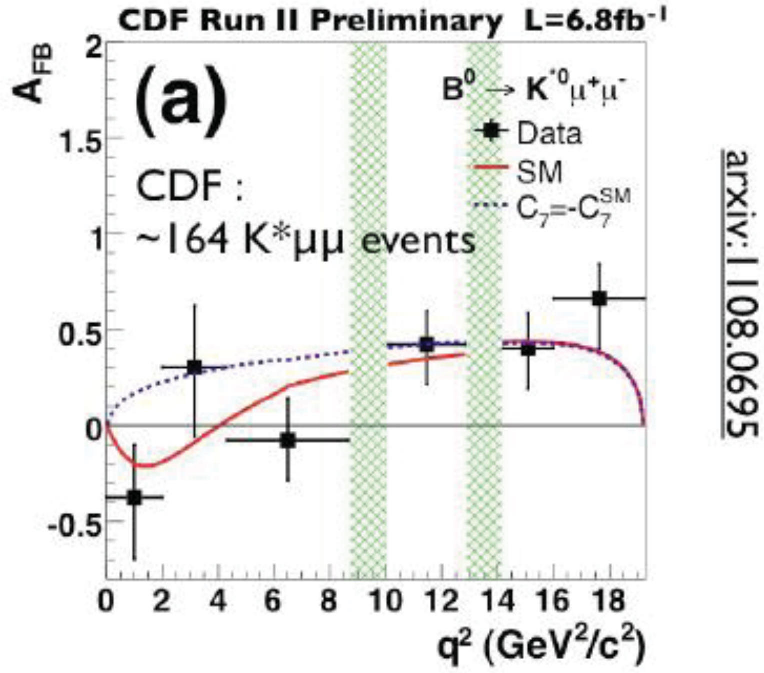




B factories and CDF results

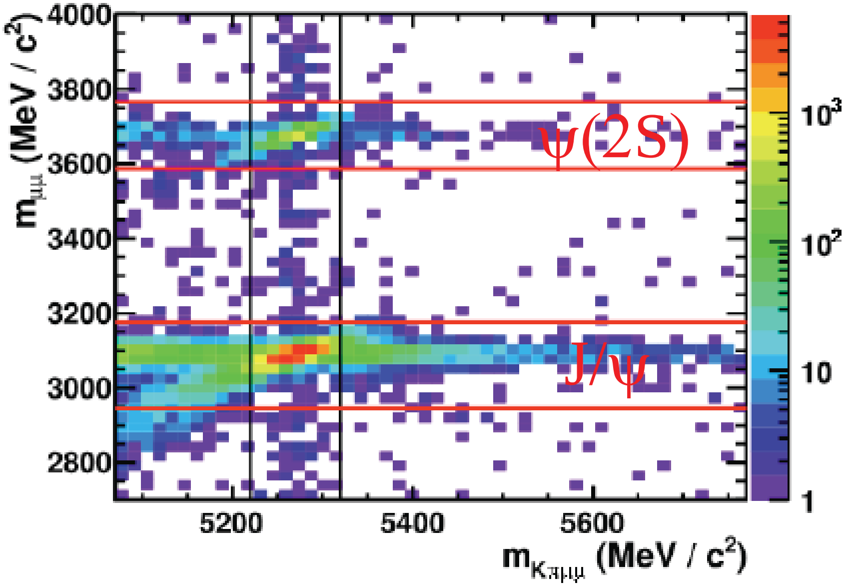
Intriguing behaviour with poor precision.

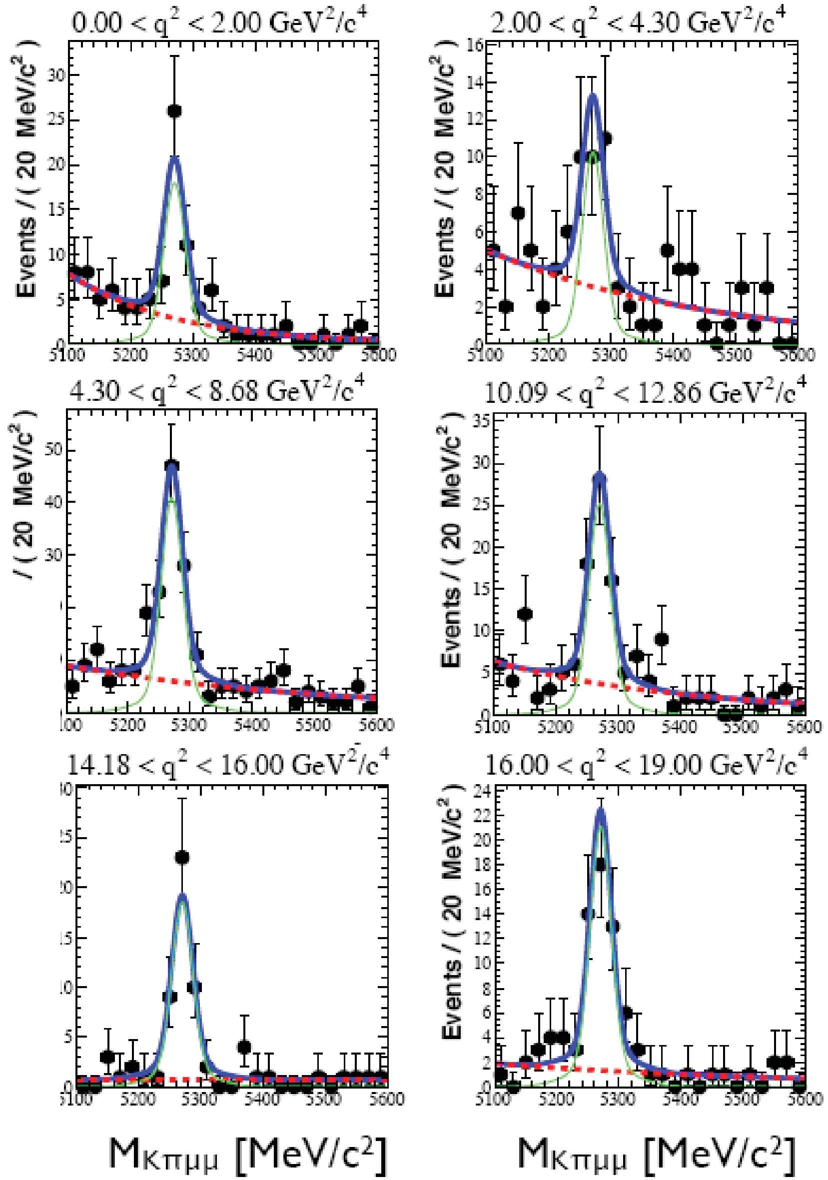




LHCb analysis

LHCb-CONF-2011-038





- Select 302±20 signals in 309 pb^{-1} using a Boosted Decision Tree
- Veto J/ψ and psi(2S)
- Perform angular fit in six bins of q^2 to measure
  - A_{FB}, longitudinal fraction F_L

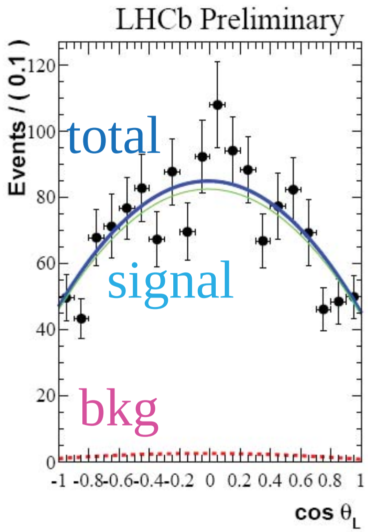
Angular fit

- Perform simultaneous fit of θ_l and θ_K

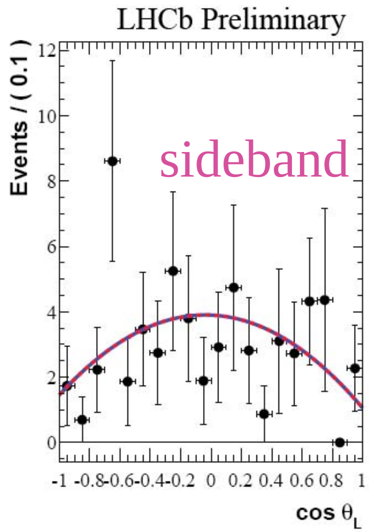
$$\frac{1}{\Gamma}\frac{\mathrm{d}^2\Gamma}{\mathrm{d}\cos\theta_K\,\mathrm{d}q^2} = \frac{3}{2}F_L\cos^2\theta_K + \frac{3}{4}(1-F_L)(1-\cos^2\theta_K)$$

$$\frac{1}{\Gamma}\frac{\mathrm{d}^2\Gamma}{\mathrm{d}\cos\theta_\ell\,\mathrm{d}q^2} = \frac{3}{4}F_L(1-\cos^2\theta_\ell) + \frac{3}{8}(1-F_L)(1+\cos^2\theta_\ell) + A_{FB}\cos\theta_\ell$$

- Angular efficiency from full MC simulation
- Fit procedure validated on $B^0 \rightarrow J/\psi K^*$ data and full MC
- Background angular parameterization obtained from B mass sidebands

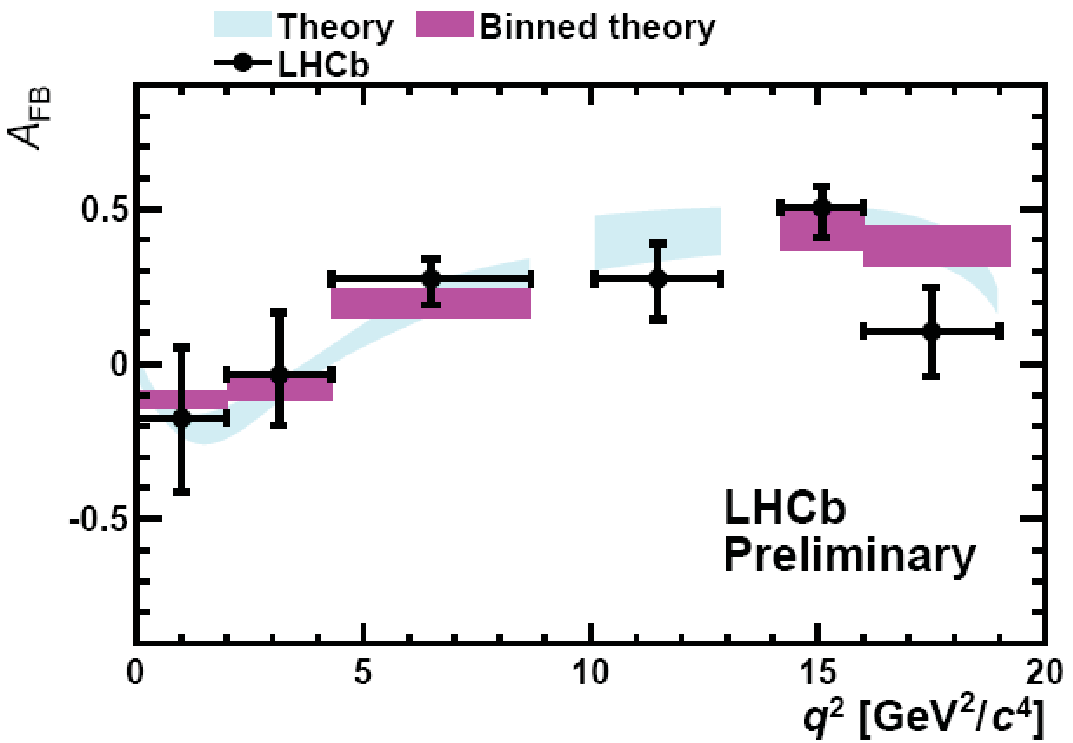


B mass signal window



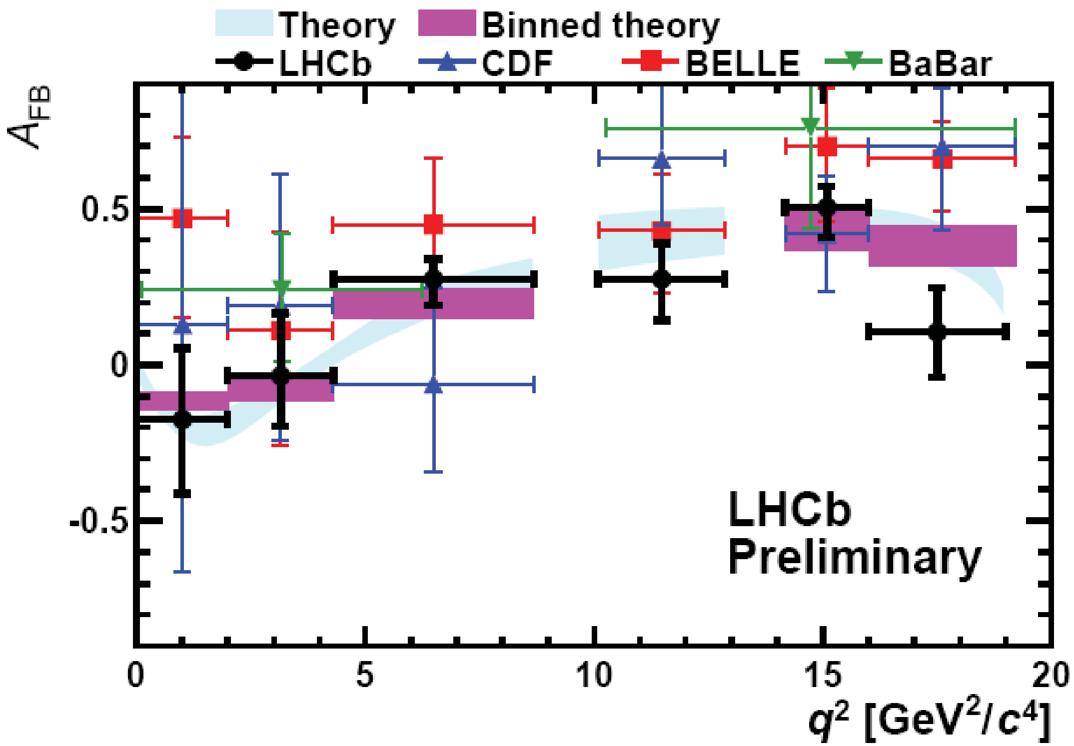
B mass sideband

LHCb results: A_{FB}



LHCb-CONF-2011-038

LHCb results: A_{FB}

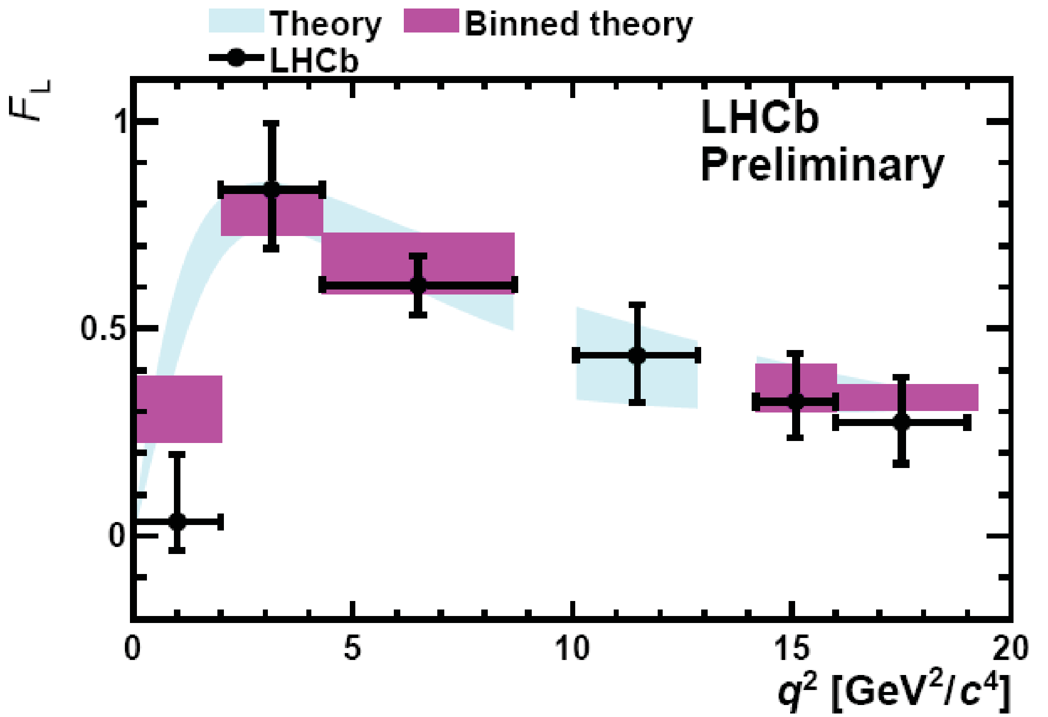


LHCb-CONF-2011-038

BaBar [PRD **79** (2009)], Belle [PRL **103** (2009)], CDF [PRL **106** (2011)]

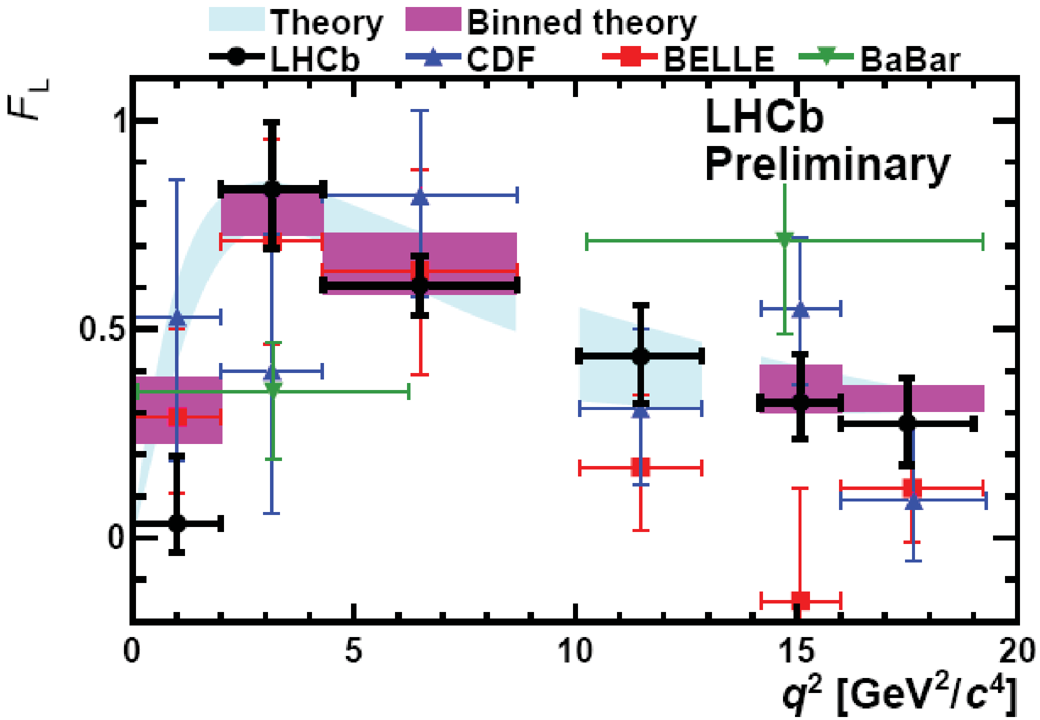
(not the latest CDF results)

LHCb results: F_L



LHCb-CONF-2011-038

LHCb results: F_L



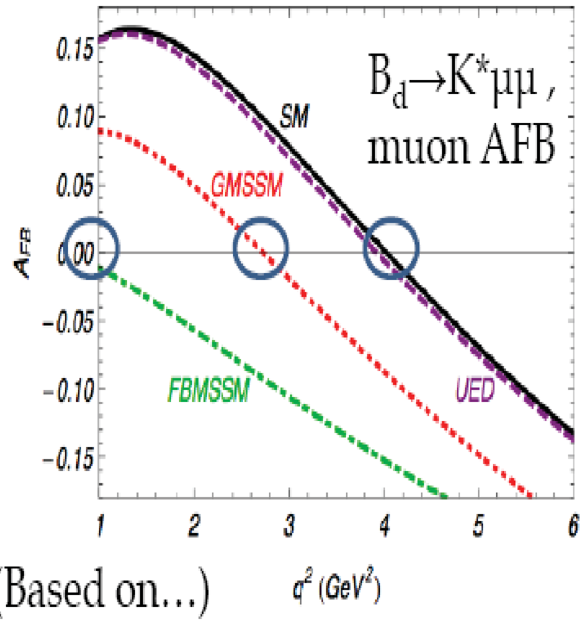
LHCb-CONF-2011-038

BaBar [PRD **79** (2009)], Belle [PRL **103** (2009)], CDF [PRL **106** (2011)]

(not the latest CDF results)

Prospects for $B^0 \to K^*\mu^+\mu^-$

- Data in good agreement with SM predictions at current precision
- Constraints on Wilson Coefficients will be studied
- Measure zero-crossing point, well predicted in SM, sensitive to NP
- Interesting to study other observables in full angular analysis
  - CP asymmetries
  - $A_T^{(2)}$,and $A_T^{(im)}$, sensitive to right handed currents (C_7')



(Based on...)

W.Altmannshofer et al. [JHEP 0901:019 (2009)]

$$\frac{d^2\Gamma(B \to K^*\ell^+\ell^-)}{dq^2 d\phi} = \frac{1}{2\pi}\frac{d\Gamma}{dq^2}\left[1 + \frac{1}{2}F_T(q^2)\left(A_T^{(2)}(q^2)\cos 2\phi + A_T^{(\mathrm{im})}(q^2)\sin 2\phi\right)\right]$$

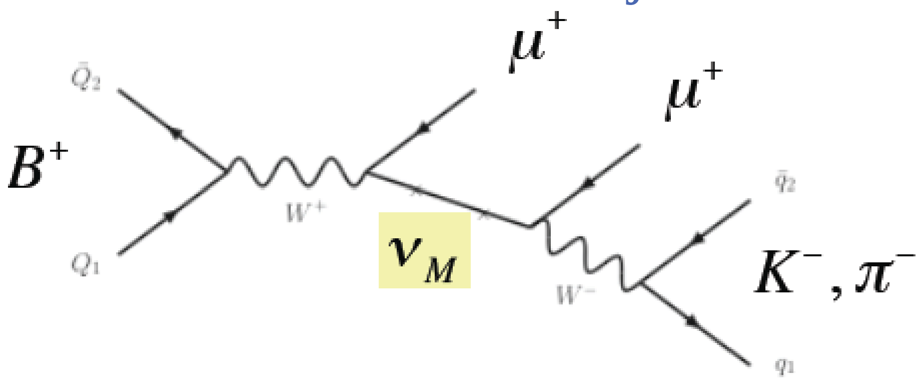
Lepton flavour violaiton

$B^+ \rightarrow h^- \mu^+ \mu^+$

Lepton flavour violation

Looking for $\Delta L=2$ processes $B^+ \rightarrow K^- \mu^+ \mu^+$ and $B^+ \rightarrow \pi^- \mu^+ \mu^+$

- Forbidden in the SM
- Allowed in NP models with a Majorana neutrio



No signal observed in 36 pb^{-1}

$$\mathcal{B}(B^+ \rightarrow K^- \mu^+ \mu^+) < 5.4 \times 10^{-8} \text{ at 95\% CL},$$

$$\mathcal{B}(B^+ \rightarrow \pi^- \mu^+ \mu^+) < 5.8 \times 10^{-8} \text{ at 95\% CL}.$$

Improved present best limits by a factor of 40 (30).

Publication in preparation.

Results not covered today

- Search for new physics in $B \to hh$ decays
  - Direct CP violation in $B \to K\pi$
  - Measurement of $B_s \to K^+K^-$ effective lifetime
- Measurements of CP violation in charm system

$A_{CP}(KK) - A_{CP}(\pi\pi)$

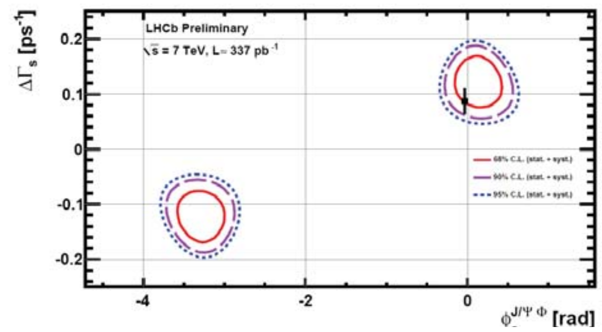
$$y_{CP} \equiv \frac{\hat{\Gamma}(K^-K^+)}{\hat{\Gamma}(K^-\pi^+)} - 1 = \frac{\tau(K^-\pi^+)}{\tau(K^-K^+)} - 1$$

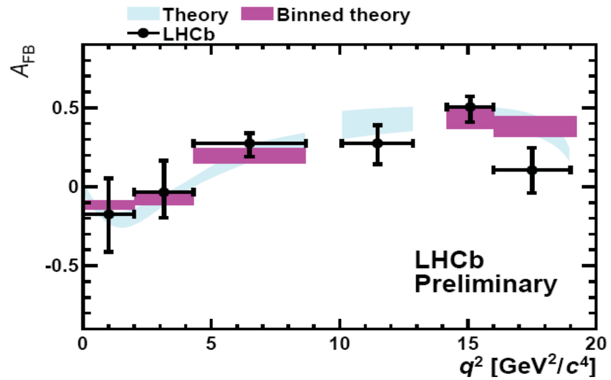
$$A_\Gamma = \frac{\tau(\bar{D}^0 \to K^-K^+) - \tau(D^0 \to K^-K^+)}{\tau(\bar{D}^0 \to K^-K^+) + \tau(D^0 \to K^-K^+)}$$

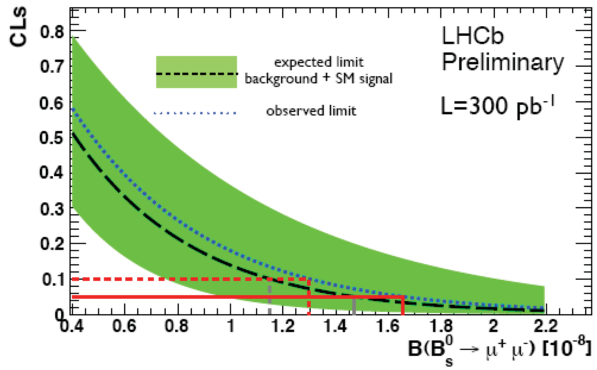
- Measurements of γ for precision test of the SM
  - Evidence for suppressed ADS mode of $B \to DK$,
  - $BR(B_s \to D_s K)$
- Search for exotics
- And more

Conclusions and prospects

- LHCb has achieved excellent results in search of new physics
- Elusive new physics is still hiding in quantum haystack
- The quest for new physics at LHCb is just beginning and will continue
  - at higher precision
  - in broader scope of search
  - with better understanding of the detector







Backup

$B_s \to J/\psi\phi$ fit results and systematics

Parameter	Value	Stat.	Syst.
Γ_s [ps^{-1}]	0.656	0.008	0.008
$\Delta\Gamma_s$ [ps^{-1}]	0.123	0.029	0.008
$\lvert A_\perp(0)\rvert^2$	0.238	0.015	0.011
$\lvert A_0(0)\rvert^2$	0.497	0.013	0.031
$\lvert A_s(0)\rvert^2$	0.041	0.016	0.019
$\delta_\perp$ [rad]	2.94	0.37	0.12
δ_s [rad]	3.00	0.36	0.12
$\phi_s^{J/\psi\phi}$[rad]	0.13	0.18	0.07

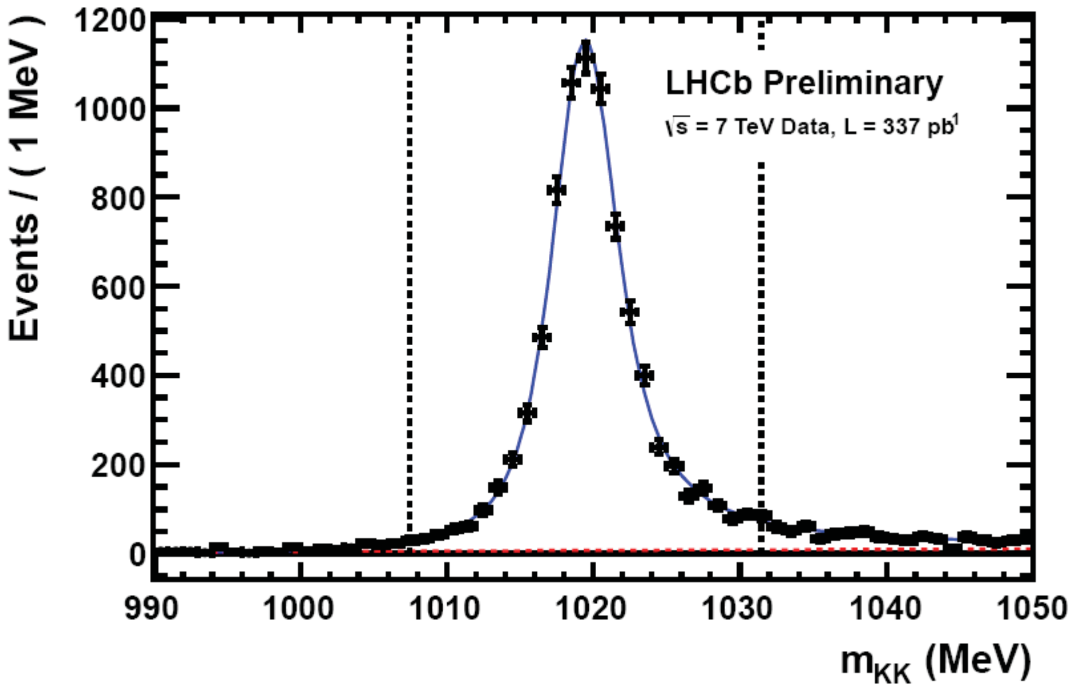
Plus ambiguous solution.

Most errors are dominated by statistical uncertainties. (Situation may change soon)

systematics Source	$\phi_s^{J/\psi\phi}$[rad]	$\Delta\Gamma_s$ [ps^{-1}]
Description of background	0.06	0.004
Angular acceptances	0.003-0.0043	0.003-0.008
z and momentum scale	–	0.002
Production asymmetry ($\pm$ 10%)	< 0.01	< 0.001
CPV in mixing & decay ($\pm$ 5%)	< 0.03	< 0.006
Quadratic sum	0.07 – 0.08	0.008 – 0.011

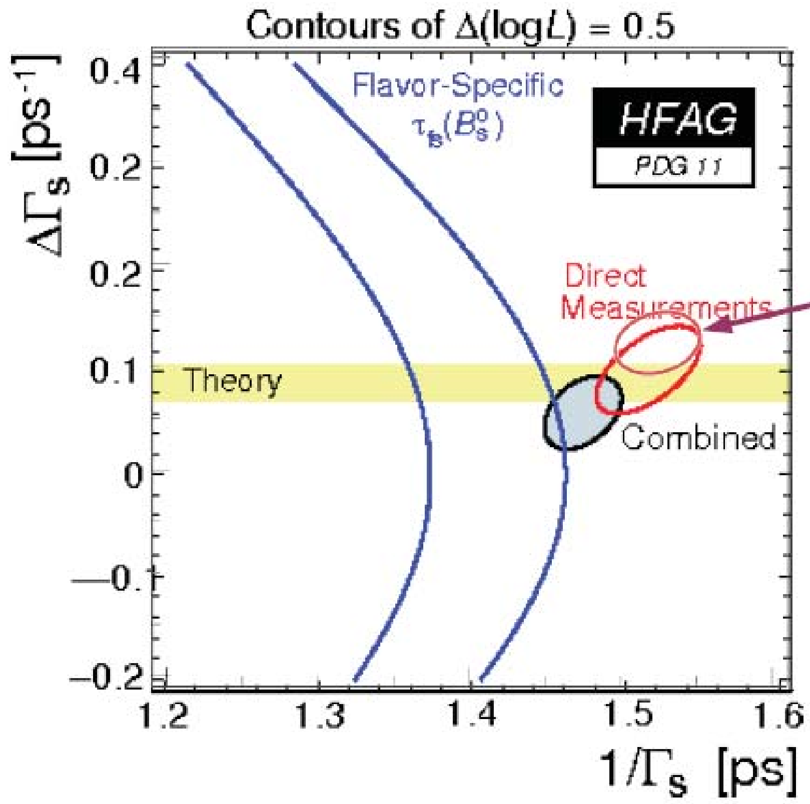
KK S-wave fraction

- S-wave fraction 4.1 ± 1.6 (stat) ± 1.9 (sys) % from angular fit.



$\Delta\Gamma_s$

- J/psi phi analysis also gives most precise single measurement of Γ_s and $\Delta\Gamma_s$



LHCb in J/psi phi (341/pb)

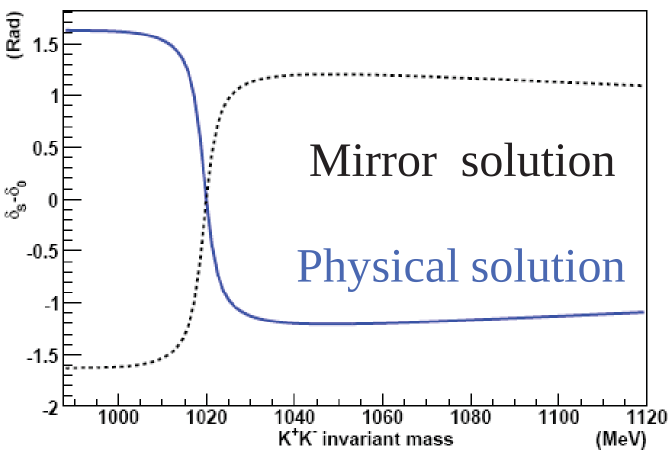
$$\tau(B_s^0)_{\rm fs} = \frac{1}{\Gamma_s} \frac{1+\left(\frac{\Delta\Gamma_s}{2\Gamma_s}\right)^2}{1-\left(\frac{\Delta\Gamma_s}{2\Gamma_s}\right)^2}$$

slight inconsistency in Γ between direct measurement and measurement with flavour specific decays?

(slide by Wouter Hulsbergen)

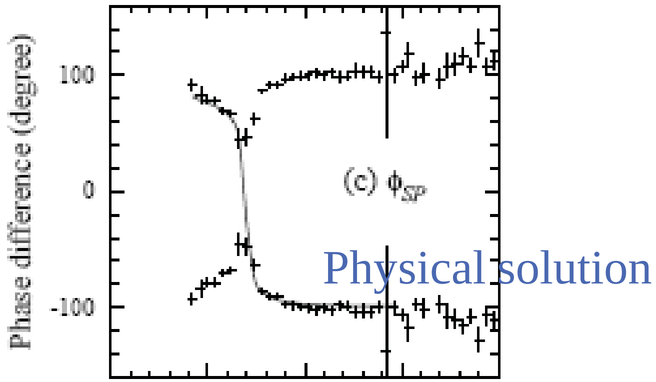
ϕ_s ambiguity removal

- Work is ongoing to remove the 2-fold ambiguity.
- Measure δ_{S0} vs m_{KK} in $B_s \to J/\psi K^+K^-$ [Y. Xie *et al.*, JHEP 0909:074,2009]
- Choose the one with falling trend at $\phi(1020)$ mass
- Similar to the way Babar measured sign of $\cos 2\beta$ in $B \to J/\psi K\pi$ [Babar, PRD 72:032005, 2007]



Simulated δ_S-δ_P phase variation

Babar, Phys.Rev.D83:052001, 2011



δ_S-δ_P phase variations measured in $D_s \to K^+K^-\pi$ by Babar .

Question to theorists: in our quantitative assessment, can we assume exactly the same variation in $D_s \to K^+K^-\pi$ and $B_s \to J/\psi K^+K^-$?

b→ccd decays

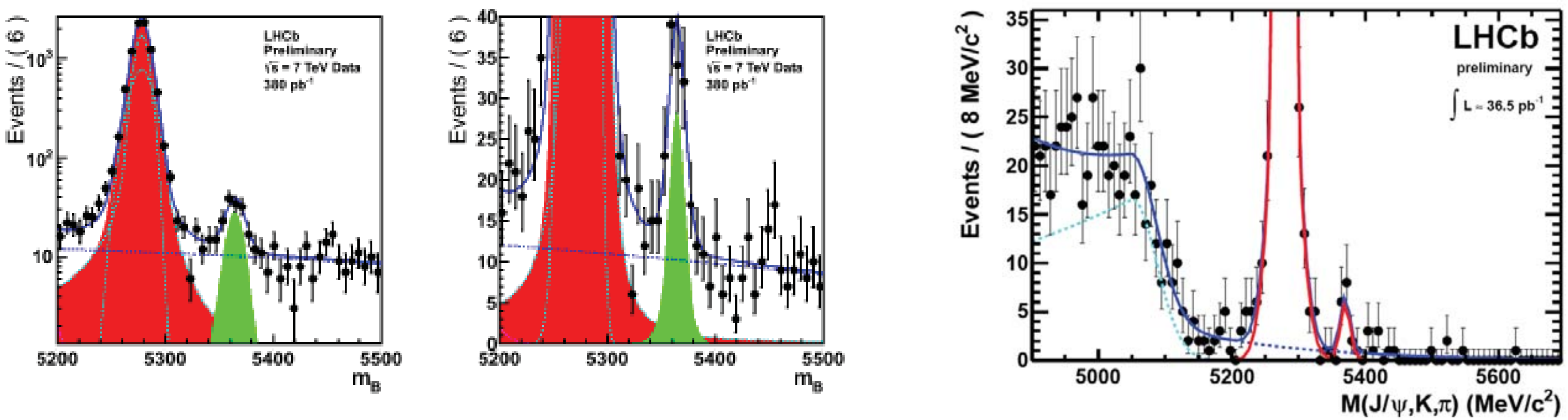
LHCb-CONF-2011-025

$$\mathcal{B}(B_s^0 \to J/\psi \overline{K}^{*0}) = (3.5^{+1.1}_{-1.0}(stat.) \pm 0.9(syst.)) \times 10^{-5}$$

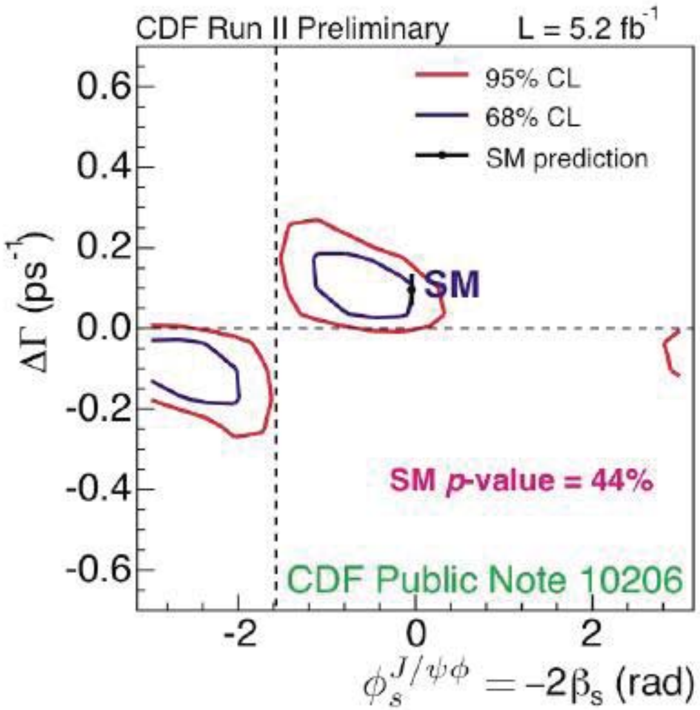
LHCb-CONF-2011-048

$$\frac{B(B_s \to J/\psi K_s)}{B(B_d \to J/\psi K_s)} = 0.0378 \pm 0.0058\,(\text{stat.}) \pm 0.0020\,(\text{syst.}) \pm 0.003\left(\text{f}_\text{s}/\text{f}_\text{d}\right)$$

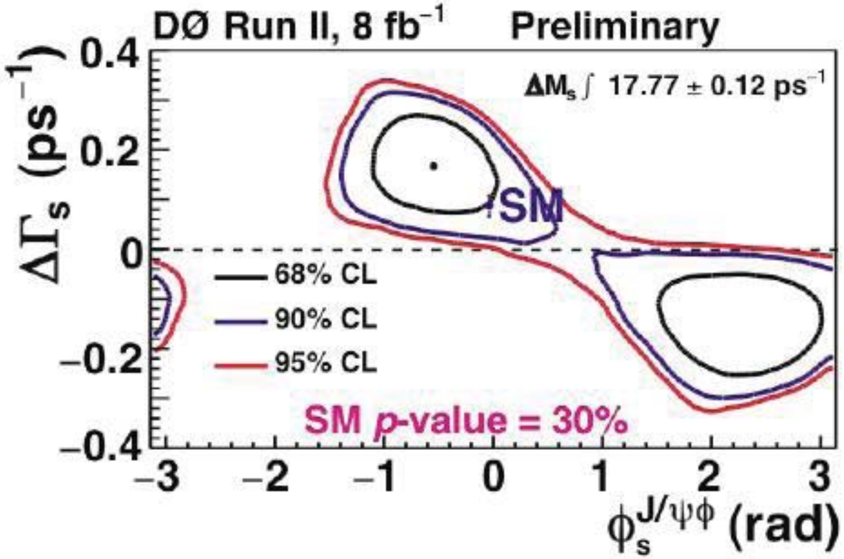
$$CDF:\ 0.0405 \pm 0.0070\,(\text{stat.}) \pm 0.0041\,(\text{syst.}) \pm 0.005\left(\text{f}_\text{s}/\text{f}_\text{d}\right)$$

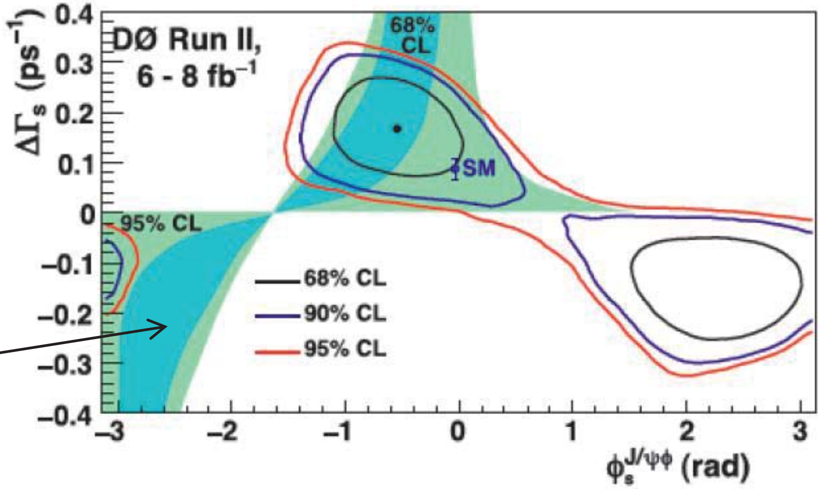


ϕ_s from CDF and D0



D0, arXiv:1109.3166

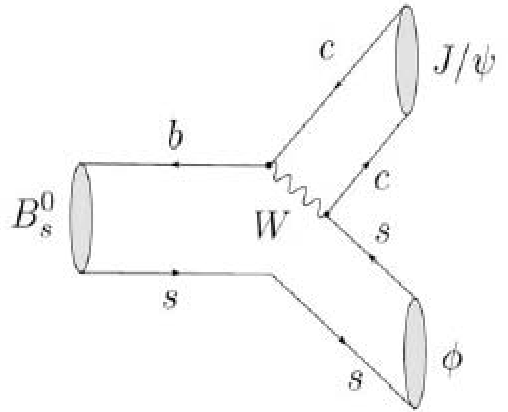


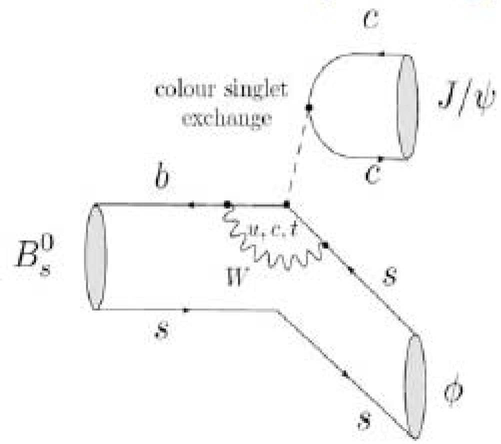


D0 A^{b}_{fs}

Penguin pollution in $B_s \to J/\psi\phi$

- In the SM, $B_s \to J/\psi\phi$ decay is dominated by a single weak phase: $V_{cs}V_{cb}^*$





$$A(\overline{b} \to \overline{c}c\overline{s}) = V_{cs}V_{cb}^*(A_T + P_c) + V_{us}V_{ub}^* P_u + V_{ts}V_{tb}^* P_t$$
$$= V_{cs}V_{cb}^*(A_T + P_c - P_t) + V_{us}V_{ub}^*(P_u - P_t)$$

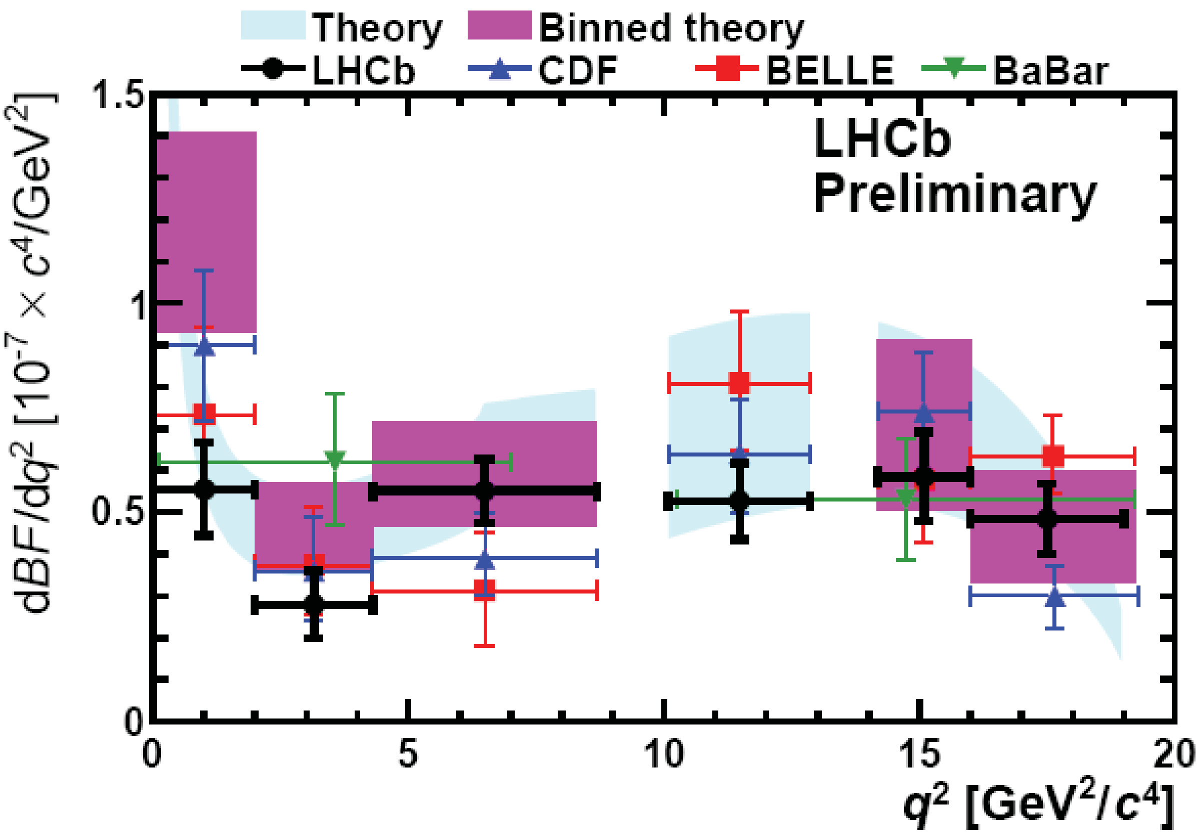
$V_{ts}V_{tb}^* = -V_{us}V_{ub}^* - V_{cs}V_{cb}^*$

$\sim A\lambda^2(1 - \lambda^2/2)$

$\sim A\lambda^4(\rho + i\eta)$

- Various penguin pollution estimates:
  - $\delta P \sim 10^{-4}$ [H. Boos et al., Phys.Rev. D70 (2004) 036006]
  - $\delta P \sim 10^{-3}$ [M. Gronau et al., arXiv:0812.4796]
  - δP up to ~0.1 [S. Faller et al., arXiv:0810.4248v1]

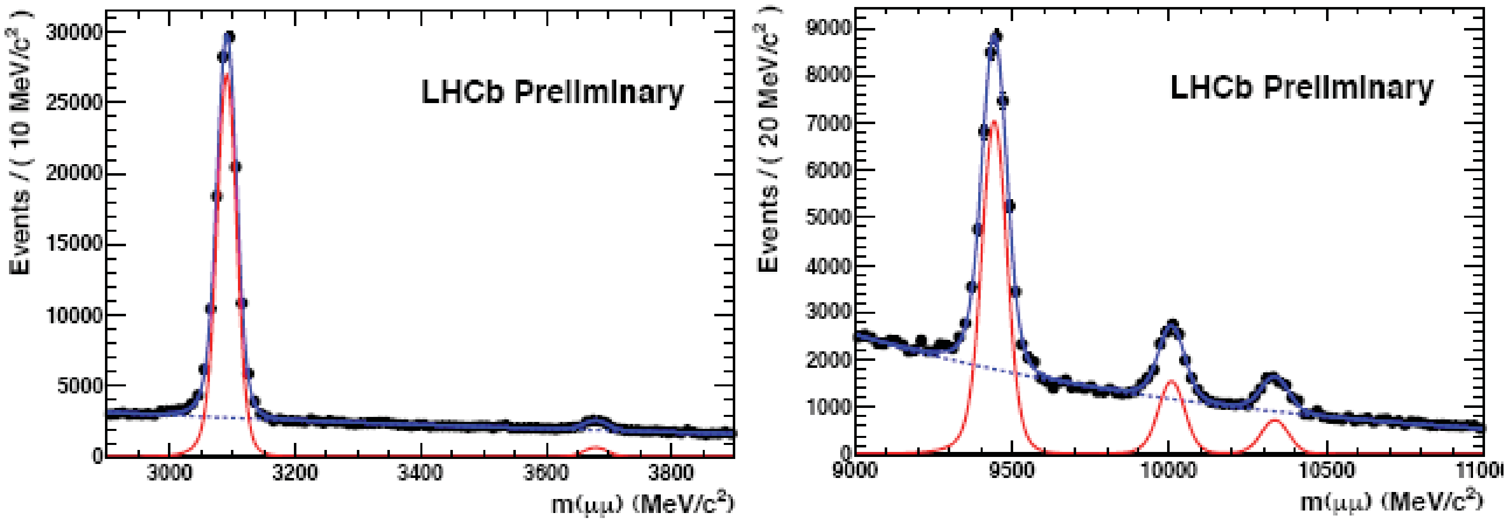
LHCb results: BR



LHCb-CONF-2011-038

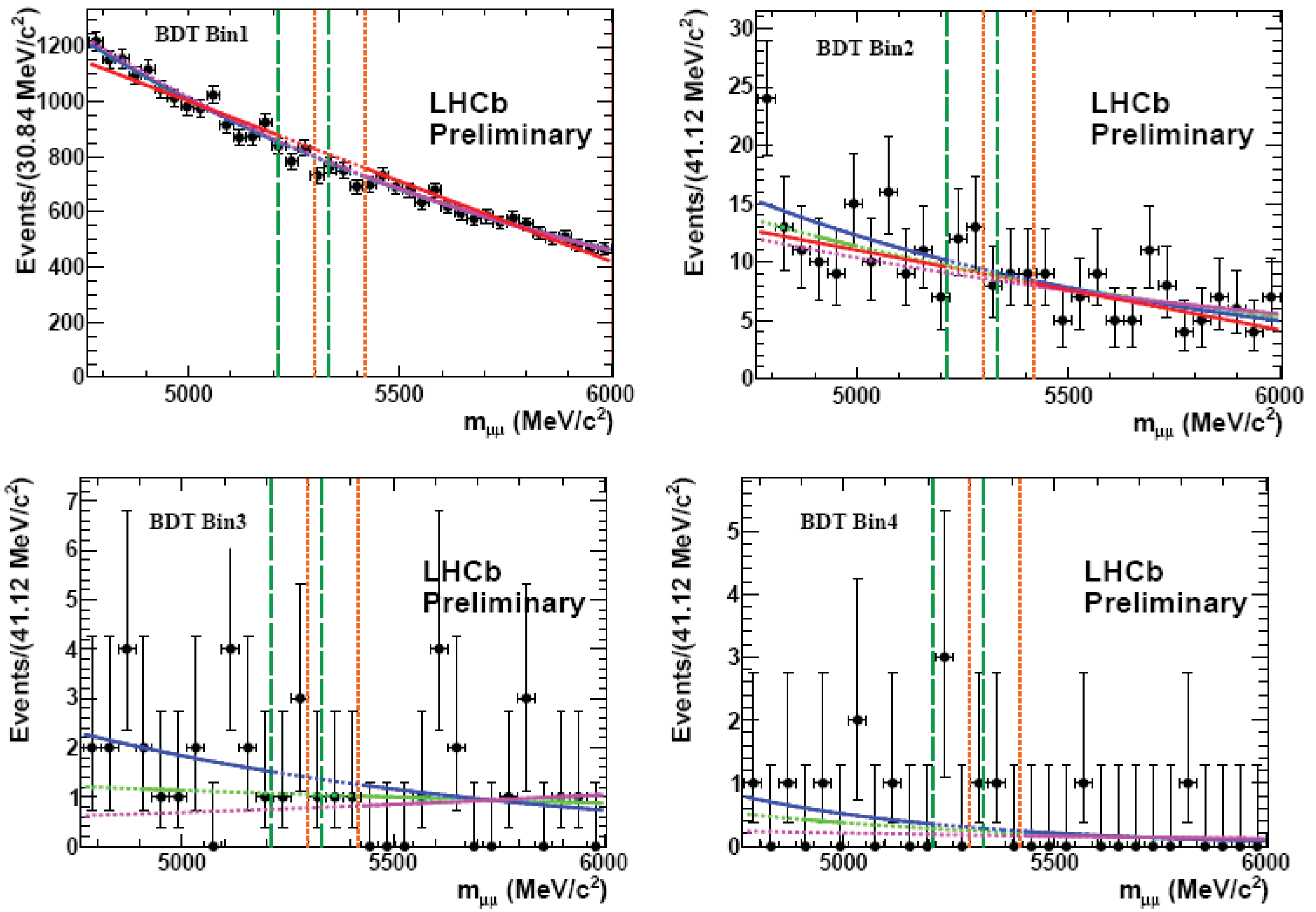
BaBar [PRD **79** (2009)], Belle [PRL **103** (2009)], CDF [PRL **106** (2011)]

$B_s \rightarrow \mu^+\mu^-$ mass shape



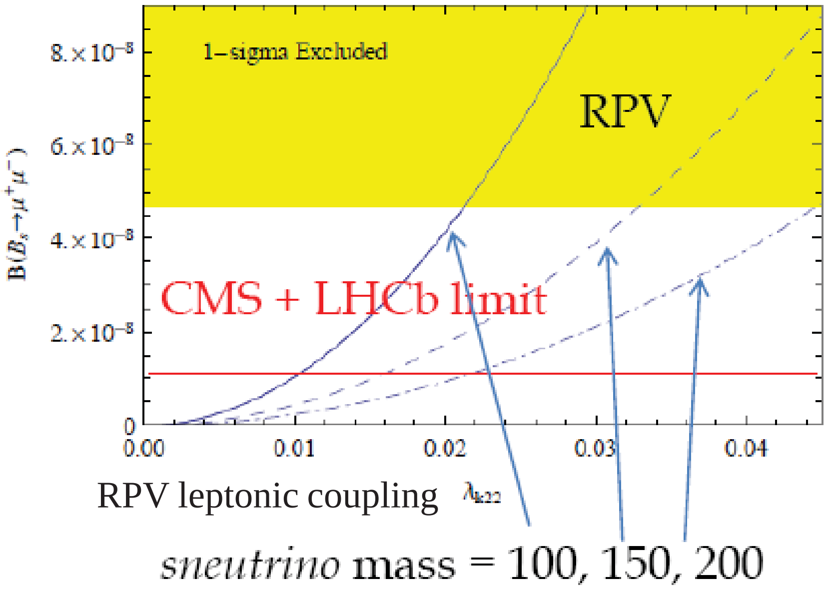
- Mass resolution obtained by interpolation between $J/\psi \rightarrow \mu\mu$, $\Upsilon(1S) \rightarrow \mu\mu$, shape verified using $B^0 \rightarrow K\pi$, $B_s \rightarrow KK$

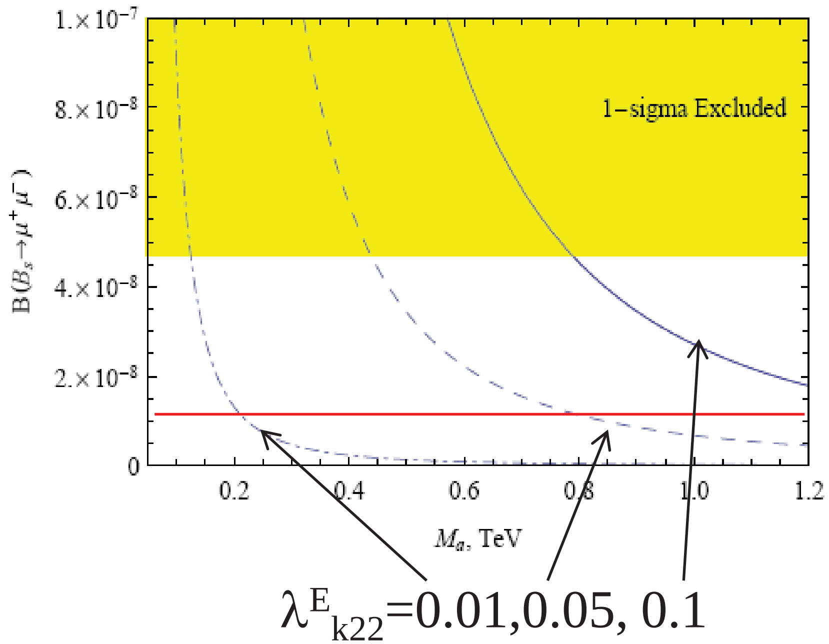
$B_s \to \mu^+\mu^-$ background mass shape



Background in B mass search window from fit including data sidebands

Implications: R-parity violating SUSY



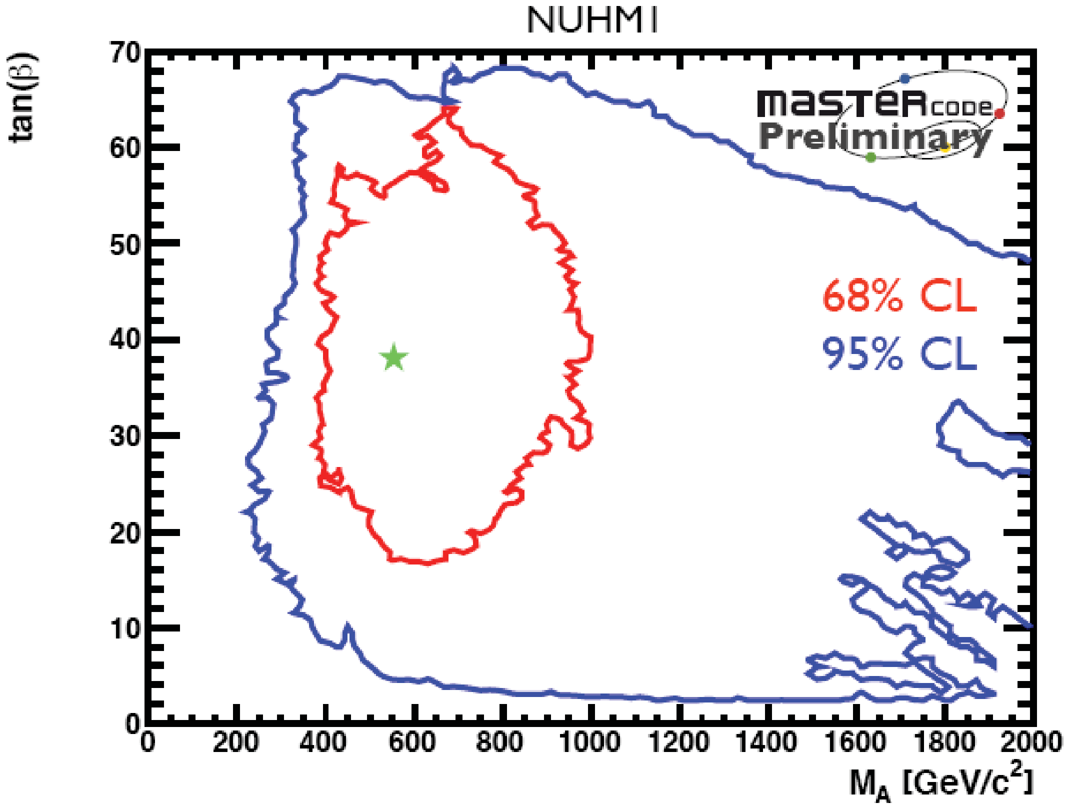


- Strong constraints on NP parameters

[E. Golowich *et al*., arXiv: 1102.0009]

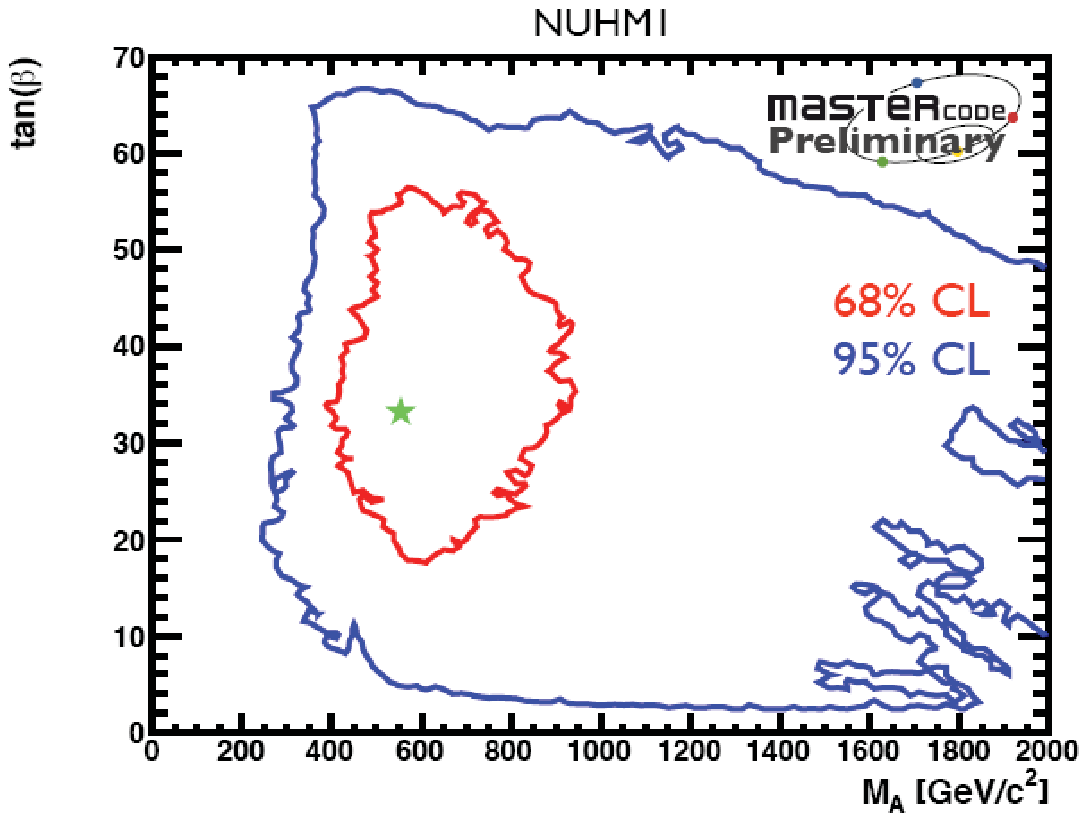
Implication on heavy Higgs search

- LHC 2011 MET searches only



Implication on heavy Higgs search

- LHC 2011 MET searches and $B_s \to \mu\mu$



LHCb and upgrade

- Phase-I: ~5 fb^{-1} at 7 TeV before the 2^{nd} LHC shutdown 2017
- Phase-II: ~50 fb^{-1} at 14 TeV

LHCb Particle ID performance