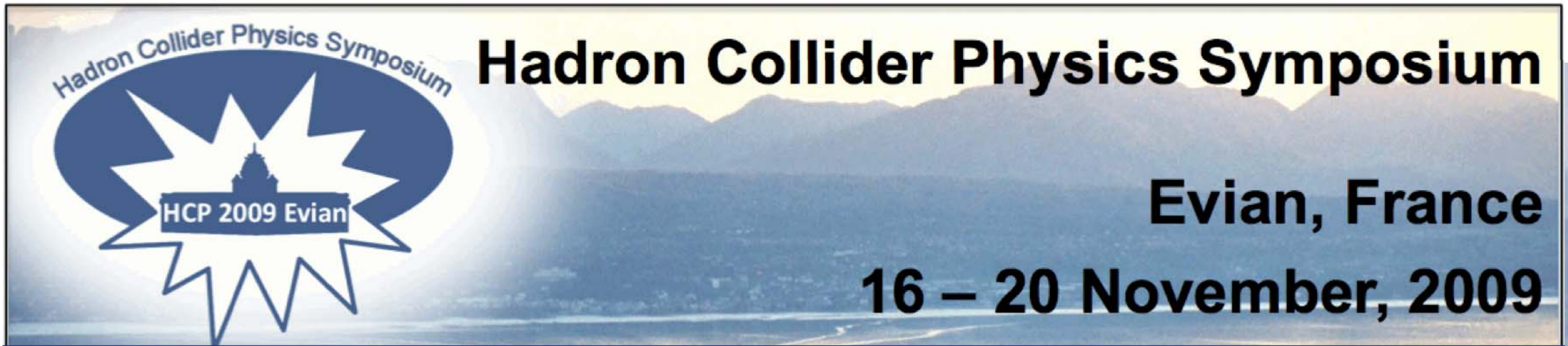
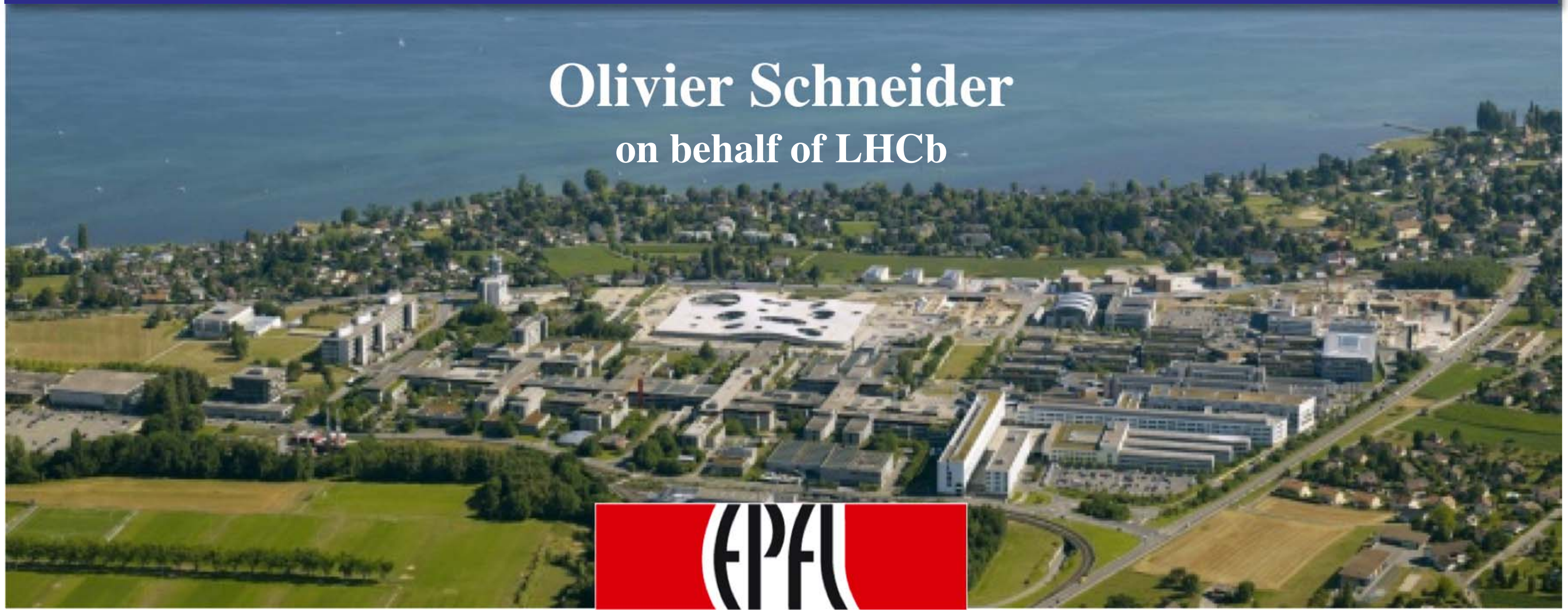


Hadron Collider Physics Symposium
Evian, France
16 – 20 November, 2009

Indirect New Physics searches with B decays at the LHC

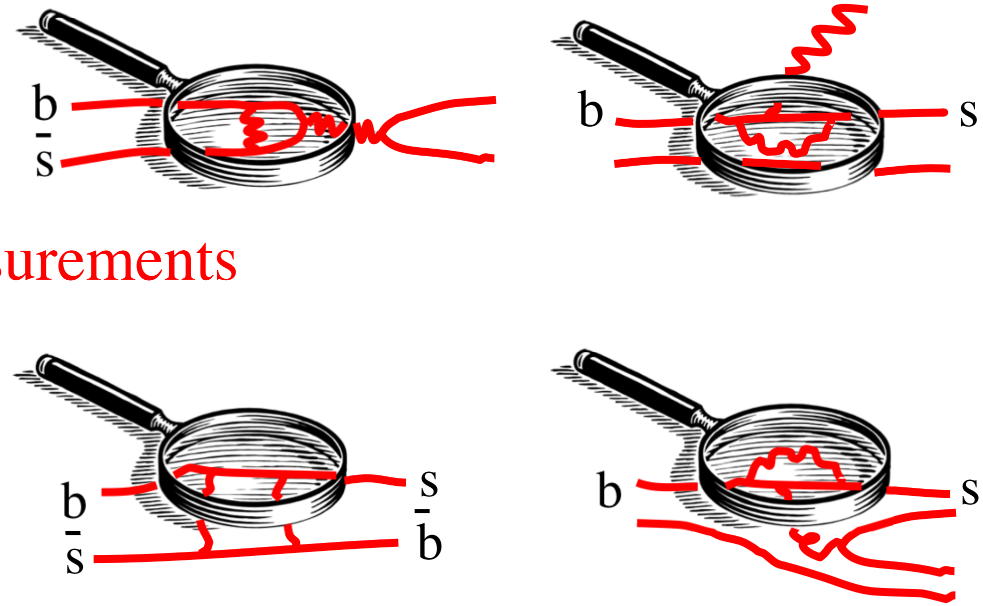


Olivier Schneider
on behalf of LHCb

ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

Indirect New Physics searches with B decays at the LHC

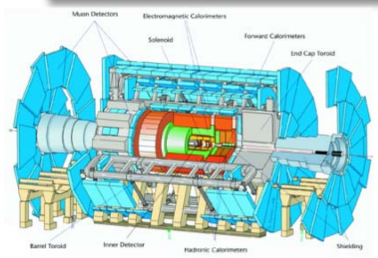
- Introduction
  - Motivation and strategy for New Physics searches with B decays
  - B physics at LHC
- Promising rare decay measurements
  - $B_s \to \mu\mu$
  - $B^0 \to K^* l^+ l^-$
  - $B_s \to \phi\gamma$
- Promising CP violation measurements
  - $B_s \to J/\psi\phi$
  - $B_s \to \phi\phi$
- Summary

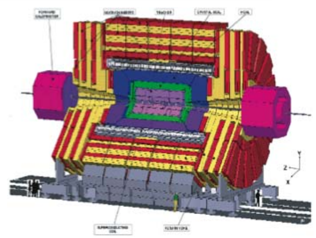


Two approaches to New Physics search

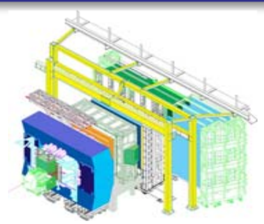
- New Physics (NP) models introduce new particles at the TeV scale or above, which could
  - be produced and observed directly as **real particles** with specific signatures
  - appear as **virtual particles in loop processes**, leading to observable deviations from the pure Standard Model expectations

Direct searches
(mostly ATLAS & CMS)





Indirect searches
(mostly LHCb)



- At LHC:
  - TeV scale accessible
  - **"direct" and "indirect" approaches are complementary**

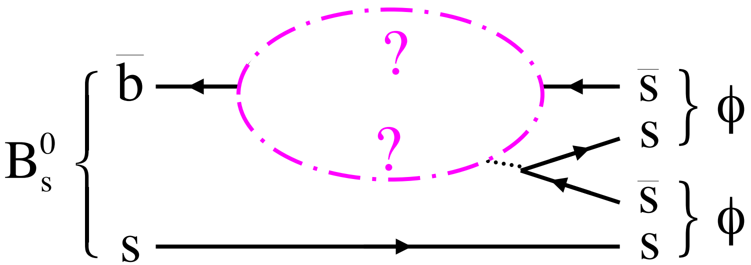
Strengths of indirect approach

- Can in principle access higher scales and therefore see effect earlier:
  - Third quark family inferred by Kobayashi and Maskawa (1973) to explain small CP violation measured in kaon mixing (1964), but only directly observed in 1977 (b) and1995 (t)
  - Neutral currents (ν+N→ ν+N) discovered in 1973, but real Z discovered in 1983
- Can in principle access the phases of the new couplings:
  - NP at TeV scale needs to have a "flavour structure" to provide the suppression mechanism for already observed FCNC processes → once NP is discovered, it is important to measure this structure (including new phases)

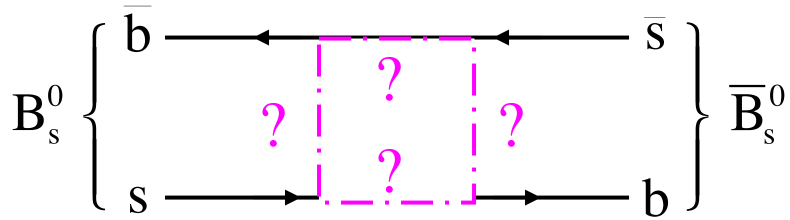
New Physics

$\Delta m_s \neq \Delta m_s^{SM} \propto |V_{ts}^2|$,

$\phi_s \neq \phi_s^{SM} = -\arg(V_{ts}^2) = 2\beta_s$



$B_s \rightarrow \phi\phi$ decay: "Penguin" diagram



B_s–$\bar{B}_s$ oscillations: "Box" diagram

Strategies for indirect NP search in B physics

- Measure FCNC transitions where New Physics is more likely to emerge, especially in b→s transitions which are less constrained by current data
  - OPE expansion:

$$H_{eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i [\underbrace{C_i(\mu) O_i(\mu)}_{\text{left-handed part}} + \underbrace{C_i'(\mu) O_i'(\mu)}_{\text{right-handed part suppressed in SM}}]$$

$i = 1,2$	Tree
$i = 3-6,8$	Gluon penguin
$i = 7$	Photon penguin
$i = 9,10$	Electroweak penguin
$i = S$	Higgs (scalar) penguin
$i = P$	Pseudoscalar penguin

  - New Physics may
    - modify $C_i^{(\prime)}$ short-distance Wilson coefficients
    - add new long-distance operators $O_i^{(\prime)}$

Single B decay measurements with NP discovery potential

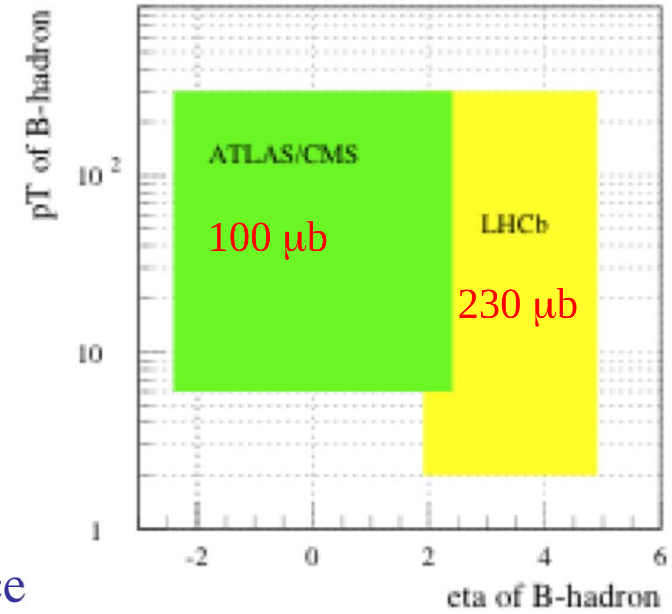
- Improve measurement precision of CKM elements
  - Compare measurements of same quantity, which may or may not be sensitive to NP
  - Extract all CKM angles and sides in many different ways
    - any inconsistency will be a sign of New Physics

Precision CKM metrology, including NP-free determinations of CKM angle γ

B acceptance at LHC

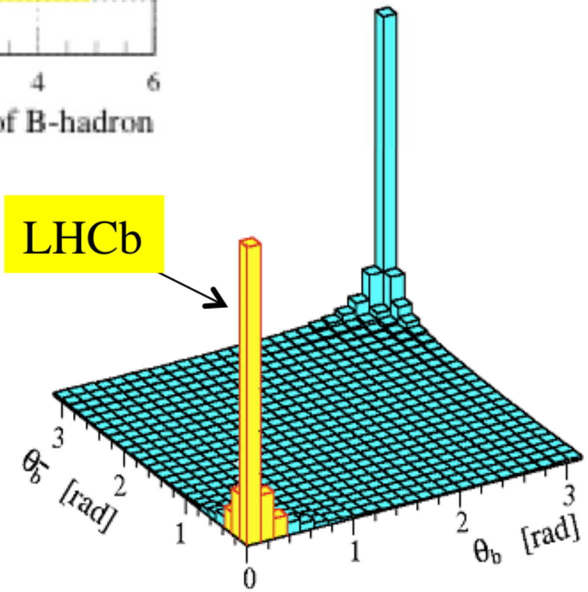
- **ATLAS/CMS:**
  - central detectors, |η|<2.5
  - B physics using high-p_T muon triggers, mostly with modes involving dimuon

$b\bar{b}$ production cross section at $\sqrt{s}$=14 TeV



Pythia predictions

$b\bar{b}$ correlation



- **LHCb:**
  - designed to maximize B acceptance (within cost and space constraints)
  - forward spectrometer, 1.9 < η < 4.9
    - more b hadrons produced at low angles
    - single arm OK since $b\bar{b}$ pairs produced correlated in space
  - rely on much softer, lower p_T triggers
  - efficient also for purely hadronic B decays

Luminosity and pileup at LHC

- **Pileup:**
  - inelastic pp interactions in a bunch crossing are Poisson-distributed with mean $n = L\sigma_{inel}/f$

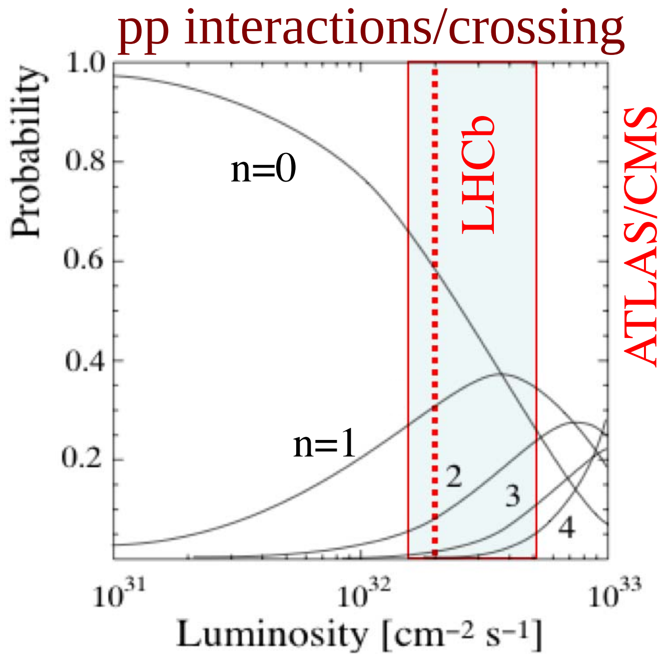
L = instantaneous luminosity
f = non-empty bunch crossing rate
$\sigma_{inel} = 80$ mb at $\sqrt{s}$ of 14 TeV

- **ATLAS/CMS** (f = 32 MHz)
  - Expect $L < 2\times10^{33}$ cm^{-2}s^{-1} ($n < 5$) for initial phase
  - At $L = 10^{34}$ cm^{-2}s^{-1} ($n = 25$), only $B\to\mu\mu$ still possible

10 fb^{-1} / year (10^7 s)
30 fb^{-1} total at low L

- **LHCb** (f = 30 MHz)
  - Baseline <L> ~ 2×10^{32} cm^{-2}s^{-1} ($n = 0.5$) expected very quickly

2 fb^{-1} / year (10^7 s)
10 fb^{-1} in 5 years

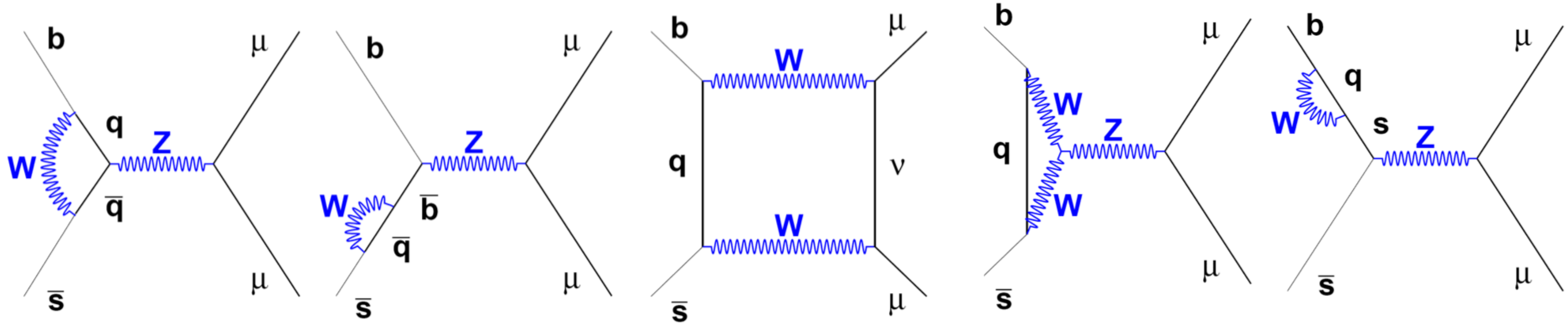


- **Startup phase:**
  - lower $\sqrt{s}$, low L and very low f $\Rightarrow$ significant pileup
  - similar L_{int} to each experiment

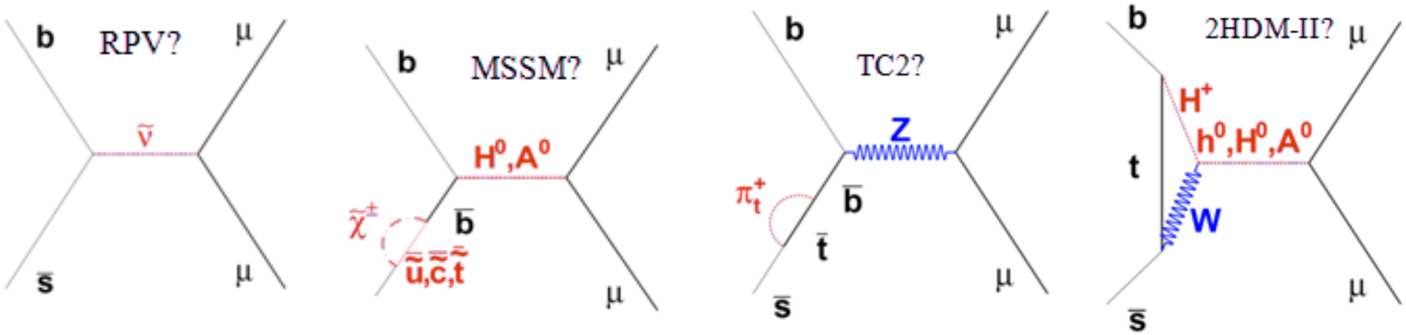
0.3 fb^{-1} at $\sqrt{s}$ = 7 TeV in 2010 (?)

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

- Very rare loop decay, helicity suppressed
  - Standard Model:
    - C_{10} dominates, C_S and C_P negligible $\Rightarrow$ BR = $(3.35\pm0.32)\times10^{-9}$ [hep-ph/0604057v5]



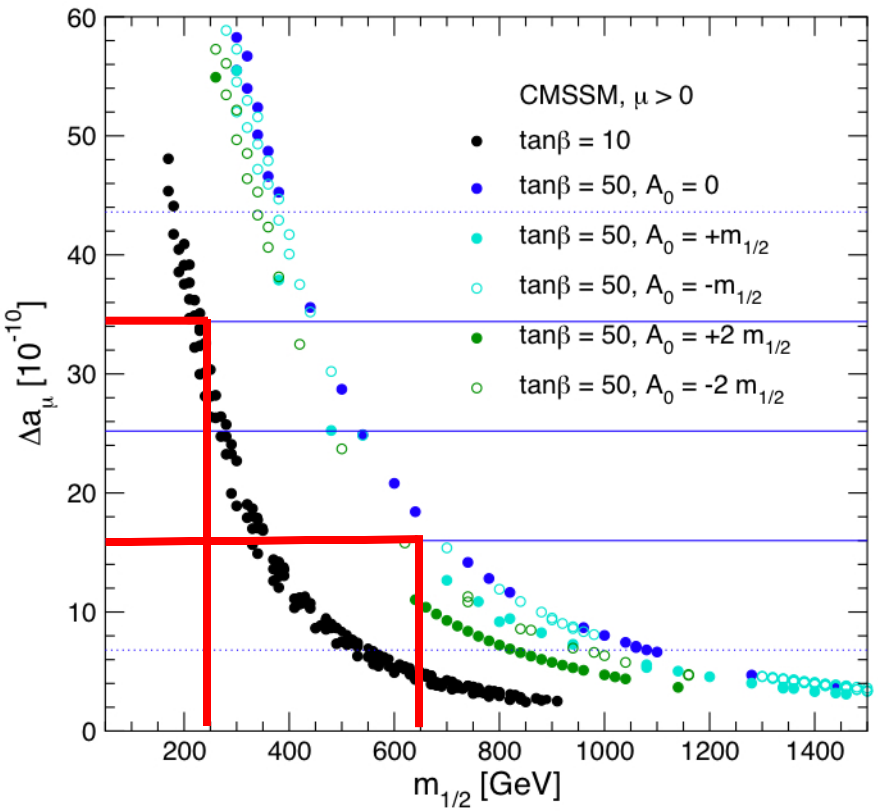
  - Can be strongly enhanced by NP:
    - e.g. CMSSM with large tanβ → next slide
    - …

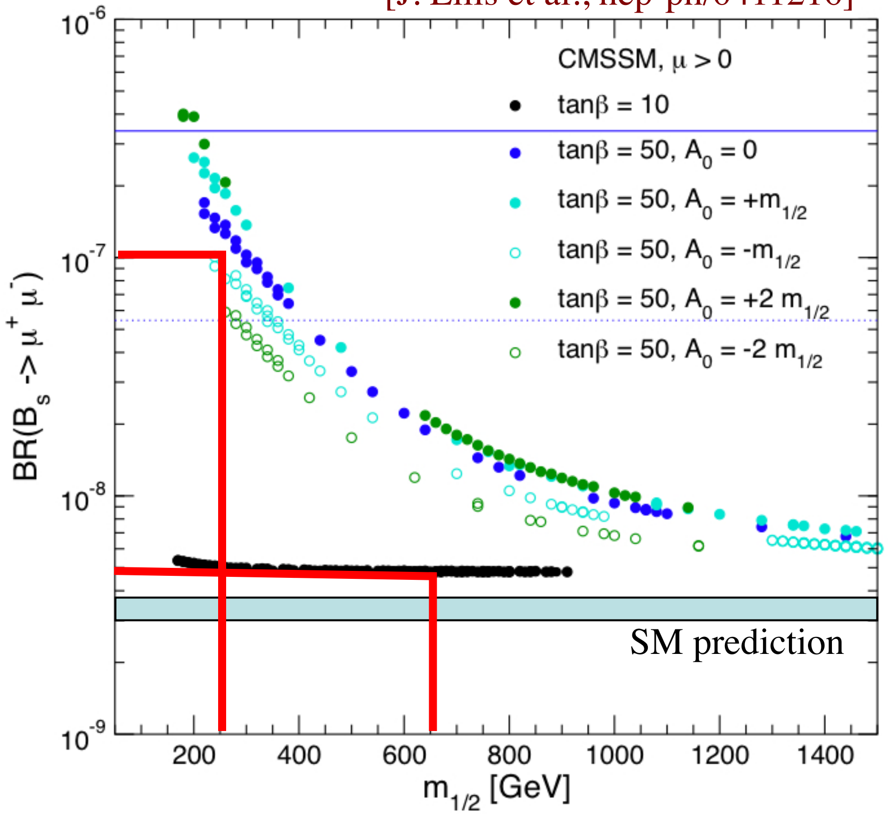


New physics in $B_s \to \mu^+\mu^-$

- Anomalous magnetic moment of the muon [PRL 92 (2004) 161802]
  - Muon g–2 collab. measurement deviates by 2.7σ from SM: $\Delta a_\mu = (25.2 \pm 9.2)\times 10^{-10}$
- Implications on $B_s \to \mu^+\mu^-$ within constrained MSSM:
  - $\Rightarrow 250 < m_{1/2}$(gaugino mass) < 650 GeV $\Rightarrow BR(B_s \to \mu^+\mu^-) = (5\text{–}100)\times 10^{-9}$

[J. Ellis et al., hep-ph/0411216]





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

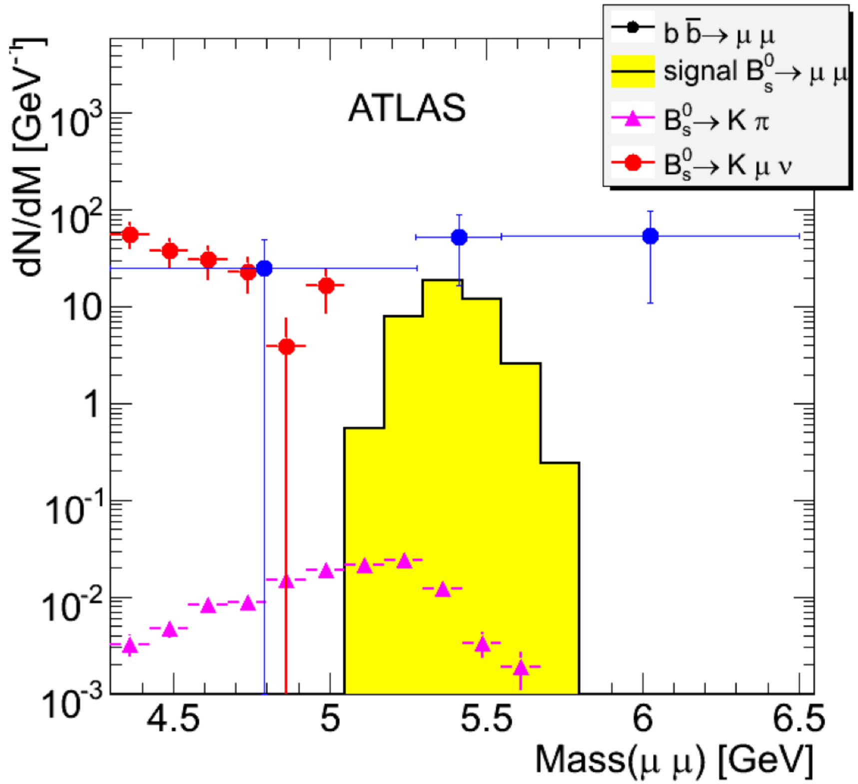
ALTAS: CERN-OPEN-2008-020
CMS: PAS BPH-07-001 (2009)
LHCb: CERN-LHCb-2008-018
CERN-LHCb-2007-033

	ATLAS	CMS	LHCb
σ_{mass} [MeV/c^2]	90	53	22

- Easy to trigger and reconstruct at LHC
- Main issue is background rejection
  - with limited MC statistics, indication that largest background is $b \to \mu$, $b \to \mu$
  - also specific backgrounds such as $B_c \to J/\psi(\mu\mu)\mu\nu$ and $B \to hh$
- Selection and analysis:
  - ATLAS/CMS:
    - cut-based selection (so far)
  - LHCb:
    - loose selection, analysis in bins of 3D space (mass, muonID, geometry)
- Event yields per fb^{-1}:

	ATLAS	CMS	LHCb [2]
SM signal [1]	5.7	2.4	3.8
background	14^{+13}_{-10}	6.5 ± 2.4	11^{+15}_{-7}

[1] Slightly different assumptions across experiments
[2] Most sensitive bin only



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

- **LHCb and CMS sensitivities:**
  - same "Modified Frequentist Approach"
    shown at Beauty 2009 (D. Martinez Santos)

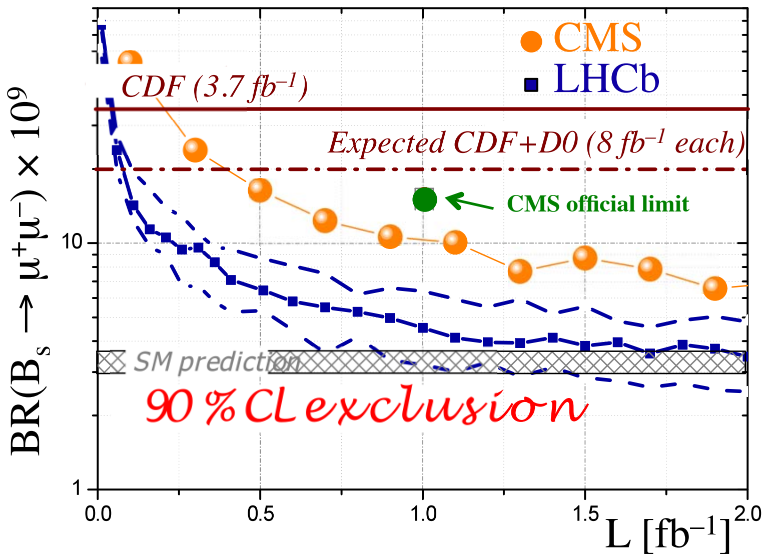
- **LHCb performance (nominal conditions)**

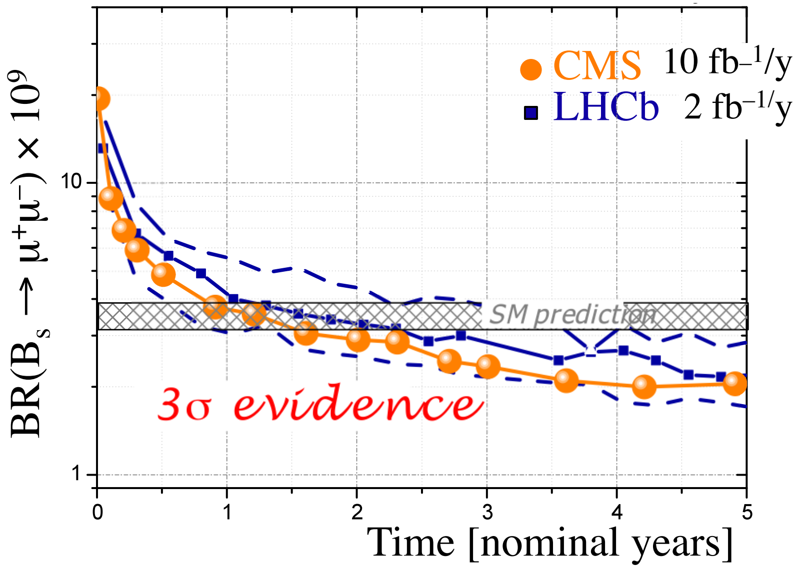
1 fb^{-1}	$\Rightarrow$	**exclude BR values down to 5×10^{-9}**
3 fb^{-1}	$\Rightarrow$	**3σ evidence of SM signal**
10 fb^{-1}	$\Rightarrow$	**5σ observation of SM signal**

  - CMS/ATLAS performance similar with 5 times more L_{int} (collected in ~equal time)

- **Startup conditions in 2010 ($\sqrt{s}$ = 7 TeV)**

LHCb can overtake Tevatron's final sensitivity with ~ 0.2 fb^{-1}

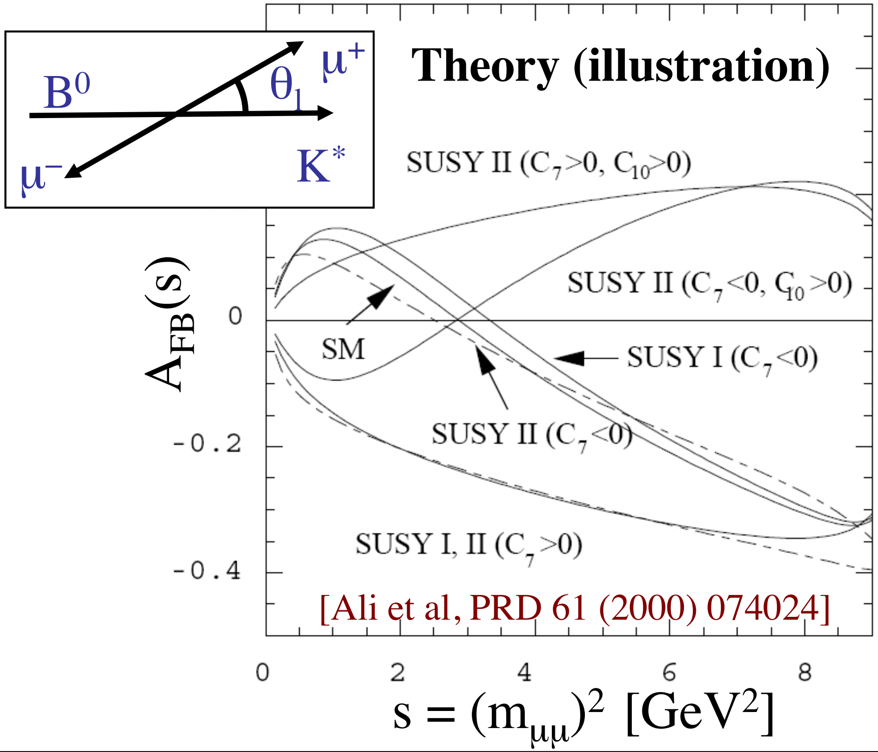




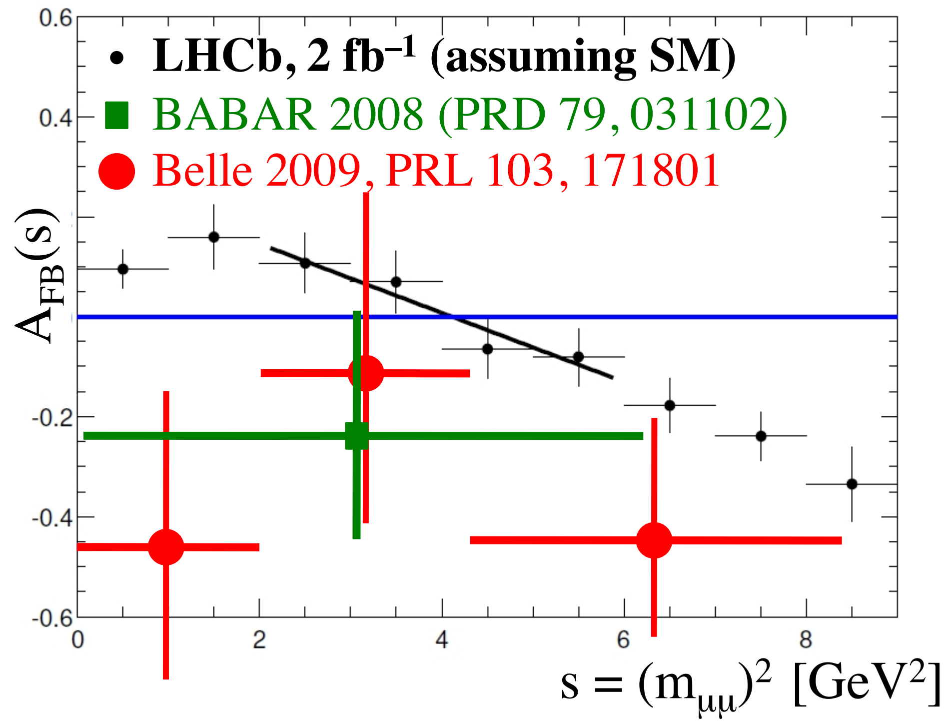
$B^0 \to K^{*0}\mu^+\mu^-$

CERN-LHCb-2007-039
CERN-LHCb-2009-009

- **Suppressed loop decay**
  - Forward-backward asymmetry $A_{FB}(s)$ in the μμ rest-frame
    - sensitive probe of New Physics
    - zero of A_{FB} gives access to ratio of Wilson coefficients C_7^{eff}/C_9^{eff}



- **LHCb sensitivity to A_{FB}**
  - 6.2k signal events/2fb^{-1}, $B_{bb}/S \sim 0.25$
    - NB: expect 0.35k/1ab^{-1} at B factories

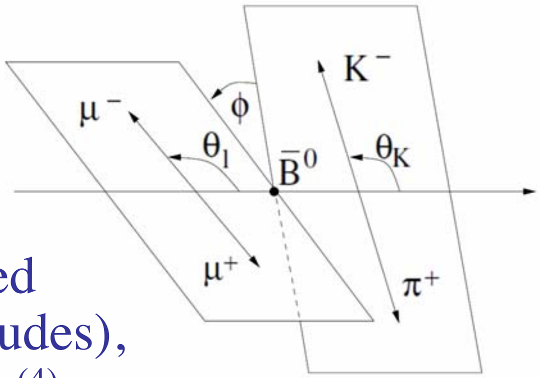


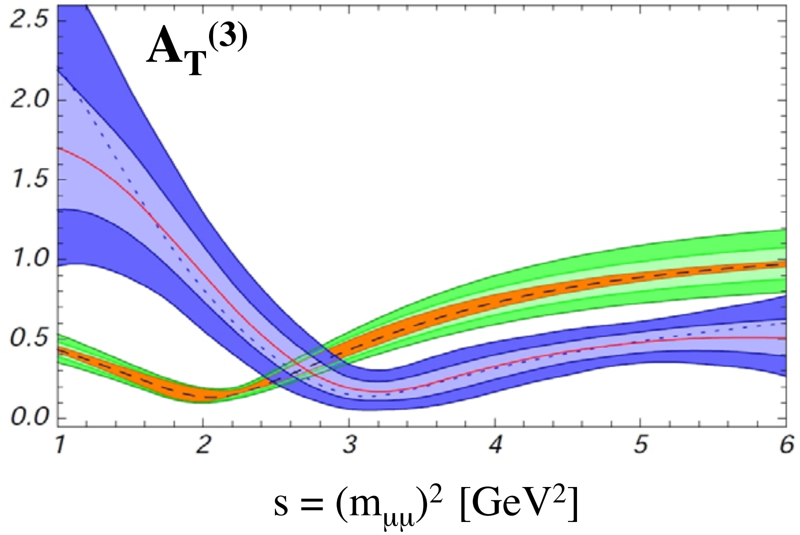
  - With 2 fb^{-1}, the zero of $A_{FB}(s)$ can be measured to ±0.5 GeV^2 (~11% of SM value)

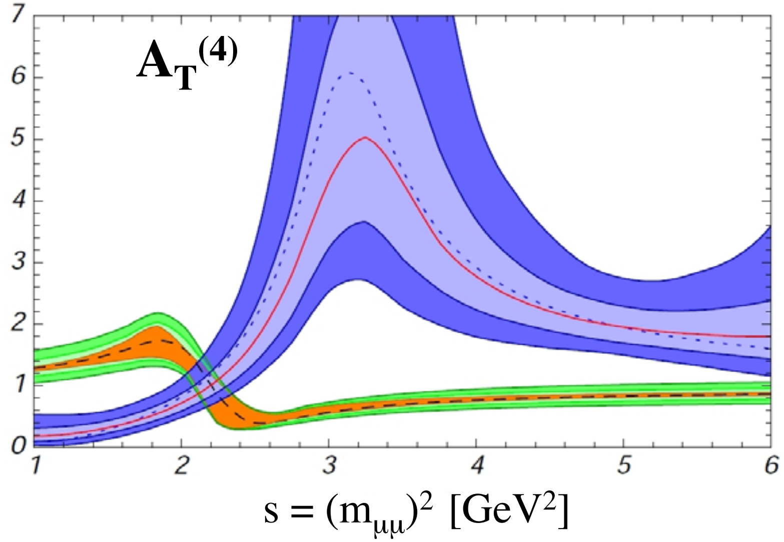
$B^0 \to K^{*0}\mu^+\mu^-$

CERN-LHCb-2008-041
JHEP 0811 032, 2008

- With > 2 fb^{-1}, a full 3-angle analysis becomes possible
  - new observables (based on transversity amplitudes), such as $A_T^{(2)}$, $A_T^{(3)}$, $A_T^{(4)}$
    - small theoretical errors in the SM
    - sensitive to right-handed FCNC, i.e. C_7'/C_7 (in addition to C_7, C_9, C_{10})
  - angular acceptance and backgrounds need to be carefully understood, e.g. using control channels ($B^0 \to J/\psi K^{*0}$)







- Some scenario with 10 fb^{-1} of LHCb data:
  - **MSSM** scenario with right-handed currents + **LHCb errors** (1σ and 2σ bands)
  - **SM** + **theory errors**

$B_s \to \phi\gamma$

- Not a CP eigenstate (because photon is polarized), but yet

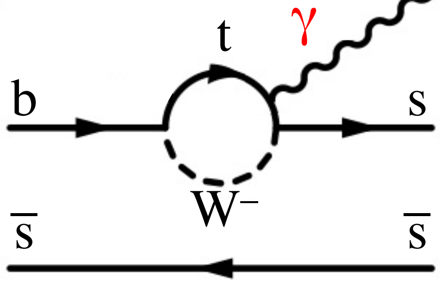
$$\Gamma\left(B_s^0(t) \to \phi\gamma\right) \propto e^{-\Gamma_s t}\left(\cosh(\Delta\Gamma_s t/2) - A^{\Delta}\sinh(\Delta\Gamma_s t/2) + C\cos(\Delta m_s t) - S\sin(\Delta m_s t)\right)$$

$$\Gamma\left(\overline{B}_s^0(t) \to \phi\gamma\right) \propto e^{-\Gamma_s t}\left(\cosh(\Delta\Gamma_s t/2) - A^{\Delta}\sinh(\Delta\Gamma_s t/2) - C\cos(\Delta m_s t) + S\sin(\Delta m_s t)\right)$$

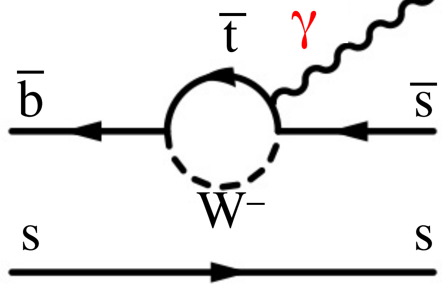
- In the SM: [Atwood et al, PRL 79 (1997) 185, PRD 71 (2005) 076003]
  - $|C| < 1\%$ (no direct CPV), $S = \sin(2\psi)\sin\phi$, $A^{\Delta} = \sin(2\psi)\cos\phi$
  - $\phi \sim 0$ (cancellation of mixing and decay phases)
  - $\tan\psi$ is the "fraction of wrong polarization"

$$\tan\psi = \left|\frac{A(\overline{B}_s^0 \to \phi\gamma_{\text{right}})}{A(\overline{B}_s^0 \to \phi\gamma_{\text{left}})}\right|$$

mostly left-handed γ



mostly right-handed γ



- Hence an untagged time-dependent analysis can yield $\tan\psi$ (without loss of sensitivity):

$$\Gamma\left(\overset{(-)}{B_s^0}(t) \to \phi\gamma\right) \propto e^{-\Gamma_s t}\left(\cosh(\Delta\Gamma_s t/2) - \sin(2\psi)\sinh(\Delta\Gamma_s t/2)\right)$$

Photon polarization in $b \to s\gamma$

- Test the V–A structure of weak interactions
  - **"wrong" polarization fraction = tanψ = $|A_R/A_L|$ ~ 0.04** in SM (m_s/m_b, gluons, …)
  - can be enhanced up to 0.4 in NP models

- Time-dependent analysis of $\mathbf{B_s \to \phi\gamma}$
  - mass resolution ~ 100 MeV/c^2
  - 11k signal events, B/S < 0.9
  - proper time resolution ~90 fs
  - efficiency vs proper time to be controlled
    - compare with B-factory $B^0 \to K^{*0}(K_S\pi^0)\gamma$ results where $\phi \cong 2\beta$: $\sigma(C) = 0.14$, $\sigma(S) = 0.22$ (A^Δ not measured because $\Delta\Gamma_d \sim 0$) ⇒ $\sigma_{stat}(A_R/A_L) \sim 0.16$
      [HFAG, 2009]

LHCb, 2 fb^{-1}
$\sigma_{stat}(C) = 0.12$
$\sigma_{stat}(S) = 0.11$
$\sigma_{stat}(A^\Delta) = 0.22$

⇒ $\sigma_{stat}(A_R/A_L) \sim 0.1$

CERN-LHCb-2007-030
CERN-LHCb-2007-147

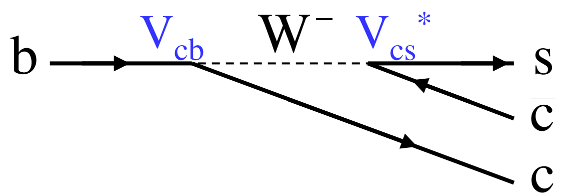
- Angular analysis of $\mathbf{B^0 \to K^* e^+ e^-}$
  - measure $A_T^{(2)}$ for m(ee) < 1 GeV/c^2
  - 200–250 signal events, B/S ~ 1

LHCb, 2 fb^{-1}
$\sigma_{stat}(A_T^{(2)}) \sim 0.2$

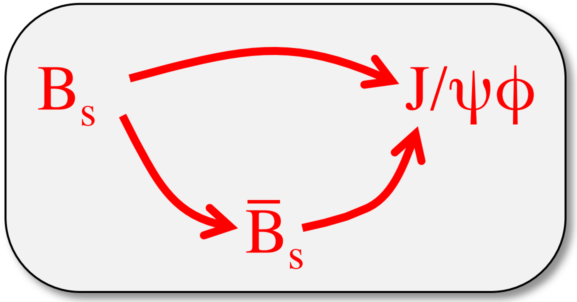
⇒ $\sigma_{stat}(A_R/A_L) \sim 0.1$

CERN-LHCb-PUB-2009-008

Access to CP-violating phase β_s



- $B_s \to J/\psi\phi$ is strange counterpart of $B^0 \to J/\psi K^0$
  - angle β_s can be measured with $B_s \to J/\psi\phi$ in the same way as β with $B^0 \to J/\psi K^0$ at the B factories
  - "golden" mode for B_s mixing-induced CP violation

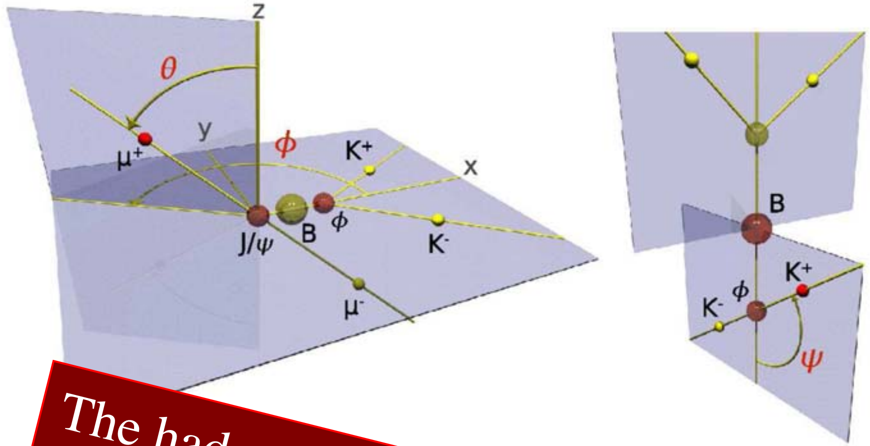


- Important differences:
  - Δm_s is much larger than Δm_d
    - need excellent proper time resolution to avoid dilution
  - $\Delta\Gamma_s$ is much larger than $\Delta\Gamma_d$;
    - access to $\cos 2\beta_s$ ($= A^{\Delta}$) in addition to $\sin 2\beta_s$, removing ambiguities
    - untagged analysis possible (but sensitive only to $\cos 2\beta_s$)
  - final state has two vector mesons, so is a mixture of CP-even (S and D waves) and CP-odd (P wave) eigenstates
    - need angular analysis to separate the two components
    - additional physics parameters (8 in total)
    - interference terms between polarization amplitudes sensitive to $\sin 2\beta_s$ and $\cos 2\beta_s$ for both tagged and untagged analyses

$B_s \to J/\psi\phi$ decay rates

$$\frac{d^4\Gamma(B_s^0 \to f)}{dt\, d\Omega} \propto \sum_{k=1}^{6} h_k(t) g_k(\Omega)$$

k	$h(t)$	$g_{J/\psi\phi}(\theta,\psi,\varphi)$
1	$\lvert A_0(t)\rvert^2$	$2\cos^2\psi(1-\sin^2\theta\cos^2\varphi)$
2	$\lvert A_\parallel(t)\rvert^2$	$\sin^2\psi(1-\sin^2\theta\sin^2\varphi)$
3	$\lvert A_\perp(t)\rvert^2$	$\sin^2\psi\sin^2\theta$
4	$\mathrm{Re}\{A_0^*(t)A_\parallel(t)\}$	$\frac{1}{\sqrt{2}}\sin 2\psi\sin^2\theta\sin 2\varphi$
5	$\mathrm{Im}\{A_\parallel^*(t)A_\perp(t)\}$	$-\sin^2\psi\sin 2\theta\sin\varphi$
6	$\mathrm{Im}\{A_0^*(t)A_\perp(t)\}$	$\frac{1}{\sqrt{2}}\sin 2\psi\sin 2\theta\cos\varphi$



The hadron experiments are going to have much more "fun" with β_s than Belle and BaBar had with β

$$|A_0(t)|^2 = |A_0(0)|^2 e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) - \cos\Phi\sinh\left(\frac{\Delta\Gamma_s t}{2}\right) + \sin\Phi\sin(\Delta m_s t)\right]$$

$$|A_\parallel(t)|^2 = |A_\parallel(0)|^2 e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) - \cos\Phi\sinh\left(\frac{\Delta\Gamma_s t}{2}\right) + \sin\Phi\sin(\Delta m_s t)\right]$$

$$|A_\perp(t)|^2 = |A_\perp(0)|^2 e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) + \cos\Phi\sinh\left(\frac{\Delta\Gamma_s t}{2}\right) - \sin\Phi\sin(\Delta m_s t)\right]$$

$$\mathrm{Re}\{A_0^*(t)A_\parallel(t)\} = |A_0(0)||A_\parallel(0)|e^{-\Gamma_s t}\cos(\delta_2-\delta_1)\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) - \cos\Phi\sinh\left(\frac{\Delta\Gamma_s t}{2}\right) + \sin\Phi\sin(\Delta m_s t)\right]$$

$$\mathrm{Im}\{A_\parallel^*(t)A_\perp(t)\} = |A_\parallel(0)||A_\perp(0)|e^{-\Gamma_s t}\left[-\cos\delta_1\sin\Phi\sinh\left(\frac{\Delta\Gamma_s t}{2}\right) + \sin\delta_1\cos(\Delta m_s t) - \cos\delta_1\cos\Phi\sin(\Delta m_s t)\right]$$

$$\mathrm{Im}\{A_0^*(t)A_\perp(t)\} = |A_0(0)||A_\perp(0)|e^{-\Gamma_s t}\left[-\cos\delta_2\sin\Phi\sinh\left(\frac{\Delta\Gamma_s t}{2}\right) + \sin\delta_2\cos(\Delta m_s t) - \cos\delta_2\cos\Phi\sin(\Delta m_s t)\right]$$

8 physics parameters:
Φ (equal to $-2\beta_s$ in the SM),
Γ_s, $\Delta\Gamma_s$, Δm_s, $R_\perp$, R_0, δ_1, δ_2

$$R_0 = \frac{|A_0(0)|^2}{|A_\perp(0)|^2 + |A_\parallel(0)|^2 + |A_0(0)|^2}$$

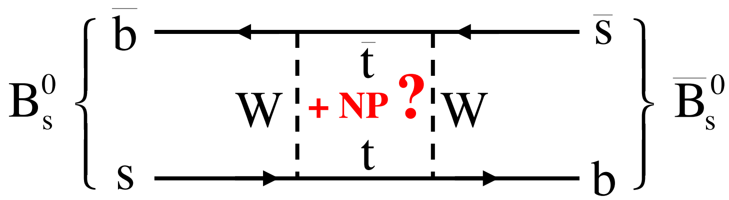
$$\delta_1 = \arg(A_\parallel^* A_\perp) = \delta_\perp - \delta_\parallel$$

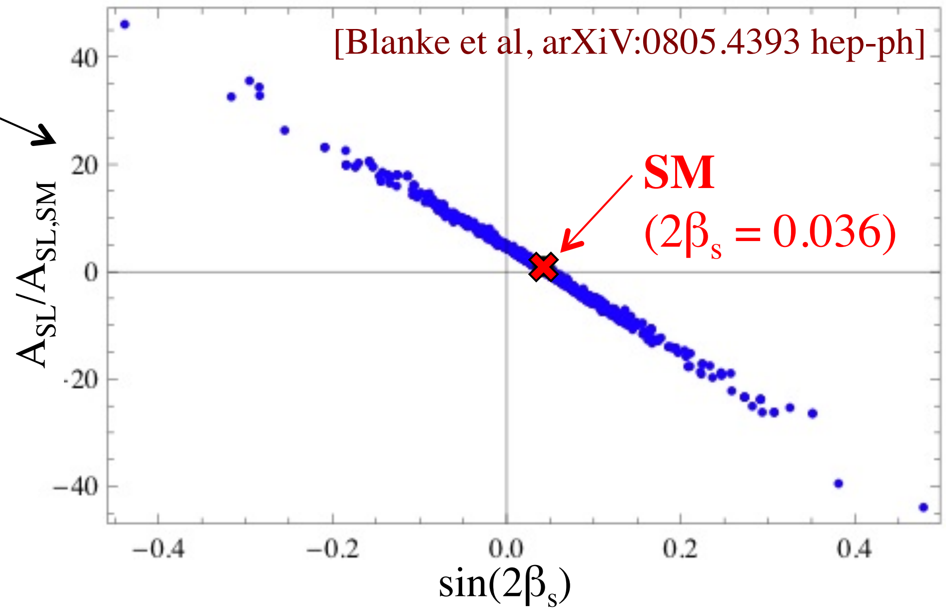
$$\delta_2 = \arg(A_0^* A_\perp) = \delta_\perp - \delta_0$$

… and similarly for the $\overline{B}_s$ decay rates (change only signs indicated with ◯)

New physics in B_s mixing

- B_s mixing phase $2\beta_s$ small in SM, hence very sensitive to NP contributions:
  - Some models predict large phase, while satisfying all existing constraints including Δm_s:
    - e.g. Little Higgs model with T-parity (significant enhancement of both β_s and B_s semi-leptonic asymmetry A_{SL})





- Measure $A_{CP}(t)$ in $b \to c\bar{c}s$ decays
  - best mode is $B_s \to J/\psi(\mu\mu)\phi$:

LHCb, 2 fb^{-1}
$\sigma_{stat}(2\beta_s)$ = 0.030

  - can also include pure CP modes $B_s \to J/\psi\eta^{(\prime)}$, $\eta_c\phi$, D_sD_s (lower stat. but no angular analysis needed)

With 10 fb^{-1}, LHCb can get evidence of CP violation (even if only SM)

β_s reach with early data

ALTAS: CERN-OPEN-2008-020
CMS: PHYSICS TDR 2006
LHCb: CERN-LHCb-2009-025
CERN-LHCb-2009-021

	LHCb	LHCb ($\sqrt{s}$ = 7 TeV)	ATLAS	CMS
Integrated luminosity	**2 fb^{-1}**	**0.3 fb^{-1}**	**0.15 fb^{-1}** [a]	**10 fb^{-1}**
$B_s \to J/\psi\phi$ signal events	117k	8k	1.14k [a]	110k
bb background/signal ratio	0.5		~ 5.5 [a]	0.33
B_s mass resolution	16 MeV/c^2		61 MeV/c^2 [a]	14 MeV/c^2 [b]
Proper-time resolution	38 fs		152 fs [a]	78 fs [c]
Flavour tagging εD^2	6.2%		4.6% [c]	–
$\sigma_{stat}(2\beta_s)$	**0.030**	**0.12**		

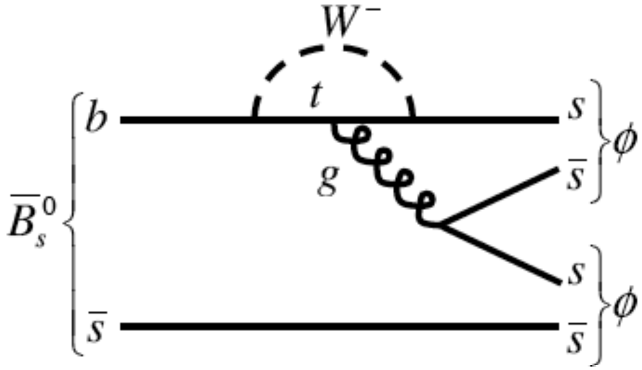
[a] Early data analysis performance
[b] J/ψ mass constrained
[c] A. Dewhurst, talk at Beauty 2009

- Compare with
  - SM prediction (CKM fitter): $2\beta_s = 0.036 \pm 0.002$
  - CDF+D0 result (2.8 fb^{-1} each): $2\beta_s \in [0.54, 1.18] \cup [1.94, 2.60]$ at 68% CL

If true value is within 68% CL interval quoted by CDF and D0, LHCb can observe New Physics with early data

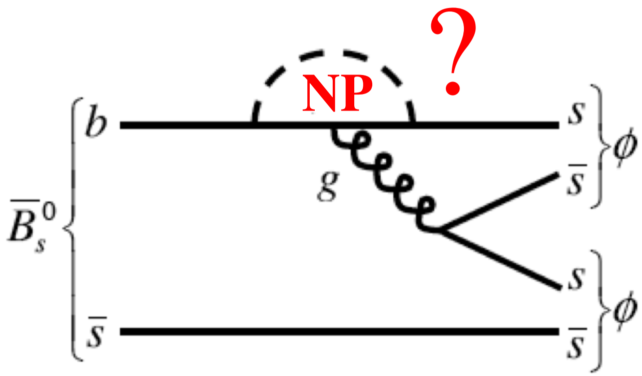
$b \to s\bar{s}s$ gluonic penguin

- Many new phases are possible in SUSY



- "Golden mode" for LHCb is $B_s \to \phi\phi$
  - CP violation < 1% in SM [Raidal, PRL 89 (2002) 231803] (V_{ts} enters both in mixing and decay amplitudes)
  - significant CP-violating phase difference $\phi_s^{\phi\phi}$ can only be due to New Physics
  - Flavour tagging and angular analysis required
  - 4.6k signal events per 2 fb^{-1} ($BR=2.4\times10^{-5}$), $B_{bb}/S < 2.4$ at 95% CL

LHCb, 10 fb^{-1}
$\sigma_{stat}(\phi_s^{\phi\phi}) = 0.06$



CERN-LHCb-PUB-2009-025

- $B^0 \to \phi K_S$:
  - 920 signal events per 2 fb^{-1}, B/S < 1.1 at 90% CL
  - After 10 fb^{-1}: **$\sigma_{stat}(\sin(2\beta_{eff})) = 0.10$**
    - to be compared with 0.17 from BaBar+Belle combined

CERN-LHCb-2007-130

Summary

- B decays can probe New Physics through off-shell corrections:
  - complementary to direct high-p_T searches
  - sensitive to higher scales, sensitive to phases
- Indirect New Physics searches at LHC:
  - several highly-sensitive B physics observables
    - some of them reachable with 2010 data already
    - LHCb front-runner
- LHC experiments now ready …
  … for a dream scenario (in a few years):
  - "same New Physics" observed both in direct and indirect searches