The LHC Heavy Flavour Programme

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Contents

Thanks to ATLAS(M. Smizanska), CMS (U. Langenegger) and LHCb colleagues.

1) Introduction

Goal of heavy flavour physics is now shifting from
understanding of CKM paradigm (SM)

to

search for physics Beyond the Standard Model (BSM) appearing in loops.

Following the past successes: e.g.

charm from $\Delta m(K^0)$, $Br(K_L \rightarrow \mu\mu)$, etc.

top from CPV, $\Delta m(B^0)$, etc.

before the c and t discoveries,

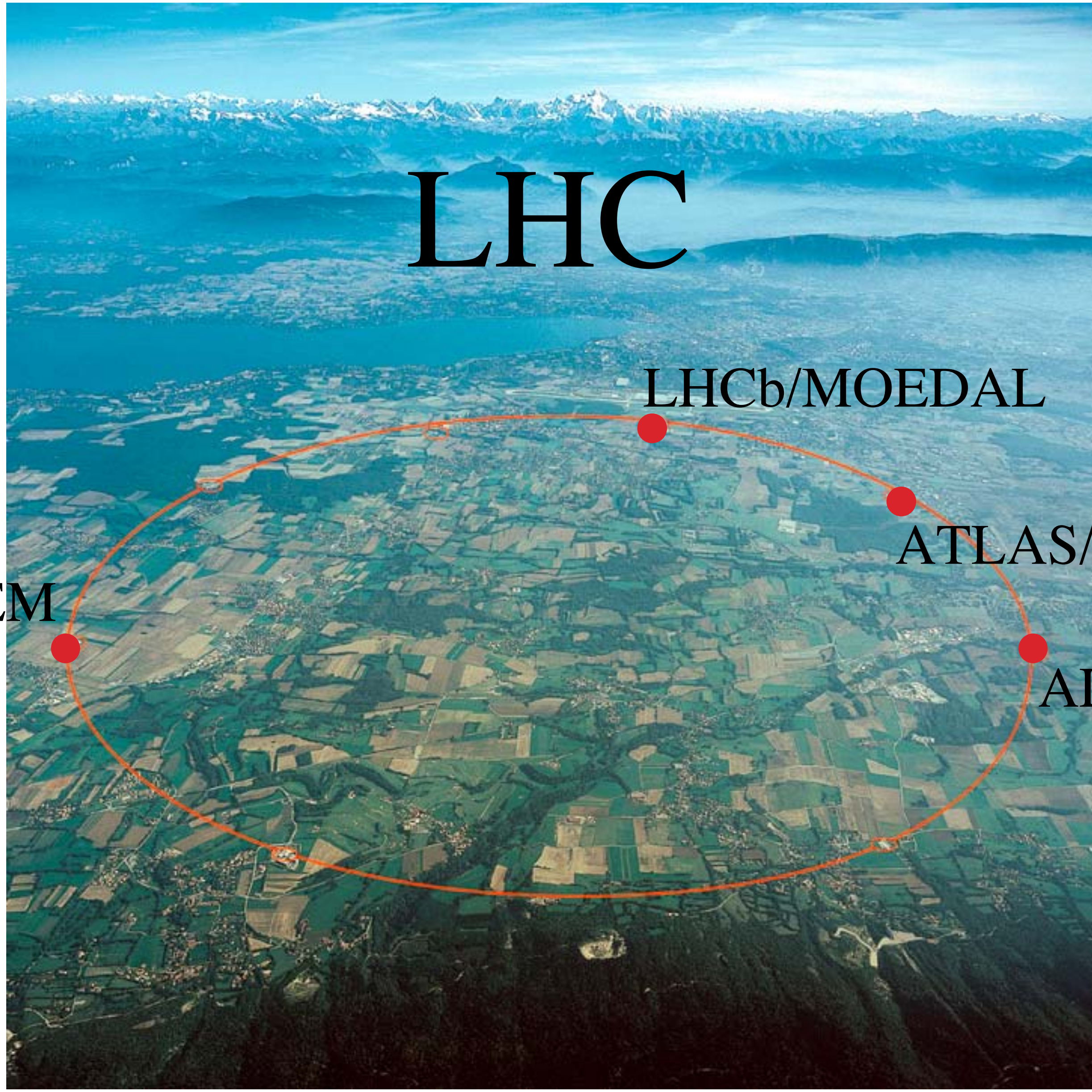
look for signs of BSM in rare processes with b-hadrons.

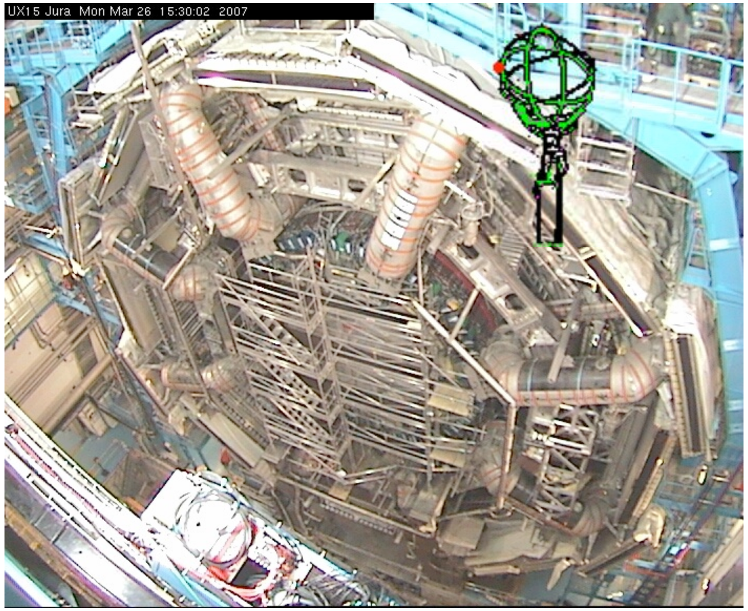
2) LHC Experiments

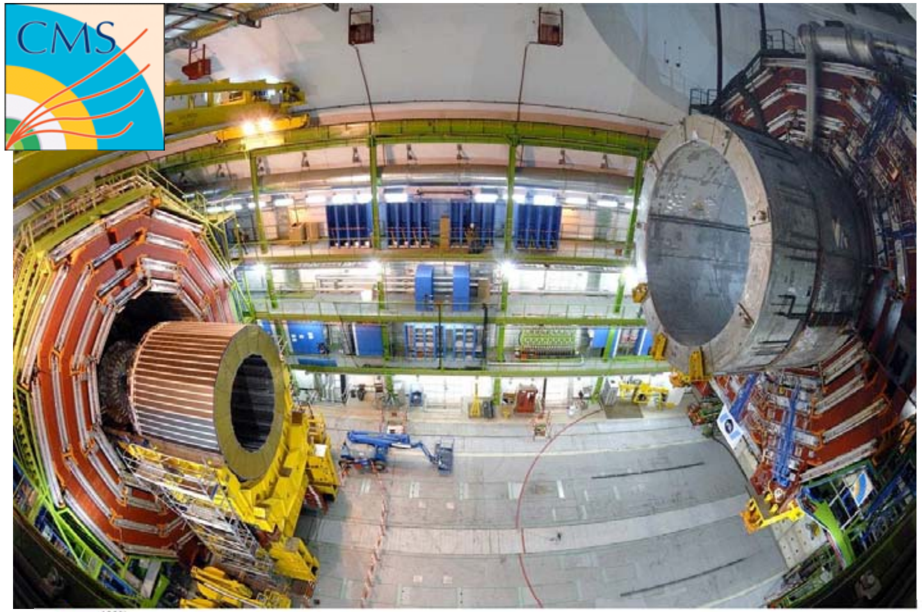
Experiments being prepared now at LHC

ALICE	heavy ion and soft-pp experiment
ATLAS	general purpose pp and heavy ion experiment
CMS	general purpose pp and heavy ion experiment
LHCb	dedicated heavy flavour experiment
LHCf	forward π^0 and γ production
MOEDAL	magnetic monopole search
TOTEM	log$s$ and diffraction physics

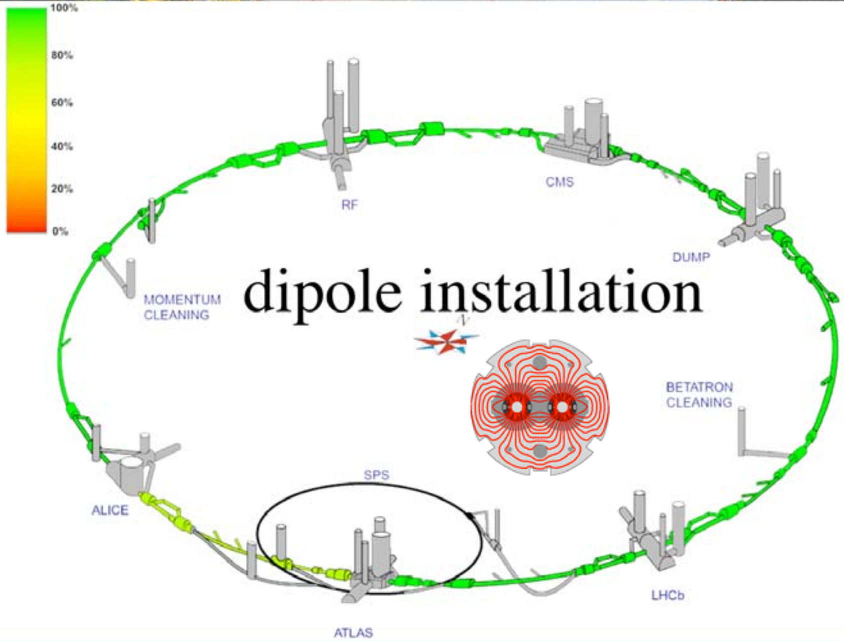
ATLAS, CMS and LHCb are relevant for the flavour physics considered here, and I do not cover production and spectroscopy


LHC
LHCb/MOEDAL
ATLAS/LHCf
CMS/TOTEM
ALICE


UX15 Jura Mon Mar 26 15:30:02 2007


CMS


LHCb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CMS
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dipole installation
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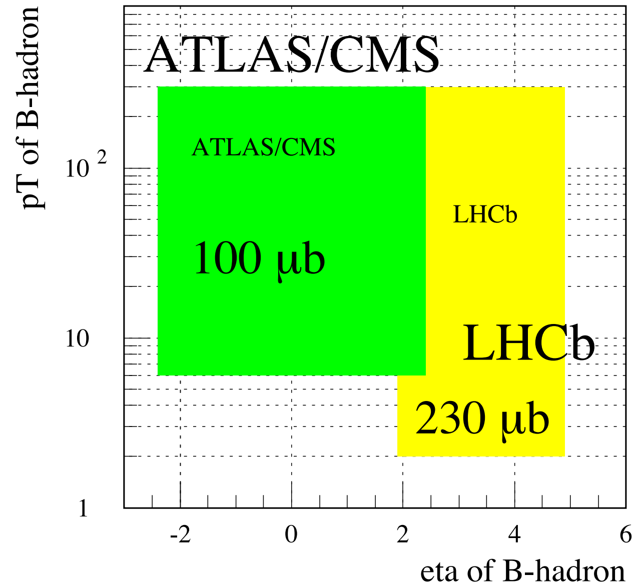
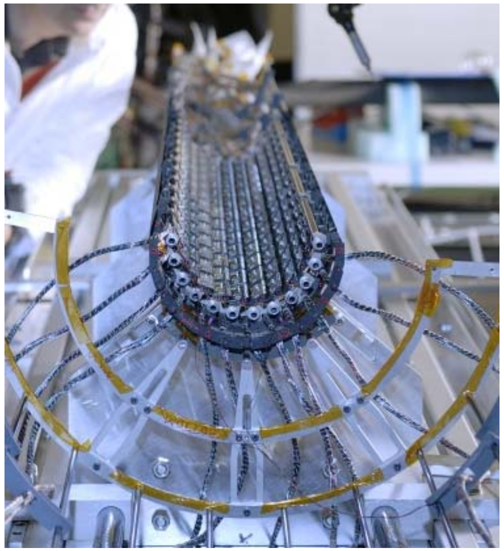
CLEANING
SPS
ALICE
LHCb
ATLAS

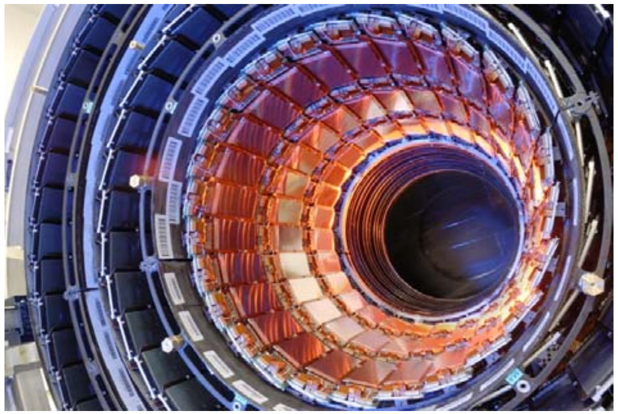
LHCb RIH-2

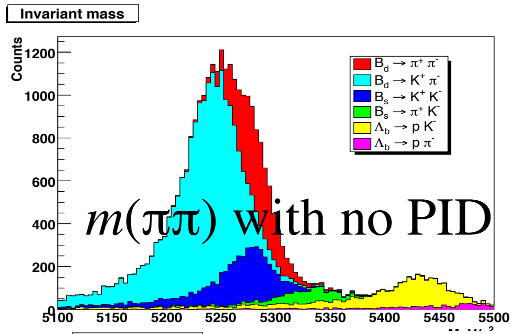


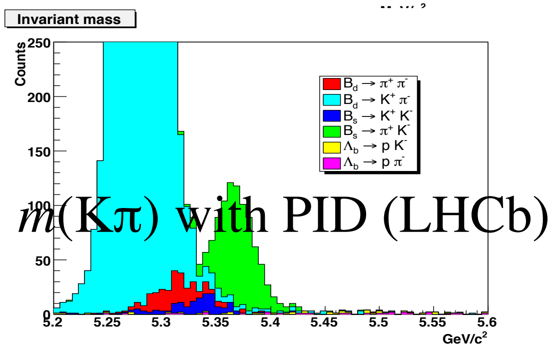
ATLAS Pixel



CMS Tracker







End of 2007: Engineering run

very low luminosity @ $\sqrt{s}$ = 900 GeV

detector commissioning, alignment and calibration

Middle of 2008: Start of run @ $\sqrt{s}$ = 14 TeV

calibration and trigger commissioning,

increasing luminosity toward 10^{33} for ATLAS/CMS and $\sim 2\times10^{32}$ for LHCb for physics

From 2009: Stable physics run @ $\sqrt{s}$ = 14 TeV

ATLAS and CMS: clear interest to increase luminosities towards 10^{34} as quick as possible.

B physics will become increasingly difficult.

LHCb: collecting data with $<10^{33}$ for some years

A possible scenario

2008

physics run for a period of 1/4 of the nominal year (10^7 sec)

$\langle L \rangle = 10^{33}$ for ATLAS and CMS (optimistic?)

$\langle L \rangle = 2\times10^{32}$ for LHCb (should be possible…)

$\int L dt$ = 2.5 fb^{-1} each for ATLAS and CMS

(if $\langle L \rangle$ is lower, trigger could be adjusted to have a similar number of b's)

$\int L dt$ = 0.5 fb^{-1} for LHCb

2009-2011

ATLAS and CMS accumulate $\int L dt$ = 30 fb^{-1} each

end of B physics era and move to 10^{34} regime (except $B_s \to \mu\mu$)

2009-2013

LHCb collect $\int L dt \gtrsim 10$ fb^{-1}

LHCb should have 10 fb^{-1} data by the end of 2013±1

3) Physics with 2008 data

Very interesting results can be obtained for B_s physics

CP violation in $B_s \rightarrow J/\psi\ \phi$ (i.e. ϕ_s measurement)

and

Search for $B_s \rightarrow \mu\mu$ decays

where large, >O(1), BSM contribution not yet excluded

Tevatron will run till 2009:

CDF and D0, well understood detectors

LHC can get b statistics fast,

We need to organize ourselves for fast analysis

Time dependent CP asymmetries in $B_s, \overline{B}_s \to J/\psi\ \phi$ decays

Final states with leptons: lepton trigger very effective
☺ for ATLAS, CMS and LHCb

Flavour tag necessary
opposite side: lepton, jet-charge and kaon
same side: "slow" kaon from the fragmentation

$$\varepsilon_{eff} = \varepsilon_{tag}(1 - 2w_{wrong})^2\ [10^{-2}]$$

	O.S.				S.S.	"combined"
	e	μ	K	Jet	K	
ATLAS	0.25	0.68	×	3.63	×	Σ=4.56
CMS	under investigation				×	
LHCb	0.46	0.70	1.64	1.04	2.71	N.N. = 7.08

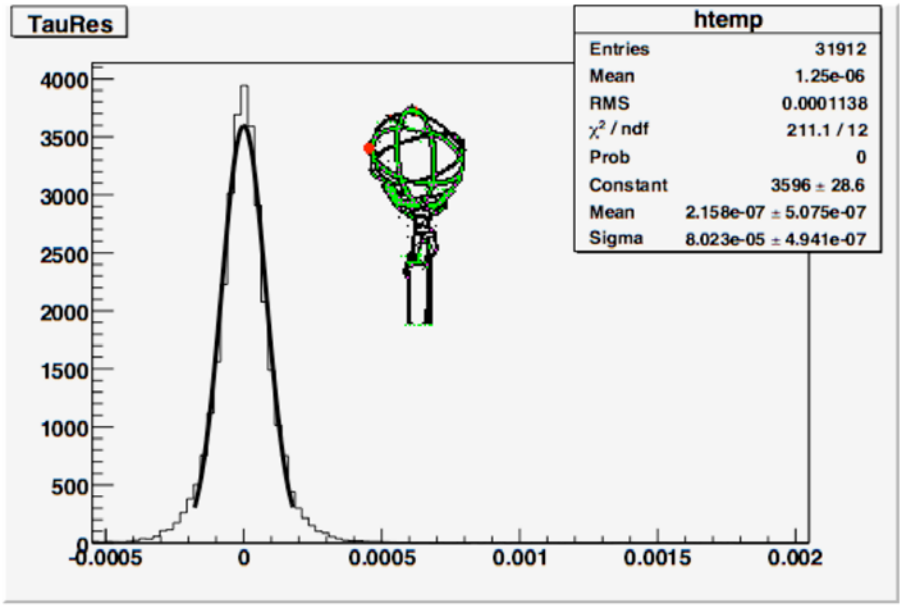
B_s-$\overline{B}_s$ oscillation has to be well resolved: good σ_τ needed

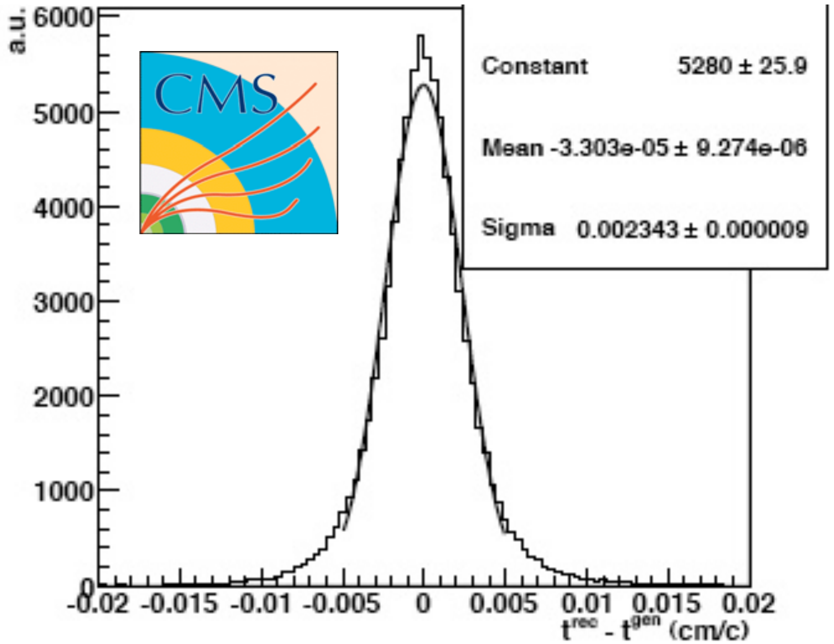
- good that Δm_s is not too big
- resolution function must be well understood
  measuring lifetimes, oscillation plot with $D_s\pi$ etc.

Proper time resolutions

	ATLAS	CMS	LHCb
σ_τ [fs]	83	77	36

NB: worse resolution = more dilution in the CP asymmetries



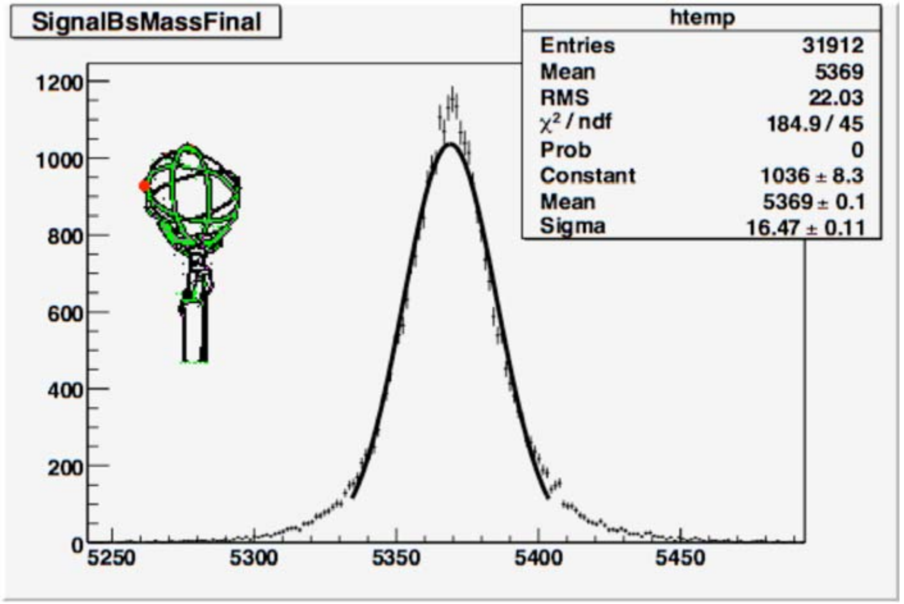


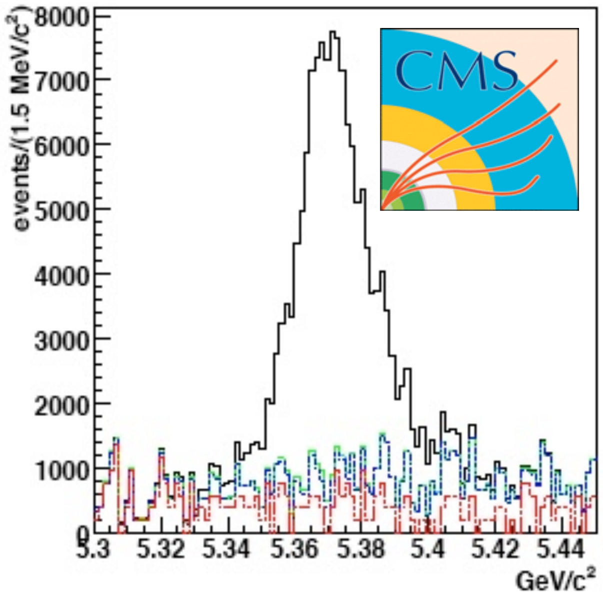
Good mass and vertex resolutions to reduce background

B_s mass resolutions and Background/Signal ratios

	ATLAS	CMS	LHCb
σ_m [MeV/c^2]	16.5*)	14*)	14+)
B/S	0.25	0.33	0.12

*)with J/ψ mass constraint
+)without mass constraint





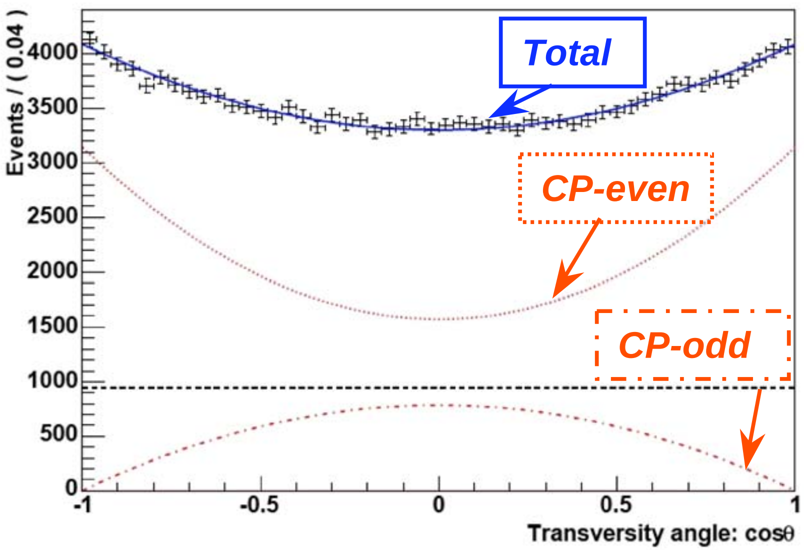
Event yields from the "2008" run

Numbers of reconstructed $J/\psi\phi$ and those effectively flavour tagged

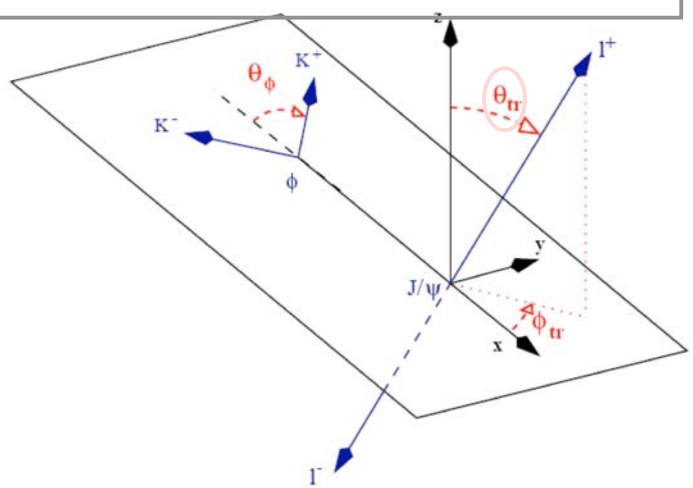
	ATLAS	CMS	LHCb
N_{rec}	23 k	27k	33 k
$N_{rec}^{eff\text{-}tag}$	1.0 k	?	2.3 k

Full decay topology analysis is needed to determine

$J/\psi\phi(CP = +1)$ / $J/\psi\phi$ $(CP = -1)$ $(L_{J/\psi\text{-}\phi} = 0, 2$ vs $L_{J/\psi\text{-}\phi} = 1)$



The background is assumed to be independent on θ_{tr}.
Should be measured from the side band data.



LHCb

B_s-$\bar{B}_s$ oscillation phase and decay width difference with 2008 data

	ATLAS	CMS	LHCb
$\sigma(\phi_s)$	0.158	?	0.042
$\sigma(\Delta\Gamma_s)/\Delta\Gamma_s$	0.41	0.13	0.12

NB
CP $\propto \phi_s$
$\Delta\Gamma_s \propto 1 - \phi_s^2/2$
less sensitive to ϕ_s

Standard model expectation: $\phi_s = -0.04$

LHCb: BSM effect down to the level of SM can be excluded/discovered with the 2008 data

LHCb: $J/\psi\ \eta$, $\eta_c\ \phi$, $D_s^+ D_s^-$ can be added and

$\sigma(\phi_s) = 0.01$ with $\int L\,dt = 10\ \mathrm{fb}^{-1}$ data

ATLAS and CMS:

$\sigma(\phi_s) \approx 0.04$ with $\int L\,dt = 30\ \mathrm{fb}^{-1}$ data

By ~2013, SM prediction of ϕ_s tested to a level of ~5σ

Search for $B_s \rightarrow \mu^+\mu^-$ decays

Final states with leptons: lepton trigger very effective

☺ for ATLAS, CMS and LHCb

Flavour tag not necessary, tough background

PID: $B \rightarrow \pi\pi$, $K\pi$, etc.

vertex resolution: $b \rightarrow \mu^- X + \bar{b} \rightarrow \mu^+ X$

mass resolution: $B \rightarrow \mu X$, etc.

+ isolation, p_T, etc.

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

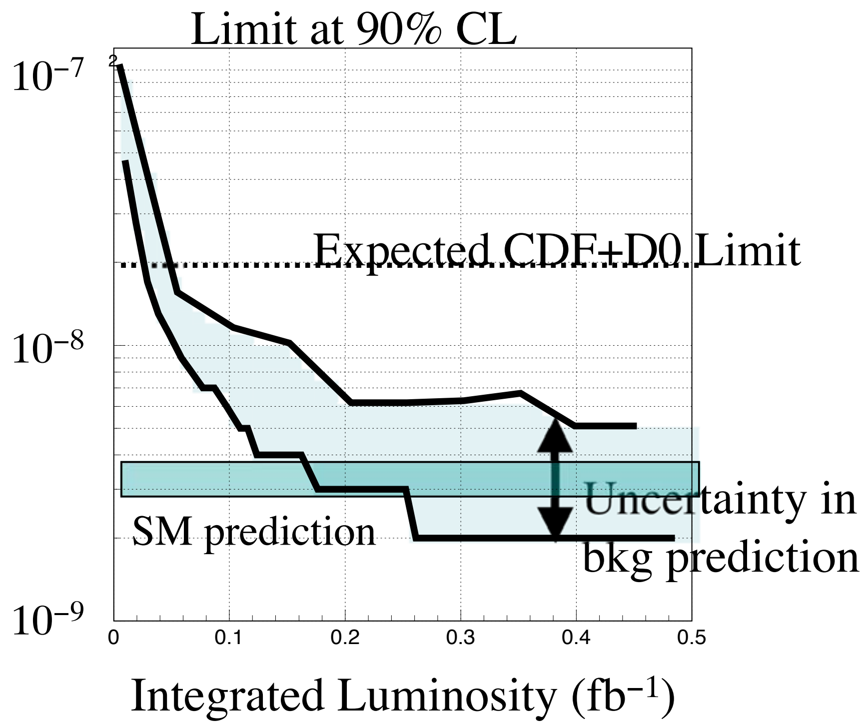
	ATLAS	CMS	LHCb
σ_m [MeV/c^2]	77	36	18

With 2008 data… *)assuming the SM Br = ~3.5×10^{-9}

	ATLAS	CMS
N_{signal} *)	~2	~2
$N_{background}$	~5	~4

<~5×10^{-8} (90%CL)

LHCb uses "distributions" for signal and background…



LHCb; BSM contribution down to the level of SM can be excluded/discovered.

LHCb: $\int L\,dt = 10\ fb^{-1}$, >5σ observation for SM Br

ATLAS and CMS: $\int L\,dt = 30\ fb^{-1}$, <~6×10^{-9} (90%CL)

(They plan to continue this programme at $L=10^{34}$, 4σ in one year)

4) Flavour physics >2008

Subjects which require

very high statistics

good control of systematics, detector and physics.

Here are some examples…

Search for a BSM Lorentz structure in b→s current using polarization of γ in b→s+"γ", for real or virtual γ

$B_d \rightarrow K^{*0}\ \mu^+\mu^-$

→detailed studies of the event structure

A_{FB}: forward-backward asymmetry of $\mu^+\mu^-$

other angular distributions

Final states with leptons: lepton trigger very effective

☺ for ATLAS, CMS and LHCb

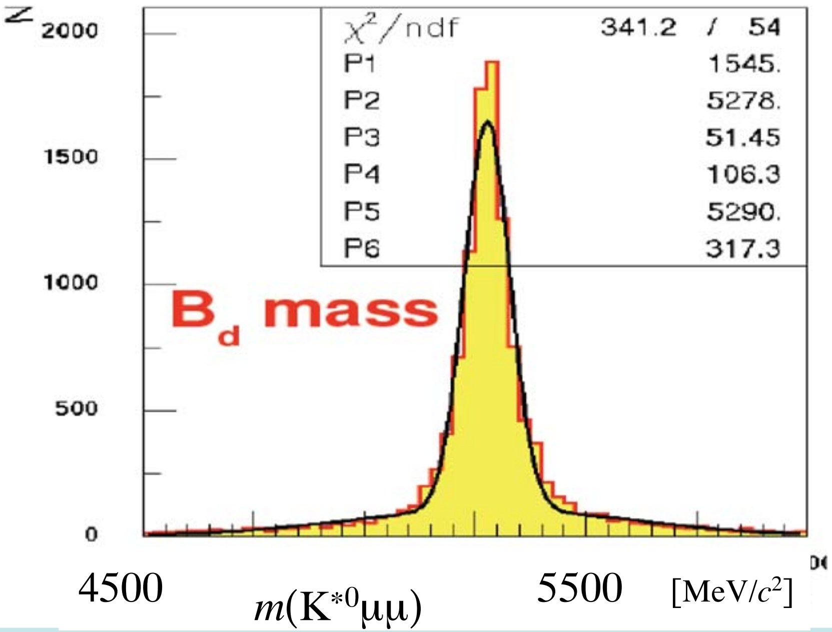
Flavour tag not necessary

(CMS study not yet available)

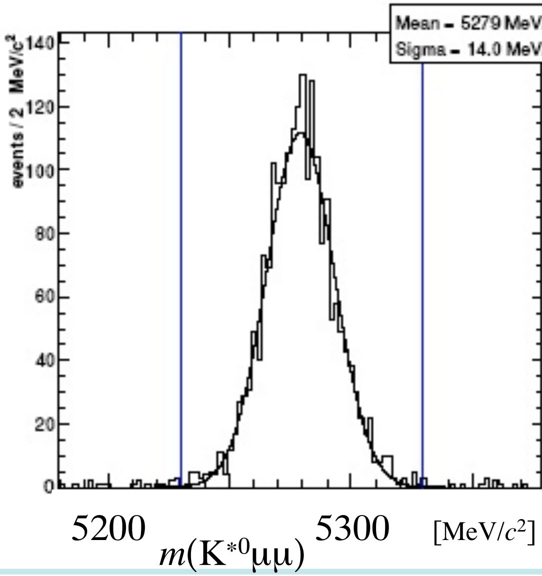
for one canonical year
10 fb^{-1} (ATLAS) and 2fb^{-1} (LHCb)

	ATLAS	LHCb
$\sigma(m)$ [MeV/c^2]	51	14
N_{signal}	800	7200
B/S	<4.8	~0.5

ATLAS

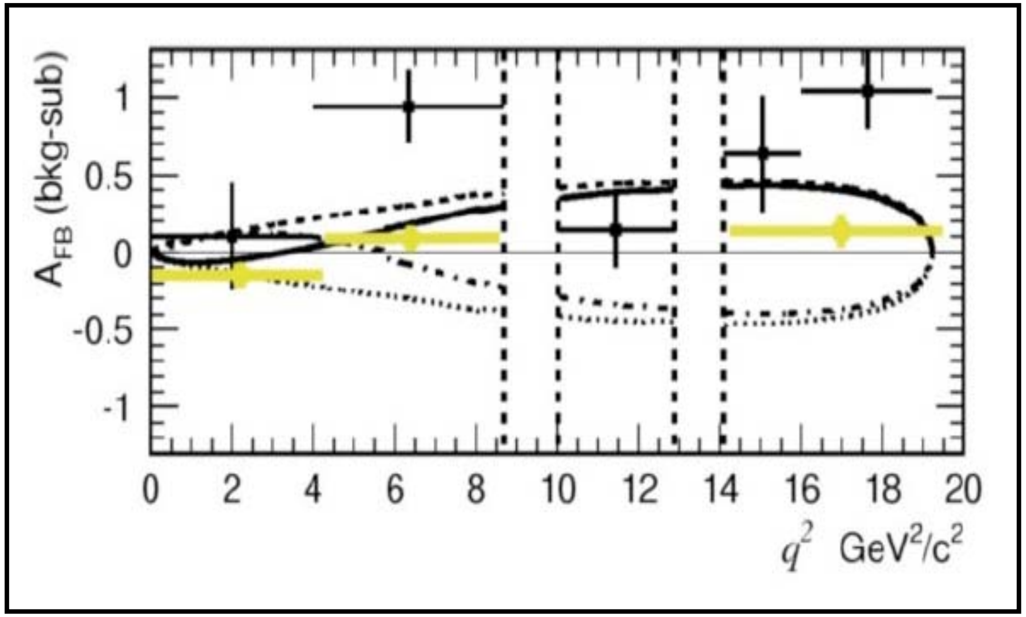


LHCb

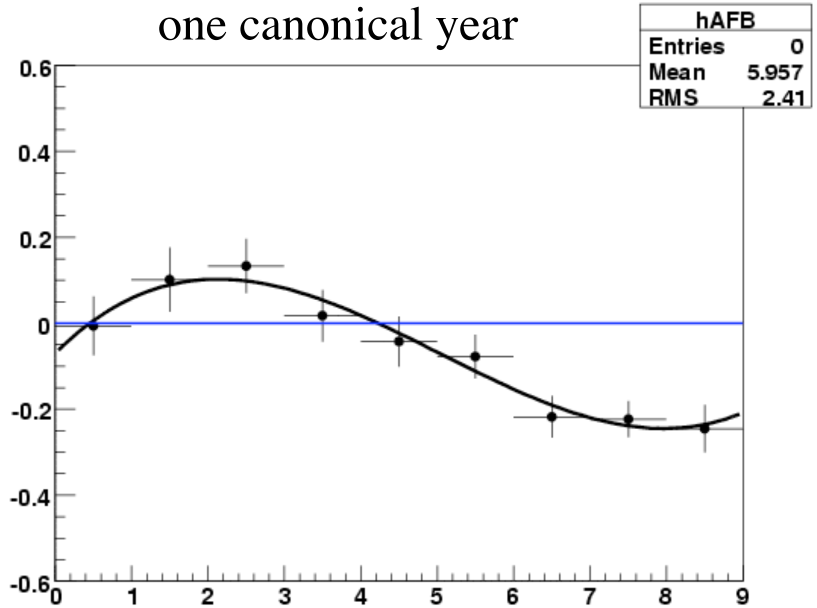


A_{FB} performance

ATLAS 30 fb^{-1} forward-backward asymmetry
three canonical years



LHCb 2 fb^{-1}
one canonical year



$m_{\mu\mu}{}^2$ [GeV^2]

+ ATLAS precision @ 30 fb^{-1}
+ Belle 2006
— SM model
...... SM extensions

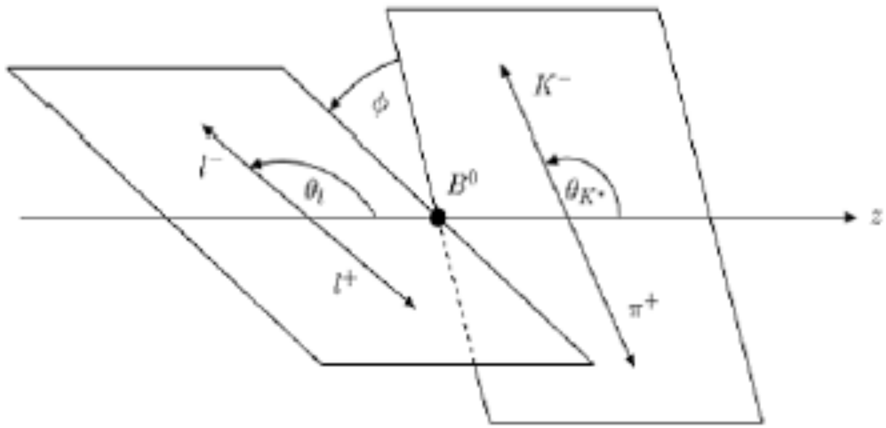
By ~2013, LHCb
zero crossing point with 10 fb^{-1}
$\sigma(s_0) = 0.28\ (\mathrm{GeV}/c^2)^2$

There is more information in $K^{*0}\mu^+\mu^-$

Kruger & Matias, Phys. Rev. D 71: 094009, 2500

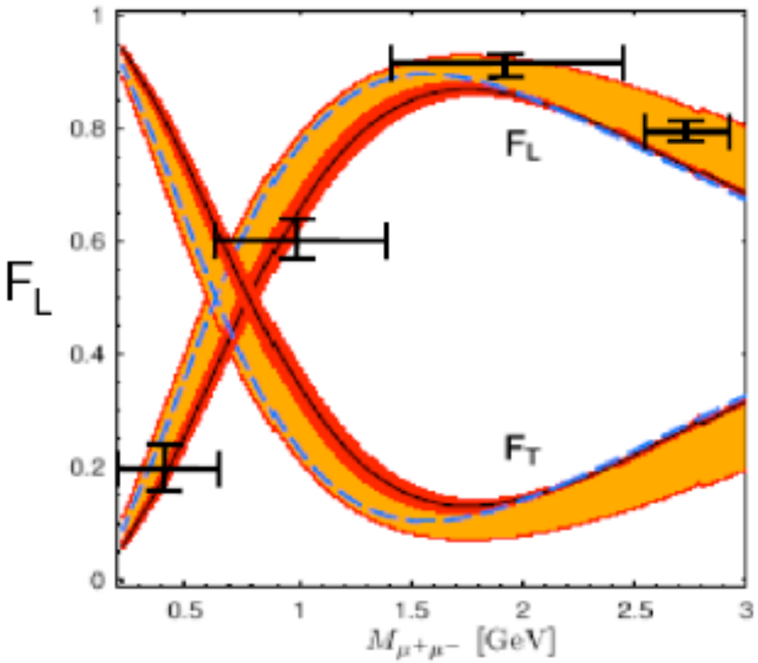
- s = μμ mass squared (=q^2)
- θ_l = angle between μ and B in μμ rest-frame (A_{FB} angle)
- θ_{K^*} = equivalent K^* angle (between K and B in K^* rest-frame)
- ϕ = angle between K^* and μμ decay planes

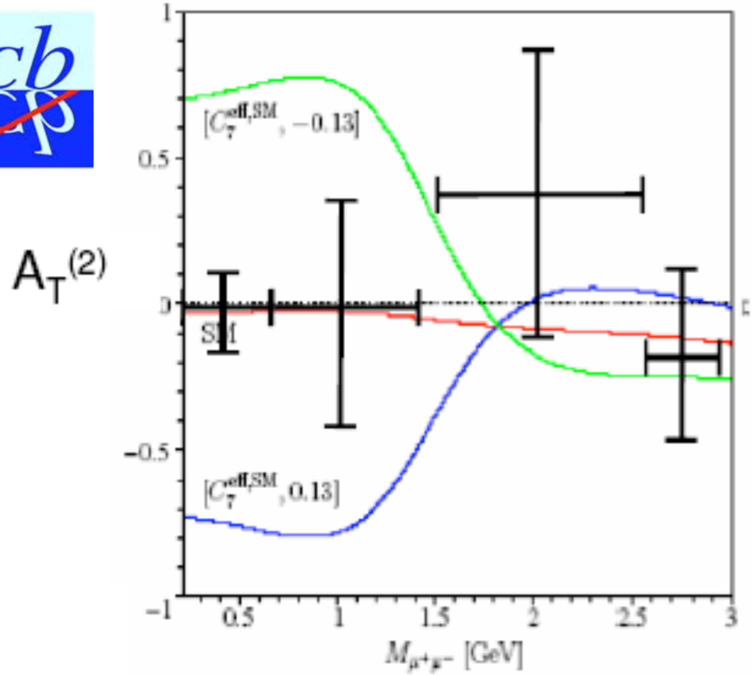
$$d^4\Gamma = \frac{9}{32\pi} I(s, \theta_l, \theta_{K^*}, \phi) ds\, d\cos\theta_l\, d\cos\theta_{K^*}\, d\phi$$



K^{*0} polarisation can be measured

Examples for K^{*0} polarisation with $2fb^{-1}$ data





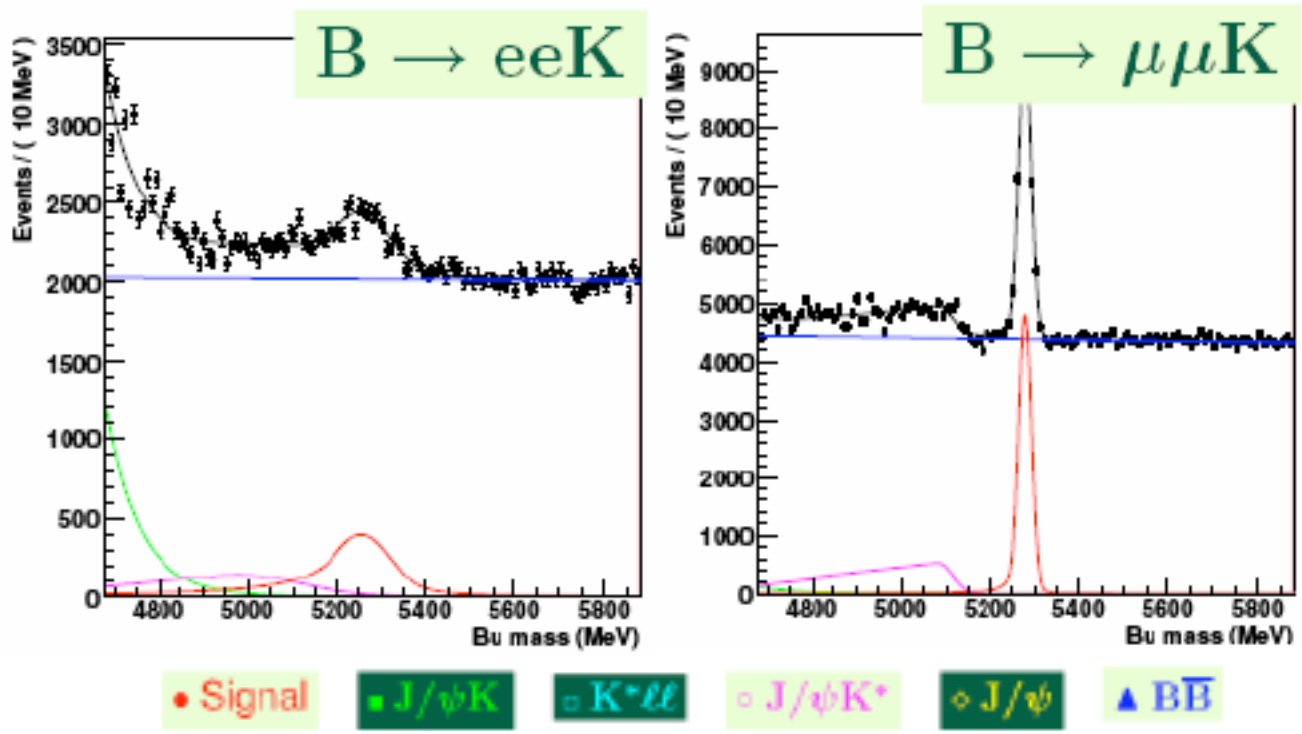
NB: Theoretical complication: K^{*0} is a wide resonance
⇒Effect of non-resonant Kπ to be better understood

LHCb will look for other radiative decays,
e.g. $B_s \rightarrow \phi\gamma$ 47k events with 10 fb^{-1}

An interesting quantity: R_K

$$R_X = \frac{\int_{4m_\mu^2}^{q^2_{max}} ds \frac{d\Gamma(B \to X\mu^+\mu^-)}{ds}}{\int_{4m_\mu^2}^{q^2_{max}} ds \frac{d\Gamma(B \to X e^+ e^-)}{ds}} \stackrel{SM}{=} \begin{cases} 1.000 \pm 0.001 & X = K \\ 0.991 \pm 0.002 & X = K^* \end{cases}$$

[Hiller & Krüger, PRD69 (2004) 074020]



With 10 fb^{-1} data

$K^\pm e^+ e^-$	10 k
$K^\pm \mu^+ \mu^-$	19 k

LHCb by ~2013
$\sigma(R_K) = 0.043$

Extraction of γ

Different ways to extract γ are considered by LHCb

1) Interfering $b \to c + W^-(\to u\bar{s})$ and $b \to u + W^-(\to c\bar{s})$

a) via B_s-$\bar{B}_s$ oscillation

time dependent decay asymmetries

b) via DCS decays of D

relative decay rates

c) via D-$\bar{D}$ state mixing

relative decay rates

d) K^0-$\bar{K}^0$ state mixing

Dalitz plot study

2) Interfering $b \to u$-tree+$b \to d$-penguins and B-$\bar{B}$ oscillations

+ U-spin

time dependent decay asymmetries

L0 hadron p_T trigger, K/π identification: essential

1-a) $B_s \to D_s^{\pm} K^{\mp}$ and $\overline{B}_s \to D_s^{\mp} K^{\pm}$

flavour tag, K/π identification ($D_s\pi$ background), σ_τ

1-b) $B^+ \to DK^+$ and $B^- \to DK^-$ or $B^0 \to DK^{*0}$ and $\overline{B}^0 \to D\overline{K}^{*0}$

with $D \to K^{\pm}\pi^{\mp}$

1-c) $B^0 \to DK^{*0}$ and $\overline{B}^0 \to DK^{*0}$

with $D \to K^{\pm}\pi^{\mp}$ and $D \to K^+K^-$, $\pi^+\pi^-$

1-d) $B^+ \to DK^+$ and $B^- \to DK^-$ or $B^0 \to DK^{*0}$ and $\overline{B}^0 \to D\overline{K}^{*0}$

with $D \to K_S\pi^+\pi^-$

K/π identification and mass and vertex resolution
to reduce combinatorial background

Detector acceptance for charge asymmetry, kinematics, …

Description of D decays: strong phases between DCS and CA decay amplitudes, Dalitz plot distribution, …

Normalization of some background channels

2) $B_d \to \pi^+\pi^-$ and $B_s \to K^+K^-$

flavour tag, K/π identification (Kπ background), σ_τ

validity of U-spin symmetry

CP asymmetries fit results corresponding to $2fb^{-1}$

	$B_d \to \pi^+\pi^-$	$B_s \to K^+K^-$
σ(C)	0.043 (0.07*)	0.042
σ(S)	0.037 (0.09*)	0.044

	$B_d \to K^+\pi^-$	$B_s \to \pi^+K^-$
$\sigma(A_{CP})$	0.003 (0.015*)	0.02

LHCb performance in γ determination with 10 fb^{-1}

	D_sK	DK			ππ/KK
		ADS	GLW+D	Dalitz	
σ(γ)	4.5°	3.6°	3.6°	6.7°	4°*)

~2013 LHCb tree determination of γ
σ = 2.4°, unaffected by BSM

*) With a weak assumption on U-spin symmetry
Could be affected by BSM

Extraction of α

For LHCb, a promising method is time dependent Dalitz plot analysis for $B_d \to \pi^+\pi^-\pi^0$ and $\overline{B}_d \to \pi^+\pi^-\pi^0$: i.e. "$\rho\pi$" mode ($\rho\rho$ modes are marginal except $\rho^0\rho^0$ channel)

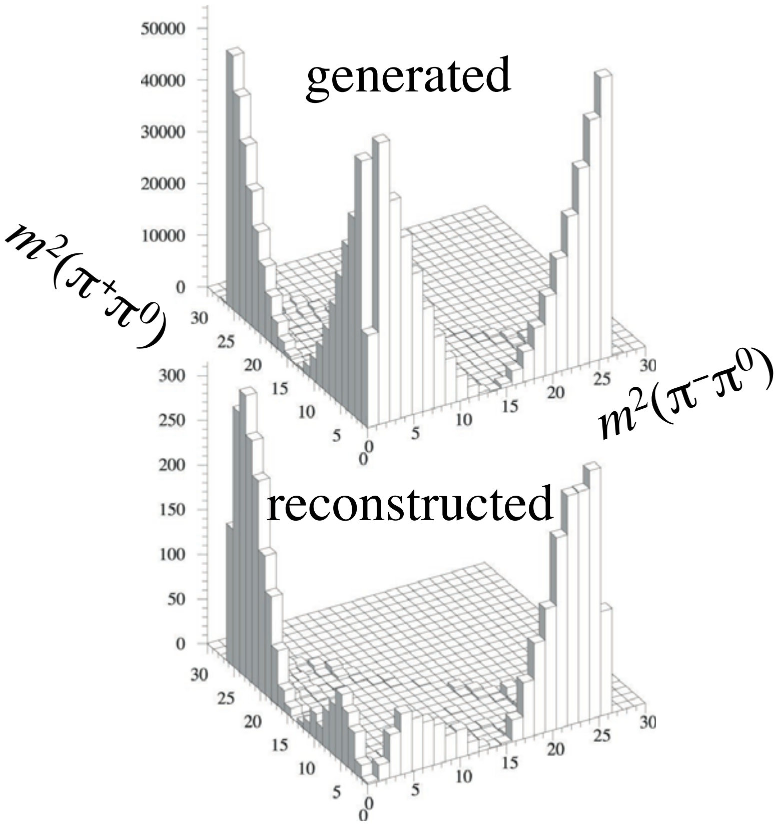
LHCb $B_d \to \pi^+\pi^-\pi^0$ 2 fb^{-1}

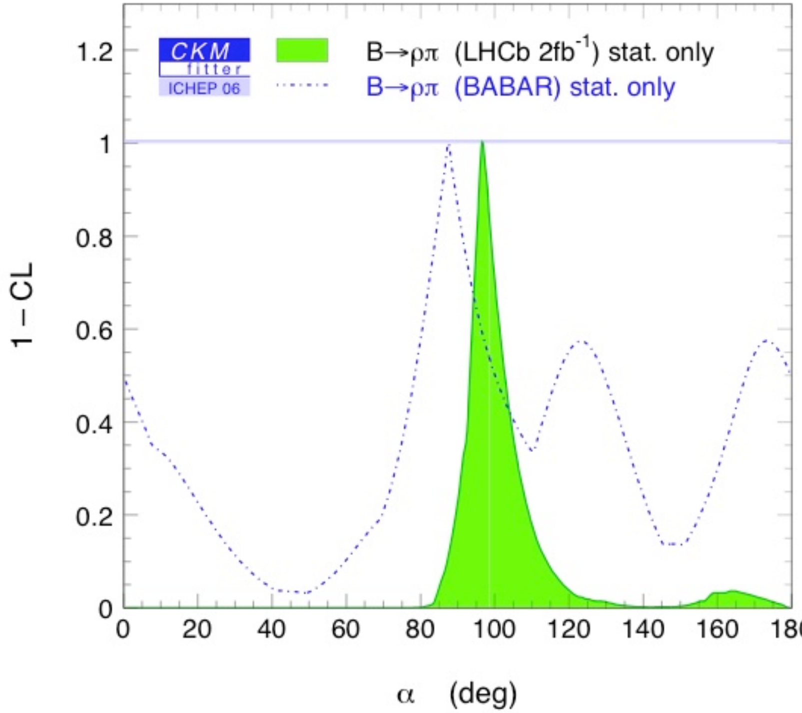
N_{signal}	B/S	$\sigma(m_{B_d})$	$\sigma(\tau)$	ε_{tag}^{eff}
14 k	1	60 MeV/c^2	50 fs	5.8%

LHCb $B_d \to \rho^0\rho^0$ 2 fb^{-1}

N_{signal}	B/S	$\sigma(m_{B_d})$	$\sigma(\tau)$
1200	<5	16 MeV/c^2	32 fs

LHCb α determination with ρπ mode with 2fb^{-1} data





together with $\rho^0\rho^0$ mode,

~2013 LHCb determination of a with 10fb^{-1}

$\sigma(\alpha) = 4.6°$, could be affected by BSM

BSM Phase of b→s penguin

Analogous to $B_d \to \phi K_S$, time dependent CP asymmetry for $B_s \to \phi\phi$ can measure the BSM phase in b→s penguin (for B_s, with only t contribution, SM makes 0 CP asymmetry)

LHCb $B_s \to \phi\phi$ performance with 2 fb^{-1} data

$\sigma(m_{B_S})$	B/S	N_{sig} *)	$\sigma(\tau)$	$\sigma(\phi_{s\text{-eff}})$
12 MeV/c^2	0.4-2.1	4000	42 fs	0.1

*) $Br = 1.4 \times 10^{-5}$

angular analysis needed to resolve CP=1 and =–1 states

~2013 with 10 fb^{-1} data:
$\sigma(\phi_{s\text{-eff}}) = 0.04$
($B_d \to \phi K_s$ for LHCb, $\sigma(\phi_{d\text{-eff}}) = 0.14$)

currently
$\sigma(\phi_{d\text{-eff}}) = 0.18$

BSM in the D system

LHCb will collect a large D^* tagged D^0 sample (also used for PID calibration)

$D^0 \rightarrow$	$K^-\pi^+$	K^+K^-	$\pi^+\pi^-$	π^-K^+
$N_{signal}[10^6]$	50	5	2	0.2

Combined with "slow π^+" to make D^{*+}

Use $B \rightarrow D^{*+}$ "$\pi^\pm$"X to determine D^{*+} vertex

$\Rightarrow$45k π^-K^+ decays/2 fb^{-1}, B/S~2.6, $\sigma(\tau_D)$=45 fs

~2013 LHCb performance with 10 fb^{-1} data
$\sigma(x'^2) = 0.06\times10^{-3}$, $\sigma(y') = 0.7\times10^{-3}$

±0.37	±5.4	BABAR
$^{+0.21}_{-0.23}$	$^{+4.0}_{-3.9}$	BELLE

$\not{CP}$ performance under study (KK and $\pi\pi$)

Other topics

Lepton favour violating τ decays

$\tau \rightarrow 3\mu$, $\rightarrow \mu ee$?

Lepton flavour violating B decays

$B \rightarrow e\mu$

Lepton flavour violating D decays

$D \rightarrow e\mu$

being or will be looked at….

(we cannot do everything now)

5) Conclusions

i) LHC is a b-factory coming online soon, experiments are busy to be ready.
Physics with $\sqrt{s}$ = 14 TeV will start in 2008.

ii) 2008 data could allow us to exclude/discover BSM effect in the B_s sector down to the SM level e.g. for $B_s \rightarrow J/\psi\ \phi$ and $B_s \rightarrow \mu\mu$.

iii) By 2013, wide range of flavour physics in B and D will be explored by LHCb extending further the results obtained by BABAR, BELLE, CDF and D0.

iv) We need help from theory. With a much better theoretical understanding for the form factors and decay constants, we might already see a deviation from CKM with, $|V_{ub}|$, Δm_d, and sin2β.

LHC experiments will soon face the reality.
There will be some bad surprises; background level is higher than expected, resolution is worse, etc…

But with real data, we can learn how to cope with them.

LHC experiments will soon face the reality.
There will be some bad surprises; background level is higher than expected, resolution is worse, etc…

But with real data, we can learn how to cope with them.

CESAR, DORIS, LEP, Tevatron, PEP-II and KEKB, all produced flavour physics results beyond the original expectations. There must be good surprises at LHC too!

My scenario matrix for 2014 at LHC

ATLAS CMS high p_T physics	BSM	Only SM	BSM
LHCb flavour physics	Only SM	BSM	BSM
Particle Physics	☺	☺	☺

Exciting moment is ahead!