Rare B decays at LHCb

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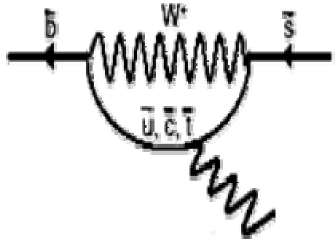
Introduction

- In the SM, b $\longrightarrow$ s only through loops (FCNC) which implies:
  - Processes are rare
  - Powerful to find/constrain NP!

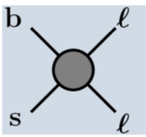


- **O**perator **P**roduct **E**xpansion allows parametrizing effect of new physics throughout different b $\longrightarrow$ s observables :

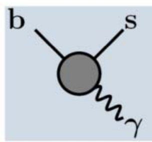
$$H_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^{*} \left\{ \sum_{i=1}^{10} c_i(\mu)\mathcal{O}_i(\mu) + c_S(\mu)\mathcal{O}_S(\mu) + c_P(\mu)\mathcal{O}_P(\mu) + c'_S(\mu)\mathcal{O}'_S(\mu) + c'_P(\mu)\mathcal{O}'_P(\mu) \right\}$$

- Observables are functions of ***C***'s.
  - Branching ratios (*BR*)
  - Polarizations
  - Angular distributions

- Three examples for LHCb:

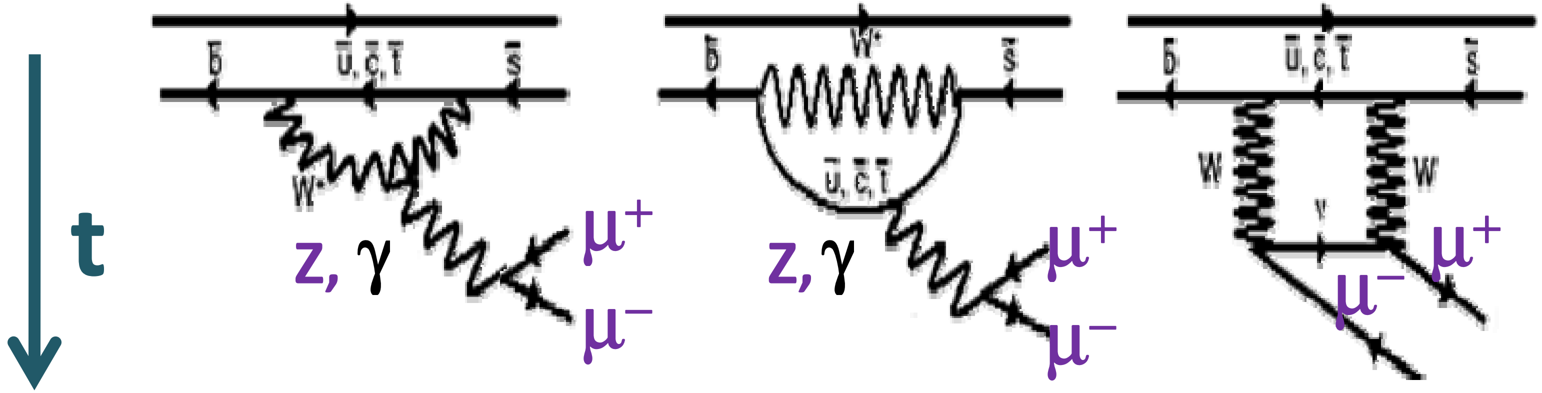


$B^0 \longrightarrow K^*(K^+\pi^-)\mu^+\mu^-$
$B_s \longrightarrow \mu^+\mu^-$



$B_s \longrightarrow \phi(K^+K^-)\gamma$

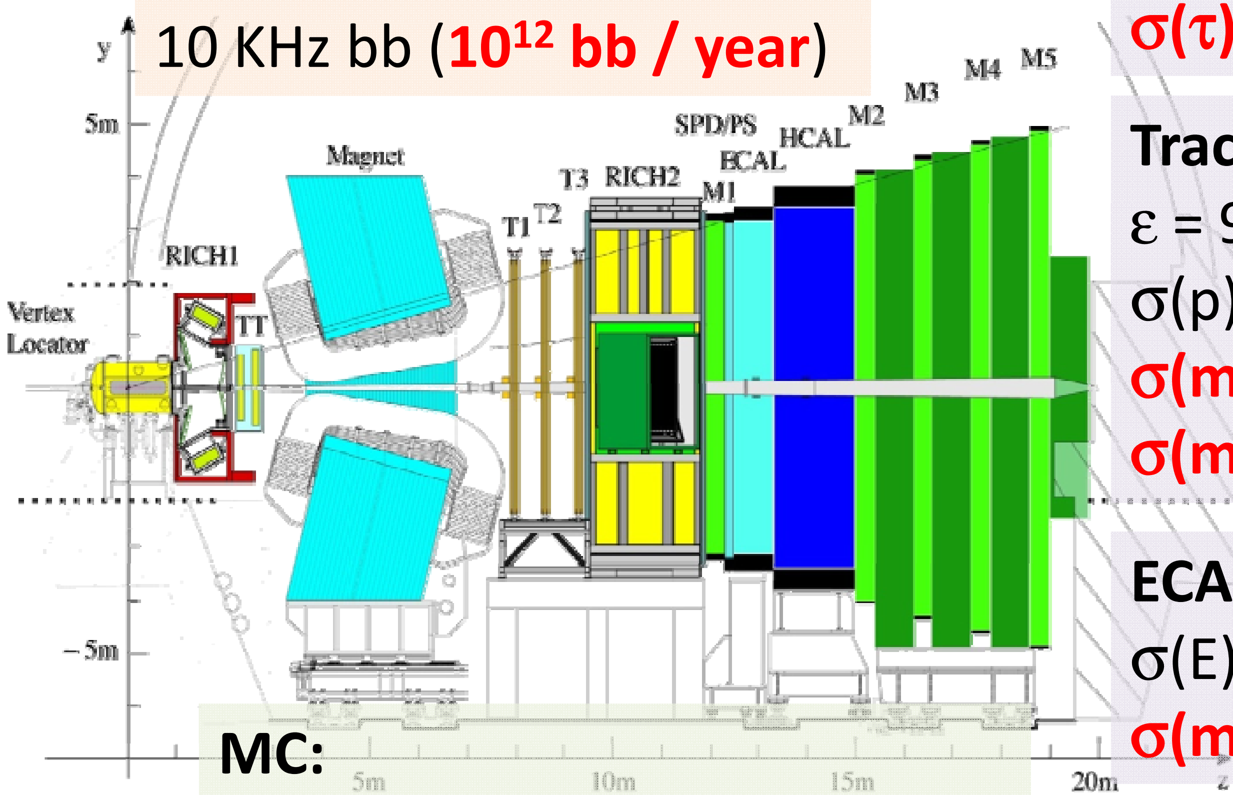
Three interesting rare decays



	NP? in	*BR*(SM)	*BR* exp	@ LHCb
$B_s \to \phi\gamma$	$\mathcal{O}_{7\gamma} \sim m_b \bar{s}_L \sigma_{\mu\nu} b_R F^{\mu\nu}$	Large theory errors on exclusive BRs	$(57^{+18}_{-12}{}^{+12}_{-11})\ 10^{-6}$ Belle'08	γ polarization
$B^0 \to K^* \mu^+\mu^-$	$\mathcal{O}_{7\gamma} \sim m_b \bar{s}_L \sigma_{\mu\nu} b_R F^{\mu\nu}$ $\mathcal{O}_{9\ell(10\ell)} \sim \bar{s}_L \gamma_\mu b_L \bar{\ell}\gamma^\mu(\gamma_5)\ell$		$(1.22^{+0.38}_{-0.32})\cdot 10^{-6}$ B factories	angular distributions
$B_s \to \mu^+\mu^-$	$\mathcal{O}_{S(P)} \sim \bar{s}_L b_R \bar{\ell}(\gamma_5)\ell$	$(3.35\pm0.32)\cdot 10^{-9}$ helicity suppressed	TeVatron @ 90% CL (2 fb^{-1}) **$< 45\times10^{-9}$**	BR

LHCb overview

$\mathcal{L}$ = 2(5)·10^{32} , **2fb^{-1}/year**
10 MHz visible interaction
10 KHz bb (**10^{12} bb / year**)



MC:
Full sim, pile-up & spillover
Photos for FSR in signal

VELO:
σ(IP) ~ 14mm + 35mm/p_T
$\sigma(\tau)$ ~ 40-100 fs

Tracking:
ε = 95% p>5 GeV, 1.9<h<4.9
σ(p)/p ~ (0.4 + 1.5 p/TeV)%
$\sigma(m[B_s \rightarrow \mu\mu])$ ~ 20 MeV
$\sigma(m[K^*\mu^+\mu^-])$ ~ 15 MeV

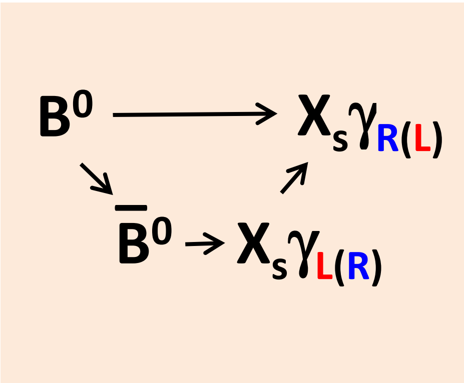
ECAL:
$\sigma(E)/E \sim (9.4/\sqrt{E} \oplus 0.83)\%$
$\sigma(m[B_s \rightarrow \phi\gamma])$: 90 MeV

Muon, RICH:
k-ID: 88% for 3% π misID
μ-ID: 95% for 5% π/k misID

$B_s \rightarrow \phi\gamma$

γ polarization in $B_s \to \phi\gamma$

- SM @ *LO*: $O_7 \Rightarrow B^0 \to X_s\gamma_R$, $\bar{B}^0 \to X_s\gamma_L$, $\tan\psi \equiv A_R/A_L \sim m_s/m_b \sim 0$
  - *NLO* (gluon interchange, etc..) $\tan\psi \sim 0.1$ [1]
  - SM extensions (left-right-symmetric [2] , unconstrained MSSM [3]) predict large $\tan\psi$ while no change on inclusive *BR* ($b \to s\gamma$)
- Interference mixing-decay gives access to γ polarization:



$$\Gamma(B_q(\bar{B}_q) \to f^{CP}\gamma) \propto e^{-\Gamma_q t}\left(\cosh\frac{\Delta\Gamma_q t}{2} - A^{\Delta}\sinh\frac{\Delta\Gamma_q t}{2} \pm C\cos\Delta m_q t \mp S\sin\Delta m_q t\right)$$

no flavour tagging required

$$A_{CP}(t) \equiv \frac{\Gamma[\bar{B}_q \to \phi\gamma] - \Gamma[B_q \to \phi\gamma]}{\Gamma[\bar{B}_q \to \phi\gamma] + \Gamma[B_q \to \phi\gamma]} \qquad A_{CP}(t) = -\frac{C\cos(\Delta m_q t) + S\sin(\Delta m_q t)}{A^{\Delta}\sinh(\Delta\Gamma_q t/2) + \cosh(\Delta\Gamma_q t/2)}$$

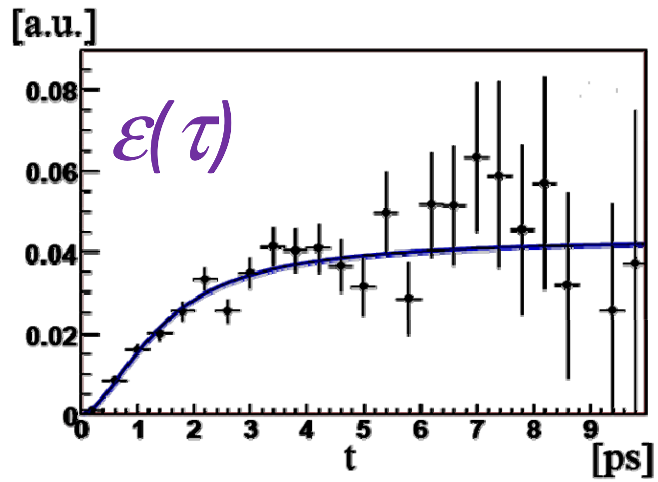
flavour tagging required

- In the SM: $C=0$, $S=\sin 2\psi \sin\phi$, $A^{\Delta}=\sin 2\psi \cos\phi$, $\cos\phi \sim 1$ (mix + CP odd weak phases)
- B-factories: A_{CP} @ $B_d \to K^*(K_s\pi^0)\gamma$: C=-0.03±0.14, S=-0.19±0.23 [HFAG]
- LHCb can study $B_s \to \phi\gamma$: $\Delta\Gamma_s \neq 0$, it probes A^{Δ} as well as C and S !!

[1] B. Grinstein et al, Phys. Rev. D **71**,011504 (2005), Phys. Rev. D **73, 014013 (2006)**
[2] R. N. Mohapatra et al, Phys. Rev. D **11 (1975) 566; (1979) 334.**
[3] H. E. Haber et al, Phys. Rept. **117 (1985) 75.**

$B_s \to \phi\gamma$ at LHCb

- **Acceptance function:** $\varepsilon = \varepsilon(\tau)$
  - because of IP, vertex displacement cuts @ trigger and selection
  - $B_d \to K^*(K^+\pi^-)\gamma$ useful x-check



- **Selection**: $\varepsilon \sim 0.3\%$
  - $\varepsilon_{L0} \sim 85\%$, $\varepsilon_{HLT} \sim 80\%$
  - $E^T_\gamma > 2.7$ GeV

Yields and purities:

	#/2fb^{-1}	rate	B/S
$B_s \to \phi\gamma$	11k	5/hour	<0.55
$B_d \to K^*\gamma$	68k	30/hour	~0.60

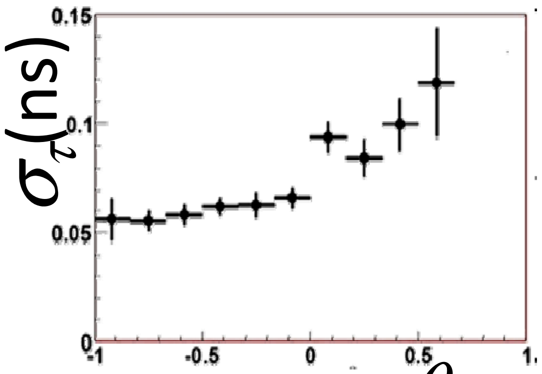
Belle: O(1 $B_s \to \phi\gamma$)/day at Υ(5S)

- **Main background:** $B \to X\phi + \pi^0$
  - $B_s \to \phi\pi^0$ < 4% CALO
  - $B \to K^{*0}\gamma$ < 0.3% RICH

$B_s \to \phi\gamma$ at LHCb

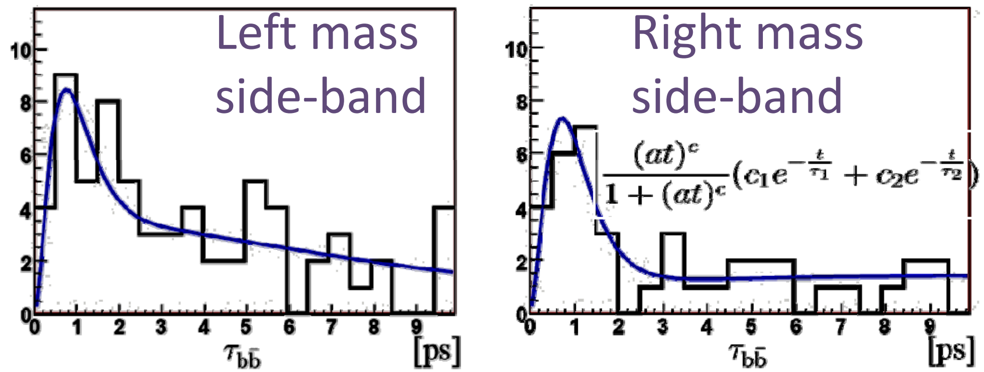
- Other analysis issues:

a) σ_τ depends on $\theta_{\phi-Bs}$



$\rightarrow$ event-by-event errors used in fit

b) Background "lifetime" vs mass:



$\rightarrow$ checked that parameter resolutions are robust under bkg lifetime, B/S, σ_τ

- Precision on A_{CP} parameters:
  - Fix m_s, Γ_s, $\Delta\Gamma_s$, acceptance, ε tagging, background "lifetime"

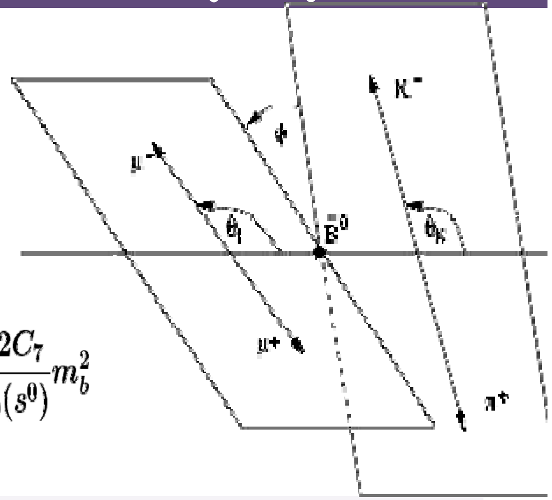
	Tagging	$0.5fb^{-1}$	$2fb^{-1}$
$\sigma(A^\Delta)$	No	0.3	0.22
σ(S, C)	Yes	0.2	0.11

$\rightarrow \sigma_\psi \sim 0.1$

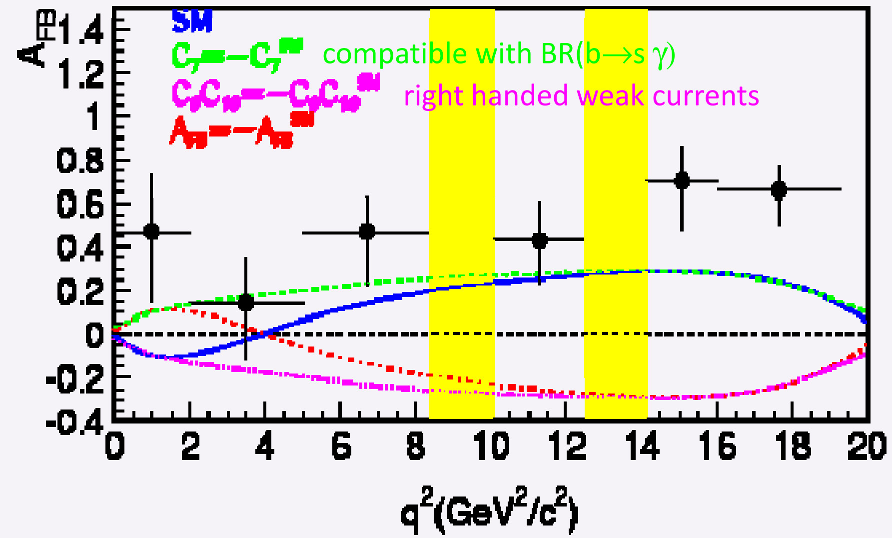
$B^0 \rightarrow K^*\mu^+\mu^-$

Angular distributions in $B^0 \to K^*\mu^+\mu^-$

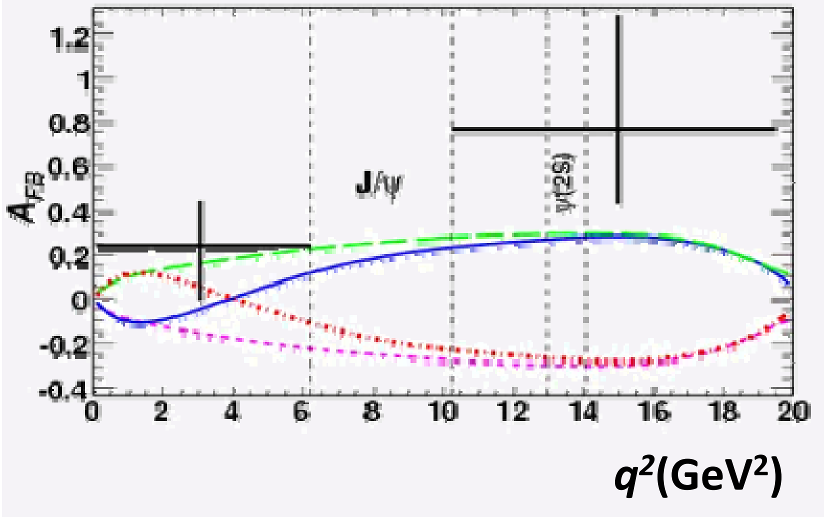
- Decay described by θ_l, ϕ, θ_K and $q^2 \equiv m_{\mu\mu}^2$
- Some observables have low theoretical error
- Ex: A_{FB} of θ_l vs q^2 in $1 < q^2 < 6$ GeV^2 low systs.
- – For 0 x-ing point s_0, cancellation of form factors, $s_0 \approx \frac{-2C_7}{C_9(s^0)} m_b^2$
- – $s_0^{SM} = 4.36^{+0.33}_{-0.31}$ GeV^2 [1]



BELLE ~230 K*ll evts (657M BB)



BaBar ~60 K*ll evts (384 M BB)



CDF ~20 K*μμ events (0.9fb^{-1})

[1] M Beneke et al, Eur Phys J C 41 173-188, 2005

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

- Selection:

	S/2fb^{-1}	B/2fb^{-1}	ε (%)	B/S	S/√S+B
Cuts	4 k	1 k	0.7	0.3	60
Fisher	8 k	3 k	1.4	0.3	80

~230@BELLE

$\varepsilon_{L0} \sim 90\%$
$\varepsilon_{HLT} \sim 75\%$

- Background:

	fraction
$b \to \mu$, $b \to \mu$	60%
$b \to \mu c (\to \mu)$	40%
$B_s \to \phi\mu\mu$ $B_{d,u} \to s\mu\mu$ μ missid	negligible

→ effect on asymmetry, ex:
$B^+ \to \mu^+ \nu\, D^0 (\to K^+ \mu^- \nu)$
but can be modeled from mass side-bands

- Developed 4 methods, with increasing:
  – Sensitivity to NP, model independence
  – Requirements in terms of statistics, control of acceptance functions

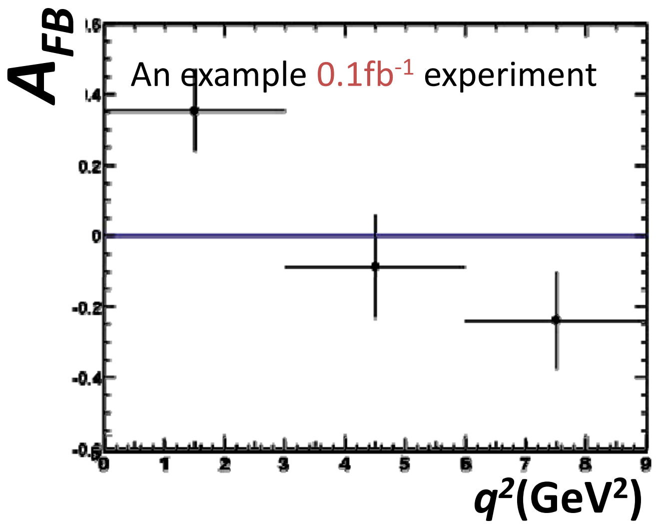
$B^0 \rightarrow K^*\mu^+\mu^-$ at LHCb

1. **Counting A_{FB} in bins of q^2**
   - Precision from linear fit, incl. bkg:

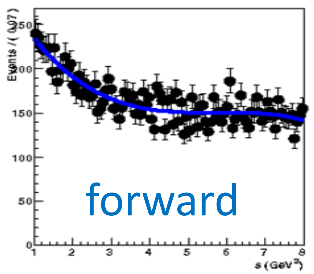
	$0.5fb^{-1}$	$2fb^{-1}$	$10fb^{-1}$
$\sigma(s^0)$	0.8 GeV^2	0.5 GeV^2	0.3 GeV^2

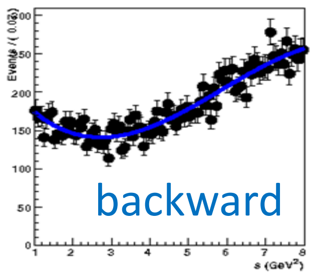
$\sim\sigma(s_0^{SM})$

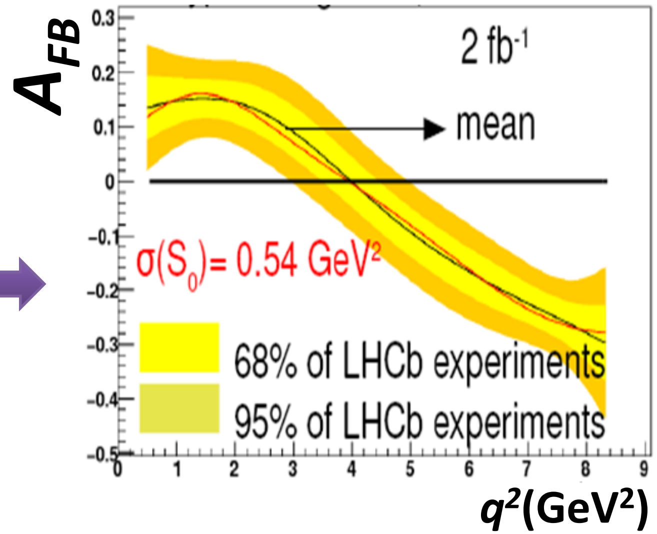
   - @ 0.07 fb^{-1} competitive with B-facts



2. **Unbinned A_{FB} vs q^2**
   - No need to assume linearity
   - Remove dependence on bin-size, fit range







$B_d \to K^*\mu\mu$ at LHCb

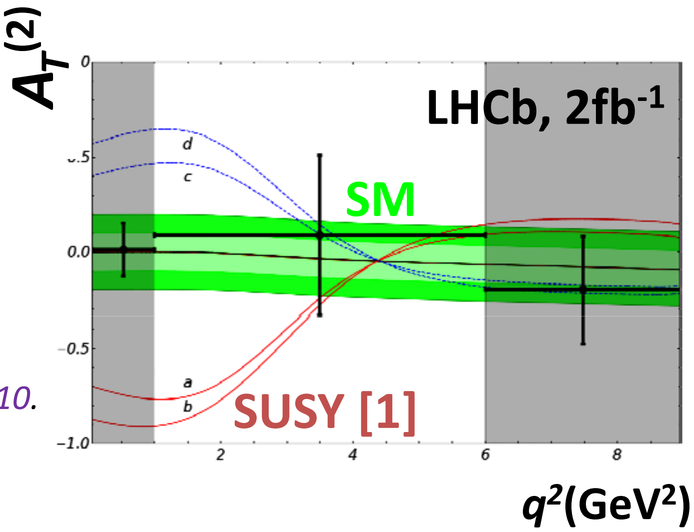
3. **Fitting projections on θ_l, ϕ, θ_{K^*}:**

$$\frac{d\Gamma'}{d\phi} = \frac{\Gamma'}{2\pi}\left(1+\frac{1}{2}(1-F_L)A_T^{(2)}\cos 2\phi + A_{Im}\sin 2\phi\right)$$

$$\frac{d\Gamma'}{d\theta_l} = \Gamma'\left(\frac{3}{4}F_L\sin^2\theta_l + \frac{3}{8}(1-F_L)(1+\cos^2\theta_l) + A_{FB}\cos\theta_l\right)\sin\theta_l$$

$$\frac{d\Gamma'}{d\theta_K} = \frac{3\Gamma'}{4}\sin\theta_k\left(2F_L\cos^2\theta_K + (1-F_L)\sin^2\theta_K\right)$$

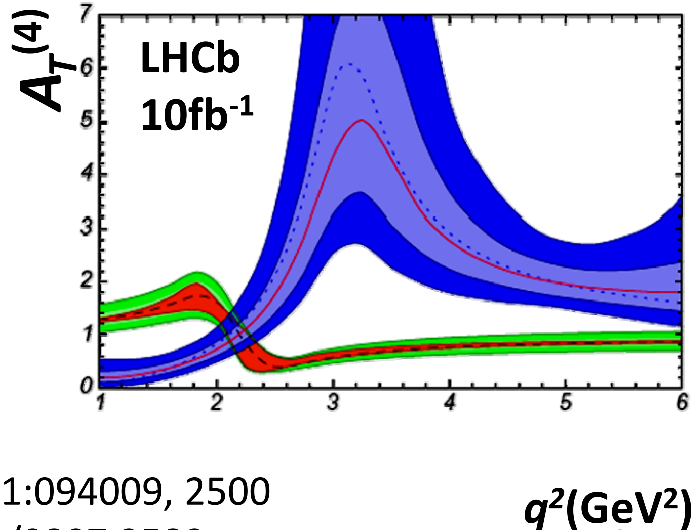
- F_L, A_T, A_{FB} model-indep. functions of C_7, C_9, C_{10}.
- $\sigma(s_0)$ factor ~2 better



4. **Full angular analysis:**

- Requires ~ 2fb^{-1}, full acceptance correction
- Can form any observable
- Eg [2]:

SUSY, large-gluino + positive mass insertion ⊗ 1σ, 2σ LHCb	vs	SM with theory error bands



[1] Kruger et al, Phys.Rev.D71:094009, 2500
[2] Egede et al, arXiv:hep-ph/0807.2589

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

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

- SM: BR = $(3.35\pm0.32)\cdot10^{-9}$ [1]

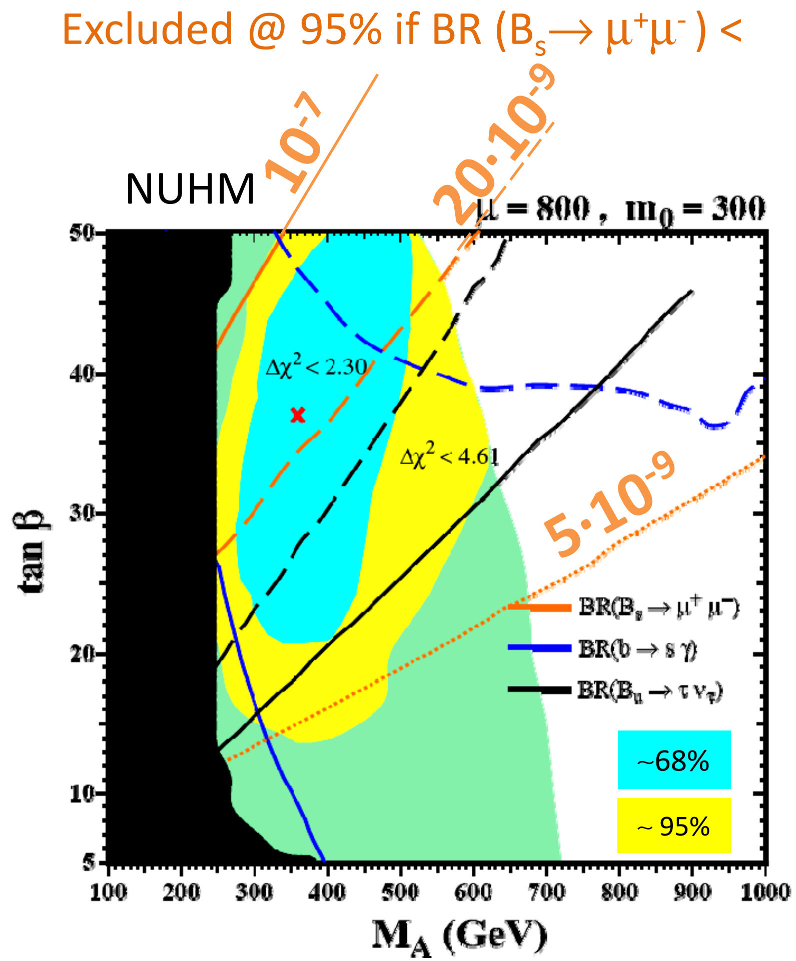
- TeVatron
  - @ 90% CL (~2 fb^{-1}) < $45\cdot10^{-9}$
  - final (8 fb^{-1}): < $20\cdot10^{-9}$ **6x BR!**

- MSSM:

$$Br^{MSSM}(Bq \to l^+l^-) \propto \frac{m_b^2 m_l^2 \tan^6\beta}{M_{A0}^4}$$

- Ex: Non-Universal Higgs Masses framework (generalization of CMSSM) [2]
  - $b \to s\gamma$, M_h>114.4 GeV, $(g_\mu-2)$ @ 3.4σ from SM, WMAP dark matter density

    $\Rightarrow$ **$BR(B_s \to \mu^+\mu^-)$~20×10^{-9}**



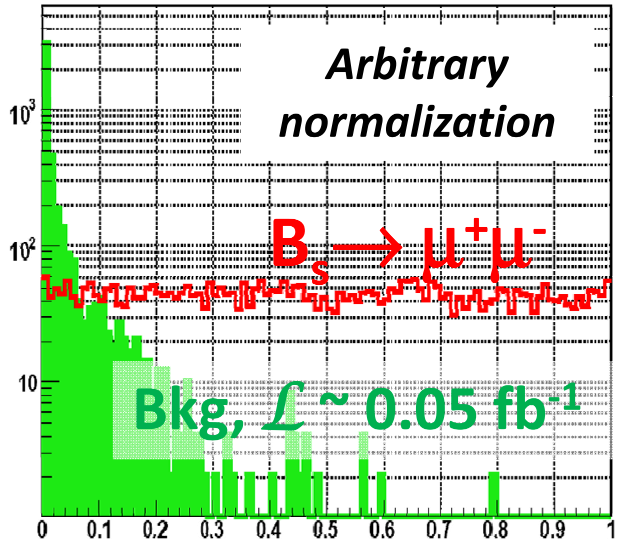
[1] arXiv:hep-ph/0604057 (2006)
[2] arXiv:0709.0098

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

1. Selection $\varepsilon \sim 6\%$

   ($\varepsilon_{L0} \sim 95\%$, $\varepsilon_{HLT} \sim 90\%$)

2. Categorization of signal likelihood:
   - **Geometry:** combination of IPS, B lifetime, isolation, B IP, DOCA
   - **Invariant mass**
   - **μ identification**



Geometry likelihood

3. Exclude/observe BR from distrib. in 3D bins, use CLs method [1]
   - BR reach 20% better than in simple cut analysis

	#/2fb^{-1} for GL>0.5
Signal	**21***
$b \to \mu b \to \mu$	172*
$B \to hh$	7.8*
$B_c \to J/\psi\mu^+\nu$ μ missid	~ 0

(*) In many bins!

[1] A. L. Read, http://doc.cern.ch/yellowrep/2000/2000-005/p81.pdf

$B_s \rightarrow \mu^+\mu^-$: calibration

- For normalization of BR, use control channels instead of MC

$$BR = \frac{BR_n \cdot \varepsilon_n^{REC} \varepsilon_n^{SEL} \varepsilon_n^{TRIG}}{\varepsilon^{REC} \varepsilon^{SEL} \varepsilon^{TRIG}} \cdot \frac{N}{N_n}$$

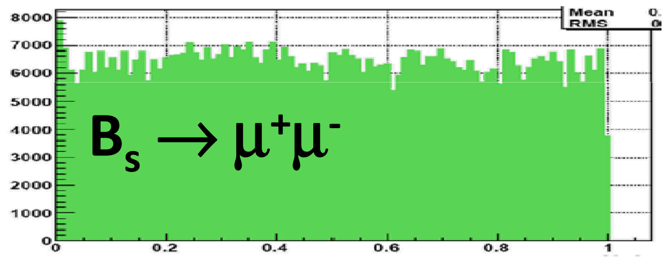
- B_s BRs measured with large errors (>20%) $\rightarrow$ use B_d, B^+
  - Then the largest syst. (13%) comes from additional factor:

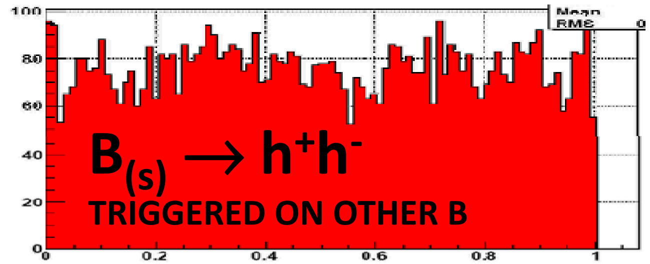
$$\frac{f_{B_s^0}}{f_{B^+}} = \frac{f_{B_s^0}}{f_{B_d^0}} = 0.265 \pm 0.034 \quad \text{[HFAG]}$$

- Useful channels:

	#/2fb^{-1}	σ_{BR}/BR
$B^+ \rightarrow J/\psi\ (\mu^+\mu^-)\ K^+$	1.6 M	~ 3%
$B \rightarrow J/\psi\ (\mu^+\mu^-)\ K^*\ (K^+\pi^-)$	1.3 M	~ 5%
$B_{(s)} \rightarrow h^+h^-(B_d \rightarrow K^+\pi^-)$	440 k	(~ 4%)

Ex: Calibration of geometry likelihood

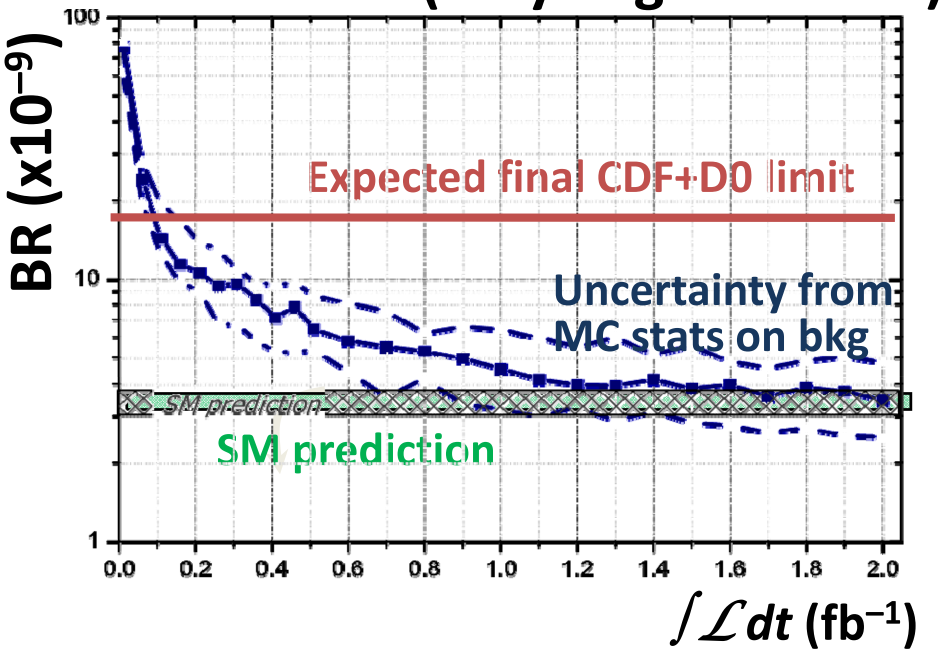


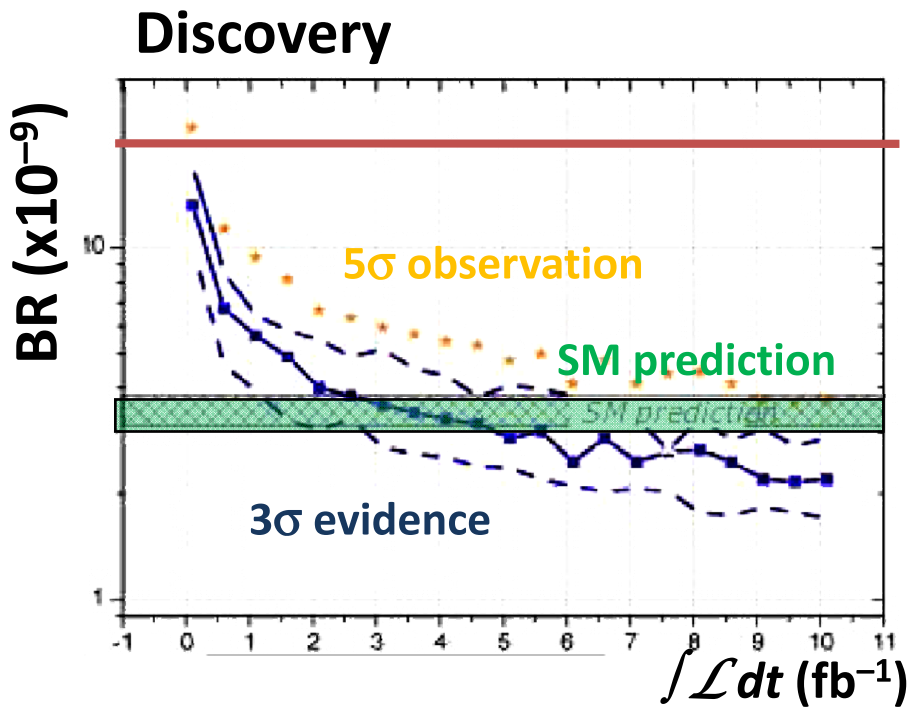


Geometry likelihood

< 6% per bin for 0.5fb^{-1} (bkg incl.)

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





Exclusion

0.25 $fb^{-1} \to$ BR < 10^{-8}

2 $fb^{-1} \to$ BR < SM

Discovery (@ SM BR):

3 $fb^{-1} \to$ 3σ evidence

10 $fb^{-1} \to$ 5σ observation

LHCb

Conclusions

- LHCb ready to exploit the B factory known as LHC
- With $2fb^{-1}$ integrated luminosity:
  - $B_s \to \mu\mu$: BR exclusion down to SM value
    - 5σ observation at SM value with $10\ fb^{-1}$
  - $B_d \to K^* \mu\mu$: $\sigma(s_0) \sim 0.5 GeV^2$
    - Start having sensitivity to other observables with more complex fits
  - $B_s \to \phi\gamma$: from CP asymmetry, $\sigma_\psi / \psi \sim 10\%$
- **Rare B decays in LHCb will constrain extensions of SM or find NP**

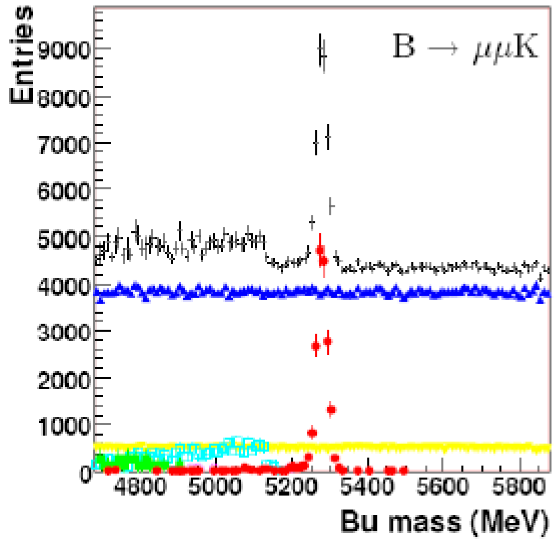
Back-up

More rare decays

- **Radiative :**
  - **Polarization through ancular distributions:**
    - $\Lambda_b \to \Lambda^0\gamma$, $\Lambda_b \to \Lambda^*\gamma$ for $\tan\psi$, @ 3σ >20-25% each with $10fb^{-1}$
    - $B^\pm \to \phi K^\pm \gamma$ for $\cos 2\psi$
  - $B \to \rho^0\gamma$, $B \to \omega\gamma$ for $b \to d$
- **Other $b \to sll$ observables:**
  - $B^+ \to K^+ll$ direct CP asymmetry in $B \to K^*\mu^+\mu^-$, $B^+ \to K^+\mu^+\mu^-$
    - small in SM <~0.01, statistical error with 10/fb: ~0.01
  - $B^+ \to K^+ll$ for ratio e^+e^- / $\mu^+\mu^-$ (R_K)
    - SM prediction 0.1% theoretical uncertainty, 4% @ LHCb after $10fb^{-1}$
  - $B_s \to \phi\mu^+\mu^-$, B_s/B_d,~ ¼, flavour tagging ~ 1/15
  - $\Lambda_b \to \Lambda\, \mu^+\mu^-$ not yet studied
- **$b \to dll$:**
  - $B_s \to K^*\mu^+\mu^-$, B_s/B_d,~ ¼, $|V_{td}/V_{ts}|^2=0.208^2$ ~ 1/25
- **Lepton Flavour Violation : $B_q \to ll'$**

$\Gamma(B \to K\mu^+\mu^-) / \Gamma(B \to Ke^+e^-)$

- $R_K = \Gamma(B \to K\mu^+\mu^-)/\Gamma(B \to K e^+e^-)$
  - precise prediction in SM (e.g. Hiller & Kruger, 2004)
    - $R(K+) = 1.000 \pm 0.001$
    - $R(K^*) = 0.991 \pm 0.002$ (for $\sqrt{s} > 2m_\mu$)
  - like $B_s \to \mu^+\mu^-$ sensitive to C_S and C_P
    - corrections can be O(10%) for instance with neutral Higgs exchange



- challenging in LHCb, due to large background
  - in particular in e^+e^- final state
  - expected number of selected events for with 10/fb
    - ~10k $B^\pm \to K^\pm e^+e^-$
    - ~19k $B^\pm \to K^\pm\mu^+\mu^-$
  - gives $\sigma(R_K) = 0.04$ in 10/fb

b b-bar
$B \to J/\Psi K$
prompt J/Ψ
$B \to X_s e^+e^-$
signal
total