Rare Decays at LHCb

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CERN Theory Institute LHC
b Focus week

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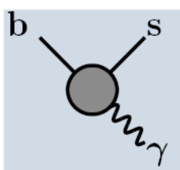
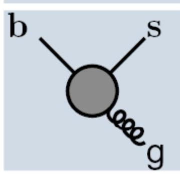
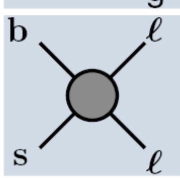
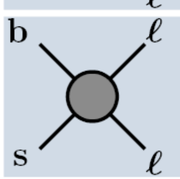
Introduction

- New physics can give effective Hamiltonian, *H*, new operators O_i or modified Wilson coefficients C_i

$$A(M \to F) = \langle F \,|\mathcal{H}_{\mathrm{eff}}|\, M \rangle \qquad \mathcal{H}_{\mathrm{eff}} = -\frac{4G_F}{\sqrt{2}} V_{ts}^{*} V_{tb} \sum_{i=1}^{10} C_i(\mu) \mathcal{O}_i(\mu)$$

- Rare B decays give a number of opportunities to constrain these contributions:

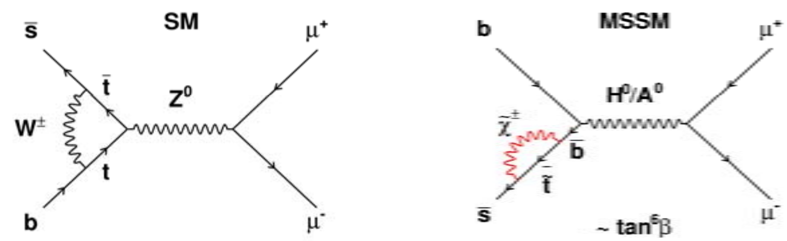
		magnitude	phase	helicity flip $\mathcal{O}_i'$
$\mathcal{O}_{7\gamma}$		$b \to s\gamma$	$a_{CP}(b \to s\gamma)$	$\Lambda_b \to \Lambda\gamma$ $B \to (K^* \to K\pi)\ell^+\ell^-$ $B \to (K^{**} \to K\pi\pi)\gamma$
$\mathcal{O}_{8g}$		$b \to s\gamma$ $B \to \not{X}_c$	$a_{CP}(b \to s\gamma)$ $B \to K\phi$	$\Lambda_b \to \Lambda\phi$ $B \to K^*\phi$
$\mathcal{O}_{9\ell,10\ell}$		$b \to se^+e^-$	$A_{FB}(b \to s\ell^+\ell^-)$	$B \to (K^* \to K\pi)\ell^+\ell^-$
$\mathcal{O}_{S,P}$		$B_{d,s} \to \mu^+\mu^-$	$B_{d,s} \to \tau^+\tau^-$	$b \to s\tau^+\tau^-$

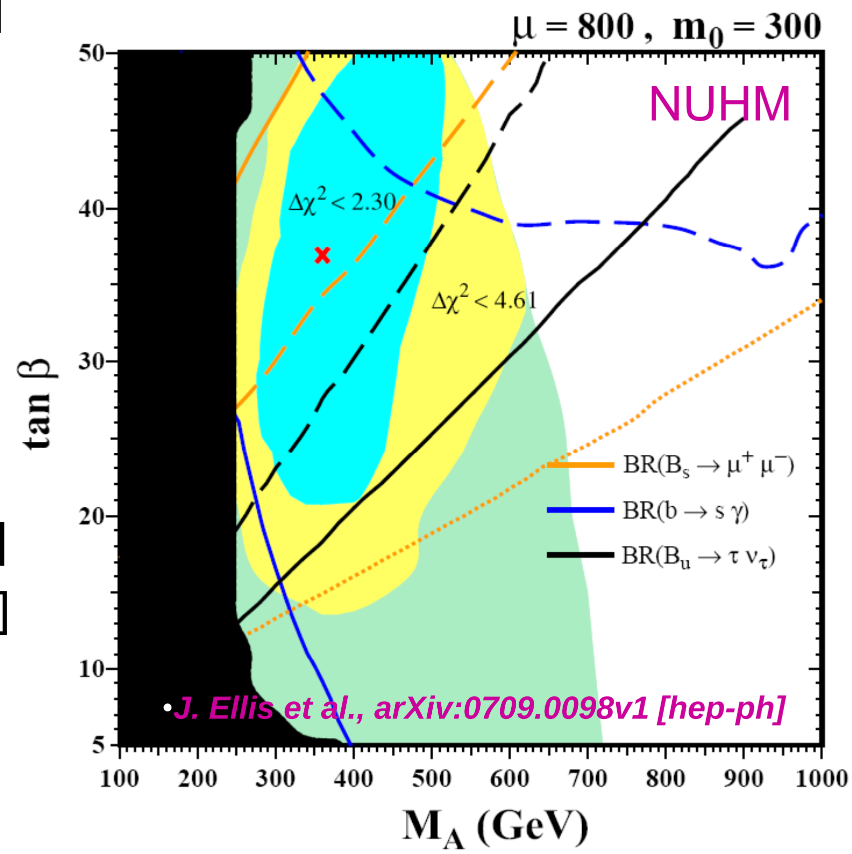
From G. Hiller [hep-ph/0308180]

$B_s \rightarrow \mu\mu$

$B_s \to \mu\mu$

- $B_s \to \mu\mu$ helicity suppressed
- Well predicted in SM:
  - $BR(B_s \to \mu\mu) = (3.35 \pm 0.32) \times 10^{-9}$ [1]
- Sensitive to (pseudo) scalar operators
  - MSSM: $\tan^6$ ®/M_A^4 enhancement
  - NUHM: favours large tan β (~30)
- Current limits from Tevatron:
  - CDF BR < 4.7×10^{-8} 90% CL [2]
  - D0 BR < 7.5×10^{-8} 90% CL [3]





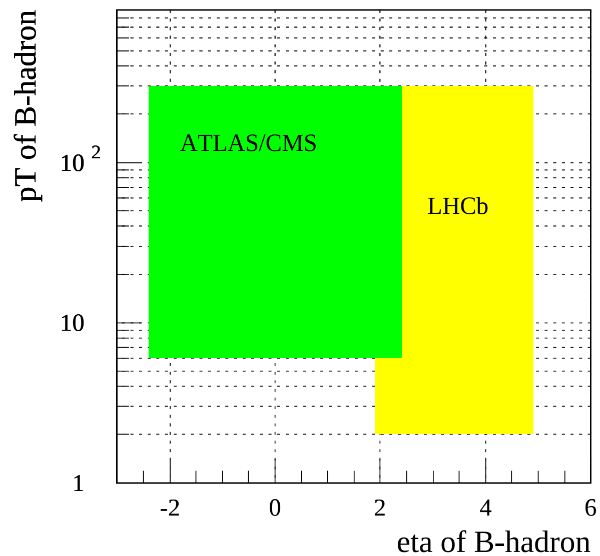
[1] hep-ph/06040507v5

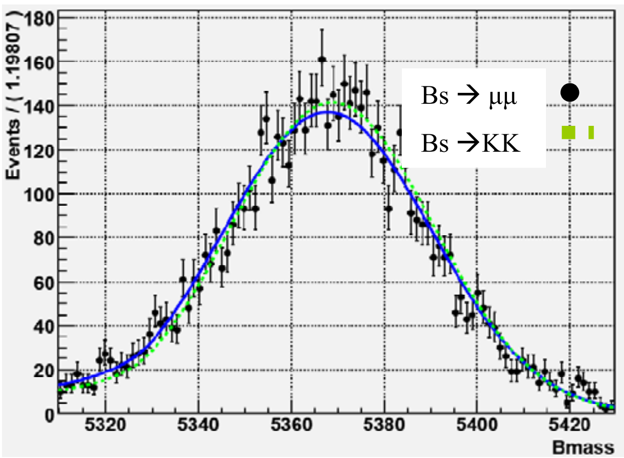
[2] arXiv:0712.1708v1 [hep-ex]

[3] arXiv:0705.300v1 [hep-ex]

$B_s \to \mu\mu$ at LHCb

- Searching for $B_s \to \mu\mu$ with LHCb:
  - Large prodn x-secn for b's at high η, low p_T
    → At $L = 2\text{x}10^{32}\ \text{cm}^2\text{s}^{-1}$, 10^{12} $b\bar{b}$ pairs in 10^7s
  - Trigger has μ p_T threshold >~1GeV
    → ~1.5kHz inclusive μ, di-μ
  - Small event size
    → Can write this rate out, open analysis – can retain max. efficiency
  - High precision magnetic spectrometer
    → B_s mass resolution ~20MeV
    (c.f. CMS ~40MeV, ATLAS ~80MeV)
  - Vertex detector very close to LHC beams
    → Excellent vtx, impact parameter resolution

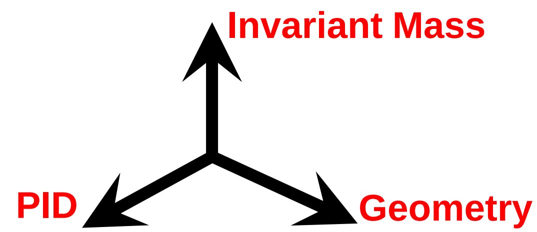


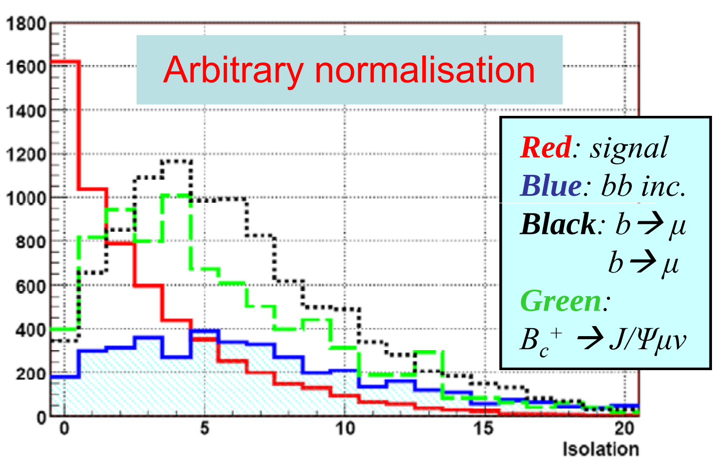


Mass *(MeV)*

$B_s \to \mu\mu$ at LHCb

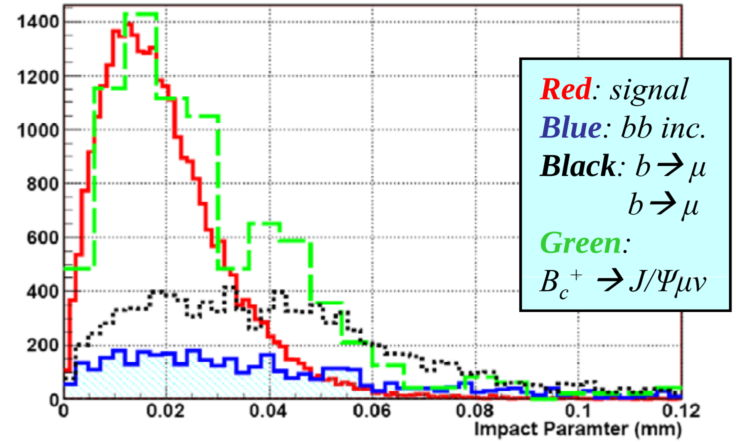
- Events classified according to geometrical likelihood, PID and B_s invariant mass:
  - Geometric likelihood:
    - B_s Lifetime
    - μ SIPS: Mu Impact Parameter Significance
    - DOCA: Distance of closest approach
    - B_s IP: B_s impact parameter to prim. vtx
    - Isolation: No. of good secondary vtx that can be made with μ candidates
  - PID:
    - Calibration muons (MIPs in calorimeter, J/ψ muons)
  - B_s Invariant Mass

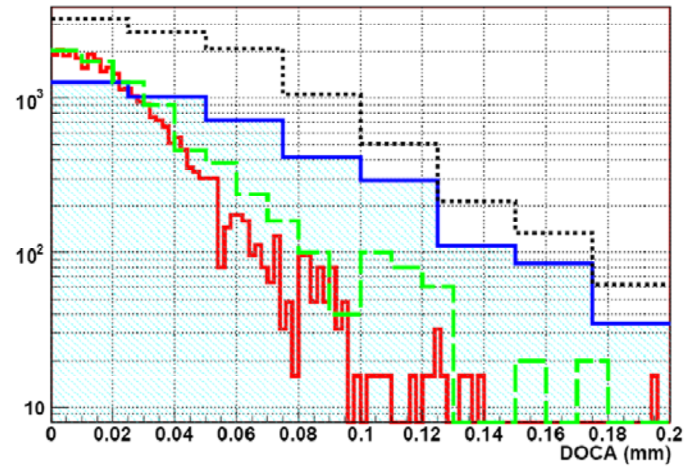




$B_s \rightarrow \mu\mu$ at LHCb

- Analysis:
  - Signal description: $B \rightarrow hh$ (~200k events/2fb^{-1})
  - Background estimation from mass sidebands
  - Normalisation: $B^+ \rightarrow J/\psi K^+$ (2M events/2fb^{-1})
  - Dominant uncertainty on BR from relative B_s, B^+ hadronisation fraction ~13%

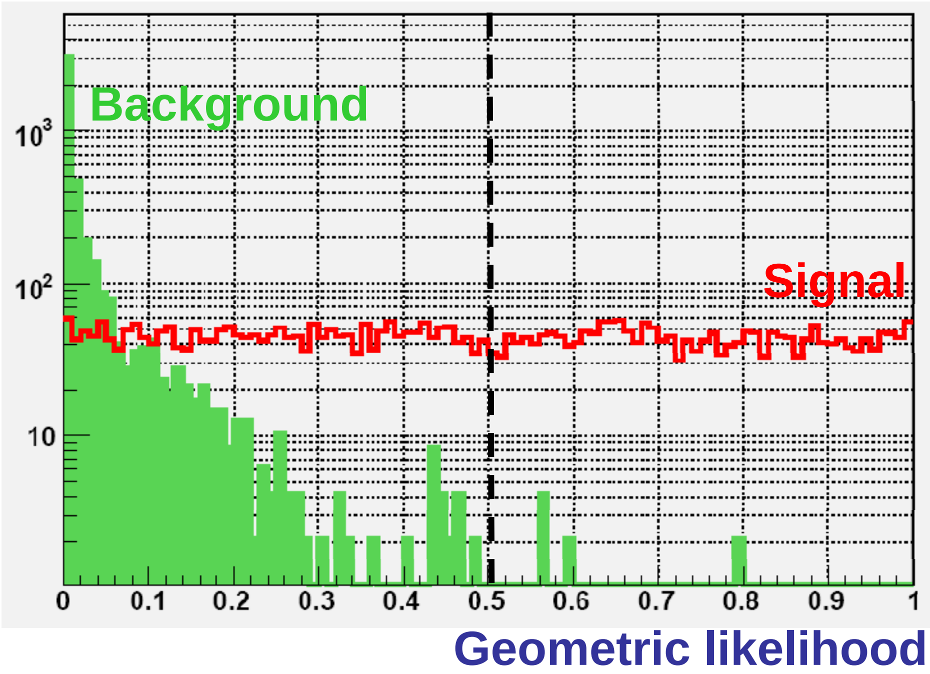




$$BR = \frac{BR_n \cdot \varepsilon_n^{REC} \varepsilon_n^{SEL} \varepsilon_n^{TRIG}}{\varepsilon^{REC} \varepsilon^{SEL} \varepsilon^{TRIG}} \cdot \frac{f_n}{f_{Bs}} \cdot \frac{N}{N_n}$$

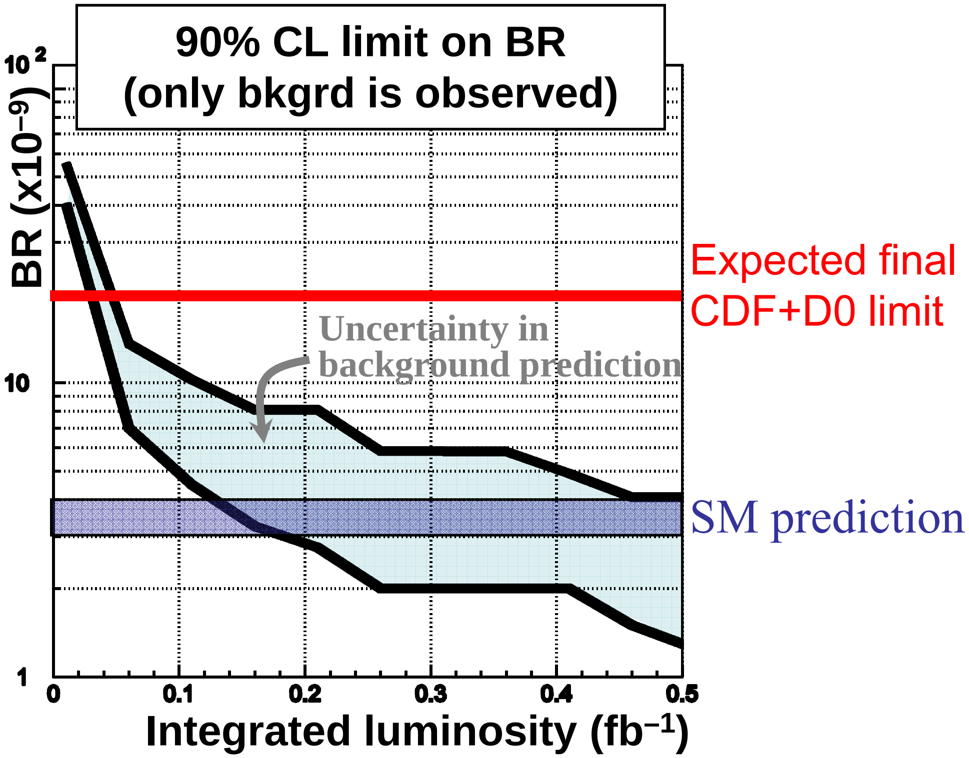
$B_s \to \mu\mu$ at LHCb

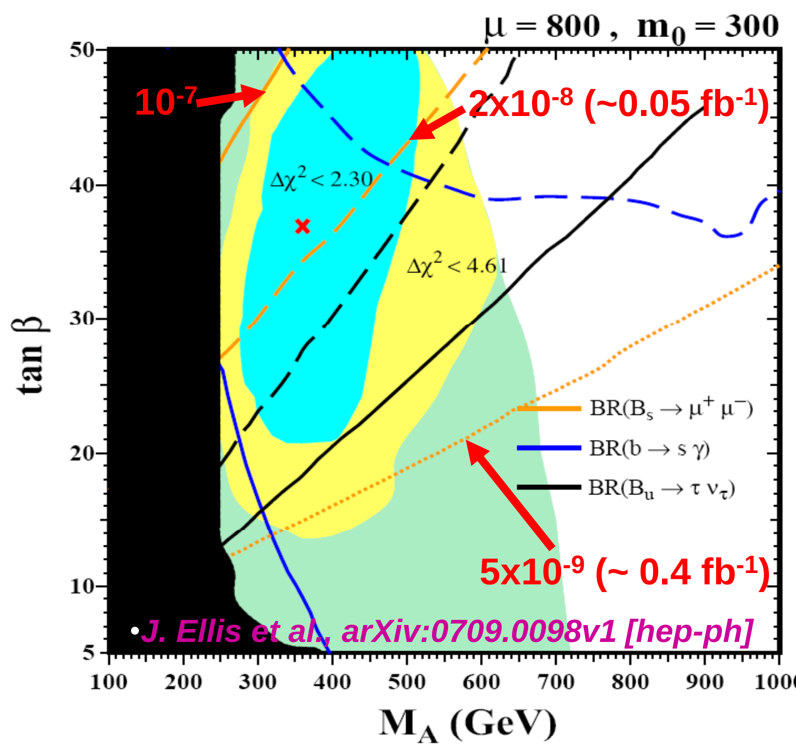
- Background:
  - Dominated by $b \to \mu$, $b \to \mu$, $b \to \mu$, $b \to c \to \mu$ also contributes
  - Mis-id ($B \to hh$), insignificant
  - Dominant exclusive bkgrd $B_c^+ \to J/\Psi \mu\nu$, tiny cf. $b \to \mu$, $b \to \mu$
  - Drell-yan insignificant at these masses



- Total efficiency for all geometric likelihood values ~10%
- Taking events with GL>0.5, assuming SM BR, with $2 fb^{-1}$:
  - Signal ~30 events
  - Bkgrd ~83 events

$B_s \to \mu\mu$ at LHCb





Exclusion:
0.1 fb^{-1} ⇒ BR < 10^{-8}
0.5 fb^{-1} ⇒ < SM

With SM Branching ratio
2 fb^{-1} ⇒ 3σ evidence
6 fb^{-1} ⇒ 5σ observation

With 0.1fb^{-1} can measure BR 9 (15)$\times10^{-9}$ at 3 (5)σ

With 0.5fb^{-1} can measure BR 5 (9)$\times10^{-9}$ at 3 (5)σ

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

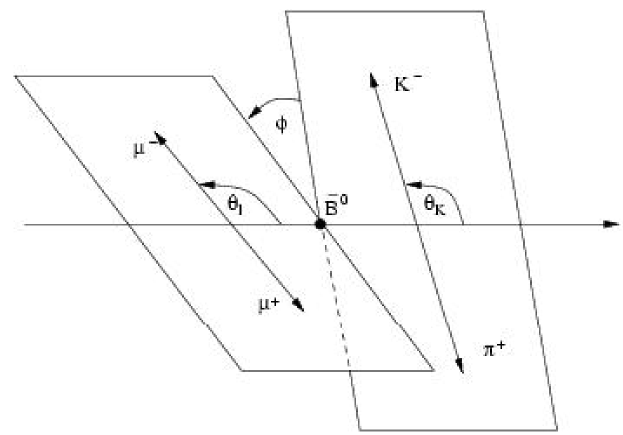
$B_d \to K^* \mu\mu$

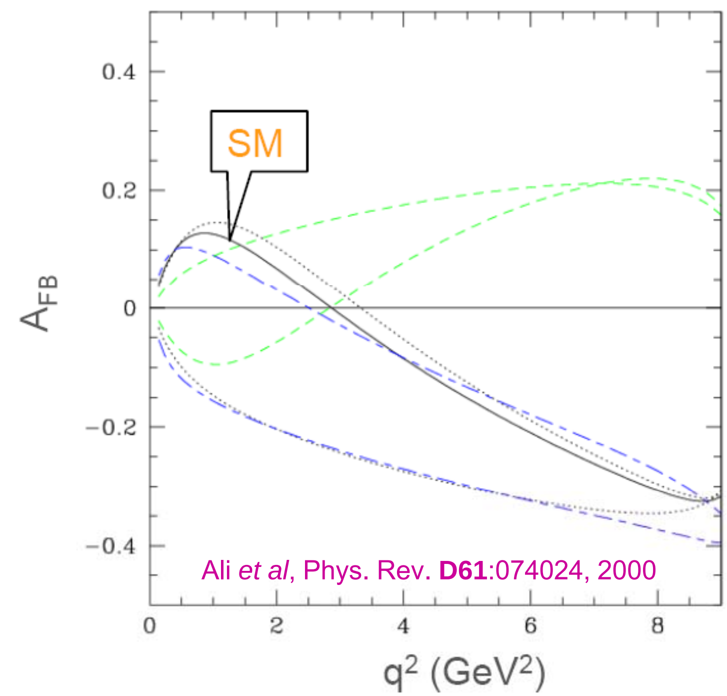
- BR measured at B-factories, in agreement with SM:
  $BR(B_d \to K^*\mu\mu) = (1.22^{+0.38}_{-0.32}) \times 10^{-6}$ [1]

- Decay described by three angles (θ_l, ϕ, θ_{K^*})

- Angular distributions as function of q^2 gives sensitivity to NP contributions

- Forward-backward asymmetry A_{FB} in θ_l angle has received particular theoretical attention – predicted in a number of different models

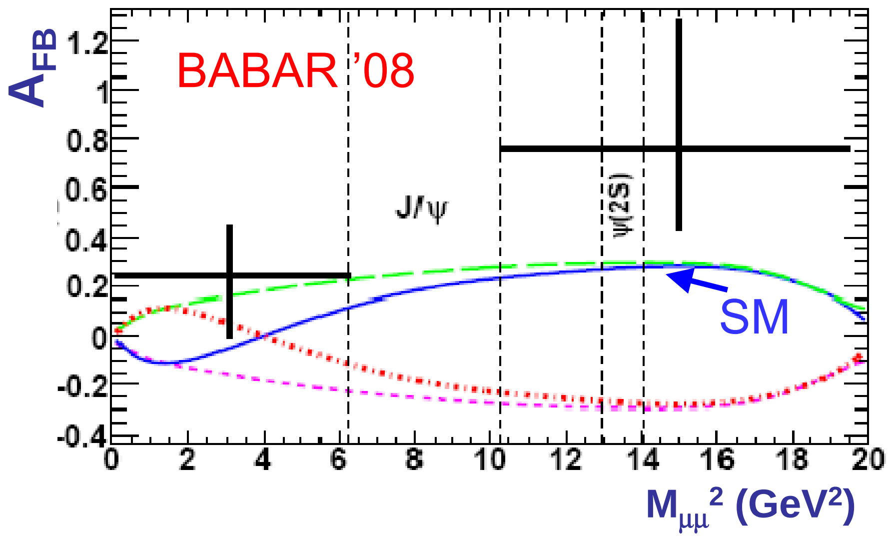


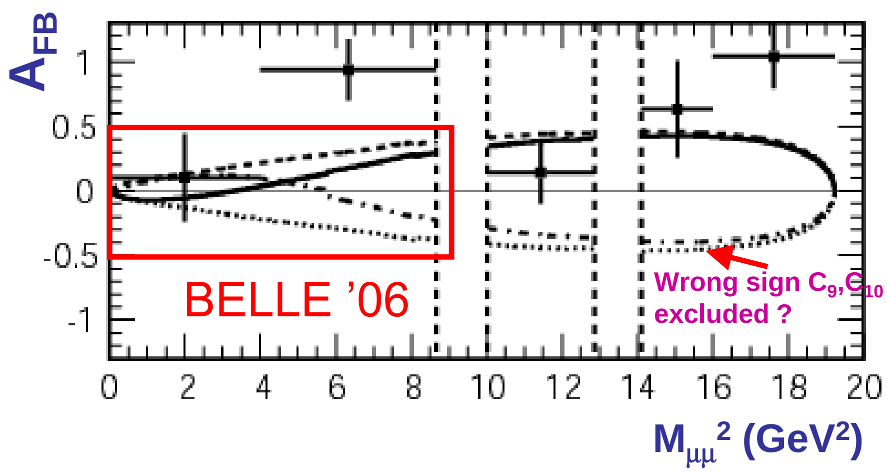


[1] PDG 2006

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

- B-factories each collected O(100) signal events
- CDF has ~35 signal events
- Given projected total datasets these experiments, a total of <1000 events might be observed at all facilities
- With L=2x10^{32} cm^{2}s^{-1}, LHCb will observe this no. of events with ~0.25fb^{-1} integrated luminosity





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

- Signal selection:
  - Total selection efficiency ~1%
  - → 7200 signal events /2fb^{-1} (~50% below $m_{J/\Psi}$)

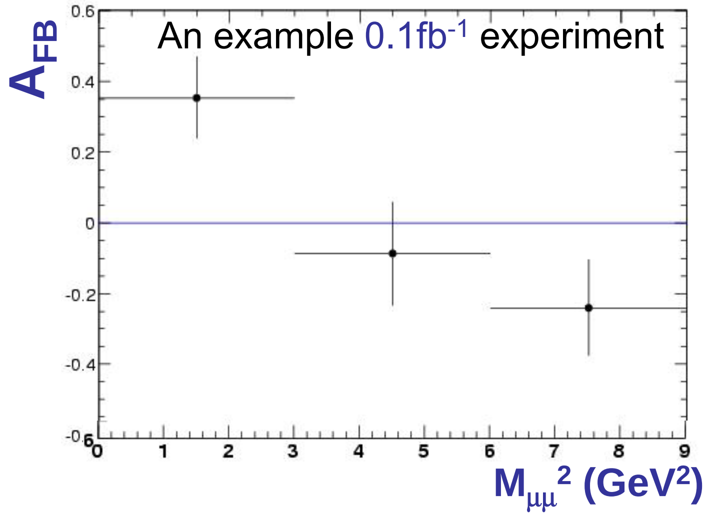
- Full A_{FB} spectrum of interest but zero-crossing point often computed:
  - $s^0_{SM} = 4.39^{+0.38}_{-0.35}$ GeV^2 [1]

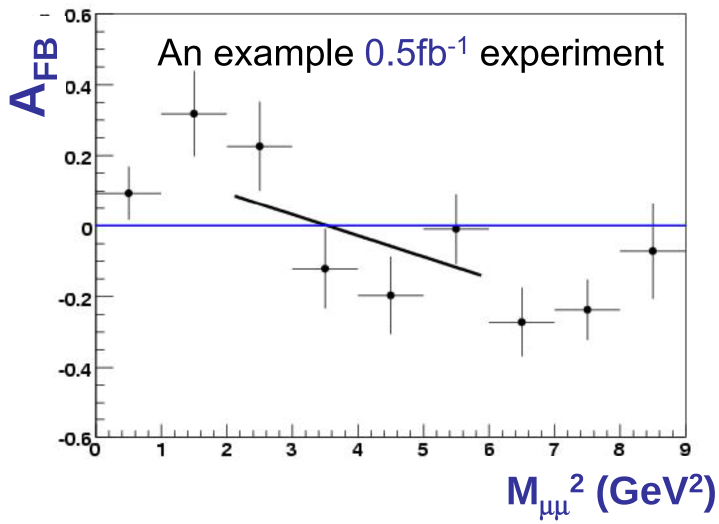
  (older value used in model →)

- Simple linear fit suggests precision:

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

- Looking at extended beyond linear fit



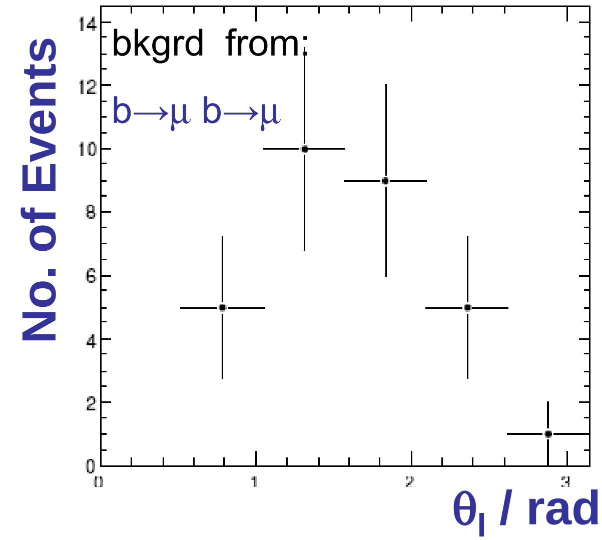


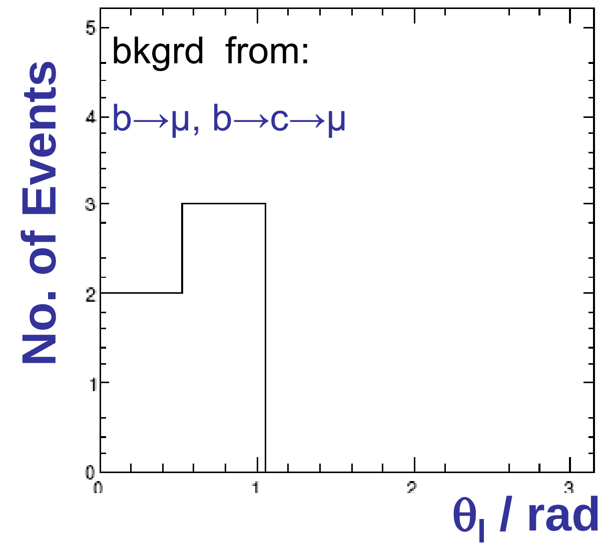
[1] arXiv:0106067v2 [hep-ph]

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

- Background:
  - $b \to \mu$, $b \to \mu$ dominant contribution, symmetric distribution in θ_l – scales A_{FB} observed
  - $b \to \mu$, $b \to c \to \mu$ significant contribution, asymmetric θ_l distribution – effect on A_{FB} depends on θ_l shape
  - As for $B_s \to \mu\mu$, don't observe any significant background from μ mis-id
  - Non-resonant $K\pi\mu\mu$ events not yet observed
  - Bkgrd rejection dependent on B_d mass resoln:
    $\sigma(m_{Bd})$ ~15MeV (c.f. ATLAS 50MeV)
  - B/S ~0.5

- Analysis issues:
  - In order to correct A_{FB} value measured, require knowledge relative angular efficiency:
    - p_T cuts on muons (in e.g. trigger), remove events with θ_l ~0,π
    - muon reconstruction requirements distort momentum spectrum





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

- Decays contain much more information than θ_l, A_{FB} distributions

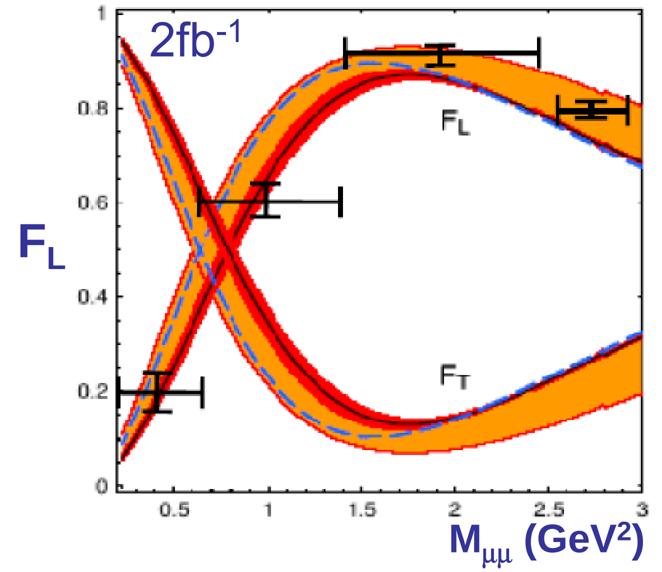
- Fitting projections of θ_l, ϕ, θ_{K^*} angular distributions:

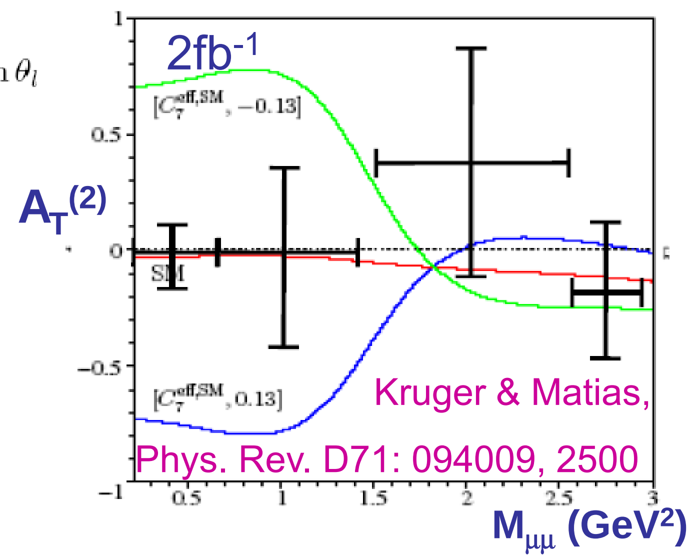
$$\frac{d\Gamma'}{d\phi} = \frac{\Gamma'}{2\pi}\left(1+\frac{1}{2}(1-F_L)A_T^{(2)}\cos 2\phi + A_{Im}\sin 2\phi\right)$$

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

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

$\rightarrow$ fraction of longitudinal polarization, F_L, and transverse asymmetry A_T^2



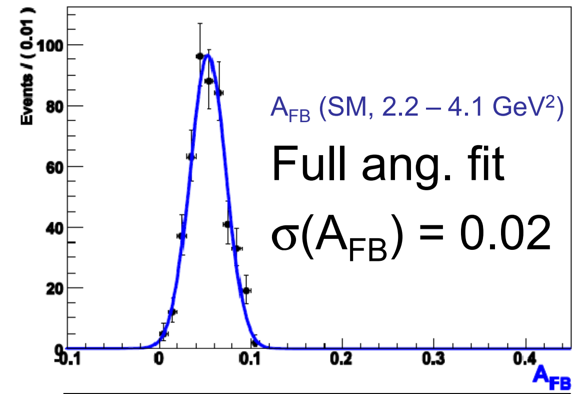


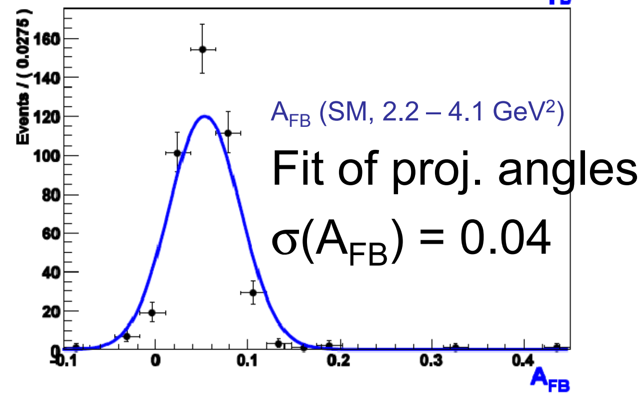
$B_d \to K^* \mu\mu$ at LHCb

- Full angular fit also under investigation:

$$\frac{d^4\Gamma_{\overline{B}_d}}{dq^2\, d\theta_l\, d\theta_K\, d\phi} = \frac{9}{32\pi} I(q^2, \theta_l, \theta_K, \phi) \sin\theta_l \sin\theta_K$$

- Parameterised in terms of transversity amplitudes
  - $A_0^{L,R}$, $A_\perp^{L,R}$, $A_\parallel^{L,R}$, 6 complex numbers
- Correlations give access to helicities
  - Probe chiral structure NP operators





- Once have enough events in each q^2 bin for fit to converge → better precision on A_{FB}, F_L, and A_T^2 (but require full acceptance correction)

- Can form any observable once have fitted all amplitudes – new theoretically clean observables with good NP sensitivity sought!

$B_s \rightarrow \phi\gamma$

B_d K*γ, $B_s \to \phi\gamma$

- BR($B_d \to X_s\gamma$) measured by B-factories, rate in agreement with SM

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

- B-factories measured CP asymmetry A_{CP} in B_d $K^*(K_s\pi^0)\gamma$:

$$A_{CP}(t) = \frac{\Gamma[\bar{B}_q \to \phi\gamma] - \Gamma[B_q \to \phi\gamma]}{\Gamma[\bar{B}_q \to \phi\gamma] + \Gamma[B_q \to \phi\gamma]}$$

$$A_{CP}(t) = -\frac{C\cos(\Delta m_q t) \quad + \quad S\sin(\Delta m_q t)}{A^{\Delta}\sinh(\Delta\Gamma_q t/2) + \cosh(\Delta\Gamma_q t/2)}$$

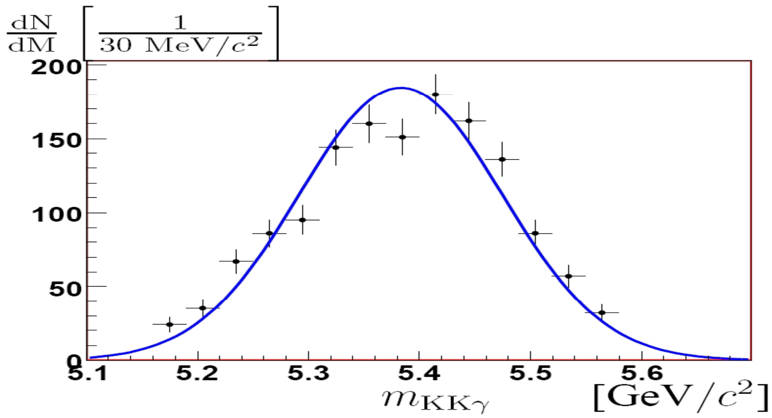
In SM,
C=0 (direct CPV)
S=sin 2ψ sin φ
A^{Δ}=sin 2ψ cos φ
where ψ fraction of "wrong" polarization

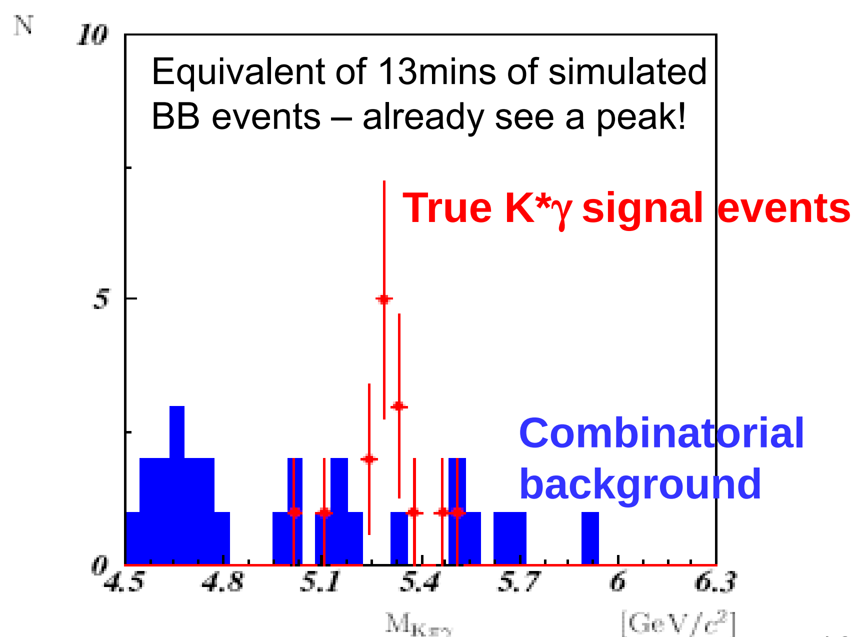
→ C=-0.03±0.14, S=-0.19±0.23 [HFAG]

- LHCb can perform analogous measurement in $B_s \to \phi\gamma$
  - As $\Delta\Gamma_s \neq 0$, $B_s \to \phi\gamma$ decay probes A^{Δ} as well as C and S

$B_s \to \phi\gamma$ at LHCb

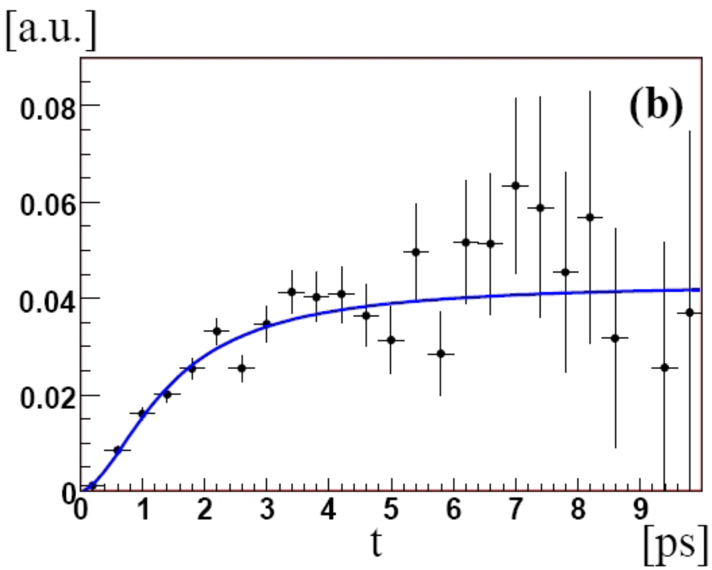
- Signal Selection:
  - E_T > 2.7GeV
  - Mass resoln ~90 MeV
  - Proper time resoln ~80 fs (not critical for measuring A^{Δ})
  - Total Efficiency ~0.3%
  - Yield:
    - $B_s \to \phi\gamma$
      - 11k / 2fb^{-1} with B/S<0.55
    - $B_d \to K^*(K^+\pi^-)\gamma$
      - 68k / 2fb^{-1} with B/S~0.60





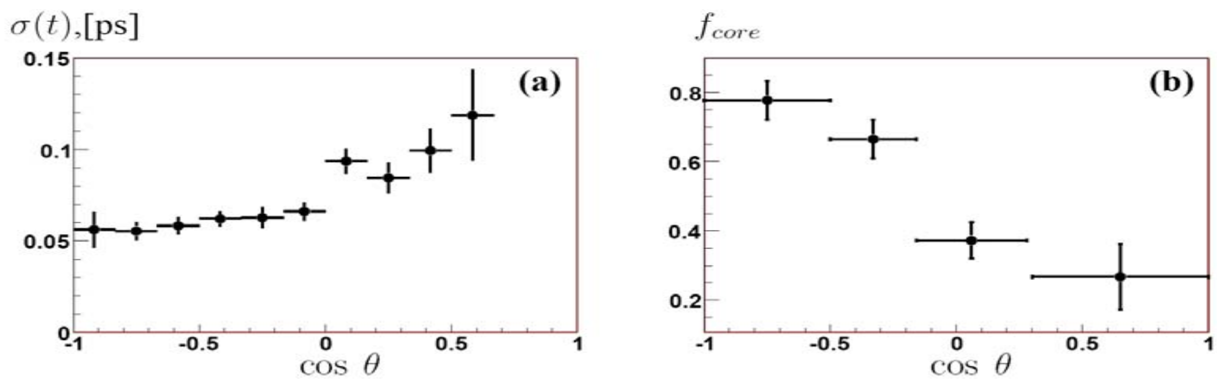
$B_s \to \phi\gamma$ at LHCb

- Analysis issues:
  - Acceptance function a(t) ($B_d \to K^*\gamma$)
  - σ(t) as function of topology



- Precision on A_{CP} parameters with $B_s \to \phi\gamma$ decays from $0.5fb^{-1}$
  - $\sigma(A^{\Delta})$ = 0.3 (no tagging required)
  - σ(S, C) = 0.2 (require tagging)

- With $2fb^{-1}$:
  - $\sigma(A^{\Delta})$ = 0.22
  - σ(S, C) = 0.11



Conclusions

- Rare B decays in LHCb will find NP or constrain extensions of SM
- With the first data:
  - $B_s \to \mu\mu$ excluded at SM value with $0.5 fb^{-1}$
  - $B_d \to K^* \mu\mu$ measure A_{FB} spectrum, $\sigma(s_0)$ ~$0.8 GeV^2$ with $0.5 fb^{-1}$
- With $2 fb^{-1}$ integrated luminosity:
  - $B_s \to \mu\mu$ evidence if SM BR (observation with $6 fb^{-1}$ data)
  - $B_d \to K^* \mu\mu$ measure A_{FB} spectrum, $\sigma(s_0)$ ~$0.5 GeV^2$, new observables with more complex fits ($A^{(2)}_T$, …)
  - $B_s \to \phi\gamma$ CP asymmetry A_{CP} → fraction of "wrong" polarization
- Host of other channels will be accessible:
  - Radiative : $\Lambda_b \to \Lambda\gamma$, $\Lambda_b \to \Lambda^*\gamma$, $B \to \rho^0\gamma$, $B \to \omega\gamma$, $\mu\mu\gamma$
  - b→sll : $B^+ \to K^+ ll$ (R_K), $B_s \to \phi\mu\mu$
  - LFV : $B_q \to ll'$
  - …

Other Channels

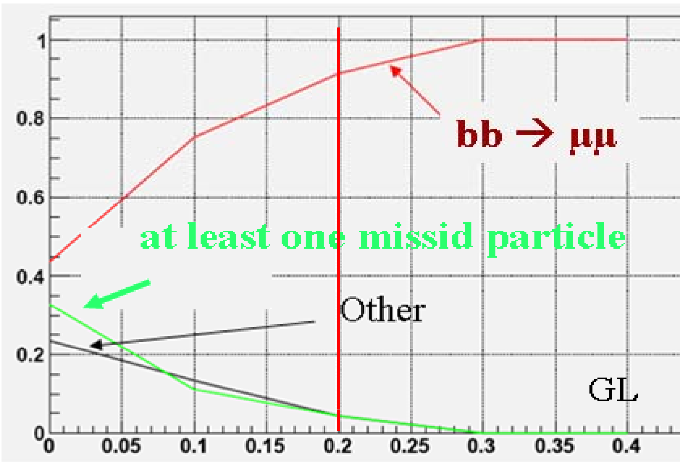
- Preliminary study of $B_s \rightarrow \phi\mu\mu$:
  - Expect ~1000 signal events from $2fb^{-1}$ data with B/S<0.9 @ 90% CL
  - Factor 4 reduction in production rate B_s cf. B_d
  - The ϕ does not tag the B → need flavour tagging, factor ~15 reduction → expect $\sqrt{60}$ worse resolution than $B_d \rightarrow K^*\mu\mu$
  - Can make CP-averaged measurement of A_{FB} (if non-zero ⇨ CPV)

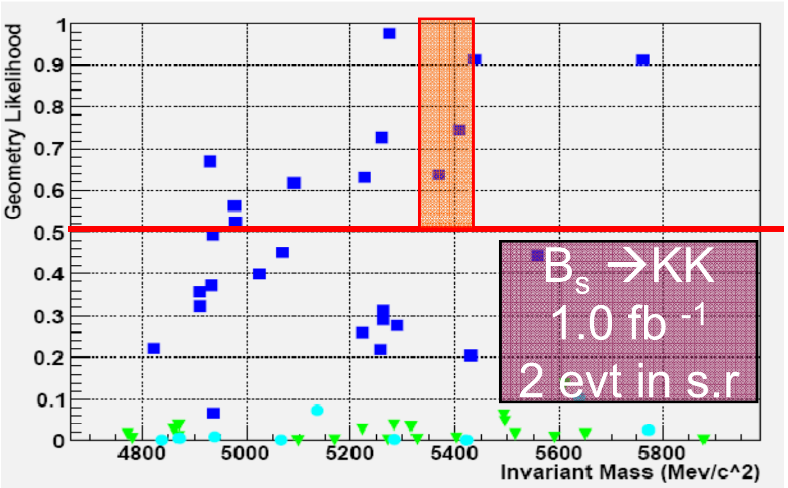
- Study of $b \rightarrow d$ transition $B_s \rightarrow K^*\mu\mu$ also planned:
  - Again, factor 4 reduction in production rate B_s cf. B_d
  - Rate reduced by $|V_{td}/V_{ts}|^2 = 0.208^2 \sim 1/25$
  - Given these reductions, expect will have to work harder to reduce background

→ ~< 700 events/ $2fb^{-1}$

PID

"Robustness" of mis-id bkg estimation:





bb inclusive above GL = 0.2:

19 b → dimuon

3 other muons

2 muon + mis-id ➔ **single mis-id probability needs to increase a factor ~10 to be of the same order as di-muon bkgrd**

Double mis-id:

- dominated by B→hh

-~4 evts/fb^{-1} ➔ a factor ~50 less than dimuon

- **Mis-id needs to increase by a factor ~7 to be of the same order as dimuon bkgrd**

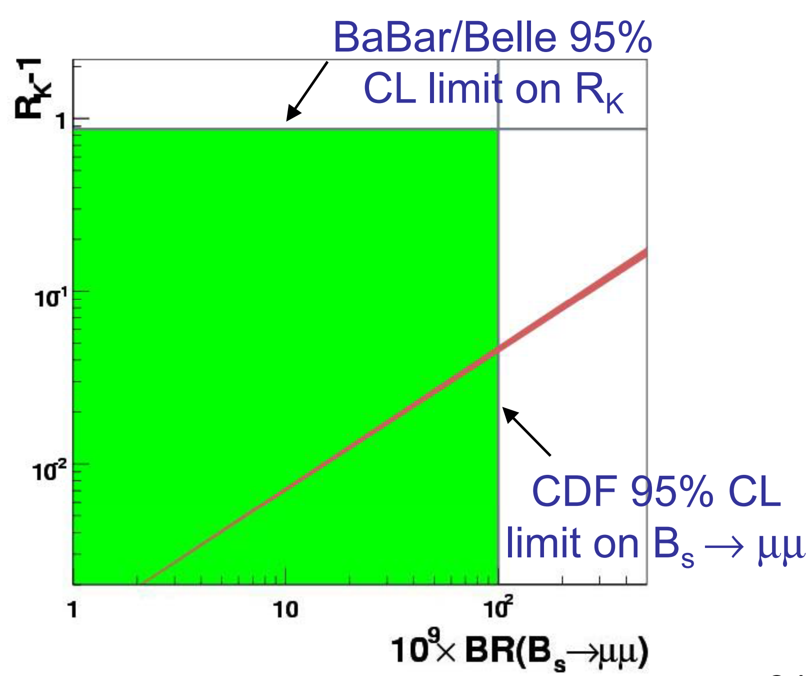
R_K in $B^+ \to K^+ ll$

- R_K theoretically well controlled in SM :

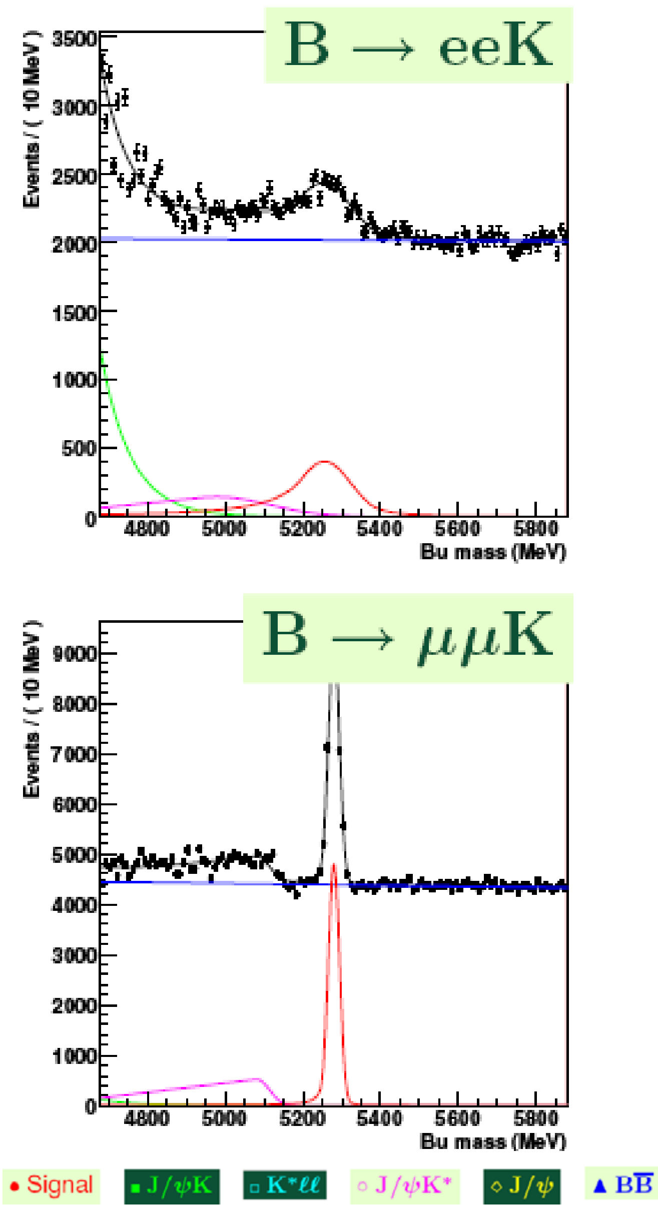
$$R_X = \frac{\int_{4m_\mu^2}^{q^2_{max}} ds \frac{d\Gamma(B\to X\mu^+\mu^-)}{ds}}{\int_{4m_\mu^2}^{q^2_{max}} ds \frac{d\Gamma(B\to X e^+ e^-)}{ds}} \overset{SM}{=} \begin{cases} 1.000 \pm 0.001 & X = K \\ 0.991 \pm 0.002 & X = K^* \end{cases}$$

[Hiller & Krüger, PRD69 (2004) 074020]

- Effect of extensions to SM can be O(10%) e.g. from neutral Higgs boson exchange
- Related to $BR(B_s \to \mu\mu)$
- LHCb sensitivity with $B^+ \to K^+ ll$ has been investigated – can also be done with the K^* decay



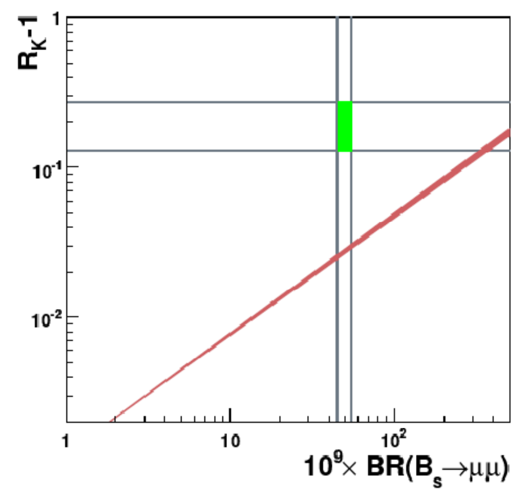
R_K in $B^+ \to K^+ ll$ (cont'd)



- From 10 fb^{-1} data :
  - $B_d \to eeK$ ~ 10k
  - $B_d \to \mu\mu K$ ~ 19k

- Gives $R_K = 1$ (fixed) ± 0.043

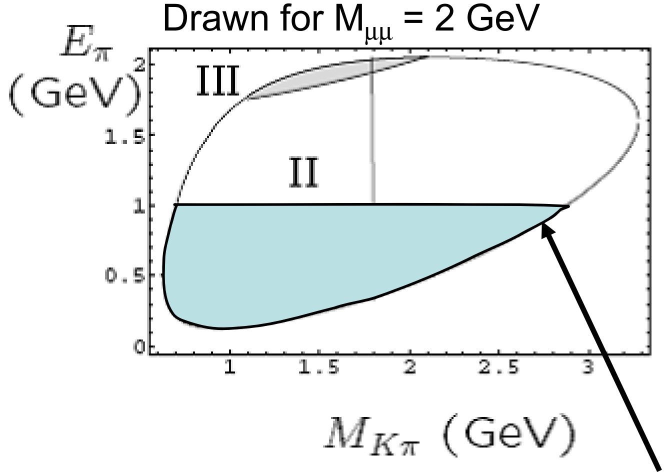
- Possible status with 10fb^{-1} data :
  - $BR(B_s \to \mu\mu) \sim 3\times10^{-9}$
    - $R_K \sim 1$ – compatible with MSSM with small tan β
    - $R_K \neq 1$ – NP : right handed currents or broken lepton universality
  - $BR(B_s \to \mu\mu) \neq 3\times10^{-9}$
    - $R_K \sim 1$ – as above
    - $R_K = 1+\varepsilon$ – MFV



$B_d \to K^*\mu\mu$ – non-resonant bkgrd

- Presently neglecting non-resonant background
- Limit can crudely be derived from BaBar data → expect ~2000 events/2fb^{-1} (→ B/S=0.5±0.2)
- Has been suggested that, under certain kinematic conditions, these can be treated as signal [Grinstein, Pirjol, hep-ph/0505155] :

Drawn for $M_{\mu\mu}$ = 2 GeV



Defined by kinematics

- **Region I: soft pion, energetic kaon**
  - **Shifts zero of A_{FB} and larger theory errors**
- Region II: energetic $K\pi$ pair
  - Can be treated as $B \to X\mu\mu$ and $X \to K\pi$
- Region III: soft kaon, energetic pion
  - Amplitude suppressed so very few events…

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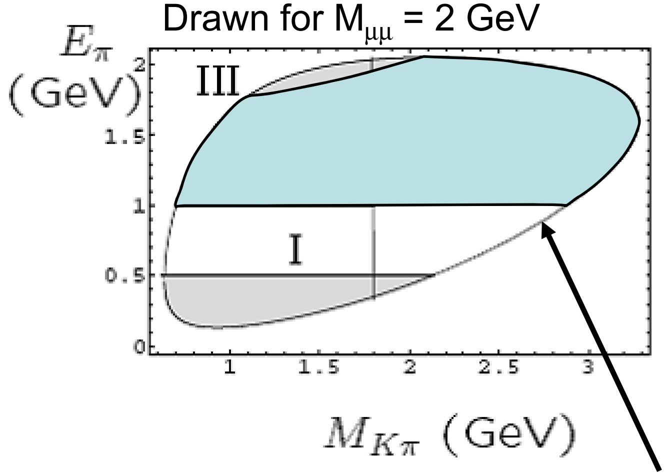

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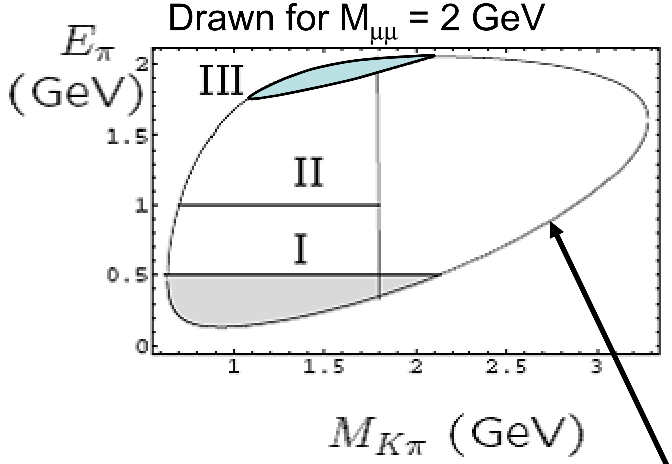

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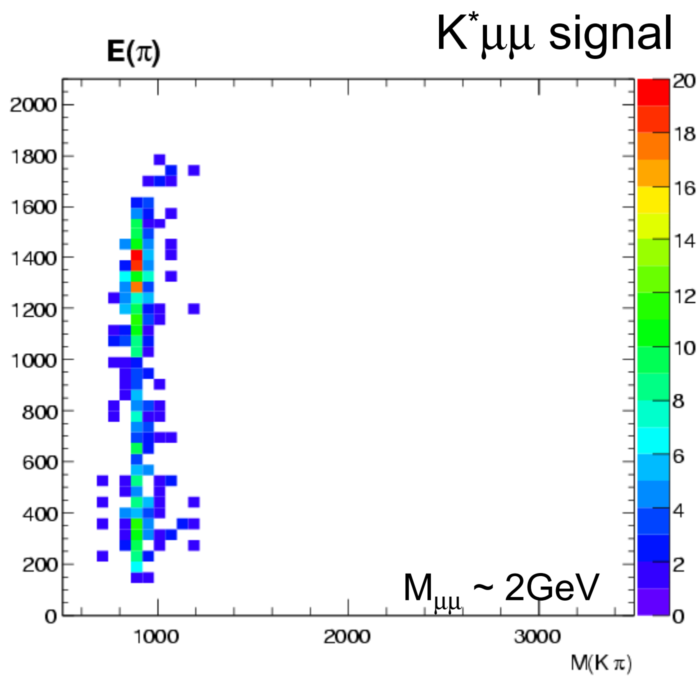
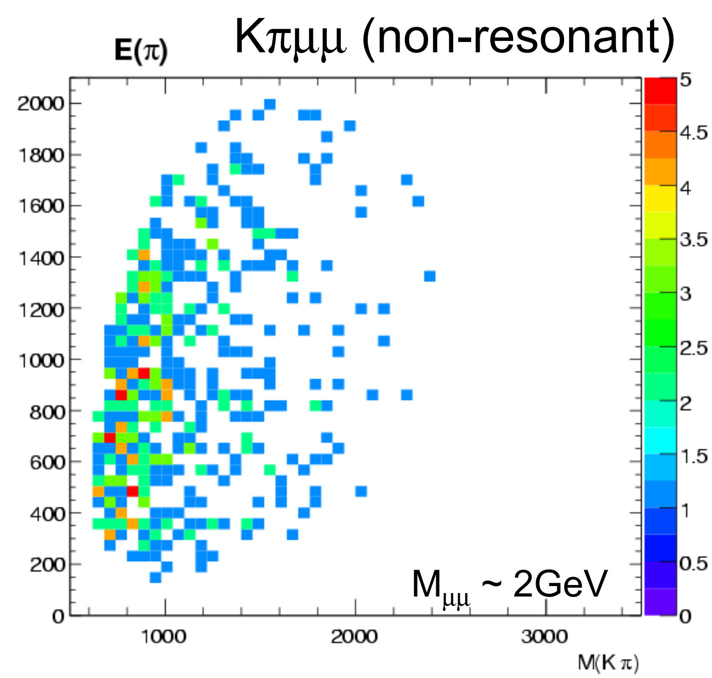
$B_d \to K^*\mu\mu$ – non-resonant bkgrd (cont'd)

- However, isolating region II has a large effect on the signal yield:





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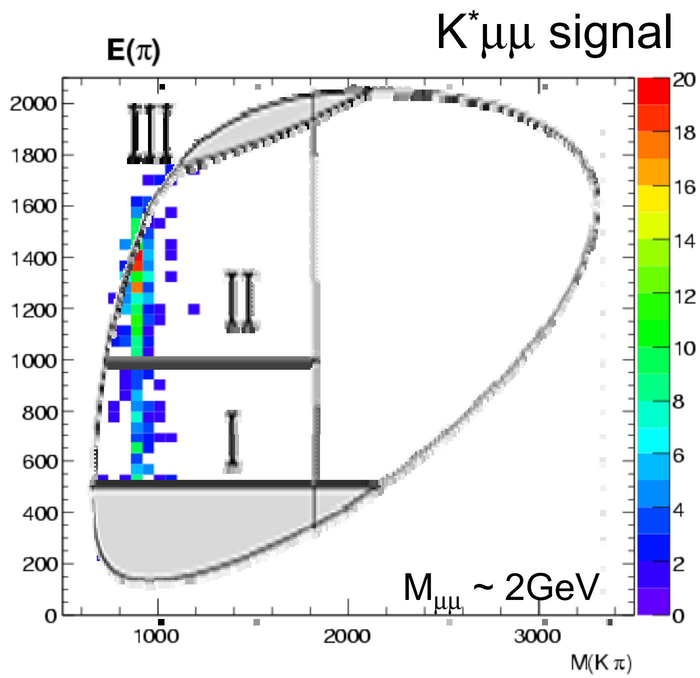

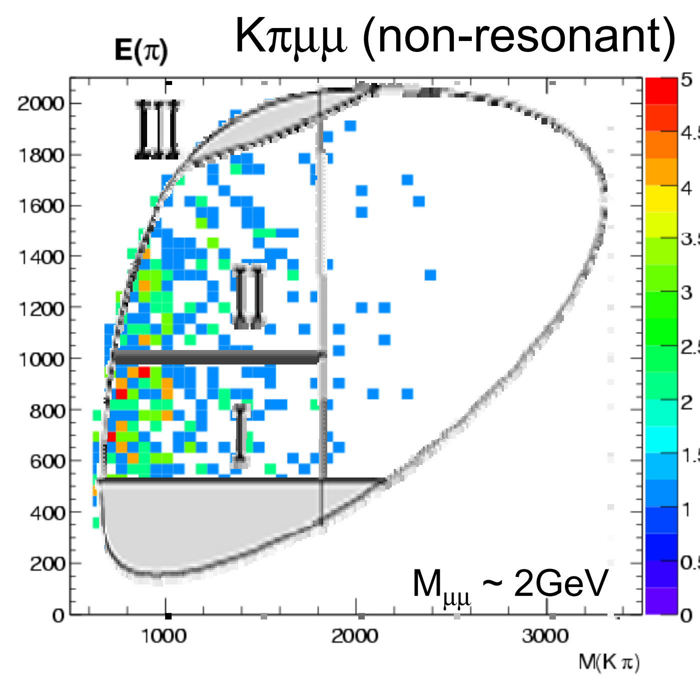

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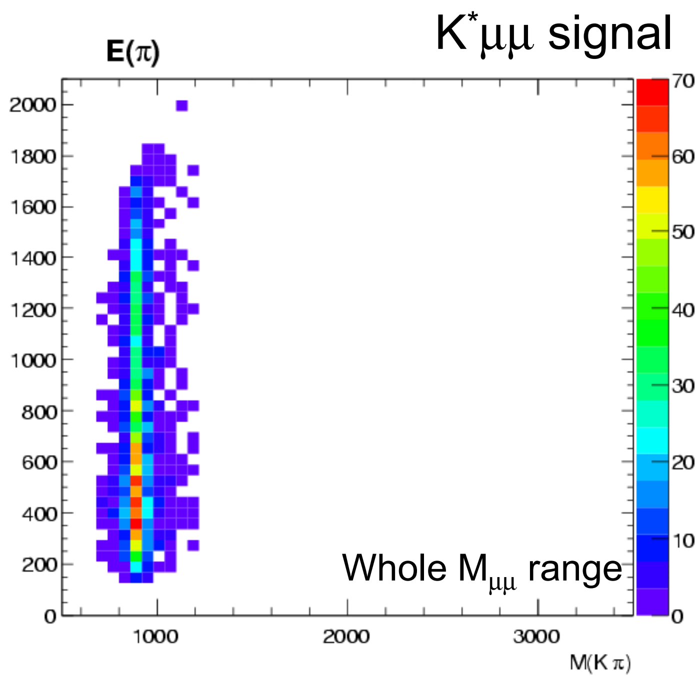

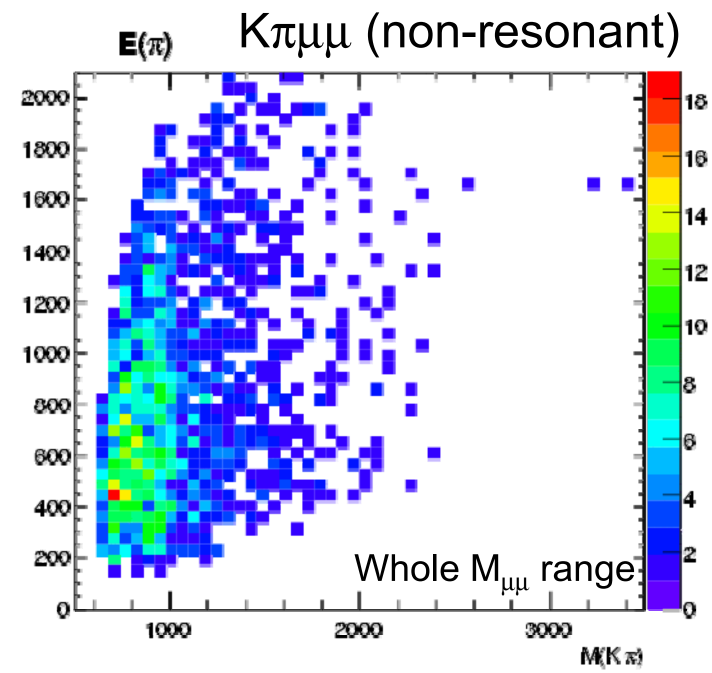

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- Plan to measure $d\Gamma/dm_{K\pi}$