Imperial College London

100 years of living science

Rare B Decays

Ulrik Egede

Flavour Physics Forum

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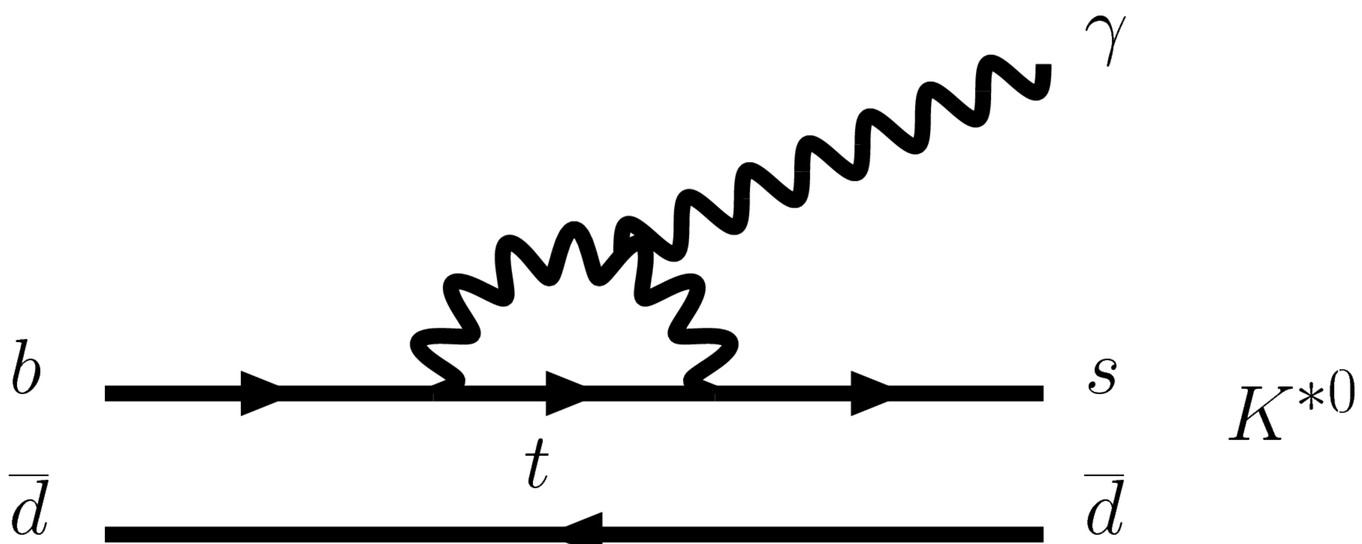
Outline

Motivation for investigating Rare B Decays

A brief history of Rare Decays

Some selected examples from current analysis

The prospect of Rare Decay analysis in the future



Rare decays

I will use the term *Rare B Decays* to mean

"FCNC penguin decays with electroweak Standard Model contributions".

Model	B_d Unitarity	Time-dep. *CPV*	Rare B decay	Other signals
mSUGRA(moderate $\tan\beta$)	-	-	-	-
mSUGRA(large $\tan\beta$)	B_d mixing	-	$B \to (D)\tau\nu$ $b \to s\ell^+\ell^-$	$B_s \to \mu\mu$ B_s mixing
SUSY GUT with ν_R	-	$B \to \phi K_S$ $B \to K^*\gamma$	-	B_s mixing τ LFV, n EDM
Effective SUSY	B_d mixing	$B \to \phi K_S$	$A_{CP}^{b\to s\gamma}$, $b \to s\ell^+\ell^-$	B_s mixing
KK graviton exchange	-	-	$b \to s\ell^+\ell^-$	-
Split fermions in large extra dimensions	B_d mixing	-	$b \to s\ell^+\ell^-$	$K^0\overline{K}^0$ mixing $D^0\overline{D}^0$ mixing
Bulk fermions in warped extra dimensions	B_d mixing	$B \to \phi K_S$	$b \to s\ell^+\ell^-$	B_s mixing $D^0\overline{D}^0$ mixing
Universal extra dimensioins	-	-	$b \to s\ell^+\ell^-$ $b \to s\gamma$	$K \to \pi\nu\overline{\nu}$

hep-ph/0503261

An effective theory for New Physics

$$\mathscr{L}_{\text{eff}} = \mathscr{L}_{\text{gauge}}(A_i, \Psi_j; \mathbf{Y}, \mathbf{C}) + \mathscr{L}_{\text{Higgs}}(A_i, \Psi_j, \phi; \langle\phi\rangle) +$$

$$\sum_{d>4} \frac{c^n}{\Lambda^{d-4}} O_n^d$$

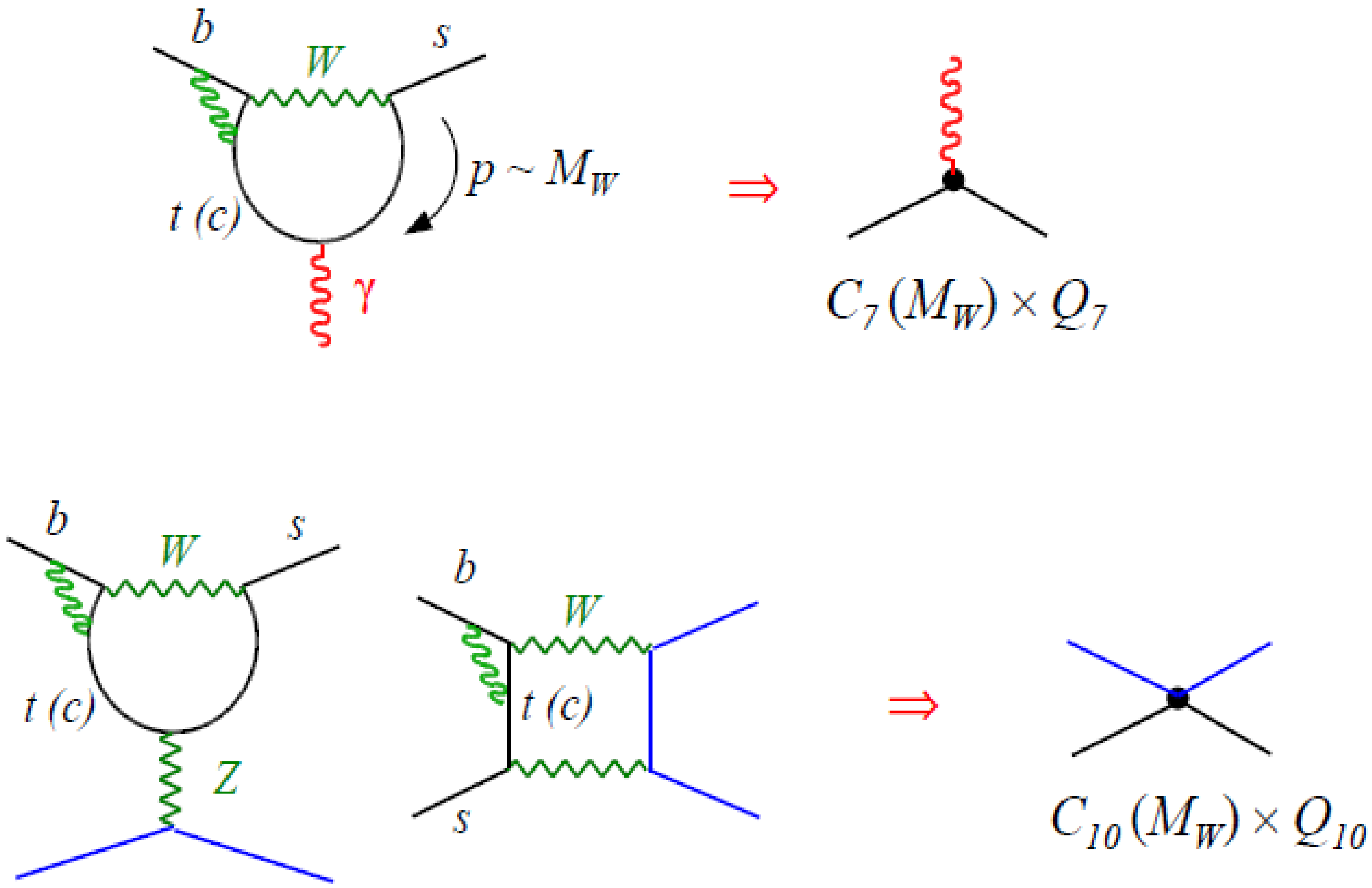
O_d^n: All possible operators with heavy d.o.f

c^n: Parameters arising from New Physics

Λ: Energy scale of New Physics

- Separate terms for left and right handed currents
  - Some left handed (C^7, C^{10}) are present through loops in the SM
  - All right handed currents represent NP.

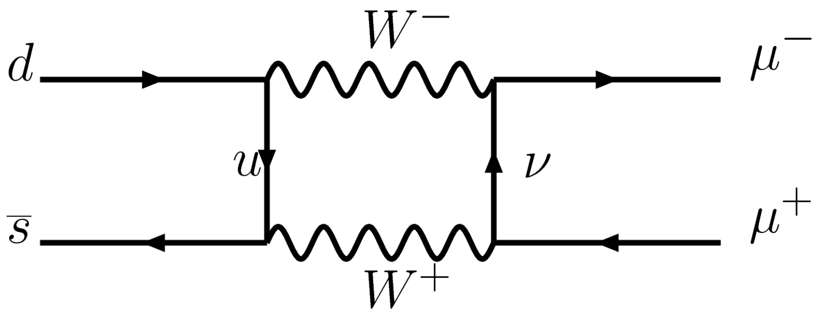
SM processes in higher order operators

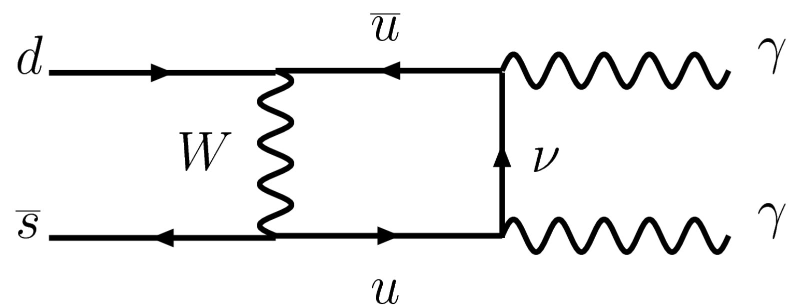


Rare decays "saw" the c quark

Look at $K^0_L \rightarrow \mu^+\mu^-$

Naive expectation is for $K^0_L \rightarrow \mu^+\mu^-$ and $K^0_L \rightarrow \gamma\gamma$ BR to be similar.





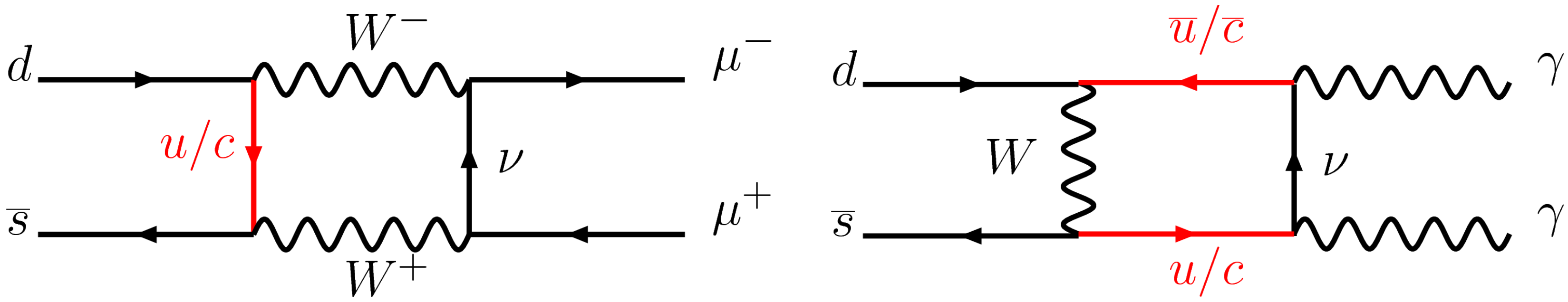
However, experimentally we observe

$$\Gamma(K^0_L \rightarrow \mu^+\mu^-) \approx 2\cdot 10^{-5}\,\Gamma(K^0_L \rightarrow \gamma\gamma)$$

Rare decays "saw" the c quark

Add a (at the time) hypothetical c quark

The GIM mechanism is creating amplitudes of the opposite sign.



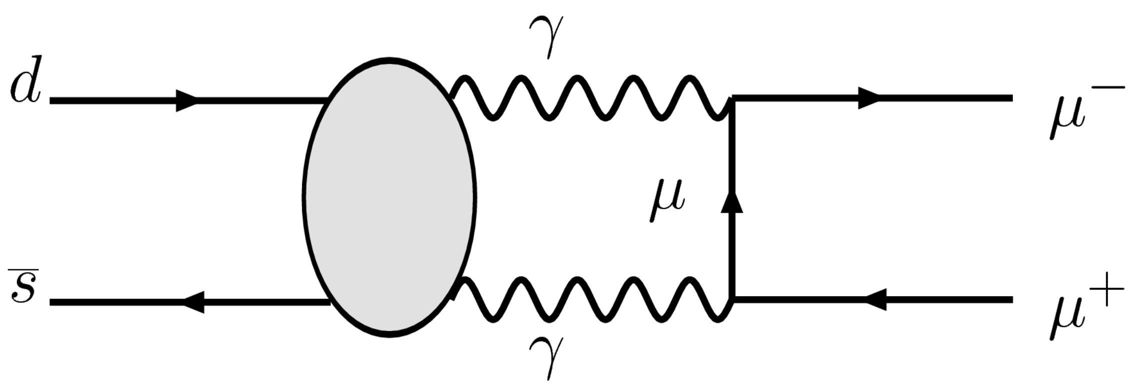
$K^0_L \rightarrow \mu^+\mu^-$ heavily suppressed.

For $K^0_L \rightarrow \gamma\gamma$ the u and c mass difference becomes important and amplitude almost unaffected.

Rare decays "saw" the c quark

Current understanding is that $K^0_L \rightarrow \mu^+\mu^-$ is dominated by the 2-photon exchange.

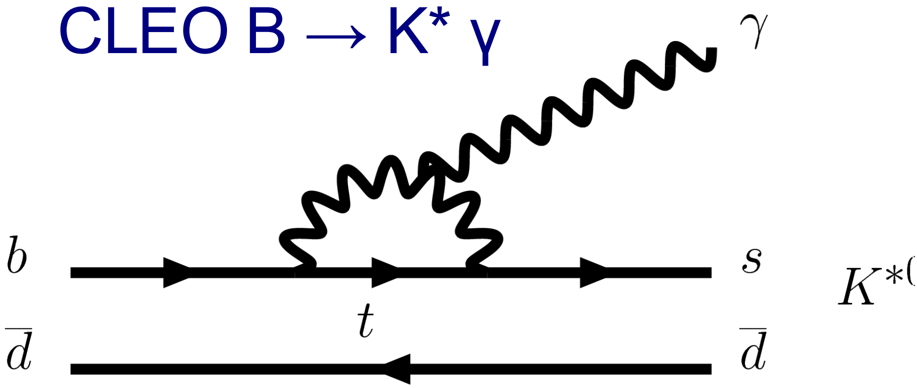
Phys Rev D10, 897 (1974)



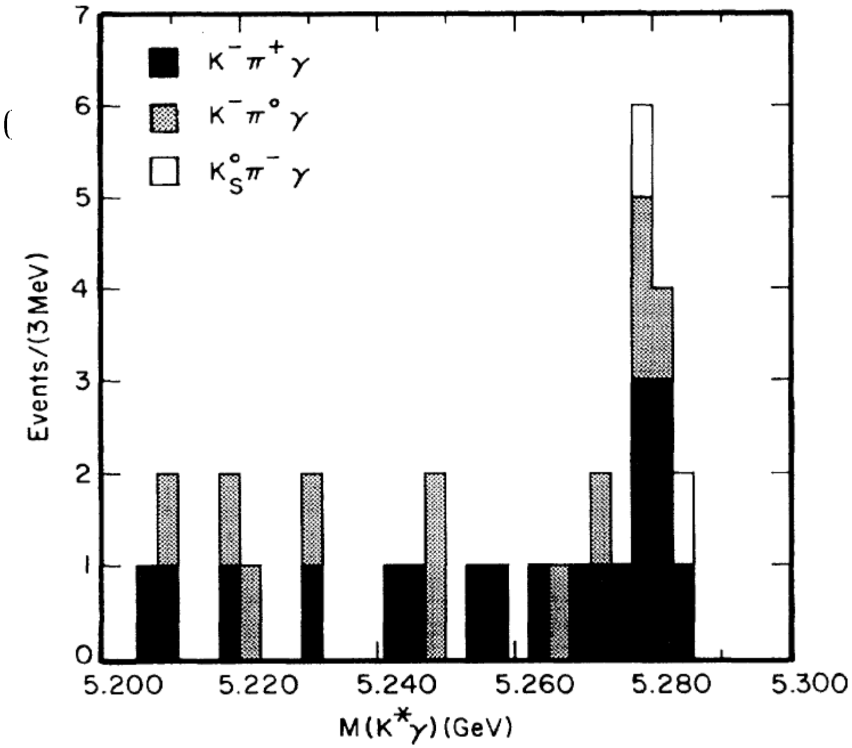
Thus $K^0_L \rightarrow \mu^+\mu^-$ suppressed at the α^2 level.

First penguin decay

CLEO B → K* γ



PRL 71,674



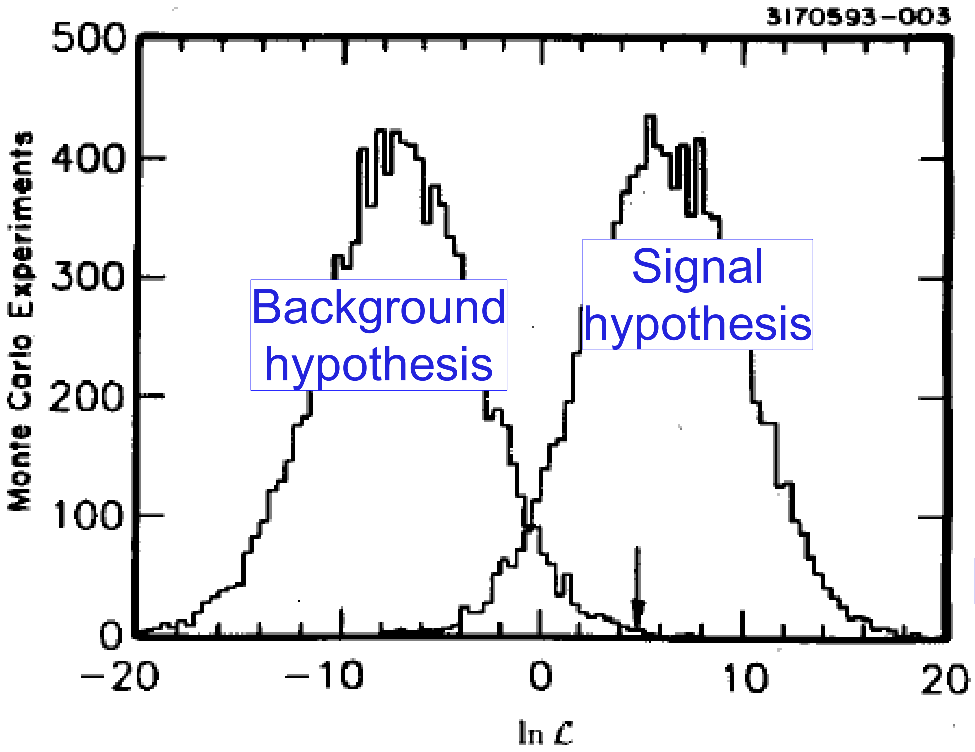
Analysis strategy

- High energy photon
  - $2.1 < E_\gamma < 2.9$ GeV
- Rejection of π^0 candidates
- Event shape criteria to reject non-B background.

First penguin decay

Significance

- Evaluated from likelihood distributions of signal and background samples
- 0.11% probability to be a background fluctuation.



PRL 71,674

First penguin decay

Huge increase in statistics for decay

Experiment	Year	Pub	Events	BR ($\times 10^{-6}$)
CLEO	1993	PRL 71,674	8	45.5 ± 7.0 ± 3.4
BELLE	2004	PR D69, 112001	474	40.1 ± 2.1 ± 1.7
BaBar	2004	PR D70, 112006	645	39.2 ± 2.0 ± 2.4
LHCb	2009?		68000	

Theoretical prediction of BR cannot match experimental precision

- Look at inclusive decays
- Look at at other observables like CP violation and polarisation

Results from running experiments

At the moment results are dominated by the B-factories

Results from the Tevatron are also starting to arrive

Far too many results so will only highlight a few

- The inclusive $b \to s \gamma$ for measurement of absolute BR
- Time dependent CP violation measurement in $B_d \to K^{*0} \gamma$
- Search for the decay $B_s \to \mu^+\mu^-$

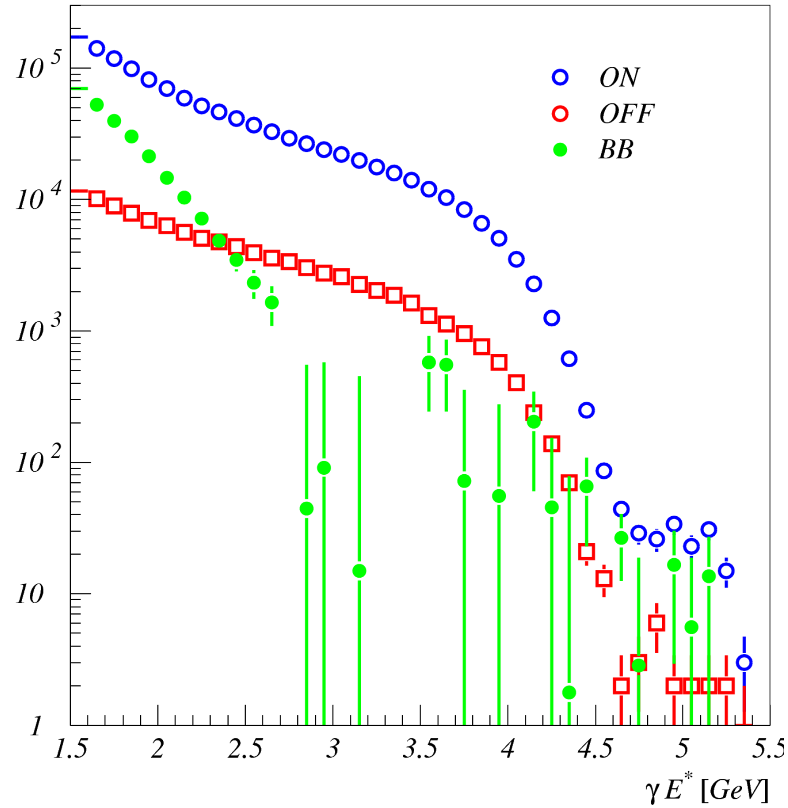
The B → K* γ inclusive analysis

Phys.Rev.Lett.93:061803,2004 (BELLE, 140 fb^{-1})

- Challenge of analysis is the very large background from light quark events

Strategy

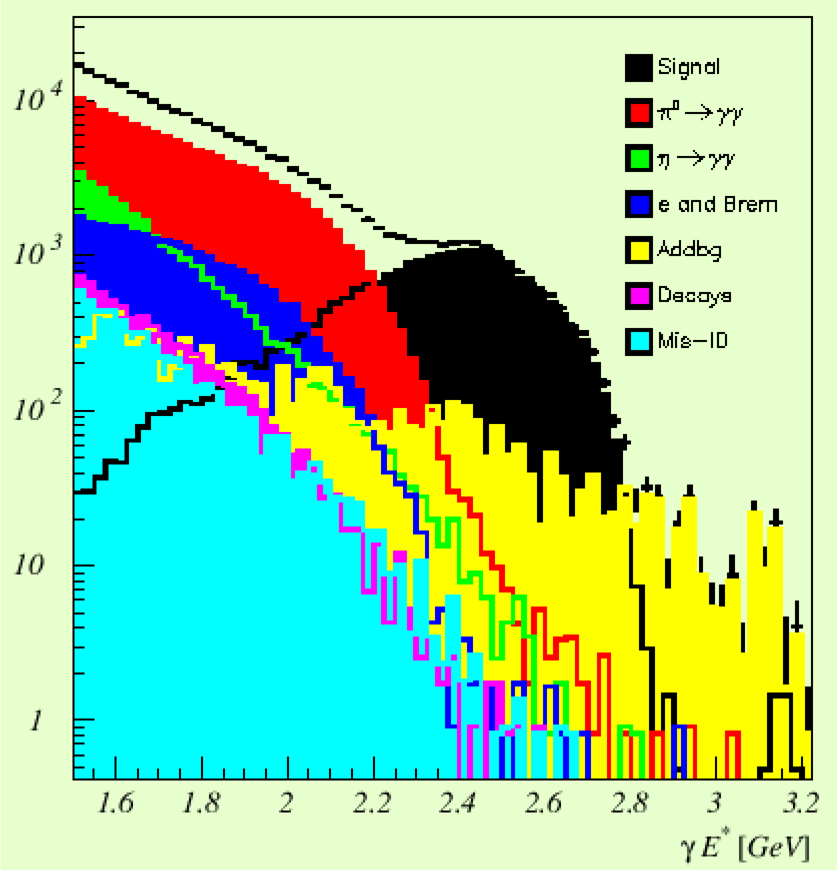
- Subtract light quark background with off resonance sample
- Use event shape for further rejection
- Apply veto on γ's compatible with π^0 and η



The B → K* γ inclusive analysis

Composition of background after off resonance subtraction

Signal	25%
Decays of π^0	52%
Decays of η	6%
e and Hadrons	8%
Bremsstrahlung	2%
Beam-gas	5%
Decays of $\omega(783)$	1%
Decays of J/ψ	1%
Other decays	1%

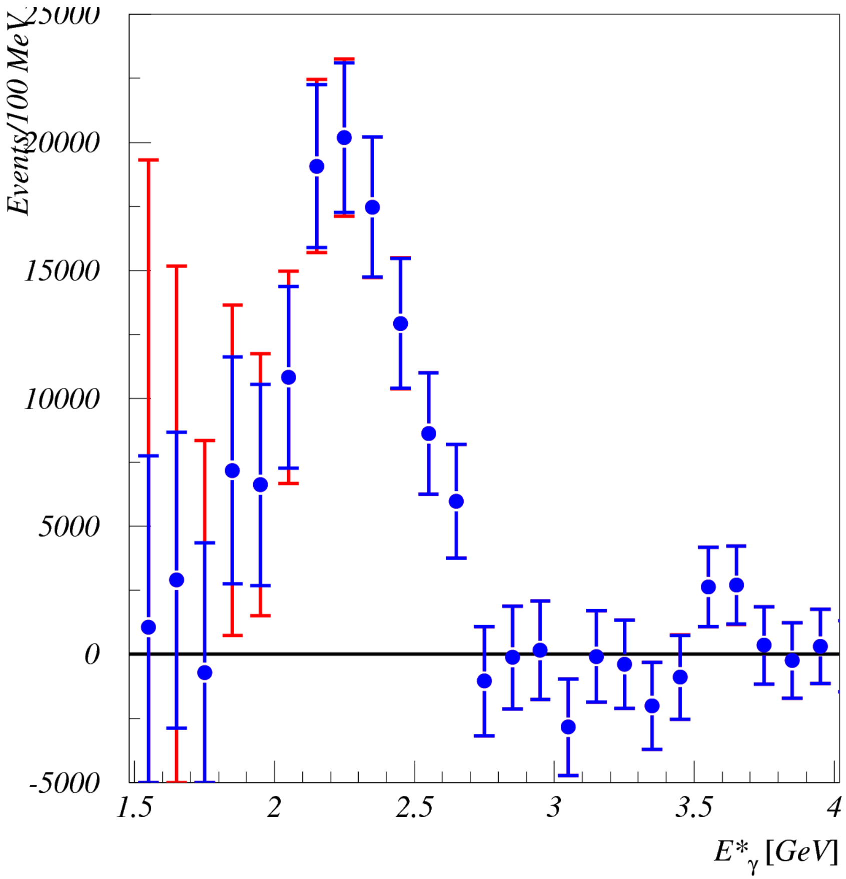


The B → K* γ inclusive analysis

Final spectra for $1.8 < E_\gamma < 2.8$ GeV

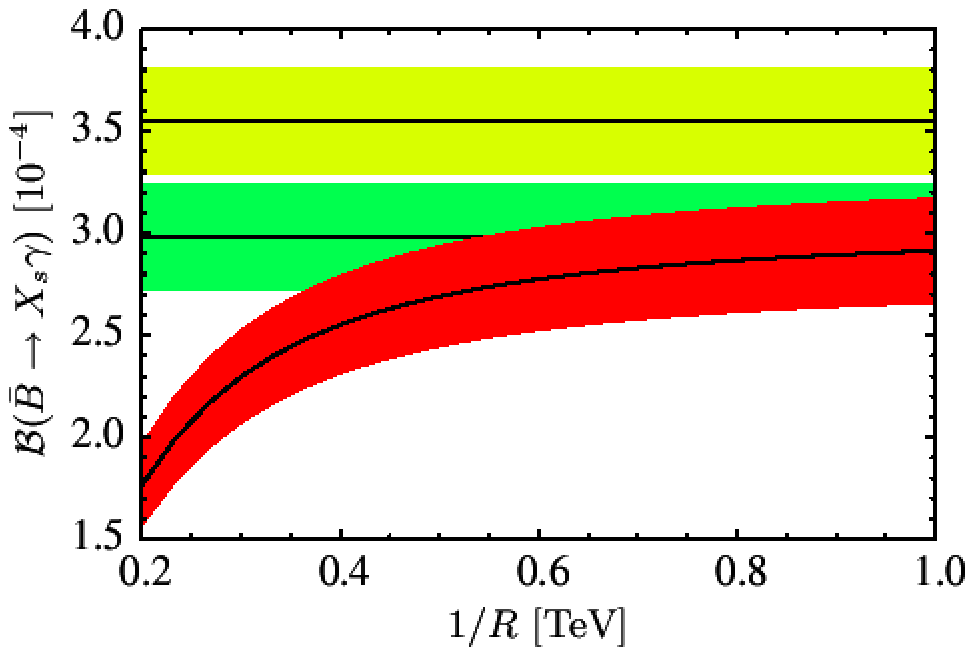
- BR = $(3.55 \pm 0.32 \pm 0.30 \pm 0.10) \times 10^{-4}$
- Energy interval contains 95% of spectra
- Spectra compatible with zero above 2.8 GeV

Moments of distribution measured as well



The B → K* γ inclusive analysis

- Many new physics models are heavily constrained by the inclusive BR.
  - The minimal Universal Extra Dimension (mUED) predicts a lower BR
  - Limits can be set on the compactification radius



Experiment

SM (NNLO)

mUE D (LO)

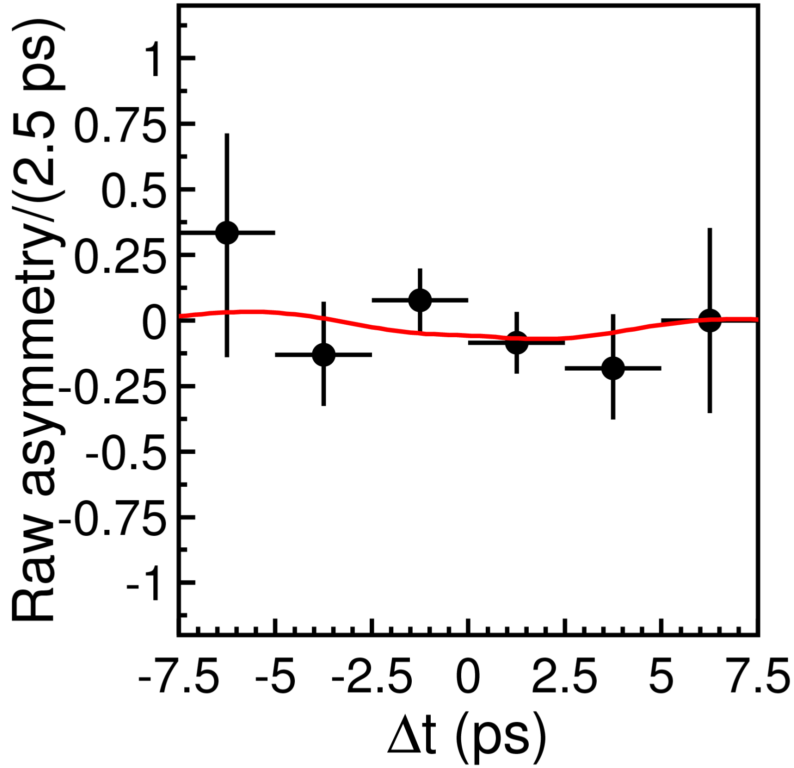
hep/ph 0703064

CP violation in B → K^{*0} γ

- In the SM there is limited interference between $B_d \to K^{*0}\gamma$ and $\overline{B}_d \to \overline{K}^{*0}\gamma$
  - First dominated by left handed photon, second by right
  - Only $O(m_s/m_b)$ effects, S_{th}=-0.022±0.015
    - Phys.Lett.B642:478-486,2006 (Ball & Zwicky)
- Time dependent CP violation probes for right handed currents from new physics
  - Need to look at $K^{*0}/\overline{K}^{*0} \to K_s^0 \pi^0$ to have CP eigenstate
  - Challenge of analysis is the reconstruction of the signal vertex
    - Intersect the reconstructed K^0_s with the Interaction Point
    - Use $B^0 \to J/\psi\ K^0_s$ as control sample after removing J/ψ.

CP violation in B → K^{*0} γ

$$A_{CP}(t) = \frac{\Gamma(\overline{B}^0 \to K_s^0 \pi^0 \gamma) - \Gamma(B^0 \to K_s^0 \pi^0 \gamma)}{\Gamma(\overline{B}^0 \to K_s^0 \pi^0 \gamma) + \Gamma(B^0 \to K_s^0 \pi^0 \gamma)} = S \sin(\Delta m \Delta t) - C \cos(\Delta m \Delta t)$$



PR D74,111104(R) (BELLE)

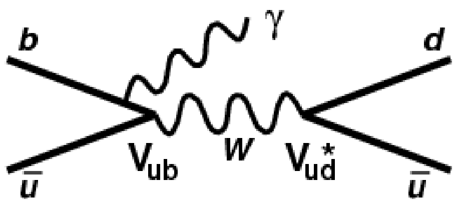
$$S_{K^{*0}\gamma} = -0.32 \pm 0.35 \pm 0.05$$
$$C_{K^{*0}\gamma} = \ \ 0.20 \pm 0.20 \pm 0.06$$

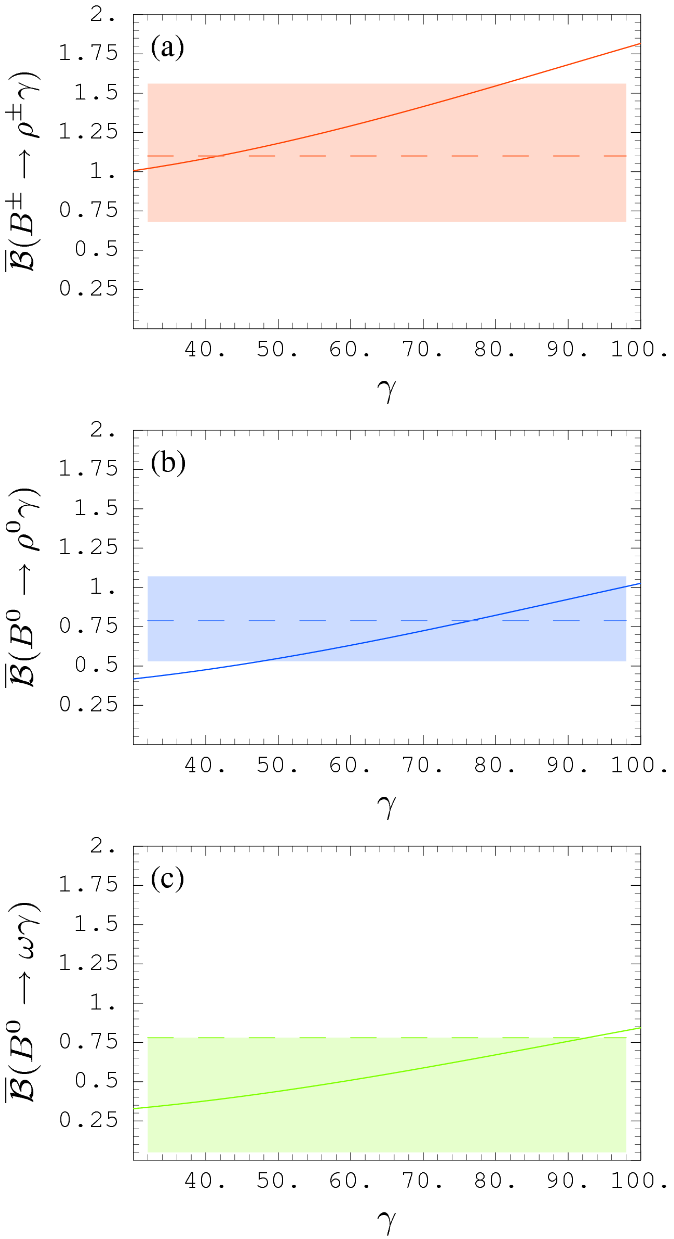
Would still like factor 10 better resolution

Super B-factory will eventually provide this.

The b → d penguin

- Rate suppressed by factor 25 relative to b → s penguin
- Assuming Unitarity give us
  - $|V_{ts}/V_{td}|^2$
  - CKM angle γ
    - Phys.Rev.D75:054004,2007, Ball, Jones Zwicky
- Small annihilation diagram for B^+ as well
  - Might give larger direct CP violation (~ 10%)

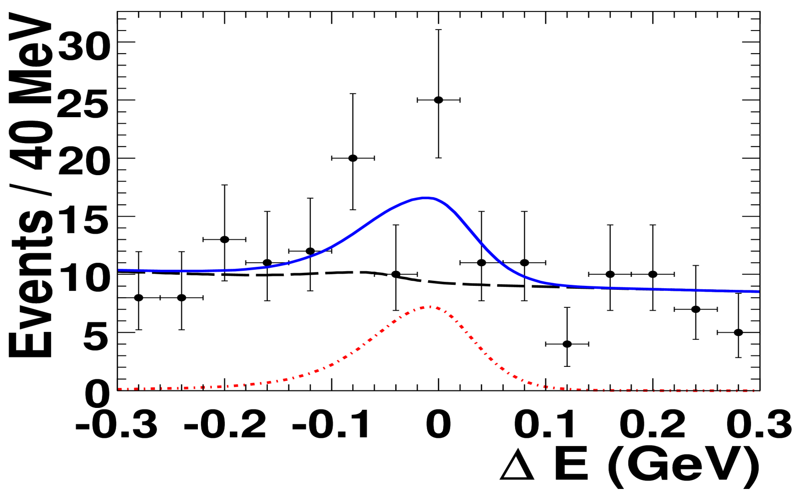


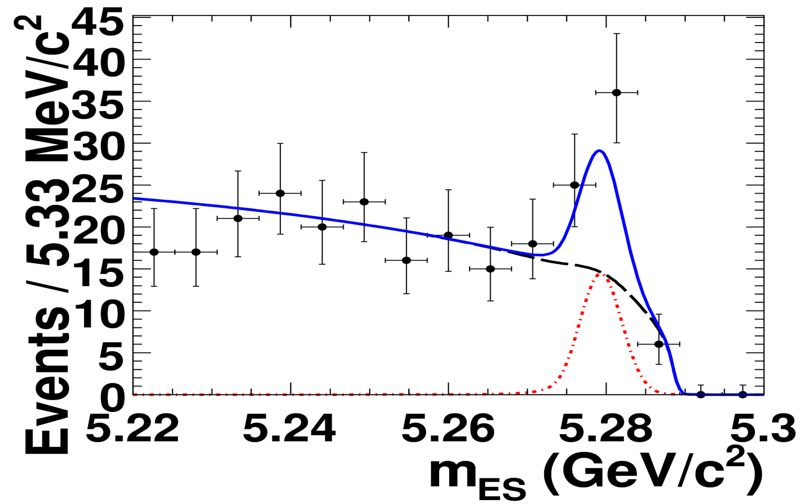


The b → d penguin

BaBar observation PRL 98, 151802 (2007)

- Experimental challenges similar to $b \to s\gamma$
  - But in addition need to reject $B \to X_s \gamma$ by using PID
- 91 events (6.4σ significance).
- BR ($B \to \rho/\omega\,\gamma$) = $(1.25 \pm 0.25 \pm 0.09) \times 10^{-6}$





$$\left|\frac{V_{td}}{V_{ts}}\right| = 0.207^{+0.028}_{-0.033}(\mathrm{exp})^{+0.014}_{-0.015}(\mathrm{th}) \quad \leftrightarrow \quad \gamma = (65.7^{+17.3}_{-20.7}(\mathrm{exp})^{+8.9}_{-9.2}(\mathrm{th}))^\circ$$

Phys.Rev.D75:054004,2007

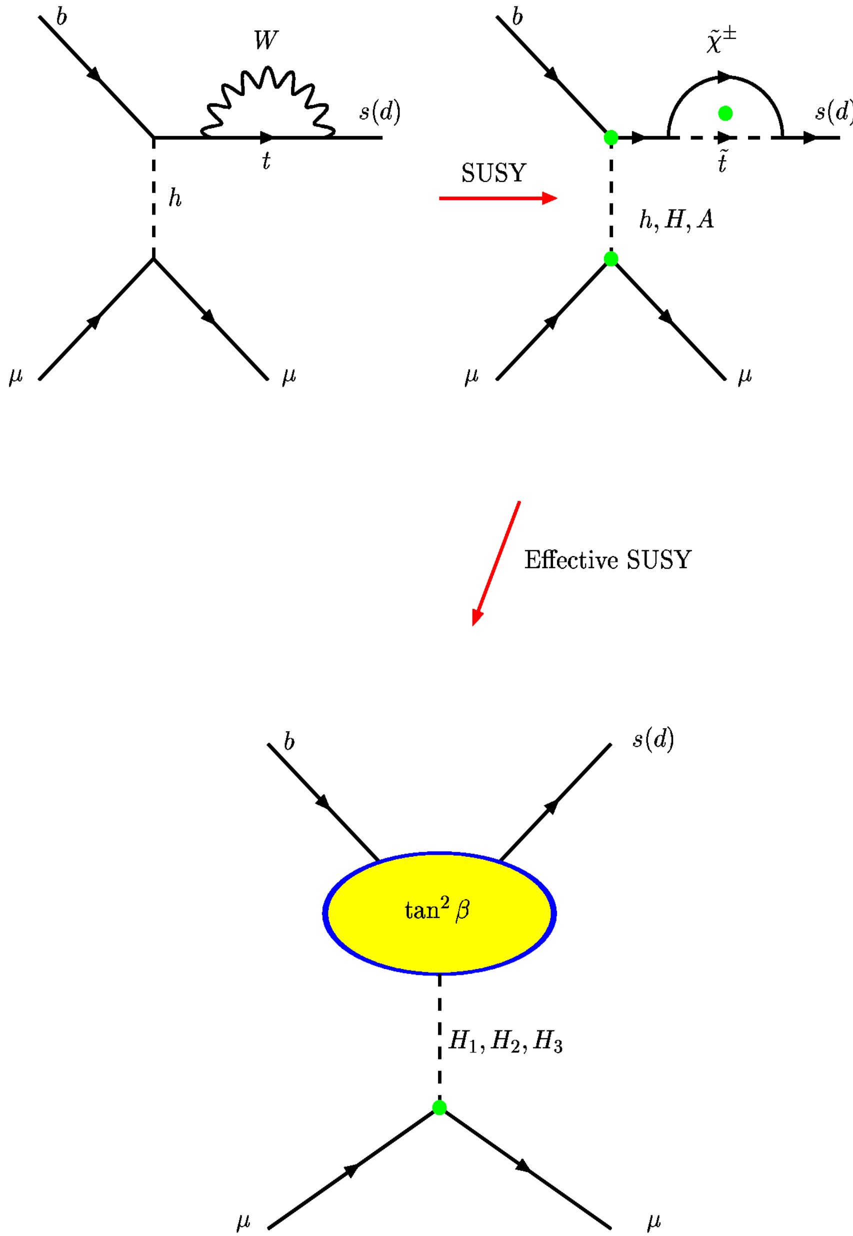
$B_s \to \mu^+\mu^-$

- Cross sections for Higgs mediated processes in SUSY enhanced by factor $\tan^6\beta$.

$$B(B_s \to \mu\mu) \sim 5 \times 10^{-7} \left(\frac{\tan\beta}{50}\right)^6 \left(\frac{300GeV}{M_A}\right)^4$$

  - Turns the decay into sensitive SUSY probe.

- At the same time SM prediction has very low uncertainty.
  - SM BR is ~ 3.5 10^{-9}



Experimental limit on BR($B_s \to \mu^+\mu^-$)

Normalise decay to $B^+ \to J/\psi K^+$

$$BR(B_s \to \mu^+\mu^-) = \frac{N_{Bs}}{N_{B+}} \frac{\alpha_{B+} \cdot \varepsilon_{B+}^{total}}{\alpha_{Bs} \cdot \varepsilon_{Bs}^{total}} \frac{f_{b \to B+}}{f_{b \to Bs}} BR(B^+ \to J/\psi K^+) BR(J/\psi \to \mu^+\mu^-)$$

Select on same data and apply identical identification criteria

Results @ 90% CL

CDF (0.8 fb^{-1})

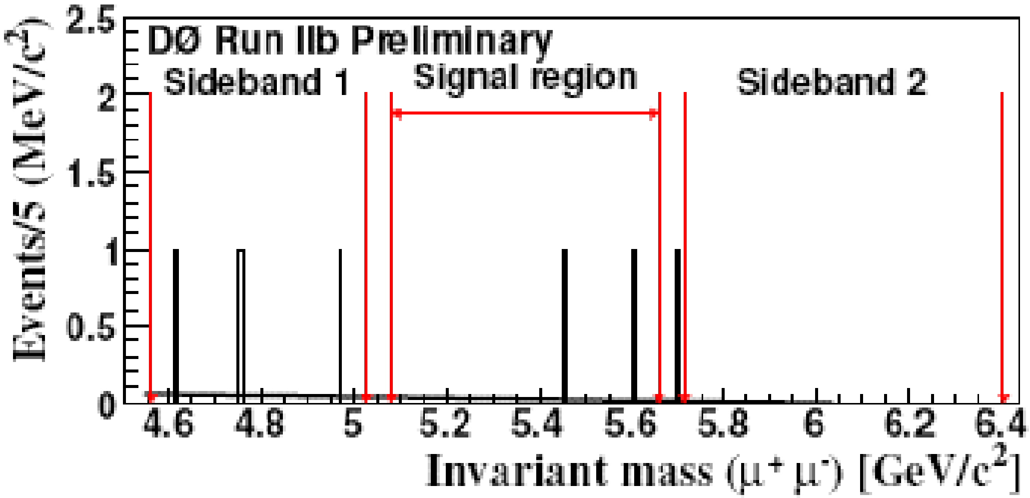
BR < 8.0×10^{-8}

D0 (2 fb^{-1})

BR < 7.5×10^{-8}

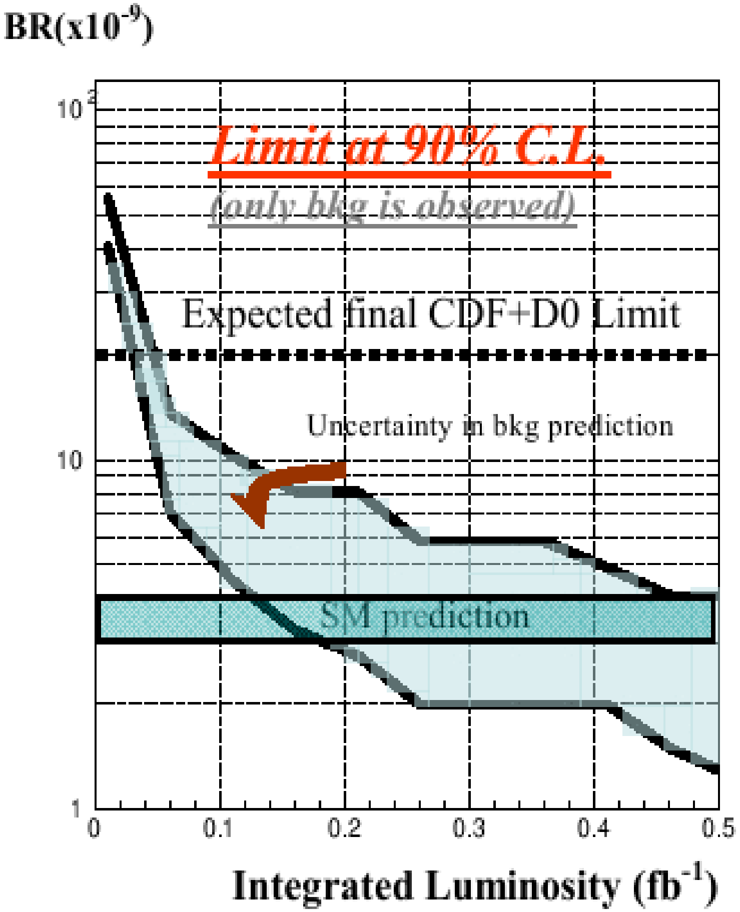
Limits about a factor 20 above SM prediction

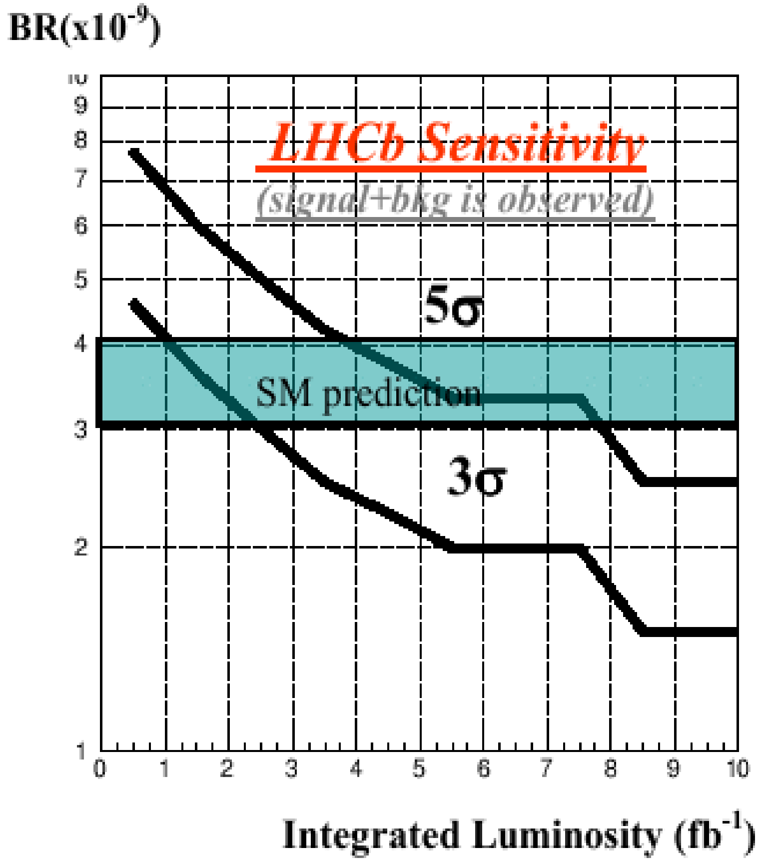
D0 : Expect 1.5±0.3, observe 2



LHCb performance on $BR(B_s \to \mu^+\mu^-)$

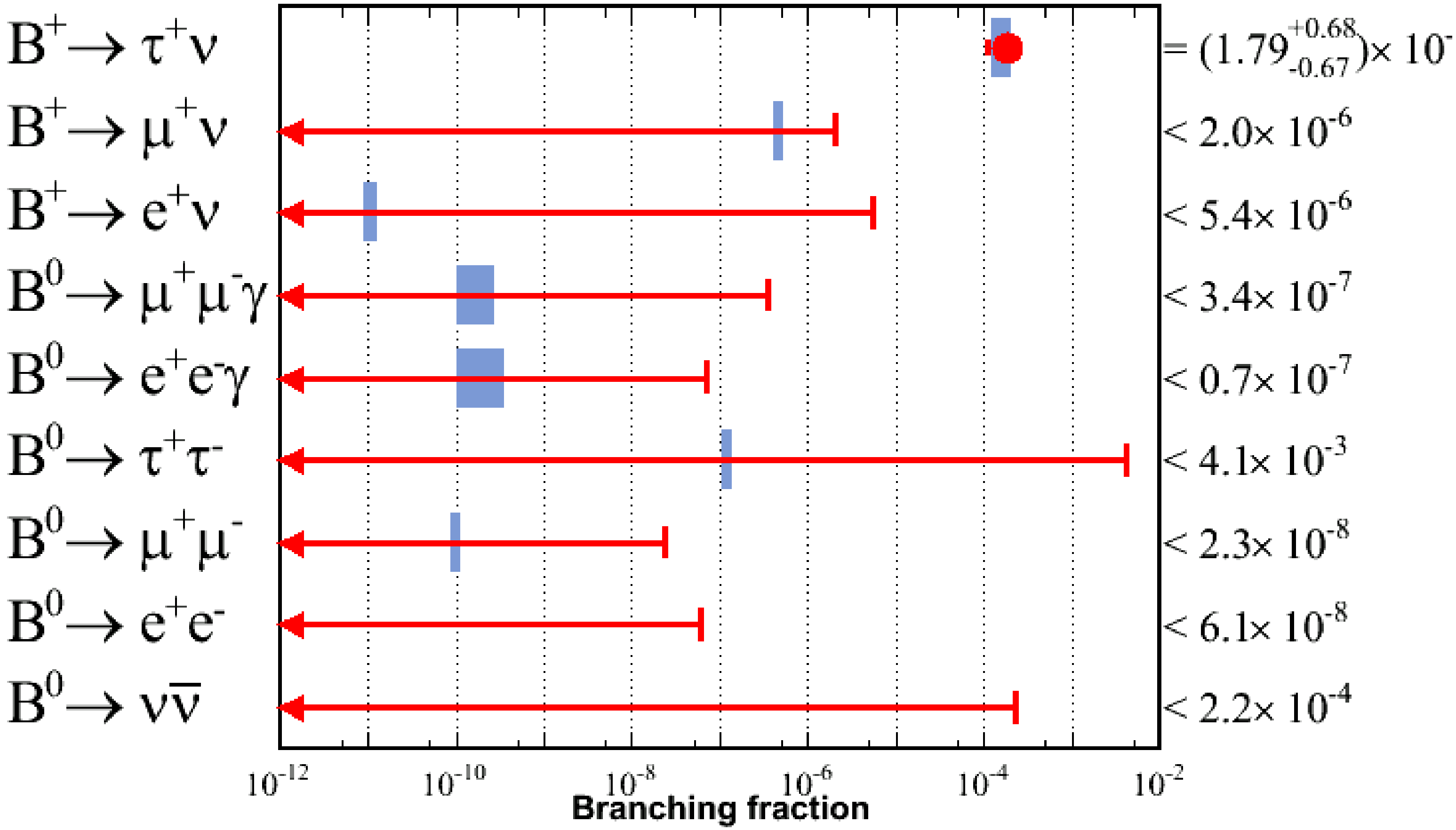
Will bring discovery and eventually precision measurement.





Rare decay searches

Comparison of current search limits and SM predictions



The strength of LHCb

The best

- Two-body decays
- Muons in the final state

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

The good

- Exclusive channels
- Muons in final state

} $\Rightarrow B \rightarrow K^{(*)} \mu^+\mu^-$

The reasonable

- γ/e in final state

$\Rightarrow B \rightarrow X_s/X_d \gamma$

The bad

- Inclusive decays

$\Rightarrow b \rightarrow s \mu^+\mu^-$

The impossible

- Invisible decays

$\Rightarrow B_{d/s} \rightarrow \nu \nu$

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

Look at decay in terms of transversity amplitudes $A_\perp, A_\parallel, A_0$ for left and right handed currents.

Good variables with small theoretical error in the Standard Model are:

- Forward backward asymmetry A_{FB} (small error on zero point)

$$A_T^{(1)}(s) = \frac{-2\mathrm{Re}(A_\parallel A_\perp^*)}{|A_\perp|^2 + |A_\parallel|^2}, \quad A_T^{(2)}(s) = \frac{|A_\perp|^2 - |A_\parallel|^2}{|A_\perp|^2 + |A_\parallel|^2}.$$

- Transverse asymmetries (insignificant error at $q^2 < 6$ GeV^2):

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

- Fraction of K* polarization (small error):

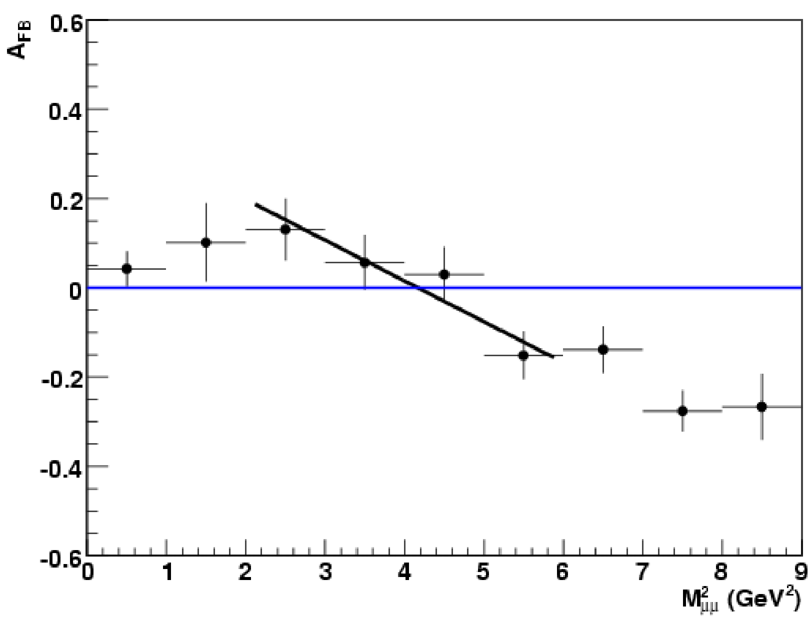
$B_d \rightarrow K^{*0}\mu^+\mu^-$ in LHCb

Overall efficiency is 1.1% with a B/S~0.5

Yield in 2 fb^{-1} of above 7000 events expected

Background dominated by semi-leptonic B decays

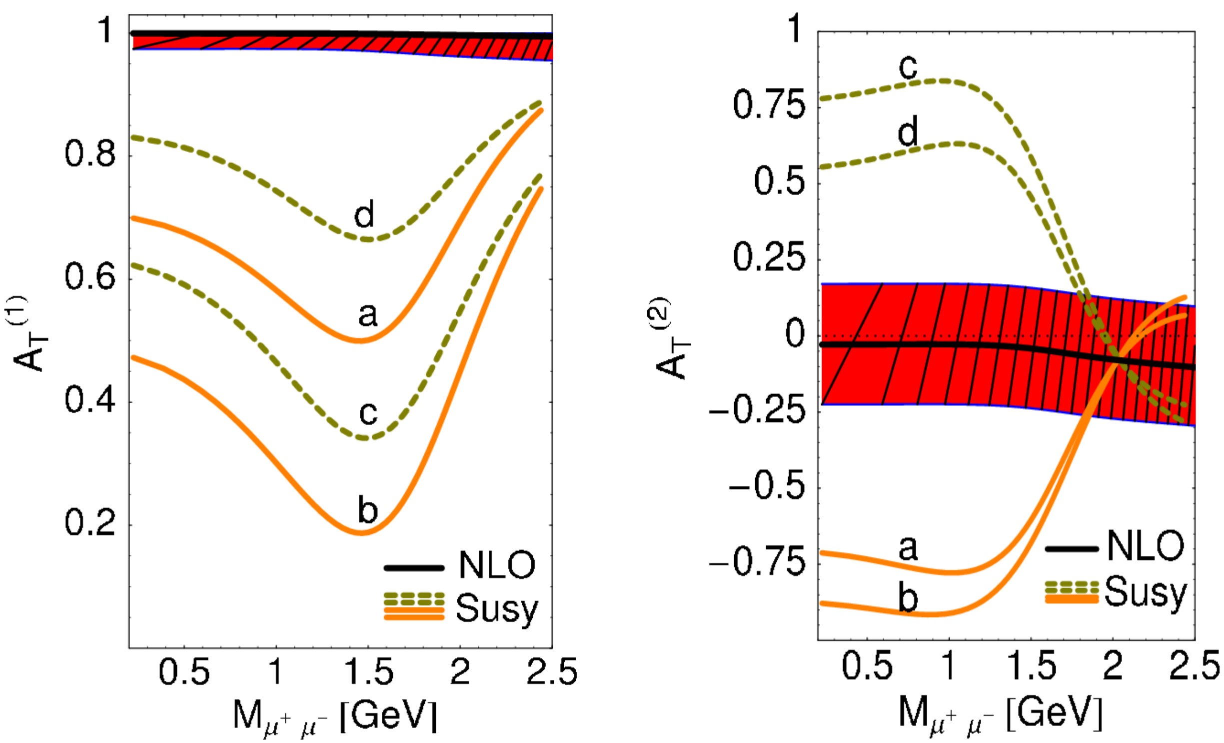
Resolution of 0.53 GeV^2 in zero point



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

The transversity asymmetries are sensitive to new right handed currents.

- As an example explore a set of MSSM models that all satisfy current experimental constraints

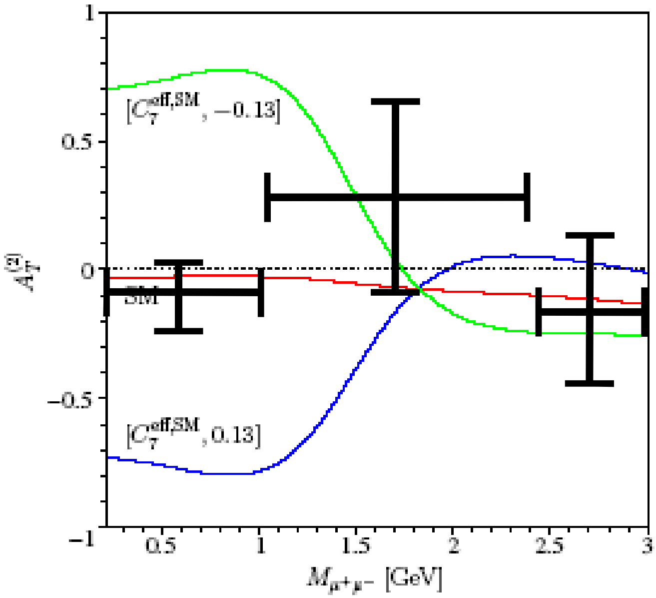


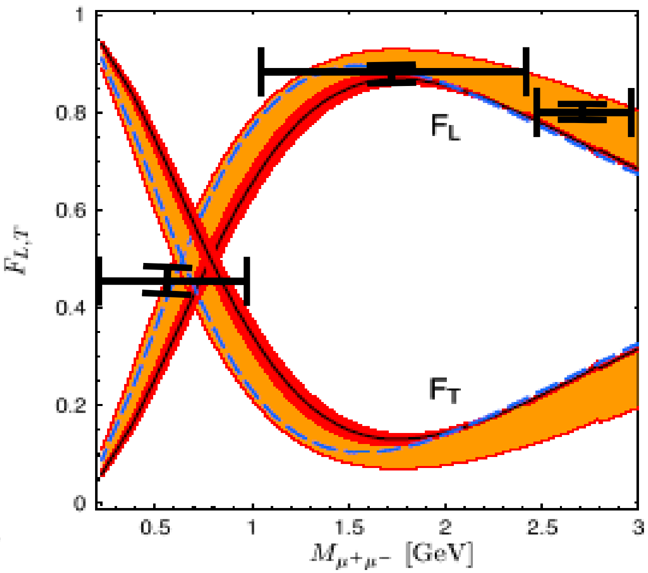
JHEP 0704, 058, Lunghi, Matias

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

Central q^2 region is favoured by theory

q^2 region (GeV^2/c^4)	A_{FB} $2\,\mathrm{fb}^{-1}$	A_{FB} $10\,\mathrm{fb}^{-1}$	$A_T^{(2)}$ $2\,\mathrm{fb}^{-1}$	$A_T^{(2)}$ $10\,\mathrm{fb}^{-1}$	F_L $2\,\mathrm{fb}^{-1}$	F_L $10\,\mathrm{fb}^{-1}$
$0.05-1.00$	0.034	0.017	0.14	0.07	0.027	0.011
$1.00-6.00$	0.020	0.008	0.42	0.16	0.016	0.007
$6.00-8.95$	0.022	0.010	0.28	0.13	0.017	0.008





Result from $2\ \mathrm{fb}^{-1}$ toy MC

Use of B-beam in a Super B-factory

- Take advantage of Υ(4S) production
  - Reconstruct very large sample of fully or partially B decays
  - Then look in remainder of event for signature of signal decay.
- Search for invisible decays like $B \to \nu\nu$ possible.
- Strategy currently used in BaBar and BELLE to set limit for $B \to K \nu\nu$ at $4\ 10^{-5}$ level.
  - A Super B-factory should be able to see signal

Summary

Rare decays has a long history of providing hints for new physics

With current results strictest limits come from

- Inclusive $b \to s \gamma$
- Searches for $B_s \to \mu^+ \mu^-$

Future will bring

- Long range of measurement for $B_d \to K^{*0} \mu^+ \mu^-$
- CP violation and polarisation results for $B_d \to K^{*0} \gamma$
- Observation and precise BR measurement of $B_s \to \mu^+ \mu^-$
- And much more ...

Combination of all Rare Decay results will provide similar constraints to current CKM fits.