Rare Decays

I'll make a (biased) picture of the status in 2014

- Assumptions
- Rare B decays
- Rare K decays
- Rare D decays

. . . and will draw some conclusions on prospects

Thanks to Adrian Bevan, Ulrik Egede, Cristina Lazzeroni, Franz Muheim, Steve Playfer, Chris Parkes, Jonas Rademacker, Maria Smizanska, . . .

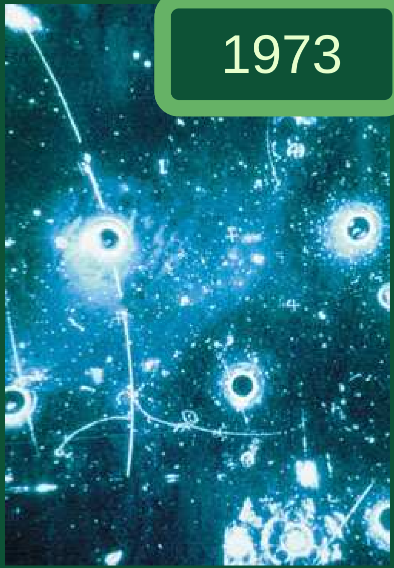
13/07/09 — PPAP community review

Patrick Koppenburg
Imperial College
London

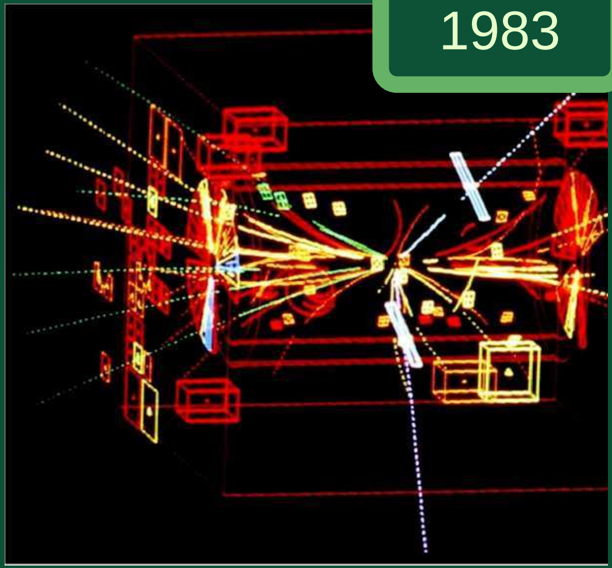
Indirect searches

- Sensitive to New Physics effects
  - When was the Z discovered?
    - 1973 from $N\nu \to N\nu$?
    - 1983 at SpS?
  - c quark postulated by GIM, third family by KM
- Estimate masses
  - t quark from $B\overline{B}$ mixing
- Get phases of couplings
  - Half of new parameters
  - Needed for a full understanding
- Look in lepton and **flavour** sectors

  ➜ CP asymmetry in the Universe



1973



1983

Questions

$b \longrightarrow s\gamma$: Is a more precise measurement of the $b \rightarrow s\gamma$ branching fraction possible?

Polarisation: What are the most promising ways to measure the photon polarisation in $b \rightarrow s\gamma$? How much data is needed for precise tests of the SM? Will the measurements be theory limited by 2014?

$B_s \longrightarrow \mu\mu$: will the precision to unambiguously confirm or exclude SM be achieved by 2014? What will be the limiting factors? (topologically similar backgrounds, normalisation channels, knowledge of B_s production fraction at high energies, etc.). Which experiment(s) are best placed to overcome these? What can we learn from $B \rightarrow \tau\nu$? What is the potential for $B_d \rightarrow \mu\mu$ and the $B_d \rightarrow \mu\mu/B_s \rightarrow \mu\mu$ ratio?

Questions

$\boldsymbol{b \longrightarrow \ell\ell s}$**:** What physics is accessible at different luminosities? (eg. How much data is needed for full angular analysis? How does the physics reach improve with the more complete analysis?). At what stage will theoretical uncertainties become limitations, and how much data is needed to do inclusive analyses to further reduce the error?

$\boldsymbol{b \longrightarrow d}$**:** How much additional data is needed to constrain new physics effects in $b \longrightarrow d\gamma$ and $b \longrightarrow \ell\ell d$ decays, compared to $b \longrightarrow s$ equivalents? What more is learnt about new physics from these?

Rare $\boldsymbol{K}$: What precision should be aimed for in $K^+ \longrightarrow \pi^+\nu\nu$ and $K_L^0 \longrightarrow \pi^0\nu\nu$ measurements? What will these measurements tell us about new physics?

Rare $\boldsymbol{D}$: Is there anything to learn from up-type quarks?

Assumptions for B physics in 2014

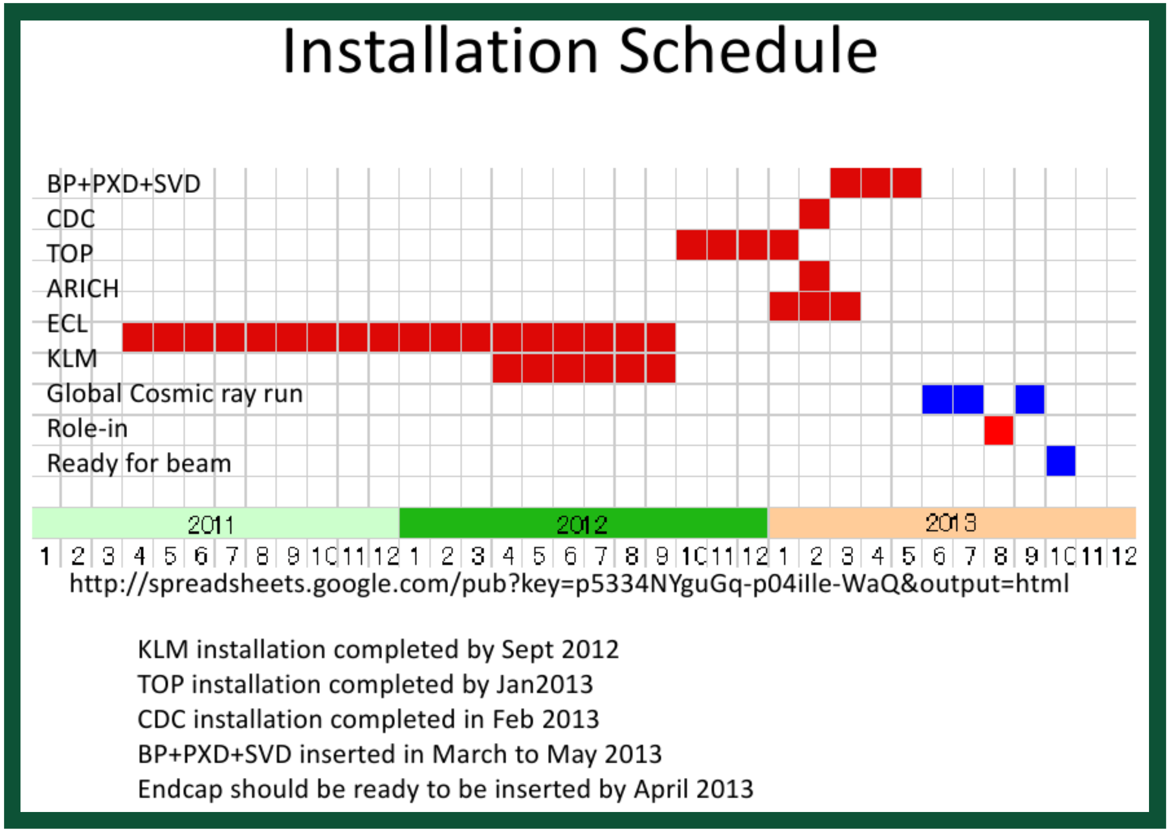
B factories:

BaBar is terminated. They are finalising their analyses.

Belle is approved until 1ab^{-1}. They will now (mainly?) run at $\Upsilon(5S)$.

Belle II collaboration is being set up. Seems unlikely (to me) they will have data in 2014...

- They **must** start in FY2013
- See 3rd Belle II Open Meeting



Assumptions for B physics in 2014

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Hadron colliders:

CDF & D0 will take data until LHC makes them redundant

Atlas & CMS have a B programme but can't compete with ...

LHCb will be the key player between 2010–14

	$\sqrt{s}$	LHCb	Atlas & CMS
Oct–Jul (?)	$\sim$8 TeV	200 pb^{-1}	300 pb^{-1}
2011 (?)	14 TeV	1 fb^{-1}	A few fb^{-1}
2012+	14 TeV	$\geq$ 2 fb^{-1}/ year	10 fb^{-1}/ year
Total to 2014	14 TeV	**10 fb^{-1}**	**30 fb^{-1}**

Assumptions for B physics in 2014

B factori

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Hence:

1. **The measurements in 2014 will be dominated by LHCb**
   - **I'll assume LHCb will have collected 10 fb^{-1}**
   - **Could be less: doesn't change conclusions**
2. ***Except* in channels that LHCb can't do**
   - **Where Belle $\oplus$ Babar will dominate**
   - **I'll point these channels out**

Oct–Jul (?)	$\sim$8 TeV	200 pb^{-1}	300 pb^{-1}
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Radiative Decays

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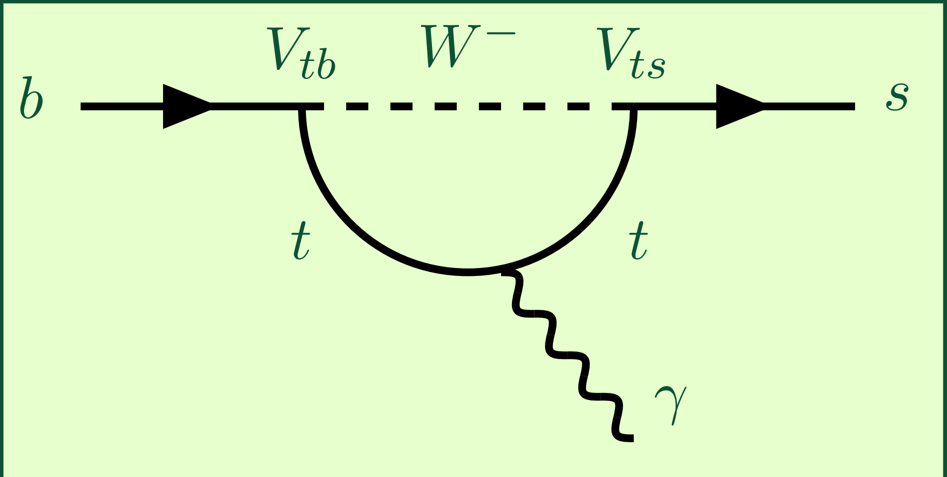
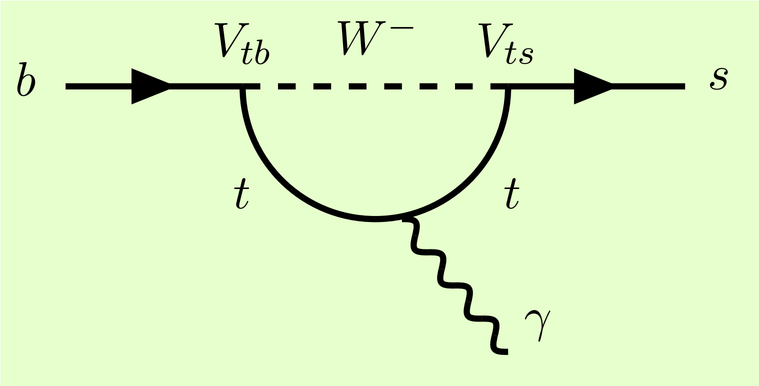
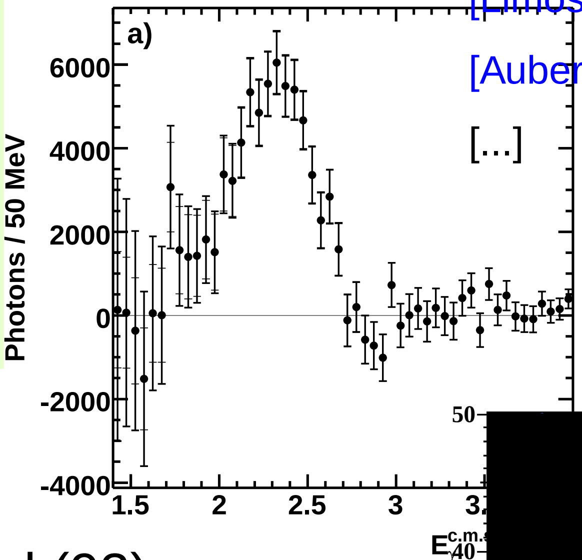


$b \to s\gamma$ branching fraction



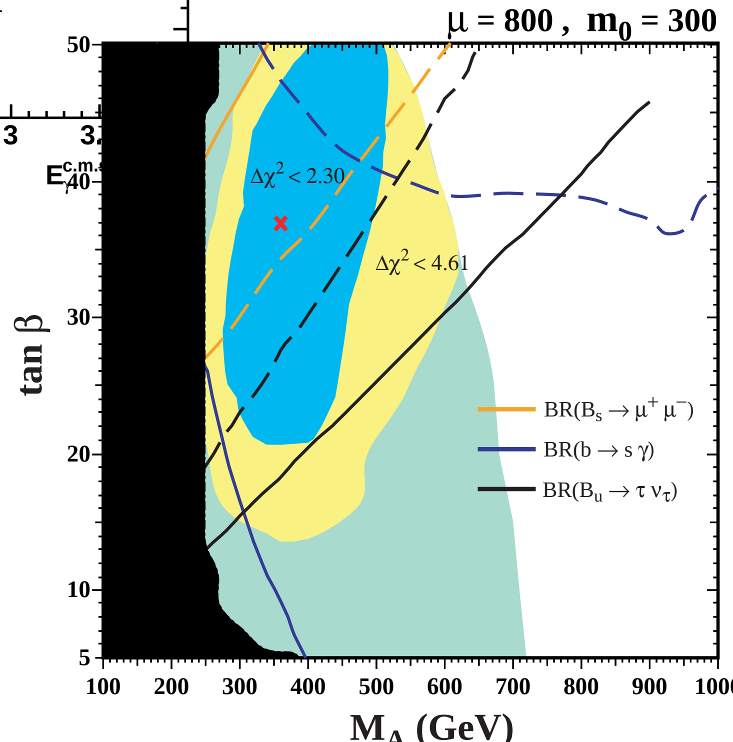


[Limosani et al., ArXiv0907.1384: (2009)]

[Aubert et al., hep-ex/0507001]

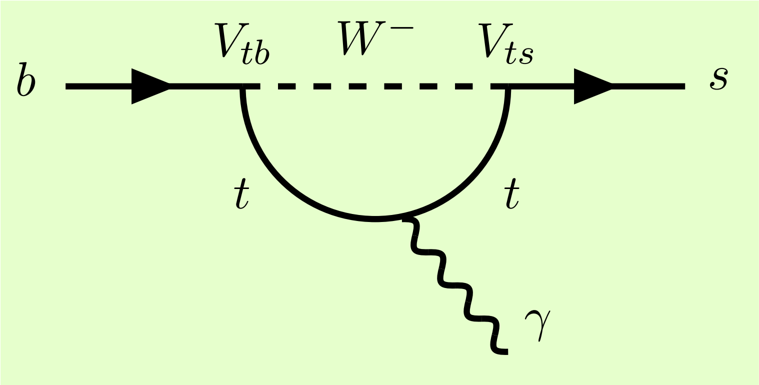
[...]

- Amplitude $\propto V_{ts}|C_7|$
- First penguin ever observed (93)
- Experiment (WA): $\mathcal{B} = (3.56 \pm 0.25) \cdot 10^{-4}$
- SM: $\mathcal{B} = (3.15 \pm 0.23) \cdot 10^{-4}$ ($E_\gamma > 1.6$ GeV) [Misiak et al., hep-ph/0609232]
- Sets a very strong constraint on New Physics



[Ellis et. al, hep-ph/0709.0098]

$b \to s\gamma$ branching fraction



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- Sets a very strong constr Physics

- Inclusive BF will be improved, down to ($E_\gamma > 1.6$ GeV)
  - After that, needs recoil
- Theory will improve as well
  - But probably not enough to change the picture
- Except if there's indication of new physics ...

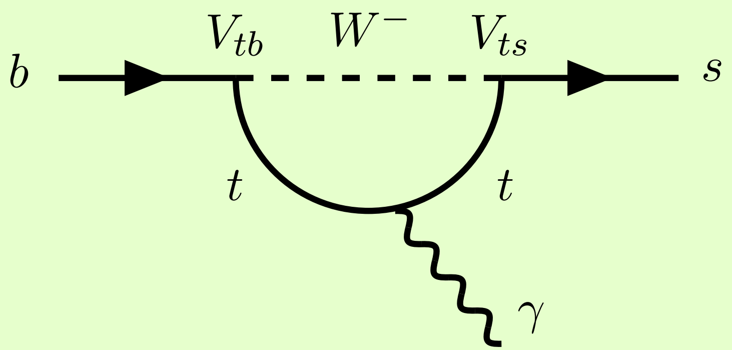
➜ Very interesting channel, but not my first bet for 2014+

1000

M_A (GeV)

[Ellis et. al, hep-ph/0709.0098]

$b \to s\gamma$ photon polarisation



The photon polarisation is not well measured.

- Naively $r = \frac{C'_{7\gamma}}{C_{7\gamma}} \overset{\text{SM}}{\simeq} \frac{m_s}{m_b}$
- Gluons contribute $0.5 \pm 1.0\%$ [Ball & Zwicky PLB642:478,2006]
- Right-handed operators could contribute

✔ Mixing-induced CP violation in $B_s \to \phi\gamma$
[Atwood et al., PRL79:185, 1997]

✔ Λ_b baryons
[Hiller & Kagan, PRD65:074038, 2002]

- $B \to \gamma K^{**}(K\pi\pi)$
[Gronau & Pirjol, PRD66 054008, 2002]
[Gronau et al., PRL88:051802, 2002]

✔ Virtual photons ($b \to \ell\ell s$)
[Melikhov et al., PLB442:381-389,1998]

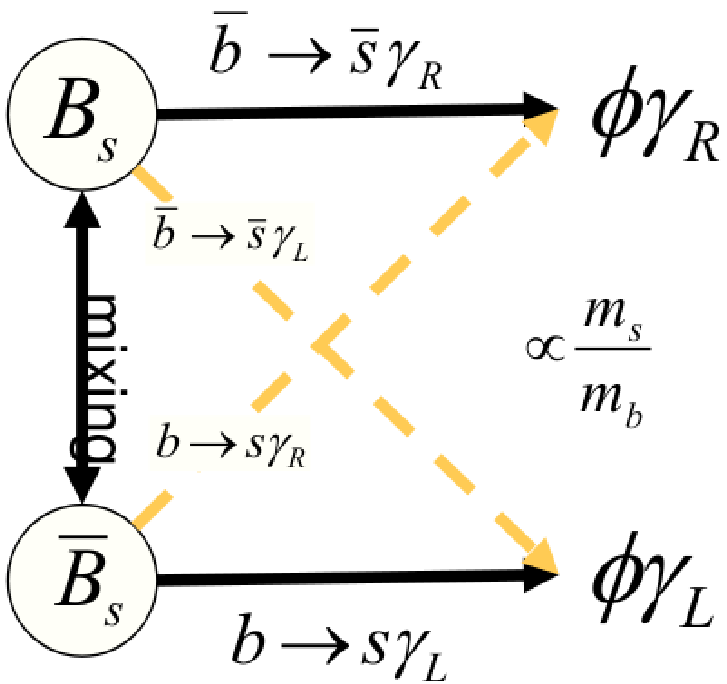
- Converted photons
[Grossman et al., JHEP06:29,2000]

$B_s \to \phi\gamma$

In SM mainly $B_s \to \phi\gamma_\mathrm{R}$ and $\overline{B}_s \to \phi\gamma_\mathrm{L}$. Mixing only if wrong polarisation.

$\mathcal{A}^{\text{mix}}$ tiny $\quad$ $\mathcal{A}^{\text{dir}} = 0$ in MFV $\quad$ $\mathcal{A}^{\Delta\Gamma} \simeq \sin(2r)$

$$\mathcal{A}_s(t) = \frac{\Gamma_{\overline{B}_s\to\phi\gamma} - \Gamma_{B_s\to\phi\gamma}}{\Gamma_{\overline{B}_s\to\phi\gamma} + \Gamma_{B_s\to\phi\gamma}} = \frac{\mathcal{A}^{\text{dir}}\cos\Delta m_s t + \mathcal{A}^{\text{mix}}\sin\Delta m_s t}{\cosh\frac{1}{2}\Delta\Gamma t - \mathcal{A}^{\Delta\Gamma}\sinh\frac{1}{2}\Delta\Gamma t}$$



LHCb combines a tagged and an untagged approach (measures all $\mathcal{A}$):

- 5% error on $\mathcal{A}^{\text{mix}}$ (10 fb^{-1})
- 9% error on $\mathcal{A}^{\Delta\Gamma}$ (10 fb^{-1})

➜ Assuming small r, LHCb can get a 5% error with 10 fb^{-1}

[LHCb-2007-147]

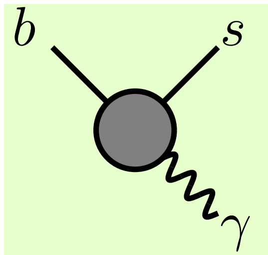
Future prospects on polarisation

- Theory error is out of reach!
- Belle can improve on $B \to K_S^0 \pi^0 \gamma$ and $B \to K_S^0 \rho \gamma$
  - But they have errors of 20–30% with $>$500fb^{-1}.
- LHCb should reach 5% error on the photon polarisation with 10 fb^{-1}
  - 5% from $B_s \to \phi\gamma$ ([LHCb-2007-147])
  - A similar error from $B \to eeK^*$ at low q^2 ([LHCb 2009-008])
  - $\Lambda_b \to \Lambda\gamma$ should get $\sim 10\%$ ([LHCb 2006-013])
- ✔ Could be improved with larger statistics beyond 2014
- I hope that in 2014 we'll have hints of right-handed currents already!

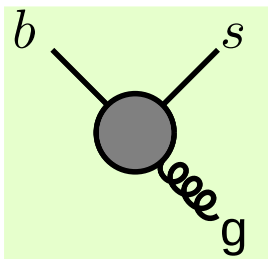
Operators

Operator

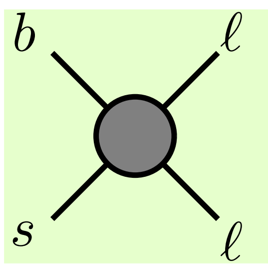
$\mathcal{O}_{7\gamma}$



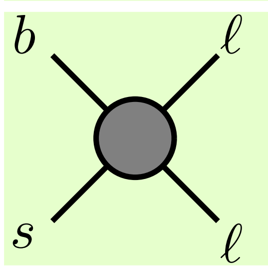
$\mathcal{O}_{8\mathrm{g}}$



$\mathcal{O}_{9\ell,10\ell}$



$\mathcal{O}_{S,P}$



Effective Hamiltonian $\mathcal{H}$

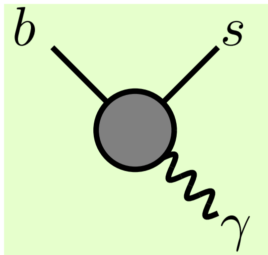
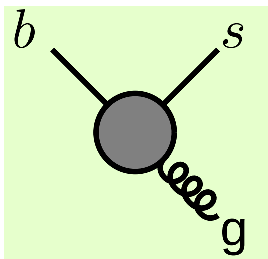
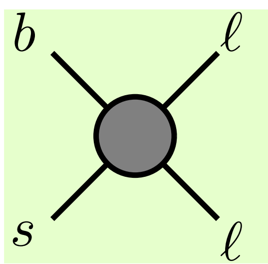
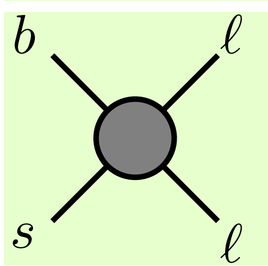
$$A(M \rightarrow F) = \langle F \left| \mathcal{H}_{\text{eff}} \right| M \rangle$$

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{ts}{}^* V_{tb} \sum_{i=1}^{10} C_i(\mu) \mathcal{O}_i(\mu)$$

- Operators $\mathcal{O}_i$: Long-distance effects
- Wilson coefficients C_i: Short-distance effects (masses above μ are integrated out)

New physics can show up in new operators or modified Wilson coefficients

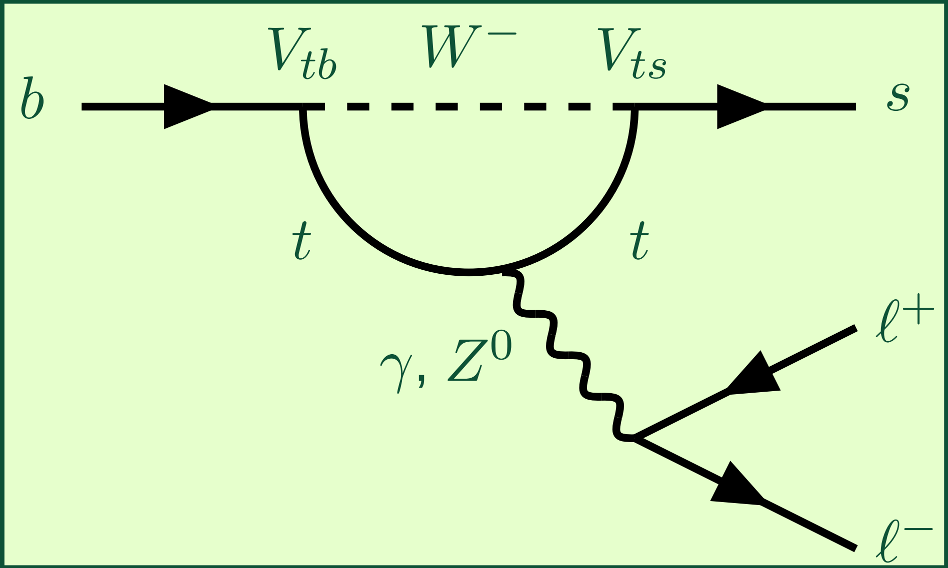
Operators

Operator		magnitude	phase	helicity flip $\mathcal{O}_i'$
$\mathcal{O}_{7\gamma}$		$b \to s\gamma$	$A_{\mathrm{CP}}\,(b \to s\gamma)$	$\Lambda_b \to \Lambda\gamma$ $B_s \to \phi\gamma$ $B \to \ell\ell K^*$
$\mathcal{O}_{8\mathrm{g}}$		$b \to s\gamma$ $b \to \{s, u, d\}$	$A_{\mathrm{CP}}\,(b \to s\gamma)$ $B \to \phi K$	$\Lambda_b \to \Lambda\phi$ $B \to K^*\phi$
$\mathcal{O}_{9\ell,10\ell}$		$b \to \ell\ell s$	$A_{\mathrm{FB}}\,(b \to \ell\ell s)$	$B \to \ell\ell K^*$
$\mathcal{O}_{S,P}$		$B \to \mu\mu$	$B \to \tau\tau$	$b \to s\tau\tau$

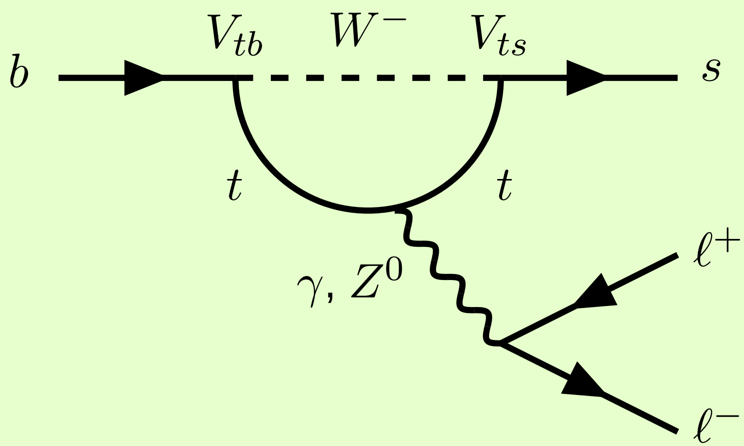
Adapted from [G.Hiller,hep-ph/0308180]

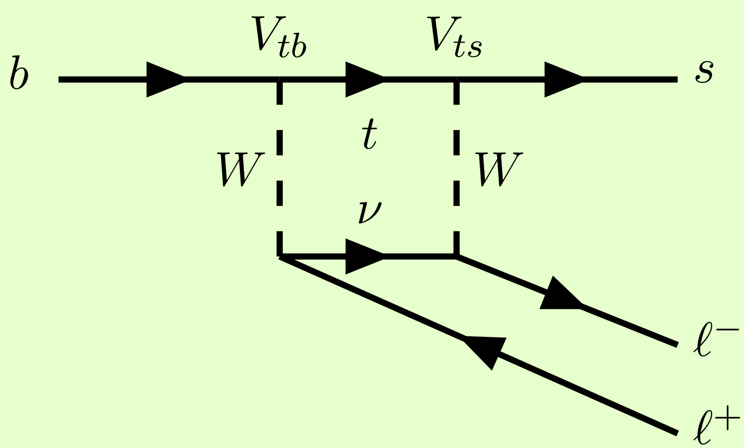
Semileptonic Penguins

$b \to \ell\ell s$: What physics is accessible at different luminosities? (eg. How much data is needed for full angular analysis? How does the physics reach improve with the more complete analysis?). At what stage will theoretical uncertainties become limitations, and how much data is needed to do inclusive analyses to further reduce the error?



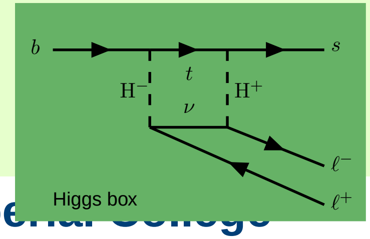
Semileptonic Penguins

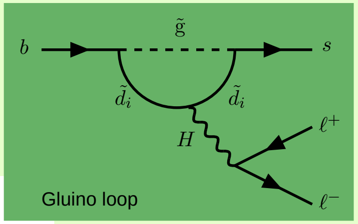


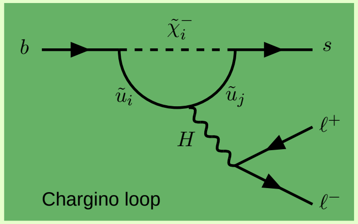


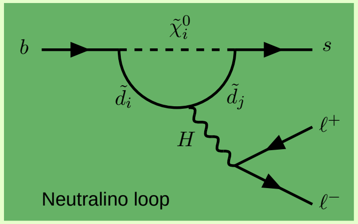
- $B \to \mu\mu K^*$ very rare in the SM
  $\mathcal{B}\left(B \to \ell\ell K^*\right) = (1.2 \pm 1.0) \cdot 10^{-6}$
  $\mathcal{B}\left(B \to \ell\ell K\right) = (0.5 \pm 0.1) \cdot 10^{-6}$
- Sensitive to
  - Supersymmetry,
  - Graviton exchanges,
  - Extra dimensions

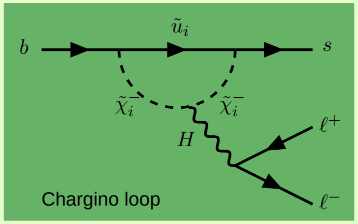
➜ Ideal place to look for new physics


Higgs box


Gluino loop


Chargino loop


Neutralino loop


Chargino loop

$b \longrightarrow \ell\ell s$ observables

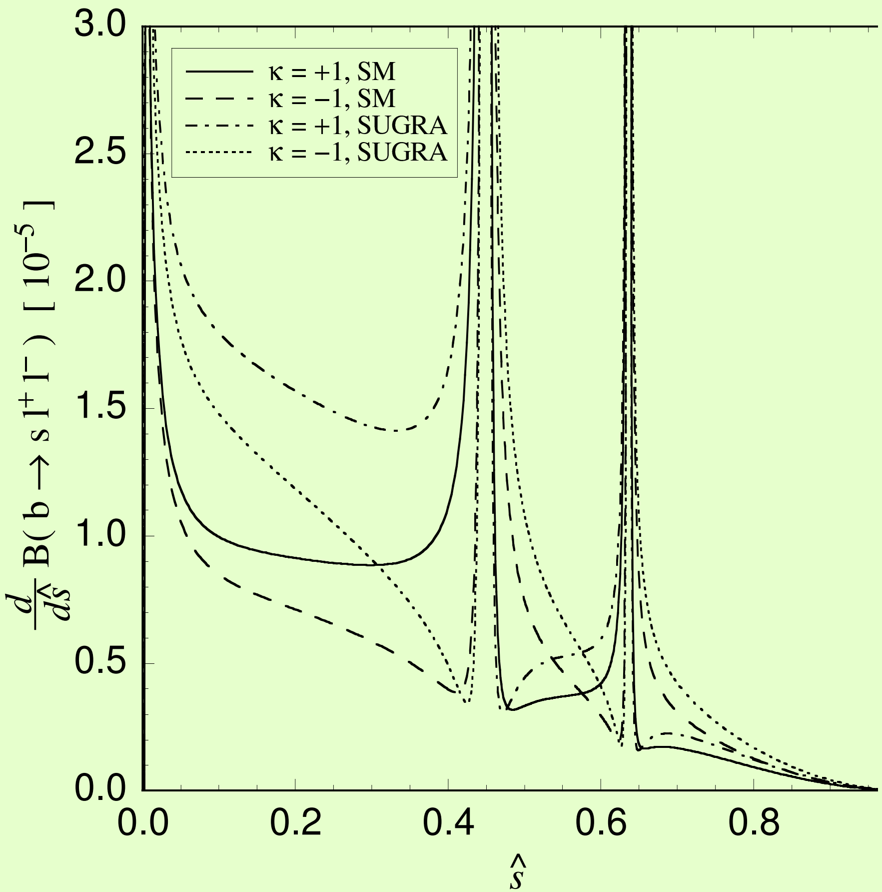
Inclusive decay well described theoretically

- Shape of dilepton mass distribution sensitive to NP
- SM branching ratio $(1.36 \pm 0.08) \cdot 10^{-6}$ (NNLL) for $s = q^2/m_b^2 < 0.25$

✗ Inclusive decays difficult to access experimentally

✗ Exclusive decays affected by hadronic uncertainties

➜ Use ratios where hadronic uncertainties cancel out



[Goto et al., PRD55 (1997) 4273]

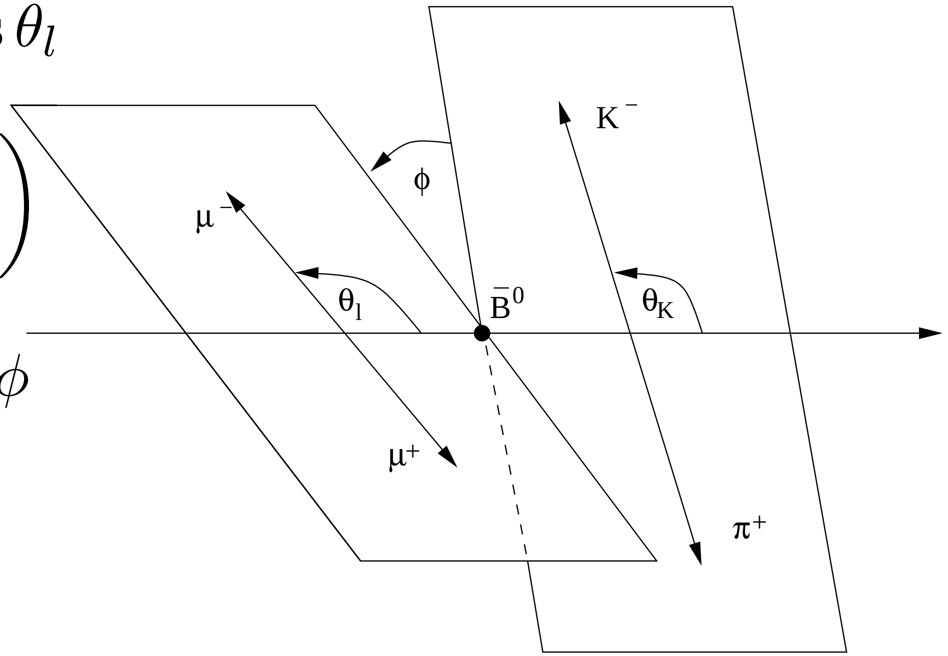
Angular Distributions

There's more information in the full θ_ℓ, θ_K and ϕ distributions

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

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

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



➜ Many observables

[Krüger & Matias] [Egede, et. al.] [Ball, et. al.]

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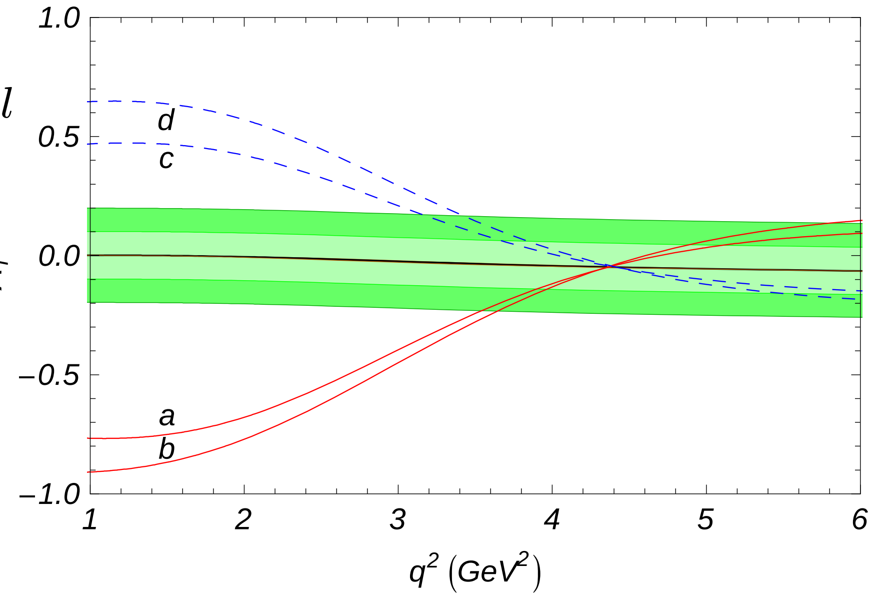

→ **Transverse asymmetry $A_T^{(2)}$ ($\propto r$, RH)**

[Krüger & Matias] [Egede, et. al.] [Ball, et. al.]

Angular Distributions

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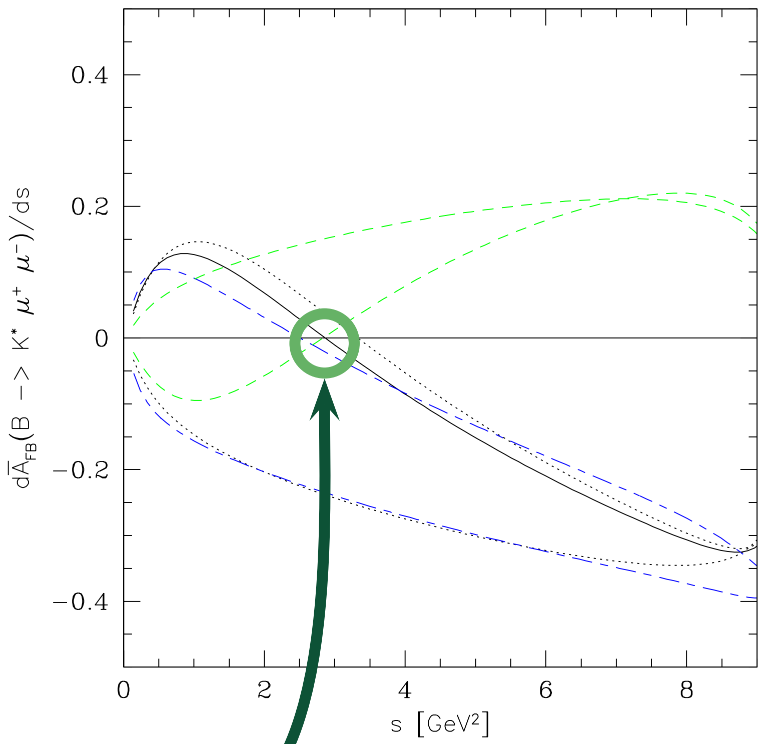
$$A_{\mathrm{FB}} = \frac{\left(\int_0^1 - \int_{-1}^0\right) d\cos\theta_l \frac{d^2\Gamma}{dq^2 d\cos\theta_l}}{\int_{-1}^1 d\cos\theta_l \frac{d^2\Gamma}{dq^2 d\cos\theta_l}}$$



➜ Zero point measures ratio of Wilson coeffs C_9/C_7.

➜ Forward-backward asymmetry A_{FB}

[Krüger & Matias] [Egede, et. al.] [Ball, et. al.]

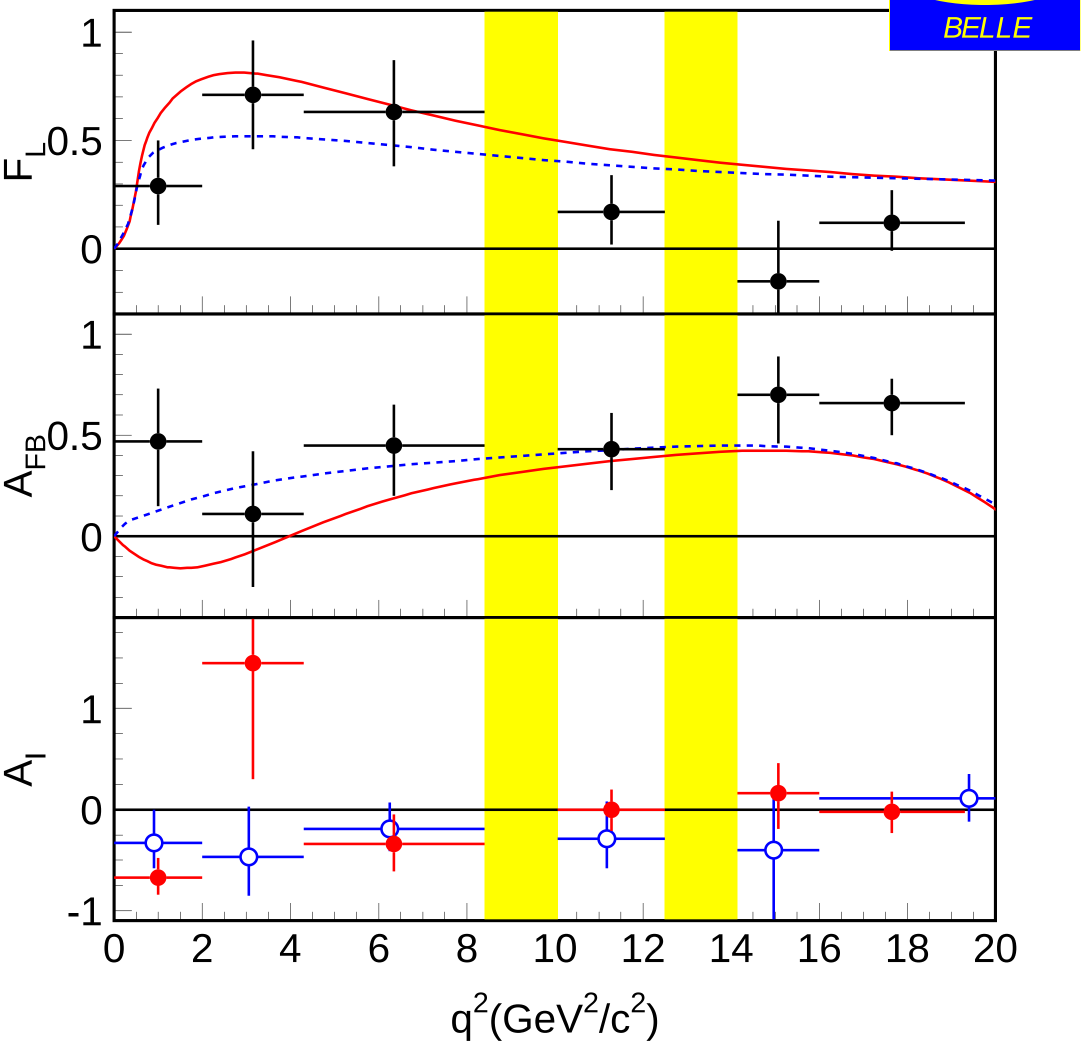
Messages from the B factories

Belle: 160+250 $B \to \ell\ell K^{(*)}$
events in $657 \cdot 10^6$ $B\overline{B}$
[J.T. Wei et al., arXiv:0904.0770v1]

Babar: 50+60 $B \to \ell\ell K^{(*)}$
events in $384 \cdot 10^6$ $B\overline{B}$
[Aubert et al., PRD 79:031102,2009]
[Aubert et al., PRL 102:091803,2009]

$\boldsymbol{F_L}$**:** Too little statistics

FB asymmetry: Not conclusive yet. . .



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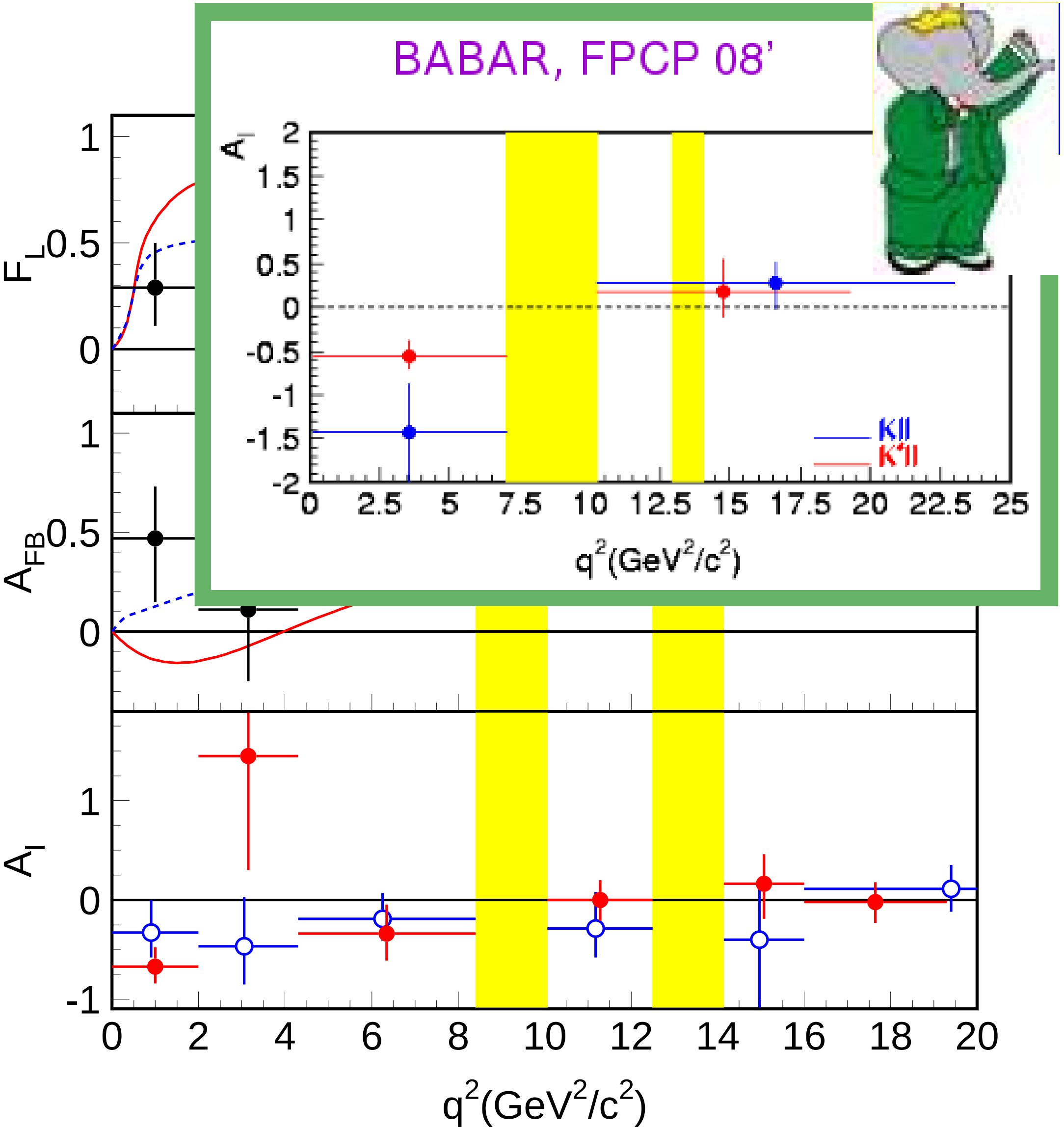
FB asymmetry: Not conclusive yet. . .

Isospin: Belle and Babar both see unexpected isospin asymmetries

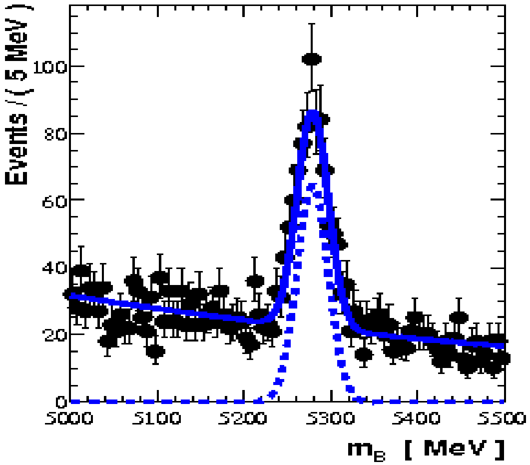
➜ Need much more statistics

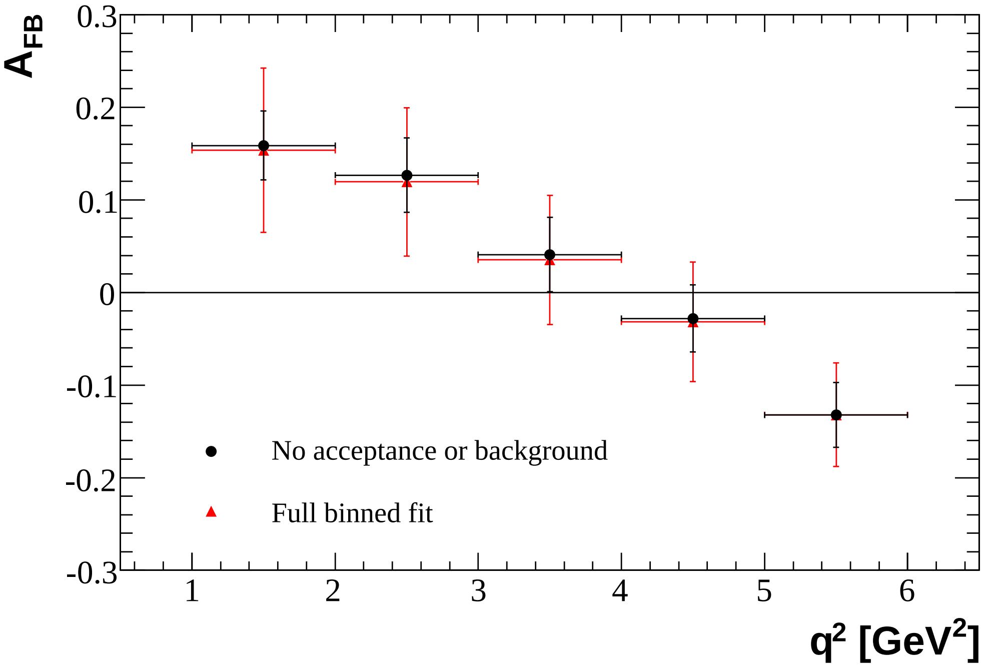


$B_d \to \mu\mu K^*$ yields with 2 fb^{-1}

Expected signal and background yields in 2 fb^{-1} of data (Assuming the SM BR of $\mathbf{12 \cdot 10^{-7}}$):

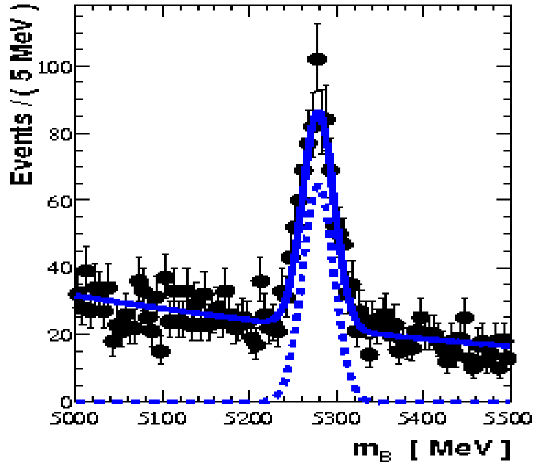
Sample	Yield
$B_d \to \mu\mu K^*$	$\mathbf{7200 \pm 2100}$
$b \to \mu\mu s$	2000 ± 100
$2(b \to \mu)$	1050 ± 250
$b \to \mu c(\mu q)$	600 ± 200
Background	3700 ± 300
B/S	$\mathbf{0.5 \pm 0.2}$



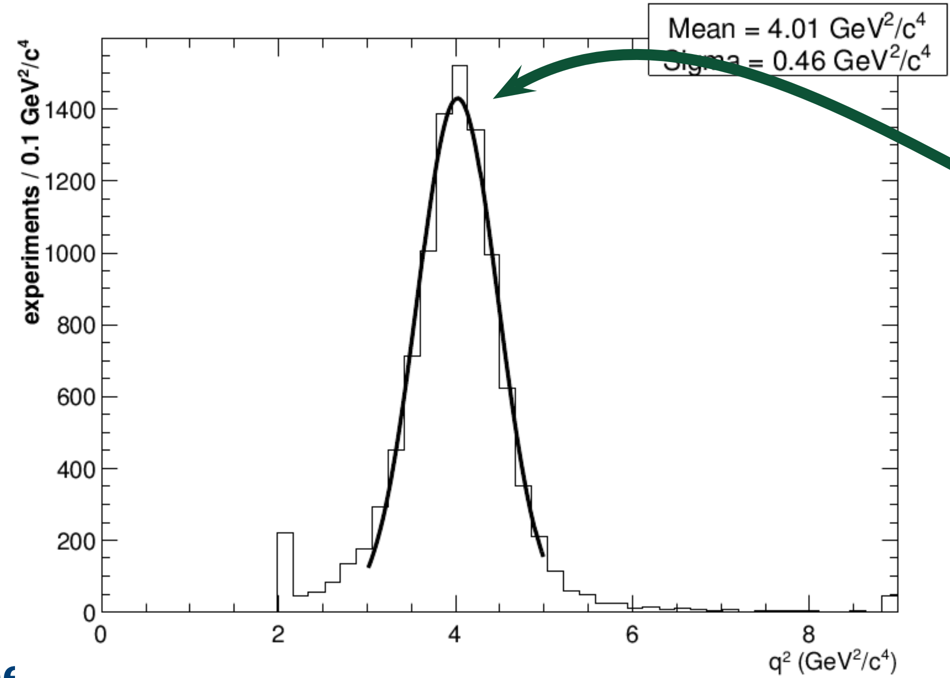


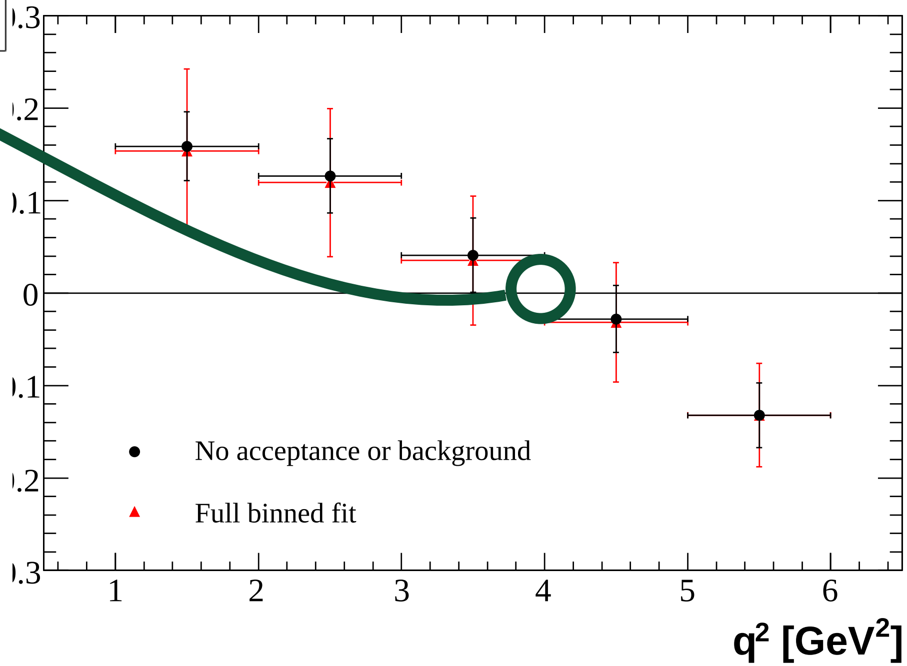
$B_d \to \mu\mu K^*$ yields with 2 fb^{-1}

Expected signal and background yields in 2 fb^{-1} of data (Assuming the SM BR of $\mathbf{12 \cdot 10^{-7}}$):

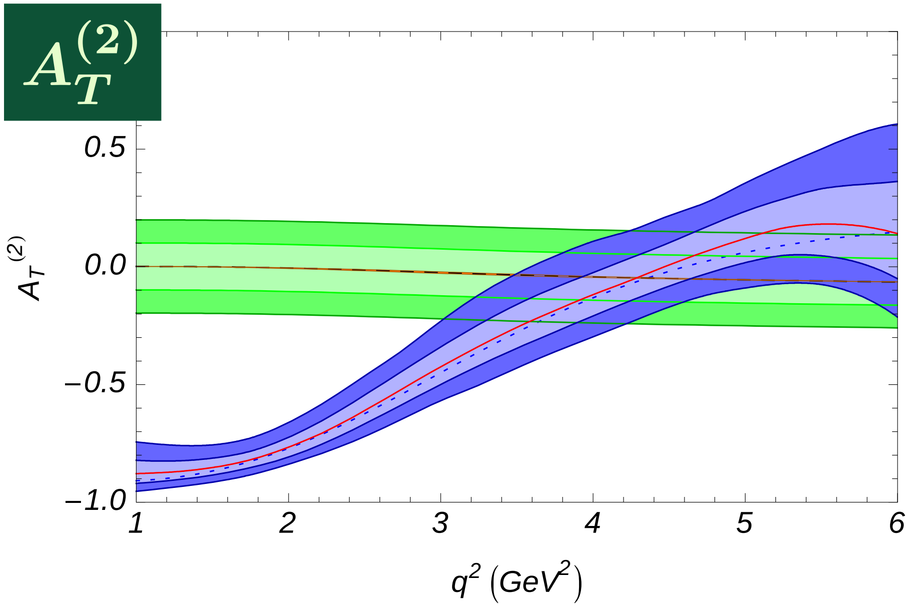


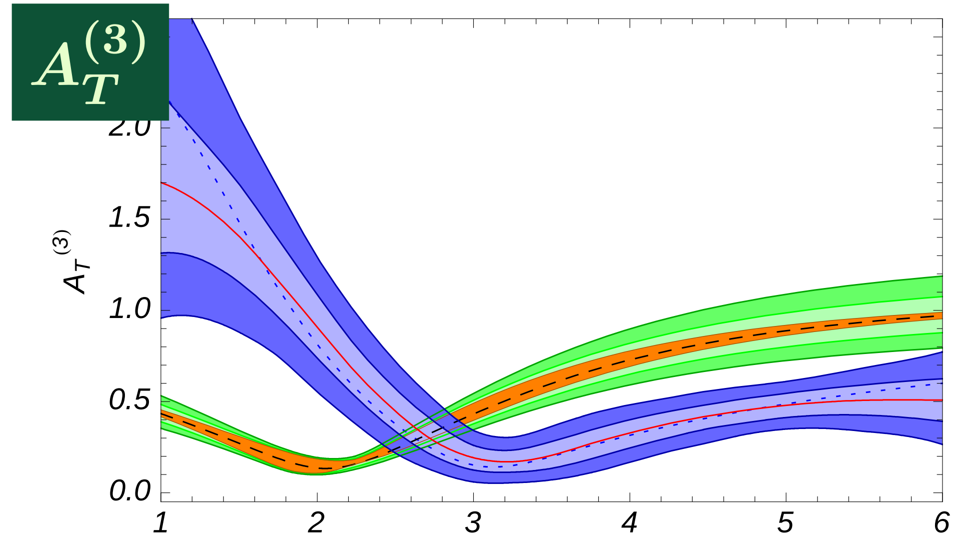
➜ Resolution on $A_{\rm FB}$ zero : ± 0.46 GeV^2 (12%) in 2 fb^{-1}





More asymmetries

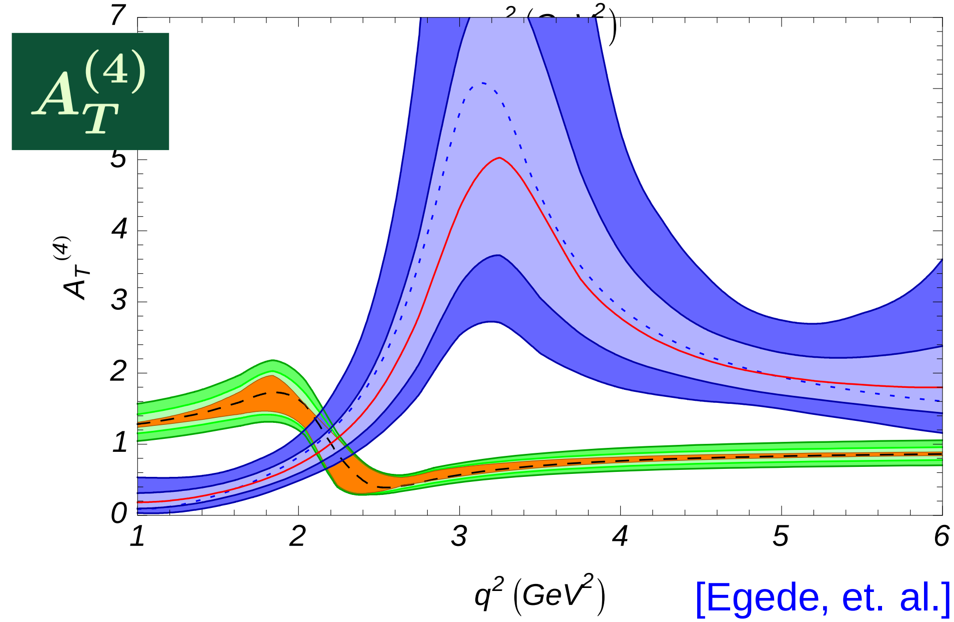




Experimental sensitivity for $10\,\text{fb}^{-1}$ for selected asymmetries [Egede, et. al.]

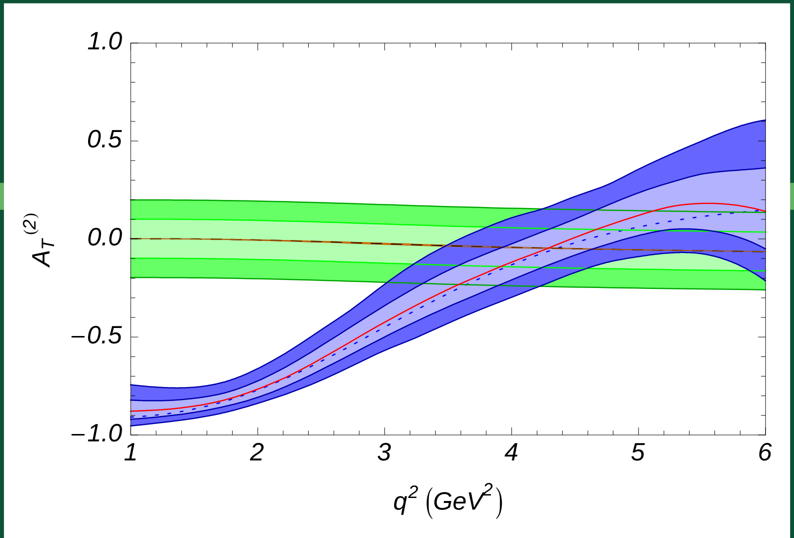
Blue band: experimental sensitivity assuming a Susy model with large gluino mass.

Green band: Standard model expectation with error



[Egede, et. al.]

$B \to \ell\ell K^{(*)}$

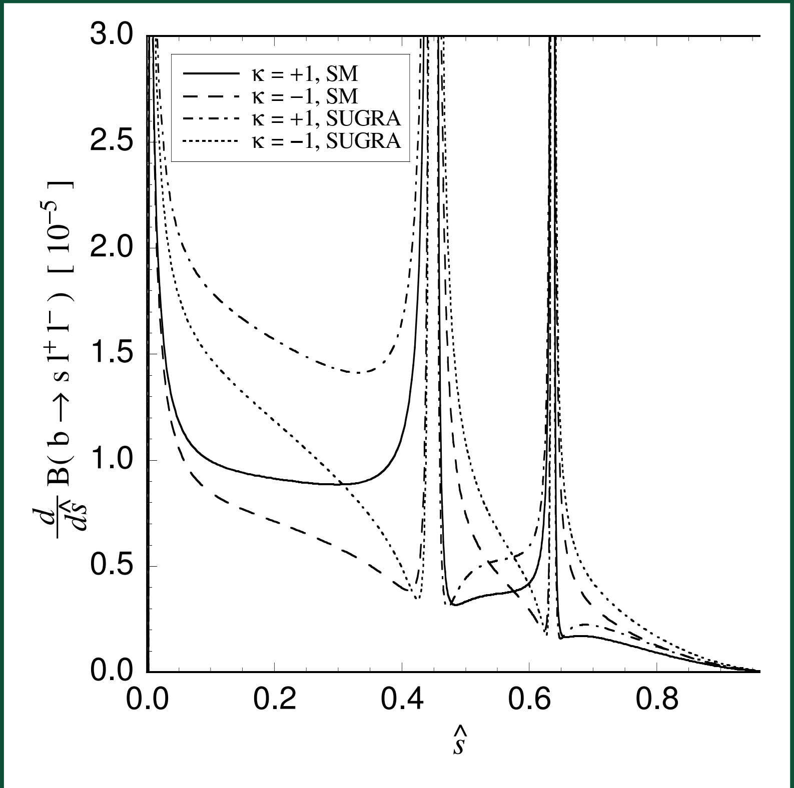


- $B \to \mu\mu K^*$ is the most complete new physics laboratory at LHCb
- Almost any contribution affecting the Wilson coefficients C_7 to C_{10} can be seen
- Including phases due to a 4th generation
  - Theory errors on CP asymmetries are tiny
- With 10 fb^{-1} LHCb will do a full angular analysis
  - The precision will be close to the *present* theoretical error
  - ➜ Theoretical and experimental errors will $\mathcal{O}(10\%)$
- In 2014 errors in some angular asymmetries will be comparable to theory, others will need more data

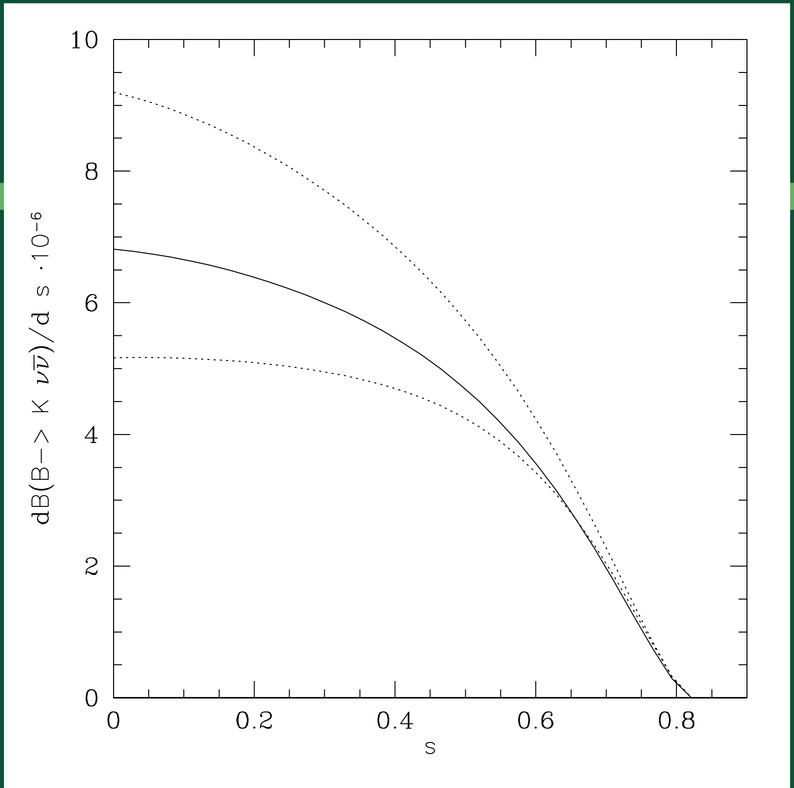
➜ Exclusive $b \to \ell\ell s$ modes will profit from more data

Beyond $B \to \ell\ell K^{(*)}$

- How will theory evolve? Which NP model will be relevant?
  - None of the used predictions include lattice QCD
  - ➜ Lattice could be **very** useful at high q^2 (where SCET doesn't work)
  - ➜ Large interference with $c\bar{c}$, potentially interesting effects
- Fully inclusive analyses are very difficult
  - $b \to \ell\ell s$ + recoil would need **huge** $\int \mathcal{L}$ to match LHCb $B \to \mu\mu K^*$ statistics
- I do not believe that semi-inclusive analyses (sum of exclusive modes) significantly reduce the errors



$B \to \nu\overline{\nu}K^{(*)}$



- $b \to \nu\overline{\nu}s$ decays are interesting probes of New Physics
  - Theoretically clean :
    - No photon penguin (C_7)
    - No $c\bar{c}$ interference
    - ➜ Only short distance
  - Coupling to 3rd generation via ν_τ
- Experimentally challenging
  - Only exclusive modes accessible : $B \to \nu\overline{\nu}K$ and $B \to \nu\overline{\nu}K^*$
  - Requires B factory with recoil tag
  - ➜ Huge statistics required
- SM $\mathcal{B}(B{\to}\nu\overline{\nu}K) = 4 \cdot 10^{-6}$
- Best limit : $< 14 \cdot 10^{-6}$ (Belle 500 fb^{-1})

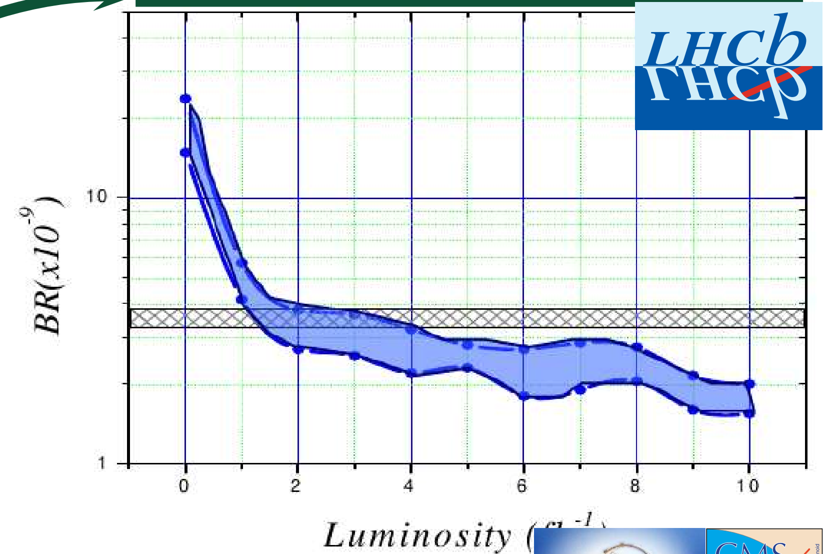
➜ A BF measurement is within reach of a high-lumi factory

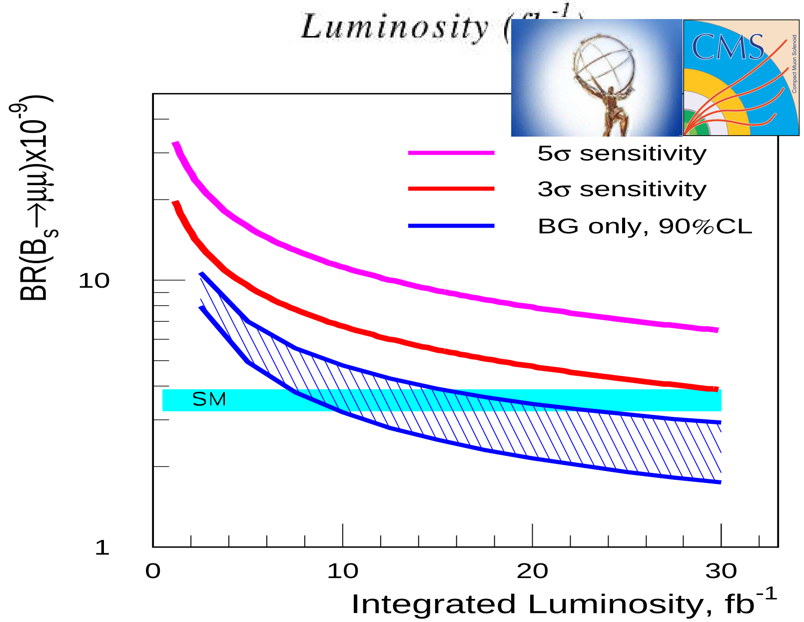
$\boldsymbol{B_s \to \mu\mu}$

$\boldsymbol{B_s \to \mu\mu}$: will the precision to unambiguously confirm or exclude SM be achieved by 2014? What will be the limiting factors? (topologically similar backgrounds, normalisation channels, knowledge of B_s production fraction at high energies, etc.). Which experiment(s) are best placed to overcome these? What can we learn from $B \to \tau\nu$? What is the potential for $B_d \to \mu\mu$ and the $B_d \to \mu\mu/B_s \to \mu\mu$ ratio?

$B_s \to \mu\mu$ at LHC

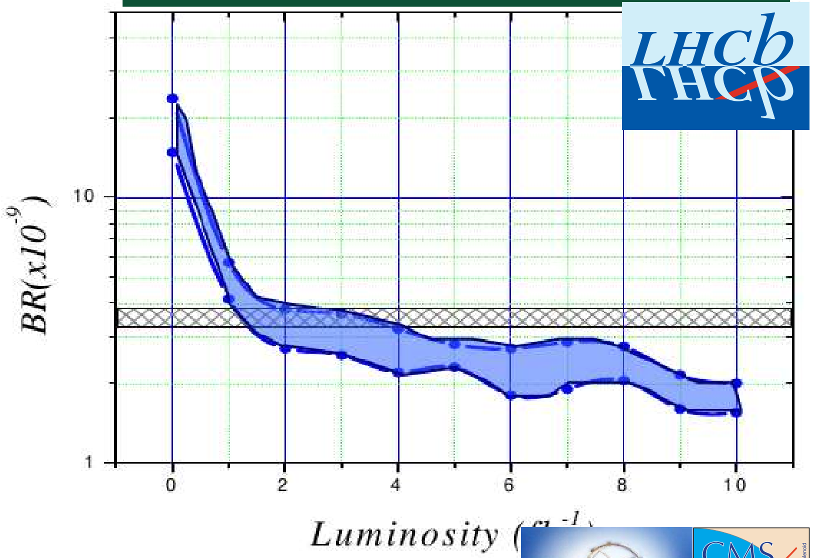
- Very rare but SM BF well predicted $\mathcal{B} = (3.5 \pm 0.3) \cdot 10^{-9}$
- Sensitive to (pseudo)scalar operators
  - MSSM: $\mathcal{B} \propto \frac{\tan^6 \beta}{M_A^4}$
- Present limit from CDF $\mathcal{B} < 5.8 \cdot 10^{-8}$ (95% CL)
- With SM BF:
  - ➜ 3σ evidence with 2 fb^{-1}
  - ➜ 5σ observation with 6 fb^{-1}
- But what if BF is *lower*?
  - Not clear how much data is needed to exclude the SM from below

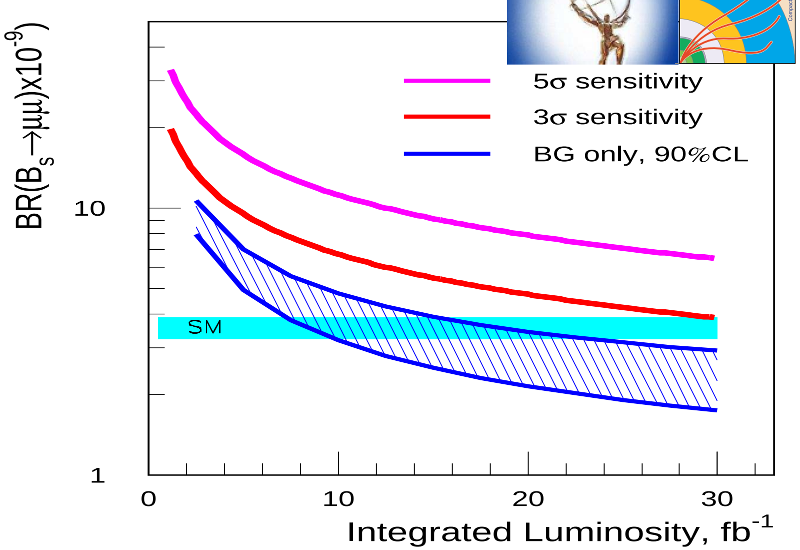




$B_s \to \mu\mu$ at LHC

- **LHCb:**
  - Mass resolution good enough to tell $B_s \to \mu\mu$ from $B_d \to \pi\pi \to \mu\mu$
  - Efficiencies determined from $B_d \to \pi\pi$ (geometry) and $B \to J/\psi K$ (trigger)
- Atlas & CMS also competitive
- Main uncertainty will be normalisation
  - No absolute cross sections at LHC
  - Can only normalise to well-measured B_s decay
  - Presently $\mathcal{B}(B_s \to D_s \pi)$ is $(3.3 \pm 0.5) \cdot 10^{-3}$ (15%)
  - Belle's running at $\Upsilon(5S)$ will help





$B_s \to \mu\mu$ at LHC

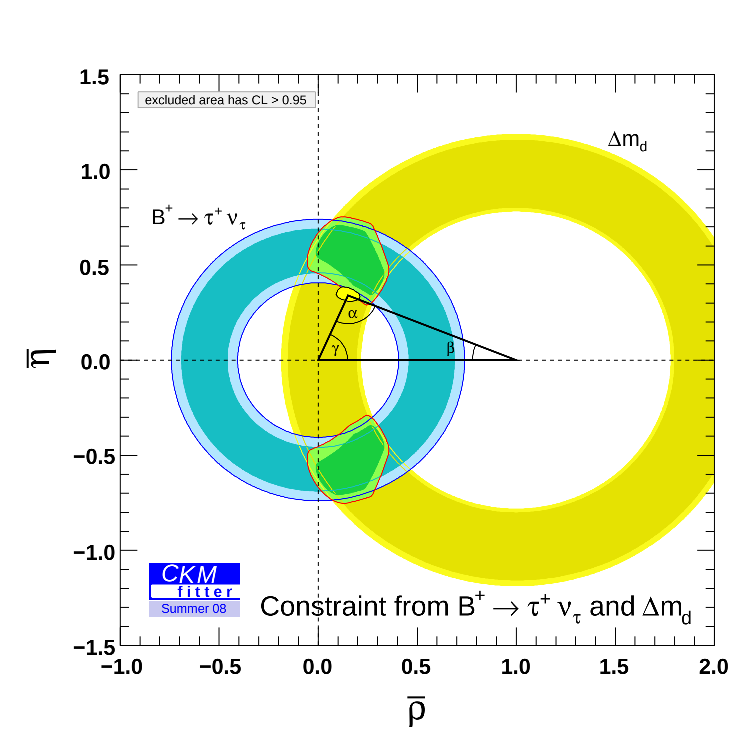
- **LHCb:**
  - Mass resolution good en
    tell $B_s \to \mu\mu$ from B_d
  - Efficiencies determine
    $\to \pi\pi$ (geometry) and
    $J/\psi K$ (trigger)
- Atlas & CMS also competi
- Main uncertainty will be no
  - No absolute cross sec
  - Can only normalise to
    well-measured B_s dec
  - Presently $\mathcal{B}(B_s \to D_s \pi$
    $(3.3 \pm 0.5) \cdot 10^{-3}$ (15
  - Belle's running at $\Upsilon(5S$

- $B_d \to \mu\mu$ suppressed by $|V_{td}|/|V_{ts}|$:
  $\mathcal{B} = (1.0 \pm 0.1) \cdot 10^{-10}$
- This could not hold for R-parity violating models
  - ➜ Test of MFV
- 5σ observation out of reach by 2014 if SM holds

➜ If $B_s \to \mu\mu$ is *not* compatible with the SM value, there will be a very strong interest in $B_d \to \mu\mu$.

$B \to \tau\nu$

- Sensitive to $\tan^2\beta / m^2_{H^+}$
- The present average $(1.4 \pm 0.4) \cdot 10^{-4}$ is higher than expected
  - Use about half of (expected) full statistics (Belle & BaBar)
  - ➜ Minor improvements expected from present experiments
- LHCb won't do it
- Might still be hot (even hotter) in 2014



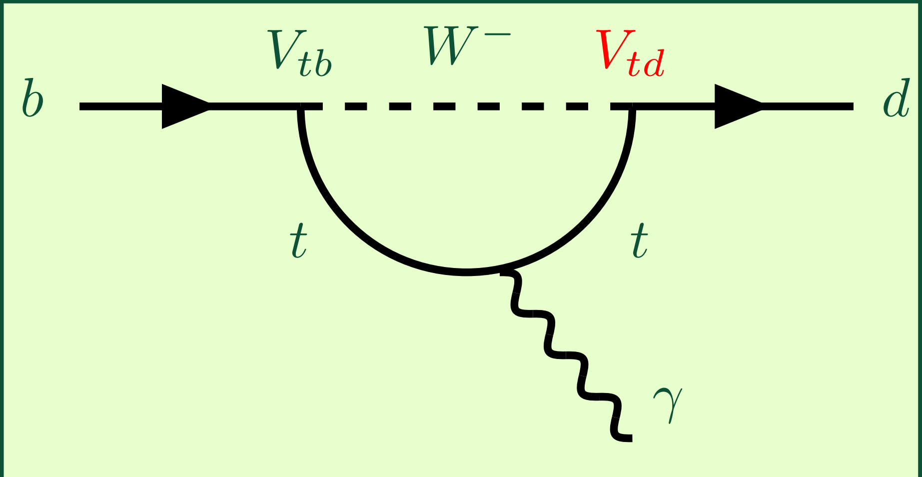
$b \longrightarrow d$

$b \rightarrow d$: How much additional data is needed to constrain new physics effects in $b \rightarrow d\gamma$ and $b \rightarrow \ell\ell d$ decays, compared to $b \rightarrow s$ equivalents? What more is learnt about new physics from these?

- $b \rightarrow d$ transitions tell us if New Physics has the same flavour structure as the SM
- SM expects

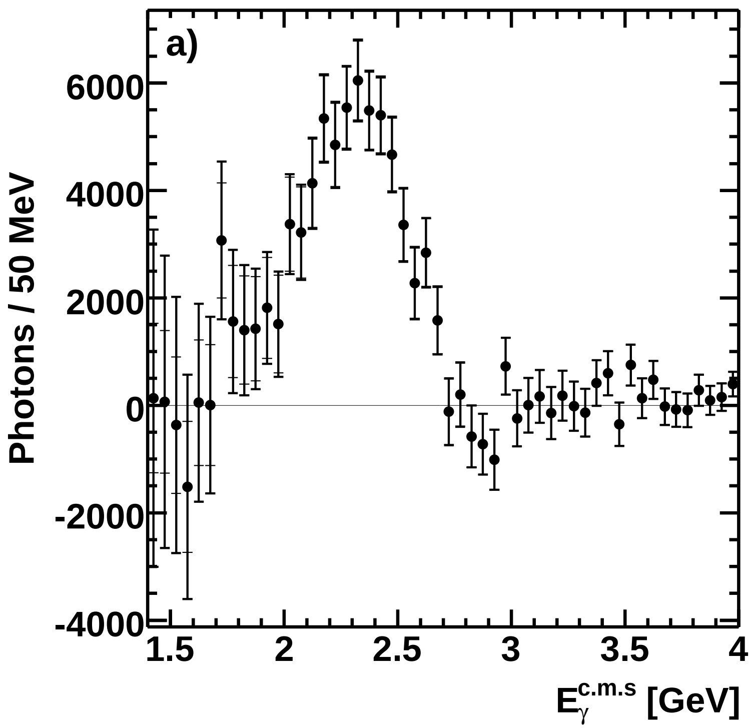
$$\frac{\mathcal{B}(b \rightarrow d\gamma)}{\mathcal{B}(b \rightarrow s\gamma)} = \frac{|V_{td}|^2}{|V_{ts}|^2} \simeq 0.04$$

- It becomes very hot when there are signs of NP elsewhere



Inclusive $b \to d$

- $b \to s\gamma$ spectrum is actually $b \to s\gamma$ + $b \to d\gamma$
- BF is then corrected for assumed $b \to d\gamma$ contribution
  - ➜ we know nothing inclusively
  - and we won't do it fully inclusively
  - But
- $b \to \ell\ell d$ is no better
- I am not fond of semi-inclusive techniques



- $A_{\mathrm{CP}}(b{\to}d\gamma + b{\to}s\gamma)$ is a good null-test of the SM.
  - Need to flavour-tag the other B, or recoil.
  - ➜ Needs large statistics at a B factory

Exclusive $b \to d$

- LHCb will improve on $b \to d\gamma$ compared to the B factories
- And observe $b \to \ell\ell d$ decays
- But it will take time
- Statistical errors will be large

- I don't expect large improvements in $b \to d\gamma$ and $b \to \ell\ell d$ by 2014
  - Some first observations, with large errors
  - Some direct CP, with large errors

➜ Higher statistics would help a lot

Expected yields at LHCb (my guesses):

$10\ \text{fb}^{-1}$	Yield	B/S
$B_d \to K^*\gamma$	350k	0.6
$B_s \to \phi\gamma$	50k	< 0.5
$B_d \to \rho\gamma$		
$B_d \to \omega\gamma$	200	
$B_s \to \overline{K}^*\gamma$	Can't do	
$B \to \mu\mu K^*$	35k	0.5
$B \to \mu\mu\rho$	100	
$B \to \mu\mu\pi$	100	
$B_s \to \mu\mu\overline{K}^*$	100	

Empty field : don't know

Kaons

Rare K: What precision should be aimed for in $K^+ \to \pi^+\nu\nu$ and $K^0_L \to \pi^0\nu\nu$ measurements? What will these measurements tell us about new physics?

I assume Gino will have said that:

If Minimal Flavour Violation: $K \to \pi\nu\nu$ strongly correlated with $B \to \mu\mu$

➜ Need precise measurement of both to test MFV

Else: No clear correlation. Potentially large effects in rare K decays.

➜ Need $K \to \pi\nu\nu$ **and** $K \to \pi\ell\ell$

$K \longrightarrow \pi\nu\bar{\nu}$

Very sensitive to many NP models:

- MFV, UED, Littlest Higgs, Susy …

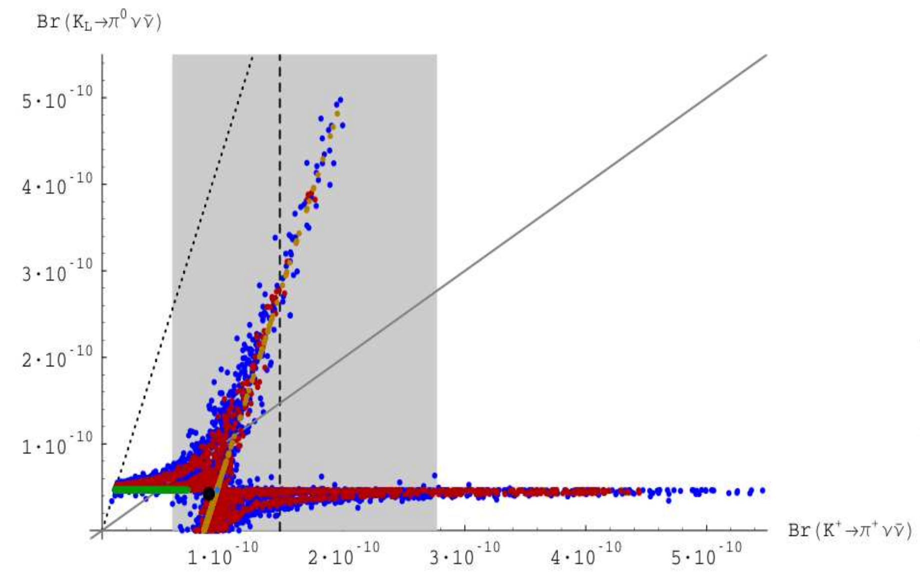
➜ Important probe to disentangle models

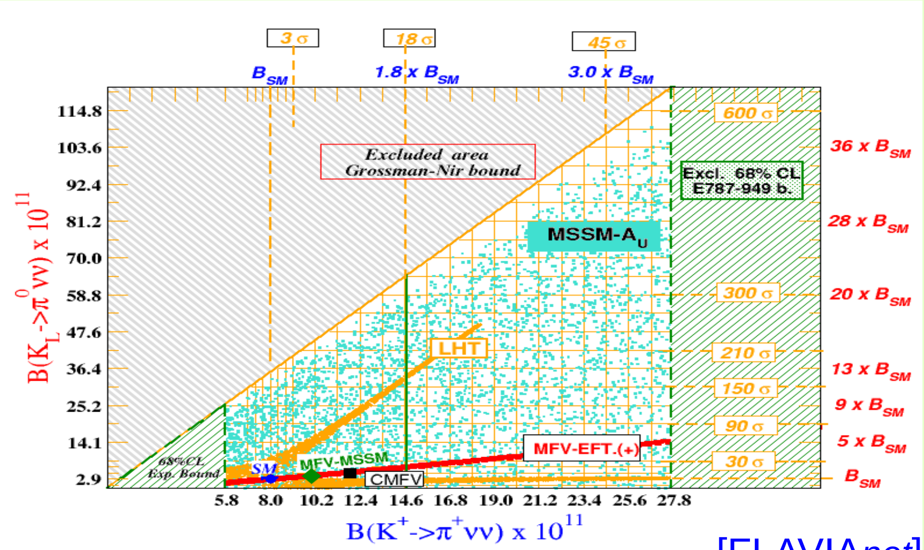
$K^+ \longrightarrow \pi^+\nu\bar{\nu}$ is 90% unaffected from long-distance contributions.

- SM $\mathcal{B} = 8 \cdot 10^{-11}$
- 5% irreducible error

$K_L^0 \longrightarrow \pi^0\nu\bar{\nu}$ is 99% unaffected from long-distance contributions.

- SM $\mathcal{B} = 3 \cdot 10^{-11}$
- 2% irreducible error





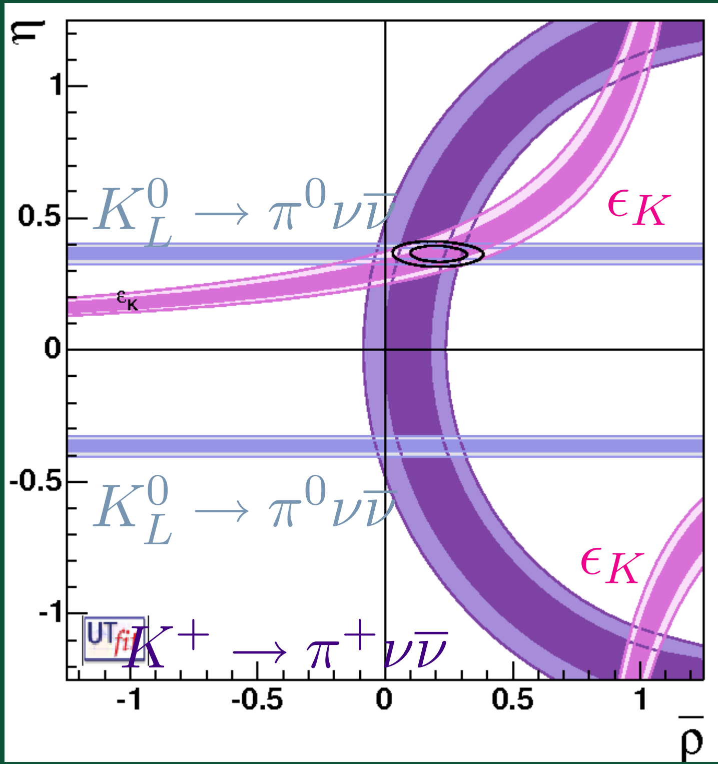
[FLAVIA*net*]

Kaon prospects

- Experimental error on BF ($K \to \pi\nu\nu$) will be $\mathcal{O}(10\%)$
  - Similar to present theoretical error
  - ✔ Constrains many models
- Still very far from irreducible error

  $\boldsymbol{K^+ \to \pi^+\nu\overline{\nu}}$: 5% irreducible error
  - $\mathcal{O}(500)$ events with $S/B \sim 10$
  - ➜ Within experimental reach

  $\boldsymbol{K^0_L \to \pi^0\nu\overline{\nu}}$: 2% irreducible error
  - ➜ $\mathcal{O}(4000)$ events with $S/B \sim 1.5$
  - ➜ Far beyond anything planned
- Rare K decays are a crucial test of NP



Impact of kaon physics on unitarity triangle in 2014

➜ **Still great interest beyond 2014, irrespective of NP discovered by then**

[UTFit]

Up-type

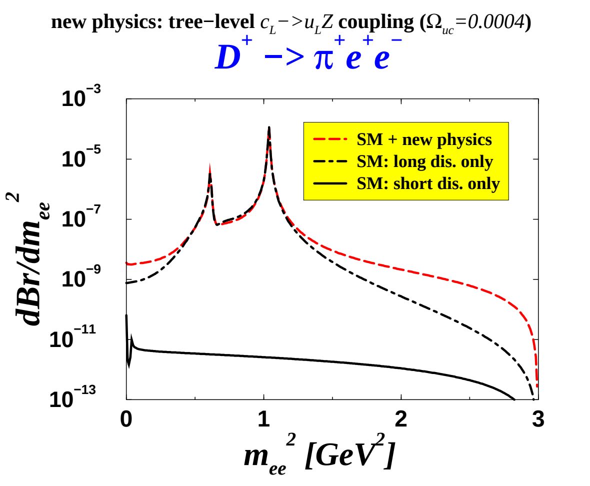
Rare D**:** Is there anything to learn from up-type quarks?

- B and K FCNC probe down-down transitions
- ✔ D accesses up-type quarks
- $D \to \ell\ell$, $D \to \ell\ell\pi$, $D \to \ell\ell\rho$, $c \to \gamma u \ldots$
  - ✗ Branching fractions **very** low ($\mathcal{B}(D\to\mu\mu) = 10^{-13}$)
  - ✗ Polluted by long-distance effects ($\phi \to \mu\mu$, $D \to \pi\pi$)
  - ➜ Large theoretical errors, but rapid developments

➜ Reaching SM sensitivity will be very hard

- Key players: B factories, BES3, LHCb
- Limits will improve significantly in next years. How this compares with theory is unclear to me.

➜ Rare D might **signal** new physics, but won't tell what it is



[Fajfer et al., hep-ph/0702172]

Summary

Mode	Improved by 2014	Limited by theory	Interesting In 2014?	Where
$B_d \to \mu\mu$	Yes	**No**	**Yes**	pp
$B \to \tau\nu$	Hardly	**No**	**Yes**	$\Upsilon(4S)$
$b \to s\gamma$ polarisation	Yes	**No**	**Yes**	Both
$B \to \ell\ell K^*$	Yes	**No**	**Yes**	pp
$B \to \nu\nu K$	Hardly	**No**	**Yes**	$\Upsilon(4S)$
CP ($b \to s\gamma$+$b \to d\gamma$)	No	**No**	**Yes**	$\Upsilon(4S)$
Exclusive $b \to d$	Yes	**No**	**Yes**	Both
BF($b \to s\gamma$)	Hardly	Yes(?)	Unlikely	$\Upsilon(4S)$
$B_s \to \mu\mu$	Yes	Yes	No	
D decays	Yes	Maybe	Unclear	Both
$K \to \pi\nu\nu$	Yes	**No**	**Yes**	Dedic.

Conclusion

$B_d \to \mu\mu$ and $B \to \tau\nu$: will need data beyond 2014

- ➜ BSM Higgs-couplings

Rare kaons: We are very far from theoretical limits

- ➜ Test of MFV

$b \to d\gamma$: The photon polarisation will not be theory limited

- ➜ Right-handed currents

$b \to \ell\ell s$: Rich NP laboratory, it would profit from more statistics

- How much can lattice help?

$b \to d$: Still large errors in 2014

- ➜ Flavour-structure of NP

Rare D: Experimentally and theoretically difficult

Wilson coefficients: In 2014 we will just start doing fits to Wilson coefficients: Need more data to over-constrain

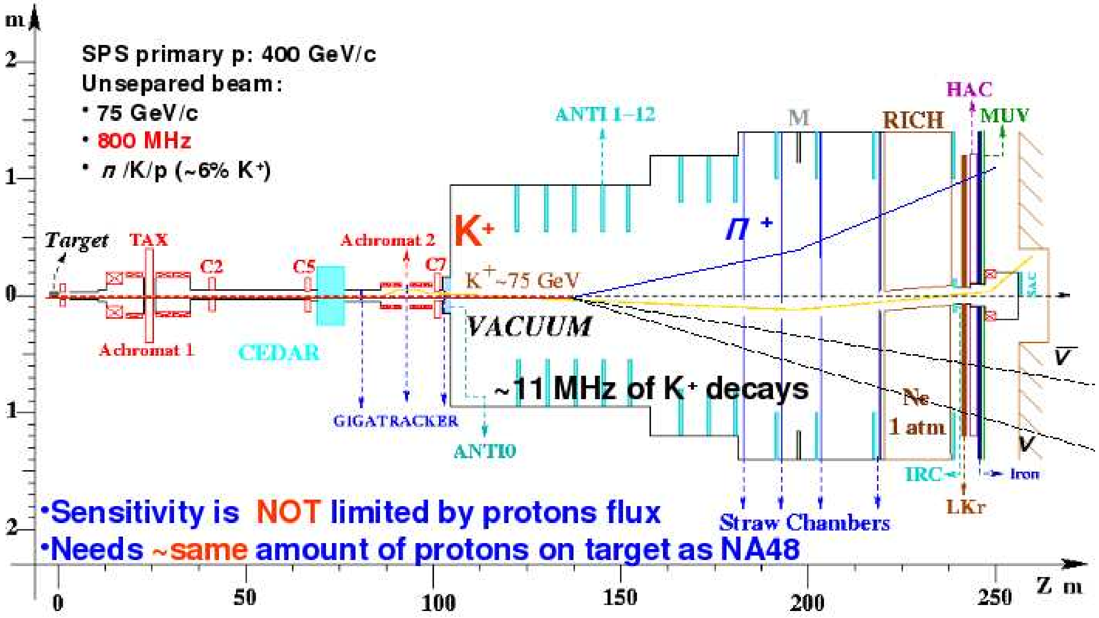
- ➜ And combine with Atlas/CMS discoveries

Backup Slides

Future Kaon Experiments

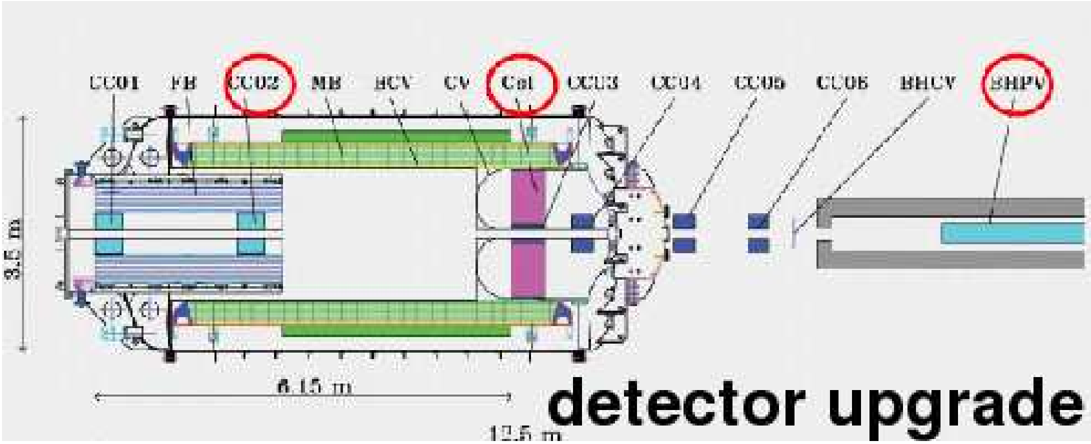
$K^+ \to \pi^+ \nu\overline{\nu}$: **NA 62 at CERN**

- Data taking 2012–2014
- Expect $\mathcal{O}(100)$ events with $S/B \sim 10$.



$K_L^0 \to \pi^0 \nu\overline{\nu}$: **E14 (KOTO) at J-PARC**

- Now upgrading detector. Start in 2011.
- Expect 100 events with $S/B \sim 1.5$.

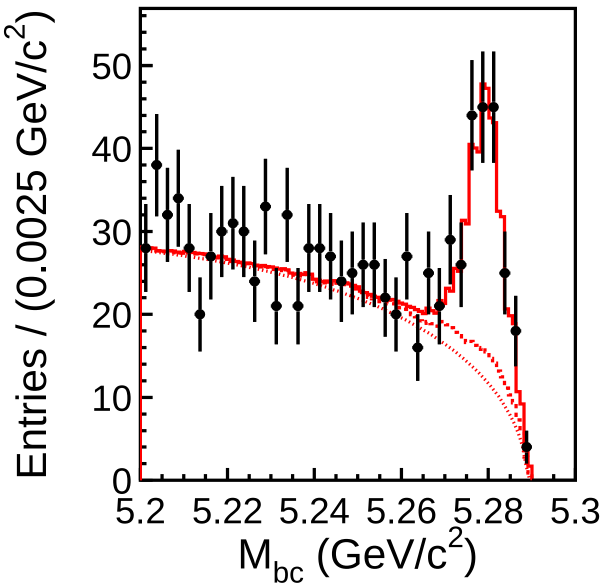


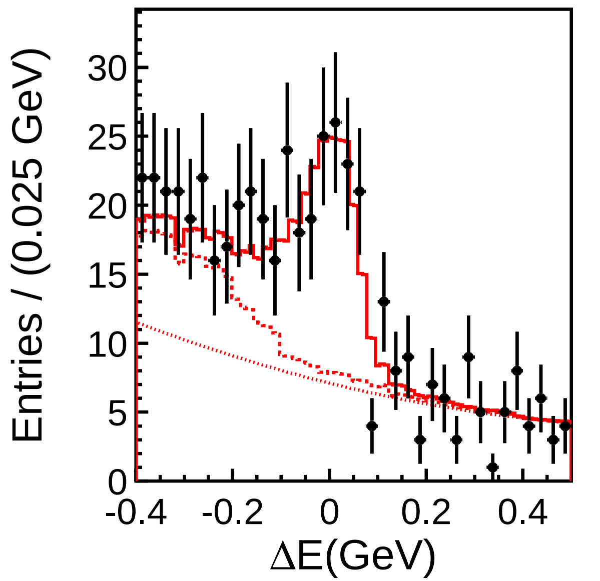
➜ See C. Lazzeroni's talk

CP-violation in $B \to K^*\gamma$

Aim to measure the time-dependent CP asymmetry in $B \to K^*$ ($K^0_S\pi^0\gamma$)

1. Select $B_d \to K^*\gamma$ events with $K^* \to K^0_S\pi^0$ and $K^0_S \to \pi^+\pi^-$
2. Get rid of $B_d \to K^*\pi^0$ background

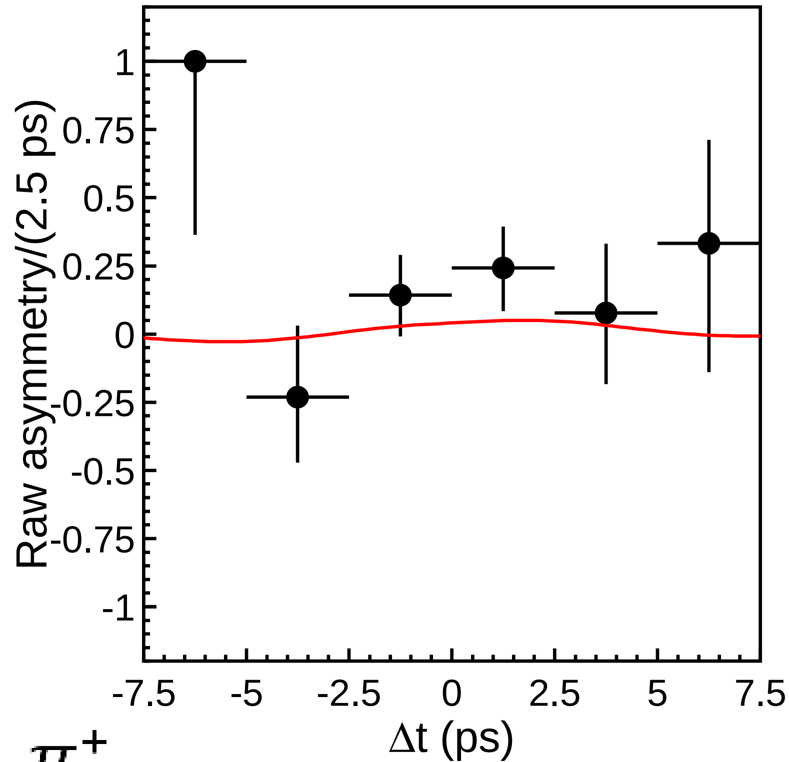




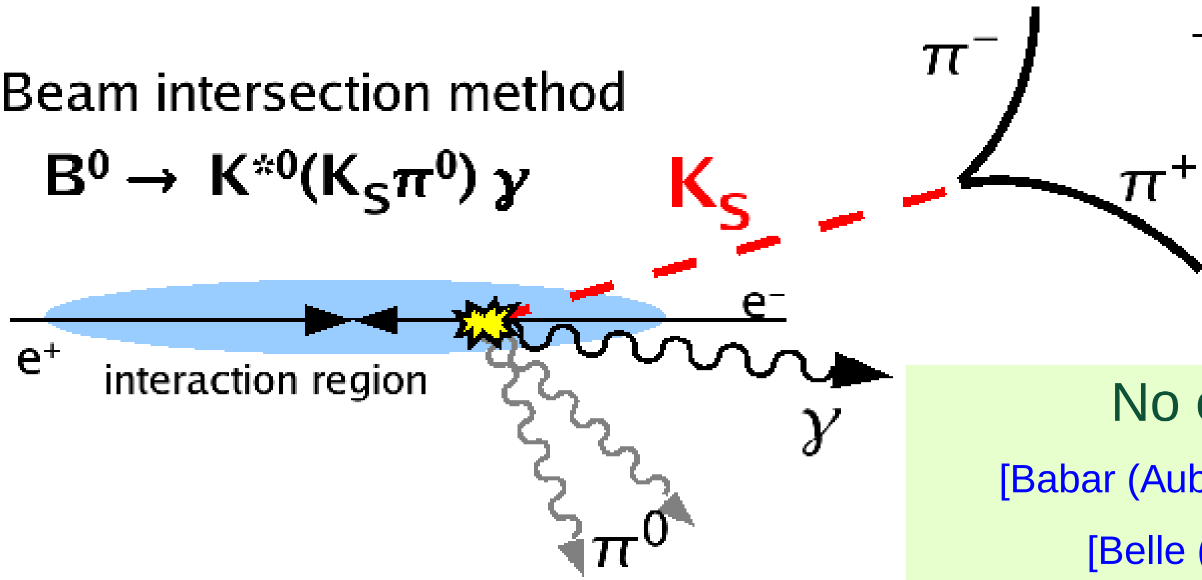
CP-violation in $B \to K^*\gamma$

Aim to measure the time-dependent CP asymmetry in $B \to K^*$ $(K_S^0\pi^0\gamma)$

1. Select $B_d \to K^*\gamma$ events with $K^* \to K_S^0\pi^0$ and $K_S^0 \to \pi^+\pi^-$
2. Get rid of $B_d \to K^*\pi^0$ background
3. Measure time by intersecting the K_S^0 with the beam line



Beam intersection method



No oscillation observed

[Babar (Aubert et al.), PRD72 (2005) 051103]

[Belle (Abe et al.), hep-ex/0507059]

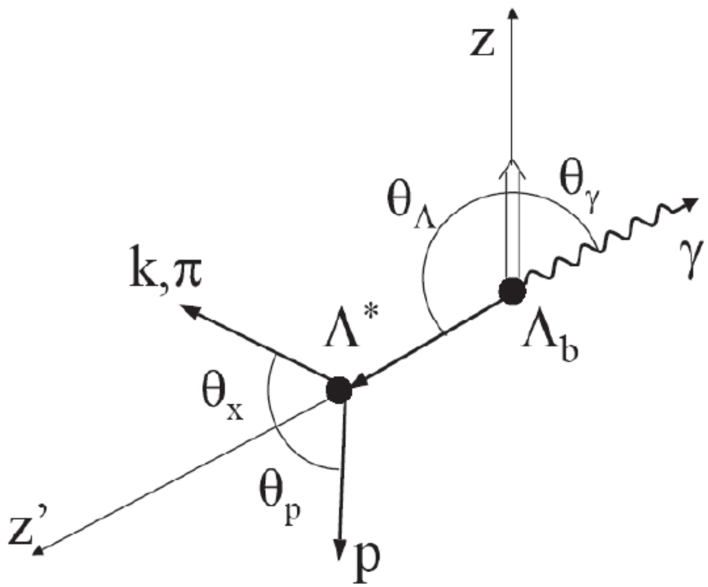
$\Lambda_b \to \Lambda\gamma$ polarisation

$$r = \frac{C'_{7\gamma}}{C_{7\gamma}} \quad \to \quad \alpha_\gamma = \frac{1-|r|^2}{1+|r|^2}$$

$$\frac{\mathrm{d}\Gamma}{\mathrm{d}\cos\theta_\gamma} \propto 1 - \alpha_\gamma P_{\Lambda_b}\cos\theta_\gamma$$

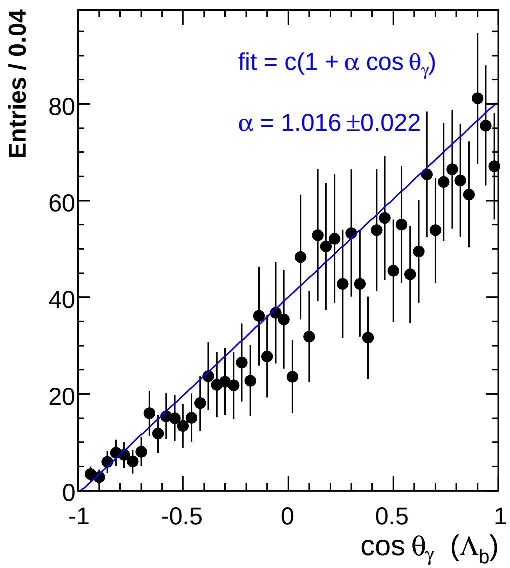
$$\frac{\mathrm{d}\Gamma}{\mathrm{d}\cos\theta_p} \propto 1 - \alpha_\gamma \alpha_{p,\frac{1}{2}}\cos\theta_\gamma$$

$$\alpha_{p,\frac{1}{2}} = 0.642 \pm 0.013$$



- Λ_b is polarised at LHC. Assume 20%.
  - Measure it at 1% with $\Lambda_b \to J/\psi\Lambda$.

    [E. Leader] [Hřivnác et al, hep-ph/9405231]
- But: $\Lambda\gamma$ does not form a good vertex
  - Most Λ decay outside of vertex detector



[F. Legger, T. Schietinger, hep-ph/0605245]

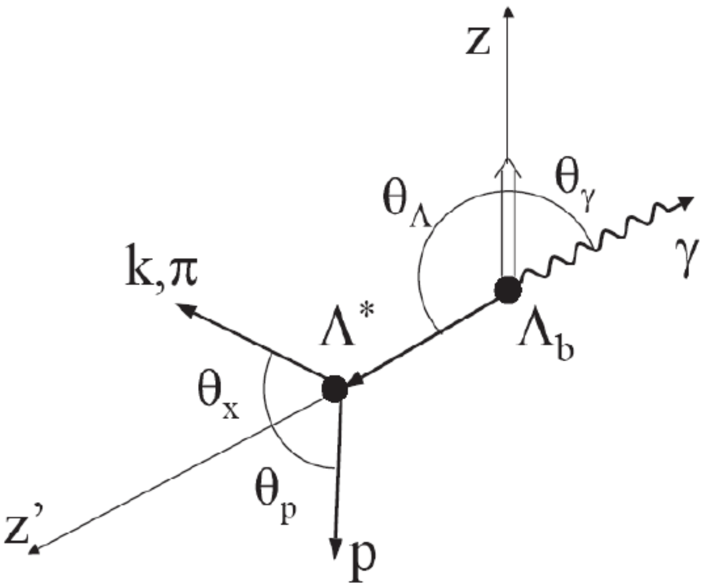
$\Lambda_b \to \Lambda\gamma$ polarisation

$$r = \frac{C'_{7\gamma}}{C_{7\gamma}} \quad \to \quad \alpha_\gamma = \frac{1-|r|^2}{1+|r|^2}$$

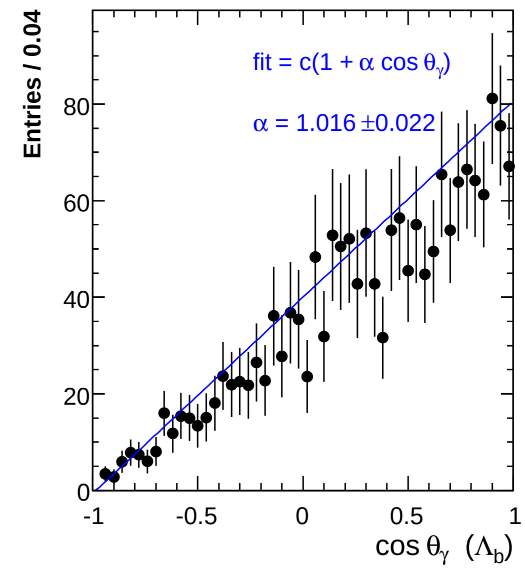
$$\frac{\mathrm{d}\Gamma}{\mathrm{d}\cos\theta_\gamma} \quad \propto \quad 1 - \alpha_\gamma P_{\Lambda_b} \cos\theta_\gamma$$

$$\frac{\mathrm{d}\Gamma}{\mathrm{d}\cos\theta_p} \quad \propto \quad 1 - \alpha_\gamma \alpha_{p,\frac{1}{2}} \cos\theta_\gamma = 1$$

$$\alpha_{p,\frac{1}{2}} = 0$$



- ➜ Use also $\Lambda_b \to \Lambda(1670)\gamma$, $\Lambda(1670) \to Kp$
  - Proton polarisation is flat ➜ less information
- Spin $\frac{3}{2}$ $\Lambda(1520)$ and $\Lambda(1690)$ can also be used.
  - Need to be disentangled from $\Lambda(1670)$



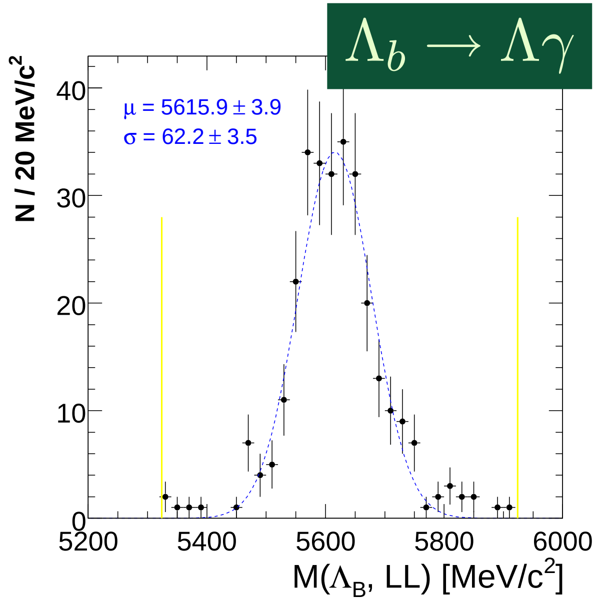
[F. Legger, T. Schietinger, hep-ph/0605245]

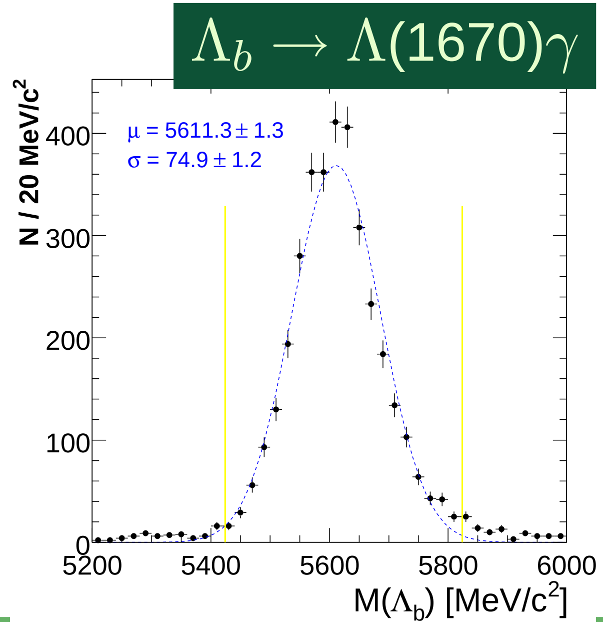
$\Lambda_b \to \Lambda\gamma$ yields

Yields/2 fb^{-1}		B/S
$\Lambda_b \to \Lambda\gamma$	750	< 42
$\Lambda_b \to \Lambda$(1520)γ	4200	< 10
$\Lambda_b \to \Lambda$(1670)γ	2500	< 18
$\Lambda_b \to \Lambda$(1690)γ	2200	< 18

- Λ^* modes have less statistical power because of strong decay
- Combined resolution on r is $\sim 20\%$ after 2 fb^{-1} .
- That's far from SM but already interesting for NP searches.

[LHCb note 2006-012] [LHCb note 2006-013]

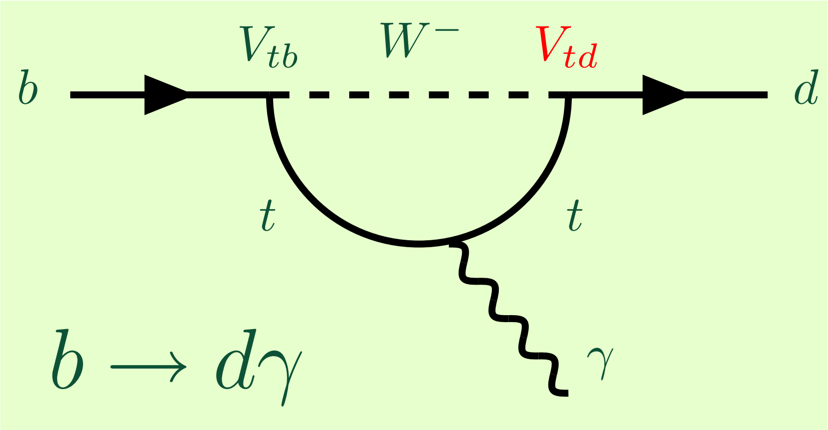




$B_d \to \omega\gamma$ and $B_d \to \rho\gamma$

$B_d \to \omega\gamma$ and $B_d \to \rho\gamma$ are suppressed by $|V_{td}/V_{ts}|^2 \sim 1/23$.

They are selected the same way as $K^*\gamma$



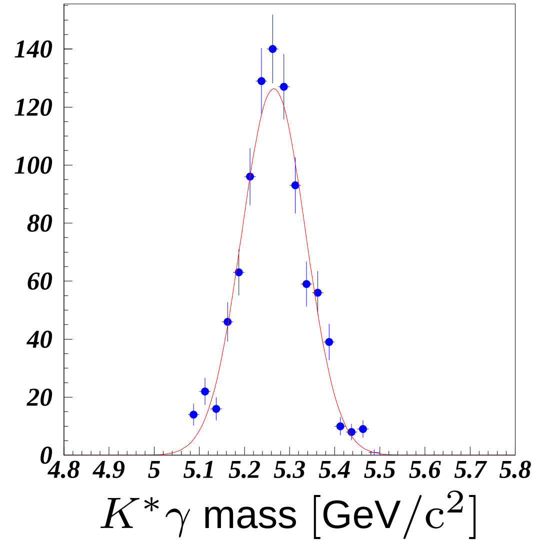
$\boldsymbol{B_d \to \omega\gamma}$**:** Additional π^0 reduces efficiency.
Earlier study expects ~ 40 events for 2 fb^{-1} .

$\boldsymbol{B_d \to \rho\gamma}$**:** More work on photon ID and suppression of merged π^0 is required to get the sensitivity to $B_d \to \rho\gamma$. We are optimistic.

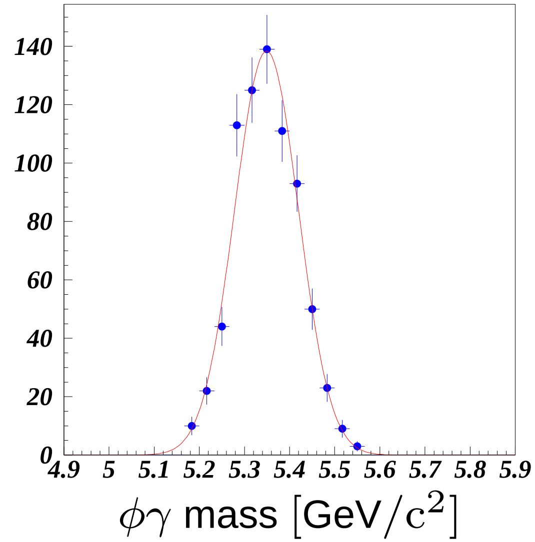
- $|V_{td}/V_{ts}|$ from $\mathcal{B}(B_d \to (\rho,\omega)\gamma)/\mathcal{B}(B_d \to K^*\gamma)$ is likely to be theory-dominated soon.
- It's difficult to make statements about CP asymmetries

$B_d \to K^*\gamma$ and $B_s \to \phi\gamma$ yields for 2 fb^{-1}

	$B_d{\to}K^*\gamma$	$B_s{\to}\phi\gamma$
Visible BR	$2.9 \cdot 10^{-5}$	$2.2 \cdot 10^{-5}$
η_{rec}	5.6%	5.4%
η_{sel}	13.3%	11.7%
η_{trg}	46%	44%
η_{tot}	0.34%	0.28%
Signal Yield	$73\,000$	$11\,000$
B/S	0.59 ± 0.26	< 0.55



The B mass resolution is 70 MeV.



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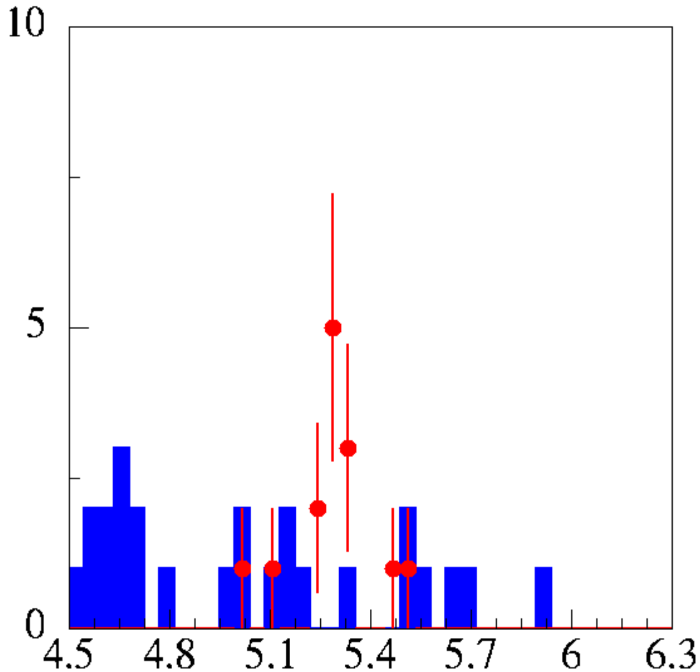


$B_d \to K^*\gamma$ and $B_s \to \phi\gamma$ yields for $2\ \mathrm{fb}^{-1}$

	$B_d \to K^*\gamma$	$B_s \to \phi\gamma$
Signal Yield	$73\,000$	$11\,000$
B/S	0.59 ± 0.26	< 0.55

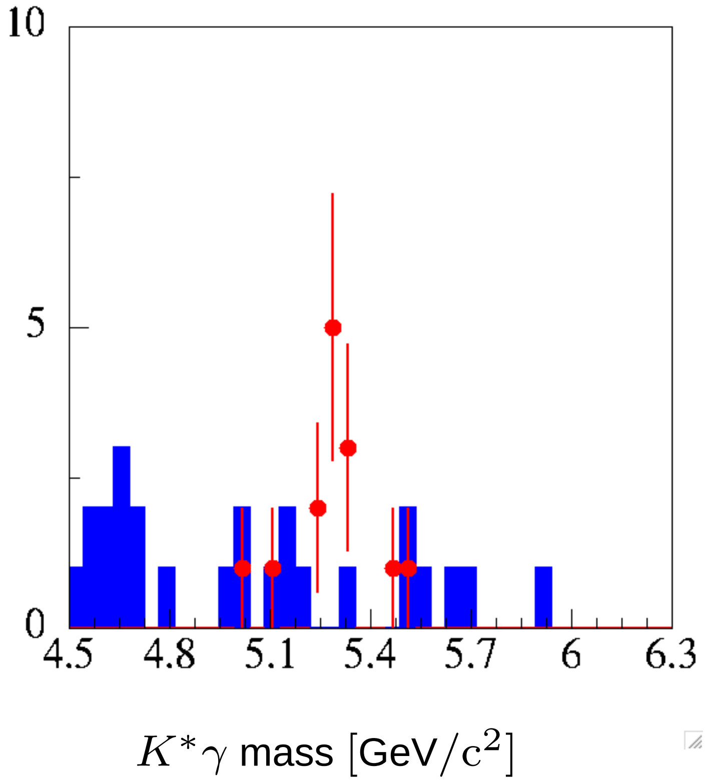
Running on 13 minutes equivalent of $b\bar{b}$ events one already gets a peak.

Expecting a *statistical* error on $A_{\mathrm{CP}}(B_d \to K^*\gamma)$ of 0.5%

➜ Will be dominated by systematics

- $K^{\pm}$ interaction with matter
- B_d, $\overline{B}_d$ production asymmetries . . .

[LHCb note 2007-030]



R_K in $B_u \to \ell\ell K$

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

[Hiller & Krüger, PRD69 (2004) 074020]

Corrections can be $\mathcal{O}(10\%)$ for instance with neutral Higgs boson exchanges.

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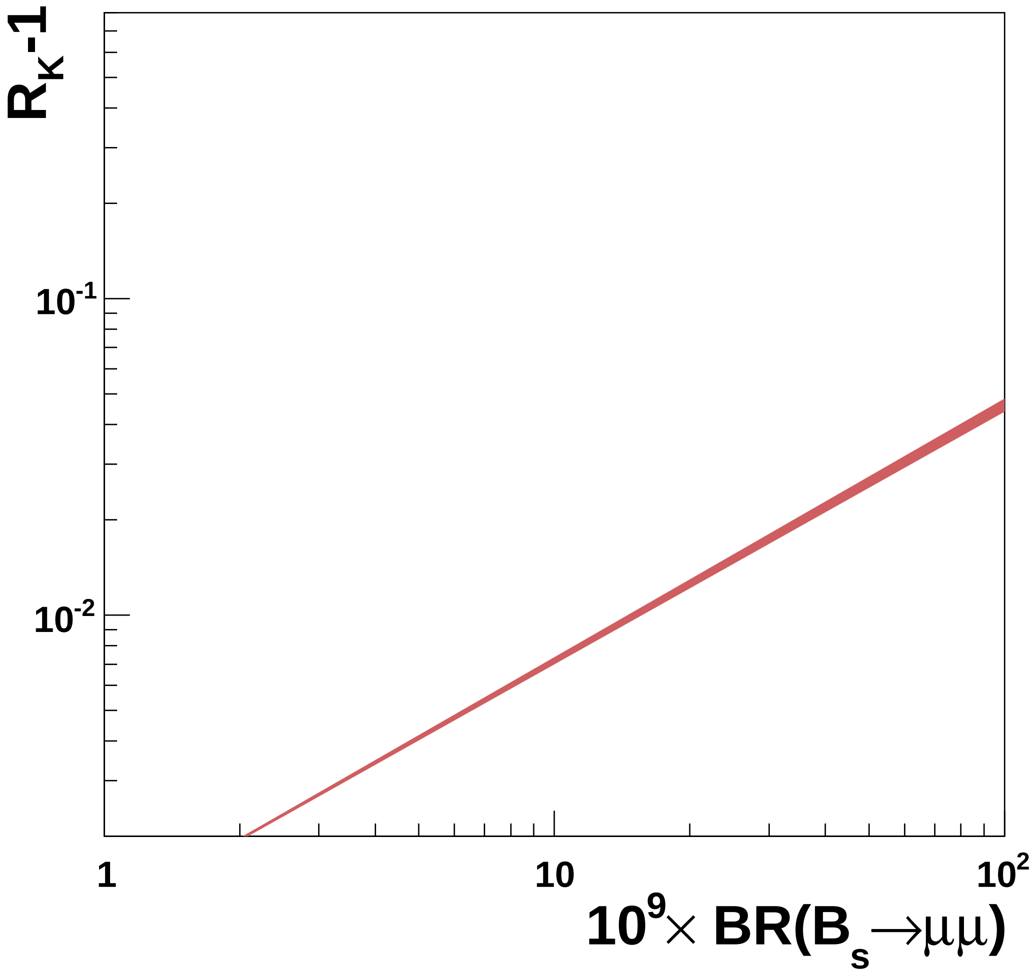
$$R_K - 1 \propto \mathcal{B}(B_s\to\mu\mu)$$

- Right-handed currents negligible
- (Pseudo-)scalar couplings $\propto m_\ell$,
- No CP-phases beyond the SM



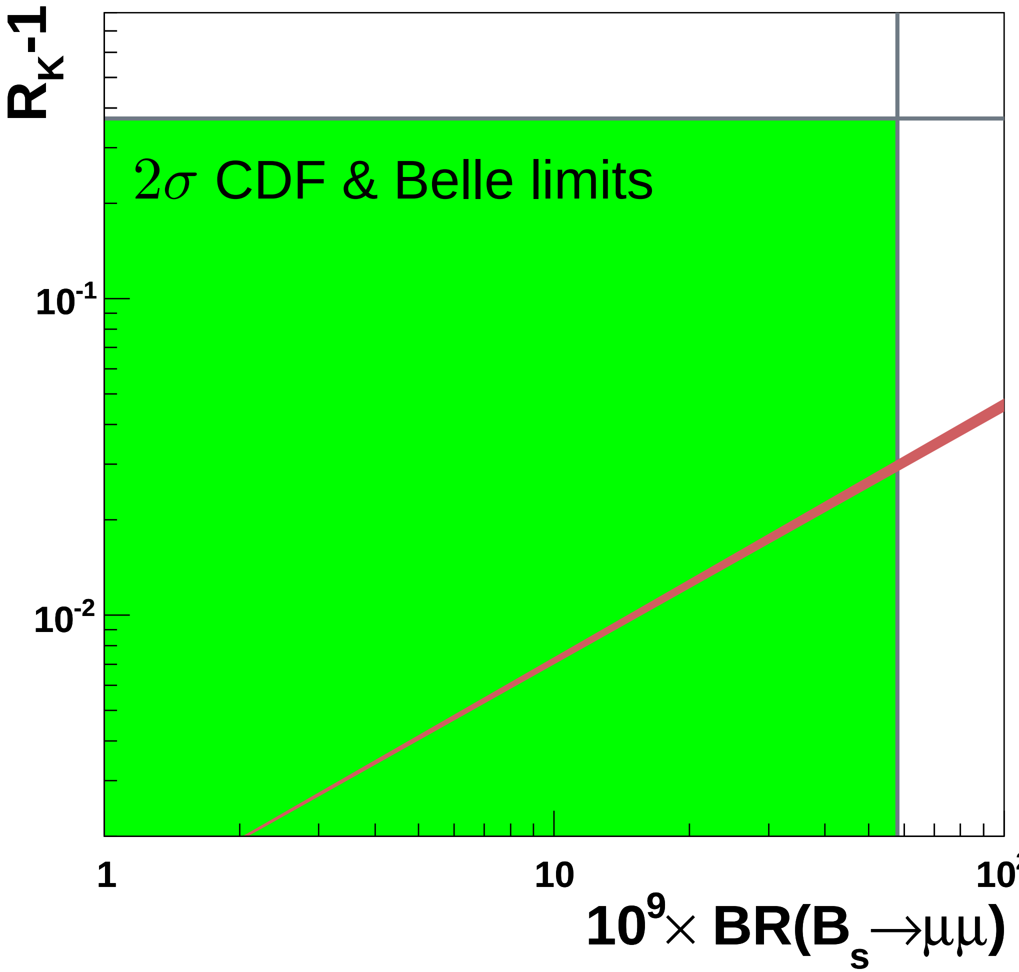
[Hiller & Krüger, PRD69 (2004) 074020]

R_K in $B_u \to \ell\ell K$

Experimental status:

	BaBar ($384 \cdot 10^6\ B\overline{B}$) [PRL 102:091803,2009]
R_K	$0.40\ ^{+0.30}_{-0.23} \pm 0.02$
R_{K^*}	$1.01\ ^{+0.42}_{-0.32} \pm 0.08$
	Belle ($657 \cdot 10^6\ B\overline{B}$) [arXiv:0904.0770v1]
R_K	$1.03 \pm 0.17 \pm 0.05$
R_{K^*}	$0.83 \pm 0.17 \pm 0.05$

$B_s \to \mu\mu$**:** The present CDF limit is $5.8 \cdot 10^{-8}$ at 95% CL [PRL 100:101802,2008]



R_K in $B_u \to \ell\ell K$

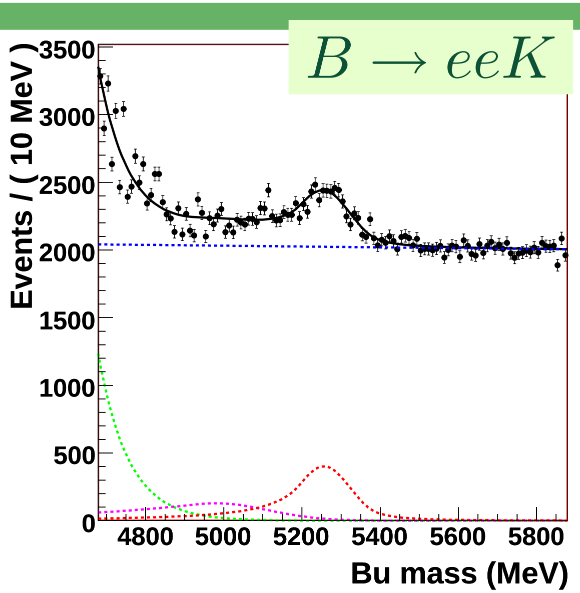
At LHCb for $10\ \text{fb}^{-1}$:

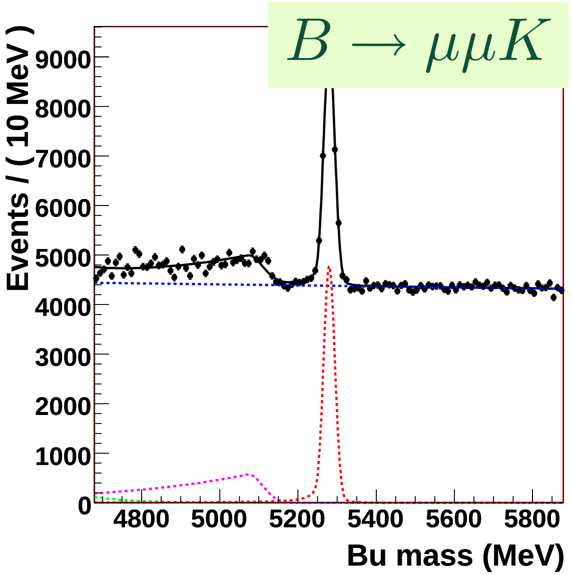
Species	Yield	Error
$B \to eeK$	$9\,240 \pm 379$	4.10%
$B \to \mu\mu K$	$18\,774 \pm 227$	1.21%

Including control samples, one gets an error:

➜ $\mathbf{R_K = 1}$ (fixed) $\pm\ \mathbf{0.043}$

for $10\ \text{fb}^{-1}$. [LHCb note 2007-034]





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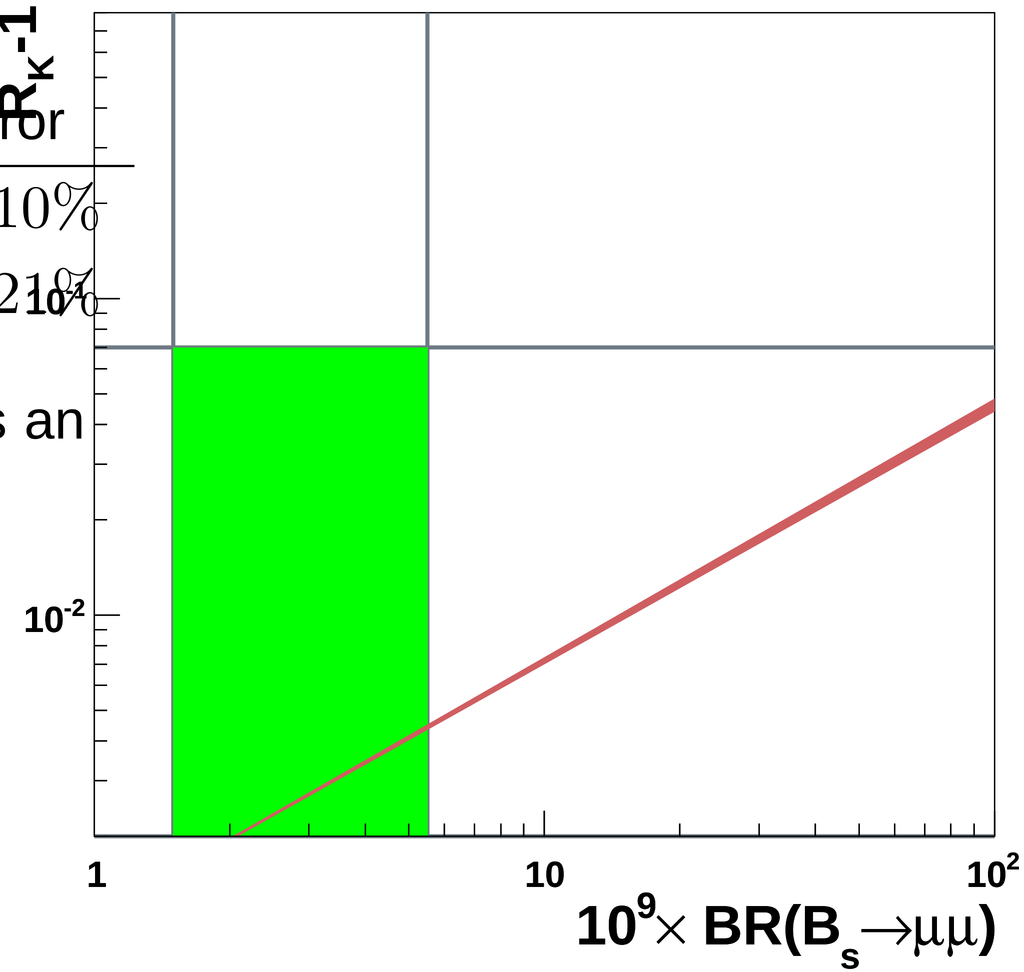

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