

RARE DECAYS

Ecole de Gif
05-10 Septembre 2010

Patrick Koppenburg



www.koppenburg.org



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Rare Decays

Ecole de Gif 05-10 Septembre 2010 [1/121]

RARE DECAYS

INTRODUCTION: **Indirect searches, CKM, Rare Decays**

APPETISER: $B_s^0 \rightarrow \mu\mu$ and $B \rightarrow \tau\nu$

A BIT OF THEORY: **Operator product expansion**

MAIN COURSE: $b \rightarrow s\gamma$ and $b \rightarrow d\gamma$

SECOND MAIN COURSE: $b \rightarrow \ell\bar{\ell}s$

DESERT: **Charm and Kaons**

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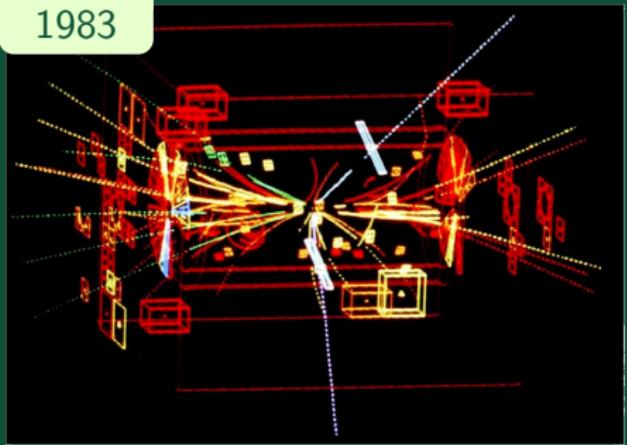
INDIRECT SEARCHES

1973

- Sensitive to New Physics effects
 - When was the Z discovered?
 - 1973 from $N\nu \rightarrow N\nu?$
 - 1983 at SpS?
 - c quark postulated by GIM, third family by KM



1983



INDIRECT SEARCHES

1973



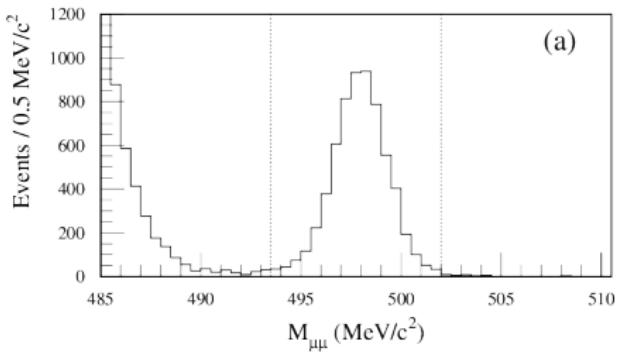
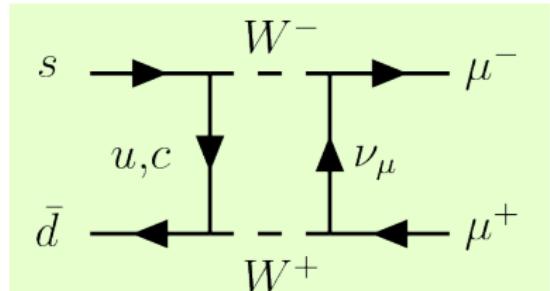
- Sensitive to New Physics effects
 - When was the Z discovered?
 - 1973 from $N\nu \rightarrow N\nu$?
 - 1983 at SpS?
 - c quark postulated by GIM, third family by KM
- Estimate masses
 - t quark from $B\bar{B}$ mixing
- Get phases of couplings
 - Half of new parameters
 - Needed for a full understanding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

1987



$$K_L^0 \rightarrow \mu\mu$$

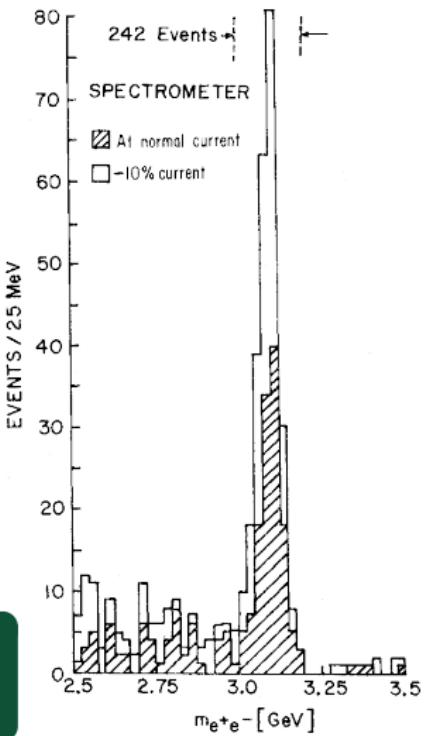
- $K_L^0 \rightarrow \mu\mu$ was not observed though expected
 - Now BF is measured to be $(6.84 \pm 0.11) \cdot 10^{-9}$ [Ambrose et al, 2000]
- Led to the postulation of the c quark “GIM mechanism” in 1970 [Glashow, Iliopoulos and Maiani, 1970]



$$K_L^0 \rightarrow \mu\mu$$

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- Led to the postulation of the c quark “GIM mechanism” in 1970 [Glashow, Iliopoulos and Maiani, 1970]
- c quark eventually observed in 1974 [Richter], [Ting]

Let's repeat the story with $B_s^0 \rightarrow \mu\mu$



NOTATION

- ① To avoid any confusions I write:

B_u^+ : ($u\bar{b}$), charge +1 (and B_u^-)

B_d^0 : ($d\bar{b}$), charge 0 (and \bar{B}_d^0)

B_s^0 : ($s\bar{b}$), charge 0 (and \bar{B}_s^0)

B_c^+ : ($c\bar{b}$), charge +1 (and B_c^-)

The B^0 notation is common to B factories. LHCb prefers B_d . I just mix them.

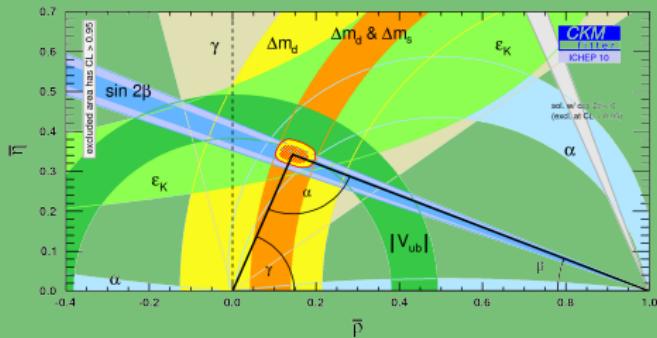
- ② Similarly

D_d^+ : ($c\bar{d}$), charge +1 (and D_d^-)

D_u^0 : ($c\bar{u}$), charge 0 (and \bar{D}_u^0)

D_s^+ : ($c\bar{s}$), charge +1 (and D_s^-)

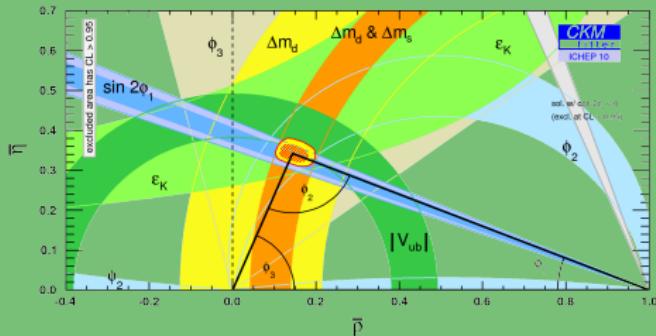
CONVENTIONS



On 18th May 2010 in
Tsukuba, Bruce Yabsley
tossed a coin.



CONVENTIONS



On 18th May 2010 in Tsukuba, Bruce Yabsley tossed a coin.

And it was decided it would be ϕ_1 , ϕ_2 , ϕ_3 , but also m_{ES} .

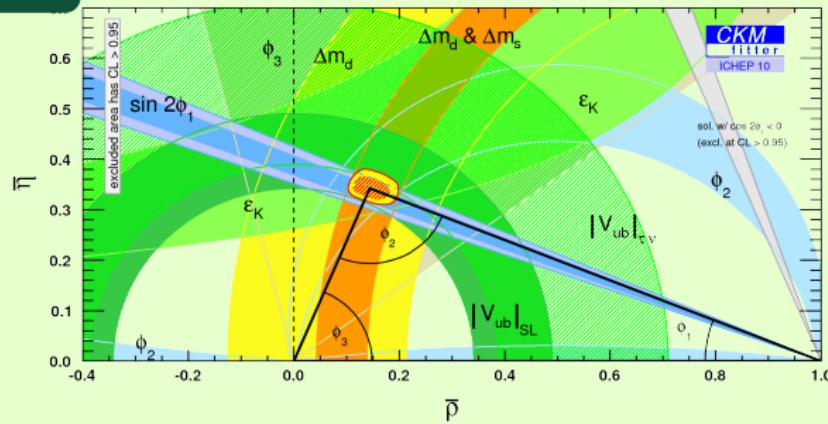
[whole story]



UNITARITY TRIANGLE

- Changed focus: No longer seeking to verify the CKM picture
- Instead look for signs of New Physics
 - Discrepancies in measurements or unitarity triangle

All constraints

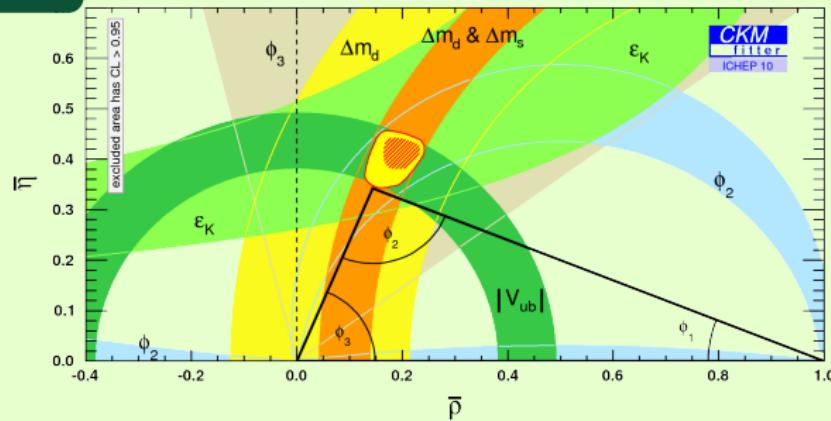


[CKMfitter 09/09]

UNITARITY TRIANGLE

- Changed focus: No longer seeking to verify the CKM picture
- Instead look for signs of New Physics
 - Discrepancies in measurements or unitarity triangle
- $(\bar{\rho}, \bar{\eta})$ fit is dominated by $\sin 2\phi_1$

All but $\sin 2\phi_1$



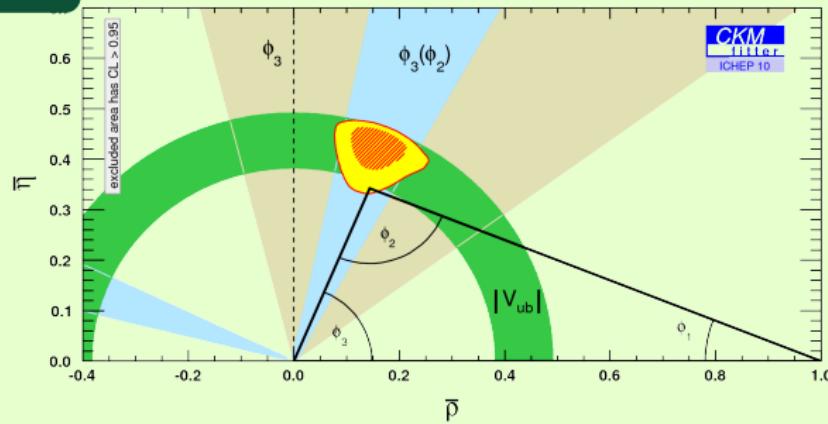
[CKMfitter 09/09]



UNITARITY TRIANGLE

- Changed focus: No longer seeking to verify the CKM picture
- Instead look for signs of New Physics
 - Discrepancies in measurements or unitarity triangle
- We don't know much about constraints from trees

Only trees



[CKMfitter 09/09]



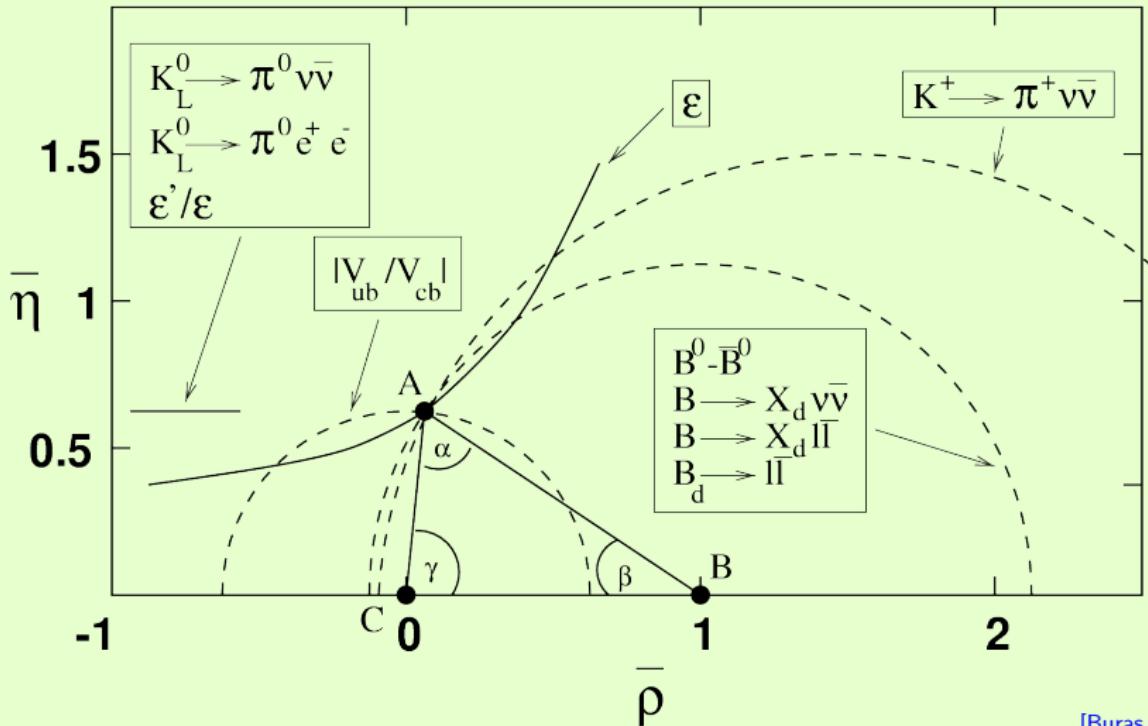
UNITARITY TRIANGLE

- Changed focus: No longer seeking to verify the CKM picture
- Instead look for signs of New Physics
 - Discrepancies in measurements or unitarity triangle
- ✓ Look for rare B & D decays (and K as well)
 - **Need a lot of data and a good precision**
- ✓ Need very good precision on all angles and sides.
 - ✓ Precise measurement of ϕ_3
- ✓ Need B_s^0 as well → β_s and more



The Large Hadron Collider beauty experiment for precise measurements of CP violation and rare decays

UT WITH RARE DECAYS



[Buras, 2000]

CKM MATRIX

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Wolfenstein parametrisation in terms of $\lambda = 0.2272 \pm 0.0010$:

$$\begin{pmatrix} 1 - \frac{1}{2}\lambda^2 - \frac{1}{8}\lambda^4 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda + \frac{1}{2}A^2\lambda^5 [1 - 2(\rho + i\eta)] & 1 - \frac{1}{2}\lambda^2 - \frac{1}{8}\lambda^4(1 + 4A^2) & A\lambda^2 \\ A\lambda^3 [1 - (1 - \frac{1}{2}\lambda^2)(\rho - i\eta)] & -A\lambda^2 + \frac{1}{2}A\lambda^4 [1 - 2(\rho + i\eta)] & 1 - \frac{1}{2}A^2\lambda^4 \end{pmatrix} + \mathcal{O}(\lambda^6).$$

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Decay	CKM factor	Example	\mathcal{B}	Γ_i
$c \rightarrow s W$	$V_{cs} \simeq 1 - \frac{\lambda^2}{2}$	$D_u^0 \rightarrow K \mu \nu$	3.5%	57 μeV

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$s \rightarrow uW$	$V_{us} \simeq \lambda$	$K^+ \rightarrow \mu\nu$	63%	$33 \mu\text{eV}$
$c \rightarrow dW$	$V_{cd} \simeq -\lambda$	$D_u^0 \rightarrow \pi\mu\nu$	0.4%	$6 \mu\text{eV}$

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$b \rightarrow uW$	$V_{ub} \simeq A\lambda^3$	$B_d^0 \rightarrow \rho\ell\nu$	0.2%	$1 \mu\text{eV}$

WHAT ARE RARE DECAYS?

DOMINANT DECAYS: Not rare

PHASE SPACE SUPPRESSED DECAYS: Not that rare

$$\frac{\Gamma(K_S^0 \rightarrow \pi\pi)}{\Gamma(K_L^0 \rightarrow \pi\pi\pi)} = 571.$$



WHAT ARE RARE DECAYS?

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CABIBBO-SUPPRESSED DECAYS: Some call them rare

$$\frac{\mathcal{B}(D_u^0 \rightarrow K^+ \pi^-)}{\mathcal{B}(D_u^0 \rightarrow \pi^+ \pi^-)} = 28 \quad \frac{\mathcal{B}(b \rightarrow q \ell^+ \nu)}{\mathcal{B}(b \rightarrow u \ell^+ \nu)} = 135$$



WHAT ARE RARE DECAYS?

DOMINANT DECAYS: Not rare

PHASE SPACE SUPPRESSED DECAYS: Not that rare

CABIBBO-SUPPRESSED DECAYS: Some call them rare

COLOUR-SUPPRESSED DECAYS: Not really rare

$$\begin{aligned}\mathcal{B}(B_d^0 \rightarrow D_d^- \pi^+) &= (3.5 \pm 0.9) \cdot 10^{-3}, \\ \mathcal{B}(B_d^0 \rightarrow \bar{D}_u^0 \pi^0) &= (2.9 \pm 0.3) \cdot 10^{-4},\end{aligned}$$

while they are both $b \rightarrow cW$ and $W \rightarrow u\bar{d}$ transitions.



WHAT ARE RARE DECAYS?

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HADRONIC FCNC DECAYS: Not the topic of this lecture

- For instance $B \rightarrow \phi K_S^0$, or $B \rightarrow K_S^0 K\pi$ recently reported by BaBar [[arXiv:1003.0640v1](#)]. Interesting ...
- Or $B_d^0 \rightarrow \phi K_S^0$, or the penguin contribution to $B \rightarrow J/\psi K_S^0$...

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ELECTROWEAK FCNC PENGUINS That's what I mean!

- $b \rightarrow s\gamma$
- $b \rightarrow \ell\ell s$
- And friends ...

WHY RARE DECAYS?

We want to find new physics indirectly!

NO NEW PHYSICS AT TREE LEVEL: We would have noticed

- $B_u^+ \rightarrow \tau \bar{\nu}$ (or anything with charged Higgs) is a counter-example



WHY RARE DECAYS?

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INTERFERENCE OF TREE INTERACTIONS AND NEW PHYSICS: This is what CP violation does

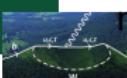
INTERFERENCE OF LOOP INDUCED DECAYS AND NEW PHYSICS:

- Only allowed in loops
- Could be SM Z and W , or anything else that is heavy

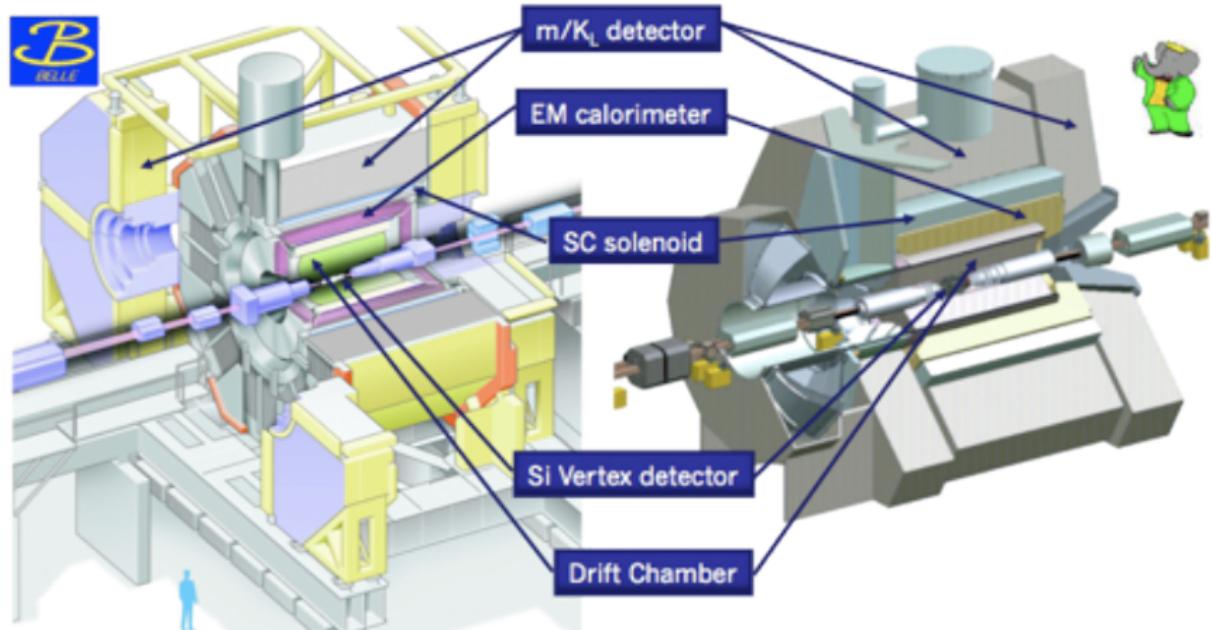
EXPERIMENTAL ASPECTS:

- You want to measure a 50% effect on a rare decay, not a 1% effect on the neutron lifetime. That's very hard.
- Statistic versus systematic error

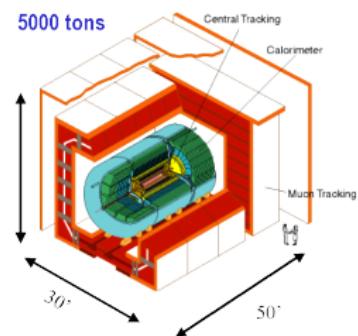
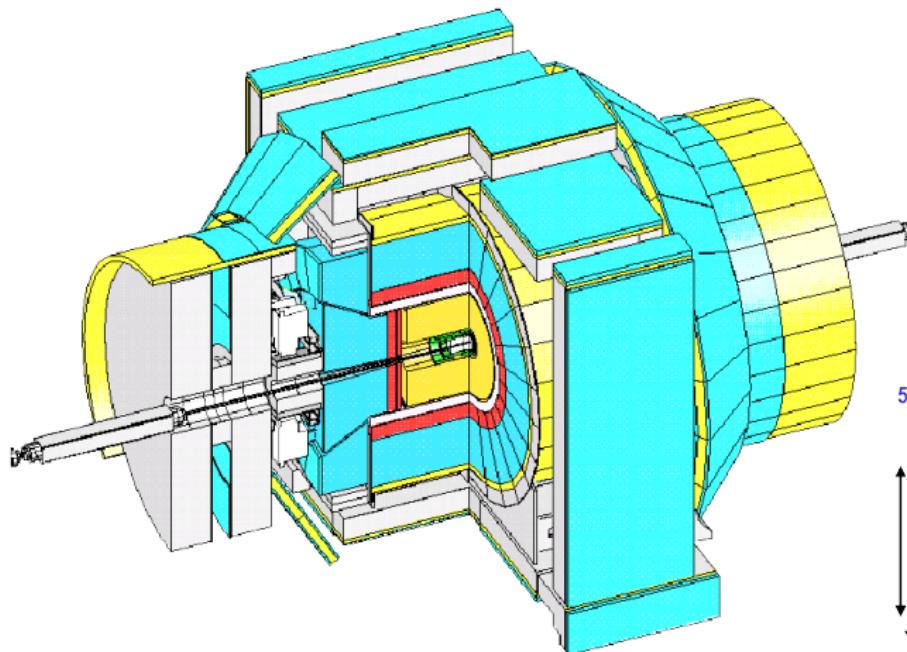
THEORETICAL CLEAN: There are many rare decays that are theoretically clean. This is needed as in the end you will compare a measured effect to an SM prediction.

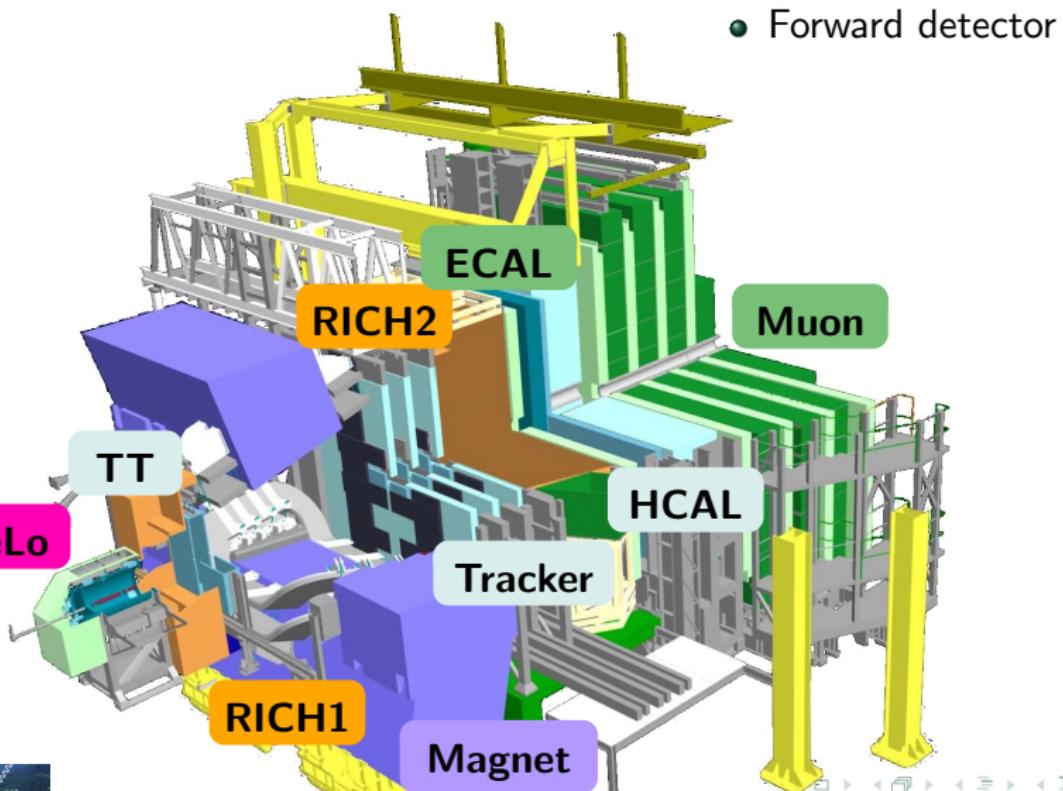


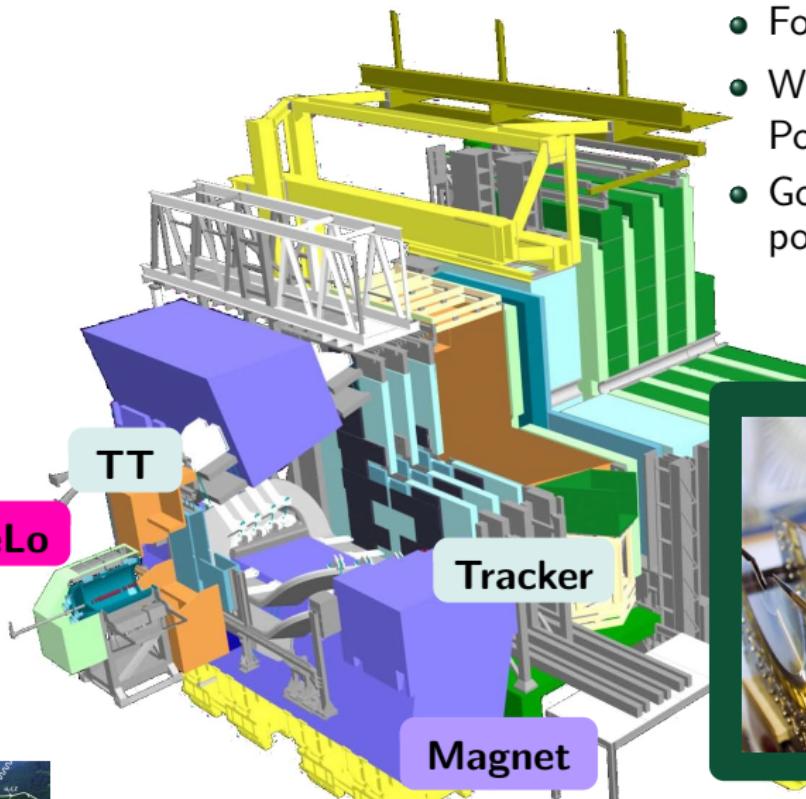
BELLE AND BABAR



CDF AND D0

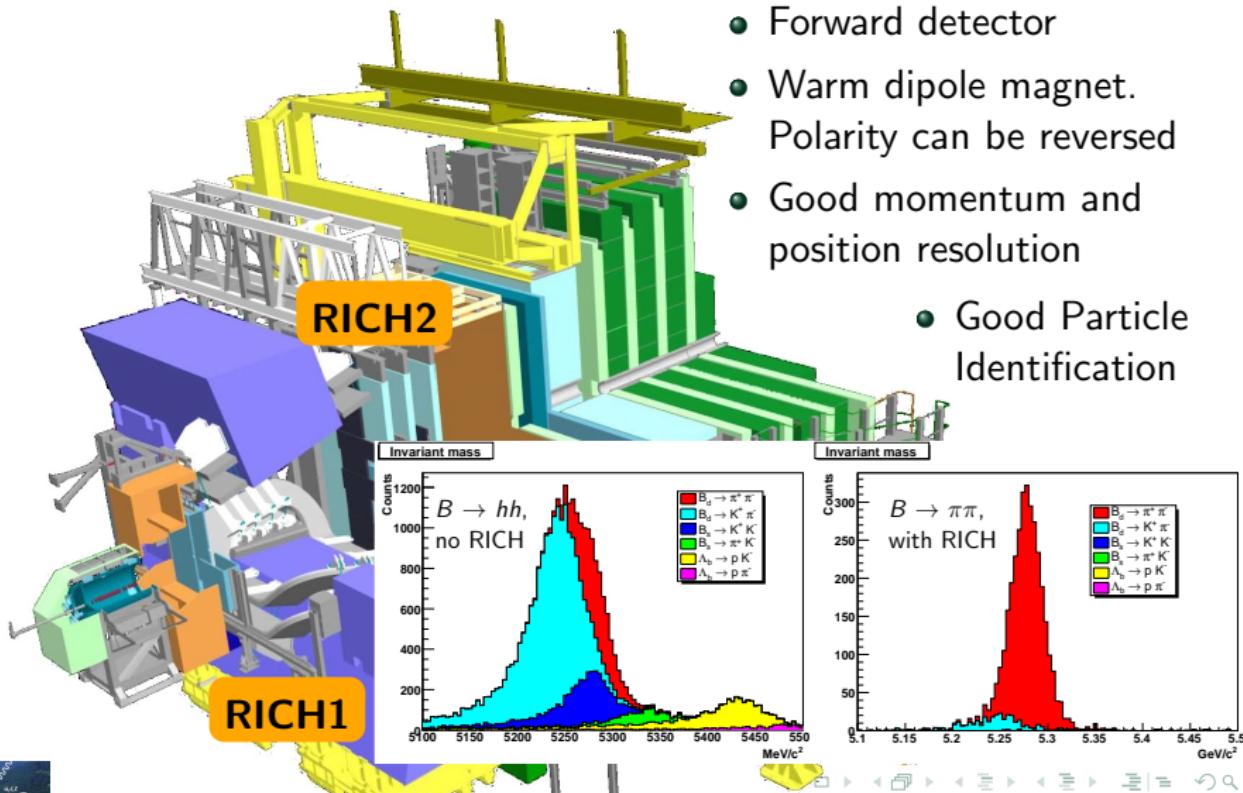






- Forward detector
- Warm dipole magnet.
Polarity can be reversed
- Good momentum and position resolution
 - Vertex detector gets 8mm to the beam

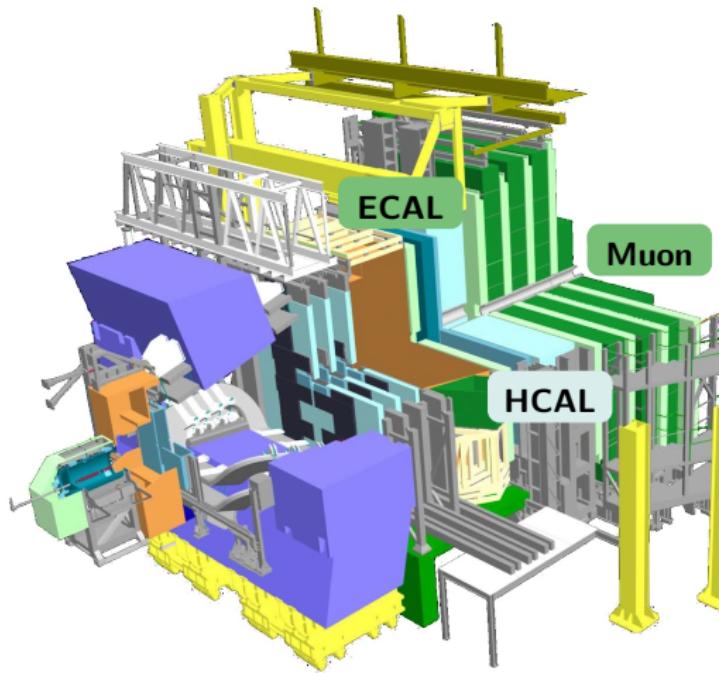




LHCb TRIGGER



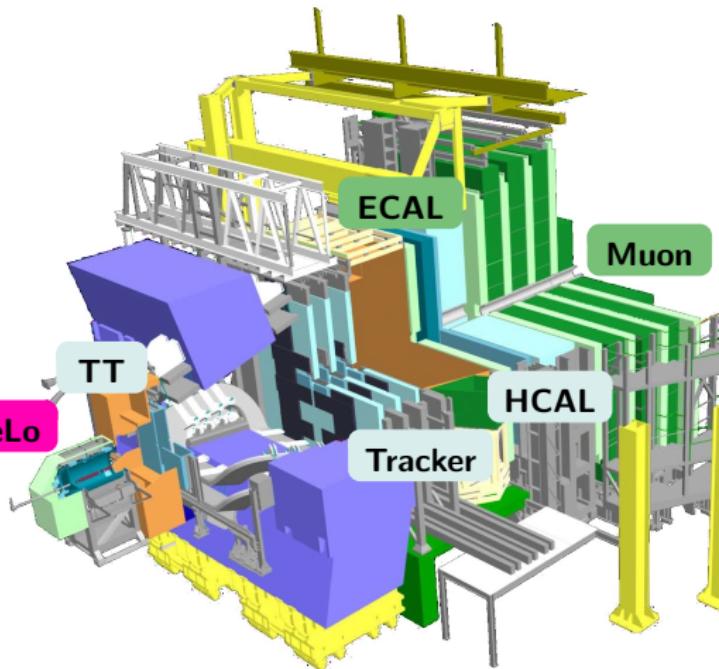
- Hardware-based L0 trigger:
moderate p_T cuts: 40 MHz
→ 1 MHz



LHCb TRIGGER



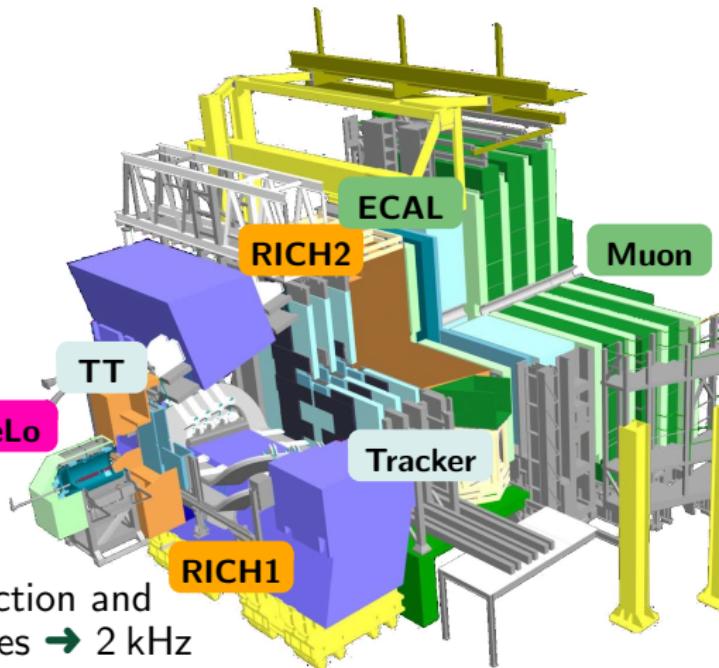
- Hardware-based L0 trigger:
moderate p_T cuts: 40 MHz
→ 1 MHz
- The whole data is then sent at 1 MHz to a farm of $\mathcal{O}(2000)$ CPUs
- HLT1 tries to confirm a L0 decision by matching the L0 candidates to tracks.
→ ~ 30 kHz



LHCb TRIGGER



- Hardware-based L0 trigger:
moderate p_T cuts: 40 MHz
 \rightarrow 1 MHz
- The whole data is then sent at 1 MHz to a farm of $\mathcal{O}(2000)$ CPUs
- HLT1 tries to confirm a L0 decision by matching the L0 candidates to tracks.
 $\rightarrow \sim 30$ kHz
- HLT2 does the full reconstruction and loose selection of B candidates $\rightarrow 2$ kHz
 - This is much less than the 10^5 b events per second



LHCb COLLABORATION



ASSUMPTIONS FOR B PHYSICS IN NEAR FUTURE

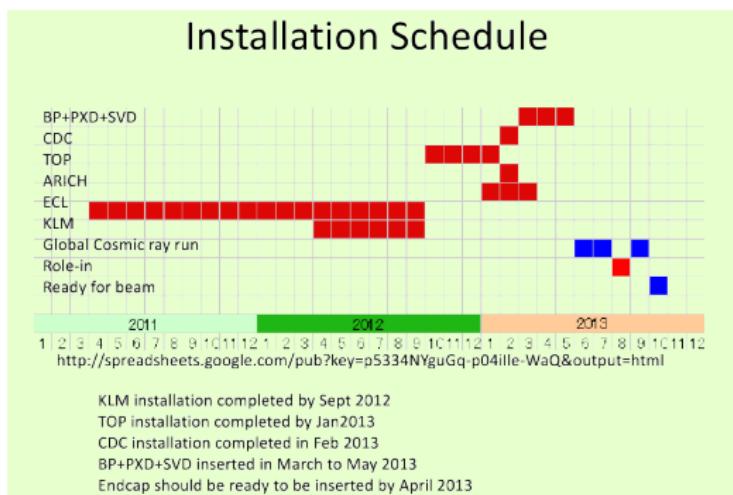
B FACTORIES:

BABAR is terminated. They are finalising their analyses.

BELLE has just stopped. Finalising as well.

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 NEAR FUTURE

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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
2010	7 TeV	50 pb^{-1}	50 pb^{-1}
2011	7 TeV	$\sim 1 \text{ fb}^{-1}$	1 fb^{-1}
2014+	14 TeV	$\geq 2 \text{ fb}^{-1}/\text{year}$	$10 \text{ fb}^{-1}/\text{year}$
Total	7–14 TeV	5–10 fb^{-1}	30 fb^{-1}

ASSUMPTIONS FOR B PHYSICS IN NEAR FUTURE

B FACTORIES:

BABAR is terminated. They are finalising their analyses.

Hence:

- ① The measurements 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

2011
2011
2011

Total

7–14 TeV

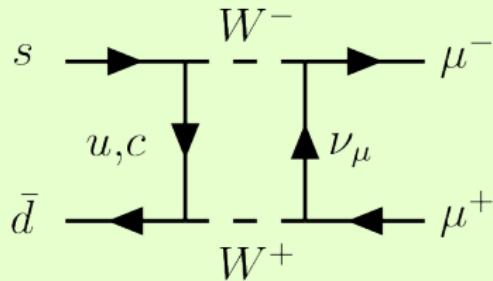
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30 fb^{-1}

$$B_s^0 \rightarrow \mu\mu$$

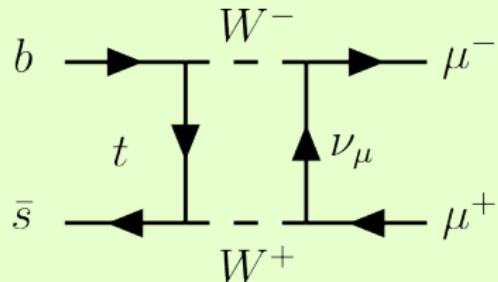
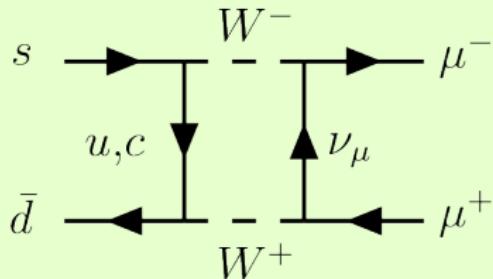


$$B_s^0 \rightarrow \mu\mu$$

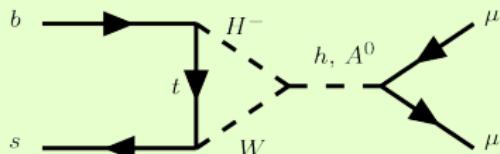
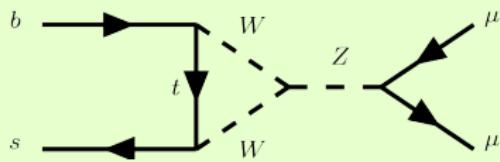


- Start with $K_L^0 \rightarrow \mu\mu$

$$B_s^0 \rightarrow \mu\mu$$



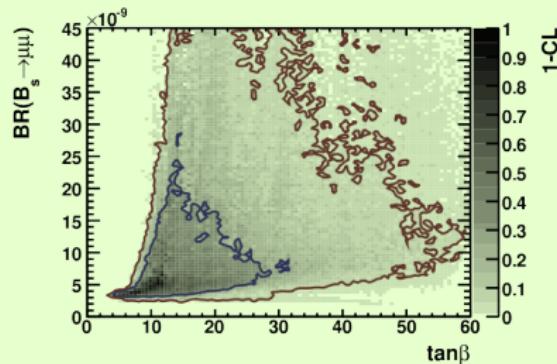
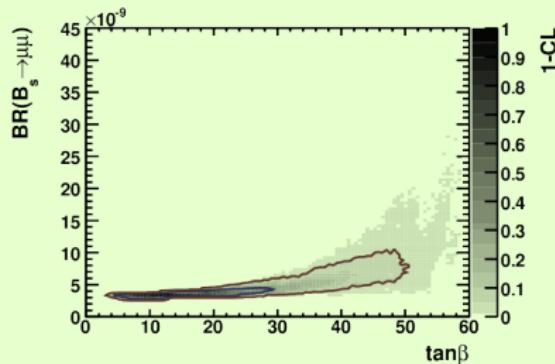
- Start with $K_L^0 \rightarrow \mu\mu$
 - Replace quarks by b and \bar{s} (for B_s^0) and t ($\propto V_{tb} V_{ts}$)
 - Add a penguin contribution ($\propto V_{tb} V_{ts}$)
 - Add a hypothetical charged Higgs contribution ($\propto ?$)
- Gets what BF?



$B_s^0 \rightarrow \mu\mu$

- Very rare but SM BF well predicted $\mathcal{B} = (3.35 \pm 0.32) \cdot 10^{-9}$ [Blanke et al., JHEP0610:003,2006]
- Sensitive to (pseudo)scalar operator : $\mathcal{B} \propto \frac{\tan^6 \beta}{M_A^4}$
- CMSSM: Constrained minimal supersymmetric model, left
- NUHM1, an extension of the above in the Higgs sector, right

[Buchmüller et al., EPJ C64:391-415,2009]



$B_s^0 \rightarrow \mu\mu$ LIMITS



$$\mathcal{B}(B_s^0 \rightarrow \mu\mu) = \frac{N_{B_s^0}^{95\% \text{ CL}}}{N_{B_u^+}} \frac{\alpha_{B_u^+}}{\alpha_{B_s^0}} \frac{\epsilon_{B_u^+}^{\text{base}}}{\epsilon_{B_s^0}^{\text{base}}} \frac{1}{\epsilon_{B_s^0}^{\text{NN}}} \frac{f_u}{f_s} \mathcal{B}(B_u^+ \rightarrow J/\psi(\mu\mu)K)$$

[CDF note 9892]

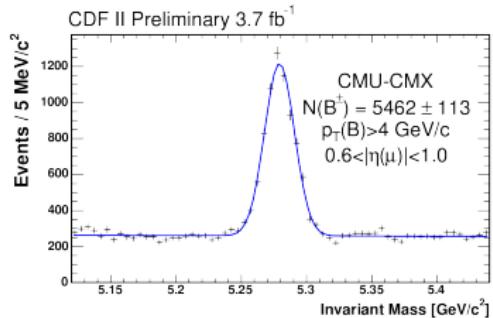
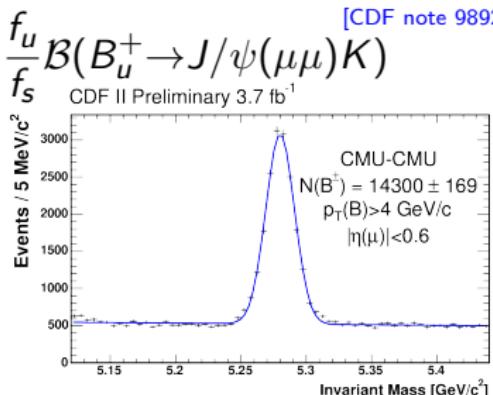
$N_{B_s^0}^{95\% \text{ CL}}$: number of $B_s^0 \rightarrow \mu\mu$ decays at 95% CL for N observed and N_b expected background events,

$N_{B_u^+} = 14300, 5460$ for two types of trigger (CMU-CMU, CMU-CMX)

α : acceptance,

ϵ : selection efficiency, For $B_s^0 \rightarrow \mu\mu$ a neural net is used on top

$\frac{f_u}{f_s} = (3.86 \pm 0.58)$ hadronisation fraction



$B_s^0 \rightarrow \mu\mu$ LIMITS



[CDF note 9892]

$$\mathcal{B}(B_s^0 \rightarrow \mu\mu) = \frac{N_{B_s^0}^{95\% \text{ CL}}}{N_{B_u^+}} \frac{\alpha_{B_u^+}}{\alpha_{B_s^0}} \frac{\epsilon_{B_u^+}^{\text{base}}}{\epsilon_{B_s^0}^{\text{base}}} \frac{1}{\epsilon_{B_s^0}^{\text{NN}}} \frac{f_u}{f_s} \mathcal{B}(B_u^+ \rightarrow J/\psi(\mu\mu)K)$$

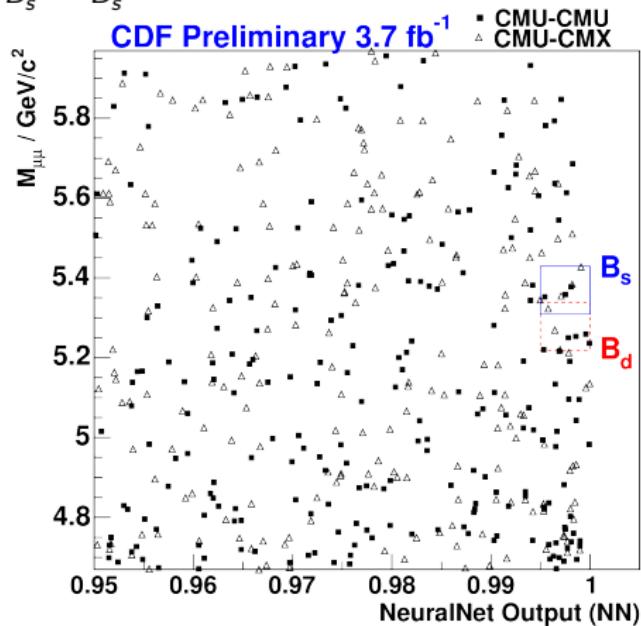
$$\begin{aligned}\mathcal{B}(B_s^0 \rightarrow \mu\mu) &< 4.3 \cdot 10^{-8} \\ \mathcal{B}(B_d^0 \rightarrow \mu\mu) &< 7.6 \cdot 10^{-9}\end{aligned}$$

at 95% CL.

This is a factor 10 away from the SM for $B_s^0 \rightarrow \mu\mu$ and 50 for $B_d^0 \rightarrow \mu\mu$ (suppressed by V_{td}/V_{ts})

DO (6.1 fb^{-1}) [1006.3469 (hep-ex)]:

$$\mathcal{B}(B_s^0 \rightarrow \mu\mu) < 5.1 \cdot 10^{-8}$$



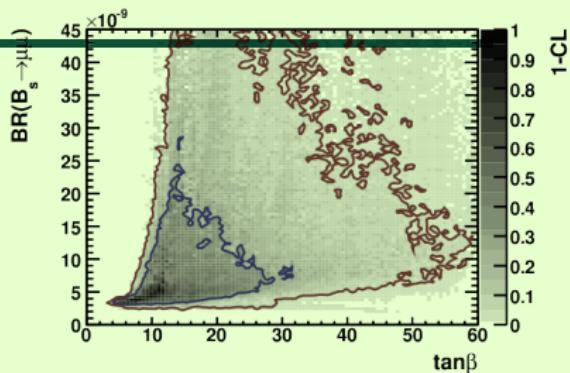
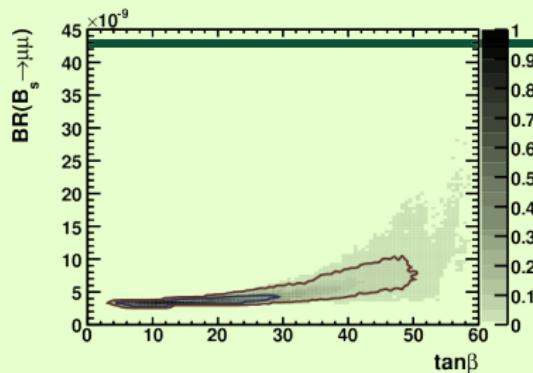
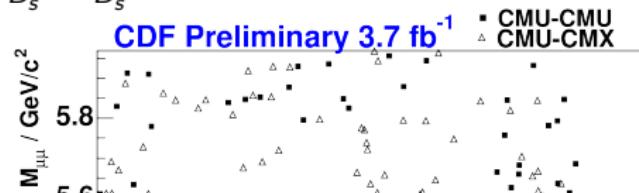
$B_s^0 \rightarrow \mu\mu$ LIMITS



[CDF note 9892]

$$\mathcal{B}(B_s^0 \rightarrow \mu\mu) = \frac{N_{B_s^0}^{95\% \text{ CL}}}{N_{B_u^+}} \frac{\alpha_{B_u^+}}{\alpha_{B_s^0}} \frac{\epsilon_{B_u^+}^{\text{base}}}{\epsilon_{B_s^0}^{\text{base}}} \frac{1}{\epsilon_{B_s^0}^{\text{NN}}} \frac{f_u}{f_s} \mathcal{B}(B_u^+ \rightarrow J/\psi(\mu\mu)K)$$

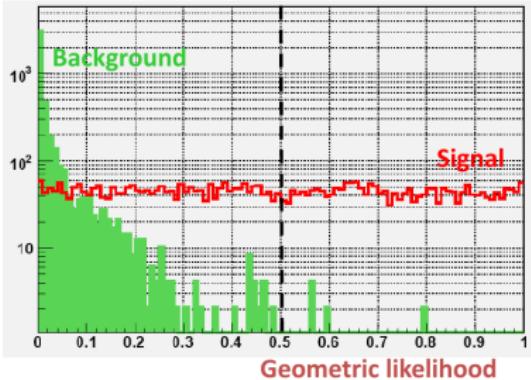
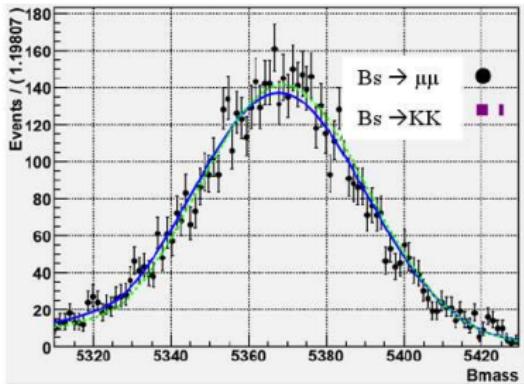
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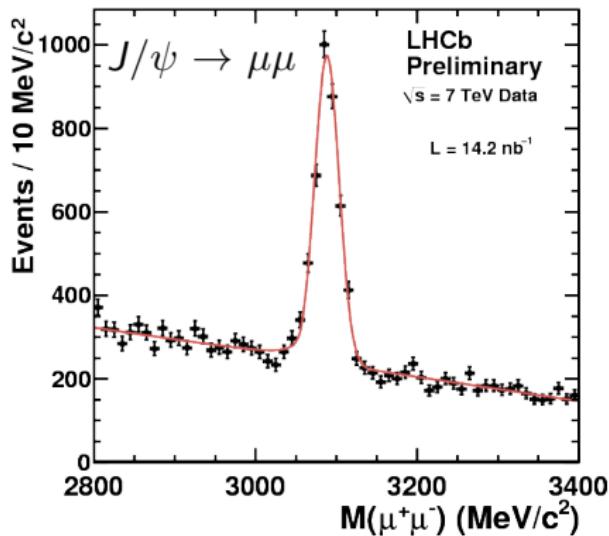
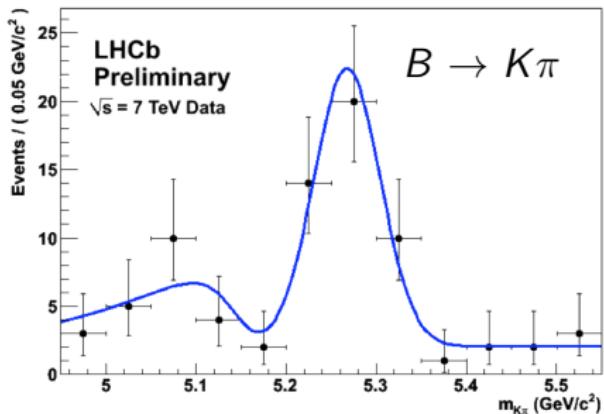
$B_s^0 \rightarrow \mu\mu$ AT LHCb



- Select signal in a 3D-box of mass, geometrical likelihood, PID likelihood
 - Uncorrelated variables with different control samples
 - $B \rightarrow hh$ & $J/\psi \rightarrow \mu\mu$
 - B mass resolution ~ 20 MeV

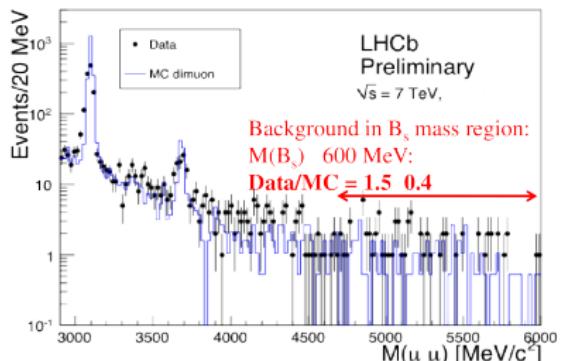


$B_s^0 \rightarrow \mu\mu$ CONTROL SAMPLES

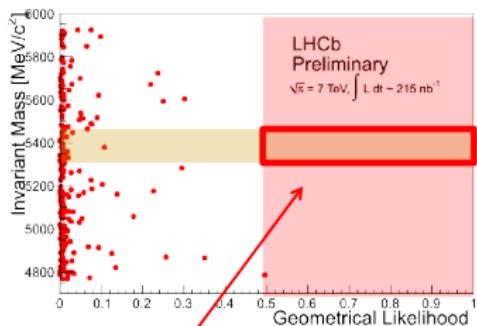


- LHCb see $B_s^0 \rightarrow K\pi$ events
- And plenty of $J/\psi \rightarrow \mu\mu$ events
- All the ingredients are there for $B_s^0 \rightarrow \mu\mu$!

FIRST $B_s^0 \rightarrow \mu\mu$ “RESULTS”



Mass vs Geometrical Likelihood:



Sensitive region:

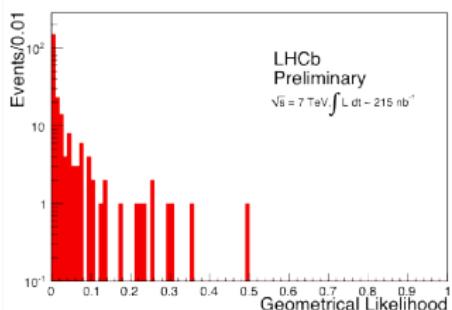
$M(B_s) > 60 \text{ MeV}/c^2 \& \& GL > 0.5$

Patrick Koppenburg

Rare Decays

- Nothing in the signal box yet
- Anything else would have been a disaster
- ✗ We should now hide the box and not open it again

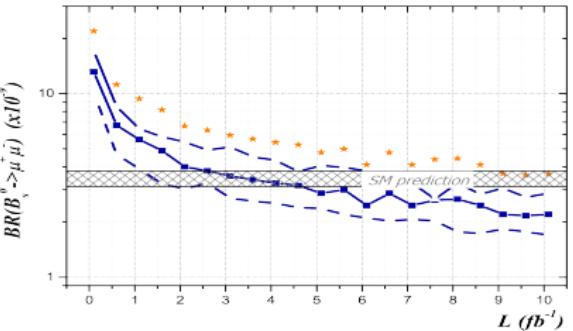
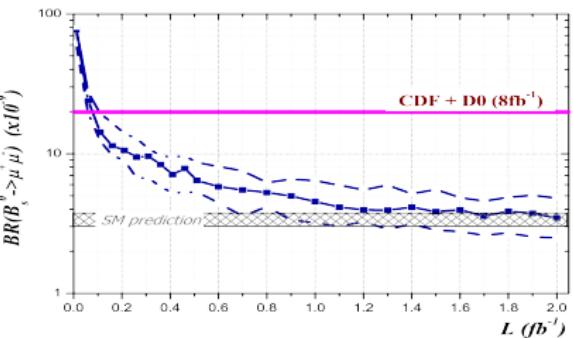
Geometrical Likelihood distribution



$B_s^0 \rightarrow \mu\mu$ AT LHCb



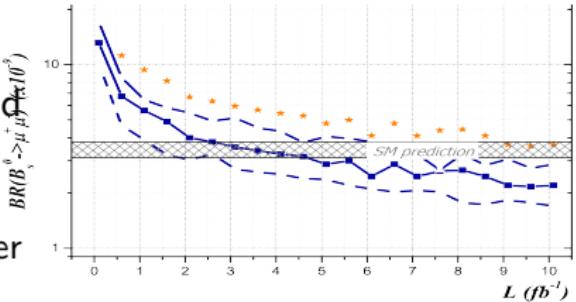
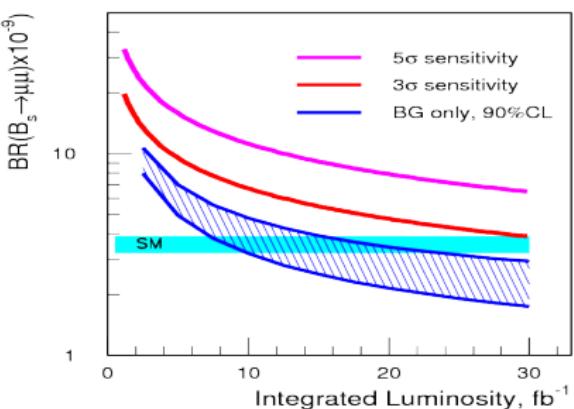
- Select signal in a 3D-box of mass, geometrical likelihood, PID likelihood
 - Uncorrelated variables with different control samples
 - B mass resolution ~ 20 MeV
- With SM BF, expect 8 signal and 12 background events in most sensitive bin in 2 fb^{-1}
 - 3σ evidence with 2 fb^{-1}
 - 5σ observation with $6\text{--}10 \text{ fb}^{-1}$



$B_s^0 \rightarrow \mu\mu$ AT LHCb



- Select signal in a 3D-box of mass, geometrical likelihood, PID likelihood
 - Uncorrelated variables with different control samples
 - B mass resolution ~ 20 MeV
- With SM BF, expect 8 signal and 12 background events in most sensitive bin in 2 fb^{-1}
 - 3σ evidence with 2 fb^{-1}
 - 5σ observation with $6\text{--}10 \text{ fb}^{-1}$
- Atlas and CMS can do it, but need more data
 - ✗ Poorer Mass resolution
 - ✗ Need to cut hard in p_T in trigger



$B_s^0 \rightarrow \mu\mu$ NORMALISATION

CDF does:

$$\mathcal{B}(B_s^0 \rightarrow \mu\mu) = \frac{N_{B_s^0}^{95\% \text{ CL}}}{N_{B_u^+}} \frac{\alpha_{B_u^+}}{\alpha_{B_s^0}} \frac{\epsilon_{B_u^+}^{\text{base}}}{\epsilon_{B_s^0}^{\text{base}}} \frac{1}{\epsilon_{B_s^0}^{\text{NN}}} \frac{f_u}{f_s} \mathcal{B}(B_u^+ \rightarrow J/\psi(\mu\mu)K)$$

The problem at hadron machines is that it's not easy to measure absolute branching fractions.

- Hence measure a BF relative to another well measured channel
 - $\mathcal{B}(B_u^+ \rightarrow J/\psi K) = (1.014 \pm 0.034) \cdot 10^{-3}$ → 3% systematic
 - $\frac{f_u}{f_s} = 3.86 \pm 0.59$ → 15% systematic
- Why not use a B_s^0 channel?
 - $\mathcal{B}(B_s^0 \rightarrow J/\psi\phi) = (1.3 \pm 0.4) \cdot 10^{-3}$ → 30% systematic
 - Need much more data at the $\Upsilon(5S)$

$B_s^0 \rightarrow \mu\mu$ NORMALISATION

LHCb will do:

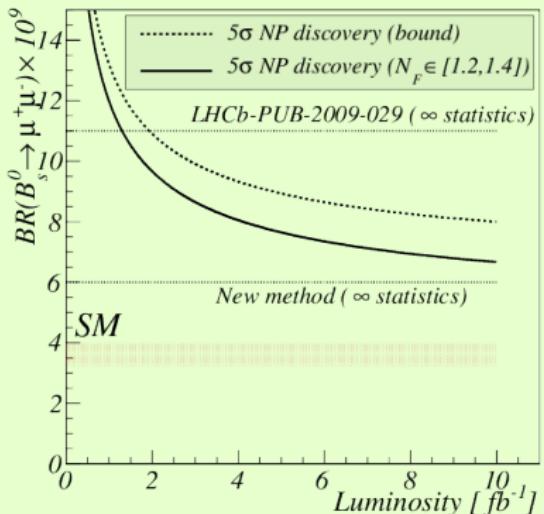
$$\mathcal{B}(B_s^0 \rightarrow \mu\mu) = \frac{N_{B_s^0}^{95\% \text{ CL}}}{N_{B_d^+}} \frac{\alpha_{B_d^0}}{\alpha_{B_s^0}} \frac{\epsilon_{B_d^0}}{\epsilon_{B_s^0}} \frac{f_d}{f_s} \mathcal{B}(B_d^0 \rightarrow J/\psi(\mu\mu) K^*)$$

But one could get $\frac{f_d}{f_s}$ from

$$\frac{N_s}{N_d} = \frac{f_s}{f_d} \frac{\epsilon(B_s^0 \rightarrow X_1)}{\epsilon(B_d^0 \rightarrow X_2)} \frac{\mathcal{B}(B_s^0 \rightarrow X_1)}{\mathcal{B}(B_d^0 \rightarrow X_2)}$$

with 2 channels of similar efficiency and calculable ratio of BF:

- $B_s^0 \rightarrow D_s^- \pi^+ \rightarrow K^- K^+ \pi^- \pi^+$
 - $B_d^0 \rightarrow D_d^- K^+ \rightarrow K^+ K^+ \pi^- \pi^-$
- 5.6% error on $\frac{f_d}{f_s}$



[Fleischer, Serra, Tuning, ArXiv:1004.3982 (hep-ph)]

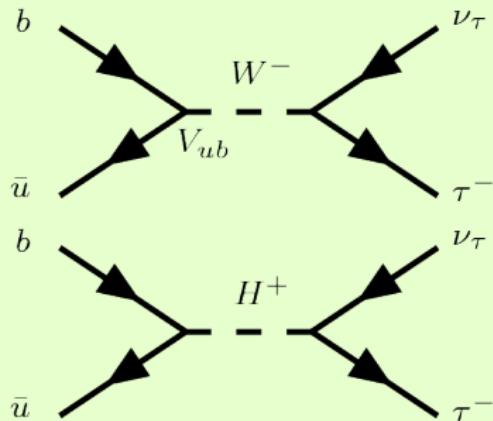
$$B \rightarrow \tau \nu$$

$$\mathcal{B} = \frac{G_F^2 m_B m_\tau^2}{8\pi} \left(1 - \frac{m_\tau^2}{m_B^2}\right) f_B |V_{ub}|^2 \tau_B$$

- Tree diagram, but quite rare:

$$\mathcal{B}_{\text{SM}} = (1.2 \pm 0.4) \cdot 10^{-4}$$

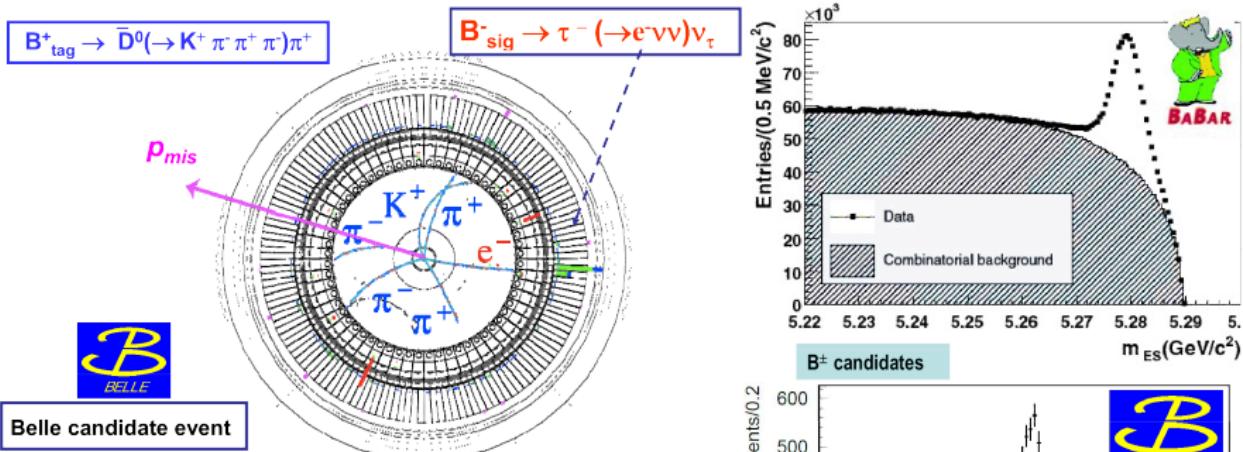
- for $B_u^+ \rightarrow \mu \nu$, replace m_τ by m_μ
and see the BF decrease...



Higgs-mediated diagram **reduces** (small $\tan \beta$) or **enhances** the BF:

$$\frac{\mathcal{B}_{\text{MSSM}}}{\mathcal{B}_{\text{SM}}} = \left(1 - \frac{m_B^2}{m_{H^\pm}^2} \frac{\tan^2 \beta}{1 + \epsilon \tan \beta} \right)^2$$

FULL RECONSTRUCTION



- (\vec{p}, E) of $\Upsilon(4S)$ is known
- Reconstruct one B fully
- ✓ Known 4-momentum (and charge) of other B
- A clean B beam at $\mathcal{O}(1\%)$ efficiency

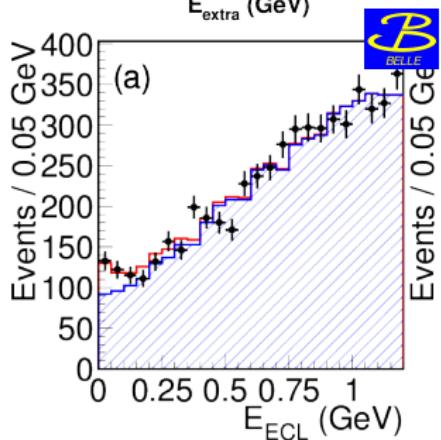
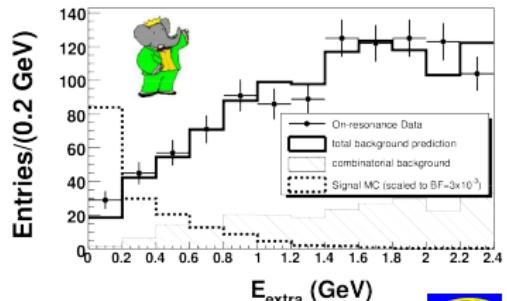
$$B \rightarrow \tau \nu$$



- Fully reconstruct a $B \rightarrow D^* \ell \nu$
- Look for a single lepton or pion from $\tau \rightarrow \ell \nu \bar{\nu}$ or $\tau \rightarrow \pi \bar{\nu}$
- Require nothing else in the detector
- Signal has 0 energy in the ECAL

$$\mathcal{B} = (1.54^{+0.38+0.29}_{-0.37-0.31}) \cdot 10^{-4} \quad \text{BELLE}$$

$$\mathcal{B} = (1.8 \pm 0.8 \pm 0.1) \cdot 10^{-4} \quad \text{BELLE}$$



[Babar, PRD81.051101 (2008)], [Belle, 1006.4201v1 (hep-ex)]



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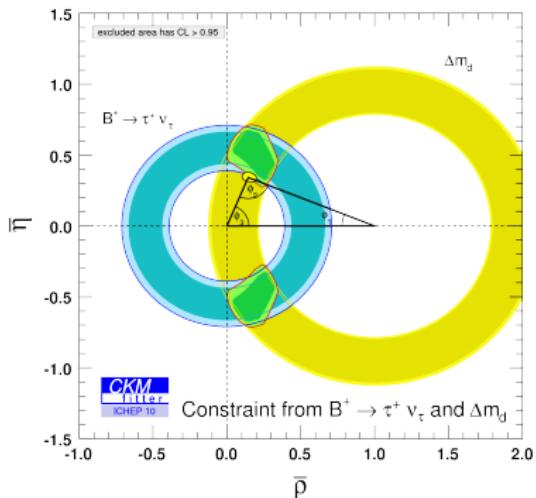
$$\mathcal{B} = (1.8 \pm 0.8 \pm 0.1) \cdot 10^{-4}$$

A bit on the high side for the SM.

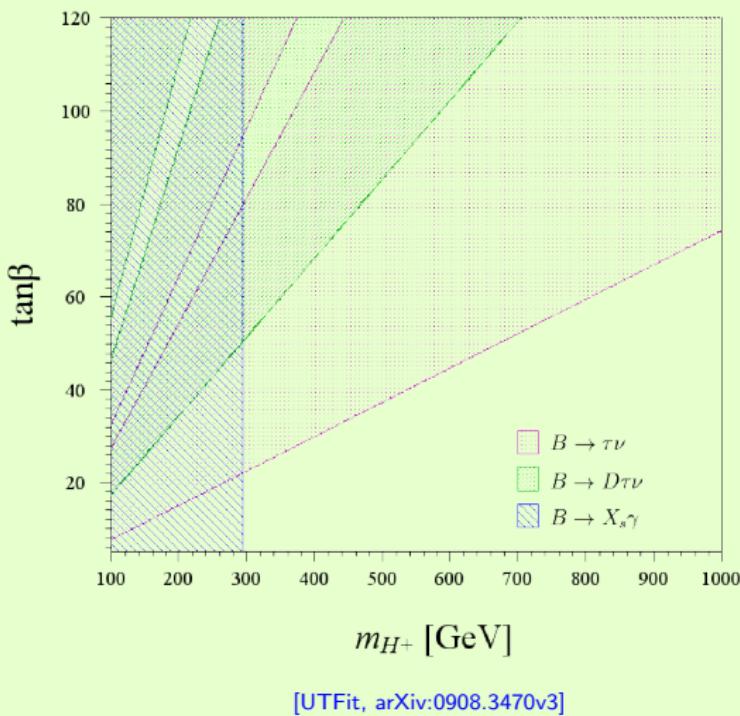
Even worse for MSSM at low $\tan\beta$

→ strong constraint on m_{H^\pm} .

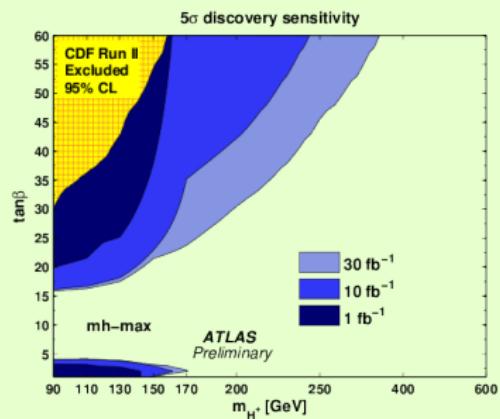
[Babar, PRD81.051101 (2008)], [Belle, 1006.4201v1 (hep-ex)]



BOUNDS ON CHARGED HIGGS



- Charged Higgs are excluded in range of reasonable masses
- Atlas and CMS are still looking [Atlas, CHARGED2008]



A BIT OF THEORY



FERMI

Fermi's "Versuch einer Theorie der β -Strahlen"

[Fermi, Z.Phys.88:161-177,1934]

- Two operators Q and Q^* : transition from a neutron to a proton and reverse
- Hamiltonian :

$$\mathcal{H} = g \{ Q\psi(x)\phi(x) + Q^*\psi^*(x)\phi^*(x) \}$$

- ψ and ϕ are the operators for the creation of an electron and a neutrino, respectively.
- Golden rule:

$$\Gamma(n \rightarrow p e \bar{\nu}) = \frac{2\pi}{\hbar} |\langle p e \bar{\nu} | \mathcal{H} | n \rangle|^2 \times (\text{phase-space}).$$

- Nowadays one would write

$$H = G_F \sqrt{2} \{ Q + Q^* \}$$

- Fermi's theory effectively absorbs the contribution from the W into the factor G_F , as the W is too heavy to be resolved in beta decays.

OPE

Write the amplitude for $K_S^0 \rightarrow \pi\pi$,
i.e. $\bar{s} \rightarrow u\bar{s}u$:

$$\begin{aligned}\mathcal{A} &= \frac{ig^2}{2(k^2 - m_W^2)} V_{us}^* V_{ud} (\bar{s} \gamma^\mu (1 - \gamma_5) u) (\bar{u} \gamma_\mu (1 - \gamma_5) d) \\ &= -i \frac{G_F}{\sqrt{2}} V_{us}^* V_{ud} Q_2 + \mathcal{O}\left(\frac{k^2}{m_W^2}\right),\end{aligned}$$

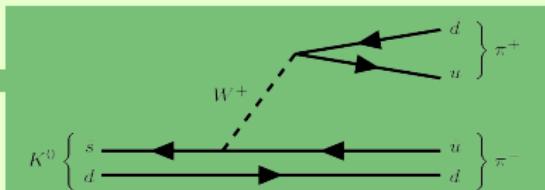
where we have defined the operator

$$Q_2 = (\bar{s}_\alpha \gamma_\mu P_L u_\alpha) (\bar{u}_\beta \gamma^\mu P_L d_\beta).$$

Since $k^2 \ll m_W^2$ we can neglect the second term in \mathcal{A} . The dominant amplitude can be obtained from an effective Hamiltonian

$$\mathcal{H}_{\text{eff}} = -\frac{G_F}{\sqrt{2}} V_{us}^* V_{ud} Q_2 + \text{H.C.}$$

→ Removed the W from the theory



OPE

Consider the QCD corrections to $K^0 \rightarrow \pi^+ \pi^+$:

$$Q_1 = (\bar{s}_\alpha \gamma_\mu P_L u_\beta)(\bar{u}_\beta \gamma^\mu P_L d_\alpha).$$

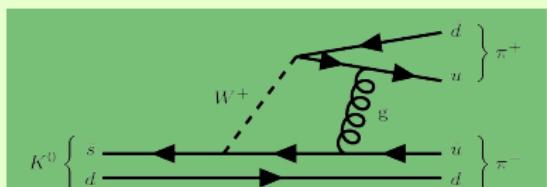
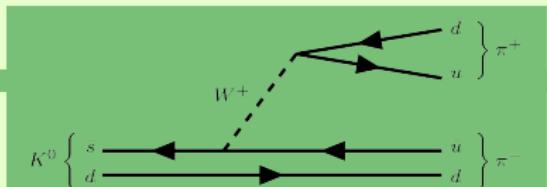
The Hamiltonian now becomes

$$\mathcal{H}_{\text{eff}} = -\frac{G_F}{\sqrt{2}} V_{us}^* V_{ud} \sum_{i=1}^2 C_i Q_i + \text{H.C.}$$

The real parameters C_i are called Wilson coefficients. At first order we have $C_1 = 0$ and $C_2 = 1$.

The amplitude of our decay can then be written as

$$\mathcal{A}(K^0 \rightarrow \pi^+ \pi^-) = \langle \pi^+ \pi^- | \mathcal{H}_{\text{eff}} | K^0 \rangle = \frac{G_F}{\sqrt{2}} V_{us}^* V_{ud} \sum_{i=1}^2 C_i \langle \pi^+ \pi^- | Q_i | K^0 \rangle$$



OPE

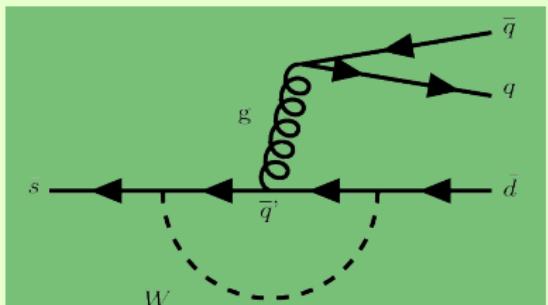
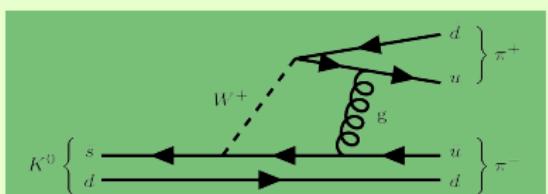
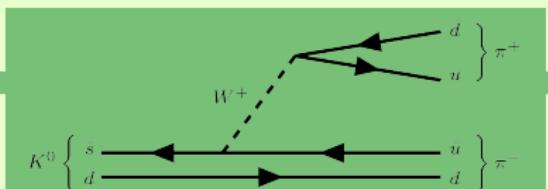
We then add penguin operators :

$$Q_3 = (\bar{s}\gamma_\mu P_L d) \sum_q (\bar{q}\gamma^\mu P_L q),$$

$$Q_4 = (\bar{s}_\alpha\gamma_\mu P_L d_\beta) \sum_q (\bar{q}_\beta\gamma^\mu P_L q_\alpha),$$

$$Q_5 = (\bar{s}\gamma_\mu P_L d) \sum_q (\bar{q}\gamma^\mu P_R q),$$

$$Q_6 = (\bar{s}_\alpha\gamma_\mu P_L d_\beta) \sum_q (\bar{q}_\beta\gamma^\mu P_R q_\alpha).$$



OPE

One gets

$$\mathcal{H}_{\text{eff}} = -\frac{G_F}{\sqrt{2}} \left[V_{us}^* V_{ud} \sum_{i=1}^{10} z_i(\mu) Q_i(\mu) - V_{ts}^* V_{td} \sum_{i=3}^{10} y_i(\mu) Q_i(\mu) \right] + \text{H.C.},$$

While we have started with the decay $K^0 \rightarrow \pi^+ \pi^-$ we actually have an effective Hamiltonian valid for all hadronic s -quark decays. Some operators will simply not contribute to a given decay $K \rightarrow F$ as $\langle F | Q_i | K \rangle$ might be 0.

OPE

One gets

$$\mathcal{H}_{\text{eff}} = -\frac{G_F}{\sqrt{2}} \left[V_{us}^* V_{ud} \sum_{i=1}^{10} z_i(\mu) Q_i(\mu) - V_{ts}^* V_{td} \sum_{i=3}^{10} y_i(\mu) Q_i(\mu) \right] + \text{H.C.},$$

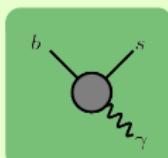
THE SHORT-DISTANCE PART: The Wilson coefficients contain all heavy degrees of freedom. They can be calculated within many models including the SM and supersymmetry at in principle any order. If new particles appear in the loops they will only affect the values of the Wilson coefficients. If we can measure the latter we have a very powerful way of identifying deviations from the Standard Model.

THE LONG-DISTANCE PART: The operators encode the non-perturbative long-distance effects involving particles of masses below the scale μ .

OPERATORS OF INTEREST

Operator

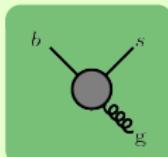
$\mathcal{O}_{7\gamma}$



Effective Hamiltonian \mathcal{H}

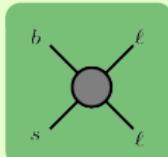
$$A(M \rightarrow F) = \langle F | \mathcal{H}_{\text{eff}} | M \rangle$$

\mathcal{O}_{8g}



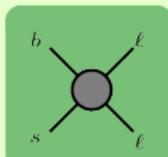
$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{ts}^* V_{tb} \sum_{i=1}^{10} C_i(\mu) \mathcal{O}_i(\mu)$$

$\mathcal{O}_{9V,10A}$



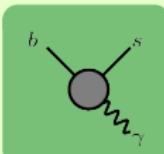
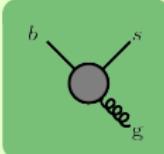
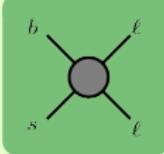
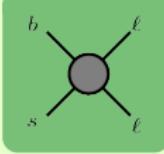
- Operators \mathcal{O}_i : Long-distance effects
- Wilson coefficients C_i : Short-distance effects (masses above μ are integrated out)

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



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

OPERATORS OF INTEREST

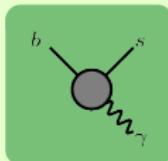
Operator	Magnitude	Phase	Helicity flip \mathcal{O}_i'
$\mathcal{O}_{7\gamma}$		$b \rightarrow s\gamma$	$A_{CP}(b \rightarrow s\gamma)$
\mathcal{O}_{8g}		$b \rightarrow s\gamma$ $b \rightarrow \{s, u, d\}$	$A_{CP}(b \rightarrow s\gamma)$ $B \rightarrow \phi K$
$\mathcal{O}_{9V,10A}$		$b \rightarrow \ell\ell s$	$A_{FB}(b \rightarrow \ell\ell s)$
$\mathcal{O}_{S,P}$		$B \rightarrow \mu\mu$	$B \rightarrow \tau\tau$
			$b \rightarrow s\tau\tau$

Adapted from [\[G.Hiller,hep-ph/0308180\]](#)

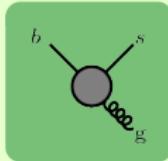
OPERATORS OF INTEREST

Operator

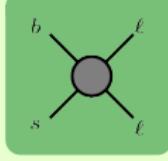
$\mathcal{O}_{7\gamma}$



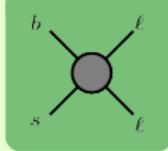
\mathcal{O}_{8g}



$\mathcal{O}_{9V,10A}$



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



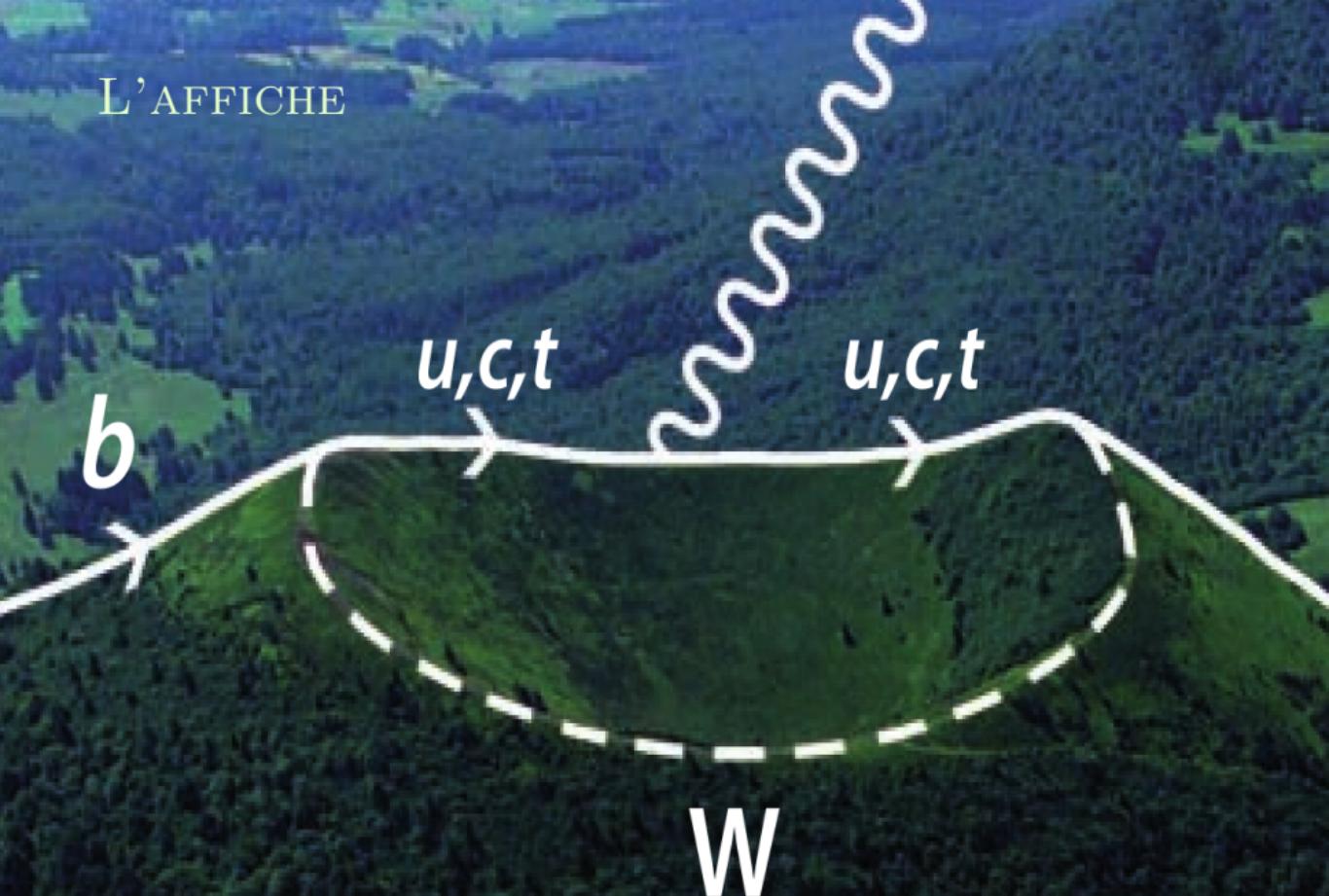
- All C_i calculated at NLO if not NNLO in SM
- We need to measure all coefficients
- Any discrepancy is a sign of New Physics



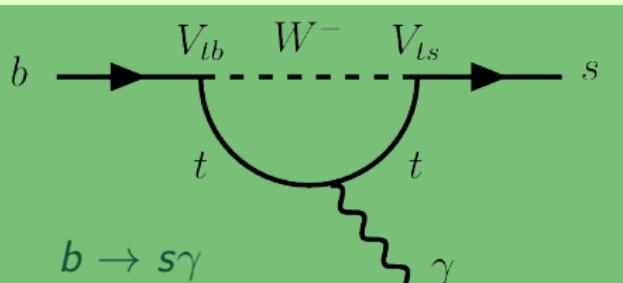
$b \rightarrow s\gamma$



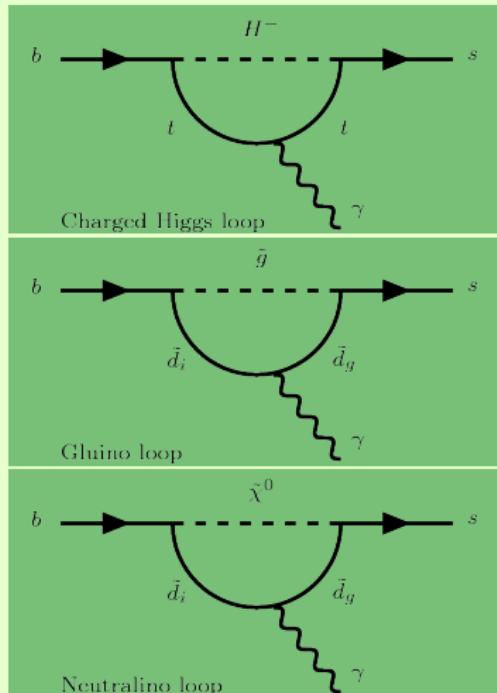
L'AFFICHE



$b \rightarrow s\gamma$



- Amplitude $\propto V_{ts} |C_7|$
- First penguin ever observed (93)
- Experiment (WA):
 $\mathcal{B} = (3.55 \pm 0.26) \cdot 10^{-4}$
- SM: $\mathcal{B} = (3.15 \pm 0.23) \cdot 10^{-4}$ [Misiak et al.,
[hep-ph/0609232](https://arxiv.org/abs/hep-ph/0609232)]
- Strong constraint on New Physics



$B \rightarrow X_s \gamma$ SPECTRUM

- $b \rightarrow s\gamma$ is a 2-body decay. The energy of the photon in the b quark frame is

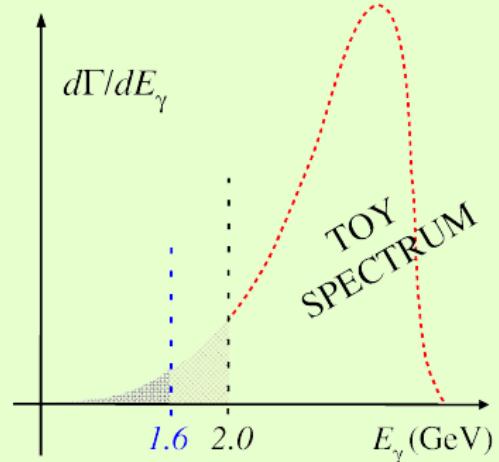
$$E_\gamma = \frac{m_b}{2} \left(1 - \frac{m_s^2}{m_b^2} \right) \simeq \frac{m_b}{2}$$

- But we measure $B \rightarrow X_s \gamma$ and in the B meson the b quark is moving which smears the energy spectrum

→ Mean $\sim \frac{m_B}{2}$

→ Width \sim Fermi motion in B meson

- The BF is calculated for some energy cutoff (1.6 GeV). For other cutoffs E_0 apply [Misiak et, al (2007)]



$$\left(\frac{\mathcal{B}(E_\gamma > E_0)}{\mathcal{B}(E_\gamma > 1.6 \text{ GeV})} \right) \simeq 1 + 0.15 \frac{E_0}{1.6 \text{ GeV}} - 0.14 \left(\frac{E_0}{1.6 \text{ GeV}} \right)^2.$$

$b \rightarrow s\gamma$ SM BRANCHING FRACTION

[Misiak et al. PRL98.022002, 2007]

- From effective Hamiltonian one gets the BF :

$$\mathcal{B}(B \rightarrow X_s \gamma) = \frac{G_F^2 \alpha_{\text{EM}} m_b^5}{32\pi^4} |V_{ts}^* V_{tb}|^2 |C_{7\gamma}^{\text{eff}}|^2 + \text{corrections}$$

- Uncertainties due to m_b^5 → normalise to well measured $b \rightarrow c e \nu$
($\mathcal{B}(B \rightarrow e \nu X_c) = (10.74 \pm 0.16) \%$)

$$R = \frac{\mathcal{B}(b \rightarrow s\gamma)}{\mathcal{B}(b \rightarrow c e \nu)} = \frac{|V_{ts}^* V_{tb}|^2}{|V_{cb}|^2} \frac{3e^2}{2\pi^2 f(\frac{m_c}{m_b})} \left| C_{7\gamma}^{\text{eff}}(\mu) \right|^2$$

- ✓ Removes m_b^5 factor [Gambino & Misiak, NPB611:338,2001]
- ✗ Introduces dependency on $0.18 < \frac{m_c}{m_b} < 0.31$
- One could be smarter: m_c/m_b is free, but $m_b - m_c$ is constrained by $b \rightarrow c e \nu$ decays

$b \rightarrow s\gamma$ SM BRANCHING FRACTION

[Misiak et al. PRL98.022002, 2007]

- From effective Hamiltonian one gets the BF
- Uncertainties due to m_b and m_c : normalise to $b \rightarrow ce\nu$ and $b \rightarrow ue\nu$ [Misiak & Steinhauser, NPB764:62,2007]

$$\frac{\mathcal{B}(b \rightarrow s\gamma)_{E_\gamma > E_0}}{\mathcal{B}(b \rightarrow ce\nu)^{(\text{exp})}} = \frac{|V_{ts}^* V_{tb}|^2}{|V_{cb}|^2} \frac{3e^2}{2\pi^2 C} \underbrace{\frac{\Gamma(b \rightarrow s\gamma)}{\Gamma(b \rightarrow ue\nu)} \frac{2\pi^2}{3e^2} \frac{|V_{ub}|^2}{|V_{ts}^* V_{tb}|^2}}_{=P(E_0)}$$

- The m_c dependence is fitted from measured moments [Bauer, Ligeti et al. PRD70:094017 (2004)]

$$C = \frac{|V_{ub}|^2}{|V_{cb}|^2} \frac{\Gamma(b \rightarrow ce\nu)}{\Gamma(b \rightarrow ue\nu)} = 0.580 \pm 0.016$$

- The P fraction can be calculated at NNLO:

$$P(E_0) = \sum_{i,j=0}^8 C_i^{\text{eff}}(\mu) C_j^{\text{eff}}(\mu) K_{ij}(E_0, \mu)$$

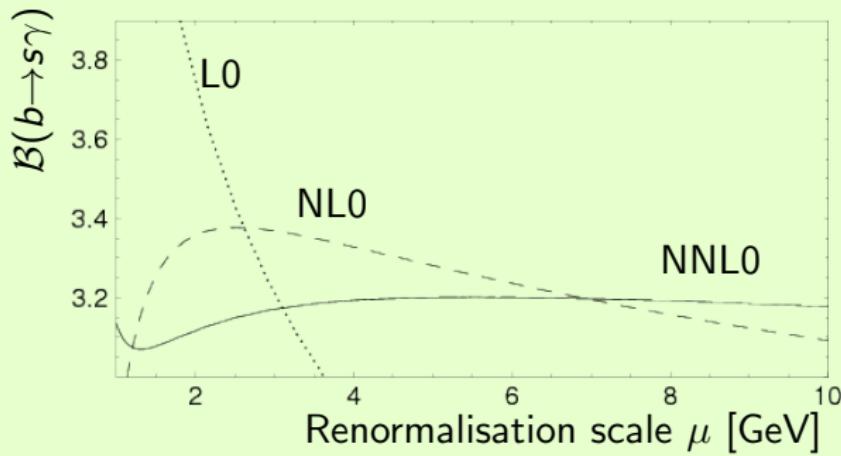
$b \rightarrow s\gamma$ SM BRANCHING FRACTION

[Misiak et al. PRL98.022002, 2007]

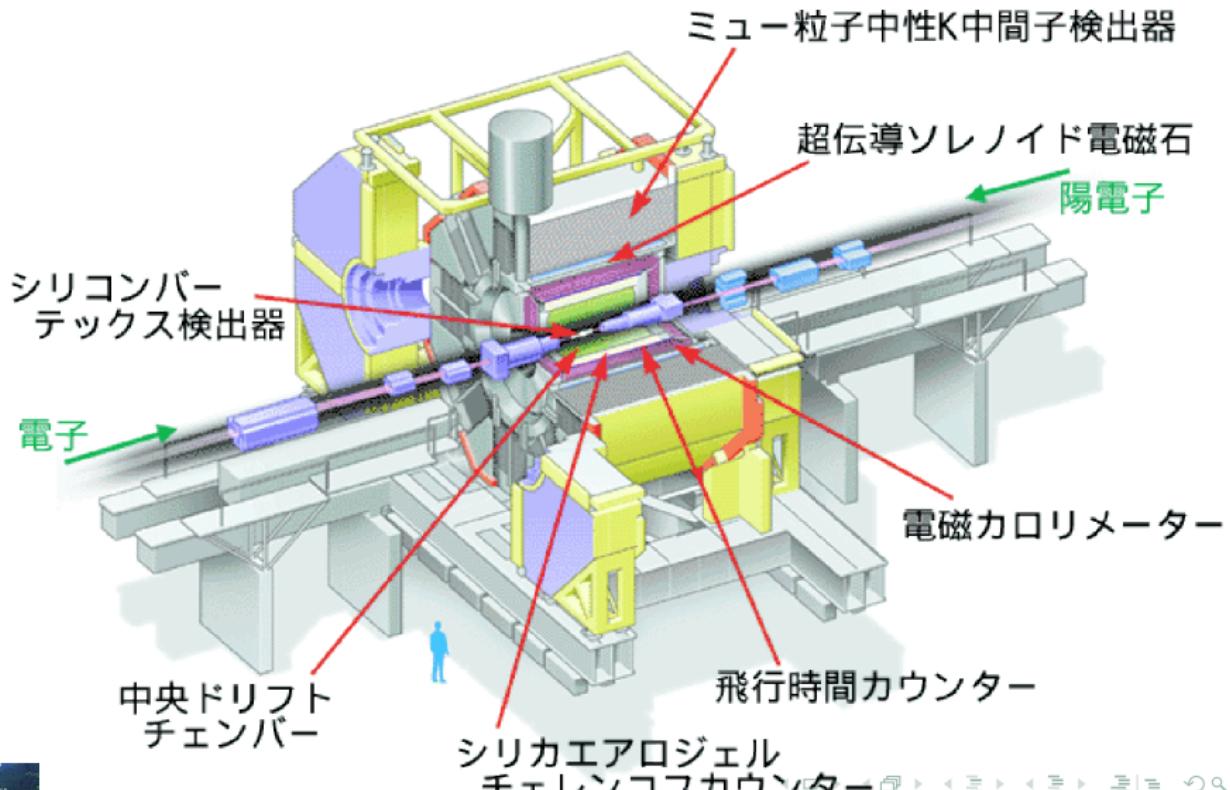
- From effective Hamiltonian one gets the BF
- Uncertainties due to m_b and m_c : normalise to $b \rightarrow c e \nu$ and $b \rightarrow u e \nu$ [Misiak & Steinhauser, NPB764:62,2007]
- $b \rightarrow s\gamma$ branching fraction calculated at all NNLO orders in 2006

$$\mathcal{B}(B \rightarrow X_s \gamma)_{E_\gamma > 1.6 \text{ GeV}} = (3.15 \pm 0.23) \cdot 10^{-4}$$

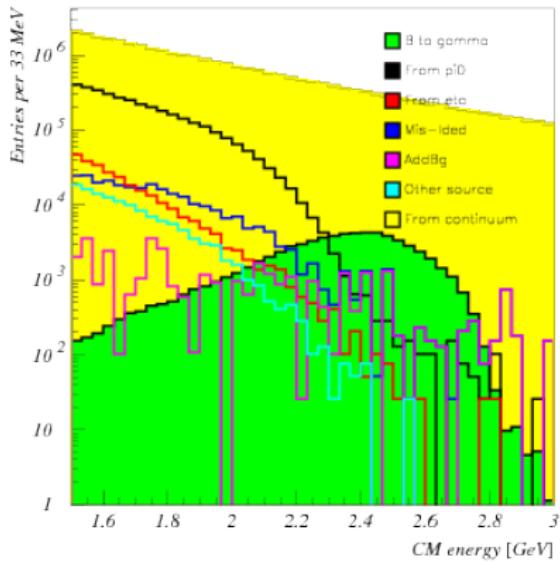
- ✓ BF very stable
versus μ



THE BELLE EXPERIMENT



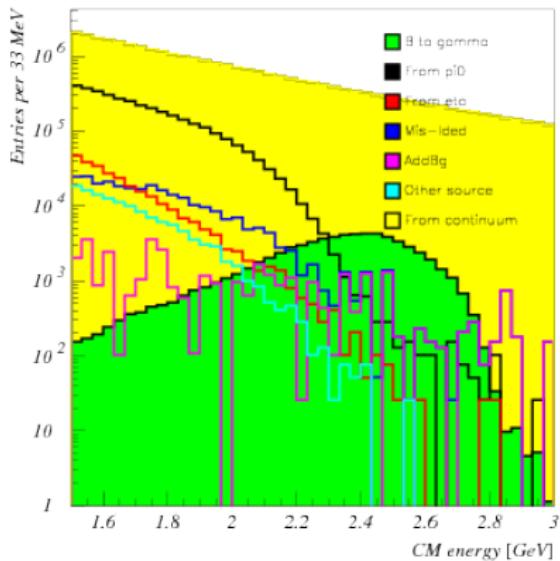
$b \rightarrow s\gamma$ SPECTRUM AT BELLE



One would like to measure the photon energy spectrum in $b \rightarrow s\gamma$ decays.

- Be unbiased: only look at the γ
- ✓ B mesons only decay to γ via $b \rightarrow s\gamma$
- ✗ But there are indirect γ from π^0 and η in $B\bar{B}$ events
- ✗ ... and a lot more π^0 and η in non- $B\bar{B}$ events
- ➔ Lots of background at low energy

$b \rightarrow s\gamma$ SPECTRUM AT BELLE



Data sets:

- 140 fb^{-1} ON-resonance
- 15 fb^{-1} OFF-resonance

Event selection:

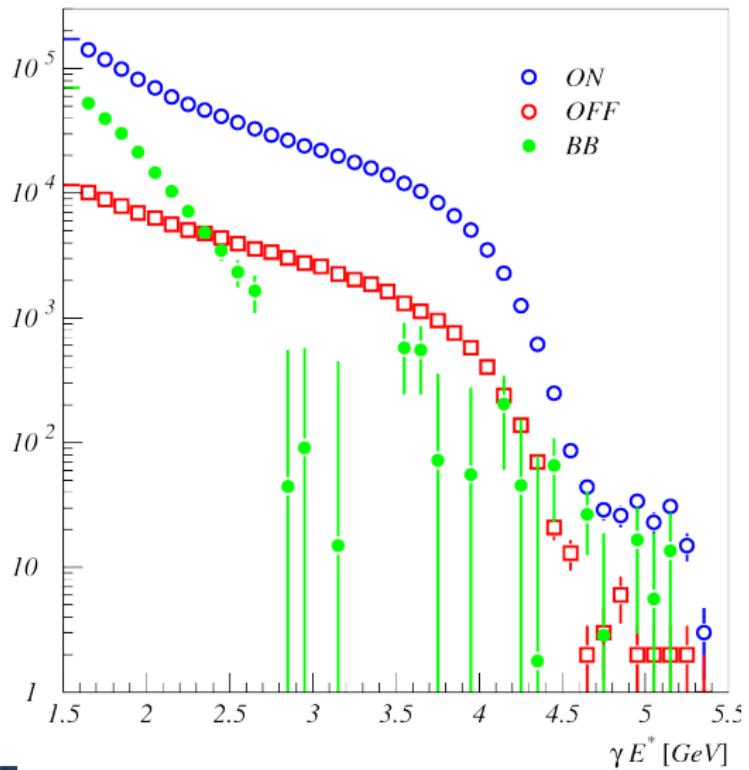
- Hadronic events with isolated photon(s) in ECL. $E^* > 1.5 \text{ GeV}$.
- Veto γ from π^0 and η .
- Apply event shape cuts to suppress continuum background.

Optimise cuts to maximise statistical significance in
 $1.8 \leq E^* \leq 1.9 \text{ GeV}$ bin

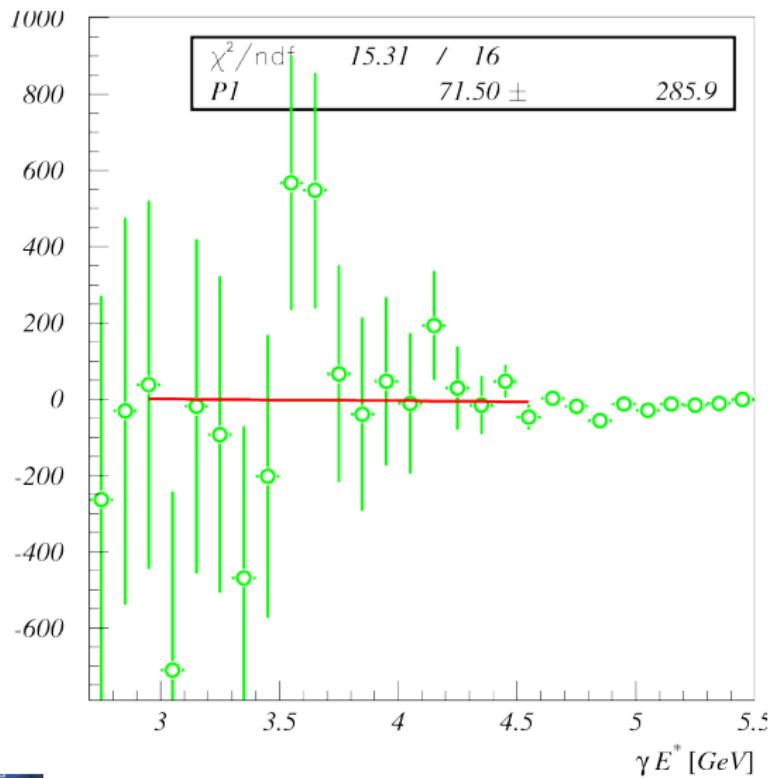
THE SPECTRUM



OFF-resonance data is scaled according to luminosities and subtracted from ON-resonance data



THE SPECTRUM



Endpoint check:

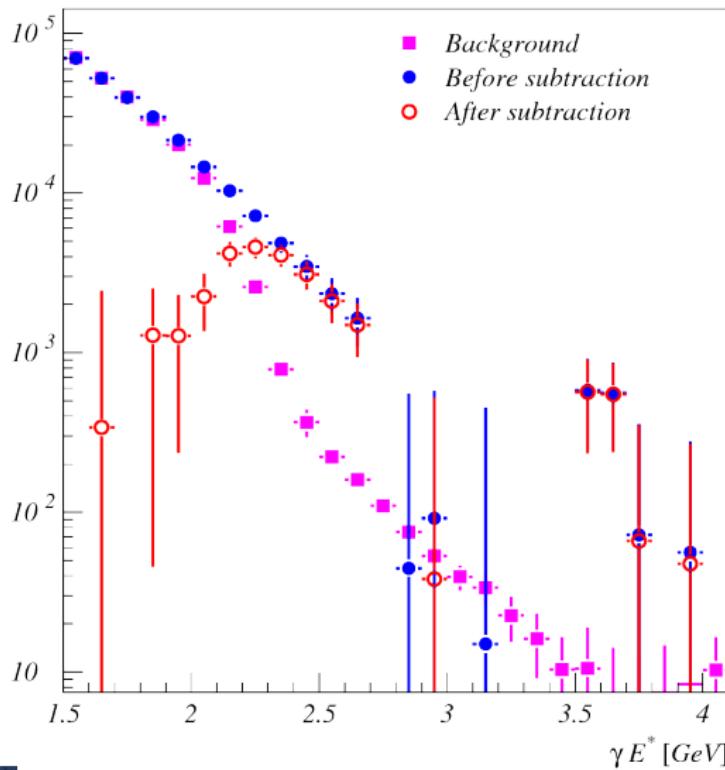
Photons from e^+e^- collisions can have an energy up to 5 GeV.

But not if they come from a B decay. The kinematic limit is $E^* = m_B/2$.

No significant deviation from **0** observed



THE SPECTRUM

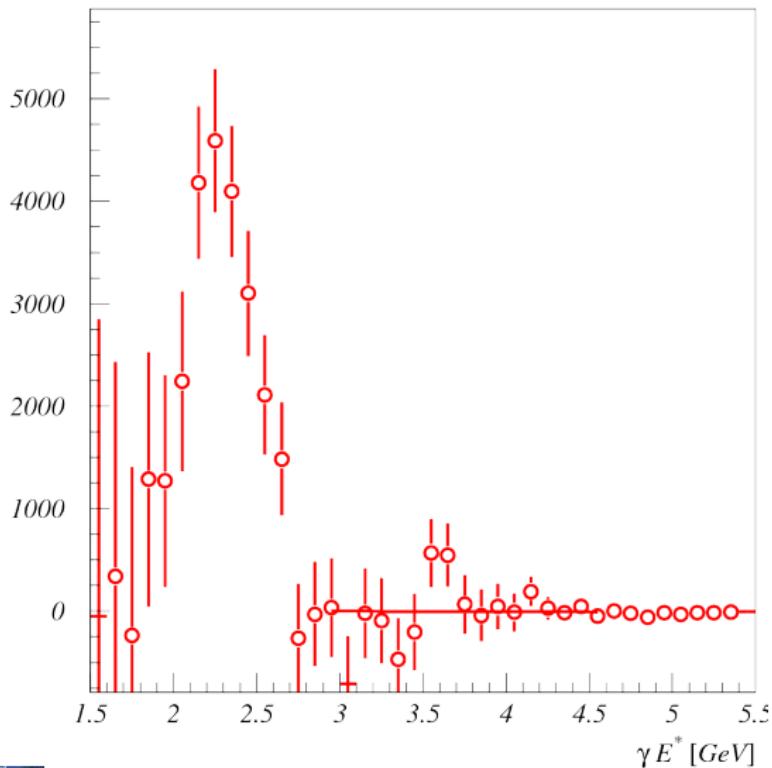


$B\bar{B}$ subtraction.

Using measured π^0 and η spectra and some efficiency-corrected MC.



THE SPECTRUM

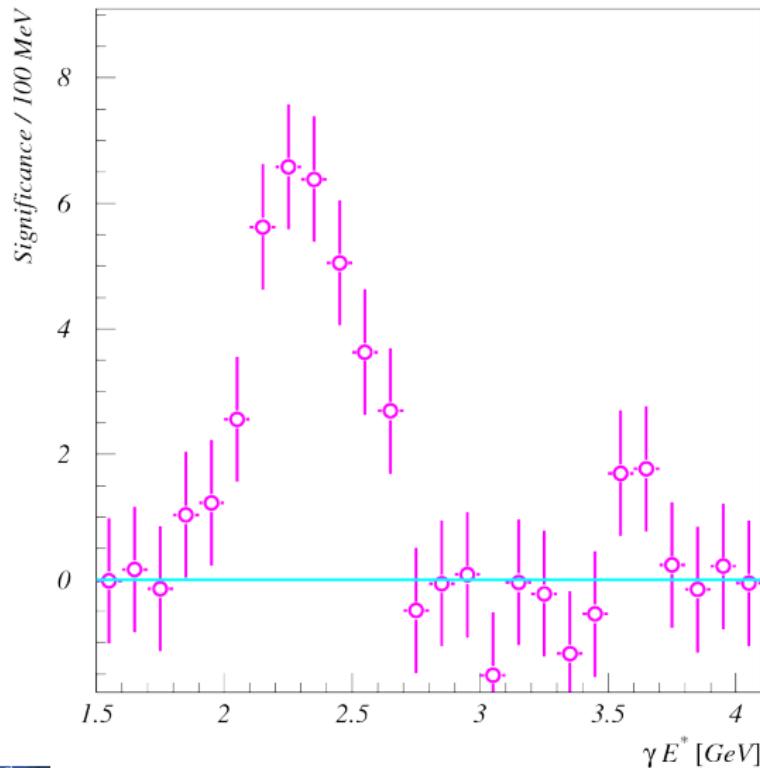


Raw spectrum after all cuts and background corrections

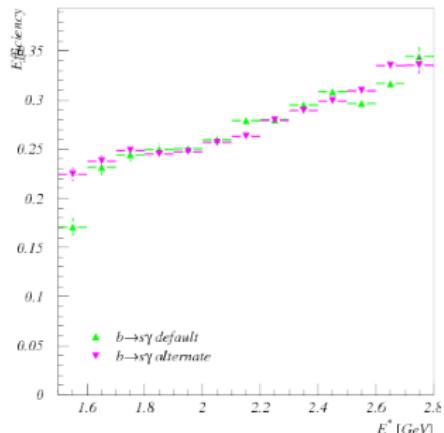
Signal yield:
 24100 ± 2200 events.



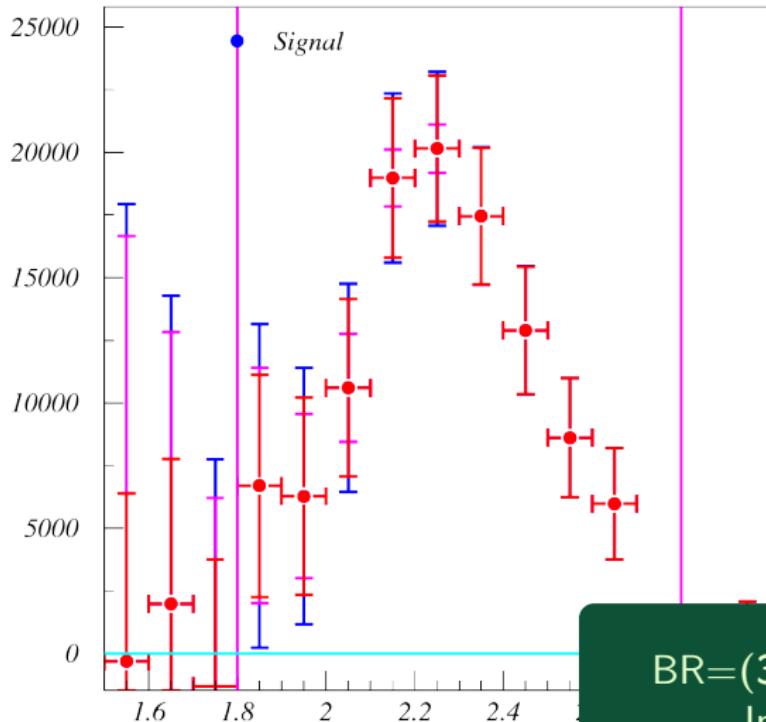
THE SPECTRUM



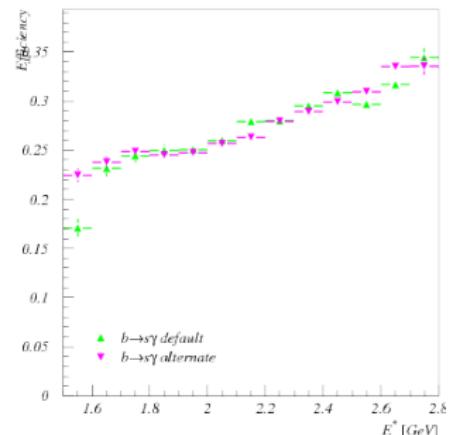
Efficiency corrected spectrum.



THE SPECTRUM



Efficiency corrected spectrum.



$$BR = (3.51 \pm 0.32^{+0.28}_{-0.29}) \cdot 10^{-4}$$

In 1.8–2.8 GeV range.

SYSTEMATICS



Source of systematic error	$\times 10^{-4}$
Raw branching fraction	3.51 ± 0.32
Efficiency and yield scaling	± 0.21
Choice of fitting functions	± 0.048
Number of $B\bar{B}$ -events = $(152.0^{+0.6}_{-0.7}) \cdot 10^6$	$+ 0.139$ $- 0.160$
ON-OFF data subtraction	± 0.026
Other $B\bar{B}$ photons	± 0.055
η veto on η	± 0.009
Signal MC	± 0.090
Photon detection efficiency	± 0.073
Energy leakage	$+ 0.036$ $- 0.000$
Sum for partial $\mathcal{B}(b \rightarrow q\gamma)$	$+ 0.29$ $- 0.30$

BRANCHING FRACTION



Raw $b \rightarrow q\gamma$ in **1.8–2.8** GeV: $(3.51 \pm 0.32^{+0.28}_{-0.29}) \cdot 10^{-4}$
 $\frac{V_{td}}{V_{ts}}$ -Corrected [hep-ph/0312260]: $(3.38 \pm 0.31^{+0.29}_{-0.30} \pm 0.02) \cdot 10^{-4}$

Full spectrum:

Kagan-Neubert [PLB539:227]: $(3.53 \pm 0.32^{+0.30 + 0.11}_{-0.31 - 0.05}) \cdot 10^{-4}$
Bigi-Uraltsev [IJMP A17, 4709]: $(3.56 \pm 0.33^{+0.30}_{-0.31} \pm 0.04) \cdot 10^{-4}$
Gambino-Misiak [NP B611, 338]: $(3.55 \pm 0.32^{+0.30 + 0.11}_{-0.31 - 0.05}) \cdot 10^{-4}$

Combined: $(3.55 \pm 0.32^{+0.30 + 0.11}_{-0.31 - 0.07}) \cdot 10^{-4}$

→ Measure $\sim 95\%$ of the full spectrum.

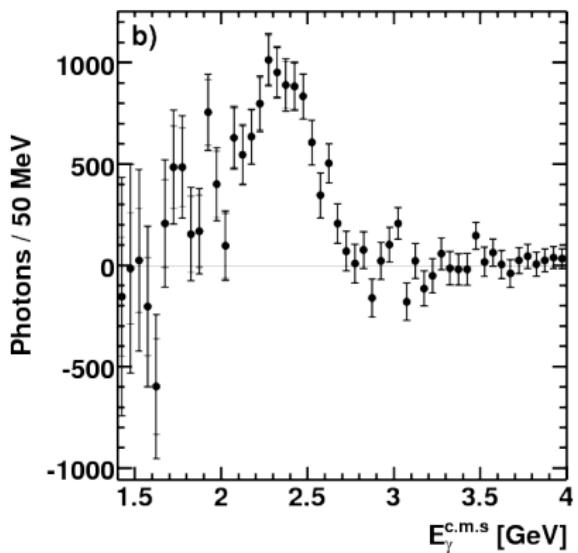
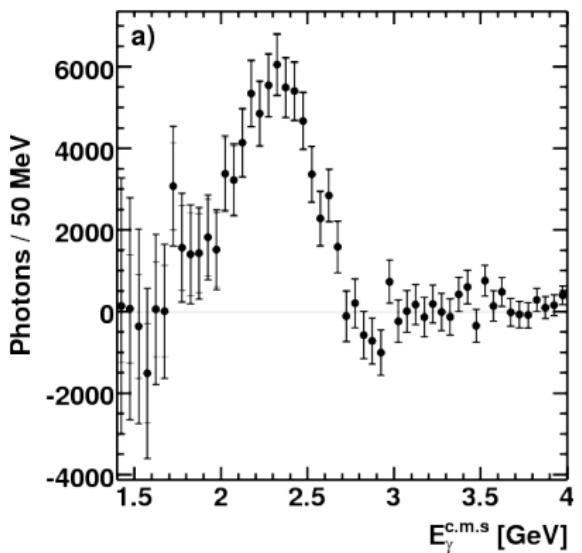
The measurement has been updated with 4 times
more statistics [Phys.Rev.Lett.103:241801,2009]

LATEST UPDATE



$b \rightarrow s\gamma$ above 1.7 GeV: $(3.45 \pm 0.15 \pm 0.40) \cdot 10^{-4}$

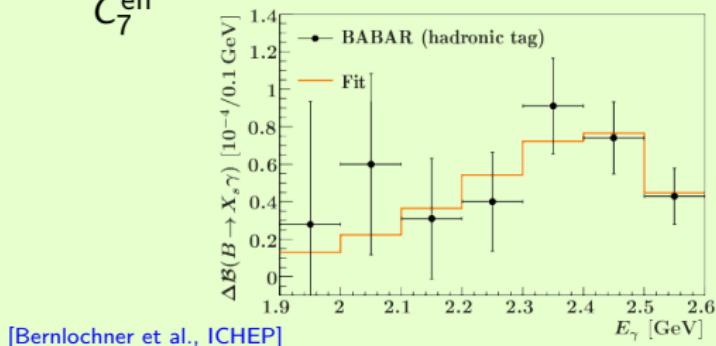
[Phys.Rev.Lett.103:241801,2009]



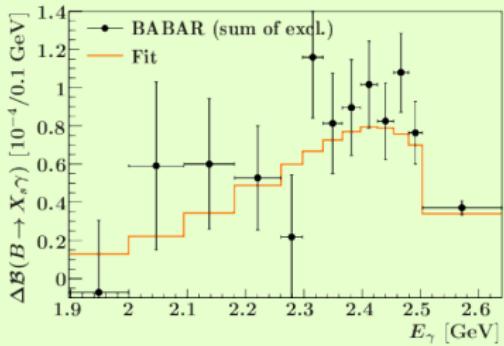
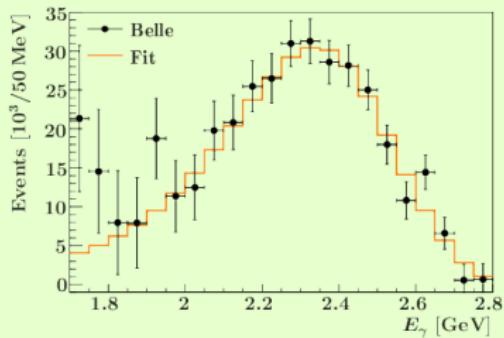
SIMULTANEOUS FIT

- Large uncertainty on $\mathcal{B}(b \rightarrow s\gamma)$ comes from extrapolation to energy cutoff
- But one can fit the spectrum!

→ Fit to spectrum and C_7^{eff}

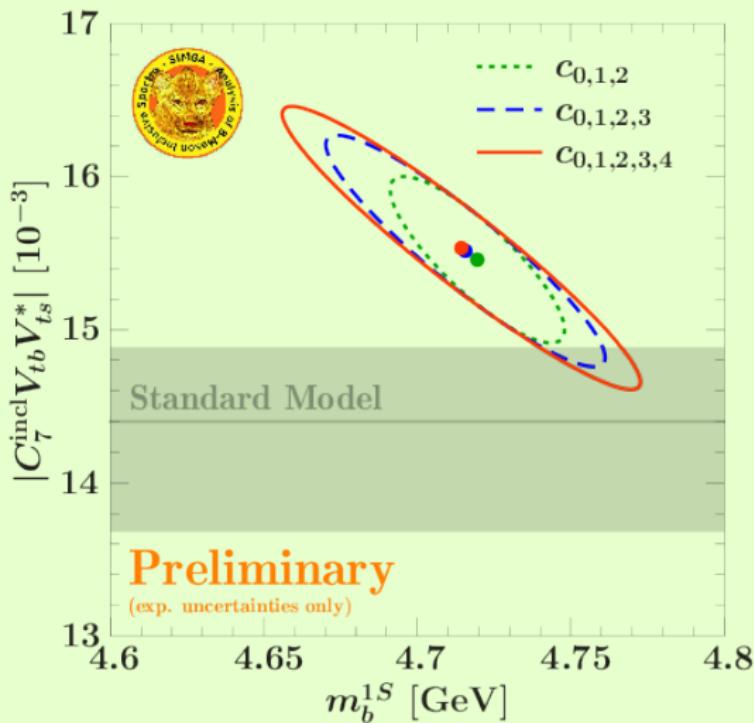


[Bernlochner et al., ICHEP]



SIMULTANEOUS FIT

- Large uncertainty on $\mathcal{B}(b \rightarrow s\gamma)$ comes from extrapolation to energy cutoff
- But one can fit the spectrum!
- Fit to spectrum and C_7^{eff}



[Bernlochner et al., ICHEP]

INCLUSIVE VS EXCLUSIVE

THEORY LIKES INCLUSIVE DECAYS “ $b \rightarrow s\gamma$ ”

- Can relate $\Gamma(B \rightarrow X_s \gamma)$ to $\Gamma(b \rightarrow s\gamma)$
- No hadronic form factors...

EXPERIMENT LIKES EXCLUSIVE DECAYS “ $B \rightarrow K^*\gamma$ ”

- Well defined final state
- Peaking mass distribution (and ΔE)
 - Lower background
- ✗ BF are rapidly theory-limited

OFTEN HADRONIC UNCERTAINTIES CANCEL IN RATIOS

- ✓ \mathcal{CP} asymmetries
- ✓ Isospin asymmetries
- ✓ Angular asymmetries
- More...

ASYMMETRIES IN $B \rightarrow K^*\gamma$

ISOSPIN ASYMMETRY:

$$\begin{aligned}\Delta_{+-} &\equiv \frac{\Gamma(B_d^0 \rightarrow K^{*0}\gamma) - \Gamma(B_u^+ \rightarrow K^{*+}\gamma)}{\Gamma(B_d^0 \rightarrow K^{*0}\gamma) + \Gamma(B_u^+ \rightarrow K^{*+}\gamma)} \stackrel{\text{SM}}{=} \mathcal{O}(0.05) \\ &= 0.062 \pm 0.027 \quad (\text{HFAG})\end{aligned}$$

- At the B factories it was long assumed that $\mathcal{B}(\Upsilon(4S) \rightarrow B_d^0 \bar{B}_d^0) = \mathcal{B}(\Upsilon(4S) \rightarrow B_u^+ B_u^-) = 0.5$ without even questioning it
- But it was found out that $\mathcal{B}(\Upsilon(4S) \rightarrow B_d^0 \bar{B}_d^0) = 0.484 \pm 0.006$
- The above result re-weights all measurements accordingly

ASYMMETRIES IN $B \rightarrow K^*\gamma$

ISOSPIN ASYMMETRY:

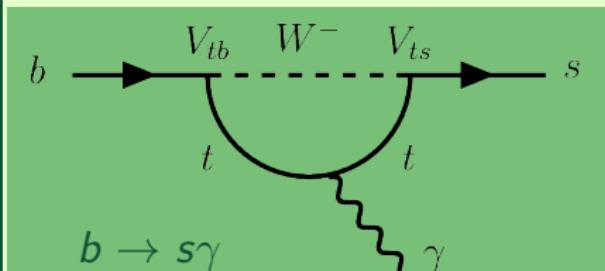
$$\begin{aligned}\Delta_{+-} &\equiv \frac{\Gamma(B_d^0 \rightarrow K^{*0}\gamma) - \Gamma(B_u^+ \rightarrow K^{*+}\gamma)}{\Gamma(B_d^0 \rightarrow K^{*0}\gamma) + \Gamma(B_u^+ \rightarrow K^{*+}\gamma)} \stackrel{\text{SM}}{=} \mathcal{O}(0.05) \\ &= 0.062 \pm 0.027 \quad (\text{HFAG})\end{aligned}$$

DIRECT CP-ASYMMETRY:

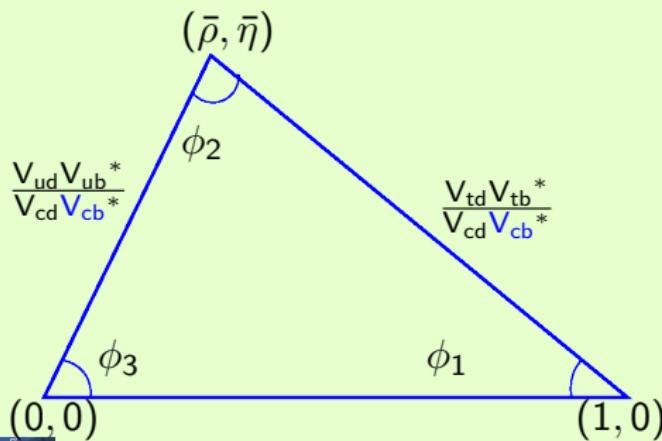
$$\begin{aligned}\mathcal{A}_{\text{CP}} &\equiv \frac{\Gamma(B_d^0 \rightarrow K^*\gamma) - \Gamma(\bar{B}_d^0 \rightarrow K^*\gamma)}{\Gamma(B_d^0 \rightarrow K^*\gamma) + \Gamma(\bar{B}_d^0 \rightarrow K^*\gamma)} \stackrel{\text{SM}}{=} \mathcal{O}(-0.1) \\ &= -0.003 \pm 0.017 \quad (\text{HFAG})\end{aligned}$$

→ nothing really exciting on that front . . .

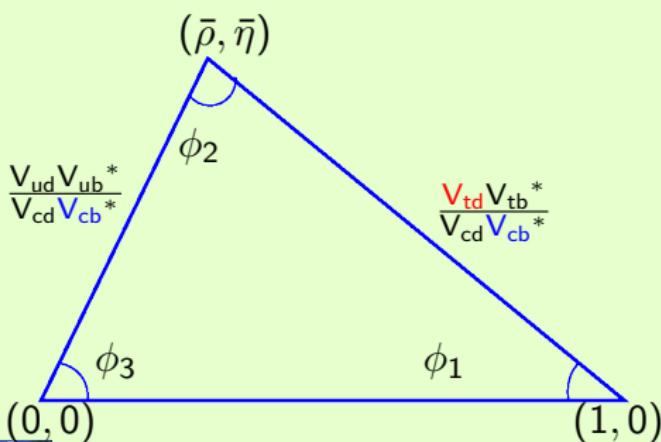
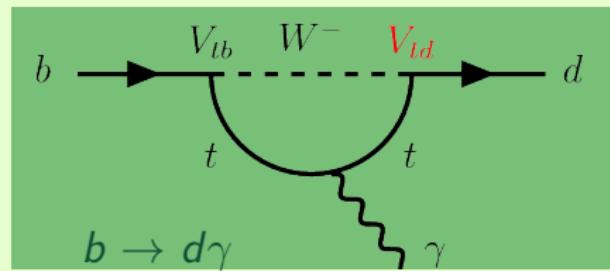
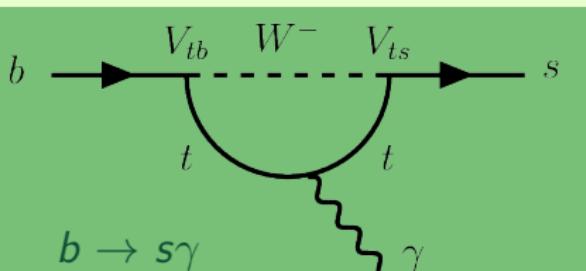
$b \rightarrow d\gamma$



- $b \rightarrow s\gamma \propto V_{ts} \sim V_{cb}$

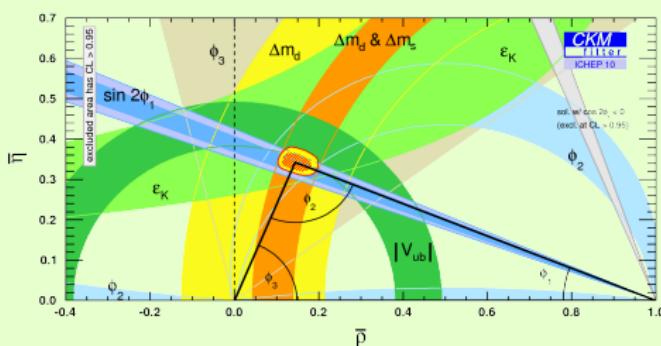
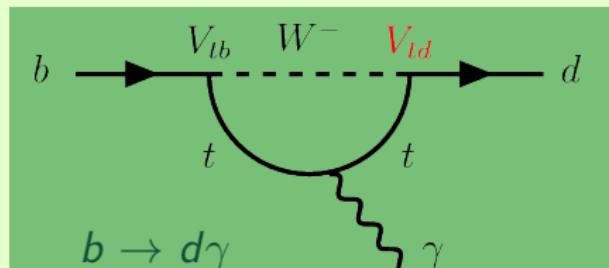
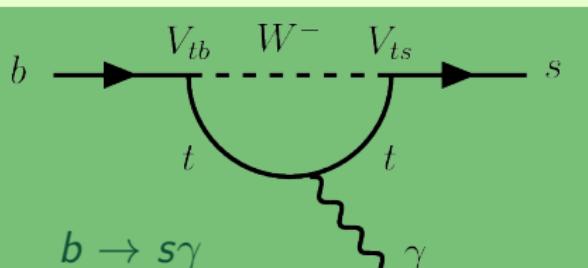


$$b \rightarrow d\gamma$$



- $b \rightarrow s\gamma \propto V_{ts} \sim V_{cb}$
- $b \rightarrow d\gamma \propto V_{td}$
- The ratio of $b \rightarrow d\gamma$ and $b \rightarrow s\gamma$ should extract $|V_{td}/V_{ts}|$
- Any significant discrepancy is new physics

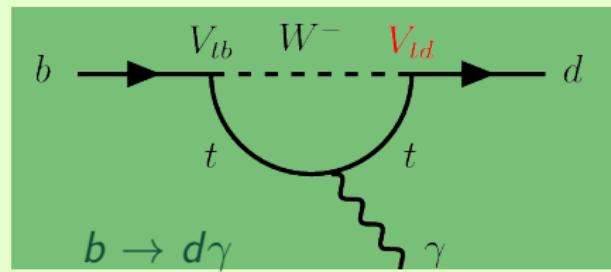
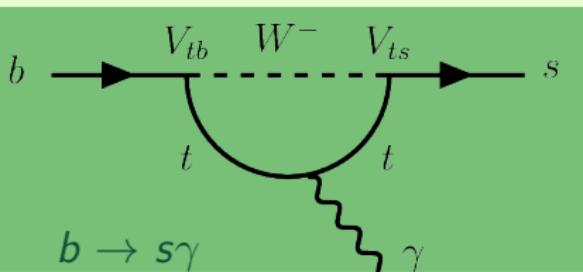
$$b \rightarrow d\gamma$$



- $b \rightarrow s\gamma \propto V_{ts} \sim V_{cb}$
- $b \rightarrow d\gamma \propto V_{td}$
- The ratio of $b \rightarrow d\gamma$ and $b \rightarrow s\gamma$ should extract $|V_{td}/V_{ts}|$
- Any significant discrepancy is new physics
- Expect 0.21 ± 0.01 from fits (mainly $\Delta m_s/\Delta m_d$)



$b \rightarrow d\gamma$



Theoretical SM prediction for the BF is

$$\frac{\mathcal{B}(B \rightarrow X_d\gamma)}{\mathcal{B}(B \rightarrow X_s\gamma)} = \left(3.82^{+0.11}_{-0.18} \Big| \frac{m_c}{m_b} \pm 0.42_{\text{CKM}} \pm 0.08_{\text{param}} \pm 0.15_{\text{scale}} \right)$$

at $E_\gamma > 1.6 \text{ GeV}$ [Hurt et al., NPB704:56-74, 2005]

Clearly dominated by CKM errors. No surprise, that's what you want to measure!

THE BELLE CONTROL ROOM

(Yes, that's really the whole thing!)

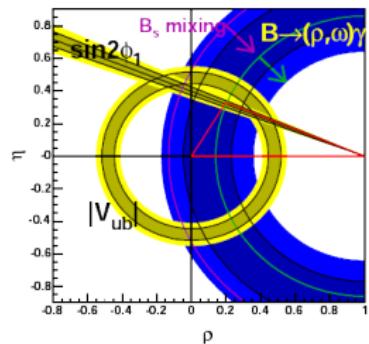
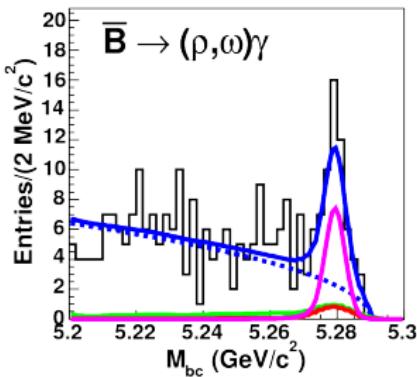
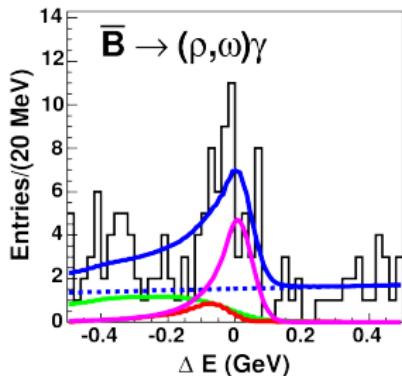
A long line →

uds event

Deb Mohapatra

Expert shifter seat

FIRST $B \rightarrow \rho\gamma$ AND $B \rightarrow \omega\gamma$ (2006)



- First observation by Belle, [D. Mohapatra, et al., PRL 96:221601, 2006]

$$\mathcal{B}(B \rightarrow (\rho, \omega)\gamma) = (1.32^{+0.34+0.10}_{-0.31-0.09}) \cdot 10^{-6} \quad (5.1\sigma)$$

- Gets $\left| \frac{V_{td}}{V_{ts}} \right| = 0.199^{+0.026}_{-0.025}$ (exp.) $^{+0.018}_{-0.015}$ (theo.)
- Matches best $(\bar{\rho}, \bar{\eta})$ fit

Almost theory-limited!



$B \rightarrow \rho\gamma$ AND $B \rightarrow \omega\gamma$

INCLUSIVE: Ideally you would like to measure the $\mathcal{B}(b \rightarrow d\gamma)/\mathcal{B}(b \rightarrow s\gamma)$ ratio inclusively to avoid hadronic uncertainties

- ✗ Fully inclusive won't work: you're not allowed to look at the X_s or X_d (Or you fully reconstruct one B and guarantee there's no K , K_S^0 , K_L^0 in the other...)
- ✗ Semi-inclusive buys you stats but not much more hadronic errors

EXCLUSIVE: You can be smarter!

- Don't mix-up ω and ρ .
- Don't mix-up B_u^+ and B_d^0 . B_u^+ measures $V_{tb}V_{td}^* \oplus V_{ub}V_{ud}^*$.

$$\frac{\mathcal{B}(B \rightarrow \rho\gamma)}{\mathcal{B}(B \rightarrow K^*\gamma)} = S_\rho \left| \frac{V_{td}}{V_{ts}} \right|^2 \frac{(m_B^2 - m_\rho^2)^3}{(m_B^2 - m_{K^*}^2)^3} \left(\frac{\overline{T}_1^\rho(0)}{\overline{T}_1^{K^*}(0)} \right)^2 [1 + \Delta R(\rho/K^*)]$$

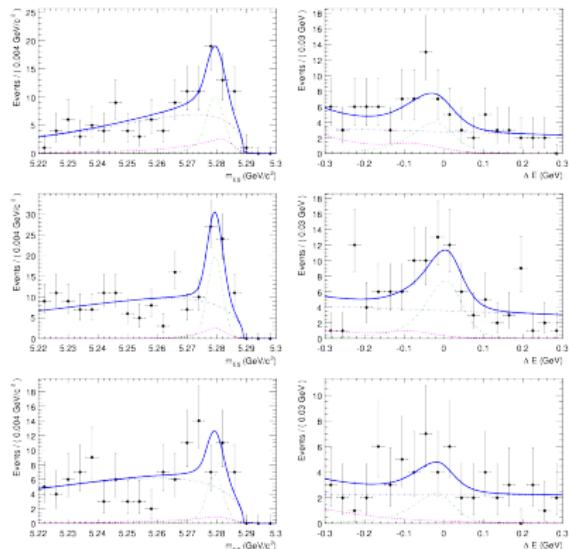
where $S_\rho = 1$ for ρ^0 and $\frac{1}{2}$ for ρ^+ , T_1 are transition form factors, and ΔR entails explicit $\mathcal{O}(\alpha_S)$ corrections [Ball et al., PRD.75.054004]

MORE V_{td}



BaBar exclusive [BaBar, PRD78.112001 (2008)]

$$\left| \frac{V_{td}}{V_{ts}} \right| = 0.233^{+0.025}_{-0.024} {}^{+0.022}_{-0.021}$$



MORE V_{td}

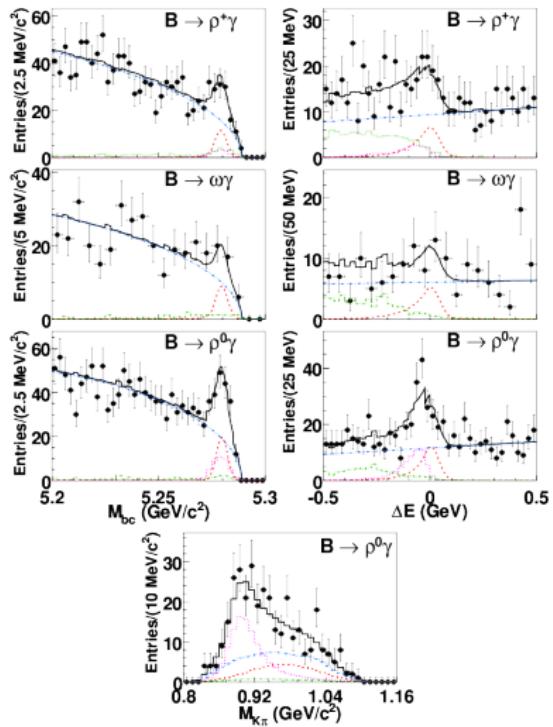


BaBar exclusive [BaBar, PRD78.112001 (2008)]

$$\left| \frac{V_{td}}{V_{ts}} \right| = 0.233^{+0.025}_{-0.024}{}^{+0.022}_{-0.021}$$

Belle exclusive [Taniguchi et al., PRL101.111801]

$$\left| \frac{V_{td}}{V_{ts}} \right| = 0.195^{+0.020}_{-0.019} \pm 0.015$$



MORE V_{td}



BaBar exclusive [BaBar, PRD78.112001 (2008)]

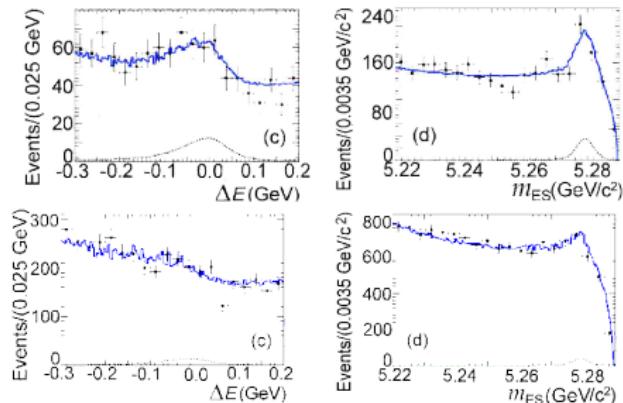
$$\left| \frac{V_{td}}{V_{ts}} \right| = 0.233^{+0.025}_{-0.024}{}^{+0.022}_{-0.021}$$

Belle exclusive [Taniguchi et al., PRL101.111801]

$$\left| \frac{V_{td}}{V_{ts}} \right| = 0.195^{+0.020}_{-0.019}{}^{\pm 0.015}$$

Babar semi-inclusive [PRL102.161803 (2008)]

$$\left| \frac{V_{td}}{V_{ts}} \right| = 0.177 \pm 0.043$$



$m_{X_d} < 1 \text{ GeV}$ (top) and $m_{X_d} > 1 \text{ GeV}$ (bottom)

All this is compatible with
 $\frac{V_{td}}{V_{ts}}$ from $\frac{\Delta m_s}{\Delta m_d}$

ASYMMETRIES



ISOSPIN ASYMMETRY:

$$\begin{aligned}\Delta_{+-} &\equiv \frac{\Gamma(B_d^0 \rightarrow \rho^0 \gamma) - \Gamma(B_u^+ \rightarrow \rho^+ \gamma)}{\Gamma(B_d^0 \rightarrow \rho^0 \gamma) + \Gamma(B_u^+ \rightarrow \rho^+ \gamma)} \stackrel{\text{SM}}{=} \mathcal{O}(0.1) \\ &= -0.46^{+0.17}_{-0.16} \quad (\text{HFAG})\end{aligned}$$

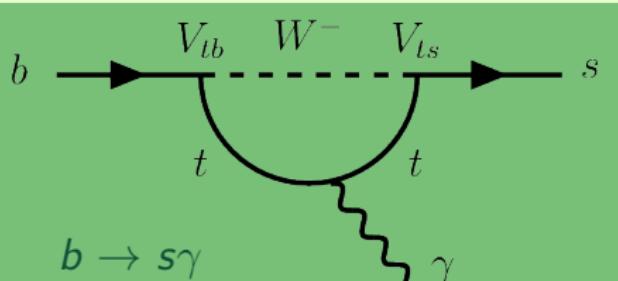
DIRECT CP-ASYMMETRY:

$$\begin{aligned}\mathcal{A}_{\text{CP}} &\equiv \frac{\Gamma(B_d^0 \rightarrow \rho \gamma) - \Gamma(\bar{B}_d^0 \rightarrow \rho \gamma)}{\Gamma(B_d^0 \rightarrow \rho \gamma) + \Gamma(\bar{B}_d^0 \rightarrow \rho \gamma)} \stackrel{\text{SM}}{=} \mathcal{O}(-0.1) \\ &= -0.11 \pm 0.31 \pm 0.09 \quad (\rho^+) \quad \text{Belle} \\ &= -0.44 \pm 0.49 \pm 0.14 \quad (\rho^0) \quad \text{Belle}\end{aligned}$$

→ much more interesting than $B \rightarrow K^* \gamma$!



$b \rightarrow s\gamma$ POLARISATION



The photon polarisation is not well measured.

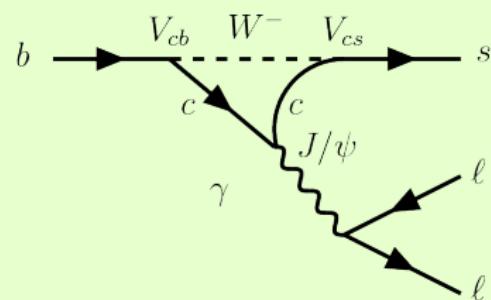
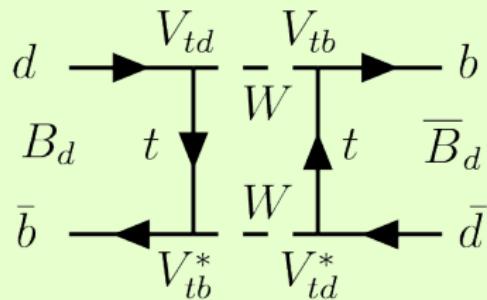
- Naively $r = \frac{C'_{7\gamma}}{C_{7\gamma}}$ SM $\simeq \frac{m_s}{m_b}$
- Gluons contribute $0.5 \pm 1.0\%$
[Ball & Zwicky PLB642:478,2006]
- Right-handed operators could contribute

Ways to measure:

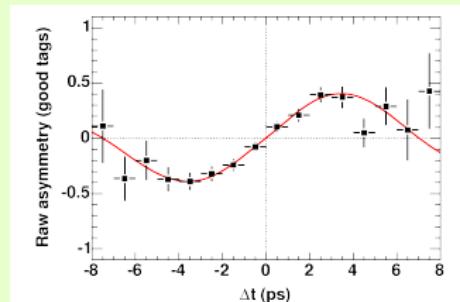
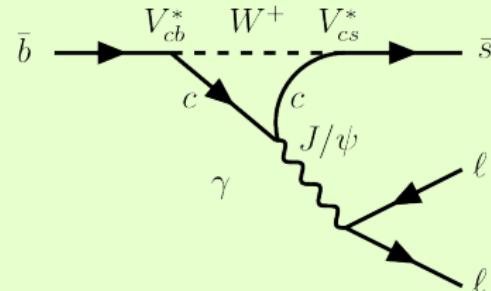
- ✓ Mixing-induced CP violation
[Atwood et al., PRL79:185, 1997]
- ✓ Λ_b baryons
[Hiller & Kagan, PRD65:074038, 2002]
- $B \rightarrow \gamma K^{**}(K\pi\pi)$
[Gronau & Pirjol, PRD66 054008, 2002]
[Gronau et al., PRL88:051802, 2002]
- ✓ Virtual photons ($b \rightarrow \ell\ell s$)
[Melikhov et al., PLB442:381-389,1998]
- Converted photons
[Grossman et al., JHEP06:29,2000]

MIXING-INDUCED CP VIOLATION

Remember $B_d^0 \rightarrow J/\psi K_S^0$:

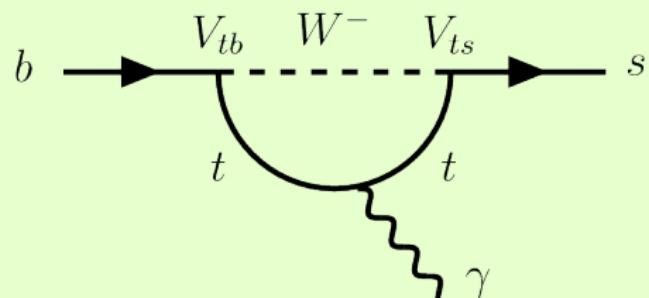
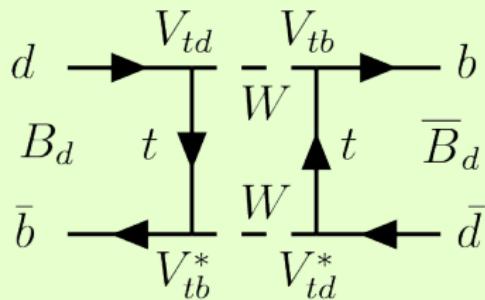


Interferes with

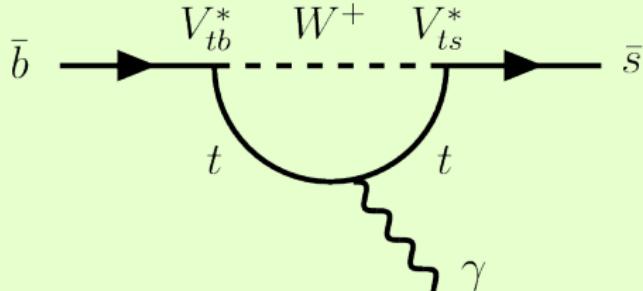


MIXING-INDUCED CP VIOLATION

What about $B_d^0 \rightarrow \gamma K_S^0 \pi^0$?



Interferes with right handed component of



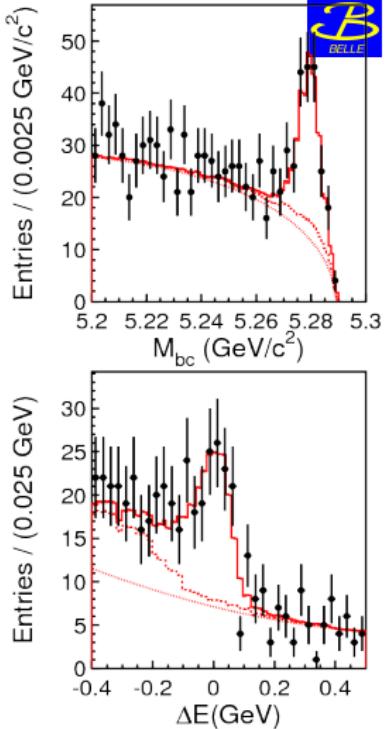
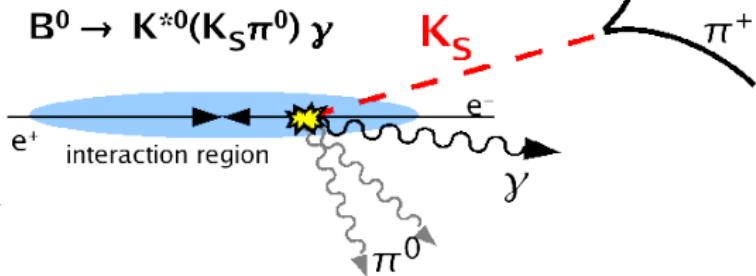
CP-VIOLATION IN $B \rightarrow K^* \gamma$



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

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

Beam intersection method



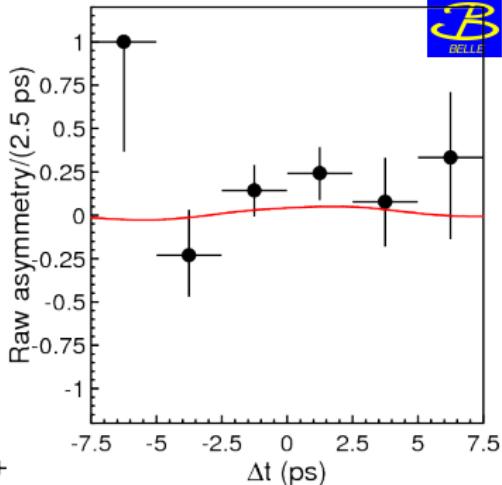
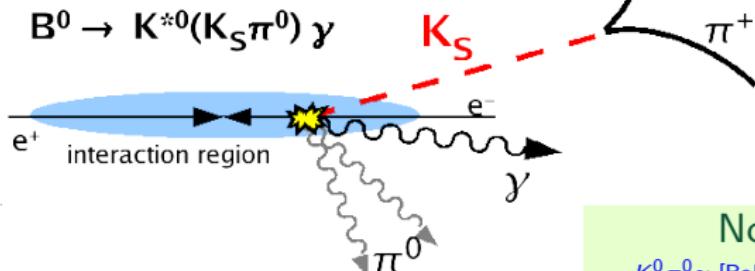
CP-VIOLATION IN $B \rightarrow K^*\gamma$



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- ② Get rid of $B_d^0 \rightarrow K^*\pi^0$ background
- ③ Measure time by intersecting the K_S^0 with the beam line

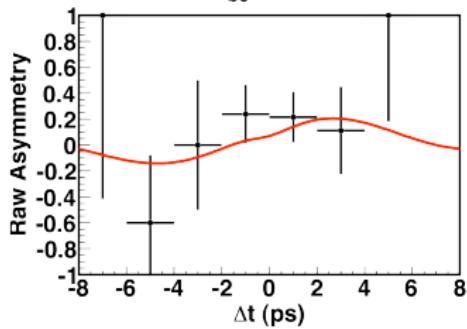
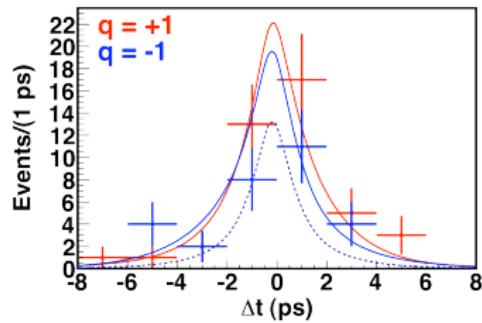
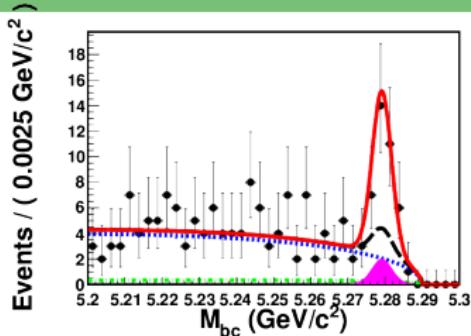
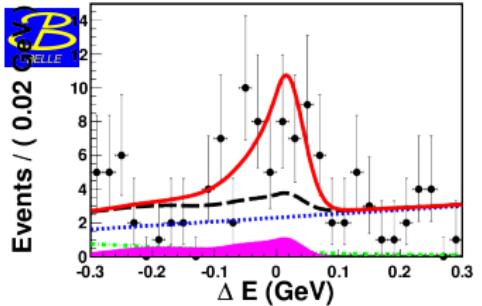
Beam intersection method



No oscillation observed

$K_S^0\pi^0\gamma$ [BaBar (Aubert et al.), PRD72 (2005) 051103],
 $K_S^0\pi^0\gamma$ [Belle (Abe et al.), PRD74:111104,2006],

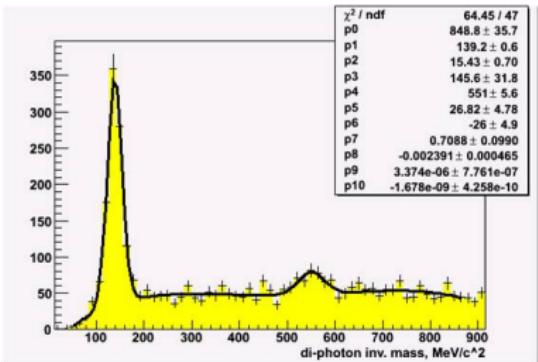
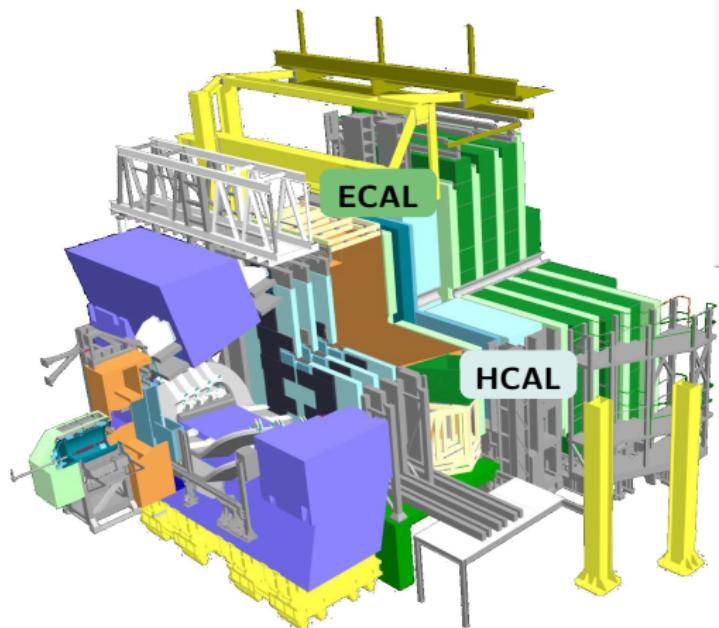
$B_d^0 \rightarrow K_S^0 \phi \gamma$, AND FRIENDS



$\eta K^0 \gamma$ [BaBar (Aubert et al.), PRD79:011102, 2009],
 $\rho \gamma$ [Belle (Ushiroda et al.), PRL100:021602, 2008],
 $K_S^0 \rho \gamma$ [Belle (Ushiroda et al.), PRL101:251601, 2008],
 $K_S^0 \phi \gamma$ [Belle, ICHEP ...]



WHAT ABOUT LHCb?



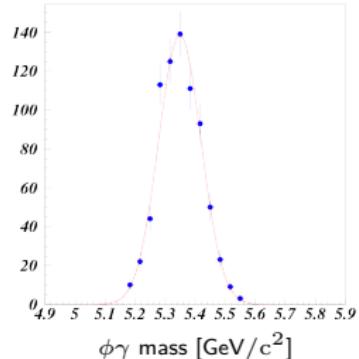
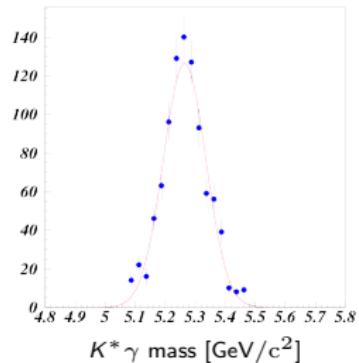
ECAL: For γ and π^0 detection, and e identification

- Layers of lead and plastic scintillators

PRESHOWER:
Lead/scintillator

$B_d^0 \rightarrow K^*\gamma$ AND $B_s^0 \rightarrow \phi\gamma$ YIELDS FOR 2 FB $^{-1}$

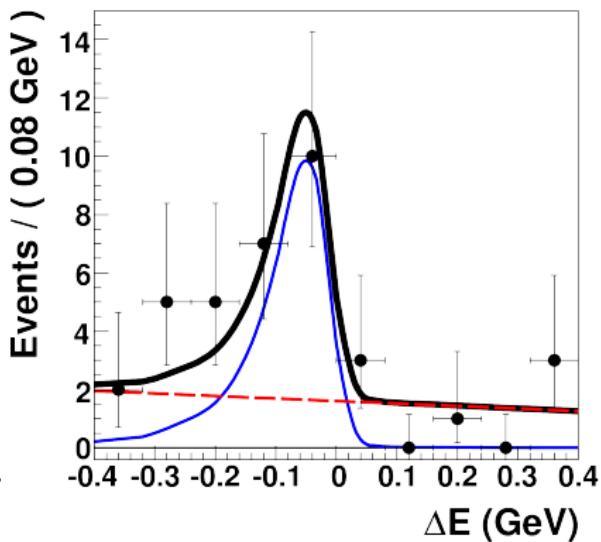
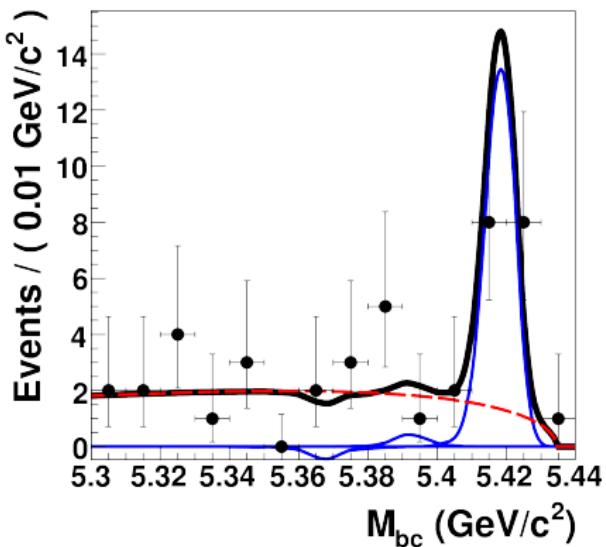
	$B_d^0 \rightarrow K^*\gamma$	$B_s^0 \rightarrow \phi\gamma$
Visible BR	$2.9 \cdot 10^{-5}$	$2.2 \cdot 10^{-5}$
η_{rec}	5.6%	5.4%
η_{sel}	13.3%	11.7%
η_{trg}	46%	44%
η_{tot}	0.34%	0.28%
Signal Yield	73 000	11 000
B/S	0.59 ± 0.26	< 0.55



The B mass resolution is 70 MeV.



$B_s^0 \rightarrow \phi\gamma$ HAS BEEN OBSERVED!



$$\mathcal{B} = (57^{+18+12}_{-12-11}) \cdot 10^{-6}$$

[Belle (Wicht et al.), PRL 100:121801,2008]



$$B_s^0 \rightarrow \phi\gamma$$



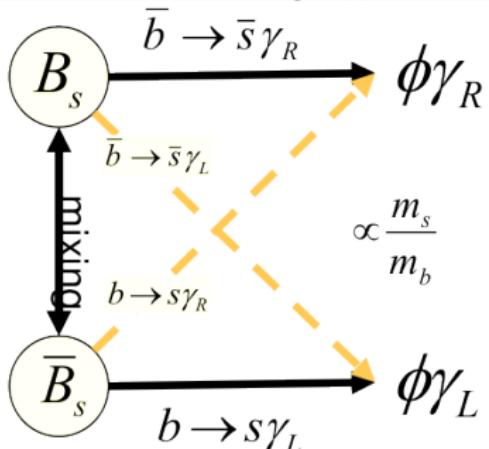
In SM mainly $B_s^0 \rightarrow \phi\gamma_R$ and $\bar{B}_s^0 \rightarrow \phi\gamma_L$. Mixing only if wrong polarisation.

\mathcal{A}^{mix} tiny

$\mathcal{A}^{\text{dir}} = 0$ in MFV

$\mathcal{A}^{\Delta\Gamma} \propto r$

$$\mathcal{A}_s(t) = \frac{\Gamma_{\bar{B}_s^0 \rightarrow \phi\gamma} - \Gamma_{B_s^0 \rightarrow \phi\gamma}}{\Gamma_{\bar{B}_s^0 \rightarrow \phi\gamma} + \Gamma_{B_s^0 \rightarrow \phi\gamma}} = \frac{\mathcal{A}^{\text{dir}} \cos \Delta m_s t + \mathcal{A}^{\text{mix}} \sin \Delta m_s t}{\cosh \frac{1}{2}\Delta\Gamma t - \mathcal{A}^{\Delta\Gamma} \sinh \frac{1}{2}\Delta\Gamma t}$$



Tagged approach (measure all \mathcal{A}):

- 12% on \mathcal{A}^{mix} (2 fb^{-1})
- 23% error on $\mathcal{A}^{\Delta\Gamma}$ (2 fb^{-1})

Untagged approach (only $\mathcal{A}^{\Delta\Gamma} \propto r$):

- 19% error (2 fb^{-1})
- 9% with 10 fb^{-1}

$\Lambda_b \rightarrow \Lambda\gamma$ POLARISATION

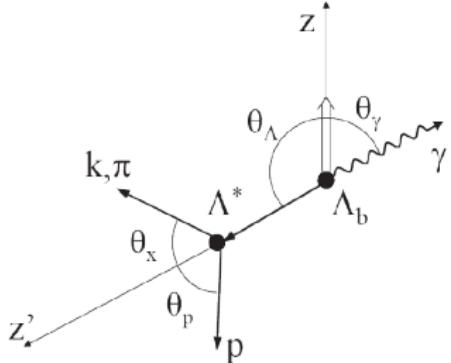


$$r = \frac{C'_{7\gamma}}{C_{7\gamma}} \rightarrow \alpha_\gamma = \frac{1 - |r|^2}{1 + |r|^2}$$

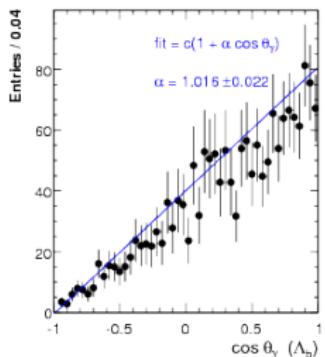
$$\frac{d\Gamma}{d \cos \theta_\gamma} \propto 1 - \alpha_\gamma P_{\Lambda_b} \cos \theta_\gamma$$

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

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



- Λ_b is polarised at LHC. Assume 20%.
 - Measure it at 1% with $\Lambda_b \rightarrow J/\psi \Lambda$.
[E. Leader] [Hřivnáč 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]

$\Lambda_b \rightarrow \Lambda\gamma$ POLARISATION

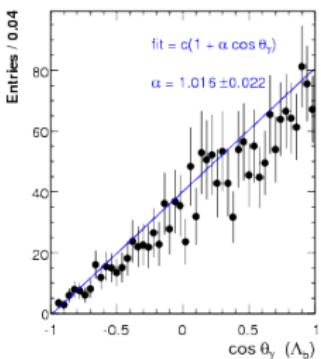
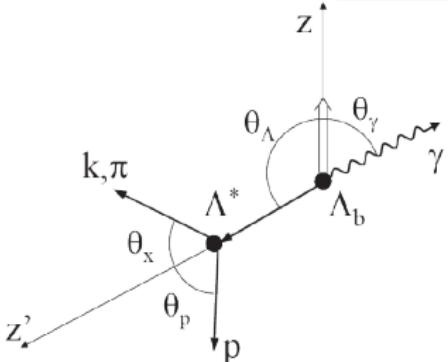


$$r = \frac{C'_{7\gamma}}{C_{7\gamma}} \rightarrow \alpha_\gamma = \frac{1 - |r|^2}{1 + |r|^2}$$

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

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

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



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

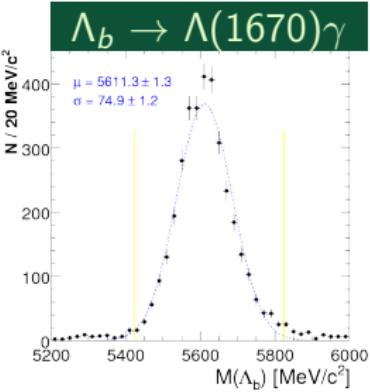
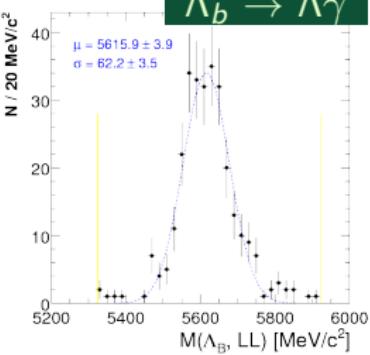
$\Lambda_b \rightarrow \Lambda\gamma$ YIELDS



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

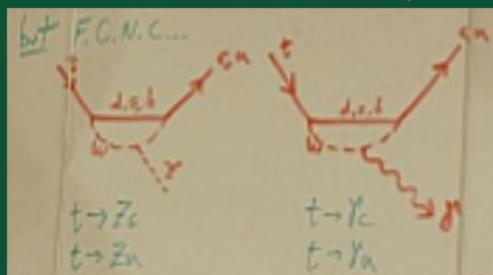


OTHER RADIATIVE DECAYS

$b \rightarrow s\gamma$ AND $b \rightarrow d\gamma$ are not the only possibility

$c \rightarrow u\gamma$ could exist: $\mathcal{B}(D_u^0 \rightarrow \rho\gamma) < 1.4 \cdot 10^{-3}$ (same for ω)

- c quark is lighter than b . That makes theoretical predictions a bit more complicated.
- ($D_u^0 \rightarrow K^*\gamma$ is seen, but is not an FCNC)



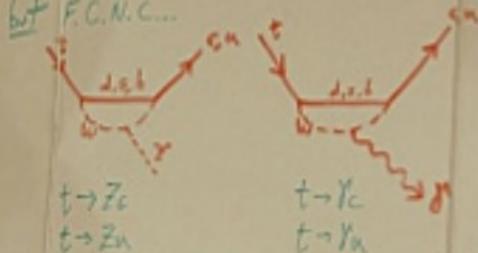
$t \rightarrow c\gamma$ AND $u\gamma$:

- $\mathcal{B} < 5.9 \cdot 10^{-3}$, from HERA single top production.
- CDF measures $\mathcal{B} < 0.032$ by looking for the decay directly

OTHER RADIATIVE DECAYS

$$t \rightarrow W^+ b \quad BR(t \rightarrow W b) = \frac{\Gamma(t \rightarrow W b)}{\Gamma(t \rightarrow W g)} \\ = \frac{|V_{cb}|^2}{|V_{cb}|^2 + |V_{cb}|^2 + |V_{cb}|^2} \\ \approx \frac{(0.9945)^2}{(0.0079)^2 + (0.04)^2 + (0.7745)^2} \\ = 99.8\%.$$

but F.C.N.C...

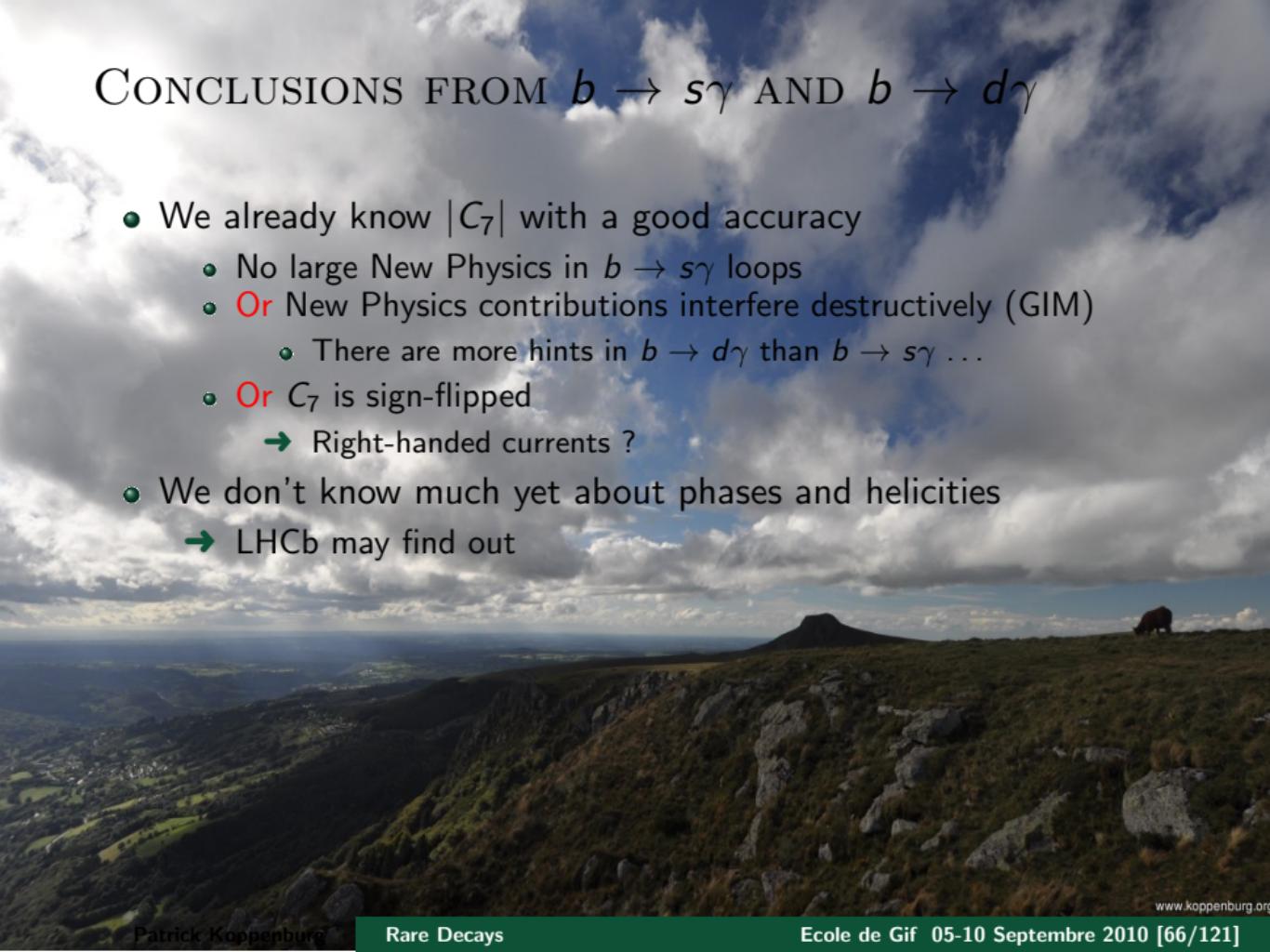


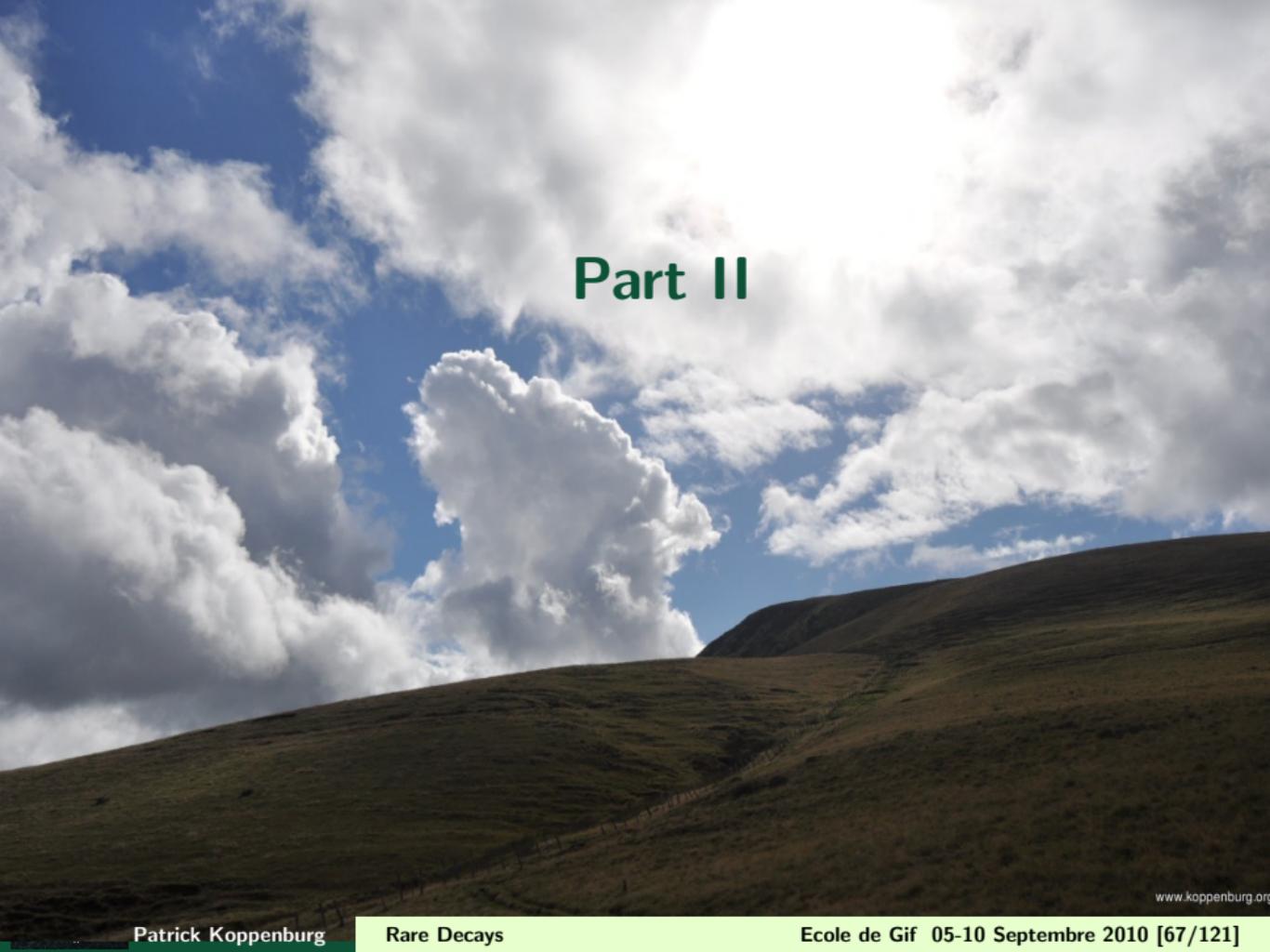
$$U_{\text{CKM}}^T = \begin{pmatrix} C_{11} & C_{12} & \dots \\ -S_{12} & C_{13} & -C_{11} S_{13} S_{13} e^{i\delta} \\ \dots & \dots & \dots \end{pmatrix}$$



CONCLUSIONS FROM $b \rightarrow s\gamma$ AND $b \rightarrow d\gamma$

- We already know $|C_7|$ with a good accuracy
 - No large New Physics in $b \rightarrow s\gamma$ loops
 - Or New Physics contributions interfere destructively (GIM)
 - There are more hints in $b \rightarrow d\gamma$ than $b \rightarrow s\gamma$...
 - Or C_7 is sign-flipped
 - Right-handed currents ?
- We don't know much yet about phases and helicities
 - LHCb may find out



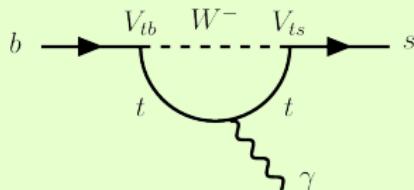


Part II

$b \rightarrow ll s$

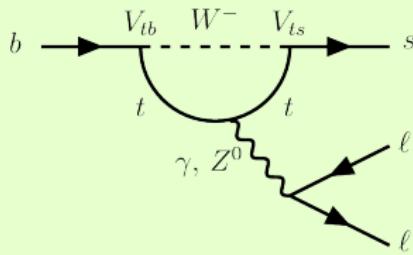


$b \rightarrow \ell\ell s$



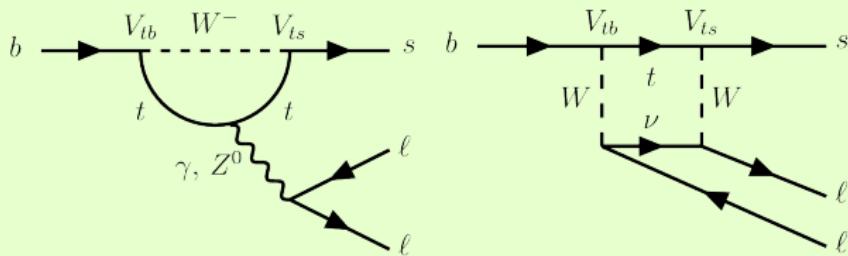
- Start with $b \rightarrow s\gamma$

$b \rightarrow \ell\ell s$



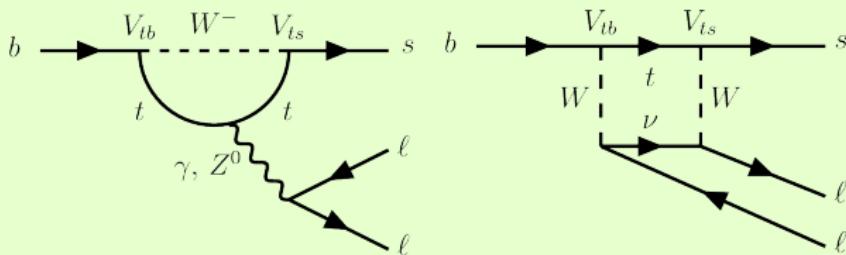
- Start with $b \rightarrow s\gamma$, pay a factor α_{EM}
→ Decay the γ into 2 leptons

$b \rightarrow \ell\ell s$

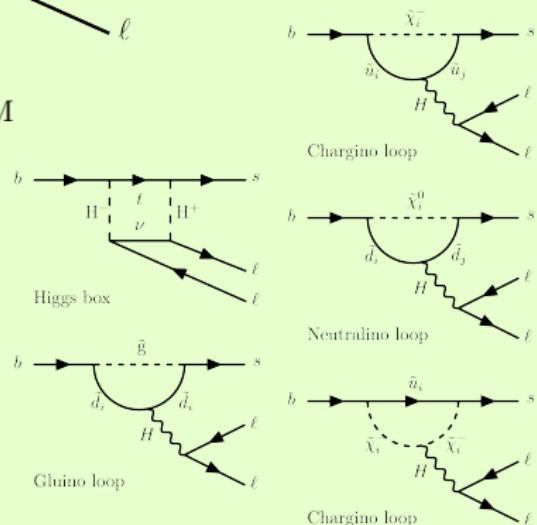


- Start with $b \rightarrow s\gamma$, pay a factor α_{EM}
 - Decay the γ into 2 leptons
 - Add an interfering box diagram
 - $b \rightarrow \ell\ell s$, very rare in the SM
- $\mathcal{B}(B \rightarrow \ell\ell K^*) = (3.3 \pm 1.0) \cdot 10^{-6}$

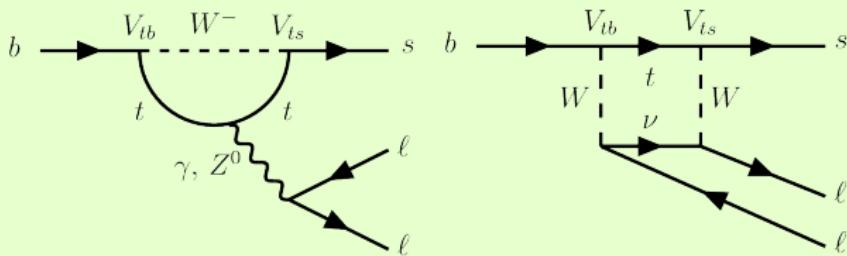
$b \rightarrow \ell\ell s$



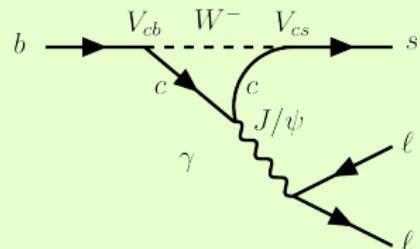
- Start with $b \rightarrow s\gamma$, pay a factor α_{EM}
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- $\rightarrow b \rightarrow \ell\ell s$, very rare in the SM
 $\mathcal{B}(B \rightarrow \ell\ell K^*) = (3.3 \pm 1.0) \cdot 10^{-6}$
- Sensitive to Supersymmetry, Any 2HDM, Fourth generation, Extra dimensions, Axions ...
- Ideal place to look for new physics



$$b \rightarrow \ell\ell s$$



- Start with $b \rightarrow s\gamma$, pay a factor α_{EM}
 - Decay the γ into 2 leptons
 - Add an interfering box diagram
 - $b \rightarrow \ell\ell s$, very rare in the SM
 $\mathcal{B}(B \rightarrow \ell\ell K^*) = (3.3 \pm 1.0) \cdot 10^{-6}$
- ✗ But beware of LD effects:
 - Tree $b \rightarrow c\bar{c}s$, $(c\bar{c}) \rightarrow \ell\ell$
 - ✓ Can be removed by mass cuts
 - ✗ ✓ Interferes elsewhere

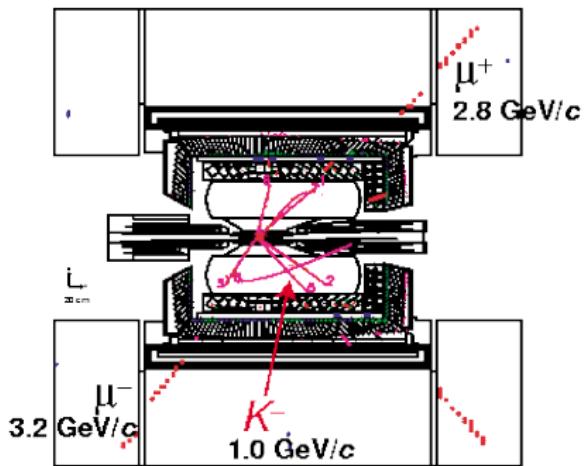
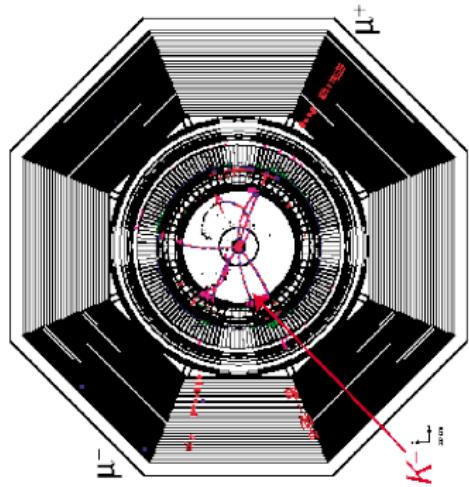


FIRST OBSERVATION



$B^+ \rightarrow K^+ \mu^+ \mu^-$ Event

lepton
photon 01

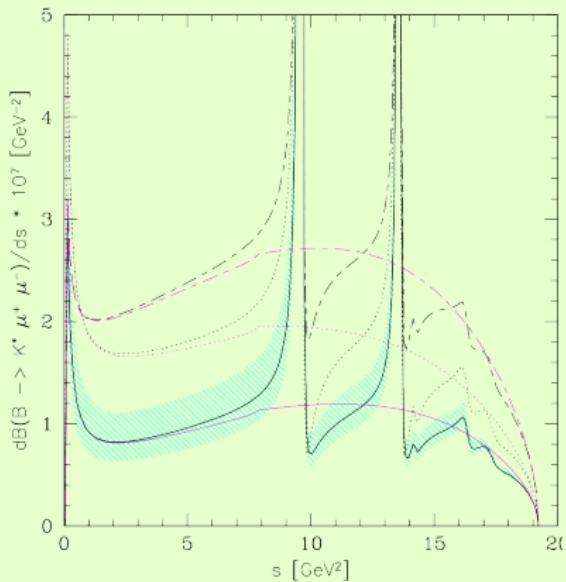


Lepton Photon 01, 2001 July 23, Roma

H.Tajima, Lepton-Photon 2001



$b \rightarrow \ell\ell s$ q^2 SPECTRUM

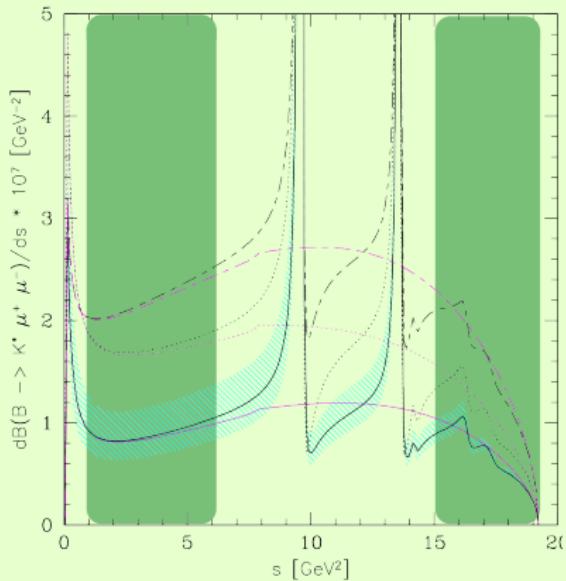


$$s \equiv q^2 \equiv \hat{s} m_b^2 \equiv \text{mass}^2 \text{ of } \ell\ell \text{ system}$$

Full is SM with and **without** LD.
Dashed is some susy model. Hashed
are QCD errors.

- ➊ Photon pole (" $b \rightarrow s\gamma, \gamma \rightarrow \ell\ell$ ")
- ➋ Non-resonant region ($1 < q^2 < 6 \text{ GeV}^2$)
- ➌ $c\bar{c}$ resonances (" $b \rightarrow J/\psi s$ ")
- ➍ Interference of $c\bar{c}$ resonances with non resonant contribution

$b \rightarrow \ell\ell s$ q^2 SPECTRUM

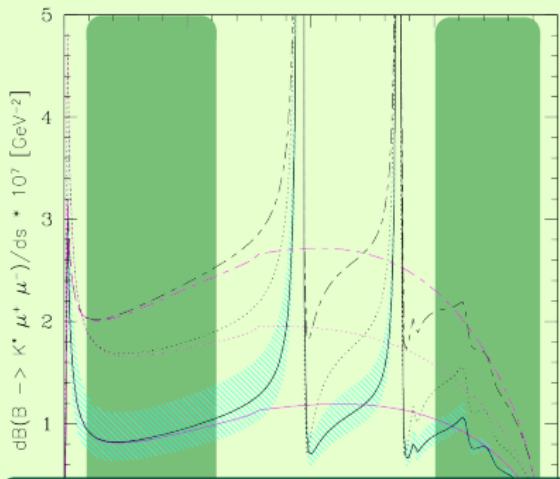


$s \equiv q^2 \equiv \hat{s}m_b^2 \equiv \text{mass}^2$
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- ➊ Photon pole (" $b \rightarrow s\gamma, \gamma \rightarrow \ell\ell$ ")
- ➋ Non-resonant region
 $(1 < q^2 < 6 \text{ GeV}^2)$
- ➌ $c\bar{c}$ resonances (" $b \rightarrow J/\psi s$ ")
- ➍ Interference of $c\bar{c}$ resonances
with non resonant contribution
 - For many measurements the "safe" region is
 $1 < q^2 < 6 \text{ GeV}^2$ (ask Tobias)
 - But the interferences are most interesting at $q^2 > 15 \text{ GeV}^2$
(ask Zoltan)

$b \rightarrow \ell\ell s$ q^2 SPECTRUM



Full is SM with and **without** LD.
Dashed is some susy model. Hashed
are QCD errors.

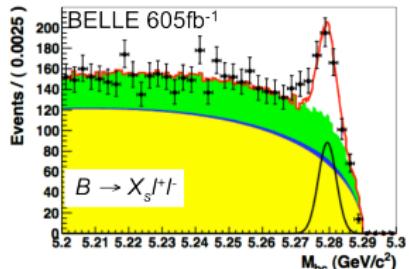
Sensitive to 3 Wilson coefficients, including sign of $C_{7\gamma}^{\text{eff}}$

$$\frac{\frac{d\Gamma(b \rightarrow s\mu^+\mu^-)}{d\hat{s}}}{\Gamma(b \rightarrow ce\bar{\nu})} = \frac{\alpha^2}{4\pi^2} \left| \frac{V_{ts}}{V_{cb}} \right|^2 \frac{(1-\hat{s})^2}{f(z)\kappa(z)} \left[(1+2\hat{s}) \left(|C_{9V}^{\text{eff}}|^2 + |C_{10A}|^2 \right) \right. \\ \left. + 4 \left(1 + \frac{2}{\hat{s}} \right) |C_{7\gamma}^{\text{eff}}|^2 + 12 \text{Re}(C_{7\gamma}^{\text{eff}} C_{9V}^{\text{eff}}) \right]$$

INCLUSIVE VS EXCLUSIVE

The same as for $b \rightarrow s\gamma$ applies

- Theory likes inclusive decays ($b \rightarrow \ell\ell s$)
 - Experiment likes exclusive decays ($B \rightarrow \ell\ell K^*$)
- ✗ But here, inclusive *cannot* be done
- How to tell $b \rightarrow \ell\ell s$ from $b \rightarrow \ell\nu c(\ell\nu s)$ without looking at the s ?
 - or give me a B factory at $\mathcal{L} = 10^{36} \text{ cm}^{-2}\text{s}^{-1}$
 - I don't count semi-inclusive as inclusive.
 - Belle does $B \rightarrow (K^+, K_S^0)n_{\pm}\pi^{\pm}n_0\pi^0\ell^+\ell^-$ with $n_{\pm} \leq 4$, $n_0 \leq 1$, $n_{\pm} + n_0 \leq 4$
→ 36 modes for 80% of BF (they say)



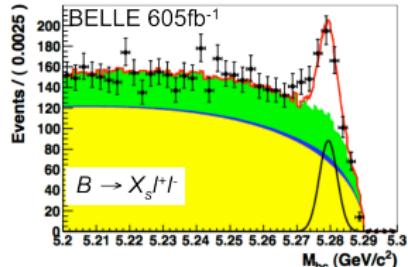
[Belle, ICHEP]



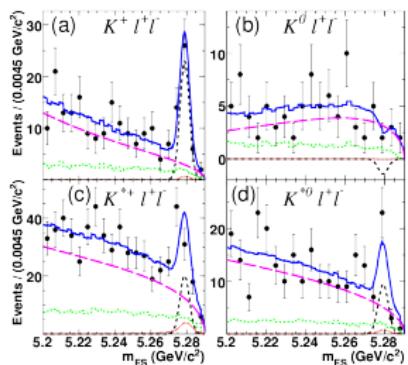
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 - How to tell $b \rightarrow \ell\ell s$ from $b \rightarrow \ell\nu c(\ell\nu s)$ without looking at the s ?
 - or give me a B factory at $\mathcal{L} = 10^{36} \text{ cm}^{-2}\text{s}^{-1}$
 - I don't count semi-inclusive as inclusive.
- ✓ But exclusive modes are **much** more interesting in $b \rightarrow \ell\ell s$ than in $b \rightarrow s\gamma$
- ➔ In particular $B \rightarrow \ell\ell K^*$



[Belle, ICHEP]



[BaBar, PRL 102:091803, 2009]

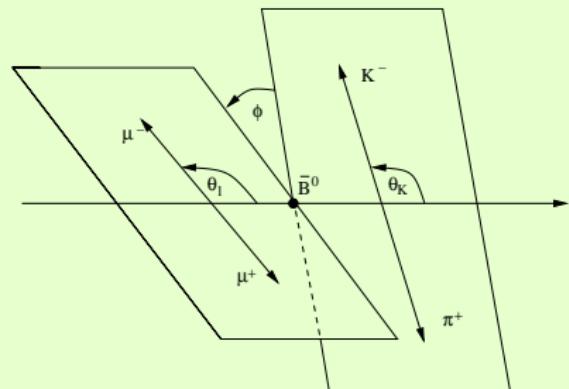
ANGULAR DISTRIBUTIONS & A_{FB}

A lot of information in the full θ_ℓ , θ_K and ϕ distributions

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

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

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



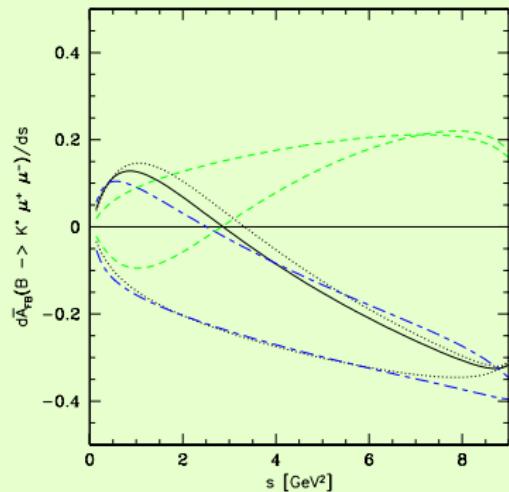
→ Many observables depending on q^2

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

ANGULAR DISTRIBUTIONS & A_{FB}

A lot of information in the full θ_ℓ , θ_K and ϕ distributions

$$\begin{aligned}\frac{d\Gamma'}{d\theta_I} &= \Gamma' \left(\frac{3}{4} F_L \sin^2 \theta_I + A_{FB} \cos \theta_I \right. \\ &\quad \left. + \frac{3}{8} (1 - F_L) (1 + \cos^2 \theta_I) \right) \\ A_{FB} &= \frac{\left(\int_0^1 - \int_{-1}^0 \right) d \cos \theta_I \frac{d^2 \Gamma}{dq^2 d \cos \theta_I}}{\int_{-1}^1 d \cos \theta_I \frac{d^2 \Gamma}{dq^2 d \cos \theta_I}} \\ &= \frac{3 \operatorname{Re}(A_{||L} A_{\perp L}^*) - \operatorname{Re}(A_{||R} A_{\perp R}^*)}{2 |A_0|^2 + |A_{||}|^2 + |A_{\perp}|^2}\end{aligned}$$



In terms of the 6 spin amplitudes of the K^*

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



FORWARD-BACKWARD ASYMMETRY

$$\frac{dA_{FB}}{d\hat{s}} = \frac{G_F^2 \alpha_{EM}^2 m_B^2}{2^8 \pi^5} |V_{ts}^* V_{tb}|^2 \hat{s} \lambda \left(1 - 4 \frac{\hat{m}_\ell^2}{\hat{s}} \right) \times \\ C_{10A} \left(\mathcal{R}(C_{9V}^{\text{eff}}) VA_1 + \frac{\hat{m}_b}{\hat{s}} C_{7\gamma}^{\text{eff}} [VT_2(1 - \hat{m}_{K^*}) + A_1 T_1(1 + \hat{m}_{K^*})] \right),$$

- Depends on **three** Wilson coefficients
 - C_{10A} (axial-vector) gives an overall scale
→ no A_{FB} if this operator is absent
 - C_{9V}^{eff} (vector)
 - $C_{7\gamma}^{\text{eff}}$ the “ $b \rightarrow s\gamma$ coefficient”. Here we have access to its sign
- Depends on some form factors V, A_1, T_1, T_2 , but they can be estimated in LEET approximation:

$$\frac{T_2}{A_1} = \frac{1 + \hat{m}_{K^*}}{1 + \hat{m}_{K^*} - \hat{s}} \left(1 - \frac{\hat{s}}{1 - \hat{m}_{K^*}} \right)$$

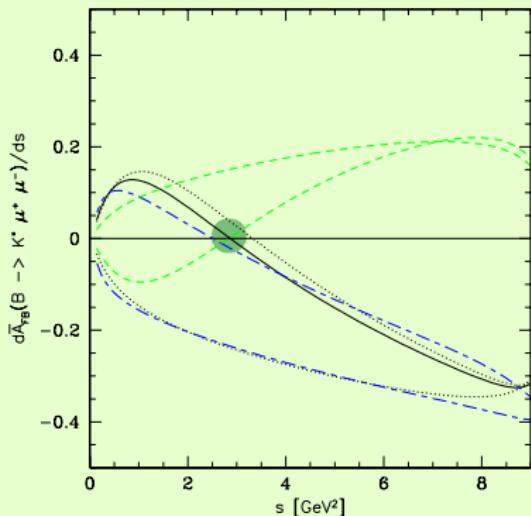
$$\frac{T_1}{V} = \frac{1}{1 + \hat{m}_{K^*}}$$

FORWARD-BACKWARD ASYMMETRY

$$\begin{aligned} \frac{dA_{FB}}{d\hat{s}} &= \frac{G_F^2 \alpha_{EM}^2 m_B^2}{2^8 \pi^5} |V_{ts}^* V_{tb}|^2 \hat{s} \lambda \left(1 - 4 \frac{\hat{m}_\ell^2}{\hat{s}} \right) \times \\ &\quad C_{10A} \left(\mathcal{R}(C_{9V}^{\text{eff}}) V A_1 + \frac{\hat{m}_b}{\hat{s}} C_{7\gamma}^{\text{eff}} [V T_2 (1 - \hat{m}_{K^*}) + A_1 T_1 (1 + \hat{m}_{K^*})] \right), \end{aligned}$$

Solving for s_0 where $\frac{dA_{FB}}{d\hat{s}} = 0$

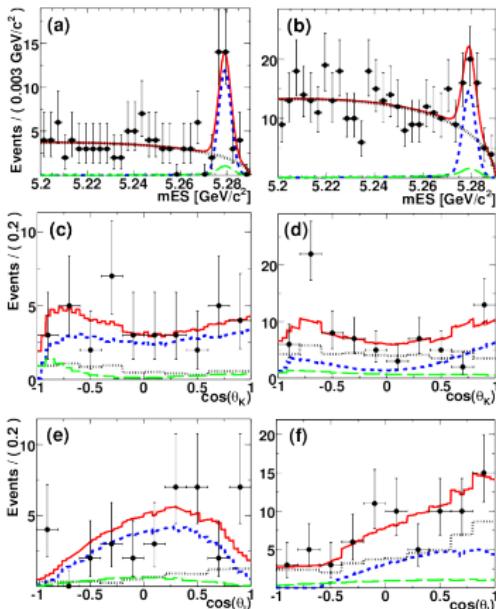
$$\begin{aligned} s_0 &\simeq \frac{m_B^2 + m_{K^*}^2 \left(\frac{2C_{7\gamma}^{\text{eff}}}{\mathcal{R}(C_{9V}^{\text{eff}})} - 1 \right)}{1 - \frac{2C_{7\gamma}^{\text{eff}}}{\mathcal{R}(C_{9V}^{\text{eff}})}} \\ &\Rightarrow -2 \frac{m_b}{s_0} \simeq \frac{2C_{7\gamma}^{\text{eff}}}{\mathcal{R}(C_{9V}^{\text{eff}})} \end{aligned}$$



The zero point is a measure of Wilson coefficients ($\text{sign}(C_{7\gamma}^{\text{eff}})\mathcal{R}(C_{9V}^{\text{eff}})$)

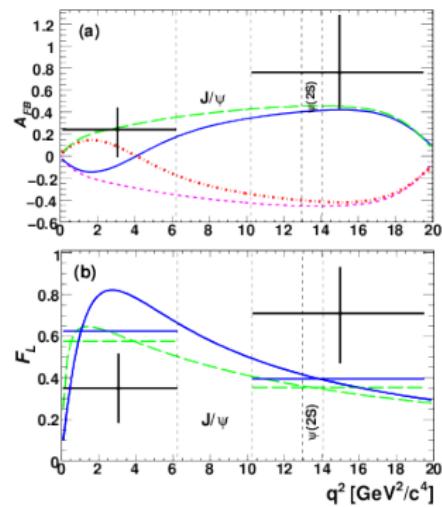


$B \rightarrow \ell\ell K^*$ AT BABAR

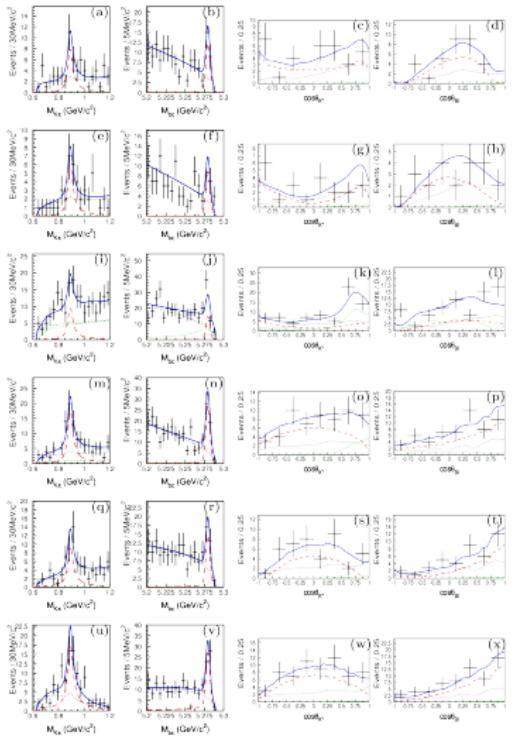


left: $q^6 < 6 \text{ GeV}^2$, right: $q^2 > 10 \text{ GeV}^2$, signal in blue

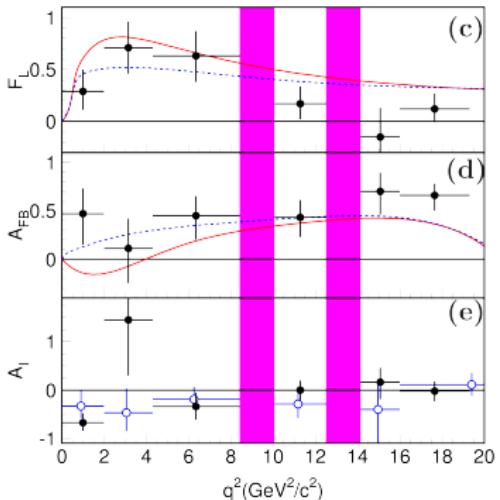
- Babar sees 60 $B \rightarrow \ell\ell K^*$ events in $384 \cdot 10^6 B\bar{B}$ [PRD79:031102,2009]
- That's good enough for peaks
- Asymmetries only in 2 bins



$B \rightarrow \ell\ell K^*$ AT BELLE



- Babar has 230 $B \rightarrow \ell\ell K^*$ events in $657 \cdot 10^6 B\bar{B}$ [PRL103:171801,2009]
- Allows 6 bins
- Fit done in $m_{K\pi}$ - m_{ES} .



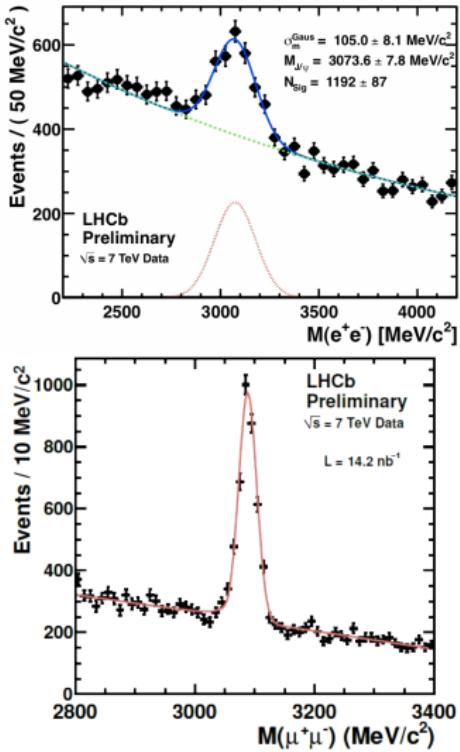
Patrick Koppenburg

Rare Decays

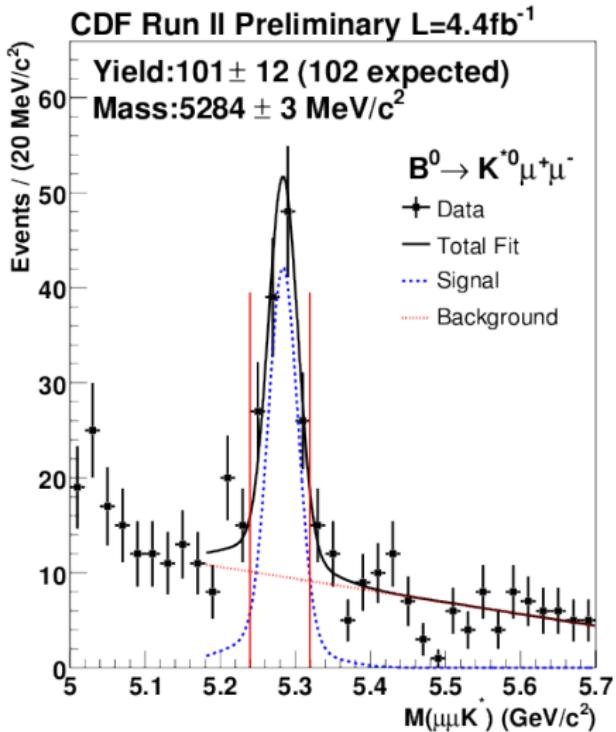
e VS μ



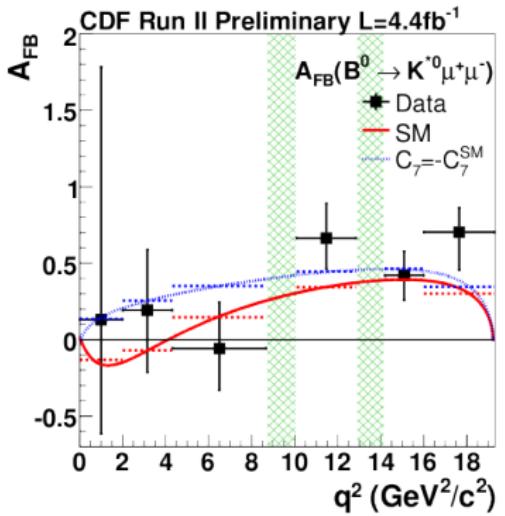
- B factories are equally good at reconstructing identifying electrons and muons
 - Slight advantage for electrons
 - In particular at BaBar
 - At hadron machines, it's very different:
 - There are a lot of electrons (conversions)
 - and very few muons (pions in flight)
 - Electrons do a lot of bremsstrahlung
 - A γ in ECAL + a track = an electron
- At LHCb, $B \rightarrow \ell\ell K^*$ is $B \rightarrow \mu\mu K^*$ (exceptions later)



$B \rightarrow \ell\ell K^*$ AT CDF



- 100 $B \rightarrow \mu\mu K^*$ events in 4.4 fb^{-1} [CDF public note]
- Use 6 bins to allow comparison with Belle



A_{FB} MEASUREMENTS SUMMARY



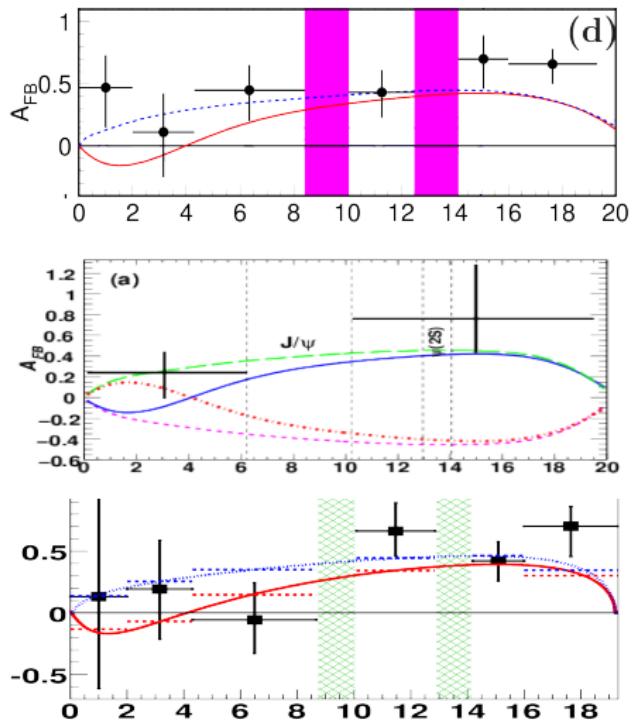
BELLE: $230 B \rightarrow \ell\ell K^*$ events in
 $657 \cdot 10^6 B\bar{B}$ [PRL103:171801,2009]

BABAR: $60 B \rightarrow \ell\ell K^*$ events in
 $384 \cdot 10^6 B\bar{B}$ [PRD79:031102,2009]

CDF: $100 B \rightarrow \mu\mu K^*$ events in
 4.4 fb^{-1} [CDF public note]

FB ASYMMETRY: All seem to favour $C_7 = -C_7^{\text{SM}}$ case. Not conclusive yet...

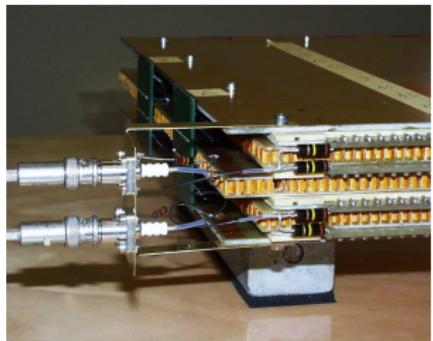
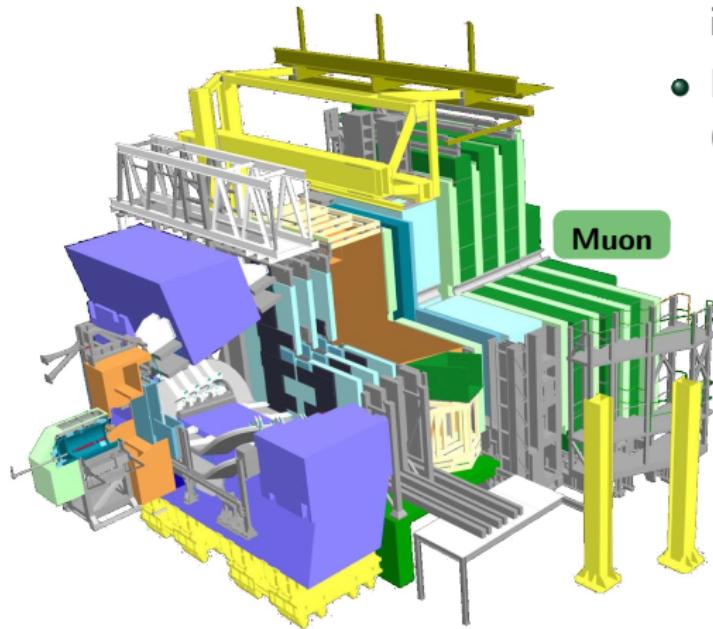
→ Need much more statistics



LHCb MUON DETECTOR

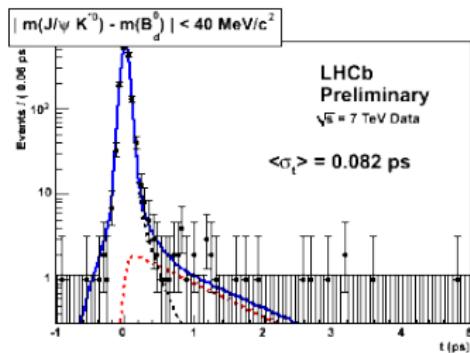
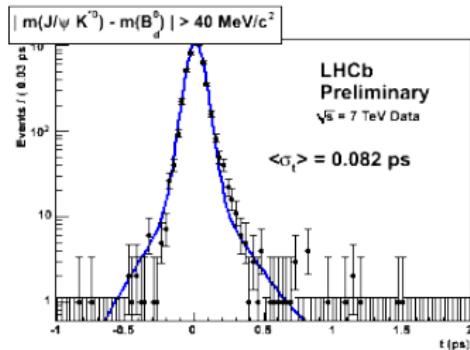
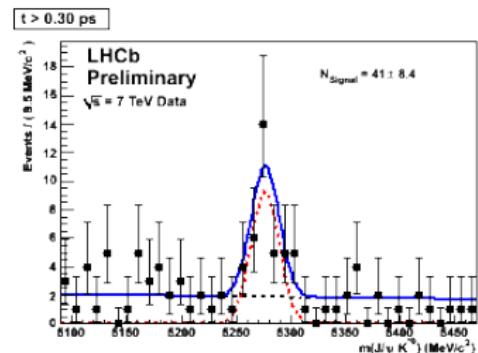
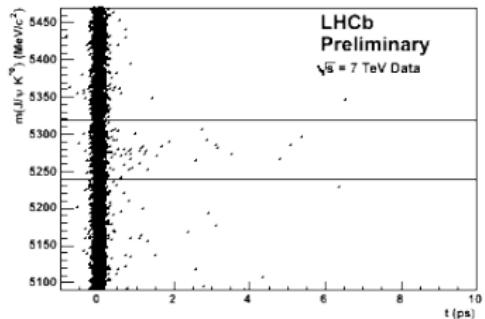


- Four stations M2–M5 embedded in an ion filter, M1 in front of ECAL
- Read out by gas detectors (triple GEM and MWPCs)



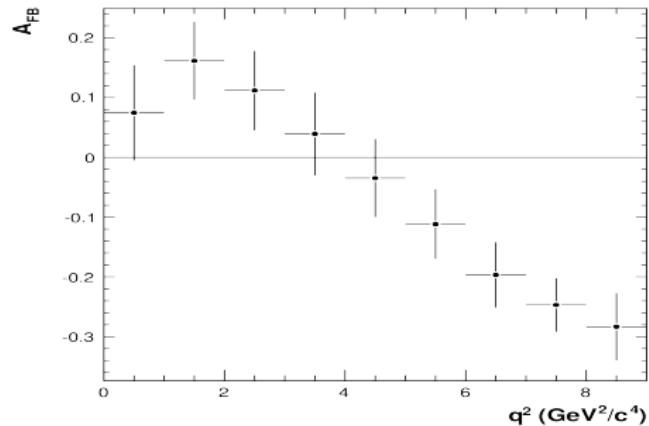
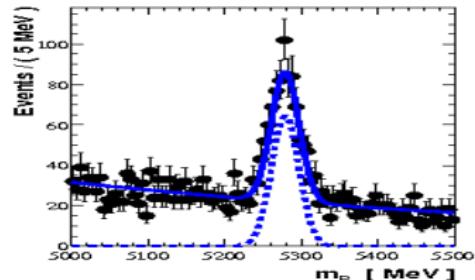
LHCb $B_d^0 \rightarrow J/\psi K^*$ (230 NB $^{-1}$)

LHCb
~~THCP~~



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

Sample	Yield
$B_d^0 \rightarrow \mu\mu K^*$	7200 ± 2100
$b \rightarrow \mu\mu s$	2000 ± 100
$2(b \rightarrow \mu)$	1050 ± 250
$b \rightarrow \mu c(\mu q)$	600 ± 200
Background	3700 ± 300
B/S	0.5 ± 0.2

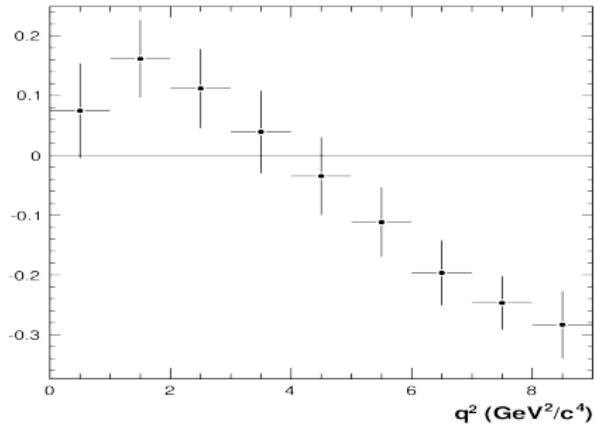
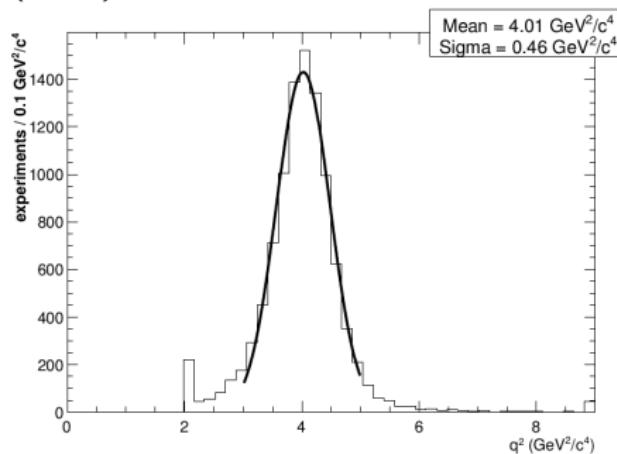
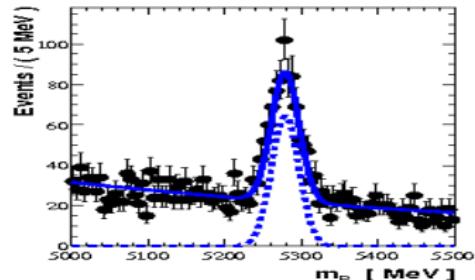


LHCb $B_d^0 \rightarrow \mu\mu K^*$ YIELDS WITH 2 fb^{-1}

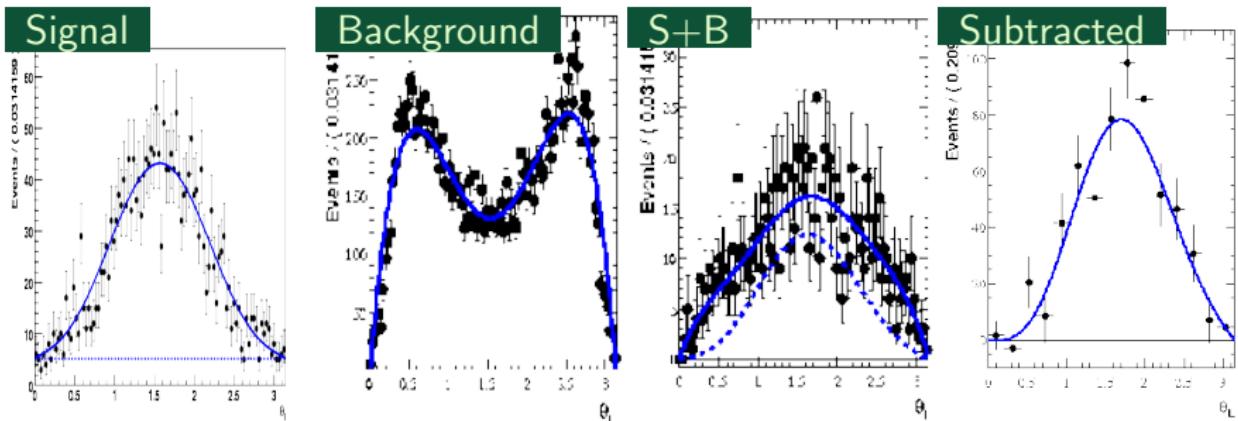


Expected signal and background yields in 2 fb^{-1} of data (Assuming the SM BR of $12 \cdot 10^{-7}$):

→ Resolution on A_{FB} zero : $\pm 0.46 \text{ GeV}^2$ (12%) in 2 fb^{-1}

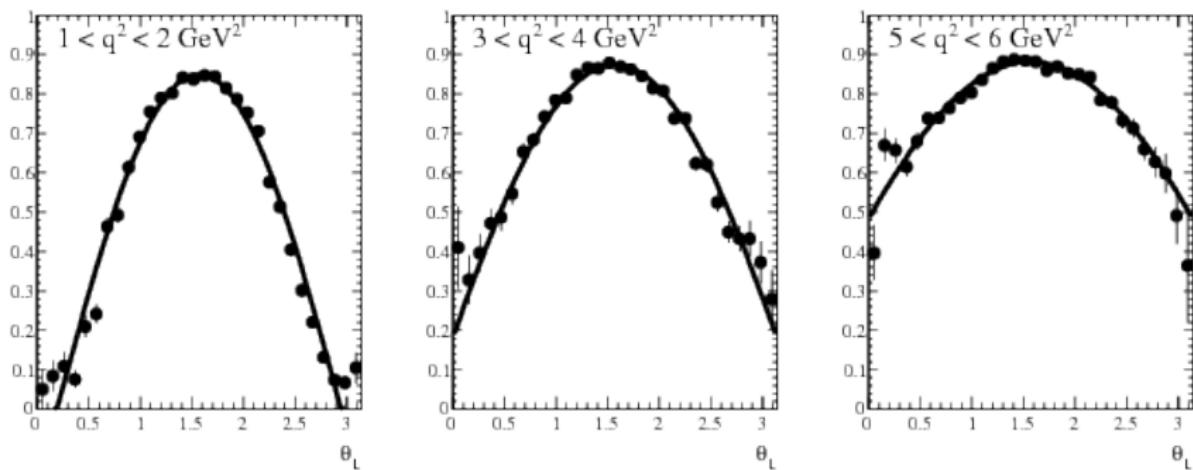


UNDERSTANDING THE θ_L DISTRIBUTION



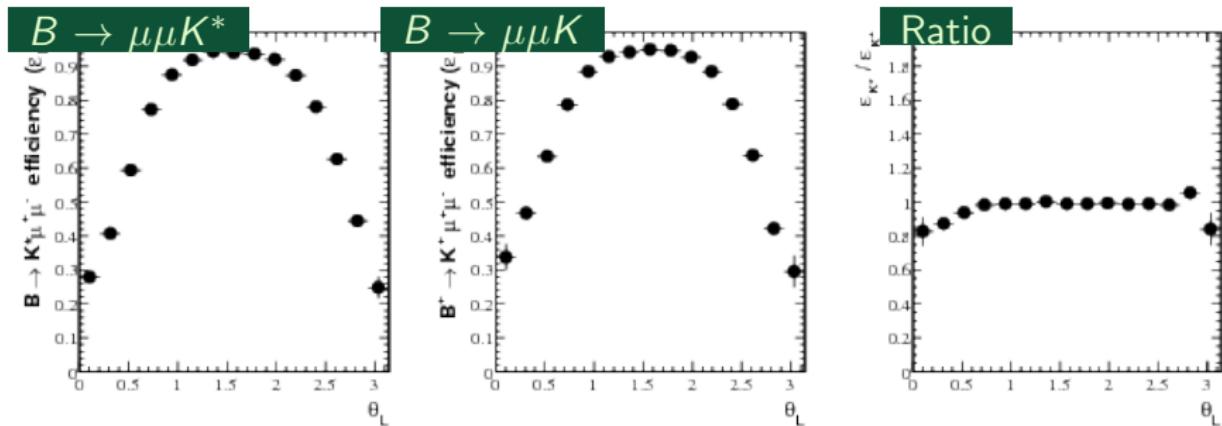
- Need to know the θ_L distribution for background → sidebands

UNDERSTANDING THE θ_L DISTRIBUTION



- Need to know the θ_L distribution for background → sidebands
- Need to understand the acceptance effects on θ_L → MC?

UNDERSTANDING THE θ_L DISTRIBUTION



- Need to know the θ_L distribution for background → sidebands
- Need to understand the acceptance effects on θ_L → MC?
 - Use control samples like $B_d^0 \rightarrow J/\psi K^*$ and $B \rightarrow \mu\mu K$

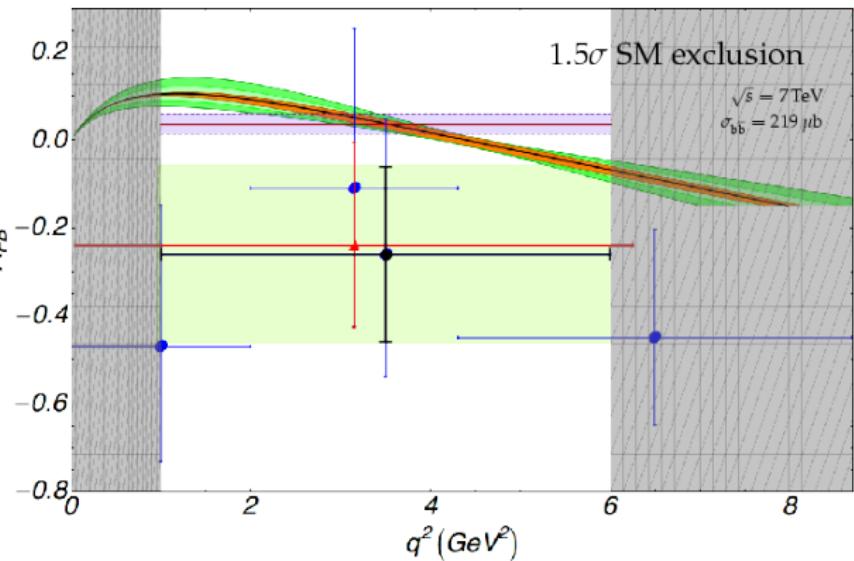
SCALING TO LOWER LUMINOSITIES



Assume Belle is right.

If we measure the mean A_{FB} in a bin 1–6 GeV^2 . How well can we exclude the SM?

100 PB^{-1} : 1.5σ



SM prediction — BaBar — Belle
LHCb at 100 pb^{-1}

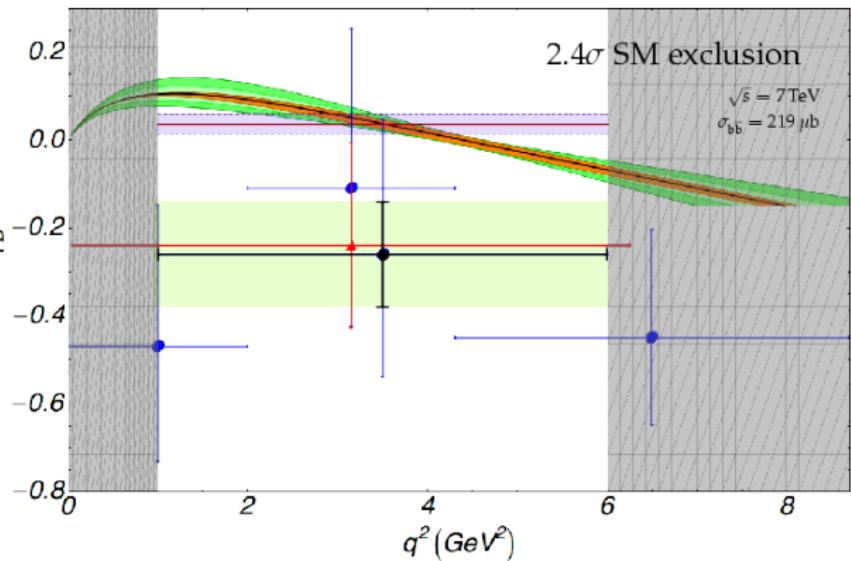
SCALING TO LOWER LUMINOSITIES



Assume Belle is right.
If we measure the mean A_{FB} in a bin 1–6 GeV^2 . How well can we exclude the SM?

100 PB^{-1} : 1.5σ

300 PB^{-1} : 2.4σ



SM prediction — BaBar — Belle
LHCb at 300 pb^{-1}

SCALING TO LOWER LUMINOSITIES



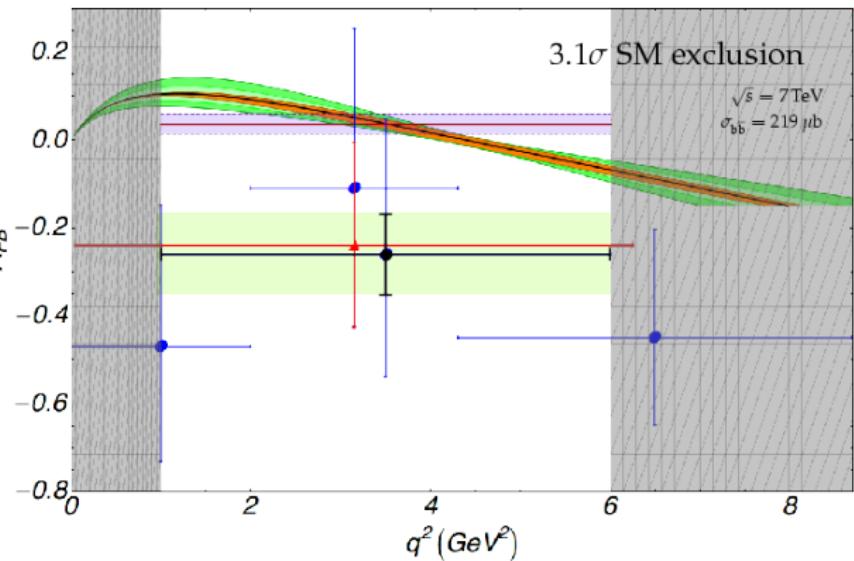
Assume Belle is right.

If we measure the mean A_{FB} in a bin 1–6 GeV^2 . How well can we exclude the SM?

100 PB^{-1} : 1.5σ

300 PB^{-1} : 2.4σ

500 PB^{-1} : 3.1σ



SM prediction — BaBar — Belle
LHCb at 500 pb^{-1}

SCALING TO LOWER LUMINOSITIES



Assume Belle is right.

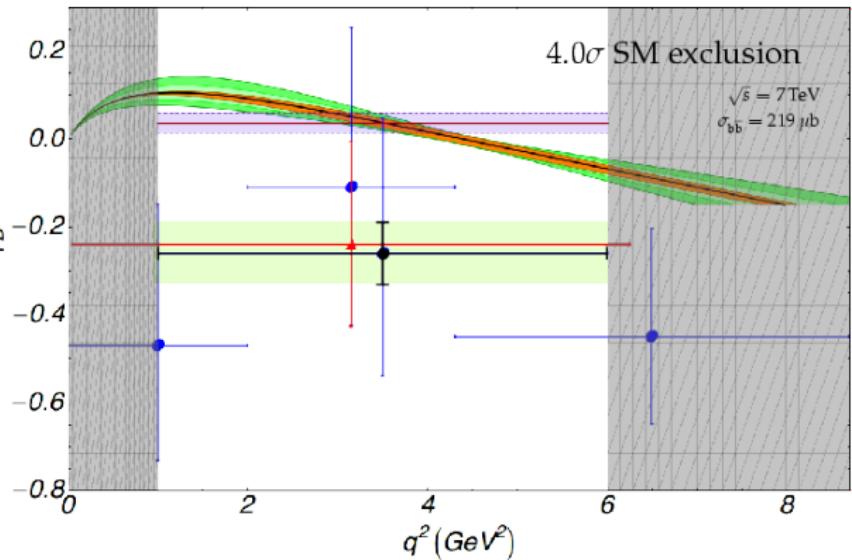
If we measure the mean A_{FB} in a bin 1–6 GeV^2 . How well can we exclude the SM?

100 PB^{-1} : 1.5σ

300 PB^{-1} : 2.4σ

500 PB^{-1} : 3.1σ

1 fb^{-1} : 4.0σ



SM prediction — BaBar — Belle
LHCb at 1 fb^{-1}

SCALING TO LOWER LUMINOSITIES



Assume Belle is right.

If we measure the mean A_{FB} in a bin 1–6 GeV^2 . How well can we exclude the SM?

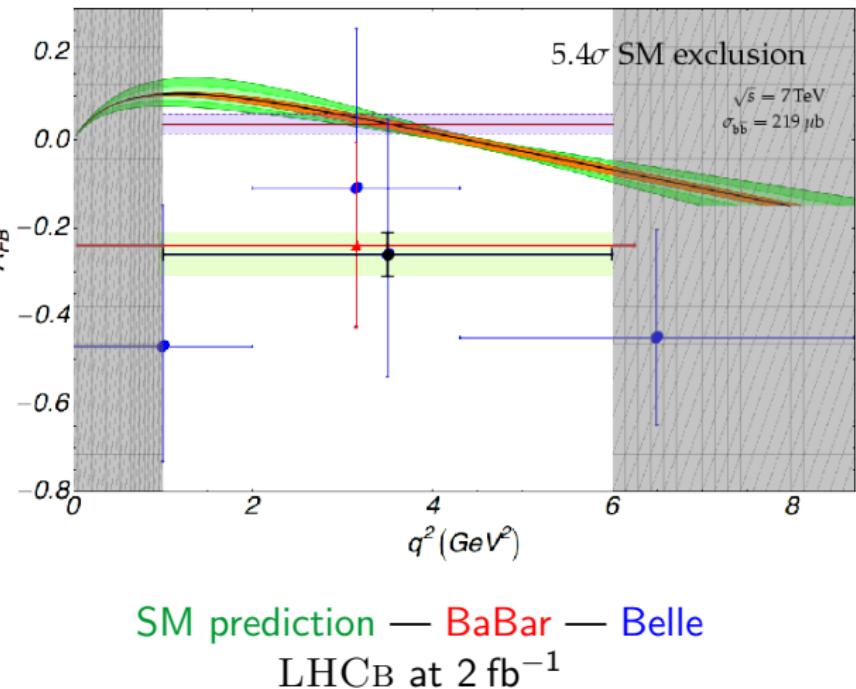
100 PB^{-1} : 1.5σ

300 PB^{-1} : 2.4σ

500 PB^{-1} : 3.1σ

1 FB^{-1} : 4.0σ

2 FB^{-1} : 5.4σ



LONGITUDINAL POLARISATION F_L

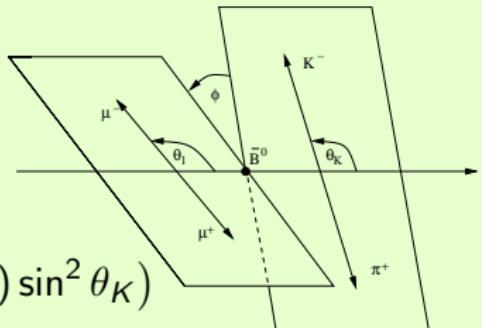
$$\frac{d\Gamma'}{d\theta_I} = \Gamma' \left(\frac{3}{4} \mathbf{F_L} \sin^2 \theta_I + A_{FB} \cos \theta_I + \frac{3}{8} (1 - \mathbf{F_L}) (1 + \cos^2 \theta_I) \right)$$

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

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

$\mathbf{F_L}$ is the K^* longitudinal polarisation fraction

$$F_L = \frac{|A_0|^2}{|A_0|^2 + |A_{||}|^2 + |A_{\perp}|^2}$$



LONGITUDINAL POLARISATION F_L

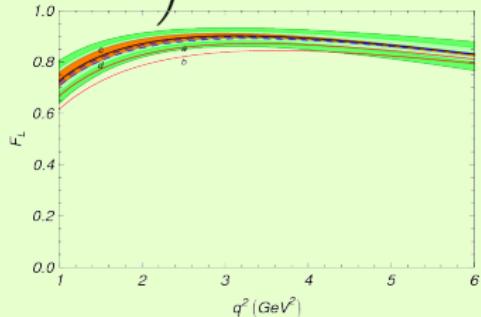
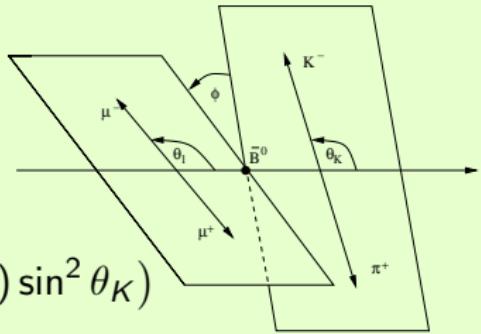
$$\frac{d\Gamma'}{d\theta_I} = \Gamma' \left(\frac{3}{4} \mathbf{F}_L \sin^2 \theta_I + A_{FB} \cos \theta_I + \frac{3}{8} (1 - \mathbf{F}_L) (1 + \cos^2 \theta_I) \right)$$

$$\frac{d\Gamma'}{d\theta_K} = \frac{3\Gamma'}{4} \sin \theta_K (2\mathbf{F}_L \cos^2 \theta_K + (1 - \mathbf{F}_L) \sin^2 \theta_K)$$

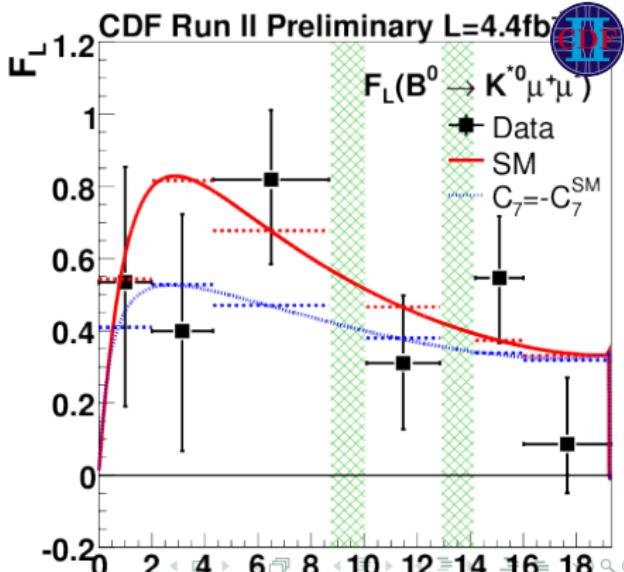
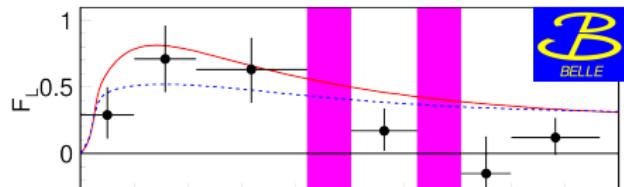
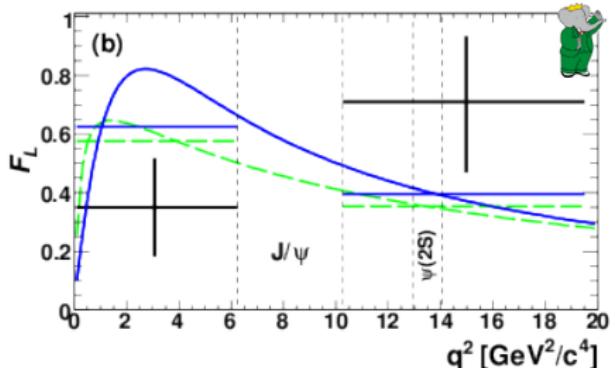
$$\frac{d\Gamma'}{d\phi} = \frac{\Gamma'}{2\pi} \left(\frac{1}{2} (1 - \mathbf{F}_L) A_T^{(2)} \cos 2\phi + A_{Im} \sin 2\phi + 1 \right)$$

\mathbf{F}_L is the K^* longitudinal polarisation fraction

- ✓ Quite easy to measure
- ✗ Close to 1 in all models
- ✗ Difference to SM close to error



F_L



- Would need much more data to disentangle SM from other models
- And other variables would get there more quickly

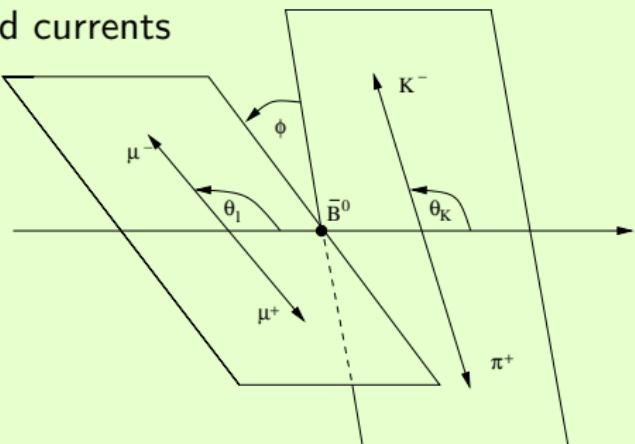


TRANSVERSE ASYMMETRY $A_T^{(2)}$

$$A_T^{(2)} = \frac{|A_{\perp}|^2 - |A_{\parallel}|^2}{|A_{\perp}|^2 + |A_{\parallel}|^2}$$

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

- ✓ $A_T^{(2)}$ is sensitive to right-handed currents
- ✗ It is suppressed by $(1 - F_L)$



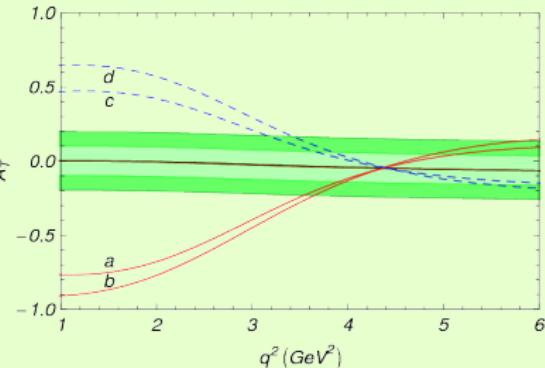
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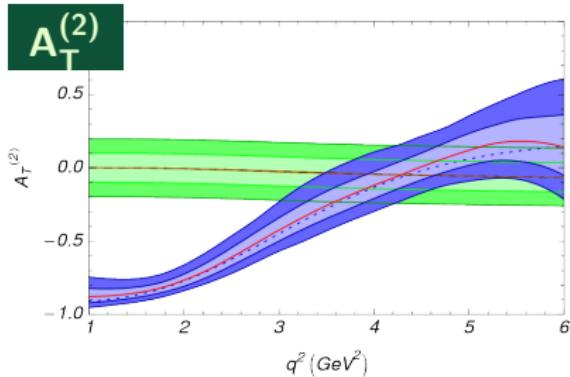
$$\frac{d\Gamma'}{d\phi} = \frac{\Gamma'}{2\pi} \left(\frac{1}{2}(1 - F_L) \mathbf{A}_T^{(2)} \cos 2\phi + A_{\text{Im}} \sin 2\phi + 1 \right)$$

- ✓ $A_T^{(2)}$ is sensitive to right-handed currents
- ✗ It is suppressed by $(1 - F_L)$
- ✓ Large variation with models
- ✗ It requires the measurement of the angle ϕ , which depends on all four final state particles
 - complicated experimental biases
- ✓ Yet good prospects at LHCb

[Egede et al., arXiv:1005.0571v1]



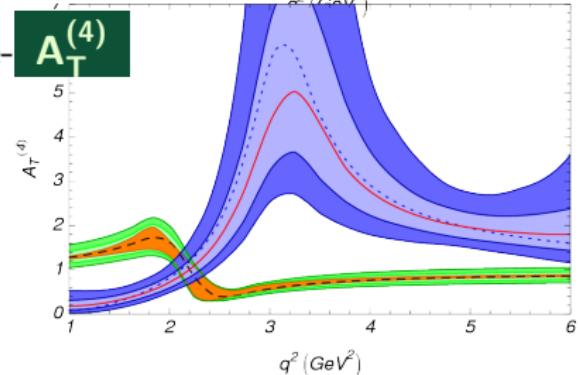
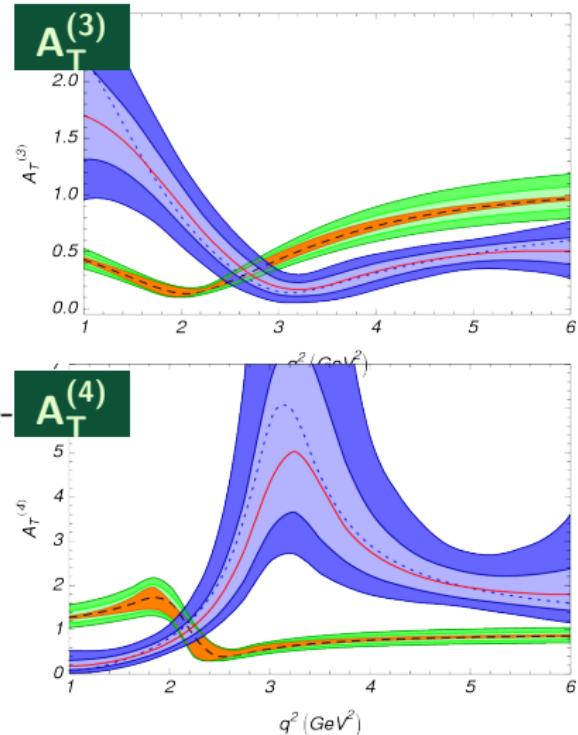
MORE ASYMMETRIES



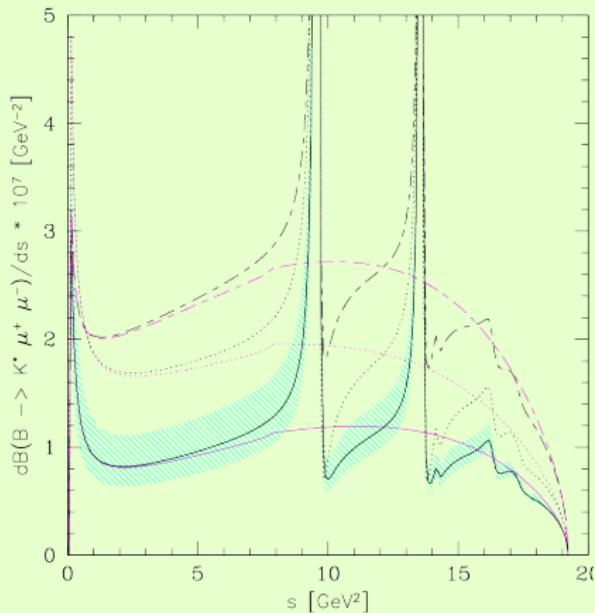
LHCb sensitivity of for 2 fb^{-1} for selected asymmetries [Egede, et al.]

BLUE BAND: experimental sensitivity assuming a susy model with large gluino mass.

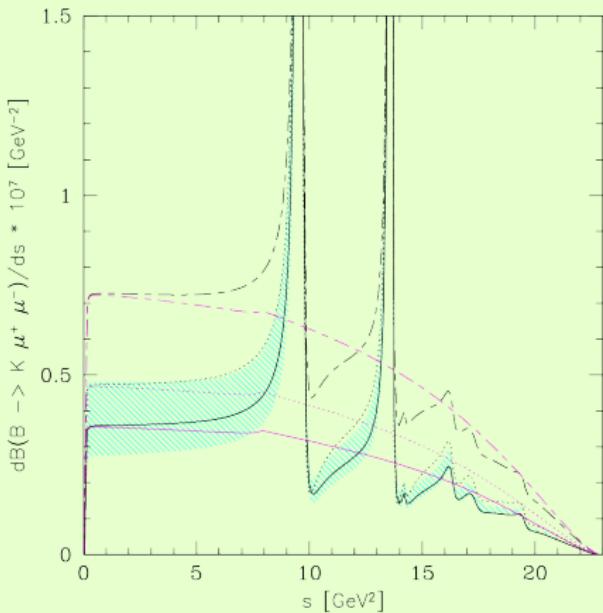
GREEN BAND: Standard model expectation with error



$B \rightarrow \ell\ell K$ AND $B \rightarrow \ell\ell K^*$

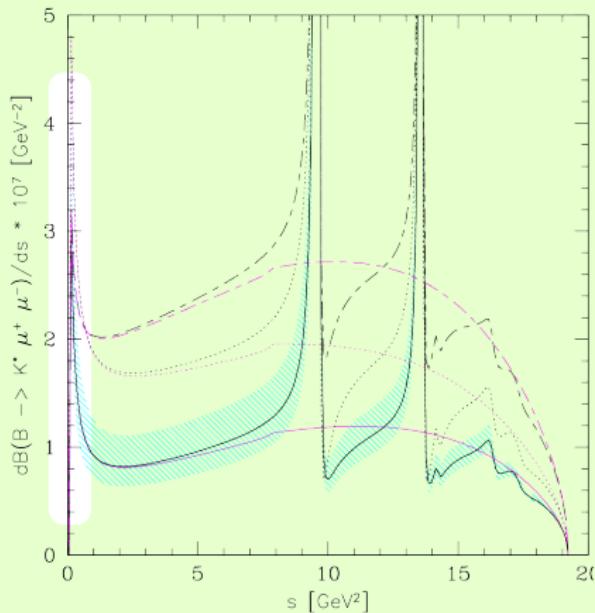


$B \rightarrow \ell\ell K^*$

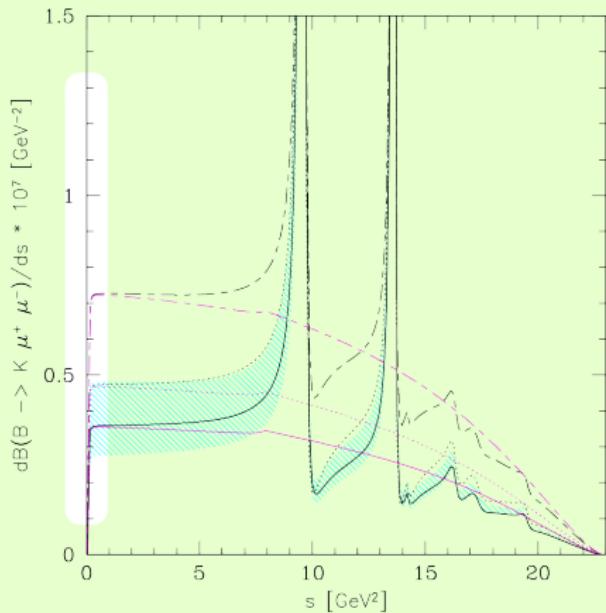


$B \rightarrow \ell\ell K$

$B \rightarrow \ell\ell K$ AND $B \rightarrow \ell\ell K^*$



$B \rightarrow \ell\ell K^*$

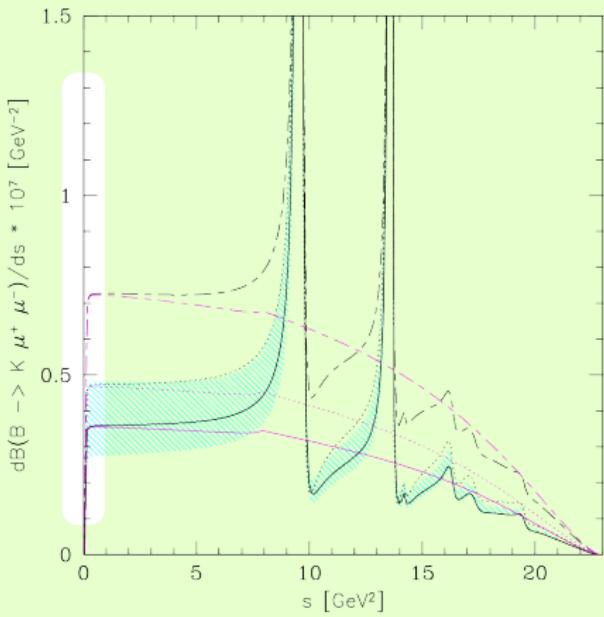


$B \rightarrow \ell\ell K$



$B \rightarrow \ell\ell K$ AND $B \rightarrow \ell\ell K^*$

- $B \rightarrow \mu\mu K$ has similar BF as $B \rightarrow \mu\mu K^*$
- It's just missing the photon pole
- $C_{7\gamma}$ does not contribute → no interference → no A_{FB}
 - Except if you add new scalar operators



$B \rightarrow \ell\ell K$

$B \rightarrow \ell\ell K$ STATUS



Remember the BaBar $B \rightarrow \ell\ell K$ and $B \rightarrow \ell\ell K^*$ plots [BaBar, PRL 102:091803,2009]

- There's no $B_d^0 \rightarrow \ell\ell K^0$

$$A_I^{(q^2 < 7 \text{ GeV}^2)} = -1.41^{+0.49}_{-0.69} \pm 0.05$$

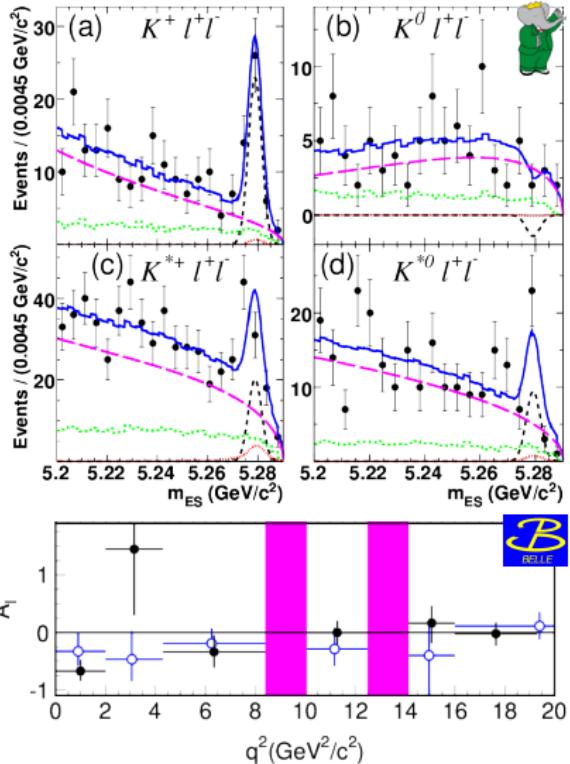
$$A_I^{(q^2 > 13 \text{ GeV}^2)} = 0.28^{+0.24}_{-0.30} \pm 0.03$$

- $A_I^{(q^2 < 7 \text{ GeV}^2)} \neq 0$ at 3.2σ (NP?)

Belle see a 2σ effect :

$$A_I^{(q^2 < 8.7 \text{ GeV}^2)} = -0.29^{+0.16}_{-0.16} \pm 0.09$$

[Belle, PRL103:171801,2009]

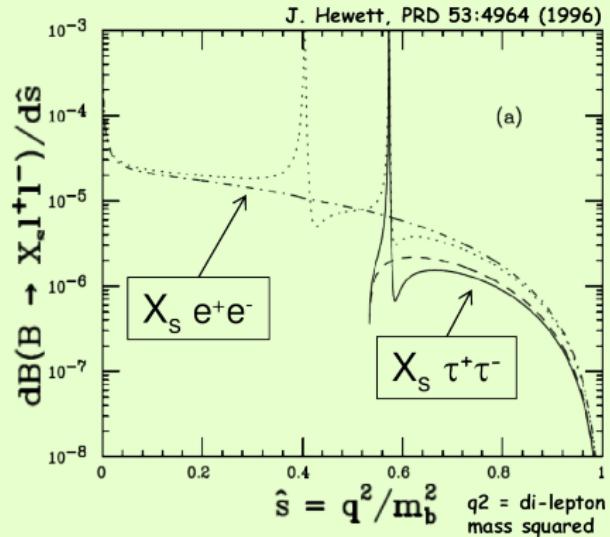


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$B \rightarrow \tau\tau$

- $B \rightarrow \tau\tau X_s$ expected to have similar $d\Gamma_i/ds$ as $b \rightarrow \ell\ell s$ in accessible range
- Any enhancement would be a sign of Higgs exchange $\propto \frac{m_\tau}{m_\mu}$
- $\mathcal{B} \sim 10^{-7}$
- Not seen at B factories yet:
 $BF(B \rightarrow \tau\tau K) < 3.3 \cdot 10^{-3}$.
Still a long way to go...
- ✗ LHCb won't see it



R_K IN $B_u^+ \rightarrow \ell\ell K$

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

[Hiller & Krüger, PRD69 (2004) 074020]

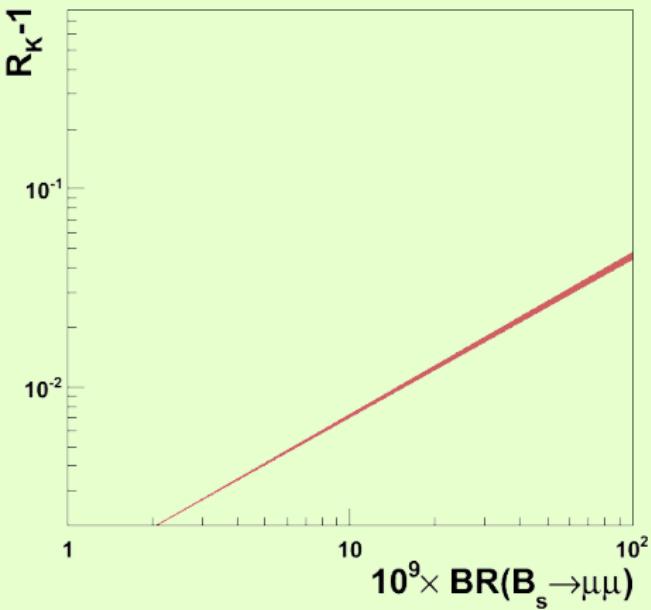
Corrections can be $\mathcal{O}(10\%)$ for instance with neutral Higgs boson exchanges.

R_K IN $B_u^+ \rightarrow \ell\ell K$

$$R_X = \frac{\int_{q_{\max}^2}^{4m_\mu^2} ds \frac{d\Gamma(B \rightarrow X \mu^+ \mu^-)}{ds}}{\int_{q_{\max}^2}^{4m_\mu^2} ds \frac{d\Gamma(B \rightarrow X e^+ e^-)}{ds}}$$

$$R_K - 1 \propto \mathcal{B}(B_s^0 \rightarrow \mu\mu)$$

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



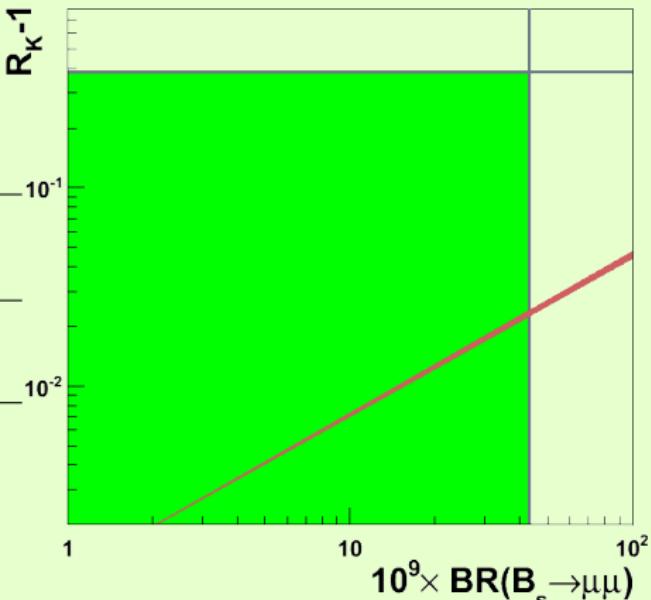
[Hiller & Krüger, PRD69 (2004) 074020]

R_K IN $B_u^+ \rightarrow \ell\ell K$

Experimental status:

Experimental status:

	BaBar ($384 \cdot 10^6 B\bar{B}$)
	[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 ($657 \cdot 10^6 B\bar{B}$)
	[PRL103:171801,2009]
R_K	$1.03 \pm 0.17 \pm 0.05$
R_{K^*}	$0.83 \pm 0.17 \pm 0.05$



$B_s^0 \rightarrow \mu\mu$: The present CDF limit
is $4.3 \cdot 10^{-8}$ at 90% CL

[CDF note 9892]

[Hiller & Krüger, PRD69 (2004) 074020]



$B \rightarrow \ell\ell K$ AT LHCb WITH 10 FB^{-1}



$$R_X = \frac{\Gamma(B \rightarrow \mu\mu X)}{\Gamma(B \rightarrow eeX)} \stackrel{\text{SM}}{=} \begin{cases} 1.000 \pm 0.001 & X = K \\ 0.991 \pm 0.002 & X = K^* \end{cases}$$

$$R_X - 1 \propto \mathcal{B}(B_s^0 \rightarrow \mu\mu)$$

[Hiller & Krüger, PRD69 (2004) 074020]

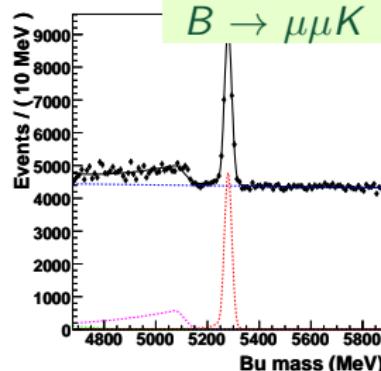
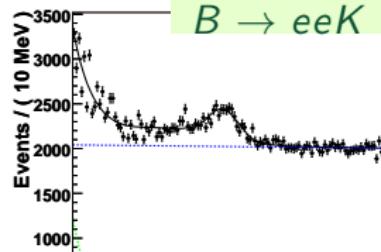
Species	Yield	Error
$B \rightarrow eeK$	$9\,240 \pm 379$	4.10%
$B \rightarrow \mu\mu K$	$18\,774 \pm 227$	1.21%

- Including control samples, one gets an error:

$\rightarrow R_K = 1 \text{ (fixed)} \pm 0.043$

[LHCb note 2007-034]

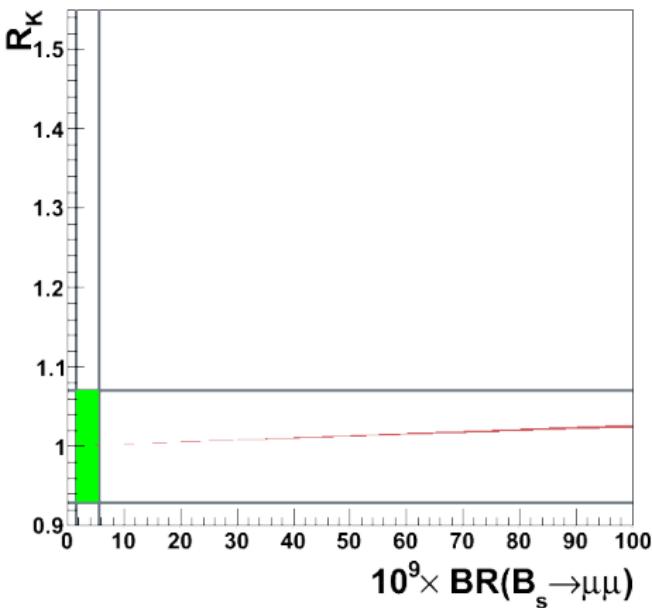
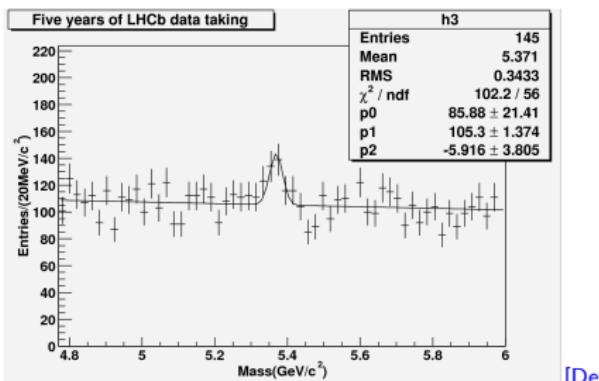
- R_{K^*} from $B \rightarrow \ell\ell K^*$ also under study.



POSSIBLE STATUS WITH 10 FB^{-1}



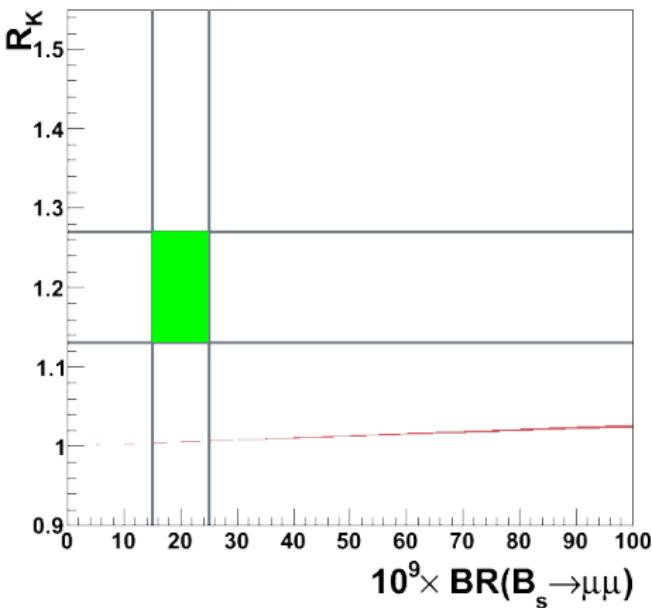
- $\mathcal{B}(B_s^0 \rightarrow \mu\mu)$ compatible with SM ($\sim 3 \cdot 10^{-9}$)
 - $R_K \sim 1$: Compatible with SM or MSSM with small $\tan \beta^3 / m_A^2$



POSSIBLE STATUS WITH 10 FB^{-1}

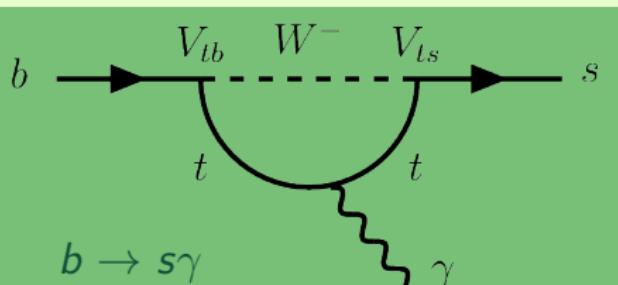
LHCb
~~FNAL~~

- $\mathcal{B}(B_s^0 \rightarrow \mu\mu)$ compatible with SM ($\sim 3 \cdot 10^{-9}$)
 - $R_K \sim 1$: Compatible with SM or MSSM with small $\tan \beta^3 / m_A^2$
 - $R_K \neq 1$: New Physics — Right-handed currents or broken lepton-universality
- $\mathcal{B}(B_s^0 \rightarrow \mu\mu)$ larger than SM: New Physics
 - $R_K \neq 1$, as above
 - $R_K \sim 1 + \epsilon$: MFV



[Hiller & Krüger, PRD69 (2004) 074020]

REMINDER: $b \rightarrow s\gamma$ POLARISATION



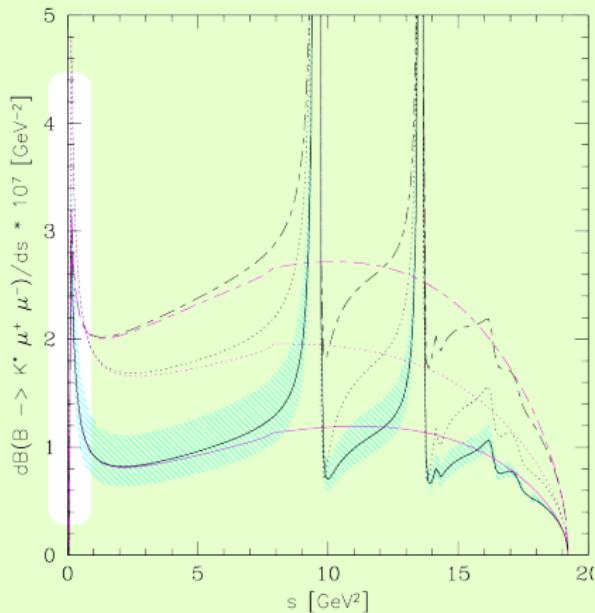
The photon polarisation is not well measured.

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

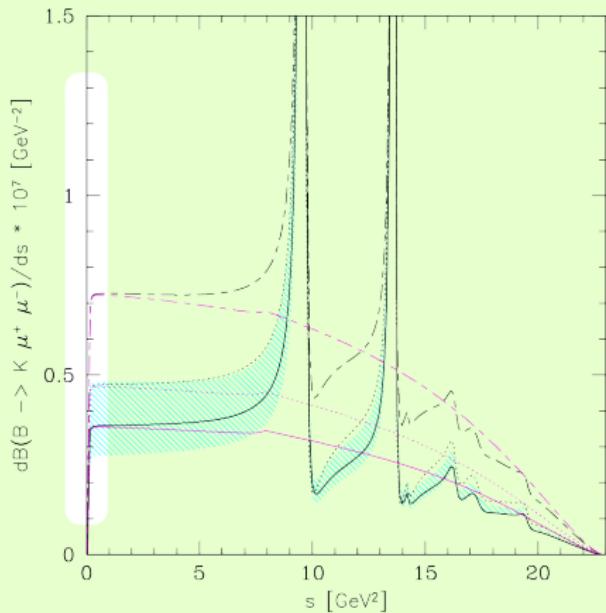
Ways to measure:

- ✓ Mixing-induced CP violation
[Atwood et al., PRL79:185, 1997]
- ✓ Λ_b baryons
[Hiller & Kagan, PRD65:074038, 2002]
- $B \rightarrow \gamma K^{**}(K\pi\pi)$
[Gronau & Pirjol, PRD66 054008, 2002]
[Gronau et al., PRL88:051802, 2002]
- ✓ Virtual photons ($b \rightarrow \ell\ell s$)
[Melikhov et al., PLB442:381-389,1998]
- Converted photons
[Grossman et al., JHEP06:29,2000]

$B \rightarrow \ell\ell K$ AND $B \rightarrow \ell\ell K^*$



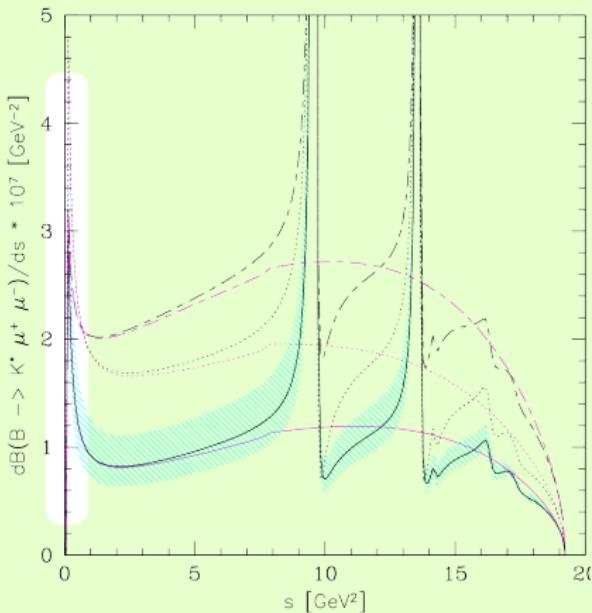
$B \rightarrow \ell\ell K^*$



$B \rightarrow \ell\ell K$



$B \rightarrow llK$ AND $B \rightarrow llK^*$



$B \rightarrow llK^*$

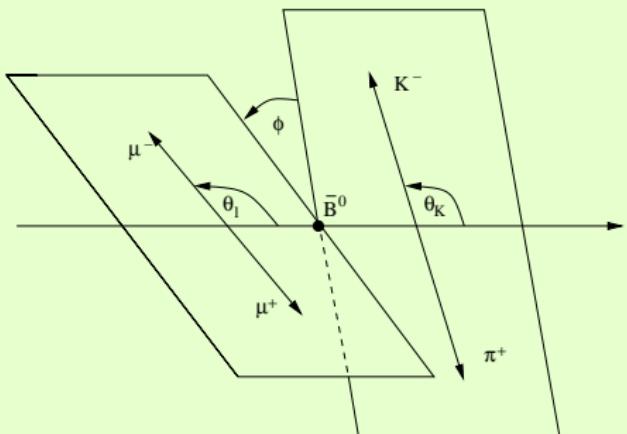
- Remember the polarisation in $b \rightarrow s\gamma$?
- Dileptons at $q^2 \sim 0$ are generated from $b \rightarrow s\gamma^*(\rightarrow ll)$
- We can measure the polarisation of the virtual photon
- And thus identify right-handed currents
- **BUT:** We need **Light** leptons, aka electrons

$B \rightarrow eeK^*$ AT LOW q^2

$$\frac{d\Gamma}{d\phi} = \frac{\Gamma(B \rightarrow K^*\gamma)}{2\pi} \left(\frac{\alpha_S}{3\pi} \log \frac{q_{\max}^2}{4m_e^2} \right) \left(1 - \frac{\operatorname{Re}(A_R A_L^*) \cos 2\phi - \operatorname{Im}(A_R A_L^*) \sin 2\phi}{|A_R|^2 + |A_L|^2} \right)$$

[Grossmann, Pirjol, JHEP 0006 (2000) 029]

- An angular analysis in ϕ allows to extract $\frac{|A_R|}{|A_L|}$
- Cutting at $q_{\max}^2 > 1 \text{ GeV}$ gets 1% of $B \rightarrow K^*\gamma \rightarrow 4 \cdot 10^{-7}$

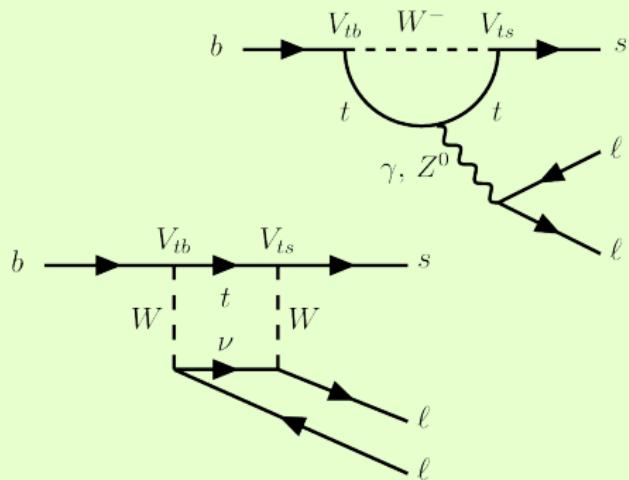


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- But of course one needs to take into account Z and box contributions that contribute at $q^2 > 0$



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- But of course one needs to take into account Z and box contributions that contribute at $q^2 > 0$

Very difficult at LHCb:
Expect 200 events in
 2 fb^{-1} and $\sigma \left(\frac{|A_R|}{|A_L|} \right) \sim 0.1$
La spécialité du LAL!

OTHER CHANNELS FOR LHCb



ISOSPIN ASYMMETRY IN $B \rightarrow \mu\mu K$: $B_d^0 \rightarrow \mu\mu K_S^0$ vs $B_u^+ \rightarrow \mu\mu K^+$.

K^+ is easy (expect $4k/2 \text{ fb}^{-1}$) but K_S^0 needs to be studied. Calibrate to $B_d^0 \rightarrow J/\psi K_S^0$ and $B_u^+ \rightarrow J/\psi K^+$.

$B_s^0 \rightarrow \mu\mu\phi$: Expect ~ 1000 events/ 2 fb^{-1} . **No FBA!** Can do a time-dependent CP analysis, like $B_s^0 \rightarrow J/\psi\phi$. What do we learn from it?

$B_d^0 \rightarrow \mu\mu\rho^0$, $B_u^+ \rightarrow \mu\mu\pi^+$, $B_s^0 \rightarrow \mu\mu\bar{K}^*$: V_{td}/V_{ts} suppressed decays
→ Measure BF. But S/B will be poor. Expect $\mathcal{O}(100)$ events/ 2 fb^{-1} .

$B \rightarrow \mu\mu X$: Semi-inclusive study. Extract q^2 spectrum. Can only do sum of K^\pm , π^\pm , K_S^0 . Is that inclusive enough?

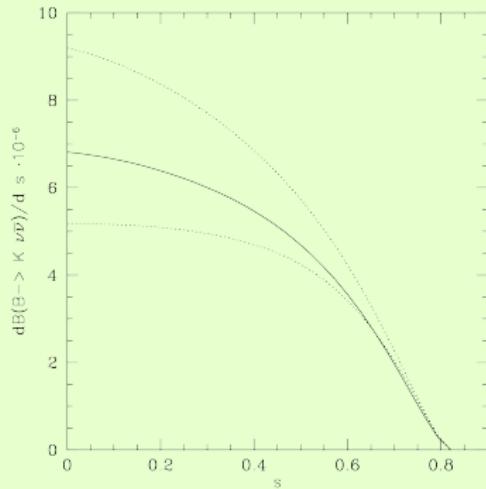
$B_s^0 \rightarrow \mu\mu\gamma$: Many papers about this channel. Not clear what we learn from it.

$B_d^0 \rightarrow e\mu$: LFV. Can probably set a good limit on BF. B_s^0 never done.



$B \rightarrow \nu\bar{\nu}K^{(*)}$

- $b \rightarrow \nu\bar{\nu}s$ 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 :
 $B \rightarrow \nu\bar{\nu}K$ and $B \rightarrow \nu\bar{\nu}K^*$
 - Requires B factory with recoil tag
 - Huge statistics required
- SM $\mathcal{B}(B \rightarrow \nu\bar{\nu}K) = 4 \cdot 10^{-6}$
- Best limit : $< 14 \cdot 10^{-6}$ (Belle 500 fb $^{-1}$)
- A BF measurement is within reach of a high-lumi factory (Belle II)



DREAMS FOR BELLE II



- $\mathcal{A}_{\text{CP}}(b \rightarrow s\gamma + b \rightarrow d\gamma) = 0$?
- $b \rightarrow s\gamma$ to $E_{\gamma}^{\min} \sim 1.6$ GeV
- $b \rightarrow d\gamma / b \rightarrow s\gamma$
- Photon polarisation
- $B \rightarrow K^{(*)}\nu\nu$ (no γ pollution, no LD)
- $B \rightarrow$ Nothing ($\nu\nu$)
- ...



RARE CHARM

A completely different landscape



RARE CHARM

- $b \rightarrow s\gamma$, $b \rightarrow \ell\ell s$, $b \rightarrow s\gamma$, $b \rightarrow \ell\ell d$ and rare kaon decays all probe down \rightarrow down penguins and boxes
 - As does B_s^0 and B_d^0 mixing
 - We know very little from up \rightarrow up transitions
- Charm physics probes $c \rightarrow u$ (up is stable, top is too hard)
- X But Charm is hard too
- CKM factors are against us :

$$\underbrace{V_{tb} V_{ts}}_{\sim \lambda^2} m_t^2 + \dots \Rightarrow \underbrace{V_{cb} V_{ub}}_{\sim \lambda^5} m_b^2 + \underbrace{V_{cs} V_{us}}_{\sim \lambda} m_s^2 + \dots$$

- The quark is lighter than the b : LD effects are larger, SD smaller

$$D_u^0 \rightarrow \mu\mu$$

- SM short-distance BF amazingly small

$$\begin{aligned}\mathcal{B}^{\text{SD}} &= \frac{F_F^2 m_W^2 f_D m_\ell}{\pi^2} \sum_{i=d,s,b} V_{ui} V_{ci}^* \frac{m_i^2}{m_W^2} \left[\frac{1}{2} + \frac{\alpha_S}{4\pi} \left(\ln^2 \frac{m_i^2}{m_W^2} + \frac{4 + \pi^2}{3} \right) \right] \\ &= \mathcal{O}(10^{-18})\end{aligned}$$

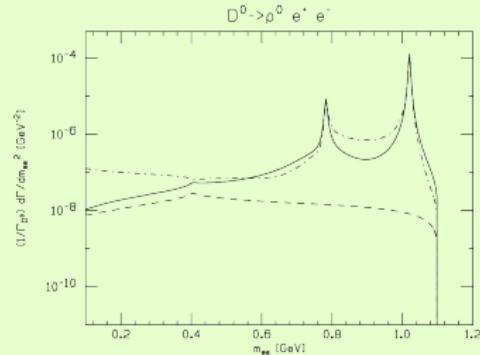
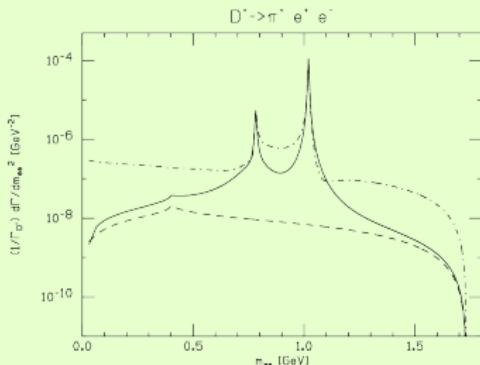
[Burdman et al., PRD66:014009, 2002]

- ✗ The long distance contribution from π rescattering and 2γ loops can be several orders of magnitude higher ($\mathcal{O}(10^{-13})$) [Bigi et al., arXiv:1008.3141v3]

- Experimentally $\mathcal{B} < 1.4 \cdot 10^{-7}$ [Belle, PRD.81.091102, 2010]
- LHCb should be able to do better soon
- For the foreseeable future any signal is a sign of new physics

$c \rightarrow u\bar{u}\ell\ell$

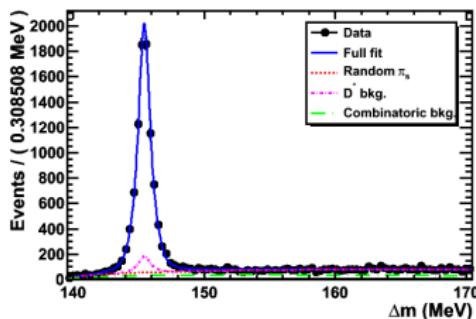
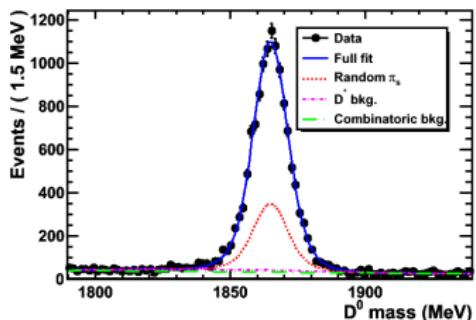
- Charm equivalent of $b \rightarrow \ell\bar{\ell}s$
- ✗ Large LD effects due to $s\bar{s}$ (ϕ) and $d\bar{d}$ (ρ) resonances
 - In $b \rightarrow \ell\bar{\ell}s$ only $u\bar{u}$ (ρ) and $c\bar{c}$ (J/ψ) resonances affect the spectrum. $1 \leq q^2 \leq 6 \text{ GeV}^2$ region is clean
- ✗ Not very meaningful mass spectrum [Burdman et al., PRD66:014009, 2002]
- ✗ No region of q^2 where FBA would be “safe”
- ➔ Go and measure it. But don’t claim New Physics!



CHARM PHYSICS AT LHCb



- Charm physics offers a unique potential to discover New Physics
 - $\sigma_{c\bar{c}} \sim 7\sigma_{b\bar{b}}$
 - $4 \cdot 10^6 D^* \rightarrow D_s^0(KK)\pi$ in 100 pb^{-1}
(BABAR has $2.6 \cdot 10^5$ [PRD.80.071103])
- Re-tuned the trigger for low luminosities ($\mathcal{L} < 10^{31} \text{ s}^{-2} \text{cm}^{-2}$)
 - Lower p_T , impact parameter thresholds
 - Improves prompt charm yields by a factor 4 compared to trigger setting optimised for B physics



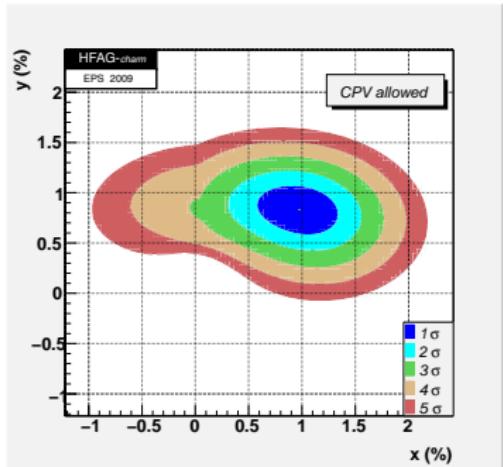
$D \rightarrow K\pi$ and $D^* \rightarrow D\pi$ with 0.2 pb^{-1}

CHARM PHYSICS AT LHCb

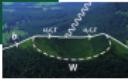


- Charm physics offers a unique potential to discover New Physics
- Re-tuned the trigger for low luminosities ($\mathcal{L} < 10^{31} \text{ s}^{-2} \text{cm}^{-1}$)
- Extensive Charm physics programme
 - Rare Decays : $D_s^0 \rightarrow \mu\mu$, $D \rightarrow h\mu\mu$
 - CP violation: $D_s^0 \rightarrow KK$, $D_s^0 \rightarrow \pi\pi$
- Mixing:
 - Significant evidence for D mixing
 - But no single 5σ measurement yet
 - Many measurements being prepared, for instance

$$y_{cp} = \frac{\tau(D_s^0 \rightarrow K^+\pi)}{\tau(D_s^0 \rightarrow K^+K^-, \pi\pi)} - 1$$



LHCb will soon have the largest D sample in the world!



KAONS

IF MINIMAL FLAVOUR VIOLATION: $K \rightarrow \pi\nu\nu$ strongly correlated with $B \rightarrow \mu\mu$

→ Need precise measurement of both to test MFV

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

BUT OF COURSE we don't know → must measure all and let the data sort it out

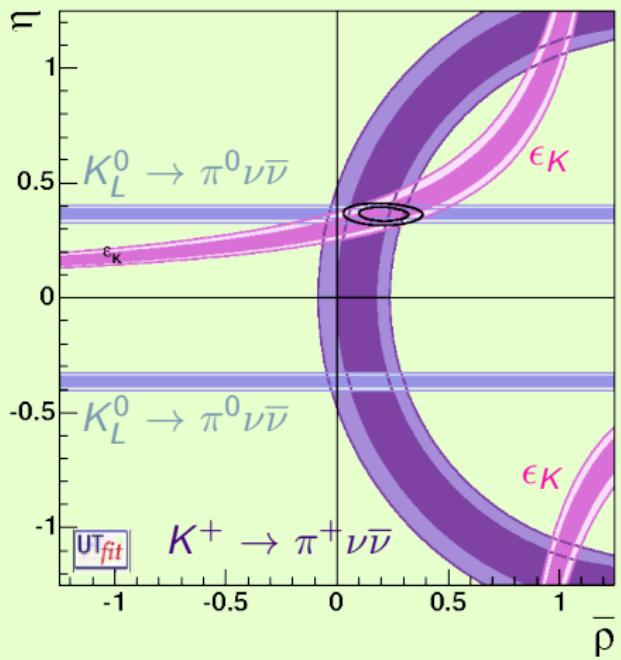
$$K \rightarrow \pi \nu \bar{\nu}$$

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

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

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

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



[UTFit]



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

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

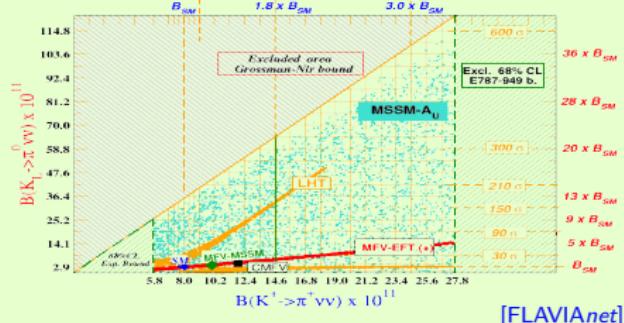
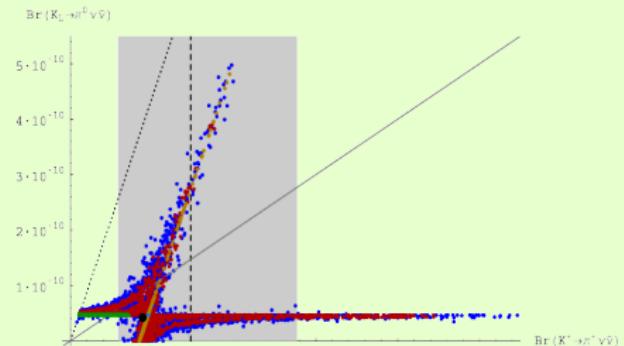
- SM $\mathcal{B} = 8 \cdot 10^{-11}$
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$K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$ is 99% unaffected from long-distance contributions.

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

Very sensitive to many NP models:

- MFV, UED, Littlest Higgs, Susy ...
- Important probe to disentangle models



[FLAVIAnet]



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

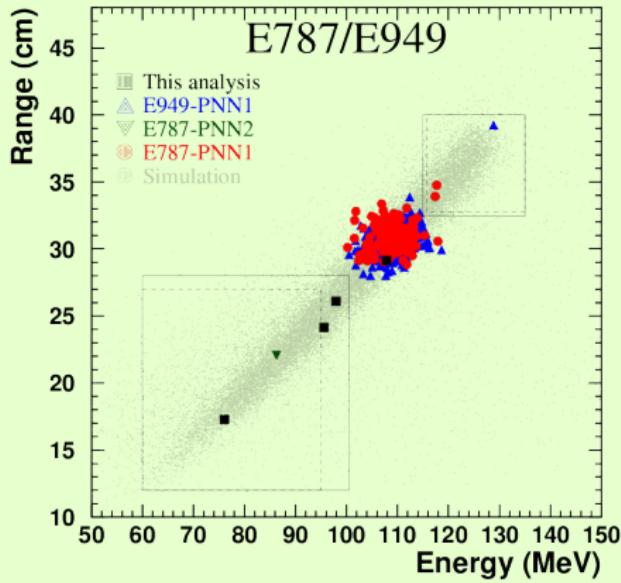
$K^+ \rightarrow \pi^+ \nu \bar{\nu}$ is 90% unaffected from long-distance contributions.

- SM $\mathcal{B} = 8 \cdot 10^{-11}$
- 5% irreducible error
- $\mathcal{B} = 1.73^{+1.15}_{-1.05} \cdot 10^{-10}$ [E949,

arXiv:0808.2459 (hep-ex)]

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

- SM $\mathcal{B} = 3 \cdot 10^{-11}$
- 2% irreducible error
- $\mathcal{B} < 2.6 \cdot 10^{-8}$ (E391a)



Signal and remaining $K^+ \rightarrow \pi^+ \pi^0$ events in π energy vs range plot [E949,

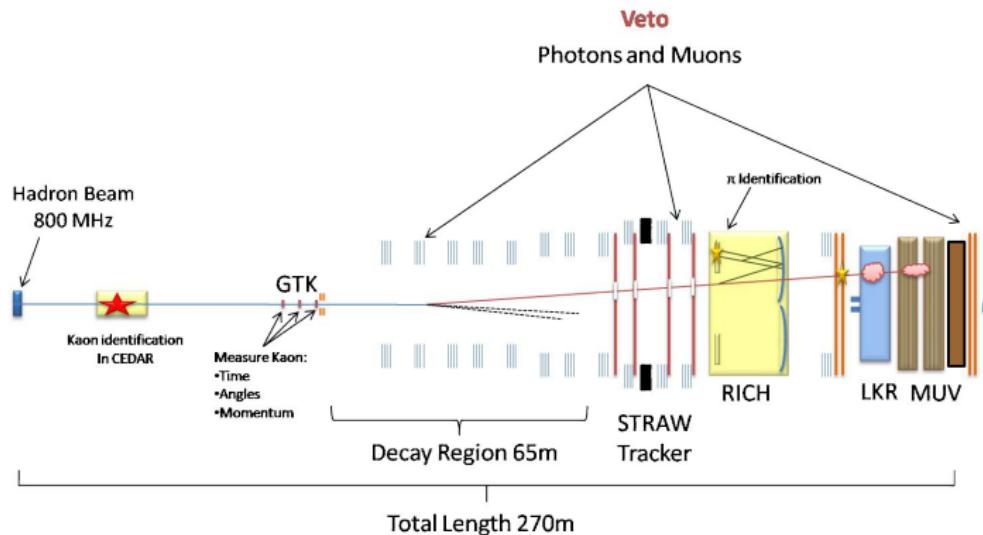
PRL 101:191802,2008]

$K^+ \rightarrow \pi^+ \nu \bar{\nu}$: NA62 AT CERN



[NA62]

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



10.12.09

Na62 Physics Handbook Workshop

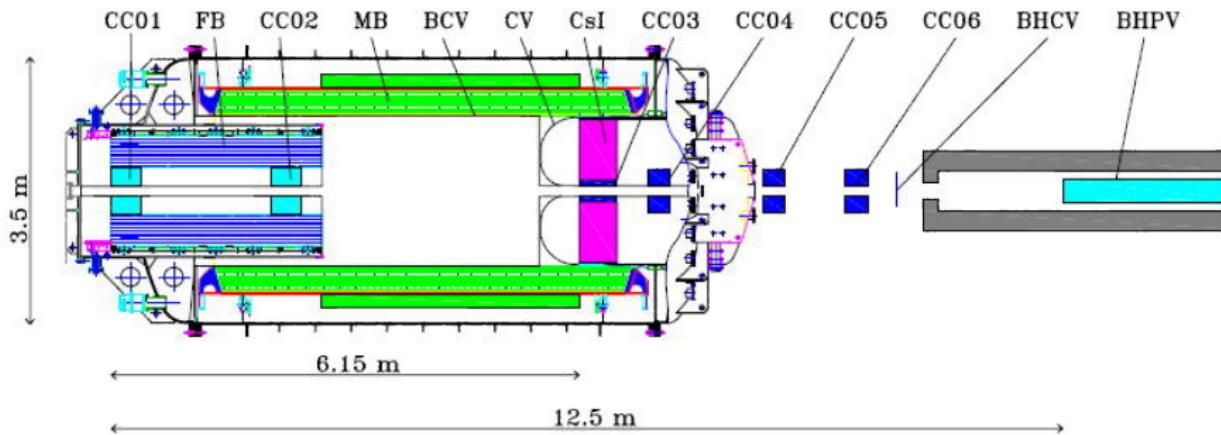
1

$K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$: KOTO AT J-PARC



[KOTO]

- Now upgrading detector. Start in 2011.
- Hermetic detector & pencil beam : all constraints needed
- Expect 3 events next year, 100 events from 2015. $S/B \sim 1.5$.



REFERENCES

Further reading:

BUCHALLA, BURAS, AND LAUTENBACHER Weak Decays Beyond Leading Logarithms. *Rev. Mod. Phys.* 68:1125–1144, 1996. [[hep-ph/9512380](#)].

ANTONELLI ET AL. Flavor Physics in the Quark Sector *Phys.Reps.* 2010.05.003, 2010. [[arXiv:0907.5386 \(hep-ph\)](#)].

TOBIAS HURTH AND MIKIHICO NAKAO Radiative and Electroweak Penguin Decays of B Mesons. Invited contribution to the Annual Review of Nuclear and Particle Science, 2010, 1005.1224. [[arxiv:1005.1224](#)].

TOBIAS HURTH Present status of inclusive rare B decays. *Rev. Mod. Phys.*, 75:1159–1199, 2003. [[hep-ph/021230](#)]

B FACTORIES LEGACY BOOK to be published soon

Conclusion

$b \rightarrow s\gamma$: We have learnt a lot from $b \rightarrow s\gamma$. The phase space for NP has been considerably reduced

RH? We we cannot prove yet that left handed currents dominate in loops

$b \rightarrow \ell\bar{\ell}s$ is the general-purpose new physics laboratory

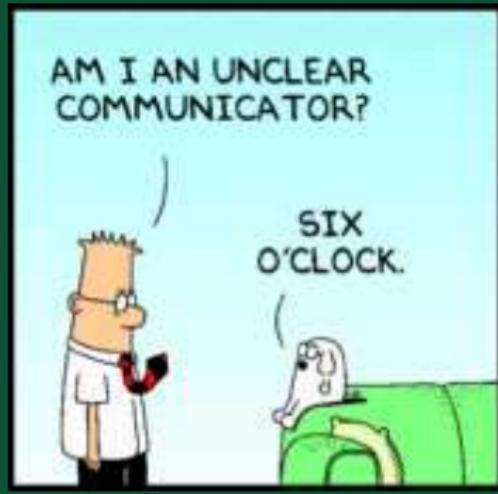
$K \rightarrow \nu\nu\pi$: K has not told us all its secrets yet.
CHARM might be getting interesting

A new era in flavour physics is starting

MERCI AUX ORGANISATEURS

Mes photos sont à <http://www.koppenburg.org/private/Gif/>



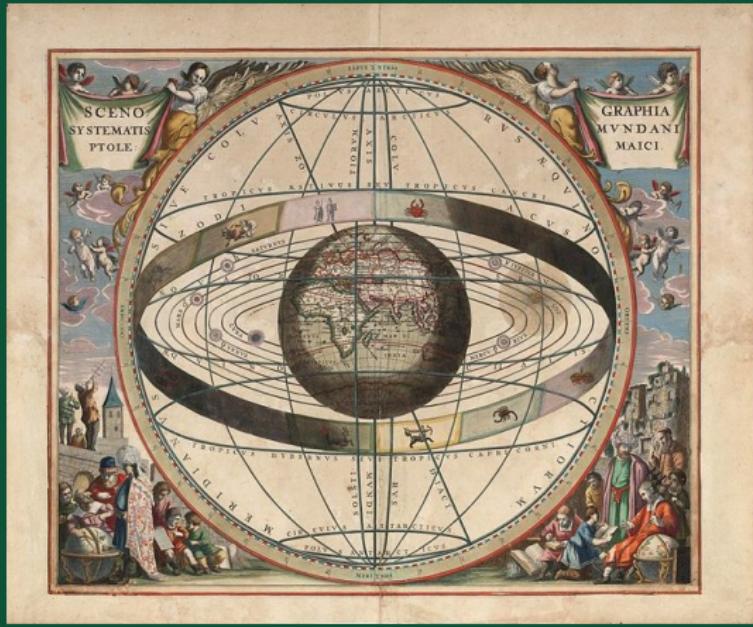


Backup

PENGUINS



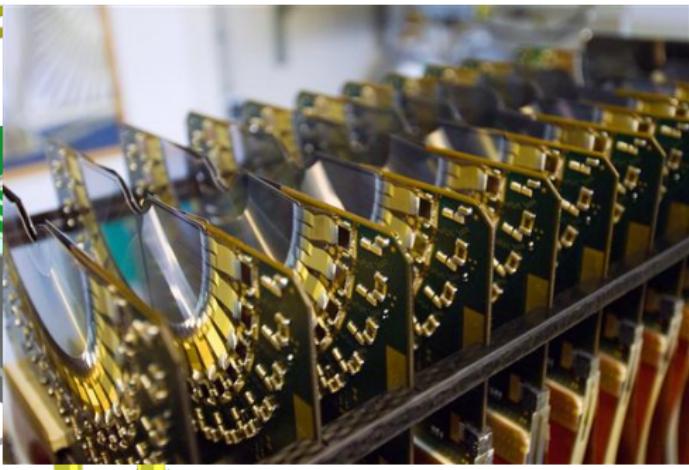
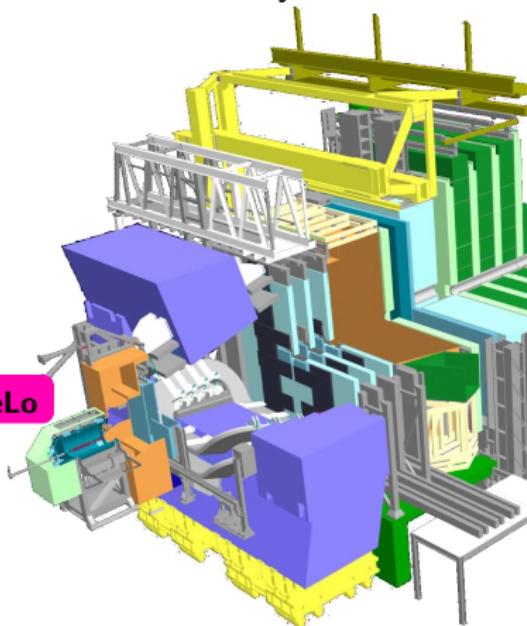
EPICYCLES MUST EXIST



- How else do the planets hold in the sky?
 - How do you explain retrograde movements?
 - They predict correctly the dates of lunar eclipses
- If we look hard enough we'll find them!

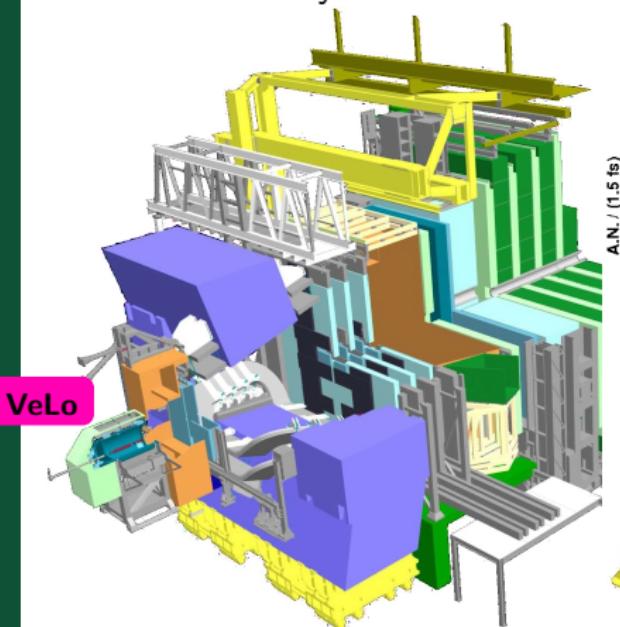
LHCb VERTEX LOCATOR

- 21 stations with r and ϕ strips
- In secondary vacuum and retracted during injection

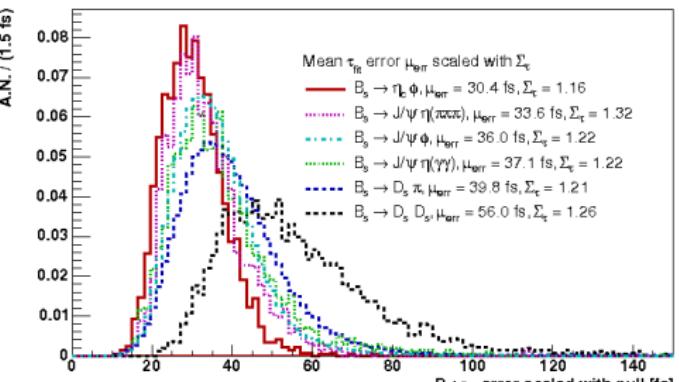


LHCb VERTEX LOCATOR

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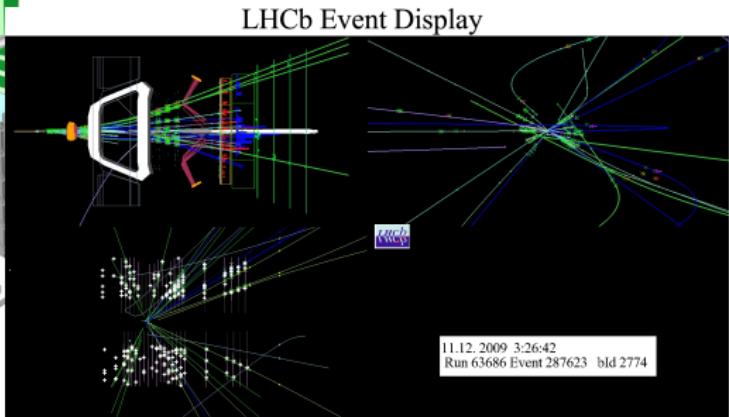
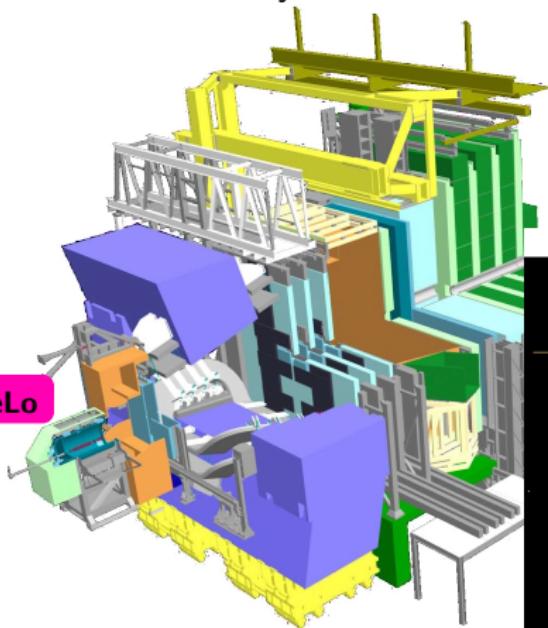


- Proper time resolution between 30 and 50 fs, depending on channel



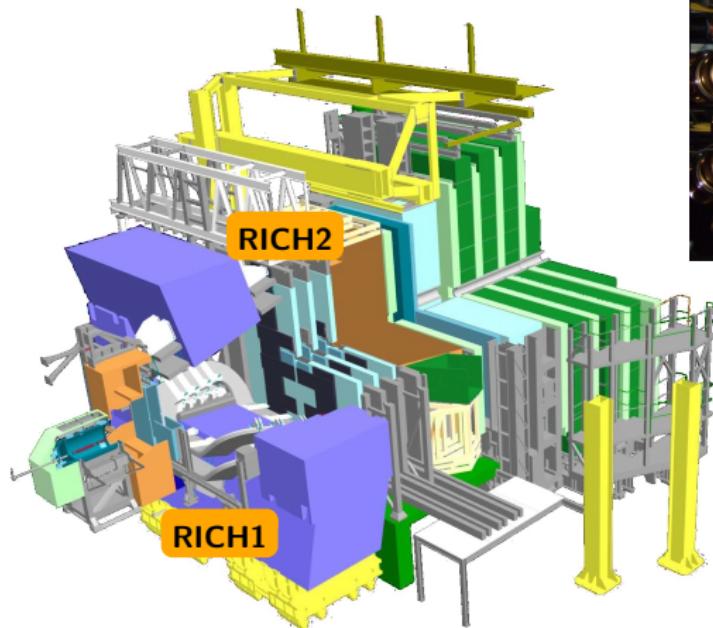
LHCb VERTEX LOCATOR

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LHCb RICH

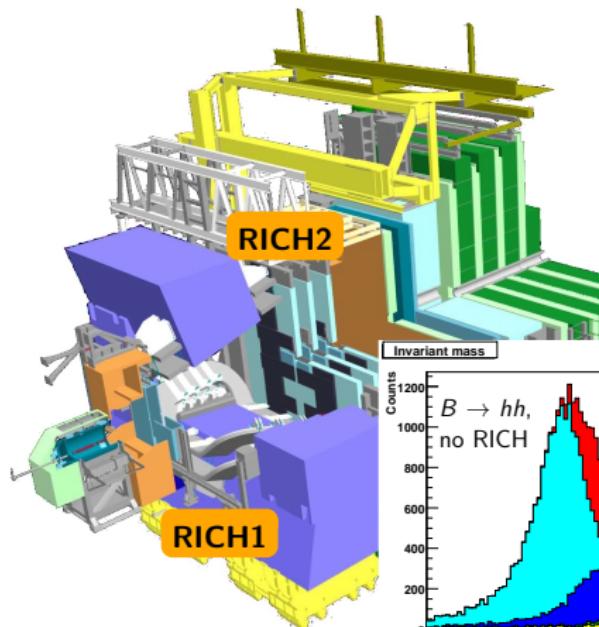
- RICH provides K/π separation using Cherenkov radiation



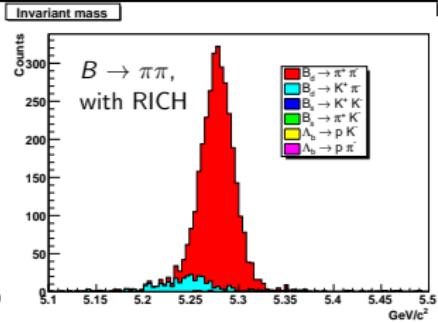
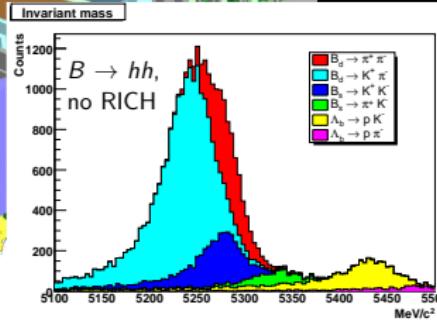
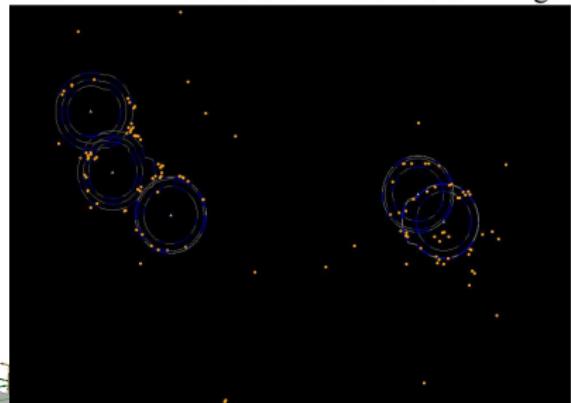
- Use gas and aerogel radiators
- Two detectors for different momentum ranges

LHCb RICH

- RICH provides K/π separation using Cherenkov radiation

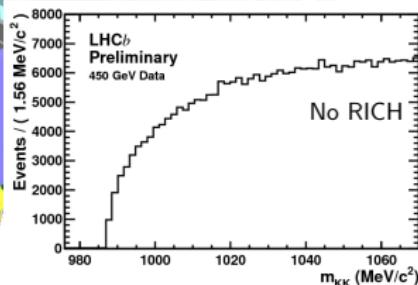
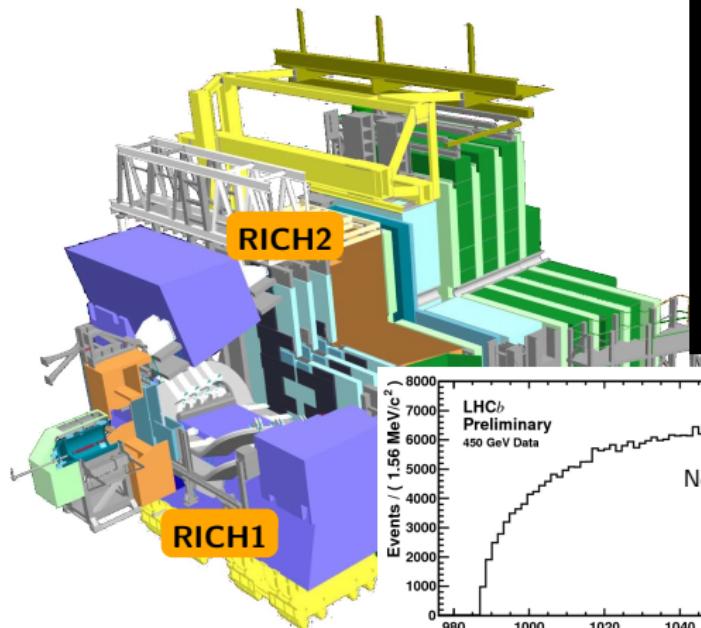


RICH2 HPD Panels with Pixels and CK Rings

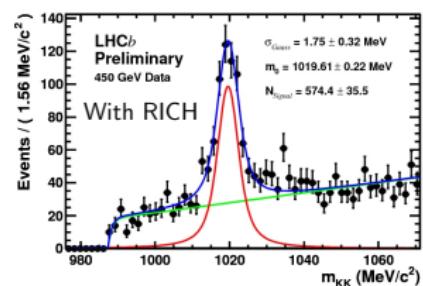
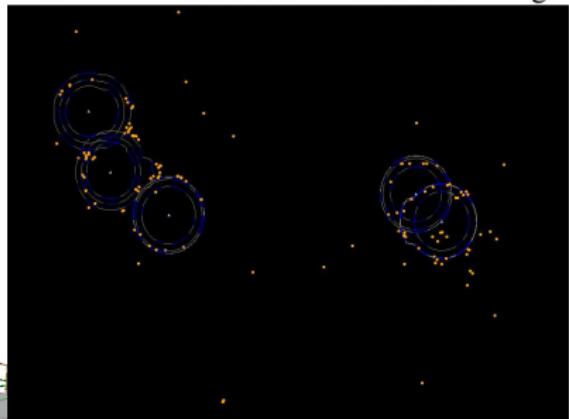


LHCb RICH

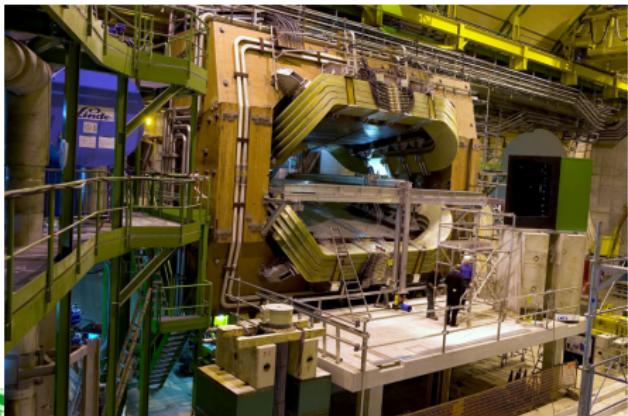
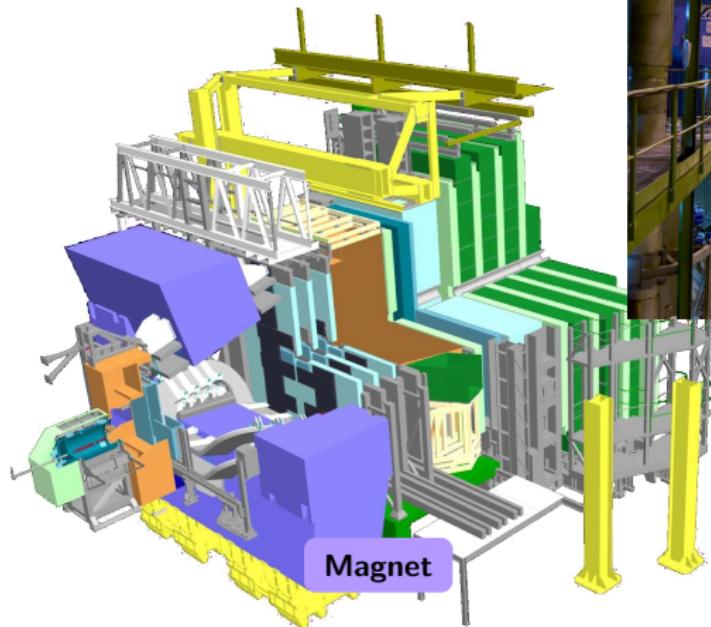
- RICH provides K/π separation using Cherenkov radiation



RICH2 HPD Panels with Pixels and CK Rings



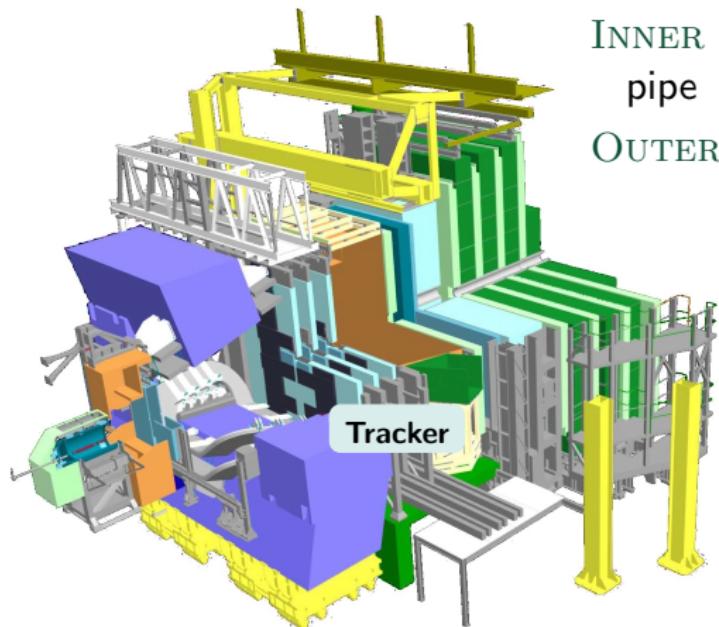
LHCb MAGNET



- Warm solenoid magnet
 - 3 Tm integrated field
 - Can swap polarity
- needed for CP studies

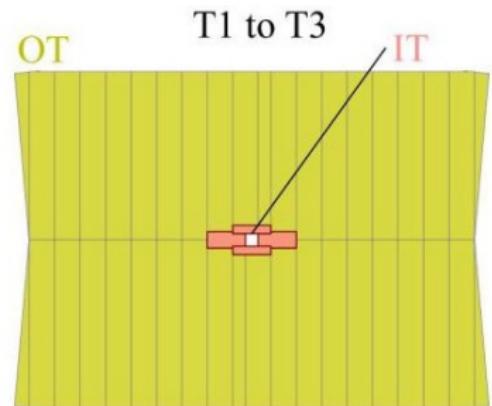
LHCb TRACKERS

TRIGGER TRACKER: before the magnet



INNER TRACKER: around the beam pipe

OUTER TRACKER: around IT



LHCb TRACKERS



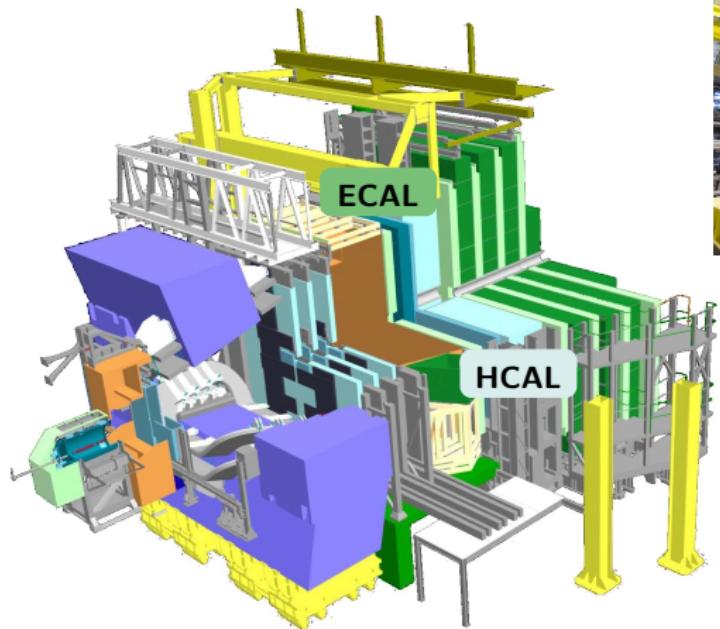
TRIGGER TRACKER: before the magnet

INNER TRACKER: around the beam pipe

OUTER TRACKER: around IT

- OT are straw tubes.
 - Close to the beam pipe the occupancy is too high
- TT and IT are silicon strip detectors

CALORIMETRY

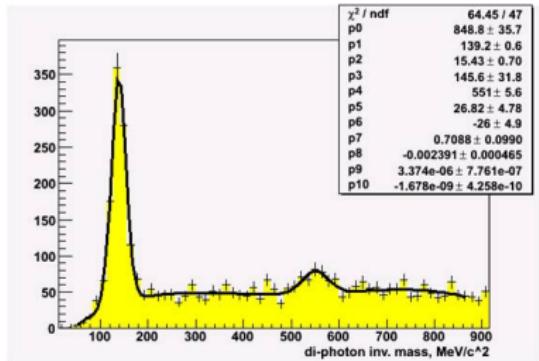
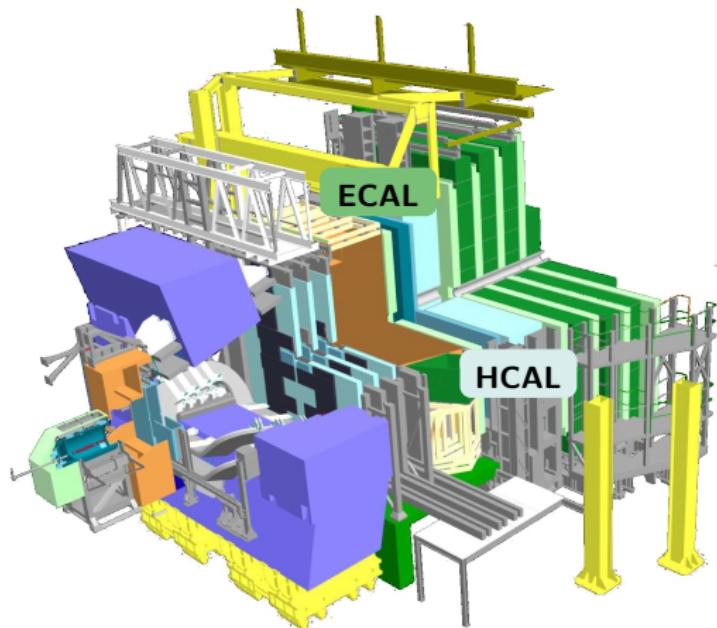


ECAL: For γ and π^0 detection, and e identification

- Layers of lead and plastic scintillators

PRESHOWER:
Lead/scintillator

CALORIMETRY



ECAL: For γ and π^0 detection, and e identification

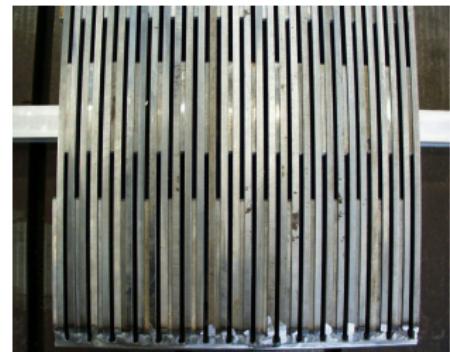
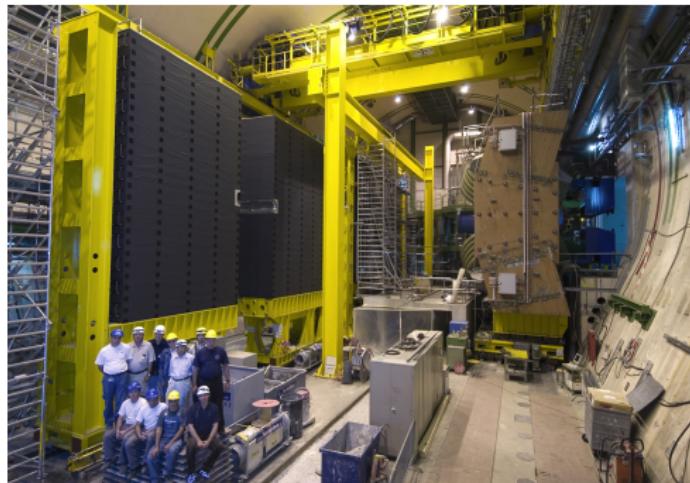
- Layers of lead and plastic scintillators

PRESHOWER:
Lead/scintillator

CALORIMETRY

HCAL: For any hadron

- Scintillator tiles embedded in an iron structure
- The HCAL is actually only used in the trigger



ECAL: For γ and π^0 detection, and e identification

- Layers of lead and plastic scintillators

PRESHOWER:
Lead/scintillator

LHCb MUON DETECTOR

- Four stations M2–M5 embedded in an ion filter, M1 in front of ECAL
- Read out by gas detectors (triple GEM and MWPCs)

