

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 [1/66]

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: $b \rightarrow \ell\ell s$

DESERT: **Charm and Kaons**

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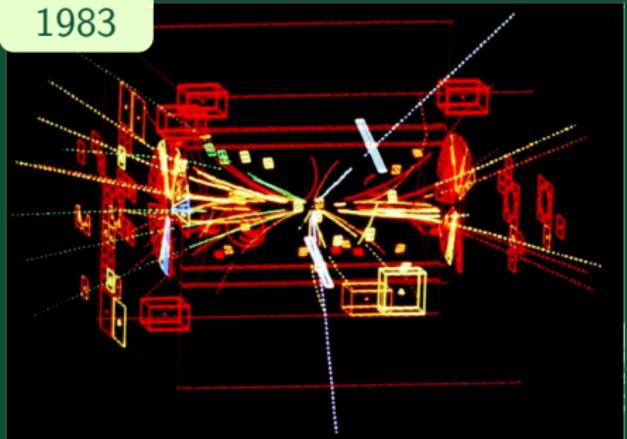
INDIRECT SEARCHES

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



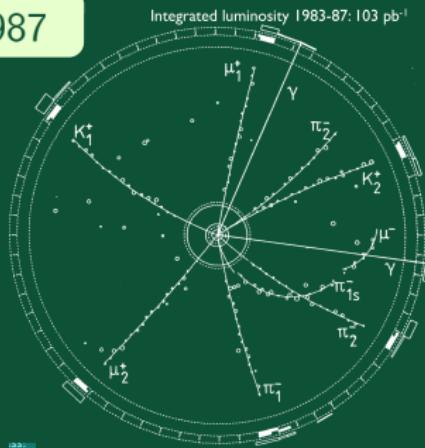
INDIRECT SEARCHES

1973



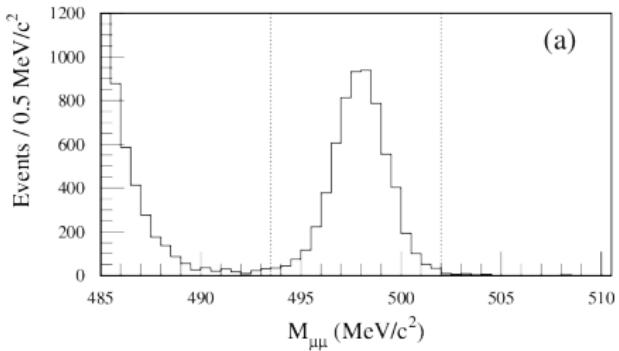
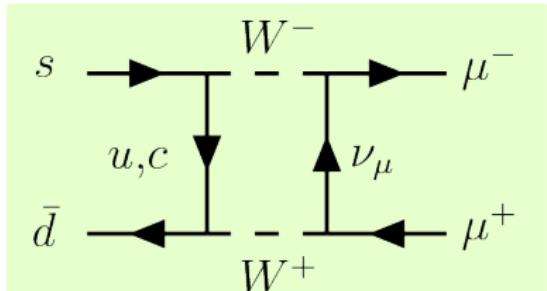
- Sensitive to New Physics effects
 - When was the Z discovered?
 - 1973 from $N\nu \rightarrow N\nu$?
 - 1983 at SpS?
 - c quark postulated by GIM, third family by KM
- Estimate masses
 - t quark from $B\bar{B}$ mixing
- Get phases of couplings
 - Half of new parameters
 - Needed for a full understanding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

1987



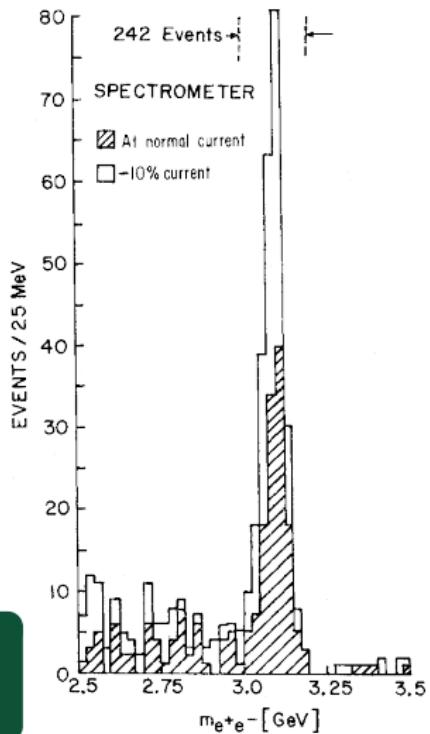
$$K_L^0 \rightarrow \mu\mu$$

- $K_L^0 \rightarrow \mu\mu$ 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]



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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.

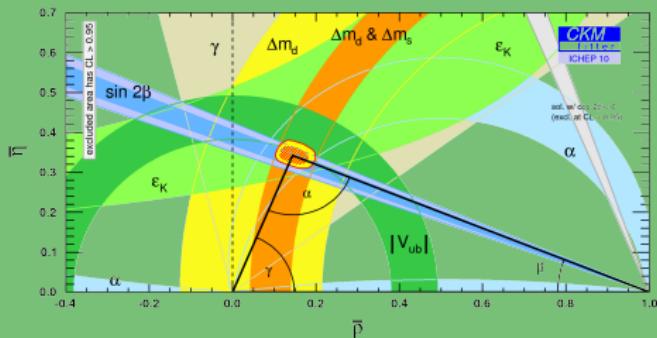
- ② Similarly

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^-)

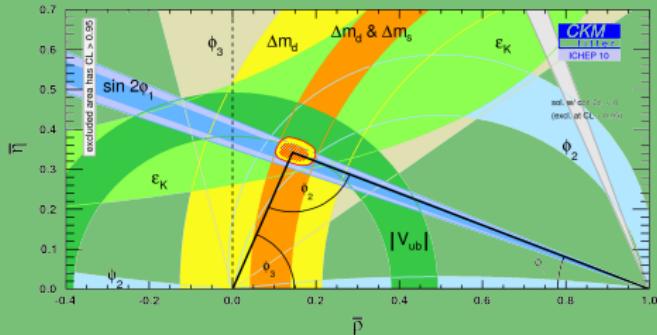
CONVENTIONS



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} .

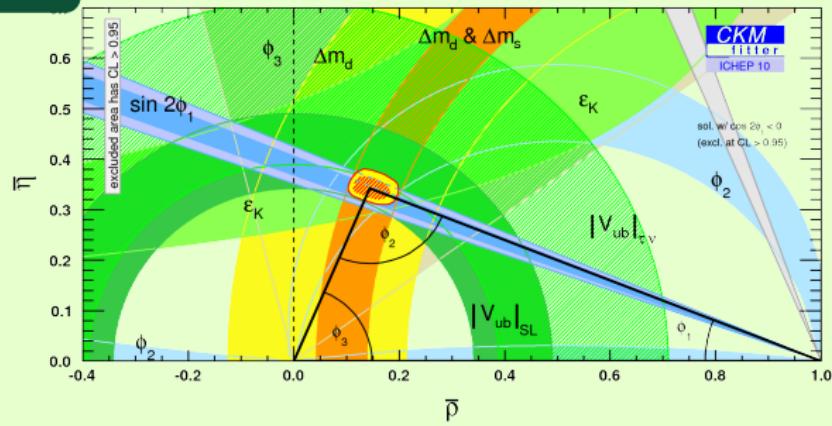
[whole story]



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

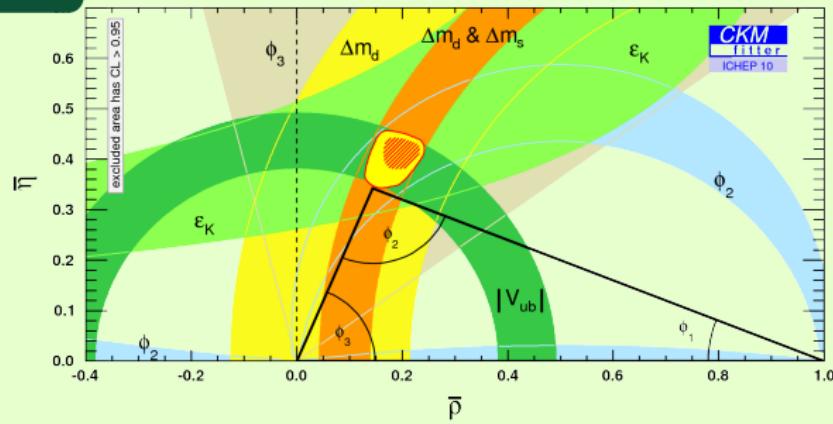
All constraints



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 $\sin 2\phi_1$



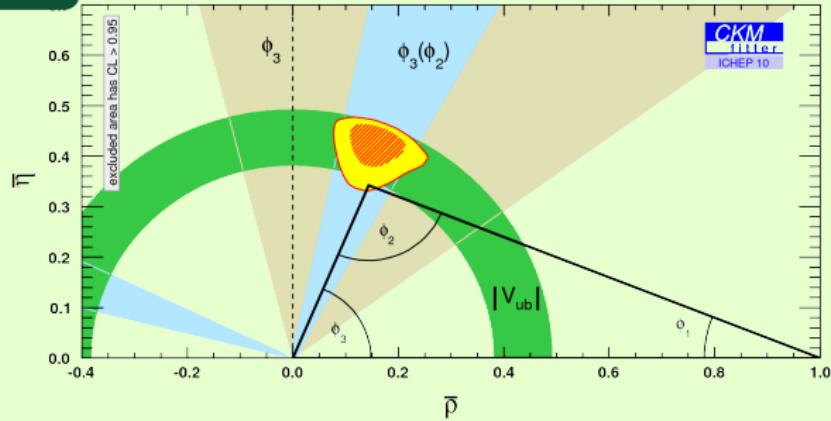
[CKMfitter 09/09]



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]

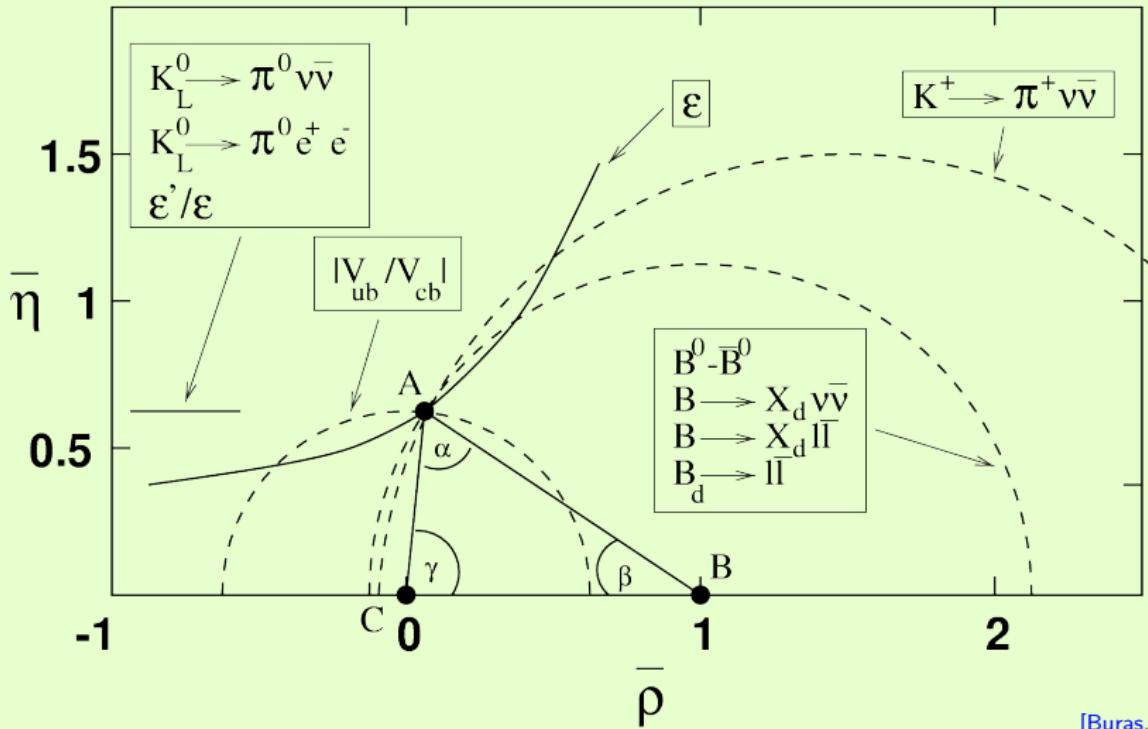
UNITARITY TRIANGLE

- 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_s
- ✓ 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.

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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](https://arxiv.org/abs/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

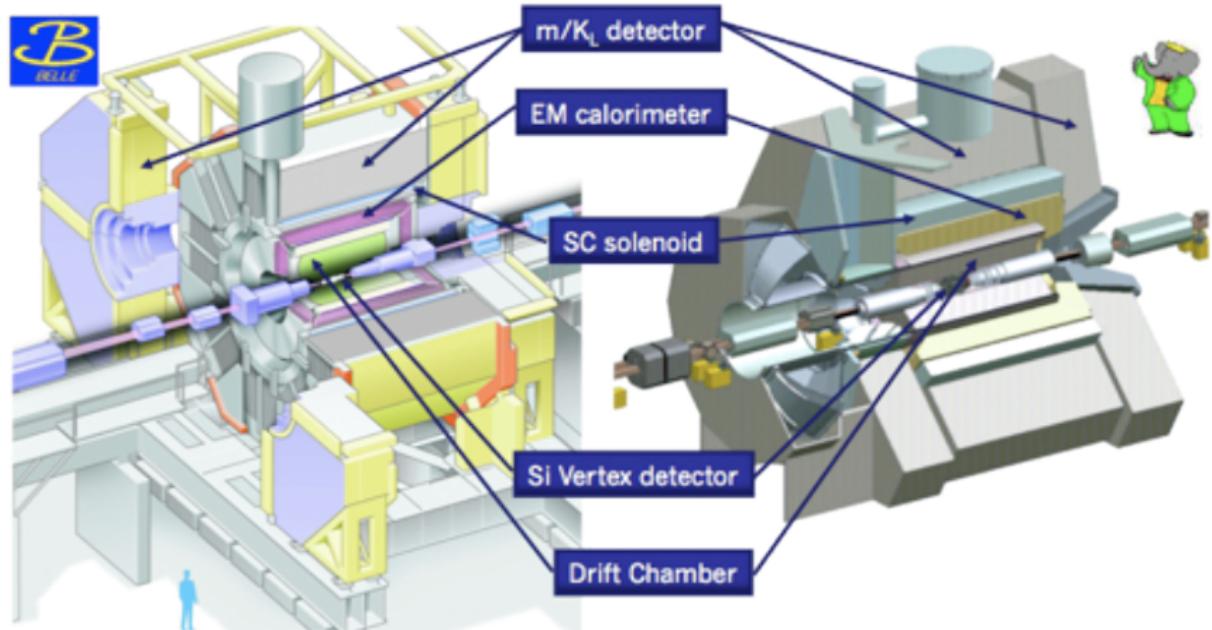
EXPERIMENTAL ASPECTS:

- 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

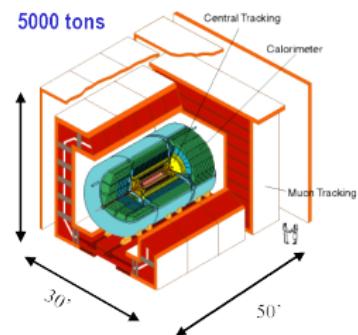
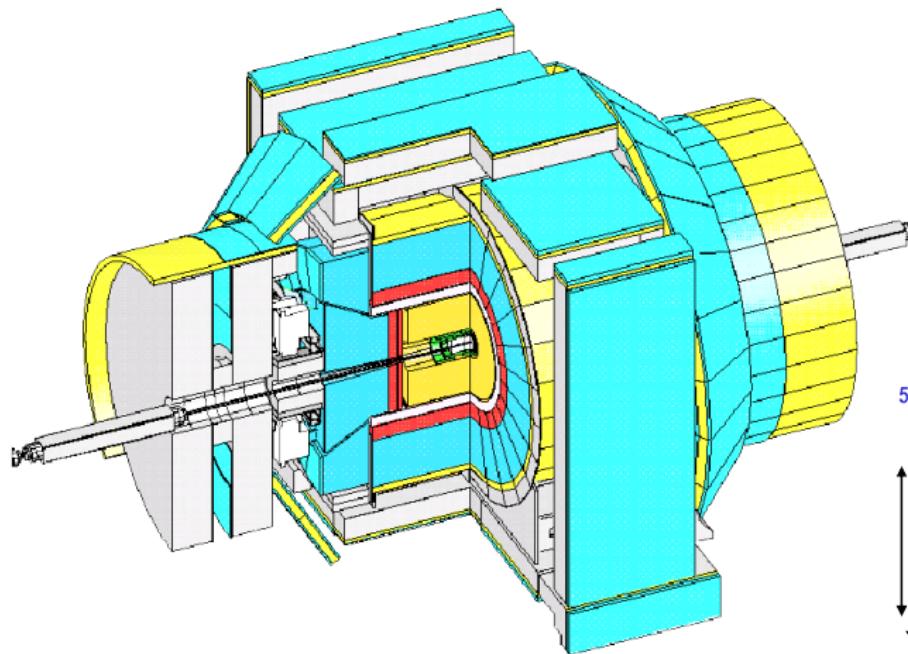
THEORETICAL CLEAN: There are many rare decays that are theoretically clean. This is needed as in the end you will compare a measured effect to an SM prediction.

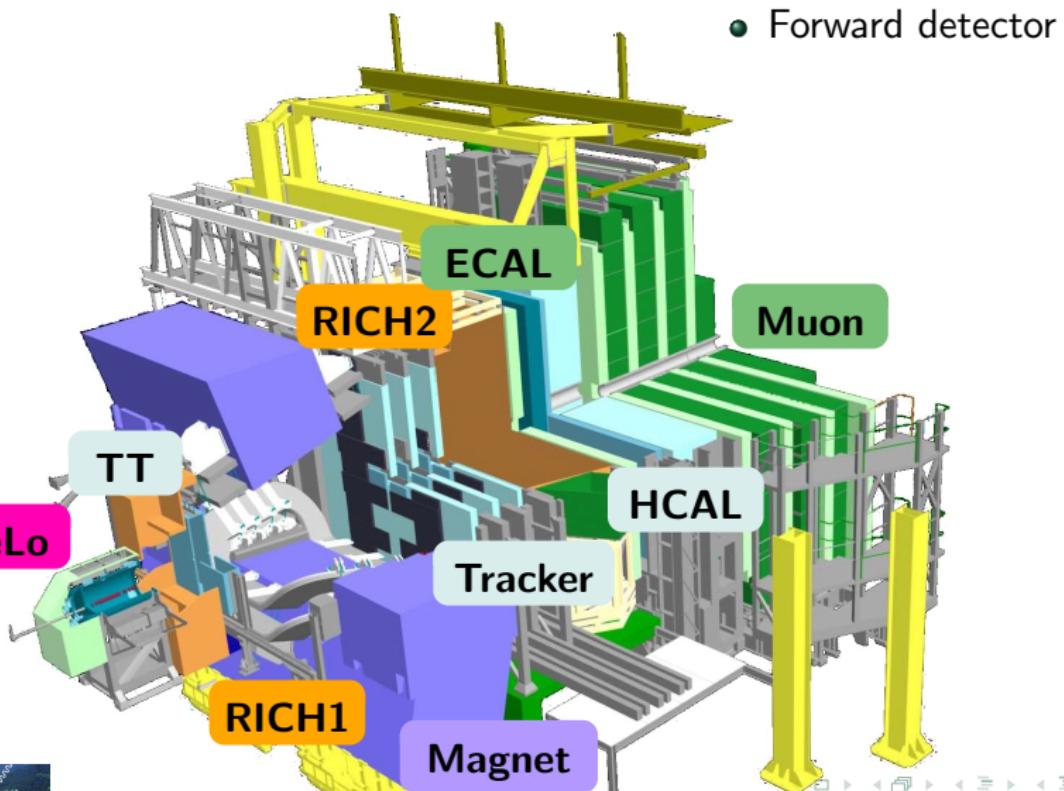


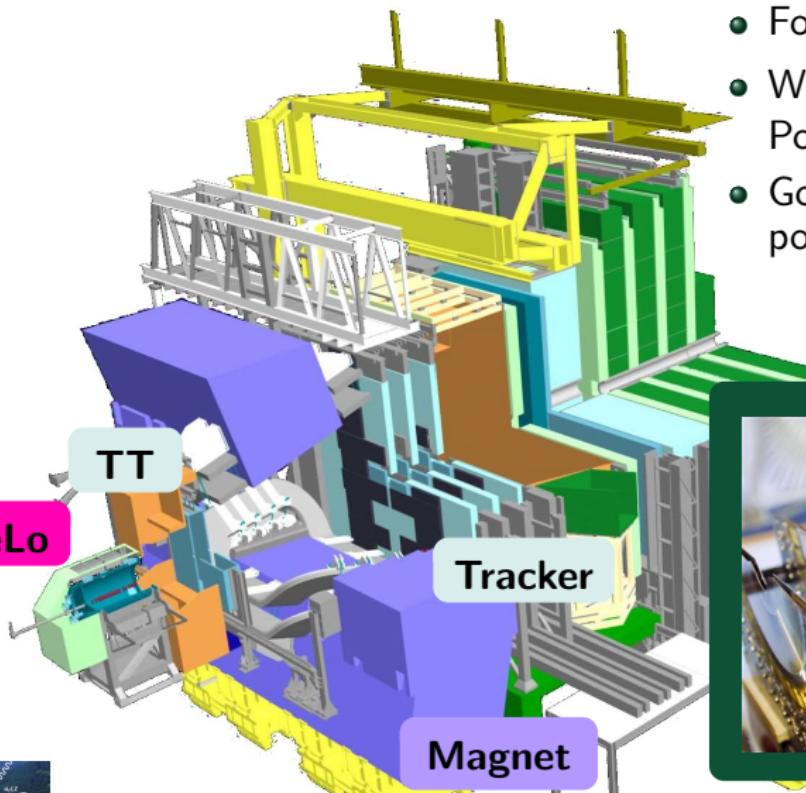
BELLE AND BABAR



CDF AND D0

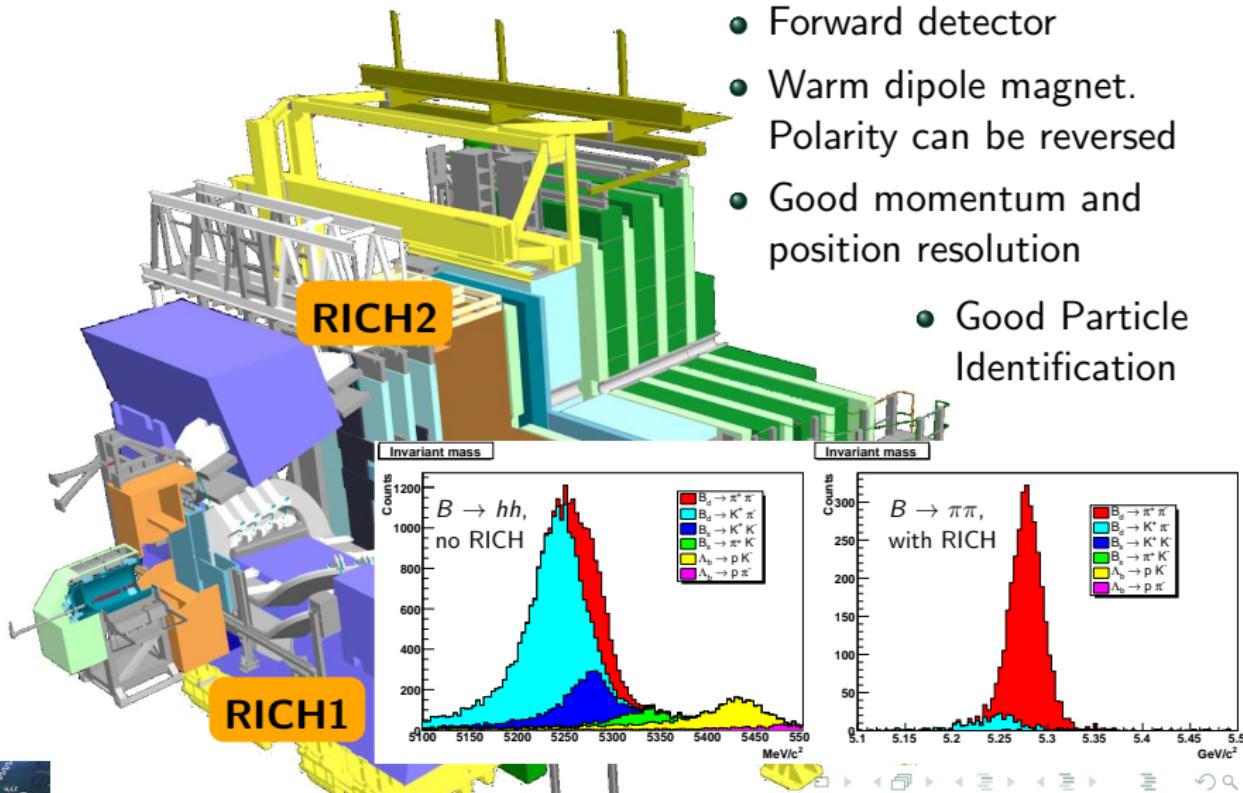






- Forward detector
- Warm dipole magnet.
Polarity can be reversed
- Good momentum and position resolution
 - Vertex detector gets 8mm to the beam

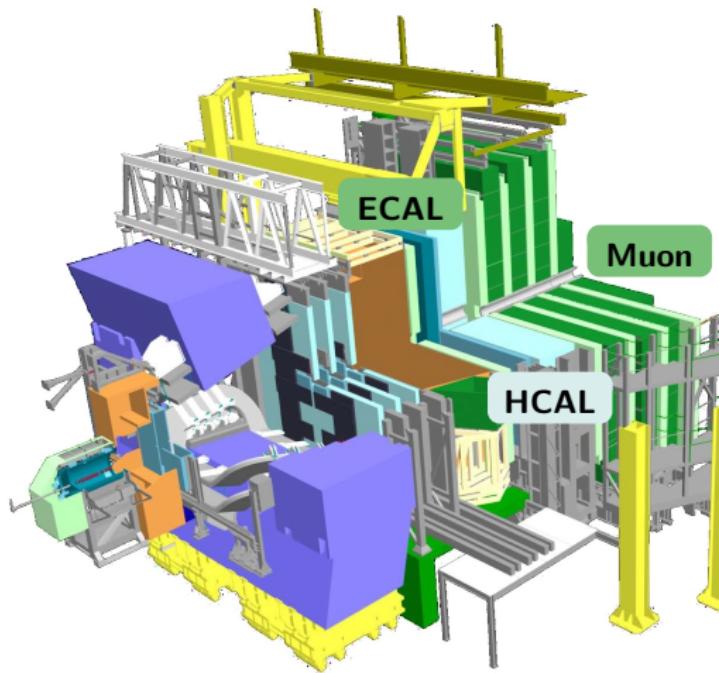




LHCb TRIGGER



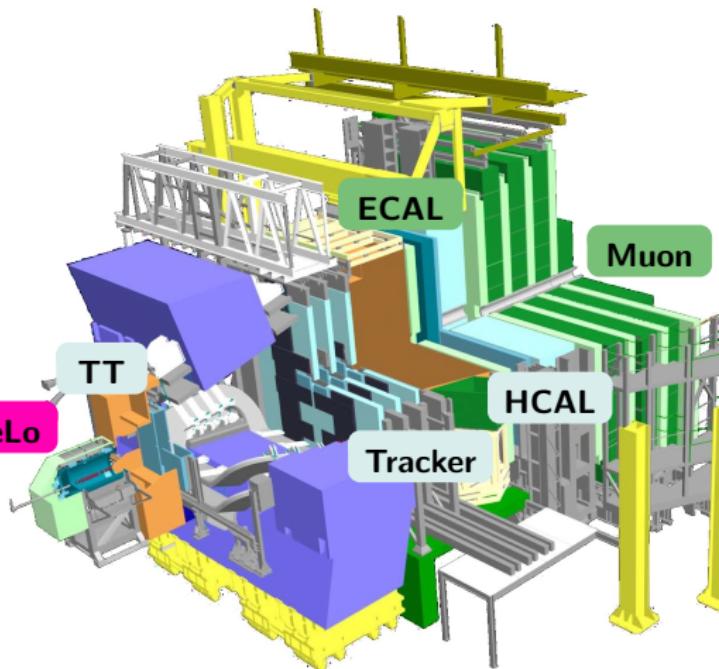
- Hardware-based L0 trigger:
moderate p_T cuts: 40 MHz
→ 1 MHz



LHCb TRIGGER



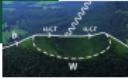
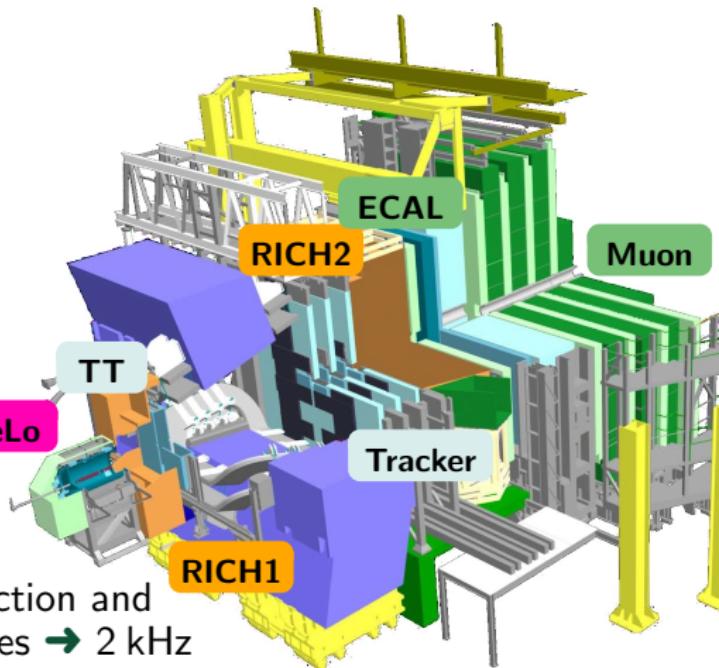
- Hardware-based L0 trigger:
moderate p_T cuts: 40 MHz
→ 1 MHz
- The whole data is then sent at 1 MHz to a farm of $\mathcal{O}(2000)$ CPUs
- HLT1 tries to confirm a L0 decision by matching the L0 candidates to tracks.
→ ~ 30 kHz



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

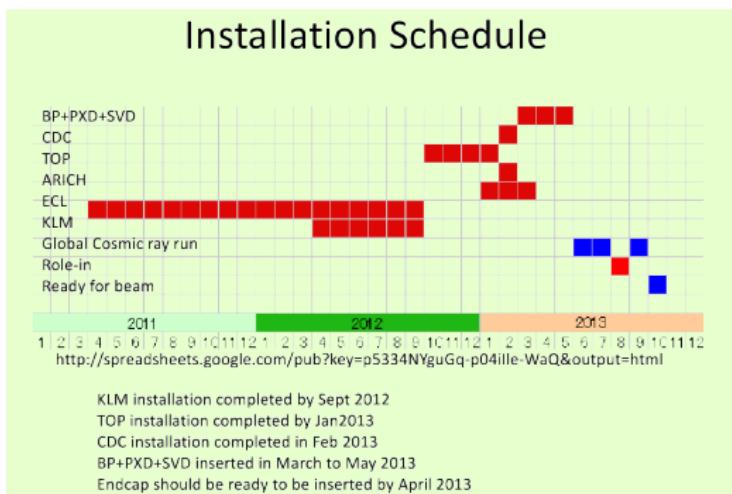
B FACTORIES:

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:

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Hence:

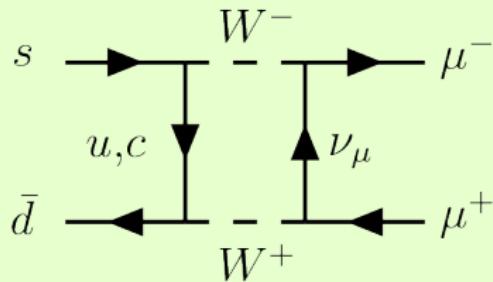
- ① The measurements will be dominated by LHCb
 - I'll assume LHCb will have collected 10 fb^{-1}
 - Could be less: doesn't change conclusions
- ② Except in channels that LHCb can't do
 - Where Belle \oplus Babar will dominate
 - I'll point these channels out

Total 7–14 TeV $5\text{--}10 \text{ fb}^{-1}$ 30 fb^{-1}

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

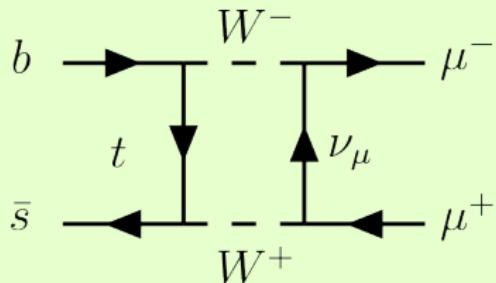
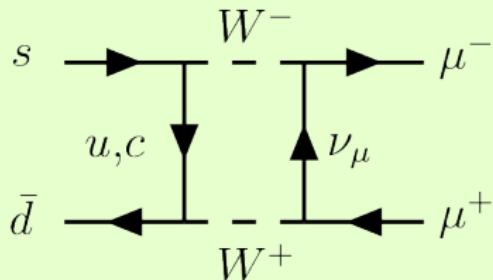


$$B_s^0 \rightarrow \mu\mu$$

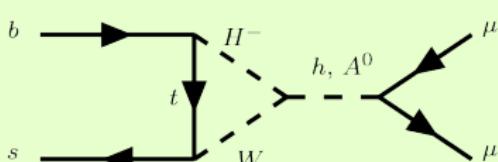
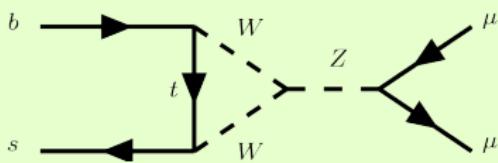


- Start with $K_L^0 \rightarrow \mu\mu$

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



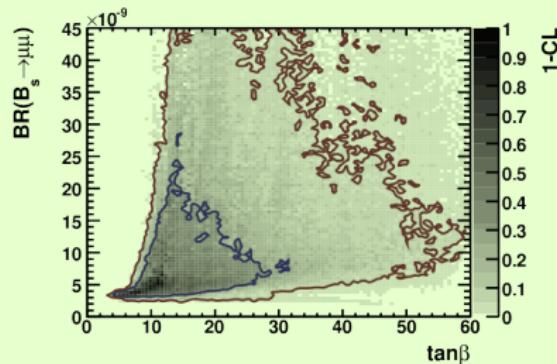
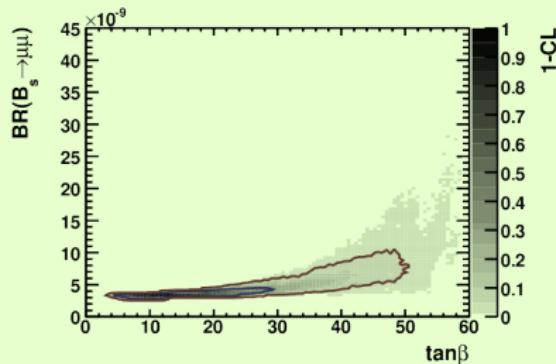
- Start with $K_L^0 \rightarrow \mu\mu$
 - Replace quarks by b and \bar{s} (for B_s^0) and t ($\propto V_{tb} V_{ts}$)
 - Add a penguin contribution ($\propto V_{tb} V_{ts}$)
 - Add a hypothetical charged Higgs contribution ($\propto ?$)
- Gets what BF?



$B_s^0 \rightarrow \mu\mu$

- 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]

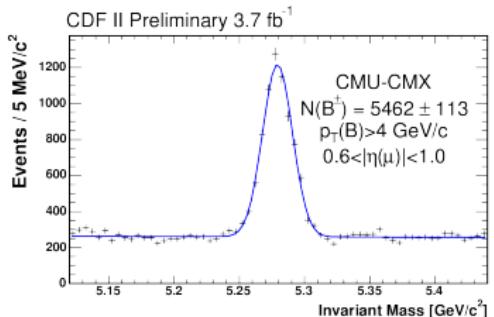
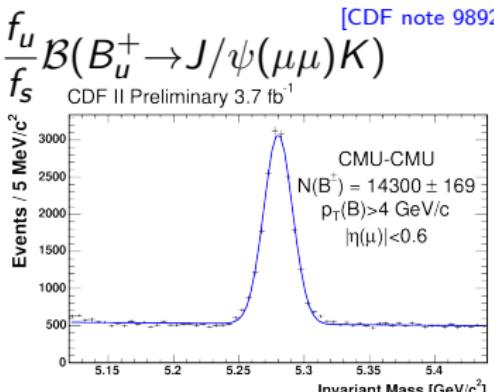
$N_{B_s^0}^{95\% \text{ CL}}$: number of $B_s^0 \rightarrow \mu\mu$ decays at 95% CL for N observed and N_b expected background events,

$N_{B_u^+} = 14300, 5460$ 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]

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

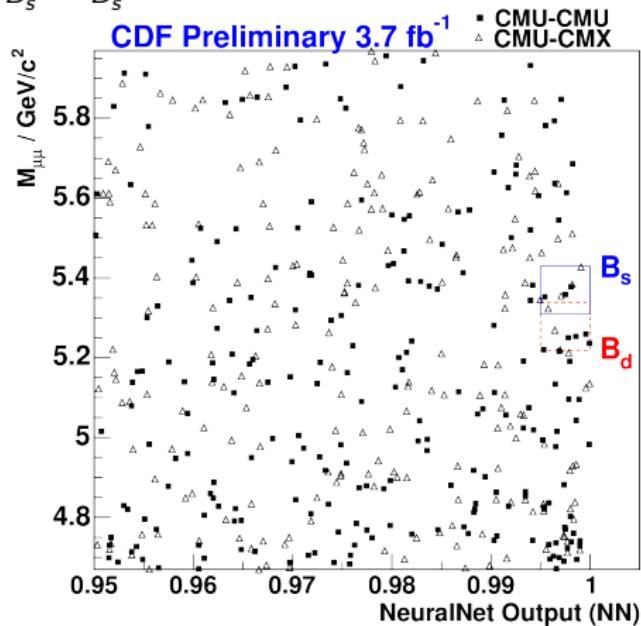
$$\begin{aligned}\mathcal{B}(B_s^0 \rightarrow \mu\mu) &< 4.3 \cdot 10^{-8} \\ \mathcal{B}(B_d^0 \rightarrow \mu\mu) &< 7.6 \cdot 10^{-9}\end{aligned}$$

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)]:

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



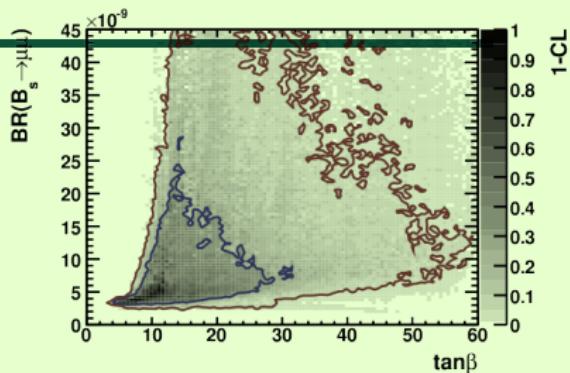
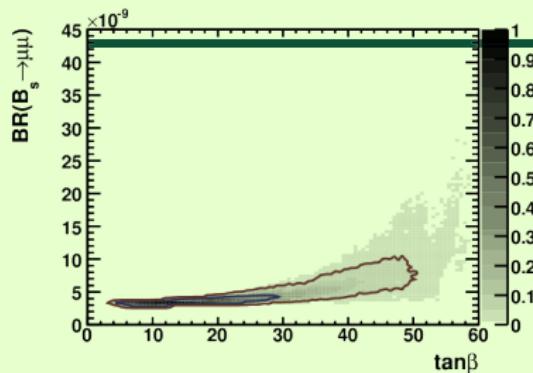
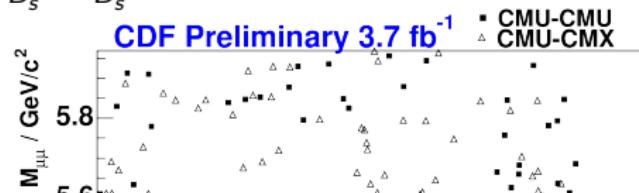
$B_s^0 \rightarrow \mu\mu$ LIMITS



[CDF note 9892]

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

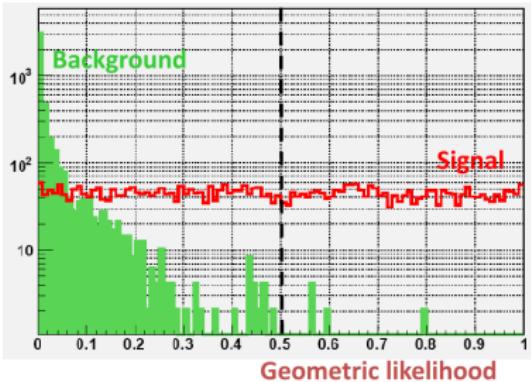
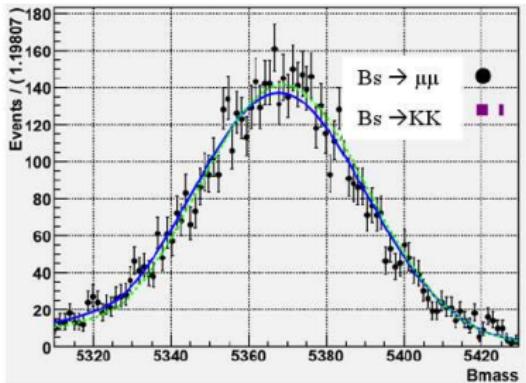
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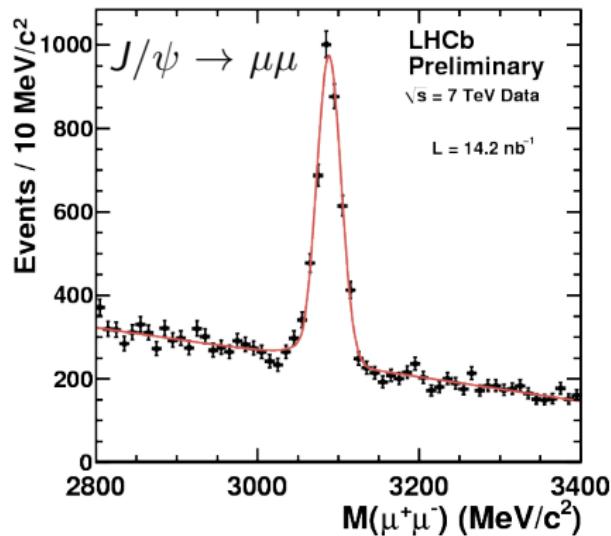
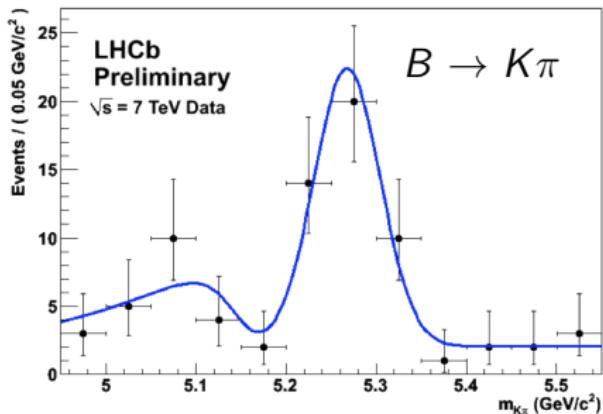
$B_s^0 \rightarrow \mu\mu$ AT LHCb



- 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

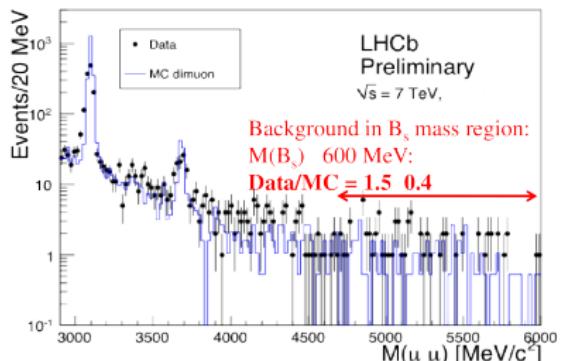


$B_s^0 \rightarrow \mu\mu$ CONTROL SAMPLES

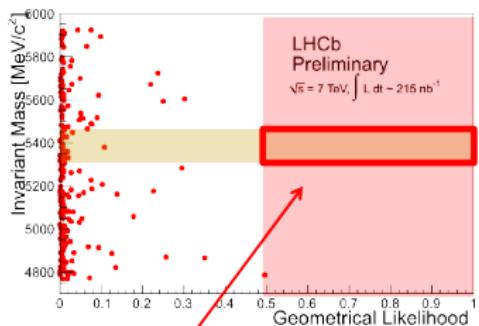


- LHCb see $B_s^0 \rightarrow K\pi$ events
- And plenty of $J/\psi \rightarrow \mu\mu$ events
- All the ingredients are there for $B_s^0 \rightarrow \mu\mu$!

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



Mass vs Geometrical Likelihood:



Sensitive region:

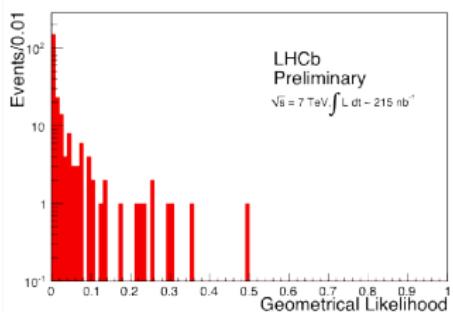
$M(Bs) > 60 \text{ MeV}/c^2 \& \& GL > 0.5$

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

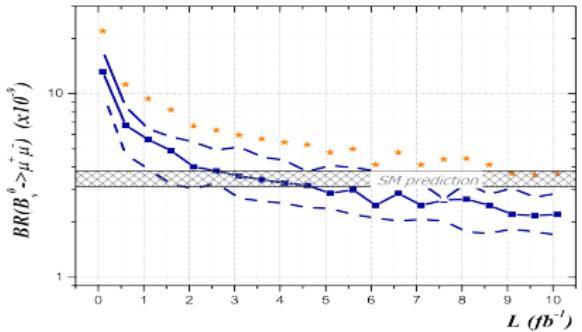
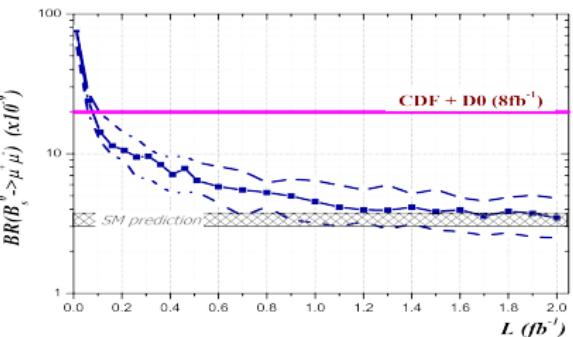
Geometrical Likelihood distribution



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



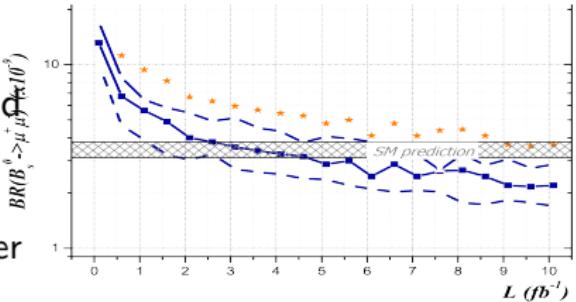
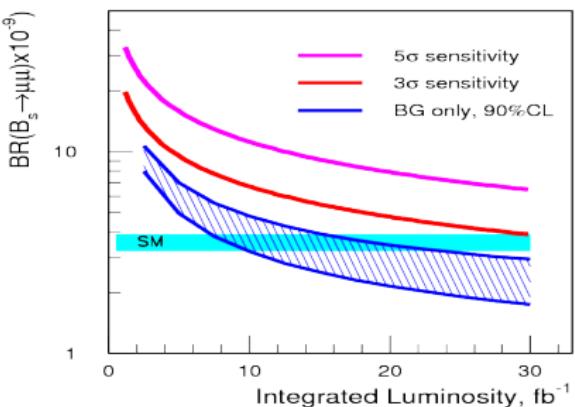
- Select signal in a 3D-box of mass, geometrical likelihood, PID likelihood
 - Uncorrelated variables with different control samples
 - B mass resolution ~ 20 MeV
- With SM BF, expect 8 signal and 12 background events in most sensitive bin in 2 fb^{-1}
 - 3σ evidence with 2 fb^{-1}
 - 5σ observation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

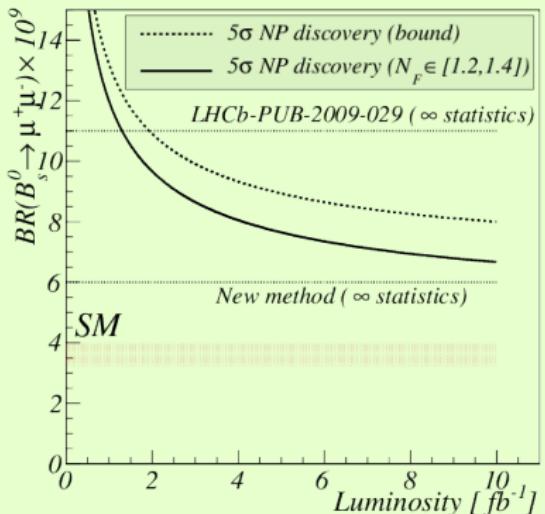
$$\mathcal{B}(B_s^0 \rightarrow \mu\mu) = \frac{N_{B_s^0}^{95\% \text{ CL}}}{N_{B_d^+}} \frac{\alpha_{B_d^0}}{\alpha_{B_s^0}} \frac{\epsilon_{B_d^0}}{\epsilon_{B_s^0}} \frac{f_d}{f_s} \mathcal{B}(B_d^0 \rightarrow J/\psi(\mu\mu) K^*)$$

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)]



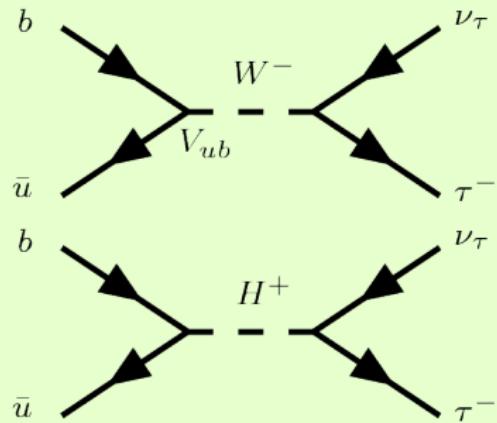
$$B \rightarrow \tau \nu$$

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

- Tree diagram, but quite rare:

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

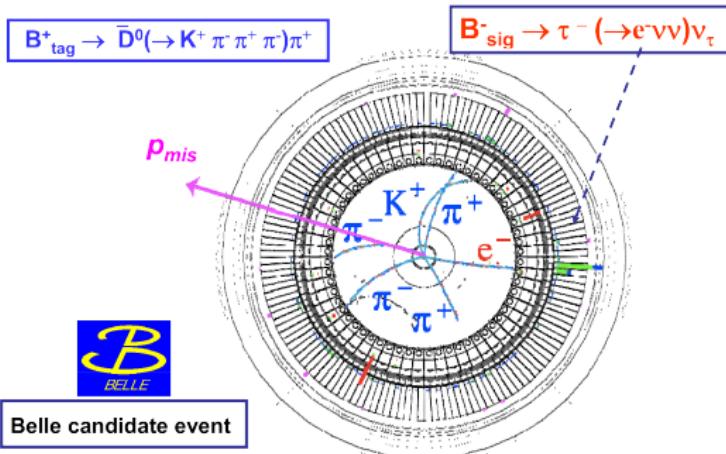
- for $B_u^+ \rightarrow \mu \nu$, replace m_τ by m_μ
and see the BF decrease...



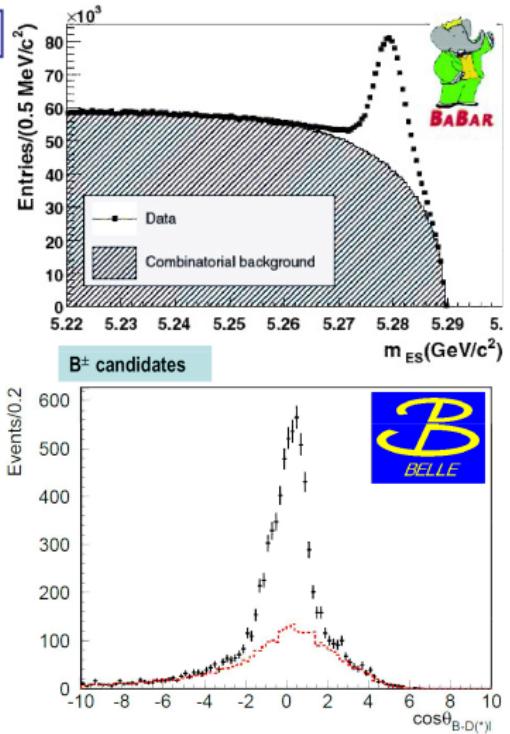
Higgs-mediated diagram **reduces** (small $\tan \beta$) or **enhances** the BF:

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

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



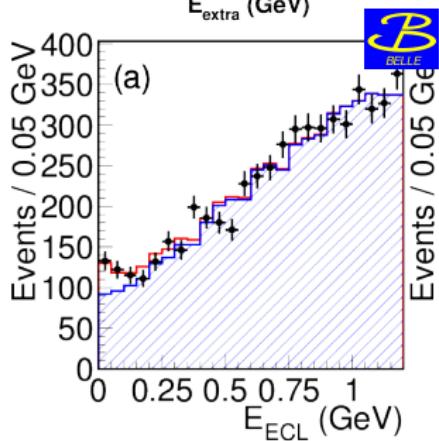
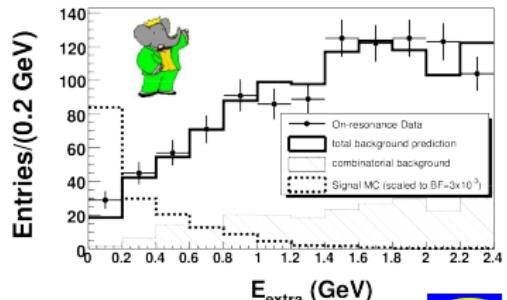
$$B \rightarrow \tau \nu$$



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

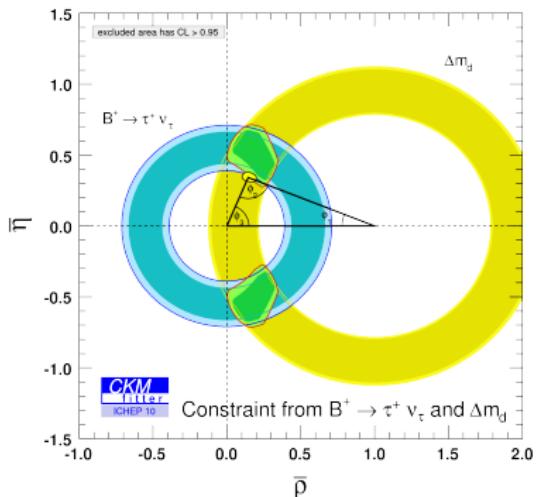
$$\mathcal{B} = (1.8 \pm 0.8 \pm 0.1) \cdot 10^{-4}$$

A bit on the high side for the SM.

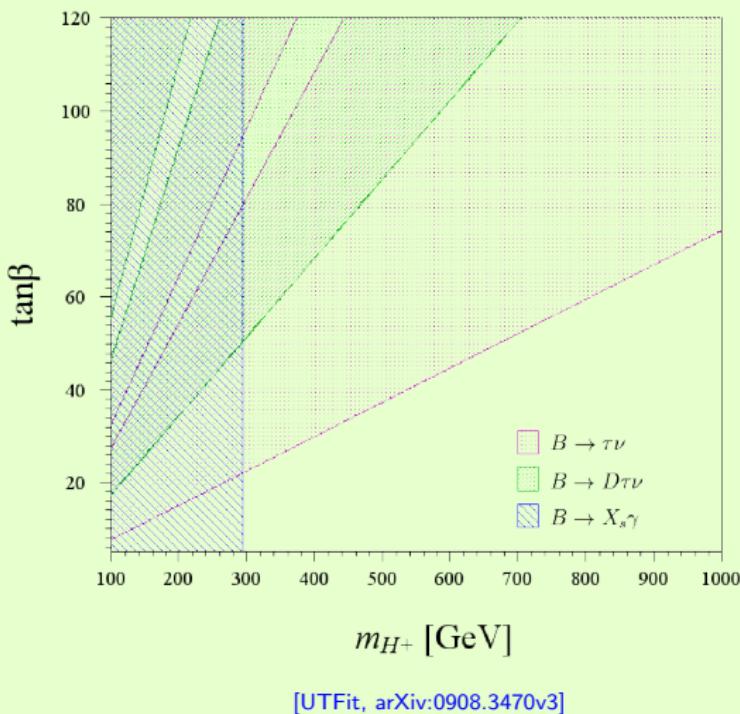
Even worse for MSSM at low $\tan\beta$

→ strong constraint on m_{H^\pm} .

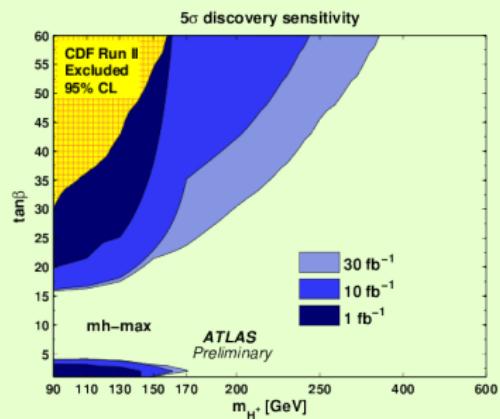
[Babar, PRD81.051101 (2008)], [Belle, 1006.4201v1 (hep-ex)]



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. $\bar{s} \rightarrow u\bar{s}u$:

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

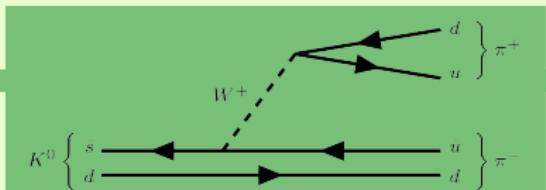
where we have defined the operator

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

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 $K^0 \rightarrow \pi^+ \pi^+$:

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

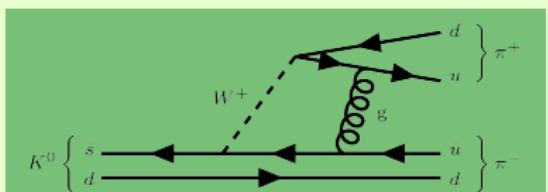
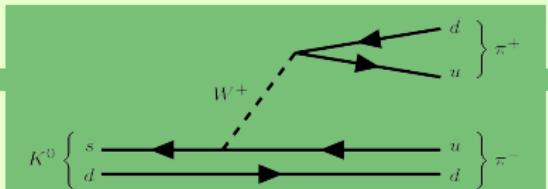
The Hamiltonian now becomes

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

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

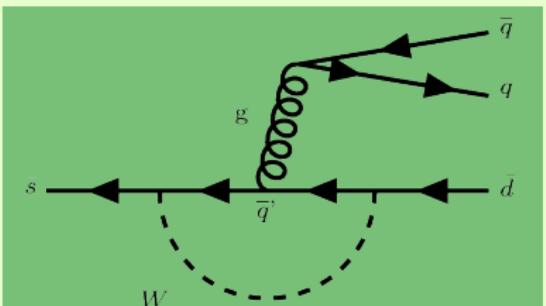
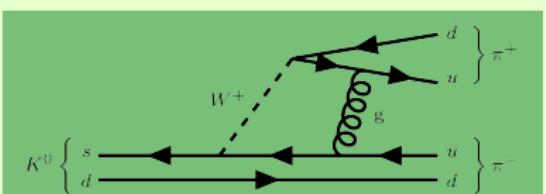
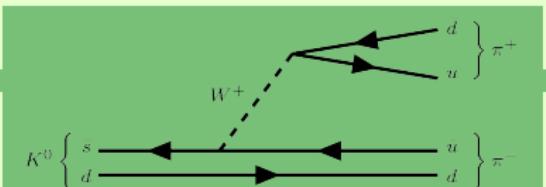
We then add penguin operators :

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

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

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

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



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

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

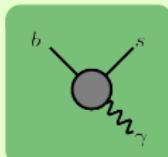
THE SHORT-DISTANCE PART: The Wilson coefficients contain all heavy degrees of freedom. They can be calculated within many models including the SM and supersymmetry at in principle any order. If new particles appear in the loops they will only affect the values of the Wilson coefficients. If we can measure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

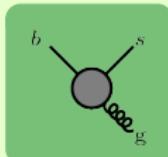
$\mathcal{O}_{7\gamma}$



Effective Hamiltonian \mathcal{H}

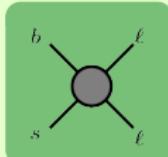
$$A(M \rightarrow F) = \langle F | \mathcal{H}_{\text{eff}} | M \rangle$$

\mathcal{O}_{8g}



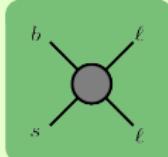
$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{ts}^* V_{tb} \sum_{i=1}^{10} C_i(\mu) \mathcal{O}_i(\mu)$$

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



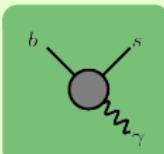
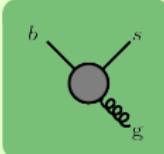
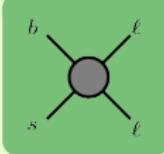
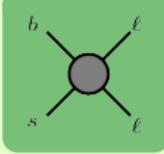
- Operators \mathcal{O}_i : Long-distance effects
- Wilson coefficients C_i : Short-distance effects (masses above μ are integrated out)

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



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

OPERATORS OF INTEREST

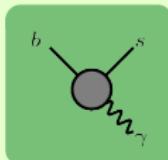
Operator	Magnitude	Phase	Helicity flip \mathcal{O}_i'
$\mathcal{O}_{7\gamma}$		$b \rightarrow s\gamma$	$A_{CP}(b \rightarrow s\gamma)$
\mathcal{O}_{8g}		$b \rightarrow s\gamma$ $b \rightarrow \{s, u, d\}$	$A_{CP}(b \rightarrow s\gamma)$ $B \rightarrow \phi K$
$\mathcal{O}_{9V,10A}$		$b \rightarrow \ell\ell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

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

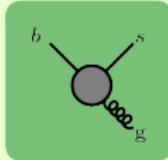
OPERATORS OF INTEREST

Operator

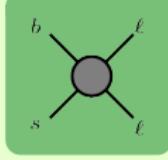
$\mathcal{O}_{7\gamma}$



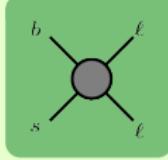
\mathcal{O}_{8g}



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



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



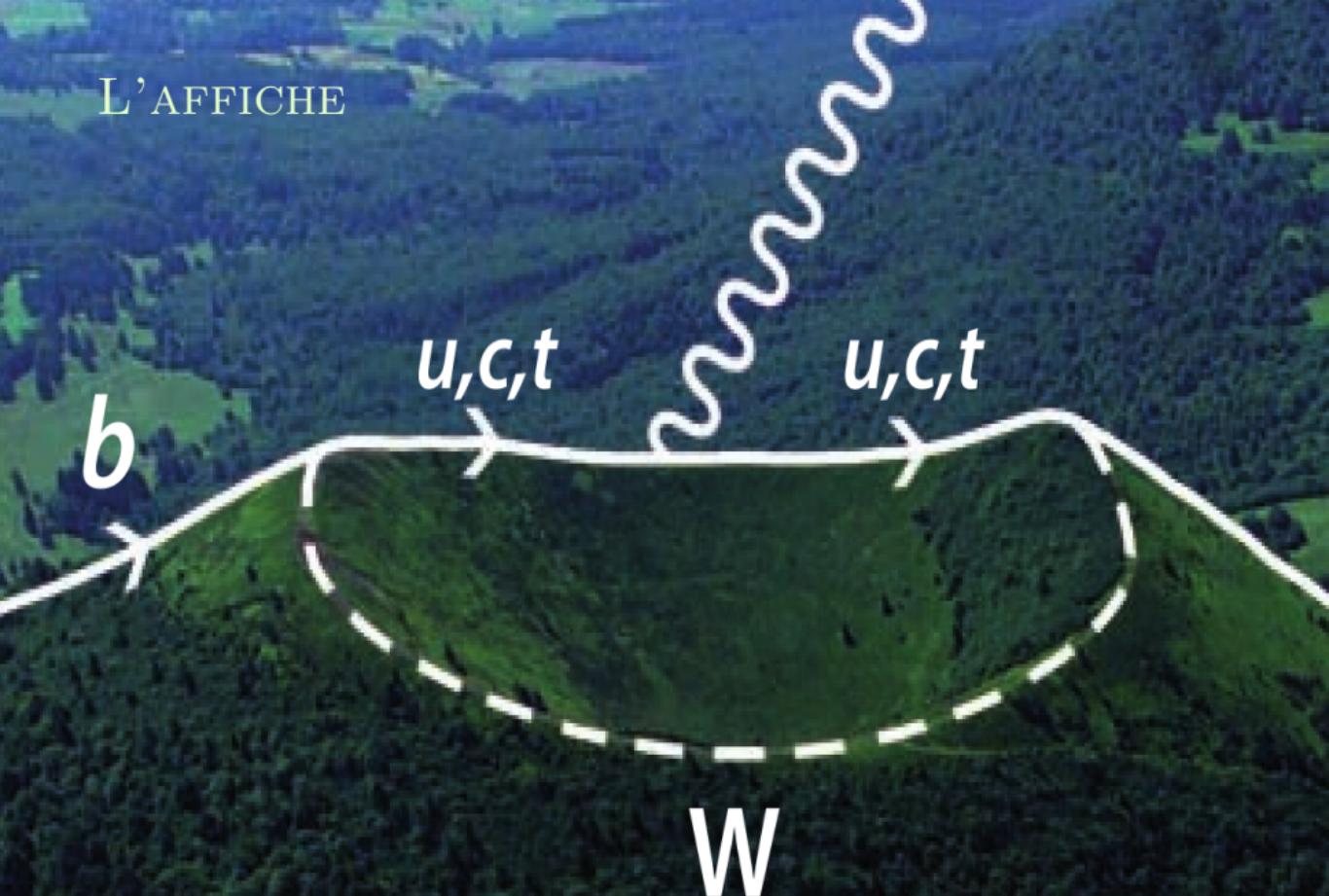
- All C_i calculated at NLO if not NNLO in SM
- We need to measure all coefficients
- Any discrepancy is a sign of New Physics



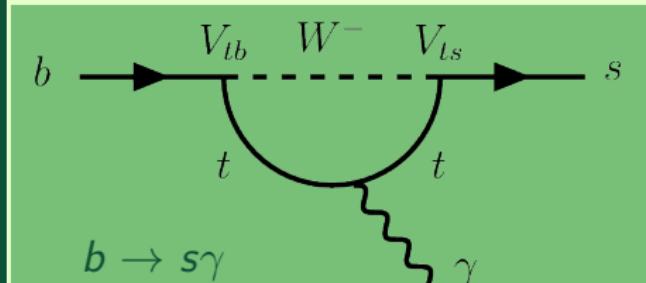
$b \rightarrow s\gamma$



L'AFFICHE

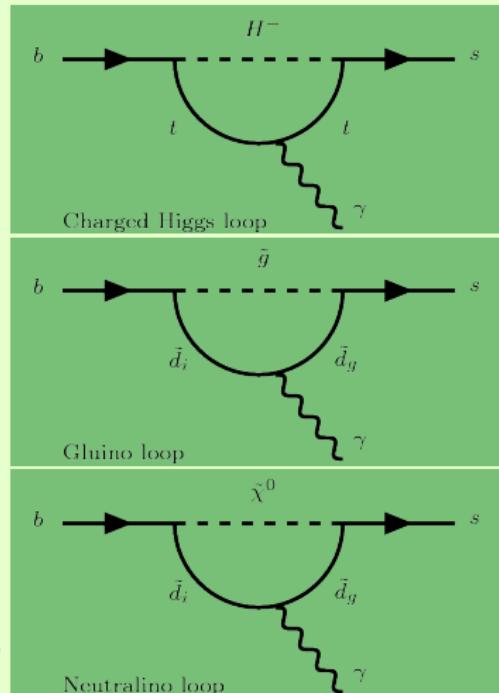


$$b \rightarrow s\gamma$$



- 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](#)]
 - 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

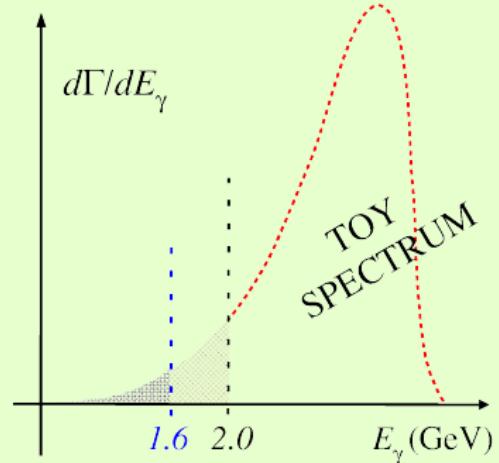
$$E_\gamma = \frac{m_b}{2} \left(1 - \frac{m_s^2}{m_b^2} \right) \simeq \frac{m_b}{2}$$

- 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 BF

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

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

- $b \rightarrow s\gamma$ branching fraction calculated at all NNLO orders in 2006

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

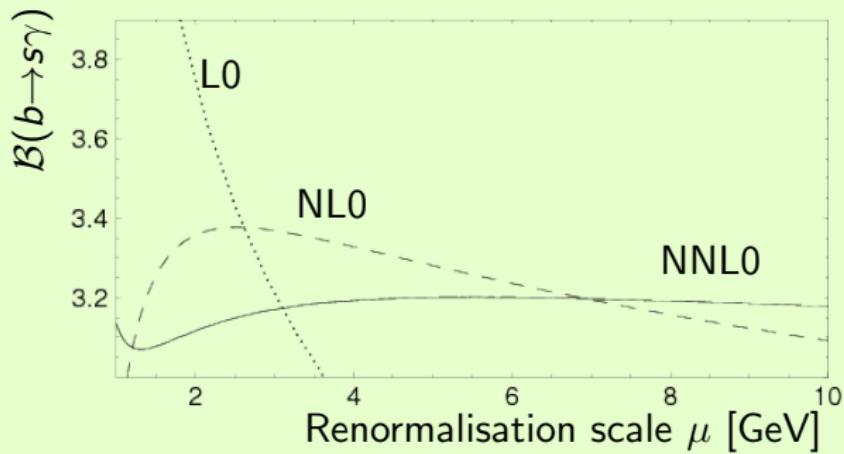


$b \rightarrow s\gamma$ SM BF

- From effective Hamiltonian one gets the BF
- Uncertainties due to m_b^5 → normalise to well measured $b \rightarrow c\bar{e}\nu$
- $b \rightarrow s\gamma$ branching fraction calculated at all NNLO orders in 2006

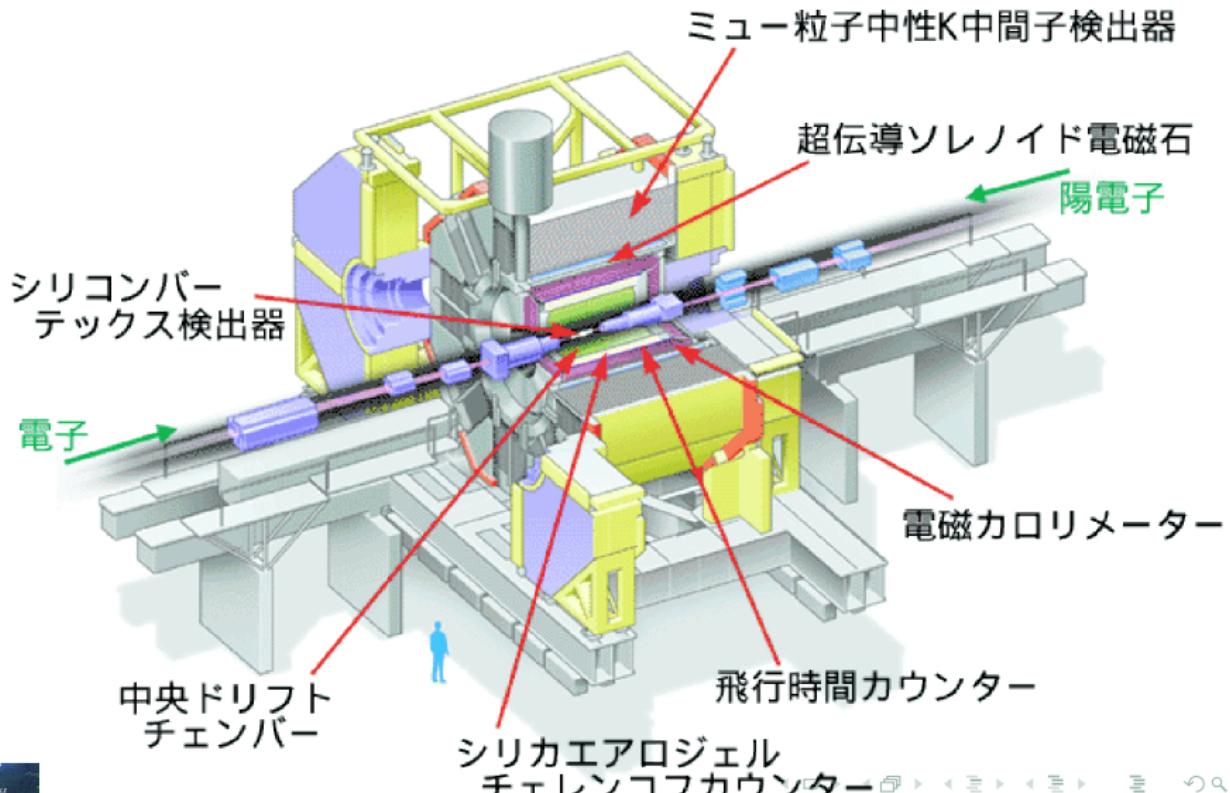
$$\mathcal{B}(B \rightarrow X_s \gamma)_{E_\gamma > 1.6 \text{ GeV}} = (3.15 \pm 0.23) \cdot 10^{-4}$$

- ✓ BF very stable vs
 μ

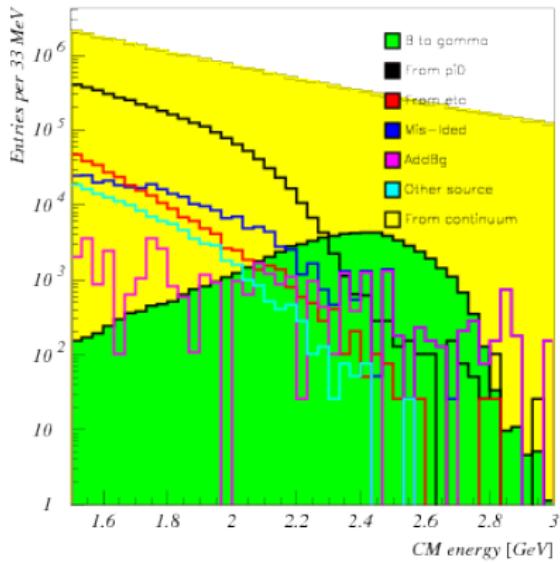


[Misiak et. al (2007)]

THE BELLE EXPERIMENT



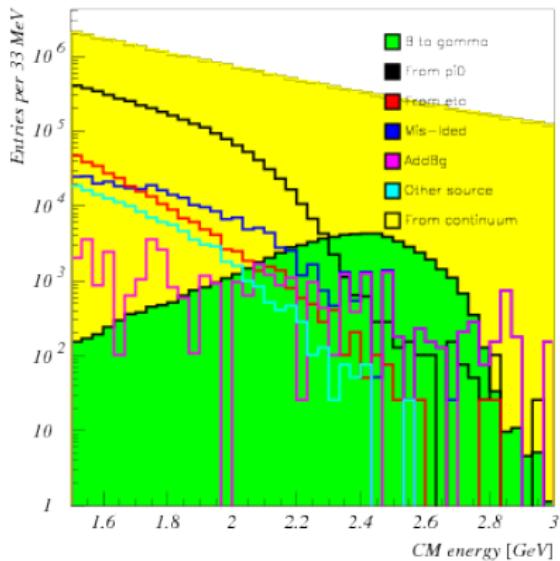
$b \rightarrow s\gamma$ SPECTRUM AT BELLE



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:

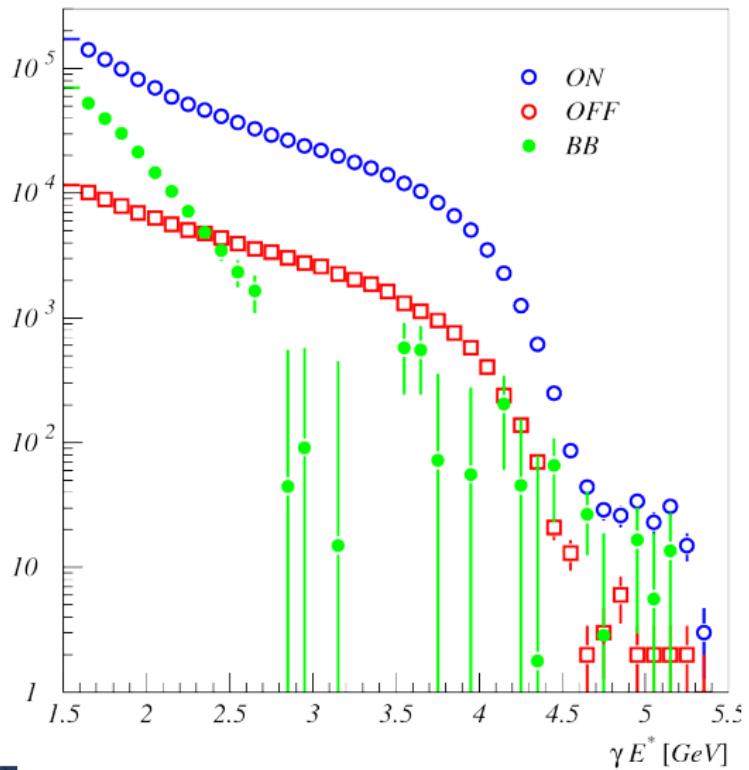
- Hadronic events with isolated photon(s) in ECL. $E^* > 1.5 \text{ GeV}$.
- Veto γ from π^0 and η .
- Apply event shape cuts to suppress continuum background.

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

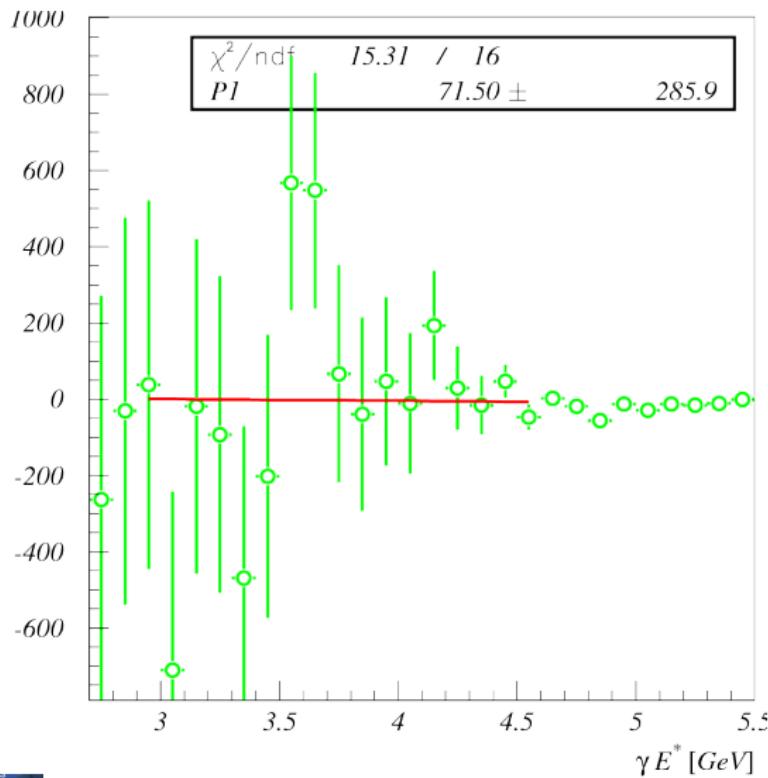
THE SPECTRUM



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



THE SPECTRUM



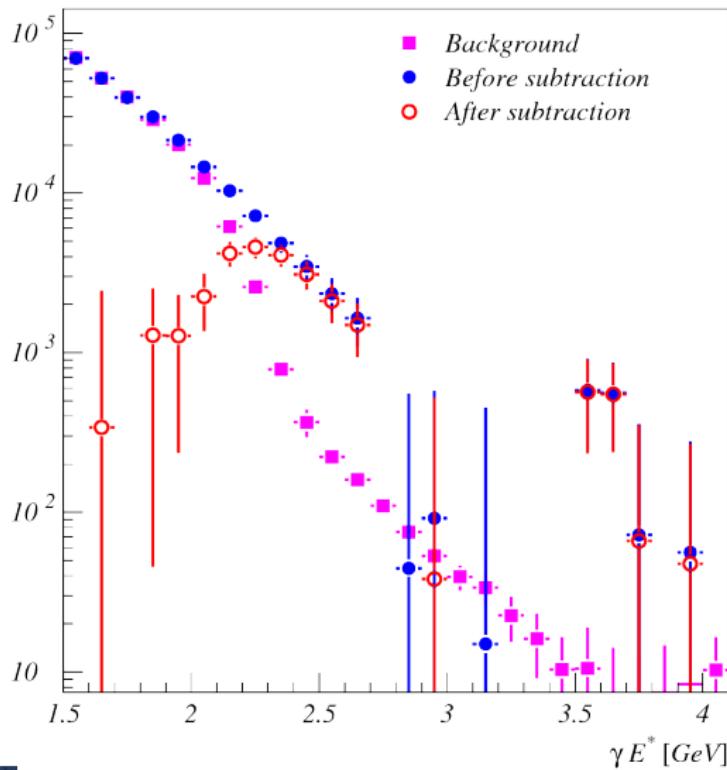
Endpoint check:

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

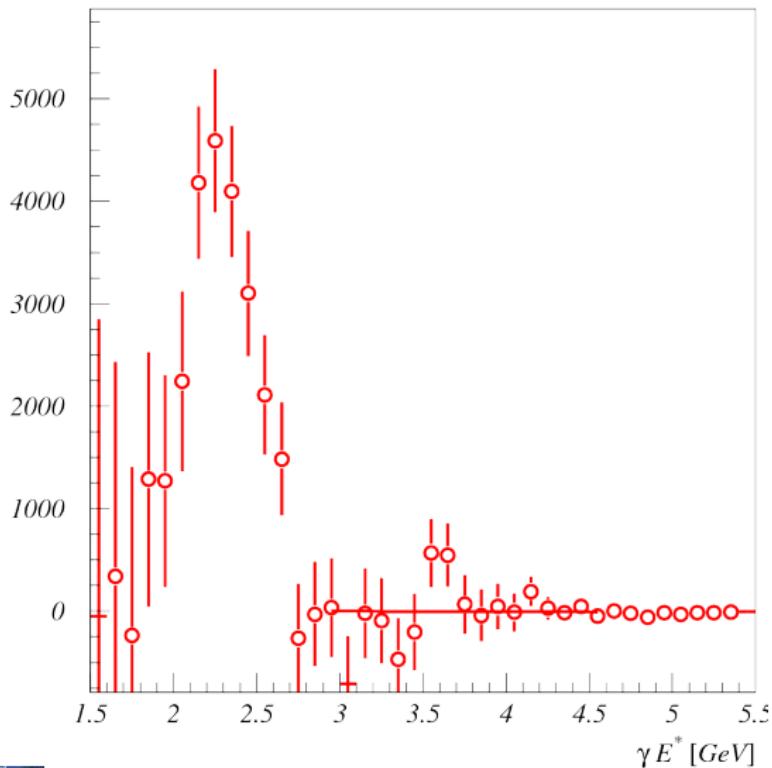
THE SPECTRUM



$B\bar{B}$ subtraction.

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

THE SPECTRUM

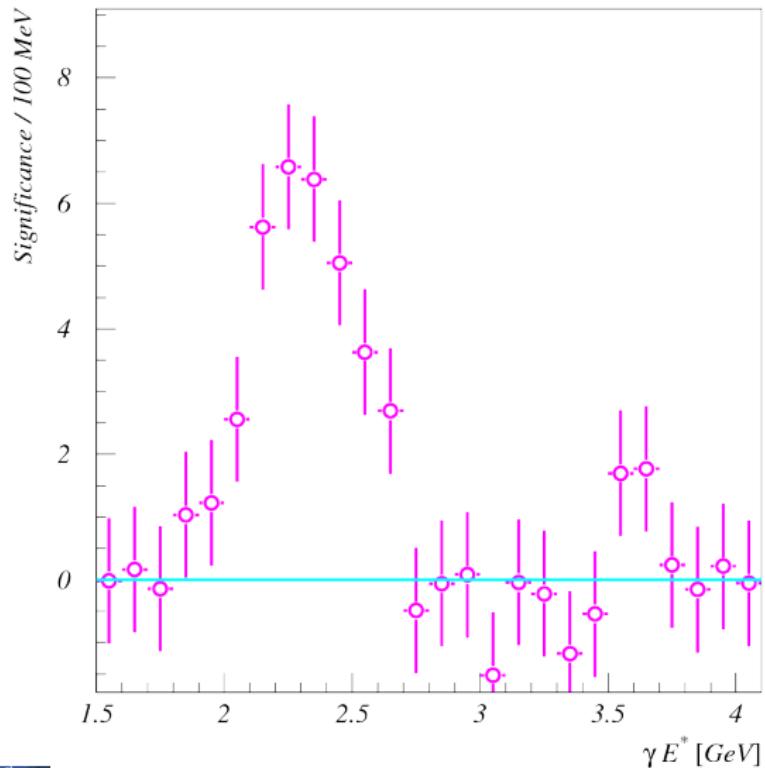


Raw spectrum after all cuts and background corrections

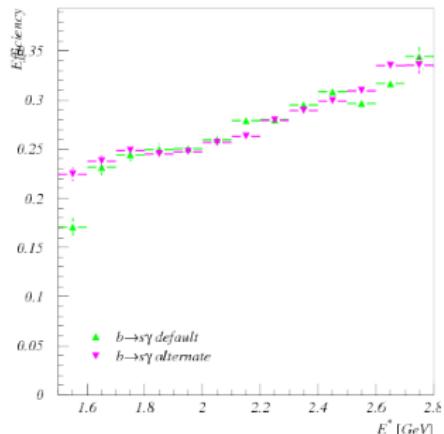
Signal yield:
 24100 ± 2200 events.



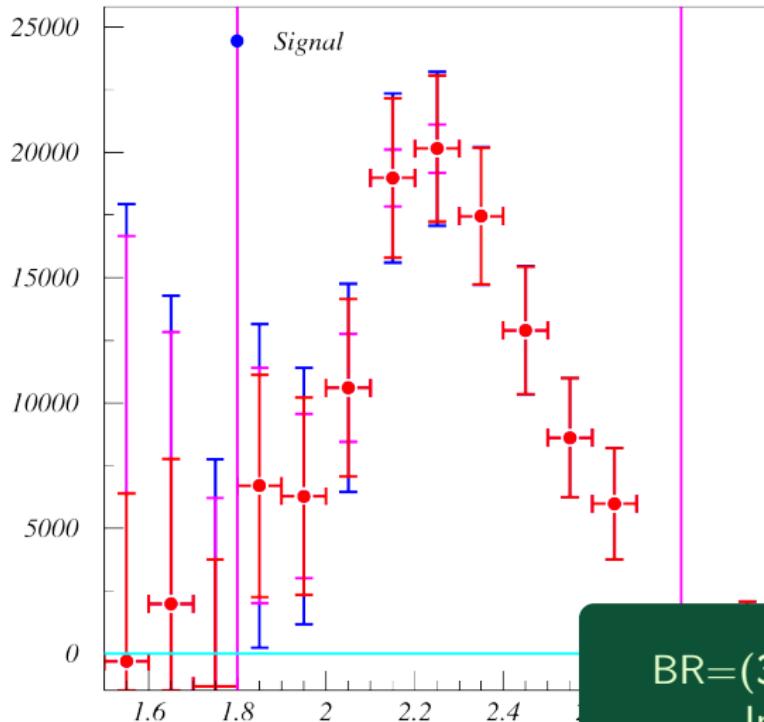
THE SPECTRUM



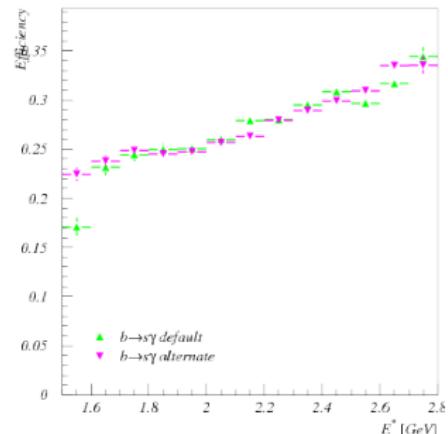
Efficiency corrected spectrum.



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]

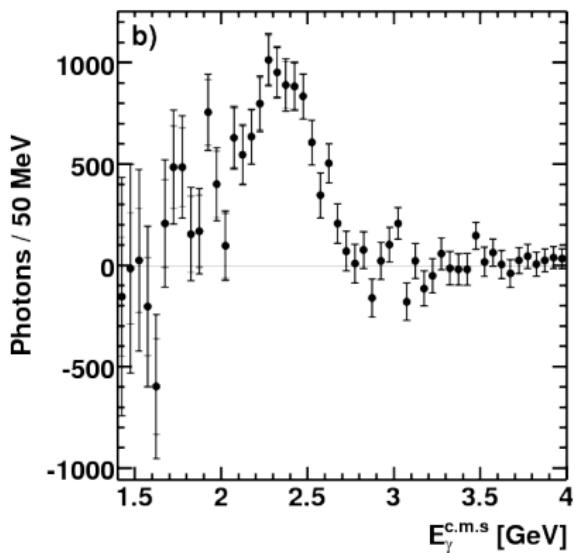
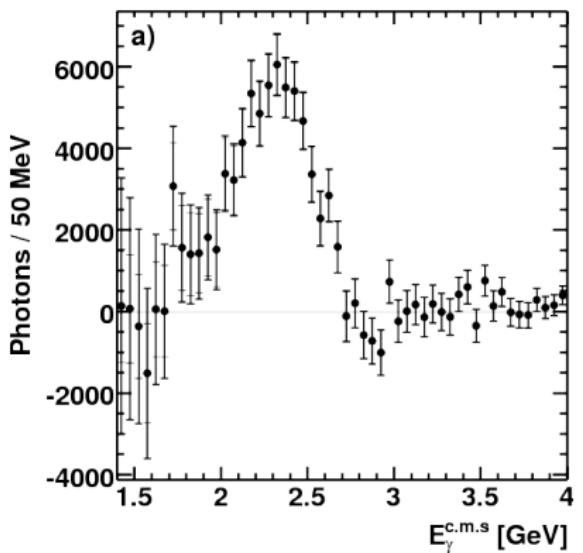


LATEST UPDATE



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

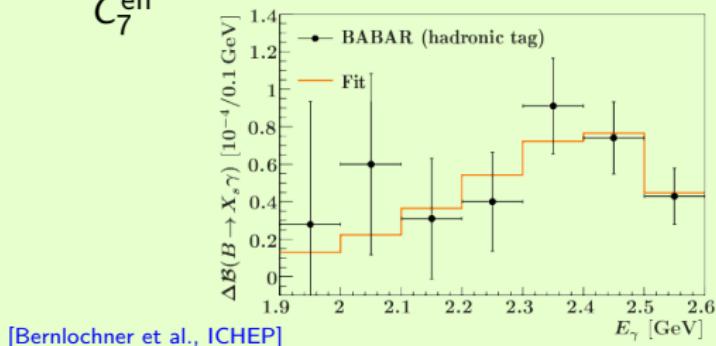
[Phys.Rev.Lett.103:241801,2009]



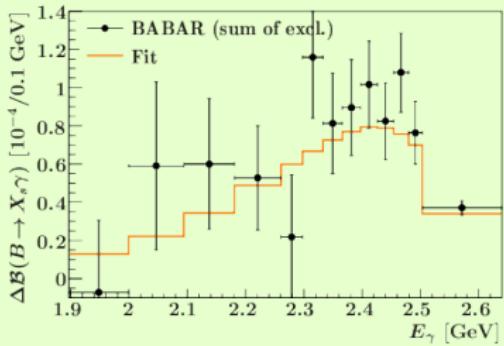
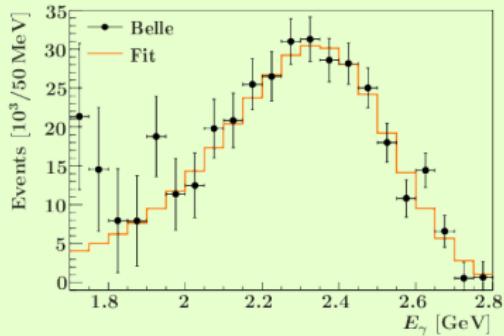
SIMULTANEOUS FIT

- 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}

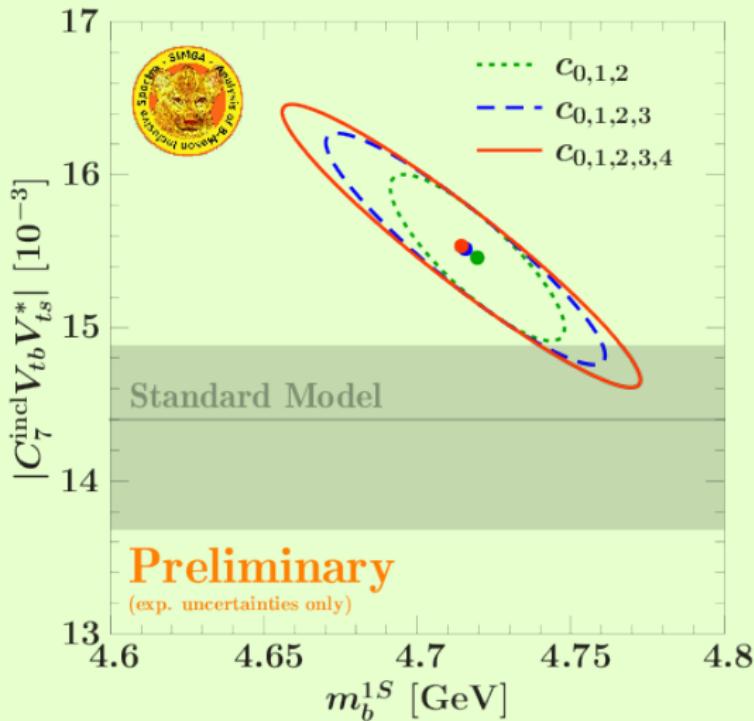


[Bernlochner et al., ICHEP]



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:

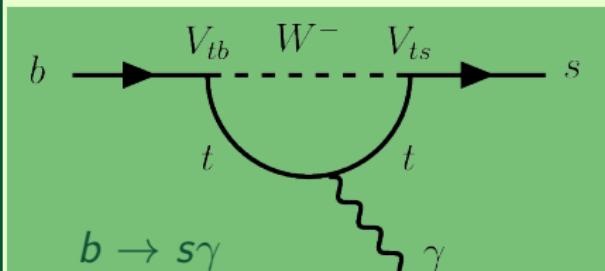
$$\begin{aligned}\Delta_{+-} &\equiv \frac{\Gamma(B_d^0 \rightarrow K^{*0}\gamma) - \Gamma(B_u^+ \rightarrow K^{*+}\gamma)}{\Gamma(B_d^0 \rightarrow K^{*0}\gamma) + \Gamma(B_u^+ \rightarrow K^{*+}\gamma)} \stackrel{\text{SM}}{=} \mathcal{O}(0.05) \\ &= 0.062 \pm 0.027 \quad (\text{HFAG})\end{aligned}$$

DIRECT CP-ASYMMETRY:

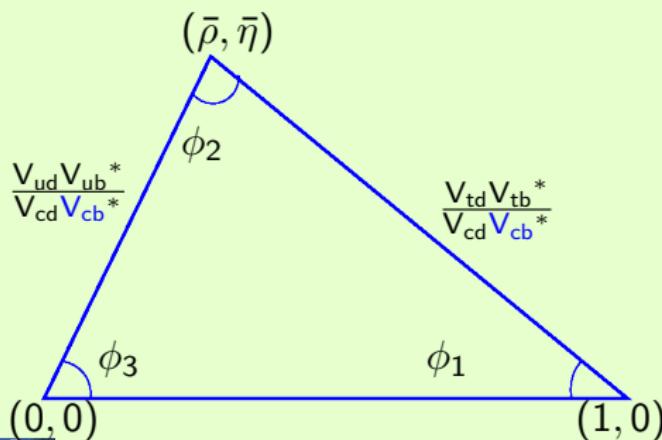
$$\begin{aligned}\mathcal{A}_{\text{CP}} &\equiv \frac{\Gamma(B_d^0 \rightarrow K^*\gamma) - \Gamma(\bar{B}_d^0 \rightarrow K^*\gamma)}{\Gamma(B_d^0 \rightarrow K^*\gamma) + \Gamma(\bar{B}_d^0 \rightarrow K^*\gamma)} \stackrel{\text{SM}}{=} \mathcal{O}(-0.1) \\ &= -0.003 \pm 0.017 \quad (\text{HFAG})\end{aligned}$$

→ nothing really exciting on that front . . .

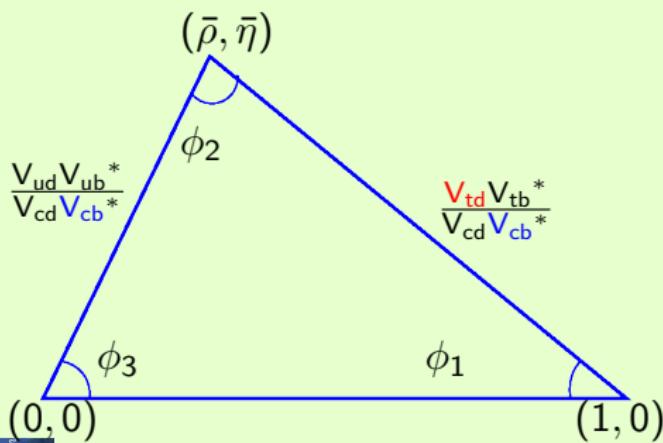
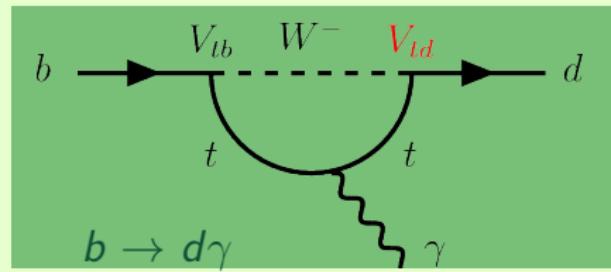
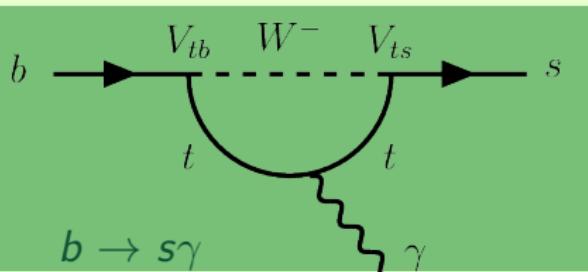
$b \rightarrow d\gamma$



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

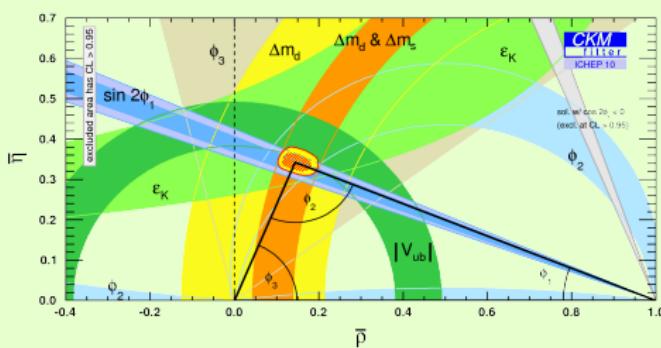
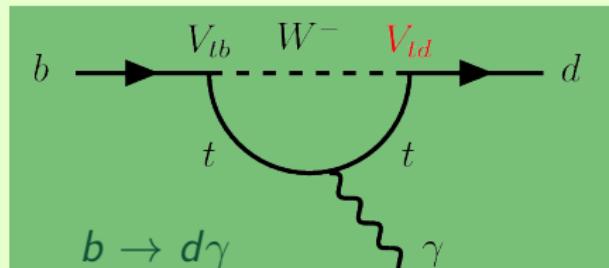
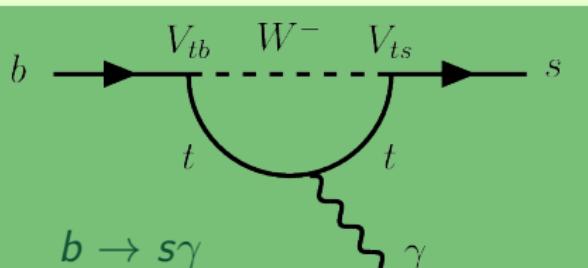


$$b \rightarrow d\gamma$$



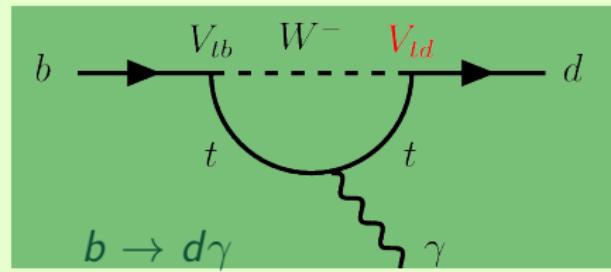
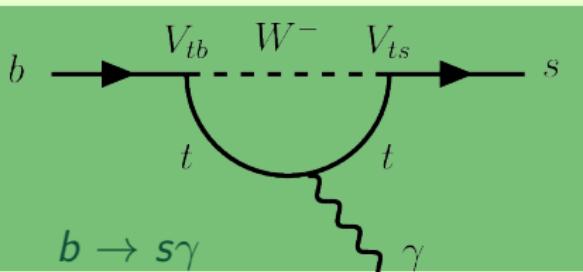
- $b \rightarrow s\gamma \propto V_{ts} \sim V_{cb}$
- $b \rightarrow d\gamma \propto V_{td}$
- The ratio of $b \rightarrow d\gamma$ and $b \rightarrow s\gamma$ should extract $|V_{td}/V_{ts}|$
- Any significant discrepancy is new physics

$$b \rightarrow d\gamma$$



- $b \rightarrow s\gamma \propto V_{ts} \sim V_{cb}$
- $b \rightarrow d\gamma \propto V_{td}$
- 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!)

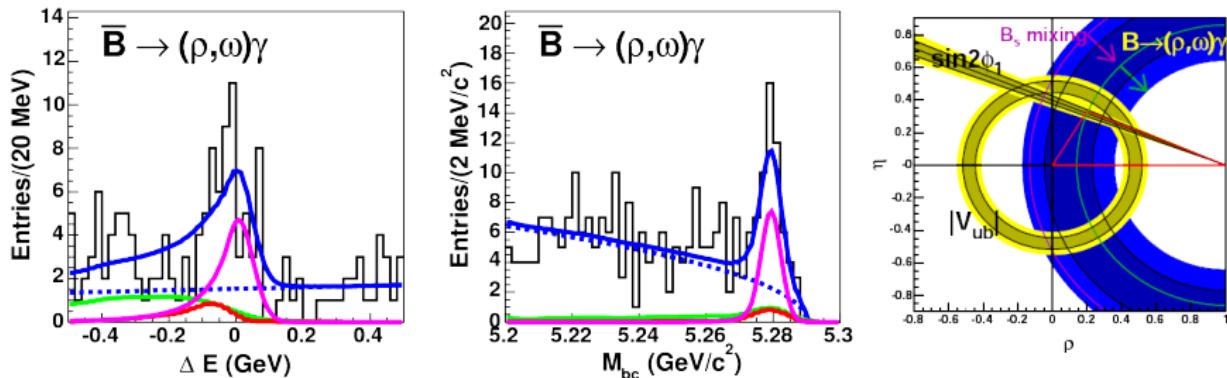
A long line →

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 $V_{tb}V_{td}^* \oplus V_{ub}V_{ud}^*$.

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

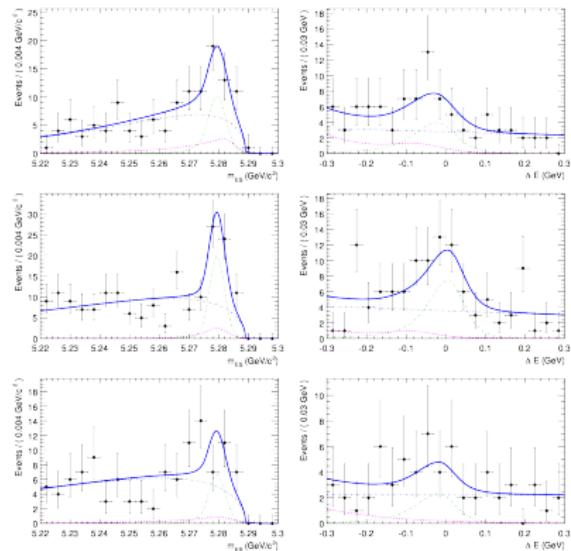
where $S_\rho = 1$ for ρ^0 and $\frac{1}{2}$ for ρ^+ , T_1 are transition form factors, and ΔR entails explicit $\mathcal{O}(\alpha_S)$ corrections [Ball et al., PRD.75.054004]

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}

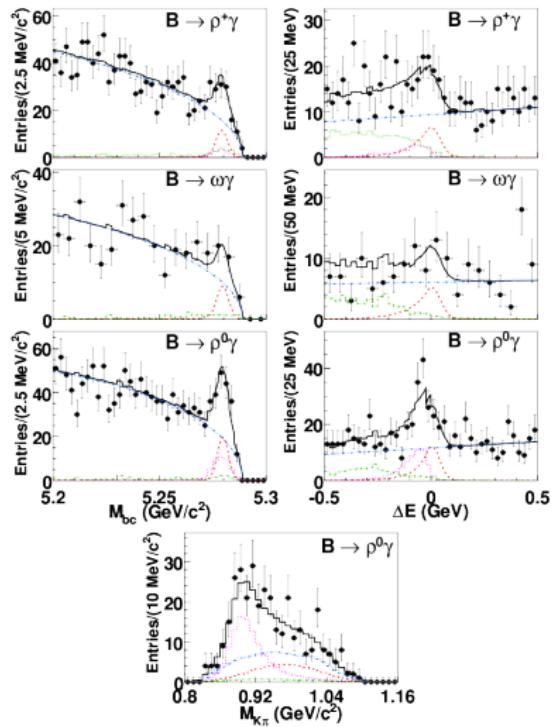


BaBar exclusive [BaBar, PRD78.112001 (2008)]

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

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)]

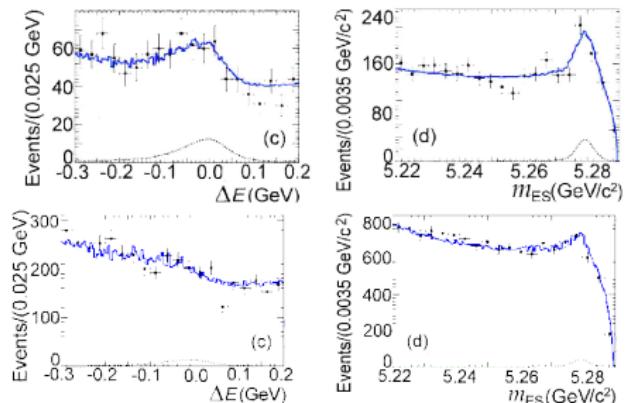
$$\left| \frac{V_{td}}{V_{ts}} \right| = 0.233^{+0.025}_{-0.024}{}^{+0.022}_{-0.021}$$

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:

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

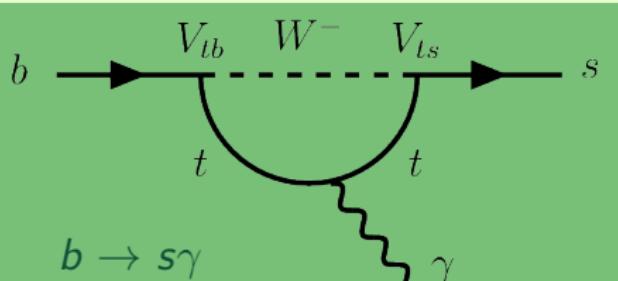
DIRECT CP-ASYMMETRY:

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

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



$b \rightarrow s\gamma$ POLARISATION



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

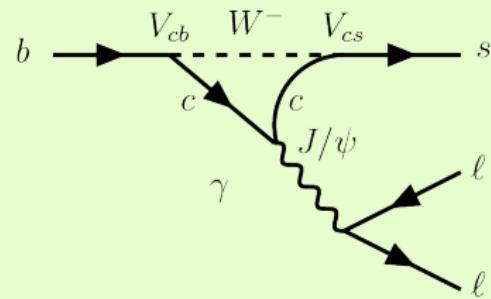
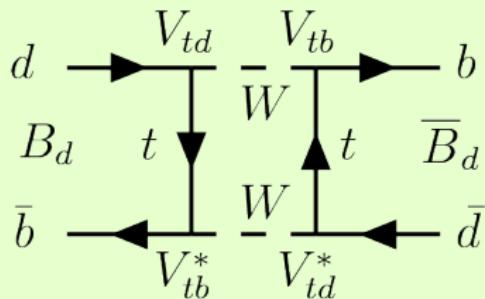
[Grossman et al., JHEP06:29, 2000]

The photon polarisation is not well measured.

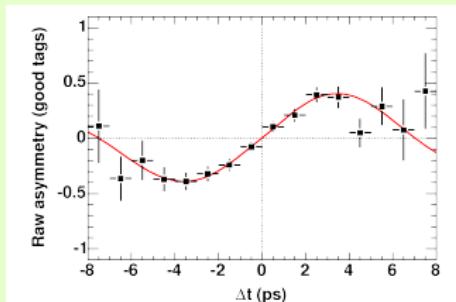
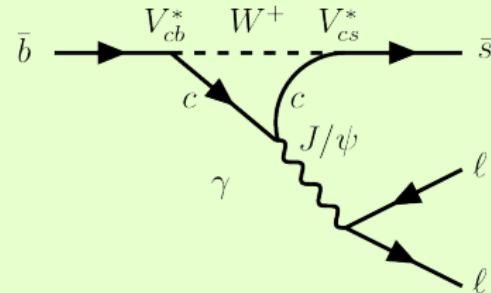
- Naively $r = \frac{C'_{7\gamma}}{C_{7\gamma}}$ SM $\simeq \frac{m_s}{m_b}$
- Gluons contribute $0.5 \pm 1.0\%$
[Ball & Zwicky PLB642:478, 2006]
- Right-handed operators could contribute

MIXING-INDUCED CP VIOLATION

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

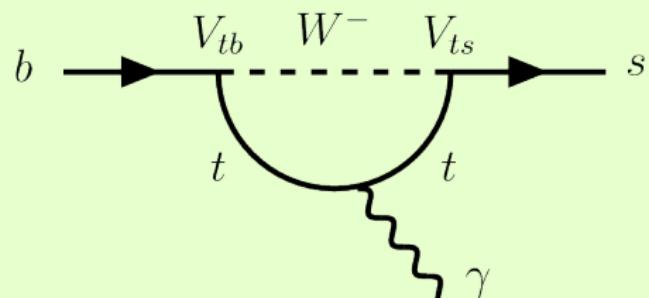
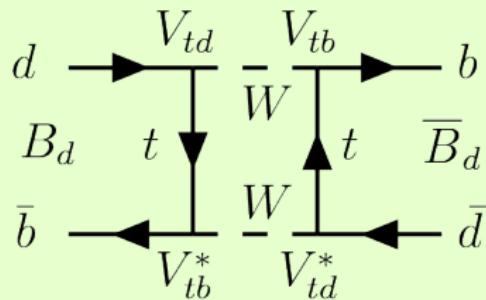


Interferes with

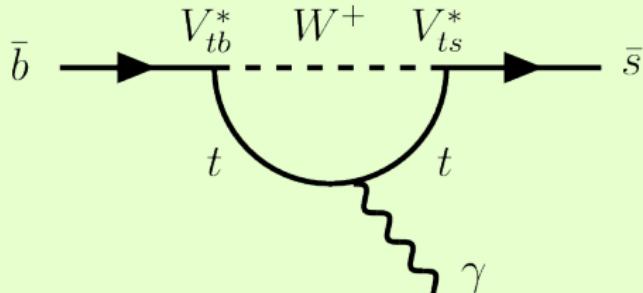


MIXING-INDUCED CP VIOLATION

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



Interferes with right handed component of



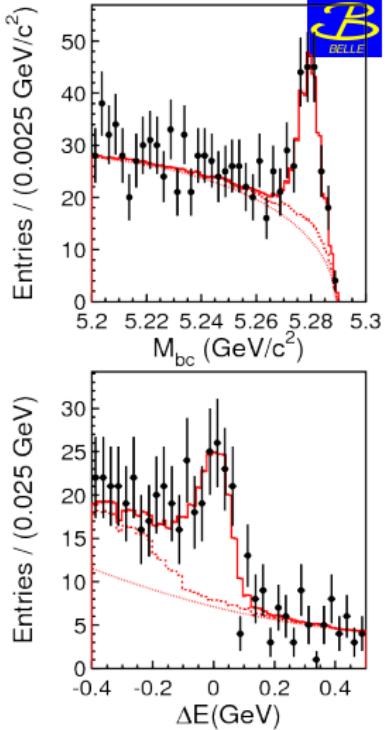
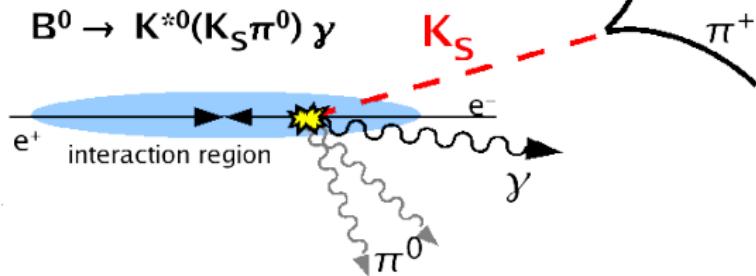
CP-VIOLATION IN $B \rightarrow K^* \gamma$



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



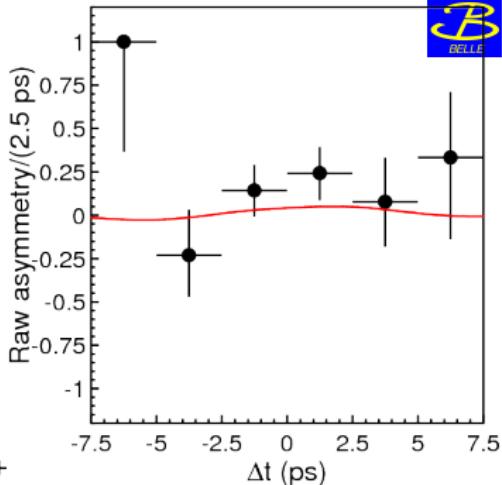
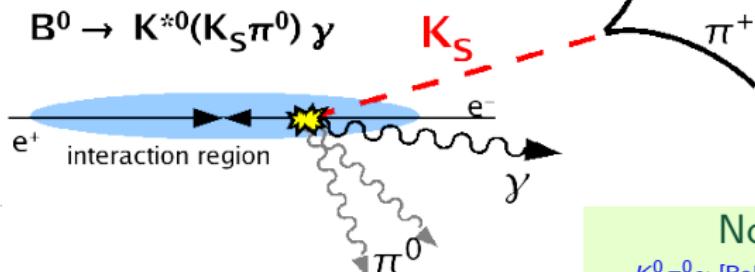
CP-VIOLATION IN $B \rightarrow K^*\gamma$



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

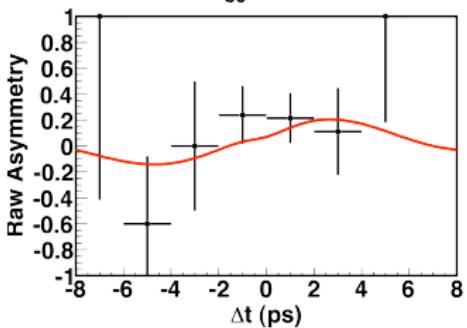
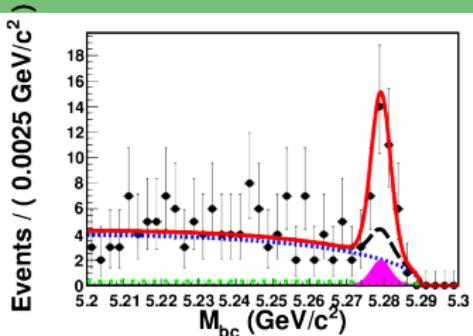
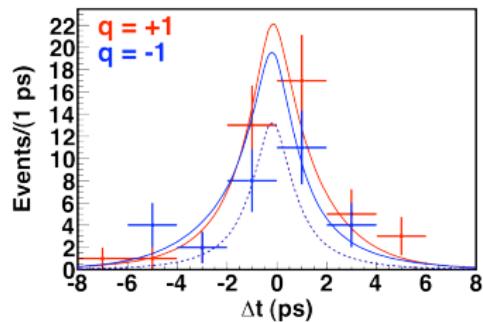
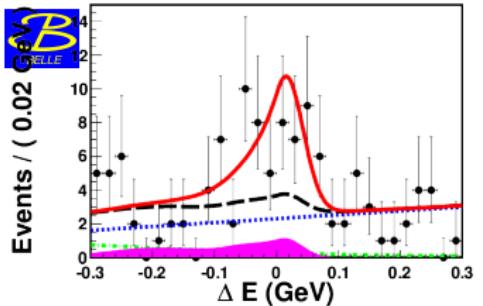


No oscillation observed

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



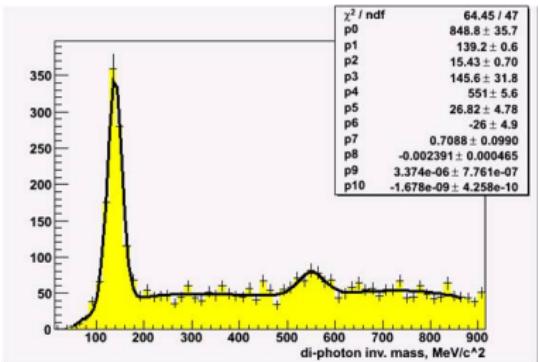
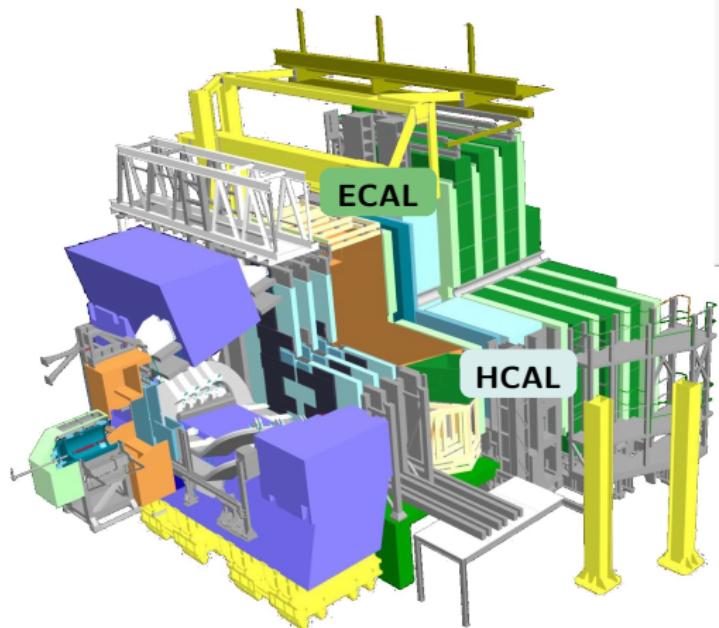
$B_d^0 \rightarrow K_S^0 \phi \gamma$, AND FRIENDS



$\eta K^0 \gamma$ [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],
 $K^0_S \phi \gamma$ [Belle, ICHEP ...]



WHAT ABOUT LHCb?



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

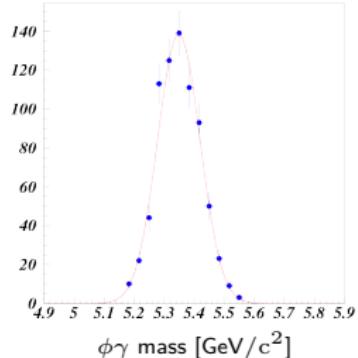
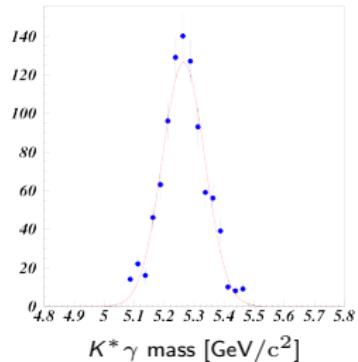
- Layers of lead and plastic scintillators

PRESHOWER:
Lead/scintillator

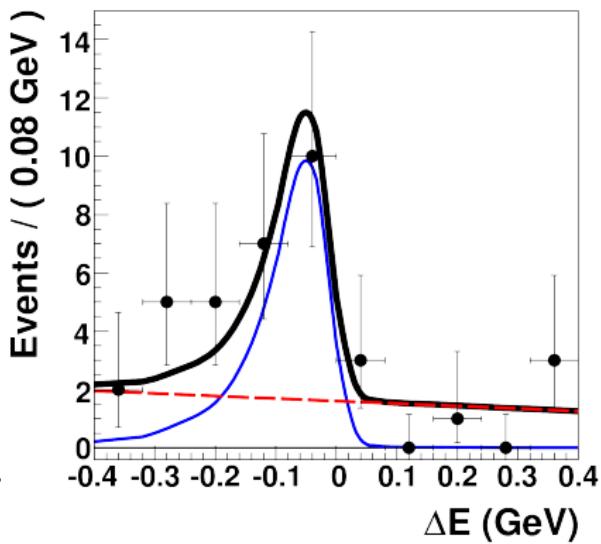
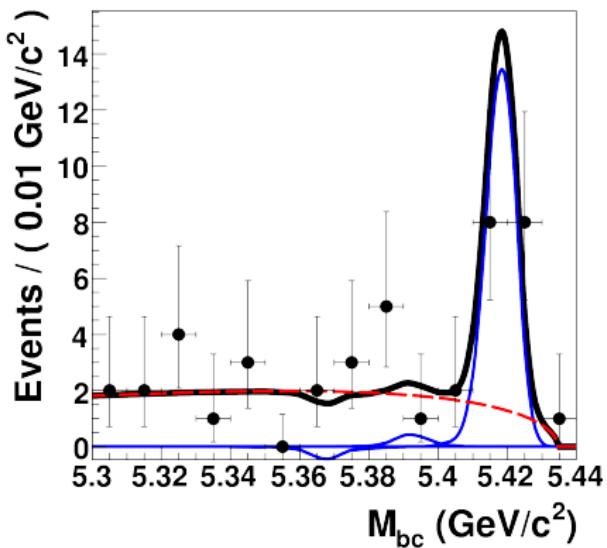
$B_d^0 \rightarrow K^*\gamma$ AND $B_s^0 \rightarrow \phi\gamma$ YIELDS FOR 2 FB $^{-1}$

	$B_d^0 \rightarrow K^*\gamma$	$B_s^0 \rightarrow \phi\gamma$
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]

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



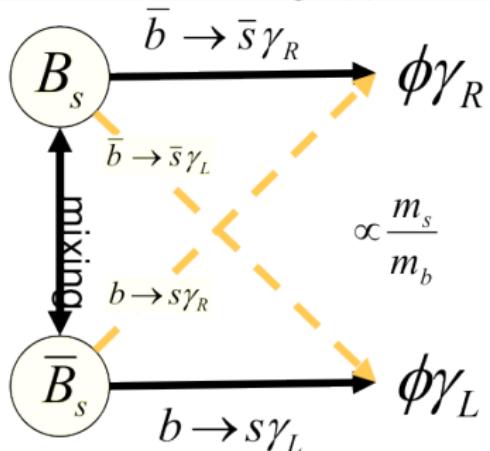
In SM mainly $B_s^0 \rightarrow \phi\gamma_R$ and $\bar{B}_s^0 \rightarrow \phi\gamma_L$. Mixing only if wrong polarisation.

\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

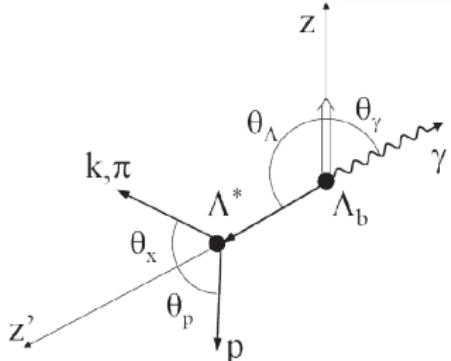


$$r = \frac{C'_{7\gamma}}{C_{7\gamma}} \rightarrow \alpha_\gamma = \frac{1 - |r|^2}{1 + |r|^2}$$

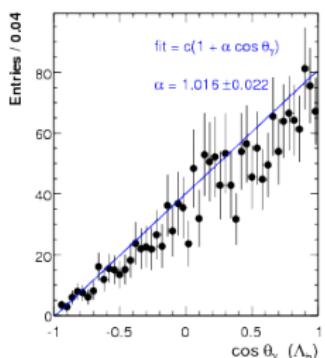
$$\frac{d\Gamma}{d \cos \theta_\gamma} \propto 1 - \alpha_\gamma P_{\Lambda_b} \cos \theta_\gamma$$

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

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



- 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

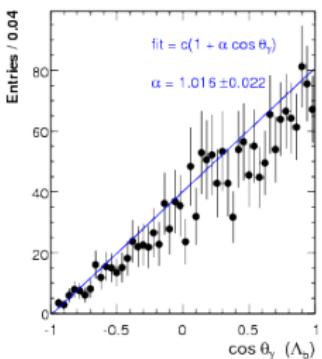
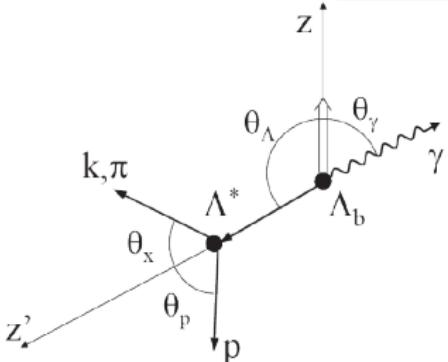


$$r = \frac{C'_{7\gamma}}{C_{7\gamma}} \rightarrow \alpha_\gamma = \frac{1 - |r|^2}{1 + |r|^2}$$

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

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

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



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



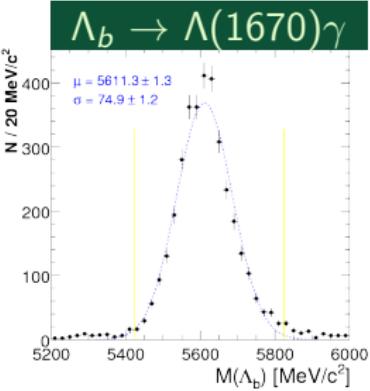
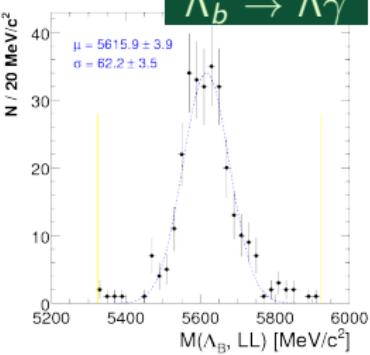
$\Lambda_b \rightarrow \Lambda\gamma$ YIELDS



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]

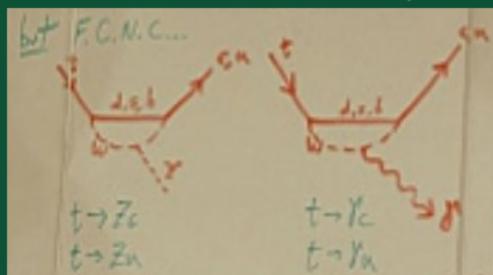


OTHER RADIATIVE DECAYS

$b \rightarrow s\gamma$ AND $b \rightarrow s\gamma$ 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)



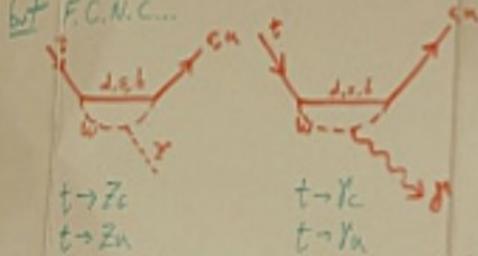
$t \rightarrow c\gamma$ AND $u\gamma$:

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

OTHER RADIATIVE DECAYS

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

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