Rare decays

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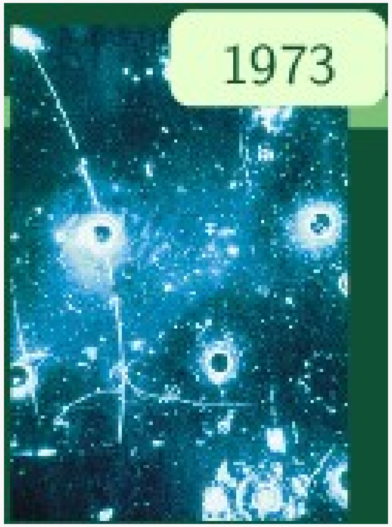
Indirect searches



Sensitive to New Physics effects

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

Estimate masses

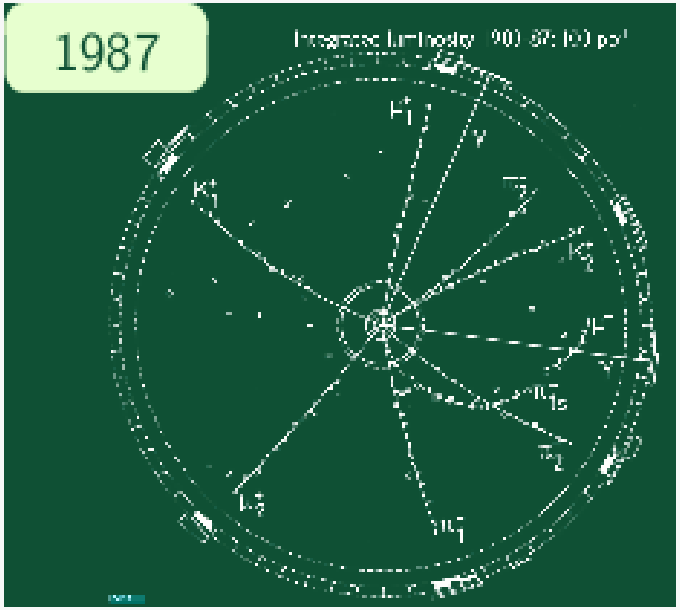
- t quark from $B\overline{B}$ mixing

Get phases of couplings

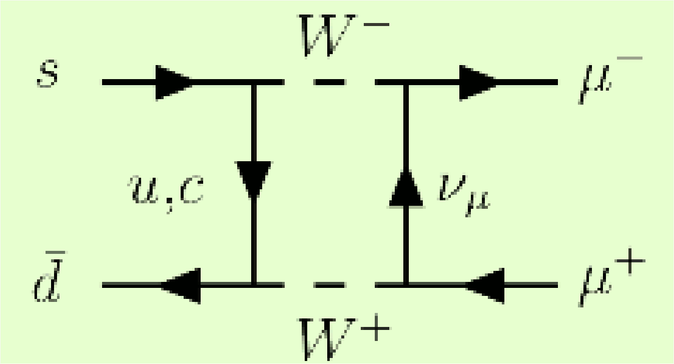
  - Half of new parameters
- Needed for a full understanding

Look in lepton and **flavour** sectors

→ CP asymmetry in the Universe

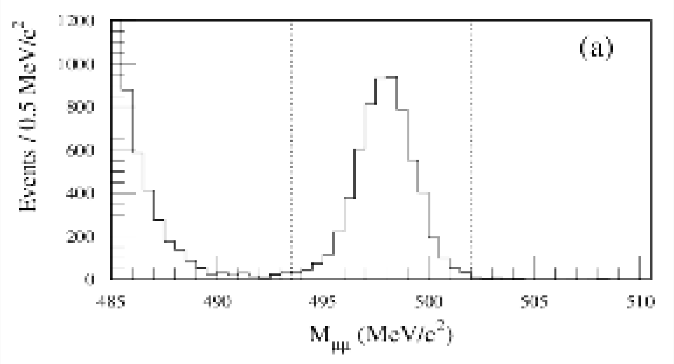


$\mathbf{K_L^0 \to \mu\,\mu}$



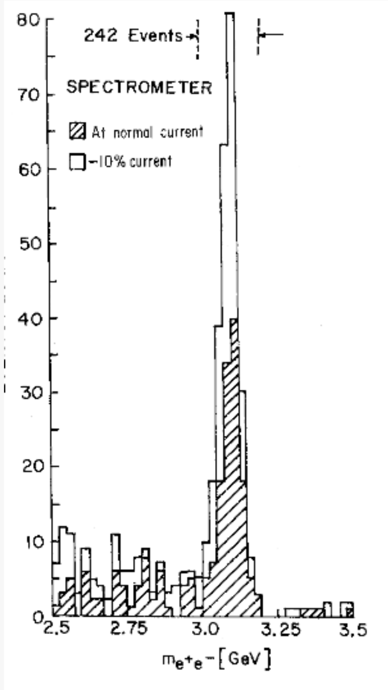
$K_L^0 \to \mu\,\mu$ was not observed though expected

- Now BF is measured to be $(6.84 \pm 0.11) 10^{-9}$ [Ambrose et al, 2000]



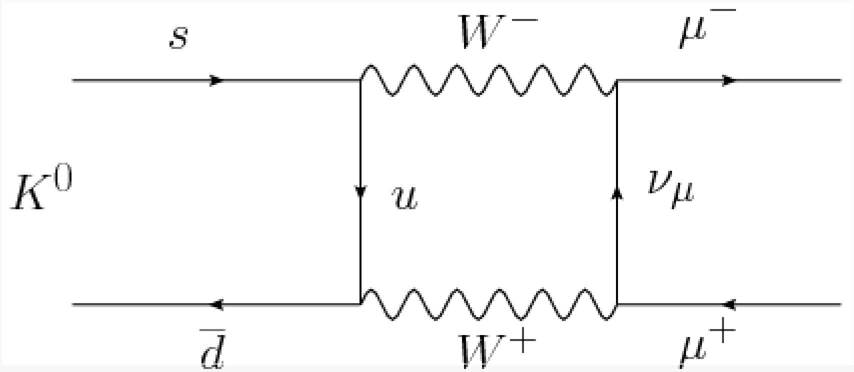
→ Led to the postulation of the c quark ''GIM mechanism'' in 1970 [Glashow, Iliopoulos and Maiani, 1970]

→ c quark eventually observed in 1974 [Richter], [Ting]

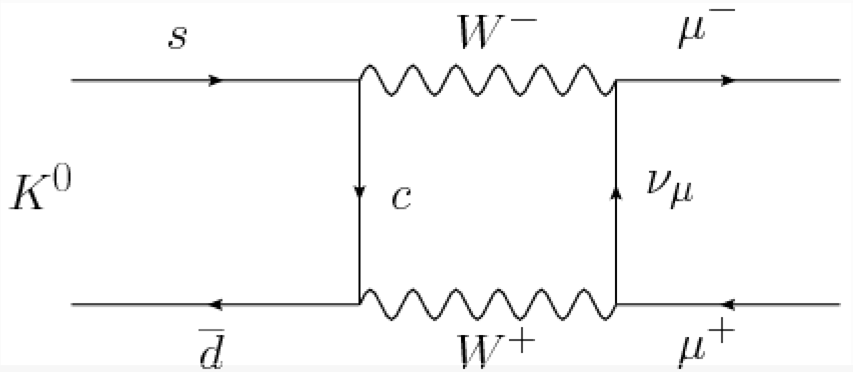


$K_L^0 \to \mu\,\mu$ (by Jean Iliopoulos)

$K_L \to \mu^+\mu^-$ decay can be generated by the box diagram:



in a renormalisable gauge theory, is expected to give a branching ratio of $g^4 \sim \alpha^2 \sim 10^{-4}$, with α the fine structure constant. GIM observed that, with a fourth quark, there is a second diagram, with c replacing u:



In the limit of exact flavour symmetry the two diagrams cancel. The breaking of flavour symmetry induces a mass difference between the quarks, so the sum of the two diagrams is of order $g^4(m_c^2 - m_u^2)/m_W^2 \sim \alpha^2 m_c^2/m_W^2$.

With the measured charm quark mass $m_c \sim 1.27$ GeV, the predicted rates are in agreement with observation.

What are rare decays ?

Dominant decays : Not rare

Phase space suppressed decays : Not that rare

$$\frac{\Gamma\left(\mathrm{K}_{\mathrm{S}}^{0} \rightarrow \pi \pi\right)}{\Gamma\left(\mathrm{K}_{\mathrm{L}}^{0} \rightarrow \pi \pi \pi\right)} = 571$$

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Cabibbo-suppressed decays : Some call them rare

$$\frac{B(\mathrm{D}^0 \to \mathrm{K}^- \pi^+)}{B(\mathrm{D}^0 \to \pi^- \pi^+)} = 28 \qquad \frac{B(\mathrm{b} \to \mathrm{q}\, \mathrm{l}^+ \nu)}{B(\mathrm{b} \to \mathrm{u}\, \mathrm{l}^+ \nu)} = 135$$

What are rare decays ?

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Cabibbo-suppressed decays: Some call them rare

Colour-suppressed decays: Not really rare

$$\mathcal{B}(\mathrm{B}^0 \to \mathrm{D}^- \pi^+) = (3.5 \pm 0.9)\, 10^{-3},$$
$$\mathcal{B}(\mathrm{B}^0 \to \overline{\mathrm{D}}^0 \pi^0) = (2.9 \pm 0.3)\, 10^{-4},$$

while they are both $\mathrm{b} \to \mathrm{c\,W}$ and $\mathrm{W} \to \mathrm{u\,\overline{d}}$ transitions.

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Hadronic FCNC decays: Not the topic of this lecture

- For instance $B \to \phi K_S^0$, or $B \to K_S^0 K \pi$...
- Or $B^0 \to \phi K_S^0$, or the penguin contribution to $B \to J/\psi K_S^0$

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Electroweak FCNC penguins: That's rare !

- $b \to s \gamma$
- $b \to s ll$
- And friends...

Why rare decays ?

We want to find new physics indirectly !

No new physics at tree level : we would have noticed

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

Why rare decays ?

We want to find new physics indirectly !

No new physics at tree level: we would have noticed

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:

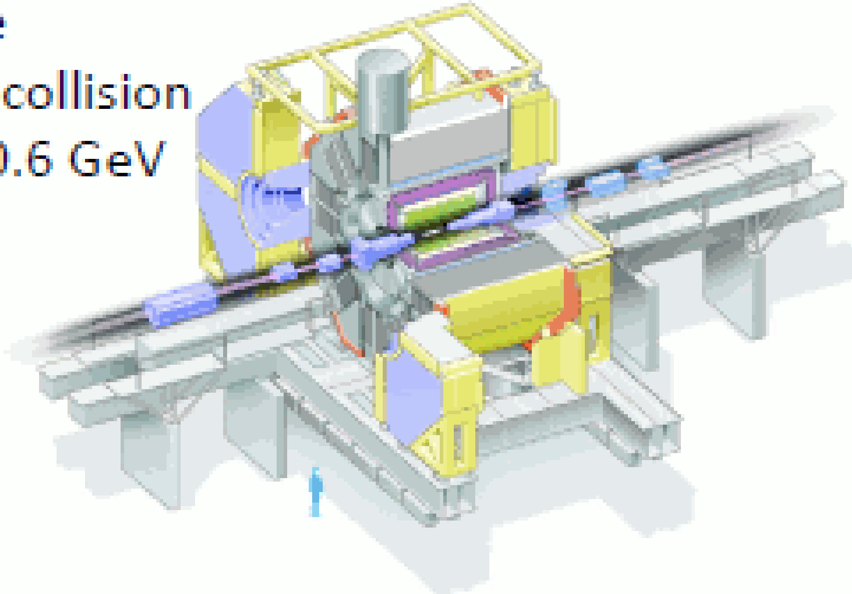
- You want to measure a 50% effect on a rare decay, not a 1% effect on the neutron lifetime. That's very hard.

  $\Rightarrow$ Statistic versus systematic error

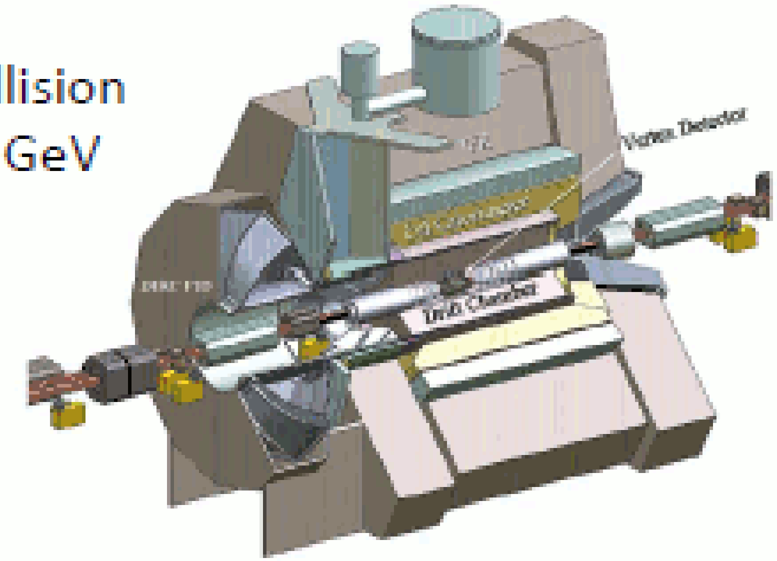
Theoretical clean: There are many rare decays that are theoretically clean. This is needed as in the end you will compare a measured effect to an SM prediction.

Main actors

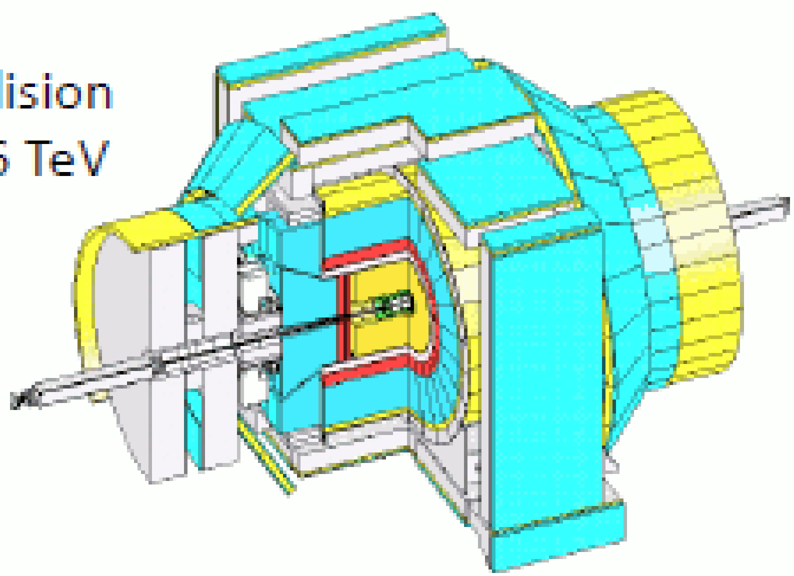
Belle
e^+e^- collision
at 10.6 GeV



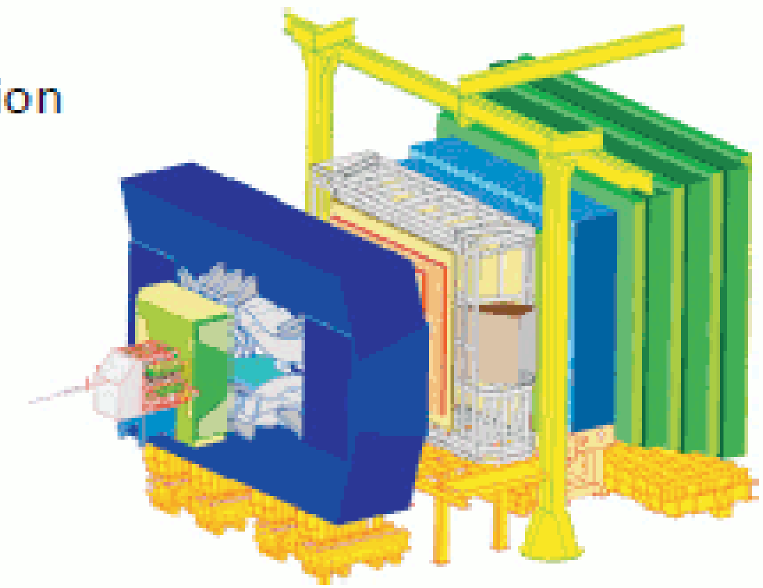
BaBar
e^+e^- collision
at 10.6 GeV



CDF
$p\bar{p}$ collision
at 1.96 TeV



LHCb
pp collision
at 7 TeV



Main actors

B factories:

BaBar is terminated. They are finalising their analyses.

Belle is terminated. They are finalising their analyses.

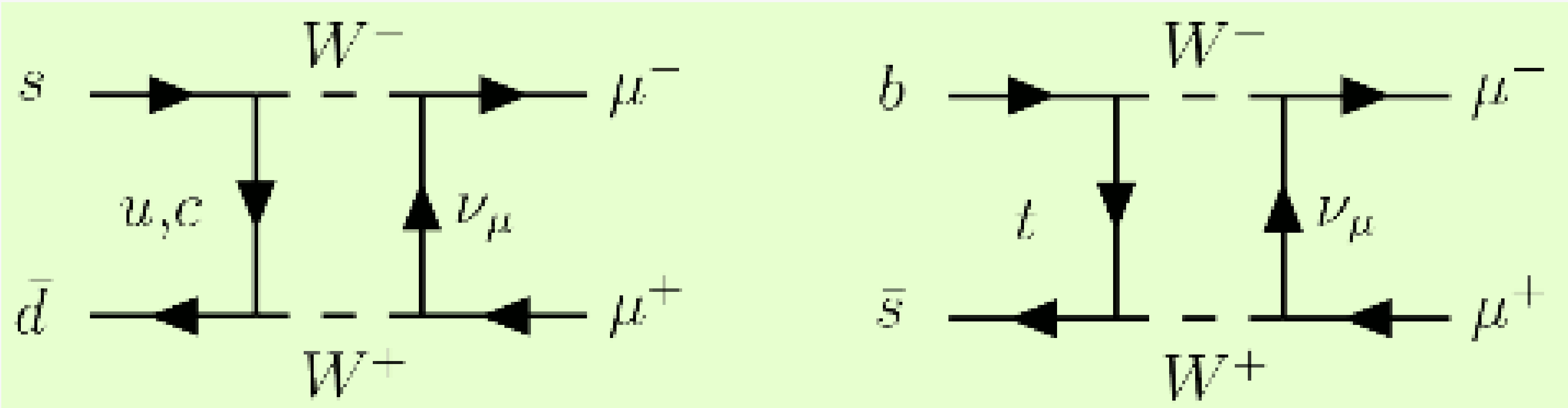
Belle II collaboration has been set up. Plan to have data in 2016.

Hadron colliders::

CDF & D0 just stopped to take data
Atlas & CMS have a B program but can't compete with...
LHCb will be the key player between 2011-2016

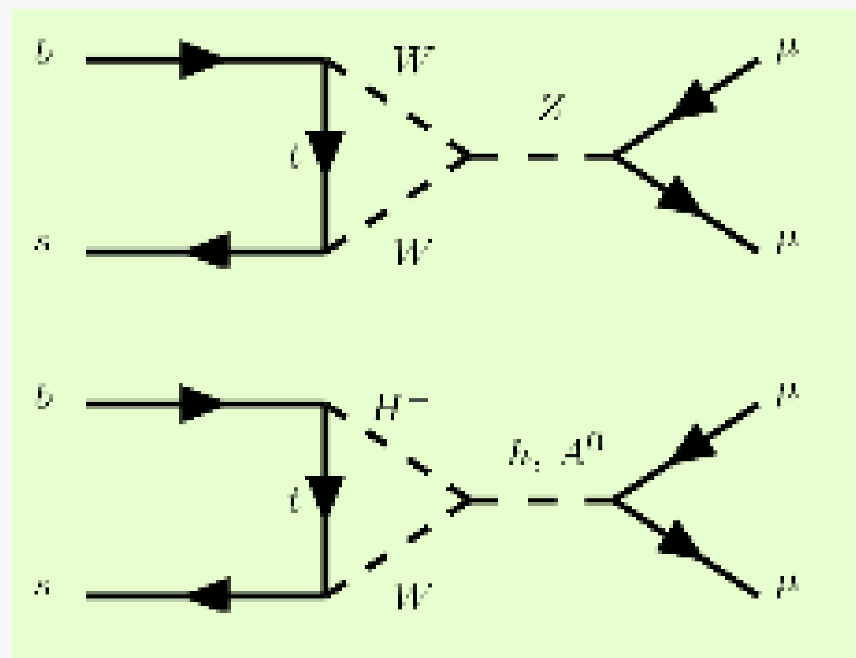
	$\sqrt{s}$	LHCb	Atlas & CMS
2010	7 TeV	50 pb^{-1}	50 pb^{-1}
2011	7 TeV	~ 1 fb^{-1}	5 fb^{-1}
2014+	14 TeV	≥ 2 fb^{-1}/ year	10 fb^{-1}/ year
Total	7–14 TeV	**5–10 fb^{-1}**	**30 fb^{-1}**

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



- Start with $K_L^0 \to \mu\,\mu$
- Replace quarks by b and $\bar{s}$ (for $\overline{B}{}_s^0$) and t ($\propto V_{tb} V_{ts}$)
- Add a penguin contribution ($\propto V_{tb} V_{ts}$)
- Add a hypothetical charged Higgs contribution ($\propto$?)

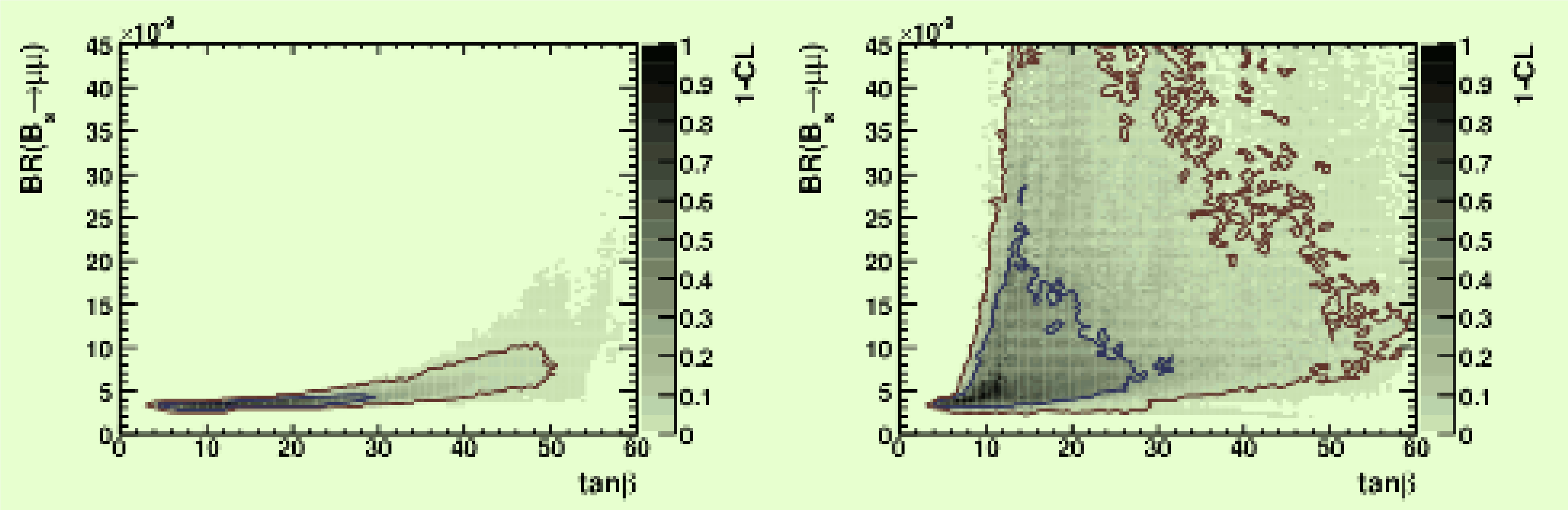
  $\Rightarrow$ Gets what BF ?



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

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

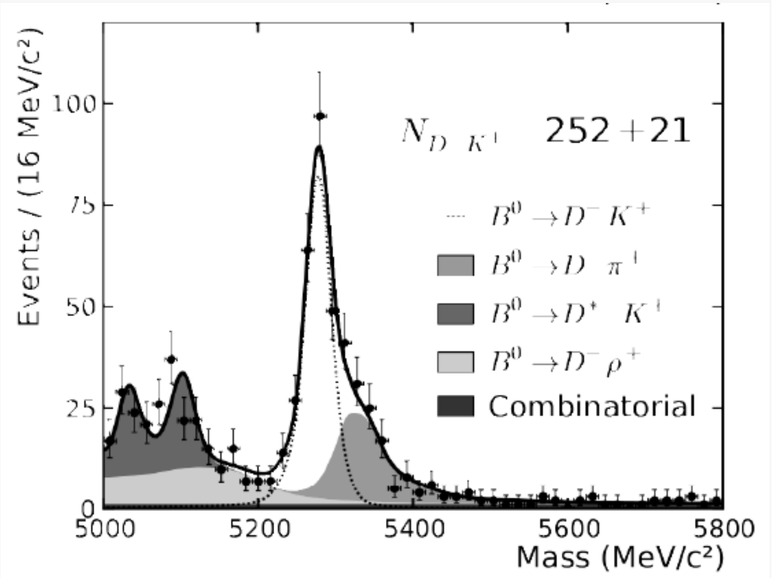
[Buchmuller et al., EPJ C64:391-415, 2009]



$\mathbf{B_s \to \mu^+ \mu^-}$ (LHCb)

Fraction of $b \to B_s X$ is an essential ingredient for $B_s \to \mu\mu$ and other rare decays

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



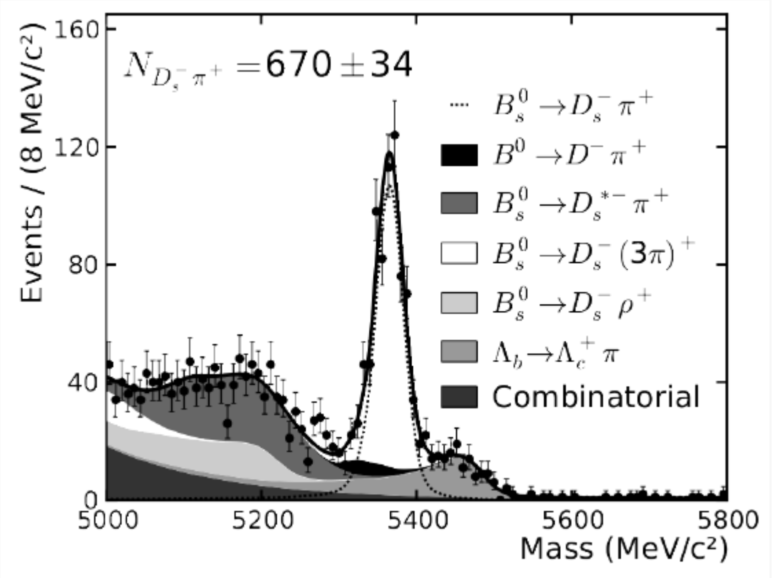
LHCb has measured it in 2 ways

- Ratio of $B \to D_s \mu X$ to $B \to D^+ \mu X$ modes [LHCb-CONF-2011-028]
- Ratio of $B_d \to DK$ and $B_s \to D_s \pi$ modes [Accepted by PRL]

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

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

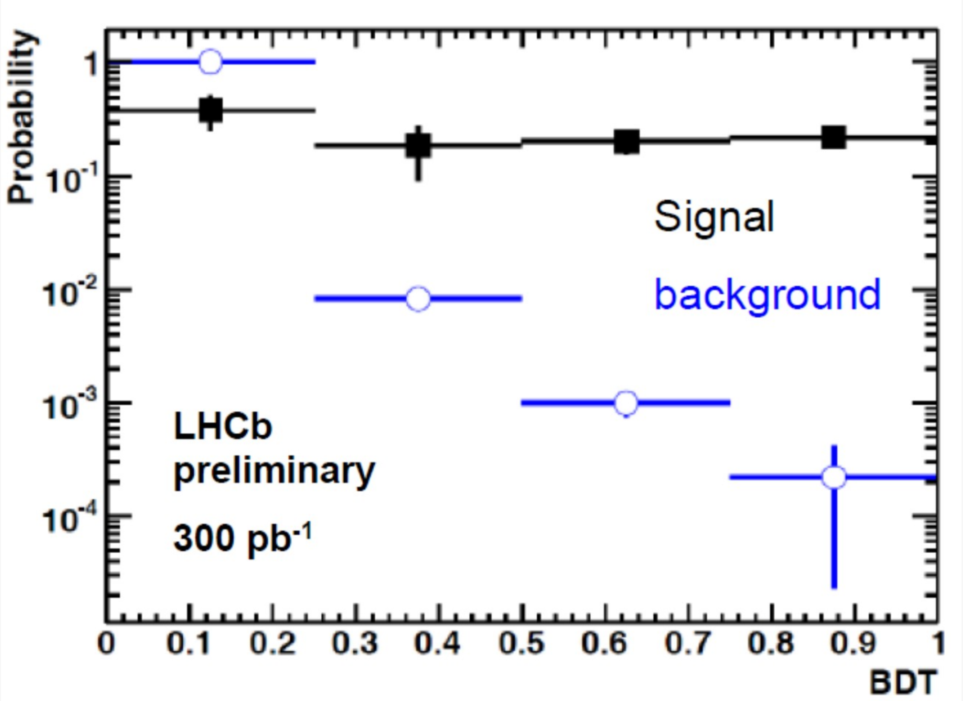
- $B_s^0 \to D_s^- \pi^+ \to K^- K^+ \pi^- \pi^+$
- $B_d^0 \to D_d^- K^+ \to K^+ K^+ \pi^- \pi^-$



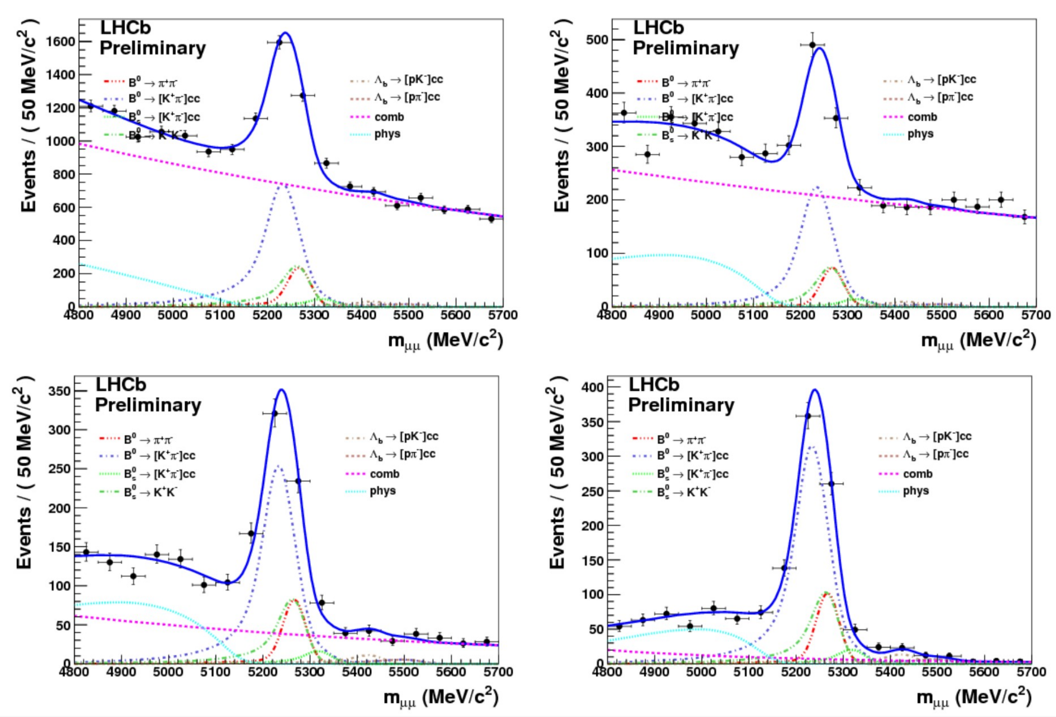
$\Rightarrow$ Combination: [LHCb-CONF-2011-034]

$$\left(\frac{f_s}{f_d}\right)_{\mathrm{LHCb}} = 0.267^{+0.021}_{-0.020}$$

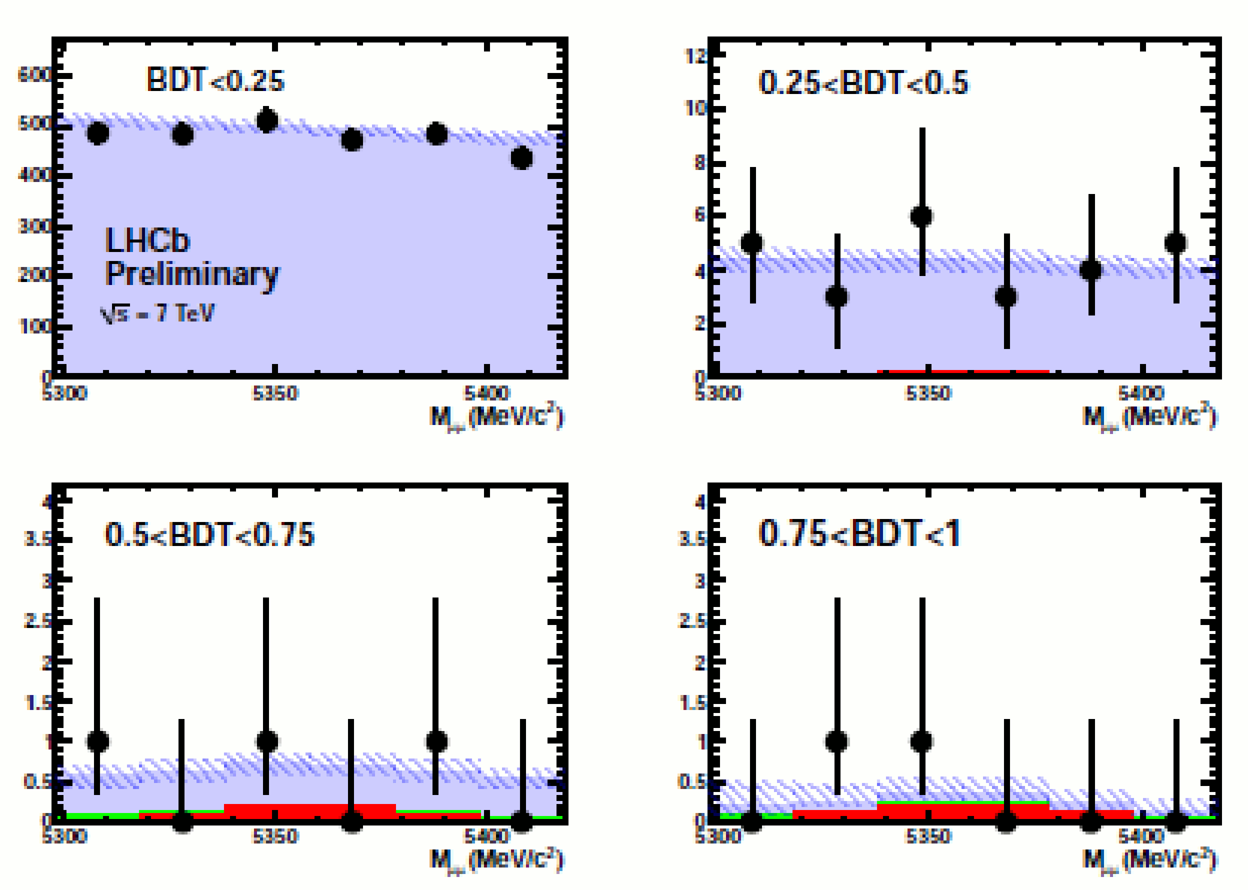
$B_s \to \mu^+ \mu^-$ (300 pb^{-1}, LHCb)



- Select $B \to \mu\mu$ using a boosted decision tree (BDT) tuned on MC but calibrated on real data $B \to hh$ and sidebands
- Mass resolution calibrated on $b \to hh$ and dimuon resonances
- Look in 4×6 bins of BDT×Mass
- Normalise to $B_s \to J/\psi\,\phi$, $B \to J/\psi\,K^*$, $B_s \to K\pi$



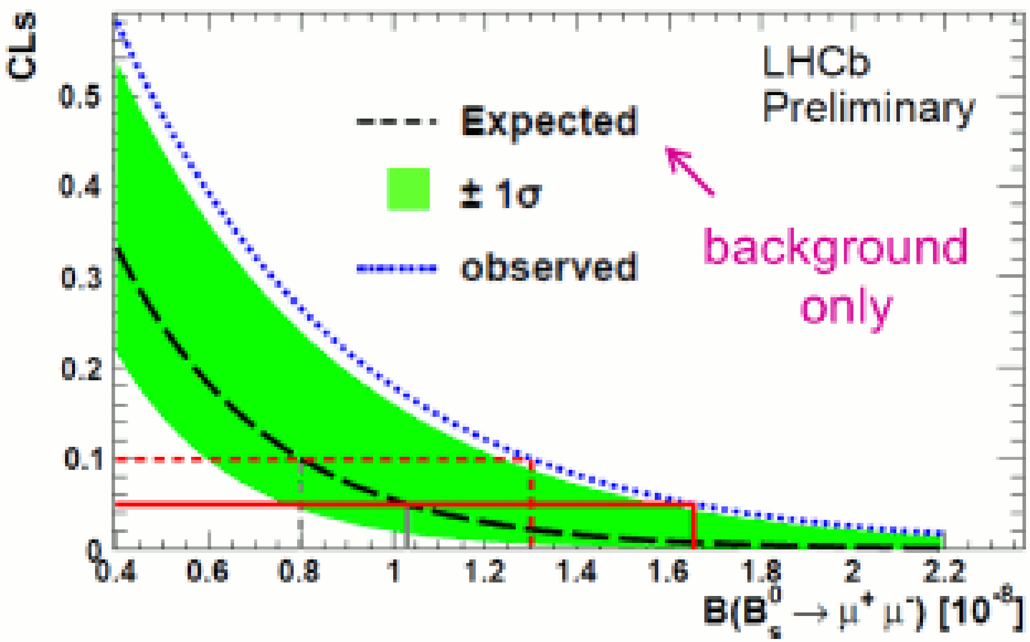
$B_s \to \mu^+ \mu^-$ $(300\,\mathrm{pb}^{-1}$, LHCb$)$

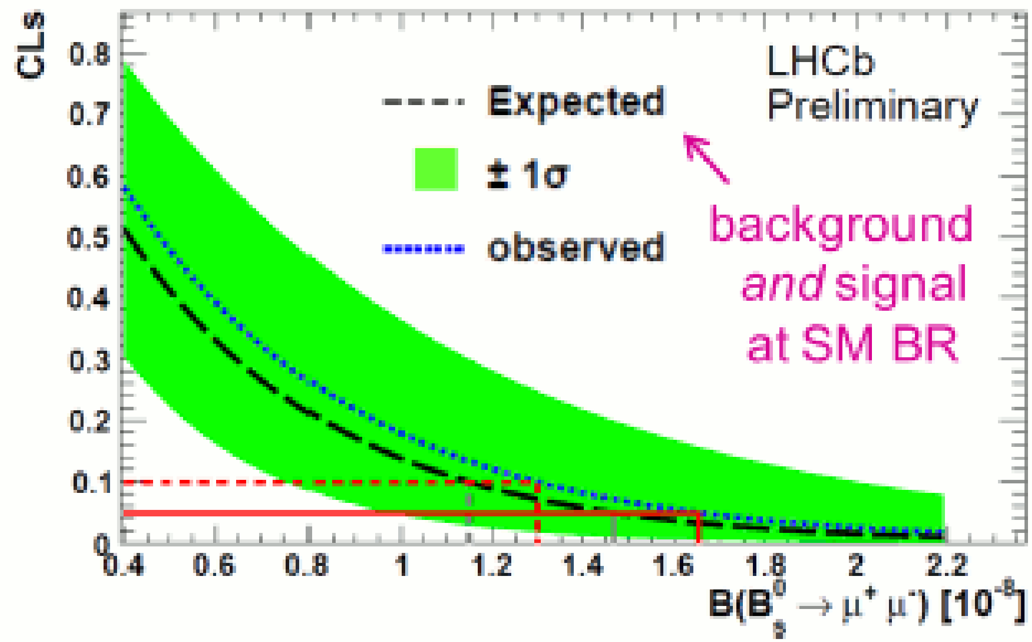


- Data
- SM signal expectation
- $B \to \pi\pi$ expectation
- Combinatorial expectation

BDT Bin	1	2	3	4
Exp. Comb. Bkg.	2969 ± 69	25 ± 3	3.0 ± 0.9	0.66 ± 0.40
Exp. SM Signal	1.26 ± 0.13	0.61 ± 0.06	0.67 ± 0.07	0.72 ± 0.07
Observed	2872	26	3	2

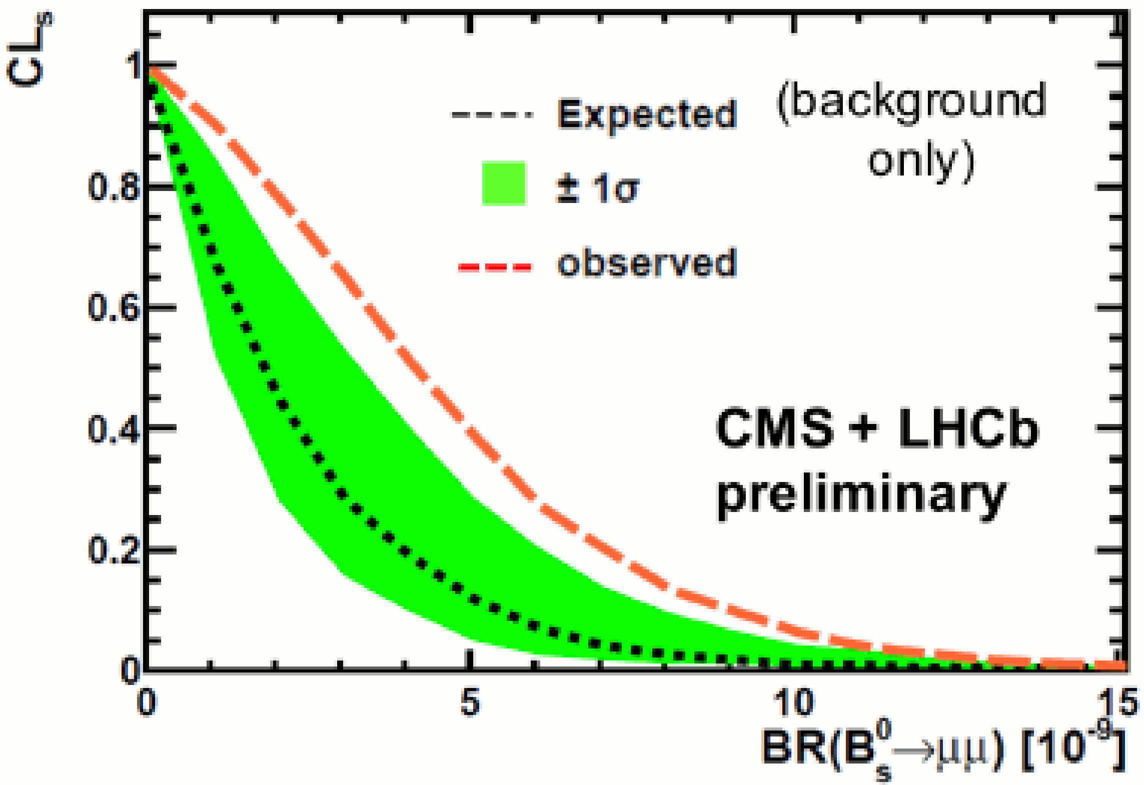
$B_s \to \mu^+\mu^-$ (300+37 pb^{-1}, LHCb)





	$B_s \to \mu\mu$	$B_d \to \mu\mu$
Expected limit assuming bkg only (95%)	$1.0 \cdot 10^{-8}$	$3.1 \cdot 10^{-9}$
Expected limit assuming bkg+SM (95%)	$1.5 \cdot 10^{-8}$	
Observed limit (95%)	$1.6 \cdot 10^{-8}$	$\mathbf{5.1 \cdot 10^{-9}}$
p-value of background only hypothesis	14%	79%
Observed limit, 2010+2011 (95%)	$\mathbf{1.5 \cdot 10^{-8}}$	

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



- Combine using LHCb's framework, with 24 LHCb plus 2 CMS bins.
- Use f_d/f_s from LHCb.

	LHCb	CMS
Expected Limit, SM+Bkg (95%)	$1.5 \cdot 10^{-8}$	$1.8 \cdot 10^{-8}$
Observed limit, 2010+2011 (95%)	$1.5 \cdot 10^{-8}$	$1.9 \cdot 10^{-8}$
Observed LHCb+CMS limit (95%)	$\mathbf{1.1 \cdot 10^{-8}}$	

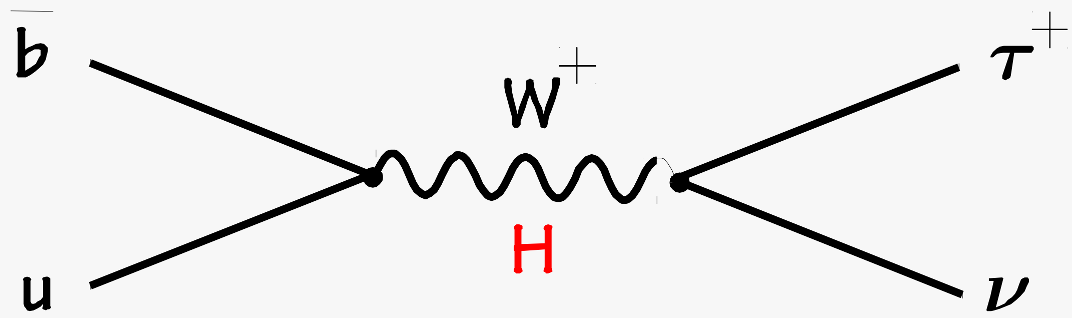
Previous measurements:

D0 ($6.1\ \mathrm{FB}^{-1}$): $\mathcal{B} < 5.1 \cdot 10^{-8}$ (95%) [Phys. Lett. B 693, 539 (2010)]

LHCb ($37\ \mathrm{PB}^{-1}$): $\mathcal{B} < 5.6 \cdot 10^{-8}$ (95%) [Phys. Lett. B 699, 330 (2011)]

CDF ($7\ \mathrm{FB}^{-1}$): $\mathcal{B} = (1.8\,^{+1.1}_{-0.9}) \cdot 10^{-8}$ Hint! [arXiv:1107.2304]

$\underline{B \to \tau \nu}$



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

Tree diagram, but quite rare: $B_{SM} = (1.2 \pm 0.4) \cdot 10^{-4}$

(for other modes, SM expectations: 10^{-11} $(e\nu)$, 5×10^{-7} $(\mu\nu)$)

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

2HDM (type II): $B(B^+ \to \tau^+ \nu) = B_{SM} \times \left(1 - \frac{m_B^2}{m_{H^+}^2} \tan^2\beta\right)^2$

uncertainties from f_B and $|V_{ub}|$ can be reduced to B_B

and other CKM uncertainties by combining with precise Δm_d

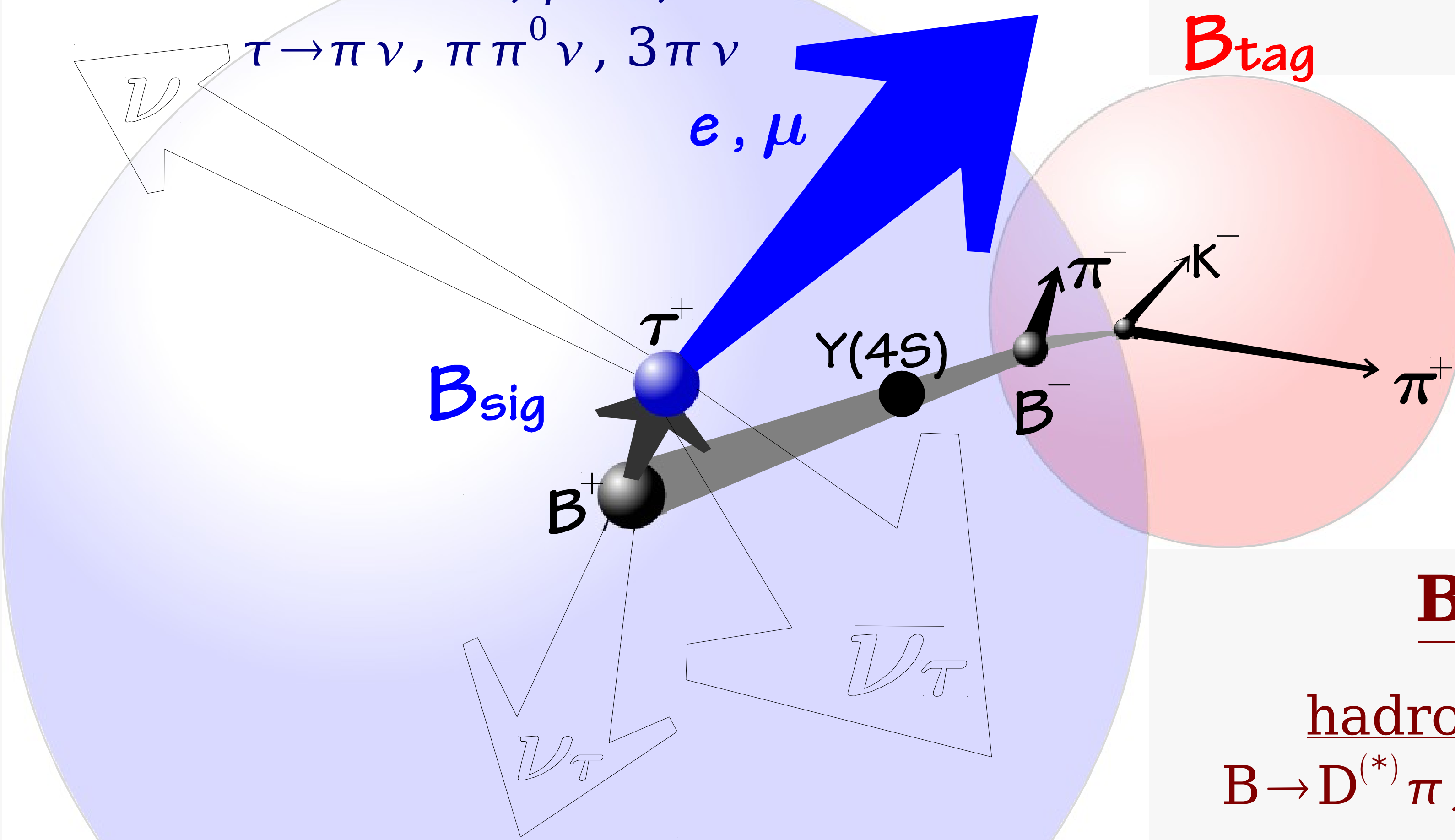
Event reconstruction in $B \rightarrow \tau\, \nu$

$B_{sig} \rightarrow \tau\, \nu$

(70 % of all τ decays)

$\tau \rightarrow e\, \nu\, \nu\,,\ \mu\, \nu\, \nu\,,$

$\tau \rightarrow \pi\, \nu\,,\ \pi\, \pi^0\, \nu\,,\ 3\pi\, \nu$



B_{tag}

hadronic tag

$B \rightarrow D^{(*)}\pi\,,\ D^{(*)}$rho....

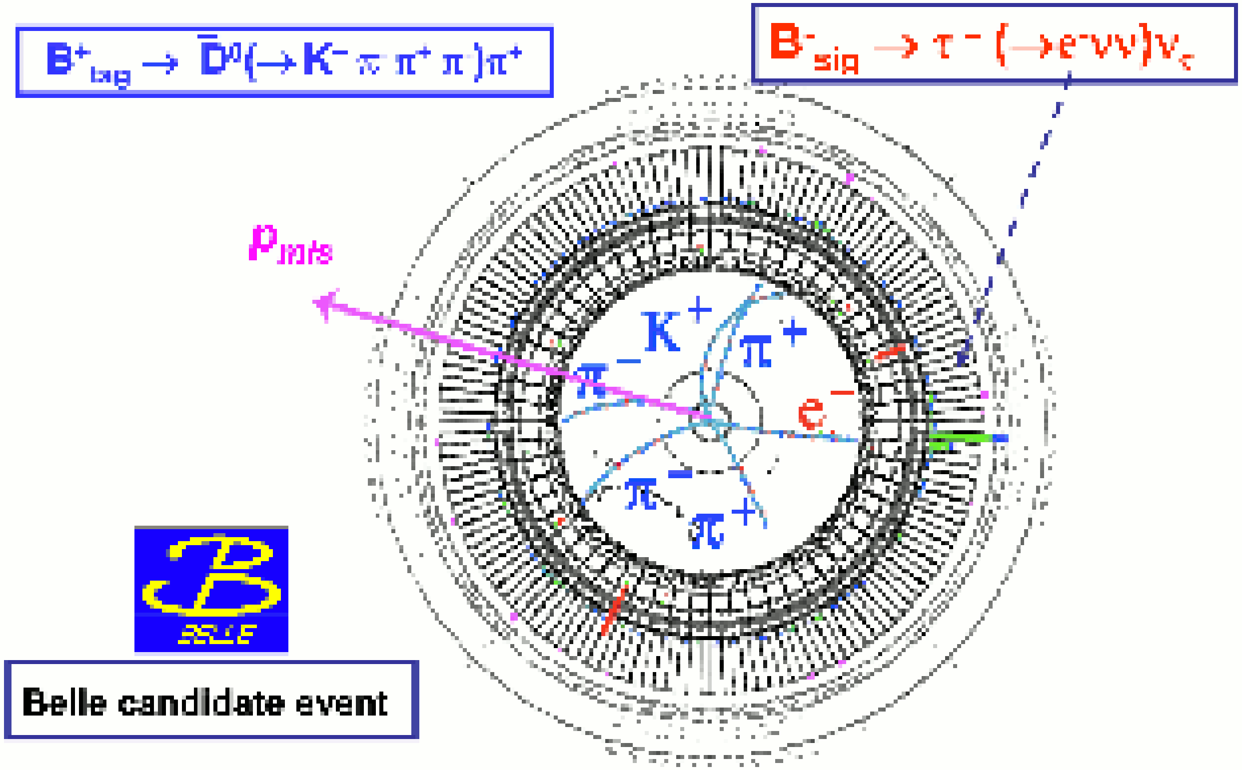
$\epsilon \sim 0.2\,\%$

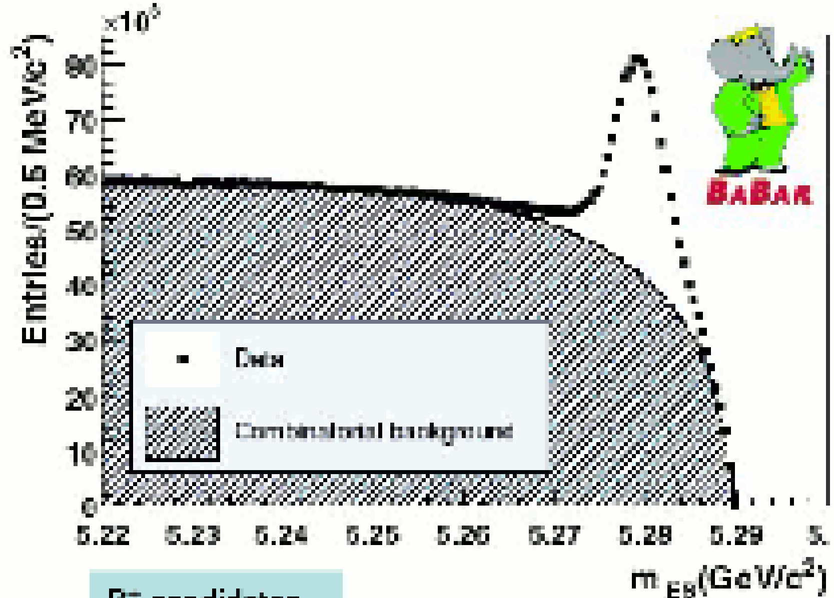
semileptonic tag

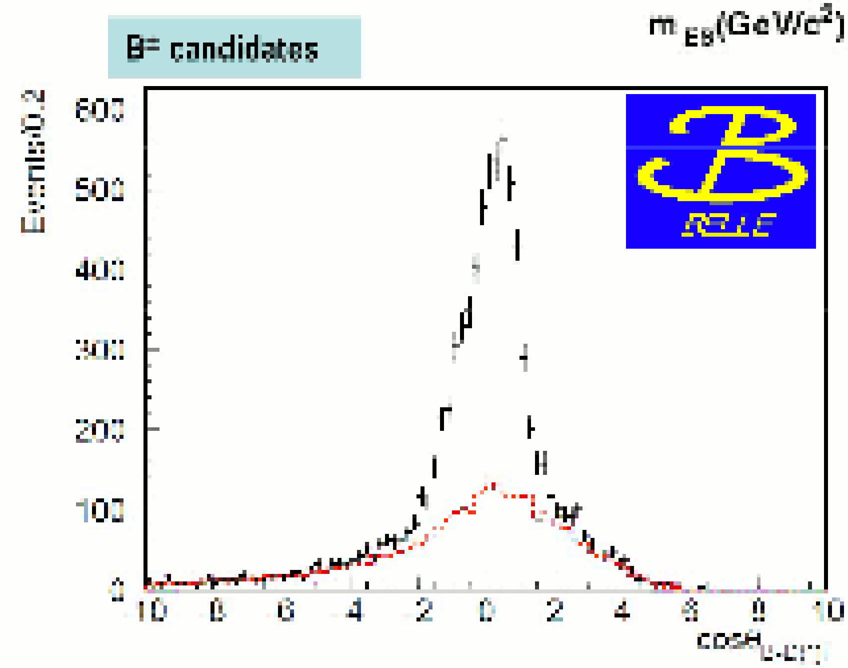
$B \rightarrow D^{(*)} l\, \nu\ X$

Require no particle
and no energy left
after removing B_{tag}
and visible particles of B_{sig}

Full Reconstruction



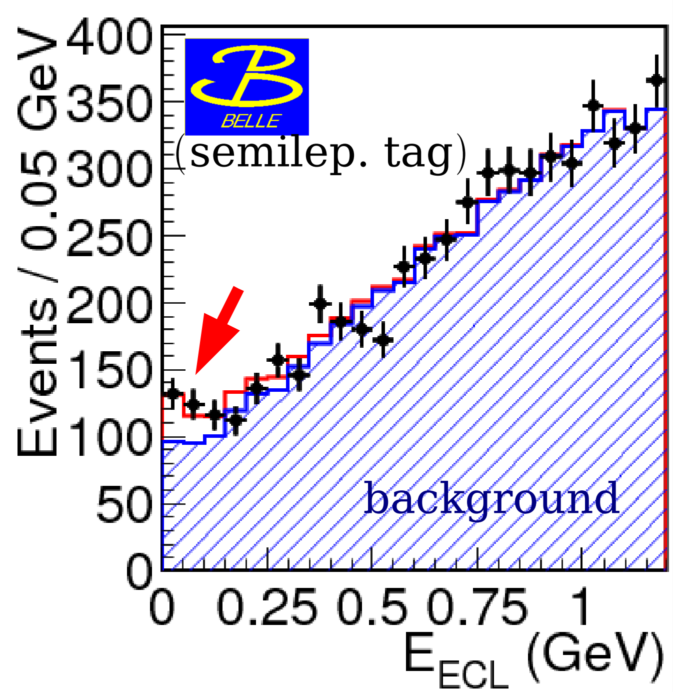


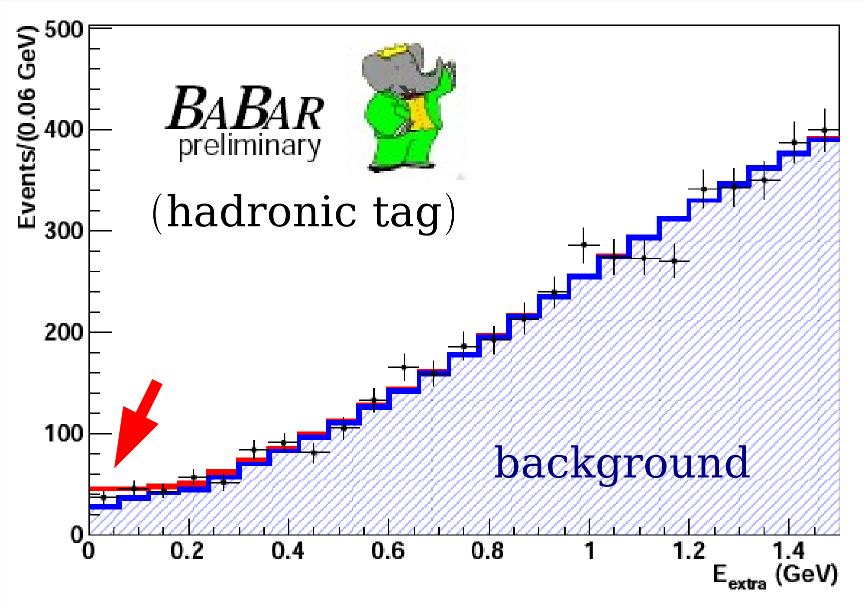


- $(\vec{p}, E)$ of $\Upsilon(4S)$ is known
- Reconstruct one B fully
- ✔ Known 4-momentum (and charge) of other B
- ➜ A clean B beam at $\mathcal{O}(1\%)$ efficiency

$B^+ \to \tau^+ \nu$ results

- Fully reconstruct one of the B (hadronic, semi-leptonic)
- Look for a single lepton or pion from $\tau \to l \nu \bar{\nu}$ or $\tau \to \pi \bar{\nu}$
- Require nothing else in the detector $\Rightarrow$ Signal has 0 energy in the ECAL





Extra calorimeter energy: $E_{ECL/extra}$ (GeV)

Belle	$N_{B\bar{B}}$	$\mathcal{B}$ (10^{-4})	$\Sigma(\sigma)$	
Hadronic tag	(449 M)	$(1.79^{+0.56}_{-0.49}{}^{+0.46}_{-0.51})$	3.5	PRL97, 251802 (2006)
Semilep. tag	(657 M)	$(1.54^{+0.38}_{-0.37}{}^{+0.29}_{-0.31})$	3.6	PRD 82, 071101 (2010)
BaBar				
Hadronic tag	(468 M)	$(1.80^{+0.57}_{-0.54} \pm 0.26)$	3.6	preliminary
Semilep. tag	(459 M)	$(1.7 \pm 0.8 \pm 0.2)$	2.3	PRD81, 051101 (2010)

$B^+ \to \tau^+ \nu$ results

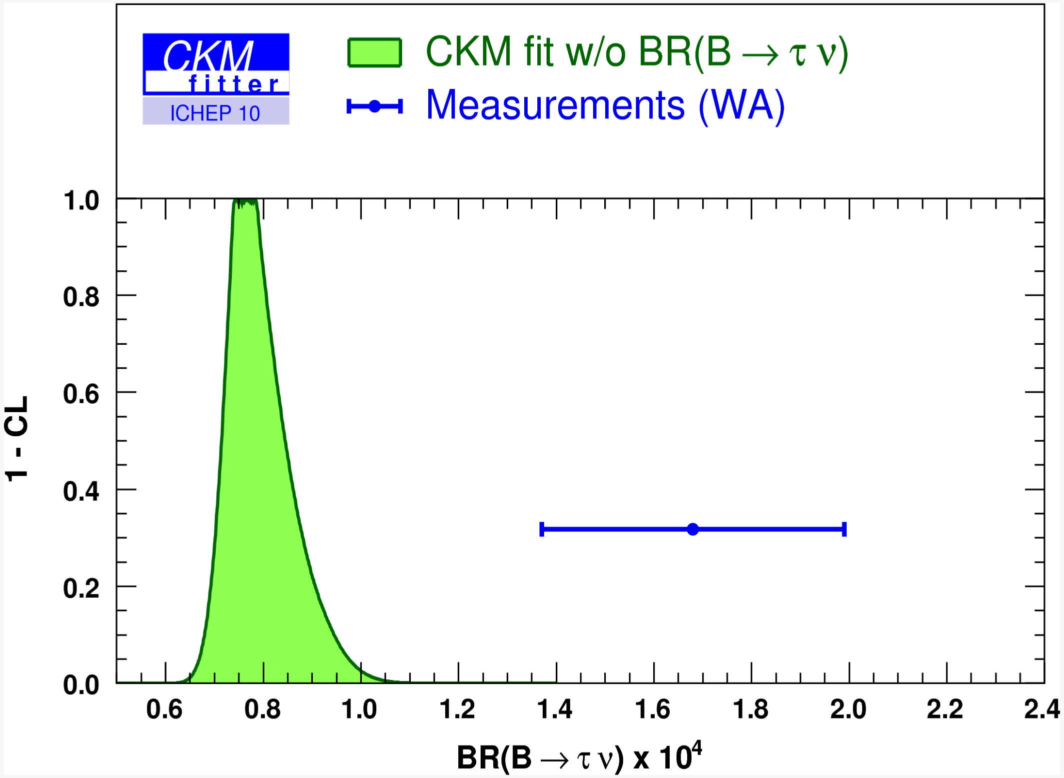
World average: $\mathcal{B}(B^+ \to \tau^+ \nu) = (1.68 \pm 0.31) \times 10^{-4}$

$$\mathcal{B}_{SM}(B^+ \to \tau^+ \nu) = (1.20 \pm 0.25) \times 10^{-4}$$

using f_B (HPQCD), $|V_{ub}|$ (HFAG)

$$\text{CKMfitter}: \mathcal{B}_{SM}(B^+ \to \tau^+ \nu) = (0.76^{+0.11}_{-0.06}) \times 10^{-4}$$

2.8σ difference



$B^+ \to \tau^+ \nu$ results

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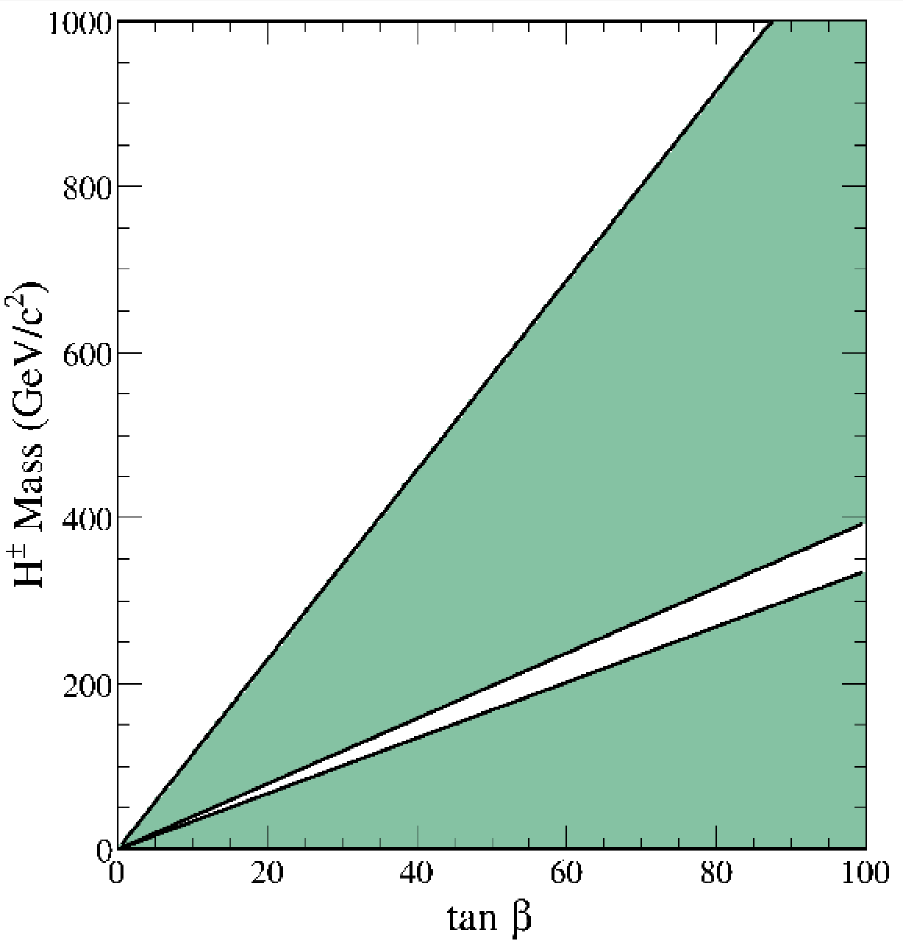
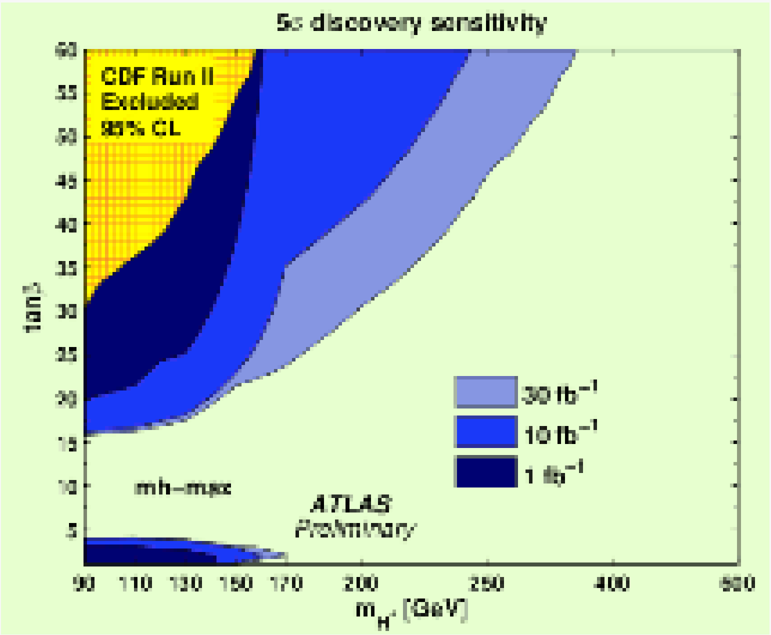
2HDM (type II):

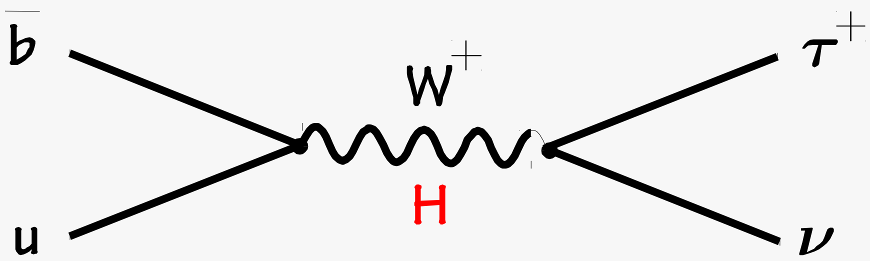
$$B(B^+ \to \tau^+ \nu) = B_{SM} \times \left(1 - \frac{m_B^2}{m_{H^+}^2} \tan^2\beta\right)^2$$

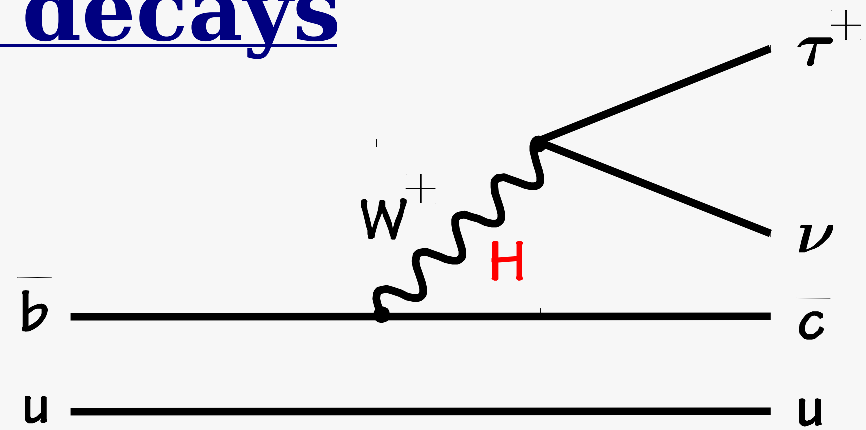


- Charged Higgs are excluded in range of reasonable masses
- Atlas and CMS are still looking [Atlas, CHARGED2008]



Tauonic B decays





$B \to \tau \nu$

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

$$\text{2HDM (type II)}: \mathcal{B}(B^+ \to \tau^+ \nu) = \mathcal{B}_{SM} \times \left(1 - \frac{m_B^2}{m_{H^+}^2} \tan^2\beta\right)^2$$

uncertainties from f_B and $|V_{ub}|$ can be reduced to B_B
and other CKM uncertainties by combining with precise Δm_d

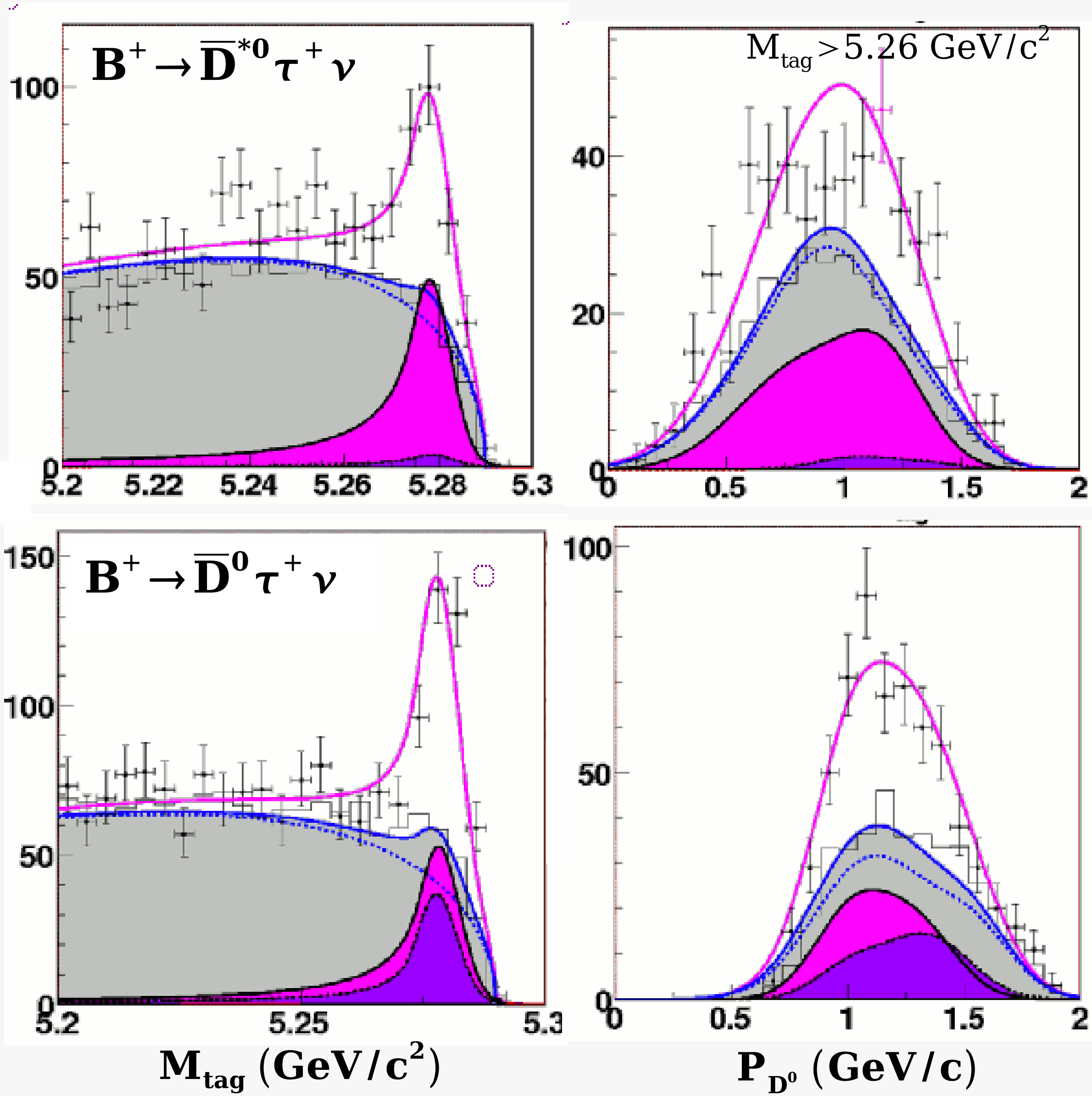
$B \to D^{(*)} \tau \nu$

$$\text{2HDM (type II)}: \mathcal{B}(B \to D \tau^+ \nu) = G_F^2 \tau_B |V_{cb}|^2 f\left(F_V, F_S, \frac{m_B^2}{m_{H^+}^2} \tan^2\beta\right)$$

uncertainties from form factors F_V and F_S can be studied
with $B \to D l \nu$ (more form factors in $B \to D^* \tau \nu$)

$B^+ \to D^{(*)} \tau^+ \nu$

arXiv: 1005.2302
submitted to PRL



- 657M $B\overline{B}$
- same method than for $B^0 \to D^{*-} \tau^+ \nu$

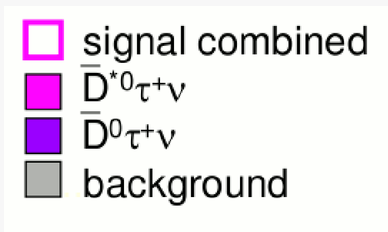
B_{sig} :

$D^0 \to K\pi,\ K\pi\pi^0$

$\tau^+ \to e^+ \nu_e \overline{\nu}_\tau,\ \mu^+ \nu_\mu \overline{\nu}_\tau,\ \pi^+ \overline{\nu}_\tau,\ \rho^+ \overline{\nu}_\tau$

13 different decay chains

B_{tag} : all remaining particles



First $B^+ \to \overline{D}^0 \tau \nu$ evidence !

	N_S	$B(\%)$	$\Sigma(\sigma)$
$B^+ \to \overline{D}^{*0} \tau^+ \nu$	446^{+58}_{-56} (226)	$2.12^{+0.28}_{-0.27} \pm 0.29$	8.1
$B^+ \to \overline{D}^{0} \tau^+ \nu$	146^{+42}_{-41} (15)	$0.77 \pm 0.22 \pm 0.12$	3.5

$\mathbf{B \to D^{(*)} \tau^+ \nu}$ summary

Branching fraction ratio (R(*)) relative to B→D(*)lν predicted in the Standard Model with reduced form-factor uncertainty

BaBar

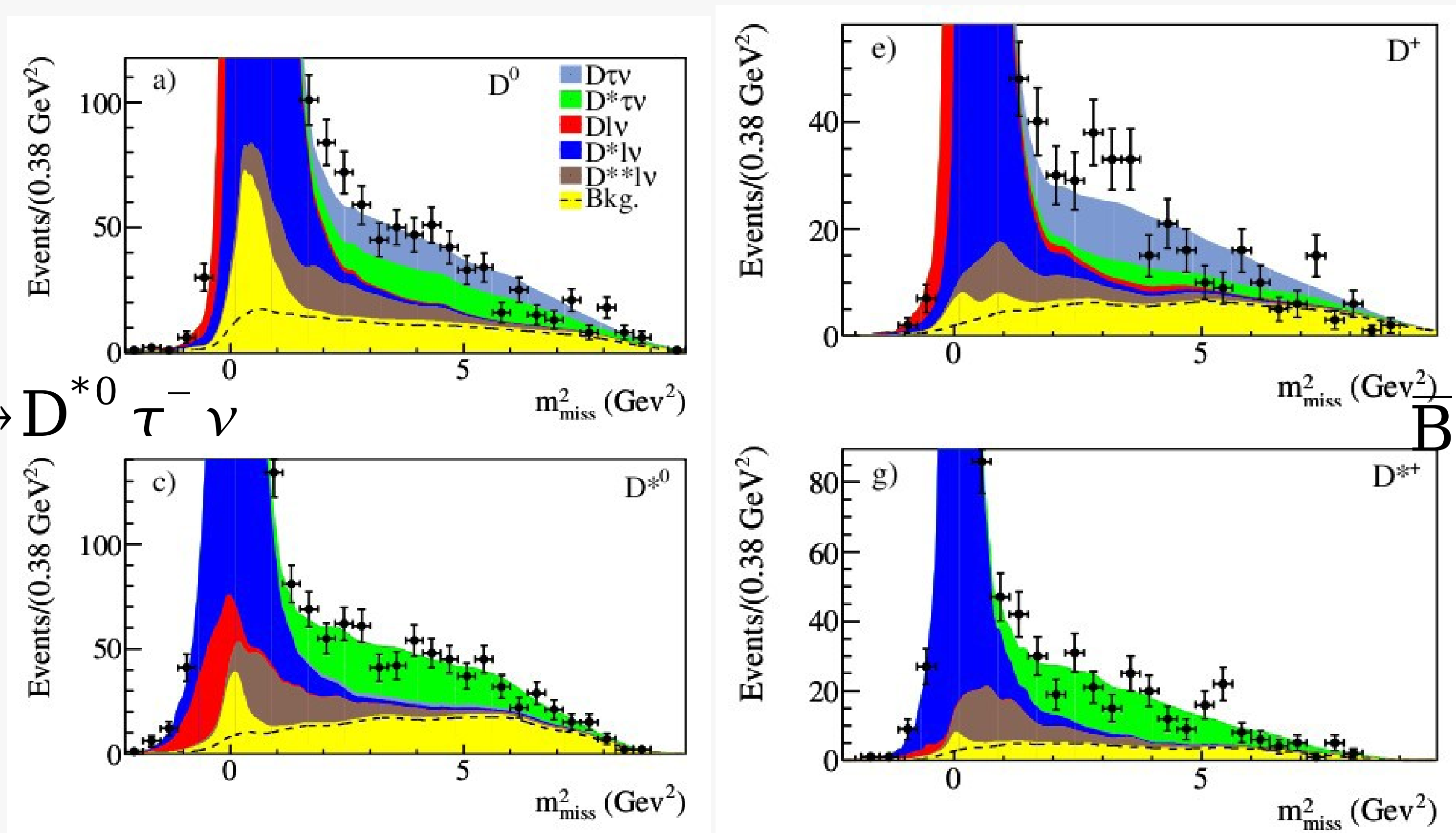
[EPS 2011 preliminary]

$B^- \to D^0 \tau^- \nu$

$\overline{B}^0 \to D^- \tau^+ \nu$

$B^- \to D^{*0} \tau^- \nu$

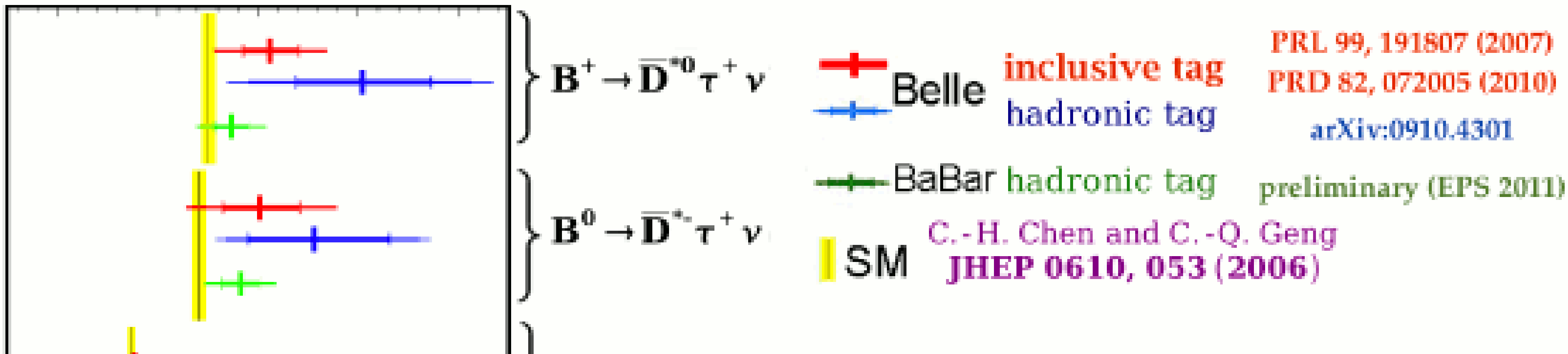
$\overline{B}^0 \to D^{*-} \tau^+ \nu$

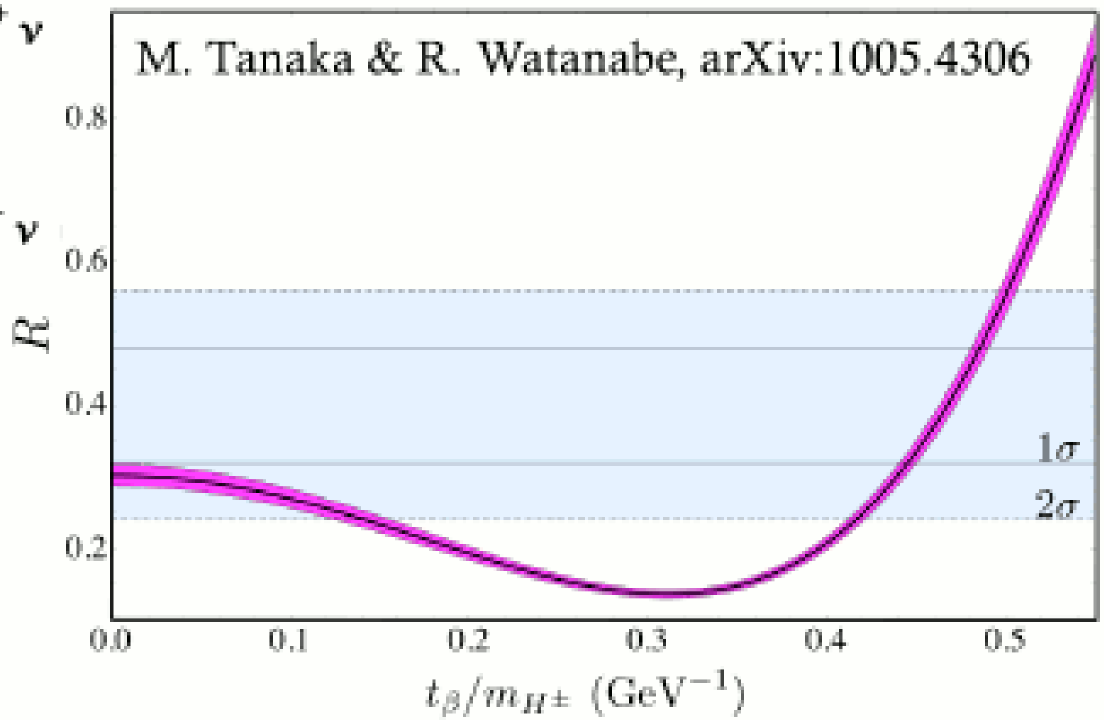


$$R(D) = 0.456 \pm 0.053 \pm 0.056 \qquad R^{SM}(D) = 0.31 \pm 0.02$$
$$R(D^*) = 0.325 \pm 0.023 \pm 0.027 \qquad R^{SM}(D^*) = 0.25 \pm 0.07$$

$\Rightarrow$ 1.8σ excess over the Standard Model

$B \to D^{(*)} \tau^+ \nu$ summary

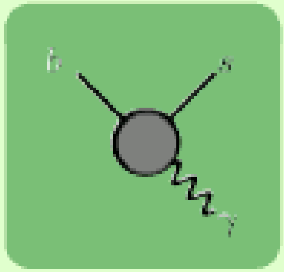




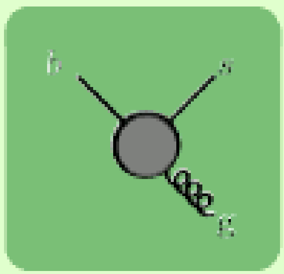
Operators of interest

Operator

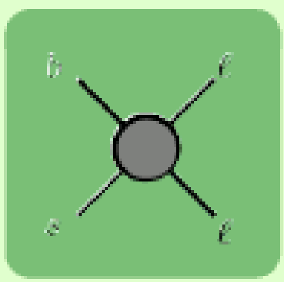
$\mathcal{O}_{7\gamma}$



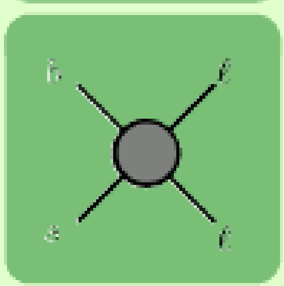
$\mathcal{O}_{8g}$



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



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



Effective Hamiltonian $\mathcal{H}$

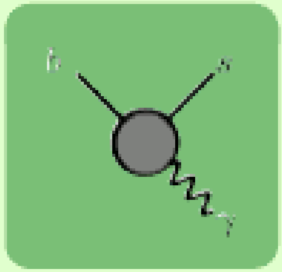
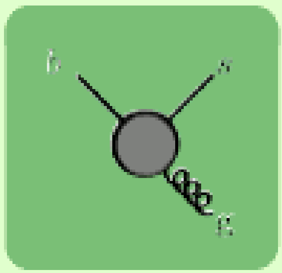
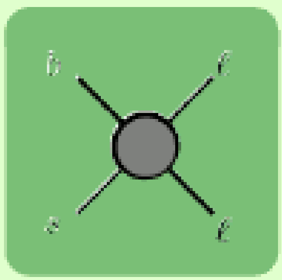
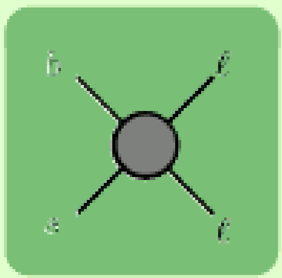
$$A(M \to F) = \langle F \,|\mathcal{H}_{\text{eff}}|\, M \rangle$$

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

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

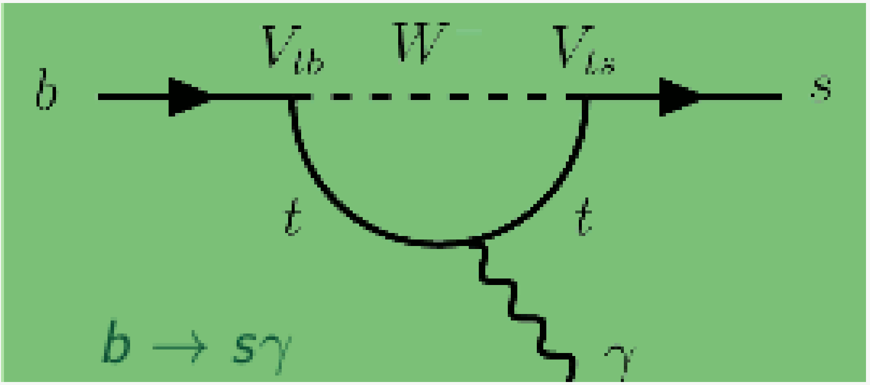
New physics can show up in new operators or modified Wilson coefficients

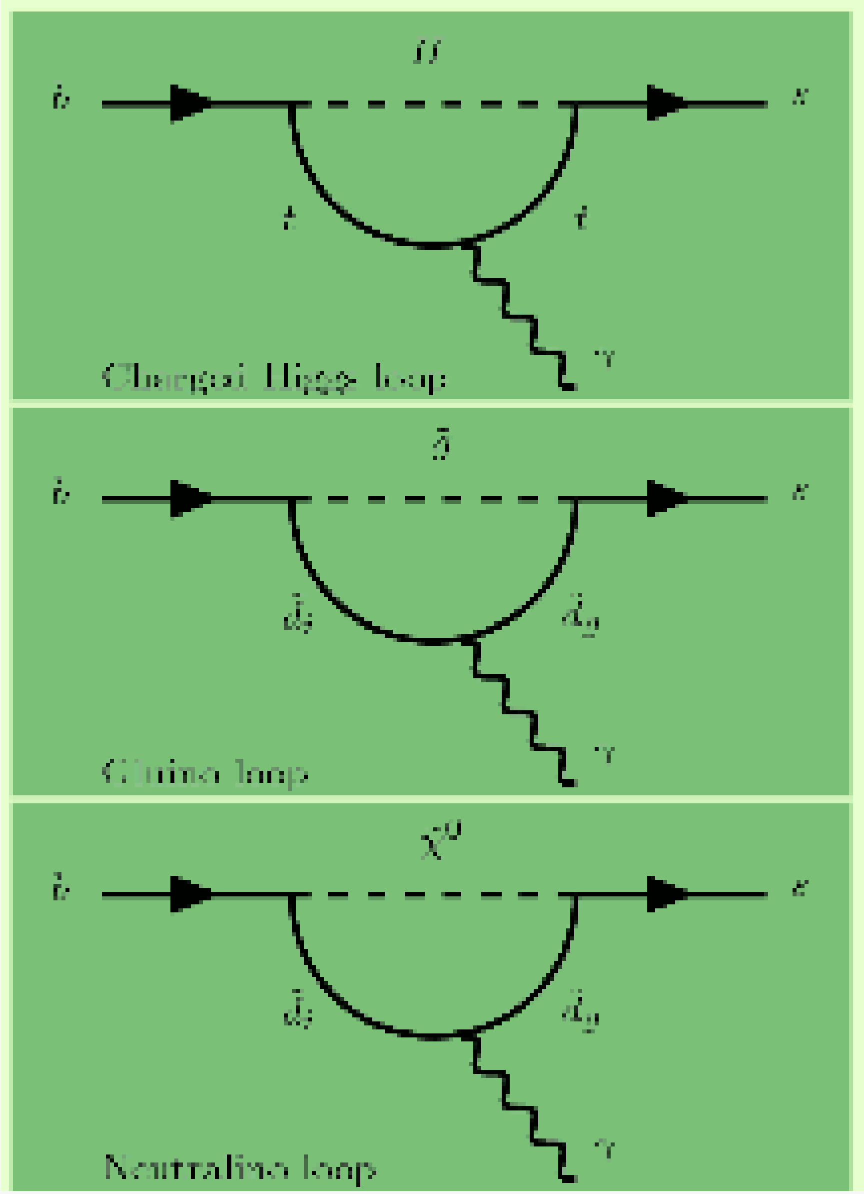
Operators of interest

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

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

$b \to s\gamma$





- Amplitude $\propto V_{ts}|C_7|$
- First penguin ever observed (93)
- Experiment (WA):

  $$B = (3.55 \pm 0.26)\,.\,10^{-4}$$
- SM: $B = (3.15 \pm 0.23)\,.\,10^{-4}$

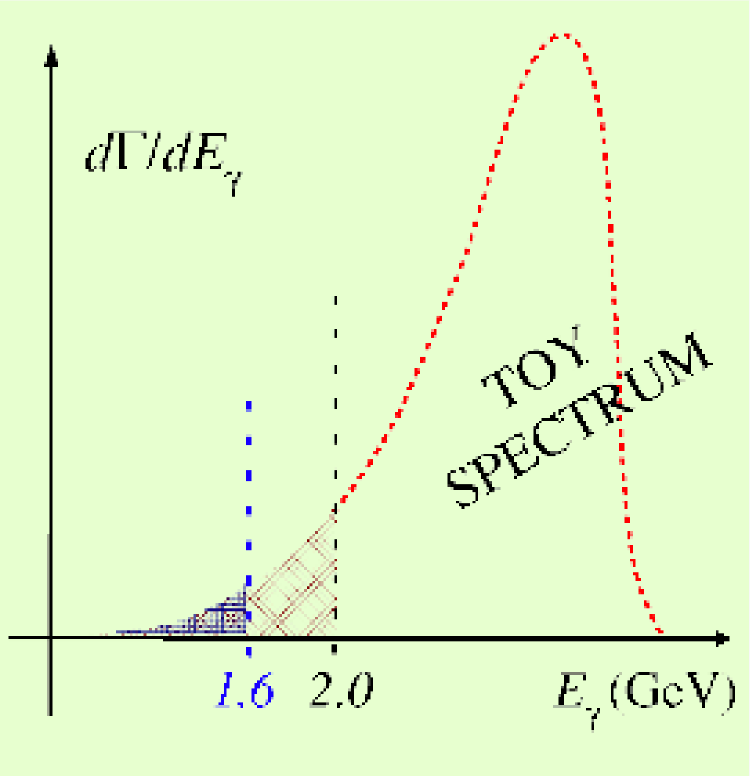
  [Misiak et al., hep-ph/0609232]
- Strong constraint on New Physics

$B \to X_s \gamma$ spectrum

- $b \to s\gamma$ 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 $B \to X_s \gamma$ and in the B meson the b quark is moving which smears the energy spectrum
  - $\rightarrow$ Mean $\sim \frac{m_B}{2}$
  - $\rightarrow$ 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)]

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

$b \to s\gamma$ SM branching fraction

[Misiak et al, PRL98, 02202, 2007]

- From effective Hamiltonian one gets the BF :

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

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

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

  - ✔ 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 $b \to ce\nu$ decays

$b \to s\gamma$ SM branching fraction

[Misiak et al, PRL98, 02202, 2007]

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

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

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

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

- The P fraction can be calculated at NNLO:

$$P(E_0) = \sum^{8} C_i^{\text{eff}}(\mu) C_j^{\text{eff}}(\mu) K_{ij}(E_0, \mu)$$

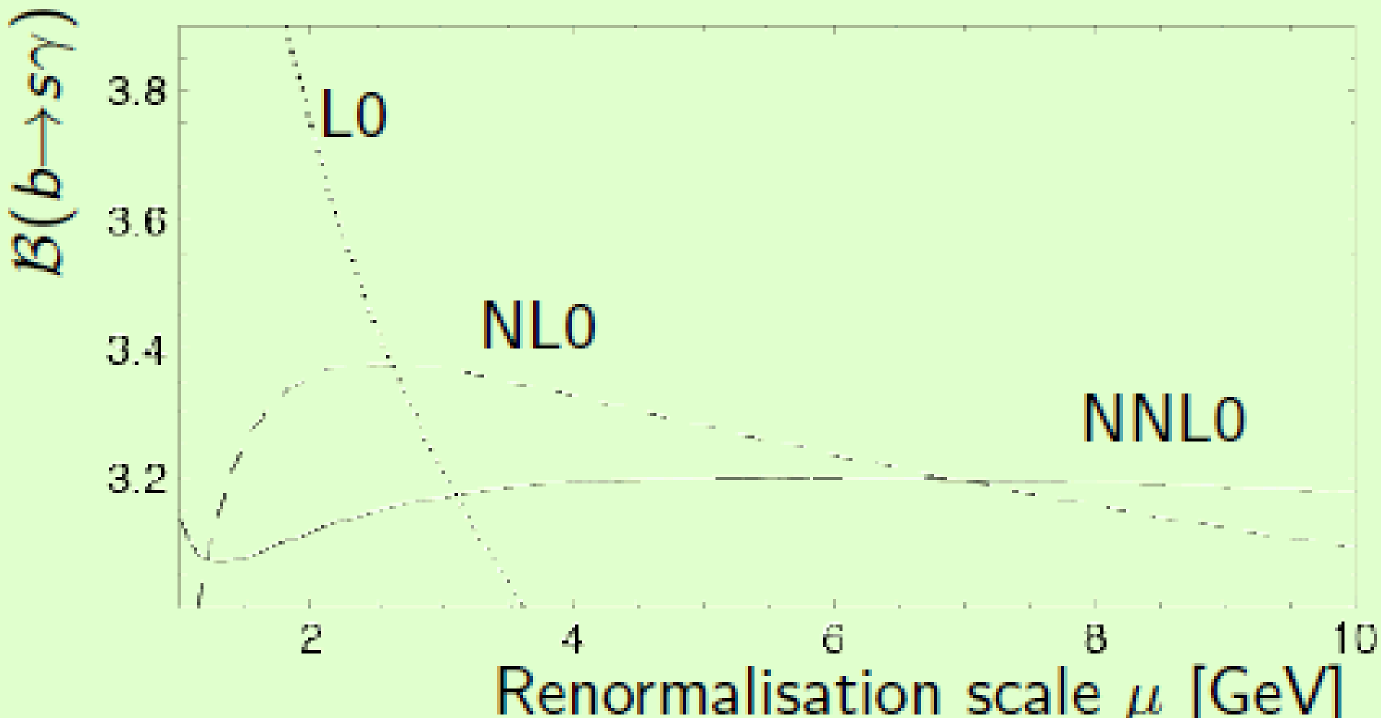
$b \to s\gamma$ SM branching fraction

[Misiak et al, PRL98, 02202, 2007]

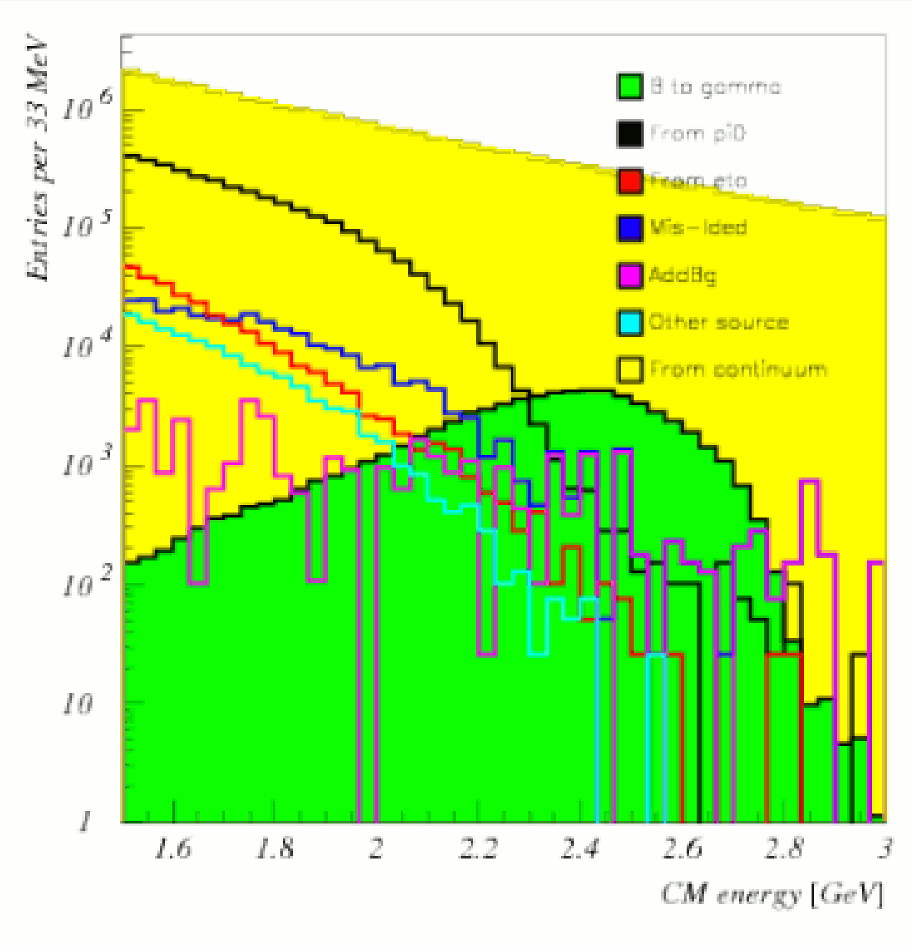
- From effective Hamiltonian one gets the BF
- Uncertainties due to m_b and m_c: normalise to $b \to ce\nu$ and $b \to ue\nu$ [Misiak & Steinhauser, NPB764:62,2007]
- $b \to s\gamma$ branching fraction calculated at all NNLO orders in 2006

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

✔ BF very stable versus μ



$b \rightarrow s\gamma$ 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 $B\overline{B}$ events
- ...and a lot more indirect π^0 and η in non-$B\overline{B}$ events

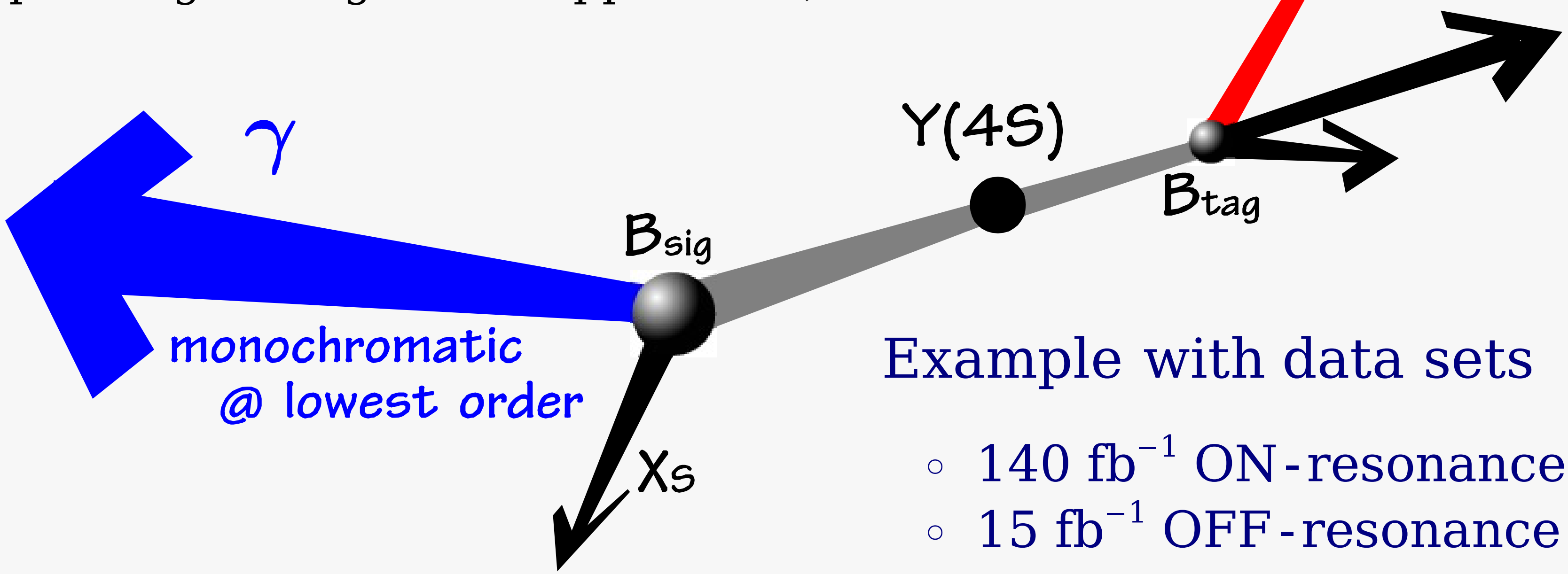
$\Rightarrow$ Lots of background at low energy

$b \to s\gamma$ spectrum at Belle

inclusive $B \to X_s \gamma$ measurement

untagged

lepton tag: background suppression, low stat



Example with data sets

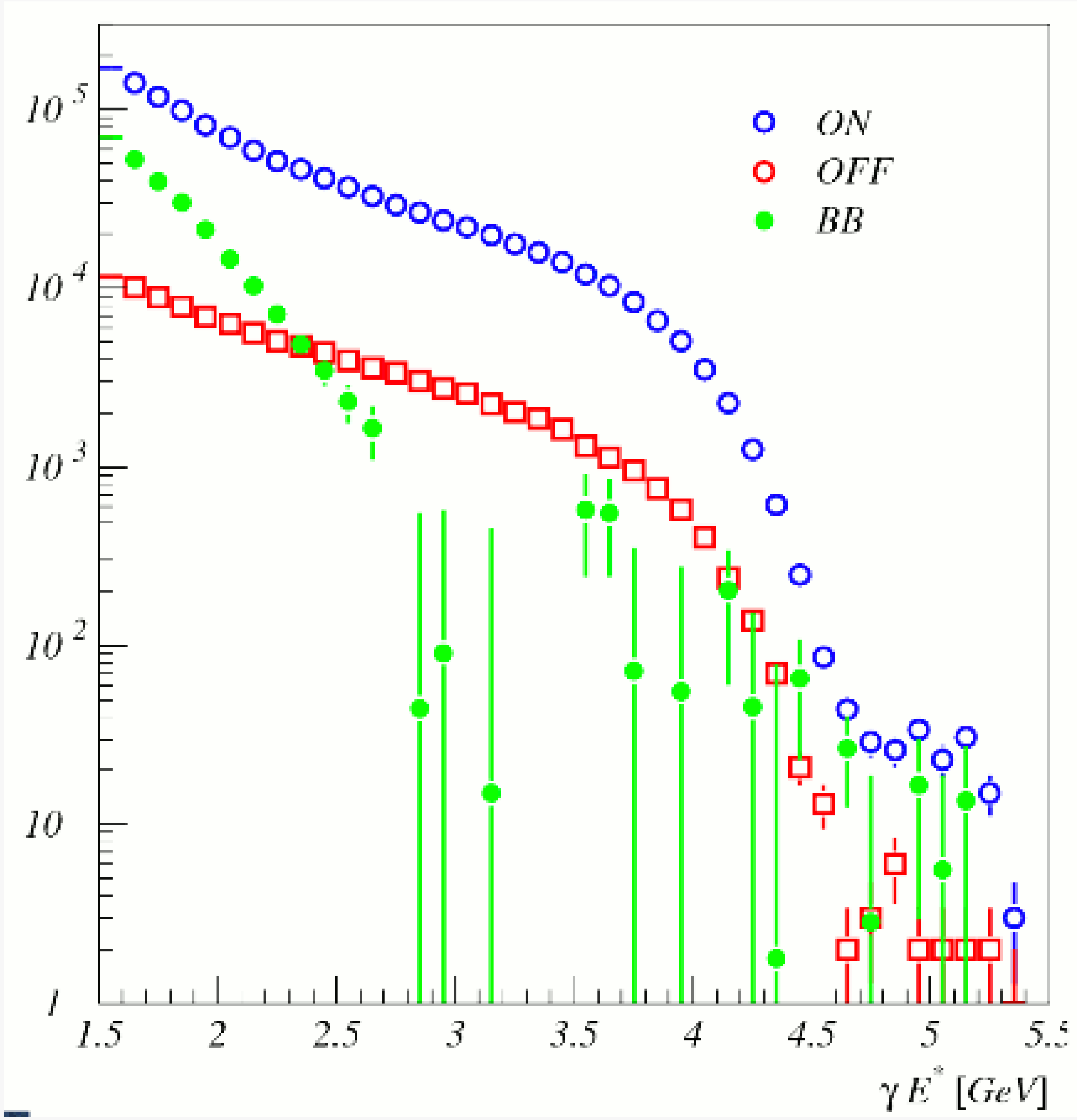
- 140 fb^{-1} ON-resonance
- 15 fb^{-1} OFF-resonance

- No kinematic constraints
- Only a high energy photon measured in $\Upsilon(4S)$ rest frame
- Lower E_γ threshold (1.7 GeV)

Event selection:

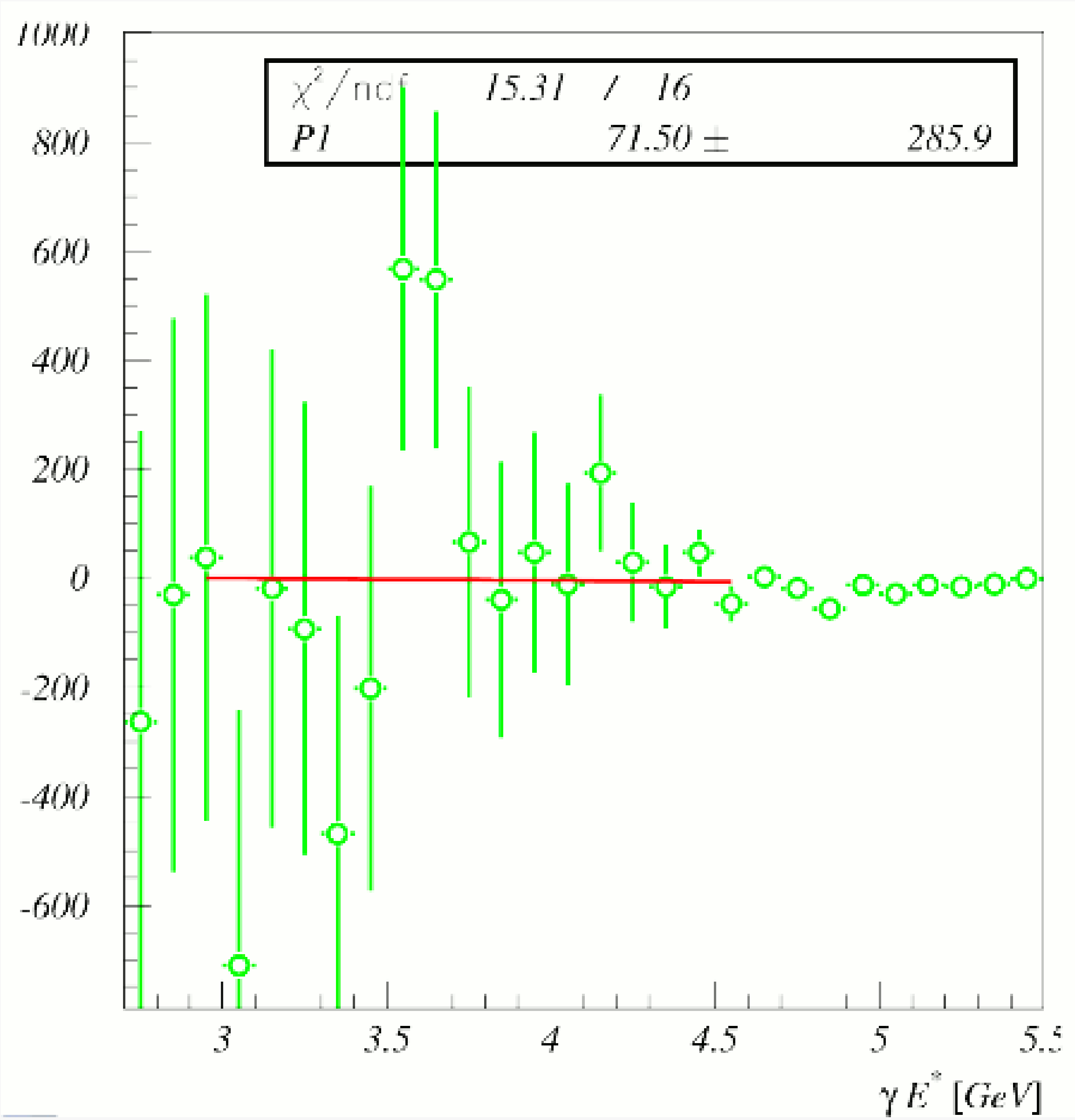
- Hadronic events with isolated photon(s) in ECL. $E^* > 1.5$ GeV.
- Veto γ from π^0 and η
- Apply event shape cuts to suppress continuum background.

The spectrum



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

The spectrum



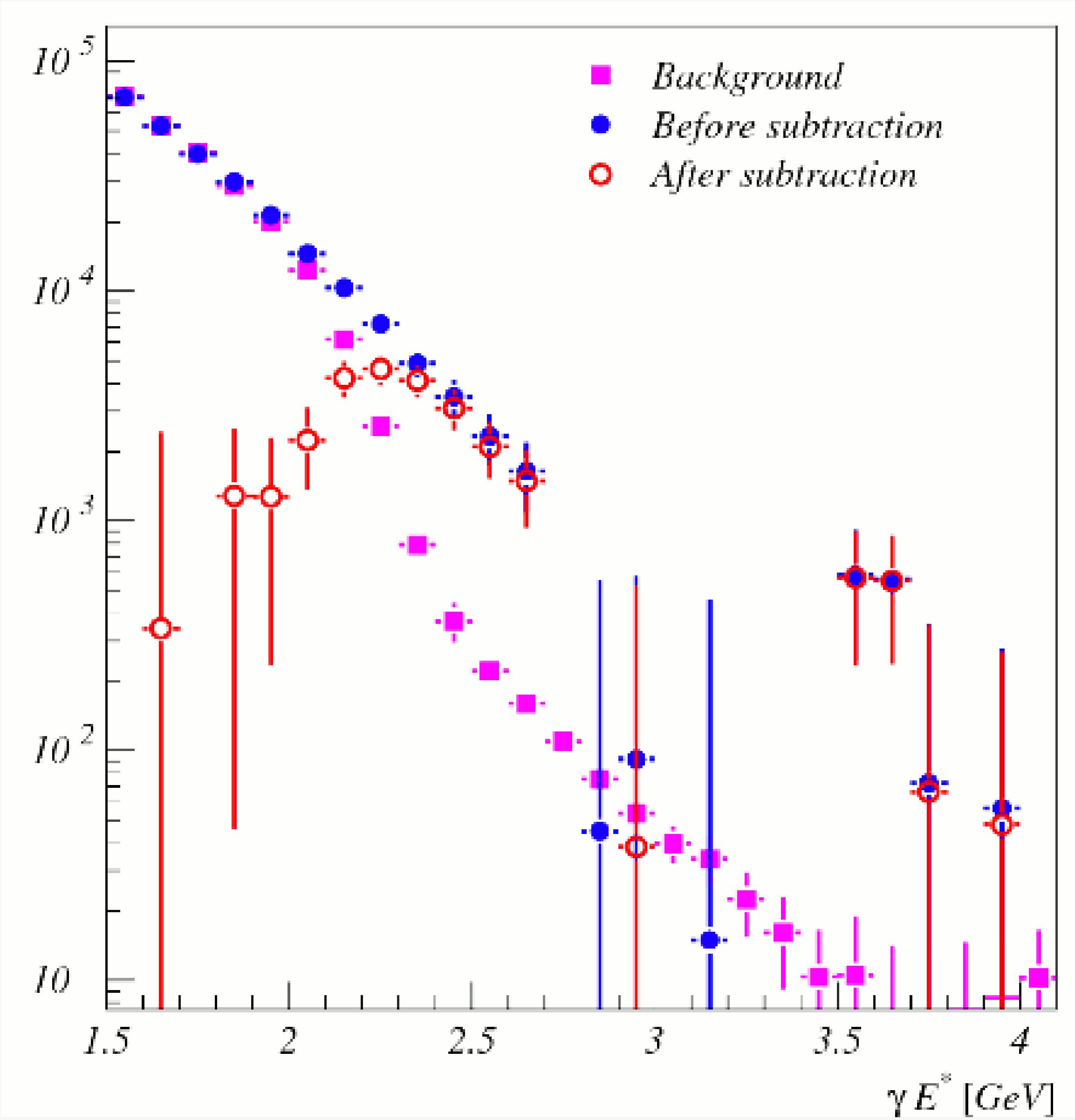
Endpoint check:

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

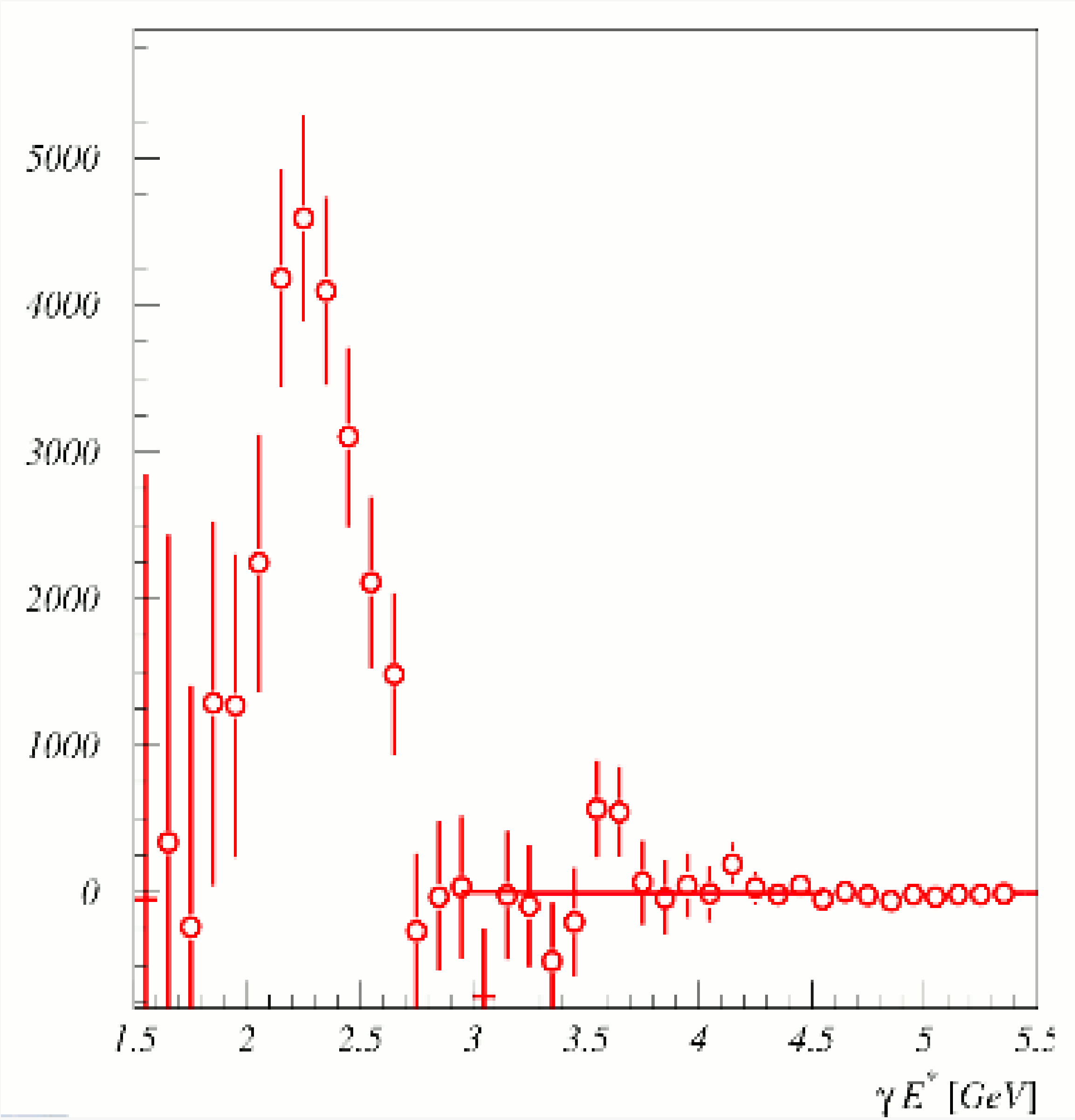
The spectrum



$B\overline{B}$ subtraction:

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

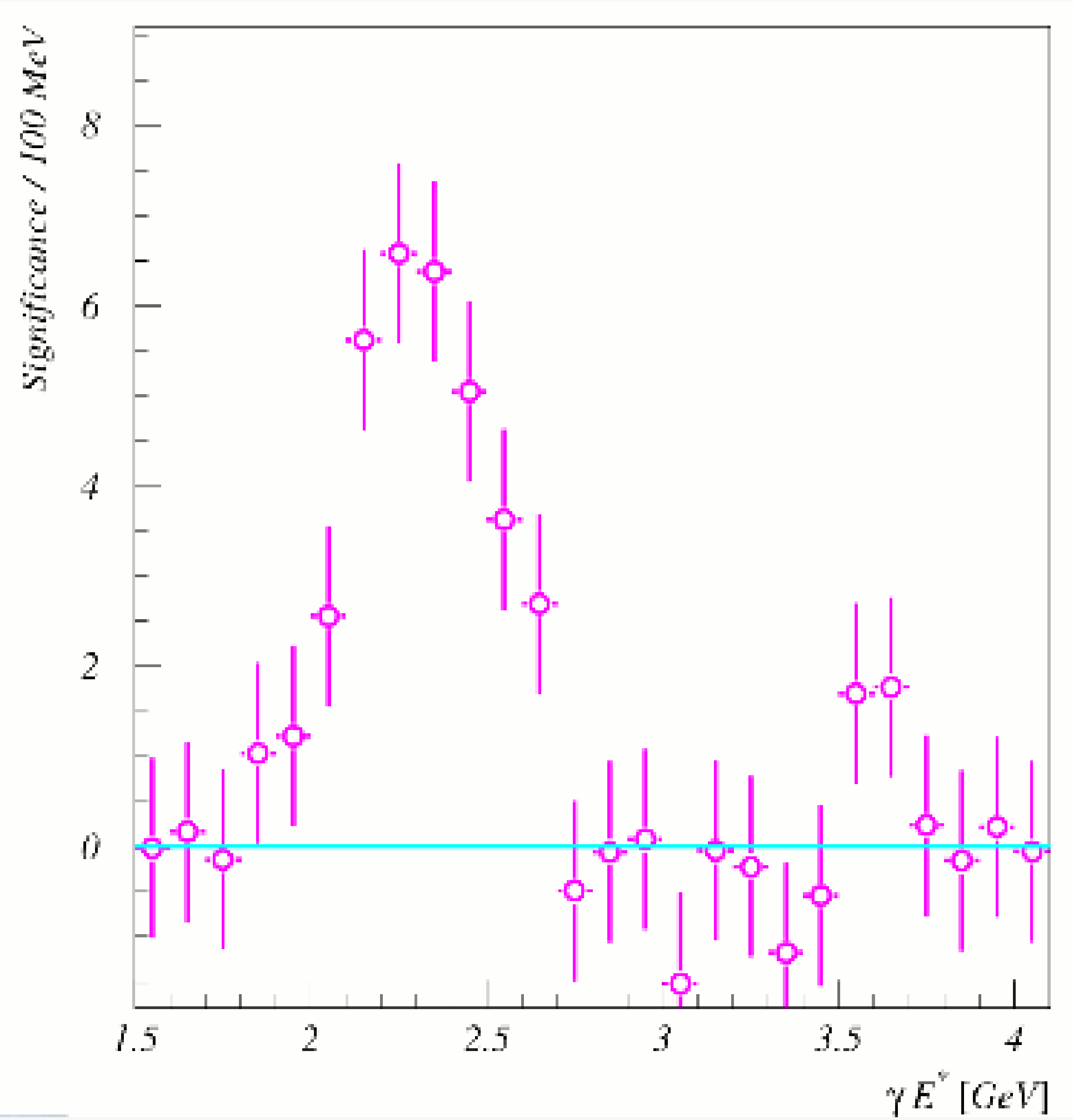
The spectrum



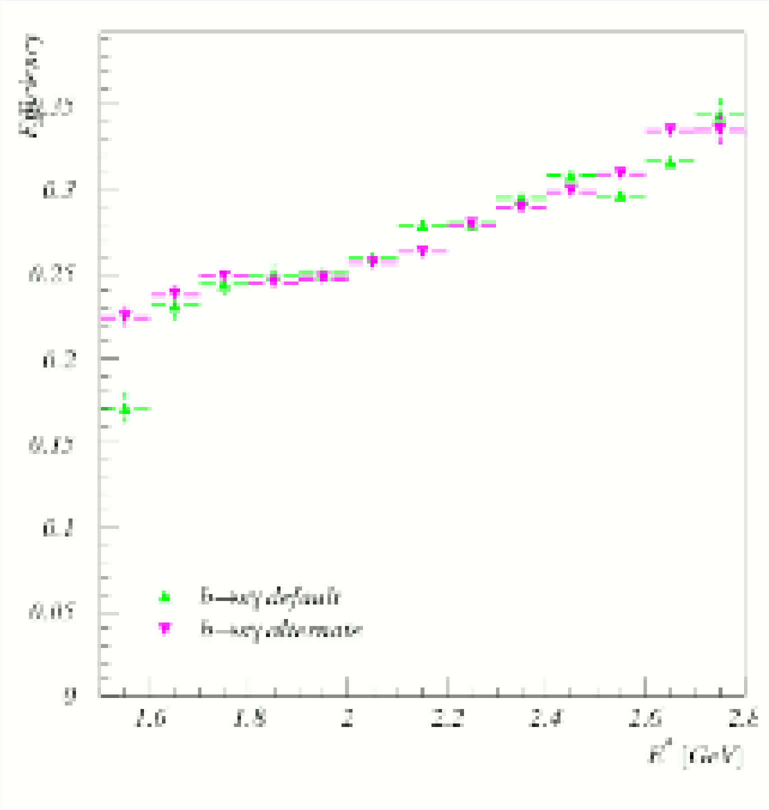
Raw spectrum after all cuts and background corrections

Signal yield:
24100 ±2200 events

The spectrum



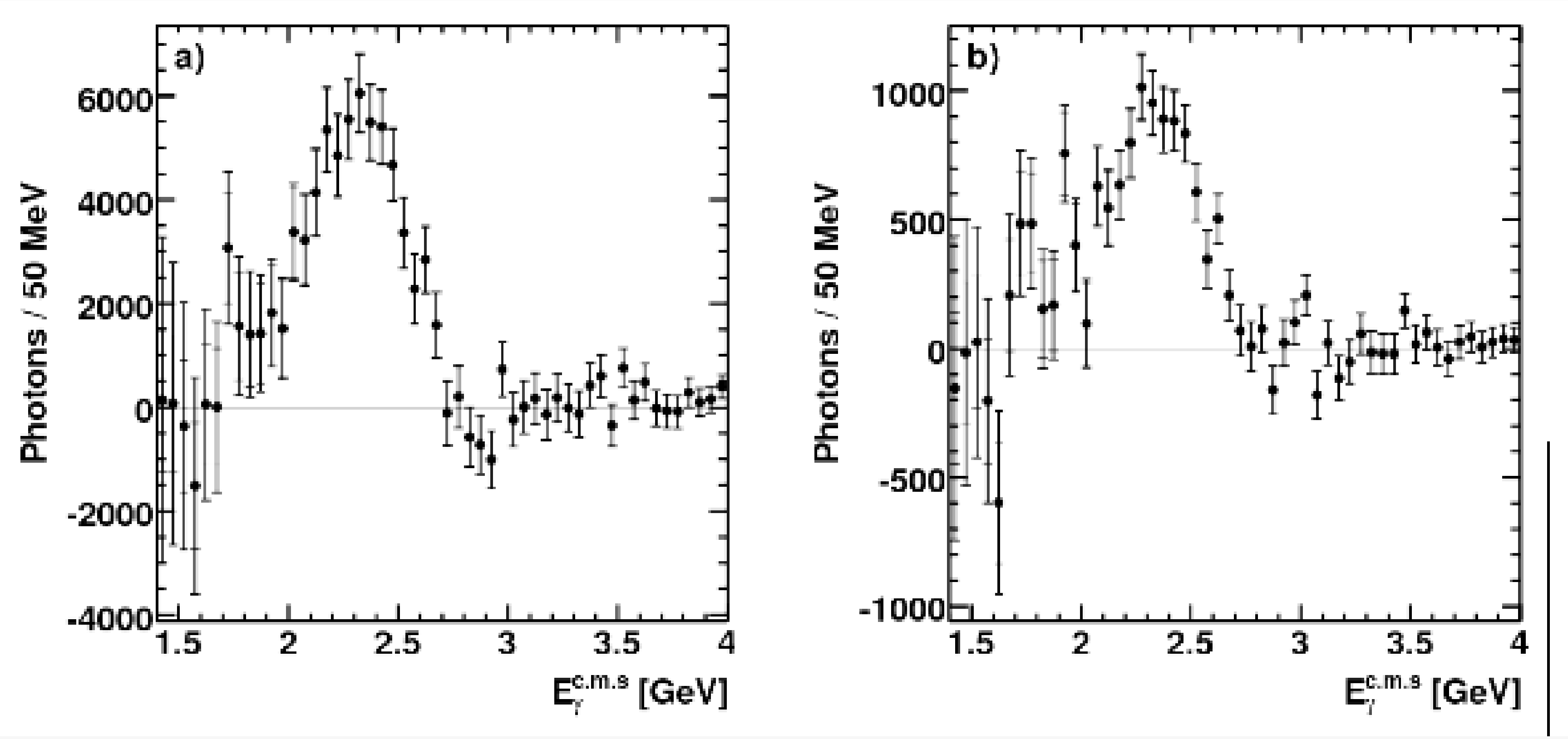
Efficiency corrected spectrum



PRL 103, 241801 (2009)

Latest update

Lower E_γ threshold (1.7 GeV) ⇒ 97% of the spectrum !



$$\mathcal{B}(B \to X_s \gamma) = (3.45 \pm 0.15 \pm 0.40) \times 10^{-4} \quad (\text{for } E_\gamma > 1.7 \text{ GeV})$$

- Most precise measurement of $\mathcal{B}(B \to X_s \gamma)$ (lowest E_γ threshold)
- Crucial input for global fit to extract $|V_{ub}|$ and $B \to X_s \gamma$ decay rate
- $\mathcal{B}$ is given for E_γ thresholds: 1.7, 1.8, 1.9, 2.0 GeV
- Systematic error is dominated by off-resonance subtraction !

Systematics

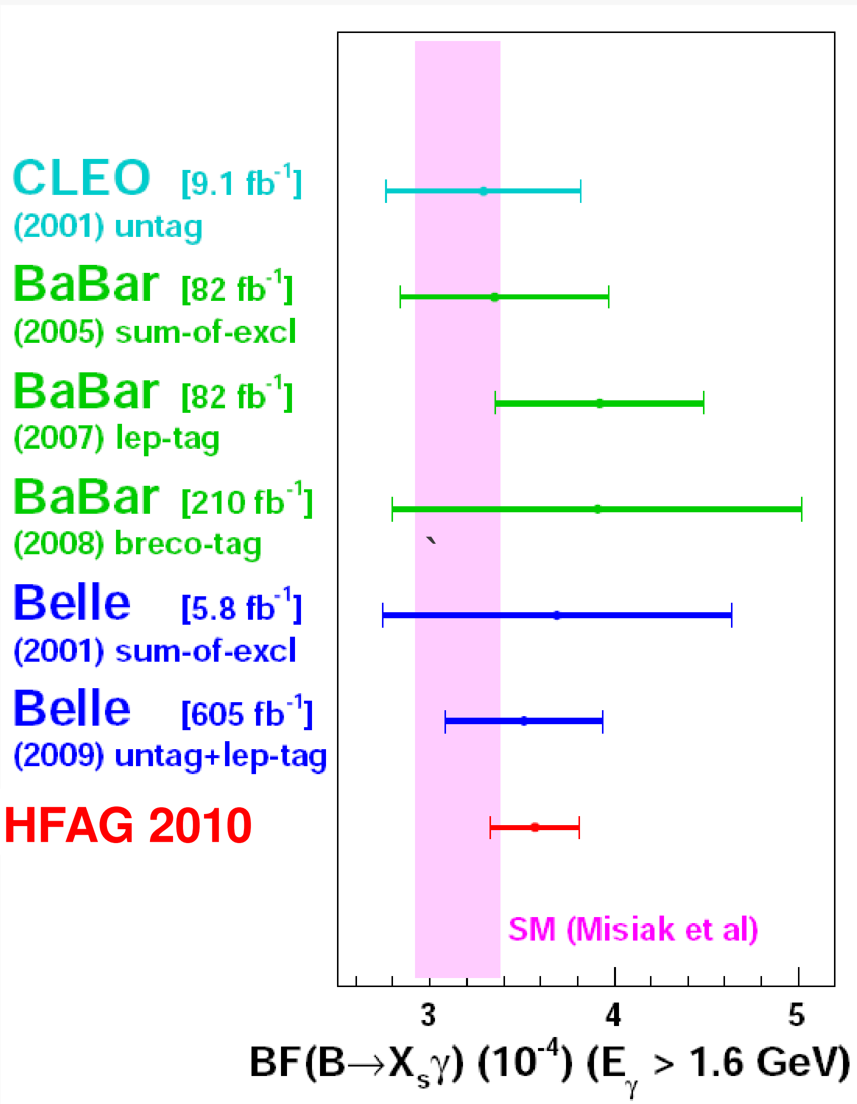
Raw branching fraction	3.45 ± 0.15
Source of systematic error	$\times 10^{-4}$
Continuum	0.26
Selection	0.15
π^0/η	0.07
Other B	0.25
Beam bkgd	0.03
Unfolding	0.01
Model	0.01
Resolution	0.05
γ detection	0.03
$B \to X_d \gamma$	0.01
Boost	0.01
Sum	± 0.40

$B \to X_s \gamma$

$$\text{HFAG 2010: } \mathcal{B}(B \to X_s \gamma) = (3.55 \pm 0.26) \times 10^{-4} \quad (\text{for } E_\gamma > 1.6\ \text{GeV})$$

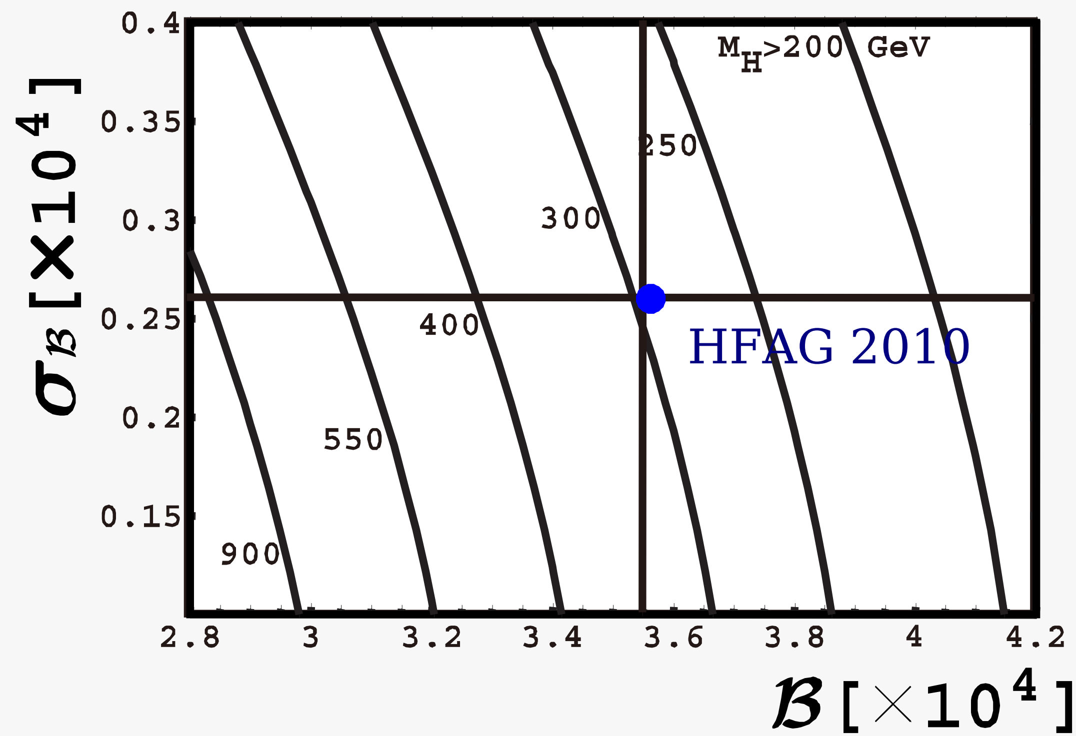
vs

$$\text{SM: } \mathcal{B}(B \to X_s \gamma) = (3.15 \pm 0.23) \times 10^{-4} \quad (\text{for } E_\gamma > 1.6\ \text{GeV})$$



Charged Higss bound (2HDM TypeII)

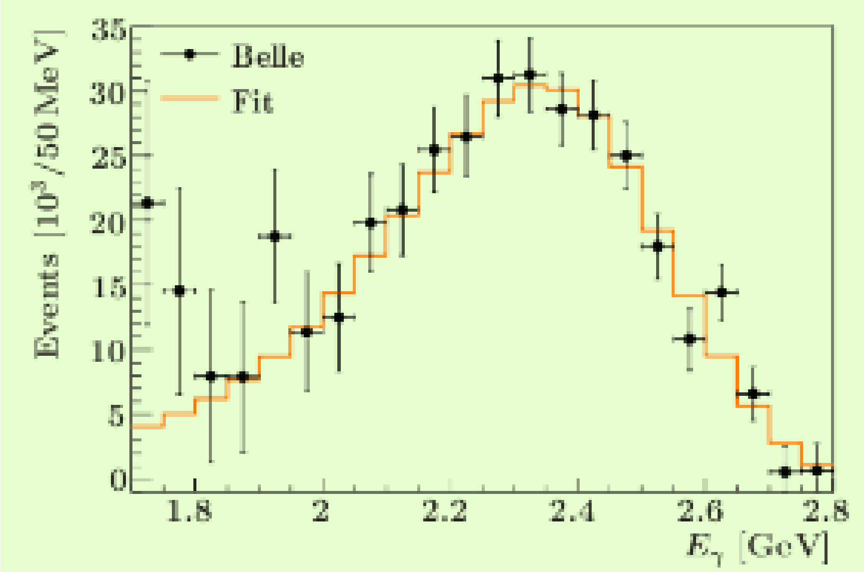
$M_{H^+} > 300$ GeV



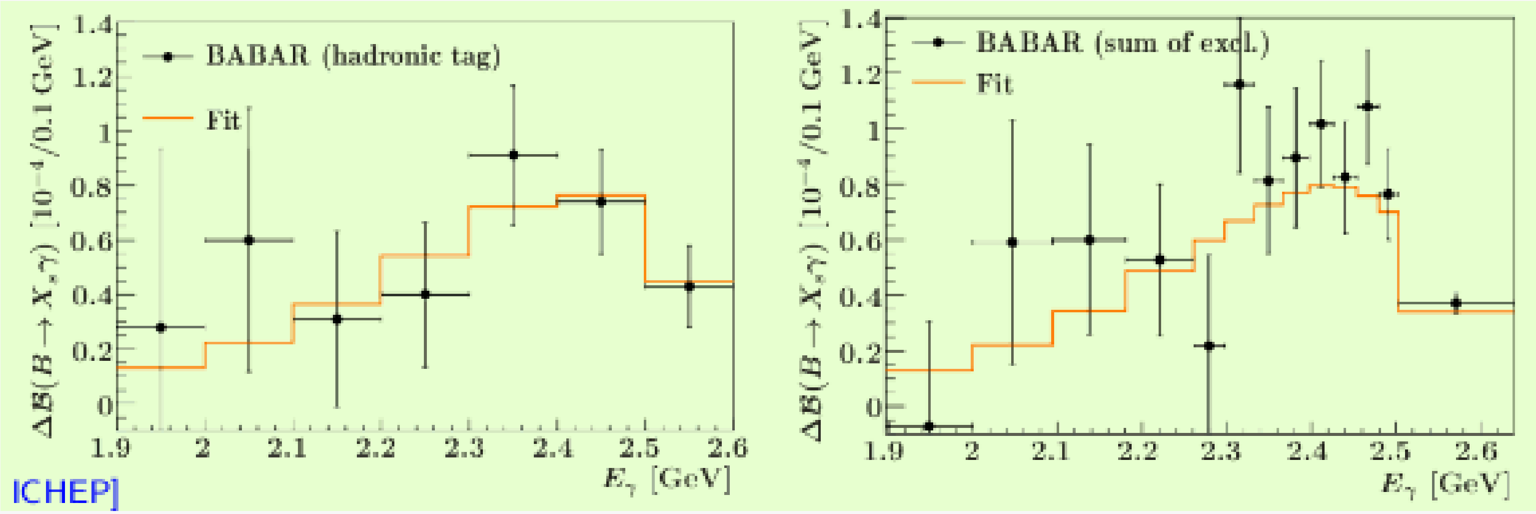
Simultaneous fit

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

$\rightarrow$ Fit to spectrum and C_7^{eff}



[Bernlchner et al., ICHEP10]



Simultaneous fit

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

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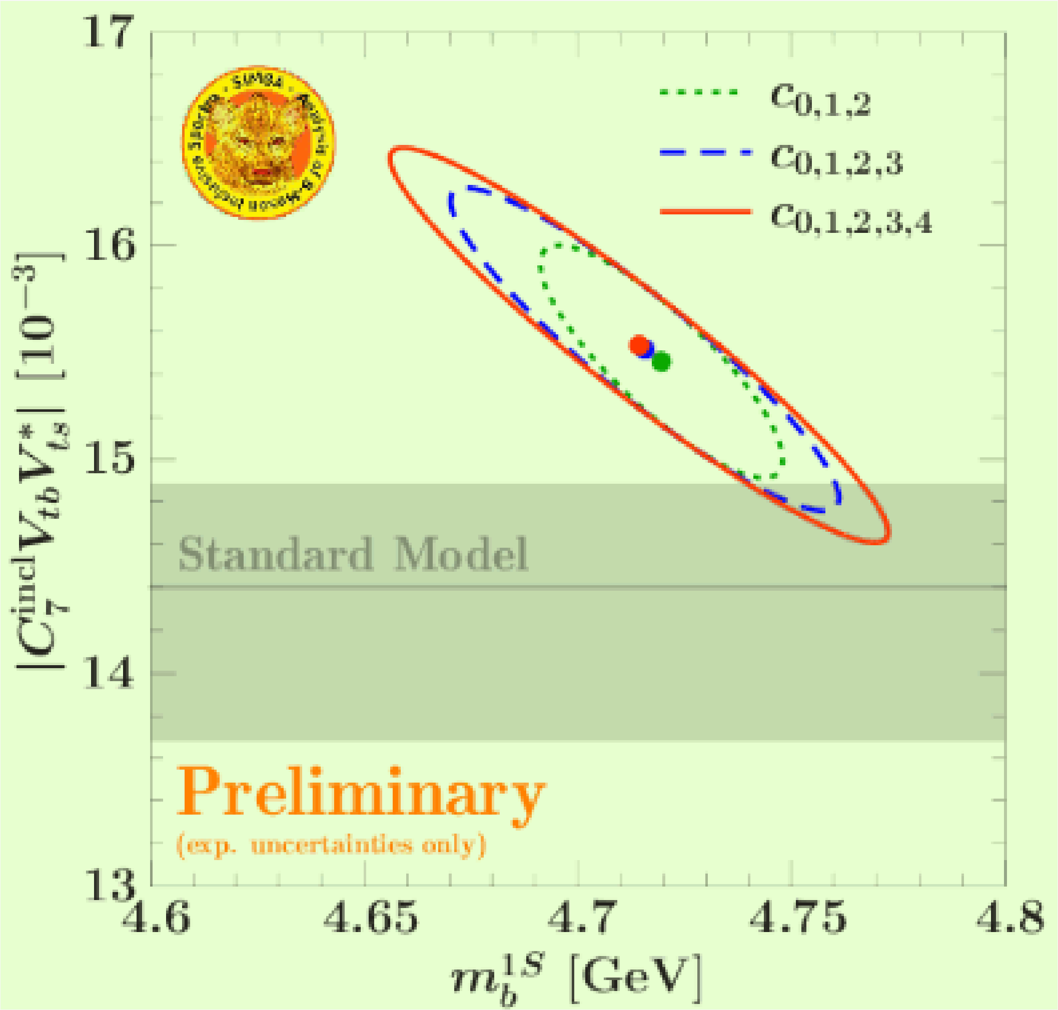


[Bernlchner et al., ICHEP10]

Inclusive vs Exclusive

Theory likes inclusive decays "$b \to s\gamma$"

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

Experiment likes exclusive decays "$B \to K^* \gamma$"

- Well defined final state
- Peaking mass distribution (and ΔE)
  $\to$ lower background
- BF are rapidly theory-limited

Often hadronic uncertainties cancel in ratios

- CP asymmetries
- Isospin asymmetries
- Angular asymmetries

Asymmetries in $B \to K^* \gamma$

Isospin asymmetry

$$\Delta_{+-} \equiv \frac{\Gamma(B^0 \to K^{*0}\gamma) - \Gamma(B^+ \to K^{*+}\gamma)}{\Gamma(B^0 \to K^{*0}\gamma) + \Gamma(B^+ \to K^{*+}\gamma)} = o(0.05) \ \ (\mathrm{SM})$$

$$= -0.062 \pm 0.027 \ (\mathrm{HFAG})$$

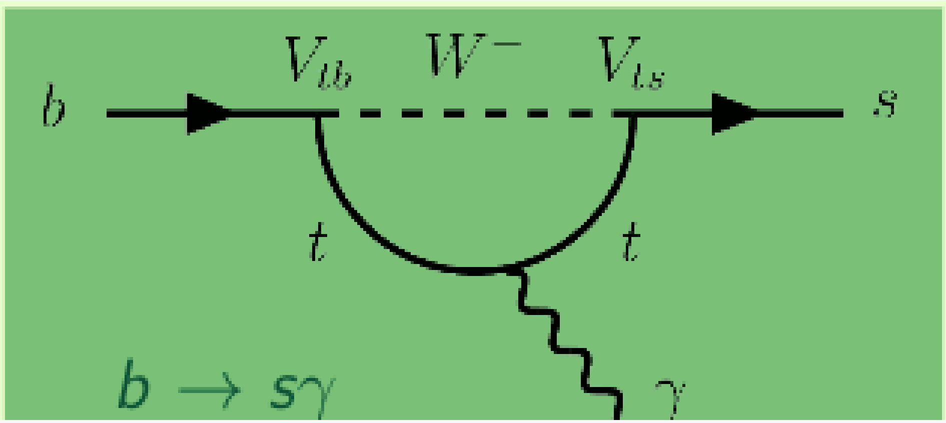
Direct CP-aymmetry:

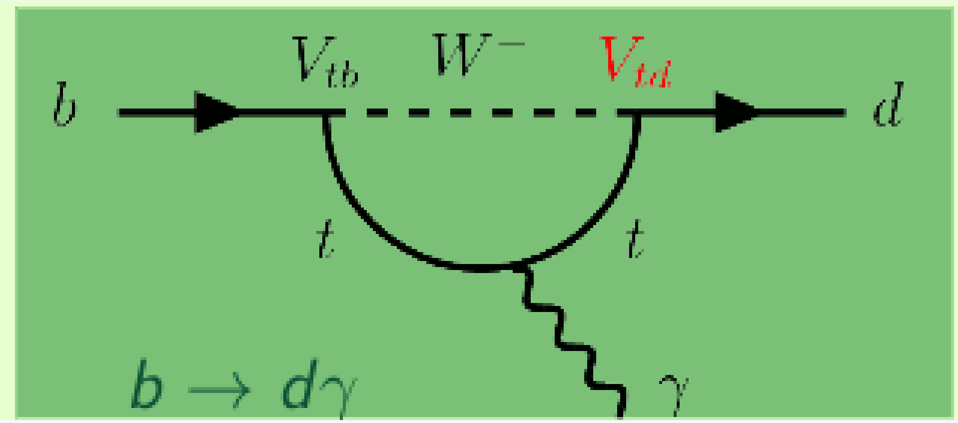
$$A_{CP} = \frac{\Gamma(B \to K^*\gamma) - \Gamma(\overline{B} \to K^*\gamma)}{\Gamma(B \to K^*\gamma) + \Gamma(\overline{B} \to K^*\gamma)} = o(-0.1) \ \ (\mathrm{SM})$$

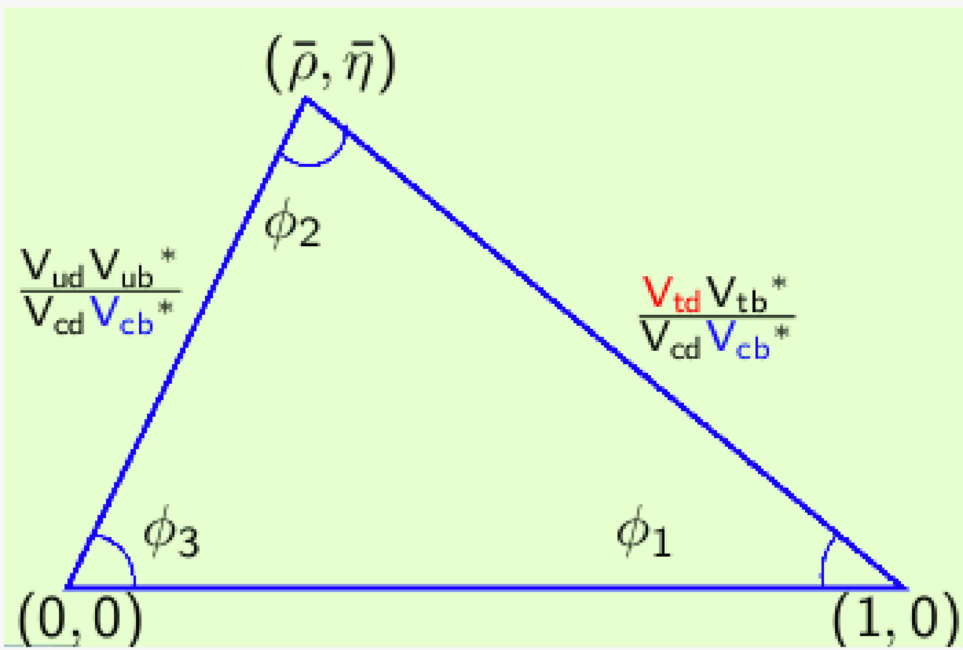
$$= -0.003 \pm 0.017 \ \ (\mathrm{HFAG})$$

$\Rightarrow$ nothing really exciting on that front...

$b \rightarrow d\gamma$

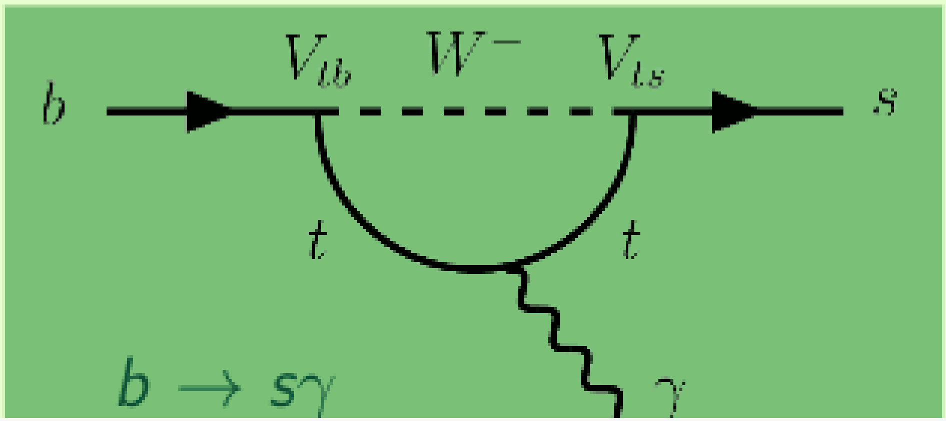


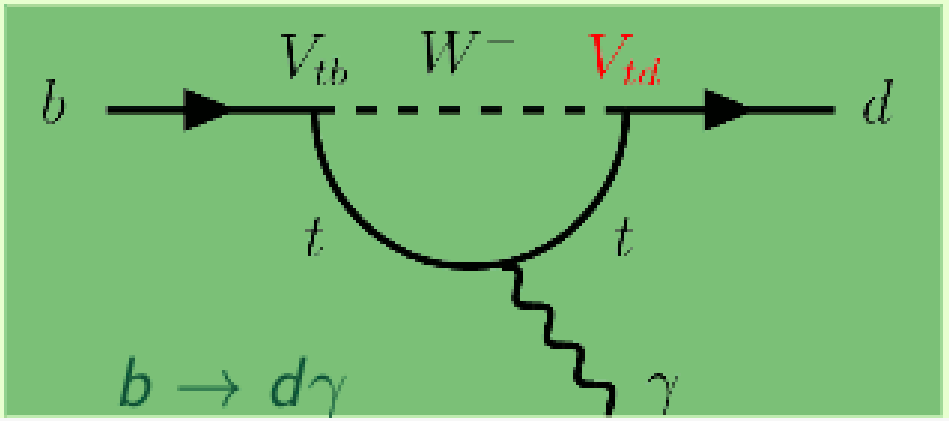




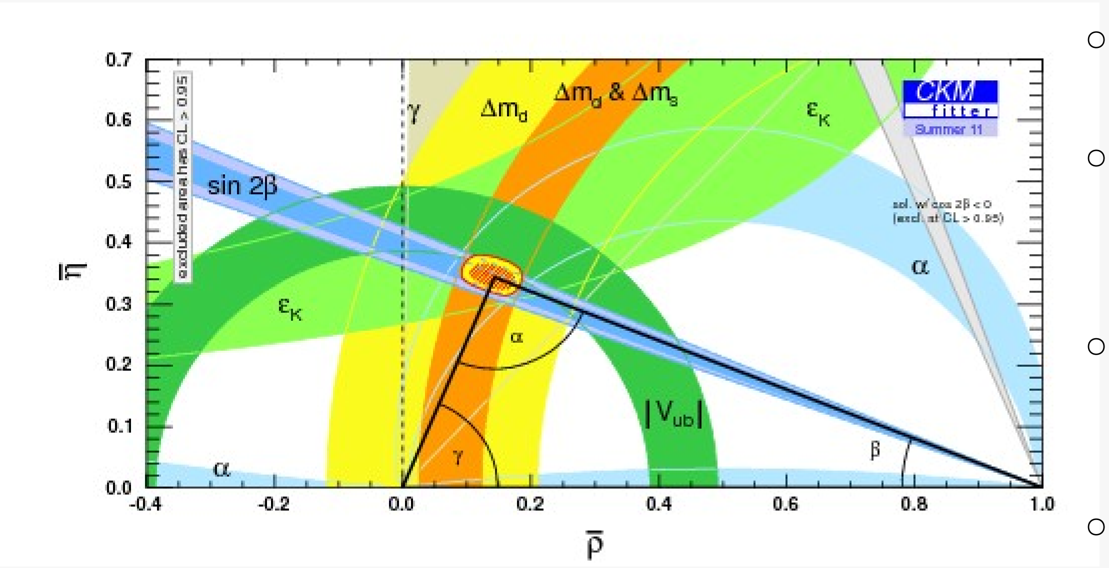
- $b \rightarrow s\gamma \propto V_{ts} \sim V_{cb}$
- $b \rightarrow s\gamma \propto V_{td}$
- The ratio of $b \rightarrow d\gamma$ and $b \rightarrow s\gamma$ should extract $|V_{td}/V_{ts}|$
- Any significant discrepancy is new physics

$b \to d\gamma$

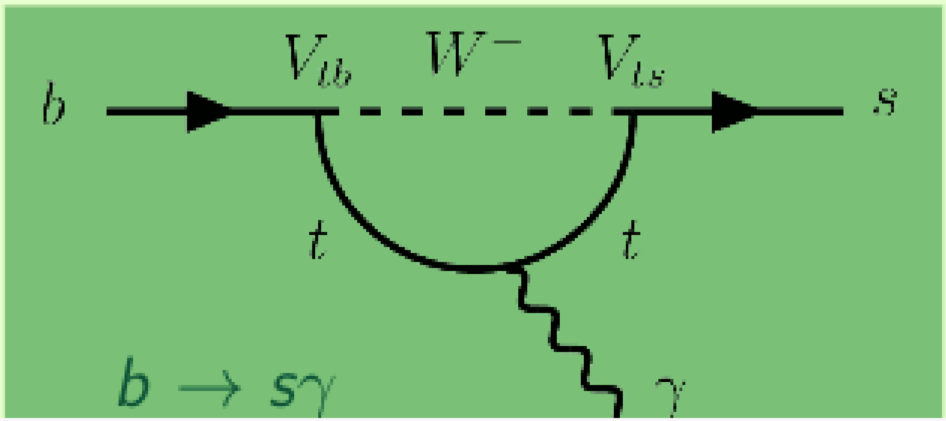


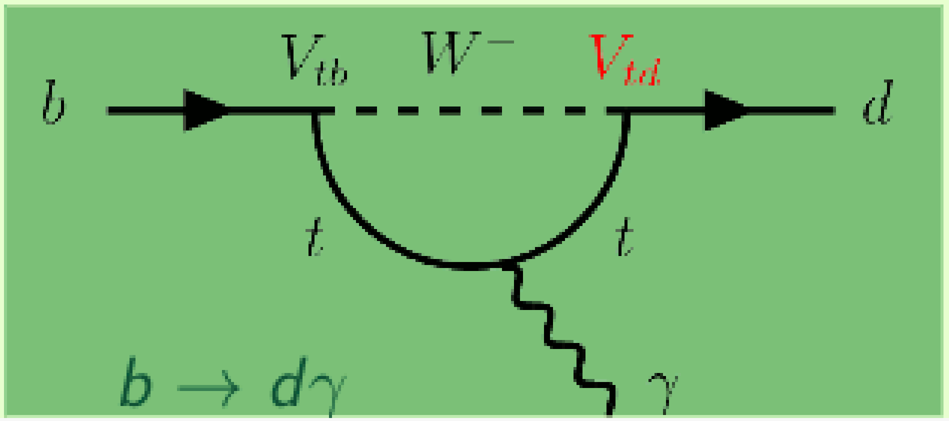


- $b \to s\gamma \propto V_{ts} \sim V_{cb}$
- $b \to s\gamma \propto V_{td}$
- The ratio of $b \to d\gamma$ and $b \to s\gamma$ should extract $|V_{td}/V_{ts}|$
- Any significant discrepancy is new physics
- Expect 0.21 ± 0.01 from fits (mainly $\Delta m_d/\Delta m_s$)



$\mathbf{b \to d\gamma}$





Theoretical SM prediction for the BF is

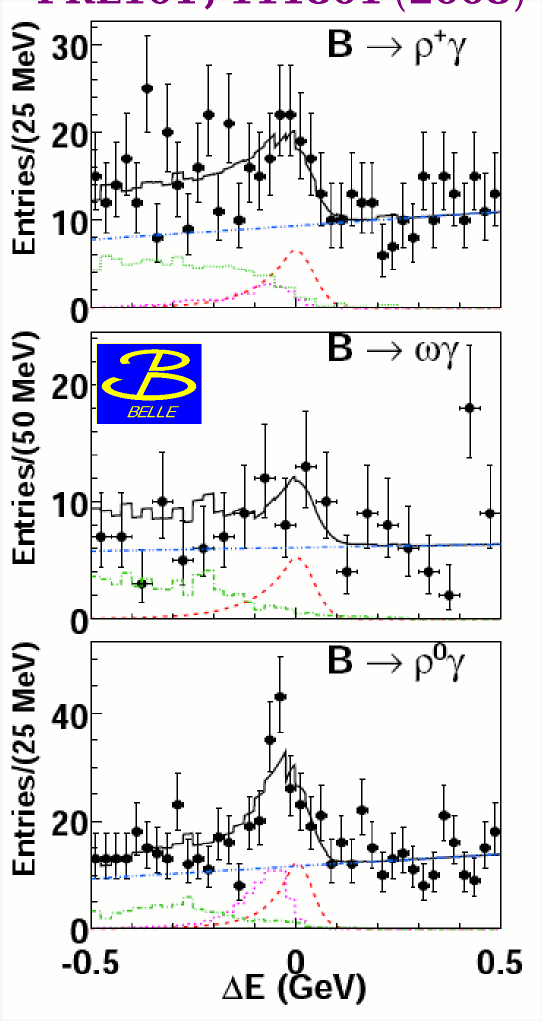
$$\frac{B(\mathrm{B}\to \mathrm{X_d}\gamma)}{B(\mathrm{B}\to \mathrm{X_s}\gamma)} = \left(3.82\,^{+0.11}_{-0.18}\Big|_{\frac{m_c}{m_b}} \pm 0.42_{\mathrm{CKM}} \pm 0.08_{\mathrm{param}} \pm 0.15_{\mathrm{scale}}\right) . \; 10^{-2}$$

at $E_\gamma > 1.6$ GeV

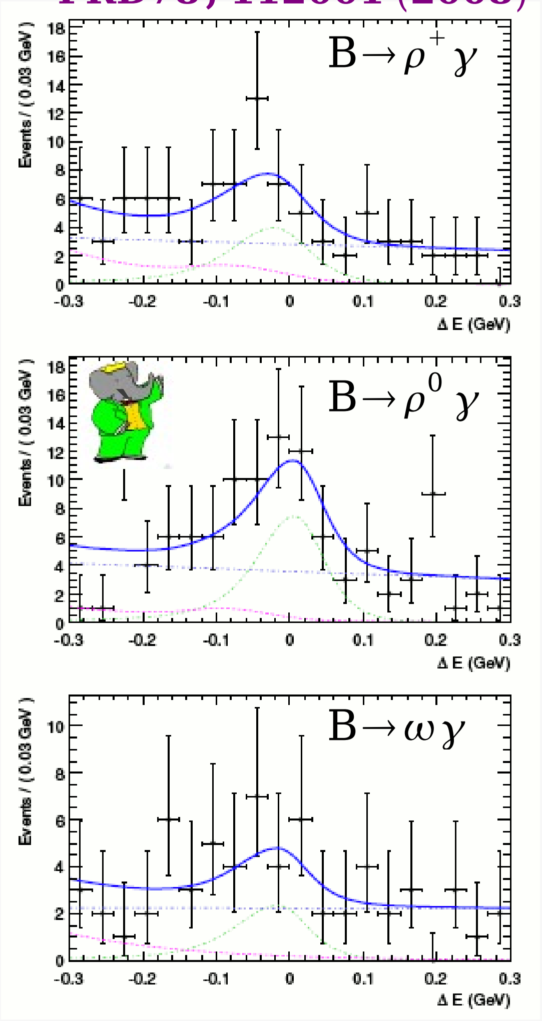
Clearly dominated by CKM errors. No surprise, that's what you want to measure !

Exclusive modes: $B\to(\rho/\omega)\gamma$, $K^*\gamma$

PRL101, 111801 (2008)



PRD78, 112001 (2008)



Combined Br with assumption:

$$\Gamma_{B\to(\rho,\,\omega)\gamma}=\Gamma_{B\to\rho\gamma}=\Gamma_{B^+\to\rho^+\gamma}=2\,\Gamma_{B^0\to\rho^0\gamma}=2\,\Gamma_{B^0\to\omega\gamma}$$

ξ, form factor ratio

ΔR, isospin violation factor

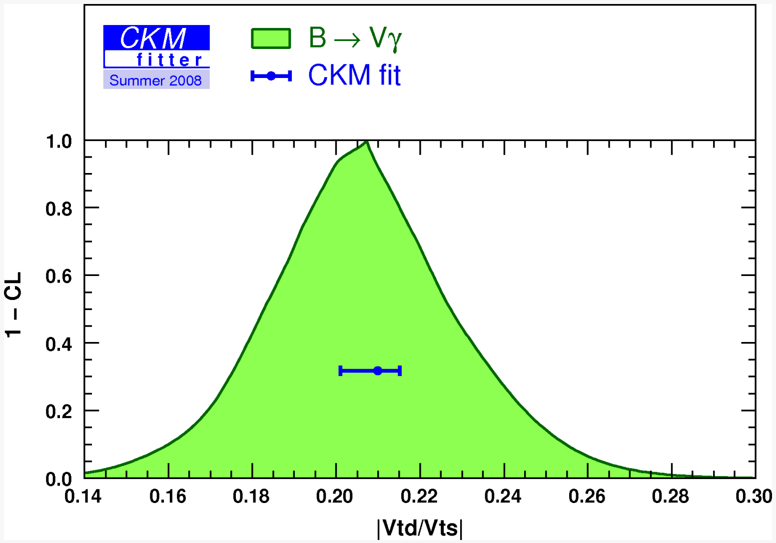
$$R=\frac{Br(B\to(\rho,\,\omega)\gamma)}{Br(B\to K^*\gamma)}=\left|\frac{V_{td}}{V_{ts}}\right|^2\frac{(1-m_{(\rho,\,\omega)}^2/m_B^2)^3}{(1-m_{K^*}^2/m_B^2)^3}\,\xi^2[1+\Delta R]$$

$B \to V\gamma$

$B \to K^*\gamma$ (charged and neutral)

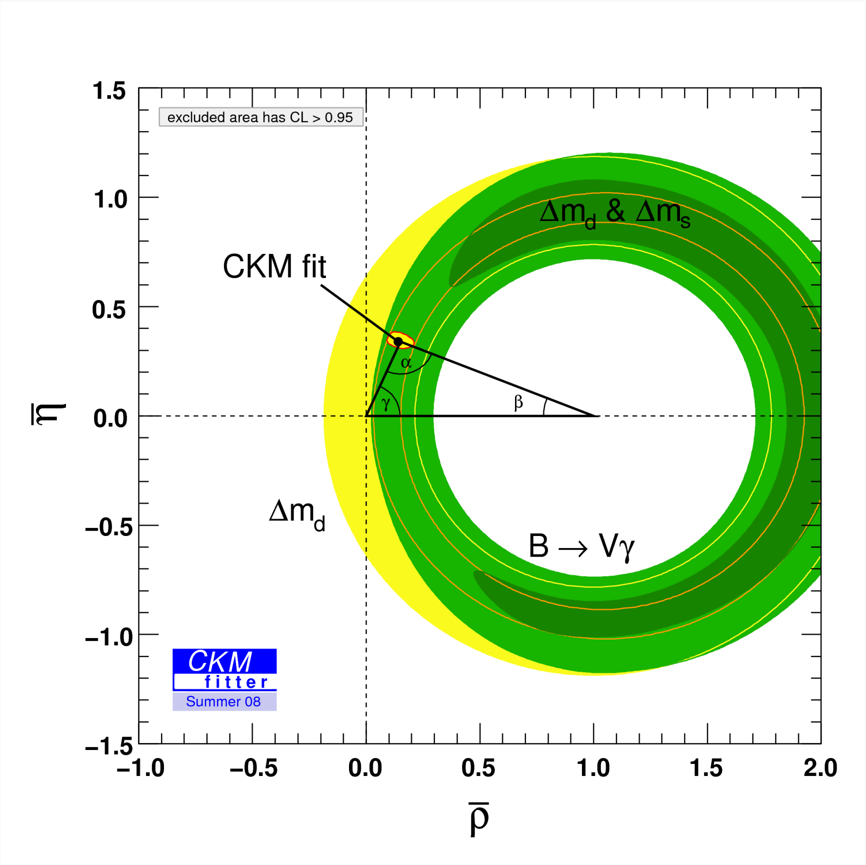
$\rho\gamma$ (charged and neutral), $\omega\gamma$

$B_s \to \phi\gamma$, asymmetry in $B^+ \to \rho^+\gamma$



$$\Rightarrow \frac{|V_{td}|}{|V_{ts}|} = 0.207^{+0.030}_{-0.032}$$

theory error $\sim 8\%$



To be compared with result from B-mixing average:

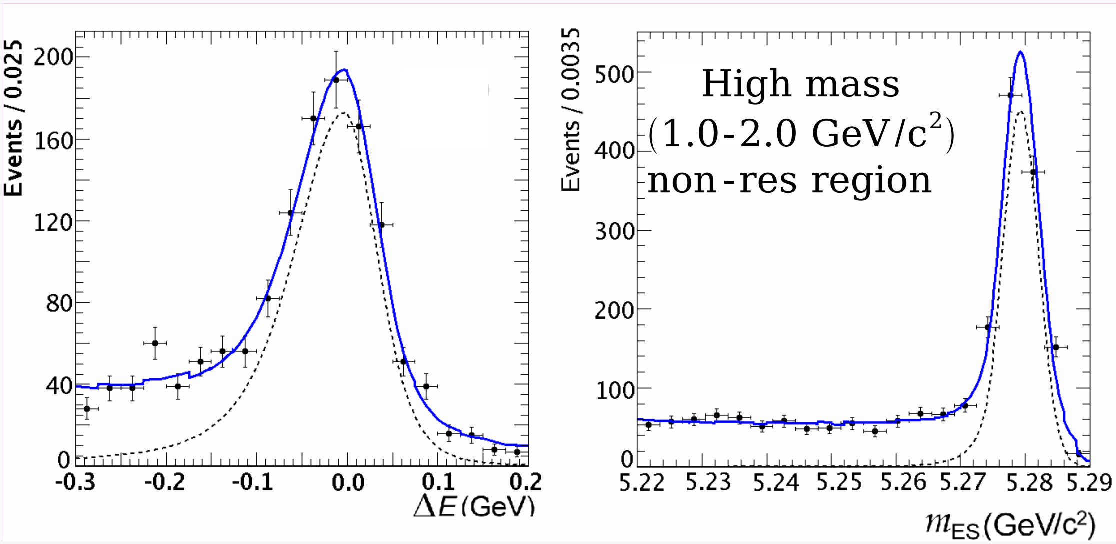
$$\frac{|V_{td}|}{|V_{ts}|} = 0.2059 \pm 0.001_{exp} \pm 0.008_{th}$$

$B \to X_{s,d}\gamma$

arXiv:1005.4087

- 471 M$B\bar{B}$
- Sum of seven exclusive final states:

$B^0 \to K^+\pi^-\gamma,\ K^+\pi^-\pi^0\gamma,\ K^+\pi^-\pi^+\pi^-\gamma,\ \ B^+ \to K^+\pi^0\gamma,\ K^+\pi^-\pi^+\gamma,\ K^+\pi^-\pi^+\pi^0\gamma,\ K^+\eta\gamma$



$\mathcal{B}(B \to X_s\gamma) =$

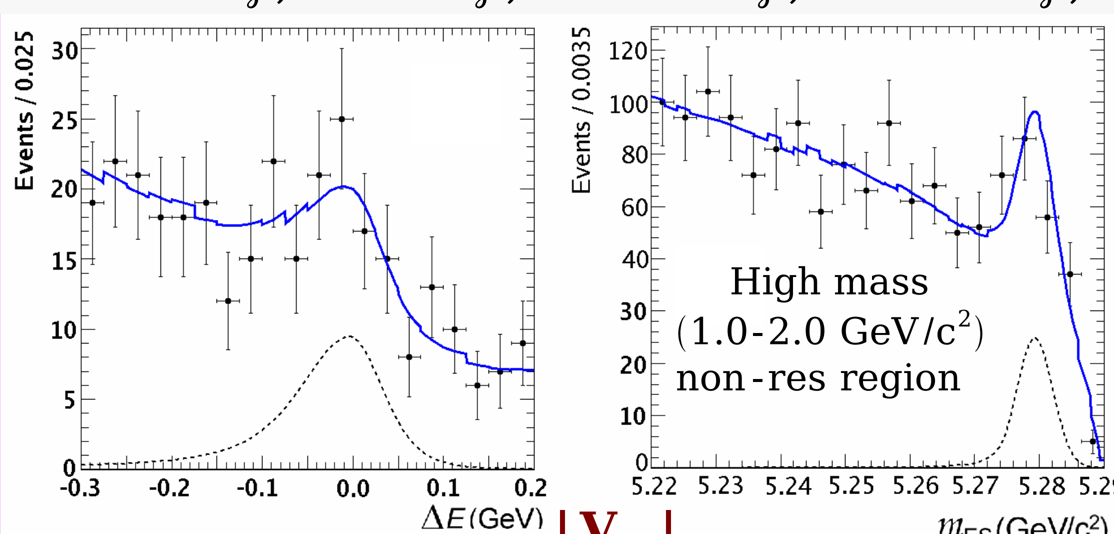
$(23.0 \pm 0.8_{stat} \pm 3.0_{syst}) \times 10^{-5}$

$(M(X_s) < 2.0\ \text{GeV})$

$b \to d\gamma$ CKM suppressed w.r.t $b \to s\gamma$ by a factor ~ 20 (in SM)

- Sum of seven exclusive final states:

$B^0 \to \pi^+\pi^-\gamma,\ \pi^+\pi^-\pi^0\gamma,\ \pi^+\pi^-\pi^+\pi^-\gamma,\ \ B^+ \to \pi^+\pi^0\gamma,\ \pi^+\pi^-\pi^+\gamma,\ \pi^+\pi^-\pi^+\pi^0\gamma,\ \pi^+\eta\gamma$



$\mathcal{B}(B \to X_d\gamma) =$

$(9.2 \pm 2.0_{stat} \pm 2.3_{syst}) \times 10^{-6}$

$(M(X_d) < 2.0\ \text{GeV})$

mass range covers ~ 60% of total spectrum in $b \to s, d\ \gamma$

theory error ~1%

$$\Rightarrow \frac{|V_{td}|}{|V_{ts}|} = 0.199 \pm 0.022_{stat} \pm 0.012_{syst} \pm 0.027_{extrapol} \pm 0.002_{th}$$

Asymmetries

Isospin asymmetry

$$\Delta_{+-} \equiv \frac{\Gamma(B^0 \to \rho^0 \gamma) - \Gamma(B^+ \to \rho^+ \gamma)}{\Gamma(B^0 \to \rho^0 \gamma) + \Gamma(B^+ \to \rho^+ \gamma)} = o(0.1) \ \ (\mathrm{SM})$$

$$= -0.46\,^{+0.17}_{-0.16}\ (\mathrm{HFAG})$$

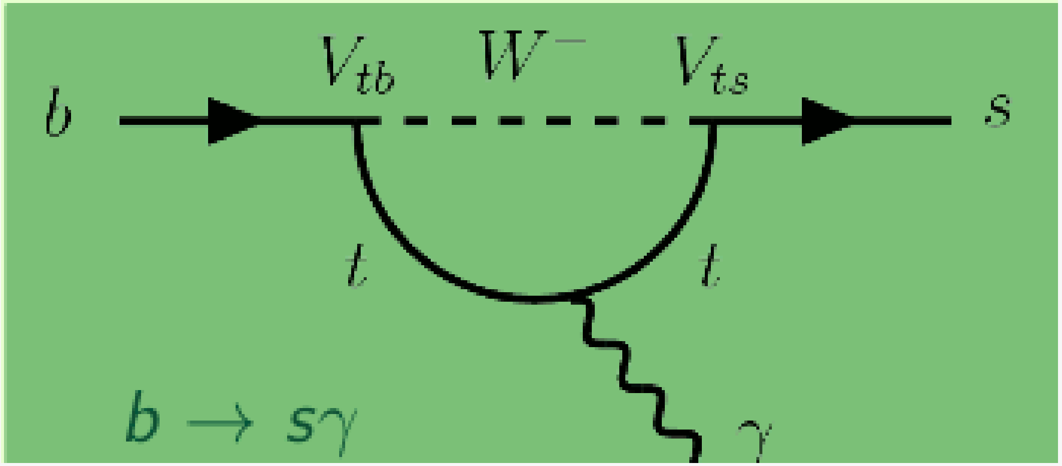
Direct CP-aymmetry:

$$A_{CP} = \frac{\Gamma(B \to \rho\gamma) - \Gamma(\overline{B} \to \rho\gamma)}{\Gamma(B \to \rho\gamma) + \Gamma(\overline{B} \to \rho\gamma)} = o(-0.1) \ \ (\mathrm{SM})$$

$$= -0.11 \pm 0.31 \pm 0.09 \ \ (\rho^+)$$
$$= -0.44 \pm 0.49 \pm 0.14 \ \ (\rho^0)$$

$\Rightarrow$ much more interesting than $K^*\gamma$!

$b \to s\gamma$ polarization



The photon polarisation is not well measured.

- Naively $r = \frac{C'_{7\gamma}}{C_{7\gamma}} \simeq \frac{m_s}{m_b}$ (SM)
- 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]
- $B \to \gamma K^{**}(K\pi\pi)$

  [Gronau & Pirjol, PRD66:054008, 2002]

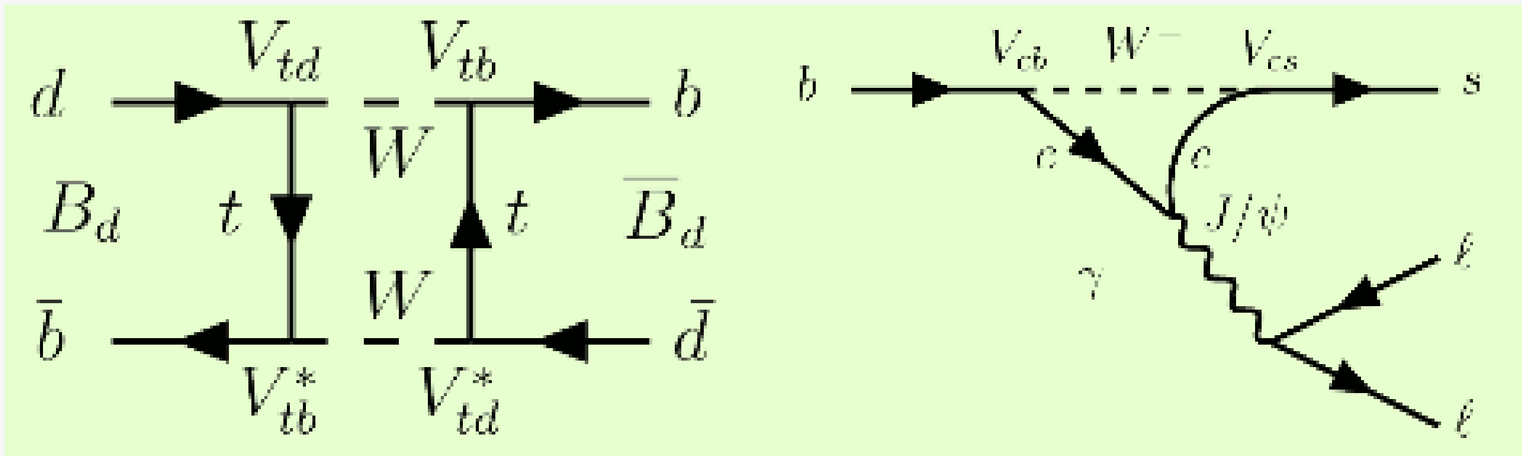
  [Gronau et al, PRL88:051802, 2002]
- Virtual photons ($b \to lls$)

  [Melikhov et al., PLB442:381-389, 1998]
- Converted photons

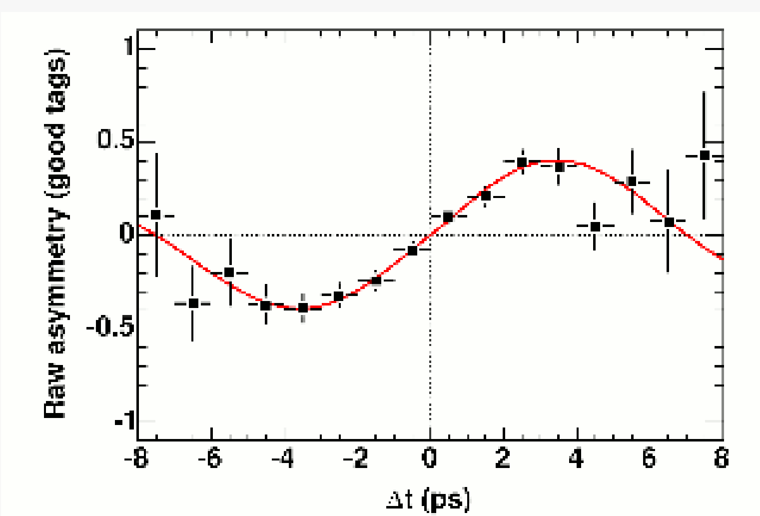
  [Grossman et al., JHEP06:29, 2000]

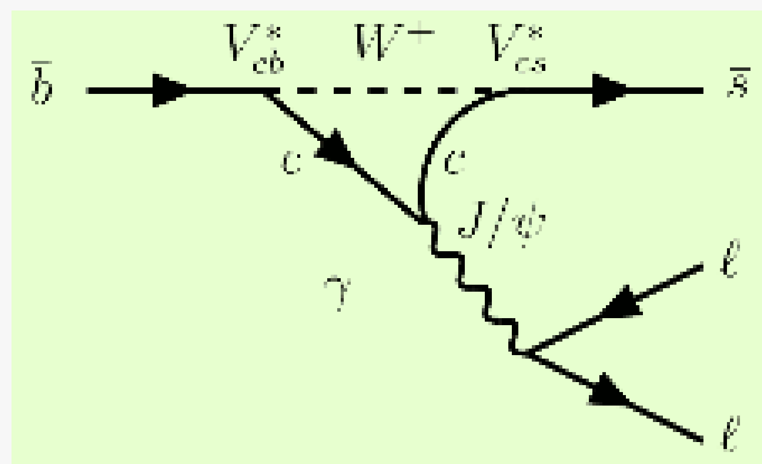
Mixing-induced CP violation

Remember $B^0 \rightarrow J/\psi\, K^0_S$:



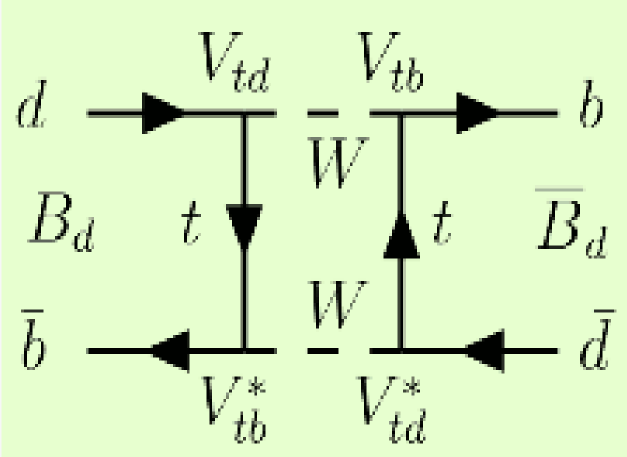
Interferes with

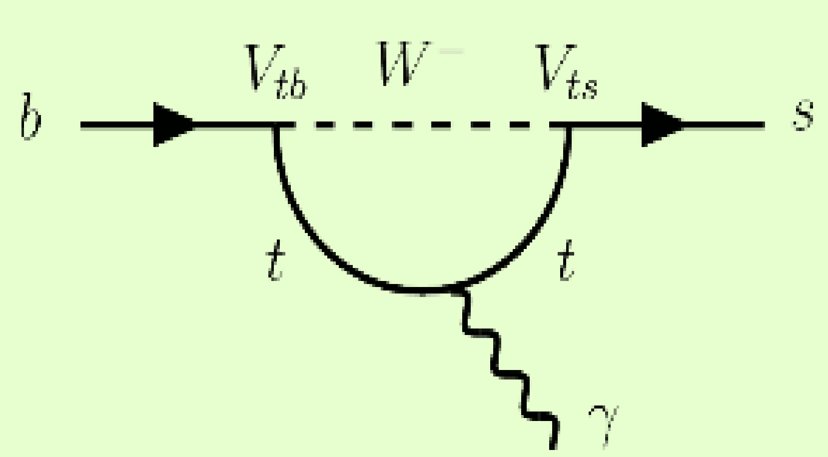




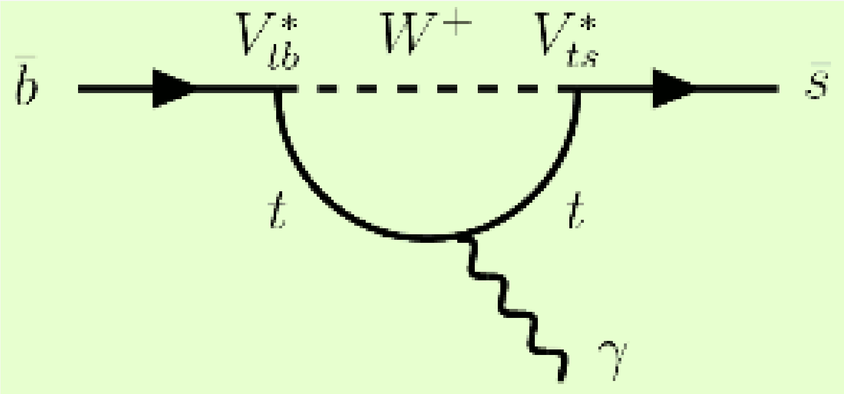
Mixing-induced CP violation

What about $B^0 \to \gamma K_S^0 \pi^0$?





Interferes with right handed component of



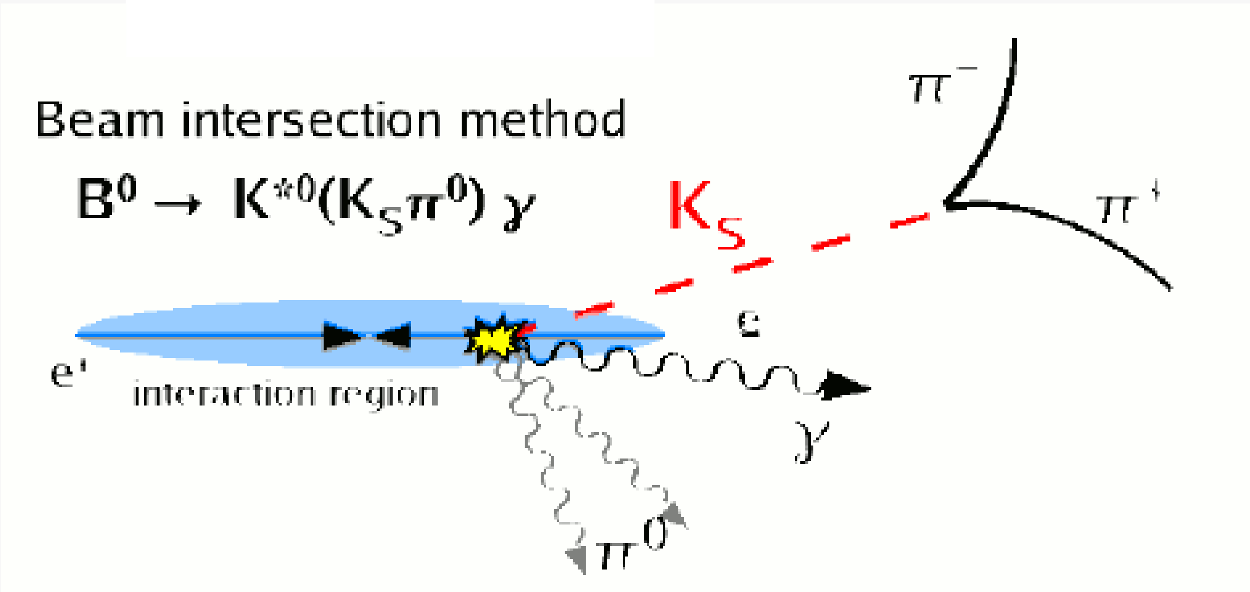
In SM mainly $B^0 \to K_S^0 \pi^0 \gamma_R$ and $\overline{B}^0 \to K_S^0 \pi^0 \gamma_L$

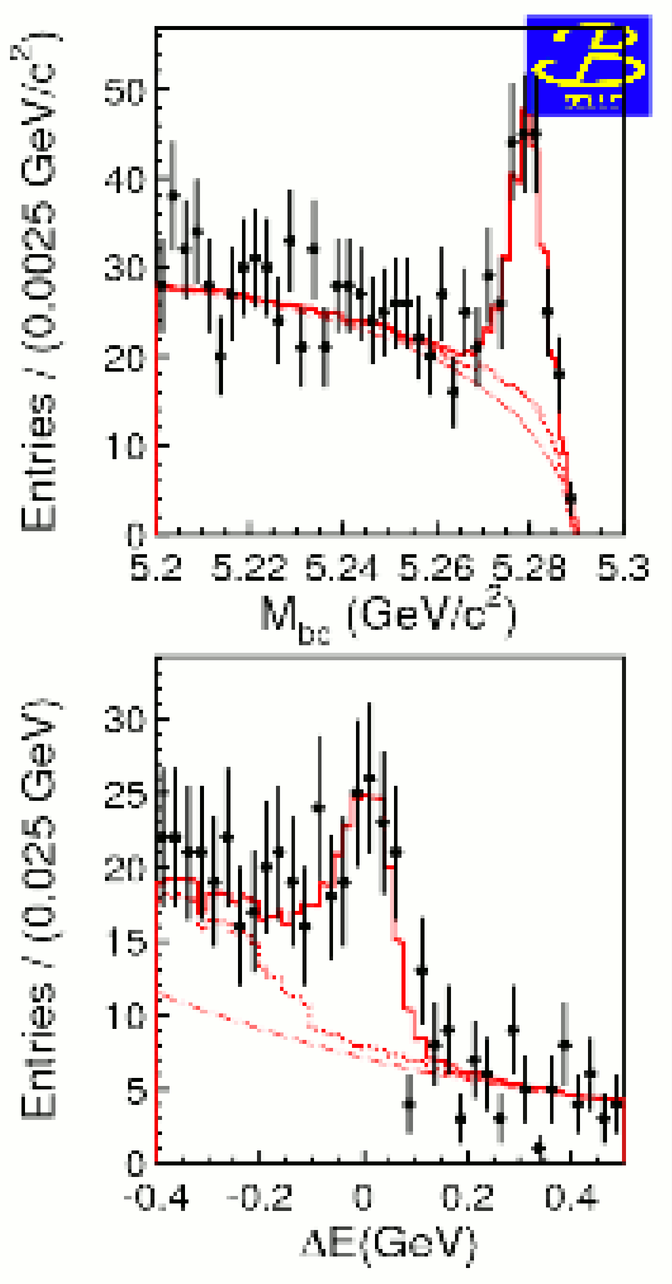
$K_S^0 \pi^0 \gamma$ behaves like an effective flavor eigenstate, and mixing-induced CP violation is expected to be small $S \sim -2(m_s/m_b)\sin(2\phi_1)$

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

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

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





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

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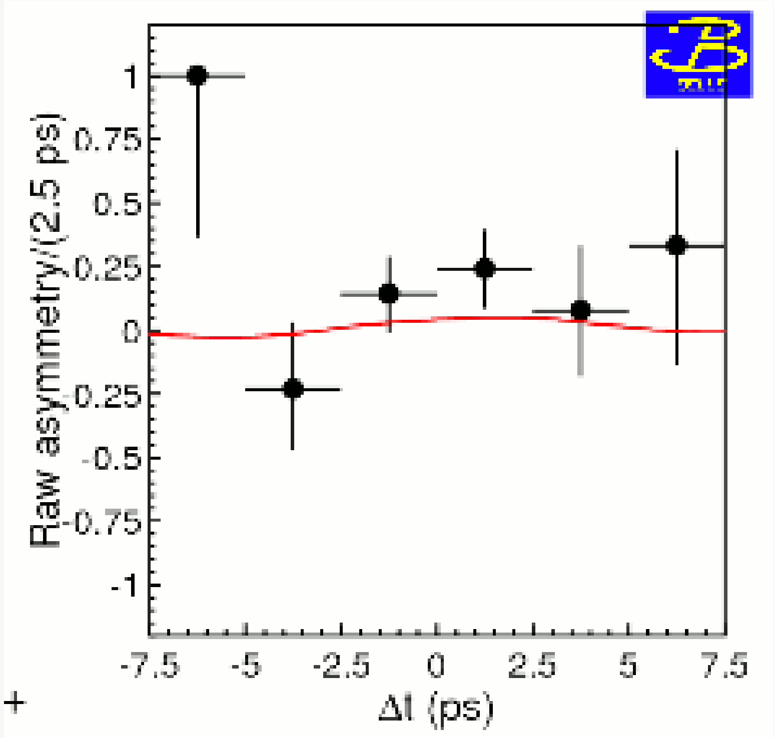
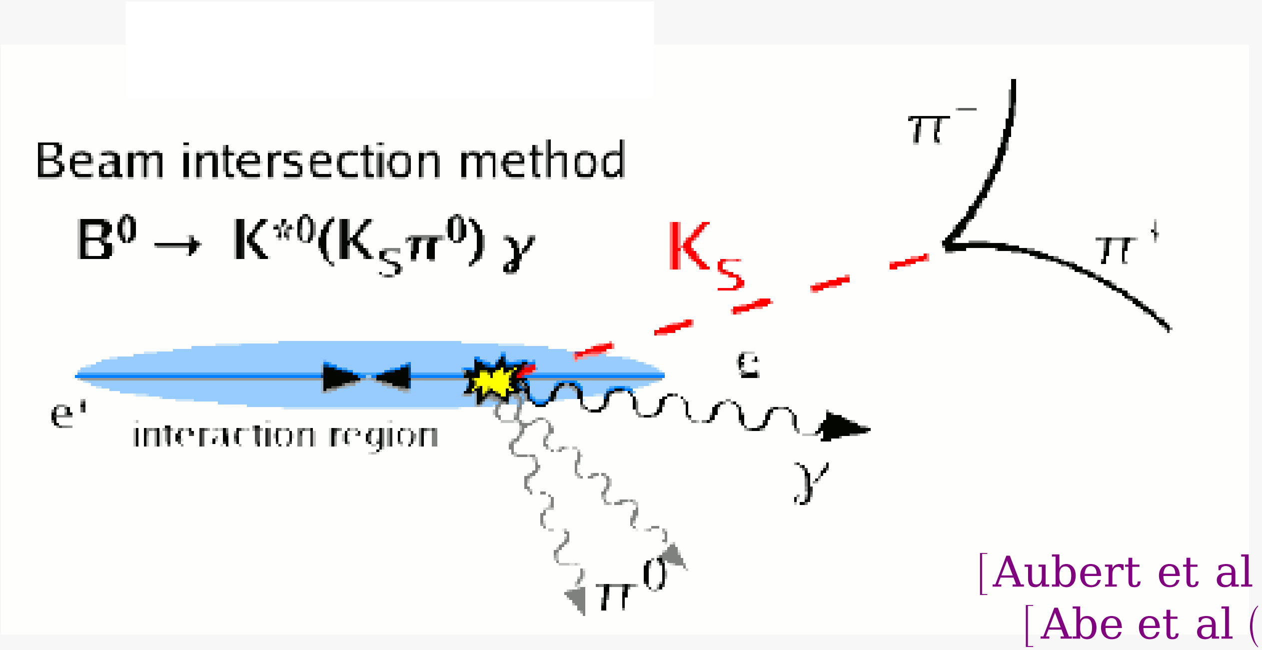
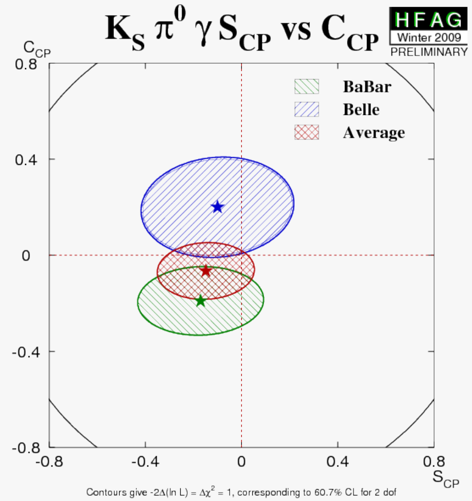
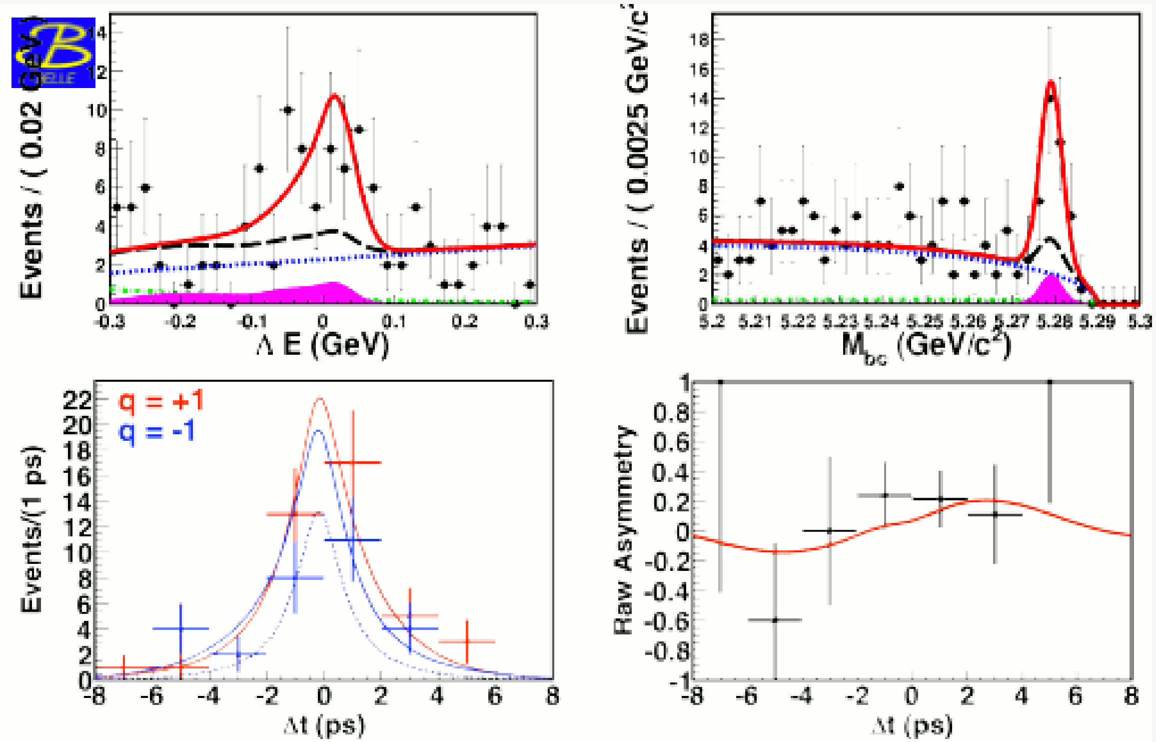


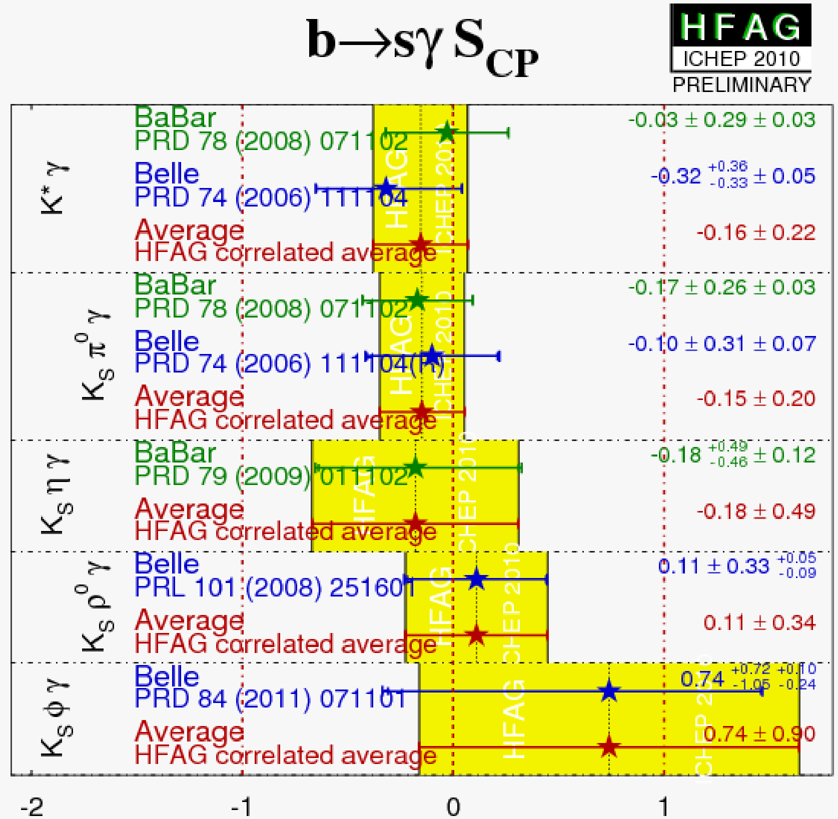




[Aubert et al (BaBar), PRD72:051103 (2005)]
[Abe et al (Belle), PRD74:111104 (2006)]

$B \to K^0_S \phi \gamma$ and friends





Conclusions from $b \to s\gamma$ and $b \to d\gamma$

We already know $|C_7|$ with a good accuracy

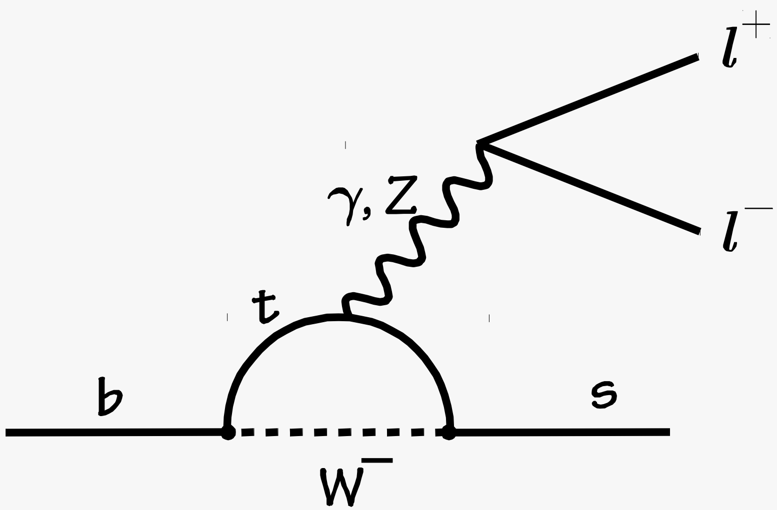
- No large New Physics in $b \to s\gamma$ loops
- Or New Physics contributions interfere destructively (GIM)
  - There are more hints in $b \to d\gamma$ than $b \to s\gamma$...
- Or C_7 is sign-flipped

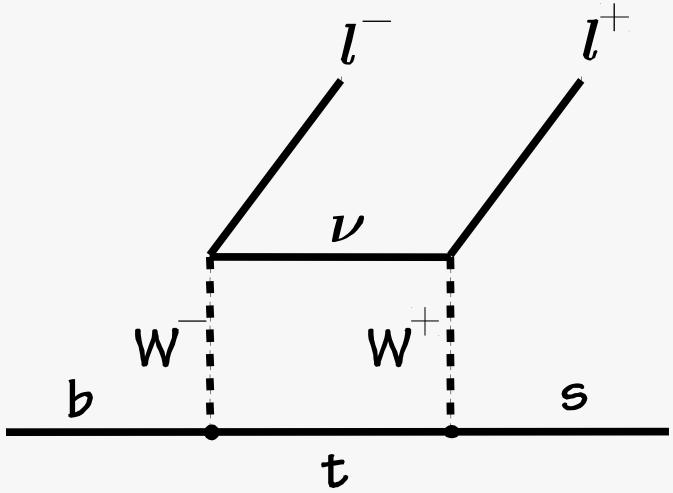
  $\to$ Right-handed currents ?

We don't know much yet about phases and helicities

$\to$ LHCb/Super B factories may find out

$b \to s\, l^+ l^-$





$\Rightarrow$ 2 orders of magnitude smaller than $b \to s\gamma$ but rich NP search potential

Amplitudes from

- ◦ electromagnetic penguin: C_7
- ◦ vector electroweak: C_9
- ◦ axial-vector electroweak: C_{10}

may interfere w/ contributions from NP

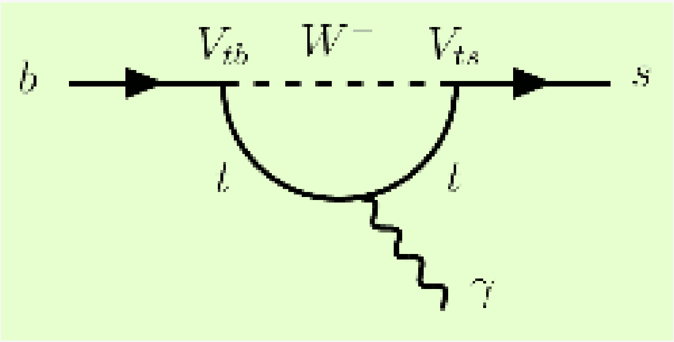
Many observables:

- ◦ Branching fractions
- ◦ Isospin asymmetry (A_I)
- ◦ Lepton forward-backward asymmetry (A_{FB})

(many other observables: Tobias Hurth's talk)

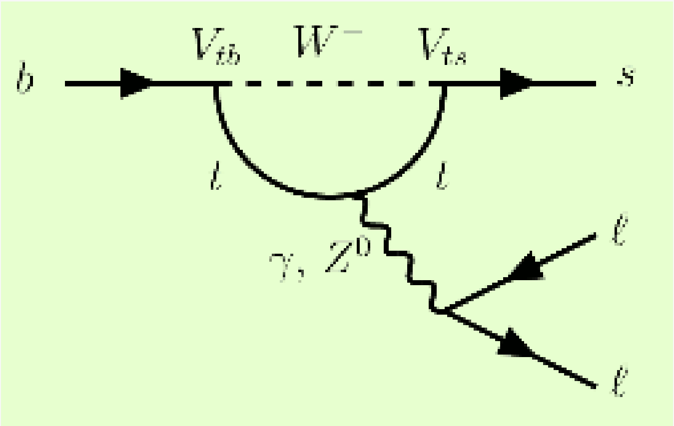
$\Rightarrow$ Exclusive ($B \to K^{(*)} l^+ l^-$), Inclusive ($B \to X_s\, l^+ l^-$)

b→lls



- Start with b→sγ

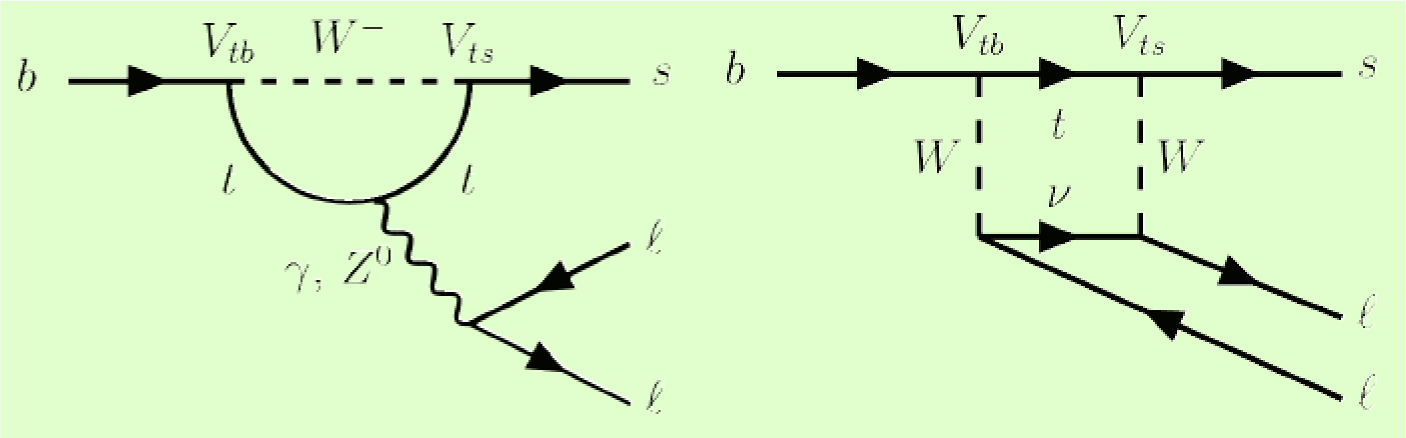
$b \rightarrow l l s$



- Start with $b \rightarrow s \gamma$, pay a factor α_{EM}

  $\rightarrow$ Decay the γ into 2 leptons

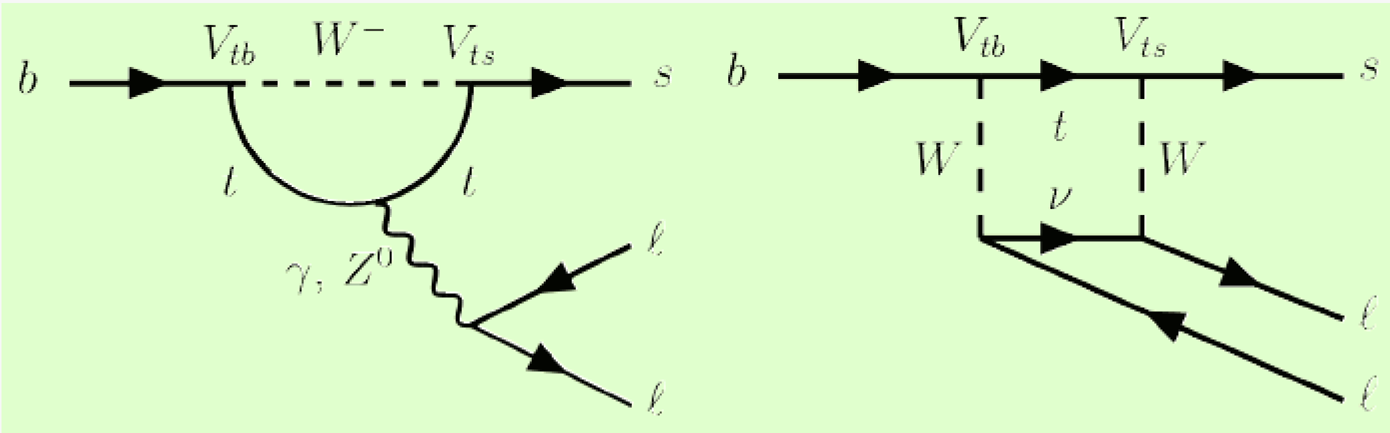
$b \to lls$



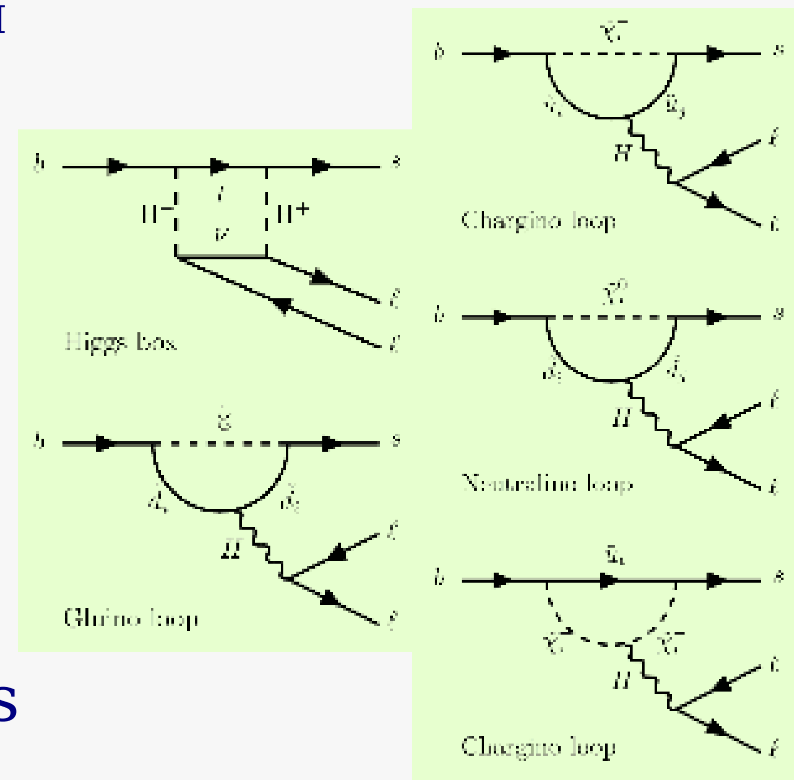
- Start with $b \to s\gamma$, pay a factor α_{EM}
  - $\to$ Decay the γ into 2 leptons
- Add an interfering box diagram
  - $\to$ $b \to lls$, very rare in the SM

$$B(B \to llK^*) = (3.3 \pm 1.0)\ .\ 10^{-6}$$

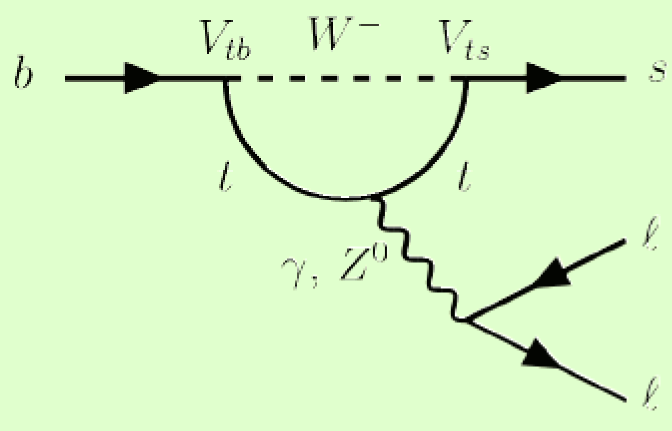
b→lls

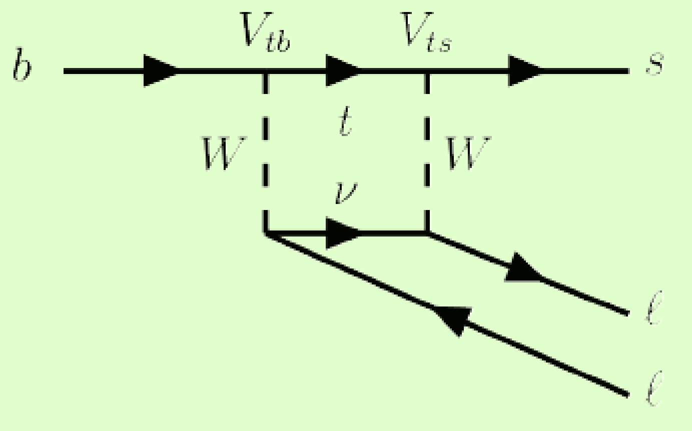


- Start with $b \to s\gamma$, pay a factor α_{EM}
  - → Decay the γ into 2 leptons
  - Add an interfering box diagram
  - → b→lls, very rare in the SM
  - $B(B \to llK^*) = (3.3 \pm 1.0) \, . \, 10^{-6}$
- Sensitive to Supersymmetry, Any 2HDM, Fourth generation, Extra dimensions, Axions…
- Ideal place to look for new physics

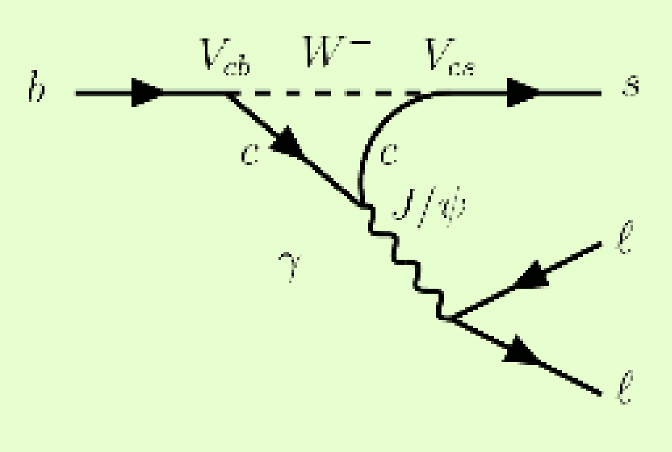


b→lls



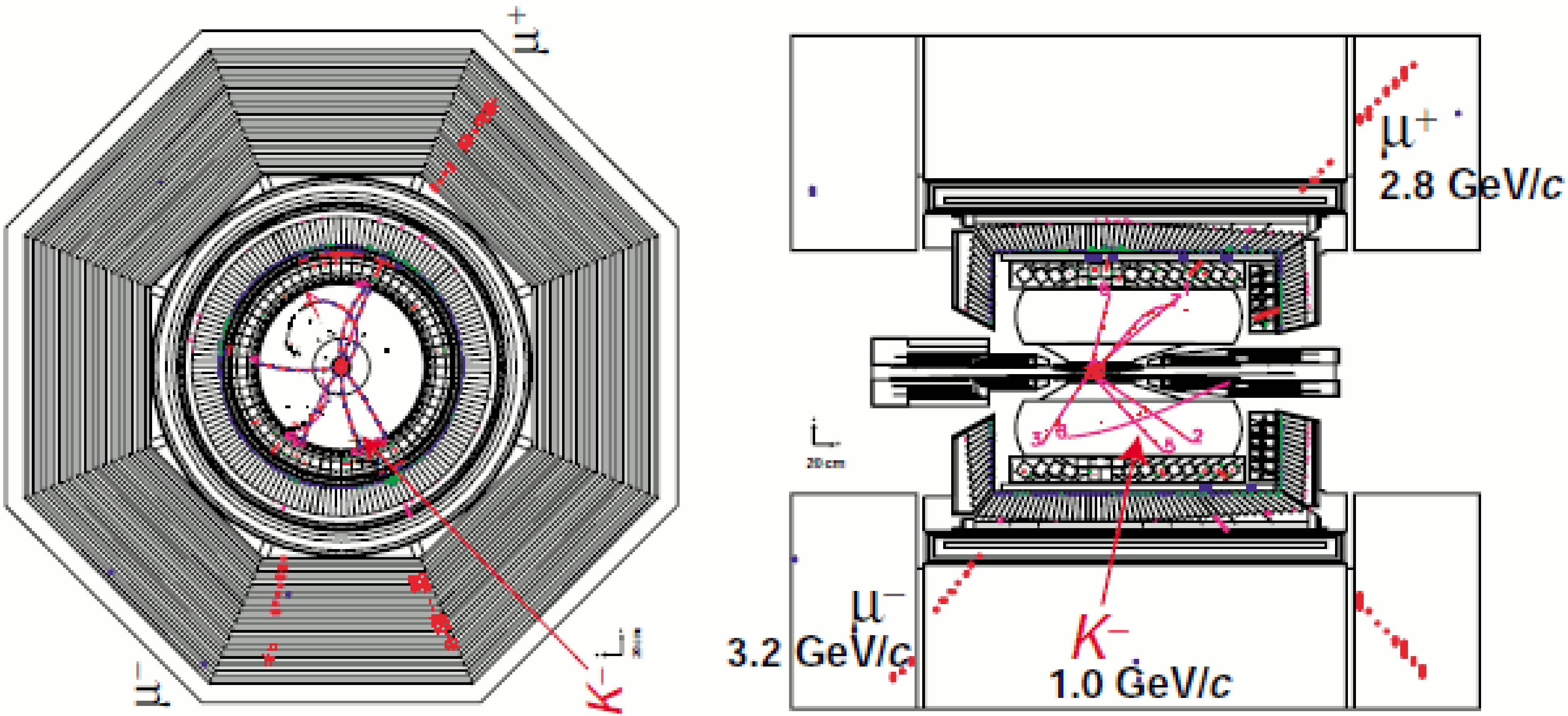


- Start with b→sγ, pay a factor α_{EM}
  - → Decay the γ into 2 leptons
  - Add an interfering box diagram
  - → b→lls, very rare in the SM
  - $B(\mathrm{B}\to \mathrm{llK}^*) = (3.3 \pm 1.0)\ .\ 10^{-6}$
- But beware of LD effects:
  - Tree b→c$\bar{c}$s, (c$\bar{c}$)→ll
  - Can be removed by mass cuts
  - Interferes elsewhere



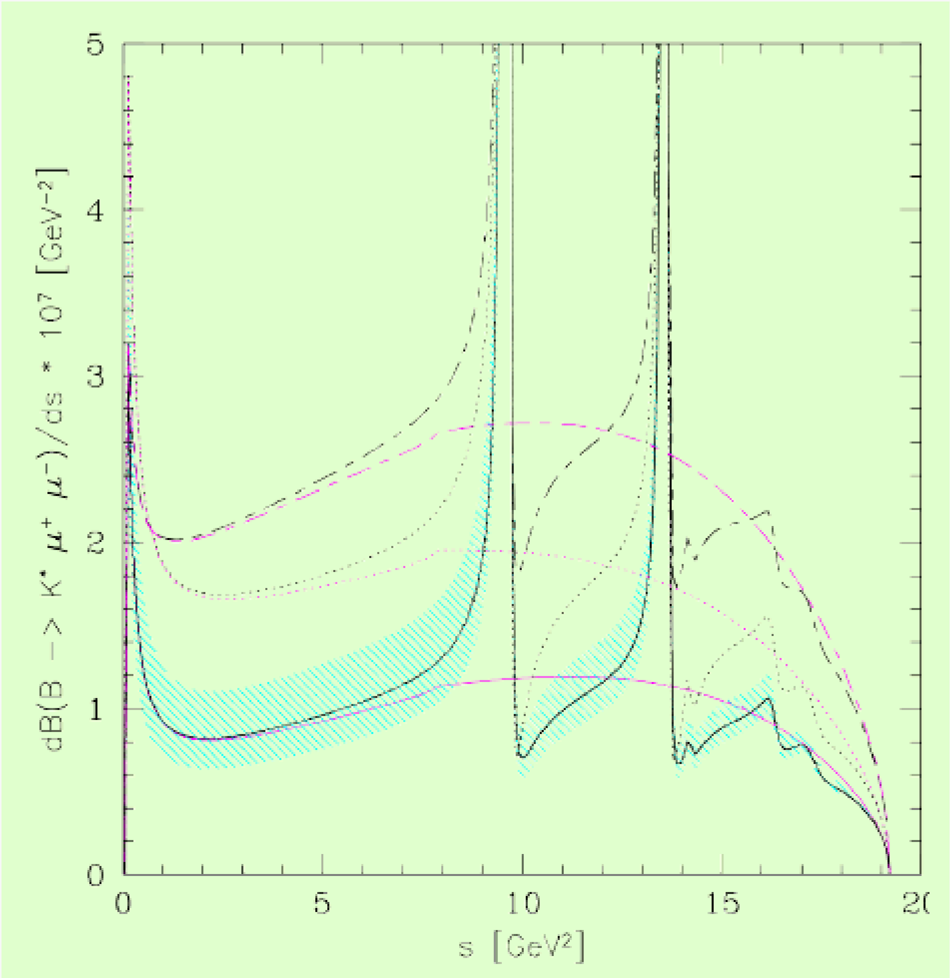
First observation

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



Lepton Photon 01, 2001 July 23, Roma

$b \to l l s$ q^2 spectrum

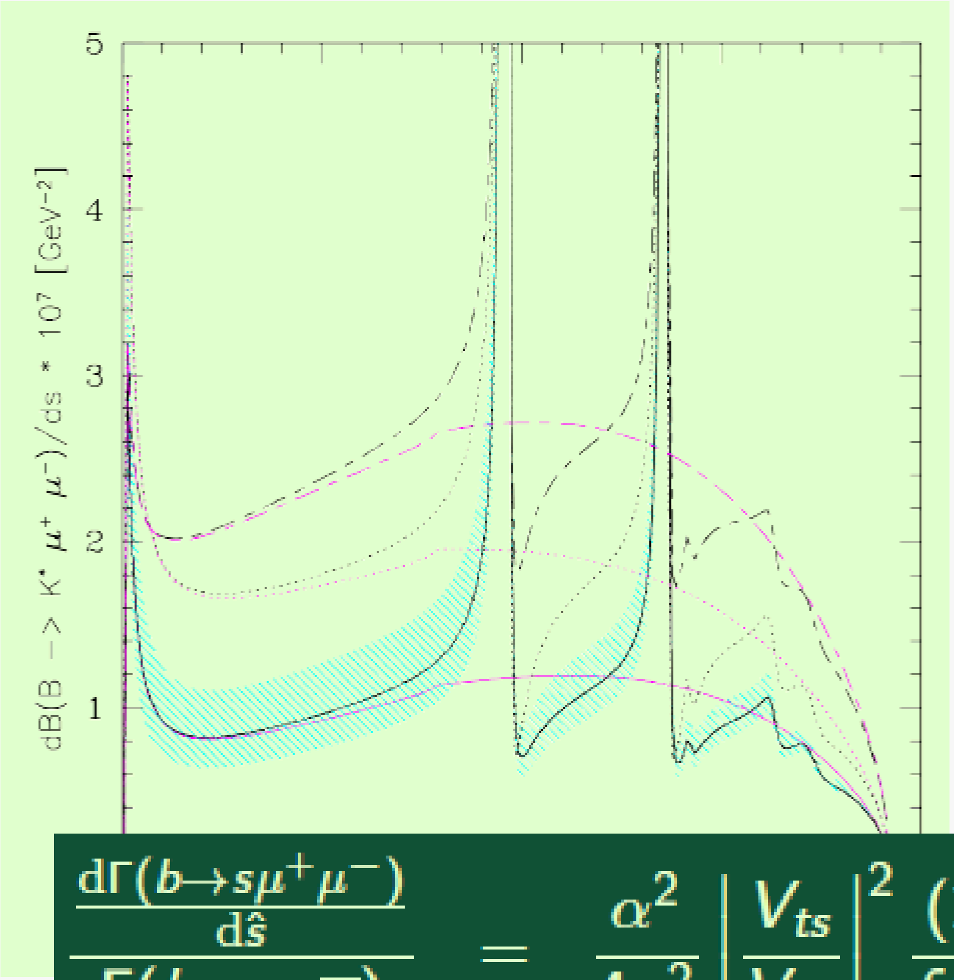


$$s \equiv q \equiv \hat{s}\, m_b^2 \equiv \text{mass}^2 \text{ of ll system}$$

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

- Photon pole ($b \to s\gamma$, $\gamma \to ll$)
- Non-resonant region ($1 < q^2 < 6$ GeV/c^2)
- $c\bar{c}$ resonance ($b \to J/\psi\, s$)
- Interference of $c\bar{c}$ resonances with non resonant contribution
  - For many measurements the ''safe'' region is $1 < q^2 < 6$ GeV/c^2
  - But the interferences are most interesting at $q^2 > 15$ GeV^2

b→lls q^2 spectrum



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

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

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

Inclusive vs exclusive

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

- Theory likes inclusive decays ($b \to ll\, s$)
- Experiment likes exclusive decays ($B \to ll\, K^*$)

But here, inclusive cannot be done

How to tell $b \to ll\, s$ from $b \to l \bar{\nu} c$ ($l \nu s$) without looking at the s?
(though might be possible with super B factory with hadronic tag ?)

Differences with $b \to s\gamma$

- inclusive = only semi-inclusive for now
- But exclusive modes are much more interesting in $b \to ll\, s$ than in $b \to s\gamma$

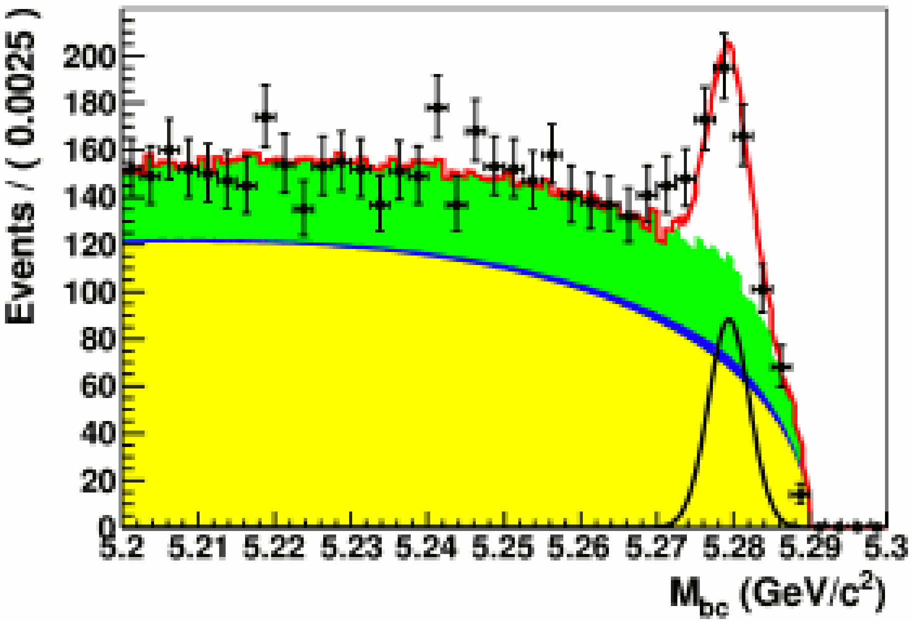
$\Rightarrow$ In particular $B \to ll\, K^*$

$B \to X_s l^+ l^-$

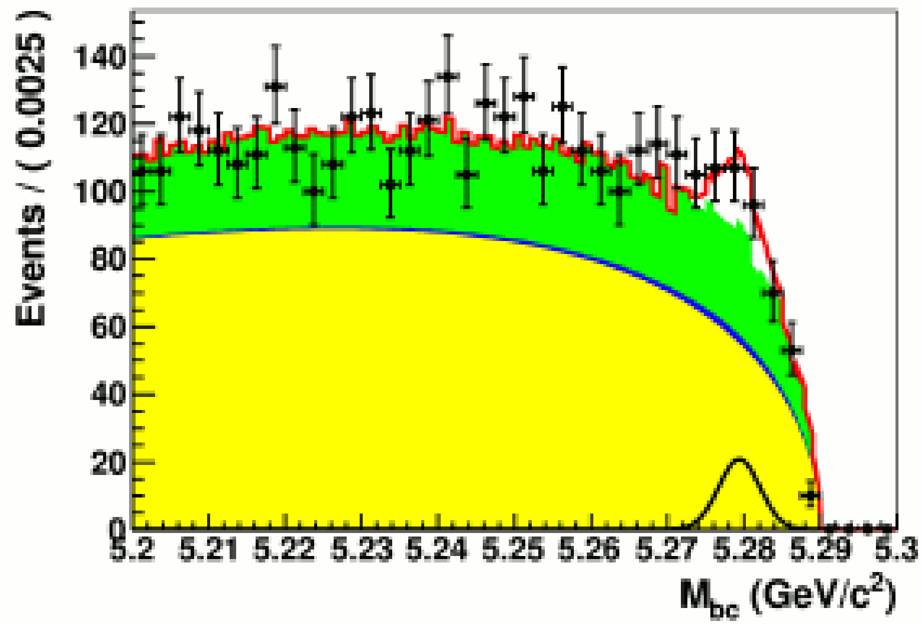
Full inclusive measurement is not feasible so far,
sum-of-exclusive technique has been used by Belle/BaBar

X_s reconstructed by: $1\ (K^{\pm}$ or $K_S) + 4\pi$'s $(N\pi^0 \le 1)$ (36 modes)

$\Rightarrow$ Belle (657 $MB\bar{B}$), preliminary (previous 152 $MB\bar{B}$)



10σ signal for entire $M(X_s)$



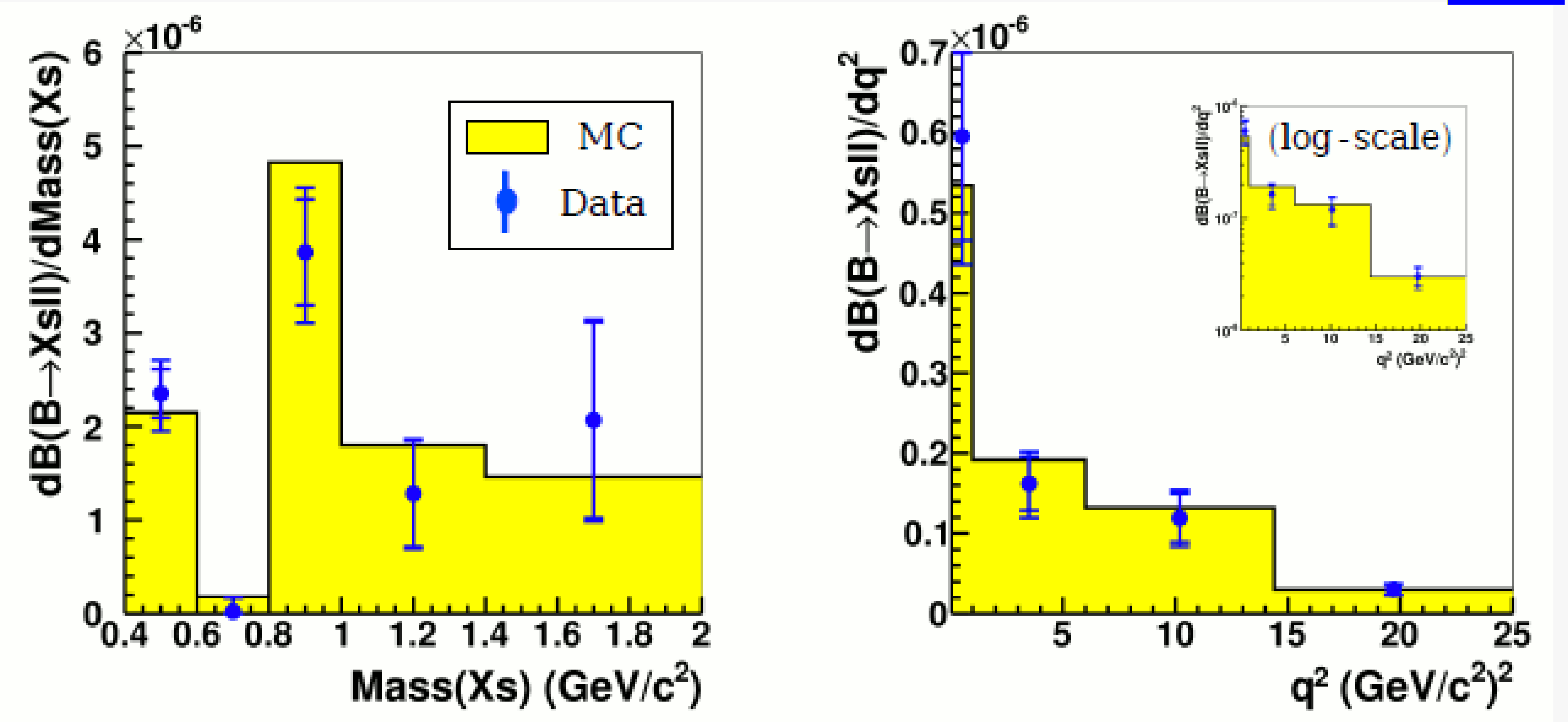
3σ signal for $M(X_s)$>1.0 GeV

Combinatorial BG (semi-leptonic B decays, continuum)

Self Cross-Feed

Peaking BG $B \to X_s \pi^+ \pi^-$ (double mis-id), leakage from J/ψ and ψ' veto,
charmonium higher resonances...

$B \to X_s l^+ l^-$



$$\boldsymbol{B}(B \to X_s l^+ l^-) = (3.33 \pm 0.80^{+0.19}_{-0.24}) \times 10^{-6}$$

[$q^2 > 0.2$ GeV^2/c^4 , extrapolated for J/ψ, ψ', and $M(X_s) > 2.0$ GeV]

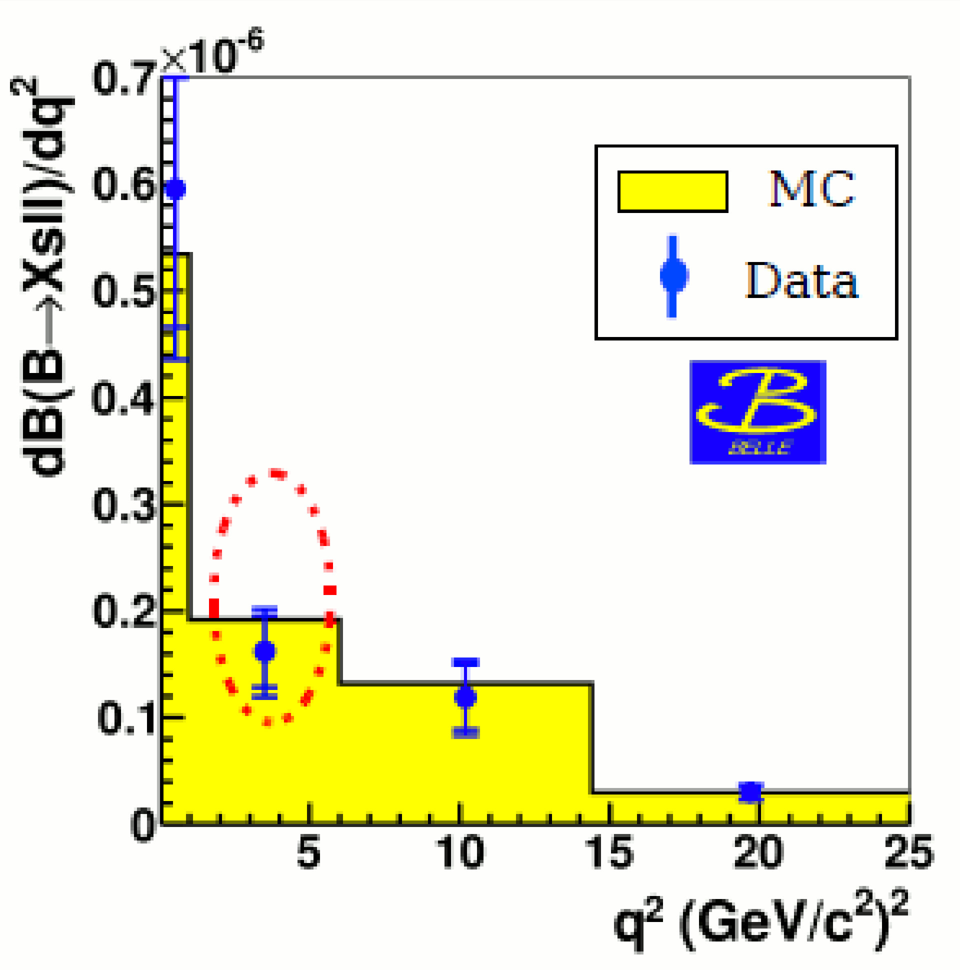
HFAG average: $B = (3.66^{+0.76}_{-0.77}) \times 10^{-6}$

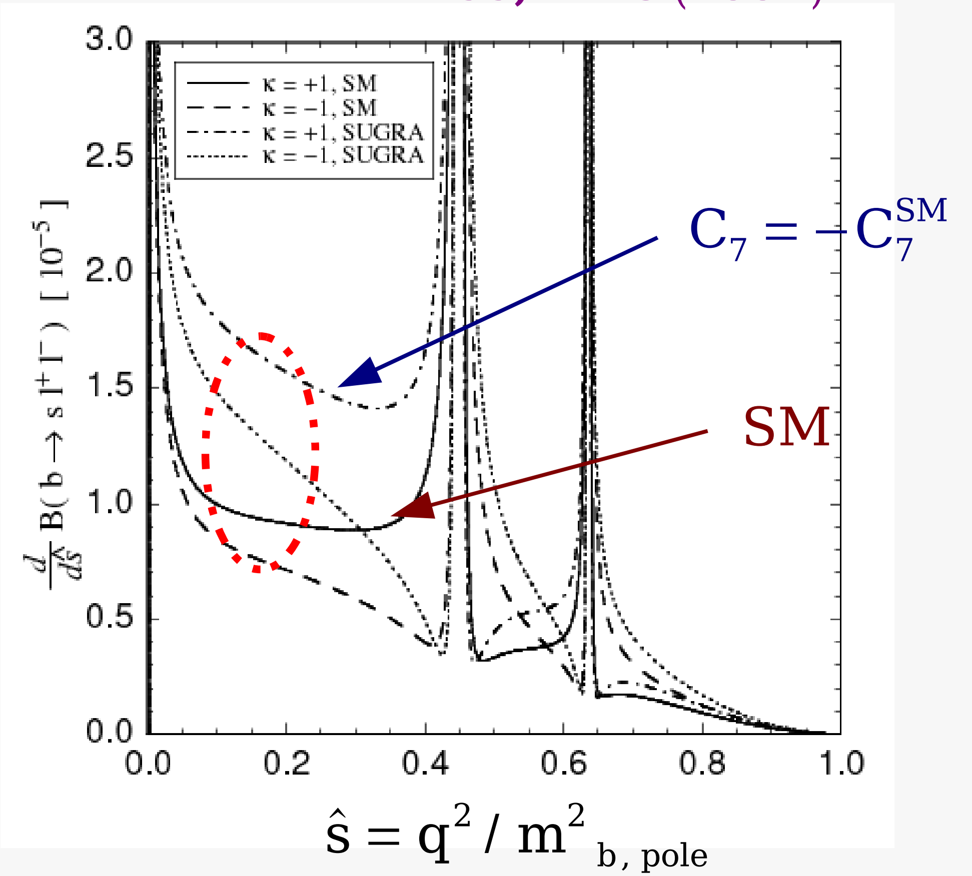
SM (Ali et al): $B_{SM} = (4.2 \pm 0.7) \times 10^{-6}$

SM (Gambino et al): $B_{SM} = (4.4 \pm 0.7) \times 10^{-6}$ **PRL 94, 061803 (2005)**

q^2 spectrum in $B \to X_s l^+ l^-$

T.Goto et al
PRD 55, 4273 (1997)





⇒ No branching fraction enhancement in this region
strongly disfavor the case with the flipped sign of C_7
(other less extreme NP possibilities are still allowed)

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

- Theory likes inclusive decays ($b \to ll\, s$)
- Experiment likes exclusive decays ($B \to ll\, K^*$)

But here, inclusive cannot be done

How to tell $b \to ll\, s$ from $b \to l\bar{\nu}c$ ($l\nu s$) without looking at the s?
(though might be possible with super B factory with hadronic tag ?)

Differences with $b \to s\gamma$

- inclusive = only semi-inclusive for now
- But exclusive modes are much more interesting in $b \to ll\, s$ than in $b \to s\gamma$

$\Rightarrow$ In particular $B \to ll\, K^*$

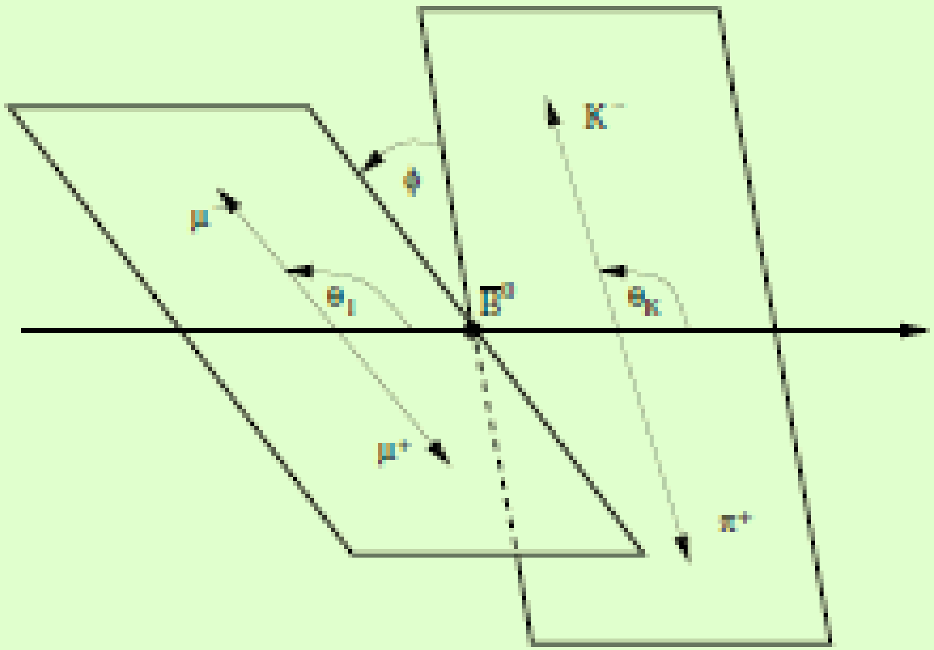
Angular distributions & A_{FB}

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

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

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

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



→ Many observables depending on q^2

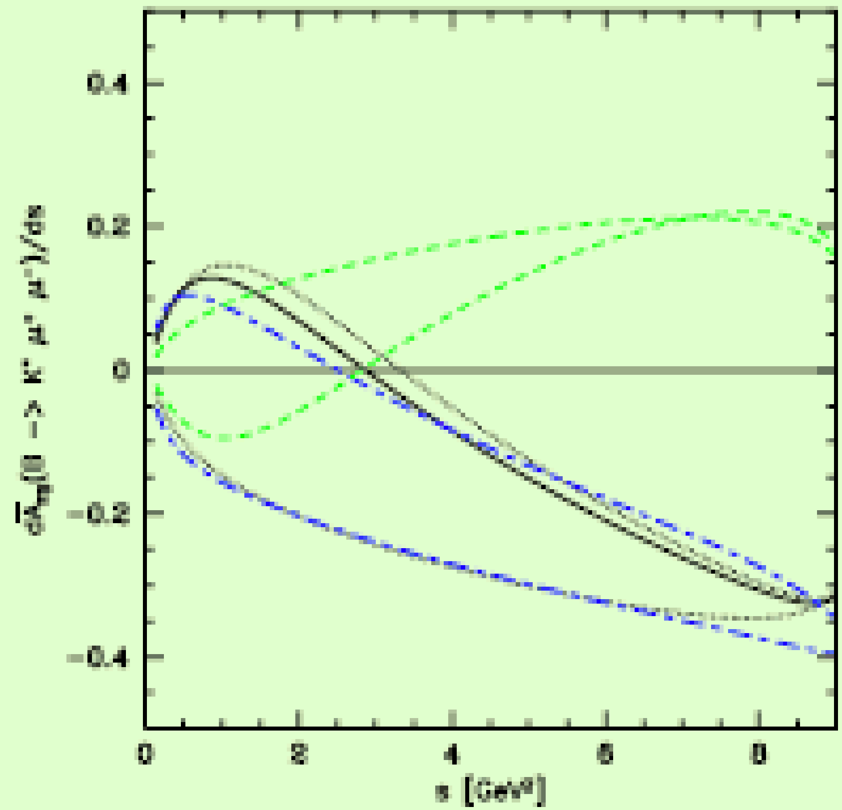
[Krüger & Matias]
[Egede, et al.] [Ali, et al.]

Angular distributions & A_{FB}

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

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

$$
\begin{aligned}
A_{\mathrm{FB}} &= \frac{\left(\int\limits_0^1 - \int\limits_{-1}^0\right)\mathrm{d}\cos\theta_l \frac{\mathrm{d}^2\Gamma}{\mathrm{d}q^2\mathrm{d}\cos\theta_l}}{\int\limits_{-1}^1 \mathrm{d}\cos\theta_l \frac{\mathrm{d}^2\Gamma}{\mathrm{d}q^2\mathrm{d}\cos\theta_l}}\\
&= \frac{3}{2}\frac{\mathrm{Re}\left(A_{\parallel L}A^*_{\perp L}\right) - \mathrm{Re}\left(A_{\parallel R}A^*_{\perp R}\right)}{|A_0|^2 + |A_\parallel|^2 + |A_\perp|^2}
\end{aligned}
$$



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

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

Forward-backward Asymmetry & A_{FB}

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

- 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)
  - $C_{7\gamma}^{\mathrm{eff}}$ the "$b \to s\gamma$ 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:

$$\frac{T_2}{A_1} = \frac{1 + \hat{m}_{K^*}}{1 + \hat{m}_{K^*} - \hat{s}} \left(1 - \frac{\hat{s}}{1 - \hat{m}_{K^*}}\right)$$
$$\frac{T_1}{V} = \frac{1}{1 + \hat{m}_{K^*}}$$

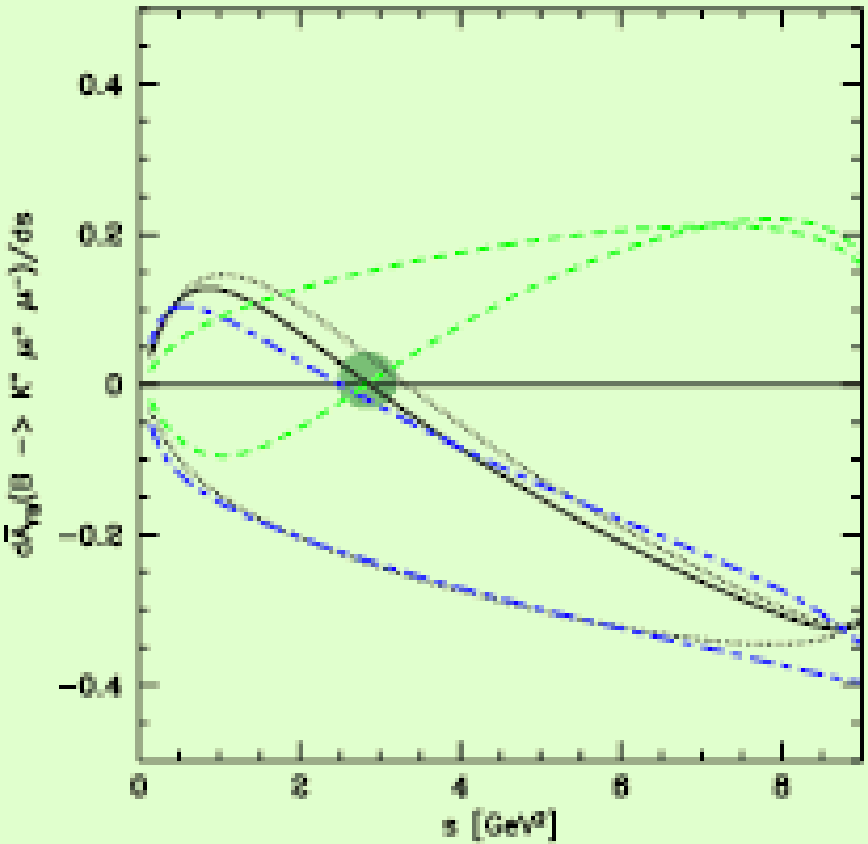
Forward-backward Asymmetry & A_{FB}

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

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

$$s_0 \simeq \frac{m_B^2 + m_{K*}^2 \left(\frac{2C_{7\gamma}^{\mathrm{eff}}}{\mathcal{R}(C_{9V}^{\mathrm{eff}})} \right) - 1}{1 - \frac{2C_{7\gamma}^{\mathrm{eff}}}{\mathcal{R}(C_{9V}^{\mathrm{eff}})}}$$

$$\Rightarrow \quad -2\frac{m_b}{s_0} \simeq \frac{2C_{7\gamma}^{\mathrm{eff}}}{\mathcal{R}(C_{9V}^{\mathrm{eff}})}$$



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

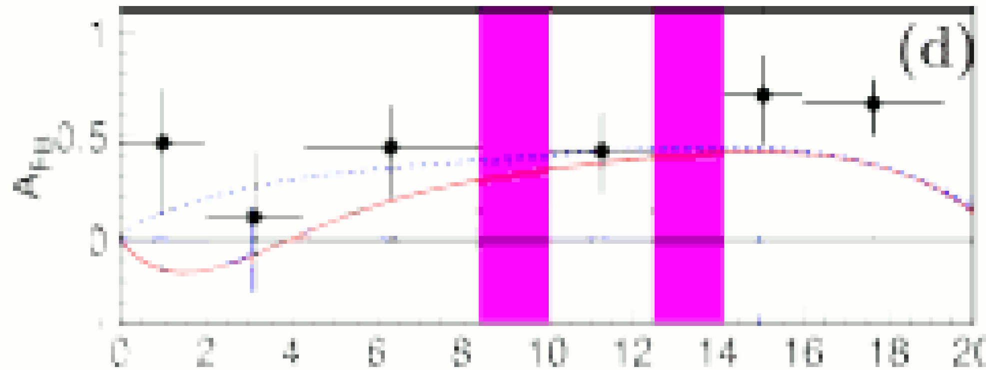
A_{FB} measurements summary

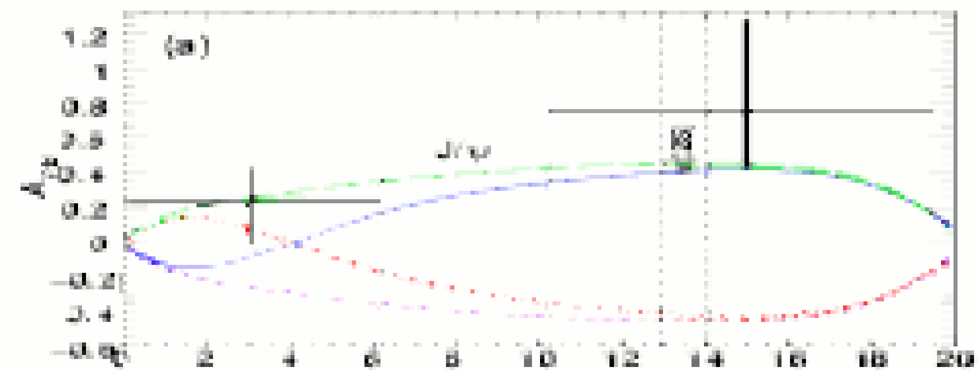
- BELLE: 230 $B \to \ell\ell K^*$ events in $657 \cdot 10^6$ $B\overline{B}$ [PRL103:171801,2009]
- BABAR: 60 $B \to \ell\ell K^*$ events in $384 \cdot 10^6$ $B\overline{B}$ [PRD79:031102,2009]
- CDF: 100 $B \to \mu\mu K^*$ events in $4.4\ \mathrm{fb}^{-1}$ [CDF public note]
- FB ASYMMETRY: All seem to favour positive values in first bins. Not conclusive yet...

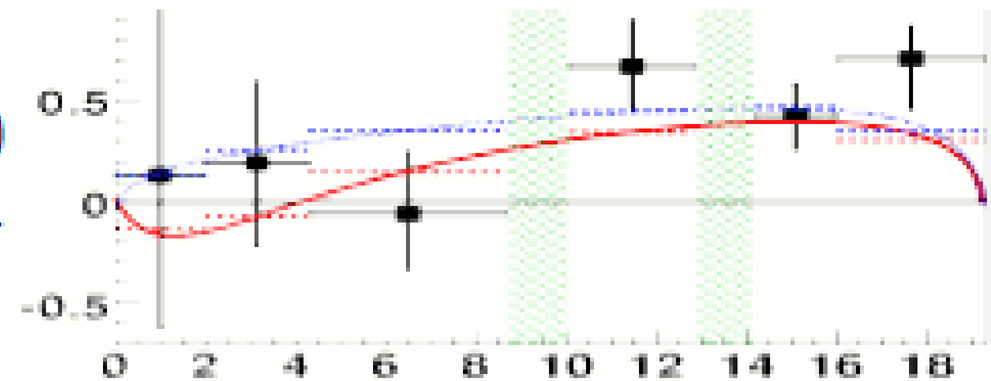
➜ Need much more statistics

LHCb presents a result with 300 events with 309 pb^{-1}: Largest sample in the world

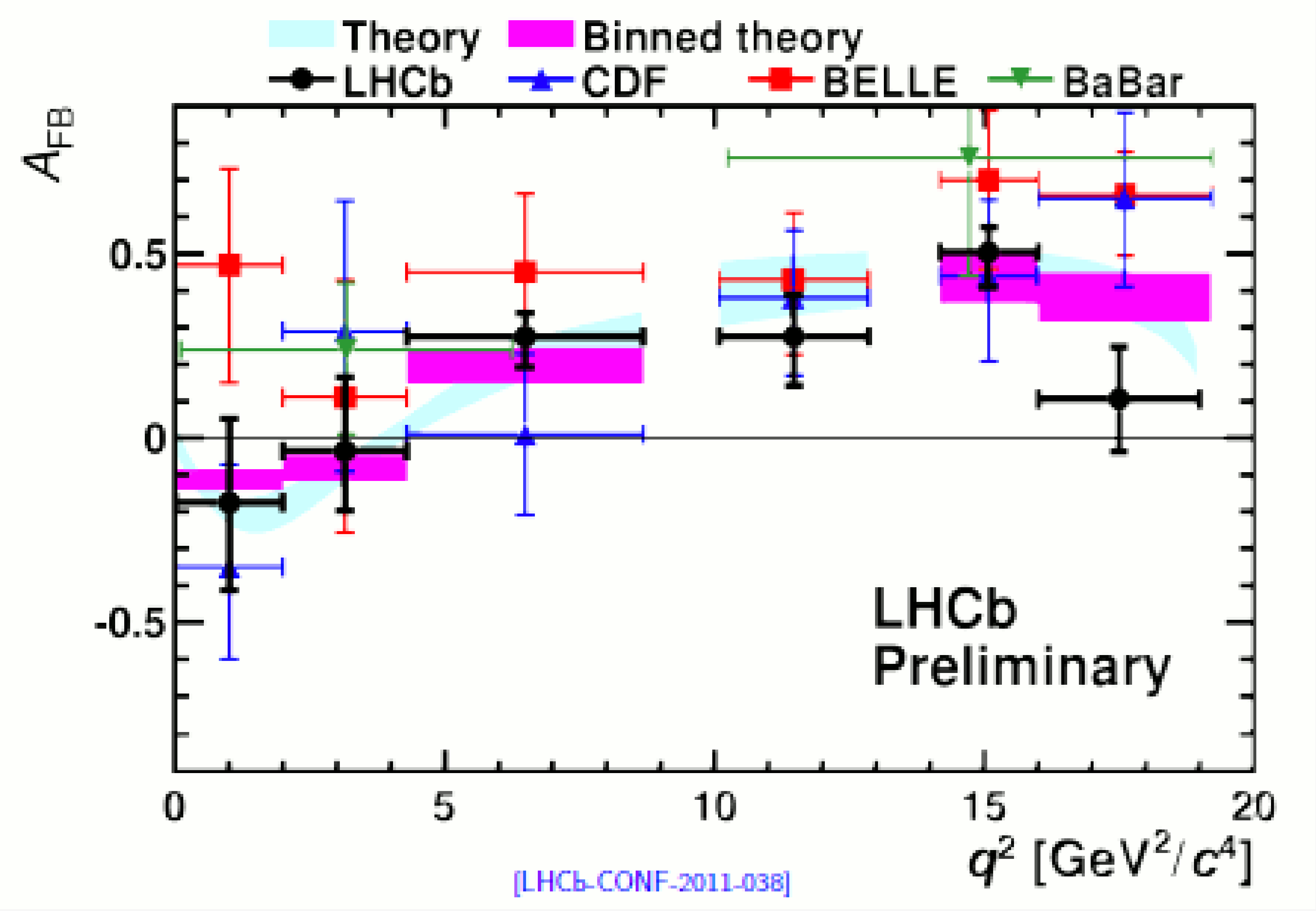
[LHCb-CONF-2011-038]





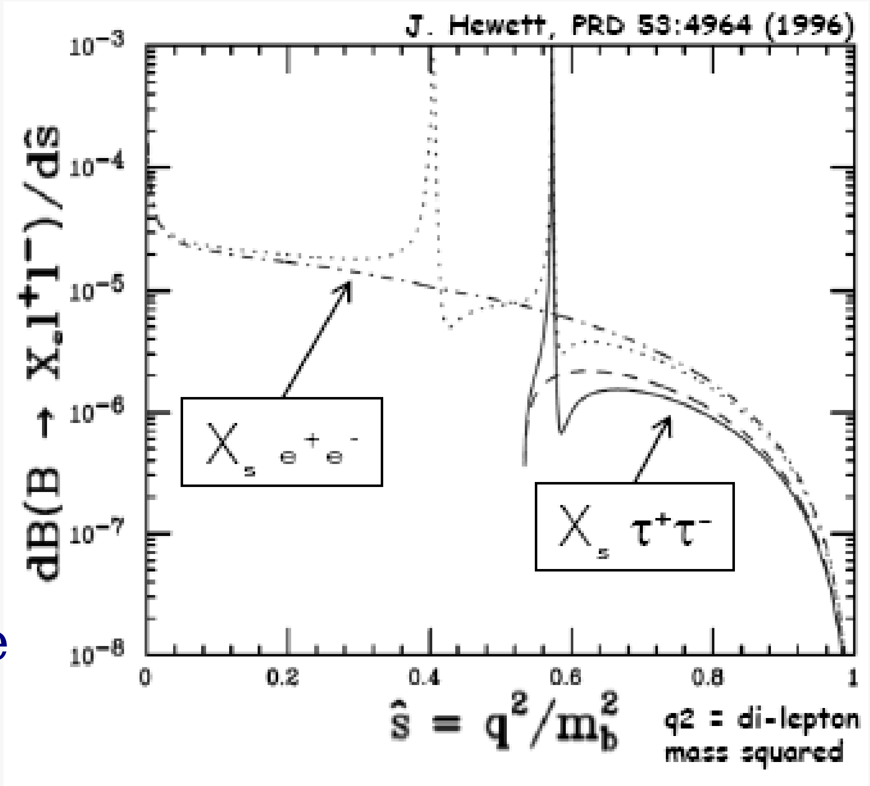


Comparison of all experiments



$\mathbf{B^+ \to K^+ \tau^+ \tau^-}$

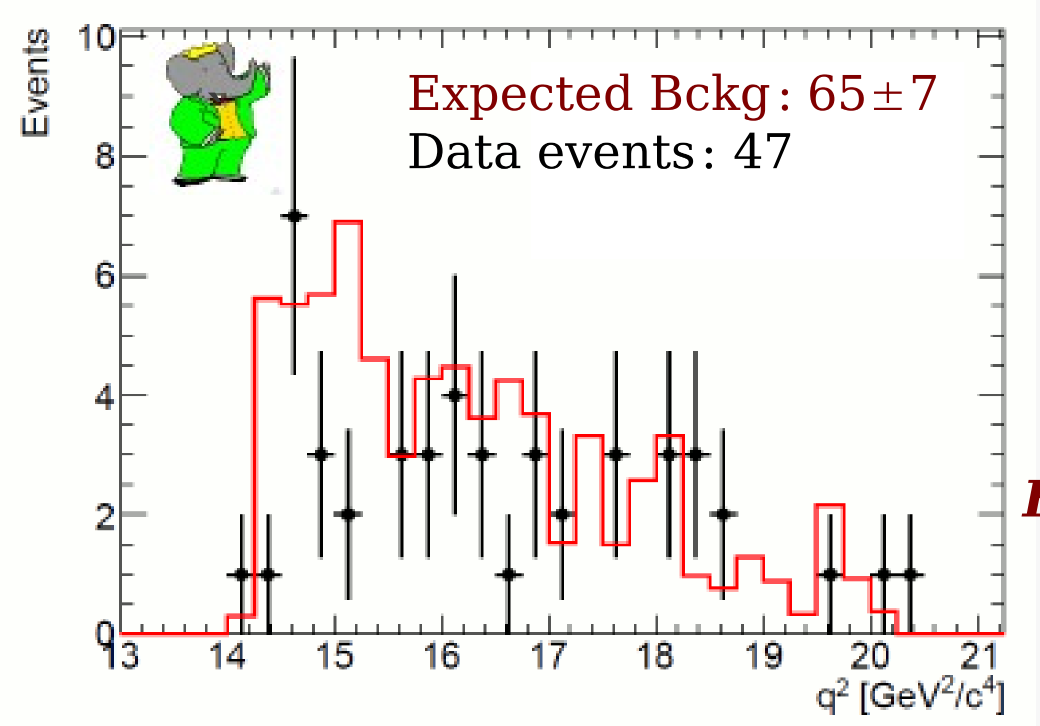
see Kevin Flood's talk



$0.6 \leq \hat{s} \leq 1:$

$$B_{SM}(B^+ \to X e^+ e^-) = 8.5 \times 10^{-7}$$
$$B_{SM}(B^+ \to X \mu^+ \mu^-) = 8.5 \times 10^{-7}$$
$$B_{SM}(B^+ \to X \tau^+ \tau^-) = 4.3 \times 10^{-7}$$

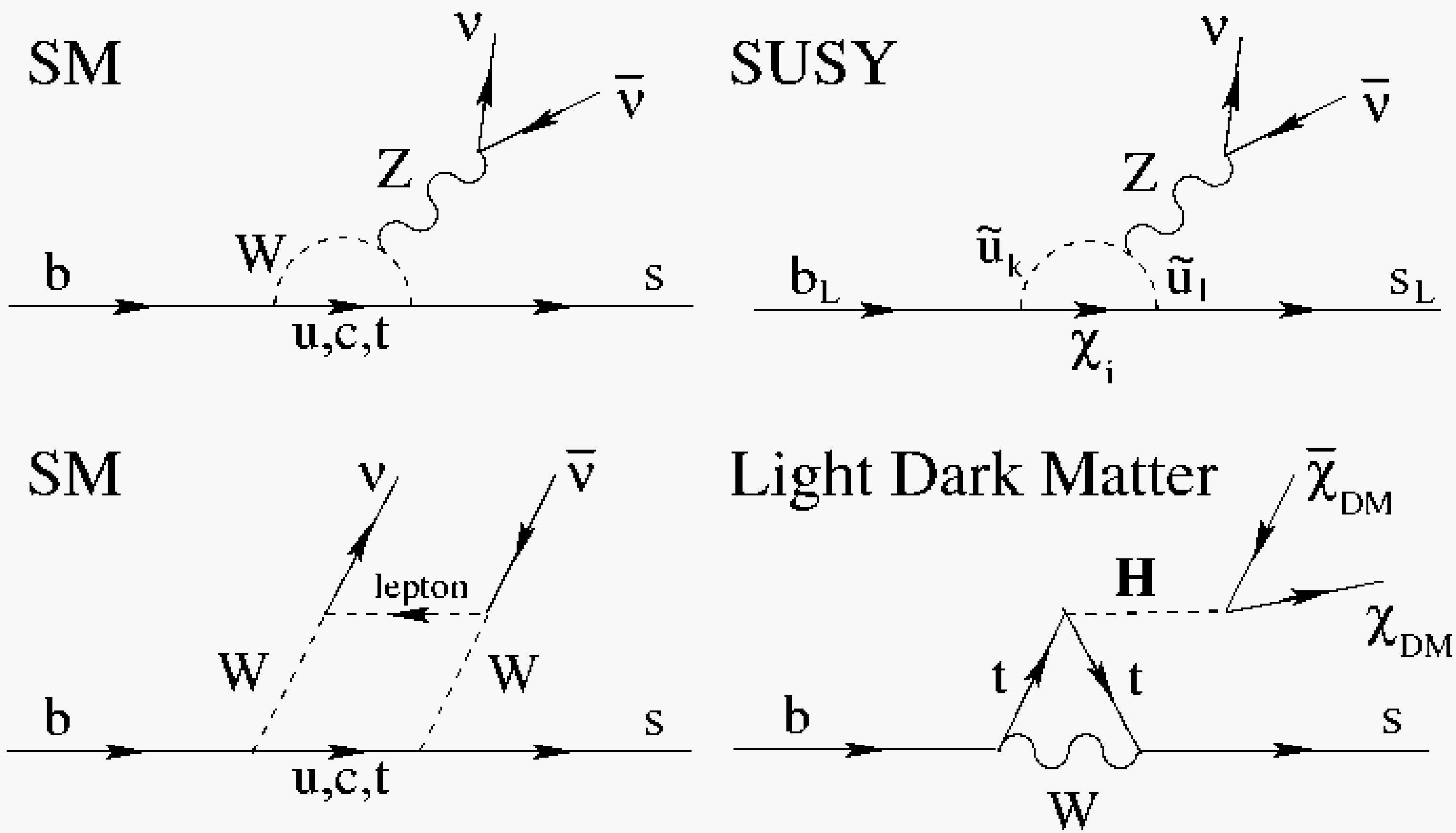
- rate can be **enhanced by NP** (NMSSM rate could be $\propto (M_\tau^2/M_\mu^2) \sim 280$)
- $B^+ \to K^+ \tau^+ \tau^-$ is ~ 50 % of total inclusive rate



- First search (preliminary)
- 468M $B\bar{B}$
- Hadronic tag ($\epsilon \sim 0.2\,\%$)
- $\tau \to e\bar{\nu}\nu,\ \mu\bar{\nu}\nu,\ \pi\nu$ (2-4 neutrinos in the final state)

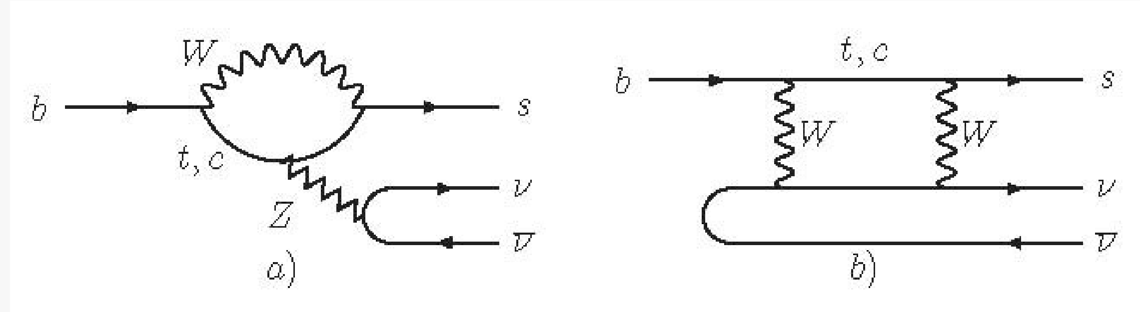
$\boldsymbol{B(B^+ \to K^+ \tau^+ \tau^-) < 3.3 \times 10^{-3}}$ **@ 90% C.L.**

$\mathbf{b \to s \nu \bar{\nu}}$



Observable	SM prediction	Experiment
$Br(B^+ \to K^+ \nu \bar{\nu})$	$(3.6 \pm 0.5) \times 10^{-6}$	$< 14 \times 10^{-6}$
$Br(B^0 \to K^{*0} \nu \bar{\nu})$	$(6.8^{+1.0}_{-1.1}) \times 10^{-6}$	$< 80 \times 10^{-6}$
$Br(\bar{B} \to X_s \nu \bar{\nu})$	$(2.7 \pm 0.2) \times 10^{-5}$	$< 64 \times 10^{-5}$
$< F_L(B^0 \to K^{*0} \nu \bar{\nu}) >$	0.54 ± 0.01	--

$B \to h \nu \bar{\nu}$



$B_{sig}\ B_{tag} \to (h\,\nu\,\bar{\nu})\,(X\,l\,\nu)$ semil. tag

$\boxed{\to (h\,\nu\,\bar{\nu})\,(X) \text{ hadronic tag}}$

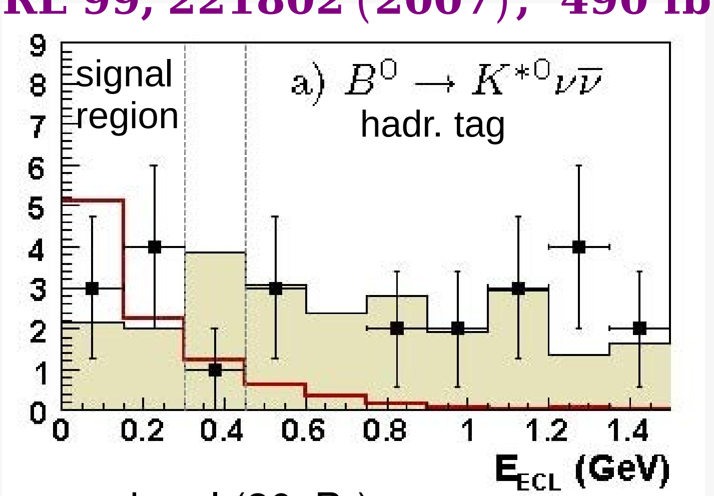
fully (partially) reconstruct B_{tag}

reconstruct h from $B_{sig} \to h\,\nu\,\bar{\nu}$

no additional energy in EM calorim.

(signal at $E_{ECL} \sim 0$)

PRL 99, 221802 (2007), 490 fb^{-1}



-- exp. signal (20xBr)

exp. bkg. (scaled to sideband)

$\int L\,dt = 50\ ab^{-1}$

semil. + hadr. tag (improved):

$N_{sig} \sim 240$, $N_{bkg} \sim 4600$

$Br(B^0 \to K^{*0}\,\nu\,\bar{\nu})$ can be measured to $\pm 30\%$

similar precision for $Br(B^0 \to K_S\,\nu\,\bar{\nu})$

$N^{exp}_{bkg} = 4.2 \pm 1.4 \quad \Rightarrow \quad Br(K^{*0}\,\nu\,\bar{\nu}) < 3.4\times10^{-4}$ @ 90%C.L.

$(N^{exp}_{sig} = 0.34,\ Br(B^0 \to K^{*0}\,\nu\,\bar{\nu}) = 1.3\times10^{-5})$

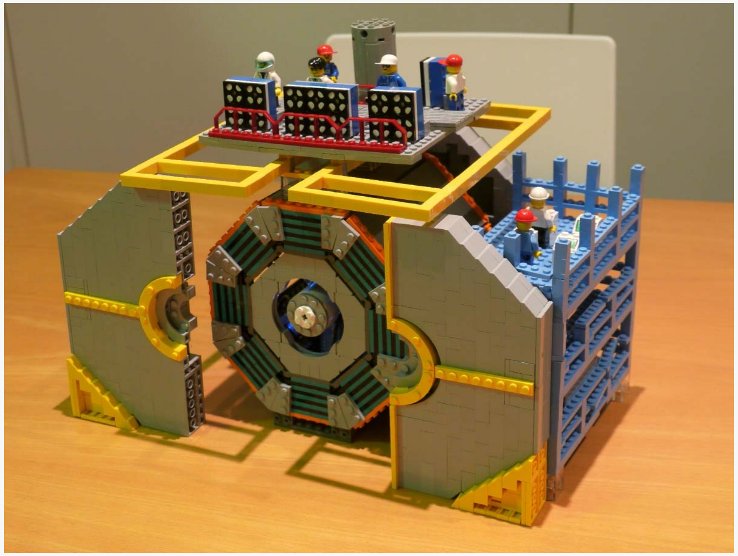
G.Buchalla et al, PRD 63, 014015 (2001)

[similarly for $K^+\,\nu\,\bar{\nu}$]

and then...

⇒ physics with $O(10^{10})$ B, τ, D....

SuperKEKB/Belle II (in Japan)



⇒ KEKB upgrade has been approved

50 ab^{-1} by ~ 2022 = 50 × present