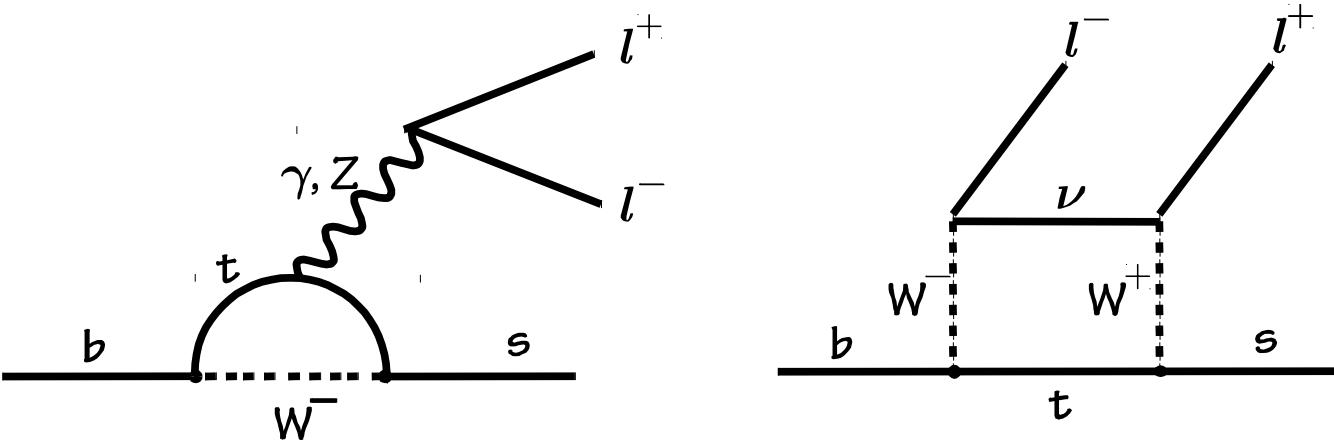


# Beautiful paths to probe physics beyond the standard model of particles

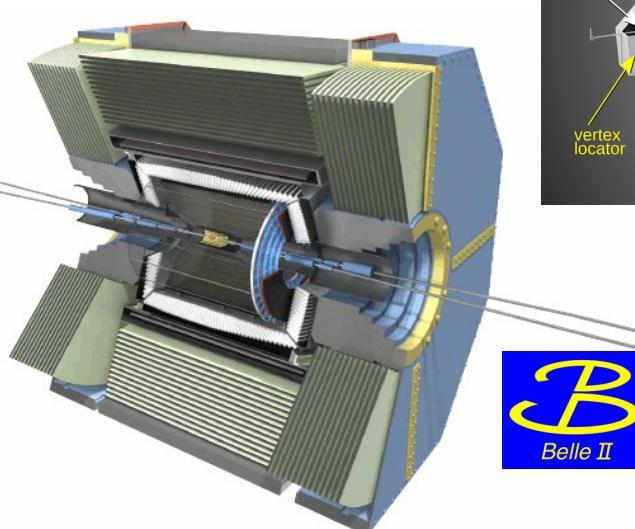
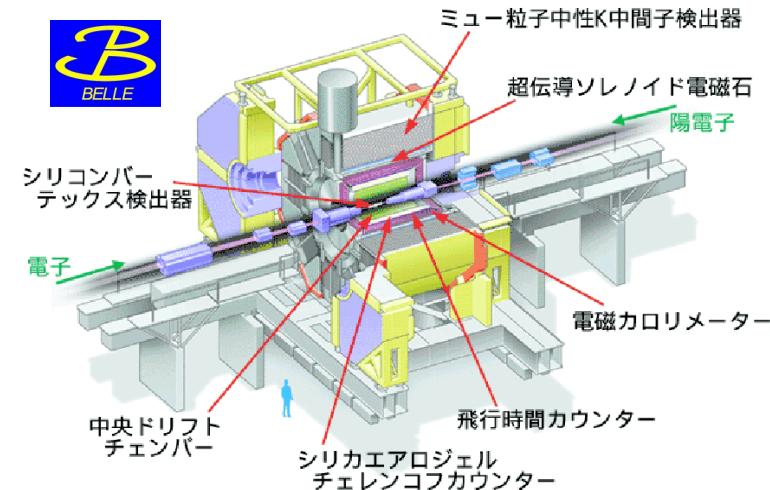


K. Trabelsi

[karim.trabelsi@lal.in2p3.fr](mailto:karim.trabelsi@lal.in2p3.fr)



Laboratoire de Physique  
des 2 Infinis



**JENNIFER: Japan and Europe Network  
for Neutrino and Intensity Frontier Experimental Research**

# Program of the lectures

- **How to study elementary particles**
  - indirect searches for New Physics
  - experiments through history of particle/flavour physics
  - what is Belle (II) experiment(s)
- **Rare B decays**
  - quest for New Physics (beyond Standard Model)
  - two approaches for the same quest (LHCb vs Belle)
  - sign of New Physics ?

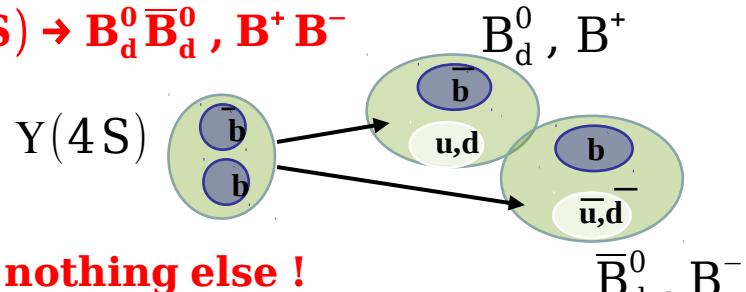
# Belle II, a flavour-factory, a rich physics program ...

- We plan to collect (**at least**)  $50 \text{ ab}^{-1}$  of  $e^+ e^-$  collisions at (or close to) the  $\Upsilon(4S)$  resonance, so that we have:

– **a (Super) B-factory ( $\sim 1.1 \times 10^9 B\bar{B}$  pairs per  $\text{ab}^{-1}$ )**

"on resonance" production

$$e^+ e^- \rightarrow \Upsilon(4S) \rightarrow B_d^0 \bar{B}_d^0, B^+ B^-$$



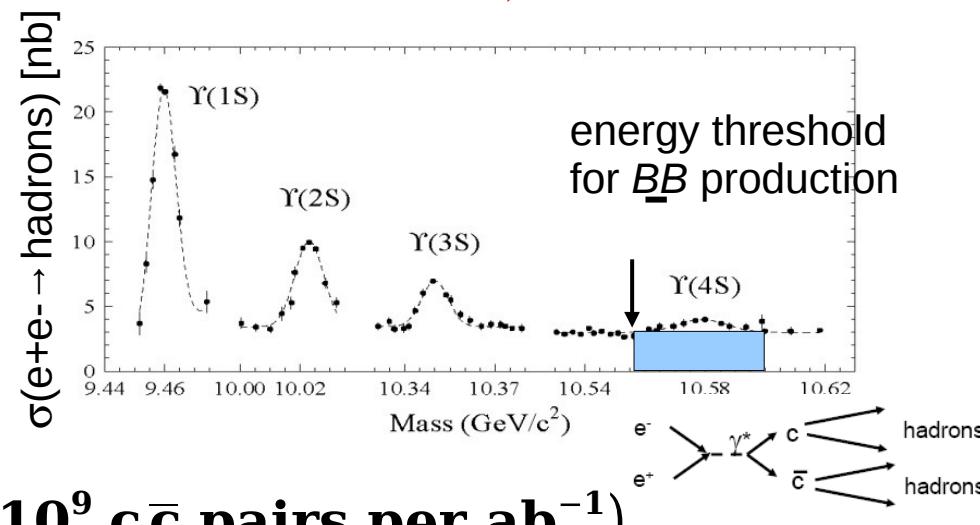
- **2 B's and nothing else !**
- 2 B mesons are created simultaneously in a  $L=1$  coherent state

– **a (Super) charm factory ( $\sim 1.3 \times 10^9 c\bar{c}$  pairs per  $\text{ab}^{-1}$ )**

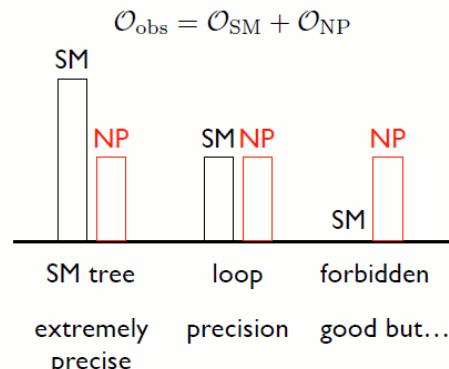
(but also charmonium, X, Y, Z, pentaquarks, tetraquarks, bottomonium ...)

– **a (Super)  $\tau$  factory ( $\sim 0.9 \times 10^9 \tau^+ \tau^-$  pairs per  $\text{ab}^{-1}$ )**

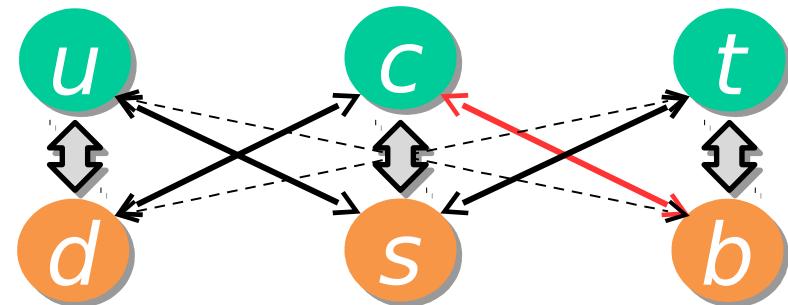
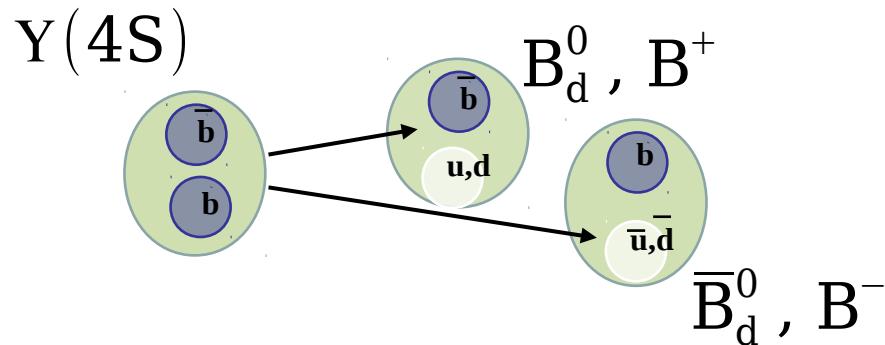
- exploit the clean  $e^+ e^-$  environment to probe the existence of exotic hadrons, dark photons/Higgs, light Dark Matter particles, ALPs, LLPs ...



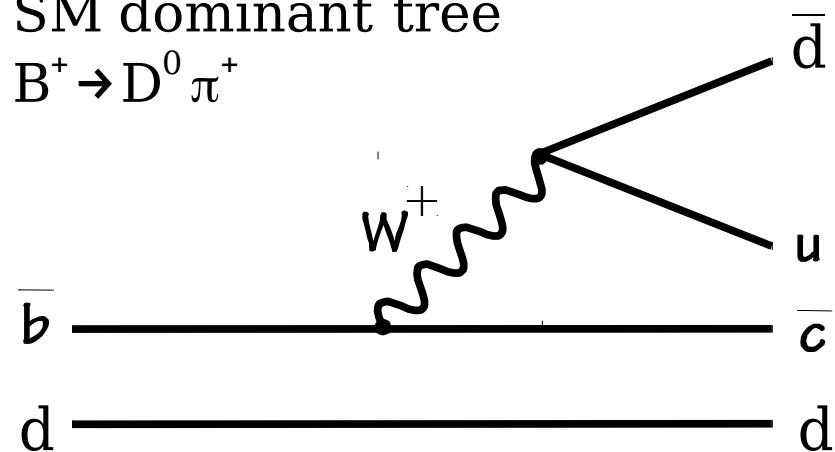
Three classes of SM processes



# At a B-factory ...



SM dominant tree  
 $B^+ \rightarrow D^0 \pi^+$



How many B candidates can I reconstruct with  $1 \text{ fb}^{-1}$  ?  
 $1 \text{ fb}^{-1} \rightarrow 1 \times 10^6 \text{ B produced}$   
but  $\text{BF}(B \rightarrow D^0 \pi^-) = 5 \times 10^{-3}$   
and  $\text{BF}(D \rightarrow K^- \pi^+) = 3.8\%$   
and reconstruction efficiency  $\sim 10\%$  ...  
signal yield  $\sim 10$  events !!

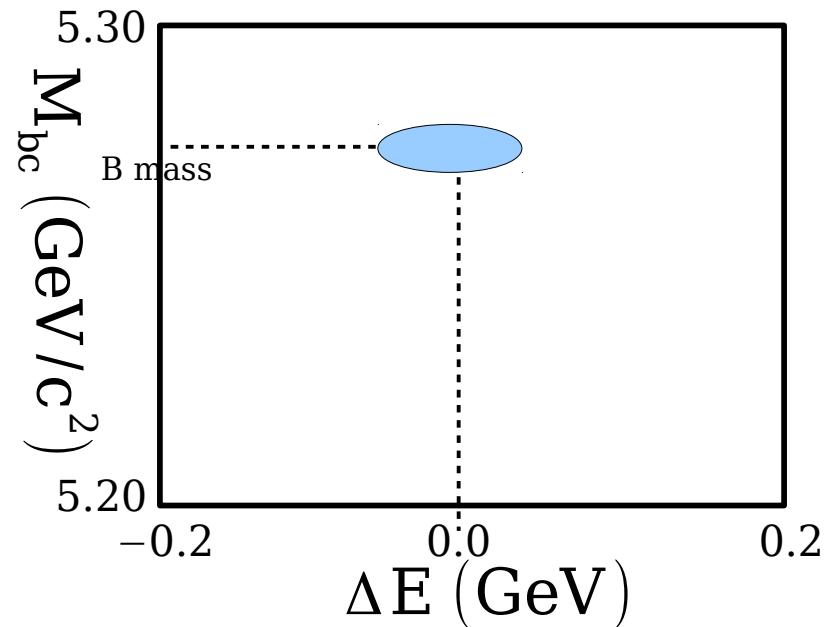
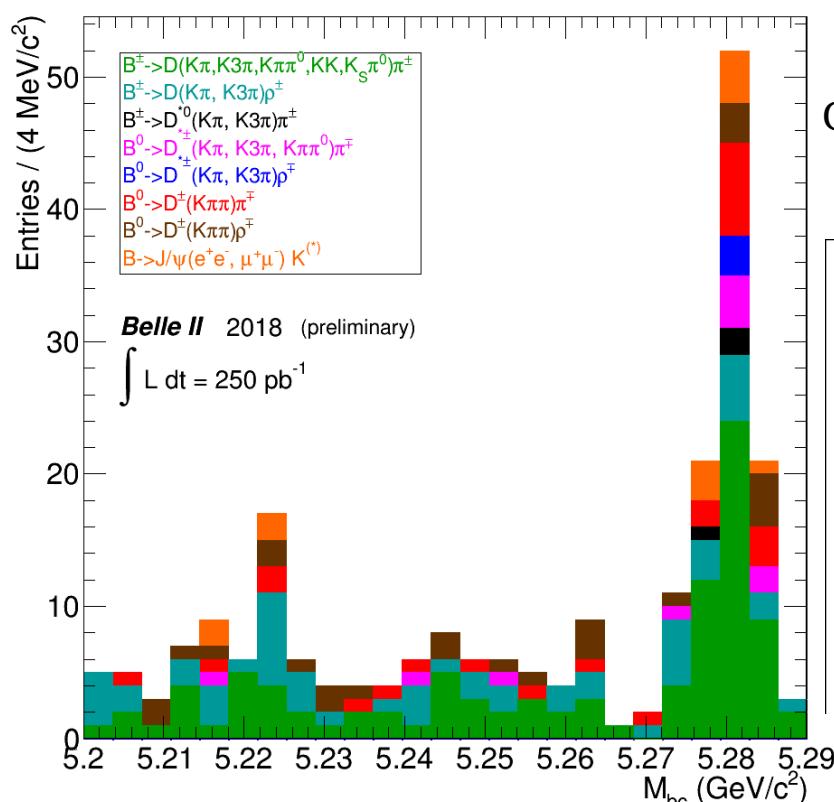
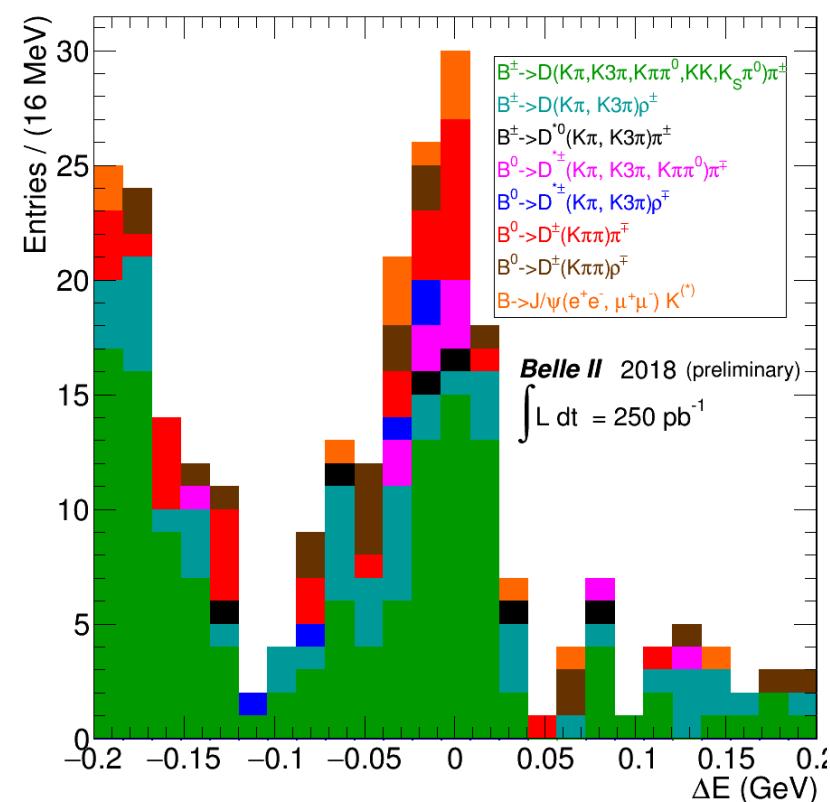
# Reconstruct a B candidate ...

Energy difference:

$$\Delta E = E_B^* - E_{\text{beam}} \quad (\text{resolution } \sim 10 \text{ MeV})$$

Beam-energy-constrained mass:

$$M_{bc} = \sqrt{(E_{\text{beam}}/c^2)^2 - (p_B^*/c)^2} \quad (\text{resolution } \sim 2.5 \text{ MeV})$$



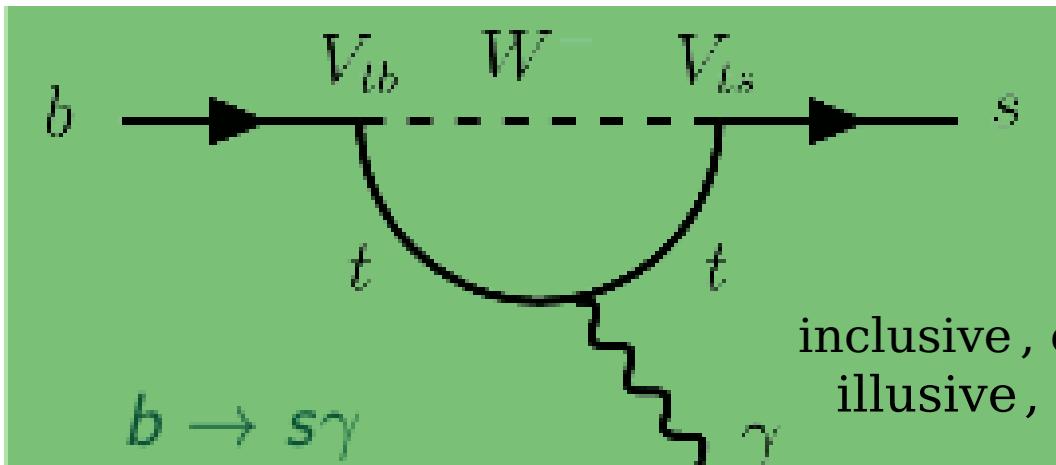
Candidates in signal box  
 $(M_{bc} > 5.27 \text{ GeV}/c^2, |\Delta E| < 0.050 \text{ GeV})$

Mode	yield
$B^\pm \rightarrow D\pi^\pm$	51
$B^\pm \rightarrow D\rho^\pm$	16
$B^\pm \rightarrow D^*\pi^\pm$	3
$B^0 \rightarrow D^*\pm\pi^\mp$	7
$B^0 \rightarrow D^*\pm\rho^\mp$	3
$B^0 \rightarrow D^\pm\pi^\mp$	13
$B^0 \rightarrow D^\pm\rho^\mp$	8
$B \rightarrow J/\psi K^{(*)}$	8

$\sim 100 \text{ evts}$

# Radiative B decays

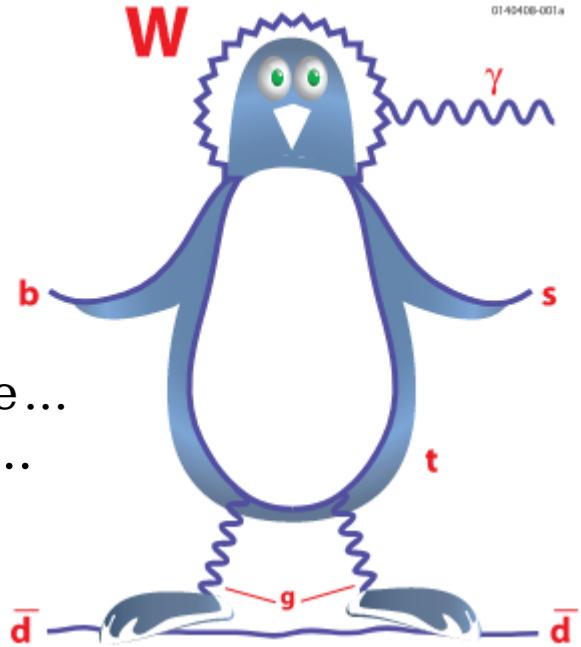
artist's view ... of the penguin diagram



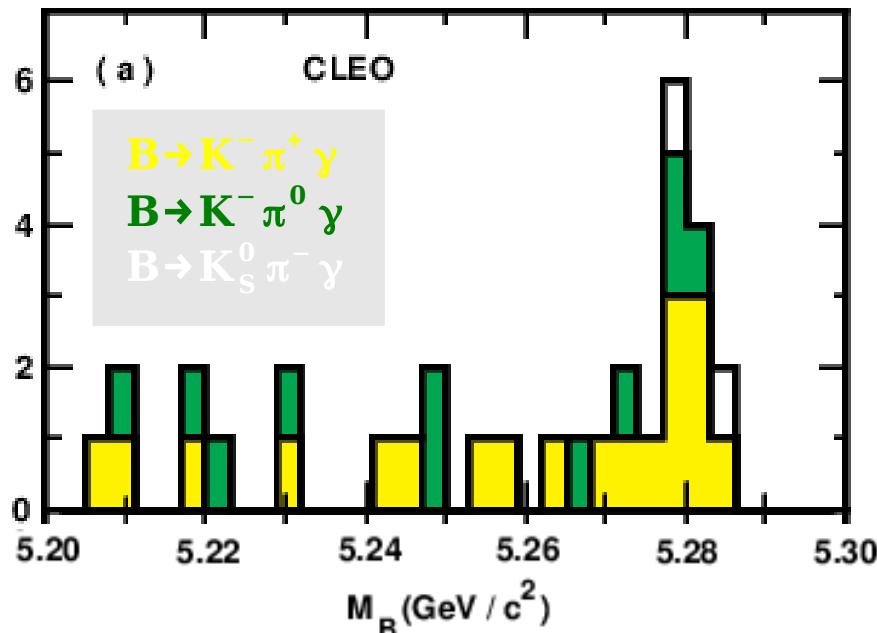
inclusive , exclusive...  
illusive , elusive ...

CLEO

- 1975: "South Area Experiment" group conceives CLEO
- 1979: First data collected
- 1980: B meson discovered
- 1983: Ds meson discovered
- 1986: CLEO II detector with CsI calorimeter installed
- 1989:  $b \rightarrow u$  transitions discovered
- 1993:  $b \rightarrow s$  penguin decays discovered
- 1995: CLEO II.V with silicon vertex detector installed
- 1999: CLEO III with RICH installed
- 2003: CLEO-c data collection started
- 2004: hc discovered and D+ meson decay constant measured
- 2008: Running ends on March 3rd
- 2009: 500th paper published

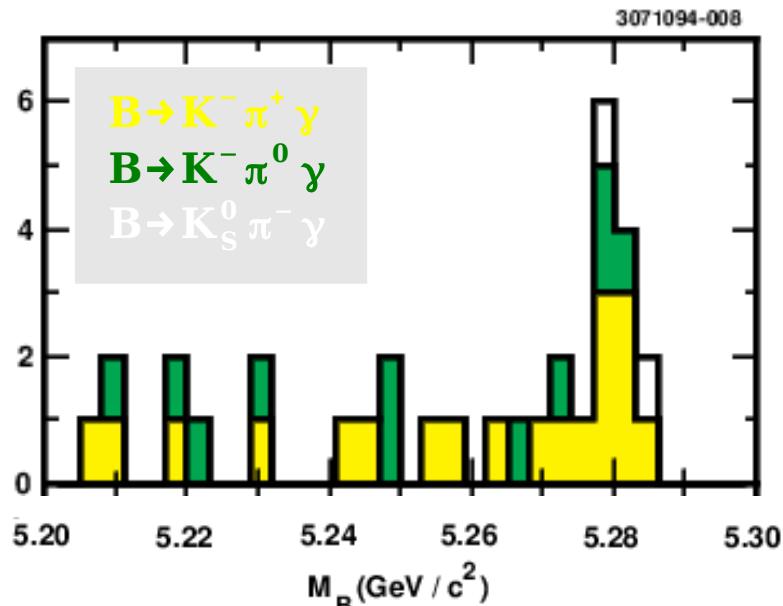


CLEO observation of  $B \rightarrow K^* \gamma$  [1993]



# B $\rightarrow$ K $^*\gamma$ measurements

CLEO observation of B $\rightarrow$ K $^*\gamma$  [1993]



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

means B $^+\rightarrow$ K $^{*+}\gamma$  or B $^0\rightarrow$ K $^{*+}\gamma$

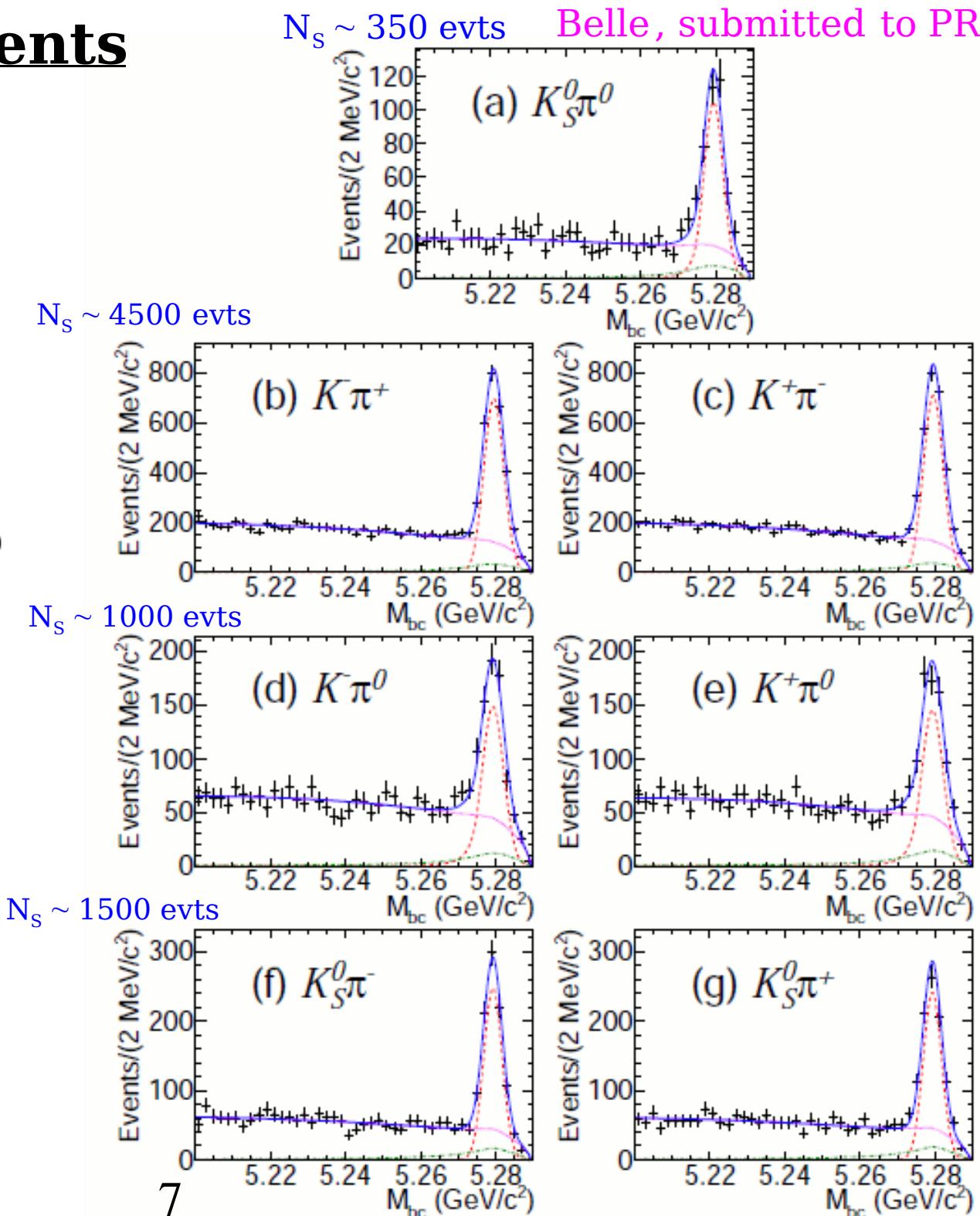
$$\text{Br}(B^0 \rightarrow K^{*0} \gamma) = (41.7 \pm 1.2) \times 10^{-6}$$

$$\text{Br}(K^{*0} \rightarrow K^+ \pi^-) \sim 2/3, \text{ Br}(K^{*0} \rightarrow K^0 \pi^0) \sim 1/3$$

$$\text{Br}(B^+ \rightarrow K^{*+} \gamma) = (39.2 \pm 1.3) \times 10^{-6}$$

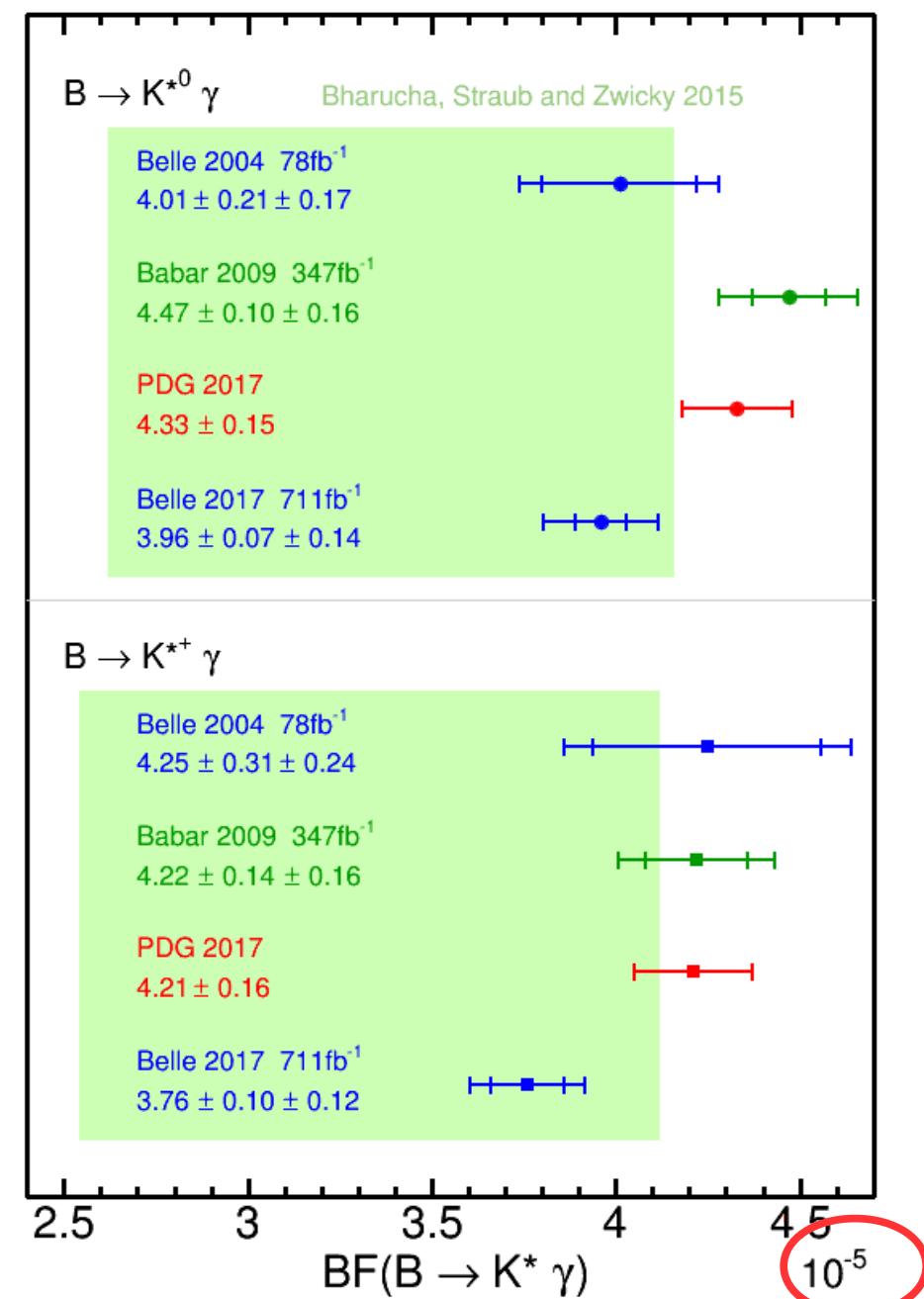
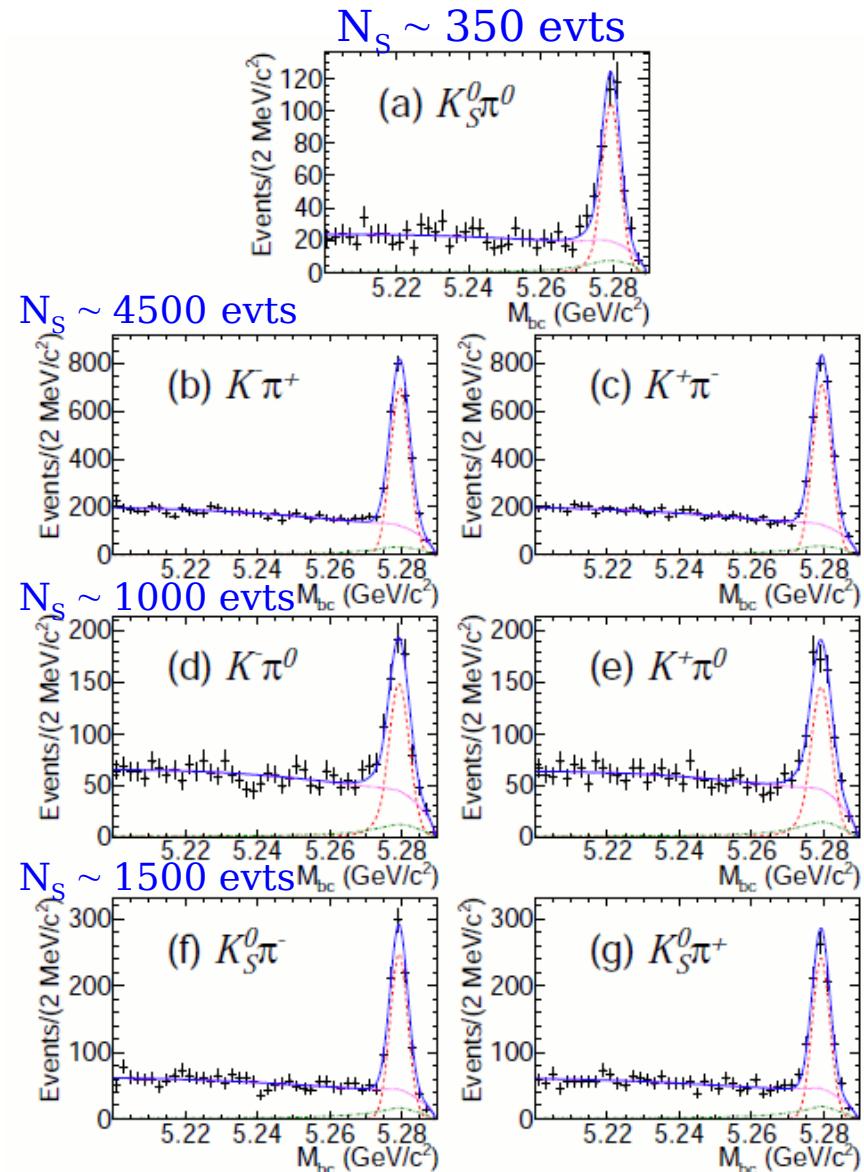
$$\text{Br}(K^{*+} \rightarrow K^0 \pi^+) \sim 2/3, \text{ Br}(K^{*+} \rightarrow K^+ \pi^0) \sim 1/3$$

N<sub>S</sub> ~ 350 evts      Belle, submitted to PRL



# B $\rightarrow$ K $^*$ $\gamma$ measurements

simultaneous fit of 4 final states  
 ⇒ extraction of BFs....

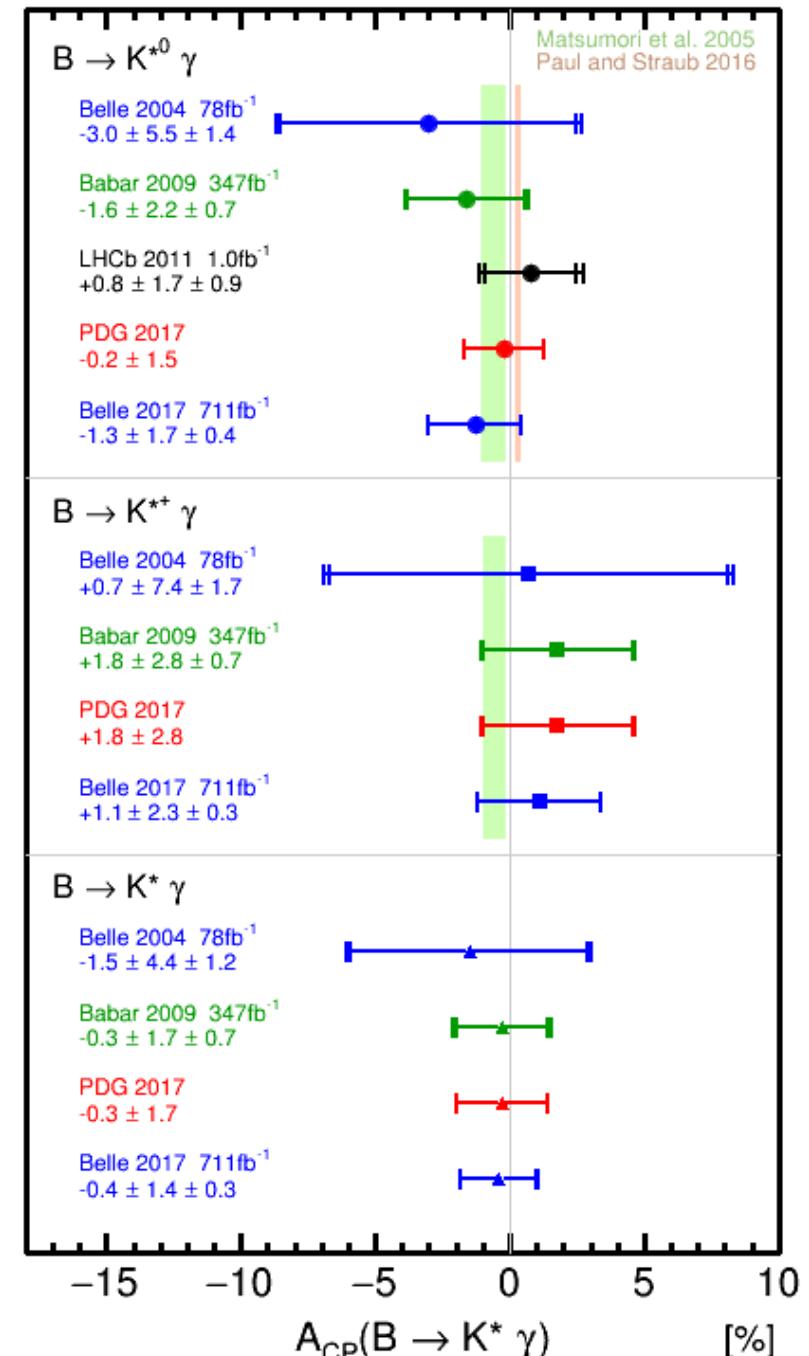
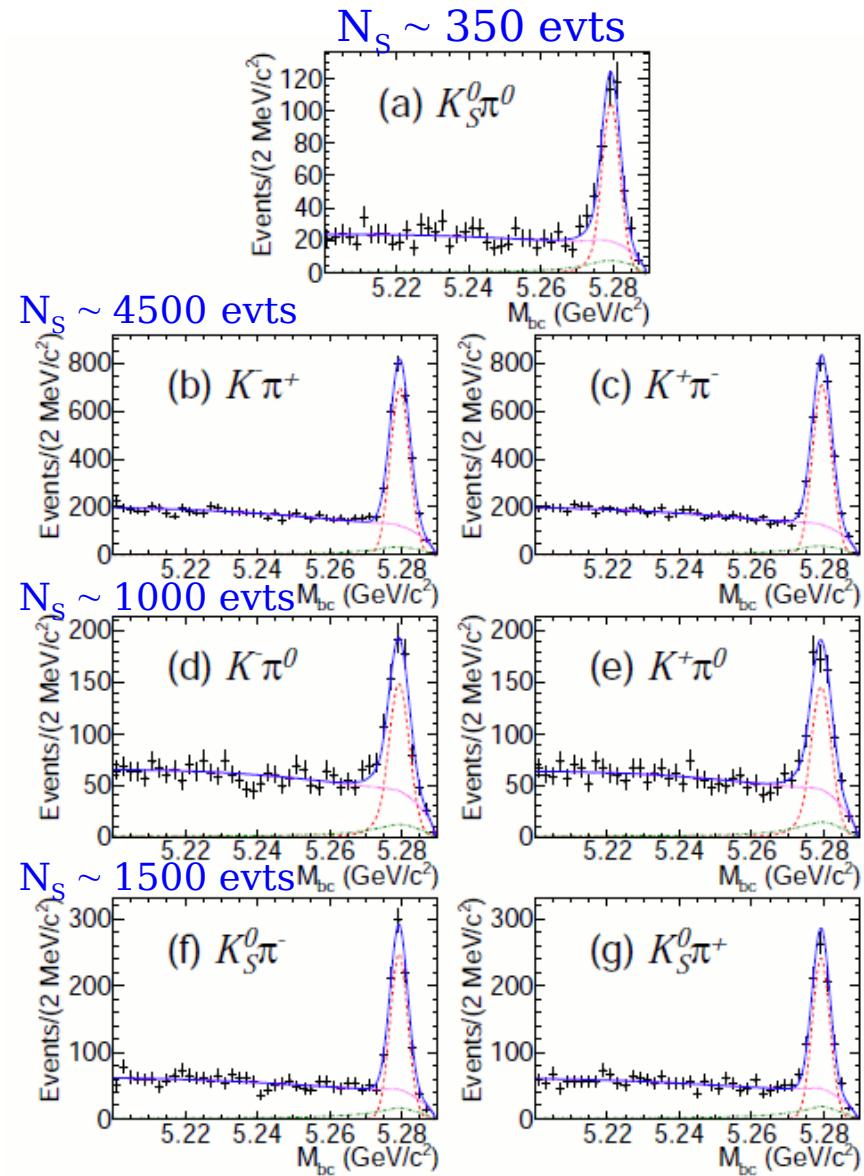


**but uncertainty in the hadronization process limits the ability to predict individual exclusive rates from first principles of the theory**

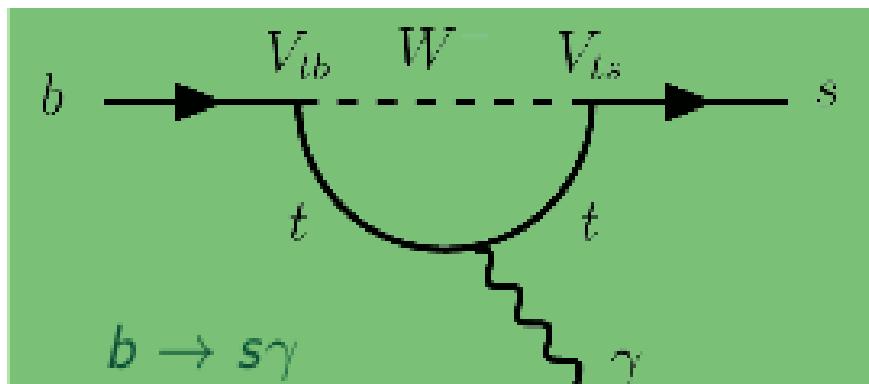
# B $\rightarrow$ K $^*$ $\gamma$ measurements

simultaneous fit of 4 final states

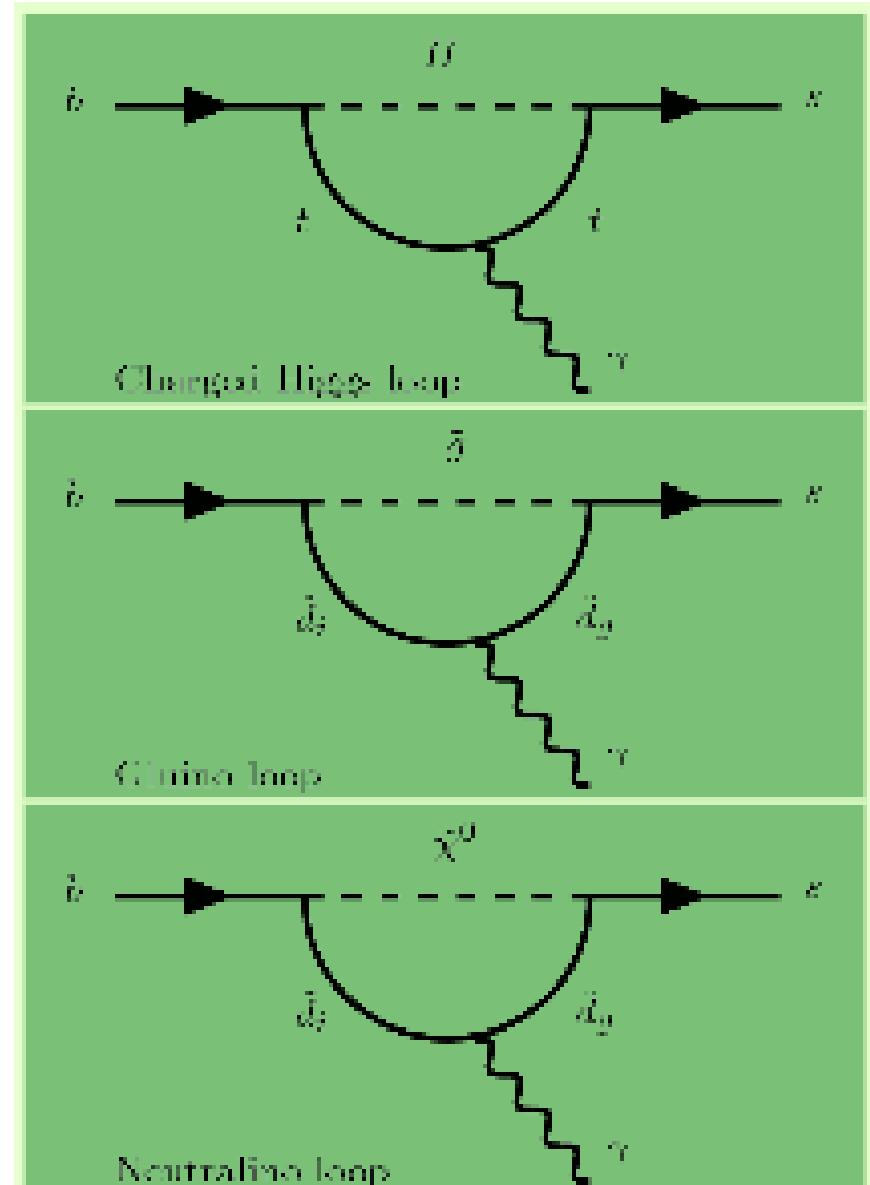
$\Rightarrow$  extraction of BFs,  $\Delta_{0+}$ ,  $A_{CP}$ ,  $\Delta A_{CP} \dots$



# $b \rightarrow s \gamma$



- Amplitude  $\propto V_{ts} |C_7|$
- First penguin ever observed (93)
- Experiment:  
 $B \simeq 3 \cdot 10^{-4}$
- SM:  $B = (3.36 \pm 0.23) \cdot 10^{-4}$   
[ Misiak et al., hep-ph/0609232 ]  
⇒ [ Misiak et al, arXiv:1503.01789 ]
- Strong constraint on New Physics



## exclusive vs inclusive

easier experimentally  
difficult theoretically

difficult experimentally  
easier theoretically (closer to  $b \rightarrow s\gamma$ )

# $b \rightarrow s\gamma$ SM branching fraction

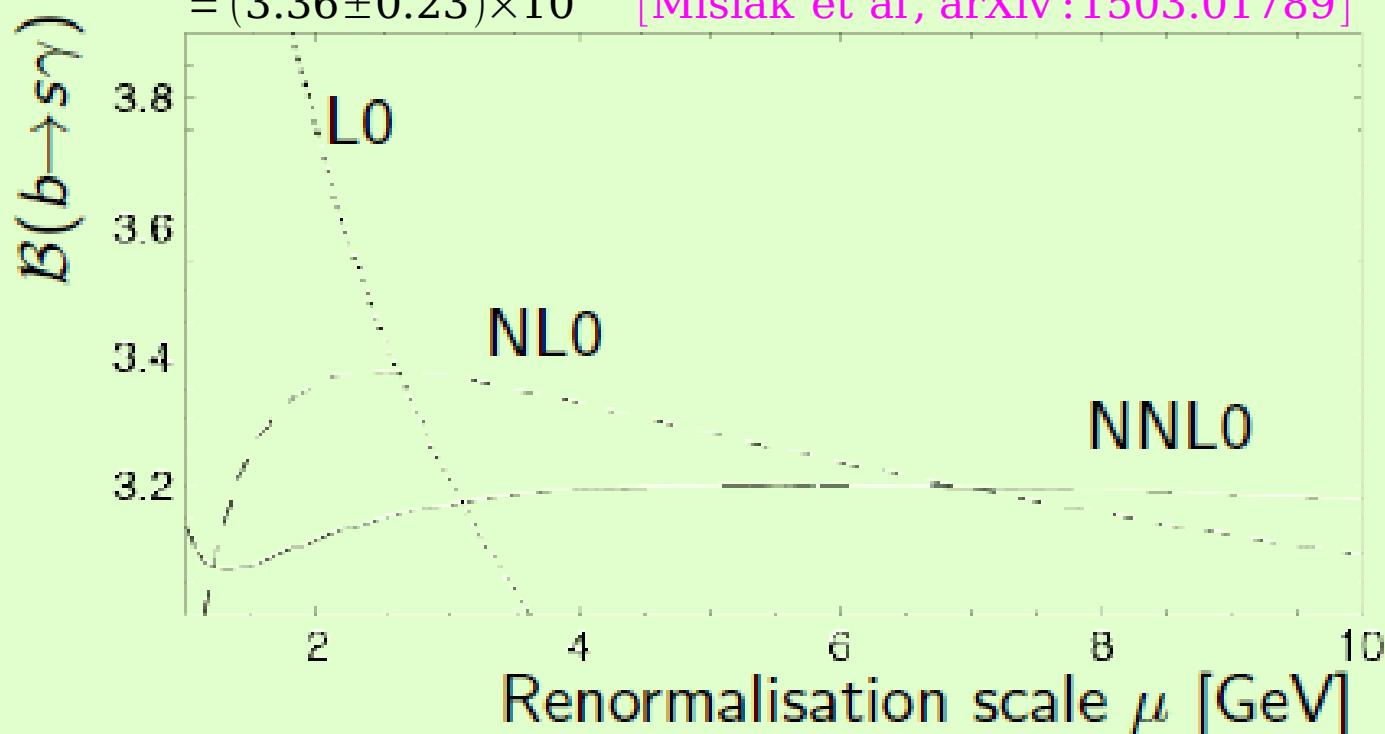
[Misiak et al, PRL 98, 02202, 2007]

- From effective Hamiltonian one gets the BF
- Uncertainties due to  $m_b$  and  $m_c$ : normalise to  $b \rightarrow ce\nu$  and  $b \rightarrow ue\nu$  [Misiak & Steinhauser, NPB 764:62, 2007]
- $b \rightarrow s\gamma$  branching fraction calculated at all NNLO orders in 2006

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

$= (3.36 \pm 0.23) \times 10^{-4}$  [Misiak et al, arXiv:1503.01789]

✓ BF very stable  
versus  $\mu$



# How to estimate the branching fraction $b \rightarrow s \gamma$ ?

## Semi-inclusive (sum-of-exclusive)

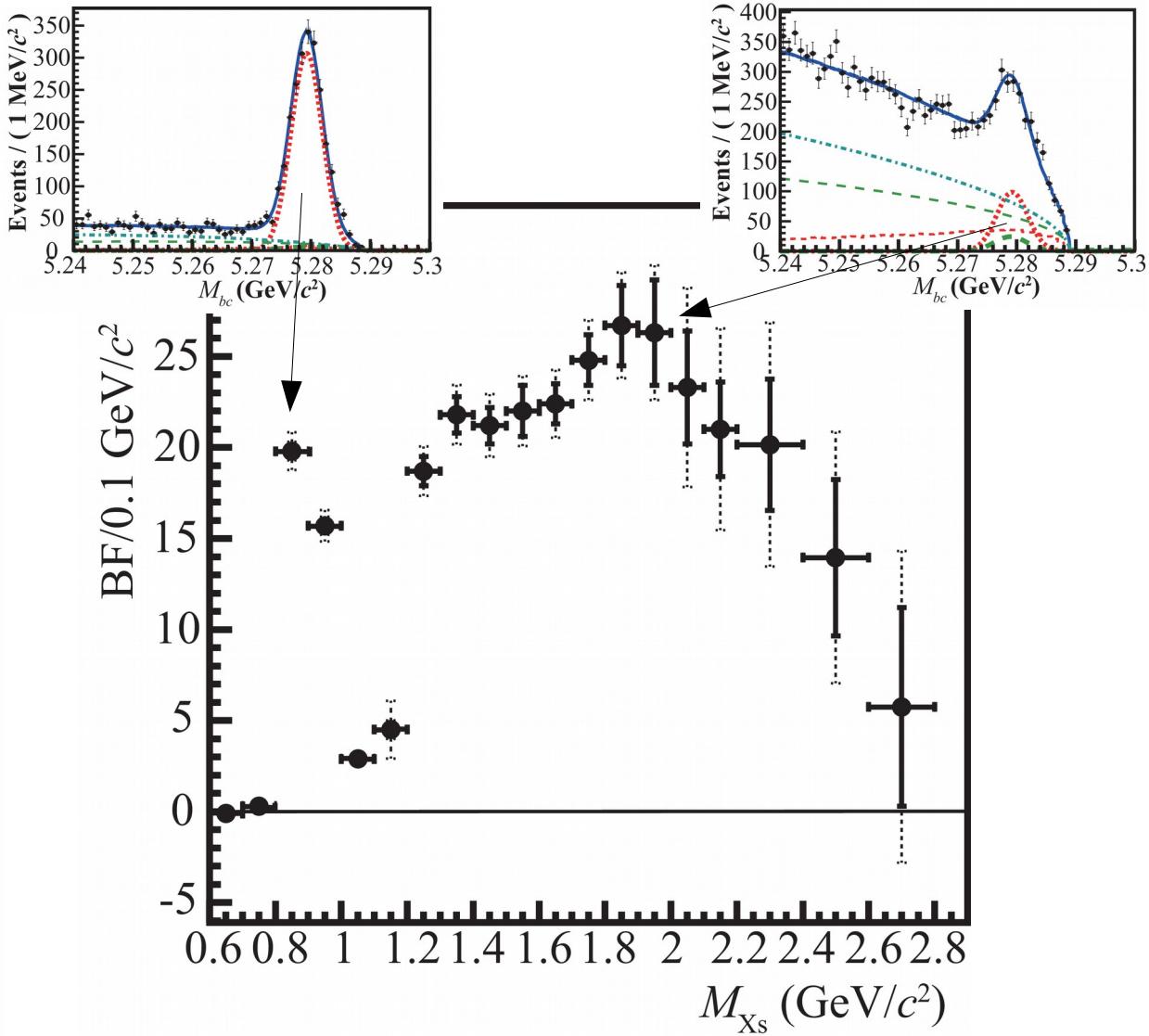


[772 MBB]  
[\[arXiv:1411.7198\]](https://arxiv.org/abs/1411.7198)

38 modes

$M_{X_s} < 2.8 \text{ GeV}/c^2$ ,  $E^* > 1.9 \text{ GeV}$

Mode ID	Final State	Mode ID	Final State
1	$K^+ \pi^-$	20	$K_S^0 \pi^+ \pi^0 \pi^0$
2	$K_S^0 \pi^+$	21	$K^+ \pi^+ \pi^- \pi^0 \pi^0$
3	$K^+ \pi^0$	22	$K_S^0 \pi^+ \pi^- \pi^0 \pi^0$
4	$K_S^0 \pi^0$	23	$K^+ \eta$
5	$K^+ \pi^+ \pi^-$	24	$K_S^0 \eta$
6	$K_S^0 \pi^+ \pi^-$	25	$K^+ \eta \pi^-$
7	$K^+ \pi^- \pi^0$	26	$K_S^0 \eta \pi^+$
8	$K_S^0 \pi^+ \pi^0$	27	$K^+ \eta \pi^0$
9	$K^+ \pi^+ \pi^- \pi^-$	28	$K_S^0 \eta \pi^0$
10	$K_S^0 \pi^+ \pi^+ \pi^-$	29	$K^+ \eta \pi^+ \pi^-$
11	$K^+ \pi^+ \pi^- \pi^0$	30	$K_S^0 \eta \pi^+ \pi^-$
12	$K_S^0 \pi^+ \pi^- \pi^0$	31	$K^+ \eta \pi^- \pi^0$
13	$K^+ \pi^+ \pi^+ \pi^- \pi^-$	32	$K_S^0 \eta \pi^+ \pi^0$
14	$K_S^0 \pi^+ \pi^+ \pi^- \pi^-$	33	$K^+ K^+ K^-$
15	$K^+ \pi^+ \pi^- \pi^- \pi^0$	34	$K^+ K^- K_S^0$
16	$K_S^0 \pi^+ \pi^+ \pi^- \pi^0$	35	$K^+ K^+ K^- \pi^-$
17	$K^+ \pi^0 \pi^0$	36	$K^+ K^- K_S^0 \pi^+$
18	$K_S^0 \pi^0 \pi^0$	37	$K^+ K^+ K^- \pi^0$
19	$K^+ \pi^- \pi^0 \pi^0$	38	$K^+ K^- K_S^0 \pi^0$



# Semi-inclusive (sum-of-exclusive)

38 modes

$M_{X_s} < 2.8 \text{ GeV}/c^2$ ,  $E^* > 1.9 \text{ GeV}$

**possible but large systematics  
(difficult to estimate/trust)**

Mode ID	Final State	Mode ID	Final State
1	$K^+\pi^-$	20	$K_S^0\pi^+\pi^0\pi^0$
2	$K_S^0\pi^+$	21	$K^+\pi^+\pi^-\pi^0\pi^0$
3	$K^+\pi^0$	22	$K_S^0\pi^+\pi^-\pi^0\pi^0$
4	$K_S^0\pi^0$	23	$K^+\eta$
5	$K^+\pi^+\pi^-$	24	$K_S^0\eta$
6	$K_S^0\pi^+\pi^-$	25	$K^+\eta\pi^-$
7	$K^+\pi^-\pi^0$	26	$K_S^0\eta\pi^+$
8	$K_S^0\pi^+\pi^0$	27	$K^+\eta\pi^0$
9	$K^+\pi^+\pi^-\pi^-$	28	$K_S^0\eta\pi^0$
10	$K_S^0\pi^+\pi^+\pi^-$	29	$K^+\eta\pi^+\pi^-$
11	$K^+\pi^+\pi^-\pi^0$	30	$K_S^0\eta\pi^+\pi^-$
12	$K_S^0\pi^+\pi^-\pi^0$	31	$K^+\eta\pi^-\pi^0$
13	$K^+\pi^+\pi^+\pi^-$	32	$K_S^0\eta\pi^+\pi^0$
14	$K_S^0\pi^+\pi^+\pi^-\pi^-$	33	$K^+K^+K^-$
15	$K^+\pi^+\pi^-\pi^-\pi^0$	34	$K^+K^-K_S^0$
16	$K_S^0\pi^+\pi^+\pi^-\pi^0$	35	$K^+K^+K^-\pi^-$
17	$K^+\pi^0\pi^0$	36	$K^+K^-K_S^0\pi^+$
18	$K_S^0\pi^0\pi^0$	37	$K^+K^+K^-\pi^0$
19	$K^+\pi^-\pi^0\pi^0$	38	$K^+K^-K_S^0\pi^0$

Mode Category	Definition	Mode ID	Data
1	$K\pi$ without $\pi^0$	1,2	$4.2 \pm 0.4$
2	$K\pi$ with $\pi^0$	3,4	$2.1 \pm 0.2$
3	$K2\pi$ without $\pi^0$	5,6	$14.5 \pm 0.5$
4	$K2\pi$ with $\pi^0$	7,8	$24.0 \pm 0.7$
5	$K3\pi$ without $\pi^0$	9,10	$8.3 \pm 0.8$
6	$K3\pi$ with $\pi^0$	11,12	$16.1 \pm 1.8$
7	$K4\pi$	13-16	$11.1 \pm 2.8$
8	$K2\pi^0$	17-22	$14.4 \pm 3.5$
9	$K\eta$	23-32	$3.2 \pm 0.8$
10	$3K$	33-38	$2.0 \pm 0.3$



[772 MBB]

[arXiv: 1411.7198]

(for  $E_\gamma^* > 1.9 \text{ GeV}$ )



[471 MBB]

[arXiv: 1207.2520]

$$\left\{ \begin{array}{l} \mathbf{B(B \rightarrow X_s \gamma) = (3.51 \pm 0.17 \pm 0.33) \times 10^{-4}} \\ \mathbf{B(B \rightarrow X_s \gamma) = (3.29 \pm 0.19 \pm 0.48) \times 10^{-4}} \end{array} \right.$$

13

[syst: cross-feed, peaking BG,  $X_s$  fragmentation]

# $B \rightarrow X_s \gamma$ spectrum

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

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

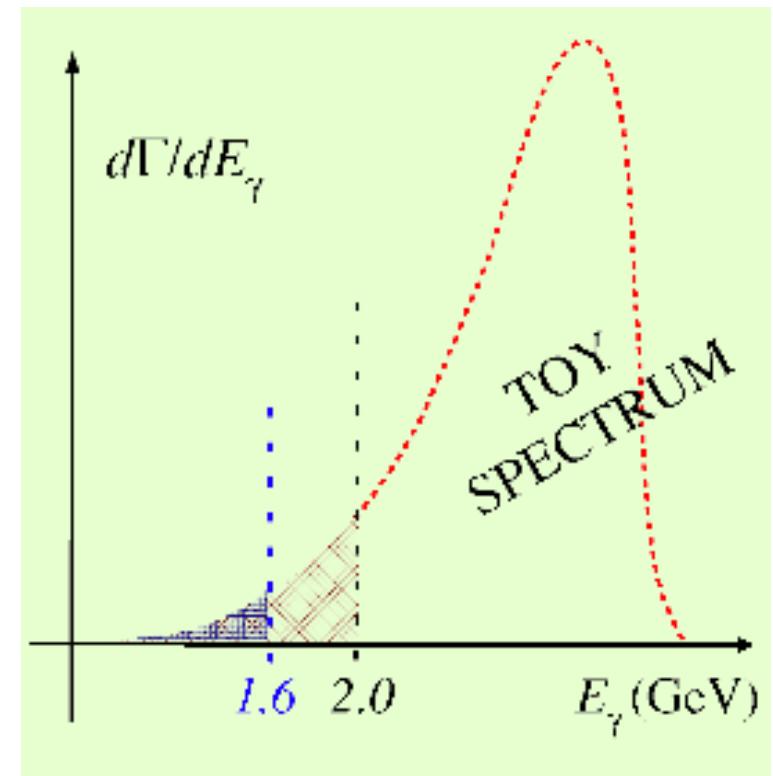
- But we measure  $B \rightarrow X_s \gamma$  and in the B meson, the b quark is moving which smears the energy spectrum

→ Mean  $\sim \frac{m_B}{2}$

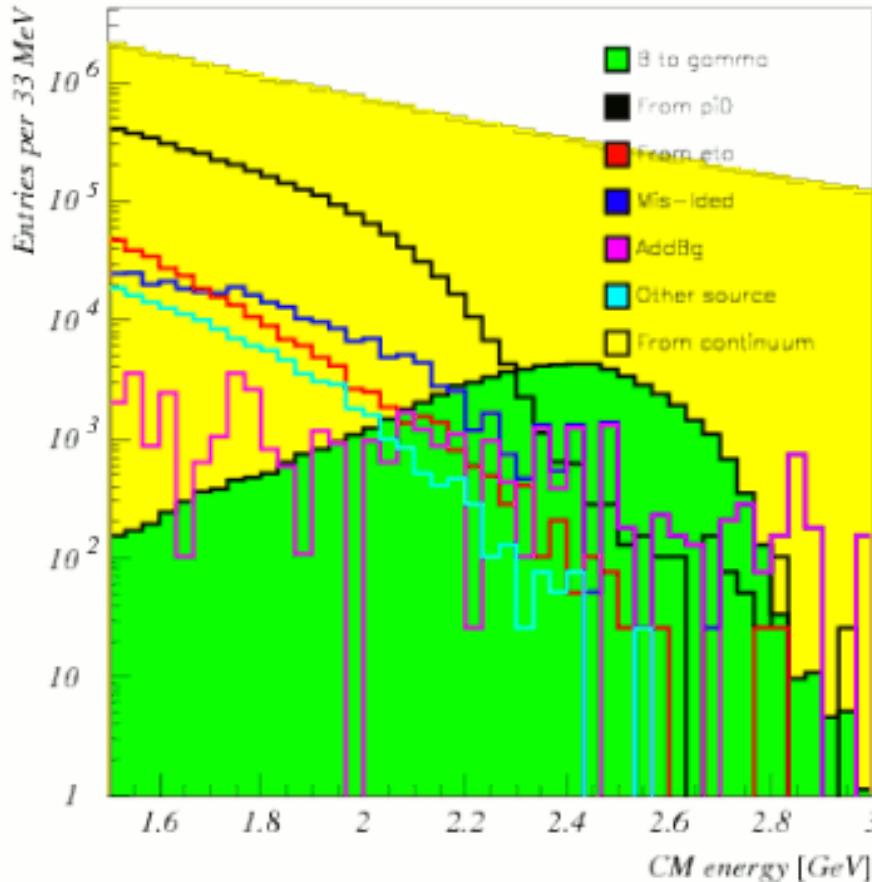
→ Width  $\sim$  Fermi motion in B meson

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

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



# b $\rightarrow$ s $\gamma$ spectrum at Belle



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

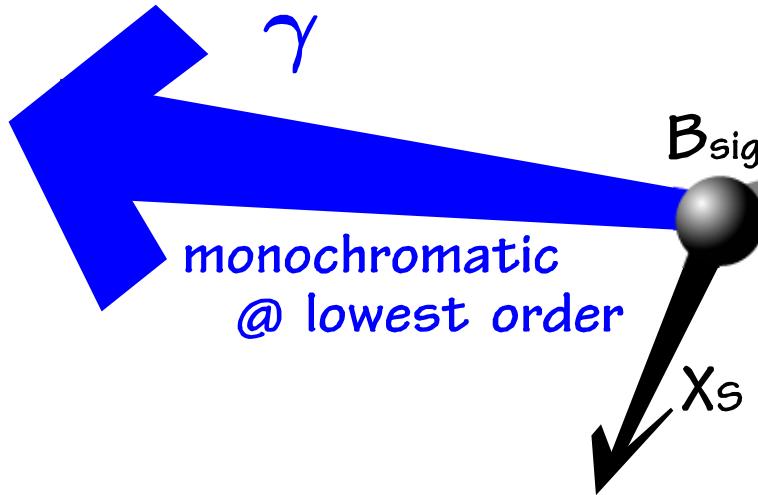
- Be unbiased: only look at the  $\gamma$
  - B mesons only decay to  $\gamma$  via  $b \rightarrow s \gamma$
  - But there are indirect  $\gamma$  from  $\pi^0$  and  $\eta$  in  $B\bar{B}$  events
  - ... and a lot more indirect  $\pi^0$  and  $\eta$  in non- $B\bar{B}$  events
- ⇒ Lots of background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

# $b \rightarrow s \gamma$ spectrum at Belle

inclusive  $B \rightarrow X_s \gamma$  measurement

untagged

lepton tag: background suppression , low stat



high  $P$  lepton  
 $1.26 \text{ GeV} < E_l < 2.20 \text{ GeV}$

Example with data sets

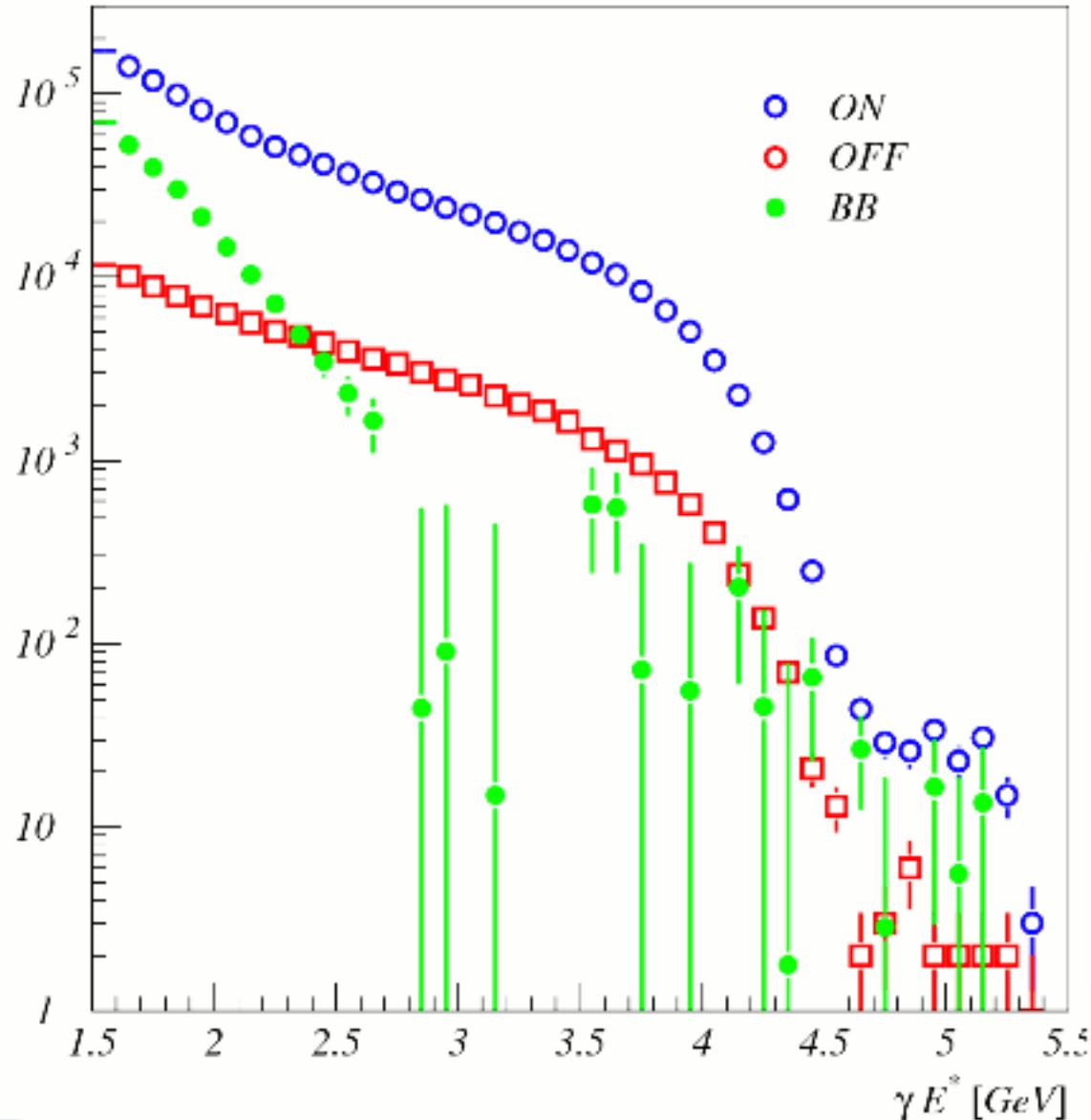
- $140 \text{ fb}^{-1}$  ON-resonance
- $15 \text{ fb}^{-1}$  OFF-resonance

Event selection:

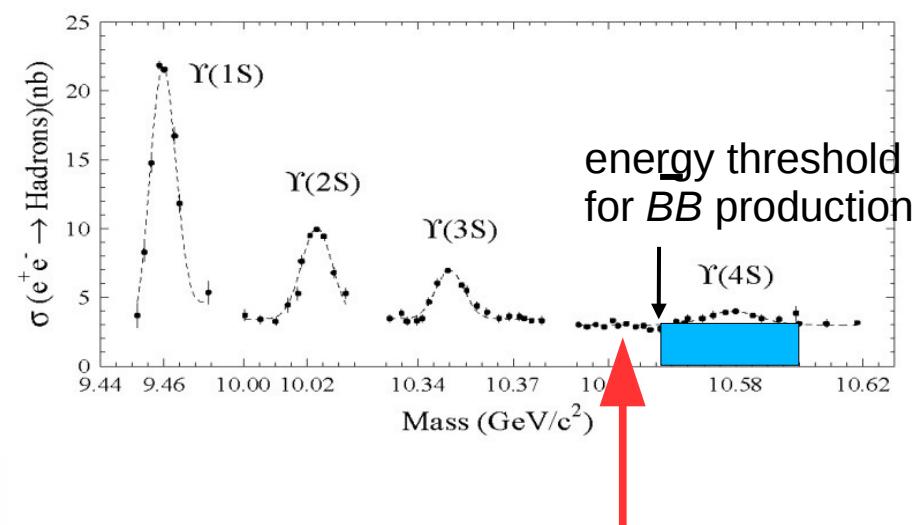
- No kinematic constraints
- Only a high energy photon measured in  $Y(4S)$  rest frame
- Lower  $E_\gamma$  threshold (1.7 GeV)

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

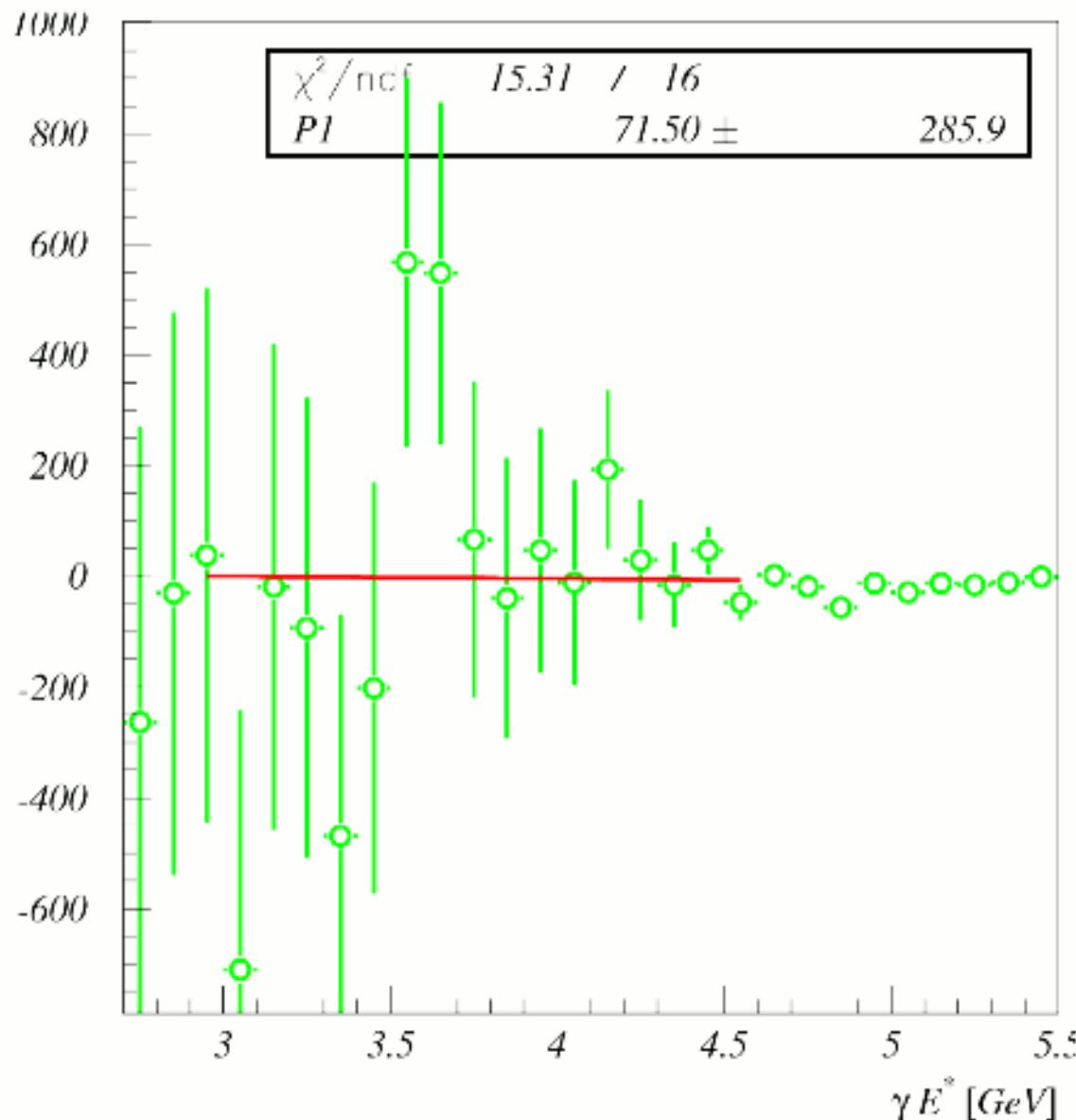
# The spectrum



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



# The spectrum



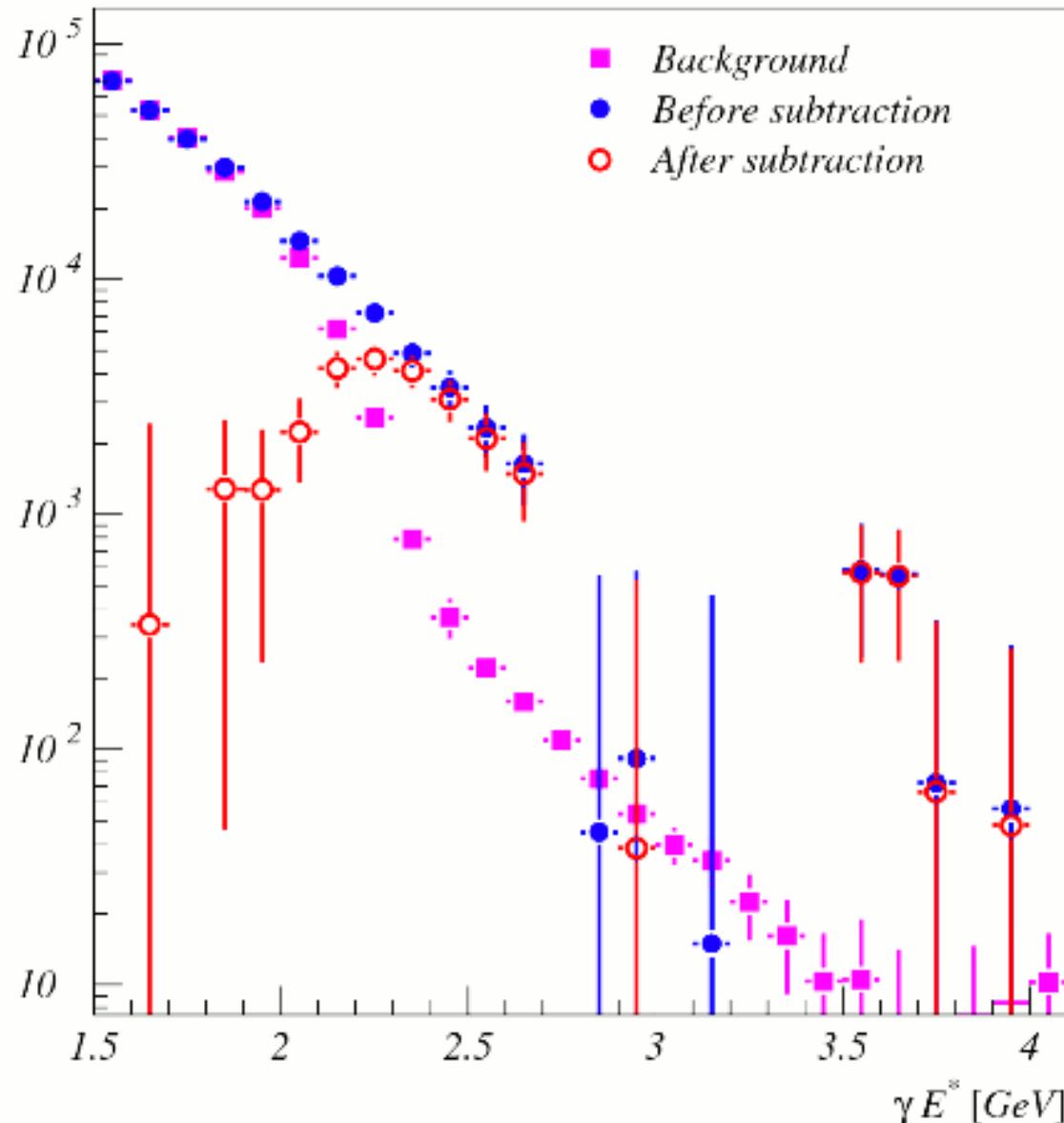
Endpoint check :

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

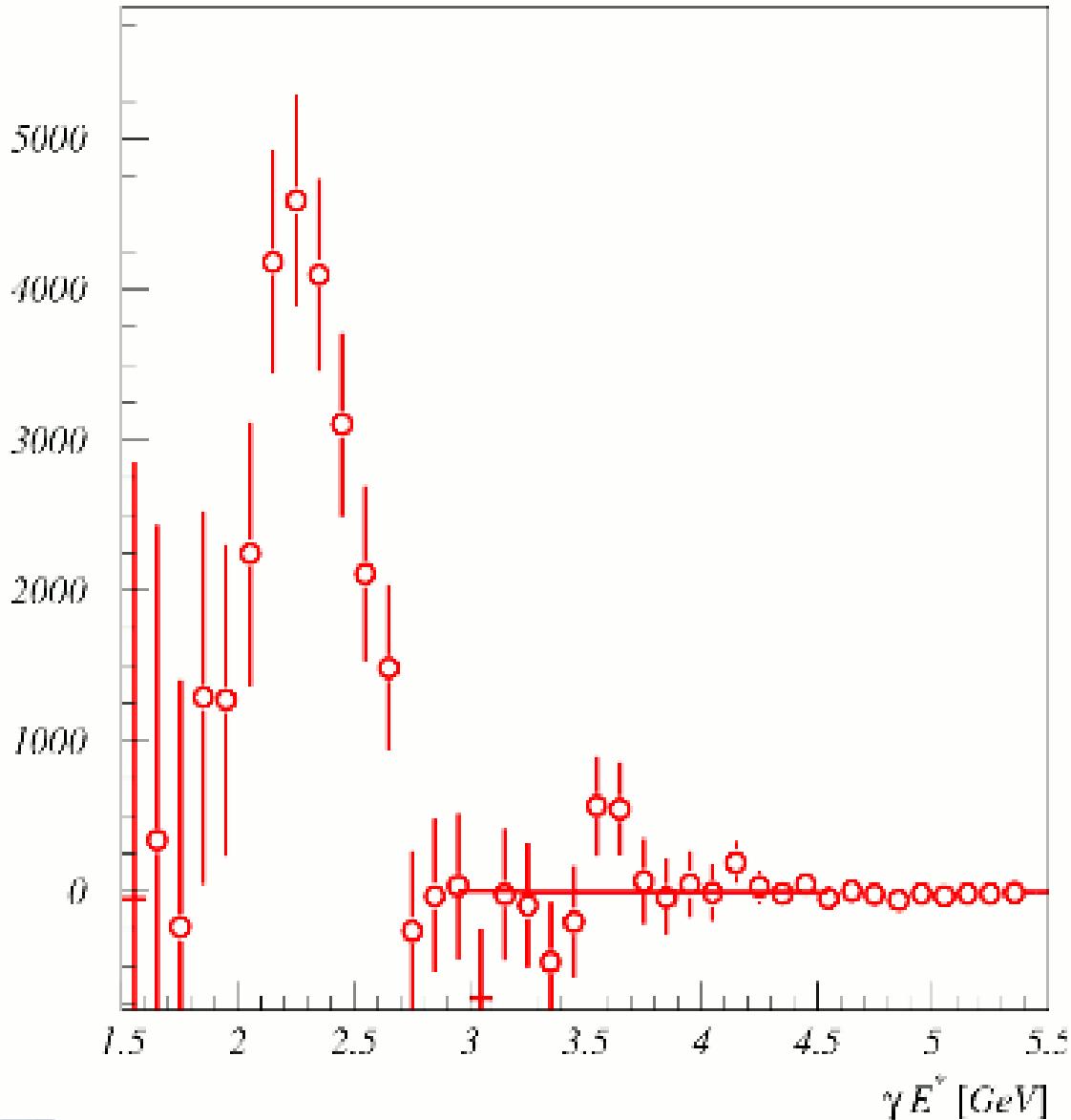
# The spectrum



$B\bar{B}$  subtraction :

Using measured  $\pi^0$  and  $\eta$  spectra and some efficiency - corrected MC.

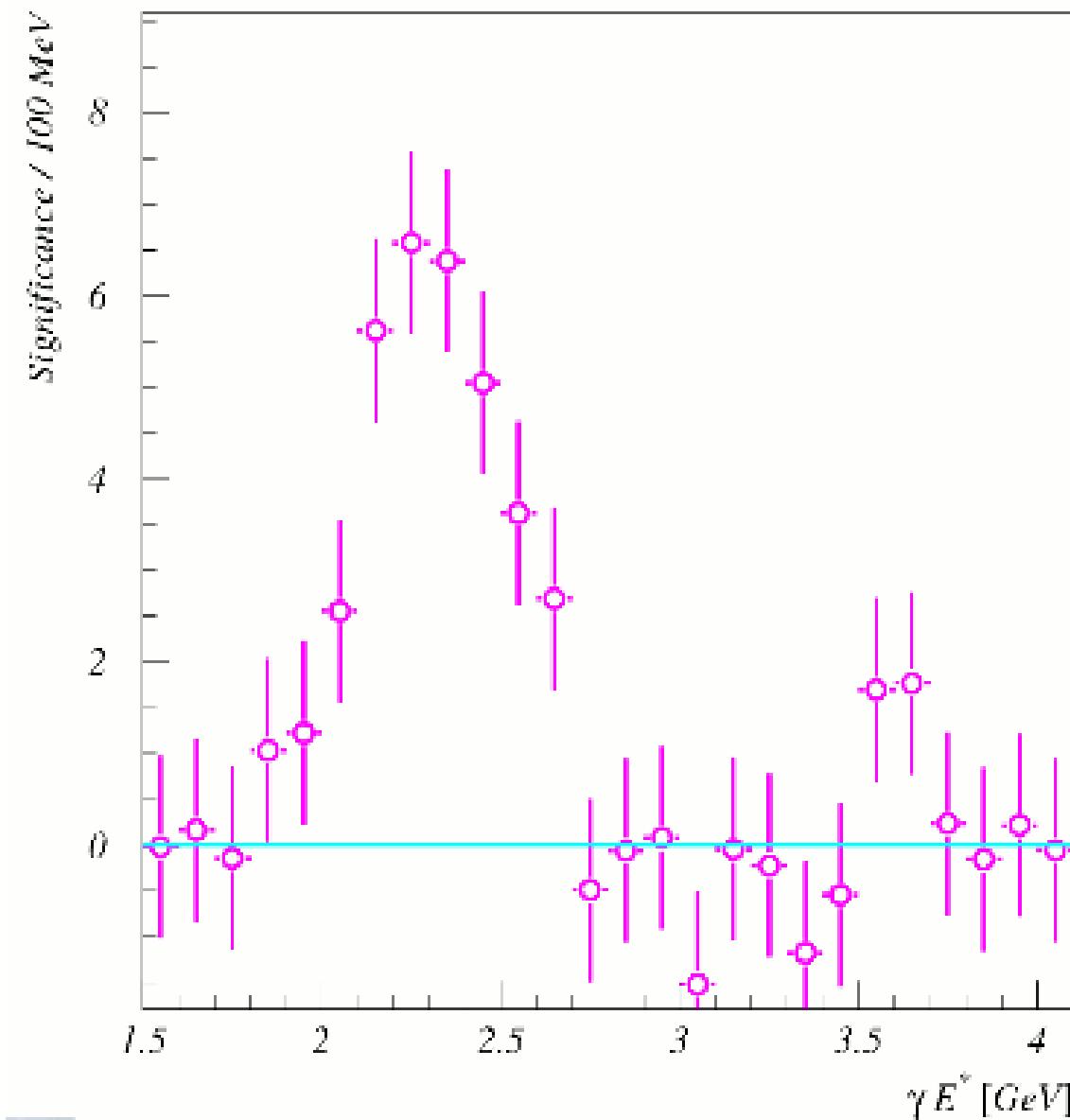
# The spectrum



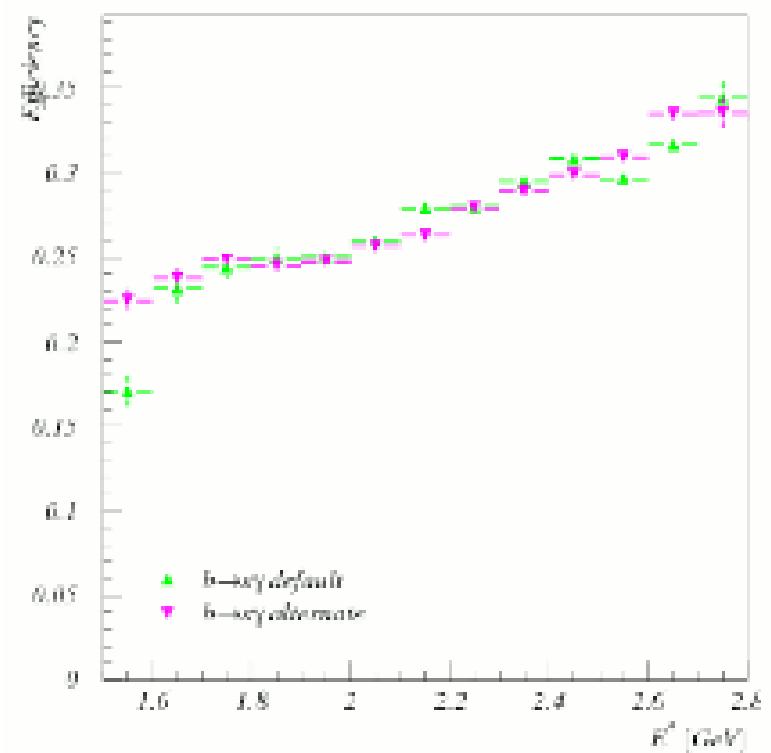
Raw spectrum after all cuts and background corrections

Signal yield:  
 $24100 \pm 2200$  events

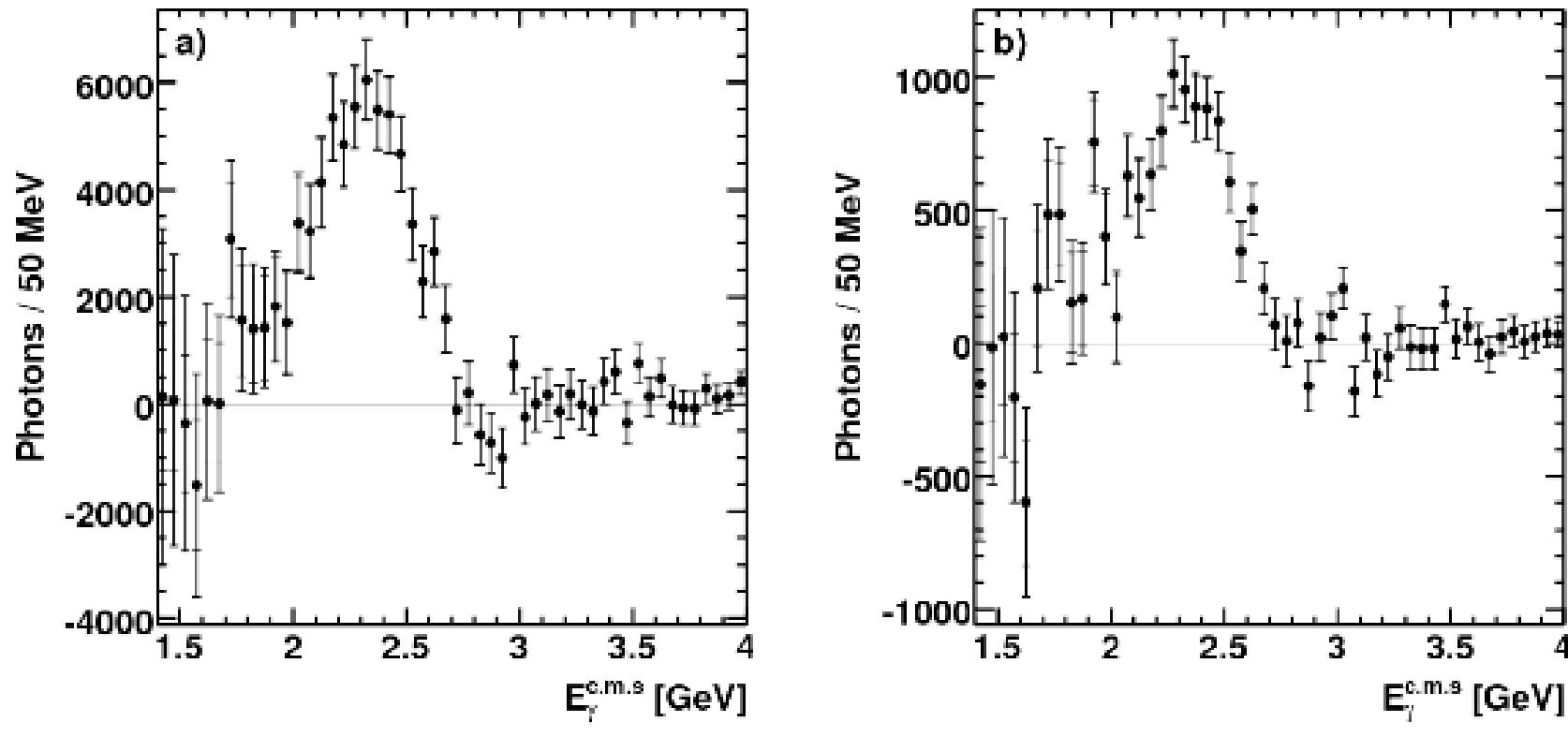
# The spectrum



Efficiency corrected  
spectrum



Lower  $E_\gamma$  threshold (1.7 GeV)  $\Rightarrow$  97% of the spectrum !



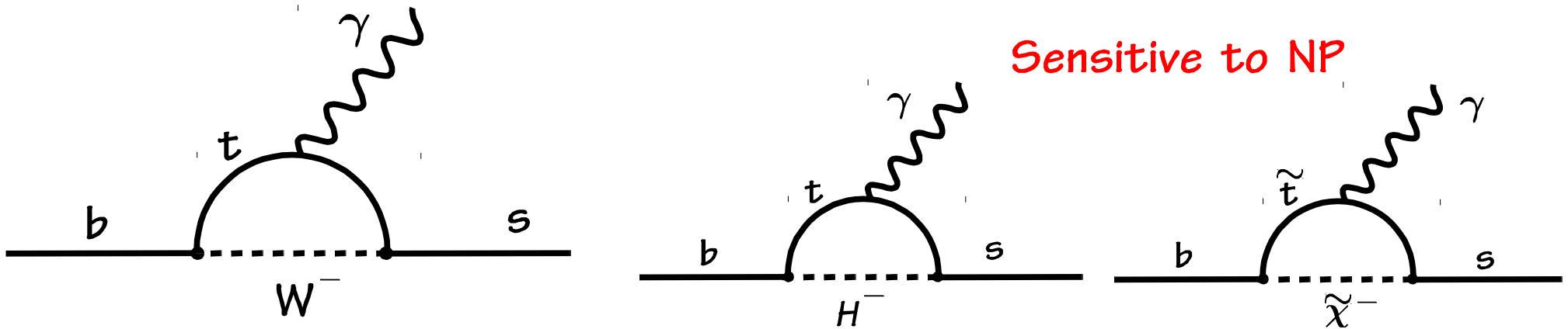
$$B(B \rightarrow X_s \gamma) = (3.45 \pm 0.15 \pm 0.40) \times 10^{-4} \quad (\text{for } E_\gamma^* > 1.7 \text{ GeV})$$

$$B(B \rightarrow X_s \gamma) = (3.21 \pm 0.15 \pm 0.29 \pm 0.08) \times 10^{-4} \quad (\text{for } E_\gamma^* > 1.8 \text{ GeV})$$

$$B(B \rightarrow X_s \gamma) = (3.06 \pm 0.41 \pm 0.26) \times 10^{-4} \quad (\text{for } E_\gamma^* > 2.0 \text{ GeV})$$

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

# $B \rightarrow X_s \gamma$ as an illustration



NNLO SM calculation:

$$B_{SM}(B \rightarrow X_s \gamma) = (3.36 \pm 0.23) \times 10^{-4}$$

(for  $E_\gamma > 1.6$  GeV)

M. Misiak et al.

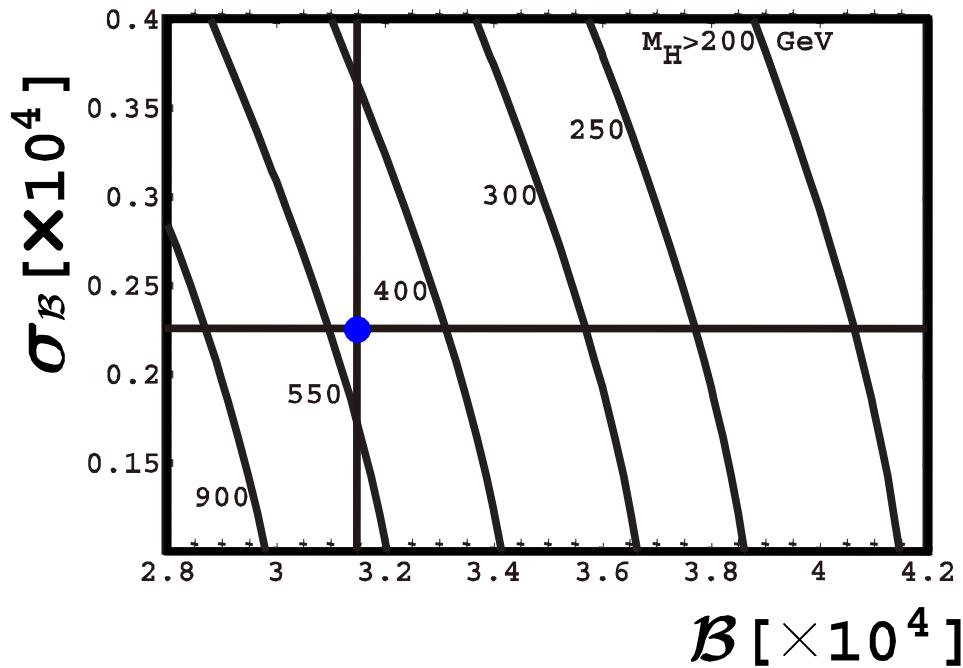
[arXiv:1503.01789]

(central value increased by 6.4% compared to 2007 value)

PRL 98, 022002 (2007)

The lower  $\gamma$  energy threshold, the smaller the model uncertainties in SM, but the larger background in measurement

Charged Higgs (2 HDM Type II) bound  
(up- and down-type quarks couple to separate doublets)



## $B \rightarrow X_s \gamma$

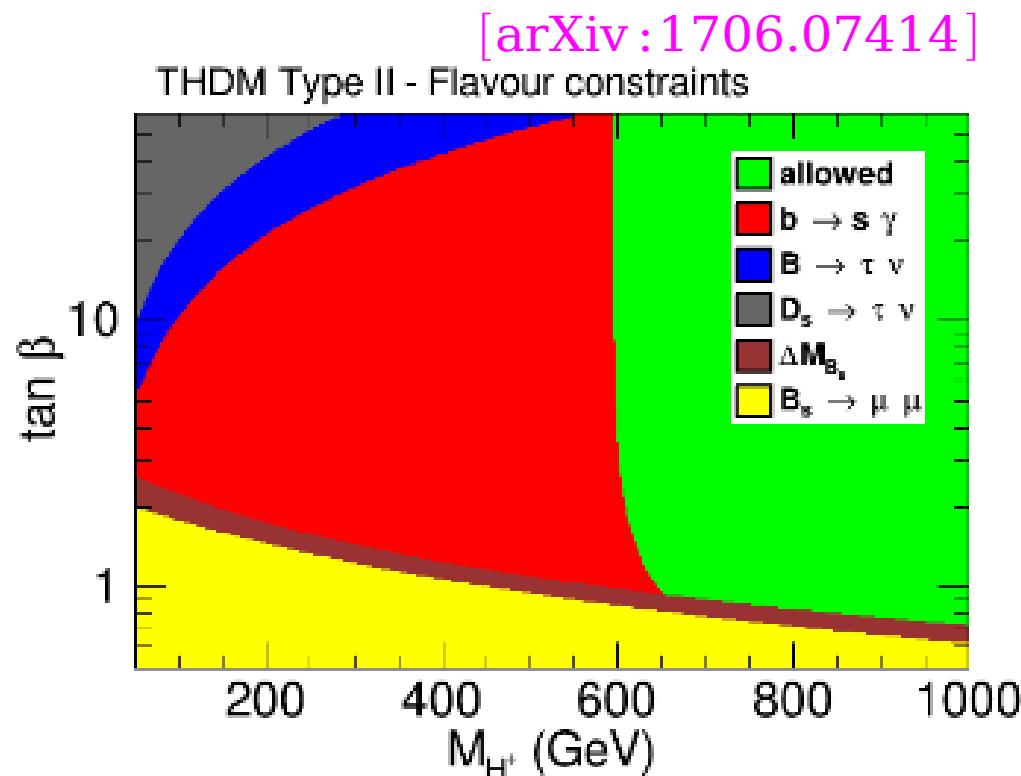
WA:  $B(B \rightarrow X_s \gamma) = (3.49 \pm 0.20) \times 10^{-4}$  (for  $E_\gamma > 1.6$  GeV)

vs

SM:  $B(B \rightarrow X_s \gamma) = (3.36 \pm 0.23) \times 10^{-4}$  (for  $E_\gamma > 1.6$  GeV)

[Misiak et al, arXiv:1503.01789]

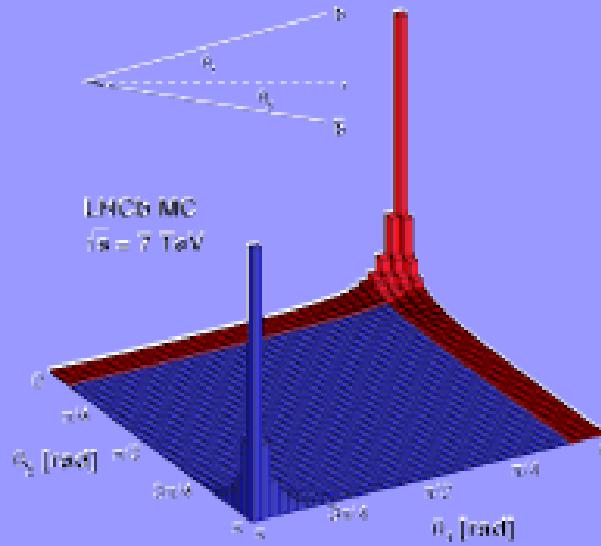
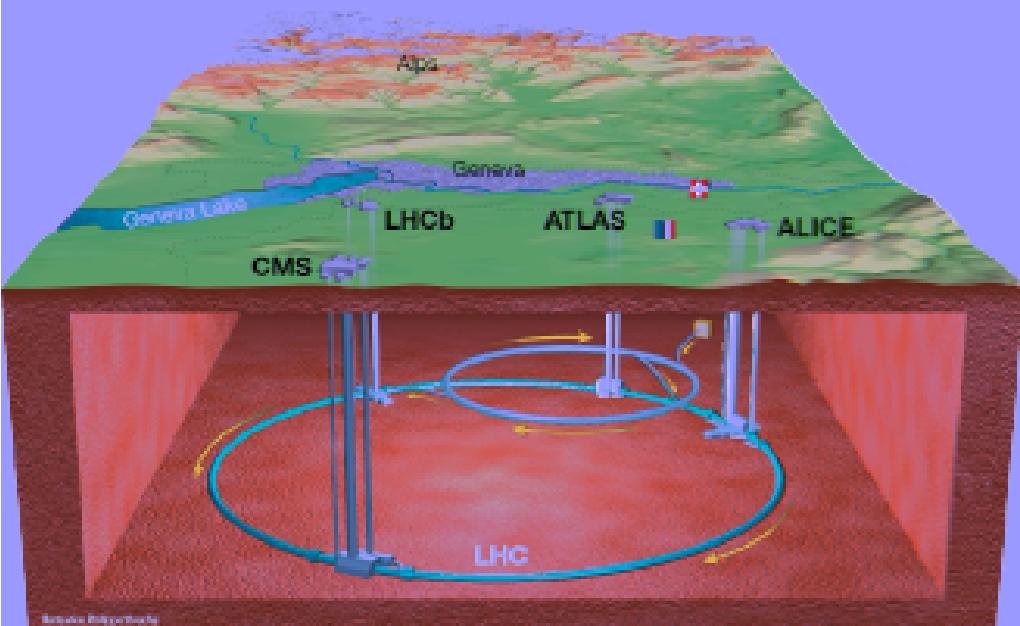
**Charged Higgs bound (2HDM TypeII):  $M_{H^+} > 400$  GeV @ 95% C.L.**



# Rare B decays at LHCb

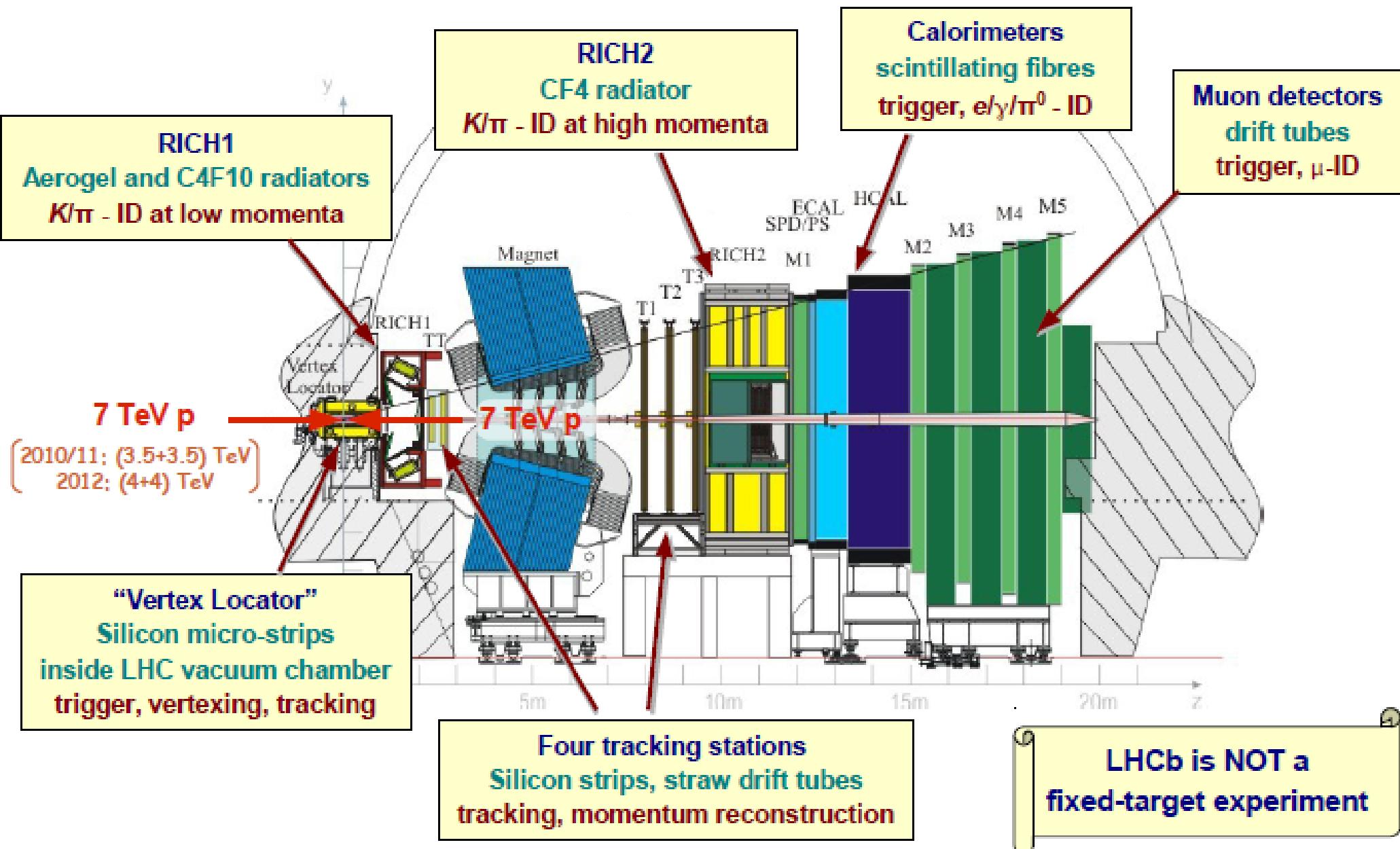
# LHCb is ...

- 1075 members, from 68 institutes in 17 countries (September 2014)
- Dedicated experiment for precision measurements of CP violation and rare decays
- *Beautiful, charming, strange physics* program



- $pp$  collisions at  $\sqrt{s} = 8(13) \text{ TeV}$  in RunI (RunII)
- $b\bar{b}$  quark pairs produced correlated in the forward region
- Luminosity of  $4 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$

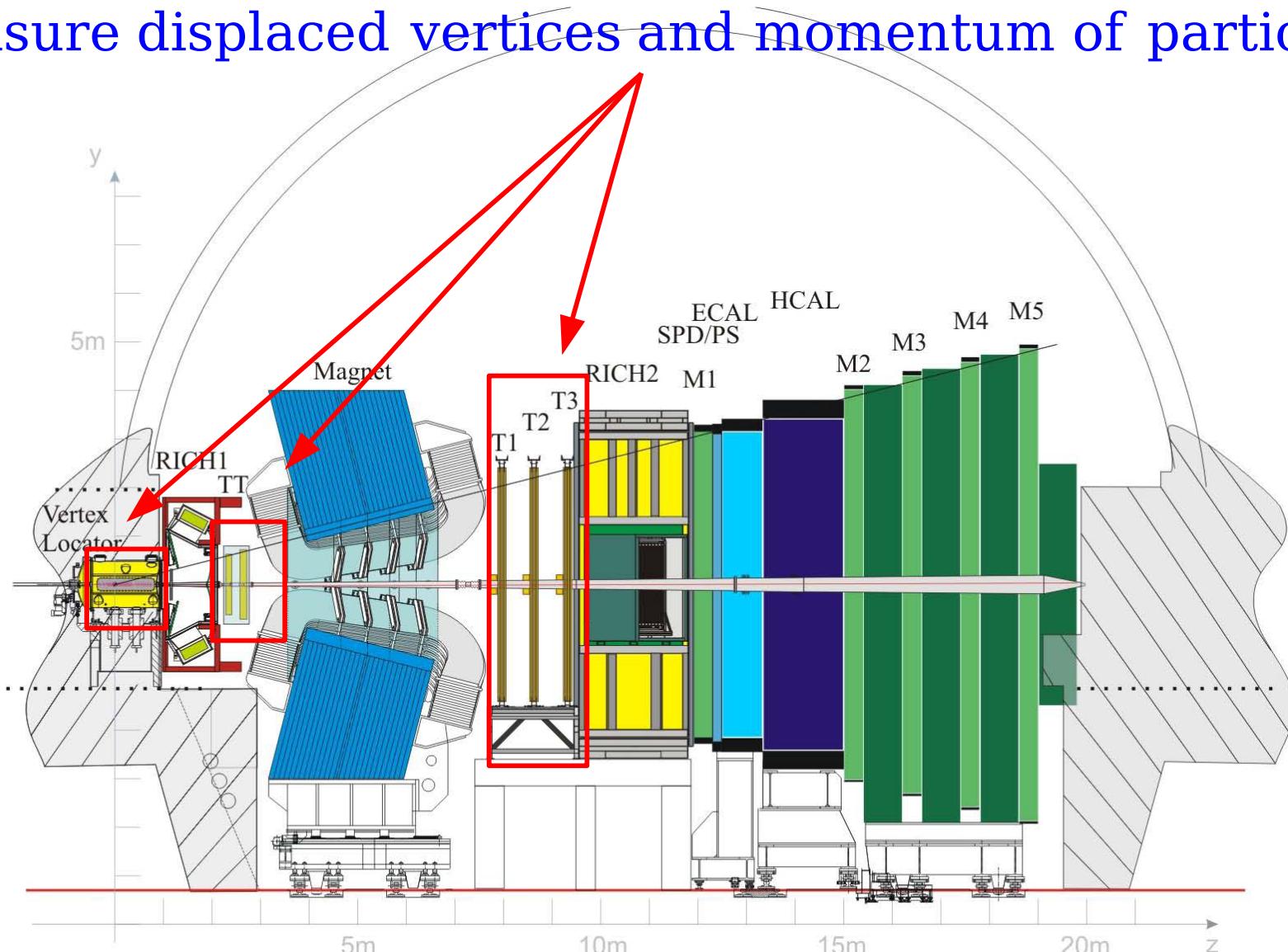
# LHCb



# LHCb

## Tracking system

Measure displaced vertices and momentum of particles



### Vertex and IP resolution

$\sigma(\text{IP}) \sim 24 \mu\text{m}$  at  $P_T = 2 \text{ GeV}/c$

$\sigma_{BV} \sim 16 \mu\text{m}$  in x, y

### Momentum resolution

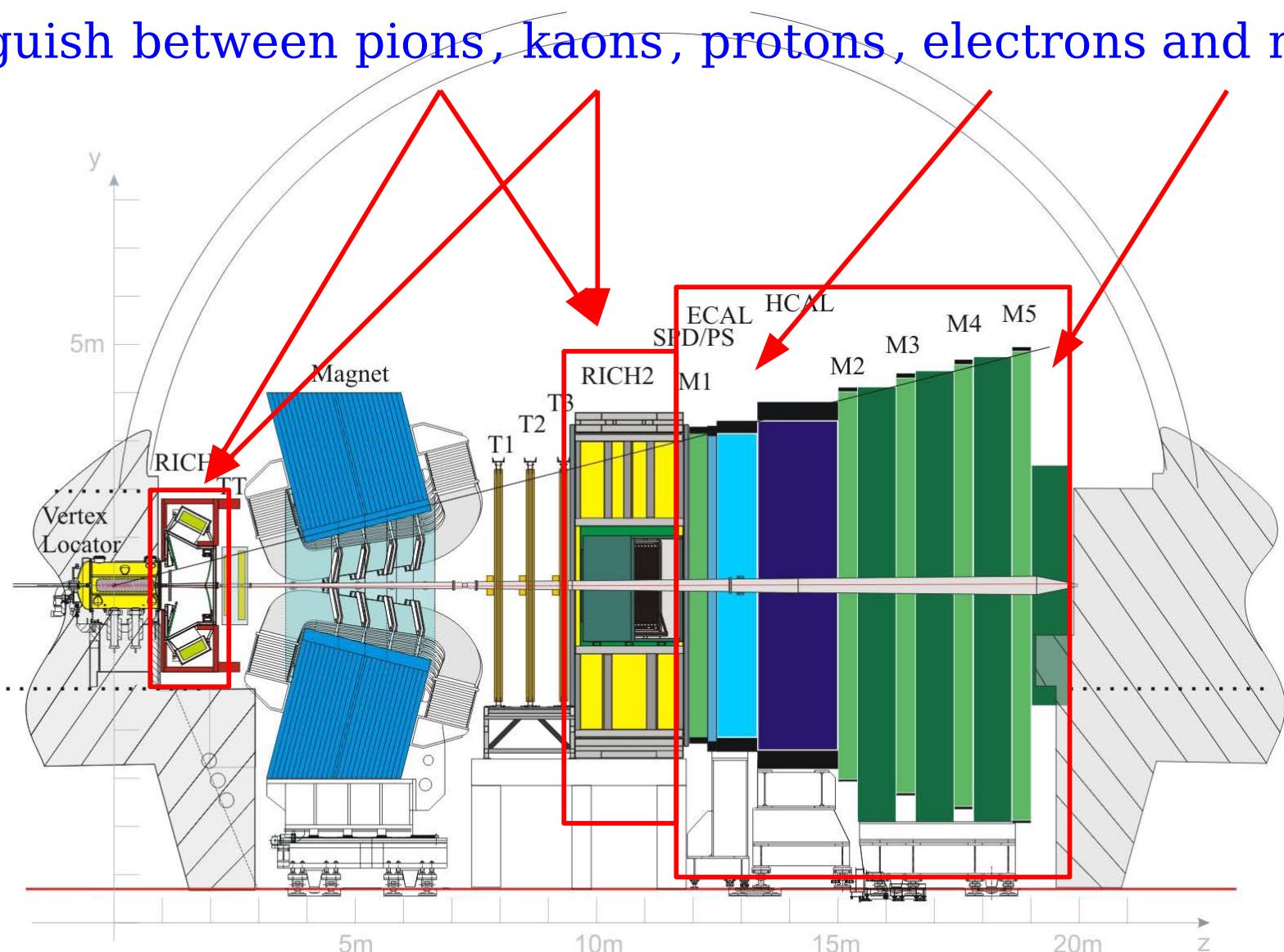
$\sigma(p)/p = 0.4\% - 0.6\%$  for  $p \in [0, 100] \text{ GeV}/c$

$\sigma(m_B) \sim 24 \text{ MeV}$  for two body decays

# LHCb

## Particle identification

Distinguish between pions, kaons, protons, electrons and muons



### Kaon identification

$\epsilon_K \sim 95\%$  ,  $\epsilon_{\pi \rightarrow K}$  few %

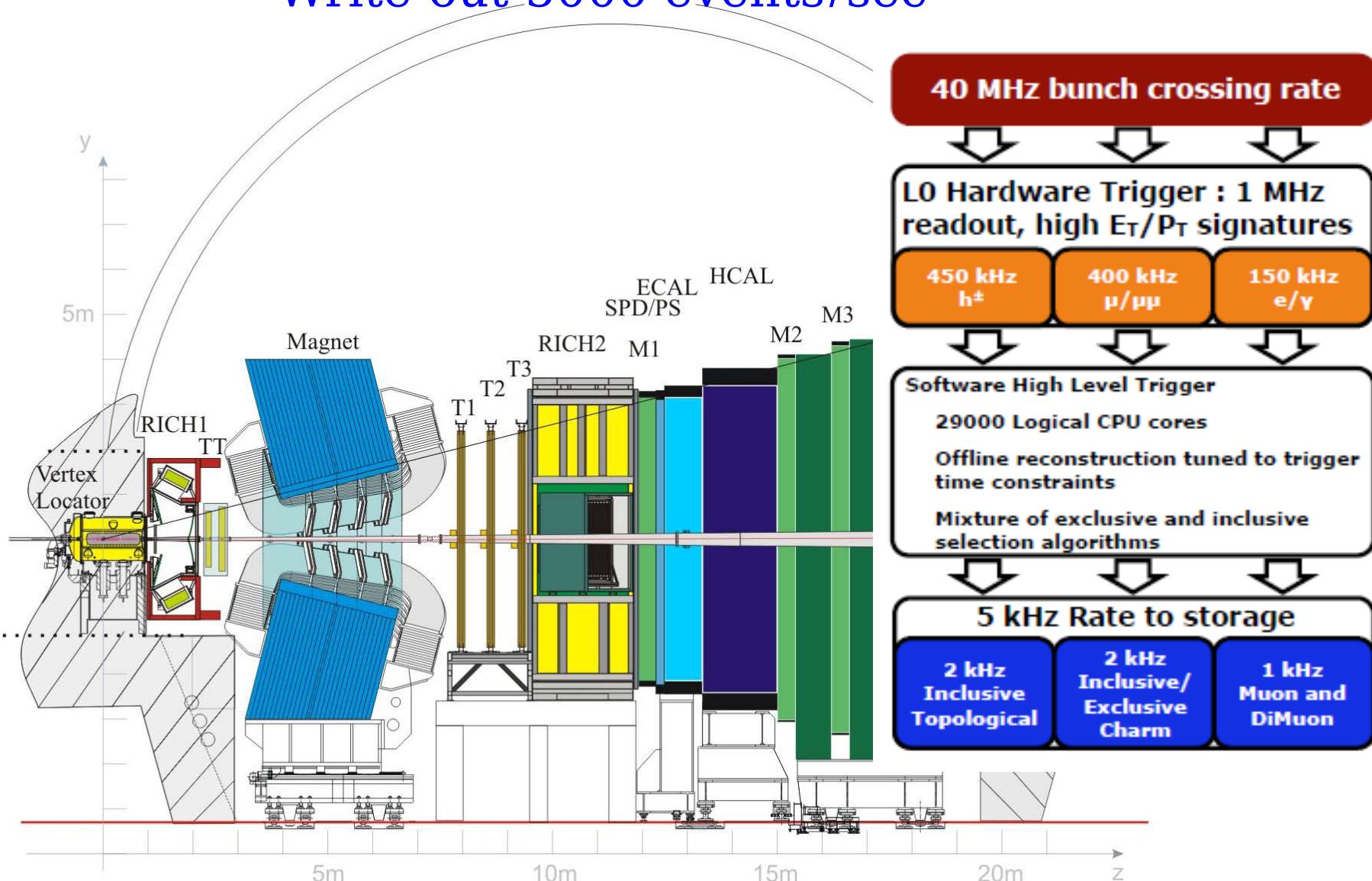
### Muon identification

$\epsilon_\mu = 98\%$  ,  $\epsilon_{\pi \rightarrow \mu} = 0.6\%$

# LHCb

## Trigger system

Write out 5000 events/sec



# Belle(II), LHCb side by side

## Belle(II)

$$e^+ e^- \rightarrow Y(4S) \rightarrow b\bar{b}$$

at  $Y(4S)$ : 2 B's ( $B^0$  or  $B^+$ ) and nothing else  $\Rightarrow$  clean events

(flavour tagging, B tagging, missing energy)

$$\sigma_{b\bar{b}} \sim 1 \text{ nb} \Rightarrow 1 \text{ fb}^{-1} \text{ produces } 10^6 B\bar{B}$$

$$\sigma_{b\bar{b}}/\sigma_{\text{total}} \sim 1/4$$

## LHCb

$$pp \rightarrow b\bar{b} X$$

production of  $B^+$ ,  $B^0$ ,  $B_s$ ,  $B_c$ ,  $\Lambda_b$ ...

but also a lot of other particles in the event

$\Rightarrow$  lower reconstruction efficiencies

$\sigma_{b\bar{b}}$  much higher than at the  $Y(4S)$

	$\sqrt{s}$ [GeV]	$\sigma_{b\bar{b}}$ [nb]	$\sigma_{b\bar{b}} / \sigma_{\text{tot}}$
HERA pA	42 GeV	~30	$\sim 10^{-6}$
Tevatron	2 TeV	5000	$\sim 10^{-3}$
LHC	8 TeV	$\sim 3 \times 10^5$	$\sim 5 \times 10^{-3}$
	14 TeV	$\sim 6 \times 10^5$	$\sim 10^{-2}$

**b $\bar{b}$  production cross-section at LHCb  $\sim 500,000 \times$  BaBar/Belle !!**

$\sigma_{b\bar{b}}/\sigma_{\text{total}}$  much lower than at the  $Y(4S)$

$\Rightarrow$  lower trigger efficiencies

**B mesons live relatively long**

mean decay length  $\beta\gamma c\tau \sim 200 \mu\text{m}$

**mean decay length  $\beta\gamma c\tau \sim 7 \text{ mm}$**

**data taking period(s)**

(displaced vertices)

$$[1999-2010] = 1 \text{ ab}^{-1}$$

$$[\text{run I: } 2010-2012] = 3 \text{ fb}^{-1},$$

$$[2019-\dots] = \dots$$

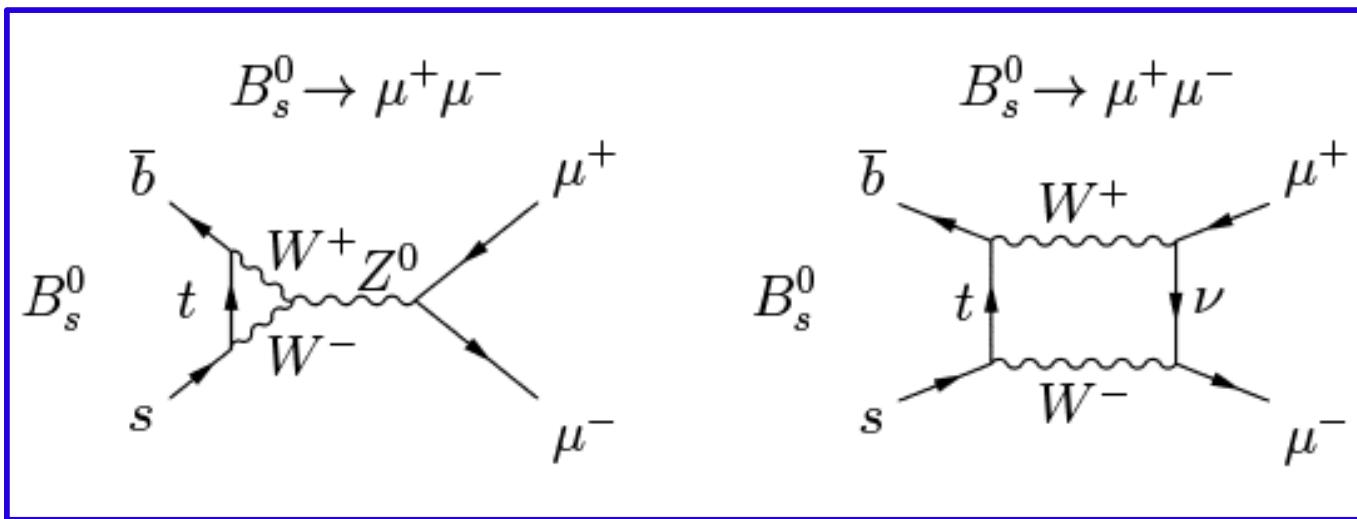
$$[\text{run II: } 2015-2018] = 6 \text{ fb}^{-1}$$

**(near) future**

$$[\text{Belle II from 2019}] \rightarrow 50 \text{ ab}^{-1}$$

# $B_{(s)} \rightarrow \mu\mu$ : ultra rare processes...

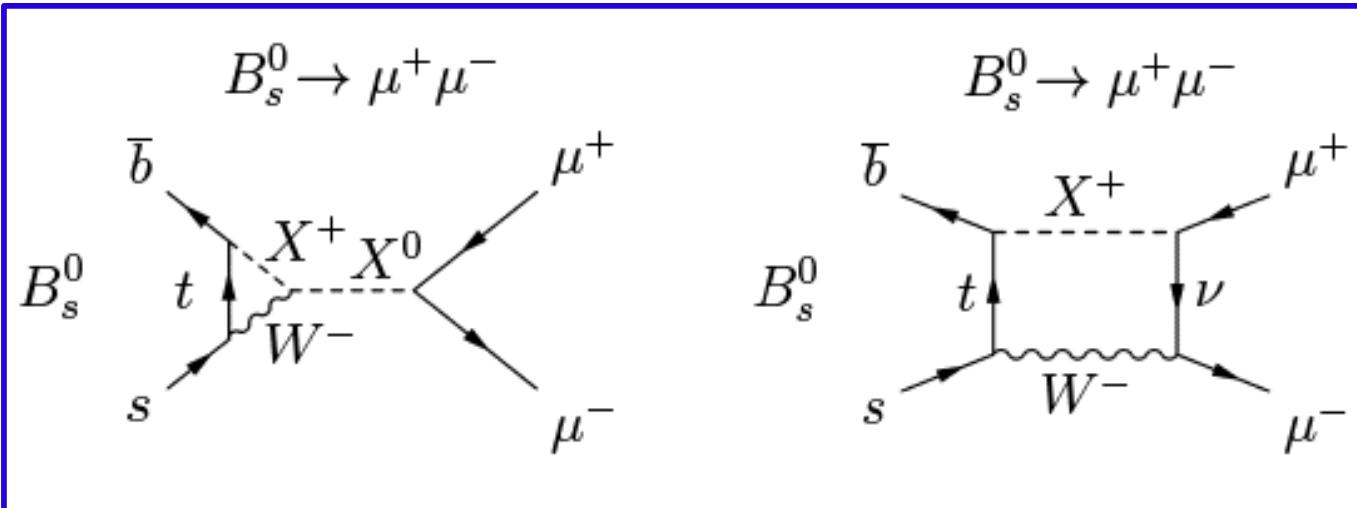
loop diagram + suppressed in SM + theoretically clean =  
**an excellent place to look for new physics**



higher-order FCNC  
allowed in SM

$$B(B_s \rightarrow \mu^+ \mu^-) = (3.65 \pm 0.23) \times 10^{-9}$$
$$B(B_d \rightarrow \mu^+ \mu^-) = (1.06 \pm 0.09) \times 10^{-10}$$

[Bobeth et al,  
PRL 112 (2014) 101801]



same decay in theories  
extending the SM  
(some of NP scenarios  
may boost the  $B \rightarrow \mu\mu$   
decay rates)

# Leptonic decays

$$B_{(s)}^0 \rightarrow \ell^+ \ell^-$$

$$BR(B_{(q)}^0 \rightarrow \ell^+ \ell^-) = \frac{\tau_B G_F^4 M_W^2 \sin^4 \theta_W}{8\pi^4} |C_{10} V_{tb} V_{tq}^*| F_B^2 m_B m_\ell^2 \times \sqrt{1 - \frac{4m_\ell^2}{m_B^2}}$$

Branching ratio proportional to the lepton mass squared

$$\frac{BR(B_{(q)}^0 \rightarrow \tau^+ \tau^-)}{BR(B_{(q)}^0 \rightarrow \mu^+ \mu^-)} \sim \frac{m_\tau^2}{m_\mu^2}$$

$$\frac{BR(B_{(q)}^0 \rightarrow \mu^+ \mu^-)}{BR(B_{(q)}^0 \rightarrow e^+ e^-)} \sim \frac{m_\mu^2}{m_e^2}$$

Helicity suppression, same reason why the pion decays into muon instead of electron  $\Rightarrow$  true only in SM

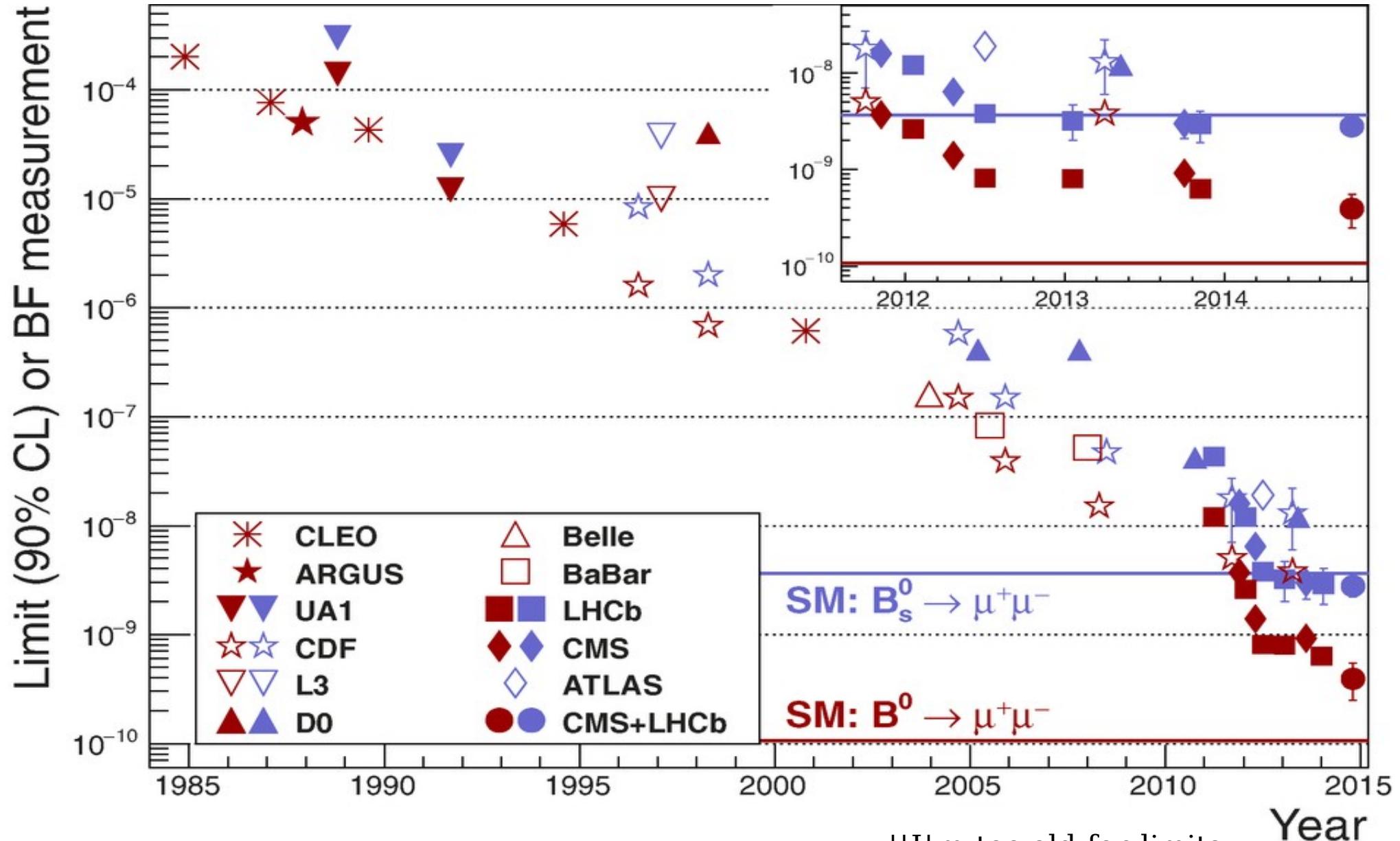
$$\frac{BR(B_{(d)}^0 \rightarrow \mu^+ \mu^-)}{BR(B_{(s)}^0 \rightarrow \mu^+ \mu^-)} = \frac{\tau_{B_d^0}}{\tau_{B_s^0}} \frac{m_{B_d^0}}{m_{B_s^0}} \frac{F_{B_d^0}}{F_{B_s^0}} \left(\frac{V_{td}}{V_{ts}}\right)^2$$

All parameters either measurable or calculable with high precision  
valid only in Minimal Flavour Violating Models  
(where the flavour structure is described only by CKM)

In a "general" NP scenarios, the branching ratio of B leptonic decay is given by

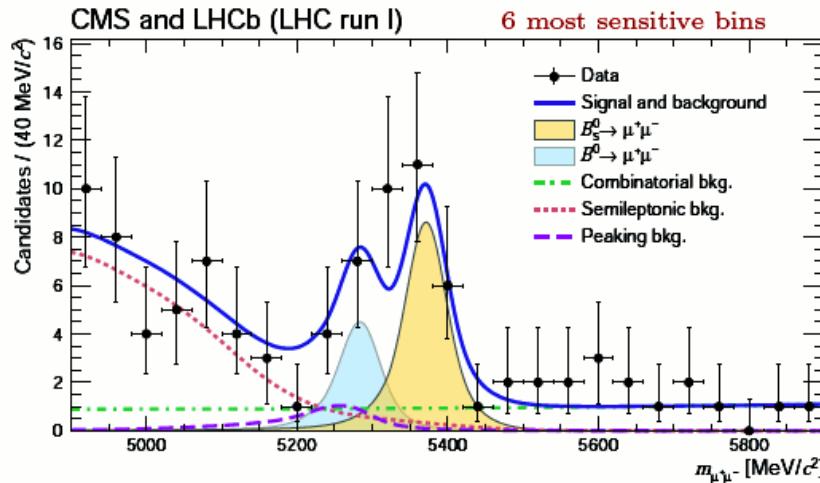
$$BR(B_s^0 \rightarrow \mu^+ \mu^-) \propto (1 - \frac{4m_\ell^2}{m_B^2}) |C_S - C'_S|^2 + |(C_P - C'_P)^2 + 2 \frac{m_\ell^2}{m_B^2} (C_{10} - C'_{10})|^2$$

# $B_{(s)} \rightarrow \mu\mu$ : ultra rare processes...



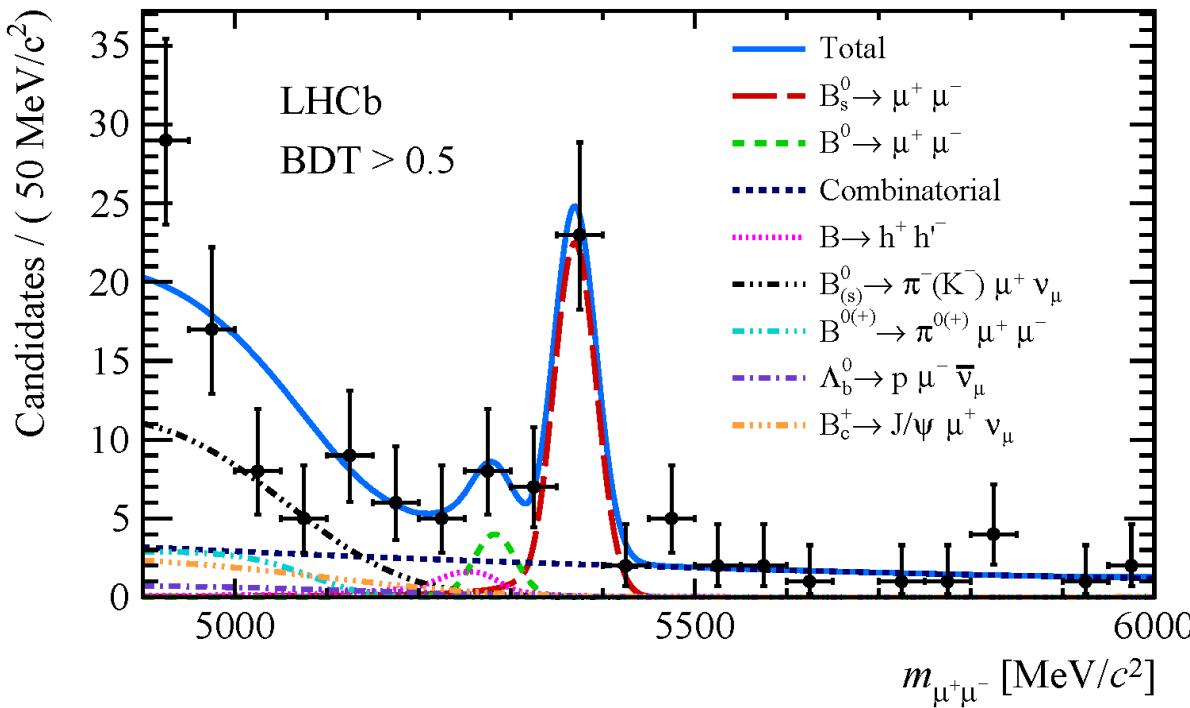
"I'm too old for limits,  
I want to see signals"  
(Francis Halzen)

# $B_s \rightarrow \mu^+ \mu^-$ results

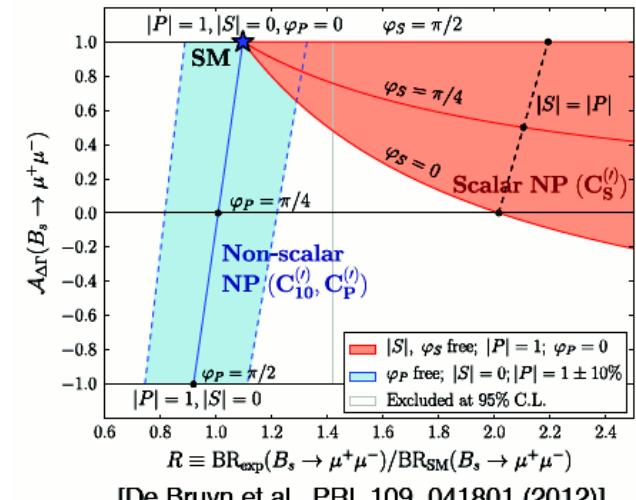


$B(B_s^0 \rightarrow \mu^+ \mu^-) = (2.8^{+0.7}_{-0.6}) \times 10^{-9}$   
**first observation :  $6.2\sigma$  significance**  
 $B(B^0 \rightarrow \mu^+ \mu^-) = (3.9^{+1.6}_{-1.4}) \times 10^{-10}$   
**first evidence :  $3.0\sigma$  significance**

[arXiv : 1703.05747]



SM: heavy state decays to  $\mu^+ \mu^-$   
first lifetime measurement:  
 $\tau(B_s \rightarrow \mu^+ \mu^-) = 2.04 \pm 0.44 \pm 0.05$  ps

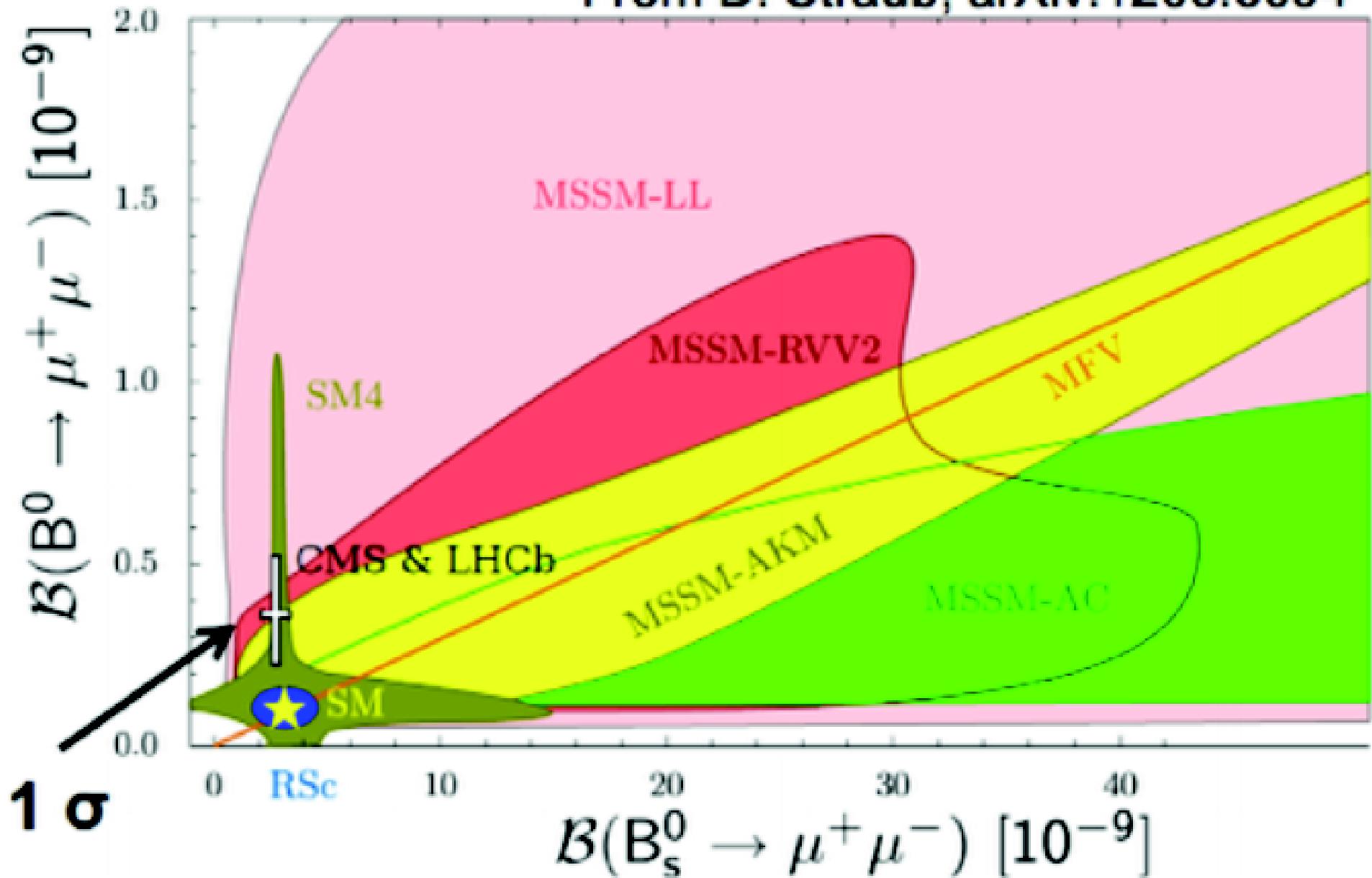


[De Bruyn et al., PRL 109, 041801 (2012)]

$B(B_s^0 \rightarrow \mu^+ \mu^-) = (3.0 \pm 0.6^{+0.3}_{-0.2}) \times 10^{-9}$  ( $7.8\sigma$  significance)  
 $B(B^0 \rightarrow \mu^+ \mu^-) < 3.4 \times 10^{-10}$  @ 90% CL

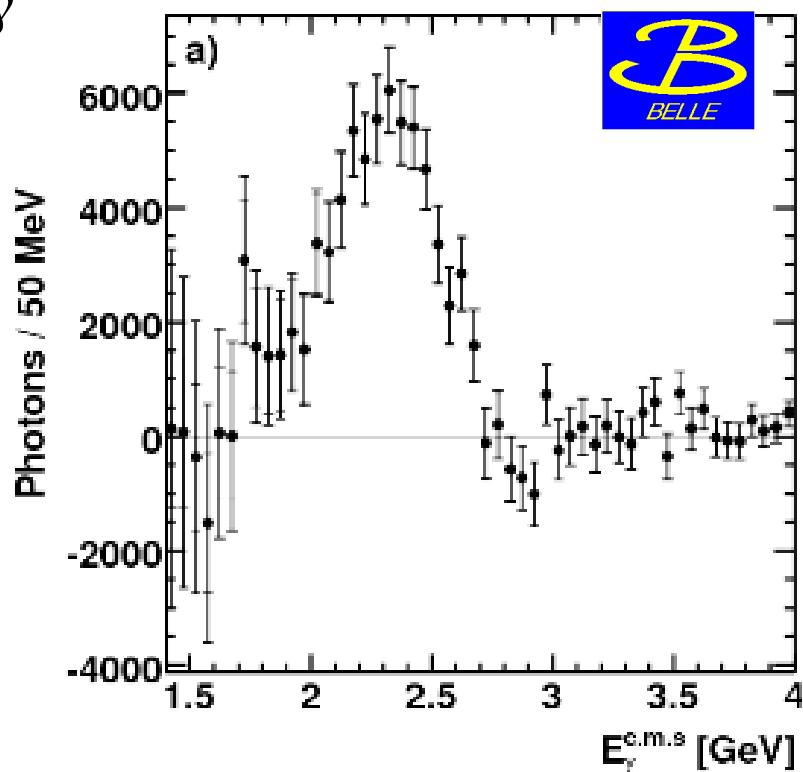
# Constraints on NP models

From D. Straub, arXiv:1205.6094

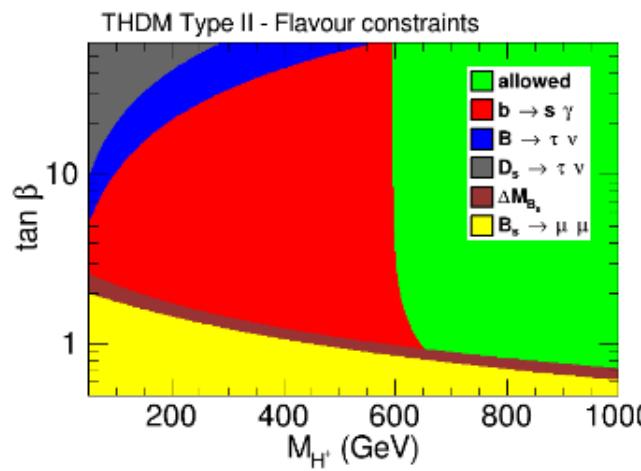
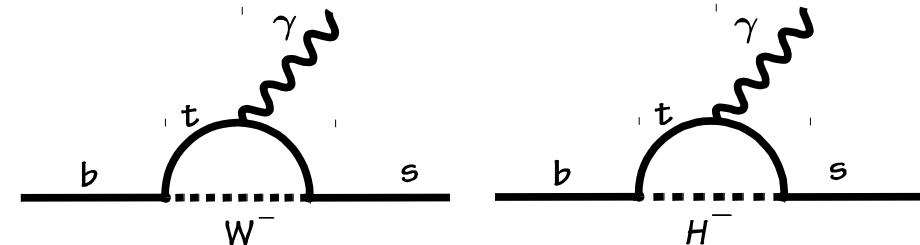
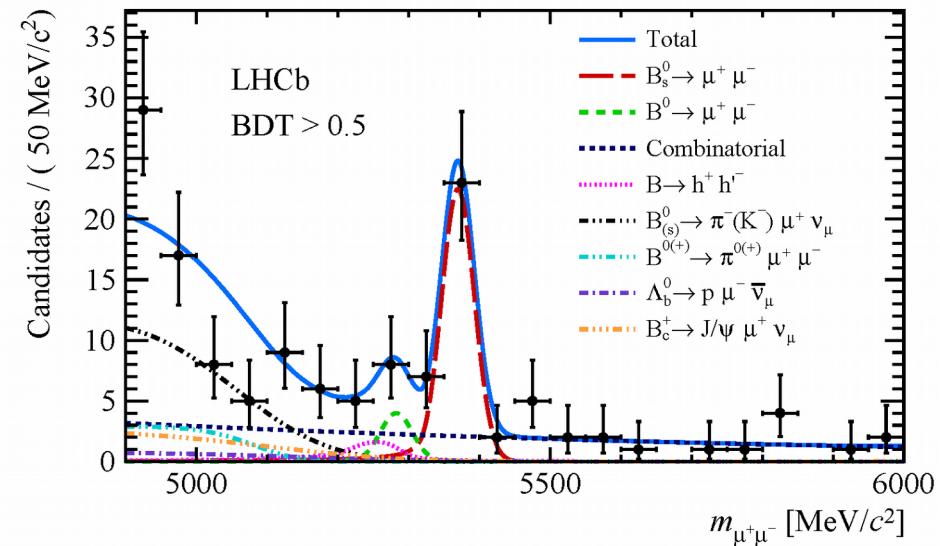


# Recent rare B decays results

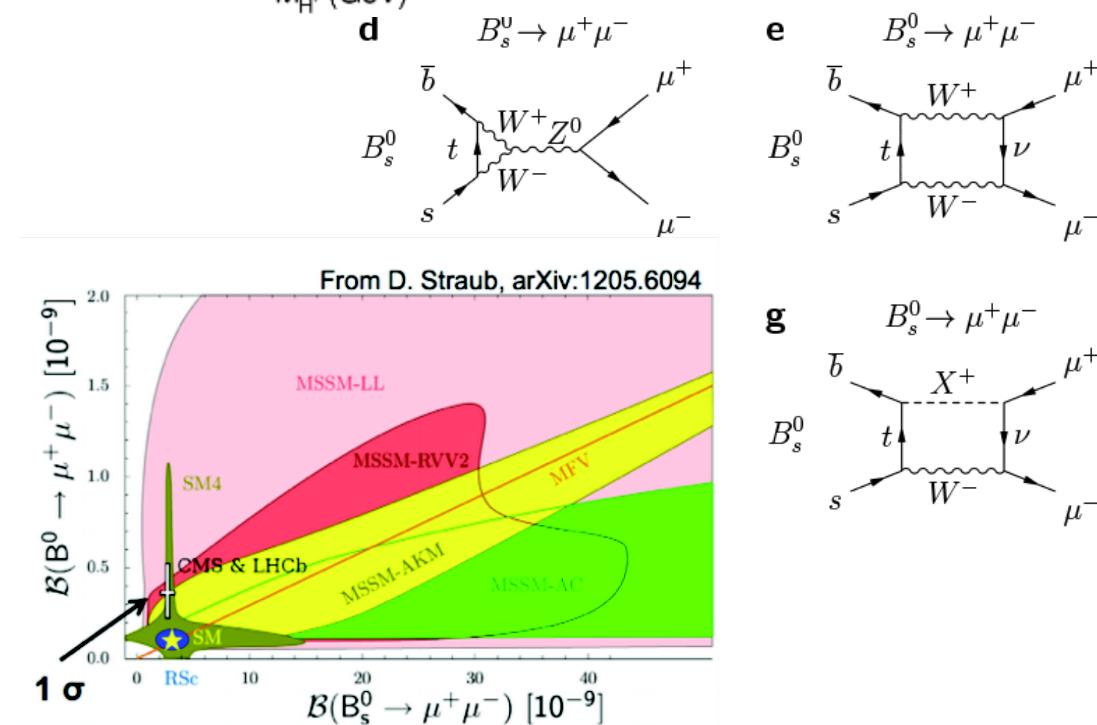
$b \rightarrow s \gamma$



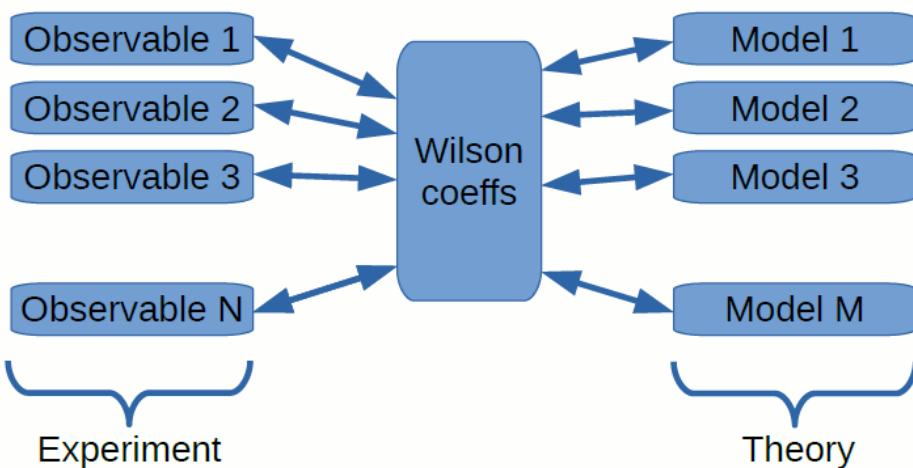
$B_s \rightarrow \mu \mu$



arXiv:1706.07414]



# Sensitivity to new physics in rare B decays



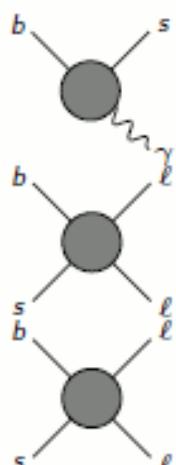
M.Ciuchini et al, arXiv:1512.07157  
T.Hurth et al, arXiv:1603.00865  
S.Descotes-Genon et al, arXiv:1510.04239...

**NP changes short-distance  $C_i$  and/or add new long-distance ops  $O'_i$**

- Model-independent description in effective field theory

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i \underbrace{C_i O_i}_{\text{Left-handed}} + \underbrace{C'_i O'_i}_{\text{Right-handed, } \frac{m_s}{m_b} \text{ suppressed}}$$

- Wilson coefficients  $C_i^{(\prime)}$  encode short-distance physics,  $O_i^{(\prime)}$  corr. operators



$O_7^{(\prime)}$  photon penguin

$O_9^{(\prime)}$  vector coupling

$O_{10}^{(\prime)}$  axialvector coupling

$O_{S,P}^{(\prime)}$  (pseudo)scalar penguin

$b \rightarrow s\gamma$      $B \rightarrow \mu\mu$      $b \rightarrow s\ell\ell$

