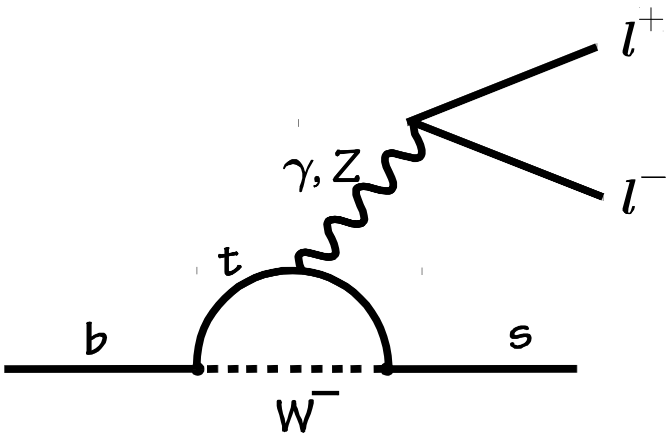
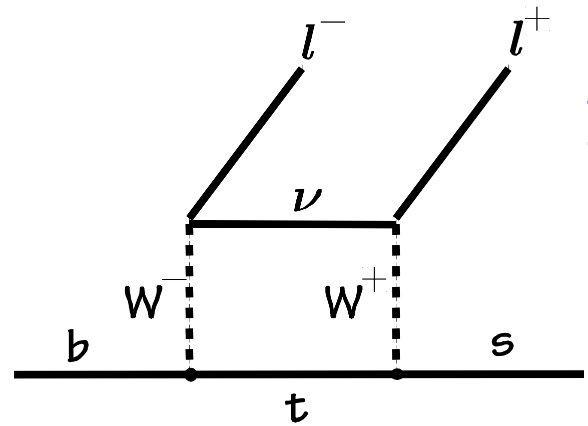
Beautiful paths to probe physics beyond the standard model of particles





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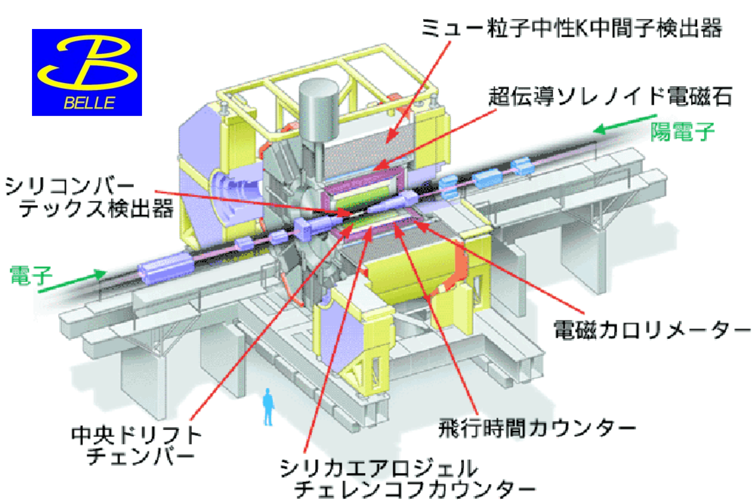
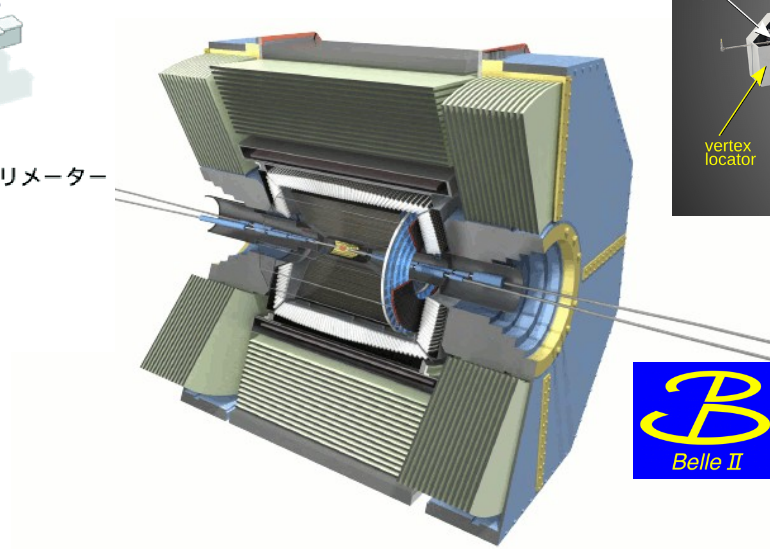
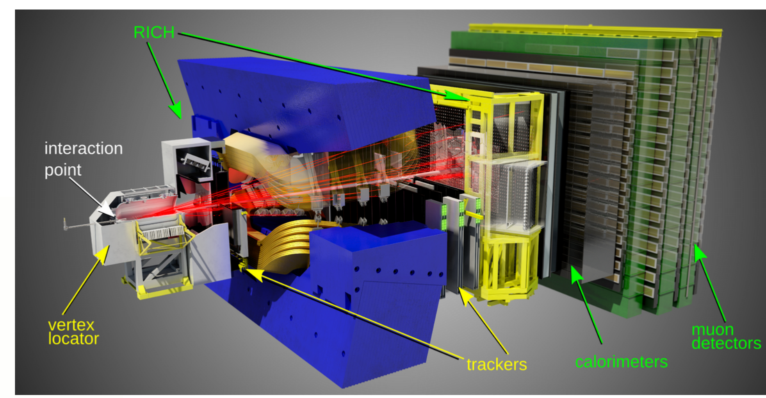






Jennifer school, Trieste, August 2nd 2018

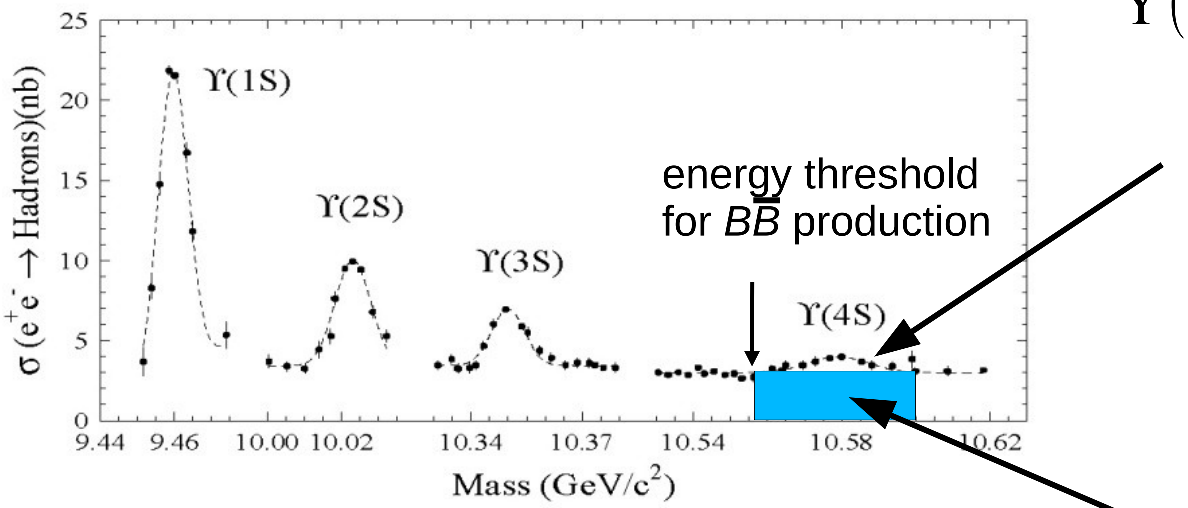
Program of the 3 lectures

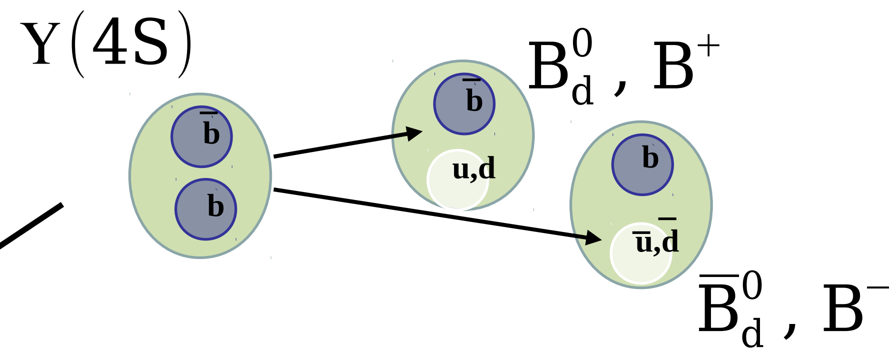
- **How to study elementary particles**
  - direct searches and indirect searches
  - experiments through history of particles physics

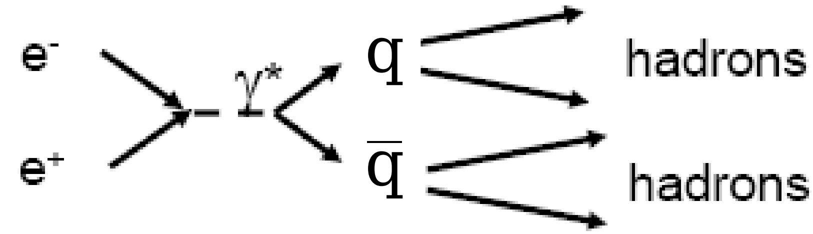
- **Rare B decays**
  - quest for New Physics (beyond Standard Model)
  - two approaches for the same quest (LHCb vs Belle)

- **CP Violation**
  - matter and anti-matter
  - fully exploiting our detector ....

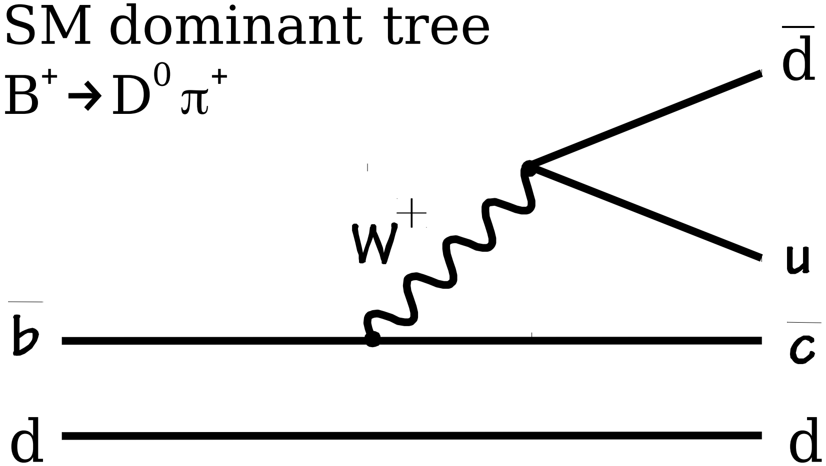
At a B-factory …







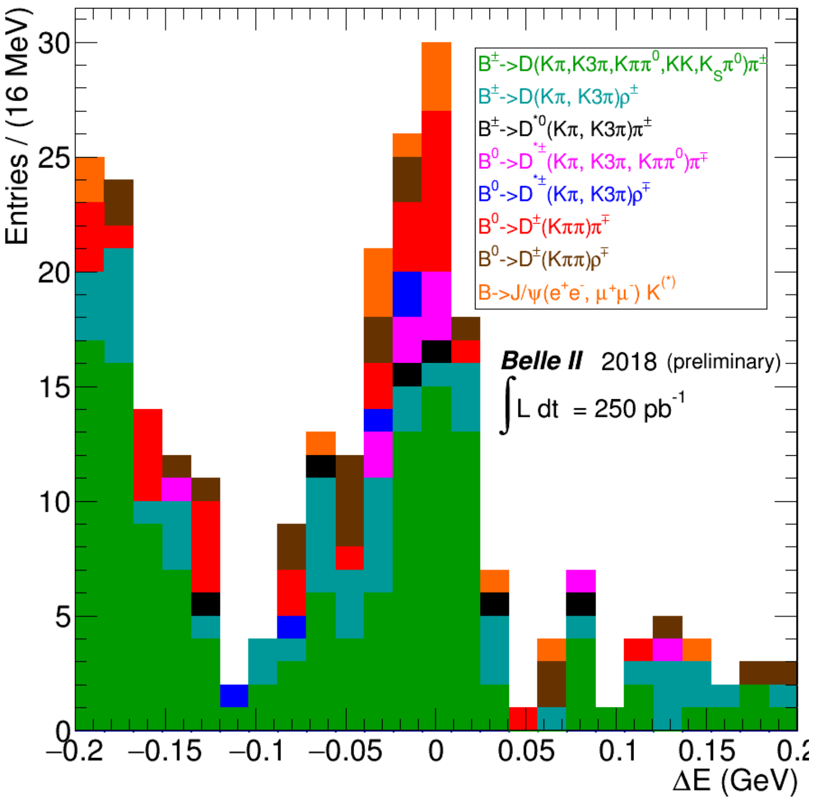
SM dominant tree
$B^+ \rightarrow D^0 \pi^+$

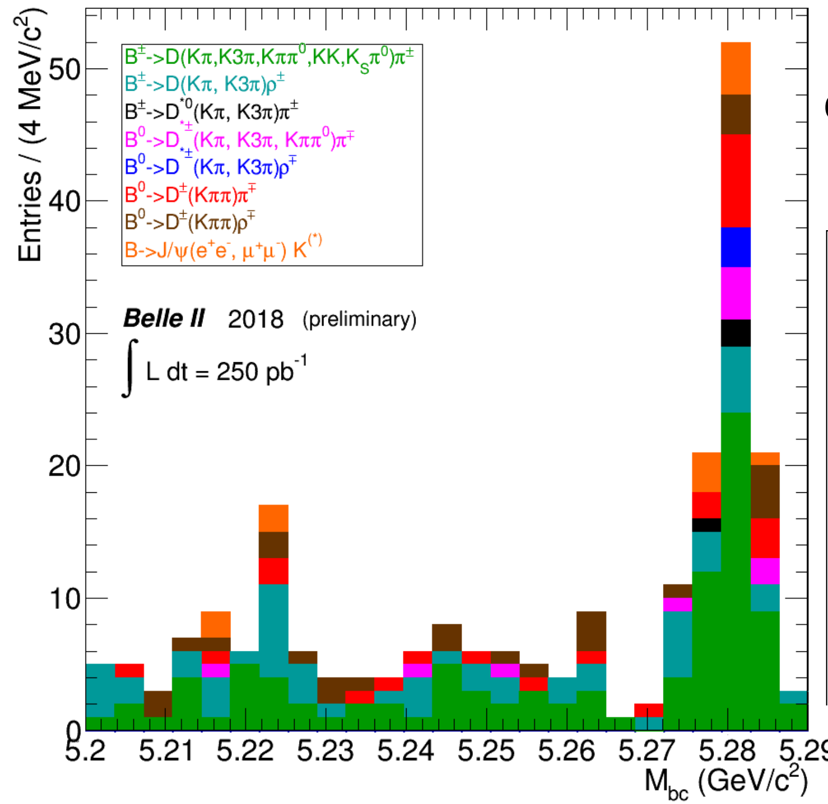


How many B candidates can I reconstruct with 1 fb^{-1} ?
1 fb^{-1} → 1×10^6 B produced
but $BF(B \rightarrow D^0 \pi^-) = 5 \times 10^{-3}$
and $BF(D \rightarrow K^- \pi^+) = 3.8\%$
and reconstruction efficiency ~ 10% …
signal yield ~ 10 events !!

Rediscovering beauty: $B \to D^{(*)}h$ + $B \to J/\psi K^{(*)}$

with very limited statistics ($< 1\ fb^{-1}$), Belle II can rediscover the B meson





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

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

~ 100 evts

Show capacity for charm physics in $e^+e^- \to c\bar{c}$

- D^0, D^+, D^*
- Cabibbo favoured and suppressed modes

that is for dominant decays....
...we are looking for rare decays

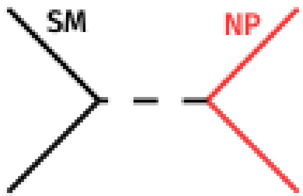
...for B-physics

- hadronic modes from $b \to c$
- semileptonic decay modes from $b \to c$

Rare B decays

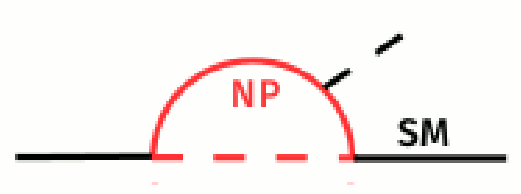
- FCNC are strongly suppressed in the SM: only loops + GIM mechanism
- Any new particle generating new diagrams can change the amplitudes

energy frontier



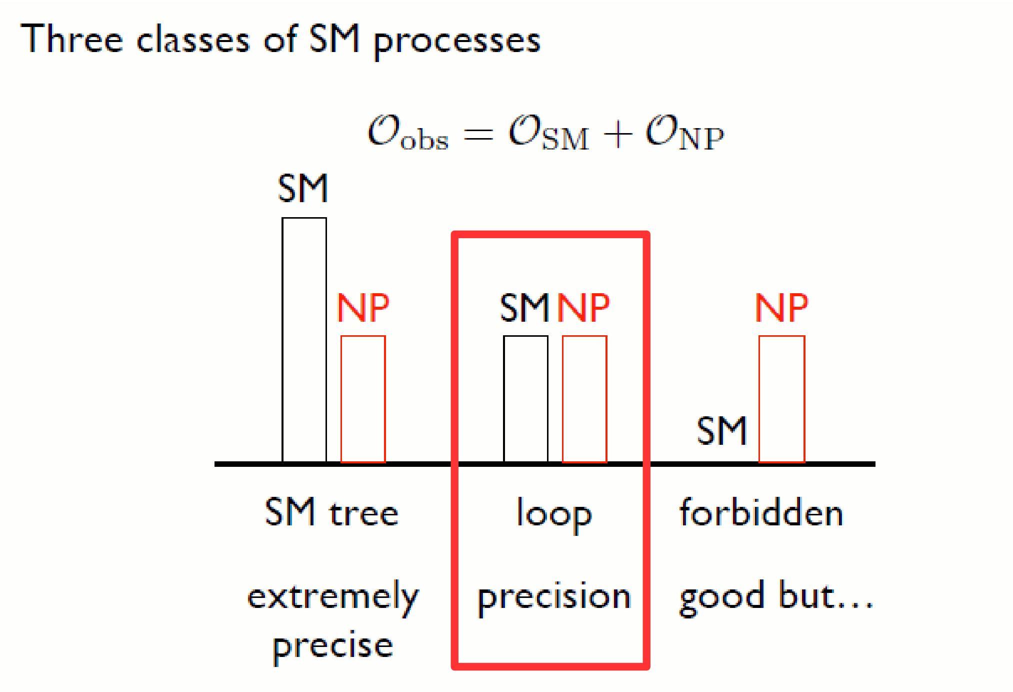
limited by beam energy

intensity frontier



limited by statistics

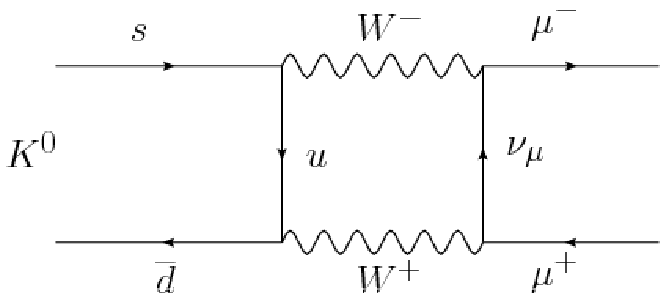
→ **NP beyond the direct reach of the LHC**



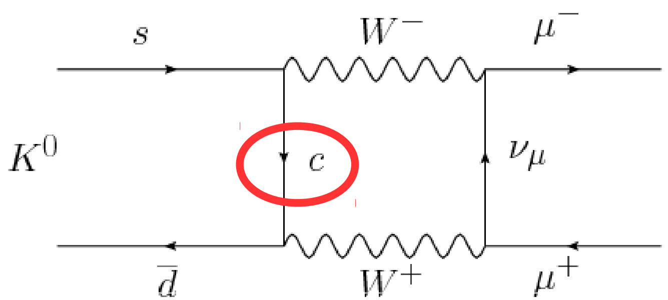
New particles can for example contribute to loop or tree level diagrams **by enhancing/suppressing decay rates, introducing new sources of CP violation or modifying the angular distribution of the final-state particles**

indirect search: $K^0_L \to \mu\mu$

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

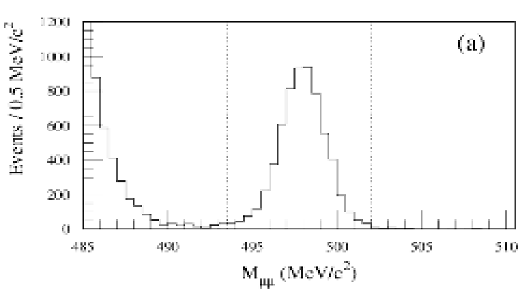


in a renormalisable gauge theory, is expected to give a branching ratio of $\mathbf{g^4 \sim \alpha^2 \sim 10^{-4}}$, with α the fine structure constant.



$K^0_L \to \mu\mu$ was not observed though expected

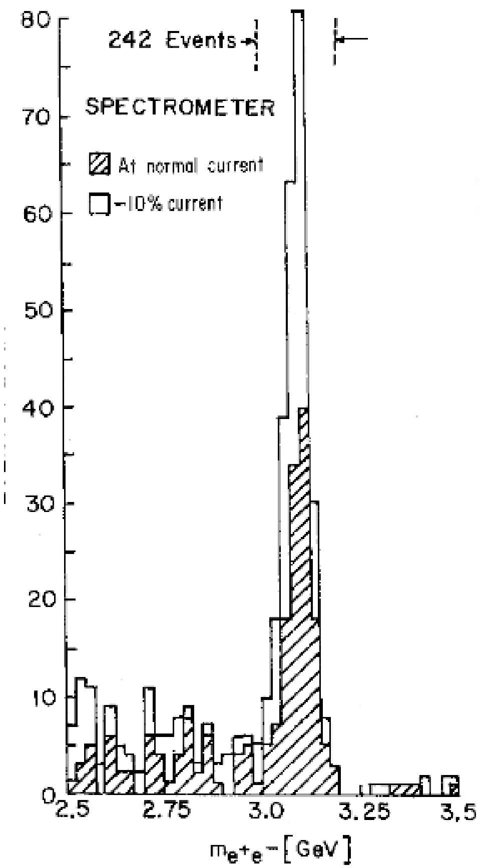
Now BF is measured to be $(6.84 \pm 0.11)\,10^{-9}$ [Ambrose et al, 2000]

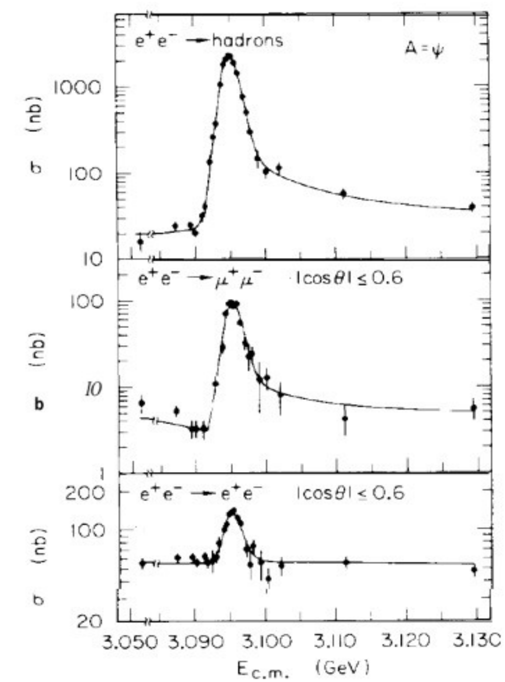


direct search: $J/\psi \to ee$

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

J/ψ

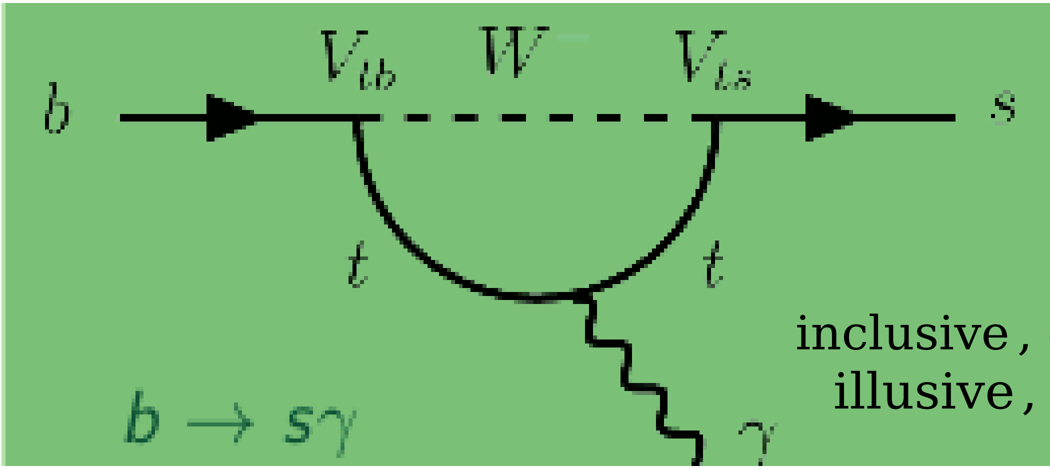




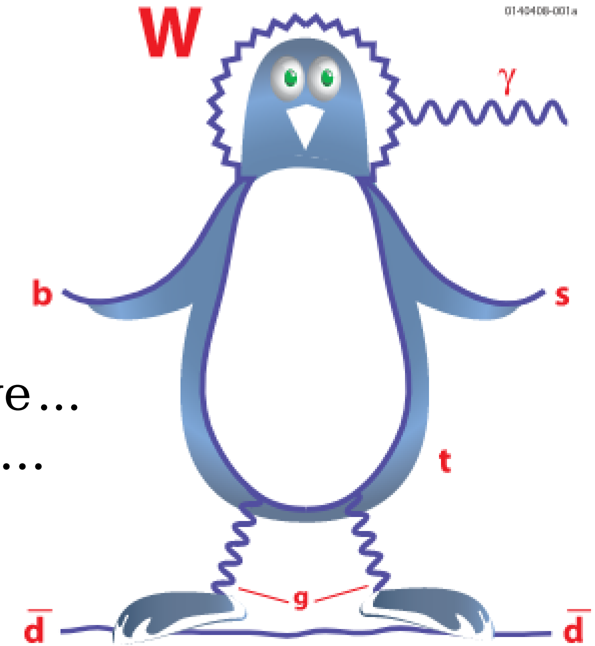
With the measured charm quark mass $m_c \sim 1.27$ GeV, the predicted rates are in agreement with observation.

Radiative B decays

artist's view ... of the penguin diagram



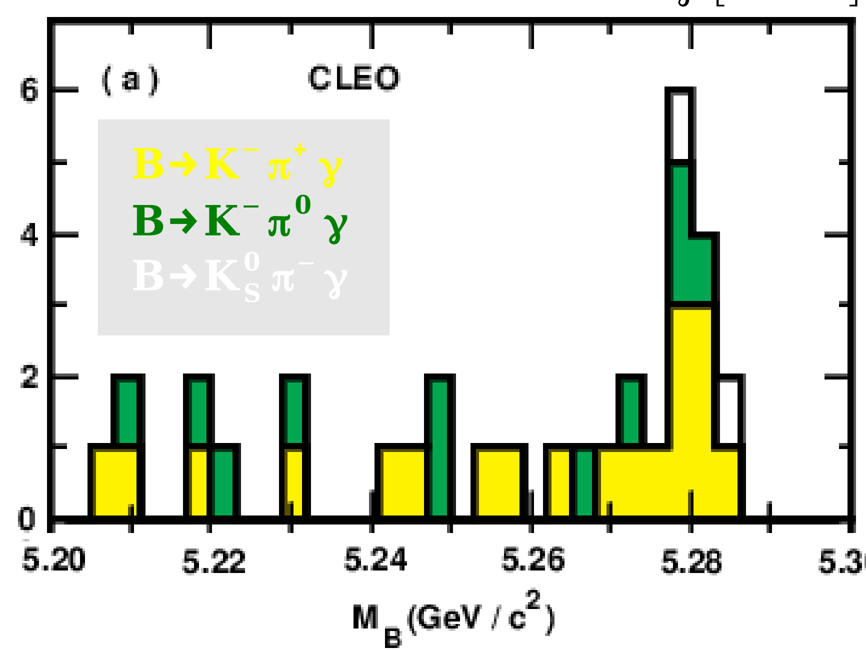
inclusive, exclusive ...
illusive, elusive ...



CLEO

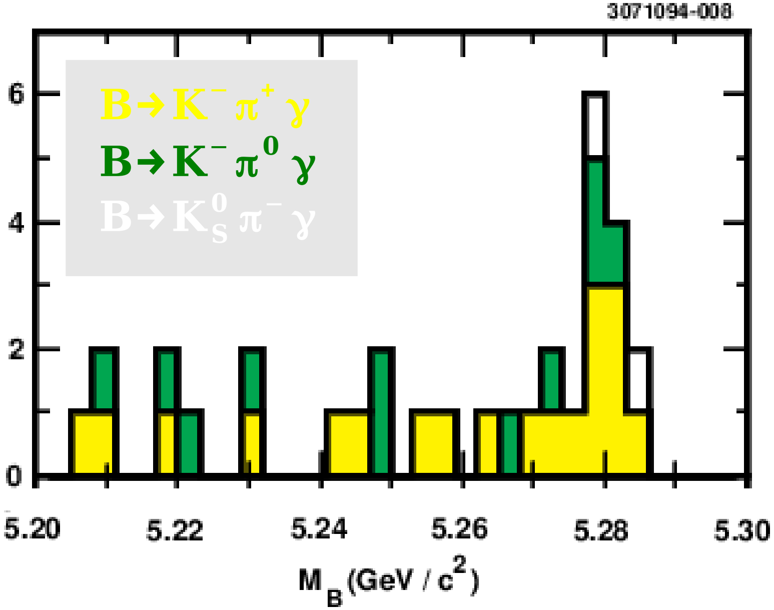
- 1975: "South Area Experiment" group conceives CLEO
- 1979: First data collected
- 1980: B meson discovered
- 1983: Ds meson discovered
- 1986: CLEO II detector with CsI calorimeter installed
- 1989: b → u transitions discovered
- 1993: b → s penguin decays discovered
- 1995: CLEO II.V with silicon 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 $B \to K^* \gamma$ [1993]

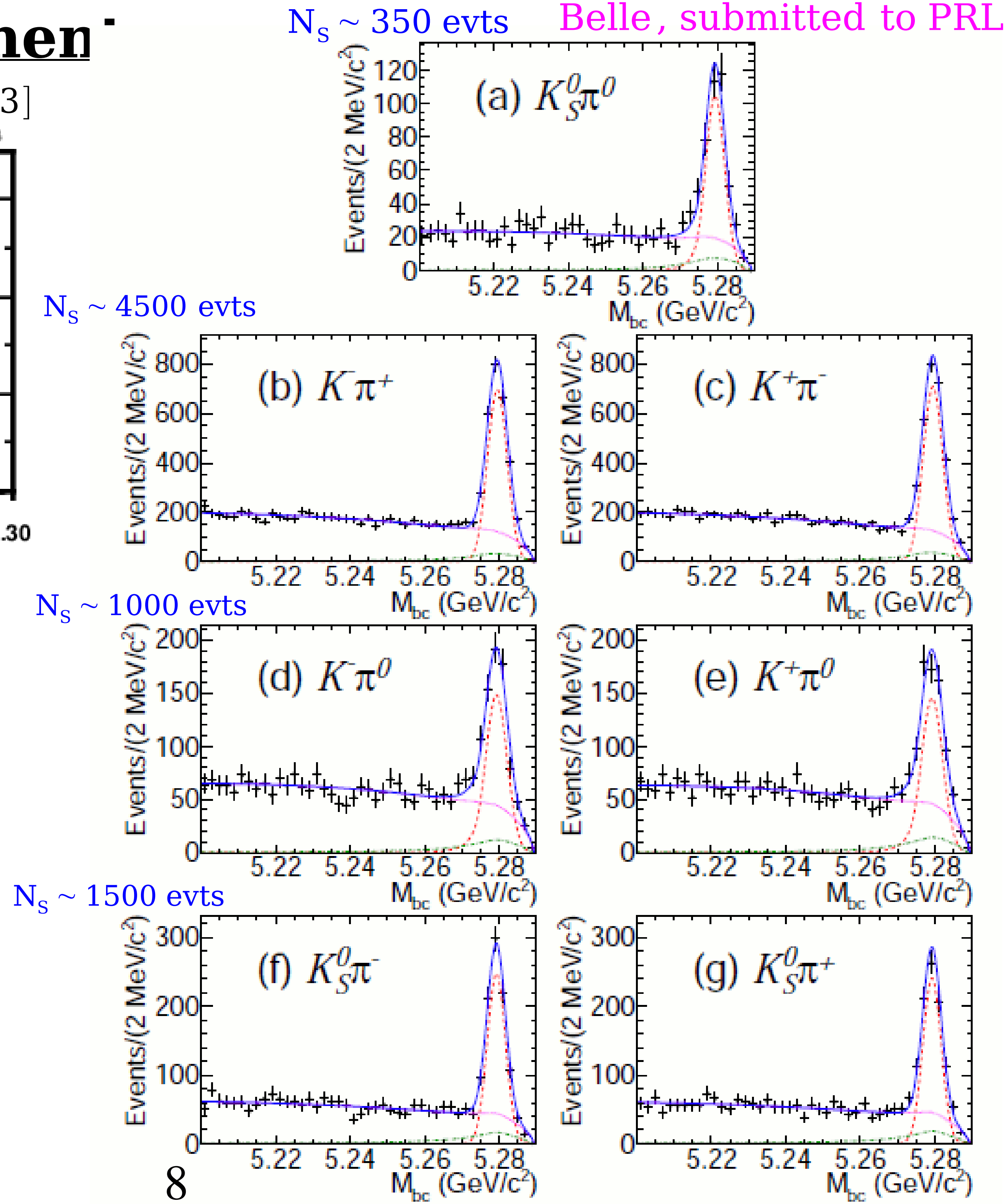


$B \to K^* \gamma$ measurement

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

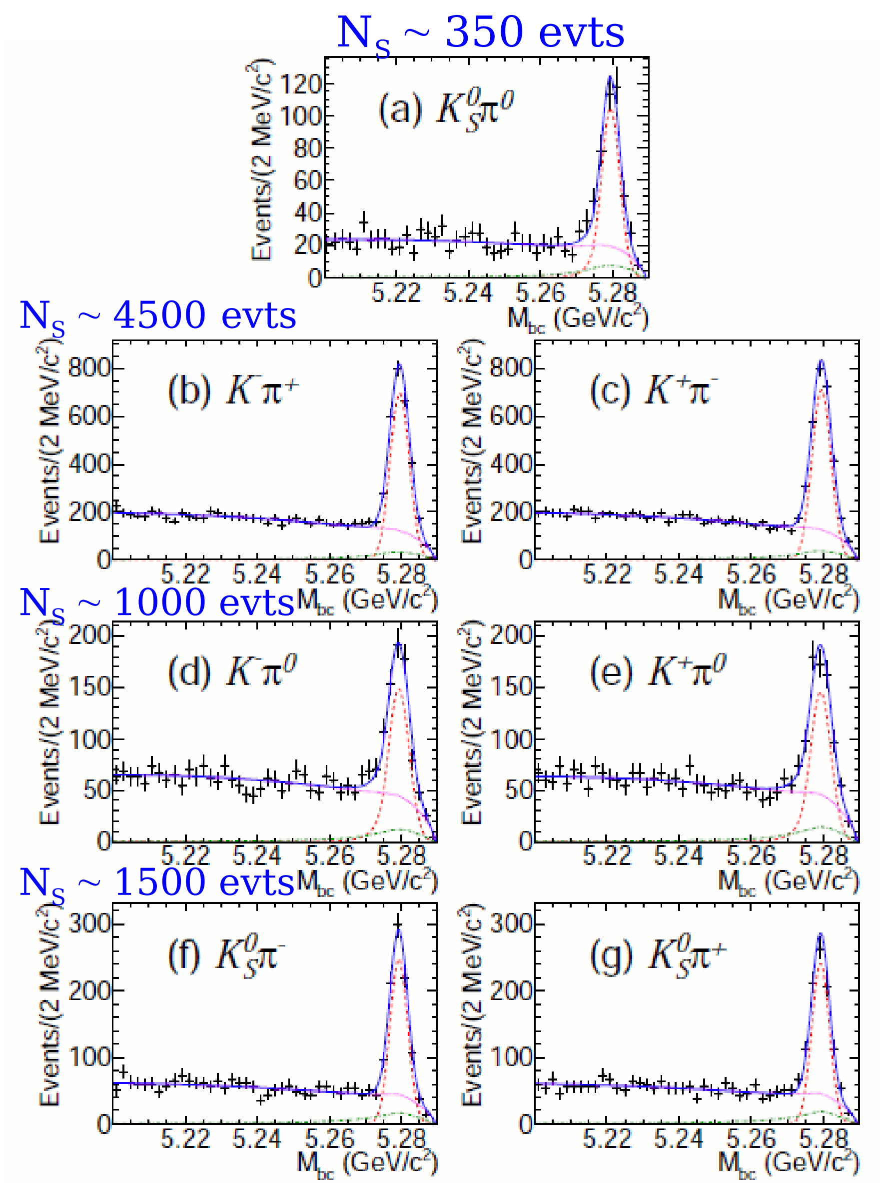


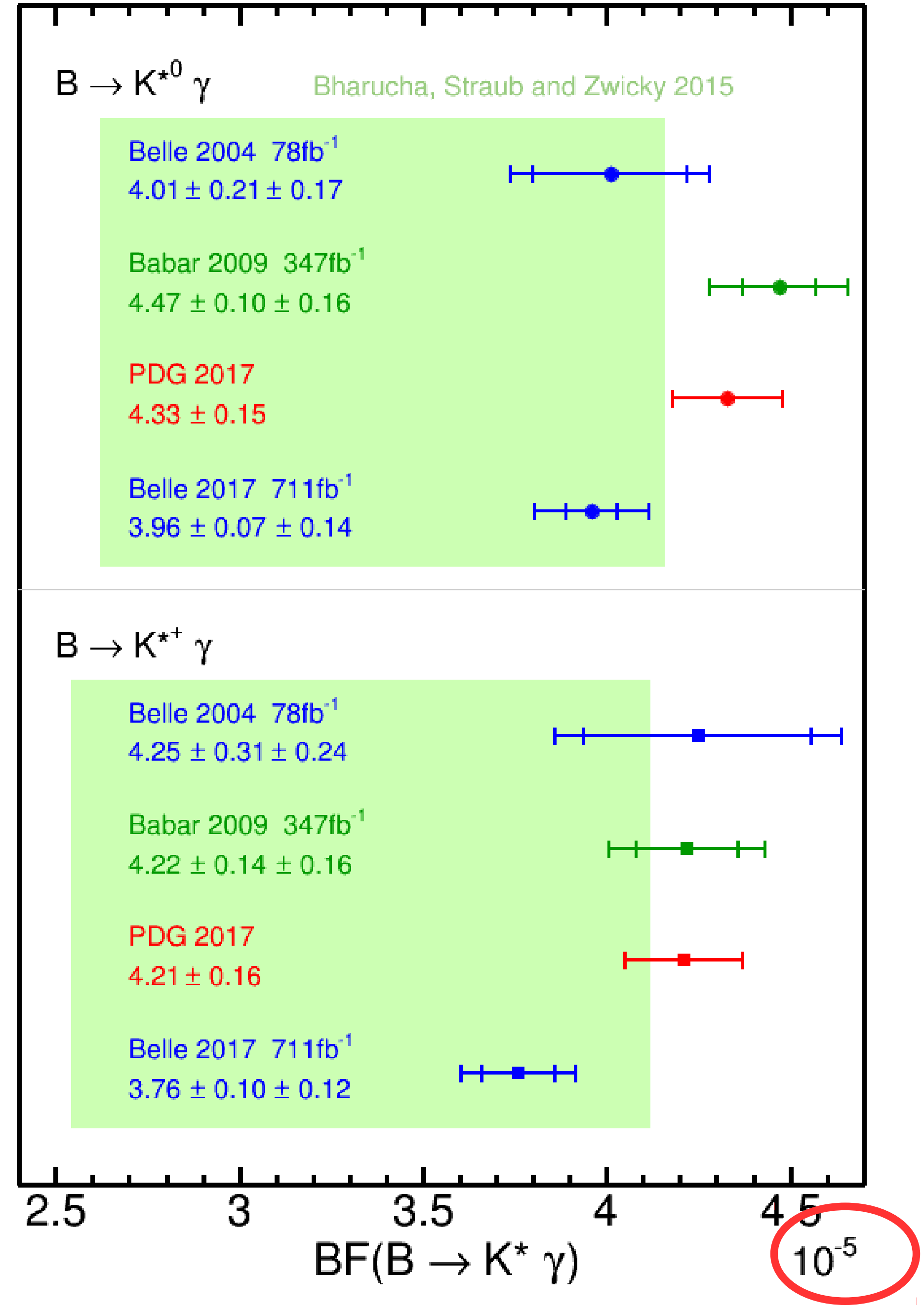
Belle, submitted to PRL



$B \to K^* \gamma$ measurements

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



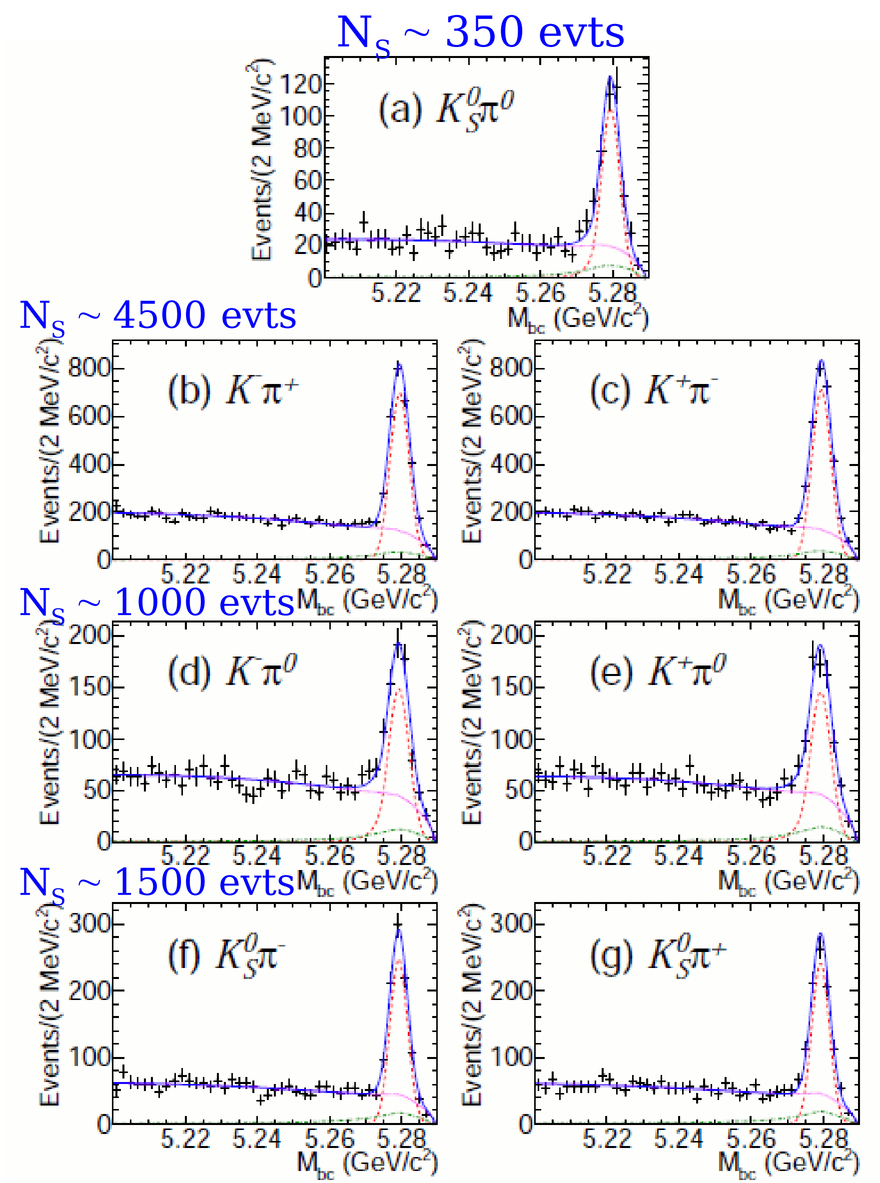


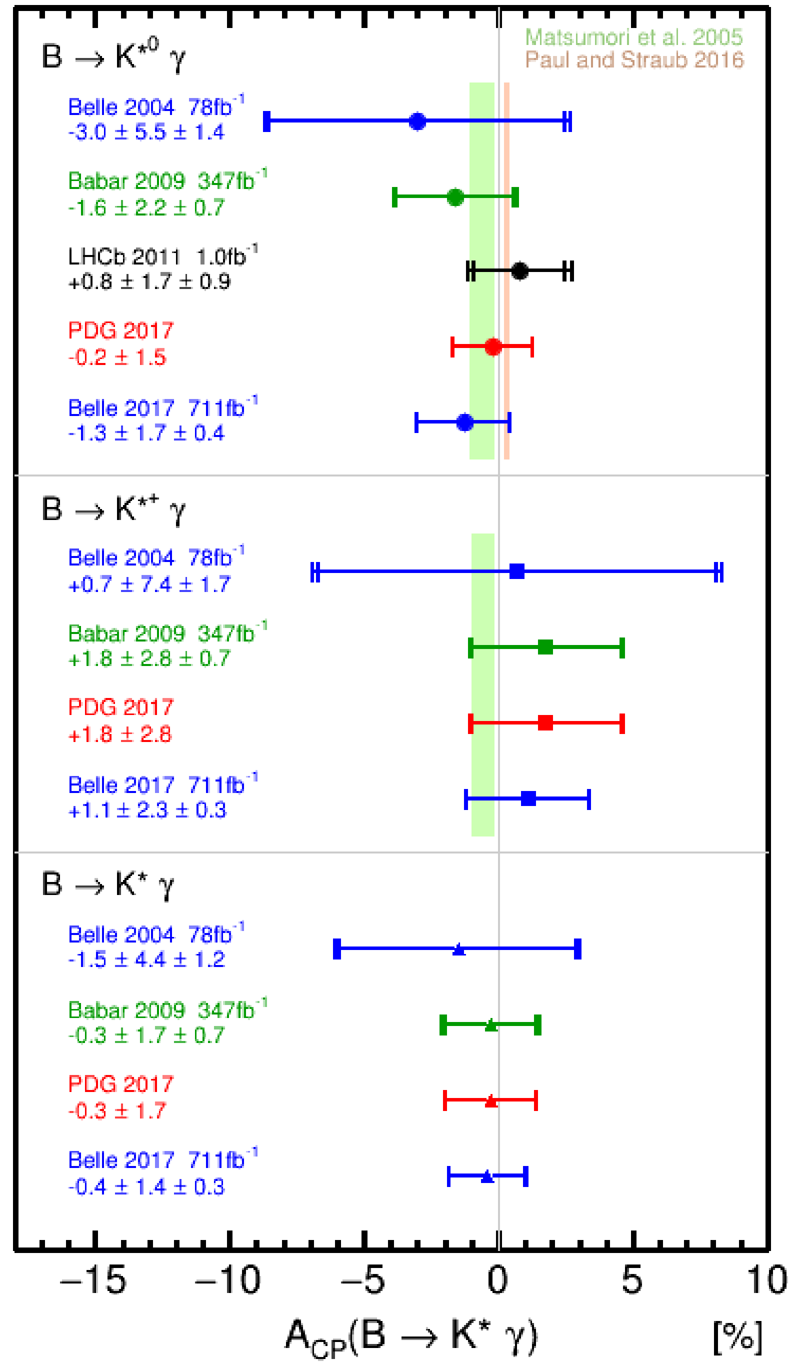
but uncertainty in the hadronization process limits the ability to predict individual exclusive rates from first principles of the theory

$B \to K^* \gamma$ measurements

simultaneous fit of 4 final states

$\Rightarrow$ extraction of BFs, Δ_{0+}, A_{CP}, ΔA_{CP} ...



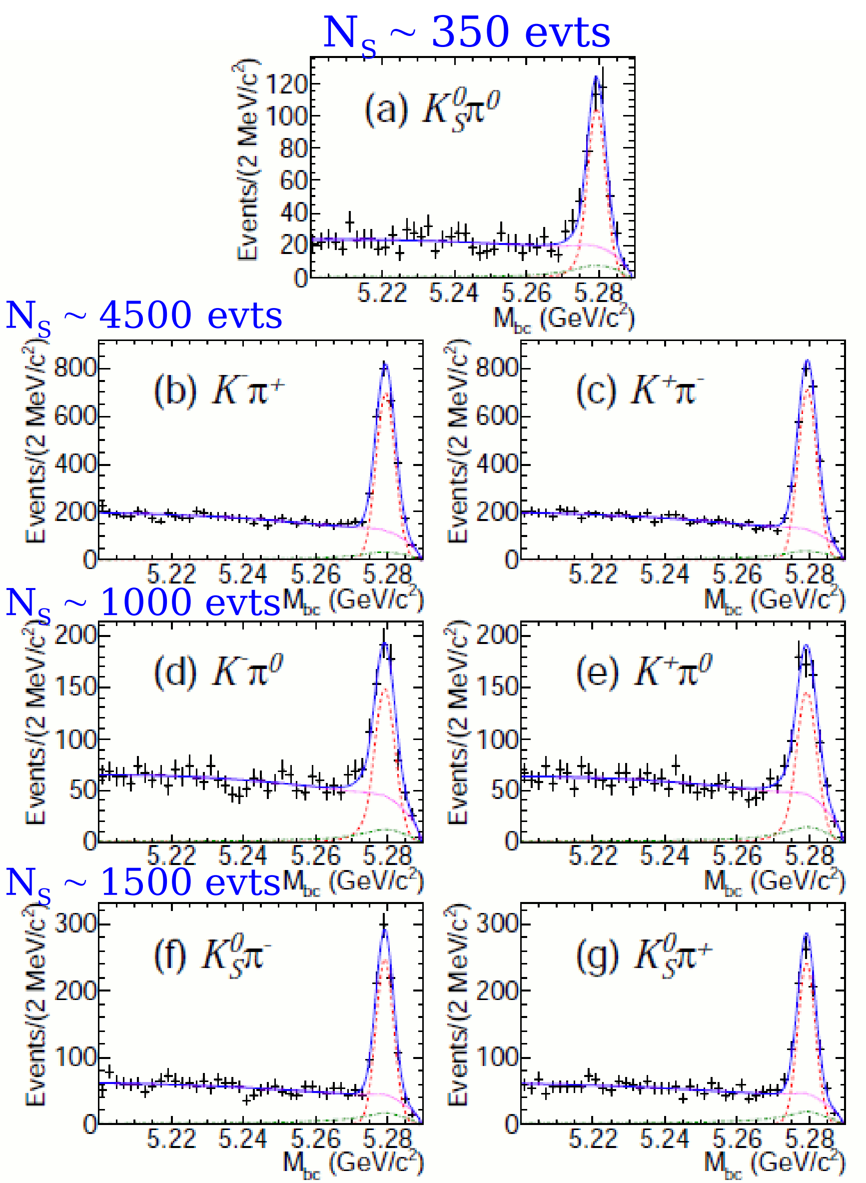


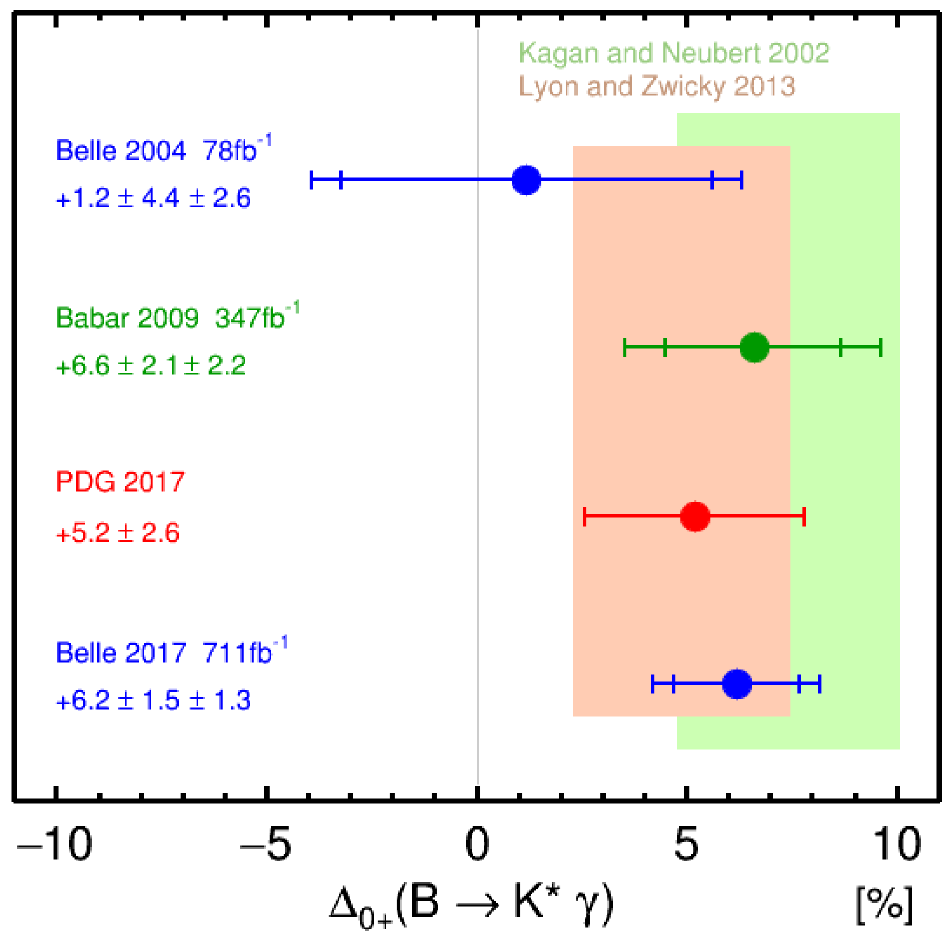
$B \to K^* \gamma$ measurements

simultaneous fit of 4 final states

$\Rightarrow$ extraction of BFs, Δ_{0+}, A_{CP}, ΔA_{CP}

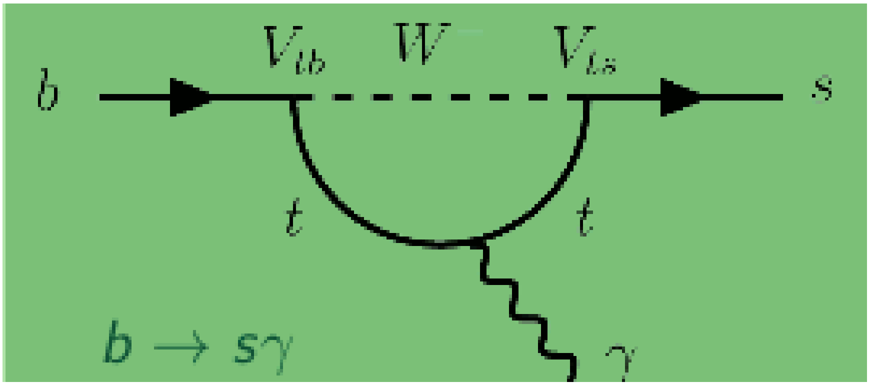
isospin asymmetry: $\Delta_{0+} = \dfrac{\Gamma(B^0 \to K^{*0}\gamma) - \Gamma(B^+ \to K^{*+}\gamma)}{\Gamma(B^0 \to K^{*0}\gamma) + \Gamma(B^+ \to K^{*+}\gamma)}$

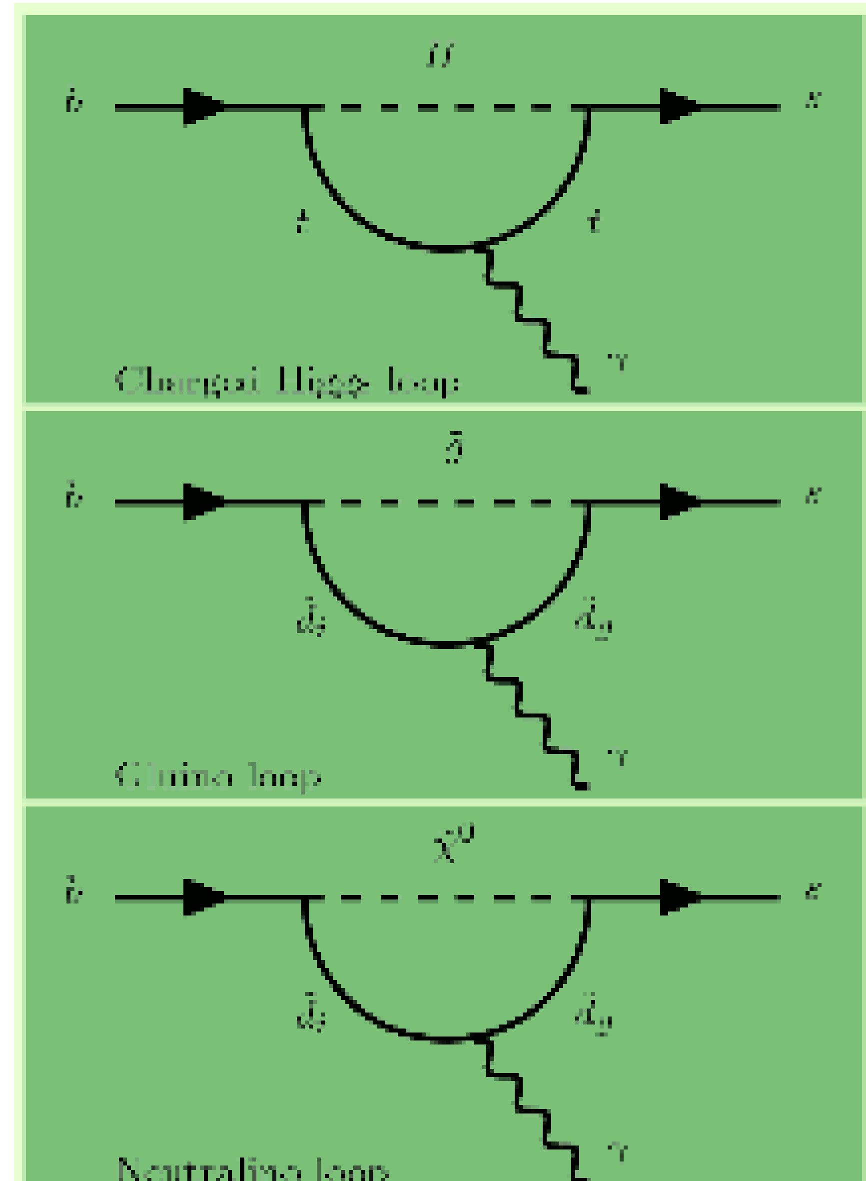




evidence of isospin violation in $K^*\gamma$!

b→s γ





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

$$B \simeq 3\ .\ 10^{-4}$$

- SM: $B = (3.36 \pm 0.23)\ .\ 10^{-4}$
  [Misiak et al., hep-ph/0609232]
  ⇒ [Misiak et al, arXiv:1503.01789]
- Strong constraint on New Physics

b→sγ SM branching fraction

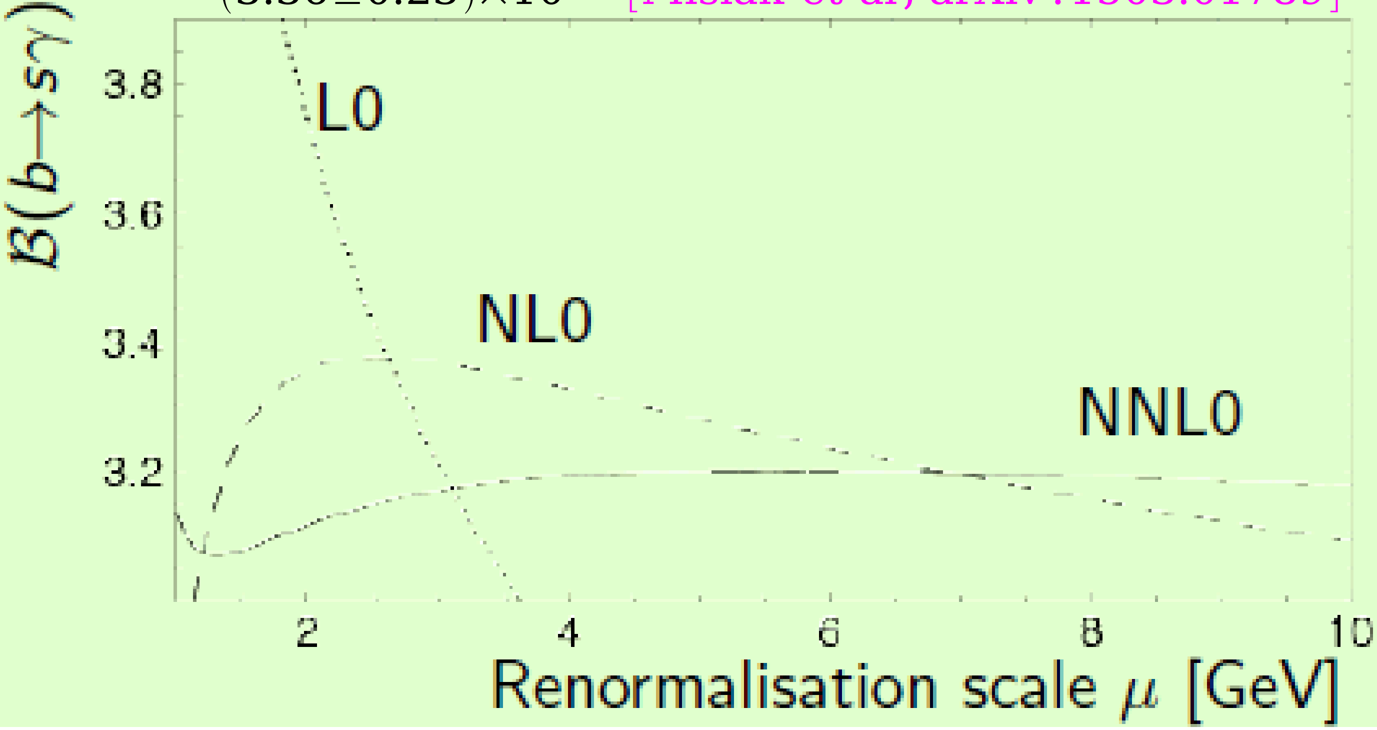
[Misiak et al, PRL98, 02202, 2007]

- 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

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

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

✔ BF very stable versus μ



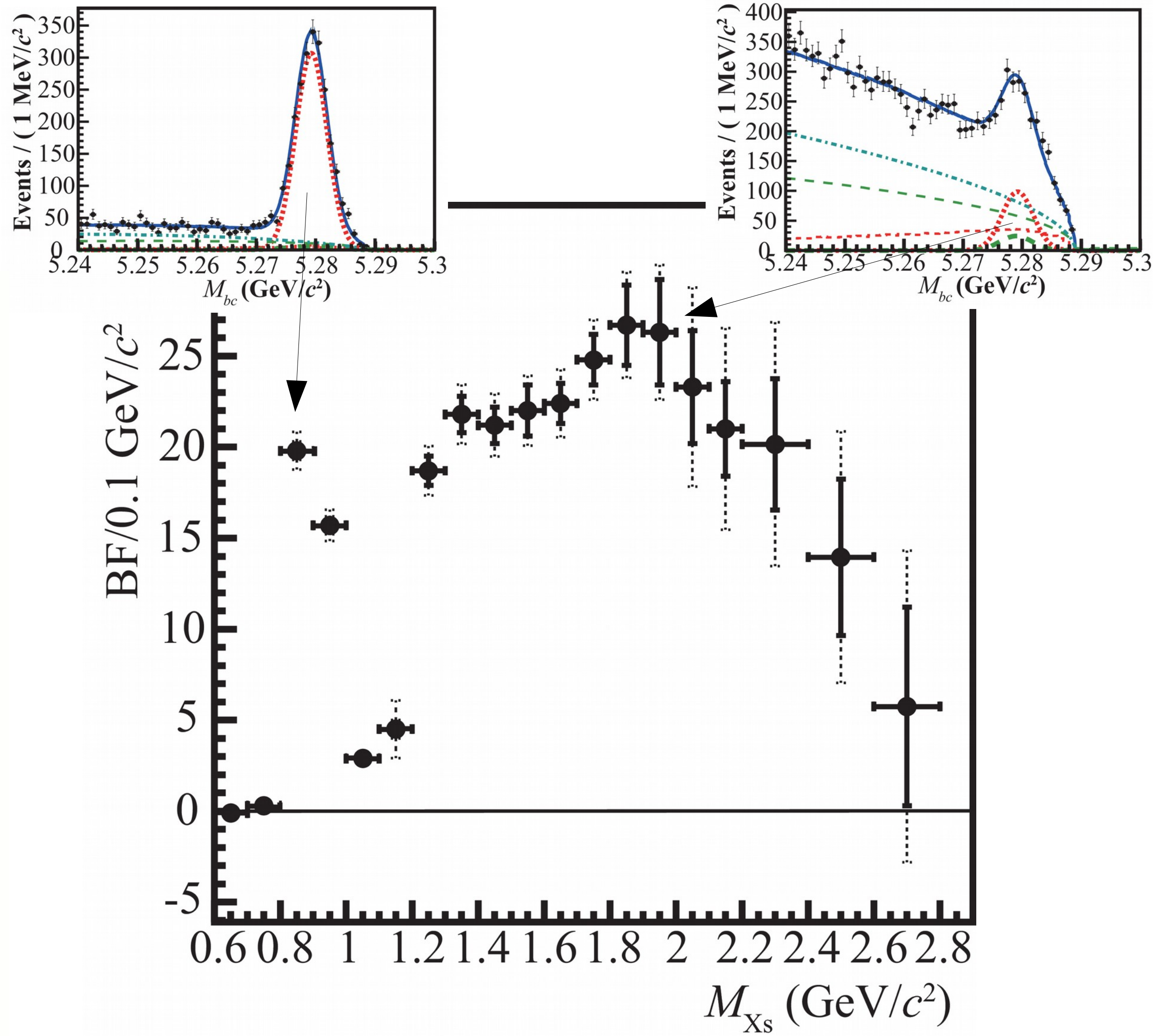
How to estimate the branching fraction b→sγ ?
Semi-inclusive (sum-of-exclusive)

[772 MBB]
[arXiv:1411.7198]

38 modes

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

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



Semi-inclusive (sum-of-exclusive)

38 modes

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

possible but large systematics (difficult to estimate/trust)

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

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

[772 MBB]
[arXiv:1411.7198]

[471 MBB]
[arXiv:1207.2520]

(for $E^*_\gamma > 1.9$ GeV)

$$\mathcal{B}(B\to X_s\gamma) = (3.51 \pm 0.17 \pm 0.33)\times 10^{-4}$$

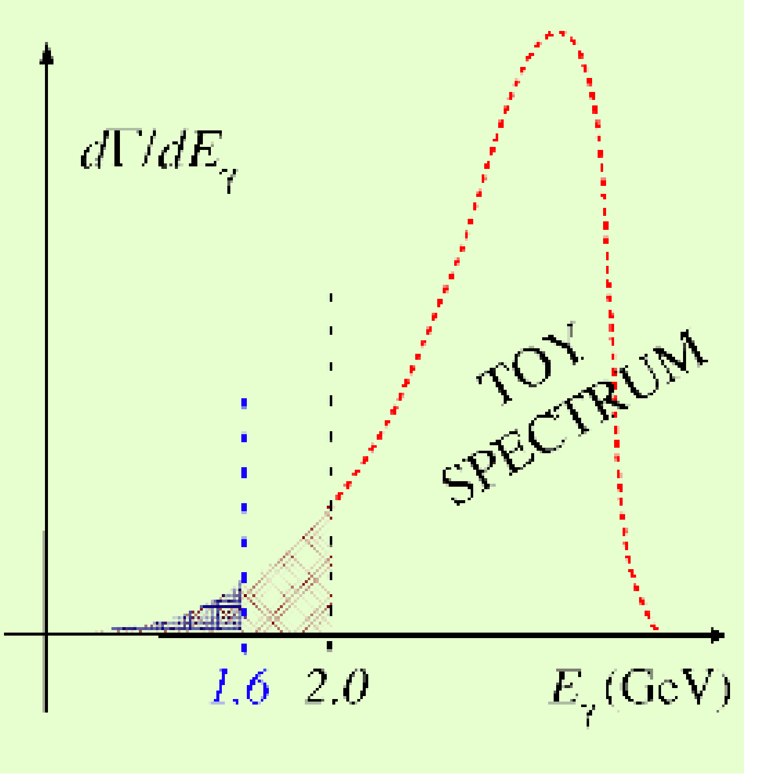
$$\mathcal{B}(B\to X_s\gamma) = (3.29 \pm 0.19 \pm 0.48)\times 10^{-4}$$

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

$B \to X_s \gamma$ spectrum

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

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

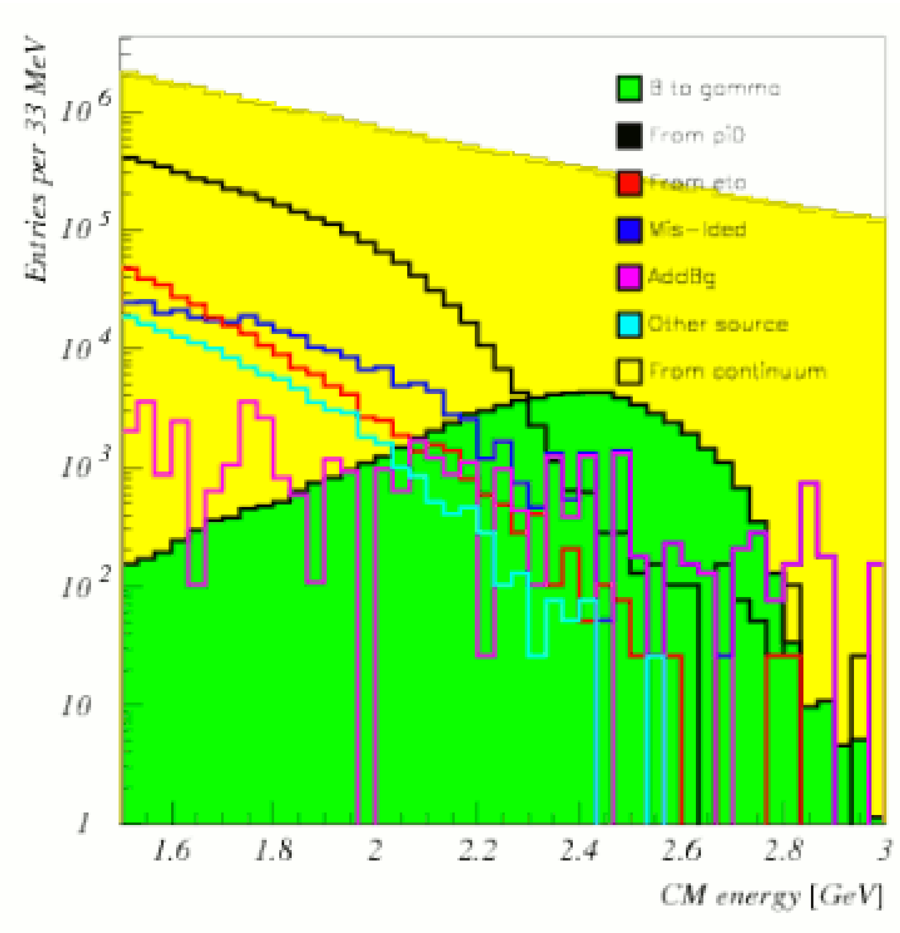


- But we measure $B \to X_s \gamma$ and in the B meson, the b quark is moving which smears the energy spectrum
  - → Mean $\sim \frac{m_B}{2}$
  - → Width ~ Fermi motion in B meson

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

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

$b \to s\gamma$ spectrum at Belle



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

- Be unbiased: only look at the γ
- B mesons only decay to γ via $b \to s\gamma$
- 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

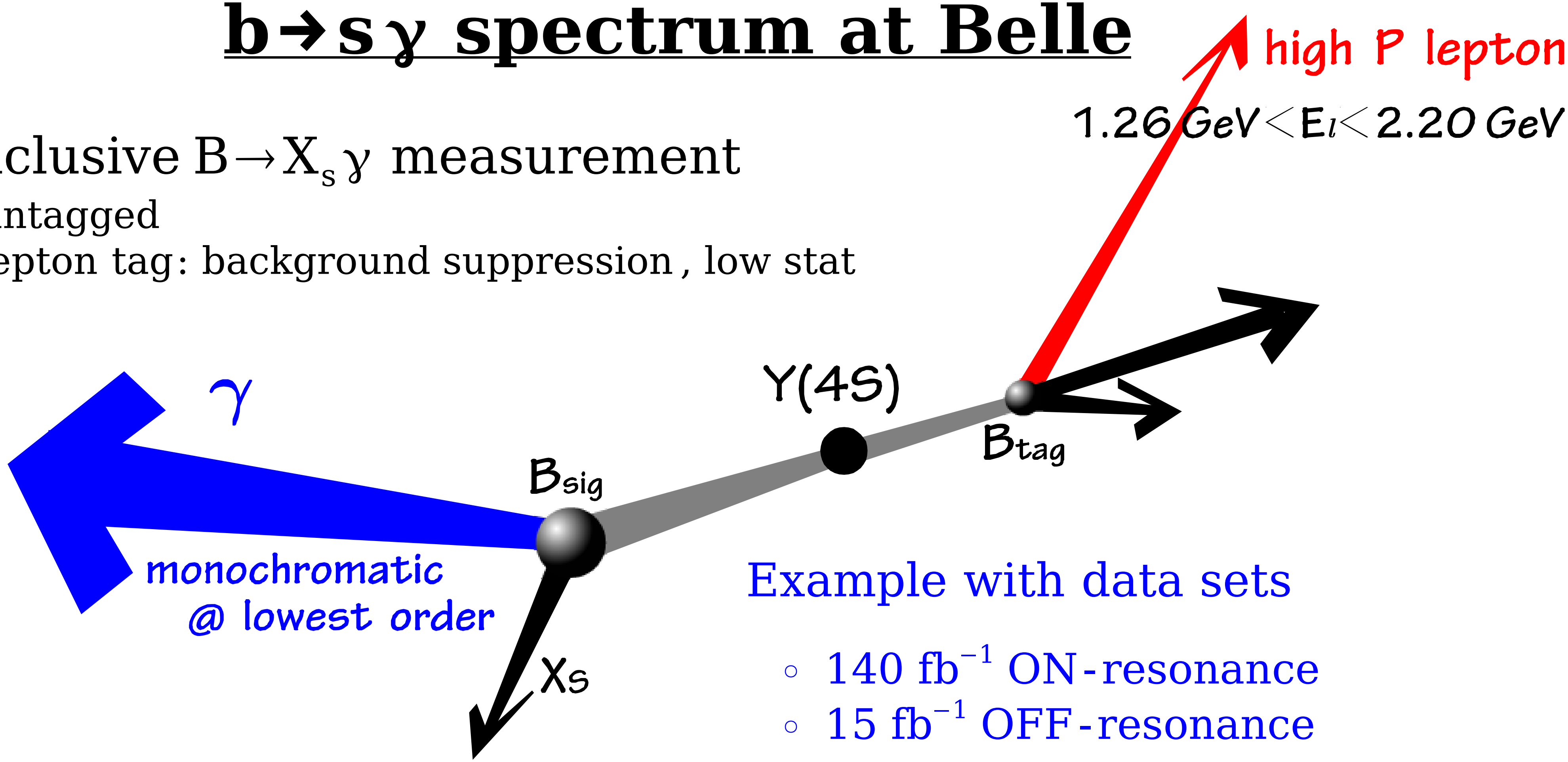
$\Rightarrow$ Lots of background at low energy

$b \to s\gamma$ spectrum at Belle

inclusive $B \to X_s \gamma$ measurement

untagged

lepton tag: background suppression, low stat



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

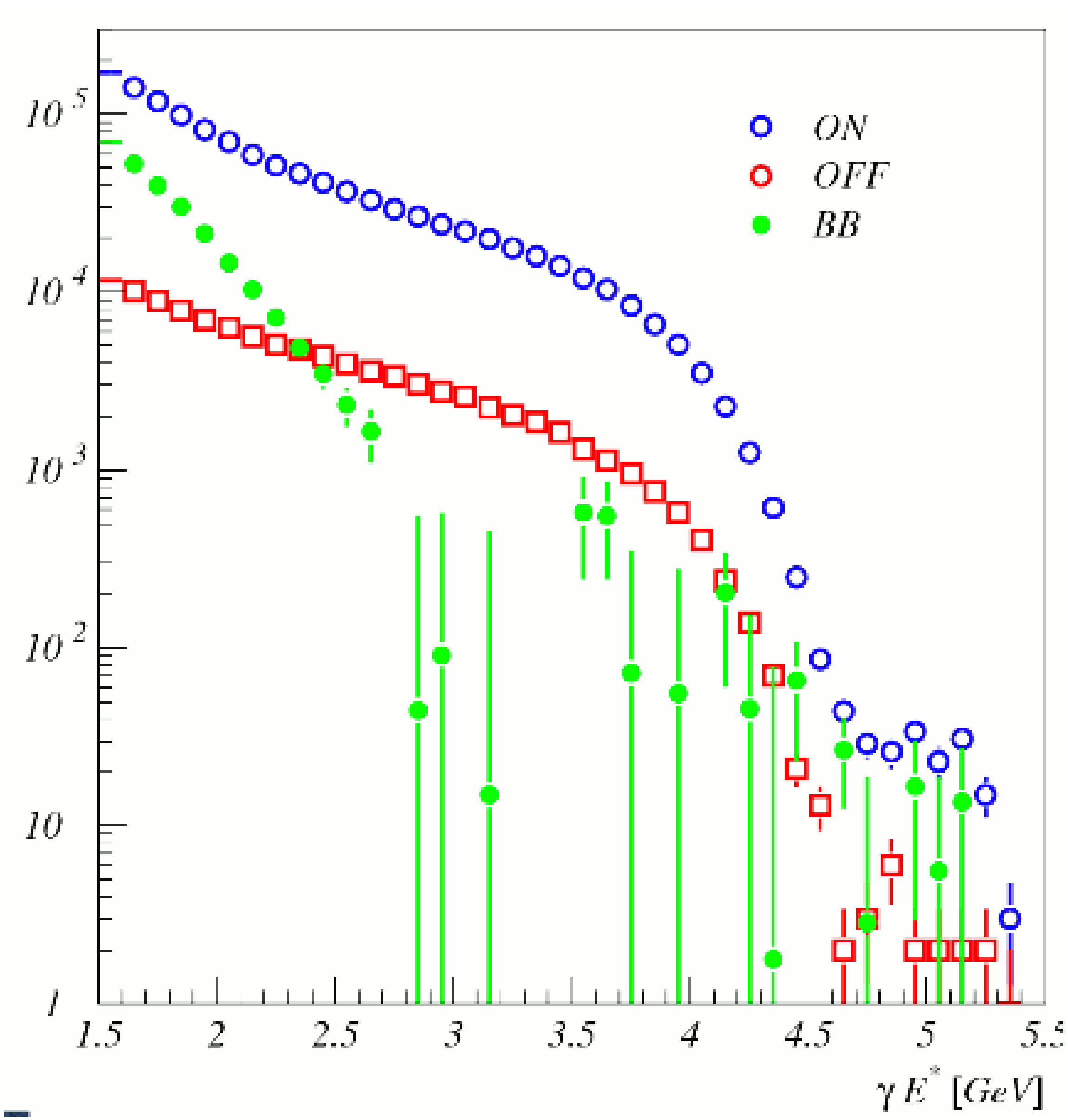
Example with data sets

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

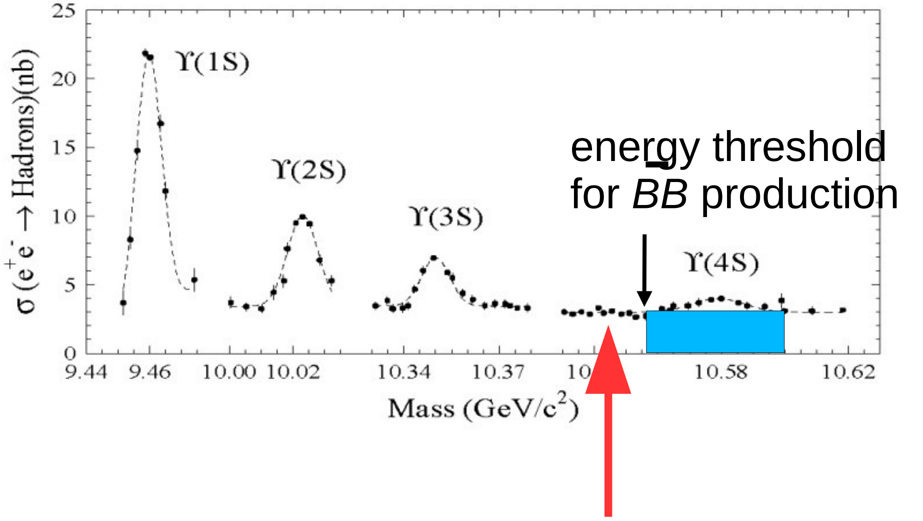
Event selection:

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

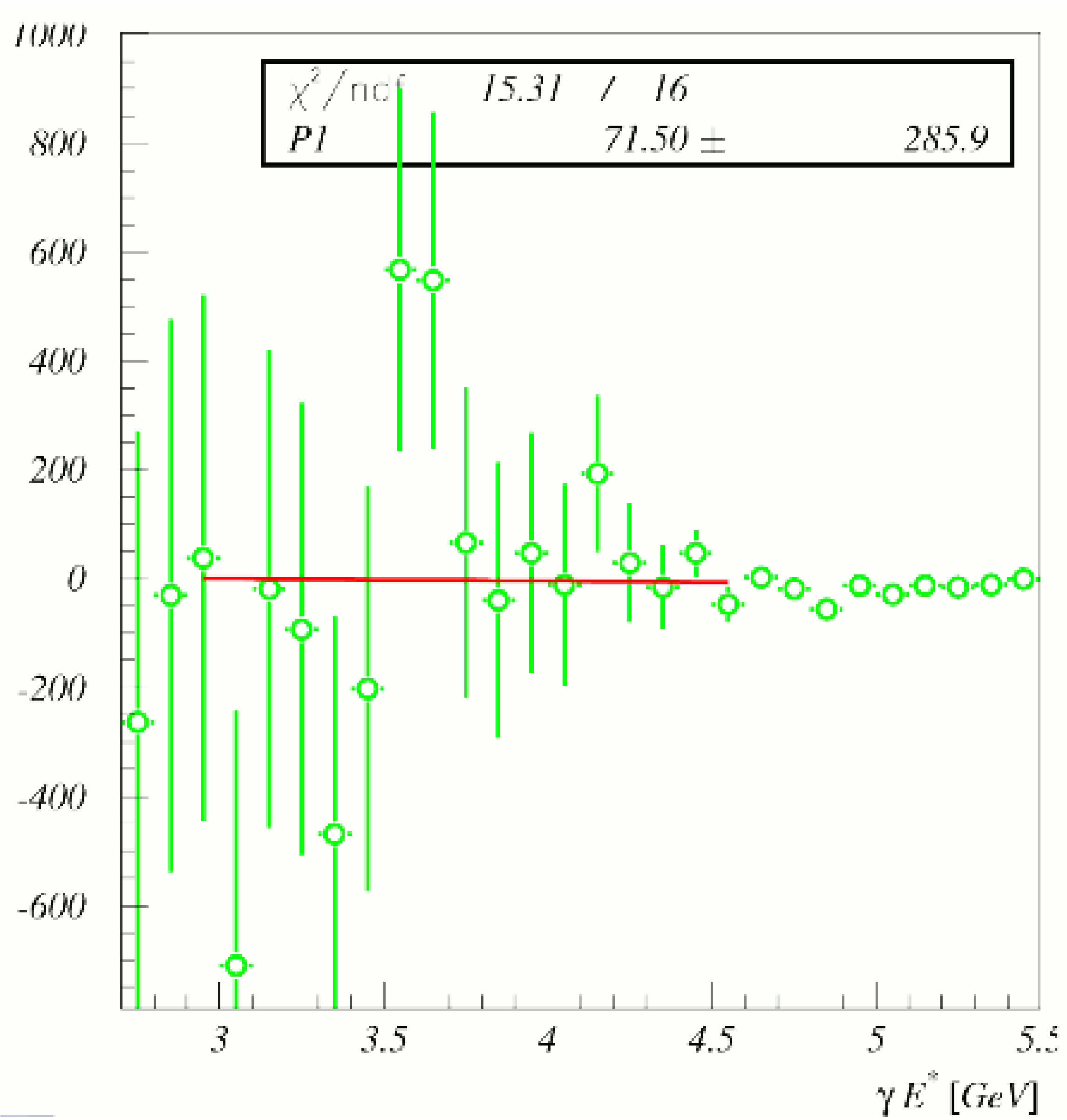
The spectrum



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



The spectrum



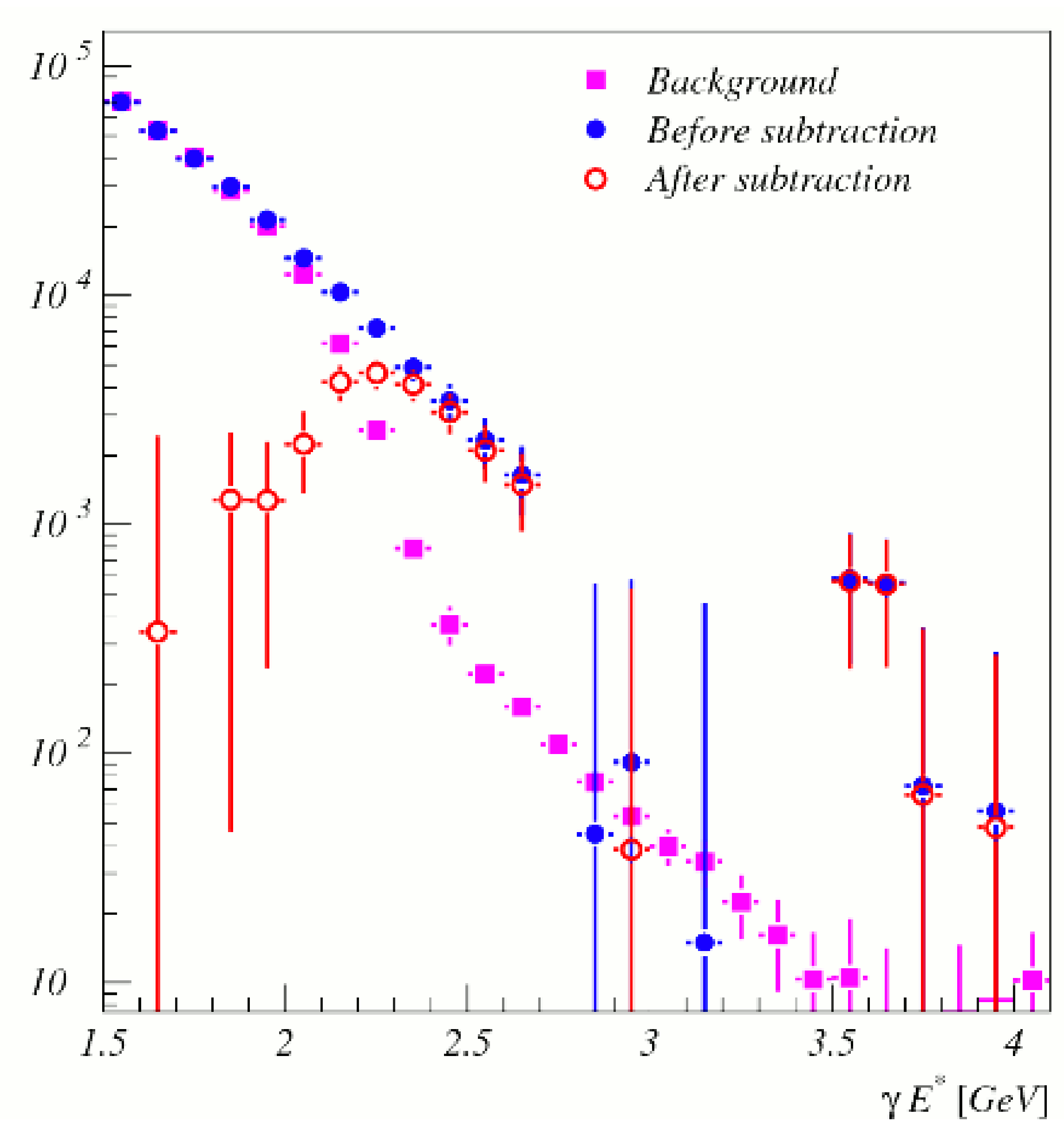
Endpoint check:

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

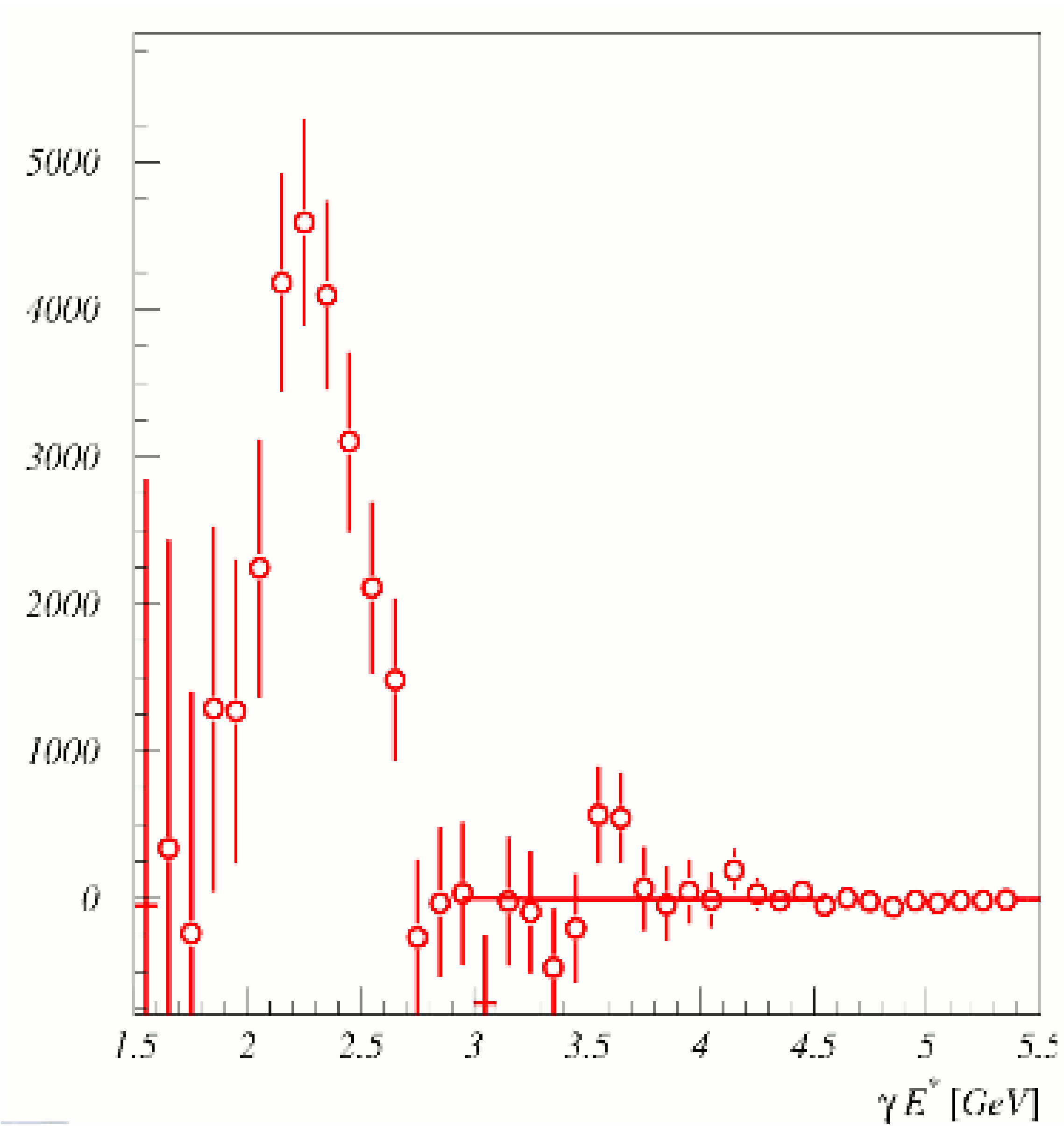
The spectrum



$B\bar{B}$ subtraction:

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

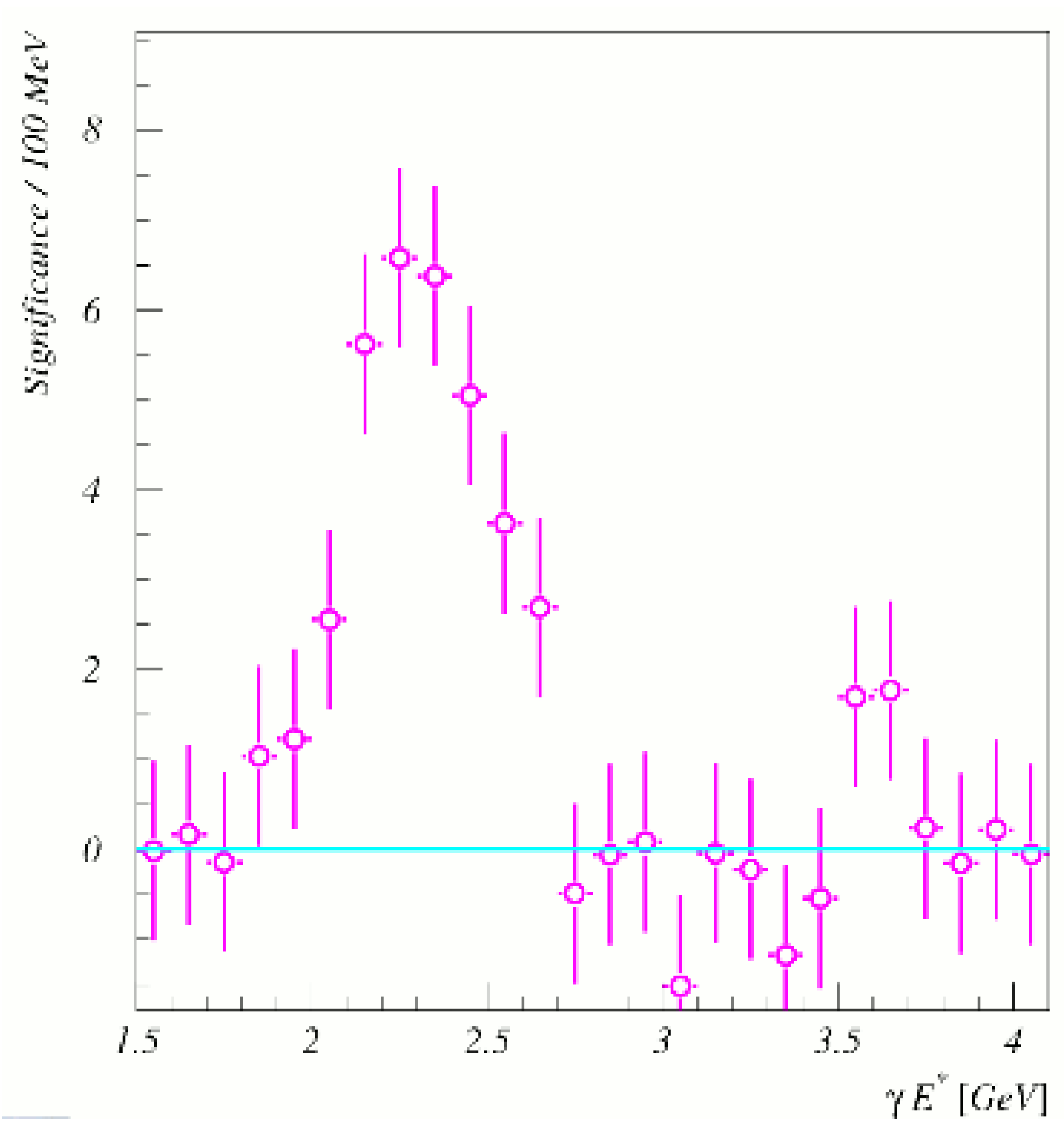
The spectrum



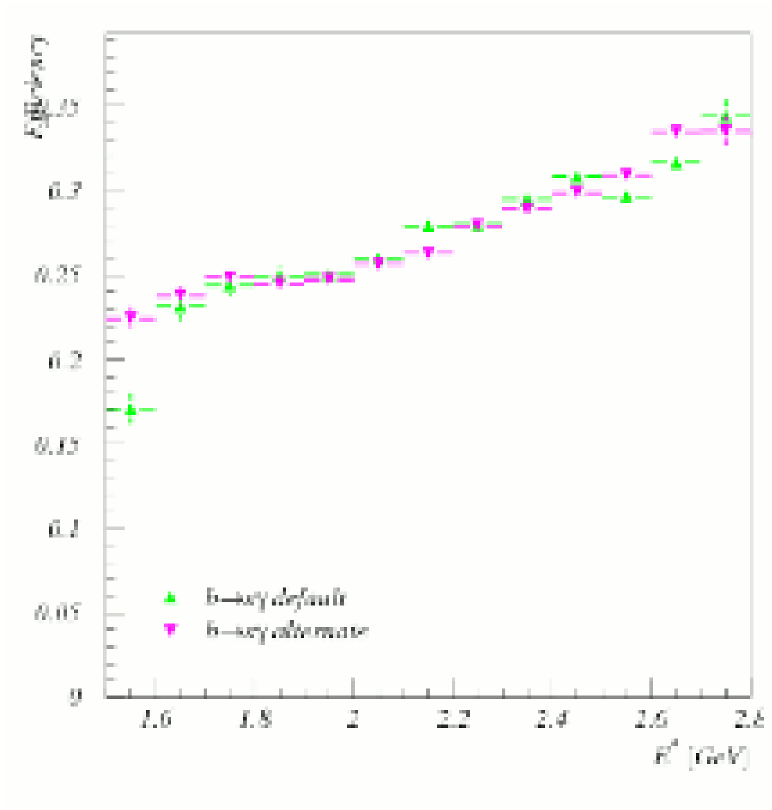
Raw spectrum after all cuts and background corrections

Signal yield : 24100 ±2200 events

The spectrum



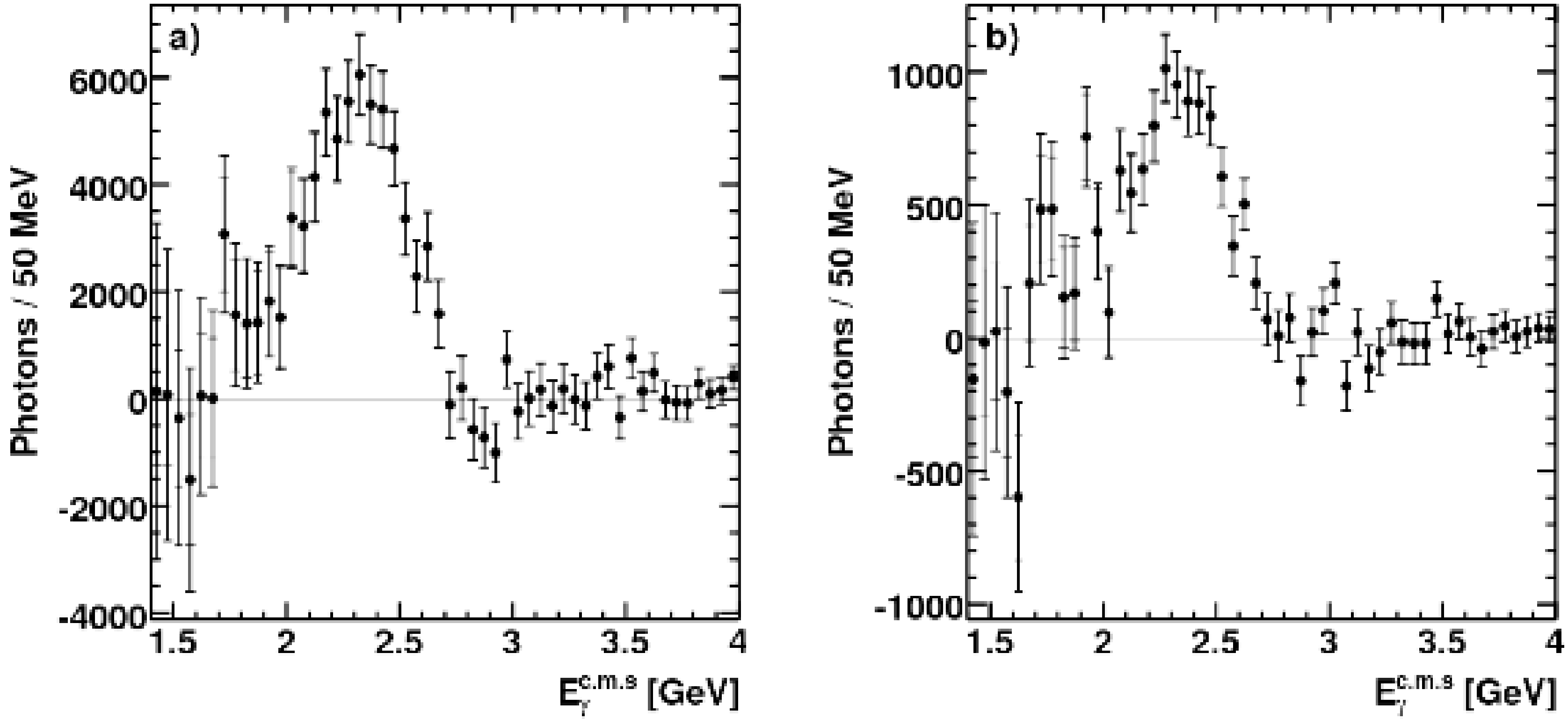
Efficiency corrected spectrum



$X_s \gamma$ inclusive

PRL 103, 241801 (2009)
arXiv:0907.1384

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



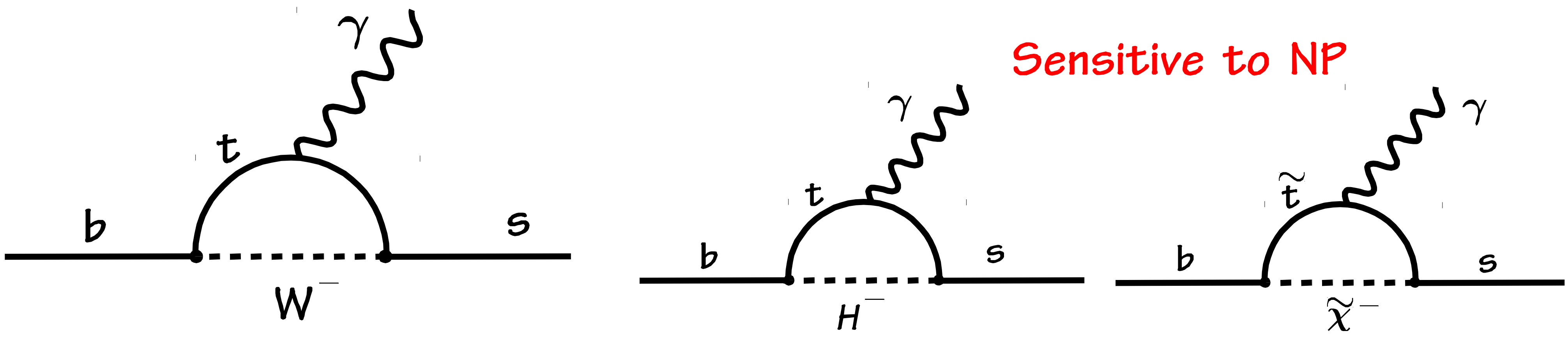
$$\mathcal{B}(B \to X_s \gamma) = (3.45 \pm 0.15 \pm 0.40) \times 10^{-4} \quad (\text{for } E_\gamma^* > 1.7 \text{ GeV})$$

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

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

- Most precise measurement of $\mathcal{B}(B \to X_s \gamma)$ (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 !

$B \to X_s \gamma$ as an illustration



NNLO SM calculation:

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

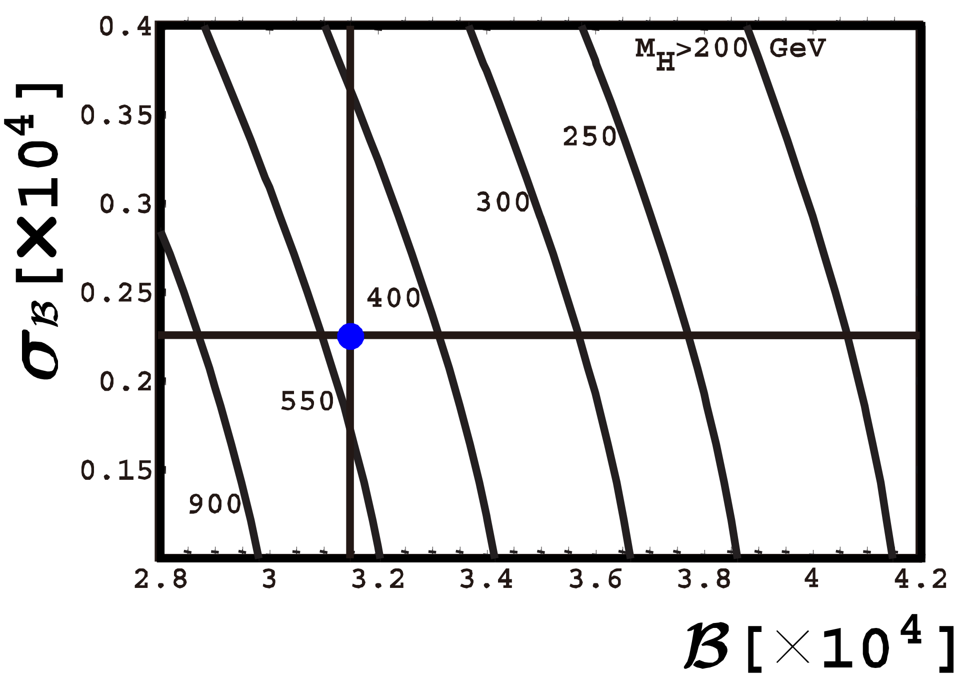
(for $E_\gamma > 1.6$ GeV)

M. Misiak et al.
[arXiv:1503.01789]

(central value increased by 6.4% compared to 2007 value)
PRL 98, 022002 (2007)

The lower γ 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)



$\mathbf{B \to X_s \gamma}$

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

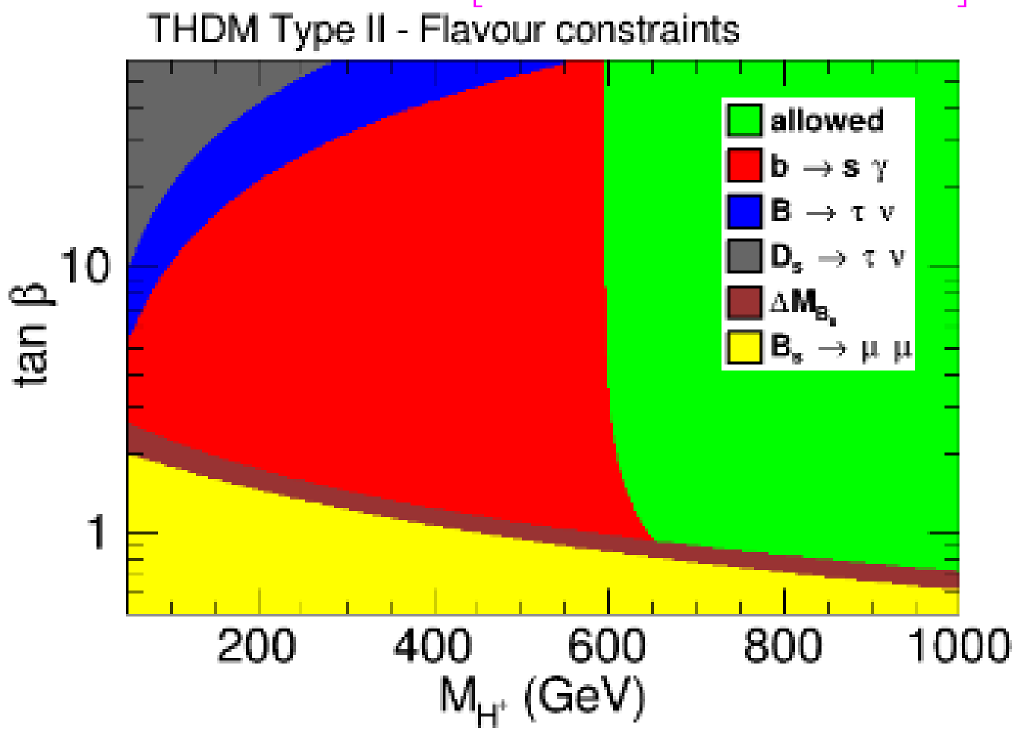
vs

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

[Misiak et al, arXiv:1503.01789]

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

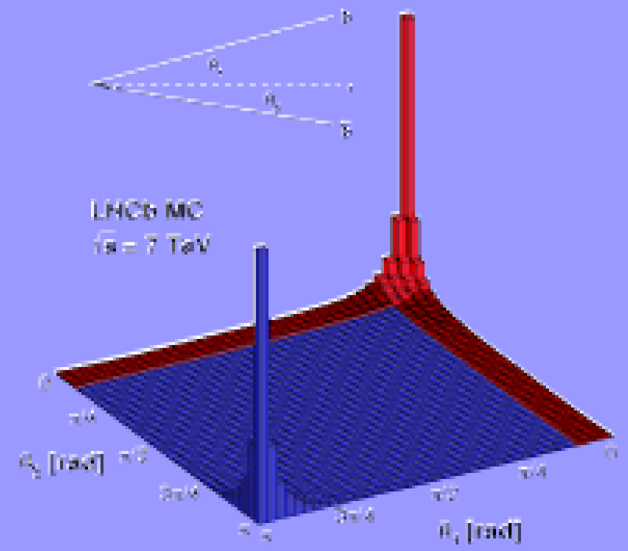
[arXiv:1706.07414]

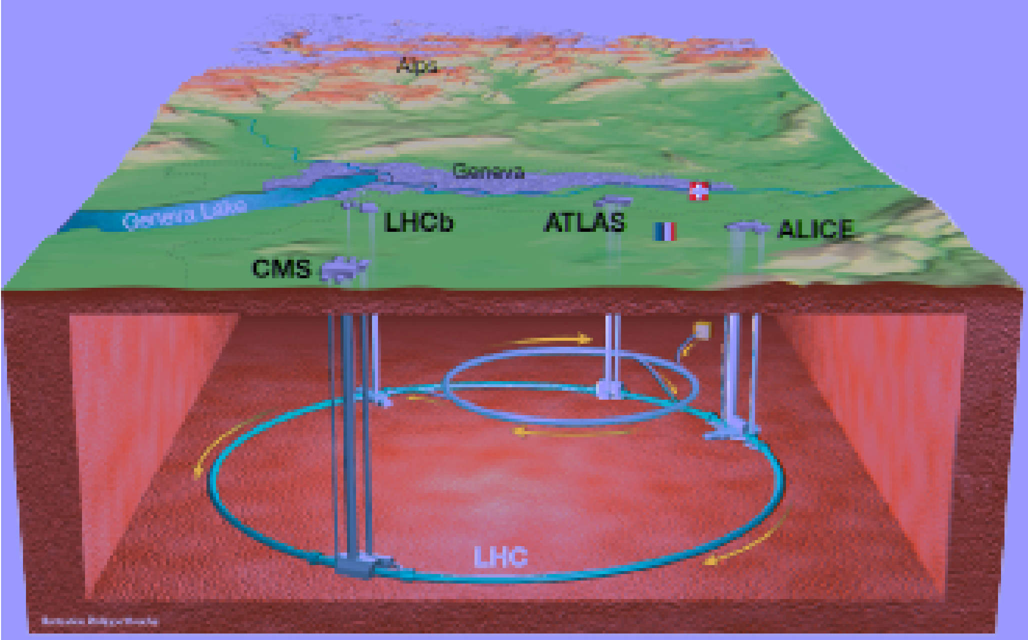


Rare B decays at LHCb

LHCb is ...

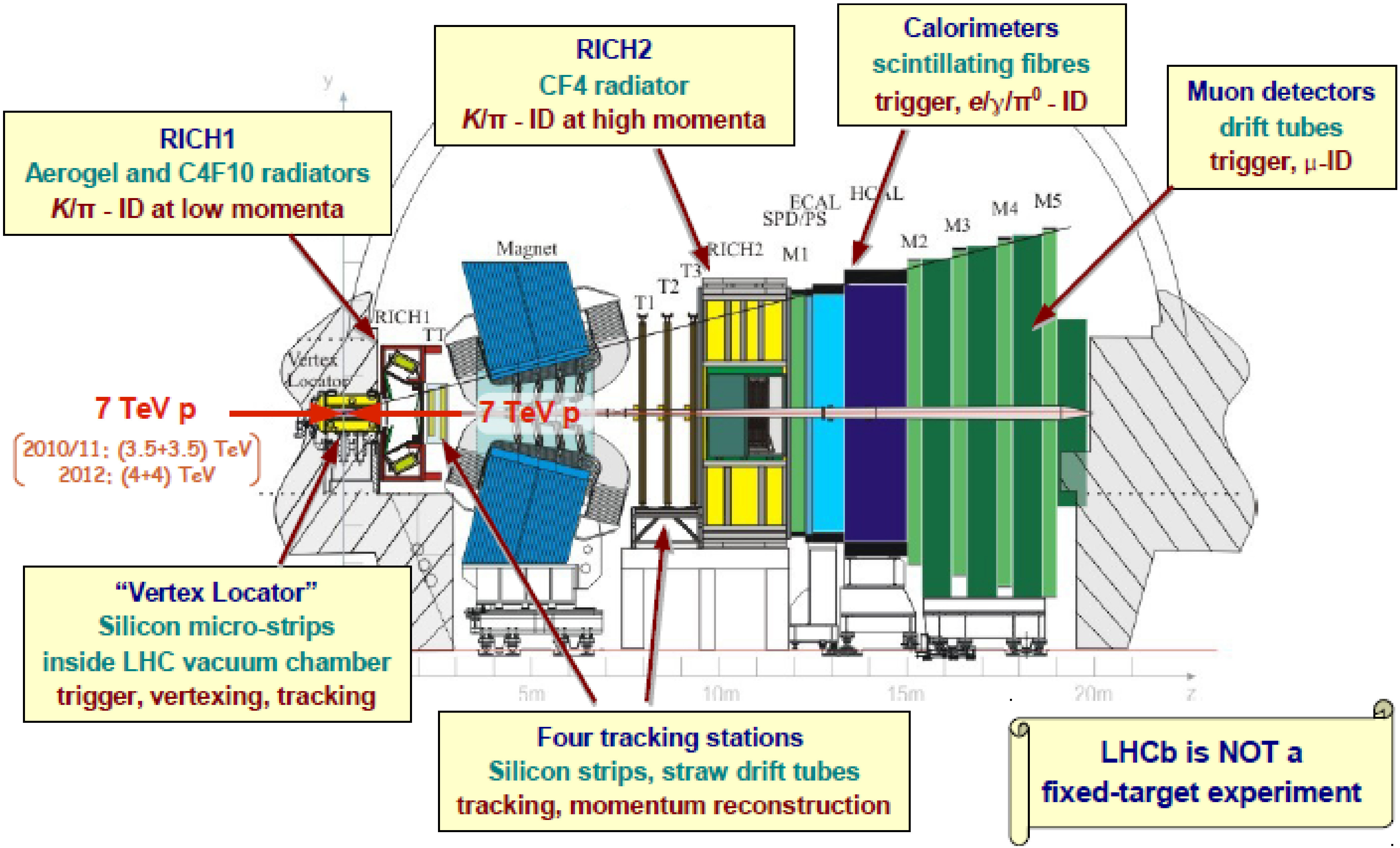
- 1075 members, from 68 institutes in 17 countries (September 2014)
- Dedicated experiment for precision measurements of CP violation and rare decays
- *Beautiful*, *charming*, *strange* physics program





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

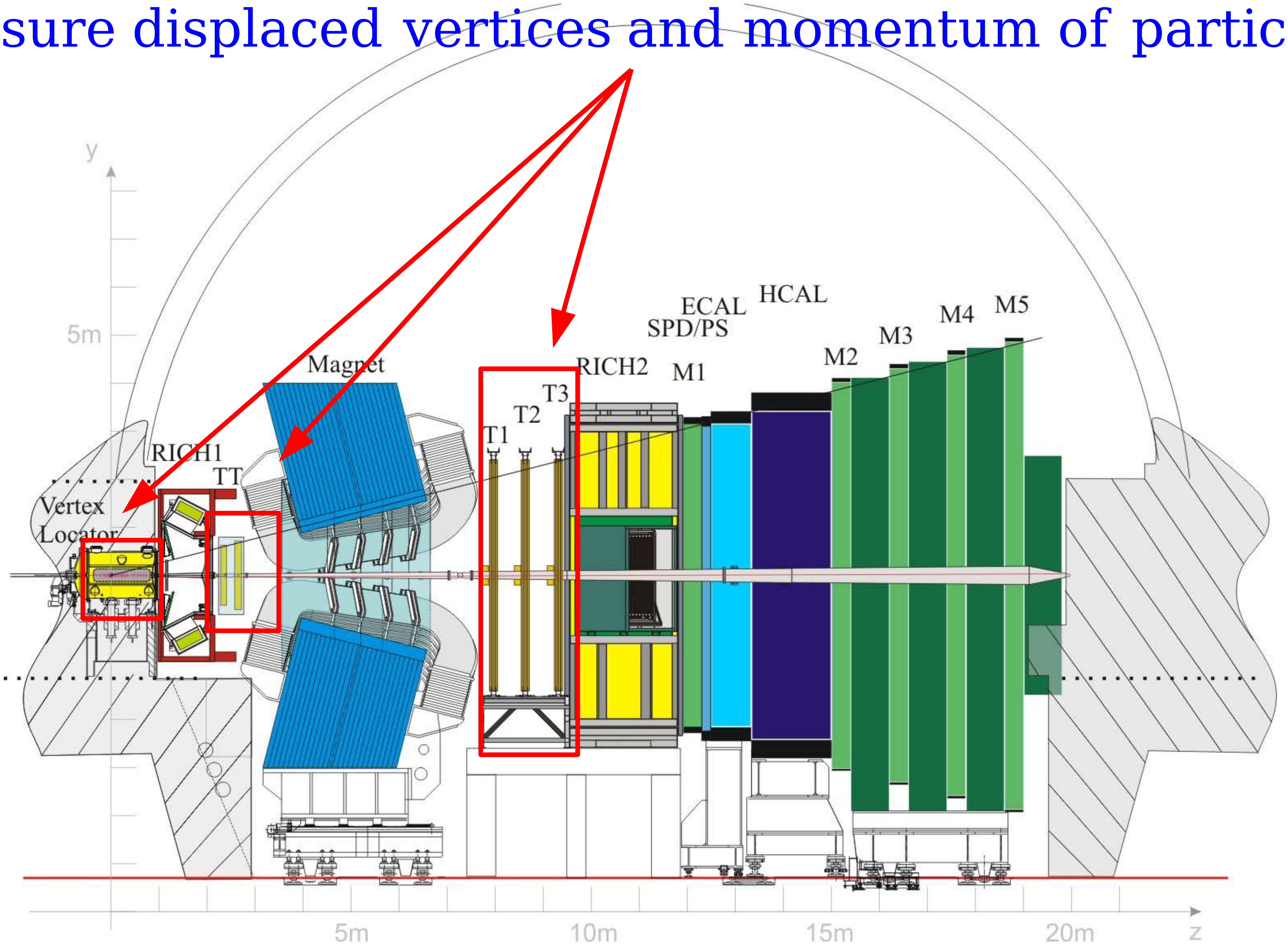
LHCb


RICH1
Aerogel and C4F10 radiators
K/π - ID at low momenta
RICH2
CF4 radiator
K/π - ID at high momenta
Calorimeters
scintillating fibres
trigger, e/γ/π⁰ - ID
Muon detectors
drift tubes
trigger, μ-ID
7 TeV p
7 TeV p
(2010/11: (3.5+3.5) TeV
2012: (4+4) TeV)
Magnet
RICH1
TT
Vertex
Locator
T1
T2
T3
RICH2
M1
SPD/PS
ECAL
HCAL
M2
M3
M4
M5
5m
10m
15m
20m
z
y
"Vertex Locator"
Silicon micro-strips
inside LHC vacuum chamber
trigger, vertexing, tracking
Four tracking stations
Silicon strips, straw drift tubes
tracking, momentum reconstruction
LHCb is NOT a
fixed-target experiment

LHCb

Tracking system

Measure displaced vertices and momentum of particles



Vertex and IP resolution

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

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

Momentum resolution

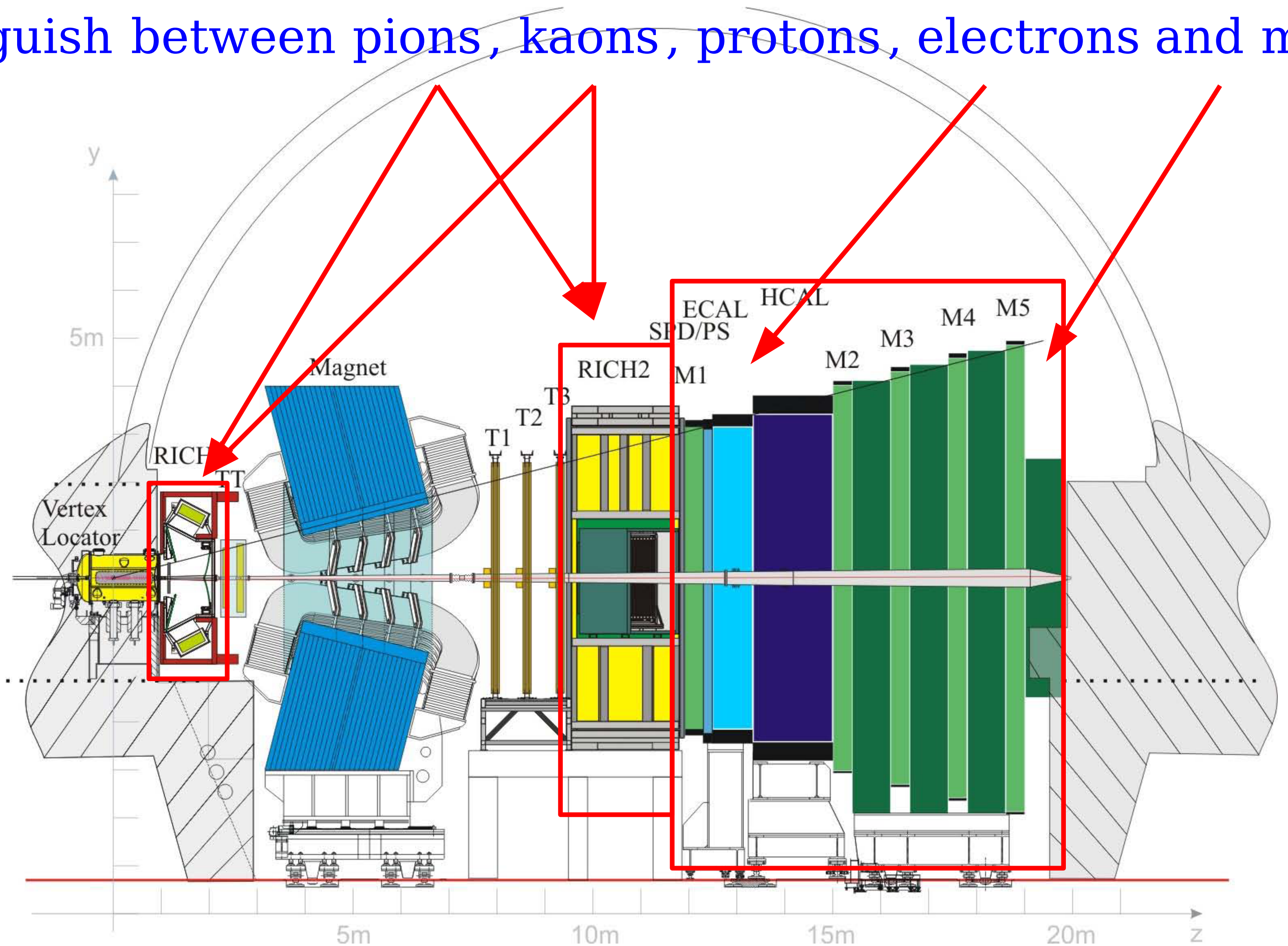
$\sigma(p)/p = 0.4\%$-0.6% for $p \in [0, 100]$ GeV/c

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

LHCb

Particle identification

Distinguish between pions, kaons, protons, electrons and muons



Kaon identification

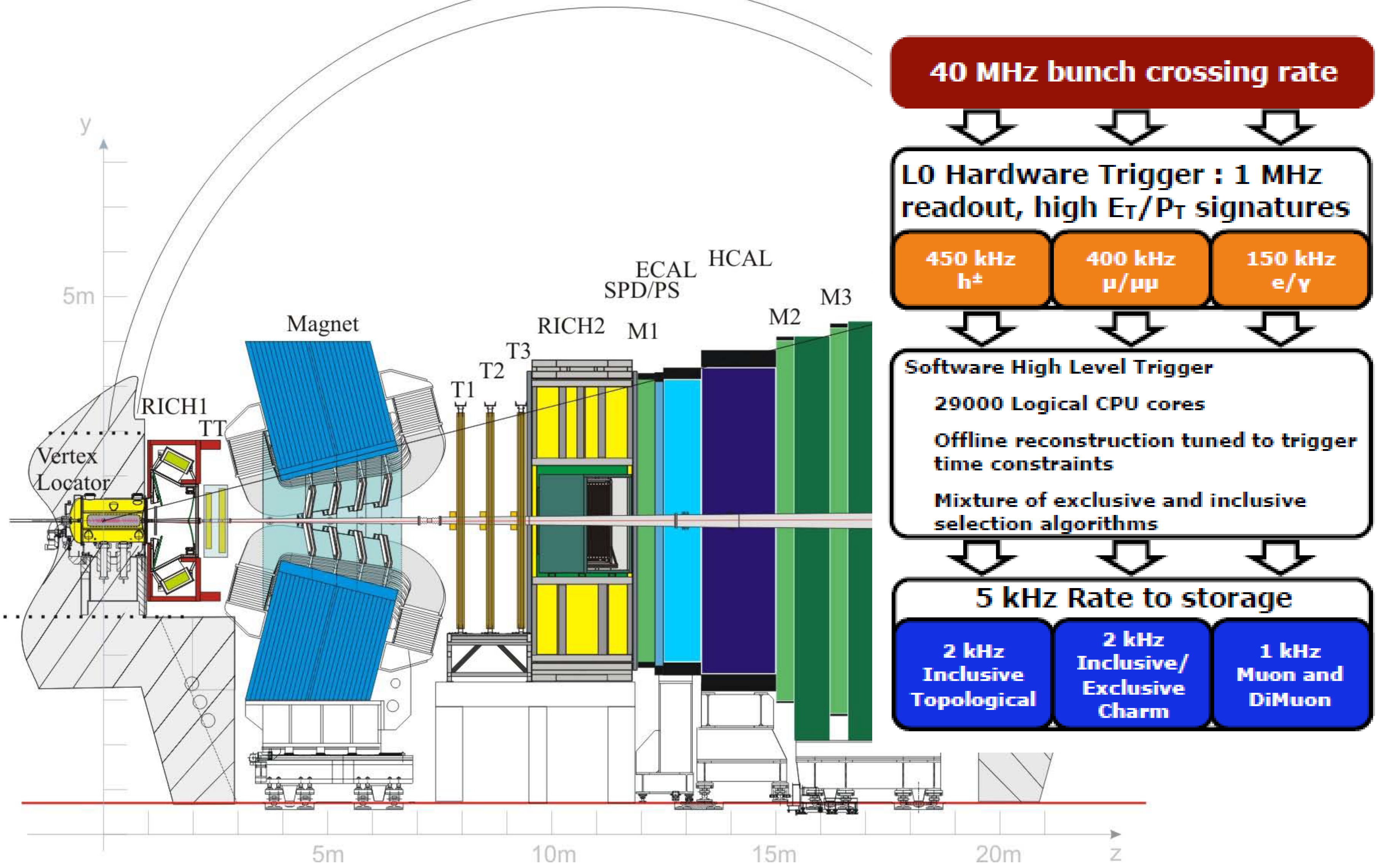
$\epsilon_K \sim 95\%$, $\epsilon_{\pi\to K}$ few%

Muon identification

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

LHCb

Trigger system
Write out 5000 events/sec



Belle(II), LHCb side by side

(in the context of B anomalies)

Belle (II)

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

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

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

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

LHCb

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

production of B^+, B^0, B_s, B_c, Λ_b...
but also a lot of other particles in the event

⇒ lower reconstruction efficiencies

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

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

$b\bar{b}$ production cross-section ~ 5× Tevatron, ~ 500,000 × BaBar/Belle !!

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

⇒ lower trigger efficiencies

B mesons live relativey long

mean decay length $\beta\gamma c\tau \sim 200\,\mu m$

mean decay length $\beta\gamma c\tau \sim 7$ mm

data taking period(s)

[1999-2010] = 1 ab^{-1}

[run I: 2010-2012] = 3 fb^{-1},
[run II: 2015-2018] = 2 fb^{-1} → 8 fb^{-1} ?

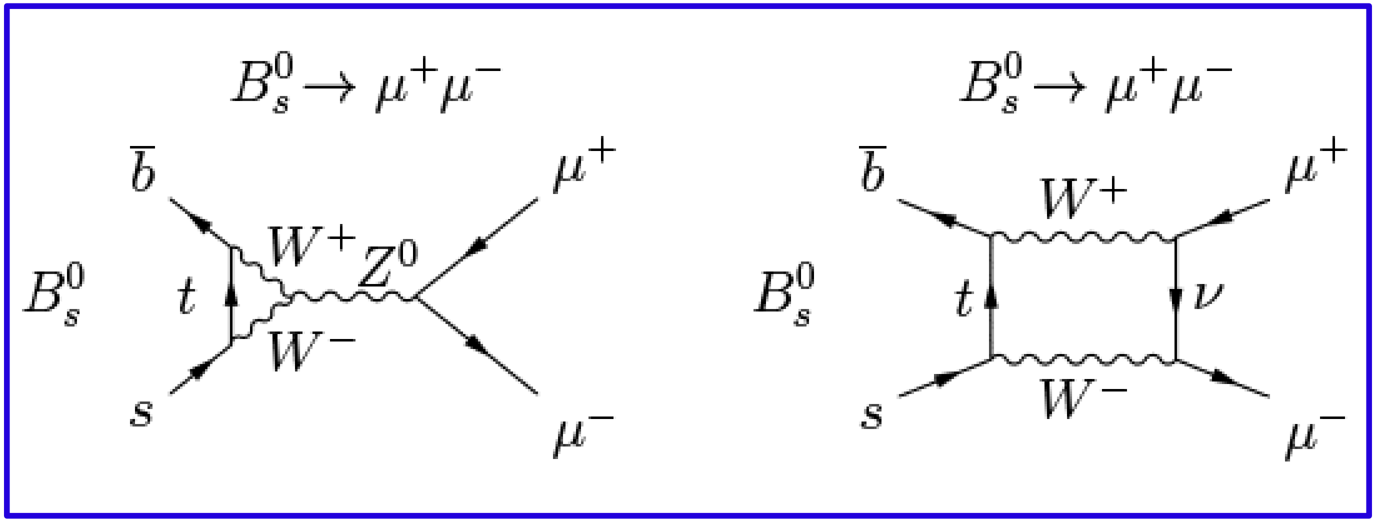
(near) future

[Belle II from 2018] → 50 ab^{-1}

[LHCb upgrade from 2020]

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

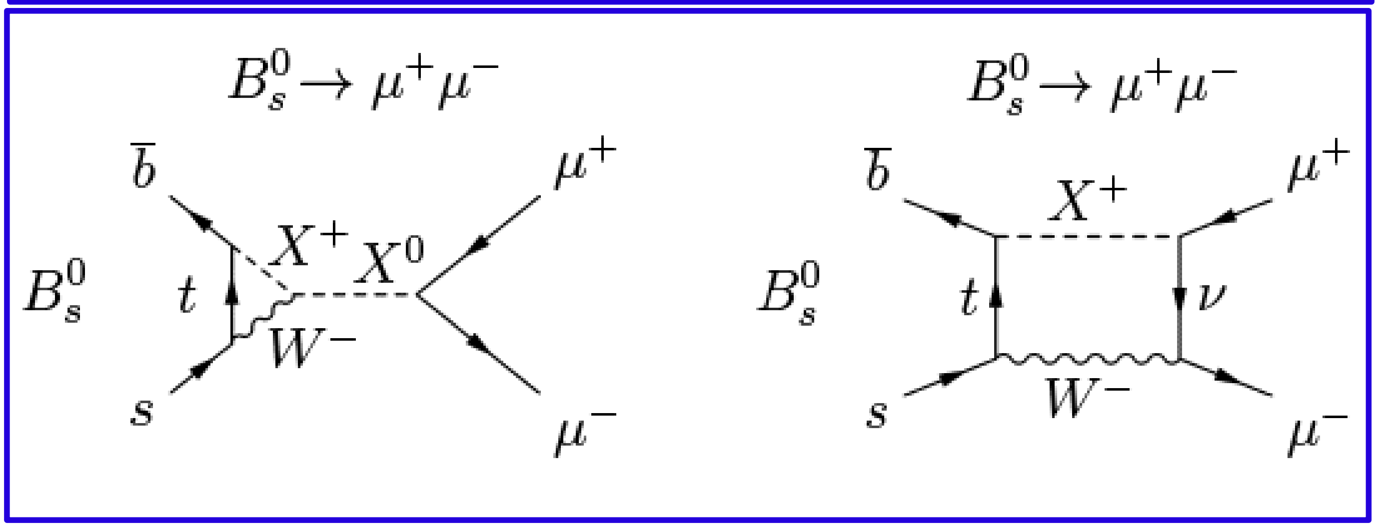
loop diagram + suppressed in SM + theoretically clean =
an excellent place to look for new physics



higher-order FCNC allowed in SM

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

[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

$$B^0_{(s)} \to \ell^+\ell^-$$

$$BR(B^0_{(q)} \to \ell^+\ell^-) = \frac{\tau_B G_F^4 M_W^2 sin^4\theta_W}{8\pi^5}|C_{10}V_{tb}V^*_{tq}|F_B^2 m_B m_\ell^2 \times \left|\sqrt{1-\frac{4m_\ell^2}{m_B^2}}\right.$$

Branching ratio proportional to the lepton mass squared

$$\frac{BR(B^0_{(q)} \to \tau^+\tau^-)}{BR(B^0_{(q)} \to \mu^+\mu^-)} \sim \frac{m_\tau^2}{m_\mu^2} \qquad \frac{BR(B^0_{(q)} \to \mu^+\mu^-)}{BR(B^0_{(q)} \to e^+e^-)} \sim \frac{m_\mu^2}{m_e^2}$$

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

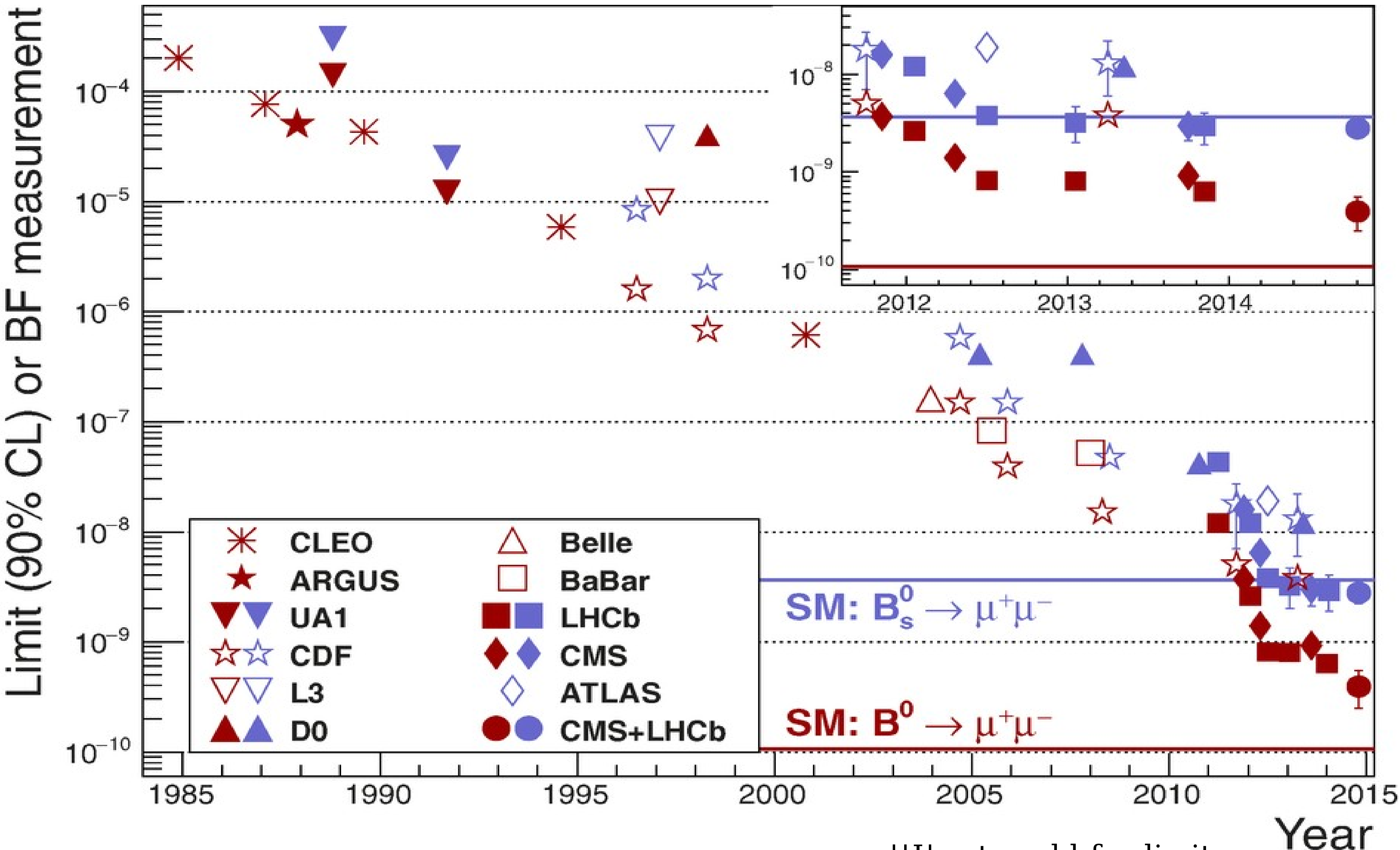
$$\frac{BR(B^0_{(d)} \to \mu^+\mu^-)}{BR(B^0_{(s)} \to \mu^+\mu^-} = \frac{\tau_{B^0_d}}{\tau_{B^0_s}}\frac{m_{B^0_d}}{m_{B^0_s}}\frac{F_{B^0_d}}{F_{B^0_s}}(\frac{V_{td}}{V_{ts}})^2$$

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

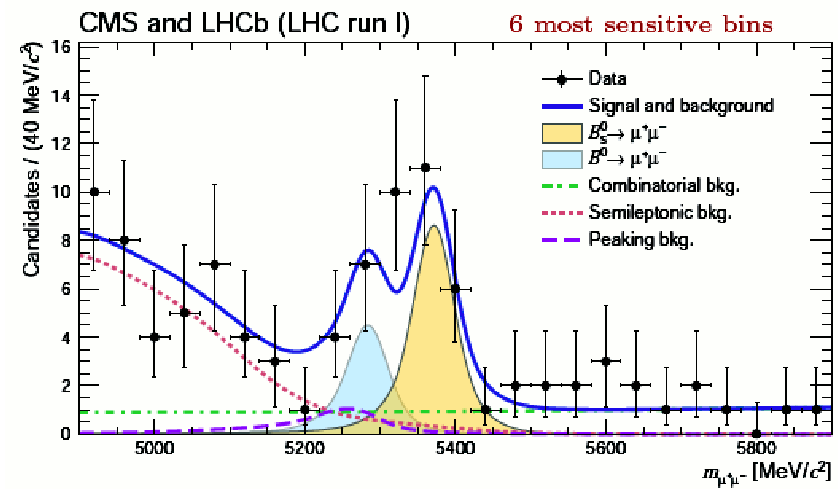
$$BR(B^0_s \to \mu^+\mu^-) \propto (1-\frac{4m_\ell^2}{m_B^2})|C_S - C'_S|^2 + |(C_P - C'_P)^2 + 2\frac{m_\ell^2}{m_B^2}(C_{10} - C'_{10})|^2$$

$B_{(s)} \to \mu\mu$: ultra rare processes…



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

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



$$B(B_s^0 \to \mu^+\mu^-) = (2.8\,^{+0.7}_{-0.6}) \times 10^{-9}$$

first observation: 6.2σ significance

$$B(B^0 \to \mu^+\mu^-) = (3.9\,^{+1.6}_{-1.4}) \times 10^{-10}$$

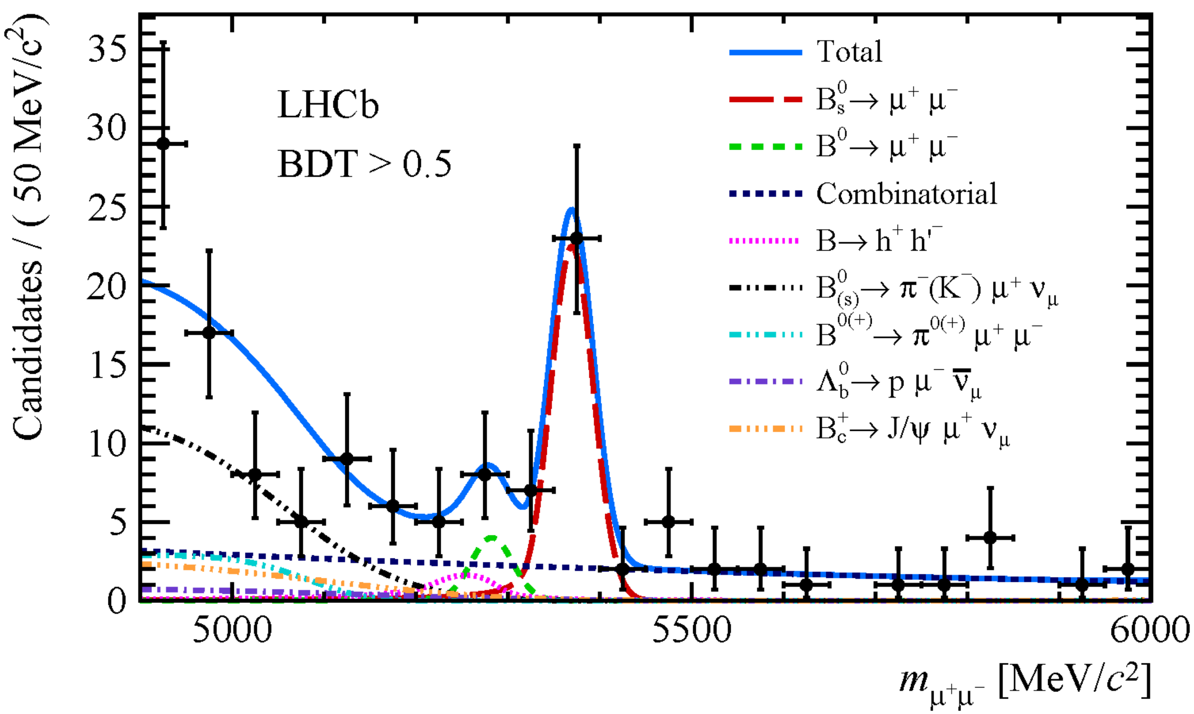
first evidence: 3.0σ significance

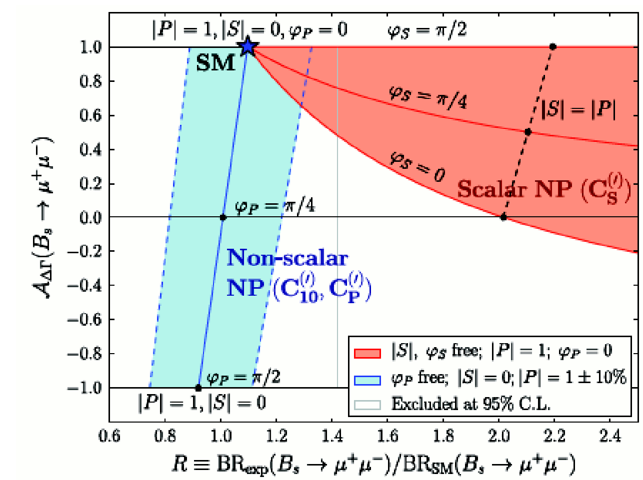
[arXiv:1703.05747]

SM: heavy state decays to $\mu^+\mu^-$

first lifetime measurement:

$\tau(B_s \to \mu^+\mu^\pm) = 2.04 \pm 0.44 \pm 0.05$ ps





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

$$\mathbf{B(B_s^0 \to \mu^+\mu^-) = (3.0 \pm 0.6\,^{+0.3}_{-0.2}) \times 10^{-9}\ (7.8\sigma\ significance)}$$

$$\mathbf{B(B^0 \to \mu^+\mu^-) < 3.4 \times 10^{-10}\ @\ 90\%\,CL}$$

Constraints on NP models