Beautiful paths to probe physics beyond the standard model of particles

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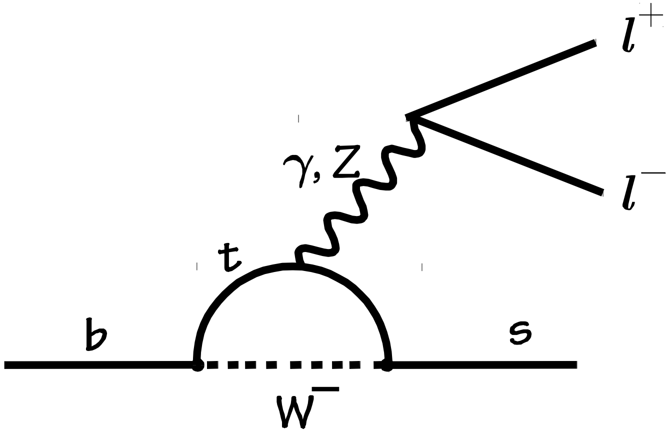
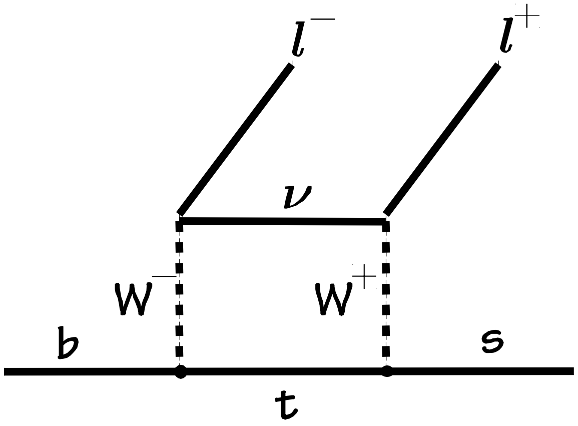
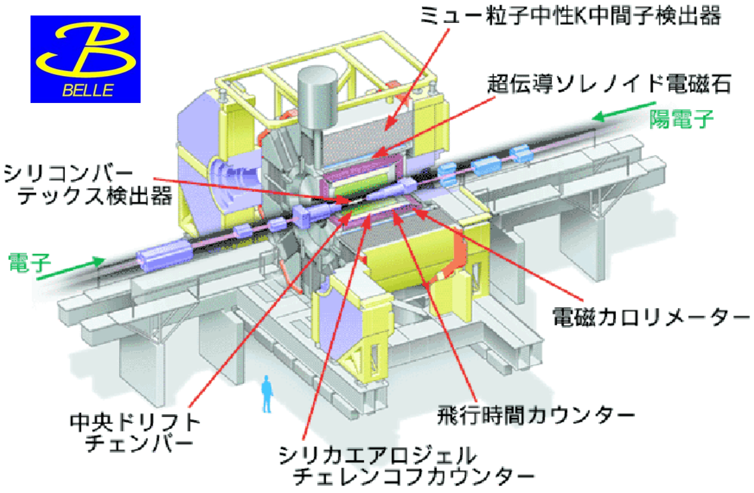
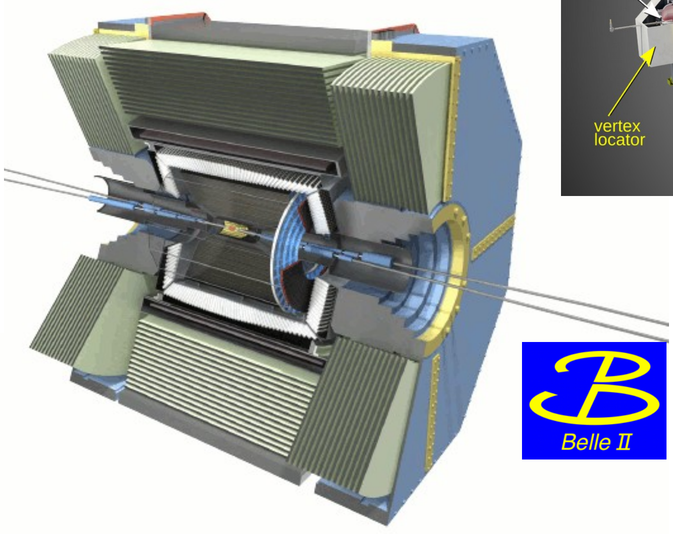
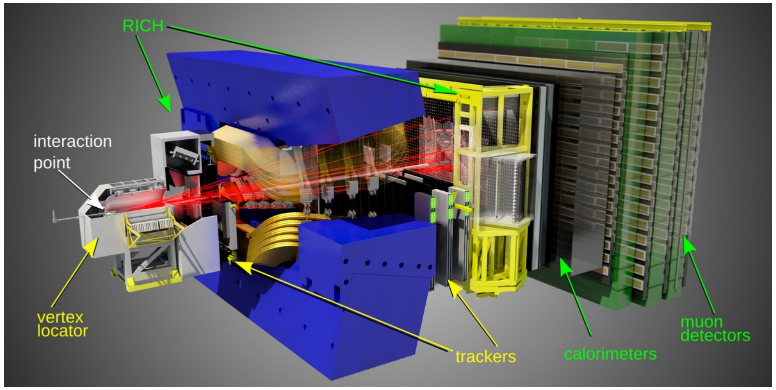






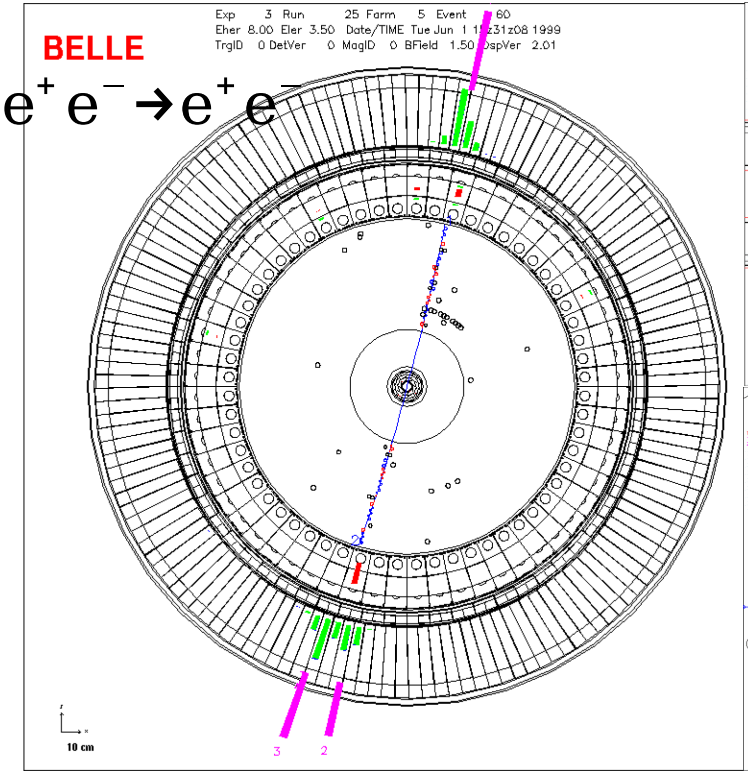


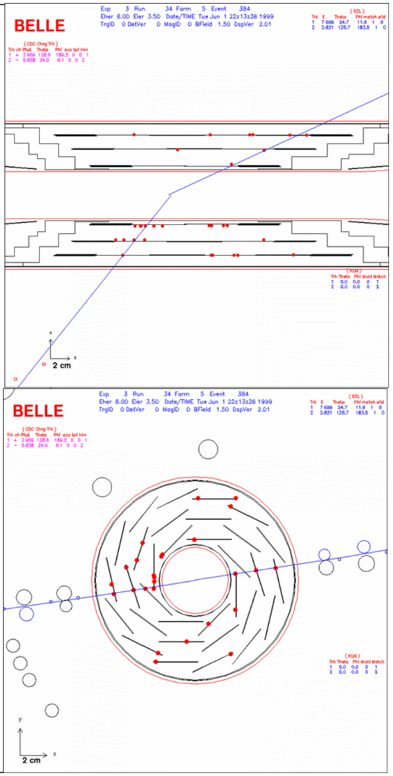


Future Flavours: Prospects for Beauty, Charm and Tau Physics , April 2022

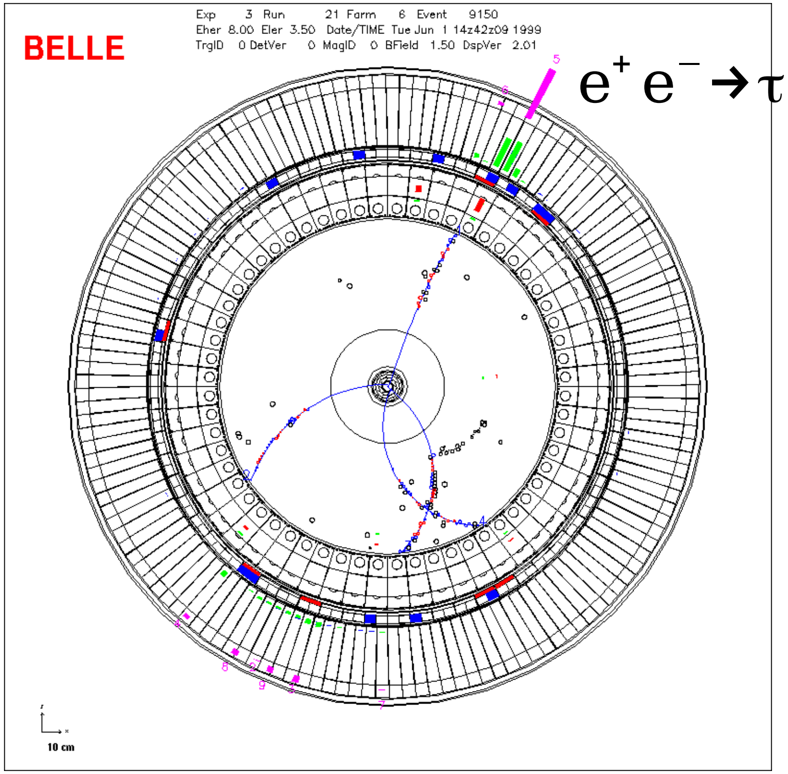
How to detect particles in Belle

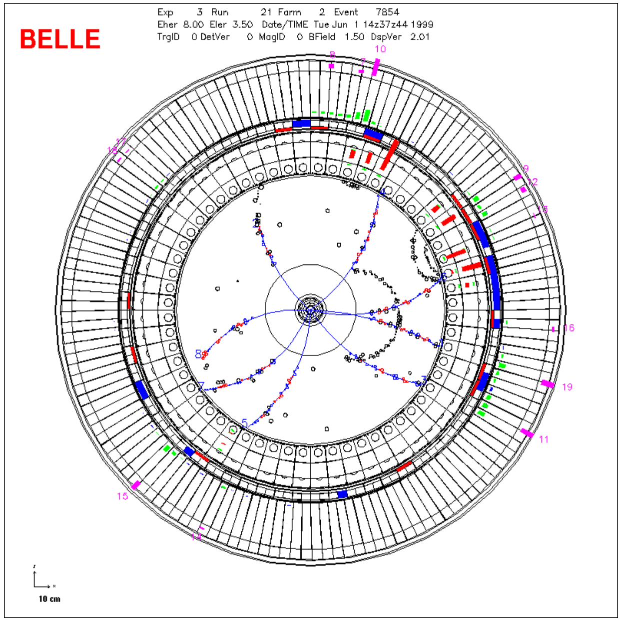
$e^+e^- \to e^+e^-$

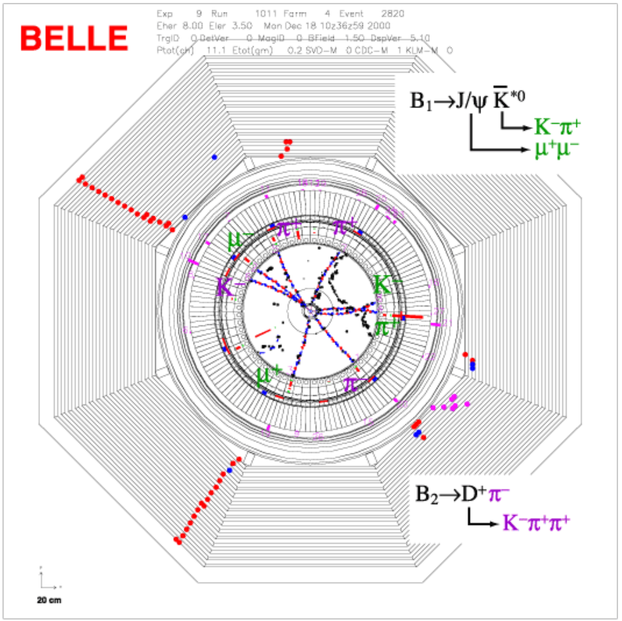


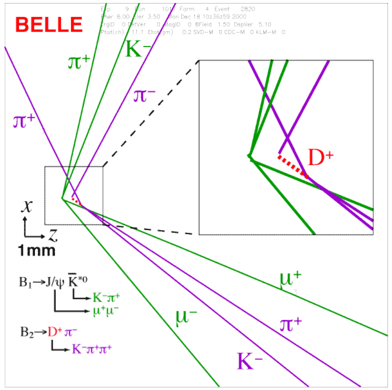


$e^+e^- \to \tau^+\tau^-$



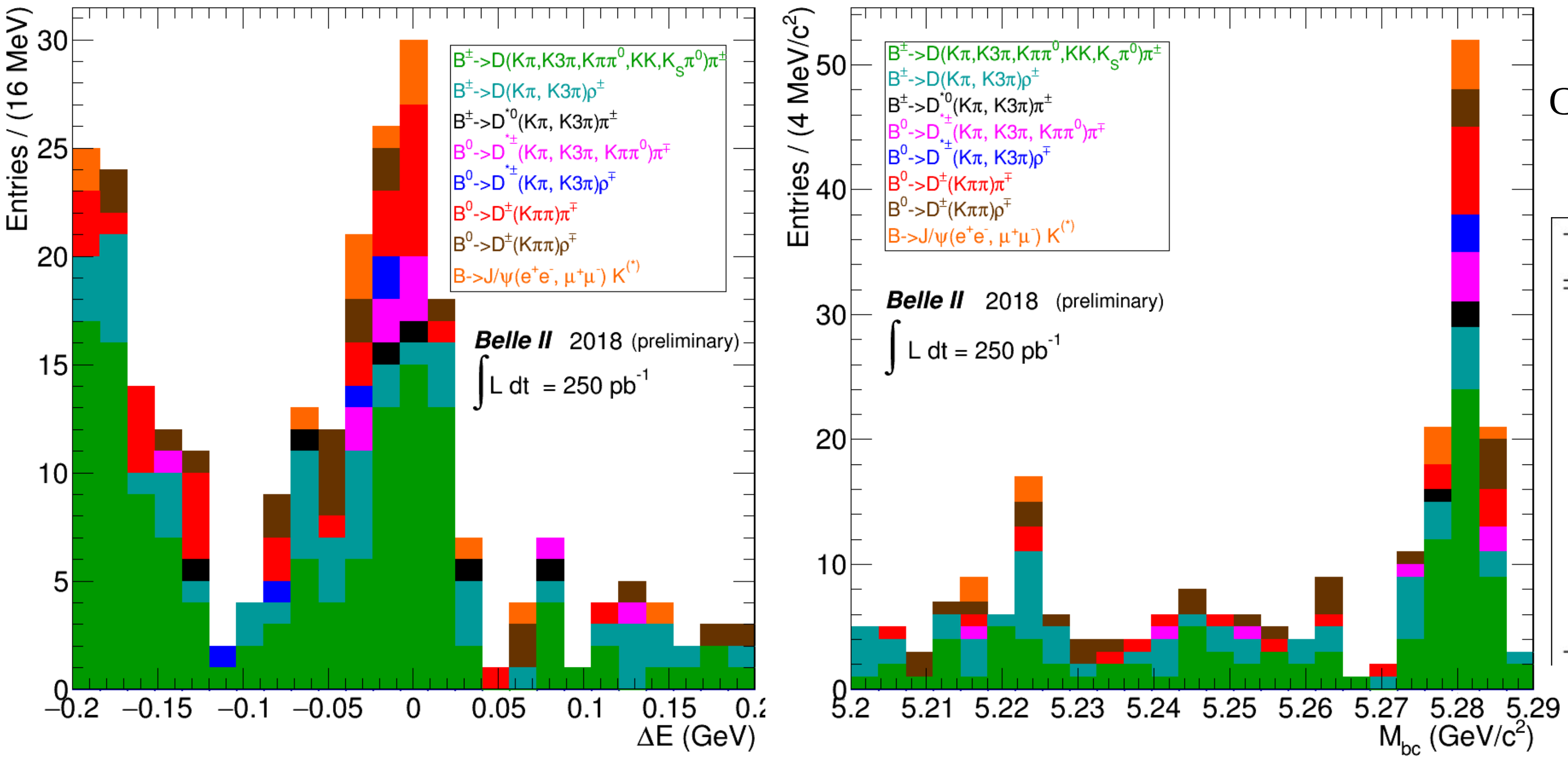






Rediscovering beauty: $B \rightarrow D^{(*)}h$ + $B \rightarrow J/\psi K^{(*)}$

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



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

~ 100 evts

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

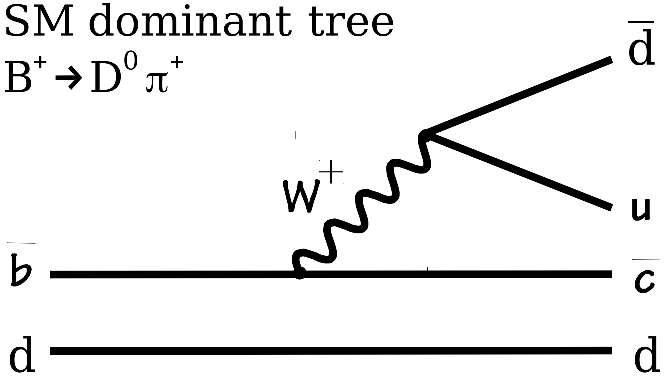
- D^0, D^+, D^*
- Cabibbo favoured and suppressed modes

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

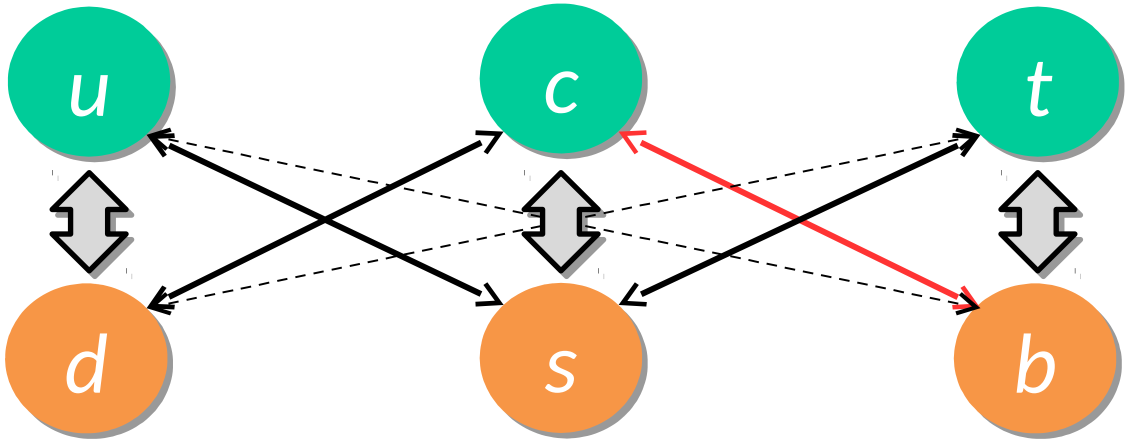
...for B-physics

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

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



But you said ''rare B decays''...



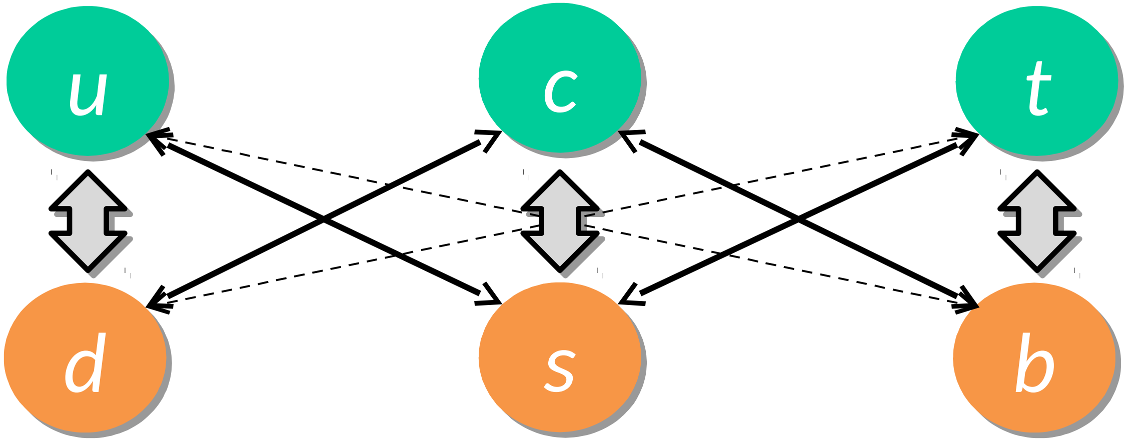
What are rare decays ?

Dominant decays: Not rare

Phase space suppressed decays: Not that rare

Cabibbo-suppressed decays: Some call them rare

$B(D^0 \to K^- \pi^+)$ versus $B(D^0 \to \pi^- \pi^+)$ $B(b \to c\, l^+ \nu)$ versus $B(b \to u\, l^+ \nu)$



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

What are rare decays ?

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Colour-suppressed decays: Not really rare

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

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

What are rare decays ?

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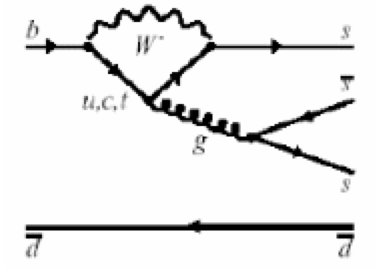
Colour-suppressed decays: Not really rare

Hadronic FCNC decays: Not the topic of our lecture

- For instance $B\to\phi K^0_S$, or $B\to K^0_S K\pi$...



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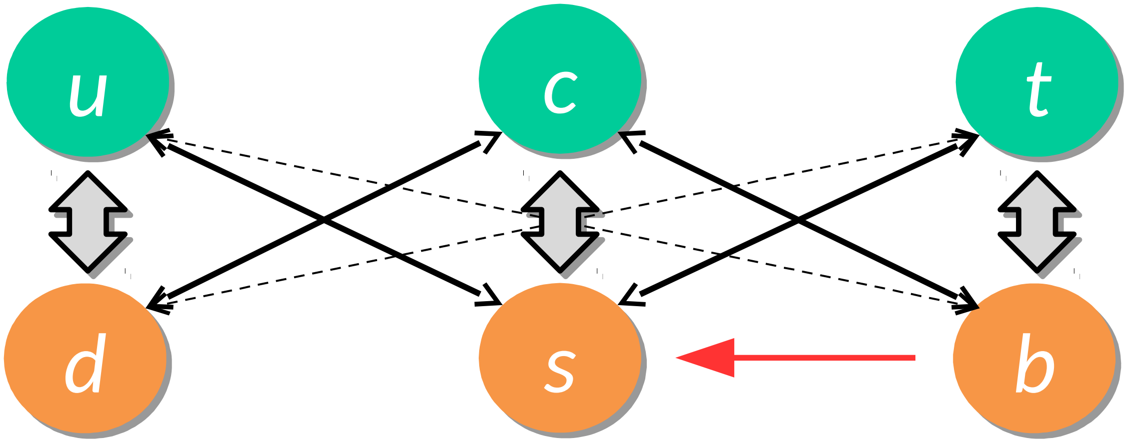
Hadronic FCNC decays: Not the topic of our lecture

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

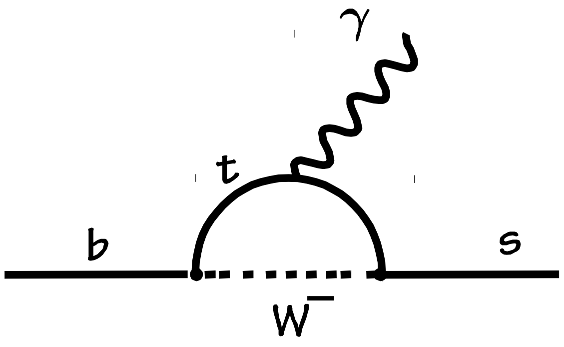
Electroweak FCNC penguins: That's rare !

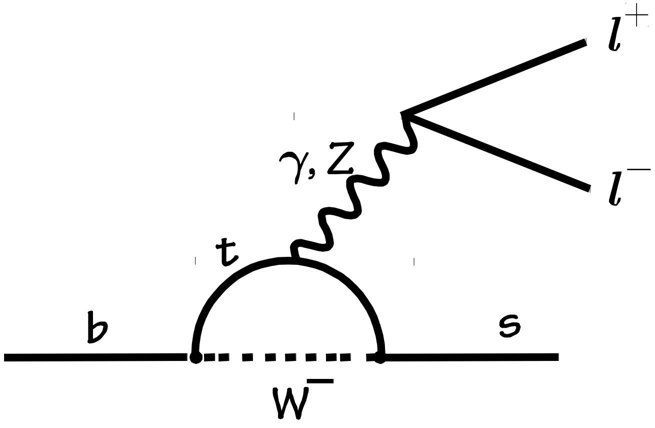
- $b \rightarrow s \gamma$
- $b \rightarrow s l l$
- And friends...

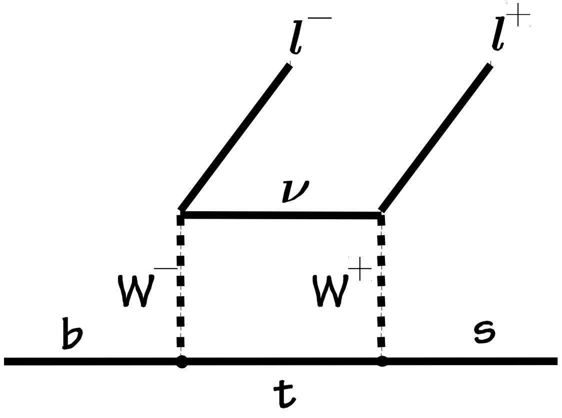
Rare B decays



- FCNC: Flavour Changing Neutral Current
- FCNC are strongly suppressed in the SM: only loops + GIM mechanism







Motivations for NP

SM , are we done ?

No. Open questions

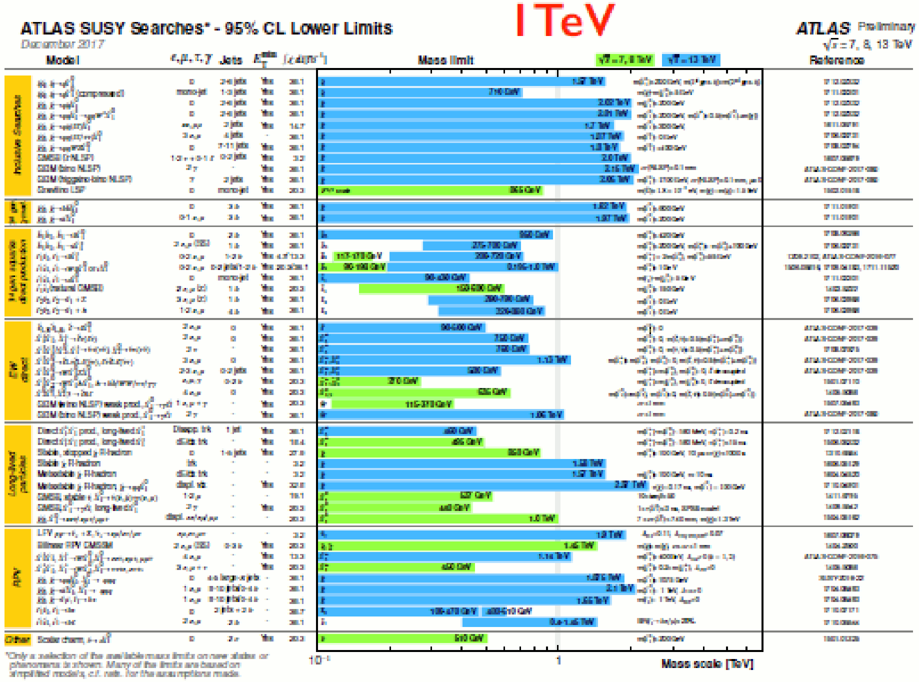
D. Tonelli

These and many other questions fuel the strong and wide-spread prejudice that the SM is completed at high-energy by new particles and interactions

How do you we search for new particles ?

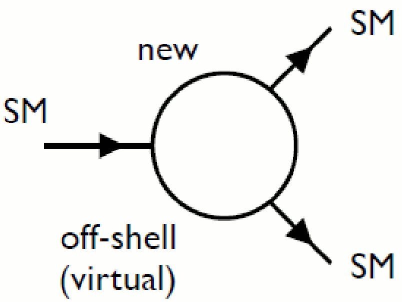
Direct vs Indirect Searches

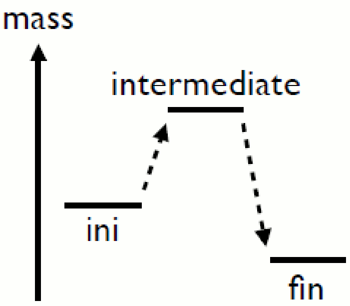
complementarity with LHC



> ~100GeV (1TeV), if interaction is weak (strong)

New particle via quantum effects

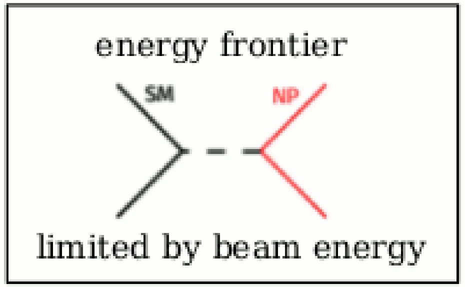


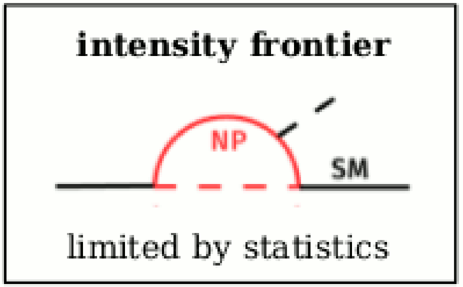


No sharp cutoff for energy scale (cf. LHC search)

— suppressed by $(E/\Lambda)^n$

Why flavor physics ?

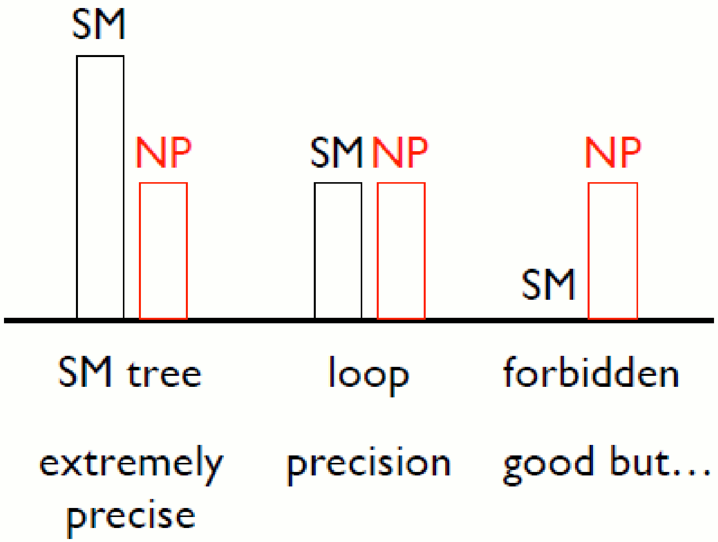




→ **NP beyond the direct reach of the LHC**

Three classes of SM processes (M.Endo)

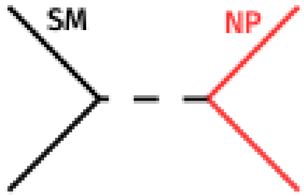
$$\mathcal{O}_{\rm obs} = \mathcal{O}_{\rm SM} + \mathcal{O}_{\rm NP}$$



Rare B decays

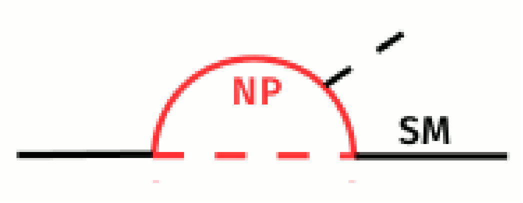
- FCNC are strongly suppressed in the SM: only loops + GIM mechanism
- Any new particle generating new diagrams can change the amplitudes

energy frontier



limited by beam energy

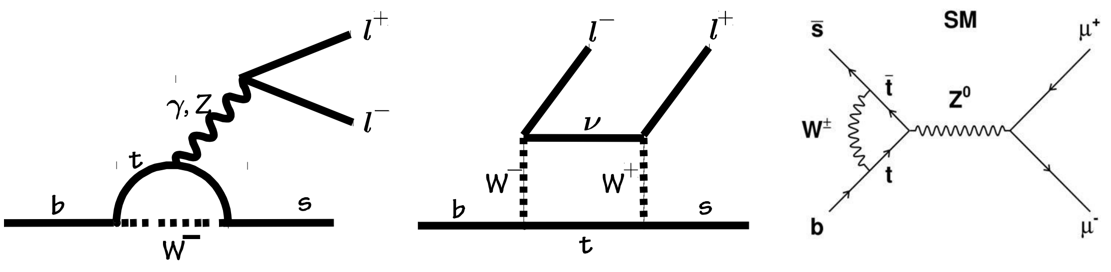
intensity frontier

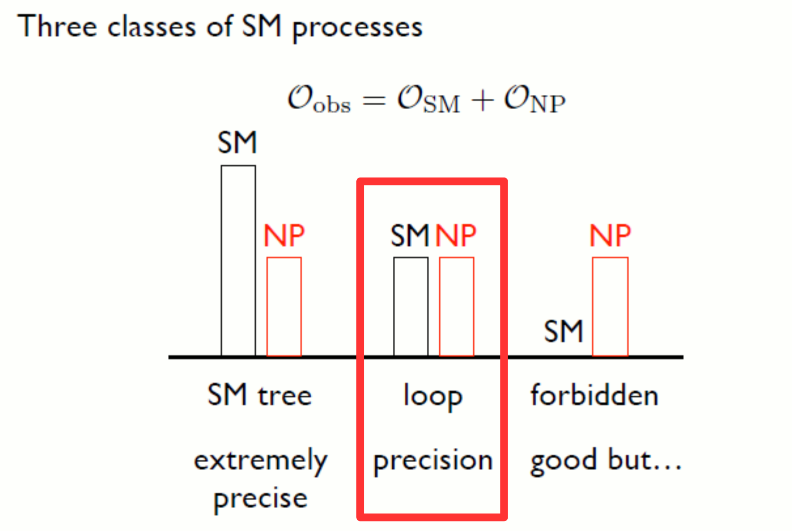


limited by statistics

➜ **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**





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

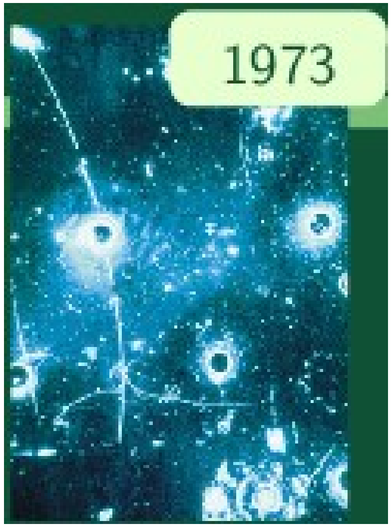
Experimental aspects:

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

  ⇒ 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.

Indirect searches

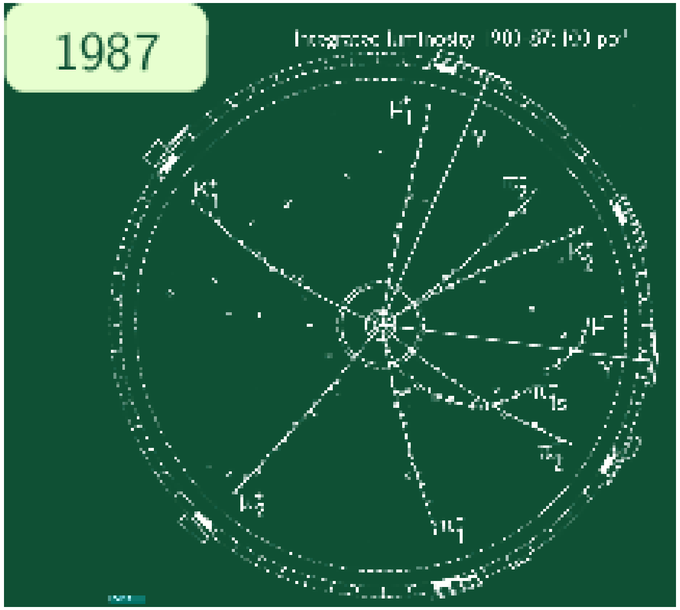


Sensitive to New Physics effects

- When was the Z discovered ?
  - 1973 from N$\nu \rightarrow$ Nν ?
  - 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

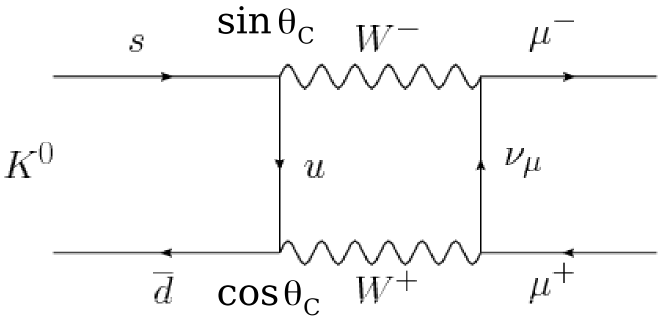
  - Half of new parameters
- Needed for a full understanding

Look in lepton and **flavour** sectors

→ CP asymmetry in the Universe

Illustration of indirect search: $K_L^0 \to \mu\mu$

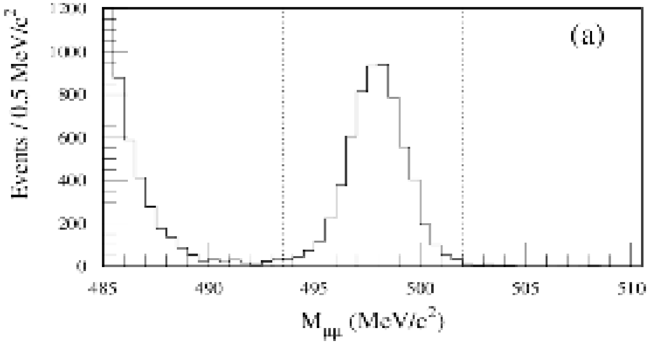
$K_L \to \mu^+\mu^-$ decay can be generated by the box diagram:



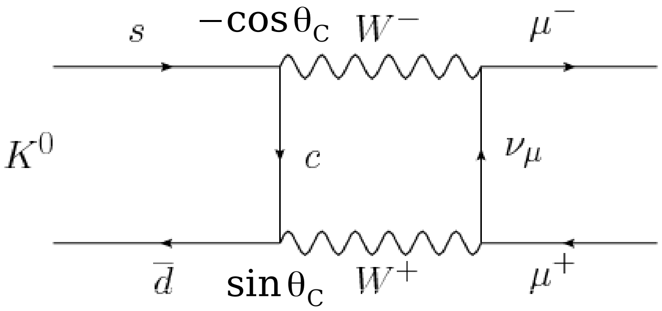
$K_L^0 \to \mu\mu$ was not observed though expected

Now BF is measured to be $(6.84 \pm 0.11)10^{-9}$

[Ambrose et al, 2000]



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.



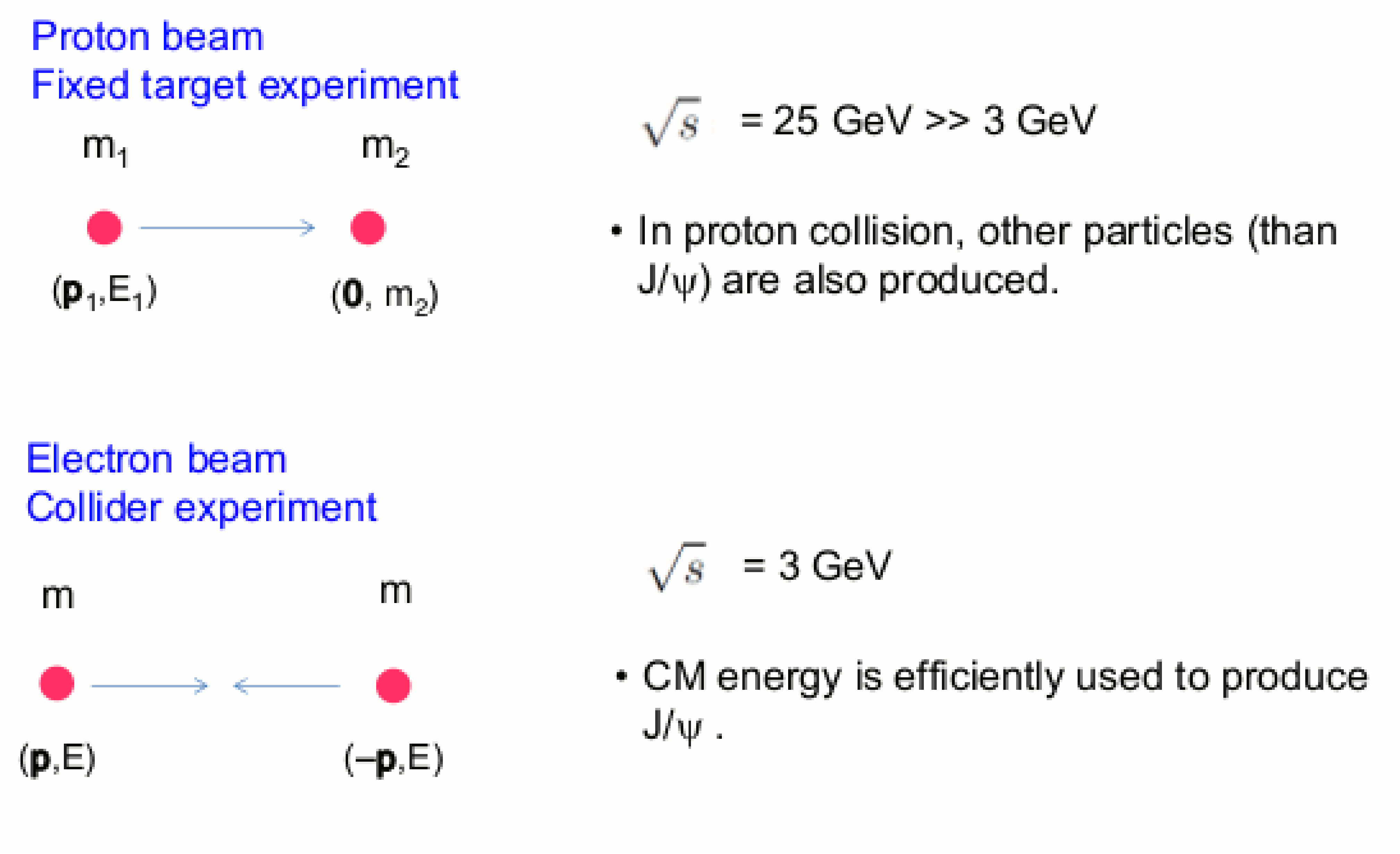
GIM observed that, with a fourth quark, there is a second diagram, with c replacing u. In the limit of exact flavour symmetry, the two diagrams cancel.

[Glashow, Iliopoulos and Maiani, 1970]

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.

⇒ but no experimental evidence of a fourth quark...



Proton beam
Fixed target experiment

m_1 m_2

$(\mathbf{p}_1, E_1)$ $(\mathbf{0}, m_2)$

$\sqrt{s}$ = 25 GeV >> 3 GeV

- In proton collision, other particles (than J/ψ) are also produced.

Electron beam
Collider experiment

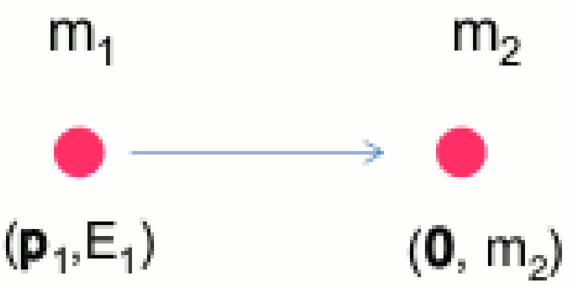
m m

$(\mathbf{p}, E)$ $(-\mathbf{p}, E)$

$\sqrt{s}$ = 3 GeV

- CM energy is efficiently used to produce J/ψ .

Proton beam
Fixed target experiment



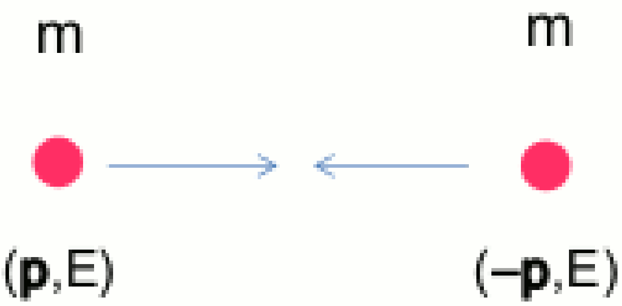
m_1 = 0.938 GeV
~ 1 GeV : proton
m_2 ~ 9 GeV : Beryllium
E_1 = 30 GeV

CM energy (center-of-mass)

$$\sqrt{s} = \sqrt{(E_1 + m_2)^2 - |\vec{p_1}|^2}$$
$$= \sqrt{2E_1 m_2 + m_1^2 + m_2^2}$$

= 25 GeV >> 3 GeV

Electron beam
Collider experiment



m = 0.511 keV

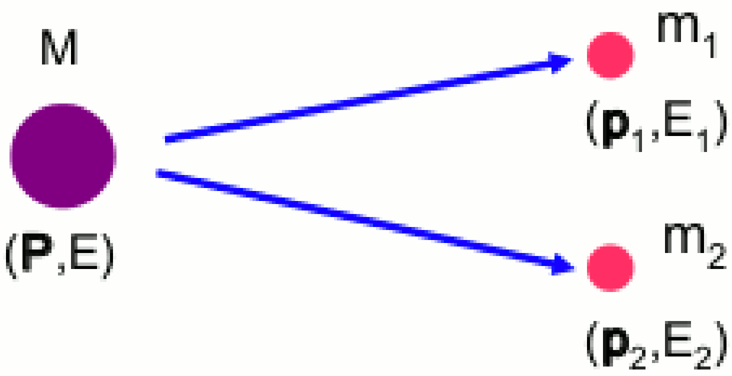
E = 1.5 GeV

CM energy $\sqrt{s} =$ 2E = 3 GeV

How to detect particles

Most short-lived particles generated by the collision (, in which we are interested), decay inside the detector, but we can reconstruct them if we know the 4-momentum of decay products.

Simple case: 2-body decay.

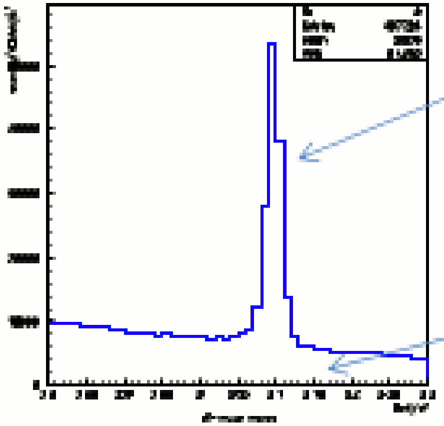


energy and momentum conservation

$$E = E_1 + E_2$$

$$\mathbf{P} = \mathbf{p}_1 + \mathbf{p}_2$$

$$M^2 = E^2-|\mathbf{P}|^2 = (E_1+E_2)^2-|\mathbf{p}_1+\mathbf{p}_2|^2$$



reconstructed particle

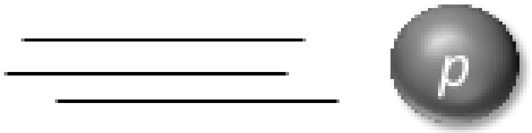
random combination

In reality, there are many particles in a final state; we don't know which is the correct combination.

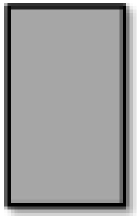
J/ψ (1974)

Experiment carried out by S. Ting group at Brookhaven National Laboratory

– fixed target experiment :



Energetic proton accelerated by an accelerator

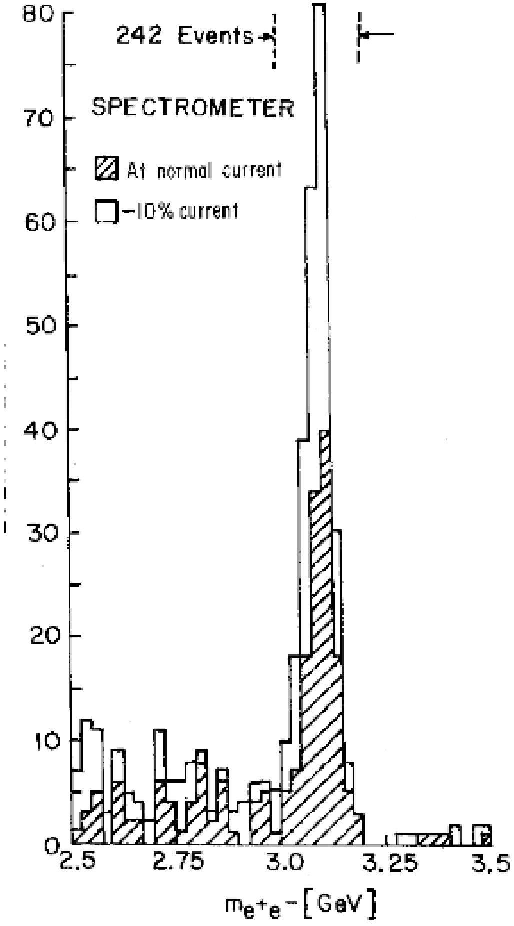


Beryllium target

$$p + \mathrm{Be} \;\rightarrow\; (e^{+} + e^{-}) + x \quad (x \ldots \text{anything})$$

– particle found at 3.0 GeV/c^2

– They coined name of ''J'' to the particle

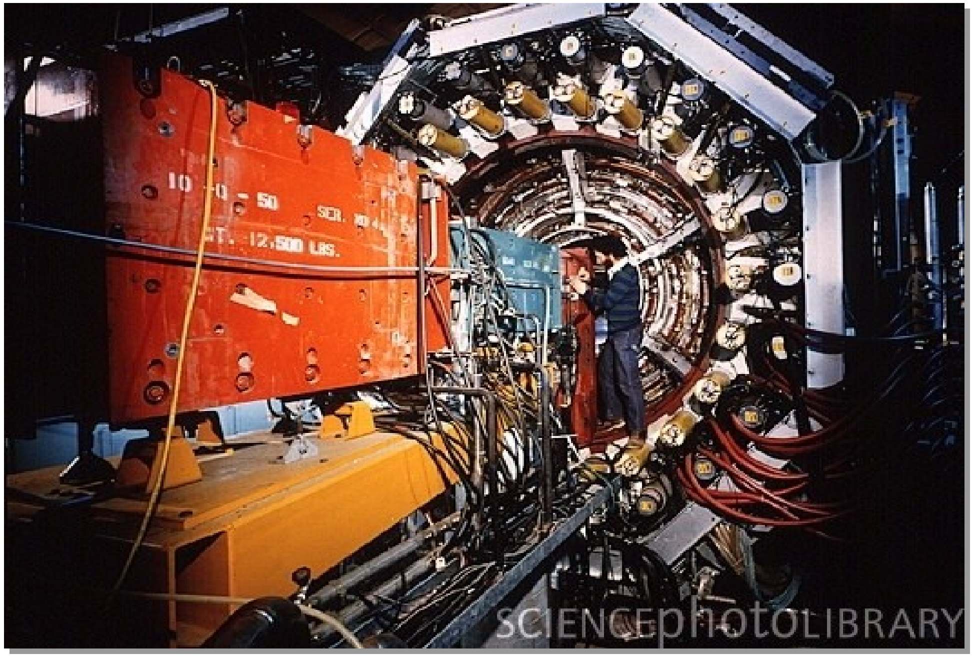


J/ψ (1974)

Experiment carried out by B. Richter group

– e^+e^- collider experiment

Contrarily to the S. Ting's group, B. Richter's group tried to find out a new particle by scanning the e^+e^- collision energy from 2.4 GeV by 0.2 GeV step



MARK-I detector at SLAC

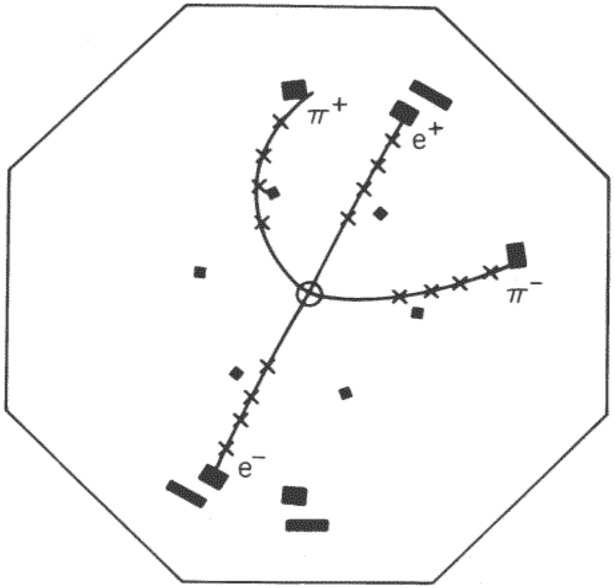
J/ψ (1974)

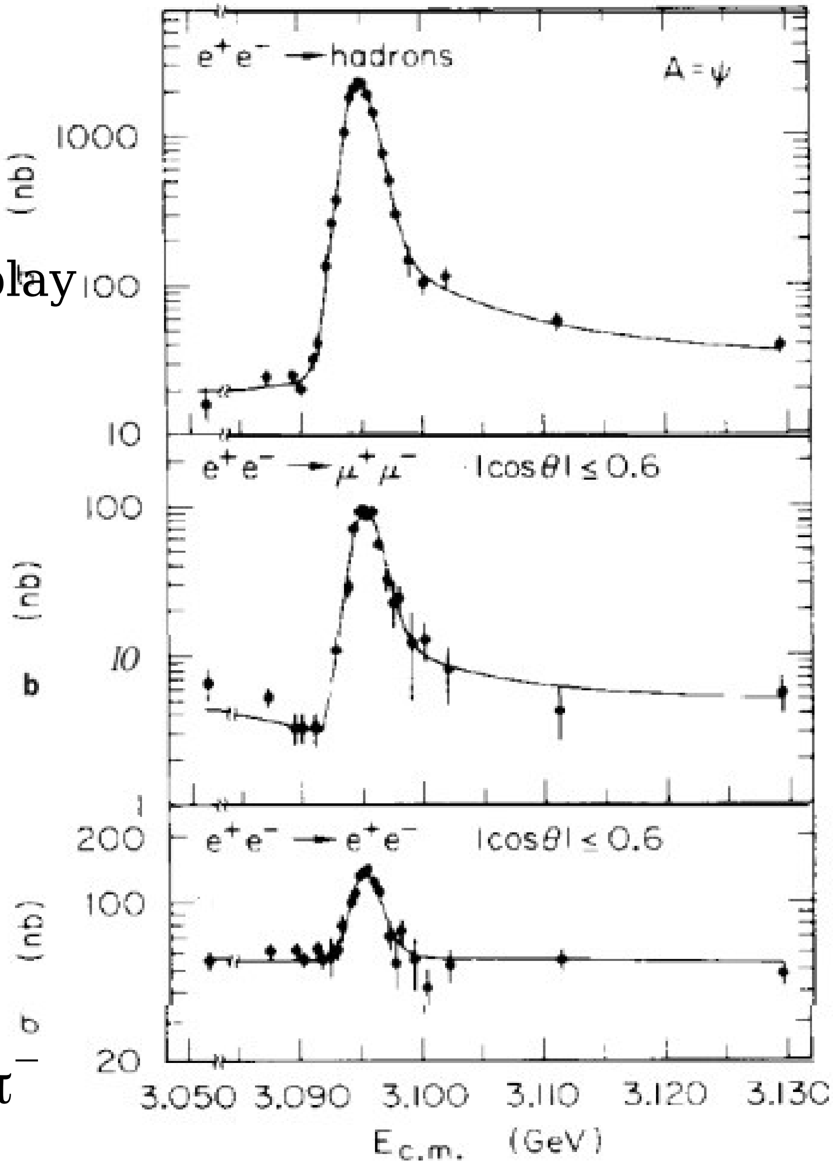
Experiment carried out by B. Richter group

– They observed a bump at 3 GeV/c^2

– Event display

The particle name was taken from its event display



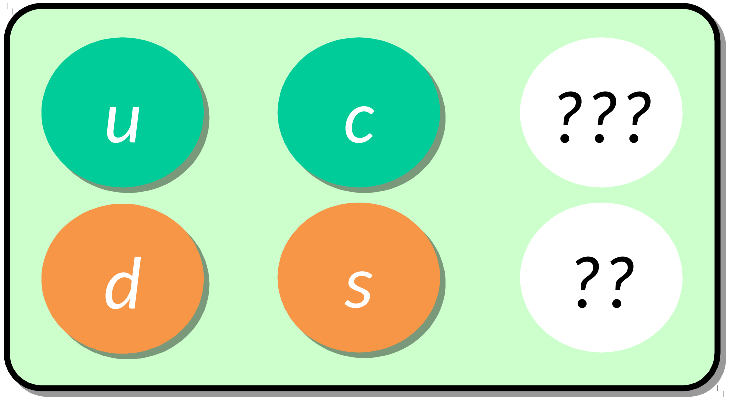


$$e^+ + e^- \rightarrow \left(e^+ + e^-\right) + \pi^+ + \pi^-$$

J/ψ (1974)

Discovery of the 4th quark

Finally, the J/ψ particles were identified as $c\bar{c}$ mesons



Two names for the same particle

As both groups published the discoveries of J and ψ on the same day (11th Nov 1974), the particle was given 2 names: J/ψ

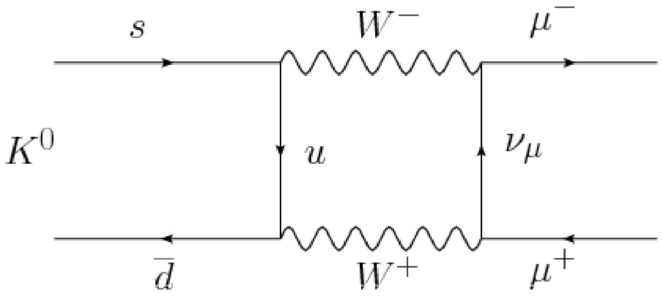
November revolution

⇒ Nobel Prize 1976 rewarded Richter and Ting

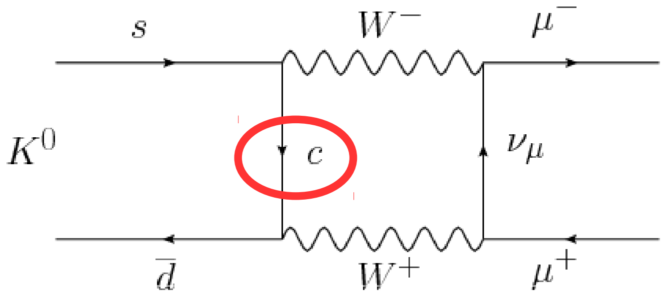
indirect search: $K_L^0 \to \mu\mu$

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

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

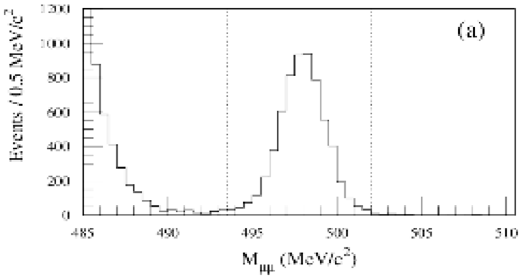


in a renormalisable gauge theory, is expected to give a branching ratio of $\mathbf{g^4 \sim \alpha^2 \sim 10^{-4}}$, with α the fine structure constant.



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

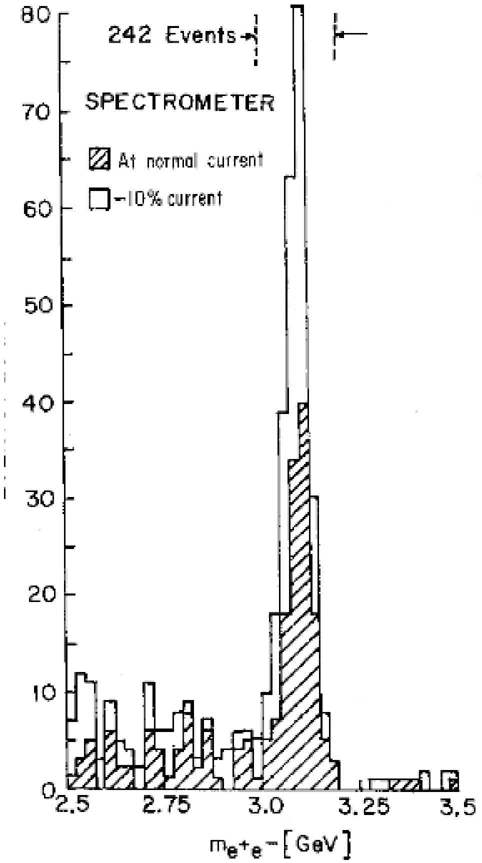
Now BF is measured to be $(6.84 \pm 0.11)\,10^{-9}$

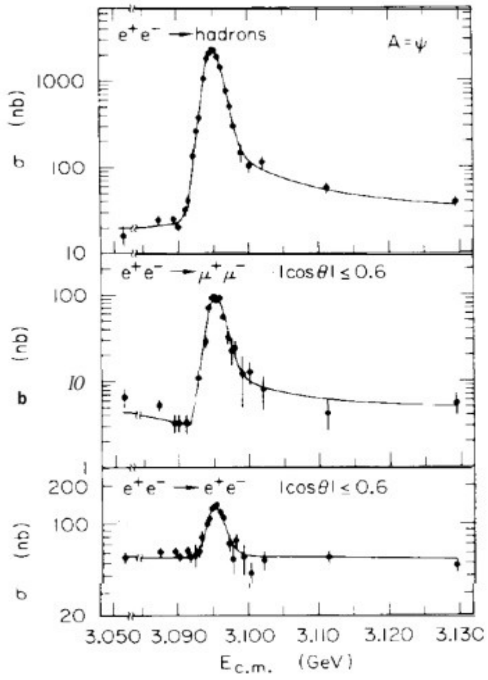


[Ambrose et al, 2000]

→ 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.

W and Z bosons discoveries

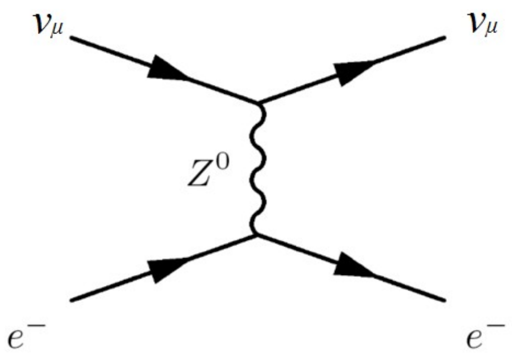
The weak force is essentially as strong as the electromagnetic force, but it appears weak because its influence is limited by the large mass of the Z and W bosons. Their mass limits the range of the weak force to about 10^{-18} meters, and it vanishes altogether beyond the radius of a single proton.

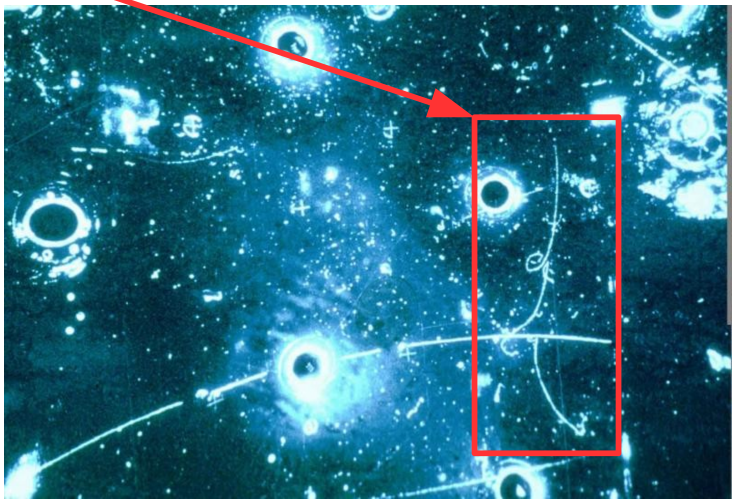
Sheldon Glashow, Abdus Salam and Steven Weinberg developed in the 1960s the theory in its present form, when they proposed that the weak and electromagnetic forces are actually different manifestations of one electroweak force.

First, in 1973, came the observation of neutral current interactions as predicted by electroweak theory at Gargamelle bubble chamber (Andre Lagarrigue et al)

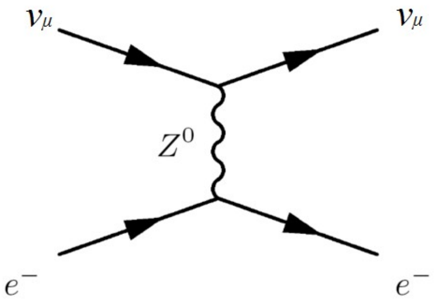
Neutrinos are particles that interact only via the weak interaction, and when the physicists shot neutrinos through the bubble chamber they were able to **detect evidence of the weak neutral current, and hence indirect evidence for the Z boson.**

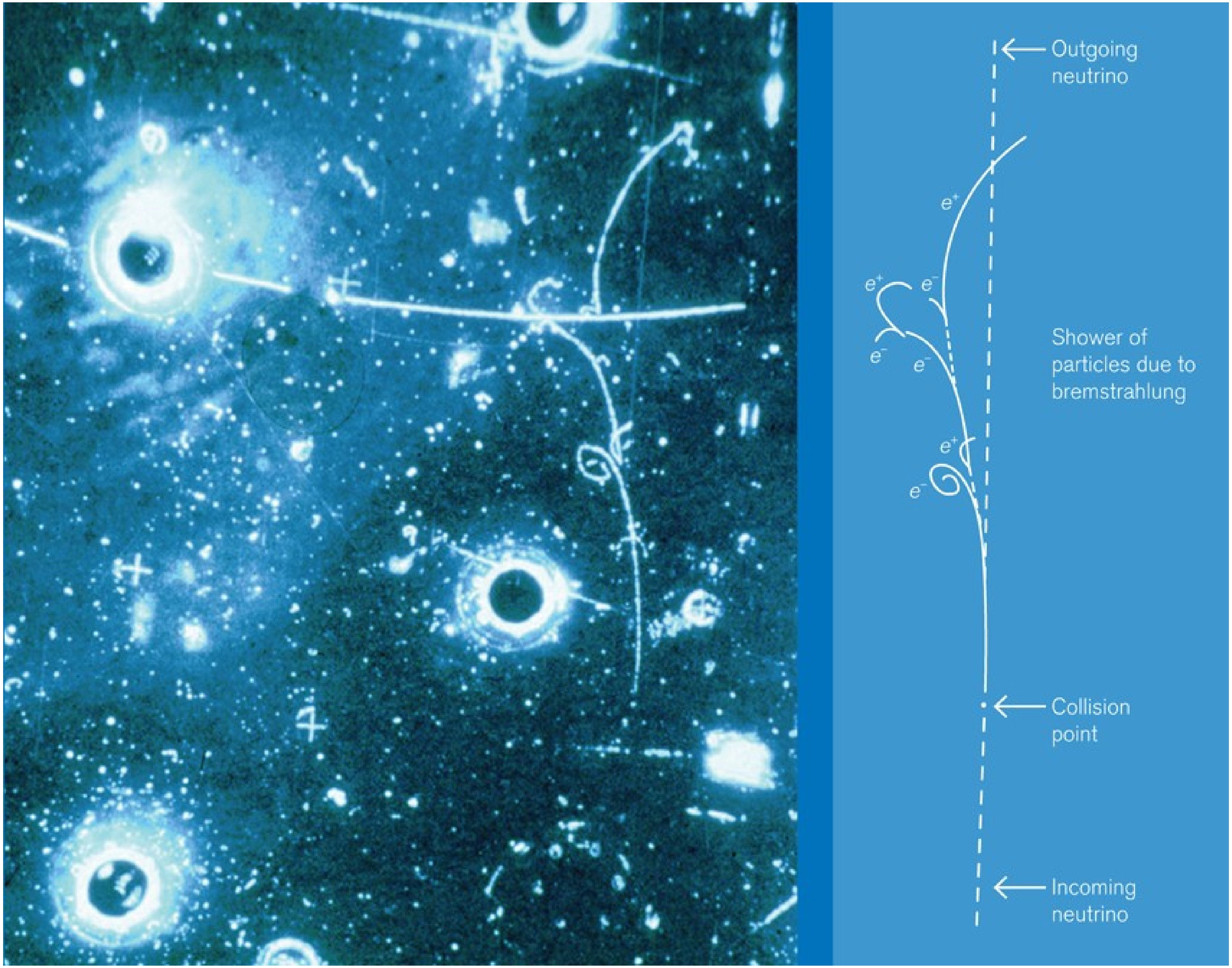
neutrino beam





W and Z bosons discoveries

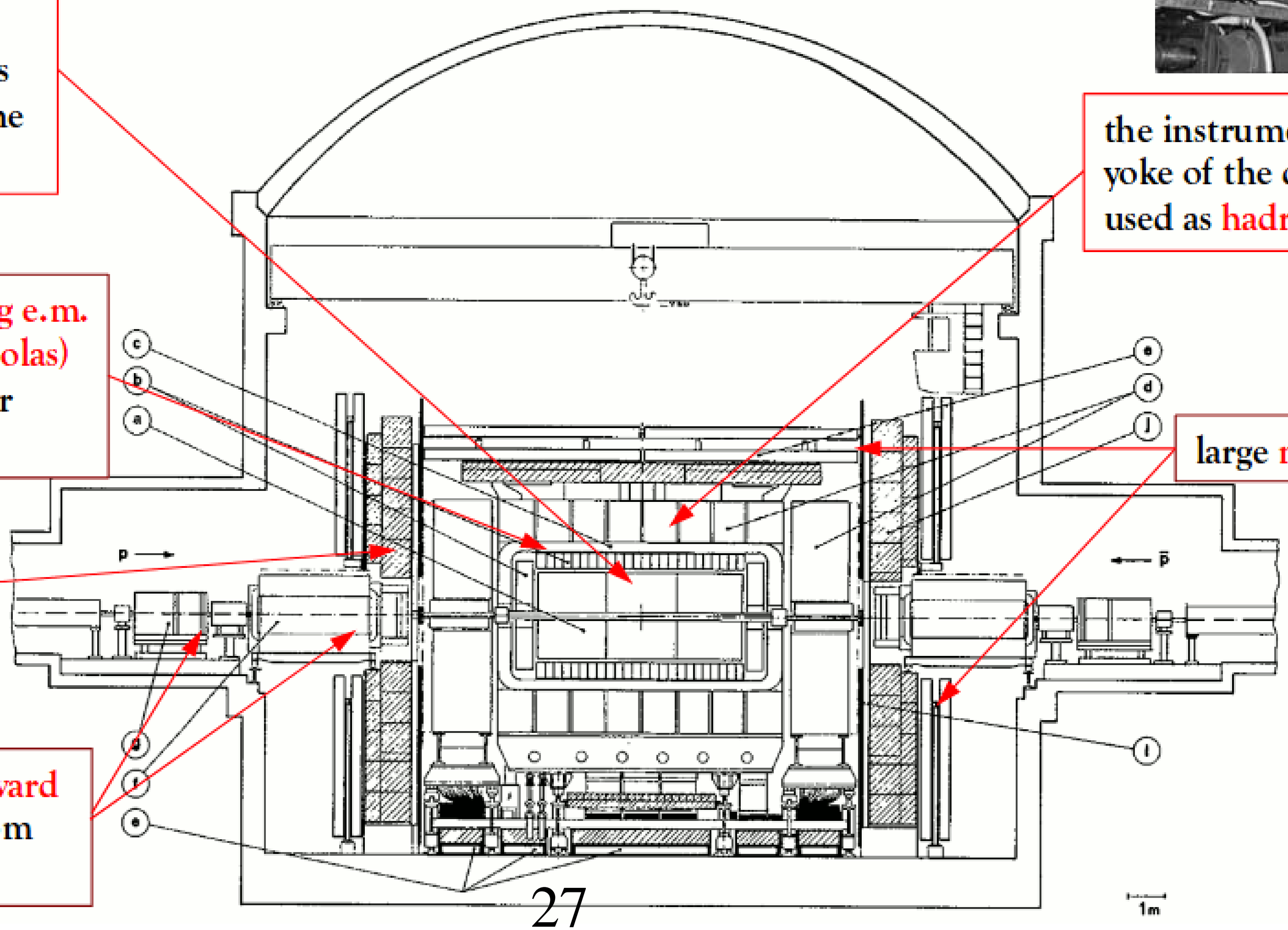




W and Z bosons discoveries

Super Proton Synchrotron, proton-antiproton collider, where unambiguous signals of W bosons were seen in January 1983 during a series of experiments made possible by Carlo Rubbia and Simon van der Meer. Experiments are UA1 and UA2.

270 GeV per beam, enough energy to produce W and Z particles
first general purpose 4π experiment in high energy physics



the Central Detector, a big drift chamber to track charged particles in the 0.7 T field of the dipole magnet

the instrumented return yoke of the dipole magnet used as hadron calorimeter

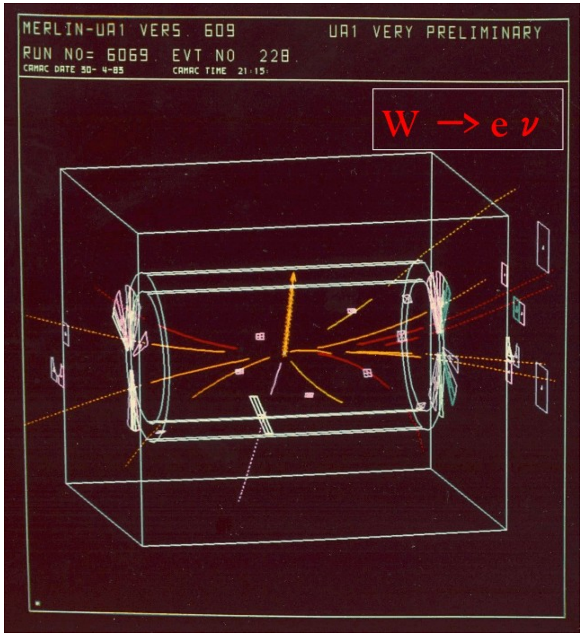
the fine grain sampling e.m. calorimeter (the Gondolas) readout by wave shifter bars (BBQ)

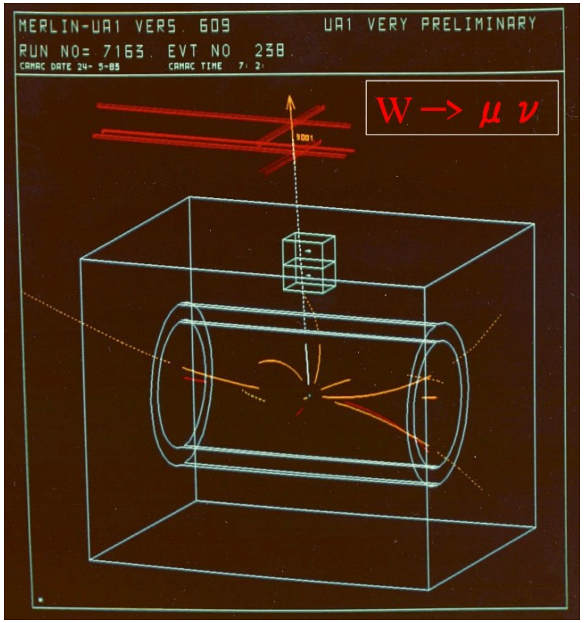
large muon chambers

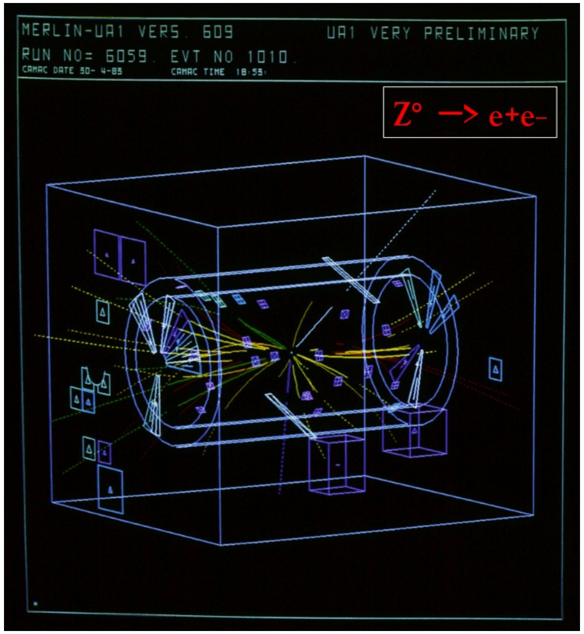
end cap detectors (the bouchons)

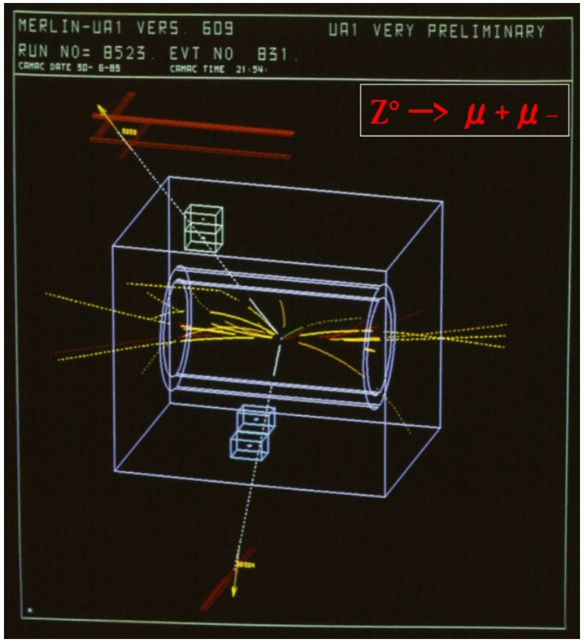
forward and very forward detectors (up to 1° from the beams)

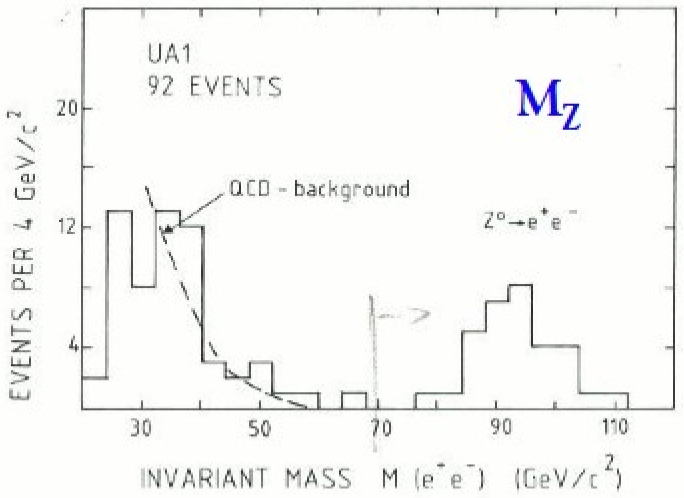
W and Z bosons discoveries





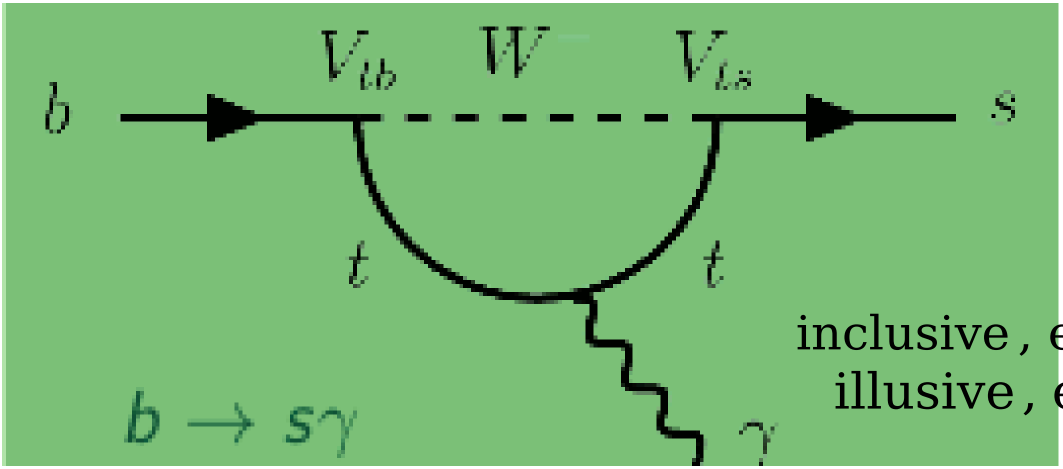




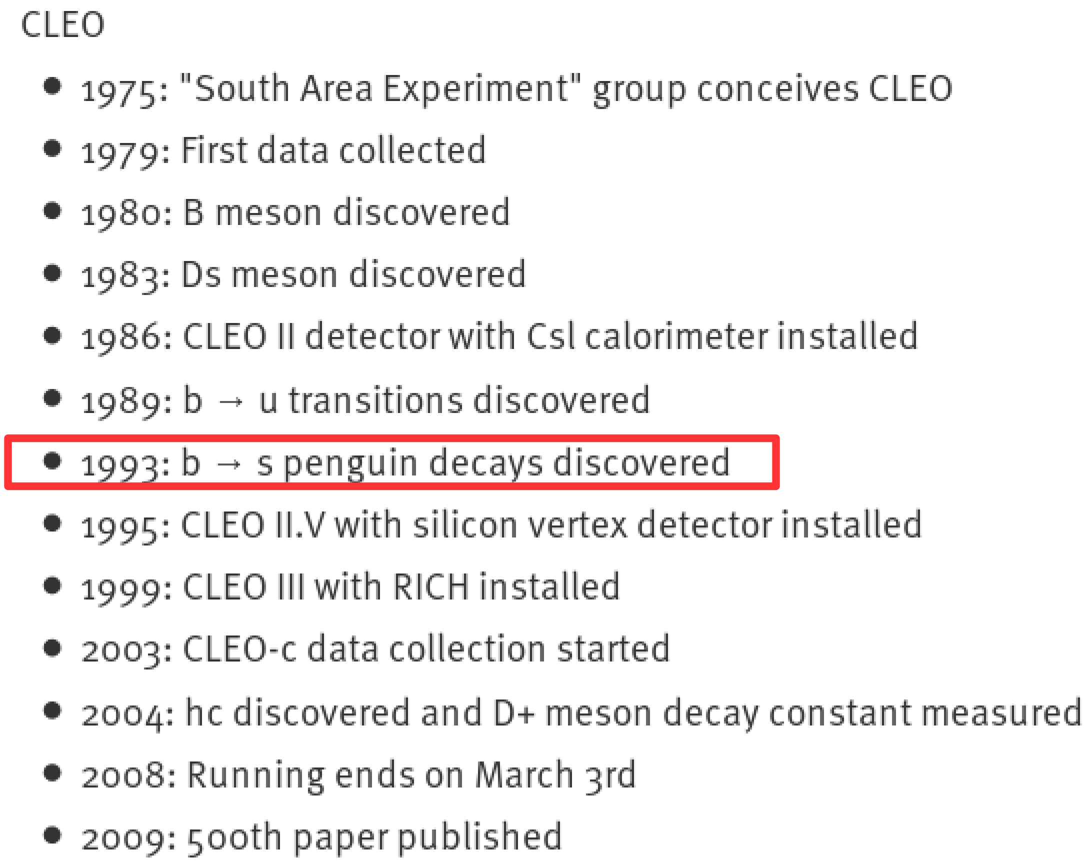


Rubbia and van der Meer were promptly awarded the 1984 Nobel Prize in Physics.

Radiative B decays

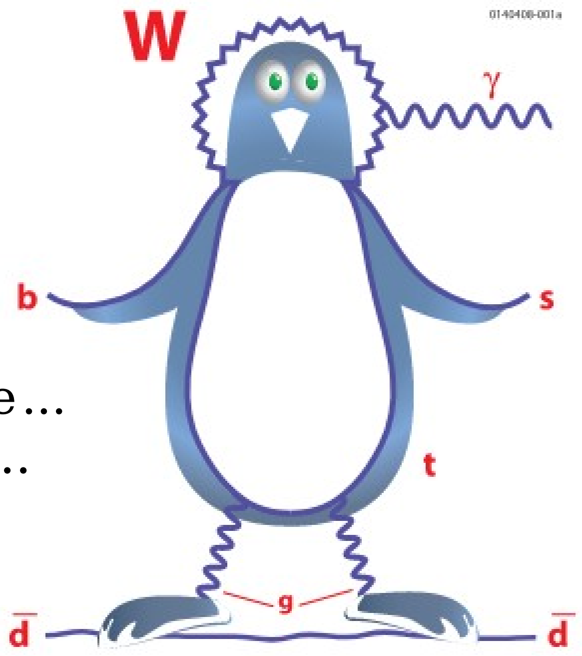


inclusive, exclusive…
illusive, elusive…

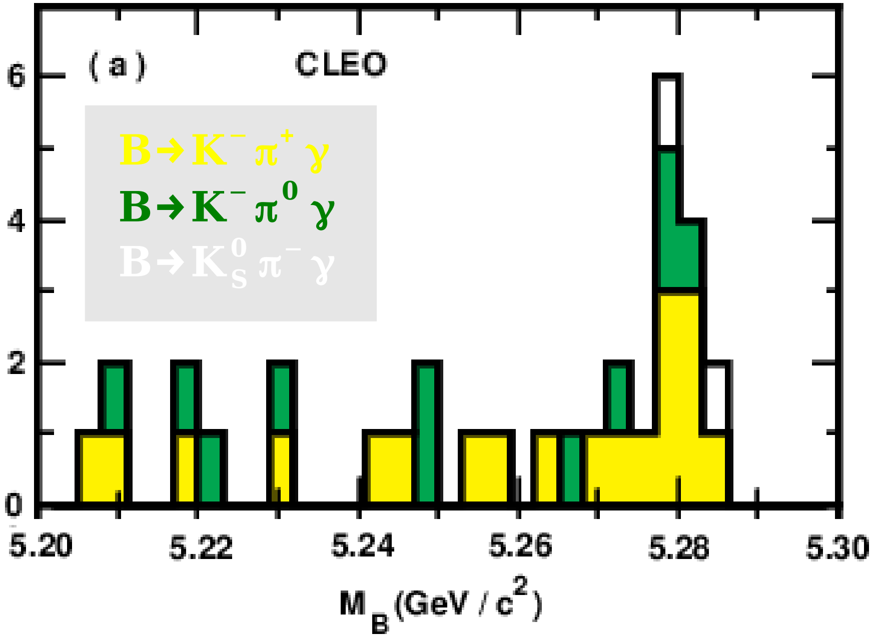

CLEO

- 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

artist's view… of the penguin diagram

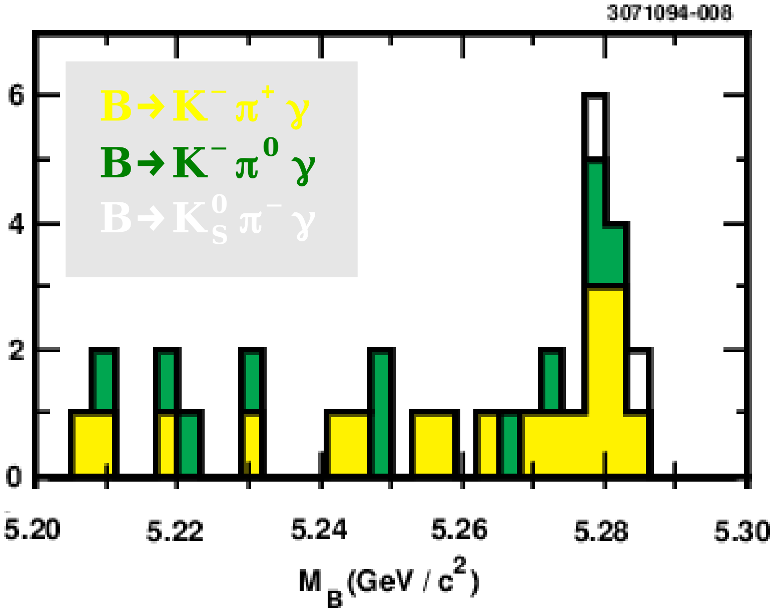


CLEO observation of $B \to K^* \gamma$ [1993]

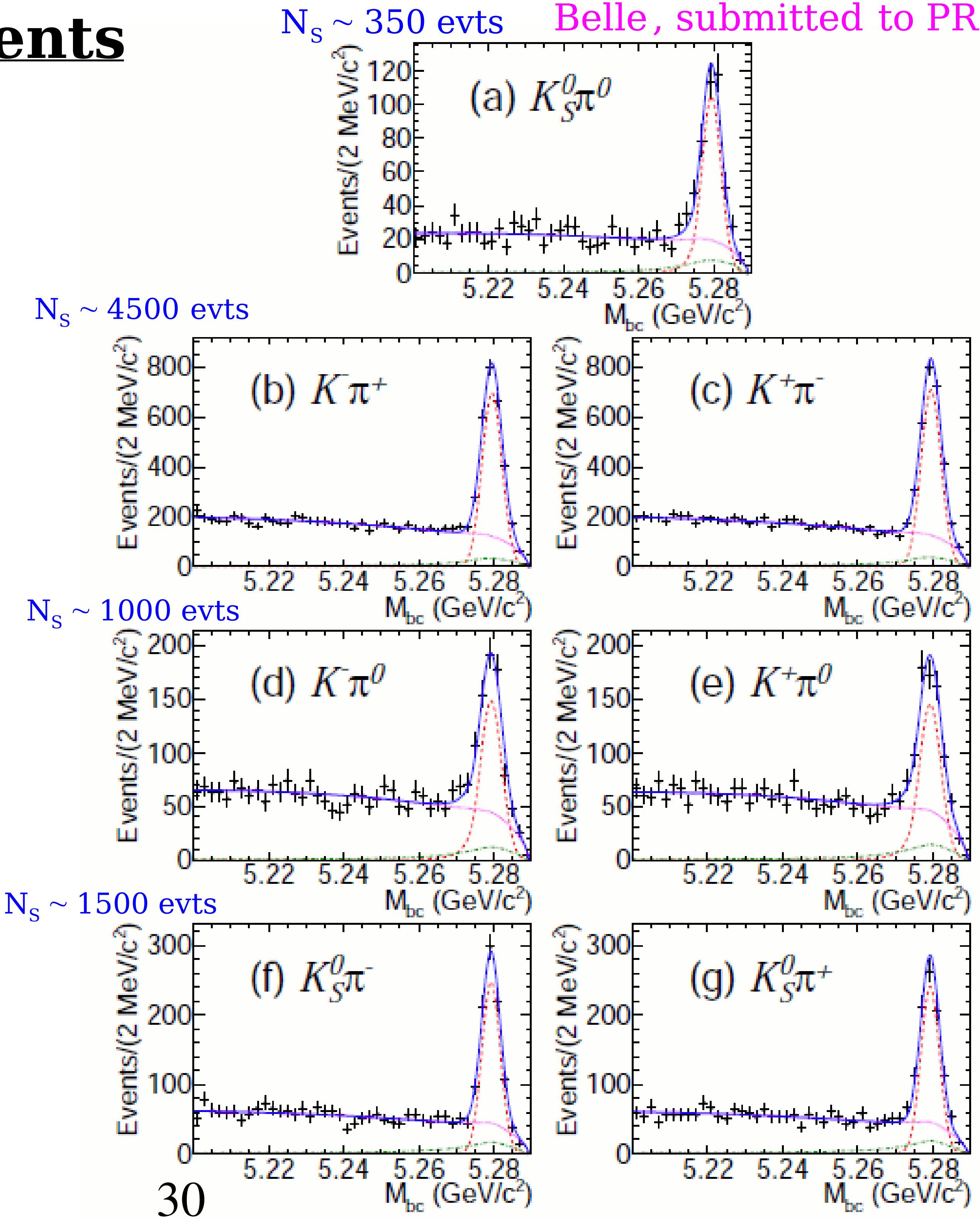


$B \rightarrow K^{*} \gamma$ measurements

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



Belle, submitted to PRL



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

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

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

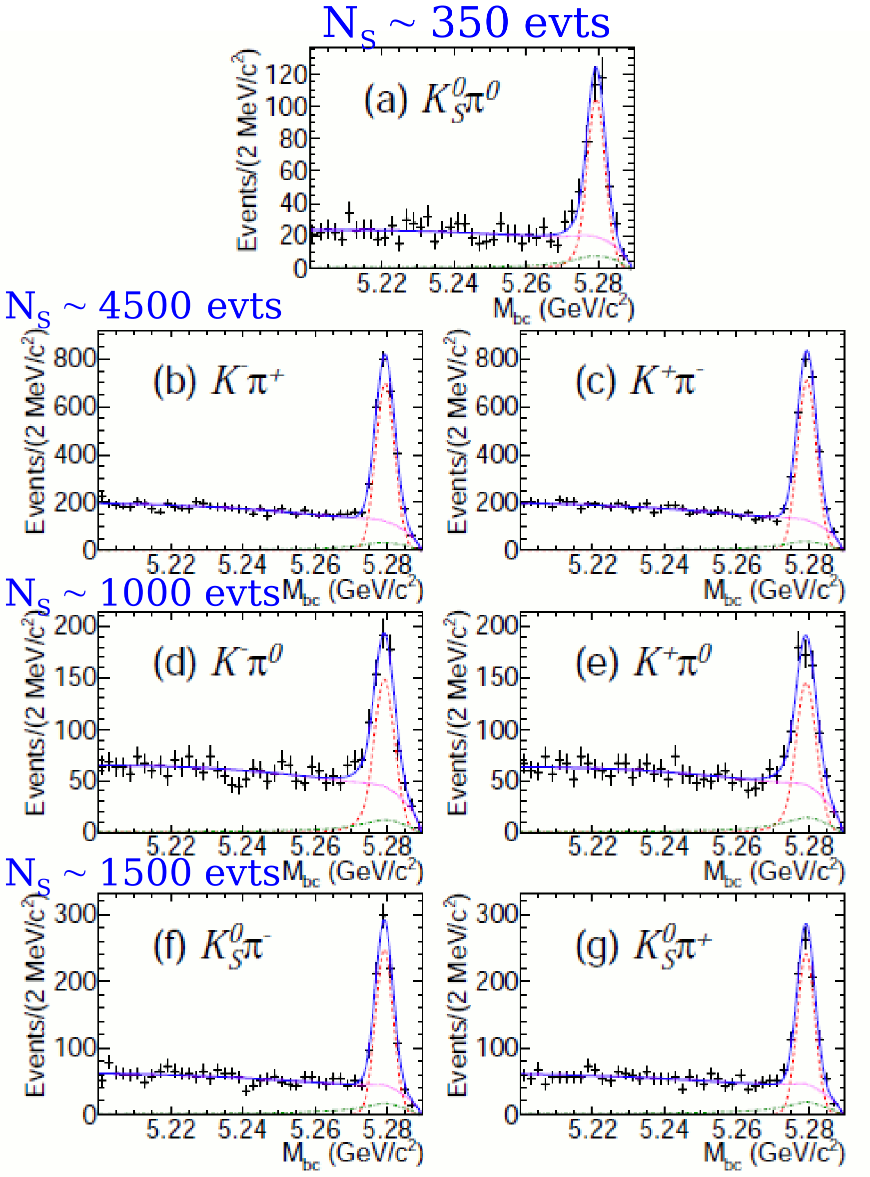
$\mathrm{Br}(K^{*0} \rightarrow K^{+} \pi^{-}) \sim 2/3$, $\mathrm{Br}(K^{*0} \rightarrow K^{0} \pi^{0}) \sim 1/3$

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

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

B→K*γ measurements

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

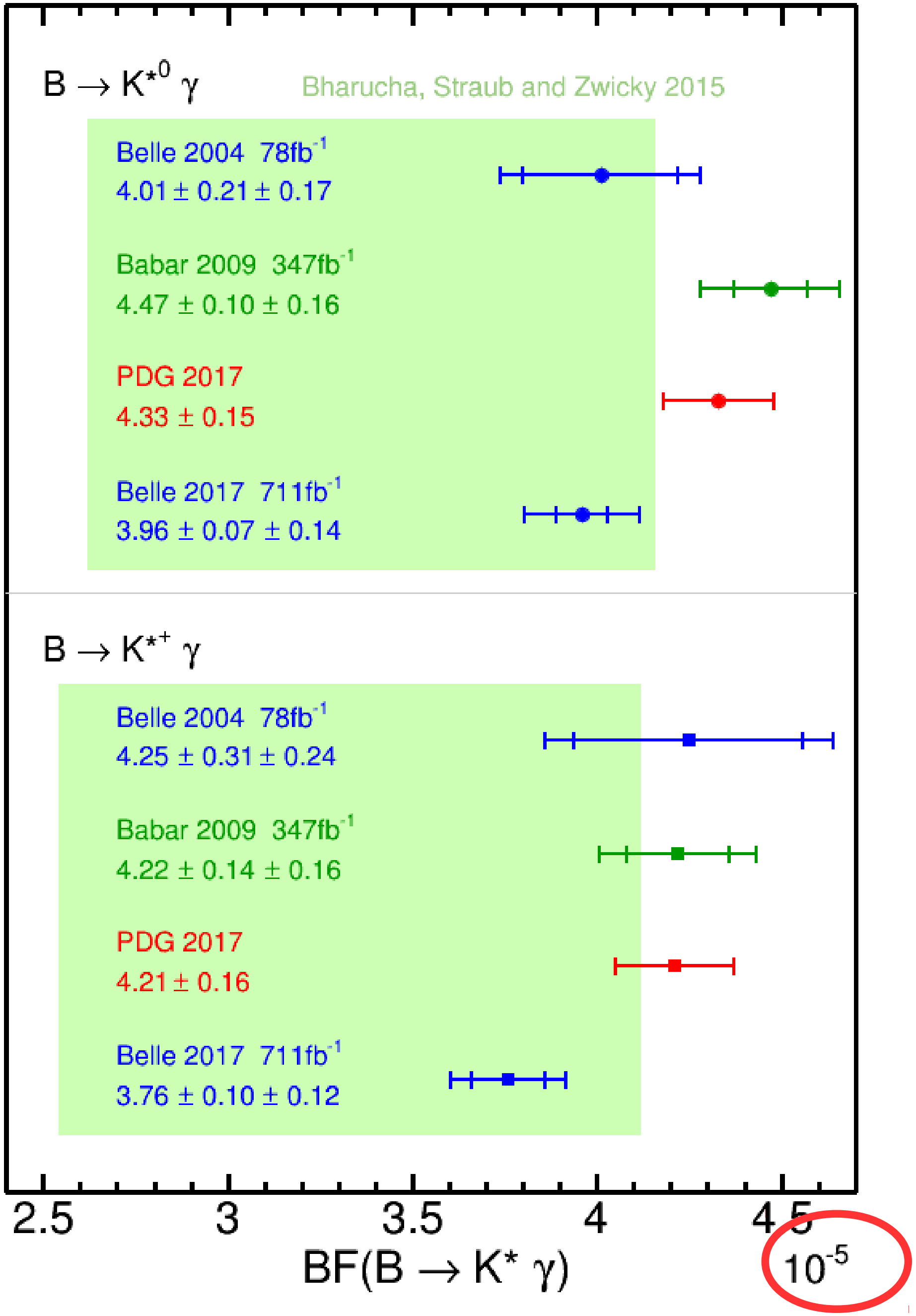


N_S ~ 350 evts

N_S ~ 4500 evts

N_S ~ 1000 evts

N_S ~ 1500 evts

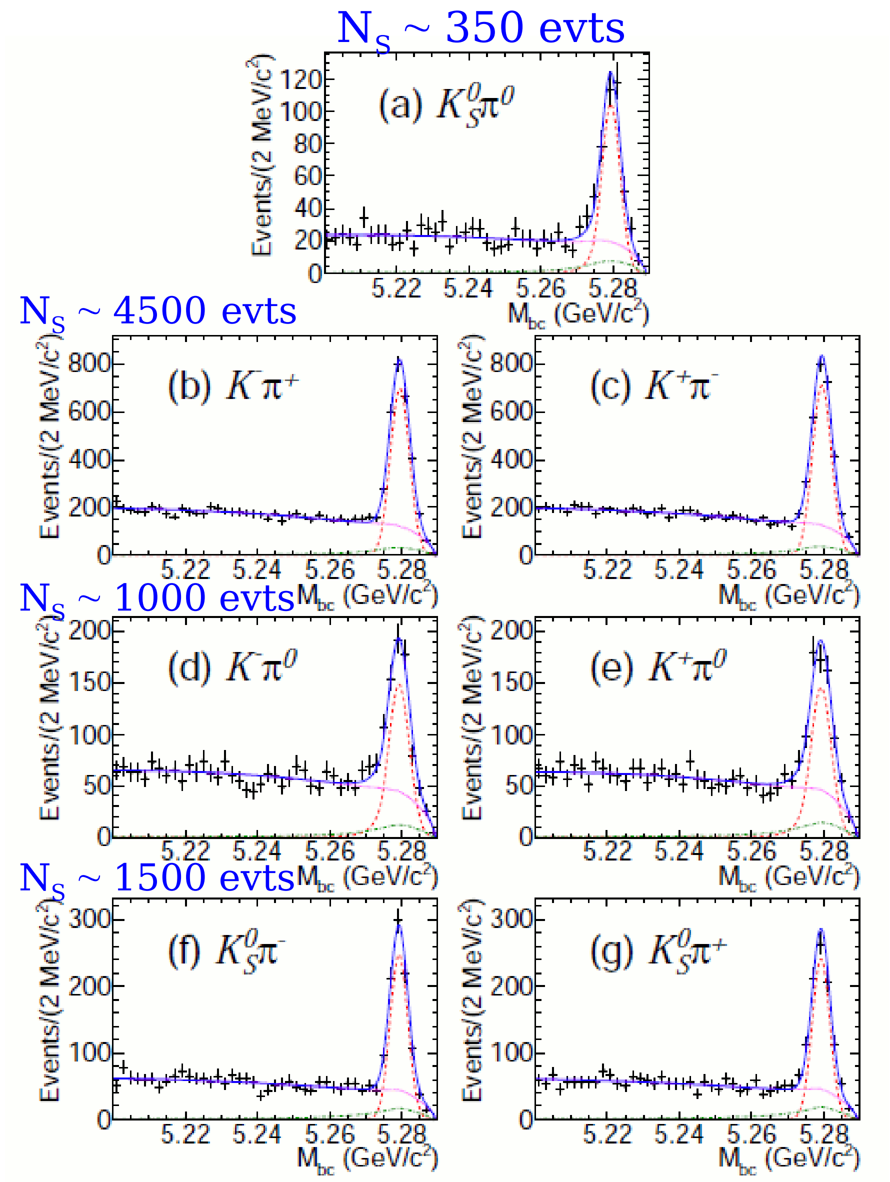


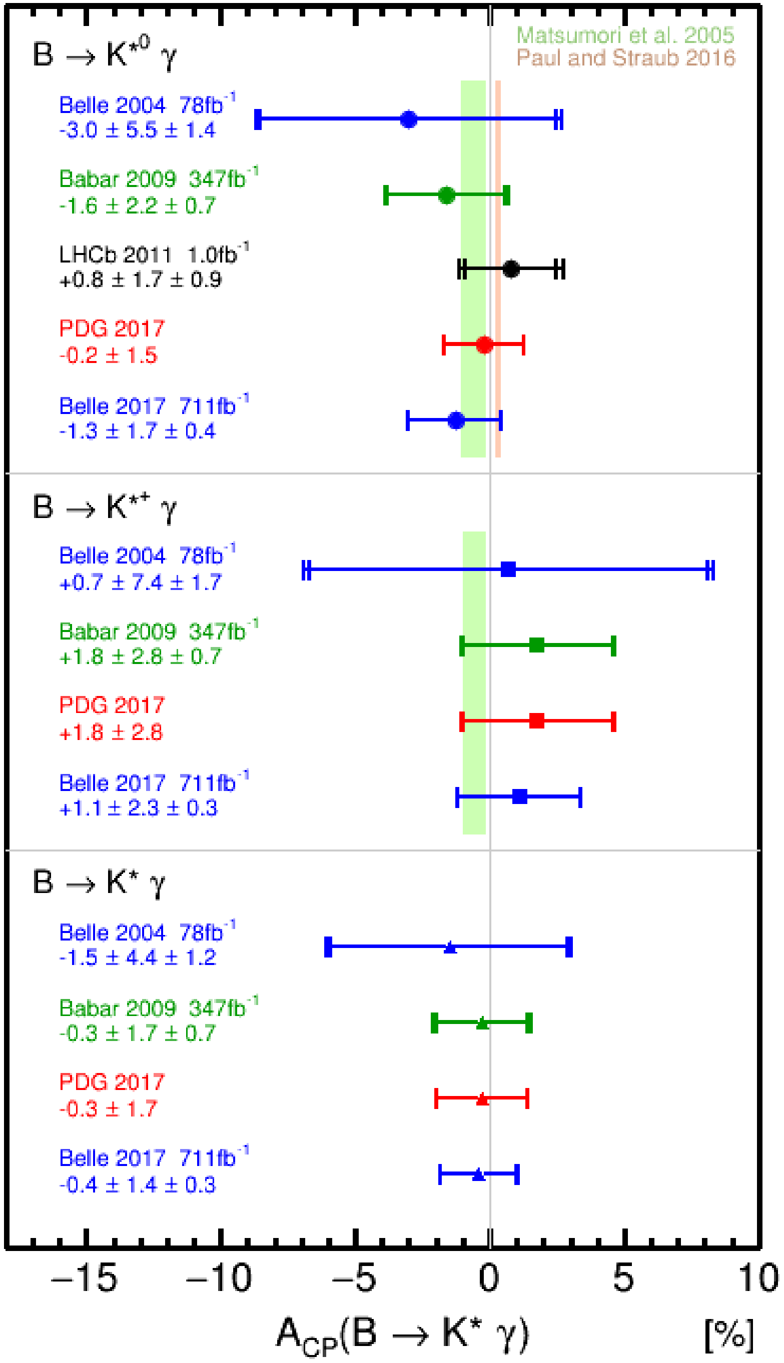
but uncertainty in the hadronization process limits the ability to predict individual exclusive rates from first principles of the theory

$B \rightarrow K^* \gamma$ measurements

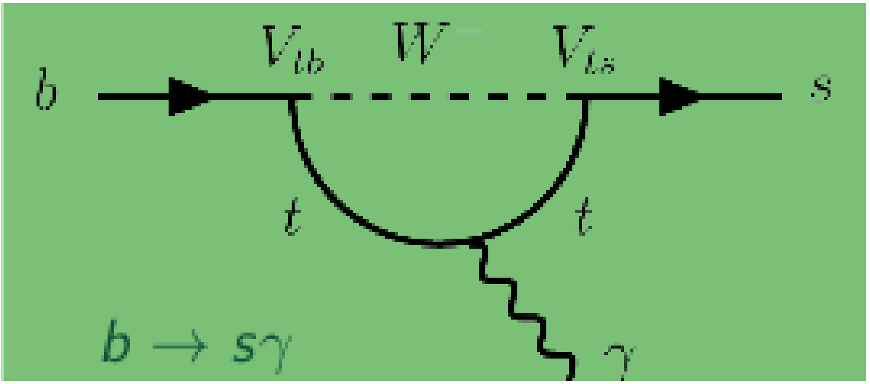
simultaneous fit of 4 final states

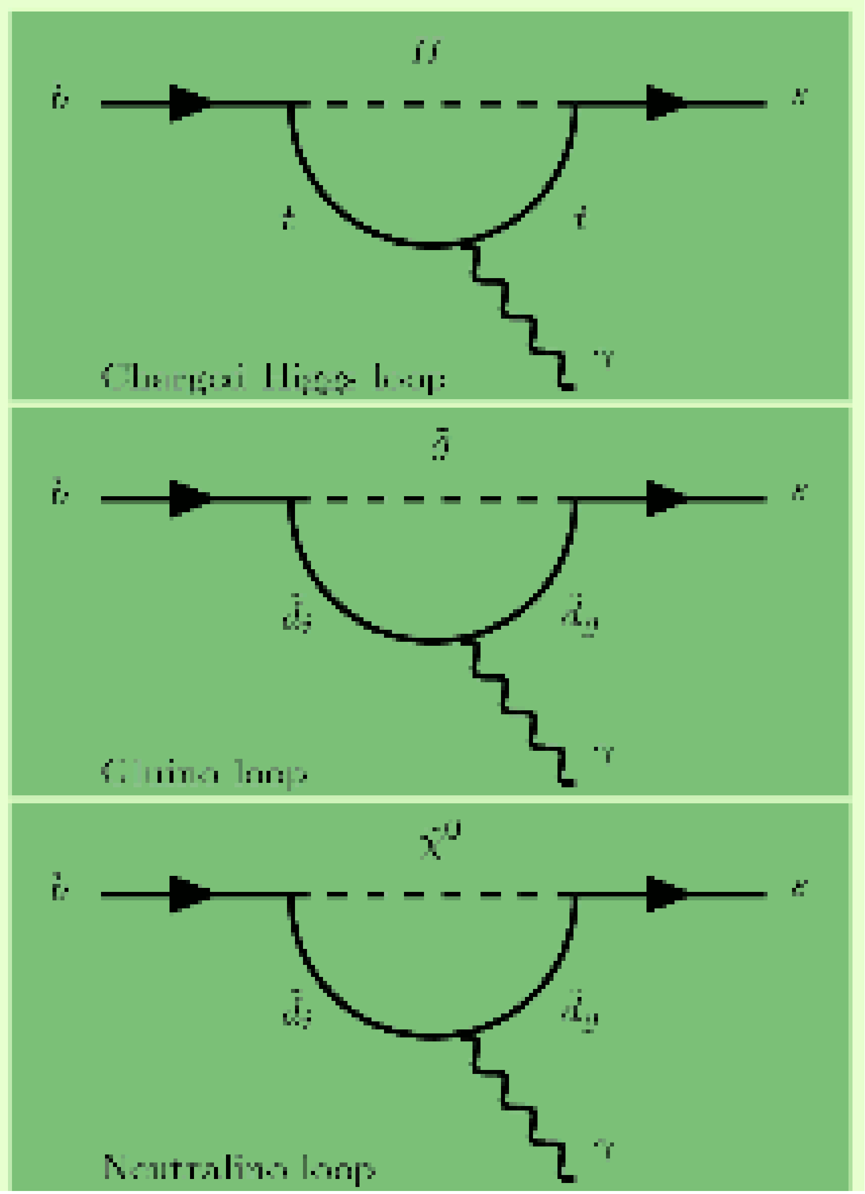
⇒ extraction of BFs, Δ_{0+}, A_{CP}, ΔA_{CP}…





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

exclusive vs inclusive

easier experimentally
difficult theoretically

difficult experimentally
easier theoretically (closer to b → s γ)

b→sγ SM branching fraction

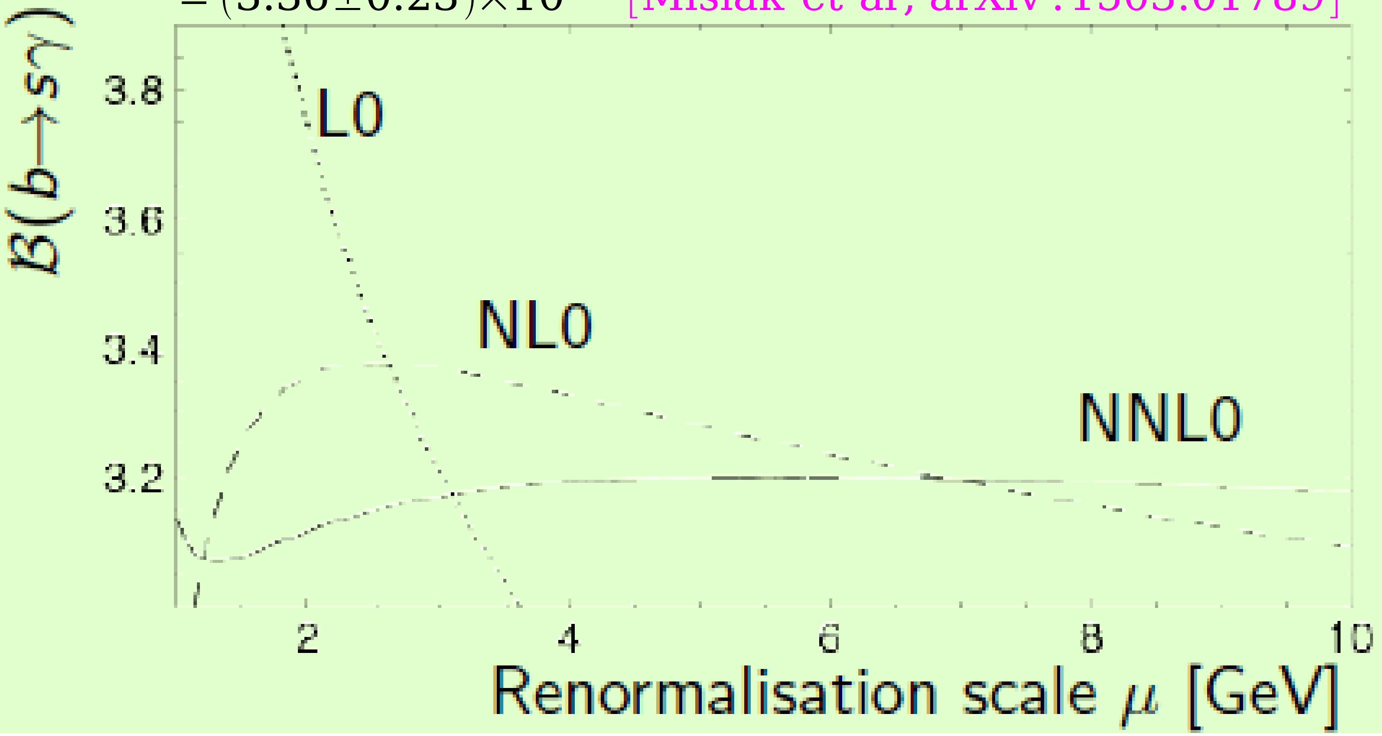
[Misiak et al , PRL98, 02202, 2007]

- 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

$$\mathcal{B}(B\to X_s\gamma)_{E_\gamma>1.6\,\mathrm{GeV}} = \cancel{(3.15\pm0.23)\cdot 10^{-4}}$$

$$= (3.36\pm0.23)\times10^{-4}$$ [Misiak et al, arXiv:1503.01789]

✓ BF very stable versus μ



How to estimate the branching fraction b→sγ ?

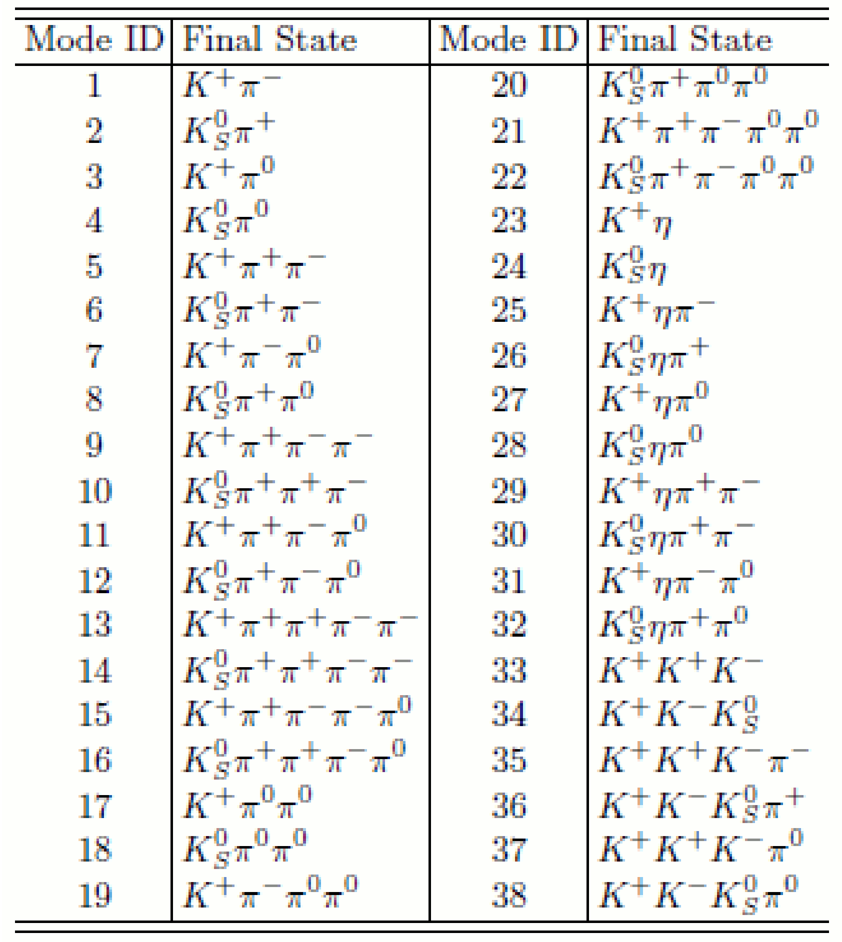
Semi-inclusive (sum-of-exclusive)

[772 MBB]

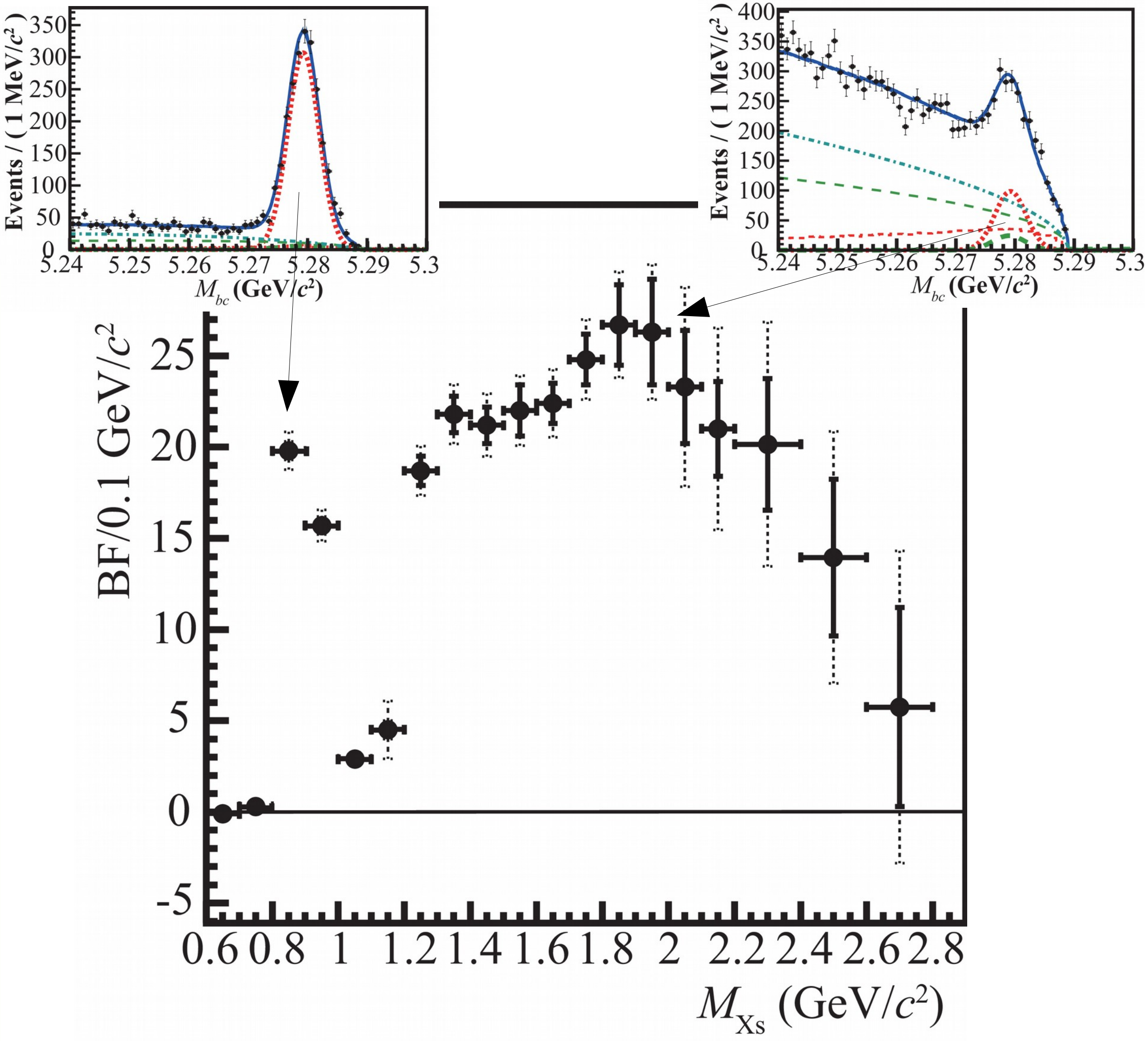
[arXiv:1411.7198]

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	$K^+K^-K^0_S\pi^0$

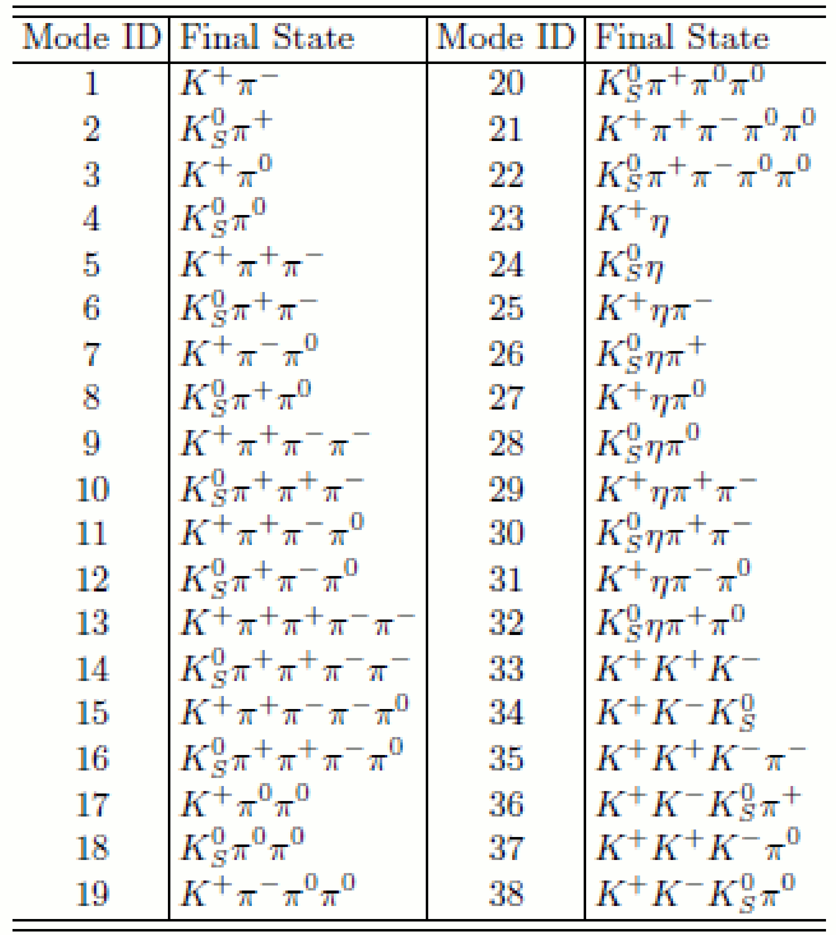


Semi-inclusive (sum-of-exclusive)

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
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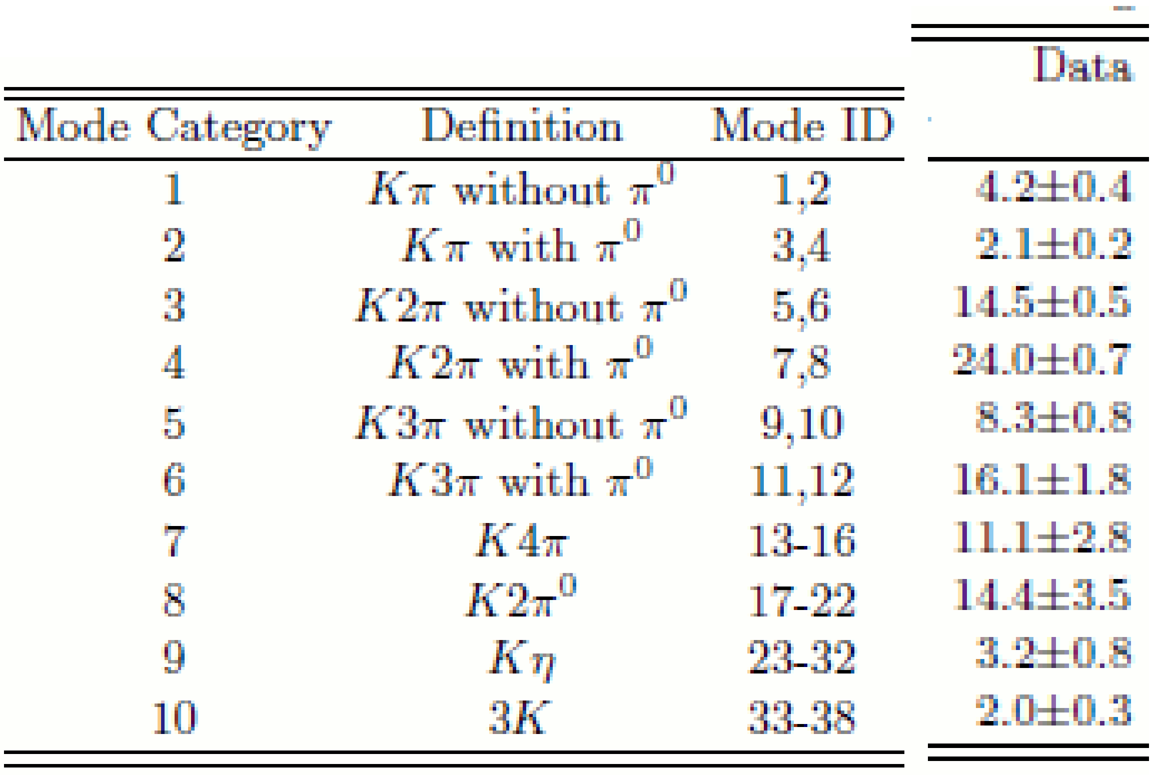
4	$K^0_S\pi^0$	23	$K^+\eta$
5	$K^+\pi^+\pi^-$	24	$K^0_S\eta$
6	$K^0_S\pi^+\pi^-$	25	$K^+\eta\pi^-$
7	$K^+\pi^-\pi^0$	26	$K^0_S\eta\pi^+$
8	$K^0_S\pi^+\pi^0$	27	$K^+\eta\pi^0$
9	$K^+\pi^+\pi^-\pi^-$	28	$K^0_S\eta\pi^0$
10	$K^0_S\pi^+\pi^+\pi^-$	29	$K^+\eta\pi^+\pi^-$
11	$K^+\pi^+\pi^-\pi^0$	30	$K^0_S\eta\pi^+\pi^-$
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]

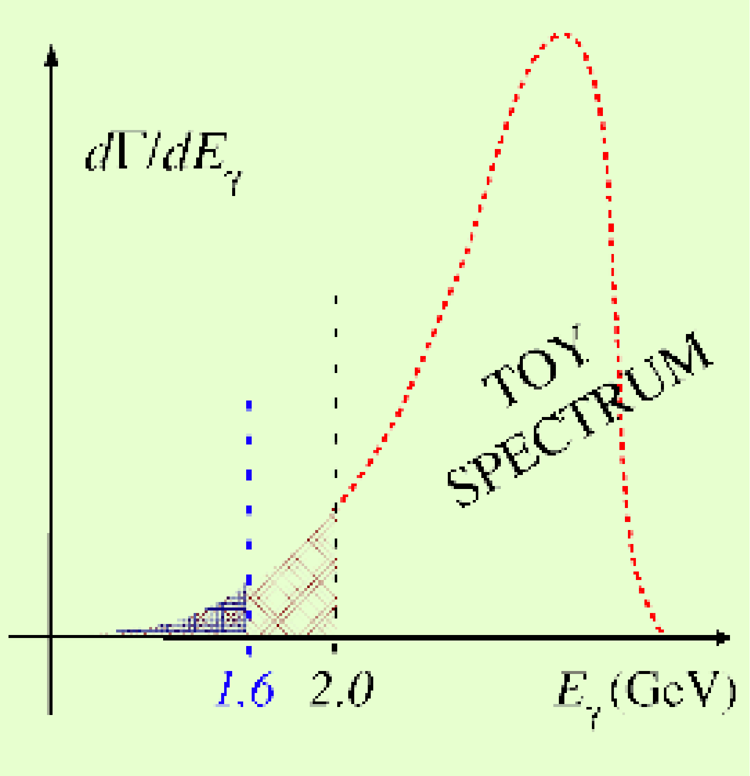
(for $E^*_\gamma > 1.9$ GeV)

[471 MBB]
[arXiv:1207.2520]

$$\begin{cases} \mathcal{B}(B\to X_s\gamma) = (3.51 \pm 0.17 \pm 0.33)\times 10^{-4} \\ \mathcal{B}(B\to X_s\gamma) = (3.29 \pm 0.19 \pm 0.48)\times 10^{-4} \end{cases}$$

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

B→X$_s$ γ spectrum



- b→s γ is a 2-body decay. The energy of the photon in the b quark frame is

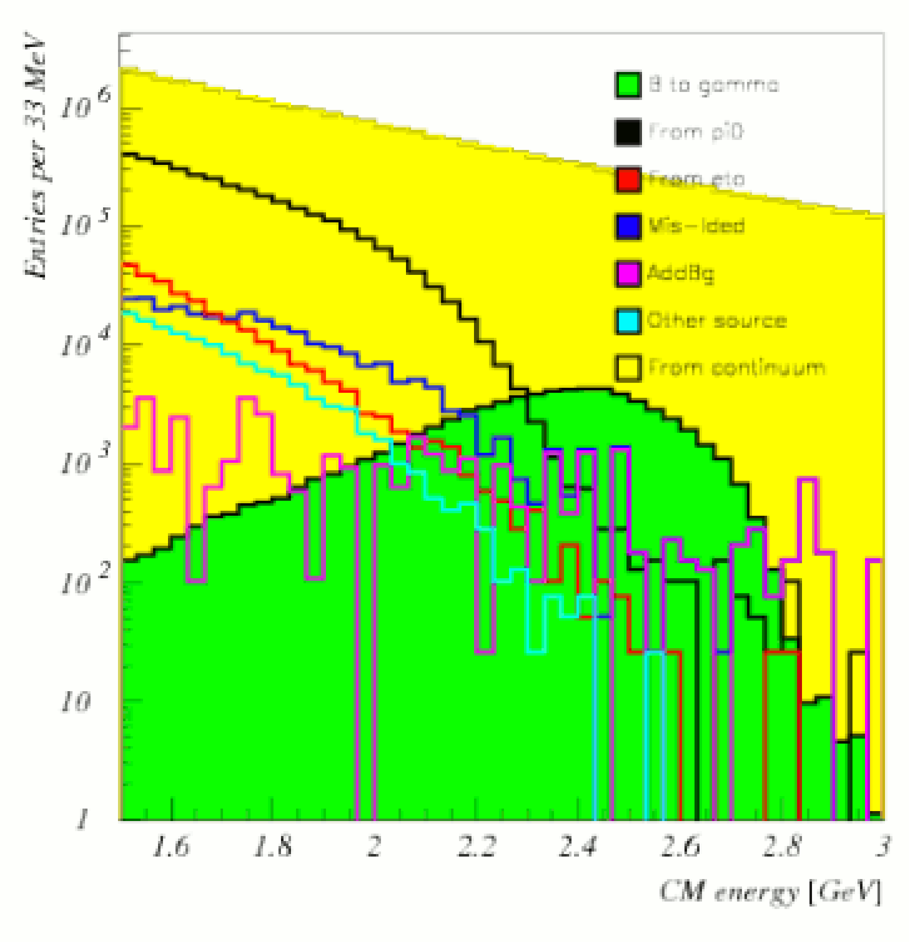
$$E_\gamma = \frac{m_b}{2}\left(1-\frac{m_s^2}{m_b^2}\right) \simeq \frac{m_b}{2}$$

- But we measure B→X$_s$ γ and in the B meson, the b quark is moving which smears the energy spectrum
  - → Mean ~ $\frac{m_B}{2}$
  - → 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)]

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

b→s γ spectrum at Belle



One would like to measure the photon energy spectrum in b → s γ decays

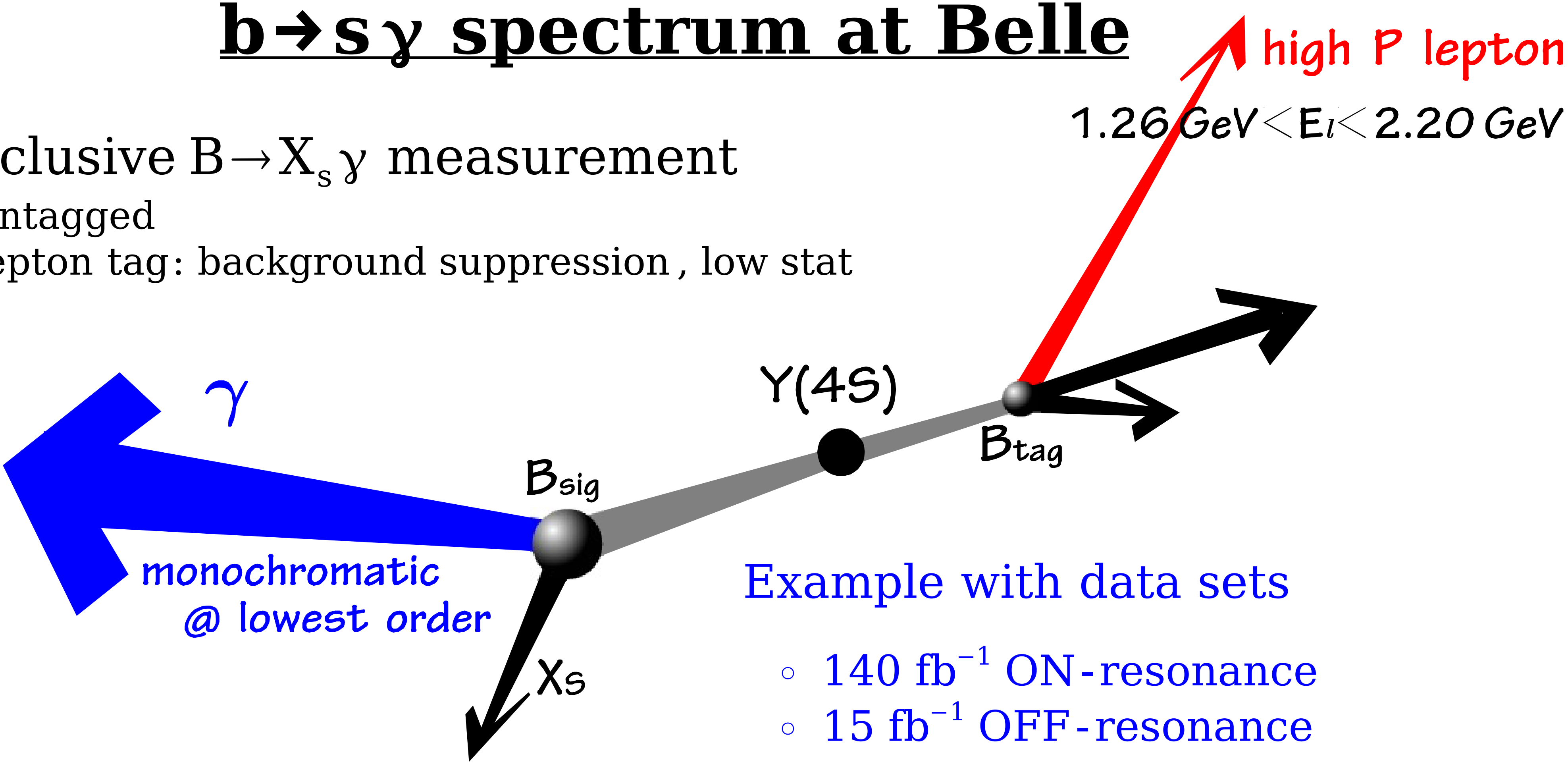
- Be unbiased: only look at the γ
- B mesons only decay to γ via b→ s γ
- But there are indirect γ from π^0 and η in $B\bar{B}$ events
- …and a lot more indirect π^0 and η in non-$B\bar{B}$ events

⇒ 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

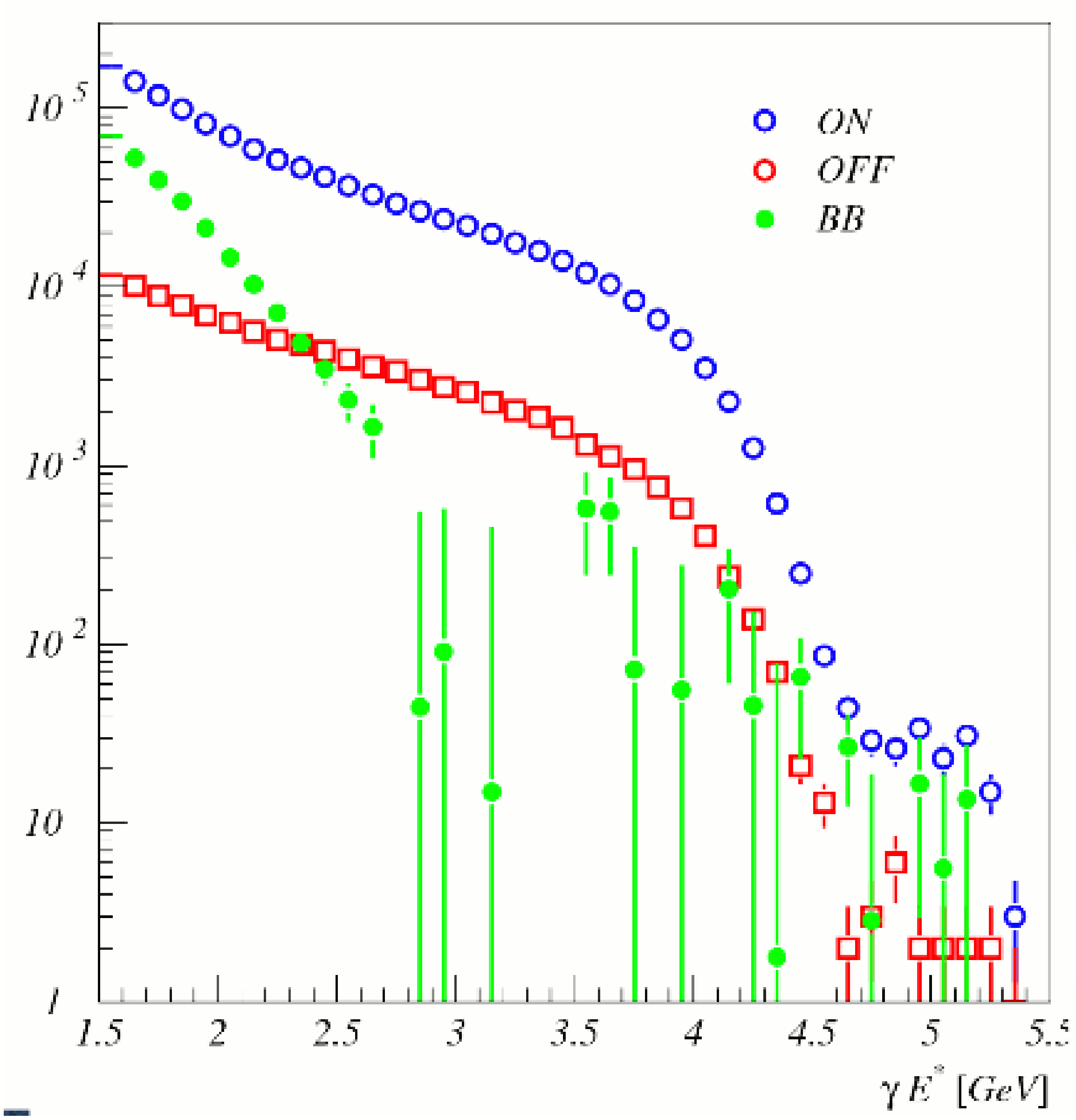
- ○ 140 fb^{-1} ON-resonance
- ○ 15 fb^{-1} OFF-resonance

Event selection:

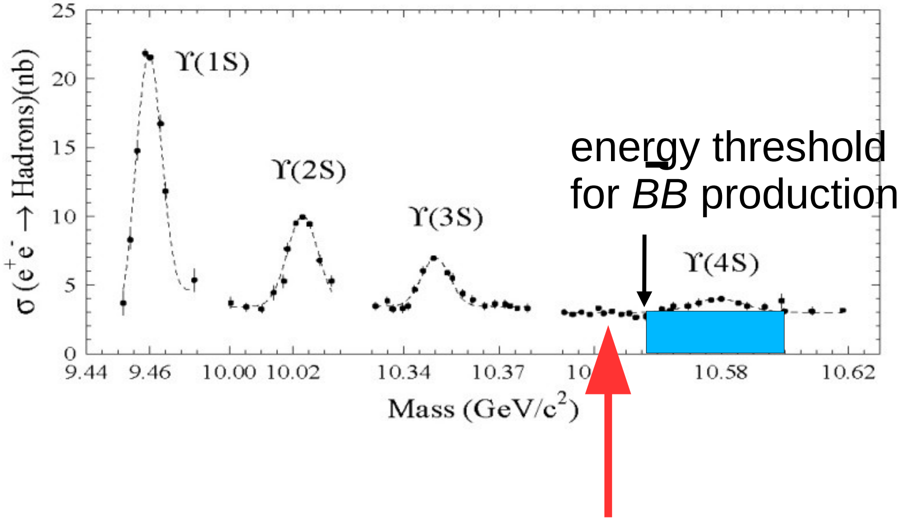
- ○ Hadronic events with isolated photon(s) in ECL. $E^* > 1.5$ GeV.
- ○ Veto γ from π^0 and η
- ○ Apply event shape cuts to suppress continuum background.

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

The spectrum

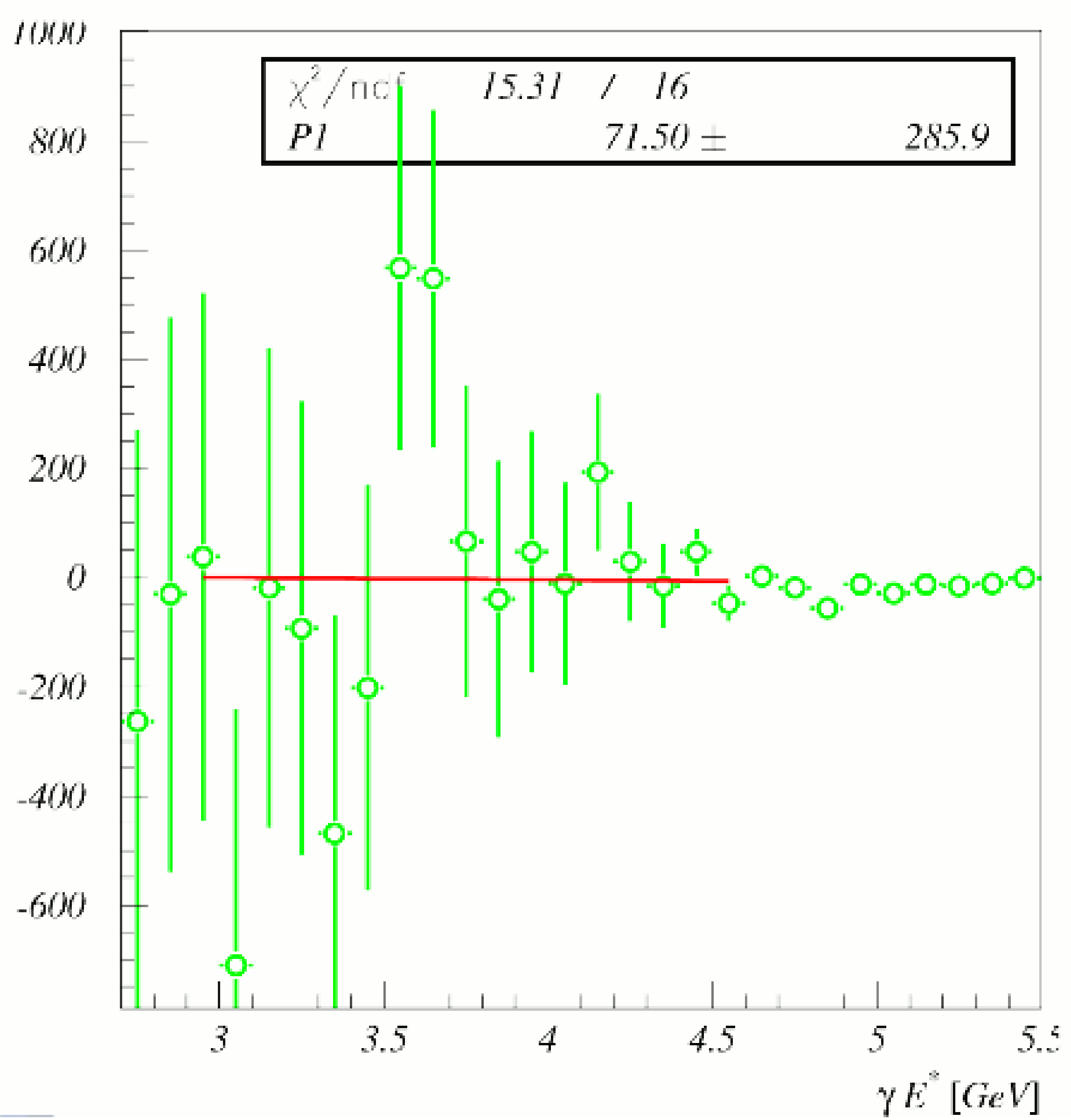


OFF-resonance data is scaled according to luminosities and subtracted from ON-resonance data



energy threshold for $B\bar{B}$ production

The spectrum



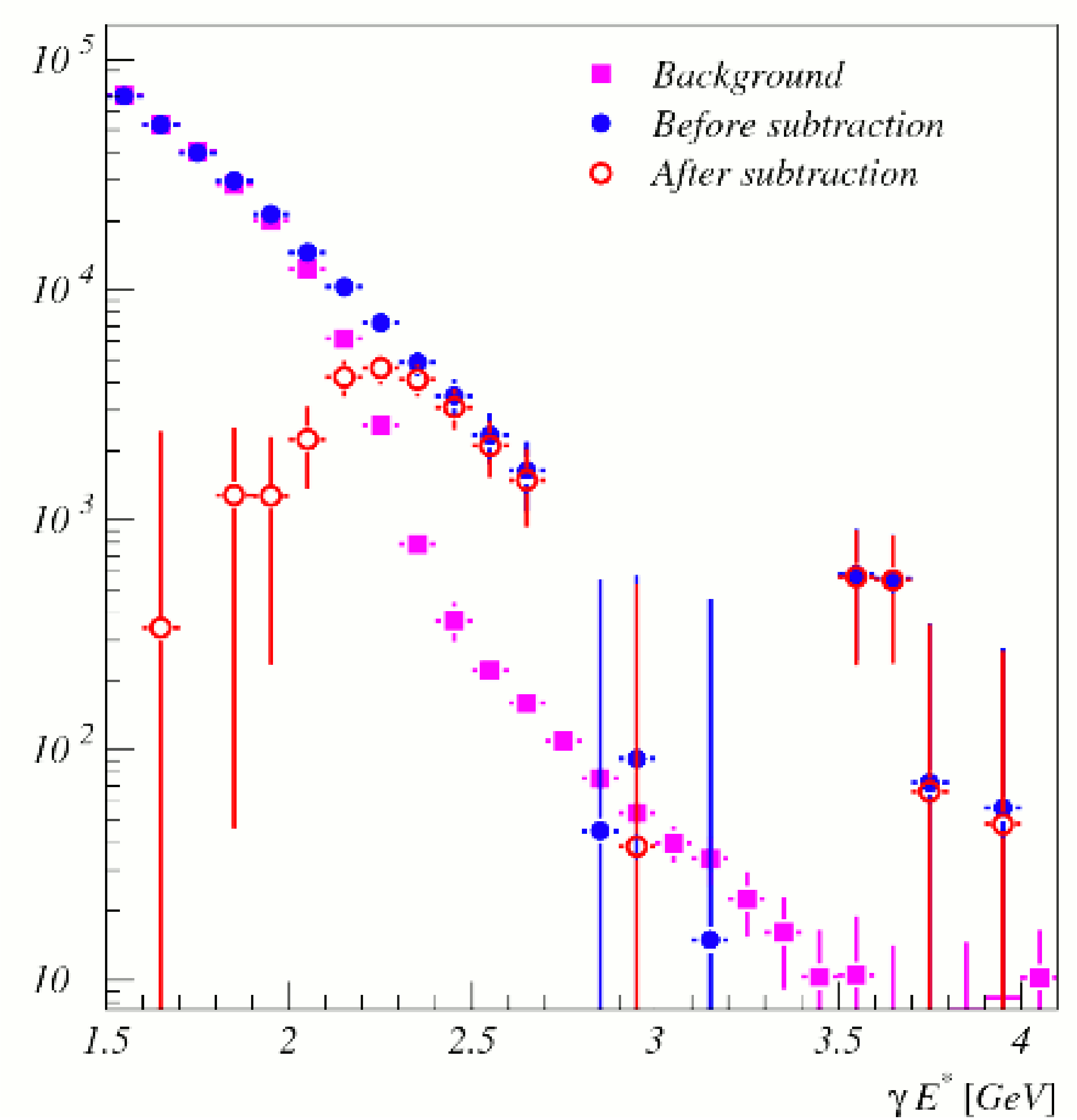
Endpoint check:

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

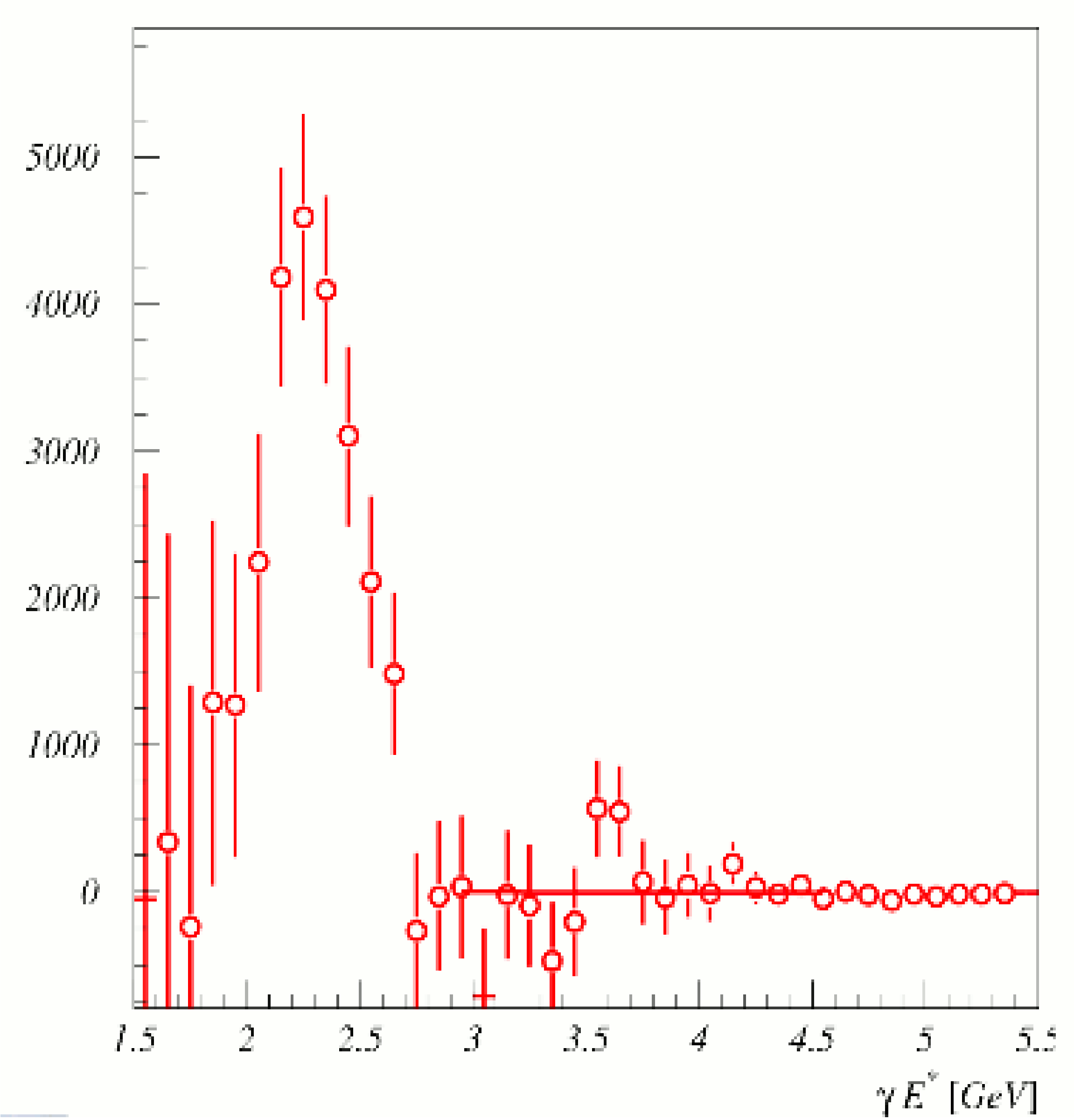
The spectrum



$B\bar{B}$ subtraction:

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

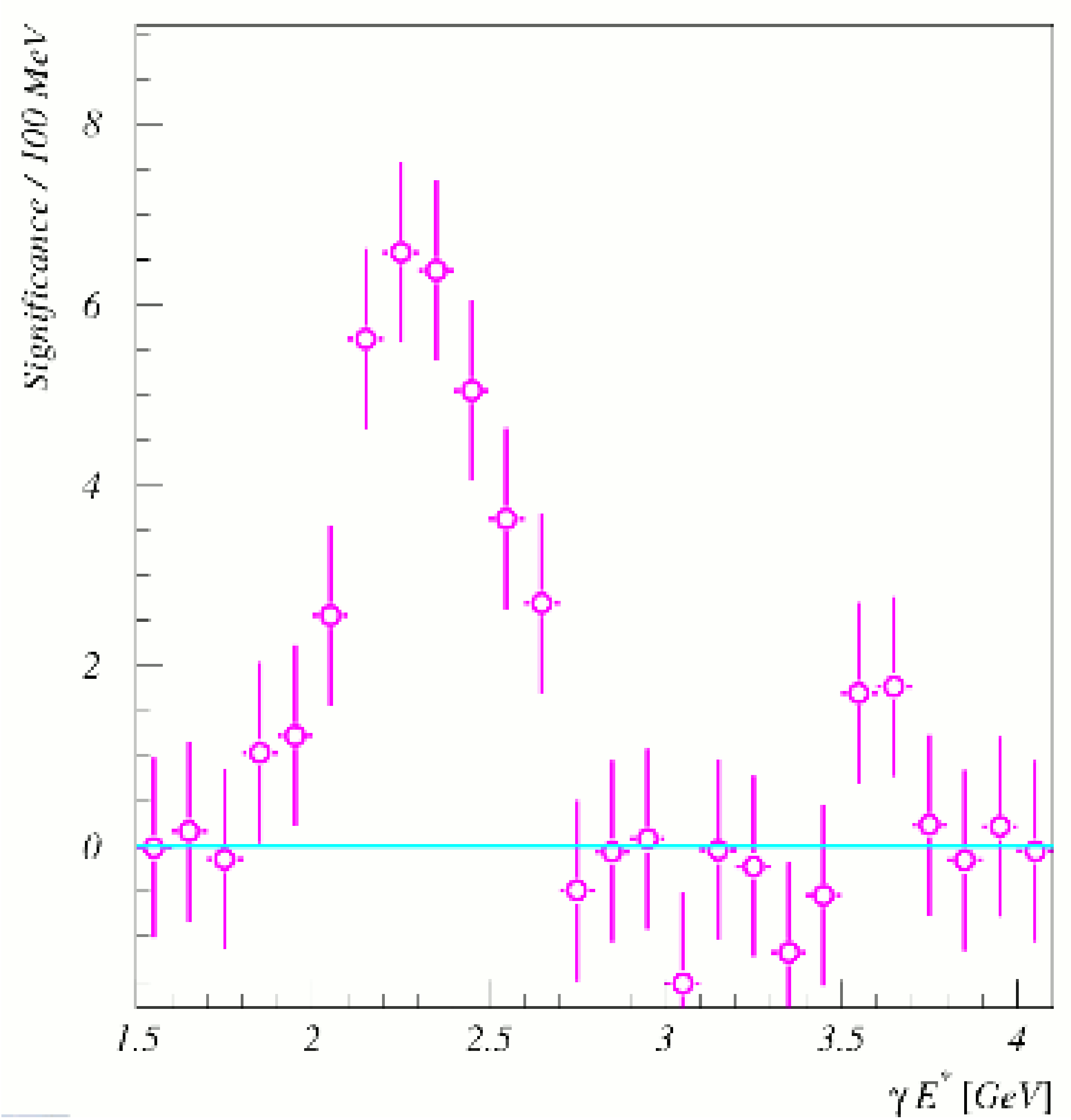
The spectrum



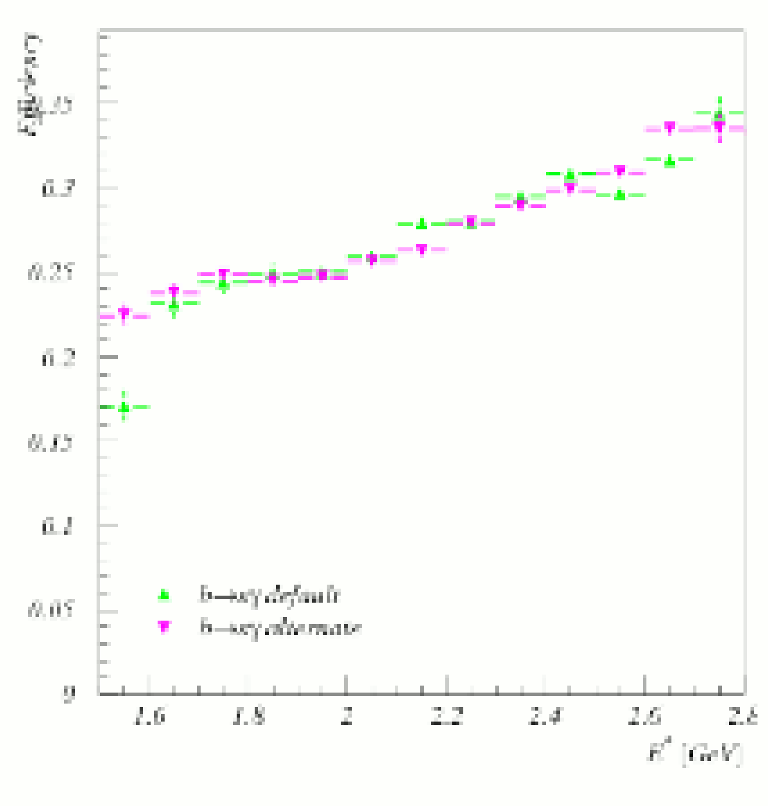
Raw spectrum after all cuts and background corrections

Signal yield:
24100 ±2200 events

The spectrum



Efficiency corrected spectrum

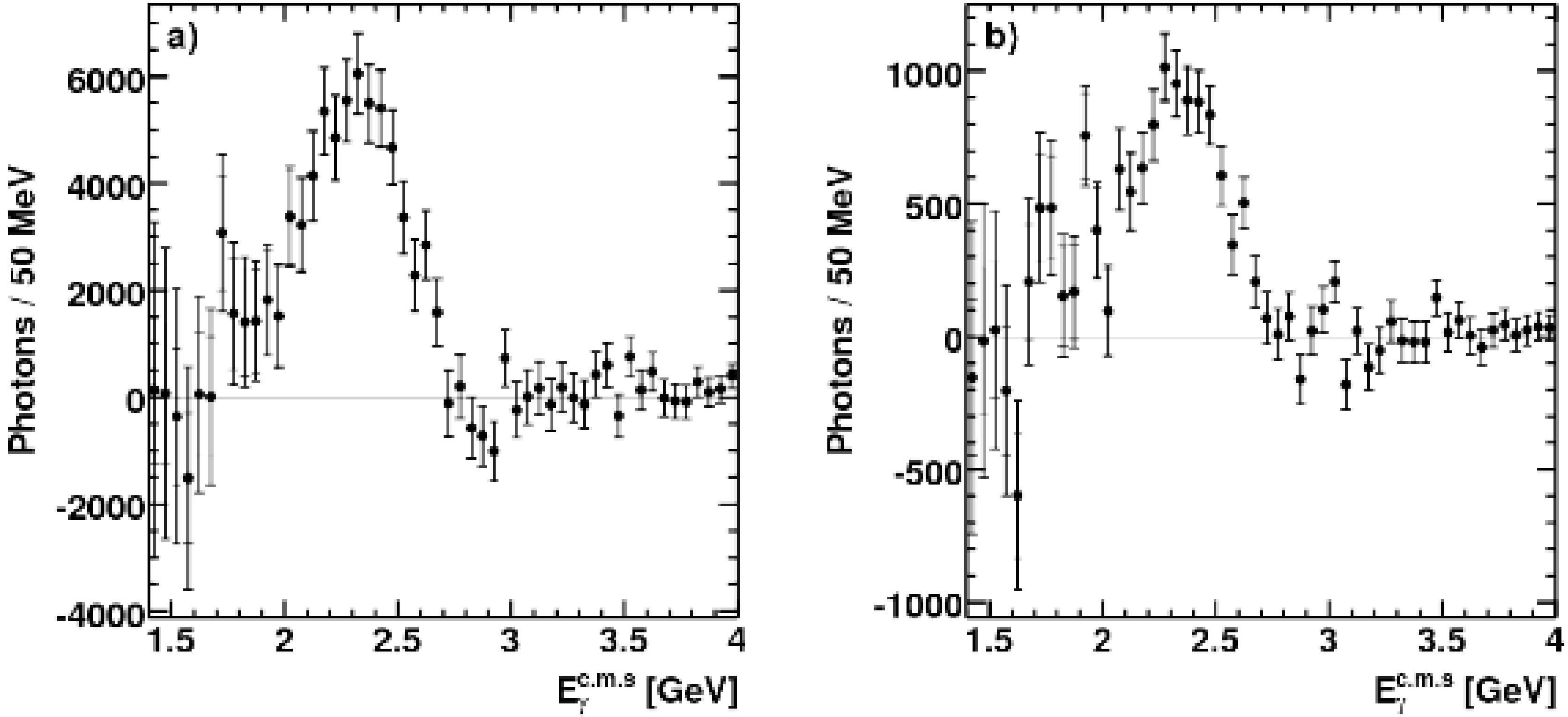


$X_s \gamma$ inclusive

PRL 103, 241801 (2009)
arXiv:0907.1384

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

BELLE



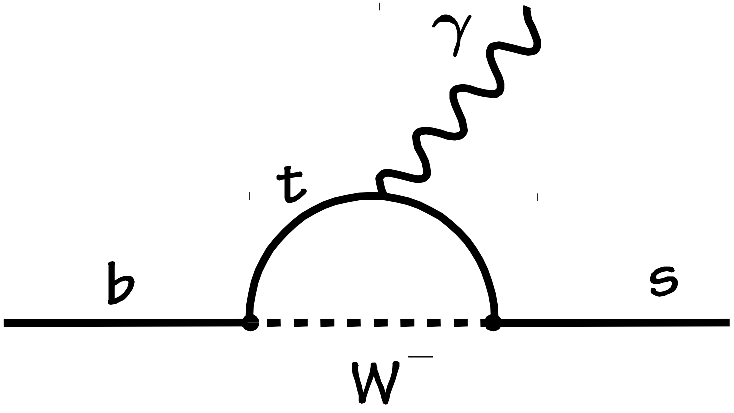
$$\boldsymbol{B(B\rightarrow X_s\gamma) = (3.45 \pm 0.15 \pm 0.40)\times 10^{-4}} \quad (\text{for } E_\gamma^* > 1.7 \text{ GeV})$$

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

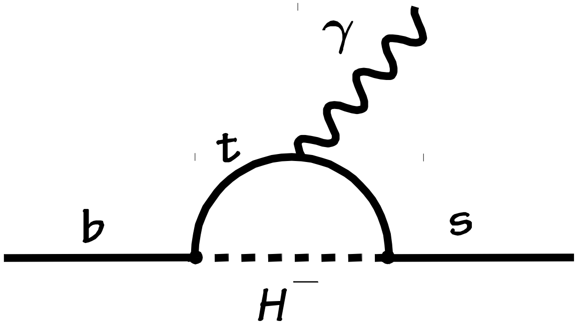
$$B(B\rightarrow X_s\gamma) = (3.06 \pm 0.41 \pm 0.26)\times 10^{-4} \quad (\text{for } E_\gamma^* > 2.0 \text{ GeV})$$

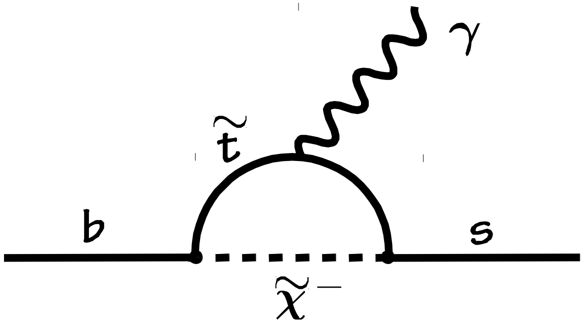
- ◦ Most precise measurement of $B\,(B\rightarrow X_s\gamma)$ (lowest E_γ^* threshold)
- ◦ Crucial input for global fit to extract $|V_{ub}|$ and $B\rightarrow X_s\gamma$ decay rate
- ◦ B is given for E_γ thresholds: 1.7, 1.8, 1.9, 2.0 GeV
- ◦ Systematic error is dominated by off-resonance subtraction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

$B \to X_s \gamma$ as an illustration



Sensitive to NP





NNLO SM calculation:

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

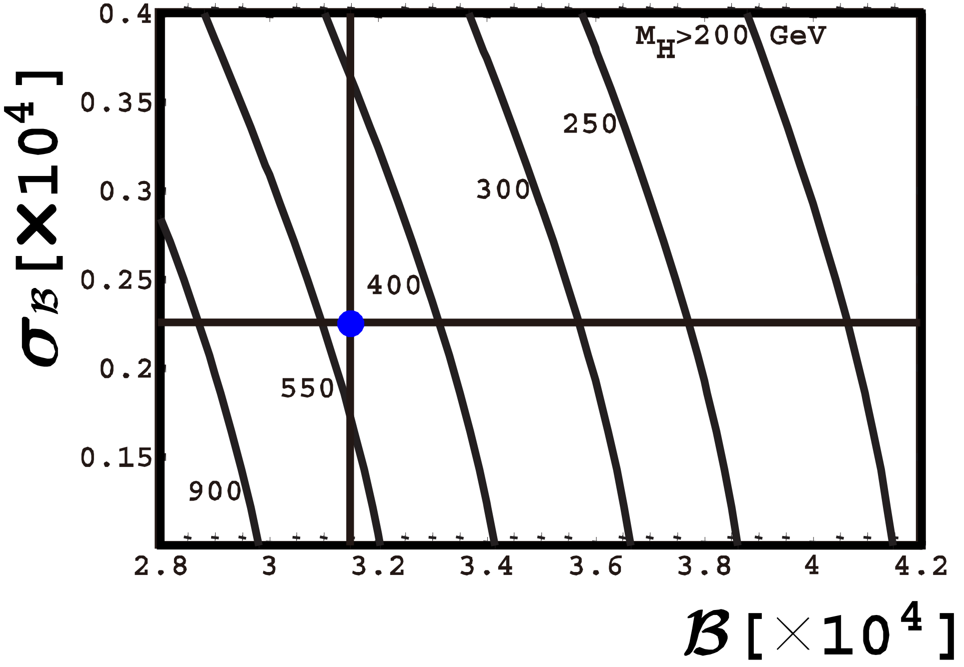
(for $E_\gamma > 1.6$ GeV)

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



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

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

vs

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

[Misiak et al, arXiv:1503.01789]

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

[arXiv:1706.07414]