Beautiful paths to probe physics beyond the standard model of particles

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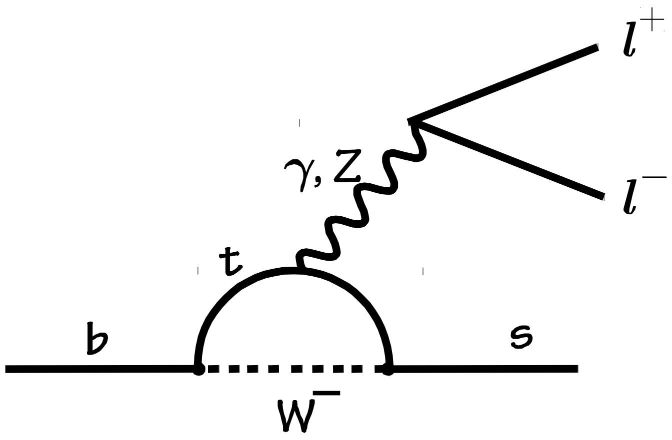
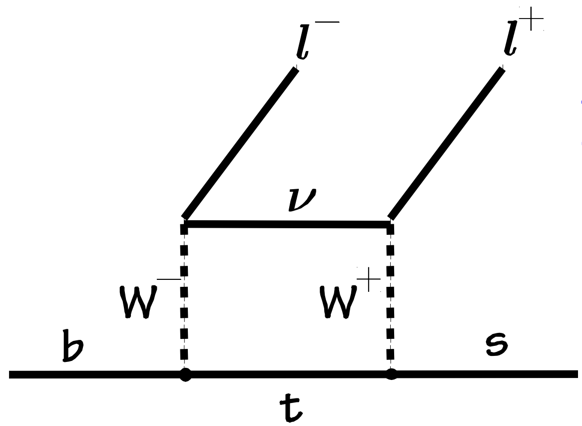
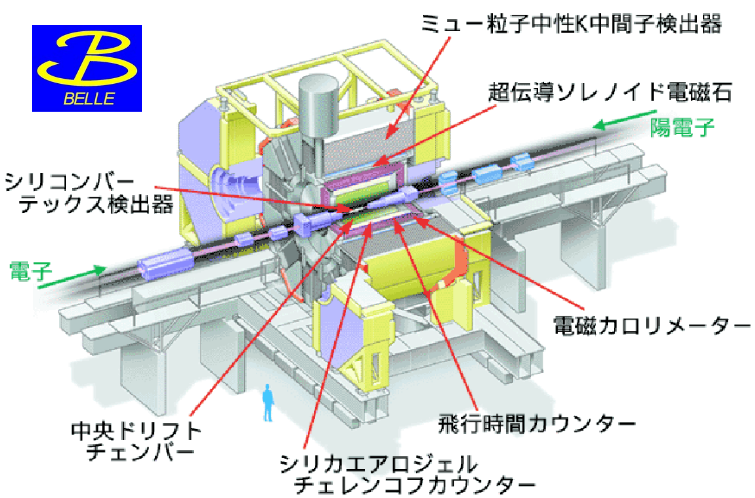
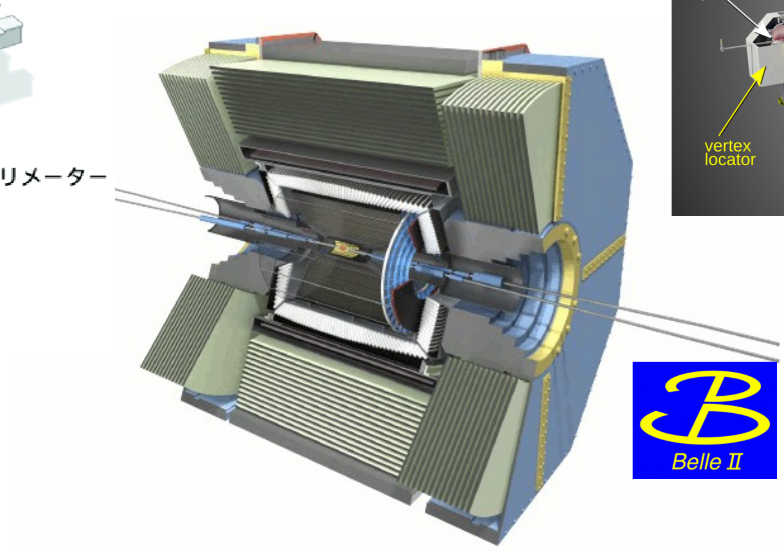
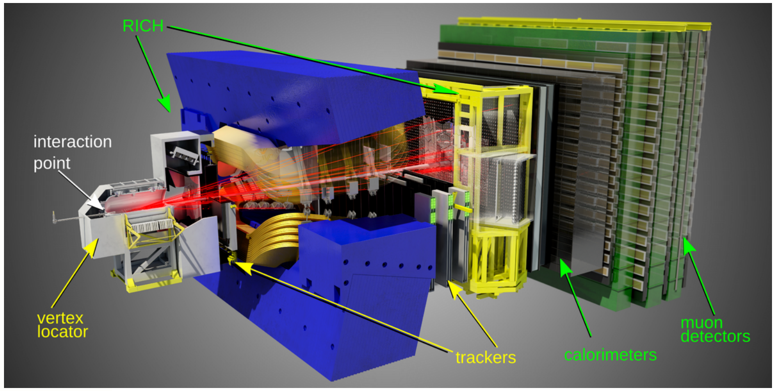










Jennifer school, Trieste, July 31th 2018

Program of the 3 lectures

- **How to study elementary particles**
  - **direct searches and indirect searches**
  - **experiments through history of particle/flavour 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, precise measurements....**

2 words on my background

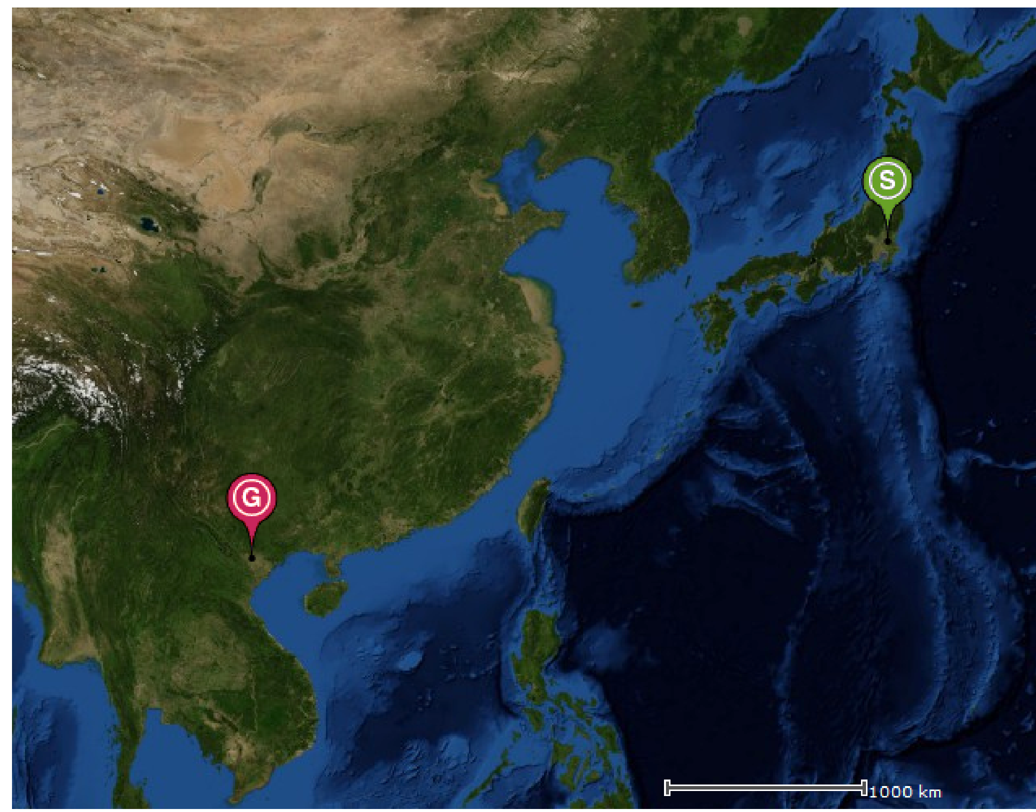
ALEPH (CERN), Belle (KEK), LHCb (CERN), Belle II (KEK)

CPPM (France), Osaka U (Japan), U Hawaii (USA), KEK(Japan), EPFL (Switzerland), LAL (France)

KEK

High Energy Accelerator Research Organization

◦ Tsukuba, Japan
◦ Largest Accelerator Facility in Japan
◦ Institute for High Energy Physics (Particle Physics)
◦ Various researches using accelerators are being done (Universe, Matter, Life)



KEK

High Energy Accelerator Research Organization

Accelerator
circumference 3 km

20 years ago…

BELLE

New generation , new experiment

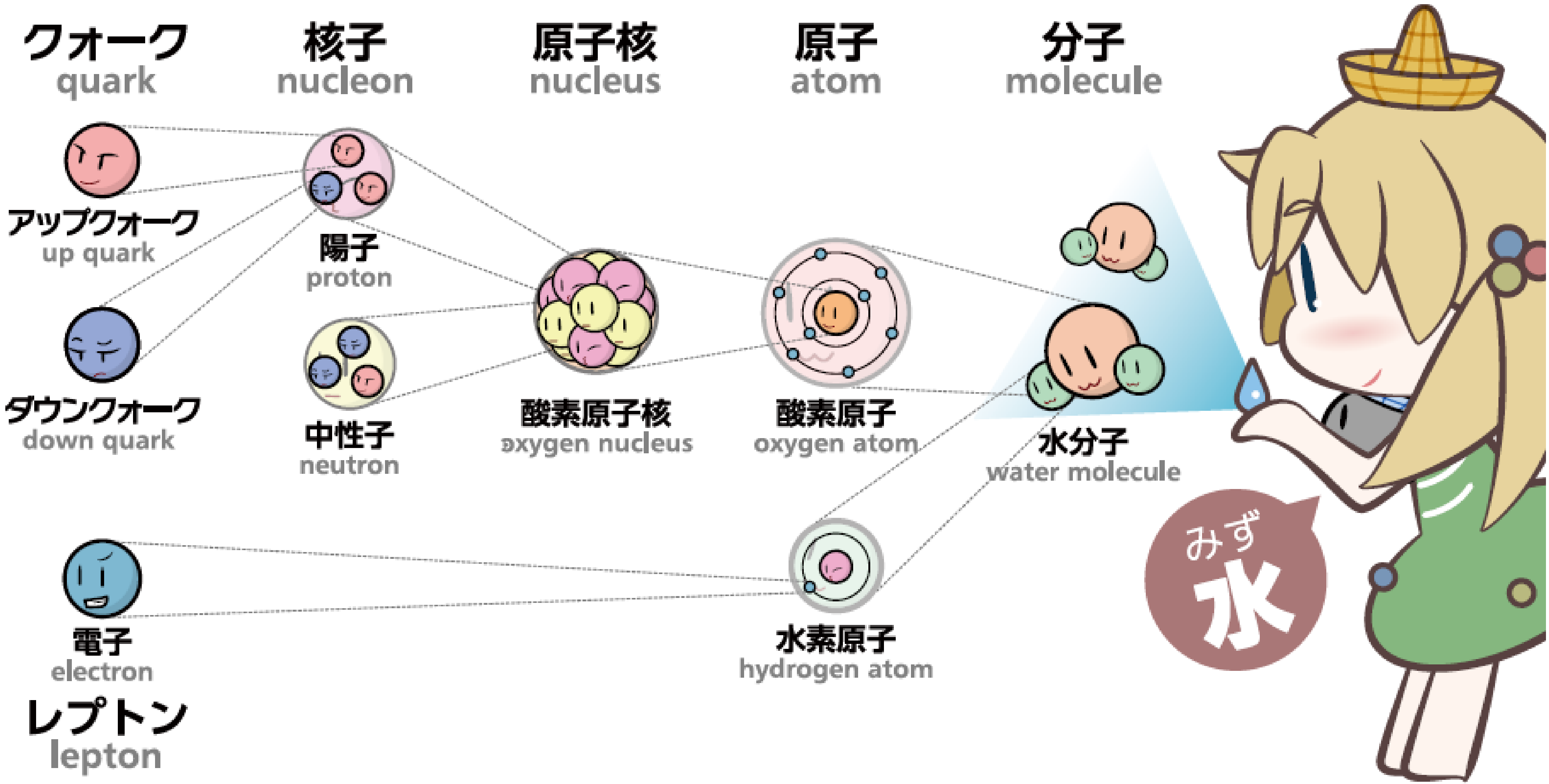
start taking data this year …

Belle II

keywords :
particle physics
flavor physics
beauty , charm , τ …
intensity frontier
indirect search

Standard Model

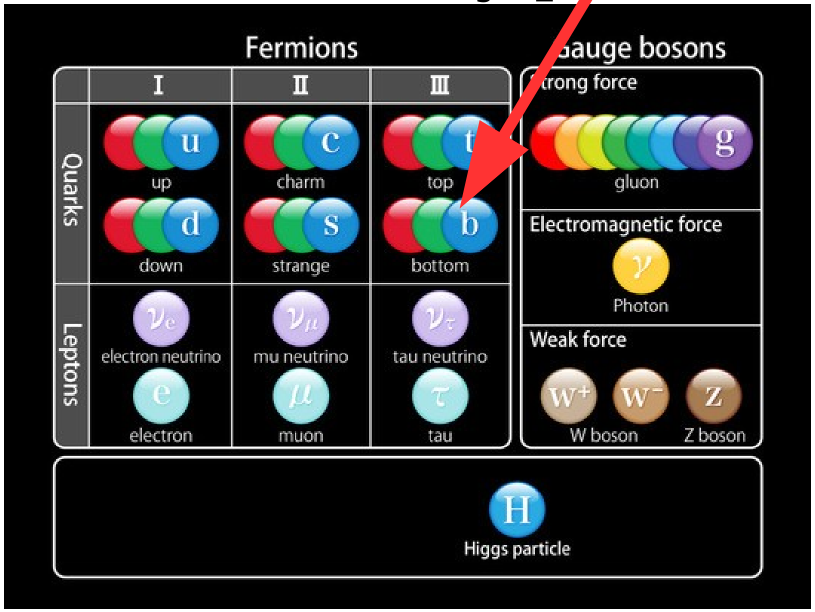
from the first generation…



Standard Model in a nutshell

b quark !

In the Standard Model (theory of the Particle Physics) following particles are considered to be elementary particles:



components of SM

Matter (fermions)

3 generations: quarks and leptons

Source of Force (Gauge bosons)

Electromagnetic γ
Weak interaction $W^{\pm}$, Z^0 } Electro-weak (unified) $SU(2)\times U(1)$

Strong interaction g (quark only) QCD $SU(3)$

Source of Mass

Higgs Boson H^0 (discovered by LHC in 2012)

(Spontaneous breakdown: vacuum expectation → mass)

Weinberg – Salam (1976) [gravity is not included]

Parameters of the Standard Model

- 3 gauge couplings + QCD vacuum angle
- 2 Higgs parameters
- 6 quark masses
- 3 quark mixing angles + 1 phase
- 3 (+3) lepton masses
- (3 lepton mixing angles + 1 phase)

flavour parameters

Cabibbo-Kobayashi-Maskawa

CKM matrix

PMNS matrix

Pontecorvo-Maki-Nakagawa-Sakata

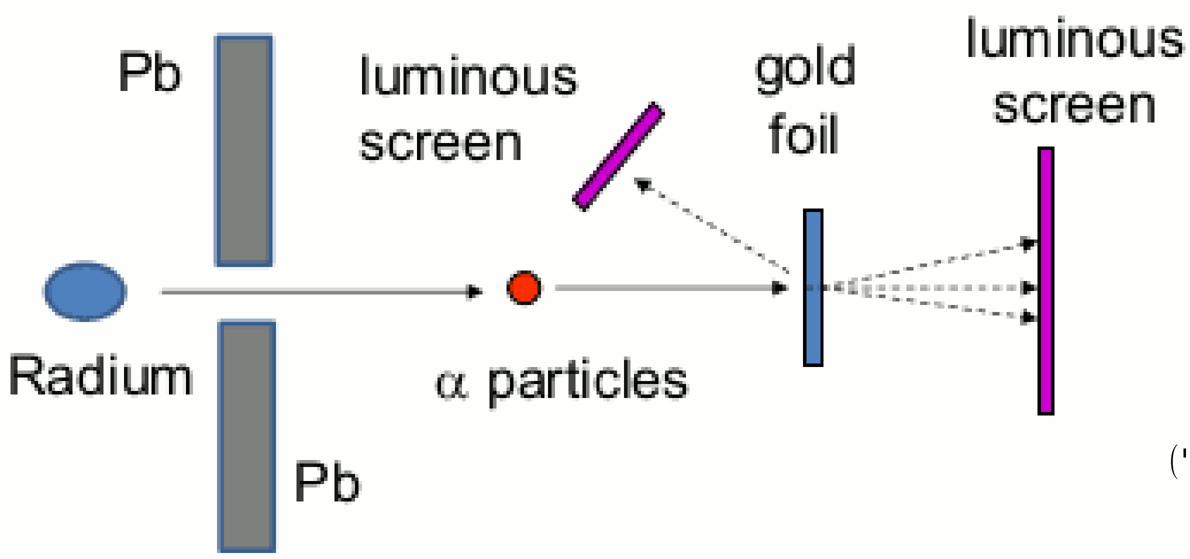
() = with Dirac neutrino masses

importance of flavour physics, indirect searches…

How to study Elementary Particles
⇒ experiments !!

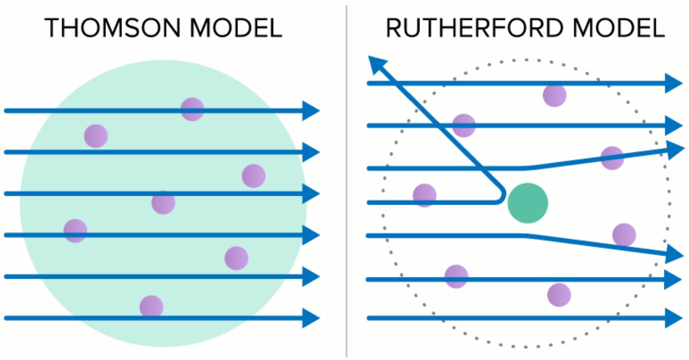
''it was as if you fired a 15-inch shell at a piece of tissue paper and it came back and hit you''
– Rutherford

- In 1911, Rutherford performed an experiment to irradiate α particles to a gold foil.
  - ✓ α particle : nucleus of He atom
  - ✓ α particle from Radium (radioactive source)



E. Rutherford

''Standard Model'' ''New Physics''
(''Panettone'' atom model)



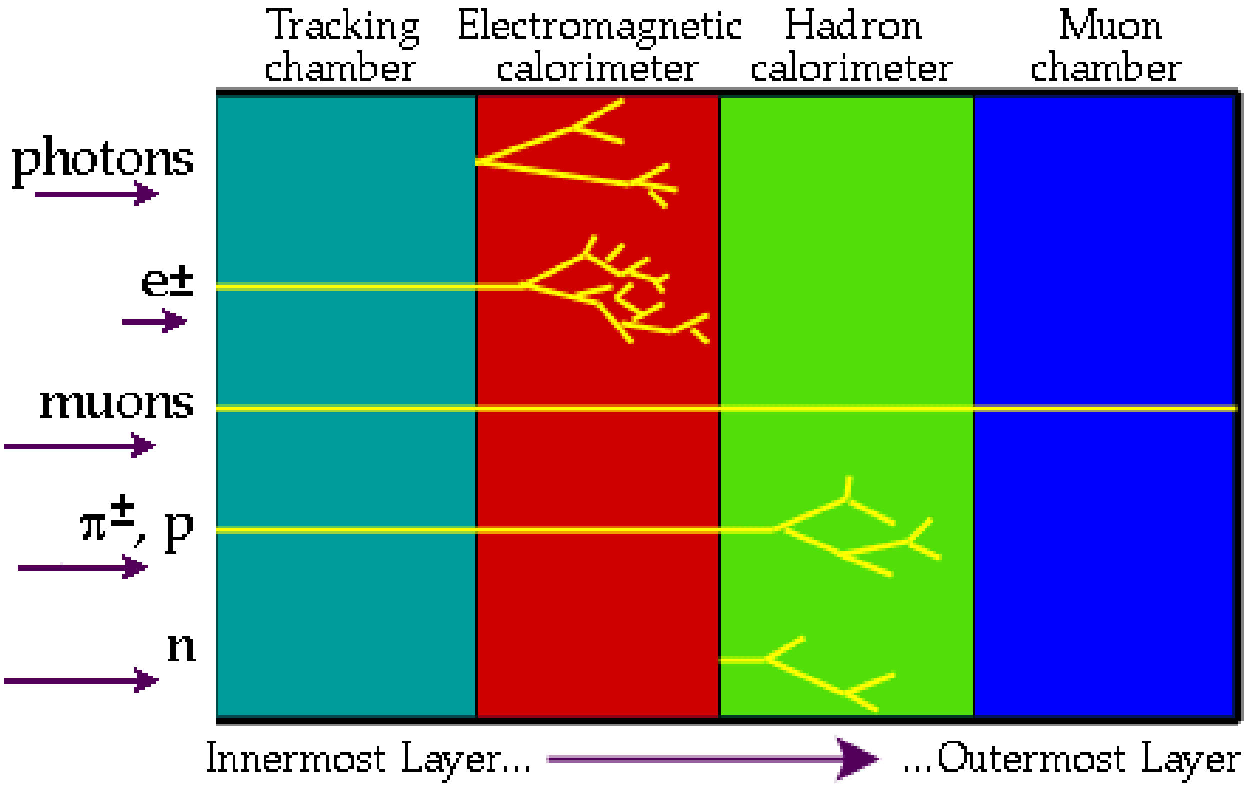
Most α particles passed through the gold foil. However, surprisingly, a very small fraction of them were deflected by much larger than 90 degrees.

Particle physics experiments

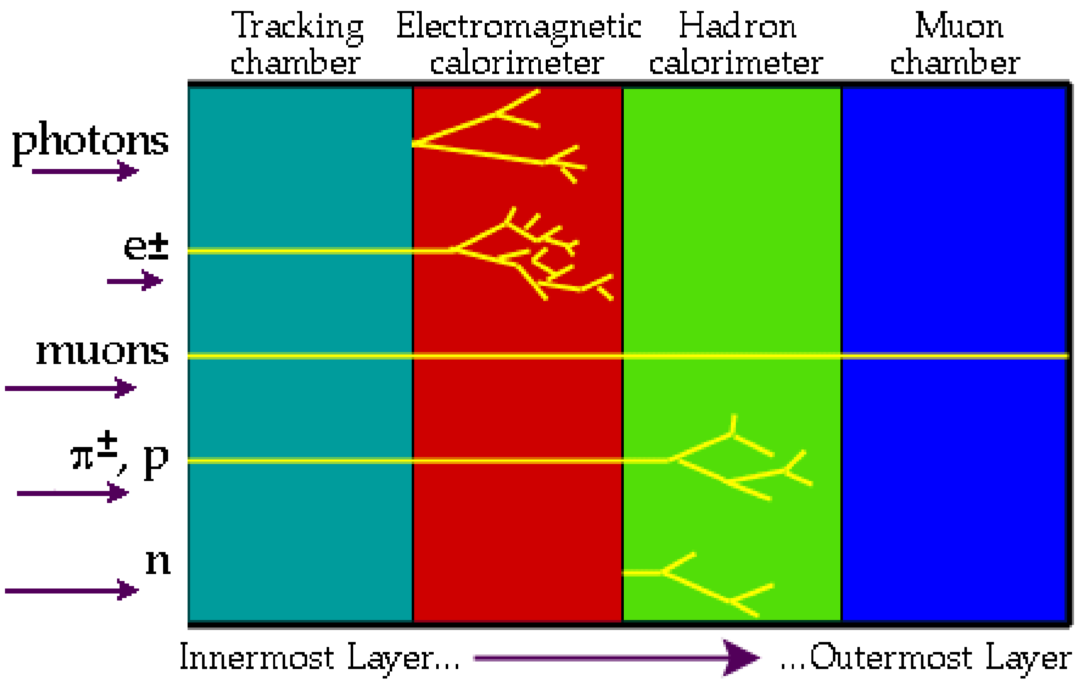
see lectures from T. Wongjirad

Detectors and other electronic apparatus are required for various purposes in every experiment. The tasks required for most experiments include:

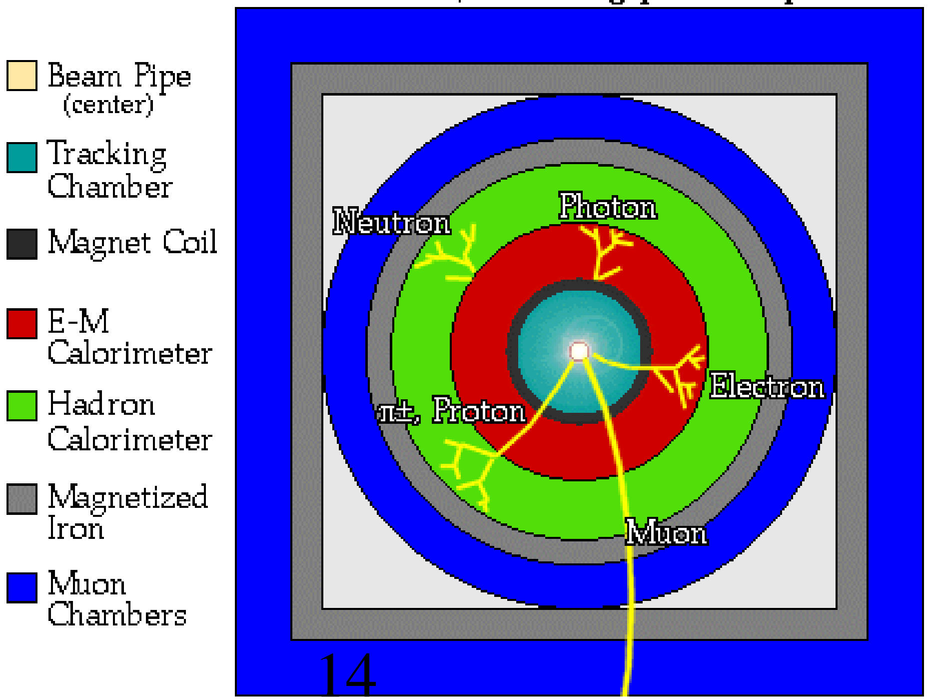
- tracking
- momentum analysis
- neutral particle detection
- particle identification
- triggering, and
- data acquisition



Identifying particles



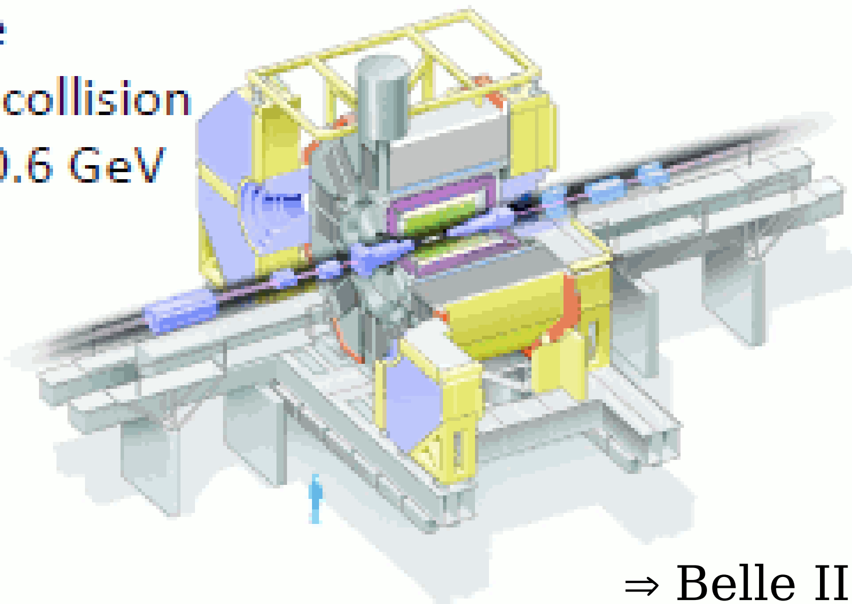
A detector cross-section, showing particle paths



Main actors in B physics

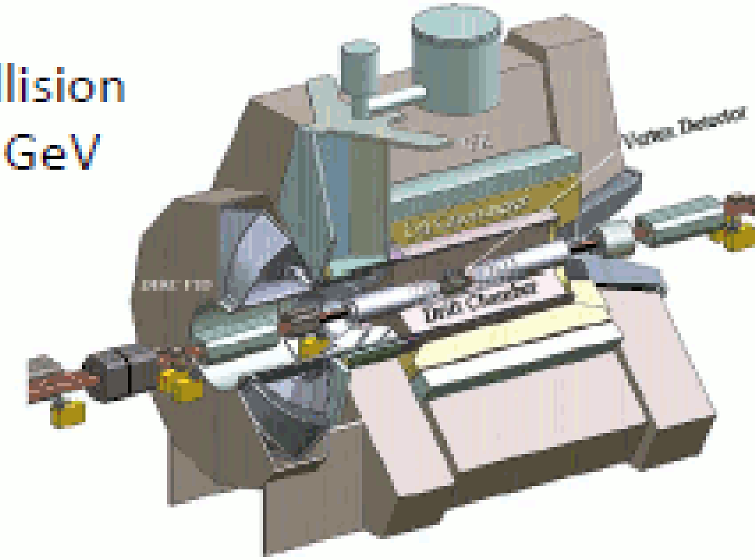
(ARGUS, CLEO)

Belle
e^+e^- collision
at 10.6 GeV

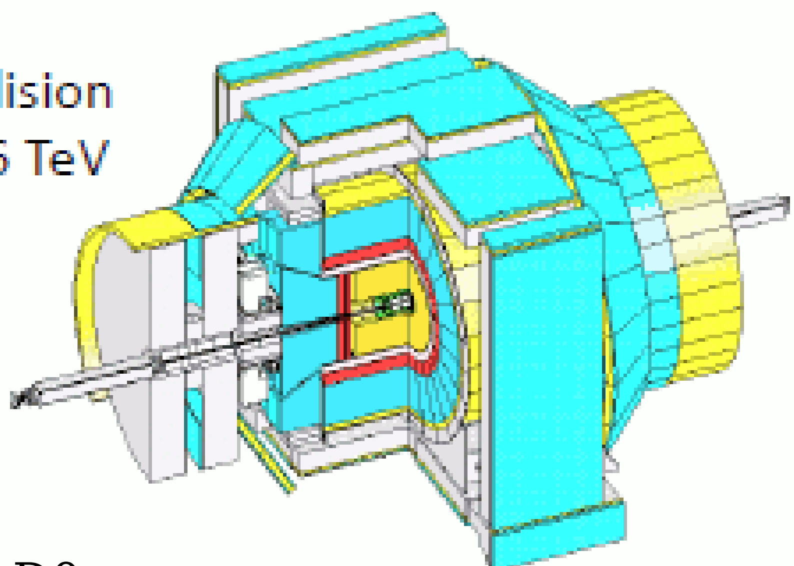


⇒ Belle II

BaBar
e^+e^- collision
at 10.6 GeV

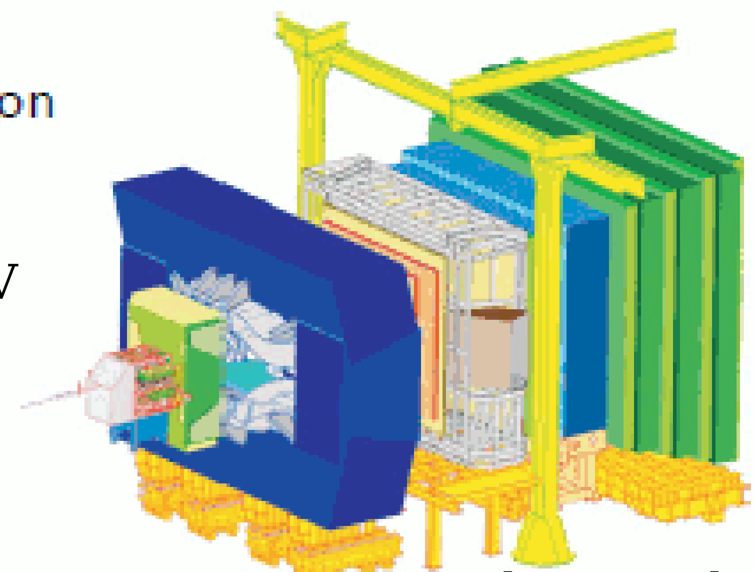


CDF
$p\bar{p}$ collision
at 1.96 TeV



... and D0

LHCb
pp collision
at 7 TeV
8 TeV
13 TeV



... and CMS

⇒ LHCb upgrade

logo designed by undergraduate student …

logo designed by undergraduate student ...

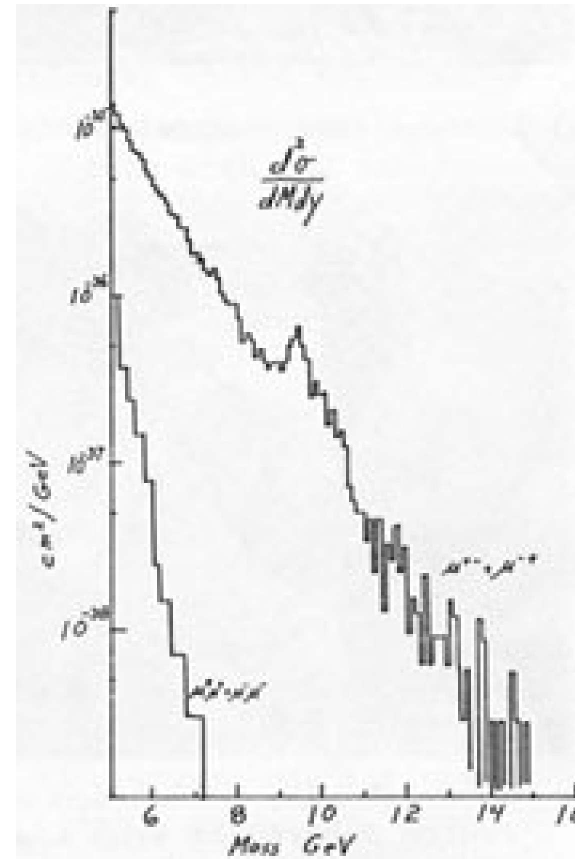
asymmetric e^+e^- collider
producing B mesons

but why running at 10.6 GeV ?

Upsilon meson discoveries

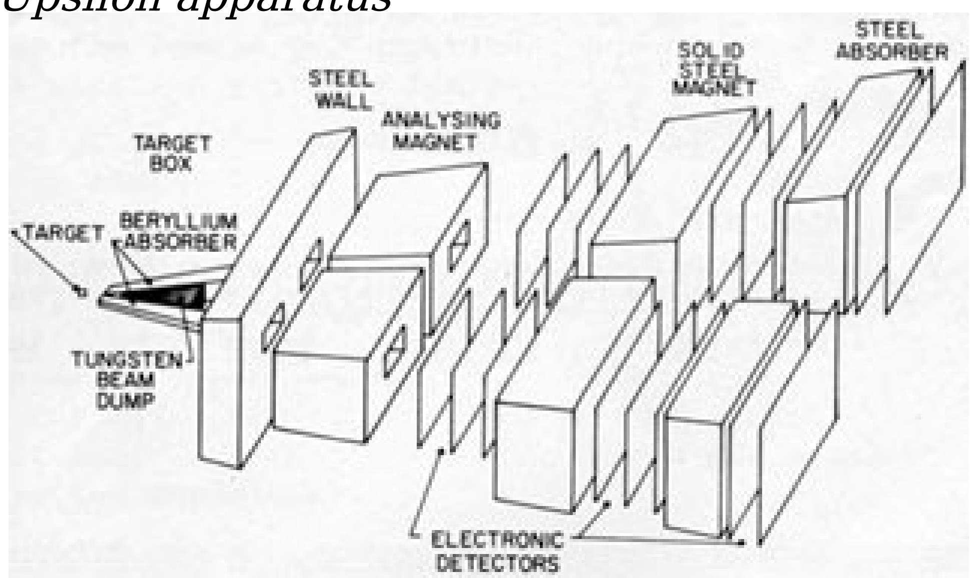
''Observation of a Dimuon Resonance at 9.5 GeV in 400 GeV Proton-Nucleus Collisions''

Summer of 1977, a team of physicists, led by Leon M. Lederman, working on experiment 288 in the proton center beam line of the Fermilab fixed target areas discovered the Upsilon Υ

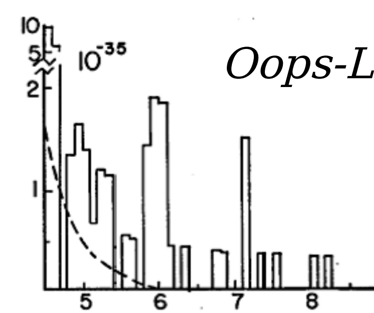


1970 proposal: study the rare events that occur when a pair of muons or electrons is produced in a collision of the proton beam from the acccelerator on a platinum target Only one Upsilon is produced for every 100 billion protons which strike the target

The Upsilon apparatus

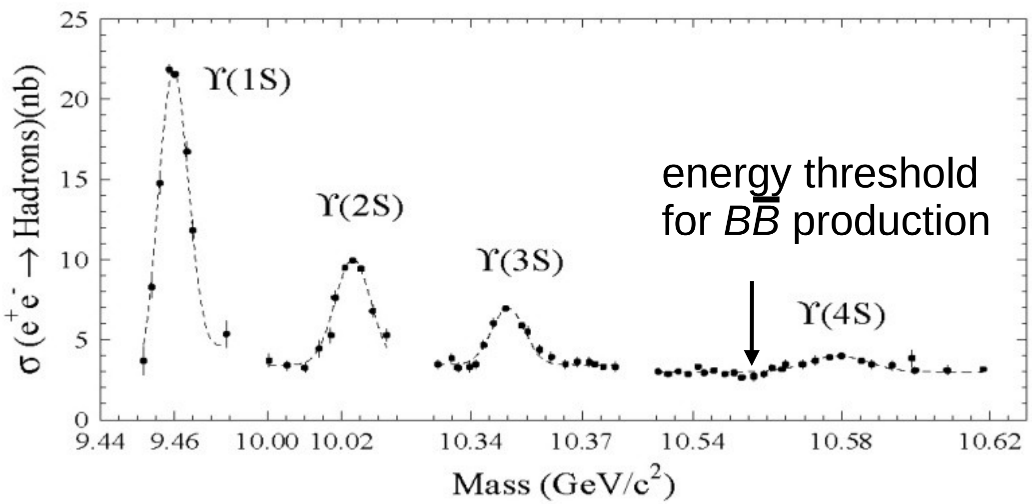


Oops-Leon !!

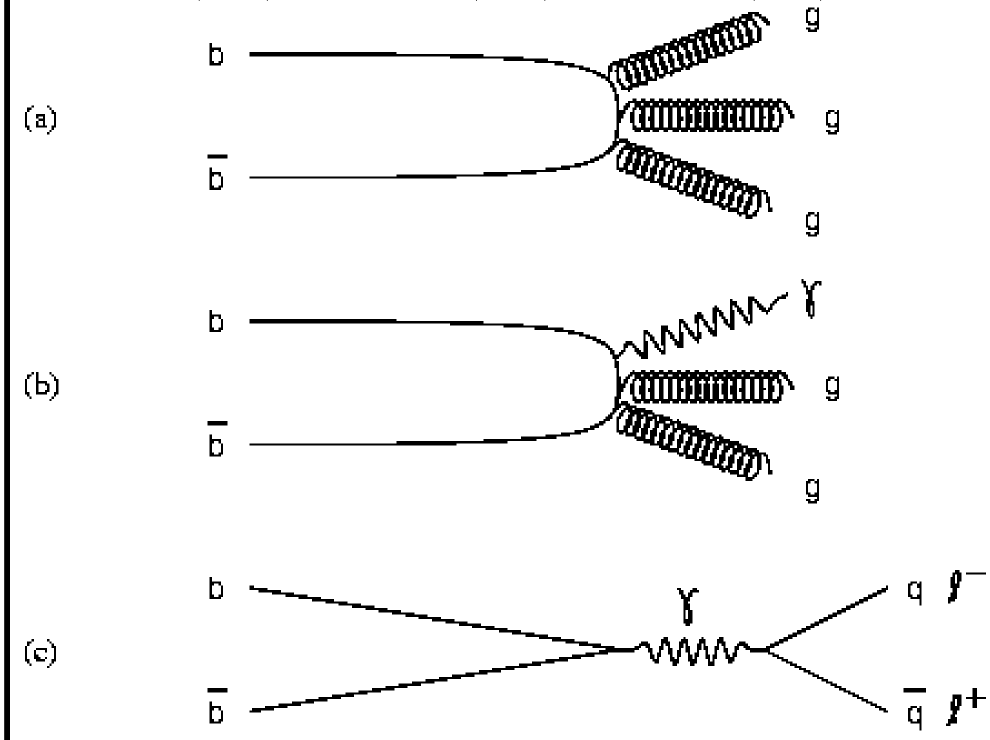


''The Upsilon fits very nicely into the picture of a super-atom consisting of the bound state of a bottom quark and antiquark.''

Υ(4S) = Υ(10580) B-factory



Υ(1S): 80%, Υ(2S): 60%, Υ(3S): 36%



Particle Data Group

Υ(1S) $I^G(J^{PC}) = 0^-(1^{--})$

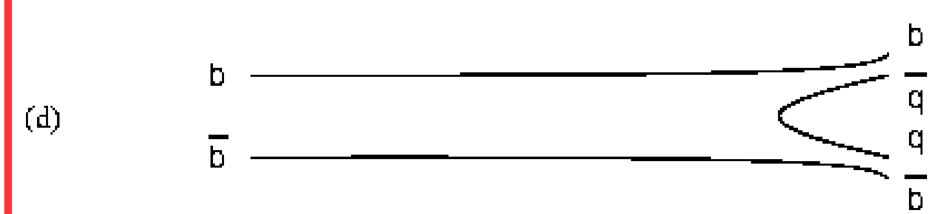
Υ(1S) MASS	9460.30 ± 0.26 MeV (S = 3.3)
Υ(1S) WIDTH	54.02 ± 1.25 keV
Γ(ggg , γ g g → $\bar{d}$ anything)/Γ(ggg , γ g g → anything)	(3.36 ± 0.34) × 10^{-5}

Υ(2S) $I^G(J^{PC}) = 0^-(1^{--})$

Υ(2S) MASS	10023.26 ± 0.31 MeV
$m_{Υ(3S)} - m_{Υ(2S)}$	331.50 ± 0.13 MeV
Υ(2S) WIDTH	31.98 ± 2.63 keV

Υ(3S) $I^G(J^{PC}) = 0^-(1^{--})$

Υ(3S) MASS	10355.2 ± 0.5 MeV
$m_{Υ(3S)} - m_{Υ(2S)}$	331.50 ± 0.13 MeV
Υ(3S) WIDTH	20.32 ± 1.85 keV

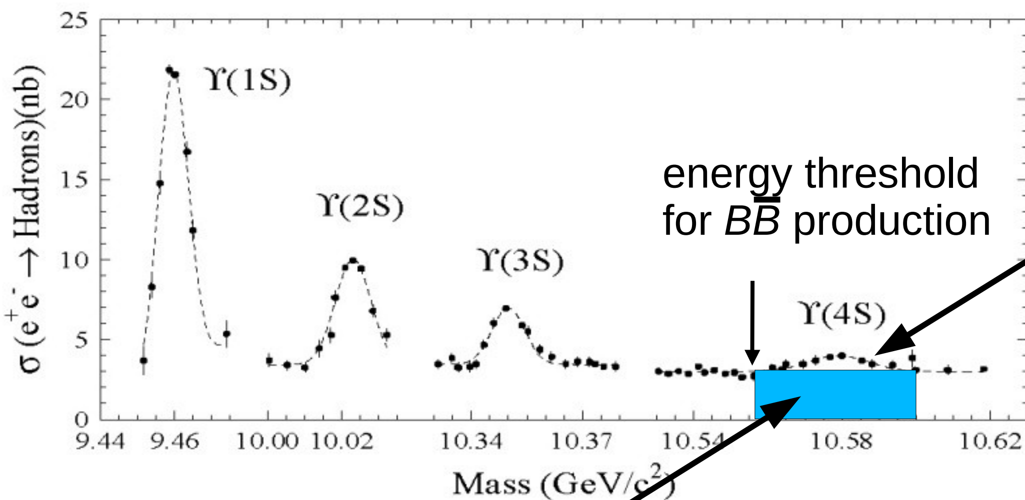


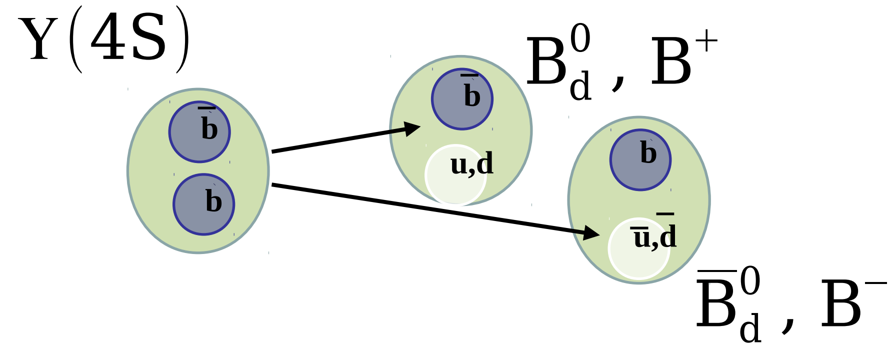
Υ(4S) $I^G(J^{PC}) = 0^-(1^{--})$

also known as Υ(10580)

Υ(4S) MASS	10579.4 ± 1.2 MeV
Υ(4S) WIDTH	20.5 ± 2.5 MeV

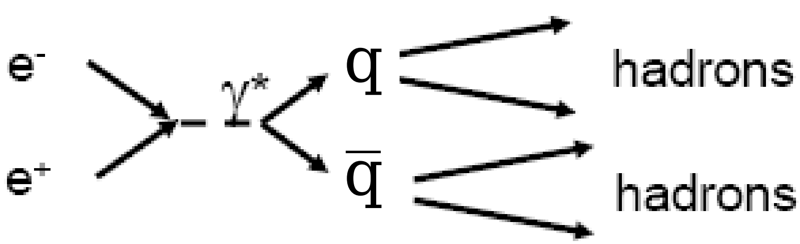
$\Upsilon(4S)$ B-factory





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

  ⇒ before first decay, the final states contains a B and a $\bar{B}$



$$R(s) = \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)} = \sum_q Q_q^2$$

The naive parton model:

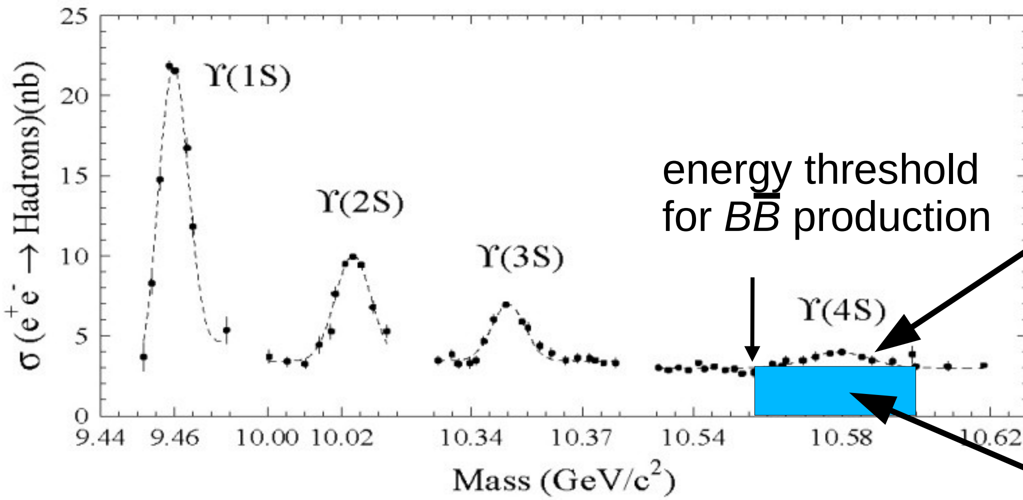
$1\ \text{GeV} \leq \sqrt{s} \leq 3\ \text{GeV}$, u, d and s quarks

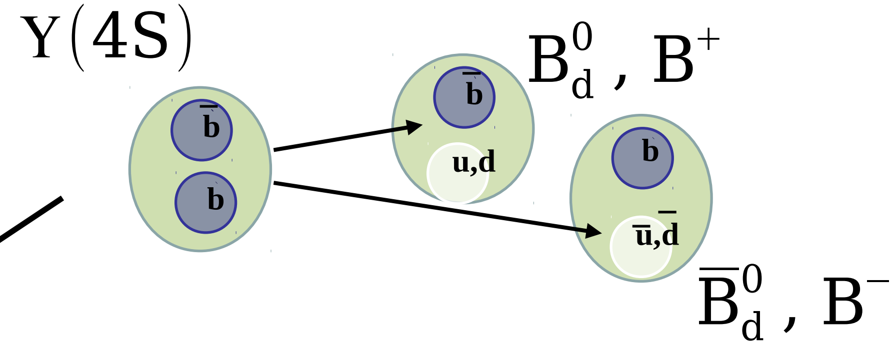
$$\mathbf{R(s) = 3.\{1.(\tfrac{2}{3})^2 + 2.(-\tfrac{1}{3})^2\} = 2}$$

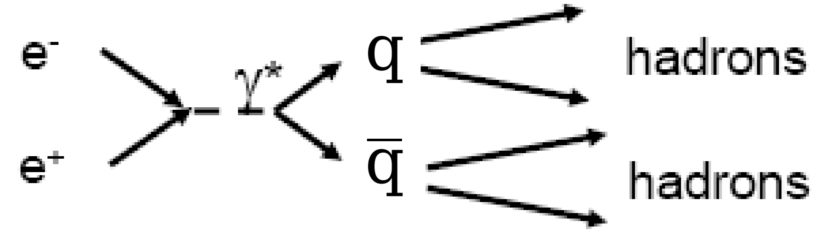
$14\ \text{GeV} \leq \sqrt{s} \leq 45\ \text{GeV}$, u, d, s, c and b quarks

$$\mathbf{R(s) = 3\{2.(\tfrac{2}{3})^2 + 3.(-\tfrac{1}{3})^2\} = \tfrac{11}{3}}$$

$\Upsilon(4S)$ B-factory



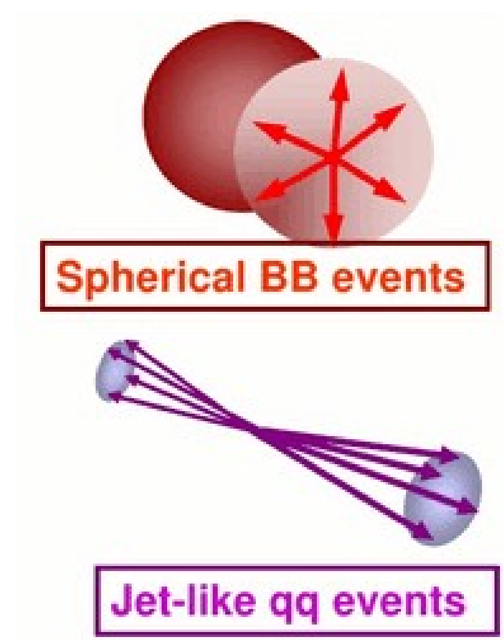




- **''on resonance'' production**
  $e^+e^- \to \Upsilon(4S) \to B_d^0\bar{B}_d^0 , B^+B^-$
  $\sigma(e^+e^- \to B\bar{B}) \simeq 1.1$ nb

- **''continuum'' production $(q\bar{q} = u\bar{u}, d\bar{d}, s\bar{s}, c\bar{c})$**
  $\sigma(e^+e^- \to c\bar{c}) = 1.3$ nb
  $\sigma(e^+e^- \to s\bar{s}) = 0.4$ nb
  $\sigma(e^+e^- \to u\bar{u}) = 1.6$ nb
  $\sigma(e^+e^- \to d\bar{d}) = 0.4$ nb

- **$\sigma(e^+e^- \to \tau^+\tau^-) \sim 1$ nb**
- **$\sigma(e^+e^- \to \mu^+\mu^-) \sim 1$ nb (calibration)**
- **bhabha: $\sigma(e^+e^- \to e^+e^-) \sim 100$ nb (luminosity)**



Why high luminosity required?

Only small fraction of collision reaction is useful for rare decays.

High statistics to search for slight difference btw matter and anti-matter

A large quantity of collision events needed.

Number of collision events/sec = Luminosity × cross-section of reaction

Luminosity: (performance of accelerator) $\mathrm{cm^{-2}s^{-1}}$

cross-section of reaction: (subject to nature) $\mathrm{cm^{2}}$

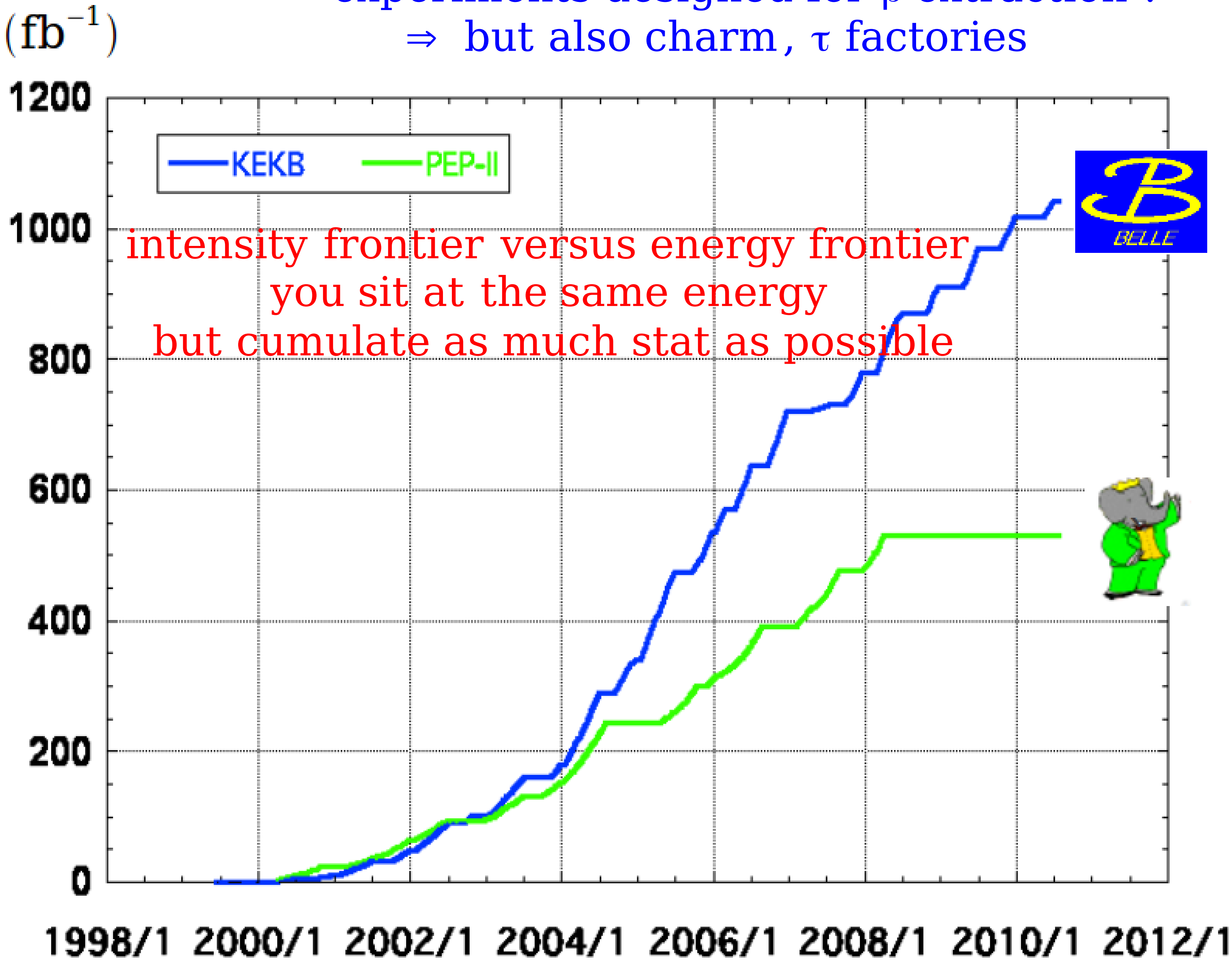
$$1\ \mathrm{barn} = 10^{-24}\ \mathrm{cm}^2 \Rightarrow \text{integrated luminosity}: 1\ \mathrm{fb}^{-1},\ \text{cross-section} = 1\ \mathrm{nb}\ (10^6\ \mathrm{fb})$$

$$\Rightarrow 10^6\ \text{events}$$

B factories: BaBar and Belle

⇒ experiments designed for β extraction !

⇒ but also charm, τ factories



> 1 ab^{-1}

On resonance:

$\Upsilon(5S)$: 121 fb^{-1}

$\Upsilon(4S)$: 711 fb^{-1}

$\Upsilon(3S)$: 3 fb^{-1}

$\Upsilon(2S)$: 25 fb^{-1}

$\Upsilon(1S)$: 6 fb^{-1}

Off reson./scan:

~ 100 fb^{-1}

~ 550 fb^{-1}

On resonance:

$\Upsilon(4S)$: 433 fb^{-1}

$\Upsilon(3S)$: 30 fb^{-1}

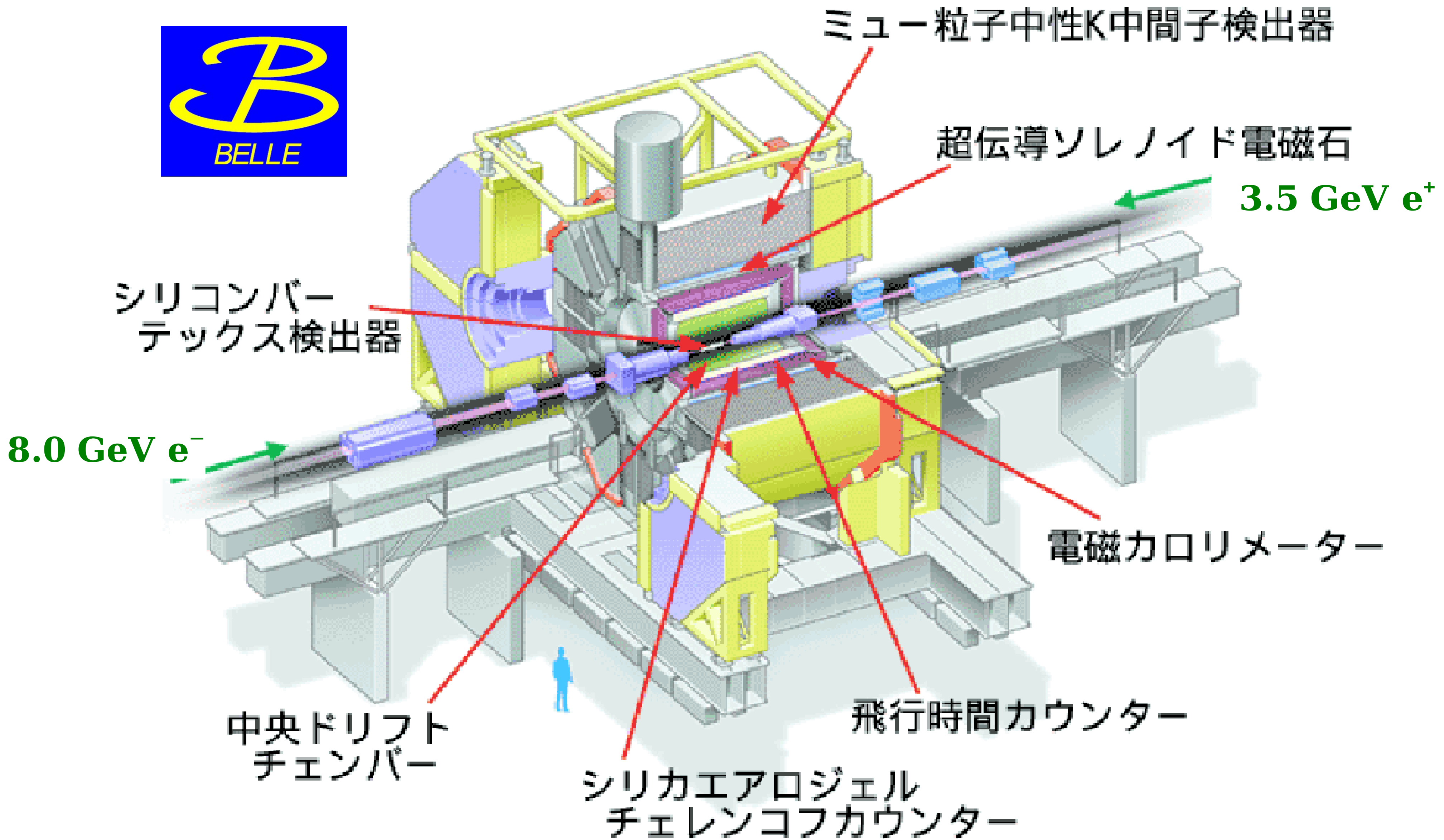
$\Upsilon(2S)$: 14 fb^{-1}

Off resonance:

~ 54 fb^{-1}

final samples
- **BaBar: $467 \times 10^6 B\bar{B}$ pairs**
- **Belle: $772 \times 10^6 B\bar{B}$ pairs**

Belle in a nutshell



very stable detector, good particle identification, (kaon, pion, proton, electron, muon),

e^+e^- is a clean environment: excellent tracking, triggering, tagging ...

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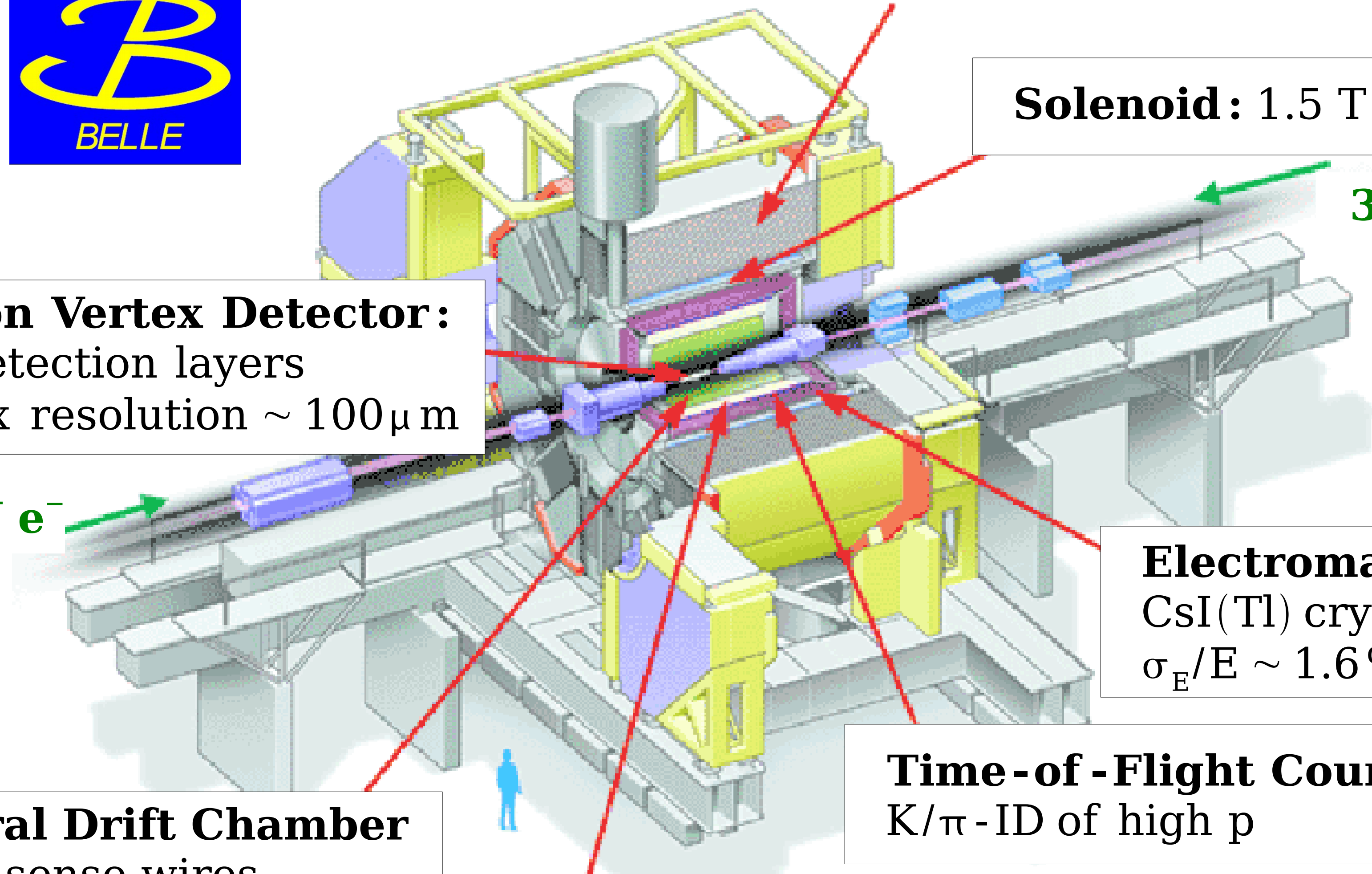

KLM ($K_L \mu$) Detector: Sandwich of 14 RPCs and 15 iron plates

Solenoid: 1.5 T

3.5 GeV e^+

Silicon Vertex Detector:
3/4 detection layers
Vertex resolution ~ 100 μm

8.0 GeV e^-

Electromagnetic Cal:
CsI(Tl) crystal
$\sigma_E/E \sim 1.6\%$ @ 1 GeV

Time-of-Flight Counter:
K/π-ID of high p

Central Drift Chamber
8,400 sense wires
PID with dE/dx

Aerogel Cerenkov Counter:
Refractive index n=1.01-1.03
K/π of middle p

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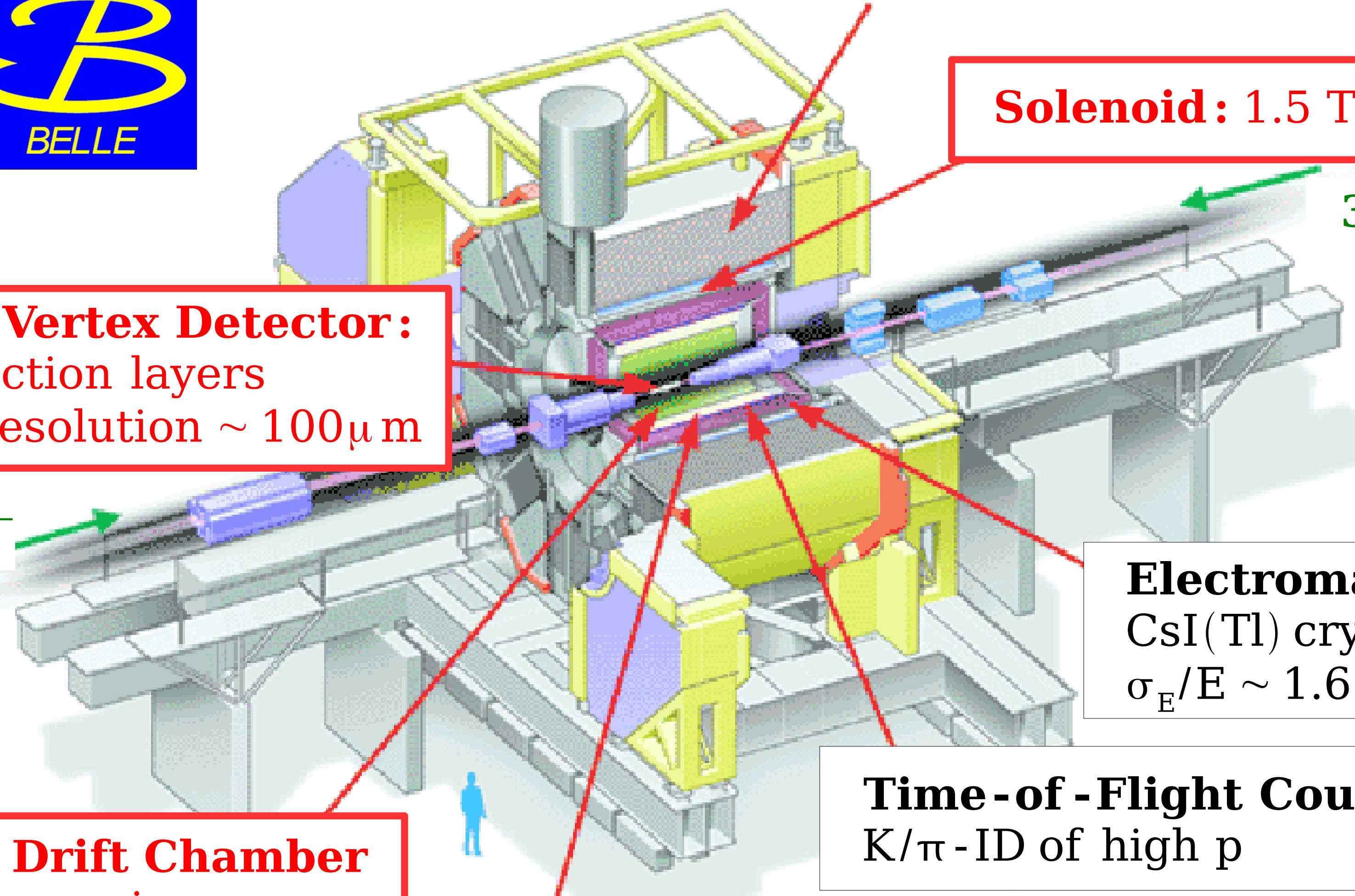

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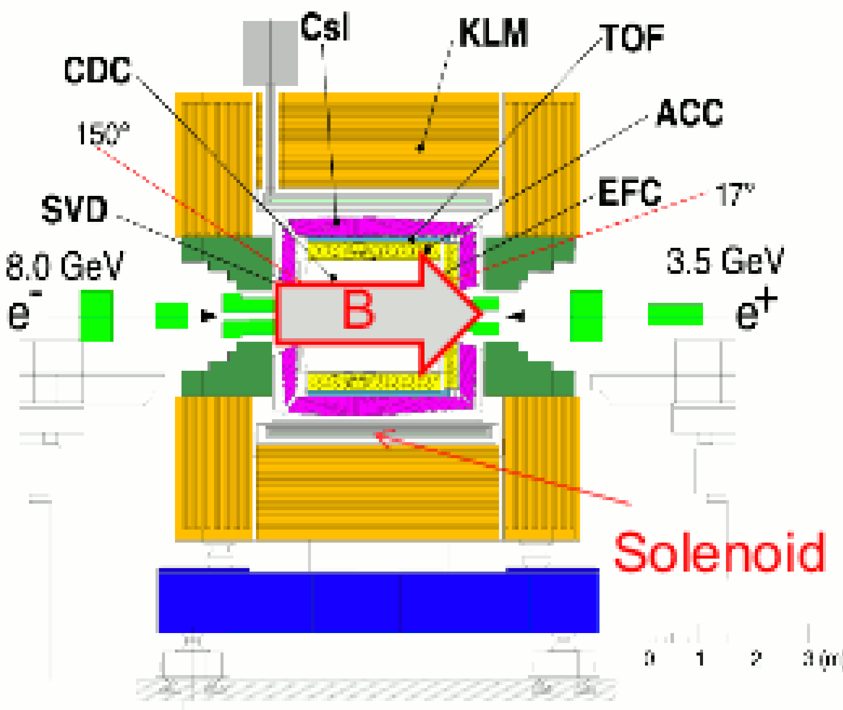
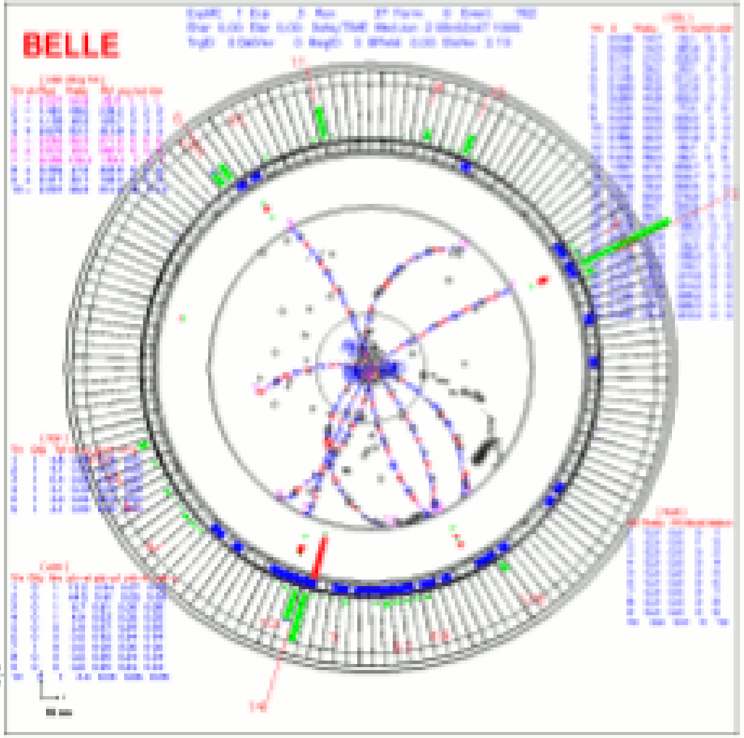
How to detect particles in Belle

How to measure charged particles.

- Magnetic field (1.5 T at Belle) is applied in parallel to the beam axis.
  - ✓ Charged particles curls in the plane perpendicular to the beam axis.
- Measure the trajectory of the charged particles.
  - ✓ Momentum can be obtained by the relation p [GeV] = 0.3 B [T] R [m].



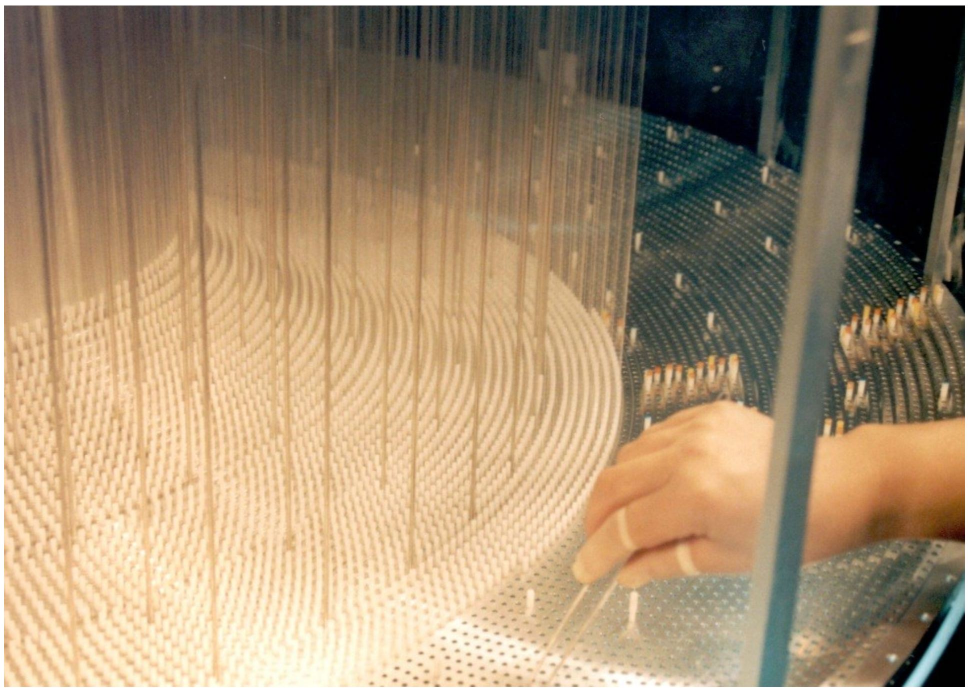


More exactly, only transverse momentum (p_T) can be obtained. But, we also know the direction of the particle. Hence the momentum vector can be calculated.

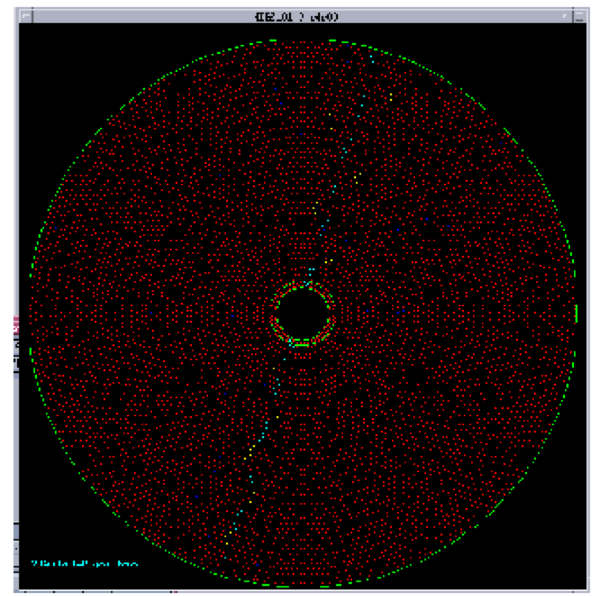
How to detect particles in Belle

Central Drift Chamber

Sense wire	30 micron diameter gold plated tungsten
Field wire	126 micron diameter aluminium
Gas	mixture of Helium 50% and C_2H_6 50%



+ superconduction magnet
inner radius = 170 cm , B = 1.5 T



Configuration

52 layers

8.4k anodes

radius = 8.5-90 cm

$-77 \leq z \leq 160$ cm

Performances

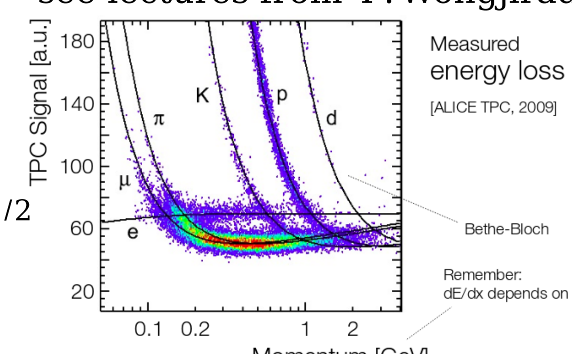
$\sigma_{r-\phi} = 130 \mu m$

$\sigma_z = 200\text{-}1400 \mu m$

$\sigma_{p_t}/p_t = 0.3\%(p_t+1)^{1/2}$

$\sigma_{dE/dx} = 6\%$

see lectures from T. Wongjirad

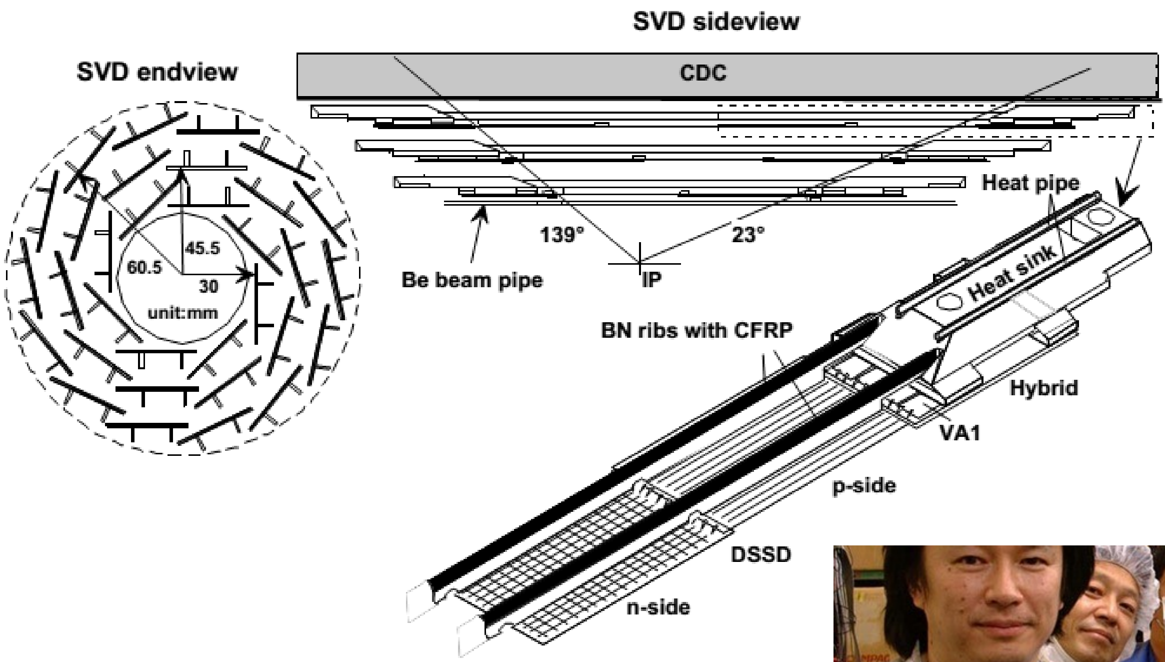


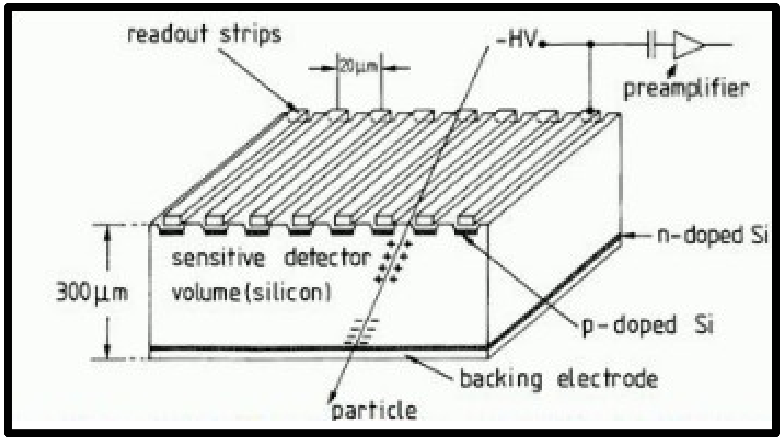
How to detect particles in Belle

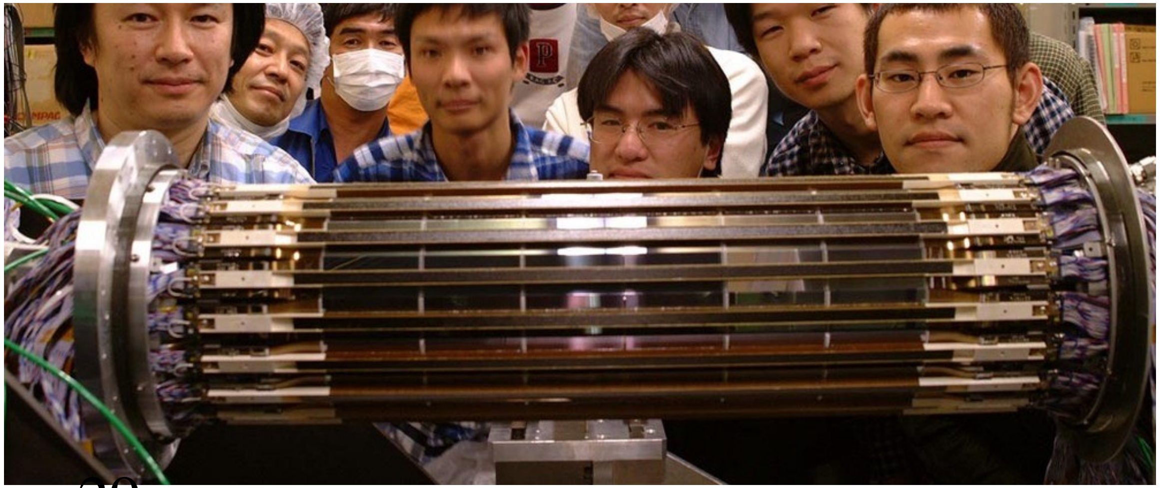
Silicon Vertex Detector

300μm thick, 3−4 layer
radius = 2.0-8 cm
Length = 22−40 cm

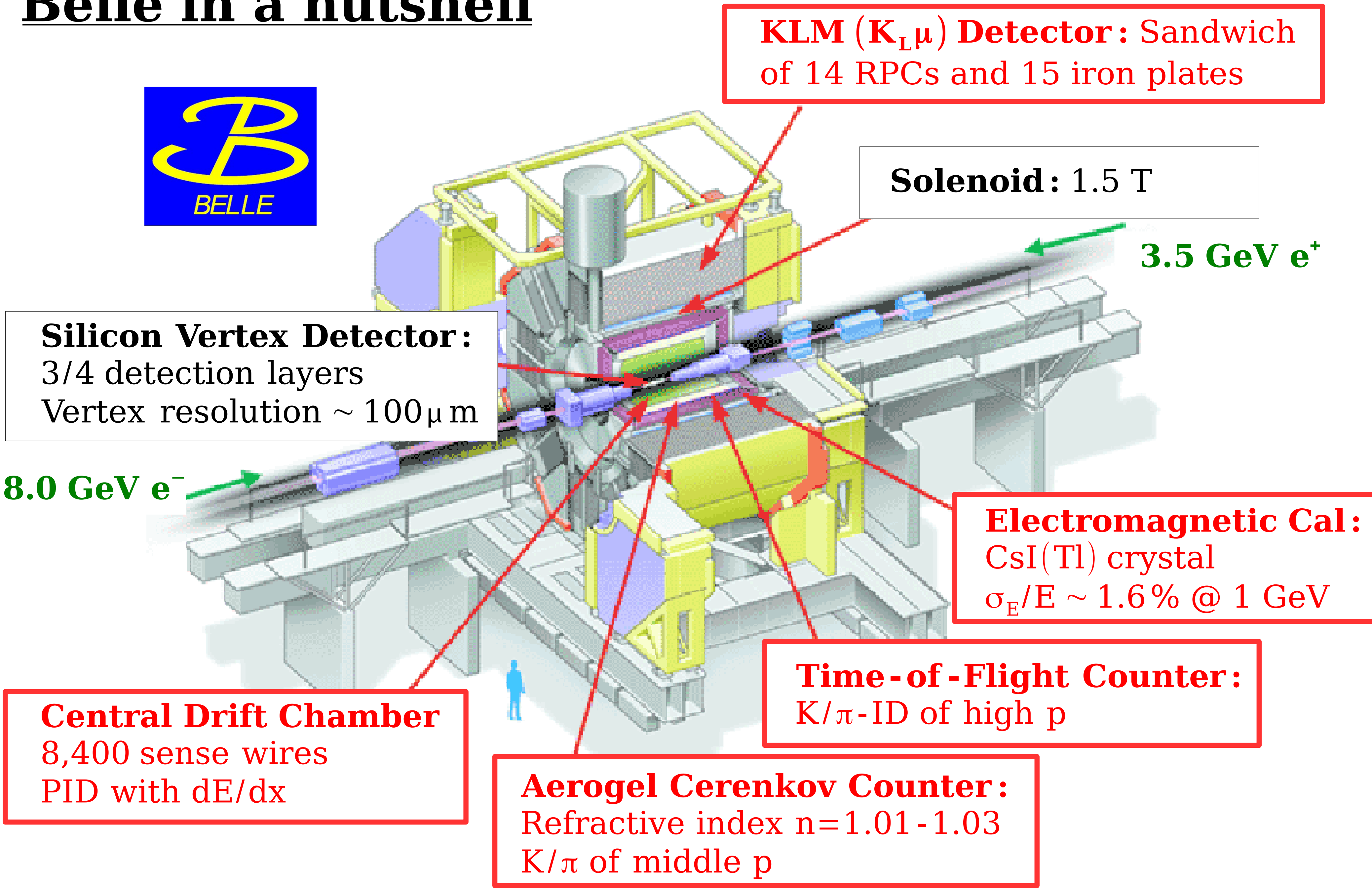
readout: $\phi \sim 40k$, $\theta \sim 40k$
resolution: $\sigma_z \sim 30\mu m$







Belle in a nutshell



very stable detector, good particle identification, (kaon, pion, electron, muon),

e^+e^- is a clean environment: excellent tracking, triggering, tagging...

examples of particle detectors

see lectures from T. Wongjirad

Comparision different PID methods for K/π separation

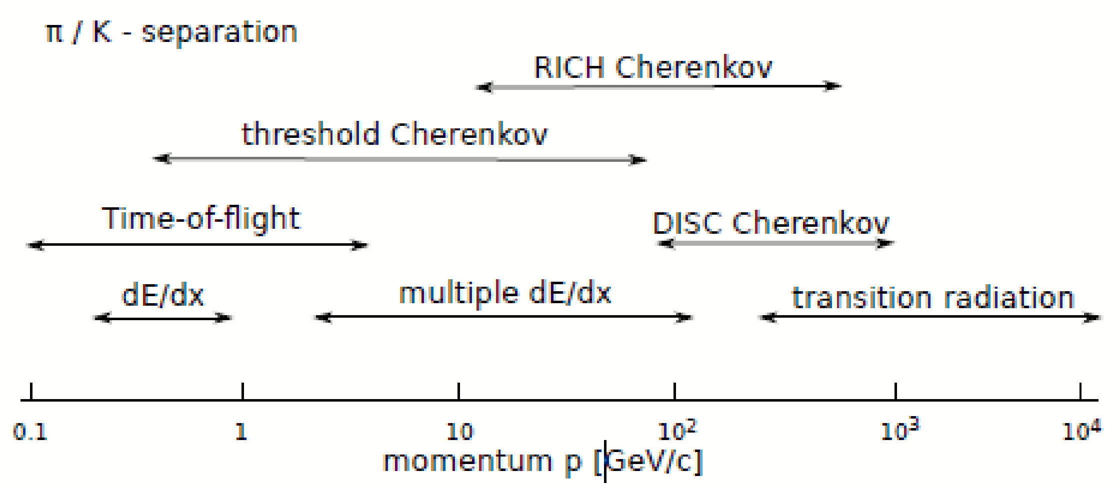
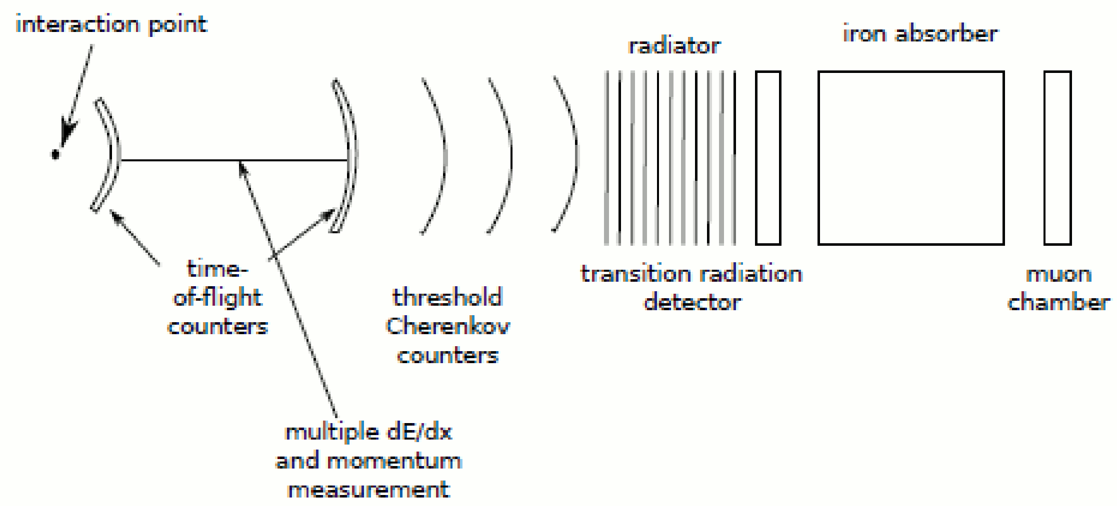


illustration of various particle identification methods for K/π separation along with characteristic momentum ranges.

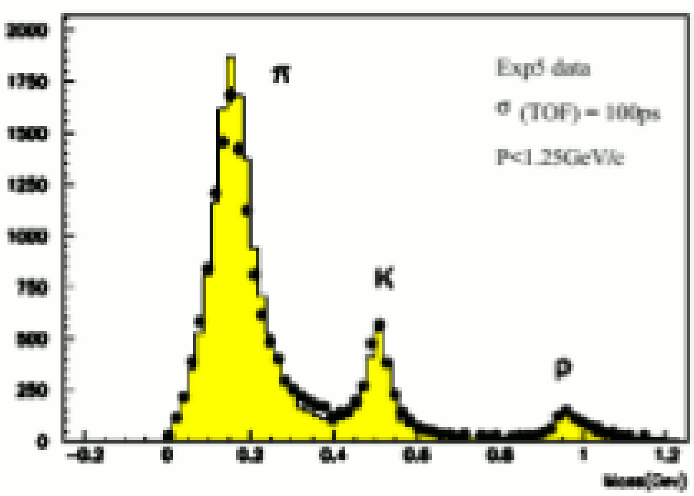


a detector system for PID combines usually several methods

How to detect particles in Belle

- We now know the momentum of the charged particles, but we don't know what the particle is.
  - ✓ Candidates : electron ($e^{\pm}$), muon ($\mu^{\pm}$), pion ($\pi^{\pm}$), kaon ($K^{\pm}$), proton (p, $\bar{p}$).
  - ✓ Other charged particles decay before reaching to the detector.
- Next step : Particle identification.

Example: TOF (time of flight)

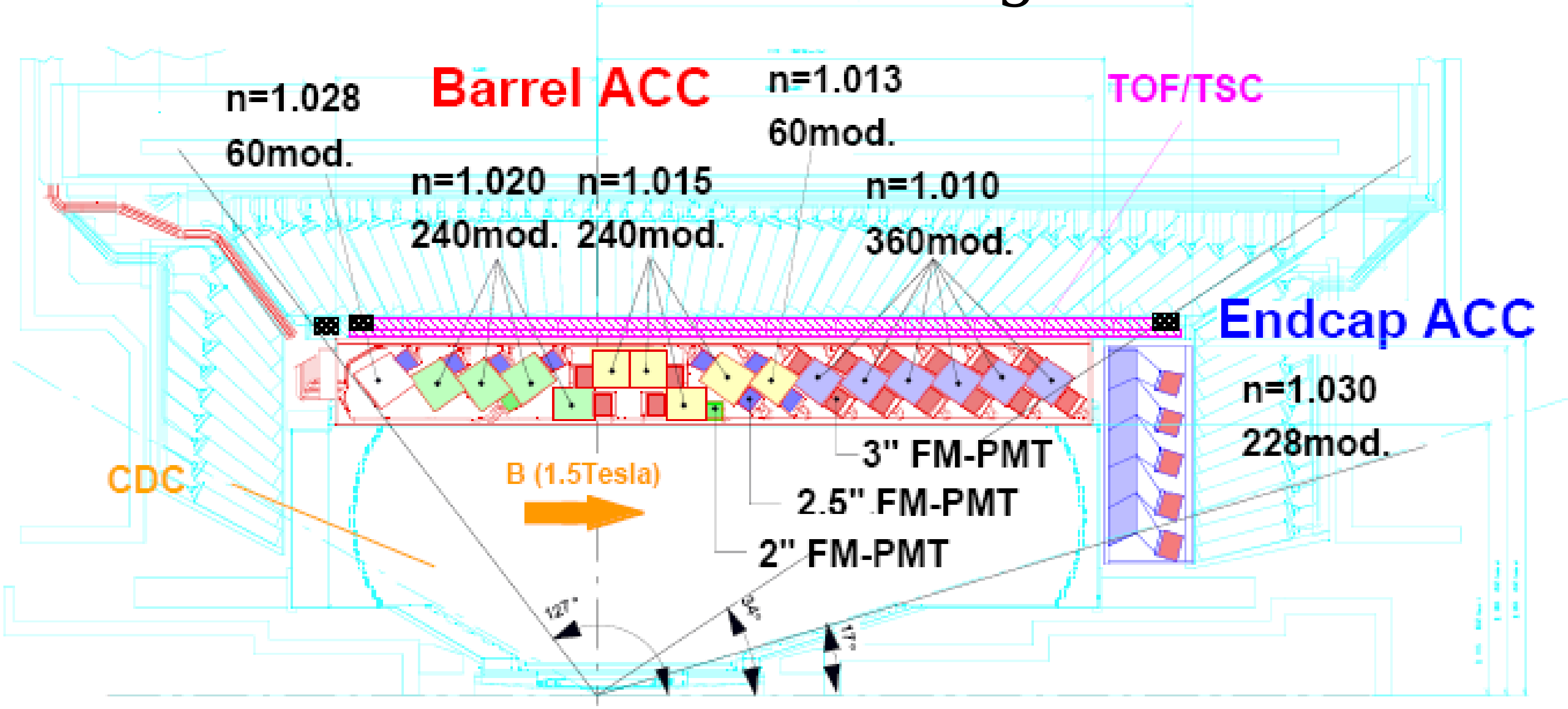


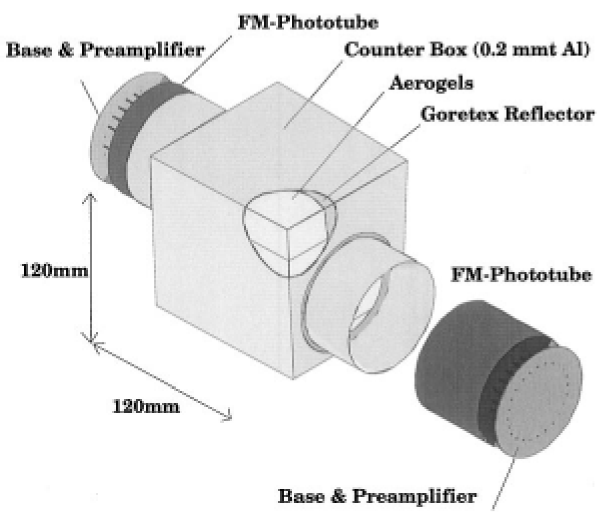
- Measure the flight time from the interaction point to the detector.
  - ✓ From the flight time, one can calculate the velocity of the particle.
  - ✓ The mass of the particle can be obtained from the velocity and momentum ($p = mv\gamma$).

The low momentum (up to 1.2GeV) $\pi^{\pm}/K^{\pm}$ is separated by the timing of plastic scintillation counters with 100ps time resolution

How to detect particles in Belle

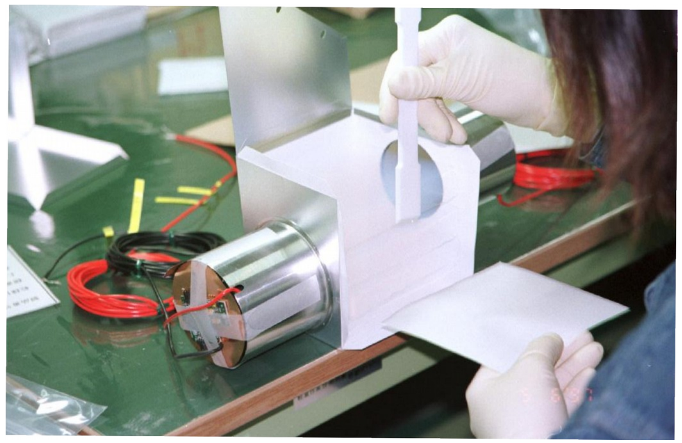
ACC = Aerogel Cherenkov Counter





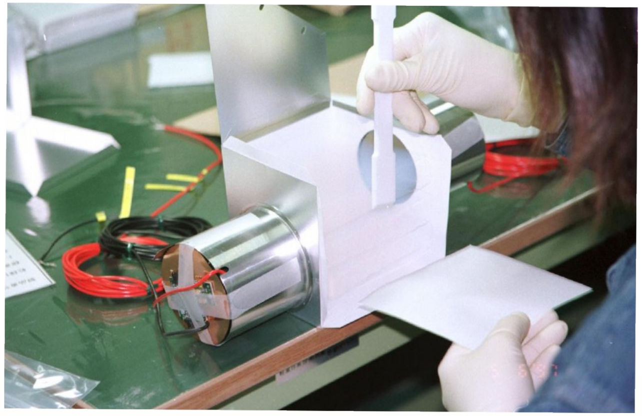
12 x 12 x 12 cm^3 blocks
960 barrel / 228 endcap
FM - PMT readout, 1788ch

20 photoelectrons
per pion detected
at 3.5 GeV

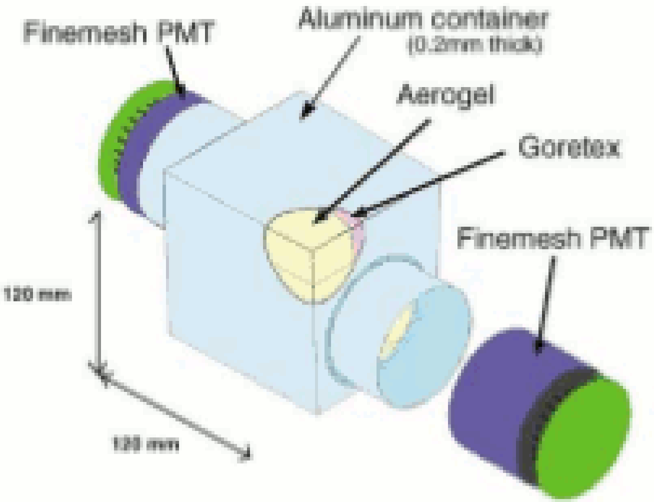


How to detect particles in Belle

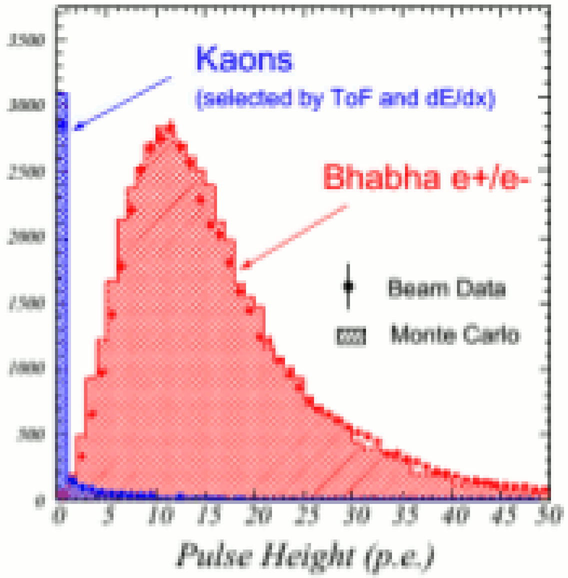
12 x 12 x 12 cm^3 blocks
960 barrel / 228 endcap
FM - PMT readout, 1788ch



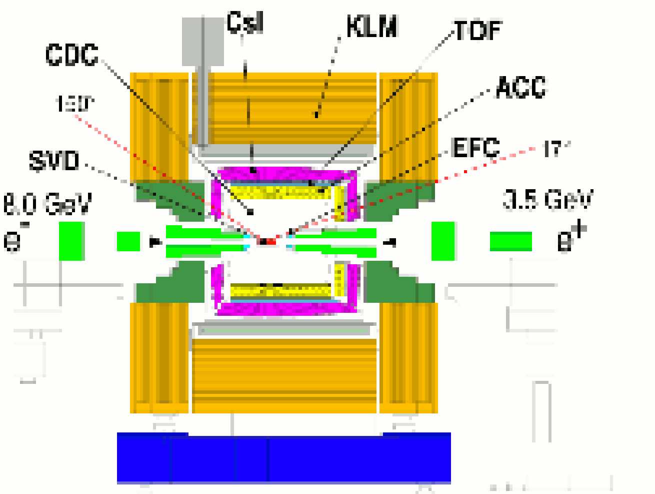
Another Example: ACC (Aerogel Cherenkov Counter)



- Aerogel : refractive index = 1.01-1.03
- Cherenkov light when v > c/n
  - ✓ For certain momentum, only light particles can emit Cherenkov light.



$\Rightarrow$ K/π separation: 1.2 to 3.5 GeV



- Electron : low mass + interaction at calorimeter.
- Muon
  - ✓ little interaction with matter, go through the detector.
  - ✓ detected by the outermost detector (KLM)

How to detect particles

Now, we know the momenta of charged particles, and their masses (form the particle species) ⇒ 4-momentum is known

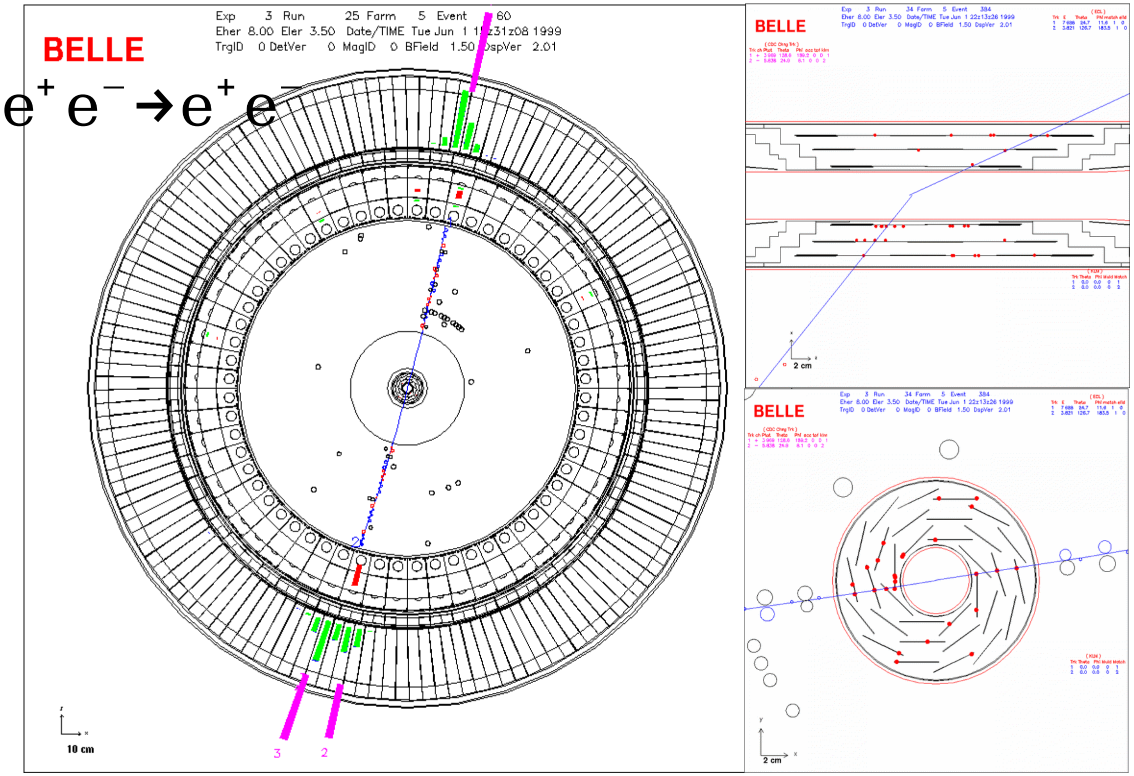
How about neutral particles?

- π^0 decays ($\pi^0 \to \gamma\gamma$). K_S^0 also decays ($K_S^0 \to \pi^+\pi^-$, $\pi^0\pi^0$ with $c\tau$ = 2.7cm).
- The most important neutral particle is the photon (γ).
  - ✓ Not detected inside the tracking device (CDC etc.).
  - ✓ But, photons lose all the energy in the calorimeter (i.e. energy of a photon is measured in the calorimeter).
  - ✓ Direction is known from the measured position ⇒ 4-momentum is measured.

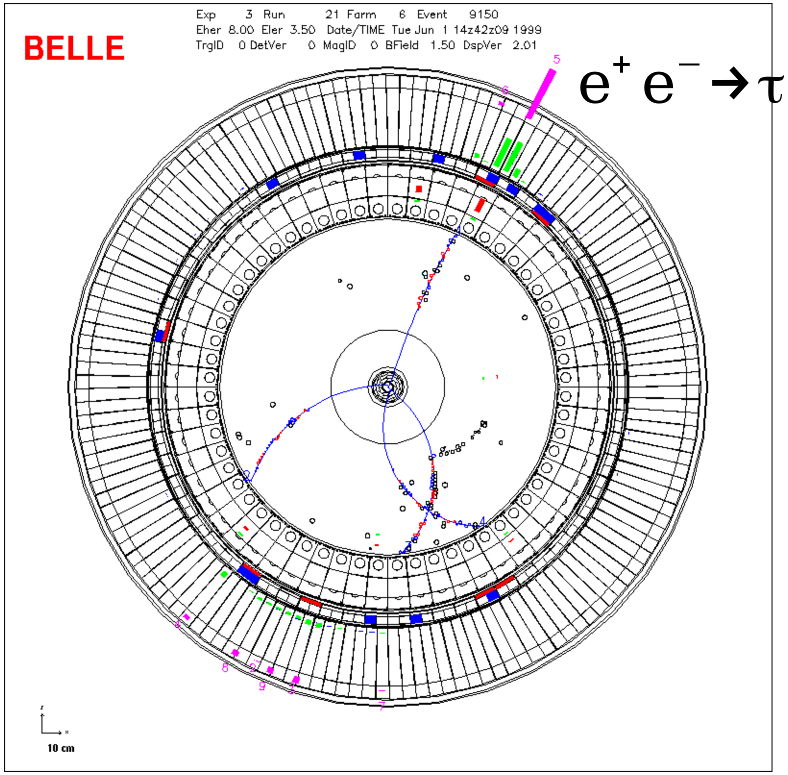
Long-lived neutral particles (neutrons, K_L^0 …) are not easy to measure (hadronic interaction). Neutrino is impossible to detect.

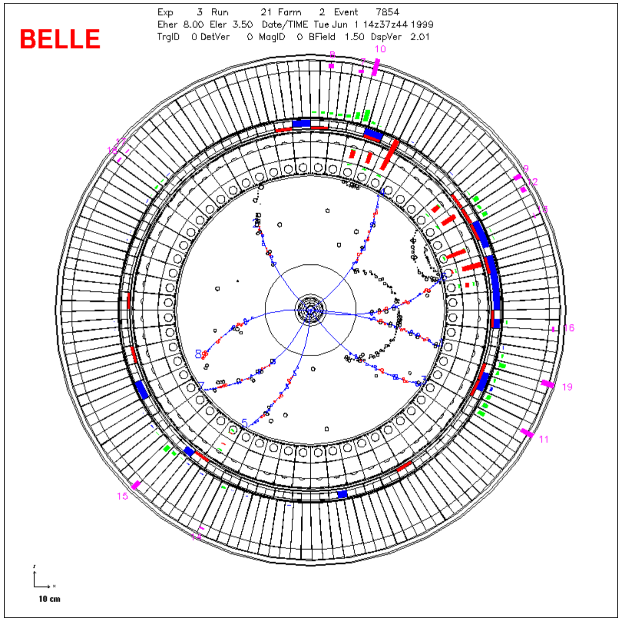
How to detect particles in Belle

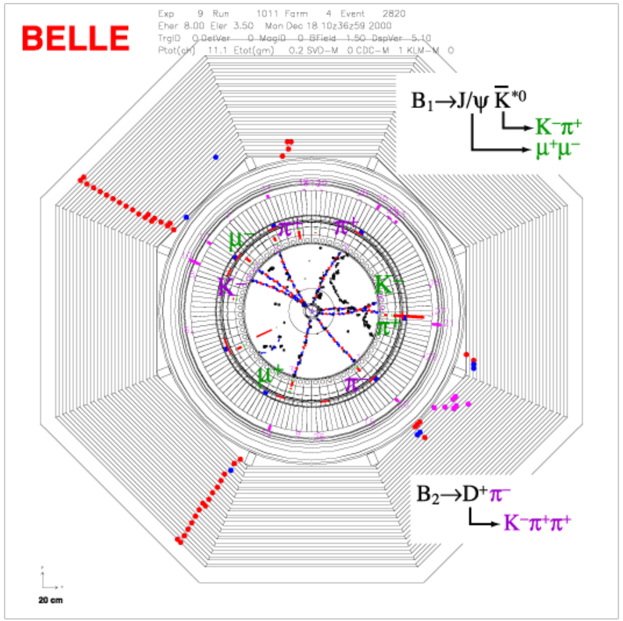
$e^+e^- \rightarrow e^+e^-$

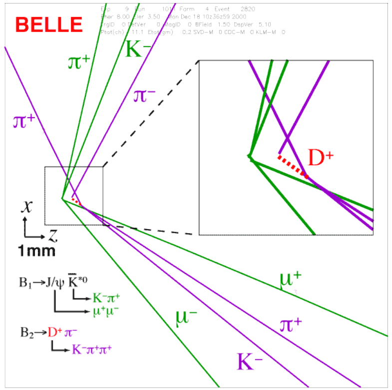


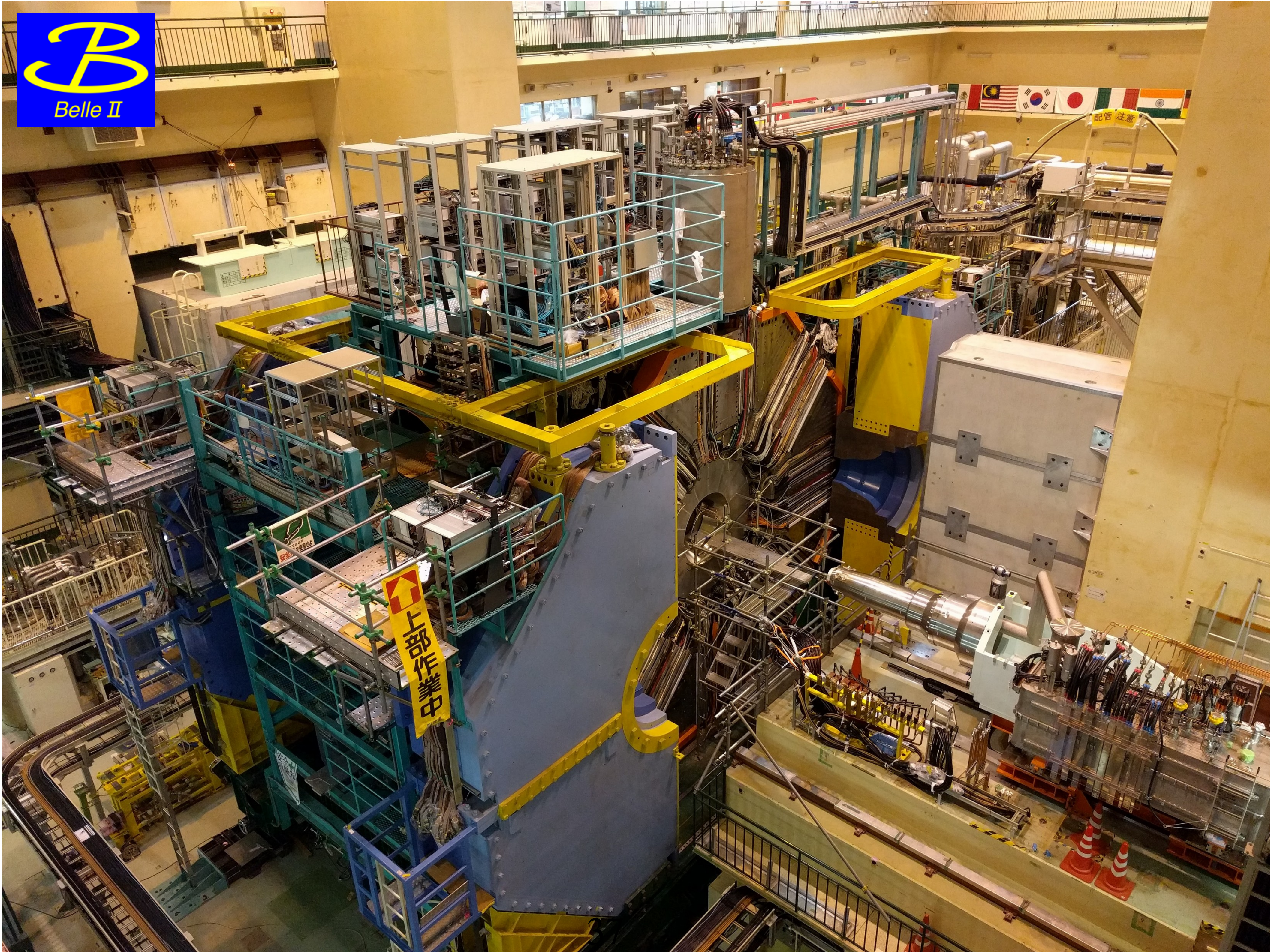
$e^+e^- \rightarrow \tau^+\tau^-$





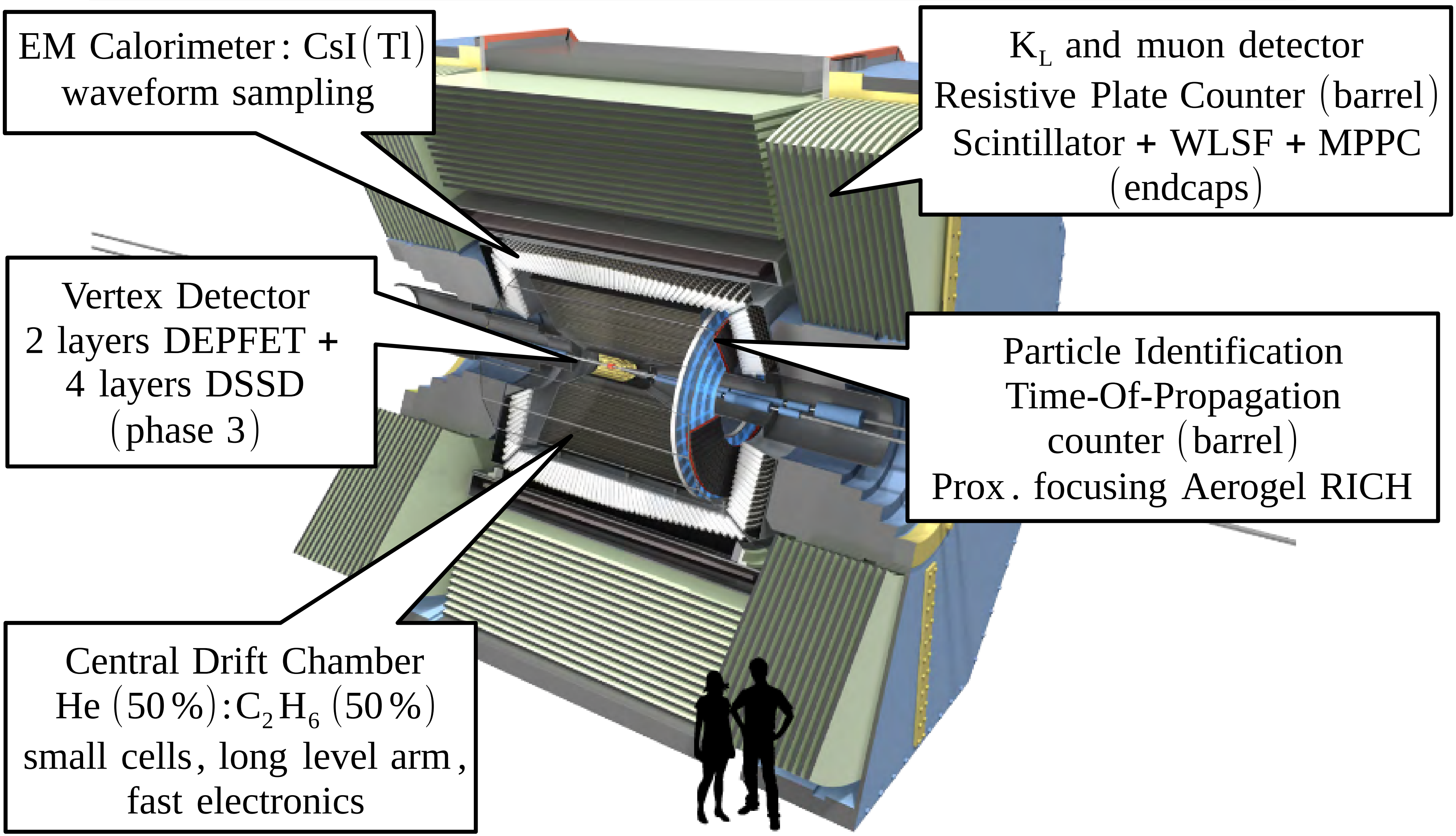


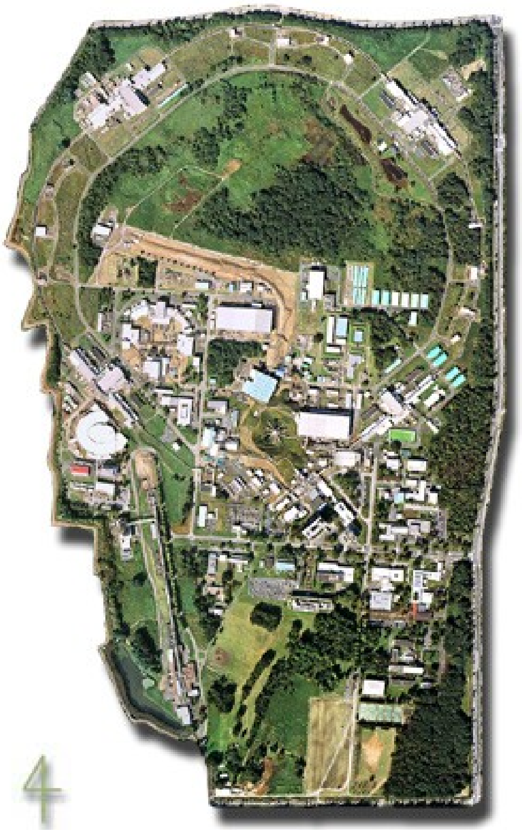



Belle II
配管 注意
上部作業中

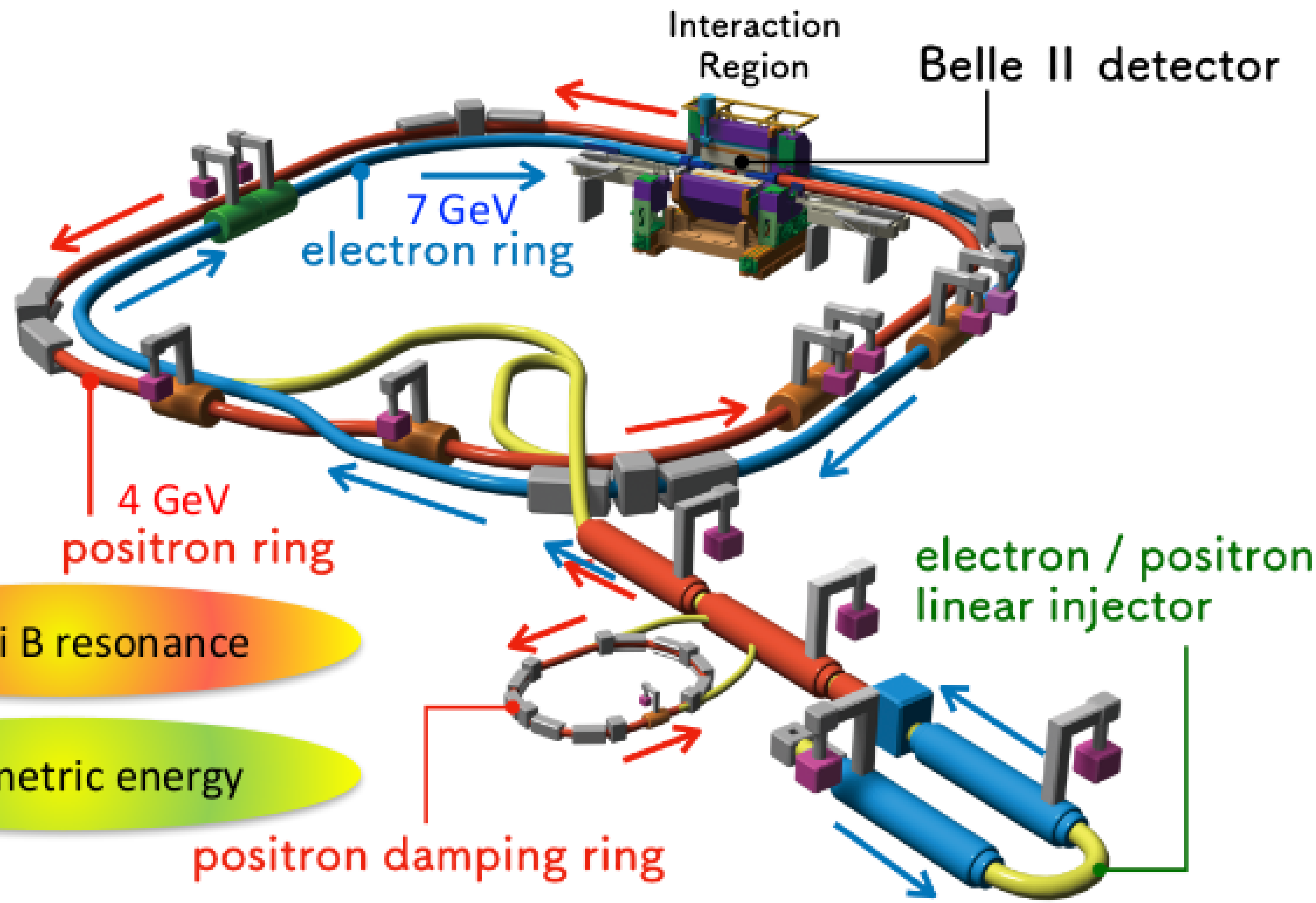
Belle II detector

successor of the Belle experiment (1999 – 2010), goal: collect 100 × larger data sample
started in May 2018 (phase 2, without vertex detectors)





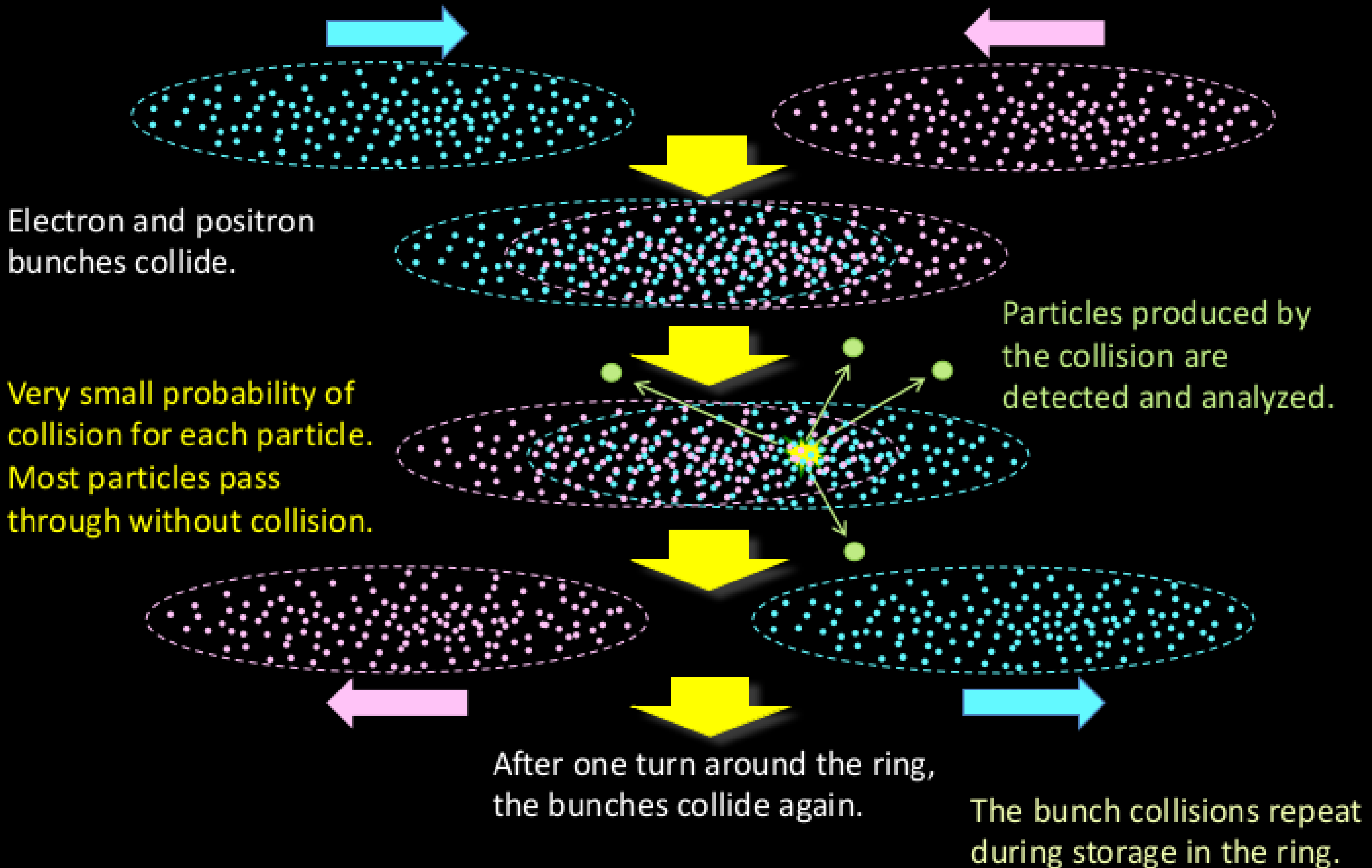
SuperKEKB accelerator complex



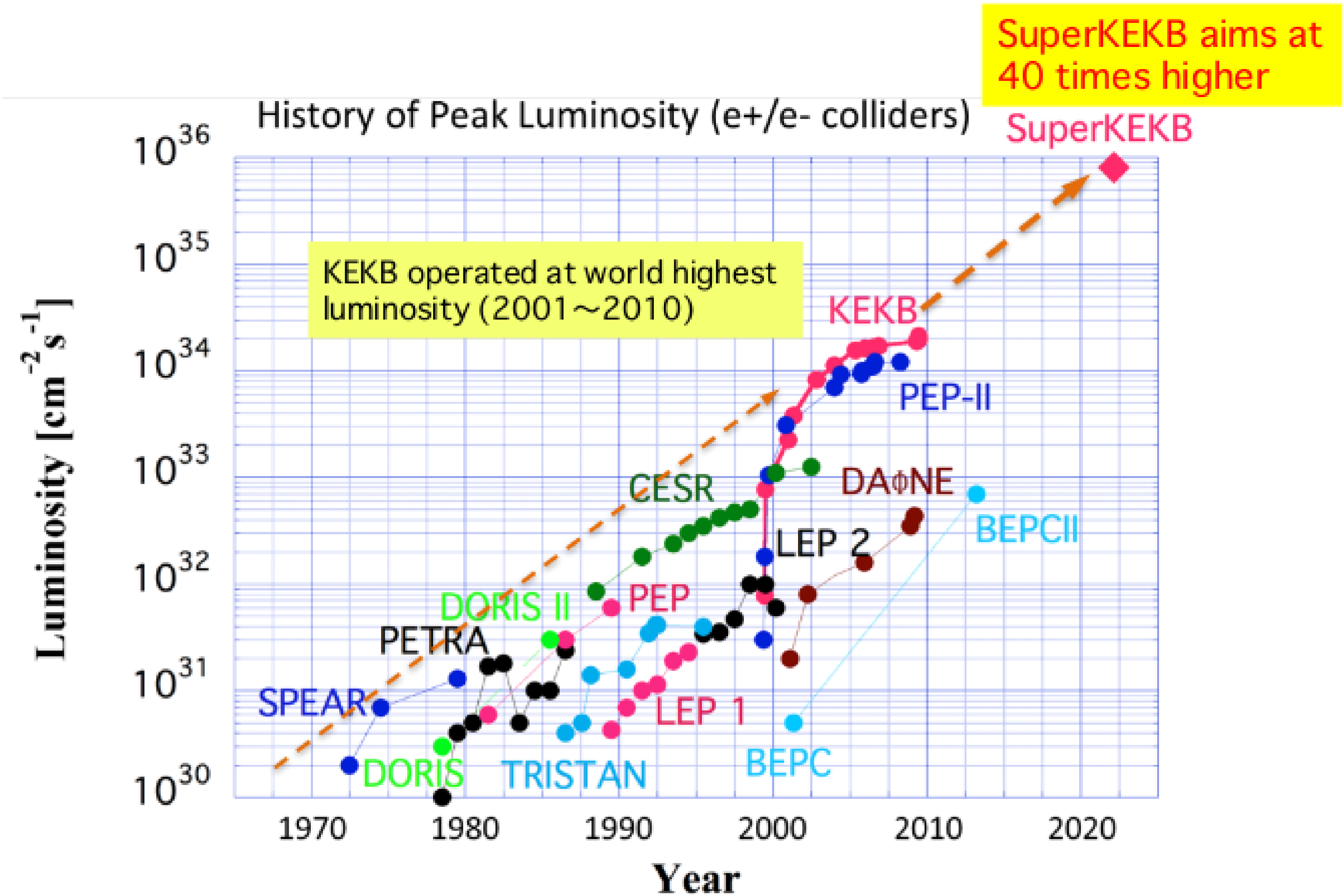
B - anti B resonance

asymmetric energy

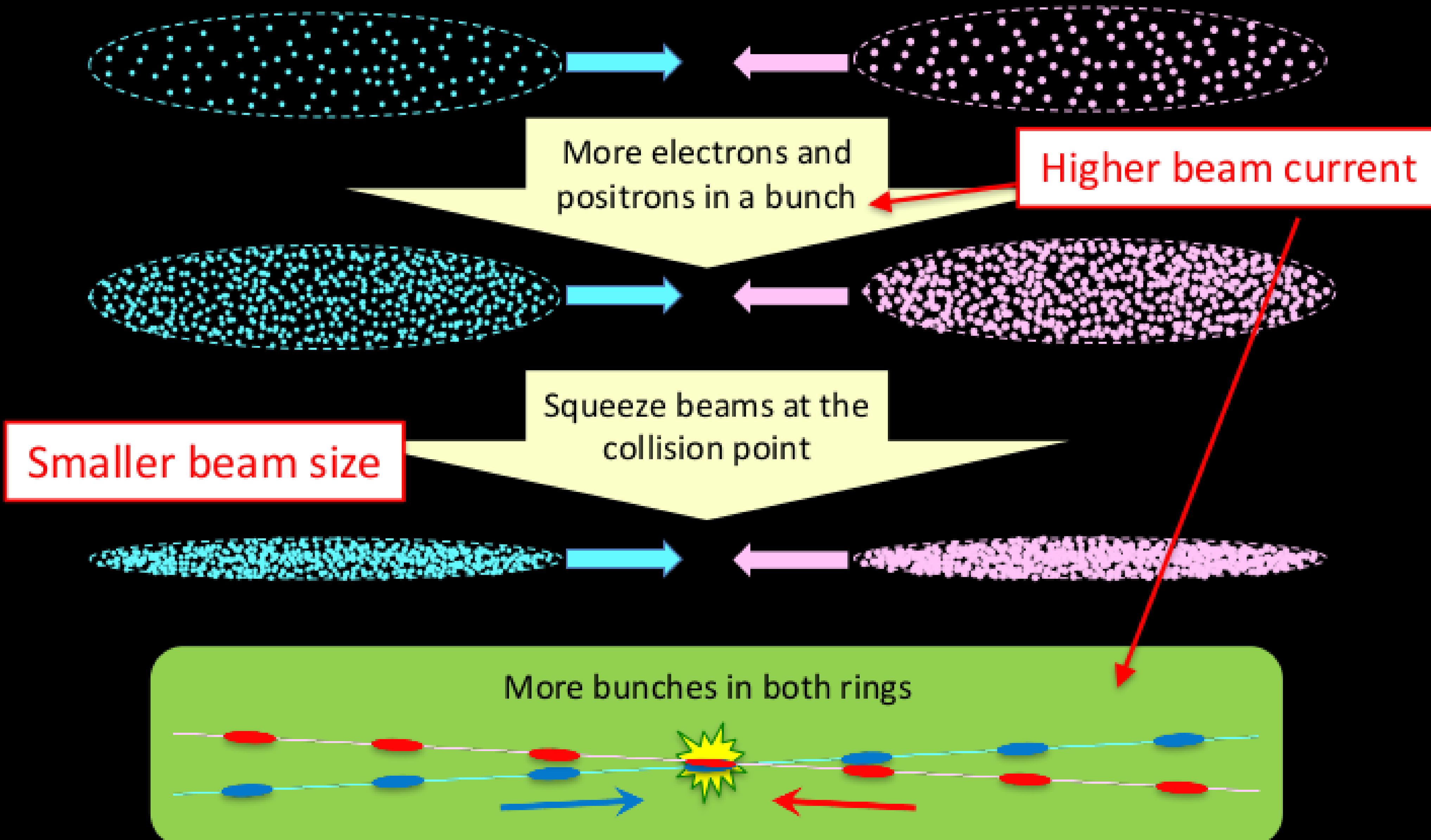
Beam collision



Luminosity frontier of e^+e^- colliders



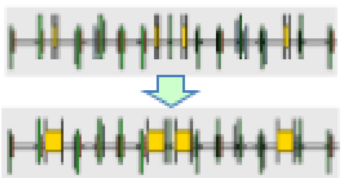
Higher and higher luminosity



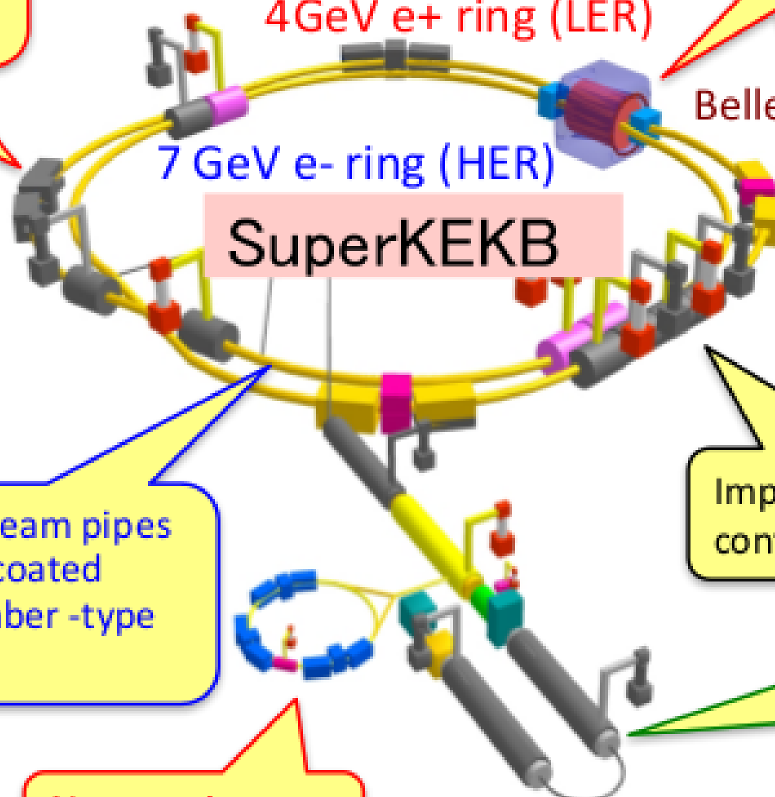
Upgrade for Nano-Beam collision scheme

- Lower emittance in the ring.
- Squeeze strongly at the IP.

Redesign the lattice to squeeze the emittance (replace short dipoles with longer ones, increase wiggler cycles)



New superconducting final-focusing magnets to squeeze beam the IP



Replace beam pipes with TiN-coated antechamber -type ones

Improve monitors and control system

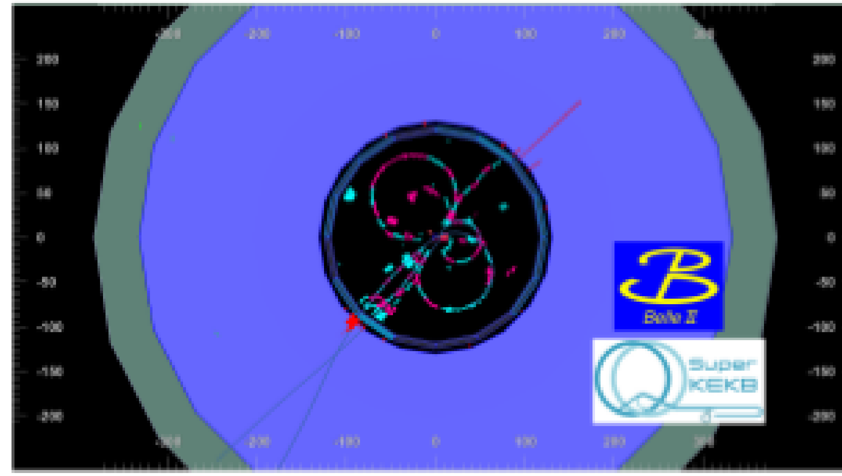
New positron damping ring

Injector Linac upgrade
RF electron gun
upgrade e+ source

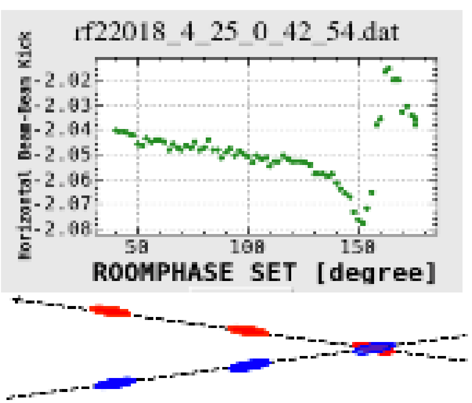
First collision

Apr. 26, 2018

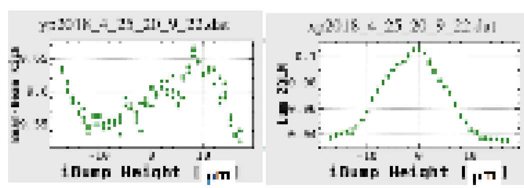
Belle II control room



First hadronic event observed by Belle II

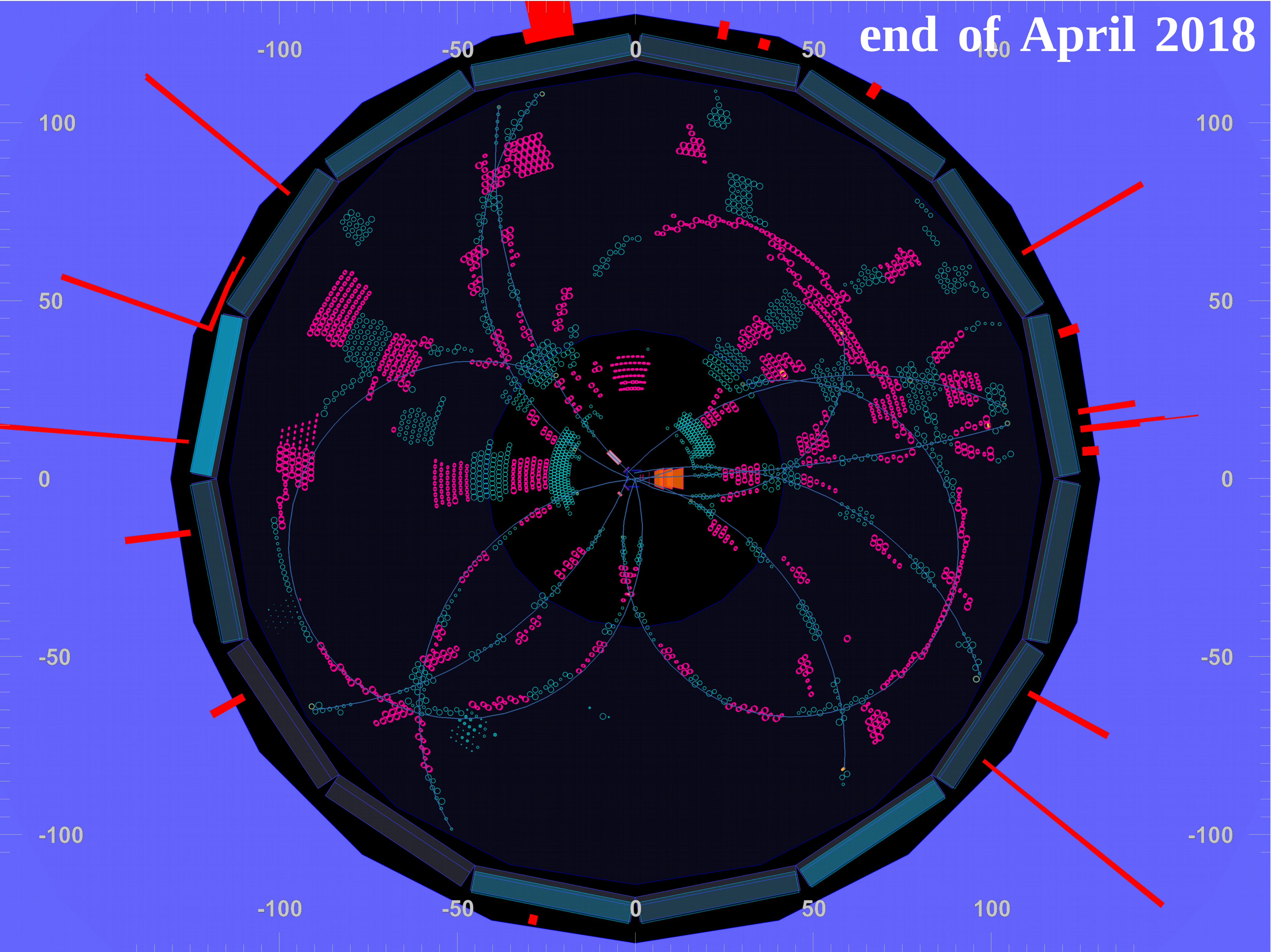


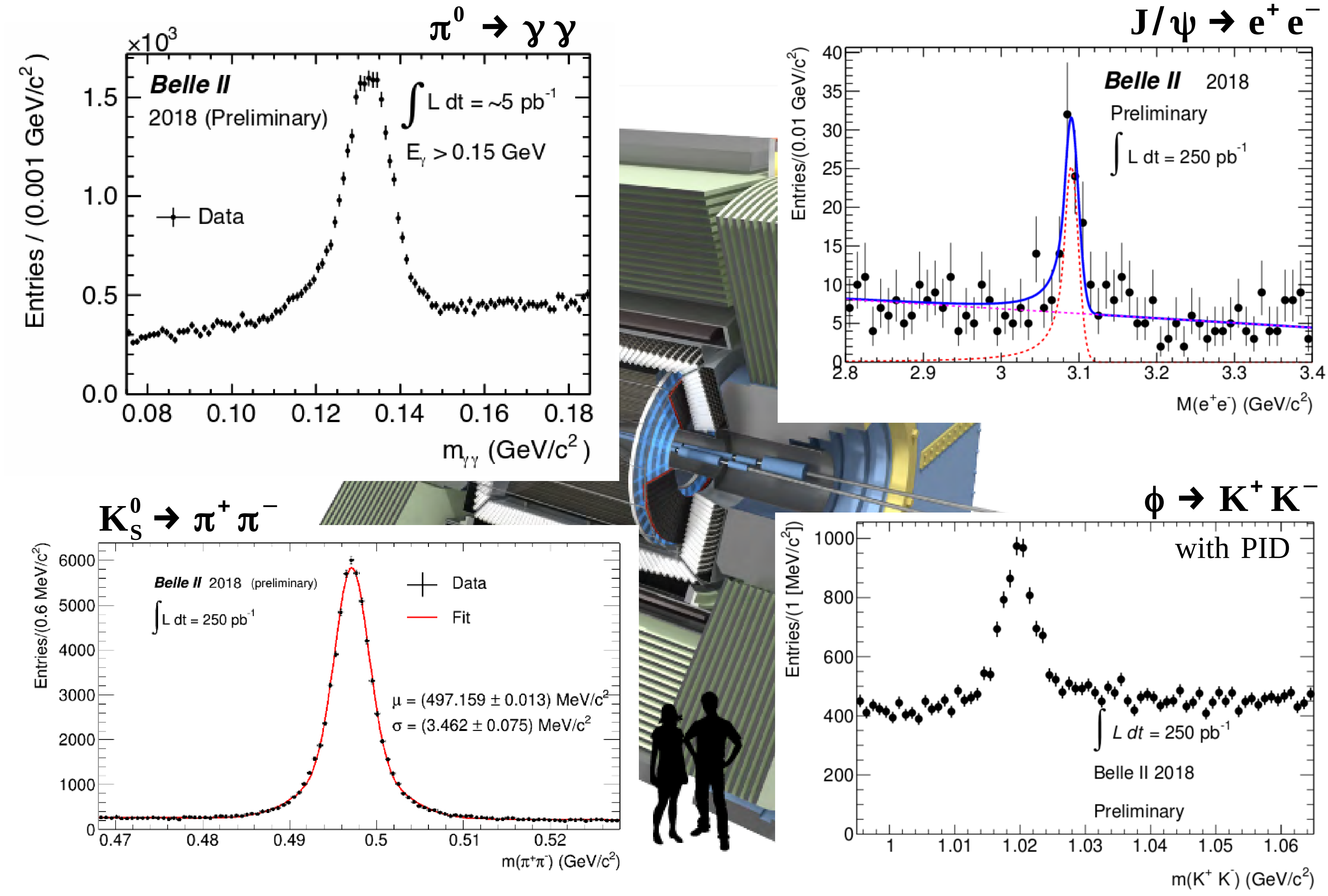
Horizontal beam-beam kick



Vertical beam-beam kick

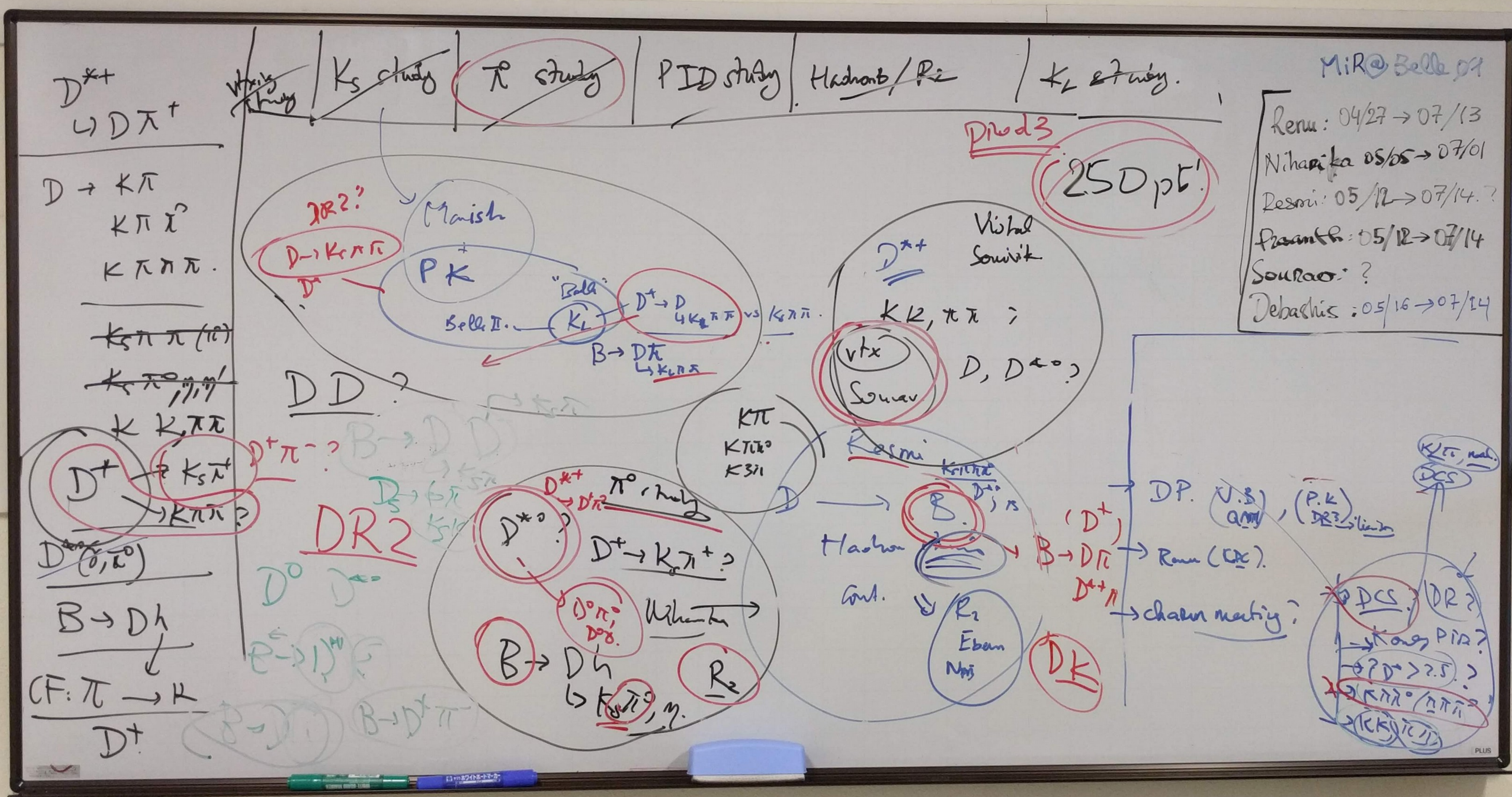
SuperKEKB control room


end of April 2018
-100
-50
0
50
100
100
50
0
-50
-100



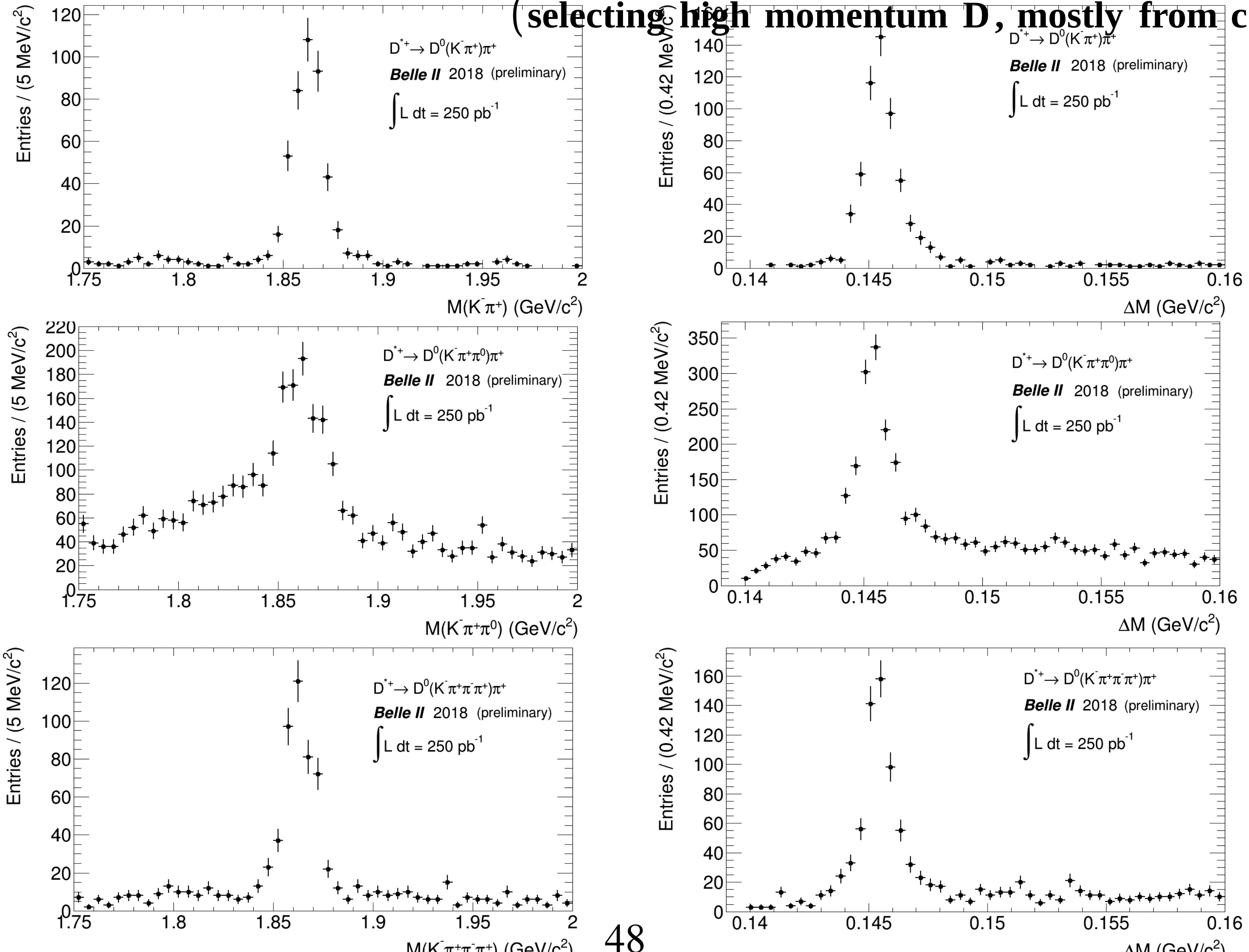
π0 → γ γ
Belle II
2018 (Preliminary)
∫L dt = ~5 pb-1
Eγ > 0.15 GeV
Data
×10^3
Entries / (0.001 GeV/c2)
mγγ (GeV/c2)
J/ψ → e+ e−
Belle II 2018
Preliminary
∫L dt = 250 pb-1
Entries/(0.01 GeV/c2)
M(e+e-) (GeV/c2)
K0S → π+ π−
Belle II 2018 (preliminary)
∫L dt = 250 pb-1
Data
Fit
μ = (497.159 ± 0.013) MeV/c2
σ = (3.462 ± 0.075) MeV/c2
Entries/(0.6 MeV/c2)
m(π+π-) (GeV/c2)
φ → K+ K−
with PID
∫L dt = 250 pb-1
Belle II 2018
Preliminary
Entries/(1 [MeV/c2])
m(K+ K-) (GeV/c2)

charm and beauty re-discoveries...
...using less than 1 fb^{-1}
(spring - summer 2018)



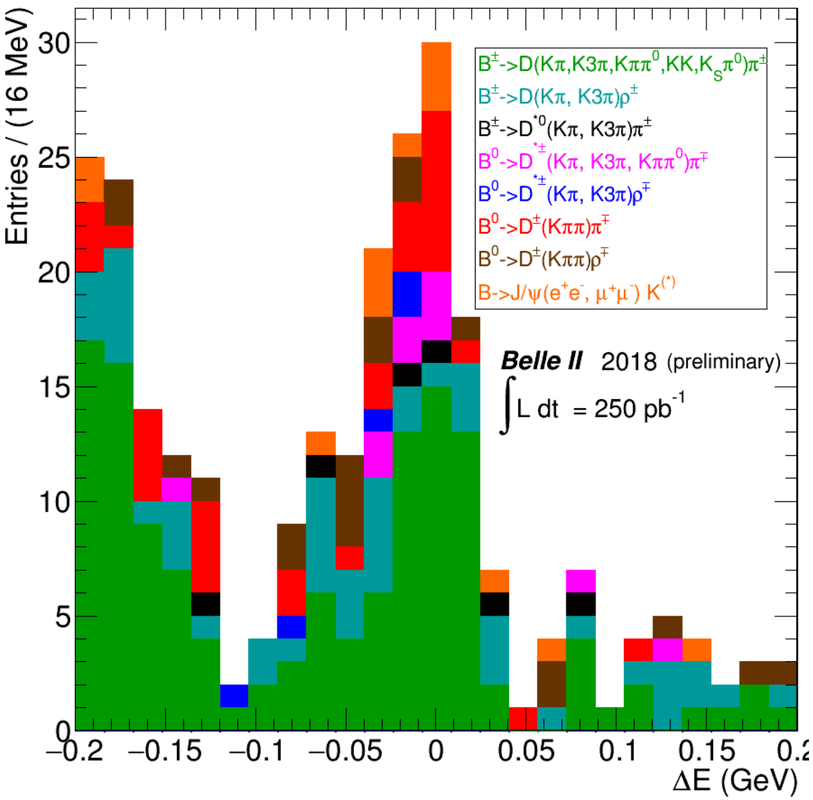
Rediscovering charm: $D^{*+} \to D\pi^+$, $D \to K^-\pi^+$, $K^-\pi^+\pi^0$, $K^-\pi^+\pi^-\pi^+$

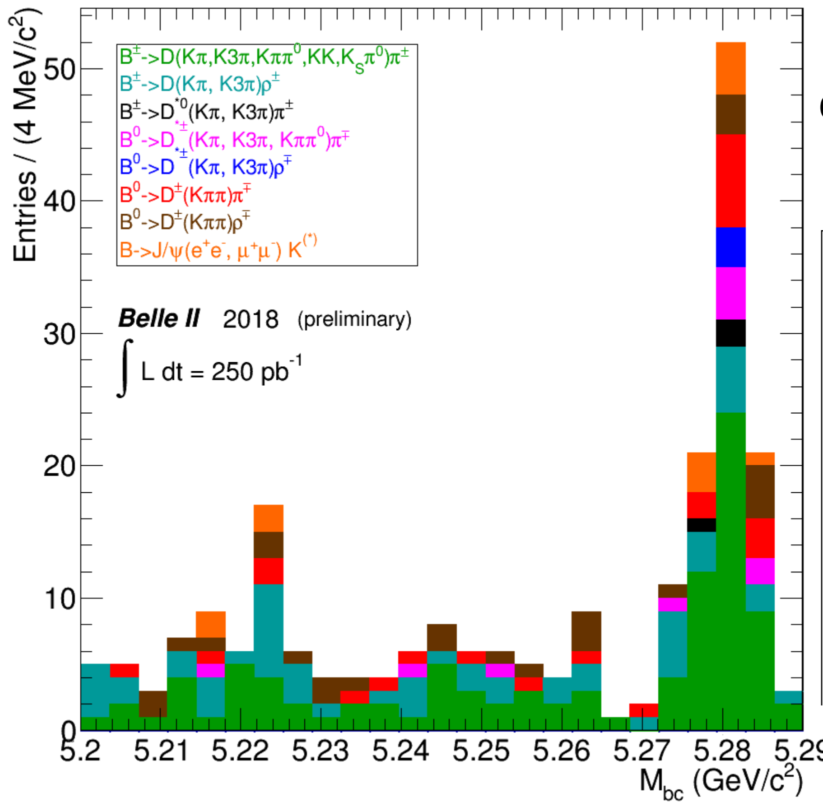
(selecting high momentum D, mostly from $c\bar{c}$)



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

Gaussian width of signal in M_{bc} is consistent with MC !





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

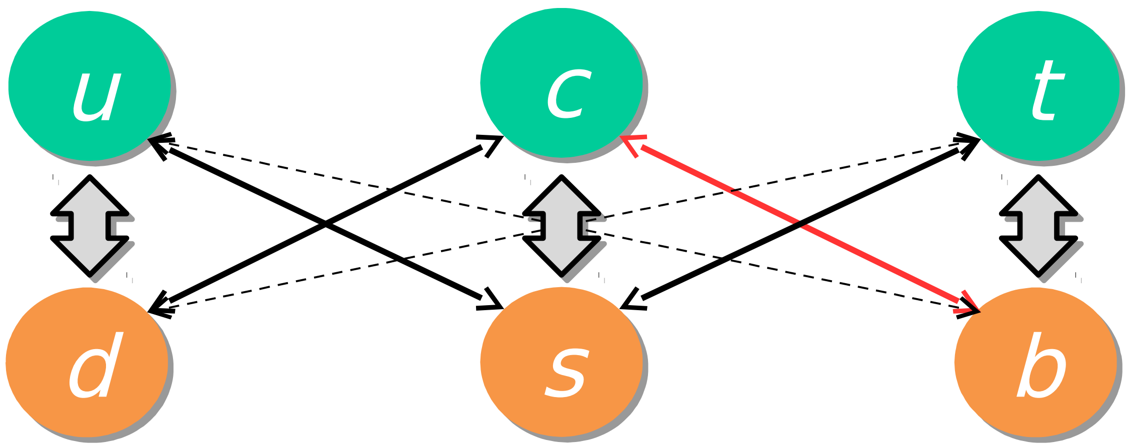
Show capacity for charm physics in $e^+e^- \to c\bar{c}$

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

...for B-physics

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

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



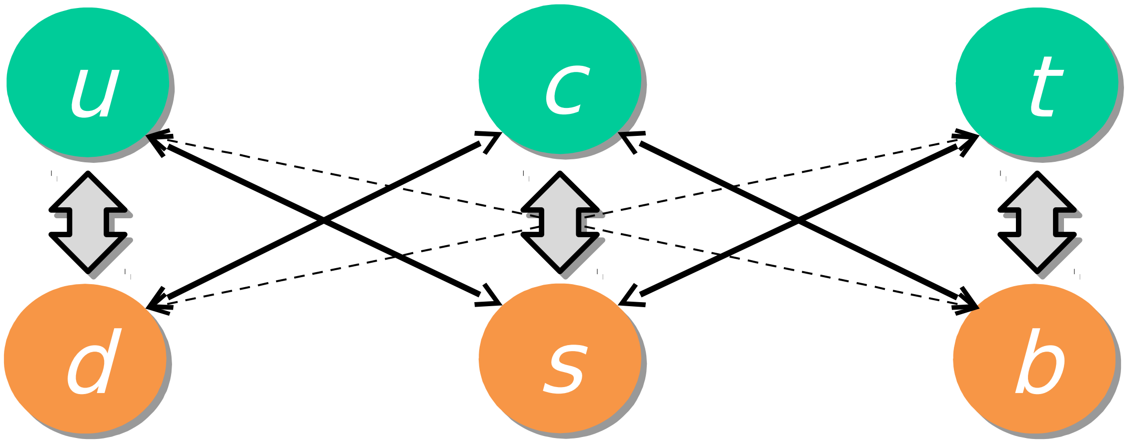
What are rare decays ?

Dominant decays: Not rare

Phase space suppressed decays: Not that rare

Cabibbo-suppressed decays: Some call them rare

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



What are rare decays ?

Dominant decays: Not rare

Phase space suppressed decays: Not that rare

Cabibbo-suppressed decays: Some call them rare

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

What are rare decays ?

Dominant decays: Not rare

Phase space suppressed decays: Not that rare

Cabibbo-suppressed decays: Some call them rare

Colour-suppressed decays: Not really rare

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

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

What are rare decays ?

Dominant decays: Not rare

Phase space suppressed decays: Not that rare

Cabibbo-suppressed decays: Some call them rare

Colour-suppressed decays: Not really rare

Hadronic FCNC decays: Not the topic of the lecture

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

What are rare decays ?

Dominant decays: Not rare

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Cabibbo-suppressed decays: Some call them rare

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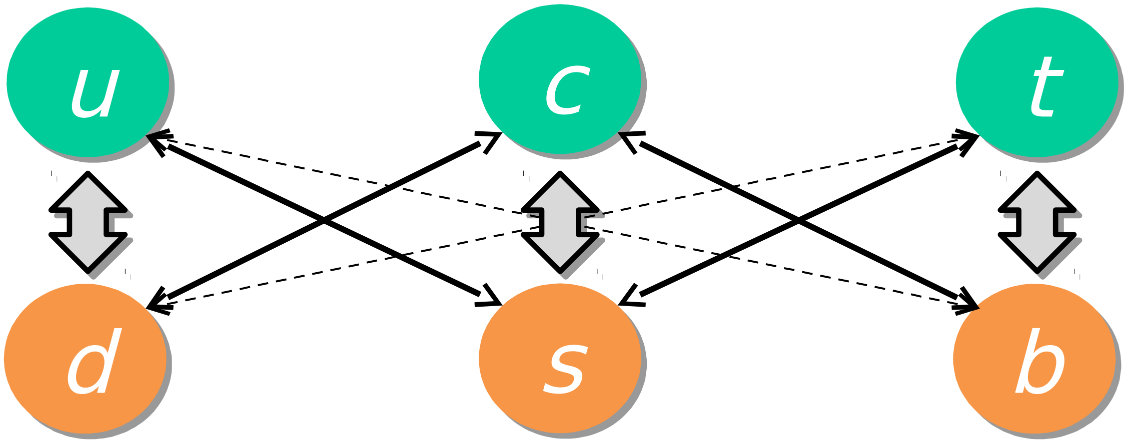
Hadronic FCNC decays: Not the topic of this talk

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

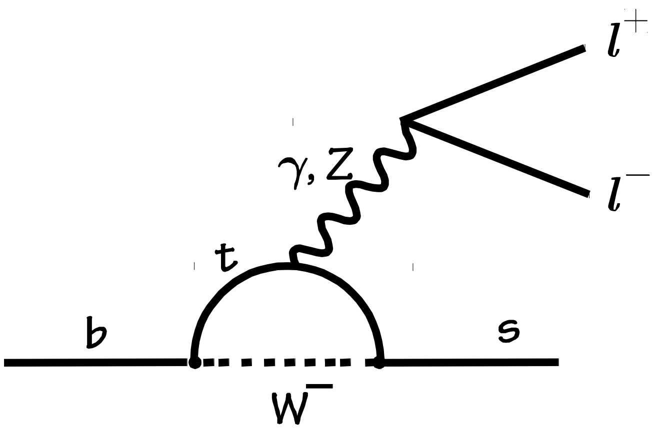
Electroweak FCNC penguins: That's rare !

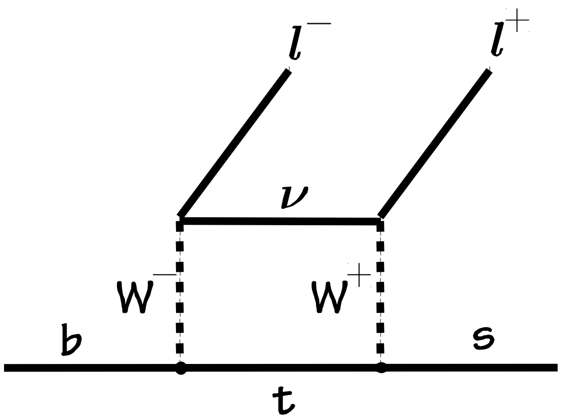
- $b \to s \gamma$
- $b \to s l l$
- And friends...

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 ?

see lectures of Filippo Sala

No. Open questions

D. Tonelli

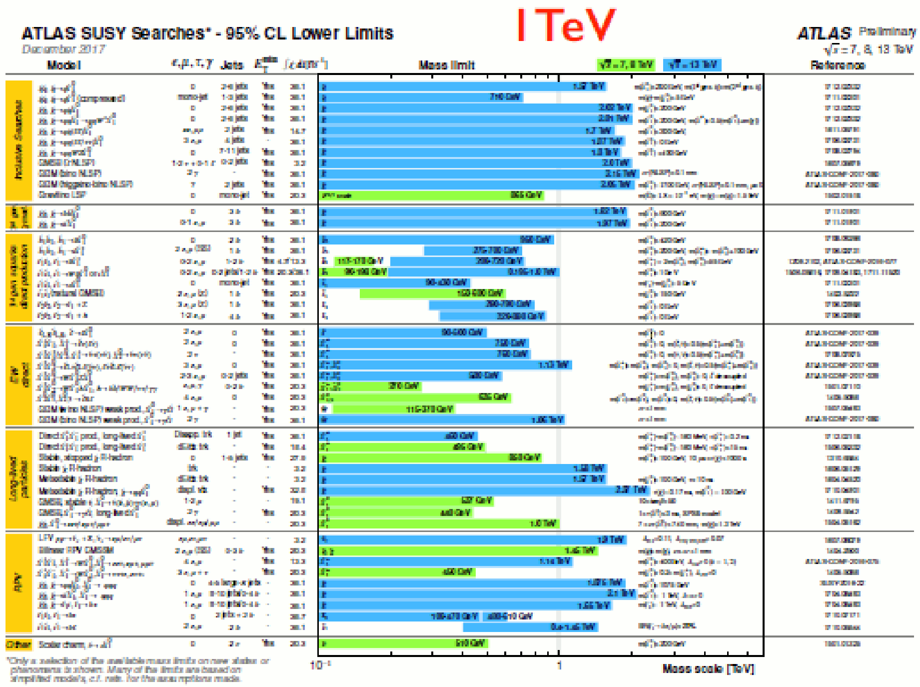
These and many other questions fuel the strong and wide-spread prejudice that the SM is completed at high-energy by new particles and interactions

How do you we search for new particles ?

Direct vs Indirect Searches

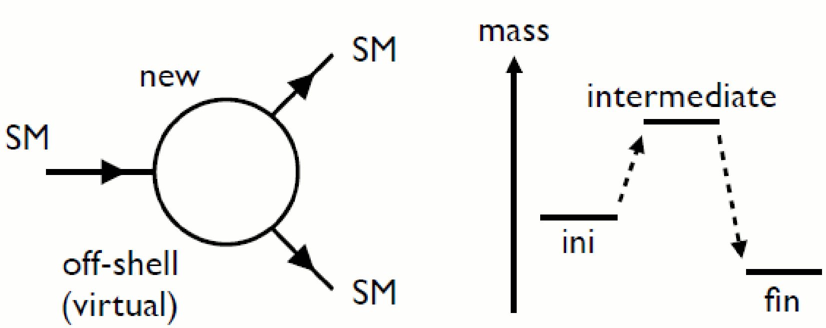
complementarity with LHC

1TeV



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

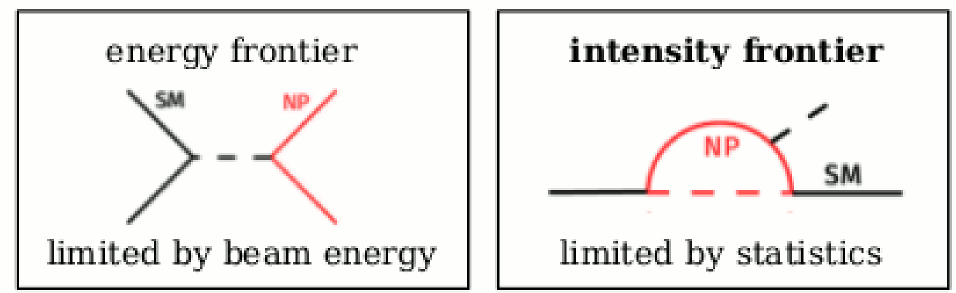
New particle via quantum effects



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

— suppressed by $(E/\Lambda)^n$

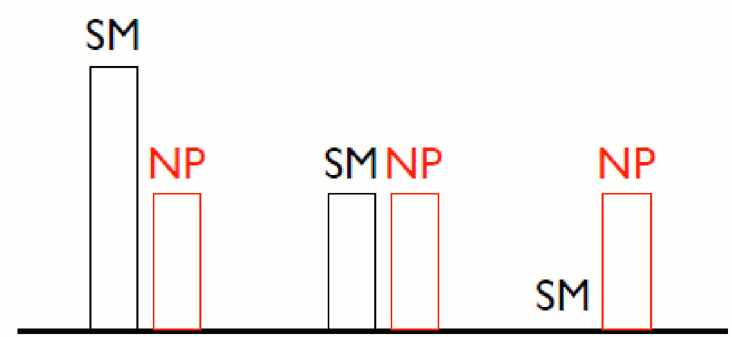
Why flavor physics ?



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

Three classes of SM processes (M.Endo)

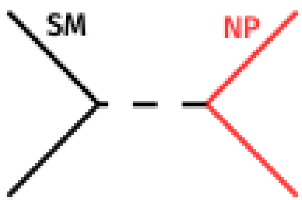
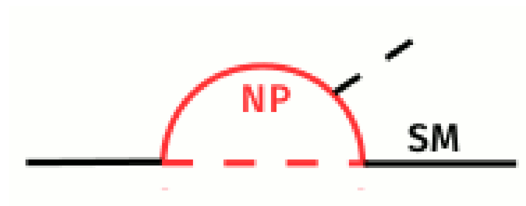
$$\mathcal{O}_{\rm obs} = \mathcal{O}_{\rm SM} + \mathcal{O}_{\rm NP}$$



SM tree	loop	forbidden
extremely precise	precision	good but…

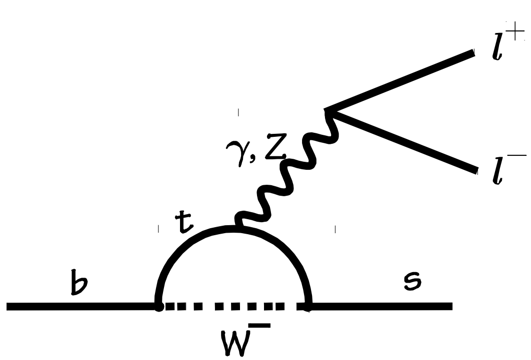
Rare B decays

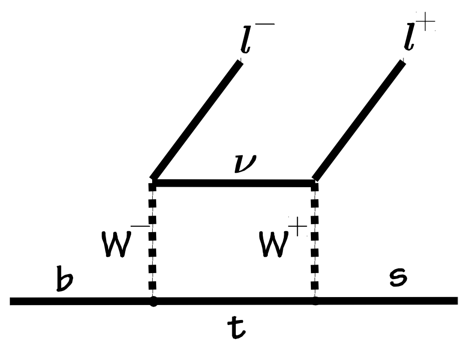
- FCNC are strongly suppressed in the SM: only loops + GIM mechanism
- Any new particle generating new diagrams can change the amplitudes

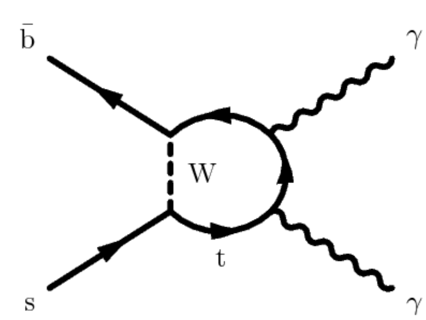
energy frontier	intensity frontier
	
limited by beam energy	limited by statistics

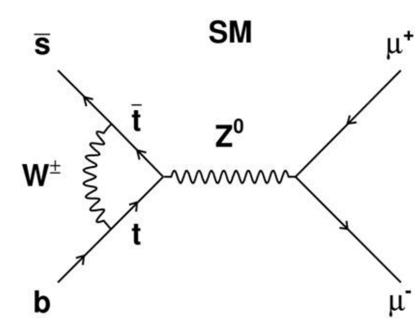
→ **NP beyond the direct reach of the LHC**

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

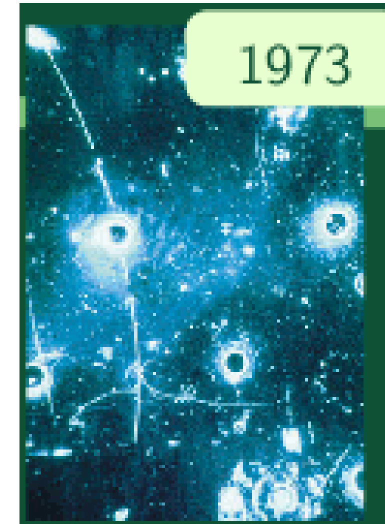
Experimental aspects:

- 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

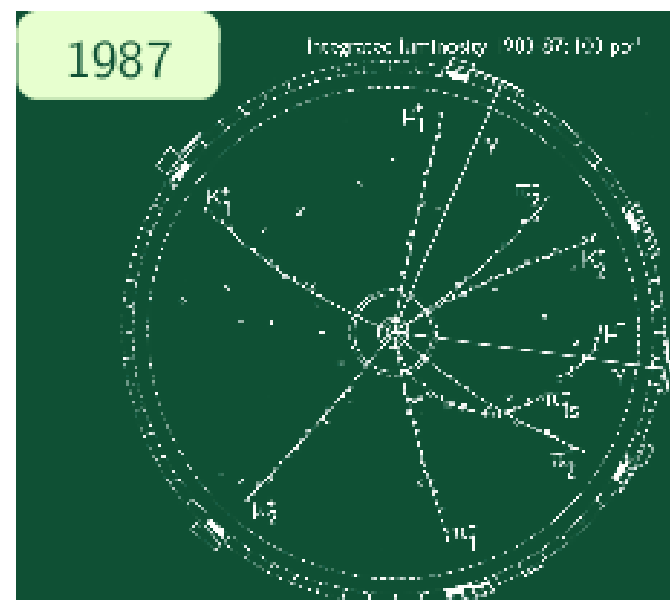


Sensitive to New Physics effects

- When was the Z discovered ?
  - 1973 from N ν → N ν ?
  - 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

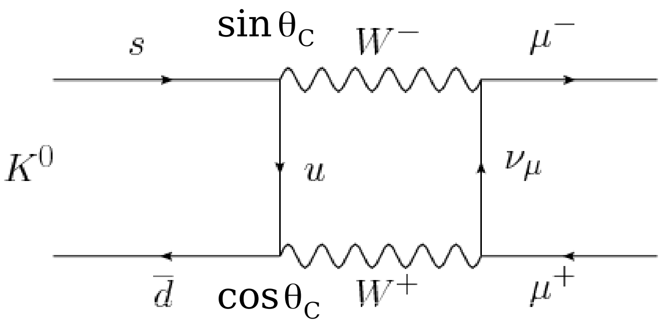
- Half of new parameters
- Needed for a full understanding

Look in lepton and **flavour** sectors

→ CP asymmetry in the Universe

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

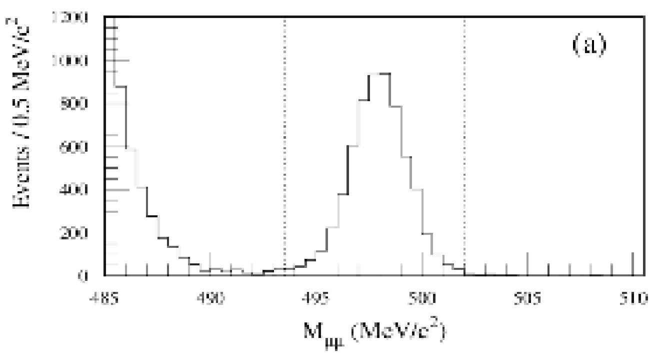
$K_L \to \mu^+\mu^-$ decay can be generated by the box diagram:



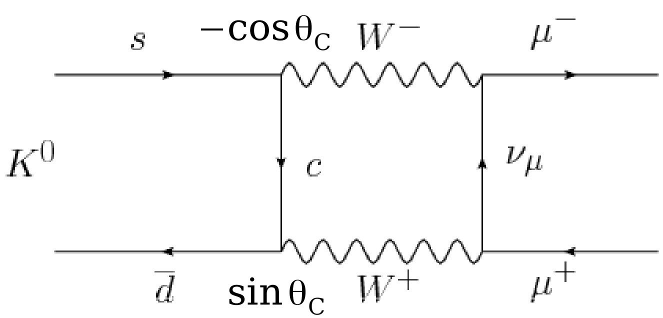
$K_L^0 \to \mu\mu$ was not observed though expected

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.

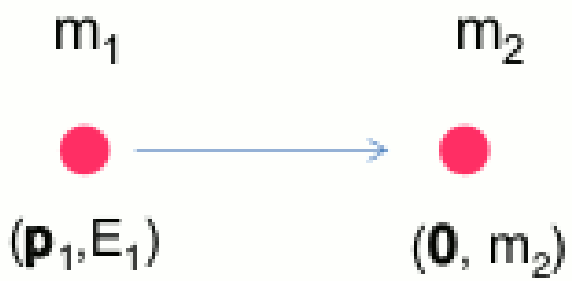
[Glashow, Iliopoulos and Maiani, 1970]

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.

$\Rightarrow$ but no experimental evidence of a fourth quark...

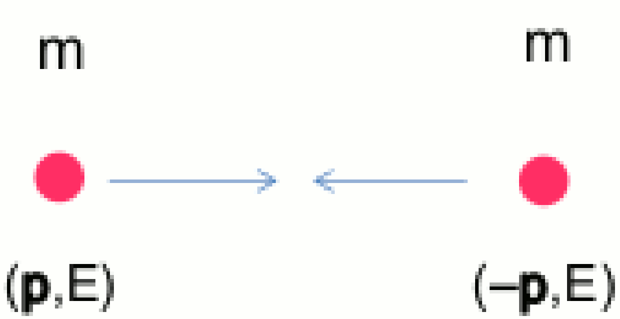
Proton beam
Fixed target experiment



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

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

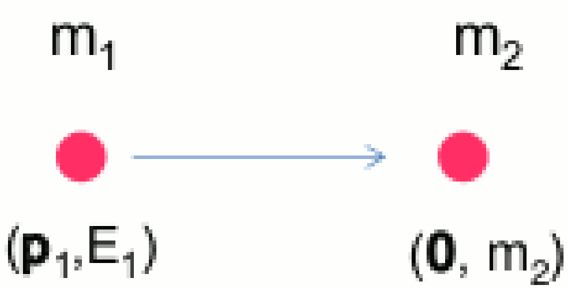
Electron beam
Collider experiment



$\sqrt{s}$ = 3 GeV

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

Proton beam
Fixed target experiment



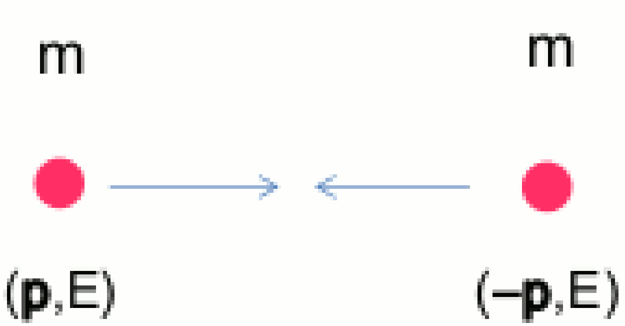
$m_1 = 0.938$ GeV
~ 1 GeV : proton
$m_2 \sim 9$ GeV : Beryllium
$E_1 = 30$ GeV

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

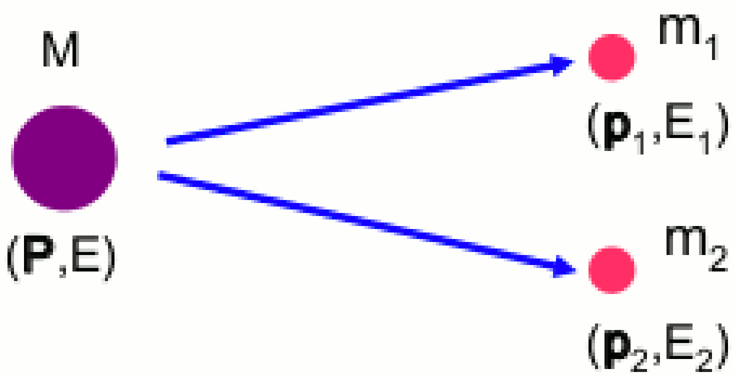
E = 1.5 GeV

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.

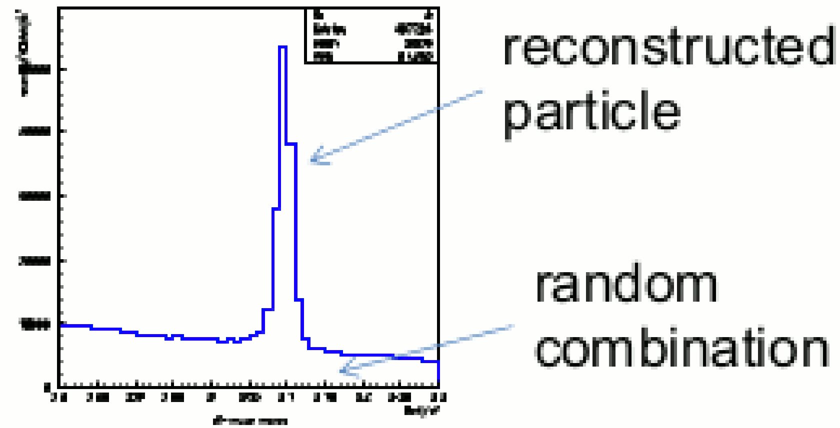


energy and momentum conservation

$$E = E_1 + E_2$$

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

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

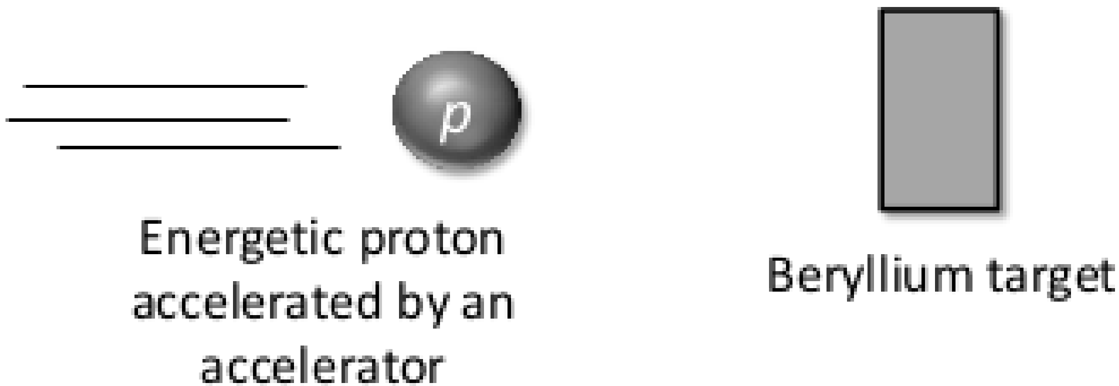


In reality, there are many particles in a final state; we don't know which is the correct combination.

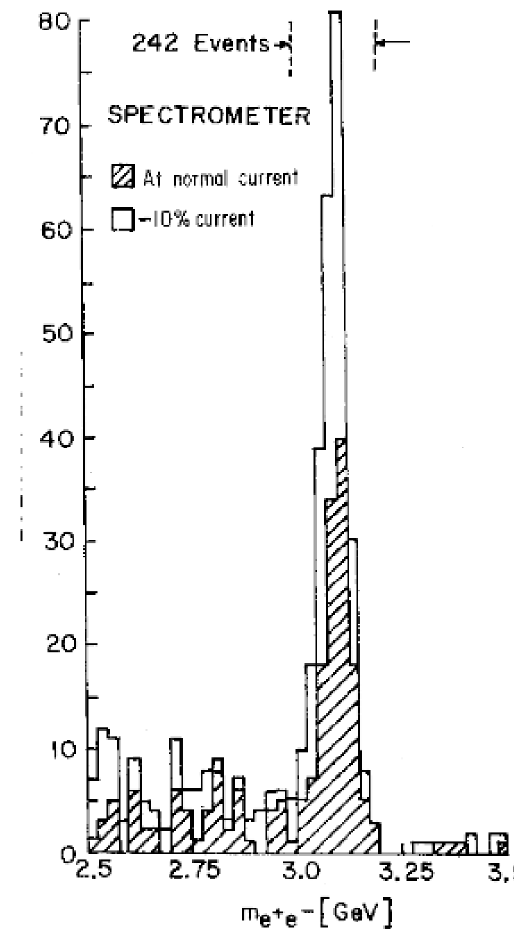
J/ψ (1974)

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

– fixed target experiment:



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



– particle found at 3.0 GeV/c^2

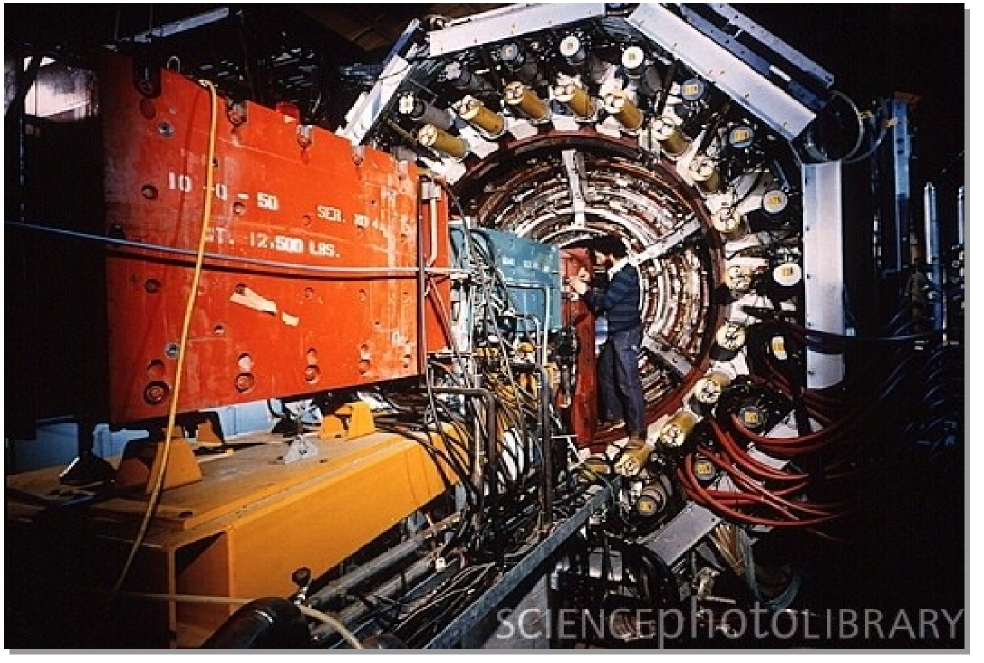
– They coined name of ''J'' to the particle

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

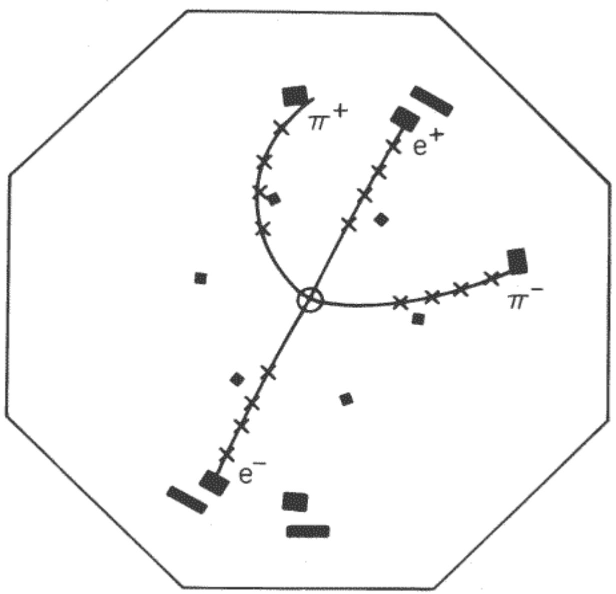
J/ψ (1974)

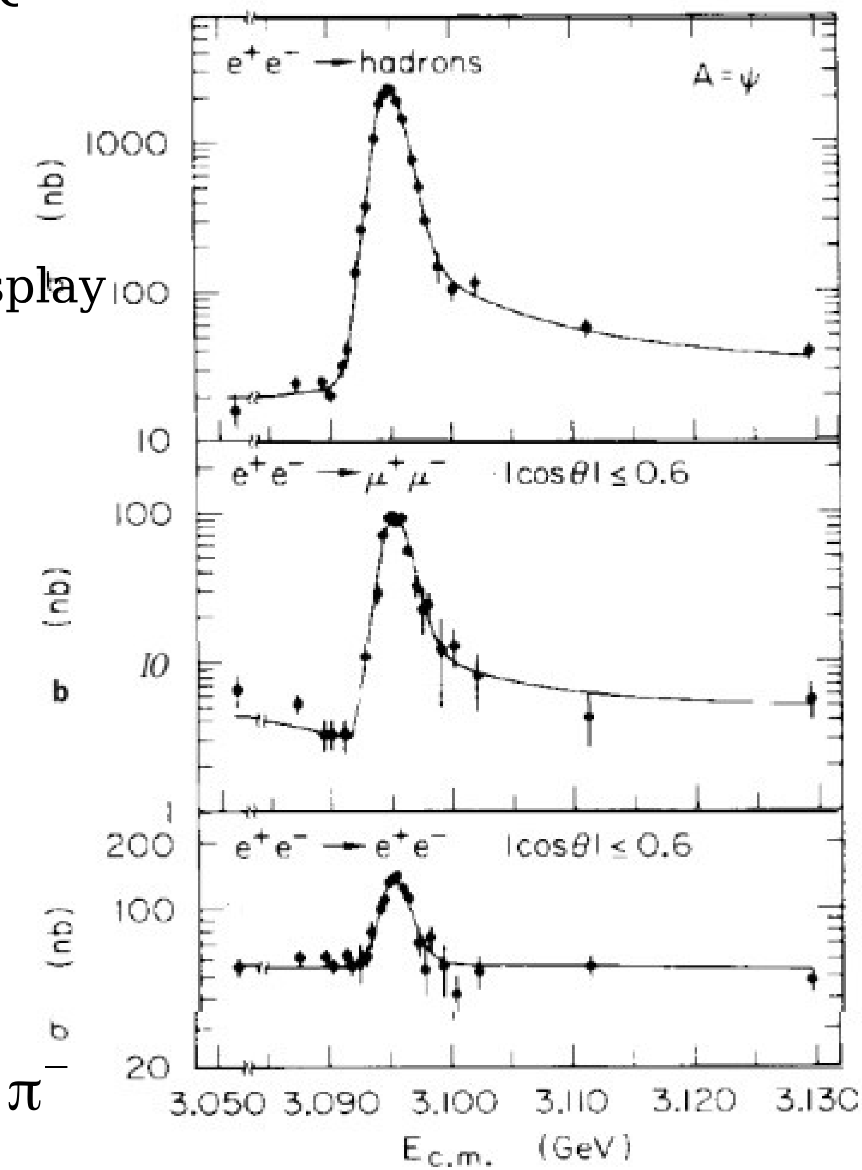
Experiment carried out by B. Richter group

– They observed a bump at 3 GeV/c^2

– Event display

The particle name was taken from its event display



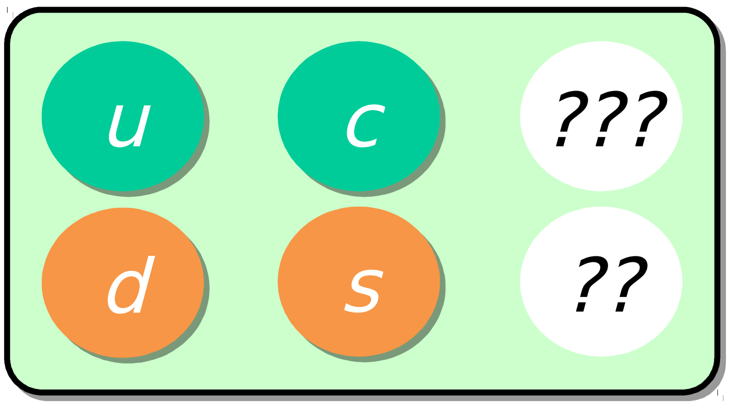


$$e^+ + e^- \rightarrow (e^+ + e^-) + \pi^+ + \pi^-$$

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

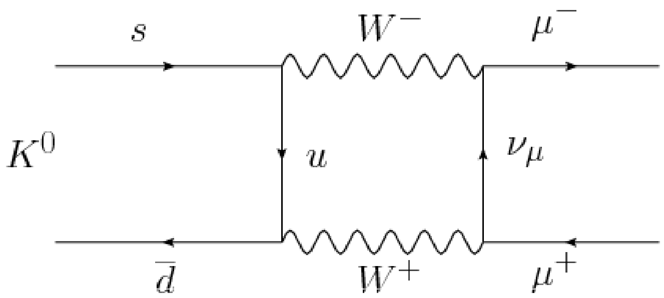
November revolution

⇒ Nobel Prize 1976 rewarded Richter and Ting

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

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

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



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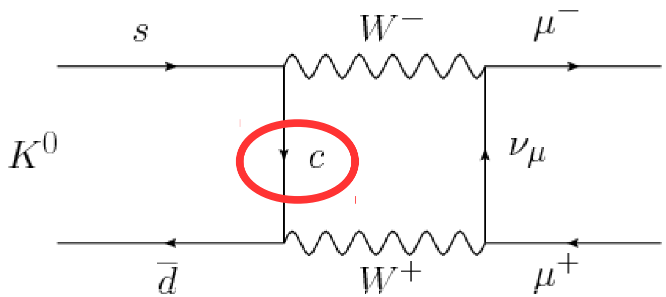

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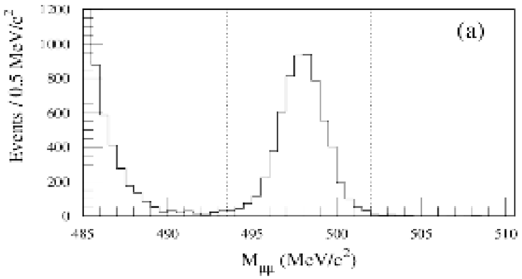
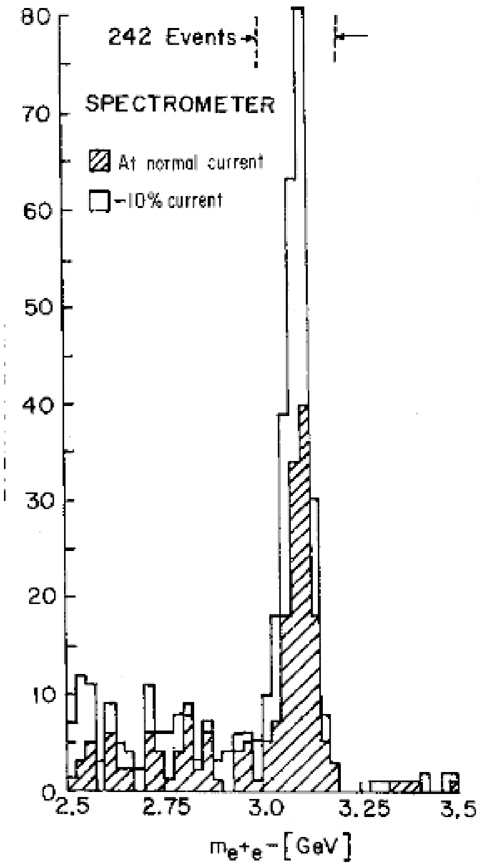
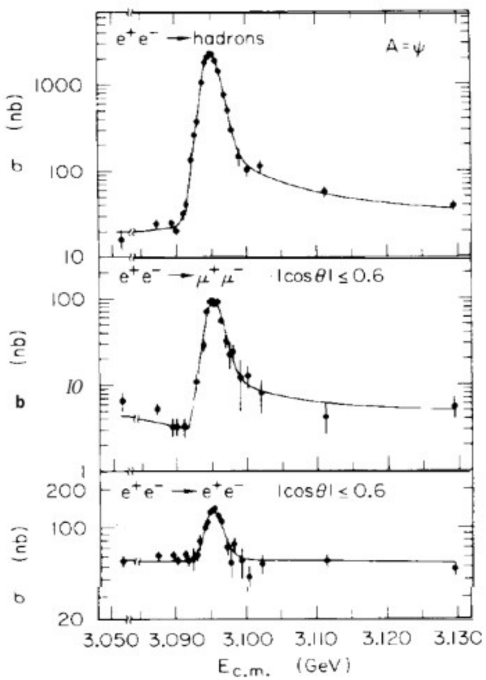


→ c quark eventually observed in 1974 [Ting], [Richter]

J/ψ





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

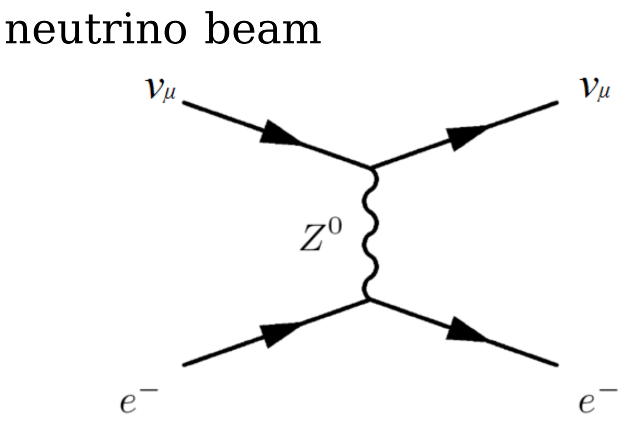
W and Z bosons discoveries

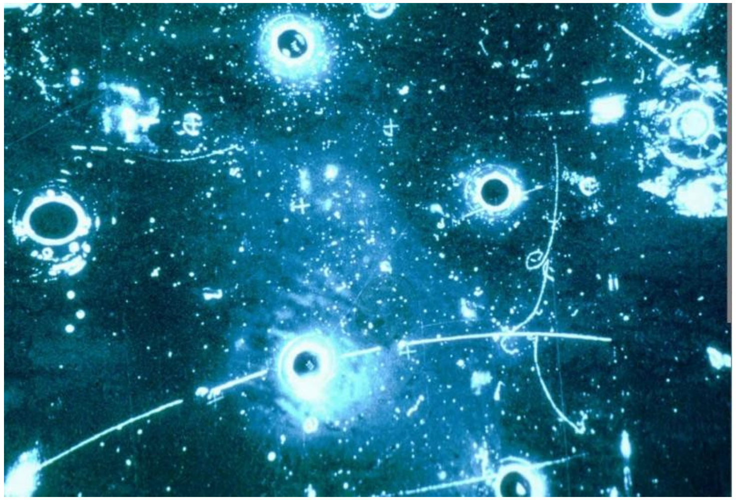
The weak force is essentially as strong as the electromagnetic force, but it appears weak because its influence is limited by the large mass of the Z and W bosons. Their mass limits the range of the weak force to about 10^{-18} meters, and it vanishes altogether beyond the radius of a single proton.

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.

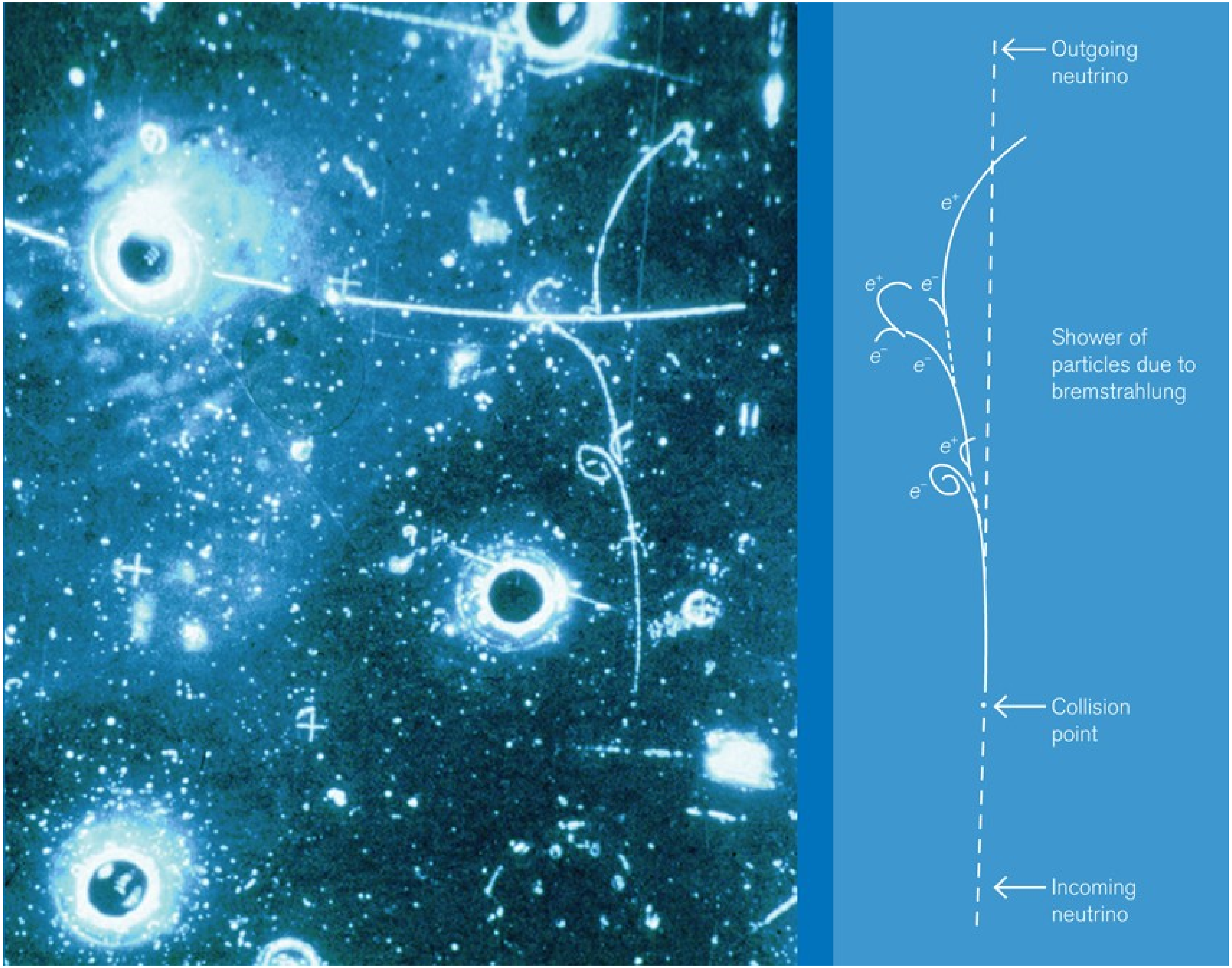
First, in 1973, came the observation of neutral current interactions as predicted by electroweak theory at Gargamelle bubble chamber (Andre Lagarrigue et al)

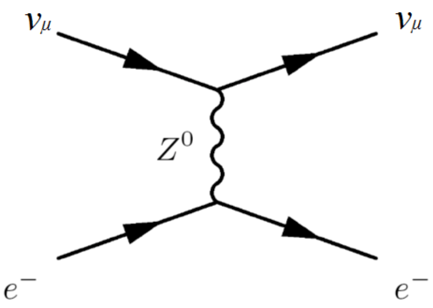
Neutrinos are particles that interact only via the weak interaction, and when the physicists shot neutrinos through the bubble chamber they were able to detect evidence of the weak neutral current,
and hence indirect evidence for the Z boson.





W and Z bosons discoveries

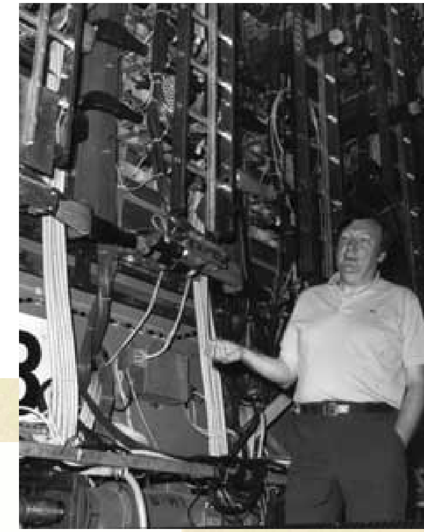


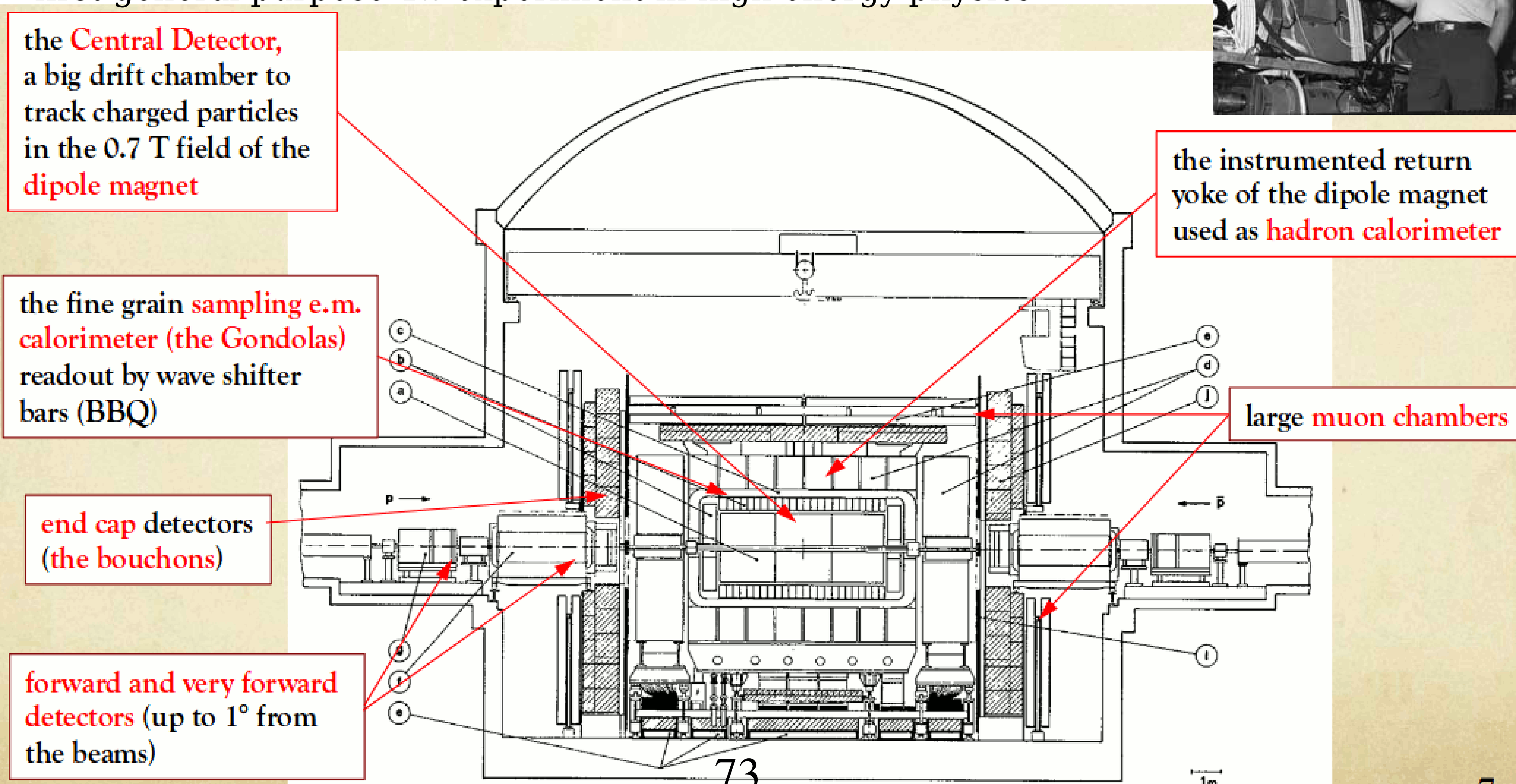


W and Z bosons discoveries

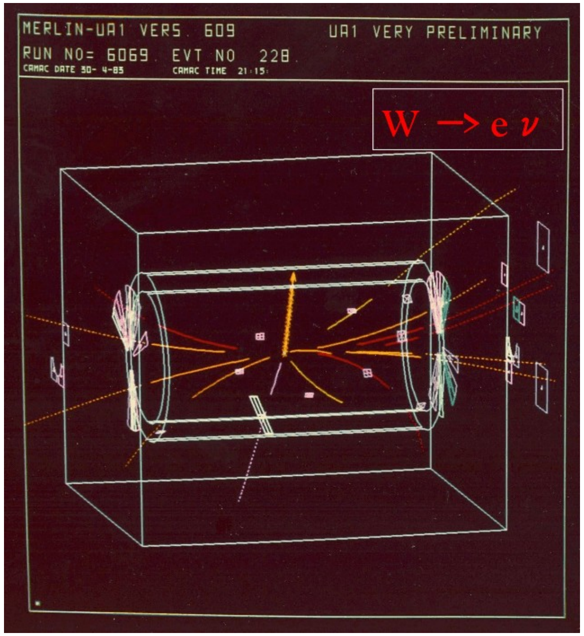
Super Proton Synchrotron, proton-antiproton collider, where unambiguous signals of W bosons were seen in January 1983 during a series of experiments made possible by Carlo Rubbia and Simon van der Meer. Experiments are UA1 and UA2.

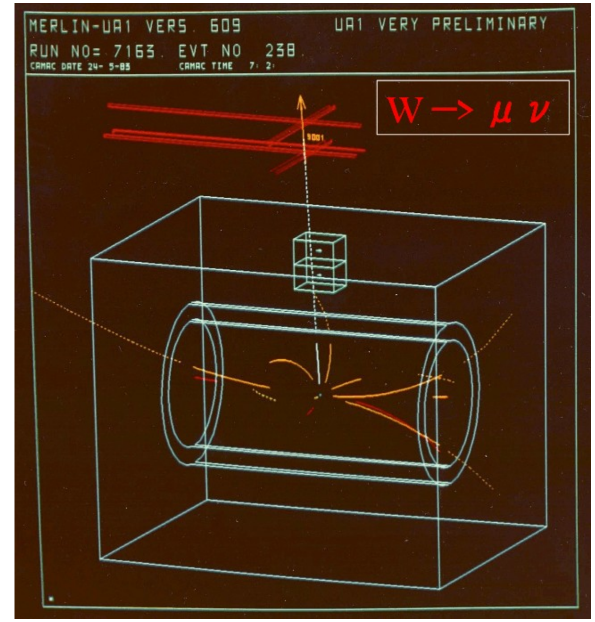
270 GeV per beam, enough energy to produce W and Z particles
first general purpose 4π experiment in high energy physics

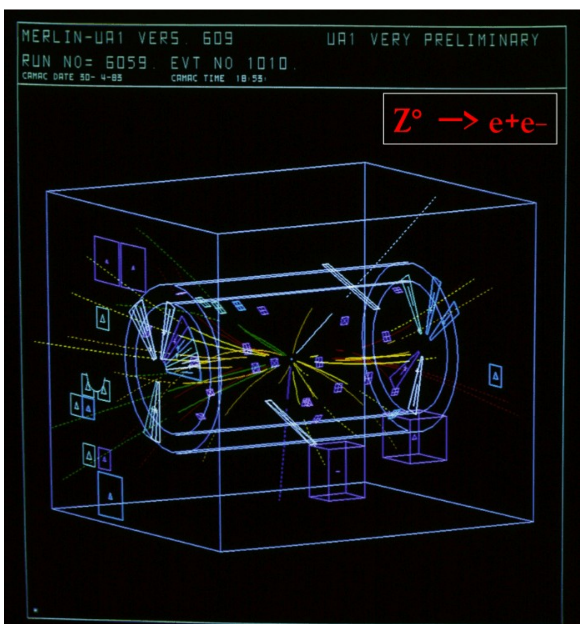


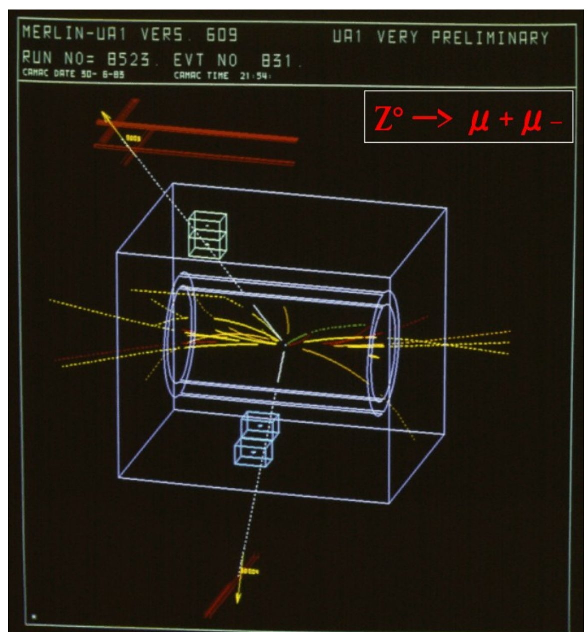


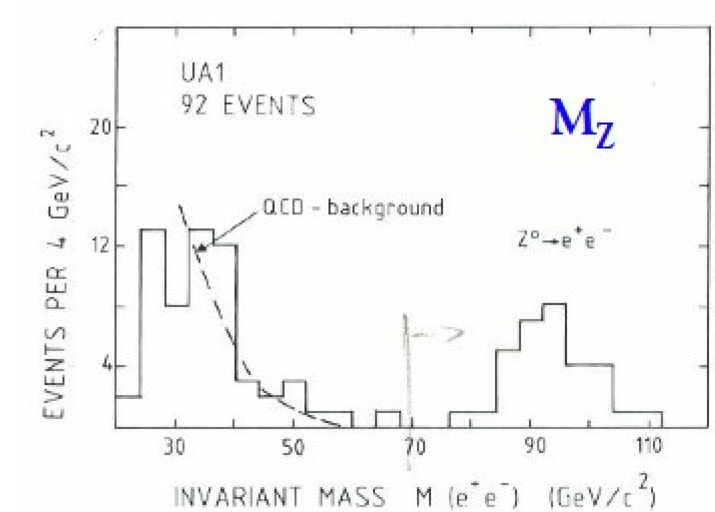
W and Z bosons discoveries











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