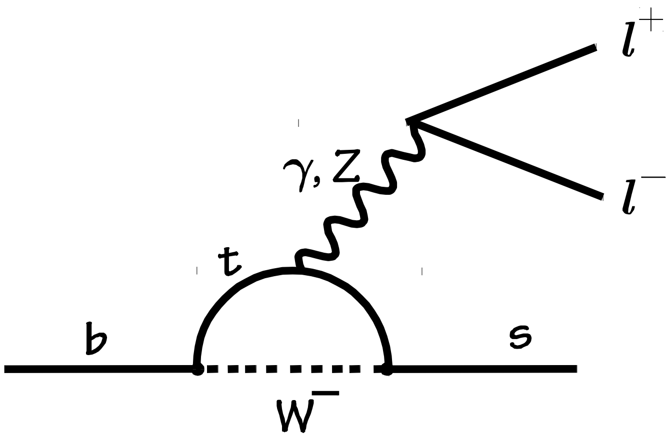
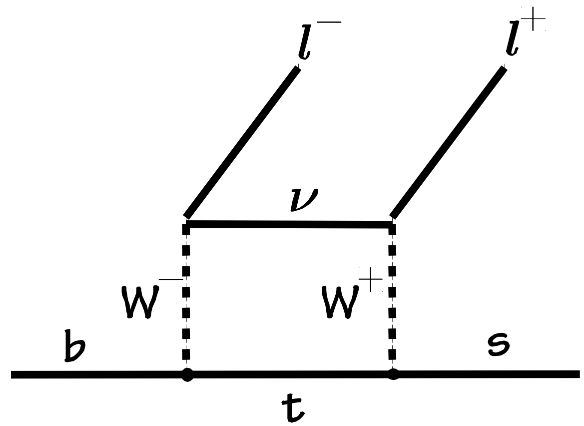
Beautiful paths to probe physics beyond the standard model of particles





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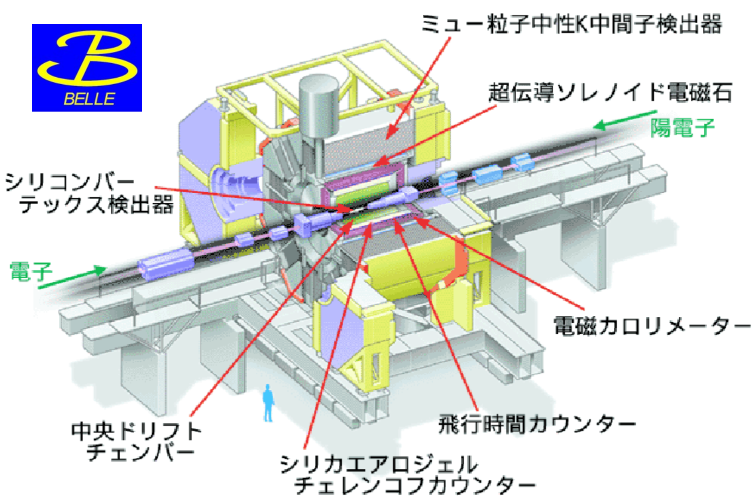
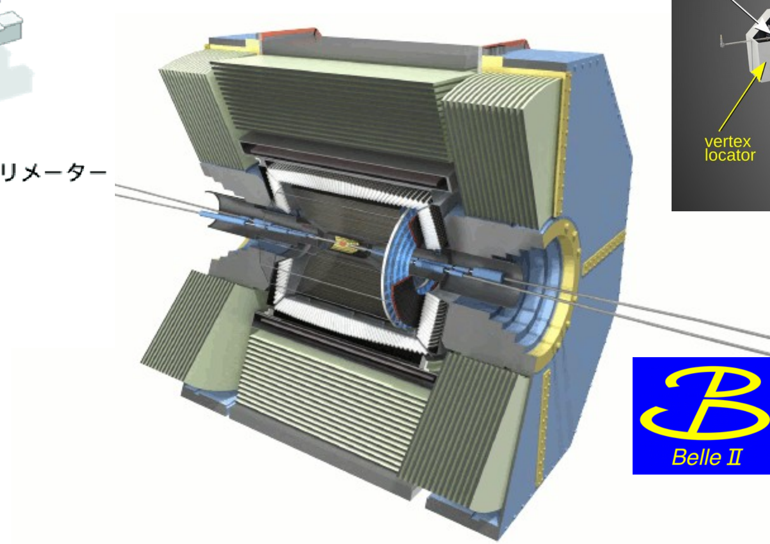
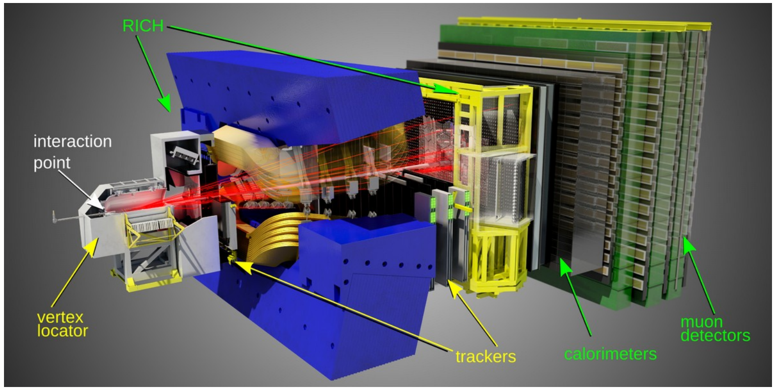






Future Flavours: Prospects for Beauty, Charm and Tau Physics , April 2022

Program of the lectures

- **How to study elementary particles**
  - indirect searches for New Physics
  - experiments through history of particle/flavour physics
  - what is Belle (II) experiment(s)

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

2 words on my background

e^+e^- @ Z | **e^+e^- @ $\Upsilon(4S)$** | **pp @ 8-13 TeV** | **e^+e^- @ $\Upsilon(4S)$**

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

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

KEK

High Energy Accelerator Research Organization

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

KEK

High Energy Accelerator Research Organization

Accelerator (Super) KEKB
circumference 3 km

more than 20 years ago...

New generation , new experiment

start taking data in 2018…

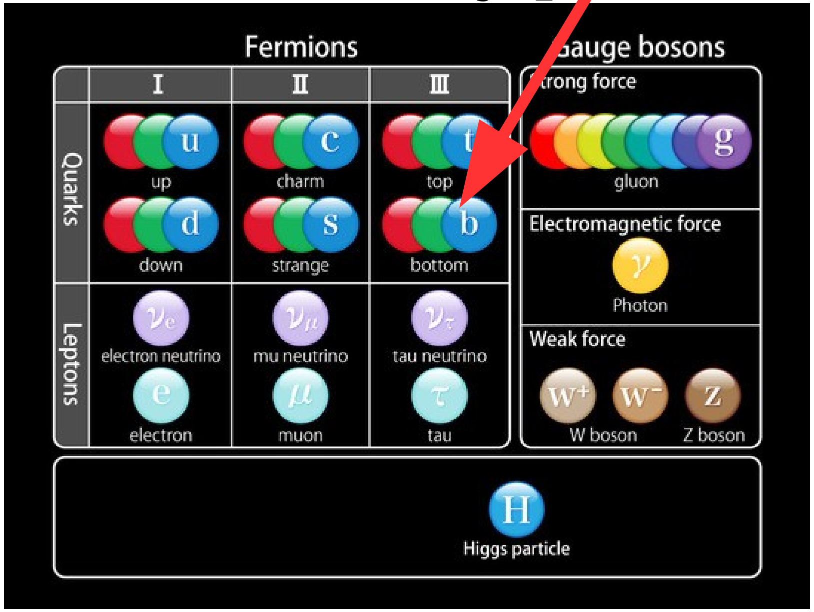
Belle II

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

Standard Model in a nutshell

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

b quark !



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

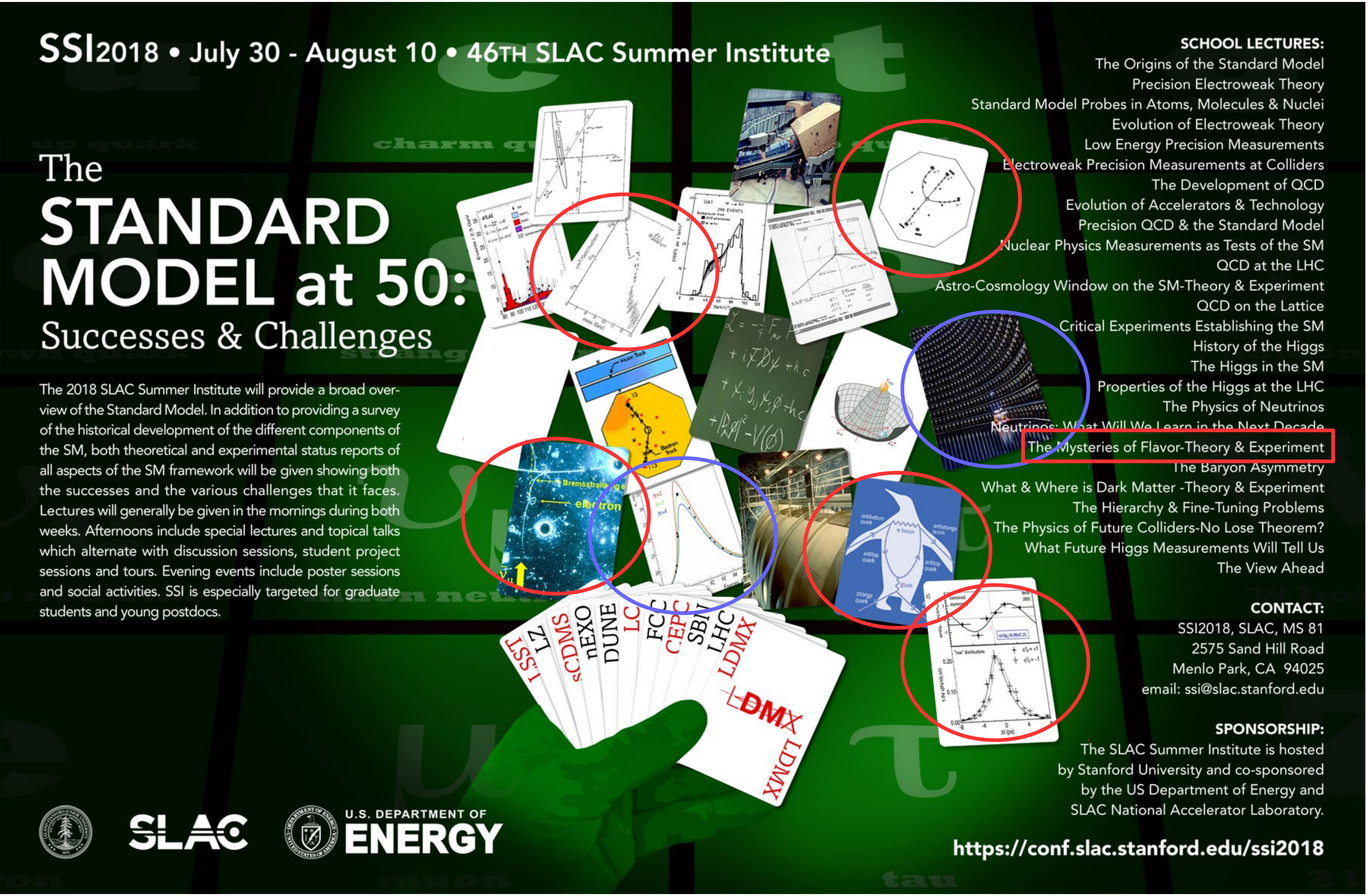
CKM matrix

PMNS matrix

Pontecorvo-Maki-Nakagawa-Sakata

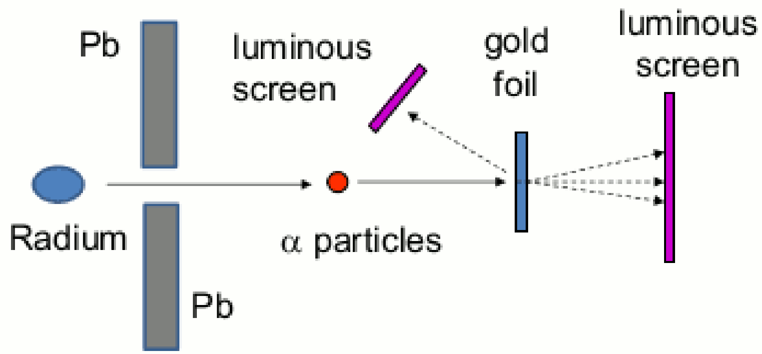
() = with Dirac neutrino masses

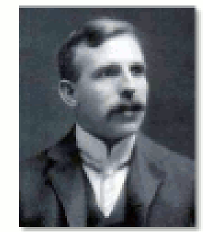
importance of flavour physics, indirect searches…



How to study Elementary Particles
⇒ experiments !!

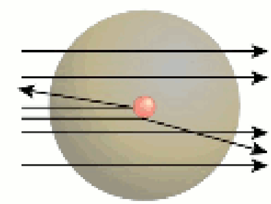
- In 1911, Rutherford performed an experiment to irradiate α particles to a gold foil.
  - ✓ α particle : nucleus of He atom
  - ✓ α particle from Radium (radioactive source)





E. Rutherford

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

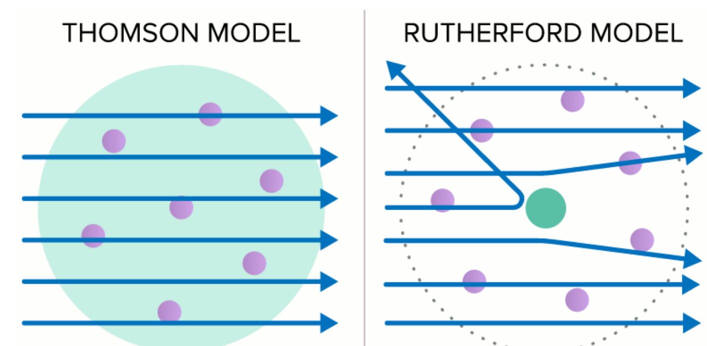


⇒ observation (''detectors are our eyes''):

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

– Rutherford

⇒ interpretation: ''Standard Model'' (''Panettone'' atom model) **''New Physics''**



⇒ good example of indirect search…

⇒ proper experimental setting is most important

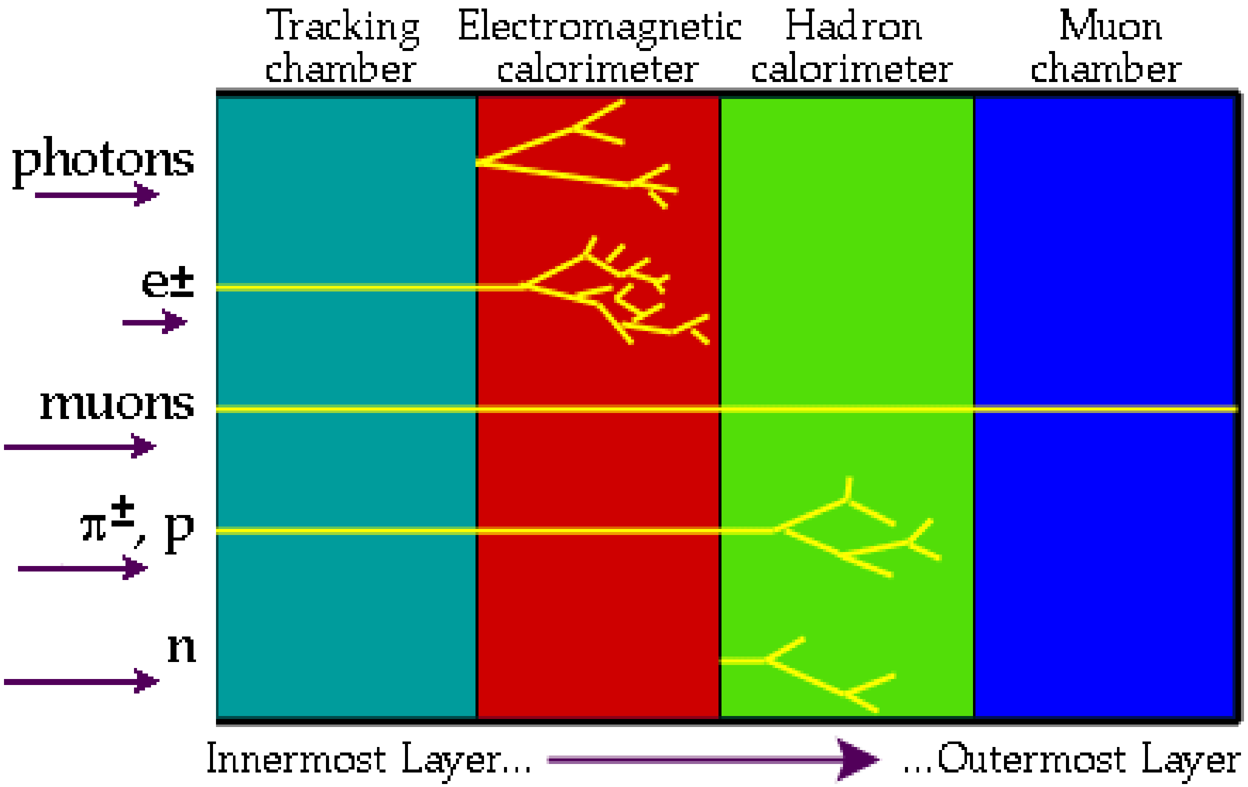
good control of the beam, good shielding…

good coverage of the detector

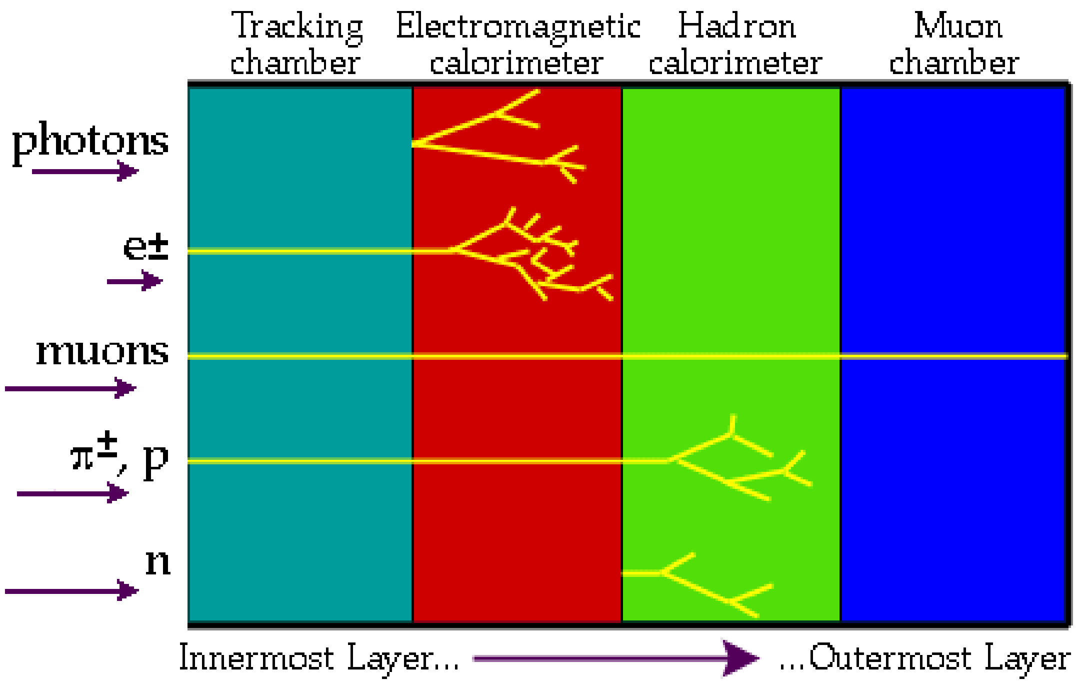
Particle physics experiments

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

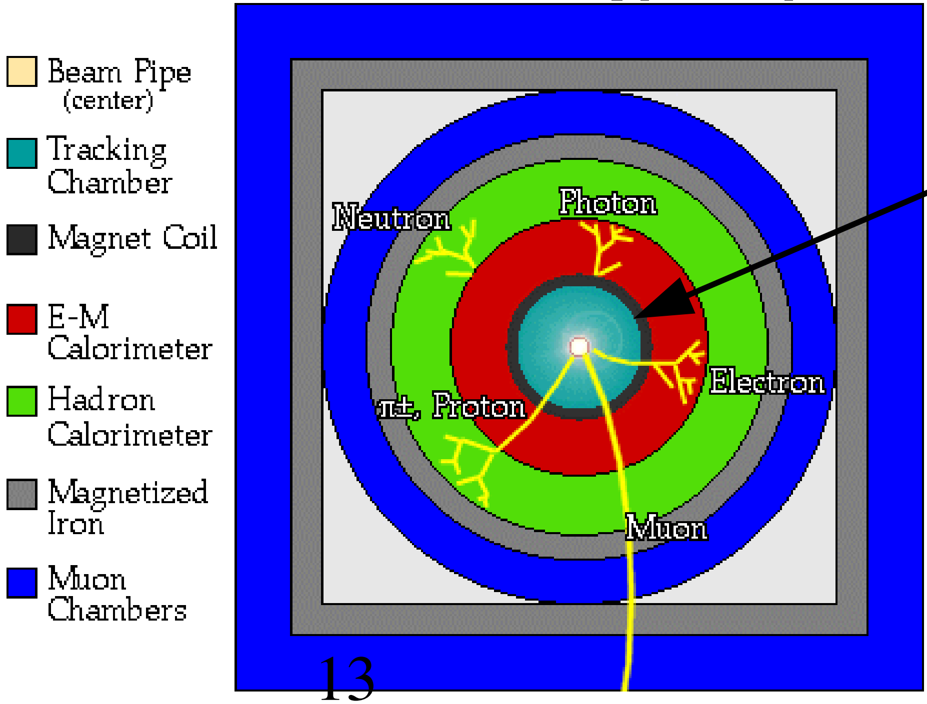
- tracking
- momentum analysis
- neutral particle detection
- particle identification
- triggering, and
- data acquisition



Identifying particles



A detector cross-section, showing particle paths

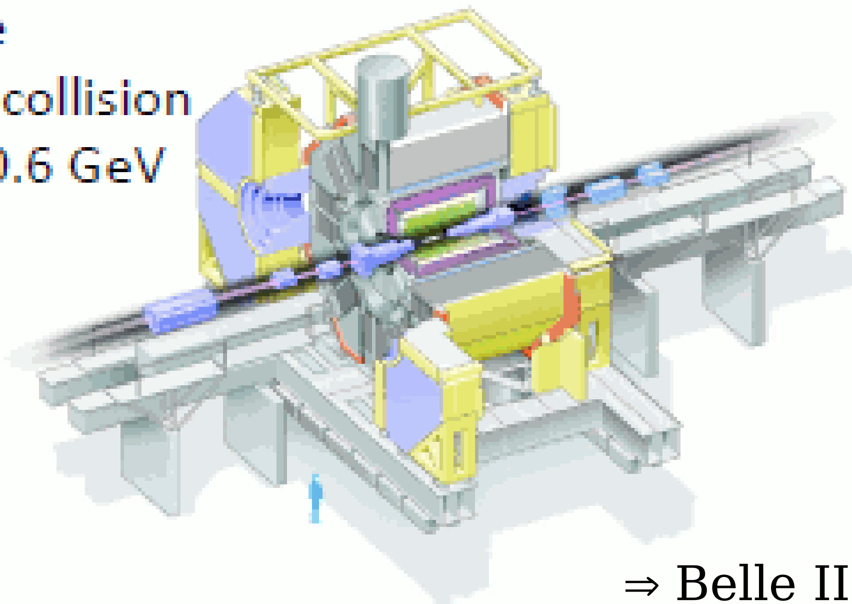


insert PID detectors
minimizing material
in front of calorimeters

Main actors in B physics

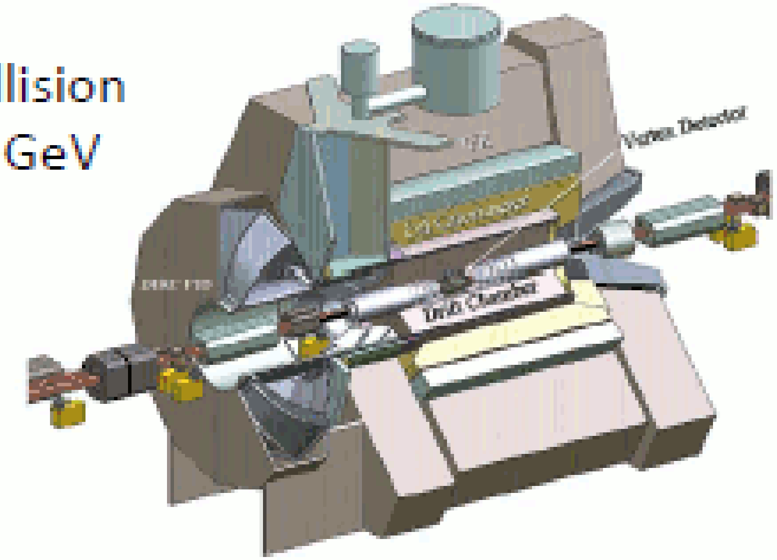
(ARGUS , CLEO)

Belle
e^+e^- collision
at 10.6 GeV

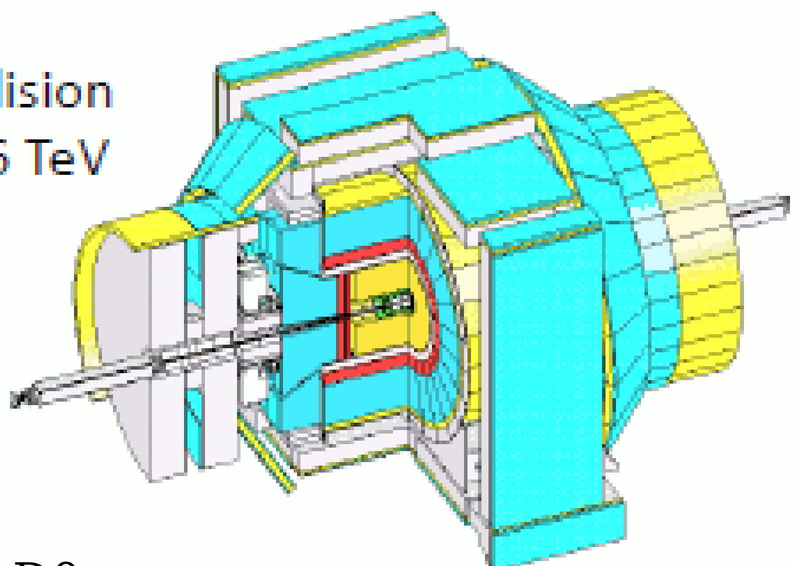


⇒ Belle II

BaBar
e^+e^- collision
at 10.6 GeV

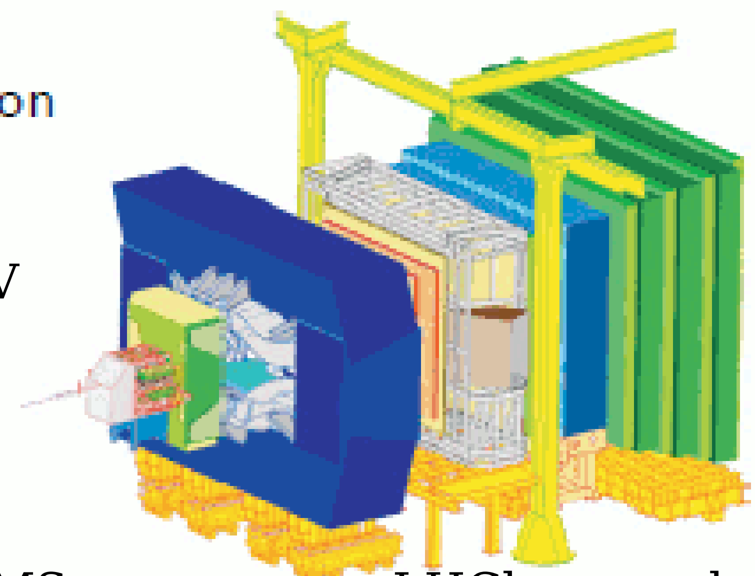


CDF
$p\bar{p}$ collision
at 1.96 TeV



... and D0

LHCb
pp collision
at 7 TeV
8 TeV
13 TeV



... and CMS

⇒ LHCb upgrade

logo designed by undergraduate student …

Belle II

logo designed by undergraduate student ...

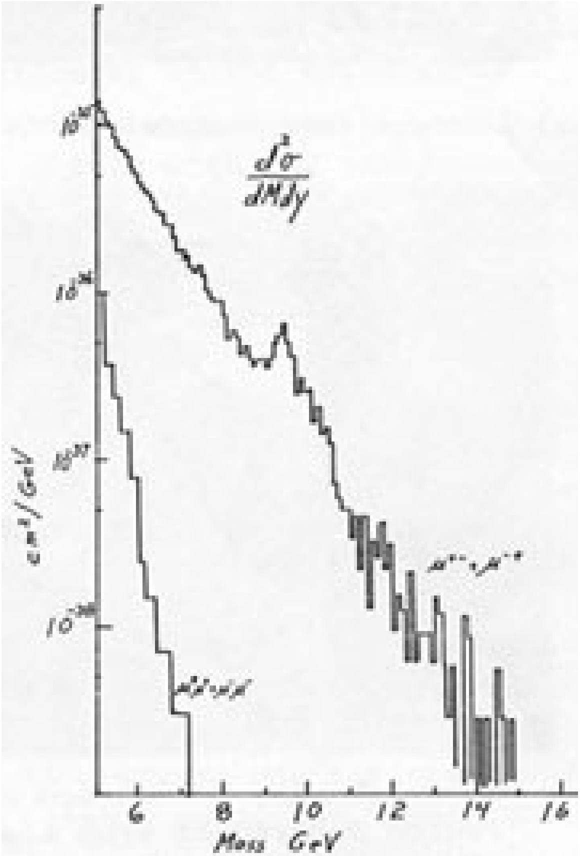
asymmetric $e^+ e^-$ collider
producing B mesons

but why running at 10.6 GeV ?

Upsilon meson discoveries

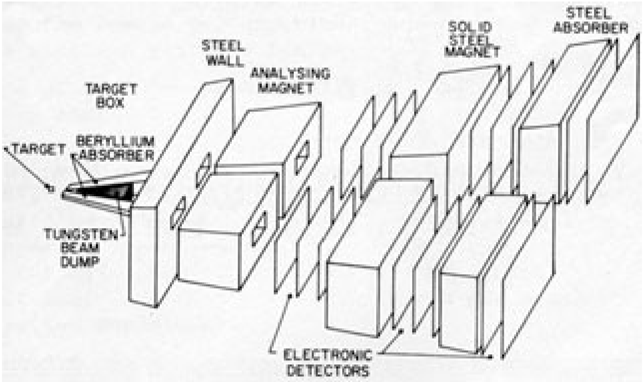
''Observation of a Dimuon Resonance at 9.5 GeV in 400 GeV Proton-Nucleus Collisions''

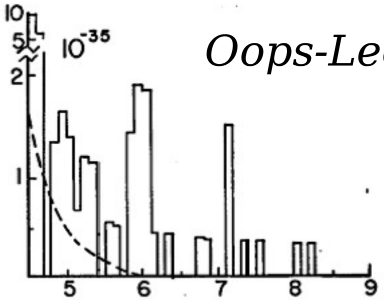
Summer of 1977, a team of physicists, led by Leon M. Lederman, working on experiment 288 in the proton center beam line of the Fermilab fixed target areas discovered the Upsilon Υ



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

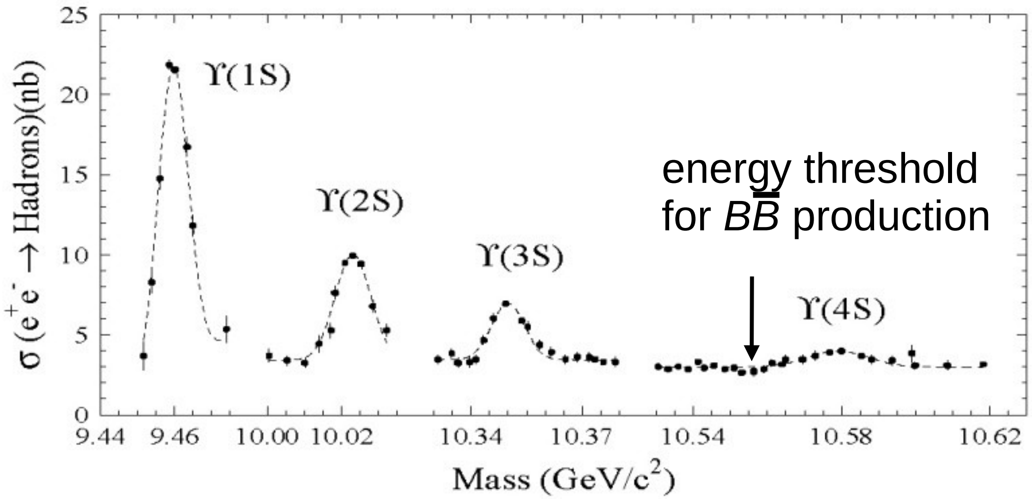




Oops-Leon !!

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

$\Upsilon(4S) = \Upsilon(10580)$ B-factory



Particle Data Group

$\Upsilon(1S)$ $I^G(J^{PC}) = 0^-(1^{--})$

$\Upsilon(1S)$ MASS	9460.30 ± 0.26 MeV (S = 3.3)
$\Upsilon(1S)$ WIDTH	54.02 ± 1.25 keV
$\Gamma(ggg, \gamma gg \to \bar{d}$ anything$)/\Gamma(ggg, \gamma gg \to$ anything$)$	$(3.36 \pm 0.34) \times 10^{-5}$

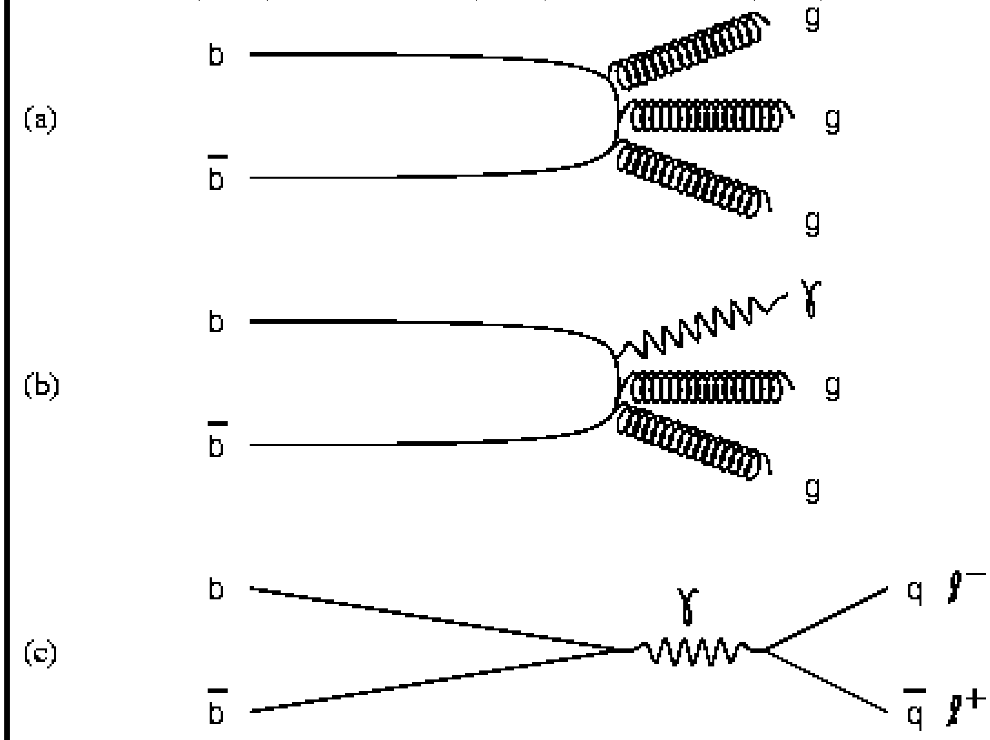
$\Upsilon(2S)$ $I^G(J^{PC}) = 0^-(1^{--})$

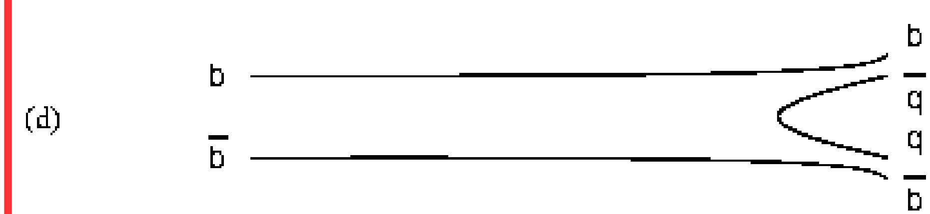
$\Upsilon(2S)$ MASS	10023.26 ± 0.31 MeV
$m_{\Upsilon(3S)} - m_{\Upsilon(2S)}$	331.50 ± 0.13 MeV
$\Upsilon(2S)$ WIDTH	31.98 ± 2.63 keV

$\Upsilon(3S)$ $I^G(J^{PC}) = 0^-(1^{--})$

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

$\Upsilon(1S)$: 80%, $\Upsilon(2S)$: 60%, $\Upsilon(3S)$: 36%



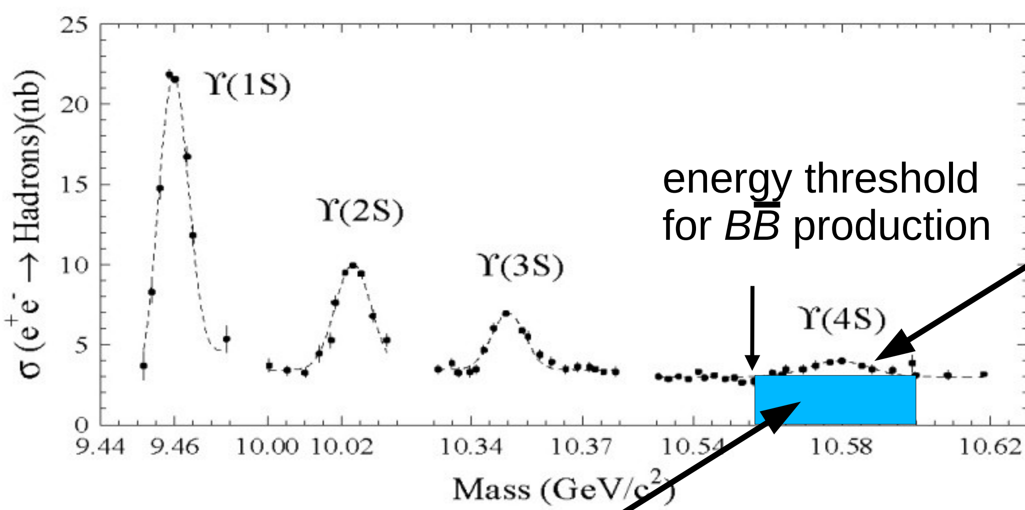


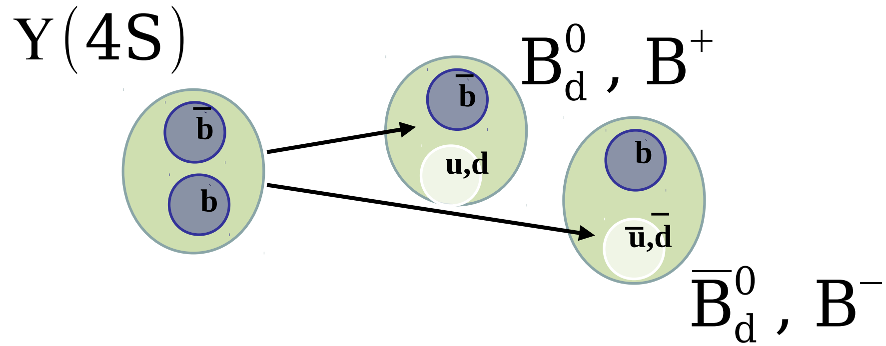
$\Upsilon(4S)$ $I^G(J^{PC}) = 0^-(1^{--})$

also known as $\Upsilon(10580)$

$\Upsilon(4S)$ MASS	10579.4 ± 1.2 MeV
$\Upsilon(4S)$ WIDTH	20.5 ± 2.5 MeV

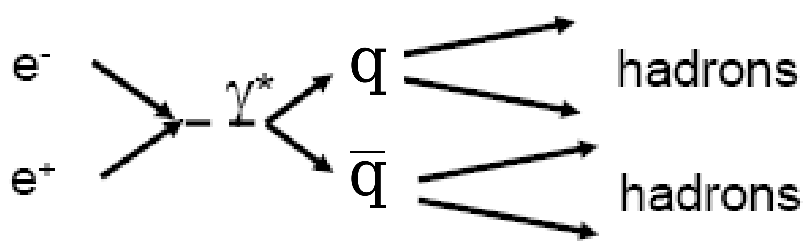
$\Upsilon(4S)$ B-factory





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

  $\Rightarrow$ before first decay, the final states contains a B and a $\overline{\text{B}}$



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

The naive parton model:

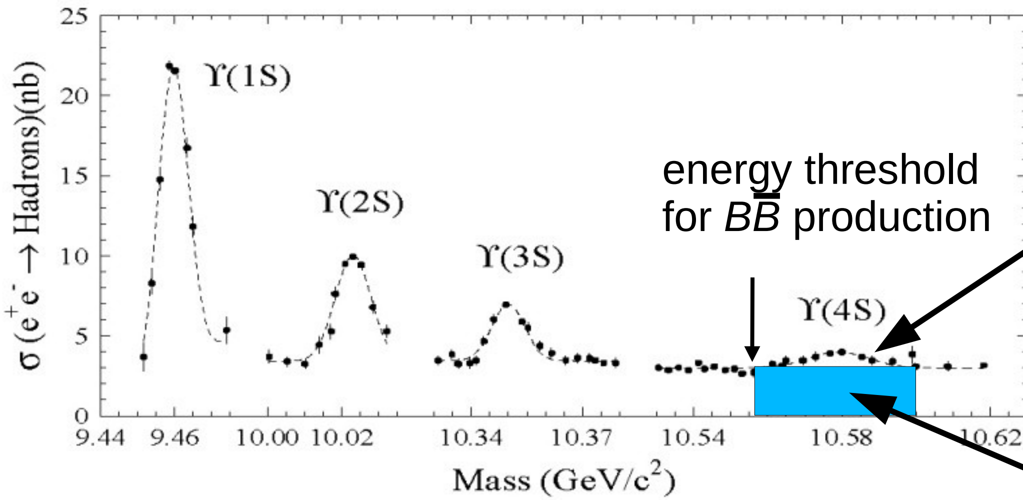
1 GeV $\leq \sqrt{s} \leq$ 3 GeV, u, d and s quarks

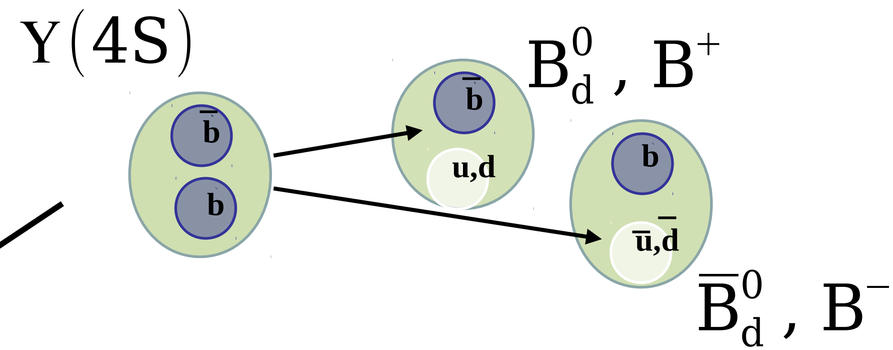
$$\mathbf{R(s) = 3.\{1.(\frac{2}{3})^2 + 2.(-\frac{1}{3})^2\} = 2}$$

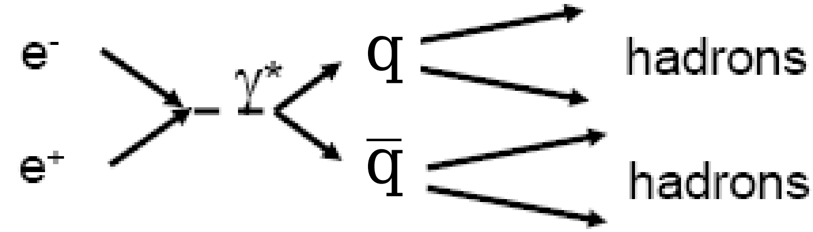
14 GeV $\leq \sqrt{s} \leq$ 45 GeV, u, d, s, c and b quarks

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

$\Upsilon(4S)$ B-factory







- **"on resonance" production**

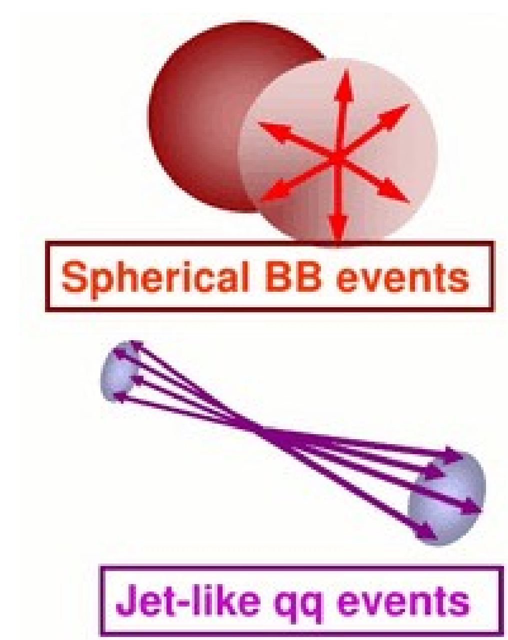
  $e^+e^- \rightarrow \Upsilon(4S) \rightarrow B_d^0\overline{B}_d^0,\ B^+B^-$

  $\sigma(e^+e^- \rightarrow B\overline{B}) \simeq 1.1$ nb

- **"continuum" production $(q\bar{q} = u\bar{u},\ d\bar{d},\ s\bar{s},\ c\bar{c})$**

  $\sigma(e^+e^- \rightarrow c\bar{c}) = 1.3$ nb
  $\sigma(e^+e^- \rightarrow s\bar{s}) = 0.4$ nb
  $\sigma(e^+e^- \rightarrow u\bar{u}) = 1.6$ nb
  $\sigma(e^+e^- \rightarrow d\bar{d}) = 0.4$ nb

- **$\sigma(e^+e^- \rightarrow \tau^+\tau^-) \sim 1$ nb**
- **$\sigma(e^+e^- \rightarrow \mu^+\mu^-) \sim 1$ nb (calibration)**
- **bhabha: $\sigma(e^+e^- \rightarrow e^+e^-) \sim 100$ 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), $\mathrm{cm^{-2}s^{-1}}$

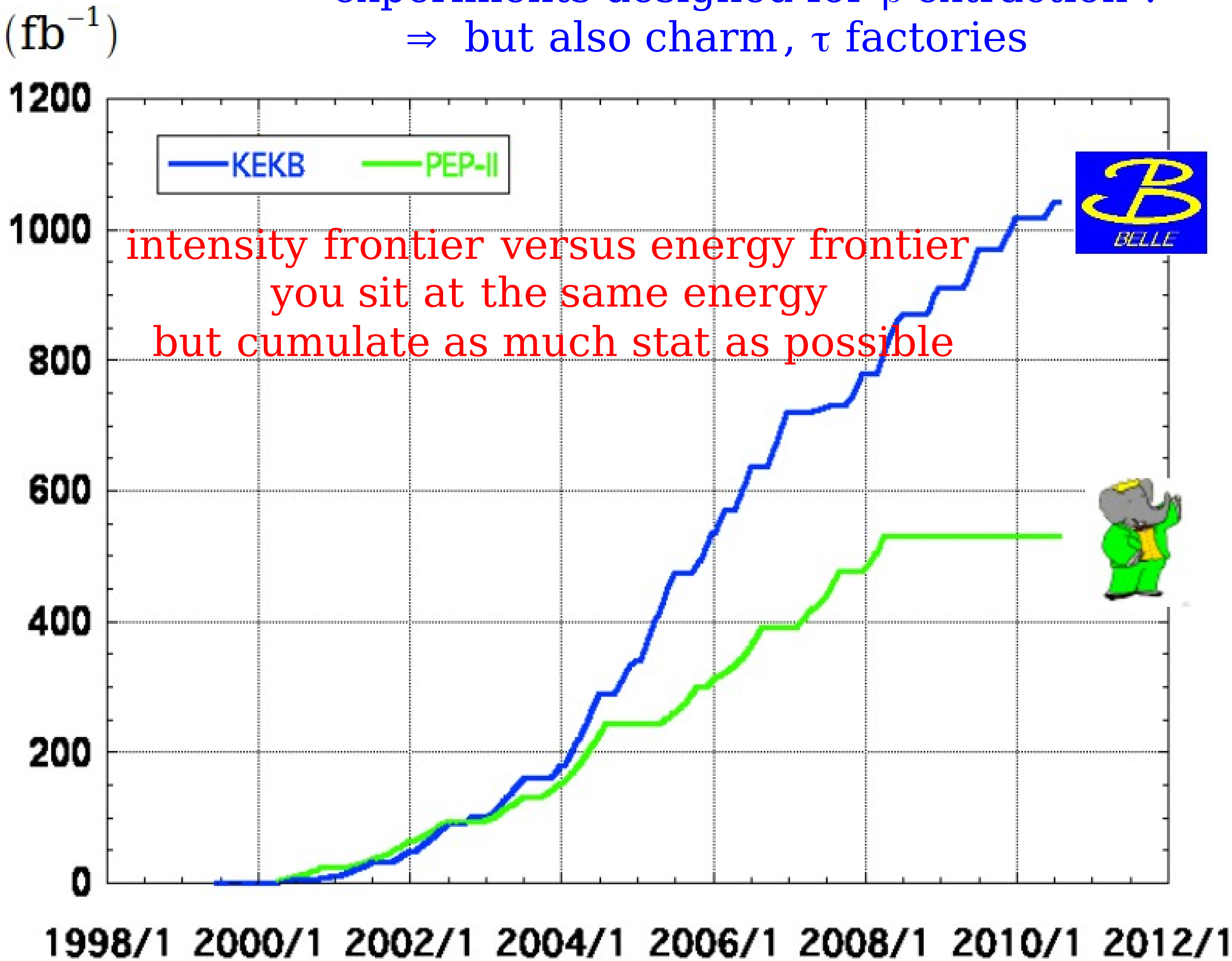
cross-section of reaction: (subject to nature), $\mathrm{cm^{2}}$

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

B factories: BaBar and Belle

⇒ experiments designed for β extraction !

⇒ but also charm, τ factories



intensity frontier versus energy frontier
you sit at the same energy
but cumulate as much stat as possible

> 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:

$\sim$ 100 fb^{-1}

~ 550 fb^{-1}

On resonance:

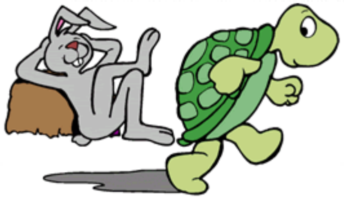
$\Upsilon(4S)$: 433 fb^{-1}

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

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

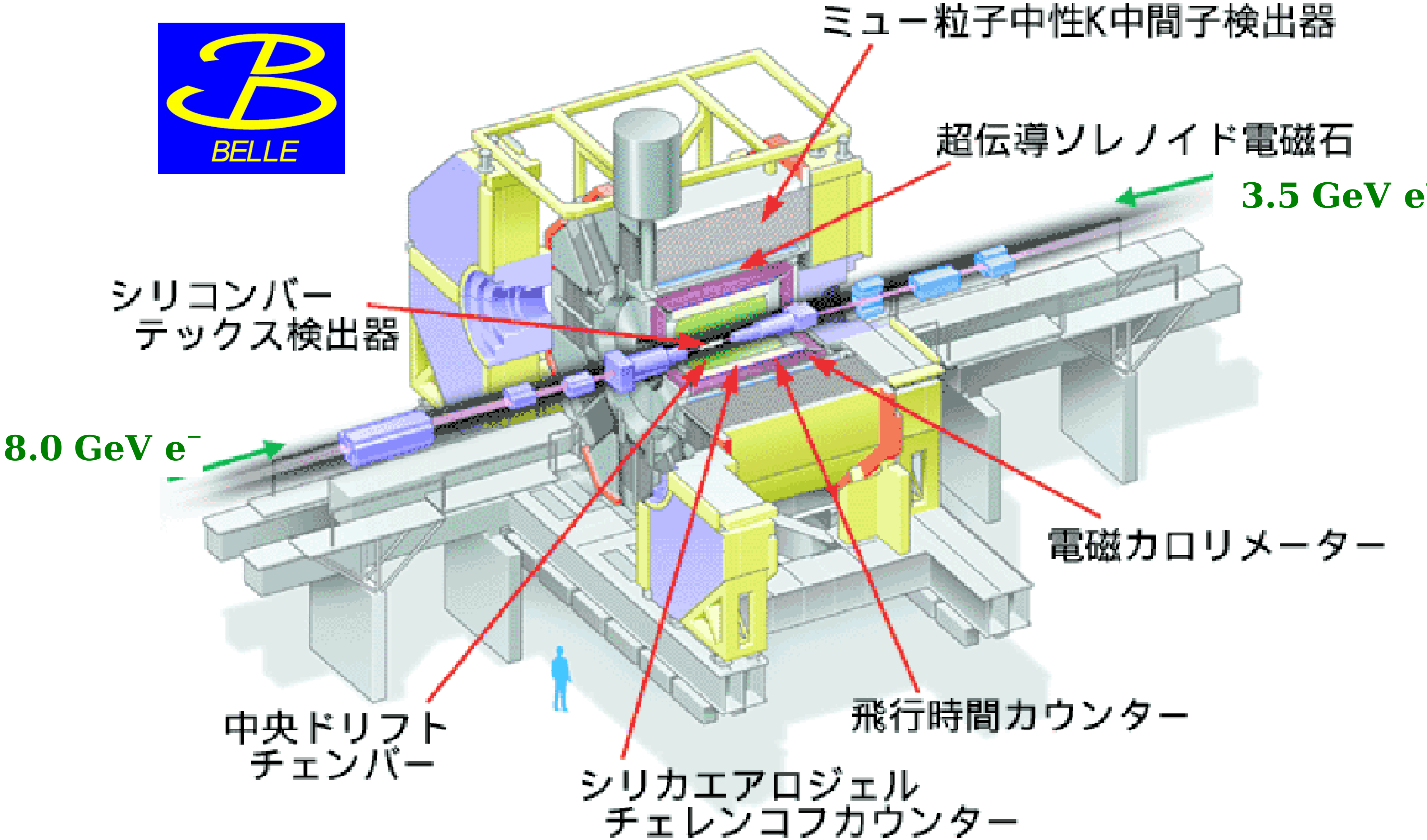
Off resonance:

$\sim$ 54 fb^{-1}



final samples $\begin{cases} \textbf{BaBar: } 467 \times 10^6 \, B\bar{B} \textbf{ pairs} \\ \textbf{Belle: } 772 \times 10^6 \, B\bar{B} \textbf{ pairs} \end{cases}$

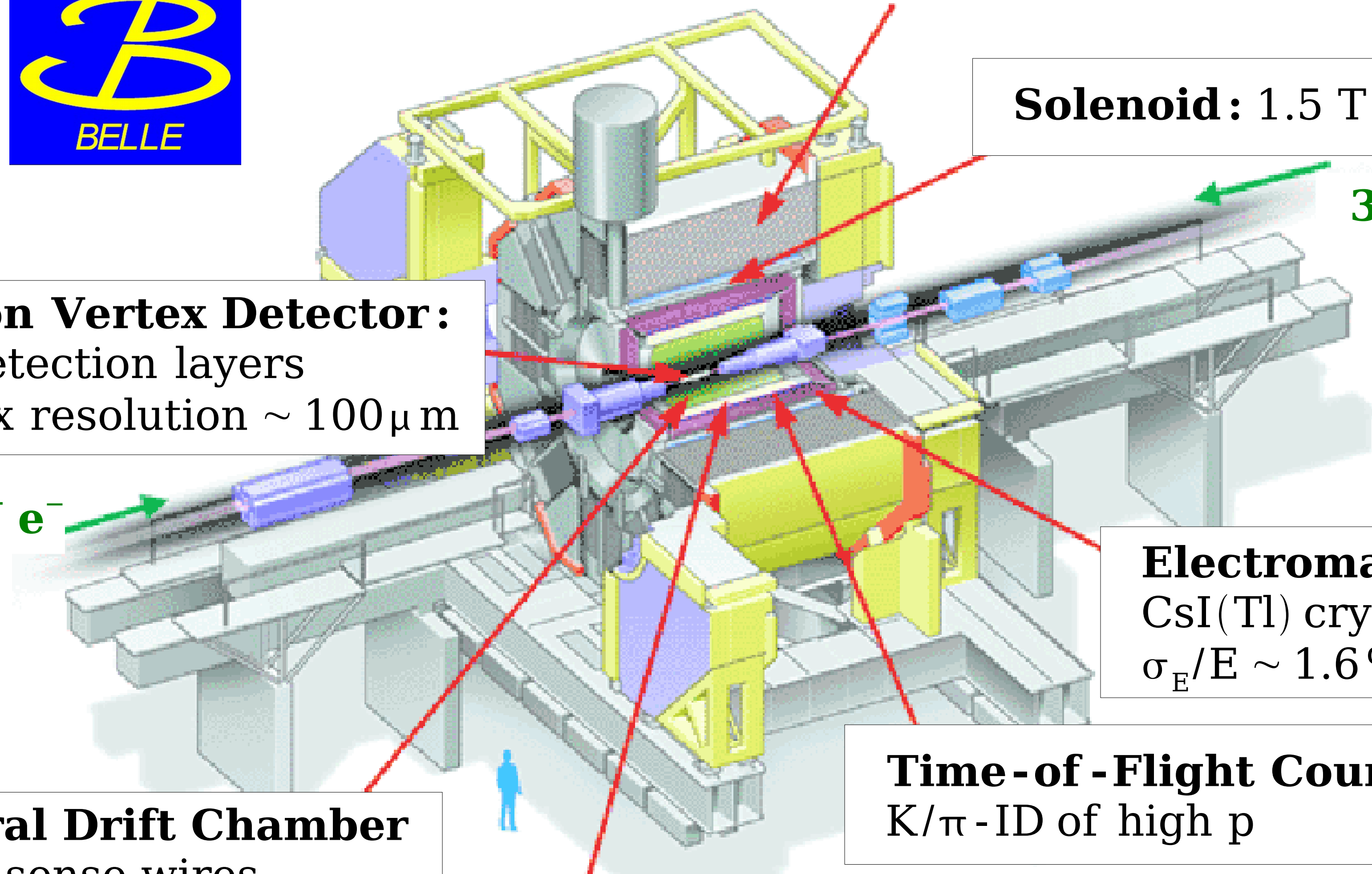
Belle in a nutshell



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

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

Belle in a nutshell



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

Solenoid: 1.5 T

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

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

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

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

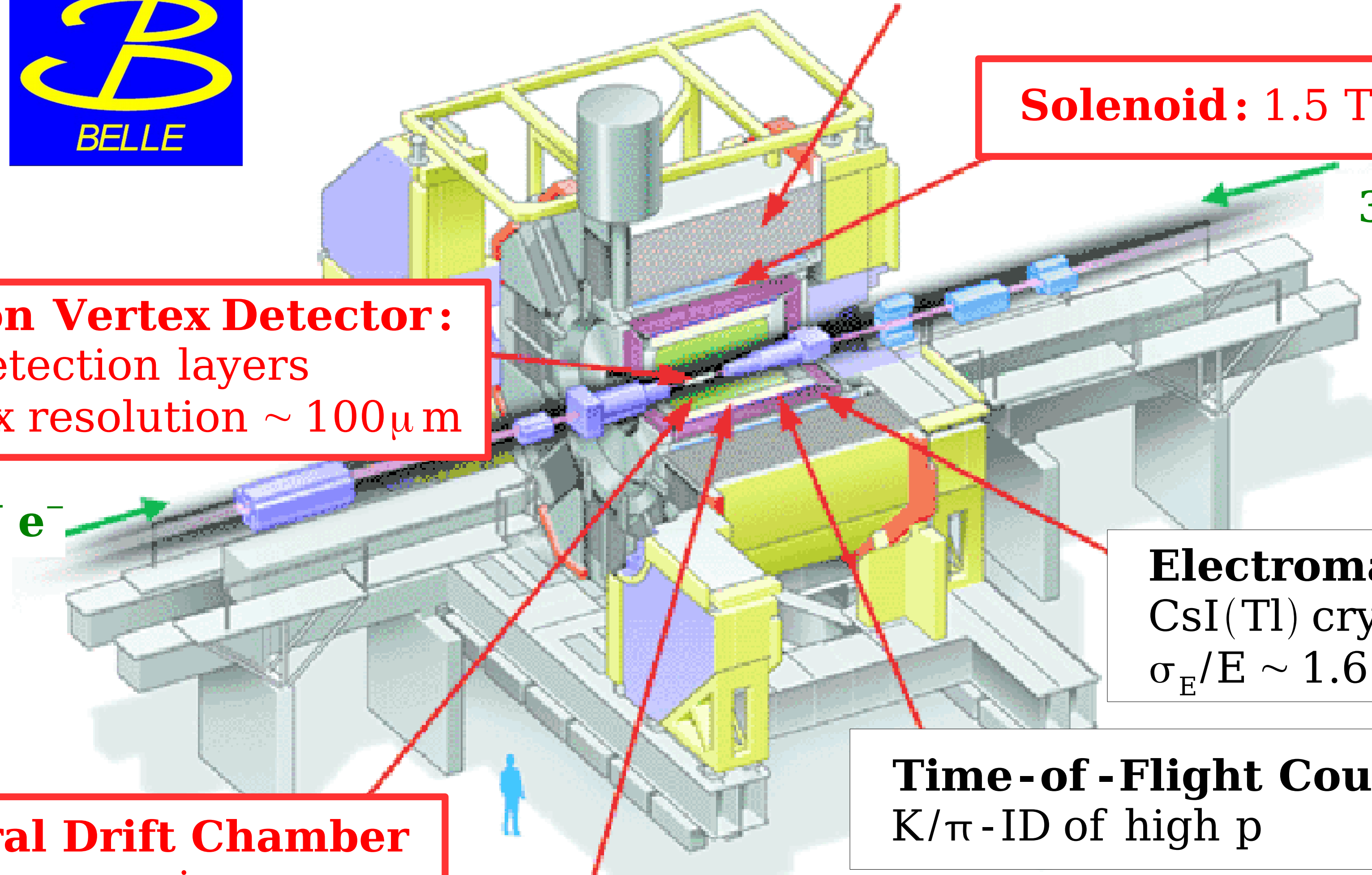
Belle in a nutshell

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 ~ 100μm



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

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

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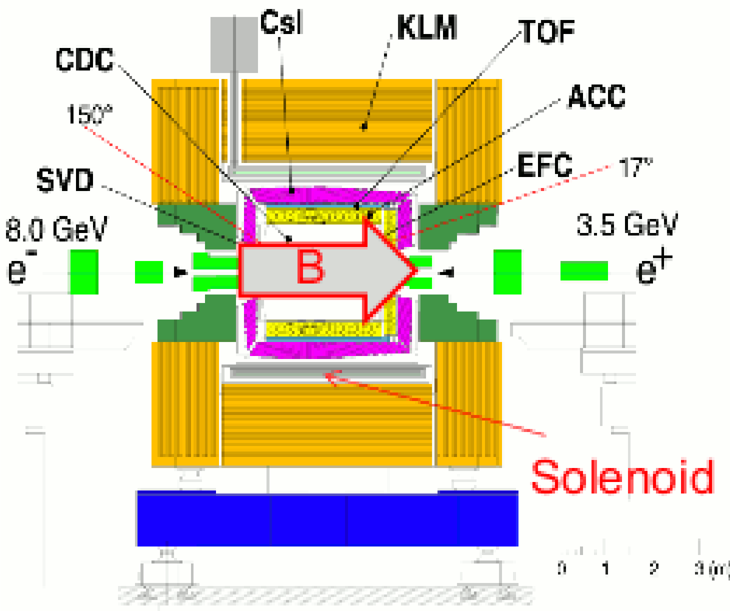
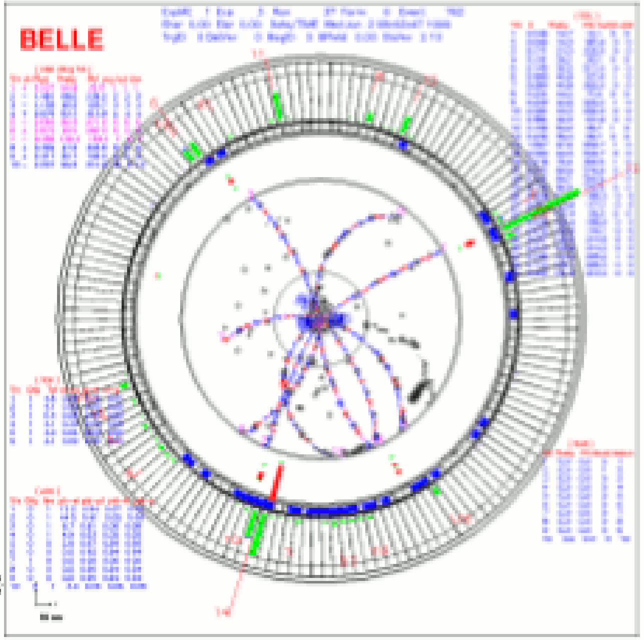
How to detect particles in Belle

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].



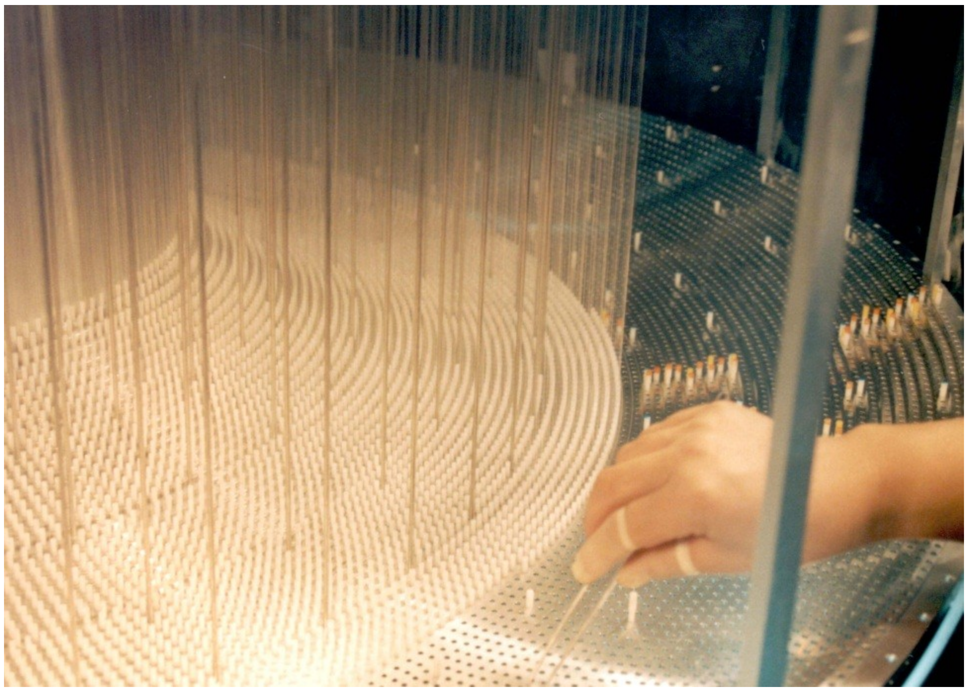


More exactly, only transverse momentum (p_T) can be obtained. But, we also know the direction of the particle. Hence the momentum vector can be calculated.

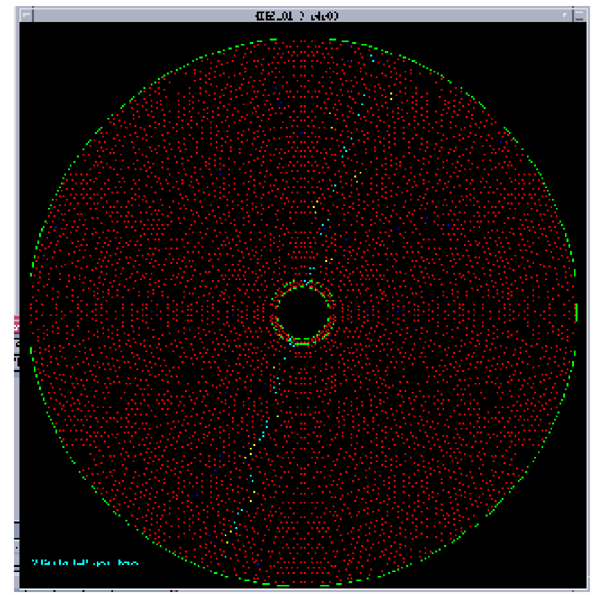
How to detect particles in Belle

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

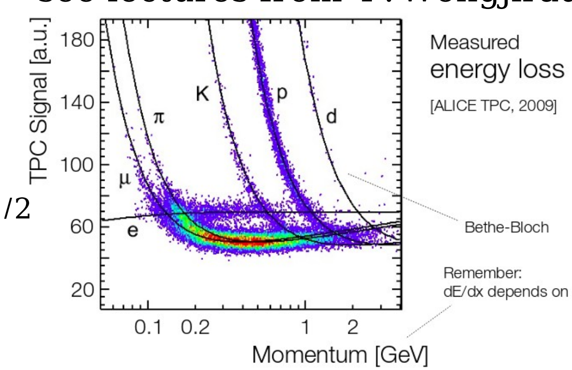
$\sigma_{r-\phi} = 130 \mu m$

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

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

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

see lectures from T.Wongjirad

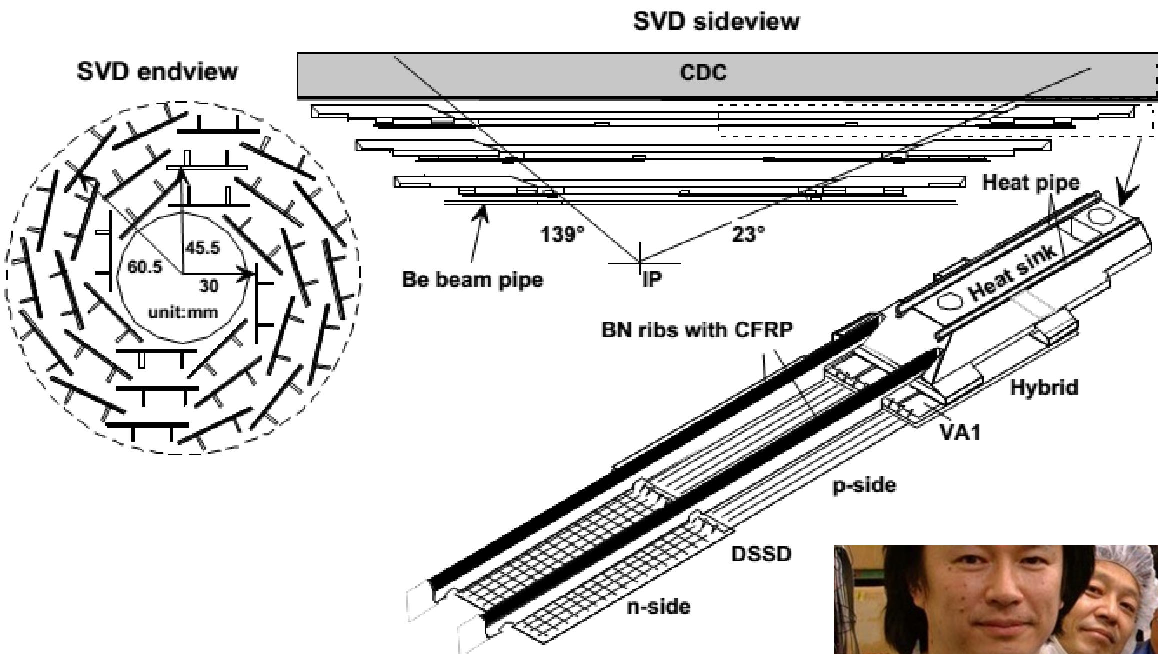


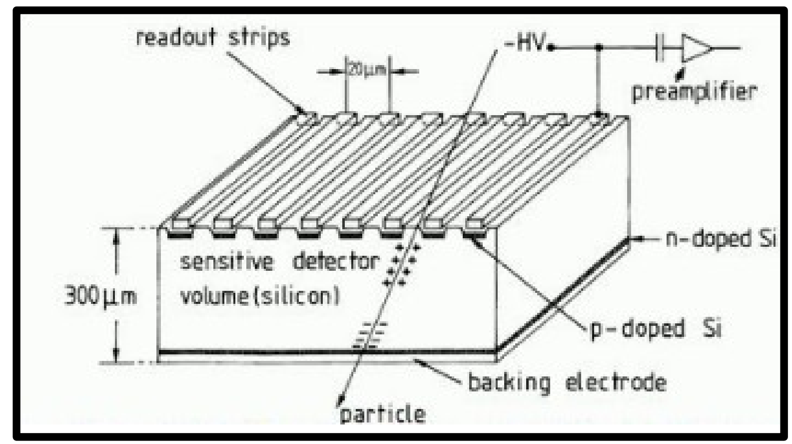
How to detect particles in Belle

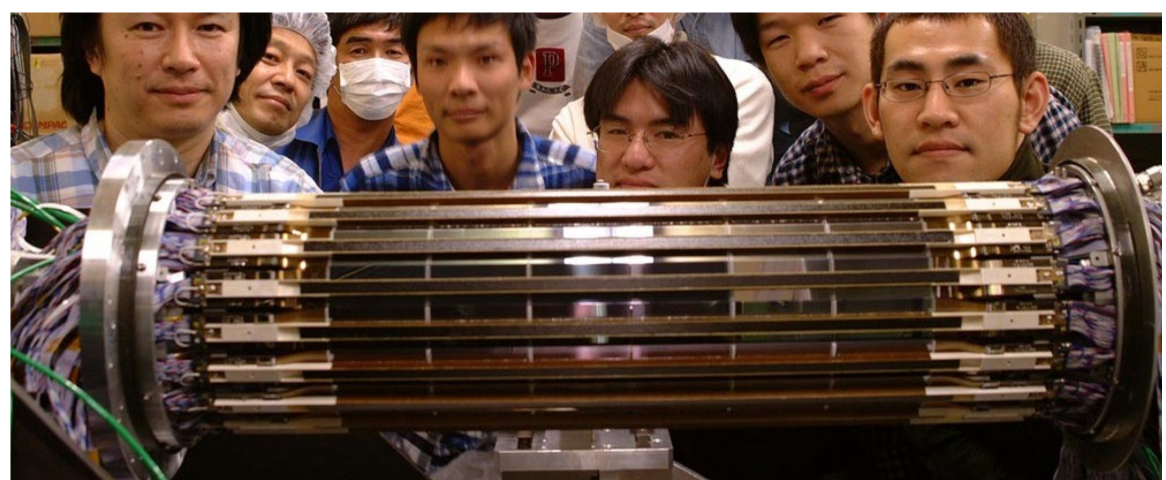
Silicon Vertex Detector

$300\mu m$ thick, 3−4 layer
radius = 2.0-8 cm
Length = 22−40 cm

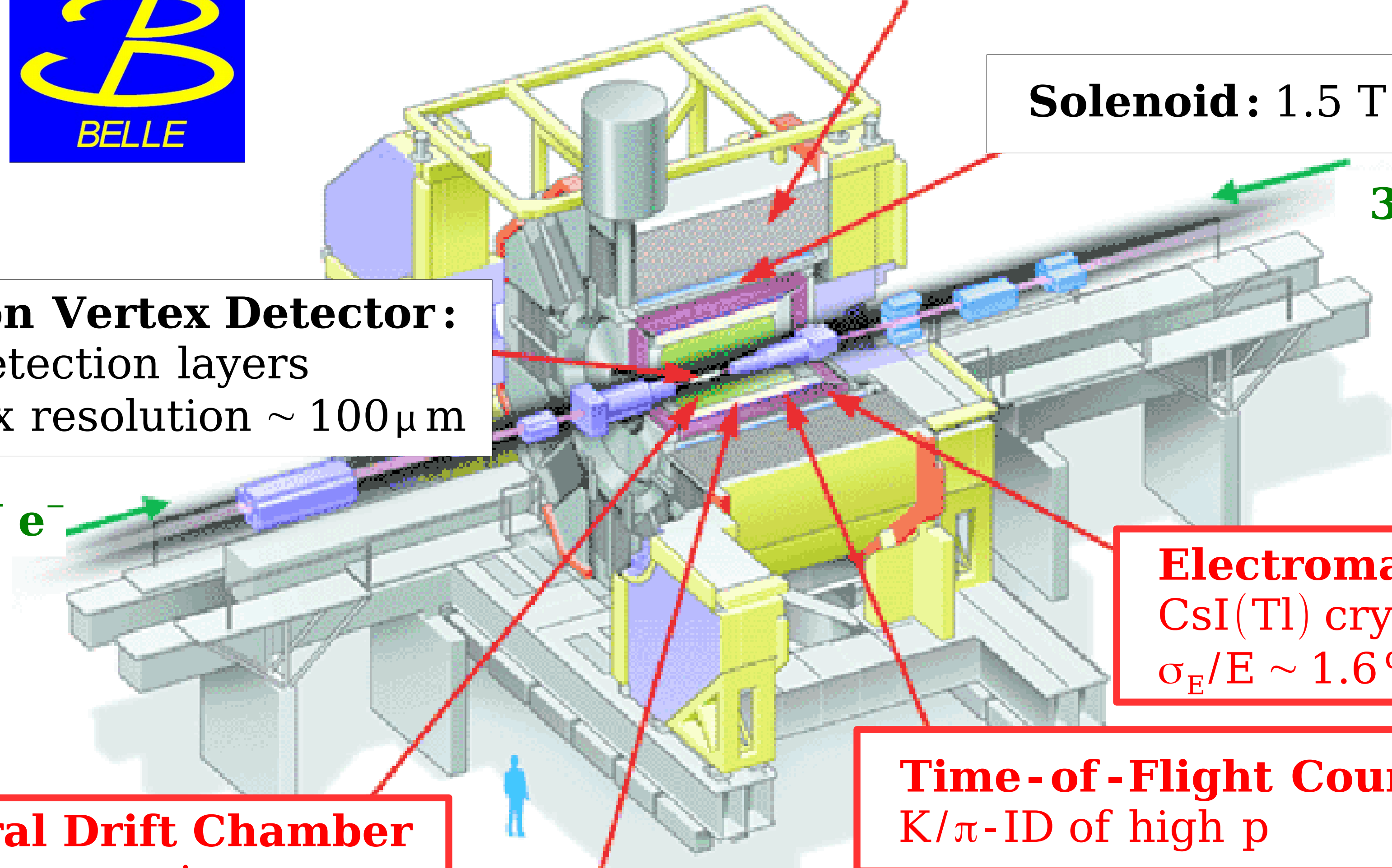
readout: $\phi \sim 40k$, $\theta \sim 40k$
resolution: $\sigma_z \sim 30\mu m$







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

Comparision different PID methods for K/π separation

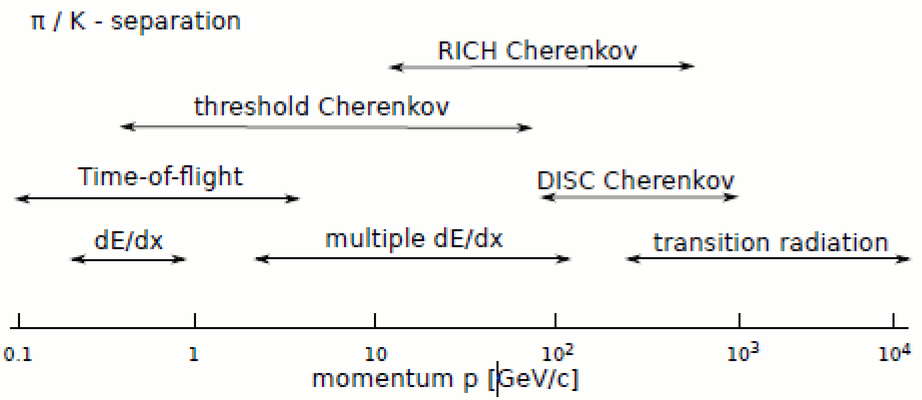
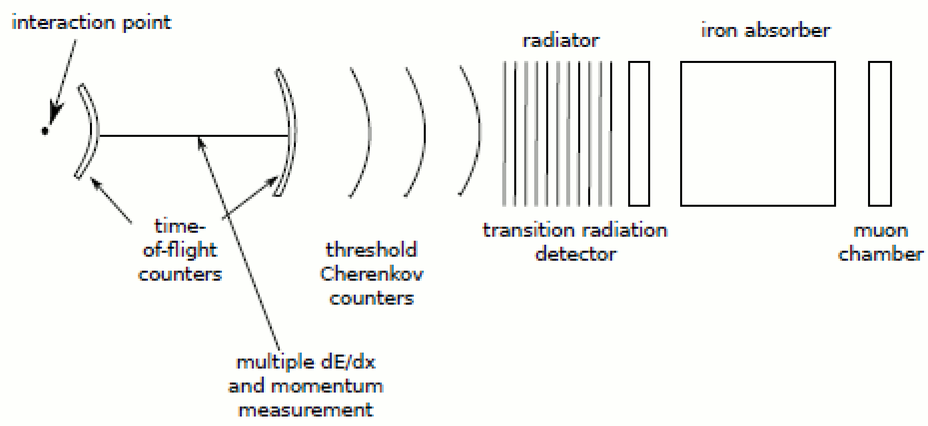


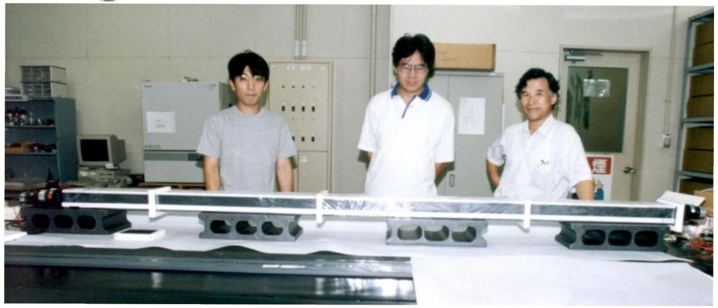
illustration of various particle identification methods for K/π separation along with characteristic momentum ranges.



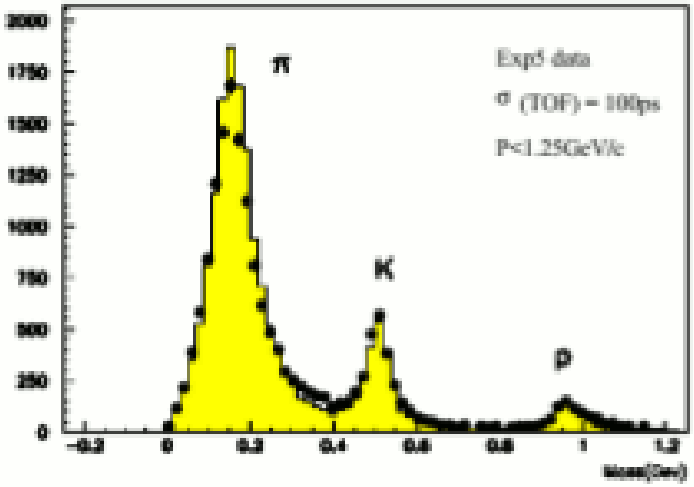
a detector system for PID combines usually several methods

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, $\overline{p}$).
  - ✓ Other charged particles decay before reaching to the detector.
- Next step : Particle identification.



Example: TOF (time of flight)

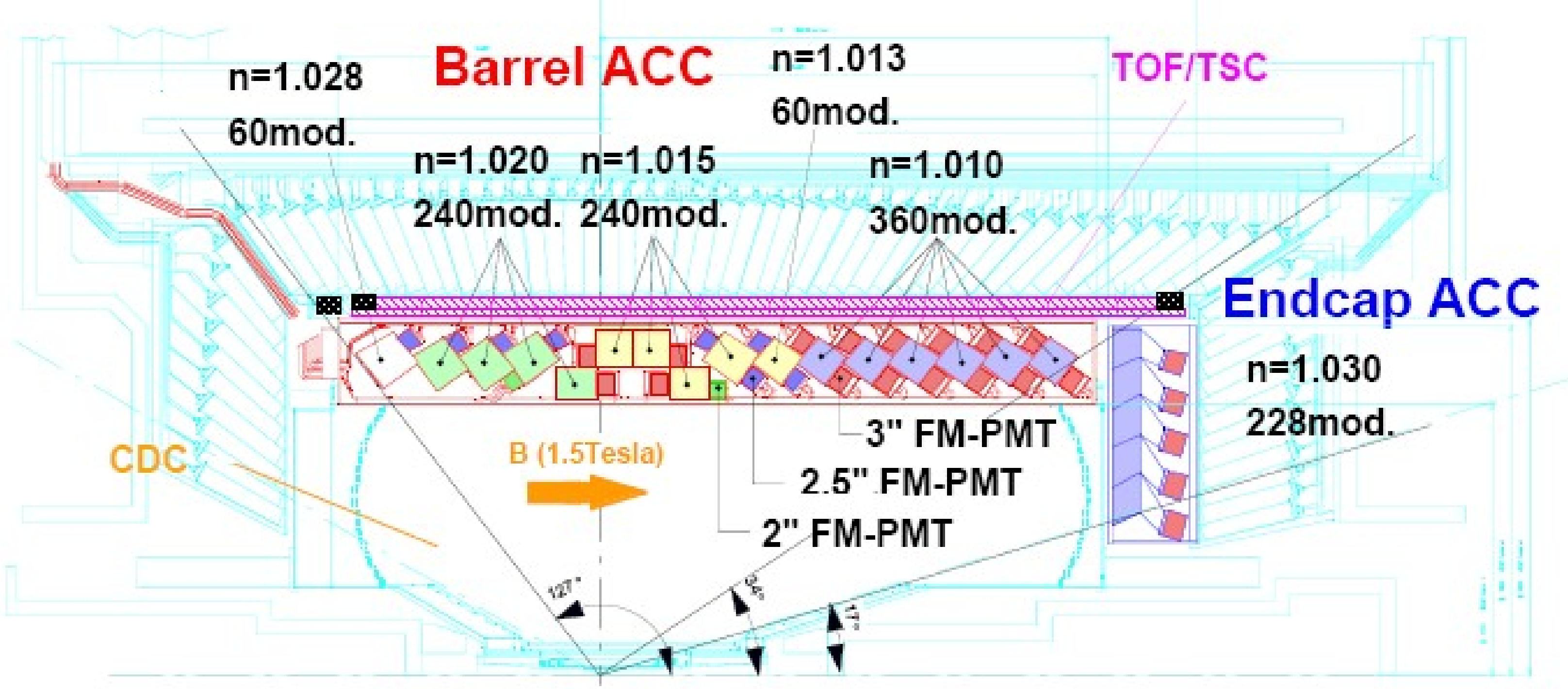


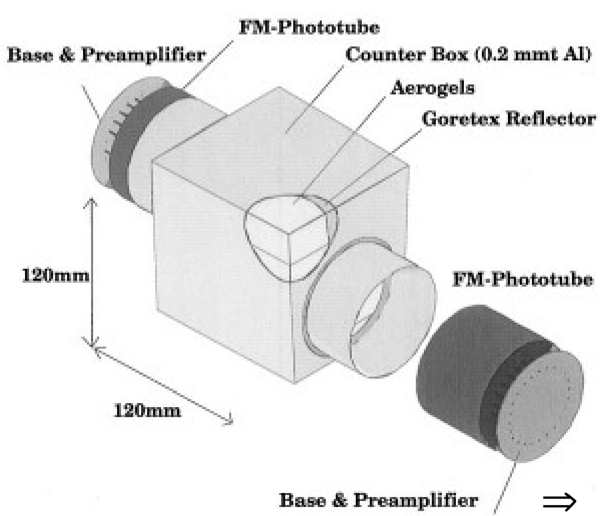
- Measure the flight time from the interaction point to the detector.
  - ✓ From the flight time, one can calculate the velocity of the particle.
  - ✓ The mass of the particle can be obtained from the velocity and momentum ($p = mv\gamma$).

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

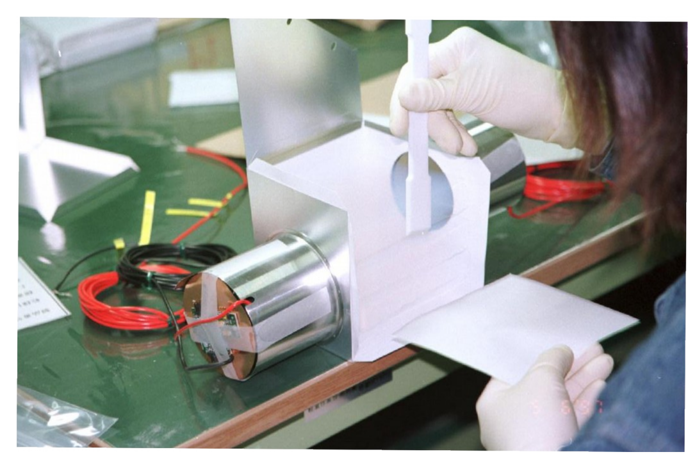
ACC = Aerogel Cherenkov Counter





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



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

How to detect particles

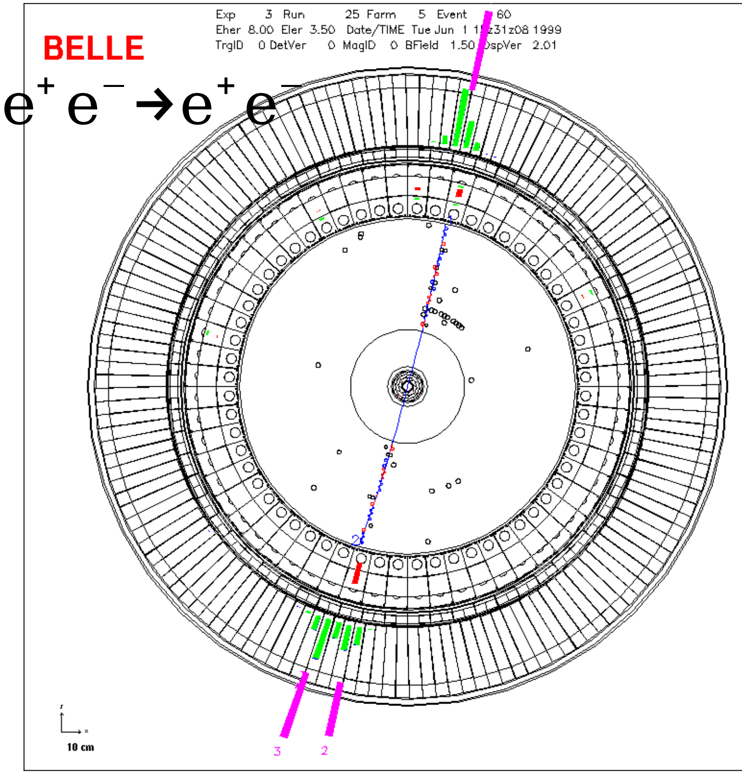
Now, we know the momenta of charged particles, and their masses (form the particle species) ⇒ 4-momentum is known

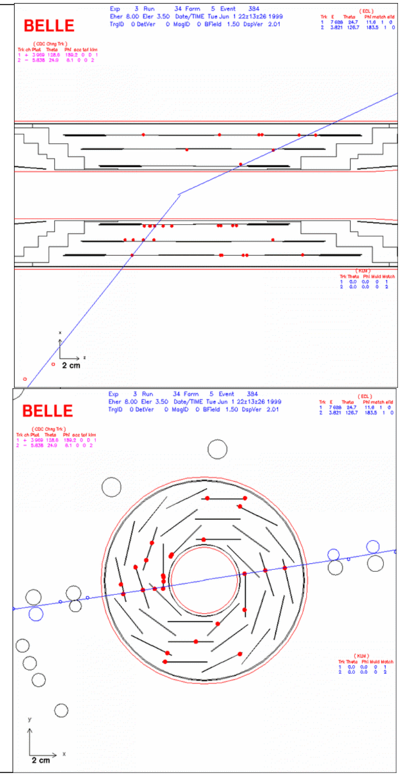
How about neutral particles?

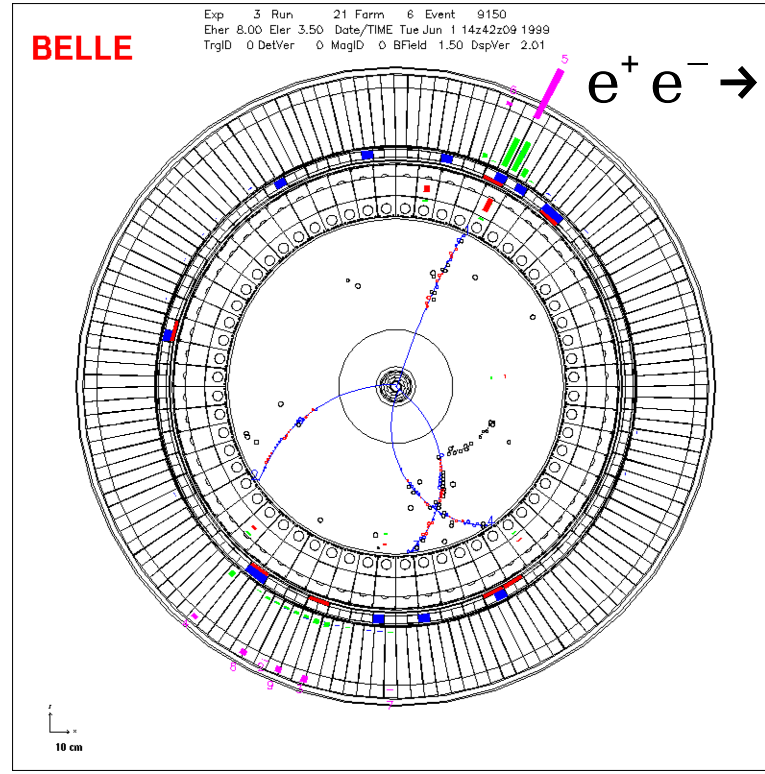
- π^0 decays ($\pi^0 \to \gamma\gamma$). $K_S{}^0$ also decays ($K_S{}^0 \to \pi^+\pi^-$, $\pi^0\pi^0$ with $c\tau$ = 2.7cm).
- The most important neutral particle is the photon (γ).
  - ✓ Not detected inside the tracking device (CDC etc.).
  - ✓ But, photons lose all the energy in the calorimeter (i.e.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

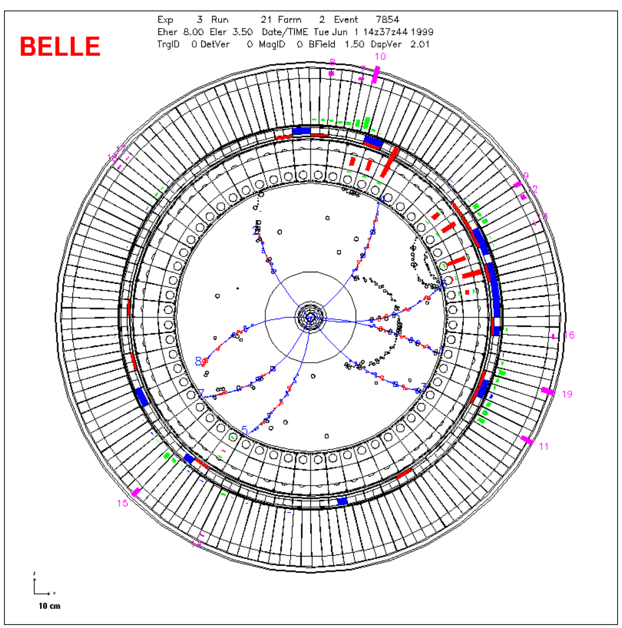
Long-lived neutral particles (neutrons, $K_L{}^0$ …) are not easy to measure (hadronic interaction). Neutrino is impossible to detect.

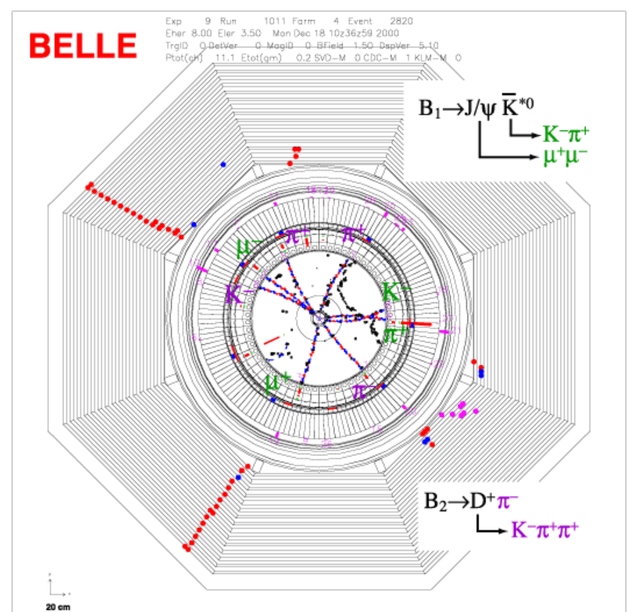
How to detect particles in Belle

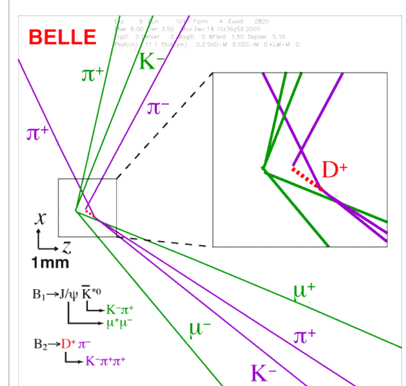


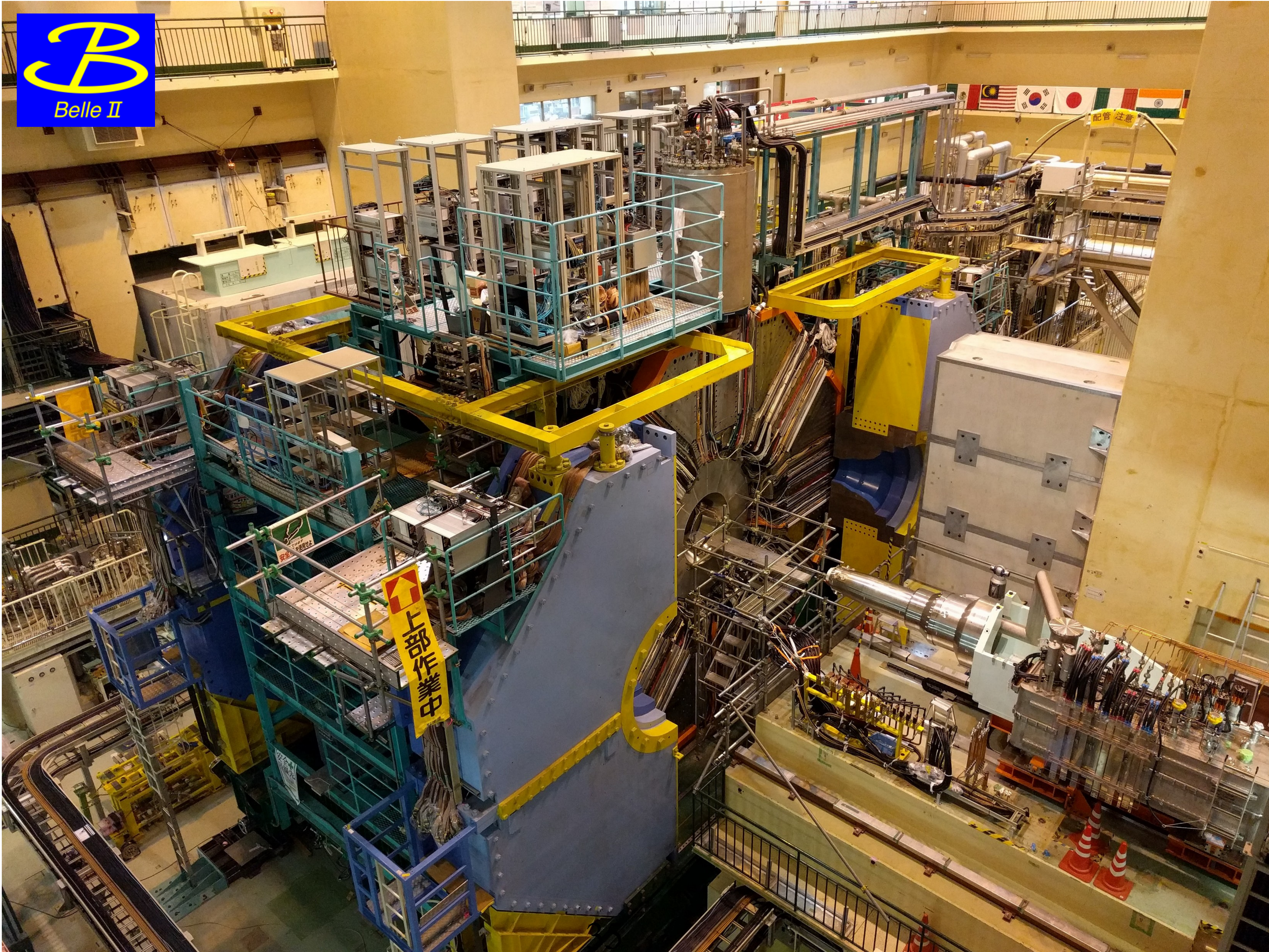






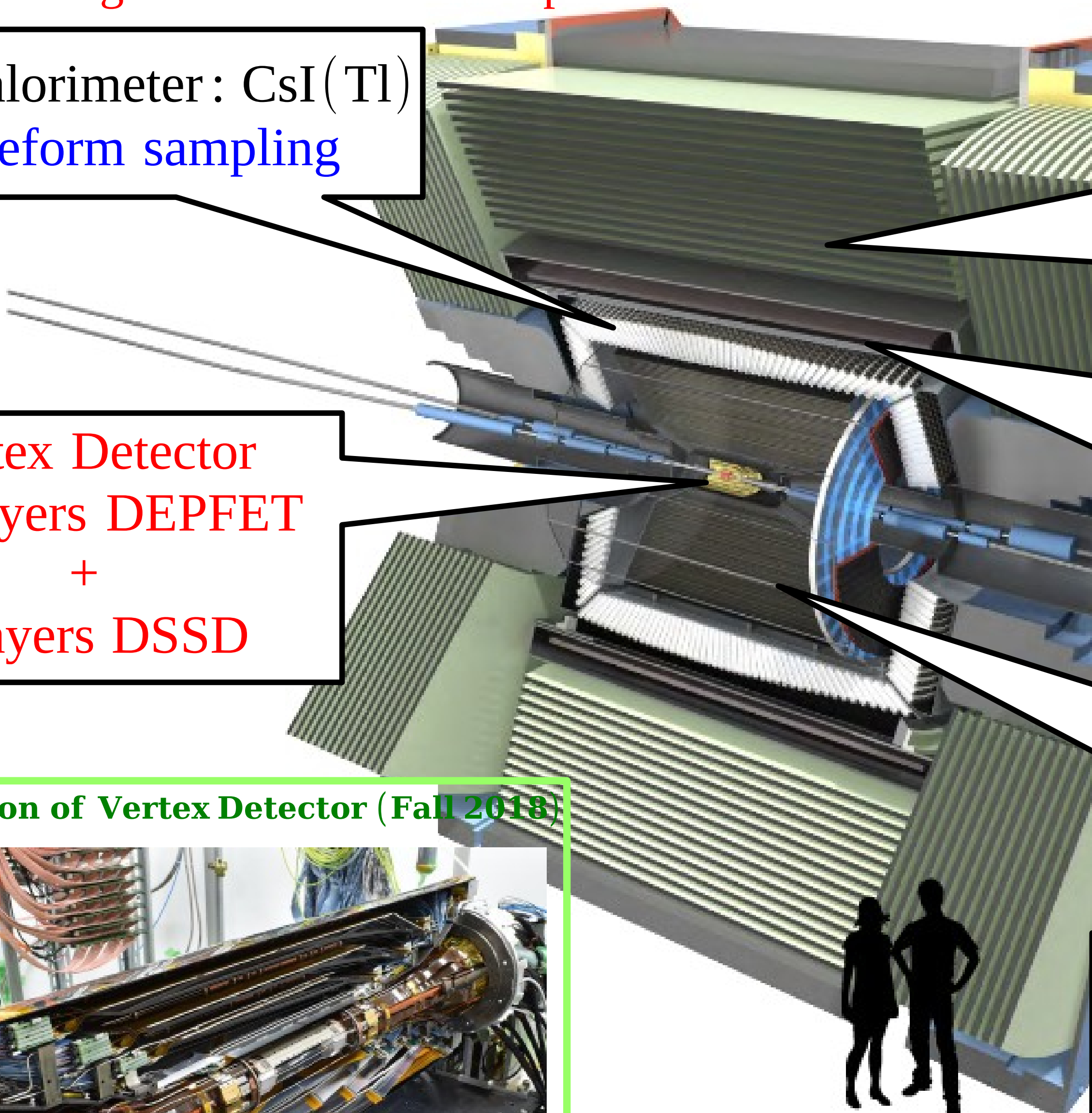





Belle II
上部作業中
配管 注意

Belle II detector

Main challenge: Preserve detector performances while luminosity (so beam background) increases



EM Calorimeter: CsI(Tl)
waveform sampling

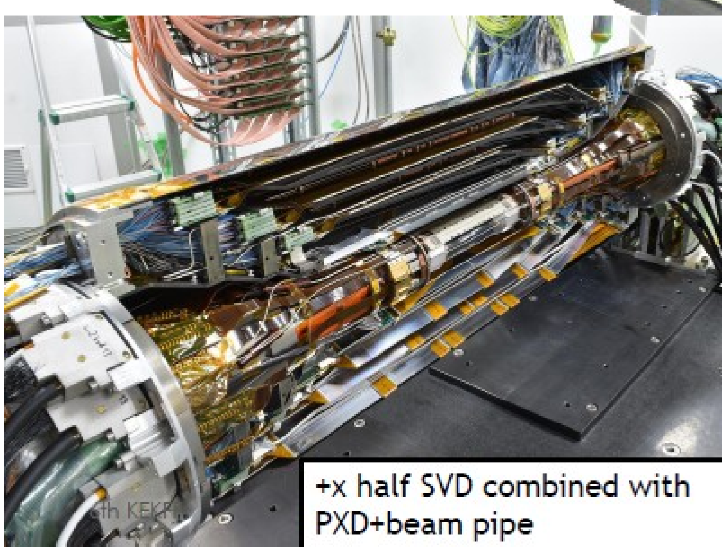
K_L and muon detector
Resistive Plate Counter (barrel)
Scintillator + WLSF + MPPC (endcaps)

Particle Identification
Time-Of-Propagation counter (barrel)
Prox. focusing Aerogel RICH

Vertex Detector
1/2 layers DEPFET
+
4 layers DSSD

Central Drift Chamber
He(50%):C_2H_6(50%)
small cells, long level arm, fast electronics

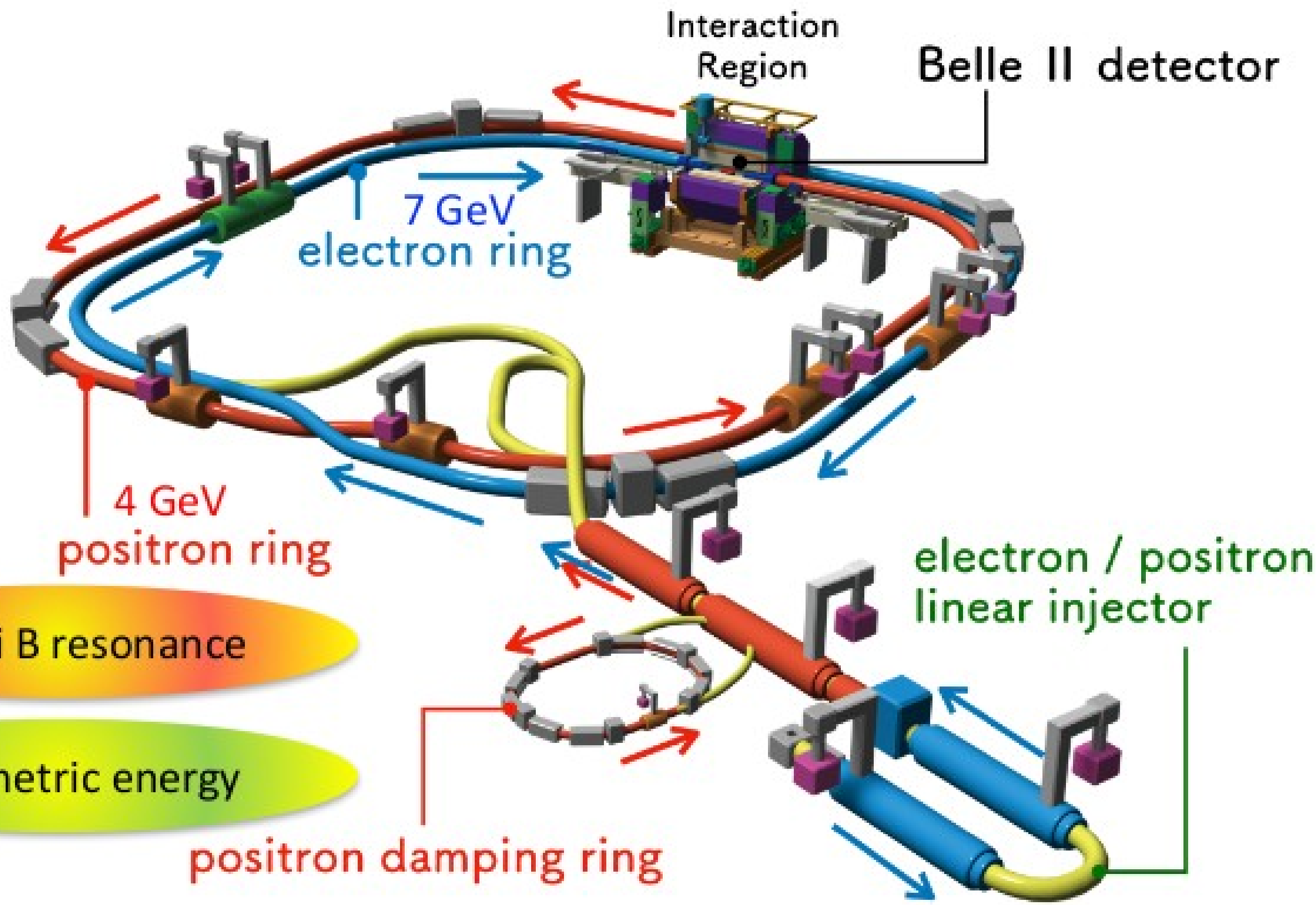
Installation of Vertex Detector (Fall 2018)



on-going DAQ upgrade
(to be installed in 2020-2021)
PCIe40 board, capable of reading via high speed optical links and to write to computer at rate of 100 Gb/s:
limited number of boards (20) enough **to read entire Belle II detector**

considering now VTX upgrade (2025 or later)

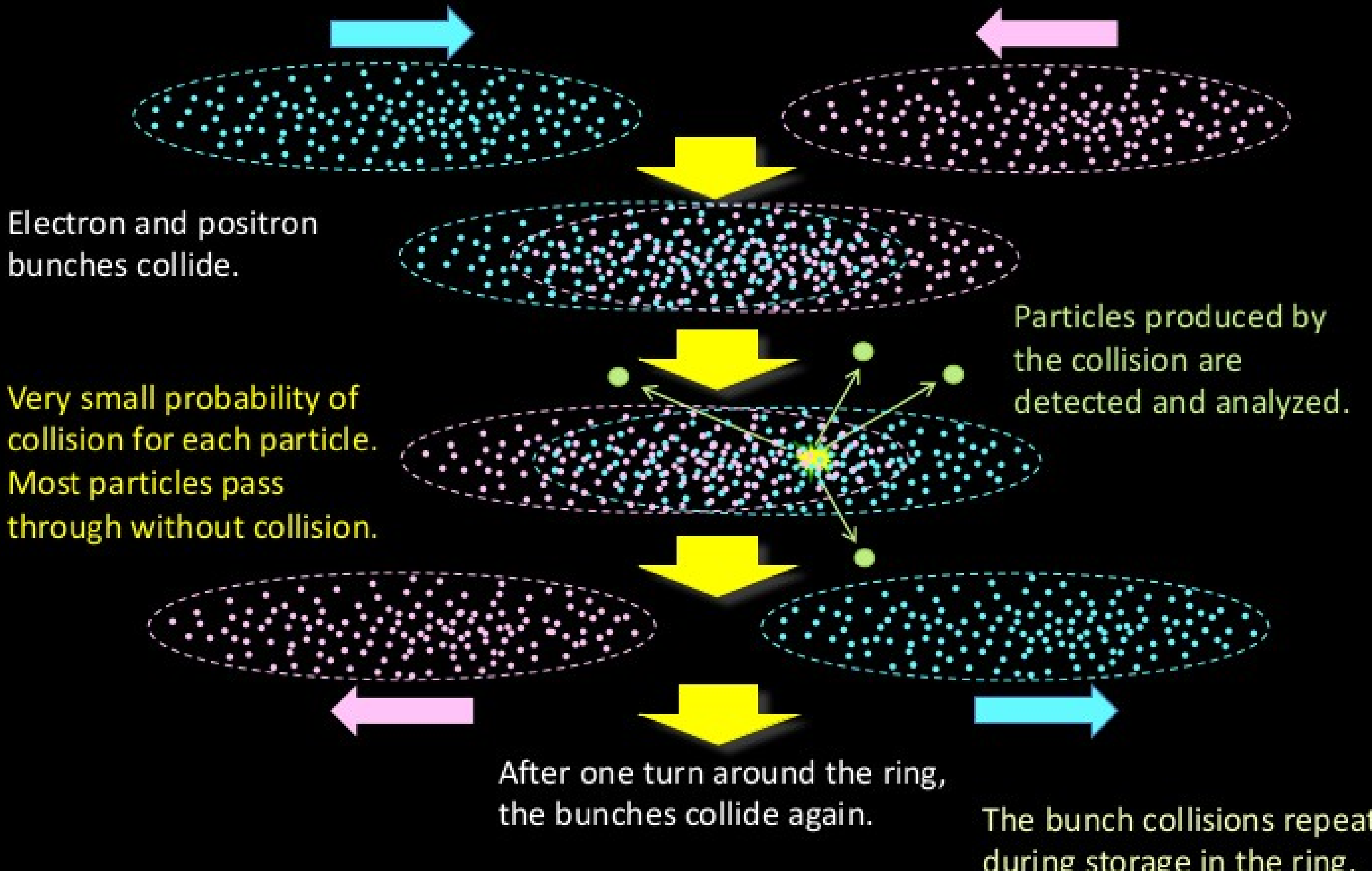
SuperKEKB accelerator complex



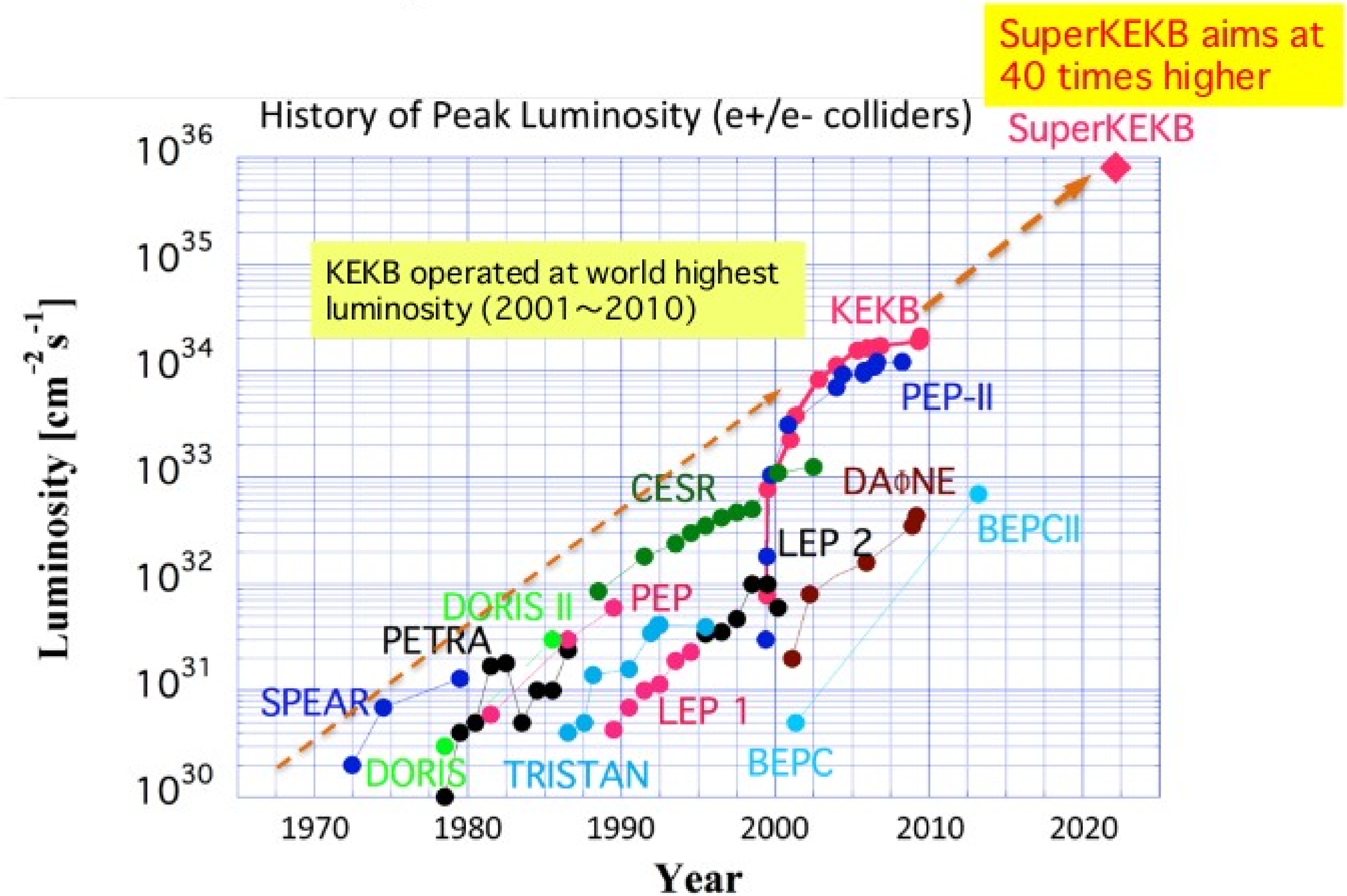
B - anti B resonance

asymmetric energy

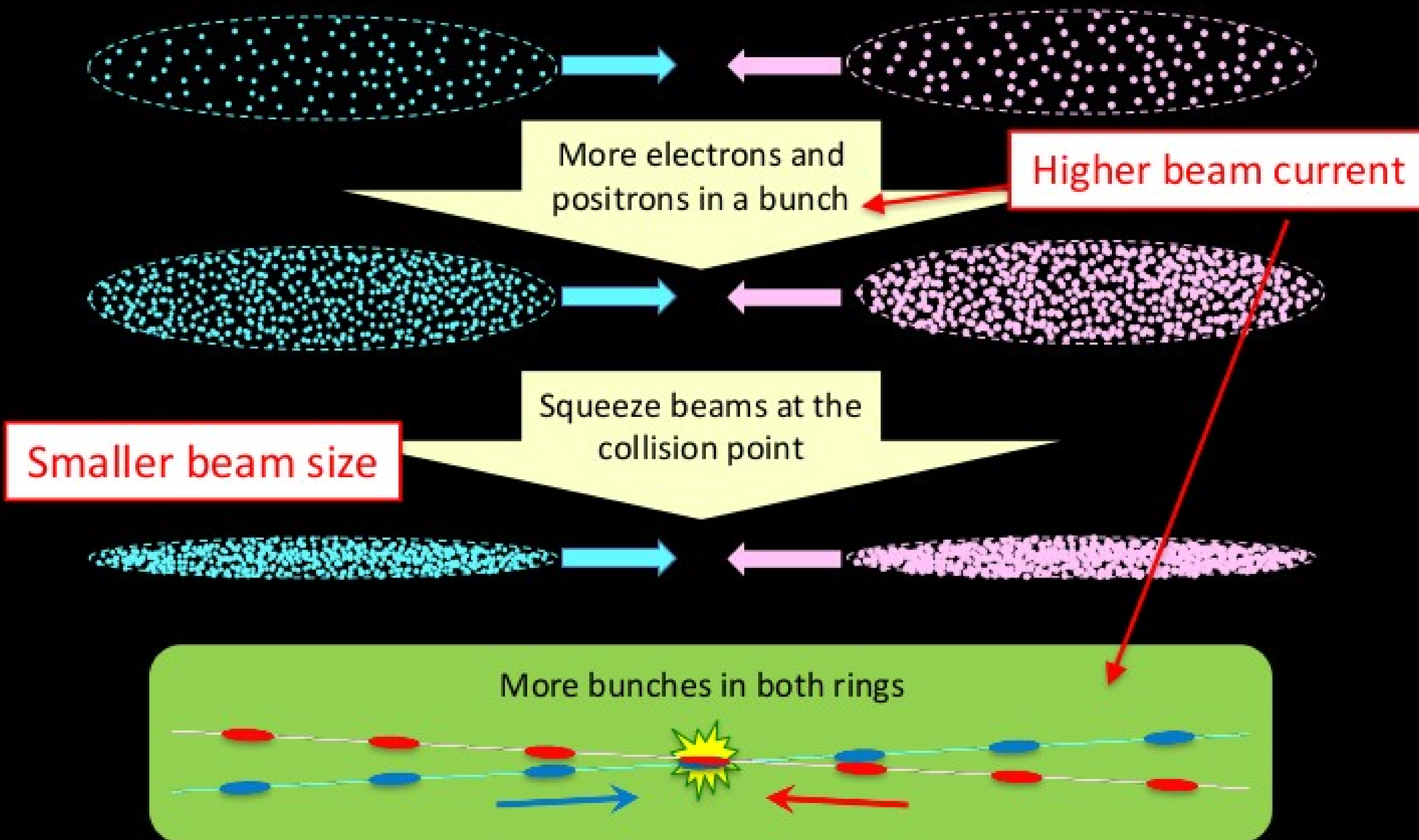
Beam collision



Luminosity frontier of e^+e^- colliders



Higher and higher luminosity



SuperKEKB, the first new collider in particle physics since the LHC in 2008 (electron-positron $(e^+ e^-)$ rather than proton-proton (p-p))

Phase 1

Background , Optics commissioning

Feb - June **2016**

Brand new 3 km positron ring

Phase 2: Pilot run

Superconducting Final Focus

add positron damping ring

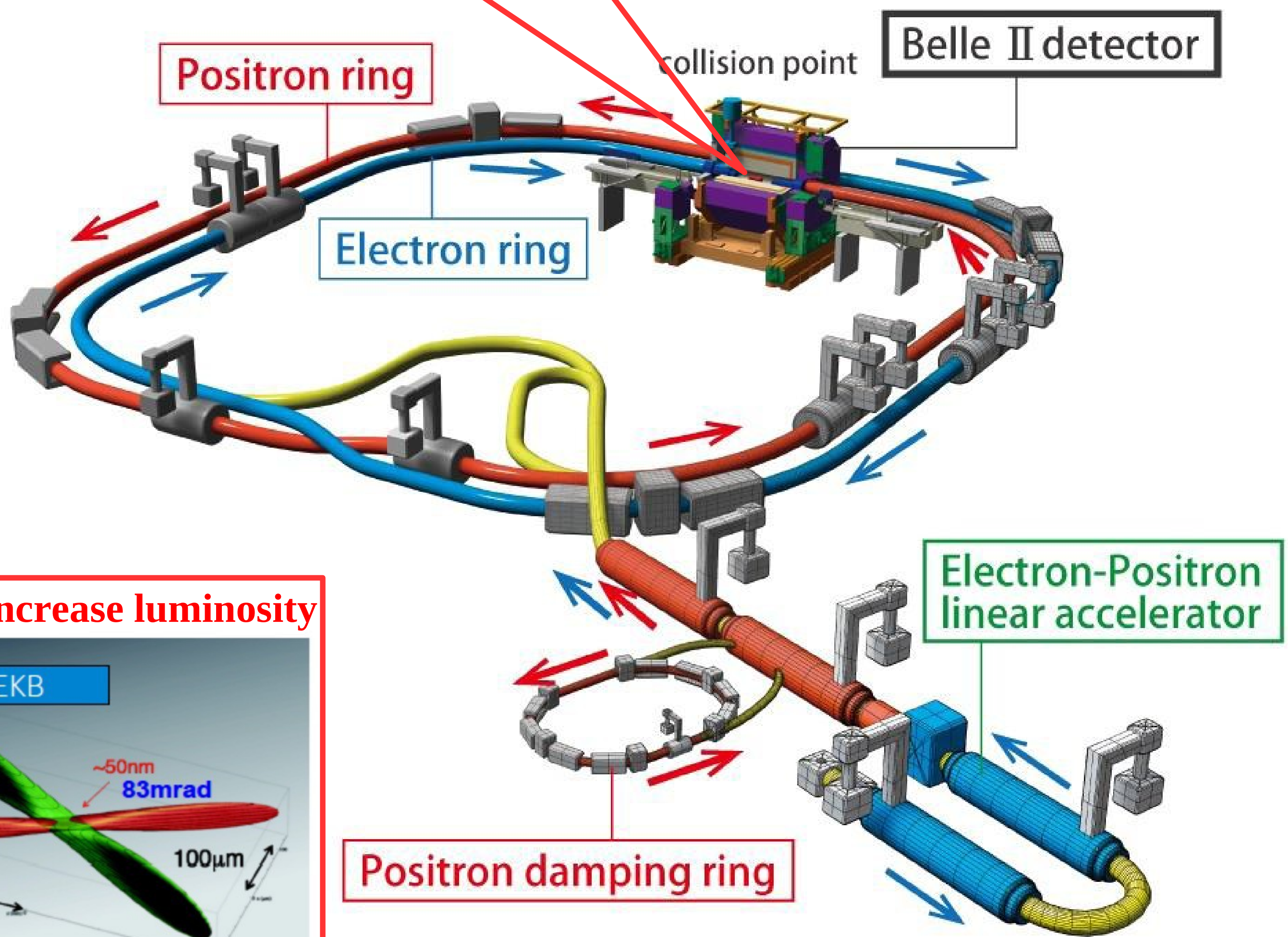
First Collisions $(0.5\ fb^{-1})$

April 27 - July 17, **2018**

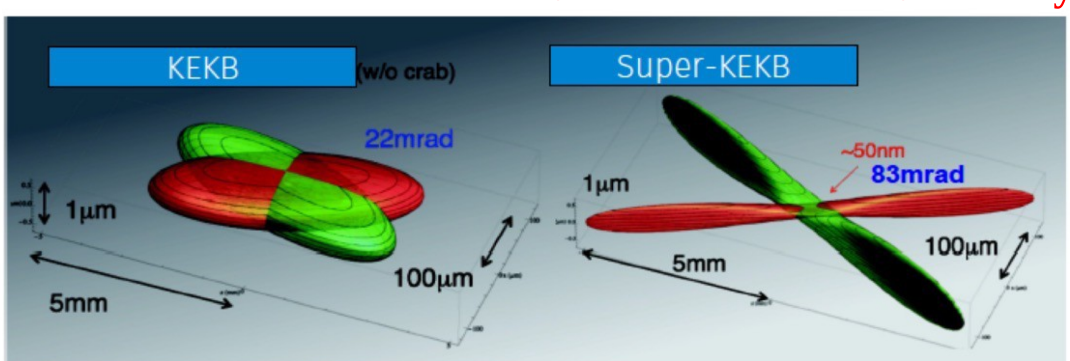
Phase 3: Physics run

Since April , **2019**

Squeeze strongly at IP



Nano-beams and more beam current to increase luminosity



	E (GeV) LER/HER	β*y (mm) LER/HER	β*x (cm) LER/HER	φ (mrad)	I (A) LER/HER	L (cm⁻²s⁻¹)
KEKB	3.5/8.0	5.9/5.9	120/120	11	1.6/1.2	2.1 x 10³⁴
SuperKEKB	4.0/7.0	0.27/0.30	3.2/2.5	41.5	3.6/2.6	80 x 10³⁴

factor 20 factor 2-3

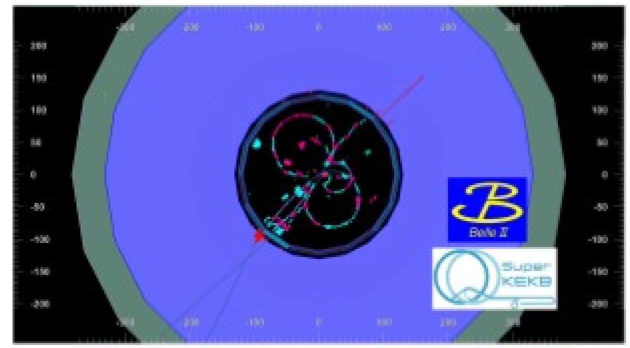
⇒ to reach $\sim 6 \times 10^{35}\ cm^{-2} s^{-1}$

⇒ cumulate 50 ab^{-1} by ~2030

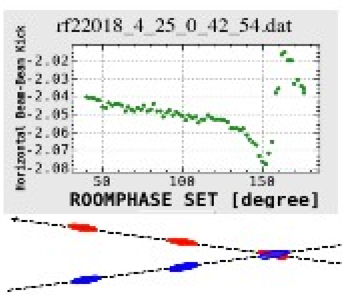
First collision

Apr. 26, 2018

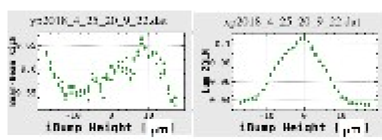
Belle II control room



First hadronic event observed by Belle II



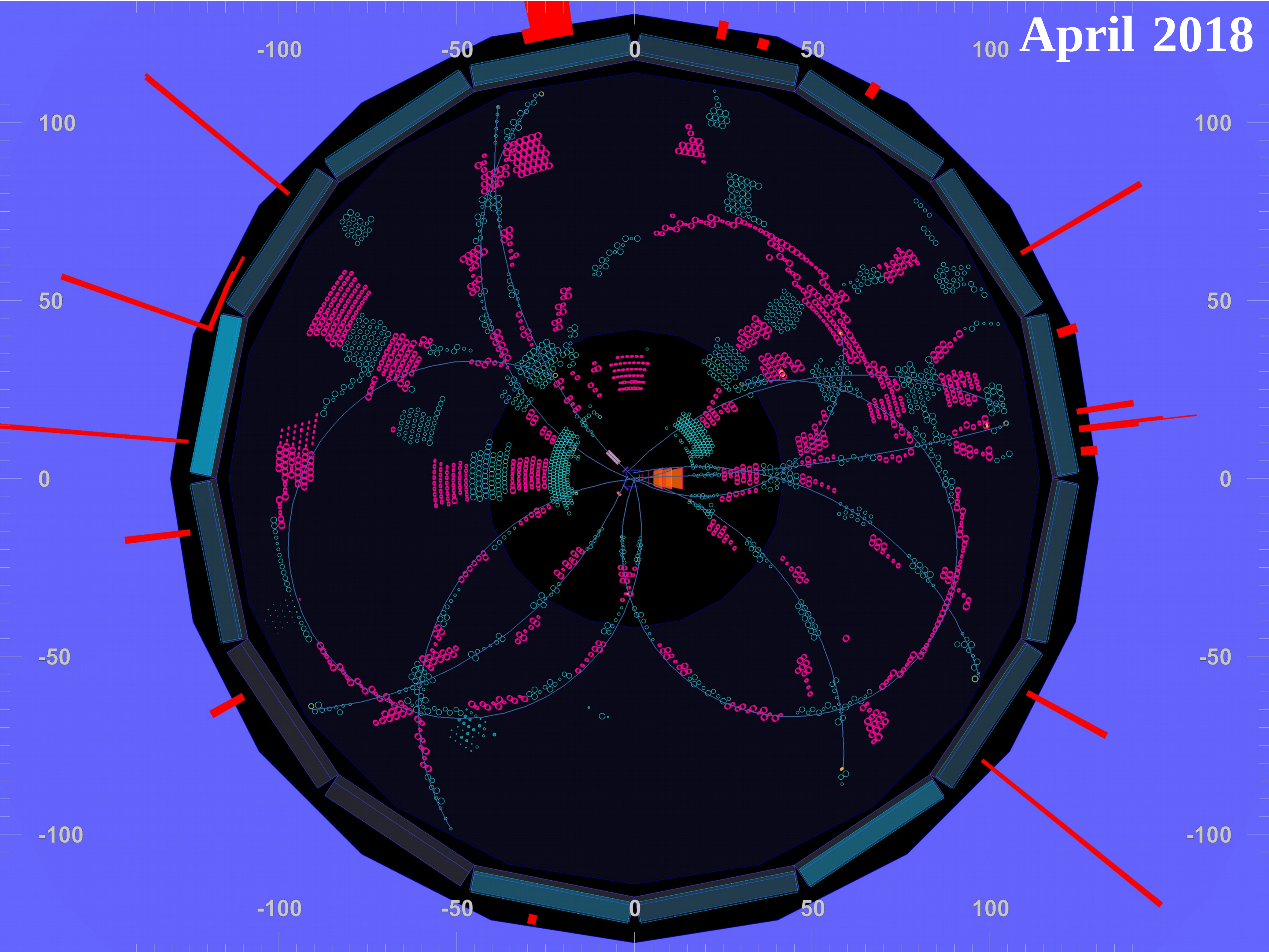
Horizontal beam-beam kick

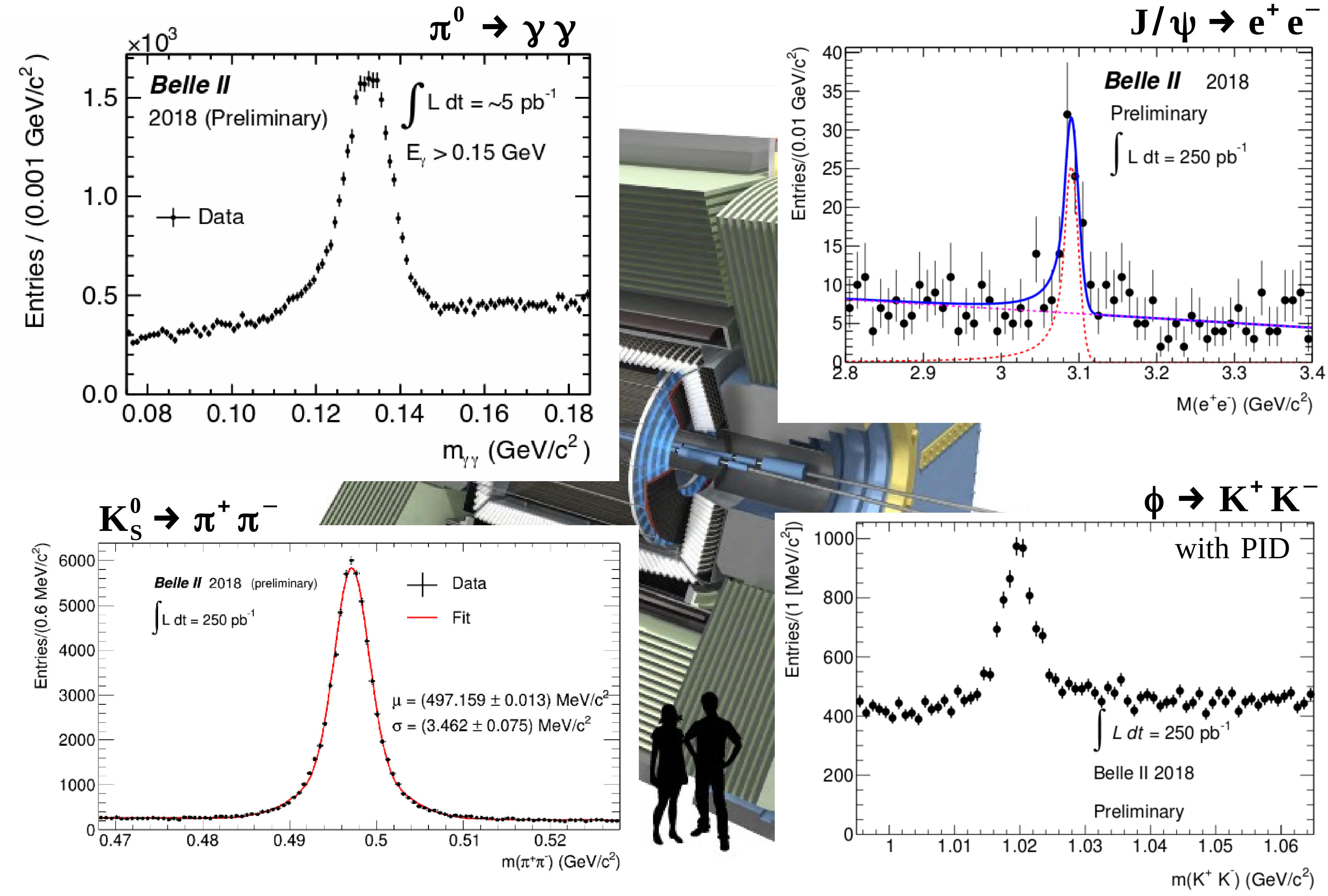


Vertical beam-beam kick

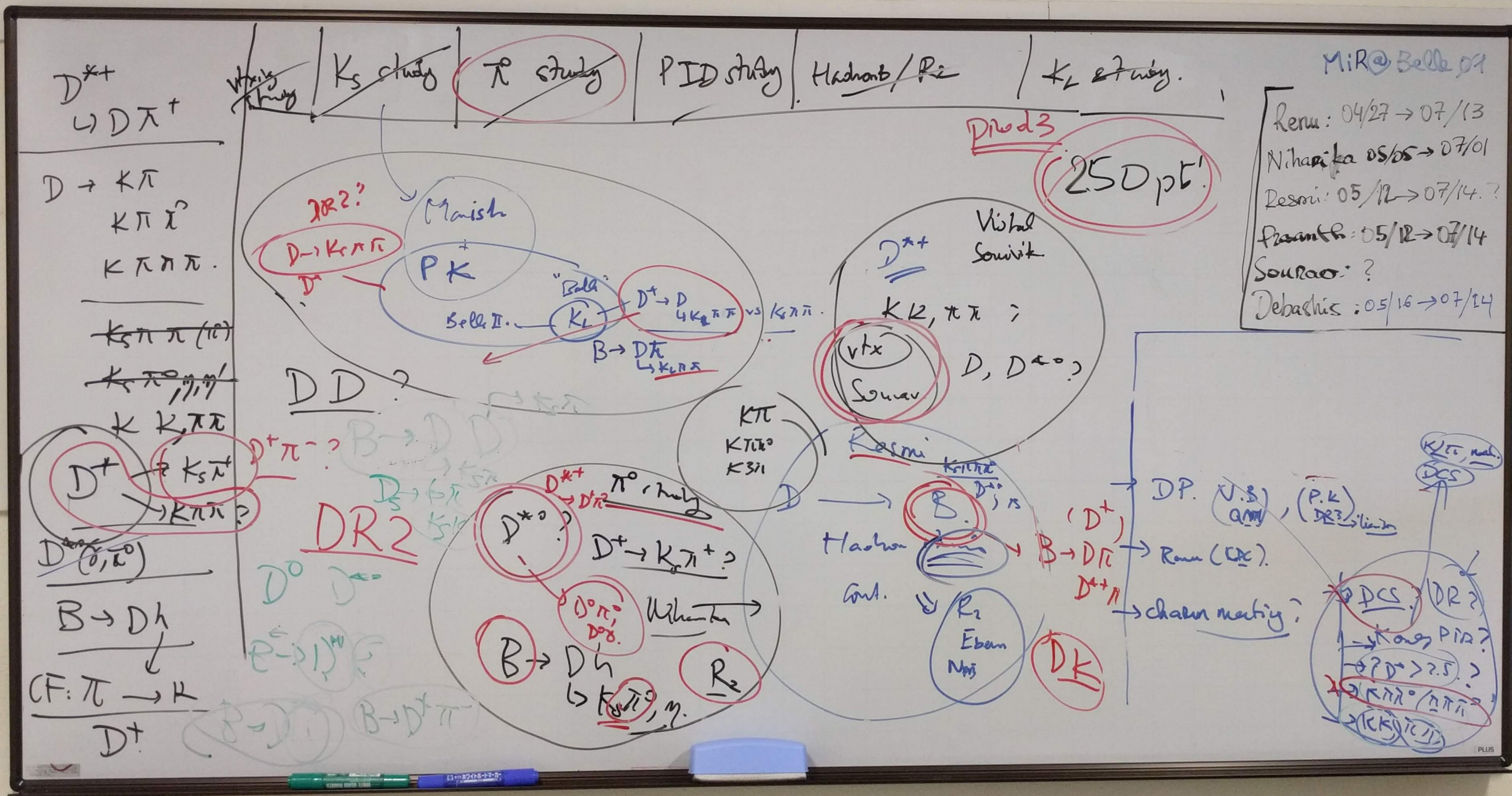
SuperKEKB control room

April 2018



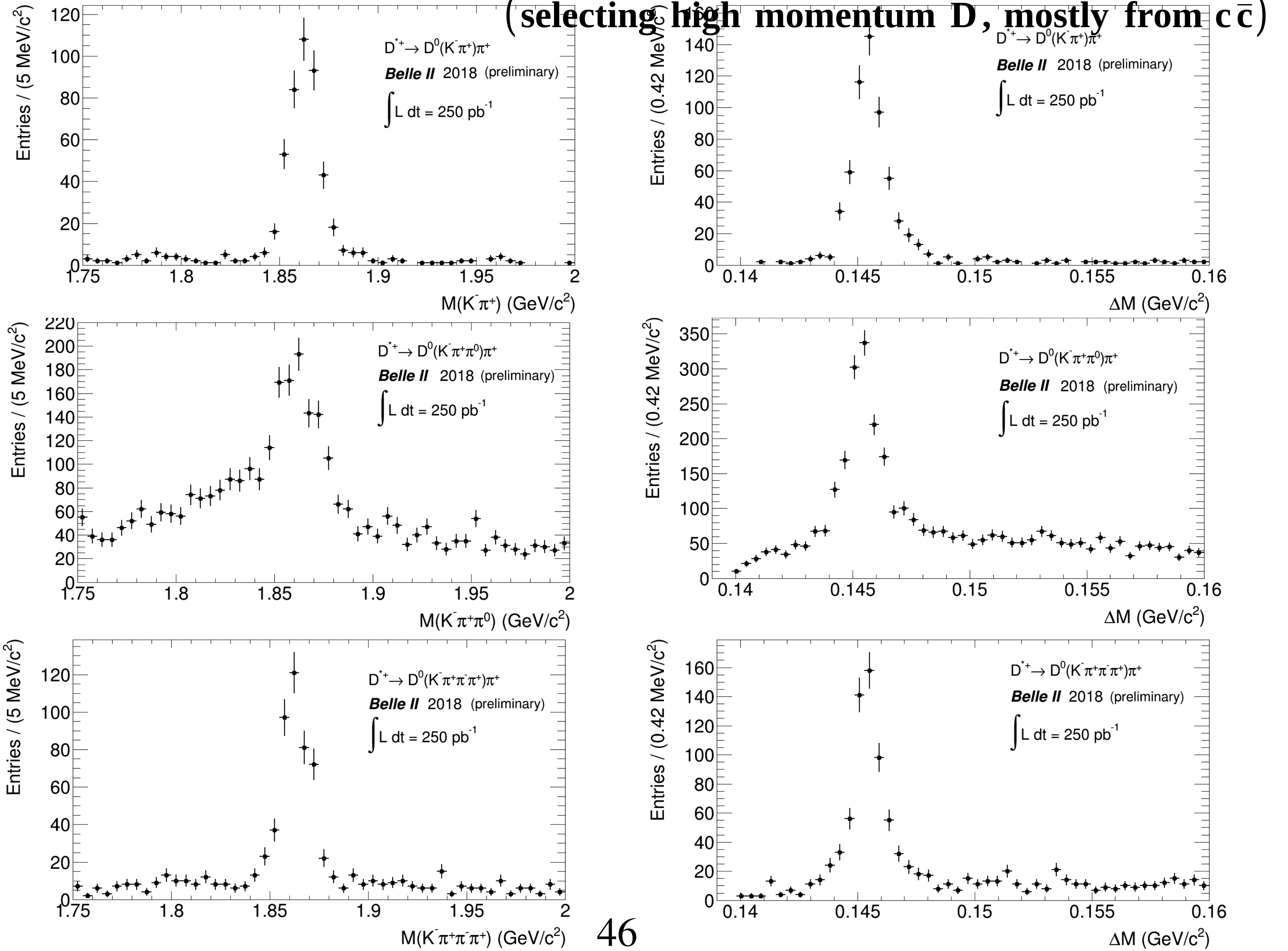

π0 → γ γ
×10^3
Entries / (0.001 GeV/c^2)
Belle II
2018 (Preliminary)
∫L dt = ~5 pb^-1
Eγ > 0.15 GeV
Data
m_γγ (GeV/c^2)
J/ψ → e+ e−
Entries/(0.01 GeV/c^2)
Belle II 2018
Preliminary
∫L dt = 250 pb^-1
M(e+e-) (GeV/c^2)
K0S → π+ π−
Entries/(0.6 MeV/c^2)
Belle II 2018 (preliminary)
∫L dt = 250 pb^-1
Data
Fit
μ = (497.159 ± 0.013) MeV/c^2
σ = (3.462 ± 0.075) MeV/c^2
m(π+π-) (GeV/c^2)
φ → K+ K−
with PID
Entries/(1 [MeV/c^2])
∫L dt = 250 pb^-1
Belle II 2018
Preliminary
m(K+ K-) (GeV/c^2)

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

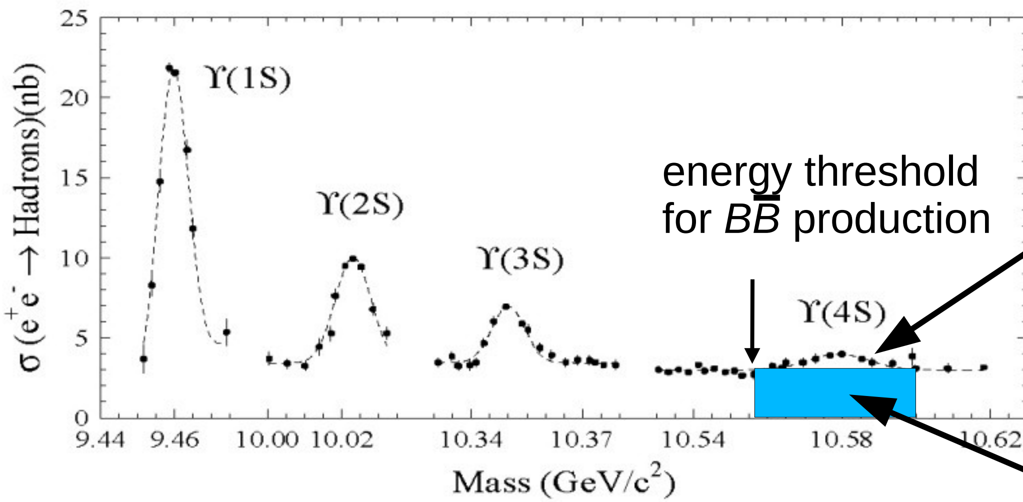


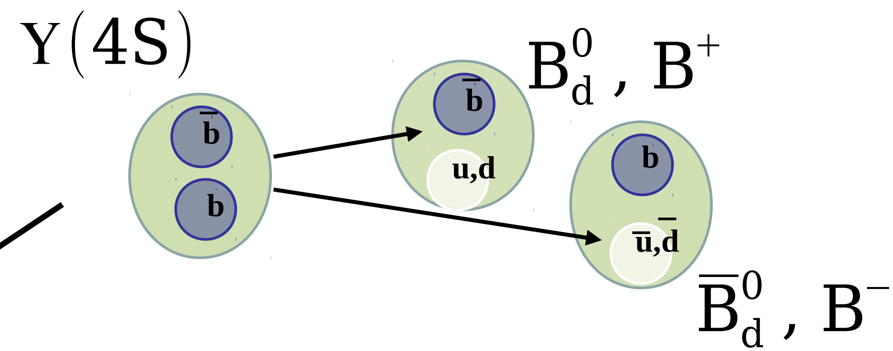
Rediscovering charm: $D^{*+} \rightarrow D\pi^+$, $D \rightarrow K^-\pi^+$, $K^-\pi^+\pi^0$, $K^-\pi^+\pi^-\pi^+$

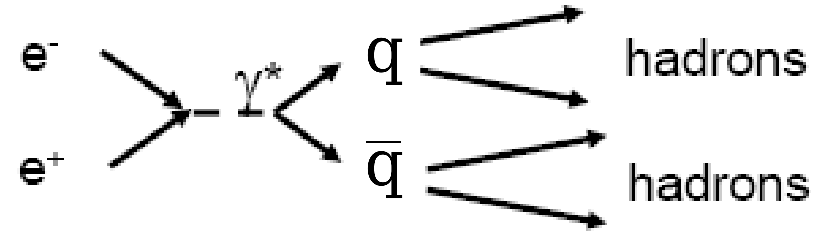
(selecting high momentum D, mostly from $c\bar{c}$)



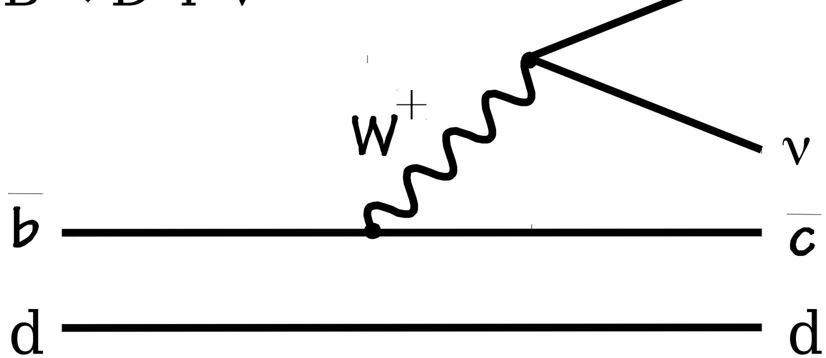
At a B-factory …

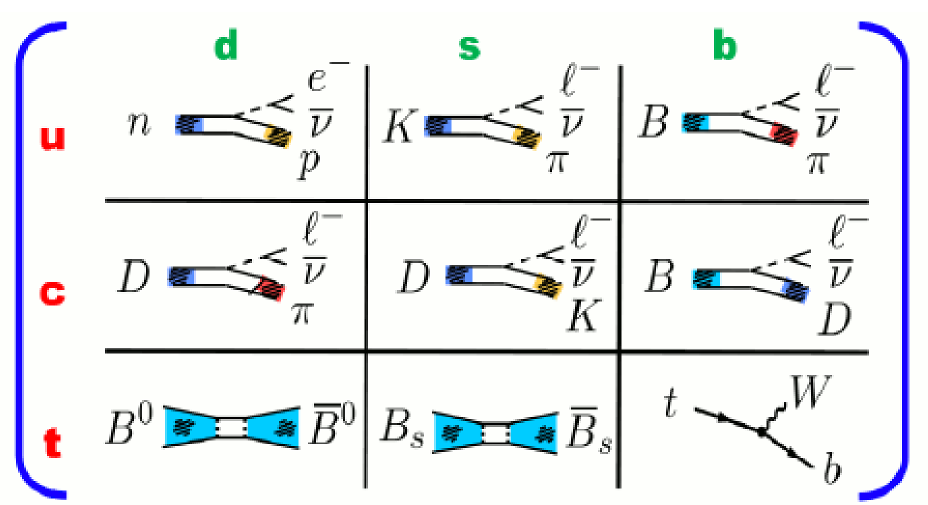




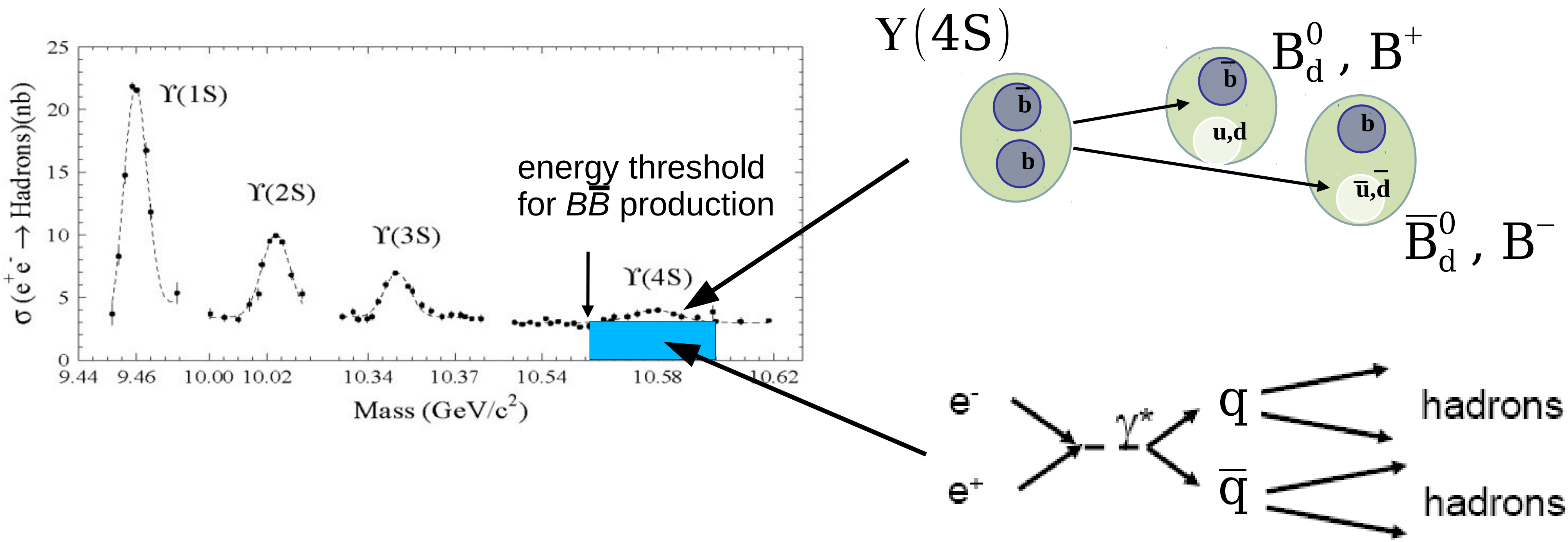


SM dominant tree
$B^+ \rightarrow D^0 l^+ \nu$

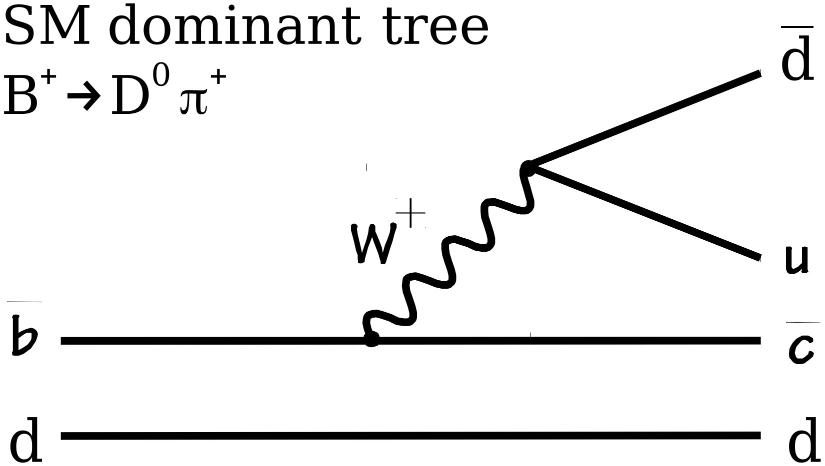




At a B-factory ...

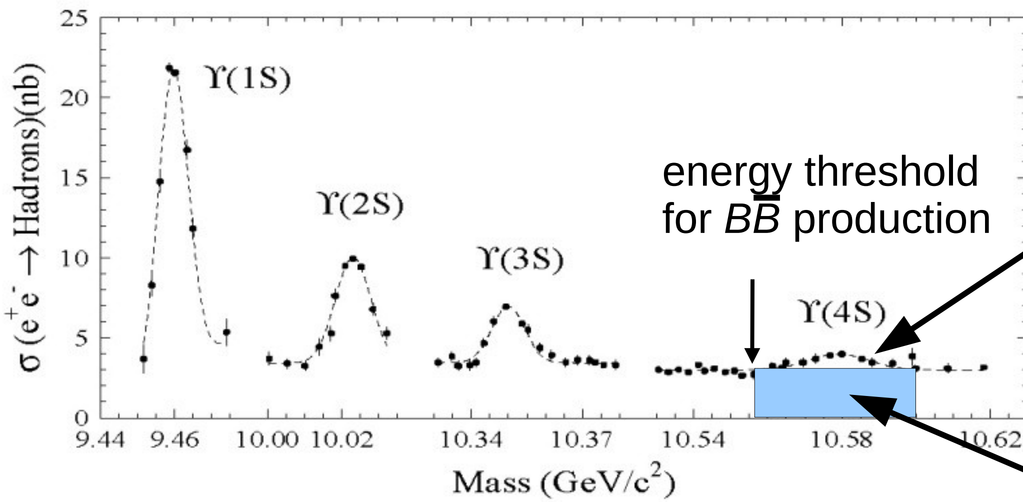


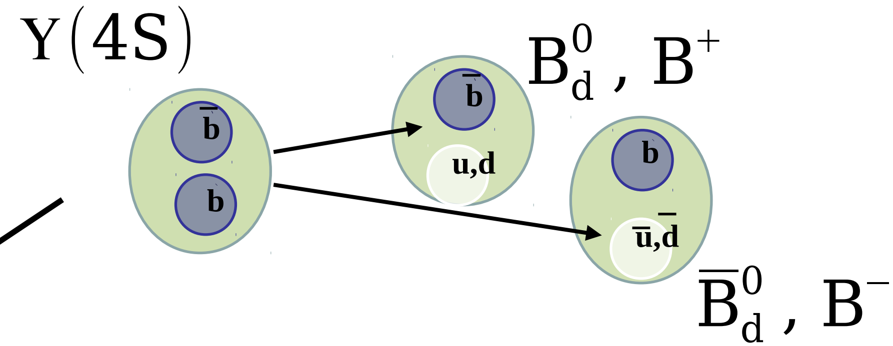
SM dominant tree
$B^+ \rightarrow D^0 \pi^+$

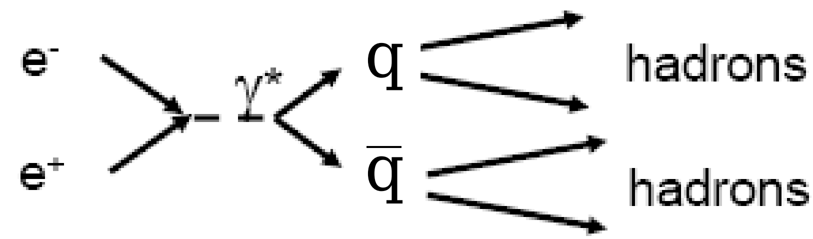


How many B candidates can I reconstruct with 1 fb^{-1} ?
1 fb^{-1} → 1×10^6 B produced
but $BF(B \rightarrow D^0 \pi^-) = 5 \times 10^{-3}$
and $BF(D \rightarrow K^- \pi^+) = 3.8\%$
and reconstruction efficiency ~ 10%...
signal yield ~ 10 events !!

Reconstruct a B candidate…







Energy difference:

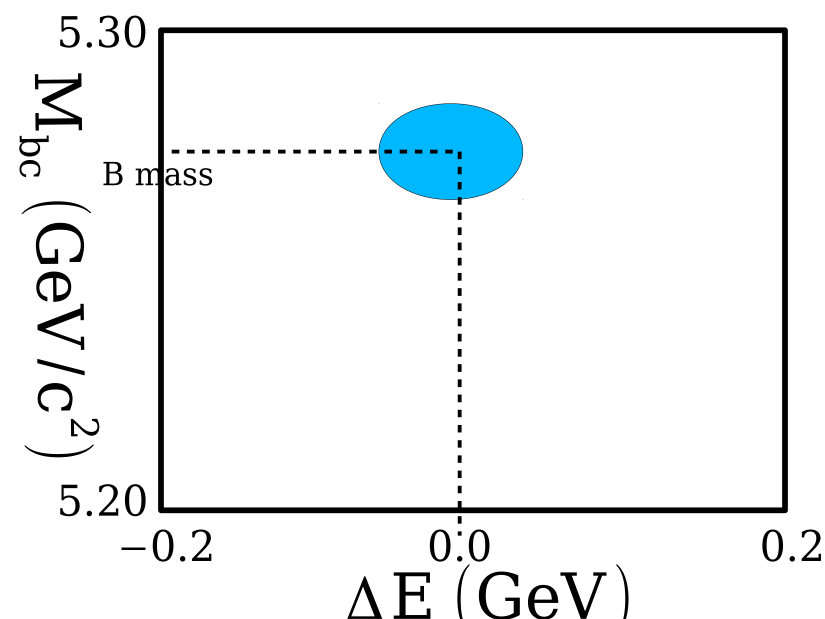
$$\Delta E = E_B^* - E_{beam}$$

(resolution ~ 10 MeV)

Beam-energy-constrained mass:

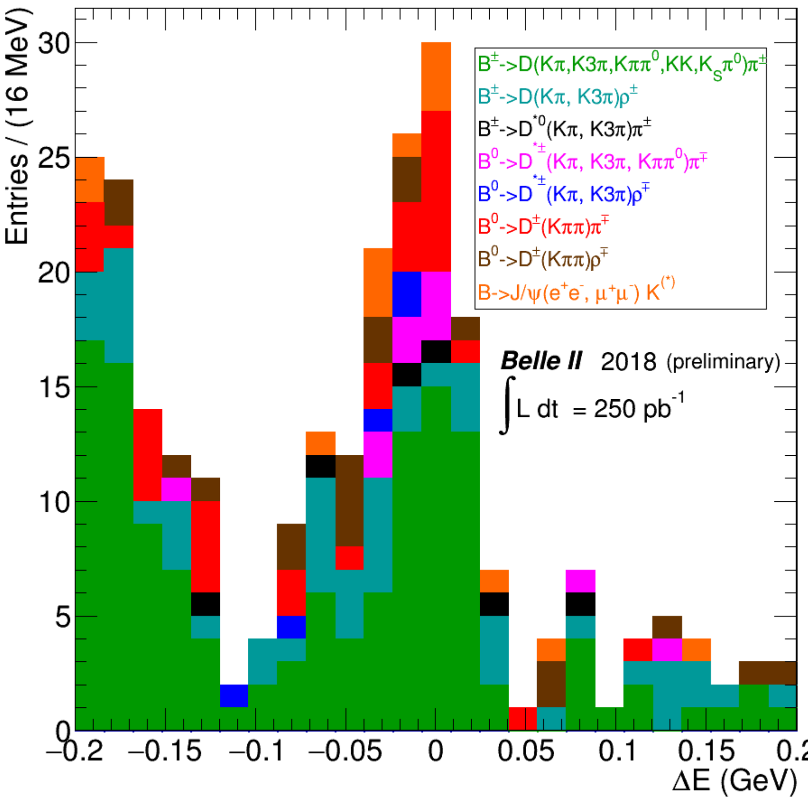
$$M_{bc} = \sqrt{(E_{beam}/c^2)^2 - (p_B^*/c)^2}$$

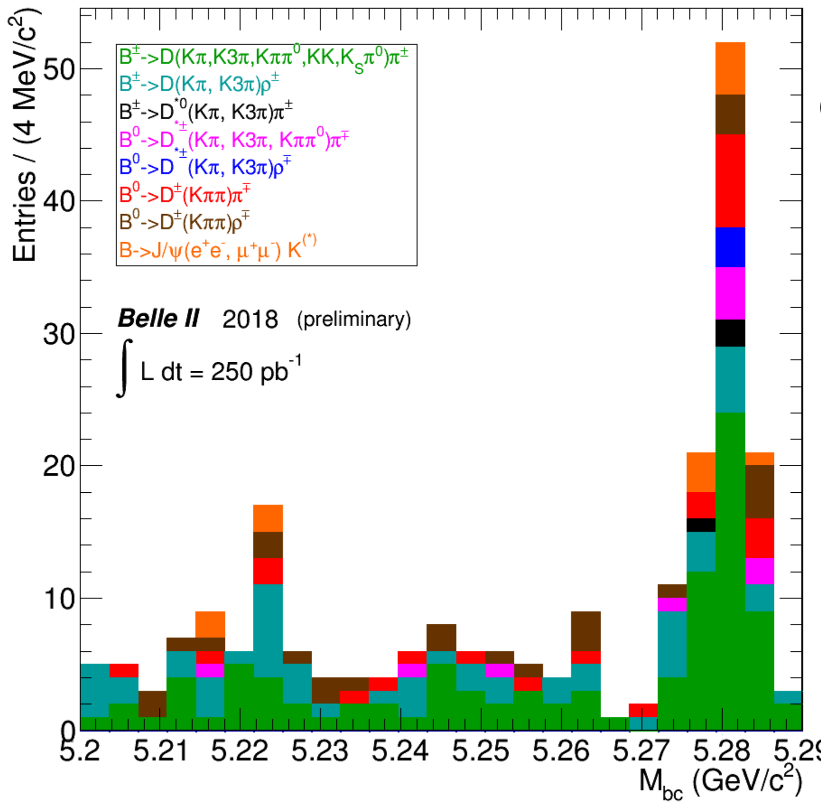
(resolution ~ 2.5 MeV)



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 $b \to c$