Large international collaborations in particle physics

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Contents

- Why is particle physics interesting at all?
- Research in experimental particle physics
- Large collaborations: a necessity and a challenge
- Example: Belle-II at SuperKEKB
- More examples
- Summary

Relation between elementary particle physics and the development of the early Universe

Early Universe: extremly dense → extremly high temperatures (like in gas after compression in the car engine)

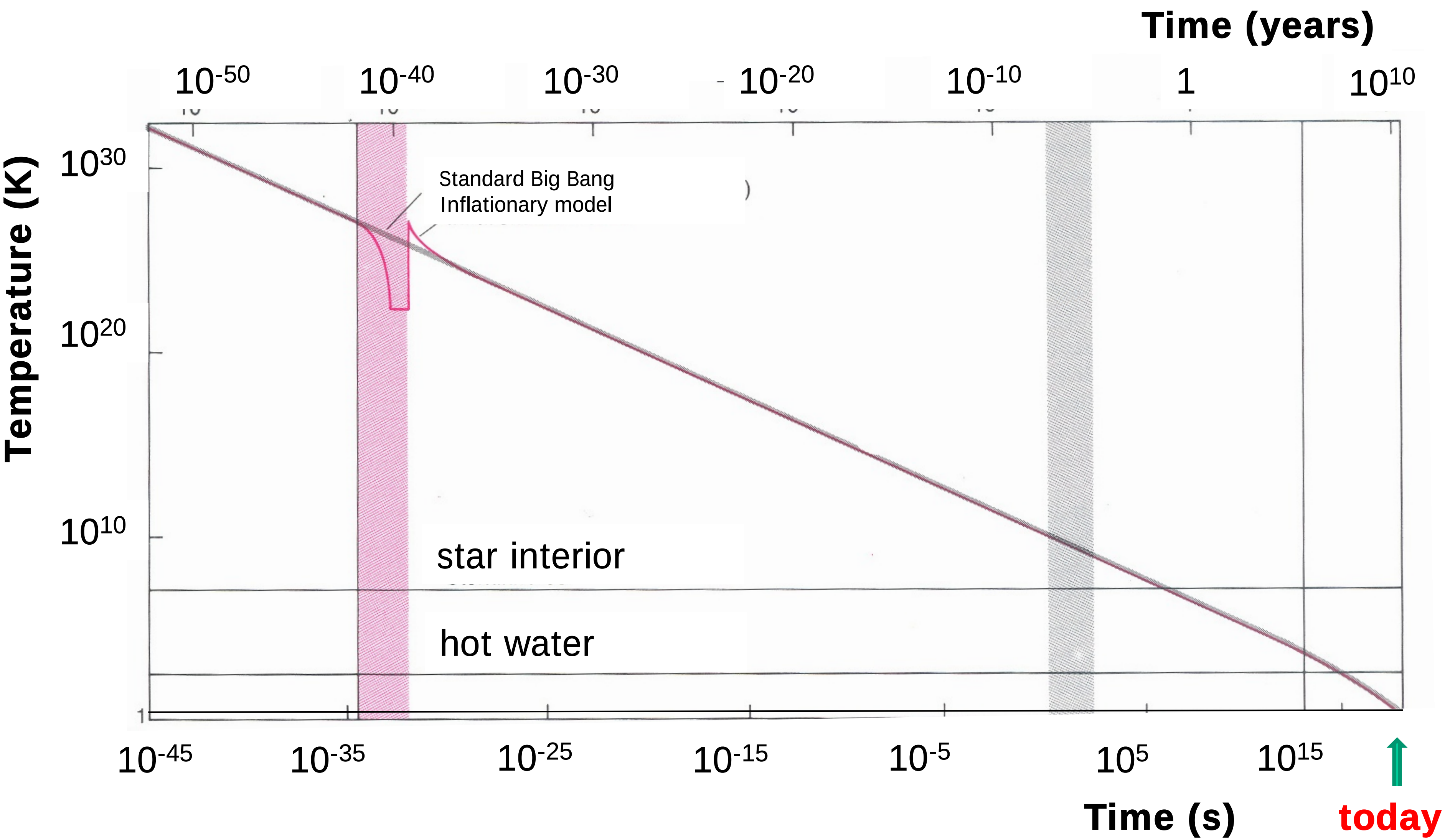
Gas at high temperatures: molecules and atoms have high velocities

Collissions between particles in the early Universe:

just like collissions of particles in accelerators

→ Similar processes

Temperature of the Universe



One of the really big questions: why is there a difference between the number of particles and anti-particles?

Out of 10 billions of particles and 10 billions of anti-particles in the early Universe only

1 particle survived!

10.000.000.000 particles | 10.000.000.000 anti-particles

1 particle | 0 anti-particles

CP symmetry and its violation

Symmetry operation CP: transforms a particle into its anti-particle

If the two do not behave in the same way – e.g., if they decay differently → violation of CP symmetry

Since there were equal amounts of particles and anti-particles in the early Universe, while today the Universe contains only matter (=particles) and almost no anti-matter (anti-particles)
→ This symmetry is obviously violated!

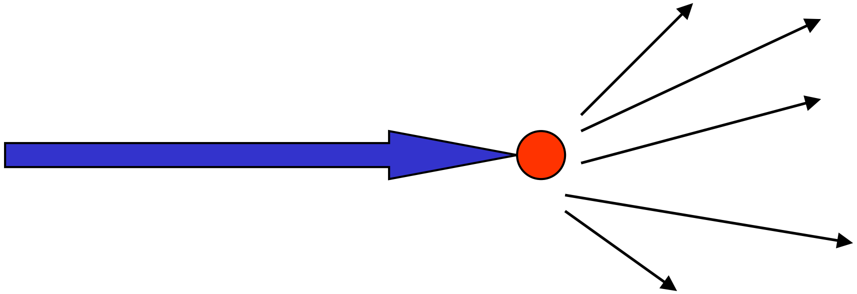
⇒ Very important to understand how and why this symmetry is violated.

Particle physics experiments

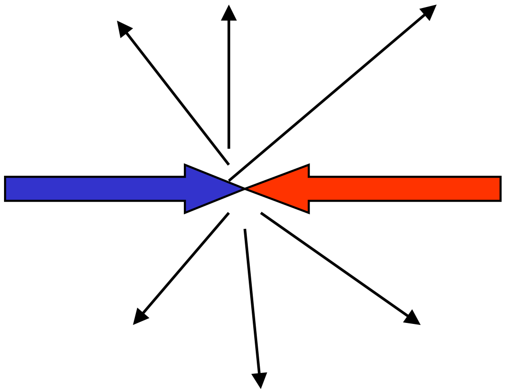
Accelerate elementary particles, let them collide → energy released in the collision is converted into mass of new particles, some of which are unstable

Two ways how to do it:

Fixed target experiments

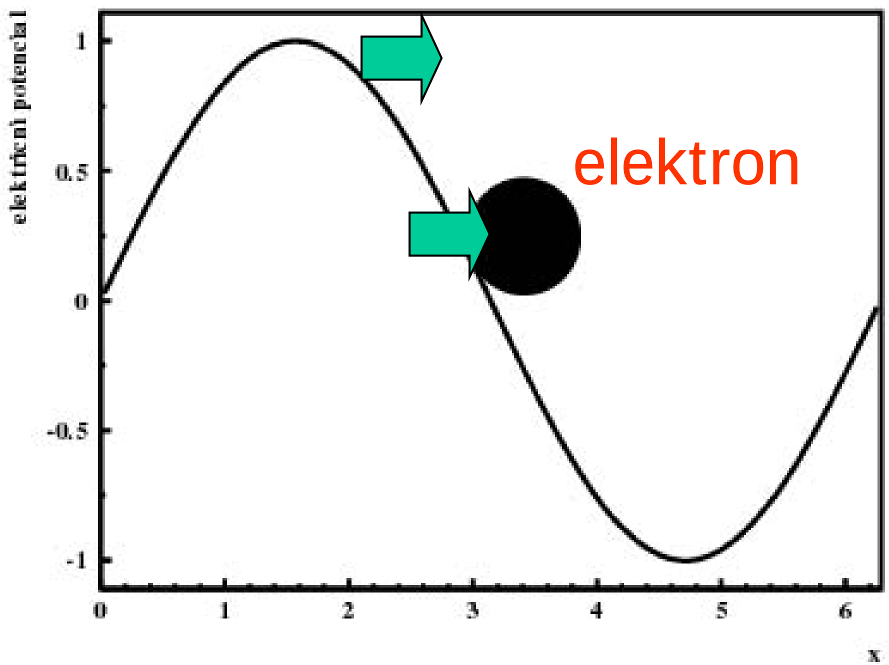


Collider experiments

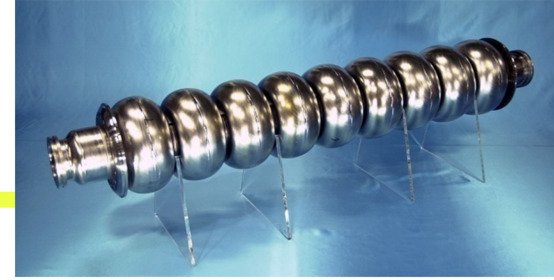


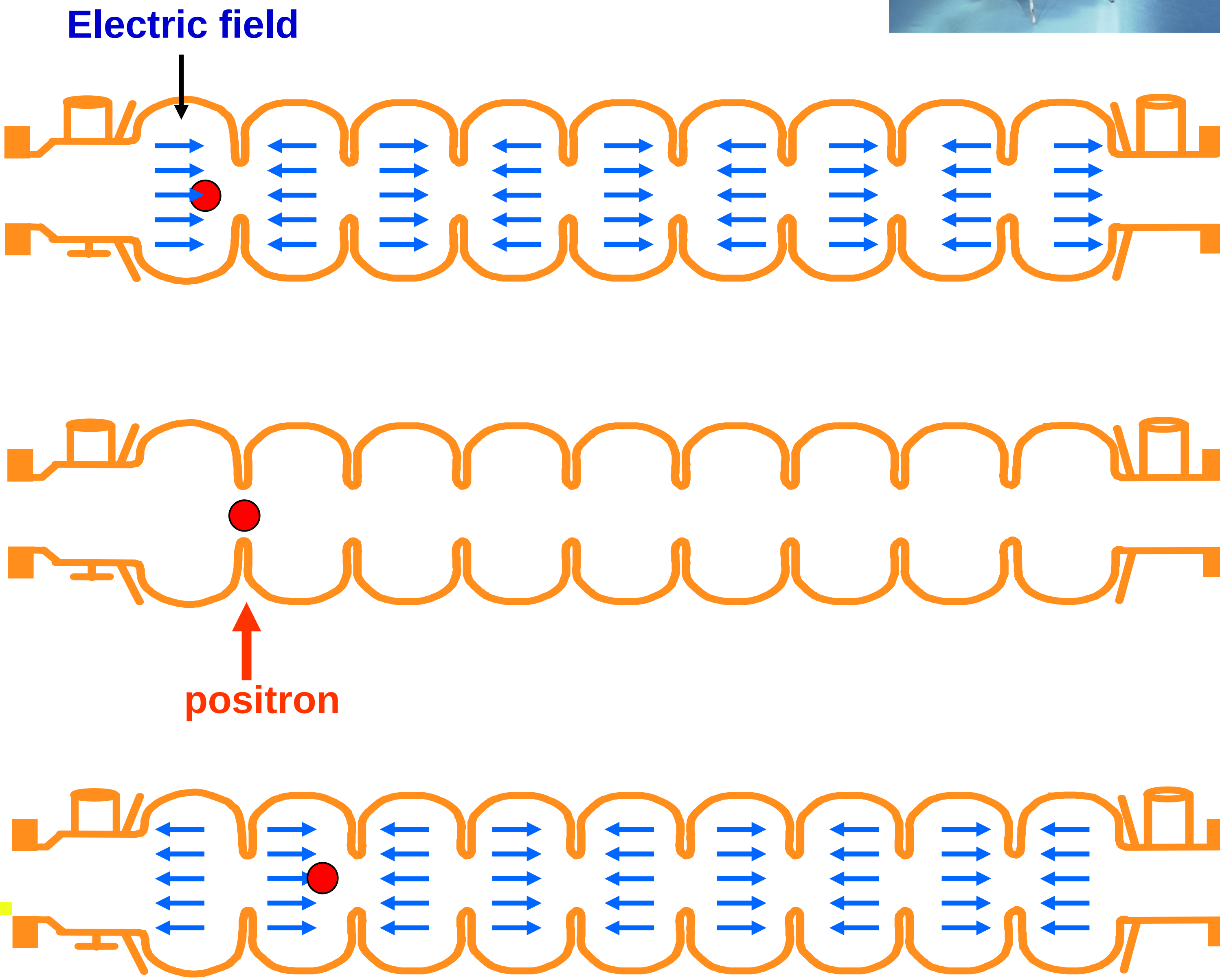
How to accelerate charged particles?

- Acceleration with electromagnetic waves (typical frequency is 500 MHz – mobile phones run at 900, 1800, 1900 MHz)
- Waves in a radiofrequency cavity: $c<c_0$

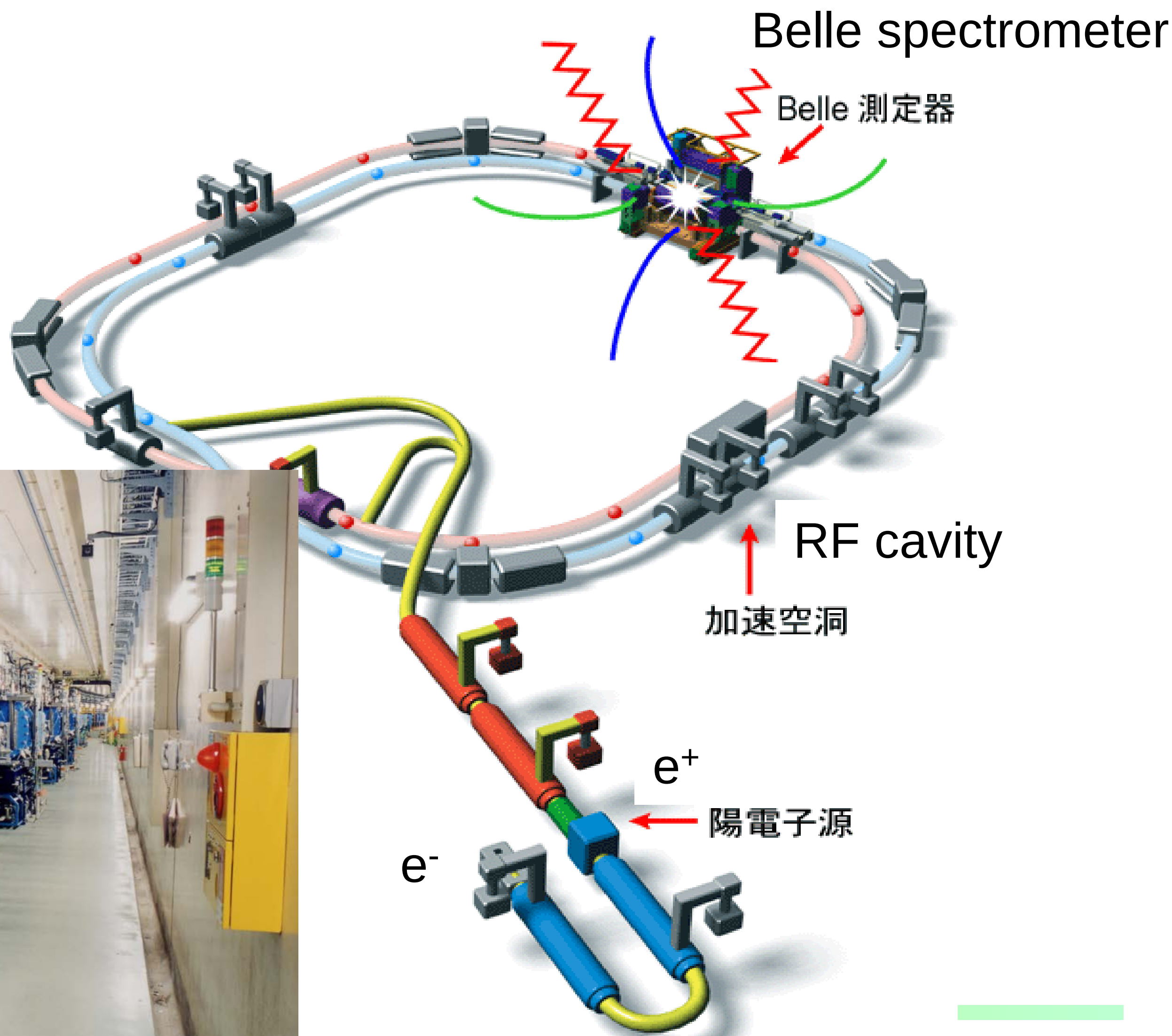


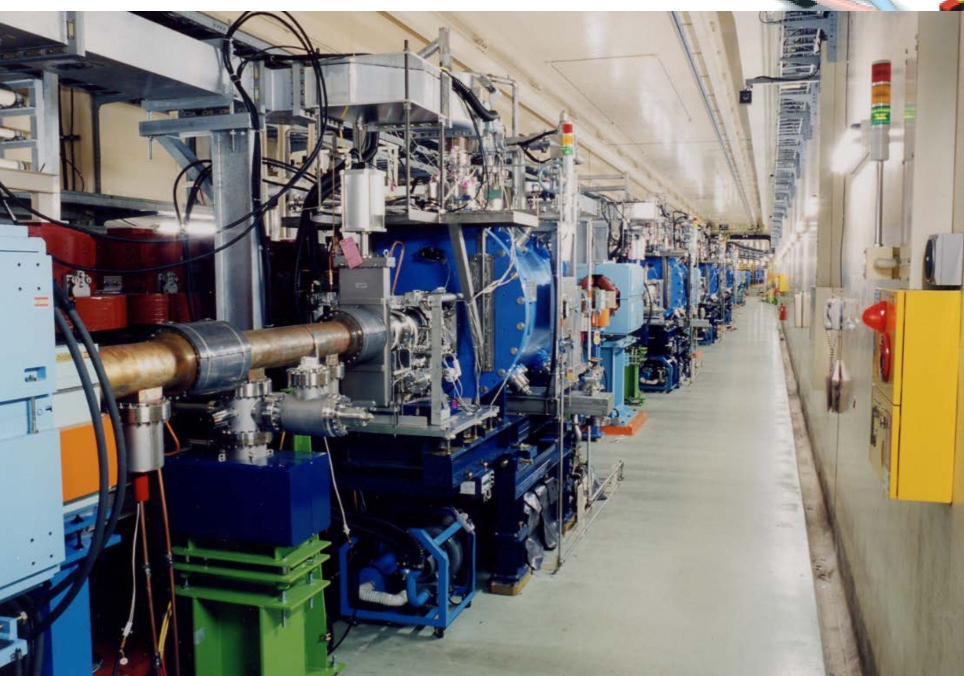
... Similar to surfing the waves



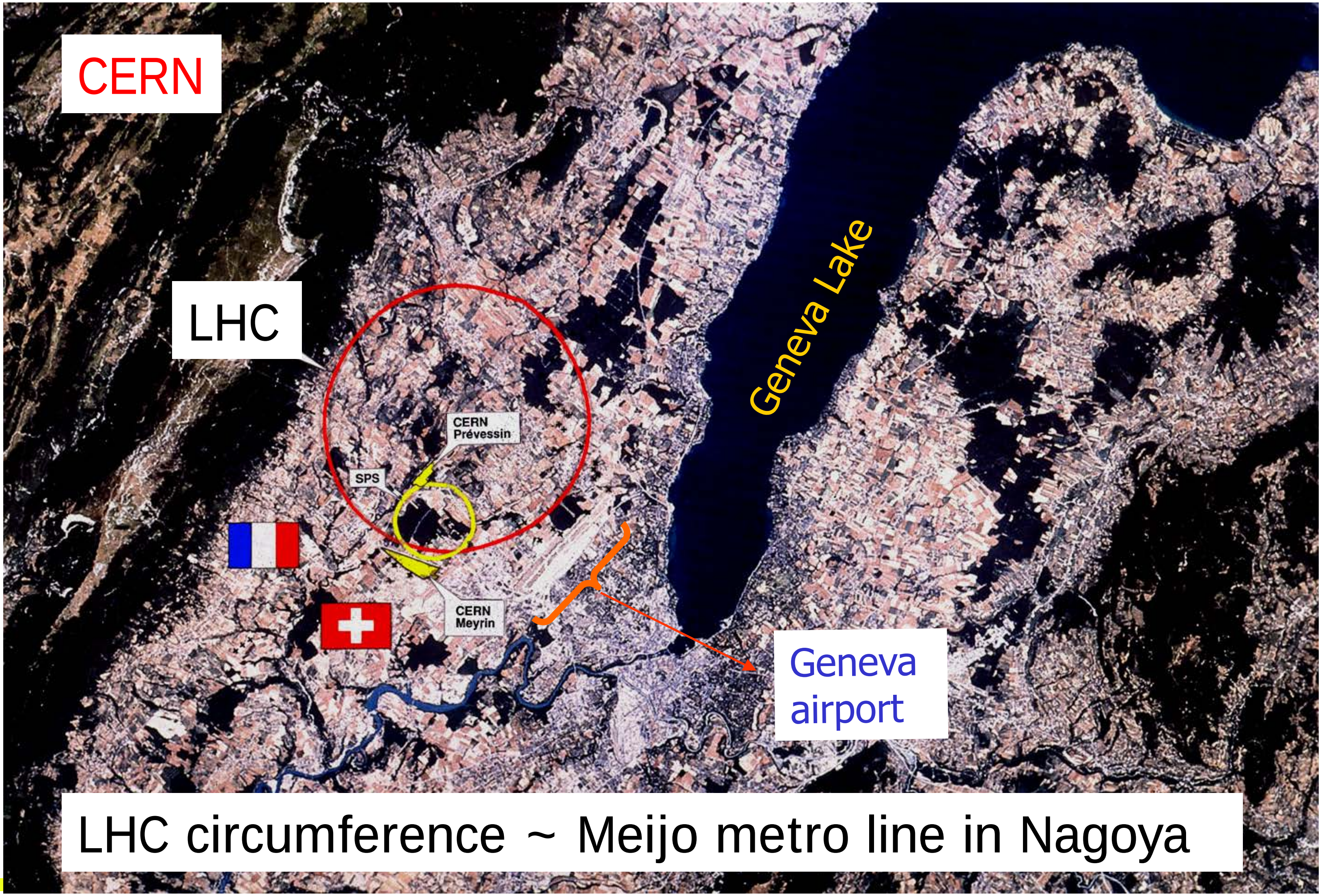

Electric field
positron

KEK-B collider
for electrons and positrons





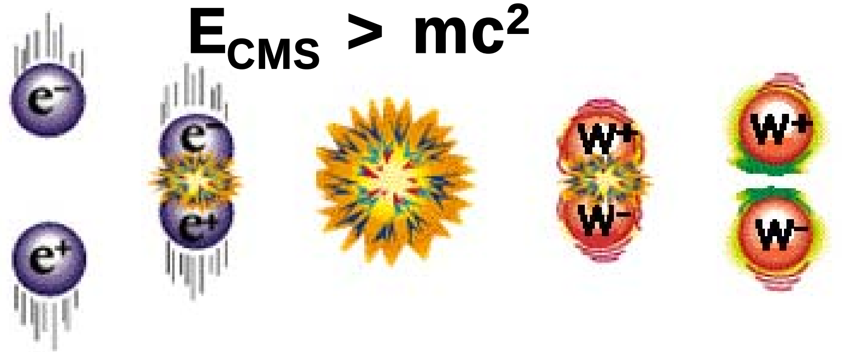
Large hadron collider

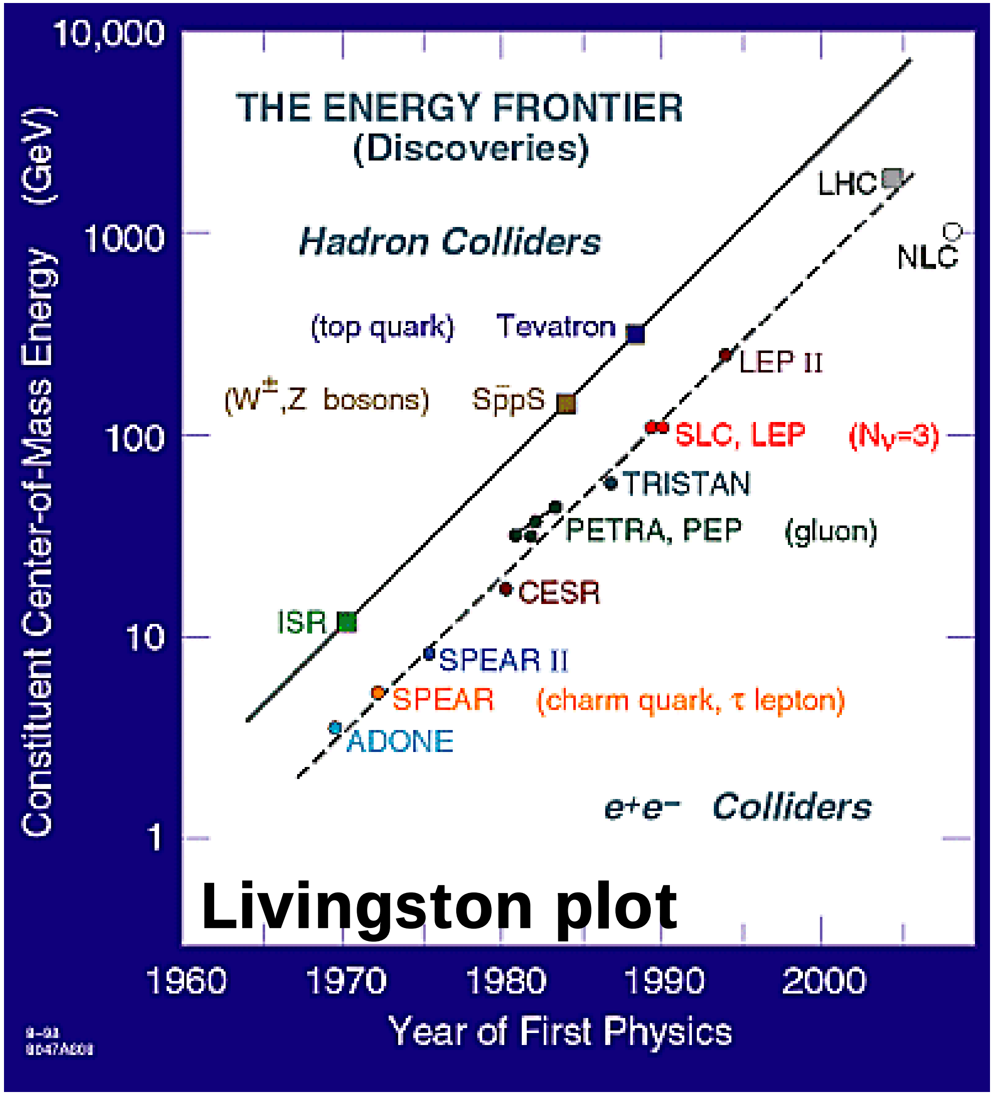


Accelerator figure of merit 1: Center-of-mass energy

If there is enough energy available in the collission, new, heavier particles can be produced.

$E_{CMS} > mc^2$





e.g. LHC, CERN: search for new particles with m > 100GeV

Two complementary approaches

Two complementary approaches to search for the so far unobserved processes and particles: the **energy frontier** and the **intensity frontier** .

Energy frontier : direct search for production of unknown particles at the highest achievable energies.

Intensity frontier : search for rare processes, deviations between theory predictions and experiments with the ultimate precision.

→for this kind of studies, one has to investigate a very large number of reactions (˝events˝) → need accelerators with ultimate **intensity** (˝luminosity˝)

Comparison of energy /intensity frontiers

To observe a large ship far away one can either use **strong binoculars** or observe **carefully the direction and the speed of waves** produced by the vessel.

Energy frontier (LHC)

Luminosity frontier (SuperKEKB)

Accelerator figure of merit 2: Luminosity

Observed rate of events = Cross section x Luminosity

$$\frac{dN}{dt} = L\sigma$$

Accelerator figures of merit: luminosity ***L***

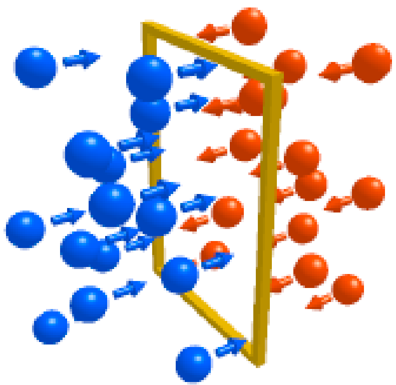
and integrated luminosity

$$L_{\text{int}} = \int L(t)dt$$

High luminosity is needed for studies of rare processes.

Luminosity vs time

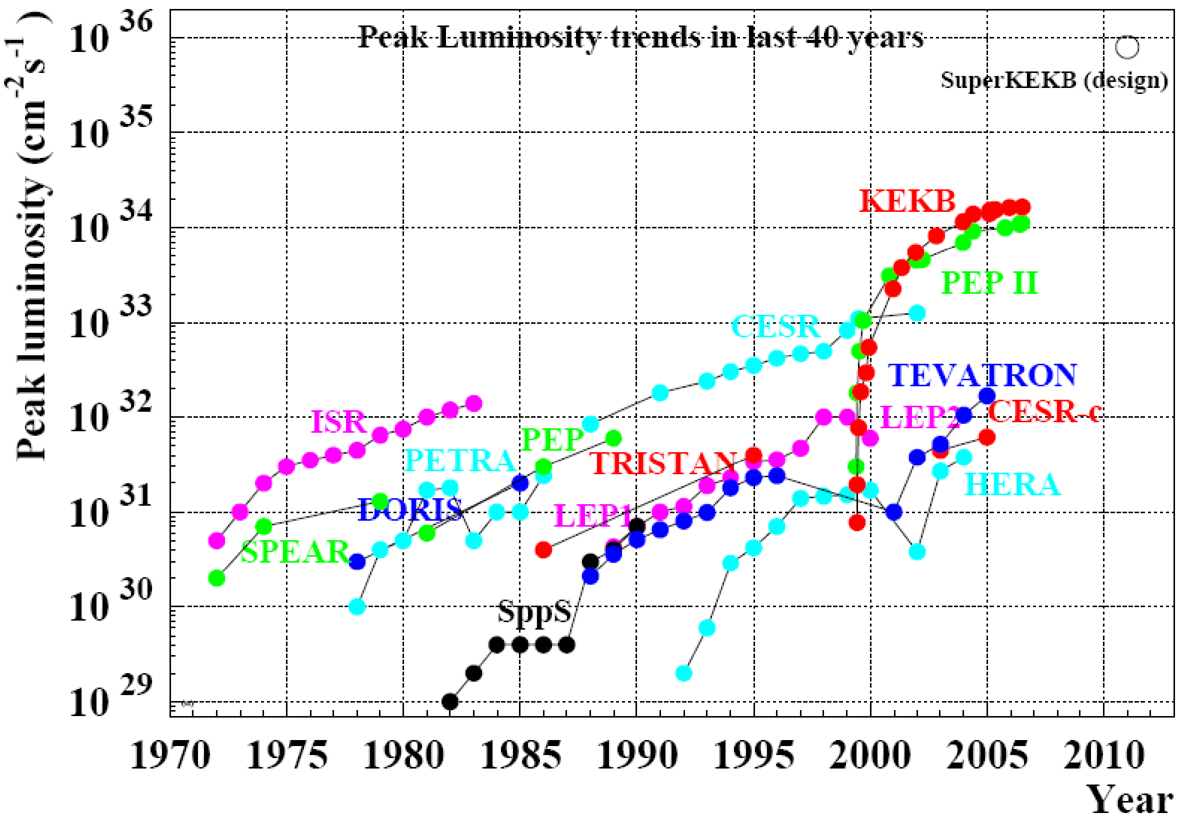
$$R = \mathcal{L}\sigma$$



(number of events/unit time)

= (cross section) X (luminosity)

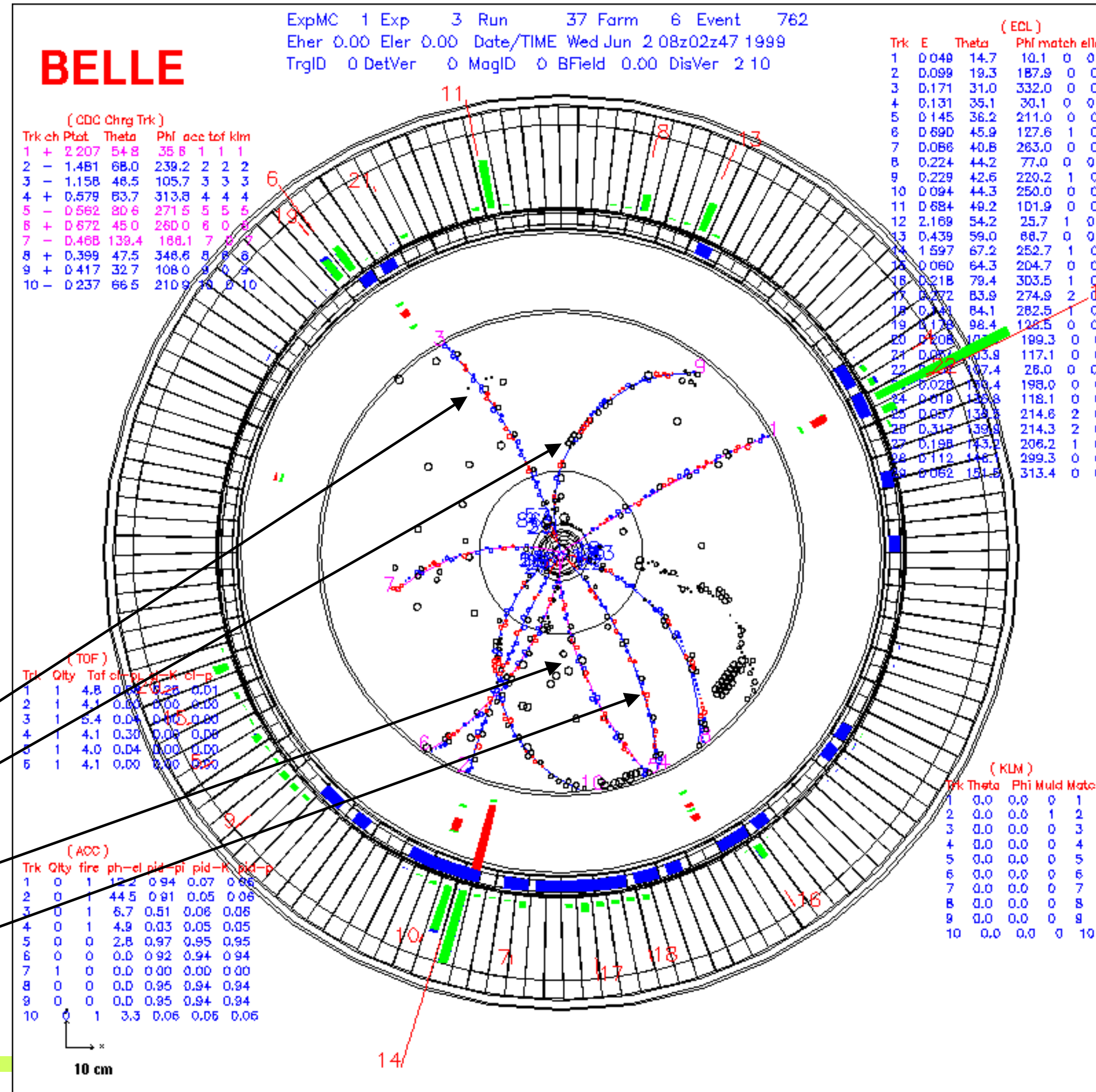
$$\mathcal{L} = \frac{I_{LER}\, I_{HER}}{e^2 f_{rev}\, N_{bunch}\, A_{eff}}$$



High luminosity is needed for studies of rare processes.

How to understand what happened in a collision?

Illustration on an example:



$B^0 \rightarrow K^0_S\, J/\psi$

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

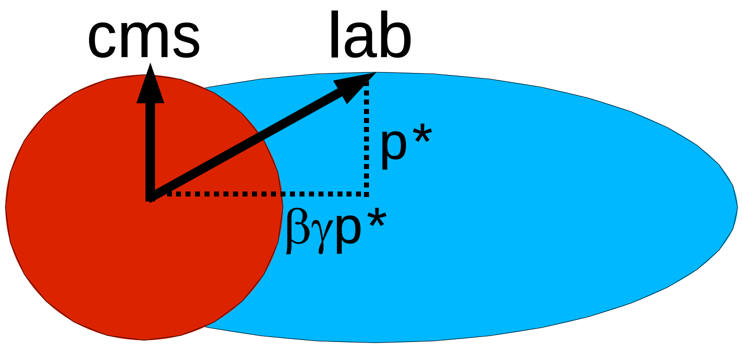
$J/\psi \rightarrow \mu^- \mu^+$

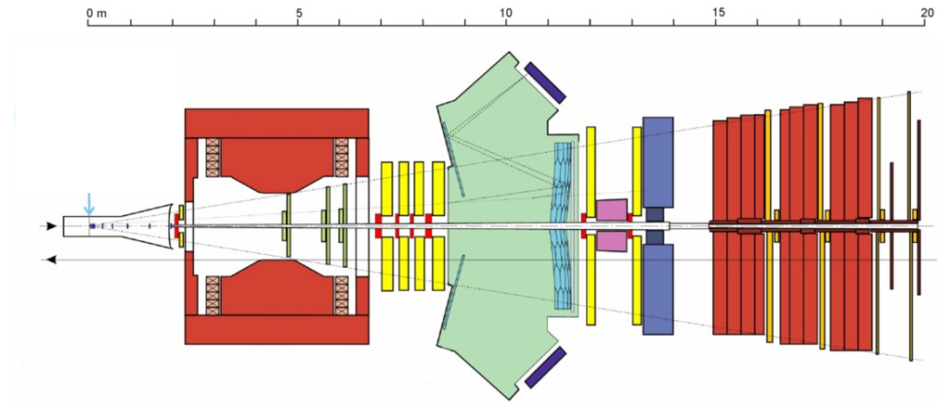
How to understand what happened in a collision?

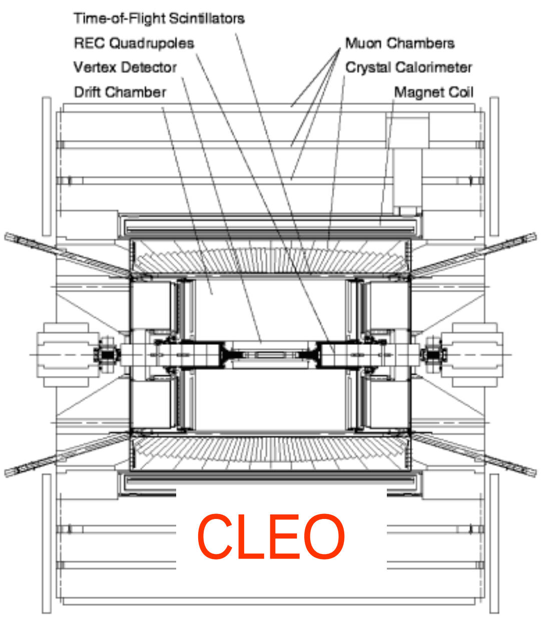
- Measure the coordinate of the point (‘vertex’) where the reaction occured, and determine the positions and directions of particles that have been produced
- Measure momenta of stable charged particles by measuring their radius of curvature in a strong magnetic field (~1T)
- Determine the identity of stable charged particles (e, μ, π, K, p)
- Measure the energy of high energy gamma rays

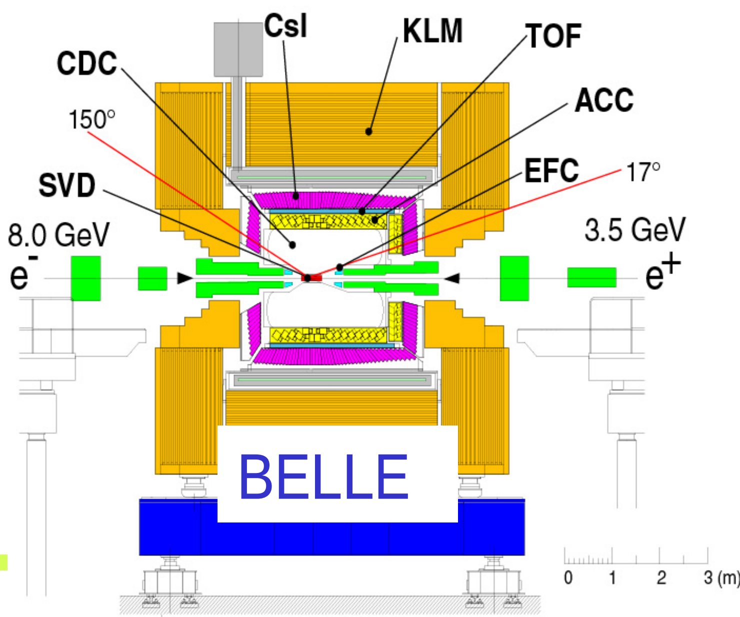
Experimental aparatus

Detector form: symmetric for colliders with symmetric energy beams; extended in the boost direction for an asymmetric collider; very forward oriented in fixed target experiments.

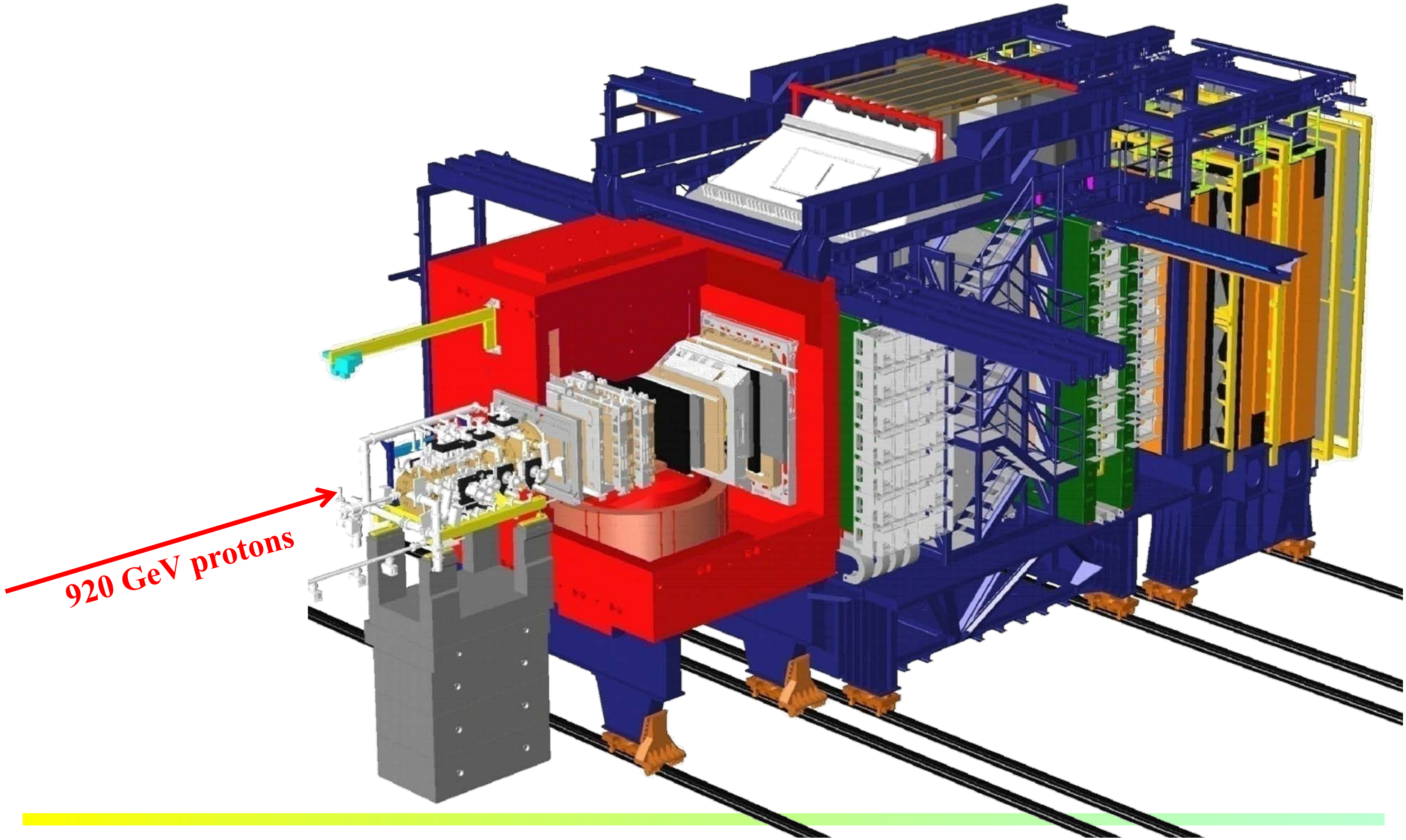




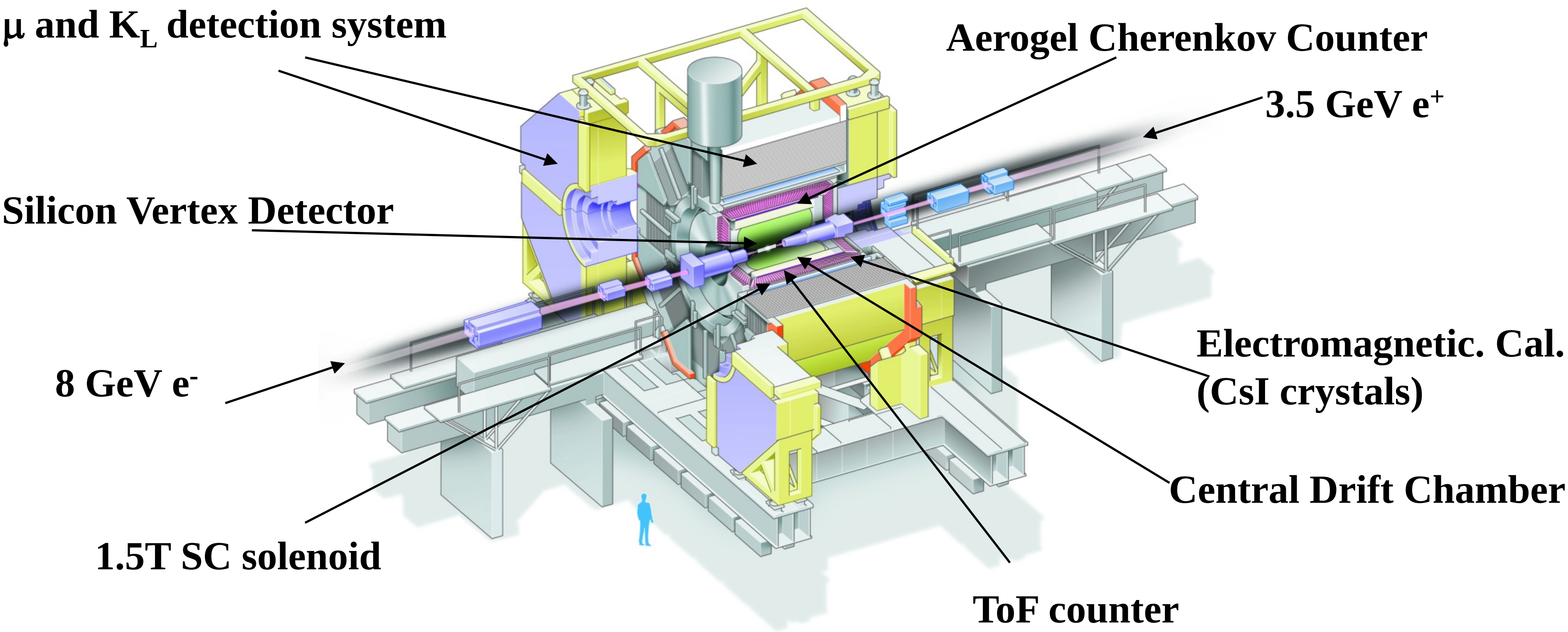




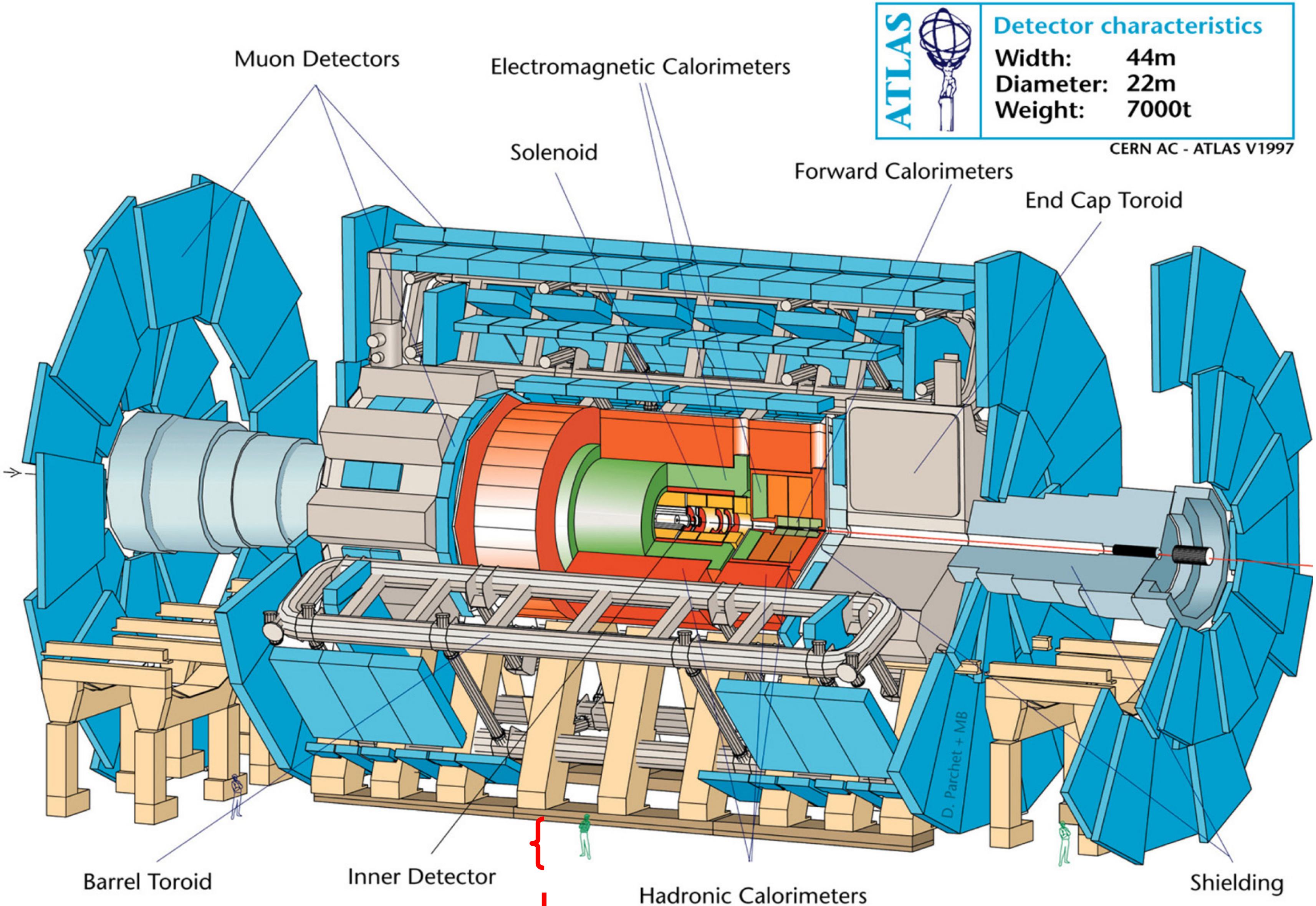
Example of a fixed target experiment: HERA-B



Belle spectrometer at KEK-B



ATLAS at LHC



A physicist...

Peter Križan, Ljubljana

How to carry out such large scale projects

For an experiment in particle physics one needs:

- an accelerator
- at least one detector

These are huge projects, requiring sizable resources both in funding and in expertize.

→ Large international collaborations: a necessity

However, scientific work in such a large international collaboration is also a challenge!

Example: Belle and Belle II detectors at the e^+e^- collider, KEK, Tsukuba

A little bit of history...

CP violation: difference in the properties of particles and their anti-particles – first observed in 1964.

M. Kobayashi and T. Maskawa (1973): CP violation in the Standard model – related to the weak interaction quark transition matrix

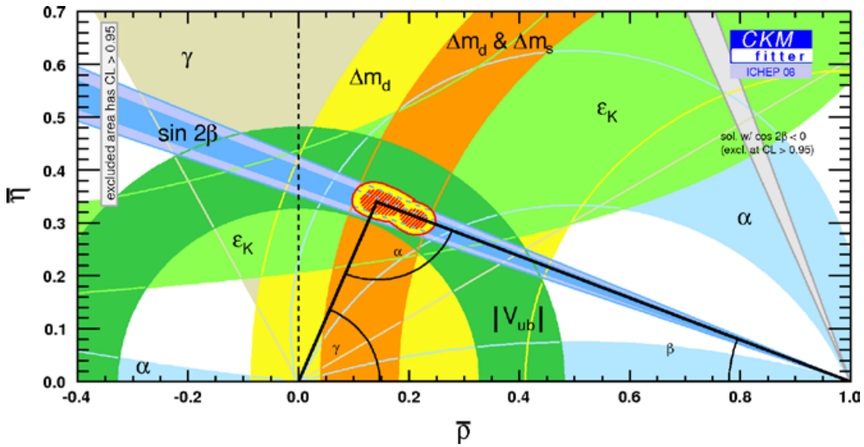
Their theory was formulated at a time when three quarks were known – and they requested the existence of three more!

The last missing quark was found in 1994.

… and in 2001 two experiments – Belle and BaBar at two powerfull accelerators (B factories) - have further investigated CP violation and have indeed proven that it is tightly connected to the quark transition matrix

KM's bold idea verified by experiment

Relations between parameters as expected in the Standard model →

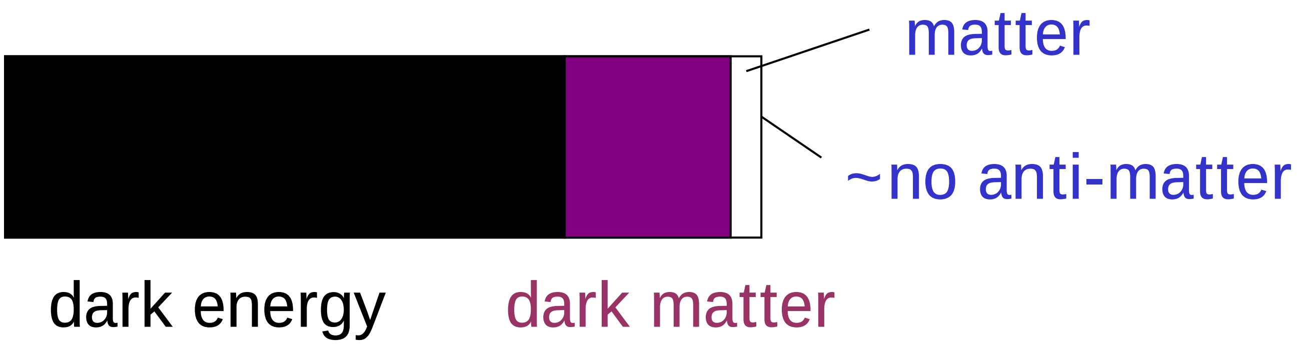


Nobel prize 2008!

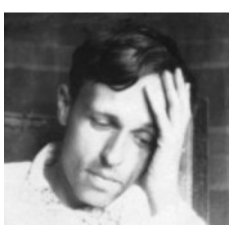
→ With essential experimental confirmations by Belle and BaBar! (explicitly noted in the Nobel Prize citation)

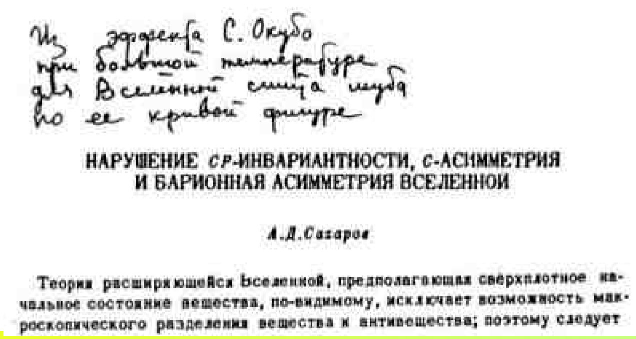
The KM scheme is now part of the Standard Model of Particle Physics

- However, the CP violation of the KM mechanism is too small to account for the asymmetry between matter and anti-matter in the Universe (falls short by 10 orders of magnitude !)
- SM does not contain the fourth fundamental interaction, gravitation
- Most of the Universe is made of stuff we do not understand...



Are we done ? (Didn't the B factories accomplish their mission, recognized by the 2008 Nobel Prize in Physics ?)




Из эффекта С. Окубо
При большой температуре
Для Вселенной сшита шуба
По ее кривой фигуре

НАРУШЕНИЕ *CP*-ИНВАРИАНТНОСТИ, *C*-АСИММЕТРИЯ
И БАРИОННАЯ АСИММЕТРИЯ ВСЕЛЕННОЙ

А.Д.Сахаров

Теория расширяющейся Вселенной, предполагающая сверхплотное начальное состояние вещества, по-видимому, исключает возможность макроскопического разделения вещества и антивещества; поэтому следует

Matter - anti-matter asymmetry of the Universe: KM (Kobayashi-Maskawa) mechanism still short by 10 orders of magnitude !!!

Comparison of **energy** /**intensity** frontiers

To observe a large ship far away one can either use **strong binoculars** or observe **carefully the direction and the speed of waves** produced by the vessel.

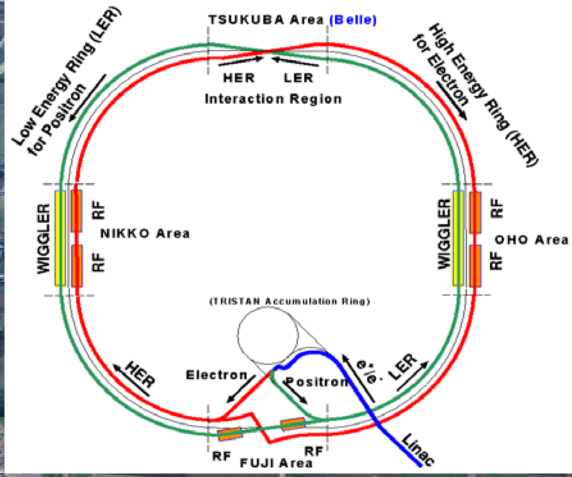
Energy frontier (LHC)

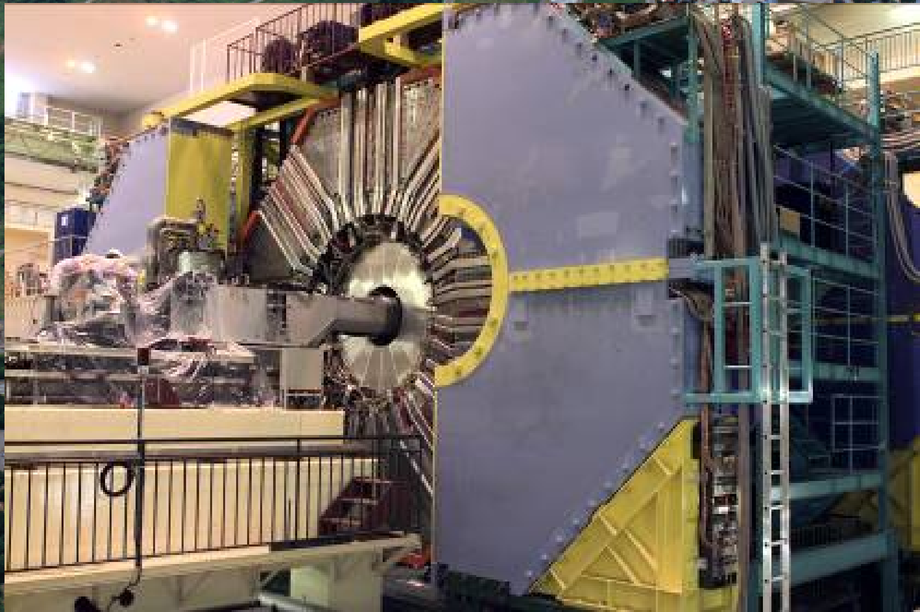
Luminosity frontier (SuperKEKB)

How to do it?

→Upgrade KEKB and Belle

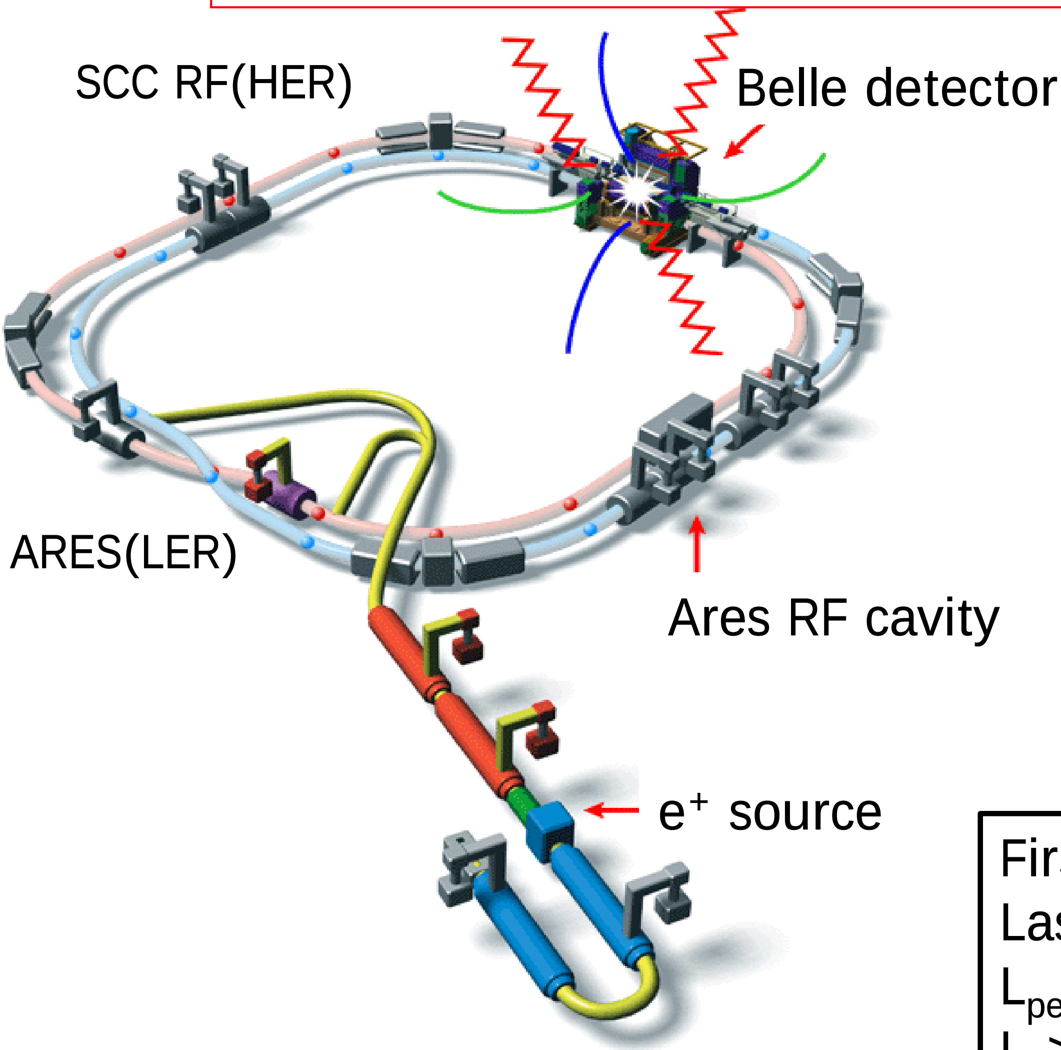
→→ SuperKEKB and Belle II





The KEKB Collider

Fantastic performance far beyond design values!



- e^- (8 GeV) on e^+(3.5 GeV)
  - $\sqrt{s} \approx m_{\Upsilon(4S)}$
  - Lorentz boost: $\beta\gamma$=0.425
- 22 mrad crossing angle

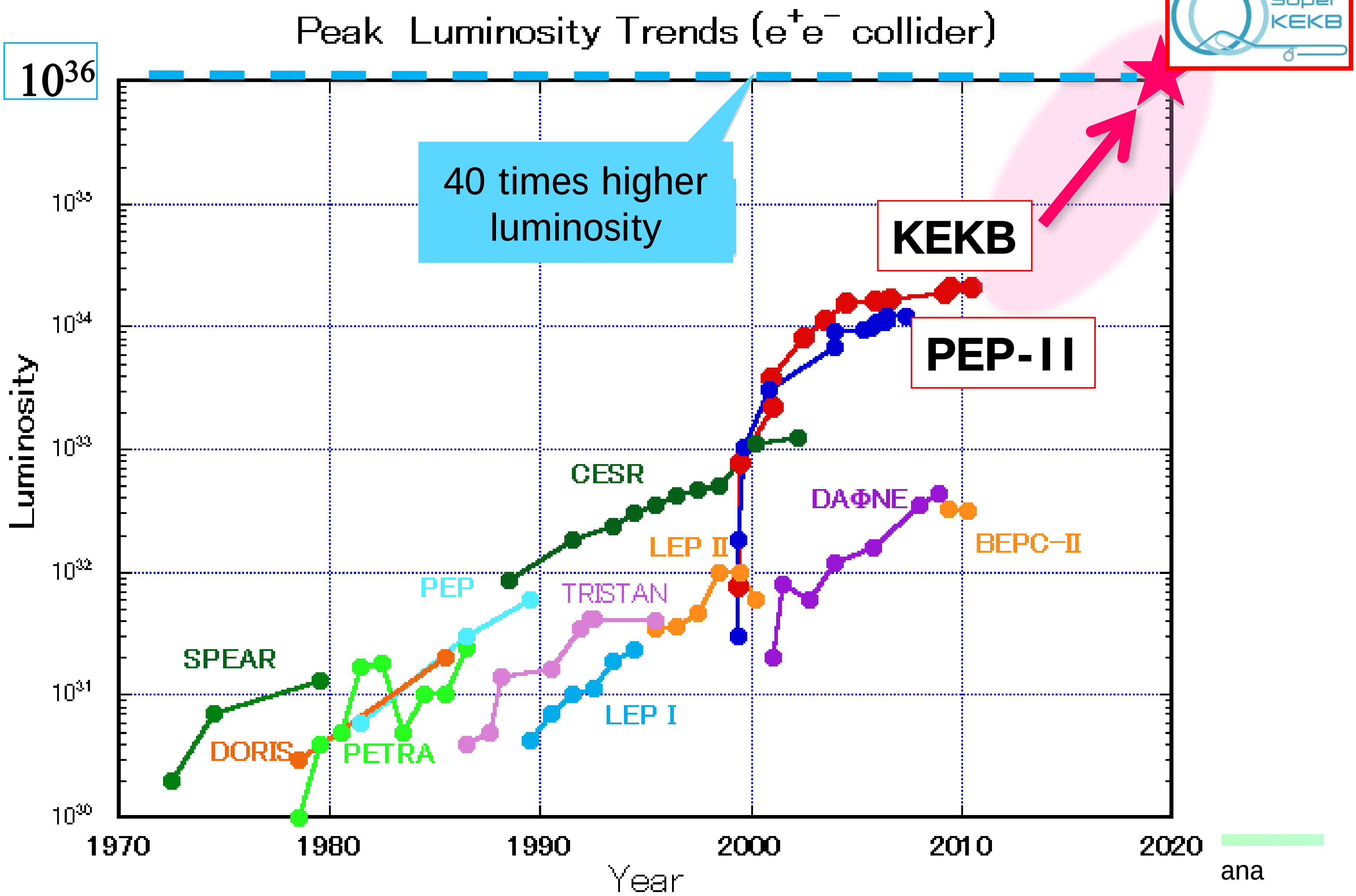
Peak luminosity (WR!) :

2. 1 x 10^{34} $cm^{-2}s^{-1}$

=2x design value

First physics run on June 2, 1999
Last physics run on June 30, 2010
L_{peak} = 2.1x10^{34}/cm^2/s
L > 1ab^{-1}

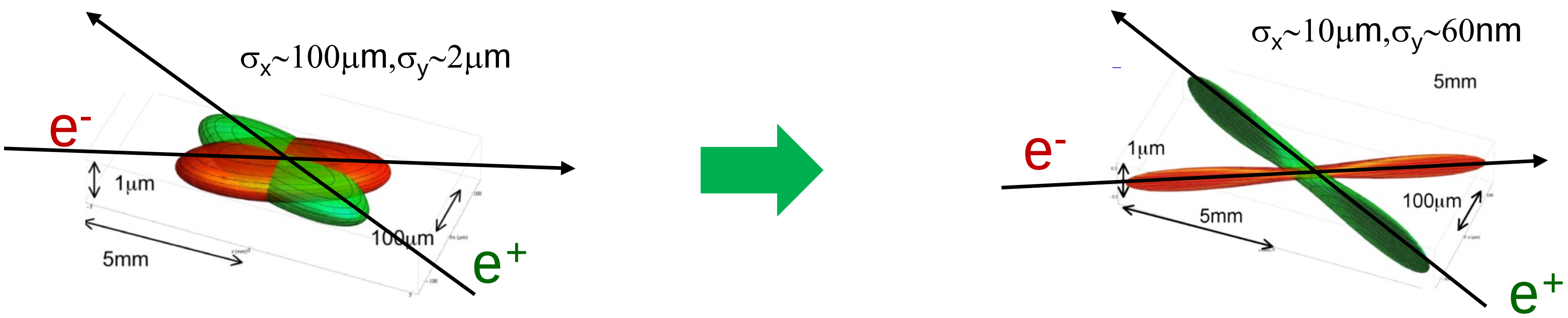
SuperKEKB is the intensity frontier



How big is a nano-beam ?

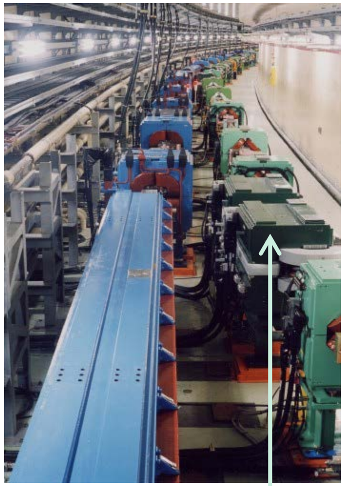
How to go from an excellent accelerator with world record performance – KEKB – to a 40x times better, more intense facility?

In KEKB, colliding electron and positron beams are much thinner than the human hair...

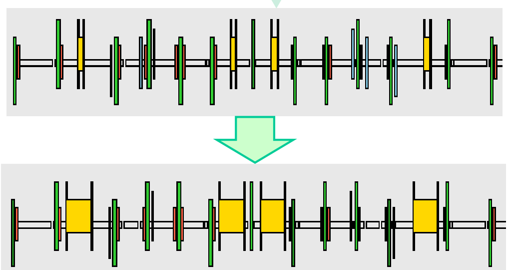


... For a 40x increase in intensity you have to make the beam as thin as 100 atomic layers!

KEKB to SuperKEKB

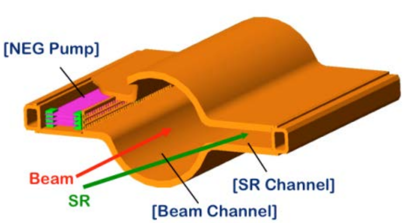


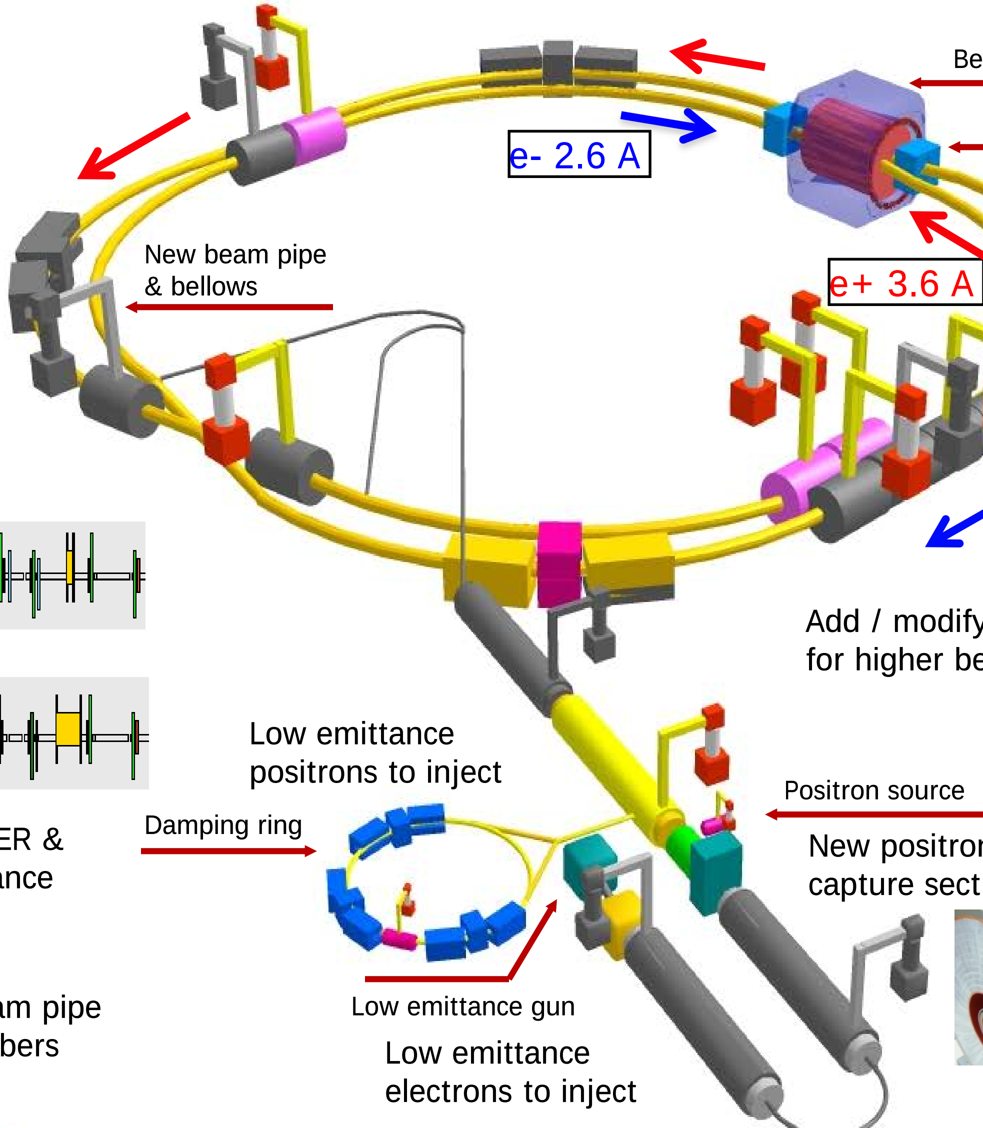
Replace short dipoles with longer ones (LER)



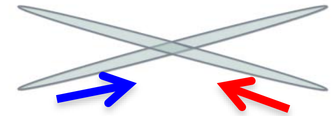
Redesign the lattices of HER & LER to squeeze the emittance

TiN-coated beam pipe with antechambers

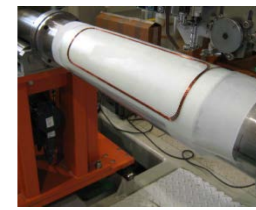




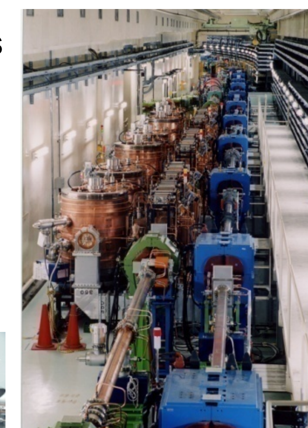
Colliding bunches



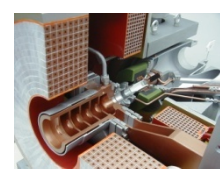
New superconducting /permanent final focusing quads near the IP



Add / modify RF systems for higher beam current



New positron target / capture section

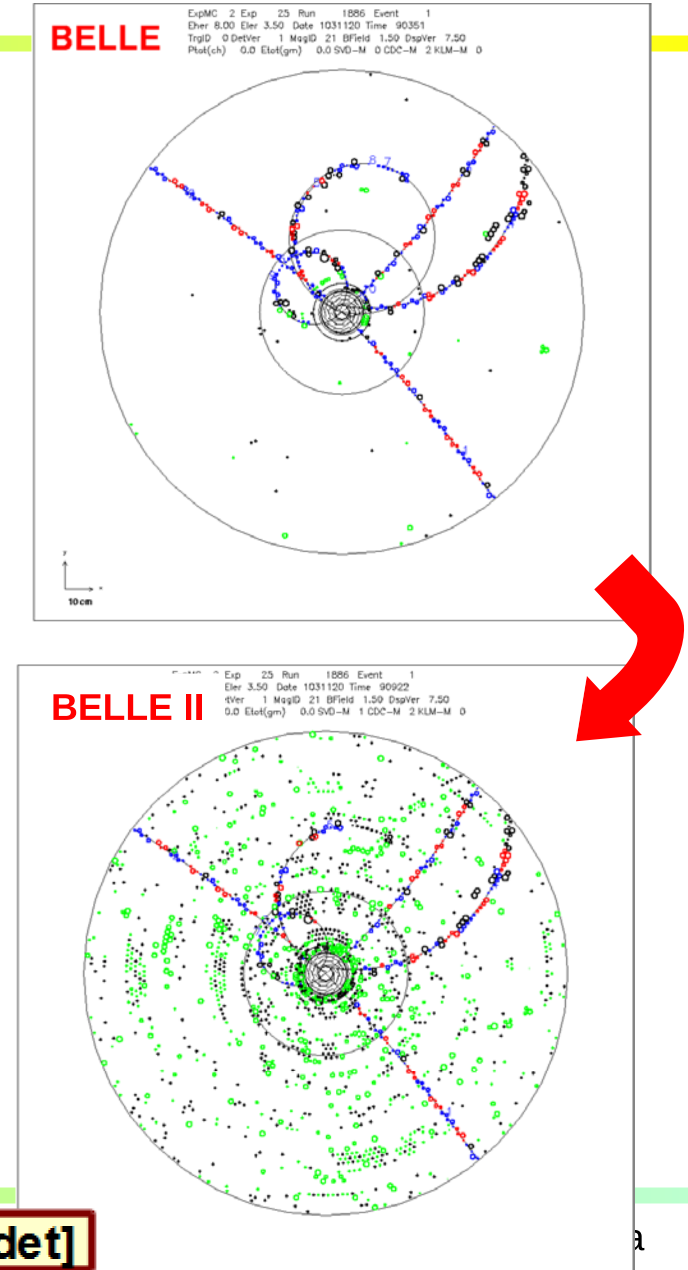


To get x40 higher interaction rate

Need to build a new detector to handle higher backgrounds

Critical issues at L= 8 x 10^{35}/cm^2/sec

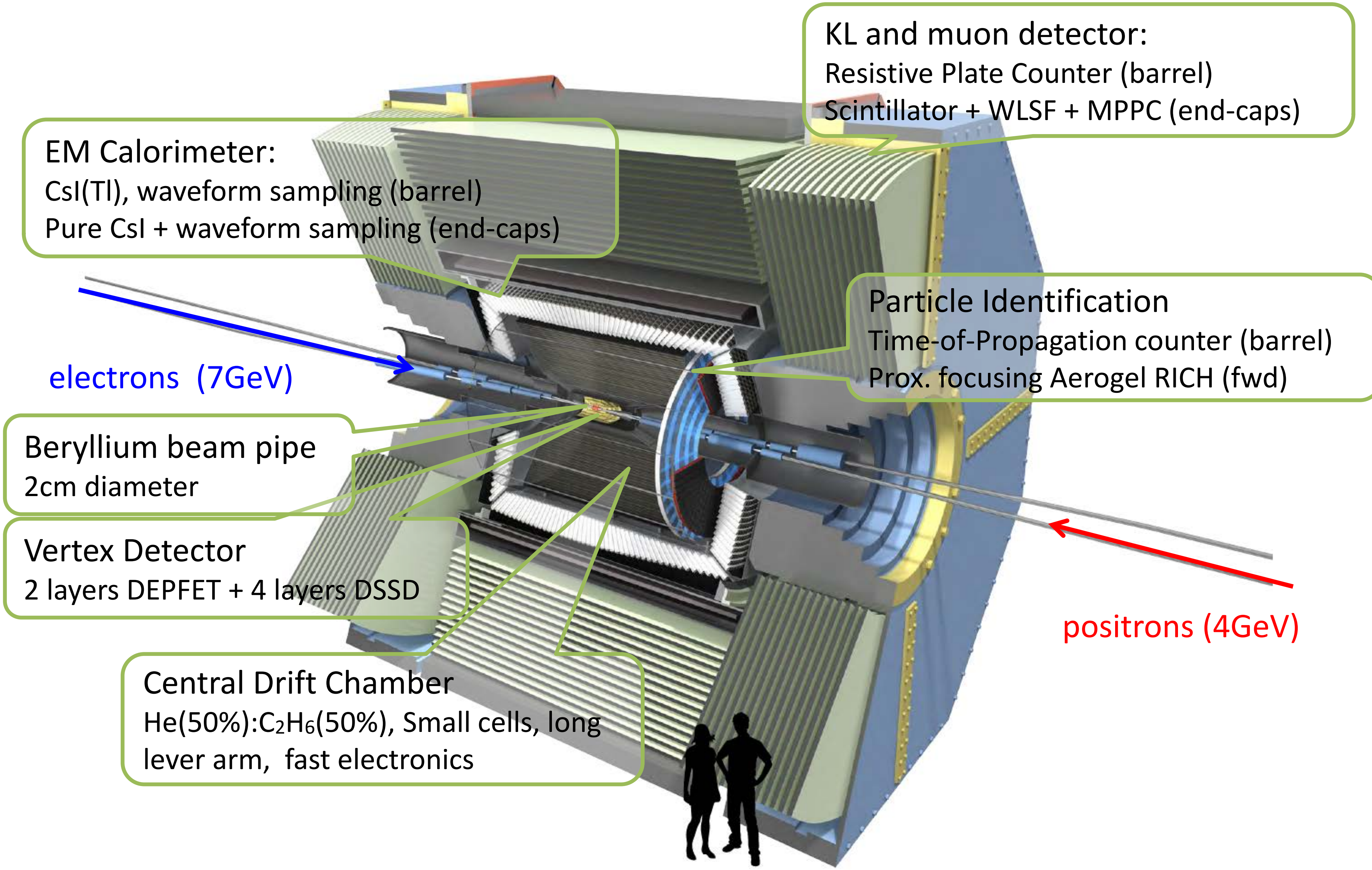
- **Higher background (×10-20)**
  - radiation damage and occupancy
  - fake hits and pile-up noise in the EM
- **Higher event rate (×10)**
  - higher rate trigger, DAQ and computing
- **Require special features**
  - low p μ identification ← $s\mu\mu$ recon. eff.
  - hermeticity ← ν "reconstruction"



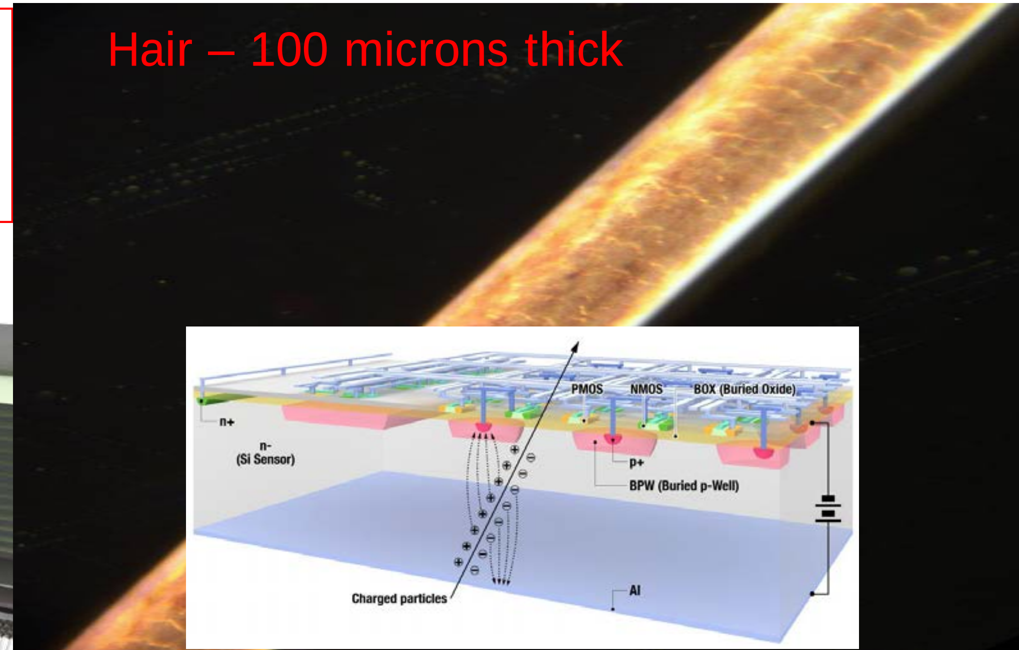
Have to employ and develop very advanced technologies to build such an appartus! →

TDR published arXiv:1011.0352v1 [physics.ins-det]

Belle II Detector

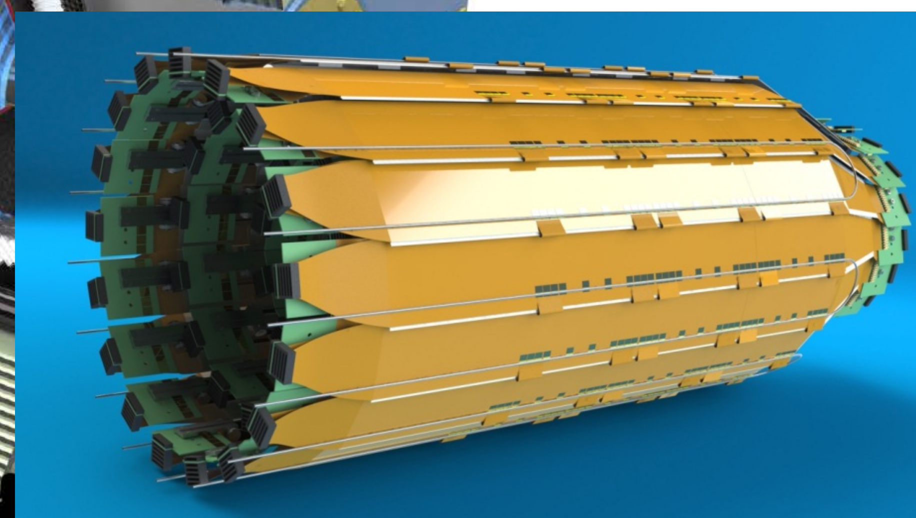


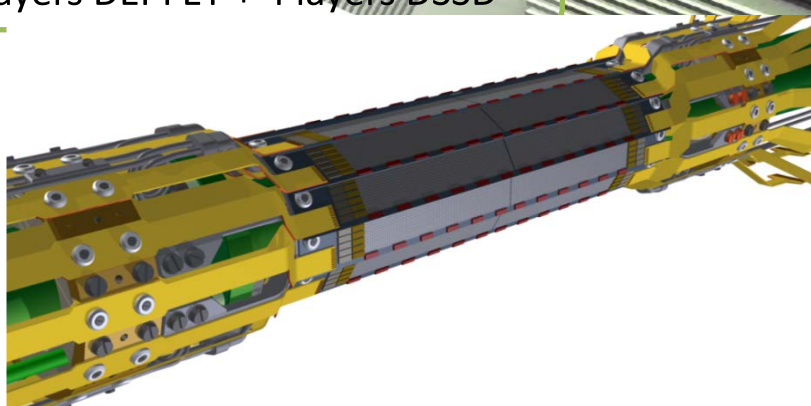
Determine the reaction point position with a fantastic precision - extremly delicate elements



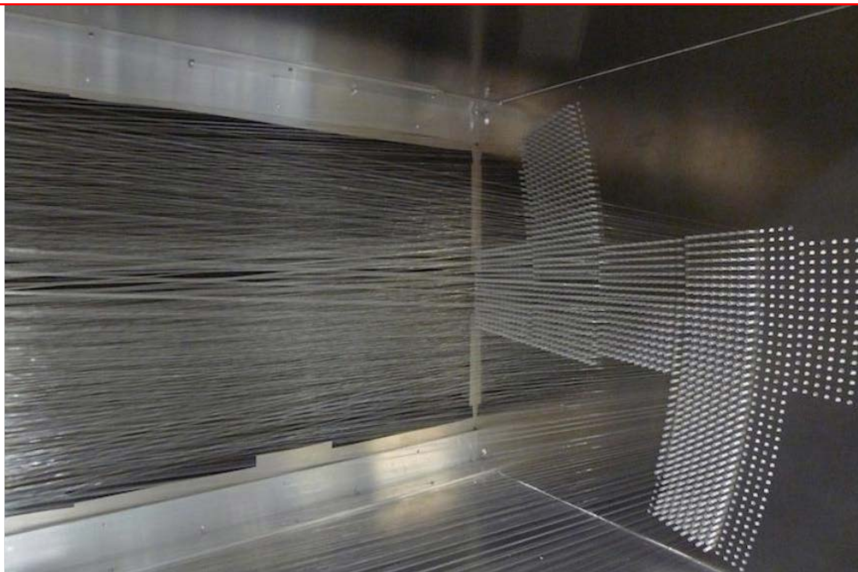
Beryllium beam pipe
2cm diameter

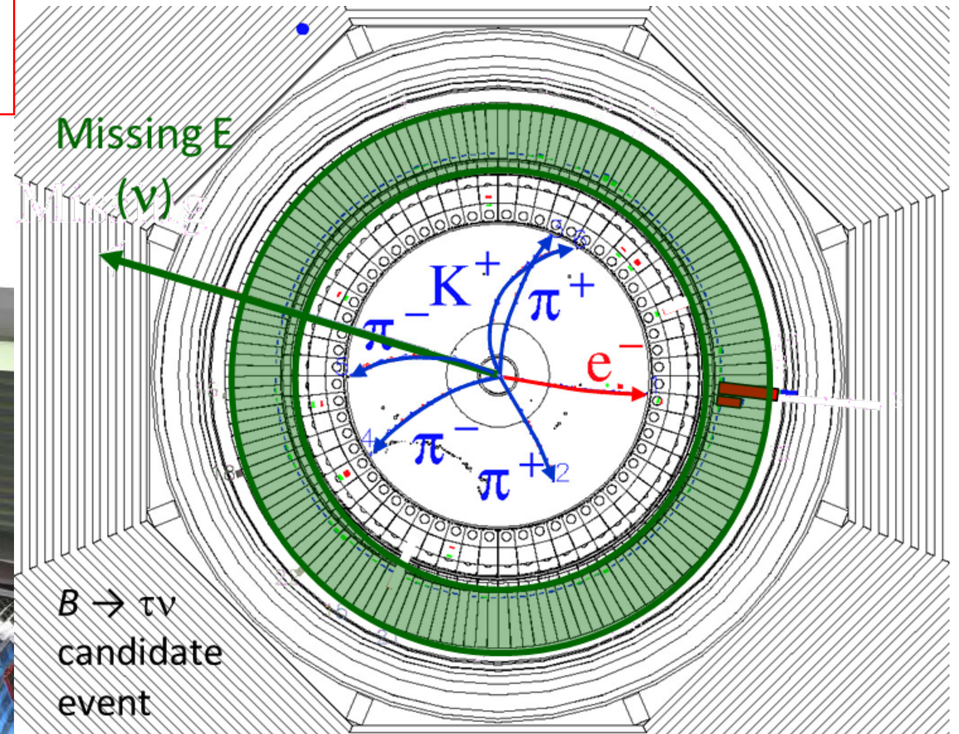
Vertex Detector
2 layers DEPFET + 4 layers DSSD

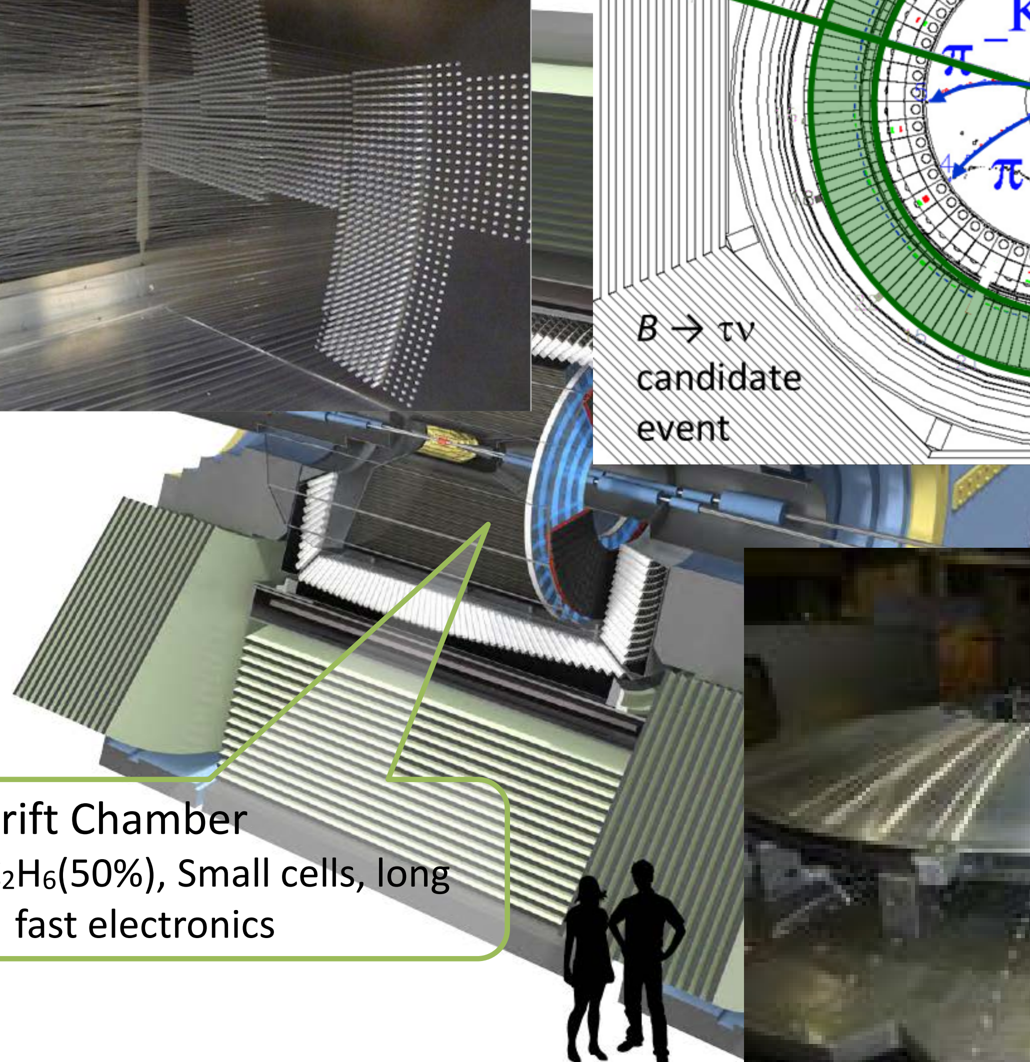




Tracking charged particles in magnetic field – measure their momenta

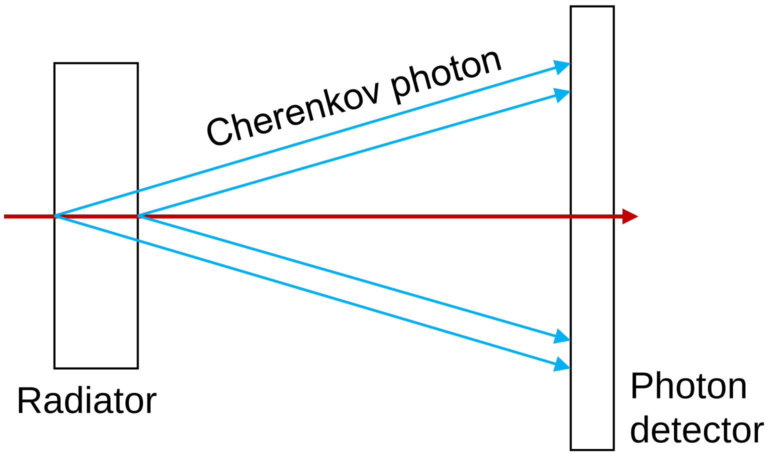


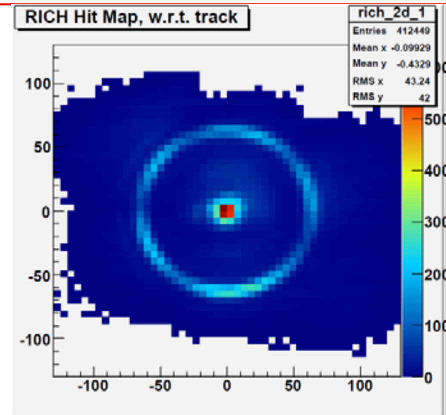


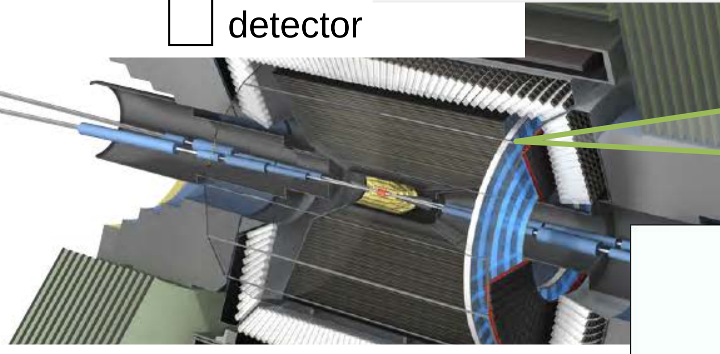


Central Drift Chamber
He(50%):C_2H_6(50%), Small cells, long lever arm, fast electronics

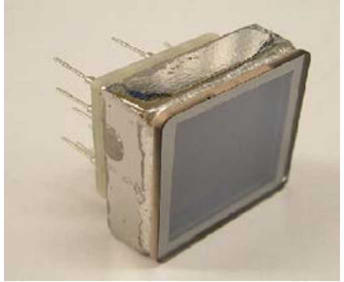
Use Cherenkov effect: light emitted by a particle faster than velocity of light in a medium - like a shock wave from a supersonic airplane!

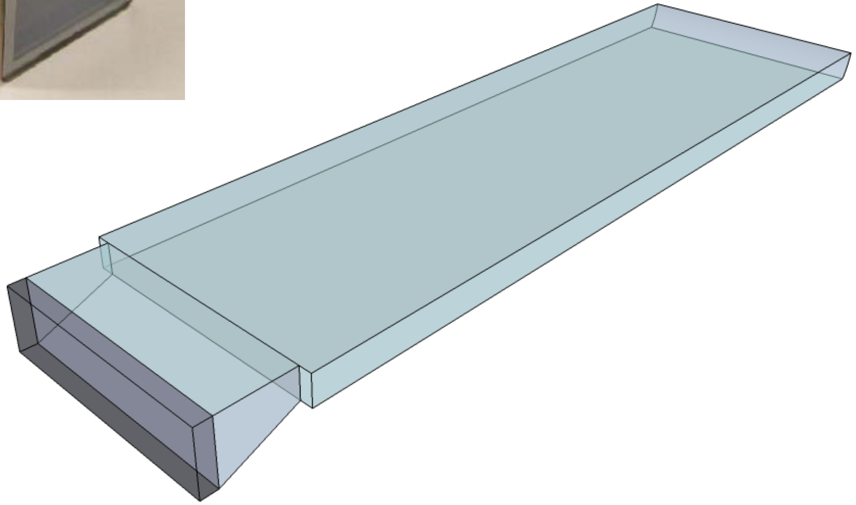


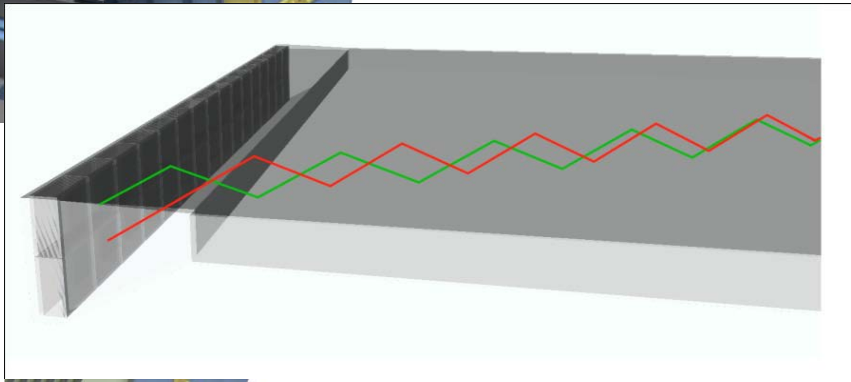




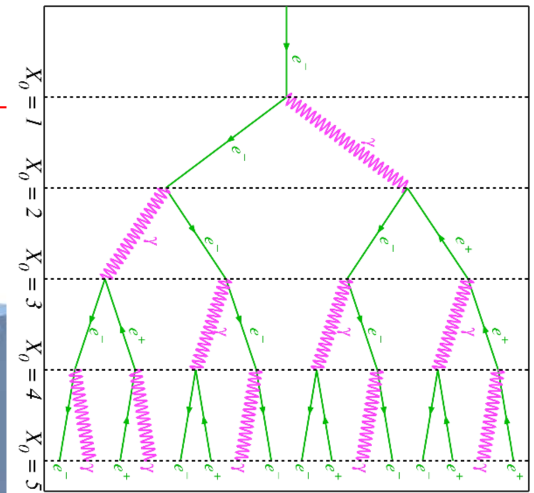
Particle Identification
Time-of-Propagation counter (barrel)
Prox. focusing Aerogel RICH (fwd)

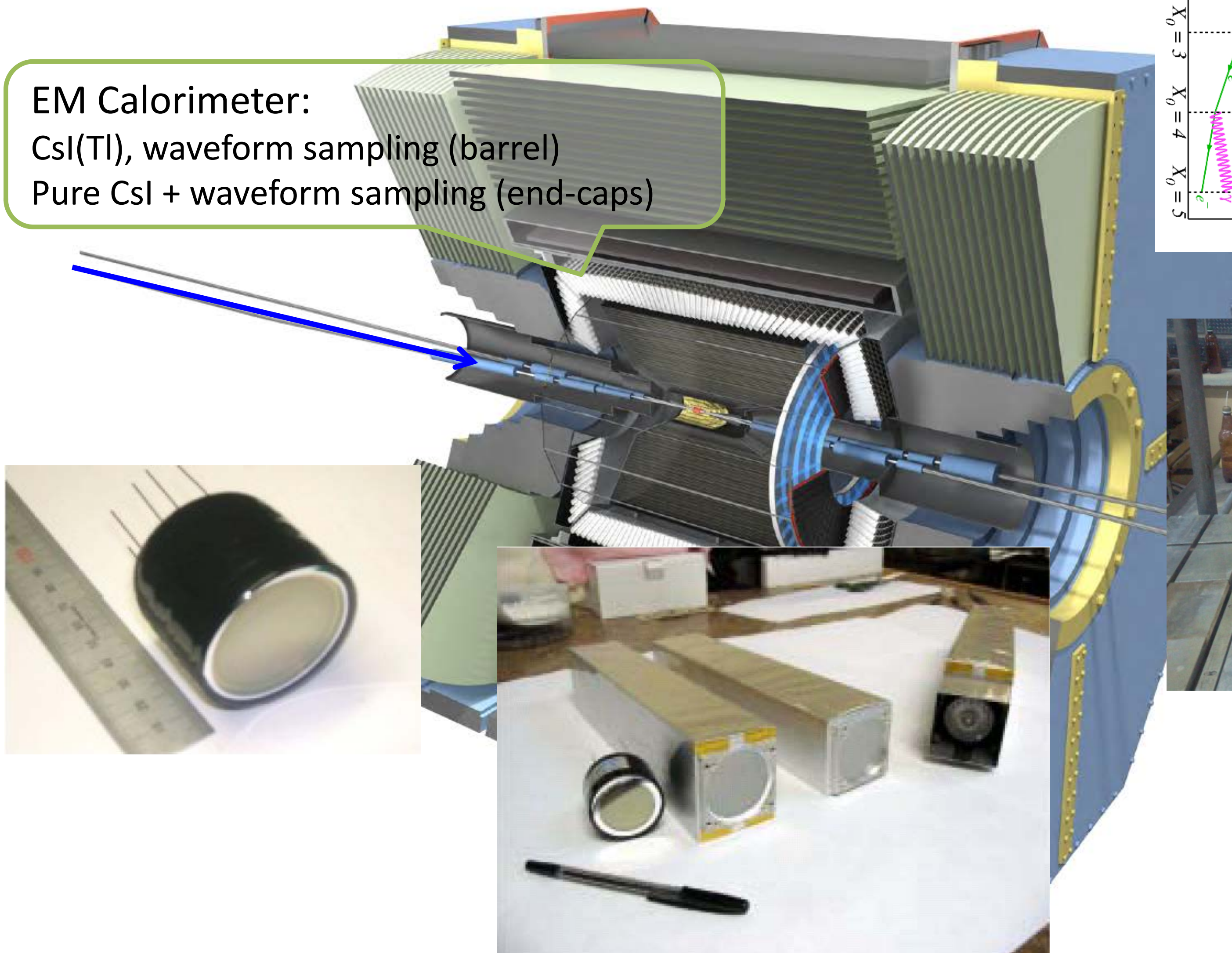






Detect electrons and high energy gamma rays by leting them produce a shower in a heavy crystal





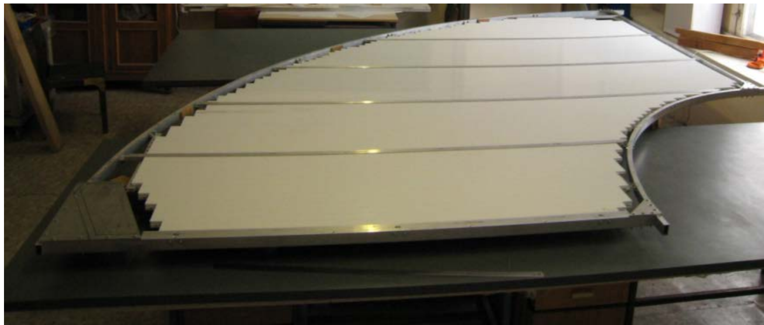
EM Calorimeter:

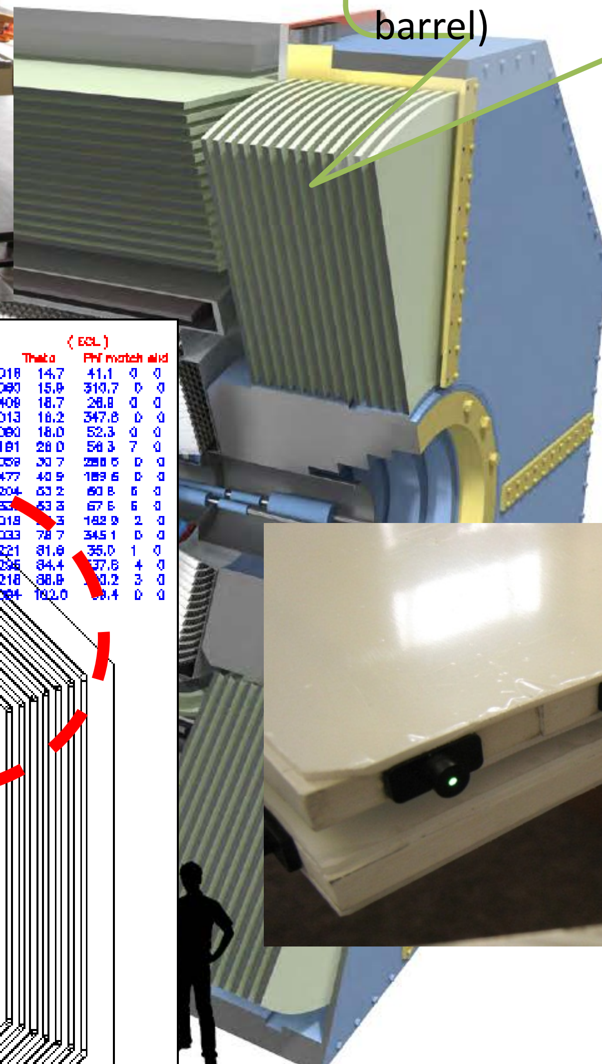
CsI(Tl), waveform sampling (barrel)

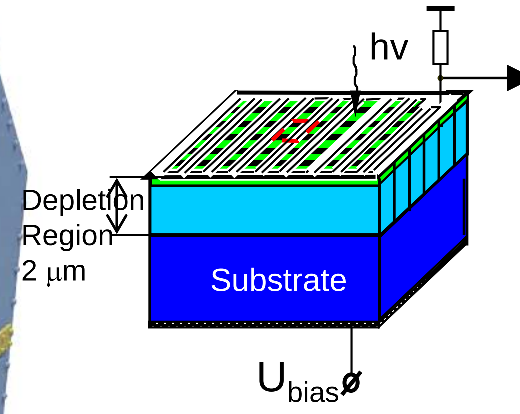
Pure CsI + waveform sampling (end-caps)

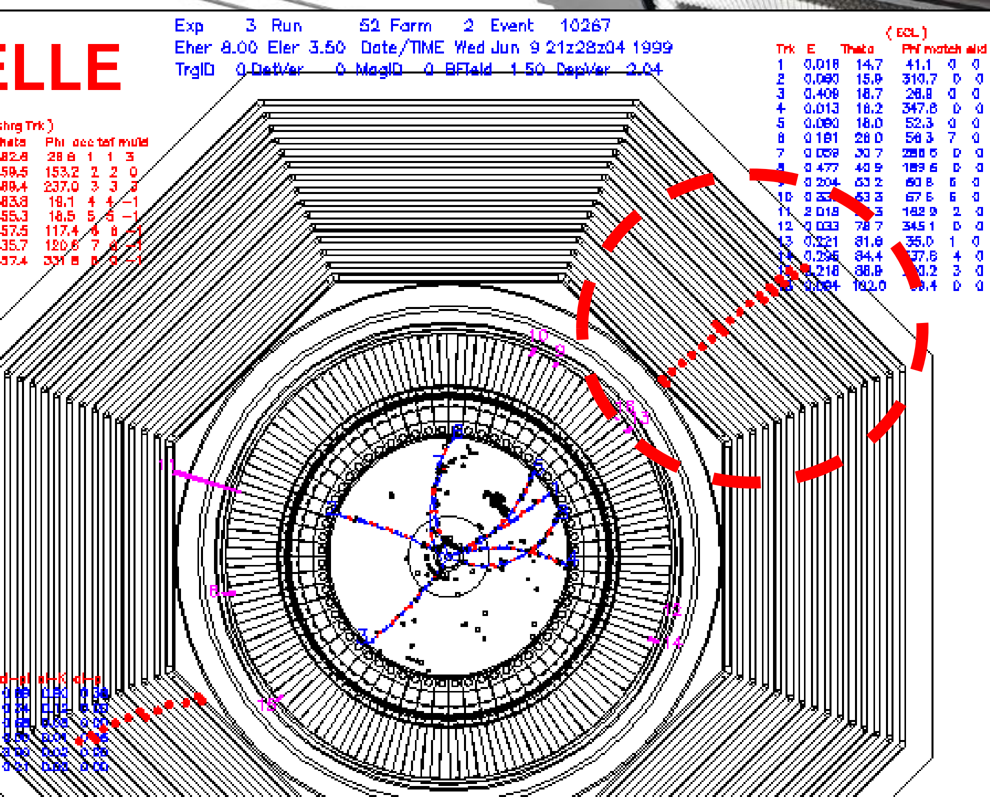
Detect muons: particles that penetrate 1m of iron

KL and muon detector:
Resistive Plate Counter (barrel)
Scintillator + WLSF + MPPC (end-caps + barrel)



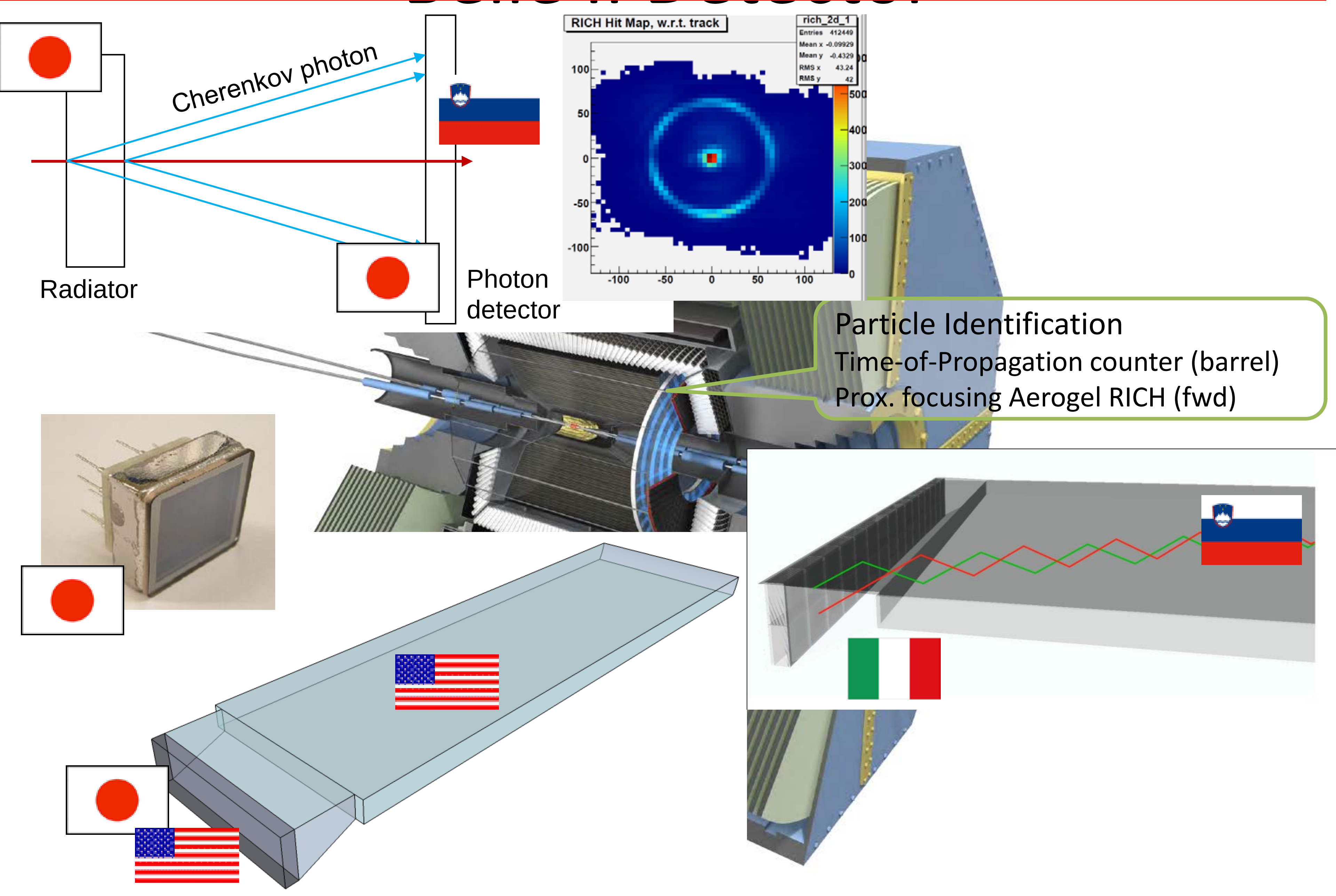




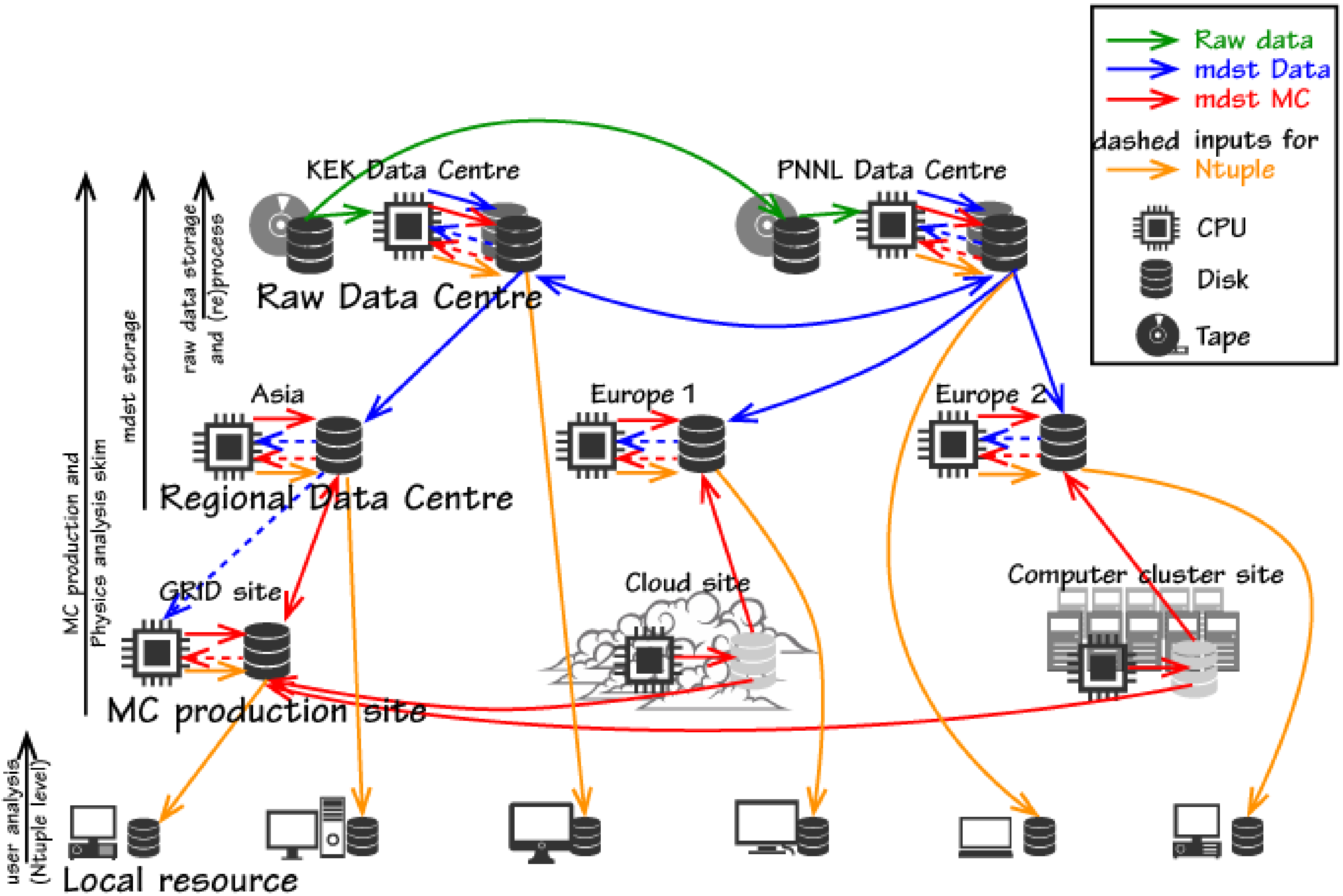


Again: this project would not be possible without a strong international collaboration!

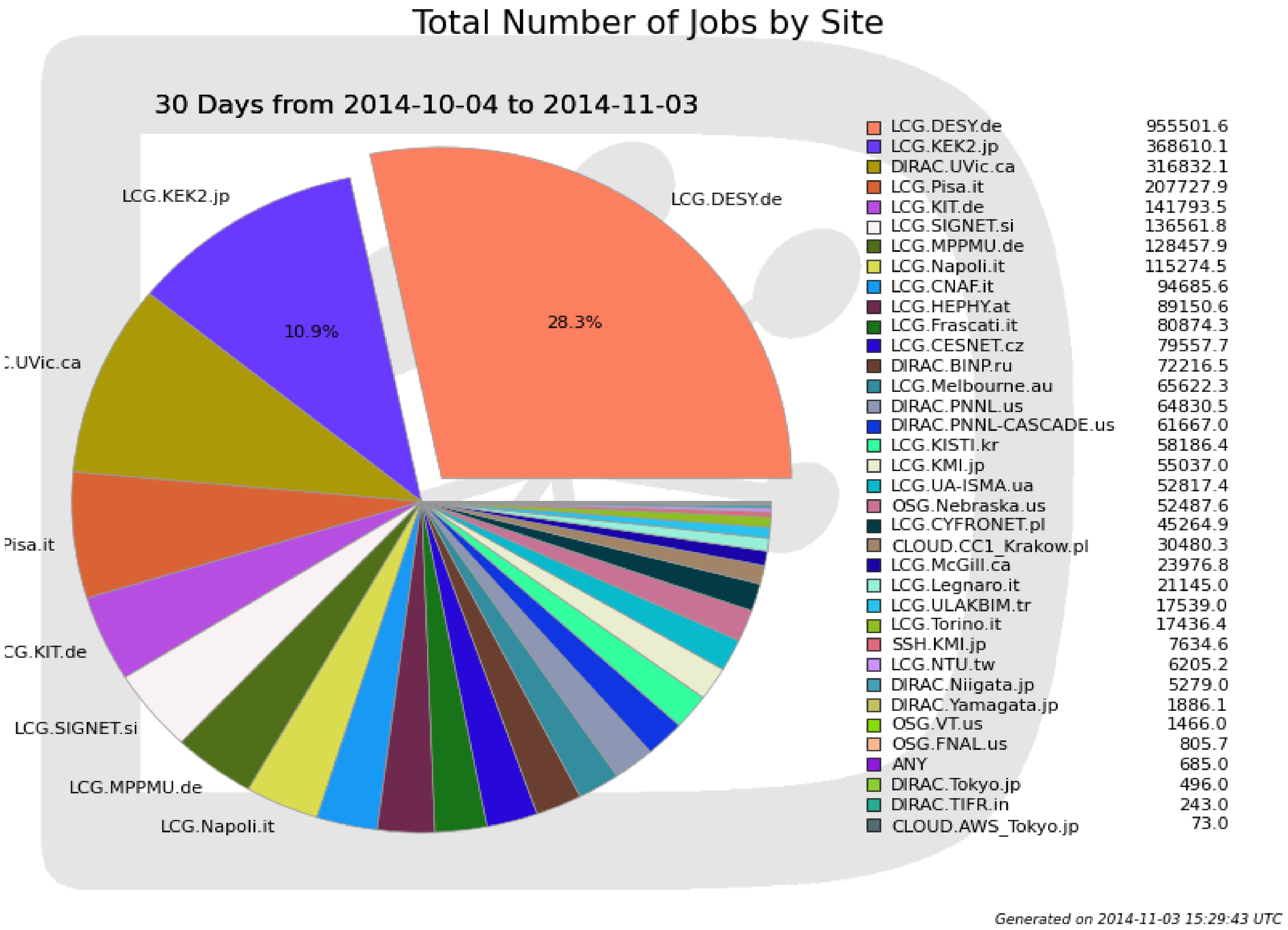
Even a single detector system requires
a broad international collaboration!



Huge data samples @ Belle II:
We need distributed computing resources



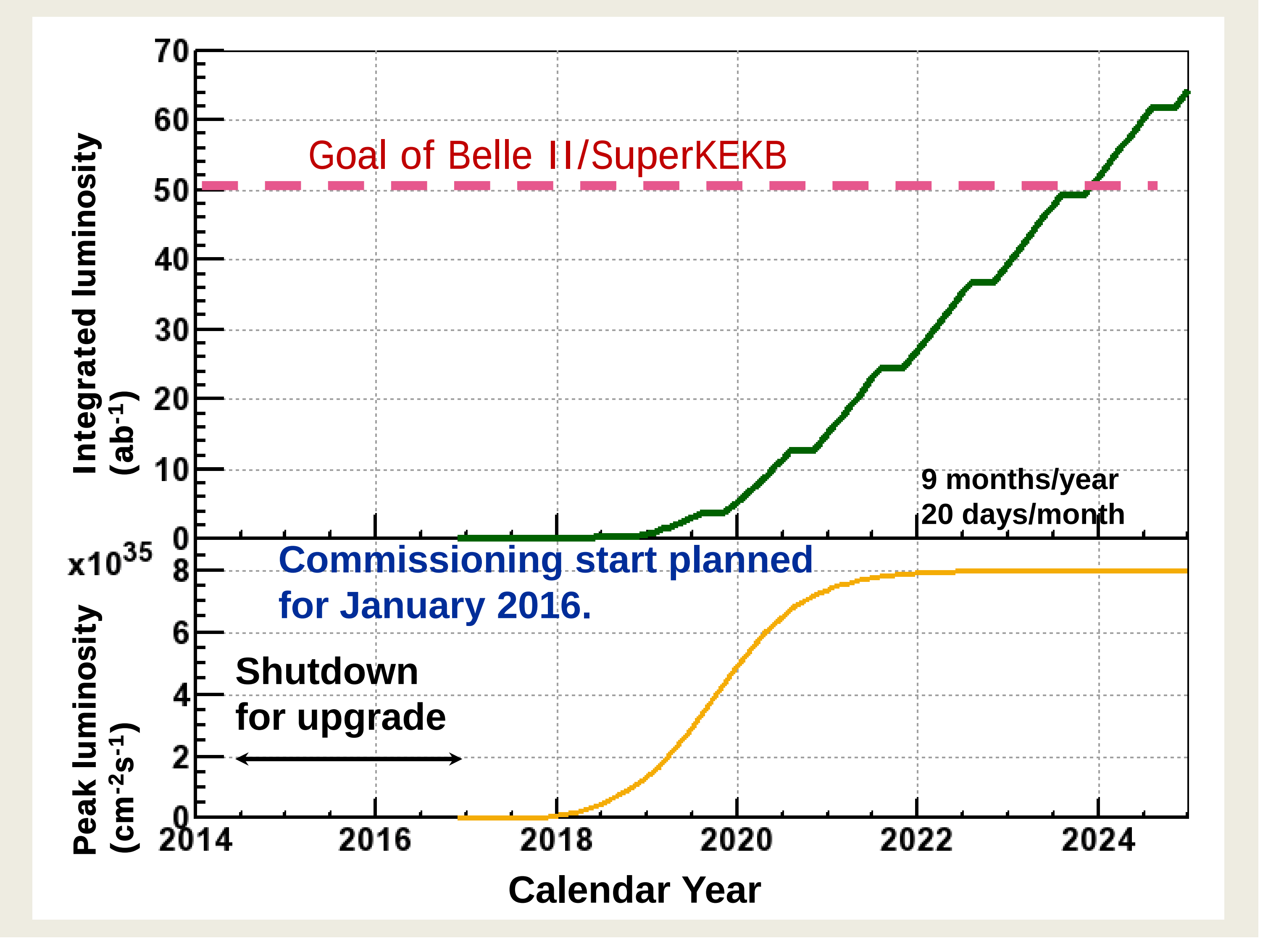
Simulated data campaign in October 2014



The Belle II Collaboration

A very strong group of ~600 highly motivated scientists!

SuperKEKB luminosity projection



Collaboration in numbers…

- 600 collaborators
- ~60 institutions (universities and institutes)
- 20 countries
- ~25 different funding agencies (ministries, agencies)
- Several dramatically different working cultures
- 8 time zones
- 9 different detector systems

How to get organized?

Formally a very loose structure (collaborating scientists are employed by their home institutions, the leader of the experiment (spokesperson) is not a director

Some typical challenges:

- 600 collaborators → a number of different personalities

- ~60 institutions (universities and institutes) → each group has its own leader, and the leader, in turn, has his boss in the home institution

- 20 countries, ~25 different funding agencies (ministries, agencies) → different ways and cycles of funding

- Several considerably different working cultures → Japanese work very long hours, scientists from US are used to fierce discussions

- 8 time zones → impossible to find a time slot for a phone conference that would suit everybody – for some it will always be in the middle of the night...

Sun never sets in the Belle II Collaboration...

Some typical challenges 2:

- 9 different detector systems → different, sometime conflicting requirements, different detector preparation methods

- Formally a very loose structure: collaborating scientists are employed by their home institutions, the leader of the experiment (spokesperson) is not a director → planning of various aspects of the project cannot be carried out by the project top management alone; same is true for the task sharing

Why and how does this work at all?

In this field of science working in large international research groups has a half a century long tradition. Large-scale experiments cannot be carried out even by a single country, let alone by a single research group.

Research groups and individual researchers are highly motivated: they know that one without the other can not succeed. The success of the whole collaboration is crucial for the promotion of individual scientists involved in the project, and for early stage researchers it facilitates the path to a permanent job…

Such a large international research group is formed on a voluntary basis: individual groups either join forces in the preparatory phase of the project, or are in a later stage of the project identified as suitable candidates, and invited to join.

Success is not guaranteed...

Caveat: projects sometimes fail:

- ...sometimes because the physics goal was not well chosen or other experiments were faster or the relevance of the research faded while the project was under preparation → not bad, a good lesson for the next experiment! After all, this is just like in sport, you cannot always win!

- ...sometimes because wrong people came together - this is not so nice, and not particularly useful as an experience...

Organisational structures

Clearly, such a group needs some organization to function.

This is a typical structure:

- Spokesperson leads the group (elected for a fixed term, often renewable)
- Executive board helps in the day-to-day decisions.
- Institutional board: highest body of a collaboration, with representatives from each of the collaborating institutions.
- Coordinators: physics, technical (detector), software, computing: coordination of the work of sub-detector leaders and working group leaders.

Belle II Organization

Executive Board
Chair : H. Aihara
aihara@phys.s.u-tokyo.ac.jp

D.M.Asner, T.Aziz, A.Bozek, P.Chang, F.Forti, T.Iijima, P.Krizan, S.Lange, P.Podesta, M.Roney, C.Schwanda, M.Sevior, E.Won, C.Z.Yuan, K.Akai

Spokesperson : Thomas E. Browder
teb@phys.hawaii.edu

Project Manager : Yoshihide Sakai
Yoshihide.Sakai@kek.jp

Financial Board
Chair : Y.Sakai
Yoshihide.Sakai@kek.jp

W.Abdullah, H.Aihara, D.Asner, R.Ayad, T.Aziz, A.Bozek, T.Browder, P.Chang, Z.Dolezal, G. Finocchiaro, P.Krizan, C.Lacasta, M.I.Martinez, H-G.Moser, C.Nieber, P.Pakhlov, A.Rekalo, M.Ronie, C.Schwanda, M.Sevior, C. P. Shen, U.Tippawan, T.Tran, N.Wermes, E.Won, M.Zeyrek

Institutional Board
Chair : Z.Dolezal
dolezal@ipnp.troja.mff.cuni.cz

Speakers Committee
Chair : A.Schwartz
alan.j.schwartz@uc.edu

T.Iijima, I. Peruzzi, Y.Sakai, C.Schwanda

Physics Coordinator : P.Urquijo
purquijo@unimelb.edu.au

- Semileptonic & Missing Energy : A. Zupanc, G. De Nardo
- Radiative & Electroweak Penguin : A. Ishikawa, J. Yamaoka
- T-Dep. CP Violation : T. Higuchi, L. Li Gioi
- Hadronic B Decay & DCPV : J. Libby, P. Goldenzweig
- Quarkonium : R. Mizuk, T. Pedlar
- Charm : R. Briere, G. Casarosa
- Tau & Low Multiplicity : K. Hayasaka, T. Ferber

Technical Coordinator : Y.Ushiroda
ushiroda@post.kek.jp

Integration Leaders : I. Adachi (Outer)
S. Tanaka (Inner)

- PXD : H.G. Moser, C. Kiesling
- SVD : C. Schwanda (deputy : T. Higuchi)
- CDC : S. Uno
- TOP : J. Fast (deputy : T. Iijima)
- ARICH : S. Nishida, S. Korpar
- ECL : A. Kuzmin
- EKLM : P. Pakhlov
- BKLM : L. Piilonen
- TRG : Y. Iwasaki
- DAQ : R. Itoh
- IR : H. Nakayama
- STR : J. Haba
- BKG : S. Vahsen (deputy : H. Nakayama)

Liaisons :
- S. Tanaka (PXD)
- T. Tsuboyama (SVD)
- I. Adachi (BPID)
- I. Nakamura (ECL)
- K. Sumisawa (BKLM/EKLM)

Software Coordinator : T.Kuhr
Thomas.Kuhr@lmu.de

- Generators : T.Ferber
- Simulation : D. Kim
- Background : M. Staric
- Tracking : M. Heck, E. Paoloni
- Alignment & Calibration : S.Yashchenko
- Database : M. Bracko : L. Wood

Computing Coordinator : T.Hara
takanori.hara@kek.jp

- Distributed Computing Architecture : I. Ueda
- Network / Data Management : M. Schram
- Production System : H. Miyake
- Monitor : K. Hayasaka
- Data Processing :
- Training :

Organisation, continued

Financial aspects are discussed in the Financial board (in some collaboration this is the job of a Resource committee).

External bodies:

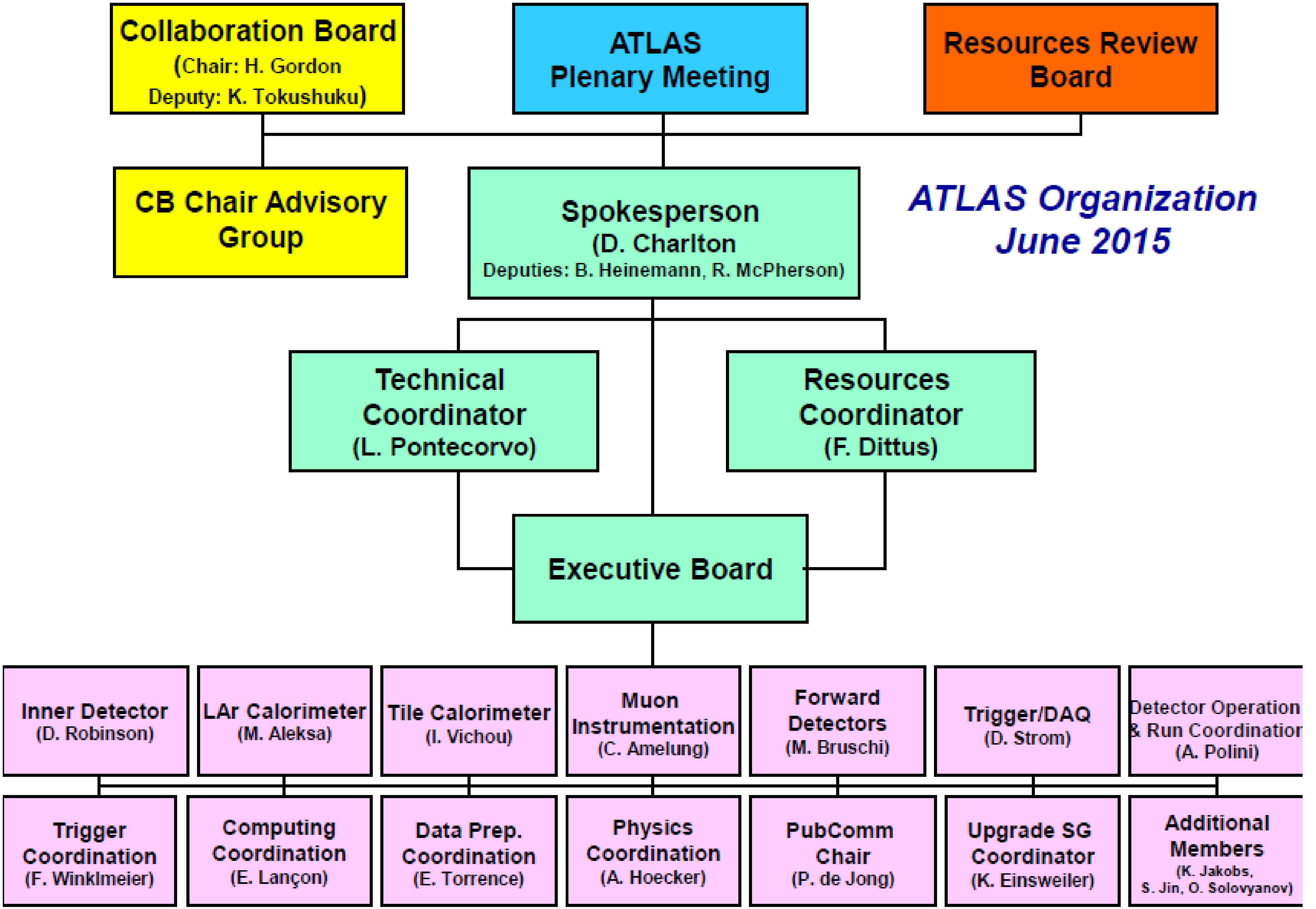
- International advisory committee (at Belle II: BPAC) internationally recognized experts on detectors and physics topics of the experiment
- Financial oversight panel (FOP): representative of funding agencies involved in the project
- Scrutiny Committee: a small body of independent experts from major contributing nations, checks the expenses for the maintenance and operation.

Rules of how to operate (‘bylaws’) are set by the Collaboration Board.

Organisation, continued

In most experiments, there are similar structures.

→ ATLAS



Collaboration Board
(Chair: H. Gordon
Deputy: K. Tokushuku)
ATLAS
Plenary Meeting
Resources Review
Board
CB Chair Advisory
Group
Spokesperson
(D. Charlton
Deputies: B. Heinemann, R. McPherson)
ATLAS Organization
June 2015
Technical
Coordinator
(L. Pontecorvo)
Resources
Coordinator
(F. Dittus)
Executive Board
Inner Detector
(D. Robinson)
LAr Calorimeter
(M. Aleksa)
Tile Calorimeter
(I. Vichou)
Muon
Instrumentation
(C. Amelung)
Forward
Detectors
(M. Bruschi)
Trigger/DAQ
(D. Strom)
Detector Operation
& Run Coordination
(A. Polini)
Trigger
Coordination
(F. Winklmeier)
Computing
Coordination
(E. Lançon)
Data Prep.
Coordination
(E. Torrence)
Physics
Coordination
(A. Hoecker)
PubComm
Chair
(P. de Jong)
Upgrade SG
Coordinator
(K. Einsweiler)
Additional
Members
(K. Jakobs,
S. Jin, O. Solovyanov)

Summary

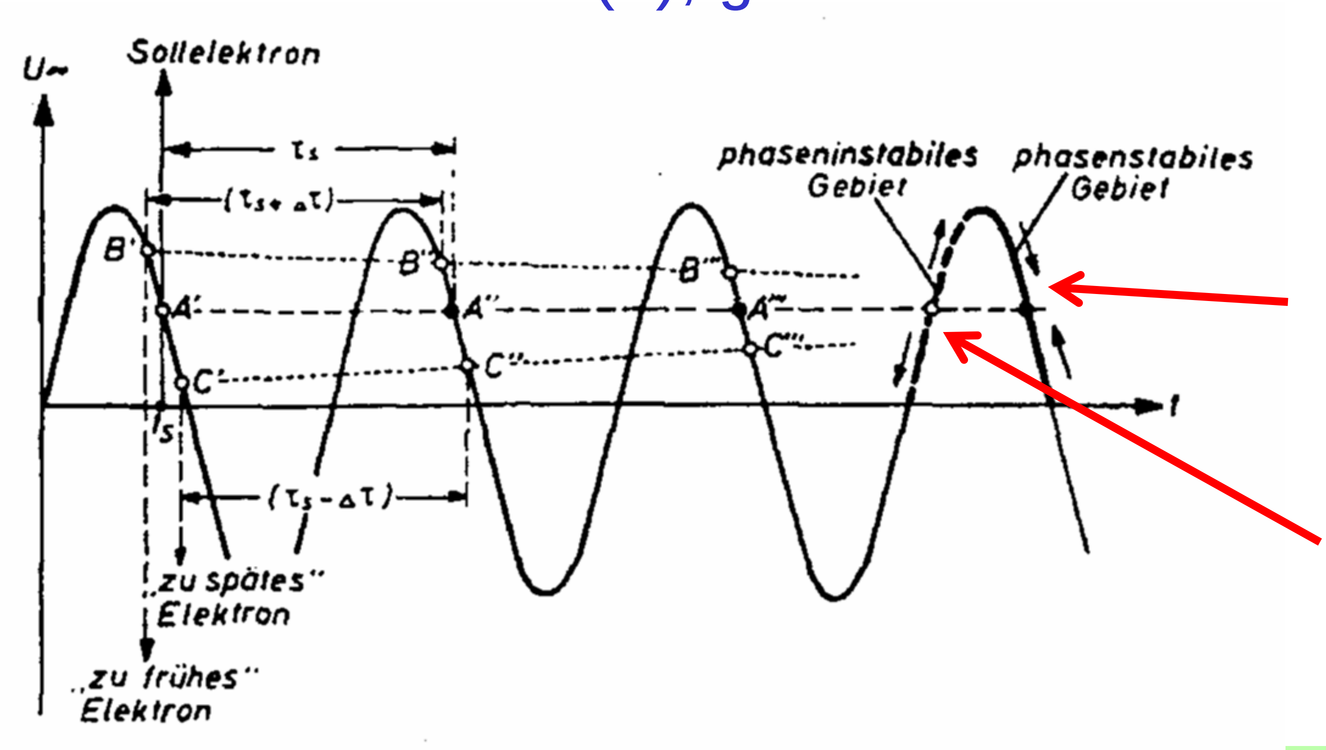
- In particle physics, working in large international research groups has a long tradition. Large-scale experiments cannot be carried out even by a single country, let alone by a single research group.
- Research groups and individual researchers are highly motivated to collaborate in the team: they know that one without the others can not succeed. The success of the whole collaboration is crucial for the promotion of individual scientists involved in the project.
- Still, some organizational structures are needed to steer the project.
- At KEK in Tsukuba a major upgrade is under way since 2010, to resume operation in 2016 → SuperKEKB+Belle II, with 40x larger event rates.
- Expect a new, exciting era of discoveries, complementary to the LHC

More slides….

Stability of acceleration

•For a synchronous particles (A): energy loss = energy received from the RF field

•A particle that comes too late (B), gets more energy, the one that is too fast (C), gets less →

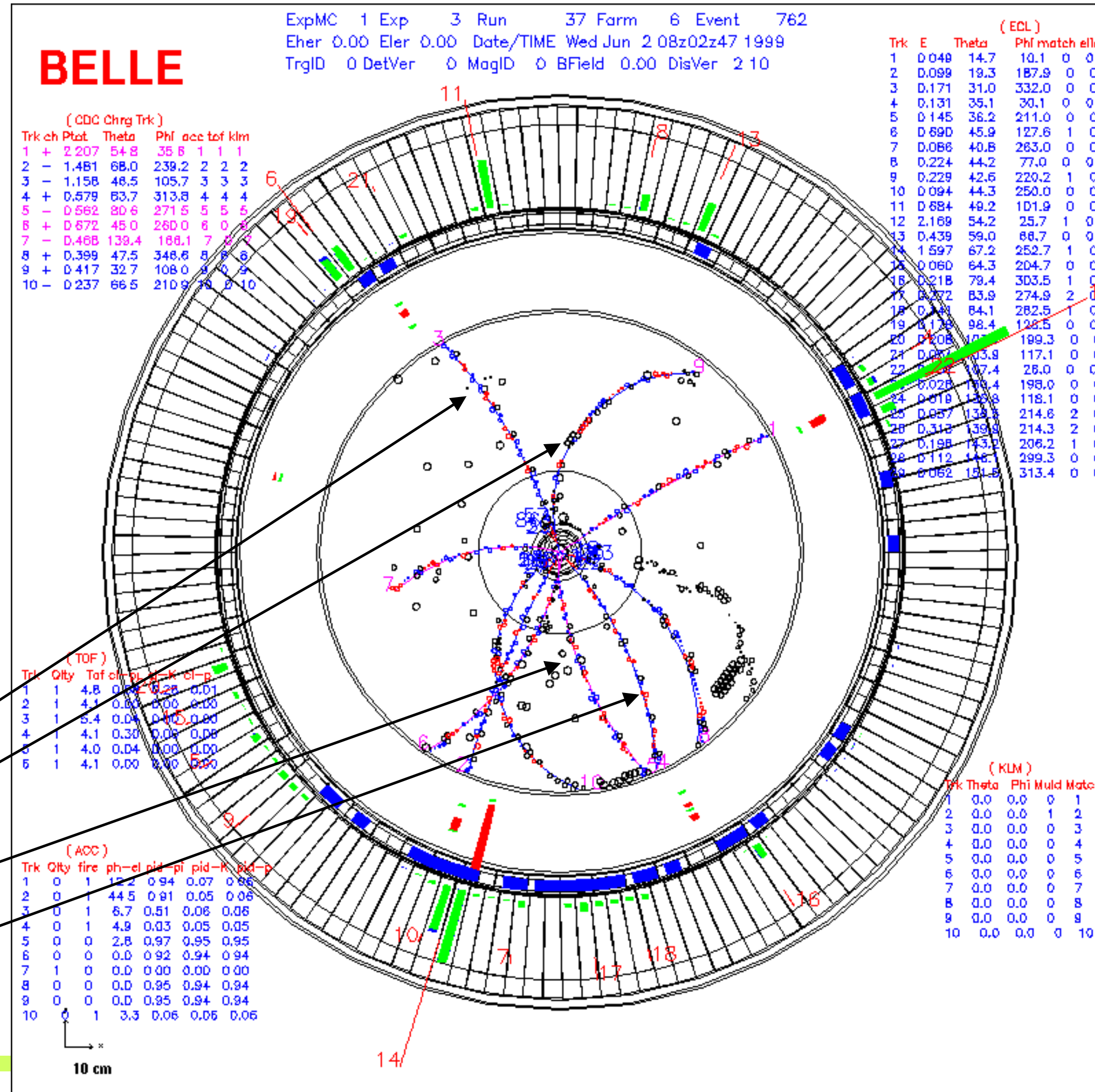


•OK if particle ~ in phase→ stable orbit

•Not OK if too far away

How to understand what happened in a collision?

Illustration on an example:



$B^0 \rightarrow K^0_S\, J/\psi$

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

$J/\psi \rightarrow \mu^- \mu^+$

Search for particles that decayed close to the production point

How do we reconstructing final states that decayed to several stable particles (e.g., x1, x2, x3), X → x1 x2 x3?

From the measured tracks calculate the invariant mass of the system (i= 1,2,3):

$$M = \sqrt{(\sum E_i)^2 - (\sum \vec{p}_i)^2}$$

The candidates for the X → x1 x2 x3decay show up as a peak in the distribution above (mostly combinatorial) background.

The name of the game: have as little background under the peak as possible without loosing the events in the peak (=reduce background and have a small peak width).

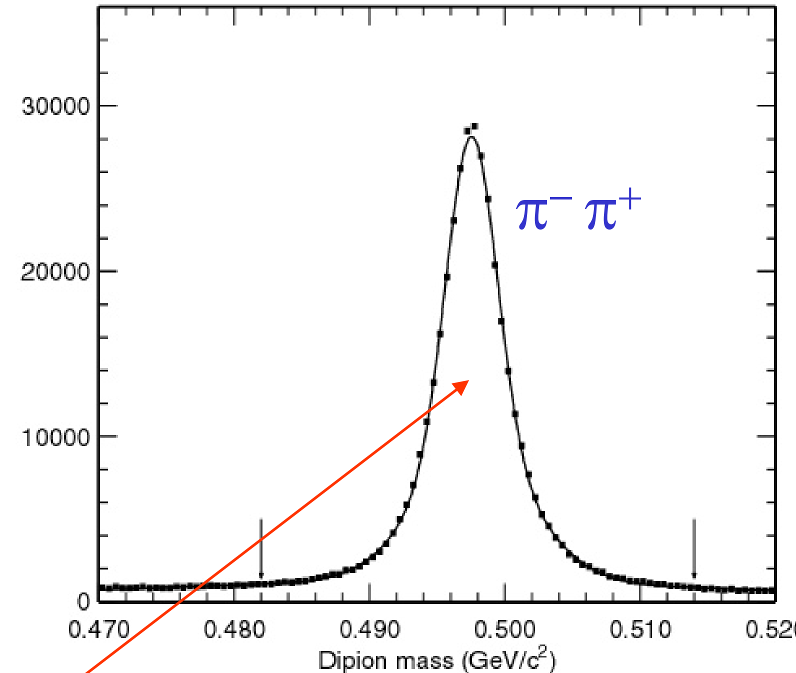
How do we know it was precisely this reaction?

$B^0 \rightarrow K^0_S \, J/\psi$

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

$J/\psi \rightarrow \mu^- \mu^+$

detect

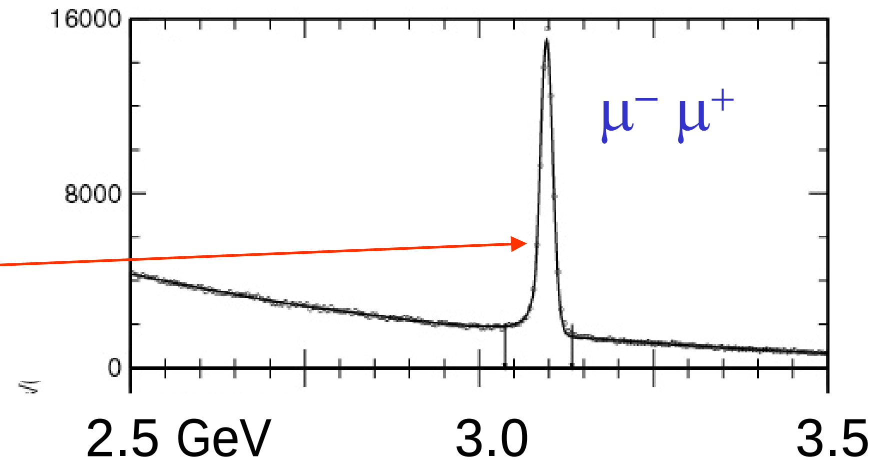


For $\pi^- \pi^+$ in $\mu^- \mu^+$ pairs we calculate the invariant mass:

$$M^2c^4 = (E_1 + E_2)^2 - (p_1 + p_2)^2$$

Mc^2 must be for K^0_S close to 0.5 GeV,

for J/ψ close to 3.1 GeV.



Background below the peaks: random coincidences ('combinatorial background')

Two complementary approaches to study shortcomings of the Standard Model and to search for the so far unobserved processes and particles (so called New Physics, NP). These are the **energy frontier** and the **intensity frontier** .

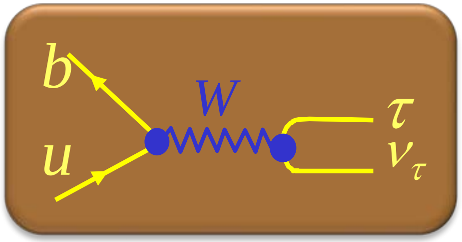
Energy frontier : direct search for production of unknown particles at the highest achievable energies.

Intensity frontier : search for rare processes, deviations between theory predictions and experiments with the ultimate precision.

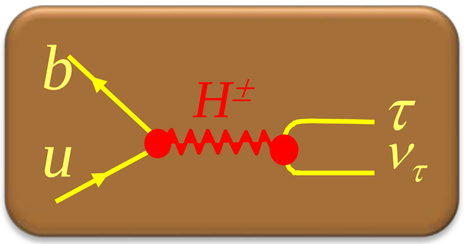
→for this kind of studies, one has to investigate a very large number of reactions (˝events˝) → need accelerators with ultimate **intensity** (˝luminosity˝)

An example: Hunting the charged Higgs in the decay $B^- \to \tau^- \nu_\tau$

In addition to the Higgs particle discovered at the LHC in 2012, in New Physics (e.g., in supersymmetric theories) there could be another one – a charged Higgs.



The rare decay $B^- \to \tau^- \nu_\tau$ is in SM mediated by the W boson

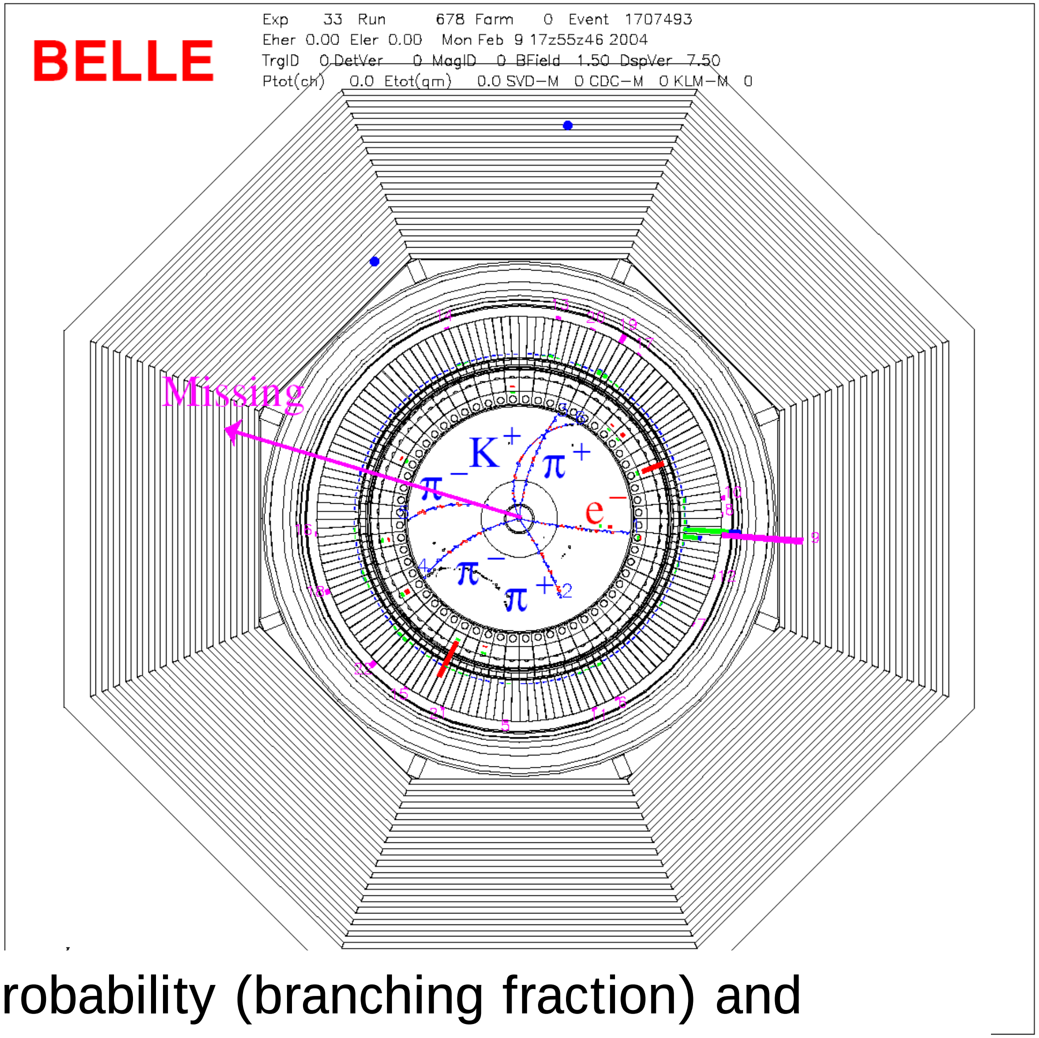


In some supersymmetric extension it can also proceed via a charged Higgs

The charged Higgs would influence the decay of a B meson to a tau lepton and its neutrino, and modify the probability for this decay.

Missing Energy Decays: $B^- \to \tau^- \nu_\tau$

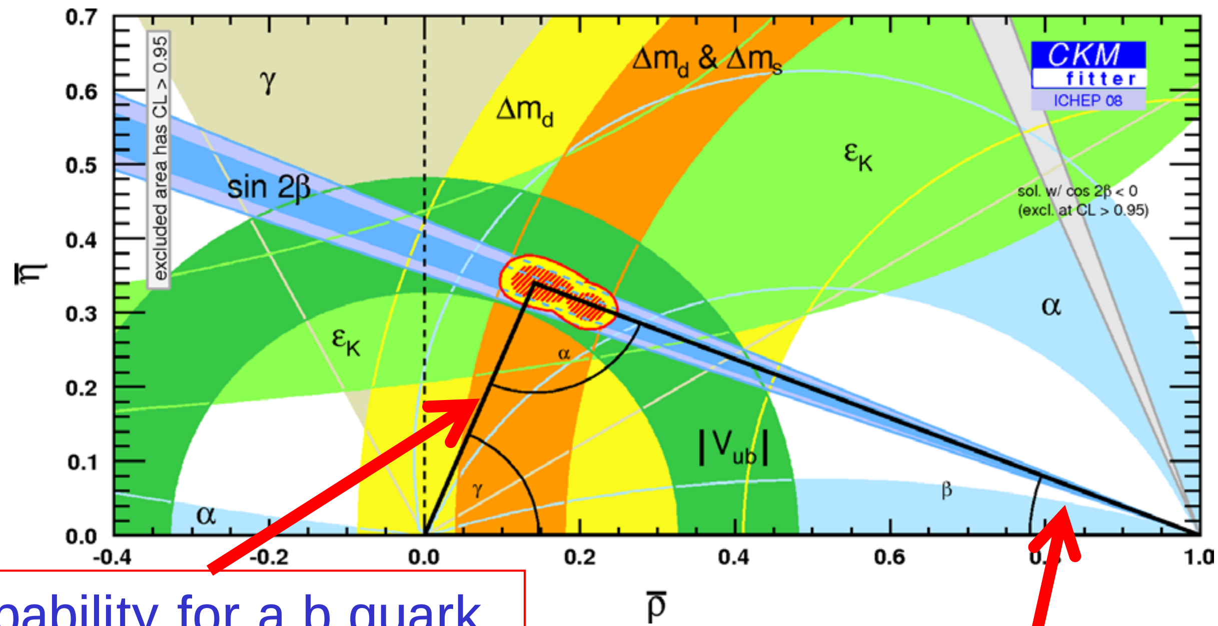
$$B^+ \to D^0\pi^+$$
$$(\to K\pi^-\pi^+\pi^-)$$
$$B^- \to \tau(\to e\nu\bar{\nu})\nu$$



By measured the decay probability (branching fraction) and comparing it to the SM expectation:

→ Properties of the charged Higgs (e.g. its mass)

All experimental studies combined...



Probability for a b quark to turn into a u quark → determines the length of the side $\mathbf{V_{ub}}$

CP asymmetry oscillation amplitude → angle $\phi_1 = \beta$

Constraints from measurements of angles and sides of the unitarity triangle

→ Remarkable agreement

Relation between the Super B Factory and the LHC

- **Physics motivation is independent of LHC**.
  - If LHC finds NP, precision flavour physics is compulsory.
  - If LHC finds no NP, high statistics B/τ decays would be a unique way to search for the >TeV scale physics (=TeV scale in case of MFV).

How big is a nano-beam ?

Beam-beam parameter

Lorentz factor

Beam current

$$L = \frac{\gamma_{e\pm}}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\left(\frac{I_{e\pm}\xi_y^{e\pm}}{\beta_y^*}\right)\left(\frac{R_L}{R_{\xi_y}}\right)$$

Lumi. reduction factor (crossing angle)&
Tune shift reduction factor (hour glass effect)
0.8 - 1
(short bunch)

Classical electron radius

Beam size ratio@IP
1 - 2 % (flat beam)

Vertical beta function@IP

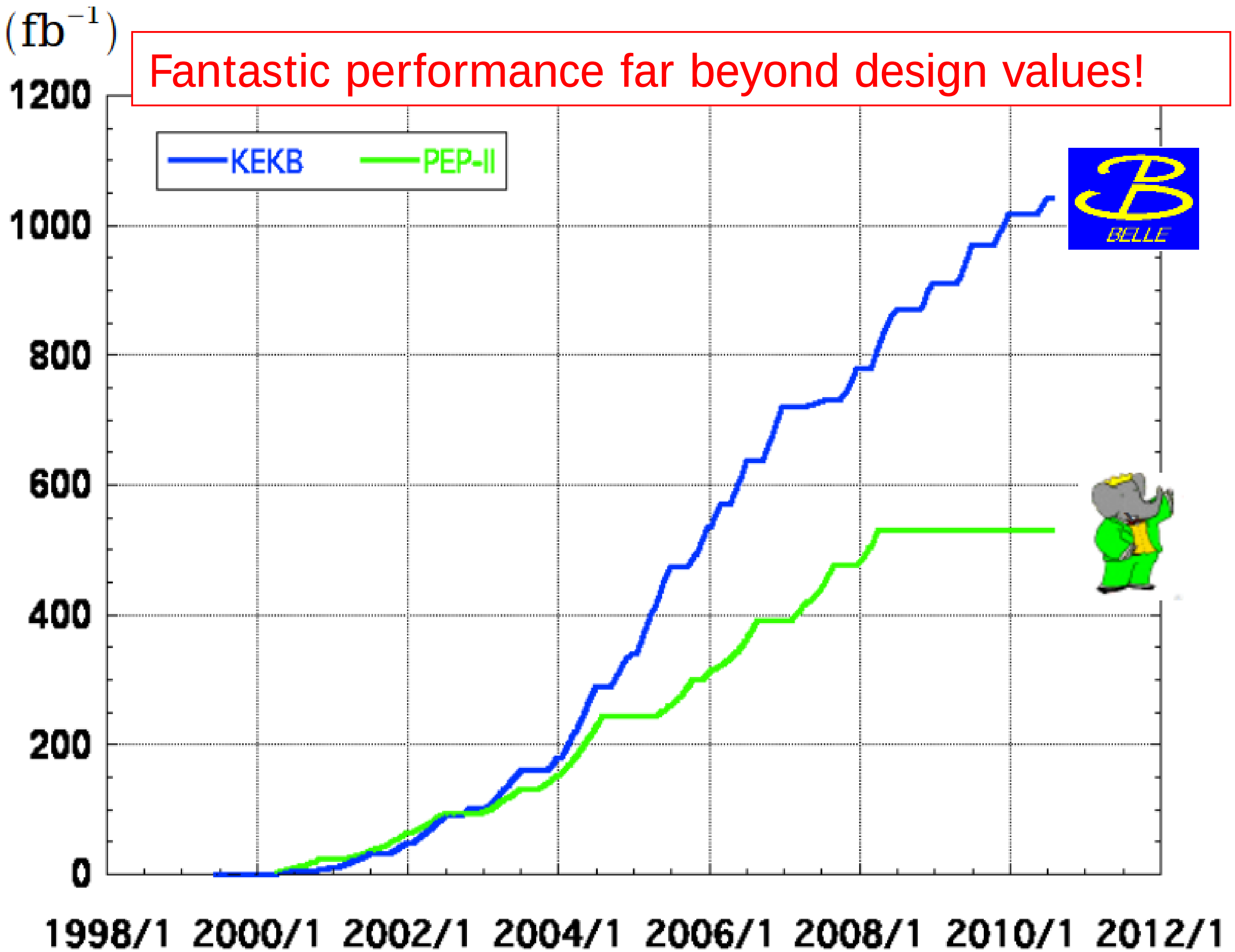
(1) Smaller β_y^*
(2) Increase beam currents
(3) Increase ξ_y

← **"Nano-Beam" scheme**

Collision with very small spot-size beams

Invented by Pantaleo Raimondi for SuperB

Integrated luminosity at B factories



$> 1\ \mathrm{ab}^{-1}$

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:

$\sim 100\ \mathrm{fb}^{-1}$

$\sim 550\ \mathrm{fb}^{-1}$

On resonance:

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

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

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

Off resonance:

$\sim 54\ \mathrm{fb}^{-1}$