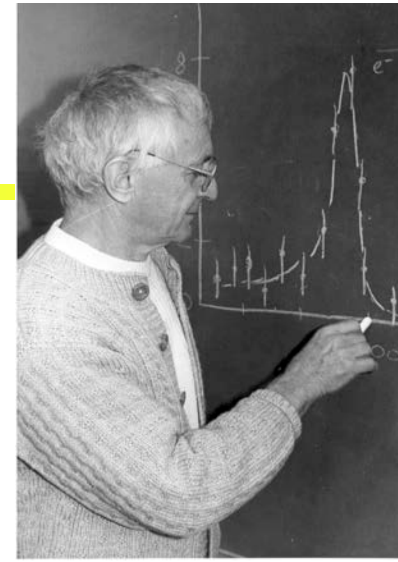
Elkofest 2012, Slavnostna akademija of 80-letnici akad. prof. dr. Gabrijela Kernela, 13. september 2012



Where did anti-matter go?

Peter Križan

University of Ljubljana and J. Stefan Institute

Contents

- What happened to the anti-matter?
- How to measure CP violation?
- The SuperKEKB / Belle II project
- Status and outlook

Open questions of particle physics (and cosmology)

- Why is the Universe predominantly made of matter, and of very little anti-matter?

→ Measure violation of the CP symmetry between particles and anti-particles

- What is the origin of mass?

→ Higgs boson search

- Why do particles have different masses, why are there several families of particles, what is dark matter?

→ Searches for new particles (e.g. supersymmetric partners of known particles) and their interactions

Difference between matter and anti-matter

Out of 10 billion particles and 10 billion 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-particle

CP symmetry and its violation

CP symmetry operation: turns a particle into its anti-particle

If particles and anti-particles behave differently – e.g. if there are differences in their decays → violation of CP symmetry.

Since the early Universe contained the same numbers of particles and anti-particles, while it is today composed only of matter (=particles), and no anti-matter, this symmetry is obviously broken!

→ Very important to understand why and how this symmetry is broken.

CP symmetry and its violation

1964: Fitch, Cronin and collaborators discover CP symmetry violation for neutral kaons

1973: Kobayashi in Maskawa: formulate a theory on how this symmetry is broken; the theory requires the existence of six quark types. A very daring hypothesis since it was formulated when only three quark types where known!

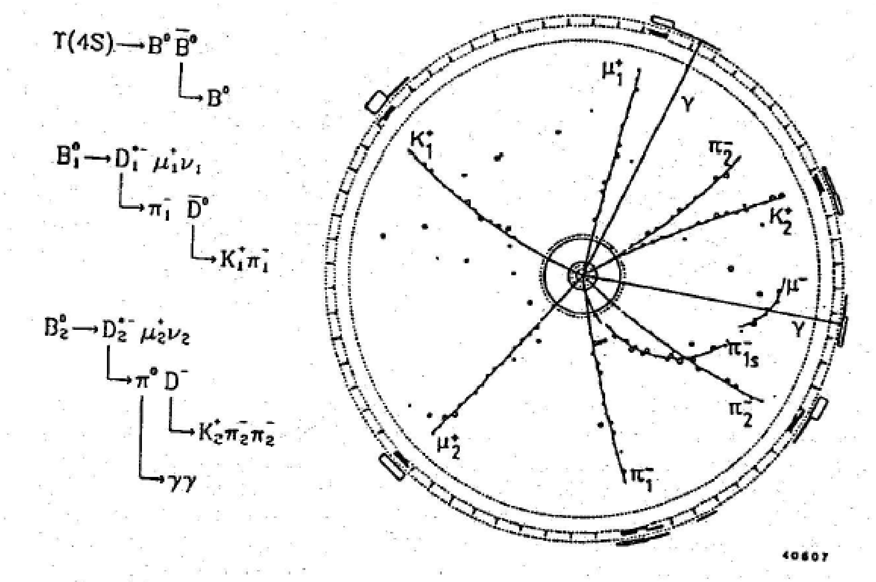
Their theory predicted that there are tight links between CP violation for various particle types, and also tight links to transitions between quark types.

1974, 1977, 1994: 21 years after their theory was published, all missing quarks were found.

However, the decisive proof of CP symmetry violation for these heavier particles only came in the last decade when we measured CP violation in B meson decays.

1987: First important step, discovery of the particle → anti-particle transitions for B^0 mesons

1987: ARGUS Collaboration discovers BB mixing: B^0 turns into anti-B^0



Reconstructed event with one B→anti-B

Integrated Y(4S) luminosity 1983-87:
103 pb^{-1} ~110,000 B pairs

(=1/7000 of the Belle data sample…)

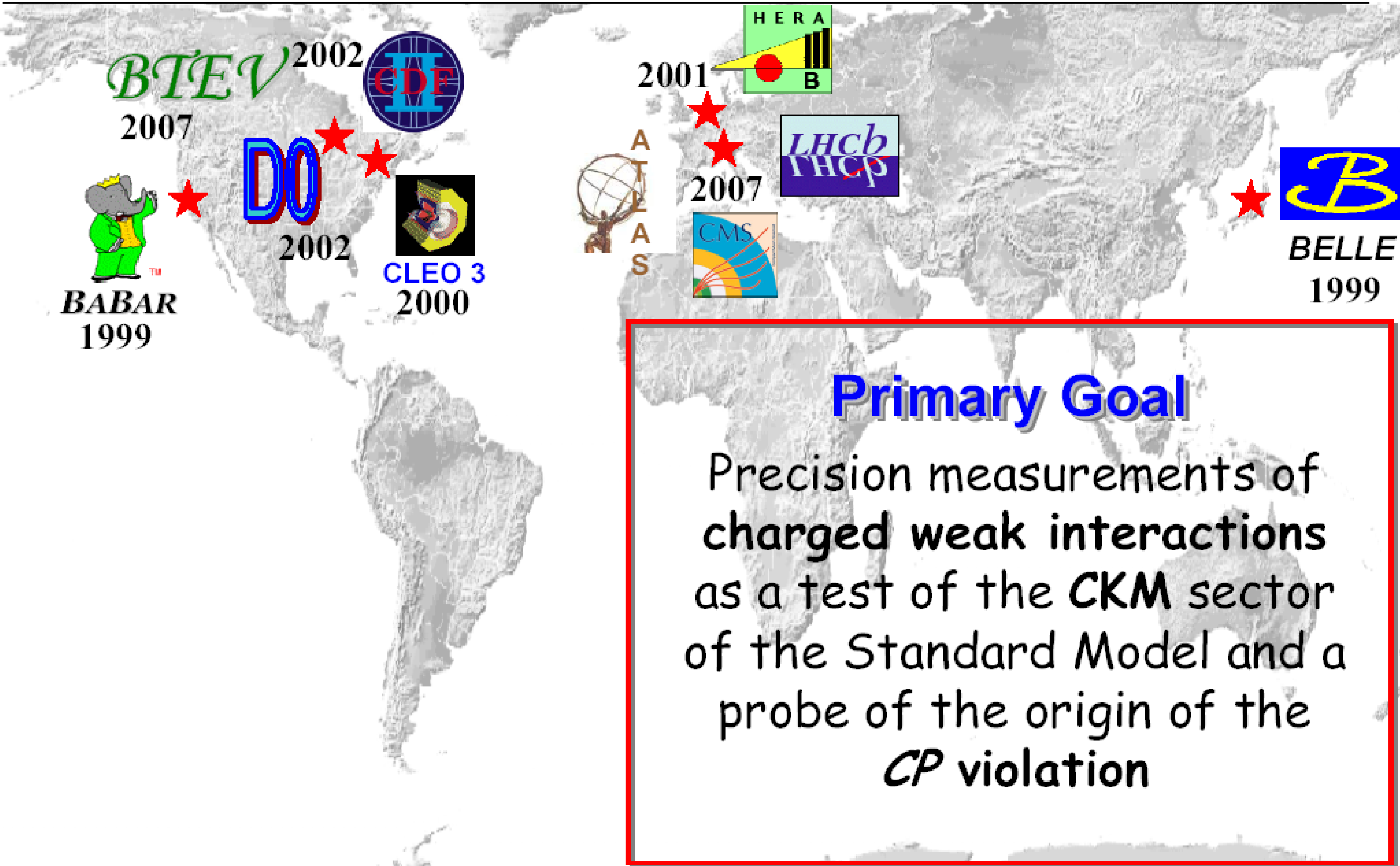
Large mixing in the B^0 system →

→ Top quark is very heavy

→ CP violation effects could be large in B decays → observable

Worldwide effort!

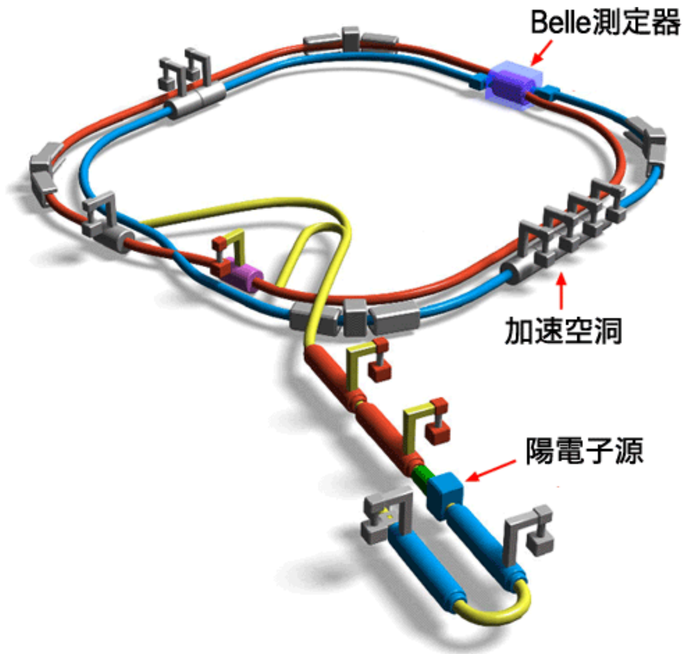
many experiments proposed around 1990, some approved, 2 succeeded...

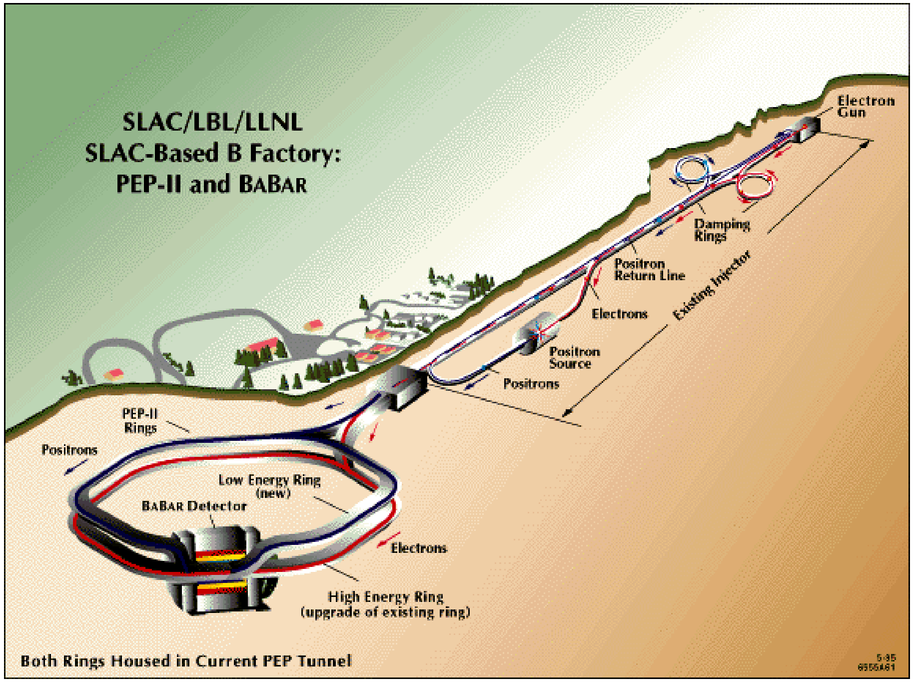


Primary Goal

Precision measurements of **charged weak interactions** as a test of the **CKM** sector of the Standard Model and a probe of the origin of the *CP* **violation**

Final winners: asymmetric B factories





$\sqrt{s}=10.58$ GeV

$e^+ \rightarrow \Upsilon(4s) \leftarrow e^-$

$\Upsilon(4s) \rightarrow B\,\bar{B}$

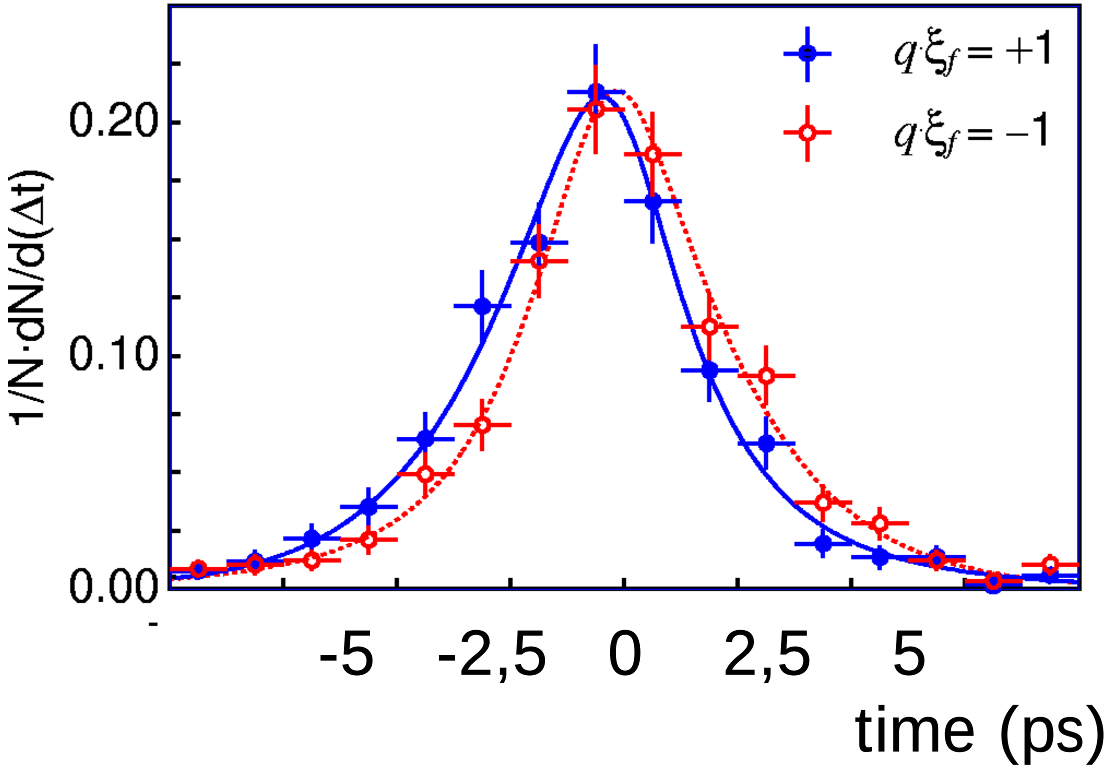
$\Delta z \sim c\beta\gamma\tau_B \sim 200\mu m$

BaBar	$p(e^-)=9$ GeV $p(e^+)=3.1$ GeV	$\beta\gamma=0.56$
Belle	$p(e^-)=8$ GeV $p(e^+)=3.5$ GeV	$\beta\gamma=0.42$

Results of our measurements: CP symmetry is violated in the B meson system!

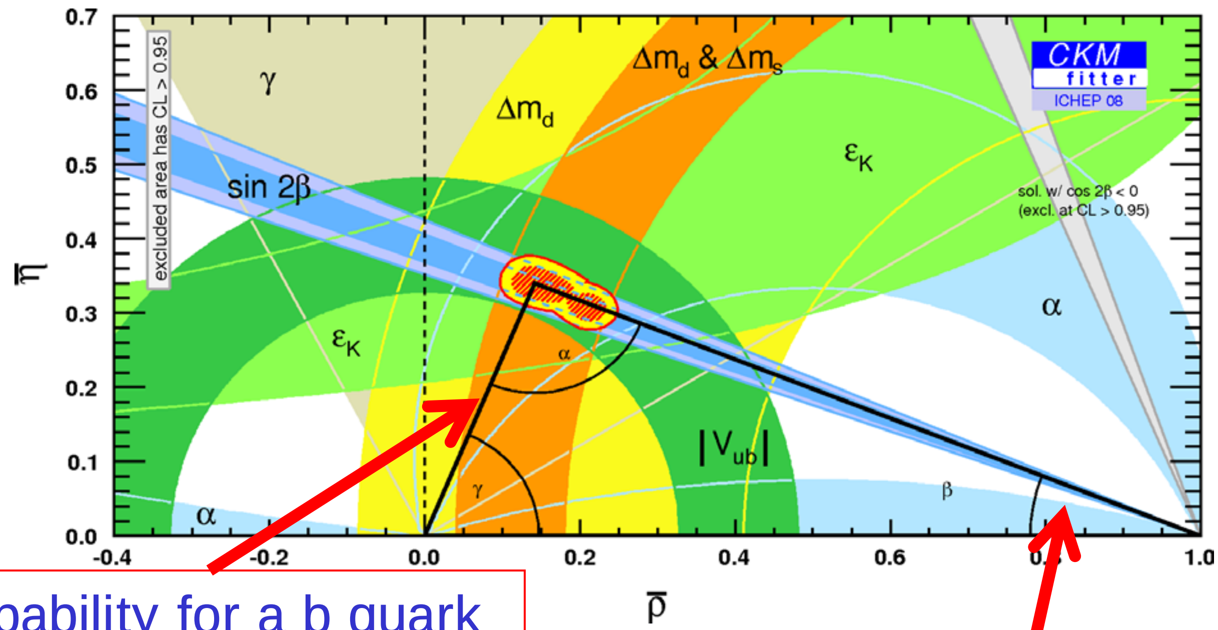
Blue: time dependence of the anti-B decays

Red: same for B decays



Obvious difference between particles in anti-particles!

All experimental studies combined...



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

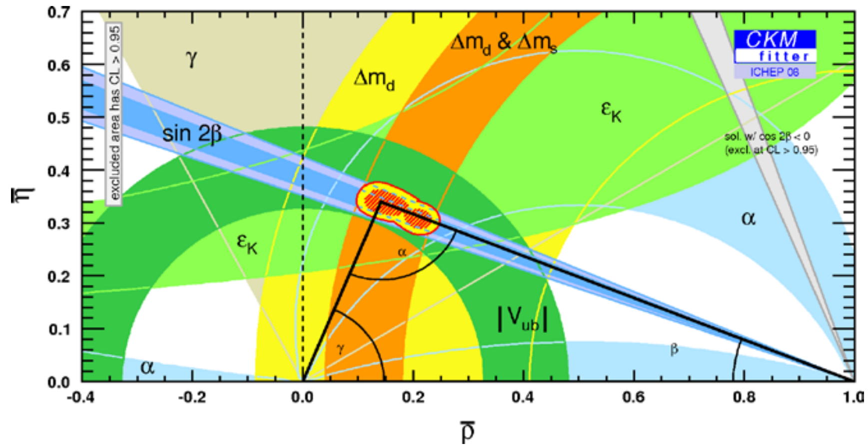
CP asymmetry oscilation amplitude → angle $\phi_1 = \beta$

Constraints from measurements of angles and sides of the unitarity triangle

→ Remarkable agreement

Bold idea of Kobayashi and Maskawa verified by experiment

Relations between parameters as expected in the Standard model →

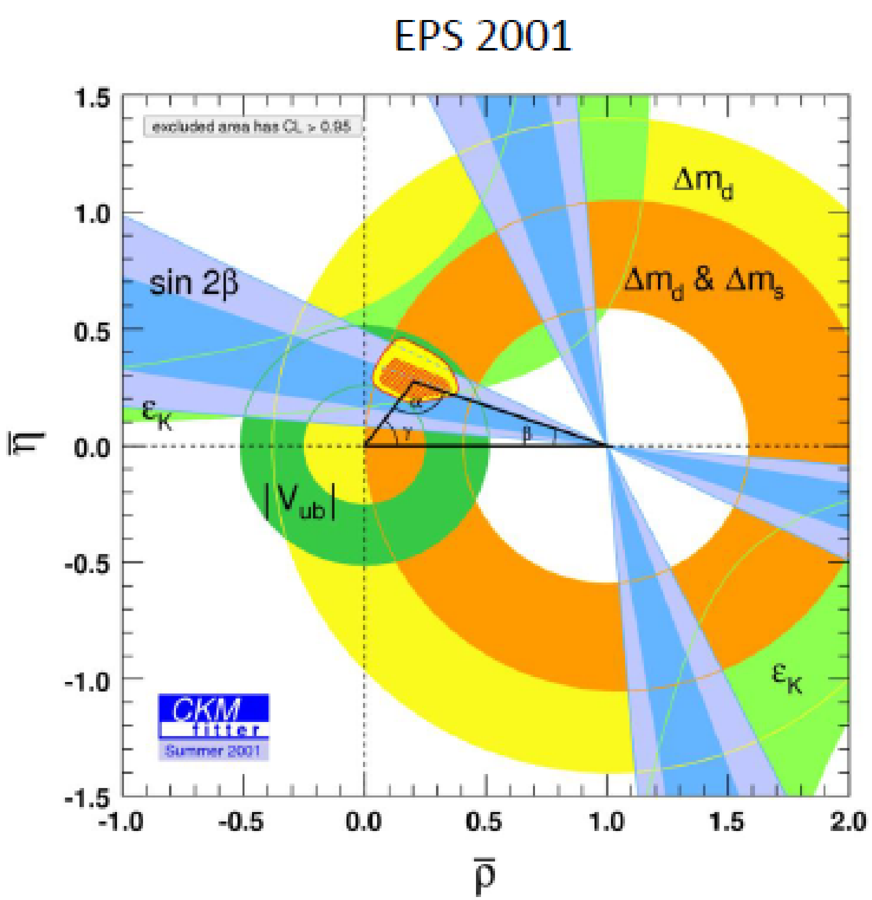


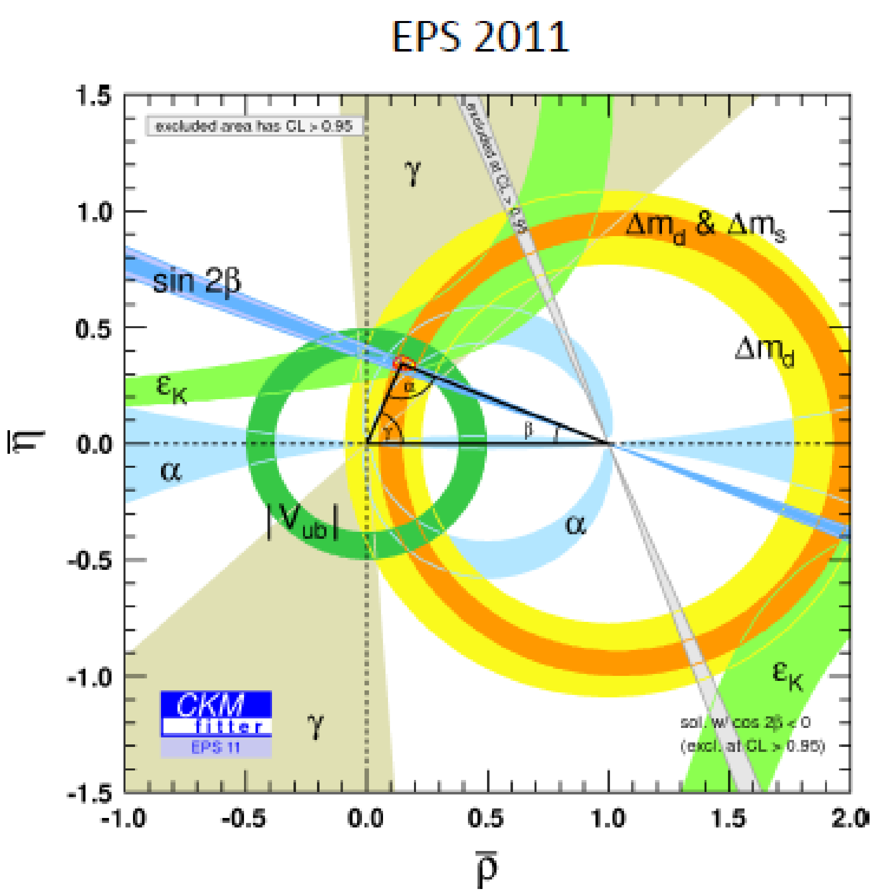
Nobel prize 2008!

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

Unitarity triangle – 2011 vs 2001

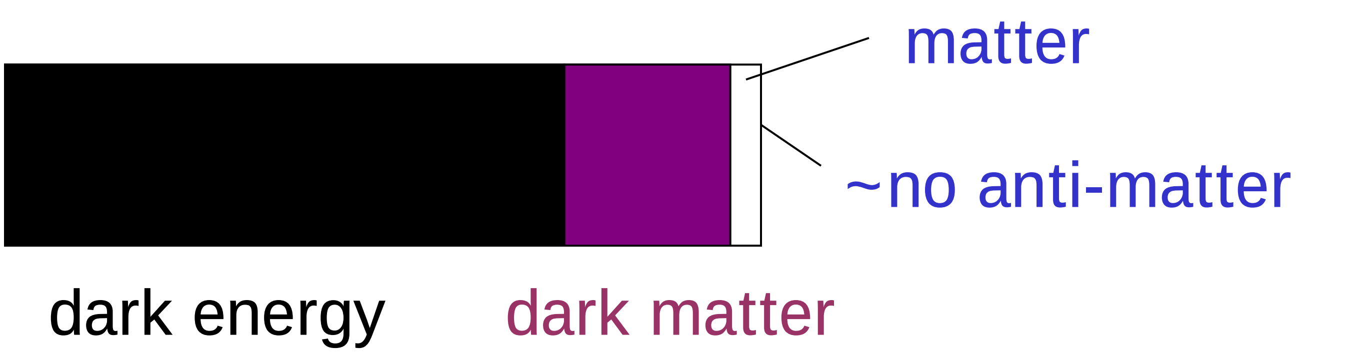
CP violation in the B system: from the discovery (2001) to a precision measurement (2011).



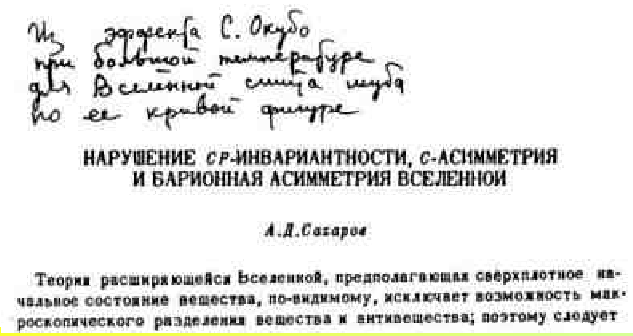


The KM scheme is now part of the Standard Model of Particle Physics

- 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 !!!

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˝)

Comparison of energy /intensity frontiers

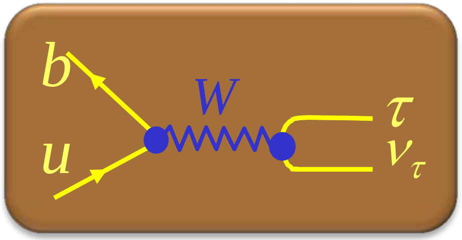
To observe a large ship far away one can either use **strong binoculars** or observe **carefully the direction and the speed of waves** produced by the vessel.

Energy frontier (LHC)

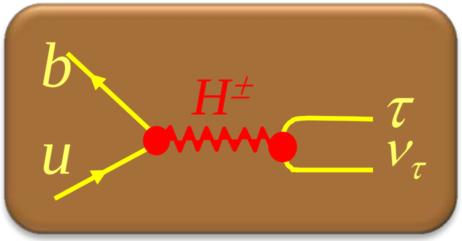
Luminosity frontier (SuperKEKB)

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

In addition to the Standard Model Higgs that was discovered at the LHC, in New Physics (e.g., in supersymmetric theories) there could be another ´God particle´– a charged Higgs.



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

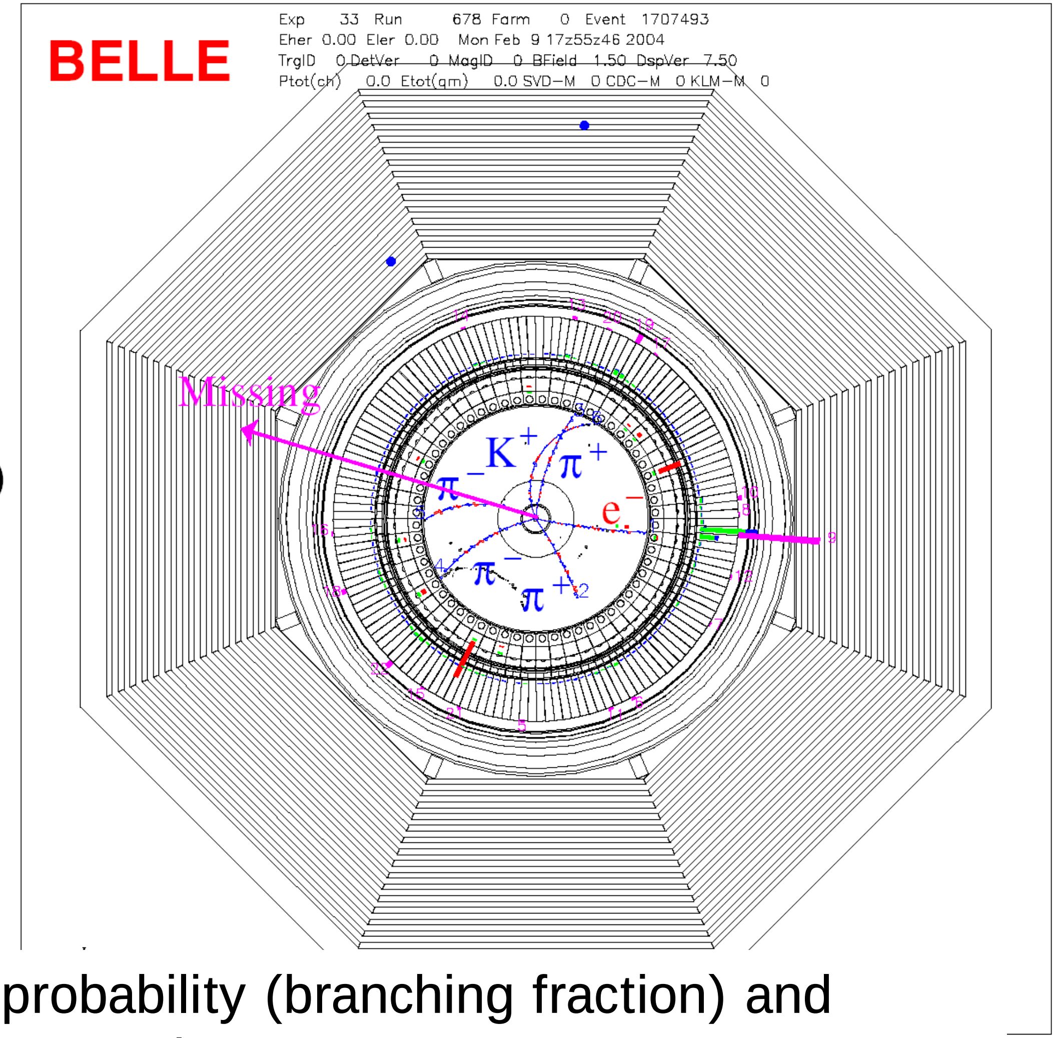


In some supersymmetric extension it can also proceed via a charged Higgs

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: $B^- \to \tau^- \nu_\tau$

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

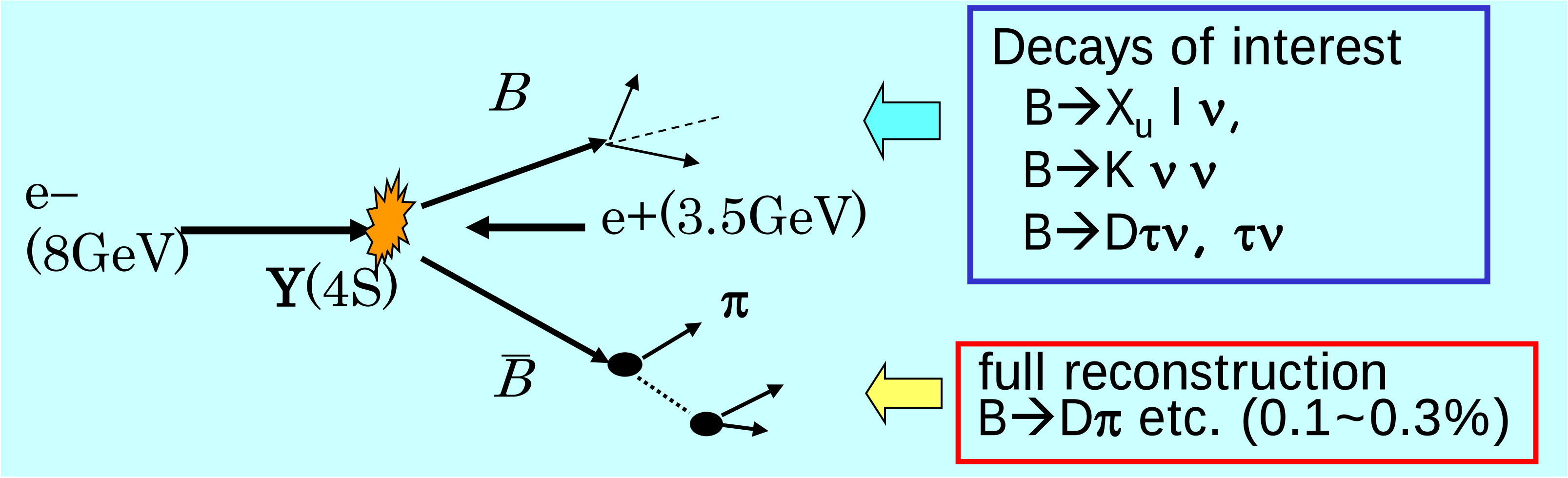


By measuring the decay probability (branching fraction) and comparing it to the SM expectation:

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

Full Reconstruction Method

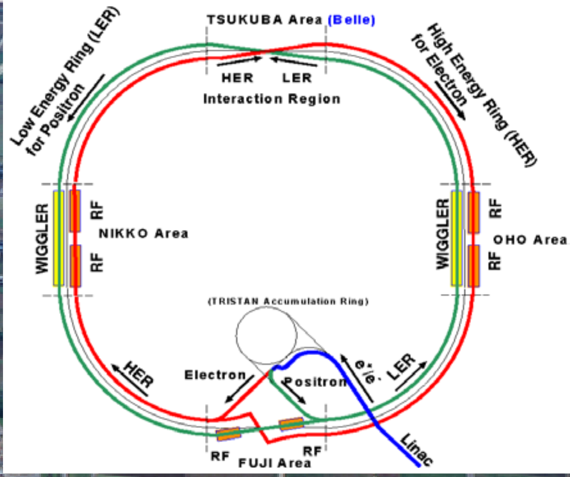
- Fully reconstruct one of the B's to
  - Tag B flavor/charge
  - Determine B momentum
  - Exclude decay products of one B from further analysis

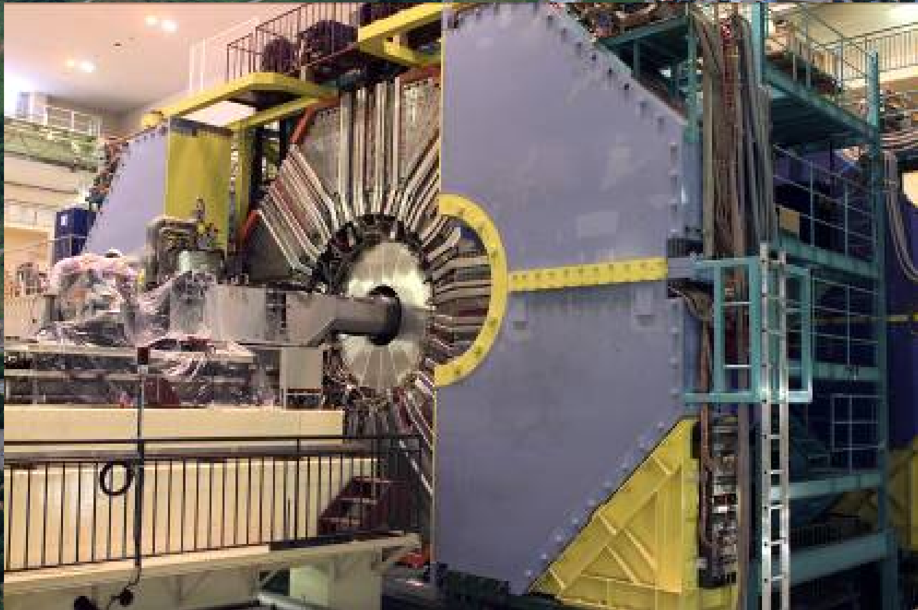


→ Offline B meson beam!

Powerful tool for B decays with neutrinos

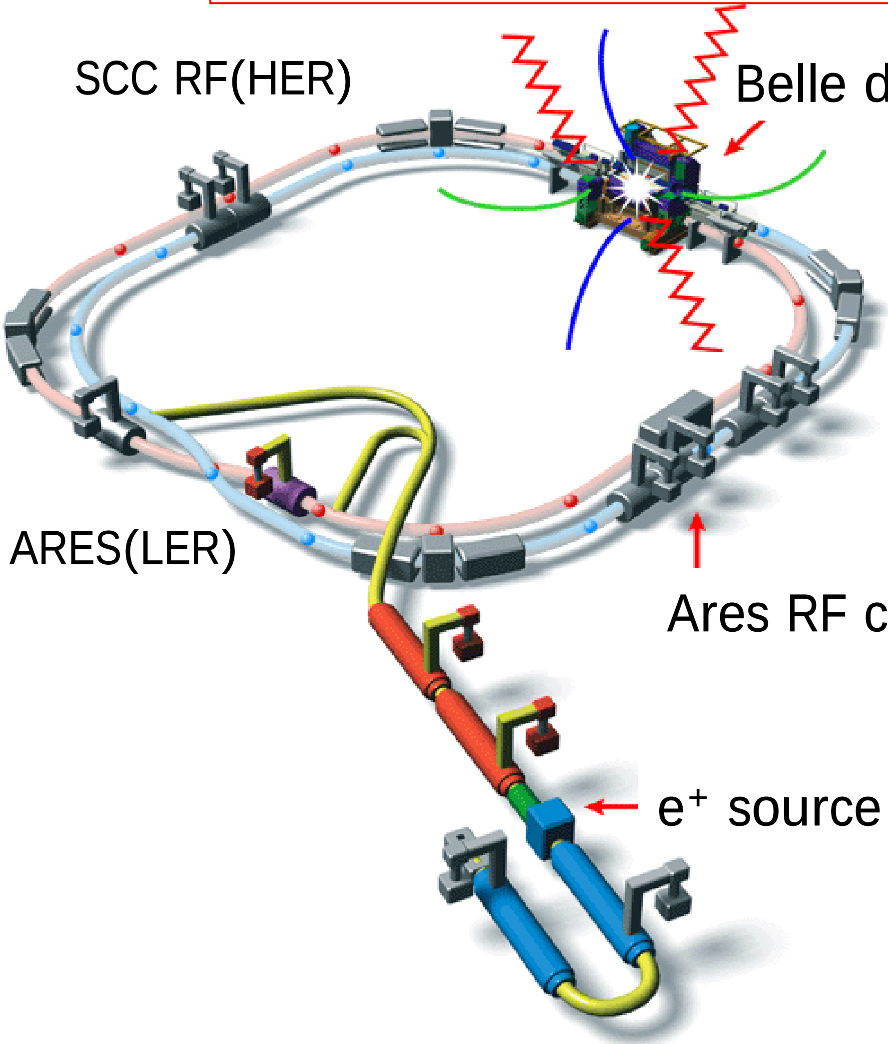
How to do it?
→ upgrade KEKB and Belle





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

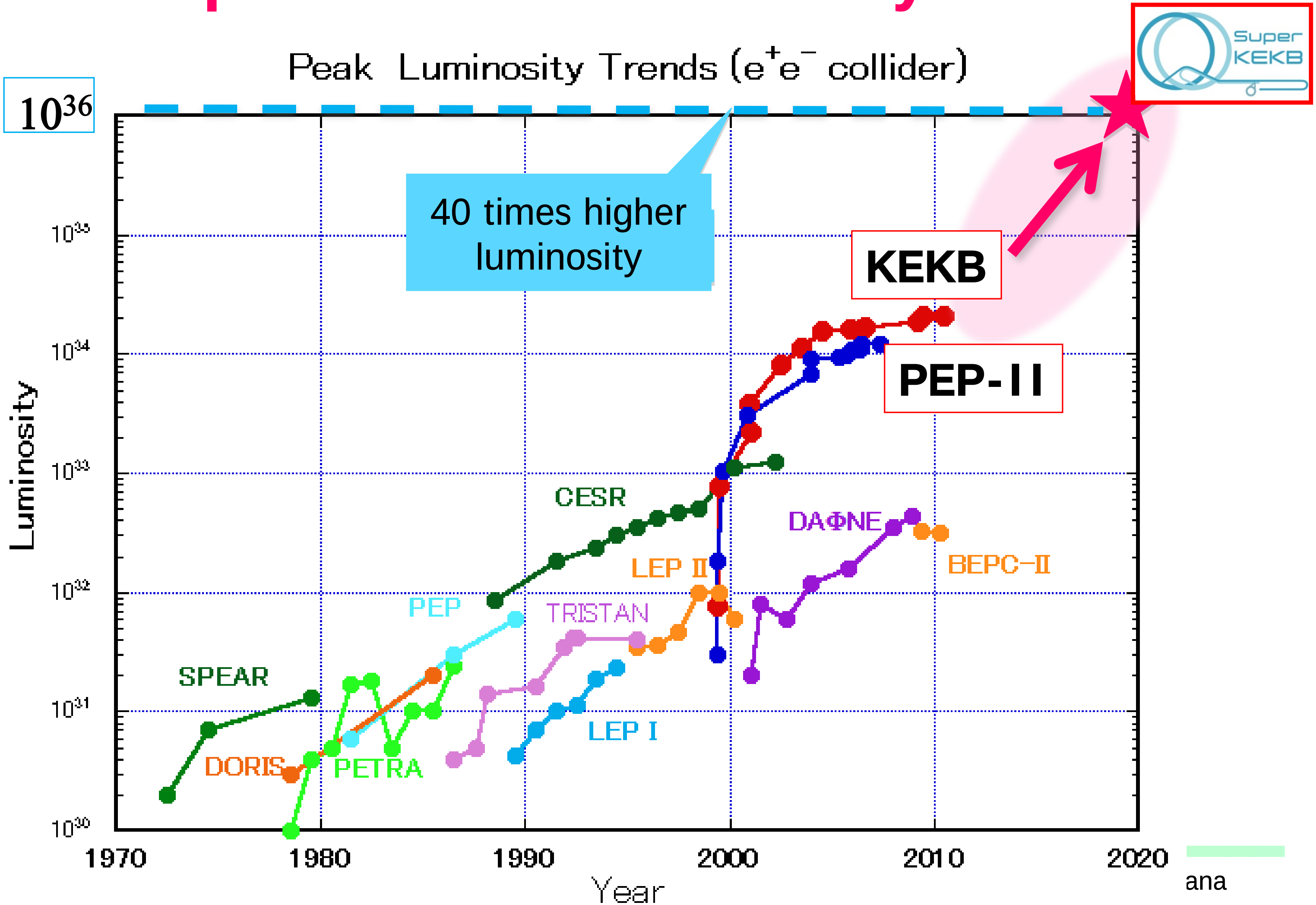
Peak luminosity (WR!) :

2.1×10^{34} cm^{-2}s^{-1}

=2x design value

First physics run on June 2, 1999
Last physics run on June 30, 2010
L_{peak} = 2.1×10^{34}/cm^2/s
L > 1ab^{-1}

SuperKEKB is the intensity frontier

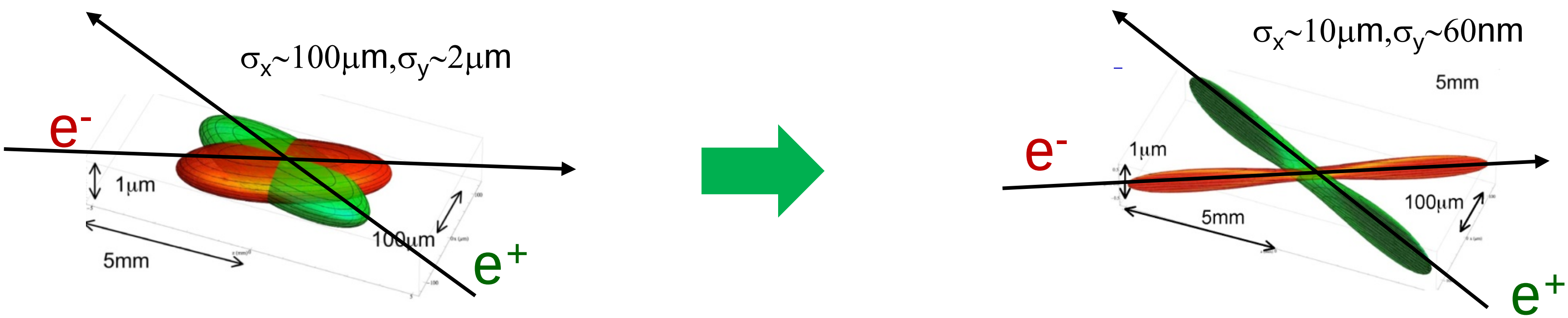


ana

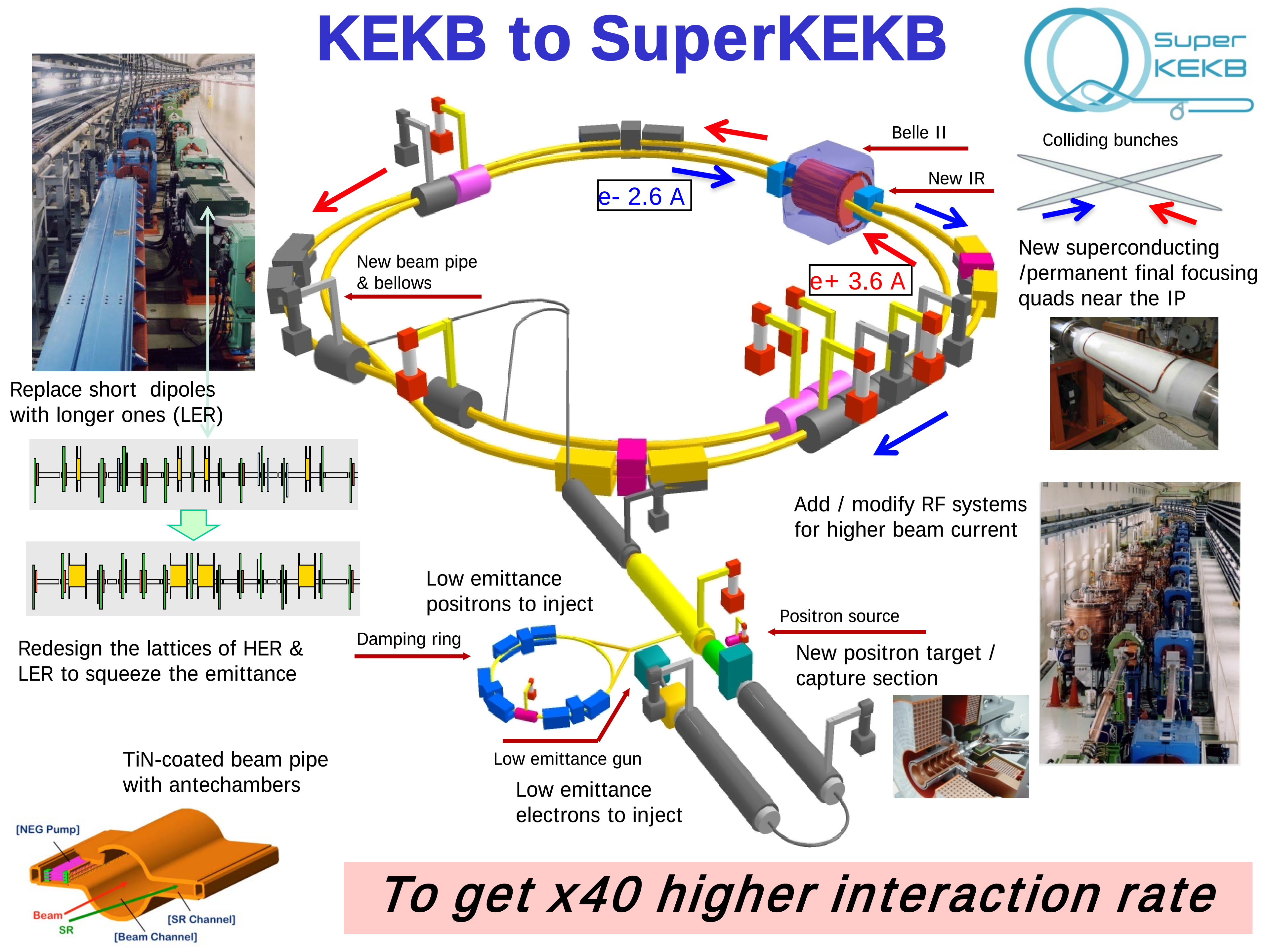
How big is a nano-beam ?

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...



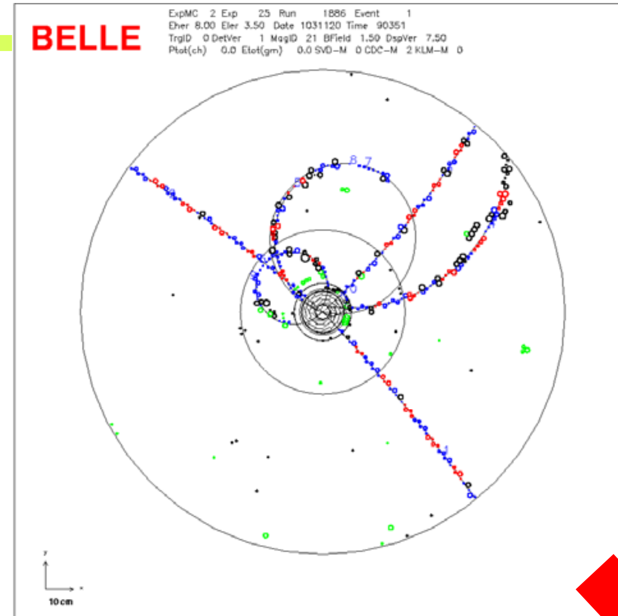
… For a 40x increase in intensity you have to make the beam as thin as 100 atomic layers!

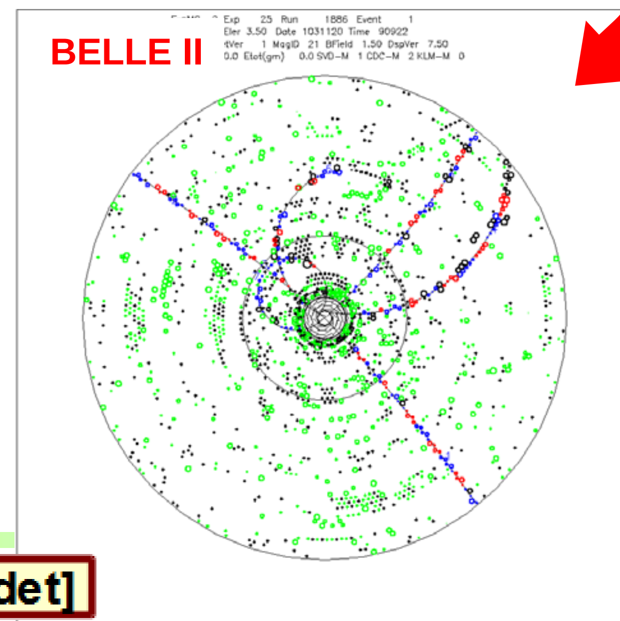

KEKB to SuperKEKB
Super KEKB
Belle II
Colliding bunches
New IR
e- 2.6 A
e+ 3.6 A
New beam pipe
& bellows
New superconducting
/permanent final focusing
quads near the IP
Replace short dipoles
with longer ones (LER)
Add / modify RF systems
for higher beam current
Low emittance
positrons to inject
Damping ring
Positron source
New positron target /
capture section
Redesign the lattices of HER &
LER to squeeze the emittance
Low emittance gun
Low emittance
electrons to inject
TiN-coated beam pipe
with antechambers
[NEG Pump]
Beam
SR
[SR Channel]
[Beam Channel]
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 ← sμμ recon. eff.
  - hermeticity ← ν “reconstruction”



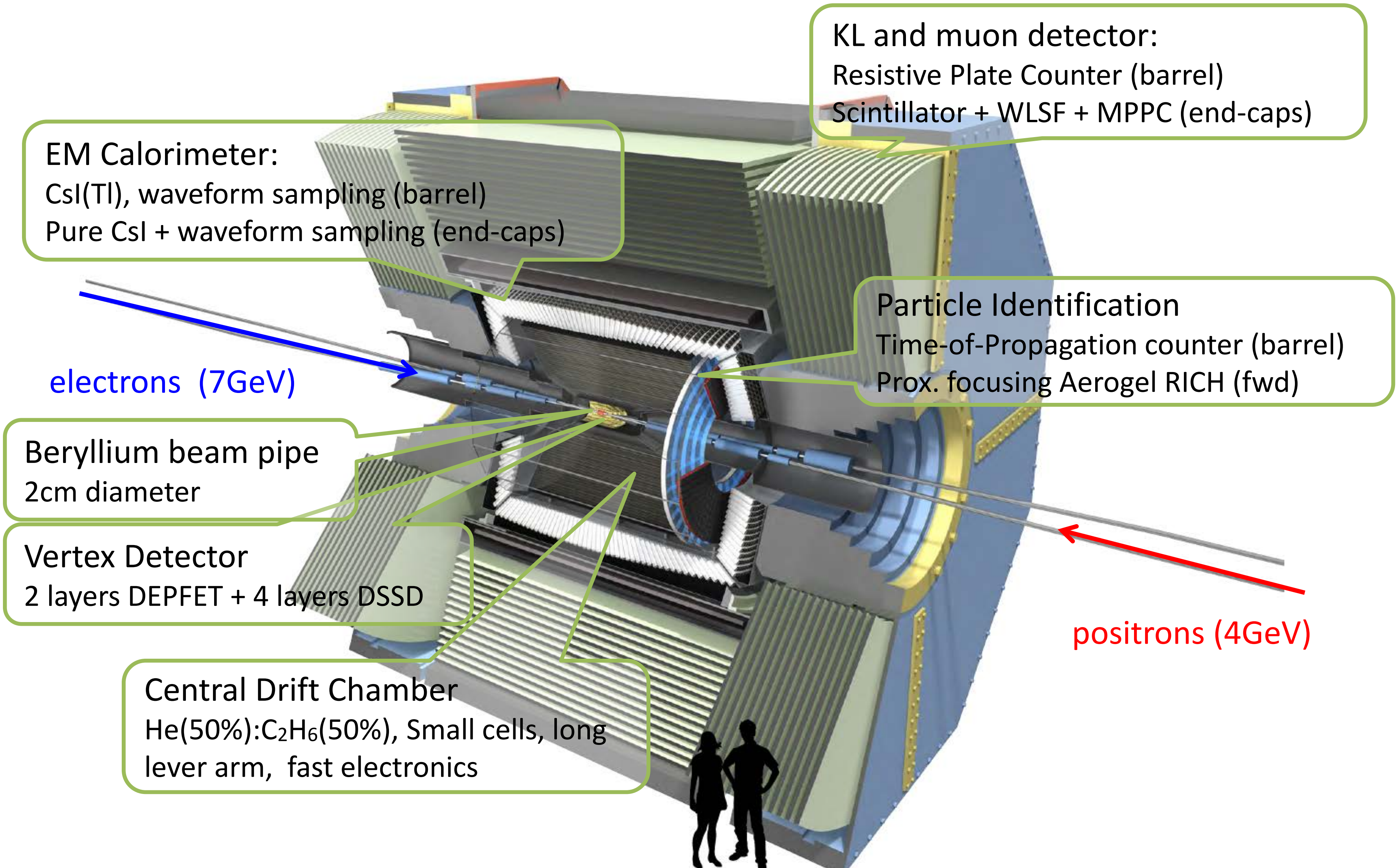


Have to employ and develop very advanced technologies to build such an appartus!

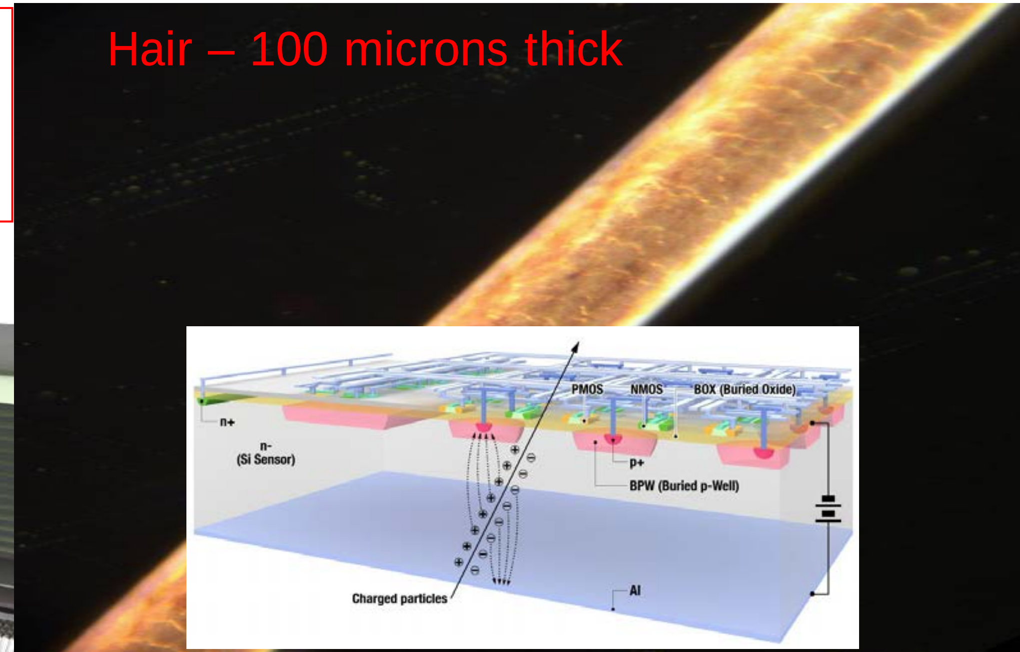
→

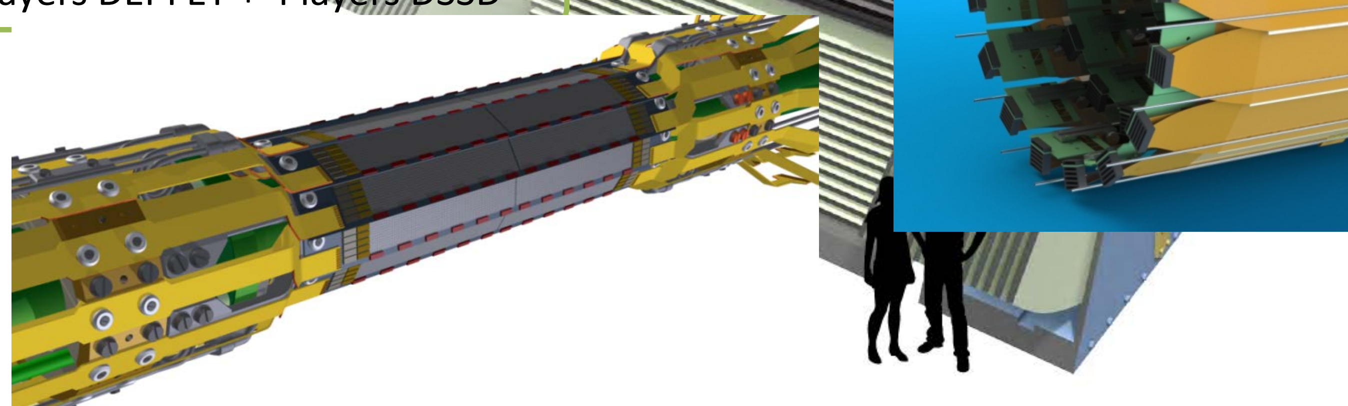
TDR published arXiv:1011.0352v1 [physics.ins-det]

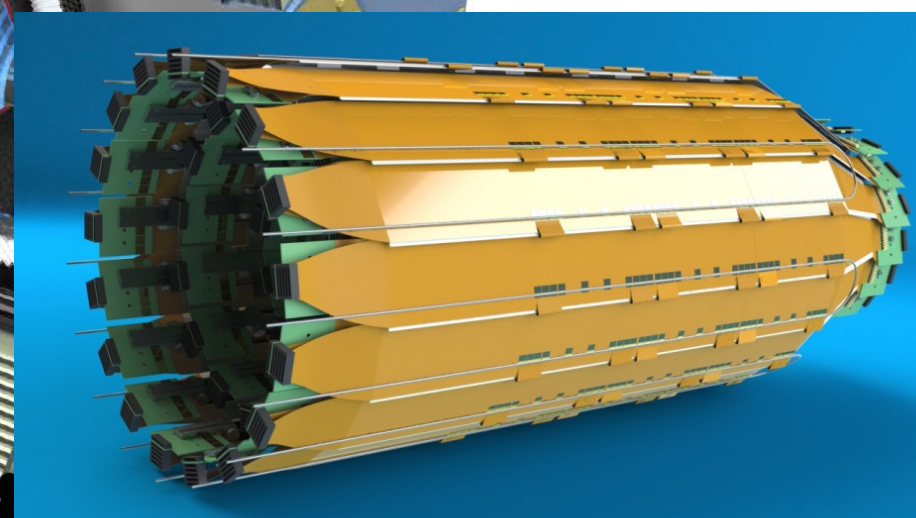
Belle II Detector



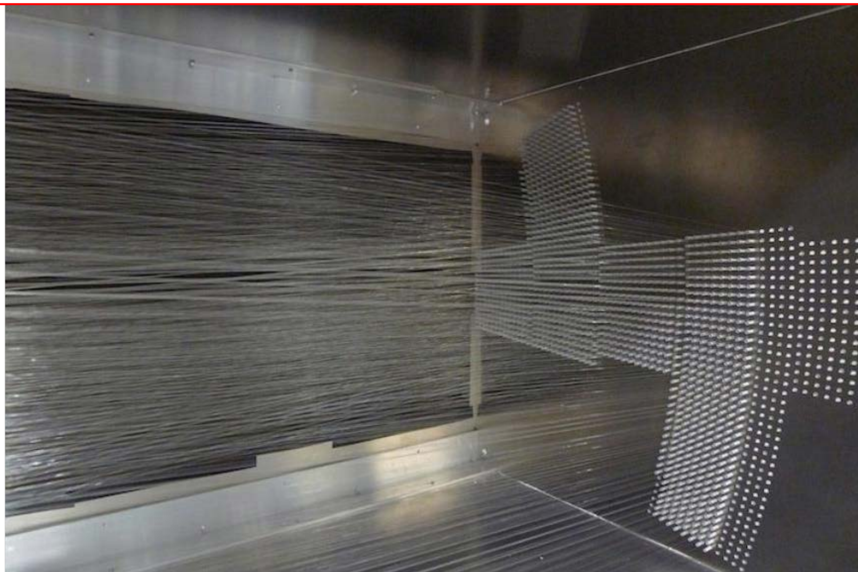
Determine the reaction point position with a fantastic precision - extremly delicate elements

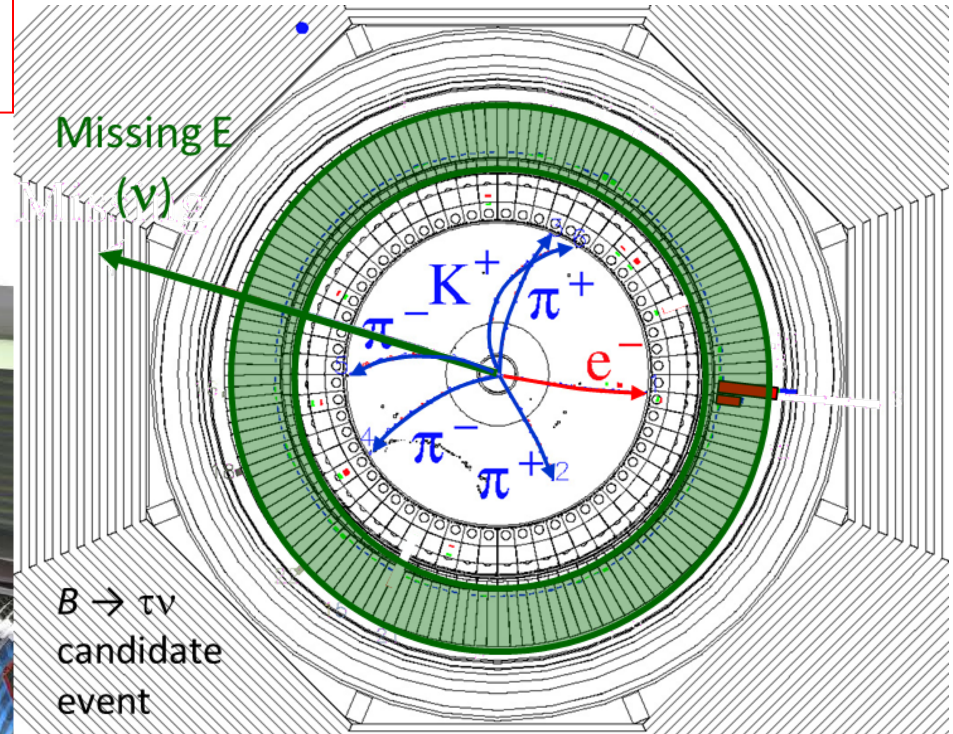


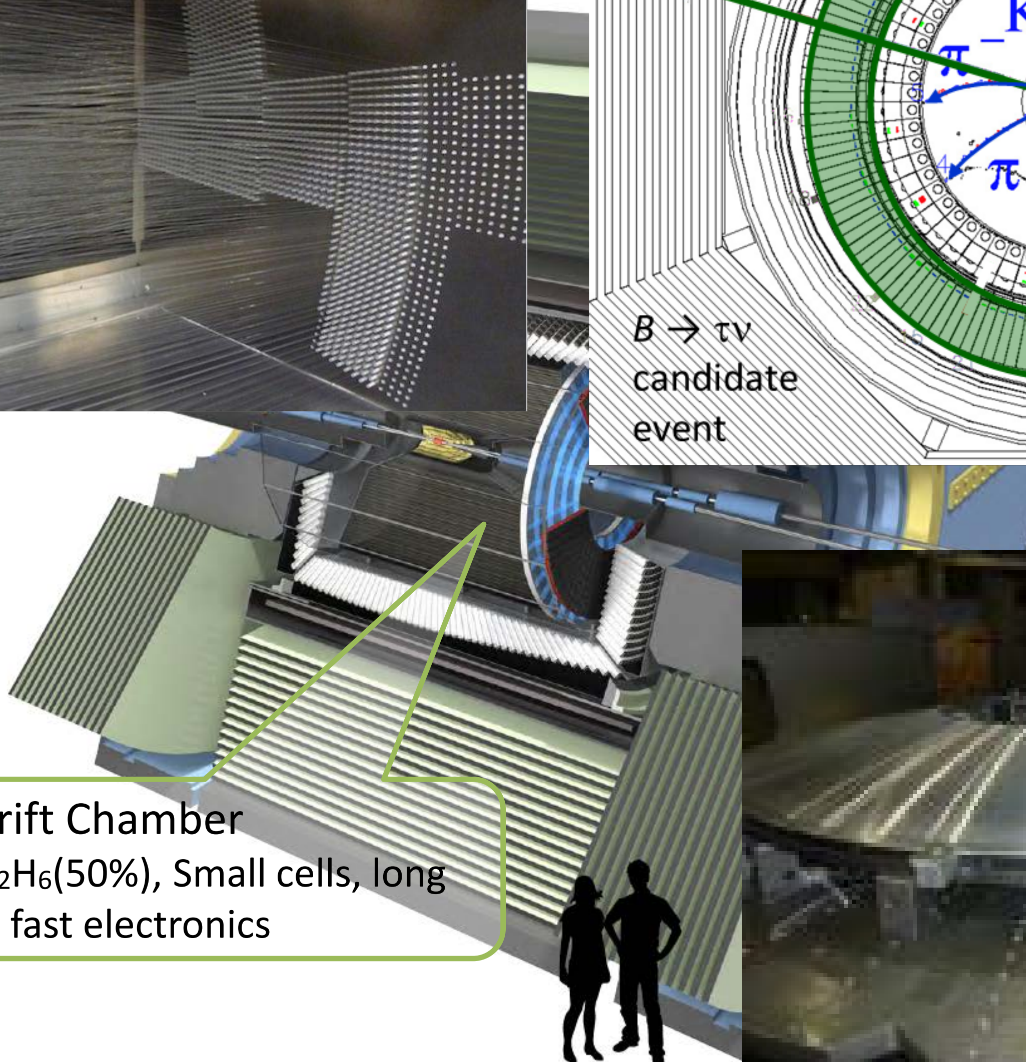




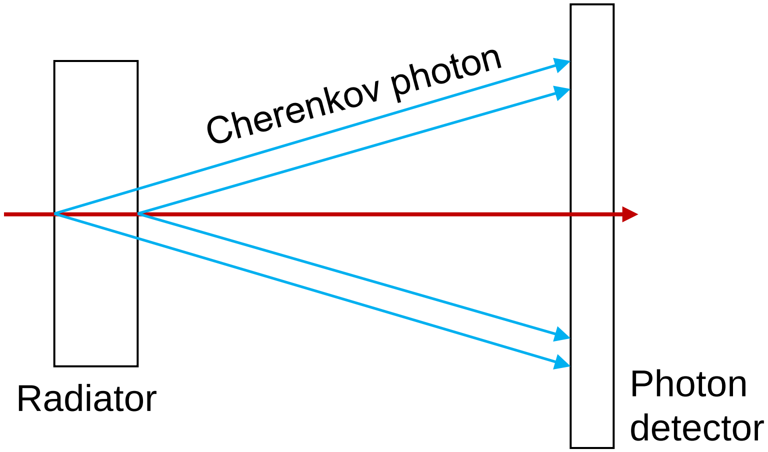
Tracking charged particles in magnetic field – measure their momenta

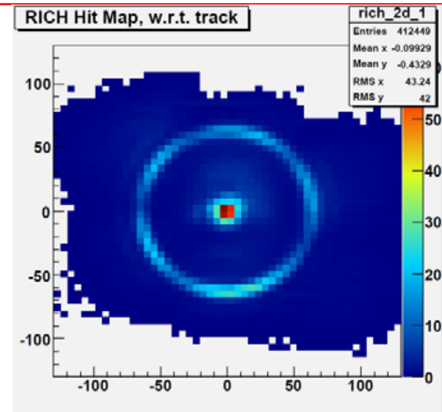


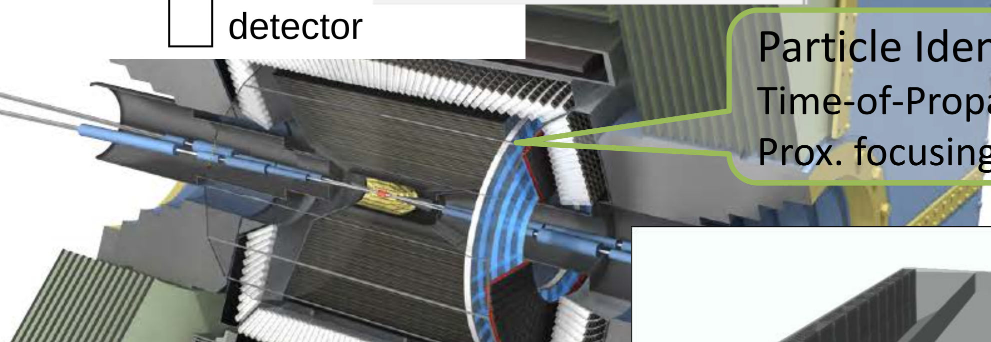




Use Cherenkov effect: light emitted by a particle faster than velocity of light in a medium - like a shock wave from a supersonic airplane!



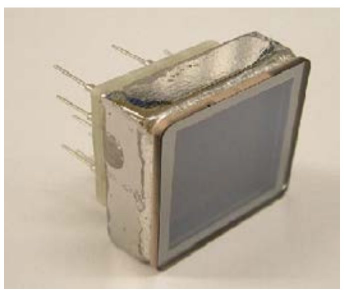


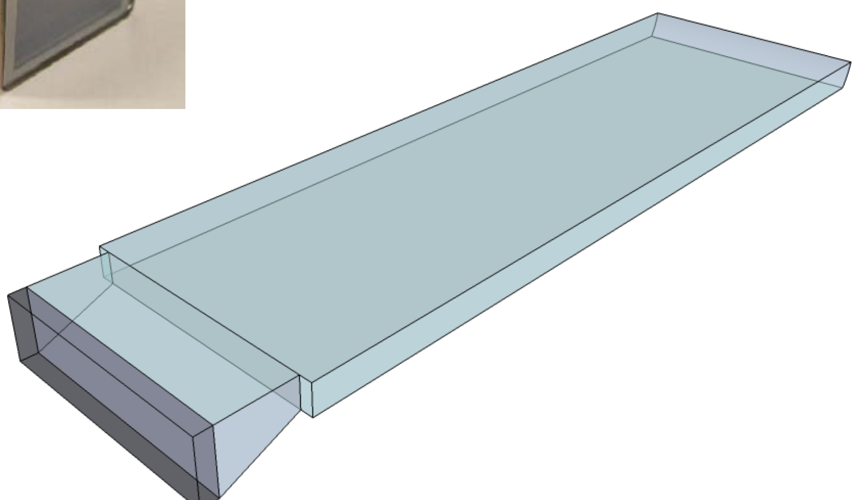


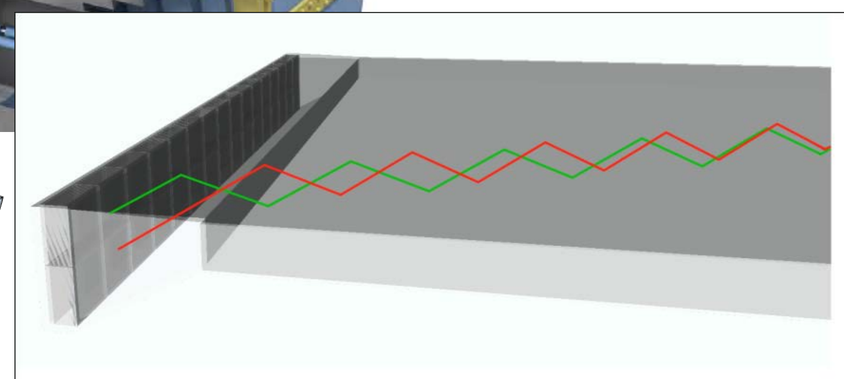
Particle Identification

Time-of-Propagation counter (barrel)

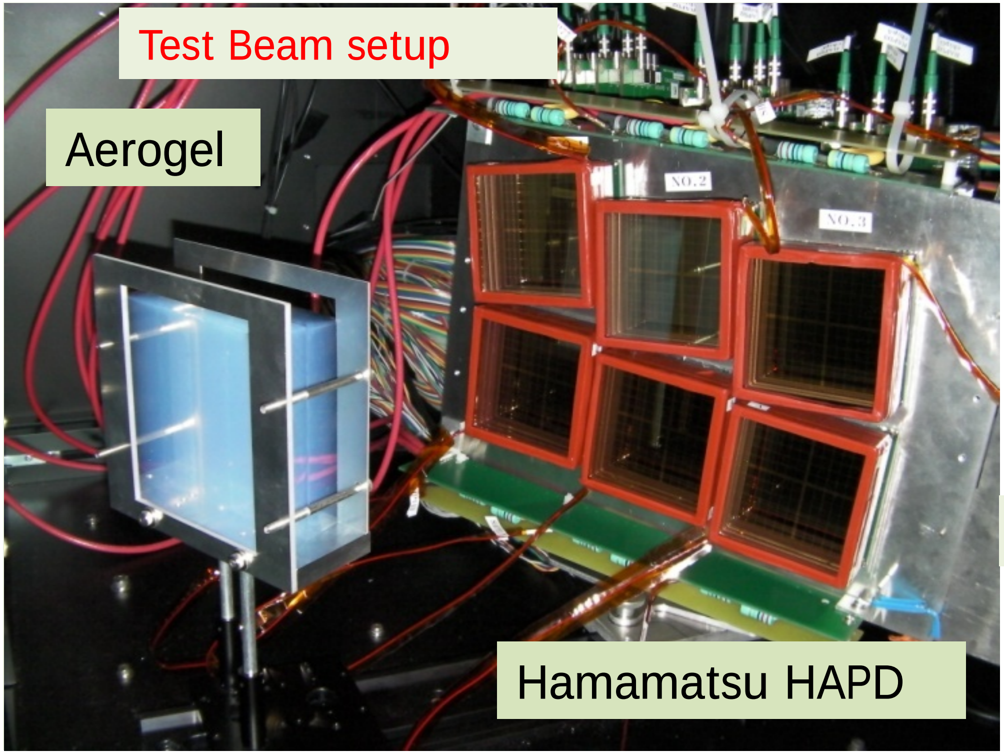
Prox. focusing Aerogel RICH (fwd)

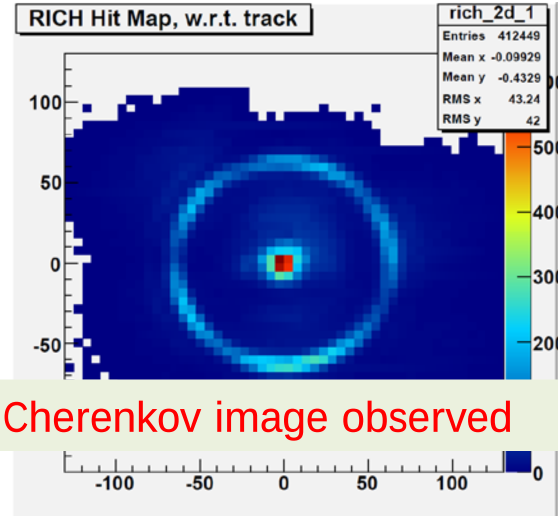






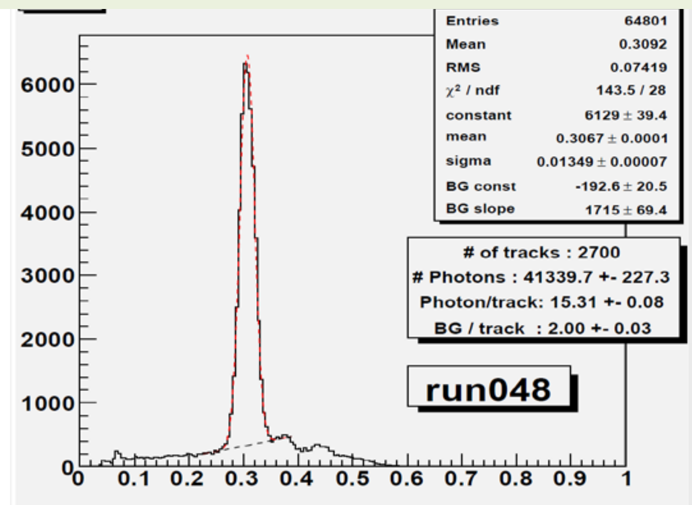
Aerogel RICH (endcap PID)



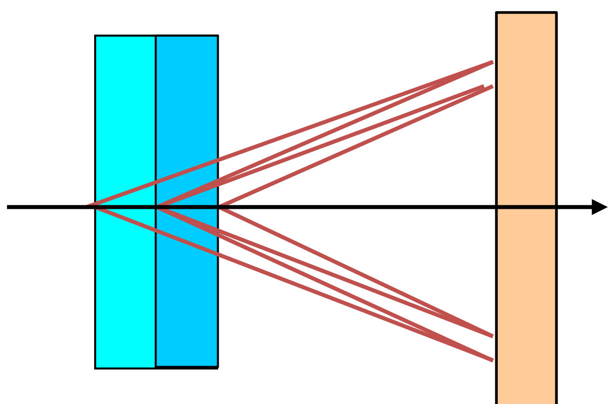


Clear Cherenkov image observed

Cherenkov angle distribution



RICH with a novel "focusing" radiator – a two layer radiator



Employ multiple layers with different refractive indices→ Cherenkov images from individual layers overlap on the photon detector.

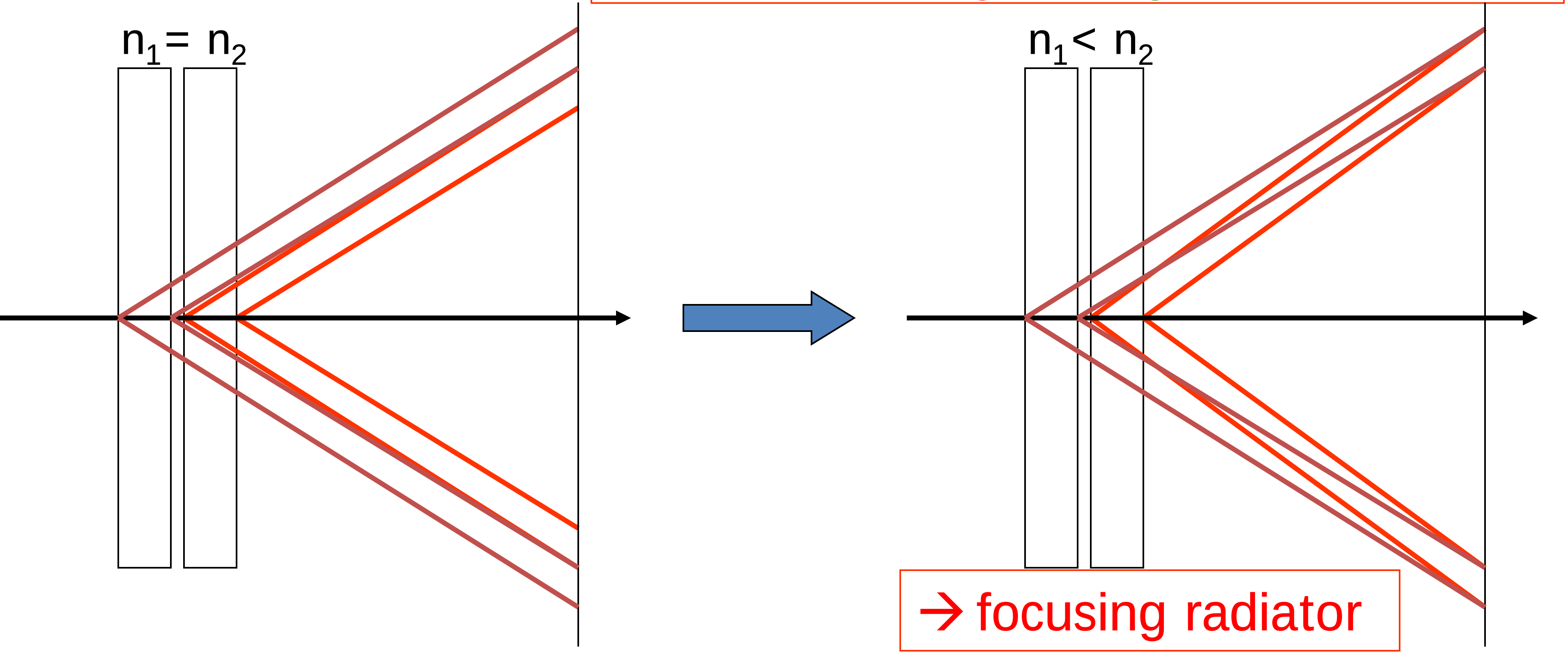
6.6 σ π / K at 4GeV / c !

Radiator with multiple refractive indices

How to increase the number of photons without degrading the resolution?

normal

→ stack two tiles with different refractive indices: “focusing” configuration

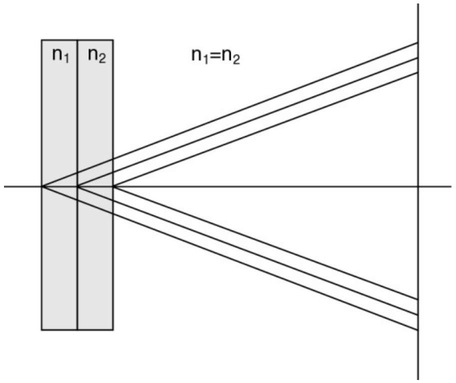


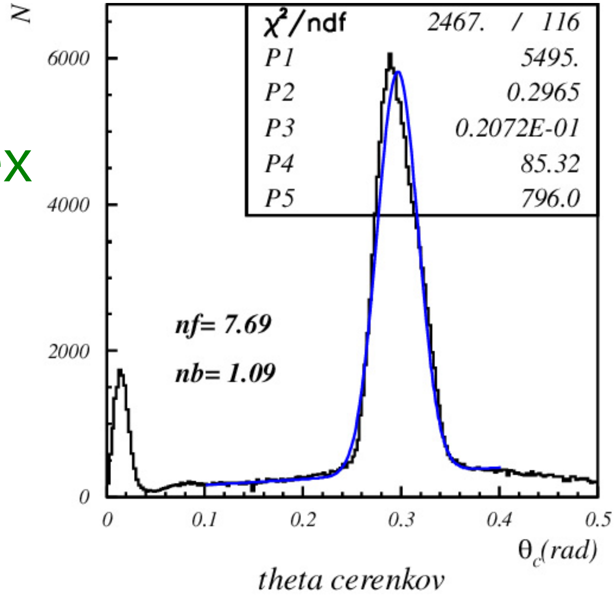
→ focusing radiator

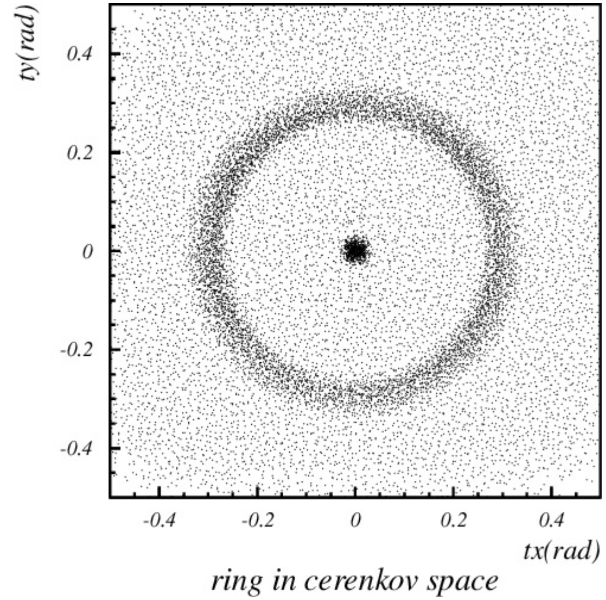
Such a configuration is only possible with aerogel (a form of Si_xO_y) – material with a tunable refractive index between 1.01 and 1.13.

Focusing configuration – data

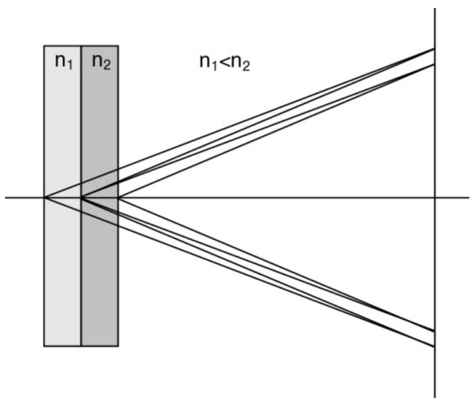
4cm aerogel single index

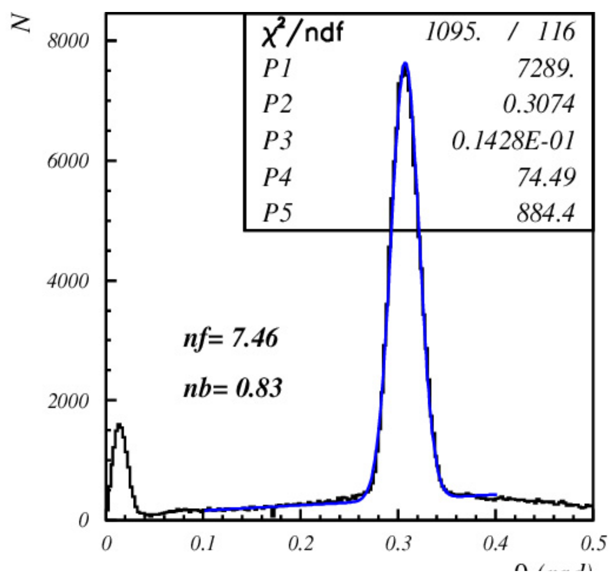


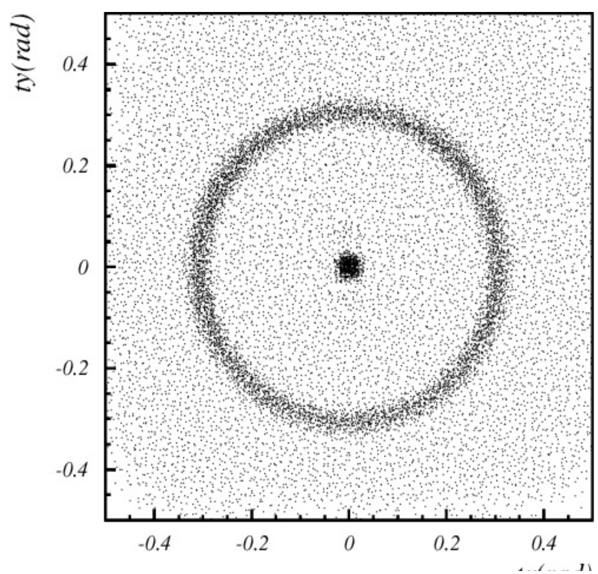




2+2cm aerogel

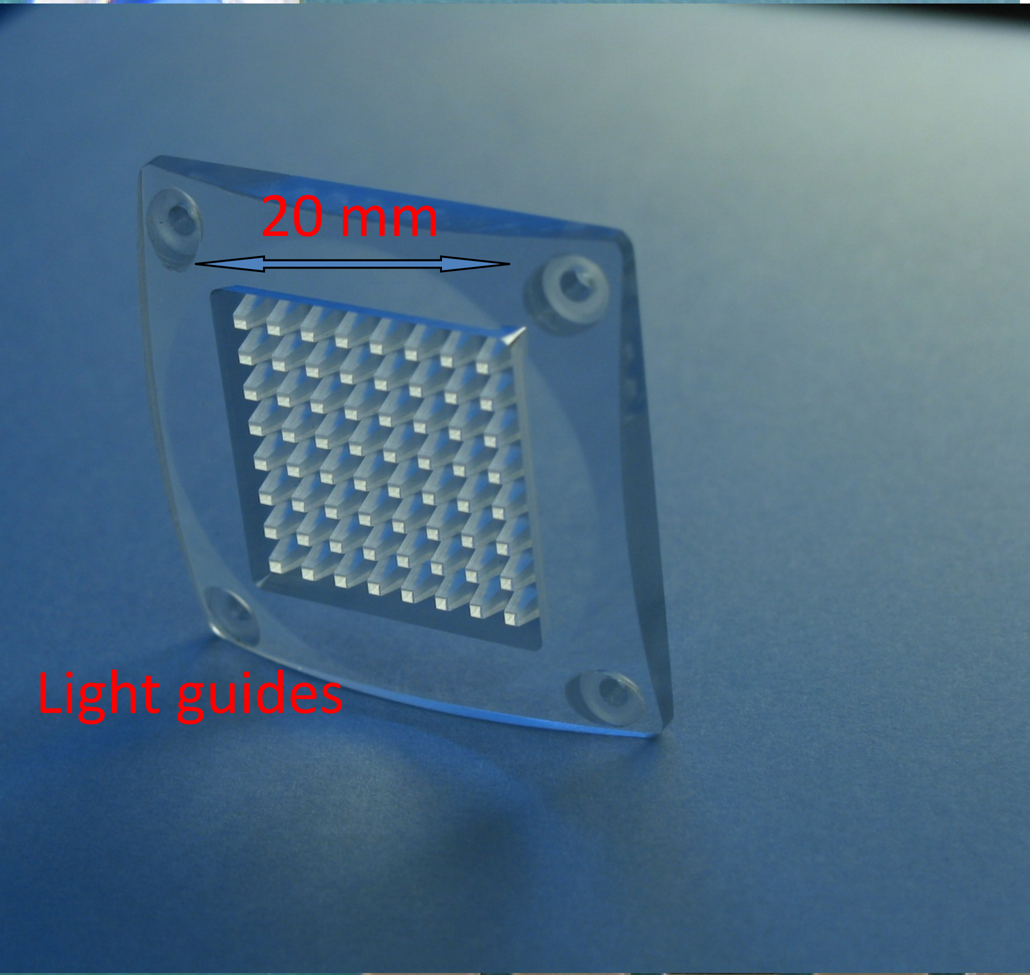


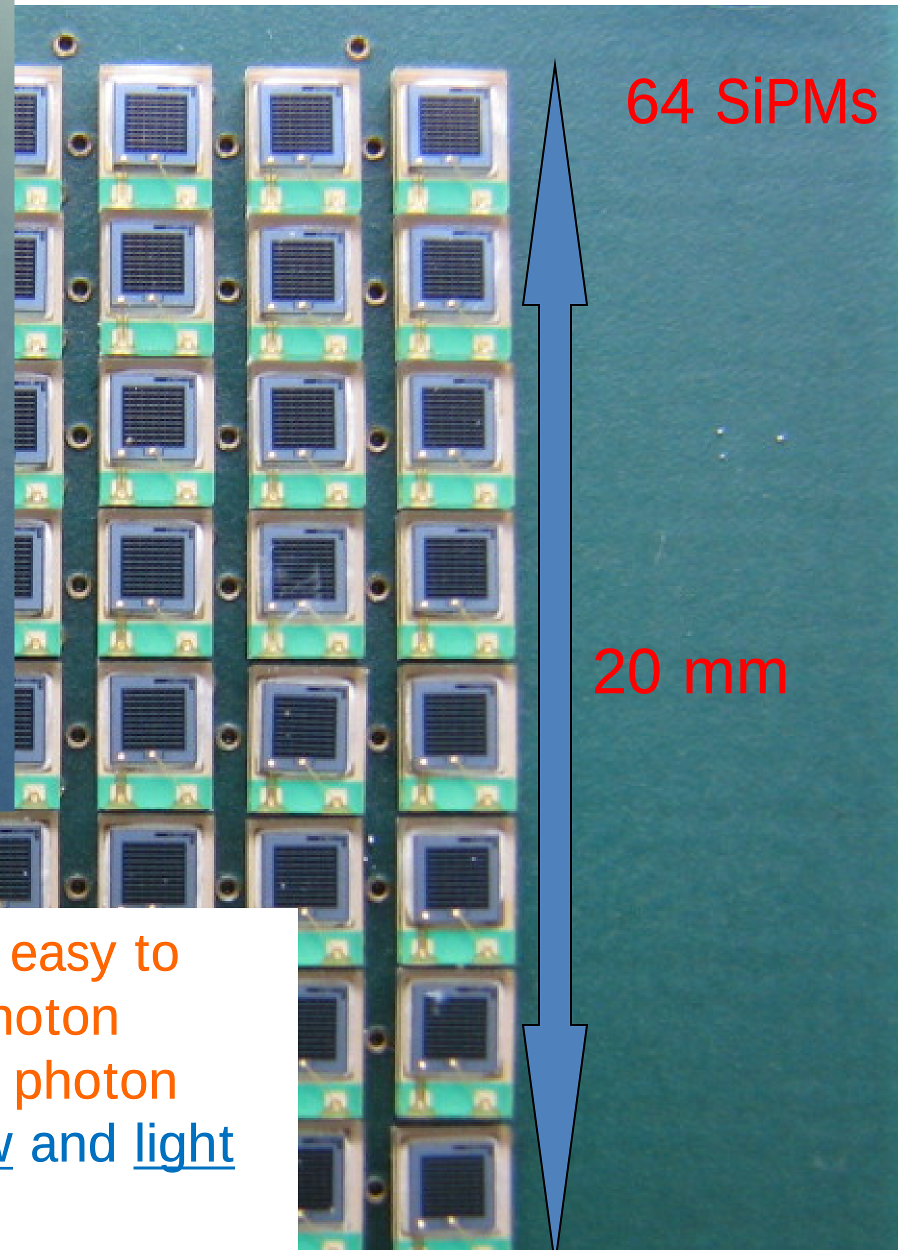




→NIM A548 (2005) 383

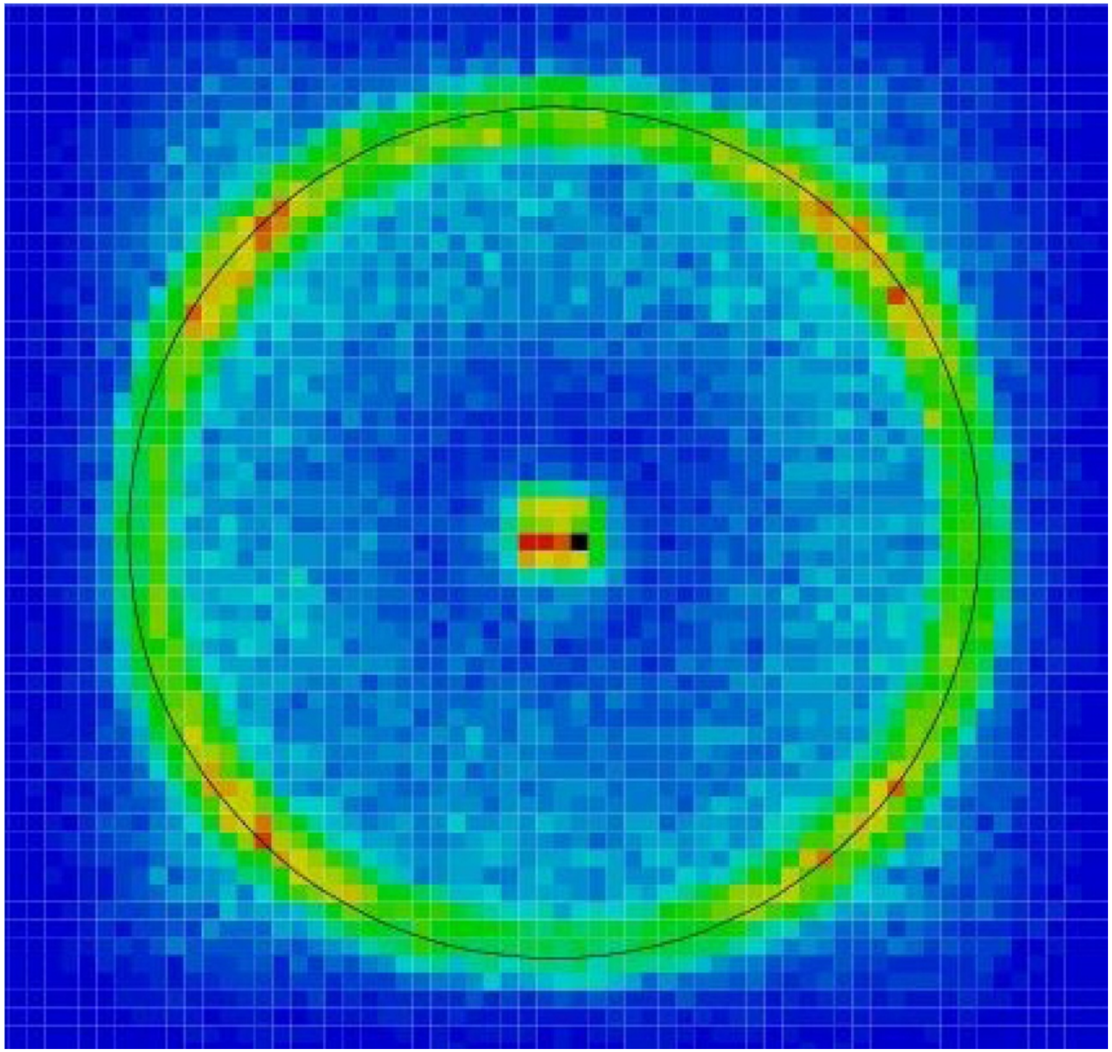
Another candidate: SiPM





Another sensor candidate: SiPMs (G-PAD), easy to handle, but never before used for single photon detection (high dark count rate with single photon pulse height) → use a narrow time window and light concentrators

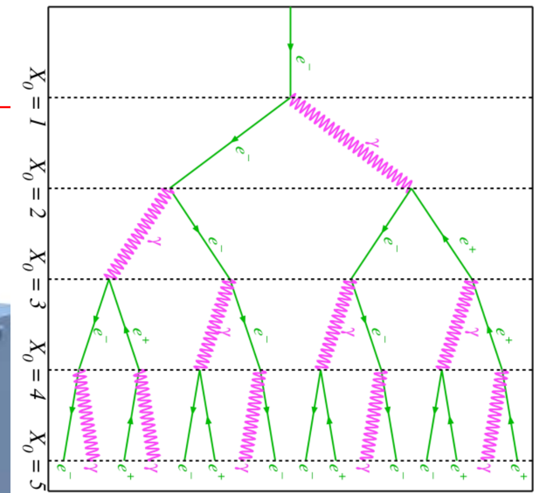
Cherenkov ring with SiPMs



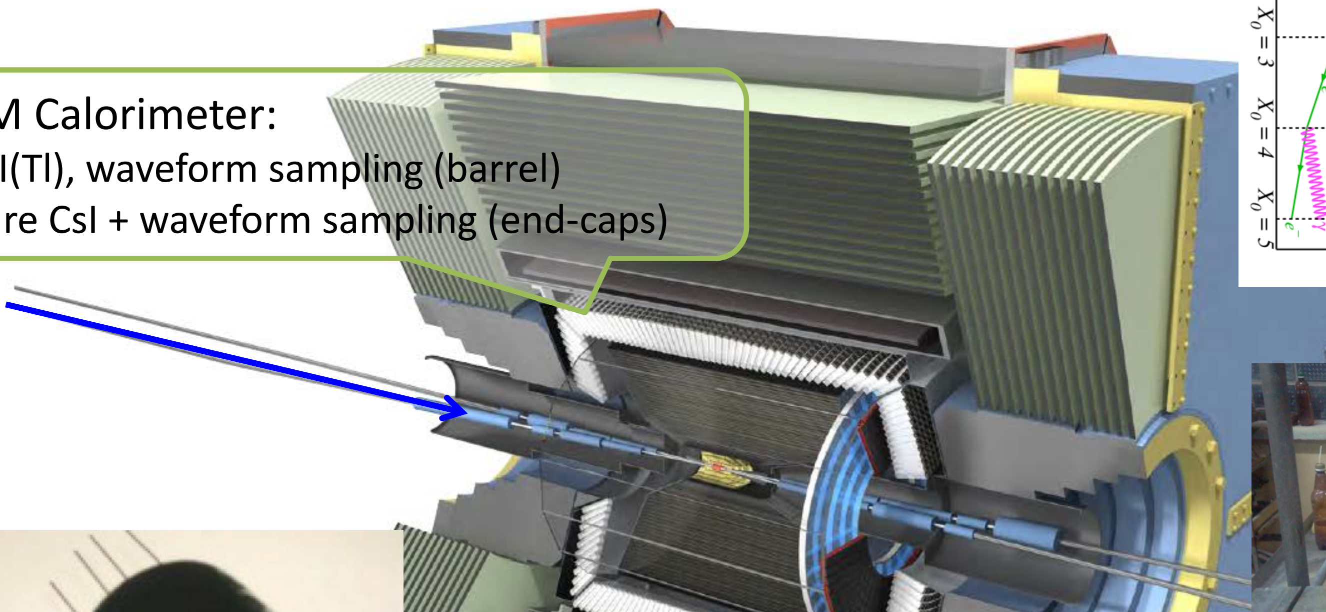
First successful use of SiPMs as single photon detectors in a RICH counter!

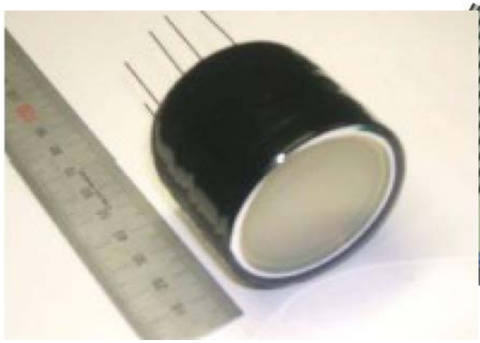
NIM A594 (2008) 13

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



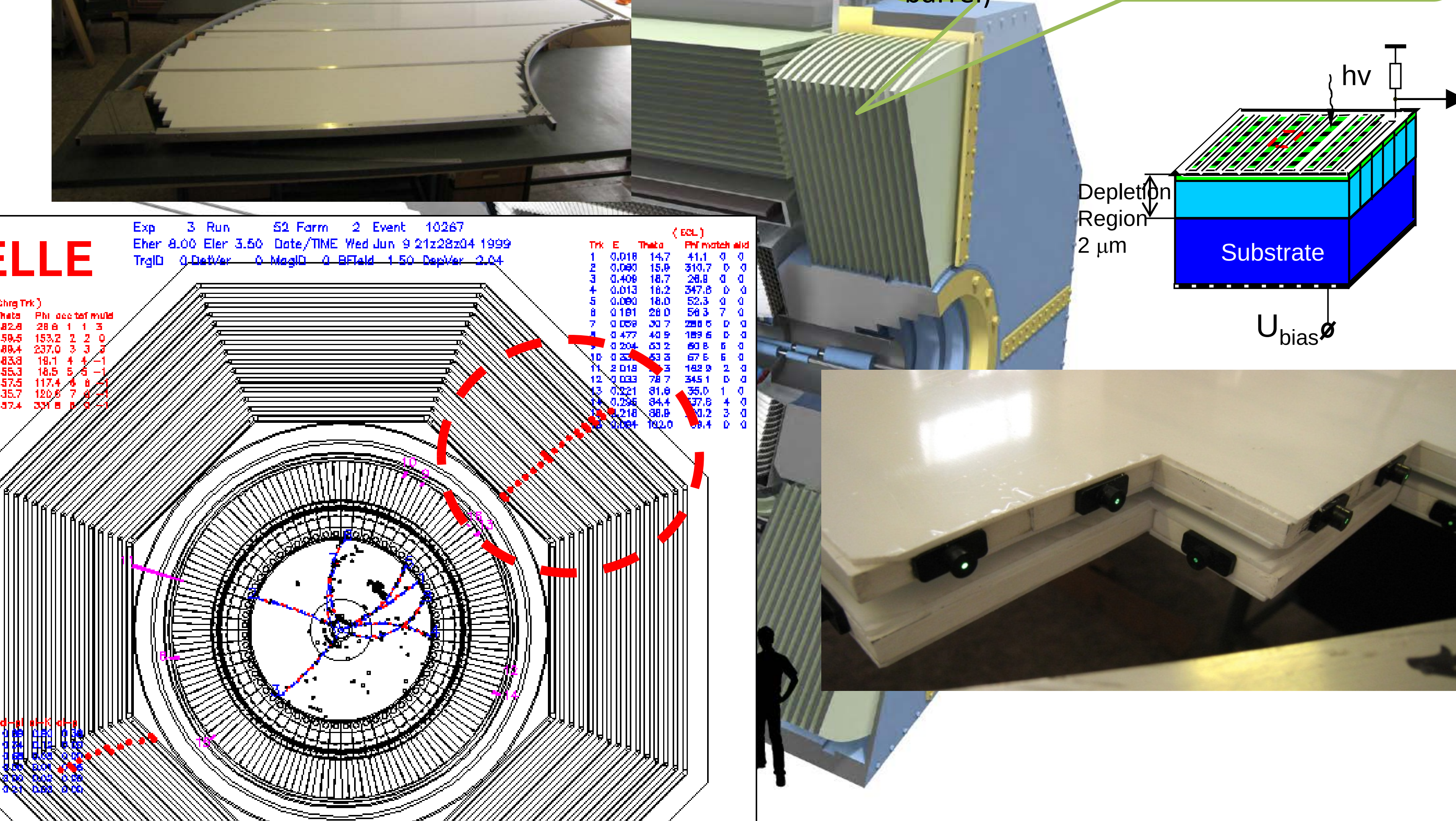
EM Calorimeter:
CsI(Tl), waveform sampling (barrel)
Pure CsI + waveform sampling (end-caps)





Detect muons: particles that penetrate 1m of iron

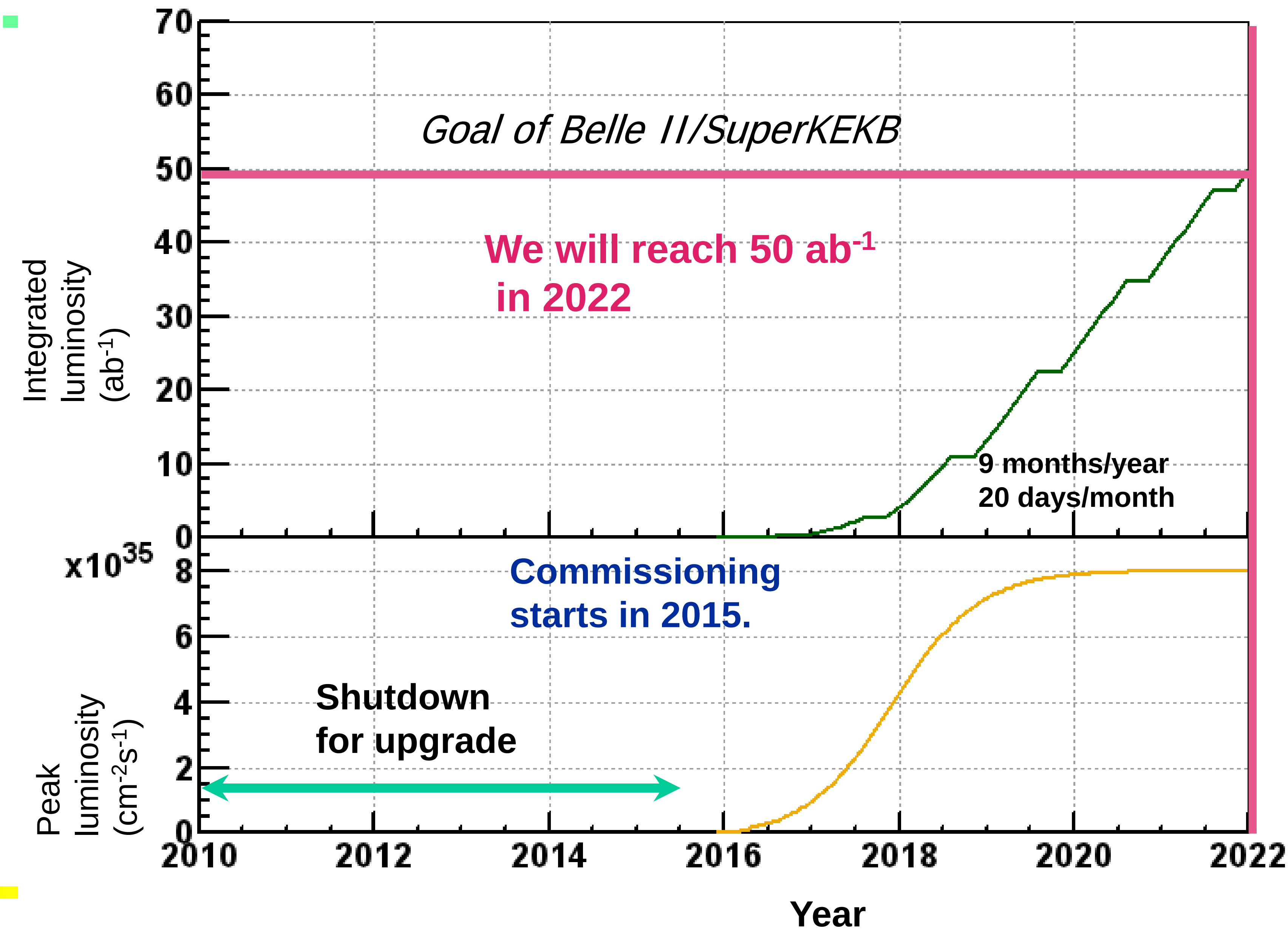
KL and muon detector:
Resistive Plate Counter (barrel)
Scintillator + WLSF + MPPC (end-caps + barrel)



The Belle II Collaboration

A very strong group of ~400 highly motivated scientists!

Schedule (Beam starts end of 2014)



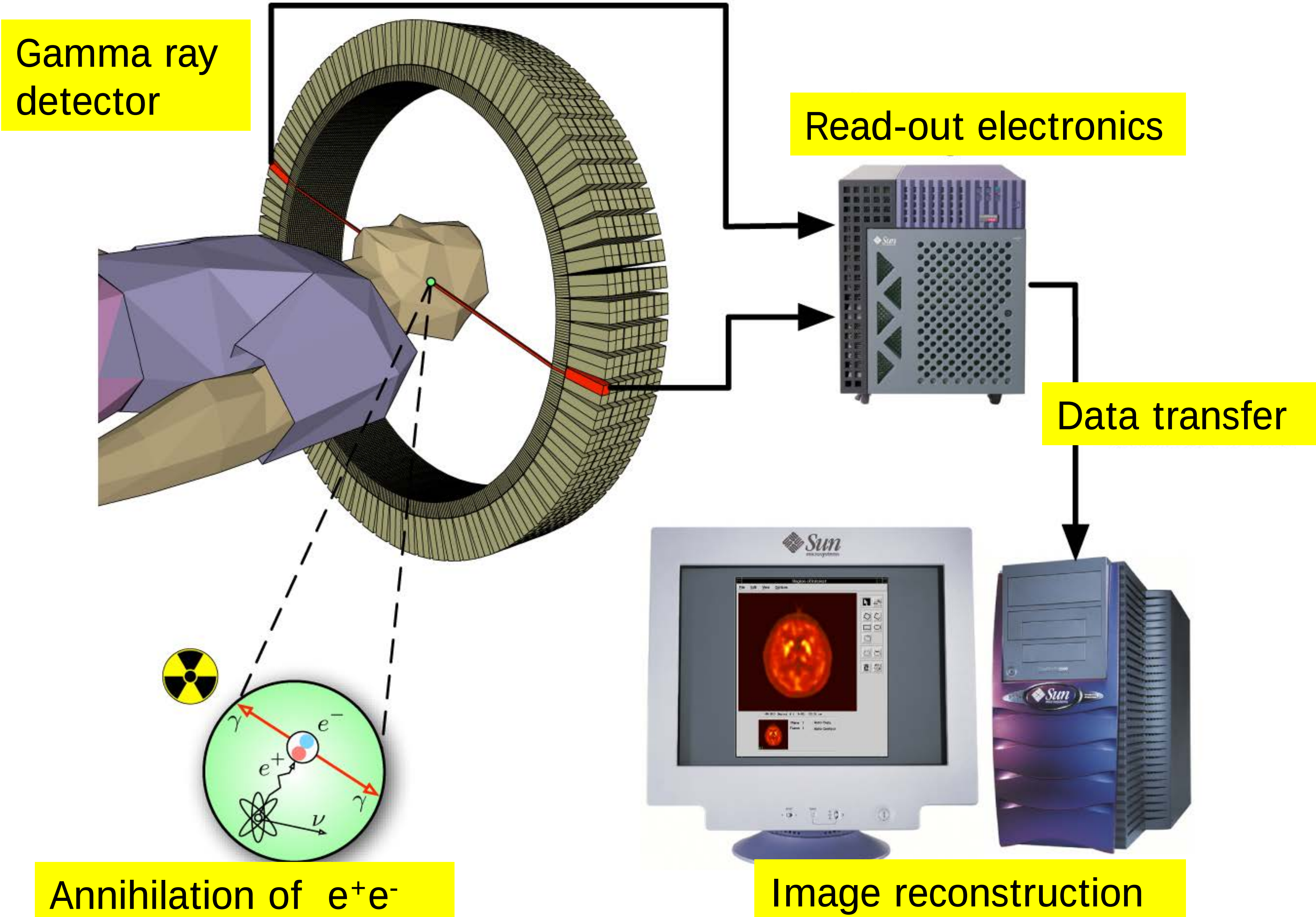
Conclusion

- Understanding of CP violation has helped to shape our understanding of Nature at small scales and in the early Universe
- A big step since its discovery in 1964, however there are many open questions left. One way how to proceed is to make very precise measurements → intensity frontier of particle physics
- Major upgrade of the KEKB accelerator and Belle detector at KEK in 2010-15 → SuperKEKB+Belle II, with 40x larger event rates, construction started
- Expect a new, exciting era of discoveries, complementary to the LHC

Slovenian physicts have been playing an important role in flavour physics, and it all started when Elko Kernel brought us young physicts into the ARGUS collaboration.

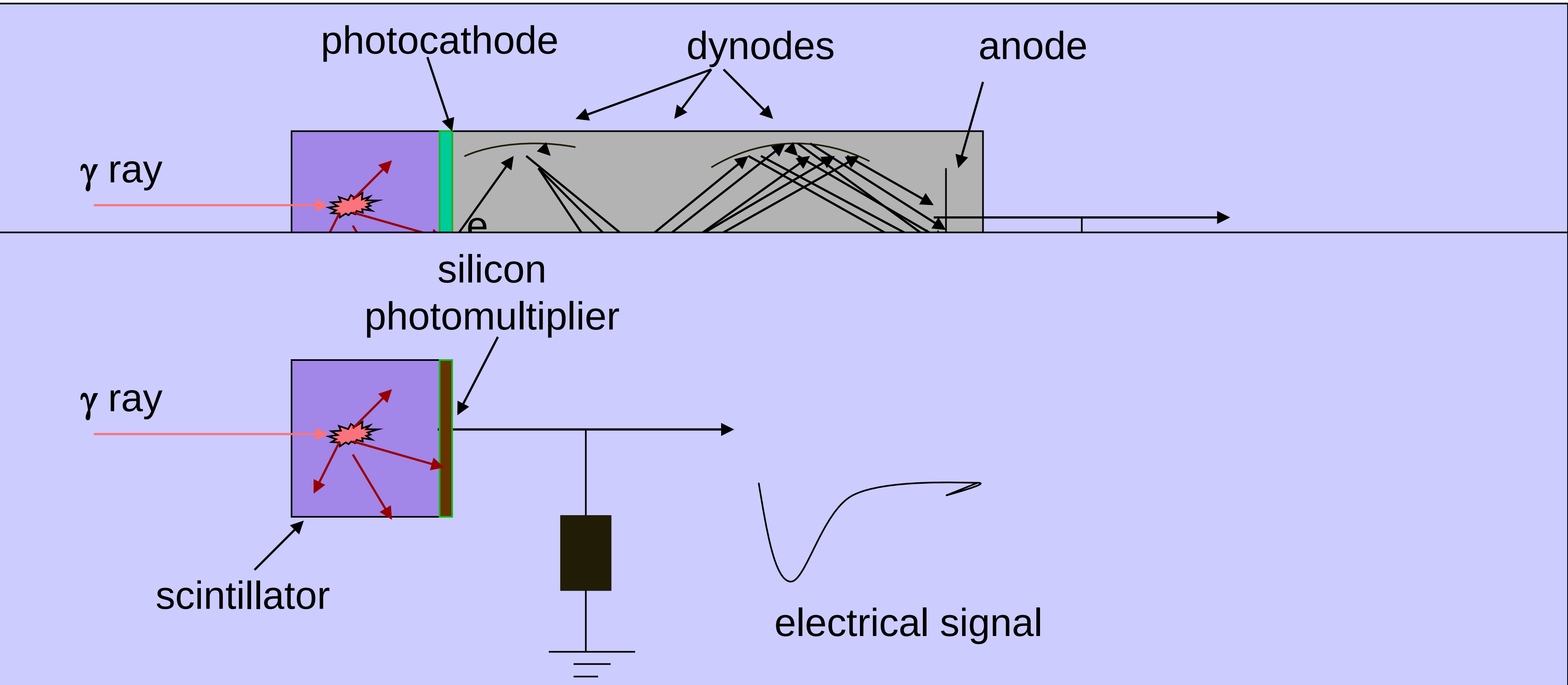
Elko also had the bright idea that we should get involved in RICH detectors, and we indeed became one of the leading labs in this challeging detection method.

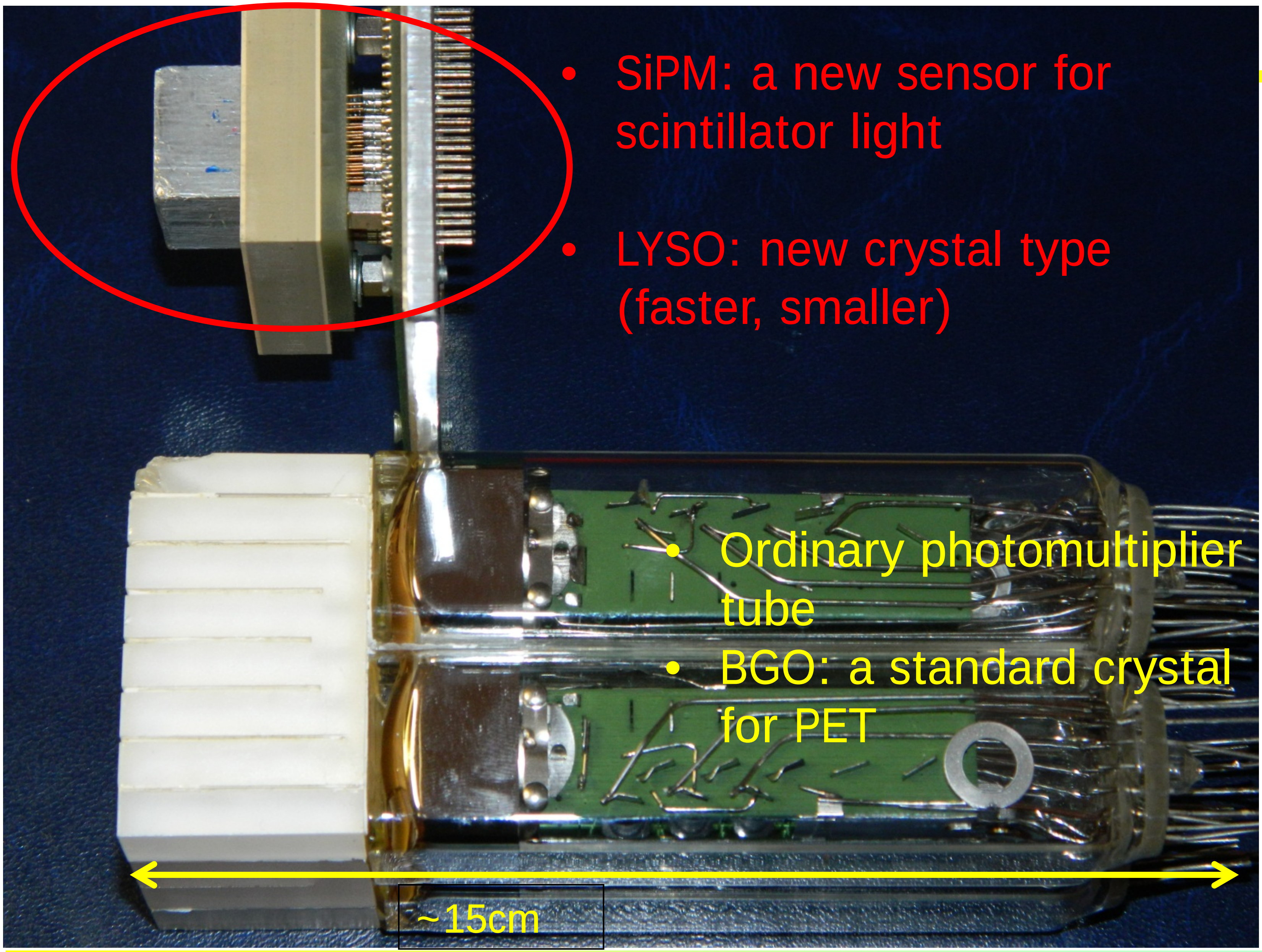
PET: positron emission tomography



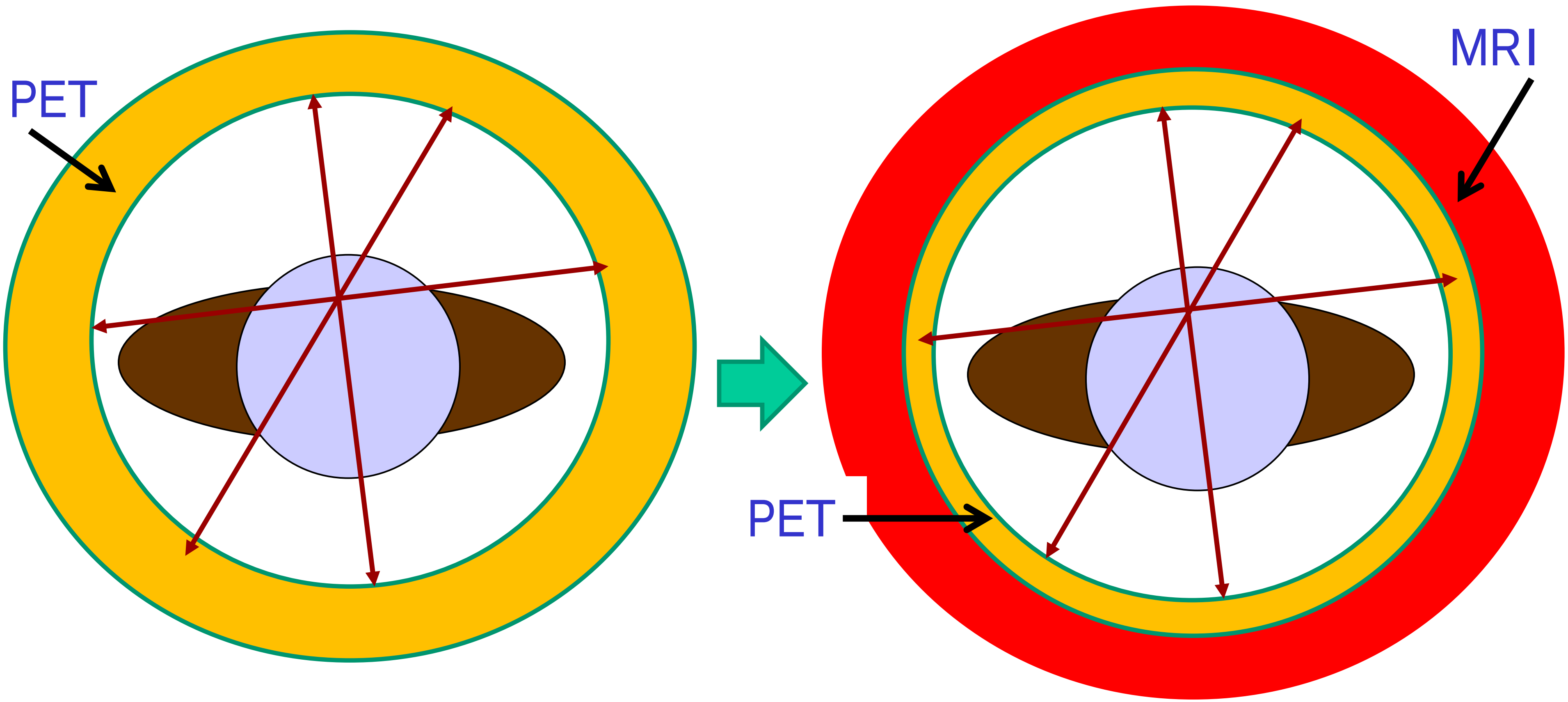
PET with a new sensor type

Silicon photomultiplier (SiPM): a new light sensor type → considerably smaller than the existing light sensors, does not need a high voltage supply, works well magnetic fields (several T).




• SiPM: a new sensor for scintillator light
• LYSO: new crystal type (faster, smaller)
• Ordinary photomultiplier tube
• BGO: a standard crystal for PET
~15cm

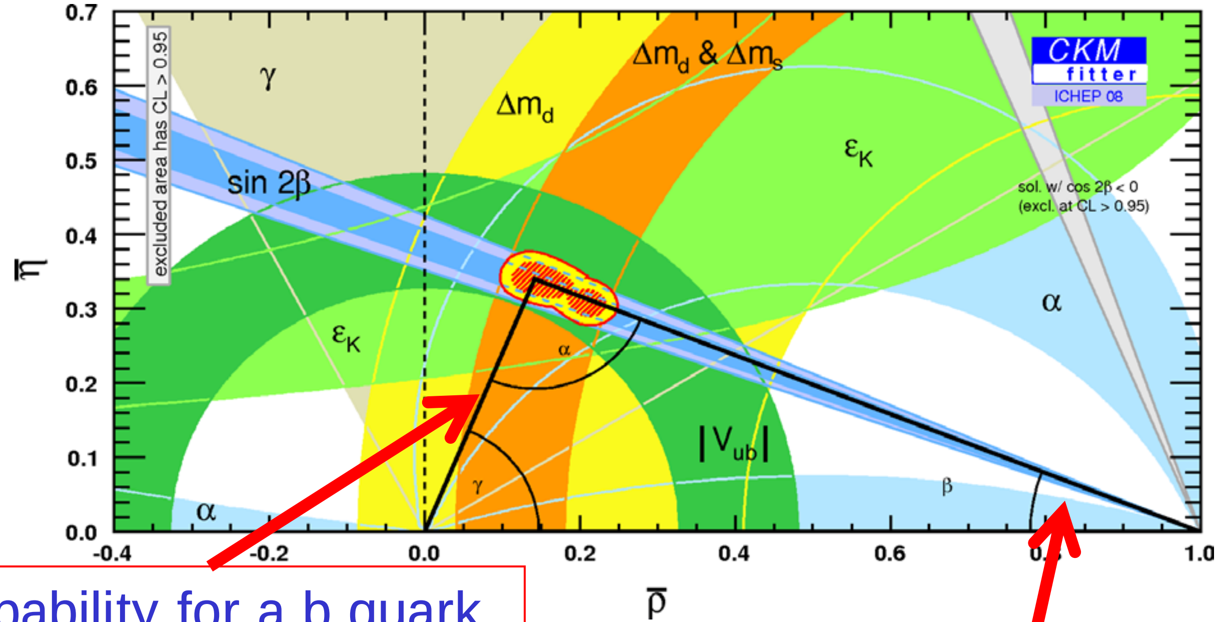
New sensor type → considerably smaller than exsisting detectors, operates well in high magnetic field



Allows a simultaneous imaging with magnetic resonance **and** PET – an important improvement in diagnostics!

More slides….

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 oscilation amplitude → angle $\phi_1 = \beta$

Constraints from measurements of angles and sides of the unitarity triangle

→ Remarkable agreement

B Physics @ Y(4S)

Observable	B Factories (2 ab^{-1})	Super$B$ (75 ab^{-1})
$\sin(2\beta)$ ($J/\psi K^0$)	0.018	0.005 (†)
$\cos(2\beta)$ ($J/\psi K^{*0}$)	0.30	0.05
$\sin(2\beta)$ (Dh^0)	0.10	0.02
$\cos(2\beta)$ (Dh^0)	0.20	0.04
$S(J/\psi \pi^0)$	0.10	0.02
$S(D^+D^-)$	0.20	0.03
$S(\phi K^0)$	0.13	0.02 (*)
$S(\eta' K^0)$	0.05	0.01 (*)
$S(K^0_S K^0_S K^0_S)$	0.15	0.02 (*)
$S(K^0_S \pi^0)$	0.15	0.02 (*)
$S(\omega K^0_S)$	0.17	0.03 (*)
$S(f_0 K^0_S)$	0.12	0.02 (*)
γ ($B \to DK$, $D \to CP$ eigenstates)	$\sim 15°$	2.5°
γ ($B \to DK$, $D \to$ suppressed states)	$\sim 12°$	2.0°
γ ($B \to DK$, $D \to$ multibody states)	$\sim 9°$	1.5°
γ ($B \to DK$, combined)	$\sim 6°$	1–2°
α ($B \to \pi\pi$)	$\sim 16°$	3°
α ($B \to \rho\rho$)	$\sim 7°$	1–2° (*)
α ($B \to \rho\pi$)	$\sim 12°$	2°
α (combined)	$\sim 6°$	1–2° (*)
$2\beta+\gamma$ ($D^{(*)\pm}\pi^\mp$, $D^\pm K^0_S \pi^\mp$)	20°	5°

Observable	B Factories (2 ab^{-1})	Super$B$ (75 ab^{-1})
$\lvert V_{cb}\rvert$ (exclusive)	4% (*)	1.0% (*)
$\lvert V_{cb}\rvert$ (inclusive)	1% (*)	0.5% (*)
$\lvert V_{ub}\rvert$ (exclusive)	8% (*)	3.0% (*)
$\lvert V_{ub}\rvert$ (inclusive)	8% (*)	2.0% (*)
$\mathcal{B}(B \to \tau\nu)$	20%	4% (†)
$\mathcal{B}(B \to \mu\nu)$	visible	5%
$\mathcal{B}(B \to D\tau\nu)$	10%	2%
$\mathcal{B}(B \to \rho\gamma)$	15%	3% (†)
$\mathcal{B}(B \to \omega\gamma)$	30%	5%
$A_{CP}(B \to K^*\gamma)$	0.007 (†)	0.004 († *)
$A_{CP}(B \to \rho\gamma)$	~ 0.20	0.05
$A_{CP}(b \to s\gamma)$	0.012 (†)	0.004 (†)
$A_{CP}(b \to (s+d)\gamma)$	0.03	0.006 (†)
$S(K^0_S \pi^0 \gamma)$	0.15	0.02 (*)
$S(\rho^0 \gamma)$	possible	0.10
$A_{CP}(B \to K^*\ell\ell)$	7%	1%
$A^{FB}(B \to K^*\ell\ell)s_0$	25%	9%
$A^{FB}(B \to X_s\ell\ell)s_0$	35%	5%
$\mathcal{B}(B \to K\nu\bar{\nu})$	visible	20%
$\mathcal{B}(B \to \pi\nu\bar{\nu})$	–	possible

Charm mixing and CP

Mode	Observable	$\Upsilon(4S)$ (75 ab^{-1})	$\psi(3770)$ (300 fb^{-1})
$D^0 \to K^+\pi^-$	x'^2	3×10^{-5}	
	y'	7×10^{-4}	
$D^0 \to K^+K^-$	y_{CP}	5×10^{-4}	
$D^0 \to K^0_S \pi^+\pi^-$	x	4.9×10^{-4}	
	y	3.5×10^{-4}	
	$\lvert q/p\rvert$	3×10^{-2}	
	ϕ	$2°$	
$\psi(3770) \to D^0\overline{D}^0$	x^2		$(1-2) \times 10^{-5}$
	y		$(1-2) \times 10^{-3}$
	$\cos\delta$		$(0.01-0.02)$

Charm FCNC

	Sensitivity
$D^0 \to e^+e^-$, $D^0 \to \mu^+\mu^-$	1×10^{-8}
$D^0 \to \pi^0 e^+e^-$, $D^0 \to \pi^0\mu^+\mu^-$	2×10^{-8}
$D^0 \to \eta e^+e^-$, $D^0 \to \eta\mu^+\mu^-$	3×10^{-8}
$D^0 \to K^0_S e^+e^-$, $D^0 \to K^0_S\mu^+\mu^-$	3×10^{-8}
$D^+ \to \pi^+ e^+e^-$, $D^+ \to \pi^+\mu^+\mu^-$	1×10^{-8}
$D^0 \to e^\pm\mu^\mp$	1×10^{-8}
$D^+ \to \pi^+ e^\pm\mu^\mp$	1×10^{-8}
$D^0 \to \pi^0 e^\pm\mu^\mp$	2×10^{-8}
$D^0 \to \eta e^\pm\mu^\mp$	3×10^{-8}
$D^0 \to K^0_S e^\pm\mu^\mp$	3×10^{-8}
$D^+ \to \pi^- e^+e^+$, $D^+ \to K^- e^+e^+$	1×10^{-8}
$D^+ \to \pi^-\mu^+\mu^+$, $D^+ \to K^-\mu^+\mu^+$	1×10^{-8}
$D^+ \to \pi^- e^\pm\mu^\mp$, $D^+ \to K^- e^\pm\mu^\mp$	1×10^{-8}

τ Physics

	Sensitivity
$\mathcal{B}(\tau \to \mu\gamma)$	2×10^{-9}
$\mathcal{B}(\tau \to e\gamma)$	2×10^{-9}
$\mathcal{B}(\tau \to \mu\mu\mu)$	2×10^{-10}
$\mathcal{B}(\tau \to eee)$	2×10^{-10}
$\mathcal{B}(\tau \to \mu\eta)$	4×10^{-10}
$\mathcal{B}(\tau \to e\eta)$	6×10^{-10}
$\mathcal{B}(\tau \to \ell K^0_S)$	2×10^{-10}

B_s Physics @ Y(5S)

Observable	Error with 1 ab^{-1}	Error with 30 ab^{-1}
$\Delta\Gamma$	0.16 ps^{-1}	0.03 ps^{-1}
Γ	0.07 ps^{-1}	0.01 ps^{-1}
β_s from angular analysis	20°	8°
A^s_{SL}	0.006	0.004
A_{CH}	0.004	0.004
$\mathcal{B}(B_s \to \mu^+\mu^-)$	-	$< 8 \times 10^{-9}$
$\lvert V_{td}/V_{ts}\rvert$	0.08	0.017
$\mathcal{B}(B_s \to \gamma\gamma)$	38%	7%
β_s from $J/\psi\phi$	10°	3°
β_s from $B_s \to K^0\bar{K}^0$	24°	11°

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

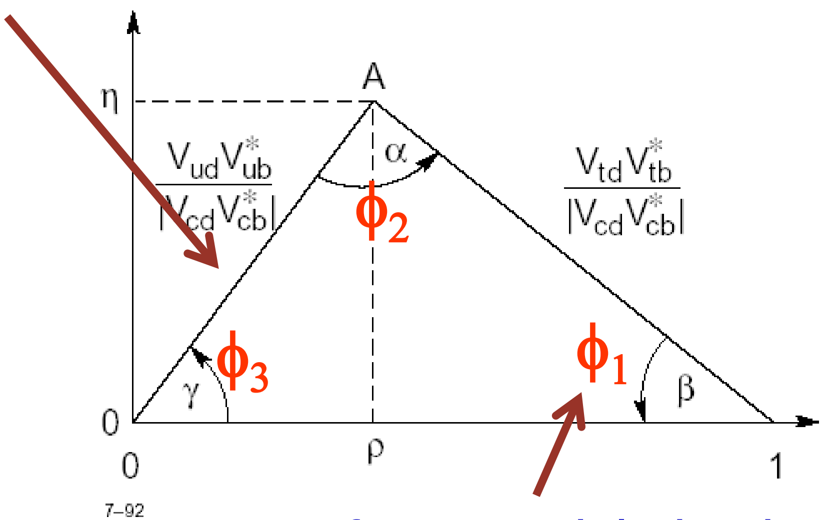
CKM matrix: determines charged weak interaction of quarks

Wolfenstein parametrisation: expand the CKM matrix in the parameter λ (=sinθ_c=0.22)

A, ρ and η: all of order one

$$V = \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

from probability of b→u transitions



from CP violation in B→J/ψ K_S decays

Unitarity condition:

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

Goal: measure sides and angles in several different ways, check consistency →