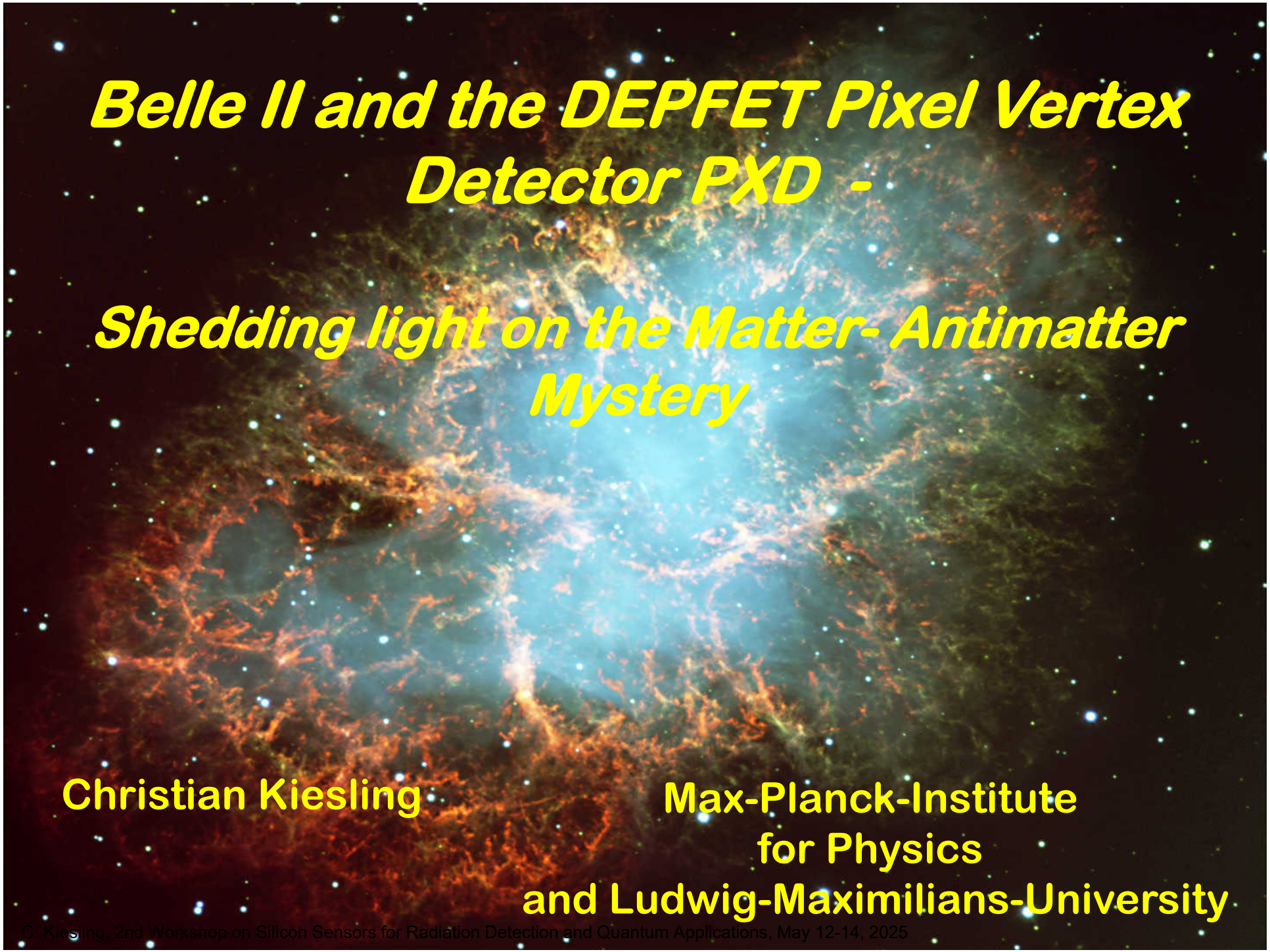


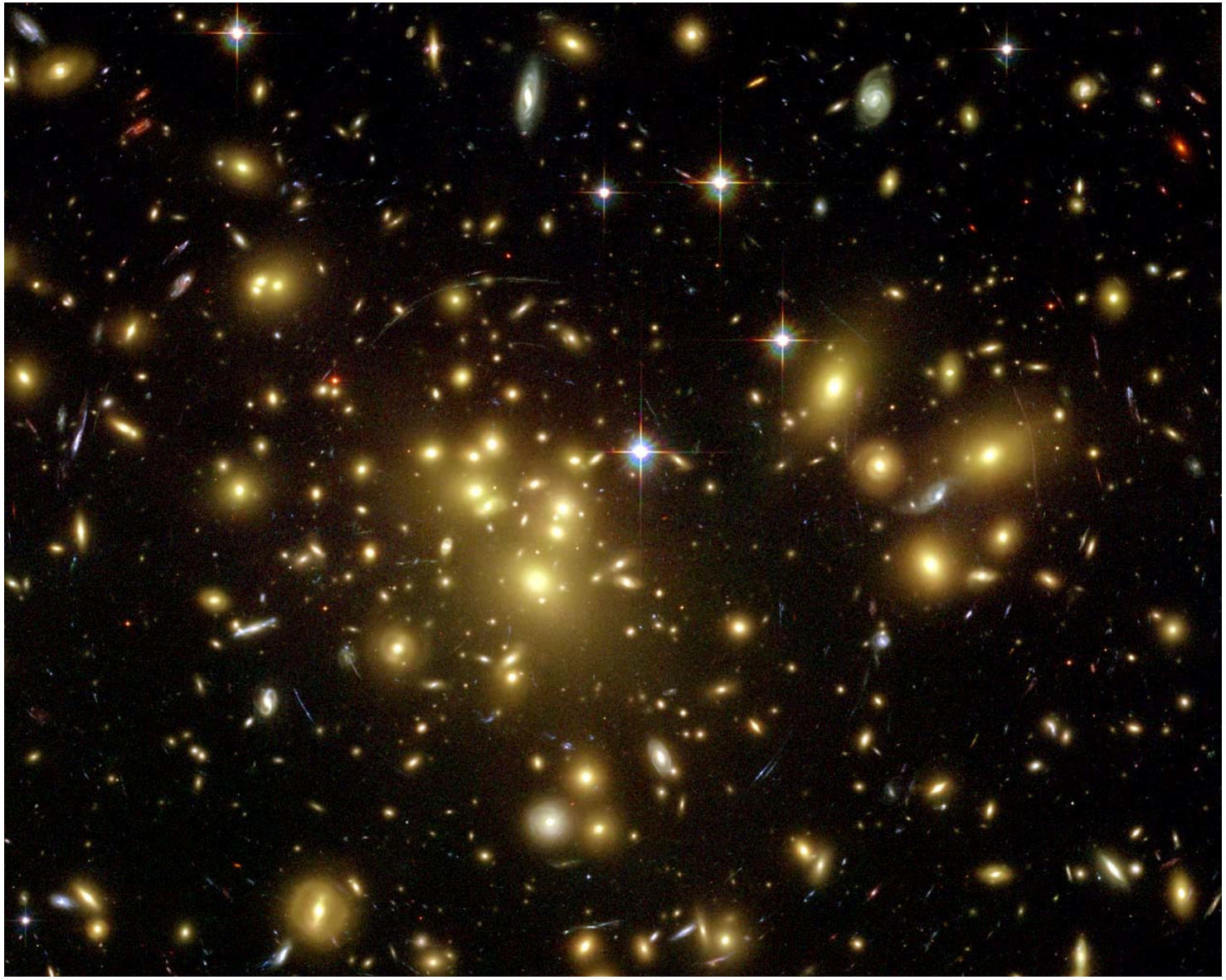
Belle II and the DEPFET Pixel Vertex Detector PXD -

Shedding light on the Matter- Antimatter Mystery

Christian Kiesling

Max-Planck-Institute
for Physics
and Ludwig-Maximilians-University

Looking into the Sky at Night …



the light from distant galaxies is „red-shifted“:

↓

the galaxies are receding

↓

the Universe is expanding

↓

… and is cooling ….

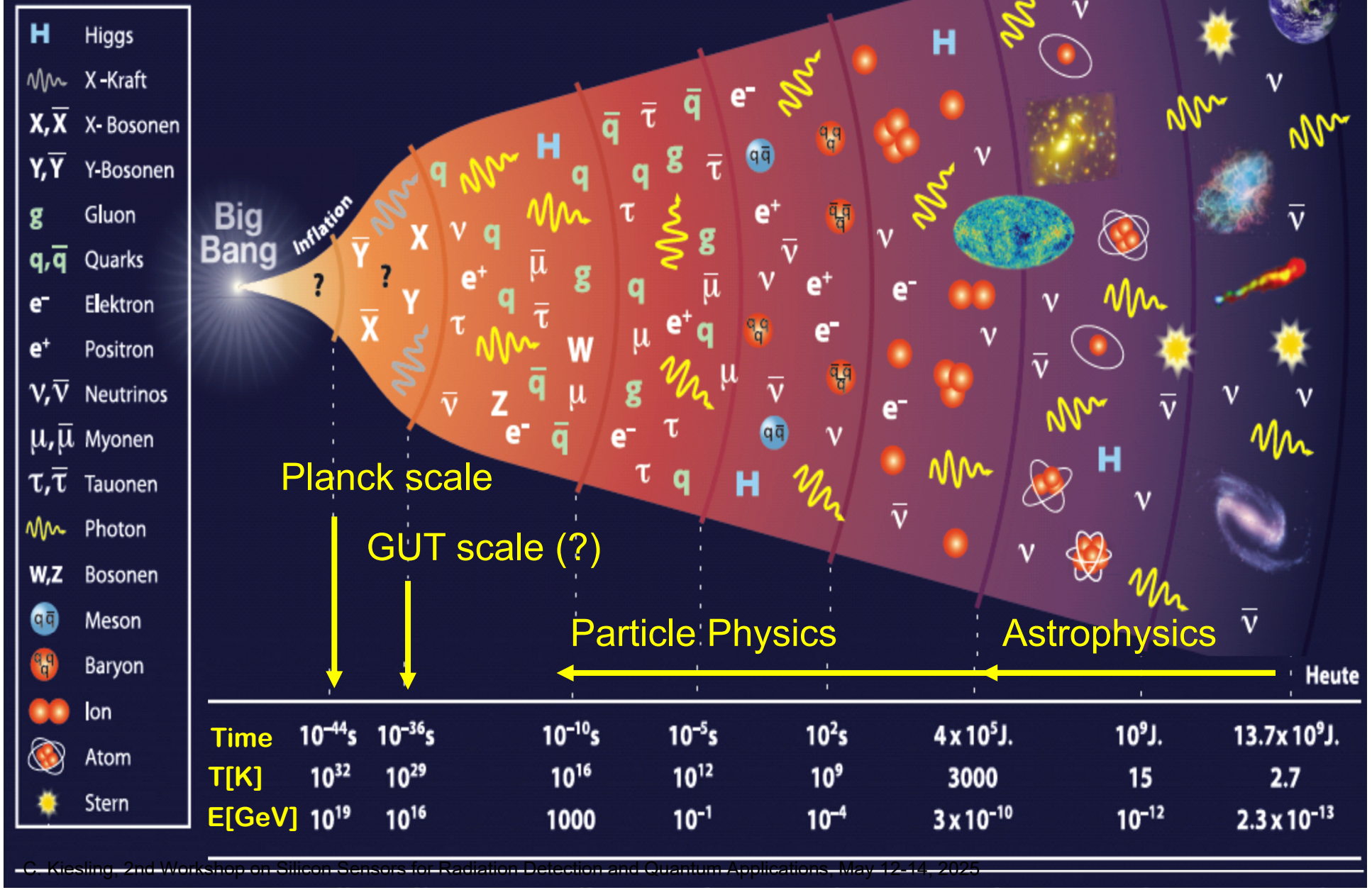
↑

was hotter at earlier times

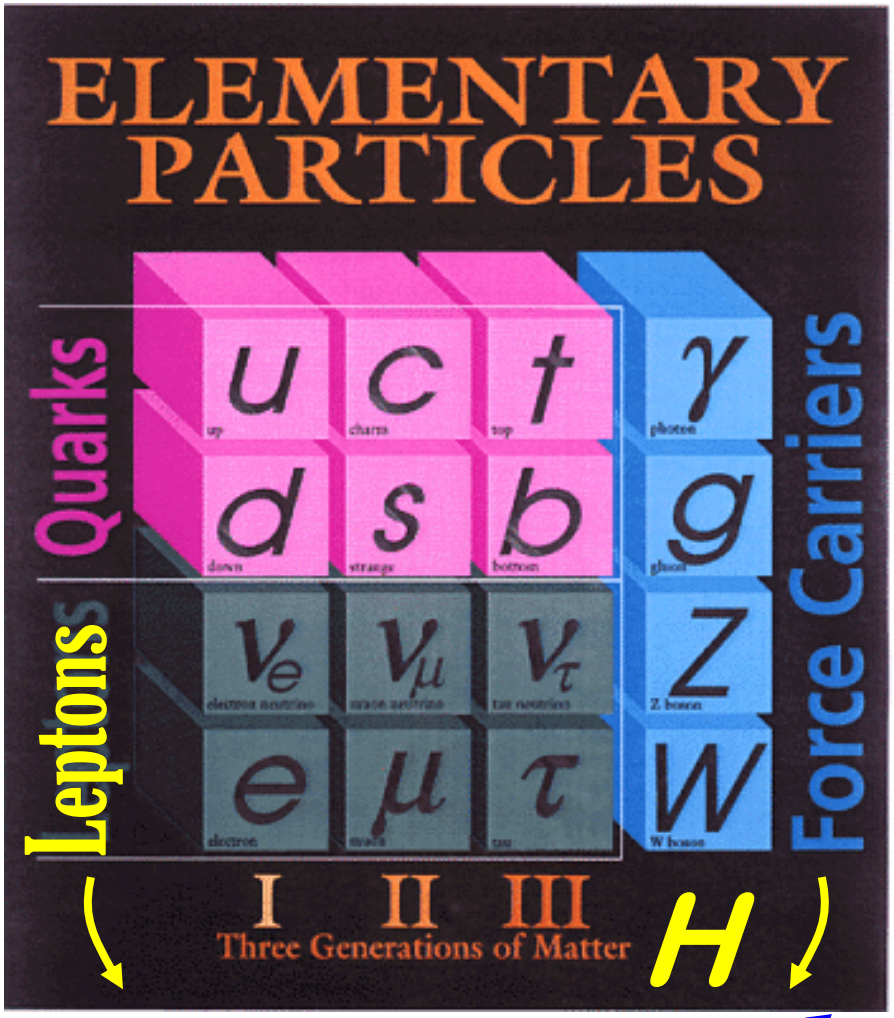
↑

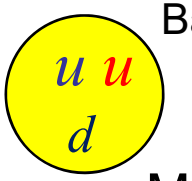
„Big Bang“

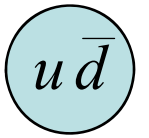
History of the Universe



The Standard Model of Particle Physics





Baryons ... , or Mesons  ...

electr. charge		Mass of particles (in GeV):			
+2/3	0	0.005	1.4	175	0
-1/3	0	0.006	0.3	4.5	0
0	0	>0	>0	>0	91
-1	±1	0.0005	0.1	1.8	80
	0				125

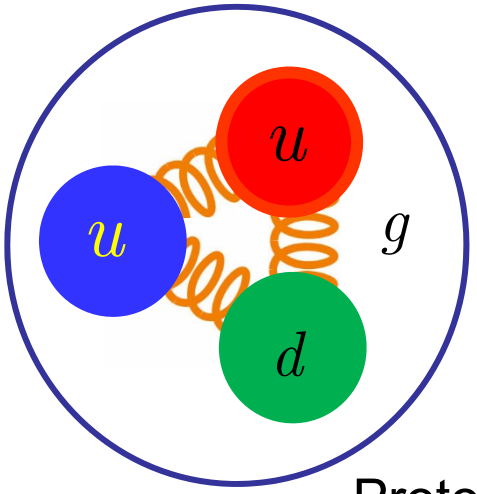
The last missing particle found !

"particles": Spin 1/2 (fermions)

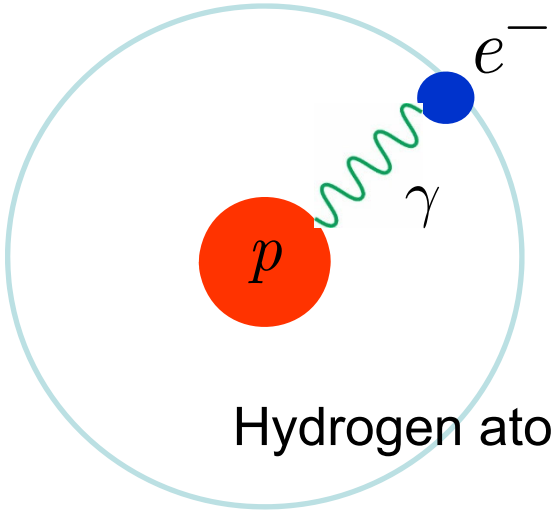
"fields": Spin 1 (0) (bosons)

the Higgs *H* (2012 @CERN)

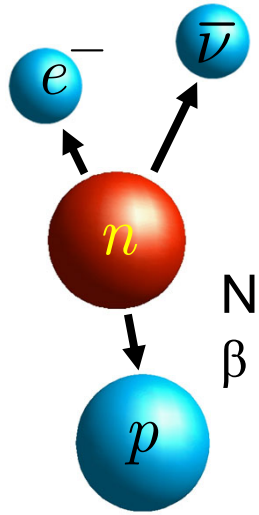
(Quantum) Forces in Nature



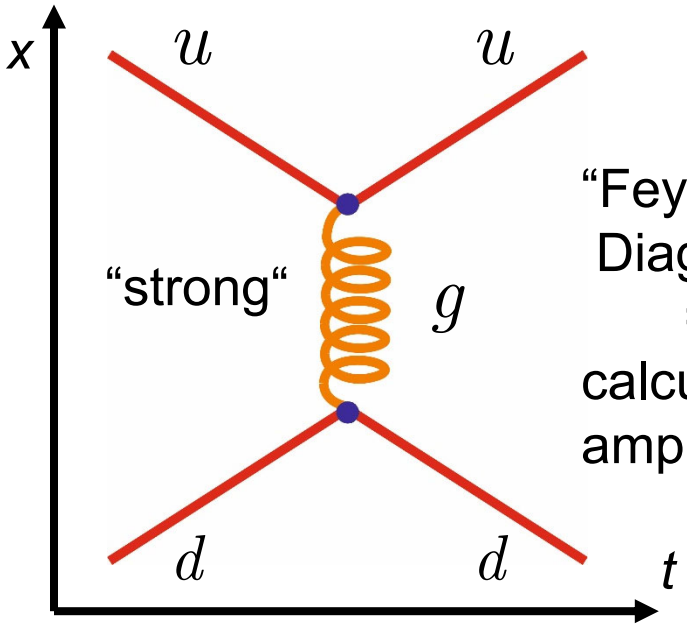
Proton



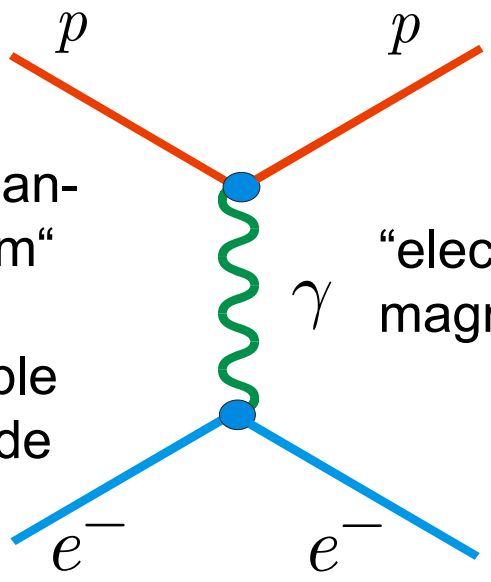
Hydrogen atom



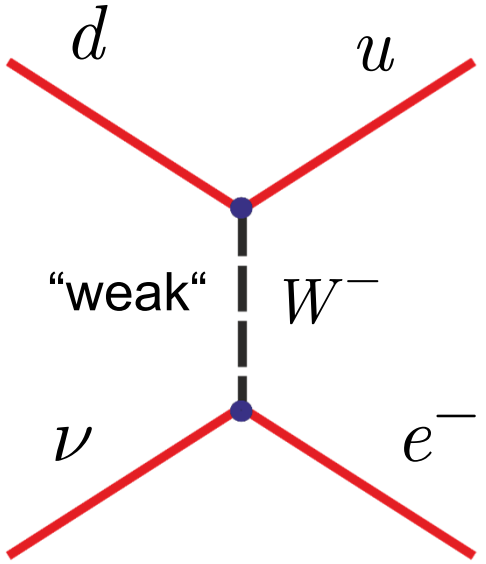
Neutron
β decay



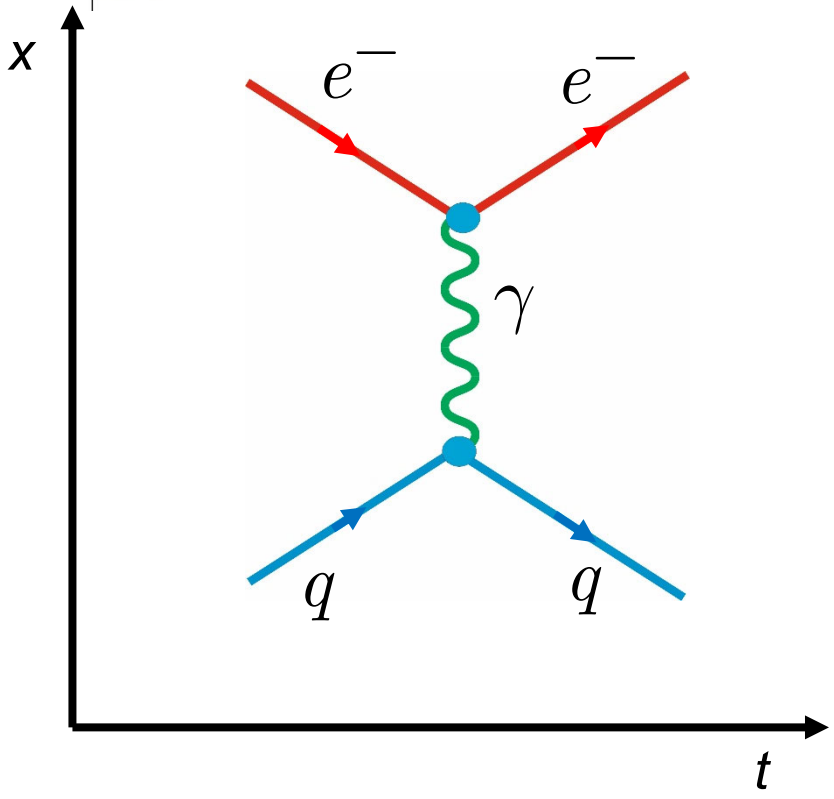
"Feynman-Diagram" = calculable amplitude

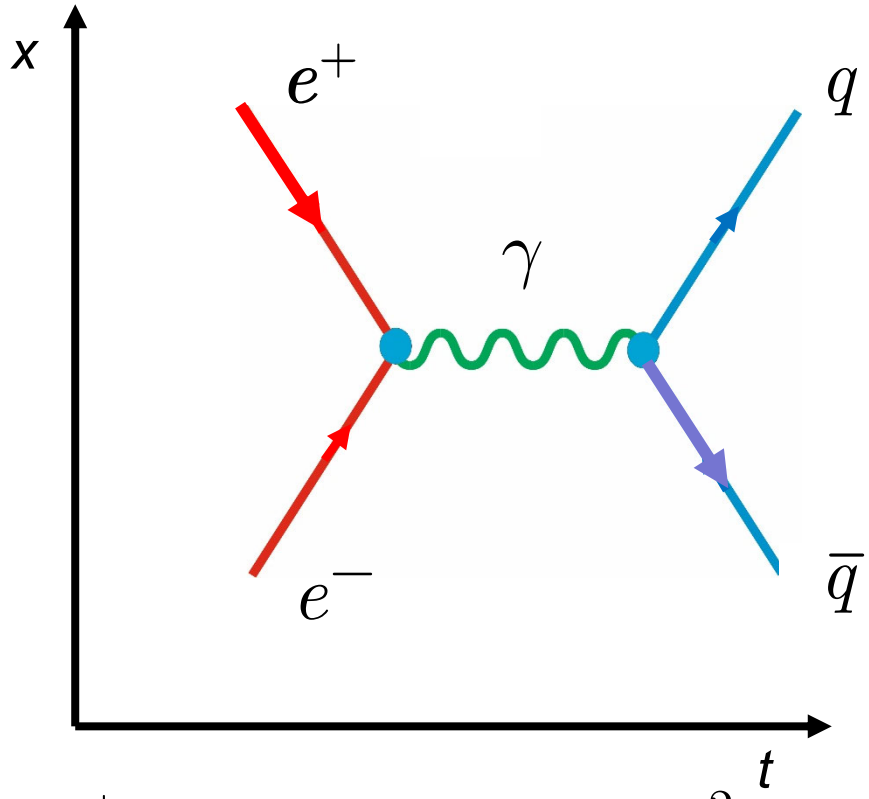


"electro-magnetic"



What about Antiparticles: Feynman's View





$$e^- q \rightarrow e^- q$$

$$\text{e.g. } e^- p \rightarrow e^- X$$

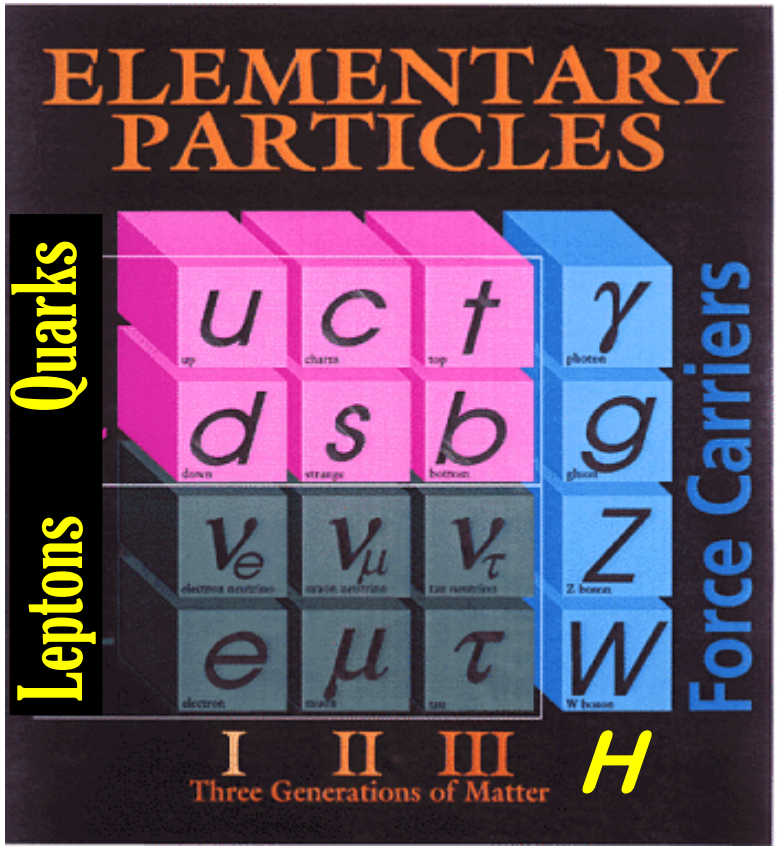
"Scattering"

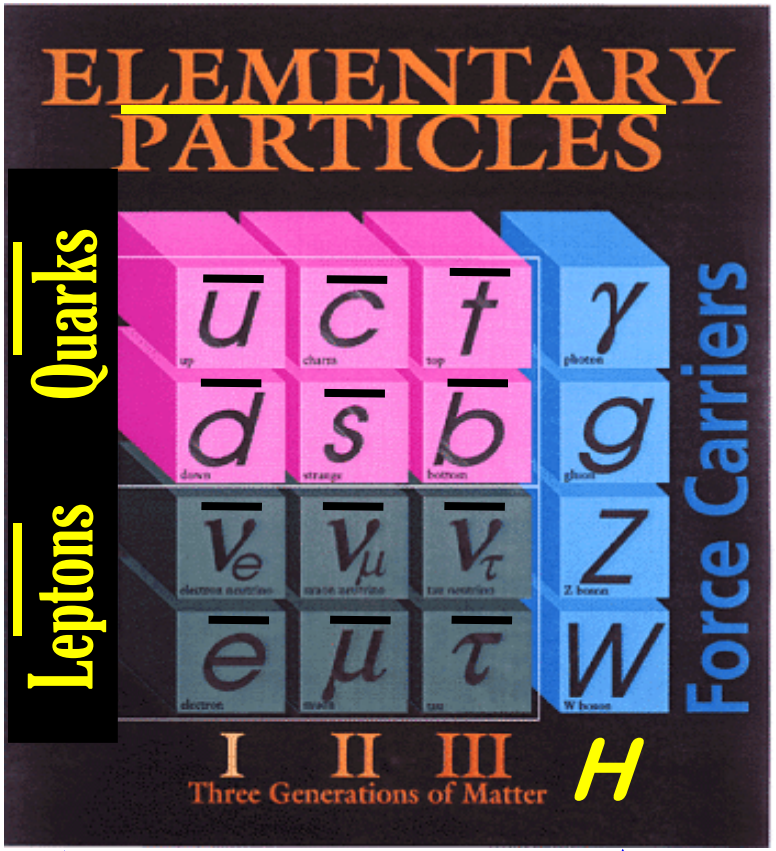
$$e^+e^- \rightarrow q\bar{q} \quad (E = mc^2)$$

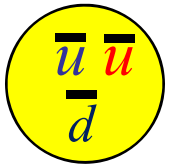
$$\text{e.g. } e^+e^- \rightarrow B\bar{B} \;:\; |B\rangle = |b\bar{d}\rangle$$

"Annihilation" -> Production of matter and antimatter in equal parts

Anti-Matter







anti proton

“particles“: Spin 1/2 (fermions)

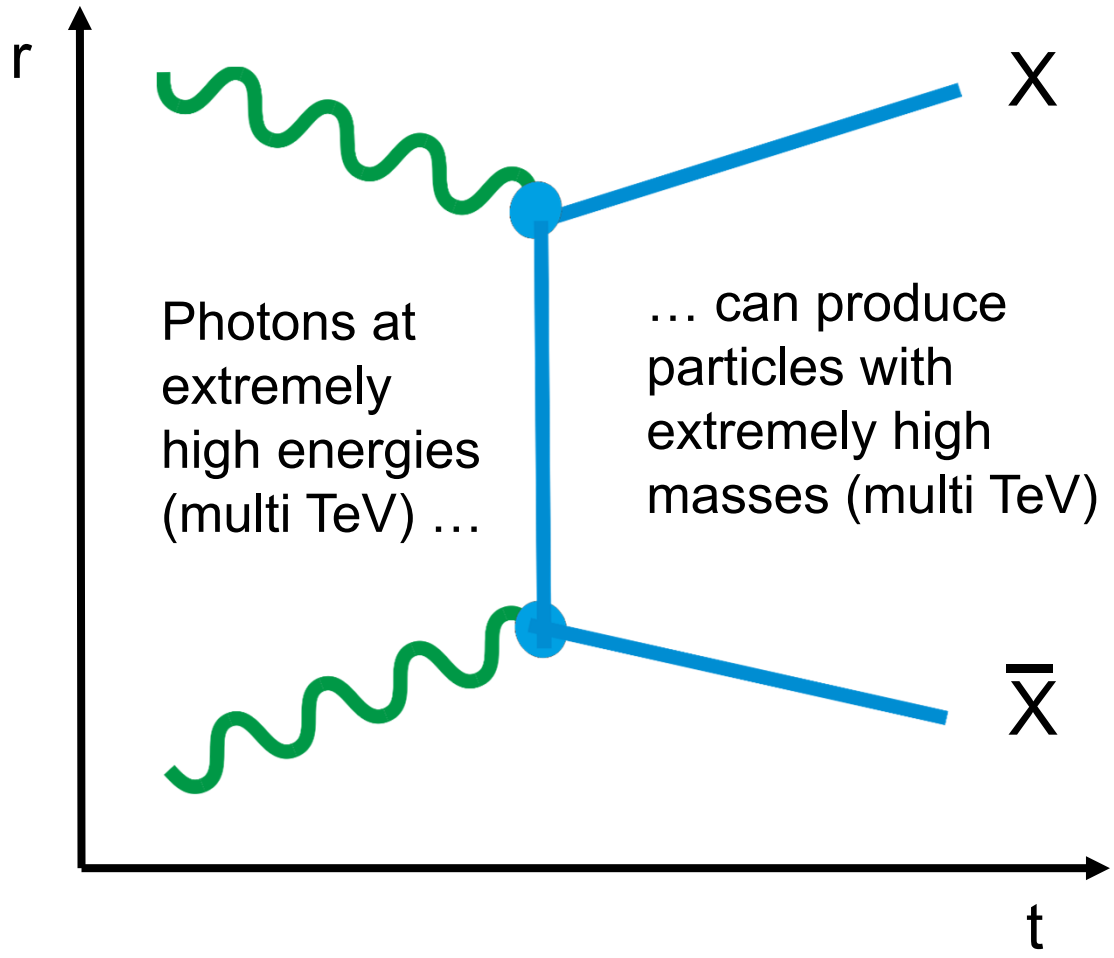
“fields“: Spin 1(0) (bosons)

“anti-particles“: Spin 1/2 (fermions)

“fields“: Spin 1(0) (bosons)

Creating Anti-Matter from Light

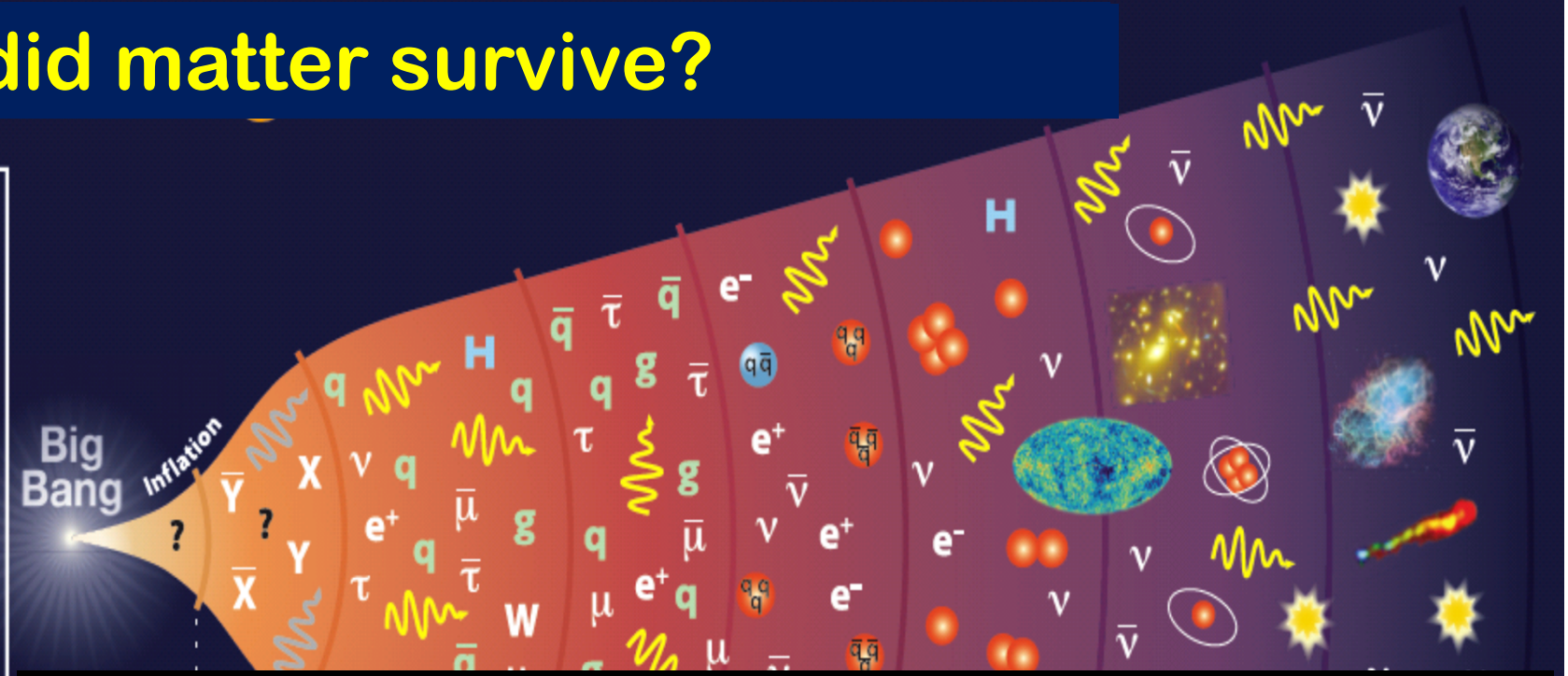
After Inflation, the very early Universe was dominated by radiation
(= extremely high energetic photons)



Matter and antimatter particles are produced in equal numbers

But: today we only "see" matter in the Universe
(earth, planets, sun, stars, galaxies …)

Why did matter survive?



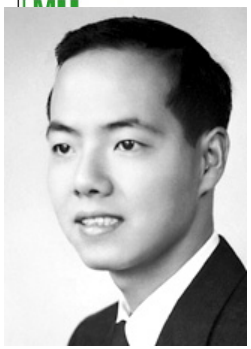
Matter survived because of a
"Violation of Symmetry between matter and antimatter"

-> matter and antimatter decay via the weak interaction

-> but matter and antimatter decay differently !!!
(violation of the „CP" symmetry)

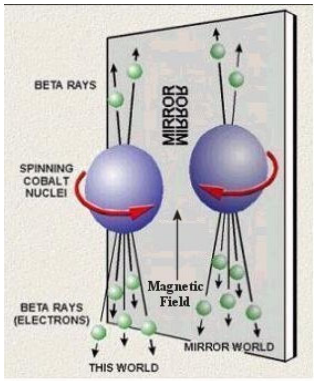
Time	10^{-44}s	10^{-36}s	10^{-10}s	10^{-5}s	10^{2}s	4×10^{5}J.	10^{9}J.	13.7×10^{9}J.
T[K]	10^{32}	10^{29}	10^{16}	10^{12}	10^{9}	3000	15	2.7
E[GeV]	10^{19}	10^{16}	1000	10^{-1}	10^{-4}	3×10^{-10}	10^{-12}	2.3×10^{-13}

Symmetry Violations in the Weak Interaction



T.D. Lee

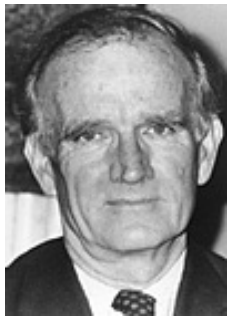
C.N. Yang



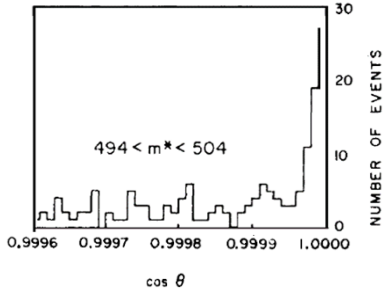
C, P violated maximally in weak interactions

1957

J. Cronin



V. Fitch

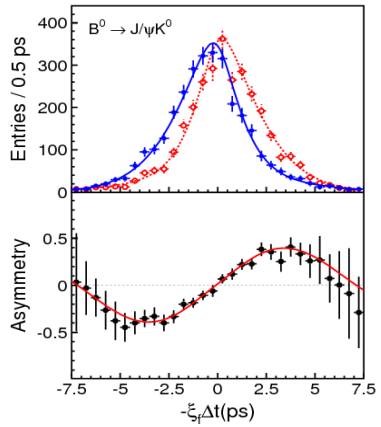


Small CP violation in neutral K system

1980

M. Kobayashi

T. Maskawa

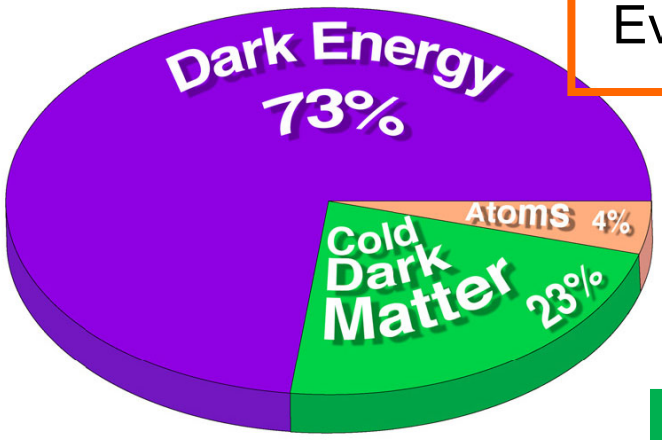


O(1) CP violation and 3 generations of quarks

2008

Why Looking for New Sources of ~~CP~~

The Standard Model (SM) describes all experimental data so far including CP violation, yet: SM is only a “low energy“ approximation



Evidence for Physics beyond the Standard Model:

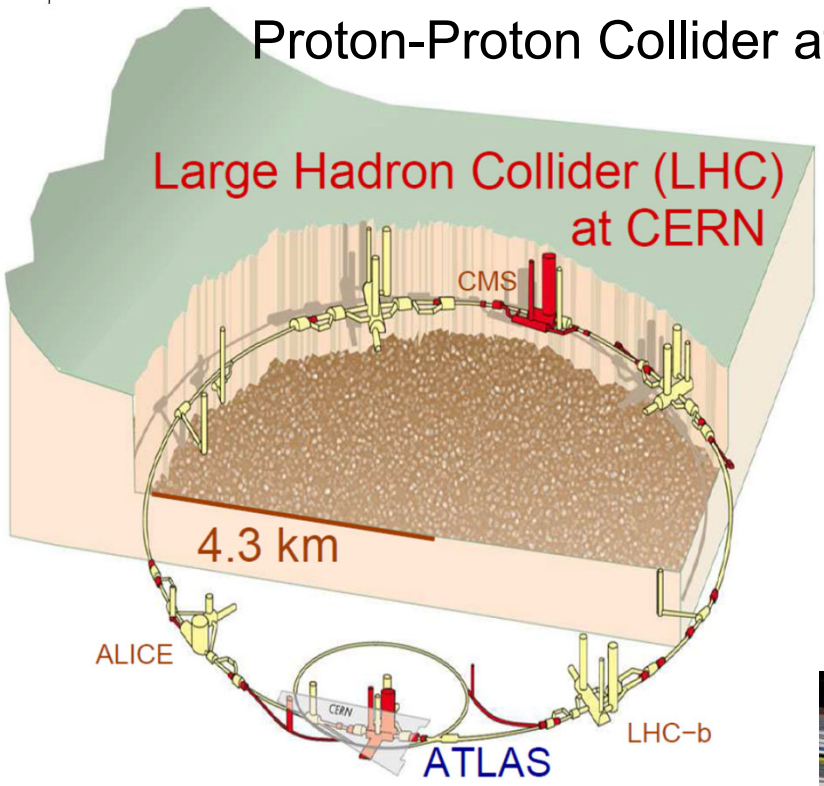
- Neutrinos have mass (Dirac, Majorana?)
- Dark Matter exists
  (only 4% of the Universe accounted for by SM)
- Baryon Asymmetry in the Universe is much too large (by 10 orders of magnitude)

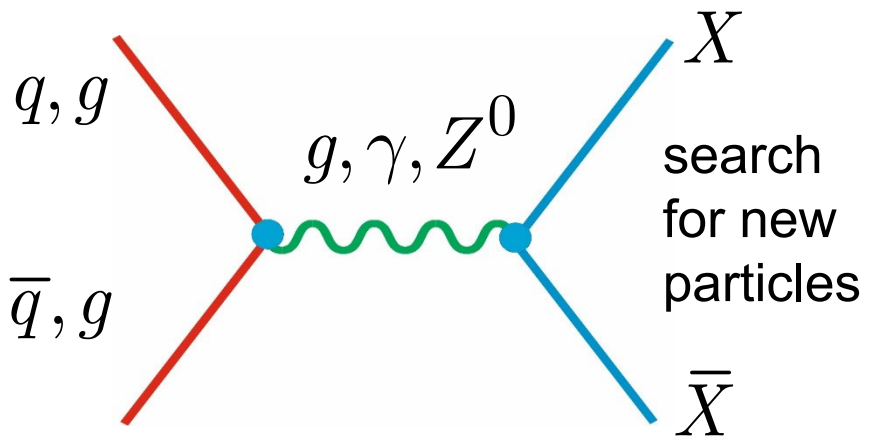
need
very high energy
(LHC) or
v. high precision
(**Super B factory**)

New (very heavy) particles must exist which are subject to a much stronger CP violation than the SM particles

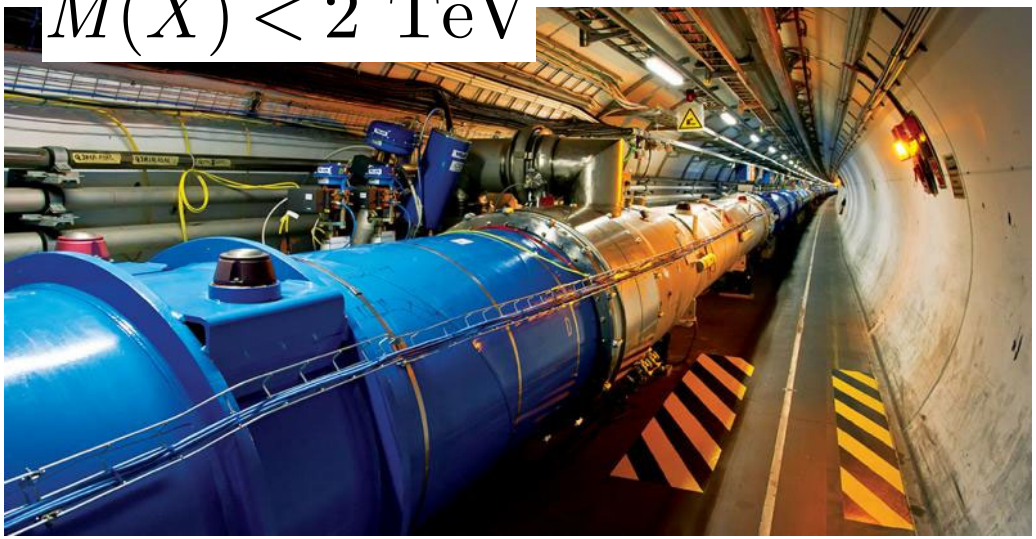
Looking for „New Particles“ at CERN

Proton-Proton Collider at 14 TeV CM Energy, CERN, Geneva, CH





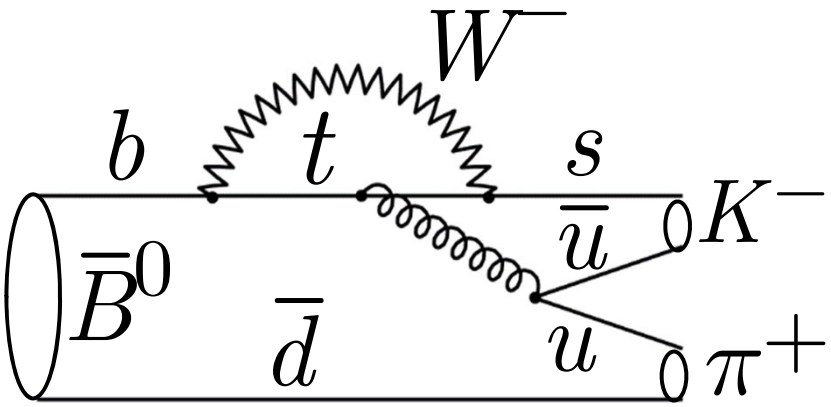
$M(X) < 2$ TeV



Highest energy particle collider

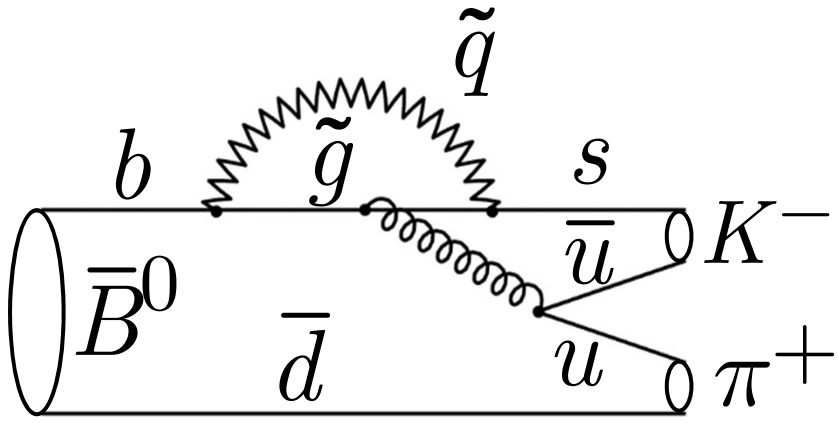
Greatest achievement so far:
discovery of the Higgs boson
in 2012 by ATLAS and CMS

Or: „New Particles“ in Quantum Loops



SM „penguin“

+



NP „penguin“

Principle:

New particles in the loop contribute new amplitudes:
->„**Quantum Loop Effects**“

Expect observables to deviate from SM prediction !!

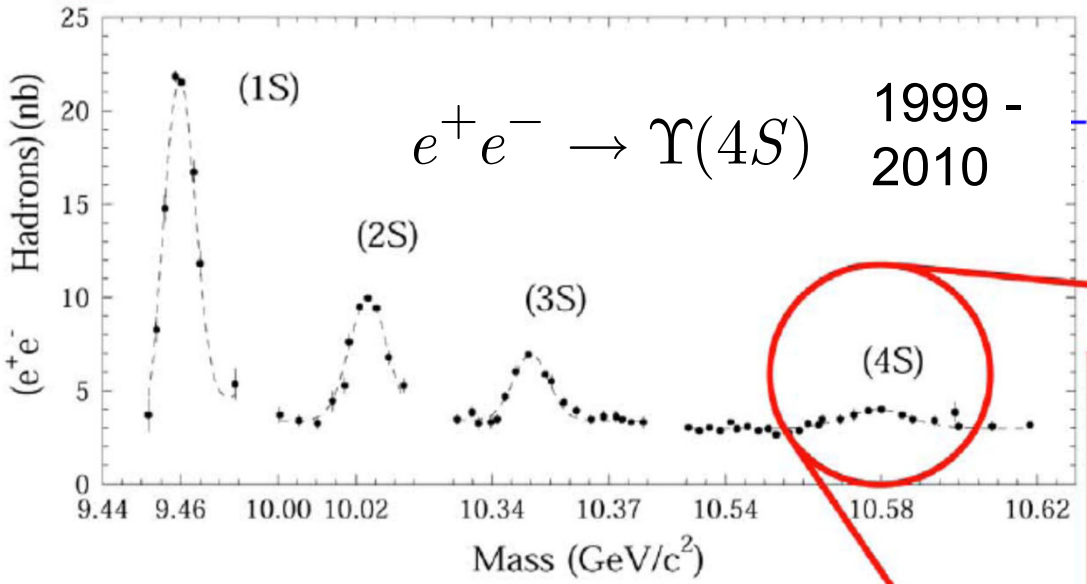
e.g. NP=SUSY:

additional diagrams, e.g. from gluino-squark contributions

→ Λ_{NP} no limit on mass !

Precision experiments with *B* mesons

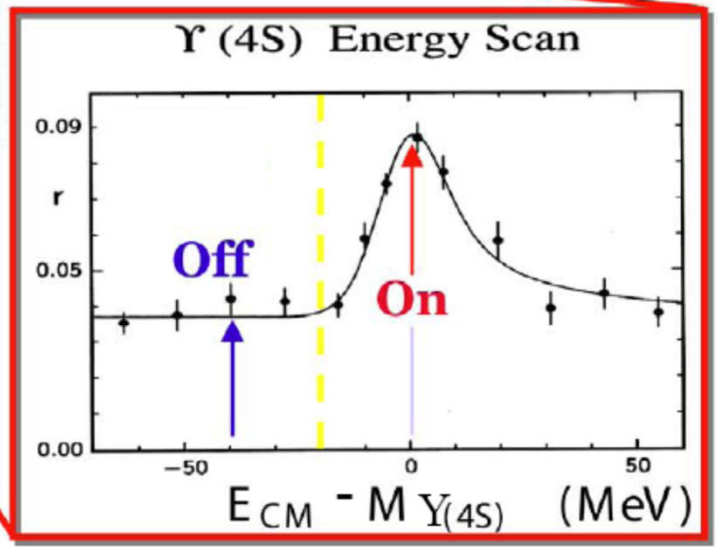
B Factories: Where do we Measure?

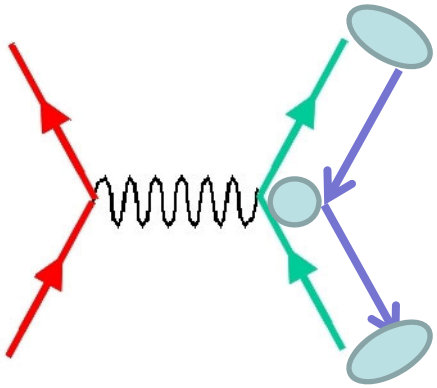


Asymmetric beam energies

-> $B^0\bar{B}^0$ (50%), B^+B^- (50%)

Belle, BaBar experiments





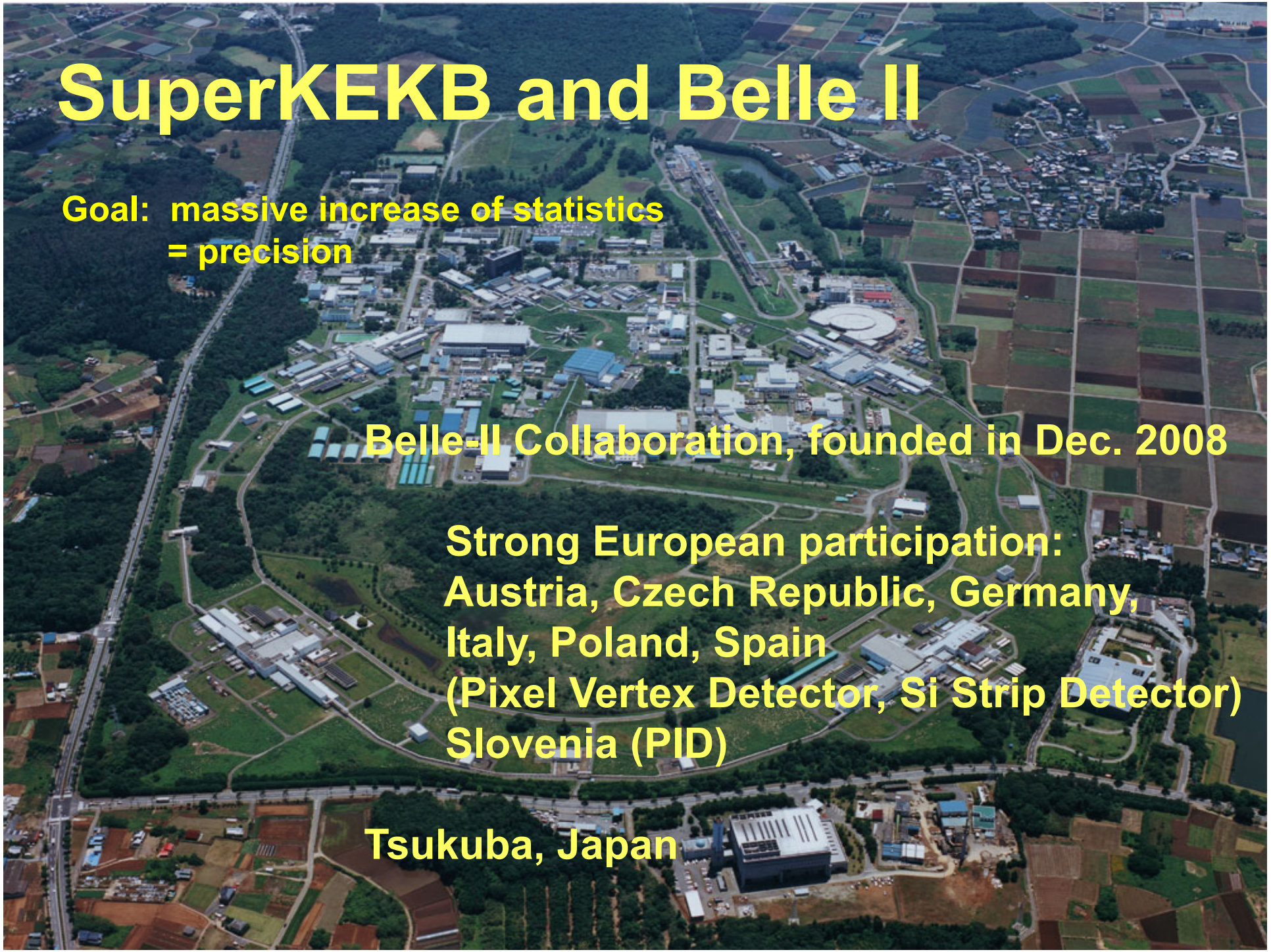
$$|\bar{B}^0\rangle = |b\bar{d}\rangle$$

$$|B^0\rangle = |\bar{b}d\rangle$$

$B^0, B^\pm$: heaviest mesons decaying only weakly

Differences found between B meson and Anti-B- Meson, as predicted by SM

NP 2008

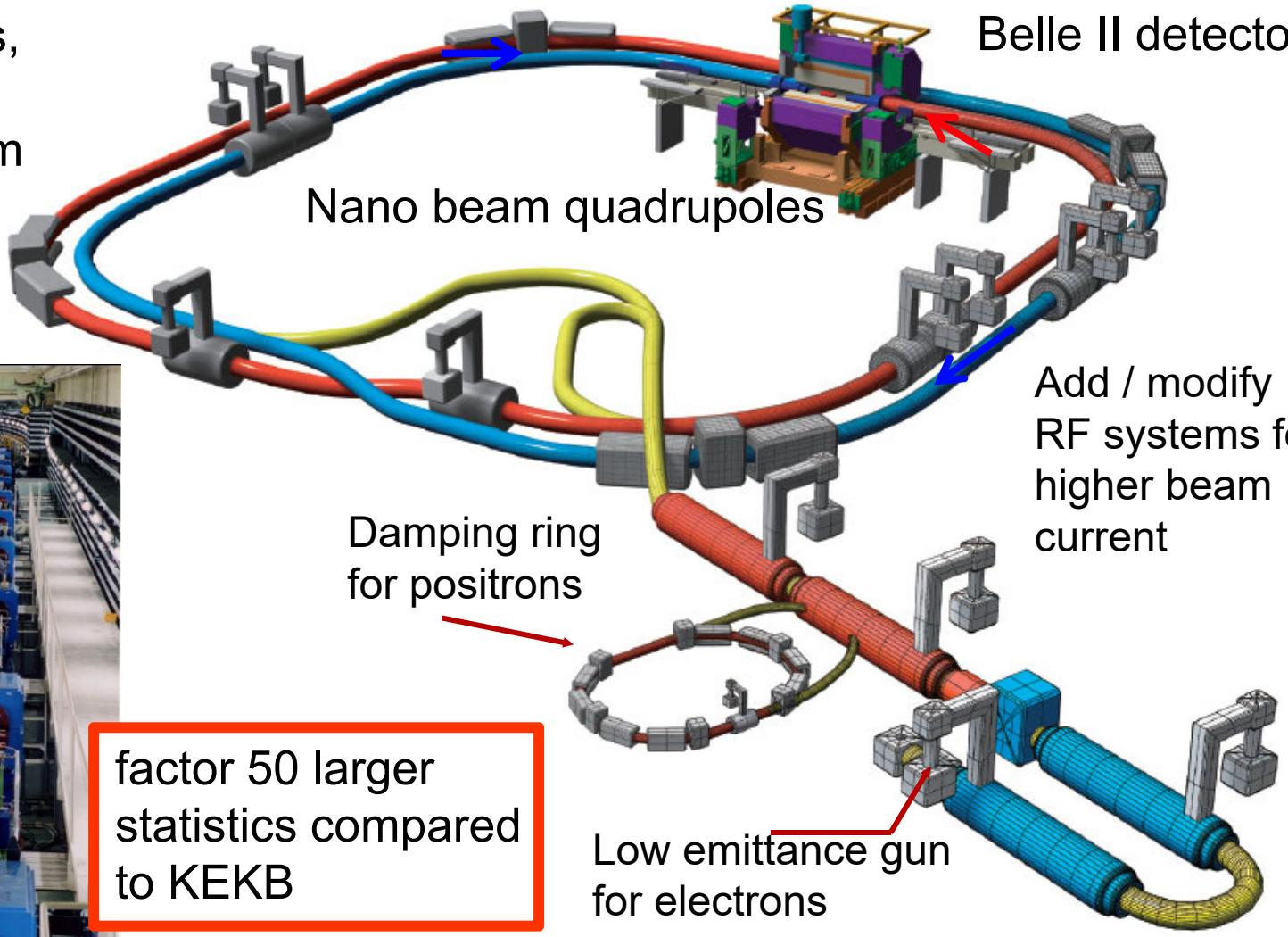

SuperKEKB and Belle II
Goal: massive increase of statistics
= precision
Belle-II Collaboration, founded in Dec. 2008
Strong European participation:
Austria, Czech Republic, Germany,
Italy, Poland, Spain
(Pixel Vertex Detector, Si Strip Detector)
Slovenia (PID)
Tsukuba, Japan

Nano-Beam Machine: SuperKEKB

e^+ 4GeV 3.5 A e^- 7GeV 2.8 A

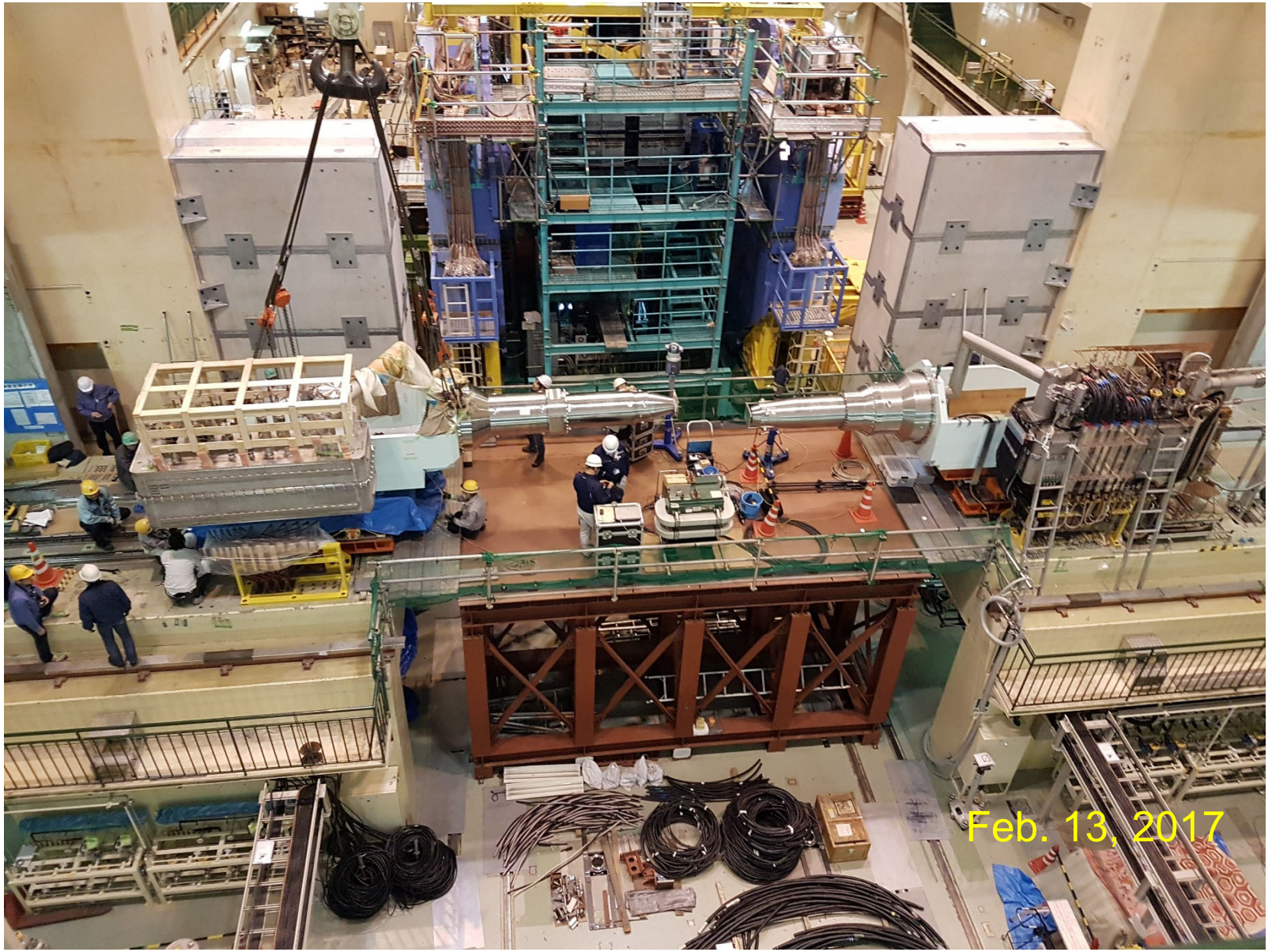
Target: L = $6 \times 10^{35}/cm^2/s$

2500 bunches,
bunch profile
50 nm x 10 μm
L=6mm, each
10^{11} particles

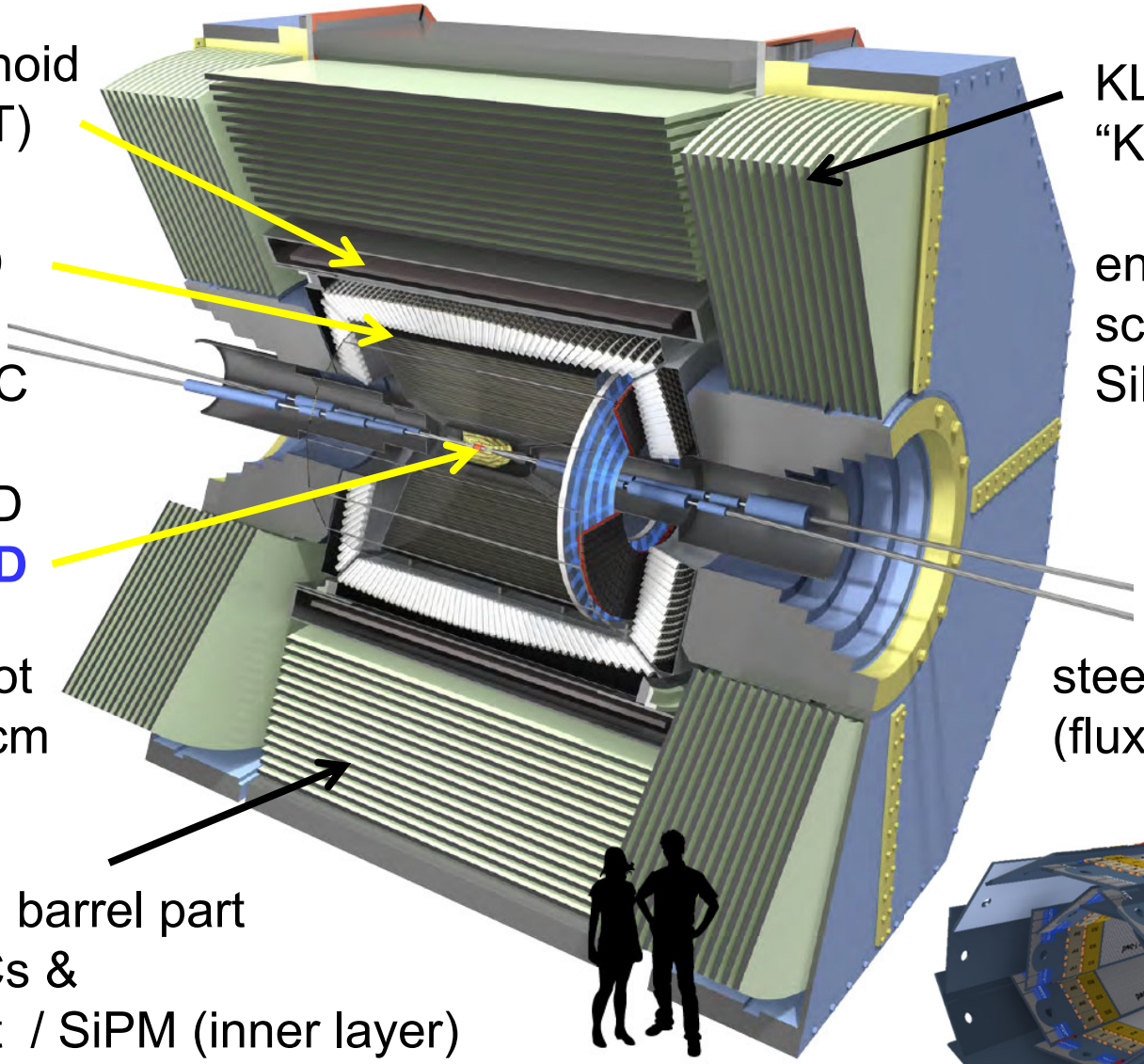


factor 50 larger statistics compared to KEKB

SuperKEKB Focusing Quadrupoles



The Belle II Detector



Solenoid
(1.5 T)

new PID

new CDC

new SVD
new PXD

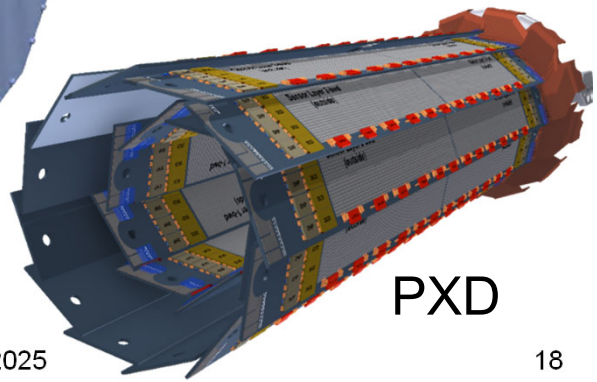
(strips will not work @1.4 cm radius)

KLM barrel part
RPCs &
scint / SiPM (inner layer)

KLM
"K_L and muon"

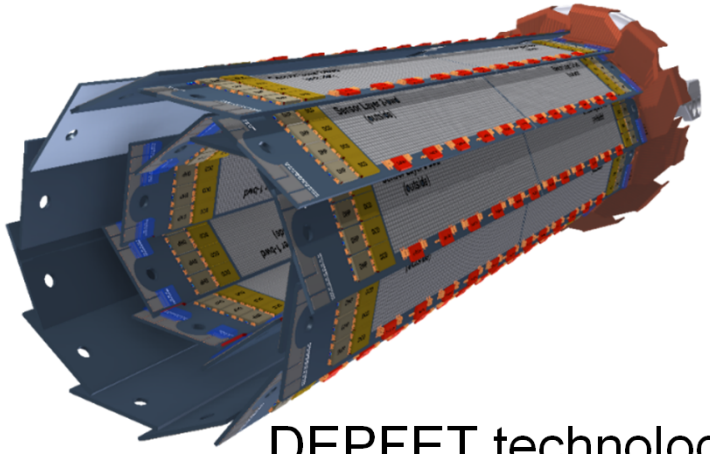
end cap:
scinillator &
SiPM

steel plates
(flux return yoke)



PXD

Vertexing: Silicon Tracking System @ Belle II

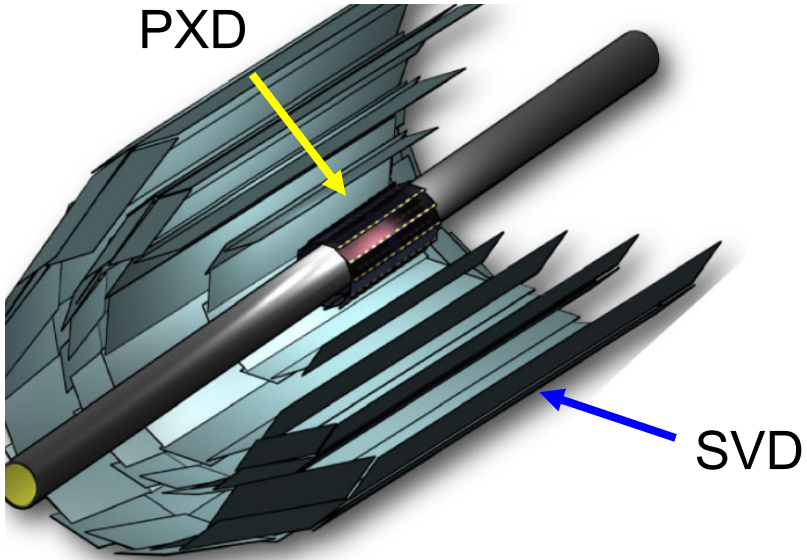


"PXD"

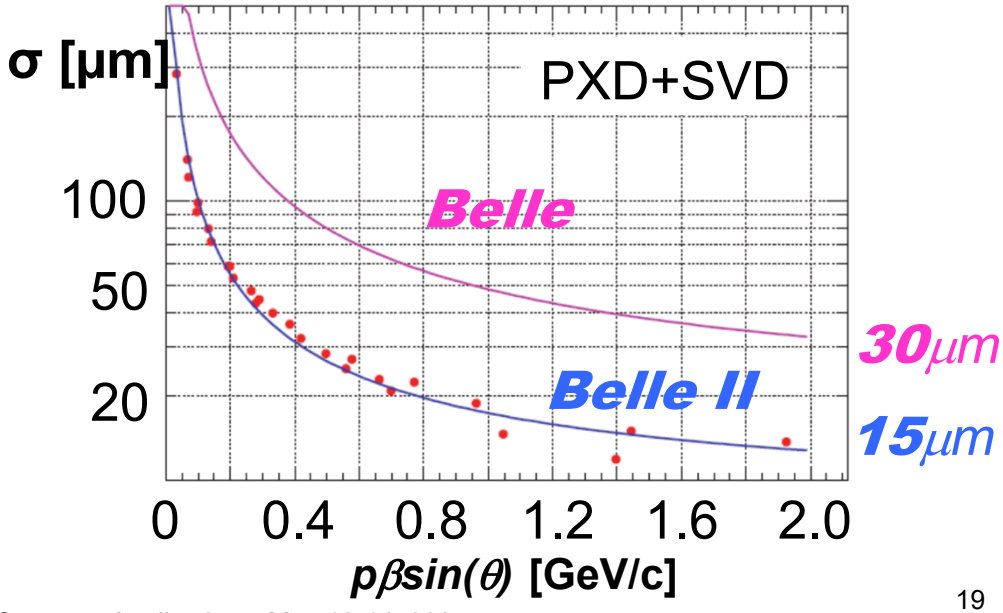
- 2 layer Si pixel detector (DEPFET technology)
  (R = 1.4, 2.2 cm) monolithic sensor
  thickness 75 µm (!), pixel size ~50 x 50 µm²
- 4 layer Si strip detector (DSSD) ← "SVD"
  (R = 3.8, 8.0, 11.5, 14.0 cm)

DEPFET technology
unique worldwide
(HLL of the MPG)

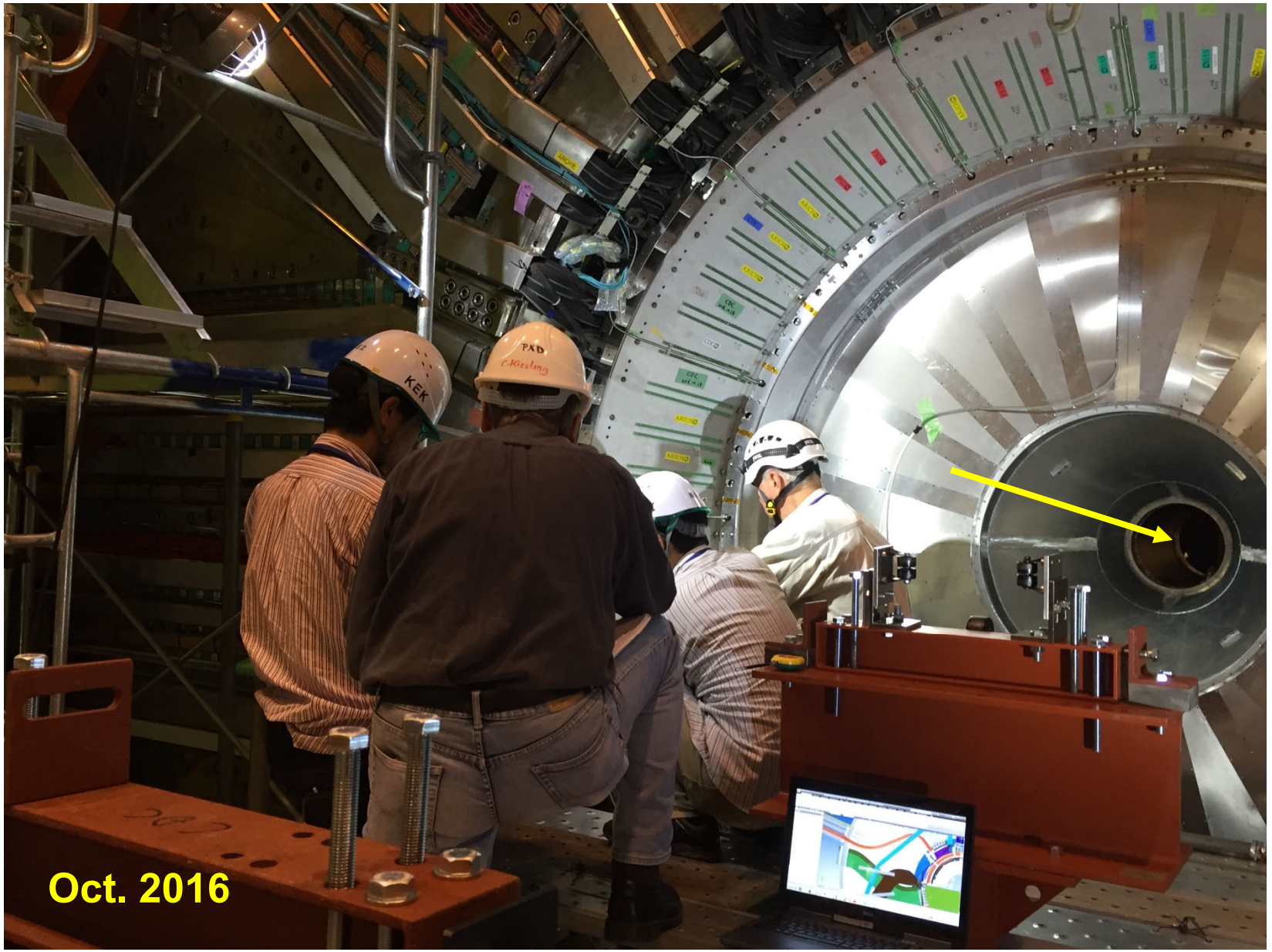
PXD



Significant improvement in vertex resolution

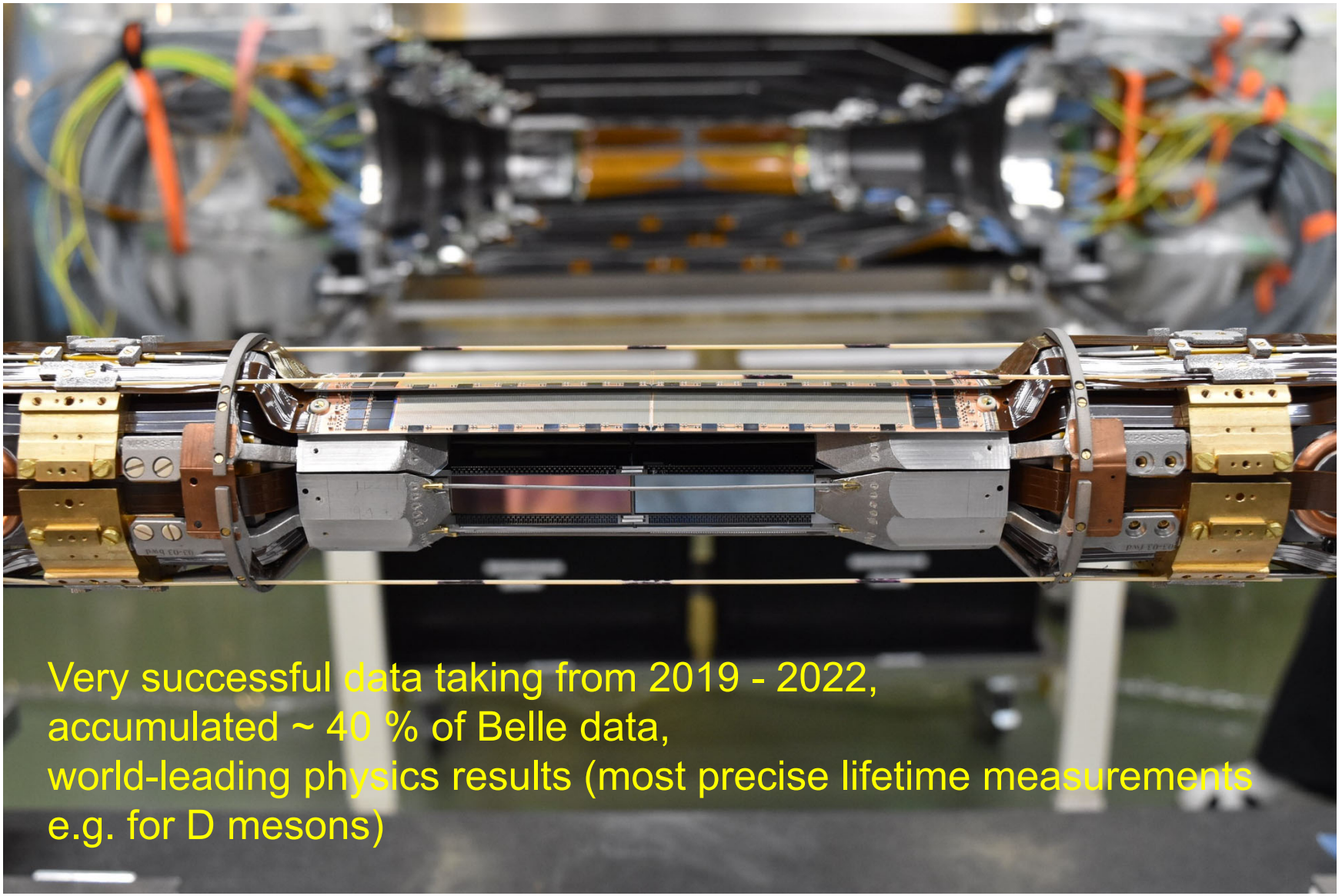


… only the Vertex Detector is missing …

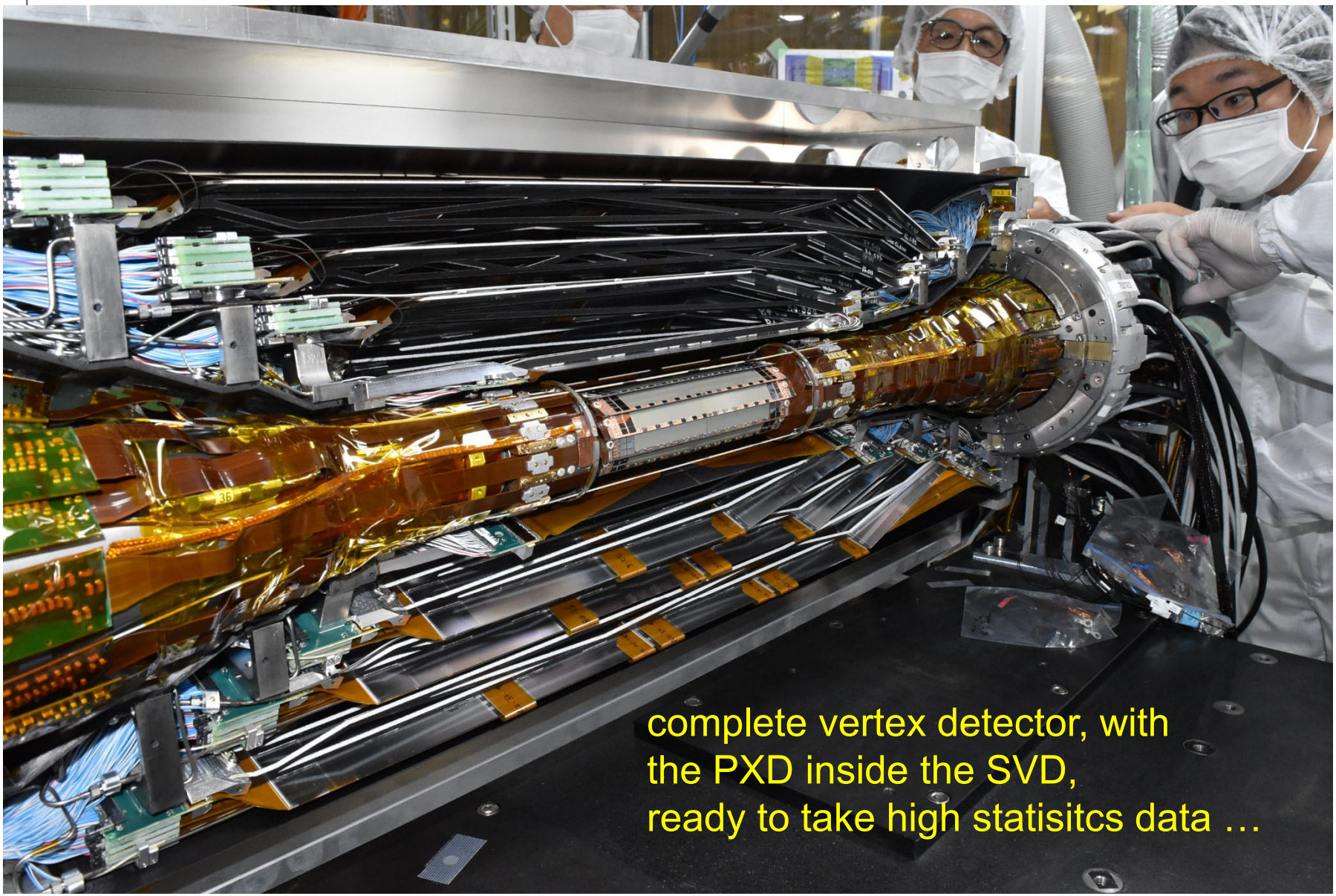


First Version of PXD, installed in 2018

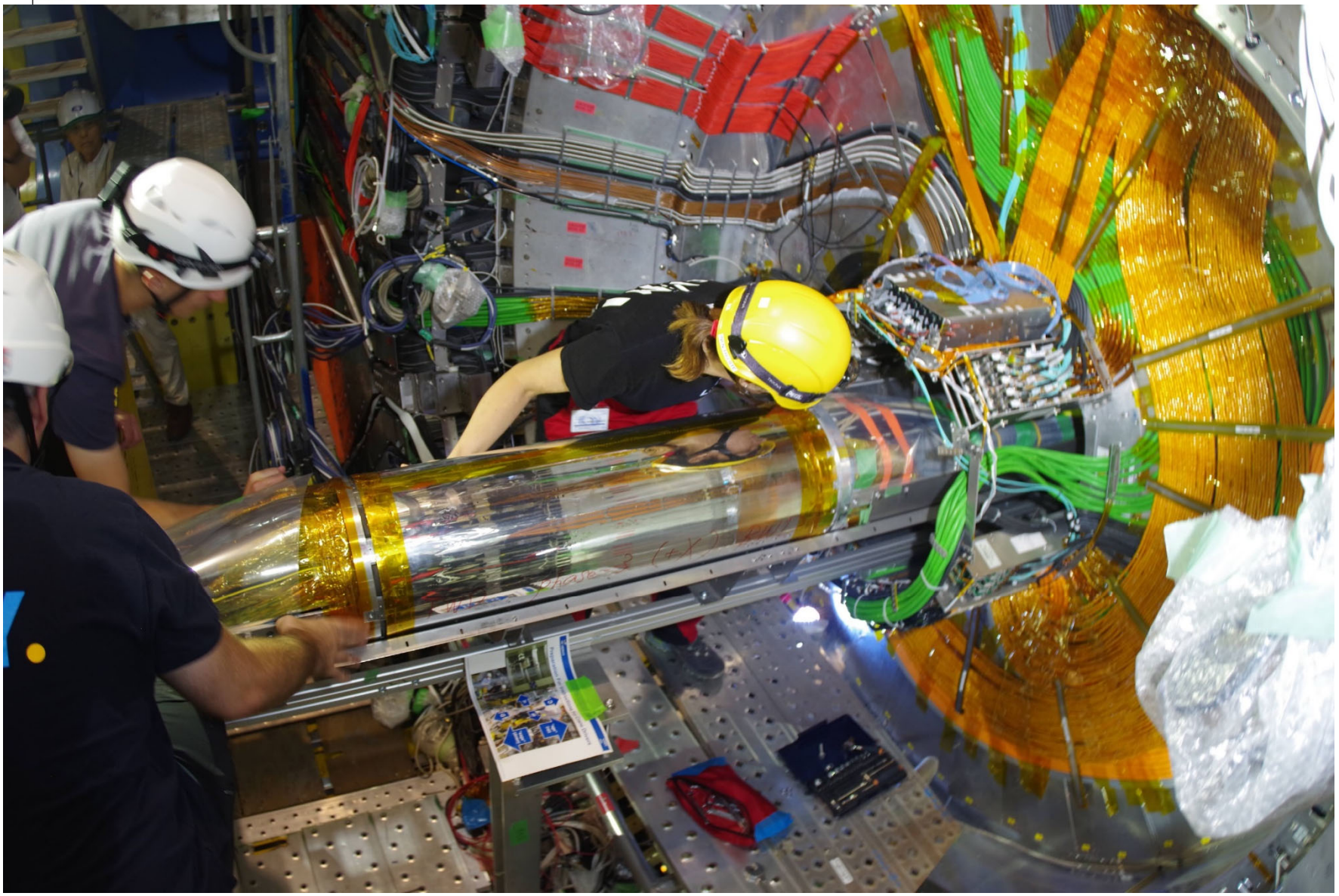
First Version of PXD, installed in 2018



2nd Version of PXD, installed in 2023



2nd Version of PXD, installed in 2023

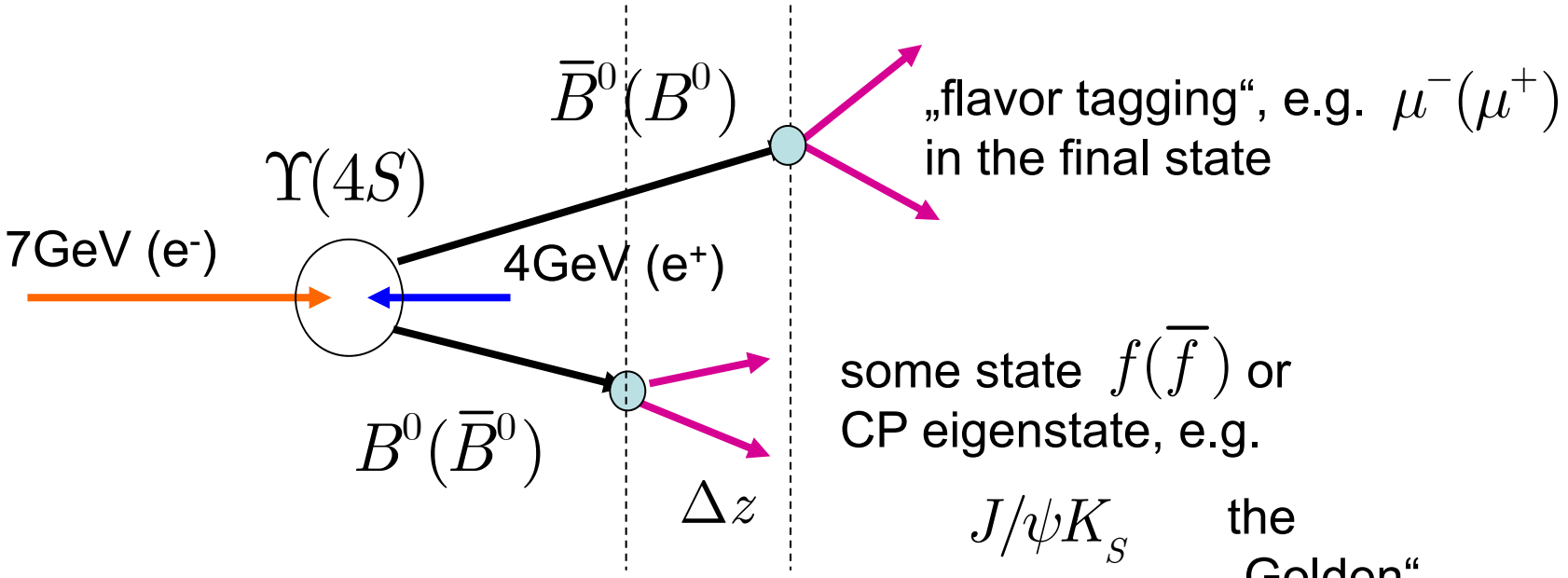


The ~~CP~~ Observables: What do we measure?

$$e^+e^- \rightarrow \Upsilon(4S) \rightarrow B^0\bar{B}^0$$

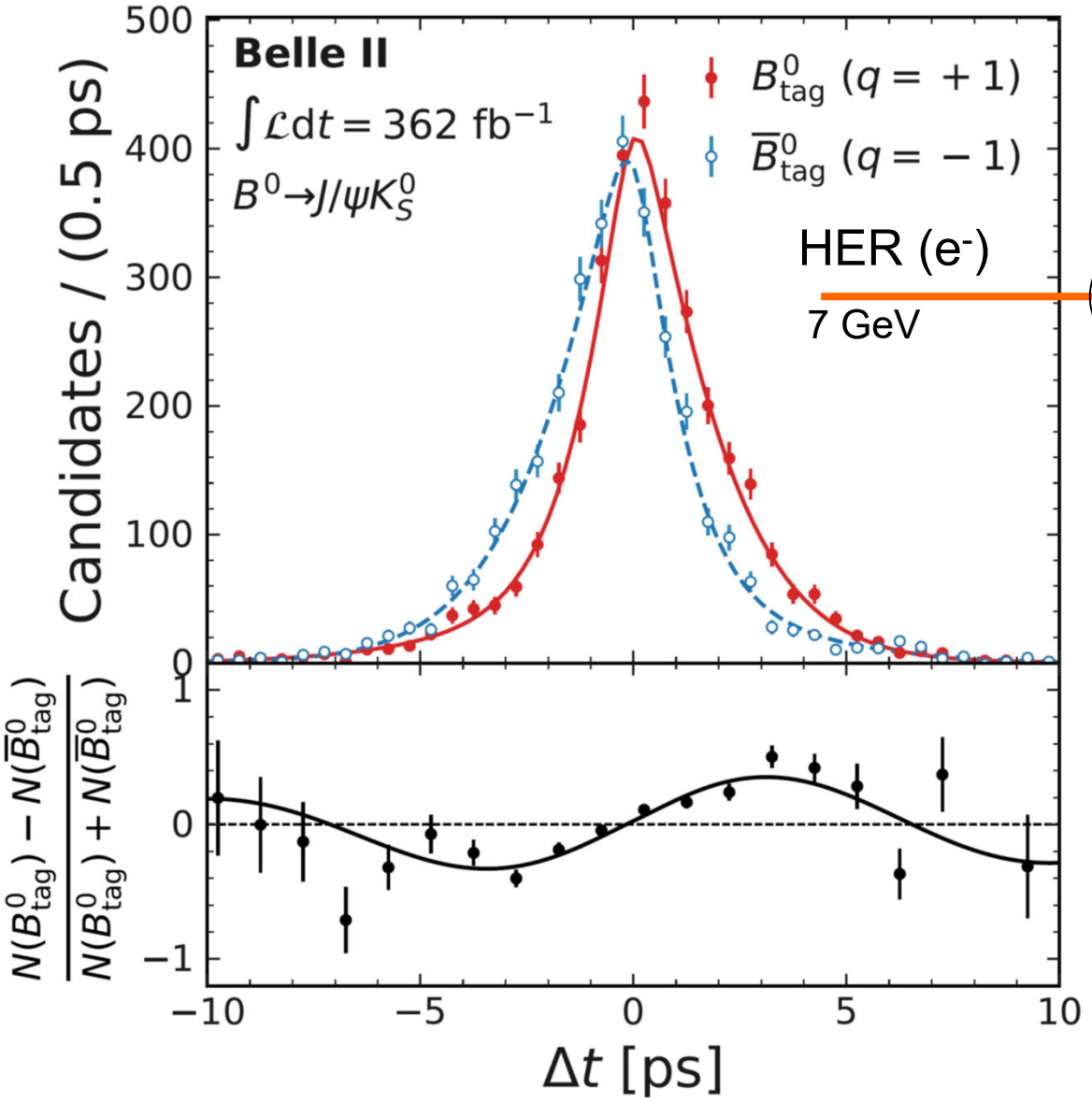
B mesons are in a quantum entangled state!

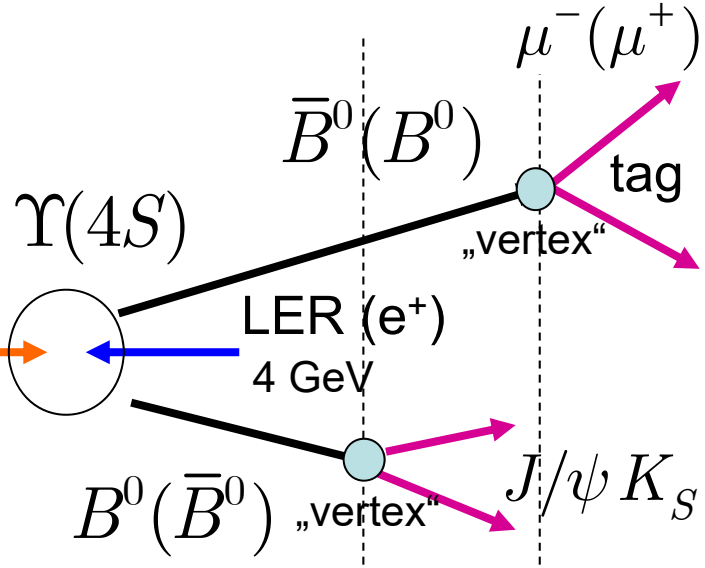
electron and positron beams at different energies -> CMS is boosted
B mesons at rest in CMS -> boosted in the lab system



Sign of CP violation:
time-ordering of the decay vertices

Example: Belle II Result on CP Violation





$$\Delta t = \frac{\Delta z}{\beta\gamma c}$$

Precise vertices from PXD !

Observation:
$B^0 \to J/\psi\, K_S$ decays earlier on average than the other *B* meson, other way around for $\bar{B}^0 \to J/\psi\, K_S$

Summary and Conclusions

SuperKEKB: How to get high and stable luminosity

Auguste Rodin, Le Penseur

Pedro Waloschek, DESY

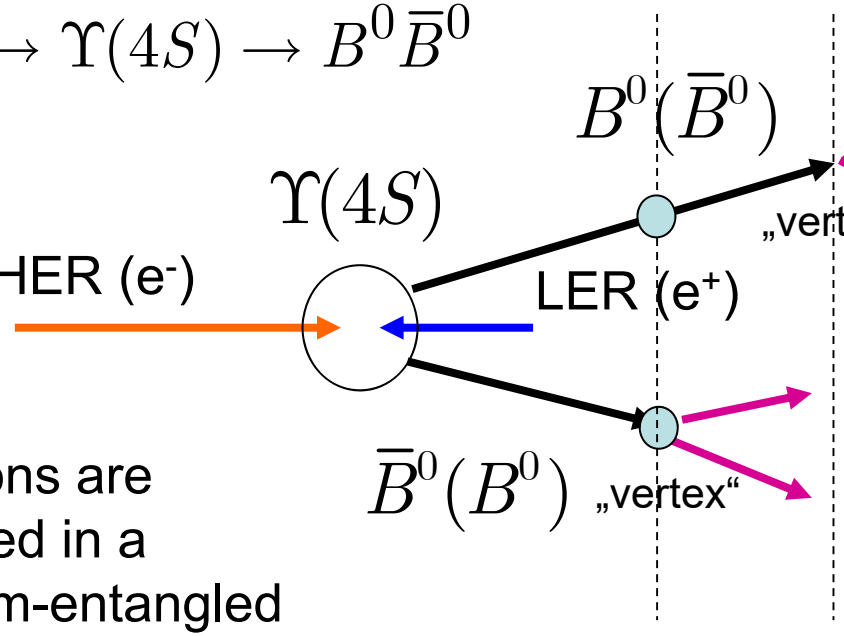
How to keep the excellent performance of the PXD also under high backgrounds

Backup

The ~~CP~~ Observables: What do we measure?

B-Mesons: $\left|B^0\right\rangle = \left|\bar{b}d\right\rangle \quad \left|B^+\right\rangle = \left|\bar{b}u\right\rangle$

$e^+e^- \rightarrow \Upsilon(4S) \rightarrow B^0\bar{B}^0$



some state $f(\overline{f})$ or CP eigenstate, e.g.

$J/\psi K_S$ $CP = -1$ the “Golden“ channel

flavor eigenstate

$Xl^{\mp}\nu, D^{*\pm}X$ “flavor tagging“

B mesons are produced in a quantum-entangled state !

$\Delta z = \beta\gamma c\Delta t$

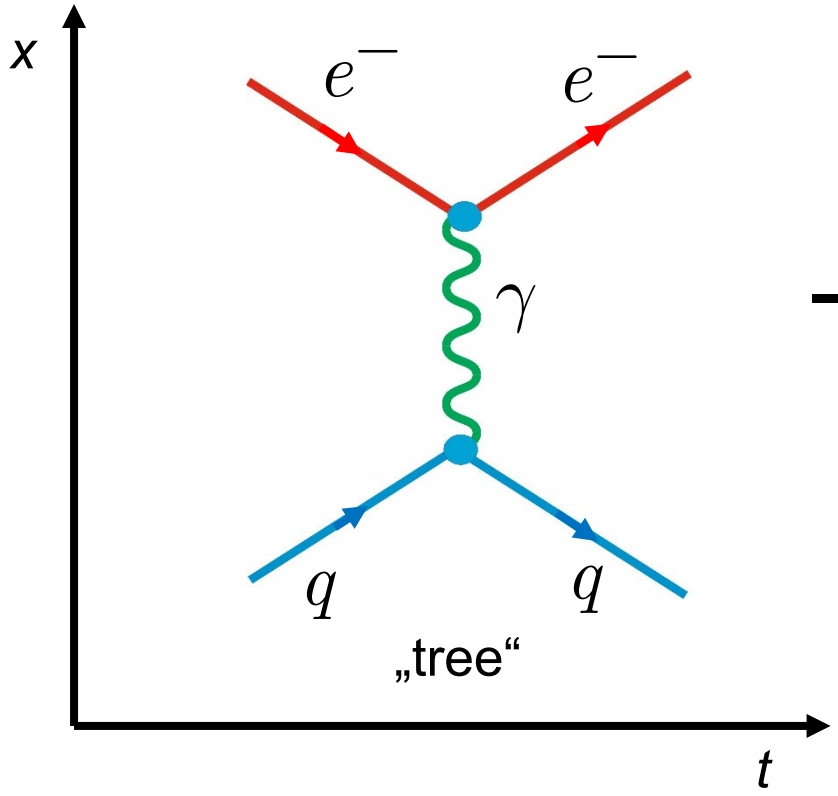
$\Delta t = t_{\mathrm{CP}} - t_{\mathrm{tag}}$

Asymmetric beam energies: translate decay time to decay length

Δz ~ 150 µm → need excellent vertex detection

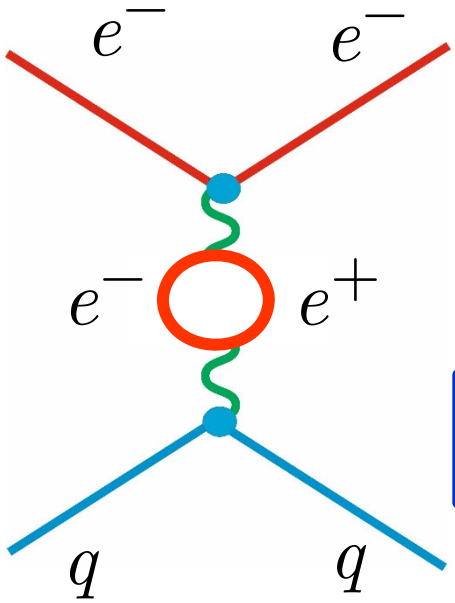
Alternative Way: “Beyond the trees”

Feymnan Diagrams at higher order: corrections to the SM observables:



„tree“

+



„loop“

“Lamb shift“
in the H atom

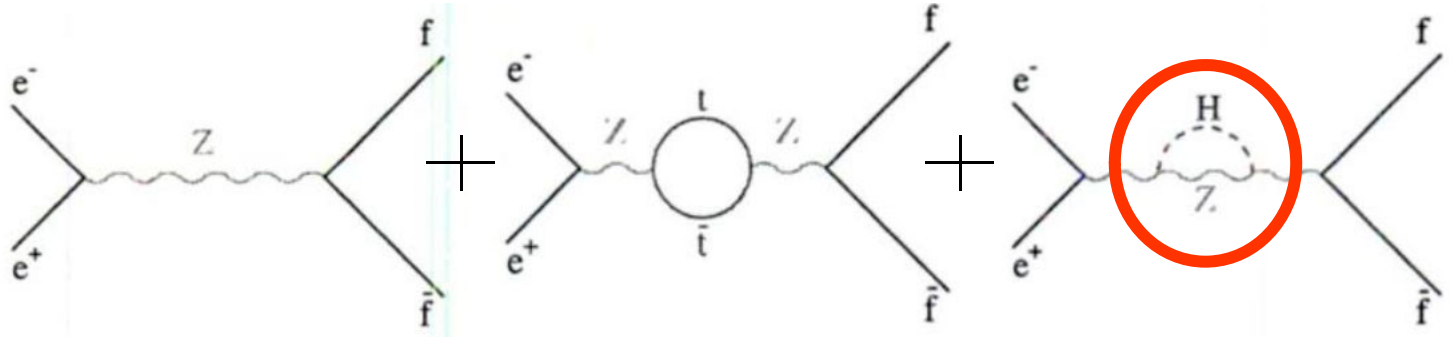
+ . . .

$$\Delta E \Delta t \geq \hbar$$

Precision measurements of quantum loop effects open the window to large mass scales.

→ LEP yielded strong limits on the top and Higgs masses

Quantum Loops @ LEP: "Finding" the Higgs



$$\sigma(e^+e^- \to f\bar{f}) = \sigma(\text{Tree})(1+\Delta r)$$

$$\Delta r = \Delta r(\text{had}) + \Delta r(\text{top}) + \Delta r(\text{Higgs})$$

"radiative correction"

"known" from L.E.measurements

loop corrections

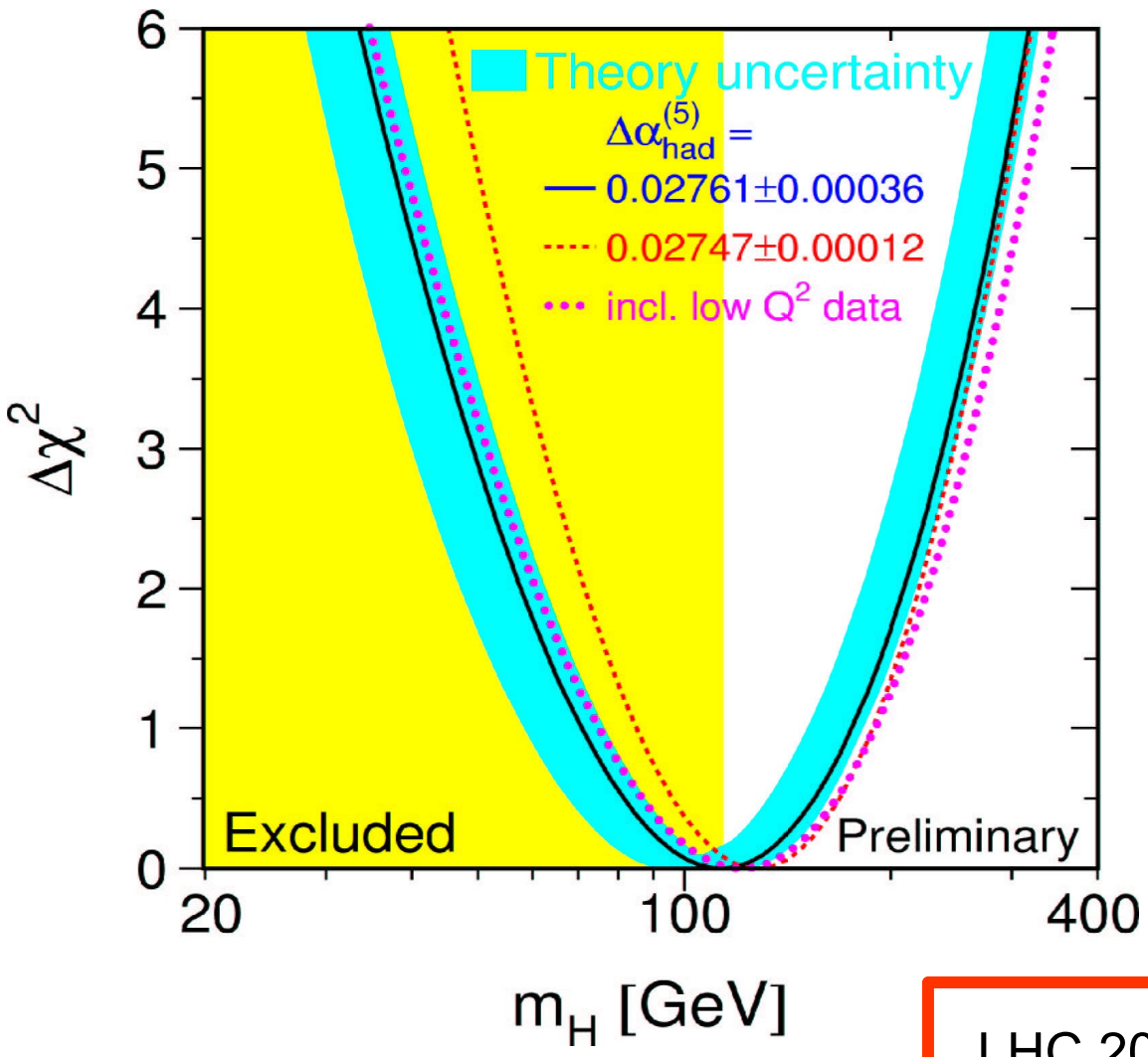
$$\Delta r(\text{top}) = \frac{3G_F}{8\sqrt{2}\tan^2\theta_W} m_t^2$$

Small, but very sensitive to the top mass

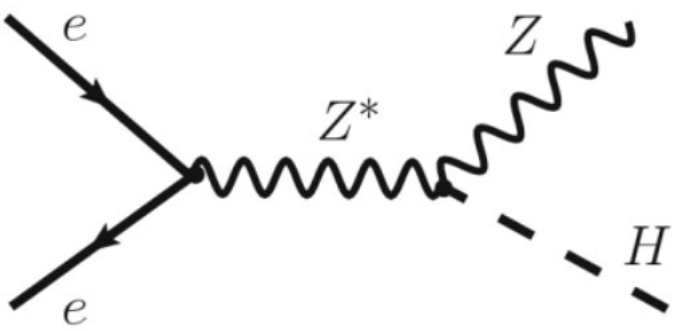
$$\Delta r(\text{Higgs}) = \frac{3G_F m_W^2}{8\sqrt{2}\pi^2}\left(\ln\frac{m_H^2}{m_Z^2} - \frac{5}{6}\right)$$

Small, logarithmic sensitivity, but "measurable" after the top mass was known precisely

LEP: „Finding“ the Higgs



LEP fits suggested a very light Higgs



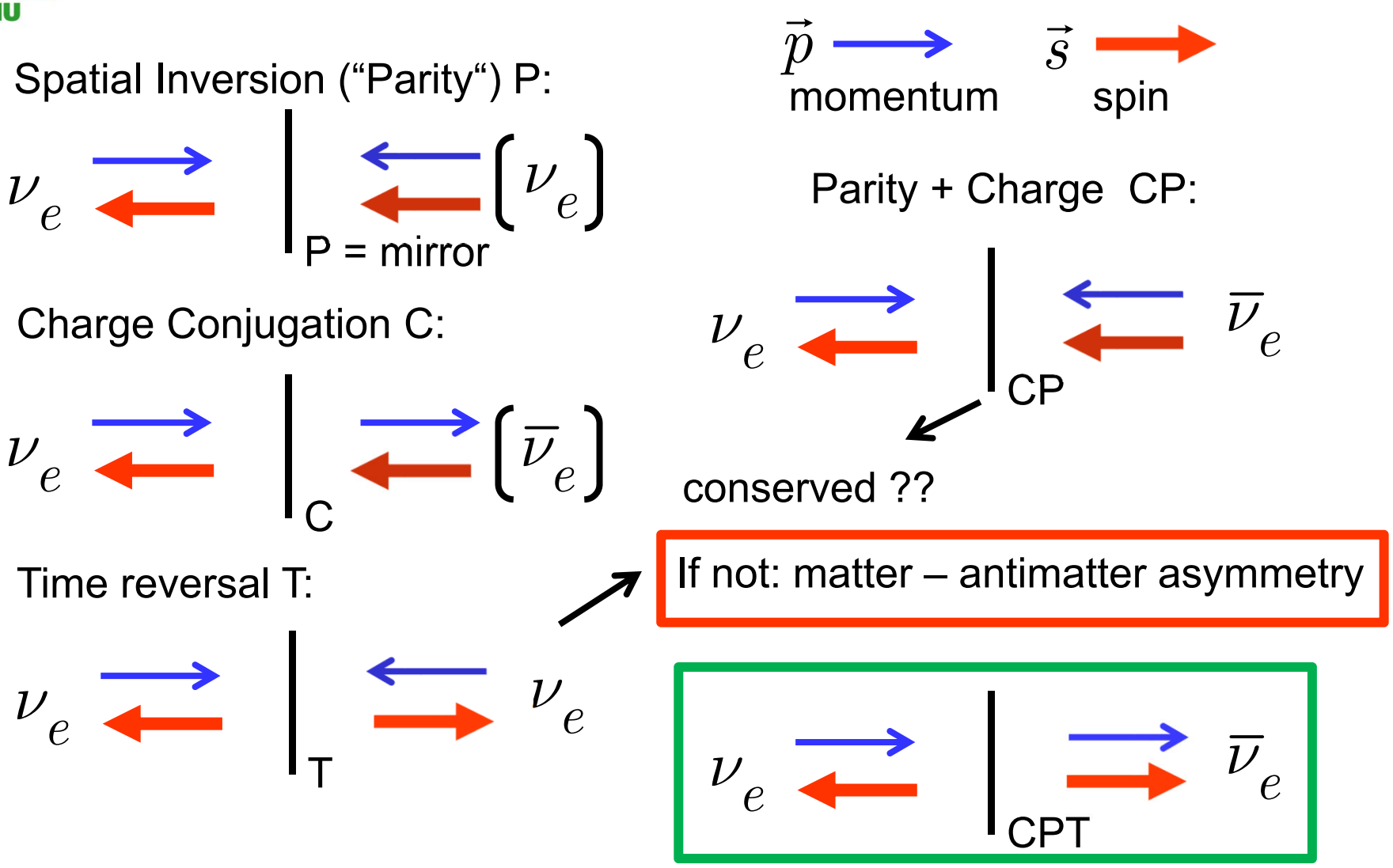
LEP2 looked for “Higgs-Strahlung“,

but no signal found …

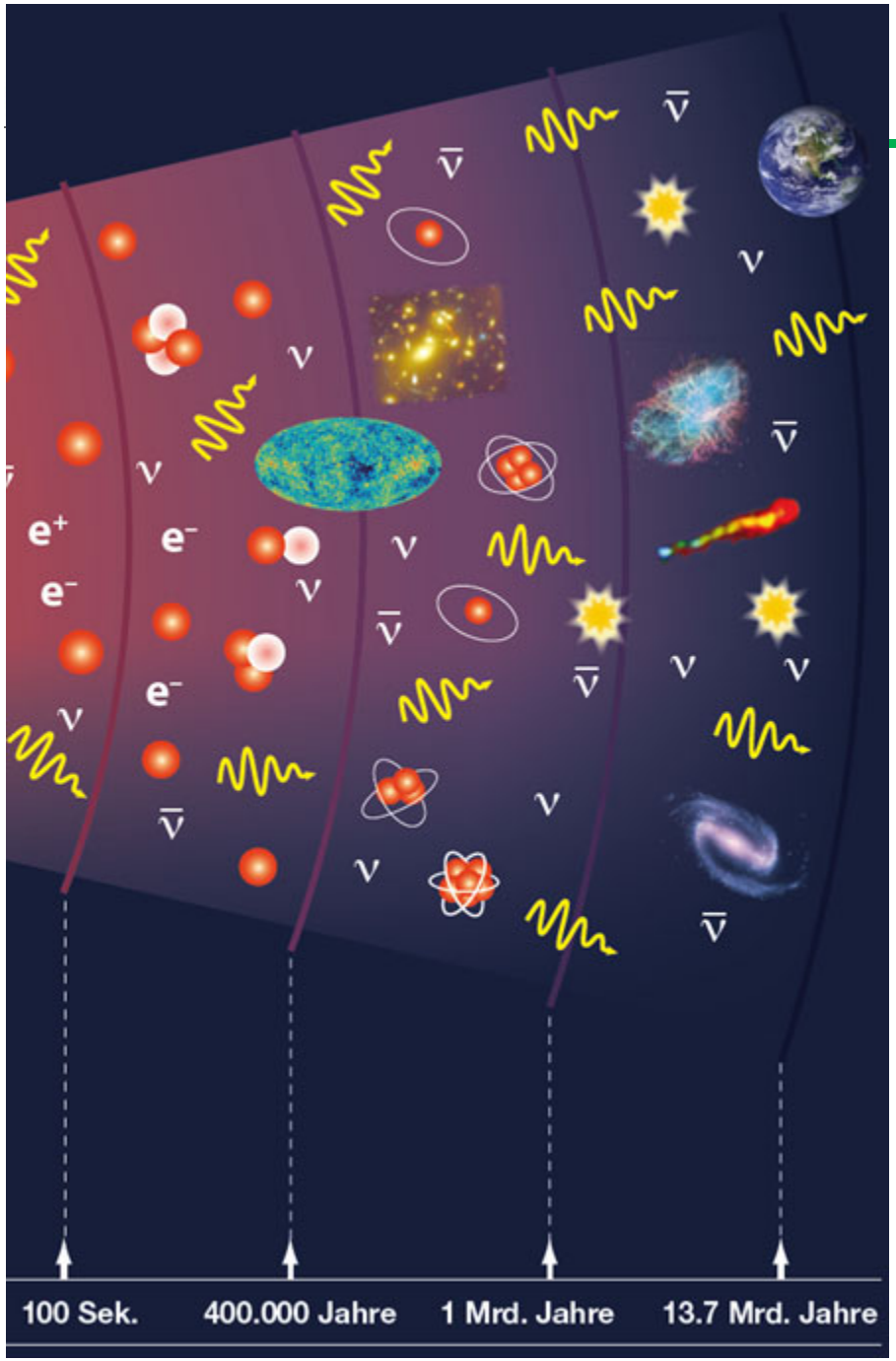
$$m_H > 113 \text{ GeV}$$

LHC 2012: $m_H = 126 \text{ GeV}$

Fundamental Discrete Symmetries



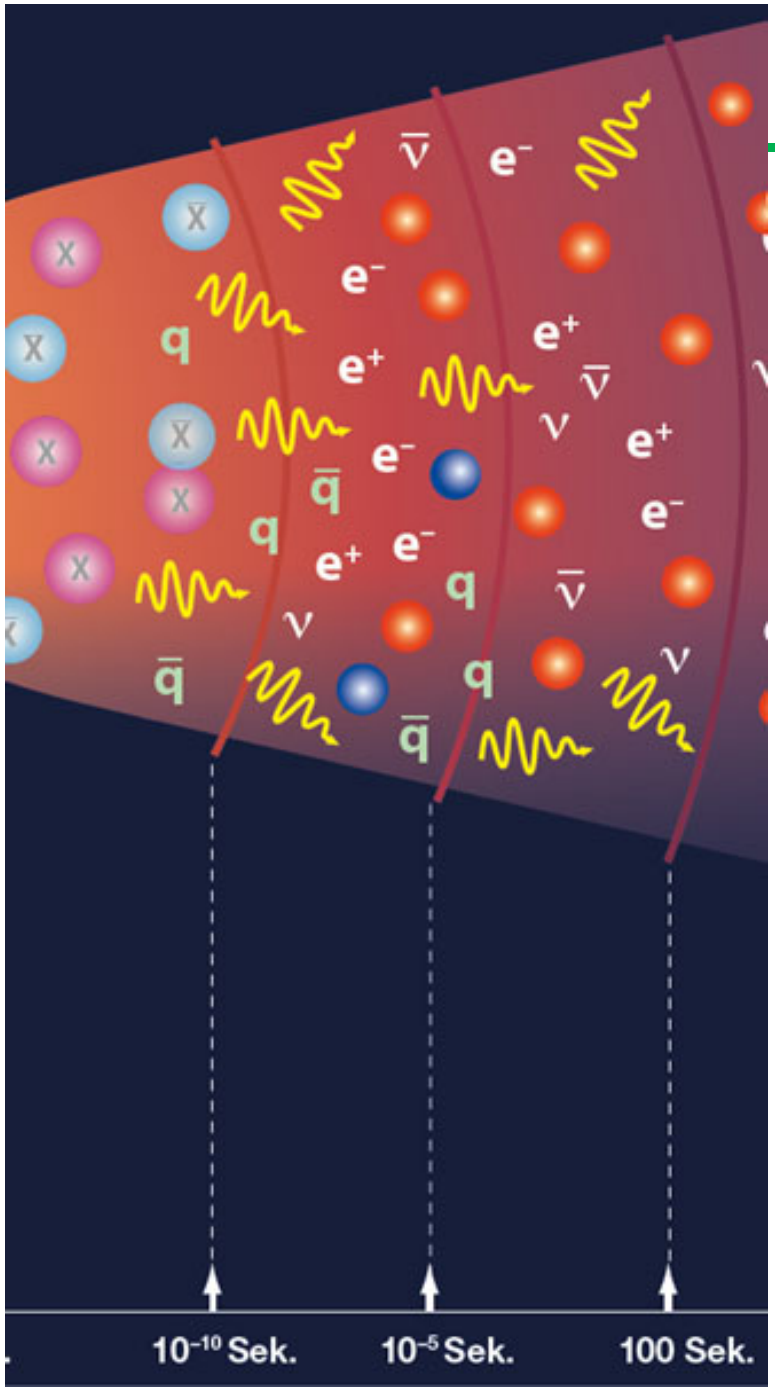
CPT: conserved in all local quantum theories exhibiting Lorentz-invariance



Going back in Time …

- Today: age of the Universe is about 13.7 billon years
  T ~ 2.7°K (CMB)
- at an age of about 1 billion years: gas nebulae, first stars and galaxies,
  T ~ 15 °K
- 400 000 years: atoms are formed, the Universe becomes transparent (photons travel freely through space -> CMB)
  T ~ 3000 °K (E = 0.3 eV)
- at an age of 3 min:
  first light nuclei are formed: p, d, ^{4}He, ^{3}He, Li (“nucleo-synthesis“)
  T ~ 10^9 °K (E ~ 100 keV)

Going back in Time …

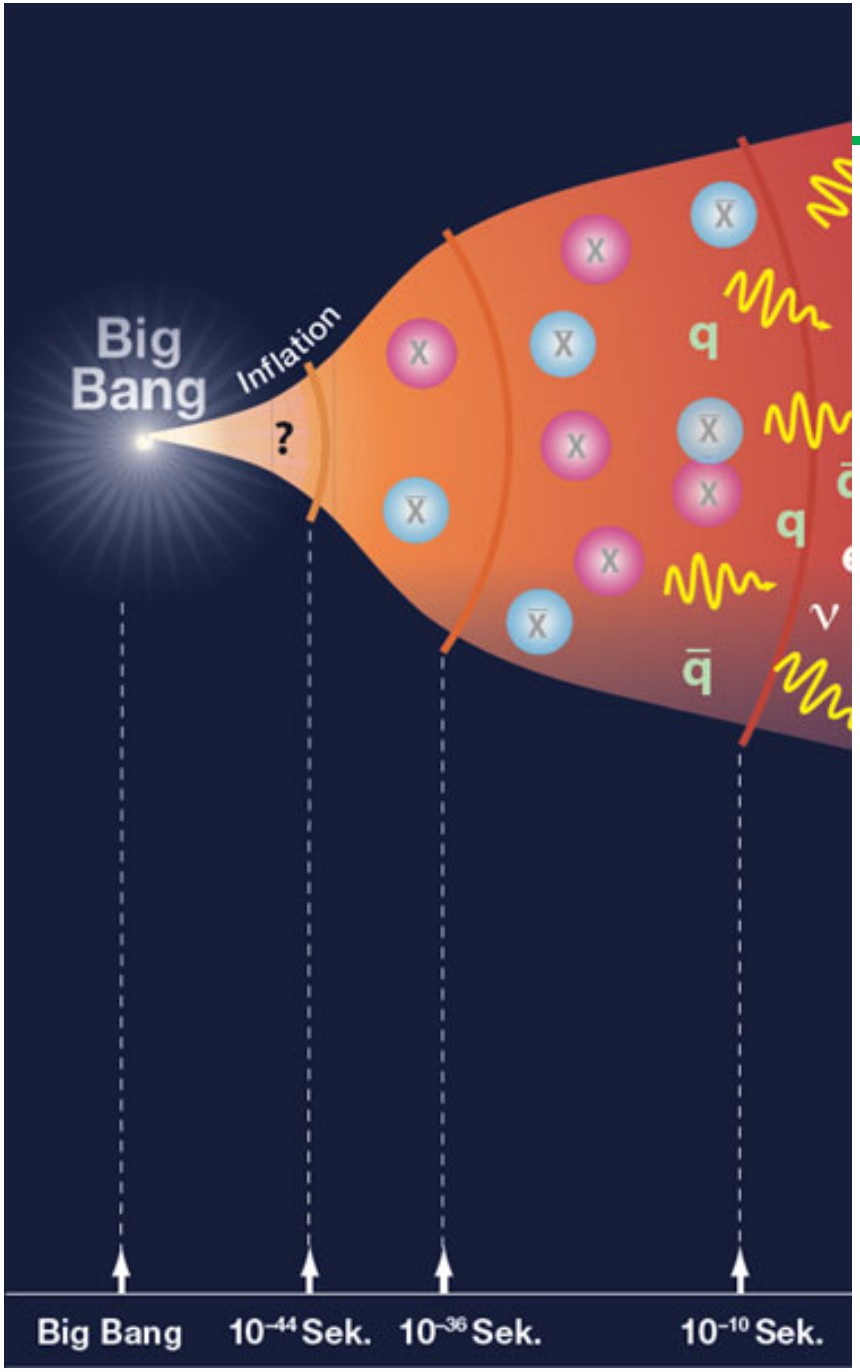


- At the age of tens of seconds:
  electrons and anti-electrons annihilate,
  a few electrons remain

- at an age of 1 µs:
  protons have mostly annihilated with anti-protons, a few protons remain

- protons and anti-protons are formed from quarks and anti-quarks
  $T \sim 10^{13}$ °K (100 MeV)

- $< 10^{-10}$ s ($E > 1000$ GeV)
  Superheavy particles X and $\overline{X}$ decay into q, $\overline{q}$, e^-,e^+ and v, $\overline{\nu}$
  slight excess of q and e^- over $\overline{q}$ and e^+ ("CP violation" in X decay).
  -> explains the disappearance of anti-matter: annihilation with matter



Going back in Time …

- < 10^{-36} s (E > 10^{16} GeV -> „GUT scale“)
  End of Inflationary period
  between 10^{-43} s and 10^{-36} s the Universe has expanded exponentially by a factor ~ 10^{50}

- Inflation necessary to explain several cosmological puzzles such as the homogeneity of CMB over (today) non-causally connected distances

- inflation driven by a hypothetical scalar field (“inflaton“)

- After inflation, the inflaton‘s kinetic energy is transformed into superheavy particles (“X“) and their anti-particles in equal numbers (“reheating“)
  “matter – antimatter symmetry“ (CPT)