Overview of
High Energy Experiments
w/o Hadron Collider and Neutrinos

Tsuyoshi NAKAYA (Kyoto U.)

2025.7.20 @ VSON2024, Quy Nhon

1

Who am I?

Professor in Kyoto University, Japan

- 1995: Ph.D.

- 1995-1997: JSPS Fellow at Fermilab, US
  - working for the Kaon experiments.

- 1997-1999: Fermi Fellow at U. Chicago, US.
  - working for the Collider experiment at Fermilab (CDF)

- 1999-now: Faculty members in Kyoto U.
  - working for neutrino experiments: K2K, Super-K, SciBooNE, T2K, NINJA, Hyper-K, AXEL

High Energy Physics

- **Study the ultimate building blocks of the universe and matter.**
  - What is matter made of? What exists in the universe? What are the properties of those components? How do they interact?
  - Standard Model of Particle Physics: quarks, leptons, gauge particles, Higgs boson.
  - Unknown entities: dark matter, dark energy, other unknown particles, unexpected phenomena.
  - Theoretical guidance: supersymmetric particles, extra dimensions
- Studies that question the meaning of time and even space (spacetime).
  - Origin of mass, space-reversal symmetry, time-reversal symmetry breaking.

- (Personal view) Differences with other disciplines and fields
  - Eliminates the complexity (diversity) of many-body systems and explores the underlying physical laws and views of physics.

Explore frontiers!

After the birth of the universe (after the Big Bang), to a world of 10^{-10} (0.1 nano) seconds.
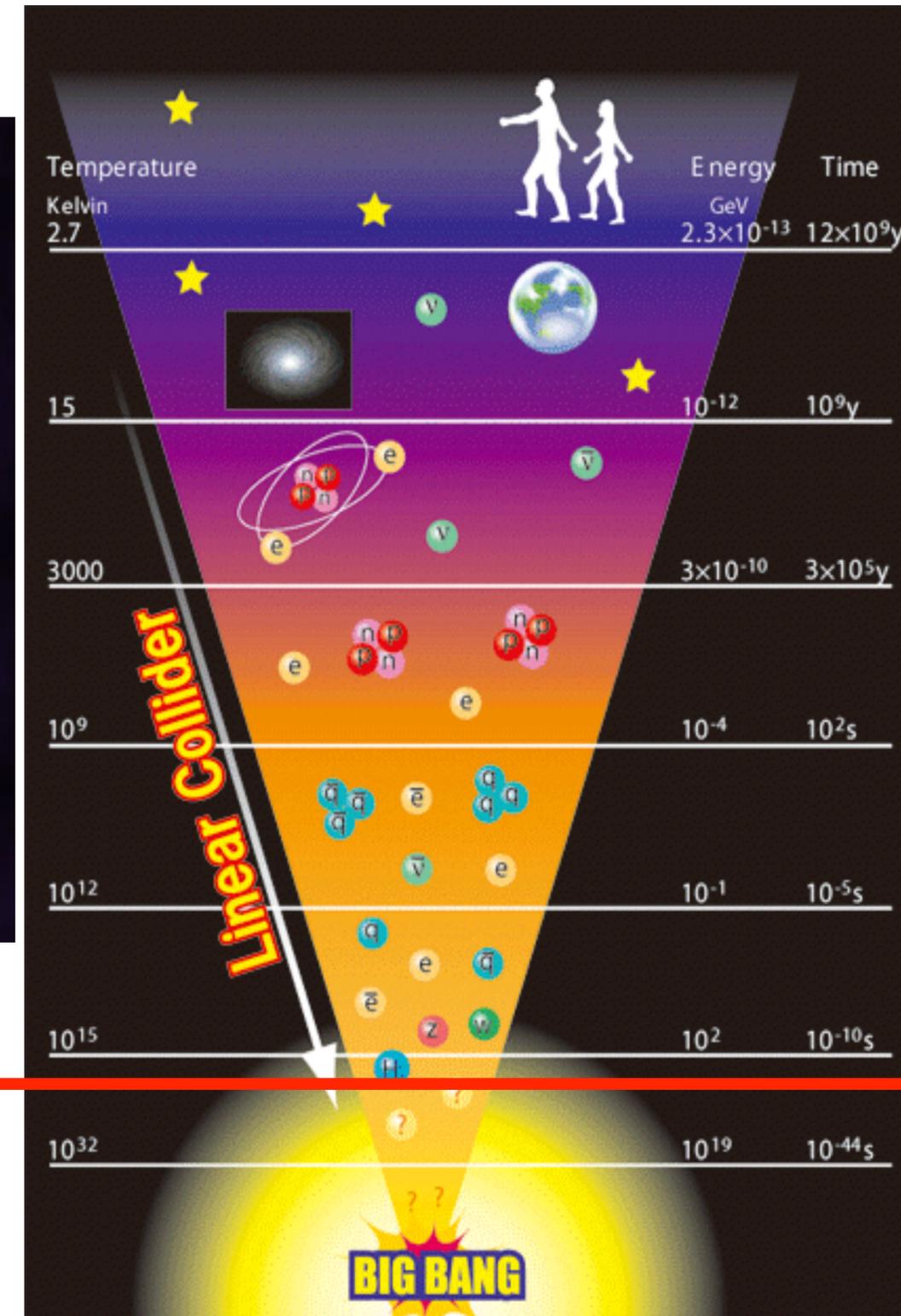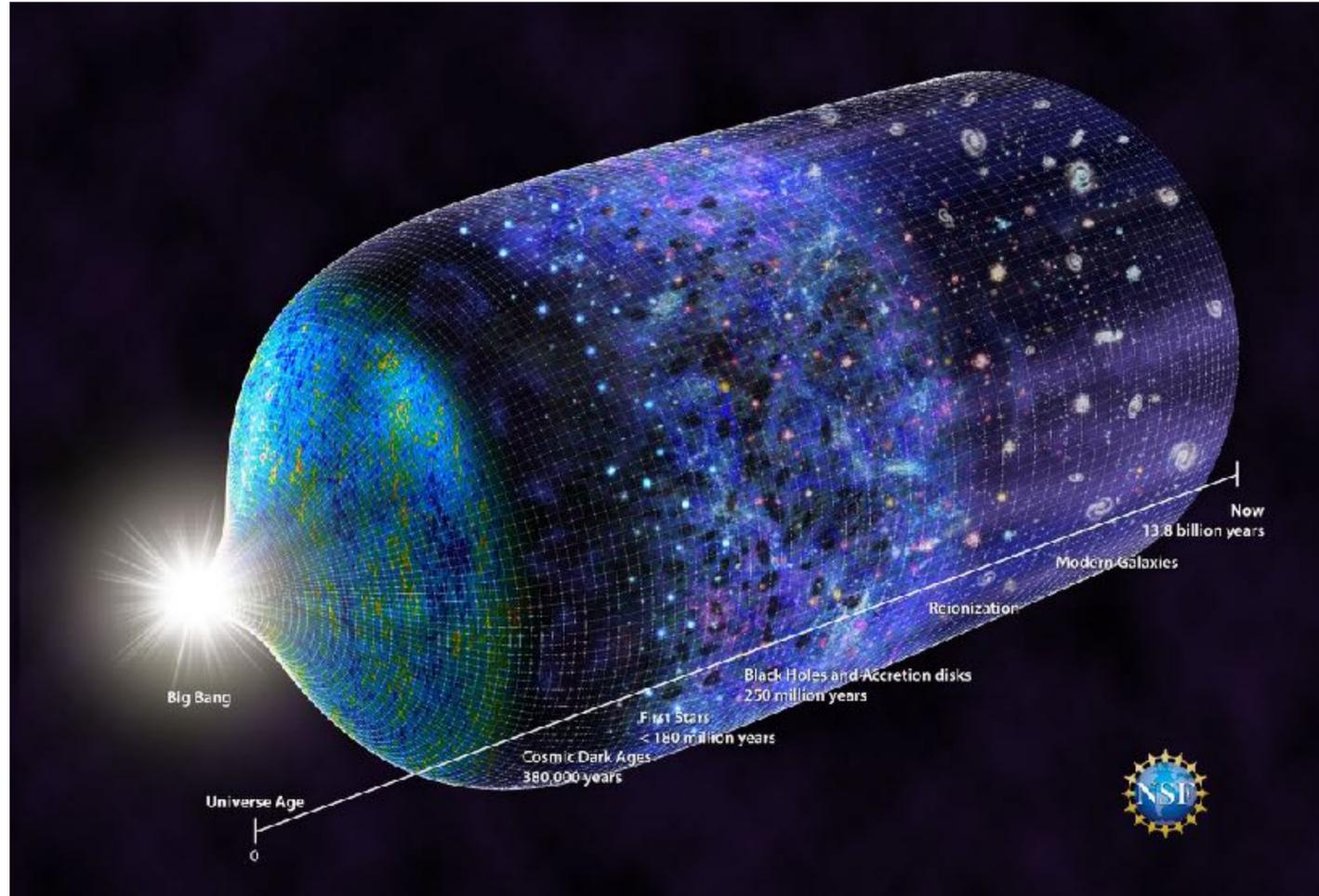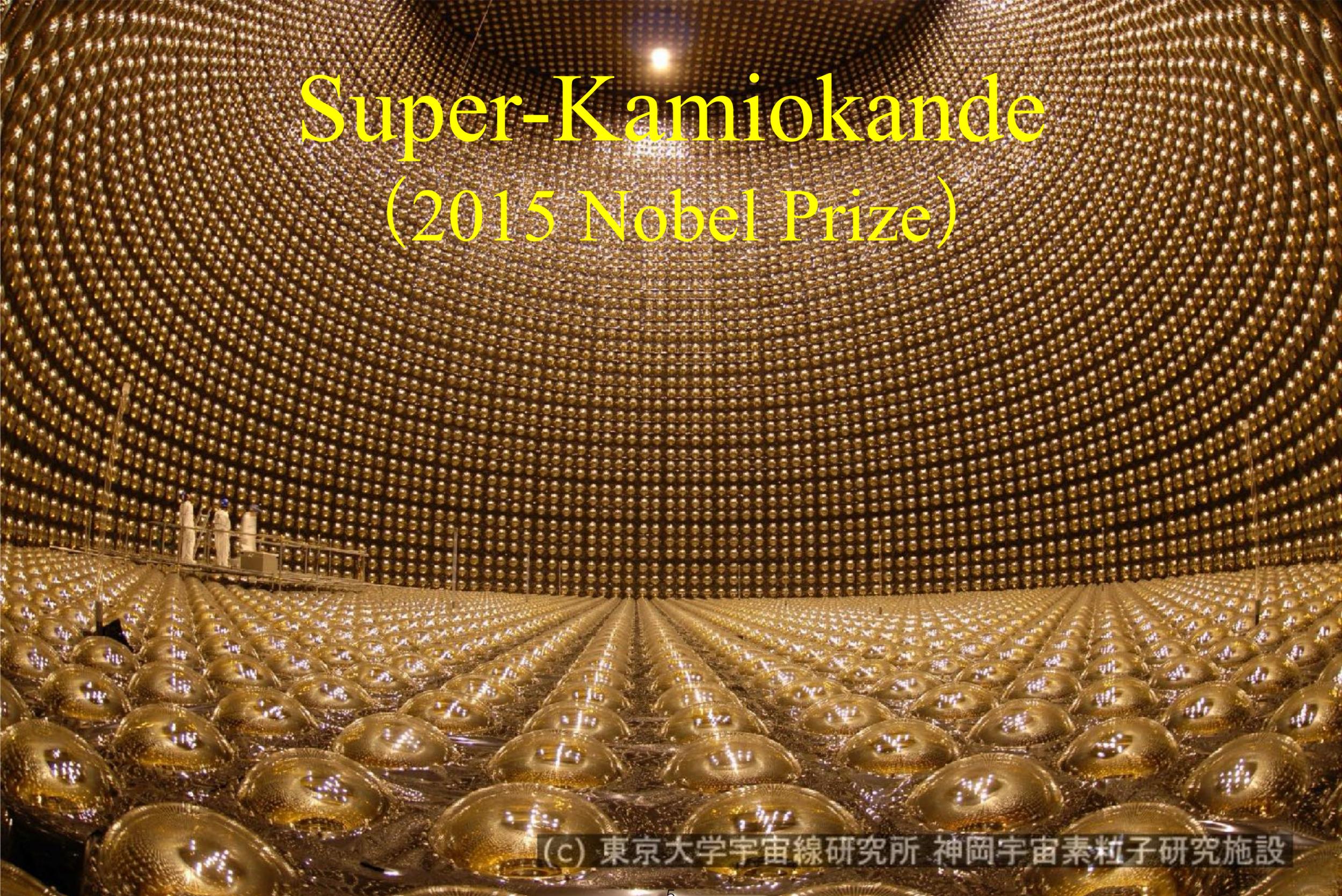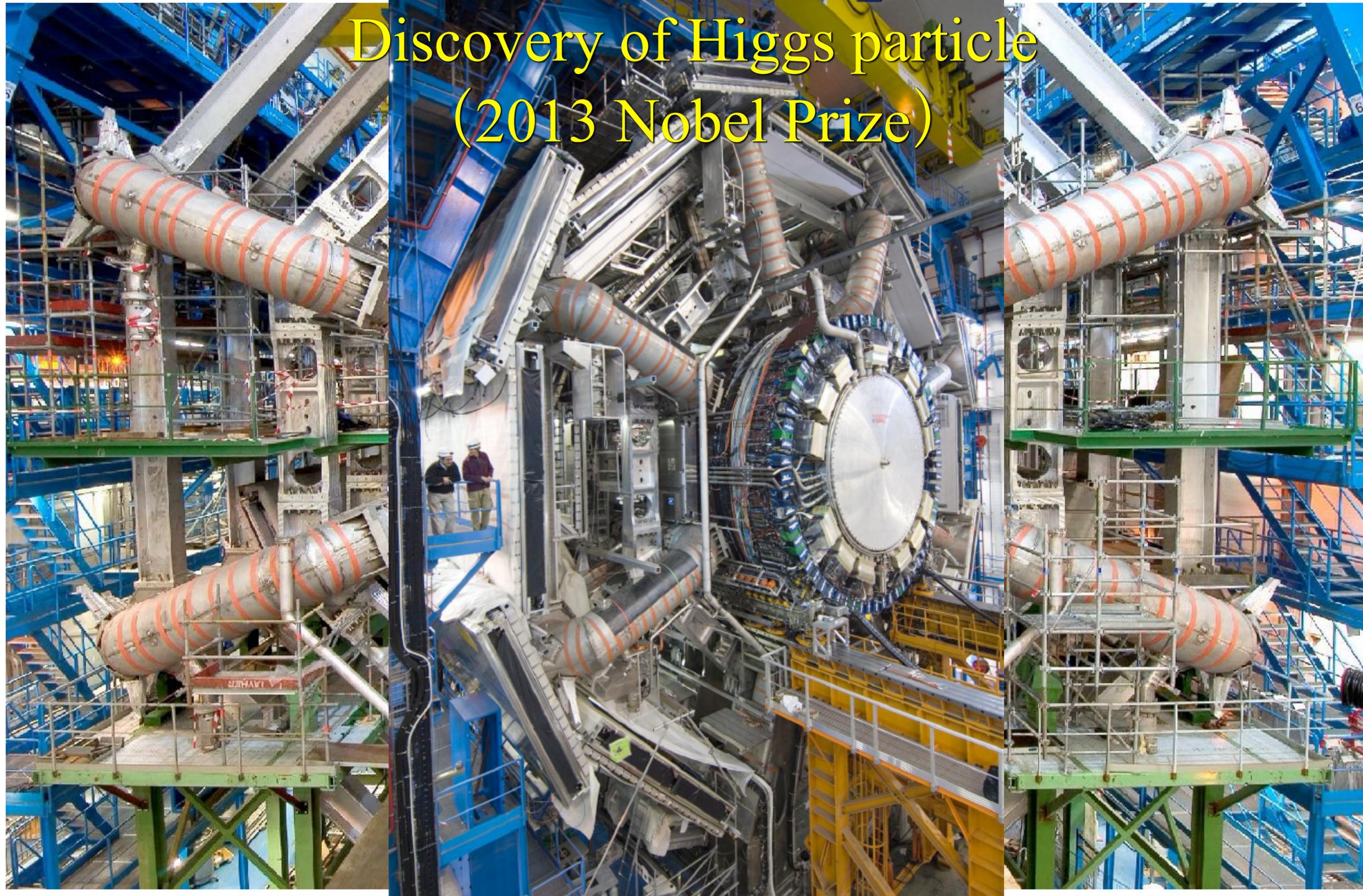
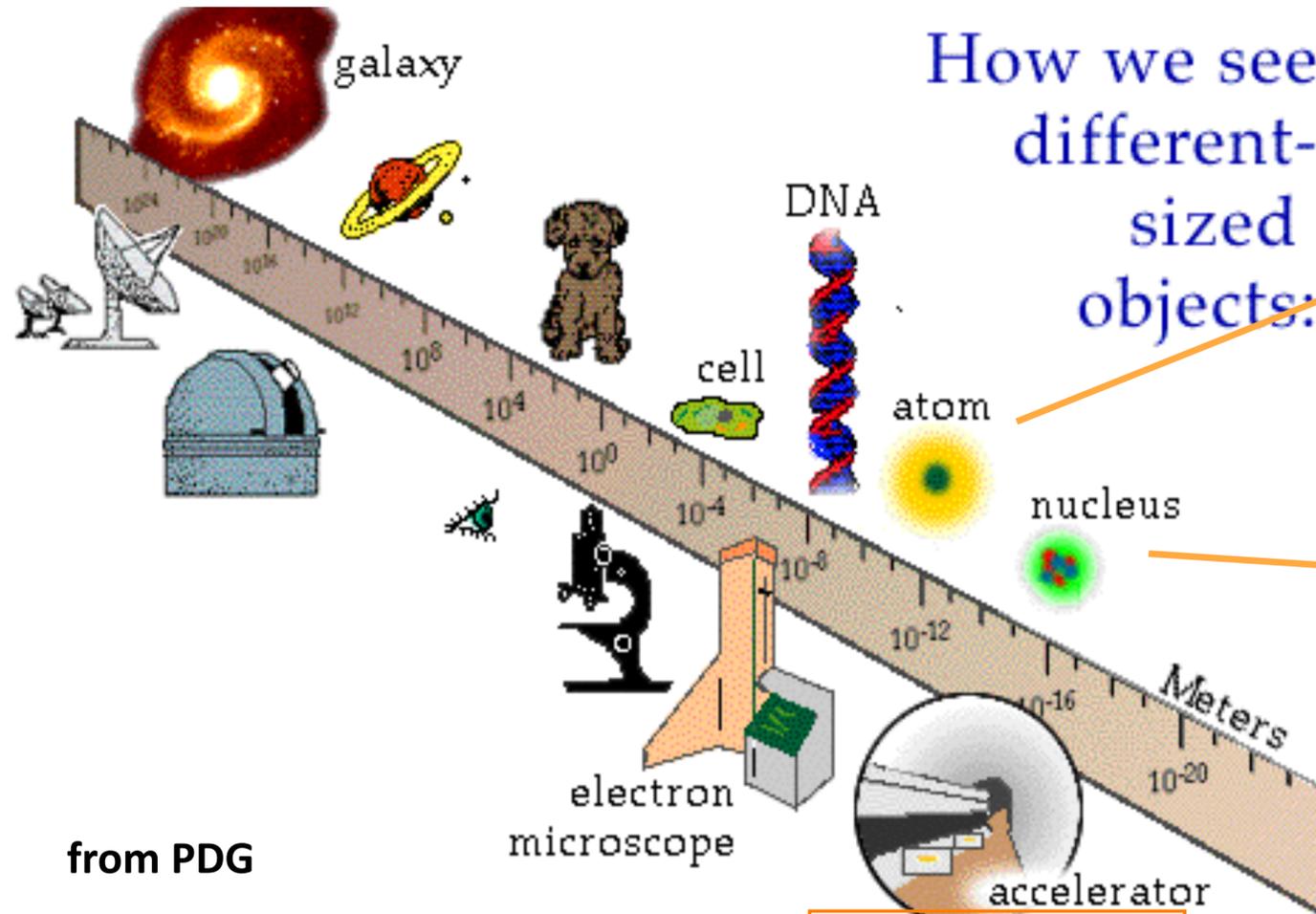Super-Kamiokande
（2015 Nobel Prize）

(c) 東京大学宇宙線研究所 神岡宇宙素粒子研究施設

LHC/ATLAS Experiment

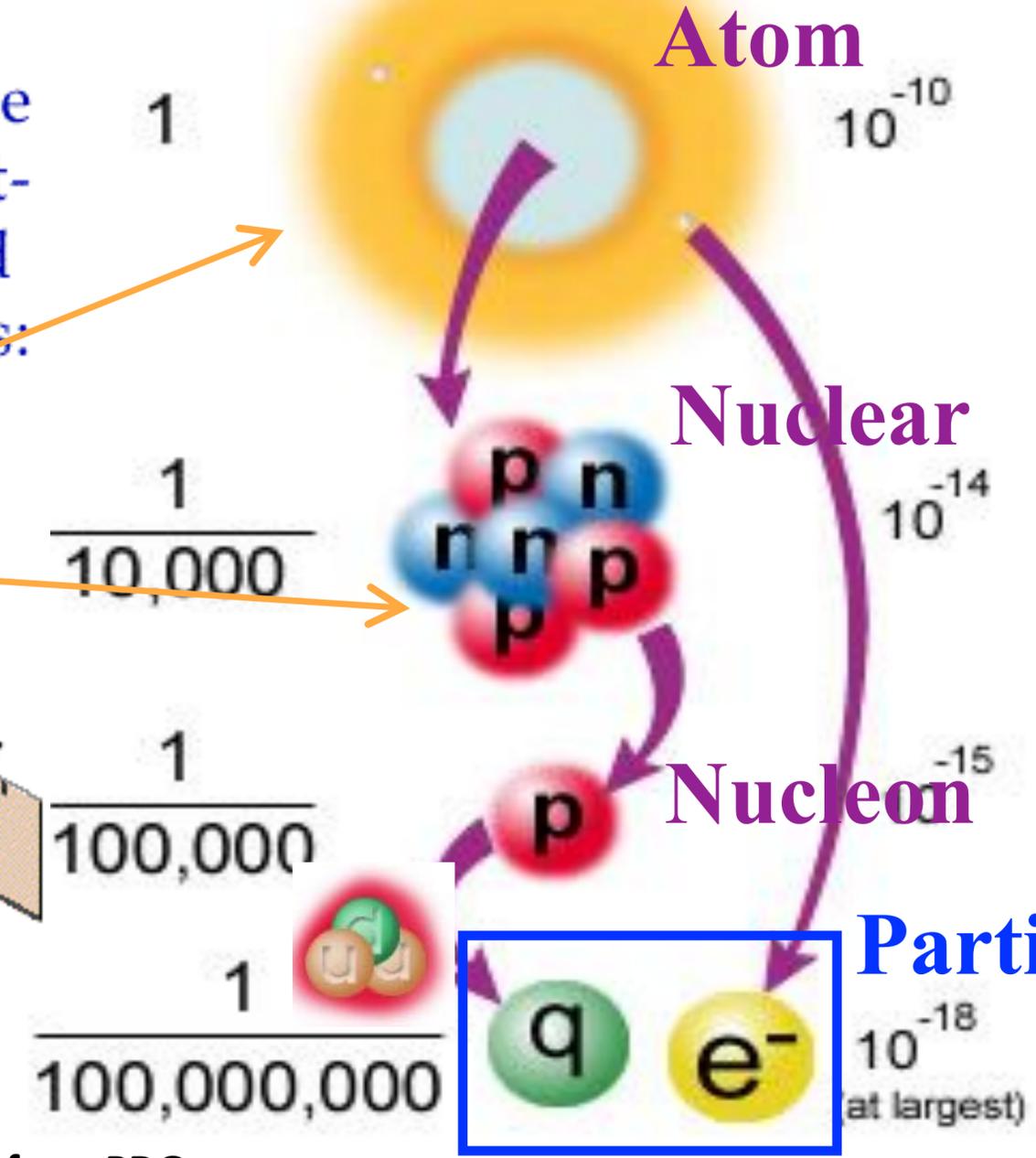## Discovery of Higgs particle
(2013 Nobel Prize)

Particle Physics

100,000,000,0000,
000,000,000,000m

galaxy

How we see different-sized objects:

DNA

cell

atom

nucleus

electron microscope

accelerator

0.000000000
0000000001m

from PDG

size in atoms

and in meters

Atom 10^{-10}

1

Nuclear 10^{-14}

$\dfrac{1}{10,000}$

Nucleon 10^{-15}

$\dfrac{1}{100,000}$

Particle

$\dfrac{1}{100,000,000}$

10^{-18}
(at largest)

from PDG

Quark and Lepton

Quark and Lepton

×2 （Antiparticles）

Quark
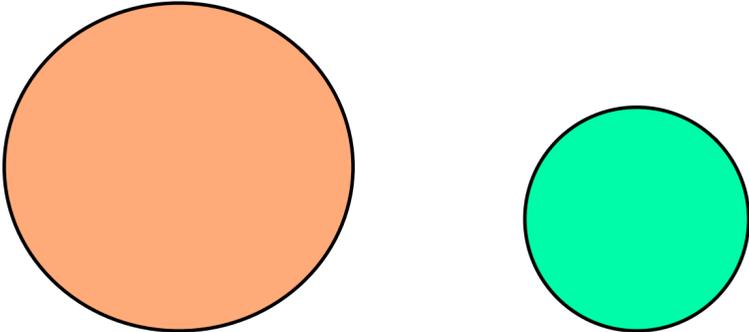
Lepton

Neutrino

Electron

uud(proton)
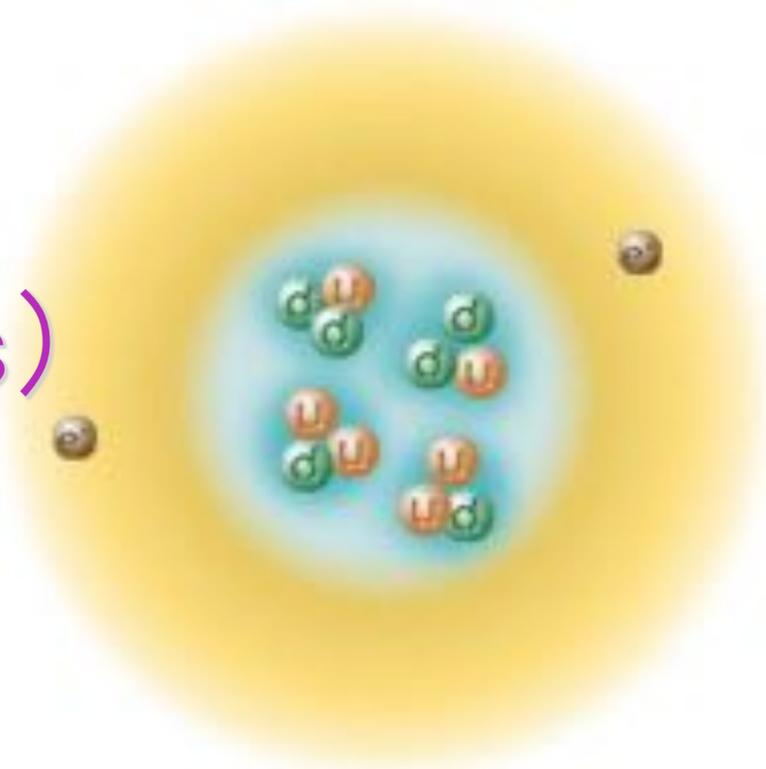
Standard Model of Elementary Particles

I II III

QUARKS

≈2.2 MeV/c²	≈1.28 GeV/c²	≈173.1 GeV/c²	0	≈124.97 GeV/c²
⅔	⅔	⅔	0	0
½ **u**	½ **c**	½ **t**	1 **g**	0 **H**
up	charm	top	gluon	higgs

≈4.7 MeV/c²	≈96 MeV/c²	≈4.18 GeV/c²	0
−⅓	−⅓	−⅓	0
½ **d**	½ **s**	½ **b**	1 **γ**
down	strange	bottom	photon

LEPTONS

≈0.511 MeV/c²	≈105.66 MeV/c²	≈1.7768 GeV/c²	≈91.19 GeV/c²
−1	−1	−1	0
½ **e**	½ **μ**	½ **τ**	1 **Z**
electron	muon	tau	Z boson

<1.0 eV/c²	<0.17 MeV/c²	<18.2 MeV/c²	≈80.360 GeV/c²
0	0	0	±1
½ **νe**	½ **νμ**	½ **ντ**	1 **W**
electron neutrino	muon neutrino	tau neutrino	W boson

mass
charge
spin

GAUGE BOSONS
VECTOR BOSONS

SCALAR BOSONS

Mass (MeV)：$m\Psi\overline{\Psi}$

quark

lepton

b

t

τ

ντ

4,000~4,400

174,000

1,777

<18.2
(~0.00000005)

family generation

10^6

10^{14}

s

c

μ

νμ

75~170

1,150~1,350

106

<0.19
(~0.00000001)

d

u

e

νe

1~5

3~9

0.51

<0.000003
(<0.00000001)
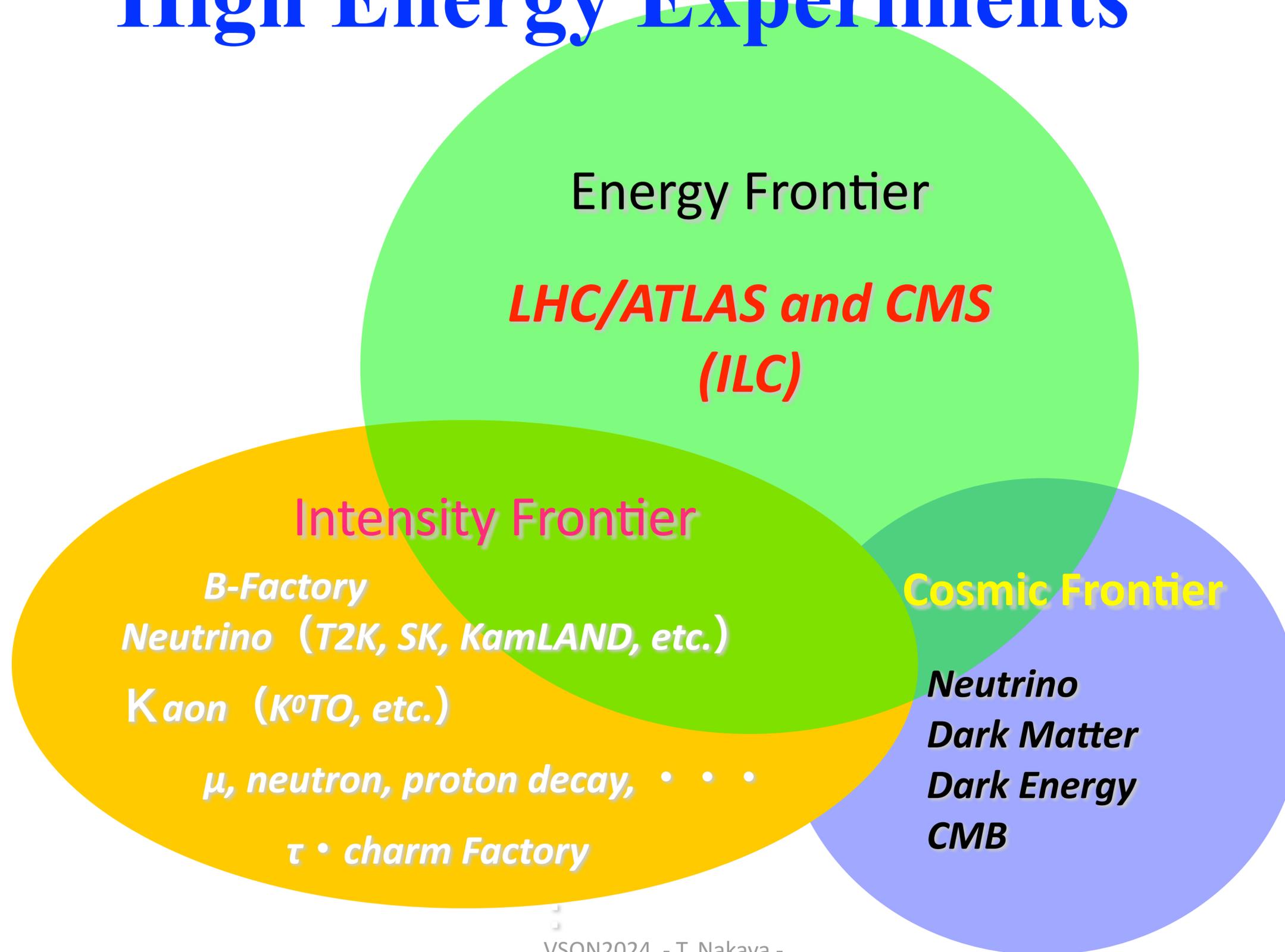
10^8

neutrino mass is so small!

Fundamental Questions!

not solved yet

- What is dark matter?

- Where are antimatter? How did they disappear?

- The accelerating universe?

- Why is neutrino mass so small?

- How are the forces are unified?

- Generation structure. Why are the masses of particles are so different?

High Energy Physics and Experiments

Three categories

- Energy Frontier
  - Study particles at high energy (~TeV)

- Intensity Frontier
  - Study particles with high precision and look for rare processes

- Cosmic Frontier
  - Observe our universe and look for footprints made by past particles.

High Energy Experiments

Energy Frontier

LHC/ATLAS and CMS
(ILC)

Intensity Frontier

B-Factory
Neutrino（T2K, SK, KamLAND, etc.）

Κ*aon（K⁰TO, etc.）*

μ, neutron, proton decay,・・・

τ・charm Factory

Cosmic Frontier

Neutrino
Dark Matter
Dark Energy
CMB

What experiments are there?

- CERN (Europe)

  - LHC/ATLAS, CMS, LHCb, FASAR, milliQan, NA62, DsTau, (CEPE)

- PSI (Switzerland)

  - MEG II

- Fermilab (US)

  - Muon g-2, Mu2e, Neutrino experiments: DUNE, NOvA, SBN, ICARUS, etc.

- KEK/J-PARC (Japan)

  - Super-KEKB/Belle II, J-PARC/T2K, KoTO, COMET, muon g-2, JSNS², Super-K, Hyper-K, KAGLA, KamLAND, (ILC)

- IHEP (China)

  - BESSIII, JUNO, (CEPC)

- *Cosmology and Astro-particle experiments*

1. Energy Frontier

→ <u>Lecture by Prof. Albert de Roeck</u>
"Overview of Hadron Collider Experiments"

LHC
Large Hadron Collider
（Superconducting Accelerator）

2. Intensity Frontier

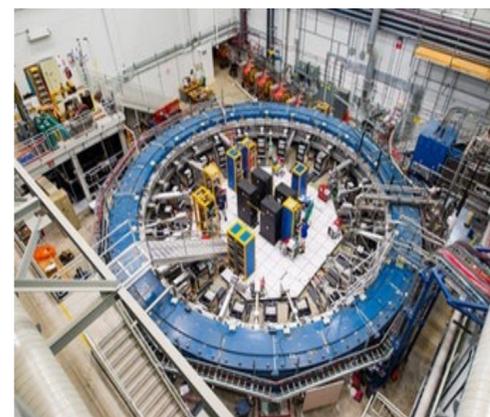# US Intensity Frontier Experiments

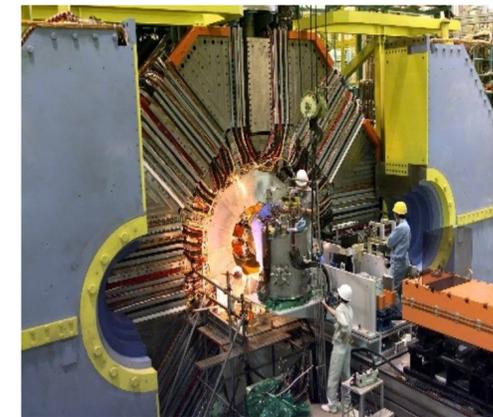by H. Murayama @ 13th ICFA seminar
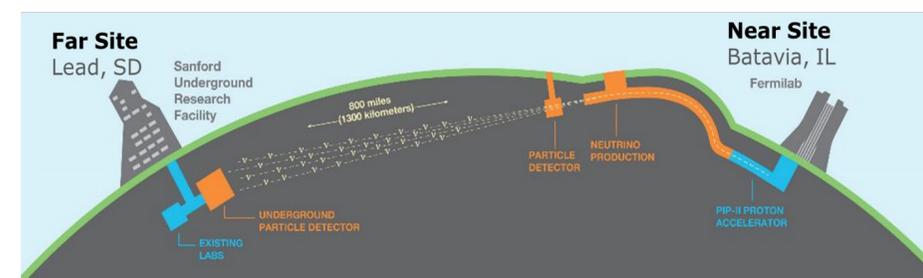
ICARUS at Fermilab

Mu2E at Fermilab

NOvA at Fermilab and Ash River

Muon g-2 at Fermilab

Belle II at KEK, Japan

COHERENT at ORNL

DUNE at Fermilab and Lead, SD

Fermilab Accelerator Complex

What experiments are there?

- CERN (Europe)

  - LHC/ATLAS, CMS, LHCb, FASAR, SND, milliQan, NA62, DsTau, (CEPE)

- PSI (Switzerland)

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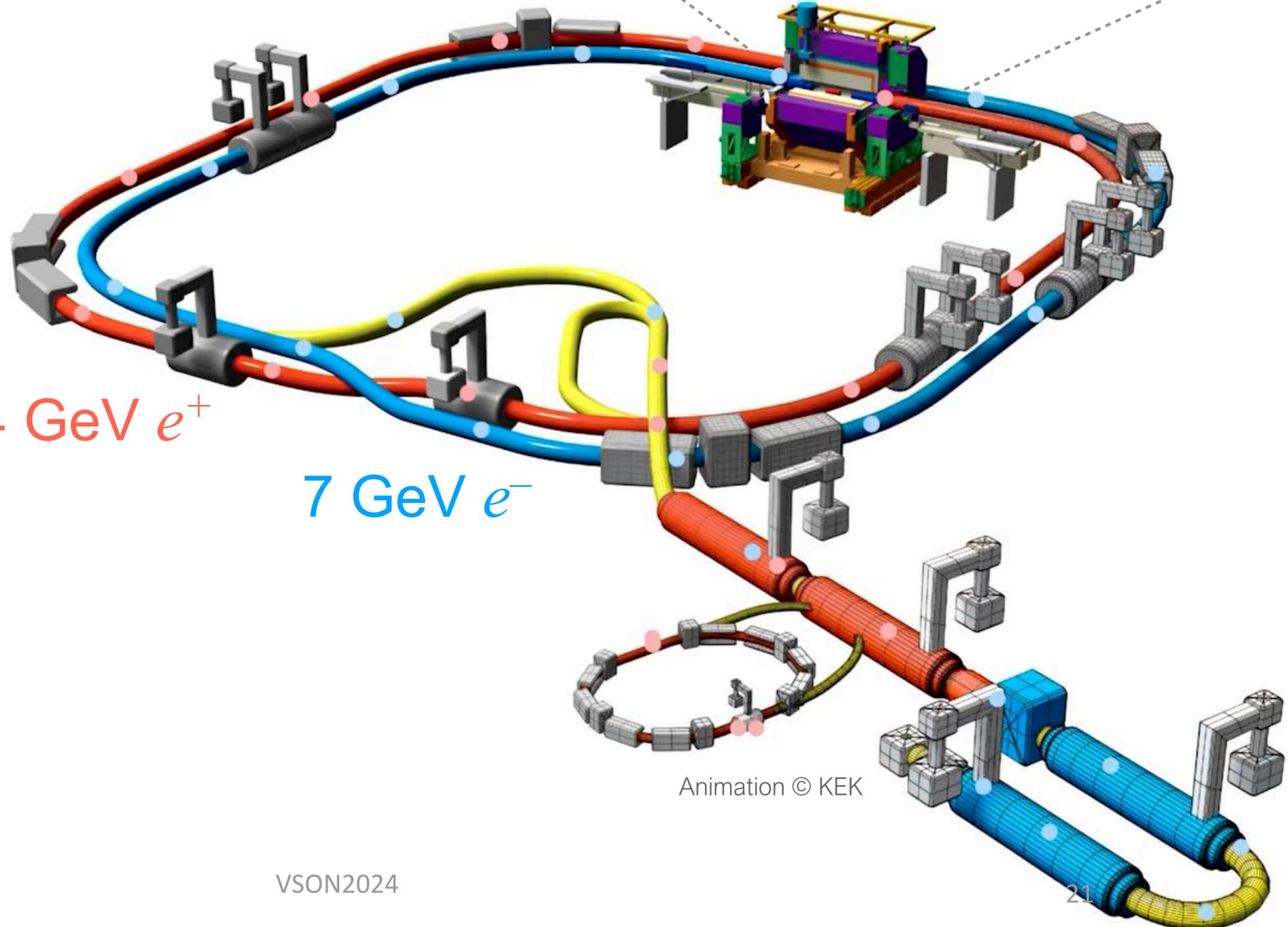
- *Cosmology and Astro-particle experiments*

B (and charm)

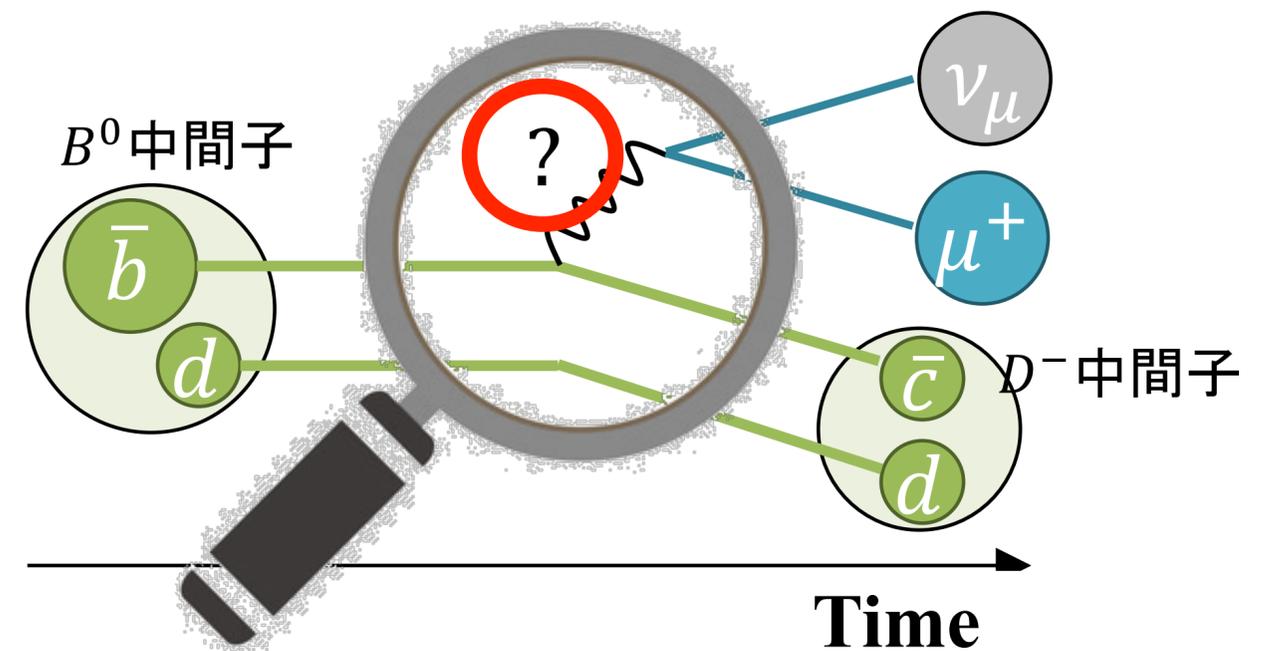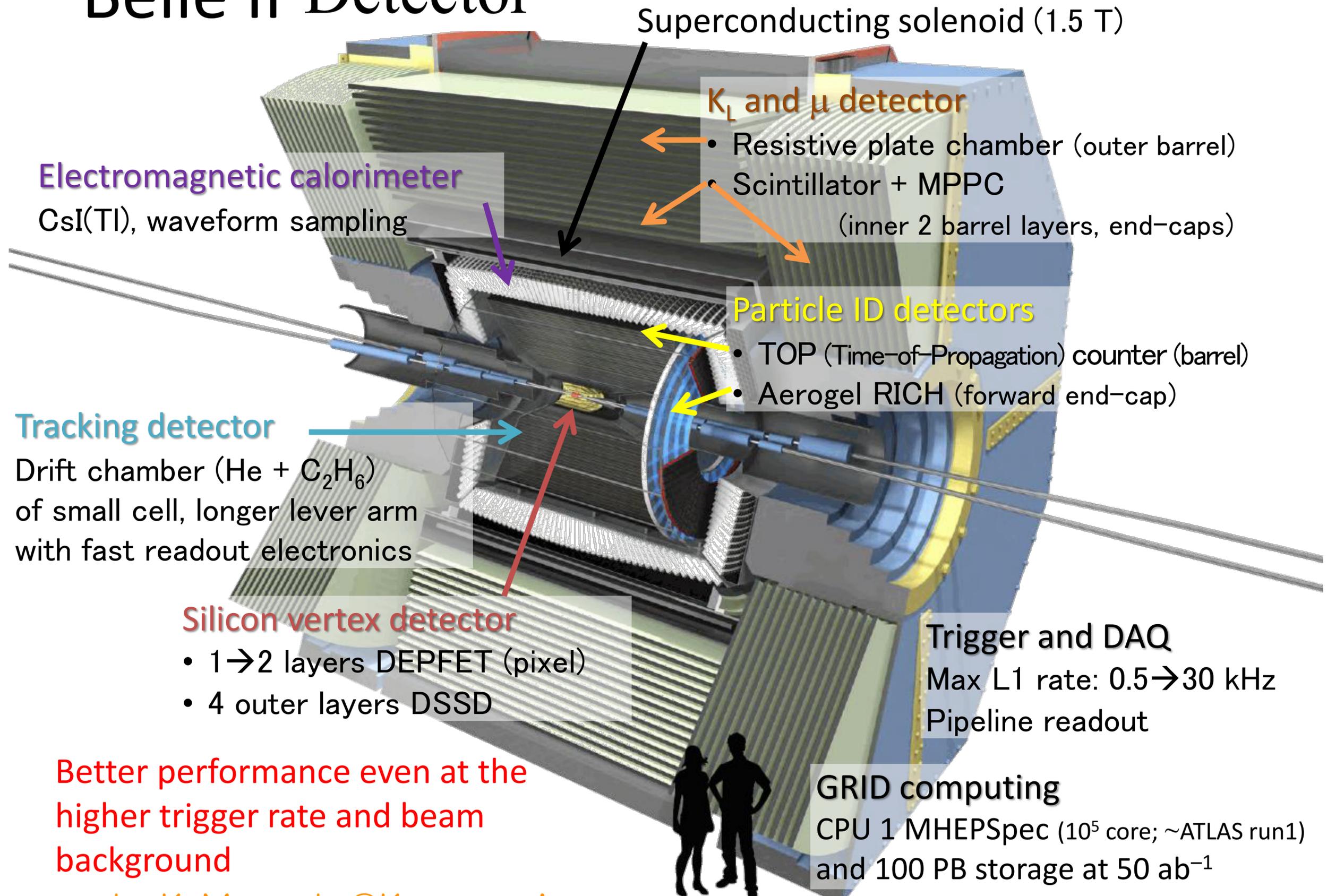# B-factory
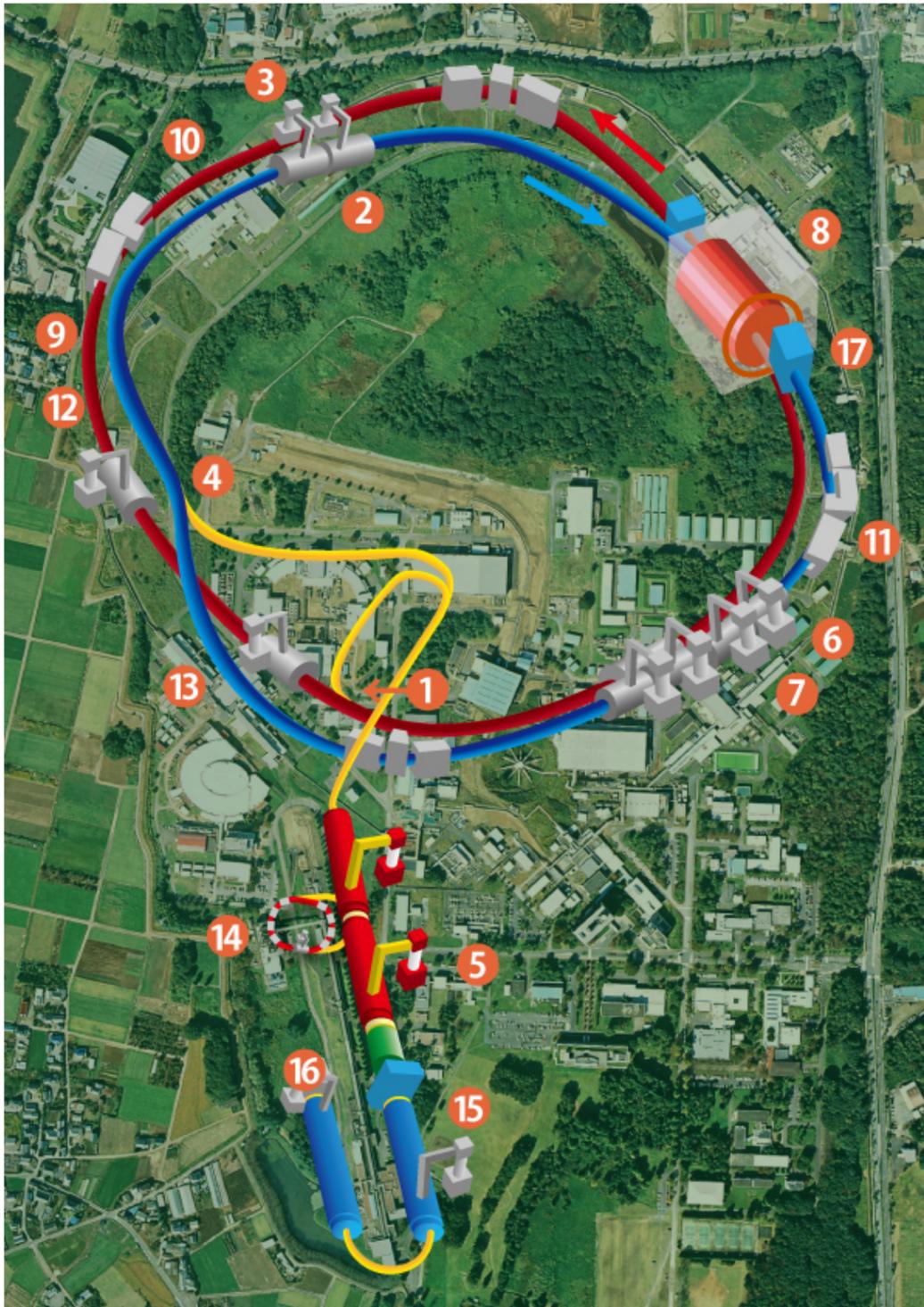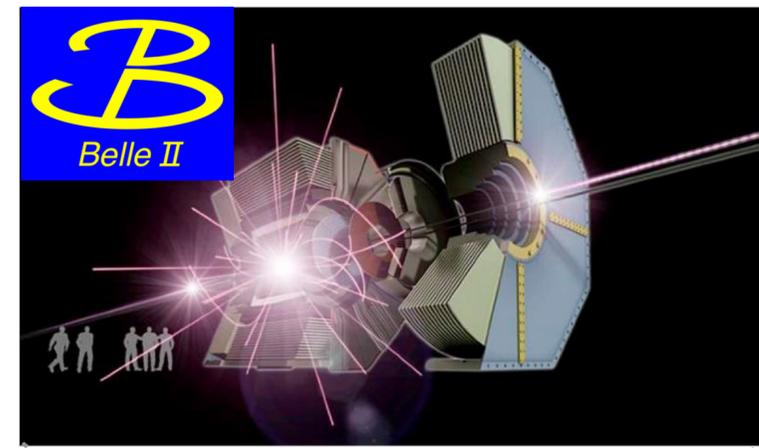
4 GeV e^+

7 GeV e^-

Animation © KEK

Basic ideas

- Quantum effects generate high-energy phenomena with a certain probability as intermediate states

- The intermediate state is indirectly probed by precise measurements because the probability including high-energy phenomena is rare.

Belle II Detector

Superconducting solenoid (1.5 T)

K_L and μ detector
- Resistive plate chamber (outer barrel)
- Scintillator + MPPC
  (inner 2 barrel layers, end-caps)

Electromagnetic calorimeter
CsI(Tl), waveform sampling

Particle ID detectors
- TOP (Time-of-Propagation) counter (barrel)
- Aerogel RICH (forward end-cap)

Tracking detector
Drift chamber (He + C_2H_6)
of small cell, longer lever arm
with fast readout electronics

Silicon vertex detector
- 1→2 layers DEPFET (pixel)
- 4 outer layers DSSD

Trigger and DAQ
Max L1 rate: 0.5→30 kHz
Pipeline readout

**Better performance even at the
higher trigger rate and beam
background**

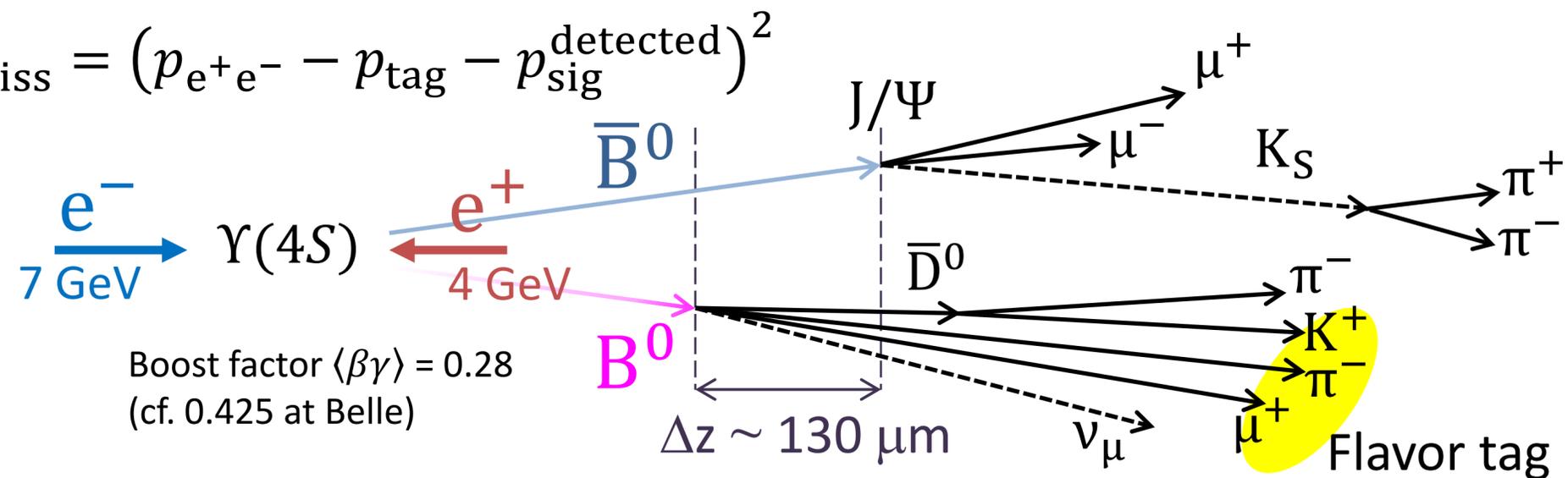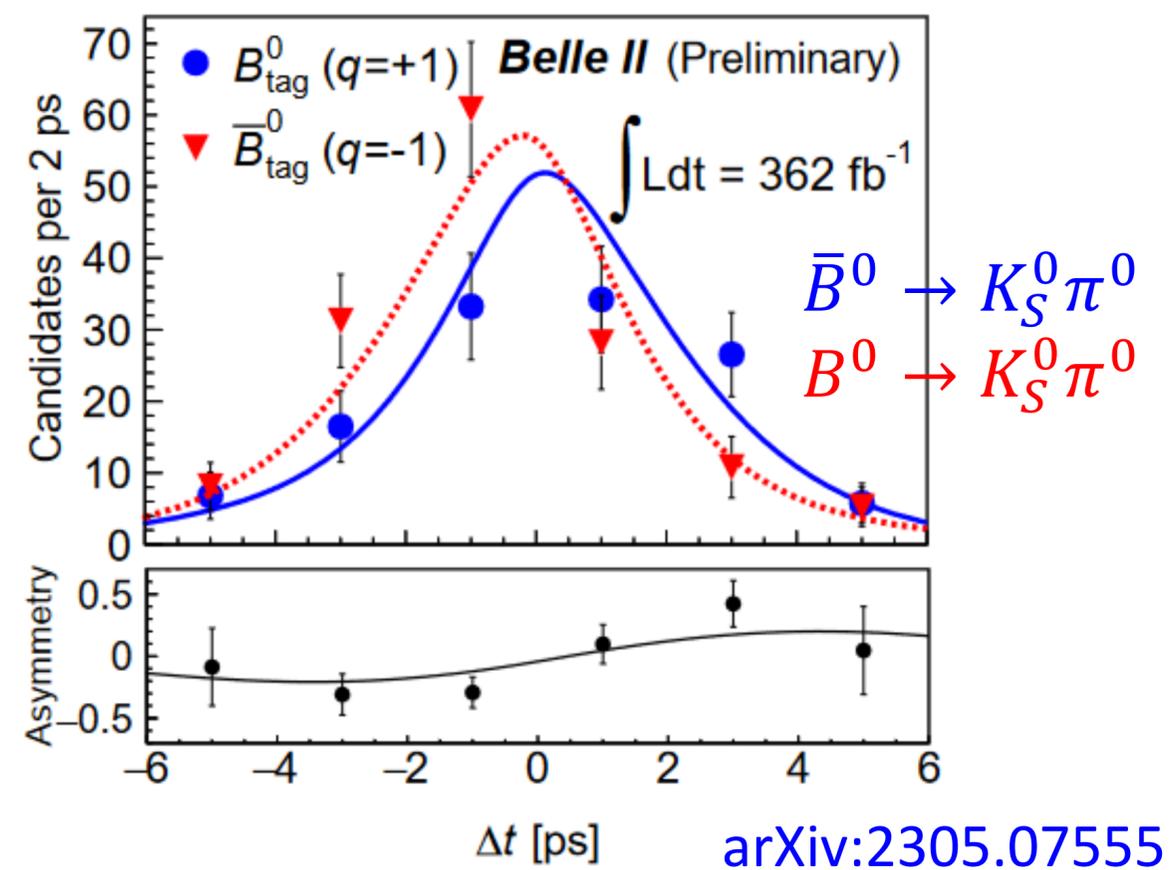**GRID computing**
CPU 1 MHEPSpec (10^5 core; ~ATLAS run1)
and 100 PB storage at 50 ab^{-1}

by K. Matsuoka@Kyoto seminar

BELLE

$B_1 \rightarrow J/\psi \, \overline{K}^{*0}$
$\quad \hookrightarrow K^-\pi^+$
$\quad \hookrightarrow \mu^+\mu^-$

$B_2 \rightarrow D^+ \pi^-$
$\quad \hookrightarrow K^-\pi^+\pi^+$

BELLE

K^-
π^+
π^-
π^+
D^+

x
z
1mm

$B_1 \rightarrow J/\psi \, \overline{K}^{*0}$
$\quad \hookrightarrow K^-\pi^+$
$\quad \hookrightarrow \mu^+\mu^-$

$B_2 \rightarrow D^+ \pi^-$
$\quad \hookrightarrow K^-\pi^+\pi^+$

μ^+
μ^-
π^+
K^-

Belle @ KEKB
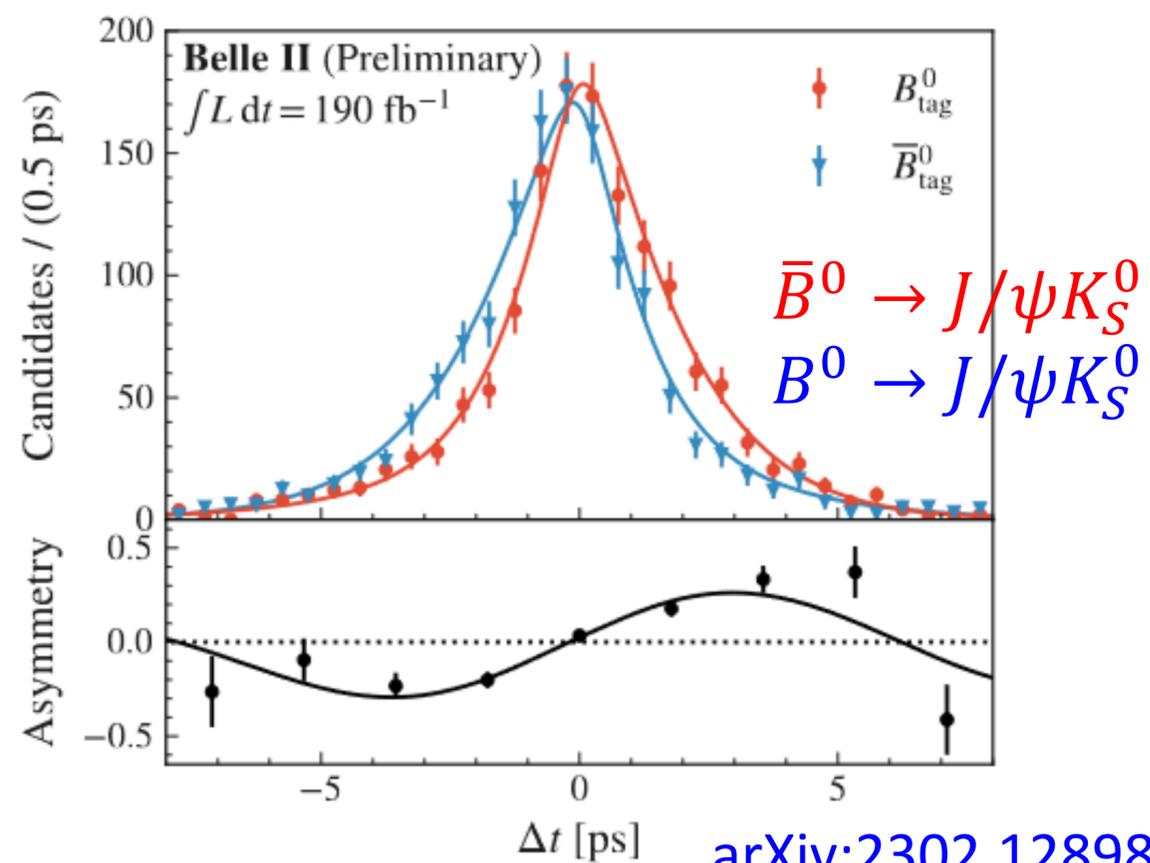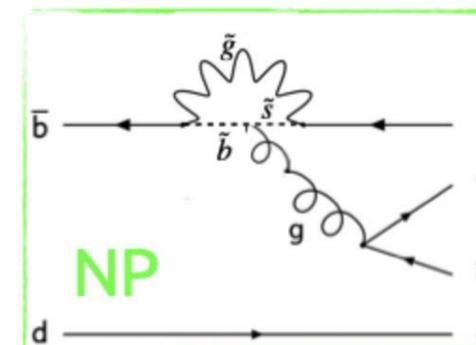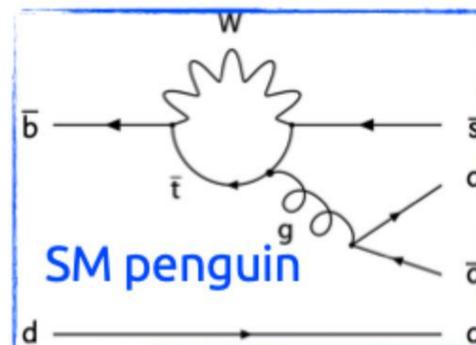
Belle @ SuperKEKB

24

The same event with simulated background at 8×10^{35} cm^{-2}s^{-1}
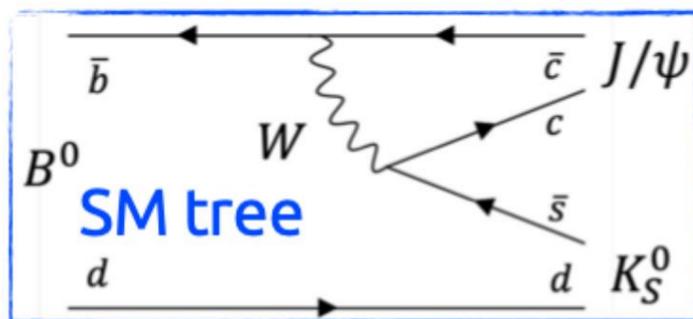
Super-KEKB/Belle II Basic

- ✓ e^+e^- collistions at (or around) $\Upsilon(4S)$
  - – Well-known initial state kinematics
  - – $B\bar{B}$ production from $\Upsilon(4S)$ without extra energy
  - – No event pile-up

- ✓ Hermetic Belle II detector capable of detecting charged particles and reconstructing neutrals (γ, π^0, K_L^0, etc) with high efficiencies.

- ➢ Tagging one of the B's to infer the other B flavor and momentum.
  - – Powerful S/N separation
  - – $m_{\mathrm{miss}}^2 = \left(p_{e^+e^-} - p_{\mathrm{tag}} - p_{\mathrm{sig}}^{\mathrm{detected}}\right)^2$

e^- 7 GeV $\Upsilon(4S)$ e^+ 4 GeV

$\bar{B}^0$, B^0, J/Ψ, μ^+, μ^-, K_S, π^+, π^-, $\bar{D}^0$, π^-, K^+, π^-, μ^+, ν_μ

Boost factor $\langle \beta\gamma \rangle$ = 0.28 (cf. 0.425 at Belle)

$\Delta z \sim 130 \ \mu m$

Flavor tag

CP Violation in B decays

SM tree

SM penguin

NP

Belle II (Preliminary)
$\int L \, dt = 190 \, \text{fb}^{-1}$

B^0_{tag}
$\bar{B}^0_{\text{tag}}$

$\bar{B}^0 \to J/\psi K^0_S$
$B^0 \to J/\psi K^0_S$

arXiv:2302.12898

B^0_{tag} (q=+1)
$\bar{B}^0_{\text{tag}}$ (q=−1)

Belle II (Preliminary)

$\int L \, dt = 362 \, \text{fb}^{-1}$

$\bar{B}^0 \to K^0_S \pi^0$
$B^0 \to K^0_S \pi^0$

arXiv:2305.07555

Belle II: $S = 0.720 \pm 0.062 \pm 0.016$
Belle: $S = 0.667 \pm 0.023 \pm 0.012$
($S \approx \sin 2\phi_1$ in this mode)

Belleの約60%のデータで凌駕する精度
Belle II: $S = 0.75 \, ^{+0.20}_{-0.23} \pm 0.04$
Belle: $S = 0.67 \pm 0.31 \pm 0.08$

by K. Matsuoka@Kyoto seminar

Precision measurements

Fig. 226 of Prog. Theor. Exp. Phys. 2019, 123C01

Before Belle II (2018)

Belle II 50 ab^{-1} + LHCb 23 fb^{-1} + LQCD
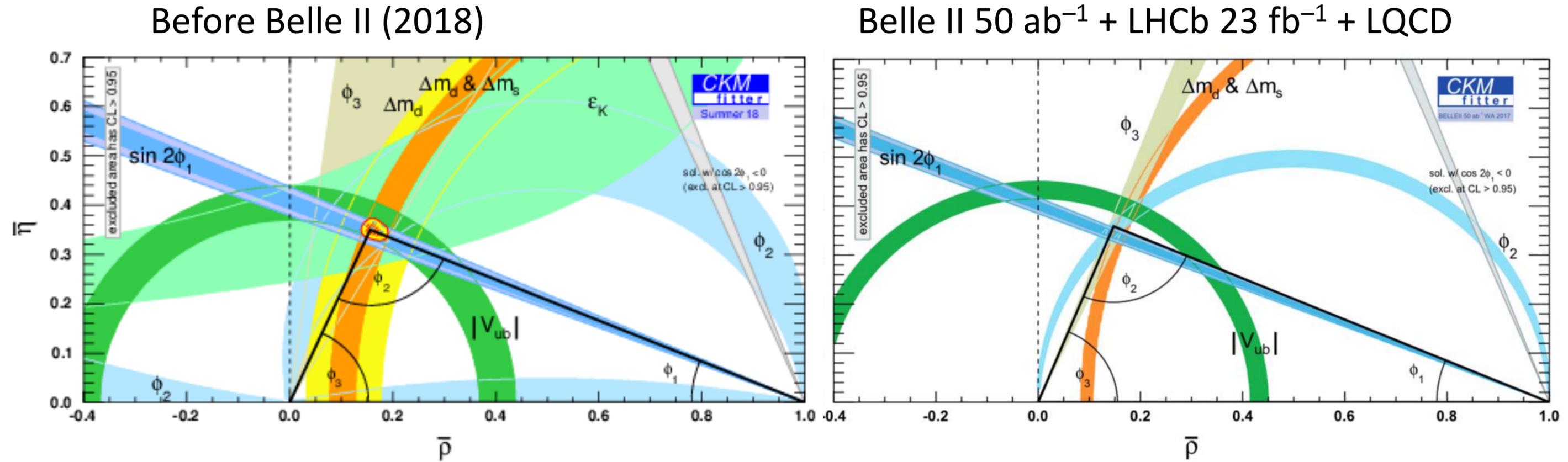
The Standard Model has been tested with ~10% precision.

→ Search for non-standard effects that can only appear as small corrections to the Standard Model.

Access higher energy scales via quantum effects than are directly reachable at current or future colliders.

e.g. $\Lambda < \sim 1000$ TeV in B^0 mixing ($\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{\Lambda^2}\mathcal{O}_{\Delta F=2}$) [arXiv:1302.0661]

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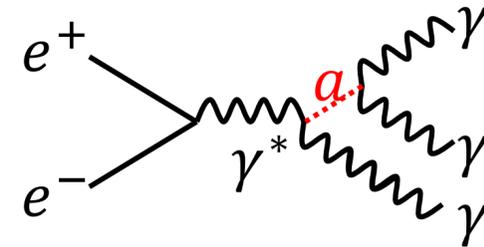
Search for Dark particles

- Z' or LFV Z' to invisible
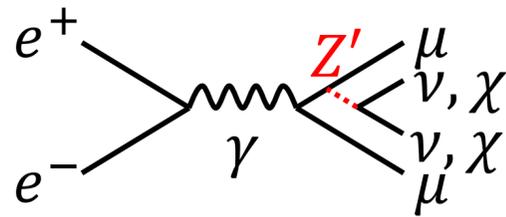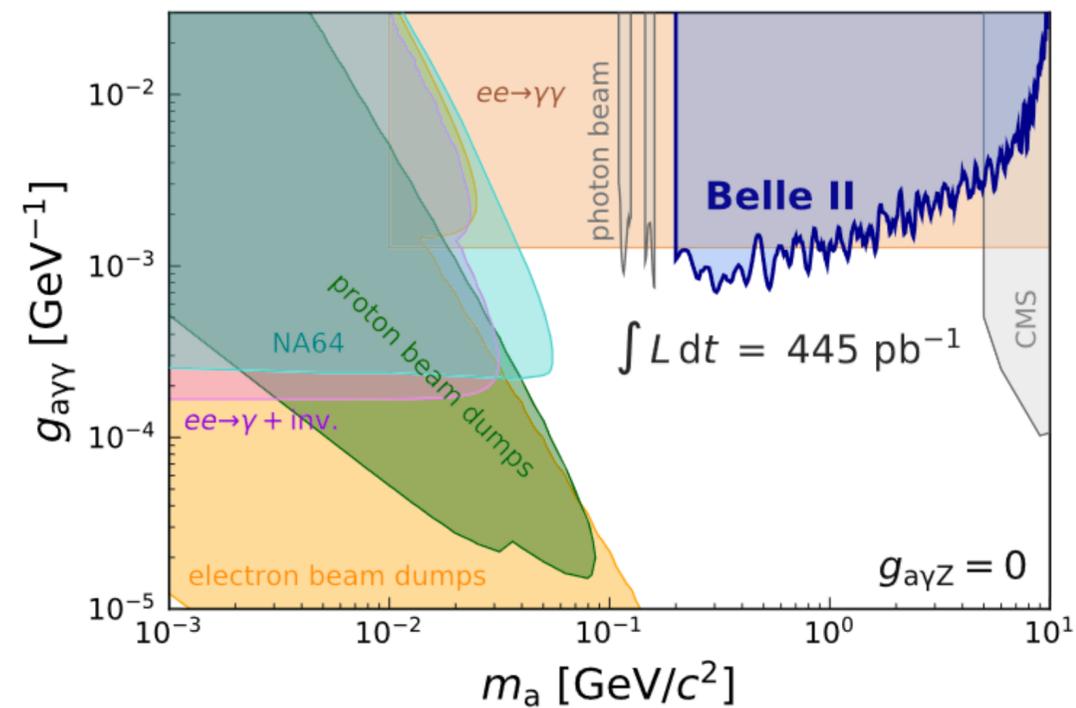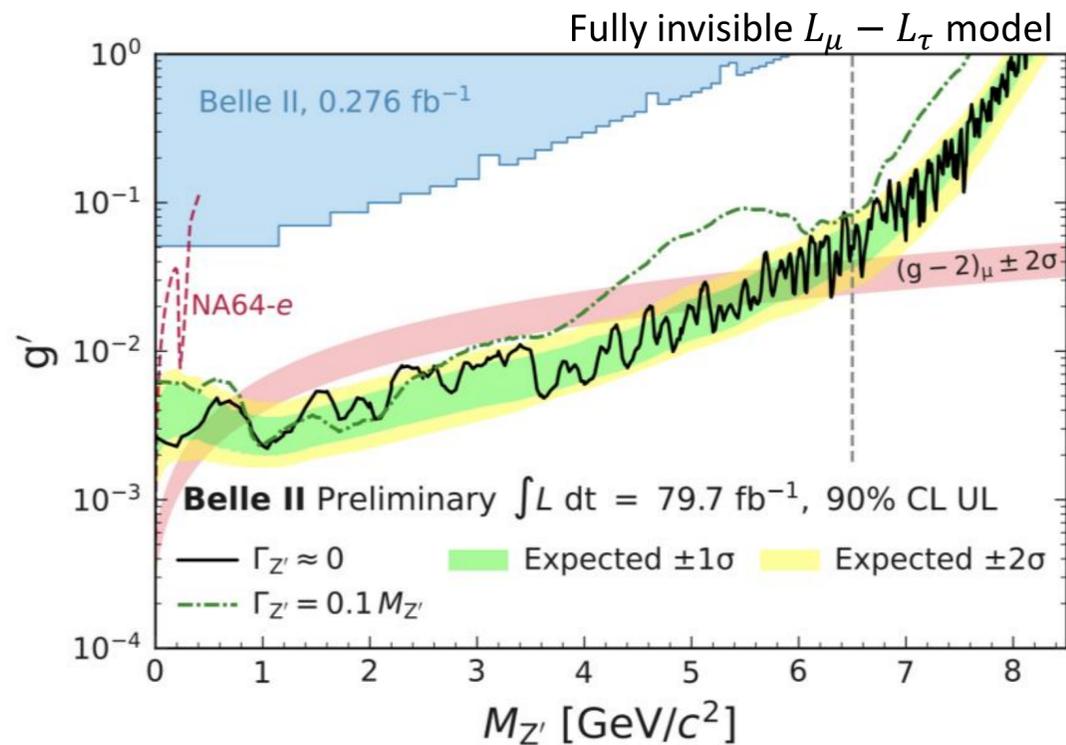

PRL 124, 141801 (2020)
··· 1st Belle II physics paper
arXiv:2212.03066 ··· update, 2022

- Axion Like Particle

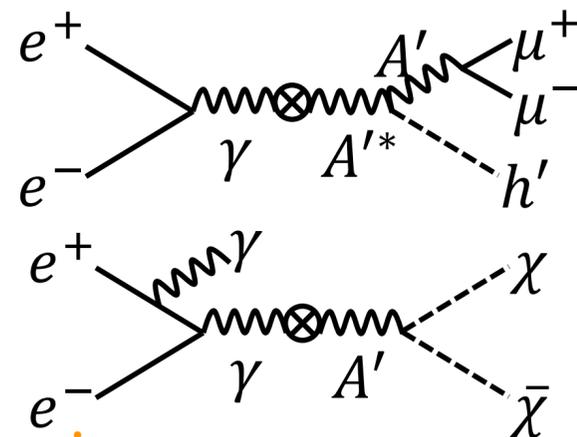

PRL 125, 161806 (2020)
··· 2nd Belle II physics paper

Fully invisible $L_\mu - L_\tau$ model

Belle II, 0.276 fb^{-1}

NA64-e

$(g-2)_\mu \pm 2\sigma$

Belle II Preliminary $\int L\, dt = 79.7$ fb^{-1}, 90% CL UL

$\Gamma_{Z'} \approx 0$ Expected $\pm 1\sigma$ Expected $\pm 2\sigma$
$\Gamma_{Z'} = 0.1\, M_{Z'}$

$M_{Z'}$ [GeV/c^2]

$ee \to \gamma\gamma$

photon beam

Belle II

proton beam dumps

NA64

CMS

$\int L\, dt = 445$ pb^{-1}

$ee \to \gamma +$ inv.

electron beam dumps

$g_{a\gamma Z} = 0$

$g_{a\gamma\gamma}$ [GeV^{-1}]

m_a [GeV/c^2]
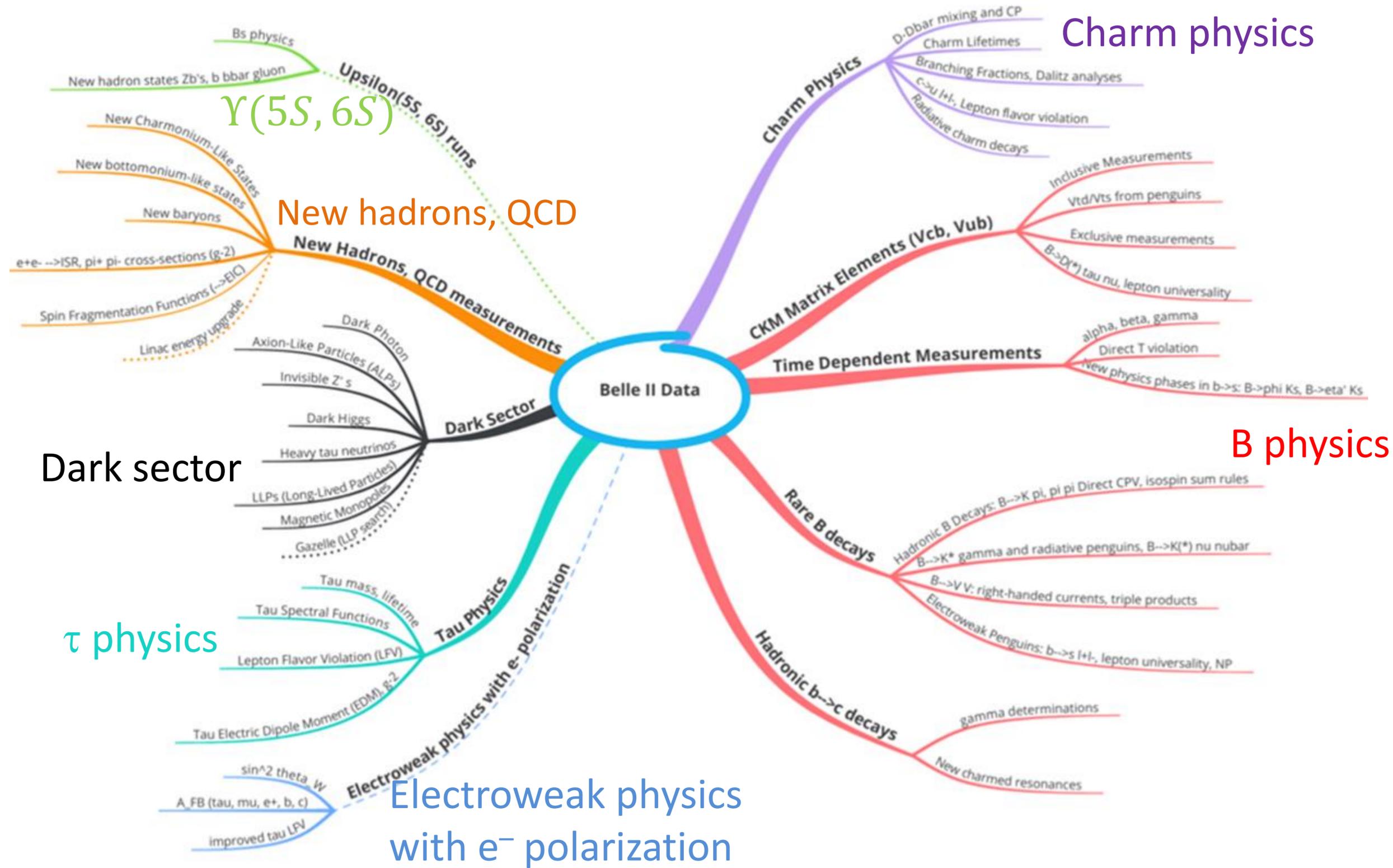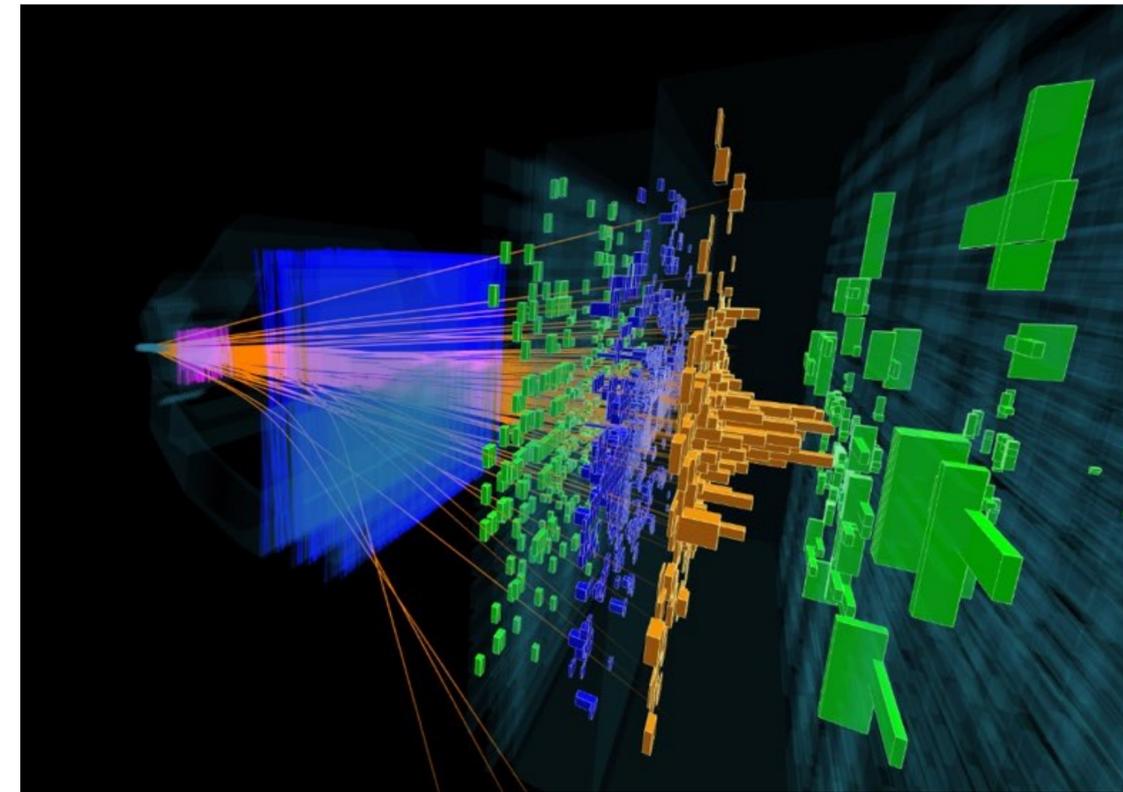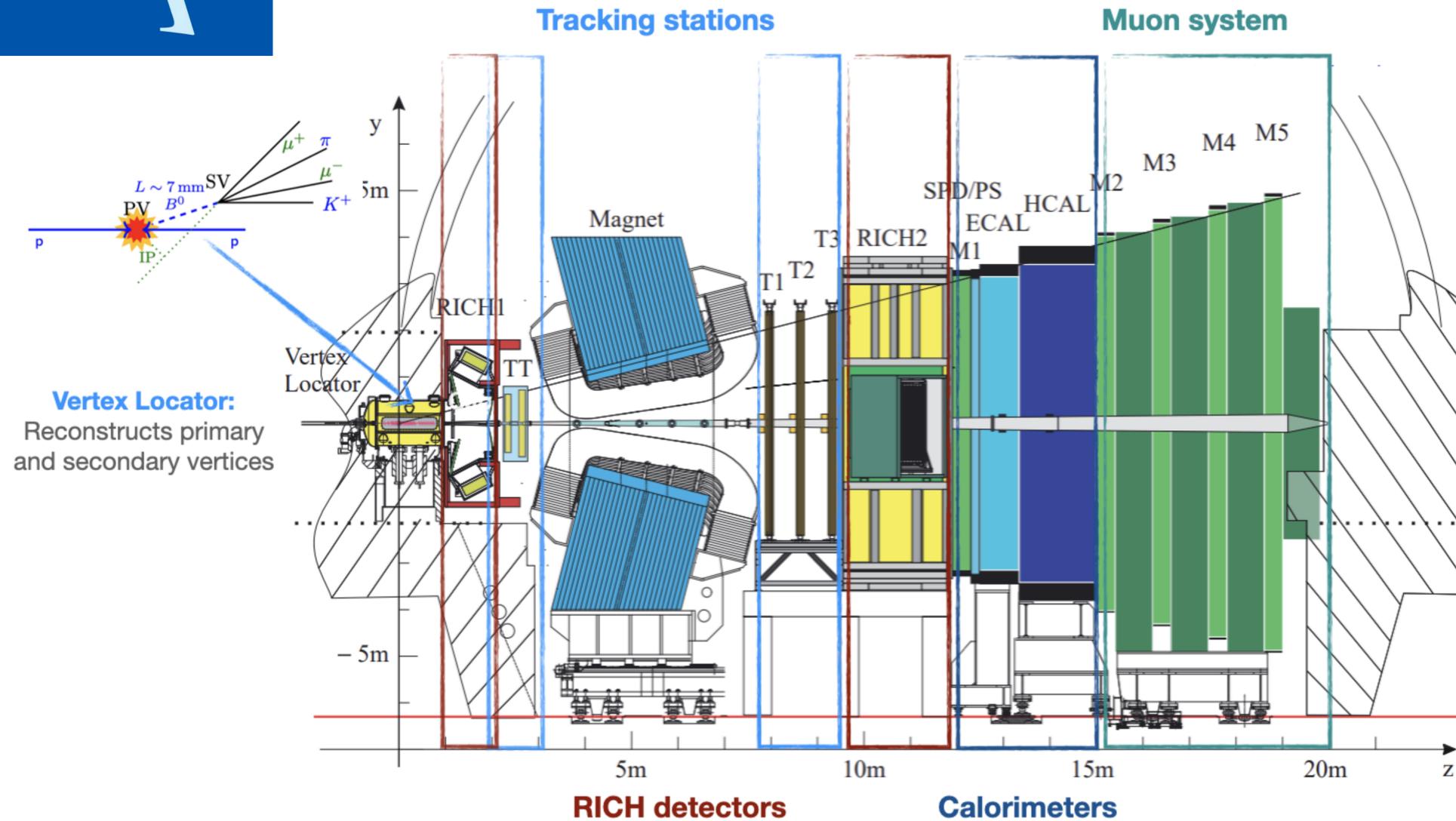
- Dark higgstrahlung
  PRL 130, 071804 (2023)

- Invisible dark photon

- Visible dark photon
- $Z' \to \mu\mu$
- Inelastic dark matter
- Dark scalar

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28

Belle II Data mind map

Charm physics
- Charm Physics
  - D-Dbar mixing and CP
  - Charm Lifetimes
  - Branching Fractions, Dalitz analyses
  - c->u l+l-, Lepton flavor violation
  - Radiative charm decays

$\Upsilon(5S, 6S)$
- Upsilon(5S, 6S) runs
  - Bs physics
  - New hadron states Zb's, b bbar gluon

New hadrons, QCD
- New Hadrons, QCD measurements
  - New Charmonium-Like States
  - New bottomonium-like states
  - New baryons
  - e+e- -->ISR, pi+ pi- cross-sections (g-2)
  - Spin Fragmentation Functions (-->E(C))
  - Linac energy upgrade

Dark sector
- Dark Sector
  - Dark Photon
  - Axion-Like Particles (ALPs)
  - Invisible Z's
  - Dark Higgs
  - Heavy tau neutrinos
  - LLPs (Long-Lived Particles)
  - Magnetic Monopoles
  - Gazelle (LLP search)

B physics
- CKM Matrix Elements (Vcb, Vub)
  - Inclusive Measurements
  - Vtd/Vts from penguins
  - Exclusive measurements
  - B->D(*) tau nu, lepton universality
- Time Dependent Measurements
  - alpha, beta, gamma
  - Direct T violation
  - New physics phases in b->s: B->phi Ks, B->eta' Ks
- Rare B decays
  - Hadronic B Decays: B-->K pi, pi pi Direct CPV, isospin sum rules
  - B-->K* gamma and radiative penguins, B-->K(*) nu nubar
  - B-->V V: right-handed currents, triple products
  - Electroweak Penguins: b-->s l+l-, lepton universality, NP
- Hadronic b-->c decays
  - gamma determinations
  - New charmed resonances

τ physics
- Tau Physics
  - Tau mass, lifetime
  - Tau Spectral Functions
  - Lepton Flavor Violation (LFV)
  - Tau Electric Dipole Moment (EDM), g-2

Electroweak physics with e⁻ polarization
- Electroweak physics with e- polarization
  - sin^2 theta_W
  - A_FB (tau, mu, e+, b, c)
  - improved tau LFV

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29

LHCb

Access to tiny BRs
All *b*-hadrons types
LHC complex environment

- Forward detector specialised in measuring properties of *b* and *c* hadrons
- Run 1 [2011-2012]: 7-8 TeV and 3 fb^{-1}
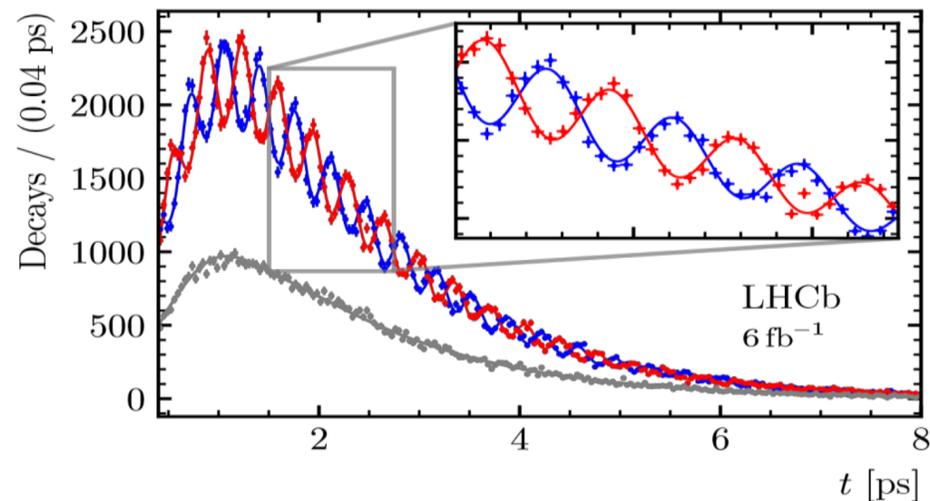- Run 2 [2015-2018]: 13 TeV and 6 fb^{-1}

▸ JINST 3 (2008) S08005

LHCb method for TD study

$$t = L \cdot \frac{m}{p}$$
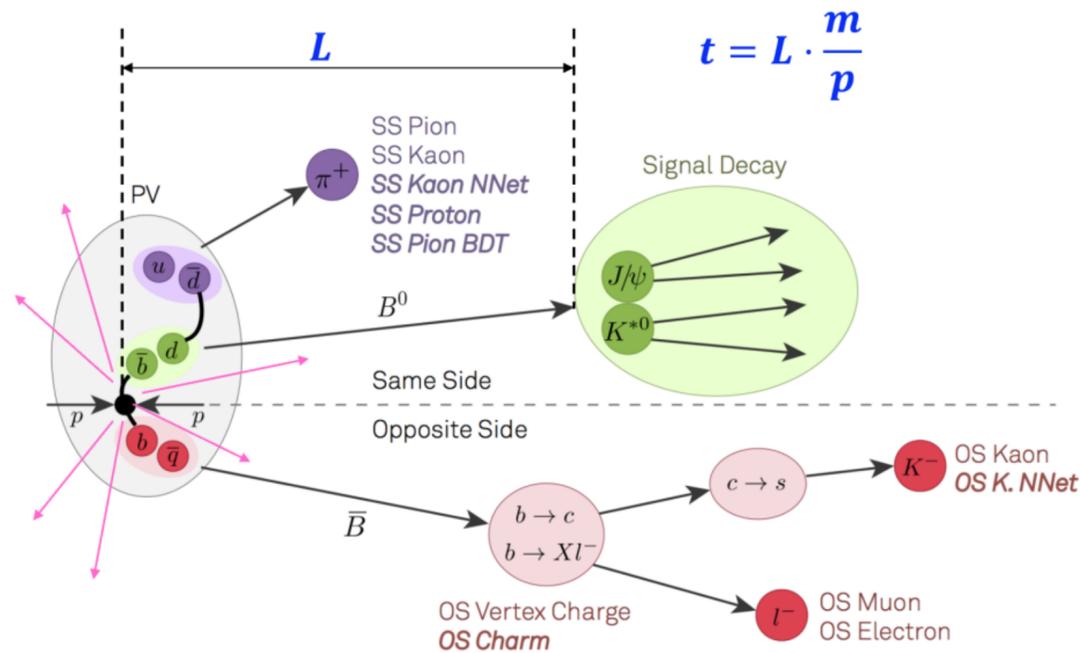
- Flavour tagging: info from other B & fragmentation particles
  $$\epsilon_{\text{tag}}(1 - 2\omega)^2 \sim 5\%$$
- Large boost from pp collision
  $$\beta\gamma \sim 10,\ L \sim 1\ \text{cm}$$
- Silicon vertex system
  $$\sigma_t \sim 45\ \text{fs}$$

Int. J. Mod. Phys. A30 (2015) 1530022

$B_s^0 \to D_s^- \pi^+$ Nature Physics 18 (2022) 1-5

$\Delta m_s = 17.7656 \pm 0.0057(\text{comb})\ \text{ps}^{-1}$

$B_d^0 \to D^{(*)-}\mu^+\nu$ EPJC 76 (2016) 412
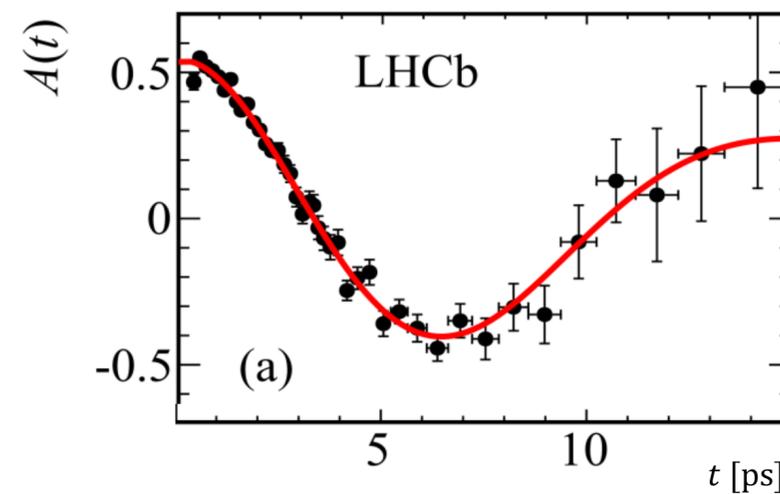
$\Delta m_d = 0.5050 \pm 0.0021(\text{stat}) \pm 0.0010(\text{syst})\ \text{ps}^{-1}$

by Y. Xie @31st Lepton Photon Conf.

15

BEPCII & BESIII

Beijing Electron Positron Collider II(BEPCII)

Double storage ring ~ 240 m

Linac ~ 200 m

IP

BESIII detector

2020: energy upgrade to 2.45 GeV
2004: started BEPCII upgrade,
      BESIII construction
2008: test run
2009-now: BESIII physics run

- **1989-2004 (BEPC):**
  $\mathcal{L}_{\text{peak}} = 1.0 \times 10^{31} \text{ cm}^{-2} \cdot \text{s}^{-1}$
- **2009-now (BEPCII):**
  $\mathcal{L}_{\text{peak}} = 1.0 \times 10^{33} \text{ cm}^{-2} \cdot \text{s}^{-1}$

Superconducting solenoid
- **0.9~1.0 T**

Muon Counter (MUC)
- **9 layers (barrel) + 8 layer (end-cap)**

Time Of Flight (TOF)
- $\sigma_t = 90$ ps (barrel)
- $\sigma_t = 65$ ps (end cap)

RPC: 9 layers

Electro Magnetic Calorimeter

RPC : 8 layers

SC Solenoid

Barrel ToF

Endcap ToF

SC Quadrupole

e^+

MDC

$\cos\theta=0.83$
$\cos\theta=0.90$
$\cos\theta=0.93$

e^-

Electromagnetic Calorimeter(EMC)
- $\Delta E/E = 2.5\%$ @ 1.0 GeV
- $\sigma_{\phi z} = 0.6$ cm @ 1.0 GeV

Main Drift Chamber (MDC)
- $\sigma_{xy} = 130$ μm
- $\Delta P/P = 0.5\%$ @ 1.0 GeV
- $\sigma_{dE/dx} = 6 - 7\%$

$$\sqrt{s} = 2.0 - 4.95 \,\text{GeV}$$

Measurements of the R value at BESIII

Hao Zhang (on behalf of the BESIII collaboration)

zh4710jj@mail.ustc.edu.cn, University of Science and Technology of China

中国科学技术大学
University of Science and Technology of China

31st Lepton Photon Conference 2023
MELBOURNE CONVENTION
& EXHIBITION CENTRE
17 – 21 JULY

Definition of R value

The R value is defined as the leading-order production cross section ratio of hadronic events and muon pairs in the e^+e^- annihilation:

$$R \equiv \frac{\sigma^0(e^+e^- \to \text{hadrons})}{\sigma^0(e^+e^- \to \mu^+\mu^-)} \equiv \frac{\sigma^0_{\text{had}}}{\sigma^0_{\mu\mu}}$$

$$\sigma^0_{\mu\mu}(s) = \frac{4\pi\alpha^2}{3s}\frac{\beta_\mu(3-\beta_\mu^2))}{2}, \text{ with } \beta_\mu = \sqrt{1-4m_\mu^2/s}$$

Measurement of R value $\Longleftrightarrow$ Measurement of **total cross section of hadron production**

Summary

R value measurement at BESIII

- Precision better than 2.6% below 3.1 GeV and 3.0% above **[Phys. Rev. Lett. 128, 062004 (2022)]**

Muon

Muon experiments

g-2

EDM

...−LFV

Real

Imaginary

χ^0

χ^0

$\tilde{B}$

large top Yukawa coupling

mixing
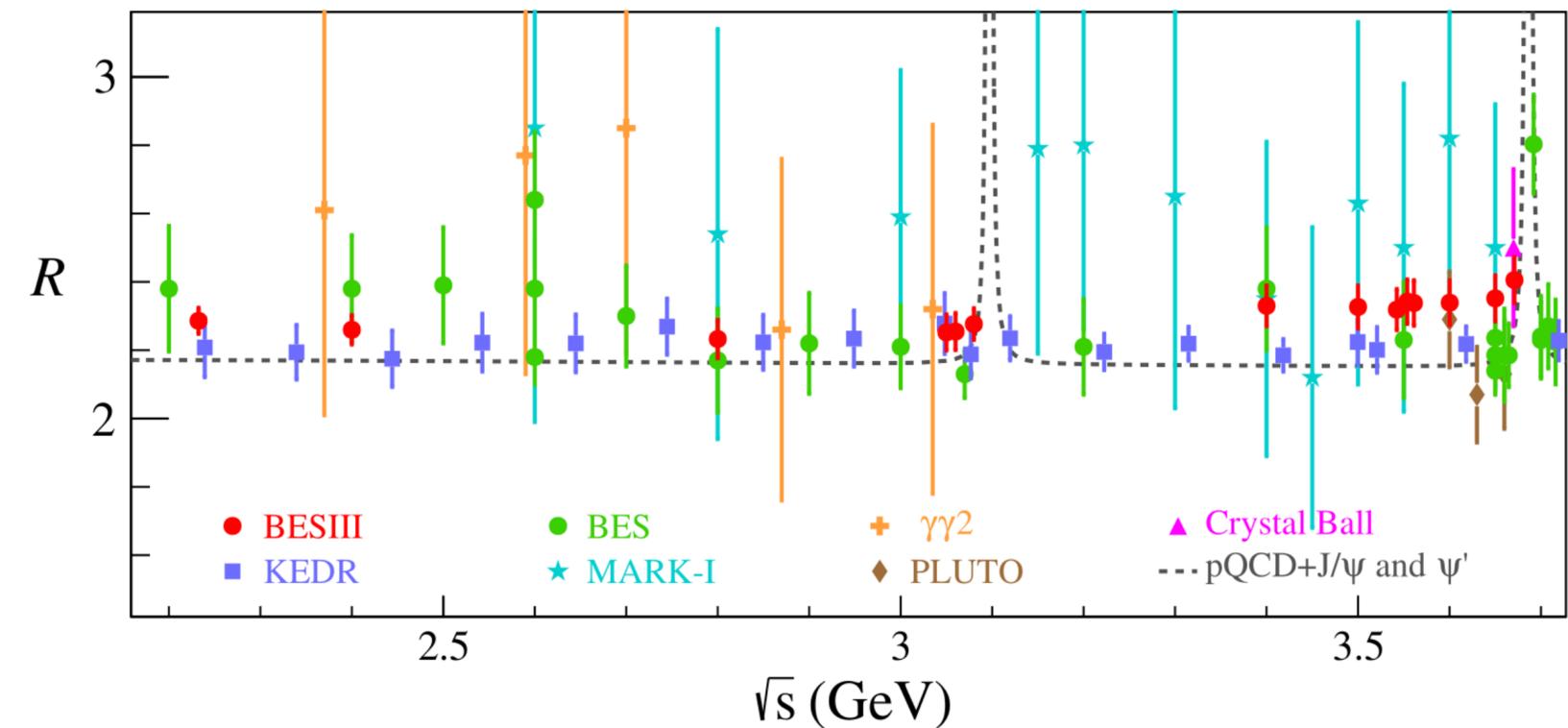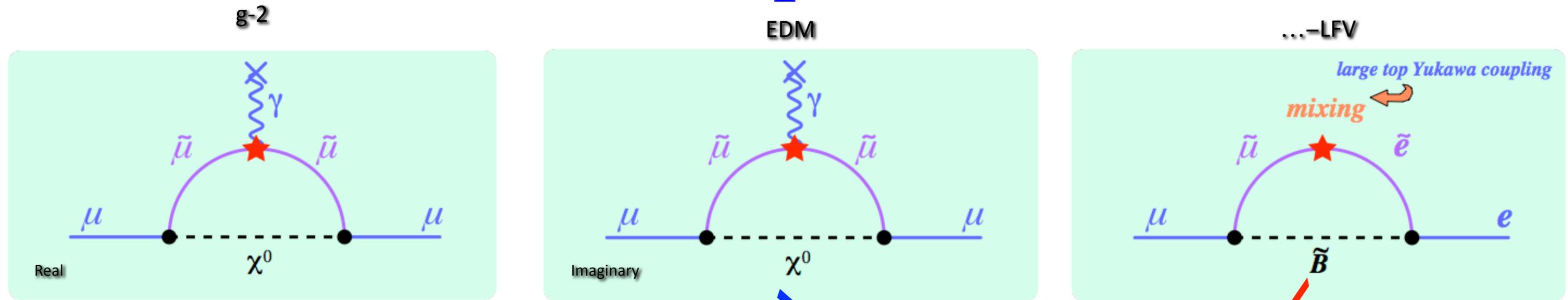
- μ→eγ search
- μ-e conversion search
- g-2
- μ-EDM

$$\begin{pmatrix} m_{\tilde{e}\tilde{e}}^2 & \Delta m_{\tilde{e}\tilde{\mu}}^2 & \Delta m_{\tilde{e}\tilde{\tau}}^2 \\ \Delta m_{\tilde{\mu}\tilde{e}}^2 & m_{\tilde{\mu}\tilde{\mu}}^2 & \Delta m_{\tilde{\mu}\tilde{\tau}}^2 \\ \Delta m_{\tilde{\tau}\tilde{e}}^2 & \Delta m_{\tilde{\tau}\tilde{\mu}}^2 & m_{\tilde{\tau}\tilde{\tau}}^2 \end{pmatrix}$$

MEG II at PSI

~60 collaborators

πE5 beam line @PSI

μ⁺ beam

γ

e⁺

COBRA SC magnet

LXe γ-ray detector

Drift chambers

Timing counters
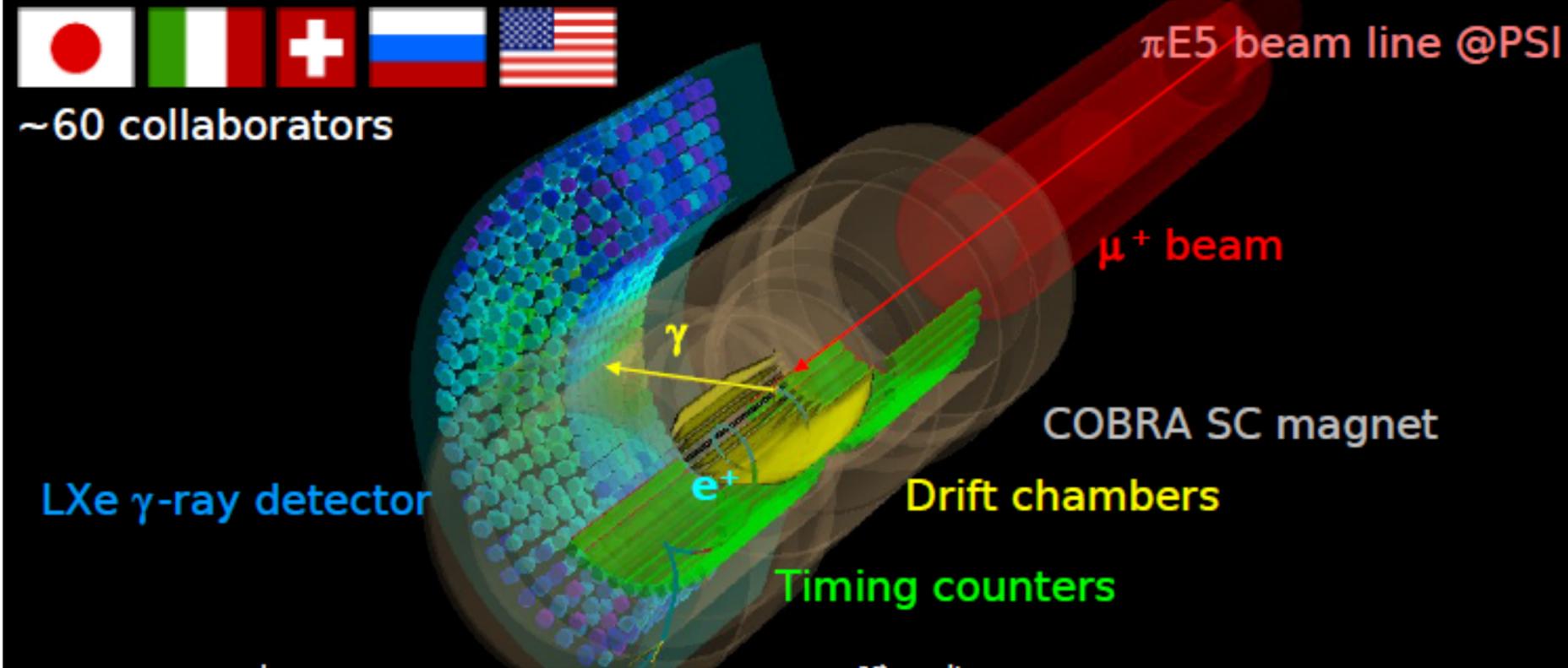
by H. Nishiguchi @13th ICFA seminar

Multi-Gamma
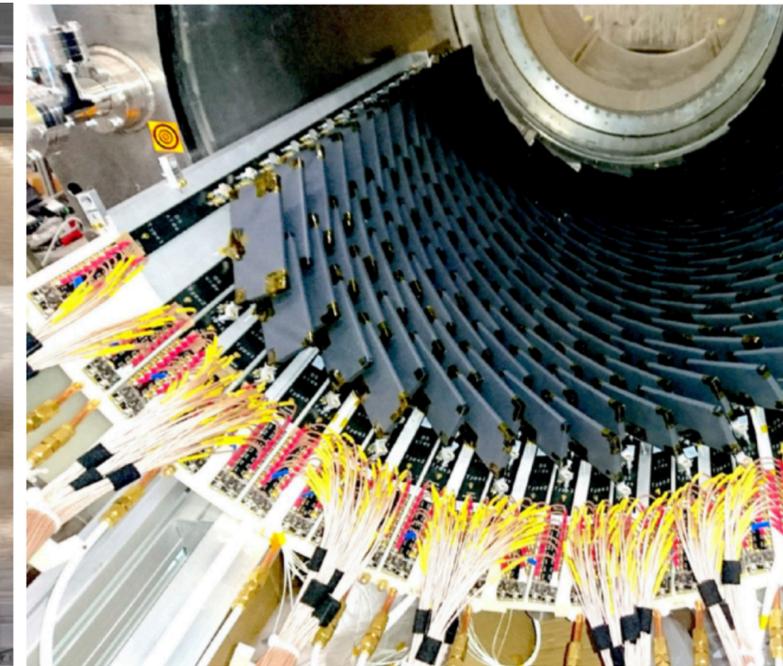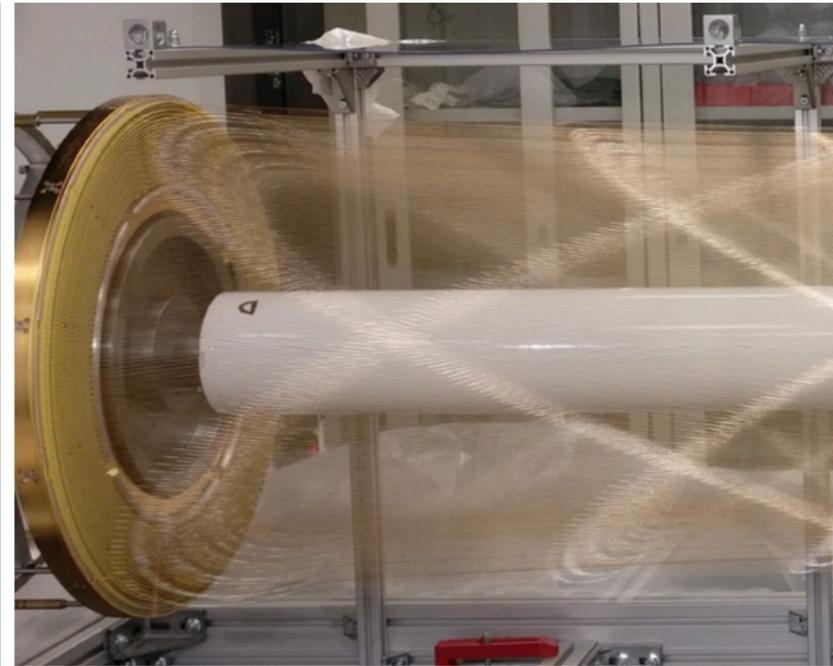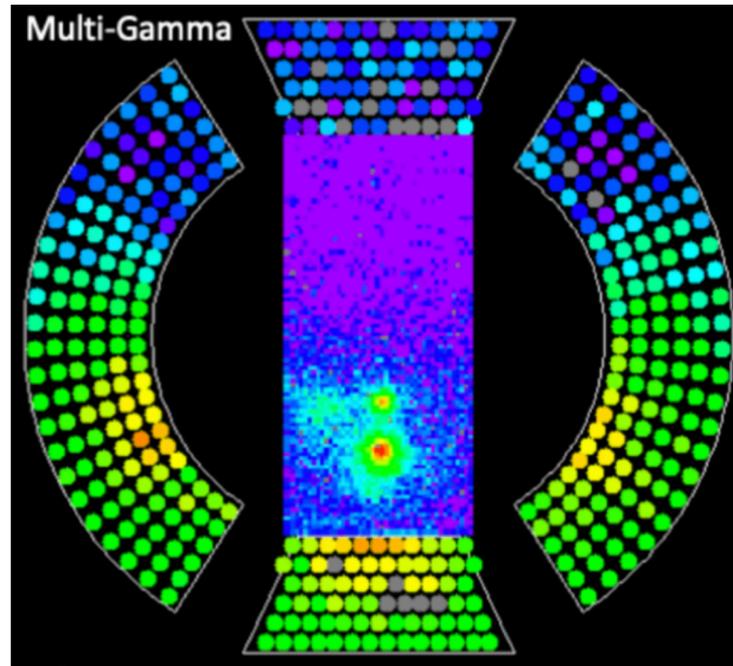
Latest Update — MEG II, First Result —

- ❖ **MEG II is running from 2021**
- ❖ **The 1st result have been published just last month !**

Unblinded 2021 Data
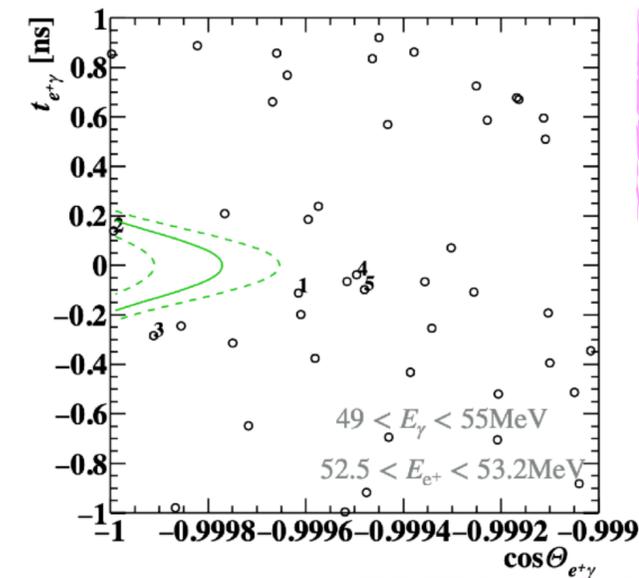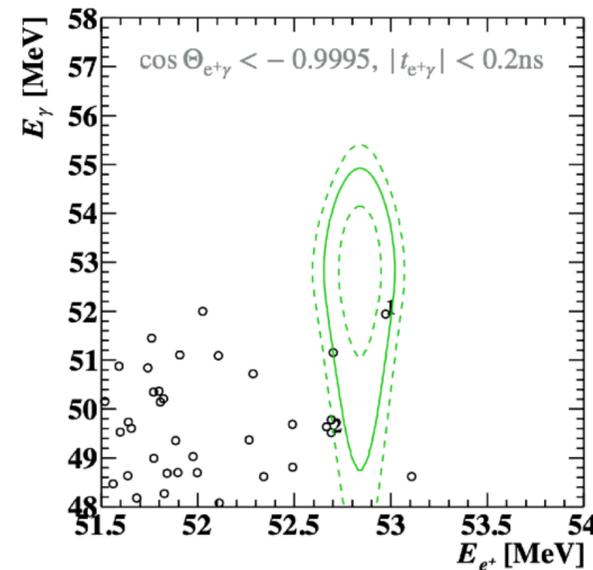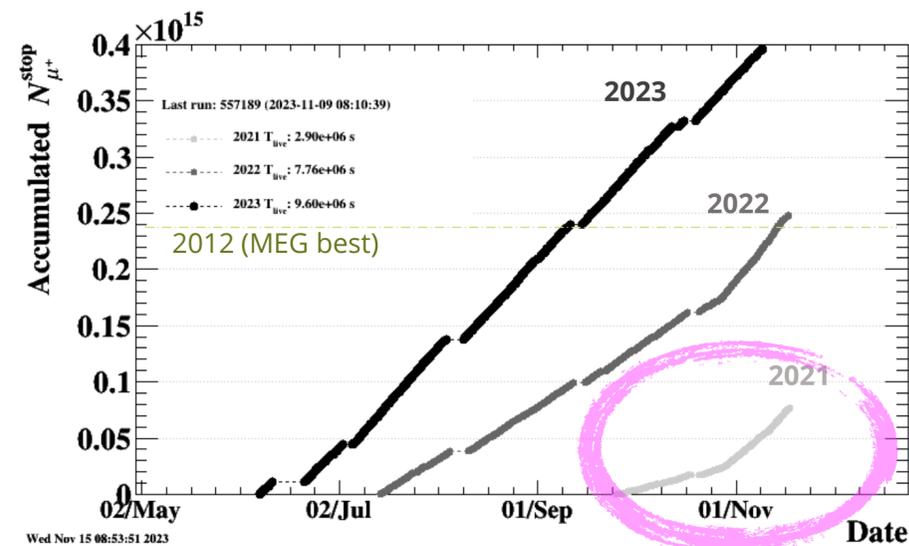
- ❖ **Only 7 weeks of physics run in 2021 = Almost equivalent to MEG data**
- ❖ **No excess of events over the expected background is observed**
  - ❖ **Upper Limit (90CL), $\mathcal{B}(\mu^+ \to e^+\gamma) < 7.5 \times 10^{-13}$, c.f. MEG result : $< 4.2 \times 10^{-13}$**
  - ❖ **Combined (MEG II 2021 + MEG): $\mathcal{B}(\mu^+ \to e^+\gamma) < 3.1 \times 10^{-13}$ (90% C.L.)**

The most stringent limit to date !

COMET

μ-e conversion

- High i   d muon beam (10^{11}/sec)
- Large   rve solenoidal electron spectro
  - Experim   ivity: BR = 10^{-17}
    - 100,0   ter than current limits
- Energy scale comparable to LHC

$$\mu^- + N(A,Z) \rightarrow e^- + N(A,Z)$$

(4) electron spectrometer

(1) proton target

(3) muon target

(2) muon transport

(5) straw chamber

(5) electron calorimeter

μ-e conversion

μ$^-$ (1S orbit)

Nucleus

	muon transport	electron transport
Mu2e	s-shape curve	straight
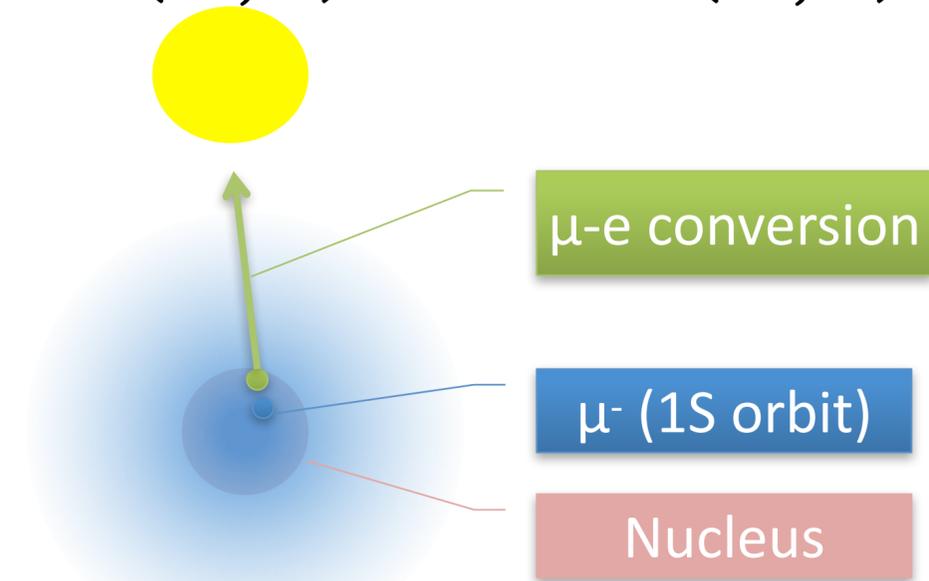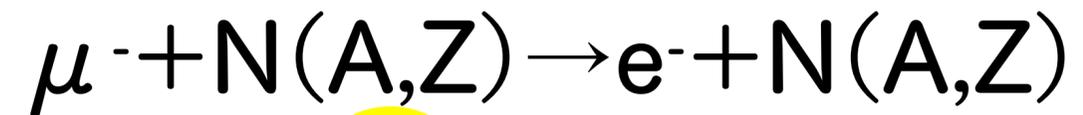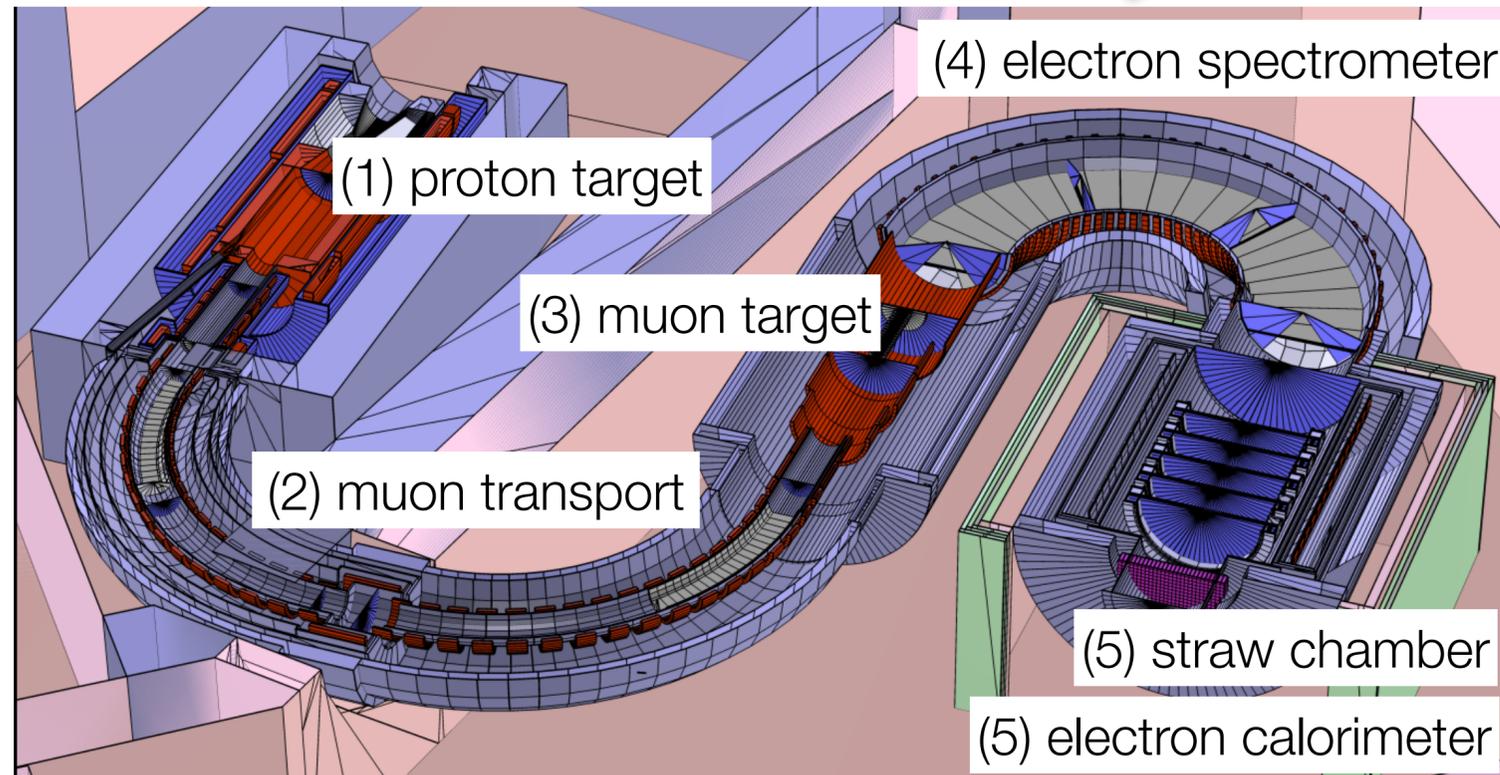
Immediate Outlook (3) — Mu2e / COMET / Mu3e —

❖ **Preparations for 3 experiments (Mu2e, COMET, Mu3e) are in the final stage**

	JFY2023				JFY2024				JFY2025				JFY2026				JFY2027			
Detector for mu-e Search									★ Ready												
Detector for beam measurement									★ Ready												
Beam line construction							Magnet Installation		Shield ★											
Engineering & Physics Runs									Eng				Physics Run							

❖ **Two detectors, for physics and BG, Ongoing and will be ready in 2025**

❖ **Beam-line commissioning w/ low-intensity proton beam, completed**

❖ **Pion Capture and Detector Solenoids, will be installed in 2026**

❖ **Engineering/Physics Runs are expected to start in 2025-2026, after radiation shield construction which leaves uncertainty in schedule.**

Muon g-2 Experiment and SM

Esra Barlas-Yucel
on behalf of the Muon g-2 Collaboration

Lepton Photon 2023
Melbourne
20 July 2023

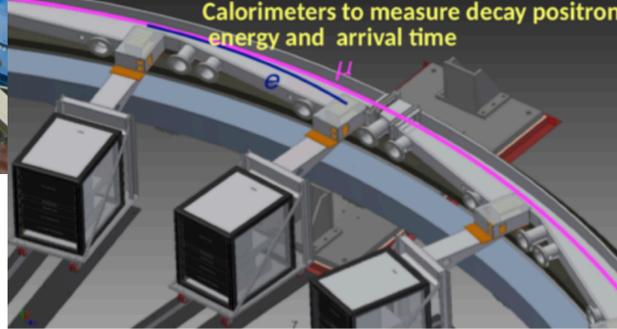# Muon Magnetic Moment and Defining the Anomaly

Magnetic Moment of Muon

$$\vec{\mu} = g_\mu \frac{e}{2m} \vec{s}$$

g: Proportionality constant between spin and magnetic moment

Dirac: g=2
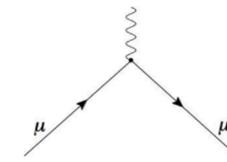
Quantum effects : g>2
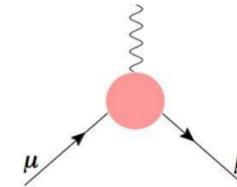
Anomalous Magnetic Moment of Muon

$$a_\mu = \frac{g_\mu - 2}{2}, \qquad \vec{\mu} = (1 + a_\mu)\frac{e}{m}\vec{s}$$

Measuring this anomaly could tell us if there are new particles or even forces that contribute to a_μ

Shows how much g differs fractionally from 2!

$$a_\mu = a_\mu(QED) + a_\mu(EW) + a_\mu(hadronic)$$

QED		+... (5 loops)	$116\,584\,718.9\,(1) \times 10^{-11}$	0.001 ppm
EW		+... x	$153.6\,(1.0) \times 10^{-11}$	0.01 ppm
HVP α^2		+... (NNLO)	$6845\,(40) \times 10^{-11}$ [0.6%]	0.34 ppm
HLbL α^3		+... (NLO)	$92\,(18) \times 10^{-11}$ [20%]	0.15 ppm

40

Detectors : Calorimeters

- **Calorimeters**
  - 24 segmented PbF$_2$ crystal calorimeters stationed around the ring
  - Detects energy and arrival time of e^+ decayed from muons: $\mu^+ \to e^+ \bar{\nu}_\mu \nu_e$

ω_a

SiPMs
6 × 9 segmented array
lead fluoride crystals

laser light calibration system

J. Kaspar
24 calorimeter stations around ring

Running time 00H : 32M : 07s

$5 < t < 100$
$100 < t < 200$
$200 < t < 300$
$300 < t < 400$
$400 < t < 500$
$500 < t < 600$

Entries / 149.2 ns

Time % 100 [μs]

Calorimeters to measure decay positron energy and arrival time

e
μ

$N(t) = N_0 e^{-t/\tau}[1 + A cos(\omega_a t + \phi)]$

$$a_\mu = \left(\frac{g_e}{2}\right)\left(\frac{\omega_a}{\langle\omega_p\rangle}\right)\left(\frac{\mu_p}{\mu_e}\right)\left(\frac{m_\mu}{m_e}\right)$$

BNL g-2

FNAL g-2

4.2σ

Theory Initiative

Standard Model

Experiment average

17.5 18.0 18.5 19.0 19.5 20.0 20.5 21.0 21.5

$a_\mu \cdot 10^9 - 1165900$

FNAL Run-1

New result

Phys. Rev. Lett. 131, 161802

BNL

FNAL Run-1

FNAL Run-2/3

FNAL Run-1 + Run-2/3

Exp. Average

20.0 20.5 21.0 21.5 22.0 22.5

$a_\mu \times 10^9 - 1165900$
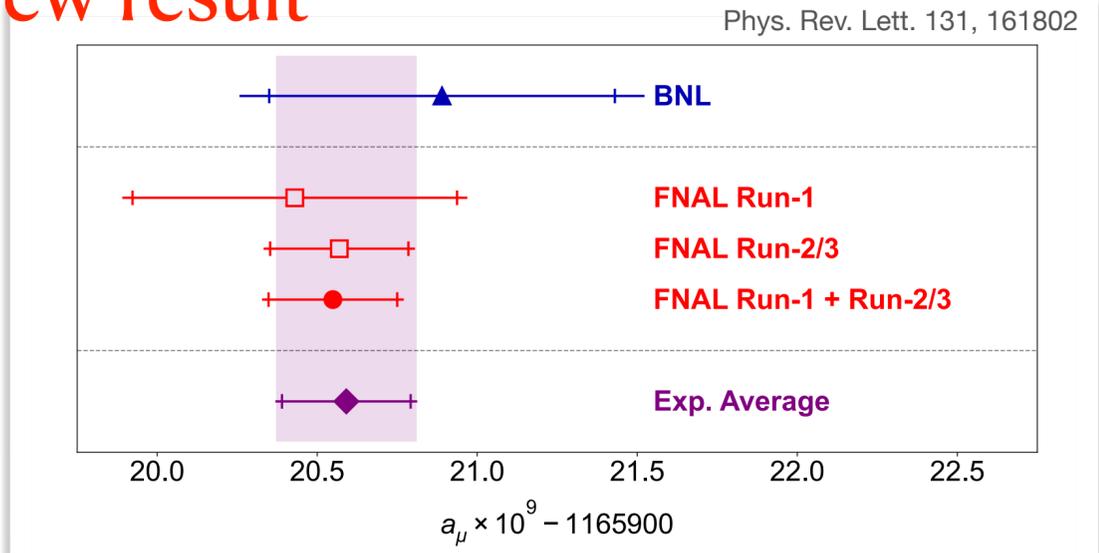
FIG. 3. Experimental values of a_μ from BNL E821 [8], our Run-1 result [1], this measurement, the combined Fermilab result, and the new experimental average. The inner tick marks indicate the statistical contribution to the total uncertainties.

J-PARC Muon g-2 experiment.

- New technology improves both statistical and systematic errors

  - Use ultra-slow muon sources

  - Storage rings about 1/20th of conventional ones

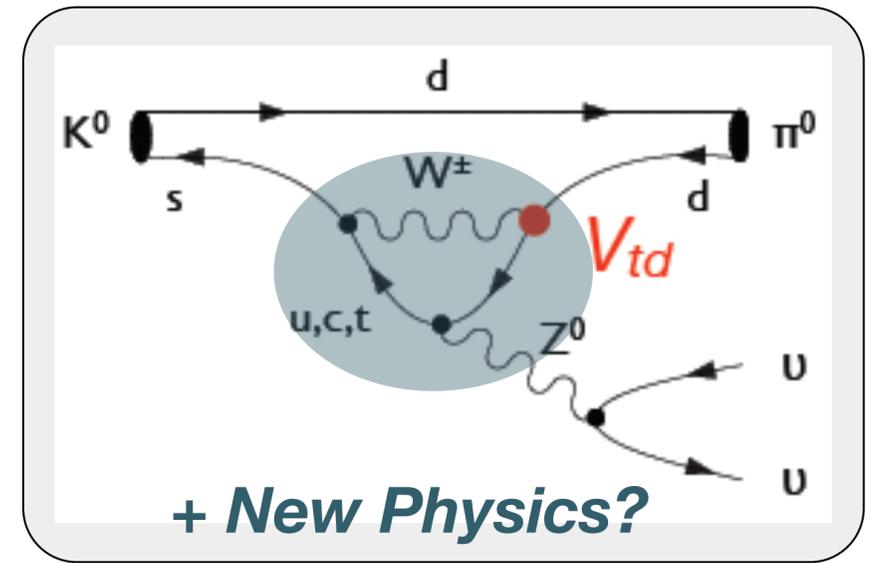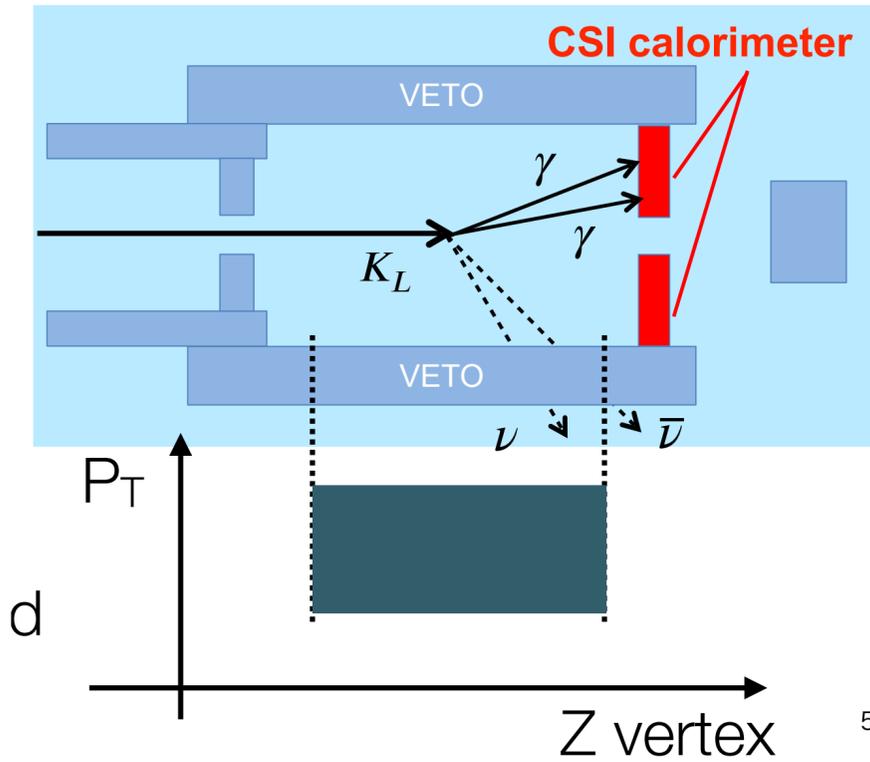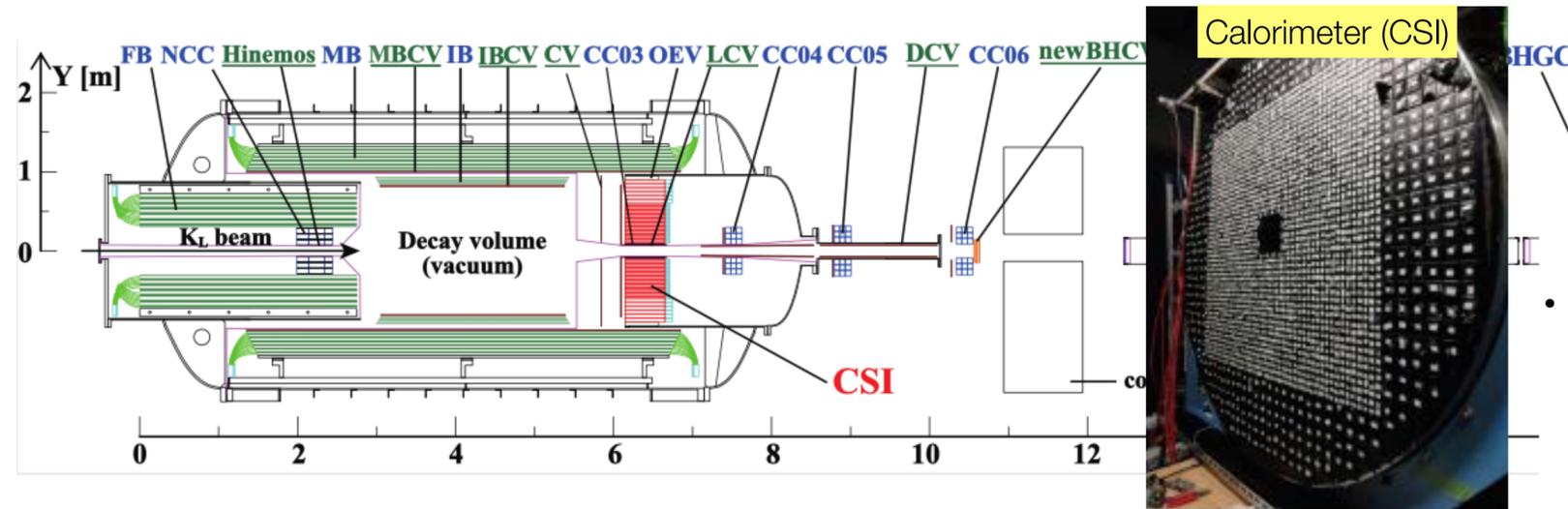 - Ultra-precise electromagnets based on MRI technology

80 cm

New g-2

Ultra Cold μ Beam

Muonium

Laser

Muonium

Surface muon

Proton beam

Ultra cold muon beam (μ+ 10^6/sec)

(3 GeV, 1MW)

Surface Muon (~30 MeV, 4×10^8/s)

Muon accelerator (300 MeV/c)

42

Other targets

Standard Model

V_{td}

+ New Physics?

K rare decay at J-PARC

KOTO detector

Front Barrel (FB)

Main Barrel (MB)

NCC

meter + Hermetic veto system

(NCC)

Main barrel (MB)

Charged veto (CV)

~2 m

Vertex calculation

pi0nunu/pi0nunu/pi0nunuann08_100.root

P_t

π^0

Z Vertex

CSI calorimeter

VETO

γ

γ

K_L

VETO

ν

$\bar{\nu}$

Reconstructed Pt [MeV/c]

Z Vertex

P_T

Reconstruc

d

P_T

Z vertex

Fig. 2.3 $K_L^0 \rightarrow \pi^0 \nu\bar{\nu}$ 分布。赤枠で囲まれた部分を信号事象と同定する。横軸の 0 は Front Barrel(§2.6.1) の上流端。

Fig. 2.2 $K_L^0 \rightarrow \pi^0 \nu\bar{\nu}$ からの π^0 の再構成。

FB NCC Hinemos MB MBCV IB IBCV CV CC03 OEV LCV CC04 CC05 DCV CC06 newBHCV

Y [m]

K_L beam

Decay volume (vacuum)

CSI

Calorimeter (CSI)

BHGC

2.3 バックグラ

実験のバ
は K_L^0 自体か

された 4 つの γ の
ムコア周りに存在す
物質と相互作用し、
B.G. について簡単

2.3.1 K 中間子 B.

Table2.1 に K_L^0
り得る。以下、各モ

by T. Nomura @37th J-PARC PAC

$\bar{\nu}$

- **No signal candidates** were observed in the signal region.

- Set the upper limit to be
  BR($K_L \rightarrow \pi^0 \nu\nu$) < 2.0×10⁻⁹
  at 90% confidence level.
  - Corresponding to SES×2.3 based on Poisson statistics.

KOTO 2021 Data

Rec. π^0 P_T (MeV/c)

215   0   0

0

0   0

Rec. π^0 Z_{vtx} (mm)

Preliminary

5
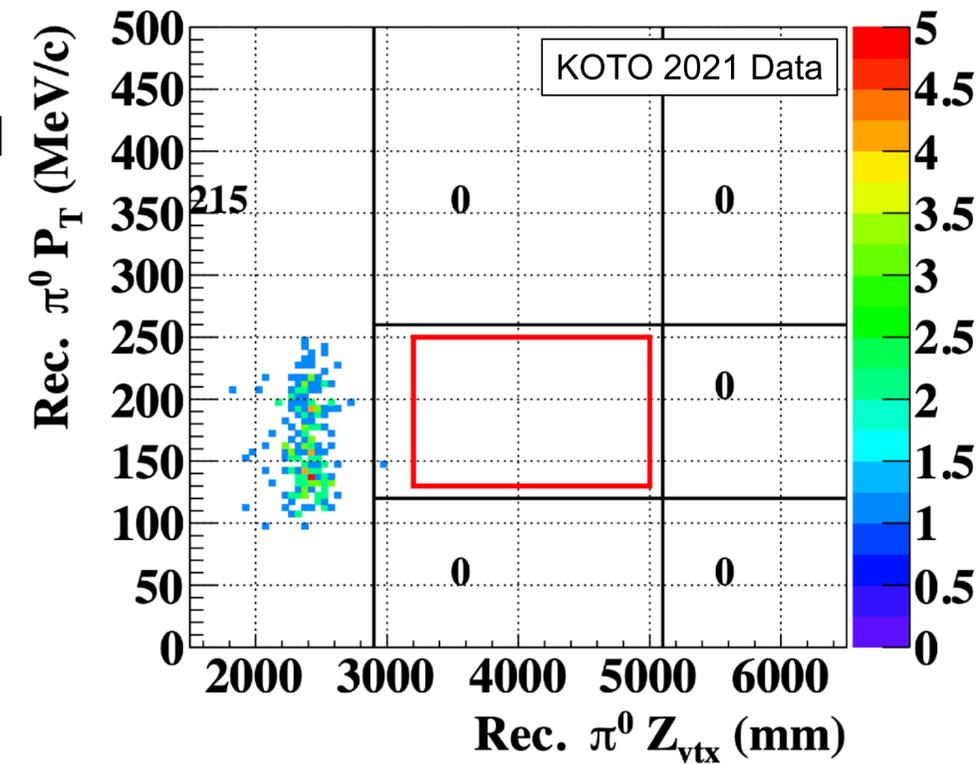
CERN NA62: Search for K⁺→π⁺νν

Dark boson searches at CERN's North Area

With their latest dark-matter searches, both the NA62 and NA64 experiments start probing several well motivated light dark-matter models

21 AUGUST, 2023 | By Kristiane Bernhard-Novotny

The NA62 (left) and NA64 (right) experiments at CERN's North Area.

Located at CERN's North Area and receiving beams from the Super Proton Synchrotron (SPS), the NA64 and NA62 experiments search for dark matter, complementing searches at the LHC, as they cover a different energy range. Both experiments recently published new results.

Related Articles

NA62 sees first significant evidence of rare ...
Physics | News | 12 August, 2020

NA62 spots two potential instances of rare pa...
Physics | News | 23 September, 2019

CERN's SPS experiments restart
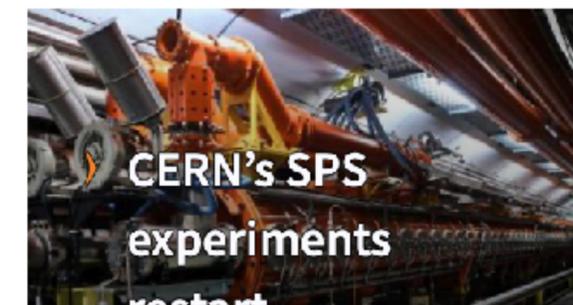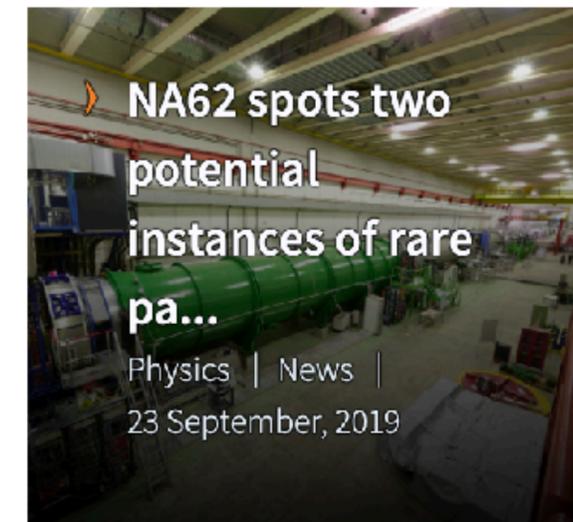
FASER experiment

FASER is a new forward experiment of LHC, located 480 m downstream from the ATLAS IP. Successfully started data taking in Run 3 from July 2022 for:

- Search for new weakly-coupled particles in the MeV-GeV range
  - proposed to CERN in 2018, approved by CERN in 2019

- Study of all flavors of neutrinos at the TeV-energy frontier
  - proposed to CERN in 2019, approved by CERN in 2020

ν_e , ν_μ , ν_τ,

A', a, mCPs, DM, …

ν_e , ν_μ , ν_τ,

A', a, mCPs, DM, …

TI12 tunnel
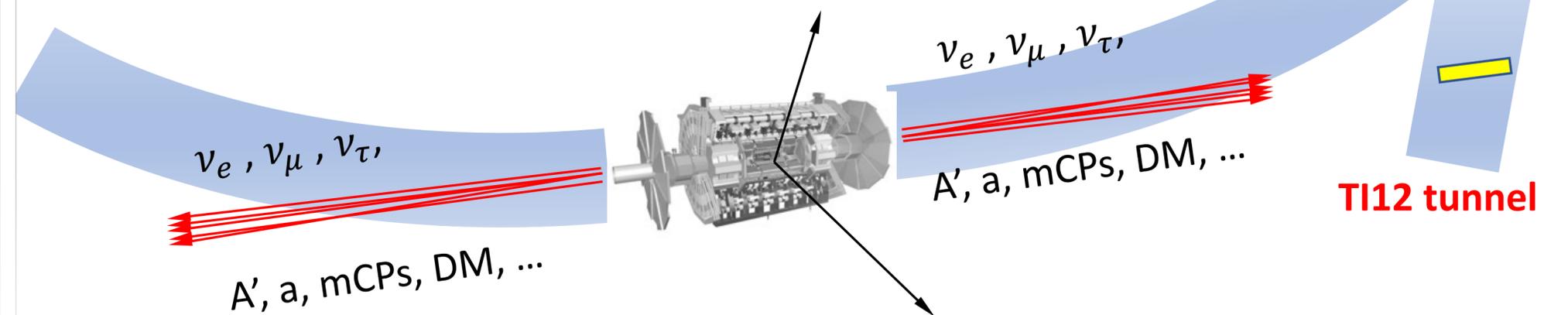
Favorable location, except that refurbishment is needed to be an experimental site.

- Background from collision point is only high-energy muon at about 1 /cm^2/sec, thanks to ~100-m rock

- Radiation level from LHC is quite low, around 4×10^{-3} Gy/year (= 4×10^7 *1*-MeV neutron/cm^2/year)

5

by H. Otono @ Kyoto seminar 2023

FASER detector

Target for neutrino

Decay volume of new particles

A′

ν

Scinti.
Emulsion/Tungsten
Silicon
Scinti.
Magnet
Scinti.
Silicon
Magnet
Silicon
Magnet
Silicon
Scinti.
Calo.

For neutrino physics:
Installation completed 2022 March

For new particle search:
Installation completed 2021 March

12

48
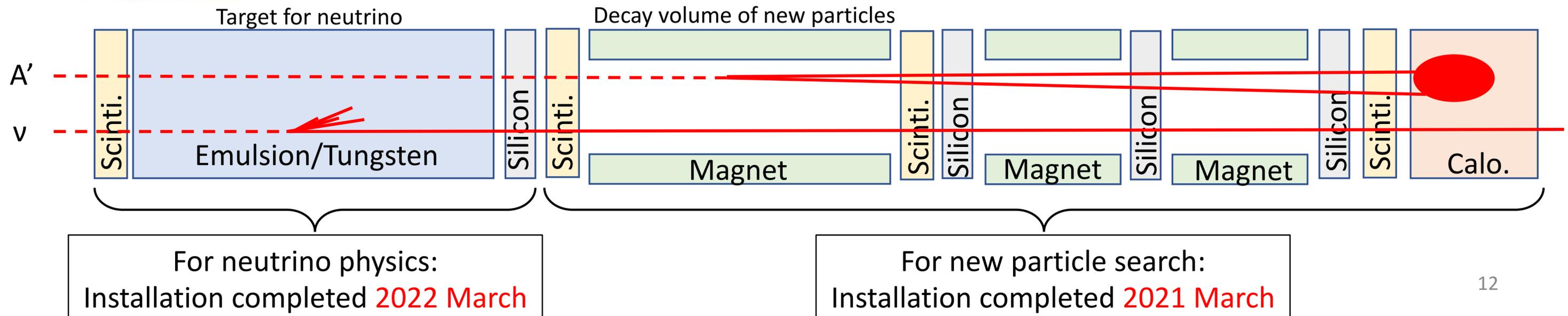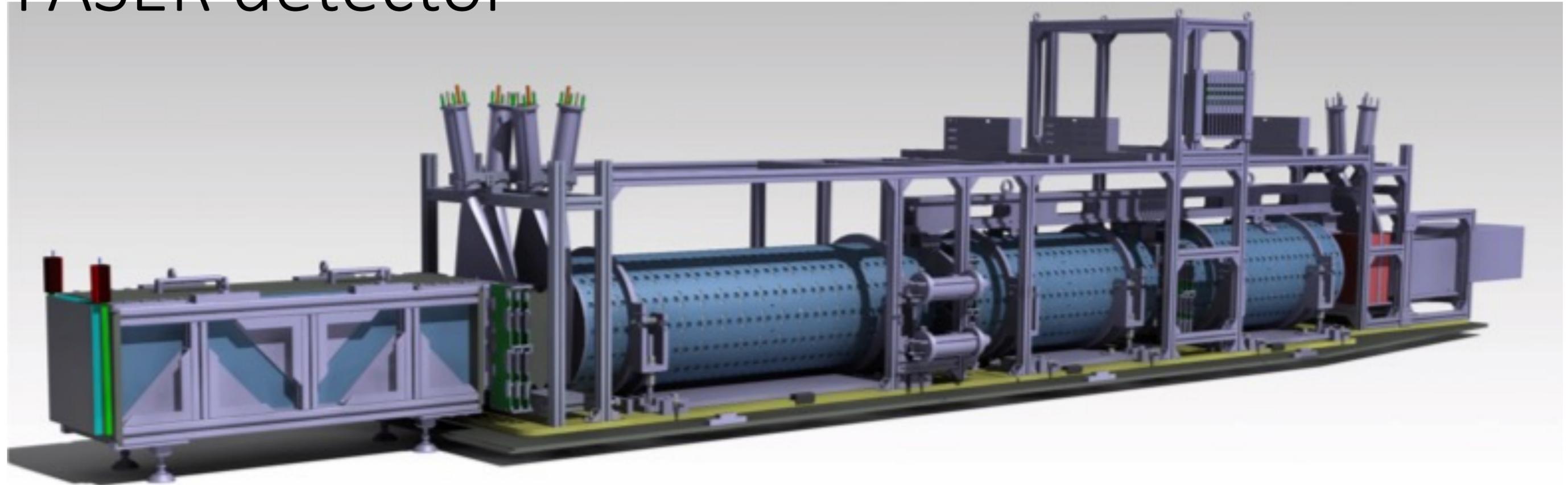
Motivated by dark matter

- Example is a dark photon (A') – vector portal to dark sector

- Could be produced very rarely in decay of a π^0

- Could be long-lived due to small coupling constant

No events seen in unblinded signal region

- Total background: **0.0020±0.0024 evts**,
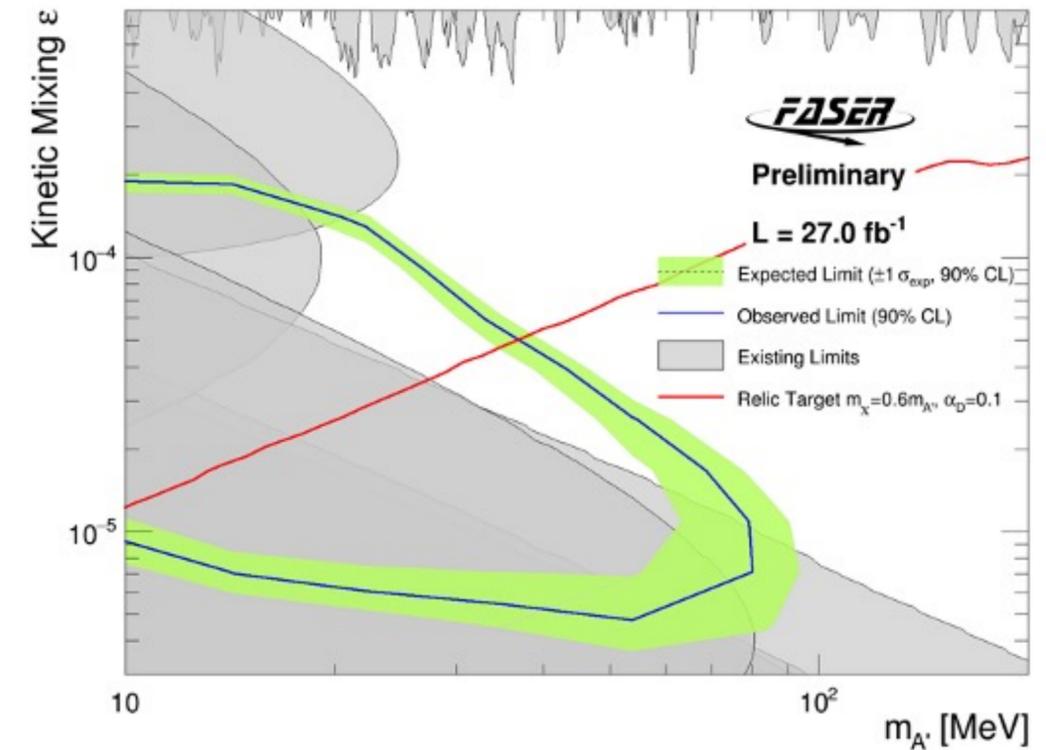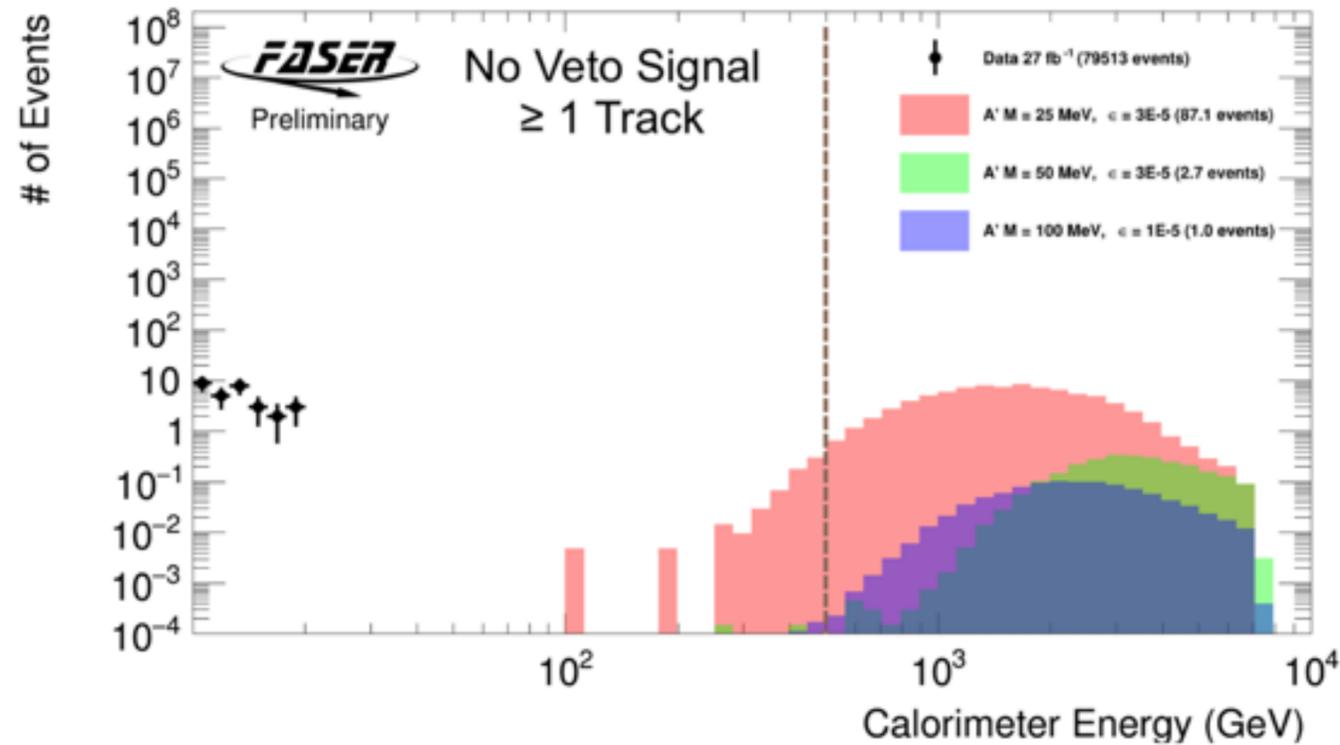
by H. Otono @ Kyoto seminar 2023

SND   First results from SciFi/Silicon tracking devices   **Faser-ν**
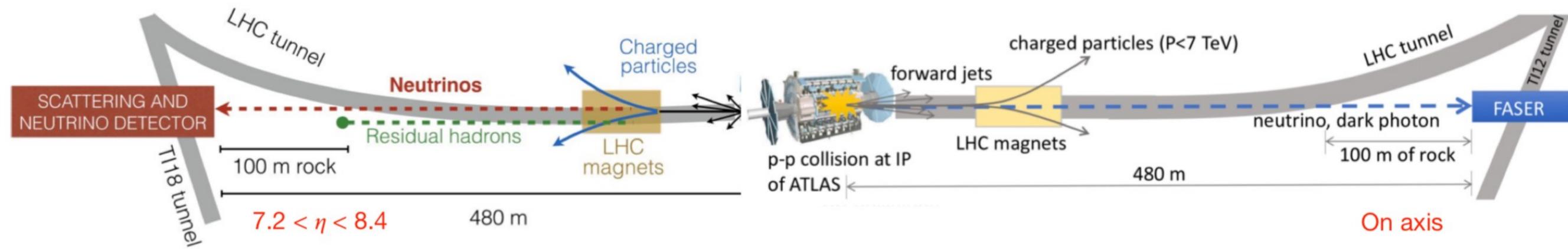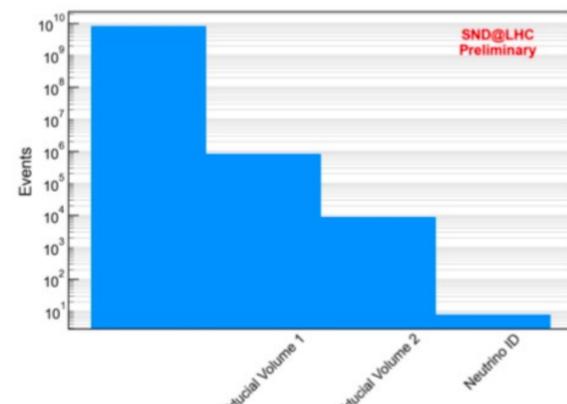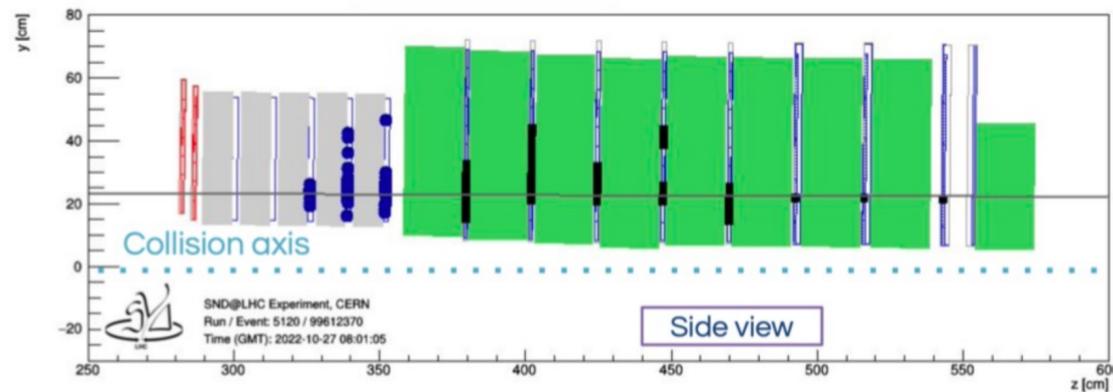
5 events expected and 8 observed (0.2 background)
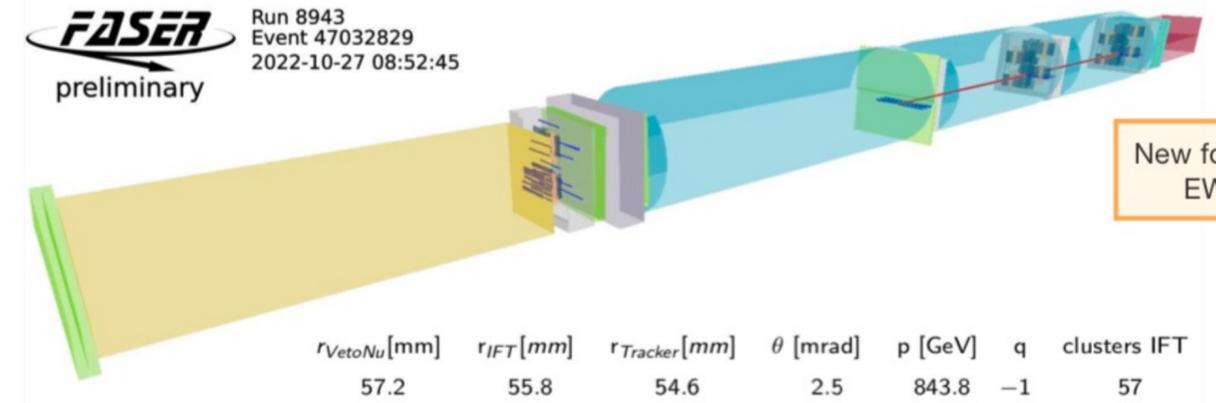
150 events expected and 153 observed (0.2 background!!)

Approximately 5σ observation!
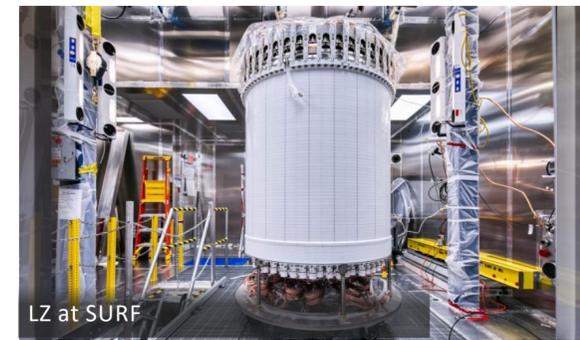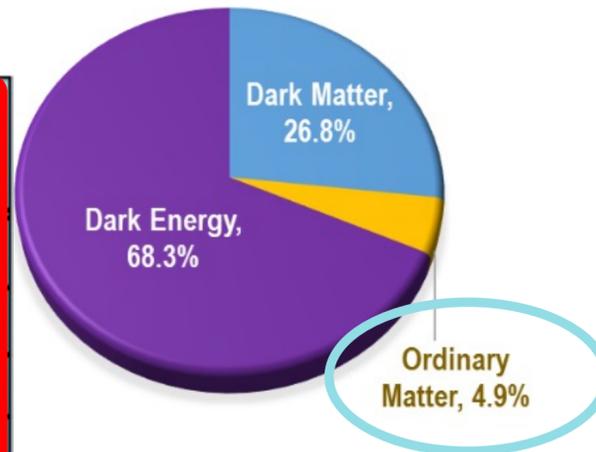
16σ observation!
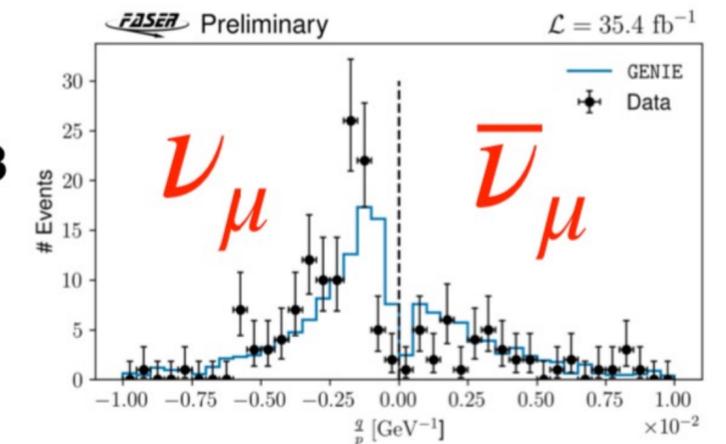
3. Cosmic Frontier

Dark Energy

Cosmic Frontier Experiments

- **Cosmic Frontier experiments** address four of five science drivers
- They use naturally occurring sources to determine the fundamental nature of matter, energy, space and time.


	Energy Frontier	Intensity Frontier	Cosmic Frontier
Higgs Boson	●		
Neutrino Mass		●	●
Dark Matter	●	●	●
Cosmic Acceleration			●
Explore the Unknown	●	●	●

Dark Matter, 26.8%

Dark Energy, 68.3%

Ordinary Matter, 4.9%

LZ at SURF

Legacy Survey of Space and Time at Vera Rubin Observatory

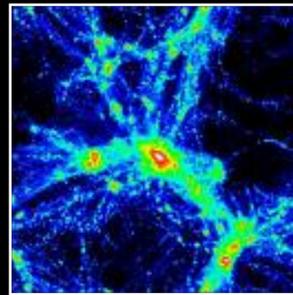South Pole Telescope

AMS at ISS

DESI at Kitt Peak
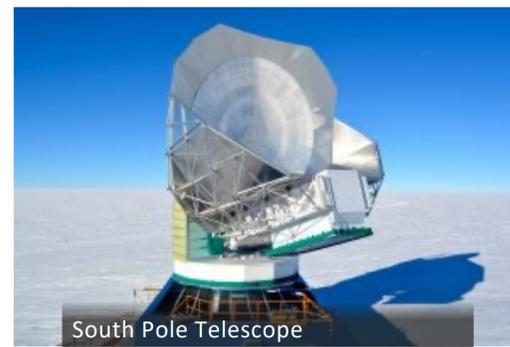
- Partnerships w/NSF (PHY, AST, OPP) NASA (AST, ISS, CLPS) are essential

Evidence of Dark Matter

OBSERVATIONS
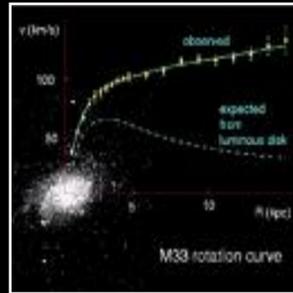
- Rotation Curves
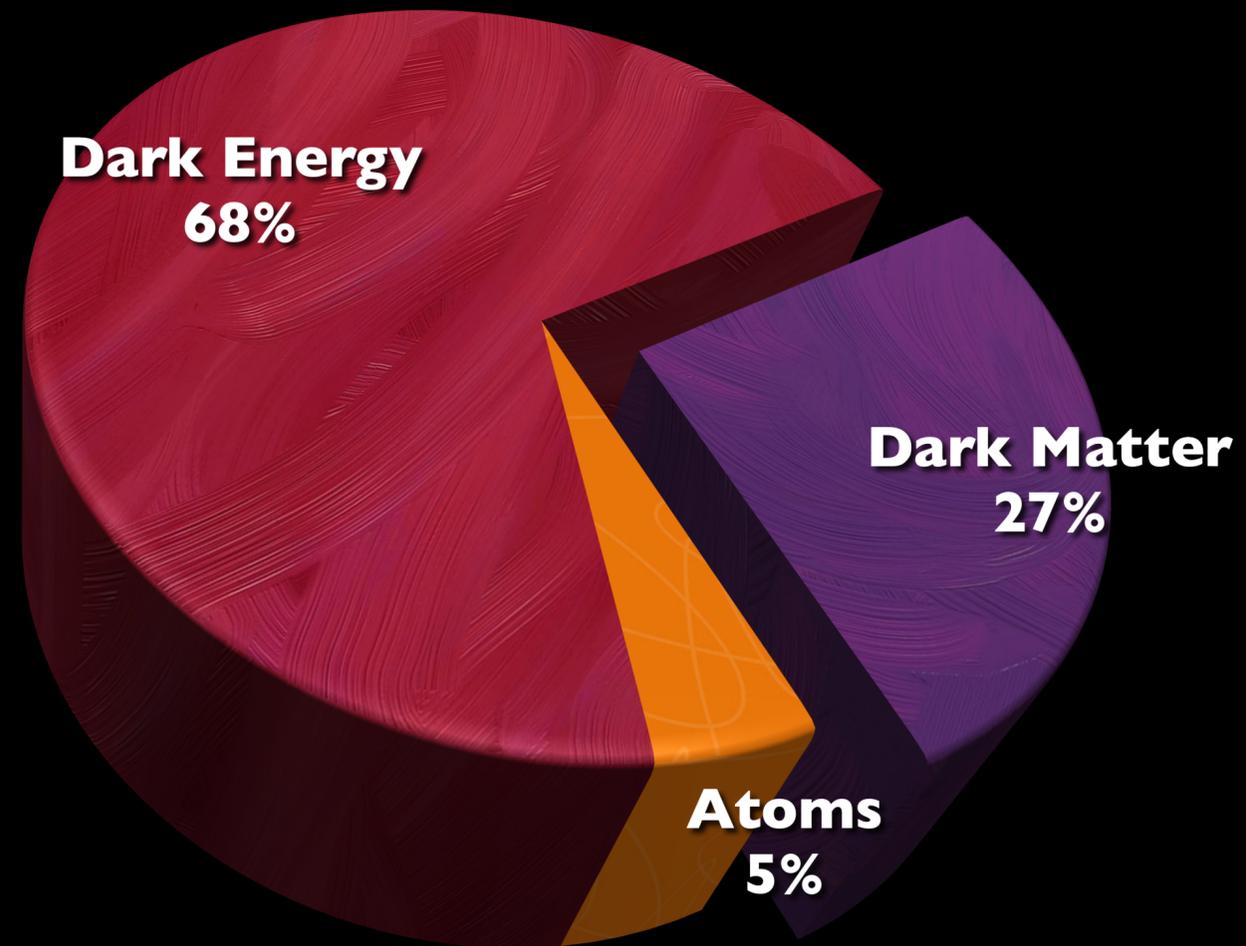
- Clusters of galaxies
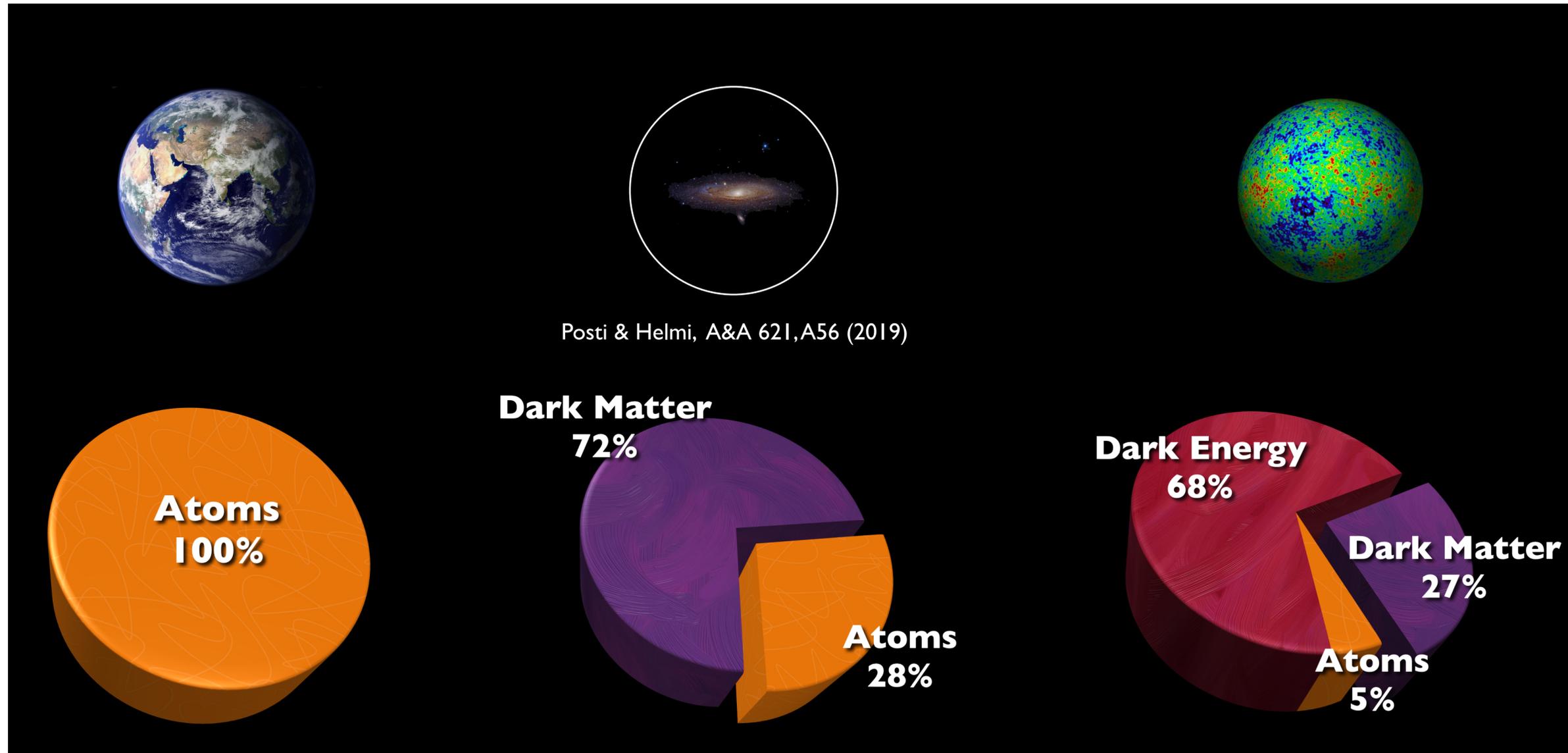
- CMB

- Type Ia Supernovae

...

Dark Energy 68%

Dark Matter 27%

Atoms 5%
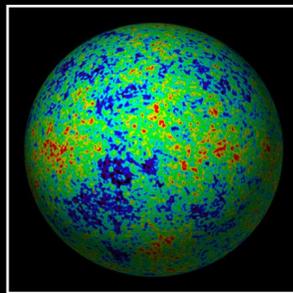
[statement valid *now*, and on *very large scales*]

by G. Bertone @ICHEP2022

Where are the dark matters?

Posti & Helmi, A&A 621, A56 (2019)

Atoms 100%

Dark Matter 72%

Atoms 28%

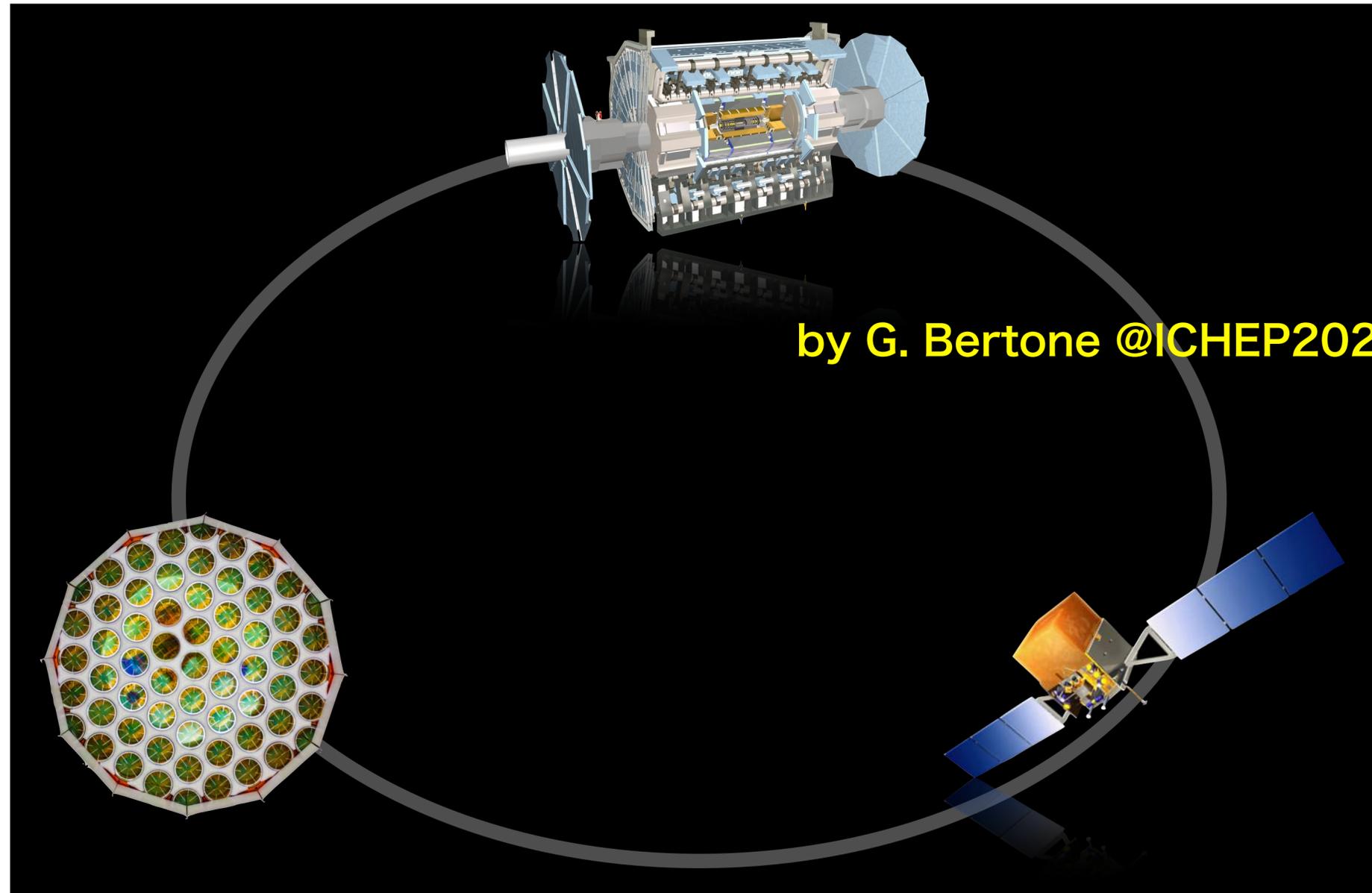Dark Energy 68%

Dark Matter 27%

Atoms 5%

by G. Bertone @ICHEP2022

What are the dark matters?
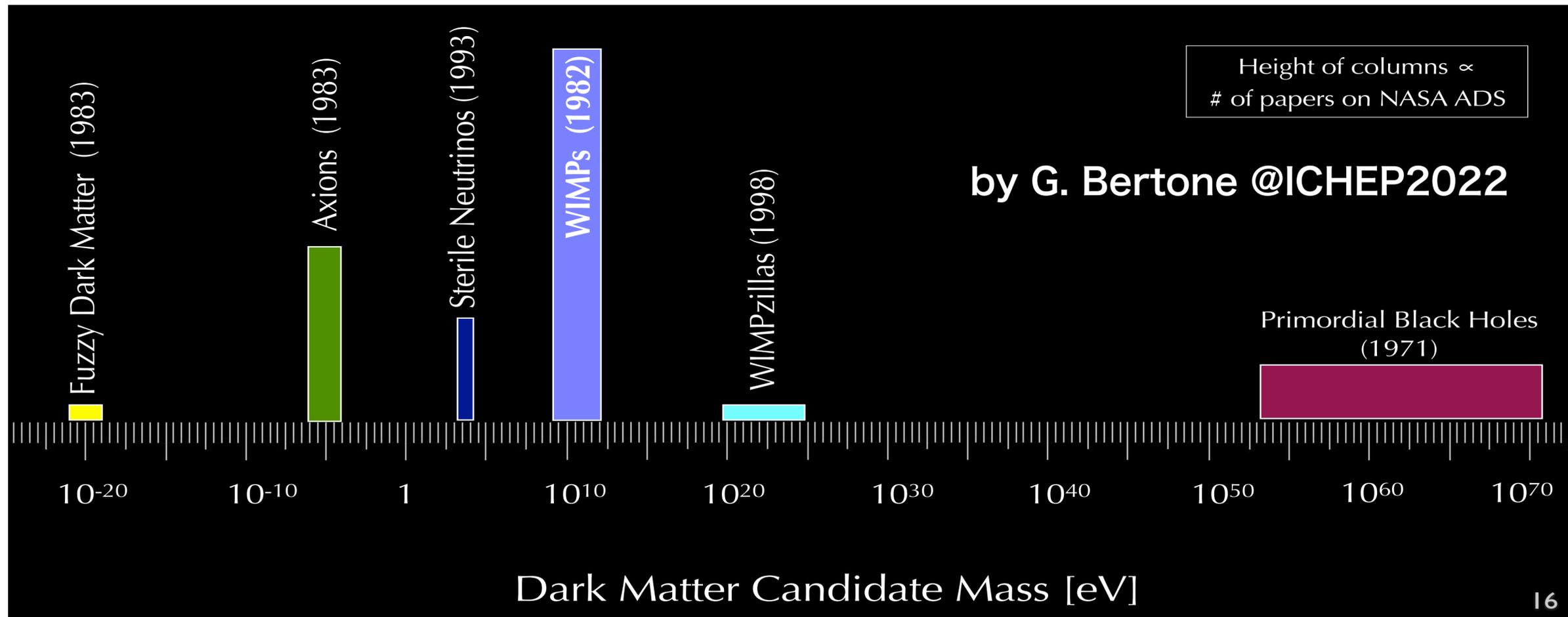
- Primordial Black Holes
- Weakly Interacting Massive Particles（WIMP）
- Sterile Neutrinos
- Axions
- others

How to find dark matters

by G. Bertone @ICHEP2022

- produce them by accelerators
- look for them by underground experiments
- search for their annihilation signal by satellite and observatory

How to find dark matters
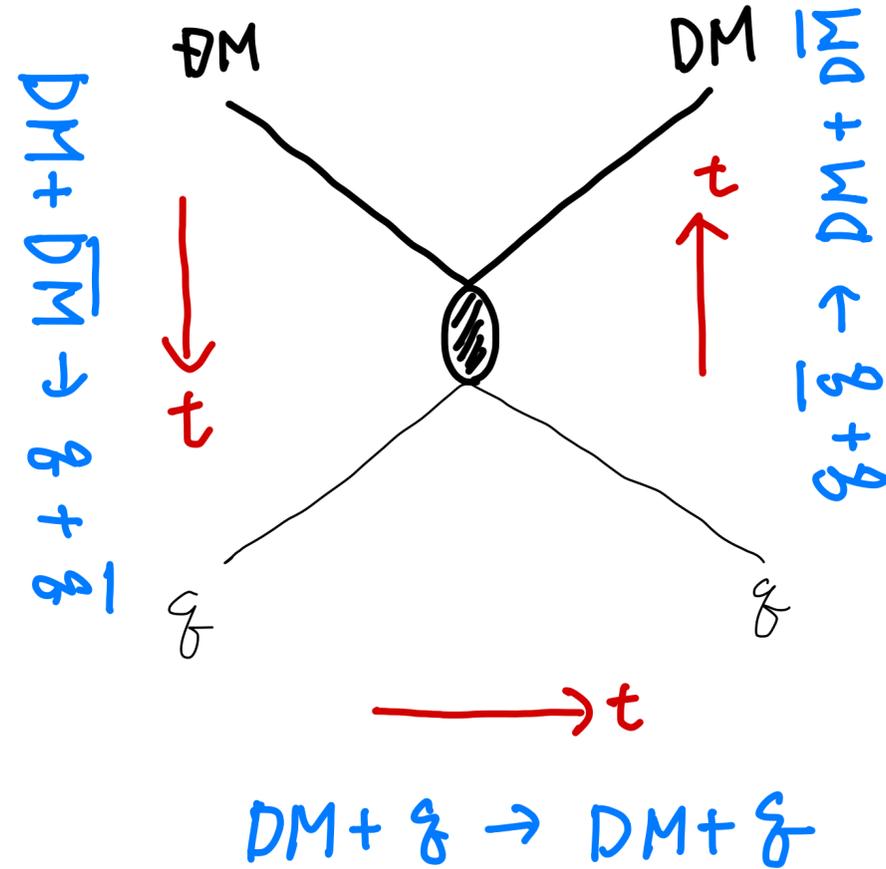
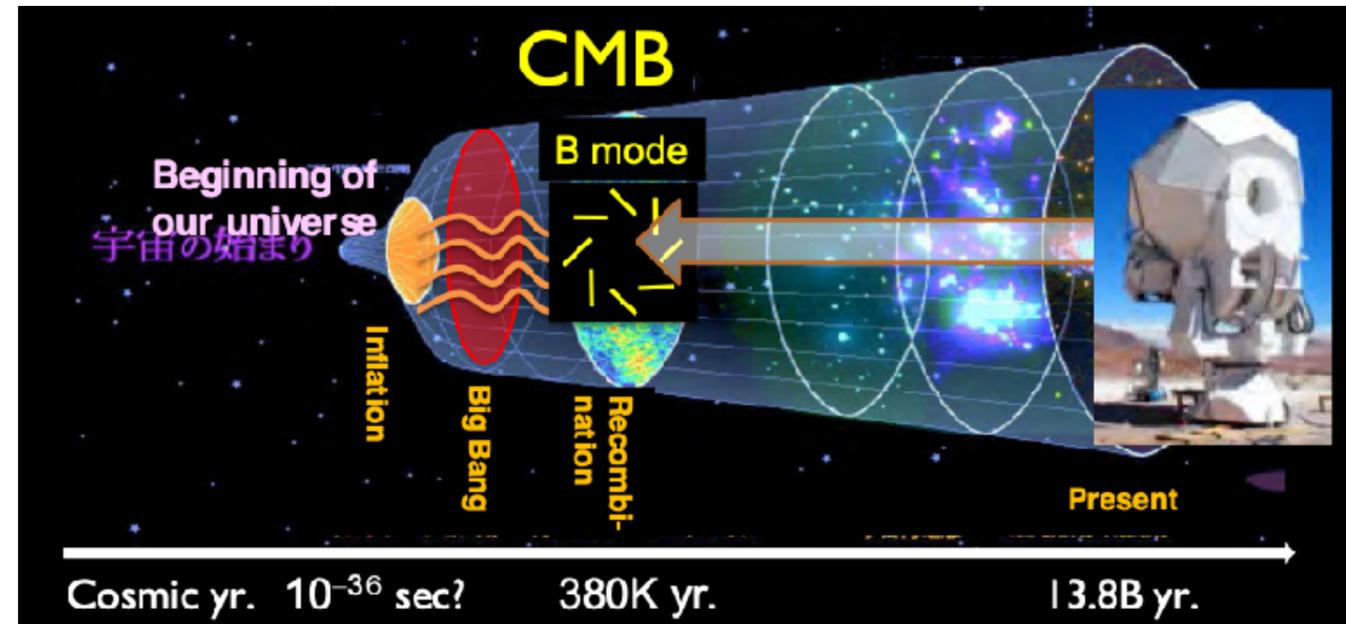- produce them by accelerators
- look for them by underground experiments
- search for their annihilation signal by satellite and observatory

CMB
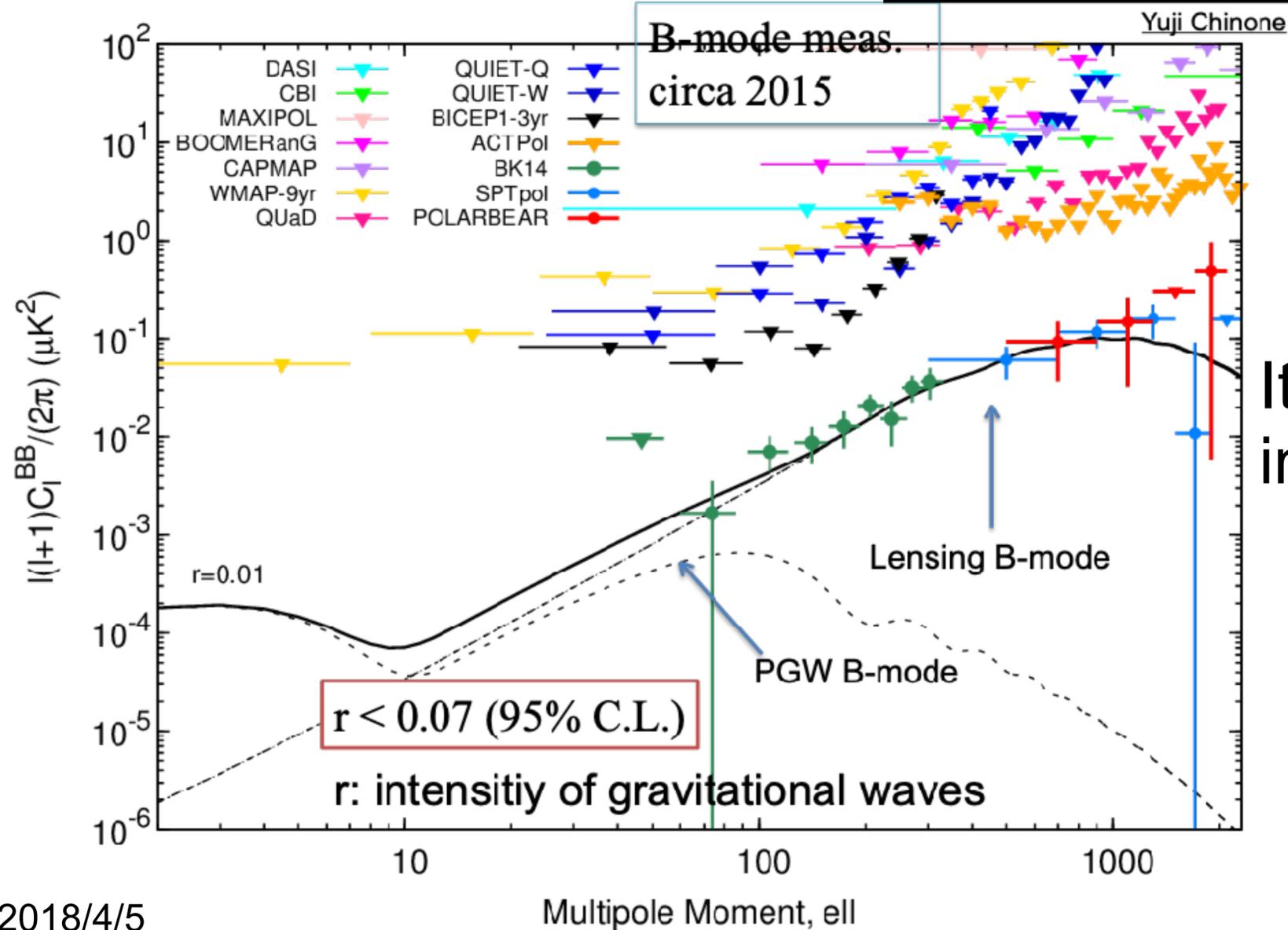
It may be an interesting dark-horse.

Message to you

- There are many types of high energy experiments with various phases.
    - Large-scale international collaboration to small (medium?) size collaboration
    - Often long term projects with different phases
        - Ideas are generated
        - Construction phase
        - Initial data commissioning
        - Stable data taking
        - Analysis phase
        - Upgrade phase

- Please consider
    1. What type of physics are you most interested in?
    2. What kind of experiences would you like to havt?
    3. What problem will you want to tackle?
    4. Enjoy the experiment with your friends.

Trust your own senses as a scientist!

Summary of High Energy Experiments

I did not cover
- neutrino experiments
- future projects
- Specific Cosmic Frontier experiments
- new types of experiments using quantum technology

Bias towards experiments involving the Japanese HEP community

Energy Frontier

LHC/ATLAS and CMS
(ILC)

Intensity Frontier

B-Factory
Neutrino（T2K, SK, KamLAND, etc.）

K aon（K⁰TO, etc.）, Dark particles

μ, neutron, proton decay, ・・・

τ・charm Factory

Cosmic Frontier

Neutrino
Dark Matter
Dark Energy
CMB