Overview of High Energy Experiments

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2024.7.17-18 @ VSON2024, Quy Nhon

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

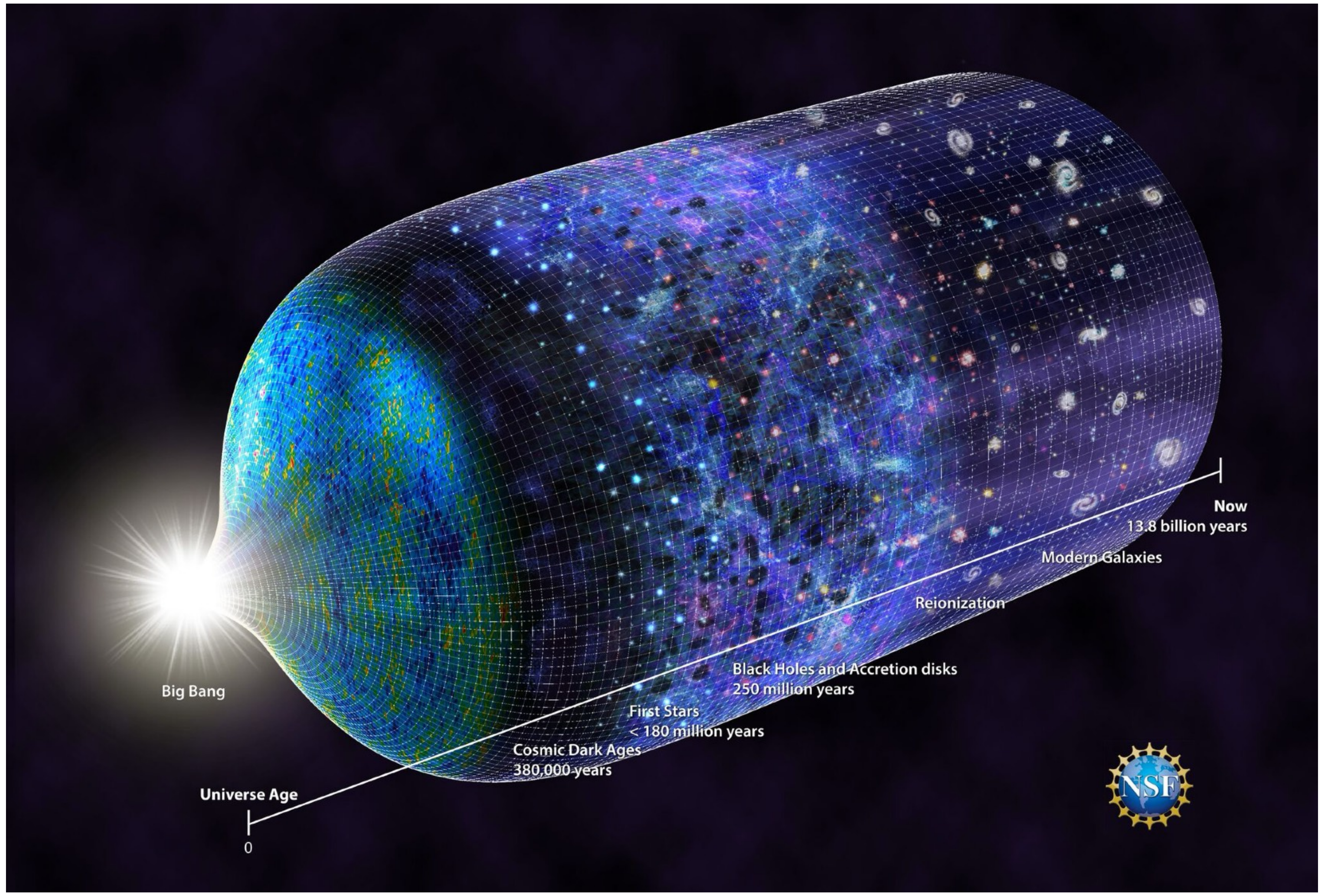
High Energy Physics

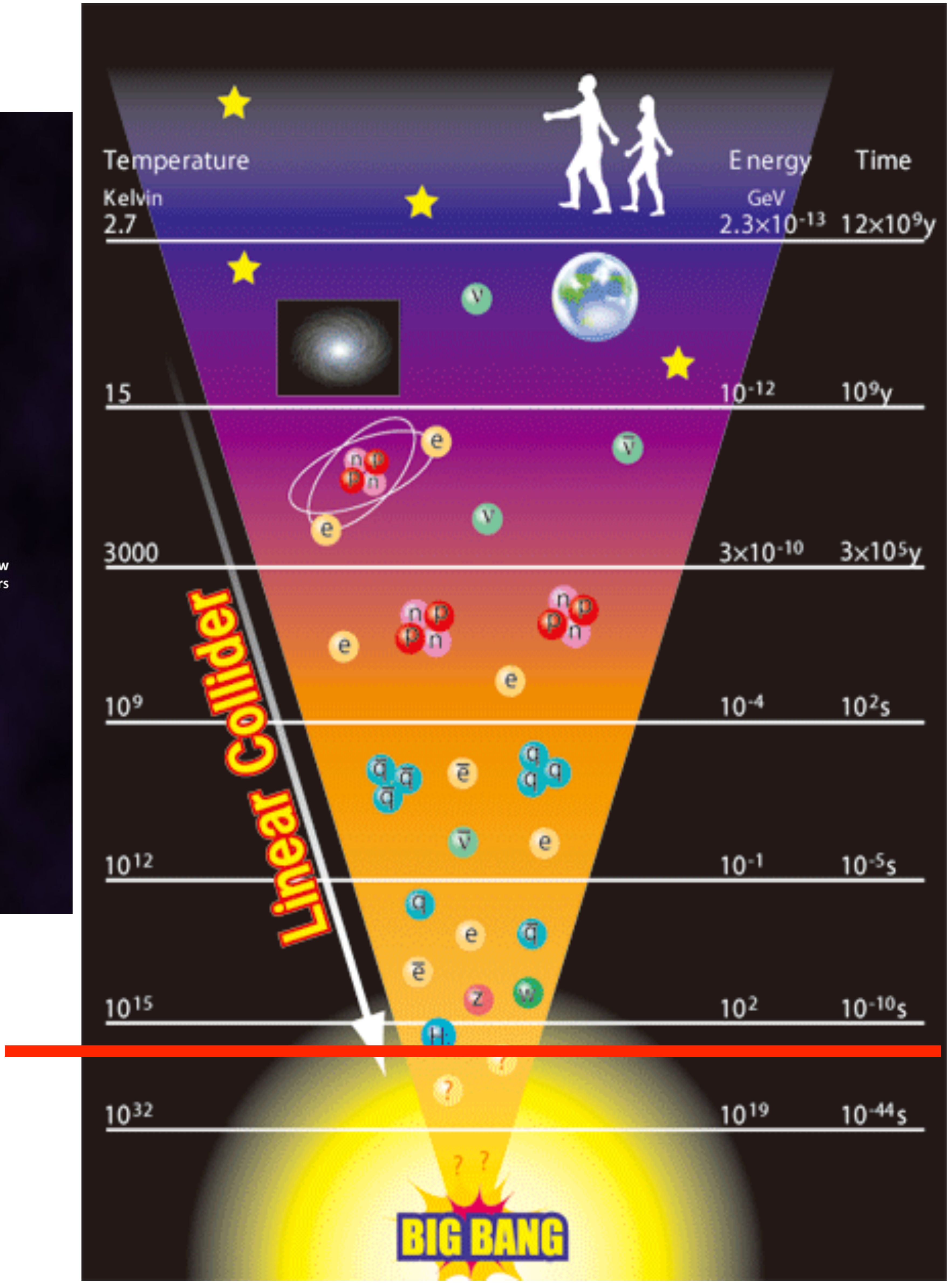
- **Study the ultimate building blocks of the universe and matter.**
  - What is matter made of? What exists in the universe? What are the properties of those components? How do they interact?
  - Standard Model of Particle Physics: quarks, leptons, gauge particles, Higgs boson.
  - Unknown entities: 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!

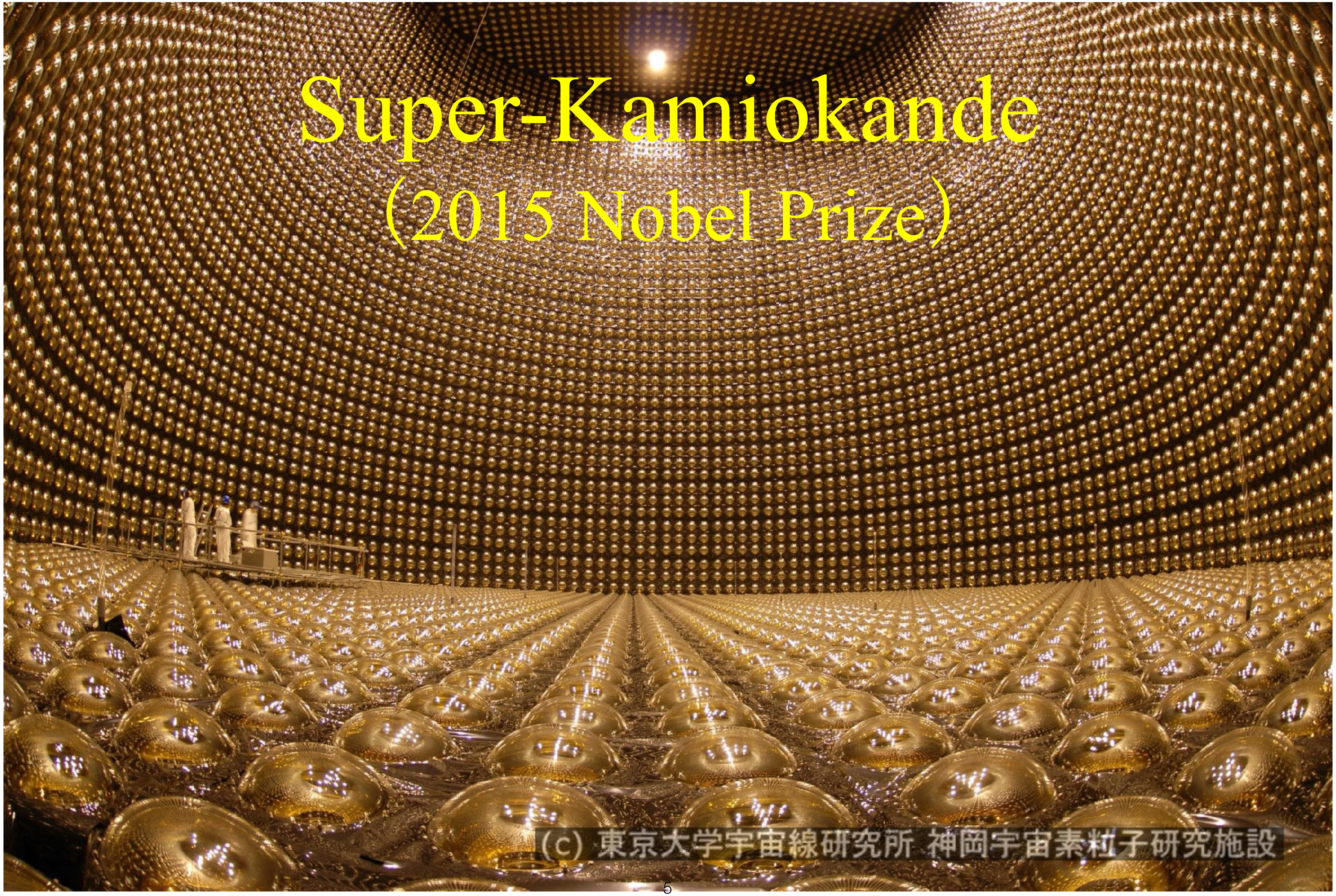
After the birth of the universe (after the Big Bang), to a world of 10^{-10} (0.1 nano) seconds.





Super-Kamiokande

（2015 Nobel Prize）



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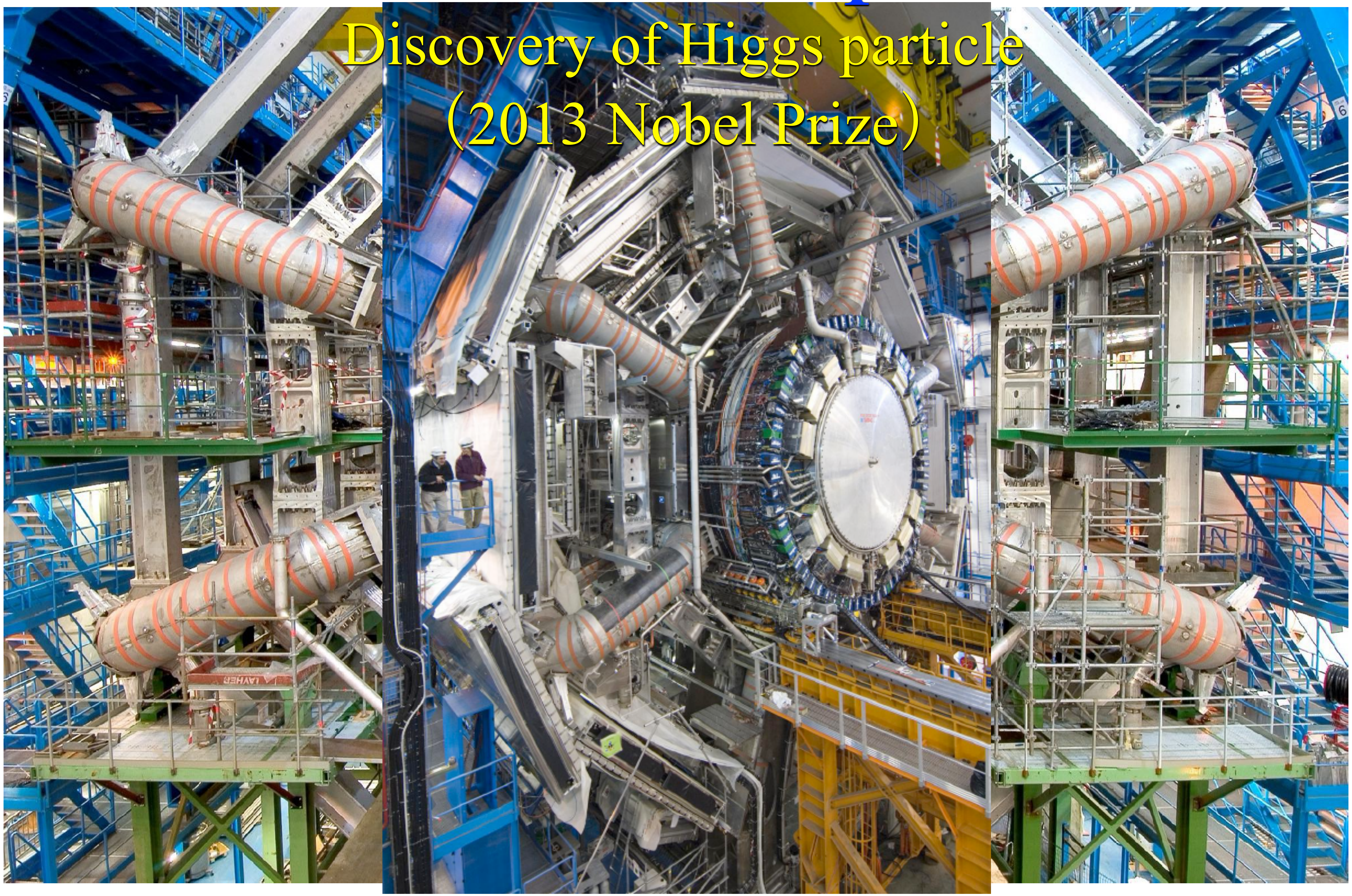
LHC/ATLAS Experiment



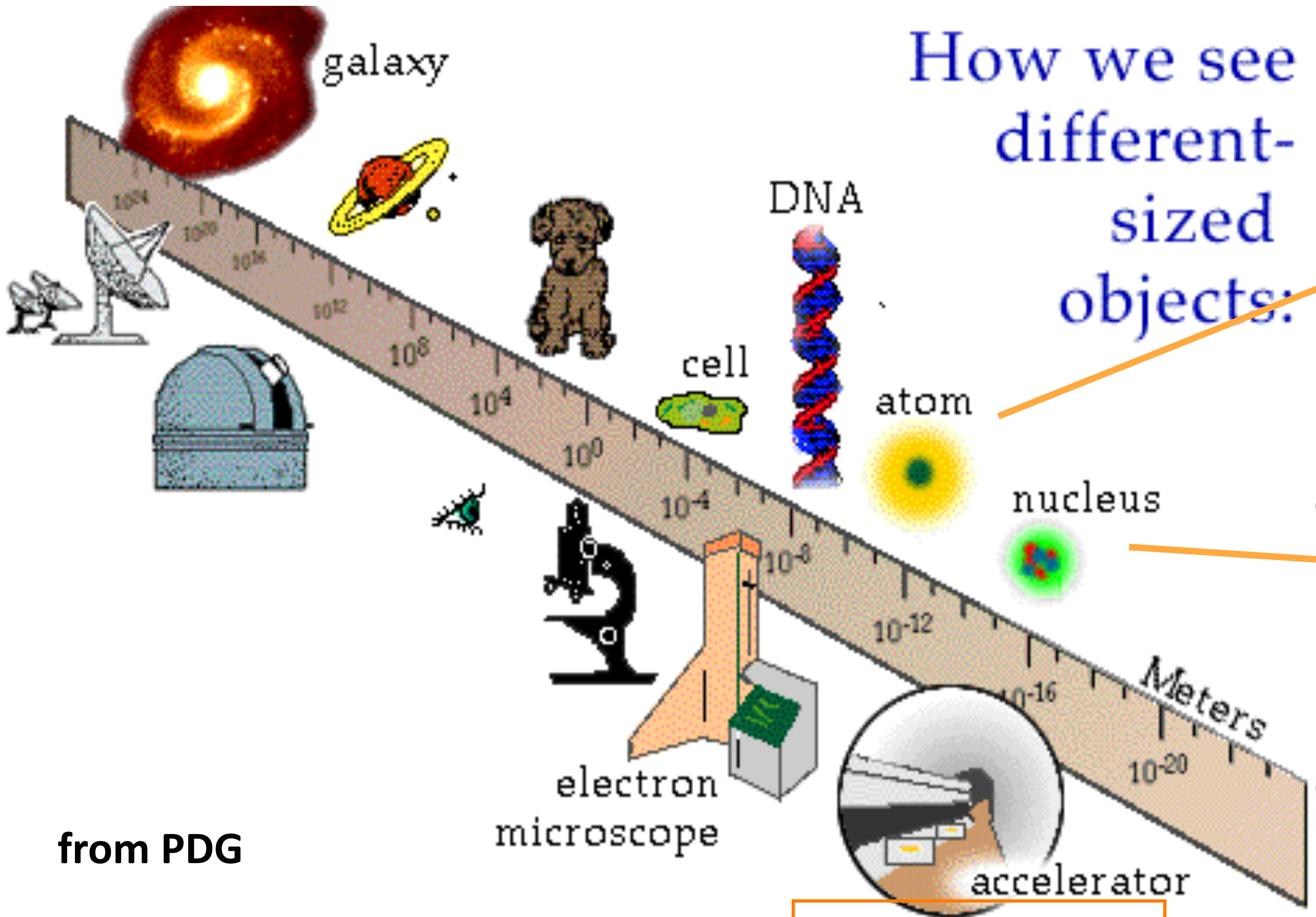
Discovery of Higgs particle

（2013 Nobel Prize）

Particle Physics

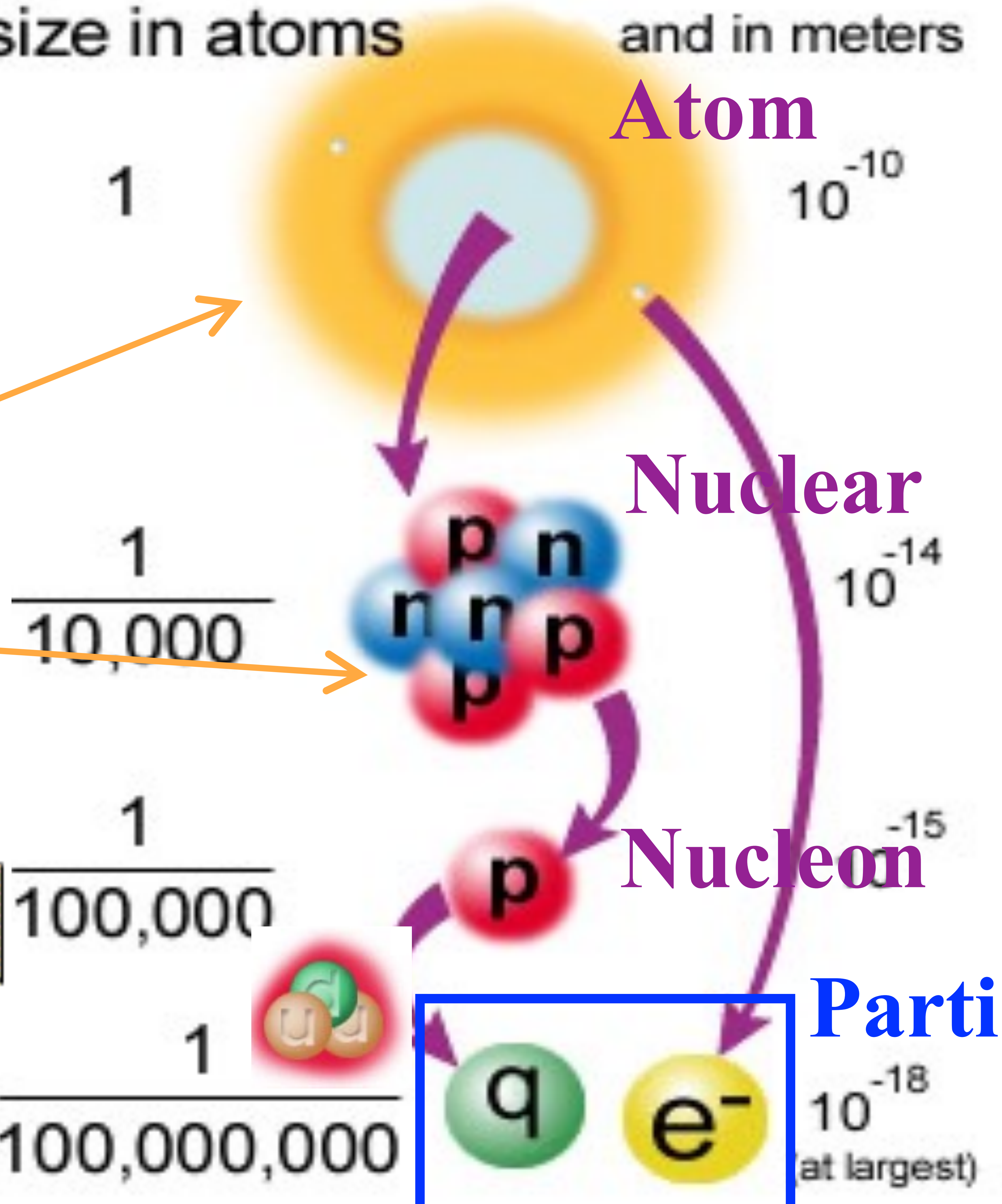
100,000,000,0000,
000,000,000,000m

How we see different-sized objects:



from PDG

0.000000000
0000000001m



Atom

Nuclear

Nucleon

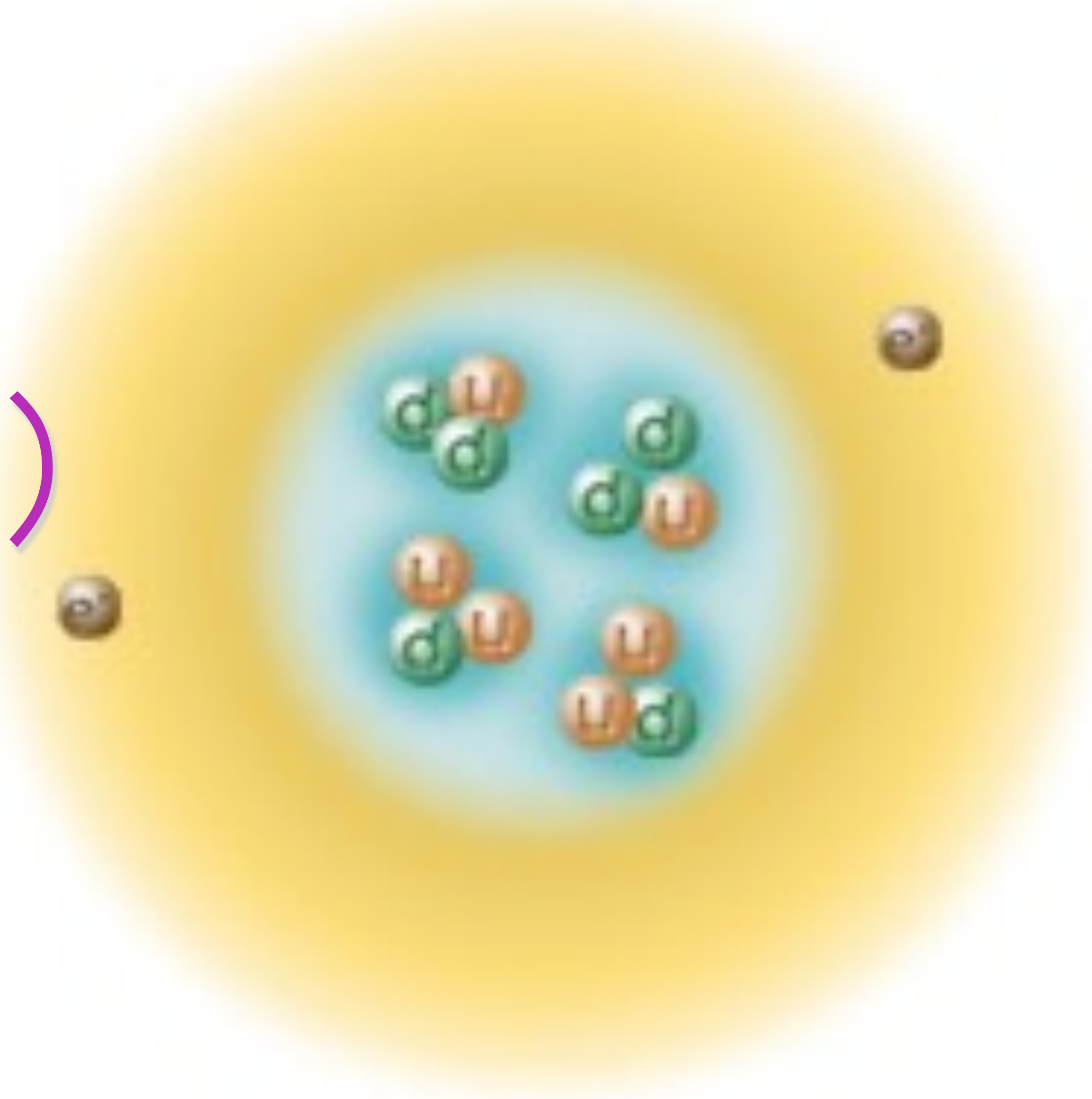
Particle

Quark and Lepton

from PDG

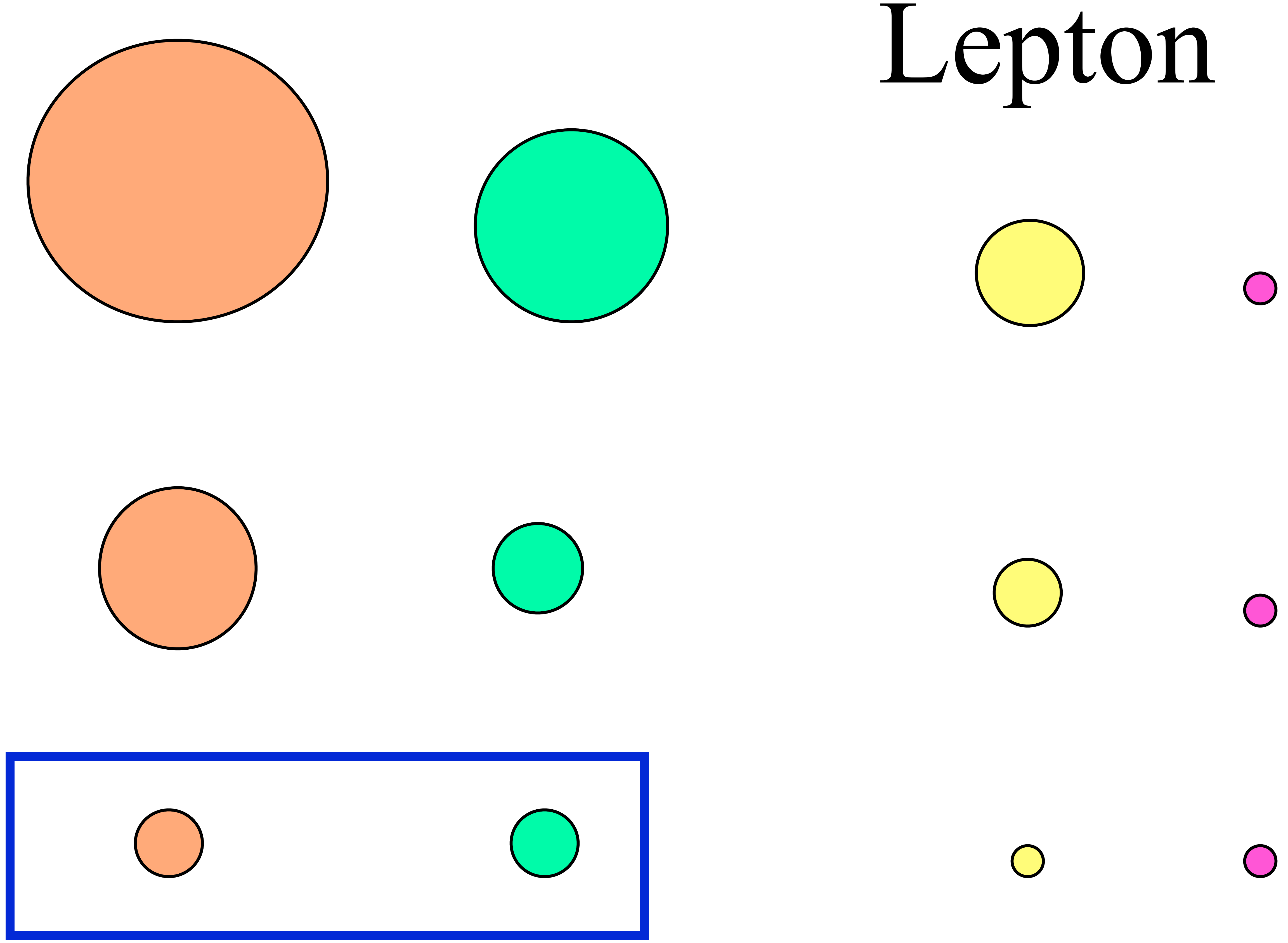
Quark and Lepton

×2　（Antiparticles）



Quark

Lepton

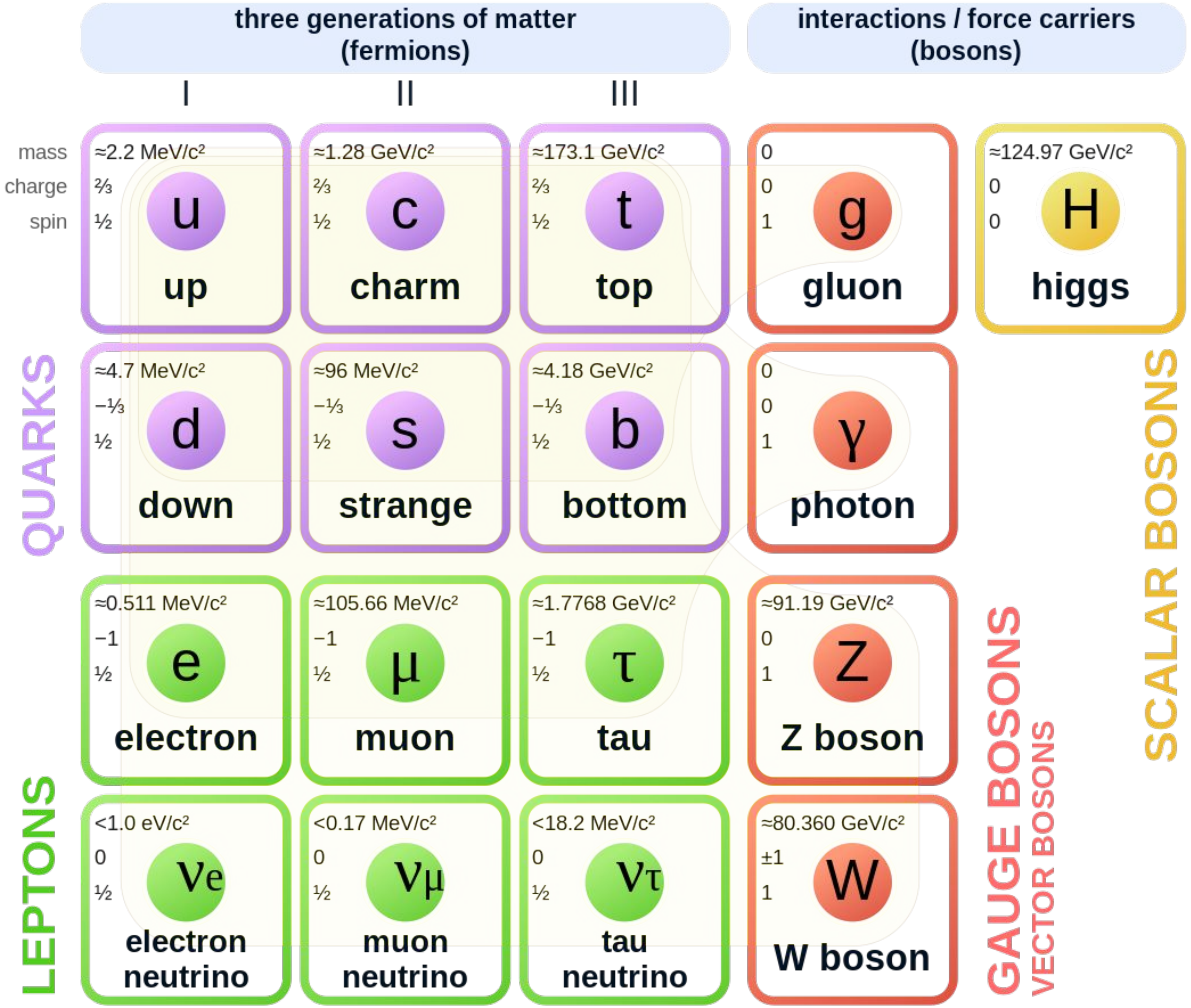


Neutrino

uud(proton)

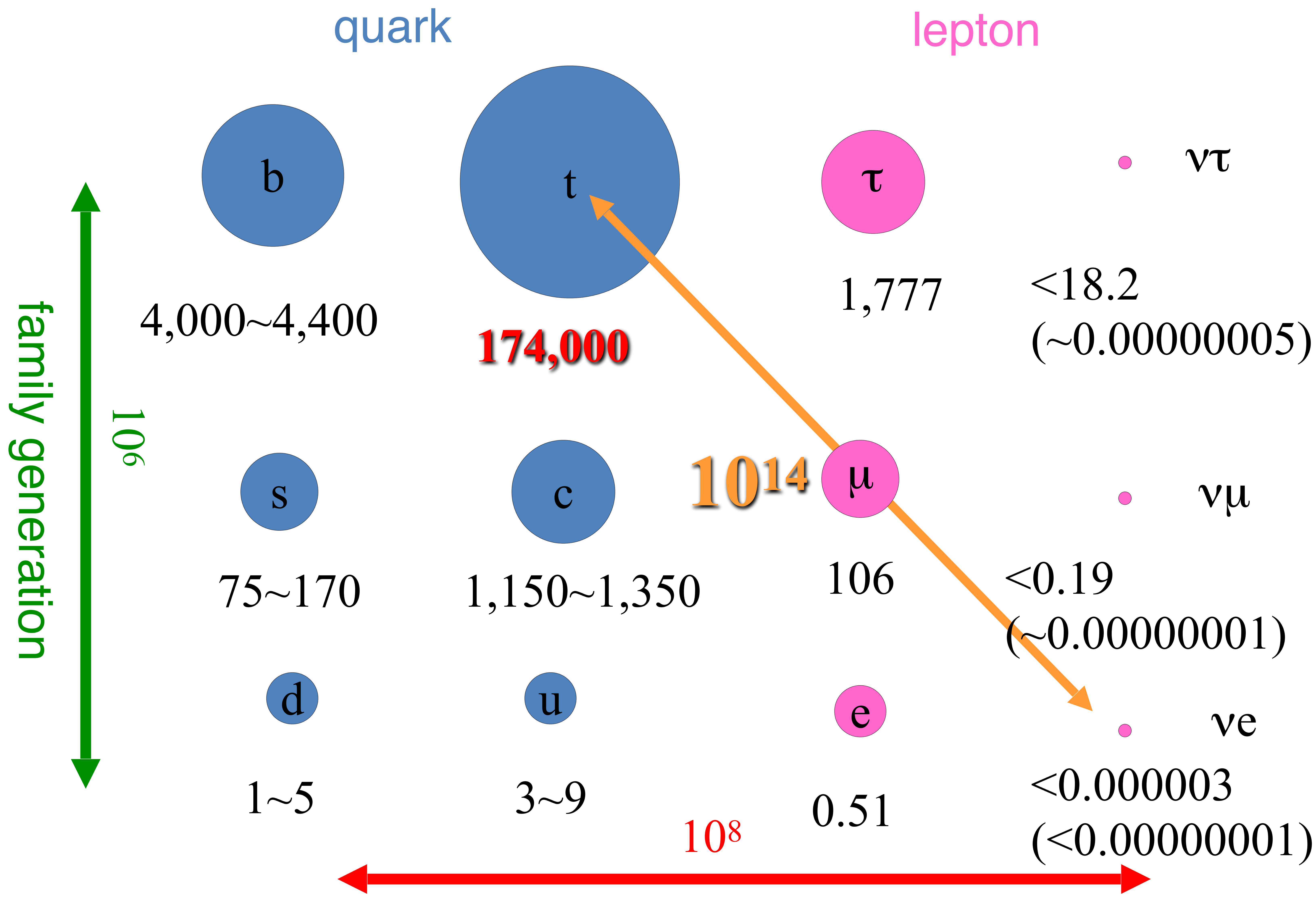
Electron

Standard Model of Elementary Particles



	three generations of matter (fermions) I	II	III	interactions / force carriers (bosons)	
mass charge spin	≈2.2 MeV/c^2 ⅔ ½ u **up**	≈1.28 GeV/c^2 ⅔ ½ c **charm**	≈173.1 GeV/c^2 ⅔ ½ t **top**	0 0 1 g **gluon**	≈124.97 GeV/c^2 0 0 H **higgs**
QUARKS	≈4.7 MeV/c^2 −⅓ ½ d **down**	≈96 MeV/c^2 −⅓ ½ s **strange**	≈4.18 GeV/c^2 −⅓ ½ b **bottom**	0 0 1 γ **photon**	SCALAR BOSONS
	≈0.511 MeV/c^2 −1 ½ e **electron**	≈105.66 MeV/c^2 −1 ½ μ **muon**	≈1.7768 GeV/c^2 −1 ½ τ **tau**	≈91.19 GeV/c^2 0 1 Z **Z boson**	GAUGE BOSONS VECTOR BOSONS
LEPTONS	<1.0 eV/c^2 0 ½ ν_e **electron neutrino**	<0.17 MeV/c^2 0 ½ ν_μ **muon neutrino**	<18.2 MeV/c^2 0 ½ ν_τ **tau neutrino**	≈80.360 GeV/c^2 ±1 1 W **W boson**	

Mass (MeV) : $m\Psi\bar{\Psi}$



quark

lepton

family generation

10^6

b

4,000~4,400

t

174,000

τ

1,777

ντ

<18.2
(~0.00000005)

s

75~170

c

1,150~1,350

10^{14}

μ

106

νμ

<0.19
(~0.00000001)

d

1~5

u

3~9

e

0.51

νe

<0.000003
(<0.00000001)

10^8

neutrino mass is so small!

Fundamental Questions!

not solved yet

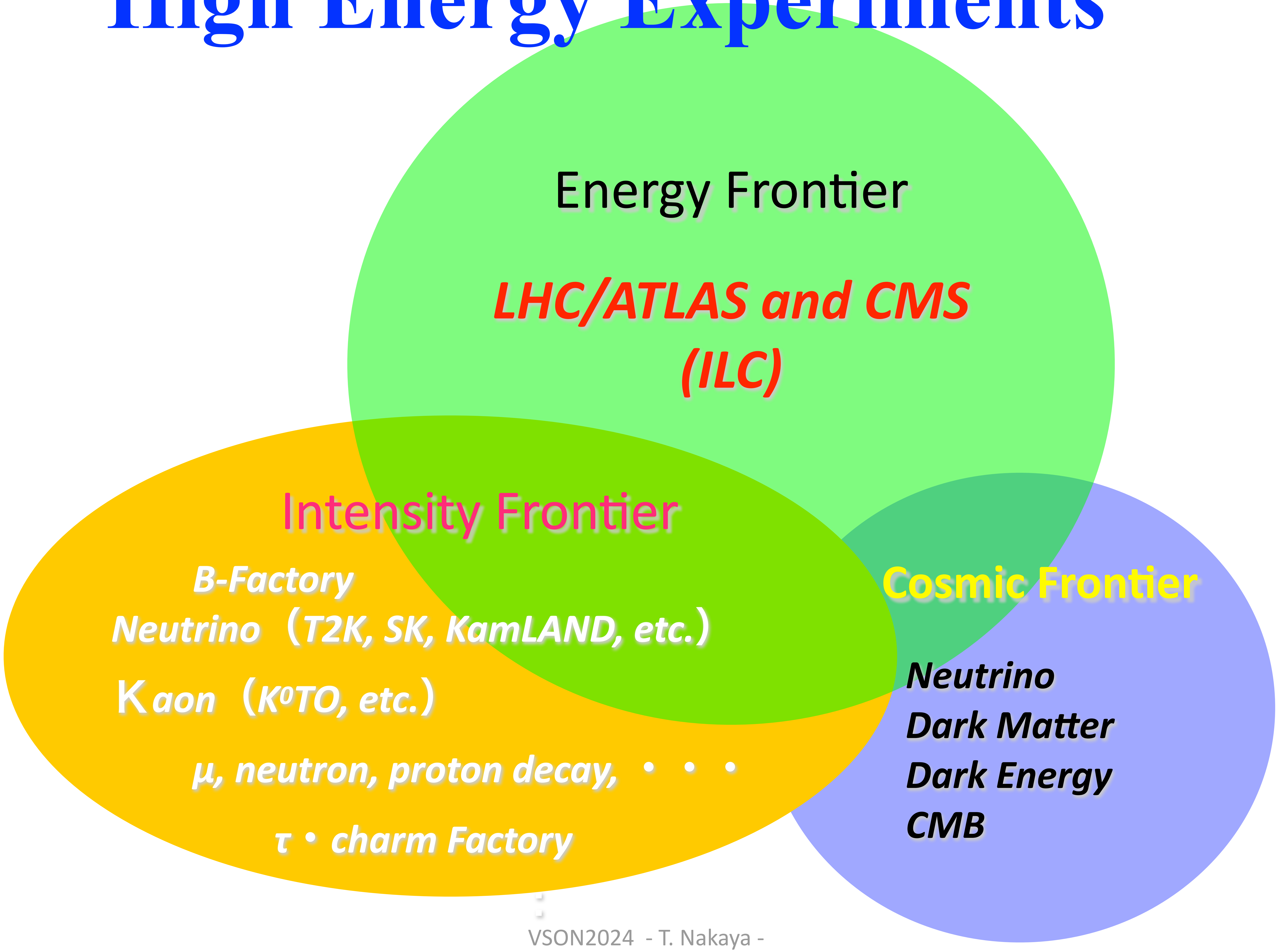
- What is dark matter?
- Where are antimatter? How did they disappear?
- The accelerating universe?
- Why is neutrino mass so small?
- How are the forces are unified?
- Generation structure. Why are the masses of particles are so different?

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.）
Kaon（K^0TO, 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, JSNS^2, Super-K, Hyper-K, KAGLA, KamLAND, (ILC)
- IHEP (China)
  - BESSIII, JUNO, (CEPC)
- *Cosmology and Astro-particle experiments*

1. Energy Frontier

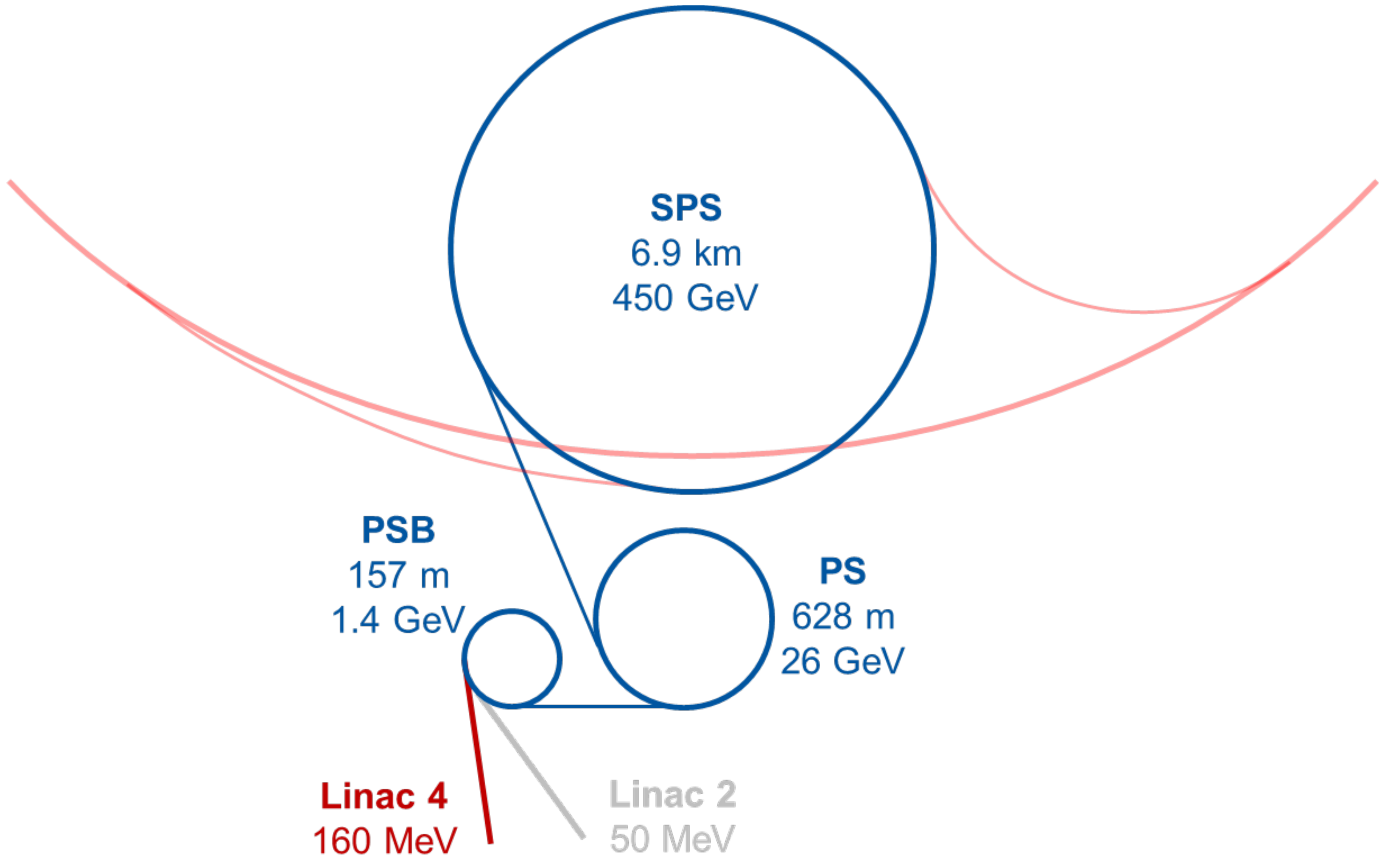
LHC
Large Hadron Collider
（Superconducting Accelerator）

CERN and LHC

Circumference 27km
（Why does it require 27km？
Magnetic field:8T）

Circular accelerator

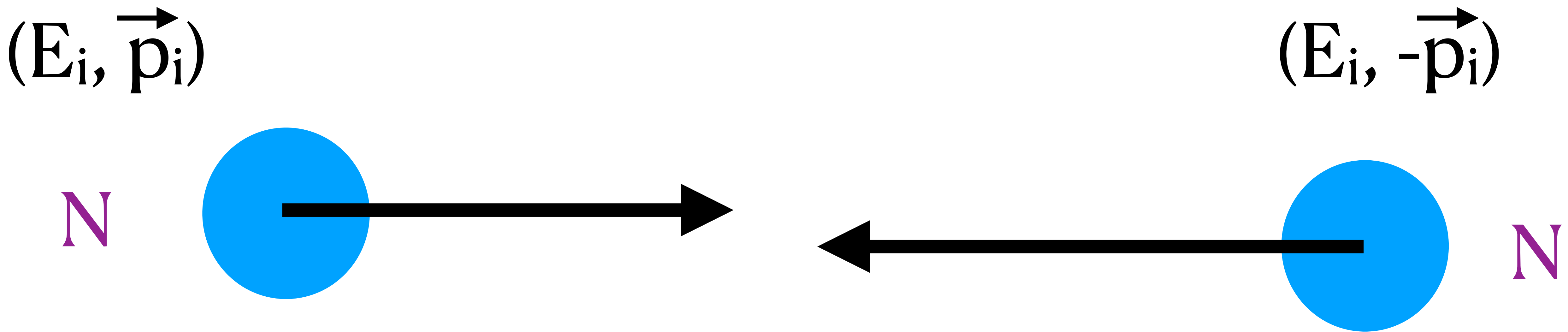
- **Proton Synchrotron**
  - Protons go round and round
    - Inject proton beam periodically
  - Acceleration mode： Increasing energy with every lap
    - LHC: 450 GeV → 6,800 GeV (6.8 TeV)
      - Increasing magnetic field synchronized with energy
  - Colliding mode： constant energy
    - How many turns per second?
    - Circumference 27km



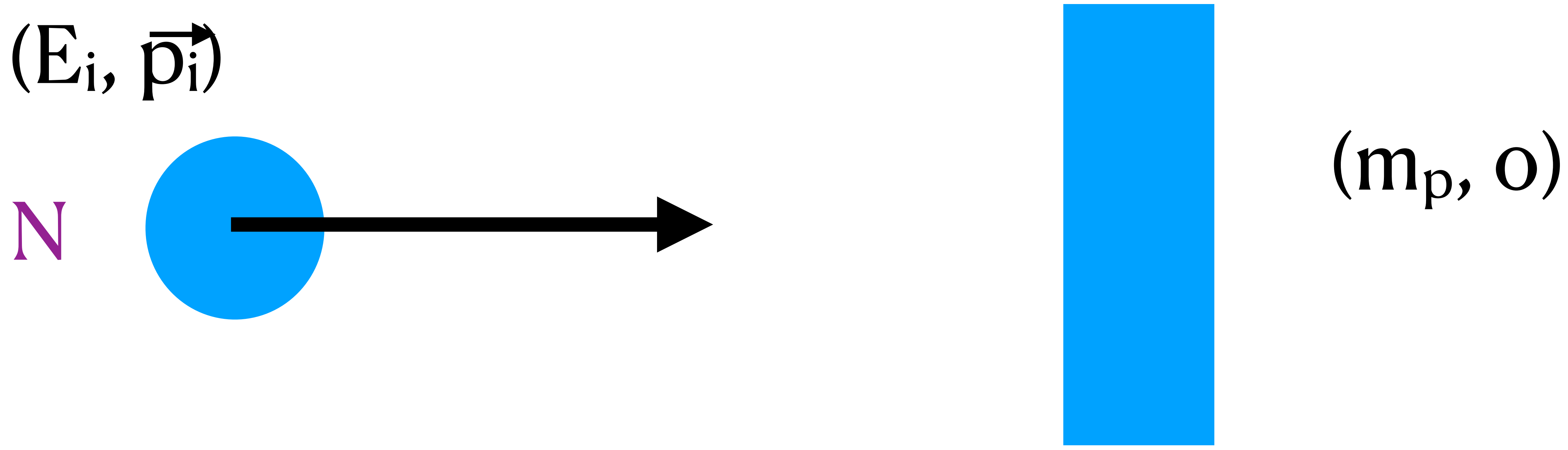
Collider experiment

How heavy subatomic particles can be made?

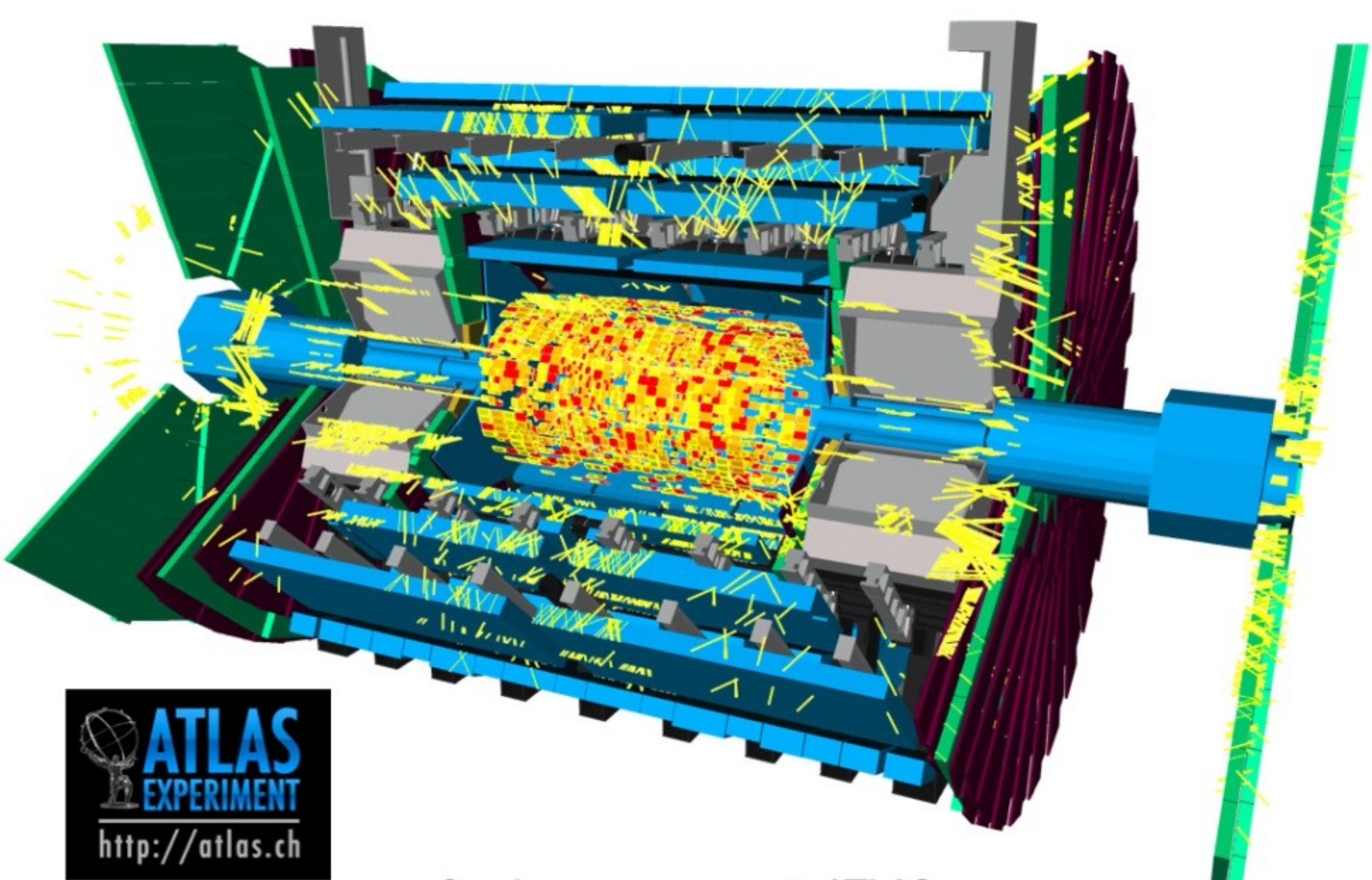
- **Collider experiment**
  - Effective use of beam energy



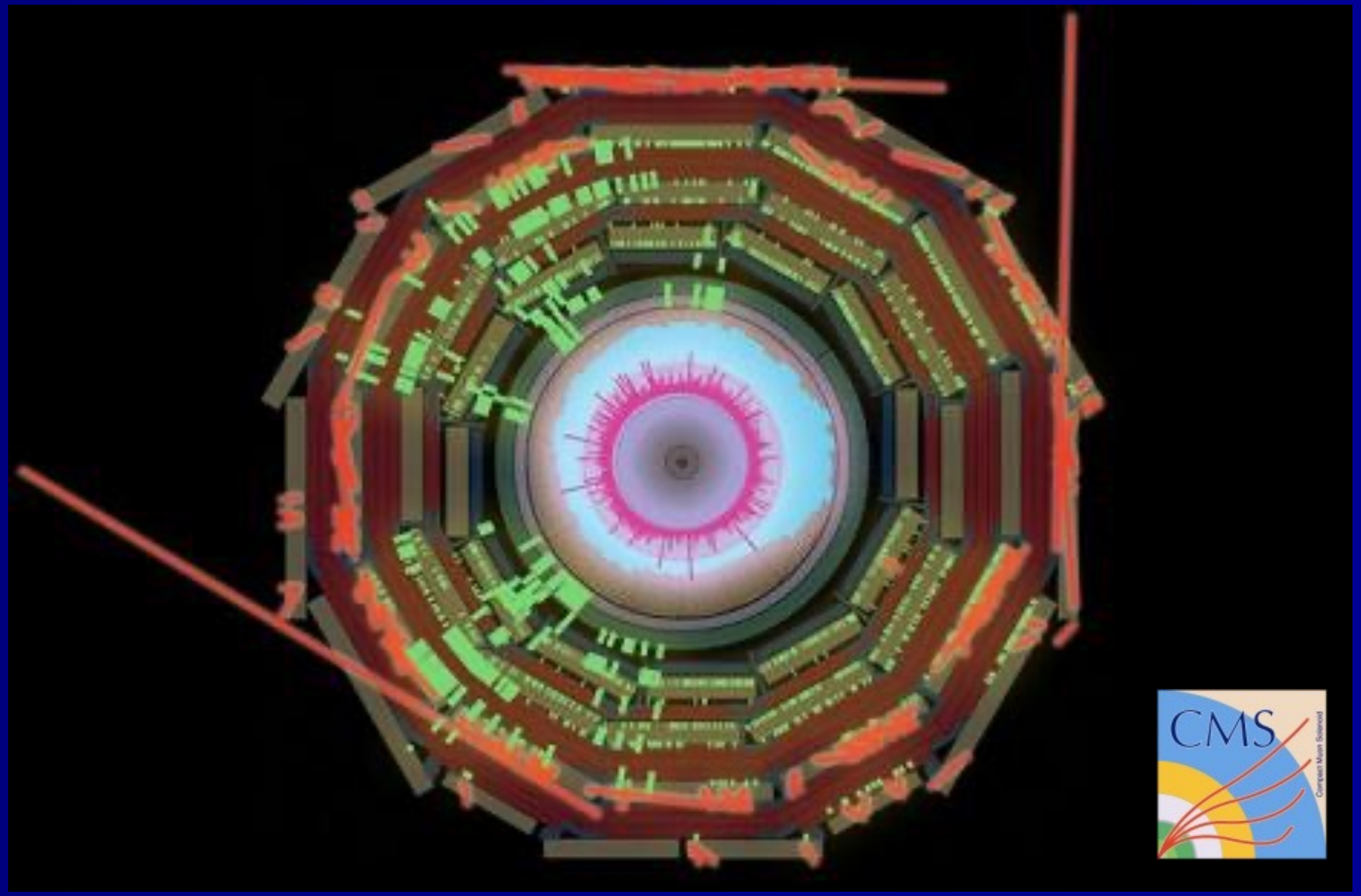
- **Fixed target experiment**
  - Effective use of beam flux

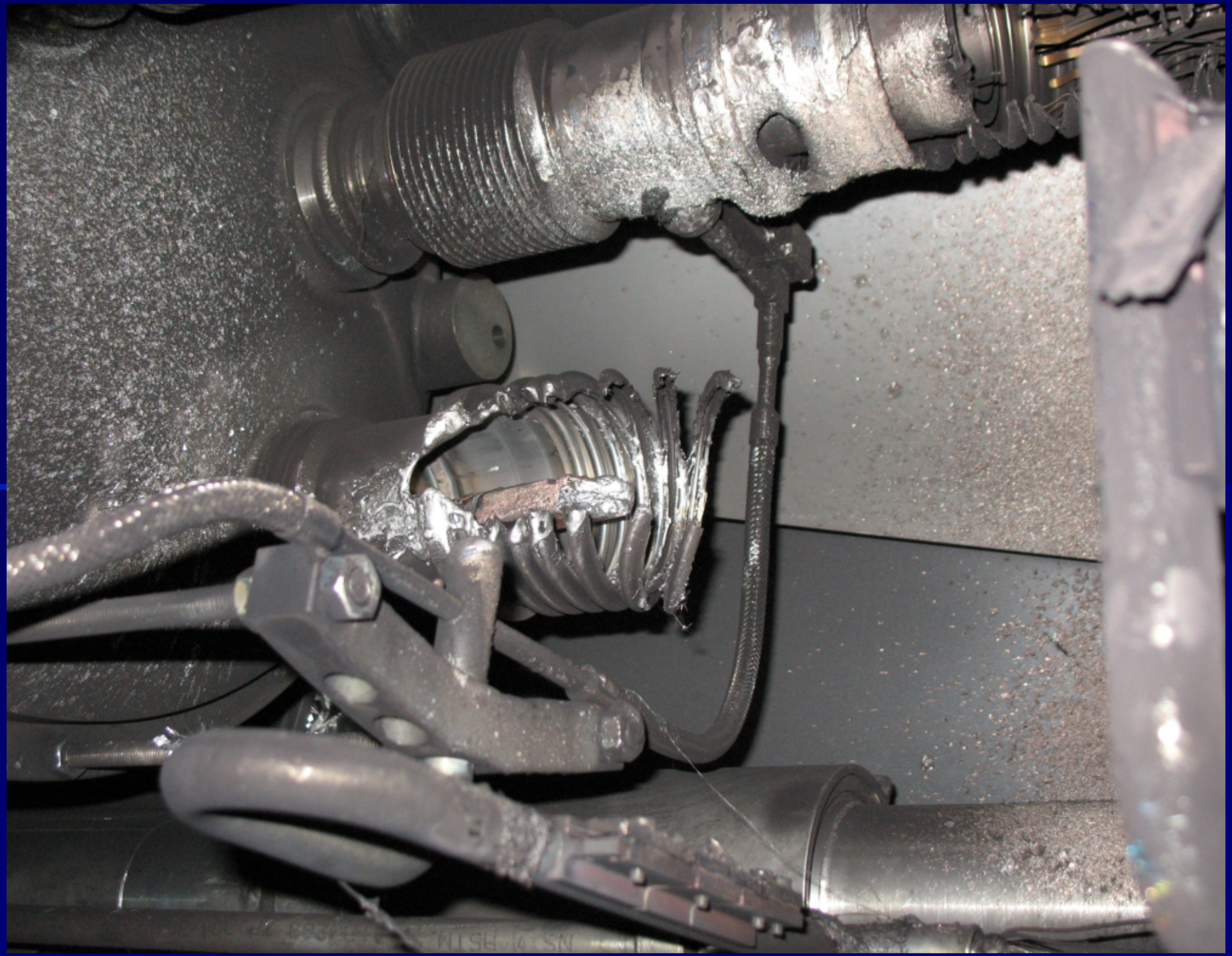


16 years ago
（2008/9/10）



first beam event seen in ATLAS





9 days after

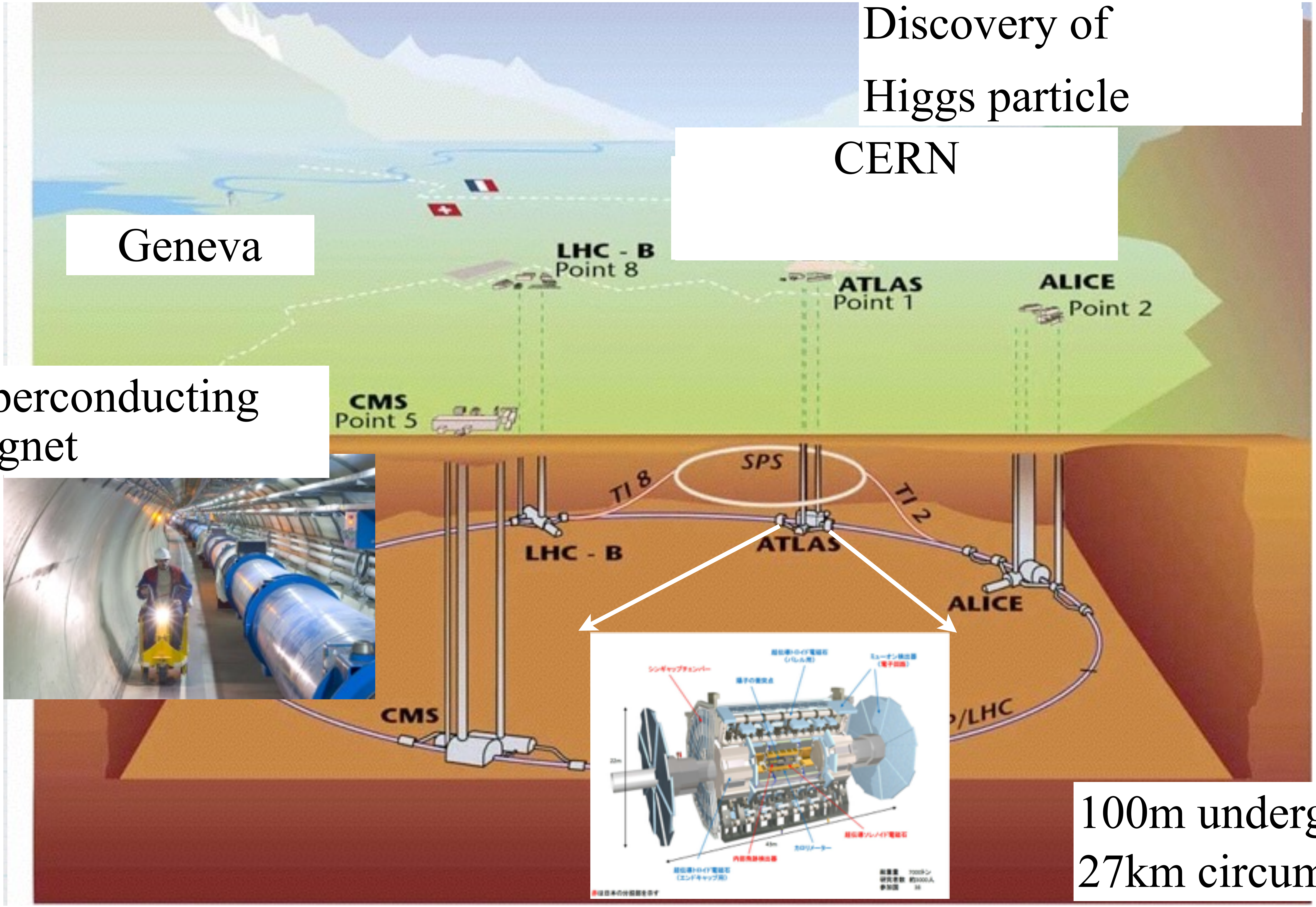
(2008/9/19)

Short circuit → superconducting collapse

→ liquid helium boiling and explosion

Restart in 2010

LHC/ATLAS/CMS Proton-Proton Collider experiments



Discovery of

Higgs particle

CERN

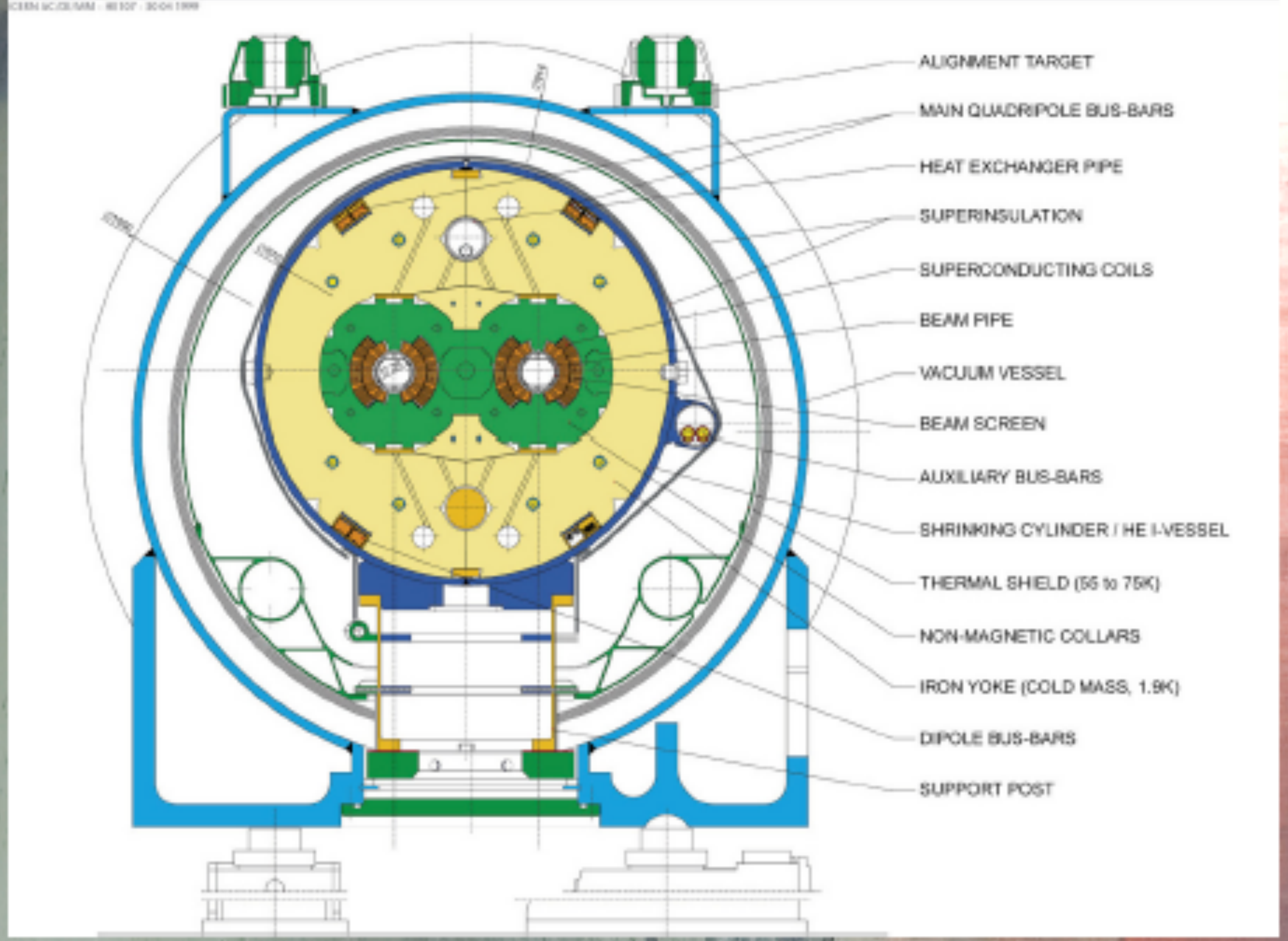
Geneva

Superconducting
magnet

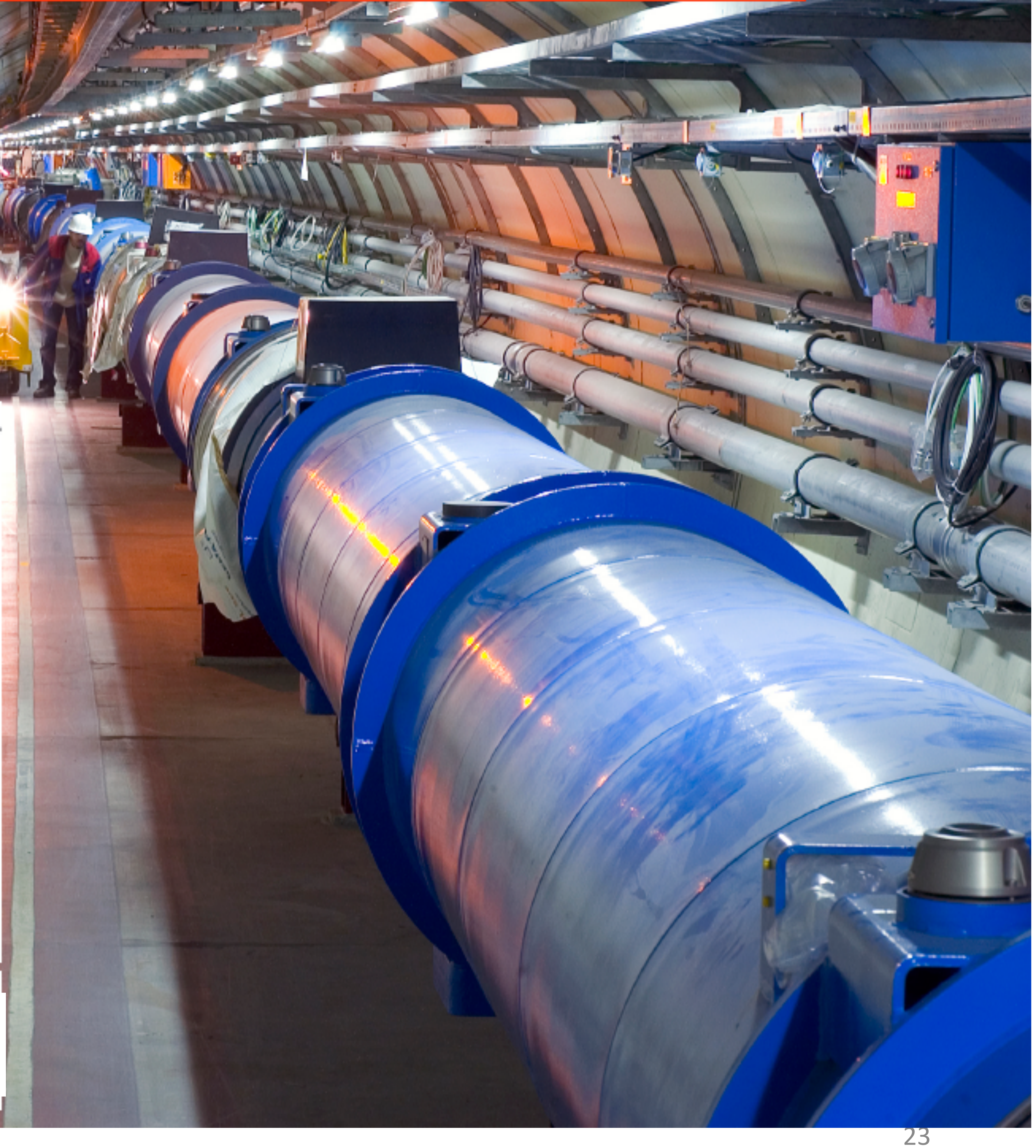
100m underground
27km circumference

Large Hadron Collider (LHC) at CERN

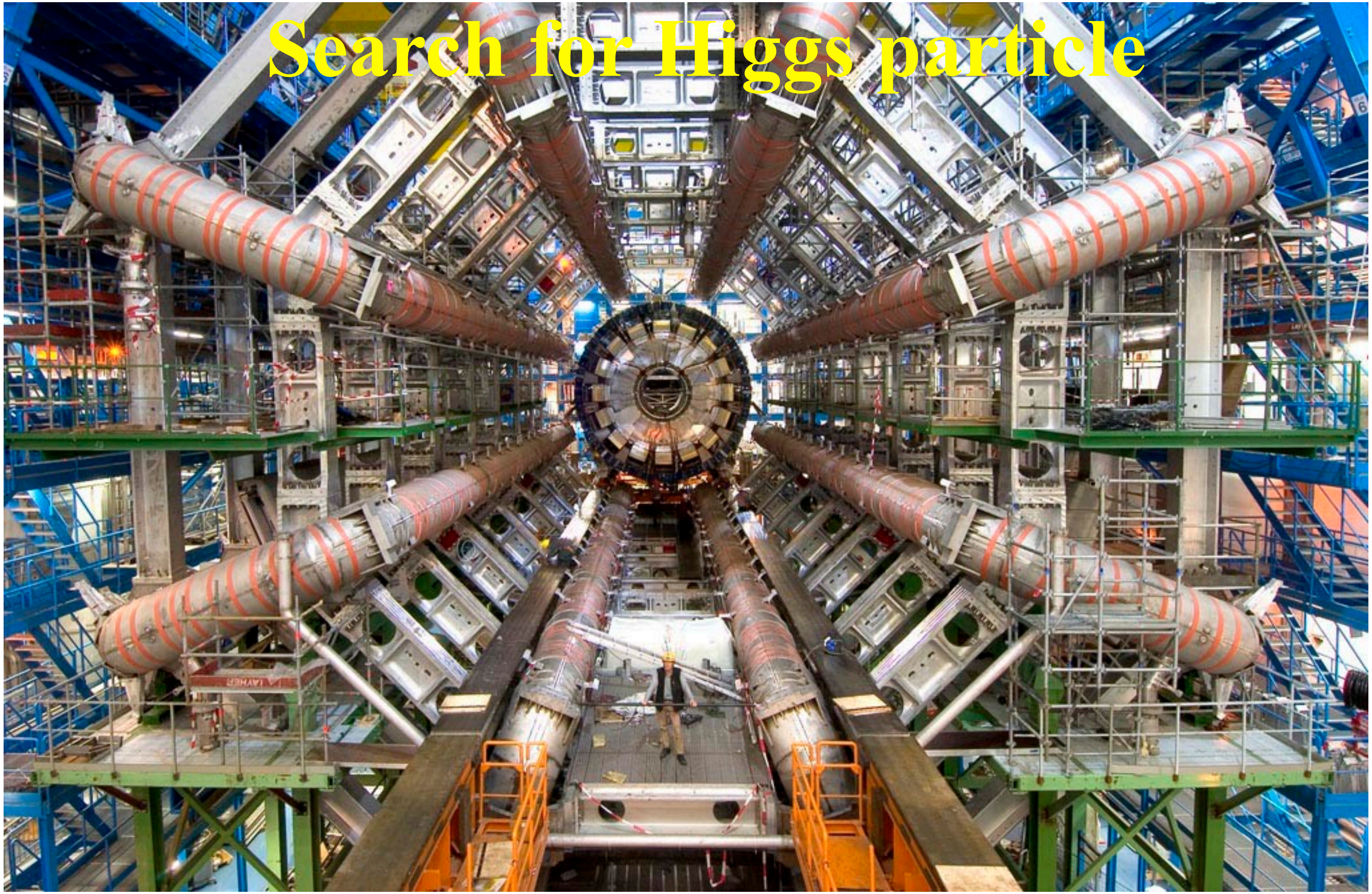
- 14 TeV proton-proton collider
- 27 km circumference
- 14 years construction
- US 5B dollar for construction



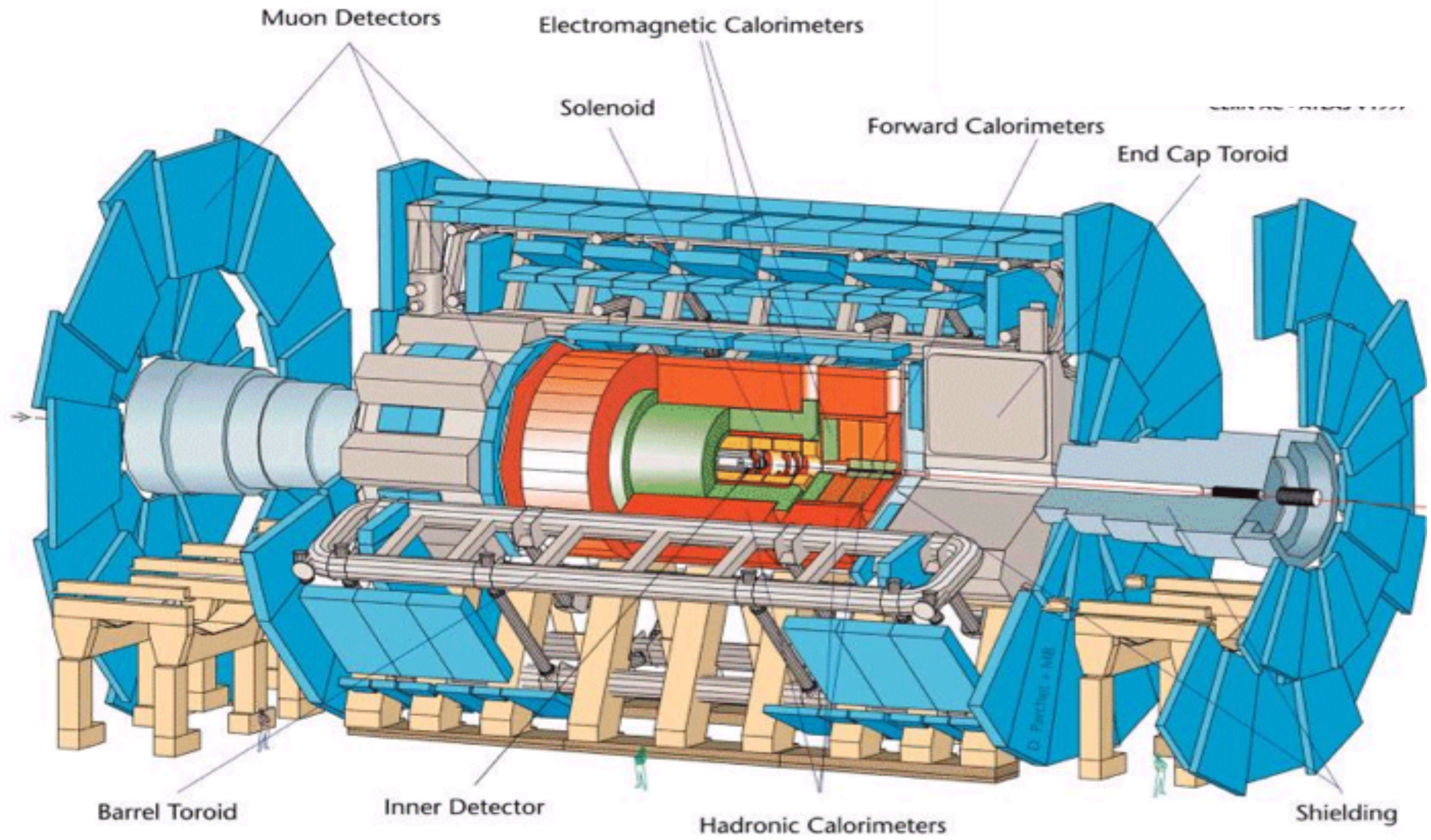
- 1.9 K cooling by Helium
- 8.3 T magnetic field with 1232 magnets



LHC/ATLAS experiments

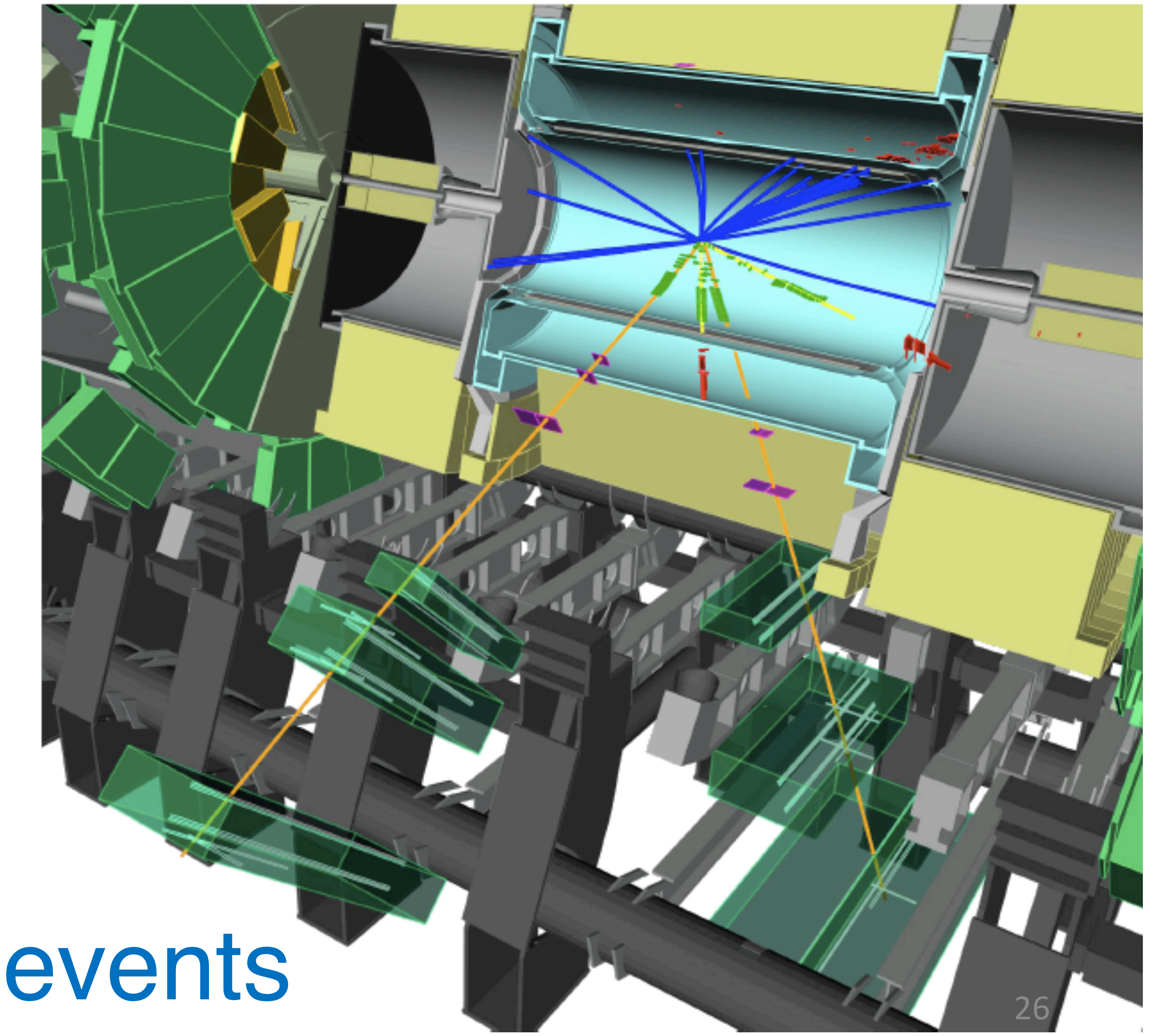

Search for Higgs particle

ATLAS detector



ATLAS detector

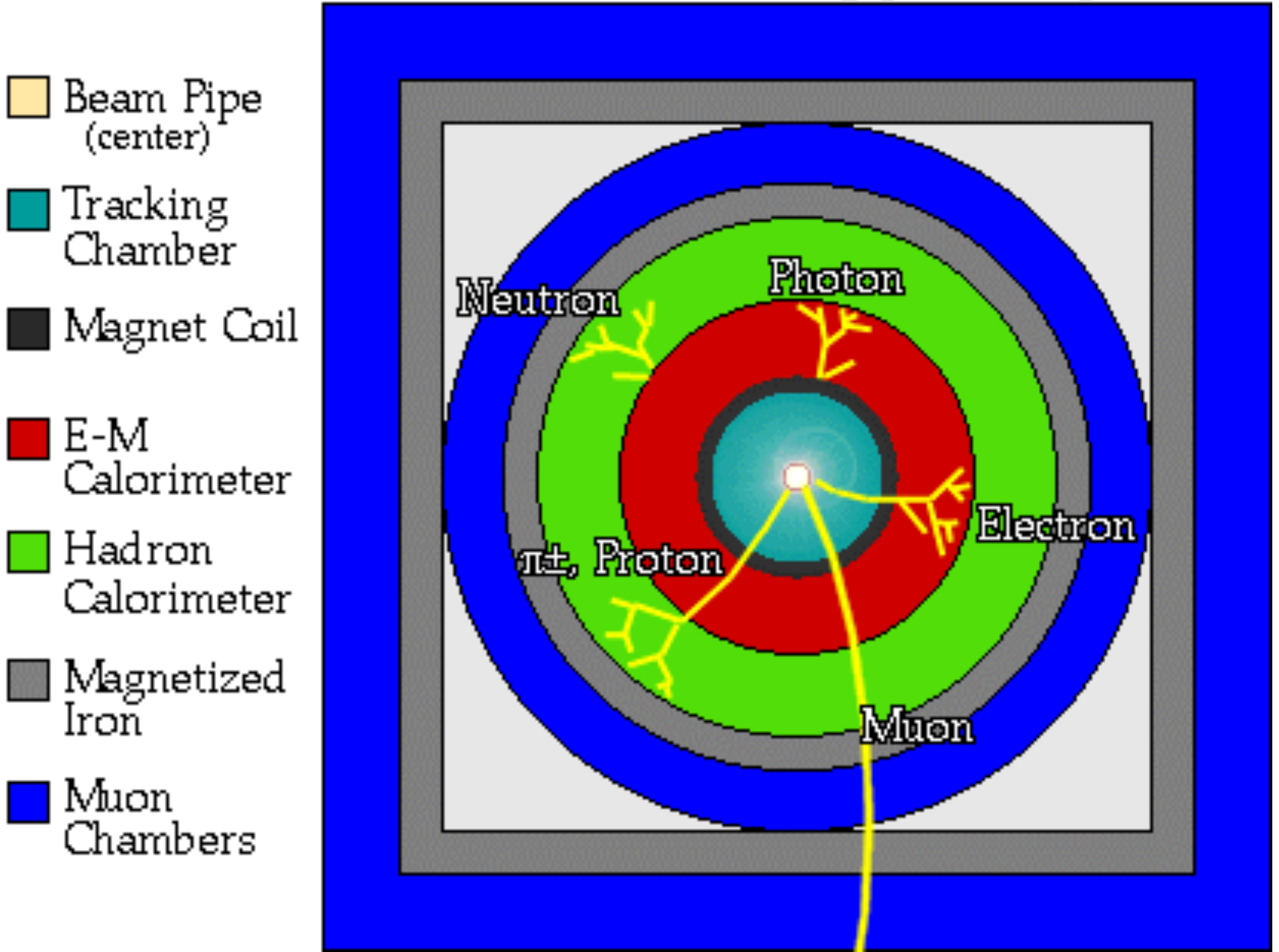
- Multi-purpose detector
  - Hight 25 m, Length 44m, Weight 7,000 ton
  - 1M signal channels



$H \rightarrow ZZ^{*} \rightarrow 4l$ events

Why is multi-purpose detector?

- Particles observed
  - Electron
  - Photon
  - Proton (uud)、π^+(ud)、 K^+(us)
  - Neutron（udd)
  - Muon
  - ?? Neutrino ??



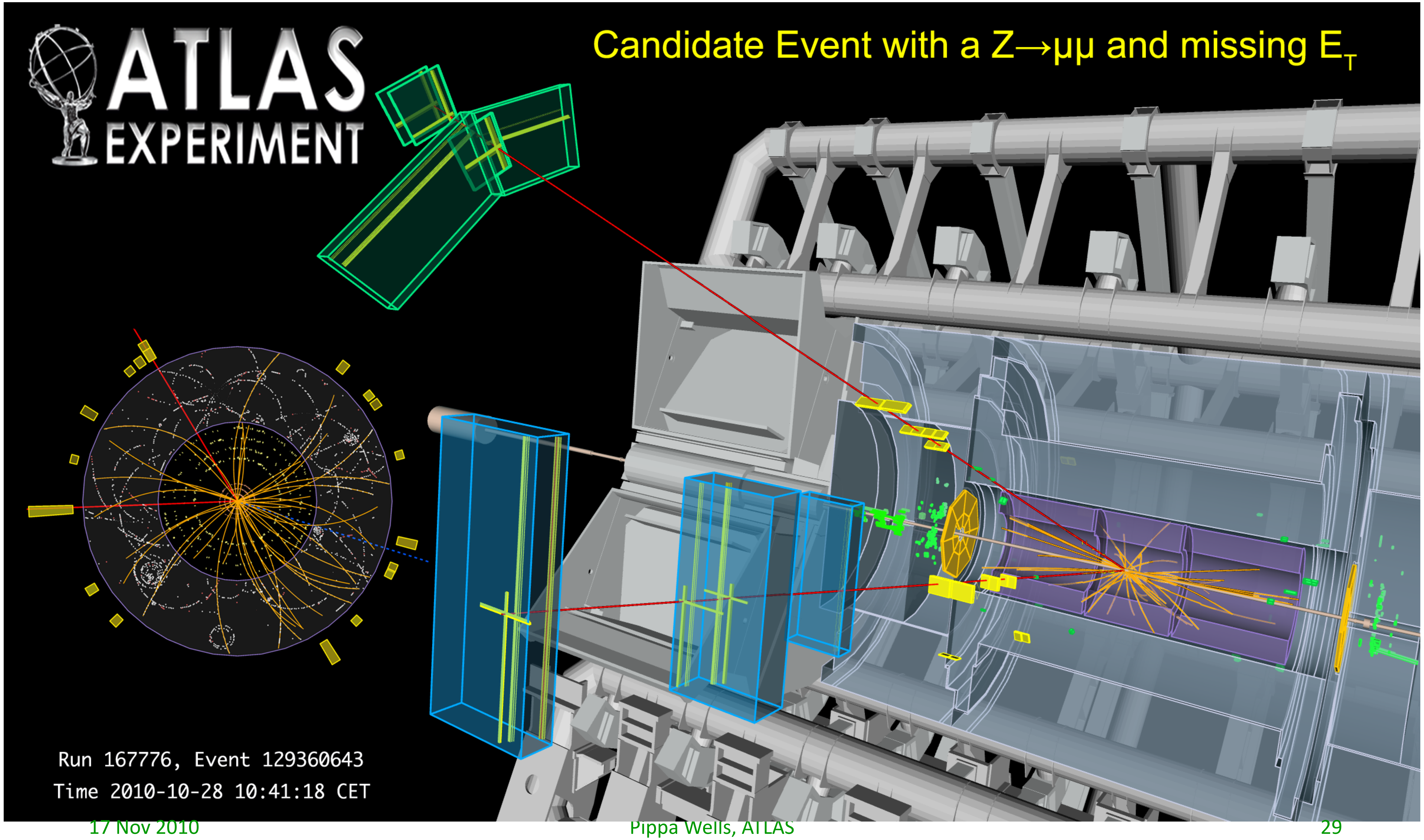
A detector cross-section, showing particle paths

Principle of Particle measurements

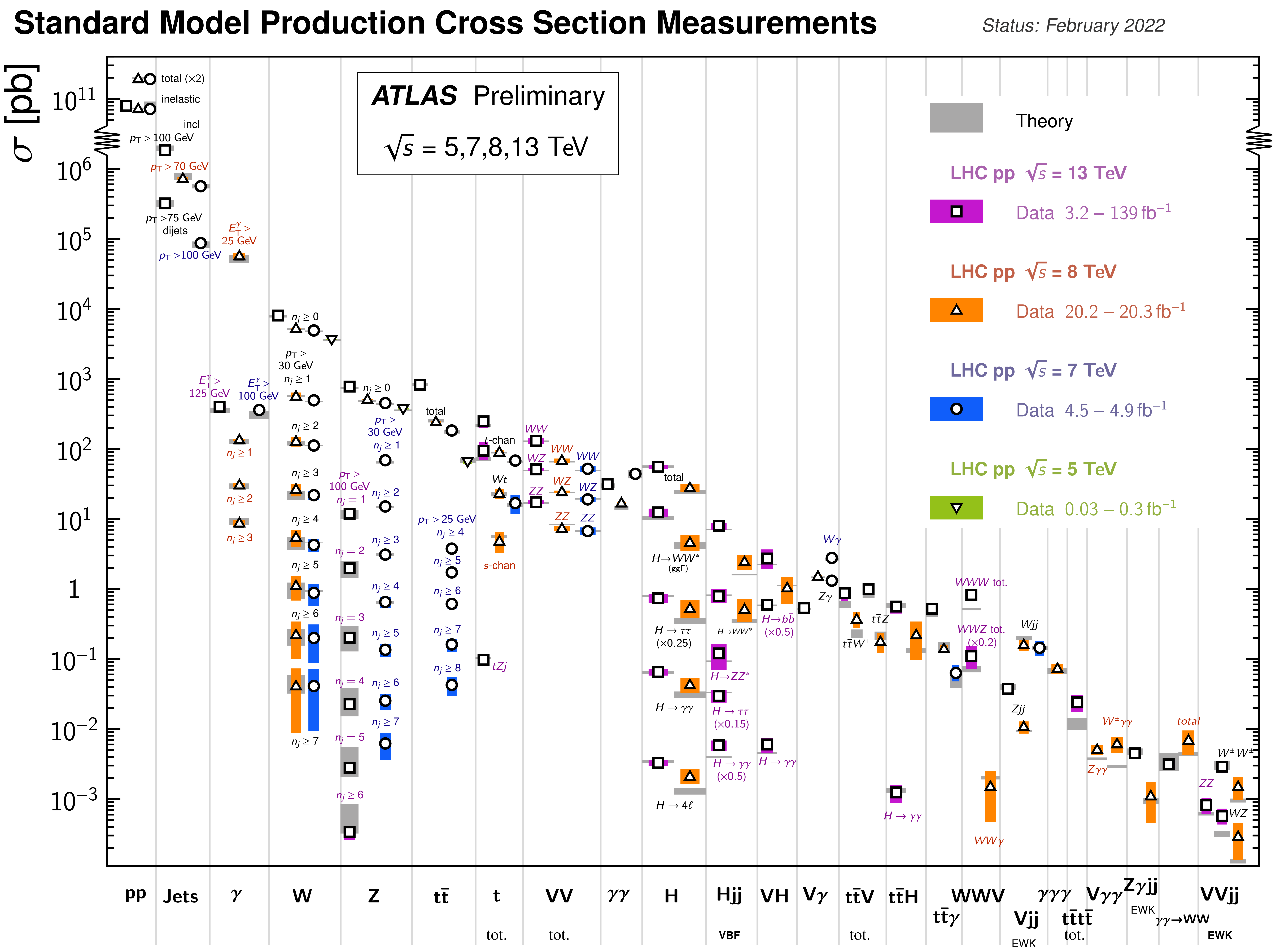
- Tracking the particle trajectories under a magnetic field, and measuring their position and momentum.
- Next, photons and electrons are stopped and their energy and position are measured.
- Hadrons (mainly protons and pions) are then stopped and their energy and position measured.
- Finally, charged particles not stopped are muons.
- Non-observed particles are neutrinos, which are identified by missing energy.

Candidate for ZZ→μμνν

- $m_{\mu\mu}$ 94 GeV, E_T^{miss} = 161 GeV



- Cross Section
  - barn [b] = 10^{-24} cm^2 = 10^{-12} cm x 10^{-12} cm
  - pb (pico-barn) = 10^{-12}b = 10^{-36} cm^2 = 10^{-20} m x 10^{-20} m

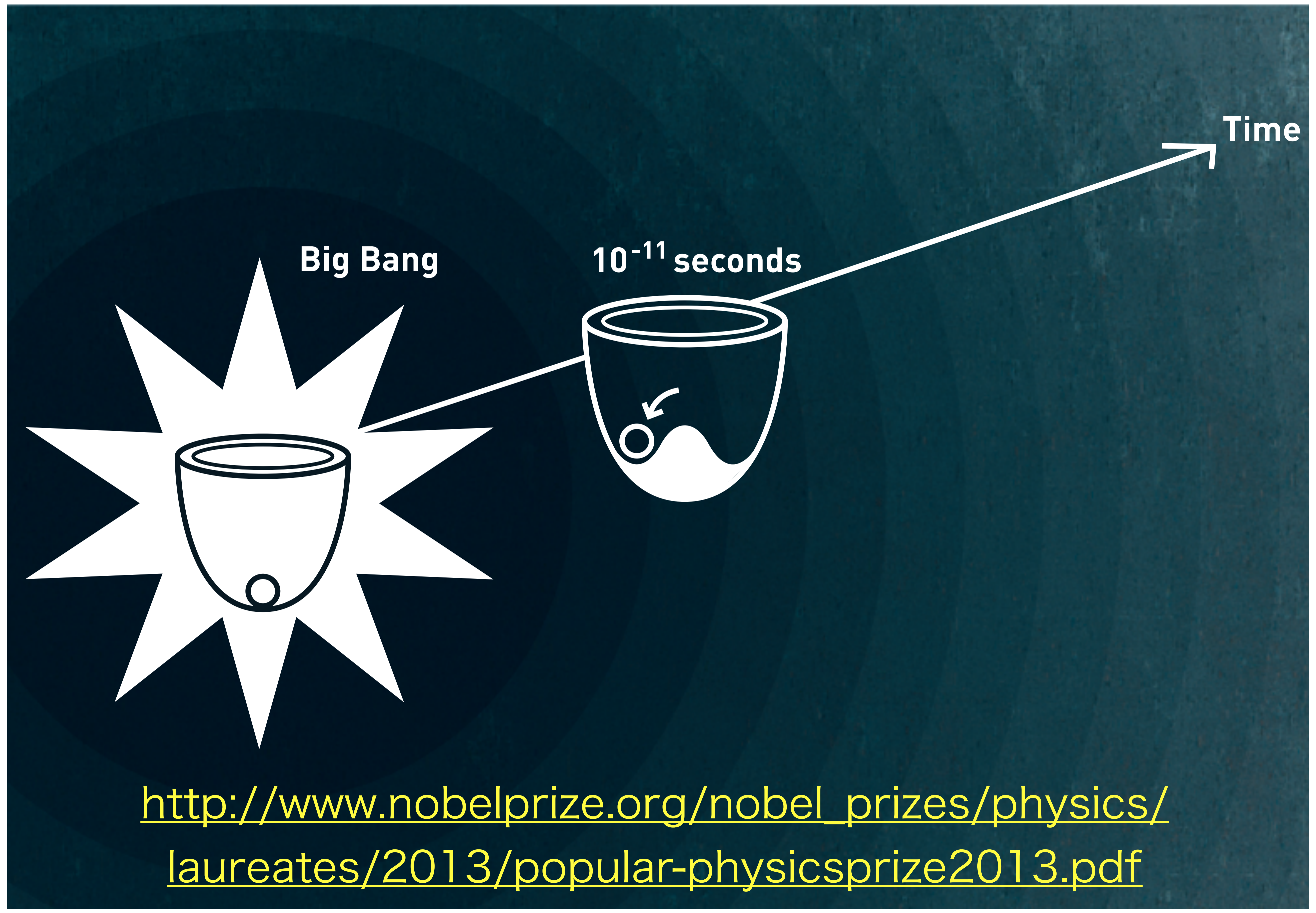


Physics by LHC at the TeV energy region

- Discovering the Higgs boson to understand the origin of mass due to spontaneous symmetry breaking.
- Search for supersymmetry particles
  - Linking space-time symmetry and internal symmetry of particles.
- Look for any new phenomena.

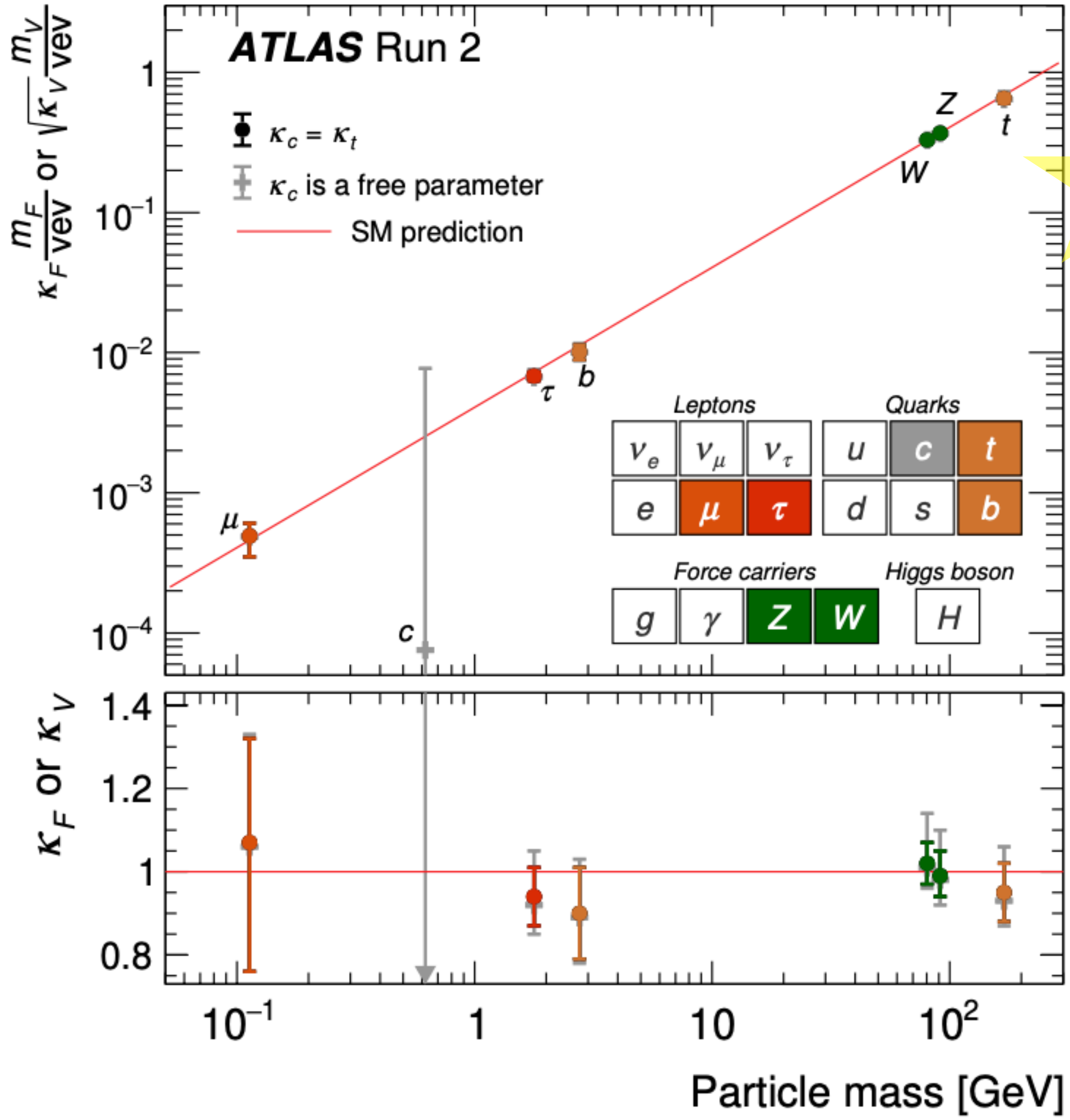
Higgs boson

- Particles (Higgs field condensate) as the source of the phase transition in the vacuum
  - Phase transition: the energy of the vacuum changes.
  - Particle is given (inertial) mass.
  - Coupling with the Higgs boson is related to the mass of the coupling particle



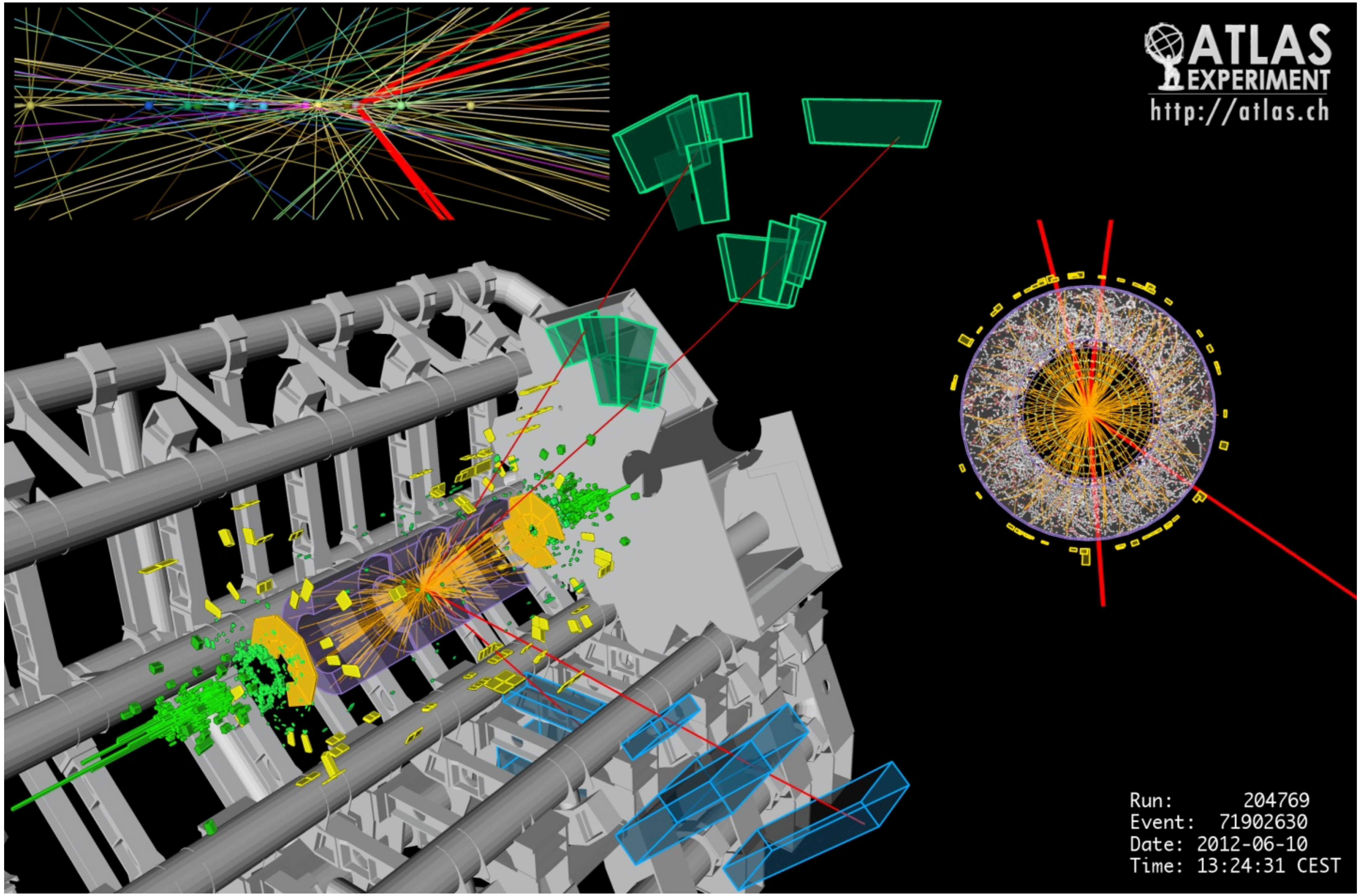
http://www.nobelprize.org/nobel_prizes/physics/laureates/2013/popular-physicsprize2013.pdf

Coupling with the Higgs boson with the mass of the coupling particle



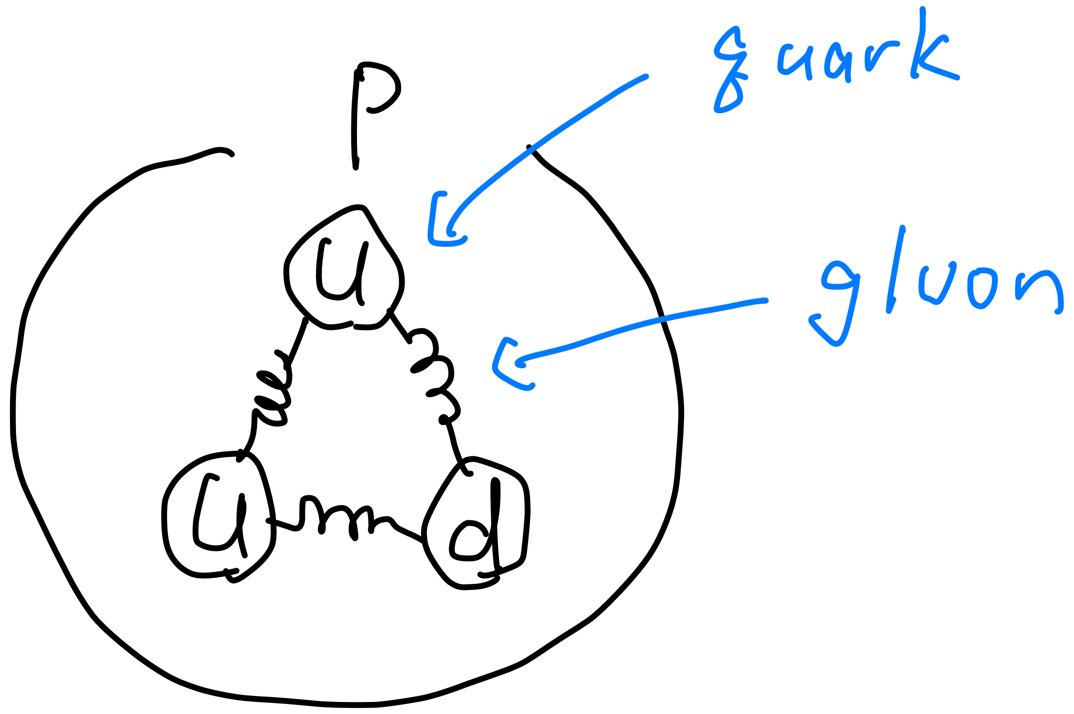
New

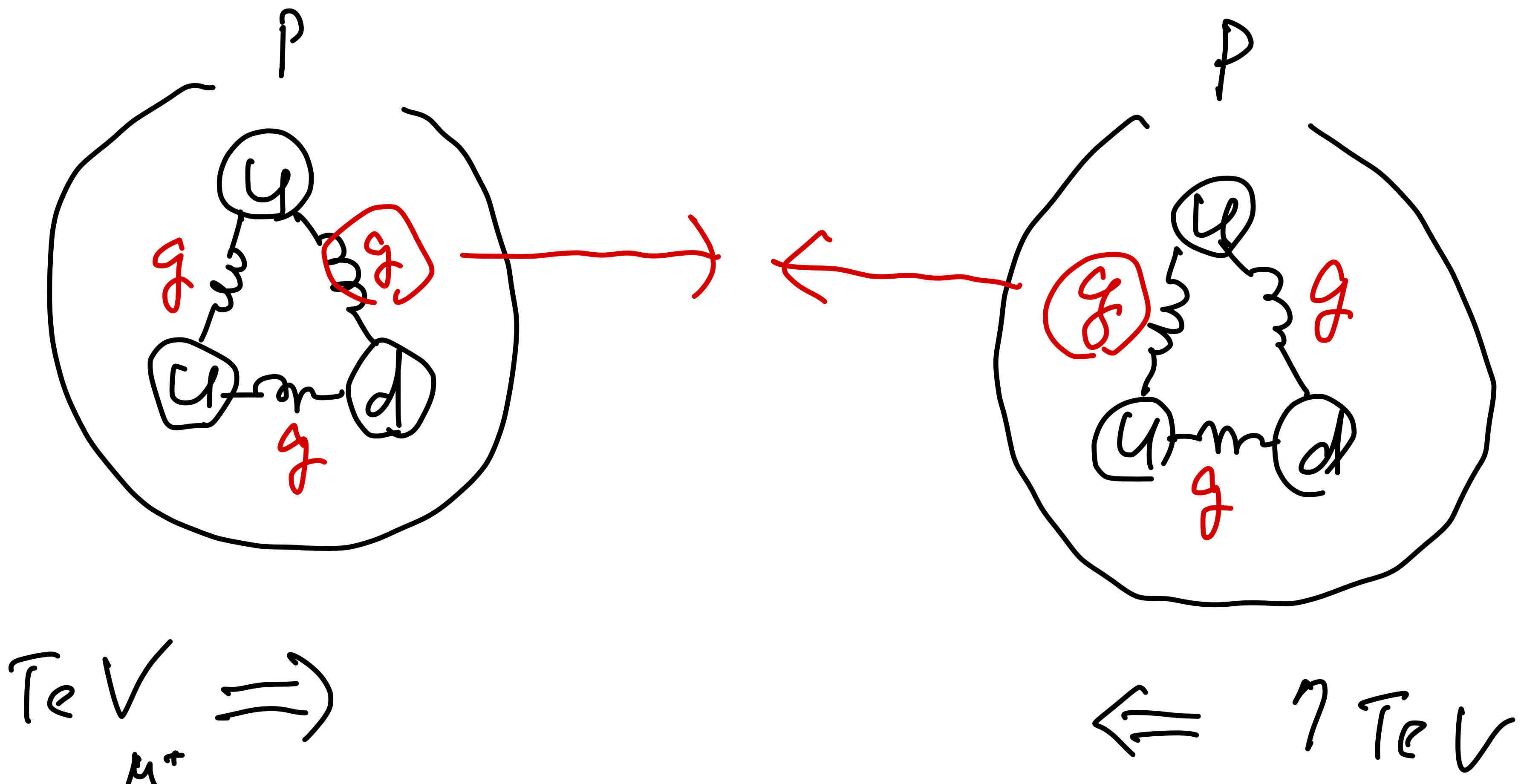
How to detect Higgs bosons

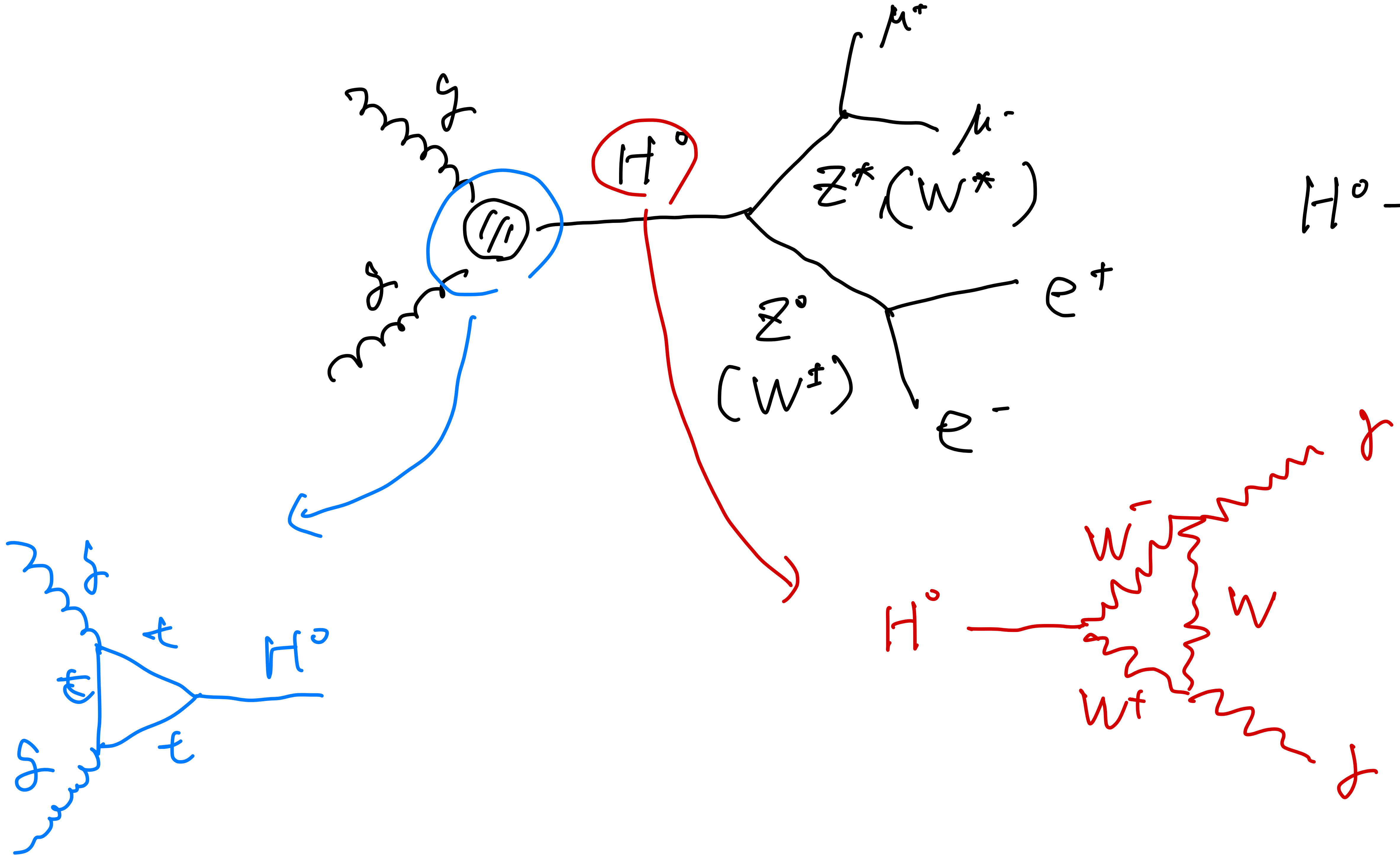


https://atlas.cern/updates/atlas-feature/higgs-boson

Proton - Proton collisions







$H^0 \rightarrow l^+ l^- l^+ l^-$

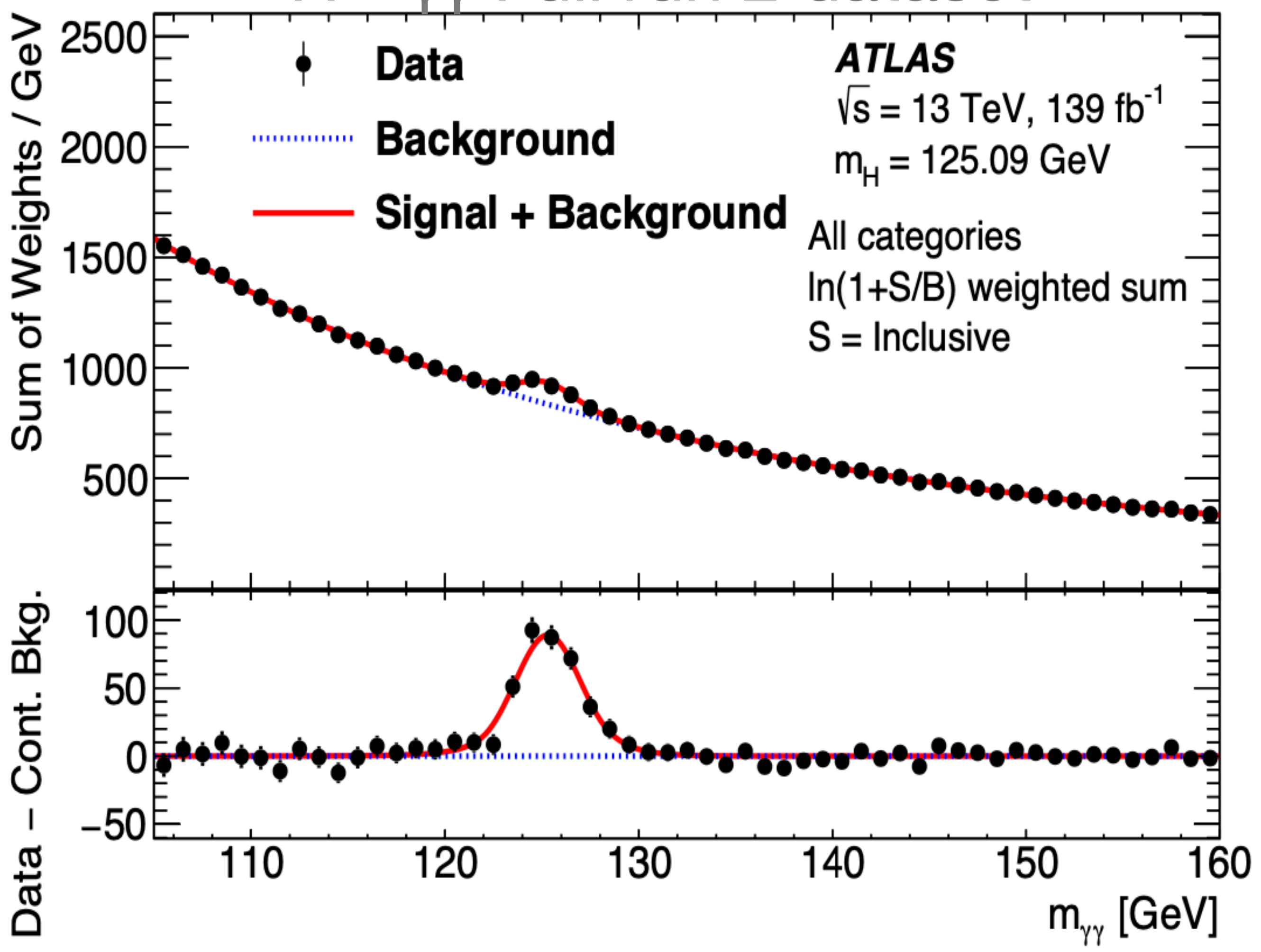
$l^+ \nu_e \; l^- \bar{\nu}_e$

Detecting Higgs bosons

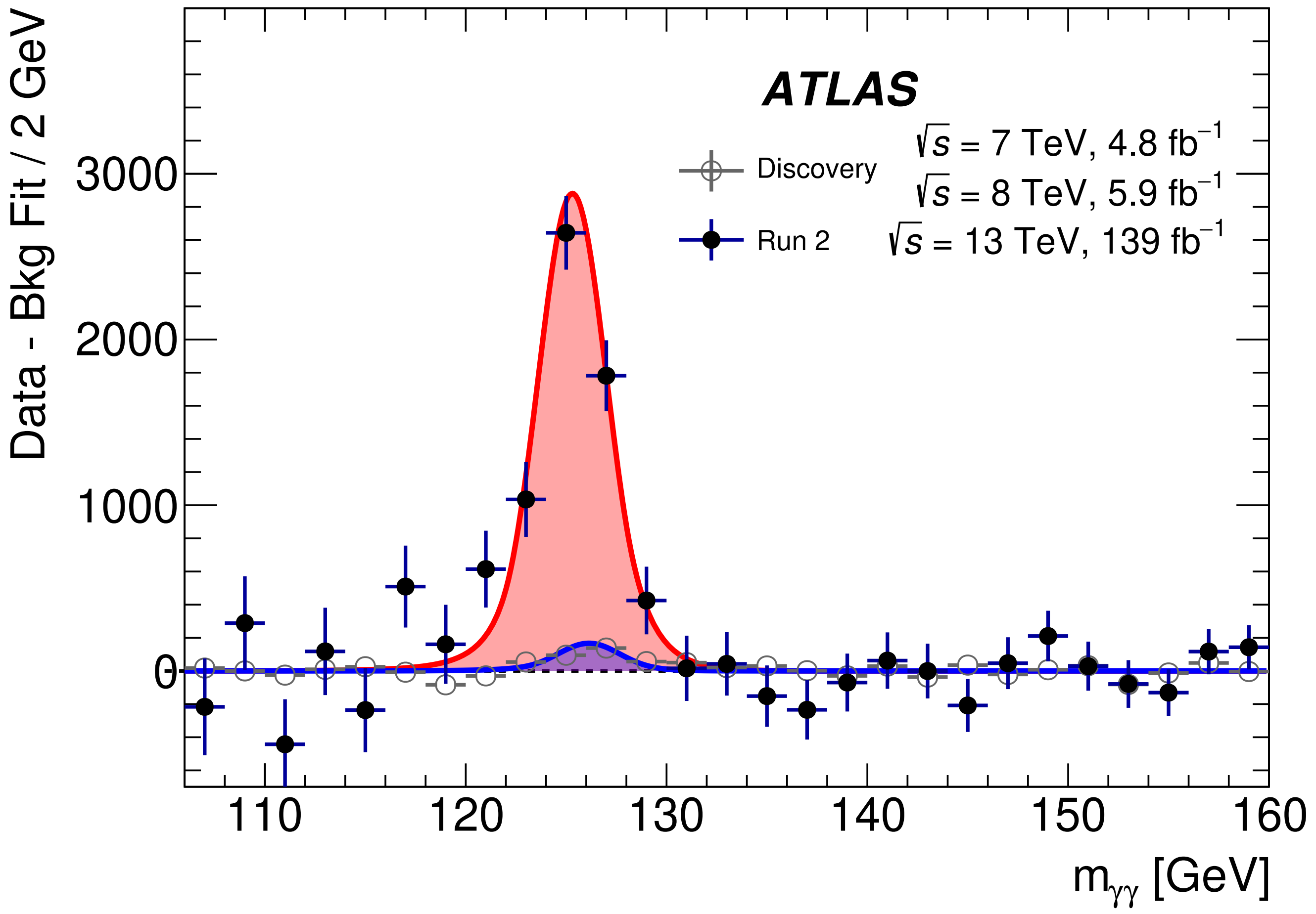
H→γγ

H→eeμμ、μμμμ、eeee

H→γγ Full run 2 dataset



Comparison with discovery dataset in 2012



Precise mass measurement using H→4l

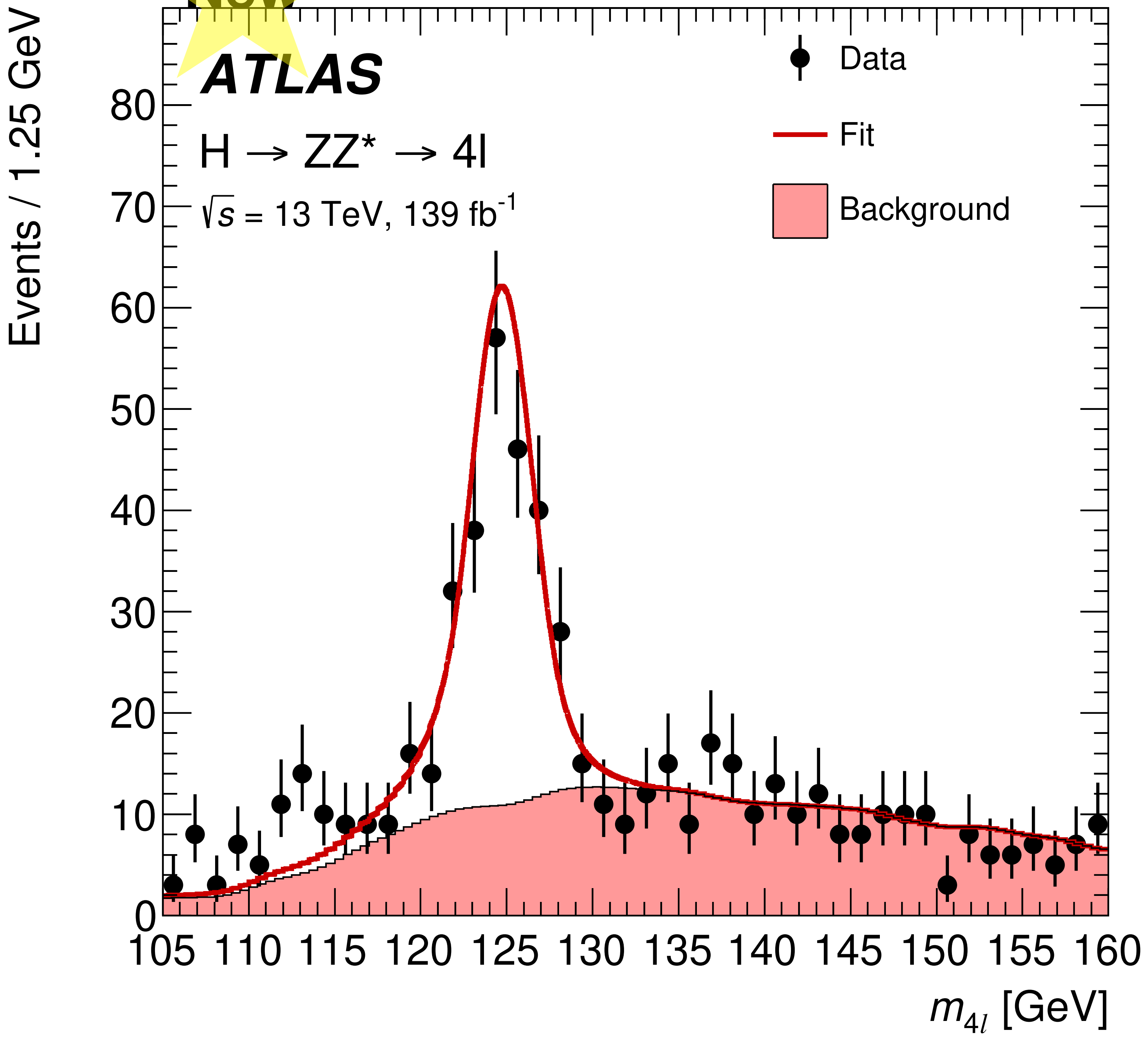
Event-by-event resolution, DNN for S/B separation, precise muon and electron momentum calibration

m_H **=124.94±0.17(stat.)±0.03(syst.)GeV**

(combined with run 1 data)

New

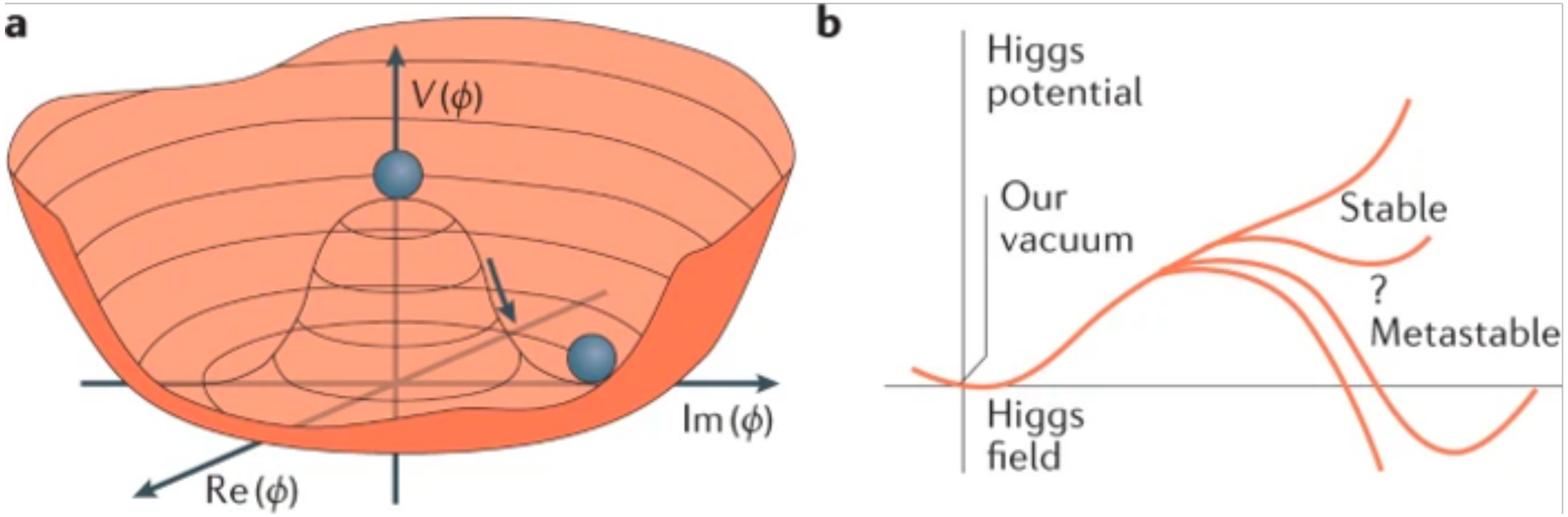
arXiv:2207.00320



What next with Higgs bosons

- Higgs potential
  - detecting a pair production of two Higgs bosons

$$\boxed{V(\phi) = \frac{1}{2}m_{\mathrm{H}}^2\phi^2 + \sqrt{\lambda/2}m_{\mathrm{H}}\phi^3 + \frac{1}{4}\lambda\phi^4}$$



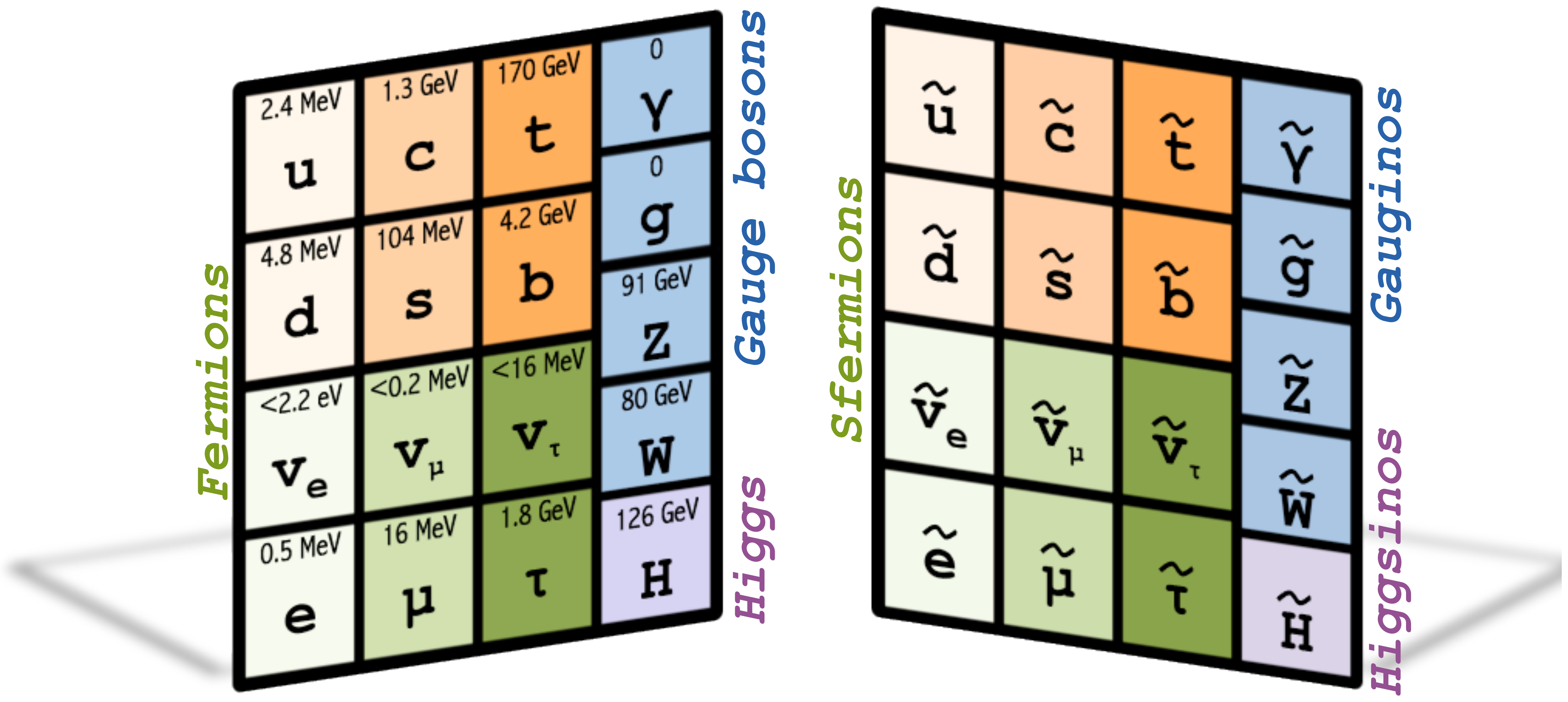
Beyond Higgs bosons

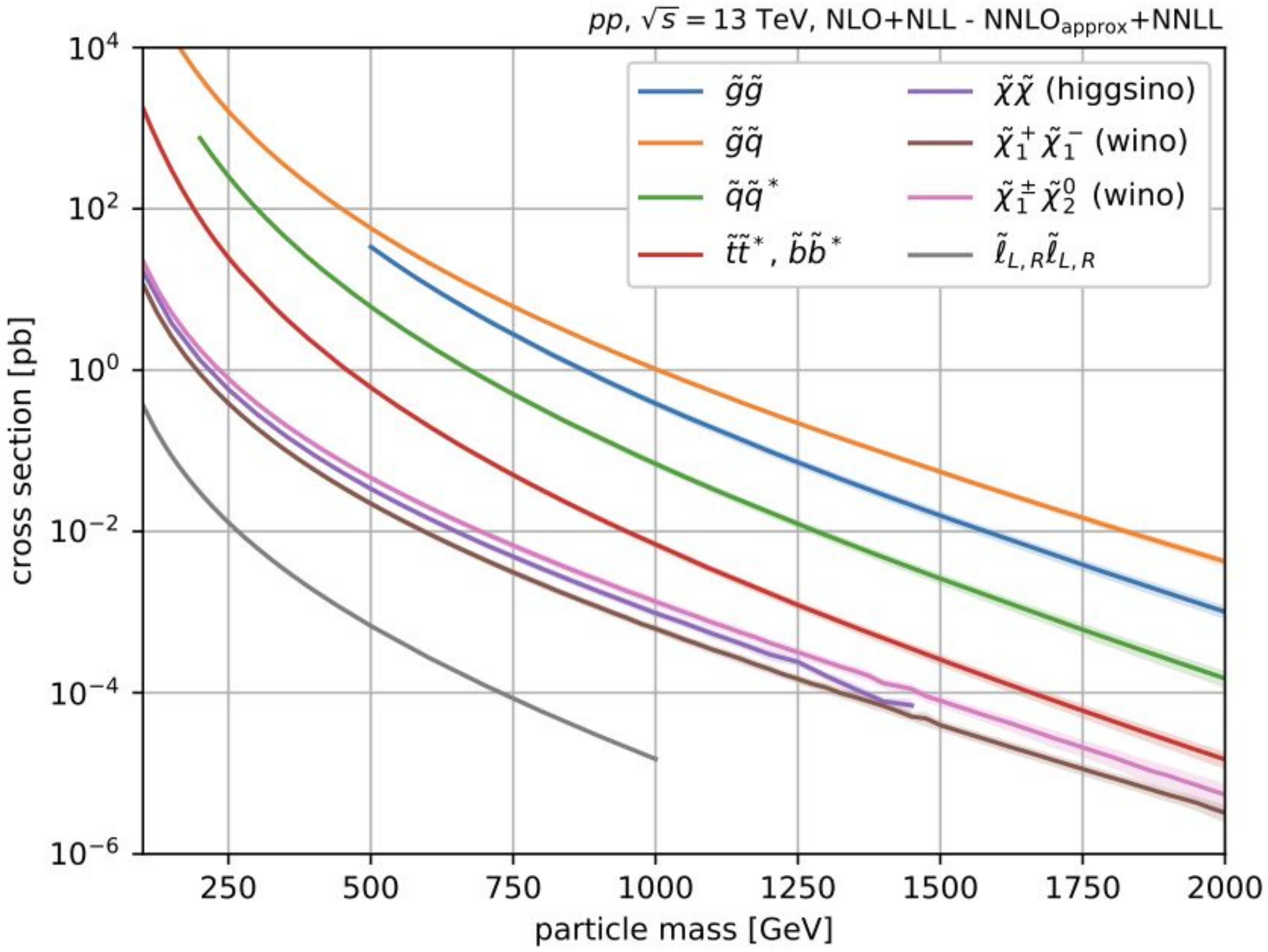
- **Supersymmetry (SUSY)**
  - Symmetry between Bose particles (spin integers) and Fermi particles (spin half-integers)
  - Example of Bose particle: photon
  - Fermi particles e.g. electrons
  - Are dark matter particles SUSY particles?
- **New Physics**
  - Extra dimensions (>4)
    - How many dimensions is space, are dimensions beyond 4 compactified?
  - Leptoquarks, Heavy majorana neutrinos, etc..

SUSY

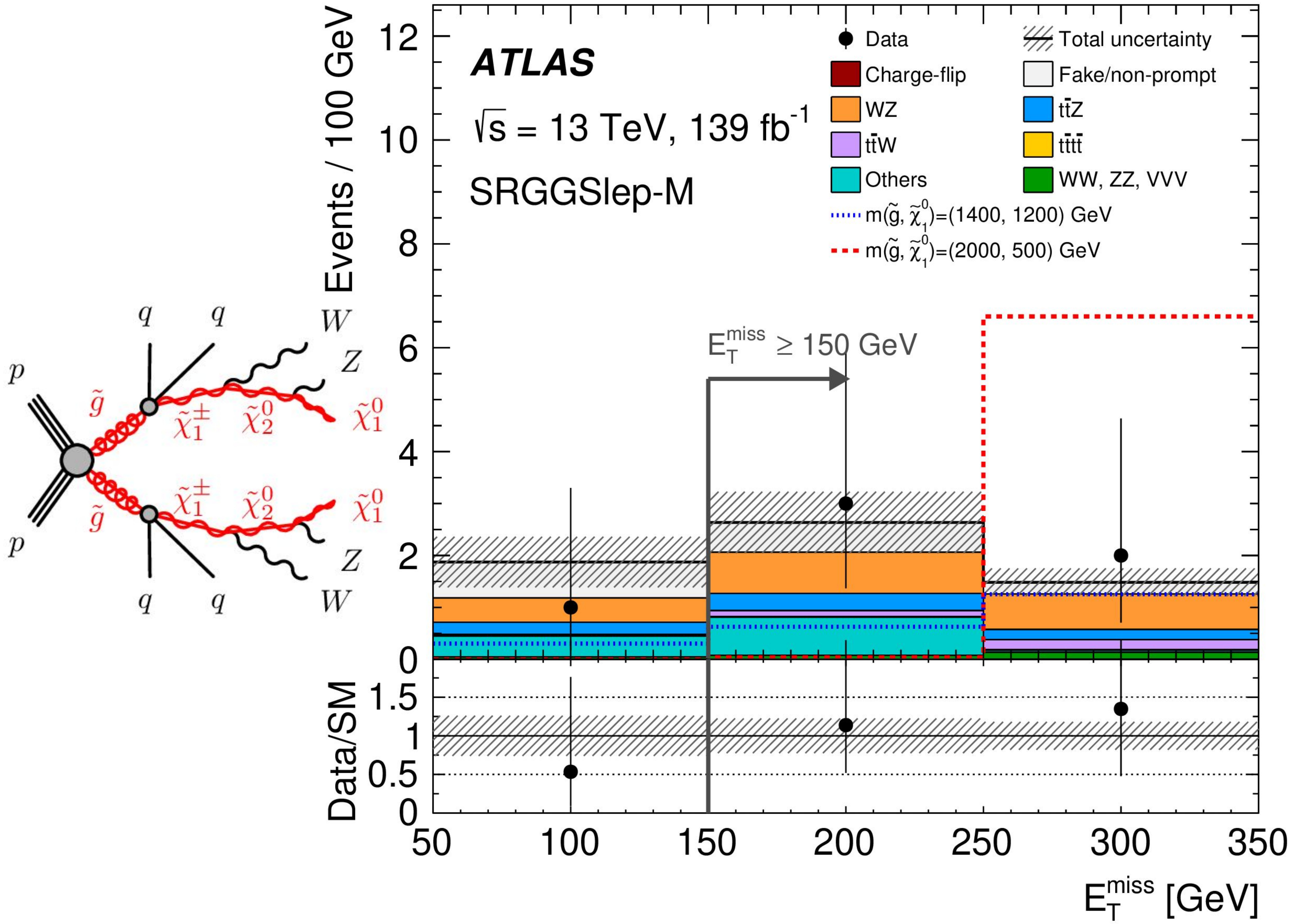
- SUSY searches covering vast regions of SUSY phase space
- Typical main signals in final states are
  - Strong SUSY: 2 same-sign or 3 Leptons
  - Electroweakino: with taus
  - Higgsinos: with b-jets and photons

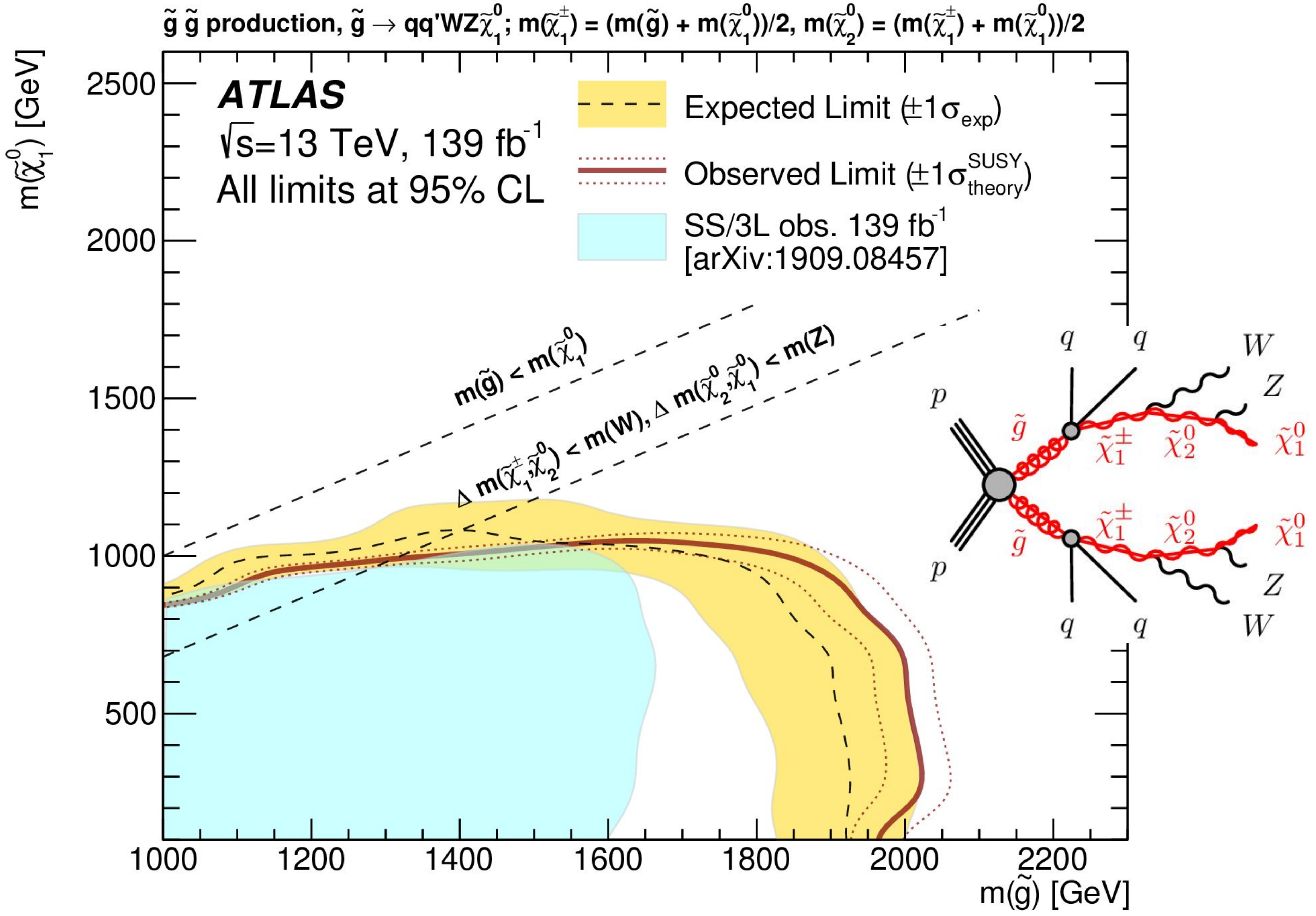
◎ **Forces ⇔ Matter**





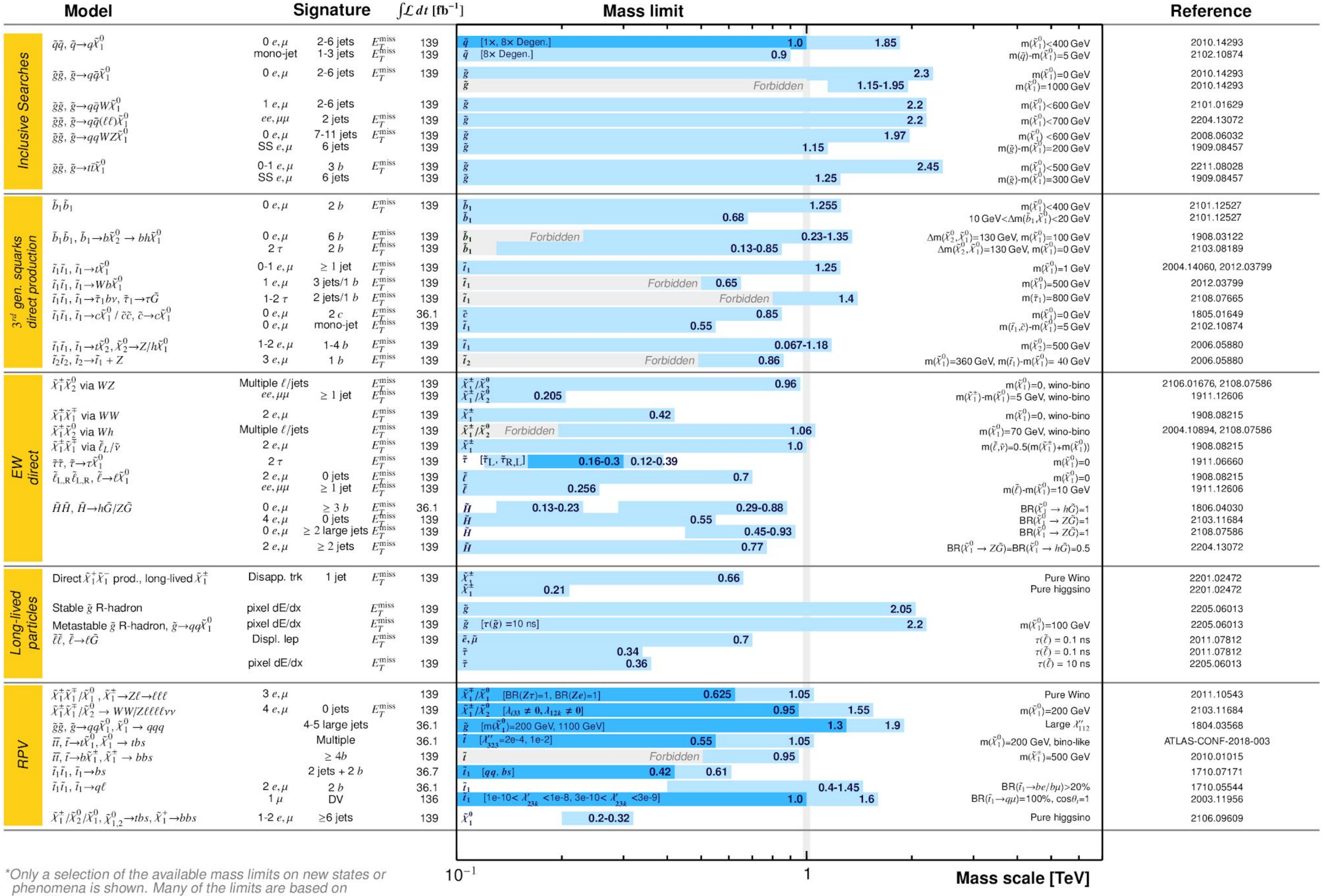
Missing energy with 2 same-sign or 3 leptons





ATLAS SUSY Searches* - 95% CL Lower Limits

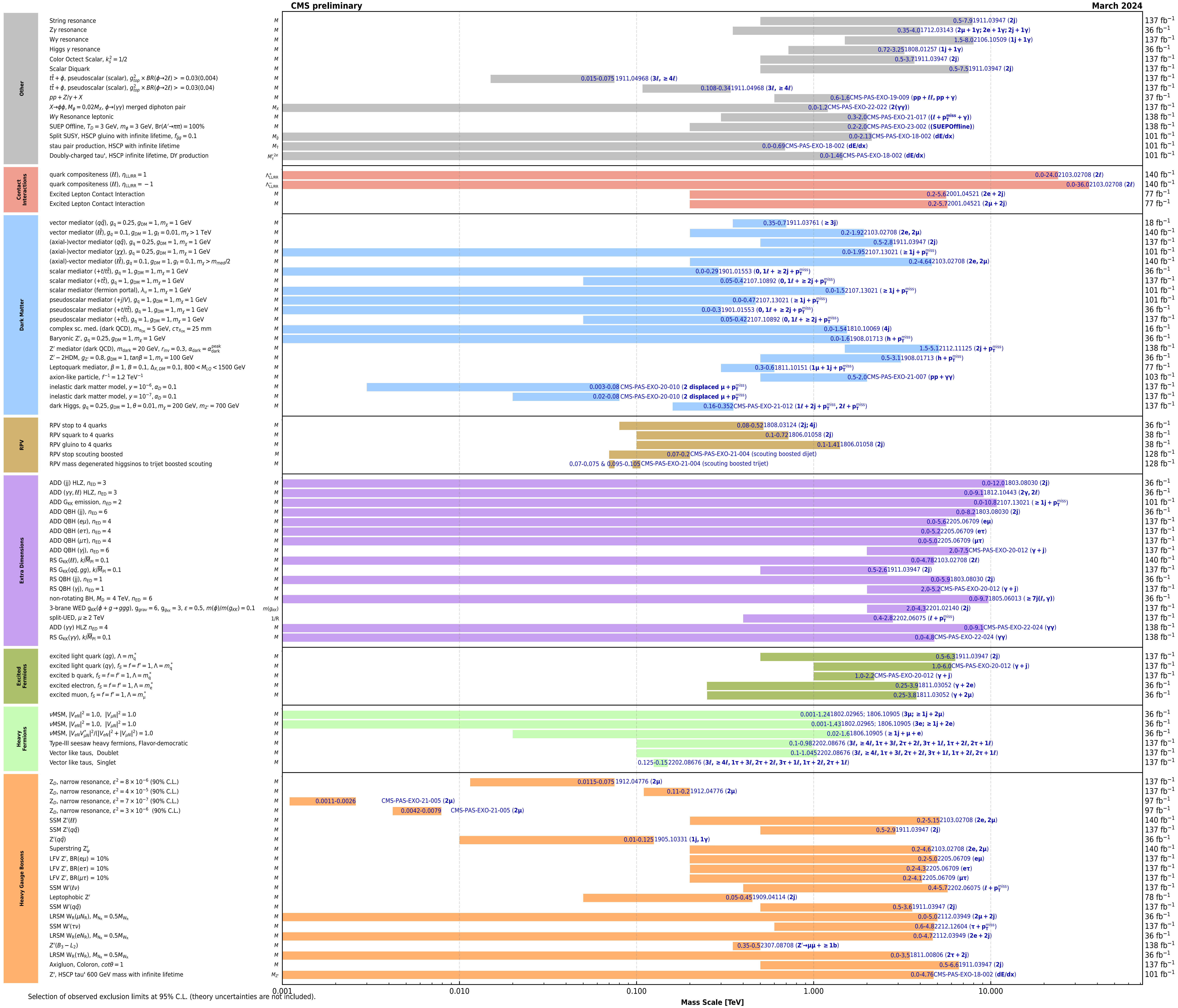
March 2023



	Model	Signature			$\int\mathcal{L}\,dt$ [fb^{-1}]	Mass limit				Reference
Inclusive Searches	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}_1^0$	0 e,μ	2-6 jets	$E_T^{\rm miss}$	139	$\tilde{q}$	[1×, 8× Degen.]	1.0 1.85	m($\tilde{\chi}_1^0$)<400 GeV	2010.14293
		mono-jet	1-3 jets	$E_T^{\rm miss}$	139	$\tilde{q}$	[8× Degen.]	0.9	m($\tilde{q}$)-m($\tilde{\chi}_1^0$)=5 GeV	2102.10874
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}\tilde{\chi}_1^0$	0 e,μ	2-6 jets	$E_T^{\rm miss}$	139	$\tilde{g}$		2.3	m($\tilde{\chi}_1^0$)=0 GeV	2010.14293
						$\tilde{g}$	Forbidden	1.15-1.95	m($\tilde{\chi}_1^0$)=1000 GeV	2010.14293
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}W\tilde{\chi}_1^0$	1 e,μ	2-6 jets		139	$\tilde{g}$		2.2	m($\tilde{\chi}_1^0$)<600 GeV	2101.01629
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}(\ell\ell)\tilde{\chi}_1^0$	$ee,\mu\mu$	2 jets	$E_T^{\rm miss}$	139	$\tilde{g}$		2.2	m($\tilde{\chi}_1^0$)<700 GeV	2204.13072
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qqWZ\tilde{\chi}_1^0$	0 e,μ	7-11 jets	$E_T^{\rm miss}$	139	$\tilde{g}$		1.97	m($\tilde{\chi}_1^0$) <600 GeV	2008.06032
		SS e,μ	6 jets		139	$\tilde{g}$		1.15	m($\tilde{g}$)-m($\tilde{\chi}_1^0$)=200 GeV	1909.08457
	$\tilde{g}\tilde{g}$, $\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0-1 e,μ	3 b	$E_T^{\rm miss}$	139	$\tilde{g}$		2.45	m($\tilde{\chi}_1^0$)<500 GeV	2211.08028
		SS e,μ	6 jets		139	$\tilde{g}$		1.25	m($\tilde{g}$)-m($\tilde{\chi}_1^0$)=300 GeV	1909.08457
3^{rd} gen. squarks direct production	$\tilde{b}_1\tilde{b}_1$	0 e,μ	2 b	$E_T^{\rm miss}$	139	$\tilde{b}_1$		1.255	m($\tilde{\chi}_1^0$)<400 GeV	2101.12527
						$\tilde{b}_1$		0.68	10 GeV<Δm($\tilde{b}_1$,$\tilde{\chi}_1^0$)<20 GeV	2101.12527
	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to b\tilde{\chi}_2^0\to bh\tilde{\chi}_1^0$	0 e,μ	6 b	$E_T^{\rm miss}$	139	$\tilde{b}_1$	Forbidden	0.23-1.35	Δm($\tilde{\chi}_2^0$,$\tilde{\chi}_1^0$)=130 GeV, m($\tilde{\chi}_1^0$)=100 GeV	1908.03122
		2 τ	2 b	$E_T^{\rm miss}$	139	$\tilde{b}_1$		0.13-0.85	Δm($\tilde{\chi}_2^0$,$\tilde{\chi}_1^0$)=130 GeV, m($\tilde{\chi}_1^0$)=0 GeV	2103.08189
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to t\tilde{\chi}_1^0$	0-1 e,μ	≥ 1 jet	$E_T^{\rm miss}$	139	$\tilde{t}_1$		1.25	m($\tilde{\chi}_1^0$)=1 GeV	2004.14060, 2012.03799
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to Wb\tilde{\chi}_1^0$	1 e,μ	3 jets/1 b	$E_T^{\rm miss}$	139	$\tilde{t}_1$	Forbidden	0.65	m($\tilde{\chi}_1^0$)=500 GeV	2012.03799
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to\tilde{\tau}_1 b\nu$, $\tilde{\tau}_1\to\tau\tilde{G}$	1-2 τ	2 jets/1 b	$E_T^{\rm miss}$	139	$\tilde{t}_1$	Forbidden	1.4	m($\tilde{\tau}_1$)=800 GeV	2108.07665
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to c\tilde{\chi}_1^0$ / $\tilde{c}\tilde{c}$, $\tilde{c}\to c\tilde{\chi}_1^0$	0 e,μ	2 c	$E_T^{\rm miss}$	36.1	$\tilde{c}$		0.85	m($\tilde{\chi}_1^0$)=0 GeV	1805.01649
		0 e,μ	mono-jet	$E_T^{\rm miss}$	139	$\tilde{t}_1$		0.55	m($\tilde{t}_1$,$\tilde{c}$)-m($\tilde{\chi}_1^0$)=5 GeV	2102.10874
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to t\tilde{\chi}_2^0$, $\tilde{\chi}_2^0\to Z/h\tilde{\chi}_1^0$	1-2 e,μ	1-4 b	$E_T^{\rm miss}$	139	$\tilde{t}_1$		0.067-1.18	m($\tilde{\chi}_2^0$)=500 GeV	2006.05880
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\to\tilde{t}_1+Z$	3 e,μ	1 b	$E_T^{\rm miss}$	139	$\tilde{t}_2$	Forbidden	0.86	m($\tilde{\chi}_1^0$)=360 GeV, m($\tilde{t}_1$)-m($\tilde{\chi}_1^0$)= 40 GeV	2006.05880
EW direct	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ via WZ	Multiple ℓ/jets		$E_T^{\rm miss}$	139	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$		0.96	m($\tilde{\chi}_1^0$)=0, wino-bino	2106.01676, 2108.07586
		$ee,\mu\mu$	≥ 1 jet	$E_T^{\rm miss}$	139	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$		0.205	m($\tilde{\chi}_1^\pm$)-m($\tilde{\chi}_1^0$)=5 GeV, wino-bino	1911.12606
	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp$ via WW	2 e,μ		$E_T^{\rm miss}$	139	$\tilde{\chi}_1^\pm$		0.42	m($\tilde{\chi}_1^0$)=0, wino-bino	1908.08215
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ via Wh	Multiple ℓ/jets		$E_T^{\rm miss}$	139	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$	Forbidden	1.06	m($\tilde{\chi}_1^0$)=70 GeV, wino-bino	2004.10894, 2108.07586
	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp$ via $\tilde{\ell}_L/\tilde{\nu}$	2 e,μ		$E_T^{\rm miss}$	139	$\tilde{\chi}_1^\pm$		1.0	m($\tilde{\ell}$,$\tilde{\nu}$)=0.5(m($\tilde{\chi}_1^\pm$)+m($\tilde{\chi}_1^0$))	1908.08215
	$\tilde{\tau}\tilde{\tau}$, $\tilde{\tau}\to\tau\tilde{\chi}_1^0$	2 τ		$E_T^{\rm miss}$	139	$\tilde{\tau}$	[$\tilde{\tau}_{\rm L}$, $\tilde{\tau}_{\rm R,L}$]	0.16-0.3 0.12-0.39	m($\tilde{\chi}_1^0$)=0	1911.06660
	$\tilde{\ell}_{\rm L,R}\tilde{\ell}_{\rm L,R}$, $\tilde{\ell}\to\ell\tilde{\chi}_1^0$	2 e,μ	0 jets	$E_T^{\rm miss}$	139	$\tilde{\ell}$		0.7	m($\tilde{\chi}_1^0$)=0	1908.08215
		$ee,\mu\mu$	≥ 1 jet	$E_T^{\rm miss}$	139	$\tilde{\ell}$		0.256	m($\tilde{\ell}$)-m($\tilde{\chi}_1^0$)=10 GeV	1911.12606
	$\tilde{H}\tilde{H}$, $\tilde{H}\to h\tilde{G}/Z\tilde{G}$	0 e,μ	≥ 3 b	$E_T^{\rm miss}$	36.1	$\tilde{H}$		0.13-0.23 0.29-0.88	BR($\tilde{\chi}_1^0\to h\tilde{G}$)=1	1806.04030
		4 e,μ	0 jets	$E_T^{\rm miss}$	139	$\tilde{H}$		0.55	BR($\tilde{\chi}_1^0\to Z\tilde{G}$)=1	2103.11684
		0 e,μ	≥ 2 large jets	$E_T^{\rm miss}$	139	$\tilde{H}$		0.45-0.93	BR($\tilde{\chi}_1^0\to Z\tilde{G}$)=1	2108.07586
		2 e,μ	≥ 2 jets	$E_T^{\rm miss}$	139	$\tilde{H}$		0.77	BR($\tilde{\chi}_1^0\to Z\tilde{G}$)=BR($\tilde{\chi}_1^0\to h\tilde{G}$)=0.5	2204.13072
Long-lived particles	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$	Disapp. trk	1 jet	$E_T^{\rm miss}$	139	$\tilde{\chi}_1^\pm$		0.66	Pure Wino	2201.02472
						$\tilde{\chi}_1^\pm$		0.21	Pure higgsino	2201.02472
	Stable $\tilde{g}$ R-hadron	pixel dE/dx		$E_T^{\rm miss}$	139	$\tilde{g}$		2.05		2205.06013
	Metastable $\tilde{g}$ R-hadron, $\tilde{g}\to qq\tilde{\chi}_1^0$	pixel dE/dx		$E_T^{\rm miss}$	139	$\tilde{g}$	[$\tau(\tilde{g})$ =10 ns]	2.2	m($\tilde{\chi}_1^0$)=100 GeV	2205.06013
	$\tilde{\ell}\tilde{\ell}$, $\tilde{\ell}\to\ell\tilde{G}$	Displ. lep		$E_T^{\rm miss}$	139	$\tilde{e}$, $\tilde{\mu}$		0.7	$\tau(\tilde{\ell})$ = 0.1 ns	2011.07812
						$\tilde{\tau}$		0.34	$\tau(\tilde{\ell})$ = 0.1 ns	2011.07812
		pixel dE/dx		$E_T^{\rm miss}$	139	$\tilde{\tau}$		0.36	$\tau(\tilde{\ell})$ = 10 ns	2205.06013
RPV	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp/\tilde{\chi}_1^0$, $\tilde{\chi}_1^\pm\to Z\ell\to\ell\ell\ell$	3 e,μ			139	$\tilde{\chi}_1^\mp/\tilde{\chi}_1^0$	[BR($Z\tau$)=1, BR(Ze)=1]	0.625 1.05	Pure Wino	2011.10543
	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp/\tilde{\chi}_2^0\to WW/Z\ell\ell\ell\ell\nu\nu$	4 e,μ	0 jets	$E_T^{\rm miss}$	139	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$	[$\lambda_{i33}\neq 0$, $\lambda_{12k}\neq 0$]	0.95 1.55	m($\tilde{\chi}_1^0$)=200 GeV	2103.11684
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to qqq$		4-5 large jets		36.1	$\tilde{g}$	[m($\tilde{\chi}_1^0$)=200 GeV, 1100 GeV]	1.3 1.9	Large λ''_{112}	1804.03568
	$\tilde{t}\tilde{t}$, $\tilde{t}\to t\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to tbs$		Multiple		36.1	$\tilde{t}$	[λ''_{323}=2e-4, 1e-2]	0.55 1.05	m($\tilde{\chi}_1^0$)=200 GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde{t}\tilde{t}$, $\tilde{t}\to b\tilde{\chi}_1^\pm$, $\tilde{\chi}_1^\pm\to bbs$		≥ 4b		139	$\tilde{t}$	Forbidden	0.95	m($\tilde{\chi}_1^\pm$)=500 GeV	2010.01015
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to bs$		2 jets + 2 b		36.7	$\tilde{t}_1$	[qq, bs]	0.42 0.61		1710.07171
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to q\ell$	2 e,μ	2 b		36.1	$\tilde{t}_1$		0.4-1.45	BR($\tilde{t}_1\to be/b\mu$)>20%	1710.05544
		1 μ	DV		136	$\tilde{t}_1$	[1e-10< λ'_{23k} <1e-8, 3e-10< λ'_{23k} <3e-9]	1.0 1.6	BR($\tilde{t}_1\to q\mu$)=100%, cosθ_t=1	2003.11956
	$\tilde{\chi}_1^+/\tilde{\chi}_2^0/\tilde{\chi}_1^0$, $\tilde{\chi}_{1,2}^0\to tbs$, $\tilde{\chi}_1^+\to bbs$	1-2 e,μ	≥6 jets		139	$\tilde{\chi}_1^0$		0.2-0.32	Pure higgsino	2106.09609

*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

Overview of CMS EXO results



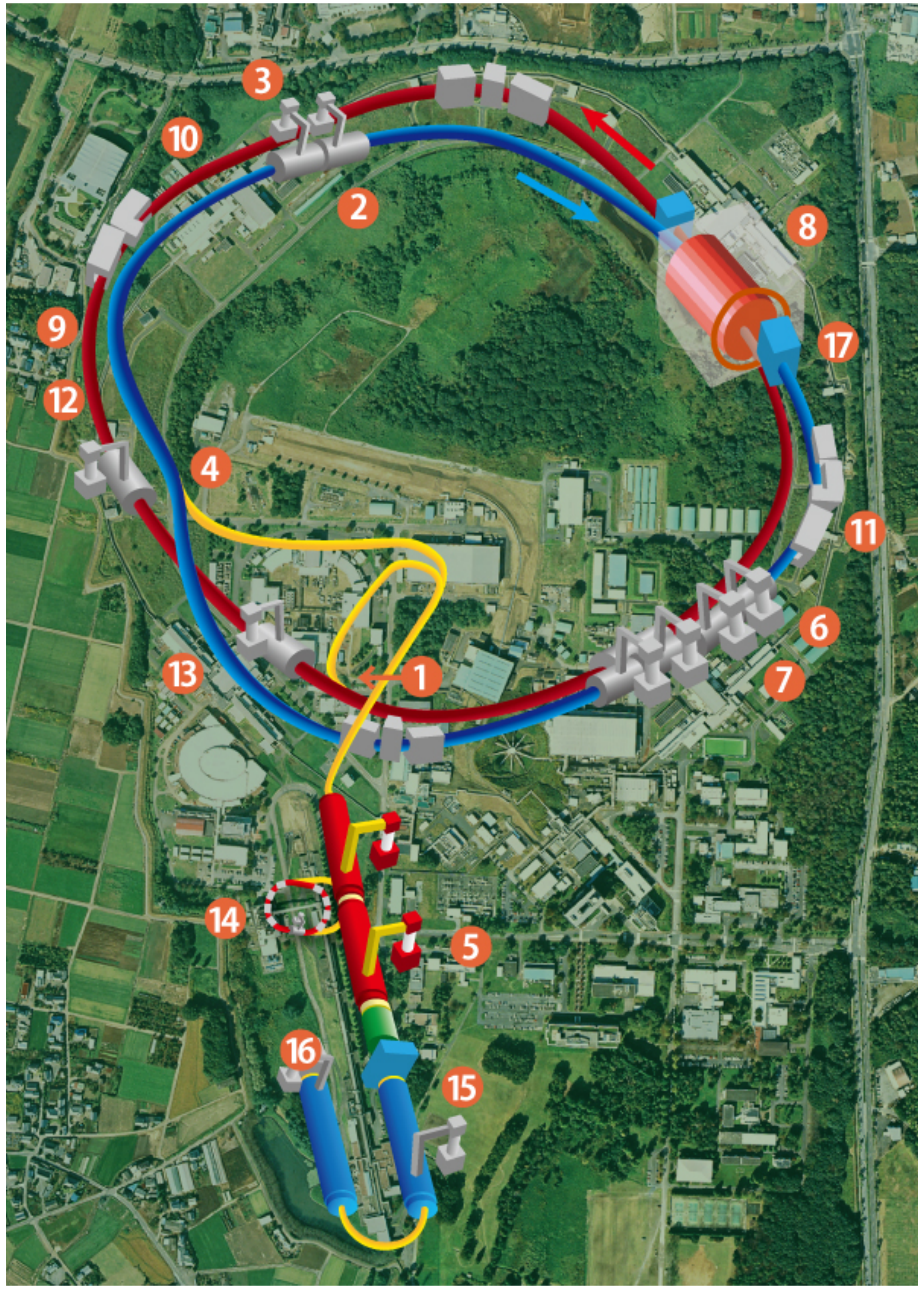
Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included).

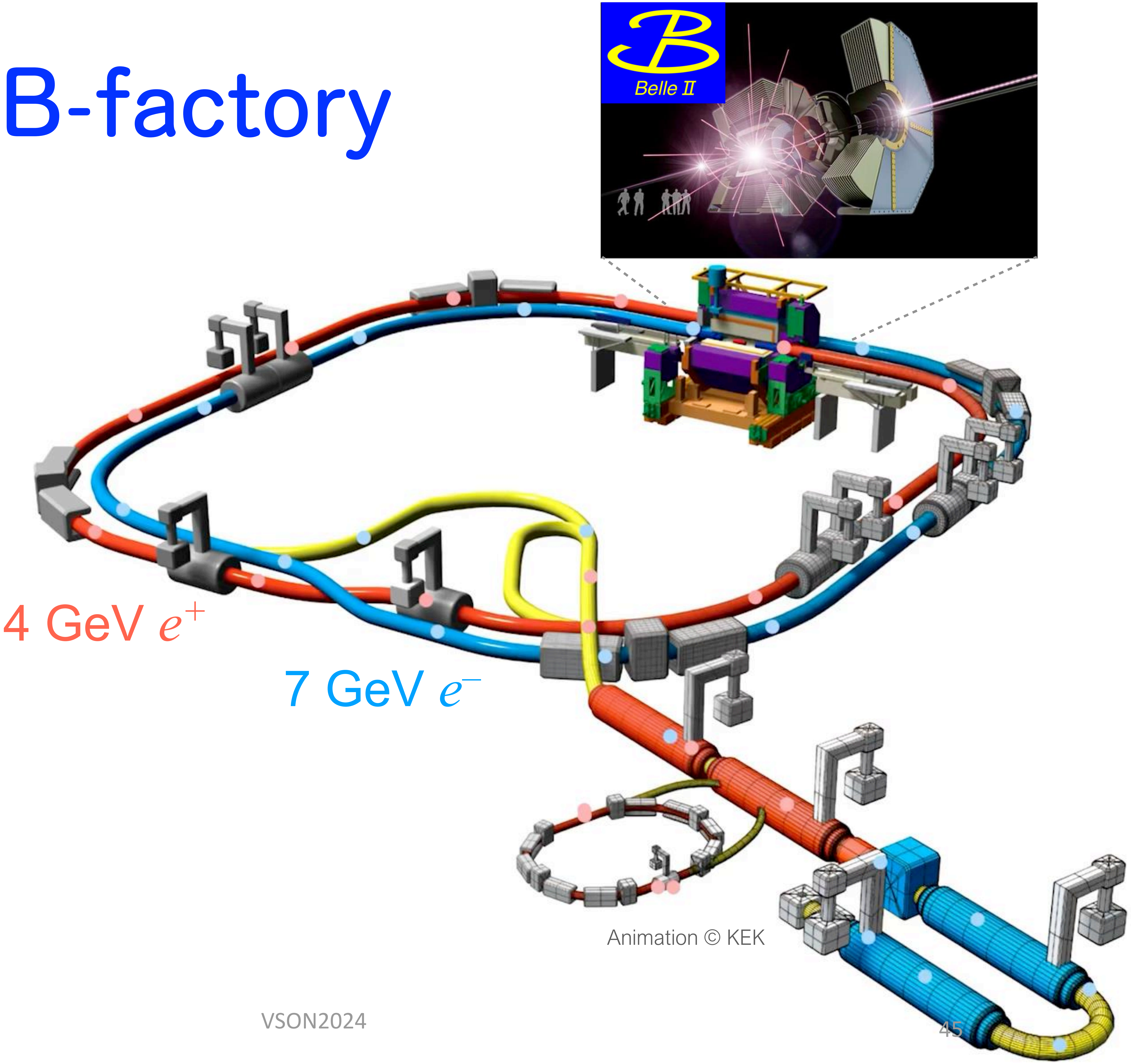
2. Intensity Frontier

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, JSNS^2, Super-K, Hyper-K, KAGLA, KamLAND, (ILC)
- IHEP (China)
  - BESSIII, JUNO, (CEPC)
- *Cosmology and Astro-particle experiments*

B-factory





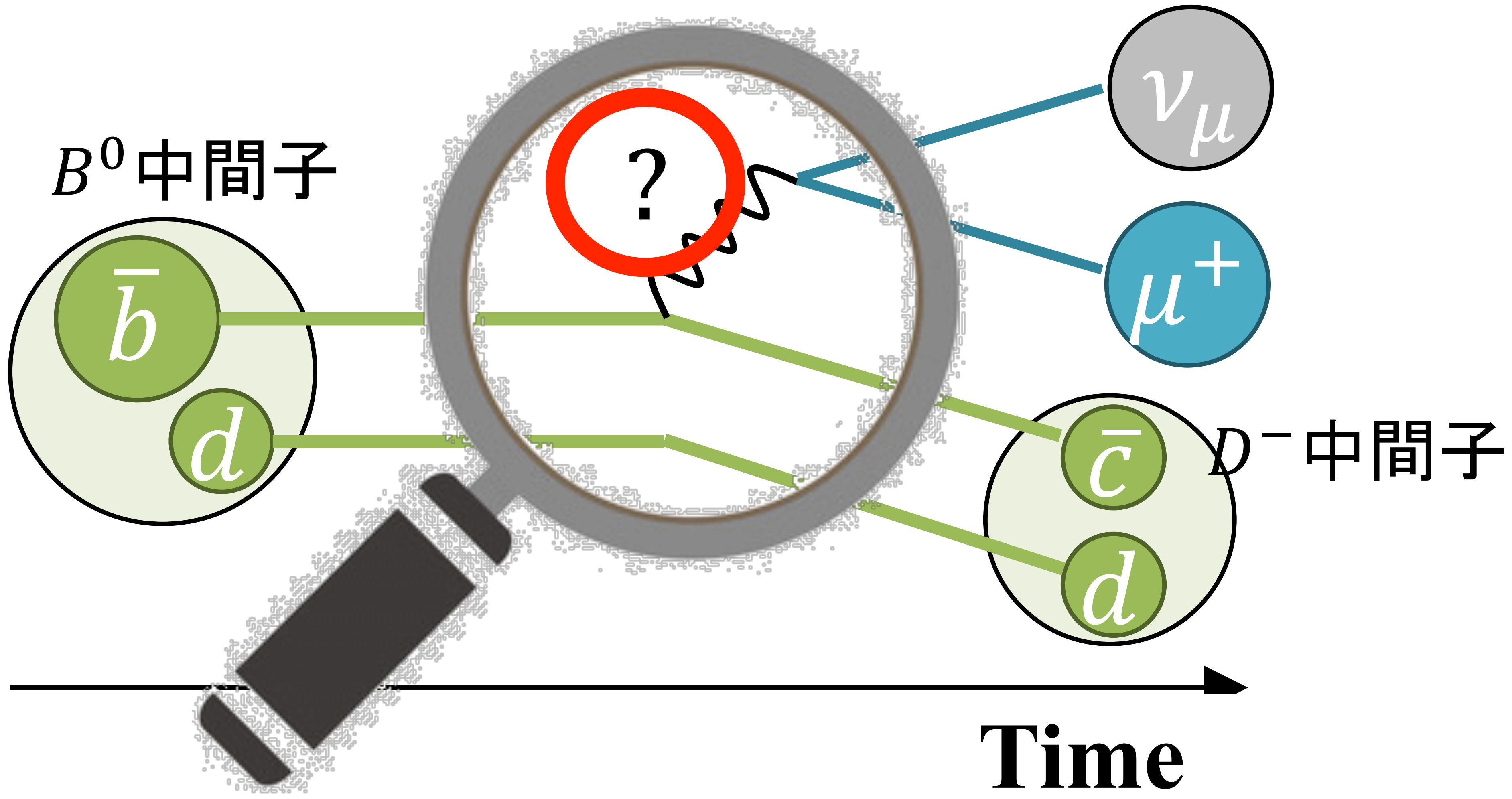
4 GeV e^+

7 GeV e^-

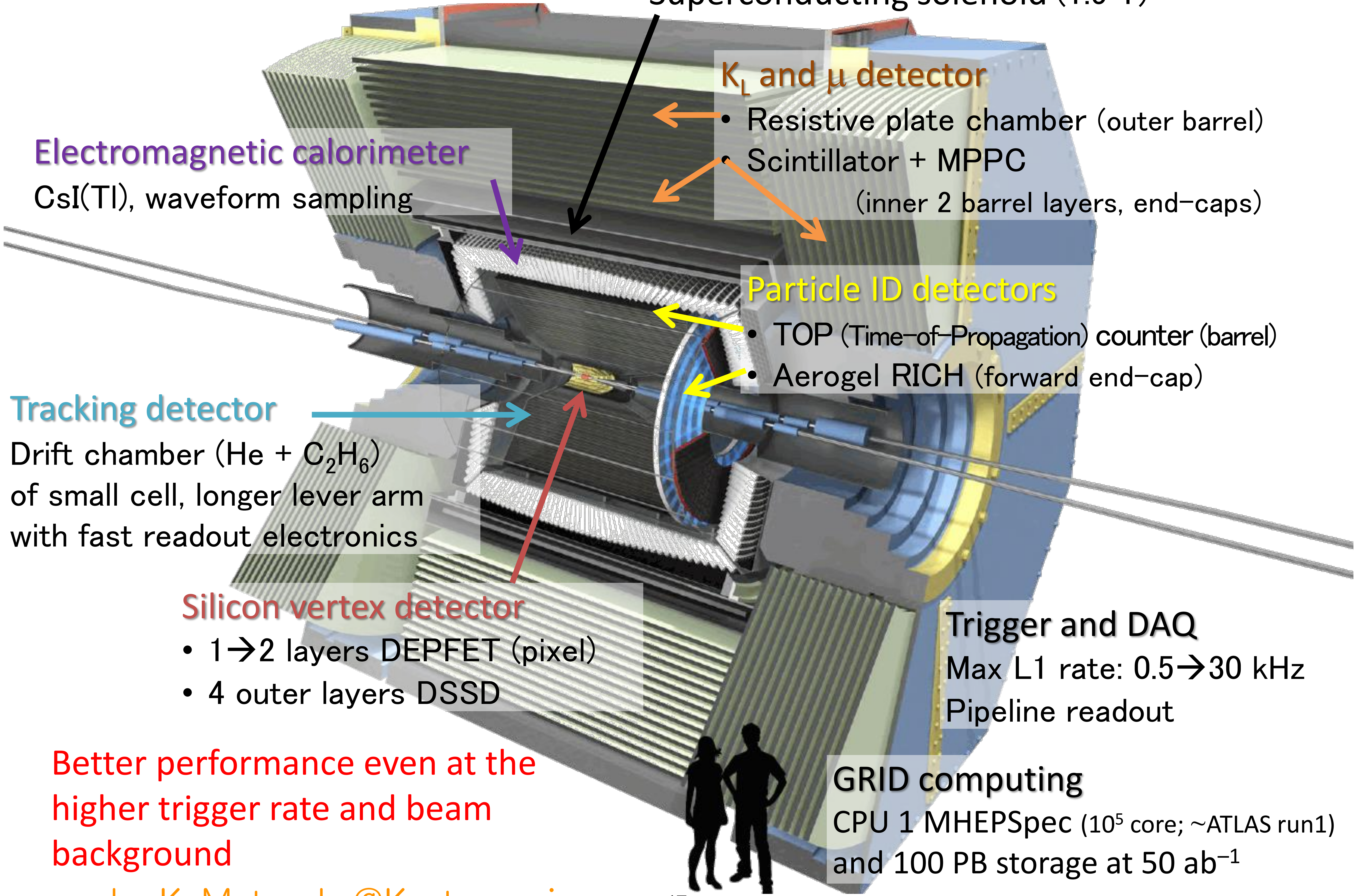
Animation © KEK

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

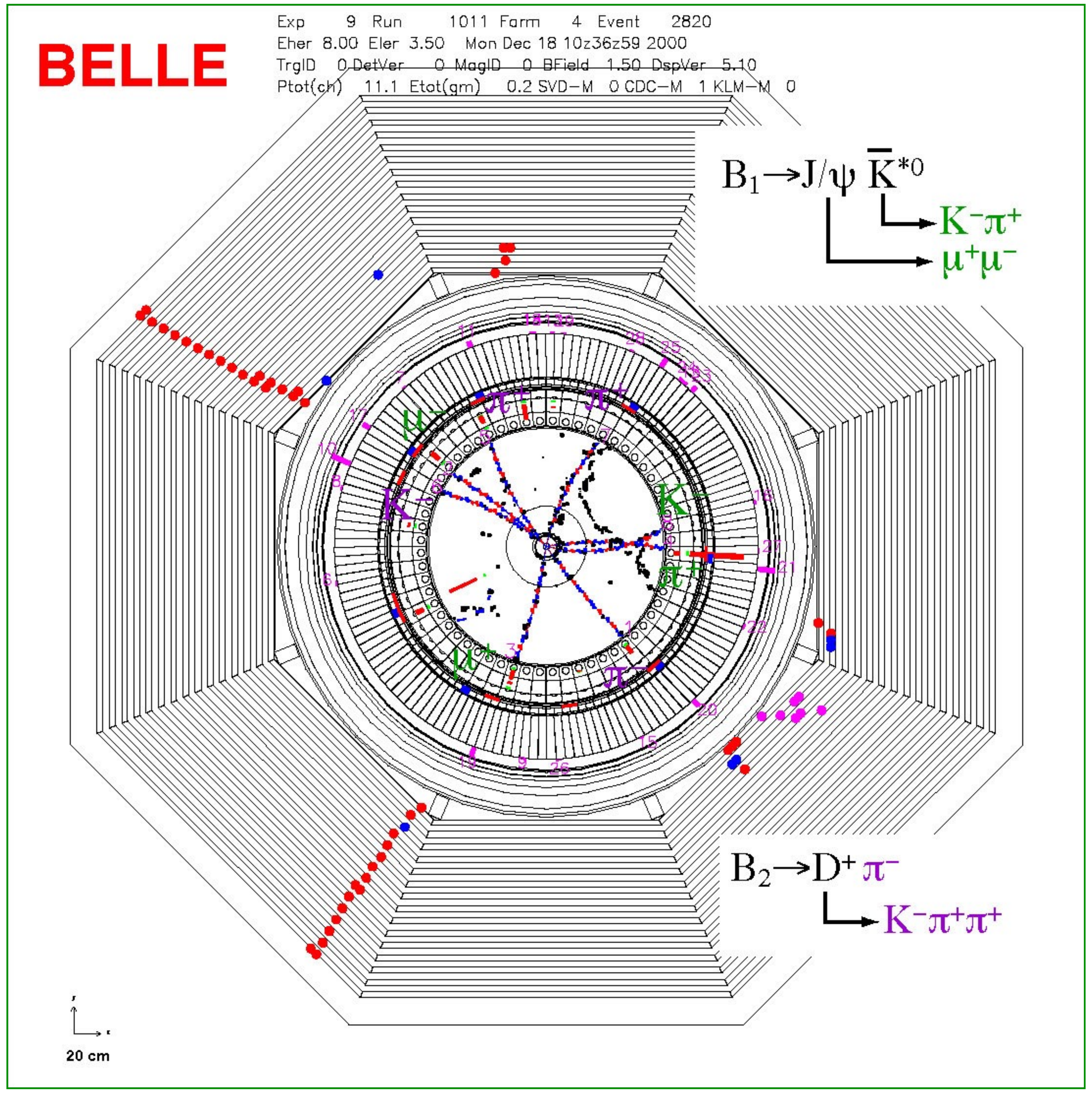
Max L1 rate: 0.5→30 kHz
Pipeline readout

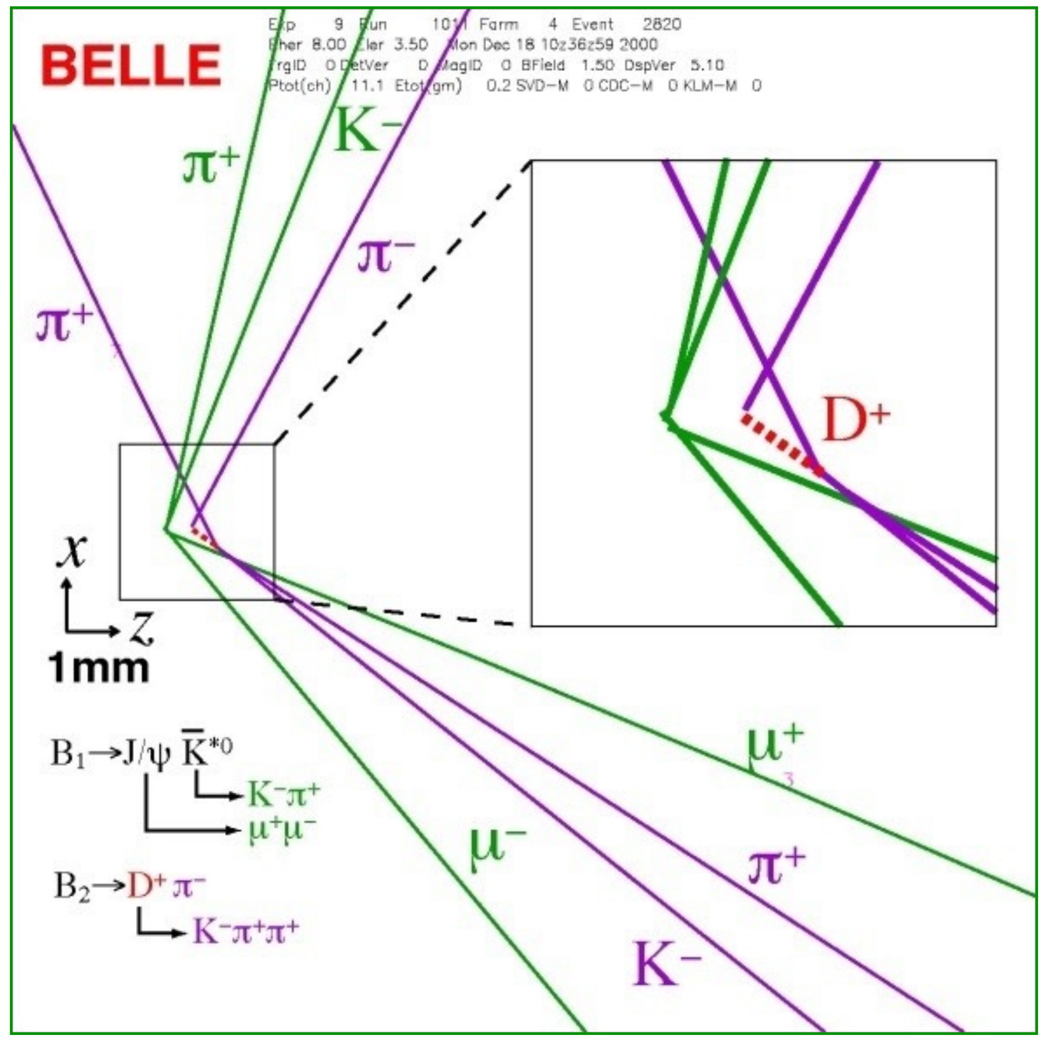
GRID computing

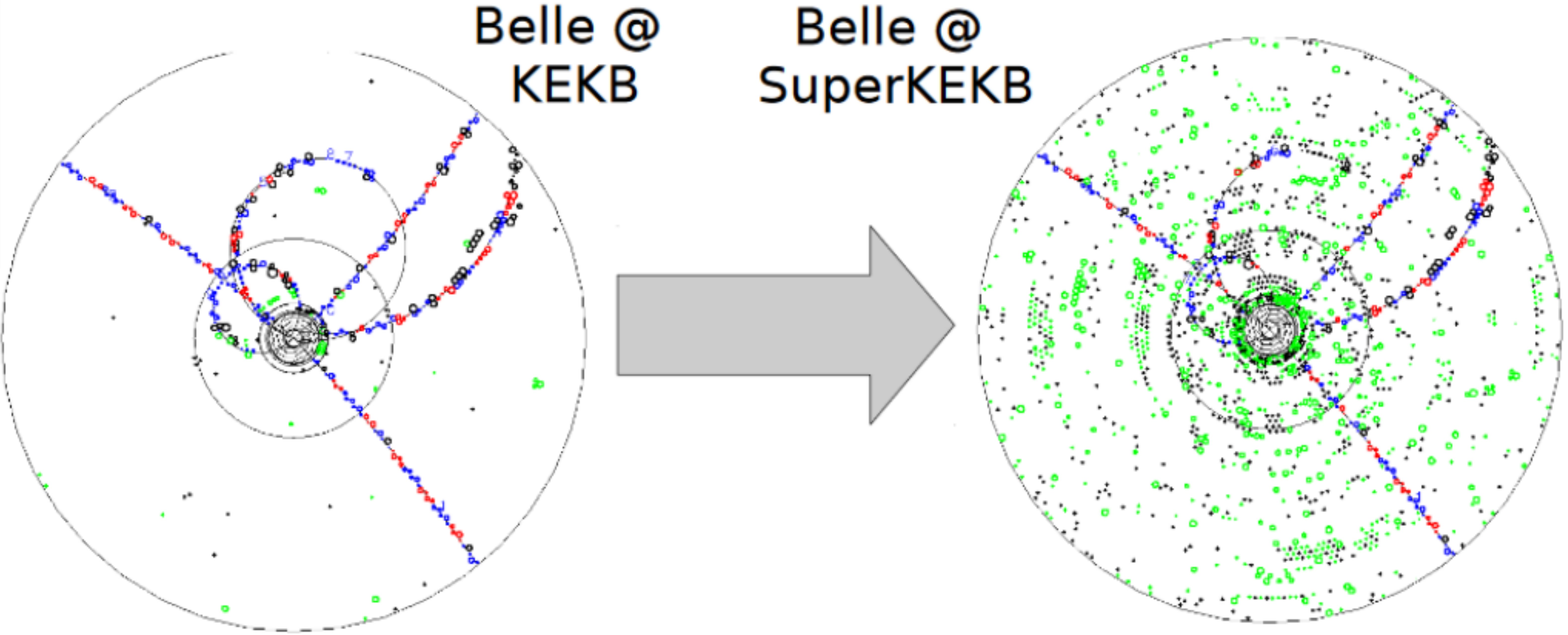
CPU 1 MHEPSpec (10^5 core; ~ATLAS run1)
and 100 PB storage at 50 ab^{-1}

Better performance even at the higher trigger rate and beam background

by K. Matsuoka@Kyoto seminar





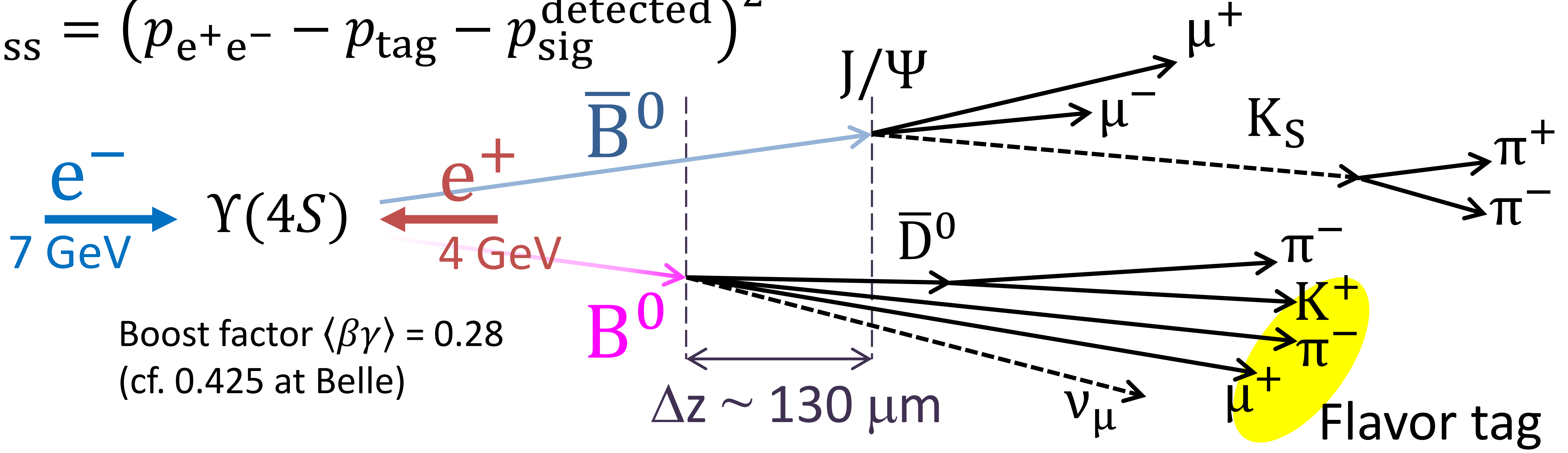


The same event with simulated background at 8 x 10^{35} $cm^{-2}s^{-1}$

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
  - $m_{\mathrm{miss}}^2 = \left(p_{\mathrm{e^+e^-}} - p_{\mathrm{tag}} - p_{\mathrm{sig}}^{\mathrm{detected}}\right)^2$



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

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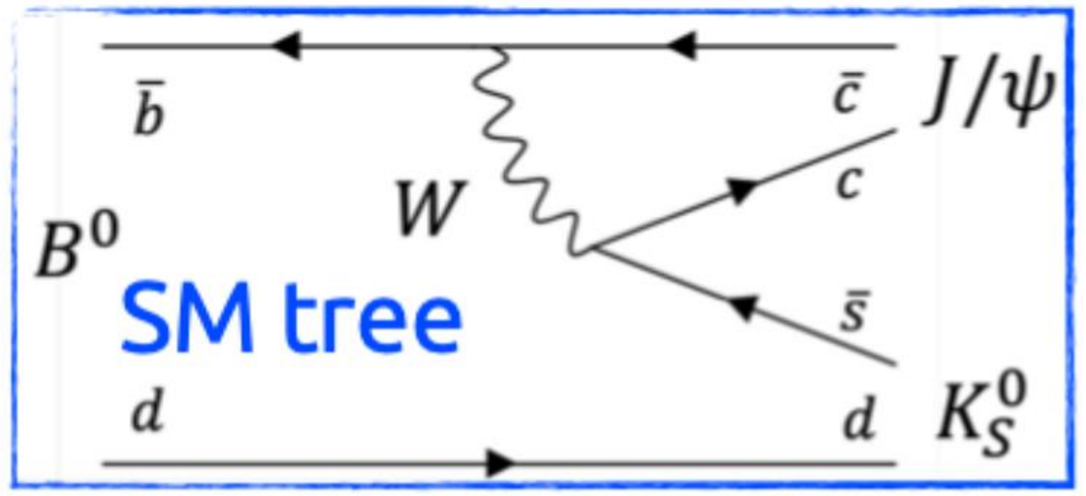
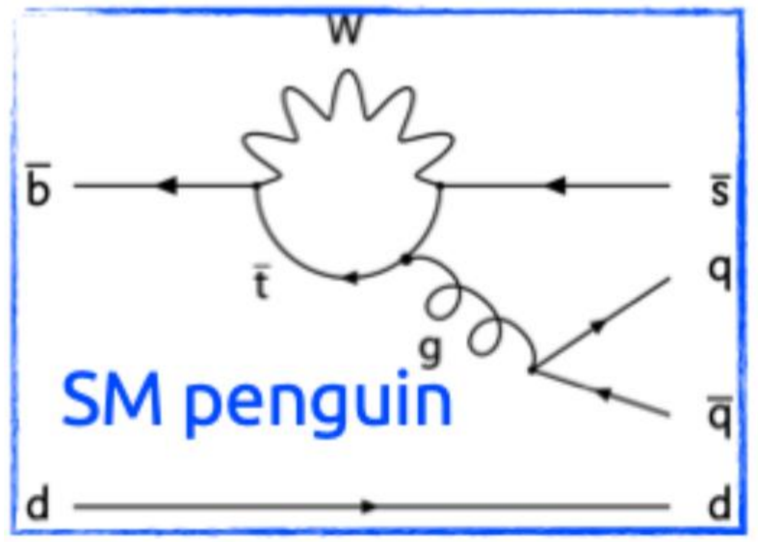
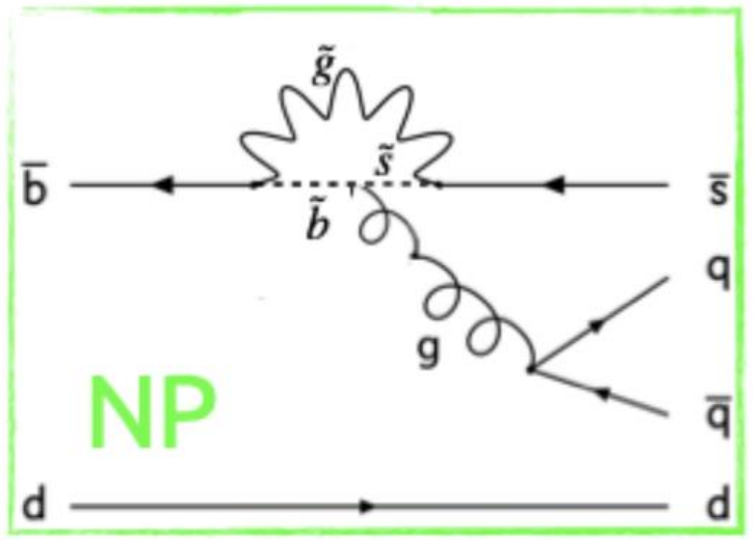
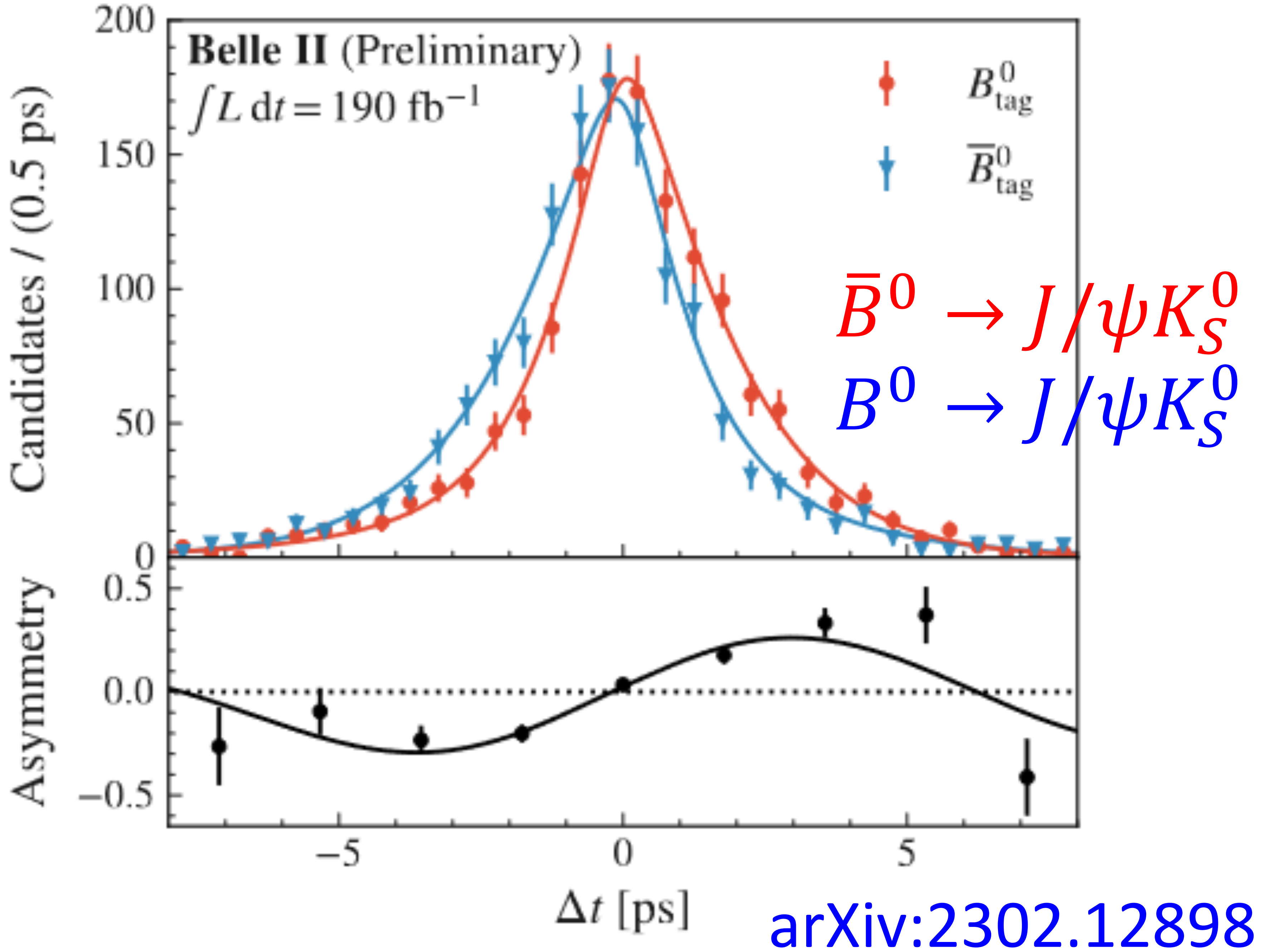
CP Violation in B decays

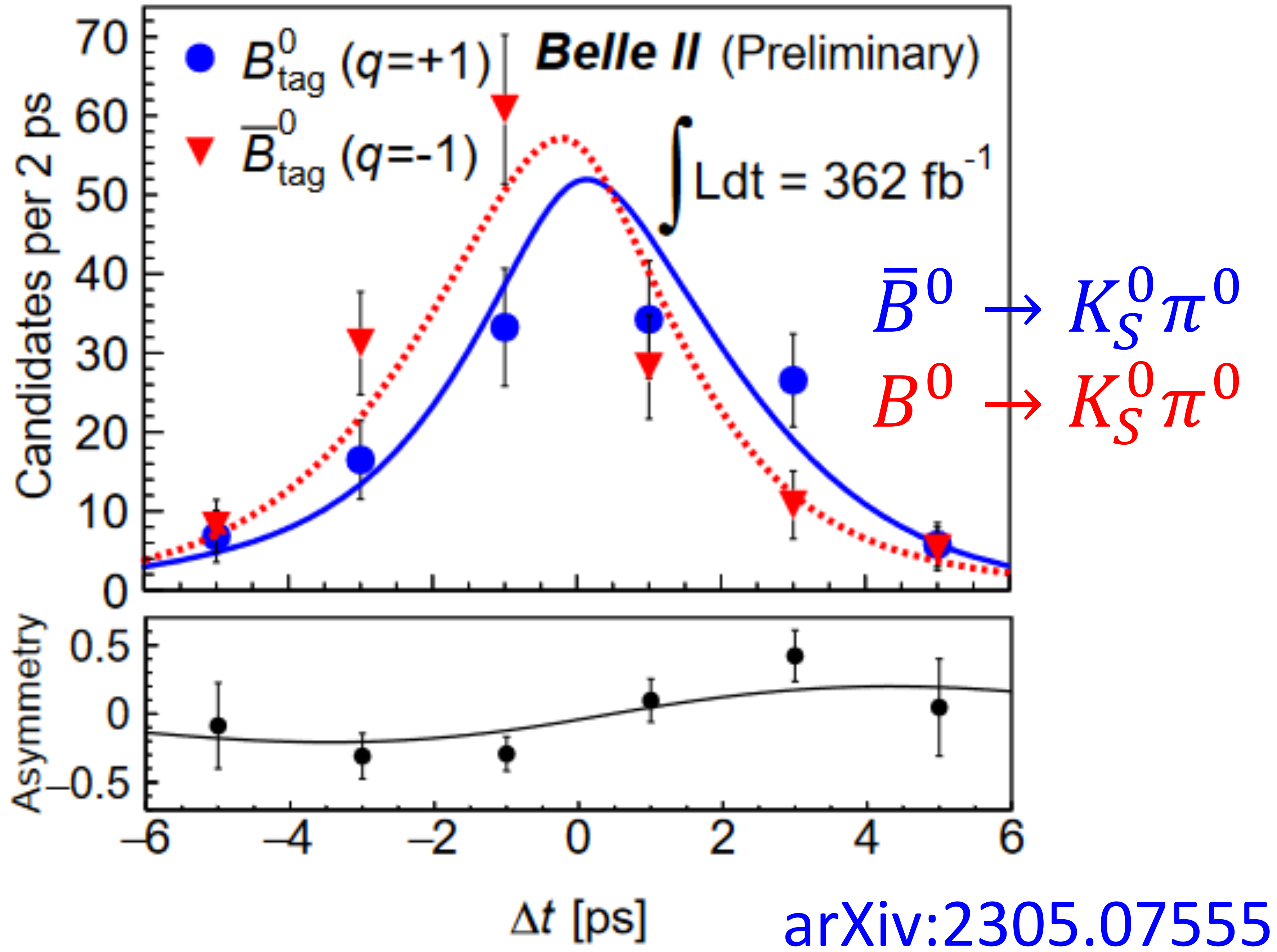








arXiv:2302.12898



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: $S = 0.67 \pm 0.31 \pm 0.08$

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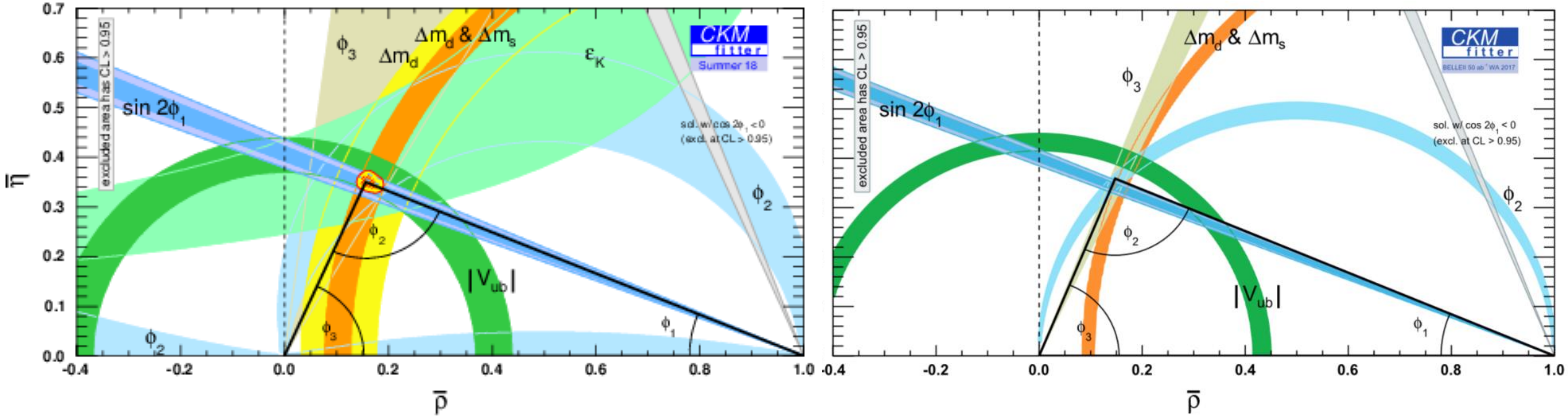
Precision measurements

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.

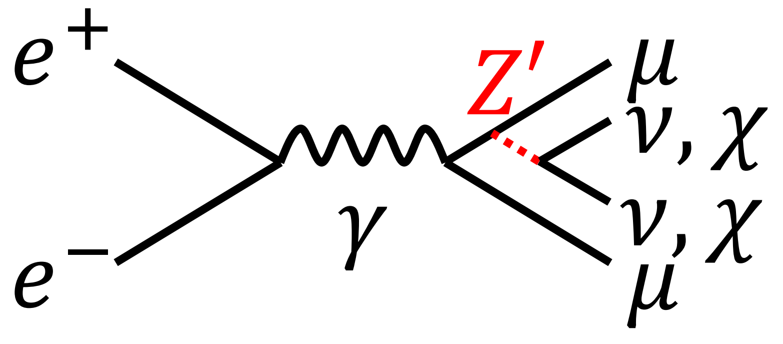
→ Search for non-standard effects that can only appear as small corrections to the Standard Model.

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

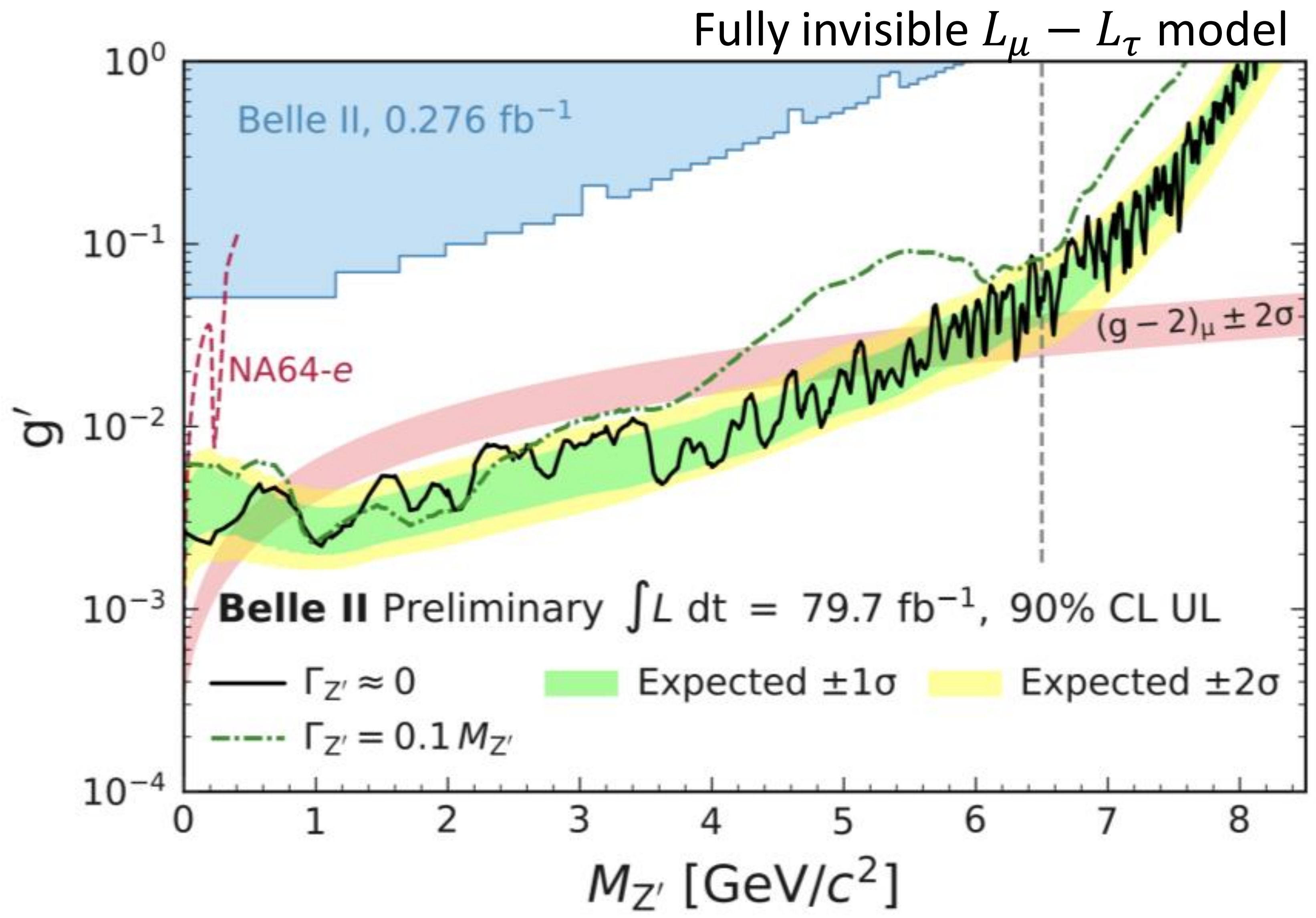
e.g. $\Lambda < \sim 1000$ TeV in B^0 mixing ($\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \frac{1}{\Lambda^2}\mathcal{O}_{\Delta F=2}$) [arXiv:1302.0661]

Search for Dark particles

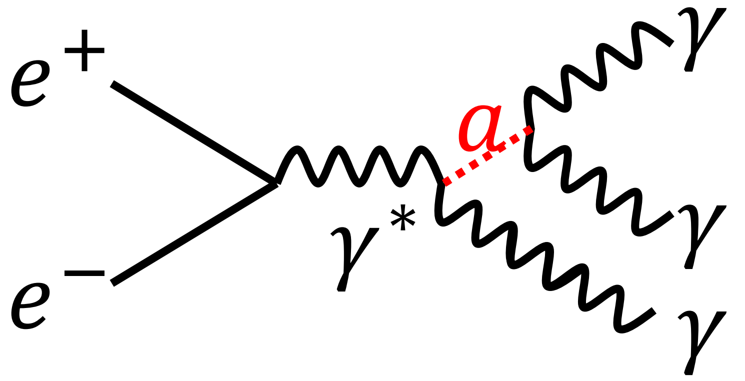
- Z' or LFV Z' to invisible



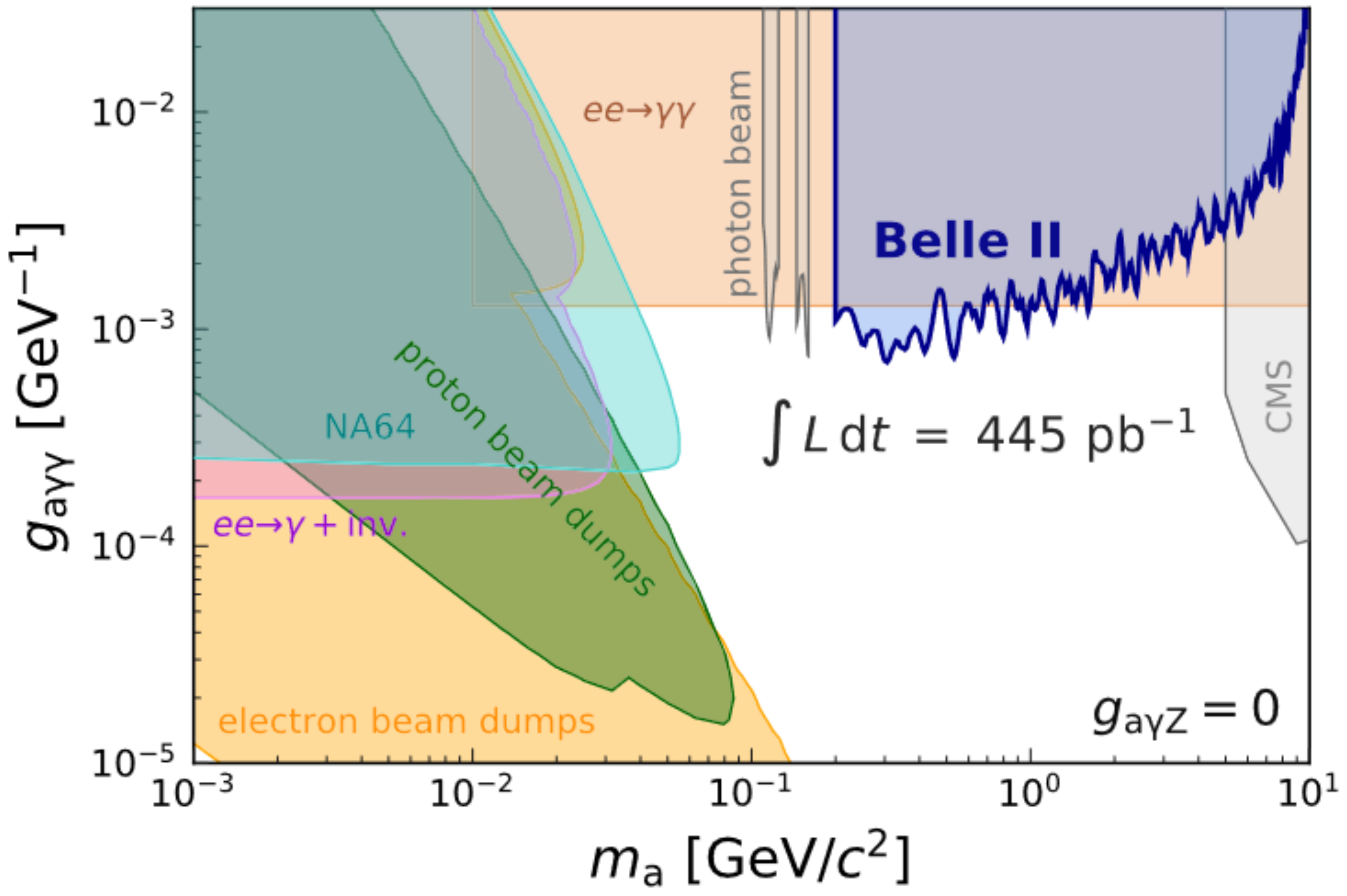
PRL 124, 141801 (2020)
… 1st Belle II physics paper
arXiv:2212.03066 … update, 2022



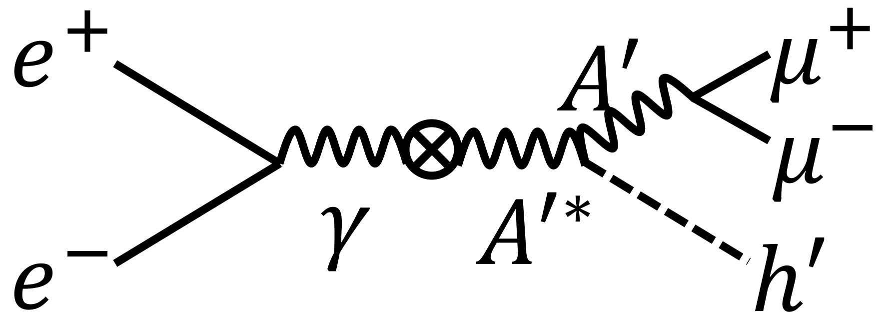
- Axion Like Particle



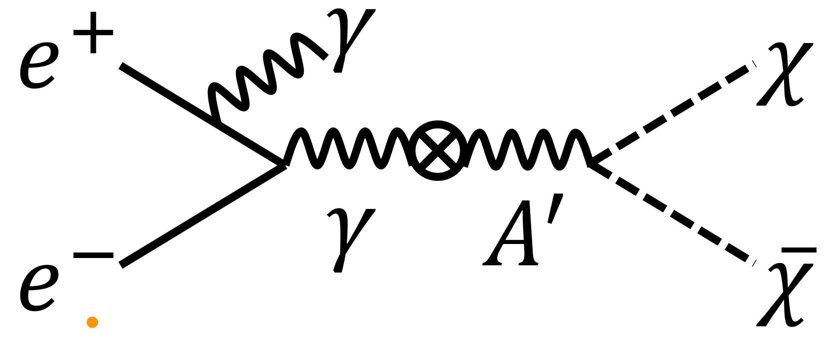
PRL 125, 161806 (2020)
… 2nd Belle II physics paper



- 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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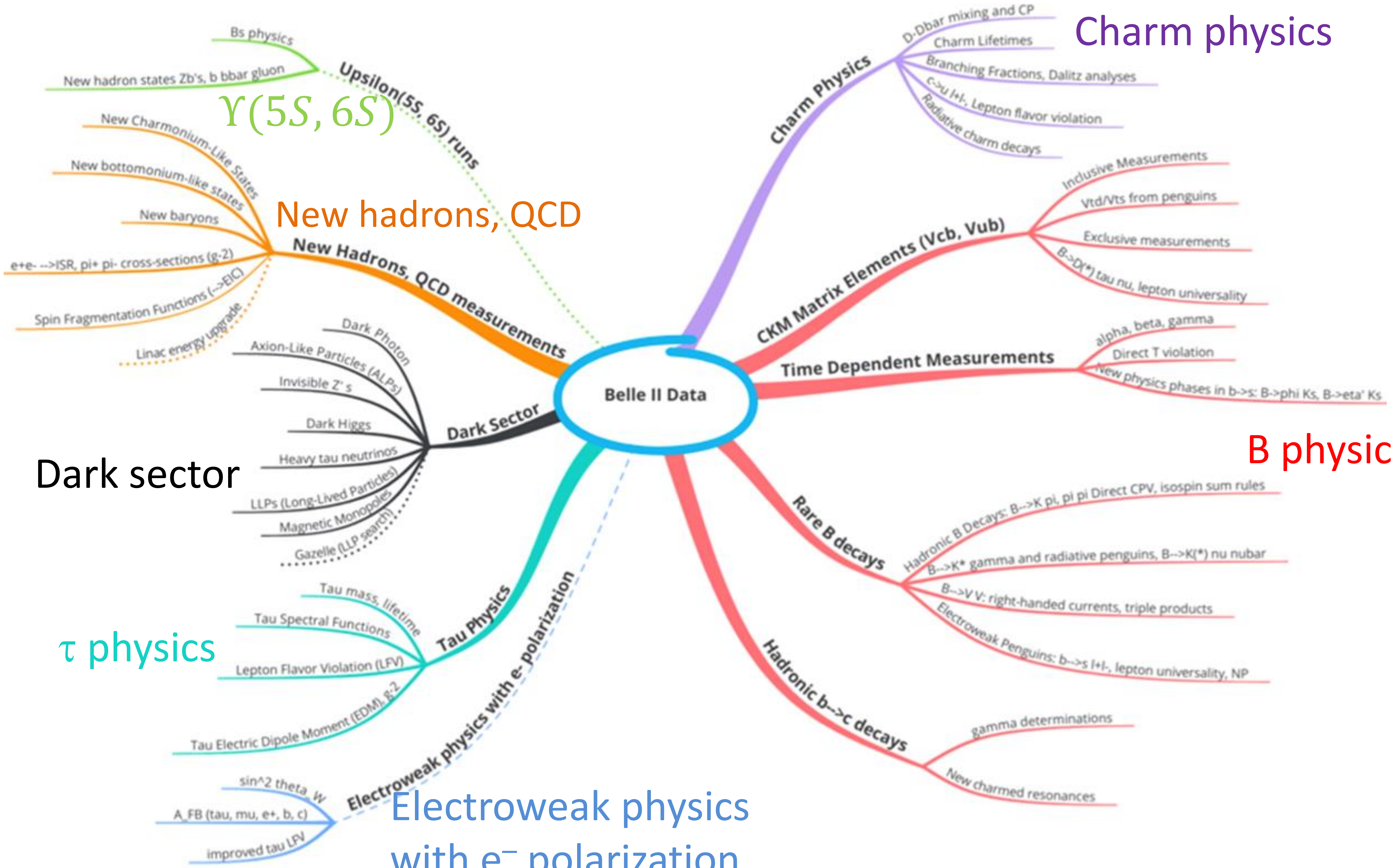

Charm physics

$\Upsilon(5S, 6S)$

New hadrons, QCD

B physics

Dark sector

τ physics

Electroweak physics
with e⁻ polarization

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